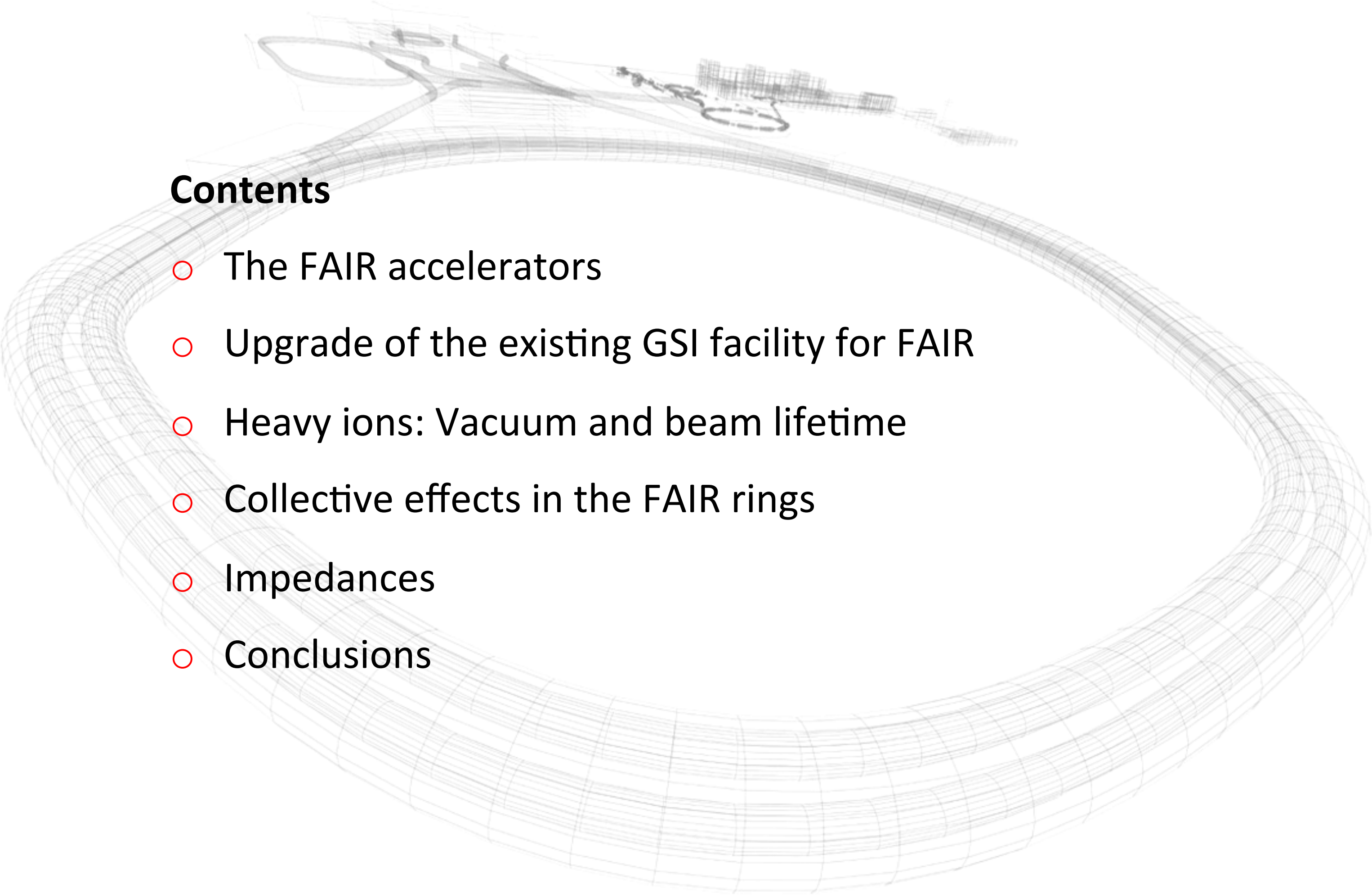
Challenges for the FAIR project at GSI

FAIR: Facility for **A**ntiproton and **I**on **R**esearch

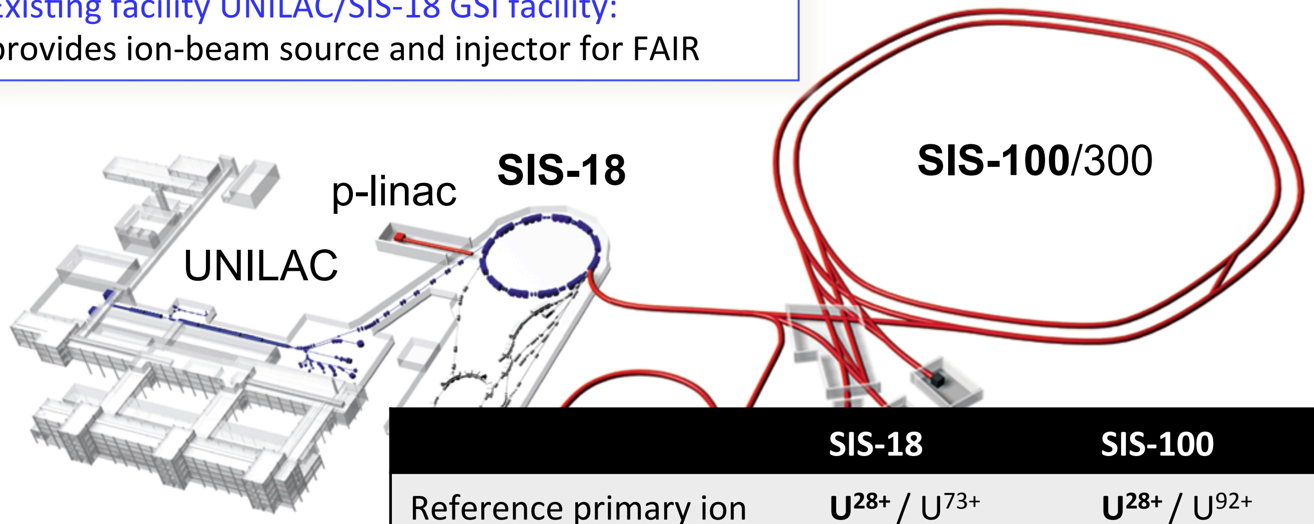


Contents

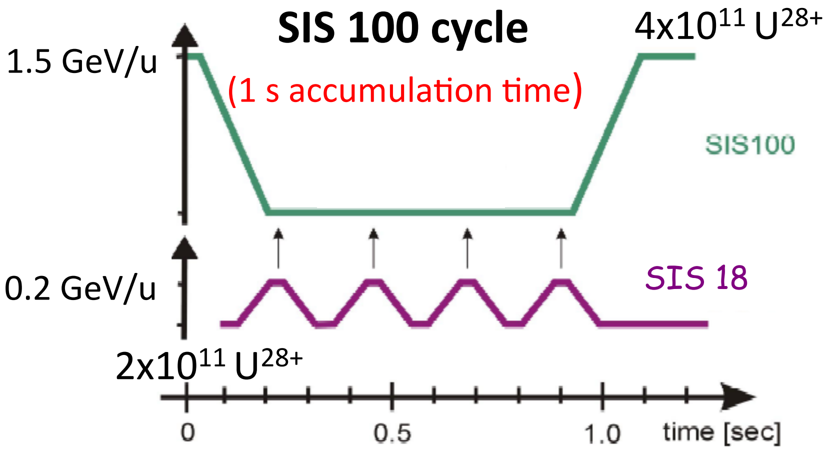
- The FAIR accelerators
- Upgrade of the existing GSI facility for FAIR
- Heavy ions: Vacuum and beam lifetime
- Collective effects in the FAIR rings
- Impedances
- Conclusions

The FAIR accelerators: Heavy-ion chain

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



SIS-100 extraction:
- short (60 ns) bunch
- slow extraction



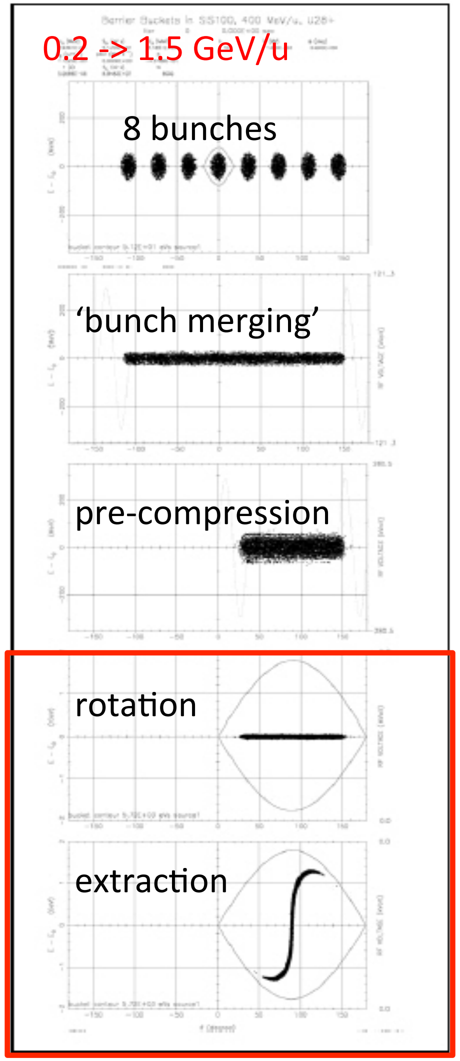
	SIS-18	SIS-100
Reference primary ion	**U^{28+}** / U^{73+}	**U^{28+}** / U^{92+}
Reference energy	**0.2** / 1 GeV/u	**1.5** / 10 GeV/u
Ions per cycle	**1.2E11** / 2E10	**4E11** / 1E10
cycle rate (Hz)	2.7	**0.5** / 0.1

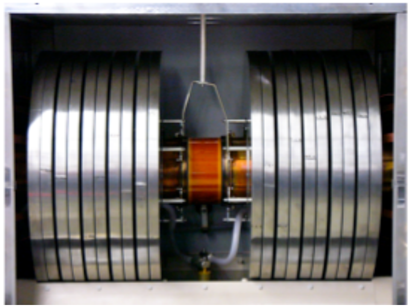
FAIR parameter booklet, **April 2007**,
(Ed.) O. Boine-F., P. Spiller, M. Steck + corrections for MSV

Protons from SIS-100: 29 GeV, 4×10^{13}, 1 bunch, 0.2 Hz

Final bunch compression in SIS-100

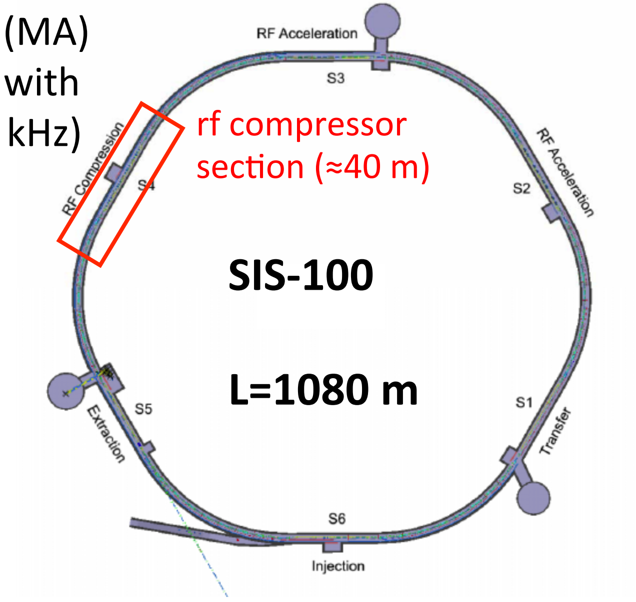
Single bunch formation



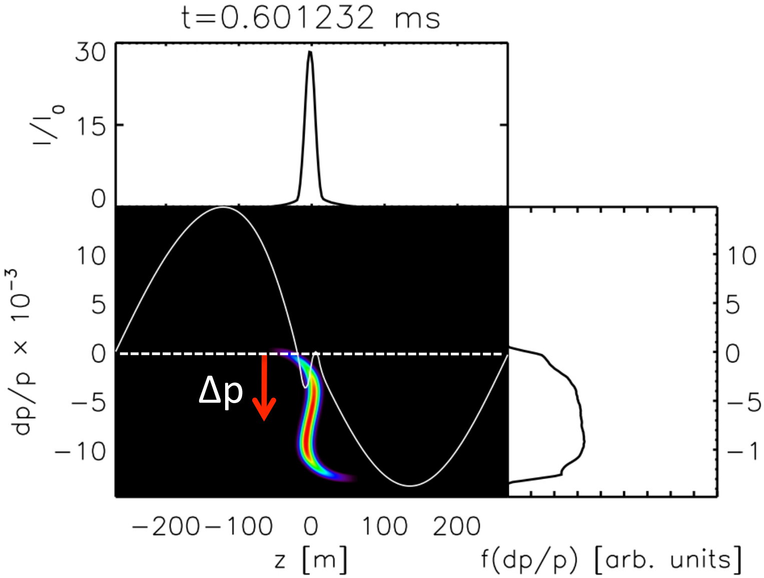


# cavities	R_s/cavity [kΩ]	Q_s	f_{res}
16	1	2	1.5 MHz

16 magnetic alloy (MA) loaded rf cavities with total: 600 kV (400 kHz)



Effect of beam loading (MA cavities) on the bunch rotation:



Challenges:

- ○ Control of beam loading effects
- ○ **Transverse space charge:**

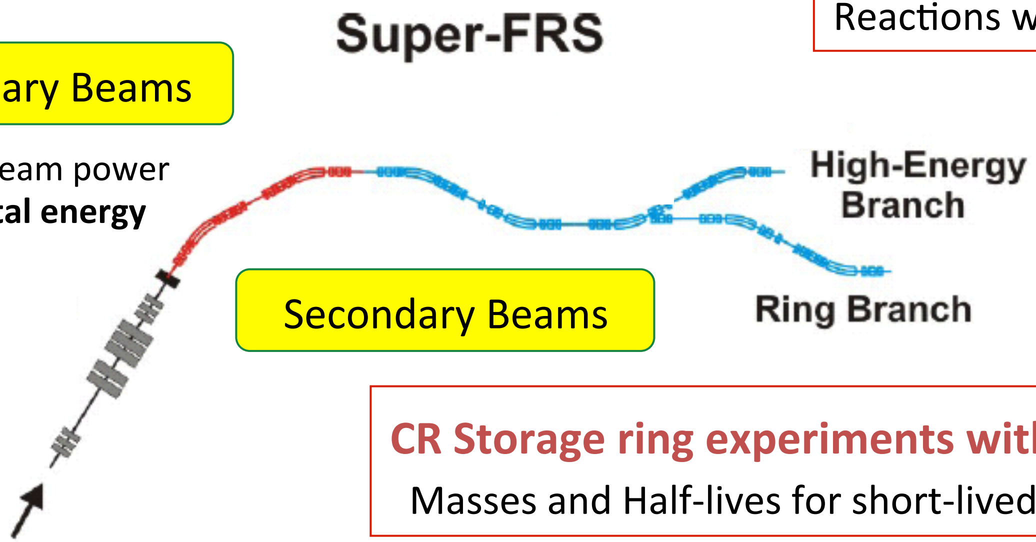
$\Delta Q_y^{sc} \approx -0.8$ (during the last turns)

End of the heavy-ion chain:
Bunch compression and production of exotic nuclei

FRS: FRagment Separator

Primary Beams

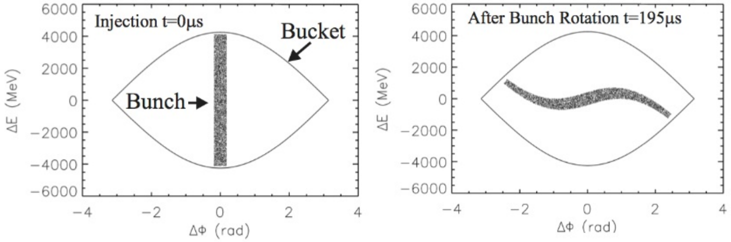
15 kW beam power
30 kJ total energy



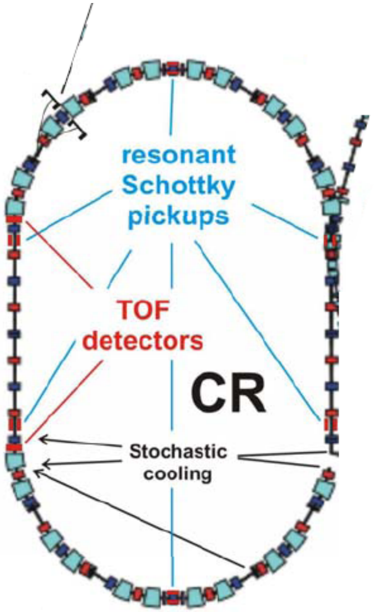
Secondary Beams

High energy branch:
Reactions with Relativistic Radioactive Beams

Bunch rotation in the CR



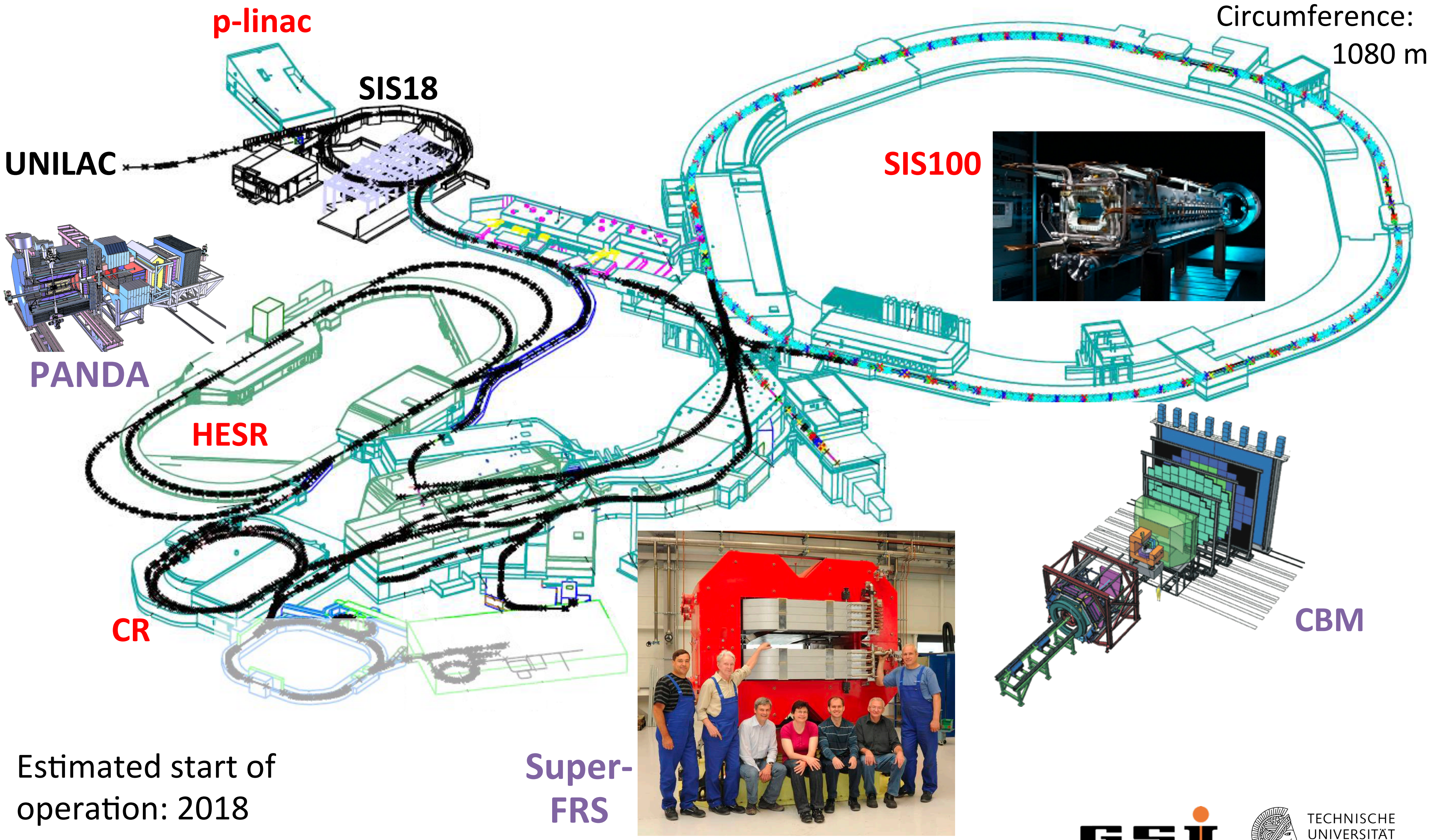
CR Storage ring experiments with RIBs:
Masses and Half-lives for short-lived ions



	SIS-100
Reference primary ion	U^{28+}
Reference energy	1.5 GeV/u
Ions per cycle	4E11
Bunch length	60 ns
Momentum spread	± 1 %
cycle rate (Hz)	0.5

Primary heavy-ion beam intensity from SIS-100 is essential for the exotic beam program at FAIR !

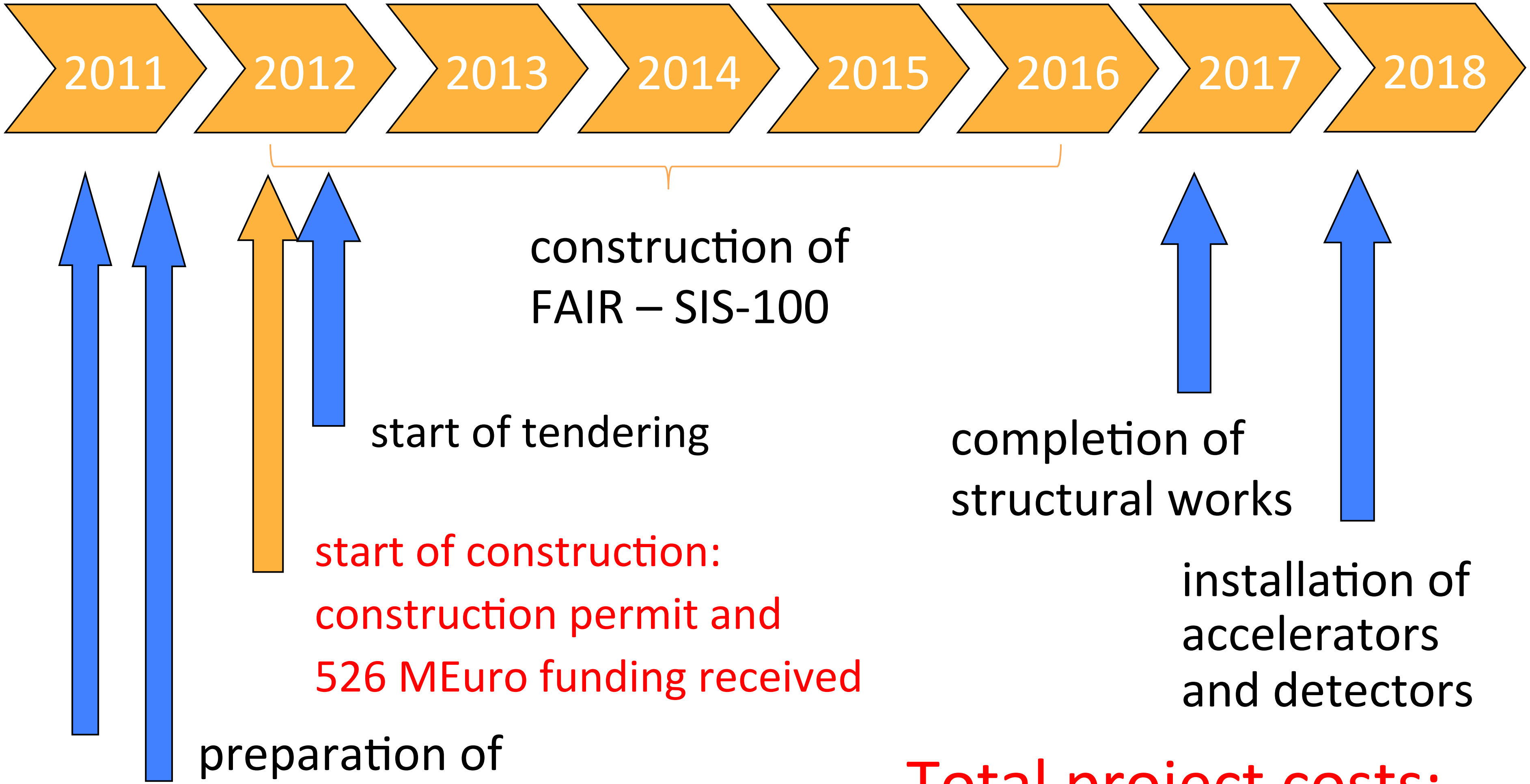
The FAIR facility



Circumference: 1080 m

Estimated start of operation: 2018

Official FAIR time line



2011 2012 2013 2014 2015 2016 2017 2018

construction of
FAIR – SIS-100

start of tendering

completion of
structural works

start of construction:
construction permit and
526 MEuro funding received

installation of
accelerators
and detectors

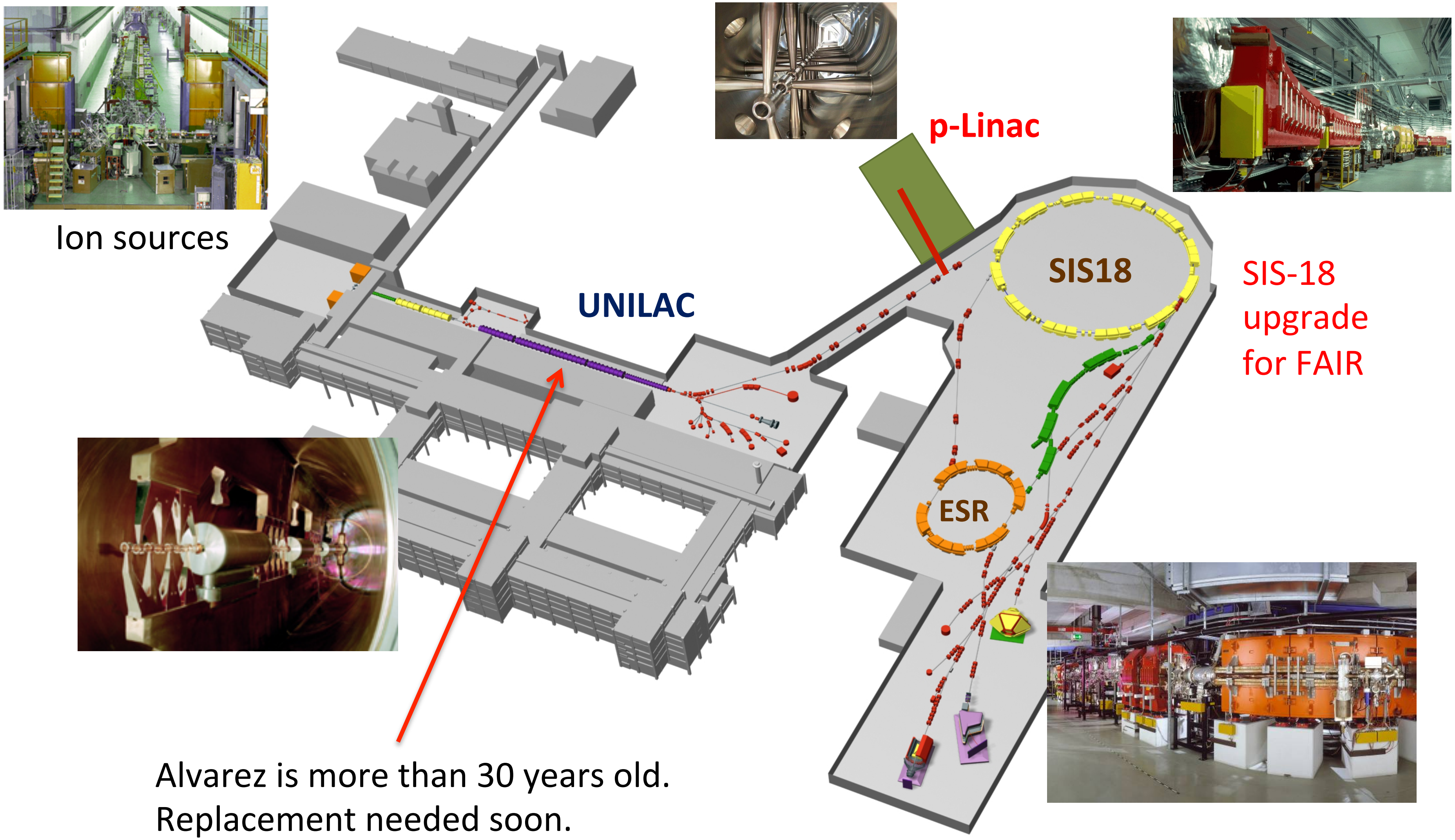
preparation of
construction site

building
applications

Total project costs:
2 Billion Euro

Status civil construction

FAIR injectors: UNILAC and SIS18

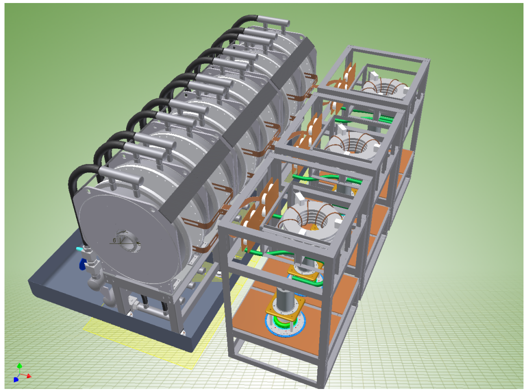


Alvarez is more than 30 years old.
Replacement needed soon.

Heavy ion intensities from SIS-18

SIS-18 upgrade program

The SIS-18 upgrade program: Booster operation with intermediate charge state heavy ions



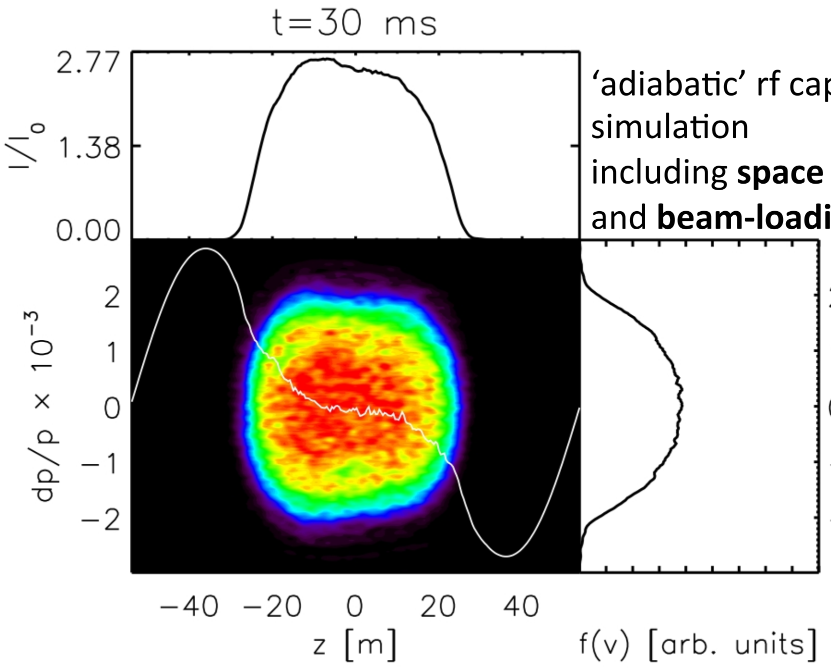
h=2 acceleration cavity for **faster ramping** and for **bunch flattening**

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

SIS-18 upgrade for the FAIR booster operation:

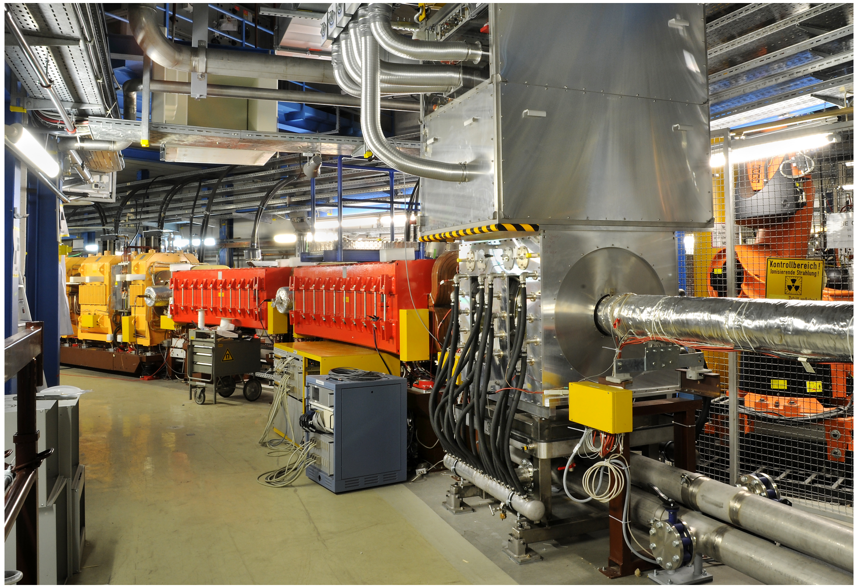
- ○ New injection system
- ○ NEG coating of the vacuum pipe
- ○ Reduction of multi-turn injection loss (ongoing)
- ○ Fast ramping with 10 T/s (ongoing)
- ○ Dual (h=2/4) rf system (-> 2016)

RF capture and fast ramping in SIS-18
(dual rf buckets)



‘adiabatic’ rf capture simulation including **space charge** and **beam-loading**

Magnetic alloy loaded rf cavity (40 kV, 400 kHz)



one of of three modules installed and tested

H. Klingbeil, P. Hülsmann

Bunch form affected by space charge and beam loading: compensation measures (adjustment of rf phases,….)

Heavy-ion intensities and beam loss in SIS-18

SIS-18 injection energy: 11.4 MeV/u (β=0.15)

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

Space charge tune shift:

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

Expected space charge limit: $\Delta Q_y^{sc} \approx -0.5$

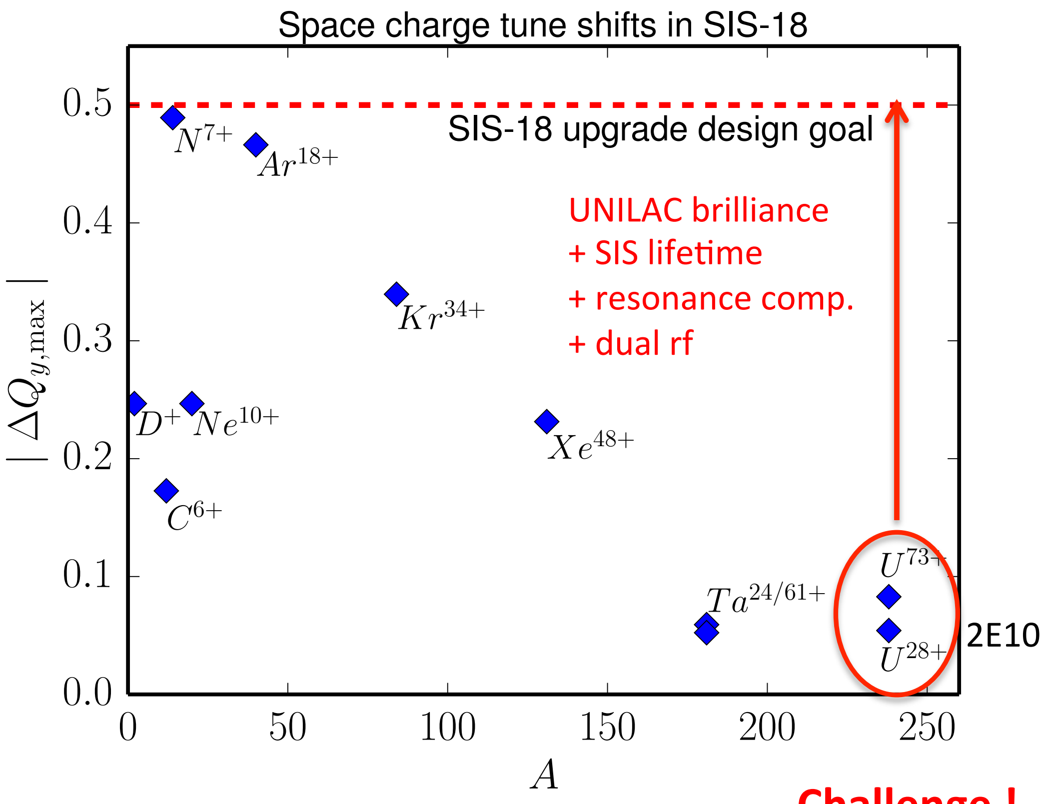
Electron stripping is a dominant loss mechanism for intermediate charge state ions at low energies:

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

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

Estimated beam loss due to stripping in SIS-18 for FAIR: 30-40 %

SIS-18: Present performance



Challenge !

SIS-18 upgrade

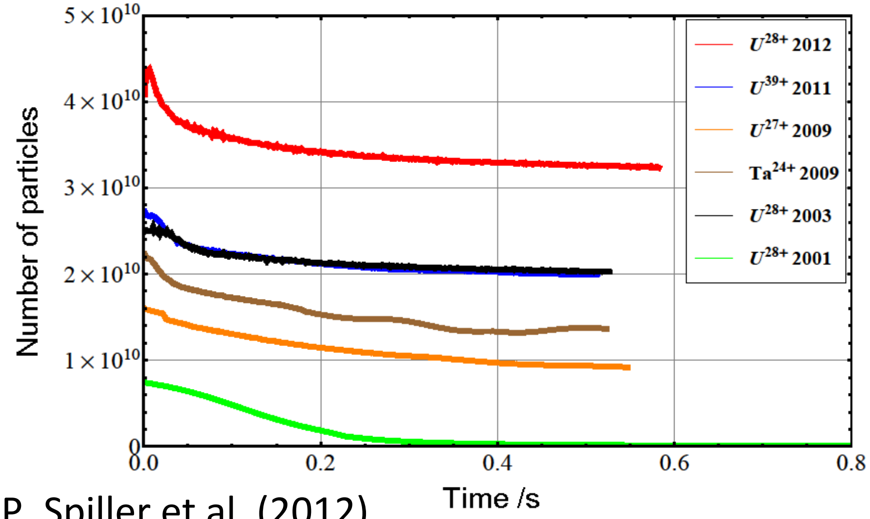
Control of the dynamic vacuum pressure

Dynamic pressure:

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

Desorption coefficient:

$$\eta = \frac{\#\ \text{desorbed molecules}}{\#\ \text{incident ions}} \propto \left(\frac{dE}{dx}\right)^2$$



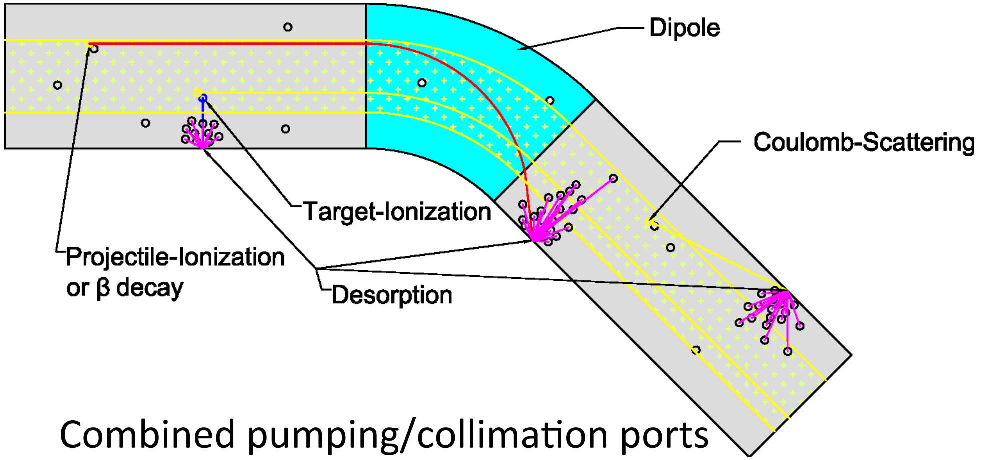
P. Spiller et al. (2012)

Challenge: Further increase of intensities for heavy ions by a factor 10 needed.

Beam loss mechanisms:

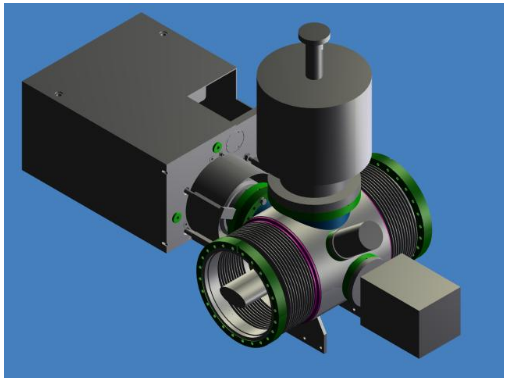
U^{28+} -> U^{29+} (stripping)

U^{73+} -> U^{72+} (capture)



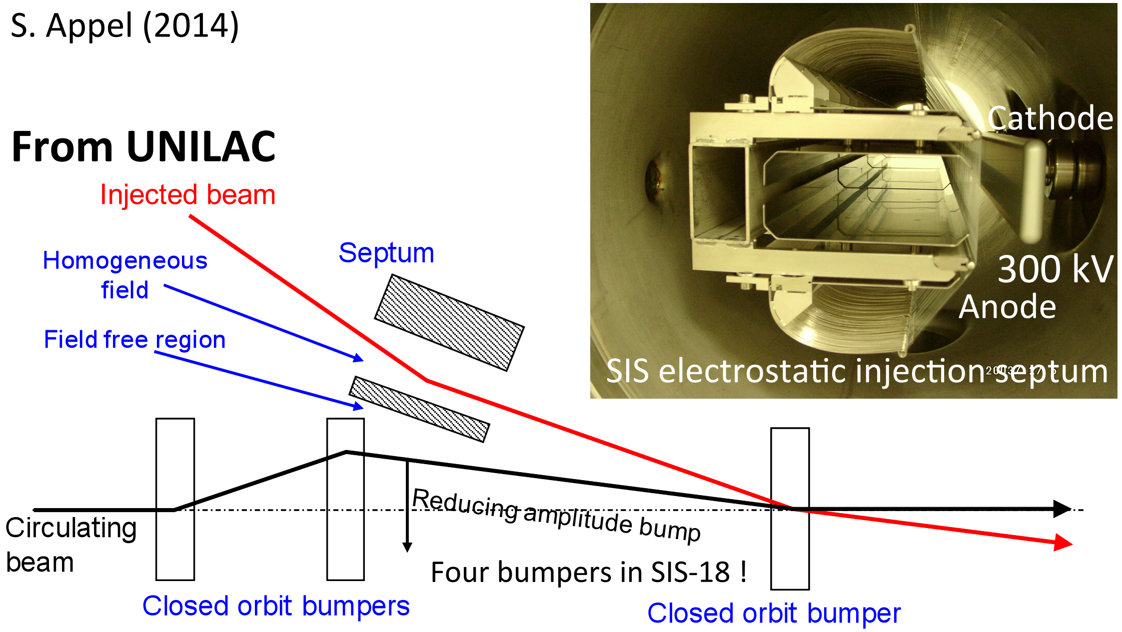
Combined pumping/collimation ports behind every dipole group.

NEG coated vacuum chambers



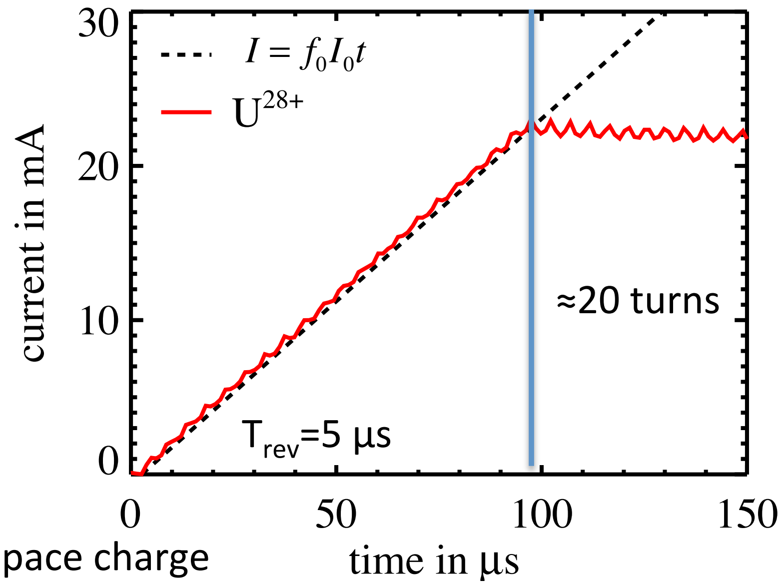
SIS-18 multi-turn injection (MTI) from the UNILAC

S. Appel (2014)

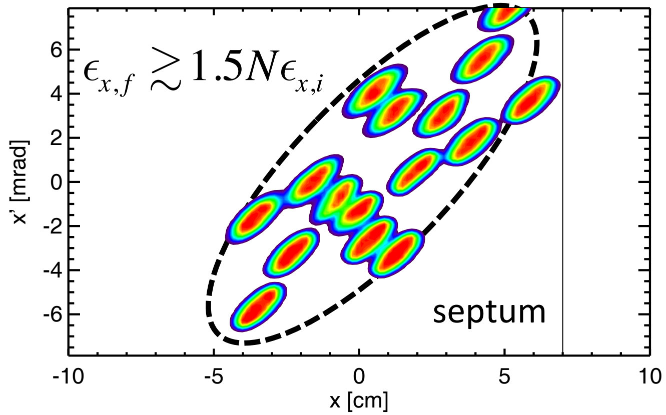


SIS electrostatic injection septum

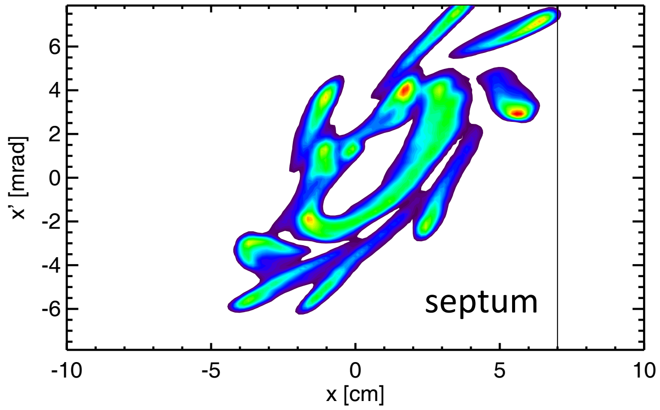
Measured MTI performance in SIS-18



Simulation: without space charge



Simulation: with space charge



Challenge:

- reduce initial loss during MTI to values below a few percent.

Space charge: Protons vs. Heavy Ions

FAIR: Operation with intermediate charge state ions (e.g. U^{28+}) to reduce space charge effects

Lifetime of intermediate charge state heavy-ions in rings

- Large cross sections for electron stripping/capture
- (stable) residual gas pressure of the order of 10^{-12} mbar required for sufficient lifetime
- Beam loss causes dynamic pressure instabilities.

-> at present beam intensities are limited by lifetime and not by collective effects !

Production of intermediate charge state ions

- Performance of ion sources compared to proton sources.
- Stripping efficiency of heavy-ions at low energies.
- Conventionally 'Liouvillian' multi-turn injection into rings.

-> 'space charge limited' intensities in rings more difficult to reach.

Other intensity effects in rings:

- Intra-beam scattering induced diffusion: $D \propto \frac{Z^4}{A^2}$

Collective effects in the FAIR rings

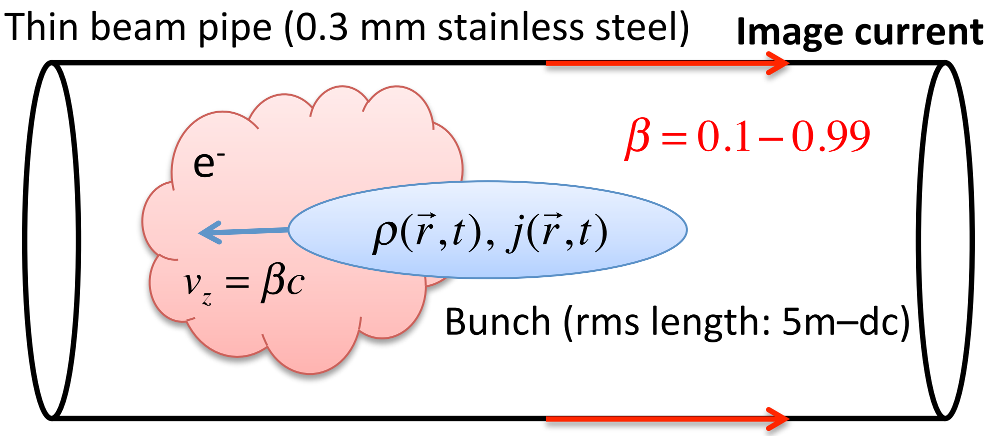
Incoherent space charge:

$\varepsilon_0 \nabla \cdot \vec{E} = \rho$ (in the rest system of the beam)

-> tune shift: $\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{4}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{1}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$

-> $\Delta Q^{sc} \lesssim 0.4$

-> beam loss and modification of coherent effects



Thin beam pipe (0.3 mm stainless steel)

Image current

$\beta = 0.1 - 0.99$

e^-

$\rho(\vec{r},t),\ j(\vec{r},t)$

$v_z = \beta c$

Bunch (rms length: 5m–dc)

Impedances:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \nabla \times \vec{B} = \mu_0 \vec{j} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$ (laboratory system)

-> image currents in the beam pipe

-> magnetic/resistive materials: ferrite, magnetic alloy

-> coherent instabilities and feedback requirements

Intrabeam scattering:

-> Laser cooling in SIS-100

Secondary particles:

electron clouds created by residual gas ionization and SEY.

-> trapping of electron during slow extraction, two-stream instability.

In the FAIR synchrotrons SIS-18 and SIS-100 different incoherent/coherent effects occur simultaneously.

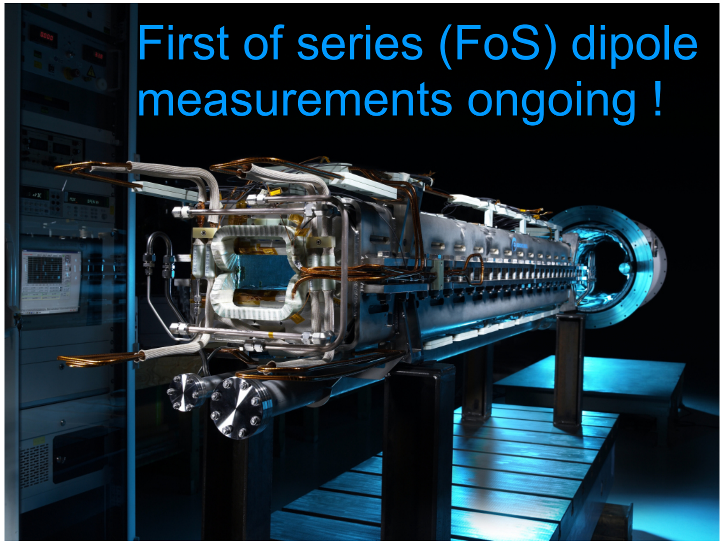
Beam loss in SIS-100 has be limited below 5 % (injection energy) and 1-2 % (extraction energy)

-> Computer modeling in combination with dedicated experiments (model validation) is essential.

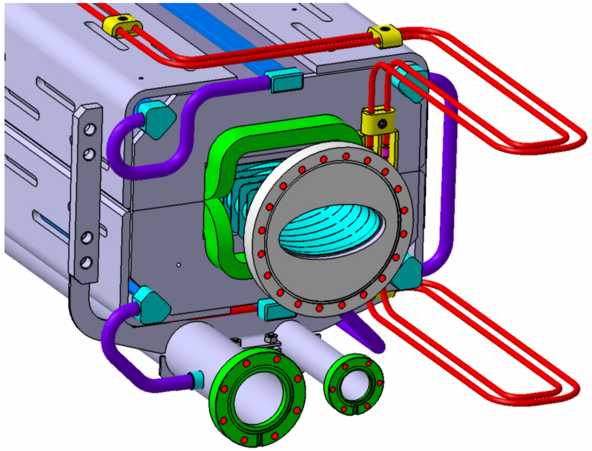
SIS-100 dipole magnets and field quality

FoS dipole from Babcock Noell GmbH

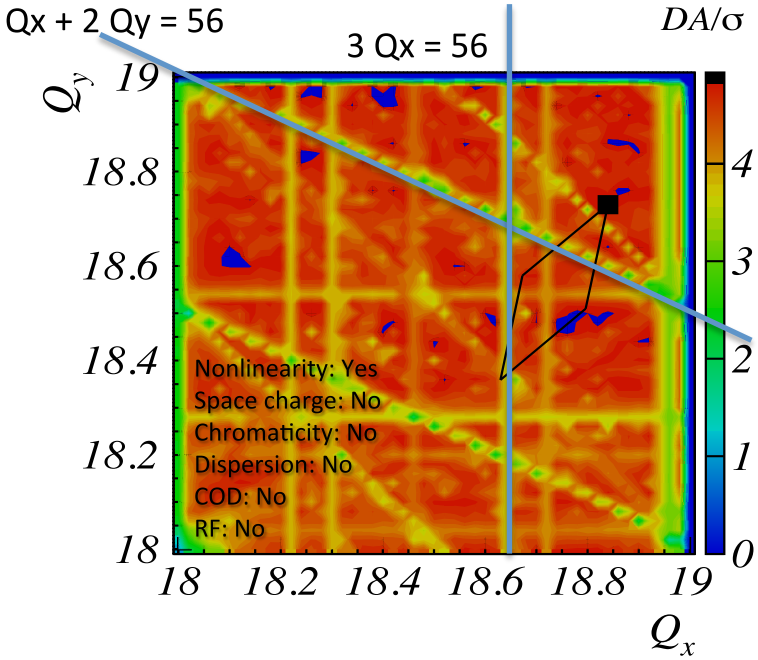
Superconducting magnet: 4 T/s, B_{max}= 1.9 T


First of series (FoS) dipole measurements ongoing !

Dipole magnet with elliptical beam pipe



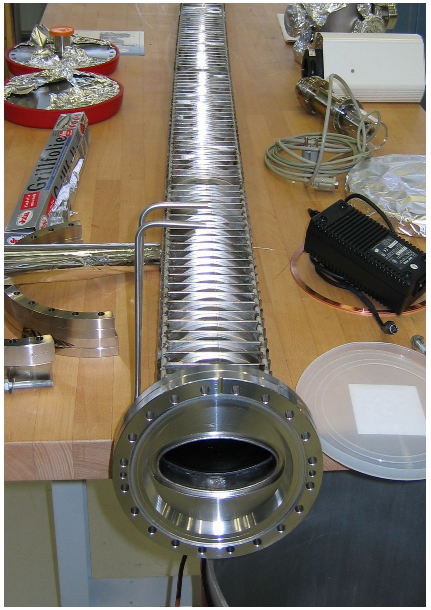
G.Franchetti (2011)



High intensity challenges for SIS-100:

- Long time scales up to 10^6 turns (1 s) with large space charge
- Bunch compression: Space charge tune shift of ΔQ_{sc}=-1
- 'Thick' medium energy beams (2/3 filling factor)
- Resonance compensation and working point for < 5 % loss.

SIS-100 ‘thin’ stainless steel beam pipe



Main functions (in SIS-100):

- To enclose the vacuum (1E-12 mbar)

- Active pumping (< 20 K)

- Shielding of beam induced EM fields (good conductor needed)

Problem:

- Eddy currents: pipe heating and magnetic field errors (bad conductor needed)

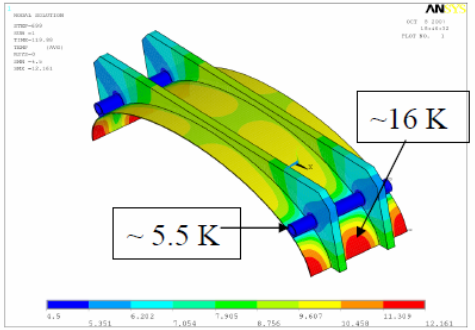
SIS-100 solution:

thin (0.3 mm) stainless steel pipe with attached cooling pipes

- still mechanically robust (with supporting rips)

- tolerable eddy current heating (< 10 W/m) and magnetic field distortion

- sufficient shielding of beam induced EM fields for frequencies > 50 kHz



Temperature distribution with attached cooling tube

The thin beam pipe (plus the kicker+network) is the dominant impedance contribution in SIS-100.

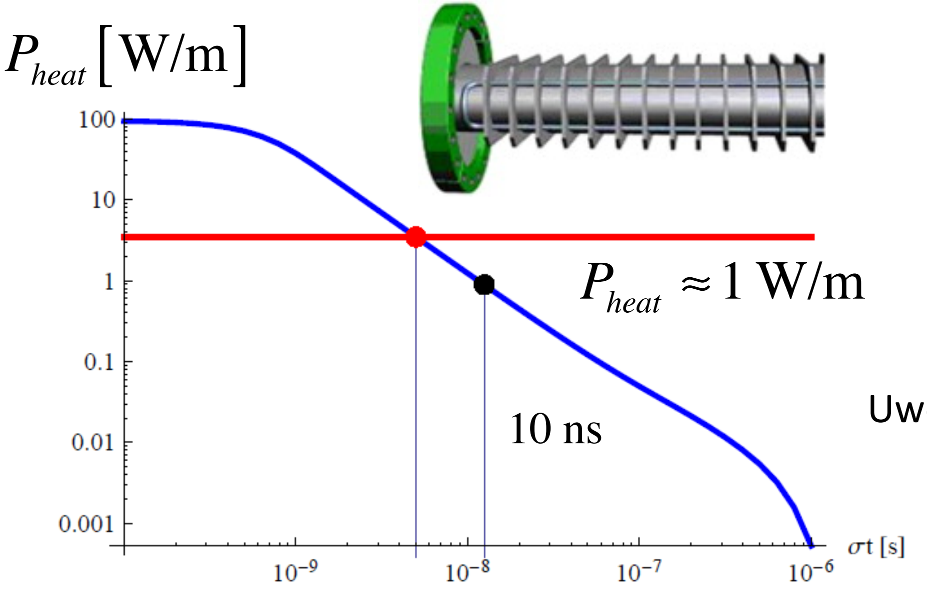
Heat load in SIS100: Longitudinal impedances

Proton bunch parameters

	SIS-100
Final energy	**29 GeV**
Protons per cycle	**2E13**
cycle rate (Hz)	**0.5**
#bunches	**1**
bunch length	**10 ns**

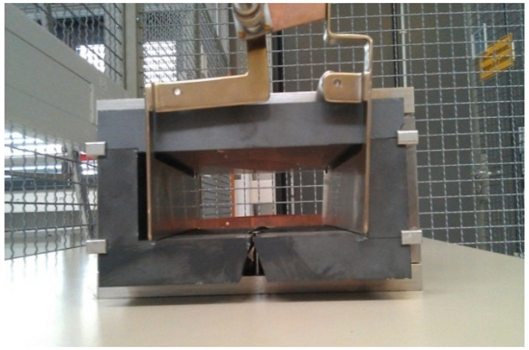
$$P_{heat} \propto \int \Re Z_{\parallel}(\omega) \cdot \mathrm{PowerSpectrum}(\omega)\,d\omega \quad \ll 25\ \mathrm{kW}\ (25\ \mathrm{W/m})$$

cryo plant



Uwe Niedermayer (2013)

proton bunch length

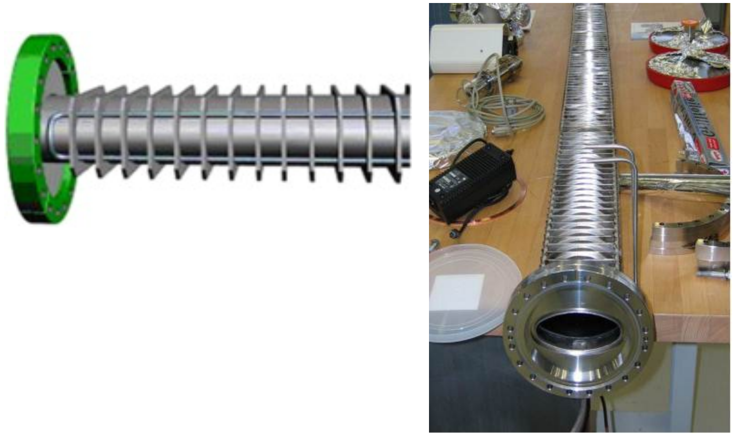


Tolerable heat load in a kicker module P_{max}=250 W (beam induced: 50 W).

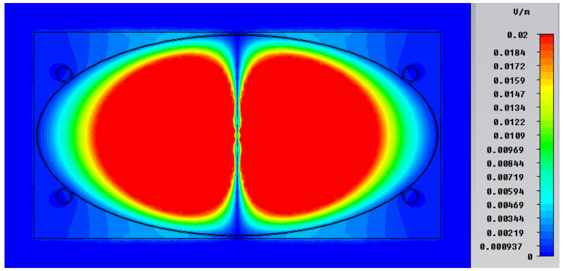
Transverse SIS-100 beam pipe impedance

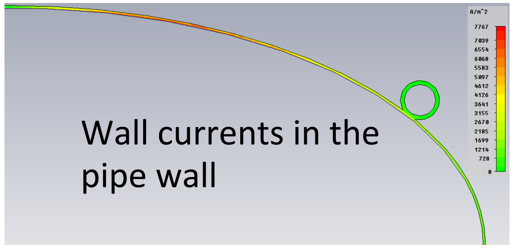
CST® EM Studio + frequency domain solvers

SIS-100 thin (**0.3 mm**) stainless steel beam pipewith cooling tubes attached.



Longitudinal electric field in the SIS100 pipe structure resulting from a dipolar excitation (300 kHz).

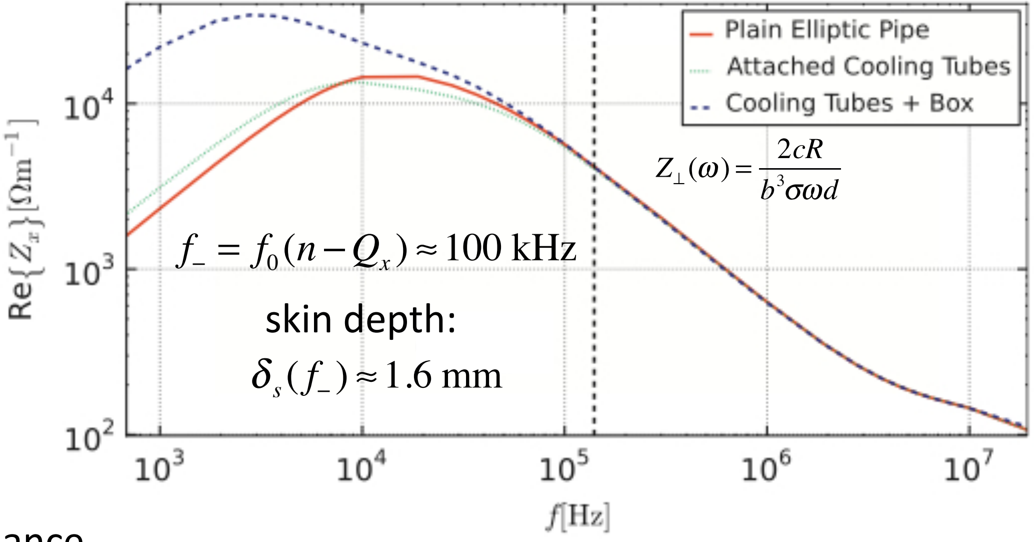




Wall currents in the pipe wall

U. Niedermayer, O. Boine-F., *Analytical and numerical calculations of resistive wall impedances for thin beam pipe structures at low frequencies*, NIM A 2012

Transverse impedance (horizontal)



$$Z_\perp(\omega) = \frac{2cR}{b^3\sigma\omega d}$$

$$f_- = f_0(n - Q_x) \approx 100\ \mathrm{kHz}$$

skin depth:

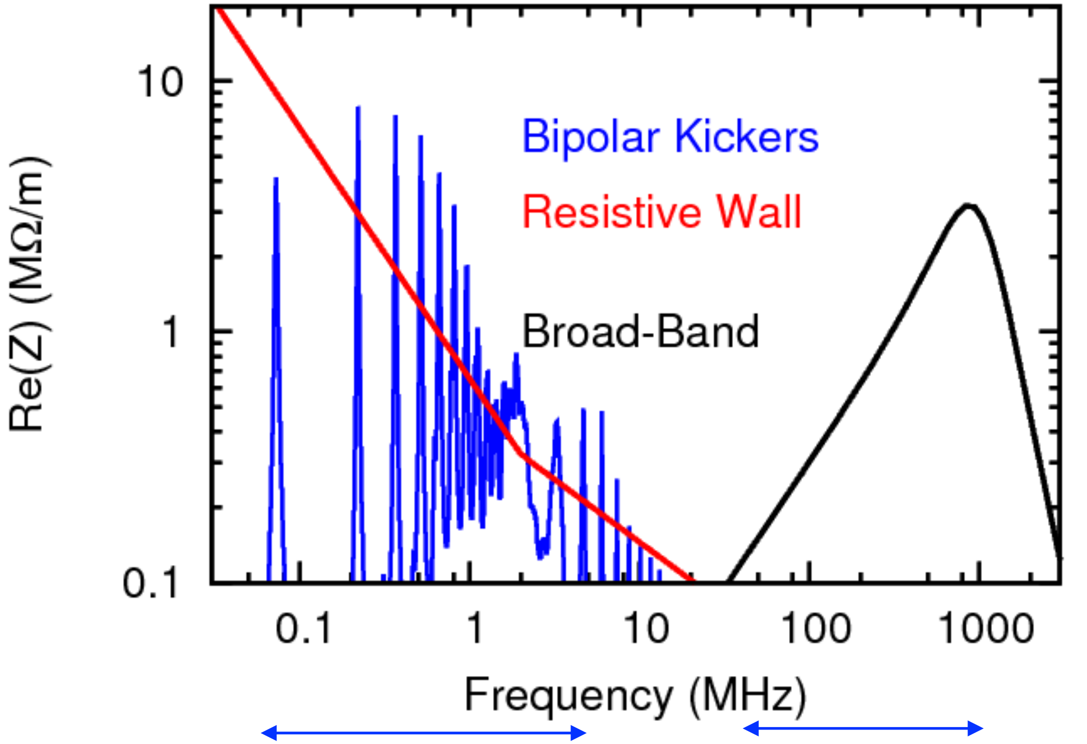
$$\delta_s(f_-) \approx 1.6\ \mathrm{mm}$$

- In the frequency range of interest outside structures do not contribute to the impedance.
- **The thin resistive beam pipe is a major source for the expected head-tail instabilities in SIS-100**.

see Contribution (Saturday) + Poster by Uwe Niedermayer

Impedances (transverse) in SIS-100

U. Niedermayer (2013)



Head-Tail instabilities
Cures:
- Feedback System
- Octupoles

High-Freq Break-Up
Cure:
Landau Damping
(ξ and δ_p)

V. Kornilov (2013)

Kicker + Pulse Forming Network (PFN)

Broad-band impedance in SIS-100:

- Distributed collimation system
- Halo collimation system
- .....

Work on the BB impedance model still ongoing.
-> Important for proton operation !

Conclusions

- The FAIR accelerator facility at GSI is presently under construction (estimated start of operation in 2018).

- Major accelerator components have been ordered or are being tested at GSI or at the FAIR partner labs.

- Besides the various challenges related to the technical project level (civil construction, specification, procurement, project control, …..) a number of accelerator physics R&D issues for high current operation with protons and heavy ion beams remain.

Important examples are:

- Control of space charge induced beam loss:
  - Magnet sorting and resonance compensation concepts

- Control of collective effects:
  - Estimation and if possible reduction of 'unconventional' impedances (beam pipe, MA loaded cavities, bi-polar ferrite kickers + networks, collimators)
  - Longitudinal and transverse digital feedback systems to damp coherent oscillations and preserve the beam quality.

- Control of the dynamic vacuum and the associated beam life time (heavy-ions):
  - Distributed system of collimator/pumping systems.
  - Cold pipe.