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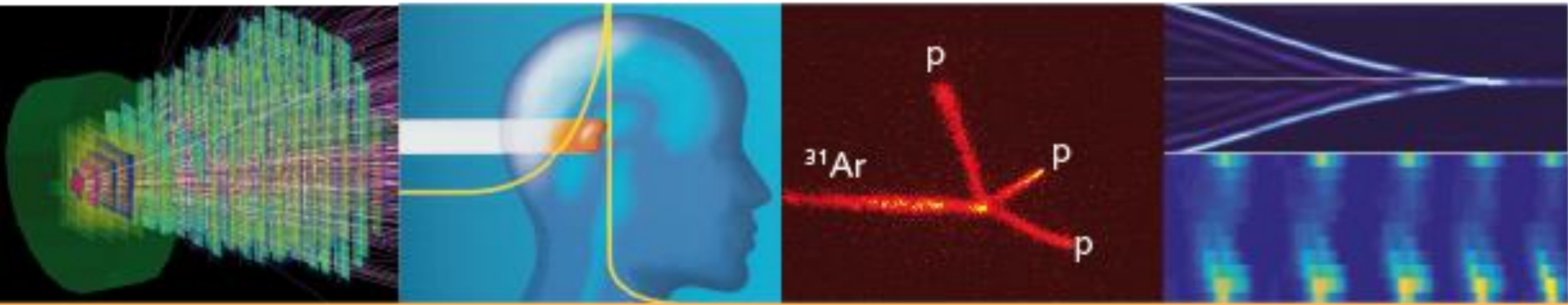
Status of the FAIR Project
Upgrade of the GSI Accelerator Facilities and Construction of FAIR

Peter Spiller

GSI-Helmholtzzentrum für Schwerionenforschung



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Start and Progress of FAIR Civil Construction

- Contract signed for site preparation area North. Excavation, retaining walls, ground water lowering etc.

- Contracts signed for building shell construction area North. Start of SIS100 tunnel construction: June 2018.

- Contract signed for site logistics.
- Contract signed for cranes and elevators.

July 4th 2017 Official Ground Breaking Ceremony

Excavation of SIS100 tunnel. Present depth: -16 m

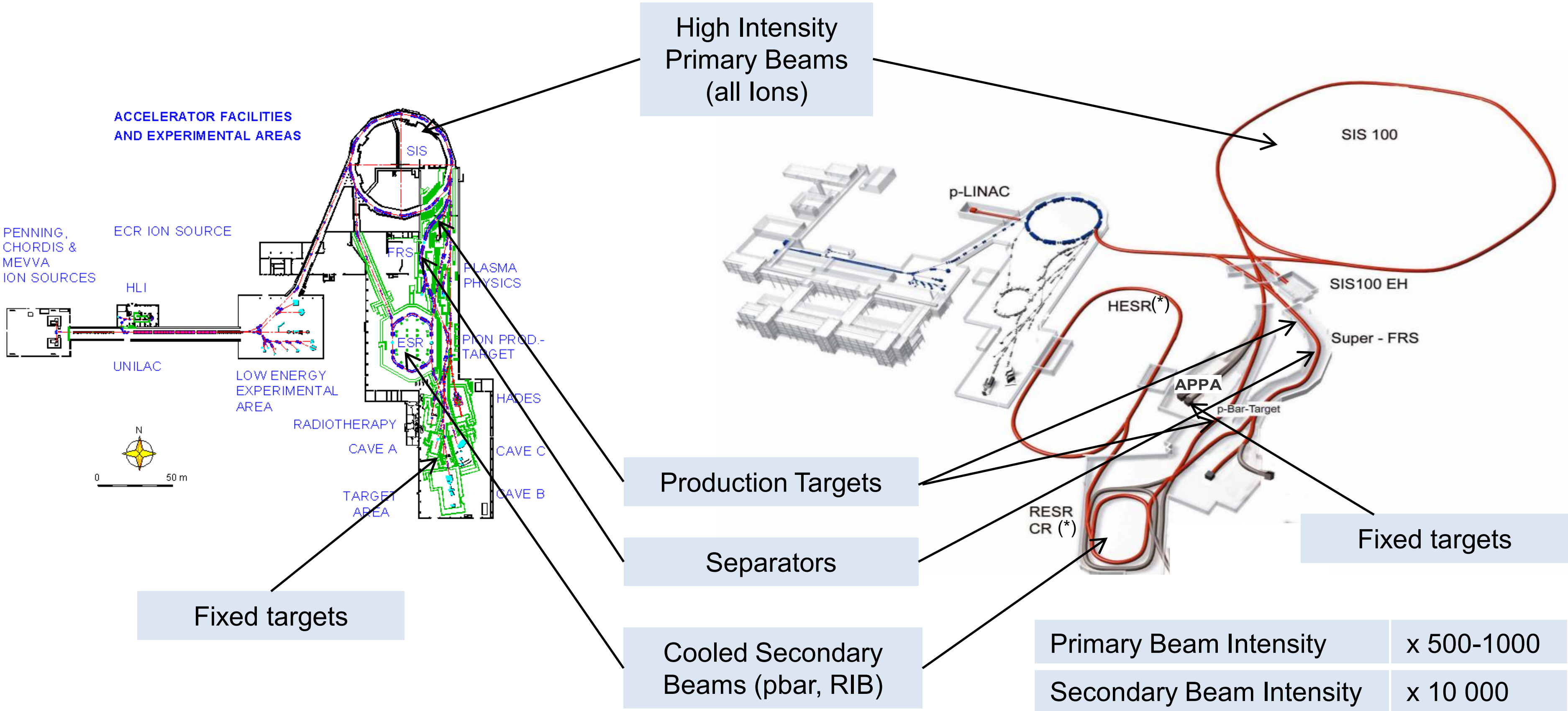
CIVIL CONSTRUCTION SITE OF FAIR

STATUS FEBRUARY 2018

FACILITY FOR ANTIPROTON AND ION RESEARCH IN EUROPE GMBH
DARMSTADT, GERMANY

Accelerator Topology of GSI and FAIR

FAIR is the big brother of GSI.
The Concept of the Facility Topology is Identical



High Intensity Primary Beams (all Ions)

Production Targets

Separators

Cooled Secondary Beams (pbar, RIB)

Fixed targets

Fixed targets

Primary Beam Intensity	x 500-1000
Secondary Beam Intensity	x 10 000
Heavy Ion Beam Energy	x 30
Cooled pbar Beams	
Parallel operation	

(*) Subproject leadership of CR and HESR tansferred to BINP and FZJ. Subproject execution conducted with big success.

RIB Generation, Debunching and Cooling

Matching primary beam to production target and storage ring

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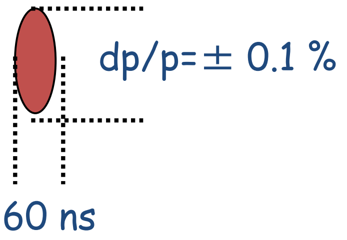
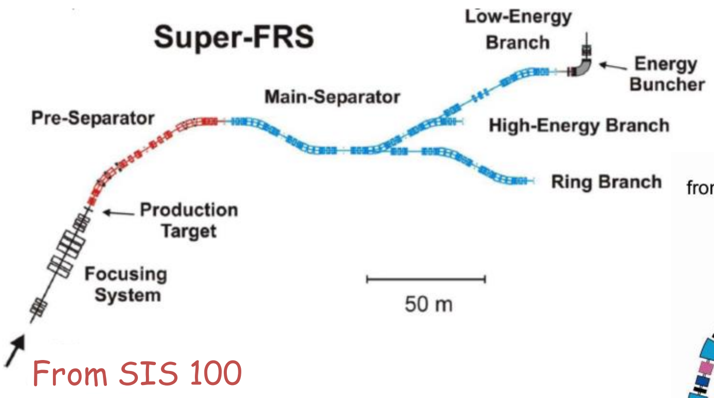
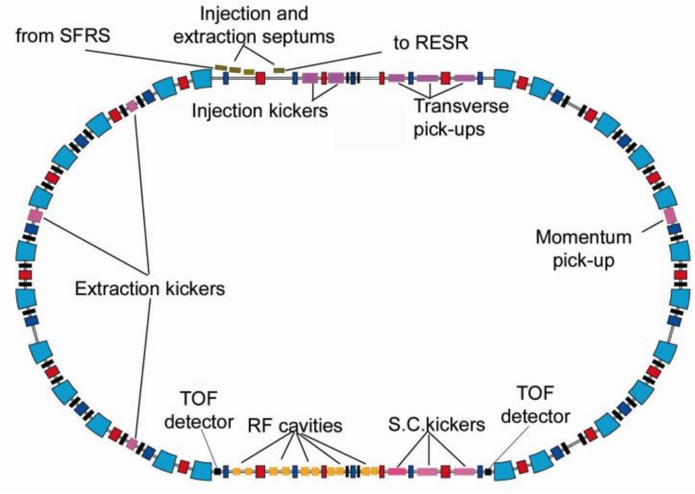
Short SIS 100 bunches:
- target matching
- RIB/pbar pre-cooling

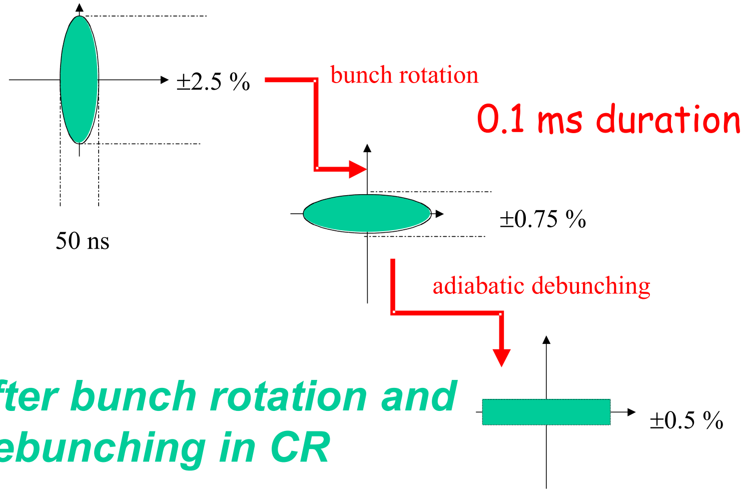




Collector Ring (CR)
circumference 212 m
rigidity 13 Tm



RF voltage in the CR: 200 kV (1.5 MHz)



after bunch rotation and debunching in CR

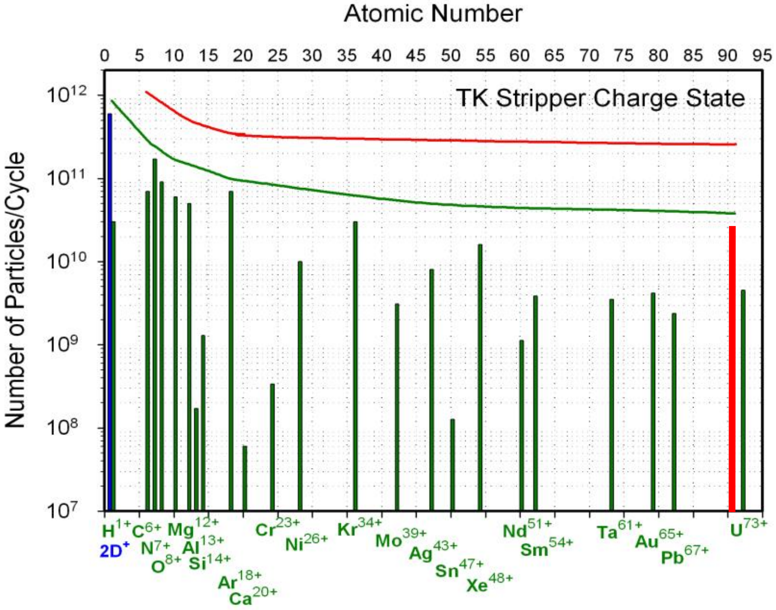
CR ring properties:

	RIB	pbar
energy	740 MeV/u	3.0 GeV
mom. accept.	± 1.5 %	± 3.0 %
transv. accept.	200x10^{-6} m	240x10^{-6} m
Cooling down time	1.5 s	10 s

Reference Primary Beam Parameters

SIS18	**Protons**	**Uranium**
Number of ions per cycle	5 x 10^{12} (x50)	1.5 x 10^{11} (x100)
Inc. s.c. tune spread	-0.5	-0.5
Initial beam energy	70 MeV	11 MeV/u
Ramp rate	10 T/s	10 T/s
Final beam energy	4.5 GeV	200 MeV/u
Repetition frequency	2.7 Hz (x3)	2.7 Hz (x3)

SIS100	**Protons**	**Uranium**
Number of injections	4	4
Number of ions per cycle	2.5 x 10^{13}	5 x 10^{11}
Inc. s.c. tune spread	-0.2	-0.3
Maximum Energy	29 GeV	2.7 GeV/u
Ramp rate	4 T/s	4 T/s
Beam pulse length after compression	50 ns	90 - 30 ns
Extraction mode	Fast and slow	Fast and slow
Repetition frequency	0.7 Hz	0.7 Hz



SIS18 peak intensities and space charge limits for high and intermediate charge states

- FAIR peak intensity goals can only be reached by lowering the projectile charge states
- Incoherent space charge tune shift limits the maximum intensity in SIS18: $-dQ \propto Z^2/A$
- Poststripper charge states will be used

  (e.g.: $Ar^{18+} > Ar^{10+}$..........$U^{73+} > U^{28+}$)
- Without stripping loss (charge spectrum) significantly enhanced particle current ($N_{uranium}$ x7) !

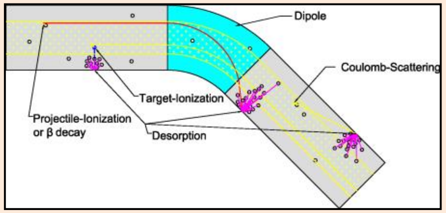
Intermediate Charge State Heavy Ions

Existing and planned Heavy Ion Accelerators operated with Low Charge States worldwide

AGS Booster	BNL, USA	$5x10^9$	Au^{31+}
LEIR	CERN	$1x10^9$	Pb^{54+}
NICA Booster	JINR; Russia	$4x10^9$	Au^{32+}
SIS18	**GSI/FAIR, Germany**	$1.5x10^{11}$	U^{28+}
SIS100	**FAIR, Germany**	$5x10^{11}$	U^{28+}
B Ring	**HIAF, China**	$1x10^{11}$	U^{34+}

Key Issue Dynamic Vacuum: SIS18 served as a pilot facility for the development of

- new accelerator concepts
- new accelerator technologies and
- understanding and benchmarking

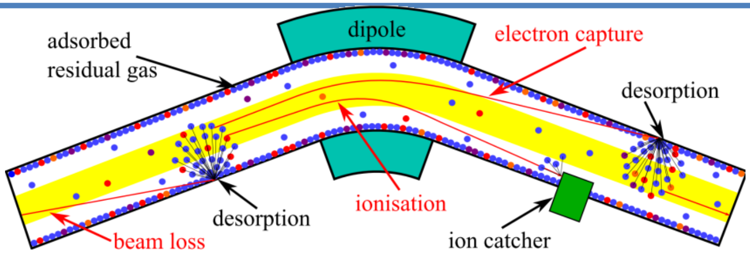


... to overcome **Vacuum Instabilities and Ionization Beam Loss** at high intensity heavy ion operation.

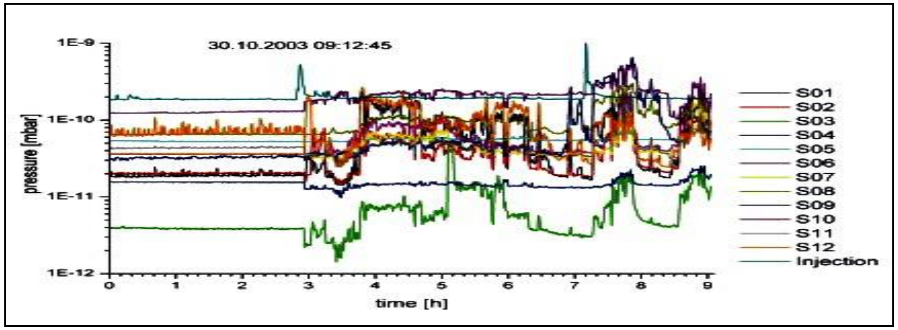
Ionization Beam Loss and Dynamic Vacuum determine the system design and the accelerator technologies of SIS18 and SIS100 and generate the biggest challenges with respect to beam loss.

Key Technologies for SIS18 and SIS100: Dynamic Vacuum and Charge Exchange

The Dominating Intensity Limitation for Heavy Ion Beams in Synchrotrons is the Interaction with the Residual Gas and thereby generated Charge State Changes. Due to Desorption Processes at High Beam Intensities the Static Residual Gas Pressure becomes the so called Dynamic Vacuum. Ionization in the Dynamic Vacuum is the dominating beam loss mechanism which appears much below the space charge limit.



Ionisation loss drives pressure bumps which itself accelerates the ionisation process.
> Dynamic vacuum instability



Static (no beam) Dynamic (with beam)

Simulations

STRAHLSIM: Unique code for dynamic vacuum and charge exchange driven beam loss in time and space comprising:

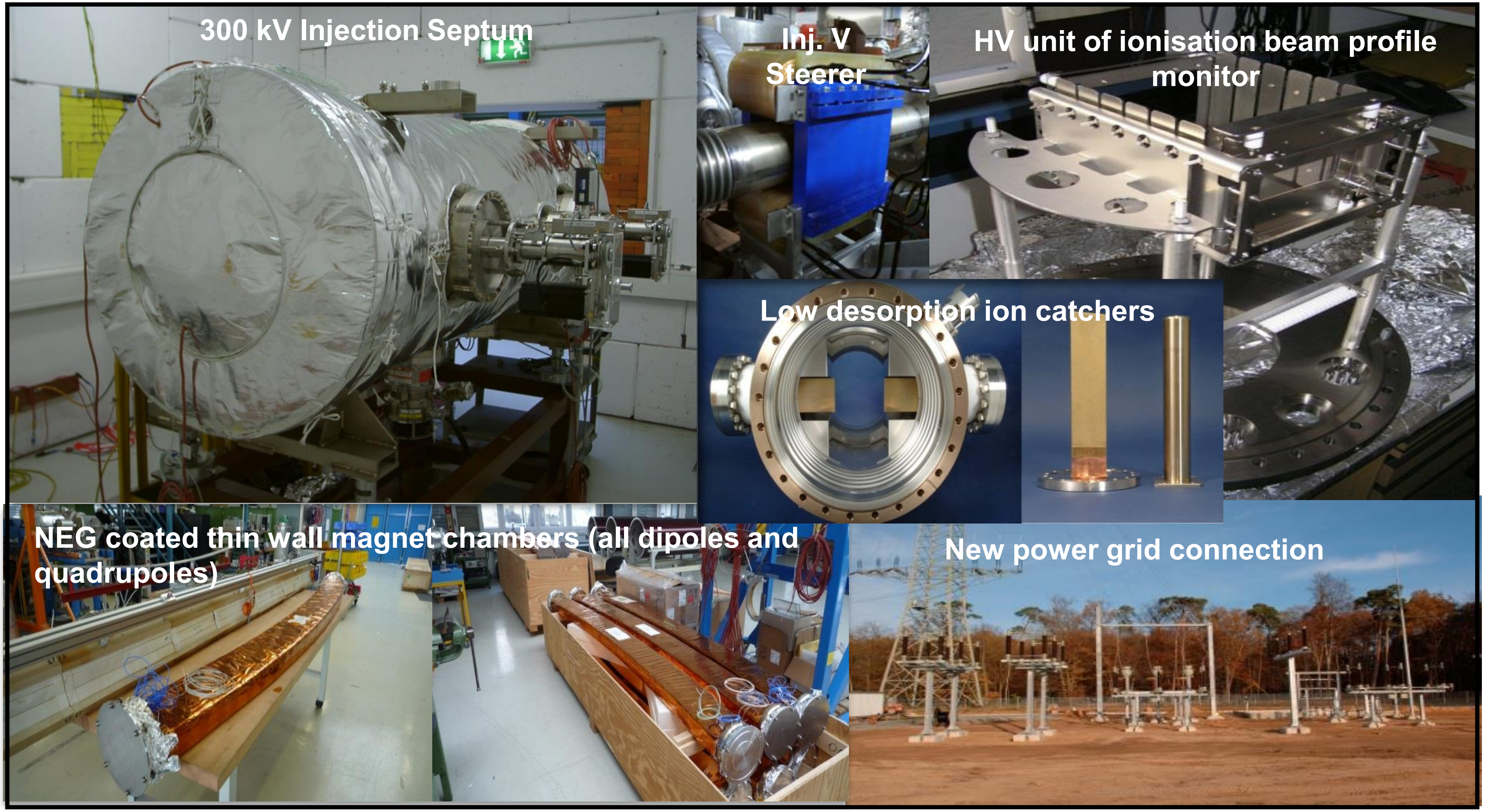
- Machine optics and collimation system
- Atomic cross sections for charge exchange (energy dependend, projectil- and target dependend etc.)
- Properties of pumping system (conventional, crogenic, NEG. local distributed etc.)
- Ion induced gas desorption processes
- Realistic machine cycles

New Technologies

- New synchrotron optics: Charge separator lattice (peaked distribution of ionizaton loss)
- NEG coating (distributed pumping)
- Low desorption surfaces and materials
- Ion catcher systems - room temperature and cryogenic
- Cryogenic (actively cooled) magnet chambers (distributed pumping)
- Cryo-adsorption pumps

SIS18 Upgrade Program 2005 – 2013 Implementation of New Key Technologies

The upgrade program is dedicated to intermediate charge state heavy ion operation for FAIR



300 kV Injection Septum

Inj. V Steerer

HV unit of ionisation beam profile monitor

Low desorption ion catchers

NEG coated thin wall magnet chambers (all dipoles and quadrupoles)

New power grid connection

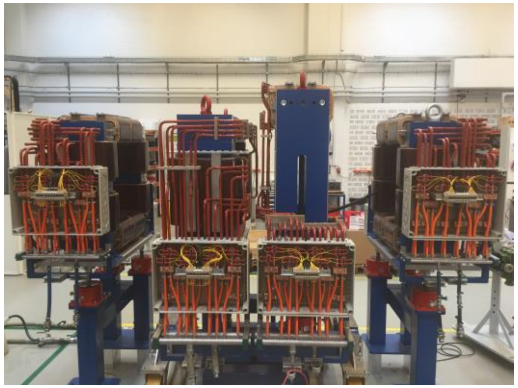
SIS18 Upgrade Program 2013 – 2018 Implementation of New Key Technologies

The upgrade program is dedicated to intermediate charge state heavy ion operation for FAIR

Three new MA acceleration cavities installed (50 kV, h=2) and power converters

Replacement of main dipole power converter (for 10 T/s, 50 MW)

In the past, the EU has supported the upgrade program as an investment in a major European Research Infrastructure.



SIS18/SIS100 IPM magnet system manufactured and delivered

Bipolar dipole magnet and power converter for the connection of transfer line to SIS100

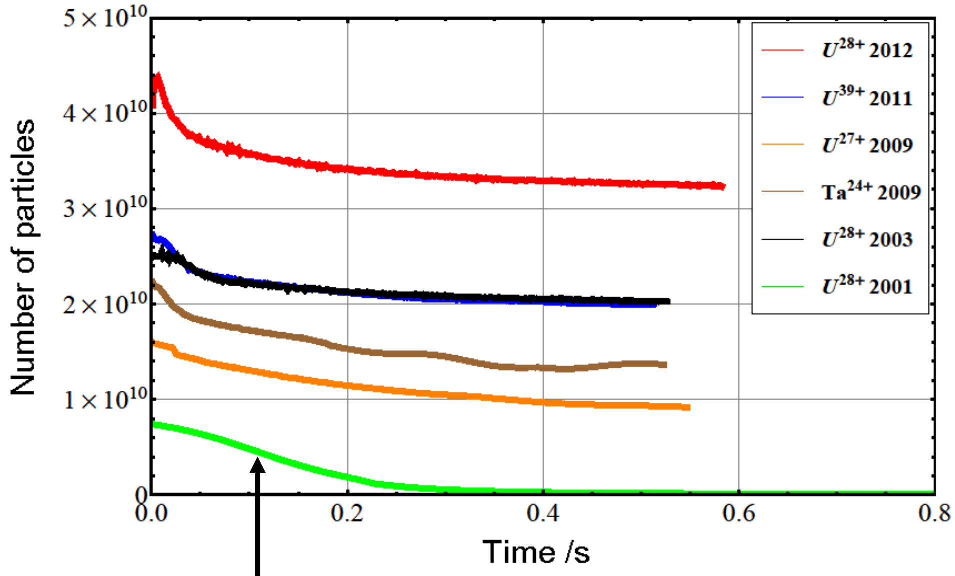
The originally defined SIS18upgrade program will be completed in 2018.

SIS18 Status U^{28+} -Beam Intensity

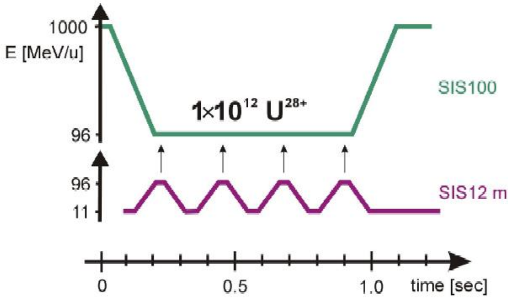
World record intensity for intermediate charge state heavy ions in heavy ion booster.

The feasibility of high intensities with intermediate charge state heavy ions has been demonstrated.

World record



2001 FAIR conceptual design report (FAIR proposal)



Stacking in SIS100 (4x)

At SIS100 commissioning:

An intensity of U^{28+}-beams of $1\text{-}2 \times 10^{11}$ per cycle is safe (rep. rate about 0.5 Hz)

Further upgrade measures are investigated for reaching the intensity goal for the most heavy ions (e.g. Uranium with 1.5×10^{11} per cycle at a (high) repetition rate of 2.7 Hz.)

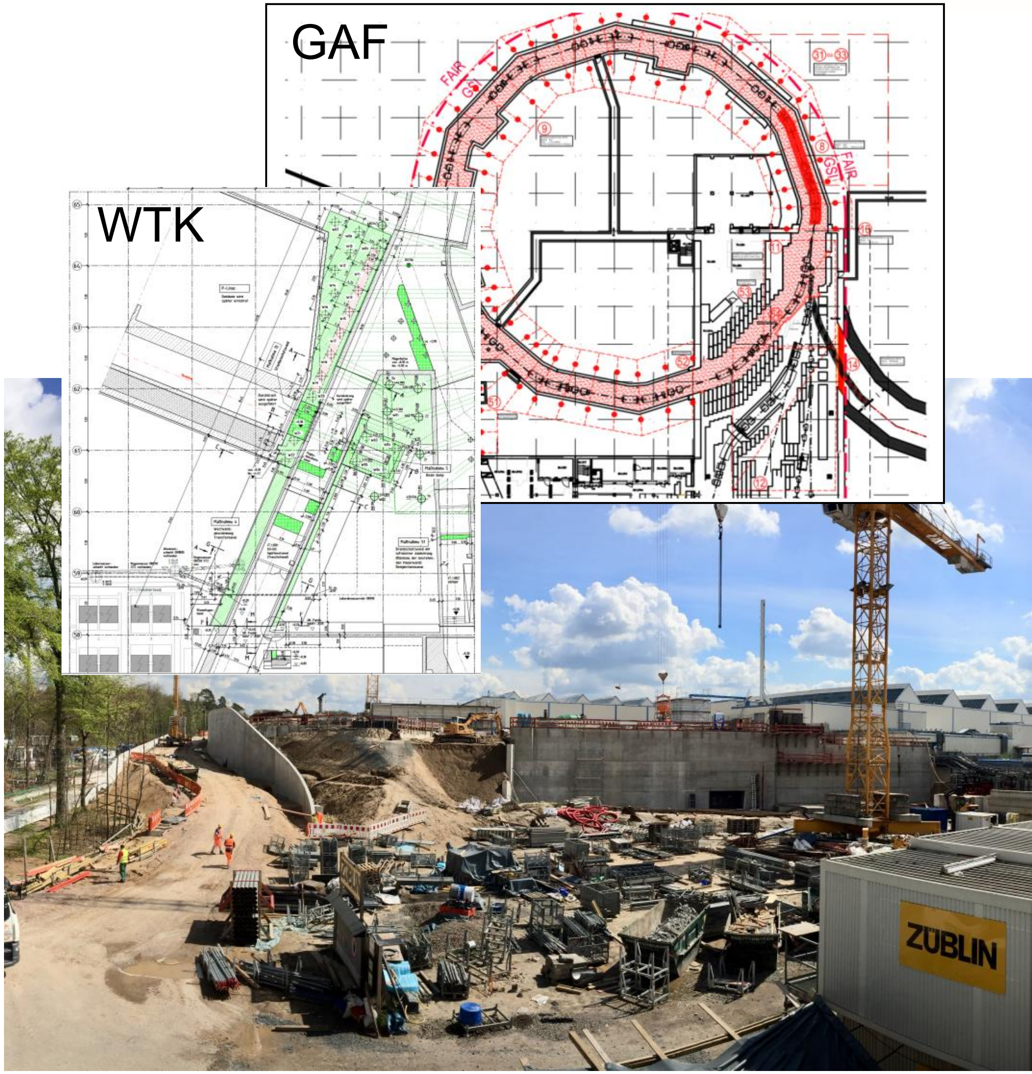
Preparation of the Existing Accelerator Tunnels and Buildings for FAIR

SIS18 Civil Construction GAF and WTK

GAF (Gebäude Anbindung FAIR):

- **Shielding enhancement** on top of the existing SIS18 tunnel and at other locations for fast cycled operation with 5x10^{12} Protons per Second. (3% Proton beam loss at final energy)

- **Radioactive air management** system
- **Fire prevention system** (nitrogen venting)
- **Interface** to the FAIR tunnel 101
- An inner and outer **reinforment wall**
- **Power link** of main operation building to new transformer station North



WTK (Westwand Transfer Kanal)

- **Beam dump** for the proton linac on the western side of the transfer channel (TK)
- Shielding enhancement of the TK eastern wall and interface for an early construction of the p-linac building

All works will be completed until May 2018.

Status GAF and WTK Project


New transformer station North completed.
(pulse power SIS18 and SIS100).


Interface for new Proton linac completed.


Reinforcement of SIS18 roof and new technical operation building TG1 completed.


Interface for FAIR tunnel 101 completed.

Progress in Subproject P-Linac

New main injector for pbar-Program

Close collaboration in development of Rf linac structures with IAP (institute for applied physics) in Frankfurt/M. Since the p-Linac will be connected to the GSI campus media infrastructure, it will be the first FAIR accelerator commissioned.

Status and Step towards Installation

- Proton source at CEA, Saclay:
  Based on IPHI sourced design.
  Peak Proton beam 60 mA extracted.

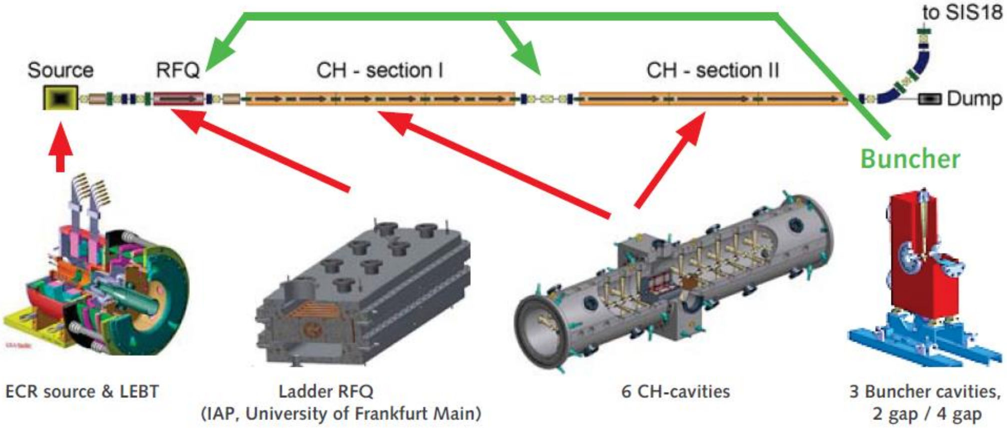
- Successful test of prototype ladder RFQ
- Manufacturing of vacuum chamber for ladder RFQ at IAP completed.

- 2018: Low level, tuning and high power tests at Rf test stand at IAP.

- Succesful test of prototyp CH cavity
- Q4 2017: Design freeze at IAP for CH structures

- Installation of ion source and ladder RFQ in final building until Q4 2020

> Commissionig with beam



ECR Proton source at CEA

New vacuum chamber for the ladder RFQ

Key Technologies

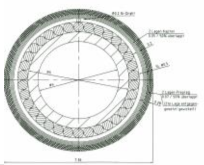
GSI has a world wide leadership in **fast ramped** superconducting magnets

1. R&D on fast ramped superconducting, window-frame magnets for SIS100

4 T/s up to 1.9 T

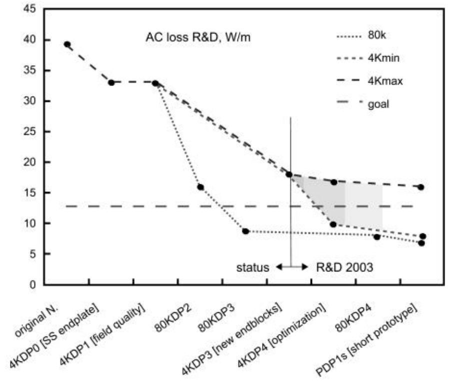
R&D goals:

1. Reduction of eddy/persistant current effects at 4 K (at most in iron yoke)
2. Optimization of field quality
3. Long term mechanical stability for (>$2 \cdot 10^8$ cycles)

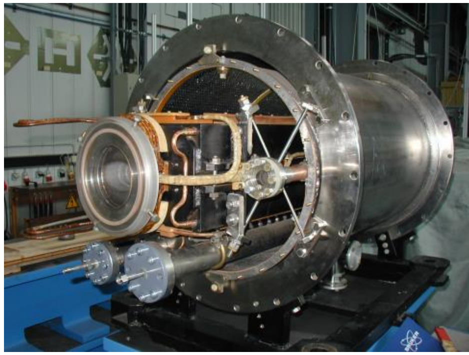


Optimization of Nuclotron Cable:

- Insulation concepts
- Winding technologies
- ANSYS models etc.



AC loss reduction 40 W>15W



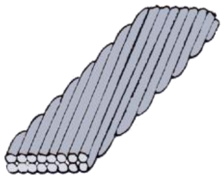
SIS100 Prototype Dipole

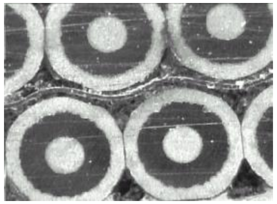
2. R&D on fast ramped, superconducting costheta magnets for SIS300 and others

1 T/s up to 4.5 T (world record ramp rate)

R&D goals:

1. Reduction of AC loss by improved cable and coil design
2. Optimizec conductor cooling (e.g.laser cutted cable)





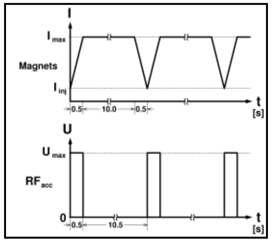
Optimization of Rutherford Cable:

- Reduced filament twist pitch
- Strand coating
- Stainless steel core

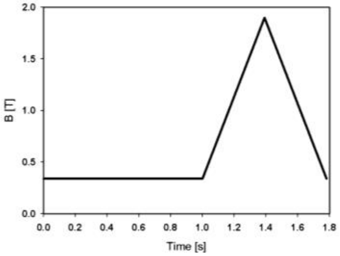
Fast ramped SIS300 Dipole in Cryostat

Key Technologies

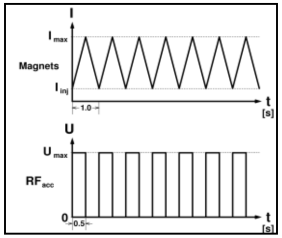
GSI builts the fastest superconducting synchrotrons with full flexibility in cycling



quasi static heat load at long extraction (DC 3.5 kW)



Reference cycle 2c



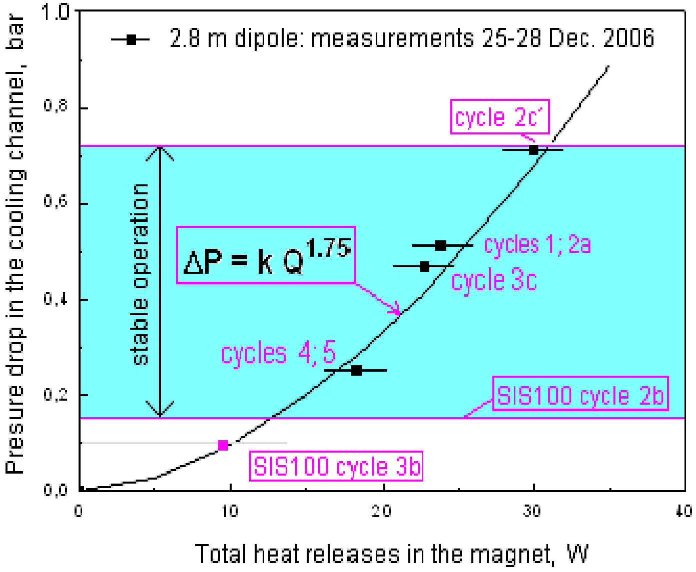
Triangular cycling with fast extraction (DC +AC14.5 kW)

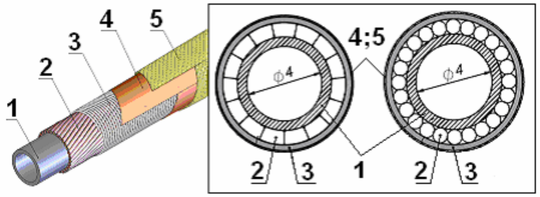
TABLE II OPERATION CYCLES AND EXPECTED LOSSES

cycle	B_{max} (T)	t_f (s)	cycle period (s)	Q_d (J/cycle)	P_d(W)	Q_q (J/cycle)	P_q(W)
1	1.2	0.1	1.4	35.2	25.2	13.1	9.4
2a	1.2	0.1	1.4	35.2	25.2	13.1	9.4
2b	0.5	0.1	1.0	8.8	8.8	3.3	3.3
2c	2.0	0.1	1.82	89	48.9	24.4	18.9
3a	1.2	1.3	2.6	35.2	13.5	13.1	5.0
3b	0.5	1.0	1.9	8.8	4.6	3.3	1.8
3c	2.0	1.7	3.4	89	26.2	34.4	10.1
4	2.0	0.1	5.0	89	17.8	34.4	6.9
5	2.0	0.1	5.0	89	17.8	34.4	6.9

Control of Magnet Cooling at Different Heat Loads:

- Single layer magnet coil with low hydraulic resistance
- High current Nuclotron cable
- Hydraulically adjusted magnet cooling circuits
- Active heaters to stabilize the crogenic load
- Variable supply LHe supply pressure
- LHe pumps





Alternative coil design and high current cable

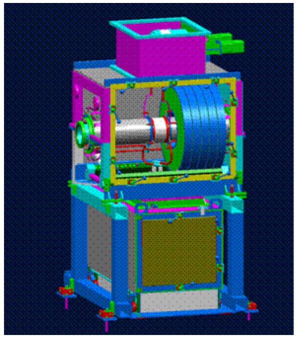
Key Technologies

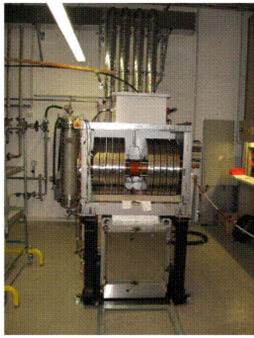
GSI has unique expertise in inductively (e.g. MA) loaded cavities

	$V_{0,total}$ peak	f [MHz]	#	Status	Technical Concept
SIS100 Acceleration Cavities	400 kV	1.1–2.7	20	FOS	Ferrit ring core, "narrow" band cavities. Fast tuning
SIS100 Compression Cavities	640 kV	0.395-0.485	16	FOS + Series	Magnetic alloy ring core, broad band cavities. Slow tuning
SIS100 Barrier Bucket Cavities	2*15 kV	1.5MHz (barrier) 110-270kHz (repetition)	2	Spec.	Magnetic alloy ring core, very broad band (low duty cycle) cavities. No tuning
SIS100 Longitudinal Feed-Back Cavities	10 kV	0.7-5.0 (3db BW)	2	Spec	Magnetic alloy ring core, very broad band (low duty cycle) cavities.. No tuning
CR Debuncher Cavities	200kV	1.1-1.5	5	FOS + series	Magnetic alloy ring core, broad band cavities (pulsed and CW operation). Slow tuning
SIS18 h=4 Acceleration Cavities	30 kV	0.8-5.4	2	Running	Ferrit ring core, "narrow" band cavities. Fast tuning
SIS18 h=2 Acceleration Cavities	48 kV	0.4-2.8	3	Running	Magnetic alloy ring core, very broad band (low duty cycle) cavities.. No tuning
SIS18 Bunch Compression Cavities	40 kV	0.8-1.1	1	Running	Magnetic alloy ring core, broad band cavities. Slow tuning

GSI is continously surveying the available nanocristalline (Fe-base) and amorphous (Co-based) magnetic alloys on the world market (Vitrovac, Vitroperm, Finemet etc.)

Samples of magnetic alloy tape wound cores, measured for the SIS bunch compressor project. The ring to the left is a FineMet core, produced by Hitachi in Japan. The right one is a VitroVac core,





Heavy Ion Synchrotron SIS100 – Unique Features

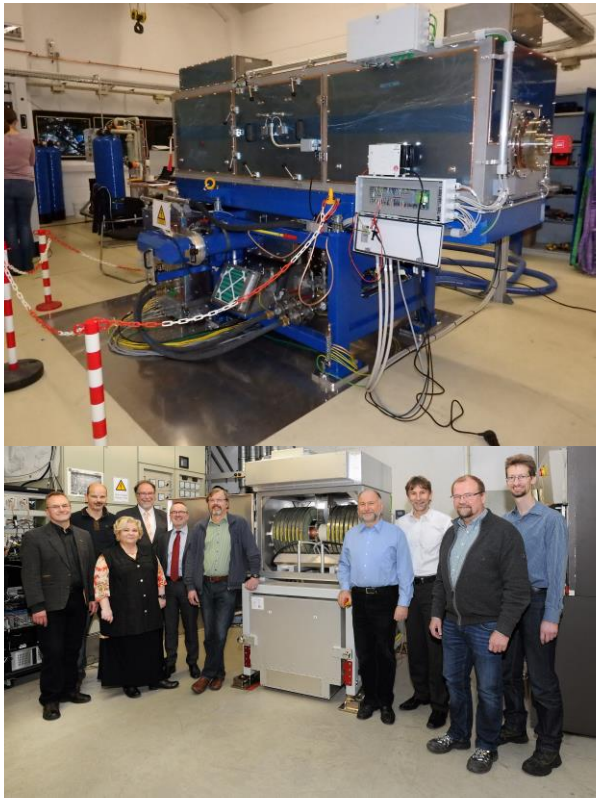
SIS100 is a world wide unique synchrotron designed and optimized for the generation of high intensity heavy ion beams.

- It has a **flexible lattice structure**, enabling different optical settings for different user modes.
- It has a lattice cell (**charge separator lattice**) with an optimized design for the control of beam loss by ionization at highest intensities of Uranium beams.
- It has a unique and **extreme XHV system**, making extensive use of cryo-pumping to suppress vacuum instabilities at highest heavy ion intensities
- It is a **fast ramped superconducting** synchrotron with ramp rates up to 4 T/s and a minimum cycle time of less than 1 second.
- It is equipped with **powerful Rf systems** for acceleration, compression, generation of barrier buckets and buckets for longitudinal stabilization.
- It provides **different extraction modes** for fixed target experiments and optimal time structures for matching to production targets and storage rings.
- Its cyrogenics system is designed to **control of a dynamic heat load** of up to 75 % (3.4 kW <> 14,7 kW) with big difference from cycle to cycle in a parallel operation of multiple users.

SIS100 Procurement Highlights

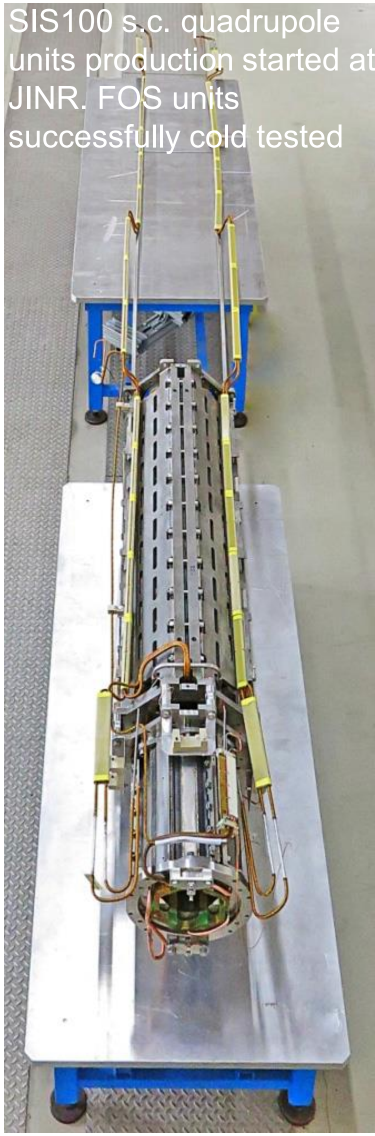
Fast ramped (4 T/s) s.c. dipole magnets
Series production started. 21 modules delivered.

First cryogenic bypass line with integrated bus bar system shipped and tested



Series production of bunch compression and acceleration cavities started.

All main magnets, all main Rf and all injection devices under contract. 50 % of procurement milestones achieved. 65 % of SIS100 value under contract.



SIS100 s.c. quadrupole units production started at JINR. FOS units successfully cold tested

World Wide Testing Infrastructure for the Series of Superconducting Magnets

GSI: Series test facility for the SIS100 s.c. dipole magnets, string test, current leads and local cryogenics components.

CERN: Test facility completed for the Super-FRS s.c. dipoles and multipletts

INFN: Test facility in Salerno for testing the series of SIS100 quadrupole modules

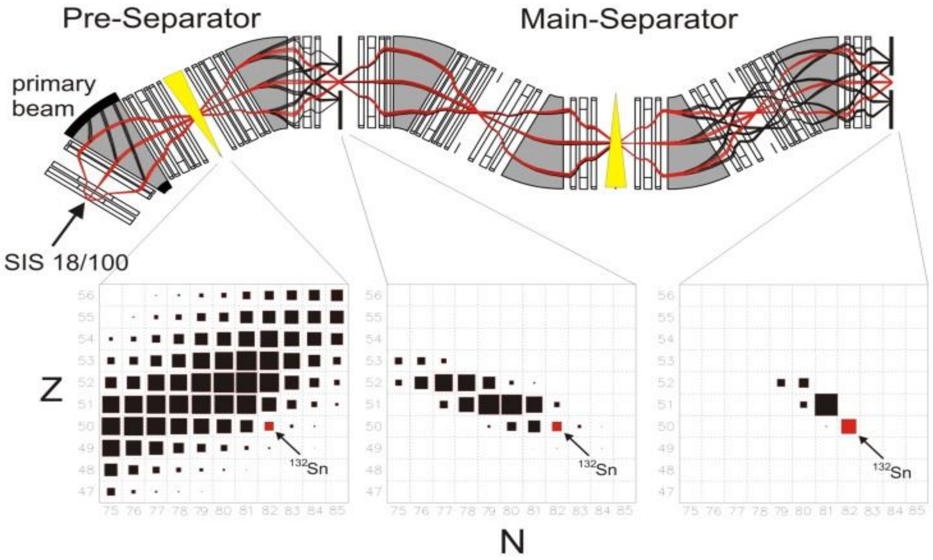
JINR, Series test facility in Dubna for testing of the series of SIS100 s.c. quadrupole units

Features of Super-FSR

The most powerful in-flight separator for exotic Nuclei world wide

Facility	Max. Magnetic Rigidity $B\rho_{max}$ / [Tm]	Momentum Acceptance $\Delta p/p$	Angular Acceptance		Momentum Resolution
			ϕ_x / [mrad]	ϕ_y / [mrad]	
FRS	18	±1 %	±7.5	±7.5	1500 ($\varepsilon=20\pi$ mm mrad)
Super-FRS	20	±2.5 %	±40	±20	1500 ($\varepsilon=40\pi$ mm mrad)

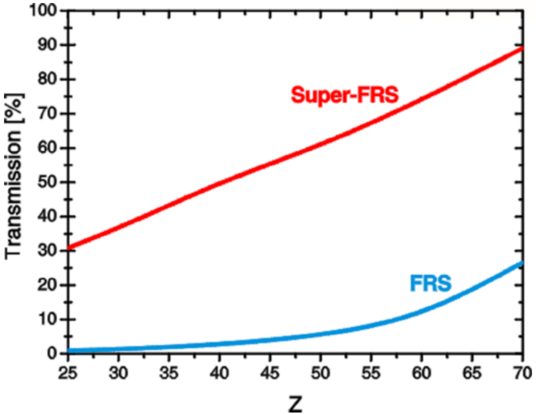
High primary rate requires two stage separation



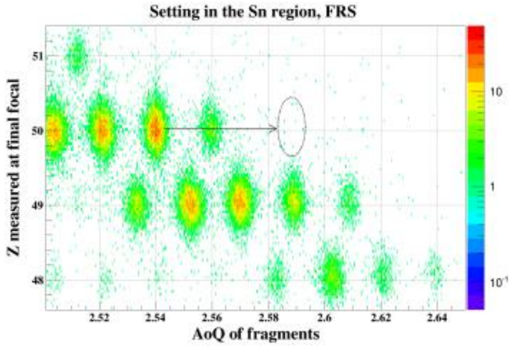
Separation of uranium fission fragments with the two degrader stages of the Super-FRS (1.1 A GeV ^{238}U on 4 g/cm^2 C target)

10^{11}/s → 1/d

High projectile energy and multiple separator stages to efficiently reduce the background from contaminations



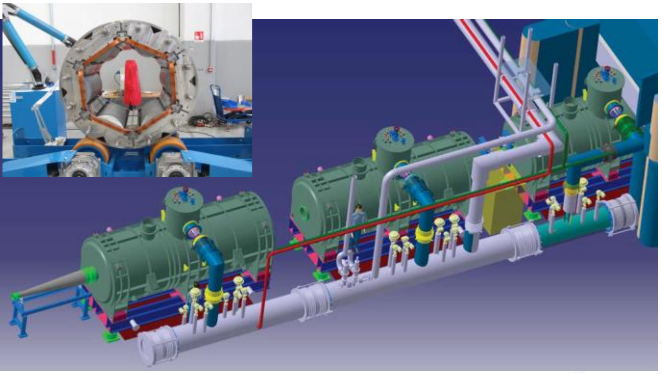
Large Acceptance and Increased Transmission of Fission Products.



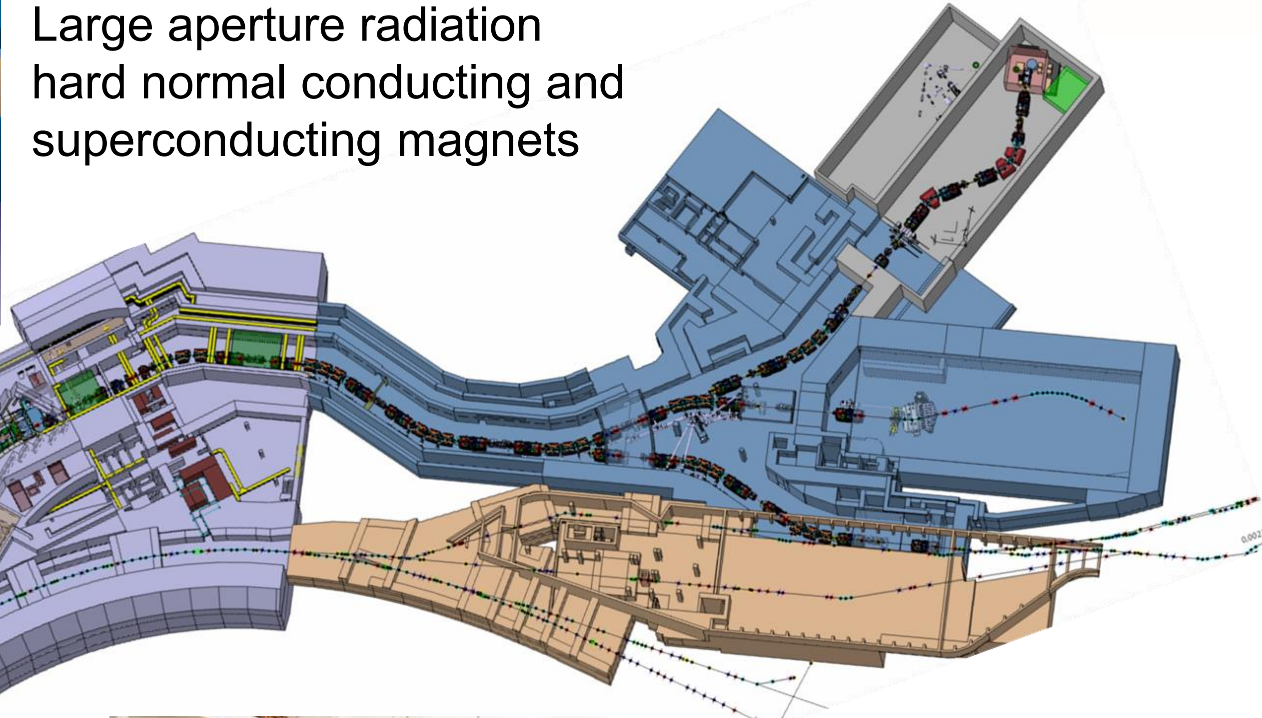
Advantage of high projectile energy: Clean mass/isotope separation without charge state contamination

Procurement Highlights of the Super-FRS

Large aperture radiation hard normal conducting and superconducting magnets



S.c multipletts awarded.
FOS short multiplett in assembly.



Prototype radiation hard dipole magnet.

Prototype superferric dipole magnet. Re-design completed by CEA.
Contract awarded for series production.

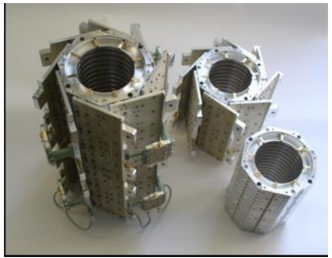
Key Technologies

GSI/FAIR makes extensive use of powerful ion beam cooling techniques

Stochastic Cooling	**Ion energy**	**Frequency band width**	**Microwave power**	**Pick-up and kicker Electrodes**	**Acceptance**
CR stochastic cooling system	Ions: 740 MeV/u Antiprotons: 3 GeV	1 - 2 GHz	8 kW	Plunging: ±80 mm (at 30 K)/ Slotline (at 300 K), no plunging, ±70 mm	$dp/p < \pm 1\,\%$ (pbar) $dp/p < \pm 0.5\,\%$ (ions) $\varepsilon < 240\ \pi$ mm mrad
HESR stochastic cooling system	Antiprotons (and heavy ions) 1.5 – 15 GeV/c	2 - 4 GHz	3x 0.6 kW (long) 3x 0.32 kW (trans)	Slot-ring couplers (at 20 K)/ Slot ring	$dp/p < 10^{-3}$ $\varepsilon < 5\ \pi$ mm mrad
ESR stochastic cooling system	Ions 400 - 550 MeV/u	0.9 – 1.7 GHz	2 kW (total)	Quarter wave structure, no plunging	$dp/p < \pm 0.35\,\%$ $\varepsilon < \pm 20\ \pi$ mm mrad

Electron Cooling (at GSI)	**Ion energy**	**Maximum electron current**	**Cathode diameter**	**Magnetic field in cooling section**	**Effective length of cooling section**	**Magnetic expansion factor**
SIS18 electron cooling system	Ions: < 60 MeV/u	1.5 A	25.4 mm	0.03 -0.15 T	1.8 m	1 to 8
ESR electron cooling system	Ions: 3 -430 MeV/u	2 A	50.8 mm	0.01 – 0.2 T	2.8 m	No magnetic expansion
CRYRING electron cooling system	Ions: ~ 100keV/u – 10MeV/u	3 A, typical 110mA	4 mm	0.01 – 0.3 T	1.1 m	10 - 100

Laser cooling	**Ion energy**	**Ion species** (e.g. Li-like ions)	**Laser power**	**Laser repetition rate**	**Effective length of cooling section**	**Final $\delta p/p$ and cooling time (calc.)**
SIS100 laser cooling (R&D)	up to 10 GeV/u	Up to Z=60	200 mW in the UV	up to 10 MHz	20 m	Down to 10^{-7} in one second



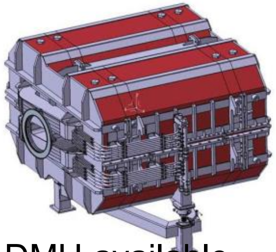
Status and GSIs Role in CR (Collector Ring and HESR (High Energy Storage Ring)

The subproject leadership for CR has been transferred to BINP.
The suproject leader for HESR is FZJ.

GSI‘s general involvement:

- Overall project management
- Definition of technical standards
- Approval of technical specifications
- DMU and integration into building
- Set-value generation
- Interfaces to controls and beam instrumentation

CR-Collector Ring



- All technical specifications and DMU available.
- Collaboration contract for dipole design and manufacturing signed with BINP.
- Contract for manufacturing of all other components (beside Rf and cooling) in preparation.
- Debuncher cavities (German inkind) delivered and accepted. Series production released.
- Stochastic cooling tank, pick-ups and amplifiers under development at GSI (German inkind).

HESR-High Energy Storage Ring

All accelerator components will be produced until end of 2018 !

- All dipole and quadrupole magnets manufactured.
- All quadrupol power converters manufactured.
- Sextupole magnets and steerers deliverd by Romanian inkind provider.
- Prototype stochastic cooling system installed in COSY ring.
- Prototype barrier bucket cavity installed in COSY.

Summary

- FAIR area North: Civil construction launched and progressing fast
- SIS18 upgrade will be completed in 2018 in time for re-commissioning for FAIR phase 0.
- GAF/WTK civil construction will be completed 2018, including interface to p-linac
- SIS100 all contracts for large series signed. Series production started. Man items delivered, e.g. 20 superconducting dipole modules
- Procurements are progressing well for all FAIR accelerators.
- Manufacturing of HESR components will be completed end of 2018 (beside dipole p.c).
- p-Linac and pbar target: Re-launched for advanced installation and early commissionig.
- Installation in FAIR buildings and tunnels will start in 2021
- First beam from SIS100 earliest in 2023

ACKNOWLEDGEMENTS

The authors would like to thank the GSI work package leaders, the department heads and all in-kind partners and other contributors for their tremendous amount of work and engagement for the realization of the FAIR project.