Electrostatic septa with heavy ions: challenges for machine protection

Björn Gålnander, D. Ondreka, GSI

5th Slow Extraction Workshop, Wiener Neustadt, 2024

Outline

- SIS18, electrostatic extraction septum
  - Damage potential of heavy ion beam loss for anode wires
  - Protective collimators, recommissioning

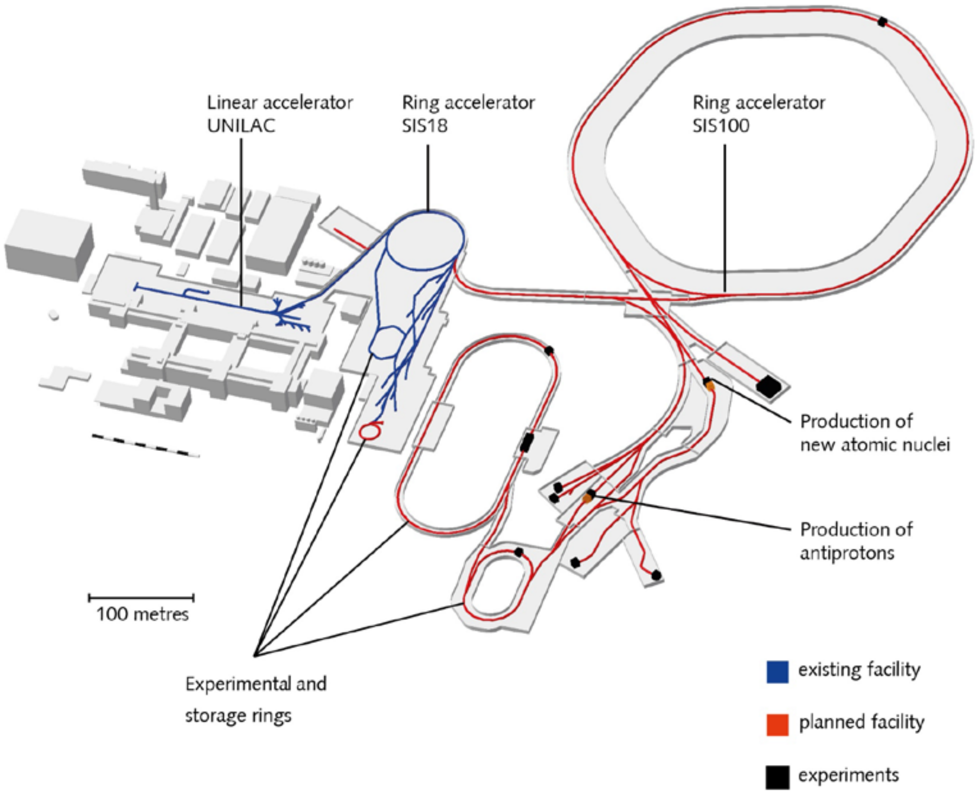
- SIS100, electrostatic extraction septum
  - High intensity heavy ion beam extraction, and extraction losses
  - Electrostatic septum design and ideas for machine protection

Overview GSI, FAIR

- GSI – Helmholtzzentrum für Schwerionenforschung
- FAIR - Future Facility for Antiproton and Ion Research
- Darmstadt, Germany

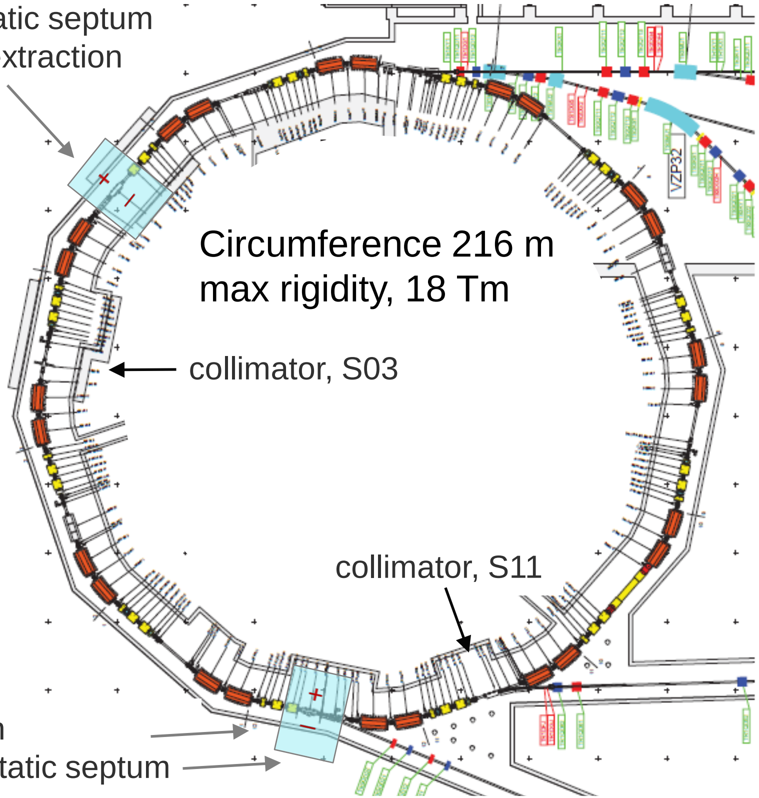
- SIS18, synchrotron 18 Tm
- SIS100, synchrotron 100 Tm

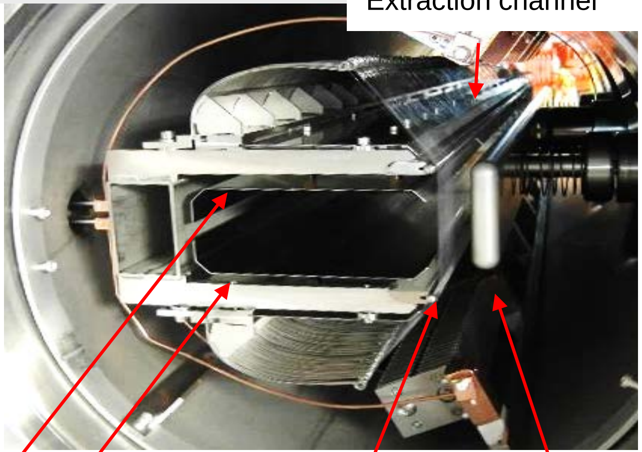
- Large range of ions from protons to uranium, multiuser facility.



see Talk by D. Ondreka

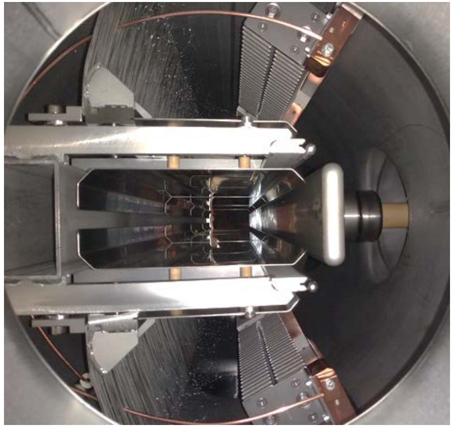
SIS18, Electrostatic extraction septum





- 1.5 m length, gap 18 mm at 160 kV.
- Deflection angle 2.5 mrad
- Anode wires $W_{75}Re_{25}$ 100 µm
- Pretension 2 N, compensating force from transverse E-field, and retract broken wires
- Cathode, Al, anodized, 50 µm

Machine protection failure, SIS18, ES



- Damaged wires, upstreams
- Springs retracted, shortening of NEG panel.

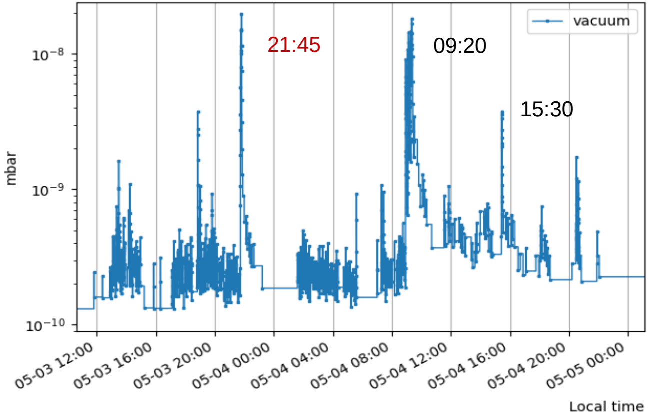
- Disassembled ES, 47% of anode wires broken, 0.71 m / 1,5 m. one wire per 2 mm, 356 wires, .

- Detail of broken wires and retracted pre-tension springs

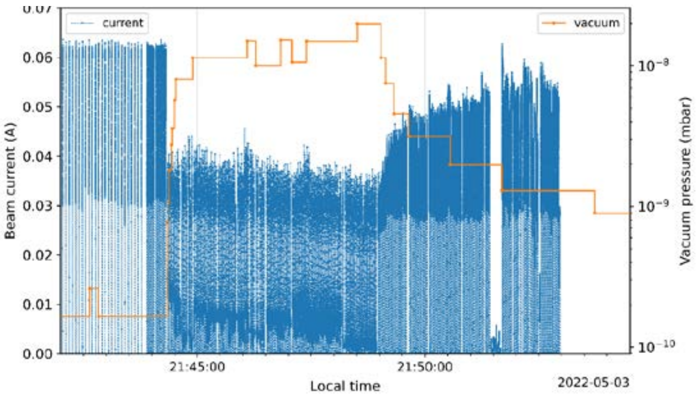
- Anode wires at SIS18 ES were damaged to 47% of the length during beam operation, in May 2022, high intensity U, about $4 \cdot 10^{10}$ ions/cycle.
- Last time wires were damaged, 2002.
- Successfully repaired, 2023, at beam shut-down.

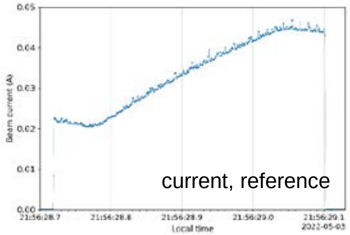
Failure analysis, vacuum at ES and beam current

Vacuum at ES, in sector 4, GS04VM2

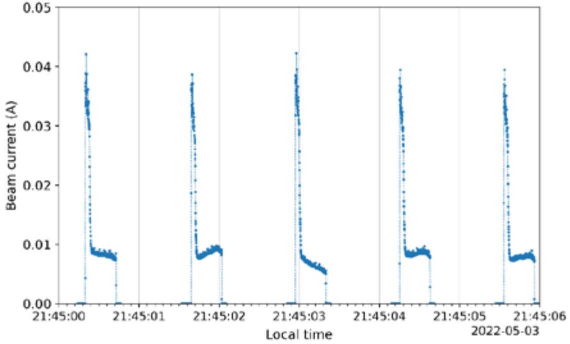


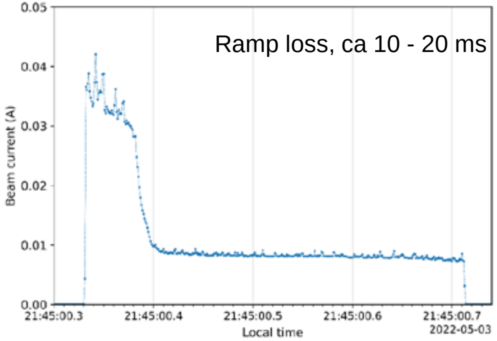
Beam current, DCCT, and vacuum at ES, 21:45 peak





Beam current DCCT, beam loss at beginning of ramp





- $^{238}U^{28+}$, loss at beginning of magnet ramp, dispersive losses, ca $1\cdot10^{10}$ ions per cycle,
- Vacuum pressure increase due to heating up of wires, gas desorption (evaporation)
- Failure of RF-cavities, too low voltage (in two cases.)
- Archiver data and LSA trim log

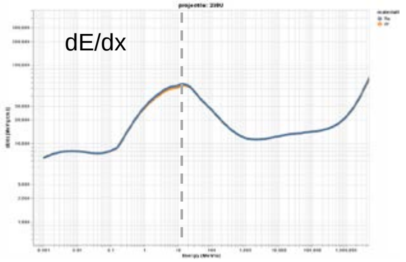
see, B. Gålnander, et al., IPAC'23, TUPM098
jacow.org/IPAC2023/pdf/TUPM098.pdf

When does an anode wire break?

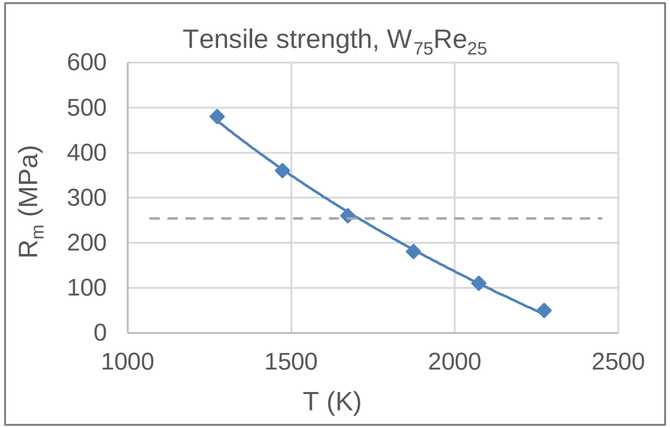
- The wire will break either when it melts, ca 3500 K, or evaporates (very low vapour pressure), or the stress is higher than the tensile strength, 1700 K.
- $^{238}U^{28+}$, at injection, 11.5 MeV/u, has a high specific energy loss, dE/dx, 104 MeV/µm, range **35 µm** in $W_{75}Re_{25}$. (Atima)
- 100 µm diam, all the kinetic energy of the ion is deposited in the first wire hit.
- 2.7 GeV per ion, or $4.35 \cdot 10^{-10}$ J. For 10^{10} particles, **4.35 J.**
- The force from the springs 2 N, stress **254 MPa**. Exceeds tensile strength at T > 1700K.
- Fast losses ~ms, *neglecting radiation and conduction*. The average heat capacity of W is C_p = 0.150 J/(g K).
- Assuming beam full height a injection, 37 mm, (50 mm mrad vert.).
- Energy needed to reach 1700 K, **1.2 J.**
- To break one wire, a loss of **$2.7 \cdot 10^{9}$** ions needed. 10^{10} ions can thus **break 3 wires**.

$$\frac{dT}{dt} = \frac{P_{loss}}{C_p(T)\,m}$$

$$\Delta T = \frac{\Delta E_{loss}}{C_{p,ave}\,m}$$



ATIMA, web-docs.gsi.de/~weick/atima,



Data from Plansee GmbH.

see, B. Gålnander, et al., IPAC'23, TUPM098
jacow.org/IPAC2023/pdf/TUPM098.pdf

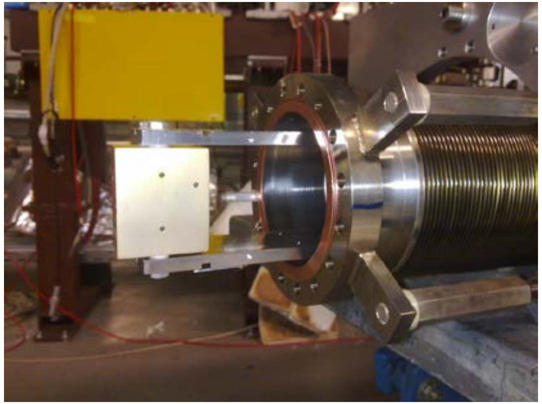
Risk of damage due to fast beam loss

- Critical intensities for wire damage, at 11.5 MeV/u:
  (fast losses ~ 10 ms, *ignoring radiation and conduction*)
  - U, $2.7 \cdot 10^{9}$ ions
  - Ar, $1.6 \cdot 10^{10}$ ions
  - N, $6 \cdot 10^{10}$ ions
  - C, $8 \cdot 10^{10}$ ions

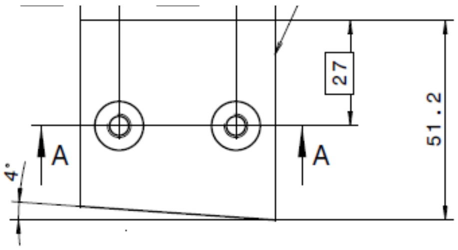
- Scales with ion mass, A_u , if range < wire diameter, for constant T_u.
- (but $dE/dx \sim Z_{ion}^2$ from Bethe-Bloch)
- For repeated losses at high repetition rate
  even increased risk, due to successive heat up
- In addition sparking could add to the problem

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Mitigation - moveable collimators for ES protection, SIS18



- Moveable collimators in S03 (GS03DS3H) and S11 (GS11DS3H), Installed for protective purposes.
- Positions not checked systematically, seems to have been forgotten since no damage for a long time, last 2002.
- Not regularly very high intensity > $1{\cdot}10^{10}$ part./cycle in operation of U or similar (Pb, Au).



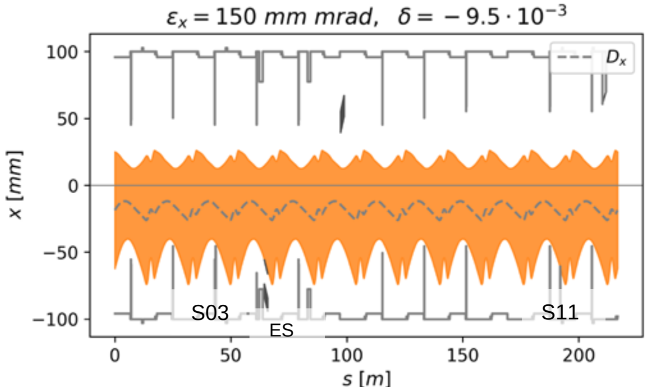
Collimator positions, as determined from beam pipe set value and position from beam axis (fba)

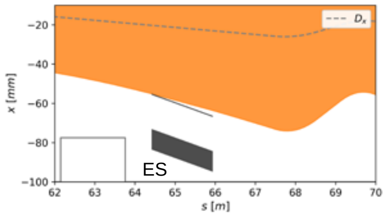
GS03DS3H	set (mm)	fba (mm)
max out	8.0	-45.4
	0.0	-37.4
beam axis	-37.4	0.0
GS11DS3H	set (mm)	fba (mm)
max out	5.20	-60.6
	0.00	-55.4
beam axis	-55.40	0.0

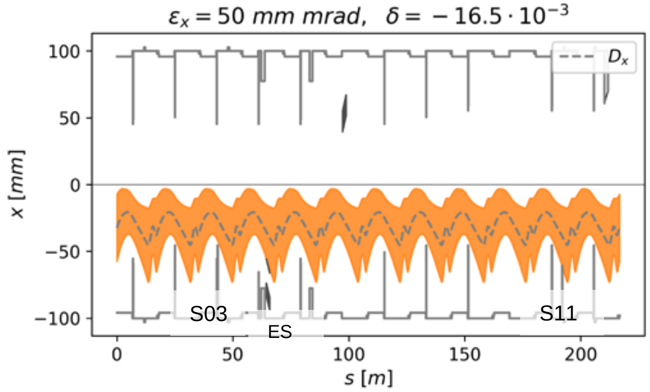
Info from L. Bozyk

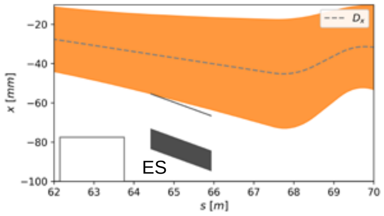
When do the collimators protect for dispersive losses?

Beam envelopes at different momentum deviation









Momentum deviation at magnet ramp, at RF-failure or non-bunched particles, *p* constant,

$$\delta = \frac{p - p_{ref}}{p_{ref}} = \frac{B\rho_{inj} - B\rho(t)}{B\rho(t)}$$

Beam envelope with momentum deviation,

$$x_{env} = \sqrt{\beta_x \varepsilon_x} + D_x \delta$$

The envelope reaches an aperture limitation, a_x,

$$x_{env} = a_x$$

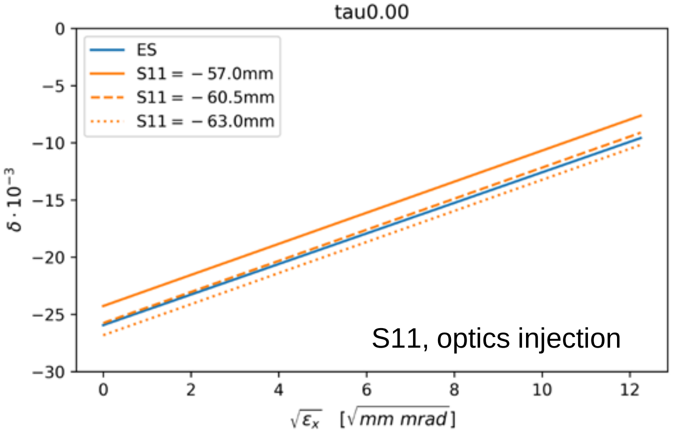
at a momentum deviation,

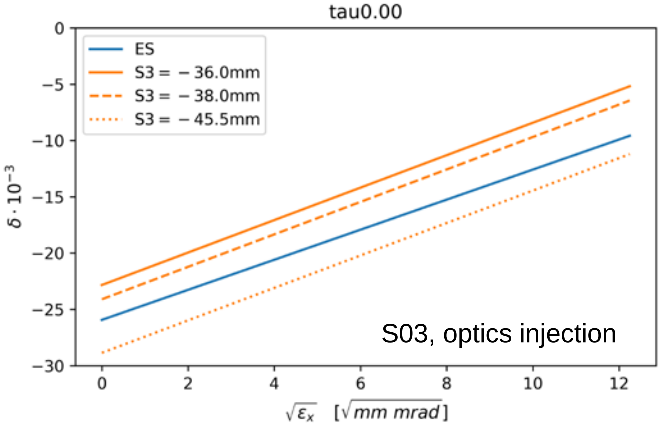
$$\delta = \frac{a_x - \sqrt{\beta_x \varepsilon_x}}{D_x}$$

When do the collimators protect for dispersive losses?

Momentum deviation, δ to reach aperture limitation, a_x vs. emittance:

$$\delta = \frac{a_x - \sqrt{\beta_x \varepsilon_x}}{D_x}$$





- Different twiss parameters at ES, S03 and S11. (slope)
- S11 preferable, since more similar to ES, optically
- S03 protects at 36 mm and S11 at 60.5 mm.
- *S11 should even protect in outer position, 60.5 mm, ideally*

twiss parameters and apertures

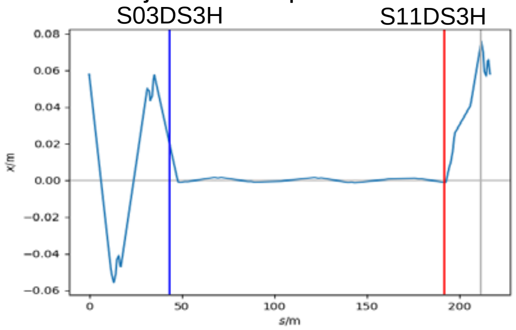
	beta_x (m)	Dx (m)	a_x (m)	A_x (um)
ES	8.14	2.14	55.4	377
S03	5.17	1.58	36.0	401
S11	10.19	1.58	57.0	359

Machine development, collimators for ES protection, SIS18

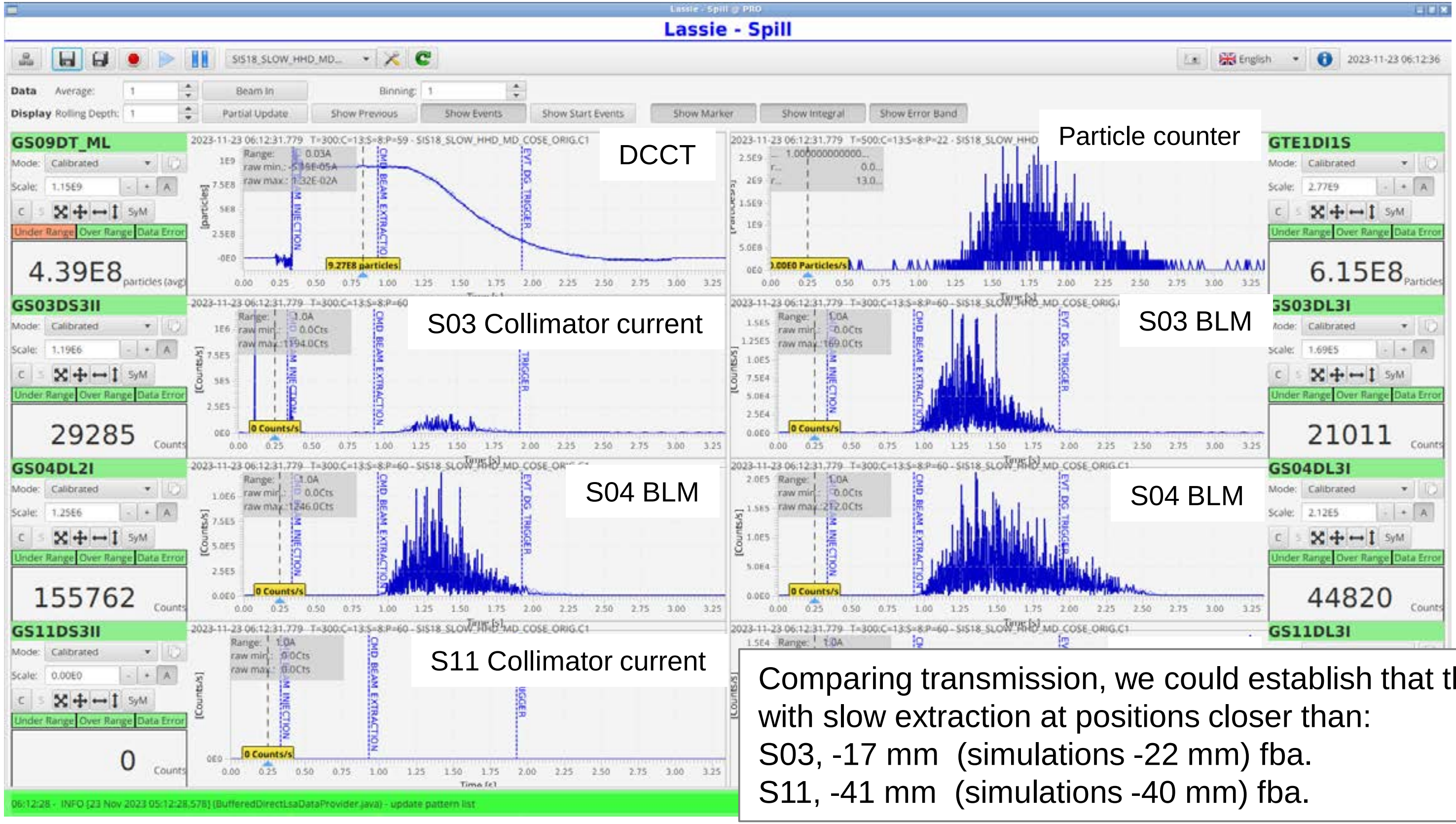
- Machine Development, 2023-12, “recommissioning” for protection of ES by means of moveable collimators in S03 and S11.

- Steps:
- Establish position of collimators in relation to beam optical axis / beam position monitors with corrected closed orbit
  - Measuring edge of beam and beam center, when beam blocked. Injection bump complicates this (details not in presentation).
  - *Found an offset of S03 and S11 with about 5-6 mm, closer to beam axis than expected.*
- Find protective position that
  - does not interfere with multiturn injection.
  - does not interfere with slow extraction
- Provoke losses to see that the scrapers protect the ES.

Injection bump closed orbit



Interference with slow extraction, GS03DS3H



Example:
S03 scraper
 -22 mm fba
(set -15 mm)

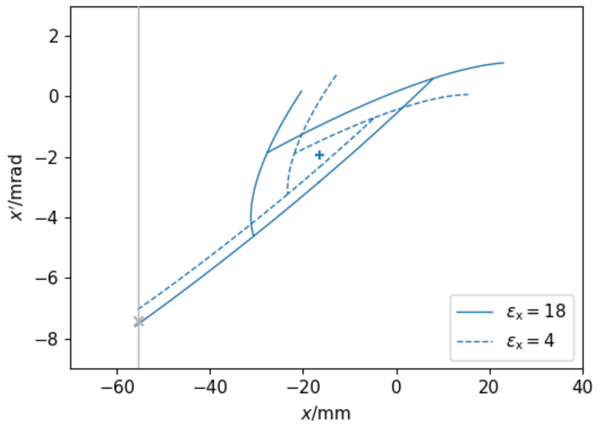
Collimator current shows losses at injection and extraction

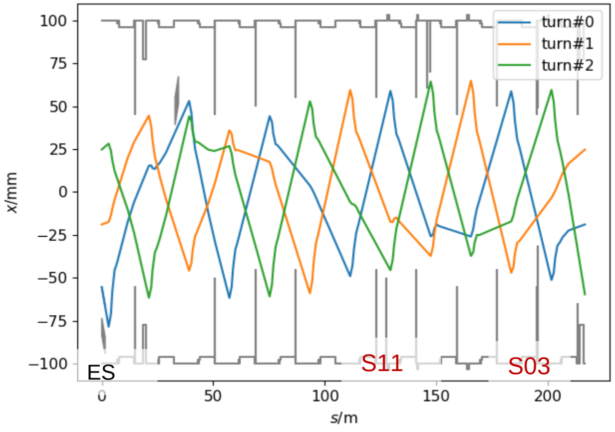
BLM shows losses at beginning of extraction (last turns of extracted beam particles), but not at injection, due to low energy

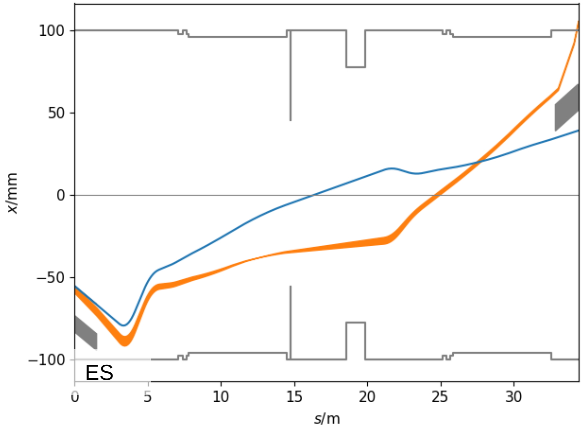
Comparing transmission, we could establish that the collimators interfere with slow extraction at positions closer than:
S03, -17 mm (simulations -22 mm) fba.
S11, -41 mm (simulations -40 mm) fba.

Margin to collimators at slow extraction,

- Simulation of margin at collimators S03 and S11 at slow extraction, quadrupole tune sweep, SIS18.
- High amplitudes of resonant particles at last turns before extraction, check margin



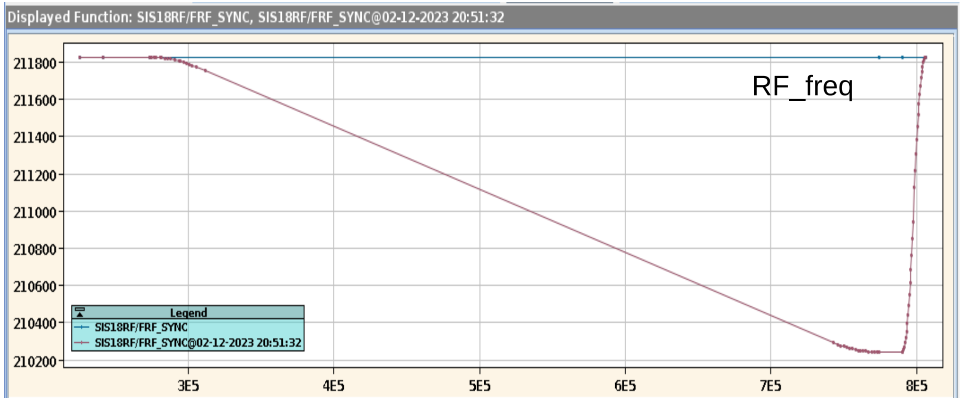


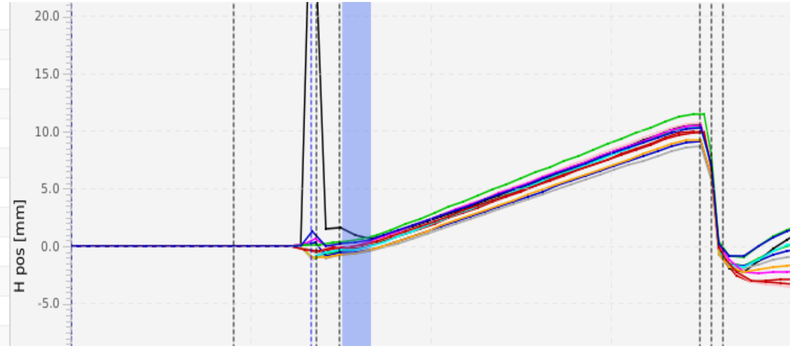


separatrix angle: x_s' = 7.6 – 7.0 mrad
margin s11 (mm): **9.5** – 19.2
margin s03 (mm): 13.1 -- **10.4**
for S11 at -50.4, and S03 at -31.8 mm

Simulate dispersive losses, RF-ramp

- Change RF frequency, with constant magnetic dipole field. Gives a dp mismatch.
- Controlled ramp, (dpfrev) ca 0.5 s, at injection energy, U^{73+}.
- To provoke dispersive losses at collimators and ES.



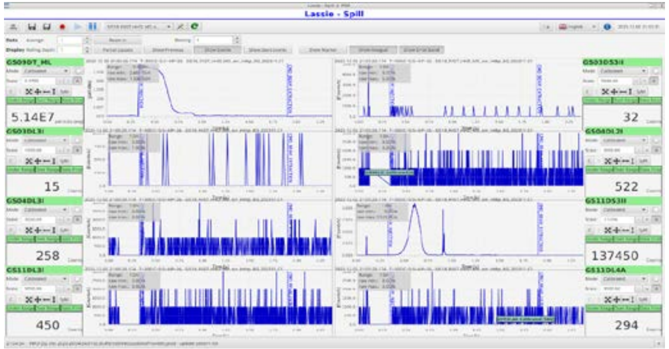


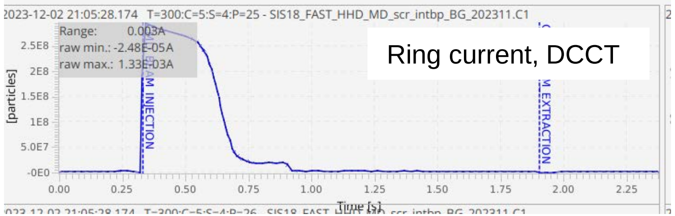
Positions at BPMs, dp = -0.5% ramp, dx = 10 mm consistent with D_x = 2.05 m.

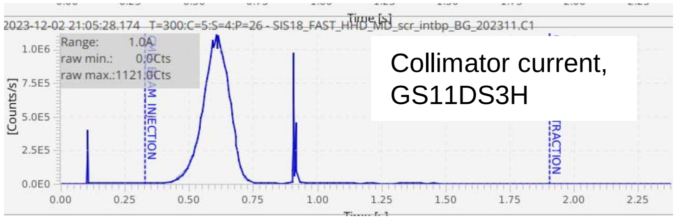
Note BI coord. system, positive x, inside of ring.

Simulate dispersive losses, RF-ramp, GS11DS3H

- U^{73+} at injection energy, 11.5 MeV/u, 3e8 ions/cycle.
  dp_ramp = -1.0 %,
- Example:
  - S11, -55 mm fba,
  - S03, fully out.
- Losses seen at collimator current, S11DS3H, as expected.
- No signals at BLMs (injection energy and low intensity 3e8), so difficult to exclude losses also at other places, e.g. ES.





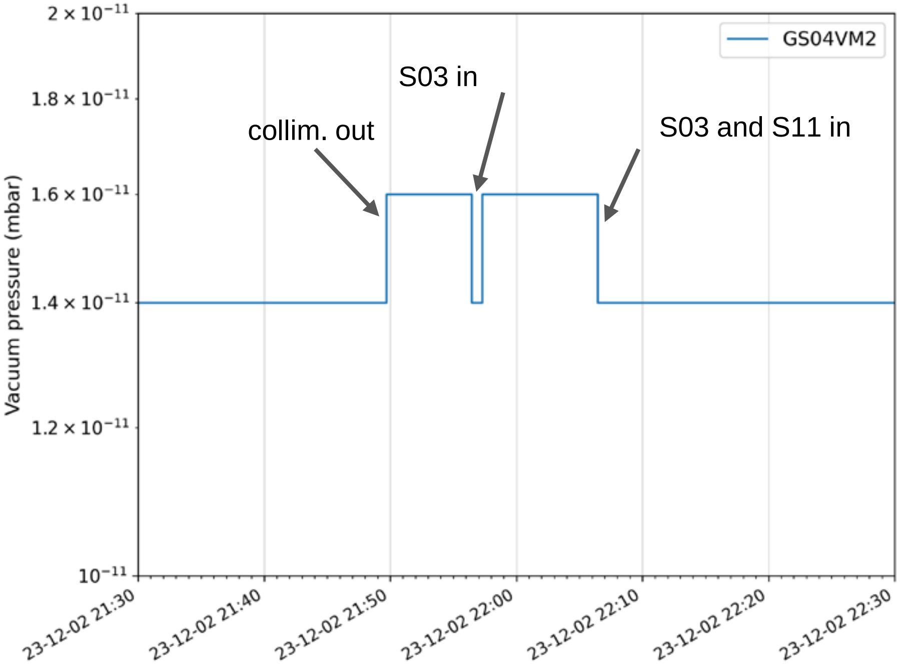


- Plan to repeat at higher energies to see BLM signals.

Dispersive losses, monitoring vacuum at ES

- Since no signals at BLMs at injection energy we monitored vacuum at the ES, to see when losses appear at ES.
- dp_ramp = -0.8%, and orbit bump of 8 mm at the ES to provoke losses.

- Correlation collimator positions and vacuum, showing the protection.
- Vacuum pressure at ES sensitive to losses at wires, could be used for machine protection / interlock.



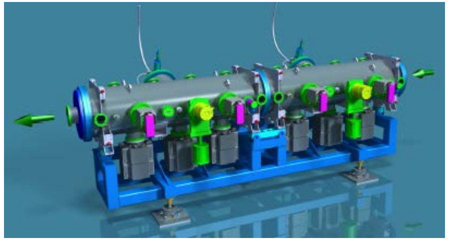
Summary – protection of SIS18 ES

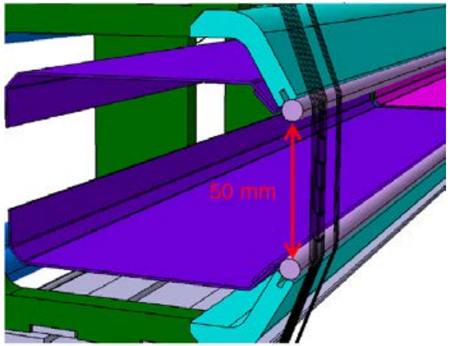
- Preliminary “recommissioning” for protection of ES by means of moveable collimators in S03 and S11, performed.
- Calculations show S03 at 36 mm and S11 at 60 mm fba should protect, if perfect alignment and no orbit distortions.
- Settings found, which ***most probably*** protects ES for injection losses: S03 at 31 mm and S11 at 50 mm from beam axis.
  - Compatible with high intensity injection.
  - Compatible with fast and slow extraction. About 10 mm margin at slow extraction.
  - Used successfully at Engineering run 2023, high intensity U.

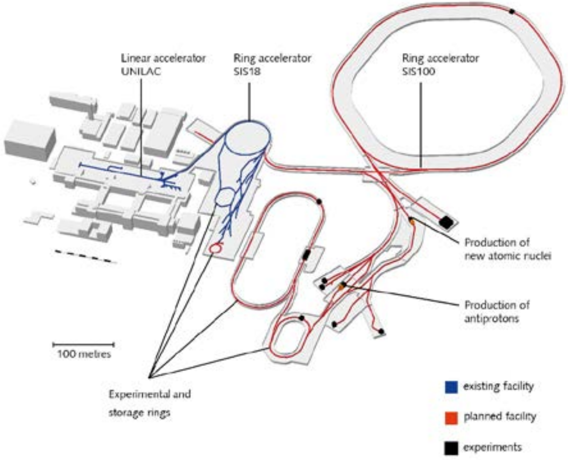
Next steps, open questions:

- More measurements with provoked losses for different beams to establish margin at ES.
- Establish procedure for **high intensity** operation of SIS18 (important for FAIR operation):
  - Beam based procedure to check protection
  - Closed orbit needs to be well corrected, e.g.
    - If we have closed orbit bump at ES, then protection can fail.
  - Interlock for collimator positions for high intensity operation.
- Further protection ideas: Vacuum monitoring and interlock at ES.

SIS100, slow extraction ES







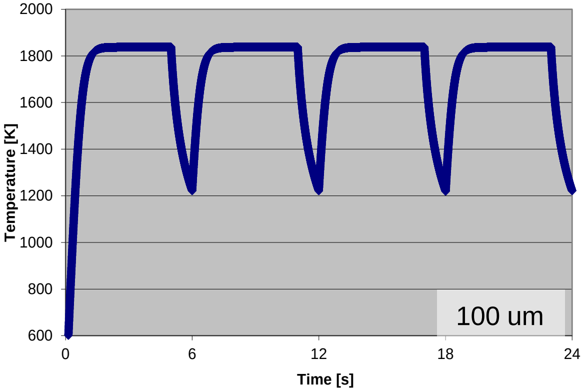
Electrostatic septum – ES

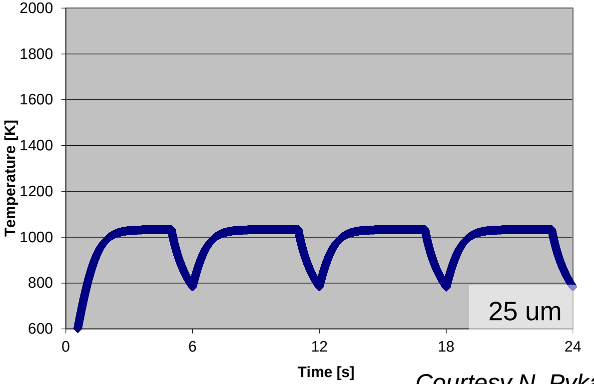
- 2 x 2.3 m length,
- Gap 20 mm, 160 kV.
- Deflection angle 1.2 mrad (2 x 0.6 mrad)
- Anode wires $W_{75}Re_{25}$ 100 µm
- Pretension 1 N (2 N, SIS18)
- Height 50 mm (62 mm, SIS18)
- Delivery 2024

see Talks by D. Ondreka, Mo, Tu

SIS100, anode wire temperature at extraction

Anode wire temperature, $5 \cdot 10^{11}$ ions/cycle, 1 + 5 s, U^{28+}, 400 MeV/u, 5 mm step size.





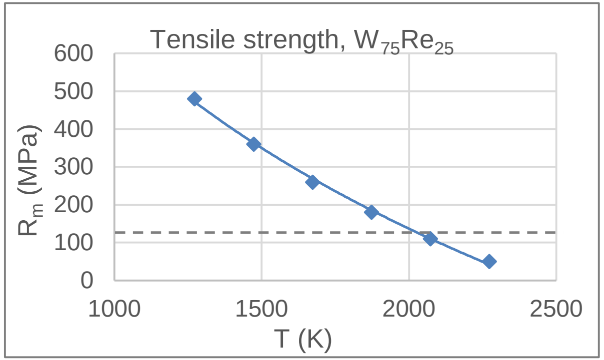
Courtesy N. Pyka GSI

Depends on slow extraction conditions, see talk by D. Ondreka, Tue

$$\frac{dU}{dt} = P_{loss} - \varepsilon\sigma_b A_s (T - T_0)^4 - \kappa \frac{A_c}{l}(T - T_0)$$

$$\frac{dT}{dt} = \frac{1}{C_p(T)\, m} \frac{dU}{dt}$$

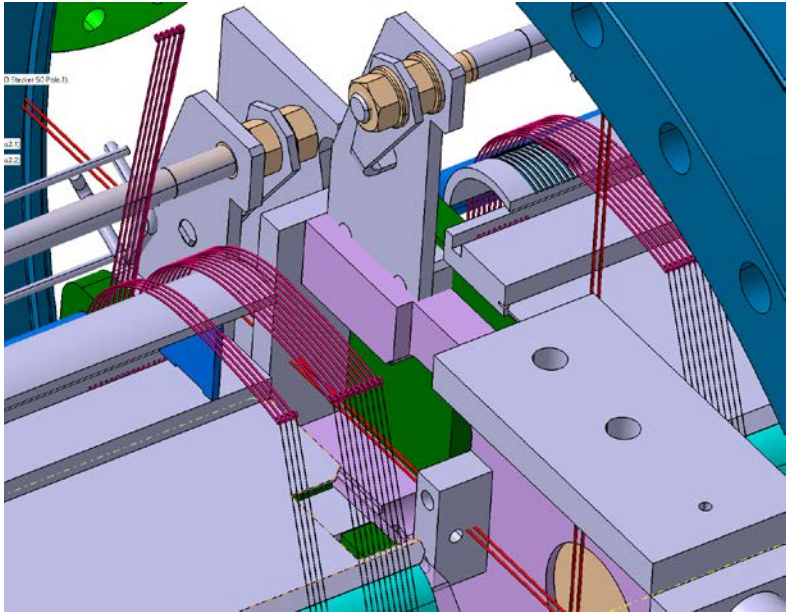
100 um, 1.0 N : 127 MPa



- Heat load from inherent beam loss at wires high dE/dx of heavy ions like U^{28+}, steady-state temperature, T_s = 1830 K, at design intensities.
- Tensile strength limit of wire: 2000 K, small margin, extraction parameters important, **step size**.
- Higher area to volume ratio of thinner wire makes radiation cooling more effective, 60 µm or 25 µm was considered.
- However: Calculations show thinner wires too sensitive to sparking. (Energy in electrode gap, ca 0.7 J).
- Decision: start early operation with 100 µm wires, before highest intensities reached.

SIS100 protection, wire damage detection system

- SIS100 ES has a system for detection of broken wires by electrical contact of the spring of the broken wire.
- The HV-supplies have detection systems for spark detection and interlock.



Summary - challenges for SIS100 ES and ideas for protection

- Slow extraction at high intensities of heavy ions, inherent losses leads to high temperature of anode wires. Difficult to monitor slow extraction conditions, e.g. step size.
- Wire damage detection system is implemented, also sparking detection and interlock.

Ideas for machine protection:

- Diffusive scatterer (passive diffuser)
  - limited space, many different ions, energies and working points makes design non-trivial
- Temperature monitoring of wires with IR-camera
  - first estimates showed no available system had sufficient performance
- Vacuum monitoring at ES, and interlock.
- Transmission and beam loss monitoring, and interlock for high intensity operation.

Questions, discussions:

- Practical experience from discharges and thin wires, 60 um, 25 um?
- Experience of temperature monitoring of anode wires, or diffusor? IR-camera, thermocouple…

- Thanks for your attention!

Different optics SIS18