Plans for Space Charge Compensation with Electron Lenses at GSI

M. Kirk

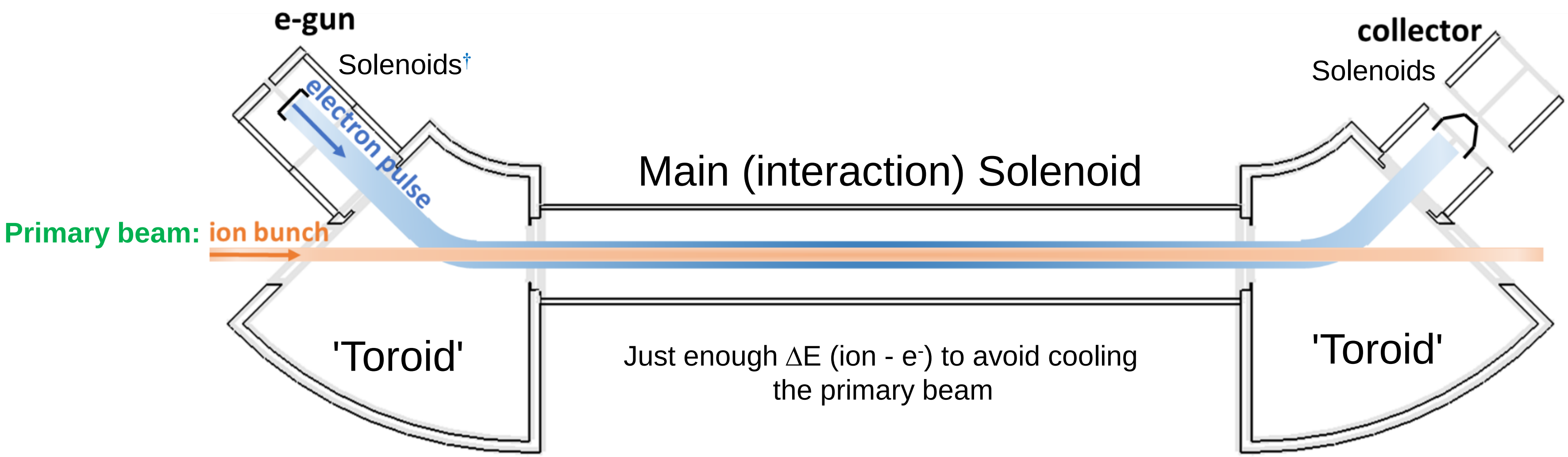
GSI Helmholtzzentrum für Schwerionenforschung GmbH

Acknowledgements

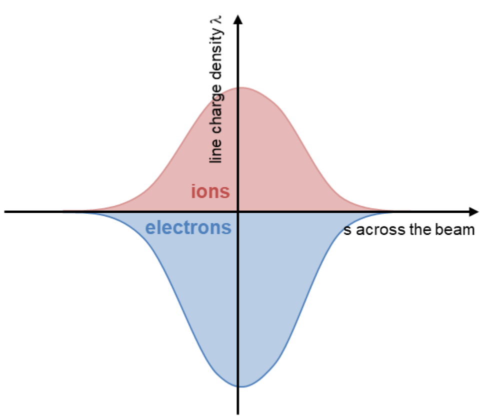
GSI: K. Schulte-Urlichs, K. Thoma, D. Ondreka, P. Spiller
CERN: G. Khatri
Riga TU: A. Ratkus, G. Pirkus, A. Moisevjes
Goethe University Frankfurt: O. Meusel, M. Droba, H. Podlech

Functional Principle of an Electron Lens

Burov et al., FERMILAB-TM-2125, September 2000 –*first* publication



Modulation to match longitudinal bunch profiles:



Primary beam (ions):

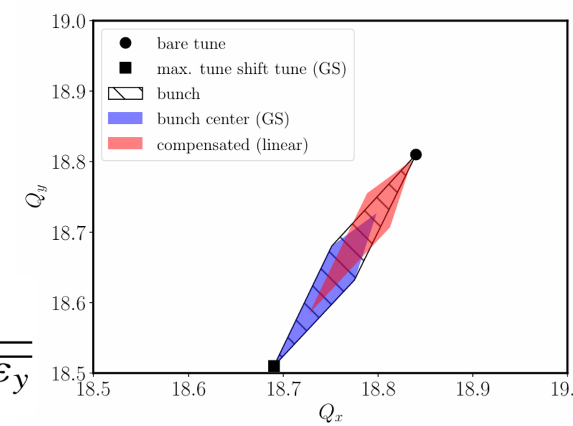
$$\Delta Q_y^{sc} \approx -\frac{NZ^2 r_p}{\pi \beta_0^2 \gamma_0^3 A B_f} \frac{1}{\varepsilon_y + \sqrt{\varepsilon_x \varepsilon_y}}$$

Compensation by electrons:

$$\Delta Q_y^e = \frac{1 \mp \beta_e \beta_0}{\beta_e} \frac{Z I_e l_e r_p}{\pi A e c \beta_0^2 \gamma_0} \frac{1}{\varepsilon_y + \sqrt{\varepsilon_x \varepsilon_y}}$$

Artikova, Boine-Frankenheim et al., 2021:

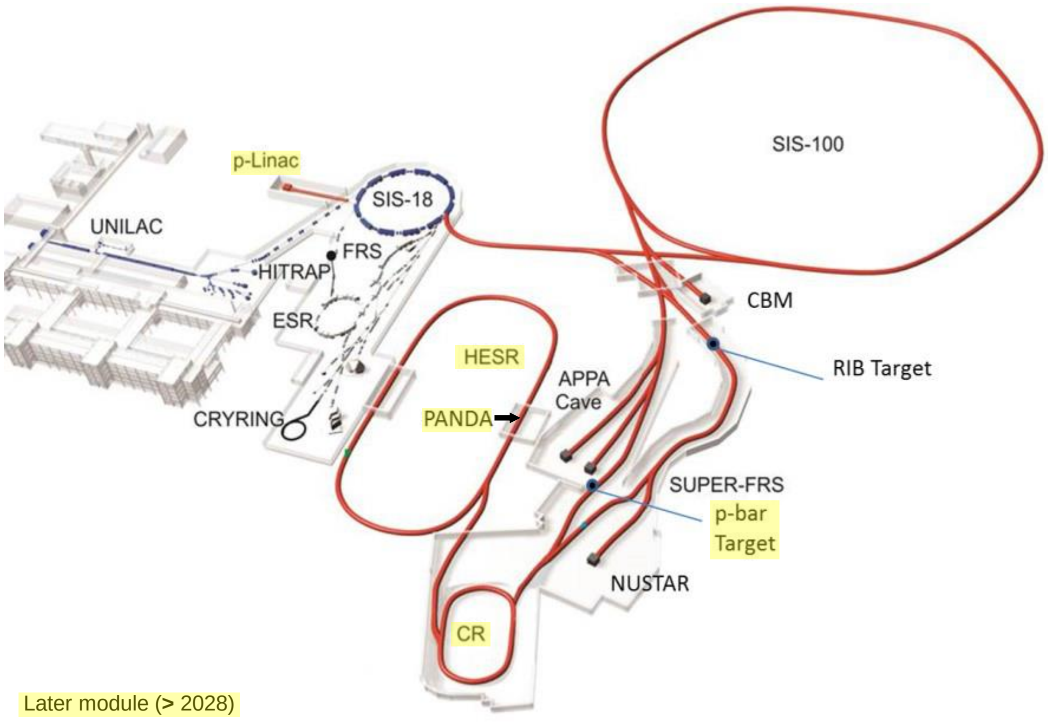
Reduced tune footprint (SIS100)



† "Gun" and "expansion" solenoid

Motivation

GSI facility… as injector for **FAIR**

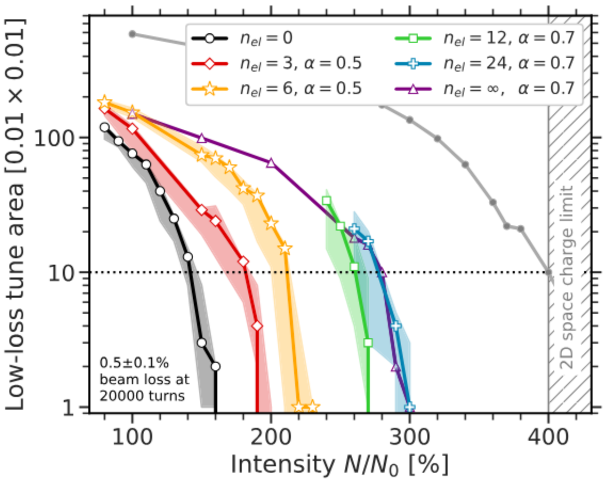


- FAIR designed to increase intensity limits of GSI:
  - Primary beam intensities up by factor 10-100
  - Lower charge states to avoid **space charge limit**

Primary Beam Intensities at GSI and FAIR					
		p	Ar	Xe	U
Charge number	GSI	1	18	48	73
	FAIR	1	10	21	28
Energy [GeV/u]	GSI	4.7	1.7	1.3	1.0
	FAIR	28.8	6.6	4.0	2.7
Intensity [Ions/s]	GSI	10^{11}	**$8\cdot10^{10}$**	$2\cdot10^{10}$	$4\cdot10^{9}$
	FAIR	**10^{13}**	**10^{12}**	**$5\cdot10^{11}$**	**$3\cdot10^{11}$**

"**Numerical studies** for SIS100 have shown that a few symmetrically distributed electron lenses could increase the space-charge limit by up to 50%, while a larger number potentially enables increase up to x 2" [1]

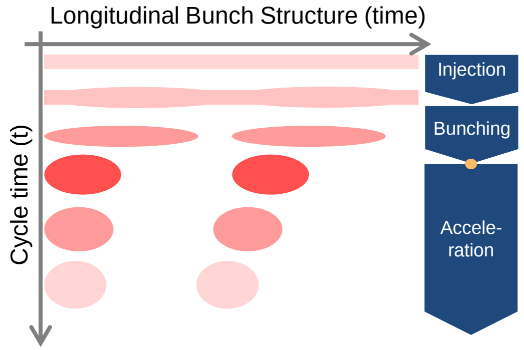
Oeftiger et al., 2024 [1]



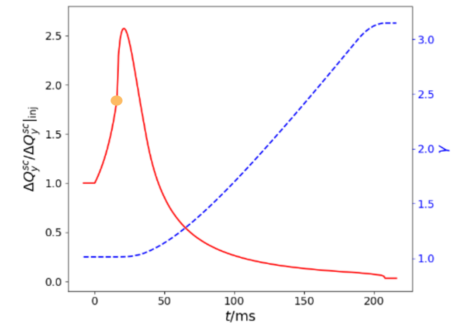
[1] A. Oeftiger and O. Boine-Frankenheim, "Pulsed Electron Lenses for Space Charge Mitigation", Phys. Rev. Lett., vol. 132, p. 175001, 2024, doi: 10.1103/PhysRevLett.132.175001

E-Lens Requirements for SIS18

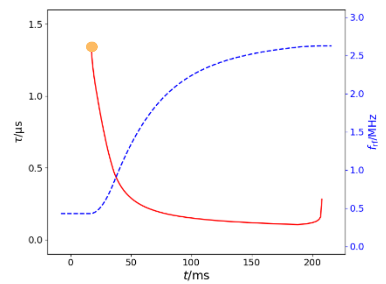
- **Synchrotron Cycle**
  - *Parameters determining modulation to superimpose ion and e⁻ bunches*
    - Tune spread peaks shortly after start of ramp
    - **Cavity RF** and ∴ **bunch length** vary strongly
- **Electron Lens Design**
  - *RF-modulated e⁻ gun*
    - Up to 15 A (peak) for space charge compensation
    - 0.4 - 1 MHz to follow longitudinal **bunch profile**, required bandwidth 10 MHz
    - Transverse homogeneous **e⁻ beam** density with **circular** cross section for ‘linear’ compensation
  - *Collector*
    - Reduce e⁻ beam power density by deceleration and e⁻ beam expansion in a *cusp*-form B-field
    - Mitigation of secondary electrons



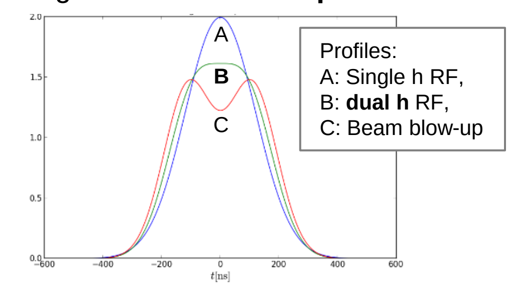
Evolution of peak tune spread



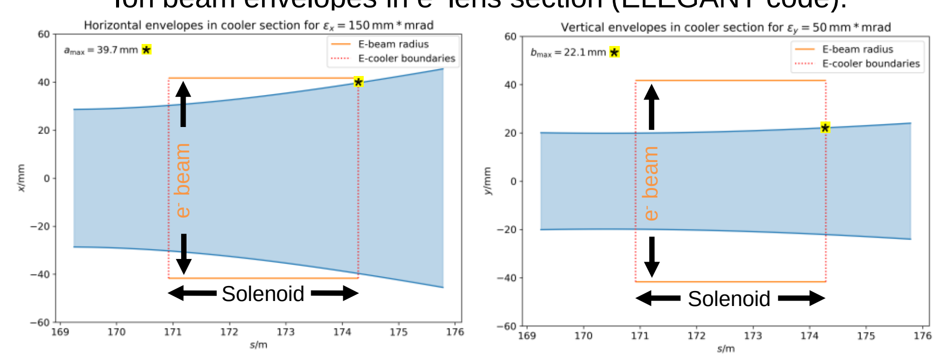
Evolution of **bunch length** & **RF**



Longitudinal ion **bunch profiles**

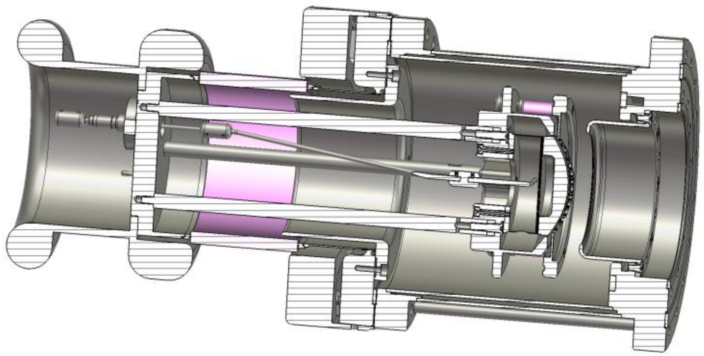


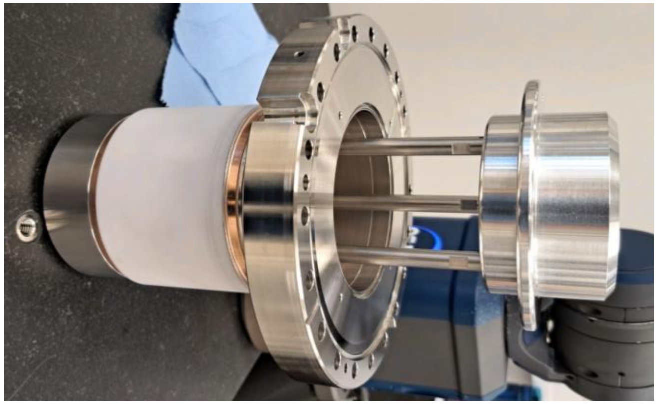
Ion beam envelopes in e⁻ lens section (ELEGANT code):



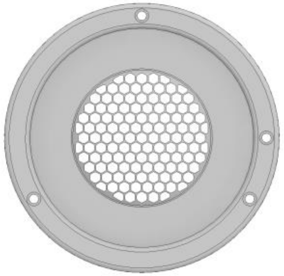
Electron lens design underway. Demonstration with SIS18 e⁻ cooler to come

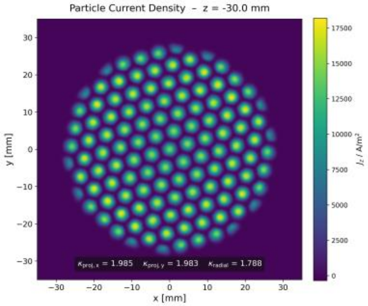
RF-Modulated Electron Gun



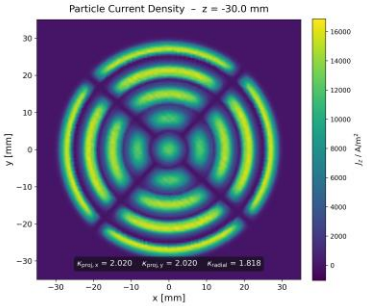


'Honey comb' grid



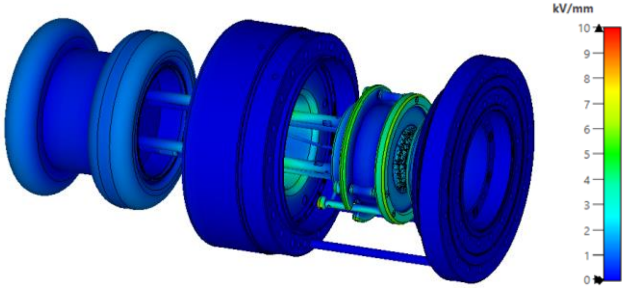


'Target' grid

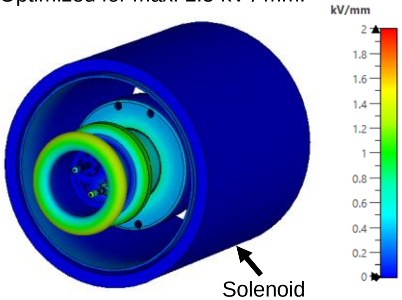


Electrostatic Analysis:

Optimized for max. 10 kV / mm:



Optimized for max. 1.5 kV / mm:



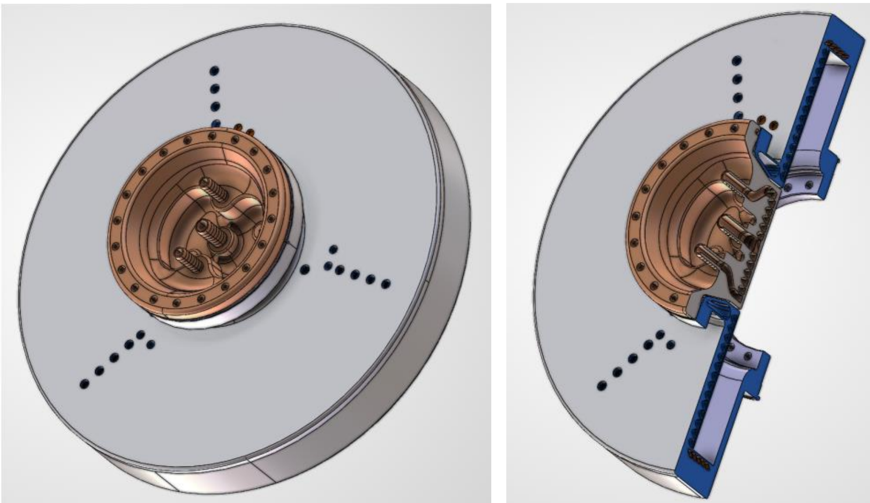
This project received funding from the European Union's Horizon Europe Research and Innovation Programme under GA No. 101290927

EPITA

GSI

Electron Collector

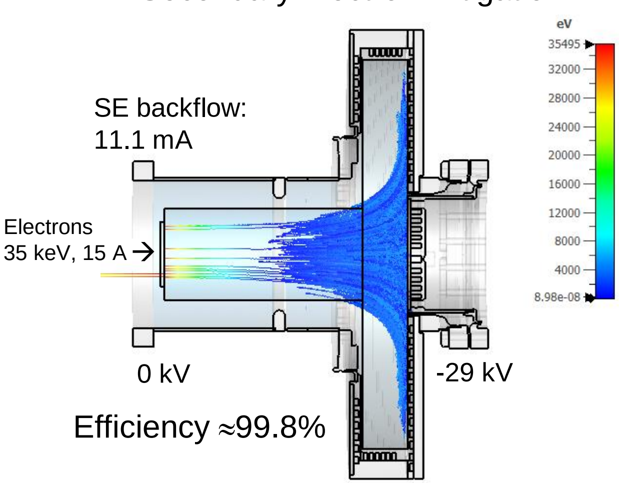
Additively manufactured



Design by G. Pikurs, A. Ratkus and A. Moisevjes, RTU, 2026

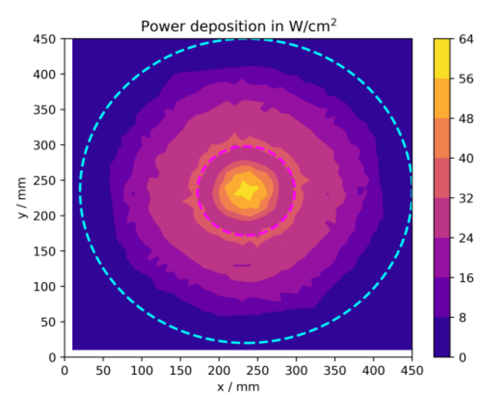
Collector Parameter		
electron current, max.	**15**	**A**
bias potential, max.	**-6**	**kV**
collector area	1452	cm^2
inner radius , max.	215	mm
outer radius, max.	242	mm
beam radius	≥ 215	mm
DC power deposition, max.	**90**	**kW**
power deposition within cycle, max.	30	kW
chamber height	66	mm
weight	>50	kg
B-field, max.	0.4	T

Secondary Electron Mitigation:



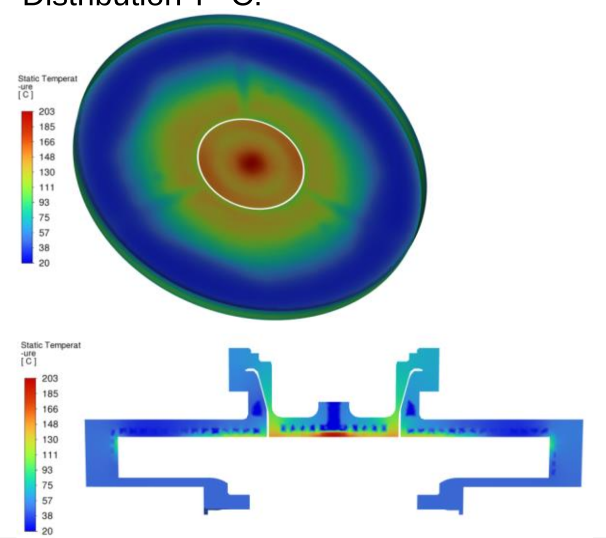
Efficiency ≈99.8%

Maximum Power Deposition in Cycle:



E-lens is used at low Bρ of SIS18 cycle thus reducing power deposition by ~0.3

Distribution T °C:



SIS18 e⁻ Cooler as Test-Bed

Modification of SIS18 e-cooler:

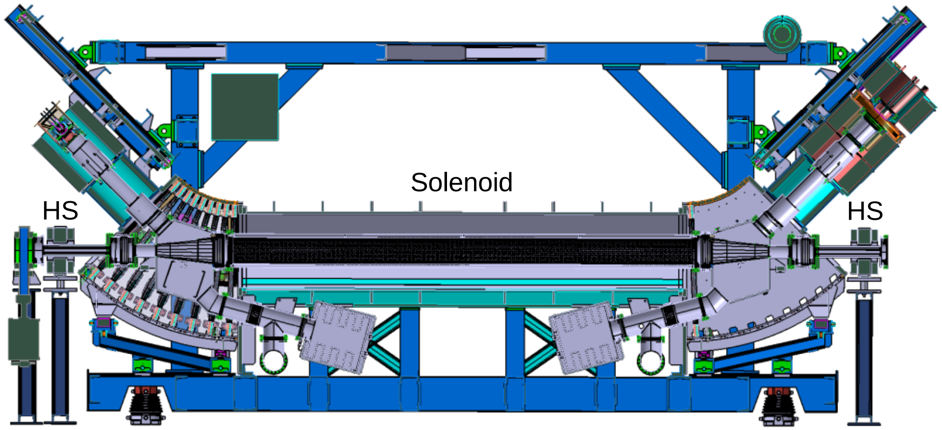
- Max. B-field: e^- & ion-beam region 0.15 T, gun & collector 0.4 T
- CO simulation indicates that the 0.15 T is feasable for experiments
- Gun and collector designs adapted to e^- cooler
- Experiments on e^- cooler carried out with more to come.

Questions:

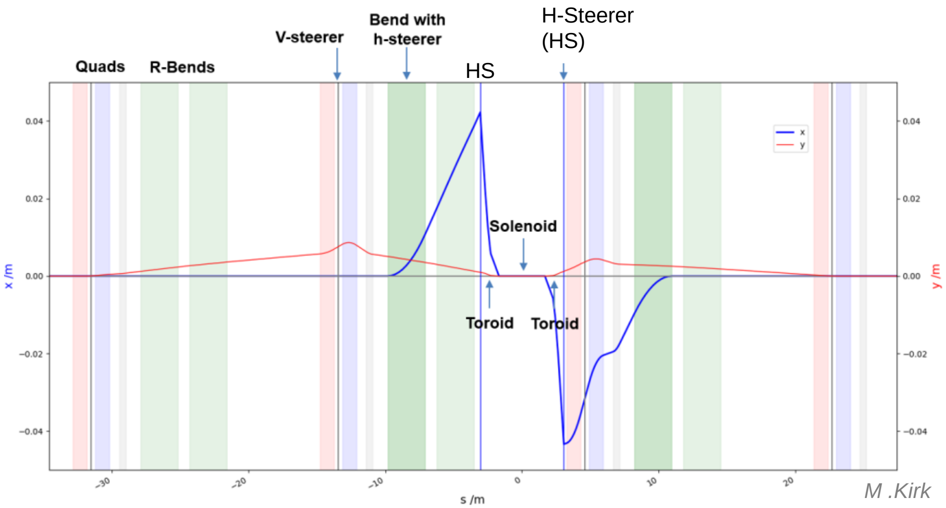
- Kicks to particles from toroids
- e^- beam's influence on ions
- 'Gridded' e^- beam current density distribution
- Compensation of coupling between transverse planes
- Resonance compensation

SIS18 e-cooler *at present*:

Modified SIS18 e-cooler design:



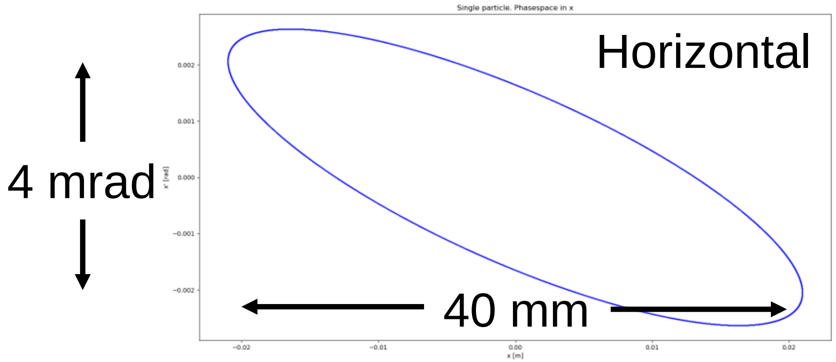
SIS18 closed orbit at 0.15 T, CST → ELEGANT with FTABLE* element:

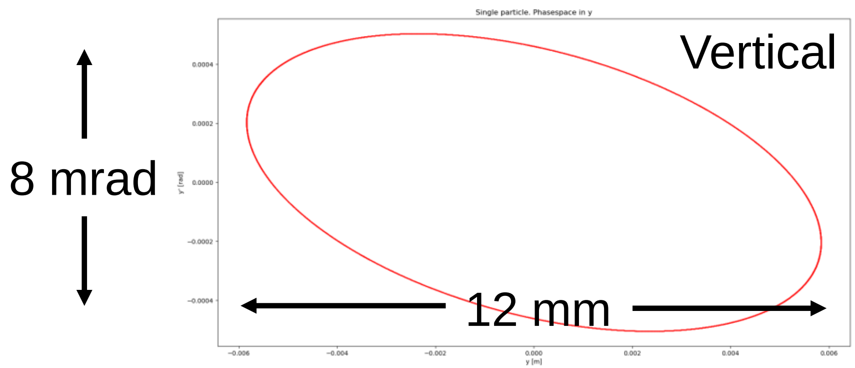


* Ref. FTABLE: A. Xiao, M. Borland et al., "Tracking particles through a general magnetic field", PAC11

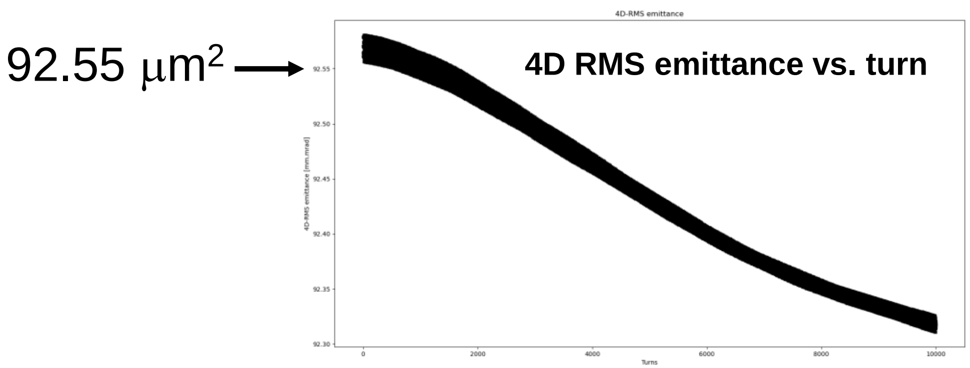
Transport Simulations with ELEGANT

NO SOLEnoids





Single particle in phase space tracked for 10k turns



1k-ion waterbag tracked for 10k turns
≈0.3% drop in emittance

Further Reading

S. Artikova, D. Ondreka, K. Schulte-Urlichs, P. J. Spiller,
“Design and Beam Dynamics of the Electron Lens for Space Charge Compensation in SIS18”,
IPAC'21, pp. 3614–3617

K. Schulte-Urlichs et al.,
“Status of the Electron Lens for Space Charge Compensation in SIS18”,
IPAC'21, pp. 1880–1883

A. Oeftiger and O. Boine-Frankenheim,
“Pulsed Electron Lenses for Space Charge Mitigation”,
Phys. Rev. Lett., vol. 132, p. 175001, 2024,
doi: 10.1103/PhysRevLett.132.175001

A. Xiao, M. Borland et al.,
“Tracking particles through a general magnetic field”,
Conf. Proc. PAC11

I. Lobach, Y. Li,
“Using neural-network Ansatz for the generating function in the Hamilton-Jacobi equation to obtain symplectic transfer maps for elements with any magnetic field configuration”,
IPAC’26

History of Electron Lenses for Space Charge Compensation

*The references above are up to **about the point** when work at GSI began.*

A. V. Burov, G. W. Foster, V. D. Shiltsev, “Space-Charge Compensation in High-Intensity Proton Rings,” FERMILAB-TM-2125, September 2000

S. Machida, 2001, KEK PS simulation

Y. Alexahin, “Effects of Space Charge and Magnet Nonlinearities on Beam Dynamics in the Fermilab Booster”, PAC 2007, DOI 10.1109/PAC.2007.4440463

M. Aiba, M. Chanel, U. Dorda, R. Garoby, J.-P. Koutchouk, M. Martini, E. Métral, Y. Papaphilippou, W. Scandale, F. Zimmermann, V. Shiltsev, G. Franchetti, “Space-Charge Compensation Options for the LHC Injector Complex”, Proceedings of PAC'07, Albuquerque, 2007, pp. 3390–3392

M. Aiba, “Benchmark of ACCSIM-ORBIT codes for space charge and electron-lens compensation”, CERN, 2008

Y. Alexahin and V. Kapin, “Study of Possibility of Space Charge Compensation in the Fermilab Booster with Multiple Electron Columns,” Fermilab Beams-doc-3108, June 2008

V. N. Litvinenko and G. Wang, “Compensating Tune Spread Induced by Space Charge in Bunched Beams”, Physical Review Special Topics — Accelerators and Beams 17, 114401 (2014)

O. Boine-Frankenheim and W. D. Stem, “Space charge compensation with pulsed electron lenses for intense ion beams in synchrotrons”, Nuclear Instruments and Methods in Physics Research A 896 (***2018***), 122–128. DOI: 10.1016/j.nima.2018.04.014

S. Artikova et al., “Pulsed electron lenses for space charge compensation in the FAIR synchrotrons”, 2021 JINST 16 P03044. https://doi.org/10.1088/1748-0221/16/03/P03044

Y. Alexahin and V. V. Kapin, “On possibility of space-charge compensation in the Fermilab Booster with multiple electron columns”, Journal of Instrumentation 16 (2021) P03049. DOI: 10.1088/1748-0221/16/03/P03049

Summary & Outlook

Electron lens is under development

Electron gun will be ready for testing at GSI

Prototype electron lens in SIS18 synchrotron will follow

Symplectic transfer map for e-lens*

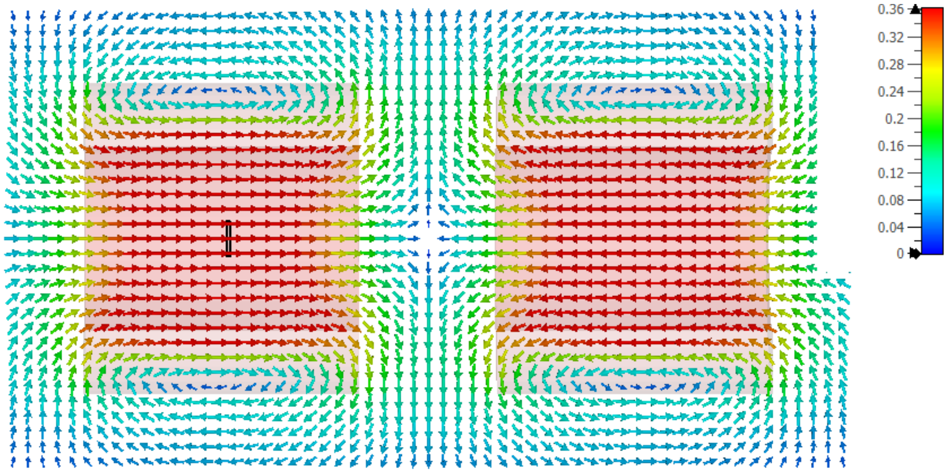
Resonance and coupling compensation

* I. Lobach, Y. Li, *Using neural-network Ansatz for the generating function in the Hamilton-Jacobi equation to obtain symplectic transfer maps for elements with any magnetic field configuration*, IPAC'26

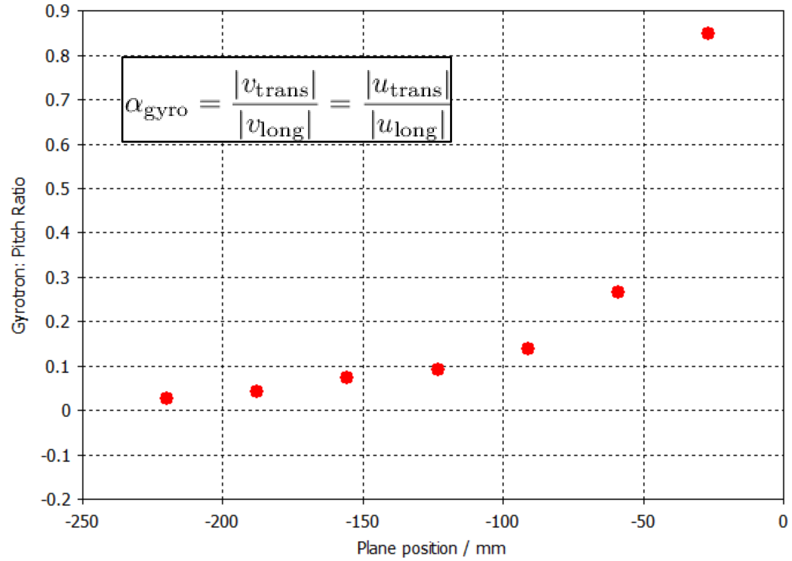
Reserve slides …

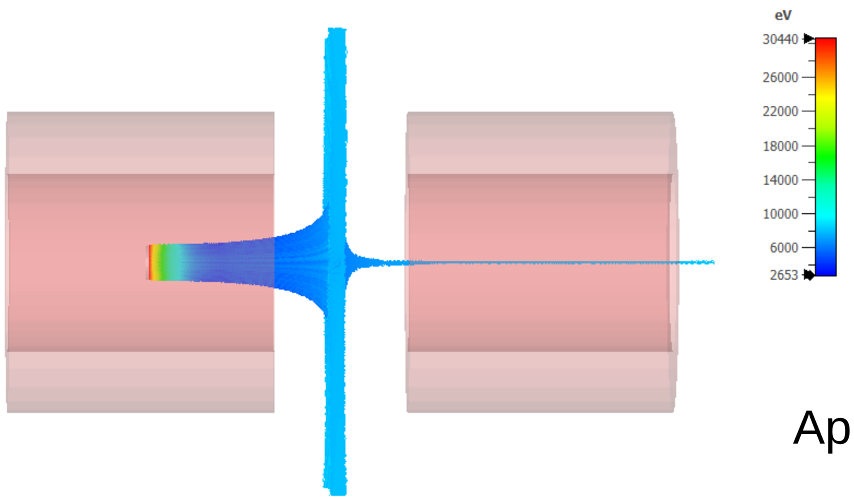
Collector - Cusp Design

Cusp field



transverse velocity vs. longitudinal velocity





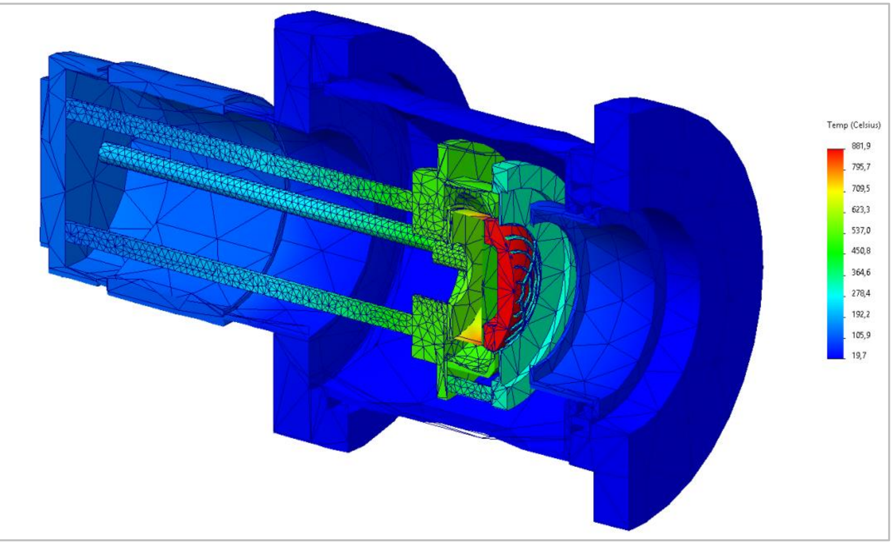
Approx. 7% losses

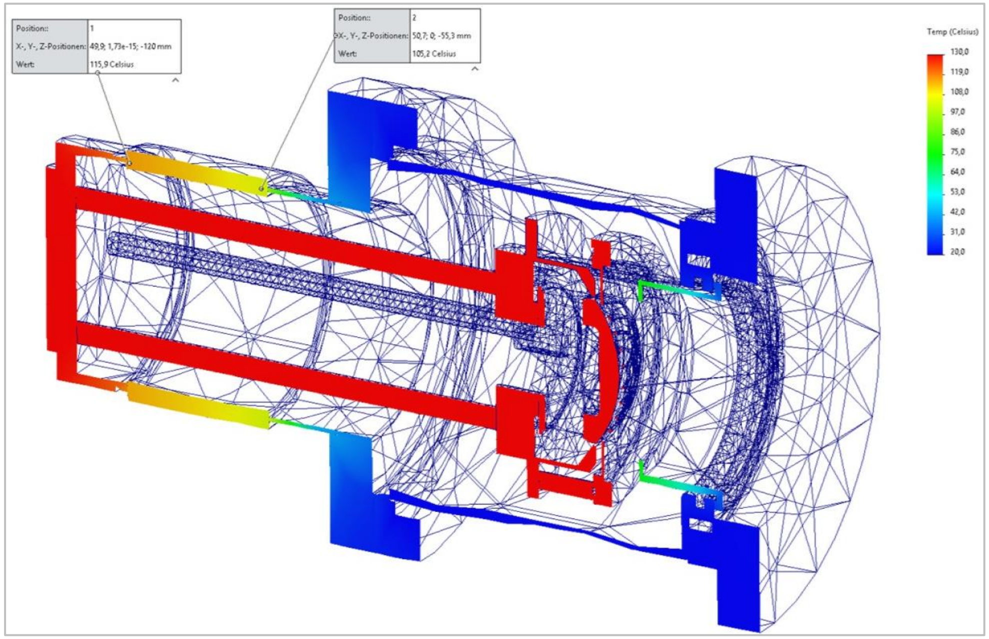
RF-Modulated Electron Gun – Choice of Materials

Body parts:	Stainless steel
Insulators:	Alumina
Dispenser cathode:	BaO, type 311XM by Spectra-Mat Inc.
Modulation grids:	Molybdenum or graphite (SIGRAFINE®)
Focusing electrode:	Molybdenum

RF-Modulated Electron Gun

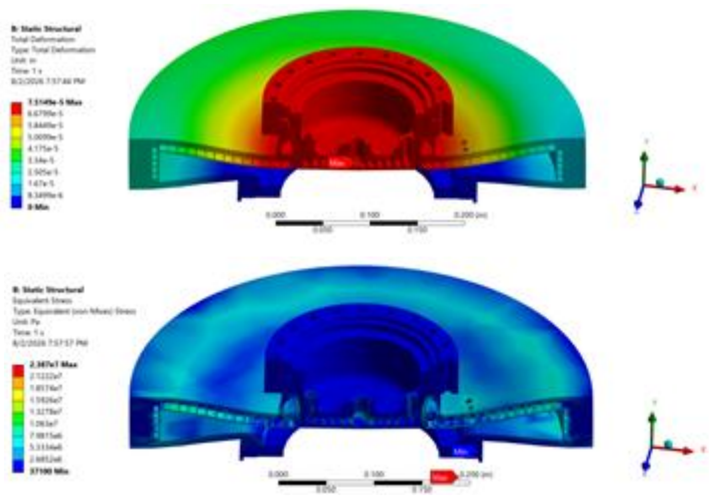
Thermomechanical analysis





Collector – Stress Distribution

Structural Analysis



Transport Simulations – undesired numerical effects

Closed orbit was computed. ELEGANT's &correct command tracks a test particle over a *single* turn per iteration until converged to closed orbit.

However tracking ions in a simulation over *many* turns around a synchrotron without incurring undersired numerical effects *will be an issue*.

ELEGANT & FTABLE based simulations have failed well within the simulated time frame of interest, i.e. ~0.2 sec (50k turns). Extreme emittance blow-up towards the end. FTABLE known to be asymplectic.

ELEGANT & SOLEnoid elements instead of FTABLE have been put to the test.

If toroids can be treated symplectically then we can reliably transport ions over many turns.

xsuite & E-Lens element is being looked into.

RF-Modulated Electron Gun

*Electron gun parts & assembly: **NTG** GmbH & Co. KG*