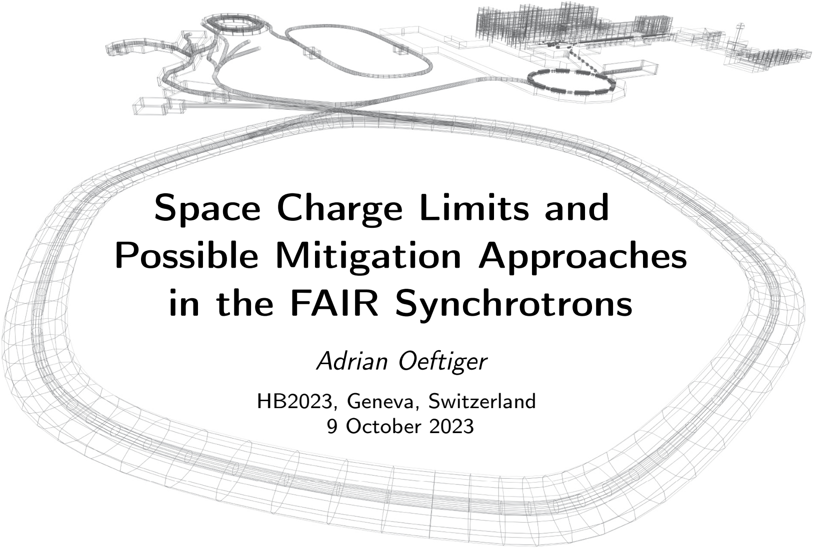
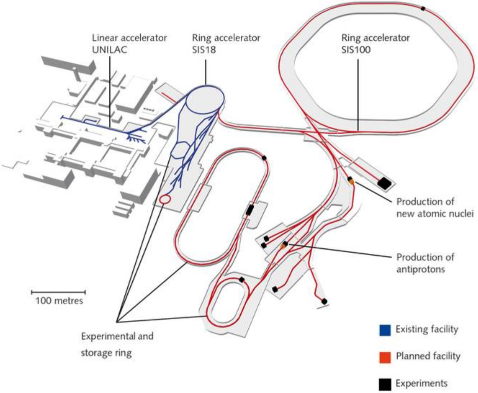


Space Charge Limits and Possible Mitigation Approaches in the FAIR Synchrotrons

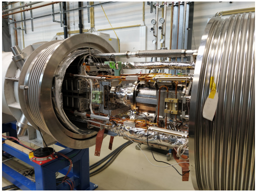
Adrian Oeftiger

HB2023, Geneva, Switzerland
9 October 2023

FAIR Status



drone video of construction site ↗



- string test of full SIS100 arc cell installed
- first SIS100 accelerator section to be installed in January 2024, IPAC'23 paper on SIS100 status ↗

Motivation

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

- SIS100: deliver high-intensity hadron beams

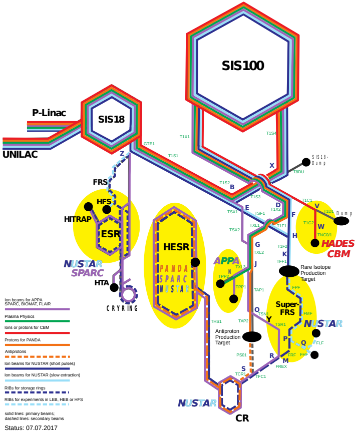


Figure: FAIR complex

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

- SIS100: deliver high-intensity hadron beams
- crucial for performance: maintain beam quality during 1-sec injection plateau
- reference case: uranium U^{28+} beam
    - largest beam size vs. transverse aperture
    - space charge induced losses
        - ⇝ important: dynamic vacuum stability
        - ⟹ low-loss operation < 5%!

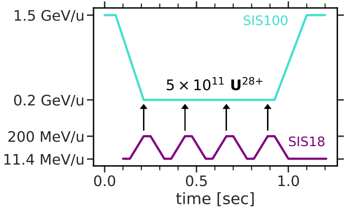


Figure: SIS18 to SIS100 transfer

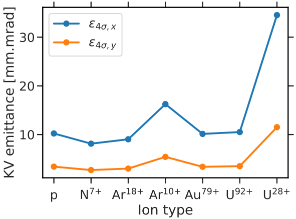


Figure: scaled beam sizes at 18 T m

Motivation

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

- SIS100: deliver high-intensity hadron beams
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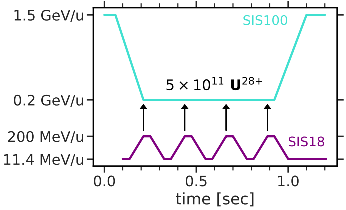


Figure: SIS18 to SIS100 transfer

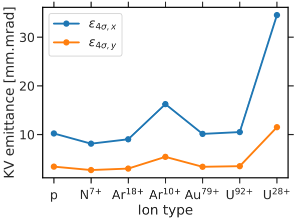


Figure: scaled beam sizes at 18 T m

key questions

- What is the maximum tolerable intensity at the space charge limit?
- How to increase the space charge limit?

Contents

Structure:

A. The Model

B. Betatron Resonances:
   - Intrinsic from Space Charge
   - External from Field Errors

C. Space Charge Limit

D. Mitigation Measures: Conventional & Novel
   - β-beat Compensation
   - Bunch Flattening
   - Pulsed Electron Lenses

A. The Model

Space Charge Modelling

Simulation model:

- track macro-particles (m.p.) through accelerator lattice & space charge kicks

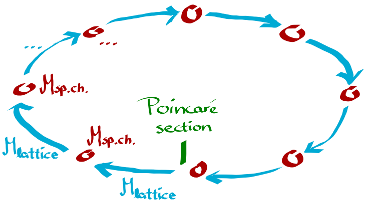


Figure: sketch of simulation model

Space Charge Modelling

Simulation model:

- track macro-particles (m.p.) through accelerator lattice & space charge kicks
- nonlinear 3D space charge (SC) models:
  - *self-consistent* ***PIC****:* particle-in-cell for open-boundary Poisson equation
  - *fixed frozen (****FFSC****):* constant field map independent of m.p. dynamics
  - (*adaptive frozen (****AFSC****):* field map scaled with m.p. distribution momenta)

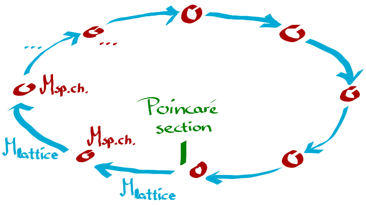


Figure: sketch of simulation model

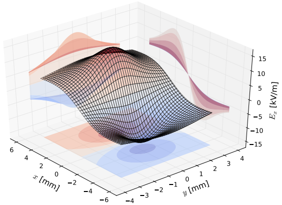


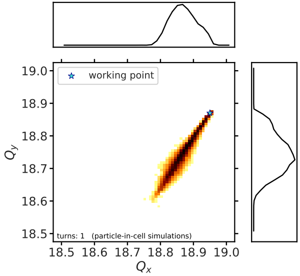
Figure: horizontal space charge field

Maximum SC Tune Shift

$$\Delta Q_y^{SC} = -\frac{r_c \lambda_{max}}{\beta_0^2 \gamma_0^3} \oint \frac{ds}{2\pi} \frac{\beta_y(s)}{\sigma_y(s)(\sigma_x(s)+\sigma_y(s))}$$

r_c : classical ion radius λ_{max} : maximum line density

β_0 : speed in $[c]$ γ_0 : Lorentz factor $\sigma_{x,y}$: local rms beam size



Hor. norm. rms emittance ϵ_x	5.9 mm mrad
Vert. norm. rms emittance ϵ_y	2.5 mm mrad
Rms bunch length σ_z	13.2 m
Bunch intensity N_0 of U^{28+} ions	6.25×10^{10}
Max. space charge ΔQ_y^{SC}	-0.30
Rms chromatic $Q'_{x,y} \cdot \sigma_{\Delta p/p_0}$	0.01
Synchrotron tune Q_s	4.5×10^{-3}
Kinetic energy	$E_{kin} = 200\,\mathrm{MeV/u}$
Relativistic β factor	0.568
Revolution frequency f_{rev}	157 kHz

B. Betatron Resonances

Only Space Charge

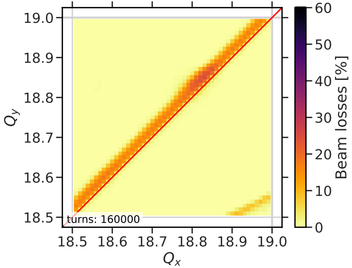


Figure: tune diagram of beam loss

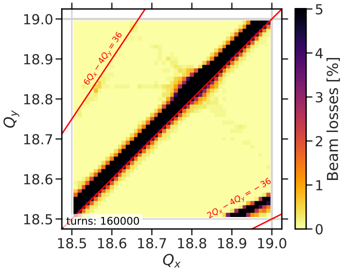
Symmetric error-free SIS100 lattice:

- perfect dipole and quadrupole magnets
- exact symmetry of $S = 6$
- space charge → only source for resonances
- simulated for 160'000 turns = 1 second

⟹ mainly Montague resonance visible

⟹ absence of low-order structure resonances!

Only Space Charge



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Montague Resonance

Montague resonance $2Q_x - 2Q_y = 0$:

- 4^{th}-order resonance
- intrinsically driven by space charge
- transverse emittance exchange for anisotropic beams

$\Longrightarrow$ stopband always present around $Q_x \approx Q_y$ for SIS100 beams

Space charge model predictions:

– bad: "adaptive frozen" resolves full exchange but predicts too large stopband extent

+ good: "fixed frozen" reproduces stopband edges well!

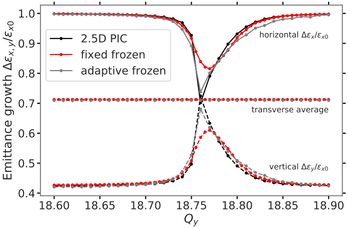


Figure: emittance exchange

Montague Resonance

Montague resonance $2Q_x - 2Q_y = 0$:

- 4^{th}-order resonance
- intrinsically driven by space charge
- transverse emittance exchange for anisotropic beams

$\Longrightarrow$ sto…
for

Observation

"Fixed frozen" model much better suited than "adaptive frozen" to approximate realistic PIC when **identifying loss-free conditions**!

Space charge model predictions:

– bad: "adaptive frozen" resolves full exchange but predicts too large stopband extent

\+ good: "fixed frozen" reproduces stopband edges well!

Figure: emittance exchange

Warm Quadrupoles

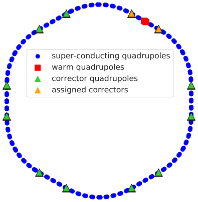


Figure: SIS100 quadrupole survey

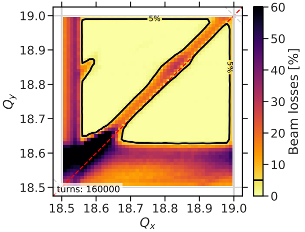


Figure: corrected warm quadrupoles

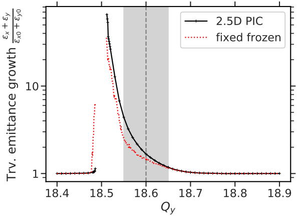
Real SIS100 lattice:

- 2 cold quadrupoles replaced by warm / normalconducting quadrupoles (radiation hardened, required in extraction region)
- breaking of $S = 6$ symmetry by gradient error

⟶ externally driven half-integer resonance

⟶ can be minimised by quadrupole correctors

⟹ FFSC reproduces PIC stopband edges!



Field Error Model

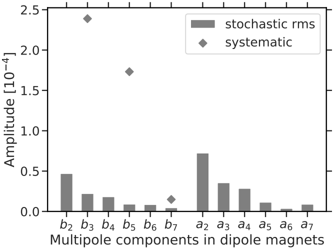


Figure: dipole magnets

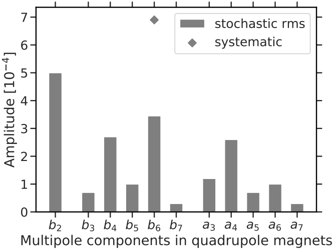


Figure: quadrupole magnets

Field error model extracted from cold bench measurements of magnet units:

- stochastic amplitudes drive non-systematic resonances
- random number sequence → multipole errors for every dipole and quadrupole magnet

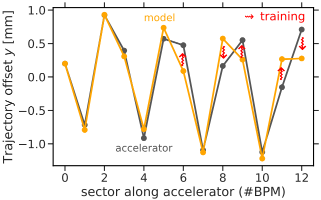
quadrupole model displayed here corresponds to PRAB paper version (based on stamped FoS), see GSI-2021-00450 report ↗ for model based on series production and its comparison

Field Error Model from Beam

HB'23 talk on Wednesday, C. Caliari on "Deep Lie Map Network" ↗:

- machine learning approach: train linear & nonlinear field errors on kick turn-by-turn data
- start from model lattice, learn error multipoles k·L

⟹ effective lattice to better reproduce machine behaviour



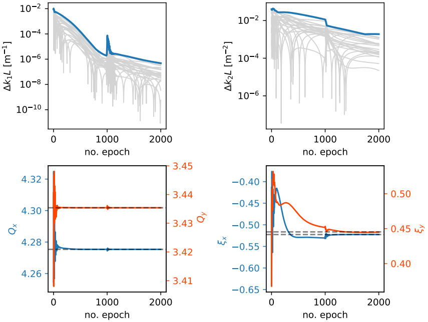


Figure: learning of quadrupole & sextupole errors

Full Model with Space Charge

Linear and nonlinear resonances driven by magnet field errors. Resonance condition without space charge:

$$mQ_x + nQ_y = p \qquad \text{for} \quad m, n, p \in \mathbb{Z}$$

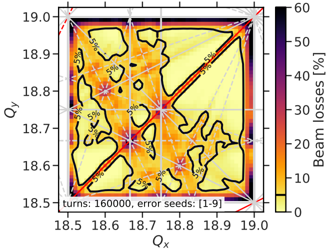


Figure: no space charge

Full Model with Space Charge

Linear and nonlinear resonances driven by magnet field errors. Resonance condition without space charge:

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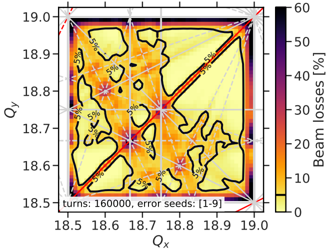


Figure: no space charge

include
$\Longrightarrow$
SC

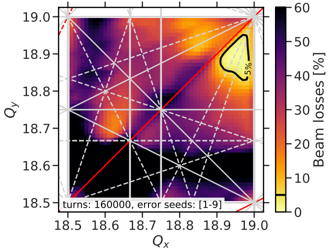


Figure: with fixed frozen space charge

$\longrightarrow$ SC broadens existing resonance stopbands

$\Longrightarrow$ optimal working point area around $(Q_x, Q_y) = (18.95, 18.87)$

Validation with Self-consistent PIC

Self-consistent PIC simulations:

- ✓ validated Montague resonance
- ✓ validated half-integer resonance
- ⟶ now validate full error model FFSC predictions for beam loss

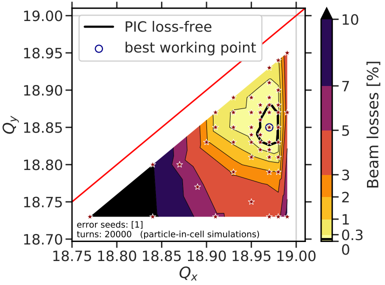


Figure: self-consistent PIC simulations

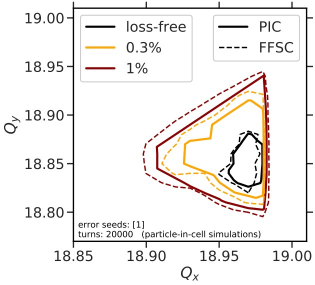


Figure: comparison between SC models

note: PIC simulations take 2 days (on NVIDIA V100 GPU) vs. FFSC simulations with 7 min (on 16 CPU cores, HPC AMD)

C. Space Charge Limit

dynamic definition of space charge limit

reached when loss-free working point area vanishes

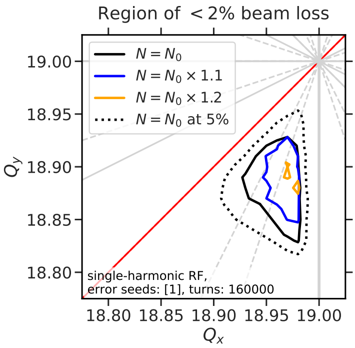


Figure: low-loss area for increasing N

Keeping all beam parameters identical, increasing N:

$\Longrightarrow$ U^{28+} space charge limit at **120%** of nominal bunch intensity N_0:

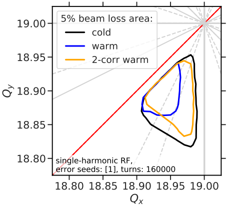
$$\max \left| \Delta Q_y^{SC} \right| = 0.36$$

D. Mitigation Measures: Conventional & Novel

Correction of β-beat

Two sources of β-beat (gradient error):

- warm quadrupoles: uncorrected = 2%



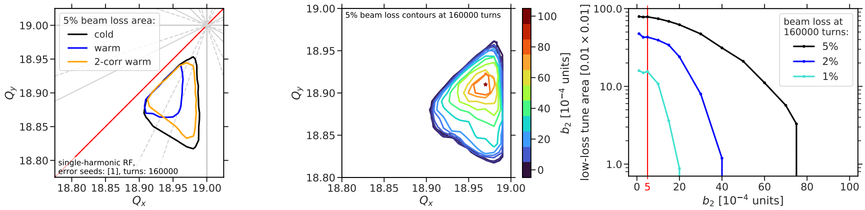
(a) low-loss area with warm quads

Correction of β-beat

Two sources of β-beat (gradient error):

- warm quadrupoles: uncorrected = 2%
- distributed b_2: $\approx 0.5\%$

$\Longrightarrow$ below $b_2 = 10$ units: no significant effect on low-loss area size



(a) low-loss area with warm quads (b) low-loss area with b_2 (c) size of low-loss area vs. b_2

A Word on Coherent Stability

For SIS100, space charge parameter $q = \Delta Q_y^{SC}/2Q_s \approx 33$ at design $N = N_0$:

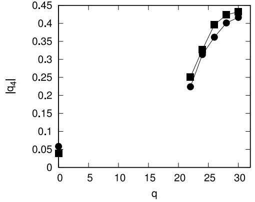
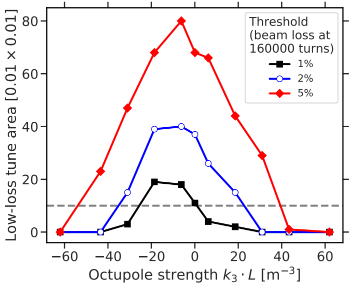


Figure 4: Results of the simulations scans for the $k = 1$ mode: stability thresholds of the octupole power in a dependency from the space-charge parameter q. The circles are for the octupole polarity $q_4 > 0$, the squares are for the octupole polarity $q_4 < 0$.

(a) Required octupole strength for stabilisation of single-bunch resistive-wall instability [V. Kornilov, IPAC'23] ↗



(b) Incoherently tolerable octupole strengths

- octupole current of $k_3 L = 35\,\mathrm{m}^{-3}$ corresponds to $q_4 = 0.55$.

⟹ single-bunch stability through Landau damping from octupoles, transverse feedback system required for coupled-bunch stability

Double-harmonic RF

Add $h = 20$ harmonic in bunch lengthening mode:

$$V_{h=20} = V_{h=10}/2$$

$\Longrightarrow$ obtain flattened bunches with reduced line density at 80% of nominal $\lambda_{\max}$.

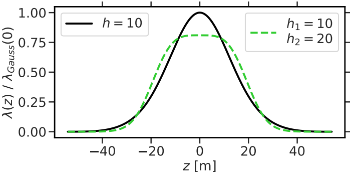


Figure: rms-equivalent line densities

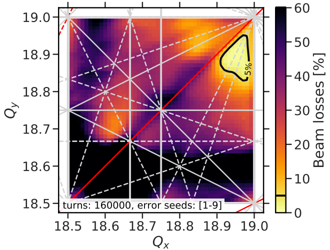


Figure: single-harmonic RF

flatten
$\Longrightarrow$
bunch

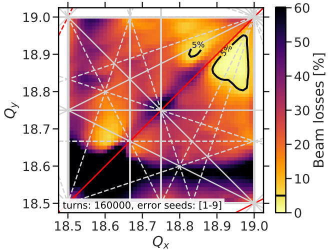


Figure: double-harmonic RF

SC Limit with Double-harmonic RF

Increasing N for double-harmonic RF:

- find space charge limit at **150%** of nominal intensity N_0

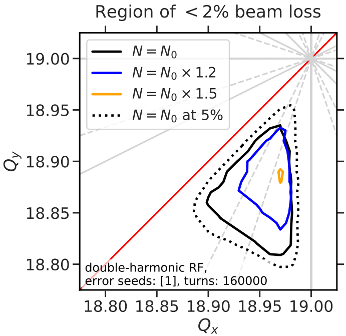


Figure: low-loss area for increasing N

Novel: Pulsed Electron Lenses

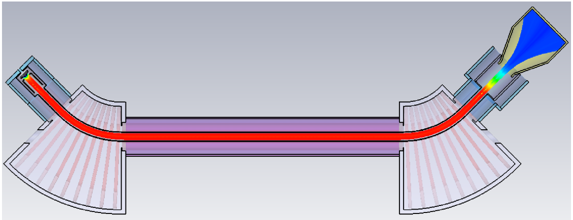


Figure: e-lens model for SIS18 [K. Schulte-Urlichs et al., IPAC'22] ↗

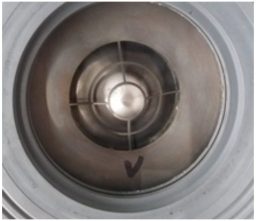


Figure: Modulation grid.

Short insertion (here $L = 3.36\,\text{m}$) with co-propagating electron beam:

- transversely homogeneous distribution
- longitudinally modulated to match ion bunch profile

⟶ compensate longitudinal dependency of space charge

⟹ **suppress periodic resonance crossing**

⟶ additionally provide strong Landau damping for head-tail modes:
V. Gubaidulin et al., PRAB 25, 084401 (2022) ↗ [tbc with strong SC]

Tune Footprint vs. E-Lens Compensation

Some n_{el} e-lenses with I_e current and rms beam size σ_e provide tune shift:

$$\Delta Q_y^{\mathrm{e}} = \frac{1}{4\pi} \sum_{k=1}^{n_{\mathrm{el}}} \beta_y(s_k) \frac{r_c}{Ze} \frac{I_e}{\sigma_e^2 \gamma_0} \frac{1-\beta_e\beta_0}{\beta_e} \frac{L}{\beta_0 c}$$

Define linear compensation degree (for Gaussian bunches $\Delta Q^{\mathrm{KV}} = \Delta Q^{\mathrm{SC}}/2$):

$$\alpha \doteq \frac{\Delta Q^{\mathrm{e}}}{|\Delta Q^{\mathrm{KV}}|}$$

Remarks:

- dipole tune increases with

$$\Delta Q_{\mathrm{dip}} = \alpha \cdot \Delta Q^{\mathrm{e}}$$

- without chroma, $\alpha = 0.5$ yields smallest tune spread!

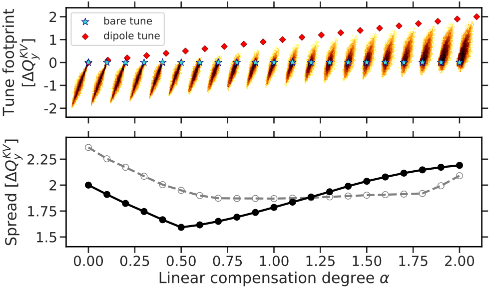
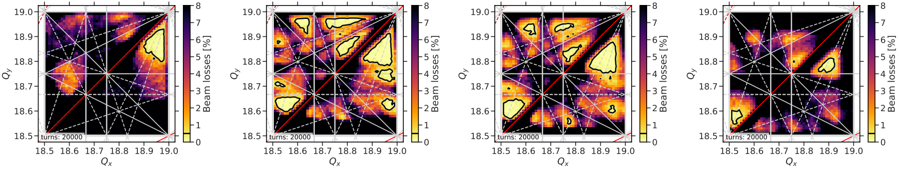


Figure: Gaussian bunch, tune footprint vs. e-lens strength (black: $\Delta p/p_0 = 0$, grey: with natural chromatic detuning)

Optimal E-Lens Configuration

In SIS100 with natural chromaticity:



(a) $\alpha = 0$ (b) $\alpha = 0.5$ (c) $\alpha = 0.7$ (d) $\alpha = 1$

Figure: FAIR design intensity $N = N_0$ with $n_{\mathrm{el}} = 3$ pulsed e-lenses.

- optimal choice of α depends on nearby resonances
  $\Longrightarrow$ depends on particularities of synchrotron
- SIS100: at low $n_{\mathrm{el}} \leq 6$, $\alpha = 0.5$ optimal vs. high $n_{\mathrm{el}} > 6$, $\alpha = 0.7$ better

SC Limit with Pulsed E-Lenses

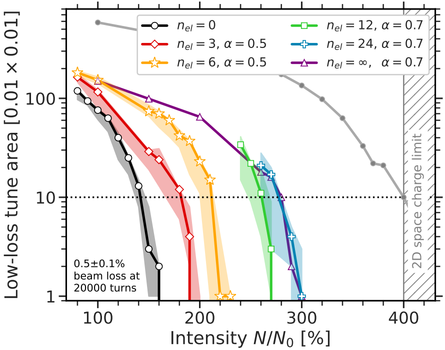


Figure: low-loss area for increasing N

Table: SC limit with electron lenses.

Number n_{el}	SC limit	Gain
0	$1.4 \cdot N_0$	100%
3	$1.8 \cdot N_0$	130%
6	$2.1 \cdot N_0$	150%
12	$2.6 \cdot N_0$	185%
$24, \infty$	$2.8 \cdot N_0$	200%

Remarks:

- SC limit scales well
- $n_{el} = 24$ case saturates gain
- theoretical 2D limit ($Q_s = 0$, no e-lenses) = by construction no periodic resonance crossing

  $\Longrightarrow$ reached after $n_{el} = 24, \infty$

Involved Publications

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25**, 054402 (2022)

Simulation study of the space charge limit in heavy-ion synchrotrons

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Vladimir Kornilov,[1] Dmitrii Rabusov,[2] and Stefan Sorge[1]

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(Received 5 November 2(

Pulsed Electron Lenses for Space Charge Mitigation

Adrian Oeftiger[1,*] and Oliver Boine-Frankenheim[1,2]

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ELECTRON LENSES FOR MODERN AND FUTURE ACCELERATORS

Pulsed electron lenses for space charge compensation in the FAIR synchrotrons

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Characterization and minimization of the half-integer stop band with space charge in a hadron synchrotron

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Conclusion

Summary:

- identified **optimal tune area** in SIS100 around $(Q_x, Q_y) = (18.95, 18.87)$
- explored **space charge limit**: $\max \left| \Delta Q_y^{\mathrm{SC}} \right| = 0.36$
  - nominal SIS100: +20% intensity
  - double-harmonic RF: +50% intensity
  - 3 pulsed electron lenses: +70..80% intensity
- FAIR start planned in 2028 with "Early Science" programme

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take-home messages

- fixed frozen SC model fast & validated tool to identify resonance-free tunes
- dynamic space charge limit: find based on tolerable loss & emittance growth
- pulsed electron lenses: optimum configuration for space charge mitigation

Thank you for your attention!

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