Technical Design Report
on the Collector Ring

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Preface

In 2001, GSI, together with a large international science community, presented a Conceptual Design Report for a major new international Facility for Antiproton and Ion Research (FAIR) at Darmstadt/Germany. Following an in-depth evaluation of the German Wissenschaftsrat conditional approval for construction of FAIR was given in 2003. The approval was contingent upon the condition of international participation and contribution of 25% of total construction cost by the international partners.

In 2006, the International Steering Committee for FAIR (ISC), comprising the FAIR partner states Austria, China, Finland, France, Germany, Great Britain, Greece, India, Italy, Romania, Russia, Slovenia, Spain and Sweden agreed to the scientific case and accelerator infrastructure as outlined in the FAIR Baseline Technical Report (FBTR). This central document provided the technical description, cost, schedule, organizational and management structure and assessment of risk for the FAIR project.

On October 17, 2007, the ISC decided on the realization of the FAIR Start Version without delay according to secure funds. Based on the proposals of the Scientific and Technical Issue Working Group together with the experiment collaborations the scope of the project first phase, FAIR Start Version, was worked out and defined. Already in the Startversion FAIR a unique unprecedented infrastructure for Nuclear- Atomic-, Astrophysics and high density plasma physics will be available that opens new fields in research.

In parallel to the preparatory activities for FAIR research and development for the accelerators and experimental facilities has advanced considerably. A series of Technical Design Reports (TDR), summarizing the actual system design, the status of R&D of key components, and technical aspects of realization for the FAIR accelerators have been composed, based on the ISC resolution and Technical Advisory Committee recommendations.

This TDR describes the actual status of the Collector Ring.

The numbering of chapters follows the systematics of the FAIR work breakdown structure, which was used in FBTR also and in associated documents as the costbook. For the ease of reference we decided to follow this earlier convention rather than to use a consecutive numbering.

The TDR is complemented by the FAIR Costbook on accelerators and associated manpower – FAIR Start Version and Phase B, Version 5.0 (June 2008), providing information on project costs based on FY 2005 prices. Furthermore, relevant legal documents between the FAIR partners are compiled in the FAIR Baseline Administrative Report.

Darmstadt, December 2008
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2.5 Collector Ring

The Technical Design Report covers the design for the accelerator system Collector Ring (PSP-code 2.5).
2.5.1 System Design

2.5.1.1 Role in the FAIR Project

The Collector Ring (CR) is a dedicated storage ring, its architecture is governed by the stochastic precooing of secondary particles, rare isotopes or antiprotons.

The CR has to fulfil three tasks:

- Stochastic precooing of antiprotons from the antiproton target at a fixed kinetic energy of 3 GeV, to be delivered to the RESR storage ring.
- Stochastic precooing of secondary rare isotope beams from the fragment seperator (SuperFRS) at a fixed kinetic energy of 740 MeV/u, to be delivered to the RESR storage ring.
- Mass measurements of short-lived secondary rare isotope beams from the SuperFRS in the isochronous mode.

2.5.1.2 General Description

Conceptual Layout

The CR is a high acceptance ring with full aperture injection and extraction kickers, RF cavities for bunch rotation, adiabatic debunching and rebunching, and a dedicated stochastic cooling system. In order to fulfil its threefold purpose, its ion optics can be set to three different ion optical modes.

The injection and extraction beam parameters for both stochastic cooling tasks are determined by the large longitudinal momentum spread, horizontal and vertical beam emittances at the end of the transport lines from the antiproton target and from the SuperFRS.

The injection kicker design guarantees that the full ring acceptance is available for the incoming hot secondary beams.

A special procedure is applied in the case of the longitudinal phase space. Because the bunch emerging from the production target is very short (<50 ns) with a large momentum width, this width is reduced by bunch rotation and subsequent adiabatic debunching. A total maximum voltage of 200 kV for the bunch rotation cavities is available. Place is reserved in one of the straight sections to increase this voltage to 400 kV by installation of five additional cavities.

System Parameters

The main system parameters of the CR are given in Table 2.5-1. The maximum magnetic rigidity is due to the choice of iron-dominated magnetic field configurations. The circumference is a result of both optical constraints and the necessity to house the injection kickers, the pick-up and kicker tanks of the stochastic cooling system, and the RF cavities in straight sections. The energy of the antiprotons follows from considerations of maximizing the overall accumulation rate with an incoming 29 GeV proton beam impinging on the antiproton production target. For the rare isotopes it allows for a maximum mass over charge ratio A/Q=2.8, corresponding to neutron-rich fully stripped nuclei.
Table 2.5-1: System parameters.

<table>
<thead>
<tr>
<th></th>
<th>Circumference 215.011 m</th>
<th>Max. magnetic rigidity 13 Tm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Antiprotons</td>
<td>Rare Isotopes</td>
</tr>
<tr>
<td>Max. particle number</td>
<td>$10^8$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>3 GeV</td>
<td>740 MeV/u</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.971 c</td>
<td>0.830 c</td>
</tr>
<tr>
<td>Lorentz $\gamma$</td>
<td>4.20</td>
<td>1.79</td>
</tr>
<tr>
<td>Transition $\gamma_T$</td>
<td>3.545</td>
<td>2.711</td>
</tr>
<tr>
<td>Frequency slip factor $\eta$</td>
<td>-0.0228</td>
<td>0.1745</td>
</tr>
<tr>
<td>Betatron tunes $Q_x$ and $Q_y$</td>
<td>4.42, 4.44</td>
<td>3.13, 3.13</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>1.37 MHz</td>
<td>1.17 MHz</td>
</tr>
<tr>
<td>RF harmonic</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>acceptance mm mrad</td>
<td>240</td>
<td>200</td>
</tr>
<tr>
<td>momentum acceptance</td>
<td>± 3 %</td>
<td>± 1.5 %</td>
</tr>
</tbody>
</table>

Table 2.5-2 lists the momentum spread and emittance parameters of the beams before and after beam cooling. The momentum spread is largest at injection, when a very short bunch from the production target (either rare isotopes or antiprotons) is injected. At this instant, the horizontal aperture of the ring is filled. After bunch rotation and adiabatic debunching the momentum width is decreased, whereas this process leaves the transverse emittance unchanged in both directions. The reduced momentum width is a necessary prerequisite for stochastic cooling at all. Otherwise the effect of unwanted mixing (see below) would exclude particles in the momentum tails from being cooled. After stochastic cooling, all phase subspaces are strongly reduced. The cooling time for the antiprotons is 10 s. The limiting effect preventing faster cooling rates is the poor Schottky signal to thermal noise ratio in case of the antiproton beams. The extraction parameters are chosen to allow for efficient antiproton accumulation in the RESR.

The cooling times for highly charged rare isotope beams, on the other hand, are much shorter (1.5 s). However, the requirement of fast electron cooling in the NESR leads to demandingly low transverse emittances, making plunging pick-up electrodes as necessary for these beams as for the antiprotons.
Table 2.5-2: Cooling Parameters of the CR

<table>
<thead>
<tr>
<th></th>
<th>antiprotons</th>
<th>Rare isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta p/p$ (2$\sigma$)</td>
<td>$\varepsilon_{xy}$ [mm mrad]</td>
</tr>
<tr>
<td>After injection</td>
<td>3 %</td>
<td>240</td>
</tr>
<tr>
<td>After debunching</td>
<td>0.7 %</td>
<td>240</td>
</tr>
<tr>
<td>After cooling</td>
<td>0.1 %</td>
<td>5</td>
</tr>
<tr>
<td>Horizontal width reduction</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Total phase space reduction</td>
<td>1.6*10^4</td>
<td>1.3*10^6</td>
</tr>
<tr>
<td>Overall cooling time [s]</td>
<td>10</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Stochastic cooling is an essential task of the CR. The optical layout of the ring is chosen such to meet the requirements for most efficient cooling. It has turned out that flexibility in setting the transition energy $\gamma_T$ to an optimal value is extremely important. This is due to the necessity to find a compromise for the required mixing between kicker and pick-up (which should be large) and the undesired mixing between pick-up and kicker (which should be small).

In a simplified model, one can write the stochastic cooling rate $\tau^{-1}$ as

$$\frac{1}{\tau} = \frac{W}{2N} \left[ 2gB - g^2 (M + U) \right].$$

The meaning of these parameters is:
- $W$ the electronic bandwidth
- $N$ the number of particles in the beam
- $g$ the system gain
- $B$, which can be written in the form

$$2 \cos \phi \equiv \frac{c_m B}{\eta} \cos \phi_c = \frac{c_m B}{\eta} \delta \eta,$$

where $c_m$ is the central harmonic in the cooling frequency band, and the undesired mixing phase angle is

$$\phi_u = x \eta \frac{\delta p}{p}.$$ 

Here, $x = \frac{s_k - s_p}{C}$ is the ratio of paths from pick-up to kicker and the closed orbit circumference $C$, $\eta_{pk}$ is the local frequency slip factor between pick-up and kicker, and $\frac{\delta p}{p}$ is the maximum momentum width to be cooled. The local frequency slip factor can be written in the familiar form

$$\eta_{pk} = \gamma^{-2} - \alpha_{pk},$$

with the local momentum compaction

$$\alpha_{pk} = \frac{1}{s_k - s_p} \int_{s_p}^{s_k} \frac{D(s)}{\rho(s)} ds.$$ 

In this equation $s_p$ and $s_k$ denote the azimuthal positions of the pick-up and the kicker, $D$ is the dispersion function, and $\rho$ is the radius of curvature. The desired mixing parameter can be written approximately as

$$M = \left( \frac{m \eta \delta p}{\rho} \right)^{-1},$$

with the familiar frequency slip factor

$$\eta_{pk} = \gamma^{-2} - \gamma_T^{-2}.$$ 

This relation holds unless there is an overlap of Schottky bands. In the latter case, $M = 1$. $U$ is the noise to Schottky signal ratio. Rare isotope beams ($\gamma = 1.79$) and antiproton beams ($\gamma = 4.20$) require different optimization procedures with respect to the lattice design in the CR.

For the antiproton beams one has to keep a certain distance between $\gamma$ and $\gamma_T$ in order to make the mixing parameter $M$ small enough. For antiproton cooling, the CR will be operated slightly above transition with $\gamma_T = 3.545$, or $\eta = -0.0228$. 
For the rare isotope beams, the undesired mixing effect limits the momentum acceptance of the system. If the parameter $m_c \phi_n$ becomes larger than $\pi/2$, then the cooling force changes sign, i.e. heats up the beam. This is minimized by making $\alpha_{pk}$ as large as possible by increasing the dispersion in the dipole magnets. Also, the ratio $x$ is minimized by placing pick-up and kicker as close together as possible. Therefore the ring layout is governed by the demands from stochastic cooling and RF manipulation. The following requirements have been taken into account:

- setting different $\gamma_T$ values for antiprotons and RI beams to reach optimized mixing parameters for stochastic cooling, both for desired and undesired mixing,
- accommodation of stochastic cooling pick-up and kickers as well as the RF cavities in regions of zero dispersion,
- controlling the horizontal and vertical betatron phase advance between pick-ups and kickers of the transverse stochastic cooling systems, reducing chromaticity over the whole momentum range. The arrangement of sextupoles and higher order correctors has to be applicable for all three (different) ion optical settings.

Furthermore, the injection and extraction elements must be placed at appropriate locations. The dynamic aperture of the CR lattice has been calculated using realistic field errors inside the large aperture magnets. The result indicates that the dynamic aperture of the CR is larger than the acceptance in all optical settings by a sufficient safety margin.

Figure 2.5-1 shows the CR together with the RESR ring sharing a common hall. The stochastic cooling elements are described in more detail in section 2.5.10. The concept for the installation of the various components of the CR has been worked out (Figure 2.5-2).
Figure 2.5-2: Schematic layout of the CR with major installations.
Lattice Design

The lattice of the CR consists of two 180 degree arcs separated by two long straight sections. If one does not take into account mirroring, it consists of four identical parts. The option of a split ring lattice (which might be favourable for fast stochastic cooling) was discarded, as it would lead to a deterioration of the dynamic aperture.

Figure 2.5-3, Figure 2.5-4, and Figure 2.5-5 display the envelopes and dispersion amplitudes for the three optical modes of the CR. As the lattice symmetry is twofold, only one half of the ring is shown, beginning in the middle of the straight section just before the stochastic cooling pick-ups. In any case, the optics is mirror-symmetric with respect to the central quadrupole magnet in the arcs. The symbols in the figures have the following meaning:

dipole magnets: light blue
horizontally focusing quadrupole magnets: red
horizontally defocusing quadrupole magnets: dark blue
sextupole magnets: black
upper curve: horizontal envelope for maximum momentum deviation and maximum horizontal emittance after injection
the dispersion amplitude for maximum momentum deviation and
lower curve: vertical envelope maximum vertical emittance after injection

Figure 2.5-3: CR lattice with envelopes for antiprotons with $\varepsilon_x = \varepsilon_y = 240$ mm mrad and $\Delta p/p = \pm 3\%$.

Figure 2.5-3 shows the lattice function for antiprotons. The dispersion function does not exceed a value of 5 m, which permits a large momentum acceptance.
Figure 2.5-4: CR lattice with envelopes for rare isotopes $\varepsilon_x=\varepsilon_y=200$ mm mrad and $\Delta p/p=\pm 1.5\%$.

Figure 2.5-4 shows a similar plot for the rare isotope setting. The dispersion function rises to 7.5 m in the arcs. This leads to the small $\gamma_T$ value needed in this optical mode to achieve a small frequency slip factor.

Figure 2.5-5: CR lattice with envelopes for the isochronous mode $\varepsilon_x=\varepsilon_y=100$ mm mrad and $\Delta p/p=\pm 0.5\%$.

For the isochronous mode (Figure 2.5-5) very large dispersion values are needed, which lead to a decrease in acceptance. The smaller betatron tune in this operation mode further reduces acceptance.

Dynamic Aperture
The CR lattice is rather densely packed with focusing elements and the momentum spread of the injected particles is relatively large. Therefore each individual quadrupole gives an essential contribution to the chromatic effect of the ring. The chromaticity correction becomes an essential aspect of the CR design. The chromaticity of the CR should be close to zero over the injected momentum acceptances of $\pm 3\%$ in the pbar, $\pm 1.5\%$ in the RIB and $\pm 0.5\%$ in the isochronous mode. Calculations show that to obtain an ideal zero chromaticity lattice one has
to foresee a large number of sextupoles magnets (ideally the same number as the wide quadrupole magnets) and additionally one has to use strong sextupolar fields for correction of the dispersion function. It is important to find a suitable arrangement of the sextupoles around the ring and to determine their strengths in order to minimize the nonlinearities leading to unstable and even chaotic motion. Presently in the CR there are 6 sextupole families (total number of magnets is 24). These sextupoles are the main source of nonlinearities. Nonlinear effects amplify the betatron tune and dispersion dependence on the momentum spread of the circulating beam. The tune and dispersion variation are critical parameters in the CR with the stochastic cooling system since they determine beam heating rates due to resonance crossing and parasitic heating, respectively. Hence one has to control these parameters very precisely. A large off-momentum dynamic aperture in all mode operation of the CR is required.

A factor that puts stricter requirements on the dynamic aperture of the ring is the large transverse emittance (240 mm·mrad at 99 %) and large momentum spread (Δp/p=6%) of the beam, which should be injected into the CR in the antiproton mode operation. It may bring part of the beam into resonance and may generate beam instabilities that will cause beam losses.

For the new layout of the CR the working points in the resonance diagram are changed in all modes of operation. In order to investigate the aperture which is useful for the stochastic cooling process, dynamic aperture calculations have been carried out for both the antiproton and RIB mode using the PTC procedure, which is implemented in the MAD-X code. These calculations so far include sextupole components and higher order multipole components of the main dipole and quadrupole magnets. In Table 2.5-3 the systematic errors, which are used in the simulations, are given. Since so far there is no information about the quality of the CR magnet, the field errors are assumed arbitrary taking into account typical values of existing magnets.

Table 2.5-3: Field harmonics of the CR dipole and quadrupoles, bₙ, are the systematic errors, The errors are expressed in units of 10⁻⁴ at the reference radius of 200 mm for wide quadrupoles, and at a radius of 70 mm for the dipoles. Harmonics of order 2 refer to a quadrupole, 3 to a sextupole component, etc.

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>0</td>
<td>0.7</td>
<td>0.03</td>
<td>0.005</td>
<td>0.009</td>
<td>-0.002</td>
<td>-0.001</td>
<td>-0.001</td>
<td>-0.007</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>0</td>
<td>0</td>
<td>0.0004</td>
<td>0.01</td>
<td>-3.0</td>
<td>0.01</td>
<td>0.0002</td>
<td>0.01</td>
<td>10.0</td>
</tr>
</tbody>
</table>

The dynamic aperture has been calculated integrating the particle trajectory over 10³ turns, which is consistent with the fact that the bunch rotation in the CR takes about 0.5 ms (which corresponds to approximately 700 turns for antiprotons) and afterwards stochastic cooling takes place. Results of these calculations are depicted in Figure 2.5-6 and Figure 2.5-7. In particular, the off-momentum dynamic aperture has been computed to determine the available dynamic momentum aperture for the various CR operation conditions. The significance of dynamics impact of the off-momentum particles is illustrated by the change in dynamic aperture as shown in the figures. One has to point out that for the new CR layout the dynamic aperture becomes larger compared to the previous CR lattice design [1].
In the CR with the large acceptance the nonlinearities associated with the motion of particles at large amplitudes play a significant role. The nonlinear effects are studied by computing the dynamic aperture and by computing the tune as a function of the betatron oscillation amplitude. Such simulations give a better understanding of the inner complex structure of the dynamic aperture which than can help to choose the best betatron tunes for every operation mode. Special characteristics of the CR ring are large beam emittances (up to 240 mm mrad) and large beam pipe apertures. This brings a variety of nonlinear effects which are a direct consequence of large particle amplitudes. The non-linearity can shift particles to undesired directions, thus decreasing the dynamic aperture. One has to take into account that resonances of lower orders are always most dangerous. However, many other resonances from low to high order are generated by sextupoles. For the resonance identification in the CR the
Laskar’s frequency map analysis is performed. A so-called frequency map has been calculated with its associated dynamic aperture.

For the antiproton optics, the working point is defined by the tunes $Q_x = 4.252$, $Q_y = 4.845$. The calculated dynamic aperture for antiproton optics for dp/p=0 shown in Figure 2.5-8 is regular and almost symmetric and larger than the acceptance, which are ±7 cm in horizontal plane and ±1.8 cm in the vertical plane. The tune spread with amplitude is plotted in Figure 2.5-9 for the antiproton optics and the whole dynamic aperture shown in Figure 2.5-8. If one looks at the tune spread within the beam acceptance one sees only one resonance which perturbs more or less the dynamic aperture. This resonance of 6th order ($Q_x - 5Q_y = 20$) is seen in Figure 2.5-9. In order to see the actual strength of this resonance and at which amplitude it acts, one has to exploit the diffusion information. As a stability index one can use the tune variation, which is characterised by the diffusion coefficient $D$ and calculated by the formula

$$D = \log_{10} \left[ \sqrt{(Q_x^{(2)} - Q_x^{(1)})^2 + (Q_y^{(2)} - Q_y^{(1)})^2} \right].$$

$Q^{(1)}_{x,y}$ are the transverse tunes computed over the first 1000 turns, and $Q^{(2)}_{x,y}$ are the transverse tunes computed over the next 1000 turns. In Figure 2.5-8 and Figure 2.5-9 this diffusion rate is illustrated by a colour code from blue (for very stable orbits) to red (for unstable and chaotic orbits).

![Figure 2.5-8: Calculated dynamic aperture for the antiproton optics for the central orbit (dp/p=0).](image)
Figure 2.5-9: The frequency map computed for the antiproton optics with dp/p=0.

The arrow shows triangle of area within which a frequency spread corresponds to the ring acceptance shown in Figure 2.5-8.

For the RIB optics the working point is Qₓ=3.188, Qᵧ=3.721. Figure 2.5-10, Figure 2.5-11 show the dynamic aperture and frequency map calculated for dp/p=0. The dynamic aperture for RIB optics (see Figure 2.5-10) is also regular and much larger in size than for antiproton optics while the acceptance for RIB optics is not much different in size from the previous one. Figure 2.5-11 represents the frequency map calculated for the whole dynamic aperture shown in Figure 2.5-10. Within the acceptance only one dangerous resonance 3Qₓ+2Qᵧ=17 is excited and it can lead to instability. According to the diffusion coefficient this resonance does not have a strong influence on the amplitude growth. Hence this resonance does not limit the ring acceptance in the RIB optics.

Figure 2.5-10: Calculated dynamic aperture for the RIB optics with dp/p=0.
Figure 2.5-11: The frequency map computed for the RIB optics with dp/p=0. The arrow shows the triangle area within which a frequency spread corresponds to the ring acceptance shown in Figure 2.5-10.
2.5.2 Magnets

As the CR is a large acceptance storage ring, field quality inside large volumes play a major role in the magnet design. For the operation with ion and antiprotons the polarity of the magnets has to be switched. All magnets are iron dominated and normal conducting.

2.5.2.1 Dipole Magnets

The CR will use normal conducting dipole magnets. There will be 24 H-type sector magnets with a deflection angle of 15° with a maximum field value of 1.6 T. The usable magnet gap will be 140 mm, while the horizontal good field region amounts to 380 mm. The radial field quality integrated over the length of the magnet is \( \Delta B \cdot l / B \cdot l = \pm 1 \times 10^{-4} \) as required from the optical calculations. This field quality is necessary to provide the very large ring acceptance, in particular for the freshly injected antiproton beams. On the other hand, due to the fixed injection energy the field quality is required only for field values in the range 0.8 T-1.6 T.

The present layout foresees a coil with 160 turns and a maximum current of 1448 A. The required dc power for this magnet amounts to 112 kW. The maximum ramp rate of 0.054 T/s allows to change polarity at maximum field levels within a minute. Figure 2.5-12 shows the 2D magnet cross section for the H-type curved sector magnet. An iron dominated magnet for a field quality as required is produced with standard technology as the quality is dominated by the yoke geometry.

Figure 2.5-12: 2D-cross section of one quarter of the CR dipole magnet.
The main parameters of the dipole magnets are given in Table 2.5-4. All 24 dipole magnets will be energized in series.

**Table 2.5-4: Main parameters of the dipole magnets.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of dipole magnets</td>
<td>24</td>
</tr>
<tr>
<td>bending angle</td>
<td>15 degrees</td>
</tr>
<tr>
<td>bending radius</td>
<td>8.125 m</td>
</tr>
<tr>
<td>useful aperture</td>
<td>$380 \times 140 \text{ mm}^2$</td>
</tr>
<tr>
<td>maximum field in gap</td>
<td>1.6 T</td>
</tr>
<tr>
<td>maximum ramp rate</td>
<td>0.054 T/s</td>
</tr>
<tr>
<td>air gap height</td>
<td>170 mm</td>
</tr>
<tr>
<td>air gap width</td>
<td>555 mm</td>
</tr>
<tr>
<td>field homogeneity (in 385 mm)</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>total length</td>
<td>2.211 m</td>
</tr>
<tr>
<td>total height</td>
<td>1.86 m</td>
</tr>
<tr>
<td>total width</td>
<td>2.32 m</td>
</tr>
<tr>
<td>total weight</td>
<td>48.3 t</td>
</tr>
<tr>
<td>coil current</td>
<td>1448 A</td>
</tr>
<tr>
<td>number of coil turns</td>
<td>160</td>
</tr>
<tr>
<td>coil resistance</td>
<td>53 m(\Omega)</td>
</tr>
<tr>
<td>coil inductance</td>
<td>312 mH</td>
</tr>
<tr>
<td>maximum dc power loss</td>
<td>112 kW</td>
</tr>
</tbody>
</table>

The dipole magnet has a trim coil which is insulated against the main coil. This trim coil can be powered by a separate power converter in order to use the dipole magnets as a horizontal orbit corrector.

### 2.5.2.2 Quadrupole Magnets

Because of the large acceptance of the CR, it is important to use large aperture magnets only where they are needed. In order to minimize both the production and operating costs, wide aperture quadrupole magnets (useful aperture 400mm $\times$ 180 mm) are used for injection and extraction and in the arcs of the CR (Quadrupoles Q01-Q02, and Q04-Q11). Narrow quadrupole magnets with reduced horizontal good field region (useful aperture 180 mm $\times$ 180 mm) are installed only in the straight sections (Q03) (see Table 2.5-5).
Table 2.5-5: Parameters of CR quadrupole magnets.

<table>
<thead>
<tr>
<th></th>
<th>wide</th>
<th>Narrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of magnets</td>
<td>36</td>
<td>4</td>
</tr>
<tr>
<td>maximum gradient [T/m]</td>
<td>4.9</td>
<td>8.0</td>
</tr>
<tr>
<td>integrated gradient [T]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>effective length [m]</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>maximum flux density in yoke [T]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>maximum ramp rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal aperture [mm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>useful aperture [mm²]</td>
<td>400 × 180</td>
<td>180 × 180</td>
</tr>
<tr>
<td>field homogeneity</td>
<td>±5×10⁻⁴</td>
<td>±5×10⁻⁴</td>
</tr>
<tr>
<td>total length [m]</td>
<td>1.100</td>
<td>0.55</td>
</tr>
<tr>
<td>total width [m]</td>
<td>1.528</td>
<td>0.63</td>
</tr>
<tr>
<td>total height [m]</td>
<td>1.834</td>
<td></td>
</tr>
<tr>
<td>total weight [t]</td>
<td>10.9</td>
<td></td>
</tr>
<tr>
<td>coil current [A]</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>number of coils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of turns per pole</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>total coil resistance [mΩ]</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>total coil inductance [mH]</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>maximum dc power loss [kW]</td>
<td>99</td>
<td></td>
</tr>
</tbody>
</table>

2.5.2.3 Sextupole Magnets

Discrete sextupole magnets will be installed in the CR for chromaticity correction. There is only one type of sextupole magnets described in Table 2.5-6.

Table 2.5-6: Parameters of CR sextupole magnets.

<table>
<thead>
<tr>
<th></th>
<th>wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of magnets</td>
<td>28</td>
</tr>
<tr>
<td>maximum sextupole strength [T/m²]</td>
<td>10.0</td>
</tr>
<tr>
<td>integrated gradient [T/m]</td>
<td>6.0</td>
</tr>
<tr>
<td>effective length [m]</td>
<td>0.6</td>
</tr>
<tr>
<td>maximum flux density in yoke [T]</td>
<td></td>
</tr>
<tr>
<td>maximum ramp rate [Tm⁻¹s⁻¹]</td>
<td></td>
</tr>
<tr>
<td>aperture radius [mm]</td>
<td></td>
</tr>
<tr>
<td>useful aperture [mm²]</td>
<td>400 × 180</td>
</tr>
<tr>
<td>Field homogeneity (in 250 mm)</td>
<td>±5×10⁻³</td>
</tr>
<tr>
<td>Total length [m]</td>
<td>0.65</td>
</tr>
<tr>
<td>Total height [m]</td>
<td>0.905</td>
</tr>
<tr>
<td>Total width [m]</td>
<td>0.934</td>
</tr>
<tr>
<td>Total weight [kg]</td>
<td>1250</td>
</tr>
<tr>
<td>coil current [A]</td>
<td>150</td>
</tr>
<tr>
<td>number of coils</td>
<td></td>
</tr>
<tr>
<td>number of turns per coil</td>
<td>48</td>
</tr>
<tr>
<td>Total coil resistance [mΩ]</td>
<td>282</td>
</tr>
<tr>
<td>Total coil inductance [mH]</td>
<td>78</td>
</tr>
<tr>
<td>maximum dc power loss [kW]</td>
<td>99</td>
</tr>
</tbody>
</table>
2.5.2.4 **Orbit Correction Magnets**

Horizontal correctors will be integrated into the main dipoles. Additional 7 separate horizontal and 15 vertical corrector magnets will be needed. A maximum kick strength of 2 mrad for both the horizontal correctors and for the vertical correctors is needed according to ion optical calculations of closed orbit corrections.

2.5.2.5 **Septum Magnets**

The CR is equipped with two different septum magnets. The magnets IS is used for injection from the SuperFRS or the antiproton target, ES serves for extraction towards the RESR. The operation scheme foresees pulsed operation with a flattop length of 1 ms and rise times below 400 ms. The parameters of the septum magnets are listed in Table 2.5-7.

**Table 2.5-7: Parameters of the CR septum magnets.**

<table>
<thead>
<tr>
<th>IS</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending angle [mrad]</td>
<td>82</td>
</tr>
<tr>
<td>bending radius [m]</td>
<td>18.3</td>
</tr>
<tr>
<td>effective length [m]</td>
<td>1.5</td>
</tr>
<tr>
<td>useful aperture [mm²]</td>
<td>160 × 150</td>
</tr>
<tr>
<td>maximum field in gap [T]</td>
<td>0.8</td>
</tr>
<tr>
<td>maximum ramp rate</td>
<td></td>
</tr>
<tr>
<td>Air gap height [mm]</td>
<td>170</td>
</tr>
<tr>
<td>air gap width [mm]</td>
<td>180</td>
</tr>
<tr>
<td>total length [m]</td>
<td>1.6</td>
</tr>
<tr>
<td>total width [m]</td>
<td>0.573</td>
</tr>
<tr>
<td>total height [m]</td>
<td>0.581</td>
</tr>
<tr>
<td>total weight [kg]</td>
<td></td>
</tr>
<tr>
<td>coil current [A]</td>
<td>1</td>
</tr>
<tr>
<td>number of coil turns</td>
<td>1</td>
</tr>
<tr>
<td>coil resistance [mΩ]</td>
<td></td>
</tr>
<tr>
<td>coil inductance [mH]</td>
<td></td>
</tr>
<tr>
<td>Dc power loss at full current [kW]</td>
<td></td>
</tr>
</tbody>
</table>

2.5.2.6 **Magnet Testing**

**Introduction**

As the FAIR project needs a large number of magnets which have to be produced within a short period of time, successful operation of all magnets in the different parts has to be guaranteed. A dedicated magnet test program is indispensable and has to cover the following procedures:

1. quality assurance (production and testing),
2. measurement of the magnetic field, field quality and magnetic axis in case of quadrupoles and higher order multipoles,
3. provision of information for the operation of the magnets.

For normal conducting magnets the following measurements have to be performed:

- geometry tests by the manufacturer
- warm magnetic measurement by the manufacturer
- insulation and electrical integrity tests by the manufacturer,
- full test of pre-series and special magnet at GSI.
Magnetic measurements are performed to ensure the required field and field quality of each individual magnet. The quantities to be measured depend on the type of magnet:

**Dipole:**

- $\int Bdl$, the magnetic field $B$ integrated over the magnet length $l$
- field direction
- field quality

**Quadrupole:**

- $\int Gdl$ with the magnetic field gradient $G$ integrated over the magnet length $l$
- axis
- field direction
- field quality

**Corrector magnets:**

- $\int C_n dl$ with $C_n$ the $n^{th}$ harmonic integrated over the magnet length $l$
- axis
- field direction
- field quality.

Ramped magnets must be measured in AC and DC mode. The time delay until the field has stabilized has to be measured for pulsed magnets as well, i.e. magnets which must reach their excitation level during a short time period (in the order of a second).

**Table 2.5-8:** Total number of conventional magnets for the CR.

<table>
<thead>
<tr>
<th>CR Magnet types</th>
<th>no. of magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>main magnets (dipoles and quadrupoles):</td>
<td>64 (24+40)</td>
</tr>
<tr>
<td>correctors, steerers.</td>
<td>22</td>
</tr>
<tr>
<td>special magnets (septa, ...)</td>
<td>2</td>
</tr>
</tbody>
</table>

**Quality Assurance and Measurement of the Magnets**

Preparative tests of normal conducting magnets, such as insulation test, cooling water flow, etc., are part of the factory acceptance tests of each individual magnet and are not considered as part of the site acceptance test. Thus magnetic measurement is the main measurement task to perform for normal conducting magnets. The measurement methods applied to the main magnet types are given in Table 2.5-9.

**Factory Acceptance Tests**

**Samples for BH Curves** have to be provided by the manufacturer. These will be used to assert that the properties of the steel match the specification. The manufacturer should also measure these samples.

**Yoke Packing Factor.** The RESR dipoles and quadrupoles are made of laminated steel. Thus the packing factor has to be measured for the whole magnet or at least for all its individual packs.
**Pole Geometry** The field quality is mainly determined by the shape of the pole. Thus the shape of the pole itself as well as the position of one pole to the other(s) has to be measured.

**Electrical Safety** The magnet producer will have to ensure the safe electrical operation of the magnet. As part of this requirement the insulation of the coils and connections has to be tested up to a voltage \( U_{\text{max}} \) of \( U_{\text{max}} = 2 U_{\text{op}} + 1000 \text{ V} \) with \( U_{\text{op}} \) the maximum operational voltage in the branch of the machine, where this magnet is to be connected. This test is typically conducted immersing the coil in water and filling the cooling channels of the coil with water at the maximum acceptable pressure level.

**Interlock Systems** The water flow and the water temperature through the magnets will be monitored special monitors. Flow and temperature meters providing an interlock in case of insufficient coolant flow or over-temperature have to be installed at the water inlet and outlet.

**Magnetic Measurement of main magnets** Machine operation requires precise data of the field of the magnet, particularly for the main magnets. The magnetic field of dipoles and quadrupoles has to be measured for DC operation at injection field mid field maximum field.

If the magnets are also ramped quickly, measurements have to be performed which allow to estimate the field strength and the field quality for all operation cycles with sufficient accuracy. For the RESR storage ring the magnetic field properties during ramping down are most important.

For magnets with less stringent field quality requirements (e.g. correctors and steerers whose field has only to be known in the range of a percent) it is sufficient to monitor the production randomly measuring a magnet. The different measurement methods foreseen for the different magnets are summarized in Table 2.5-9. The curvature of the used search coils for the dipoles is 8.125 m for the RESR and the radius of the rotating coil is 128 mm.

**Matching Magnet Length** For storage rings with relatively small numbers of dipole and quadrupole magnets (e.g. 24 pieces) the length of the magnets has to be matched. For this purpose laminations are inserted at the end of the yoke. The field of the magnet has to be re-measured after such mechanical modifications.
Table 2.5-9: Magnetic measurement method to apply for the different normal conducting magnets.

<table>
<thead>
<tr>
<th></th>
<th>field strength</th>
<th>field direction</th>
<th>field homogeneity</th>
<th>midplane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>dipoles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>search coil</td>
<td>pole shoes</td>
<td>search coil</td>
<td>pole shoes</td>
</tr>
<tr>
<td>NESR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RESR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-FRS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>quadrupoles / correctors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIS 300</td>
<td>rotating coil</td>
<td>pole shoes</td>
<td>rotating coil</td>
<td></td>
</tr>
<tr>
<td>HESR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIS 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>rotating coil</td>
<td>pole shoes</td>
<td>rotating coil</td>
<td></td>
</tr>
<tr>
<td>NESR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RESR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-FRS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Site Acceptance Tests**

Each first main magnet will be measured magnetically at GSI. The same measurements as described before will be performed. Additionally the end field will be mapped for all main magnets.
2.5.3 Power Converters

2.5.3.1 General Aspects of Power Converters

Definition of Power Converters
In this report the term Power Converter is used with the following meaning:

- A Power Converter is a device with power part and control part for supplying current and voltage to a load in a controlled way.
- The power part can be a single inverter or a distributed system of inverters.

Interfaces of Power Converters
There are interfaces for electrical power, for cooling, for protection and for control and display. Some basic considerations are listed:

- Electrical power input:
  Small power converters are connected to the common 400V three phase supply of the accelerator (not loaded by pulse power).
  Medium power converters are connected to the common 400V three phase supply or to the 400V three phase supply derived from the pulse loaded 20 kV system.
  All input contactors are part of the power converter.

  Power converters of high power have usually own 20 kV transformers (part of the power converter) which are connected via 20 kV switch gear either to the common 20 kV supply system or to the pulse loaded 20 kV supply system.
  However the 20 kV switch gear is not part of the power converter, and the transformer has to be placed in a nearby transformer box of the building.

  The electrical supply for the control electronics of pulsed medium or high power converters is derived from the common supply system (not pulsed, 230V or 400V) via a miniature circuit breaker in the power converter.

- Cooling arrangements:
  Both, air cooling and water cooling can be used. In the case of air cooling all necessary fans are parts of the power converter.
  In the case of water cooling all water flow meters are included and all material of the cooling circuits must be suited for non conductive water.

- Control and Display:
  All power converters for magnets are equipped with a high precision current measuring device, i.e. DCCT.
  Digital control algorithms are implemented whenever possible.

  Full manual control is possible at the power converter without external control system.
  Full remote control is possible. Therefore all electronics are included to communicate on a basic digital level with the external control system. The external control system must be able to load or read all parameters of the implemented control algorithm.
Appropriate displays are provided to show the controlled quantities. Status and fault indications are mandatory.

- Protection:

The power converters must be self protecting from internal and external faults. There are fault detecting devices: for instance over current detection. There are fault clearing devices: for instance fuses and predefined actions. There are direct protecting devices: for instance voltage limiters.

The power converter must protect the load:
- from overcurrent
- from overvoltage
- by predefined reactions to interlocks of the load such as temperature interlocks, water interlocks, quench detection signals.

**Locations of Power Converters**

The basic concept is to place all power electronics outside the restricted area of the beam transport system whenever possible. The advantages are:

- Measurements, repairs and service are possible without accessing restricted areas, thus avoiding machine shut downs.

- There is no waiting time to have access to faulty power converters.

- There is no uncertainty on the influence of radiation on the proper operation of components of power electronics and on the impact on life time of the components.

- There is no need for automatic redundancy.

**Choice of Power Converter Circuit Configurations**

Every selected power converter configuration must fulfil the criteria listed below:
- it meets the specifications
- it is reliable
- its circuit structure is as simple as possible.

**SCR structure**

Regarding high power requirements combined with high currents and energy recovery as in the case of SIS100 a line commutated converter (SCR) is the best choice. High amounts of energy can be transmitted in two directions by using one active semiconductor circuit only. Reactive power can be reduced by adding freewheeling thyristors while an active switch mode filter circuit (PE, 50...100 kHz) will improve the poor dynamics of the SCR as well as it reduces the ripple content of the load current. The SCR will be set up as a line commutated 12 pulse system in series or parallel connection as shown in Figure 2.5-13.

**Switch Mode structure (SM): hard switching**

For small and medium power requirements with energy recovery capability switch mode circuits in hard switching configuration are well suited. Limits are given by high load currents because of the number of parallel IGBTs and the switching current capability of the storage capacitor in the dc-link.
Benefits are the small filter for blocking the switching frequency from the load, the good dynamics and the energy storage which allows reduction of grid loading by pulsed currents. Switch mode circuits can be designed for 1-quadrant (chopper), 2-quadrant (half bridge) or 4-quadrant (full bridge) operation. The full bridge enables precisely controlled zero crossing of currents for bipolar applications. The full bridge configuration is already given in

**Switch Mode structure (SM-s): soft switching**

For DC applications demanding nearly noise free load currents soft switching circuits are well suited. Using medium frequency transformers to adapt to the wanted load voltage allows very compact construction of power converters. However the current of one circuit is limited to about 200 A because of the Schottky diodes in the output rectifier. For higher load currents several circuits have to be connected in parallel.

**Accuracy and current ripple**

The requirements for current control performance with respect to accuracy, stability, ripple and time lag of actual current to the set value are summarized in the total deviation. The definition of the total deviation is illustrated in Figure 2.5-14 and can be expressed as a relative or absolute quantity. For bipolar power converters which can be operated at zero current the total deviation can only be given as an absolute quantity. In the relative definition the reference is always the actual value while in the absolute definition the reference is the nominal value.
a) series connection

T1, T2 identical transformers: phase shift of +/-15° el by interchange of L1, PE: active parallel filter

b) parallel connection

c) 4 quadrant switch mode converter as active parallel filter

**Figure 2.5-13:** 12 pulse SCR in series or parallel connection with freewheeling thyristors and active parallel filter PE. c) 4-quadrant (full bridge) switch mode converter (hard switching).
a) Chopper circuit

b) Half bridge

Thyristors and active parallel filter PE.

Figure 2.5-14: Basic circuit diagrams for switch mode converters (hard switching).

For converters with one current polarity and defined minimum current there is a relative total deviation defined.

\[ \Delta I / I \]

For bipolar currents there is an absolute total deviation defined.

\[ I_N = \text{nominal current} \]

\[ \Delta I / I_N \]

Figure 2.5-15: Definition of total deviation.
**Proposed Control of Power Converters**

In Figure 2.5-16 the general structure of a power converter is presented. There are three main components: the Power Part, the Power Converter Control and a Basic I/O-system.

![Figure 2.5-16: General structure of power converters.](image)

The Power Converter Control is a modular system consisting of a multifunction unit, an ADC unit for fast analog signals and a control unit. The multifunction unit is the user interface for manual operation and service and diagnosis by computer or oscilloscope. It also contains the communication ports to the external accelerator control system via the basic I/O-unit, and the control loops and the control topology of the power converter are also implemented in the multifunction unit.

The ADC unit acquires fast analog signals of the power part, for example the load current, for control, protection and documentation purposes.

The control unit generates command signals and firing pulses for the power electronics of the power part. Additionally it handles status and interlock signals and slow analog signals for protection purposes.

As illustrated in Figure 2.5-17 the power converter can communicate on a basic digital I/O-level in real time with a link to the external control system. This link generates the real time data of the set value for the power converter from data provided by the external control system. Thereby the communication to the external control system is not in real time. The link mentioned before is an electronic card which is not part of the power converter. However it can be integrated into the power converter.
The controller for the load quantities can be realized by analog electronics or by digital control algorithms. Wherever possible digital control is preferred. Excellent results have been achieved with digital control algorithms based on analog control strategies enhanced by the possibilities of digital signal processing.

The link to the external control system as well as the power converter control have been decided to have the same design and the same technical realization in all power converters of FAIR. That applies to the load current measuring devices, the DCCTs, too.

2.5.3.2 Power Converters

As the CR ring is designed both for antiprotons and heavy ions with opposite charge, the magnet power converters must be able to reverse the current polarity. This is achieved by a true bipolar design for the converters of the corrector magnets, whereas the other converters are unipolar and have reversing mechanical switches to change the current polarity.

In order to change the operation conditions of the CR from rare isotopes to antiprotons and vice versa as fast as possible without exceeding the allowed insulation voltage inside the superconducting dipole, all CR currents are required to be ramped up to nominal current or down to zero within 30 s. No particular requirements have to be fulfilled for the current accuracy during the ramp.

The basic parameters of the power converters are listed in Table 2.5-10 and Table 2.5-11. Summarized data on power cabling is included. Information on the number of cabinets and the floor space required is given, too (Figure 2.5-22).

Power Converter Dipoles

The CR dipole magnets are normal conducting magnets and do not need quench protection. The power converter for the dipole magnets, which are all connected in series (see Figure 2.5-18), will drive the magnets to the maximum field level within 30 s.
The power converter is a 12 pulse line commutated converter (SCR) with parallel active filter (PE). It is able to return the stored magnet energy (12.3 MJ) to the mains. Current reversing is accomplished by mechanical switches operated at zero current. Overvoltage triggered thyristors allow current flow in case of faults of the mechanical switches. A basic circuit diagram is given in Figure 2.5-19.

**Figure 2.5-18:** Power converter and dipole magnets.

**Figure 2.5-19:** Ramped power converter PS-D1 having active parallel filter and mechanical switches for current reversal.

The active parallel filter PE is a switch mode circuit with high switching frequency (50kHz).

**Power Converters Quadrupoles**

The quadrupole magnets are normal conducting magnets. As their natural time constant is much smaller than the required current fall time the power supplies are 1-quadrant switch mode chopper circuits. Mechanical switches are used to reverse the polarity of the current when it is zero. Anti-parallel connected thyristors with overvoltage triggering protect the load from overvoltage in case of a malfunction of the switches. Figure 2.5-20: shows the schematic circuit diagram of the current reversing unit.
Power Converters Sextupoles

The sextupole magnets are normal conducting magnets. Current reversing is achieved by using a switch mode hard switching circuit in full bridge (H-bridge) configuration. This allows for 4-quadrant operation by the natural characteristics of the circuit.

Power Converters Octupoles

The octupole magnets are normal conducting magnets. Current reversing is achieved by using a switch mode hard switching circuit in full bridge (H-bridge) configuration. This allows for 4-quadrant operation by the natural characteristics of the circuit.

Power Converters Septum Magnets

The septum magnets demand for very high peak power. The peak power is taken from a storage capacitor which is charged by a small charging unit. The current begins to rise upon firing a thyristor. Once the flattop of the load current is reached, switch mode operation of the current bypass PE starts. At the end of the flattop the bypass circuit PE is turned off, and the storage capacitor discharges to negative voltage before the current reverses, feeding energy back into the storage capacitor. The charging unit charges the storage capacitor with constant current to the initial voltage needed for the next cycle. As the cycling frequency of the current swing is much higher (approximately a factor of 10) than its repetition rate the rated power of the charging unit is significantly smaller than the peak power of the load. A basic circuit diagram is given in Figure 2.5-21.

Figure 2.5-20: Mechanical current reversing switch with over voltage protection.

A current reversing unit RU as described in Figure 2.5-20: allows for changing the polarity of the load current. The use of mechanical switches is justified due to the very high peak currents of the load (up to 16 kA).
Figure 2.5-22: Planned arrangement of power converters inside the CR/RESR building.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole Magnets PC</td>
<td>2.5.3.1</td>
<td>1</td>
<td>1</td>
<td>45**</td>
<td>63</td>
<td>30000</td>
<td>any</td>
<td>2143</td>
<td>2550</td>
<td>5128</td>
<td>5128</td>
<td>any</td>
<td>2143</td>
</tr>
<tr>
<td>Quadrupole Magnets PC</td>
<td>2.5.3.2</td>
<td>1</td>
<td>8</td>
<td>3,2x0,8</td>
<td>100</td>
<td>30000</td>
<td>any</td>
<td>104</td>
<td>188</td>
<td>347</td>
<td>347</td>
<td>any</td>
<td>104</td>
</tr>
<tr>
<td>Sextupole Magnets PC</td>
<td>2.5.3.3</td>
<td>1</td>
<td>1</td>
<td>0,8x0,8</td>
<td>12</td>
<td>30000</td>
<td>any</td>
<td>12</td>
<td>167</td>
<td>57</td>
<td>57</td>
<td>any</td>
<td>12</td>
</tr>
<tr>
<td>Octupole Magnet PC</td>
<td>2.5.3.4</td>
<td>1</td>
<td>1</td>
<td>23</td>
<td>1</td>
<td>30000</td>
<td>any</td>
<td>1</td>
<td>167</td>
<td>6</td>
<td>6</td>
<td>any</td>
<td>1</td>
</tr>
<tr>
<td>Injection/Extraction Septum</td>
<td>2.5.3.5</td>
<td>1</td>
<td>1</td>
<td>3,2x0,8</td>
<td>448</td>
<td>250</td>
<td>0,005</td>
<td>82</td>
<td>470</td>
<td>12</td>
<td>12</td>
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<td>0,8x0,8</td>
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<td>4448</td>
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<td>82</td>
<td>470</td>
<td>12</td>
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<td>470</td>
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<td>82</td>
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<td>12</td>
<td>12</td>
<td>any</td>
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<td>7</td>
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<td>4</td>
<td>30000</td>
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<td>any</td>
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<td>any</td>
<td>62</td>
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** floor space incl. transformer boxes

* included in converters
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<th>Power Converters of CR</th>
<th>Max. Apparent Power</th>
<th>Effective Apparent Power</th>
<th>Total Deviation</th>
<th>Magnet Type</th>
<th>No. of Magnets in Series</th>
<th>L per magnet</th>
<th>R per magnet</th>
<th>R of cable</th>
<th>Cross section</th>
<th>Cable length</th>
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<td></td>
<td></td>
<td>[kVA]</td>
<td>[kVA]</td>
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<td>5380</td>
<td>rel +/-0,5 w</td>
<td>24</td>
<td>253</td>
<td>44</td>
<td>9,6</td>
<td>750</td>
<td>410</td>
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<td>2.5.3.2</td>
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<td>358</td>
<td>358</td>
<td>rel +/-0,5 w</td>
<td>4</td>
<td>10,6</td>
<td>7</td>
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<td>1500</td>
<td>360</td>
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<td>2.5.3.2.2</td>
<td>Wide Quadrupole 2 PC</td>
<td>190</td>
<td>190</td>
<td>rel +/-0,5 w</td>
<td>2</td>
<td>10,6</td>
<td>7</td>
<td>3</td>
<td>1500</td>
<td>260</td>
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<td>2.5.3.2.3</td>
<td>Narrow Quadrupole 1 PC</td>
<td>252</td>
<td>252</td>
<td>rel +/-0,5 w</td>
<td>4</td>
<td>1,22</td>
<td>3</td>
<td>4,2</td>
<td>1500</td>
<td>360</td>
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<td>2.5.3.3</td>
<td>Sextupole Magnets PC</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>2.5.3.3.1</td>
<td>Wide Sextupole PC</td>
<td>30</td>
<td>30</td>
<td>rel +/-0,5 w</td>
<td>4</td>
<td>117</td>
<td>423</td>
<td>126</td>
<td>50</td>
<td>180</td>
<td></td>
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<td>2.5.3.3.2</td>
<td>Narrow Sextupole PC</td>
<td>16</td>
<td>16</td>
<td>rel +/-0,5 w</td>
<td>4</td>
<td>9</td>
<td>78</td>
<td>126</td>
<td>50</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>2.5.3.4</td>
<td>Wide Octupole Magnet PC</td>
<td>5,4</td>
<td>5,4</td>
<td>rel +/-0,5 w</td>
<td>4</td>
<td>850</td>
<td>1730</td>
<td>1260</td>
<td>5</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>2.5.3.5</td>
<td>Injection/Extraction Septum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5.3.5.1</td>
<td>Injection Septum (IS) PC</td>
<td>52</td>
<td>52</td>
<td>rel +/-0,5 w</td>
<td>1</td>
<td>0,245</td>
<td>7</td>
<td>0,79</td>
<td>700</td>
<td>15</td>
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</tr>
<tr>
<td>2.5.3.5.2</td>
<td>Extraction Septum (ES) PC</td>
<td>52</td>
<td>52</td>
<td>rel +/-0,5 w</td>
<td>1</td>
<td>0,245</td>
<td>7</td>
<td>0,79</td>
<td>700</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>2.5.3.6</td>
<td>Steering Magnets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5.3.6.1</td>
<td>Steerer hor./vert.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5.3.6.2</td>
<td>Steerer vert.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5.3.6.3</td>
<td>Steerer hor.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5.3.6</td>
<td>Reversing switch</td>
<td>abs=ΔI/I_N</td>
<td>rel=ΔI/I_N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.5.4 RF Systems

A special RF system called 'CR Debuncher' [1, 2] will be installed in the CR consisting of five cavities. The RF cavities [1, 2] in the CR have to fulfil two tasks:
Right after injection the short bunch is rotated in longitudinal phase space by a quarter of a synchrotron period within a mismatched bucket in order to reduce the momentum spread of the particles. Then the voltage is reduced rapidly to form a matched bucket. Finally the voltage is adiabatically reduced to debunch the beam prior to stochastic cooling.
The RF system is also prepared for adiabatic rebunching after stochastic cooling to allow a bunch-to-bucket transfer to the RESR.
All RF operations are performed at harmonic number \( h = 1 \). The results of analytical and numerical calculations (neglecting collective effects because of the low beam current) are listed in Table 2.5-12 which summarizes the main functional parameters of the RF system.

Table 2.5-12: Main requirements imposed on the CR Debuncher RF system (1 cavity).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>( 1.18 \text{MHz} &lt; f \leq 1.38 \text{MHz} )</td>
</tr>
<tr>
<td>Gap voltage in continuous operation (kV)</td>
<td>0.05 to 1.35</td>
</tr>
<tr>
<td>Gap voltage in pulsed operation (kV)</td>
<td>5 to 20</td>
</tr>
<tr>
<td>Maximum duty cycle in pulsed operation</td>
<td>1.5 \cdot 10^{-4} (2 \cdot 10^{-4})</td>
</tr>
<tr>
<td>Maximum pulse duration(^1) (μs)</td>
<td>750 (1000)</td>
</tr>
<tr>
<td>Maximum repetition rate (Hz)</td>
<td>0.2</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1</td>
</tr>
<tr>
<td>Maximum impedance (Ω)</td>
<td>3000</td>
</tr>
<tr>
<td>Maximum time available for a full sweep of the operating frequency (s)</td>
<td>60</td>
</tr>
<tr>
<td>Aperture of the beam pipe, circular diameter (mm)</td>
<td>150</td>
</tr>
<tr>
<td>Available installation length, flange to flange (m)</td>
<td>1</td>
</tr>
<tr>
<td>Available installation width (m)</td>
<td>±0.75</td>
</tr>
<tr>
<td>Available installation height (m)</td>
<td>+0.8/-1.3 (with respect to the beam axis)</td>
</tr>
<tr>
<td>Height of the beam axis (m)</td>
<td>1.3</td>
</tr>
<tr>
<td>Maximum pressure of beam pipe (mbar)</td>
<td>1 \cdot 10^{-9}</td>
</tr>
<tr>
<td>Flanges</td>
<td>CF160</td>
</tr>
</tbody>
</table>

The installation length of RF systems in the CR is restricted to 10m; however in FAIR stage A, only 5m are available for the RF system. Therefore, a combined RF system performing pulsed operation (associated with bunch rotation) as well as continuous operation (for debunching and rebunching) will be built.

\(^1\) The first value denotes the useful time for beam manipulations, the numbers in brackets describes the total operation time of the RF system.
Figure 2.5-23: Block diagram of the CR Debuncher RF system indicating the location and the interaction of the subsystems.

Figure 2.5-23 shows an overview of all components of the CR Debuncher RF system. The cavity, the power amplifier as well as the gap- and grid voltage monitors will be located inside the accelerator hall. The supply room, which will be located in the inner part of the CR on the same level and in close vicinity to the cavities will house the driver amplifiers, control systems (amplitude and phase), supply units of the power amplifiers (anode voltage, DC control grid voltage, screen grid voltage, filament heating) and a programmable logic control for process monitoring and control. The interface to the FAIR central control system will also be located here.

It is planned to construct five cavities of 1m length, respectively. Each cavity will consist of two inductively loaded coaxial quarter wave resonators operating on a common gap. The cavity will be loaded with an amorphous magnetic alloy (VitroVac6030F manufactured by Va-kuumschmelze). The behaviour of this material in the frequency range required for its application here is presented in Table 2.5-13.

| Material | VitroVac 6030F, amorphous magnetic alloy |
| Inner radius | 145mm |
| Outer radius | 313mm |
| Width | 25.4mm (including pertinax covers: ≈29mm) |
| Parallel inductivity | ≈5μH |
| Parallel resistance | ≈100Ω |
| Q value | 2.5-3 |
| μpQf value | ≈4GHz |
A sketch of the cavity which will be similar in design to the existing SIS12/18 bunch rotating cavities [3] is shown in Figure 2.5-24 and Figure 2.5-25. A total number of twelve ring cores will be distributed on both sides of the gap. The power amplifier will operate in a push pull configuration; each of the two tubes will be inductively coupled to the ring cores located at one side of the cavity.

The shunt impedance (@1.18MHz) of the cavity amounts to about 1150Ω, its unloaded Q value accounts for 2.8. A peak power dissipated in the cavity of about 700kW corresponds to a gap voltage of 40kV, and 1.7kW are commensurate to 2kV. Therefore, the average power, dissipated in the cavity is about 2kW (170W per ring core) allowing the usage of forced air cooling.

The cavity will be equipped with two fast semiconductor switches able to short circuit each side of the gap to ground potential.

An in situ heating of the cavity beam pipe is not required.

Figure 2.5-24: Scheme of the CR cavity driven by a push-pull amplifier.
The power amplifier will be mounted below the cavity; it will consist of two Thales TH555A tetrodes working in class A operation. Both tubes will be driven by a single driver amplifier via an input transformer. To allow the high voltages during pulsed operation as well as the lower voltages associated with c.w. operation, it is mandatory to switch the working point of the tubes. In pulsed operation, the DC voltage of the control grid will be shifted to allow the high anode currents needed here. During c.w. operation it will be shifted to more negative values in order to protect the tube. A monitoring system has to be implemented which ensures that the power dissipated in the anode, which will exceed the given maximum ratings of the tube for c.w. operation (250kW) by a factor of two, won't be applied for excessive time spans and therefore prevents damage to the tubes.

Table 2.5-14 describes the power amplifier of one CR Debuncher cavity.

**Table 2.5-14**: Main parameters of the push-pull amplifier driving the CR cavities (operation at 1.18MHz).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Push Pull, inductively coupled</td>
</tr>
<tr>
<td>Tube</td>
<td>$2 \times$ Thales TH555A</td>
</tr>
<tr>
<td>Maximum c.w. anode dissipation</td>
<td>$2 \times 250\text{kW}$</td>
</tr>
<tr>
<td>Anode voltage (DC, working point)</td>
<td>22kV</td>
</tr>
<tr>
<td>Anode current (DC, working point)</td>
<td>$\approx 40\text{A (pulsed), }\approx 3\text{A (c.w.)}$</td>
</tr>
<tr>
<td>Driver</td>
<td>3kW</td>
</tr>
</tbody>
</table>
The CR debuncher cavity will be operated with two control loops. An amplitude control loop has to ensure that the amplitude of the gap voltage follows a set value given by the FAIR central control system. Secondly, a phase control loop is responsible for the synchronisation of the CR Debuncher cavities with each other as well as relatively to the bunch. Due to the broadband nature of the cavity, a dedicated control loop to stabilize the resonant frequency of the cavity is not required. The resonant frequency will be modified in an open loop operation by adjusting remotely controllable capacitors that are connected in parallel to the cavity gap.

A total length of 10m is reserved to house RF systems in the CR, the additional 5m, which will not be used at the beginning of the FAIR project, are reserved for an upgrade of the CR Debuncher system. This will allow the installation of ten instead of five cavities, thereby doubling the available RF voltage.

To enforce standardization within the RF systems of different FAIR synchrotrons, the CR Debuncher RF system will be split down into several self-contained work packages which may be delivered by different FAIR suppliers:

- cavity (including tuneable capacitors to control the resonant frequency, excluding gap switches), power amplifier, gap- and grid voltage dividers and amplitude control loop,
- vacuum gap relays,
- gap switches,
- supply units (anode voltage, control and screen grid DC voltages, filament current) including the PLC and PLC software,
- driver amplifier,
- phase control loop including DDS, connection to the FAIR control system (e.g. DAC to provide target amplitude).
2.5.5 Injection/Extraction

2.5.5.1 Injection

Injection into the CR takes place only from the common end of the injection lines from the Super Fragment Separator or from the Antiproton target. The emittances can be inferred from Table 2.5-2. Except for the isochronous mode, all beams are extracted towards the RESR after stochastic cooling. The emittances are again as in Table 2.5-2.

The CR needs injection and extraction systems consisting of fast pulsed kickers, septum magnets and inflectors. For the injection procedure full aperture kickers are required. On the other hand, the extraction of the cooled beams can be accomplished by C-type partial aperture kickers.

Because of the limited space in the CR the injection and extraction of the beam are provided at one region downstream of the dipole magnet as shown in Figure 2.5-26. This causes crossing of the injection and extraction transfer channels.

Figure 2.5-26: Schematic diagram of the injection/extraction region of the CR.

The injection requires one magnetic septum IS (Injection Septum) and three full aperture kicker magnets (Kicker 1, 2, 3) shown in the schematic of the CR injection region in Figure 2.5-27. The injection septum and kickers are located in adjacent drift spaces separated by quadrupole magnets. This arrangement produces a phase advance of about 90 Grad from the injection septum to the kicker 3. An important feature of the CR is its large injection acceptance, which is guaranteed by installing three full aperture kickers and by adjusting the injection channel to the ring acceptance.

Figure 2.5-27: Injection and extraction region of the CR.

To provide a separation of about 40 mm between the septum edge and the circulating beam at the location of the injection septum one needs a strong deflection angle, which can be produced by three kicker magnets with a the total kick angle of 18 mrad. In Figure 2.5-28 the beam envelope in the injection channel of the CR going through the septum and all three
kicker magnets is shown. One can see that the injection septum can be placed at a distance of 70 mm from the reference orbit of the CR. The effective septum thickness is about 20 mm, from which 8 mm are required for the vacuum chamber and 2 mm for magnetic screening in order to reduce the stray field. The kicker magnets numbered 1 and 2 should not be placed exactly on the optical axes of the CR. Instead, they must follow the displaced beam as shown in Figure 2.5-28. Because this displacement of the injected beam is gradually reduced from first to the third kicker, different apertures are required for the individual kicker magnets. In Figure 2.5-29, Figure 2.5-30, and Figure 2.5-31 the required aperture for each kicker is shown.

**Figure 2.5-28:** Beam envelope in the injection channel going through the injection septum IS and three kicker magnets. The injected emittance is 240 mm*mrad.

**Figure 2.5-29:** Apertures of kicker-1. The ellipses show the width of the injected beam at the beginning and at the end of the kicker.
Figure 2.5-30: Aperture of kicker-2.

Figure 2.5-31: Apertures of kicker-3.
2.5.5.2 Extraction

One needs one septum and one kicker magnet, which are placed in the straight sections close to the arc. The phase advance between the kicker and septum magnets is $n\pi/2$, where $n$ is an integer. In the antiproton optics $n=7$ and in the RIB optics $n=5$, providing a maximum beam deviation at the position of the extraction septum after beam deflection in the kicker magnets (Figure 2.5-32 and Figure 2.5-33.). Compared to injection, the extraction acceptance requirements are much more relaxed, as the beam to be extracted is already cooled, leading to relatively small aperture requirements for the extraction septum magnet. In spite of the fact that the extraction kicker magnet is used for the cooled beams, its aperture requirements are rather strong, as it must provide passage of an injected beam with large emittance. In Figure 2.5-34 the aperture of the extraction magnet is shown for both the antiproton and RIB operation.

Figure 2.5-32: Antiproton beam extraction from the CR.

Figure 2.5-33: RIB beam extraction from the CR.
Figure 2.5-34: Aperture for extraction kickers (left: RIB mode, right: pbar mode).
2.5.6 Beam Diagnostics

2.5.6.1 Basic Layout of Beam Diagnostics

Physical beam parameters, Requirements

The main task for the CR is stochastic cooling of a wide range of beam intensities, varying from $10^6$ antiprotons or $10^3$ radioactive ions to up to $10^9$ heavy ions. Therefore the beam diagnostic system needs high sensitivity as well as a large dynamic range. Although the pickups for stochastic cooling can serve as a sensitive diagnostic device, an independent and direct measurement of the beam parameters is required for cross checking and absolute normalization. Furthermore, bunch-rotation is a critical process and has to be monitored precisely with turn-by-turn resolution. A common technical realization of the diagnostic instruments for all storage rings and synchrotrons is foreseen to make use of synergies and save manpower and costs during the R&D and construction phases. Some modifications of the devices are required, e.g. due to varying mechanical properties and the intricate cryogenic requirements for the synchrotrons. Moreover, highest sensitivity is required to monitor low intensity beam properties down to the detection of single ions.

Tasks of BD, operating phases, Feedback systems

The task of beam diagnostics is the measurement of all relevant beam parameters. These parameters may be subdivided into "standard measurements" usually displayed online, like beam current, position or profile, and "non-standard measurements", like e.g. tune measurements using BTF or Schottky scans, which are performed more rarely and on demand only. Nevertheless these "non-standard" techniques are used for detailed investigations during the commissioning phase as well as for machine tuning. For routine operation the beam diagnostic equipment supplies online data of the standard systems and, additionally, deduced beam parameters, like transmission data, time-dependent beam losses, evolution of transverse profile and longitudinal structure etc. Concerning the beam diagnostic hardware supplementary functions like fast generation of error signals for feedbacks (e.g. closed-orbit feedback in connection with BPM readout) are foreseen, as well as preparative installations for interlock generation and machine protection issues.

Constituents of BD elements, Topology

The notion "beam diagnostic device" in this document is defined as a complete measurement system, including the following constituents: 

- detector/sensor
- related mechanics (pneumatic drives, stepping motors, special vacuum chambers)
- all necessary subsystems (HV-supplies, pressurized air controllers and hoses, stepping motor controllers, detector gas pipes)
- analogue and digital electronics
- data acquisition system (now a separate building block, see following paragraph)
- complete cabling

Because of the wide variety of beam diagnostic systems the detailed composition and interfaces of the "beam diagnostic device" have to be defined in far more detailed specifications.

Generally each beam diagnostic system can be subdivided into five levels, as described in Table 2.5-15. In this simplified scheme the beam diagnostic system consists of a detector and related electronics at the beam line (1st level), long cables and driver electronics for signal
transmission (2\textsuperscript{nd} level) and the data acquisition electronics in the electronics room (3\textsuperscript{rd} level). Additionally some of the beam diagnostic systems require a data concentrator for pre-processing of individually digitized data channels, which is implemented in the 4\textsuperscript{th} layer of the schematic breakdown. The 5\textsuperscript{th} level includes all technical subsystems necessary to supply the technical infrastructure for the detectors (‘slow controls’), like control of pneumatic actuators, stepping motors, high-voltage supplies, status information etc.

However, due to the large diversity of diagnostic devices and their various requirements for signal treatment, no common intersection of the "sensor", "transmission" and "DAQ" segments is feasible and the population of the five levels with subcomponents varies significantly. As a consequence the separation has to be discussed for each system individually. The details concerning the subcomponents and their interfaces are presented in the next paragraphs.

\textbf{Table 2.5-15:} Five-level breakdown for the electronic part of beam diagnostic devices.

<table>
<thead>
<tr>
<th>Level</th>
<th>Task</th>
<th>Subcomponents</th>
<th>Segment Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Physical signal detection and conditioning</td>
<td>detector, pre-amplifier</td>
<td>Sensor</td>
</tr>
<tr>
<td>2</td>
<td>Signal transport</td>
<td>converters, long cables</td>
<td>Transmission</td>
</tr>
<tr>
<td>3</td>
<td>Digitization, data buffering and transmission</td>
<td>ADC, Scaler, Digitizer, embedded controller</td>
<td>DAQ</td>
</tr>
<tr>
<td>4</td>
<td>Data accumulation, network communication</td>
<td>Network adapter, Server, Data concentrator</td>
<td>Network</td>
</tr>
<tr>
<td>5</td>
<td>Motion, control of technical infrastructure, status information</td>
<td>Controllers for: pneumatic actuators, stepping motors, HV-supplies, detector gas</td>
<td>Slow Controls</td>
</tr>
</tbody>
</table>

In principle all beam diagnostic systems have to obey the boundary conditions given by civil construction and radiation safety regulations. For the 1\textsuperscript{st} level electronics the radiation level during machine operation plays an important role. In order to prevent device failure due to radiation damage, the amount of digital electronics located near the beam line has to be restricted to a minimum. For all digital electronics, where installation at the beam line is unavoidable, like e.g. CCD-cameras, detailed investigations on radiation hardness of the devices are necessary. The limited accessibility of the accelerator tunnel due to radiation safety issues requires not only long-term planning of service and maintenance but also precautions to minimize system failure rates (e.g. redundant layouts) have to be considered.

In order to be accessible during routine accelerator operation, the majority of data acquisition systems will be placed in "electronic rooms" in the ground buildings. This requires e.g. that many detector signals have to be transmitted over several hundred meters from the accelerator tunnel to the electronic rooms. Again, the optimal solution for the layout of a beam diagnostic system is considered independently for each individual device.

\textbf{Intercepting / non-intercepting devices, Timing}

Whereas during machine commissioning and troubleshooting also intercepting beam diagnostic elements will be used, all non-intercepting devices, like Beam Current Transformers (BCT), Beam Position Monitors (BPM) etc. are the standard tools for routine operation of the accelerator and transfer lines. Additionally, non-intercepting devices offer the possibility of permanent beam monitoring and could therefore serve as signal sources for interlock generation and machine protection issues. In this context an exact correlation of the measured data in a bunch-to-bunch manner is necessary and therefore an adequate time resolution of the whole data acquisition process is needed. With regard to the demanded high degree of parallel operation of the FAIR facility an intricate timing system together with real-time data pre-processing
and accumulation of coherent data sets are imperative. Additionally, the facility-wide distrib-
uted electronic rooms make special demands on the timing system in order to correlate the
streams of data originating from different electronic rooms. The general timing system for
FAIR will provide synchronization with a precision on the µs timescale and, additionally, a
dedicated high-resolution timing device for the RF system is foreseen. It is an important re-
quirement that technical solutions for interfaces to both timing systems will be available for
the use with beam diagnostic devices.

**System costs**

As mentioned above, the "beam diagnostic device" is understood as a complete measurement
system; therefore the system costs include all necessary constituents from the sensor at the
beam line to the network socket.

Wherever possible throughout the FAIR facility standardized diagnostic elements are used, to
enable quantity discounts, improve the facility-wide exchangeability and to minimize the
spares inventory. This concept of standardization covers not only DAQ electronics and inter-
faces but also the mechanical parts. Additionally the demands on manpower for
(re-)production, service and maintenance of the devices are significantly reduced for similar
technical solutions throughout the facility.

**Overview**

Table 2.5-16 presents an overview of the beam diagnostic devices. The table lists the quanti-
ties of beam diagnostic devices and the measured beam parameters. Additionally, the main
application of the device is shown, in some cases neglecting possible additional functional-
ities (e.g. interlock generation) that will be described in more detail in the following para-
dgraphs.
Table 2.5-16: Overview of beam diagnostic devices in CR, numbers in brackets indicate retrofit options.

<table>
<thead>
<tr>
<th>Diagnostic device</th>
<th>Qty</th>
<th>Measured parameter</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Transformer</td>
<td>1</td>
<td>DC current (1 µA-20 A)</td>
<td>Stored current, beam lifetime</td>
</tr>
<tr>
<td>Cryogenic Current Comparator</td>
<td>1</td>
<td>DC current (1 nA- 10 µA)</td>
<td>Stored current, beam lifetime</td>
</tr>
<tr>
<td>Pulse Current Transformer</td>
<td>1</td>
<td>Pulse current</td>
<td>Injection efficiency</td>
</tr>
<tr>
<td>Transmission Interlock inj.</td>
<td>(1)</td>
<td>Beam current</td>
<td>Transmission control</td>
</tr>
<tr>
<td>BPM</td>
<td>18</td>
<td>Beam centre-of-mass</td>
<td>Closed orbit, turn-by-turn variations, K-modulation, lattice functions, closed orbit feedback</td>
</tr>
<tr>
<td>Exciter+BPM</td>
<td>1</td>
<td>Beam centre-of-mass after excitation</td>
<td>Tune by BTF, tune by noise excitation, tune by Q-kick</td>
</tr>
<tr>
<td>Quadrupole Exciter+Pickup</td>
<td>(1)</td>
<td>Quadrupole moment</td>
<td>Second beam moments, injection matching, quadrupole BTF</td>
</tr>
<tr>
<td>Schottky pickup</td>
<td>1</td>
<td>Momentum distribution, transverse Schottky</td>
<td>Δp/p determination, tune, chromaticity</td>
</tr>
<tr>
<td>Fast Current Transformer</td>
<td>1</td>
<td>Broadband bunch structure</td>
<td>Longitudinal emittance, bunch gymnastics</td>
</tr>
<tr>
<td>Residual Gas Profile Monitor</td>
<td>1</td>
<td>Beam profile</td>
<td>Transverse emittance, injection matching</td>
</tr>
<tr>
<td>Beam Loss Monitor</td>
<td>8</td>
<td>Beam loss</td>
<td>Mis-steering of magnets, halo detection at scrapers</td>
</tr>
<tr>
<td>shared</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEM-Grid</td>
<td>2</td>
<td>Beam profile</td>
<td>First turn diagnostics</td>
</tr>
<tr>
<td>Scintillating Screen</td>
<td>2</td>
<td>Beam profile</td>
<td>First turn diagnostics</td>
</tr>
<tr>
<td>Beam-Stopper</td>
<td>2</td>
<td>---</td>
<td>First turn diagnostics</td>
</tr>
<tr>
<td>Scraper - horizontal</td>
<td>8</td>
<td>Beam profile</td>
<td>Transverse profile, beam alignment</td>
</tr>
<tr>
<td>- vertical</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.5.6.2 Data Acquisition Concept

The data acquisition system (DAQ) represents a separate building block of each beam diagnostic system, responsible for signal digitization, pre-processing and, in close connection to the accelerator control system, data collection and network transport. With regard to the system modularity and scalability the use of commercially available electronic products, if existent and applicable, is an absolute must. Furthermore, a unified layout for all electronic components (form factors, controllers, boards, bus systems etc.) is foreseen, using identical components wherever adequate. In order to facilitate system integration on the hardware side, technical solutions observing industrial standards (network protocols, field busses, pin assignments etc.) are employed. Also in relation to the software the DAQ is standardized to a maximum extent, in order to minimize the number of specifications needed for the interfaces to the accelerator control system (ACS). Each DAQ system is provided with a well-defined interface to accelerator control system and uses a standardized communication model, like for example the "Front-End Software Architecture" (FESA) developed at CERN [4]. In order to
integrate beam diagnostics into the overall accelerator control system all requirements concerning data rates, system performance, network and command protocols, as well as data storage mechanisms have to be included in the basic ACS concept from the very beginning. In many cases the DAQ is directly linked to the timing system, therefore real-time data acquisition and pre-processing, e.g. using FPGAs or DSPs, is mandatory. A distinction has to be made between two acquisition modes with different demands: a) "online acquisition" of relatively small sets of data but the requirement for high data rates and b) "high resolution acquisition", where large data sets are recorded for offline analysis at the expense of a reduced data rate.

For the online display of beam diagnostic devices a real-time visualization of the measured data on the graphical user interface is needed, with high demands on the overall system performance and data rates, but less requirements concerning e.g. the sampling rate and data volume. Other modes of operation, like turn-by-turn or even bunch-by-bunch measurements need the highest performance on the low-level DAQ (3rd and 4th level) but relatively low data rates for the transport of the reduced data to the graphical user interface.

For high resolution measurements (e.g. bunch-to-bunch measurements) the DAQ system (3rd level) has to be capable of high data rates (e.g. Gigabit Ethernet) and embedded controllers have to be equipped with sufficient memory to buffer large sets of data before their collective transport to the accelerator network. In principle all embedded controllers are equipped with real-time operating systems with a well defined maximum interrupt latency and context switching time.

For some systems even dedicated data concentrators/servers are needed (4th level), using FPGAs or purpose-built DSP boards, which also serve as a buffer memory to prevent data loss.

### 2.5.6.3 Current Measurement

#### DC Transformer

One key information of a storage ring is the precise determination of the stored and accelerated beam current. The typical beam parameters are at the performance limit of commercially available DCT with a dynamic range of 10µA-20A [5]. The bandwidth of 10 kHz is sufficient for beam lifetime determination. With the beam current monitored on a ms timescale also coarse beam loss determination is possible.

The sensor (1st level) consists of a toroid on a ceramic vacuum gap equipped with a magnetic shielding against stray fields from surrounding magnets. The front-end electronics (3rd level) works on the principle of the zero-flux DC current transformer. The DC component of the current passing through the toroid is detected by a magnetic modulator and is cascaded on a common feedback loop with the separately detected AC component. The current needed to cancel out the primary magnetic flux is then fed into a precise resistor to produce the output voltage of the device. For digitization a relatively slow ADC (0.2 MSa/s) is sufficient (3rd level).

#### Cryogenic Current Comparator

To determine the circulating current, one Cryogenic Current Comparator (CCC) will be installed with a detection limit of 1 nA, well below the threshold of regular transformers. Its technical realization is comparable to the CCC for the HEBT installation. Only the non-intercepting CCCs allow online monitoring at this low detection limit. The CCC measures the beam current via high-resolution detection of the beam's magnetic field by a flux transducer. The magnetic field of the passing beam current is then fed into a precise resistor to produce the output voltage of the device. For digitization a relatively slow ADC (0.2 MSa/s) is sufficient (3rd level).
The magnetic flux is measured using a thin film DC SQUID with a gradiometric configuration of a Josephson junction. All detector parts of the CCC are mounted in a liquid He bath-cryostat with a "warm hole" for the passing ion beam, as depicted in Figure 2.5-35. This device was successfully tested at GSI [6] and an improved version designed in collaboration with DESY is being commissioned for the XFEL [7]. The detection threshold of this non-intercepting and absolutely calibratable current measurement device is about 1nA of dc-current at a bandwidth of 1 kHz. The CCC sensor consists of the flux transducer inside the bath cryostat connected to SQUID detector and the DC SQUID control unit (1st level) [7]. The output signal of the control unit is digitized using a 0.2 MSa/s 14 bit ADC-board (3rd level).

**Figure 2.5-35:** Left: Schematic view of a CCC sensor set-up, Right: Cryostat with built-in CCC sensor at the beam diagnostic test bench in the High Energy Beam Line at SIS18.

**Pulse Current Transformer**

The injection efficiency is measured by the comparison of the signals from a resonant Transformer, installed in the injection beam line and a Pulse Current Transformer inside the CR respectively. They have a bandwidth of 3 kHz to 500 MHz and a system dynamic range of 80 dB. Additionally, an appropriate timing system for the gating of the related integrator allows measuring the evolution of individual bunches with a resolution of approx. 30µA. It is foreseen, to utilize the signal of the pulse transformers also for machine protection interlocks, e.g. in case of unacceptably high beam losses [8].

The sensor consists of a 50 Ω-terminated current transformer equipped with a switchable gain broadband pre-amplifier (1st level). Data acquisition is performed using a fast (GSa/s) digitizer board (3rd level).

**2.5.6.4 Beam Position Measurement**

**Beam Position Monitors**

Typically beam position monitors (BPM) serve as the main diagnostic tool in synchrotrons and storage rings. A high accuracy of 100 µm beam position reading is required for the determination of the closed orbit. A fast turn-by-turn (or even bunch-by-bunch) readout of the beam position monitors can be used for the control of the injection matching and the rf-manipulations. Also other advanced investigations to determine e.g. linear couplings or higher order magnet strength can be performed by a fast BPM readout [9]. During the commissioning phase the so called K-modulation [10] will be applied using the BPMs in order to investigate the residual mechanical alignment uncertainties of all quadrupoles and corrector magnets. Additionally, the lattice functions have to be mapped using BPM measurements. It is foreseen to provide the position data of the BPMs for a prospective closed orbit feedback sys-
tem, calculating magnetic corrector settings on a ms time scale [8]. Due to their excellent linearity and enhanced sensitivity linear-cut type BPMs are foreseen [11]. According to the tune value, 18 BPMs will be installed in the CR [8]. These room temperature installations are simpler than the cryogenic version of SIS 100. Due to space restrictions in the CR an installation of the BPMs inside quadrupoles might become necessary, implying a tailor-made design of both, the vacuum chamber and the shoe-box type BPM plates. The 1st level of the BPM system consists of the linear cut pickup plates, each connected via matching transformers to precise, automatically calibrating pre-amplifiers with a large dynamic range of 120 dB. These pre-amplifiers, containing a low impedance amplification chain (cut-off frequency 500 kHz) with flat frequency characteristic up to 100 MHz are currently under development at GSI [12]. The pre-amplified signals are digitized using dedicated electronic boards (Figure 2.5-36) with 14-bit ADCs and a sampling rate of 125 MSa/s (3rd level). For real-time filtering and data reduction the boards include a FPGA and, depending on the application, the data can be evaluated in bunch-by-bunch mode or in a time average or narrowband-mode for closed orbit measurements [13]. The electronic boards of the 3rd level also generate control signals for a possible closed orbit feedback system and provide the signal on a fast digital port [14]. Furthermore, the BPM system requires a data concentrator (4th level) in order to accumulate, buffer and pre-process the large data streams of all 16 BPMs in real-time and organize the network transport.

Figure 2.5-36: Photo of the prototype BPM front-end digitalization board (i-tech/Slovenia).

2.5.6.5 Longitudinal Diagnostics and Tune Determination

Tune – Measurements

As a standard method for precise tune determination beam transfer function (BTF) measurements are foreseen, using weak beam excitation [15]. For the dynamic tune determination a system consisting of an RF-exciter for the generation of a broadband noise excitation (the same hardware as for the BTF measurement) will be implemented. Many important beam parameters, e.g. tune, chromaticity, lattice functions and coupling coefficients are determined using the method of coherent beam excitation by a fast kicker, to observe the beam response and its damping time. To follow the behaviour of a single kicked bunch several BPMs have to be read out on a bunch-by-bunch basis. The capability of this mode is a stringent design criterion for the advanced BPM digitalization front-end electronics, as described in section 2.5.6.4. For the BTF measurements the signal of 1 BPM (out of the 18 installed BPMs) is used as input signal and, secondly, an RF-exciter is installed in the storage ring (1st level). In order to prevent priority conflicts between BTF and BPM measurements (e.g. different gain settings of the pre-amplifier in BTF- and BPM-mode), the BPM-DAQ needs additional functionality to exclude parallel operation in the two measurement modes of the identical beam position.
monitor. Data acquisition for the BTF measurement can be performed using a network analyzer accessible via the accelerator network (4th level). For the tune determination with broadband noise excitation and fast kicker excitation the BPM front-end digitization is well suited. By dedicated online analysis tools the required accuracy can be achieved.

**Quadrupole Exciter + Pickup**

If the beam is not injected with a proper transverse matching with respect to the CR lattice function, quadrupolar oscillations may result, leading to an emittance growth after decoherence. Magnetically coupled BPMs are used to determine the differences in the second moments of the horizontal and vertical beam distribution [16]. A careful design is required to reject the much more prominent dipole signal i.e. the first moment of the beam. BTF excitation of the quadrupolar oscillations yields information about the in-coherent tune spread and coupling coefficients.

The radial magnetic field of the beam is measured using four rectangular antenna loops at 45°, 135°, 225° and 315°, mounted circularly around the beam axis. A carefully designed current read-out from the antenna loop (1st level) is needed, to avoid e.g. parasitic couplings [17]. The combined signals of the analogue electronics (hybrids) are pre-amplified and transmitted to the electronics room. The data is recorded using a fast (100 MSa/s) digitizer board (3rd level), e.g. the BPM front-end digitization board. An additional digitizer channel has to be foreseen, because the signal of the quadrupolar pickup needs to be normalized in real-time to the beam current.

**Schottky diagnostics (longitudinal / transverse)**

The Schottky-setup is capable of both, longitudinal and transverse Schottky measurements. Longitudinal Schottky spectra allow measuring the momentum distribution without affecting the beam and this technique is intensively used at GSI [18]. Furthermore, dynamic effects can be visualized by Schottky spectra, e.g. the properties of the RF-capture process preceding the acceleration [19]. The tune value, as well as the incoherent tune spread can be determined precisely from the transverse Schottky spectrum, again without any beam excitation.

The sensor consists of two pairs of capacitive pickup electrodes and a broadband (2 GHz) pre-amplifier. As the 3rd level a digital real-time spectrum analyzer with a bandwidth of dc to 3 GSa/s will be used for the data acquisition. The spectrum analyzer will be directly accessed via network to supply the data to the accelerator control system.

**Fast Current Transformer**

For the observation of the bunch rotation process, a commercially available Fast Current Transformer (FCT) [20] will be installed offering a bandwidth of 500 MHz. It will be of the same type as that foreseen for the synchrotrons and storage rings. Modern methods like tomographic reconstruction of the longitudinal phase space for bunched beams can be performed with the digitized broad-band data in offline mode.

The sensor of the Fast Current Transformer consists of a 50 Ω-terminated current transformer and equipped with a switchable gain broadband pre-amplifier/attenuator (1st level). Data acquisition is performed using a fast (GSa/s) digitizer board (3rd level).

2.5.6.6 **Beam Profile Measurement**

**Ionization Profile Monitor**

The measurement of the transverse beam profile is an important tool to determine the emittance and its evolution during the acceleration and cooling process. The Ionization Profile
Monitor in the CR will be used for this purpose [21]. Additionally fast changes of the transverse profile caused by any beam manipulation can be monitored in a turn-by-turn mode.

The basic principle of the IPM is the creation of secondary ions from the residual gas by the beam's energy loss. These ions are accelerated by an electric field towards a multi-channel plate (MCP) followed by a phosphor screen, as presented in the left part of Figure 2.5-37. The optical signal is either digitized using a CCD camera allowing a high spatial resolution down to ~50 µm. Due to lower currents compared to SIS100, the ionization profile monitor does not need a magnetic field, which leads to a simpler mechanical construction and thus lower cost. Moreover, high statistical accuracy even for low currents can be achieved by long integration times up to several minutes.

As part of an EU FP6 Construction project the design of the electric field, the detectors, fast multi-channel electronics, as well as the according acquisition and analysis software is currently developed at GSI [22], [23]. GSI has experiences in the IPM construction and operation in a heavy-ion synchrotron from existing realizations at SIS18 and ESR, presented in the right part of Figure 2.5-37.

The 1st level of the IPM system consists of the electrical field box with HV connectors, the multi-channel plate and CCD camera and/or the photomultiplier array. The overall insertion length of the device is approx. 1 m for a design without magnetic field. For the IPM a multi-channel remote-controlled HV-supply is needed as additional infrastructure. Since digitization is performed already in the 1st system level, a powerful digital bus (e.g. IEEE1394b, Gigabit Ethernet) with highest data rates is necessary in the 2nd level. An adequate adapter board receives the digital image data in the 3rd level and a high-performance embedded controller buffers, compresses and pre-processes the data.

2.5.6.7 **Beam Loss Detection**

Beam Loss Monitors (BLM) can measure even small fractions of local beam loss during e.g. injection or cooling with high time resolution. These relatively cheap devices can be mounted at critical locations, e.g. close to the electric and magnetic septa, at switching magnets and at quadrupoles with large beam envelopes. For cost reasons, 8 manually movable BLM stations are foreseen for flexible response to installation requirements. It is planned to share BLMs with the synchrotrons and storage rings CR, NESR and RESR. Different types of BLMs were...
tested at GSI [24]. Scintillators are the most sensitive beam loss monitors, but require calibration, whereas ionization chambers measure directly the physical dose. It is so far not foreseen to use BLMs for machine protection or interlock generation. It is so far not foreseen to use BLMs for machine protection or interlock generation. While scintillators equipped with photomultipliers deliver countable pulses, the ionization chambers are readout by current-to-frequency converter (1st level) to provide countable pulses for the scaler board. The pulses of the scintillators are discriminated (3rd level) and distributed to the DAQ. All digitized signals from the detectors are counted in dedicated 200MHz, 32-bit scaler boards (3rd level), which allow sampling of any channel with up to 1 MHz/channel [25].

2.5.6.8 First Turn Diagnostics (intercepting)

SEM-Grid

The layout of the first turn diagnostics follows the concept foreseen for NESR.

Figure 2.5-38: Left: Vacuum installation of a SEM-Grid with 64 wires per plane mounted on an Ø150mm flange (as used for the HICAT facility). Right: An Ø100mm Scintillation Screen vacuum feed-through mounted on an Ø 150 mm flange.

The beam profile will be measured using well established Secondary Electron Emission-Grids (SEM-Grids). Figure 2.5-38 presents a standard GSI SEM-grid. The wire grid consists of up to 64 wires per plane (horizontal or vertical) with a grid spacing of 1.1 mm. The wire signals are fed into I/U-converters and are individually amplified using pre-amplifiers with a large dynamic range of 120 dB (1st level). The wire signals are multiplexed and sequentially digitized using a slow (1 MSa/s) ADC-board (3rd level).

As a cost efficient re-design of the preamplifier chain, for example, modern multi-channel analogue electronics with a comparable dynamic range could be implemented instead. The digitization can be performed on the same printed circuit board enabling an inexpensive design. A prototype of an ASIC realization has been developed by the GSI Experimental Electronics group using current-to-frequency converters [26]. Here the ASIC integrates 1st and 3rd level in a single device.

Scintillating Screens

Scintillating screens offer a direct image of the beam and will be installed in the injection and extraction section as a first turn diagnostics. The screen is typically mounted on a pneumatic drive and the beam image is observed through a vacuum view port using a digital CCD camera for quantitative profile evaluation, see Figure 2.5-38. GSI has large experiences in this subject, and several types of materials were tested for various beam parameters [27] and [28]. The optical signal is digitized at the beam line by a digital CCD camera (1st-3rd level). Hence the signal noise is reduced to a minimum, because of the pure digital signal transmission (e.g. using IEEE1394b, Gigabit Ethernet) to the distant electronics room. For the low beam intensi-
ties very sensitive screen materials have to be chosen, and in order to monitor also a broad range of intensities eventually several different screen materials have to be used.

**Scraper**

Scraper allow a reliable method to measure the beam size destructively. As frequently performed at the existing ESR, the beam is aligned within the straight sections by scrapers. For this application a precise control of the scraper position is a crucial, but well established technology at GSI. In total 8 horizontal and 4 vertical scrapers equipped with stepping motor drives are foreseen.
2.5.7 Ultra High Vacuum System

As the requirements on storage time are comparatively moderate for the rare isotope beams, it is sufficient to keep the CR vacuum below a value of $10^{-9}$ mbar. This implies that no bakeout is needed. The design of all vacuum components is straightforward following the specifications and techniques applied in the existing accelerator complex at GSI. A schematic layout of the CR vacuum system is shown in Figure 2.5-39.

Figure 2.5-39: Schematic layout of CR vacuum system.

2.5.7.1 Pumps

The pumping system must avoid contamination of the vacuum system by hydrocarbons. Therefore only oil-free pumps are allowed. Roughing will be provided by oil-free turbomolecular pumps. For the ultrahigh vacuum regime a combination of 40 titanium sublimation pumps with a pumping speed 2000 l/s and sputter ion pumps, with a pumping speed of 500 l/s each, will be employed. All required pumping systems are commercially available and well established at the existing GSI facility. Table 2.5-17 summarizes the main parameters of the pumps foreseen for the CR UHV system.

Table 2.5-17: Main parameters of vacuum pumps.

<table>
<thead>
<tr>
<th>Pump type</th>
<th>Number</th>
<th>Pumping speed</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping station roughing</td>
<td>2</td>
<td>500 l/s &amp; 10 m³/h</td>
<td>TMP &amp; dry forepump</td>
</tr>
<tr>
<td>Sputter ion pumps</td>
<td>40</td>
<td>500 l/s</td>
<td>DN160CF</td>
</tr>
<tr>
<td>Ti sublimation pumps</td>
<td>40</td>
<td>2000 l/s</td>
<td>DN160CF</td>
</tr>
<tr>
<td>NEG coating</td>
<td></td>
<td></td>
<td>Not applicable</td>
</tr>
</tbody>
</table>
All pumps described in this chapter have to be delivered together with the required controller/power supply and all necessary cables. The controller/power supply of the pumps has to be controlled by the overall FAIR control system. The type of the interface to be used will be defined later in the detailed technical specifications.

For standardization reasons, like number of spare parts, maintenance and operation, it’s absolutely necessary that for all vacuum systems at the FAIR facility only one or two different manufacturers for each type of pump will be used.

**Roughing Pumping Stations**

The pumping station consists of a magnetic bearing turbomolecular pump together with a compatible roughing pump (regarding pressure, pumping speed). The turbomolecular pump and the roughing pump have to be oil free. In the roughing vacuum line between roughing pump and turbomolecular pump a t-piece and a valve has to be mounted to connect a leak detector. The pumping station has to be built in a way that in the case of a power failure venting of the accelerator via the pumping station is not possible (powerless closed roughing vacuum valve). All vacuum parts (KF vacuum tubes and bellow, gaskets, ring, manual angle valve, etc) are part of the pumping station.

All functions of the pumping station have to be controlled and monitored by the overall FAIR accelerator control system. Therefore the pumping station is connected via an interface (which has to be defined) to the accelerator control system.

The pumping station (including controls) has to be delivered as a fixed mounted unit (movable with wheels), where only the turbo pump has to be mounted. All pumps must be operated with 250V AC. The pumping station can be operated at 250V AC or 400V AC.

**Sputter ion pumps**

The bundle consists of the ion pump itself, the controller/power supply and the necessary HV cable including the connectors.

Noble gas stable sputter ion pumps with an ultimate pressure <10^{-11} mbar after bakeout will be used. It must be possible to measure the pressure via the pump in this pressure region.

The power supplies/controllers will be mounted in building 007a. To reduce the cable length it’s foreseen to distribute them to four places in the building. From each of these places 10 sputter ion pumps have to be controlled. The controllers must control one or more sputter ion pumps. They will be mounted in standard 19-inch racks. The cable length from pump to controller can be up to 50 m.

They must control one or more sputter ion pumps. Following functions are required by the power supply unit:

- Read-out of vacuum pressure for <10^{-5} mbar
- Analogue output for pressure and ion pump current of each pump
- 2 individual adjustable thresholds per ion pump
- Interface with control of all pump functions

Additional: the power supplies must guarantee that the sputter ion pumps can only switched on a pressure <10^{-5} mbar. The controls will be used to for the interlock system and the pressure read-out.

All functions of the sputter ion pumps have to be controlled and monitored by the overall FAIR accelerator control system. Therefore the pumping station is connected via an interface (which has to be defined) to the accelerator control system.
Titanium Sublimation Pumps
The bundle consists of the Titanium pump (sublimator & pump body) itself, the controller/power supply and the necessary cable including the connectors. The size of the pump body and the flange will be defined in the ongoing process of the system design. The pump body will be made out of stainless steel AISI 316LN.
The controller for the pump must allow a remote control of the sublimation process and therefore has to be connected with an interface, which will be defined later, to the overall FAIR control system. The controllers will be mounted in standard 19-inch racks distributed to four places in building 007a. Therefore the cable length between controller and pump can be up to 50 m.

2.5.7.2 Beam Pipe Vacuum Chambers

General Vacuum Chambers
All devices installed inside the vacuum chambers must be produced following the rules for ultrahigh vacuum systems. Only stainless steel with low hydrogen content and pure ceramic materials may be used, other materials are only allowed on special demand. All vacuum joints use metallic gaskets (silver-plated OFHC copper) of ConFlat (CF) or COF type for apertures larger than 250 mm.

Dipole Vacuum Chambers
The dipole vacuum chambers have a length of 2.625 m with a free aperture of 380×140 mm². Their shape is curved, following the dipole bending radius of 8.128 m. The chambers will be made out of stainless steel.

Quadrupole Vacuum Chambers
There are four types of quadrupole chambers. Wide ones with an aperture of 400×180 mm² and a length of 1.3 m and ESR type wide quadrupoles with an aperture of 400×180 mm² and a length of 1.15 m. They will have an octagonal shape with a wall thickness of 8 mm. Then there are narrow quadrupoles with an aperture of 180×180 mm² and a length of 0.75 m, and narrow septum quadrupoles with an aperture of 180×180 mm² and a length of 0.6 m. These chambers will be round with a wall thickness of 2 mm. All quadrupole vacuum chambers will be made out of stainless steel.

Multipole and Corrector Vacuum Chambers
The narrow sextupole chambers will be round with a diameter of 180 mm and a length of 0.6 m. The wide sextupole will have octagonal shaped chambers with an aperture 400×180 mm² and length of 0.85 m.
The narrow horizontal orbit correctors will have octagonally shaped vacuum chambers with an aperture of 200×180 mm² and a length of 0.4 m. The wall thickness is 5 mm. The wide vertical orbit correctors have an aperture of 400×180 mm² and a length of 0.6 m, their vacuum chamber wall is octagonal with 8 mm wall thickness. The narrow orbit correctors have a round vacuum chamber with 180 mm inner diameter and a length of 0.6 m. The wall thickness is 3 mm.
All sextupole and corrector vacuum chambers will be made out of stainless steel.

A summary of physical dimensions of CR magnet vacuum chambers is given in Table 2.5-18.
Table 2.5-18: Geometrical dimensions of beam pipe magnet vacuum chambers.

<table>
<thead>
<tr>
<th>Vacuum chambers inside magnets</th>
<th>Number</th>
<th>Length [m]</th>
<th>Aperture [mm x mm]</th>
<th>Shape</th>
<th>Wall thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>24</td>
<td>2.625</td>
<td>380 x 140</td>
<td>Rectangular, bended</td>
<td>10</td>
</tr>
<tr>
<td>Wide Quadrupole</td>
<td>28</td>
<td>1.3</td>
<td>400 x 180</td>
<td>octagonal, straight</td>
<td>8</td>
</tr>
<tr>
<td>Sextupole Wide</td>
<td>28</td>
<td>0.85</td>
<td>400 x 180</td>
<td>octagonal, straight</td>
<td>8</td>
</tr>
<tr>
<td>Horiz. Correctors</td>
<td>4</td>
<td>0.4</td>
<td>180 x 180</td>
<td>round, straight</td>
<td>3</td>
</tr>
<tr>
<td>Vert. Correctors</td>
<td>15</td>
<td>0.6</td>
<td>400 x 180</td>
<td>octagonal, straight</td>
<td>8</td>
</tr>
<tr>
<td>Narrow Horriz. Orbit Correctors</td>
<td>3</td>
<td>0.4</td>
<td>200 x 180</td>
<td>octagonal, straight</td>
<td>5</td>
</tr>
</tbody>
</table>

2.5.7.3 Valves

The vacuum system of CR will be divided into eight vacuum sectors, separated by all-metal sealed gate valves because of the limited radiation exposition. The sections where the stochastic cooling pick-up tanks are located define an own vacuum section due to the built-in electronics and their increased outgassing, when they are not cooled. Therefore eight all-metal sealed valves DN160CF are needed for the mobile roughing stations. To protect the vacuum system in case of a leak two fast shutters are foreseen. A list of valves used in CR can be found in Table 2.5-19.

Table 2.5-19: Vacuum Valves in CR.

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Type</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate valve</td>
<td>5</td>
<td>all-metal</td>
<td>DN200CF</td>
</tr>
<tr>
<td>Gate Valve</td>
<td>3</td>
<td>all-metal</td>
<td>DN400CF</td>
</tr>
<tr>
<td>Valve for roughing</td>
<td>8</td>
<td>all-metal</td>
<td>DN160CF</td>
</tr>
<tr>
<td>Fast valve</td>
<td>2</td>
<td></td>
<td>DN160CF</td>
</tr>
</tbody>
</table>

All valves are commercially available and can be purchased according to requirements. All valves have to be controlled by the overall FAIR control system. The required hardware will be similar over the whole FAIR facility. The type of the interface used for the connection to the control system will be defined later in the detailed technical specifications. The bundle of the gate and roughing valve consists of the valve, the valve control (hardware) and the required cables. The bundle of the fast closing valves consists of fast closing valve, the high vacuum gauge (sensor), the control unit, the cable between fast closing valve and control unit and the cable between high vacuum pressure gauge and control unit. The required electronic interface cards (lowest hardware level) will be mounted in standard 19-inch racks. They also deliver the required voltages for the valves. The cable length between the interface card and the valve can be up to 50 m. The main valve control electronics will be also mounted in standard 19-inch racks. All these racks will be distributed to four places in building 007a.

For standardization reasons, like number of spare parts, maintenance and operation, it’s absolutely necessary that for all vacuum systems at the FAIR facility only one or two different manufacturers for each type of valve will be used.
2.5.7.4 **Bake-out System**

A bake-out of the vacuum system is not necessary.

2.5.7.5 **Vacuum Diagnostics**

For the measurement of the total pressure a system of 16 calibrated wide range ion gauges (for redundancy two per vacuum sector) and 6 calibrated Residual Gas Analyzers (RGA) with high sensitivity and resolution will be installed. These systems are commercially available. All vacuum diagnostics described in this chapter have to be delivered together with the required controller/power supply and all necessary cables. The controller/power supply of the ion gauges has to be controlled and monitored by the overall FAIR control system. The type of the interface to be used will be defined later in the detailed technical specifications. All controllers/power supplies for the measurement equipment will be mounted in standard 19-inch racks, which will be located in building 007a. Therefore the cables for the wide range ion gauges can have a length of up to 50 m. For the RGA a cable length of 50 m is needed. For standardization reasons, like number of spare parts, maintenance and operation, it's absolutely necessary that for all vacuum systems at the FAIR facility only one or two different manufacturers for each type of ion gauge will be used.

*Total Pressure Diagnostics: Wide Range Ion Gauge*

The bundle includes the wide range ion vacuum gauge, the operating units/power supply and cables. The pressure range must be $5 \times 10^{-10} < p < 1000$ mbar. The gauges must have a DN40CF or a DN63CF stainless steel flange.

*Partial Pressure Diagnostics*

The bundle consists of a quadrupole mass spectrometer for residual gas analyzes in the UHV range including the controls hardware and software. The mass spectrometer must have a mass range from 1-100amu, a detection limit (SEM) of $1 \times 10^{-14}$ mbar, bakeable up to 350°C and an open ion source. The components of the analyzer must be vacuum fired. The electronics of the analyzer must be separable from the analyzer head with a cable of at least 5m length. The analyzer has to be mounted on a DN40CF or a DN63CF stainless steel flange.
2.5.8 Particle Sources

n./a.
Electron Cooling
n./a.
2.5.10  Stochastic Cooling

2.5.10.1  General Layout

The CR stochastic cooling system consists of three pick-up tanks (labelled P1-P3) in straight sections with zero dispersion, three kicker tanks (K1-K3) in straight sections with zero dispersion, and a pick-up tank (PP) at high dispersion (see Figure 2.5-2). All systems will work in the frequency band 1-2 GHz. The distance between the electrodes and the shrinking beam can be kept constant due to appropriate mechanical movement. The microwave noise floor is minimized by using electrodes and preamplifiers at a temperature of about 20 K.

Table 2.5-20: Stochastic cooling paths in the CR.

<table>
<thead>
<tr>
<th>Pick-up</th>
<th>Kicker</th>
<th>Purpose of cooling pick-up or kicker</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>K3</td>
<td>Antiprotons longitudinal, rare isotopes longitudinal final stage</td>
</tr>
<tr>
<td>P2</td>
<td>K2</td>
<td>Antiprotons vertical, rare isotopes vertical final stage</td>
</tr>
<tr>
<td>P3</td>
<td>K1</td>
<td>Antiprotons horizontal, rare isotopes horizontal final stage</td>
</tr>
<tr>
<td>PP</td>
<td>K1</td>
<td>Rare isotopes horizontal first stage</td>
</tr>
<tr>
<td>PP</td>
<td>K2</td>
<td>Rare isotopes longitudinal first stage</td>
</tr>
<tr>
<td>PP</td>
<td>K3</td>
<td>Rare isotopes vertical first stage</td>
</tr>
</tbody>
</table>

The paths depicted in Table 2.5-20 satisfy the needs of a proper betatron phase advance for transverse cooling. An important feature of rare isotope cooling is that the Palmer pick-up PP serves for the detection of signals in all three phase planes.

Antiproton cooling makes use only of pick-ups and kicker located in zero dispersion straight sections. Longitudinal cooling is performed using the notch filter technique. Antiproton cooling needs cryogenic pick-ups at temperatures of about 20 K. In order to improve the signal to noise ratio for longitudinal cooling, signals from all pick-ups taken in a sum mode will be used (see below).

For rare isotope cooling only the Palmer pick-up PP is useful in the first stage directly after debunching. The pick-ups P1-P3 cannot be used at this instance because of the undesired mixing effect. Longitudinal cooling will apply the Palmer method. Only after the momentum width has decreased below ±0.1 %, it is possible to switch off the signals from the Palmer pick-up PP and turn to cooling from P1-P3, in order to achieve the smallest possible emittances.

Table 2.5-21: Full beam width at pick-ups and kickers after debunching

<table>
<thead>
<tr>
<th>Antiprotons</th>
<th>Rare Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>P1, K3</td>
<td>70-111 mm</td>
</tr>
<tr>
<td>P2, K2</td>
<td>70-112 mm</td>
</tr>
<tr>
<td>P3, K1</td>
<td>66-112 mm</td>
</tr>
<tr>
<td>PP</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.5-21 shows the full beam width after debunching in the CR in the pick-up and kicker tanks. Because of the FODO lattice of the CR, there are large variations along the circumference, both in x and y. Therefore the pick-up and kicker electrode arrays will be slanted with respect to the beam direction. All pick-up and kicker tanks will have plunging electrode arrays, following the decreasing beam size during the cooling process.
2.5.10.2 **Slotline Electrodes**

The pick-up and kicker electrodes will use slotline structures, which are being developed for the CR. These structures have been chosen because of the following properties:

- High beam impedance both for $\beta=0.83$ (rare isotopes) and $\beta=0.97$ (antiprotons)
- Good properties with respect to plunging
- UHV compatible production with ceramic substrate

![Figure 2.5-40: Slotline array with eight slots arranged perpendicular to the beam](image)

Figure 2.5-40 shows an array of eight slotlines. The base material for this construction is copper-clad alumina ($\text{Al}_2\text{O}_3$). The slots are made by milling. The beam direction is transverse to
the slots. The beam induces two counter-propagating waves into the slots which are coupled out by microstrip lines on the rear side of the structure. Alumina bridges are left in the slots as a substrate for these microstrip lines as shown in Figure 2.5-41, which presents the rear side of the array. The two counter-propagating signals are combined in a one-stage Wilkinson combiner. Then the signal is fed out perpendicular to the plane as is depicted in Figure 2.5-42. The signal is transported to a second printed board serving for combination of the signals from the eight slotlines. In order to get the utmost signal from the single charged antiprotons, the signal combination on this board is optimized for $\beta=0.97$. The phase error for the rare isotopes is acceptable. The signals from many of these slotline arrays are combined outside the vacuum with proper velocity matching for either antiprotons or rare isotopes.

The array has a total length of 200 mm in the beam direction. Each pick-up and kicker tank has a total inner free length of 2000 mm.
Figure 2.5-41: View of rear side of module casing with preamplifiers.
Figure 2.5-42: View of slotline signal transport.
2.5.10.3 **Signal Processing**

Figure 2.5-43 depicts schematically how signals from a pair of slotlines as processed in pick-ups P1-P3 to give vertical or longitudinal signals. A horizontal pick-up is turned by 90 degrees with respect to Figure 2.5-43.

![Diagram of signal processing](image)

**Figure 2.5-43:** Sum and difference signal from vertical pick-up.

For longitudinal cooling, two different methods are used: Notch filter cooling for antiproton cooling and for the second stage of rare isotope cooling. Palmer cooling for the first stage of rare isotope cooling.

Notch filter cooling makes use of the dependence of the revolution time (or frequency) on momentum. Its basic layout is shown in Figure 2.5-44. The signal is split into two identical parts. One of them is delayed by exactly one revolution period. Then the signal is subjected to a 90 degree rotation in the complex amplitude-phase plane. Such a device is called a correlator notch filter and is used in many stochastic cooling installations (CERN, FNAL, Cosy Jülich). Notch filter systems cannot be used for longitudinal rare isotope cooling in the CR during most of the cooling process.
2.5.10.4 **Movable Pick-up and Kicker Modules**

In order to get the largest possible electrode sensitivity during the cooling process, the position of the electrodes can be moved, following the shrinking diameter of the beam. 8 linear synchronous drives (one for two modules) provide the forces needed for the acceleration of the modules. The force due to the pressure gradient between atmosphere and vacuum tank are overcompensated by suitable spring forces. In case of voltage glitches the modules will thus be moved automatically towards the most outward position.
2.5.10.5 Cryogenic Pick-ups and Preamplifiers

The signal to noise ratio of the pick-ups will be maximized by using electrodes and the first amplification at an ambient temperature of 20 K. The amplifiers, based on GaAs FETs, are integrated into the modules. Cooling at 20 K is achieved by two helium cold heads per tank delivering a cooling power of 18 W each. The movable modules are connected to the cold heads via copper beryllium (CuBe2) sheets (100 μm thickness) that are flexible even at 20 K. They are coated on both sides with a thick 200 μm silver layer providing the necessary thermal conductivity. Each cold head has a second stage which can deliver 110 W at 80 K. This power is used to cool an intermediate shield. The shield is a 1800 mm long gilded 3 mm OFHC copper cylinder which is coated with 10 μm nickel. The gold surface on the nickel is 2 μm thick. It has been chosen because it is chemically robust with respect to oxidization and because its thermal emissivity is below 3%. The intermediate nickel layer is needed as a barrier.

2.5.10.6 Power Requirement

The power requirement for the stochastic cooling system depends on the coupling impedance of the kicker electrodes. The largest power is needed at the beginning of the cooling cycle. First estimates using different models yield a total cw power of 1.6 kW to be installed at each of the kickers K1, K2 and K3. One should mention at this point that the installed power should be roughly 6 dB higher than the average power due to the stochastic nature of the signal.

The power amplifiers must fulfil stringent conditions on amplitude flatness and phase linearity (see Table 2.5-22). Furthermore, the out-of-band performance of the amplifiers must be such that no cooling deterioration occurs due to signals outside the specified band.
Table 2.5-22: Part of power amplifier specification.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency band, lower limit</td>
<td>GHz 1</td>
</tr>
<tr>
<td>frequency band, upper limit</td>
<td>GHz 2</td>
</tr>
<tr>
<td>output power at each output port</td>
<td>dBm 50</td>
</tr>
<tr>
<td>2-signal 3rd order interception point at each output port</td>
<td>dBm 61</td>
</tr>
<tr>
<td>minimum amplification</td>
<td>dB 30</td>
</tr>
<tr>
<td>maximum amplification</td>
<td>dB 50</td>
</tr>
<tr>
<td>variation of amplification inside the frequency band, 10 dB below 1 dB compression</td>
<td>dB ±1</td>
</tr>
<tr>
<td>variation of phase inside the frequency band, 10 dB below 1 dB compression</td>
<td>degrees ±10</td>
</tr>
<tr>
<td>variation of amplification inside the frequency band, at the 1 dB compression point</td>
<td>dB ±1.5</td>
</tr>
<tr>
<td>variation of phase inside the frequency band, at the 1 dB compression point</td>
<td>degrees ±15</td>
</tr>
<tr>
<td>variation of amplification among any of each amplifiers of series production, 10 dB below 1 dB compression</td>
<td>dB ±1</td>
</tr>
<tr>
<td>deviation from phase linearity among any of each amplifiers of series production, 10 dB below 1 dB compression</td>
<td>degrees ±10</td>
</tr>
<tr>
<td>total electric length</td>
<td>ns &lt;20</td>
</tr>
<tr>
<td>noise figure</td>
<td>dB 5</td>
</tr>
<tr>
<td>input VSWR</td>
<td>&lt;1.6</td>
</tr>
<tr>
<td>output VSWR</td>
<td>&lt;1.6</td>
</tr>
<tr>
<td>minimum tolerable load impedance</td>
<td>Ω 0</td>
</tr>
<tr>
<td>maximum tolerable load impedance</td>
<td>Ω ∞</td>
</tr>
<tr>
<td>EMC screening</td>
<td>dB &gt;80</td>
</tr>
<tr>
<td>maximum loss power dissipated to air</td>
<td>W 50</td>
</tr>
</tbody>
</table>
2.5.11 Experimental Devices/Insertions

Insertions are for the mass measurements of rare isotopes in the isochronous mode: Two time-of-flight detectors, similar to the one already operated in the ESR and a high sensitivity resonant Schottky noise detector.
2.5.12 Cryogenics

n/a
2.5.13 Accelerator Controls

This section gives a brief description of the FAIR accelerator control system (ACS). Taking into account the international distributed project structure and extraordinary technical complexity of the FAIR accelerators, a policy of strict standardization is essential. The same common accelerator control architecture, infrastructure, hardware and software base will be used for all FAIR machines. The main characteristics of the FAIR control system are described here, even if not all might be relevant for this specific machine. A more detailed description is in preparation.

The common FAIR accelerator control system will be defined, designed, implemented and commissioned as an in-kind contribution of Germany, under the responsibility of the Controls group at GSI. Architecture and interface definitions will be worked out in co-operation with partners and are obligatory and well enforced within the project such that all software and hardware developments must comply with the interface definitions specified. The ACS development will be supported and aided by partner specialists to implement device drivers, specific GUI applications and dedicated solutions within the defined general frameworks. Special measures have to be taken to impose project standards as solutions in order to achieve a coherent controls solution.

The FAIR facility will present unique challenges for the ACS which are well beyond the capacity of the existing system. From the very beginning, the design of the ACS has to consider all aspects of the expected functionality needed to operate the FAIR facility. The existing GSI control system will be modernized, with obsolete technology replaced, and will be integrated into the new FAIR control system. The ACS does substantially build on proven principles and solutions of the existing system and is based on a strictly modular design with well defined interfaces. In the design of the system, industrial and widely available commercial hardware and open software components will be used as much as possible. In addition, proven solutions and complete building blocks from other control systems (e.g. collaboration with CERN) will be used in order to reduce development effort. The ACS will be validated and tested already at the existing GSI machines in order to avoid parallel commissioning of a new control system and new FAIR machines.

2.5.13.1 General System Architecture

The architecture of the common FAIR accelerator control system is illustrated in Figure 2.5-46. The architecture foresees three tiers:

The **Presentation Tier** consists of applications for operators and end-users. Typically, these are graphical user interfaces (GUI) applications, but can also be web applications or command-line scripting tools.

The **Business Tier** provides services to the control system. Services are provided both to presentation tier (e.g. name service, archive data) and to the resource tier. The services are responsible for managing almost orthogonal aspects of a control system across the entire facility. All applications reside upon this common layer to benefit from the common software infrastructure.

The **Resource Tier** is closest to the devices that the control system manages. Components of the resource tier map device-specific protocols (e.g. reading/writing of process variables, alarm detection, etc.) to the device-independent protocols standardized across the facility (abstraction). Also, some resource tier components might perform low-level closed-loop control of devices.
The FAIR control system will be implemented as an object-oriented decentralized distributed system. It will be based on a strictly modular design with well defined interfaces. This allows breaking down the project in interconnected work packages that can be implemented independently.

### 2.5.13.2 Hardware for Equipment Interfacing

The ACS will support several ways of connecting equipment of different types. However, the number of interfaces to the ACS must be kept limited as a large variety of different interfaces cannot be supported and maintained with limited personal resources. At the resource tier, the various actuators, sensors and data acquisition devices are interfaced to the ACS through the following types of front-end controllers:

VME, PCI and emerging PCI-express single board computers are dealing with high-performance real-time processing and data acquisitions. Such systems can employ a large variety of standardized and custom I/O modules (ADC, DAC, binary I/O, Counters, etc.). Typically, the accelerator timing systems, beam diagnostic systems, and interlocks are implemented in this technology.

Most accelerator devices (e.g. all power supplies, rf-systems, kickers, etc.) are interfaced by a dedicated and cost-effective front-end controller (FEC) instead of being connected via a fieldbus. This FEC is defined as the “FAIR standard controller”. It is a network node, connected to the timing network (wherever necessary), and provides local CPU-power for real-time control, fast data acquisition as well as any specific functionality needed (e.g. state-dependent tolerance band control). The FEC is a processor board with one operating system (e.g. Linux). Time critical functions are implemented in FPGA technology. A dedicated parallel bus is defined as an interface to electronics boards of devices. The FEC provides and features a device-implemented function generator (FG) for equipment that needs to be controlled by time-
dependent functions (ramps). The FG provides linear and quadratic interpolation at 1 MHz
data rate between base points with 24 bit output resolution.

Programmable Logic Controllers (PLCs) are increasingly used for controlling industrial
equipment. This type of controller can be chosen when the process is not synchronized to ac-
ccelerator timing and when sampling periods are longer than ~100 ms. Being highly reliable,
cost effective and easy to program via standard high-level languages, PLCs are foreseen to
manage and control vacuum components, machine cryogenics, rf monitoring, personal safety
system, interlocks, etc.

### 2.5.13.3 Timing System

The FAIR facility involves a long chain of accelerators which need to be tightly synchronized.
An important consideration in the design of the FAIR facility is a high degree of truly parallel
operation of the different machines to facilitate the different research programs.

The primary task of the timing system is to trigger and synchronize equipment actions, timed
according to the accelerator cycles, and to synchronize devices which have to operate simulta-
neously. The timing system must handle 20 ms cycles (present UNILAC) as well as ma-
chine cycles and manipulation phases in the order of several seconds for the synchrotrons and
up to several hours for the storage rings. Careful analysis of machine requirements have re-
sulted in a two staged timing solution: A general machine timing (GMT) system will be im-
plemented as an event based system. It will provide concurrency of events by transmission
time compensation, event resolution of at least 1 µs and event separation of follow-up events
of better than 10 µs as well as absolute timestamps. For high-precision synchronization be-

tyond the parameters of the GMT (e.g. distributed rf- and kicker-control, bunch-to-bucket
transfers, time-of-flight measurements) a bunch timing system (BuTiS) will distribute high
precision clock trains (100 kHz, 200 MHz) on carefully selected fibers, properly delayed and
stabilized to compensate propagation delays to every BuTiS end-point and achieve a timing
jitter of no more than 200 ps.

The GMT will broadcast centrally generated timing telegrams in a star topology. Distribution
is based on Gigabit Ethernet transmission technology using fiber and Copper transmission
lines. Transmission rate will be 1 MHz. A dedicated bi-directional timing network is used
with active switches and fan-out modules to distribute the timing telegrams to an array of
*event receivers* (EVR). Upstream signal propagation allows measuring the fiber and transmis-
sion delays with sub-microsecond precision. The emerging standard Precision Time Protocol
(PTP) as defined in IEEE 1588 is foreseen to be used to synchronize distributed clocks in the
timing network and compensate for transmission delays.

A key requirement of the FAIR control system is the need of an absolute timing reference to
timestamp the accelerator data. UTC will be adopted as the standard of date and time for all
FAIR accelerators as it is the basis for the worldwide system of civil time. Source of date and
time for all FAIR accelerators will be a Global Positioning System (GPS) time receiver to
which the GMT event transmission and the BuTiS clock trains will be synchronized and
phase locked.

The outline of the GMT system is shown in Figure 2.5-47. For each of the FAIR machines a
dedicated timing *event generator* (EVG) generates all timing signals utilizing internal count-
ers, event sequencers and hardware inputs. The EGV broadcasts information about the beam
to be handled next and is pre-loaded with an event table for cycles or beam manipulation
phases. Alternative event tables are supported to handle abort of beams even during run-time
of a cycle. In addition to timing events other meta-information (e.g. accelerator cycle identi-
fier, context, safe-beam flags) can be transmitted or broadcasted.
A master cycle sequencer (MCS) will coordinate beams and cycles throughout the FAIR accelerators. It will orchestrate and synchronize every single machine EVG, establish a pattern of beams featuring a high level of truly parallel operation, take care of general restrictions, and will be able to handle alternative beam delivery scenarios in case of emergency or non-availability machines in the accelerator chain. The timing telegrams of all EVG and the MCS will be concentrated such that all information is available at any timing receiver in the facility. Event receivers (EVR) decode the event stream and provide hardware outputs or software interrupts based on event information. The EVR has a synchronized local clock such that data can be time-stamped to the microsecond level. EVR shall be available in all relevant form factors such as VME, PMC, cPCI as well as an integrated module for the FAIR standard device controller. Propagation and transmission delays will be compensated in the EVR in order to achieve synchronous event reception all over the facility. The upstream channel of the GMT system can be used to synchronously and deterministically exchange short telegrams between dedicated devices as is needed e.g. for bunch-to-bucket transfer. It is being investigated whether the upstream communication will be also used to gather interlock and safety-critical state information from the device level.

2.5.13.4 Networking

The FAIR controls network is a 100-Mbps switched Ethernet network, with a backbone at 1 Gbps. The number of nodes is about 2000. The chosen network design will provide enough flexibility for the number of nodes to be increased without difficulty if required. Each node will be connected to a switch by a point-to-point link. The switches are connected to the site high-speed backbone though 1-Gbps uplinks. To contain and control network traffic and impose cyber security, the technical accelerator network (ACCNET) will be separated from the campus general purpose network by using virtual LAN technology (VLAN network segregation). The technical network is connected with other network domains via dedicated network routers. The traffic crossing two domains is restricted to a minimum by use of routing tables, and only mandatory traffic can pass such boundaries.
2.5.13.5 Computer Systems, FAIR Control Center

The upper layers of the FAIR control system (presentation tier) will be deployed on operation consoles and fixed displays, files and application servers to meet the requirements of the FAIR applications software. The servers run a Linux operating system and are used to run the FAIR business-tier software, to host operational programs and also offer specific services. Emphasis will be put on the hardware reliability and availability issues by selecting multi-CPU architectures with redundant and hot-swappable power supplies, discs and fans. RAID techniques will be used to ensure data integrity and disaster recovery. All FAIR machines including the existing injector chain machines are operated and controlled from a central FAIR Control Center (FCC). Some machines or facility parts (CR/RESR, NESR, HESR, SFRS, FLAIR complex) additionally have local control stations for commissioning, experimental runs or autonomous control. Whether there shall the possibility to remotely operate parts of the facility from outside the GSI/FAIR-site has not been discussed and decided yet.

The operator consoles in the FCC and local control stations will run the GUI applications and will be based on standard PC systems. They will also run a Linux operating system and will support multiple screens to display the data. The total number of operating consoles, screens and fixed displays to be deployed has not been evaluated at this time.

2.5.13.6 Front-End Software Architecture

The software running in the front-end equipment controllers (FECs) will be developed using an adequate front-end framework. This framework is a complete environment for specialists to design, develop, test and deploy real-time control software for the FECs and will also be the new standard for the GSI injector chain. Taking up a proven principle of the present GSI control system, the front-end systems of the resource tier are split in two logical layers: equipment control, which implements the device connection and real-time equipment handling, and device presentation which models the equipment and implements the network access. Both functional layers can be physically implemented on the same hardware platform.

Devices are implemented as objects in the object-oriented software terminology. They provide access by services and applications via the controls network and will be modeled by similar patterns for all devices. This allows access through identical mechanisms for all devices. Devices are set, read or controlled by properties via the controls middleware.

Devices will support several beams at a given time (time multiplexing). The setting and configuration data for all beams reside in the equipment controllers. By this, no download from higher layers of the control system is needed between accelerator cycles, except for changes. By this, several sets of reference and actual data can be handled simultaneously, one for each of the beams configured in the accelerator facility. Switching the components settings to fit to the actual beam parameters is done in the equipment control sub layer, according to information which is distributed by the timing system.

2.5.13.7 Controls Middleware

The controls middleware is an ensemble of protocols, Application Programming Interfaces (API) and software frameworks, which allows seamless communication between the software entities of the ACS. Two conceptual models are supported: the device access model and the messaging model. The device access model is mainly used in the communication between the resource and business/presentation tier while the messaging model is mainly used within the business tier or between the business tier and applications running in the presentation tier.
The devices access model is implemented by using the CORBA protocol which provides a high level of abstraction. Complementary, the messaging model is based on the Java Message Service (JMS) as the messaging solution for Java based control applications.

### 2.5.13.8 Services and Application Software Architecture

Applications controlling the GSI/FAIR accelerator chain must handle a great variety of tasks such as visualization of data and significant computation, together with database and equipment access. These applications rely on several services such as security, transactions, and remote access and resource management. These requirements dictate a modular and distributed architecture with a clear separation between the user interfaces (GUI), the control core or service, the model, and the devices that are controlled.

In the general system architecture, the consoles of the presentation tier are responsible for GUI applications and translate the operator’s actions into commands invocation in the business tier. The business tier, through its centralized shared processing power is in charge for providing services, coordination of the client applications, and accessing databases. It also ensures coherence of operator actions and enforces separation between presentation and application logic.

The business and presentation tier services and applications are based on the Spring framework. Spring, being an industrial standard defined by a set of specifications and APIs, is based on Java programming language. Components are the key technology to write modular object-oriented distributed applications.

The GUI applications will be based on a set of common control system services and generic components in order to avoid duplication of effort and solutions. All operational applications will use the provided interfaces which represent the "software view" of the ACS. The operational software development process relies on common development tools, guidelines and procedures for the design, implementation, testing, integration, deployment and change management.

By defining and implementing such a software development framework for services and GUI applications, the developers can concentrate on writing code for the accelerator controls components such as parameter management, setting generation, cycle handling, trim management; they do not have to write system level services.

### 2.5.13.9 Accelerator Settings and Management

The GSI/FAIR accelerators and beam lines will be set and manipulated as much as possible on the base of high level physical values. The generation and management of complex settings is a functionality provided by dedicated services in the business tier of the ACS. They are based on theoretical machine models and ion-optical simulation programs. Additionally, operators and machine specialists can apply small corrections (trims) to settings that need to be handled.

In order to obtain and preserve a comprehensive and coherent architecture for setting generation and management a modular framework will be provided. Every machine (linac, synchrotrons, storage rings, beam lines, etc.) will be represented by a machine manager (MM) service that provides an API to individual machine models. These might be implemented highly machine specific based on a set of make-rules which derive device specific settings from high level machine parameters. For the ring-machines (synchrotrons and storage rings) a generic model that can be highly customized is foreseen by the machine specialists.

In order to handle dependencies from other machines, organize and optimize the timing for cycle management of the FAIR complex a coordinating beam manager (BM) service will be implemented. The BM interfaces with all individual MM, accounts for maximum parallel operation, external constraints like dynamic cryogenic and energy load, and can be operated...
by the central cycle management application. This application allows editing cycles in the accelerator chain and will assist the user in finding an optimal sequence.

2.5.13.10 Industrial Controls

Some of the technical subsystems of the FAIR facility (e.g. machine cryogenics, vacuum system, facility monitoring) are not time-critical and highly industrial related. The control of these systems is foreseen to be realized based on a common industrial automation system (SCADA, supervisory control and data acquisition system) and integrated into the ACS. There are several advantages to this approach: A SCADA system is highly available and reliable and will run autonomously, decoupled from the ACS which is an important aspect for cryogenics and vacuum. Experience shows that industrial partners can be contracted to follow technical and functional specification to deliver turn-key solutions. Despite the autonomous controls, the industrial control system will however be fully integrated into the ACS by a gateway functionality.

The UNICOS framework (unified industrial control system) developed at CERN which is based on the commercial SCADA product PVSS2 is a strong candidate to be evaluated for use at FAIR. This framework provides components, methodology and tools to design, build and program industrial based control systems.
2.5.14 Survey and Alignment

2.5.14.1 General Considerations

This section describes common aspects of Survey and Alignment (S&A) that are significant for the accurate positioning of FAIR components in general. Surveying activities in support of any constructional work are not covered here and are not in the scope of the S&A team.

2.5.14.2 Role of Survey and Alignment in FAIR: Major Tasks

The fundamental task of survey and alignment in the context of the construction of accelerators is the precise physical and geometrical positioning of machine elements, especially dipoles, quadrupoles, beam diagnostic devices, collimators etc. according to an exactly specified nominal position – the lattice – and the required alignment tolerances. It has to be emphasized that a precise alignment is needed not only for first installation; also a regular control of the actual position of the accelerator and the preservation of the nominal values over a long period is under the responsibility of the S&A team.

In order to be able to fulfil the given tasks, fundamental boundary conditions concerning building design, machine geometry or positioning tolerances – typically some tenth of millimetre – have to be available at an early stage of planning, since the choice of measuring technology is substantially dependent on these parameters. Likewise, exerting an influence of S&A experts on design criteria in the areas of shielding, tunnel size, stay clear areas, cable routing, component supports and adjustment devices among others, is essential, to plan effective survey and alignment procedures.

2.5.14.3 Basic Survey and Alignment Steps (installation phase)

Accelerator components need to be aligned to very tight tolerances. In order to perform these tasks, fundamental work packages are essential:

- Definition of appropriate coordinate systems
- Design, lay-out and installation of a primary network on the surface for the orientation of the connected machines (existing and planned) and increasing the accuracy of the tunnel network
- Network densification by transferring the primary net into the single machine buildings. These networks are the basis for the mark out of the ideal positions of the supports and accelerator components (accuracy ± 1-2 mm) and the pre-alignment.
- Precise three-dimensional reference network measurements including component positions for each individual machine (accuracy ± 0.1 mm)
- Relative alignment of neighbouring magnets, beam diagnostic devices and other components that have to be positioned to tight tolerances
- Precise three-dimensional measurement for quality control in order to detect failings in initial alignment or meanwhile occurred deformation.

Independent of the methods that will be used to align any component, it has to be clear, that every component, which requires alignment, needs to be fiducialized before installing it into the ring or beamline.
2.5.14.4 Work Packages: Description of Basic Principles

Fiducialization

Fiducialization is a term for relating the magnetic respectively mechanical axis of a component to some kind of reference marks – the fiducials – that can be seen or touched by instruments. These fiducials are used for positioning the accelerator components within the tunnel. Fiducialization is a two-step-process. Firstly the axis has to be determined; secondly the position of this axis has to be related to the external fiducials [29]. The results of any fiducialization should be 3D-coordinates $x$, $y$, $z$ of the fiducials with respect to the magnetic axis and the field vector. This allows an explicit description of the six degrees of freedom – that is position and orientation in space – for every component.

During installation and maintenance of the existing GSI-machines extensive experiences in the field of fiducialization of resistive or conventional magnets and other components could be gained [30]. The fiducials at warm magnets are usually located directly on the laminations. Once measured it is assumed that the fiducial marks do not change their position. The mechanical axis can easily be visualized by a mandrel as shown in Figure 2.5-48.

![Existing quadrupole with inserted mandrel.](image)

A very close collaboration of magnetic and geometric measurement groups is essential to fulfil the requirement on giving realistic, precise values for the relation between axis and external reference marks. Additional information is necessary in order to be able to give reliable quantities for the accurate positioning of an invisible object – the magnetic axis. Therefore the dimensional control of the magnets to ensure the production tolerances has to be carried out.

Re-using components

It should be mentioned, that all components of existing machines which will be re-used (e.g. the magnets which were installed in the ESR), and which were already prepared for a precise, polar, three-dimensional alignment procedure must be fiducialized again. Only this way an updated, modern survey and alignment concept can be implemented.
**Considerations on total error budget**

Undoubtedly the process of fiducialization has to be at least as accurate as the positioning of the component to their nominal coordinates; actually much more accurate than that, due to the different sources of errors, which form the total error of a final magnet position within the tunnel [31].

Possible sources of error:
- Manufacturing
- Determination of the axis / "magnetic measurements"
- Relating axis to fiducials / "geometric measurements"
- Residuals after least square network adjustment
- Uncertainty of measurements during alignment procedure
- Movement of the floor (long / short term)
- etc.

\[ s^2 = s_1^2 + s_2^2 + s_3^2 + s_4^2 + \ldots \]

This quadratic sum of all individual errors has to be taken into account when reflecting on positional tolerances, which are usually several times the r.m.s. again. Note that assumed errors of 0.1 (0.15 / 0.2 / ...) mm for all above mentioned error sources (which does not reflect the truth in either case) yield to a total error of 0.3 (0.4 / 0.6 / ...) mm.

The knowledge of a total error budget can help to derive or re-evaluate reasonable tolerances.

**Tolerances**

A high degree of accuracy is required in the spatial positioning of accelerator components. Up to now for FAIR alignment tolerances are in no case finalized; thus accuracy of reference points, which will be needed in the entire ring tunnel etc. to create a survey network, is not defined yet; neither global nor relative uncertainty.

However, tolerances can be assumed to be in the range of some hundred microns, similar to the existing machines. This assumption leads to the choice of the measuring technology, whose accuracy of measurement – following a rough rule of thumb – has to be at least three to five times better than the given tolerance.

Up to now there are no indications of a demand for very high accuracies (10µm or similar) for any setup. In this case fundamental changes in the so far traced measuring philosophy would be necessary.

**Instrumentation**

**Measuring devices**

State-of-the-art Laser Tracker, which is a mobile three-dimensional coordinate measurement machine, precision Total Stations and precise digital levels, will be the preferred instruments to fulfil the tasks of surveying and alignment in the majority of cases – both in initial installation phases and in regular periods of realignment.

The Laser Tracker is a dynamic measurement system which consists of a laser interferometer and a device for an absolute distance measurement, motor driven rotating mirrors with angle
encoders to follow a corner cube reflector to the desired spot. The tracker gives 3D coordinates of a target in space with single point accuracy of ~27 µm (2σ) at a distance of 2 m (~50 µm @ 10 m / ~110 µm @ 30 m). Due to its multiple use this kind of instrument will attend the entire project duration: from quality checks on components to test measurements at the magnet test facility, from fiducialization via reference network measurements within the tunnel to the alignment of magnets, detectors and other experiment installations.

![Figure 2.5-49: Type of a laser tracker (left) and an industrial total station (right).](image)

At GSI a Laser Tracker Figure 2.5-49 is regularly applied since 1996 for fiducialization and in some cases for network measurement and alignment [32].

The measurements for the primary surface network and the transfer into the tunnel will partly require receiver of the satellite system GPS and an optical plummet. Due to the forest that has to be protected as far as possible, some problems will arise with GPS, thus classical triangulation/trilateration with Total Stations has to be performed, too.

In order to reach positioning accuracies in a range of few millimetres (3D, 1σ) while using the Global Positioning System, it is inevitable to use several geodetic double frequency receivers simultaneously that carry out static measurements of a duration up to 20 h; the data post-processing is necessary using e.g. the Bernese GPS software. A meanwhile well known 'real time kinematic' solution is not suitable to obtain the required high relative accuracies [33].

![Figure 2.5-50: General design floor nest (left) and floor nest in-ground (right).](image)

Again, the predetermination of measuring technology guides to the design of reference points in the tunnel floors and walls just like on the magnets and other components, which have to be aligned to very tight tolerances (fiducial points). No permanent instrument monuments (like pillars) will be installed within any tunnel. Each reference point will be shaped in a way, that removable targets with a diameter of 1,5 inch can be inserted with highest repeatability (e.g.
ball mounted retroreflectors, etc. – see Figure 2.5-50 and Figure 2.5-51 © Metronom Automation GmbH).

![Figure 2.5-51: Wall nest with 1.5" corner cube reflector (left) and design drawing wall nests and component fiducials.](image)

**Software**

Suitable metrology software that provides running a number of different instrument - and hence - observation types, simulating point accuracies from expected observational uncertainties and, with this, planning a network layout, exists at GSI (PANDA, WinGeonet/Lego). The already existing, long time utilised hard- and software modules (TASA) for network measurement, data analysis, online-alignment, data presentation and documentation etc., are based on the primary use of Total Station [30]. This proved system was meanwhile adapted to newer techniques, thus a new data flow to LEGO adjustment module for combined Laser Tracker and Level measurements using TASA software package was realized.

**Survey networks**

**Simulation**

The design of survey networks, represented by fixed reference points within the different facilities, is a major task, which results in scheduling the most suitable number and position of the points and the quantity and kind of observations. The still undefined requirements of network accuracy in the various areas of the facility have to be achieved. Detailed simulation calculations result in a prediction of global and relative uncertainties of all reference points including fiducial points on magnets etc.

Up to now no simulation was performed for the subsystems, for which reliable, definite information concerning final size, detailed lattice, tunnel layout, location of the rings in relation to each other, design of buildings and much more are needed.

**Free stationing**

The actual survey and alignment plan relies on a Laser Tracker combined with levelling, and in some cases combined with a Total Station. Laser Tracker uses free stationing technique for orientation. Free stationing technique has no need for fixed instrument monuments. The measurement system can be set up very flexibly, only visual contact to evenly spread points on the wall and floor is required. However, the number of necessary points – compared to a centred instrument setup – has to be higher; it has to be paid careful attention to the configuration of reference marks. This makes clear, that a robust, consolidated floor and side walls – at least during the survey and alignment period - is imperative.
The principles of installing a three-dimensional net and the determination of the net parameters with the help of Laser Trackers are state of the art; they correspond to the proceeding of the international community in accelerator alignment.

Alignment – positioning of components

The precise, fast and correct alignment of machinery in three dimensions within the facility depends on the network configuration and quality as well as on suitable mechanics respectively the adjustment ability of a component at all. With the knowledge of the position of the pre-aligned magnets et al. with respect to the reference network points, adequate correction values can be calculated due to the comparison of actual coordinates with ideals. An online alignment (absolute control of component movement) can be carried out by using a Laser Tracker.

Expected temperatures within the tunnel during operation, which will fundamentally differ from the values during installation and adjustment, have to be considered while computing the nominal values for the initial positioning of the components. Unequal behaviour of expansion of different used materials for components and related fiducials, supports, girders etc. must be taken into account. Furthermore, possible different temperature zones within a single machine during operation have to be considered: non-systematic positional changes or offsets between neighbouring components due to this influence must be compensated.

Monitoring

For a successful operation of particle accelerators the long-term as well as the short-term stability of the concrete floor supporting the beam components is crucial. Settlements have impact on the position of magnets and experiment setups. Excavation, increased traffic on the construction site among other things can cause significant deformation at adjacent buildings. Due to the fact that the already existing machine is intended to remain operational while constructional works for FAIR will happen – respectively the accelerator of FAIR in its first stage is working while the next phase of civil construction takes place – a monitoring system becomes necessary. For this purpose, Hydrostatic Levelling Systems, which allow measurement of deformations in real-time with a very high accuracy (µm), can be used - like performed for example at JASRI / SPring-8 [34].

For the determination of long-term settlements within the existing buildings, surveys in approximately yearly intervals had been performed until year 2002. Critical areas within the different existing and planned buildings, which possibly need stationary monitoring systems in the future in order to see short-term positional changes during construction work, are not yet identified.
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