Technical Design Report on the Proton Linac

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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 p-Linac.

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 man power – 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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2.7 p-Linac

The Technical Design Report covers the design for the accelerator system of p-Linac (PSP-code 2.7).
2.7.1 System Design

2.7.1.1 The Role in the FAIR Project

A significant part of the experimental program at FAIR is dedicated to antiproton physics. For the various experiments an ultimate number of up to $7 \cdot 10^{10}$ cooled pbar/h is required. Taking into account the pbar production and cooling rate, this is equivalent to a primary beam of $2 \cdot 10^{16}$ protons/h to be provided by the chain of accelerators comprising a proton linac and the two synchrotrons SIS18 and SIS100 (Figure 2.7-1).

![Figure 2.7-1: Schematic overview of the accelerator chain for the pbar physics program at FAIR. Proton beam lines are depicted as a solid orange line and pbar beam lines are dashed orange lines.](image)

The achievable primary proton rate is limited by the space charge limit (SCL) in the synchrotron SIS18 being filled by horizontal multi-turn injection (MTI). During injection into the SIS100 a maximum stacking factor of 4 is achieved. Accordingly, the number of primary protons per SIS100 spill scales as the SCL of SIS18, i.e. $\beta^2 \gamma^3$. The maximum rate of cooled pbars is limited by the stochastic cooling power since the cooling time scales proportional to the number of hot pbars for a sufficiently high signal-to-noise ratio. Typical cooling times in case of a non-ideal signal-to-noise ratio are about five seconds. During the stochastic cooling process in the CR the SIS100 can be used to accelerate ion species different from protons. Figure 2.7-2 summarizes these dependencies as function of the proton linac energy. The proton linac energy of 70 MeV allows for the maximum rate of cooled pbars. Increasing the proton energy does not change the cooled pbar rate but it disengages SIS100 cycle time, since the stochastic cooling time is longer than five seconds in this case. For a multi-ion facility like FAIR the choice of the proton injector energy is a trade-off between efficient use of...
accelerator cycle times and of linac economics, since the linac cost increase with the linac final energy.

![Figure 2.7-2: Dependence of the space charge limit of proton beams in the SIS18 (green curve) and corresponding relative duty time for primary proton beam delivery by the SIS100 (black) as function of the proton linac energy. The achievable rate of cooled pbars is presented by the red curve.](image)

### 2.7.1.2 General Description

#### 2.7.1.2.1 Conceptual Layout

The choice of a proton energy of 70 MeV delivered by the proton linac is an adequate compromise. It results in a proton duty cycle of the SIS100 synchrotron of 38% and allows for linac operation at a single RF-frequency, i.e. 325 MHz. The minor increase in gain in SIS100 cycle time at energies in excess of 70 MeV does not pay for the required jump in RF-frequency and the resulting increase of overall system cost. Although at SIS18 injection a current of 35 mA is required a maximum design current of 70 mA for the linac was chosen. In case that the stochastic cooling power is increased in future the accelerator chain will demand for higher proton linac currents. The normalized transverse emittance of the linac was set to a design value of 2.1 mm mrad. A current of 35 mA results in a proton linac beam pulse length of 36 µs equivalent to the filling time in the SIS18 within one MTI cycle, i.e. 18 turns; thus the space charge limit is reached.

The conceptual layout of the proton linac is depicted in Figure 2.7-3, the main parameters are listed in Table 2.7-1. The proton beam is foreseen to be generated in an ECR type proton source and a proton current of up to 100 mA can be extracted at 95 keV. The subsequent Low Energy Beam Transport (LEBT) is based on two-solenoid magnetic focusing and provides the required separation of H3+, H2+, and H2 fractions from the proton beam. Bunching and acceleration to 3.0 MeV will be accomplished in an RFQ.
Table 2.7-1: Main design beam parameters of the FAIR proton linac.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>70 MeV</td>
</tr>
<tr>
<td>Maximum design current</td>
<td>70 mA</td>
</tr>
<tr>
<td>Current at SIS18-injection</td>
<td>35 mA</td>
</tr>
<tr>
<td>Protons per pulse</td>
<td>$7.9 \times 10^{12}$</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>36 µs (35 mA)</td>
</tr>
<tr>
<td>RF-frequency</td>
<td>325.224 MHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>≤ 4 Hz</td>
</tr>
<tr>
<td>Beam emittance (transv., tot., norm.)</td>
<td>≤ 2.1 mm mrad (35 mA), 4.2 mm mrad (70 mA)</td>
</tr>
<tr>
<td>Beam momentum spread (tot., norm.)</td>
<td>≤ $10^{-3}$</td>
</tr>
<tr>
<td>Overall length</td>
<td>≈ 34 m</td>
</tr>
</tbody>
</table>

Figure 2.7-3: Conceptual layout of the proton linac of FAIR comprising a proton source, an RFQ, and a Drift Tube Linac (DTL) based on 12 CH-cavities.

The main linac, preceded by a re-buncher for longitudinal beam matching, comprises 12 Crossed-bar H-mode cavities (CH) accelerating the beam to its final energy of 70 MeV. CH-cavities (Figure 2.7-4) represent the extension of well established Interdigital H-cavities to higher particle velocities [1]. In connection with the applied KONUS beam dynamics [2] they provide high effective shunt impedances which in turn allow for a compact and cost efficient linac. In order to reduce the number of RF-power sources, the 12 CH-cavities are grouped to six independent pairs of RF-coupled cavities.

Figure 2.7-4: A pair of RF-coupled CH-cavities. The drift tubes in the centre and at the end plates will house a focusing quadrupole triplet each.
Transverse beam focusing is accomplished in quadrupole triplets housed inside the cavity end plates and in the cavity pair coupling cells. The beam dynamics layout is in progress. Full transmission of a 70 mA beam was achieved in simulations showing growth of the transverse emittances (Figure 2.7-6, Figure 2.7-7). Further optimization is required to reduce this growth. In order to assure operation within the design emittance of 4.2 mm mrad a beam dynamics design for a total output current of 90 mA is in preparation [3]. An extended diagnostic section after the 6th CH-cavity is integrated into the DTL. It includes transverse scrapers to eliminate particles with large emittances with respect to the beam core. Additionally, an advanced error analysis study was initiated [4]. Parameters that enter into beam dynamics simulations are subject to errors following a Gaussian distribution. Many runs were made with different assumptions on errors in quadrupole alignments as well as in RF-amplitudes & -phases. The sources of errors and their amounts are listed in Table 2.7-2. A resulting average beam loss scenario is plotted in Figure 2.7-5. For time being the studies do not include corrections by steerers. This feature is currently implemented. It turned out that the losses are dominated by quadrupole translations.

**Table 2.7-2:** Sources and amounts of errors (rms) used for error studies.

<table>
<thead>
<tr>
<th>Source</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole translation hor., ver.</td>
<td>± 0.1 mm</td>
</tr>
<tr>
<td>Quadrupole rotation around hor., ver. axis</td>
<td>± 1 mrad</td>
</tr>
<tr>
<td>Quadrupole rotation around beam axis</td>
<td>± 5 mrad</td>
</tr>
<tr>
<td>Cavity voltage error</td>
<td>± 1%</td>
</tr>
<tr>
<td>Single gap voltage error</td>
<td>± 1%</td>
</tr>
<tr>
<td>Cavity phase error</td>
<td>± 1°</td>
</tr>
</tbody>
</table>

**Figure 2.7-5:** Uncorrected beam losses along the DTL resulting from systematic error studies on quadrupole alignment and RF-voltages and -phases.
Figure 2.7-6: Simulated horizontal (red) and vertical (black) beam envelopes along the DTL section for a current of 70 mA. The envelopes include 95% of the particles and the transmission is 100%. The extended diagnostic section is not included yet.
Figure 2.7-7: Simulated transverse and longitudinal phase space distributions after the RFQ (upper), after the DTL (centre), and at the injection into the SIS18 (lower) for a current of 70 mA. The emittances including 95% of the particles are indicated. The beam transmission is 100%.

The RF-pulse length of 200 µs (Chapter 2.7.4) and a maximum repetition rate of 4 Hz result in a low RF-duty factor of 0.08%. This simplifies the mechanical design of the normal conducting RF-cavities with respect to cooling.

After an achromatic 90°-inflection into the existing transfer channel UNILAC-SIS18, a second re-buncher tilts the longitudinal phase space distribution in order to provide a minimized momentum spread at injection into the synchrotron SIS18.
2.7.1.2.2 System Parameters

The basic beam parameters and technical parameters of the proton linac are summarized in Table 2.7-3.

Table 2.7-3: Main design parameters of the FAIR proton linac.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton Source</strong></td>
<td></td>
</tr>
<tr>
<td>source type</td>
<td>ECR</td>
</tr>
<tr>
<td>beam pulse length</td>
<td>≤ 1 ms</td>
</tr>
<tr>
<td>proton fraction</td>
<td>≥ 70%</td>
</tr>
<tr>
<td>extracted proton current</td>
<td>≥ 100 mA</td>
</tr>
<tr>
<td>extraction voltage</td>
<td>95 kV</td>
</tr>
<tr>
<td>LEBT</td>
<td></td>
</tr>
<tr>
<td>focusing scheme</td>
<td>2 solenoids</td>
</tr>
<tr>
<td>molecule fraction analysis (H^+, H^+_2, H^+_3)</td>
<td>time of flight</td>
</tr>
<tr>
<td>beam chopping</td>
<td>electrostatic to 100 µs</td>
</tr>
<tr>
<td>output proton current</td>
<td>100 mA</td>
</tr>
<tr>
<td>output emittance (norm., tot.)</td>
<td>≤ 1.8 mm mrad</td>
</tr>
<tr>
<td>mechanical length</td>
<td>≤ 2.5 m</td>
</tr>
<tr>
<td><strong>RFQ</strong></td>
<td></td>
</tr>
<tr>
<td>cavity type</td>
<td>4-rod, water cooled</td>
</tr>
<tr>
<td>output energy</td>
<td>3.0 MeV</td>
</tr>
<tr>
<td>cavity cooling requirements</td>
<td>water, 10 l/min, T_{cool}–T_in ≤ 4 K, δT ≤ ± 2 K</td>
</tr>
<tr>
<td>max. accelerated output current</td>
<td>≥ 90 mA</td>
</tr>
<tr>
<td>output emittance (transv., norm., tot.)</td>
<td>≤ 2.0 mm mrad</td>
</tr>
<tr>
<td>output emittance (long., tot)</td>
<td>≤ 930 keV deg</td>
</tr>
<tr>
<td>cavity Q₀-value</td>
<td>2500 - 8000</td>
</tr>
<tr>
<td>total RF-power (peak)</td>
<td>≤ 1.0 MW</td>
</tr>
<tr>
<td>electric field strength</td>
<td>≤ 36.6 MV/m = 2.0 E₀</td>
</tr>
<tr>
<td>mean aperture radius</td>
<td>≤ 3.9 mm</td>
</tr>
<tr>
<td>mechanical length</td>
<td>≤ 3.5 m</td>
</tr>
<tr>
<td><strong>Drift Tube Linac</strong></td>
<td></td>
</tr>
<tr>
<td>number of RF-cavities</td>
<td>12, grouped to 6 independent pairs</td>
</tr>
<tr>
<td>cavity type</td>
<td>Crossed-bar H-cavity (CH), water cooled</td>
</tr>
<tr>
<td>cavity cooling requirements</td>
<td>water, 10 l/min, T_{cool}–T_in ≤ 4 K, δT ≤ ± 2 K</td>
</tr>
<tr>
<td>output energy</td>
<td>70 MeV</td>
</tr>
<tr>
<td>maximum design output current</td>
<td>70 mA (within design emittance)</td>
</tr>
<tr>
<td>current at injection into SIS18</td>
<td>35 mA (within design emittance)</td>
</tr>
<tr>
<td>output emittance (transv., norm., tot.)</td>
<td>≤ 2.1 mm mrad (35 mA), 4.2 mm mrad (70 mA)</td>
</tr>
<tr>
<td>output momentum spread Δp/p (tot.)</td>
<td>≤ 10⁻³</td>
</tr>
<tr>
<td>cavity Q₀-value</td>
<td>16500 – 18000</td>
</tr>
<tr>
<td>single tank length</td>
<td>0.40 – 2.00 m</td>
</tr>
<tr>
<td>number of gaps per cavity</td>
<td>9 – 15</td>
</tr>
<tr>
<td>tot. RF-power per pair of cavities (peak)</td>
<td>≤ 2.5 MW</td>
</tr>
<tr>
<td>accelerating field strength</td>
<td>8.5 – 2.8 MV/m (depending on part. velocity)</td>
</tr>
<tr>
<td>ratio E_{surface} / E_{acc}</td>
<td>≤ 4.3, i.e. E_{surface} ≤ 1.9 E_k</td>
</tr>
<tr>
<td>effective shunt impedance</td>
<td>93 – 41 MΩ/m (depending on part. velocity)</td>
</tr>
<tr>
<td>focusing scheme (transv.)</td>
<td>separated function quadrupole triplets</td>
</tr>
<tr>
<td>focusing scheme (long.)</td>
<td>KONUS [2]</td>
</tr>
<tr>
<td>mechanical length</td>
<td>≈ 24 m</td>
</tr>
<tr>
<td><strong>Beam Pulse Time Structure</strong></td>
<td></td>
</tr>
<tr>
<td>RF-frequency</td>
<td>325.224 MHz</td>
</tr>
<tr>
<td>RF-pulse length</td>
<td>200 µs</td>
</tr>
<tr>
<td>beam pulse length</td>
<td>36 µs</td>
</tr>
<tr>
<td>repetition rate</td>
<td>≤ 4 Hz</td>
</tr>
</tbody>
</table>
2.7.2 Magnets

All magnets for the proton linac are operated at room temperature. Their main design parameters are listed in Table 2.7-4. Although the main purpose of the linac is to deliver protons to generate antiprotons for the physics program, the accelerator chain might occasionally request proton beams at reduced proton intensities for dedicated experiments. Due to the high space charge forces in the linac, different beam optics have to be applied for different beam currents. Therefore and to reduce operation cost the magnets and their power converters are designed for pulsed operation.

Table 2.7-4: Main design parameters of the proton linac magnets, i.e. type, location, number to be used, field strength or field gradient, effective field length, and aperture radius.

<table>
<thead>
<tr>
<th>Type</th>
<th>Location</th>
<th>#</th>
<th>B(B') / T(T/m)</th>
<th>Leff. /mm</th>
<th>Ap. Rad./mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid</td>
<td>LEBT</td>
<td>2</td>
<td>0.75</td>
<td>200</td>
<td>80</td>
</tr>
<tr>
<td>Steerer (hor/ver)</td>
<td>LEBT</td>
<td>2</td>
<td>B*L_eff = 0.00045 Tm</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Steerer (hor/ver)</td>
<td>DTL, Dump</td>
<td>6</td>
<td>B*L_eff = 0.0125 Tm</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Quad Type A</td>
<td>MEBT, DTL</td>
<td>18</td>
<td>67</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>Quad Type B</td>
<td>DTL</td>
<td>6</td>
<td>67</td>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>Quad Type C</td>
<td>DTL</td>
<td>8</td>
<td>67</td>
<td>90</td>
<td>15</td>
</tr>
<tr>
<td>Quad Type D</td>
<td>DTL</td>
<td>12</td>
<td>67</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Quad Type E</td>
<td>Inflect., Dump</td>
<td>2</td>
<td>40</td>
<td>179</td>
<td>20</td>
</tr>
<tr>
<td>Dipole 45°</td>
<td>Inflection</td>
<td>2</td>
<td>1.30</td>
<td>1571</td>
<td>20<em>20 (hor</em>ver)</td>
</tr>
</tbody>
</table>

2.7.2.1 Solenoids

Two solenoids will be used in the LEBT section. Each solenoid will be powered individually.

2.7.2.2 Steering Magnets

In total seven steerer pairs (horizontal/vertical) are foreseen to be installed in the linac, each of them powered individually. Two steerers in the LEBT allow for on-axis injection into the RFQ; one steerer directly behind the RFQ corrects eventual angle offsets at the RFQ exit; along the DTL section three steerers are foreseen: two within the extended drift between the 6th and the 7th CH-cavity and another one after the last cavity. One steerer is foreseen in the transfer line to the beam dump.

2.7.2.3 Quadrupole Magnets

Five different types of quadrupole lenses are used along the linac and the beam transport sections. The amount of types results from the variation of the beam focusing with the beam energy due to enhanced space charge defocusing for energies below 20 MeV. The low energy end is more sensitive to emittance growth and to preserve a high beam quality in this section the section should be designed as compact as possible, i.e. using short quadrupoles. However, all quadrupoles used along the DTL have the same aperture to reduce the number of types. Outer quadrupoles of triplets are powered in series except for the triplet in front of the first cavity of the DTL and the triplet after the last cavity of the DTL.
2.7.2.4 Dipole Magnets

The two inflection dipoles deflect the beam twice by 45° into the transfer channel UNILAC-SIS18. In case of intolerable beam losses the dipoles are set to zero deflection in order to dump the beam in forward direction. The dipoles have the same horizontal and vertical aperture and are powered in series.
2.7.3 Power Converters

The main parameters of the power converters for the proton linac are defined on the basis of the requirements given in the above chapters. Parameters of devices that could not been defined yet are indicated as "to be defined (tbd)" in the respective table.

2.7.3.1 Magnet Power Converters

The design of the magnet power converters is straightforward. The load data are based on the magnet design specifications and on the supply cable lengths. Cost and sizes of the power converters are estimated with high reliability. The power converters of the steerers and of the quadrupoles are designed very compact, such that two independent power converters fit into one standard rack of 800 mm width. Table 2.7-5 lists the power converters and their load specifications. The ramping time for each power converter is 100 ms except for the solenoid converters being dc-devices.

2.7.3.2 RF Power Source Power Converters

The RF power sources together with their power converters represent a considerable part of the overall project cost. In order to obtain an optimized concept, different scenarios of the RF power alimentation for the given number of RF cavities were investigated technically and with respect to investment cost. Nine different scenarios based on different RF-power source types and on different circuit options (No. of cavities per RF source, No. of RF sources per power converter) were studied in detail and their costs were estimated based on vendor quotations [5]. It was found that a solution based on one power converter driving one klystron which in turn drives an RF coupled pair of cavities results in the best price.

The power converters for pulsed klystrons at 325 MHz need special efforts for the design, specification, and production. Converters for cw-klystrons were operated at LEP. However, for a pulsed machine at this frequency converters are not available yet. For the FAIR proton linac the development aims for devices that can be operated without crow bars in order to be efficient in cost and spacing. A conceptual design as well as a preliminary specification is available.

A power converter system driving a klystron comprises four power converters. The main converter has to deliver the klystron electron beam current pulse of 45 A with a cathode-to-ground voltage of 110 kV. It delivers pulses of 200 µs at 4 Hz. Assuming an electron current of 45 A, a total charge of about 9 mC is required per RF pulse. This charge is stored in a capacitor of 1 µF such that the total amount of energy that might be released in case of a voltage break down (arc voltage of 100 V) will not exceed 11 J (100 V · 110 kV · 1 µF), which is not critical for the klystron. The main part of the energy released in case of a break down, i.e. the equivalent to the total charge in the 1 µF capacitor, will be dissipated in a resistor of about 30 W being in series with the klystron cathode. In the time between pulses the capacitor is re-charged by a 110 kV / 60 mA high voltage source.

A second converter provides the voltage of the modulation anode to control the electron beam current. Additionally, a cathode heater power converter as well as converters for the solenoid circuits is required.
Table 2.7-5: Main parameters of the proton linac power converters, i.e. type, number to be used, load, maximum current, maximum voltage, maximum power, apparent power, and rise time. Parameters not been defined yet are indicated as "tbd".

<table>
<thead>
<tr>
<th>Type</th>
<th>#</th>
<th>Load</th>
<th>Imax/A</th>
<th>Umax/V</th>
<th>Pmax/kW</th>
<th>Papp/kW</th>
<th>T/ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solenoid</td>
<td>2</td>
<td>Solenoid</td>
<td>415</td>
<td>42.0</td>
<td>21.8</td>
<td>19.5</td>
<td>dc</td>
</tr>
<tr>
<td>PS_S1</td>
<td>4</td>
<td>Steerer_S1</td>
<td>200</td>
<td>6.80</td>
<td>3.80</td>
<td>3.10</td>
<td>100</td>
</tr>
<tr>
<td>PS_S2</td>
<td>12</td>
<td>Steerer_S2</td>
<td>200</td>
<td>6.80</td>
<td>3.80</td>
<td>3.10</td>
<td>100</td>
</tr>
<tr>
<td>PS_QA</td>
<td>6</td>
<td>Quad_A</td>
<td>371</td>
<td>16.7</td>
<td>8.60</td>
<td>6.90</td>
<td>100</td>
</tr>
<tr>
<td>PS_QA</td>
<td>6</td>
<td>Quad_B</td>
<td>378</td>
<td>22.4</td>
<td>12.3</td>
<td>9.40</td>
<td>100</td>
</tr>
<tr>
<td>PS_QA</td>
<td>8</td>
<td>Quad_C</td>
<td>378</td>
<td>23.1</td>
<td>12.8</td>
<td>9.70</td>
<td>100</td>
</tr>
<tr>
<td>PS_QA</td>
<td>6</td>
<td>Quad_A – Quad_A</td>
<td>371</td>
<td>29.0</td>
<td>15.2</td>
<td>11.9</td>
<td>100</td>
</tr>
<tr>
<td>PS_QB</td>
<td>6</td>
<td>Quad_D – Quad_D</td>
<td>371</td>
<td>257</td>
<td>120</td>
<td>105</td>
<td>100</td>
</tr>
<tr>
<td>PS_QC</td>
<td>1</td>
<td>Quad_E – Quad_E</td>
<td>370</td>
<td>58.5</td>
<td>21.8</td>
<td>19.5</td>
<td>100</td>
</tr>
<tr>
<td>D1</td>
<td>1</td>
<td>Dip_45° – Dip_45°</td>
<td>425</td>
<td>46.8</td>
<td>150</td>
<td>99.5</td>
<td>100</td>
</tr>
<tr>
<td><strong>RF-pow.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kl_HV</td>
<td>7</td>
<td>Klystron Cathode</td>
<td>60</td>
<td>110000</td>
<td>tbd</td>
<td>tbd</td>
<td>&lt;10⁻²</td>
</tr>
<tr>
<td>Kl_An</td>
<td>7</td>
<td>Klystron Anode</td>
<td>0.02</td>
<td>100000</td>
<td>tbd</td>
<td>tbd</td>
<td>&lt;10⁻²</td>
</tr>
<tr>
<td>Kl_Heat</td>
<td>7</td>
<td>Klystron Heater</td>
<td>26</td>
<td>15</td>
<td>0.39</td>
<td>0.39</td>
<td>dc</td>
</tr>
<tr>
<td>Kl_Sol_1</td>
<td>7</td>
<td>Klystron Sol_1</td>
<td>20</td>
<td>20</td>
<td>0.40</td>
<td>0.40</td>
<td>dc</td>
</tr>
<tr>
<td>Kl_Sol_1</td>
<td>7</td>
<td>Klystron Sol_2</td>
<td>20</td>
<td>94</td>
<td>1.88</td>
<td>1.88</td>
<td>dc</td>
</tr>
<tr>
<td>Kl_Sol_2</td>
<td>7</td>
<td>Klystron Sol_3</td>
<td>20</td>
<td>375</td>
<td>7.50</td>
<td>7.50</td>
<td>dc</td>
</tr>
<tr>
<td>Tube A.</td>
<td>2</td>
<td>Tube Amp.</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
<td></td>
</tr>
</tbody>
</table>
2.7.4 RF-Systems

2.7.4.1 RF-Power Sources

For a pair of RF-coupled CH-cavities the total amount of required peak RF-power including safety margin is 2.5 MW at maximum. As pointed out in Chapter 2.7.3.2 nine different RF-power alimentation schemes employing different RF power sources were investigated in detail [5]. The two re-bunchers require RF-sources with an output power of less then 50 kW, implying the use of tube amplifiers as already operated at GSI.

2.7.4.1.1 Klystrons

The RF-pulse to be provided by the power sources for each pair of cavities is shown in Figure 2.7-8. During the beam pulse, the total forward RF-power is 2.5 MW at maximum and about half of this value for the unloaded cavities. The stability must be better than 0.1%.

A survey on the market with respect to available power sources indicated that adapting the Toshiba klystron 3740A® might give a minimum in investment cost. This klystron is designed for an operation frequency of 324 MHz, a routine operation output peak power of 2.5 MW, and a duty cycle of 3.25%. It is employed at the JPARC linac and it will be used at the ISIS project. Adapting to our frequency of 325.224 MHz is straight forward. Seven klystrons will be used in total, i.e. six to power the DTL cavities and one for the RFQ. The rf-bandwidth is ± 0.75 MHz. The first Toshiba klystron has been delivered to GSI in April 2008 (Figure 2.7-9).

![Figure 2.7-8: Shape of the RF-pulse to be provided by the RF-power sources for the accelerating cavities of the proton linac including a safety margin of 25%. The RF-power is initially switched on and regulated to the unloaded cavity level. The input power is increased within less then one microsecond after the beam entered into a pair of two RF-coupled cavities.](image-url)
2.7.4.1.2 Tube Amplifiers

The two bunchers need RF-power of less than 50 kW and solutions based on conventional tube amplifiers as already used at GSI are foreseen. However, klystron manufacturers were contacted as well in order to receive proposals.

2.7.4.2 RFQ Cavity

The beam parameters at the entrance to and at the exit of the RFQ were defined and are listed in Table 2.7-3. At frequencies above 300 MHz cavities of the 4-vane type are commonly in use as for example the LEDA-, IPHI-, and the BARC-RFQ [6, 7]. The investment cost for these RFQs are usually significant. This is partially due to the high duty cycles of the respective machines and to the corresponding cooling efforts. As an alternative, a 4-rod type RFQ is much simpler in mechanical design and thus less expensive. However, it has not been built so far for frequencies above 300 MHz. The University of Frankfurt gained huge experience on 4-rod RFQs. For the proton linac both cavity types were considered and conceptual designs are completed for both cases [8-11].

The results of the 4-rod RFQ are very promising. With a maximum surface electric field of less than two Kilpatrick (Ek) a transmission of accelerated particles of 98% is reached. Low energy particles which are not trapped into RF-buckets are not transmitted. The normalized transverse emittance almost reaches the design value of 2.0 mm mrad. Figure 2.7-7 (upper) depicts the particle distributions at the exit of the 4-rod RFQ being the proposed option for the FAIR proton linac. The longitudinal output emittance is still too large by a factor of two.

A cold model (352 MHz) of the 4-rod RFQ with eight stems and elliptical electrodes was built [9] in order to verify the results of simulations on the RF-properties (Figure 2.7-10). It was demonstrated that eventual differences in the voltages of the upper and lower rods could be eliminated by proper adjustment of the stem slope. The closest parasitic oscillation mode was found to be a dipole mode at 379 MHz.

---

Figure 2.7-9: A modified version of the Toshiba klystron 3740A used at J-PARC has been delivered to GSI in April 2008.
However, design studies on a 4-vane RFQ are still ongoing at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow [10,11]. With respect to transmission and emittances the design values are achieved. The maximum surface electric field strength of the 4-vane cavity is 1.8 E\textsubscript{k}. The parameters of the two RFQ cavities as achieved in simulations are summarized in Table 2.7-6.

Table 2.7-6: Parameters of the RFQ cavity types for the proton linac as achieved in simulations. The quoted output emittances enclose 95\% of the accelerated output particles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>4-rod RFQ</th>
<th>4-vane RFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>input energy</td>
<td>0.095 MeV</td>
<td>3.00 MeV</td>
</tr>
<tr>
<td>input current</td>
<td>100 mA</td>
<td></td>
</tr>
<tr>
<td>input emittance (transv., norm., tot.)</td>
<td>1.8 mm mrad</td>
<td>2.1 / 2.1 mm mrad</td>
</tr>
<tr>
<td>frequency</td>
<td>325.224 MHz</td>
<td></td>
</tr>
<tr>
<td>output energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total output (accelerated) current</td>
<td>98 (98) mA</td>
<td>94 (94) mA</td>
</tr>
<tr>
<td>output emitt. (transv., norm., tot., 95%)</td>
<td>2.1 / 2.1 mm mrad</td>
<td>2.1 / 2.0 mm mrad</td>
</tr>
<tr>
<td>output emittance (long., tot, 95%)</td>
<td>2095 keV deg</td>
<td>940 keV deg</td>
</tr>
<tr>
<td>cavity Q\textsubscript{0}-value</td>
<td>3100</td>
<td>6640</td>
</tr>
<tr>
<td>distance to closest mode</td>
<td>54 MHz</td>
<td>2.0 MHz</td>
</tr>
<tr>
<td>total RF-input power</td>
<td>0.74 MW</td>
<td>0.83 MW</td>
</tr>
<tr>
<td>electrode voltage</td>
<td>90 kV</td>
<td>100 kV</td>
</tr>
<tr>
<td>max. electric field strength</td>
<td>34.7 MV/m = 1.94 E\textsubscript{k}</td>
<td>32.7 MV/m = 1.83 E\textsubscript{k}</td>
</tr>
<tr>
<td>aperture radius</td>
<td>3.2 m – 3.8 mm</td>
<td>3.9 mm (av.)</td>
</tr>
<tr>
<td>length</td>
<td></td>
<td>3.4 m</td>
</tr>
</tbody>
</table>

2.7.4.3 Re-Bunchers

Two re-bunchers will be used along the linac. The first one is needed to longitudinally match the beam from the RFQ to the first CH-cavity [12] of the DTL as depicted in Figure 2.7-11. The longitudinal dynamics along the DTL is based on the KONUS principle [2], which requires a small phase spread at the entrance to the cavity. The space between the RFQ and the first CH-cavity must house two quadrupoles, a steerer, a phase probe, and a beam current.
monitor. Without a re-buncher the longitudinal drift would result in too long bunches at the DTL entry. The re-buncher is a two-gap cavity requiring less than 50 kW of total RF-power. The second re-buncher is placed in the existing transfer channel from the UNILAC to the SIS18. Its purpose is to tilt the longitudinal phase space distribution in order to minimize the momentum spread for a given longitudinal emittance. It has six gaps and will require less than 15 kW of total RF-power. The cavity type corresponds to the type for the CH-DTL (see following chapter).

![Figure 2.7-11: Mean Energy Beam Transport (MEBT) section beginning at the RFQ end plate and ending in front of the first CH-tank.](image)

### 2.7.4.4 CH-Cavities

The drift tube linac will comprise 12 CH-cavities grouped to six pairs. Each pair comprises two RF-coupled cavities as shown in Figure 2.7-4 and Figure 2.7-12. The distribution of the electromagnetic fields inside such a pair was simulated with Microwave Studio®. Configurations of the electric and the magnetic field are shown in Figure 2.7-12. The polarity of the electric field inside one cavity alternates from gap to gap while it is equal in the subsequent gaps enclosing the central drift tube. This enlarged drift tube represents the RF-coupling transition between the two cavities forming the pair and it will house a focusing quadrupole triplet. Inductive RF-coupling into the cavity pair will be performed opposite to the stem that supports this centre drift tube.
To increase the voltage in the end-cells and to achieve a good flatness of the electric field, the magnetic inductance at the cavity ends is increased. In case of IH-cavities, this is accomplished by large undercuts in the base girder. For the FAIR proton linac design no girder is foreseen and the tuning can be achieved by enlarging those end tubes that do not represent an RF-coupling transition to the neighboring cavity. This drift space can be used as well to host quadruple lenses and beam diagnostic devices.

The stainless steel stems are welded into the cylindrical cavity wall avoiding any screws inside the cavity. As shown in Figure 2.7-13 the design will result in a good flatness of field distributions together with high effective shunt impedances. Each cavity is equipped with several independent tuning plungers and its total weight is well below two tons, such that a fixed crane in the linac tunnel can be avoided.

The energy gain per cavity ranges from 3.1 to 6.7 MeV and the cavities lengths are between 0.41 m and 2.1 m. Velocity-dependent effective shunt impedances varying from 93 to 41 MΩ/m were achieved in simulations as shown in Figure 2.7-13. The number of gaps per cavity ranges from 9 to 15 and the Q0-values are about 17000. However, RF-coupled CH-
cavities have not been built so far and the RF-design as well as the mechanical layout requires some R&D effort including a prototype pair of cavities. A cold model single cavity with eight equidistant gaps has been built [13] as shown in Figure 2.7-14. In a next step a cold model of an RF-coupled cavity has been successfully fabricated (Figure 2.7-15) being a milestone towards the realization of a DTL based on coupled CH-cavities. The experience gained with the models is currently transferred to the construction of a prototype cavity pair that started in summer. Table 2.7-7 summarizes the cavities parameters.

Figure 2.7-14: Cold model of a CH-cavity (314 MHz). Design and construction has been done at University of Frankfurt. The copper plating has been done at GSI.
Figure 2.7-15: Assembly of the cold model (650 MHz) of an RF-coupled pair of two CH-cavities.

Table 2.7-7: Parameters of the 325 MHz RF-cavities of the proton linac, i.e. type, mechanical length, number of gaps, effective shunt impedance, energy gain, peak beam power at 70 mA, peak heat loss power, total peak power, and number of RF-power unit (K for klystron, T for tube amplifier).

<table>
<thead>
<tr>
<th>Type</th>
<th>L / cm</th>
<th># Gaps</th>
<th>Rs / M(Ω/m)</th>
<th>DE / MeV</th>
<th>Pbeam / kW</th>
<th>Ploss / kW</th>
<th>Ptot / kW</th>
<th>RF-Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-rod RFQ</td>
<td>3.24</td>
<td></td>
<td></td>
<td>2.91</td>
<td>203</td>
<td>537</td>
<td>740</td>
<td>K_1</td>
</tr>
<tr>
<td>Re-Buncher_1</td>
<td>8.06</td>
<td>2</td>
<td>120</td>
<td>0.00</td>
<td>0</td>
<td>12</td>
<td>22</td>
<td>T_1</td>
</tr>
<tr>
<td>CH-Cavity_1</td>
<td>40</td>
<td>10</td>
<td>91.1</td>
<td>3.09</td>
<td>216</td>
<td>262</td>
<td>1460</td>
<td>K_2</td>
</tr>
<tr>
<td>CH-Cavity_2</td>
<td>68</td>
<td>12</td>
<td>78.2</td>
<td>5.60</td>
<td>392</td>
<td>590</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH-Cavity_3</td>
<td>96</td>
<td>13</td>
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<td>6.84</td>
<td>479</td>
<td>650</td>
<td></td>
<td></td>
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<td>15</td>
<td>54.2</td>
<td>5.95</td>
<td>417</td>
<td>430</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH-Cavity_6</td>
<td>168</td>
<td>15</td>
<td>50.5</td>
<td>6.18</td>
<td>433</td>
<td>450</td>
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</tr>
<tr>
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<td>15</td>
<td>48.3</td>
<td>5.93</td>
<td>415</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH-Cavity_8</td>
<td>194</td>
<td>15</td>
<td>45.1</td>
<td>5.99</td>
<td>419</td>
<td>410</td>
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<td>43.9</td>
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<td>5.93</td>
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<td>13</td>
<td>38.6</td>
<td>5.60</td>
<td>392</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-Buncher_2</td>
<td>0.72</td>
<td>6</td>
<td>44.0</td>
<td>0.00</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>T_2</td>
</tr>
</tbody>
</table>
2.7.5 Injection/Ejection

n./a.
2.7.6 Beam Diagnostics

The beam diagnostic components (Table 2.7-8) are defined as well as their locations along the linac and the beam transport lines (Figure 2.7-16). The given lengths do not include the respective vacuum chamber.

Table 2.7-8: Beam diagnostic devices of the proton linac, their locations, numbers to be used, installation lengths (not including the respective vacuum chamber), and aperture radii.

<table>
<thead>
<tr>
<th>Device</th>
<th>Location</th>
<th>#</th>
<th>Length / mm</th>
<th>Aperture Radius / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faraday Cup</td>
<td>LEBT</td>
<td>2</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>Faraday Cup</td>
<td>DTL, LEBT</td>
<td>2</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>ACT Beam Transformer</td>
<td>LEBT</td>
<td>2</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>ACT Beam Transformer</td>
<td>MEBT, DTL(3)</td>
<td>4</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>ACT Beam Transformer</td>
<td>Transfer Channel, Dump</td>
<td>2</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Profile Measurement (grid)</td>
<td>LEBT</td>
<td>1</td>
<td>150</td>
<td>80</td>
</tr>
<tr>
<td>Profile Measurement (grid)</td>
<td>DLT, Dump, Inflection</td>
<td>3</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Profile Measurement (residual gas)</td>
<td>LEBT</td>
<td>1</td>
<td>150</td>
<td>80</td>
</tr>
<tr>
<td>Profile Measurement (residual gas)</td>
<td>DLT, Dump, Inflection</td>
<td>3</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Beam Position Monitor / Phase Probe</td>
<td>MEBT(2), DTL(7)</td>
<td>9</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>Beam Position Monitor / Phase Probe</td>
<td>Inflection, Dump(3)</td>
<td>4</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>Beam Position Monitor / Phase Probe</td>
<td>Transfer Channel</td>
<td>1</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Bunch Structure Monitor</td>
<td>Dump</td>
<td>1</td>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td>Slit Pair</td>
<td>DTL, Dump, Inflection</td>
<td>3</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Iris</td>
<td>LEBT / Dump</td>
<td>1 / 1</td>
<td>150</td>
<td>80 / 50</td>
</tr>
<tr>
<td>TOF Measurement</td>
<td>LEBT</td>
<td>1</td>
<td>300</td>
<td>80</td>
</tr>
</tbody>
</table>

2.7.6.1 Faraday-Cups

The properties of Faraday-cups are well known. Beside the current measurement they also serve as a beam dump for the full beam power (4.9 MW peak, 0.7 kW average). GSI has large experience with the technical realization using a special shaped water-cooled copper block coated with tungsten [14].

2.7.6.2 ACT Beam Transformers

High performance active current transformers (Alternating Current Transformers ACT (Figure 2.7-17) were developed and are in operation at the UNILAC [15] since several years. They are well suited for beam pulse lengths from a few µs up to the maximum design length of 36 µs offering high sensitivity and large dynamic range. For readout and presentation a versatile data acquisition system is in preparation for the UNILAC. This system can be duplicated for the proton linac.
Figure 2.7-16: Locations of beam diagnostic devices along the FAIR proton linac.

Figure 2.7-17: The ACT system (left) and the capacitive beam position monitor installed at the UNILAC (right).

2.7.6.3 Profile Measurements (Grid)

At GSI Secondary EMission (SEM)-grids are used very frequently. The technology of the mechanical construction as well as the sensitive pre-amplifier electronics is well developed. SEM-grids offer a large dynamic range and in connection with slits they serve as transverse emittance measurement devices. For cost reduction a re-design for the electronics is under preparation using modern multi-channel integrated circuits and standard digital equipment.
2.7.6.4 Profile Measurements (Residual Gas)

The high beam power does not permit the use of SEM-grids for profile measurements. Therefore the use of non-destructive techniques, like the measurement of the profile by Beam Induced Fluorescence (BIF), is under consideration. This technique was also successfully demonstrated for protons at the IPHI front-end at CEA/Saclay [16,17]. Encouraged by the FAIR Technical Advisory Committee it is planned to profit from this development [18]. The mechanical length of the set-up of about 150 mm does not indicate installation of more than one unit within the DTL. Although GSI has experience with BIF profile measurements for ions [19], R&D is needed especially with respect to the extension of this technique to protons.

2.7.6.5 Beam Position Monitors & Phase Probes

Beside the current the beam position will be monitored permanently. Capacitive Beam Position Monitors (BPM) will be used (Figure 2.7-17), forming a compact mechanical unit together with the current transformers. The technique is well developed at GSI including modern low-noise RF-electronics. Due to the higher accelerating frequency of the proton linac compared to the UNILAC (108 MHz), the front-end electronics have to be modified to provide large enough bandwidth. For a concise display of the beam position along the beam path a versatile software package has to be developed taking into account various operational considerations as well as archival storage requirements. As for the transformer readout the system can be duplicated from the UNILAC. Using the BPM the matching of bunches with respect to the phases of the various cavities can be controlled precisely. A high bandwidth RF-electronics and digitalization system is mandatory for this monitoring. With two consecutive BPMs the mean energy can be determined to high precision using Time-Of-Flight (TOF) technique.

2.7.6.6 Bunch Structure Monitor

A novel non-intersecting method for the high resolution bunch structure measurement was developed at GSI, where the time spectrum of secondary electrons from the residual gas reflects the bunch structure [20]. First promising tests were performed at the UNILAC. A phase resolution of 2° has been achieved with this non-destructive method. This complex system has to be copied and modified for the higher frequency of the proton linac. It will be used during the section-wise commissioning of the linac. Concerning the data acquisition system further developments are required transforming this experimental device into an operating tool.

2.7.6.7 Slit Pairs and Irises

Pairs of slits and irises are required for transverse beam limitation. They also serve as slits for the emittance measurement. The slit diaphragm is made of tungsten coated copper and it is water-cooled and driven by a precise stepping motor. Using stepping motor driven horizontal and vertical slits and a SEM-grid with 0.5 mm wire spacing, the transverse emittances can be determined. This technique and its offline analysis are well established. Due to the intersecting material the macro-pulse length has to be reduced during the measurements.
2.7.7 Vacuum

The layout of the vacuum system for the proton linac is straightforward in comparison to the synchrotrons and storage rings. Table 2.7-9 lists the required components.

Table 2.7-9: Components of the vacuum system for the proton linac and their respective numbers to be used. Their locations are given in the text.

<table>
<thead>
<tr>
<th>Component</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo Pump 2000 l/sec</td>
<td>1</td>
</tr>
<tr>
<td>Turbo Pump 500 l/sec</td>
<td>9</td>
</tr>
<tr>
<td>Ion Pump</td>
<td>34</td>
</tr>
<tr>
<td>Sector Valve</td>
<td>9</td>
</tr>
<tr>
<td>Fast Valve</td>
<td>4</td>
</tr>
<tr>
<td>Pressure Meas. Unit</td>
<td>15</td>
</tr>
<tr>
<td>Diagnostic Box</td>
<td>6</td>
</tr>
</tbody>
</table>

2.7.7.1.1 Pumps

One powerful turbo pump (2000 l/sec, oil-free) will be installed at the proton source. The other pumps provide a pumping speed of 500 l/sec. The LEBT section is equipped with one turbo- and with two ion pumps. RF-cavities are pumped with one ion-pump per meter in average, thus that the number of pumps is given by the integer part of the sum over all cavity lengths plus one. The RFQ and the two re-bunchers are pumped by a single turbo pump at each device. The CH-cavities No.1 to No.6 are grouped to one turbo-pump section, similarly the cavities No.7 to No.10 and No.11 to No.12, respectively. The extended diagnostic section after cavity No.6 needs a turbo- and an ion pump. Two ion- and a single turbo pump are installed along the inflection into the transfer channel to the SIS18 and along the beam line to the proton beam dump, respectively.

2.7.7.1.2 Valves

Ten vacuum sections, separated by nine sector valves, comprise the proton linac beam line, which are: source, LEBT, RFQ, MEBT, CH-cavities No.1 – No.6, extended diagnostic section, CH-cavities No.7 – No.10, CH-cavities No.11 – No.12, inflection into SIS18 transfer channel, and beam line to the dump. Fast valves are installed in the following sections: LEBT, MEBT, extended diagnostic section, and dump.

2.7.7.1.3 Pressure Measurement Units

Dedicated pressure measurement probes are installed in each RF-cavity.
2.7.8 Proton Source

An ECR type proton source is planned be used for the FAIR proton linac. The extraction energy is 95 keV and the proton fraction must be at least 100 mA. Joint measurements of CEA, GSI, and University of Frankfurt on the beam quality of the SILHI ECR source [16] have been done [21]. It was shown that a modified version of the SILHI, i.e. optimized for pulsed operation, could be used for the FAIR proton linac. The stability of the source as well as the reproducibility of its beam parameters was impressive. As an example two different measurements of the vertical emittance close behind the virtual injection point into the RFQ are shown in Figure 2.7-18. Both measurements were done with the same source & LEBT settings, but they are separated by four days including an opening of the plasma chamber, and employed two different data acquisition systems. The measured phase space distribution includes all fractions of the beam as H2, H+, H2+, and H3+.

![Figure 2.7-18: Two independent measurements of the vertical beam emittance at the exit of the SILHI LEBT. Further explanations are given in the text.](image)

The proton beam emittance still exceeds the design emittance for RFQ injection of 1.8 mm mrad by 30%. However, this excess is mainly due to the pulsed operation of the dc-source. Additionally, the LEBT was built from existing components and it is not optimized with respect to overall length. Accordingly, an optimization of the source for pulsed operation together with a dedicated compact LEBT is expected to allow for the envisaged emittance values. Finally, it is foreseen to integrate a H1-3+-molecule analyzer into the LEBT, for determination of the H+, H2+, and H3+ fraction of the total beam current using the Time-Of-Flight (TOF) technique. An electrostatic chopper right in front of the RFQ will shorten the beam pulse current to 100 µs.
2.7.9 Survey and Alignment

2.7.9.1 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 scope of the S&A team.

2.7.9.1.1 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. Additional part of the scope of work is the metrological support to the physics experiments like providing geodetic infrastructure in the experimental areas, aid on installation of physics detectors and precise spatial measurement of physics detectors.

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 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.

2.7.9.1.2 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 them into the ring or beamline.

The basic principles together with important preparatory work are described in section 2.7.9.2.
2.7.9.1.3 Concept development

Accelerator alignment is no ready-made service; concepts have to be individually developed or adapted to a certain machine, although some state-of-the-art procedures – known in accelerator community – can be used. The determination of requirements, development of special hard- and software, measuring methods and procedures as well as system tests, personnel planning (form a team, training) and last but not least the development of an appropriate data management system have to be taken into account while talking about survey and alignment.

These developments are no specific R&D tasks, but need certain preliminary lead time.

2.7.9.1.4 Requirements on building structures: alignment point of view

The following section should give some indications of an appropriate building design, which has to allow the survey and alignment ability, and that must provide a good position stability of the accelerator.

It is recommended that each accelerator ring or functional separated section get its own stable foundation in order to obtain deformations - within one ring due to unavoidable movements of the underground - as small as possible. Machine lay-out should provide space for steering magnets at sensitive building crossings.

Generally, it was communicated to the responsible person of the civil engineer team that - within one ring as well as between the beam lines and the adjacent rings - lines of sight are to be kept free or to be created. These lines of sight enable to measure a reference network, which represents the basis for the adjustments of the individual components. That is, special openings, which can easily be opened and closed for measurement purposes, have to be taken into account within specified building design respectively within shielding concept. Details can only be specified after final machine lay-outs and building designs - and with this a coherent design of measurement network - are available.

In order to be able to perform high-precision measurements on accelerator components it is inevitable to have balanced climate conditions within the machine buildings during a measurement period; i.e., air turbulences, draft or strong temperature differences that affect optical measurement procedures have to be avoided within the working area; technical mechanisms are to be planned for these demands.

During design of gateway to the machines for installation, survey and alignment or maintenance in general, it has to be paid careful attention on an easy accessibility of the machine areas and a good approach to the individual components – in accordance with requirements of radiation protection.

The space required for the metrological infrastructure – besides storage room suitable places for test measurements and periodical calibration procedures are needed – were already communicated to the construction engineer.

The surface network, which is needed for the absolute orientation of the different machines in space and relative to each other as well as for the strengthening of the tunnel network, calls for the construction of vertical sight shafts and some concrete pillars. The number and position of shafts and pillars needed at GSI site depend on a suitable net design. Appropriate simulation computations for the estimation of achievable accuracies are reasonable when geometry and position of the accelerators are finalized. A very preliminary investigation
yielded to a number of three sight shafts for the link between the surface and the SIS100-tunnel network Figure 2.7-19.

Figure 2.7-19: Preliminary result of tunnel network simulation (SIS100).

2.7.9.2 Work packages: description of basic principles

2.7.9.2.1 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 [22]. 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 [23]. However, up to now there was no need or possibility to engage in superconducting magnets.

With the focus on fiducialization some differences in magnets have to be mentioned: 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 2.7-20.

In contrast to the normal conducting magnets the sc-magnets are mostly enclosed in a cryostat. Therefore the yoke is not directly accessible when cooled down i.e. in normal
working condition. The fiducials have to be placed on the cryostat, which has in fact no stable relationship to the magnet.

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

**Figure 2.7-20:** Existing Quadrupole with inserted mandrel.

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 as well as extensive analysis of possible movements of the magnet versus cryostat under different conditions. For instance quenches or the transport from measuring place into the tunnel can produce changes in position of yoke compared to the cryostat. Due to the fact that the cryostat will need to provide stable supports for the fiducials, it was already recommended to attach great importance to the stability of the cryostat itself.

Fiducialization of superconducting magnets is a challenge, that needs careful preparatory work – some points are mentioned above –, which goes far beyond a single measurement to relate some points to each other.

**2.7.9.2.2 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 [24].

Possible sources of error:
- Manufacturing
- Determination of the axis / "magnetic measurements"
- Relating axis to fiducials / "geometric measurements"
- Deformation of cryostat / deformation of correlated fiducials
- Displacement magnet versus cryostat due to transport
- Residuals after least square network adjustment
- Uncertainty of measurements during alignment procedure
- Movement of the floor (long / short term)
Total error of final magnet position within the tunnel, which can be expressed as

\[ s^2 = s_i^2 + s_j^2 + s_k^2 + s_l^2 + ... \]

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 derivate or re-evaluate reasonable tolerances.

### 2.7.9.2.3 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 a range of some hundred microns, similar to the existing machine(s). 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 (experimental) setup. In this case fundamental changes in the so far traced measuring philosophy would be necessary.

### 2.7.9.2.4 Instrumentation

**Measuring devices**

State-of-the-art Laser Tracker (Figure 2.7-21), 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 (2sigma) at a distance of 2 m (~50µm @ 10m / ~110µm @30m). 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.
At GSI a Laser Tracker is regularly applied since 1996 for fiducialization and in some cases for network measurement and alignment [25]. 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, 1sigma) 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 20h; 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 [26].
Test laboratory

Instrument testing should be an important part of the internal quality assurance program. Establishing an appropriate test laboratory to do performance checks, investigate test procedures, calibrate and maintain the definitely forthcoming manifold systems in the scope of metrology should happen as early as possible. Conceptual work including formulation of a catalogue of requirements on laboratory design – especially climatic condition and building stability -, along with specification of inspection equipment and much more, is to be started soon.

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 mainly use of Total Station [2]. 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.

2.7.9.2.5 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 to be defined - required network accuracy in the various areas of the facility has to be achieved. Detailed simulation calculations yields to a prediction of global and relative uncertainties of all reference points including fiducial points on magnets etc.

Up to now no simulation was calculated 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; whereas a first coarse estimation was made about the number of vertical shafts, needed to connect the surface network with the machine network in the SIS100/300 tunnel. From this follows a requirement of three connections, based on an assumption of a needed global accuracy of ±2 mm (1σ) for the SIS100/300 network of reference points (see Figure 2.7-24).
Free stationing
The actual survey and alignment plan relies on Laser Tracker combined with levelling, and in some cases combined with 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 flexible, 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 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.

2.7.9.2.6 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.

2.7.9.2.7 Physics experiments – metrological support
No conceptual work concerning alignment or other measurements of installations of any planned physics experiment has begun so far.
2.7.9.2.8 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 at 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 [27].

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.

2.7.9.3 Machine characteristics: impact on alignment procedures

The variety of the components of each beamline of HEBT, of the various storage rings or synchrotrons as well as of the Super-FRS must be aligned to the ideal beam axis with the help of 3D-measurements. The relevant positions of magnets etc. have to be determined with high accuracy. If it is assumed, to have no tighter requirements on component position accuracy than some hundred microns, and no local peculiarities are obstructive, the basic survey and alignment strategy that is described above can be applied to all different machines, at least for the initial installation.

In spite of this statement and although important aspects are still not known, some unique characteristics of single machines are already obvious. In some of these cases it is sufficient to make special effort in constructional engineering, in design of magnets and supports or other mechanical components, in order to be able to maintain or to improve the alignment-ability of components. In other cases machine characteristics lead to a necessary substantial adaptation of survey and alignment methods – not for initial installation but especially for needed realignment activities after some time of operation.

Remote alignment system

FAIR will have some areas - especially parts of Super-FRS - that will be hardly to reach or inaccessible for maintenance staff after some time of operation. This will be true even in shutdown periods due to an expected high level of radiation. Concerning future survey and realignment tasks these circumstances prohibit the use of well-established stationary monitoring systems or "classic" measurement instruments like Total Station or Laser Tracker. The basic necessity for using automated, remote systems for position control and realignment within these zones is therefore obvious.

A dedicated R&D project that was called RALF (Remote ALignment on the Fly) dealt with the conceptual work on an approach for a high-precision survey and alignment system in inaccessible, high-radiation areas in order to preserve the survey ability in spite of limited access and in accordance with safety regulations and radiation protection requirements. The new measurement system has to meet following requirements:

- No access of human personnel
- Great demands on accuracy (some 1/10 mm)
- Very fast data acquisition
- Automated, remotely controlled adjustment of accelerator components
- Handling a nonlinear beamline with a length up to several decametre

The method will not be used as a permanent monitoring system but for regularly determination of the actual condition of the machine geometry.

Fundamental ideas of RALF are based on a photogrammetric solution: close-range photogrammetry is the only non-contact geodetic measurement technique that works without human impact on the object and accomplishes flexible measurement and monitoring tasks with highest accuracies.

The approach relies on a number of high-precision digital cameras that are installed on an automated guided vehicle system. Via tracks this device will be driven along the beamline in the activated area, which has to be surveyed. Appropriate fiducial points are mounted on the magnets / cryostats. In addition, photogrammetric tie-points and calibrated scale-bars are distributed in object space to guarantee a stable photogrammetric network. At least two adjacent components are captured in one shot, before the vehicle starts to move to the next stop for taking the following picture. After finishing data acquisition the camera system is lead out to a radiation-protected storage room to download the image data. A bundle adjustment provides correction values for the alignment of the accelerator components that is completed by remotely controlled adjustment devices. Another camera run is performed to check the quality of remote alignment [28].

![Figure 2.7-25](image)

**Figure 2.7-25:** Schematic view of a possible configuration in accelerator tunnel. The camera vehicle (green) carries two divergent digital cameras. By moving the vehicle along the tunnel (red arrows), any part of the magnets will be captured by two or more images. This results in an image bundle for the whole tunnel to be processed in a photogrammetric bundle adjustment.

Different digital cameras for industrial application have been tested at a photogrammetric test field, in order to analyze their geometric stability and the accuracy of image measurement. In the context of possible camera damages during operating time of RALF by *remaining* radiation after machine-shutdown, some experimental tests were performed at ambient conditions of gamma dose rates of up to 10 mSv/h, which can be expected at PF2 (pre-separator focus point 2 of Super-FRS). Although image analysis tools detected a slight influence, the tests showed no significant loss of image point accuracy.
Considerations to a photogrammetric network design, regarding stretched objects, have been carried out; extensive simulations were computed, which resulted in satisfactory, homogeneous object point accuracies in 3D (approx. 0.1 to 0.2 mm) [29]. Aspects of image analysis, camera vehicle and motion system, data transfer and power supply as well as adjustment devices appropriate to the environmental conditions were investigated. Fiducials of later on strongly shielded magnets and a measuring method to connect precisely the adjacent, accessible sections to the inaccessible areas were studied.

In order to verify the simulations, to test cameras, to try different types of targets and image analysis and to investigate the influence of different configurations of the bundle adjustment a test installation of RALF was done, which yielded excellent results. Thus the remote-controlled alignment system RALF is able to achieve a single point accuracy of below 0.1mm [30].

However, the crux of the problem will not be the metrological part but rather various practical aspects and constraints on the future accelerator facility that require more discussion with several departments (e.g. civil construction, radiation protection, beam physicists). So, a storage room for the pausing measuring system (during operation of the accelerator) and an appropriate connecting path is needed, preferably far away from the target area. Otherwise a constant influence of neutron and gamma radiation on CCD / CMOS image sensors of cameras will lead to damage of the imagery (and thus to a loss of accuracy).

Space for the installation of a linear motion system must be predefined; the illumination of the areas to be surveyed has to be optimized accordingly; shielding of magnets must enable their metrological accessibility anyway. Last but not least adequate adjustment devices for remote-handling have to be designed.

Nonetheless, the concept of RALF is – owing to its fast data acquisition and thus its little need of access time to the machine - a promising alternative to traditional alignment methods as it is applicable at many accelerator areas of FAIR, not only in activated sections.

It has to be emphasized that implementation of an "S&A system in high-radiation environment" (RALF) into future activated areas has to take place during first installation of the machine, at least before starting operation, although initial alignment can be done by "classical" measurement systems.

Tilted planes
A previous proposal of the civil engineering team has suggested that the plane of the SIS100/300 ring-tunnel should be tilted by approximately 2%. From an accelerator alignment point of view, a sloped tunnel plane is controllable; however, any use of easy manageable spirit levels, plummets as well as systems like hydrostatic levelling systems (HLS) is stopped or complicated. The 'natural reference plane' for height measurements – the equipotential plane of earth – will be abandoned; hence every relatively modest installation must be assisted by real 3D-measurements. A tilted plane will increase error rates and costs due to a needed higher effort of personnel, time and equipment not only during initial installation but also during entire lifetime.
Re-using components
It should be mentioned, that – even if components of the existing machines will be re-used (that is the case for RESR), which were already prepared for a precise, polar, three-dimensional alignment procedure – every magnet must be fiducialized again. Only this way an updated, modern survey and alignment concept can be implemented.

Assembling, support structures, chronological flow of construction work: influence on position accuracy
At present the height of the beam line of some machines is planned to be 2 to 3m above the floor. Together with a magnet height of additional ~1m (e.g. half yoke ESR quadrupole dedicated for the RESR), a working height for maintenance or alignment is reached, which is practicable but not very friendly. This has to be taken into account, when estimating time- and consequential costs - that is needed for any survey and alignment activity. Furthermore, support frames and floor conditions have to be planned very carefully to avoid high lever arm effects. Small footprints compared to a high beam line level can cause big tangential deviations of the beam (respectively of the magnet) due to little deformations of the floor.

When two rings or a machine part and an experimental device will finally share the same building without any constructional separation, the installation of the last will definitely affect the position of the components of the first that will possibly be installed and initially aligned in a previous phase. Both machines need of course all fundamental survey and alignment processes, but a realignment of the components that were set up sooner will be required when the installation of the elements of the other machine is finished. It is therefore recommended to survey additionally a common reference network for both, as a basis for the initial precise alignment of the last installed machine and the re-alignment of the components of the first. This fact must find its way into any time schedule.

2.7.9.4 Closing words
Generally it must be emphasized that survey and alignment tasks – that are predominantly service-oriented (i.e. personnel / expenditure of time) and less material intensive – bear significant dependencies to other work packages, which do not appear as obvious as they are actually. After machines were turned on, the survey and alignment has to be repeated at regular intervals, which distinguishes it from other construction and installation activities. It has to be kept in mind during design phase, that decisions in civil and mechanical engineering, magnet design as well as accelerator physics have great impact on labour-intensive alignment processes and thus on needed service- or shutdown time and finally costs. Efficient adjustment devices, reasonable alignment tolerances or tunnel width are named here representatively.

Furthermore, survey and alignment are 'driven' activities: most of the described tasks have to be seen as iterative or split processes. Hence, an 'exact' scheduling for S&A activities concerning flow of work, time needs and costs is only possible shortly before realisation. They are strongly dependent on design information, time of delivery or installation etc. A scenario such as installing the HEBT as a whole, carrying out network measurements and align all components one after another within one period is not realistic; it has to be assumed strongly, that in several areas multiple iterations of survey and alignment activities are required – independently of (respectively in addition to) different construction phases – in order to get an effective, exact positioning of all elements that is essential for high beam quality.
Planning and coordination of accelerator alignment tasks as well as performing the measurements itself need skilled people with consolidated knowledge. One problem in getting FAIR aligned may be, to find at the same time enough (internal and external) survey professionals, qualified in large-scale metrology. Even though it is planned to hire external service providers for temporary peaks, it should not be missed to form a core team very early, which is to be trained and sworn in, in order to be able to guarantee a high quality of positioning the FAIR components.
2.7.10 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.

2.7.10.1 General System architecture

The architecture of the common FAIR accelerator control system is illustrated in Figure 2.7-26. 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 befit 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.

### 2.7.10.2 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 field-bus. 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 accelerator 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.

2.7.10.3 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 simultaneously. The timing system must handle 20 ms cycles (present UNILAC) as well as machine 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 resulted in a two staged timing solution: A general machine timing (GMT) system will be implemented 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 beyond 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 MGT 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 transmission 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 2.7-27. For each of the FAIR machines a dedicated timing event generator (EVG) generates all timing signals utilizing internal counters, 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 identifier, context, safe-beam flags) can be transmitted or broadcasted.

Figure 2.7-27: Structure and topology of the general machine timing (GMT).

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.

2.7.10.4 Networking

The FAIR controls network is a 1-Gbps switched Ethernet network, with a backbone at 10 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 10-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.

2.7.10.5 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.

2.7.10.6 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.
2.7.10.7 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.

2.7.10.8 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.
2.7.10.9 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.

2.7.10.10 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.
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