Status of SIS100 Slow Extraction Design including Effects of Measured Magnetic Field Errors

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Abstract

The synchrotron SIS100 at FAIR, currently under construction in Darmstadt, Germany, will deliver slow extracted proton and ion beams up to 100 Tm employing resonant extraction. Its compact super-ferric dipole and quadrupole magnets allow fast ramping of magnetic field up to 4 T/s and 57 (T/m)/s, respectively. Recently, field errors have been measured for the dipole magnets and the first batch of quadrupole magnets. Higher order multipoles may interfere with resonant extraction, changing the geometry of the separatrix and conditions for resonant particles. The latter are affected most during their last turns and in the extraction channel owing to their large amplitudes, which amplify the effect of higher order multipoles. SIS100 comprises a set of corrector magnets up to octupole order, which can be used to compensate the impact of magnetic field errors. In this contribution, we report on the status of the slow extraction simulation studies including field errors. Furthermore, we present alternative working points for slow extraction, which are necessary to avoid the transition energy for some of beams required by the FAIR experiments.

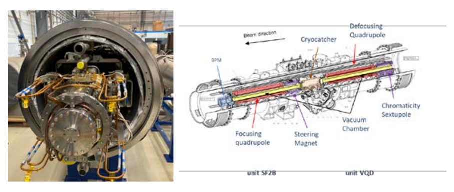
Magnetic field errors and influence on slow extraction

- Field measurements of main dipoles (108) and the first of series quadrupoles (28/168) [1, 2]:
- Systematic field errors, SC Dipoles, b_3 = 2 - 7 ·10^{-4}, b_5 = 1.7·10^{-4} , at 0.85 - 1.9T, R_{ref} = 30 mm.
- Systematic field errors, SC Quadrupoles, b_4 = 1 ·10^{-4}, b_6 = 8 ·10^{-4}, R_{ref} = 40 mm.

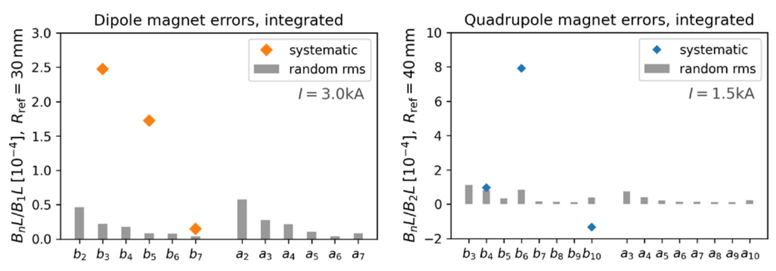
  (integrated fields)

$$B = B_{main} \sum(b_n + i a_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

SIS100 dipole module

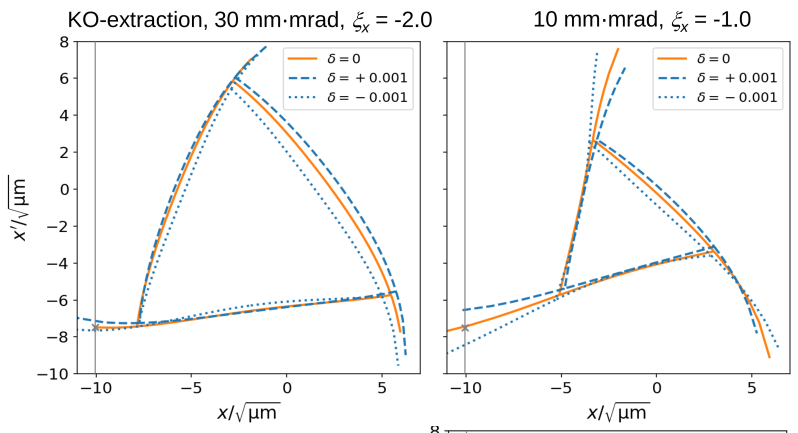


SIS100 quadrupole module

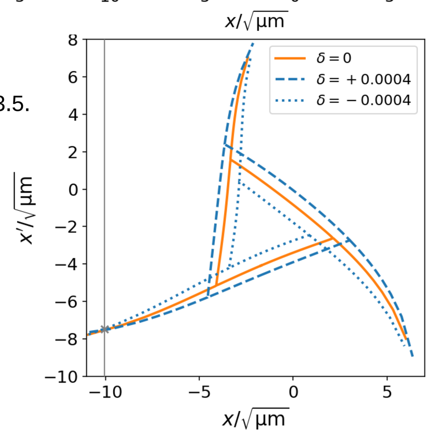


- Influence of systematic field errors on slow extraction:
- Even field harmonics b_4, b_6…, generate Amplitude Dependent Tune Shift (ADTS)
- b_6 from quads, can be compensated with octupole corrector magnets, for specific amplitude and sepatrix size
- b_5 of dipoles, generate ADTS by feed-down for off-momentum particles, in places where dipoles are in dispersive positions. Cannot easily be compensated.
- See effect in Figure, variation of separatrix bending with momentum, for 30 mm·mrad (27 Tm, 0.4 GeV/u U^{28+}) and 10 mm·mrad (100 Tm, 1.5 GeV/u U^{28+}).
- Variation of separatrix angle leads to losses at ES.
- For KO-extraction with constant separatrix, the area can be chosen larger, not so sensitive (left).
- For quadrupole-driven extraction, separatrix area vanishing => angle varies more, leads to higher losses (right).
- Possible mitigations:
  - Install decapole (b_5) correctors at dispersive positions for compensation.
  - Using constant optics [1], COSE scheme to match separatrix sizes for different momenta by adapting chromaticity. Minimizes angular spread at ES.
  - Will be studied in more detail.

Bending of the separatrices, caused by the b_5 error of the dipoles. Leads to angular spread and loss at the ES.



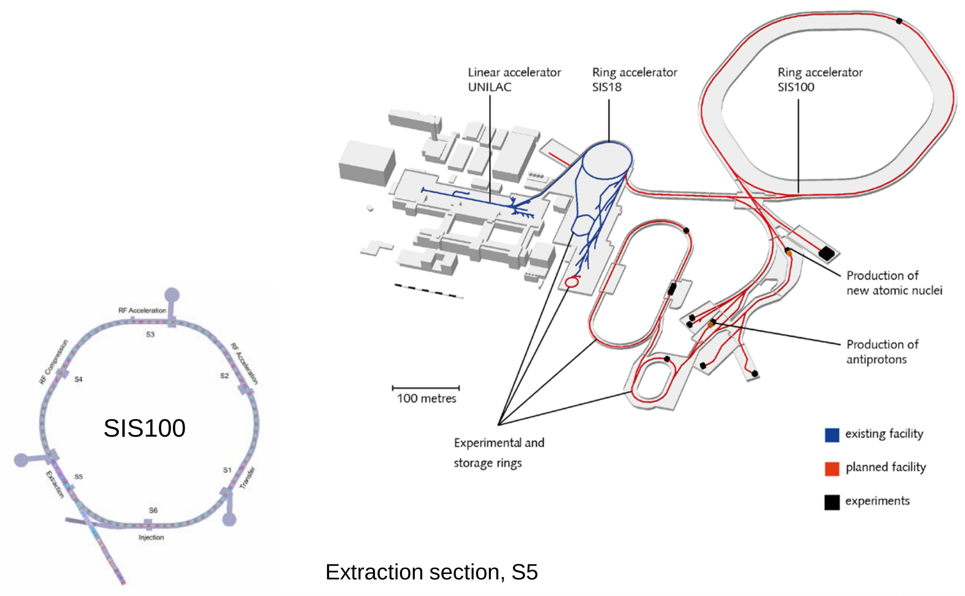
COSE, 10 mm·mrad, ξ_x = -3.5. Reduced angular spread, lower losses



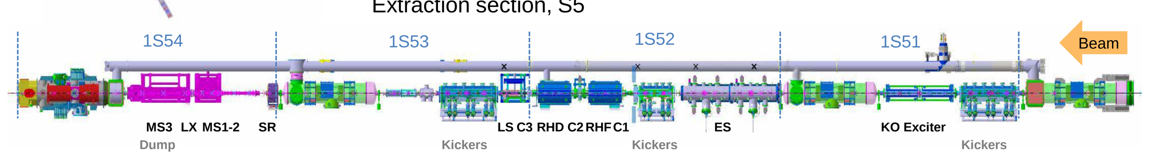
[1] V. Kain et al, PRAB 22, 2019, doi:10.1103/PhysRevAccelBeams.22.101001.

See also, C. Roux, WEPM067, *Superconducting Magnets for SIS100 at FAIR - Status Update*

SIS100 Slow extraction

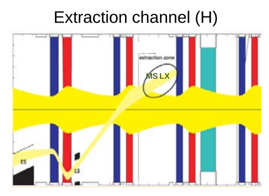


Extraction section, S5

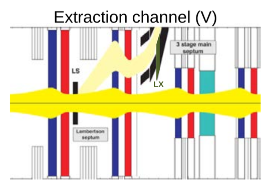


Extraction elements for slow extraction
- Electrostatic extraction septum, ES
- Lambertson septum, LS
- Magnetic extraction septa, vertical, MS1-3
- KO exciter

Extraction channel (H)



Extraction channel (V)

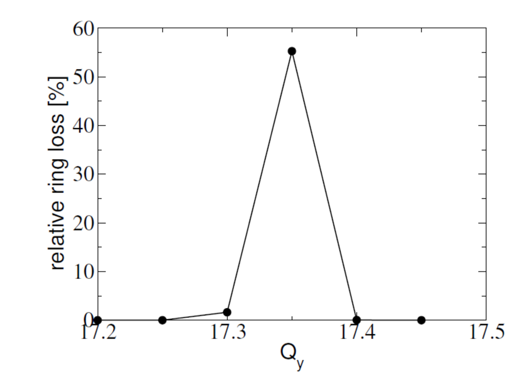


See also,
P. Spiller, MOPA062, *Technological Features and Status of the New Heavy Ion Synchrotron SIS100 at FAIR*
J. Blaurock, THYD1, *FAIR completion of construction works, towards commissioning and first science*.

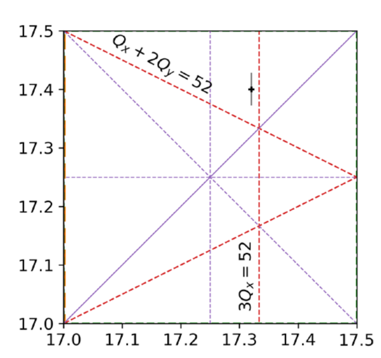
Coupling resonance and losses

- Multiparticle simulations of extraction, show ring losses due to vertical beam blow-up from $Q_x + 2Q_y$ = 52.
- Resonant sextupoles excite extraction resonance $3Q_x$, driving term h_{3000}.
- Coupling resonance $Q_x + 2Q_y$, driving term h_{1020}, blowing up emittance vertically and leading to losses.
- Avoid by staying away from resonance, and possibly vertical chromaticity correction to smaller values.

Losses at coupling resonance for different vertical working points.



Resonances, normal, up to 4th order, around Q_x, Q_y = 17.3, 17.4,



- Driving term h_{1020}, varies with Q_y, coupling resonance is excitation, e.g. Q_y = 17.8 better than 17.4.

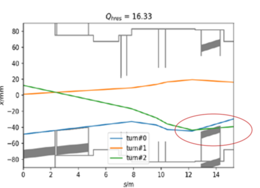
Q_y	h_{1020}/h_{3000}
17.2	1.25
17.4	**0.93**
17.8	0.04

Driving term of coupling resonance, h_{1020} $(Q_x + 2Q_y)$ relative to the extraction resonance, h_{3000} $(3Q_x)$ for different vertical tunes.

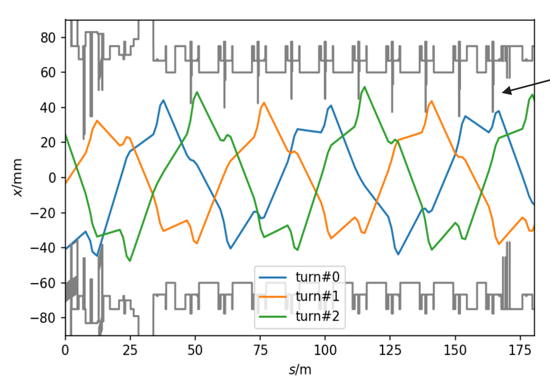
- But Q_y = 17.8 gives high losses at injection, due to high density of systematic resonances close to Q_y = 18. (superperiod of SIS100 is 6.)
- Q_x, Q_y = 17.3, 17.4 selected as standard working point for slow extraction

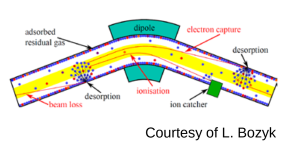
Alternative working points with different transition energy
-- for access of full range of particle energies at slow extraction

- The standard working point (WP) for slow extraction is Q_x , Q_y = 17.3, 17.4, with γ_{tr} = 14.2, T_{tr} = 12.3 GeV/u
- Slow extraction not possible for γ close to γ_{tr} , $\gamma \approx \gamma_{tr} \pm 1$ Energy not available for slow extraction, *11.4 < T < 13.2 GeV/u*
- FAIR experiments, especially CBM, needs a wide range of ions up to the highest energy, (rigidity 100 Tm).
  - e.g.$^{40}Ar^{18+}$, 12.6 GeV/u not available with standard WP.
- New working points considered in the range 16 - 18, Q_x = ~~16.3~~, 16.7, ~~17.7~~, ~~18.3~~, 18.7
  - 16.3 and 17.7 limited by the LS last three turns →
  - 18.3 many systematic resonances, SIS100 superperiod 6.
- => New working points: Q_x = 16.7, 18.7



Analysis of margin, last turns before extraction

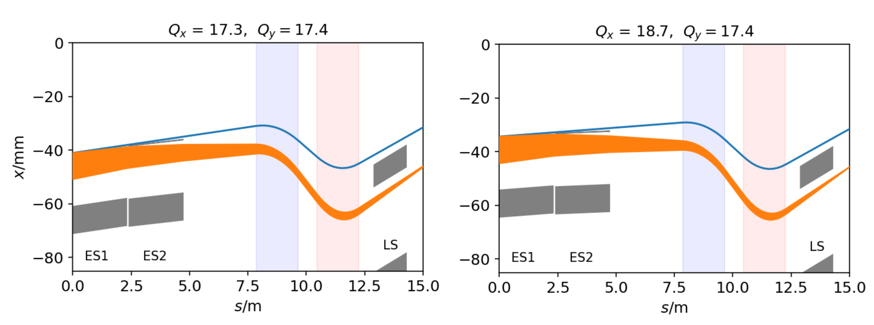




Cryo-catchers [1] to prevent gas desorption due to charge exchange losses, $U^{28+} \rightarrow U^{29+}$.

- Trajectories of last turns before extraction differs different WPs. => cryocatcher collimators positions have been moved to larger distances [1, 2]
- Restrictions, Lambertson septum (LS) fixed, Electrostatic septum (ES) moveable, possible to adapt to focusing of different WPs, but will limit the aperture.

Moveable ES, adapted to different working points



Working points for slow extraction

Q_x	γ_{tr}	T_{tr} (GeV/u)	forbidden range, T (GeV/u)
16.7	13.5	11.7	10.7 – 12.6
17.3	14.2	12.3	11.4 – 13.2
18.7	15.3	13.3	12.4 – 14.2

Aperture limitations, ES postion

Q_x	ES position (mm)	Acceptance (mm mrad)
16.7	-45.5	100 (at LS)
17.3	-41.0	100 (at LS)
18.7	-34.3	73

Ions available at highest energy (100 Tm)

$^{14}N^{7+}$: 14 GeV/u *
$^{40}Ca^{20+}$: 14 GeV/u
$^{40}Ar^{18+}$: 12.6 GeV/u, available with new WP
$^{58}Ni^{28+}$: 13.6 GeV/u
$^{107}Ag^{79+}$: 12.3 GeV/u, available with new WP
$^{197}Au^{92+}$: 11 GeV/u

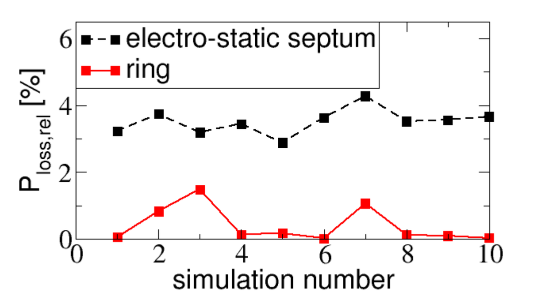
* Simulations show crossing of transition energy is possible with ~10^{10} particles

[1] L. Bozyk et al. Proc. IPAC'17, Copenhagen, Denmark, doi:10.18429/JACoW-IPAC2017-TUPVA056.
[2] B. Galnander et al. Internal report FAIR, *Cryocatcher positions SIS100 revised*, EDMS 2610690, 2022.

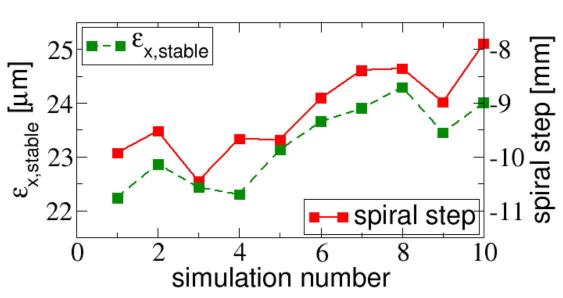
Simulations including random magnet errors

- Simulations of extraction in MADX for 0.4 GeV/u U^{28+}, 27 Tm, KO-extraction. Stable separatrix phase space area ~ 27 π mm·mrad,
- Random samples of measured magnet errors included:
  - dipole magnet errors, $b_3 - b_7$
  - quadrupole errors, $b_3 - b_{10}$
  - main quadrupole strength , rms
- For each error sample, the sextupole orientation (relative strength of the main sextupole magnets) is adjusted to match the angle of the electrostatic septum.

Losses vs. error samples



Stable emittance and spiral step vs. error samples



- Results show that the lattice is relatively robust to errors, with ring losses up to 2% at this energy/separatrix size.
- Ring losses not correlated to spiral step.
- Ring losses seen at vertical aperture (magnetic septa) probably related to excitation of nearby coupling resonance, $Q_x + 2Q_y$ = 52.
  - different sextupole errors (in dipoles) in error samples and need for adjust main sextupole magnets to separatrix orientation.
- Further simulations needed at different energies/stable areas, and studies of possible influence of space charge.

Conclusions

- Systematic field errors of dipole and quadrupole magnets influence slow extraction by distorting the separatrix,
  - Compensation of errors needed to avoid increased losses at the ES anode wires.
  - Promising compensation scheme found using COSE.
- Simulations of random errors at 0.4 GeV/u, show that the lattice design is relatively robust, with ring losses < 2%.
- Influence of a nearby third order coupling resonance, $Q_x + 2Q_y$ leads to ring loss when Q_y close to resonance.
- Standard working point Q_x, Q_y = 17.3, 17.4, relatively strong excitation of coupling resonance, disadvantage,
  - but 17.3, 17.8 gives high losses at injection.
- Alternative working points for different transition energies allowing a wider range of ions at the highest possible energy have been selected.
- Cryo-catcher positions has been modified to accommodate these working points.
- Moveable ES, possible to adapt to focusing, but will restrict the aperture for larger horizontal tunes.

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# Presenter