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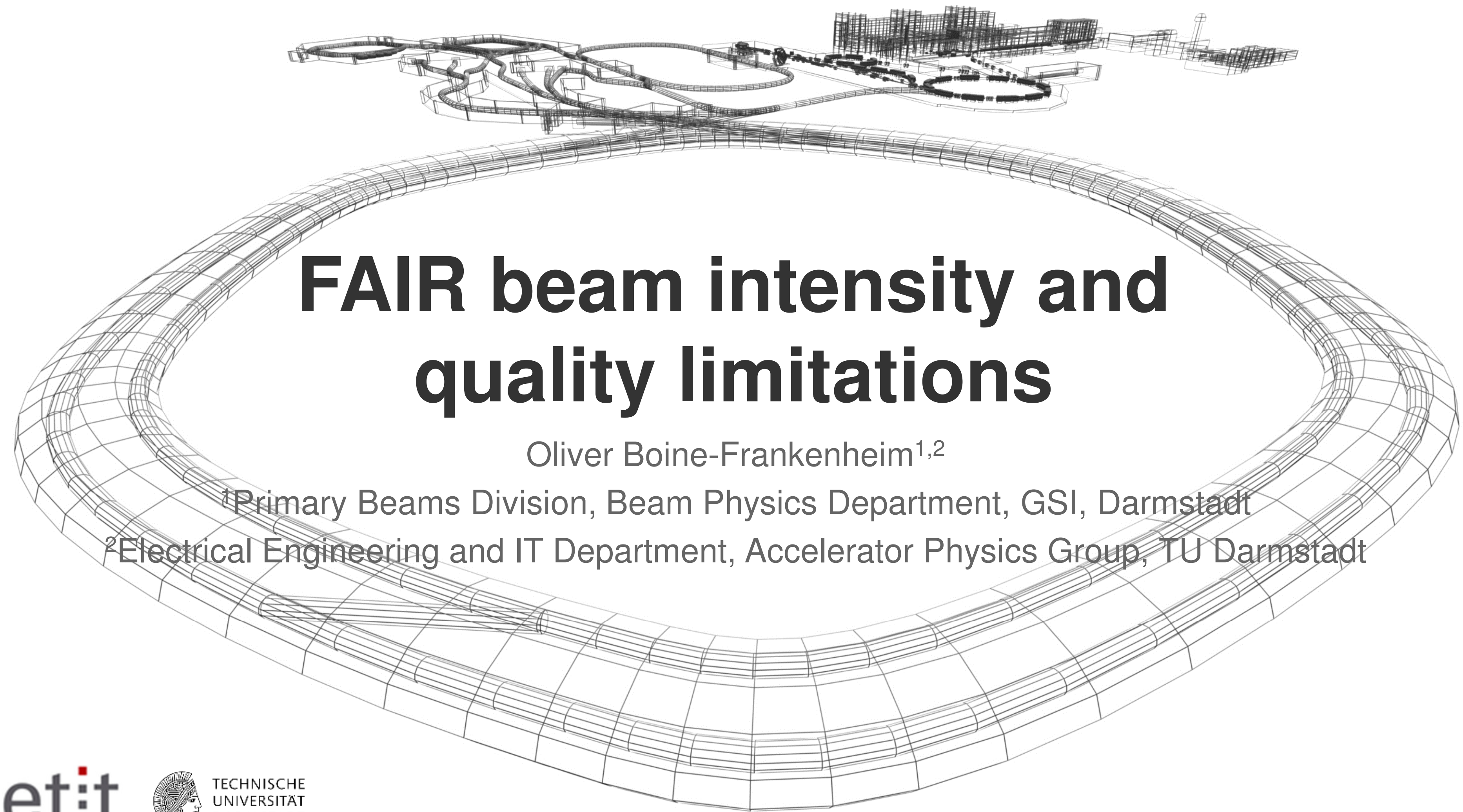

FAIR beam intensity and quality limitations

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TECHNISCHE UNIVERSITÄT DARMSTADT

Contents

- Beam intensity and quality limitations (simplified)
  - Space charge, beam instabilities, beam lifetime, intra-beam scattering
- Extraction to targets: Slow, Fast with bunch compression
- Future trends
- Other contributions related to the FAIR beam parameters:
  - **Today:** Halo collimation, Beam induced activation (Ivan Strasik)
  - **Tomorrow:** Beam parameters on targets (Vladimir Kornilov)

Glossary (ring accelerators)

Resonances: $mQ_x + nQ_y = Sp$
(that's why you better order a Linac :-)

Lifetime and (dynamic) pressure:

$$\tau^{-1} = \beta_0 c \sigma_{loss} \frac{P(N,t)}{k_B T} \quad \text{(beam lifetime)}$$

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

(Dynamic) aperture:

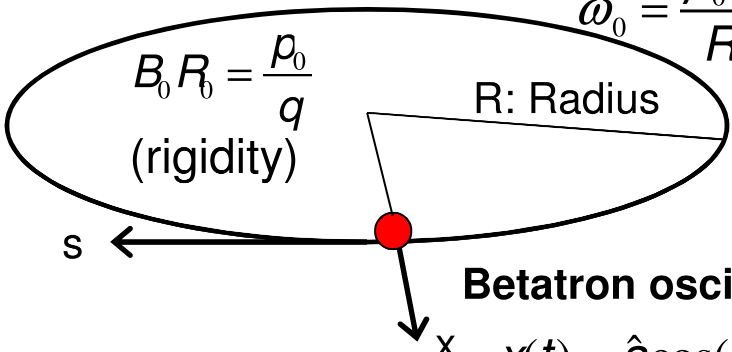
- Symplectic motion for hadrons
- Unstable chaotic orbits for $\hat{a} > \mathrm{DA}$

Emittance, Bunch area (Liouville: should be conserved)

Emittances: $\langle \varepsilon_x \rangle = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$ [mm-mrad]

Bunch area: $A_B = \Delta E \tau$ [eVs]

$\omega_0 = \frac{\beta_0 c}{R}$ revolution frequency



Betatron oscillations:

$x(t) = \hat{a}\cos(Q_x \omega_0 t + \varphi_0)$

Q_x : Betatron "tune"

Beam parameters (at extraction):

- # ions per cycle
- Emittances
- Bunch length, dp/p (bunch area)

Machine parameters:

- apertures
- bucket areas
- cycle rate
- cooling rates
- ......

Collective effects in the FAIR rings

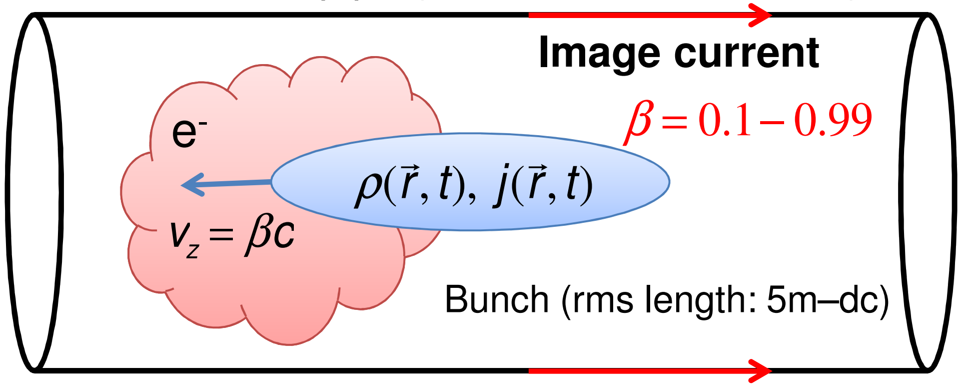
Incoherent space charge:

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

tune shift: $\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{4}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{1}{1+\sqrt{\varepsilon_y/\varepsilon_x}} \lesssim 0.3-0.5$

-> beam intensity and emittance limits

Thin beam pipe (0.3 mm stainless steel)



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: heat load
- magnetic/resistive materials: ferrite, magnetic alloy

-> beam intensity limits and feedback requirements

Intrabeam scattering:

- e.g. laser cooling in SIS-100

-> emittances and momentum spread

Secondary particles:

electron clouds created by residual gas ionization and wall emission.

-> beam intensity limits (slow extraction)

In the FAIR synchrotrons SIS-18 and SIS-100 different collective 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.

‘Incoherent space charge limit’

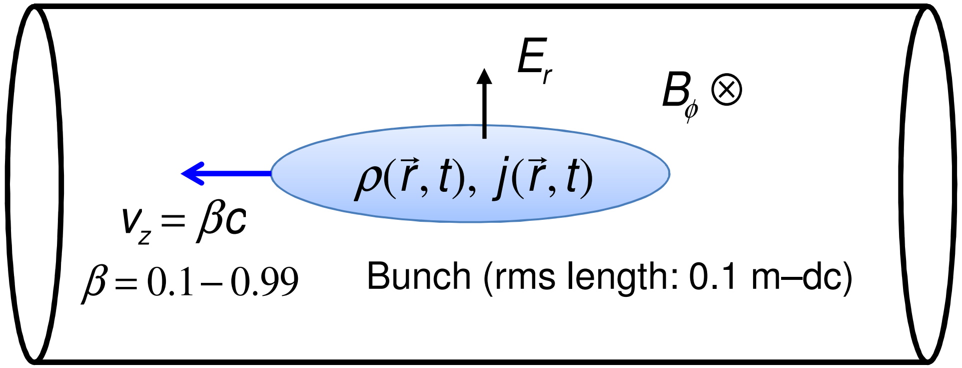
Incoherent space charge:

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

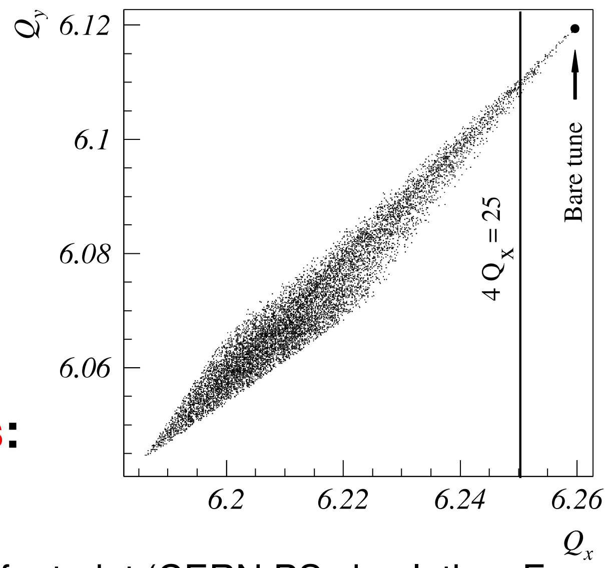
-> tune shift: $\Delta Q_y^{sc} \propto -\frac{q^2}{m} \frac{N}{B_f} \frac{4}{\varepsilon \beta_0^2 \gamma_0^3}$

-> tune spread: $Q_x(\hat{a}_x, \hat{a}_y) = Q_{0,x} - \Delta Q_x^{sc}(\hat{a}_x, \hat{a}_y)$

-> intensity limit: $|\Delta Q^{sc}| \lesssim 0.1 - 0.5$



The (incoherent) transverse space charge force is the main intensity limiting effect in the LHC injector chain and in the FAIR synchrotrons



Tune footprint (CERN PS simulation, Franchetti 2003)

Estimated ‘limits’ in SIS100 with dual rf buckets:

U^{28+}: 6-7 x 10^{11} (4-5 x 10^{11}/s) p: 4 x 10^{13}

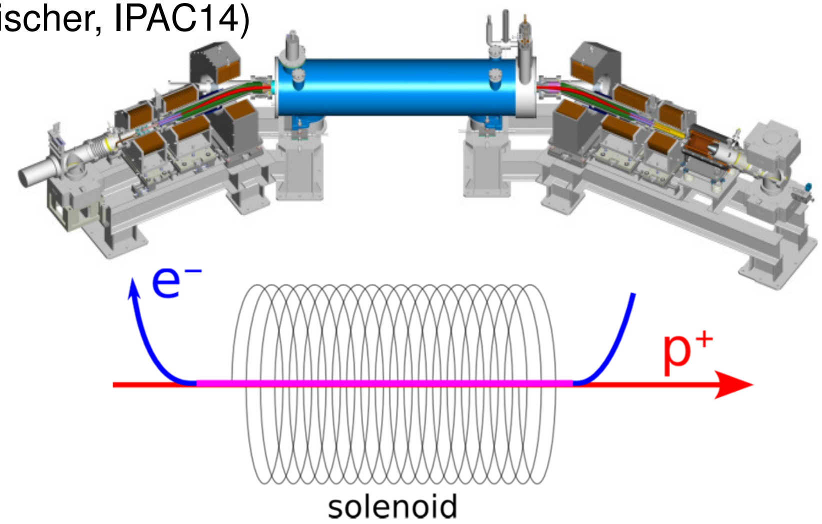
Compensation ? M. Aiba et al., PAC 2007

BMBF project: Compensation of space charge effects in hadron bunches for low and high energies

Tune shift induced by a counter-propagating electron beam (electron-lens):

$$\Delta Q^e \propto \frac{q}{m}\frac{LI_e}{\beta_e}\frac{1+\beta_e^2}{\varepsilon_h \beta_h^2 \gamma_h}$$

E-lens in RHIC (Fischer, IPAC14)



Electron lens to compensate (partially) for the beam-beam tune shift

Questions to be addressed:

- Co-moving vs. counter-propagating beams
- Tune spread compensation !
- Required number of compensators
- Effect of the induced error resonances
- Transport of low-β electron bunches

Can space charge (at least partially) be compensated ?

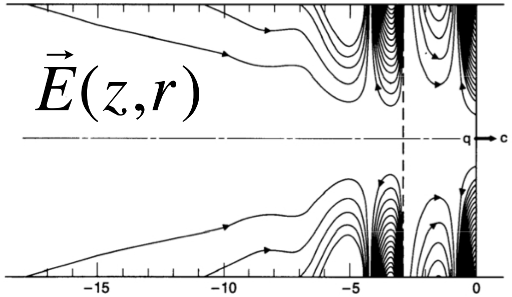
Simulations and dedicated experiments needed !

Goal: Detailed compensations studies for FAIR and CERN.

Beam instabilities and impedances

Thin (0.3 mm) beam pipe

Electric field of a moving charge in a beam pipe



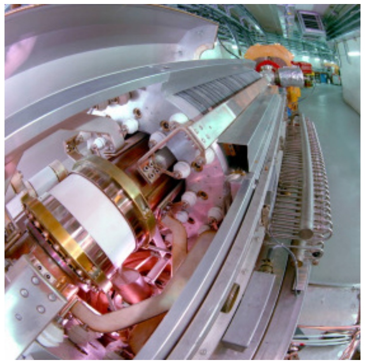
Longitudinal impedance:

$$Z_{\parallel}(\omega) = -\frac{1}{\hat{I}} \int_{z=0}^{L} E_z(z) e^{-i\omega z/c}\, dz \quad [\Omega]$$

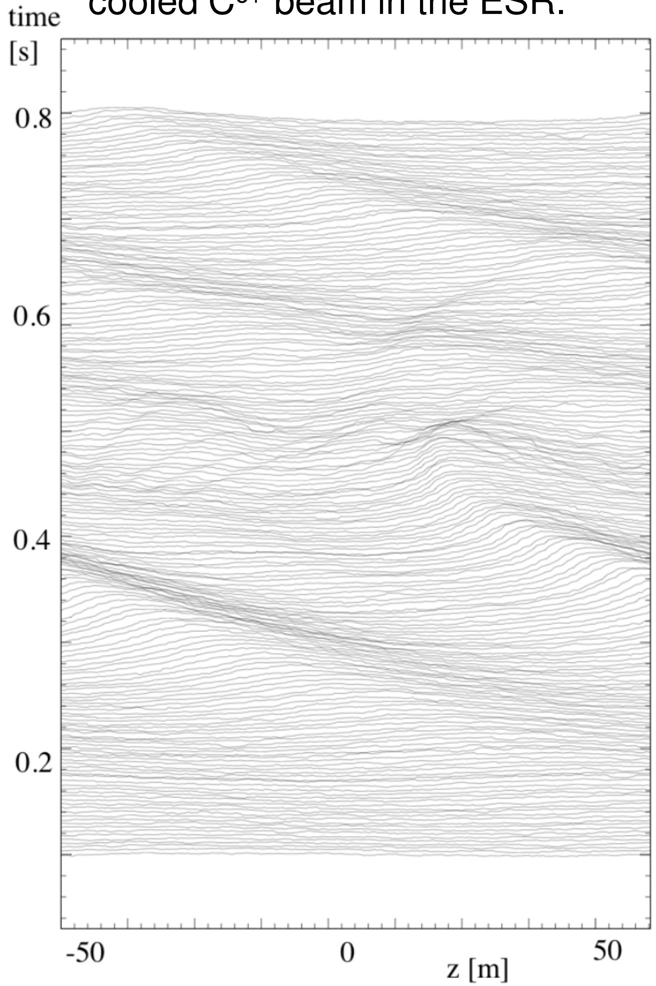
$$P_{heat} \propto \int \Re Z_{\parallel}(\omega) \cdot \lambda(\omega) \mathrm{d}\omega$$

Heat load is a possible limitationfor the proton bunch length (approx. 1-2 W/m for design parameters).

rf cavity



Observed self-bunching in an electron cooled C^{6+} beam in the ESR.



Boine-F., Hofmann, Rumolo, Phys. Rev. Lett. 1999

'Keil-Schnell' criterion:

$$\left|\frac{Z_n}{n}\right| < \frac{mc^2 \beta^2 \gamma |\eta| (\Delta p / p_0)^2}{q I_0}$$

Protons vs. heavy ions: Intensity limits

Primary beams: Intermediate charge state ions (like U^{28+}) to reduce space charge + light ions + protons

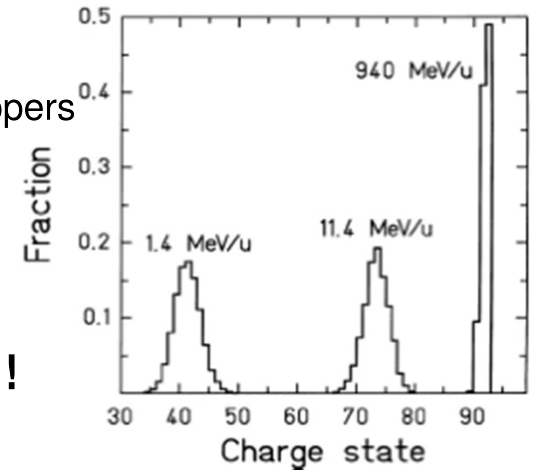
Beam intensity and quality limitations for protons (and light ions):
- Space charge at SIS18/100 injection energies !
- Transitions crossing in SIS100 (protons).
- Beam instabilities !

Intensity limitations for intermediate charge state heavy-ions in SIS18/100:
- Beam lifetime: Large cross sections for electron stripping/capture
  -> residual gas pressure of the order of 10^{-12} mbar required for sufficient lifetime
- Uncontrolled beam loss causes dynamic pressure instabilities.

Heavy-ions (continued):
- Injector: Current/emittances
  - Ion sources
  - Stripping efficiency of heavy-ions at low energies.
- Efficiency of the multi-turn injection !

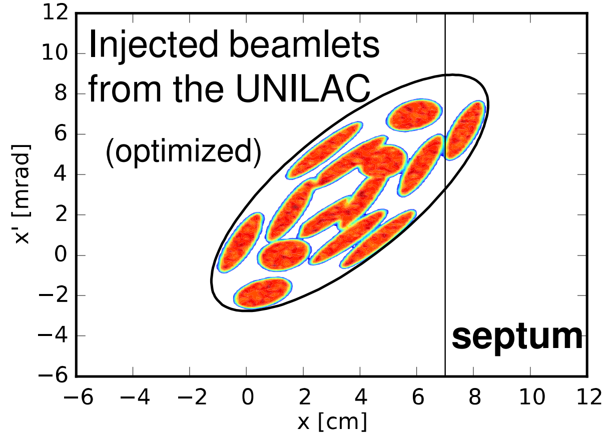
-> at present HI intensities are not limited by space charge !

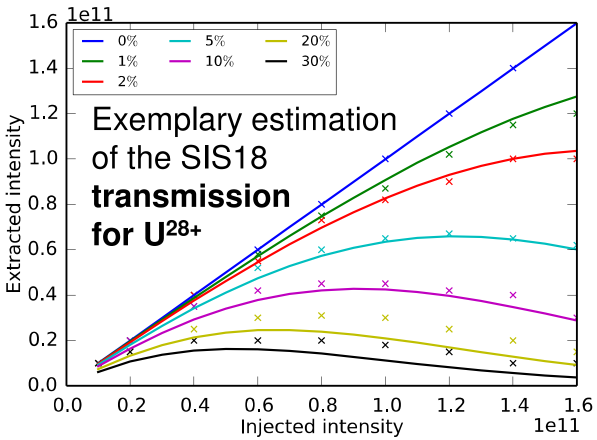
Charge distributions at different Energies for 238U behind foil strippers (Ch. Scheidenberger et al.)

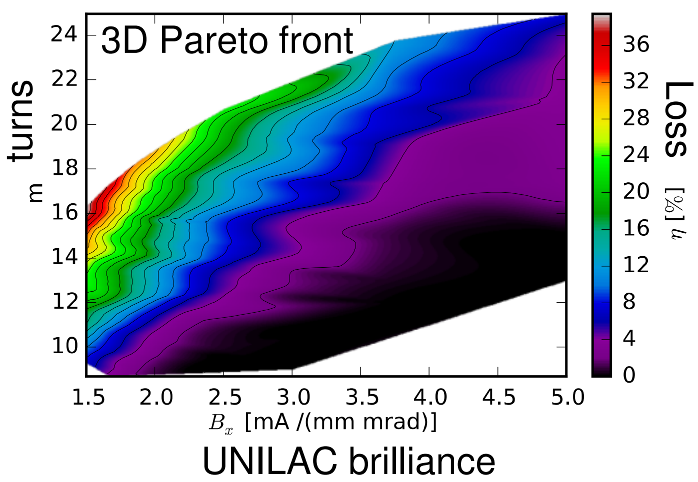


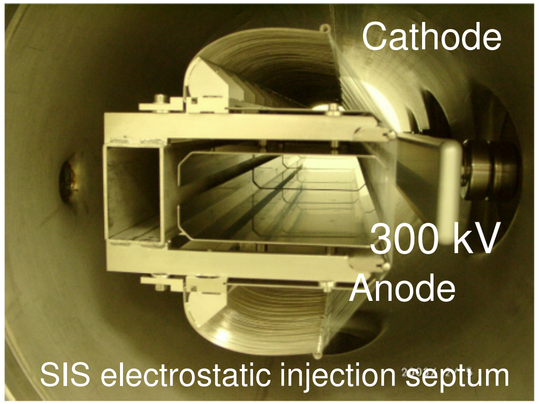
SIS18 multi-turn injection (MTI) efficiency

- The UNILAC->SIS18 multi-turn injection is one of the main “bottlenecks” for FAIR.
- **Design goal:** the UNILAC should provide the current and emittance (brilliance) to fill the (horizontal) SIS aperture to the space charge limit.
- Intermediate charge state heavy-ions: Losses well below 10 % to avoid vacuum + lifetime degradation.





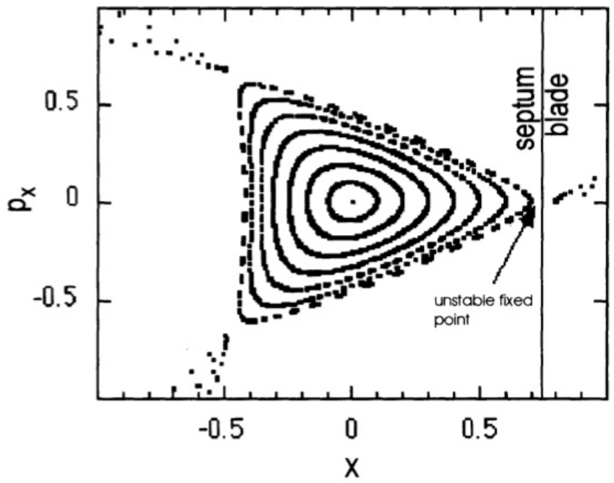




Goal: GA optimization of MTI and transmission.

S. Appel, F. Petrov, under preparation

Slow extraction

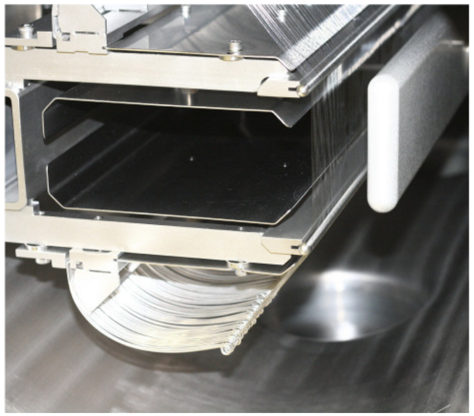


Limitations of the extracted beam intensity:

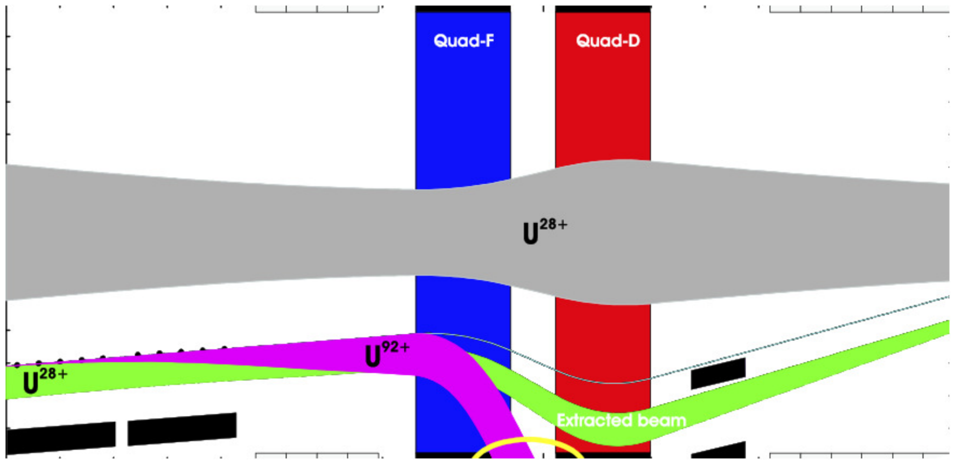
- Loss at septum (activation, desorption for HI)
- Beam instabilities. Cures: rf bunching dp/p blow up.

Extracted emittance determined by dp/p and separatrix.

Questions: Optimum extraction length, spill structure, dp/p ?

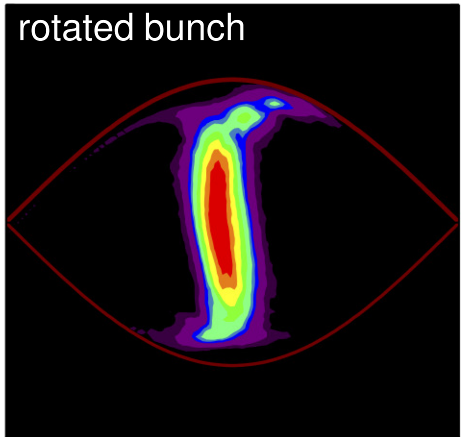


Septum wires: Ø 0.025 mm (W-Re alloy)
wires are mounted under tension



Optics and beam envelopes for heavy-ion slow extraction

Fast extraction to targets: Bunch compression



$$\frac{\Delta p}{p} = \pm 10^{-2}$$

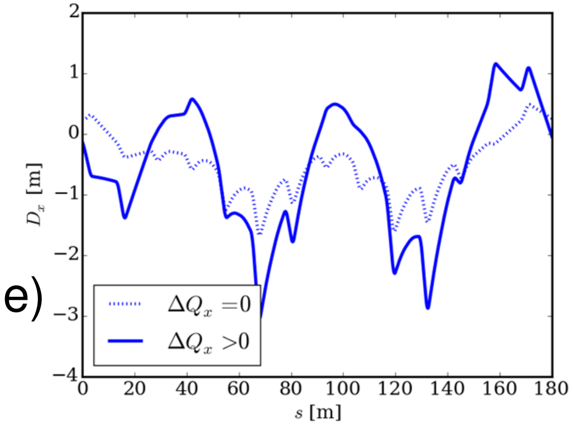
$$\tau = \pm 25\ \text{ns}$$

Bunch length limited through
SIS18/100 momentum acceptance !

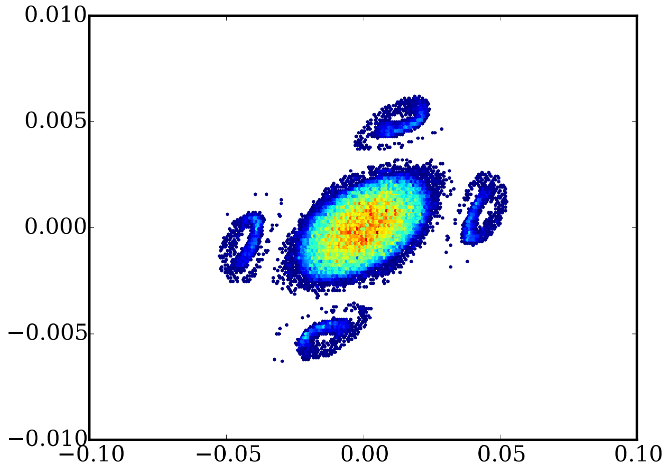
$$\tau \approx \frac{1}{\omega_s} \frac{\Delta p}{p}$$

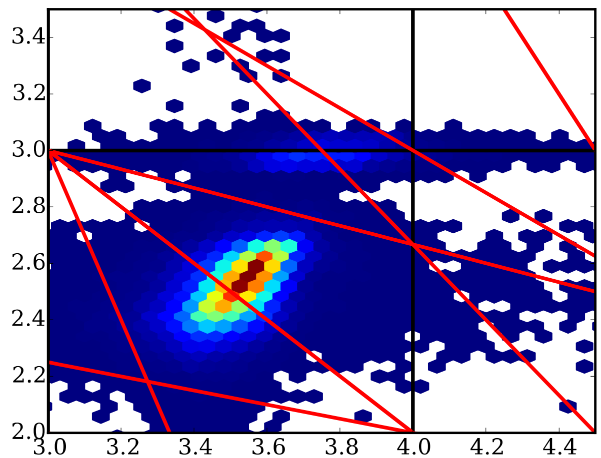
$$\Delta D_x \sim \frac{R}{Q_x^3} \Delta Q_x$$

(Dispersion vs. space charge)



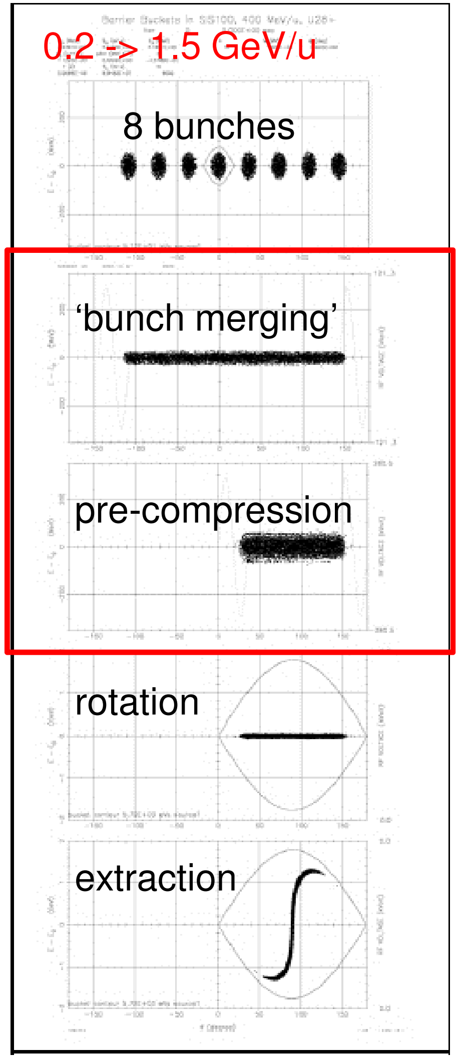
For the FAIR design parameter:
Bunch emittance increases due to transverse space charge.





Fast barrier pre-compression in SIS-100

Single bunch formation



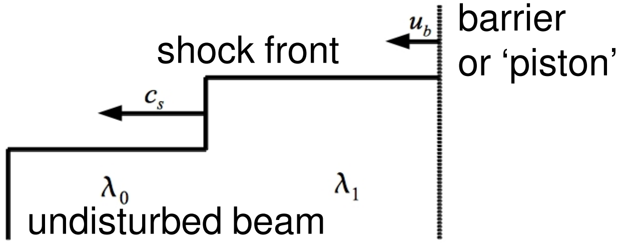
Non-adiabatic barrier rf phase ramp:

T=100 ms (ramp time) T_{s0} > 100 ms ('synchrotron period')

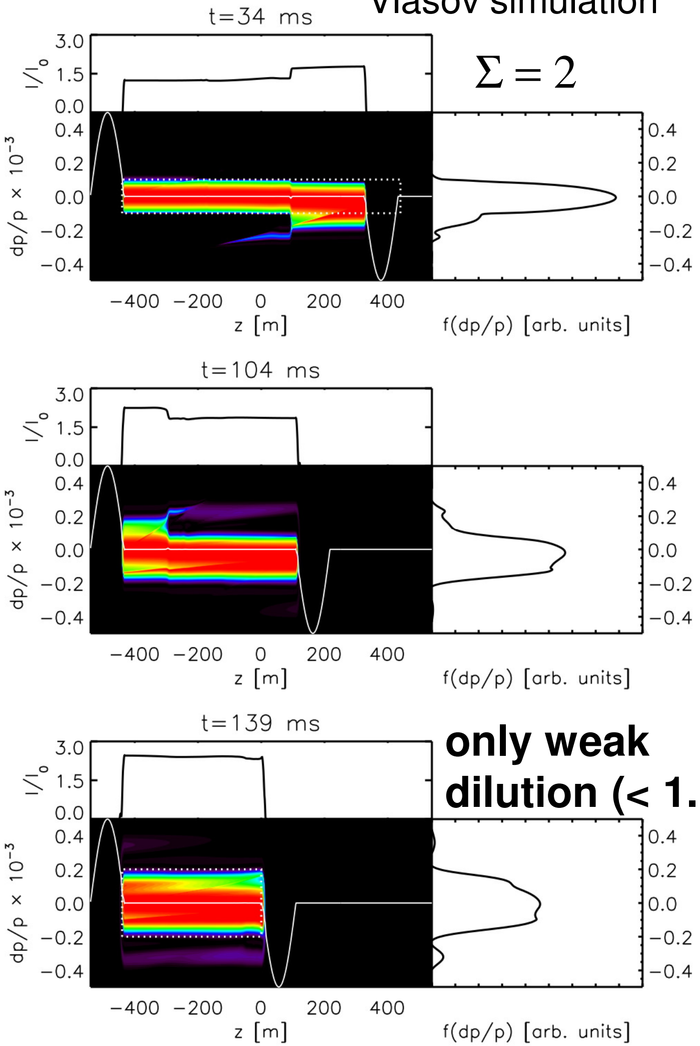
u_b (barrier velocity) v_{th} ('thermal velocity')

$$v_{th} = -\eta_0 \beta_0 c \frac{\Delta p}{p}$$

Shock compression:



Space charge helps !



only weak dilution (< 1.1)

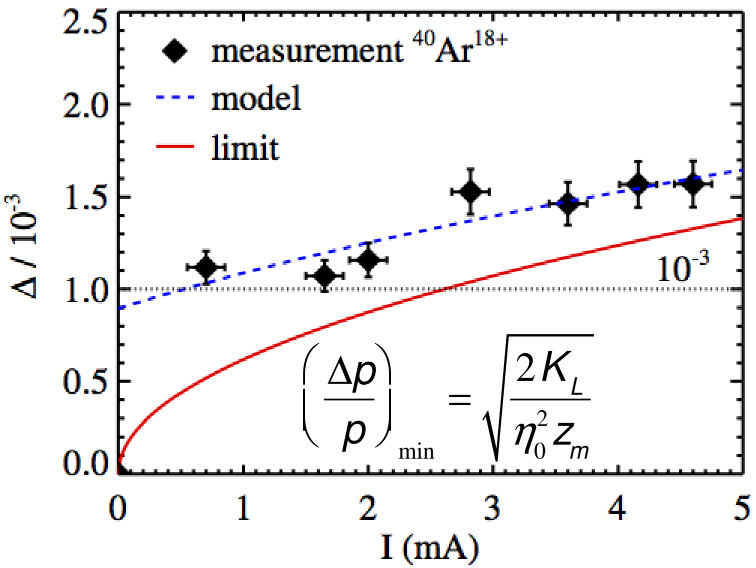
Conclusions

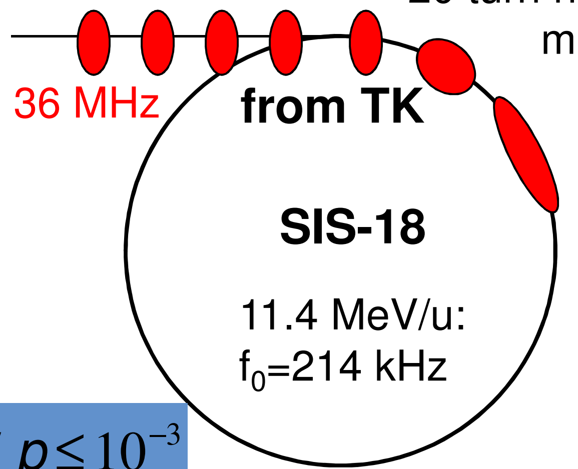
- Basic ring accelerator terminology
- Key beam intensity and quality limitations:
  - Apertures and bucket areas (all species)
  - Space charge and impedances (Protons and fully-stripped ions)
  - Intermediate charge state HI: Multi-turn injection and transmission
  - Activation: see next talk by I. Strasik
- Future options: sc compansation, bb digital feedback, …..
- Extraction to targets (see also talk by V. Kornilov)
  - Slow extraction: ideal cycle length and time-structure ?
  - Fast extraction: ideal bunch length and emittances ?
- Set of reference parameter for key experiments !

Zusatzfolien

UNILAC/SIS-18 multi-turn injection: initial dp/p

Measured momentum spread for coasting beams in SIS-18





rf is off !

The micro-bunches debunch and form a 'coasting' beam within a few turns.

$\Delta p / p \leq 10^{-3}$

High UNILAC currents: Initial momentum spread in SIS-18 determined by longitudinal space charge !

S. Appel, et al. Phys. Rev. ST-AB (2012)

NuSTAR requirements

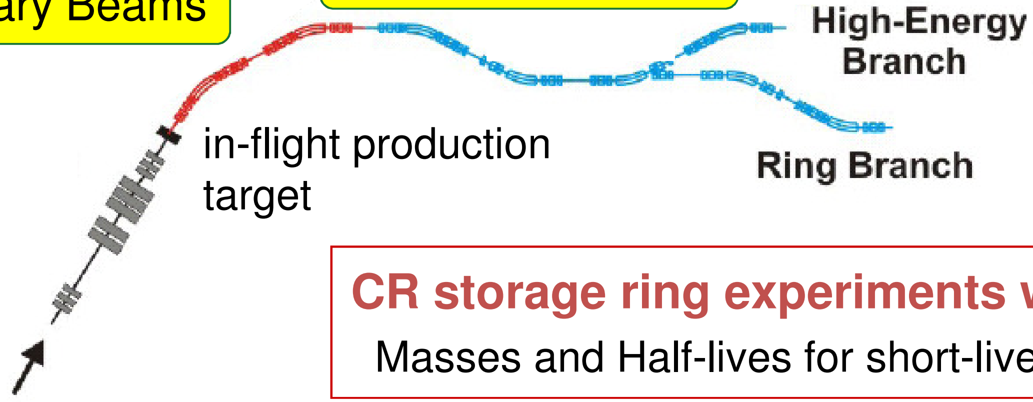
Super-FRS

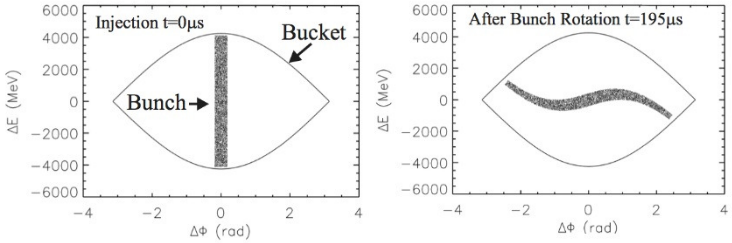
High energy branch: Fixed-target experiments

Primary Beams

Secondary Beams

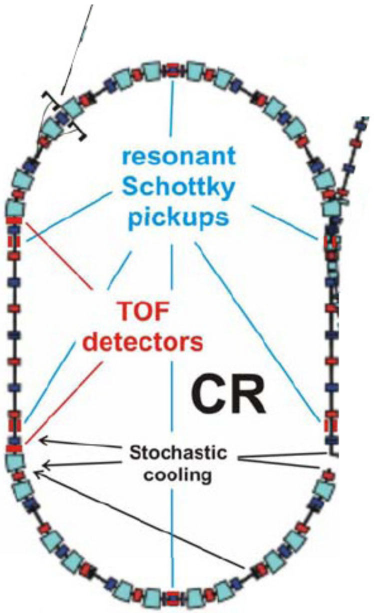
Bunch rotation in the CR: smaller momentum spread





CR storage ring experiments with RIBs:

Masses and Half-lives for short-lived ions



SIS 100

Beam parameter	
Reference primary ion	U^{28+}
Reference energy	1.5 GeV/u
# ions	5E11
Bunch length	50-100ns / 1-10 s
Rep. time	2 s

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

CDR/2001 -> 1E12/s

(NuPECC/2000 recommendation for the next generation in-flight radioactive beam facility)

- Cooling time: ≅ 1 s
- Isochronous mode: fast measurements

‘Space charge limit’

We presently assume that the maximum beam intensities in the FAIR SIS-18 and SIS-100 synchrotrons are ‘space charge limited’

High current working point: $(Q_x, Q_y) = (4.17, 3.29)$

Space charge tune spread:

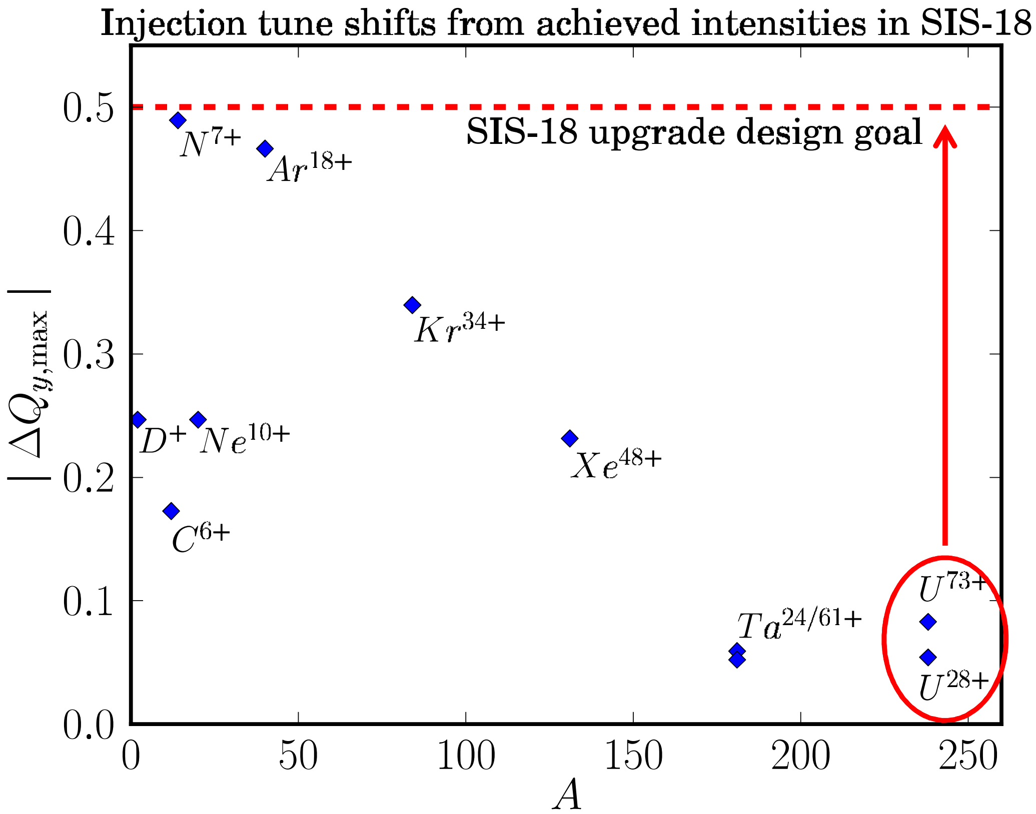
$$\Delta Q_y^{sc} \propto -\frac{Z^2}{A}\frac{N}{B_f}\frac{4}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{1}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$$

‘Space charge limit’: $\left|\Delta Q_y\right| \lesssim 0.5$

$B_f^{-1} = \frac{I_p}{I_0}$: bunching factor

$\varepsilon_{x,y}$: transverse emittances

N: number of particles in the ring



‘Cures’: flattened bunch profiles + resonance compensation

SIS-100 bucket areas and acceptances: U^{28+}

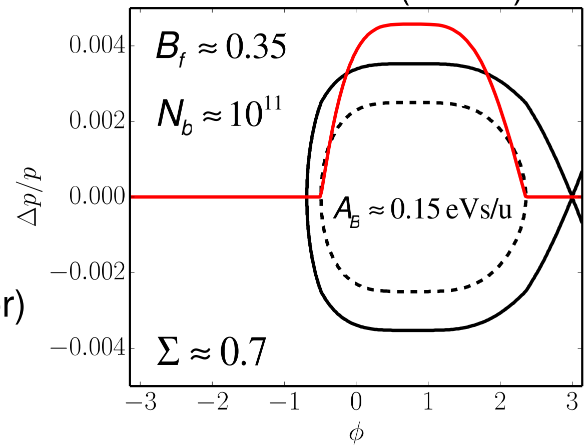
Voltage requirement:

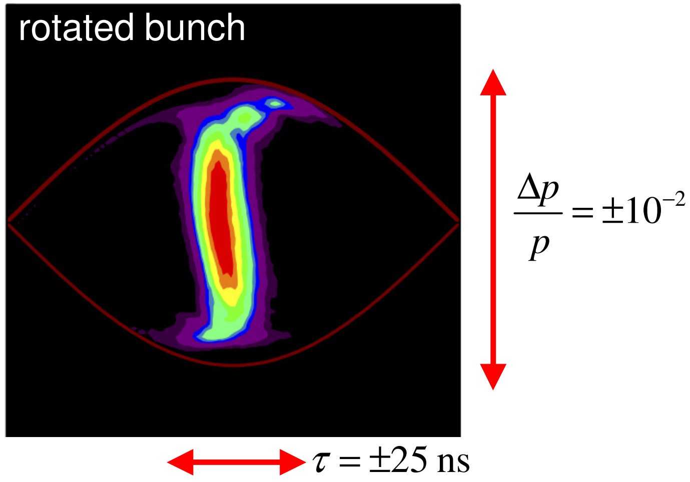
$$V(\sin\phi_s - a\sin\phi_2) = 2\pi R\rho\dot{B}$$

$$A_B = h\Delta E\tau$$ (bucket area)

$$\Sigma = \frac{1}{\frac{V_{rf}}{V_{sc}} - 1}$$ (space charge factor)

dual rf bucket (SIS18)

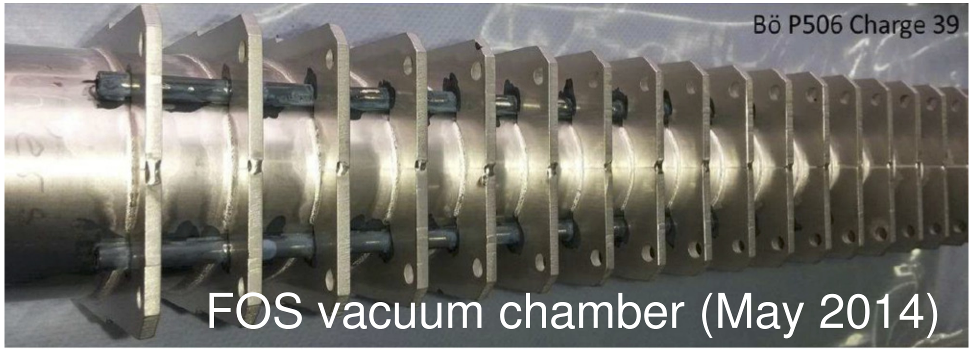


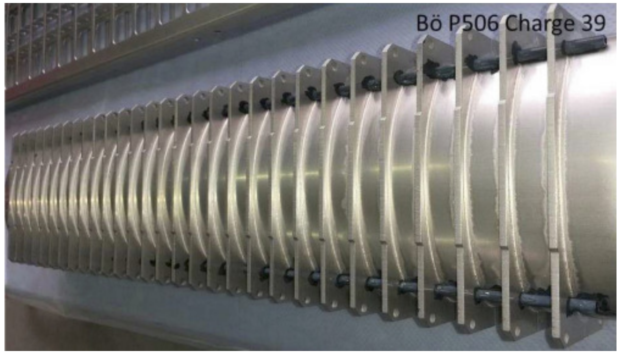


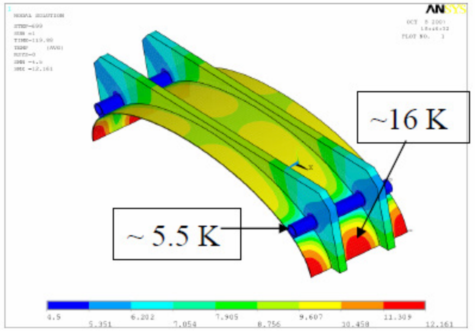
	SIS18 injection	SIS100 injection	SIS100 extraction
Bucket area eVs/u	**0.15 x 2 (10 T/s)**	**0.25 x 10 (3 T/s)**	**1.6 x 1**
Bunch area eVs/u	0.1 x 2	0.15 x 8 = 1.2	1.6 x 1
Space charge factor	**0.7**	**0.5**	< 0.1
Acceptance mm mrad	150/50	100/40	100/40
Emittances mm mrad	150/50	35/15	12/5
SC tune shift ΔQ_v	**-0.5**	**-0.3**	**-0.8**

Tolerable longitudinal dilution : 1.5 (SIS18), 1.3 (SIS100 with compression)

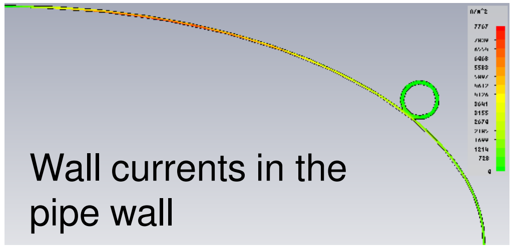
SIS100 beam pipe







Temperature distribution with attached cooling tube



Wall currents in the pipe wall

Special stainless steel (Böhler P506) for all dipole and quadrupole magnet chambers.

SIS100 beam pipe: thin (0.3 mm) stainless steel pipe with attached cooling pipes

- still mechanically robust (with supporting rips) for 10^{-12} mbar
- tolerable eddy current heating (< 10 W/m) and field distortion
- sufficient shielding of beam induced EM fields above 50 kHz
- active pumping (< 20 K wall temperature)

One of the most critical components in SIS100 !

Antiprotons: HESR and PANDA requirements

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

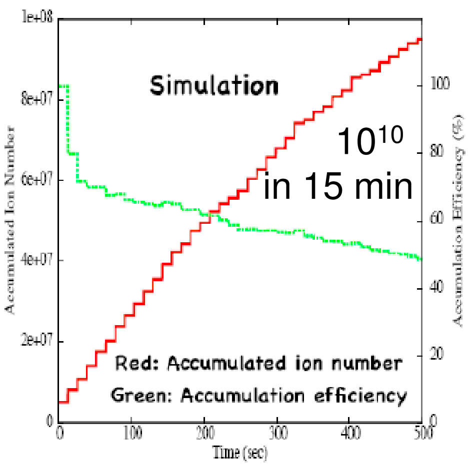
	High Resolution Mode	High Luminosity Mode
Energy range	0.8 - 14.5 GeV	3 – 14.5 GeV
# antiprotons	10^{10}	10^{11}
Peak luminosity	$2 \cdot 10^{31}$ cm^{-2}s^{-1}	$2 \cdot 10^{32}$ cm^{-2}s^{-1}
Momentum spread	$5 \cdot 10^{-5}$	$1 \cdot 10^{-4}$

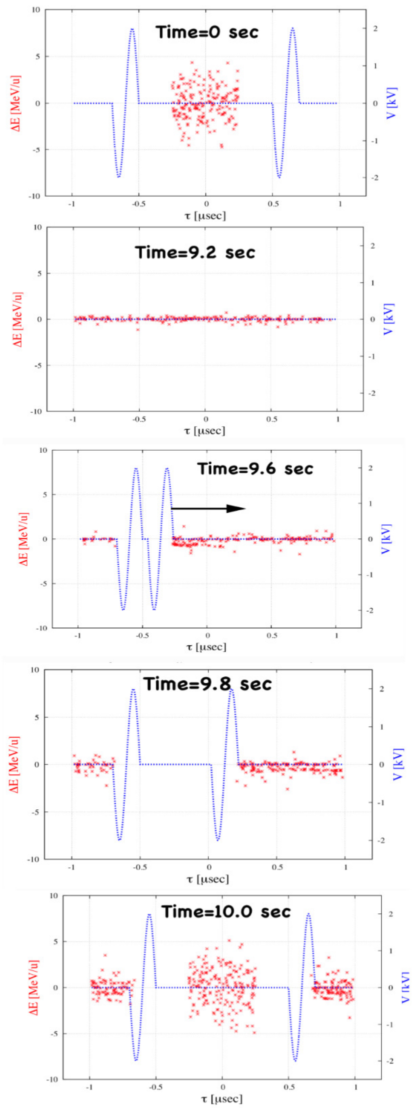
MSV: HR mode + heavy ions.

Consistent with 2E13 protons every 10 s.

Barrier bucket stacking in the HESR with stochastic momentum Cooling.

Successful demonstration in the GSI ESR.



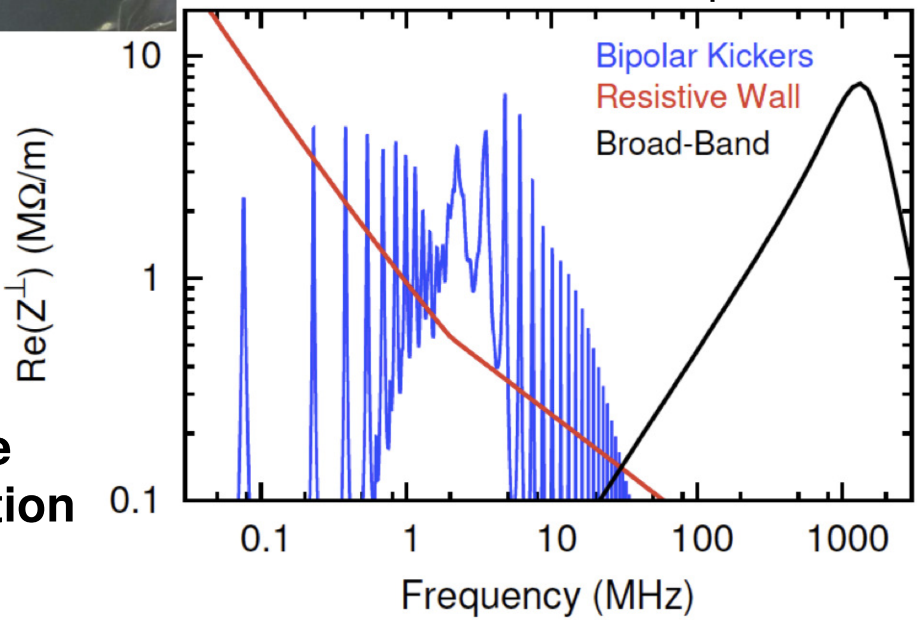


Beam instabilities and impedances in SIS-100

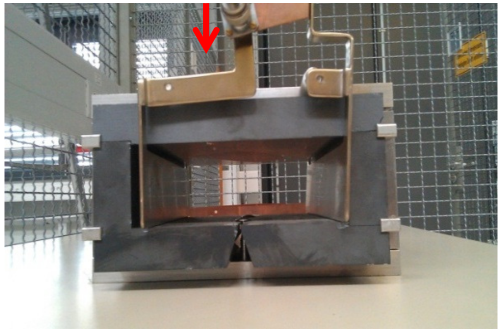
Thin (0.3 mm) beam pipe

U. Niedermayer et al.,
NIMA 2014, PRSTAB 2015

Estimates transverse impedances



Kicker + Pulse Forming Network



Broad-band impedance:
- Collimation systems
- …..

(Remark: eclouds are not expected to be a problem)

Not expected to be an intensity limitation for heavy-ions.

The detailed thresholds for protons are currently under study.

Head-Tail instabilities
Cures:
- Feedback System
- Octupoles

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

V.Kornilov, ICFA-HB 2013

Beam loss in SIS-100: „Hands-on-maintenance“

Loss estimates (example: U^{28+})

SIS-18 beam loss/cycle		Fractional (%)
injection		**10**
rf capture		5
space charge	2E11->1.2E11	**10**
ionization		**30**
fast extraction		2

SIS-100 beam loss/cycle		Fractional (%)
injection		2
space charge		**10**
ionization	4.5E11->3.5E11	**5**
slow extraction		10

Expected main beam loss mechanisms:

- Charge exchange (dynamic vacuum)

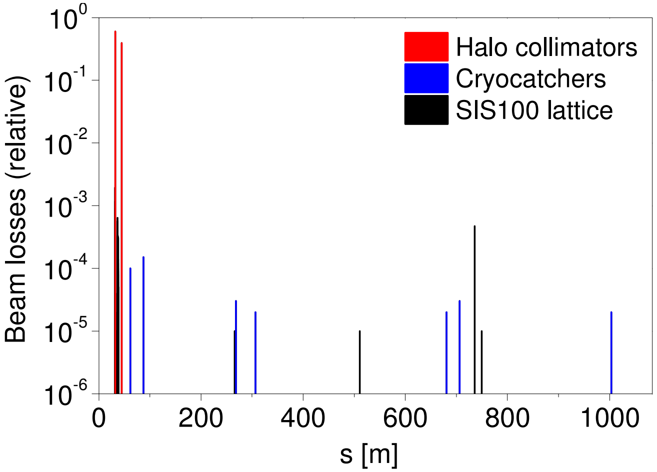
$U^{28+} + X \rightarrow U^{29+} + X + \epsilon$ (Lifetime)$^{-1}$: $\tau^{-1} = \beta_0 c \sigma_{loss} \frac{P(N,t)}{k_B T}$

- Space charge induced resonance crossing
- Injection/Extraction

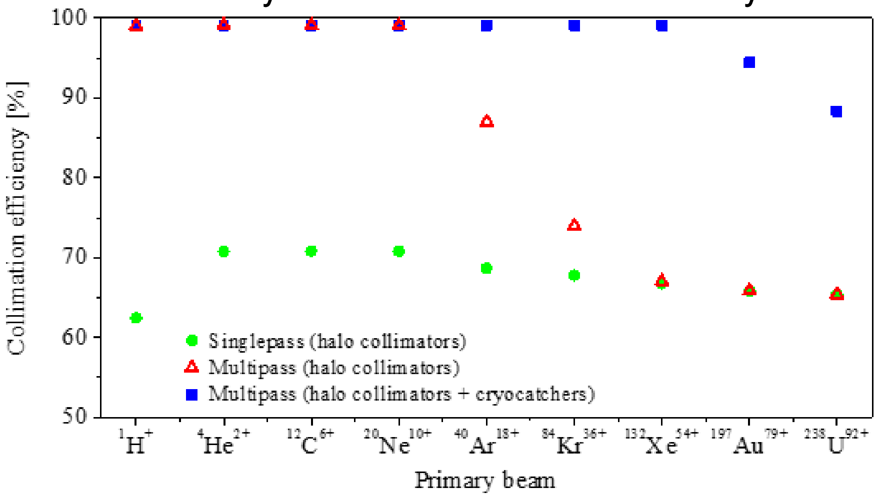
Uncontrolled loss below 1 W/m (1 GeV Protons).

Design goal: controlled losses on collimators

Halo-collimation for protons at 4 GeV



Efficiency of the SIS-100 collimation system.



Strasik, et al., PRSTAB 2010, Strasik, et al., PRSTAB 2015

Conclusions: Beam parameter and intensity limitations

User requirements, primary beams:

- NuSTAR: short heavy ion bunch (50-100 ns) or slow extraction (≥ 1 s)
  extracted intensity: N/s > 1E11/s (was 1E12/s in the CDR/2001)
- PANDA: short (50 ns) proton bunch (2E13)
- cycle times determined by cooling times in CR collector ring
  (approx. 1 s for HI, 10 s for pbars) or extraction plateau.

Expected intensity limitations for primary beams (SIS-100):

- 'space charge limit'
- acceptances and rf bucket area (reduced by space charge)
- activation/damage due to beam loss
- beam instabilities (protons)

-> estimated limits (large errors bars):

U^{28+}: 6-7 x 10^{11} per cycle (for other HI according to space limit and injector performance)

p: 4 x 10^{13}

UNILAC/SIS-18 limitations:

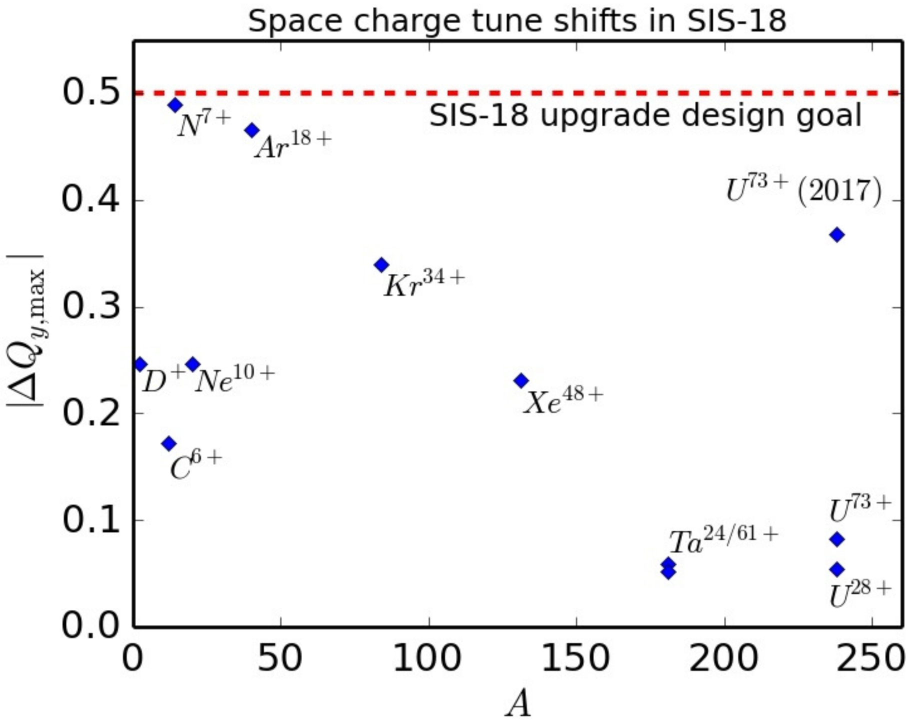
- UNILAC current/emittance and multi-turn injection efficiency
- rf bucket area for fast ramping
- charge exchange and dynamic vacuum (HI)
- space charge and resonance crossing

UNILAC/SIS18 Beam parameter

	UNILAC today	FAIR	2017
Reference primary ion	**U^{28+}/U^{73+}**	**U^{28+}**	**U^{73+}**
Current (mA)	5/1	15	3
Emittance, 4σ (h, mm mrad)	**7/7**	**5**	**7**
Momentum spread (2σ)	**1E-3/1E-3**	**5E-4**	**5E-4**

	SIS-18 today	FAIR design	2017
Reference primary ion	**U^{28+}/U^{73+}**	**U^{28+}**	**U^{73+}**
Reference energy GeV/u	0.2/1	0.2	1
Ions per cycle	**4E10/4E9**	**1.5E11**	**2E10**
cycle rate (Hz)	0.5 Hz	2.7 Hz	2 Hz
Long. dilution	**> 2**	**1.5**	**2**

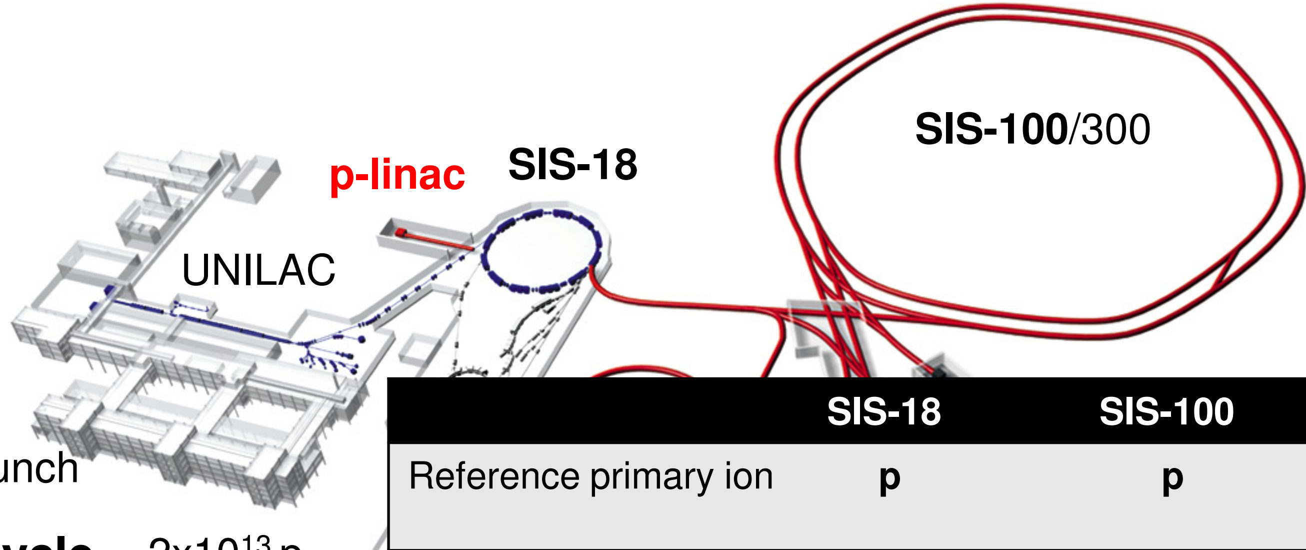
Present SIS-18 intensities



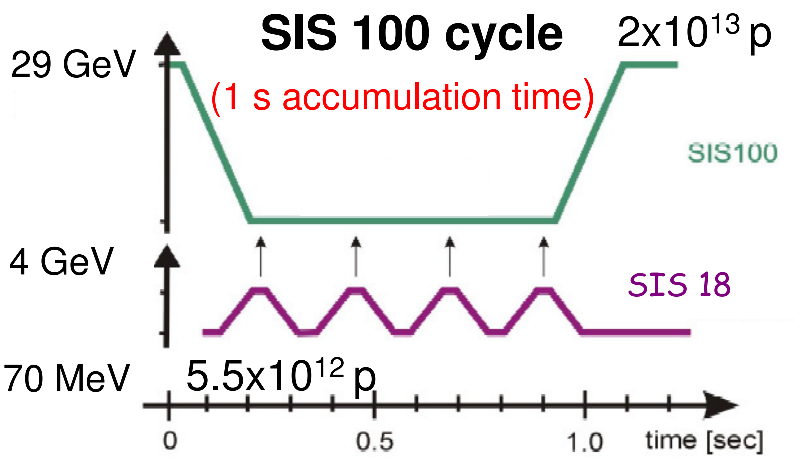
$$\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{4}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{1}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$$

UNILAC/SIS-18 presentations: L. Groening, J. Stadlmann

FAIR primary beam chain: Protons



SIS-100 extraction:
Single, short (50 ns) bunch



	SIS-18	SIS-100
Reference primary ion	**p**	**p**
Reference energy	4 GeV	**29 GeV**
Protons per cycle	**5.5E12**	**2E13**
cycle rate (Hz)	2.7	0.1 Hz (adapted to CR cooling rate)

Optional: 8 injections and up to 4E13 protons (‘space charge limit’).

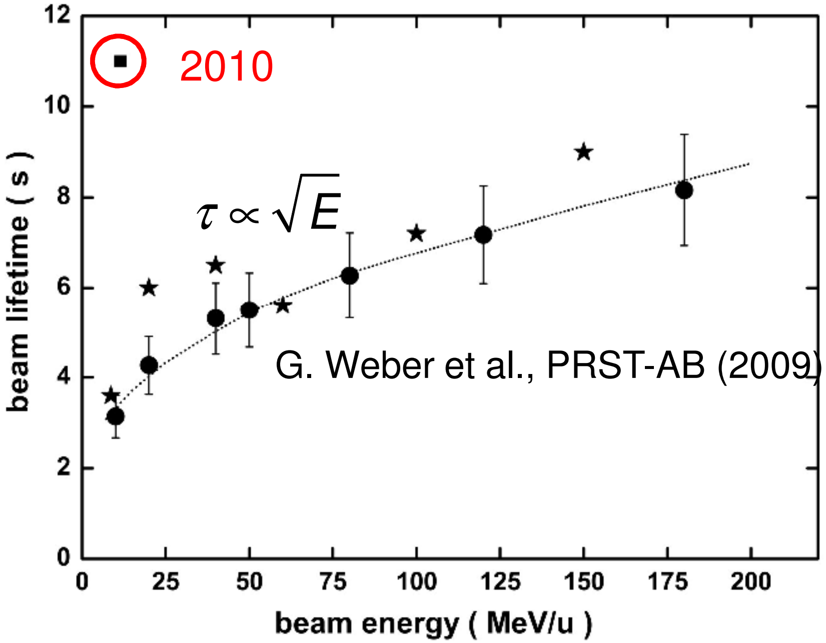
Dynamic residual gas pressure

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

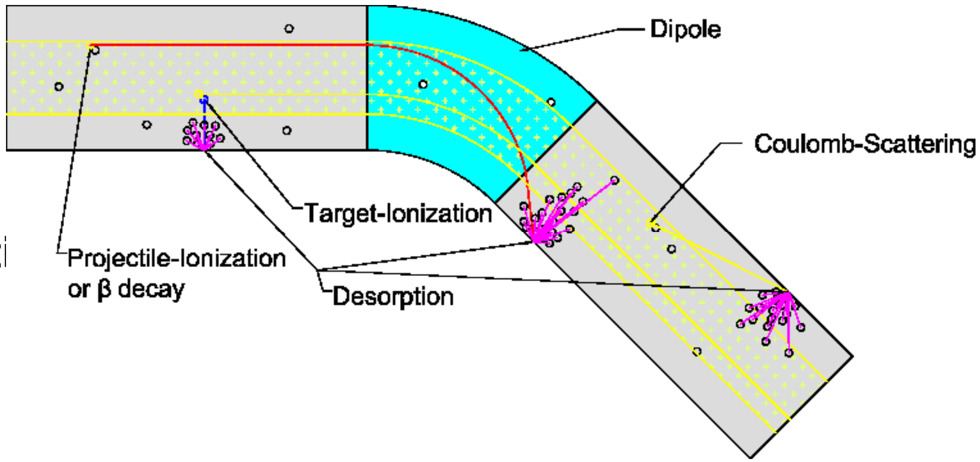
(Lifetime)$^{-1}$: $\tau^{-1}(P) = \beta_0 c \sigma_{loss} \frac{P}{k_B T}$

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

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



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

Lifetime increase (factor 3) due to NEG coating

NuSTAR: other primary ions (fast extraction)

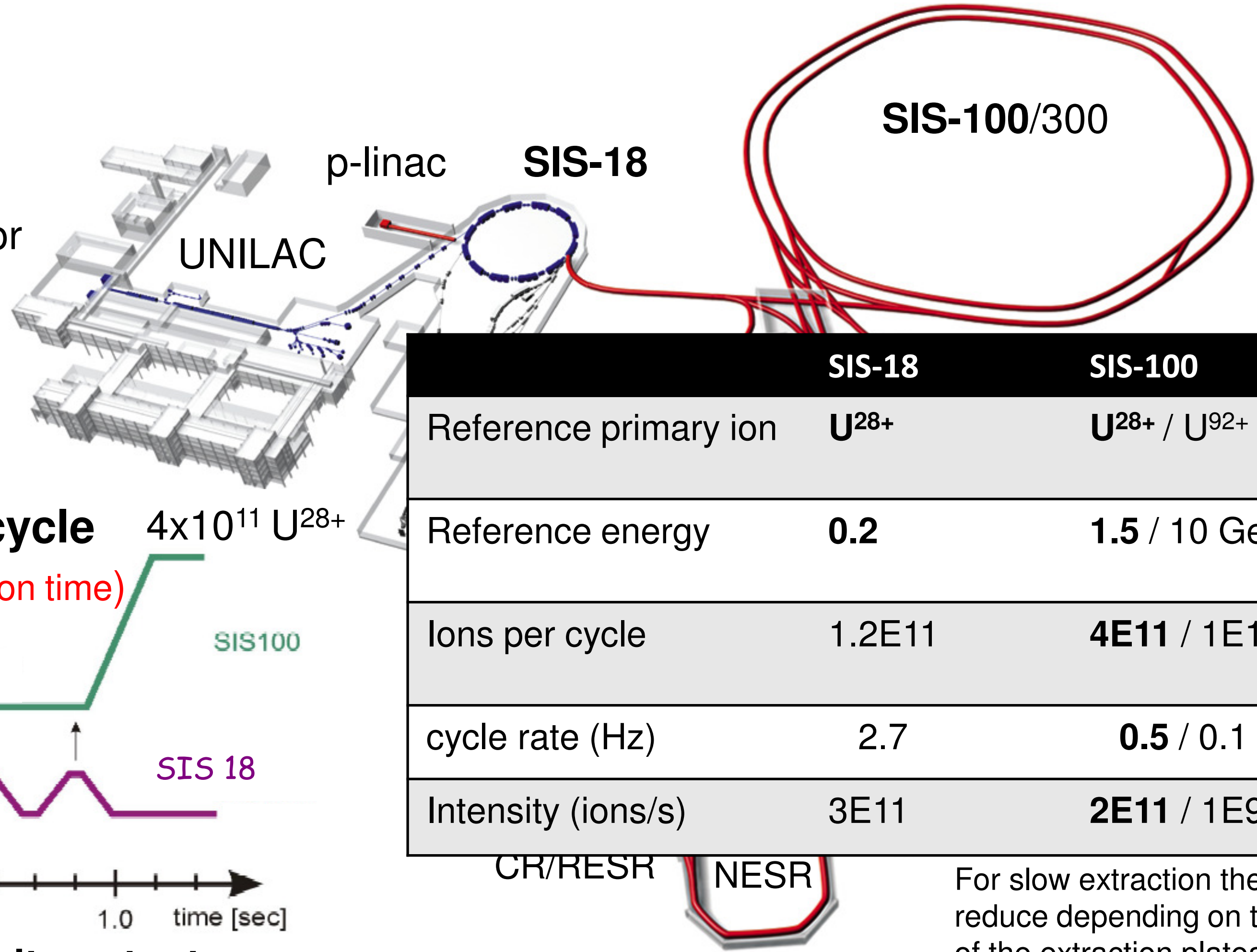
Beam Parameters	Ref. Ion: U^{28+}	Bi^{26+}, Pb^{26+}, Au^{26+}	Xe^{21+}, Kr	Ar^{10+}	Ref. Ion: U^{28+}	Bi^{26+}, Pb^{26+}, Au^{26+}	Xe^{21+}, Kr	Ar^{10+}
	Commissioning				Future operation in MSV			
Time structure	fast extraction							
Repetition rate	0.5-0.01 Hz				0.7-0.1 Hz			
Number of ions per 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]	0.5-1.5							
Transverse emittance [mm mrad]	11(h)x 4(v)							
Pulse length [ns]	70				50-100			
Momentum spread	$5x10^{-4}$							
Beam spot radius [mm]	1x2-4x6		2x3	3x5	1x2-4x6		2x3	3x5

Stand: 08.08.2014

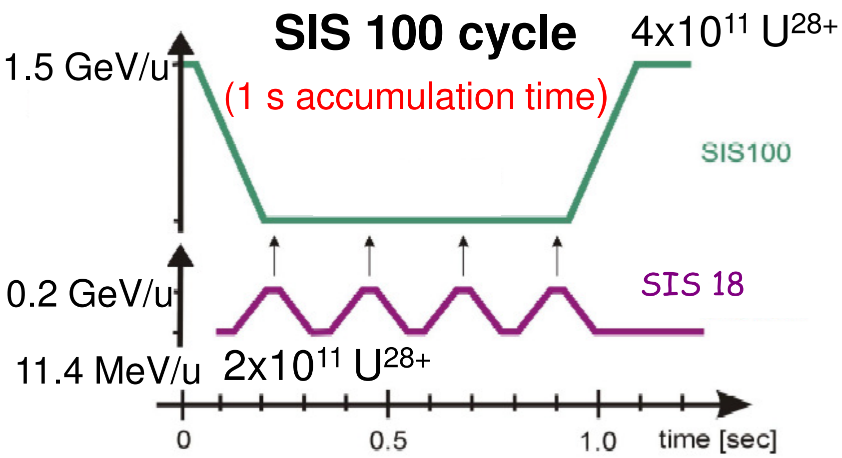
NESR SPARC

FAIR primary beam chain: Uranium

SIS-100 extraction:
- Single, short bunch for storage ring physics
- Slow extraction for fixed-targets



	SIS-18	SIS-100
Reference primary ion	**U^{28+}**	**U^{28+}** / U^{92+}
Reference energy	**0.2**	**1.5** / 10 GeV/u
Ions per cycle	1.2E11	**4E11** / 1E10
cycle rate (Hz)	2.7	**0.5** / 0.1
Intensity (ions/s)	3E11	**2E11** / 1E9



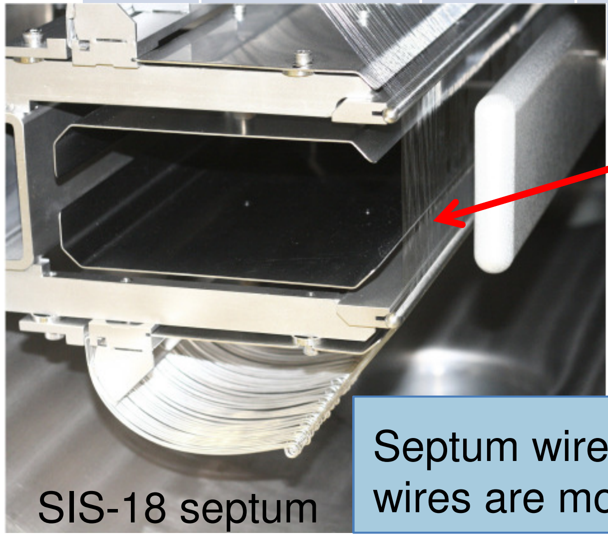
For slow extraction the ions/s reduce depending on the length of the extraction plateau and 10 % slow extraction losses.

Maximize SIS100 intensity output:
Fill synchrotron to the 'space charge limit' (within allowed phase space area).

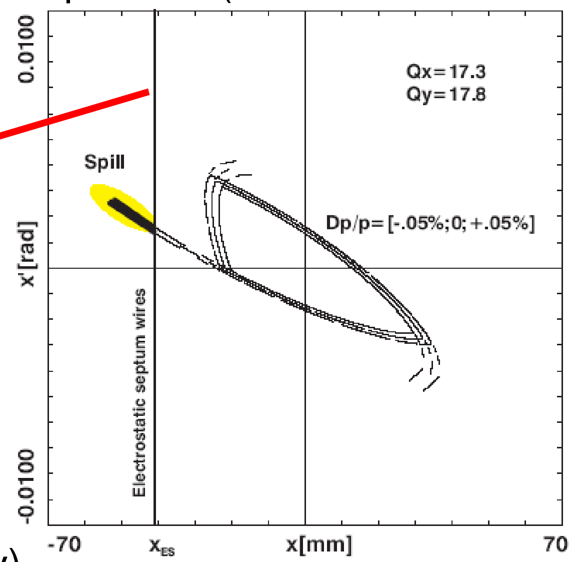
Slow extraction from SIS-100

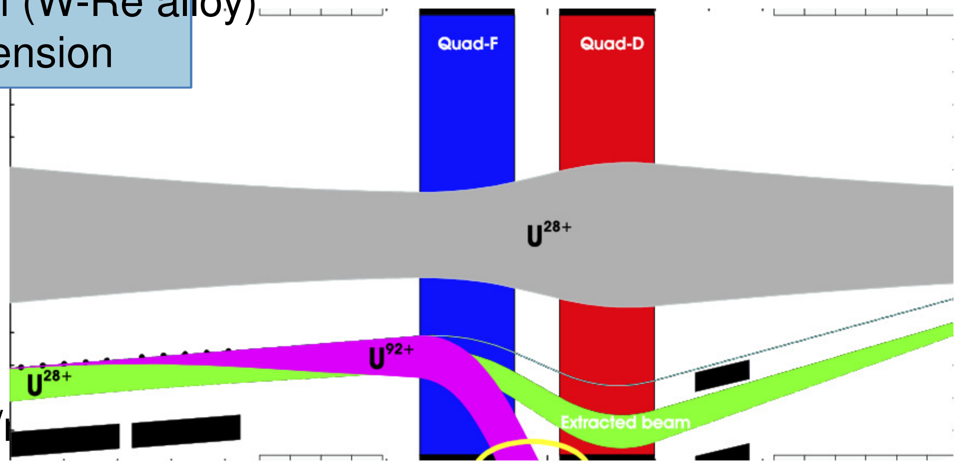
extraction of intense heavy-ion beams for NuSTAR and CBM

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



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/
(hands-on-maintenance limit)

Heat load in SIS100: Longitudinal impedances

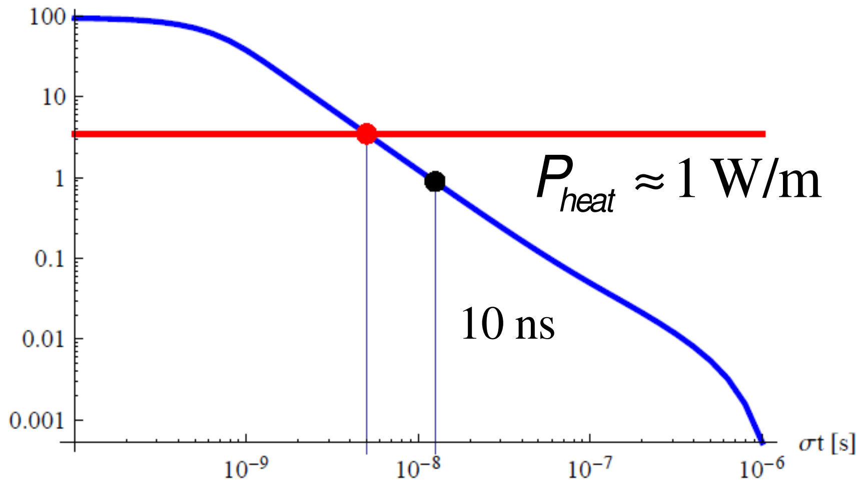
Thin (0.3 mm) beam pipe

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

Proton bunch parameters

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

$P_{heat}\,[\mathrm{W/m}]$



proton bunch length