FAIR Operation Modes

Reference Modes for the Modularized Start Version (MSV)

This document summarizes the deliverables of the FAIR MSV.

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Change history:

Version	Date	Name	Details
V1-0	November 2012	P. Schütt	First Version for Review
V1-1	January 2013	P. Schütt	HESR-Acronym corrected
V1-2			Comments from V.R.W. Schaa, M.Steck etc., Ions in HESR, shorter Spills for CBM, Au for CBM, update of U-Bahn-Drawing, update of Table 2-1 (beam production chains)
V2-0	October 2013	O. Geithner, P. Fork, P. Schütt	Merging with Technical Concept, Beam parameter requirements from experiments
V3-0	October 2015	O. Geithner, P. Schütt	Update of the beam parameter requirements according to the HIC4FAIR Workshop (Hamburg, 2015). Removal of the production chains Input from R Steinhagen: update of the concept for parallel operation Feedback of all FAIR experiment Communities is included

Table of Content

1 Introduction

The goals of the present document are:

- Summarize the deliverables of the FAIR Modularized Start Version (MSV) as defined in the FAIR Green Paper [2]
- Give an overview of beam parameter requirements of FAIR experiments
- Analyze operational requirements for experiments and propose a concept of parallel operations

The scope of the present document is the FAIR MSV with a focus on modules 0-3. FAIR phase 0 includes the existing target halls (Cave A and Cave M) and facilities (UNILAC, SIS18, HITRAP, ESR and CRYRING). Since they are already implemented, they are not detailed followed in this document. The present status of the design beam parameters and production chains for the new accelerators can be found in [3].

2 Glossary

Name	Description
FAIR	The Facility for Antiproton and Ion Research
HTA	Halle Target A (Cave A)
HTM	Halle Target M (Cave M)
SIS18	SchwerIonen Synchrotron with magnetic rigidity 18Tm
SIS100	SchwerIonen Synchrotron with magnetic Rigidity 100Tm
UNILAC	UNIversal Linear ACcelerator
FRS	FRagment Separator
Super-FRS	Super FRagment Separator
CR	Collector Ring
HESR	High Energy Storage Ring
NESR	New Experimental Storage Ring
RESR	Recuperated Experimental Storage Ring
APPA	Atomic, Plasma Physics and Application
HEBT	High Energy Beam Transport
HADES	High Acceptance Di-Electron Spectrometer
CBM	Compressed Baryonic Matter
PANDA	Proton Antiproton Annihilations at DArmstadt
SPARC	Stored Particles Atomic physics Research Collaboration
FLAIR	a Facility for Low-energy Antiproton and Ion Research
HEDgeHOB	High Energy Density matter generated by Heavy iOn Beams
WDM	Warm Dense Matter
NUSTAR	NUclear STructure, Astrophysics and Reactions
R^3B	Reaction with Relativistic Radioactive Beams
BIOMAT	BIOphysics and MATerial research
HISPEC	HIgh resolution SPECtroscopy
DESPEC	DEcay SPECtroscopy
MATS	precision Measurements of very short-lived nuclei with Advanced Trapping System
LASPEC	LAser SPECtroscopy of short-lived nuclei
ILIMA	Isomeric beams LIfetimes and MAsses
EXL	EXotic nuclei studied in Light-ion induced reactions
ELISE	ELectron-Ion Scattering Experiment
QCD	Quantum ChromoDynamics
LSR	Low-energy Storage Ring (present name CRYRING)
MEVVA	MEtal-Vapor Vacuum-Arc ion source
ECR	Electron-Cyclotron-Resonance ion source
RIB	Rare Isotope Beam
MSV	Modularized Start Version of FAIR (includes modules 0-3)
HEB	High Energy Branch
LEB	Low Energy Branch
Ring-Branch	CR, RESR, HESR, NESR
MPL	Machine Project Lead
CDB	Component Data Bank
pLINAC	proton LINear ACcelerator
HITRAP	Heavy Ion TRAP facility
ESR	Experimental Storage Ring

3 Facility overview

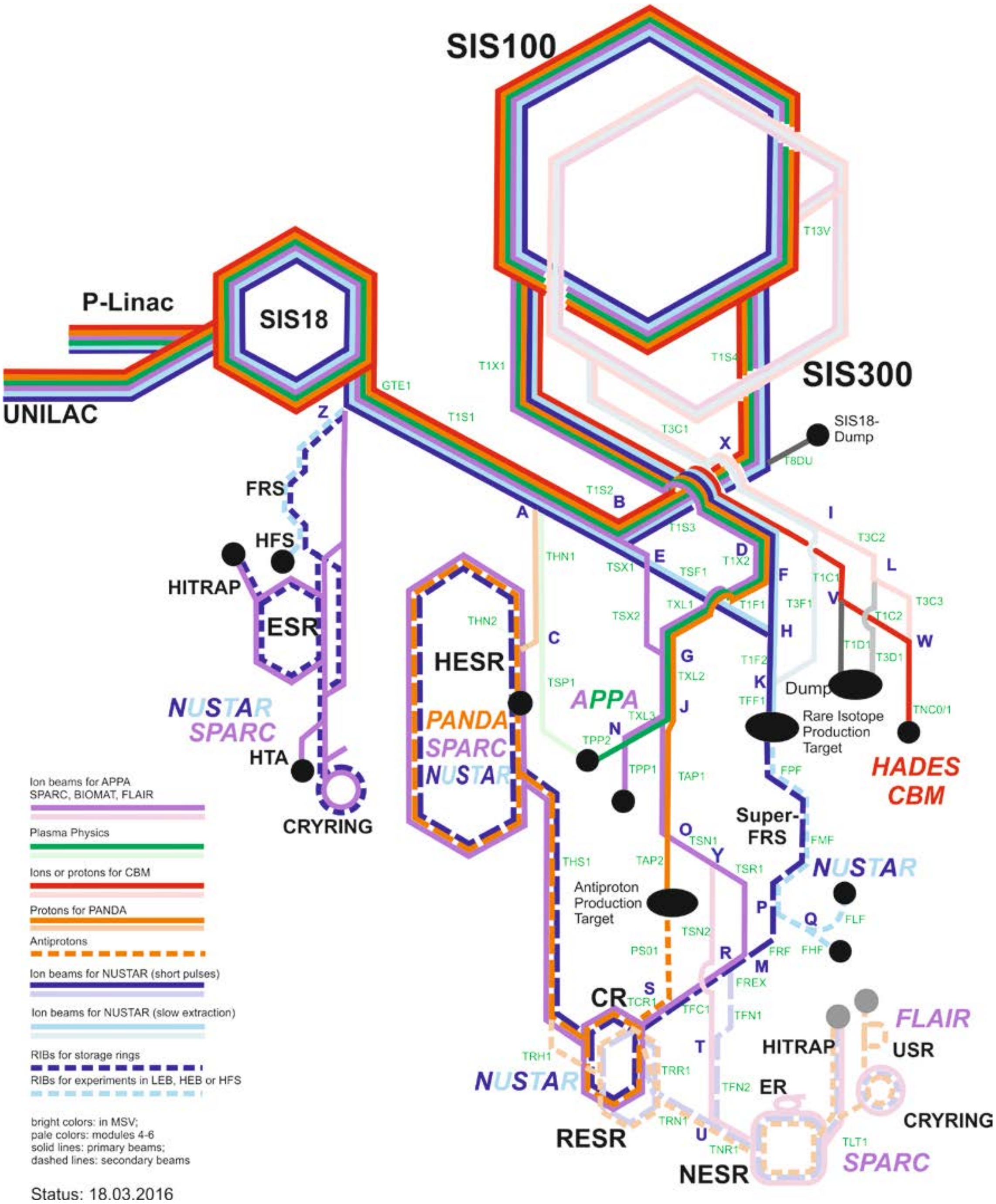

Figure 3-1: Schematic overview of the Modularized Start Version. Modules 0-3 to be built in the first step are shown in bright colors. In pale colors the modules 4-6 are shown.

Figure 3-1 gives a schematic overview of the FAIR accelerator complex. The colors indicate, which accelerators and beam lines are intended for the beam production for the core FAIR experiments NUSTAR (blue), CBM (red), PANDA (orange), and APPA (violet for Atomic Physics and Applications and green for Plasma Physics).

The following accelerator systems will be built/upgraded in the MSV:

– Upgrade of SIS18 and UNILAC
– SIS100 (with reduced number of accelerating rf cavities)
– CRYRING

- Super-FRS
- FRS
- CR
- P-LINAC
- Antiproton Target and Separator
- HESR
- ESR will be maintained in operation and will deliver beams to HITRAP, CRYRING and Cave A
- UNILAC will continue to serve experiments in the experimental hall
- SIS18 will continue to serve Cave A and Cave M
- HEST

The new connecting beam lines are listed in Table 3-1. It is assumed that the beam emittance stays a constant within HEBT. Max horizontal and vertical acceptances are calculated with momentum offset zero in a following way: beam is enlarged in the ion optical simulations (MIRKO-command 'BLOW') until it strikes against a vacuum chamber. Further horizontal and vertical acceptances are calculated with predefined momentum offset.

Table 3-1 Connecting Beam Lines (HEBT). Beam lines in grey color will not be available in MSV 0-3 [12].

#	from	to	particles species	rigidity range [Tm]	max. hor. acceptance [mm*mrad]	max. vert. acceptance [mm*mrad]	at momentum offset: [± ‰]
c0	SIS18	Dump	ions, protons	9-18	89	49	3
c1	SIS18	SIS100	ions, protons	9-18	90	42	3
c2	SIS18	SFRSTarget	ions	9-18	45	23	3
c3	SIS18	PP1-Target	ions, protons	18	53	26	3
c4	SIS18	NESR	ions	13	36	14	3
c4*	SIS18	CR	ions	13	78	19	3
c5	SIS18	PP2 perp.	ions, protons	9-18	82	23	3
c6	SIS18	HESR	protons	1-13	18	26	3
c7	SIS300	Dump	ions, protons	27-300	30	21	2
c8	SIS300	CBM	ions, protons	27-300	5	7	2
c8	SIS300	HADES	ions, protons	27-100	13	18	2
c9	SIS300	SFRSTarget	ions	27-100	21	21	2
c10	SIS100	Dump	ions, protons	27-100	38	22	3
c11	SIS100	CBM	ions, protons	27-100	28	4	2
c11	SIS100	HADES	ions, protons	27-100	28	11	2
c12	SIS100	SFRSTarget	ions	27-100	43	30	10
c13	SIS100	pbarTarget	protons	100	40	18	10
c14	SIS100	PP1-Target	ions, protons	13-100	43	21	10
c15	SIS100	PP2-Target	ions, protons	27-100	43	20	10
c16	SFRS	CR	r-ions	13	229	203	15
c17	SFRS	NESR	r-ions	13	67	29	5
c18	pbarSep	CR	antiprotons	13	layout will be made by CR group		
c19	CR	RESR	r-ions, antiprotons	13	layout will be made by CR group		
c20	CR	HESR	Antiprotons, ions	1-13	10	9	5
c21	RESR	NESR	r-ions, antiprotons	13	65	39	5
c22	RESR	HESR	antiprotons	1-13	10	8	5
c23	NESR	FLAIR	ions, r-ions, antiprotons	0.3-4.5	no layout available. will be built in module 6		

Note,

- c4*: this connection includes the bypass of the antiproton target (point Y to point M). The status of the corresponding change request is pending (ECR 0163).
- c6: SIS18-HESR is a very long connection comprising c4*, the CR and c20. The short connection from Point A to Point C (see Figure 3-1), which was planned to allow a clockwise injection of protons into HESR, will not be available in the MSV.
- Since the RESR will not be built in the MSV, the CR will be directly connected to the HESR (c20). This temporary beam line will be replaced by the beam lines CR-RESR (c19) and RESR-HESR (c22) in the final setup.

4 Beam parameter requirements and production chains for the core experiments

According to the FAIR Green Paper [1], the FAIR research program has been approved by the International Steering Committee of FAIR (ISC) in 2006. It includes 14 initial experiments, which form the four scientific pillars of FAIR.

Table 4-1 lists these experiments and the corresponding beam production chains. The color code corresponds to the schematic overview in Figure 3-1. Details of the beam production processes are described below.

Table 4-1: Beam production chains for the FAIR core experiments in the MSV and full version.

N°	Name of experiment	Avail-ability in MSV	Experimental Area		Beam production chains	
			MSV	Full Version	MSV	Full Version
NUSTAR						
1	R^{3}B	yes	HEB		SIS18-(SIS100)-Super-FRS-HEB	
2 - 4	HISPEC/DESPEC, MATS & LaSpec	yes	LEB		SIS18-(SIS100)- Super-FRS-LEB	
5	Super-FRS	yes	Super-FRS		SIS18-(SIS100)-Super-FRS	
6	ILIMA	yes[1]	CR (or HESR) FRS–ESR (CRYRING)	Super-FRS-Ring-Branch	SIS18-(SIS100)-Super-FRS-CR-(HESR) SIS18-FRS-ESR-(CRYRING)	SIS18-(SIS100)-Super-FRS-CR or SIS18-(SIS100)-Super-FRS-NESR or SIS18-(SIS100)-Super-FRS-CR-RESR-NESR
7	EXL	Yes[1]	FRS-ESR, (CRYRING)		SIS18-FRS-ESR-(CRYRING)	
8	ELISE	no	--		--	
QCD Physics						
9	CBM/HADES	yes	CBM Cave		SIS18-SIS100-CBM	SIS18-SIS100-SIS300-CBM
10	PANDA	yes	PANDA in HESR		Protons: SIS18-SIS100-Target Antiprotons: CR-HESR	Protons: SIS18-SIS100-Target Antiprotons: CR-RESR-HESR

[1] Only a limited/restricted program will be possible without NESR

<table>
<tr><th rowspan="2">N°</th><th rowspan="2">Name of experiment</th><th rowspan="2">Avail-ability in MSV</th><th colspan="2">Experimental Area</th><th colspan="2">Beam production chains</th></tr>
<tr><th>MSV</th><th>Full Version</th><th>MSV</th><th>Full Version</th></tr>
<tr><td colspan="7">APPA</td></tr>
<tr><td rowspan="5">11</td><td rowspan="5">SPARC[2]</td><td rowspan="5">yes</td><td colspan="2">APPA cave</td><td>SIS18-(SIS100)-APPA</td><td>SIS18-(SIS100)-APPA</td></tr>
<tr><td>SIS100</td><td>SIS300</td><td>SIS18-SIS100</td><td>SIS18-SIS100-SIS300</td></tr>
<tr><td>HESR</td><td>NESR</td><td>SIS18-CR-HESR</td><td>SIS18-(SIS100)-NESR-FLAIR</td></tr>
<tr><td>ESR, HITRAP</td><td>--</td><td>SIS18-ESR-(HITRAP)</td><td>--</td></tr>
<tr><td>CRYRING</td><td>--</td><td>SIS18-ESR-CRYRING</td><td>--</td></tr>
<tr><td rowspan="3">12</td><td rowspan="3">FLAIR</td><td rowspan="3">no</td><td rowspan="3">--</td><td rowspan="3">FLAIR</td><td rowspan="3">--</td><td>SIS18-(SIS100)-NESR-FLAIR</td></tr>
<tr><td>Antiprotons: CR-RESR-NESR-FLAIR</td></tr>
<tr><td>SIS18-SIS100-SuperFRS-CR-RESR-NESR-FLAIR</td></tr>
<tr><td rowspan="2">13</td><td rowspan="2">BIOMAT</td><td rowspan="2">yes</td><td colspan="2">APPA Cave</td><td colspan="2">SIS18-(SIS100)-APPA</td></tr>
<tr><td>Cave A
Cave M[3]</td><td>--</td><td>SIS18-Cave A or Cave M</td><td>--</td></tr>
<tr><td rowspan="2">14</td><td rowspan="2">HEDgeHOB/WDM</td><td rowspan="2">yes</td><td colspan="2" rowspan="2">APPA cave</td><td rowspan="2">SIS18-SIS100-APPA</td><td>SIS18-SIS100-APPA</td></tr>
<tr><td>SIS18 – APPA (2^{nd} Beamline PP)</td></tr>
</table>

Note:

The experiment requirements tables below are agreed with the radiation protection department. Some of them are subdivided into commissioning phase and late operation in MSV. The commissioning phase means the ‘first days experiments’ in MSV. The future options are defined individually depending on experiment.

[2] Experimental area of the full version for the SPARC Experiment will not replace MSV hence means MSV plus SIS300 and NESR.

[3] The existing Cave A and Cave M will be served from SIS18 as a temporary installation as long as NESR is not built.

4.1 NUSTAR - Nuclear Structure, Astrophysics and Reactions

All NUSTAR experiments use as a central instrument the Super-FRS. Beams of unstable nuclei are produced in a thick (≈1gcm^{-2}) target mostly by disintegration of stable projectiles.

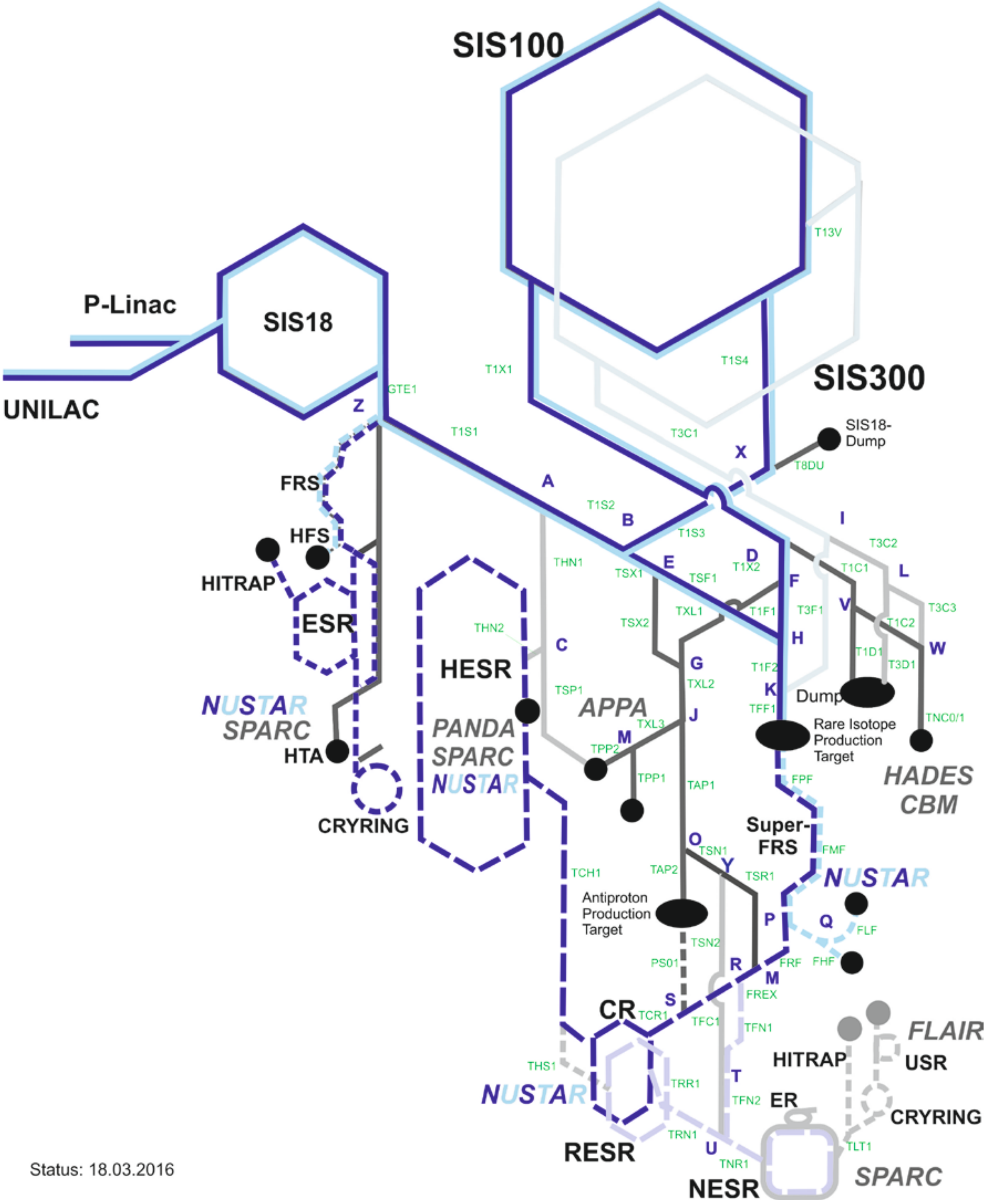

Figure 4-1: Schematic view of the accelerators and beam transport systems used for the experiments with radioactive ion beams. The colors are dark blue for storage ring experiments and light blue for fixed target experiments. Solid lines indicate primary beams, broken lines secondary beams. Bright colors indicate the MSV, shaded colors future options.

After separation of one specific isotope, the secondary beams are used by two groups of experiments:

- Experiments in LEB and HEB:
  - R^3B at the HEB
  - HISPEC/DESPEC, LaSpec and MATS at the LEB of the Super-FRS
  - Super-FRS experiments employing the device itself as particle spectrometer
- Storage Ring Experiments:
  - ILIMA (CR, HESR or ESR, CRYRING in the MSV)
  - EXL (will use ESR in the MSV. Eventually, an experimental place in HESR is under discussion)

Both groups need intense primary ion beams. The reference primary ion in SIS18 and SIS100 is $^{238}U^{28+}$. The accelerator concept aims at

- an average flux of $\sim 3 \cdot 10^{11}$ uranium ions per second at 1.5 GeV/u for the experiments in LEB and HEB
- $\sim 5 \cdot 10^{11}$ uranium ions in a single bunch for the Storage Ring Experiments.

The reference primary ion $^{238}U^{28+}$ is expected to be used approximately 30% of the dedicated beam time. It is noted, that dependent on the particular experiment any stable (including enriched) isotope from H to U might be required (with preference for heavy ions, Z>50). Depending on the experiment goal usually either most neutron-rich or most proton-rich isotopes of a given element are needed for reference purposes, the often used projectiles U, Bi, Pb, Au, Xe, Kr, Ar and protons are used in the following.
Inert gas ions are produced with required intensities by MUCIS source. The heavy metallic projectiles Au, Bi and Pb are produced by MEVVA ion source. Recent MEVVA developments have improved the high current output up to 10 mA (charge state analyzed). Nevertheless, the pulse rate is presently limited to 1 Hz. It is expected that Au can be produced with higher pulse rate (2 Hz). Further ion source development must be performed.
In particular the fixed target experiments HISPEC/DESPEC and R^3B rely on a uniform spill structure. Any non-stochastic beam intensity spikes would overload the experiments leading to severe data losses. This is one of the open topics, see Chapter 5.5.
Parallel operation for the NUSTAR experiments will be very important (typical running times of one week, with parasitic startup commissioning of experiments) and shall allow a fast switching between experiments.

4.1.1 NUSTAR experiments in LEB and HEB

Table 4-2: Requirements for the primary beam in front of the Super-FRS target

Requirement of NUSTAR Experiments in HEB and LEB												
Beam Parameters	Ref. Ion: U^{28+}	Bi^{26+}, Pb^{26+}	Au^{25+}	Xe^{21+}, ^{86}Kr	Ar^{10+}	p	Ref. Ion: U^{28+}	Bi^{26+}, Pb^{26+}	Au^{25+}	Xe^{21+}, ^{86}Kr	Ar^{10+}	p
	Commissioning phase						Operation in MSV					
Time structure	Slow extraction											
Number of ions per cycle	$2x10^{10}$	$3x10^{9}$		$7x10^{9}$	$8x10^{10}$	10^{11}	$5x10^{11}$			$7x10^{11}$	10^{12}	10^{12}
Ref. energy [GeV/u]	1.5					2.5	1.5					2.5
En. Range [GeV/u]	0.4-2.7											
Transverse emittance, 2σ [mm mrad]	2x2- 5x5											
Pulse length, 4σ [s]	0.5-10											
Momentum spread, 2σ	$\pm 10^{3}$											
Beam spot radius on target [mm]	1(h)x2(v) (favored 0.5x1)											

Reference chain UNILAC-SIS18 – (SIS100) – Super-FRS – HEB(LEB)

NUSTAR has five main experiment phases. The initial phase can be performed already after upgrade of UNILAC and SIS18 with U^{73+} and other projectiles presented in the table above.

- UNILAC
  - U^{4+} is produced in the MEVVA source,
  - U^{28+} is produced in the UNILAC gas stripper at 1.4 MeV/u,
  - Accelerated in UNILAC to 11.4 MeV/u ,
  - 4 pulses[4] of uranium beam are produced in 1.11 s (2.7 Hz).
- SIS18
  - Each pulse is accelerated at harmonic Number h=2 to 200 MeV/u
  - The acceleration of 4x2 bunches in SIS18 requires 1.6 s in total including pre- and post-processing.
- SIS100
  - Duration of injection into SIS100 is 1.11 s,
  - Acceleration to 1.5 GeV/u,
  - KO-Extraction, spill length ~2 s,
  - Cycle length 3.95 s in MSV with reduced number of RF cavities,
    3.85 s in final set-up.

[4] **Note**: 1/(2.7Hz)=370ms. The time between the first pulse and the fourth is 3*370ms=1,110 s.

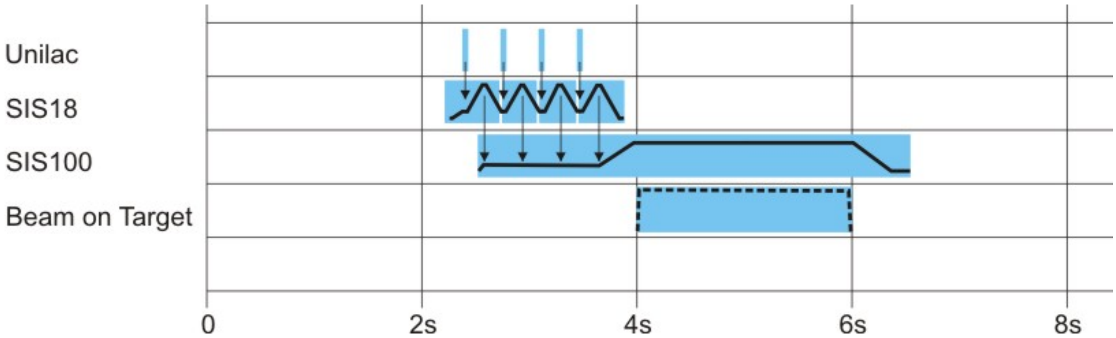

Figure 4-2: Reference Chain "Beam for NUSTAR Fixed Target Experiments"

Reference chain P-LINAC-SIS18 - Super-FRS – HEB(LEB)

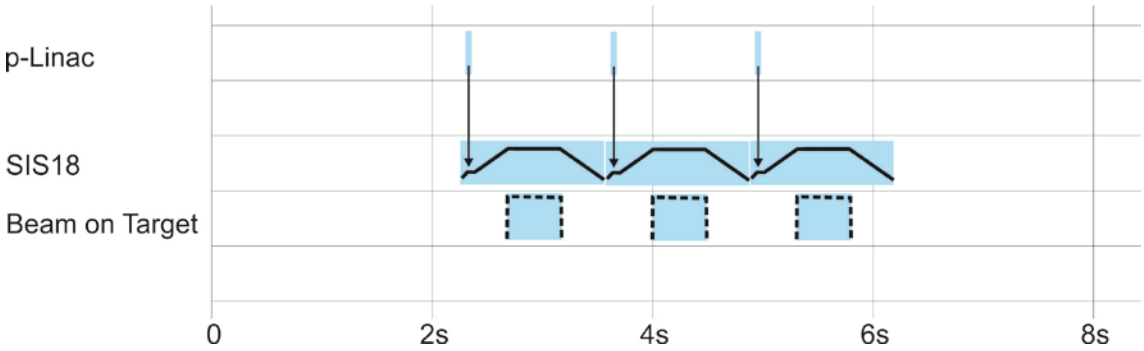

Figure 4-3: Reference Chain "Proton Beam for NUSTAR Experiments in HEB and LEB"

4.1.2 NUSTAR Storage Ring Experiments

4.1.2.1 Experiments in ESR-CRYRING

Tests and first experiments for EXL during the MSV as well as the Schottky mass and lifetime spectrometry part of the ILIMA will be done in the CR, HESR, ESR and CRYRING.

The beam production chain includes the SIS18-(FRS)-ESR-(CRYRING) machines. The already operational procedure to inject the ions from SIS18 into the ESR via the direct or via the FRS lines will be further employed. All range of possible stable ions (p-U) as well as radioactive beams are required. The beams in the ESR will be slowed down to few MeV/u, electron cooled, fast extracted to CRYRING. The extraction energy from the ESR depends on the capability of the CRYRING injection kicker magnet. The CRYRING injection will accept beams with rigidities from 0.8 Tm (for the beginning) up to 1.4 Tm. Depending on the specific physics goals, the CRYRING cycles will have different durations starting from several 100 ms up to several 10 s. However, the preparation of the beam in the ESR will take about 10 s, which defines the maximal repetition rate of the SIS18-ESR cycling.

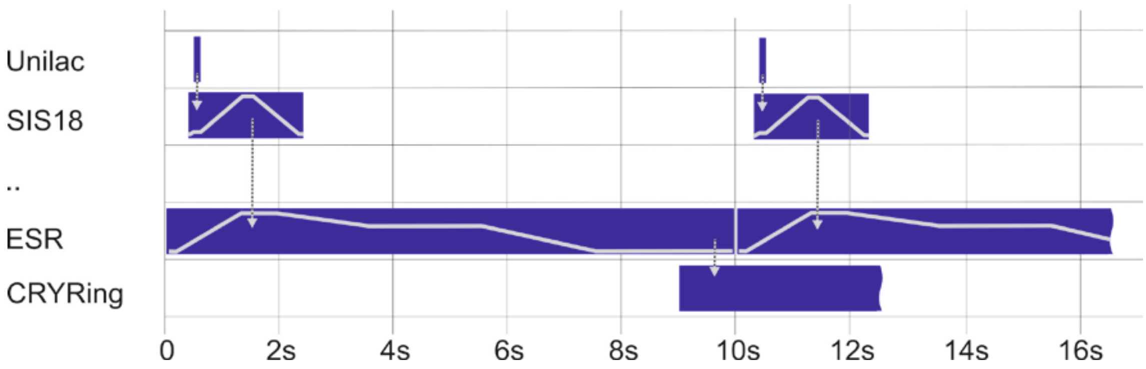

Figure 4-4: Reference Chain "Beam for EXL and ILIMA in ESR"

4.1.2.2 Experiments in CR-HESR

For the storage ring experiments the primary beam is extracted from SIS18 or SIS100 in a single bunch (fast extraction) using bunch rotation.
The table below lists the user requirements on the primary beams in front of the Super-FRS target. All NUSTAR experiments in storage rings require the highest repetition rate.

Table 4-3: Requirements for the primary beam in front of the Super-FRS target

Requirements of NUSTAR Experiments in Storage Rings								
Beam Parameters	Ref. Ion: U^{28+}	Bi^{26+}, Pb^{26+}, Au^{26+}	Xe^{21+}, Kr	Ar^{10+}	Ref. Ion: U^{28+}	Bi^{26+}, Pb^{26+}, Au^{26+}	Xe^{21+}, Kr	Ar^{10+}
	Commissioning				Operation in MSV			
Time structure	fast extraction							
Repetition rate	0.5-0.01 Hz				0.7-0.1 Hz			
Number of ions per cycle	$2x10^{10}$	$3x10^{9}$	$7x10^{9}$	$8x10^{10}$	$5x10^{11}$		$7x10^{11}$	10^{12}
Ref. energy [GeV/u]	1.5			1.0	1.5			1.0
Energy range [GeV/u]	0.4-1.5							
Transverse emittance, 2σ [mm mrad]	11(h) x 4(v)							
Pulse length, 4σ [ns]	70				50[5]-100			
Momentum spread, 2σ	$\pm 10^{-2}$							
Beam spot radius on target [mm]	1x2-4x6[6]		2x3	3x5	1x2-4x6		2x3	3x5

Experiments with very exotic ions (yield ~ 1 per bunch) would require intense (1-2 10^{10}), energetic (1 GeV/u), short U^{73+} bunches from SIS18 with maximum repetition rate (>1 Hz).

[5] The bunch length requirement arises from the max momentum spread acceptance of 1% (4σ) after fast debunching in CR. However, longer bunches could be tolerated for optimized RF voltage profiles. It has to be clarified with CR team.
[6] Some experiments require relatively large beam spots

Reference chain SIS100 – Super-FRS – CR

The initial experiment phase can be performed already after upgrade of UNILAC and SIS18 with U^{73+} and other projectiles presented in the table above.

The single bunch is generated after acceleration in SIS100. A dedicated bunch compressor system is designed for the compression of the ion bunch to a pulse duration of 100 ns at 0.4 GeV/u and 50 ns at 1 GeV/u. As soon as the minimum pulse length is attained, the beam is extracted by fast kickers and delivered to the Super-FRS target.

The Collector Ring CR is designed for fast stochastic cooling of antiprotons and the secondary fragment beams (RIB) at the fixed magnetic rigidity of 13 Tm, which corresponds to the antiproton energy of 3 GeV and RIBs of 740 MeV/u. It will also allow time-of-flight mass spectrometry for short-lived isotopes (operation in isochronous mode). To allow for a large area of mass surface to be covered and for different atomic states of the secondary ions, it will be possible to tune the isochronous mode of the CR in the range of magnetic rigidity from 8 to 13 Tm. The time needed in the ring for the measurements depends on the life time of the isotopes, which will be in the range of 0.1 – 1000 ms.
Alternately, the beam may be transferred to the HESR for measurements. Both chains are shown in Figure 4-5

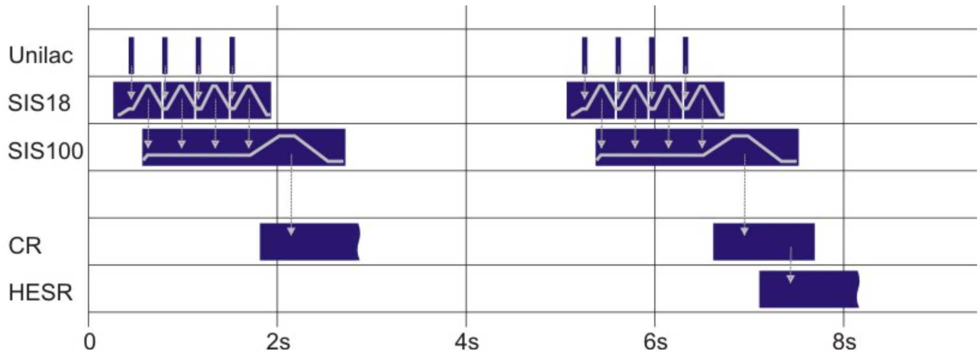

Figure 4-5: Reference Chains "Beam for ILIMA from SIS100"

Reference chain SIS18 - c4 - CR*

For the commissioning and fine tuning of the CR in the isochronous mode, primary beam may be sent via the Super-FRS (target removed) or via the c4* beam line directly from SIS18:

- UNILAC
  - U^{4+} is produced in the MEVVA source,
  - U^{28+} is produced in the UNILAC gas stripper at 1.4 MeV/u,
  - Accelerated in UNILAC to 11.4 MeV/u ,
  - U^{73+} is produced in the foil stripper in the transfer channel
- SIS18
  - Acceleration to 740 MeV/u (cycle length ~ 1 s)
- CR
  - Adjusts Isochronous mode for ILIMA experiments.

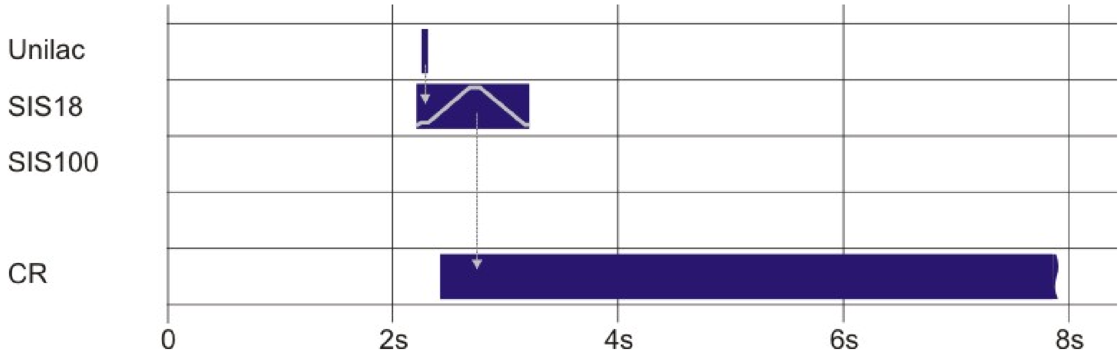

Figure 4-6: Reference Chain "Beam for ILIMA from SIS18"

4.1.3 Future Options

At an intermediate stage, an additional beam line connecting HESR to the ESR can be constructed which would enable SPARC and ILIMA program at HESR, allow parallel operation of HESR and SIS100 or CR. Such line would push for an early commissioning of HESR and PANDA with protons.

In the final set-up, there will be additional options:

- For fixed target experiments, preferably the accelerated beam is transferred to SIS300, which then is operated in its stretcher mode. A duty cycle of nearly 100% can be reached, if the beam is slowly extracted from SIS300 during the next acceleration cycle of SIS100 and only shortly interrupted for a refill.
- In the ring branch, after stochastic pre-cooling in the CR, the RIB is rebunched and transferred to the RESR, which is foreseen for the fast deceleration of rare isotopes to energies between 100 MeV/u and 500 MeV/u.
- RIBs can be delivered to the new experimental storage ring NESR on three ways: directly from the Super-FRS, after the stochastic cooling in the CR (via RESR) or after deceleration in the RESR. The NESR is equipped with an electron cooling device which will cover the whole range of energies at which ions can be stored in the NESR. This provides optimum beam quality for the various experimental arrangements and supports the further deceleration of beams before they are extracted and delivered to the FLAIR cave.
- One straight section of the NESR can be employed for the investigations of electron scattering on radioactive nuclei. The electrons will circulate in a separate storage ring which has a common straight section with the NESR. Precautions have been taken in the arrangements of buildings and beam lines to allow – as another future option – the injection of antiprotons into this electron storage ring.

4.2 Antiproton Beams

Antiprotons in FAIR will be used for two types of experiments:

1. high energy experiments in the HESR, namely PANDA
2. low energy experiments in the FLAIR cave.

In the MSV, only PANDA is foreseen as a user of antiprotons.

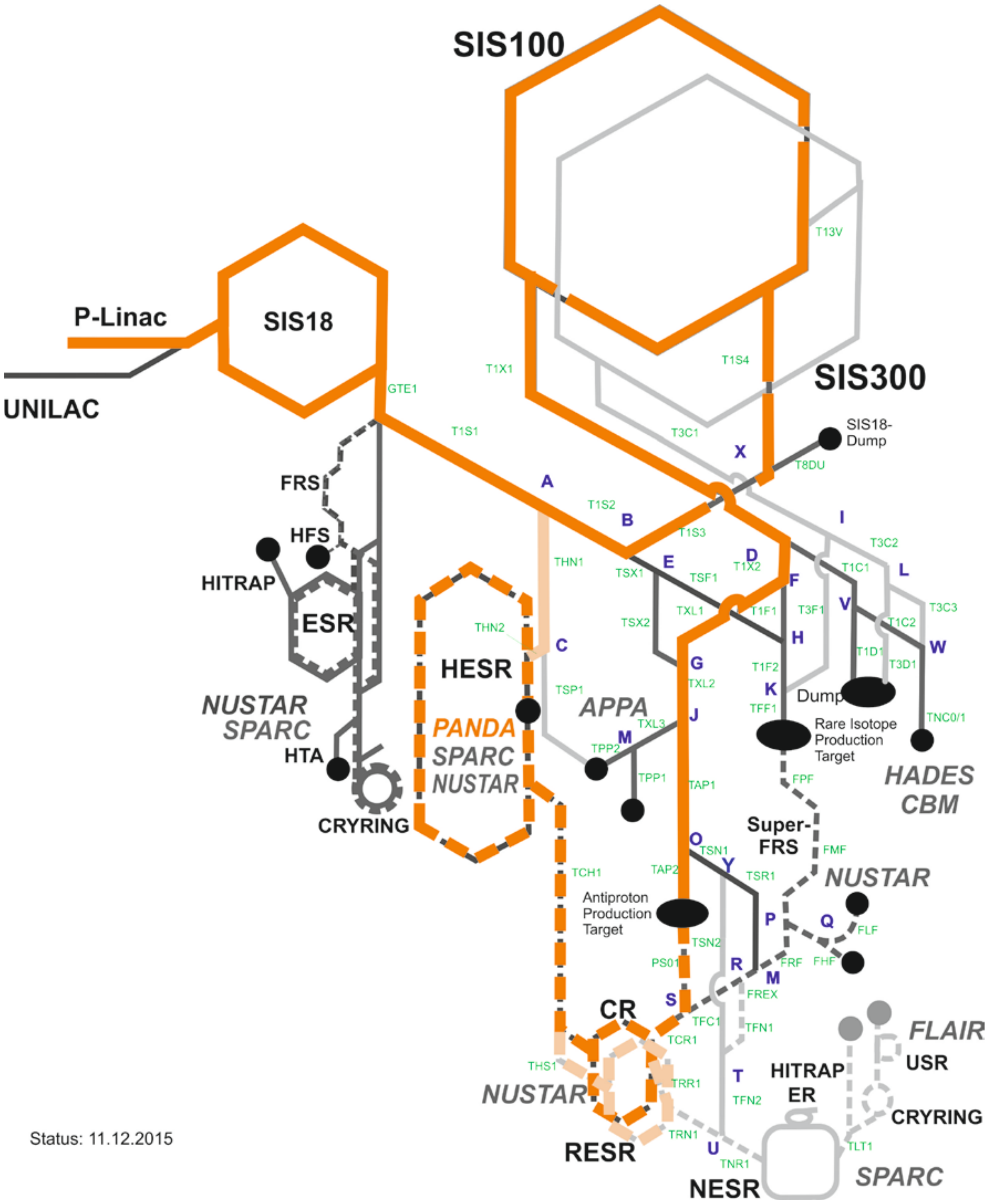

Figure 4-7: Schematic view of the accelerators and beam transport systems used for antiproton production and experiments. Solid orange lines indicate the intense proton beams, broken lines the paths of the antiprotons. Modules 0-3 to be built in the first step are shown in bright colors. In pale colors the modules 4-6 are shown.

4.2.1 PANDA

The HESR is dedicated to supply PANDA with high intensity and high quality antiproton beams over a broad momentum range from 1.5 GeV/c to 15 GeV/c [11]. Table 4-7 summarizes the experimental requirements of the High Resolution (HR) operation mode. The High Luminosity mode (HL) will not be supported in the MSV.

The RESR will not be available for accumulation of the cooled antiprotons in MSV. Therefore, accumulation will be done in HESR with a barrier bucket method assisted by stochastic cooling. Antiproton accumulation of $1 \cdot 10^{7}$ s^{-1} for 1000 s is envisioned for MSV, alternating with acceleration/deceleration and measurements for a similar time span.

The chain for the antiproton production in MSV comprises as following: A dedicated proton LINAC of 70 MeV final energy, SIS18 is used for acceleration to 4 GeV and SIS100 for an acceleration to 28.8 GeV. The antiproton generation takes place in a dedicated target equipped with a magnetic horn for focusing (with production rate of 10^{-5} antiprotons per primary proton). After magnetic separation the antiprotons are collected, bunch rotated and stochastically cooled in the CR. In HESR the stochastic and electron cooling is used to compensate a transverse beam blow up and to achieve a low momentum spread.

Table 4-4 Beam Parameters at HESR requirements for the PANDA experiment

PANDA Experiment requirements		
Beam Parameters	High Resolution Mode	
	Commissioning	Operation in MSV
Time structure	debunched	
Momentum range [GeV/c]	1.5-8.9	
Accumulation time[7] [s]	1000	
Number of particles after accumulation	10^{9}	10^{10}
Reference energy [GeV]	8.0	
Energy range [GeV]	0.83-8.0	
Transverse emittance, 2σ [mm rad]	2 x 2	
Peak Luminosity [$cm^{-2}s^{-1}$]	$2x10^{30}$	$2x10^{31}$
Momentum spread, 2σ	$\leq 8x10^{-5}$	
Beam spot radius on target [mm]	1 x 1	

[7] Is necessary only for the MSV.

Reference chain p-Linac – SIS18 – SIS100 – pBar – CR - HESR

- P-Linac
  - Produces one proton beam pulse every 0.37 s (2.7 Hz),
  - Accelerates it to 70 MeV.
- SIS18
  - Accelerates it at harmonic no. h=1 to 4 GeV,
  - Needs ~1.6 s in total for the 4 bunches including pre- and post-processing.
- SIS100
  - Injection of 4 bunches from SIS18 needs 1.11 s,
  - Merged into one single bunch at h=5,
  - Acceleration to 28.8 GeV/u,
  - Compression to a bunch length of ~50 ns,
  - Cycle length ~2.84 s in MSV with reduced no. of RF cavities, 2.77 s in final set-up.
- Antiproton Production Target
  - The yield is expected to be 10^{-5} antiprotons per proton, antiprotons at 3 GeV
- CR
  - Bunch rotation to reduce momentum spread,
  - Adiabatic de-bunching,
  - Stochastic cooling down to $\delta p/p \approx \pm 0.1\%$, $\varepsilon_{h,v} \approx 1.3\ \pi$ mm mrad,
  - Repetition time 10 s.
- HESR
  - Accumulation of ~$1 \cdot 10^{10}$ antiprotons in 1000 s,
  - Deceleration/acceleration to the experiment energy (0.83 GeV – 8.0 GeV),
  - Beam on PANDA target for ~1000s

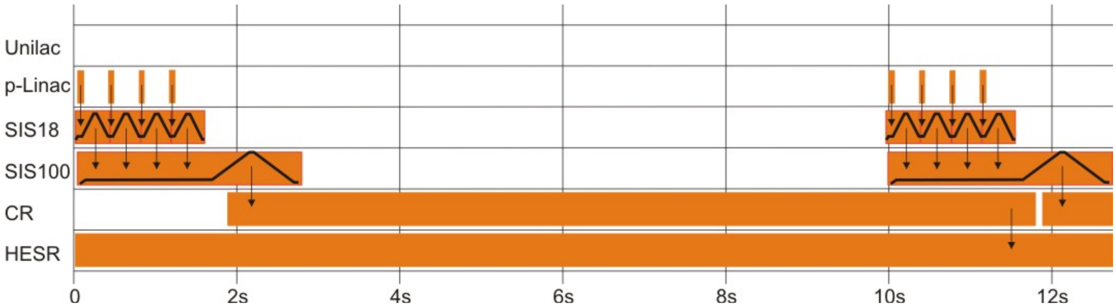

Figure 4-8: Reference Beam Production Chain "Production and Accumulation of Antiprotons"

For the experiment preparation the following topic must be clarified:

For the merging in SIS100 of 4 single bunches into one, γ_t must be shifted above the maximum Energy. As an alternative, a γt-jump is under discussion, which would allow to merge bunches at extraction energy and thus reduce the space charge effects.

4.2.2 Future Options

The final set-up will include additional options:

PANDA

- The RESR will be added for accumulation of the antiprotons. This will allow for optimized accumulation times in RESR, hence higher luminosity for PANDA and a factor of 2 longer periods of beam on target (luminosity of 2×10^{32}).
- The HESR will be equipped with an electron cooler to enable high precision experiments with cooled antiproton beams (with 4MV or even 8MV accelerating voltage).

Low Energy Experiments

- Some 25% of the antiprotons, which have been accumulated in the RESR will be transferred to the NESR. It is foreseen to separate a fraction of the accumulated beam in the RESR and transfer it via NESR with additional deceleration to the CRYRING with a repetition rate of up to $(1\ \mathrm{min})^{-1}$. The CRYRING is equipped with an electron cooler, which allows fast and efficient deceleration of the antiprotons down to 30 MeV-300keV for low energy experiments in FLAIR.
- At the intermediate stage, before the construction of the NESR, a transfer line between HESR and ESR-CRYRING is considered to enable low-energy antiproton physics with in-ring as well as with extracted antiproton beams.

Table 4-5 PANDA Experiment requirement for the future options

PANDA Experiment requirements		
Beam Parameters	High Luminosity Mode	High Resolution Mode
Time structure	debunched	
Momentum range [GeV/c]	1.5-15	1.5-8.9
Number of particles after accumulation	10^{11}	10^{10}
Reference energy [GeV]	14.1	8.0
Energy range [GeV]	0.83-14.1	0.83-8.0
Transverse emittance, 2σ [mm rad]	1x1	
Peak Luminosity [$cm^{-2}s^{-1}$]	2×10^{32}	2×10^{31}
Momentum spread, 2σ	10^{-4}	$\leq4\times10^{-5}$
Beam spot radius on target [mm]	0.3(h) x 0.3(v)	

4.3 CBM/HADES – Compressed Baryonic Matter

The high-energy nucleus-nucleus collision experiments are used to investigate the properties of strongly interacting matter under extreme conditions. HADES and CBM at SIS100/300 will explore the QCD phase diagram in the region of very high baryon densities and moderate temperature.
The proposed nuclear physics experiments CBM and HADES require ion beams with kinetic energies up to 45 GeV/u. Figure 4-9 shows the accelerators used for these beams.

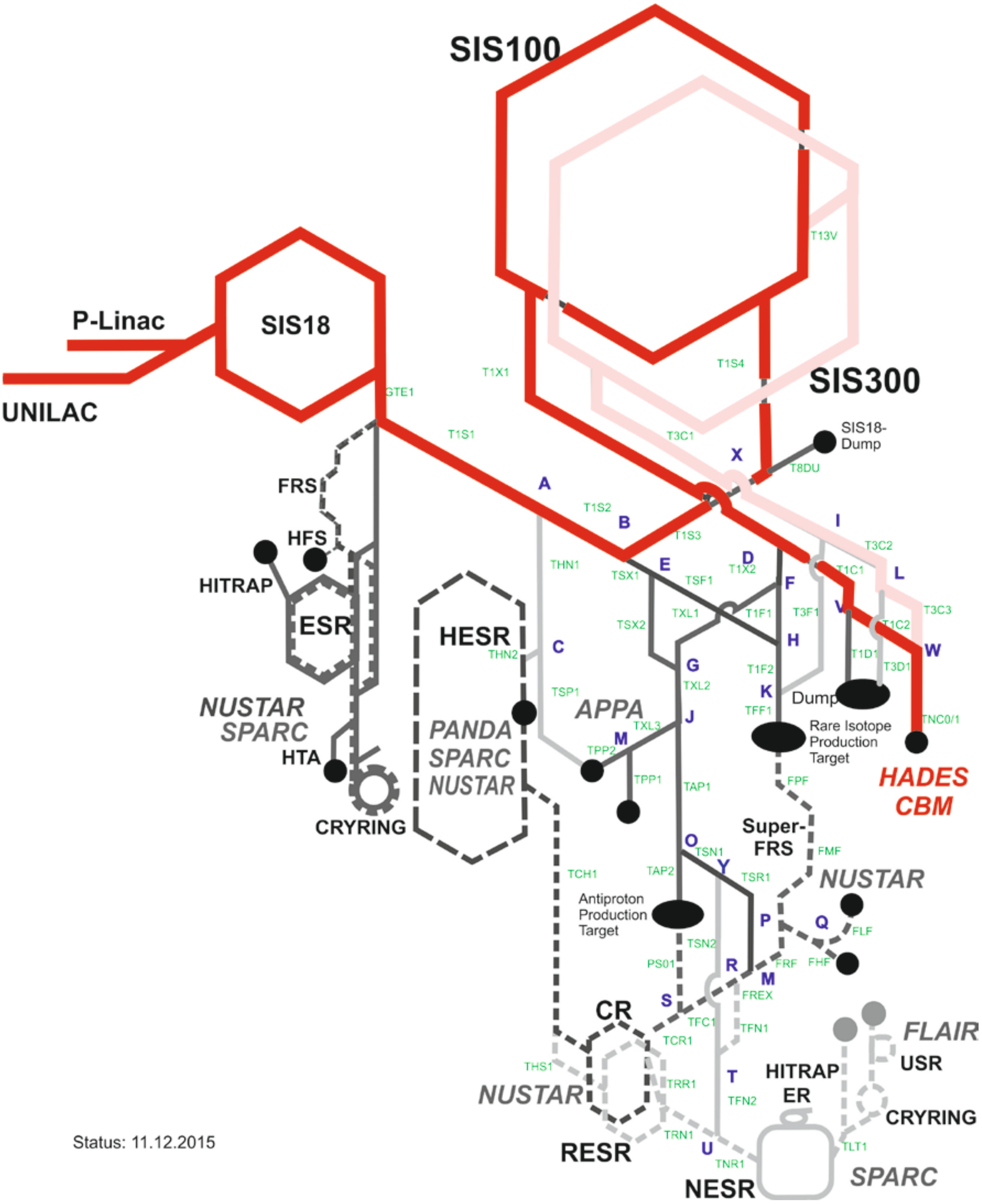

Figure 4-9: Use of the FAIR accelerators for high energy nuclear physics. Bright red lines show the accelerators available in the MSV. SIS300 and the corresponding beam lines are shown in pale red.

The measurements will be done in CBM/HADES cave with a broad range of projectiles (from light to heavy). Due to the spherical nuclei, gold serves as the reference ion instead of Uranium. The production of the gold was already discussed in the NUSTAR chapter (see 4.1). For ^{107}Ag is a similar situation: can be produced in MEVVA source with 1Hz. Further ion source optimization is necessary. ^{40}Ca is not expected to be produced with required intensity. Alternatively, ^{40}Ar could be used. ^{12}C is delivered from ECR source with lower intensity (10^8 per cycle).

The HADES experiment requirements for the beam parameters are quite moderate in comparison to CBM. Hence, only CBM parameters will be followed.

As MSV provides only SIS100, the beam energy will be a factor of 3 lower as originally designed for the experiments.
Further specific beam quality requirements are:

- At the distance greater than 5 mm from the beam axis the beam halo must be below 10^{-5} of the total beam intensity;
- The intensity fluctuations of the spill structure must be below 50% (average value normalized to the max value), down to tens of nanosecond time scale. This condition is not fulfilled by the SIS18 at the present status.

Table 4-6: CBM Experiment requirements for the beam parameters from SIS100

CBM[8] Experiment requirements												
	Ion type[9]											
	p	^{12}C	^{40}Ca	^{58}Ni	^{107}Ag	Ref. Ion ^{197}Au	p	^{12}C	^{40}Ca	^{58}Ni	^{107}Ag	Ref. Ion ^{197}Au
	Commissioning						Operation in MSV					
Time structure	slow extraction											
Number of ions per cycle	10^{10}	10^9	$4\text{x}10^8$		$2\text{x}10^8$	10^8	10^{12}	10^{11}	$4\text{x}10^{10}$		$2\text{x}10^{10}$	10^{10}
Ref. energy [GeV/u]	4											
Energy range[10] [GeV/u]	5-29	3-14	3-14	2-13	2-12	2-11	5-29	3-14	3-14	2-13	2-12	2-11
Transverse emittance, 2σ [mm mrad]	3 x 3											
Pulse length, 4σ [s]	10											
Momentum spread, 2σ	$\pm 5 \times 10^{-4}$											
Beam spot radius on target [mm]	2											

Another important criterion for the experiments is a beam abort system. Although the components of the HADES/CBM detection systems are constructed of state-of-the-art radiation hard materials, radiation damage is one of the main concerns in the long term operation scenario at SIS100/SIS300. Any accidental irradiation by direct beam ions can damage the detection system components and has to be avoided. For this purpose a fast, fail-safe beam abort system (in SIS100) will be able to block the beam transport to the HADES/CBM experimental area within 100-200 µs time and will be triggered by the beam abort signal delivered by a dedicated detection system from the experiments.

[8] HADES experiment requirements are more moderate than from CBM, hence they are not followed here.
[9] As a maximum energy has to be achieved in SIS100, the ions have to be completely stripped.
[10] For low beam energies at SIS100, below 4GeV/u, the beam emittance will be worse than requested.

4.3.1 Beams for CBM in the MSV

Reference chain: Source-UNILAC-SIS18-SIS100-CBM

The Au beam is produced in the following steps:

- UNILAC
  - Au^{4+} is produced in the MEVVA source,
  - Au^{25+} is produced in the UNILAC gas stripper at 1.4 MeV/u,
  - Accelerated in UNILAC to 11.4 MeV/u ,
  - Stripping of Au^{25+} ions to Au^{65+} ions in the TK Stripper,

- SIS18
  - Accelerates the bunch up to 1 GeV/u,
  - Needs ~0.5 s (including pre- and post-processing).

- HEBT

  - transfer and stripping of Au^{65+} ions to Au^{79+} ions.

- SIS100
  - Acceleration to 11 GeV/u
  - KO-Extraction, spill length 1 - 10 s
  - Repetition Time ~2 - 11 s

With $1x10^{10}$ ions in the pulse, the average ion flux during a 10 s long spill is approximately $1{\cdot}10^9\,s^{-1}$. The intensity averaged over the 11 s cycle is approximately 90%.

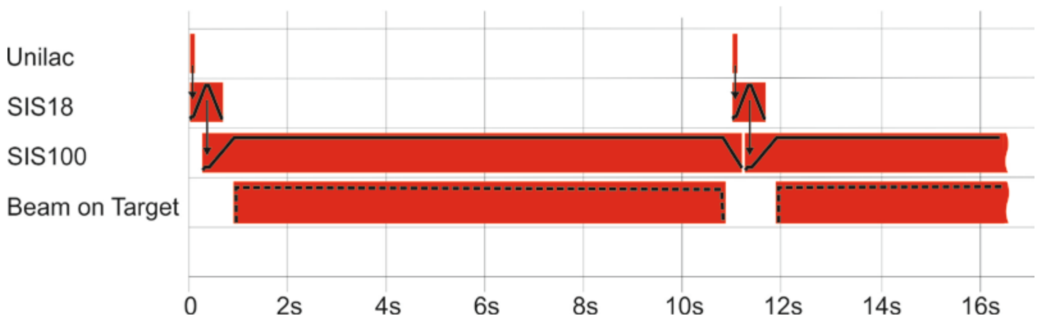

Figure 4-10: Reference Beam Production Chain for CBM for 10 s extraction.

For the experiment preparation the following topics must be clarified:

- The microstructure of the beam pulse,
- Beam halo,
- For the low beam energies at SIS100, below 4 GeV/u, the beam emittance could be worse than requested,
- Not all required intensities of the planned projectiles can be provided by the ion source.
- Gamma-t shift can be made for the protons lattice for the fast extraction. For the slow extraction it is still open and has to be studied.

4.3.2 Future Options

The main purpose of SIS300 is the production of the high energy beams for CBM. The super-conducting cosθ-magnets allow for an operation at maximum bending field B_{max} = 6 T and with maximum ramping rate dB/dt = 1 T/s. The maximum specific energies range from 35 GeV/u for fully stripped gold ions up to 45 GeV/u for neon ions.

Table 4-7: Experiment Requirements for beams from SIS300

CBM Experiment requirements		
Isotope	Energy range [GeV/u]	Beam intensity in spill [s^{-1}]
p	29-89[11]	10^{11}
^{12}C	14-44	10^{10}
^{40}Ca	14-44	$4x10^{9}$
^{58}Ni	13-42	$4x10^{9}$
^{107}Ag	12-38	$2x10^{9}$
^{197}Au	11-35	10^{9}

The basic steps for a gold beam are:

- acceleration of Au^{65+} ions to 1 GeV/u in a single short SIS18 cycle,
- transfer and stripping of Au^{65+} ions to Au^{79+} ions
- acceleration of Au^{79+} ions to 11 GeV/u in a short SIS100 cycle,
- transfer of the Au^{79+} beam to SIS300,
- acceleration to 35 GeV/u in a long SIS300 cycle consisting of 2×4 s for ramping the magnetic fields up and down and 10 s for slow beam extraction, and
- Repetition of the procedure every 20 seconds.

High energy beams with a duty factor of about δ = 50 % can be provided this way. In this mode of operation the injector machines SIS18 and SIS100 may be used for other experiments during more than 95% of their operation time.

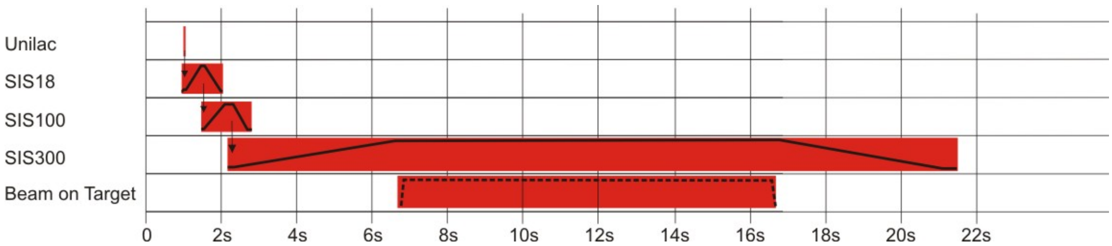

Figure 4-11: High Energy Beam Production for CBM in the final set-up.

[11] Reduced proton intensity for highest energy due to shielding and beam dump limitations.

4.4 APPA: Atomic and Plasma Physics and Applications

APPA is a consortium of five experiment collaborations (SPARC, BIO, MAT, WDM and HEDgeHOB) with a large variety of experimental areas and beam production paths as indicated in Figure 4-12. For experiments with radioactive ion beams, see chapter 4.1 on NUSTAR.
The feasibility of the new experimental opportunities for the SPARC research program in the frame of MSV (CRYRING@ESR and SPARC@HESR) was investigated and discussed during 2012. Both studies were presented to the FAIR GmbH committees and recommended to be included in MSV. Furthermore, the BIOMAT research programs will continue using the existing irradiation setups in the cave M and cave A.

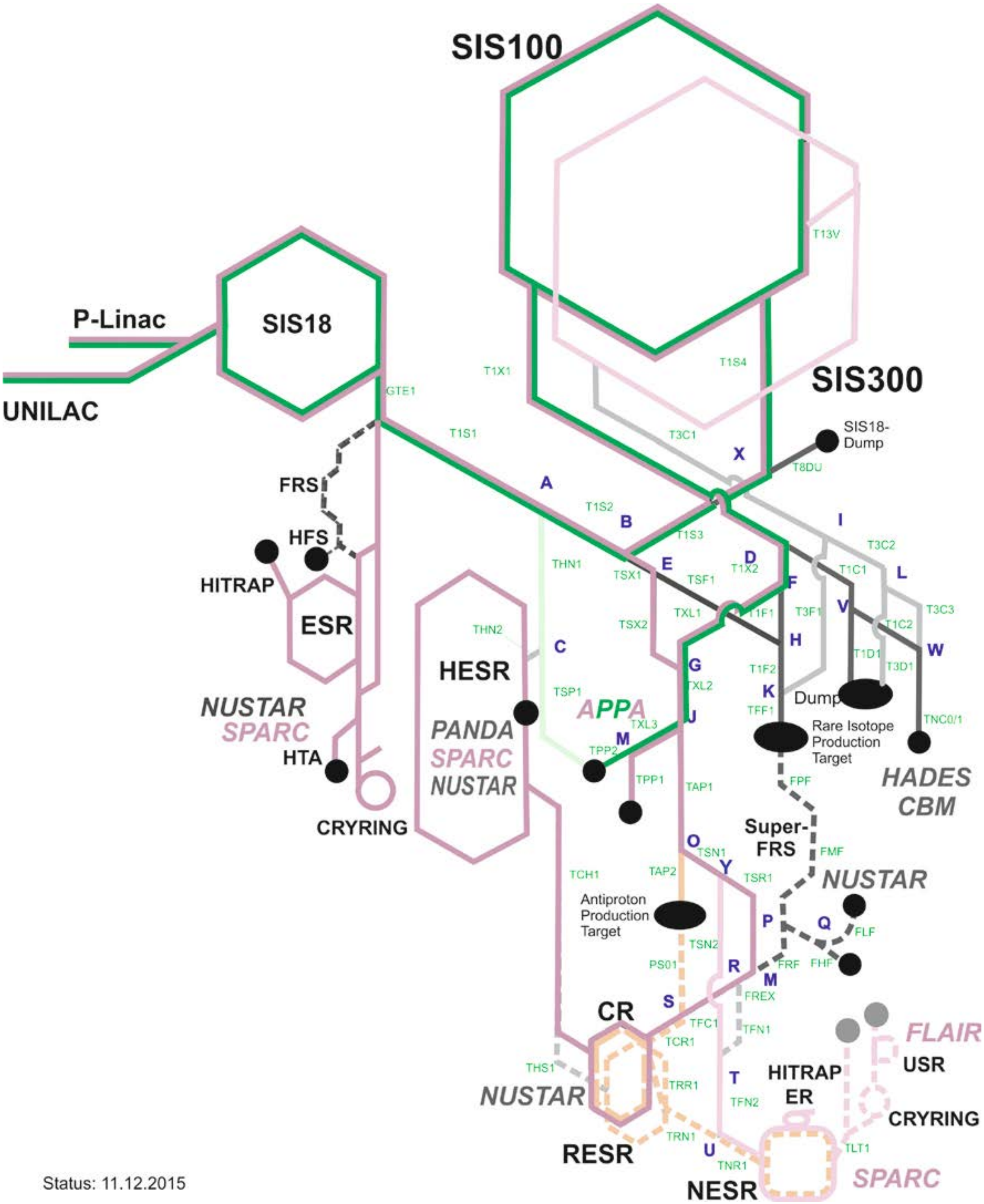

Figure 4-12: Schematic lay-out of the requested accelerators for APPA. The colors are green for plasma physics and violet for atomic physics experiments. Bright colors indicate the MSV, pale colors future options, including slow antiprotons for FLAIR (pale orange). For clarity, secondary ion beams are not colored, see Figure 4-1.

4.4.1 SPARC: Atomic Physics

Atomic physics experiments with highly charged ions and radioactive beams[12] will be addressed in the context of the MSV.
The experiments proposed for the MSV will be set up in several locations: APPA cave, SIS100, HESR, ESR, CRYRING, HITRAP and cave A.

4.4.1.1 SPARC: fixed target experiments

Fixed target atomic physics experiments will be performed in the APPA cave and in the Cave A, as long as ESR will be maintained operational [2].Beams of highly charged ions with energies up to 10 GeV/u will be delivered to the APPA cave by slow extraction (typically 10 sec) from SIS18 or SIS100. Some of the planned experiments require high transverse beam quality (beam divergence of 10^{-4}), which requires electron cooling in SIS18 at injection energy. For experiments in the existing Cave A beam energies up to 1 GeV and momentum spread better than 10^{-3} are required. Also the beam spot size should not be larger than 3mm (beam radius @1RMS).
Table 4-14 presents some beam parameters for the heaviest and the lightest ion beams required for this category of experiments (it is by no means exhaustive).

Table 4-8 Beam parameters for fixed target atomic physics experiments (SPARC) at APPA Cave

SPARC Experiment requirements at APPA Cave				
Beam Parameters	Ion species: U^{90+}, U^{91+}, U^{92+}, U^{28+}, U^{63+}		Ar^{18+}, H^{3}_{+}	
	Commissioning	Operation in MSV	Commissioning	Operation in MSV
Time structure	slow extraction			
Number of ions per cycle	10^{8}	10^{8}	10^{10}	
Ref. energy [GeV/u]	2		0.120	
Energy range [GeV/u]	0.05-10		0.1-10	
Transverse emittance, 2σ [mm mrad]	8(h) x 3(v)			
Pulse length, 4σ [s]	10			
Momentum spread, 2σ	$\pm 10^{-3}$	$\pm 10^{-4}$	$\pm 10^{-3}$	$\pm 10^{-4}$
Beam spot radius on target [mm]	<4	2	<4	2

Reference chain UNILAC – SIS18 – (SIS100) – APPA Cave

The U^{92+} beam is produced in the following steps:

- UNILAC
  - U^{4+} is produced in the MEVVA source,
  - U^{28+} is produced in the UNILAC gas stripper at 1.4 MeV/u,
  - Accelerated in UNILAC to 11.4 MeV/u ,
  - Stripping of U^{28+} ions to U^{73+} ions in the TK Stripper,
  - 4 pulses are produced in ~1.1 s (2.7 Hz).

- SIS18
  - Accelerates each pulse to 1 GeV/u,
  - Needs ~1.75 s for 4 batches (including pre- and post-processing)

[12] for details of the production of radioactive beams see NUSTAR chapter 4.1.2

- Either slow extraction to APPA cave
- Or fast extraction and transfer to SIS100.

- HEBT
- transfer and stripping of U^{73+} ions to U^{92+} ions

- SIS100
  - Injection of 4 batches from SIS18 needs ~1.2 s
  - Acceleration to 10 GeV/u
  - KO-Extraction, spill length 1 - 10 s
  - Repetition Time ~3 - 13 s

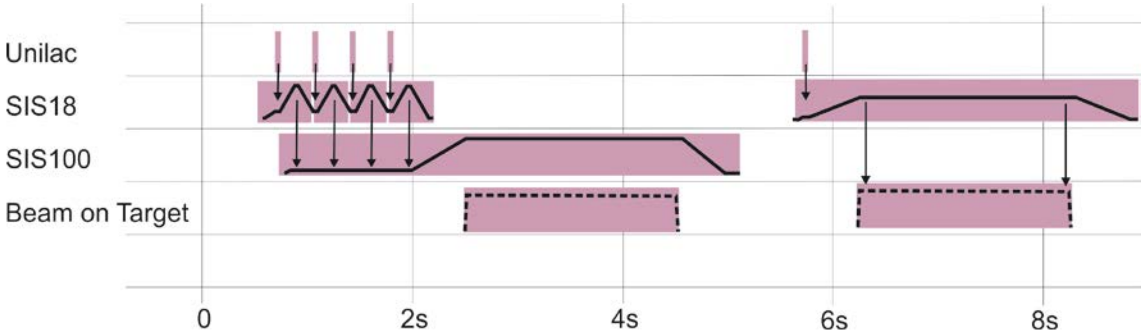

Figure 4-13: Beam Production for Atomic Physics in the APPA cave.

4.4.1.2 SPARC Storage Ring experiments

Within the modularized start version of FAIR, there are several locations for SPARC ring experiments:

- ESR-(CRYRING)
- ESR-HITRAP
- HESR
- SIS100

a) ESR-(CRYRING):
This chain includes the SIS18-(FRS)-ESR-CRYRING machines. The already operational procedure to inject the ions from SIS18 into the ESR via the direct or via the FRS lines shall be further employed. All range of possible stable ions (p-U) as well as radioactive beams in various charge states are required. The beams in the ESR will be slowed down to few MeV/u and electron cooled. For the experiments in CRYRING the beam will be the fast extracted. The extraction energy from the ESR depends on the capability of the CRYRING injection kicker magnet. The CRYRING injection will accept beams with rigidities from 0.8 Tm up to 1.4 Tm. Depending on the specific physics goals, the CRYRING cycles will have different durations starting from several 100 ms up to several 10 s. However, the preparation of the beam in the ESR will take several 10 s, which defines the maximal repetition rate of the SIS18-ESR cycling.

b) ESR-HITRAP
This chain is similar to the ESR-CRYRING chain, but the beam extracted from ESR will be directed to the HITRAP (fast extraction at 4 MeV/u).

c) High Energy Storage Ring:
This chain includes the SIS18-(SIS100)-(c4* or SuperFRS)-CR-HESR machines. Not all foreseen experiments require SIS100.
Stable and radioactive beams of all elements, protons up to uranium, with different charge states (U^{88+} - U^{92+}) are considered for the experiments. The beam parameters table 4-16 below includes only two kind of projectiles, however, the parameters for other ion species can be scaled from these data. Depending on the atomic number and extraction energy from the SIS18, stable ions will be stripped either in T1X1 or in TSX1 or in the target station of the SuperFRS. The RIBs from SuperFRS or beam from SIS18/SIS100 will be stochastically precooled in the CR (5-10s). The cooled ions will then be transferred at an energy of 740 MeV/u to the HESR.
The beams in the HESR will be either electron- or stochastically cooled; they will be slowed down or accelerated up to the maximal magnetic rigidity of the HESR of 50 Tm, depending on the specific experimental requirements. The required beam intensities are the maximal permitted by the radiation protection (beamlosses of 10^6/s), and will be determined by the production rates, transmission, beam lifetimes and space-charge effects. The anticipated beam intensity for highly-charged ^{238}U ions is 10^9 particles per cycle. In the case the intensity cannot be provided by a single SIS18/SIS100 pulse, the accumulation scheme in the HESR can be applied prior to the de/acceleration procedure (for details see PANDA Section).

Table 4-9 Beam paramenters required by atomic physics experiments (SPARC) in HESR

SPARC Experiment requirements in HESR				
Beam Parameters	Ref. Ion: U^{92+}		Ar^{18+}	
	Commissioning	Operation in MSV	Commissioning	Operation in MSV
Number of ions per cycle	10^9			
Time structure	d.c.			
Injection energy [GeV/u]	0.74			
Energy range [GeV/u]	0.2-5.5			
Transverse emittance, 2σ [mm mrad]	0.08			
Momentum spread, 2σ	10^{-5}-10^{-4}			
Beam spot radius on target [mm]	1			

Reference chain UNILAC – SIS18 –CR – HESR

For the stable beams, no thick targets will be employed which allows for fixing the SIS18/SIS100 energies to the injection energy of the CR of 740 MeV/u.

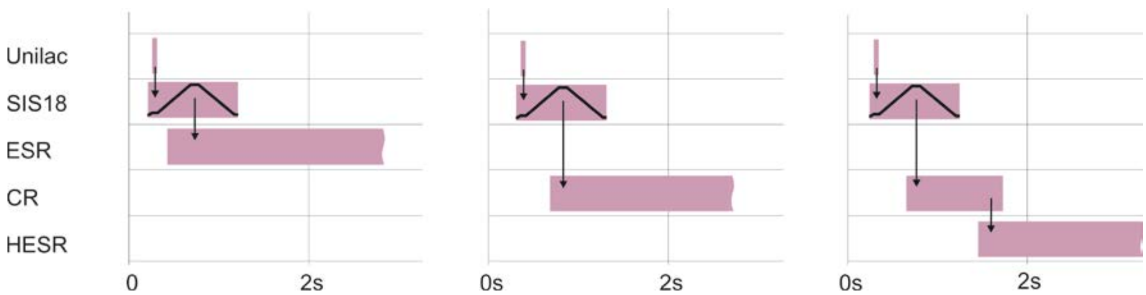

Figure 4-14: Beam production chains for SPARC Storage Ring experiments

d) SIS100

Initially, the SPARC laser cooling and laser spectroscopy experiments were planned for the SIS300 because of its huge magnetic rigidity, yielding a gamma-factor of about γ=25. Since the SIS300 is not part of the MSV, the scientific and accelerator communities decided to conduct these experiments at the SIS100. Here, γ=13 can be reached, which is still very large. This causes a dramatic Doppler-boost of the laser light \`seen´ by the relativistic heavy highly charged ions, enabling laser cooling and spectroscopy of transitions in such ions which are otherwise not accessible. At the SIS100, laser cooling of ions with atomic number (Z) between 10 and 60, and with a small number of electrons (3-19), will be possible.

Being the only cooling technique available for the SIS100, laser cooling can provide high-quality ion beams with very small relative momentum spread ($\Delta p/p$) and emittance (ε). In principle, $\Delta p/p=10^{-7}$ could be reached on a time scale of a second. It is also planned to extract the laser-cooled ion beams from the SIS100 and uniquely deliver very cold and very short ultra-relativistic ion bunches to experiments.

At GSI, laser cooling experiments have successfully been performed at the ESR with $^{12}C^{3+}$ ions at 47% of the speed of light (γ=1.13). Future test experiments at the ESR, CRYRING, HESR (γ=6), and at the CSRe in Lanzou, China, are also planned.

During the planned laser cooling experiments, the SIS100 will be blocked for other measurements.

4.4.1.3 SPARC: Future Options

The FAIR stages beyond the MSV will offer additional experimental possibilities for SPARC experiments:

- An extraction beam line at CRYRING for low-energy highly charged ions which will permit additional experiments using very low-energy, highly charged ions
- The option for a high duty cycle for the CRYRING is essential for all experiments on collisions with coincidence techniques
- A beam line connecting the CR/HESR to the ESR/CRYRING will allow for RIBs and antiprotons transfer to ESR/CRYRING. With this extension the low energy research program with highly charged ions and antiprotons, originally designed to be performed at the FLAIR facility, became feasible even before the NESR will be built. The beams of ions and antiprotons, once transferred to the ESR, will be decelerated and cooled down and finally, fast transferred to the CRYRING where the cooling and further deceleration to lower energies will be performed. So prepared beam will be used for experiments in the CRYRING or can be fast or slow extracted toward external experimental setups connected to the extraction beam line mentioned above.
- High-precision laser spectroscopy in SIS300.

4.4.2 BIOMAT: Biophysics and Material Sciences

The BIOMAT beamline serves a large variety of experiments of Biophysics and Materials Research communities. Experiments in both fields require high flexibility concerning irradiation conditions and target areas. Access to a broad range of beams (protons up to uranium) and ion energies from the SIS18 as well as the SIS100 synchrotron from 100 MeV/u up to 10 GeV/u is therefore necessary. Also the cycle intensities will vary from 1×10^4 up to 5×10^{10} ions/cycle in both modes (slow and fast extraction) which causes special demands on beam diagnostics.

BIOMAT will continue their studies with heavy ions of the upgraded SIS18 in Cave A and Cave M. According to the Green Paper Caves A and M will be maintained in operation during the MSV realization.
Typical intensities for biophysical experiments correspond to the delivery of a homogeneous dose of 10 Gy to a target area of 100 cm^2 in about 1 min. Slow extraction during 1-10 s will be used. One important aspect for this group of experiments is to switch off the beam within ms reaction time when the desired dose is reached. For homogeneous irradiation of larger areas, a spill regulation is highly desirable. For fast irradiation of living animals, a block modus shall be planned instead of the regular parallel operation schema.
The Materials Research experiments also require large flexibility with respect to ion species, energies and cycle intensities to be used by a large user community from different science communities. High intensities for fluence accumulation (slow extraction) as well as ultra-short high intense pulses for shock experiments (fast extraction) will be of interest. The values in table below indicate extreme cases at the reference energies (2 GeV/u for slow extraction; 0.7 GeV/u for fast extraction). It has to be noted that the energy for the experiments range from 0.1-10 GeV/u and the ion type will also cover the full spectra from proton up to uranium. A typical beam for fluence accumulation experiments would be an Au beam with 500 MeV/u and intensities around $5x10^{10}$ ions/cycle.

Table 4-10 Reference beam parameters for BIOMAT experiments at APPA Cave and Caves A and M for the MSV commissioning phase

BIOMAT Experiment requirements								
Beam Parameters	Biophysics						Materials Research	
	Ion type							
	protons	He	C	Ne	Ar	Fe, Kr, Xe, U	Protons - U	
Time structure	slow extraction						slow extraction	fast extraction2Hz
Number of ions per cycle	$5x10^{10}$	$1.5 x10^{10}$	$1.5 x10^{9}$	$5x10^{8}$	$1.5 x10^{8}$	10^{8}	10^{9*}	$5x10^{10*}$
Ref. energy [GeV/u]	2							0.7
Energy range [GeV/u]	0.1-10							
Pulse length, 4σ [s]	1-10						1-10	minimum
Beam spot radius on target [mm]							min20	

*) Values are given for an Uranium beam at ref. energy.

The beam production chain for high energy beams is similar to the one for NUSTAR in HEB/LEB and not followed here.
Carbon ions are produced in the ECR source and can be delivered with lower than required intensity (10^8 per cycle)

The timing pattern of this operation are schematically shown in the following beam production chains, which need to be included in the standard operation patterns.

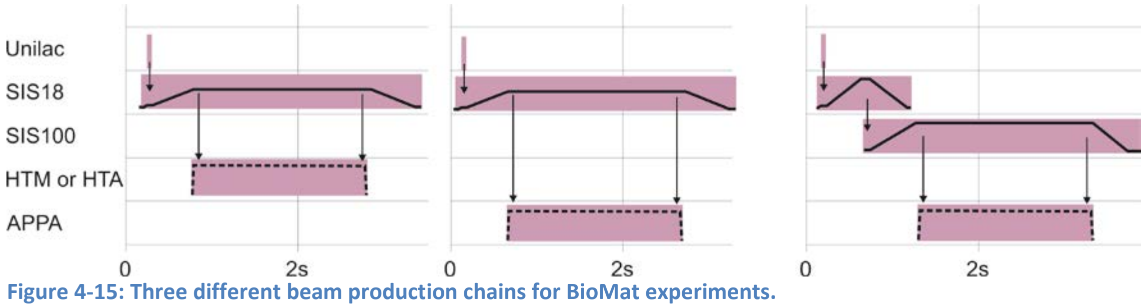

Figure 4-15: Three different beam production chains for BioMat experiments.

4.4.3 HEDgeHOB/WDM: Plasma Physics

There are two collaborations for plasma physics experiments in FAIR: HEDgeHOB and Warm Dense Matter (WDM). Both will operate in the APPA cave using the beam from SIS100 and/or SIS18. Different experimental schemes will be pursued demanding different beam parameters. For heating the target to plasma state usually heavy projectiles, preferably Uranium, with highest intensities and shortest pulse length are required at moderate energies of 0.4 to 2 GeV/u. On the other side the proton microscopy with protons from SIS18/SIS100 is an powerful diagnostic method, that will need protons at maximum intensity and either in a single compressed bunch (50 – 100 ns) or the full train of 8 uncompressed bunches from SIS100, within approximately 2.9 µs.

Table 4-11 Beam parameters for plasma physics experiments (HEDgeHOB and WDM) in the APPA cave

Plasma Physics Experiment requirements				
Beam Parameters	Ref. Ion: U^{28+}		Protons	
	Commissioning	Operation in MSV	Commissioning	Operation in MSV
Time structure	Single compressed bunch			
Number of ions per cycle	$1x10^{11}$	$5x10^{11}$	$2x10^{12}$	$2.5x10^{13}$
Repetition rate	2 – 20 shots/h			
Ref. energy [GeV/u]	2.0		4.5	10.0
Energy range [GeV/u]	0.4-2.0		3.0-10.0	
Transverse emittance 2σ [mm mrad]	8(h) x 3(v)		4.2(h) x 1.4(v)	
Pulse length, 4σ [ns]	100	50	50ns – 3.4µs	50ns – 3.4µs
Momentum spread, 2σ	$\pm 10^{-2}$		$\pm 5x10^{-4}$	
Beam spot radius on target [mm]	0.8(h) x 1(v)		5mm -15 cm[13]	

The beam intensity per SIS100 cycle as well as the pulse length required for plasma physics is comparable to that for the NUSTAR storage ring experiments described above in 4.1.2.
As a target is completely destroyed and has to be changed after every shot, the experiment will get a beam pulse approximately every 3 minutes. In the commissioning phase the pauses could be longer (up to 15 minutes).

These single shots will not be integrated in a standard beam production pattern. Instead, the running pattern will be stopped, an exclusive pattern for the plasma physics will run for a sin-

[13] For imaging purposes with protons the whole target hast to be illuminated.

gle shot (possibly with one or more preceding test shots) and afterwards the original pattern will be resumed.

The end focusing system of the plasma physics beam line is designed to focus the ion beam onto various spot sizes, from smallest spot up to large, flat top profiles, depending on the demands of the experiment. At the target, an intense laser beam will be available for diagnostics and target modification purposes, which must be synchronized with the ion beam with a precision of 1 ns.

There are some radiation protection issues for these experiments mentioned in Open Topics chapter.

The beam production process for protons is similar to the one for PANDA. Other high energy beams are produced similar to the those for NUSTAR storage ring experiments and not followed here.

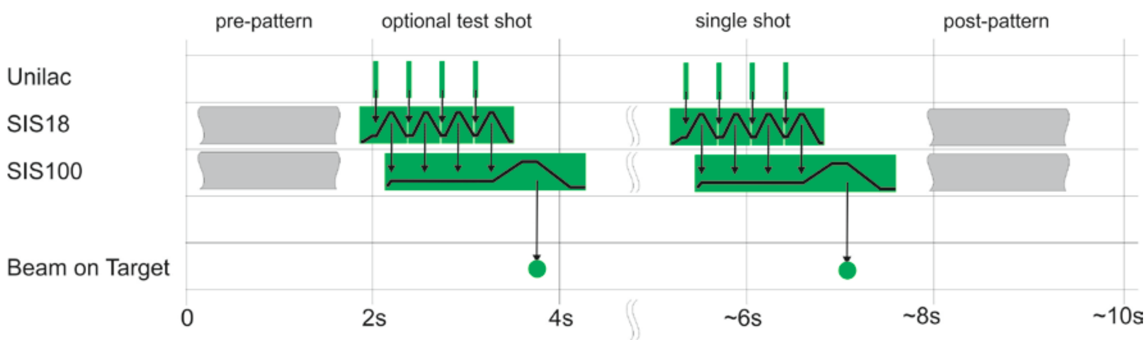

Figure 4-16: Reference Pattern #5 for Plasma Physics shots.

4.4.3.1 HEDgeHOB/WDM : Future Options

An additional beam line could be added to deliver from SIS18 a proton beam (4.5GeV, $5x10^{12}$ part/s) perpendicular to the SIS100 beam line for radiography. For this set up, a cave design shall include a corresponding beam dump. The perpendicular proton beam will have the same repetition rate as an ion beam (max. 1 pulse every 3 minutes).

5 Parallel Operation

Besides interleaving experiments and time-sharing of a given accelerator, already the Modularized Start Version (MSV0-3) of FAIR can serve two (or more) experiments at the same time (true parallelism) with, for example, slowly extracted beam out of SIS18 and SIS100 (e.g. APPA & Super-FRS, Super-FRS & CBM, APPA&CBM).
Other parallel operation options may be based on exploiting, for example, the finite cooling time in the CR or long storage times of some experiments (e.g. p-bar HESR operation) during which the pre-injector accelerator chain could be (re-)configured and re-used to accommodate other shorter experiments.

5.1 Reference Beam Production Pattern

Beam production for different experiments is generally possible in a pulse to pulse sharing of the accelerators. However, interferences between experiments affecting the quality of the beam and particle spill structure are known effects, and have already been observed at SIS18 and ESR. They are mostly due to dynamic magnetic effects, which can be mitigated, if the magnetic history is known and does not change. The present FAIR parallel operation strategy thus targets a quasi-periodic cycle operation:
A group of beam production-chains that are executed periodically is called a *Beam Production Pattern.* Concerning the ramp rates of the transfer lines (see Figure 5-8), only “fast pulsed” lines can be shared by different beam production chains in one pattern.

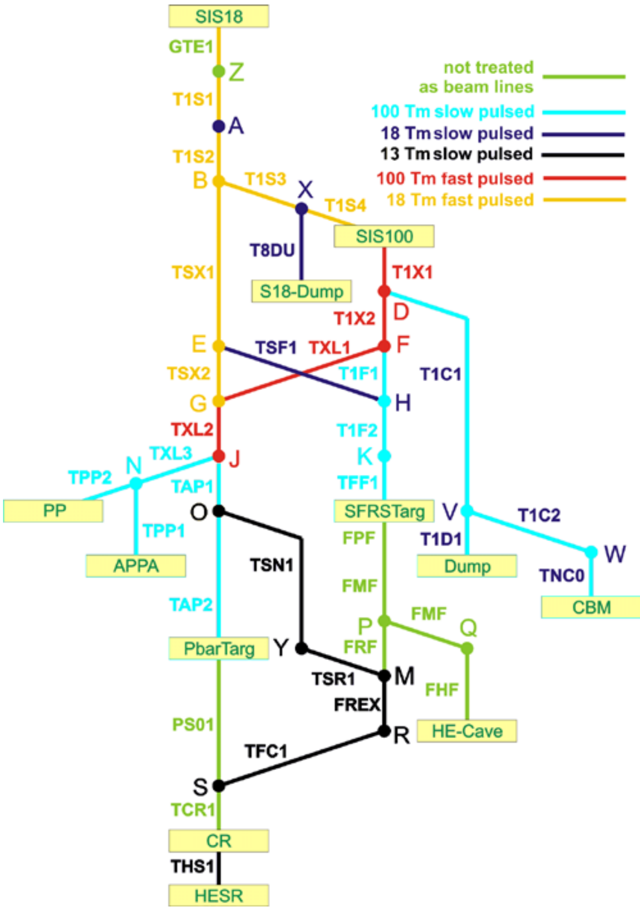

Figure 5-1: HEBT beam rigidity and ramp rate layout. 'Slow pulsed' denoted transfer-line segments correspond to rigidity changes within a time-scale of about 10 seconds, 'fast' for changes on the time-scale of the minimum pre-injector cycle lengths (SIS18: 2.7 Hz, SIS100: 1 Hz). Figure courtesy S. Ratschow and F. Hagenbuck [16]

There are five independent experimental areas within the MSV of FAIR (see Figure 5-2), which can in principle be served in one pattern. However, the setup time for such a complicated beam pattern may be so high, that it is not efficient to run it for short experiments. It is assumed, that typically two low priority experiments will be served in parallel to one high priority production run.

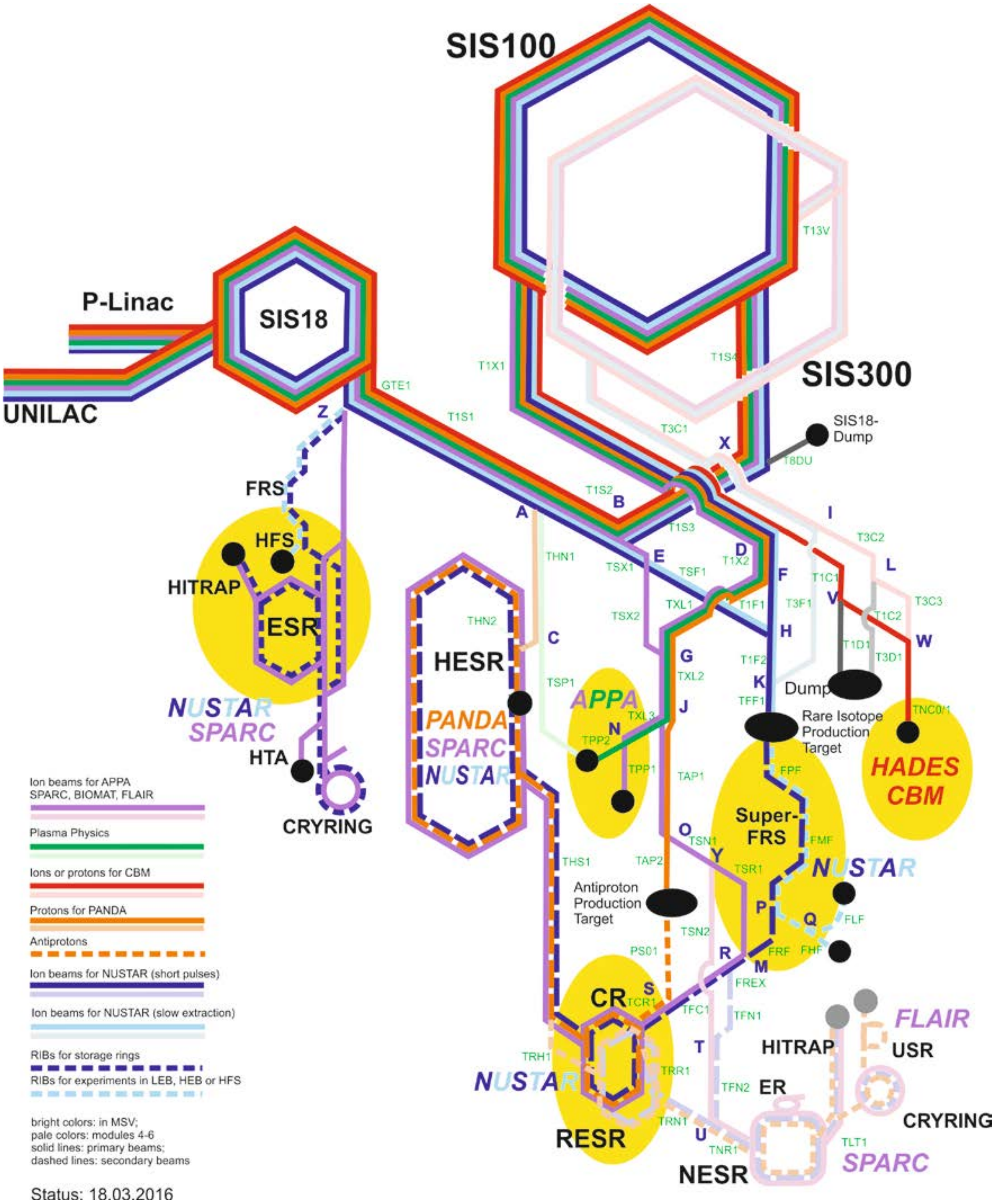

Figure 5-2: Independent Experimental Areas which can be served in parallel.

Below, reference patterns are defined, which are meant to cover the nominal parallel mode of operation the facility has been designed for.

5.2 Highest Intensity for NUSTAR

Optimal beam production for NUSTAR will use the SIS100 exclusively. However, it will leave idle times in SIS18, which may be used to serve experiments in Cave A, Cave M or in the APPA cave.

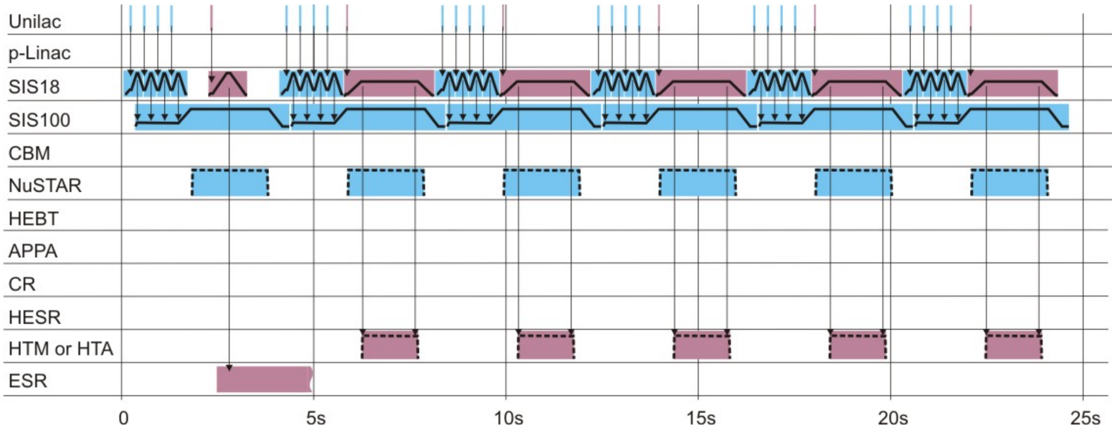

Figure 5-3: Reference Pattern #1 with NUSTAR as the main user.

5.3 Antiproton Production

Antiproton production runs naturally leave the synchrotrons idle for a typically 10 s period (the cooling time in the CR), which permits additional experiments to be served. Therefore, we define three reference patterns, serving NUSTAR, CBM and APPA, respectively.

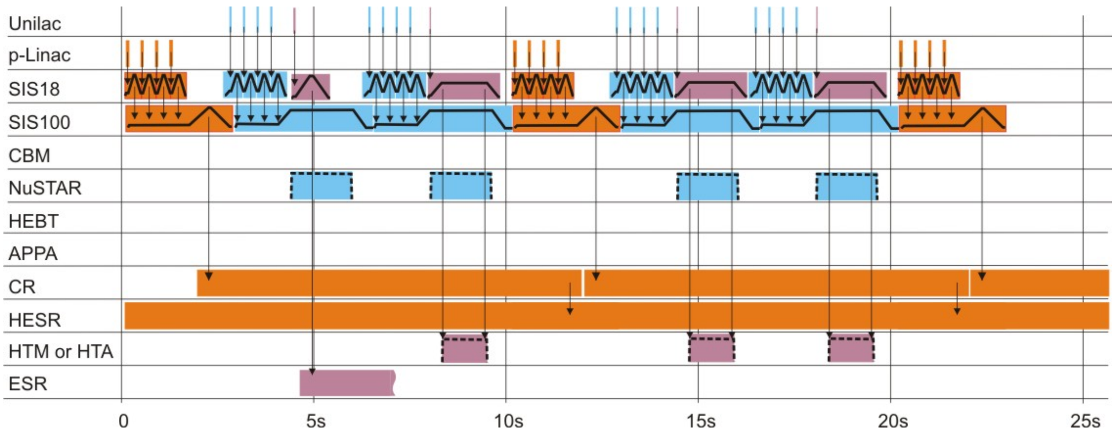

Figure 5-4: Reference Pattern #2 with Antiproton Production as Main Process and NUSTAR as second priority user.

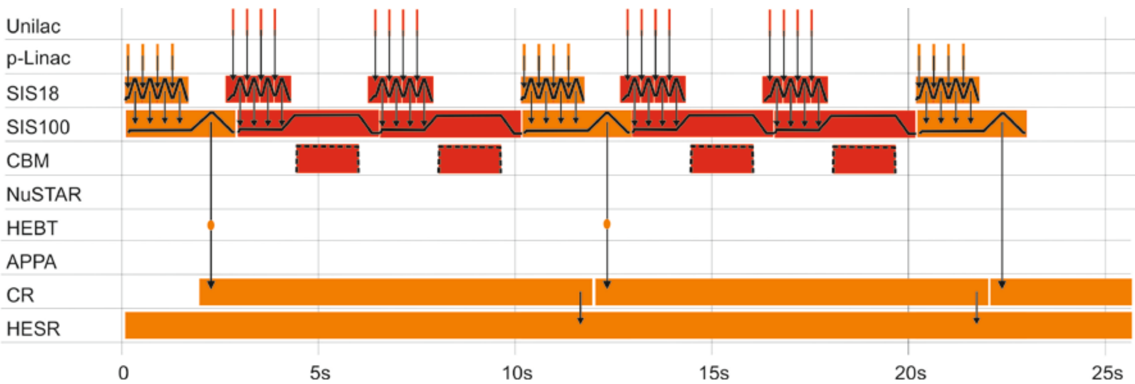

Figure 5-5: Reference Pattern #3 with Antiproton Production as Main User and CBM as secondary User.

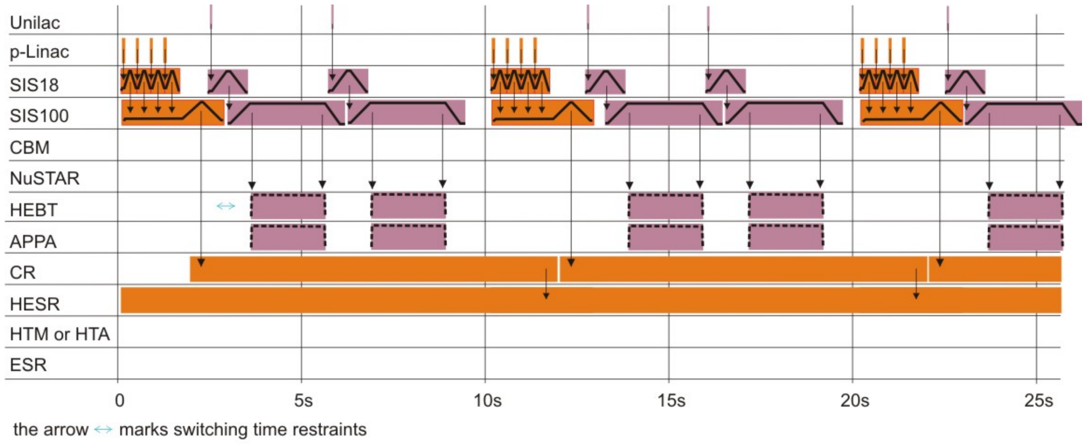

Figure 5-6: Reference Pattern #4 with Antiproton Production as Main User and APPA high energy experiments as secondary User.

Antiproton accumulation of $1 \cdot 10^7$ s^{-1} for 1000 s is envisioned, alternating with acceleration/deceleration and measurements for a similar time span. During these experiments, the HESR runs “stand alone” and the synchrotrons and the CR are fully available to serve other users. This includes ion operation in the CR, which requires change of the magnets polarities; the overhead time for such a pattern change would be a few minutes.

5.4 Storage Ring Experiments in the CR or HESR

In the HESR, NUSTAR and SPARC experiments with ions are foreseen as well as the PANDA experiments with antiprotons. The experimental setups are located in different sections of the ring. However, the change between SPARC or NUSTAR on one hand to PANDA operation on the other, requires removal of SPARC/NUSTAR equipment from the HESR which might distort ring parameters that are critical for PANDA.

The cycling time will be determined mainly by the lifetime of the investigated beam in the CR or HESR and its preparation (cooling, changing energy, etc.) and can span from a few seconds to several 10 minutes. Experiments, which need frequent refill of the CR with a beam production chain including the SIS100 may run in an exclusive mode similar to the pattern shown in Figure 5-3. Those, which have long measuring periods in the CR, may share beam time in a mode similar to the antiproton production. We define a reference pattern[14] #6, which is shown in Figure 5-7. Note, that the CBM production chain may be replaced by a NUSTAR or an APPA fixed target experiment.

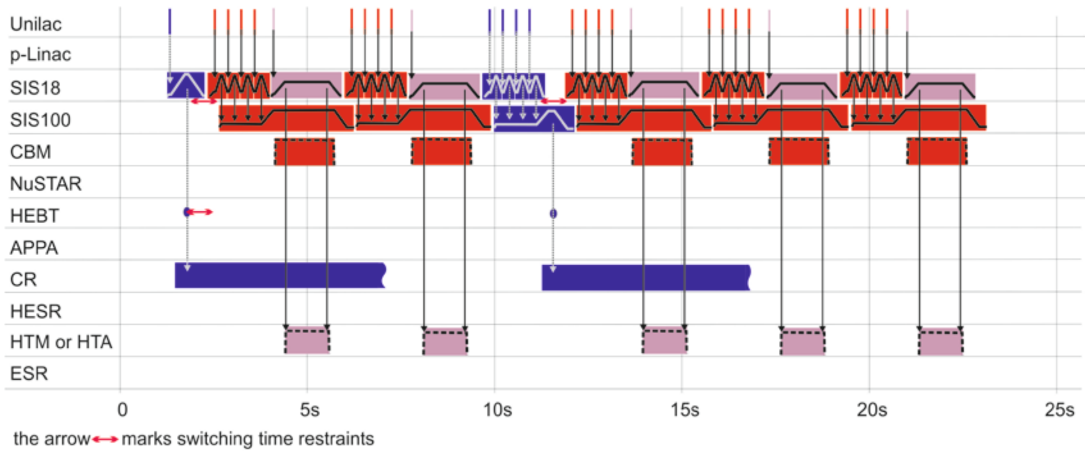

Figure 5-7: Reference Pattern #6 with Storage Ring experiments as Main User.

[14] Note that #5 is defined in chapter 4.4.3 HEDgeHOB/WDM: Plasma Physics

5.5 Nominal Design Parallel Operation Modes

The matrix in Figure 5-8 lists the main nominal parallel operation scenarios used for the design of FAIR. The names and color codes of the beam production chains are used as defined in Table 4-1.

see text for explanation of the color codes.

rows: main user / columns: parasitic user	SIS18 - SIS100 - SuperFRS	SIS18 - SIS100 - SuperFRS - CR	SIS18 - SuperFRS	SIS18 - SuperFRS - CR	SIS100 - CBM	Antiprotons: CR - HESR	SIS18 - SIS100 - APPA	SIS18 - SIS100 - APPA (Plasma physics)	SIS18 - APPA	SIS18 - CR - HESR	SIS18 - ESR (- Cryring)	SIS18 - HTA or HTM
SIS18 - SIS100 - SuperFRS								#5	#1	#1	#1	#1
SIS18 - SIS100 - SuperFRS - CR					#6		#6		#6		#6	#6
SIS18 - SuperFRS												
SIS18 - SuperFRS - CR					#6		#6		#6		#6	#6
SIS100 - CBM												
Antiprotons: CR - HESR	#2		#2		#3		#4	#5	#4		#4	#4
SIS18 - SIS100 - APPA												
SIS18 - SIS100 - APPA (Plasma physics)	#5	#5	#5	#5	#5	#5				#5	#5	#5
SIS18 - APPA												
SIS18 - CR - HESR	#1		#1		#6		#6	#5	#6			#1
SIS18 - ESR (- Cryring)	#1	#6	#1	#6	#6	#4	#6	#5	#6			#1
SIS18 - HTA or HTM												

- Sharing is not desired
- Sharing is not possible
- change overhead/penalty
- time-sharing
- reference pattern

Figure 5-8: Matrix of parallel operation. See text for explanation of color codes.

Four categories of parallel operation can be distinguished:

1. The main user leaves times in the machine where the pre-injectors are kept idle, and which could thus be used by a secondary experiment. As an optimal case, this is covered by one of the reference pattern. This pattern is named in the cell (green colour code).
2. Sharing is possible, but may be less efficient because
   a. the main user actually looses beam time which is given to the secondary experiment (time-sharing, orange color code).
   b. switching from one experiment to the other implies long overhead costs (1 minute up to ~10 minutes, e.g. inverting the CR magnet polarity , or changing the rigidity of the Super-FRS) (change overhead/penalty, dark orange color code)

3. Sharing is not possible, because both chains need a common accelerator or transfer-line sub-section (e.g. the Super-FRS), which cannot be pulsed on the same time scale as the pre-injectors (dark red color code)
4. Sharing is not desired, because both beam production chains serve the same experimental area. (grey color code)

The rows indicate the main experimental user, columns indicate a secondary experimental user. The matrix is not fully symmetric. For example, sharing between anti-proton production and a NUSTAR fixed target experiment is category 1, if the anti-proton production is the main user, but falls into category 2, if NUSTAR is main user.

5.6 Actual Beam Time Planning

One of FAIR's main strengths is its flexibility of accommodating a wide range of diverse experiments., and thus there are innumerable other parallel operation scenarios to the ones outlined above. Without diminishing the importance of each of these experiments, this makes it impossible to list each and every one of these possibilities. Many of the defined beam production chains may be combined in one beam production pattern. It will be the challenging task of the beam time coordinator to group experiments in the most efficient way.
To balance the number of experiments running in parallel versus the overhead produced by the additional set-up time, some guidelines will be followed:

- minimize the number of different ion species used in parallel

All experiments will need low priority beam times with low repetition rate for detector and system tests. Therefore, during a production run of one main experiment, several different beams must be commissioned, tuned and delivered. This must be possible with minimum beam time loss for the main production run. It is easier (and thus faster) to setup or re-establish operation for ions that are used in a previously commissioned beam production chain (e.g. sharing of similar settings for magnets, RF, extraction, etc.)

- minimize major beam pattern changes

In case one of the experiments does not request the beam, the magnets will still run the cycle, just the beam injection will be inhibited. However, the pattern can be changed within a few minutes, and will be, if the overhead cost in (re-)tuning time is lower than the gain in additional beam time. Planned pattern changes will be synchronised with experiment changes.

- group experiments by the rigidity that is injected, accelerated and extracted between the various accelerators and transfer-lines.

From an accelerator point of view it is more convenient to use the magnetic rigidity $(B\rho) = \frac{Q}{A} \cdot p \left[\frac{GeV}{c}\right]$ which drives most real-world technical machine parameters (i.e. main dipole field B and bending radius ρ) and their constraints (min-max range, ramp-rate), rather than the specific particle energies that typically depend on the given isotope charge Q and mass number A.
Interference effects are smaller for beam production patterns that contain beam production chains with similar rigidity requirements.

5.7 Other Parallel Operation Constraints

Interference effects between experiments are particularly important for beam patterns containing experiments that require slowly extracted beam with significantly different magnetic rigidity requirements and/or high primary beam intensities. Since beam intensities are expected to be significantly higher at FAIR, these effects will become more important, may impact certain machine protection functionalities (for highest beam intensities), and thus certain constraints on how fast one may (safely) change between different beam patterns may need to be imposed in the future. This is independent on whether the individual beam production chain requires only low-intensity beam but is determined by the beam production chain inside the beam pattern that requires highest beam intensities.

Some of these effects are partially mitigated by the new LSA-based accelerator control system (for details, see [17] and reference therein) which can modify existing cycles by adding, for example, 'chimneys' at the end of each cycle or by adding dedicated preconditioning cycles that improve the hysteresis by defining a known fixed magnetization prior to a potentially cross-talk sensitive experiment cycle. However, while these techniques enable a more flexible pairing of any experiments, they also reduce facility's duty cycle as an inevitable drawback.

Another important source for inter-experiment interferences beyond these magnetic hysteresis effects are the limited HEST and planned HEBT beam transfer-line beam diagnostic. For cost minimization reasons, these systems have been stripped down to an absolute necessary minimum to operate the facility and need to rely largely on invasive beam measurement techniques, needed for the setup of low-intensity beams. However, the latter limit the setup or tuning of new – in particularly high intensity – beams in parallel to other experiments (e.g. for anti-proton production, plasma physics, etc.). In view of these limitations, the present FAIR parallel operation strategy targets thus

1. a quasi-periodic cycle operation that minimizes major beam pattern changes by design (e.g. beam time schedule being optimised for synchronised beam and experiment changes).
2. to minimize the known overhead costs of changing between experiment combinations through putting more emphasis on deploying semi-automatic (beam-based) tools and procedures that aid operators during day-to-day operation (e.g. beam-based feedbacks, sequencer, etc.).

To first order this implies for a given beam production chain (i.e. experiment) inside a defined beam pattern that intermittently may not require beam (i.e. user-request being 'off'), that its associated magnetic cycles are being kept running without beam inside the pattern in favour of maintaining a stable (e.g. slow-extraction) working point for another high-intensity beam production chain inside the same beam pattern.

To second order, if the same beam production chain is not required for an extended period of time (e.g. tens of minutes to hours), the global beam pattern may still be changed. If another beam production chain operates with high-intensity beam sensitive to hysteresis effects, this procedure may include a formalised 'intensity ramp-up' after each pattern change for safety and reliability reasons

The related 'intensity ramp-up', related 'accelerator & beam mode', and 'Beam-Presence-' and 'Setup-Beam-Flag' concepts are described in more detail in [18,19].

6 Open Topics

- Microstructure of the spill, especially for the CBM/HADES, but also for NUSTAR fixed target experiments
- In the commissioning phase a radiation protection of the plasma physics cave is only partially provided (in the MSV only 2 m of shielding concrete is foreseen instead of 6.5 m for maximum beam intensity).
- Presently the CR stochastic cooling can provide the antiproton momentum spread $5x10^{-4}$ (RMS). After re-bunching this value is increased by factor of about 2 (up to 10^{-3}). The stochastic cooling acceptance of the HESR is $6x10^{-4}$. That means about 30% of particles will be lost at HESR during cooling. A working group from GSI, BINP and HESR is investigating possible solutions.
- Stripper behind SIS18 to serve SPARC Experiments in APPA cave and HESR has to be designed
- It has to be clarified for which elements the Ion Source group needs to do further development
- Comparison of the scientific advantages vs costs might be done between the line c4* and direct line SIS18->HESR. Feasibility of the line CR->HESR->ESR->CRYRING could be considered.
- Slow extraction of protons from SIS18/SIS100 is required

7 References

1) FAIR, „Technical Design Report High Energy Beam Transport," December 2008.
2) FAIR, „Green Paper: The Modularized Start Version," October 2009.
3) O Geithner, O Boine-Frankenheim "Beam Parameters of the International Facility for Anti-proton and Ion Research FAIR", 2015,
4) P. Spiller, „Beam Loss in SIS18/100/300 HEBT - Version 10.0".
5) O. Boine-Frankenheim, „Strahlparameter," 2012.
6) Spiller and Ondreka, „Zyklus-Papier," 2012.
7) MPL, „Technische Parameterlisten," 2012.
8) APPA Hal: FAIR Start Version, 2011, A. Bräuning-Demian
9) FAIR Operation Modes, 2012, P. Schütt
10) TDR for the PANDA Micro Vertex Detector, 2011
11) Technical coordinators of experiments: private communication
12) Akzeptanzen der FAIR HEBT Strahlführungen, Mai 2014, S. Ratschow
13) H. Liebermann, D. Ondreka, "SIS100 Cycles", Version 2.4.1, 2014-02-26
14) H. Weick, "Overview Accelerator Systems: Secondary Beams RB", HIC4FAIR Workshop, Hamburg, Germany, 2015 07 29 [N.B. need better primary source]
15) "Technical Design Report on the Collector Ring", 2013 11 XX
16) F. Hagenbuck, "HEBT Requirements and Staging Plan", MAC Meeting #14, 2015 12 10, http://www.fair-center.eu/fair-gmbh/organisation/machine-advisory-committee-mac/14th-mac-meeting.html
17) J. Fitzek, R. Müller, D. Ondreka, "Settings Management within the FAIR control system based on the CERN LSA framework", Proceedings of PCaPAC 2010, Saskatoon, Saskatchewan, 2010
18) R. Steinhagen, "FAIR Accelerator & Beam Modes", FC2WG Meeting #3, 2015 06 17, https://fair-wiki.gsi.de/FC2WG
19) R. Steinhagen and R. Bär, "Accelerator & Beam Modes", FAIR Technical Concept, F-TC-C-07, 2015-10-02