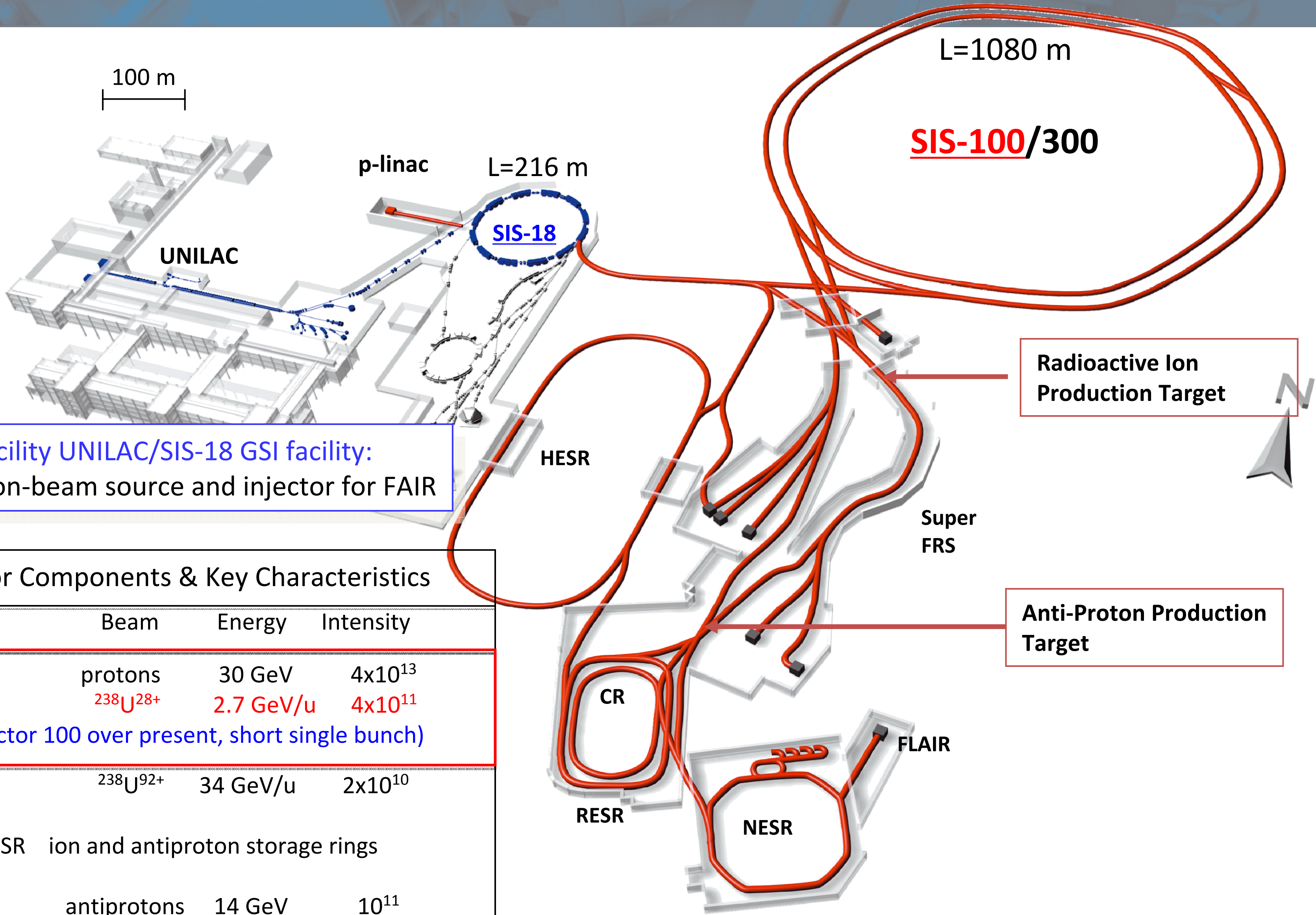
The FAIR accelerators: Highlights and Challenges

Oliver Boine-Frankenheim, GSI, Darmstadt, Germany

Contents

- **Status of the FAIR project:**
  Modularized Start Version and experiments
- **The SIS-18 and SIS-100 synchrotrons**
  Present and predicted beam intensities
- **'Beam loss budget' in SIS-100:**
  Activation and damage of accelerator components
- **Sources of beam loss in SIS-100**
  Resonances, Impedances, Cures
- **Conclusions**

The Accelerator Facility for Antiproton and Ion Research (FAIR)
baseline layout



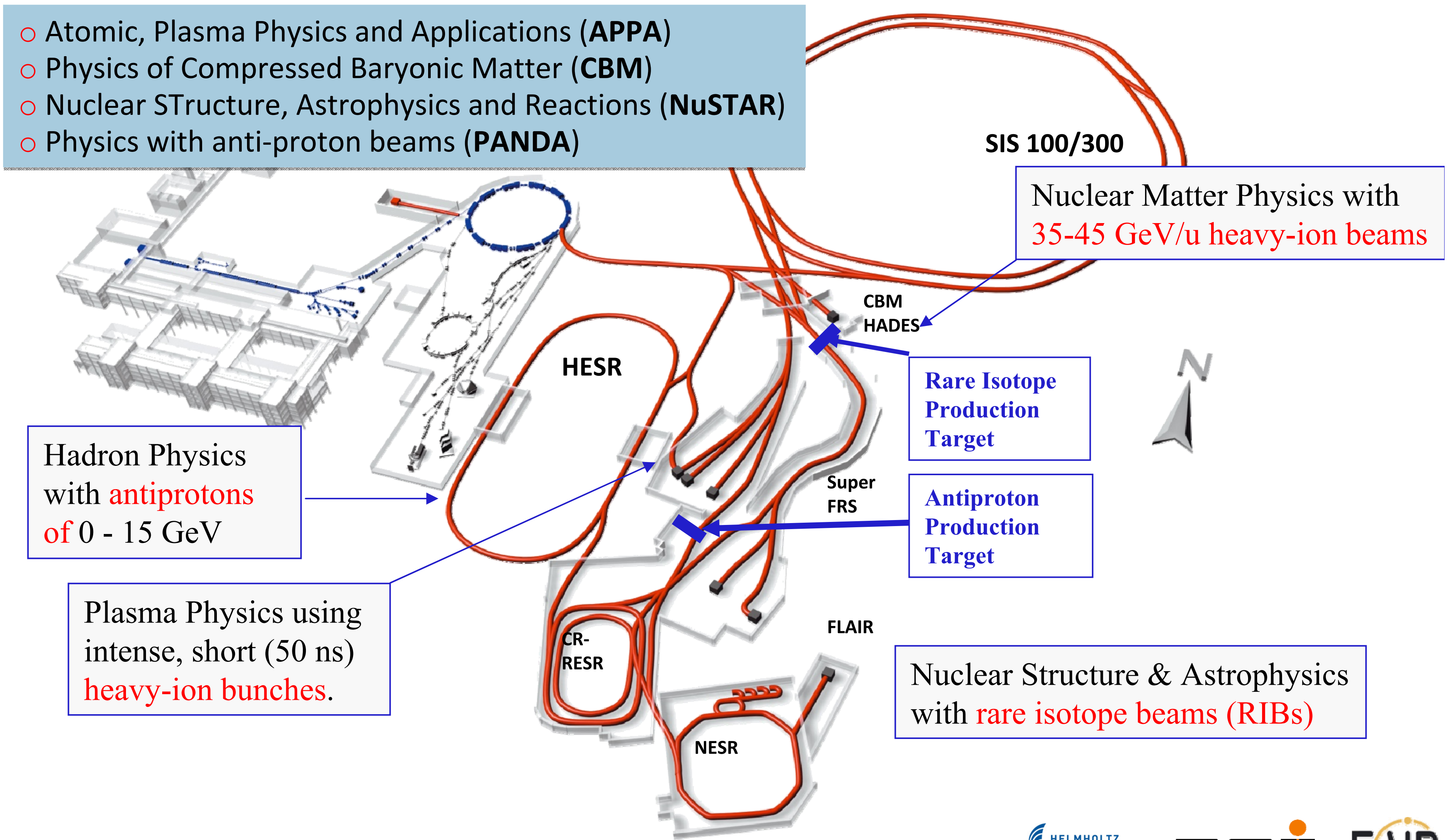
Existing facility UNILAC/SIS-18 GSI facility:
provides ion-beam source and injector for FAIR

Accelerator Components & Key Characteristics

Ring/Device	Beam	Energy	Intensity
SIS-100 Tm	protons	30 GeV	4×10^{13}
	$^{238}U^{28+}$	2.7 GeV/u	4×10^{11}
(intensity factor 100 over present, short single bunch)			
SIS-300 Tm	$^{238}U^{92+}$	34 GeV/u	2×10^{10}
CR/RESR/NESR	ion and antiproton storage rings		
HESR	antiprotons	14 GeV	10^{11}
Super-FRS	rare isotope beams	1 GeV/u	$<10^{9}$

Research communities at FAIR

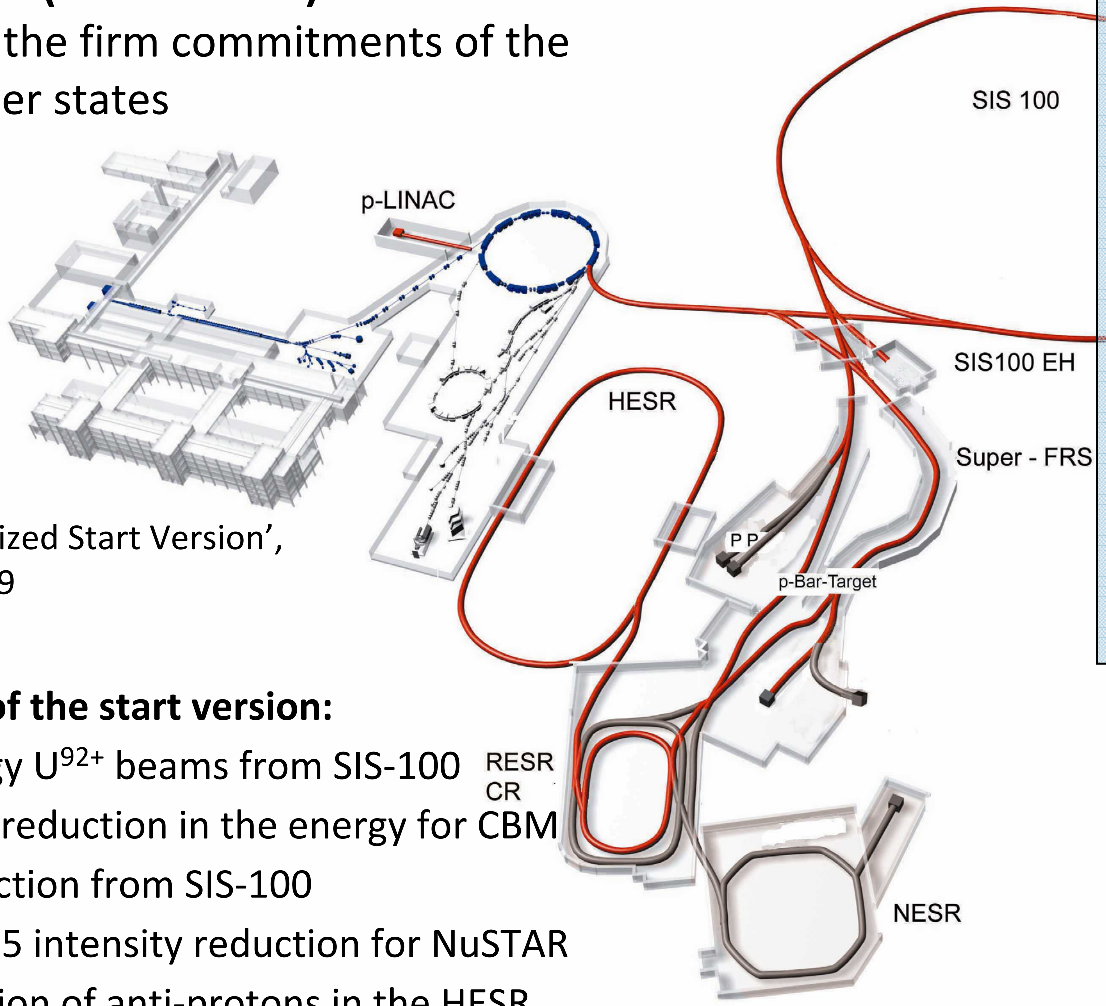
- Atomic, Plasma Physics and Applications (**APPA**)
- Physics of Compressed Baryonic Matter (**CBM**)
- Nuclear STructure, Astrophysics and Reactions (**NuSTAR**)
- Physics with anti-proton beams (**PANDA**)



Project staging

Modularized Start Version

Start version (Modules 0-3): based on recent cost estimates covered by the firm commitments of the FAIR member states



Green Paper,
'The Modularized Start Version',
GSI, Oct. 2009

Limitations of the start version:

- High-energy U^{92+} beams from SIS-100
  - -> Factor 3 reduction in the energy for CBM
- Slow extraction from SIS-100
  - -> Factor 1.5 intensity reduction for NuSTAR
- Accumulation of anti-protons in the HESR
  - -> Only 'high-resolution' mode for PANDA

Module 0:
SIS100 and connection to existing GSI facility

Module 1:
Experimental areas

Module 2:
Super-Fragment separator

Module 3:
High-energy antiprotons (p-linac, pbar-target, CR, HESR)

Module 4:
NESR, low energy RIB and low energy antiprotons

Module 5:
RESR storage ring

Module 6: SIS-300

Start Version: Anti proton accumulation in the HESR

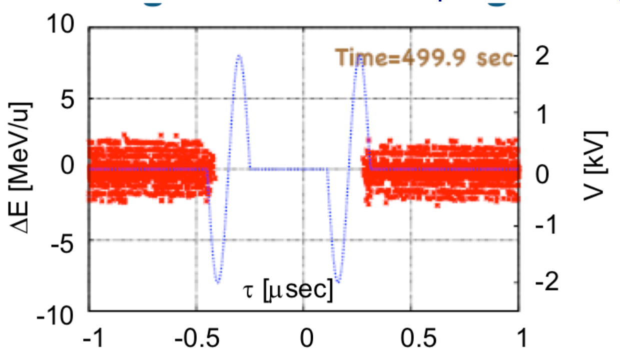
High resolution mode

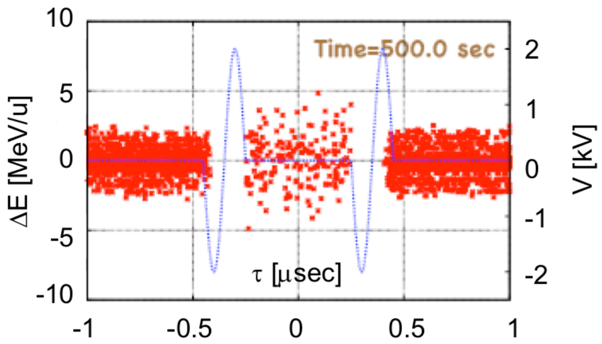
Effective target thickness (pellets): $4 \cdot 10^{15}$ cm^{-2}

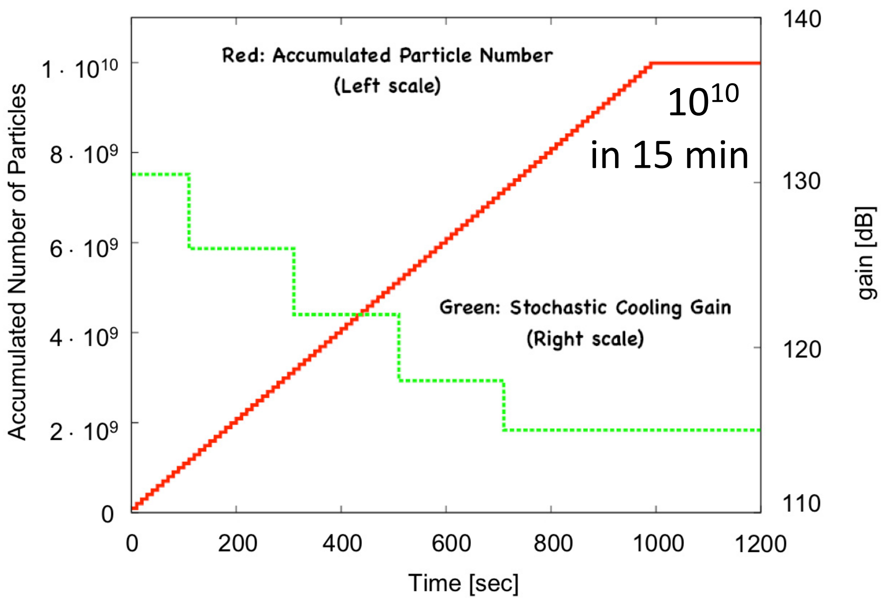
	High Resolution Mode	High Luminosity Mode
Energy range	0.8 - 8 GeV	3 – 14.5 GeV
Number of antiprotons	10^{10}	10^{11}
Peak luminosity	$2 \cdot 10^{31}$ cm^{-2}s^{-1}	$2 \cdot 10^{32}$ cm^{-2}s^{-1}
Momentum spread	$5 \cdot 10^{-5}$	$1 \cdot 10^{-4}$

For the the HL mode the RESR will be required (Module 5).

H. Stockhorst et al. MOPD068 poster
T. Katayama et al. MOPD065 poster







Barrier bucket stacking with stochastic momentum cooling.

NuSTAR experiments in the Start Version

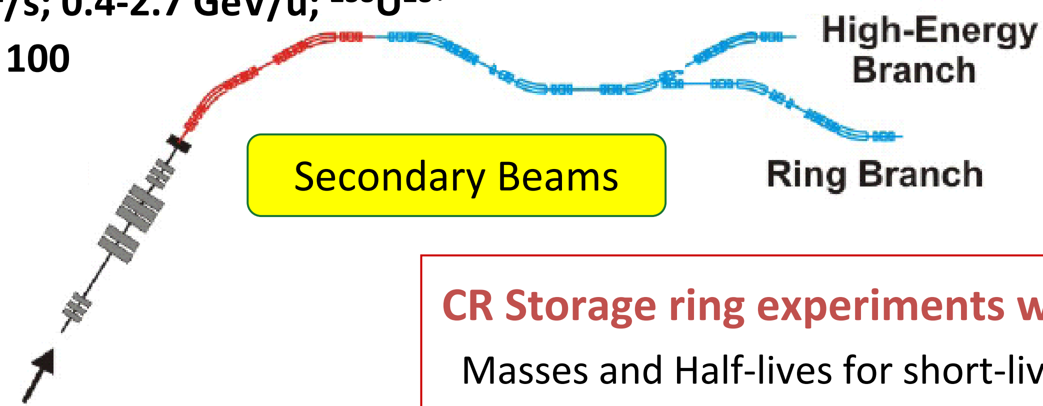
Fragment separator and CR

High energy branch:
Reactions with Relativistic Radioactive Beams in complete kinematics

Primary Beams

Super-FRS

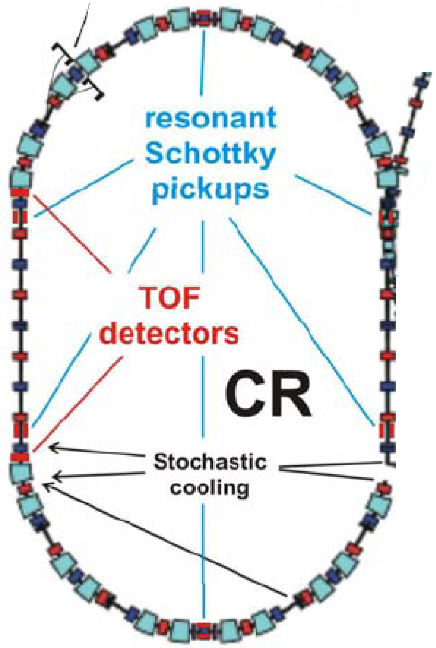
$2x10^{11}$/s; 0.4-2.7 GeV/u; $^{238}U^{28+}$
factor 100



Secondary Beams

SIS 100

CR Storage ring experiments with RIBs:
Masses and Half-lives for short-lived ions
Isochronous mode or fast stochastic cooling



Isochronous mass spectroscopy:

$$\frac{\Delta f}{f} = -\frac{\Delta T}{T} = -\frac{1}{\gamma_t^2} \cdot \frac{\Delta(m/q)}{m/q} + \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}$$

NuSTAR: Primary heavy-ion beam intensity from SIS-100 is essential !

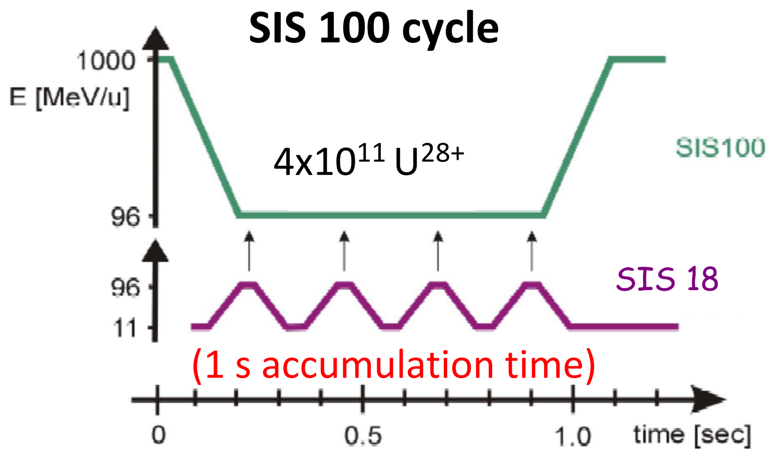
Heavy ion intensities from SIS-18 and SIS-100

SIS-18 upgrade

Intense primary heavy-ion beams:

RIB production (NuSTAR) and plasma physics.

	SIS-18 (today/required)	SIS-100
Reference primary ion	U^{28+}	U^{28+}
Reference energy	200 MeV/u	1.5 GeV/u
Ions per cycle	**2E10** / **1.5E11**	**4E11**
cycle rate (Hz)	1 / 2.7	0.5



SIS-18 upgrade for SIS-100 injection:

- New injection system (completed)
- NEG coating of the vacuum pipe (completed).
- Reduction of multi-turn injection loss (ongoing).
- Fast ramping with 10 T/s (ongoing)
- Dual rf system (ongoing).

P. Hülsmann, et al., MOPD029 poster
P. Spiller, MOPD002, Poster

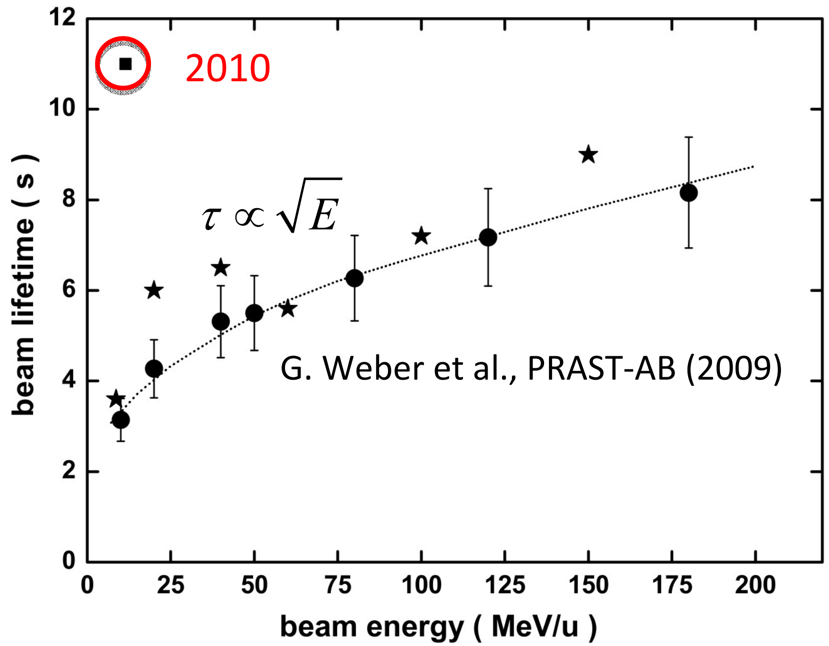
Beam loss in SIS-18: U^{28+} lifetime and residual gas pressure

Electron stripping: $U^{28+} + X \rightarrow U^{29+} + X + e$

(Lifetime)$^{-1}$: $\tau^{-1}(P) = \beta_0 c \sigma_{loss} \frac{P}{k_B T}$

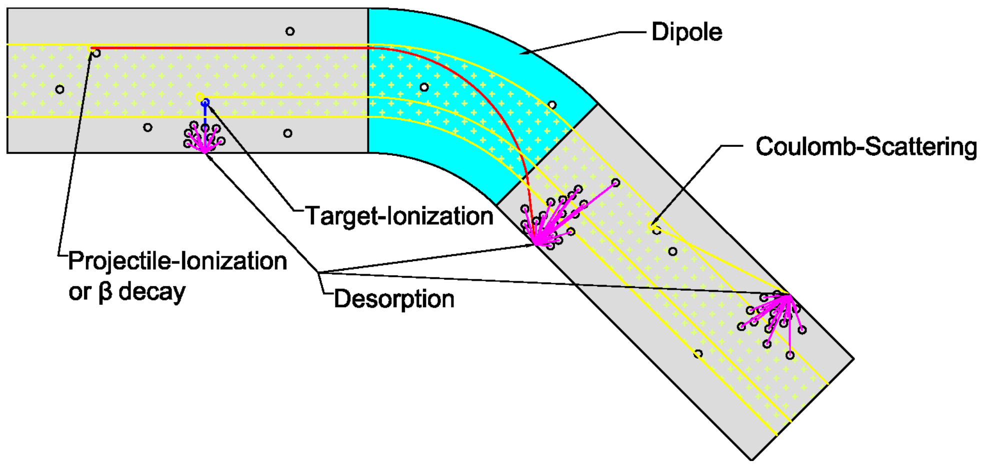
Born approximation: $\sigma_{loss} \propto E^{-1}$

Measured U^{28+} life time for **low intensities**



Lifetime increase (factor 3) due to NEG coating

High intensities



$$\eta = \frac{\#\ \text{desorbed molecules}}{\#\ \text{incident ions}} \propto \left(\frac{dE}{dx}\right)^n$$

Stopping power: $\frac{dE}{dx} \propto \frac{Z^2}{A}$

H. Kollmus et al., J. Vac. Sci. (2009)

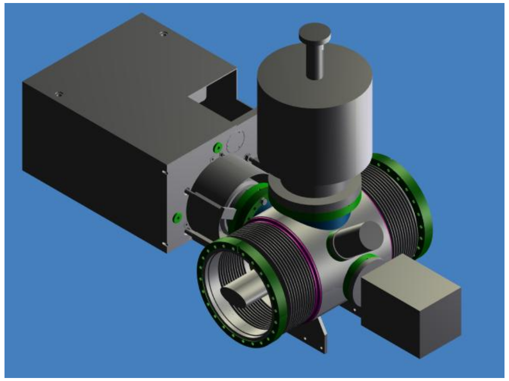
Dynamic pressure: $\frac{dP}{dt} = \tau_p^{-1}(P - P_0) + \alpha \eta_{loss} N P$

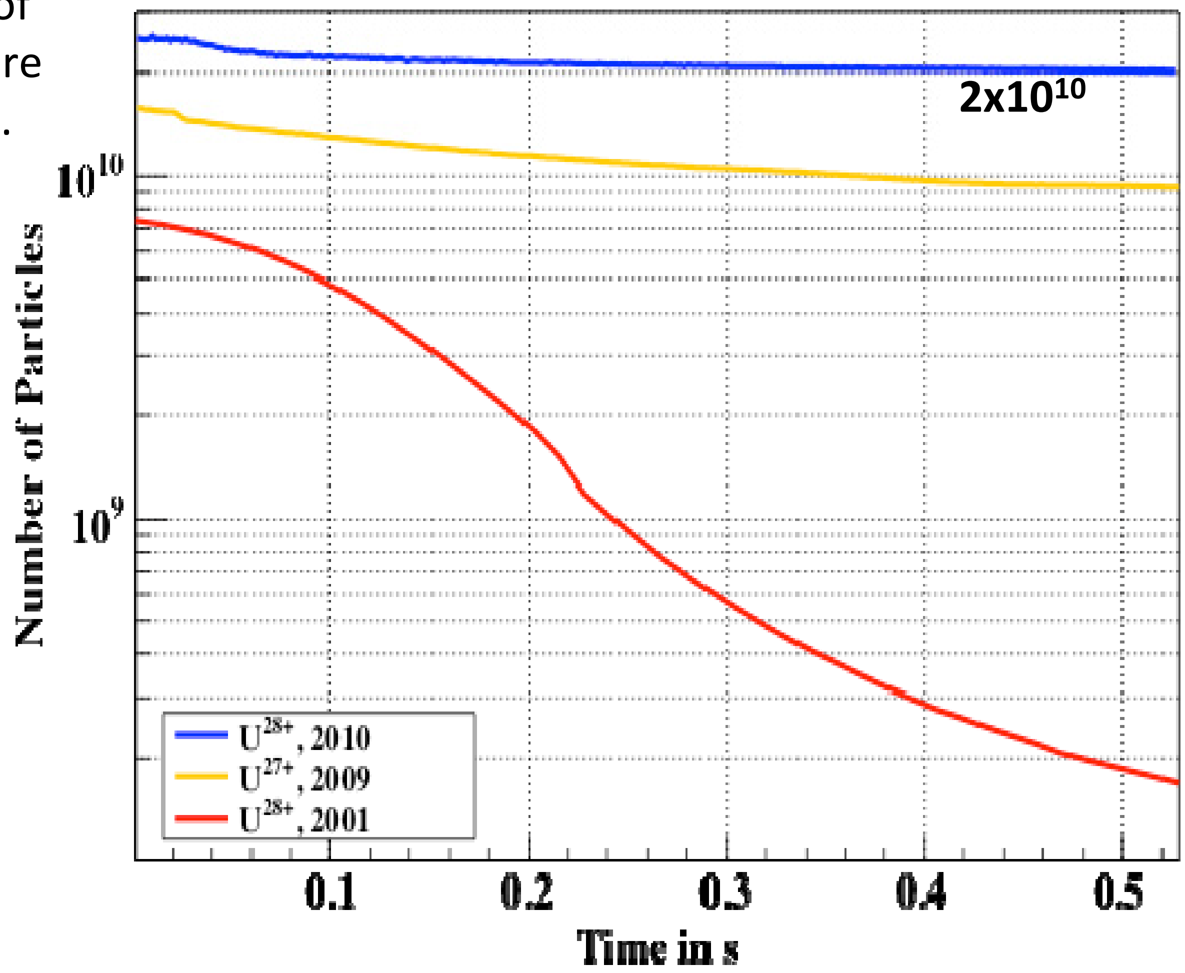
Challenge: Control of dynamic pressure.

New SIS-18 'record' intensity for U^{28+} ions

SIS-18 highlight:
Demonstration of the control of beam loss and dynamic pressure for moderate beam intensities.

Combined pumping/collimation ports behind every dipole group.





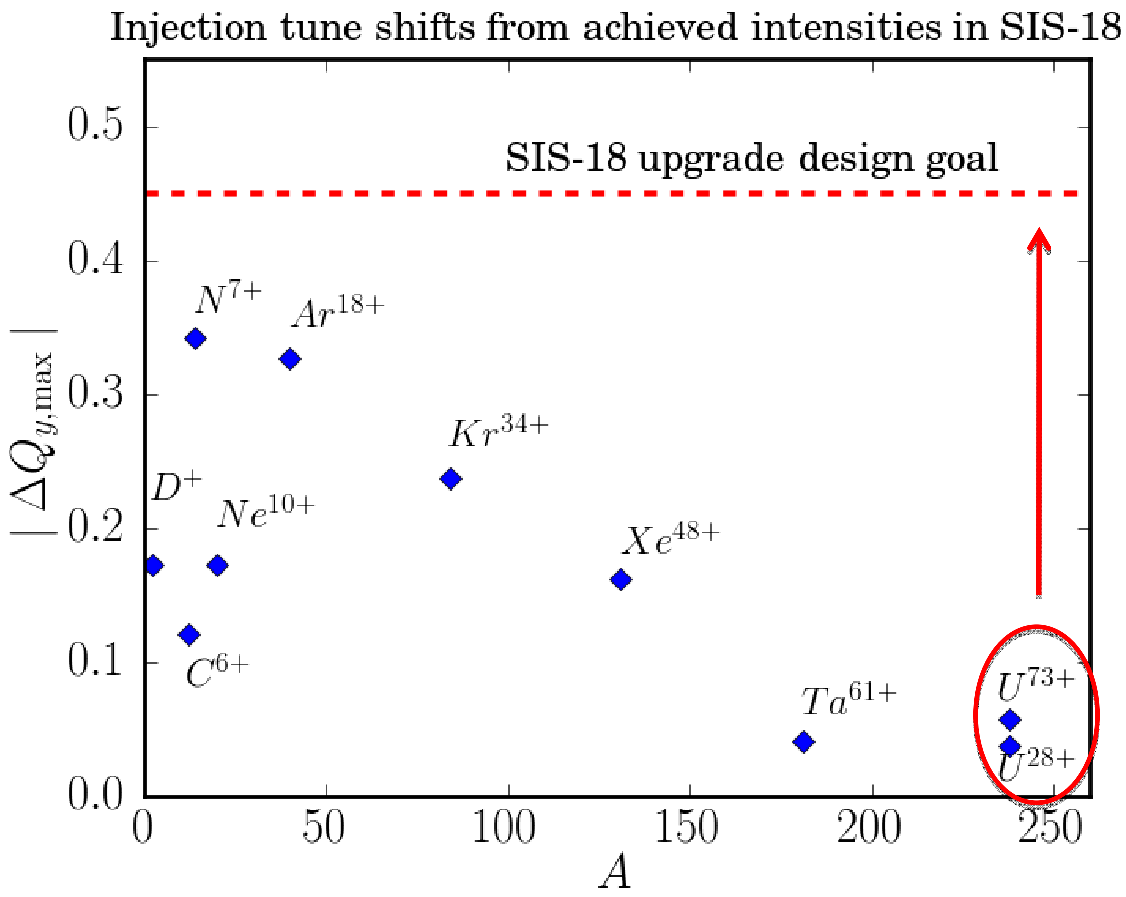
P. Spiller, MOPD002, Poster
P. Puppel, MOPEC058, Poster

SIS-18 beam intensities

SIS-18 injection energy: 11.4 MeV/u

$\varepsilon_{x/y} = 150/50$ mm mrad (acceptance)

Space charge tune shift: $\Delta Q_y^{sc} = -\frac{2NZ^2 g_f}{\pi A \beta_0^2 \gamma_0^3 B_f \left(\varepsilon_y + \sqrt{\varepsilon_y \varepsilon_x}\right)}$

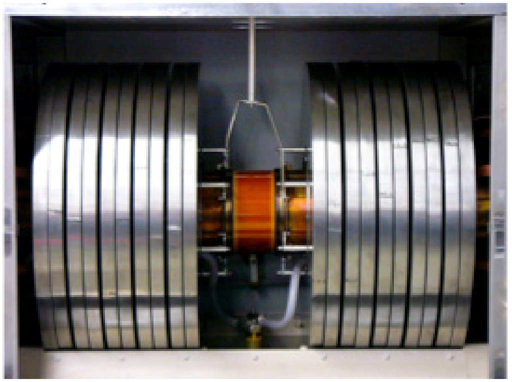


Remaining SIS-18 challenges:

- factor of 10 for heavy ions
- control of beam loss and quality for high intensities

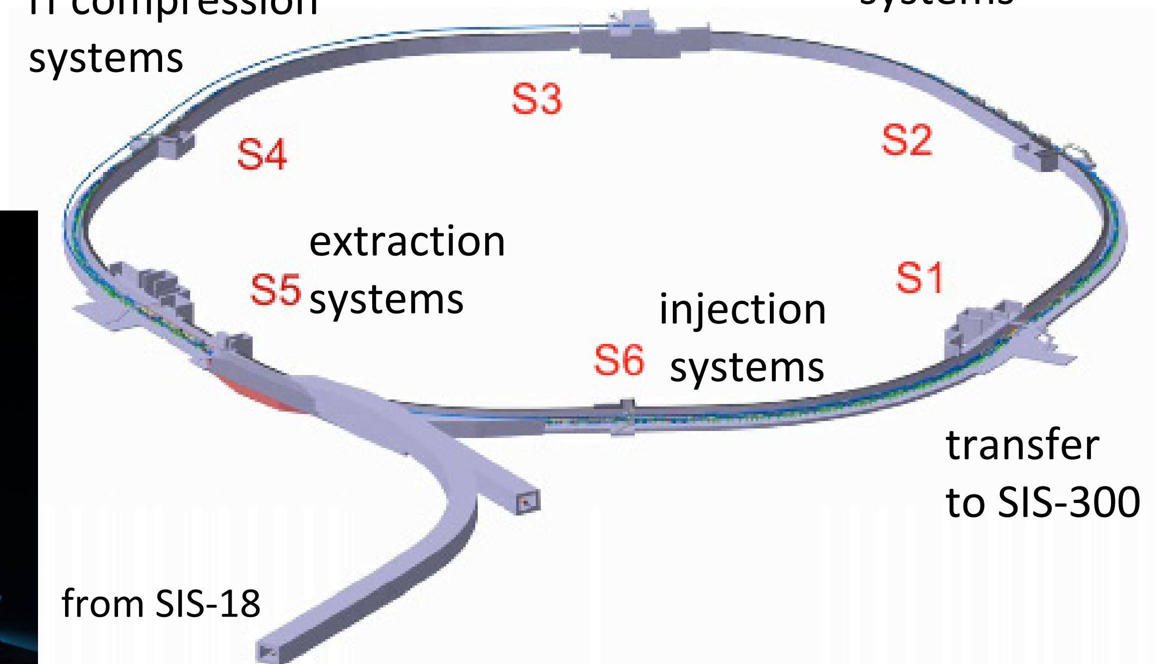
The SIS-100 synchrotron: FAIR 'workhorse'

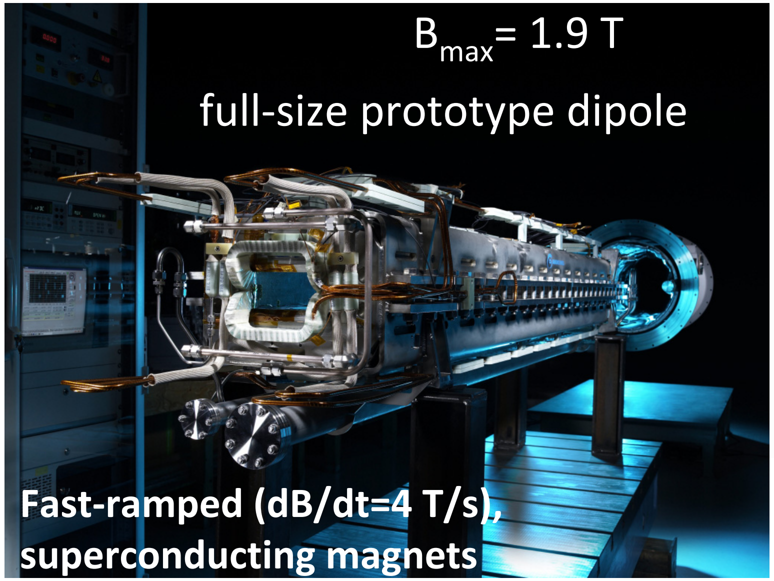
MOPD003 poster, *Engineering Status of SIS-100*, P.Spiller



High-gradient magnetic alloy loaded bunch compressor cavities

Circumference=1080 m





E. Fischer, et al., MOPEB025 poster

‘Beam loss budget’ in SIS-100

Beam loss induced effects in the vacuum chamber or accelerator components:

activation: loss of ‘hands-on-maintenance’
-> important only for localized losses e.g. during slow extraction

ion induced damage: persistent change of material properties
-> energetic heavy ions can cause higher damage than protons

ion induced desorption: increase of the vacuum pressure
-> distributed combined collimation/pumping system for ‘stripping’ losses in SIS-100

We presently expect that max. 5-10 % percent beam loss can be tolerated.

Beam loss induced residual activation and damage:
Heavy ions vs. protons

Electronic energy loss in matter (stopping power): $\frac{dE}{dz} \propto \frac{Z^2}{A}$

(Z: projectile charge state, A: projectile mass number)

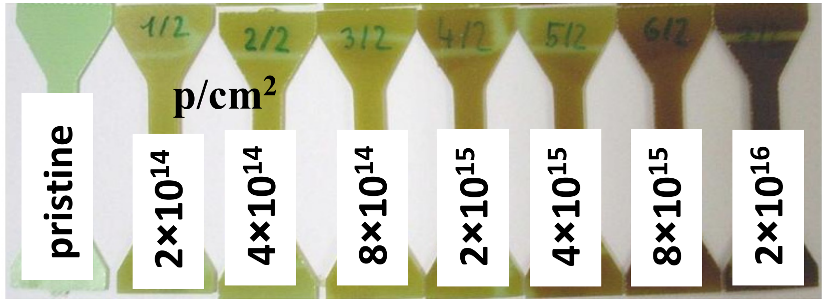
Range in stainless steel for 1 GeV/u:
Uranium: ≈ 1.5 cm, Protons ≈ 60 cm

- Below approx. 1 GeV/u heavy ions are stopped mostly by Coulomb interaction with target electrons.
- Heavy ions experience less nuclear interactions than protons -> less activation, more damage.

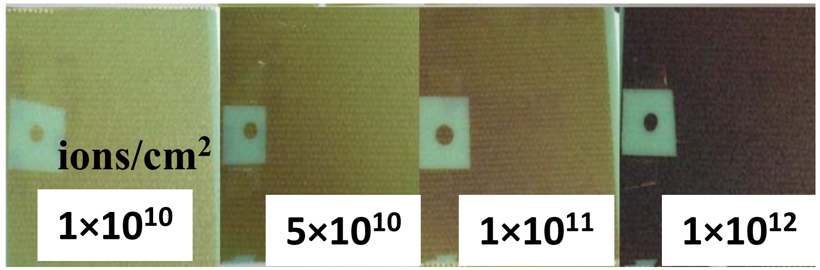
'Hands-on maintenance' criterium
Literature: 1 W/m for 1 GeV proton beams.
GSI studies: 5 W/m for 1 GeV/u uranium beam.

I. Strasik, E. Mustafin et al., submitted to Phys. Rev. ST Accel. Beams

proton (21 MeV) irradiated G11 (ITEP Moscow)



Pb ions (11 MeV/u) irradiated G11 (UNILAC)



10^{12} heavy ions make the same damage as 10^{16} protons in organic insulators.

E. Mustafin, et al. (2009)

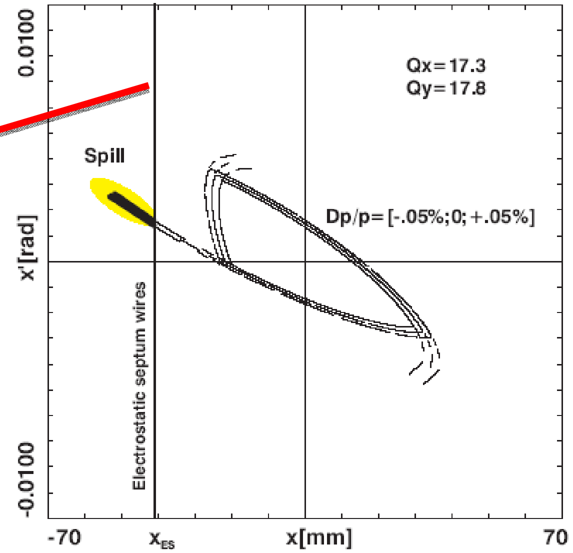
J. Stadlmann et al., THPEC079 poster (COLLMAT project)

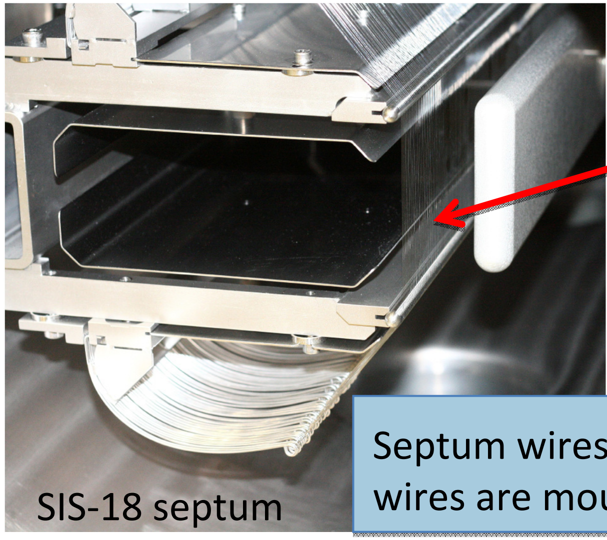
Beam loss example: Slow extraction from SIS-100

extraction of intense heavy-ion beams for NuSTAR and CBM

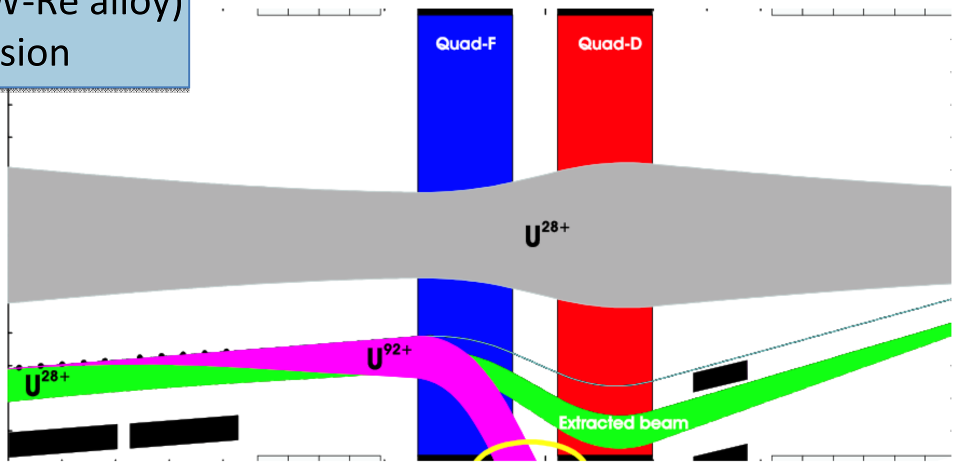
Ion	Energy	N/s	spill	Power
U^{28+}	1.5 GeV/u	2E11	> 1 s	10 kW

Separatrix (third order resonance)





Septum wires: Ø 0.025 mm (W-Re alloy)
wires are mounted under tension



Tracking simulations:

5 % (approx. 500 W) loss in the septum wires

U^{92+} localized beam loss in warm magnet > 5 W/m

Challenge: slow extraction of <u>intense</u> beams

e.g. eclouds: F. Petrov, et al., TUPD003 poster

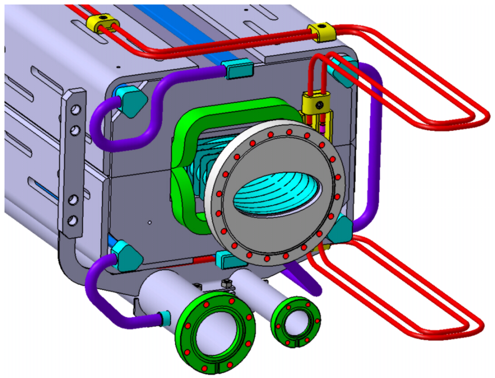
S. Sorge et al., THPEB002 poster

SIS-300: A. Saa Hernandez, N. Pyka, et al. THPEB004 poster

SIS-100 dipole magnets

field quality and tracking studies

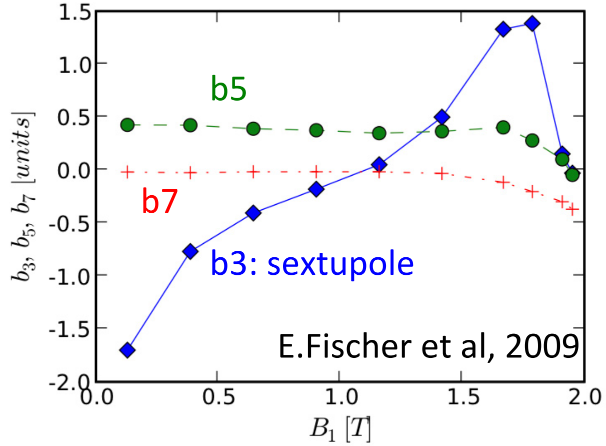
3D model of the SIS-100 dipole with elliptical beam pipe



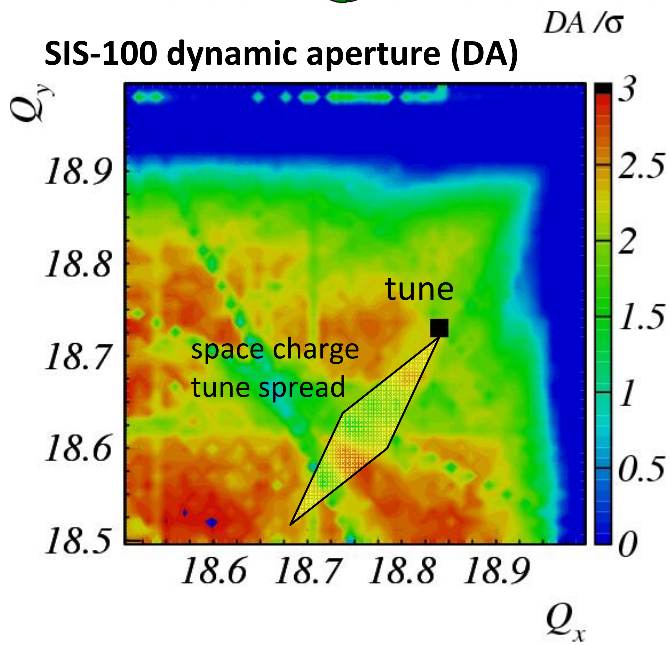
Field errors:

- 2D/3D static calculations
- Measurements
  (prototype magnet)

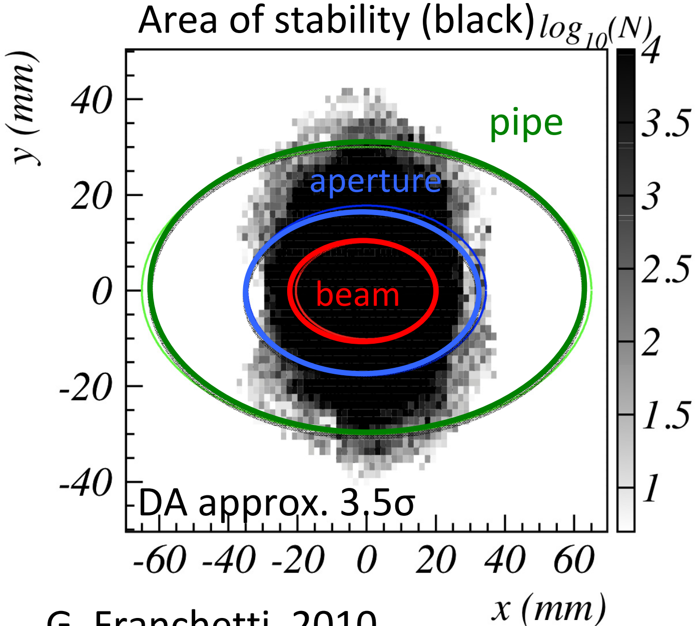
Static 2D field harmonics



SIS-100 dynamic aperture (DA)



Area of stability (black)



G. Franchetti, 2010

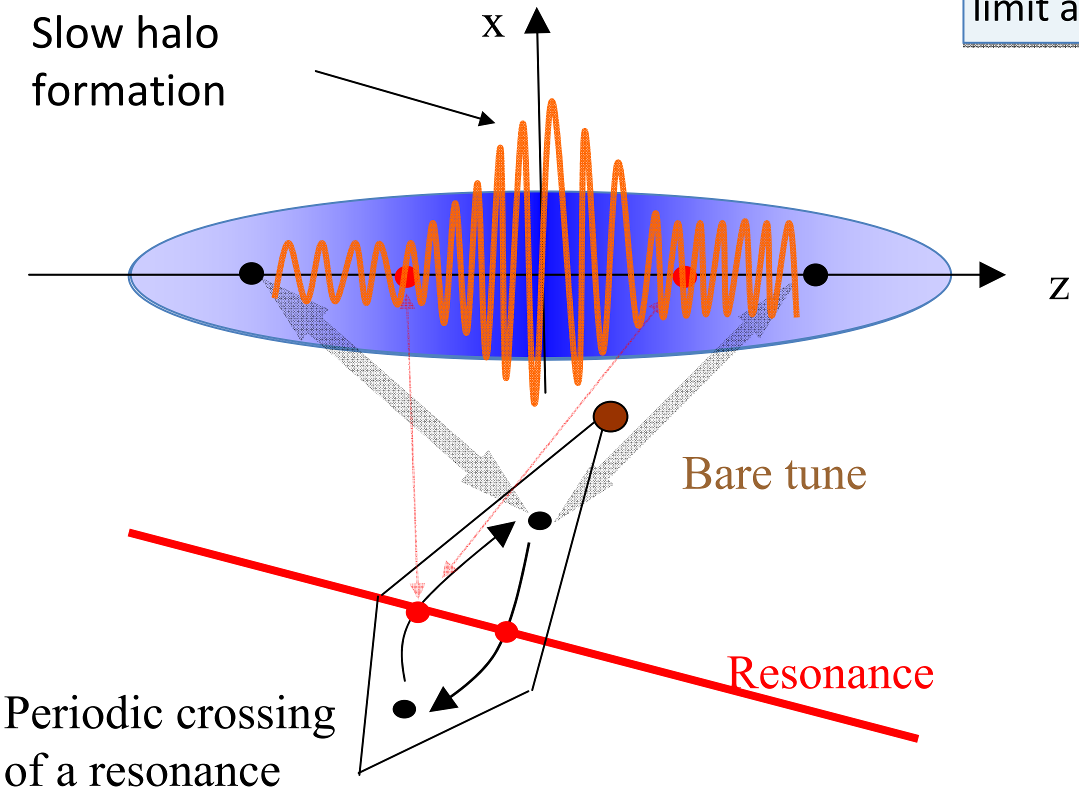
Tracking simulations:

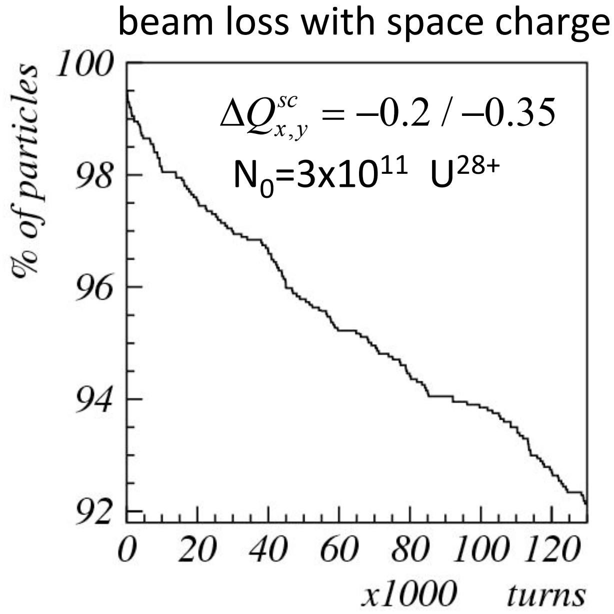
- closed orbit errors
  (feed-down)
- 10^5 turns
- dynamic aperture (DA)

Space charge induced gradual beam loss
'island trapping' mechanism

G. Franchetti, I. Hofmann, W. Fischer, F. Zimmermann
Phys. Rev. ST Accel. Beams 12, 124401 (2009)
G. Franchetti, et al., TUPEB038 poster

Long-term (up to 1 s) 3D particle tracking studies with 'frozen' space charge indicate a space charge limit at 3×10^{11} U^{28+} (design 4×10^{11}).

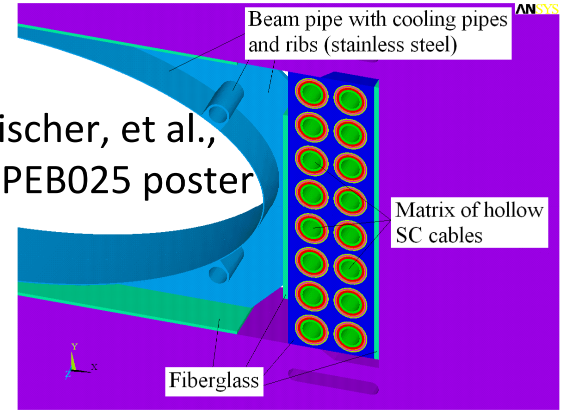




Challenge: 'Thick' beam, 1 s storage time, space charge
Possible cures: 'Bunch flattening', resonance correction (A. Parfenova, next talk)

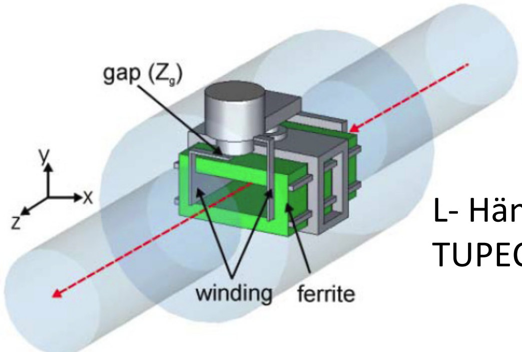
Impedance studies:

✓ <u>Thin (0.3 mm) resistive beam pipe:</u>



E. Fischer, et al., MOPEB025 poster

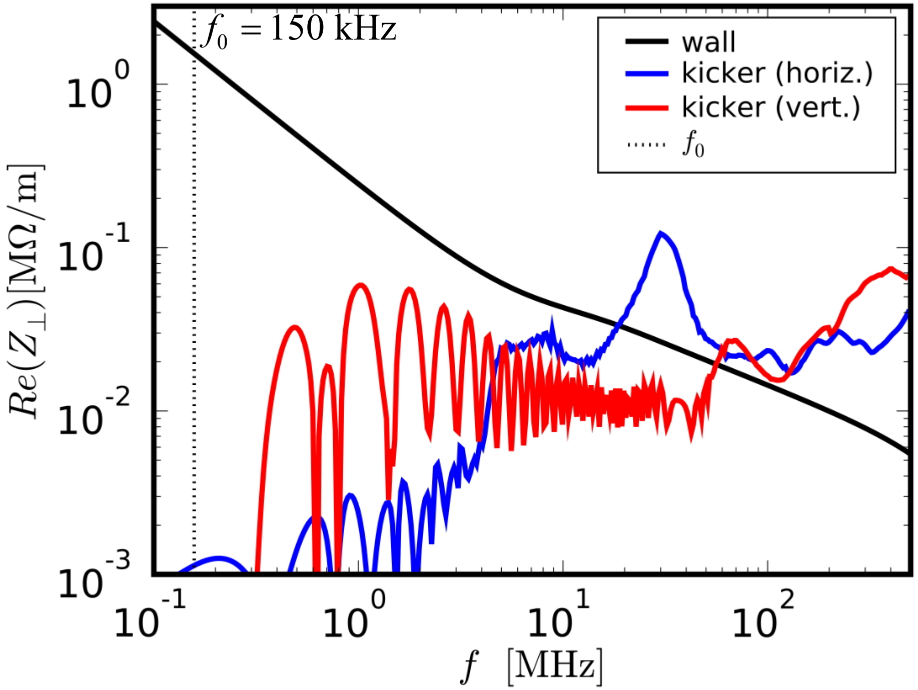
✓ Ferrite loaded kicker modules:



L- Hänichen, Th. Weiland, TUPEC048 poster

✗ distributed collimator system,…..

Estimated impedance spectrum at 200 MeV/u



Skin length at f_0=150 Hz is 1.5 mm !
-> Thin pipe is 'transparent' below 30 MHz.
-> Impedance contributions from cooling tubes,…

A. Al-Khateeb, et al., PRST-AB 10, 064401 (2007)

Octupoles as a cure for transverse coherent instabilities in SIS-100

coasting beams at SIS-100 injection

Resistive wall instability:

$$\Delta Q_{coh} \propto -i \frac{q^2 N}{m \gamma_0 Q_0} Z_{\perp}^{rw} \qquad \tau = \left(f_0 \Im \Delta Q_{coh} \right)^{-1} \approx 10 \text{ ms}$$

Ion	Energy	N	$\Delta p / p$	ΔQ_{sc}
U^{28+}	200 MeV/u	4E11	**4E-4**	**-0.1**

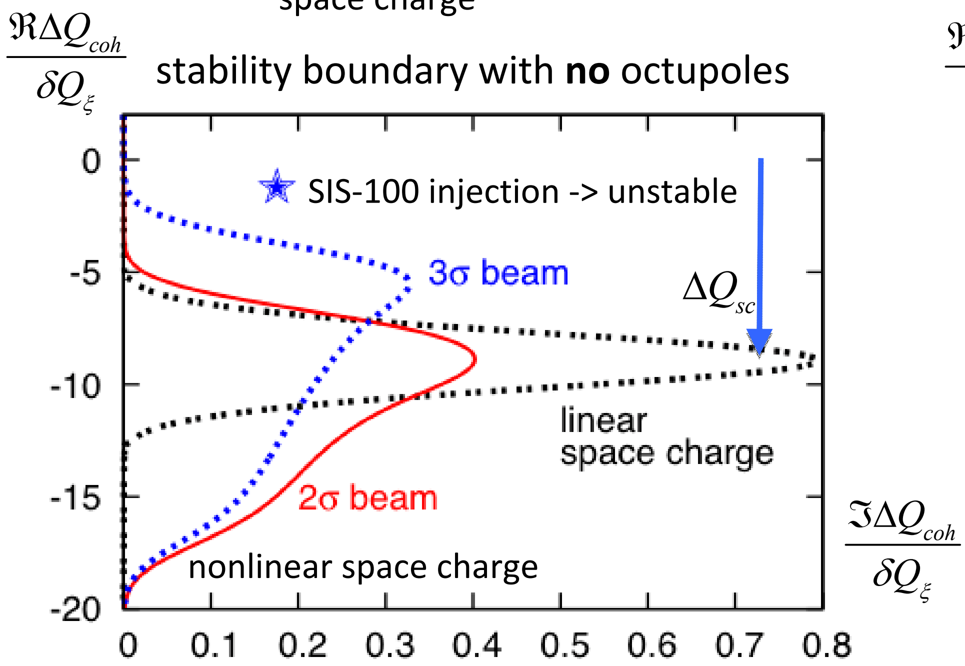
Incoherent tune:

$$Q_x(\hat{x},\hat{y}) = Q_0 - \Delta Q_{sc}(\hat{x},\hat{y}) + \Delta Q_{oct}(\hat{x},\hat{y}) + \delta Q_{\xi}(\Delta p / p)$$

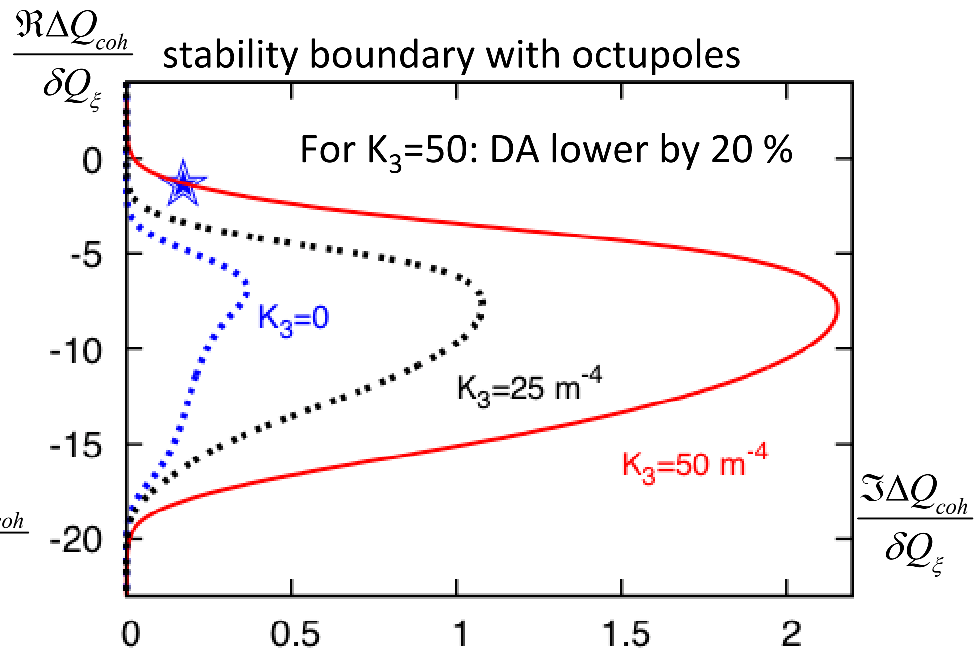
nonlinear space charge — octupoles — chromaticity

V. Kornilov et al., PRST-AB (2007)
V. Kornilov et al., TUPD029, Poster

stability boundary with **no** octupoles



stability boundary with octupoles



Octupoles in combination with space charge can be used for the stabilization of dc and head-tail instabilities in SIS-100.

Conclusions

FAIR status:

- The FAIR Modularized Start Version is based on recent cost estimates covered by the firm commitments of the FAIR member states.
- Modules 0-3 enable a unique experimental programme.
- The facility can be smoothly upgraded towards the full version of FAIR (modules 4,5,6).

Highlights:

- SIS-18 'record' intensity for uranium ion: successful control of dynamic pressure
- SIS-100 full-size prototype dipole (measured): still tolerable beam losses
- Advanced machine design for intense heavy-ion beams: e.g. handling of slow extraction loss
- New insights into heavy-ion beam induced effects: e.g. tolerance for activation
- … into space charge effects in rings.

Remaining challenges (work to do):

- Intensity for heavy-ions in SIS-18 up to the space charge limit (completion of upgrade)
- Control of high intensity effects in SIS-100 (some of the measures can be implemented later).