

A detailed wireframe model of a particle accelerator, showing a large circular ring with various internal components and a complex network of smaller structures and pipes extending from the main ring.

# **Plans for Space Charge Compensation with Electron Lenses at GSI**

M. Kirk

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# Acknowledgements



## **GSI:**

K. Schulte-Urlichs, K. Thoma\*, D. Ondreka, P. Spiller, O. Boine-Frankenheim

## **FNAL:**

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## **CERN:**

G. Khatri

## **Riga TU:**

A. Ratkus, G. Pirkus, A. Moisejevs

## **Goethe University Frankfurt:**

O. Meusel, M. Droba, H. Podlech, S. Artikova, K. Thoma\*

## **University of Oxford:**

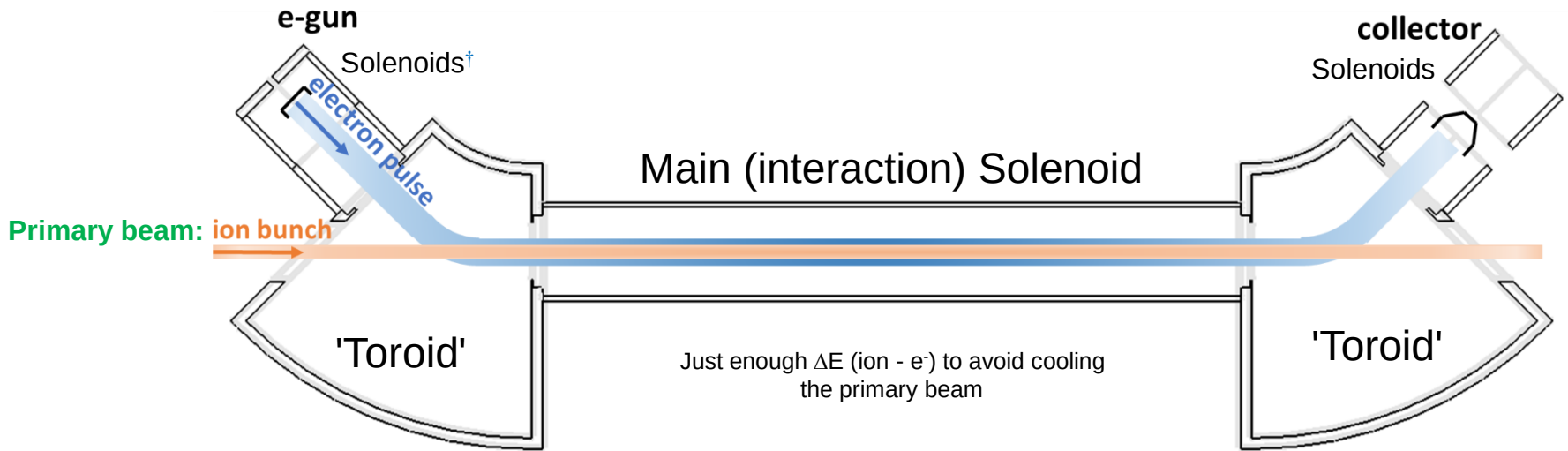
A. Oeftiger

## **LLNL:**

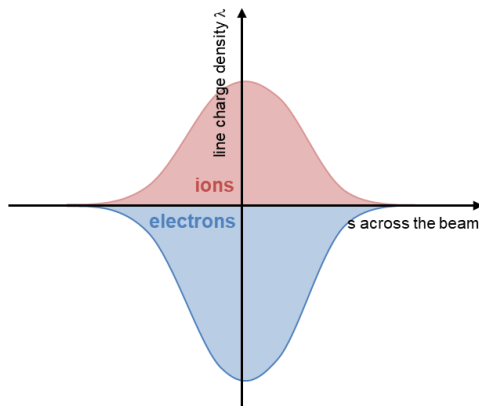
W. Stem

# Basic concept of an electron lens

1<sup>st</sup> publication: Burov et al., FERMILAB-TM-2125, September 2000



**Modulation** to match longitudinal bunch profiles:



**Primary beam (ions):**

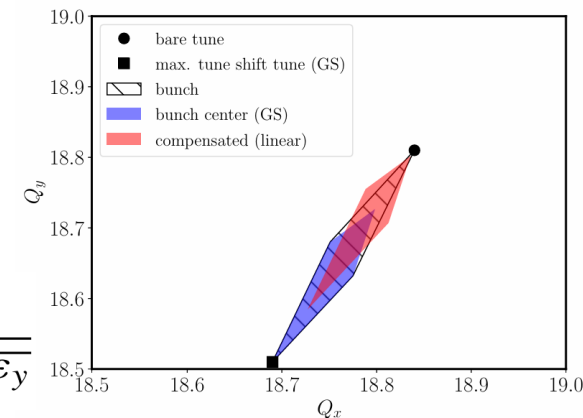
$$\Delta Q_y^{\text{sc}} \approx -\frac{NZ^2 r_p}{\pi \beta_0^2 \gamma_0^3 A B_f} \frac{1}{\epsilon_y + \sqrt{\epsilon_x \epsilon_y}}$$

**Compensation by electrons:**

$$\Delta Q_y^e = \frac{1 \mp \beta_e \beta_0}{\beta_e} \frac{Z I_{el} e r_p}{\pi A e c \beta_0^2 \gamma_0} \frac{1}{\epsilon_y + \sqrt{\epsilon_x \epsilon_y}}$$

Artikova, Boine-Frankenheim et al., 2021:

**Reduced tune footprint (SIS100):**

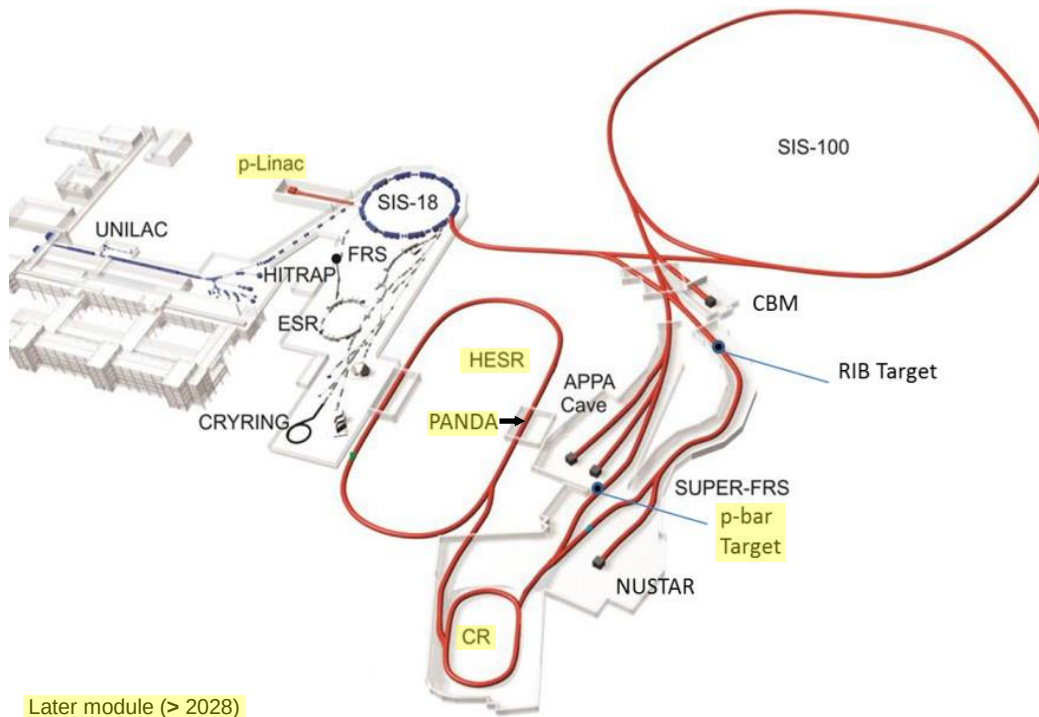


# Motivation

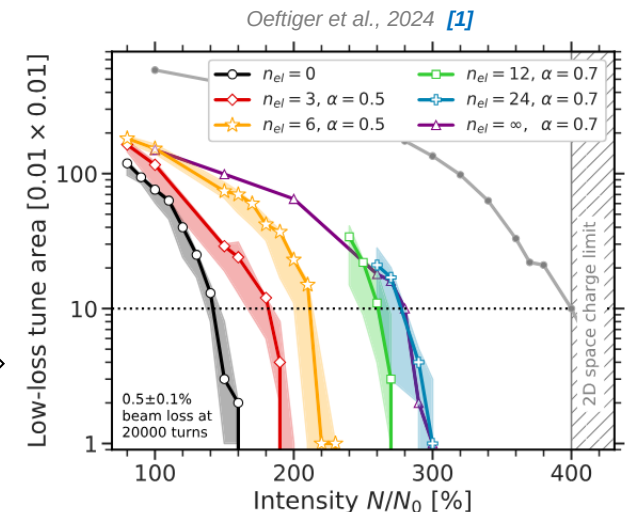
GSI facility...

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  | $10^{11}$ | $8 \cdot 10^{10}$ | $2 \cdot 10^{10}$ | $4 \cdot 10^9$    |
|                                          | FAIR | $10^{13}$ | $10^{12}$         | $5 \cdot 10^{11}$ | $3 \cdot 10^{11}$ |



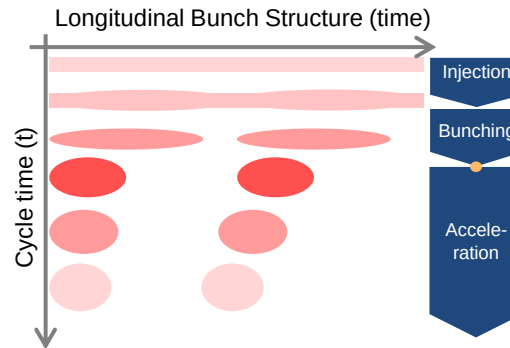
"Numerical studies for SIS100 have shown that a few symmetrically distributed electron lenses could increase the space-charge limit by up to 50%, while a larger number potentially enables increase up to x 2" [1]

[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

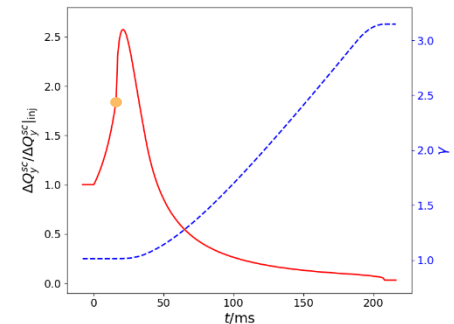
# E-Lens Requirements for SIS18

## Synchrotron Cycle

- Parameters determining modulation to superimpose ion and  $e^-$  bunches
  - Tune spread** peaks shortly after start of ramp
  - Cavity RF and  $\therefore$  **bunch length** vary strongly



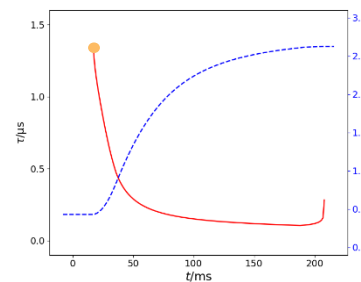
## Evolution of peak **tune spread**



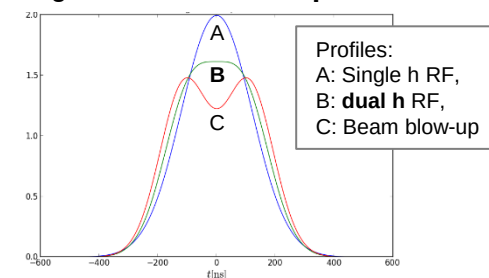
## Electron Lens Design

- RF-modulated  $e^-$  gun**
  - Up to 15 A (peak) electron beam current 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

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



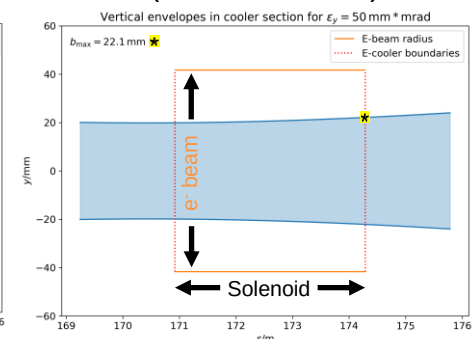
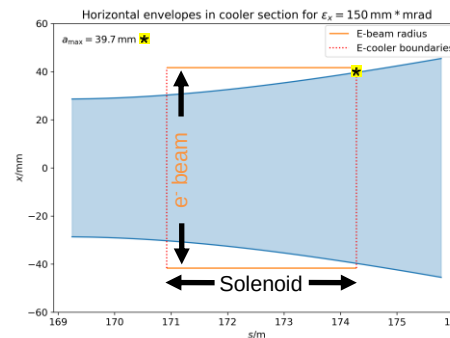
## Longitudinal ion bunch profiles



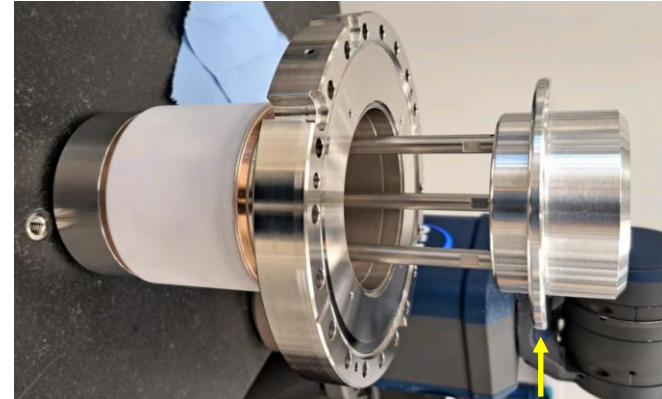
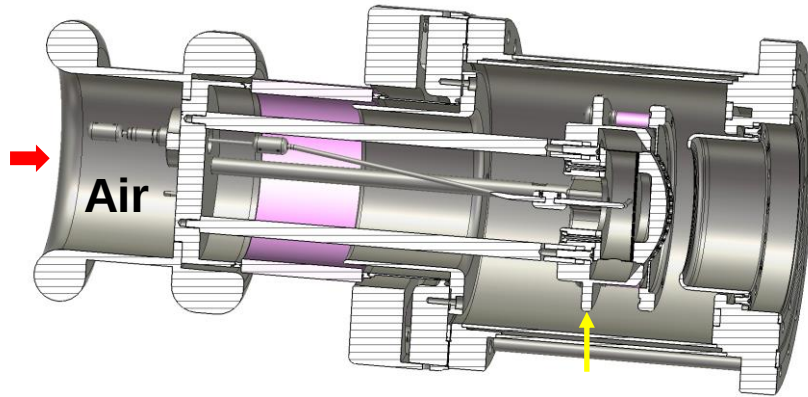
## Collector

- Reduce  $e^-$  beam power density by deceleration and  $e^-$  beam expansion in a *cusp*-form B-field
- Mitigation of secondary electrons

## Ion beam envelopes in $e^-$ lens section (ELEGANT code):

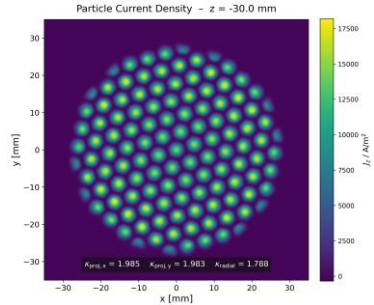
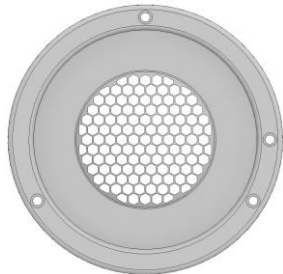


# RF-Modulated Electron Gun

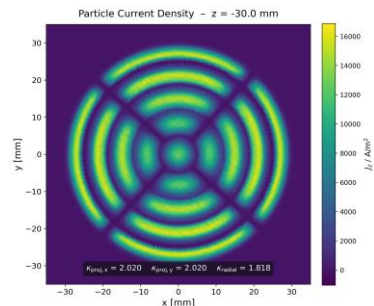


Being assembled

'Honey comb' grid

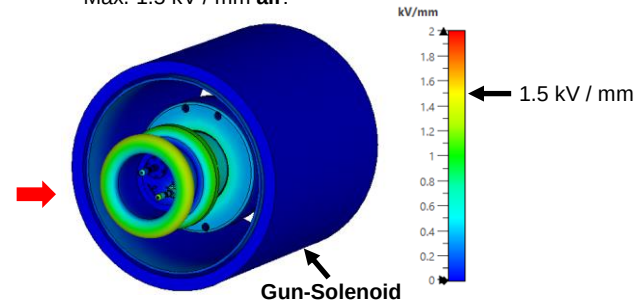


'Target' grid

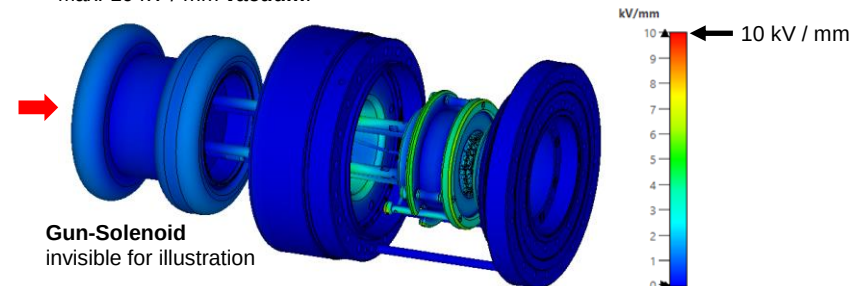


Electrostatic Analysis:

Max. 1.5 kV / mm air:



Max. 10 kV / mm vacuum:

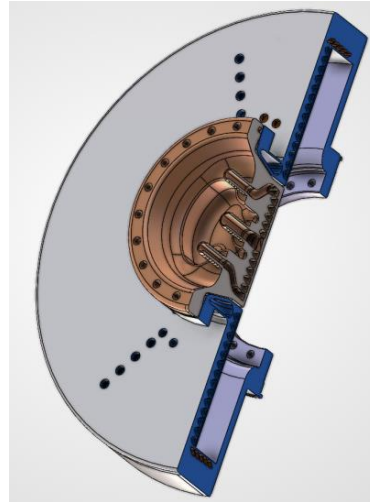
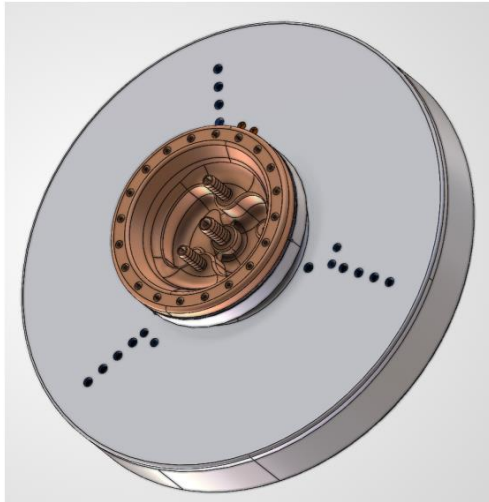




# Electron Collector



Additively manufactured

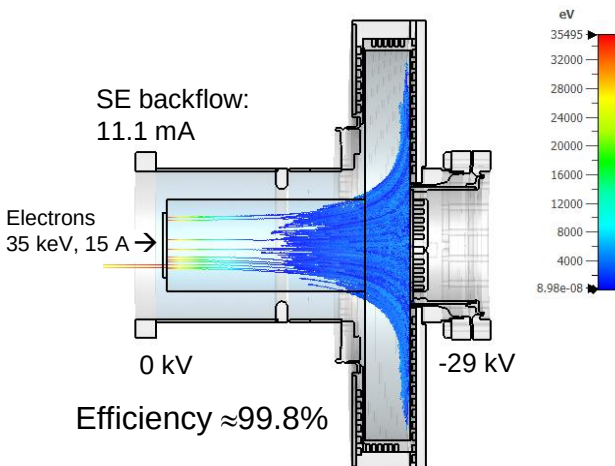


Design by G. Pikurs, A. Ratkus and A. Moisejevs, RTU, 2026

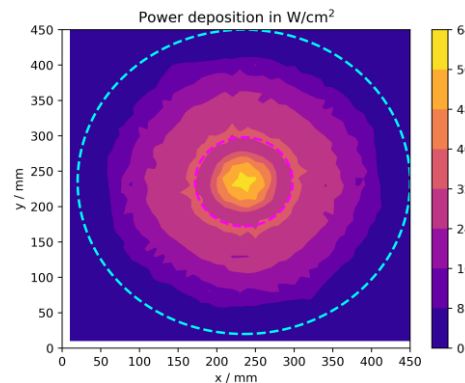
## Collector Parameter

|                                     |       |                 |
|-------------------------------------|-------|-----------------|
| electron current, max.              | 15    | A               |
| bias potential, max.                | -6    | kV              |
| collector area                      | 1452  | cm <sup>2</sup> |
| 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:

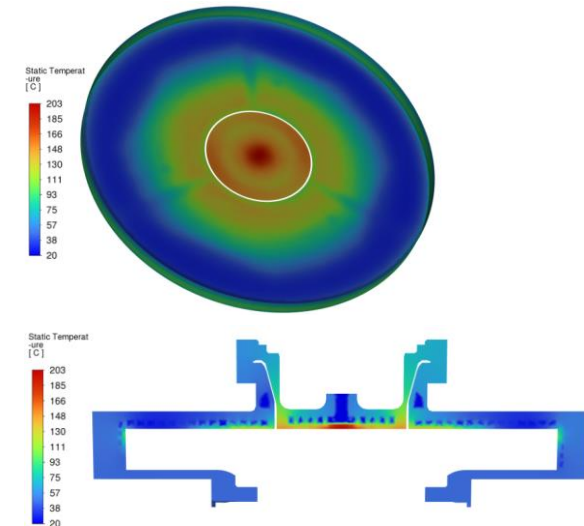


## Maximum Power Deposition in Cycle:



E-lens is used at low B<sub>p</sub> of SIS18 cycle thus reducing power deposition by ~0.3

## Distribution T °C:



# SIS18 e<sup>-</sup> Cooler as Test-Bed

## Modification of SIS18 e-cooler:

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

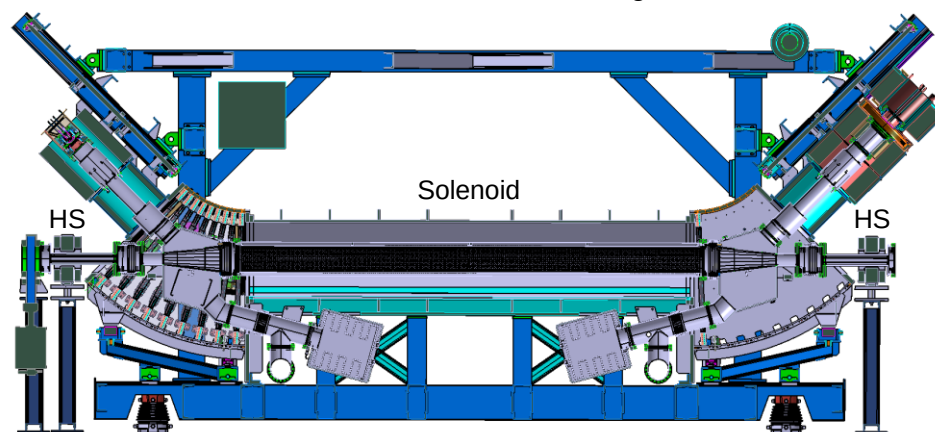
## Questions:

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

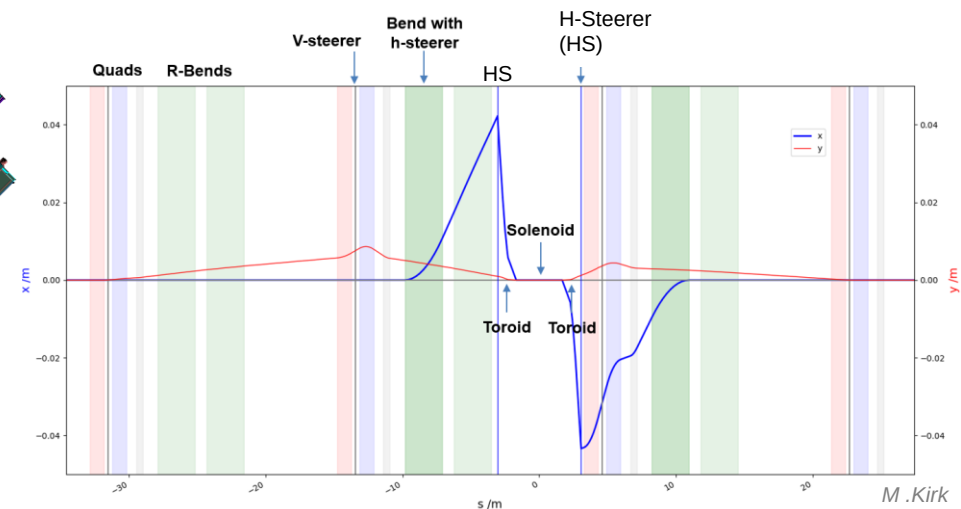
SIS18 e-cooler at present:



**Modified** SIS18 e<sup>-</sup> cooler design:



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



# 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

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\*

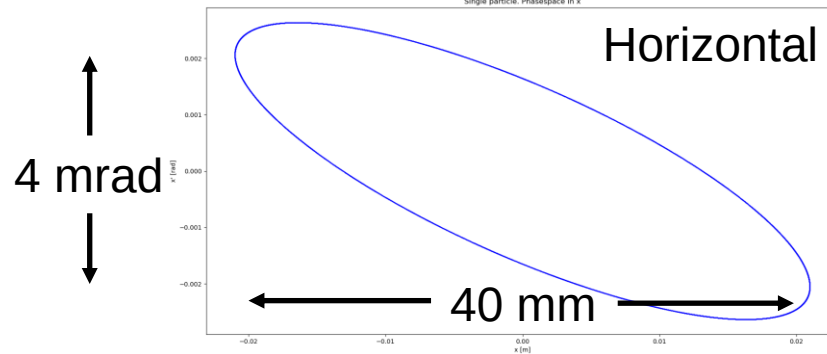
Resonance and coupling compensation

# Reserve slides ...

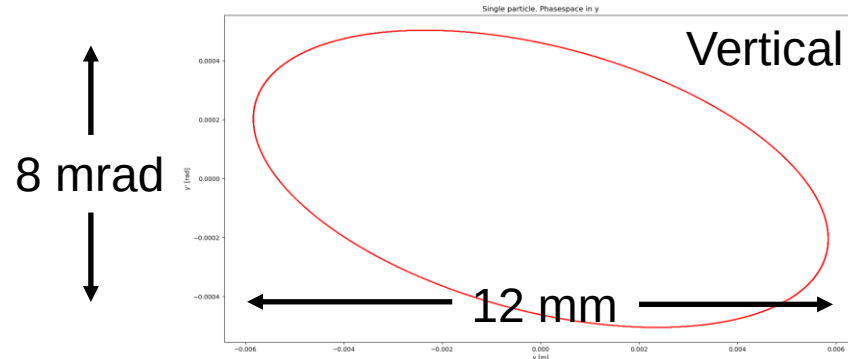
# Transport Simulations with ELEGANT



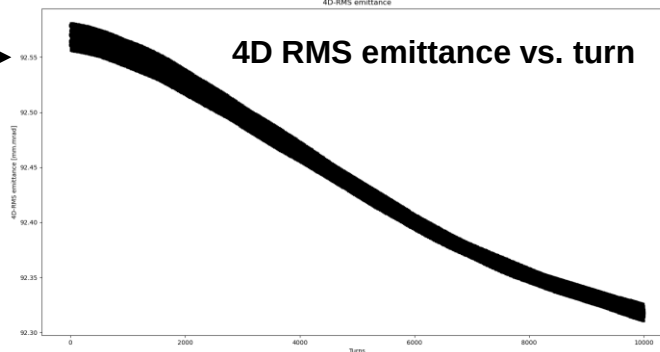
Lattice with EDRIFTs, CSBENDS (EDGE\*\_EFFECTS = 3), KQUADS. SOLEnoids at 0 mT. Tunes (4.28, 3.3),  $^{12}\text{C}^{6+}$  11.5 MeV/u



Single particle in phase space tracked for 10k turns



$92.55 \mu\text{m}^2 \rightarrow$



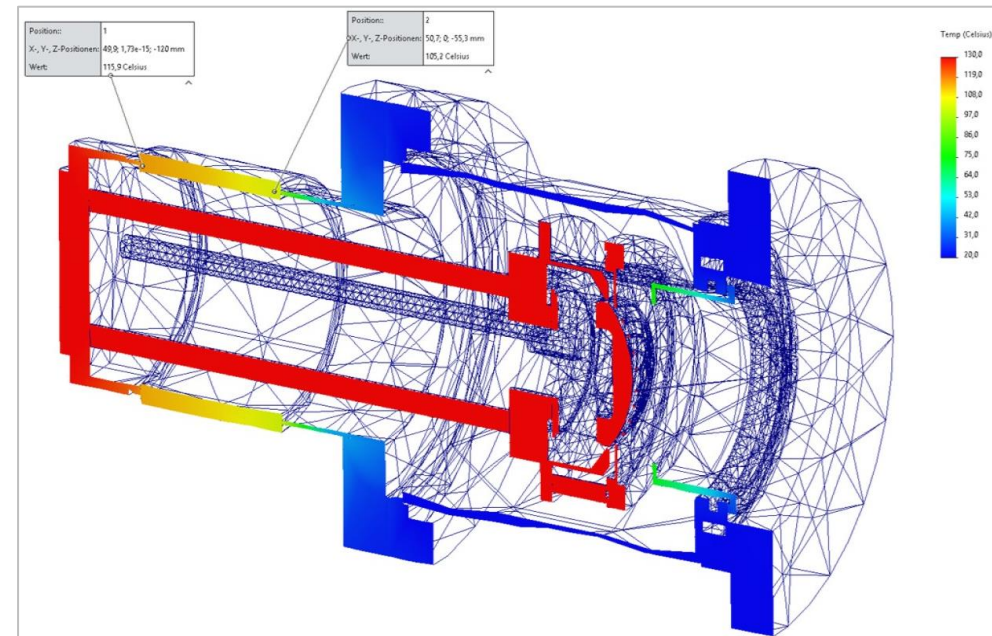
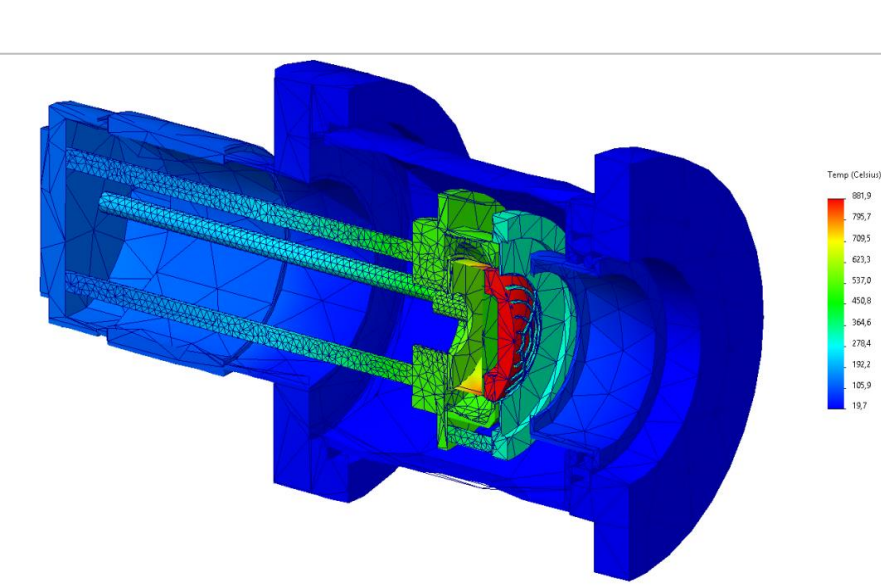
1k-ion waterbag tracked for 10k turns  
 $\approx 0.3\%$  drop in emittance

# RF-Modulated Electron Gun – Choice of Materials

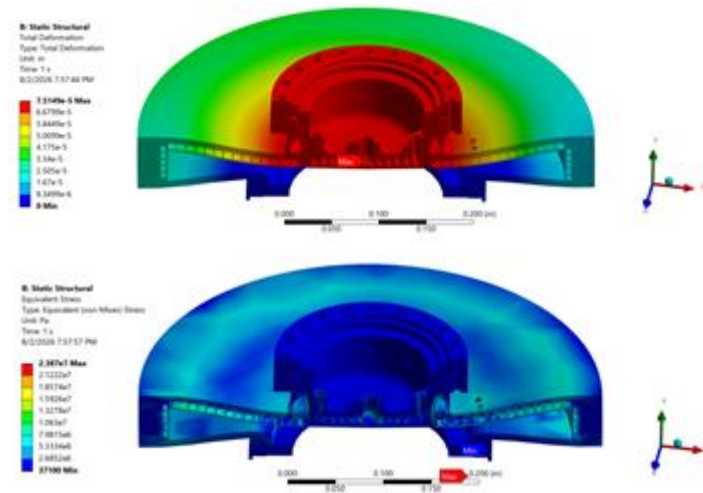


|                     |                                                  |
|---------------------|--------------------------------------------------|
| Body parts:         | Stainless steel                                  |
| Insulators:         | Alumina                                          |
|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

## Thermomechanical analysis

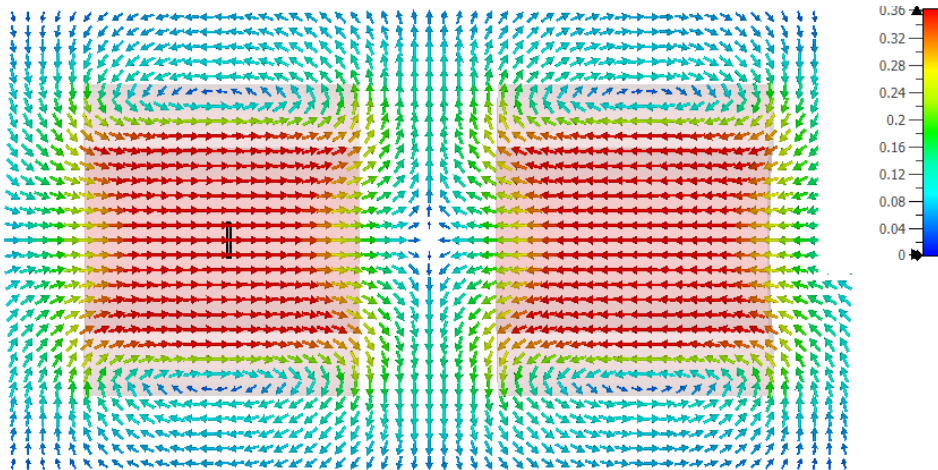


## Structural Analysis

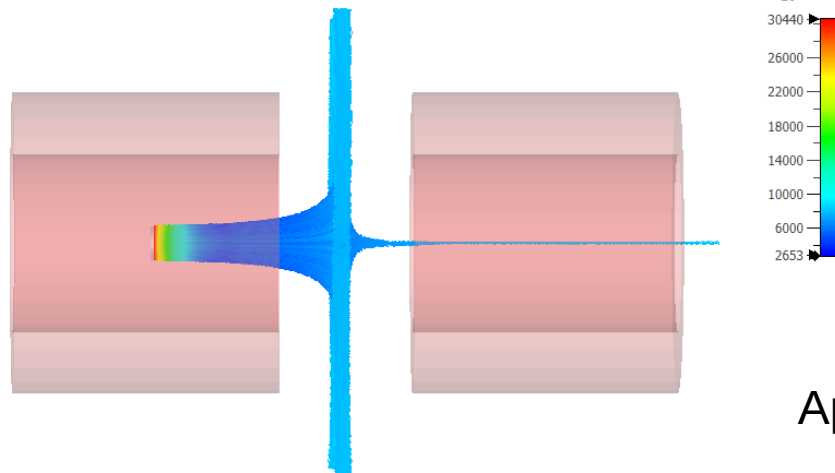
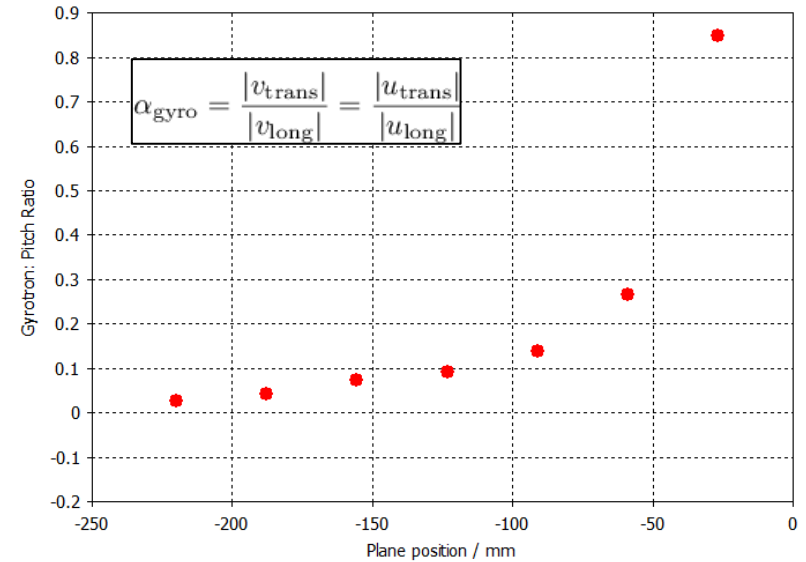


# Collector - Cusp Design

Cusp field



transverse velocity vs. longitudinal velocity



Approx. 7% losses

# RF-Modulated Electron Gun

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

