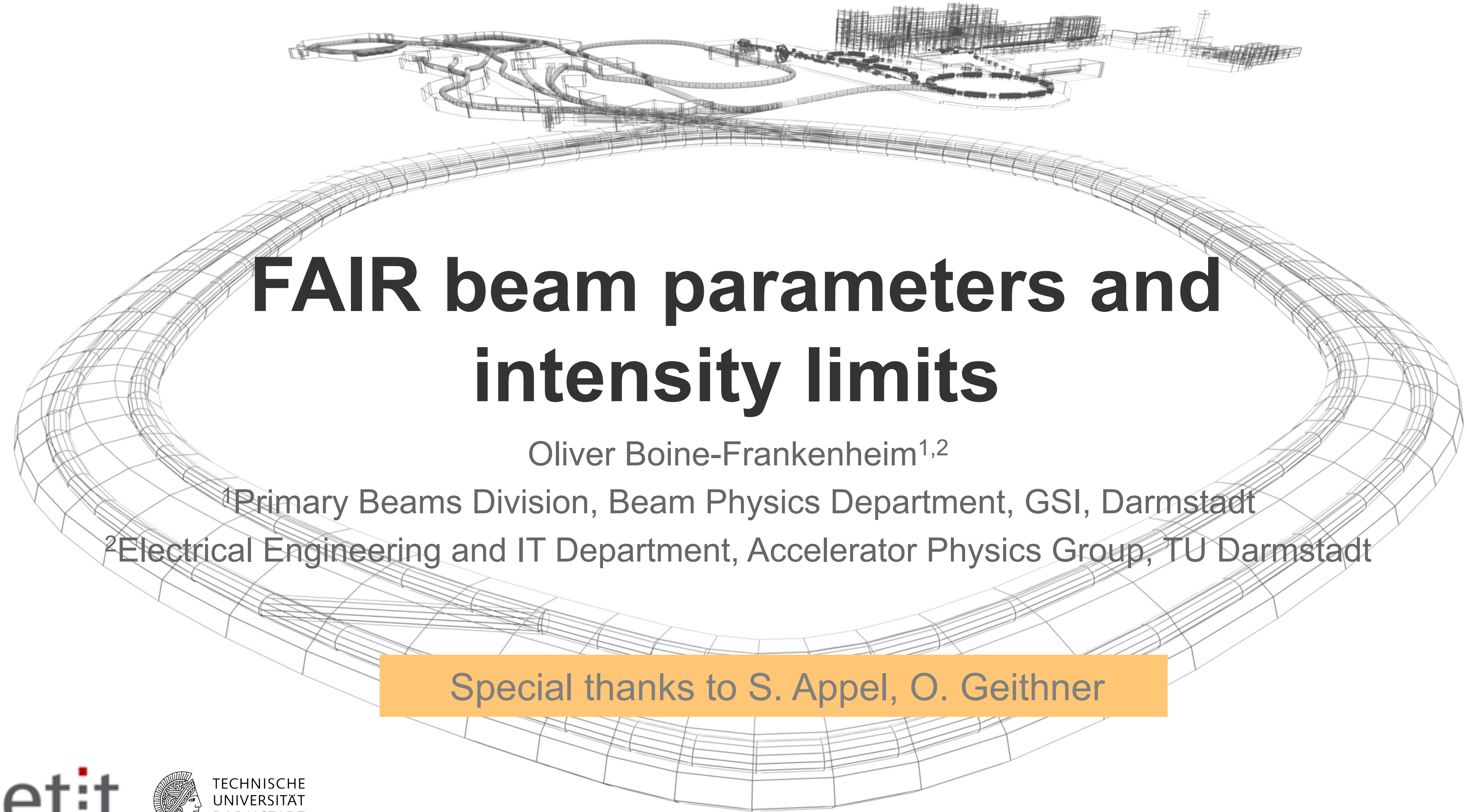

# FAIR beam parameters and intensity limits

Oliver Boine-Frankenheim[1,2]
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Special thanks to S. Appel, O. Geithner

# Contents

- NuSTAR/Panda beam requirements and perfomance goals
  - Production targets, storage rings
- Beam intensity limits for primary beams in SIS-100
  - Acceptances, activation, space charge, beam instabilities
- UNILAC/SIS-18 performance estimates
  - Optimization of beam parameters

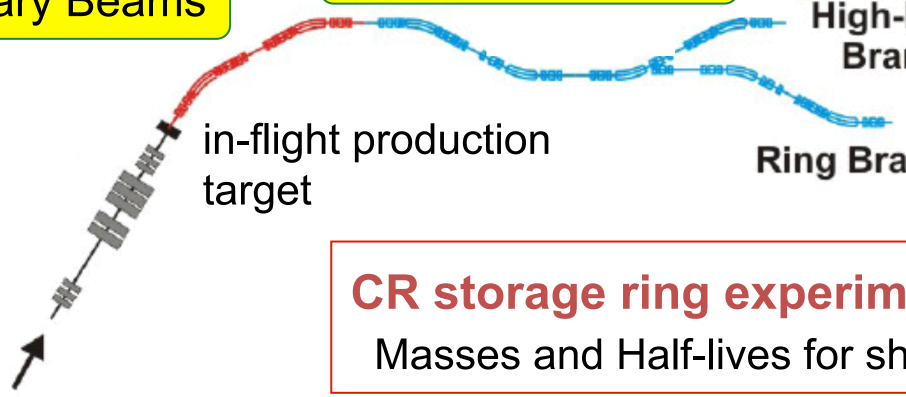
# NuSTAR requirements

**Super-FRS**

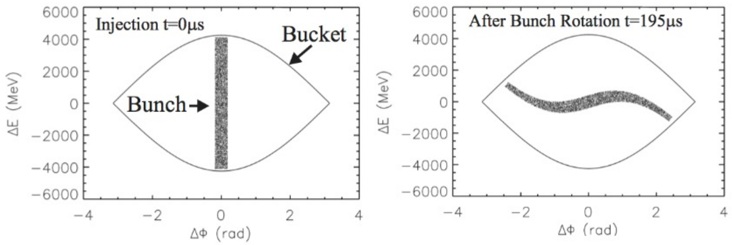
**High energy branch**: Fixed-target experiments

Primary Beams

Secondary Beams




Bunch rotation in the CR: smaller momentum spread




**CR storage ring experiments with RIBs**:

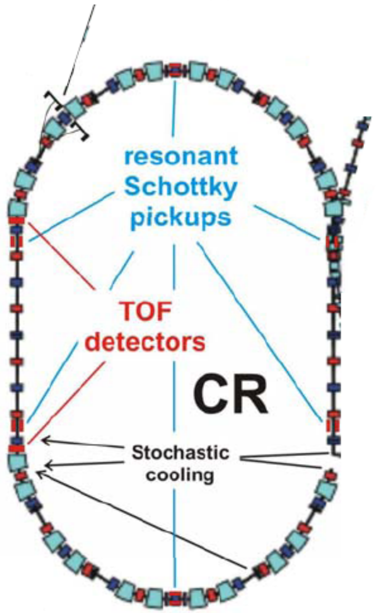
Masses and Half-lives for short-lived ions

**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 !**

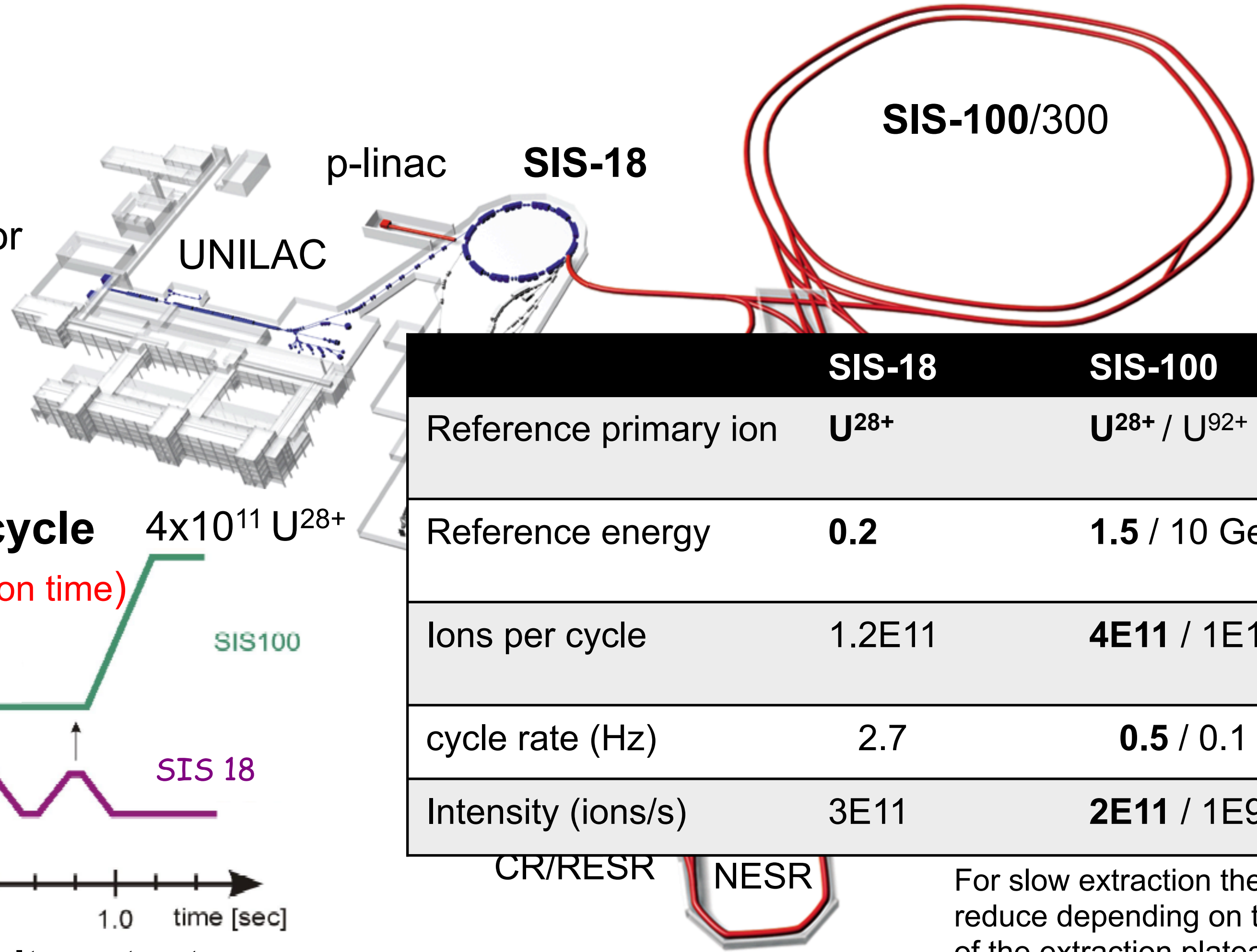
CDR/2001 -> 1E12/s
(NuPECC/2000 recommendation for the next generation in-flight radioactive beam facility)




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

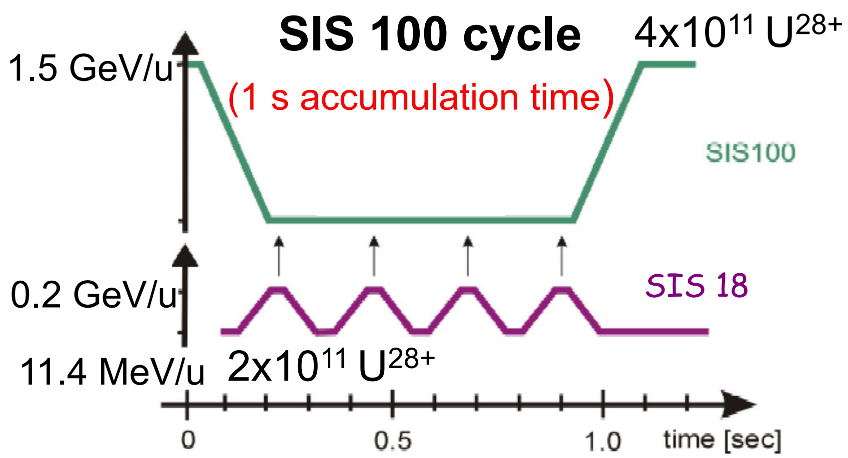
# FAIR primary beam chain: Uranium

**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).

# 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

# Antiprotons: HESR and PANDA requirements

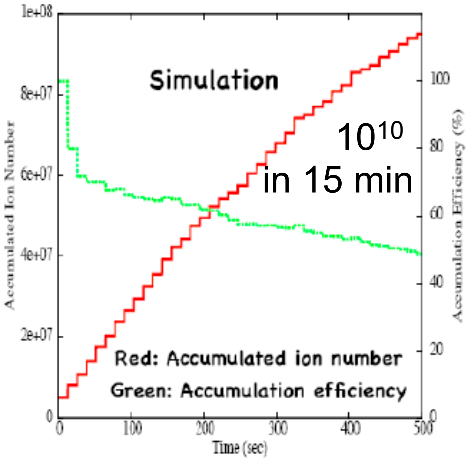
| Effective internal target thickness (pellets): $4 \cdot 10^{15}$ cm$^{-2}$ | | |
|---|---|---|
| | **High Resolution Mode** | **High Luminosity Mode** |
| **Energy range** | **0.8 - 14.5 GeV** | **3 – 14.5 GeV** |
| **# antiprotons** | **$10^{10}$** | **$10^{11}$** |
| **Peak luminosity** | **$2 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$** | **$2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$** |
| **Momentum spread** | **$5 \cdot 10^{-5}$** | **$1 \cdot 10^{-4}$** |

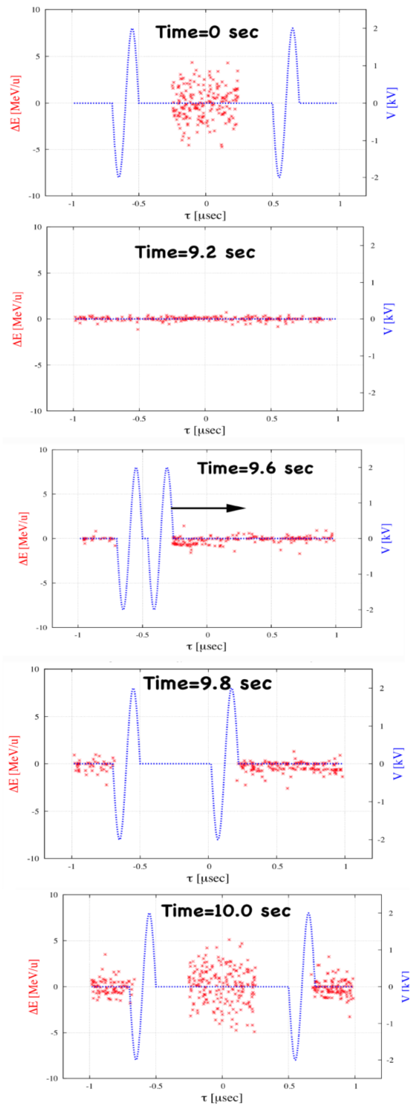
**MSV:** HR mode
+ heavy ions.

Consistent with 2E13 protons every 10 s.

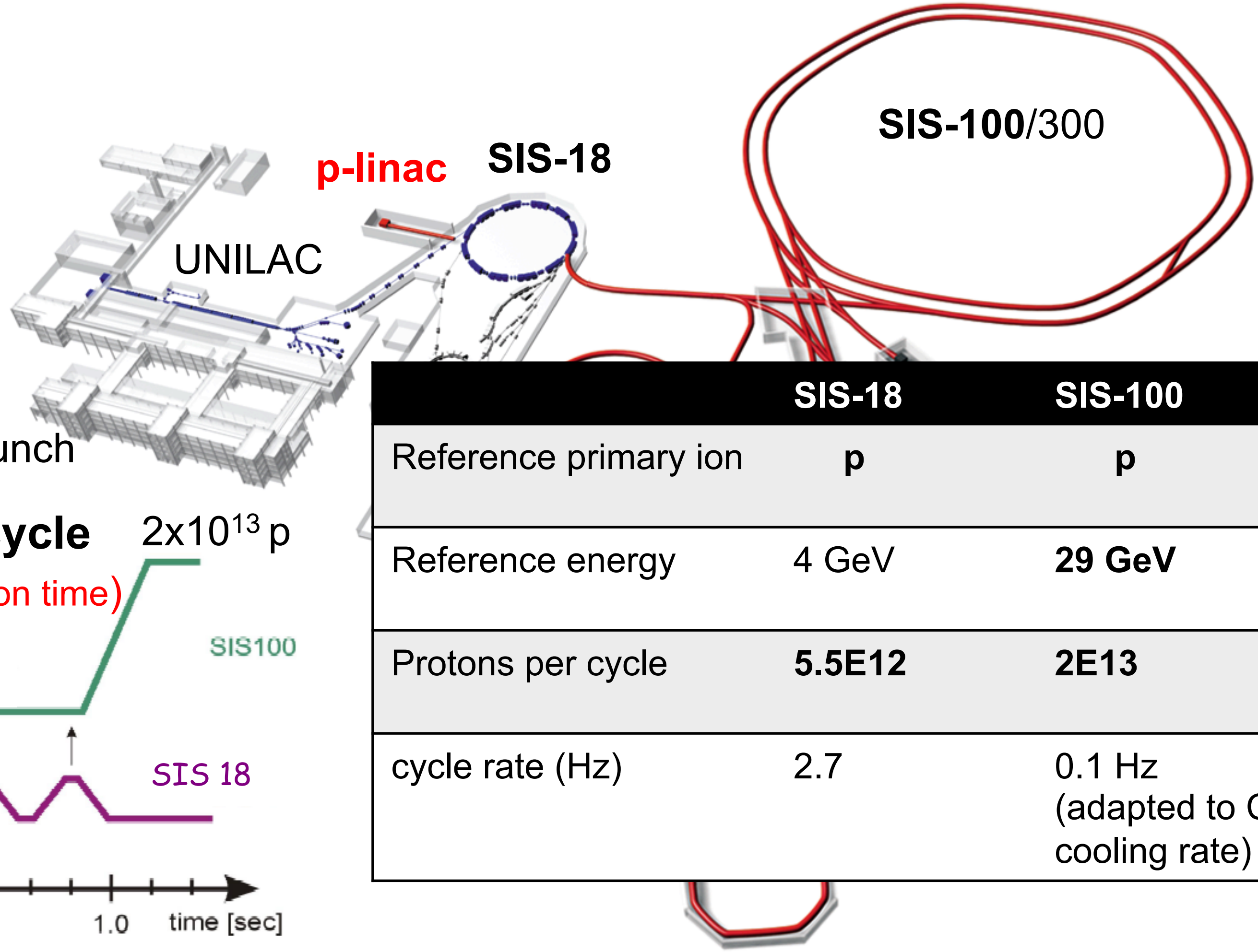
Barrier bucket stacking in the HESR with stochastic momentum Cooling.

Successful demonstration in the GSI ESR.

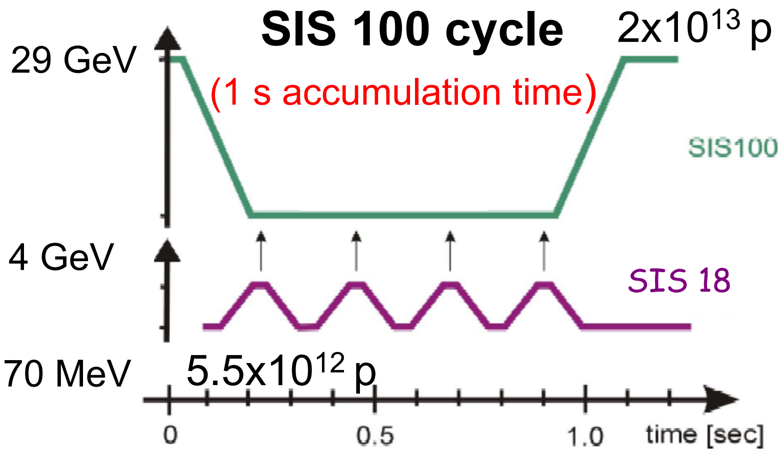


# FAIR primary beam chain: Protons




**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').

# 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)

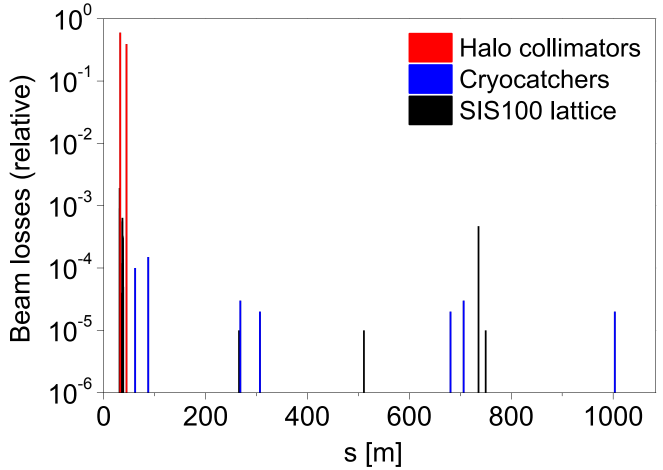
$U^{28+} + X \rightarrow U^{29+} + X + e$ (Lifetime)$^{-1}$: $\tau^{-1} = \beta_0 c \sigma_{loss} \frac{P(N,t)}{k_B T}$

- Space charge induced resonance crossing
- Injection/Extraction

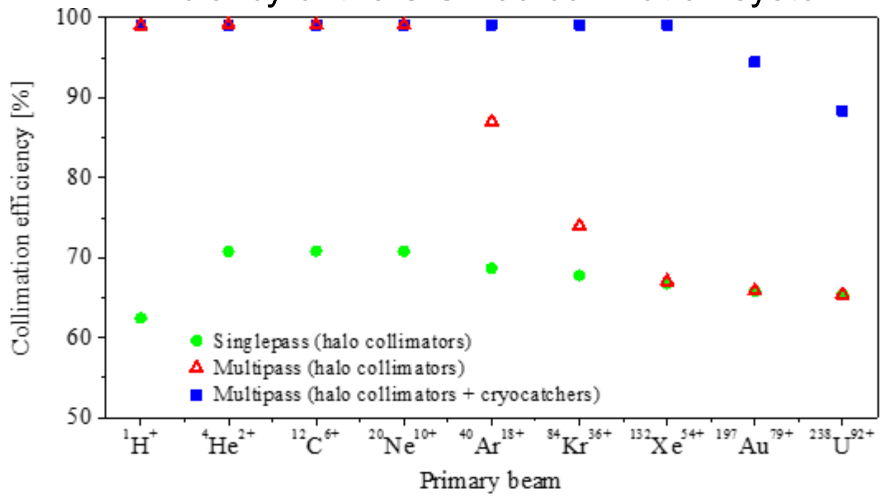
Uncontrolled loss below 1 W/m (1 GeV Protons).

**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

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

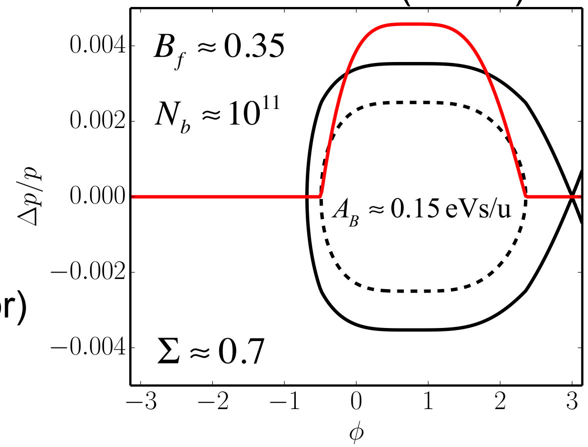
Voltage requirement:

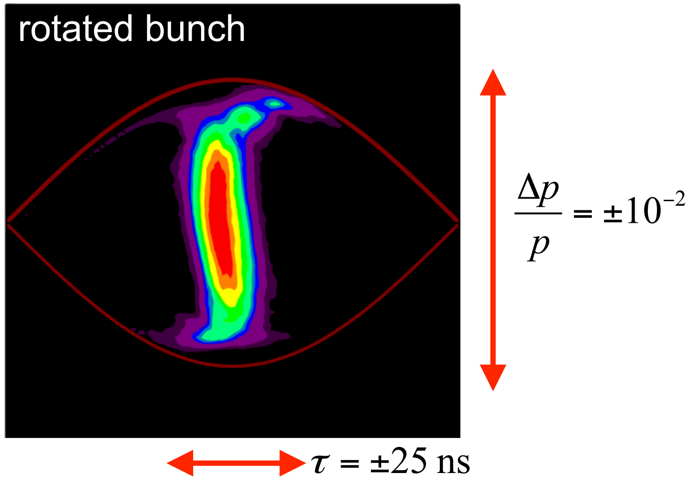
$$V(\sin z_s - a \sin z_{s2}) = 2r R t \dot{B}$$

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

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

dual rf bucket (SIS18)



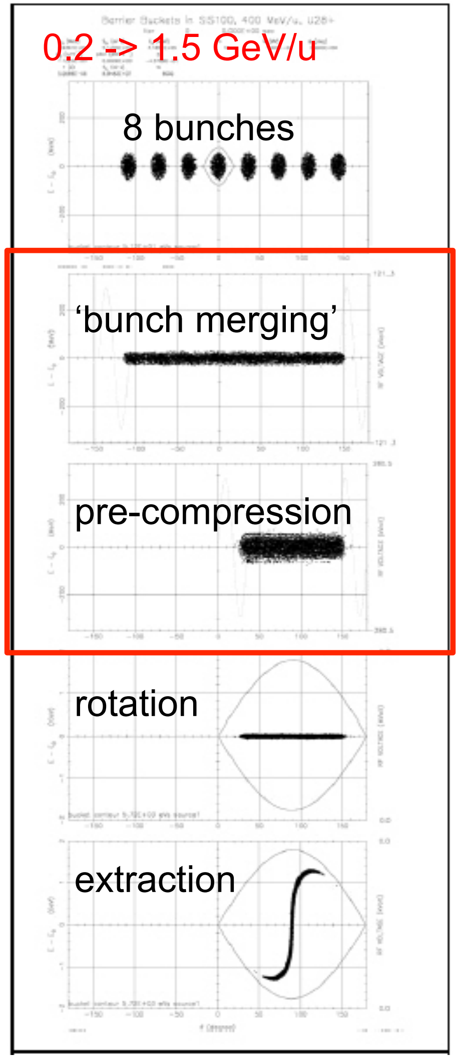




| | SIS18 injection | SIS100 injection | SIS100 extraction |
|---|---|---|---|
| Bucket area eVs/u | **0.15 x 2 (10 T/s)** | **0.25 x 10 (3 T/s)** | **1.6 x 1** |
| Bunch area eVs/u | 0.1 x 2 | 0.15 x 8 = 1.2 | 1.6 x 1 |
| Space charge factor | **0.7** | **0.5** | < 0.1 |
| Acceptance mm mrad | 150/50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

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

# Fast barrier pre-compression in SIS-100

Single bunch formation




**Non-adiabatic barrier rf phase ramp:**

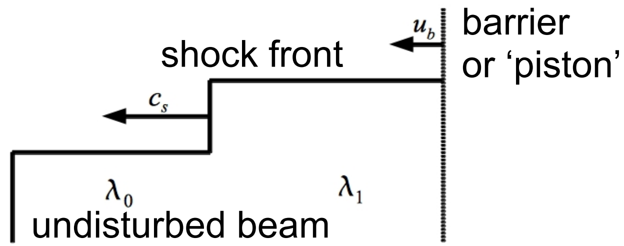
T=100 ms $T_{s0}$ > 100 ms

(ramp time) ('synchrotron period')

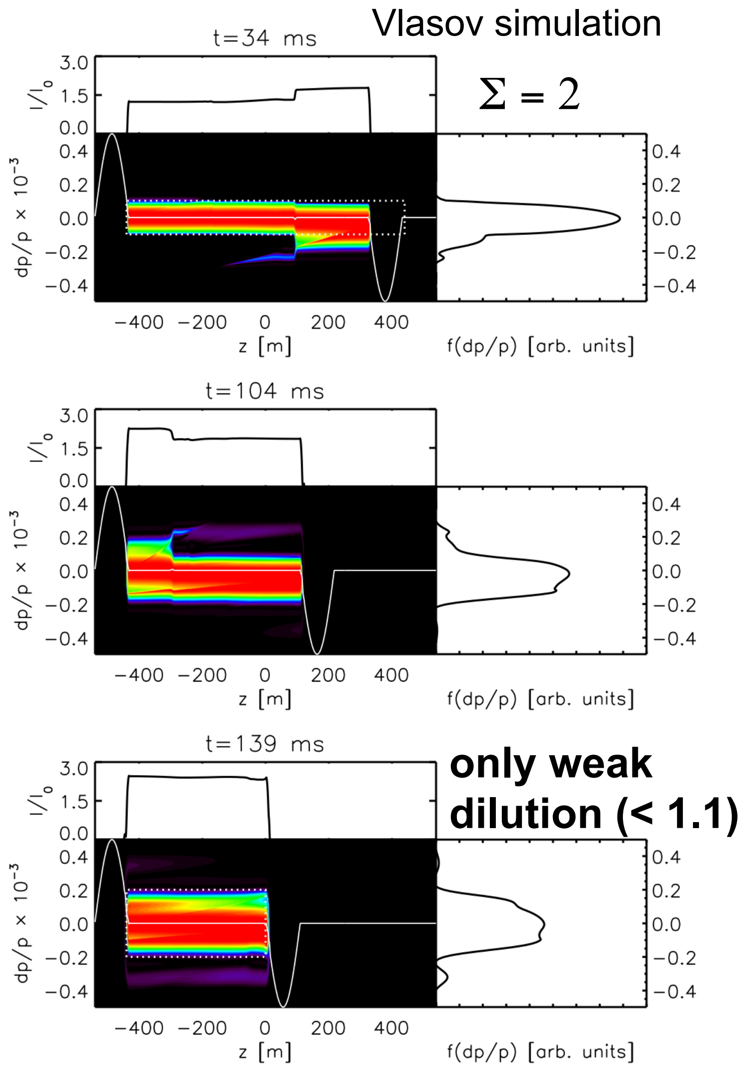
$u_b$ $v_{th}$ $v_{th} = -\eta_0 \beta_0 c \frac{\Delta p}{p}$

(barrier velocity) ('thermal velocity')

**Shock compression:**

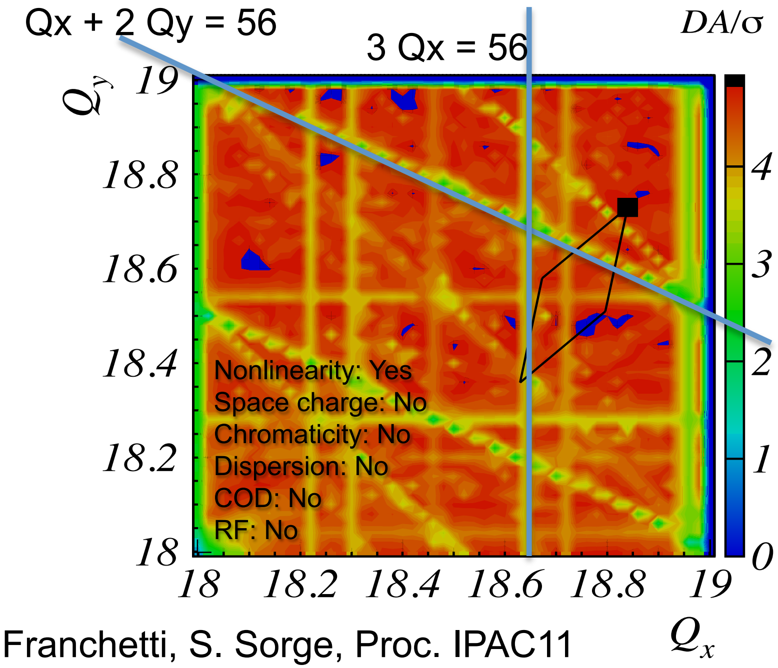



Space charge helps !



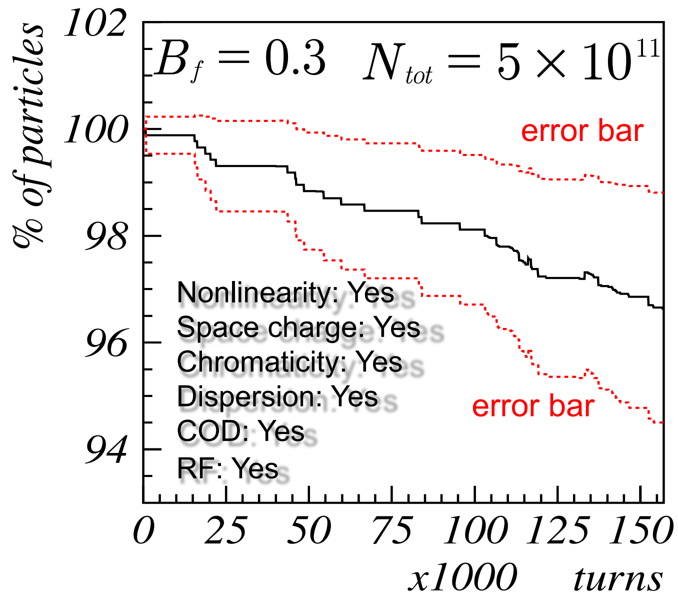
# SIS-100 ‘incoherent space charge limit’

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




G. Franchetti, S. Sorge, Proc. IPAC11

beam loss simulation of the accumulation with space charge after resonance compensation





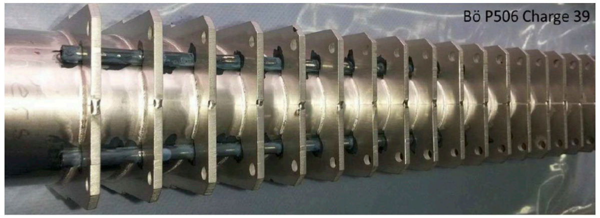

**Present predictions come with a large error bar !**

**Estimated ‘limits’ with dual rf buckets:**
$U^{28+}$: 6-7 x $10^{11}$ (4-5 x $10^{11}$/s) p: 4 x $10^{13}$

**Future options:**
(partial) space charge compensation

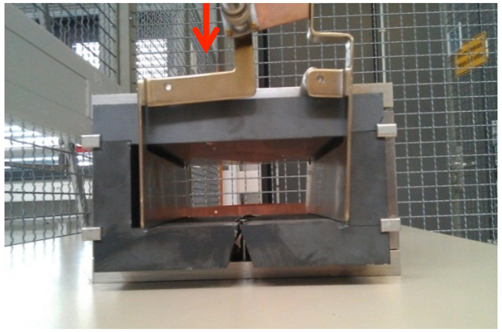
# Beam instabilities and impedances in SIS-100

**Thin (0.3 mm) beam pipe**

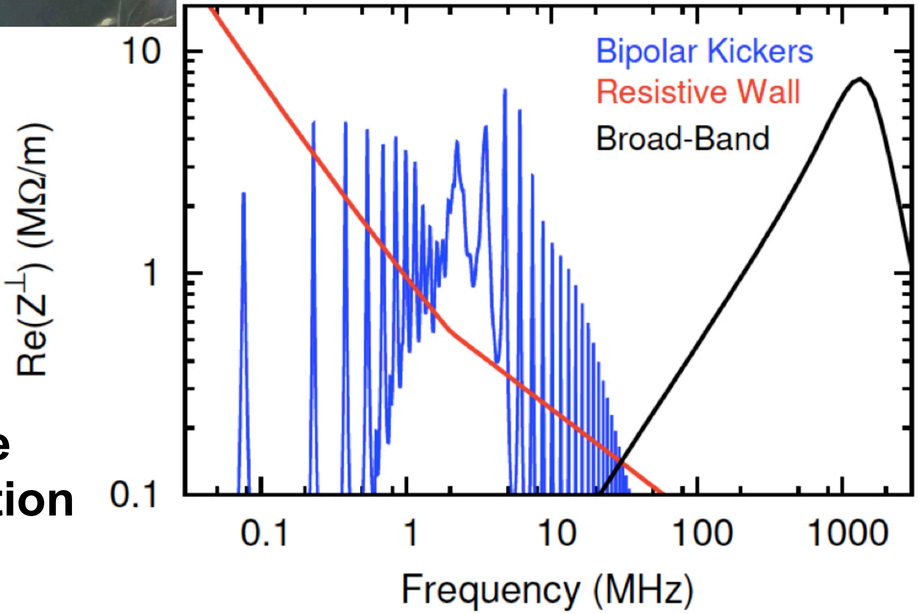



U. Niedermayer et al.,
NIMA 2014, PRSTAB 2015

**Kicker + Pulse Forming Network**



Estimates transverse impedances




**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 ($\xi$ and $\delta_p$)

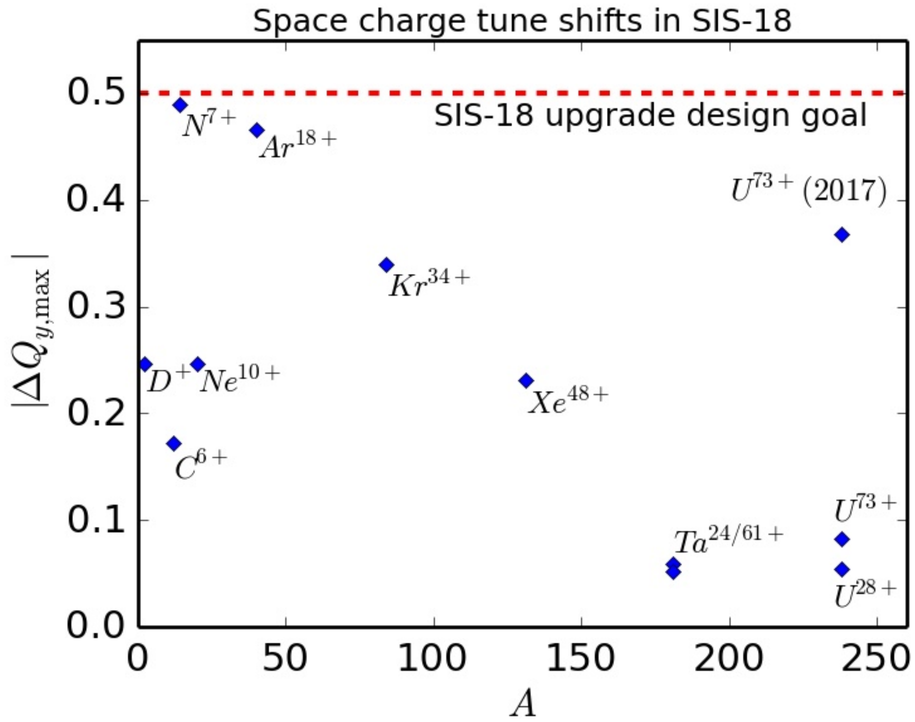
V.Kornilov, ICFA-HB 2013

# 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

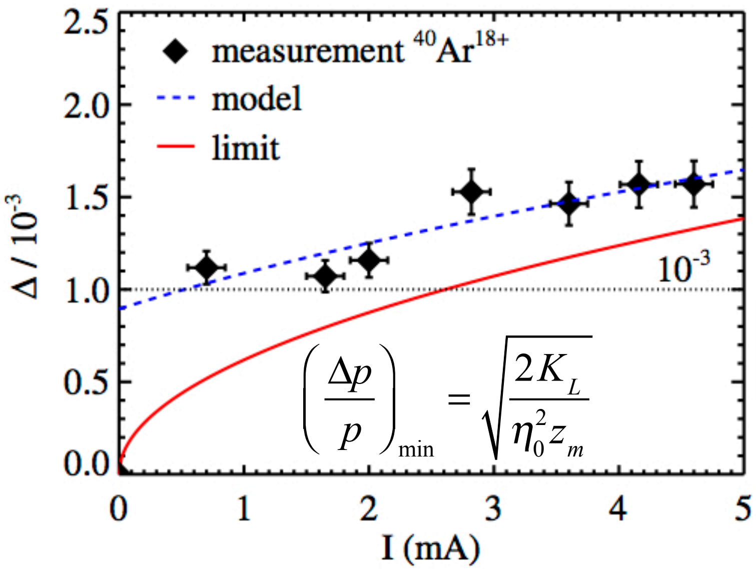



$$\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{4}{\varepsilon_y \beta_0^2 \gamma_0^3}\frac{1}{1+\sqrt{\varepsilon_y/\varepsilon_x}}$$

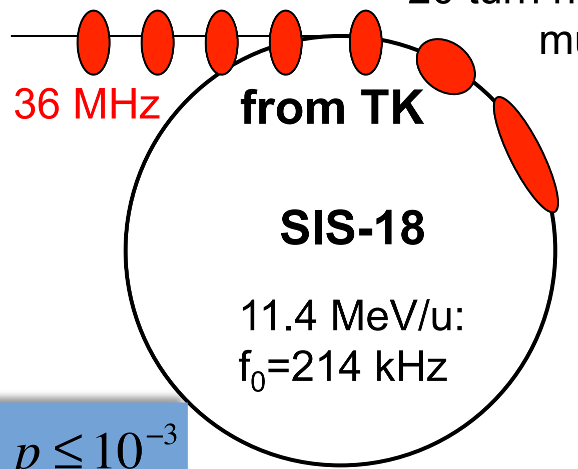
UNILAC/SIS-18 presentations: L. Groening, J. Stadlmann

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

Measured momentum spread for coasting beams in SIS-18




≈ 20 turn horizontal multi-turn injection (MTI)




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 !**

microbunches and subsequent formation of filaments.

$\Delta \approx 2\sigma_p$ the momentum spread of the debunched beam.

054201-4

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

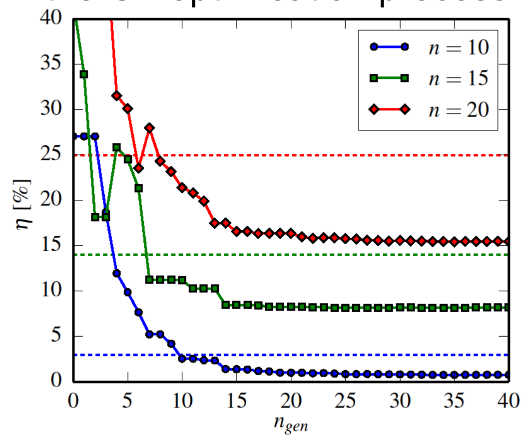
# Optimized beam parameters:
# $U^{28+}$ multi-turn injection (MTI) efficiency

| | UNILAC | SIS18 |
|---|---|---|
| Current (mA) | **15 mA** | **15x14 (->2E11)** |
| Emittance (mm mrad) | **7/7** | **150/50** |

Currently MTI losses are about 30 %

Optimized injection parameters:
**Genetic algorithm** + pyORBIT(space charge)
-> Lower injection losses and larger transmission (depends on initial loss).

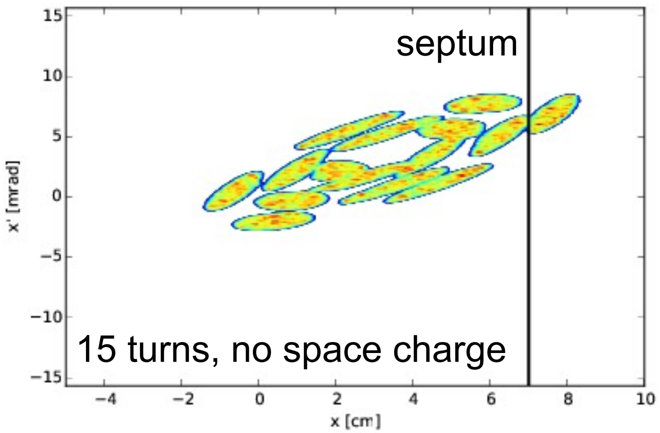
Evolution of the beam loss in the GA optimisation process.



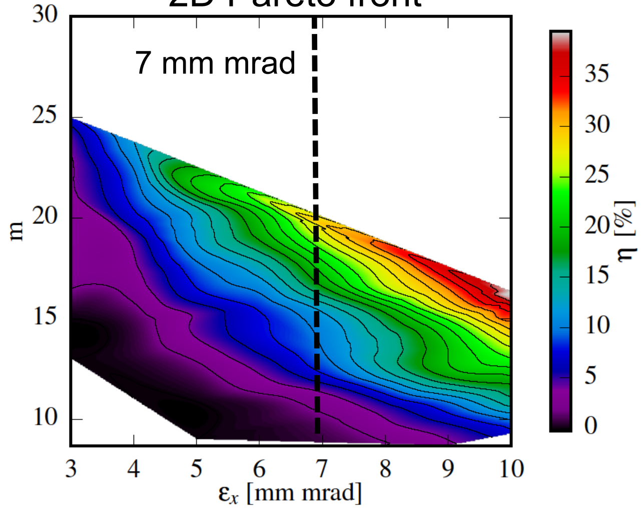

m: multiplication factor
n: injected turns
η: loss factor

$$m = n(1-\eta)$$

2.4E11 -> 16 %
**2E11 -> 8 %**
1.4E11 -> 1 %




2D Pareto front




**Next step:** include transmission (charge exchange losses) in optimization.

S. Appel, et al. IPAC15

# 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

**Additional material (not part of the presentation)**

# Short remark: protons vs. heavy ions

**UNILAC, SIS18/100:**
Operation with intermediate charge state ions to reduce space charge effects
+ light ions + protons

**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 heavy-ion intensities are limited not limited by space charge !**

**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 more difficult to reach for heavy-ions.**

**Protons and light ions:** Operation close or above transition energy in SIS-100

**-> possible additional beam loss for protons**

# Collective effects in SIS18/100: interplay

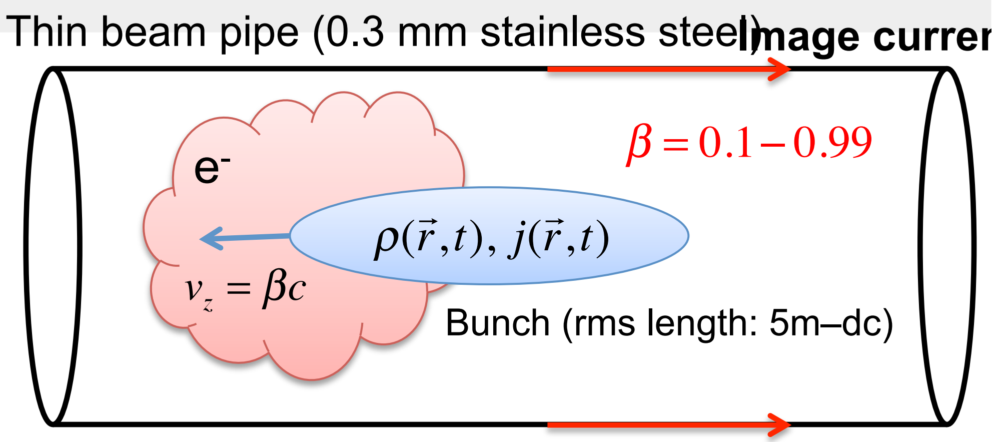
**Incoherent space charge:**

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

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

-> $\Delta Q^{sc}$ à $0.3$

-> beam loss, modification of coherent effects




**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

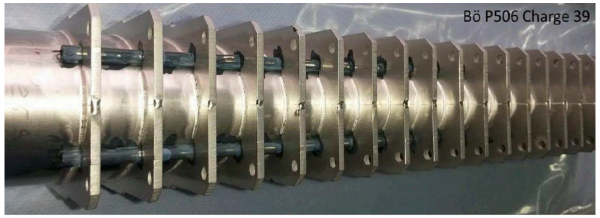
**Intrabeam scattering:**
-> Laser cooling in SIS-100

**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.**

# Heat load in SIS100: Longitudinal impedances

**Thin (0.3 mm) beam pipe**

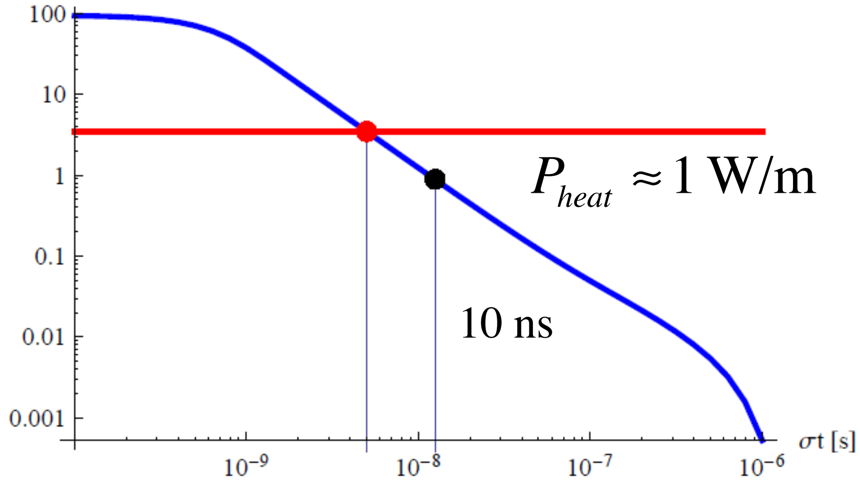



$$P_{heat} \propto \int \Re Z_{\|}(\omega) \cdot \mathrm{PowerSpectrum}(\omega)\, d\omega \quad \ll 25\ \mathrm{kW}\ (25\ \mathrm{W/m})$$

Proton bunch parameters

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

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



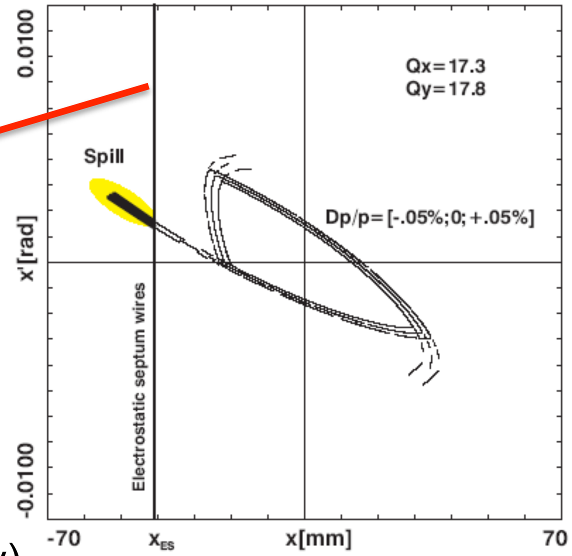

proton bunch length

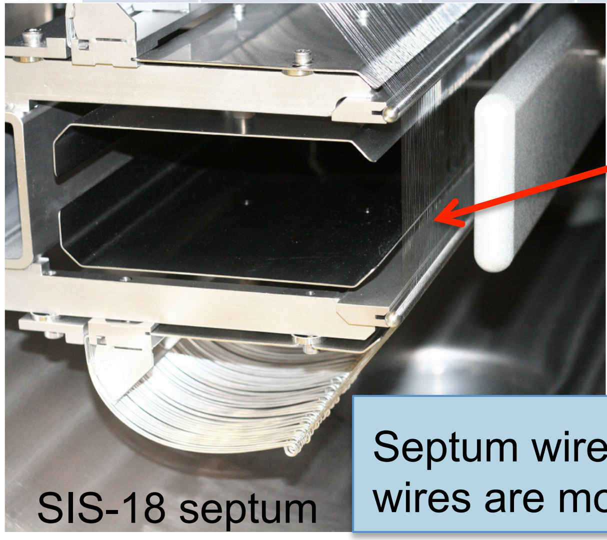
# Slow extraction from SIS-100

## extraction of intense heavy-ion beams for NuSTAR and CBM

| Ion | Energy | N/s | spill | Powe r |
|---|---|---|---|---|
| $U^{28+}$ | 1.5 GeV/ | 2E11 | > 1 s | 10 kW |

Separatrix (third order resonance)



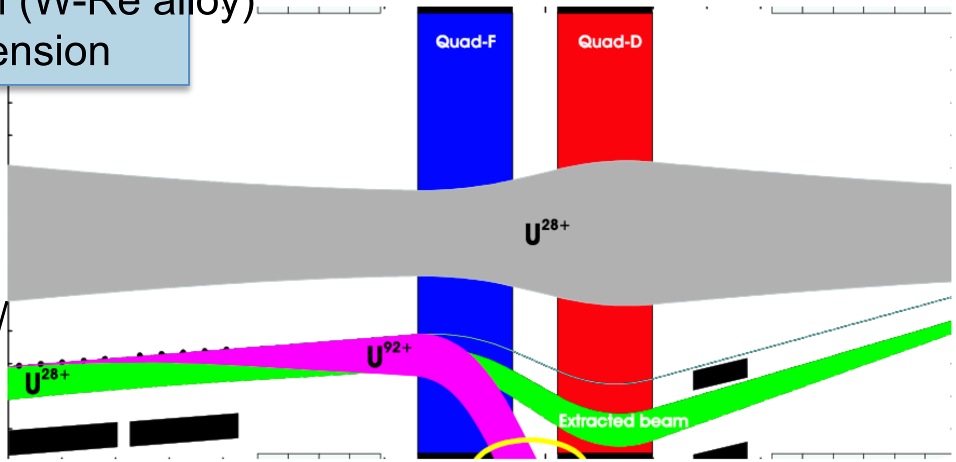



SIS-18 septum

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

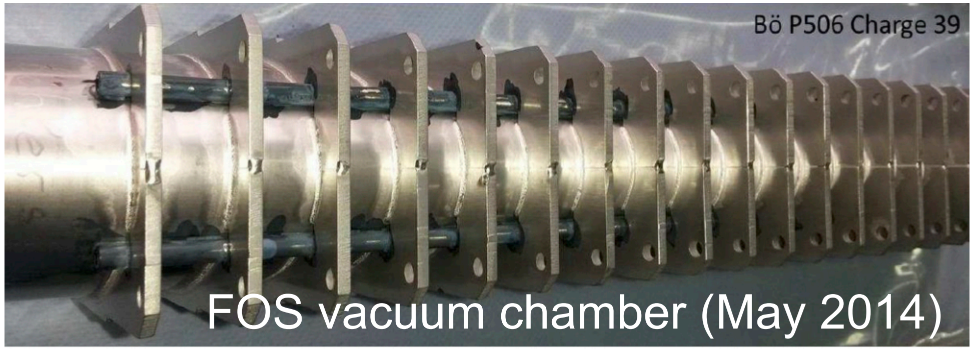
**Tracking simulations:**
5 % (approx. 500 W) loss in the septum wires

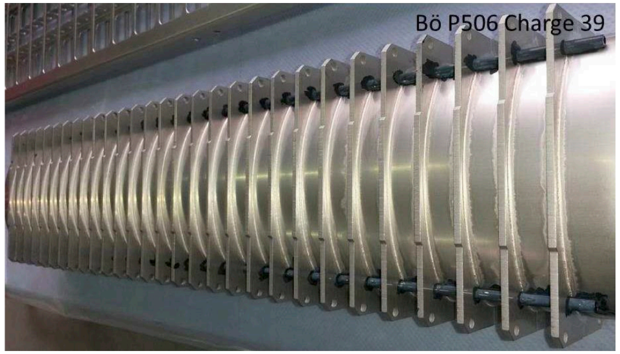
$U^{92+}$ localized beam loss in warm magnet > 5 W/
(hands-on-maintenance limit)

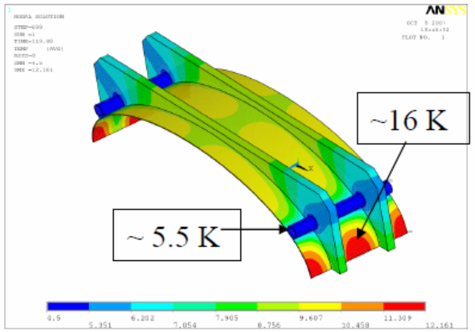



S. Sorge, FAIR-MAC 2010 and IPAC 2010
N. Pyka, IPAC 2010

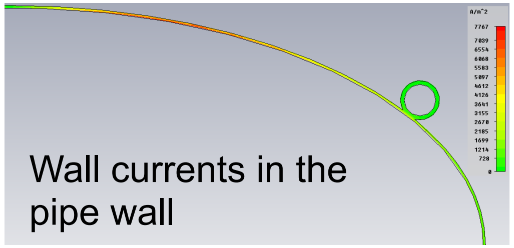
# SIS100 beam pipe




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 !**