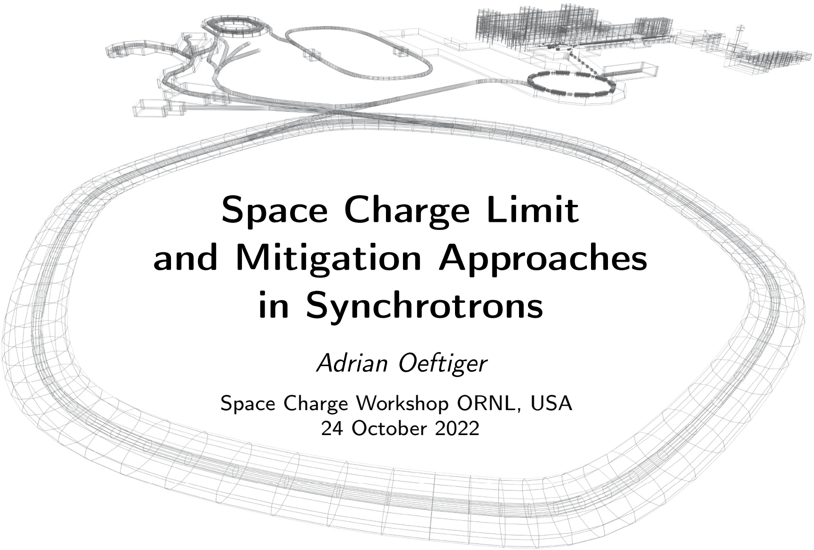

Space Charge Limit and Mitigation Approaches in Synchrotrons

Adrian Oeftiger

Space Charge Workshop ORNL, USA
24 October 2022

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

- SIS100: deliver high-intensity beams

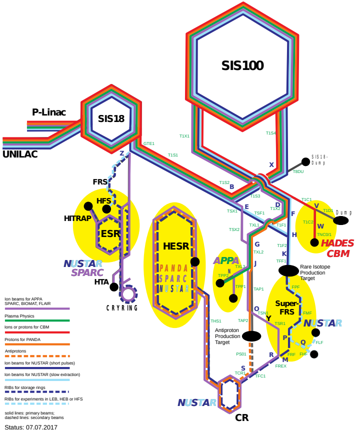

Figure: FAIR complex

Motivation

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

- SIS100: deliver high-intensity beams
- crucial for performance: maintain beam quality during 1-sec injection plateau
- uranium U^{28+} beam most critical:
  - largest beam size vs. transverse aperture
  - space-charge induced losses
    - $\rightsquigarrow$ dynamic vacuum issues
    - $\Longrightarrow$ low-loss operation $< 5\%$!
- key question:
  what is the space-charge limit?

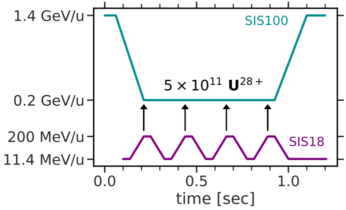

Figure: SIS18 to SIS100 transfer

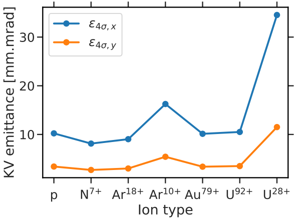

Figure: scaled beam sizes at 18 T m

Contents

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

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

Adrian Oeftiger,[1,*] Oliver Boine-Frankenheim,[1,2] Vera Chetvertkova,[1]
Vladimir Kornilov,[1] Dmitrii Rabusov,[2] and Stefan Sorge[1]
[1]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany*
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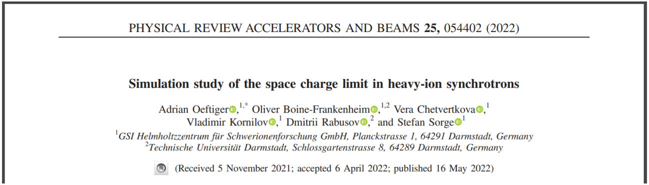
(Received 5 November 2021; accepted 6 April 2022; published 16 May 2022)

Key ingredients of study:

1. detailed model for **magnetic field errors** from cold bench measurements
2. **full tracking model** of machine lattice
3. detailed **space charge** models
   - self-consistent 3D PIC solver (particle-in-cell)
   - fast (approximative) frozen field maps

$\Longrightarrow$ parallelised on multi-core CPU and GPU architectures

Contents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Structure:

A. The Model
B. Betatron Resonances:
   - Intrinsic from Space Charge
   - External from Field Errors
C. Space-Charge Limit
D. Mitigation Measures

A. The 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)

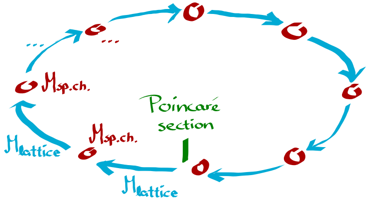


Figure: sketch of simulation model

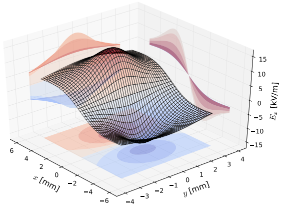


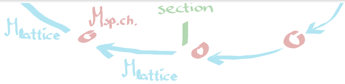
Figure: horizontal space charge field

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

Maximum SC Tune Shift

$$\Delta Q_y^{\mathrm{SC}} = -\frac{Ze}{4\pi\epsilon_0 m_0 c^2}\,\frac{\lambda_{\mathrm{max}}}{\beta^2\gamma^3}\,\frac{1}{2\pi}\oint ds\,\frac{\beta_y(s)}{\sigma_y(s)\left(\sigma_x(s)+\sigma_y(s)\right)}$$



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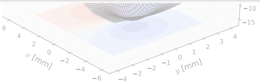


Figure: horizontal space charge field

Beam Parameters

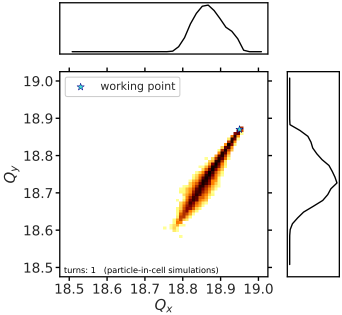


Figure: space charge tune footprint

Table: Considered Parameters for $^{238}U^{28+}$ Accumulation at SIS100 Injection Energy

Parameter	Value
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	0.625×10^{11}
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

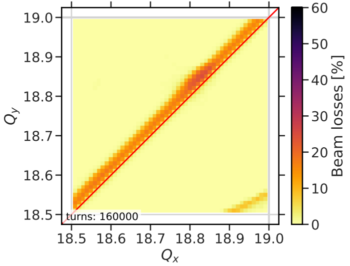


Figure: tune diagram of beam loss

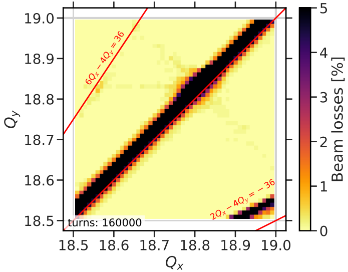
Cold, error-free, symmetric SIS100 lattice:

- perfect dipole and quadrupole magnets
- symmetry of $S = 6$ maintained (no warm / normalconducting quadrupoles)
- 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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⟹ absence of low-order structure resonances!

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" resolves stopband edges well!

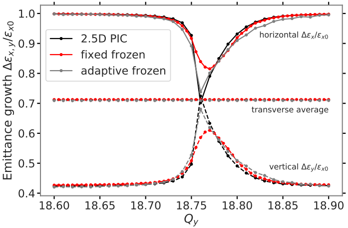

Figure: emittance exchange

Montague Resonance

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

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

$\Longrightarrow$ sto
for

Observation

"Fixed frozen" model 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" resolves stopband edges well!

Figure: emittance exchange

Warm Quadrupoles

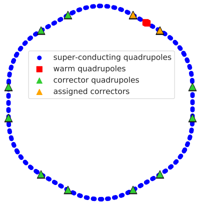

Figure: SIS100 quadrupole survey

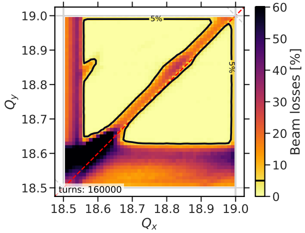

Figure: corrected warm quadrupoles

Real SIS100 lattice:

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

$\Longrightarrow$ gradient error

$\Longrightarrow$ externally driven half-integer resonance

$\Longrightarrow$ can be minimised by quadrupole correctors

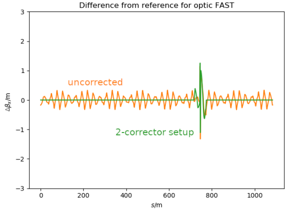

Figure: β-beat around SIS100 [courtesy D. Ondreka]

Half-integer Resonance

Half-integer stopband:

- without space charge, without $\Delta p/p_0$: $\delta Q_{\text{stopband}} = 0.023$
- without space charge, with $\Delta p/p_0$: $\delta Q_{\text{stopband}} \sim 0.1$
- with space charge: $\delta Q_{\text{stopband}} \sim 0.25$

$\Longrightarrow$ fixed frozen SC model reproduces stopband edges from PIC

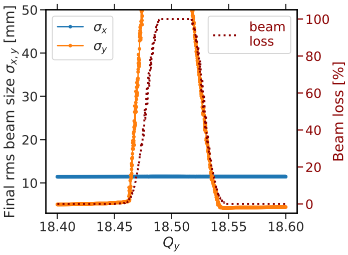

Figure: no space charge

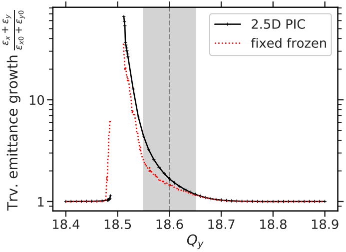

Figure: with space charge

Field Error Model

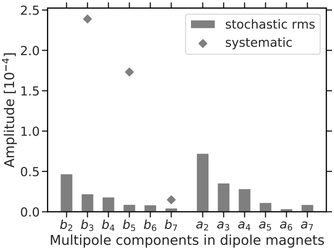

Figure: dipole magnets

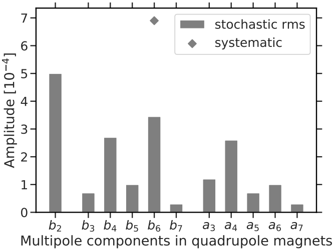

Figure: quadrupole magnets

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

Full Model with Space Charge

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

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

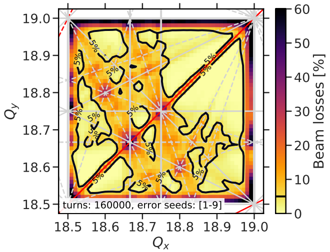

Figure: no space charge

include $\Longrightarrow$ SC

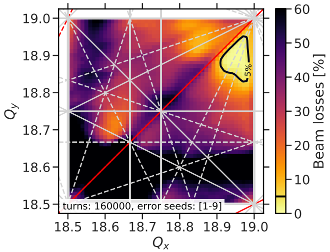

Figure: with fixed frozen space charge

$\longrightarrow$ SC broadens existing resonance stopbands

$\Longrightarrow$ optimal working point area around $(Q_x, Q_y) = (18.95, 18.87)$
[requires transverse feedback system to fight resistive wall instability!]

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

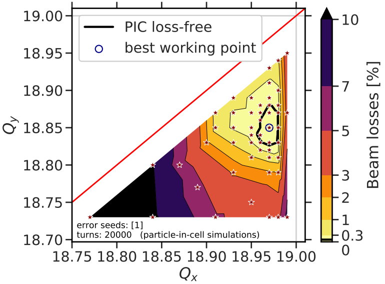

Figure: self-consistent PIC simulations

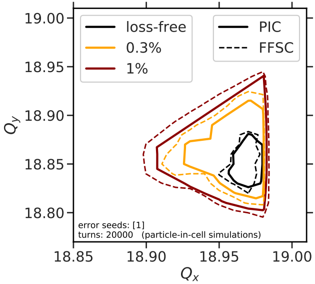

Figure: comparison between SC models

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

Relevant Field Error Orders

Major resonances confining low-loss area:

- top left: Montague resonance
- right: integer resonance $Q_x = 19$
- bottom: higher-order resonances

Simulations with reduced field error model:

- identify sextupole and octupole orders $n = 3, 4$ as main limitation towards low Q_y

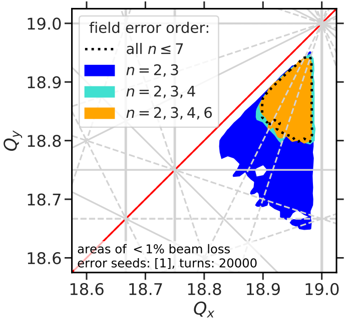

Figure: low-loss tune areas vs. multipole order

C. Space-Charge Limit

Space-Charge Limit

dynamic definition of space-charge limit

reached when loss-free working point area vanishes

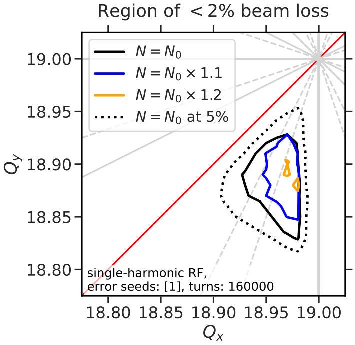

Figure: low-loss area for increasing N

Keeping all beam parameters identical, increasing N:

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

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

D. Mitigation Measures

Correction of β-beat

Two sources of β-beat (gradient error):

- warm quadrupoles: uncorrected = 2%
  - $\longrightarrow$ significant effect on low-loss area size
  - $\Longrightarrow$ important to control

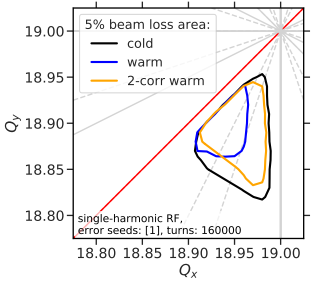

Figure: low-loss area with warm quadrupoles

Correction of β-beat

Two sources of β-beat (gradient error):

- warm quadrupoles: uncorrected = 2%
  - $\longrightarrow$ significant effect on low-loss area size
  - $\Longrightarrow$ important to control
- distributed b_2: $\approx 0.5\%$ (according to field error model)
  - $\Longrightarrow$ below $b_2 = 10\,$units: no significant effect on low-loss area size

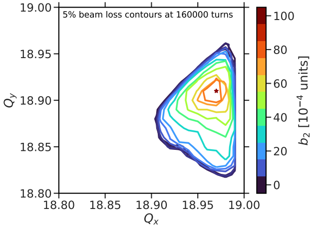

Figure: low-loss area with b_2

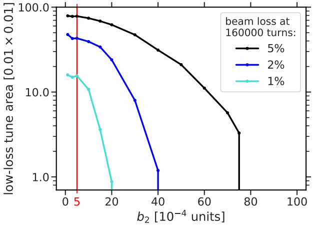

Figure: size of low-loss area vs. b_2

Double-harmonic RF

By adding $h = 20$ harmonic at half base RF voltage in bunch lengthening mode,

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

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

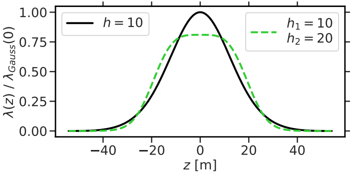

Figure: line densities

Results with Double-harmonic RF

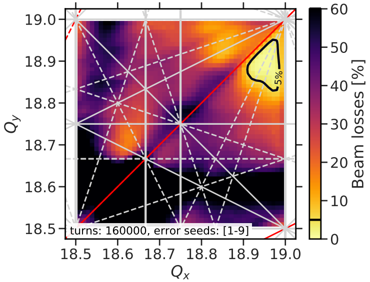

Figure: single-harmonic RF

flatten
$\Longrightarrow$
bunch

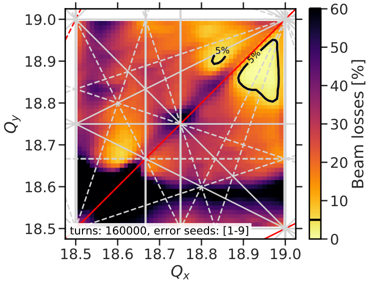

Figure: double-harmonic RF

Observations:

- black half-integer stopband shrinks by $\approx 20\%$
- low-loss area opens up

SC Limit with Double-harmonic RF

Increasing N for double-harmonic RF:

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

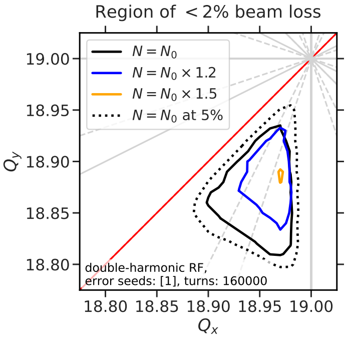

Figure: low-loss area for increasing N

Pulsed Electron Lenses

Pulsed electron lenses:

- short insertion with co-propagating electron beam
- transversely homogeneous distribution
- longitudinally modulated to match ion bunch profile

⟶ compensate longitudinal dependency of space charge
(ideal: half compensation of linear space charge tune shift, $\Delta Q_{\mathrm{elens}} = \Delta Q_{\mathrm{KV}}/2$)

⟹ installing 3 such electron lenses shrinks stopbands!

⟹ space-charge limit increased significantly!

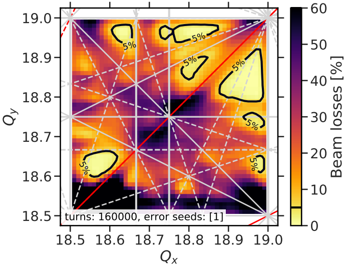

Figure: tune diagram at nominal N

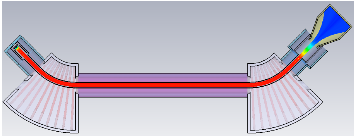

Figure: e-lens model for SIS18

Pulsed Electron Lenses

Pulsed electron lenses:

- short insertion with co-propagating electron beam
- transversely homogeneous distribution
- longitudinally modulated to match ion bunch profile

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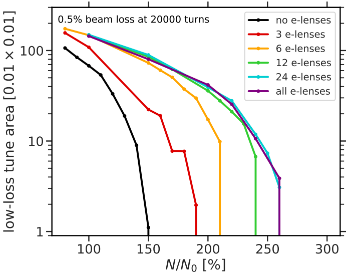


Figure: low-loss area for increasing N [preliminary, unpublished results]

Conclusion

Summary:

- **validated** fixed frozen SC model predictions by long-term PIC simulations
- identified **optimal tune area** around $(Q_x, Q_y) = (18.95, 18.87)$
  - ⟶ rigid constraints: Montague resonance (top left), integer resonance (right)
  - ⟶ soft constraint: higher-order resonances (bottom)
- 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: +80..90% intensity

take-home message

- dynamic space-charge limit: find based on tolerable loss & emittance growth
- nominal FAIR intensity → feasibility confirmed

Next steps:

- coherent stability with space charge (resistive-wall, nonlinear electron lenses)
- quantify impact by indirect space charge

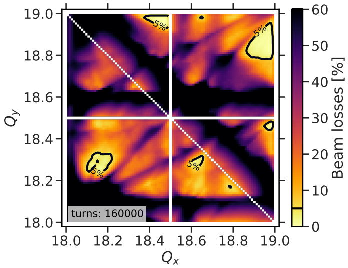


Figure: GPU simulation results for latest magnet field error model

Thanks to GSI's new high-performance GPU cluster in Green Cube:

- 400 GPU cards of today's most performant model (AMD Radeon Instinct MI100)
- even faster simulations, larger tune scans in shorter times

⟹ following up magnet series production and doublet assembly

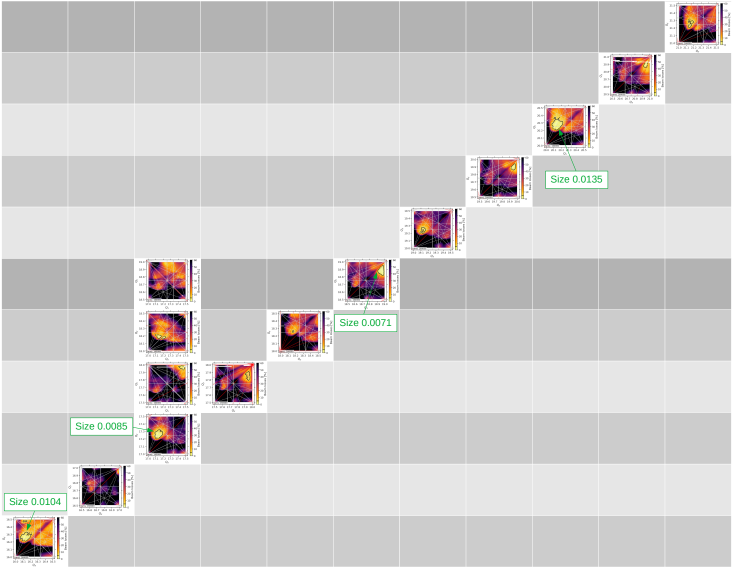
Thank you for your attention!

Acknowledgements:

GSI: O. Boine-Frankenheim, V. Chetvertkova, V. Kornilov, D. Rabusov, S. Sorge, D. Ondreka, A. Bleile, V. Maroussov, C. Roux, K. Sugita

CERN: R. de Maria, G. Iadarola, M. Schwinzerl

Grand Overview Tune Diagrams



Emittance Growth at Low-loss Area

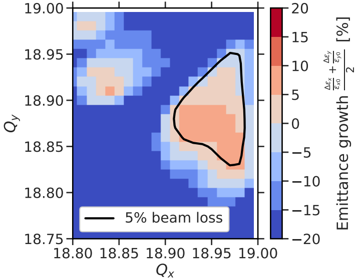


Figure: with space charge, emittance growth

PIC Results for Best Working Point

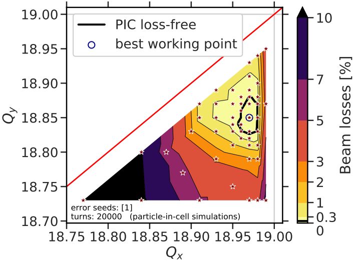


Figure: tune diagram with self-consistent PIC simulations

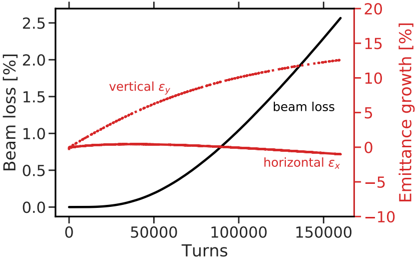


Figure: optimal working point $(Q_x, Q_y) = (18.97, 18.85)$

Comparison 2.5D to 3D PIC

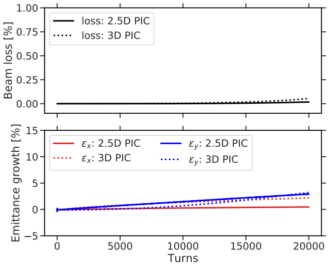


Figure: good working point $(Q_x, Q_y) = (18.97, 18.85)$

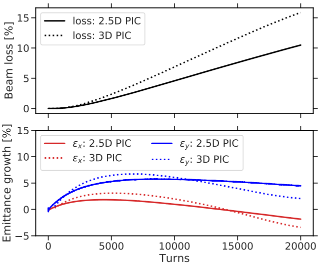
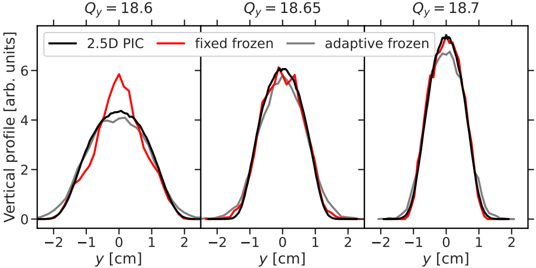


Figure: lossy working point $(Q_x, Q_y) = (18.84, 18.73)$

Adaptive Frozen SC Model



Half-integer Resonance vs. SC

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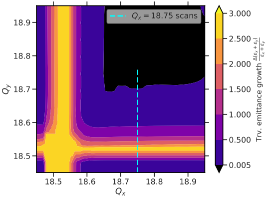

Figure: emittance growth in 2D tune diagram

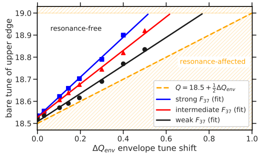

Figure: space-charge limit for Gaussian bunches

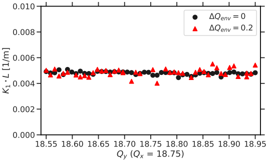

Figure: correction independent of space charge

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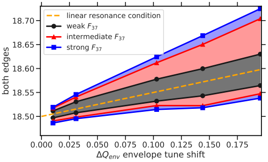

Figure: coasting beam stopband edges vs. space charge

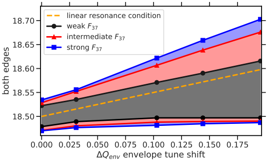

Figure: bunched beam stopband edges vs. space charge

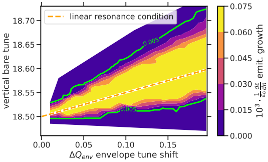

Figure: choose a threshold