The Particle-in-Cell Code bender and Its Application to Non-Relativistic Beam Transport

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Overview

- Accelerator physics at IAP Frankfurt
- Motivation for a new code
- Structure of the code *bender*
- Simulation of space-charge compensation
  - Drift sections
  - Compensation in the presence of solenoidal magnetic fields
- Other applications of the code
  - E×B chopper at the Frankfurt Neutron Source (FRANZ)
  - Electron lenses for IOTA at Fermilab
- Conclusion and outlook

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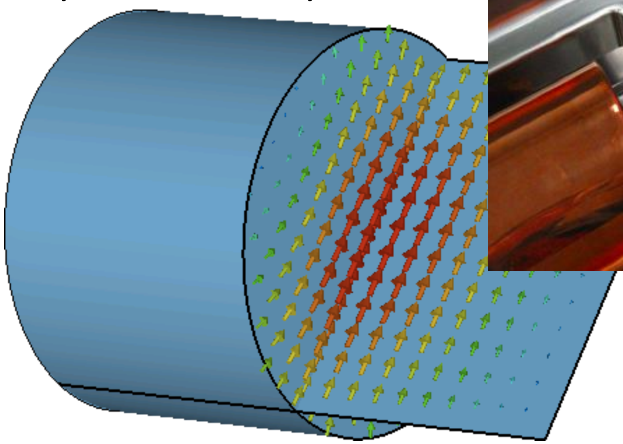
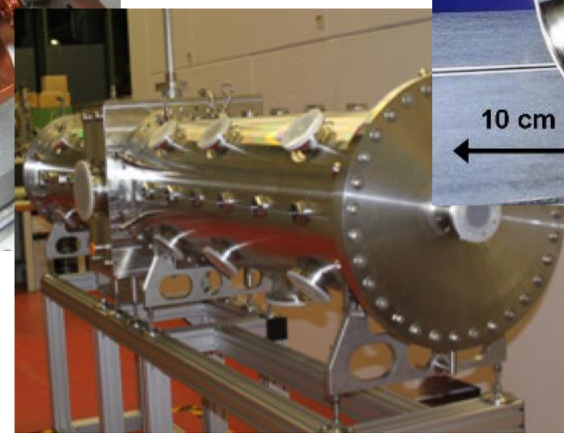
Cavity development at IAP

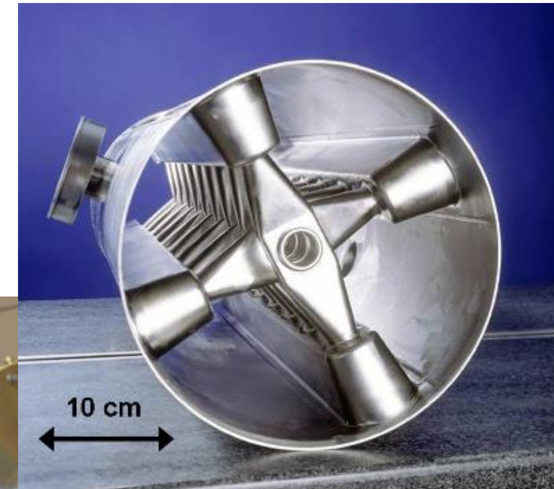
TE$_{111}$ mode in a cylindrical cavity



IH cavity



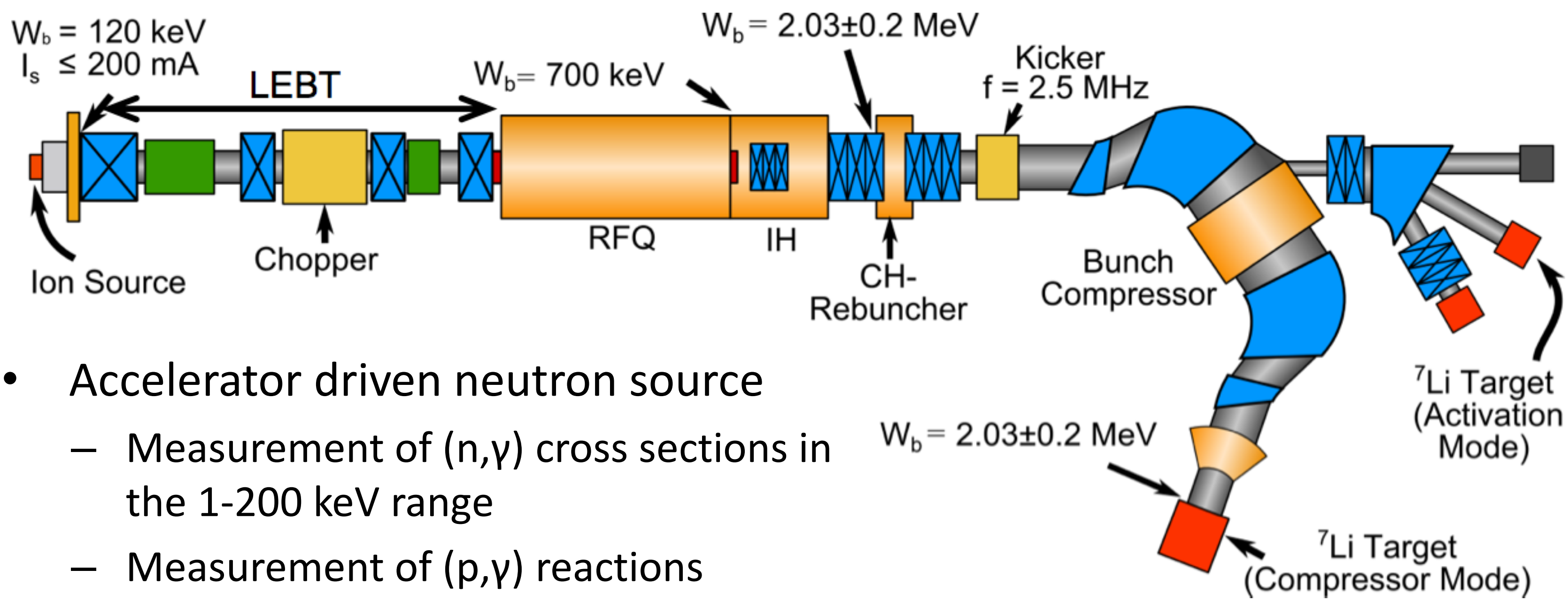
p-linac
CH-cavity 2



Superconducting CH prototype

- Development of H-mode cavities (U. Ratzinger, H. Podlech)
  - Normal-conducting CH-/IH for GSI p-linac, post-acceleration for laser-produced proton beams
  - Superconducting CH for GSI Super-Heavy Element Linac, MYRRHA ADS research reactor
- Development of RFQs (A. Schempp)

Frankfurt Neutron Source FRANZ

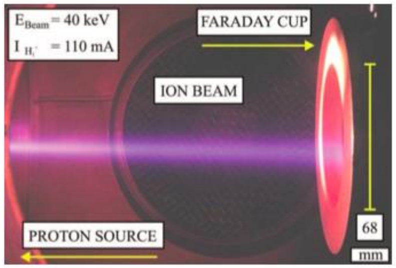


- Accelerator driven neutron source
  - Measurement of (n,γ) cross sections in the 1-200 keV range
  - Measurement of (p,γ) reactions
  - High-intensity accelerator test stand
- Neutrons produced by ^{7}Li(p,n)^{7}Be reaction
  - Beam energy E = 2 MeV
- High-neutron flux
  - Beam current I= 50 mA (- 200 mA)

- Operation modii:
  - Activation mode – integrated cross sections, I_{dc}≈2 mA
  - Compressor mode – energy resolved measurements
    - Pulse length ≈ 1 ns
    - I_{peak} ≈ 8 A (for $I_{primary}$=140 mA)

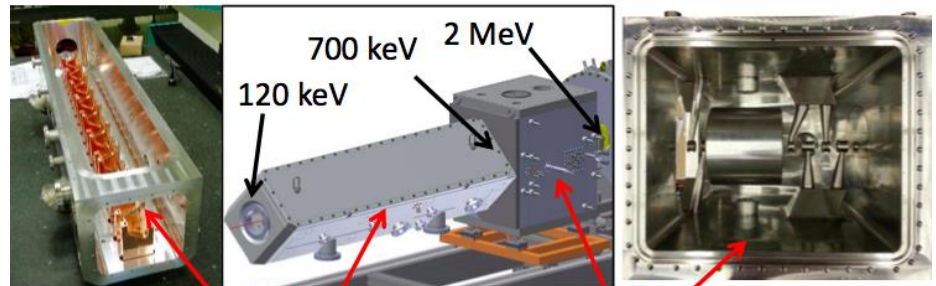
Frankfurt Neutron Source FRANZ

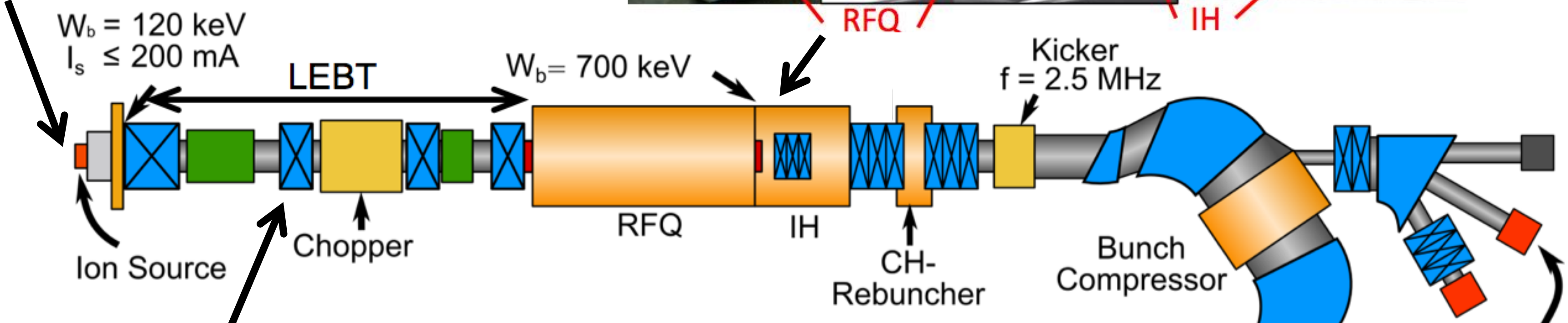
200 mA ion source (W. Schweizer, K. Volk)

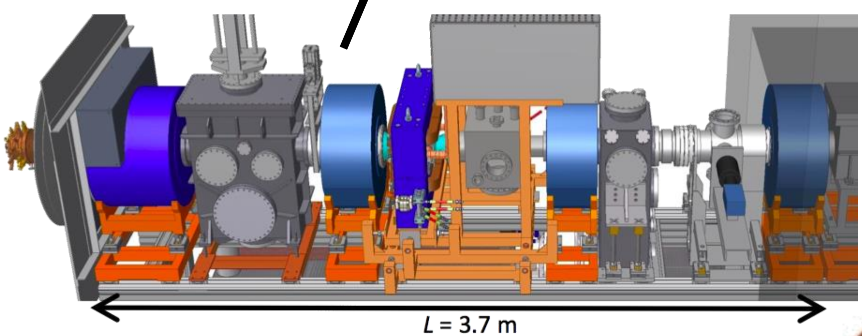


© K. Volk, W. Schweizer

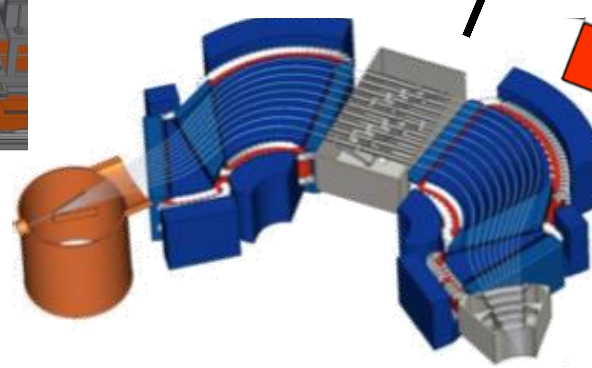
Coupled RFQ-IH section (M. Heilmann, U. Ratzinger, A. Schempp)







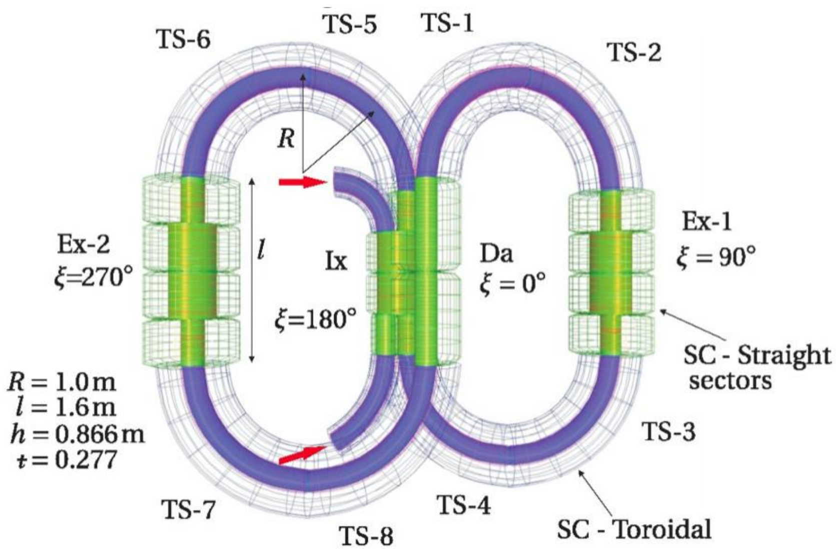
Low-energy beam transport section
(O. Meusel, P. Schneider, O. Payir, C. Wagner, C. Wiesner)



Bunch compressor
“Armadillo”
(L.P. Chau)

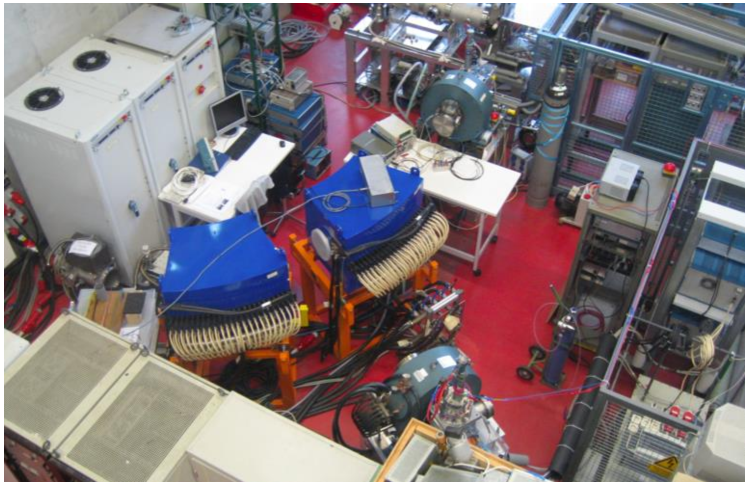
Figure 8 storage ring

M. Droba, H. Niebuhr, J. Wagner, A. Ates



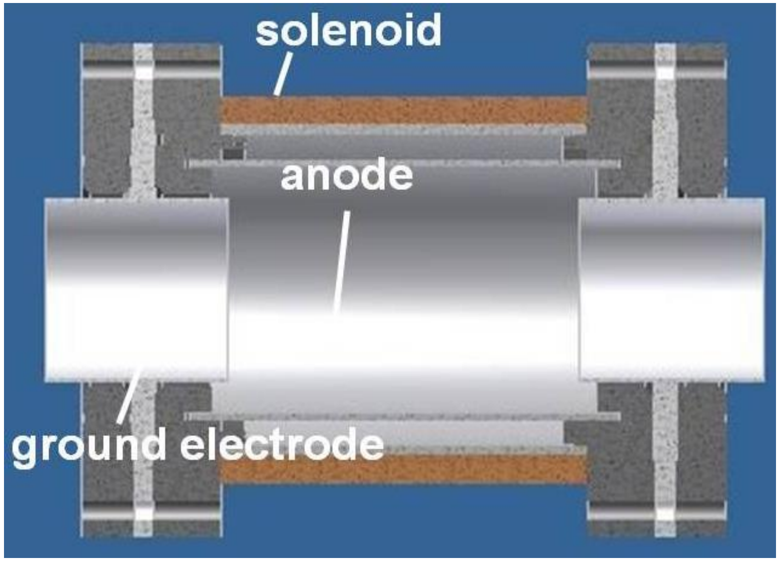
- Design study for a magnetostatic storage ring:
  - Superconducting, B ≈ 6 T
  - Beam energies (protons): 150 keV – 1 MeV
  - Beam currents: I < 10 A
- Possible experiments:
  - Measurement of fusion / astrophysical cross sections
  - Beam-plasma interaction

- Experiments on a scaled-down version ongoing:
  - Beam injection
  - Beam diagnostics
- Simulation studies on long-term confinement and beam compensation



Gabor lenses

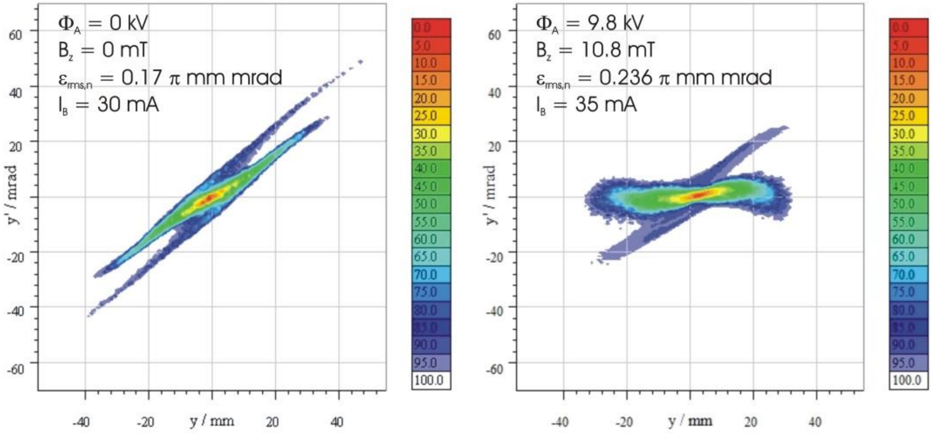
K. Schulte, O. Meusel, S. Klaproth, C. Zerbe



Technical layout of a typical Gabor lens

- Electron trap
  - Longitudinal magnetic field for transversal confinement
  - Potential well for longitudinal confinement
- Can be used to focus ion beams… or investigate the properties of the confined non-neutral plasma

- Measurements in Frankfurt
  - Temperature determination
  - Time-resolved investigation of instabilities
  - Loss mechanisms



High-intensity beam measurement at GSI [1]

[1] K. Schulte et al., Gabor Lens Performance Studies at the GSI High Current Test Injector, Proc. Of IPAC2013, THPWO21

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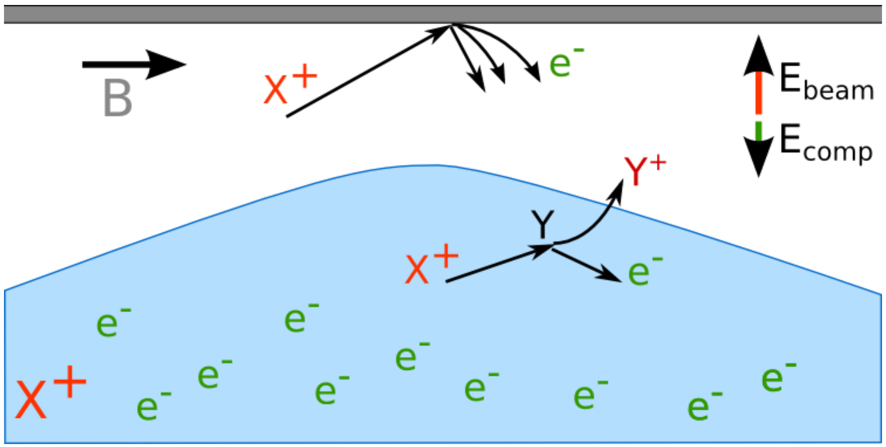
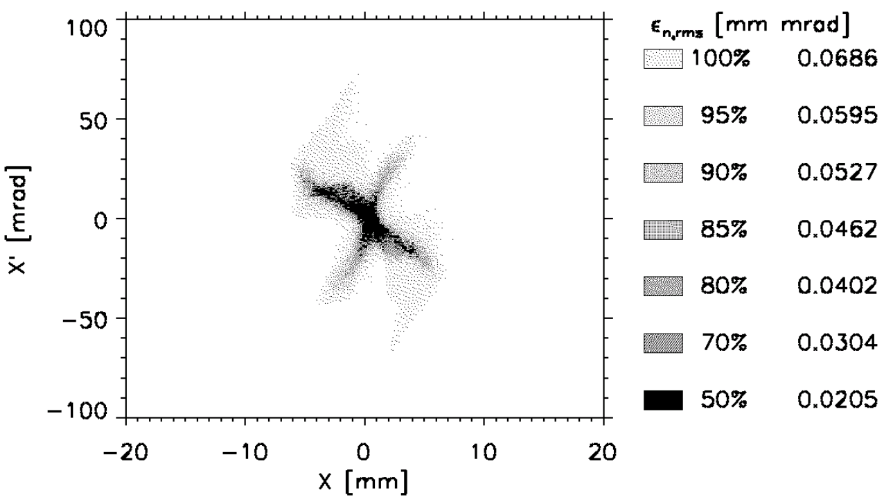
Space charge compensation





Measured beam distribution after compensated transport through 2 solenoids [1]

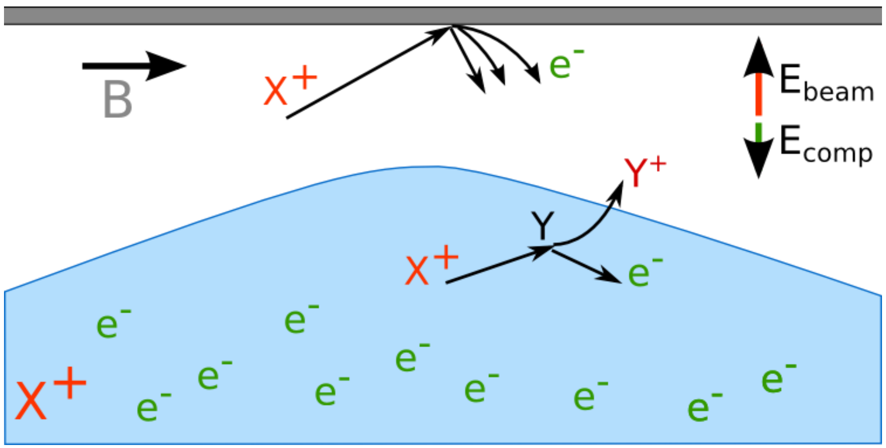
- Accumulation of secondary particles in the beam potential
- "Traditional" treatment: Constant compensation factor

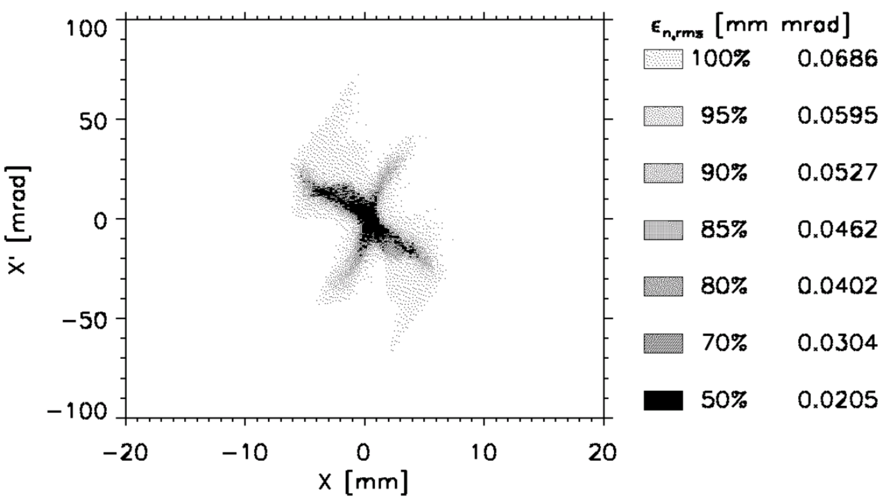
Two options:

- Decompensate the beam…
  Aberration due to high beam radii in lenses with non-linear fields
- Allow for compensation…
  Aberration due to "non-ideal" distribution of compensation particles

[1] P. Groß, Untersuchungen zum Emittanzwachstum intensiver Ionenstrahlen bei teilweiser Kompensation der Raumladung, Dissertation, Frankfurt 2000

Space charge compensation





Measured beam distribution after compensated transport through 2 solenoids [1]

- Include dynamics of compensation particles in self-consistent simulation

(Computational) challenges:

- Long simulation times

$$t_{\text{Compensation}} = \frac{kT}{vp\sigma} = 17\mu s$$

120 keV p+, N_2, p=10^{-3} Pa

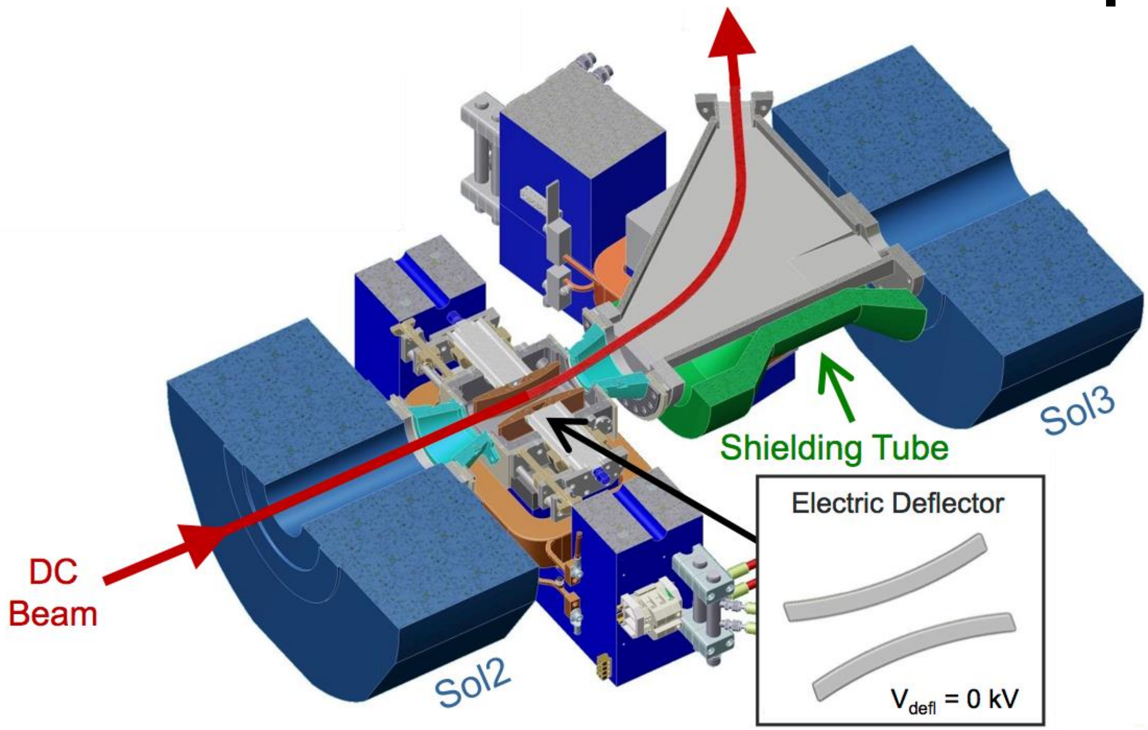
- Magnetic fields

$$t_{\text{cyclotron}} = \frac{2\pi m}{qB} = 71\ ps,\ \ B = 0.5\ T$$

- What is the “correct” physics?

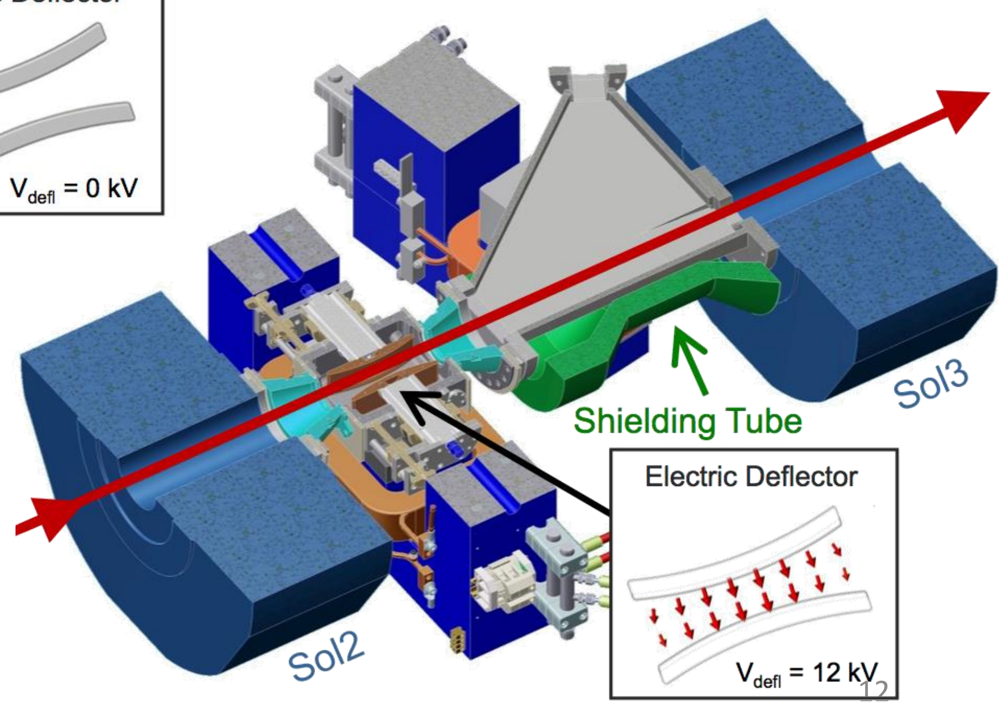
[1] P. Groß, Untersuchungen zum Emittanzwachstum intensiver Ionenstrahlen bei teilweiser Kompensation der Raumladung, Dissertation, Frankfurt 2000

FRANZ E×B chopper [1]



Questions for the simulation:

- Is it possible to form a pulse with 50 ns flat-top?
- Is it possible to transport the produced proton pulse with full space charge?



(Computational) challenges:

- Complex geometry
- Time-dependent fields

[1] C. Wiesner et al., Chopping High-Intensity Proton Beams Using a Pulsed Wien Filter, Proceedings of IPAC 2012, THPPP074
[2] C. Wiesner et al., Proton Driver Linac for the Frankfurt Neutron Source, VIII Latin American Symposium on Nuclear Physics and Applications

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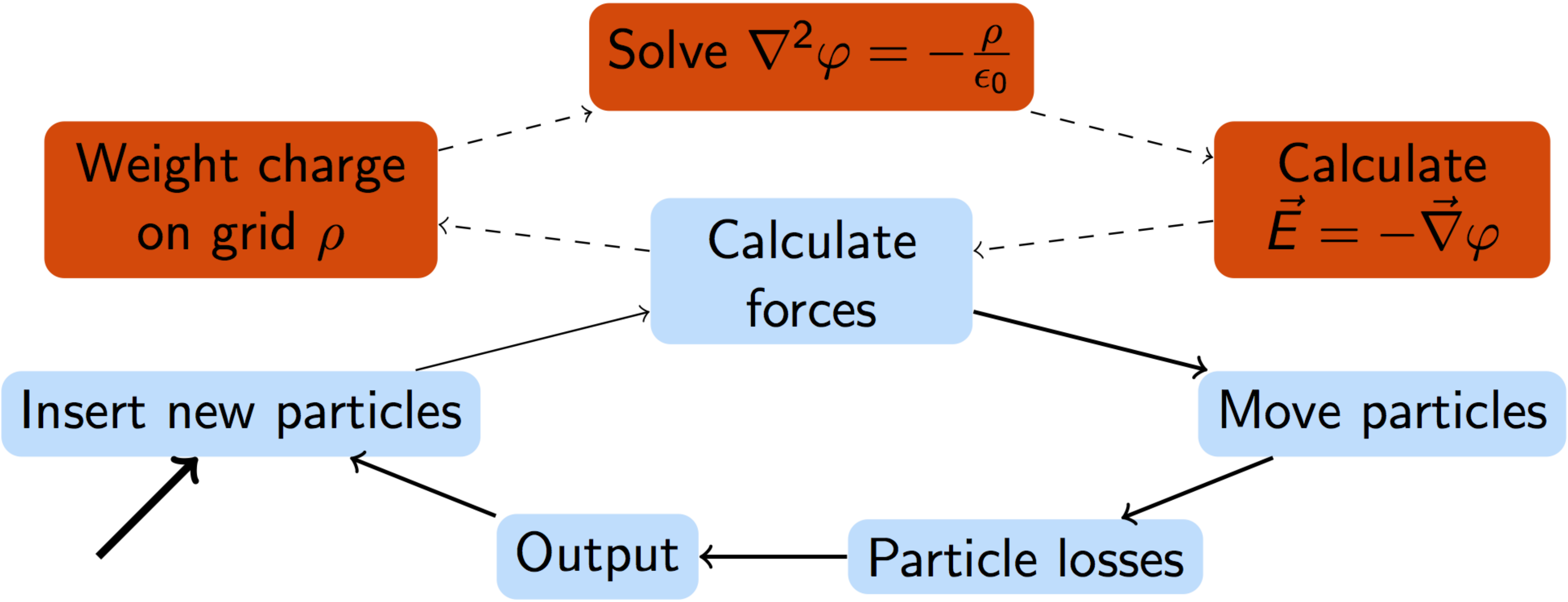
The Particle-in-Cell method

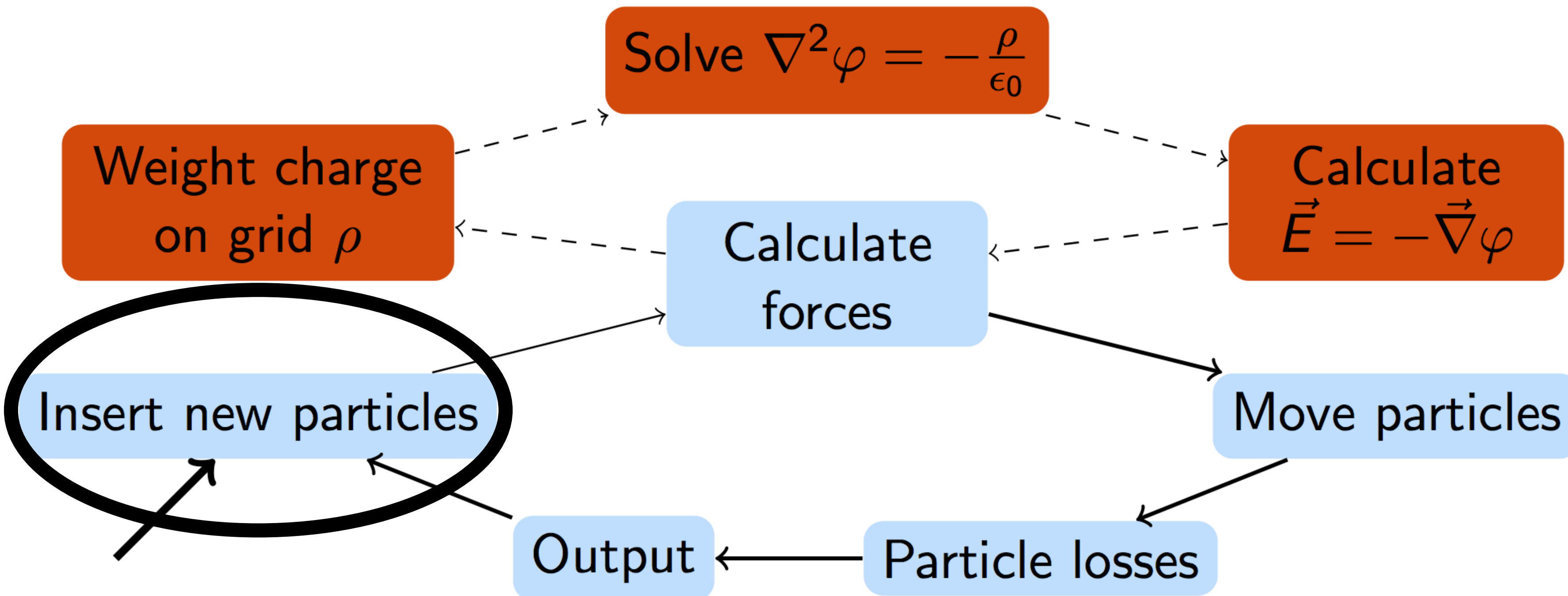


The Particle-in-Cell code bender

- Written in C++
- Parallelized using MPI:
  - Configurable load balancing
- Input in XML-style format
  - All values read with units
- Flexible geometric positioning using "coordinate systems":
  - Translation, Rotation, Scaling
  - Comoving
- Configurable output:
  - Particle distributions
  - Fields / Space charge potential
  - Particle tracking
  - Particle losses
- Geometric objects
  - Primitive objects: Plane, Pipe, Plates, …
  - STL import
  - Usable for particle losses / boundaries in Poisson solver

Bending unit 22 "Bender"
TV series "Futurama"

The Particle-in-Cell method

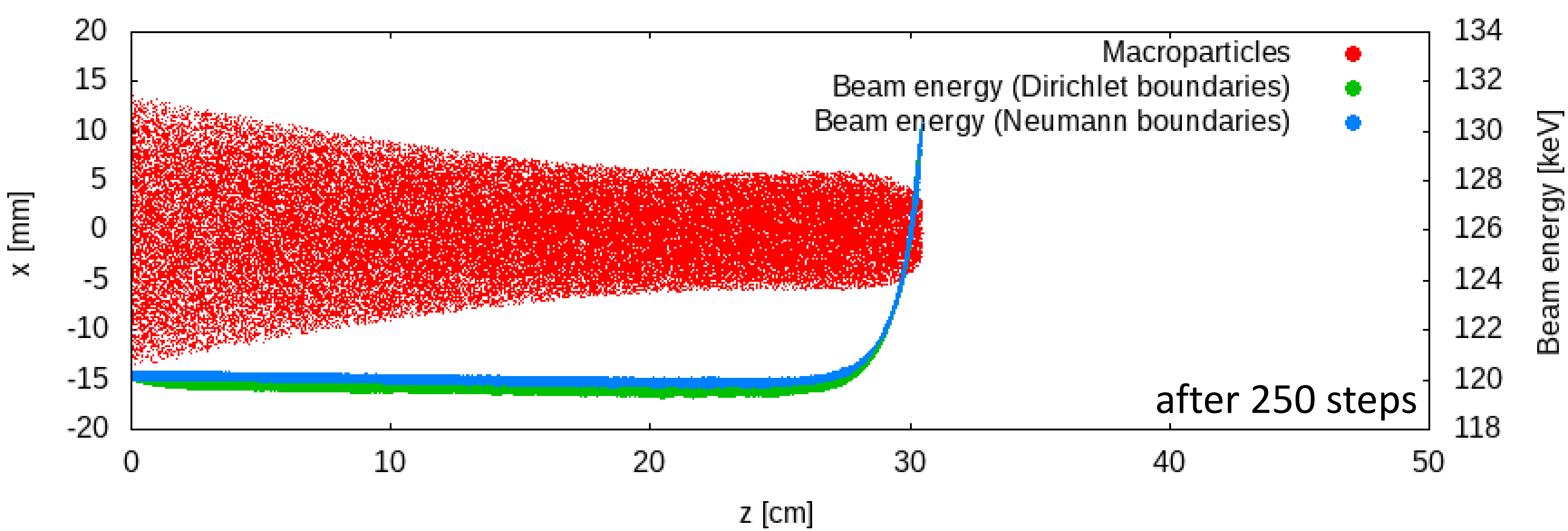


The Particle-in-Cell code bender

Particle injection

- Particle sources for
  - DC and bunched beams
  - Secondary particle emission
  - Residual gas ionisation
- Multiple species

- Available distributions:
  - Import from file
  - Model distributions: KV, Gaussian, Waterbag, …



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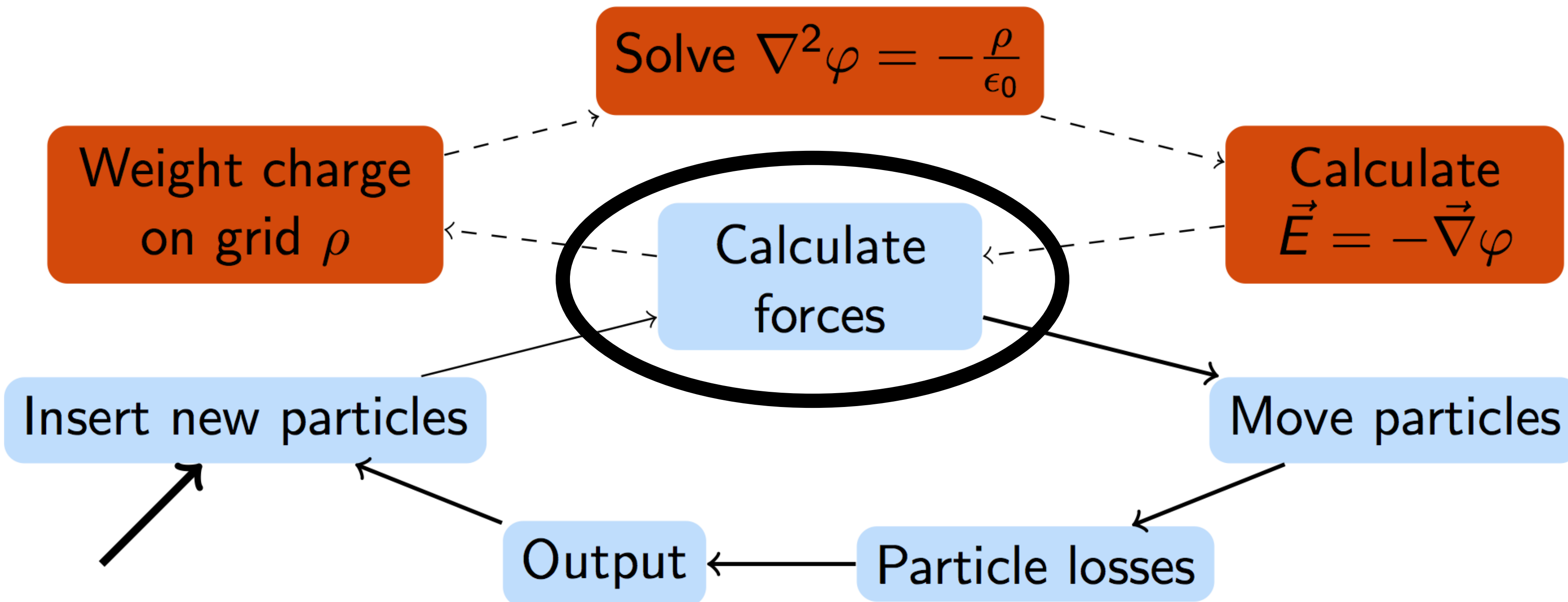


The Particle-in-cell Code bender

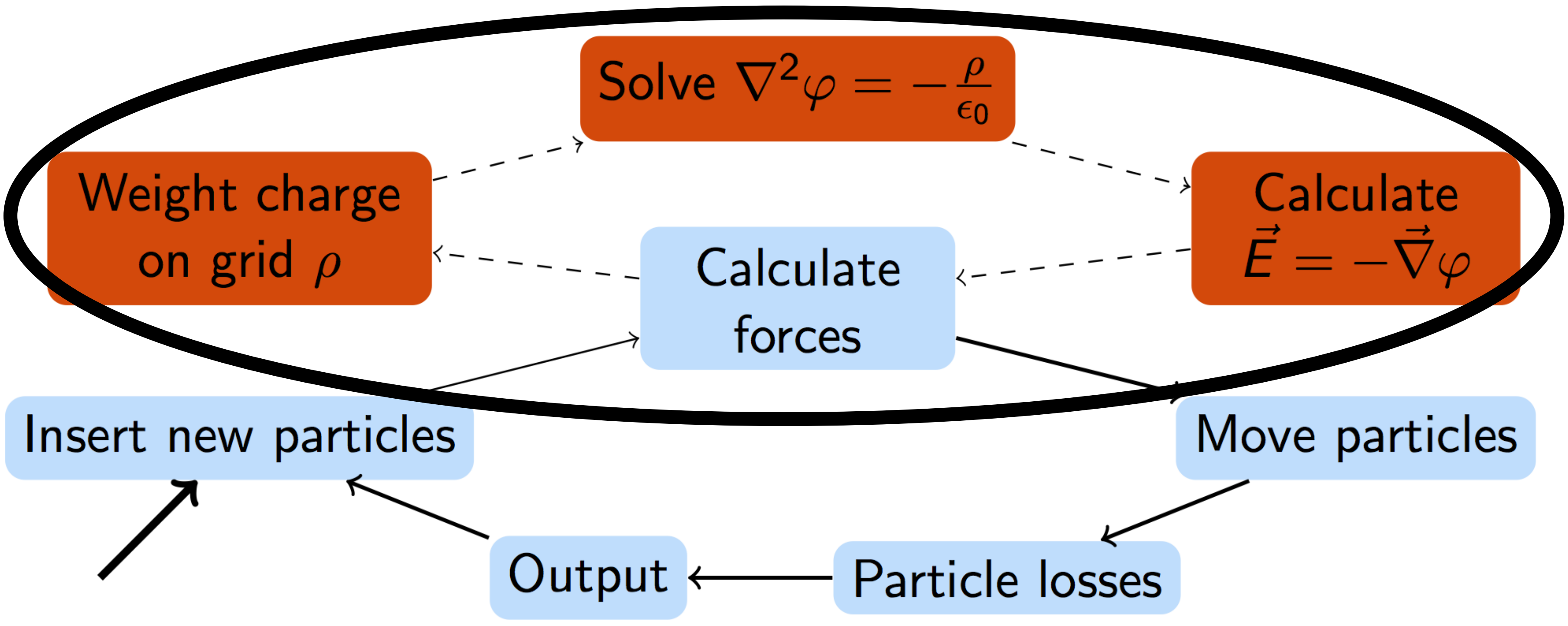
External fields

Fields from

- Import from CST, Opera
- Field models: Solenoid, Multipole fields
- Magnetic fields from Biot-Savart solver
- Electric fields from Laplace solver
- Analytic description

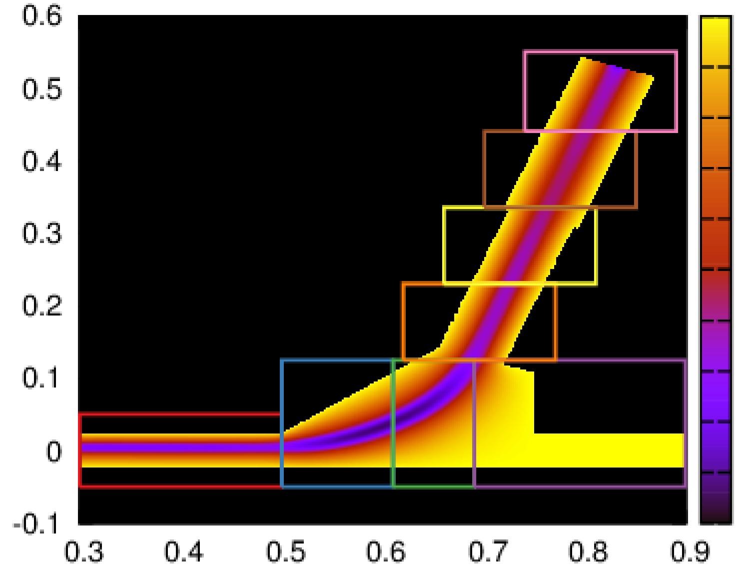
- Placeable via coordinate system definitions
  - Translation, Rotation, Scaling
- Arbitrary time dependencies: harmonic, piecewise linear, …

The Particle-in-Cell code bender



The Particle-in-Cell code bender

Self-fields



3D finite difference solver:

- Non-equidistant mesh
- Dirichlet boundaries on arbitrary geometric objects
- Distributed in arbitrary boxes
- Solution of sytem matrix using PetSc [1]

3D fast fourier solver:

- Rectangular equidistant grid
- Neumann & Dirichlet boundaries
- Distributed in z
- Implentation using FFTW [2]

2D finite difference RZ solver

- Neumann & Dirichlet boundaries, mixable on portions of the boundary
- Distributed in z
- Implemented using PetSc

[1] http://www.mcs.anl.gov/petsc

[2] http://www.fftw.org/

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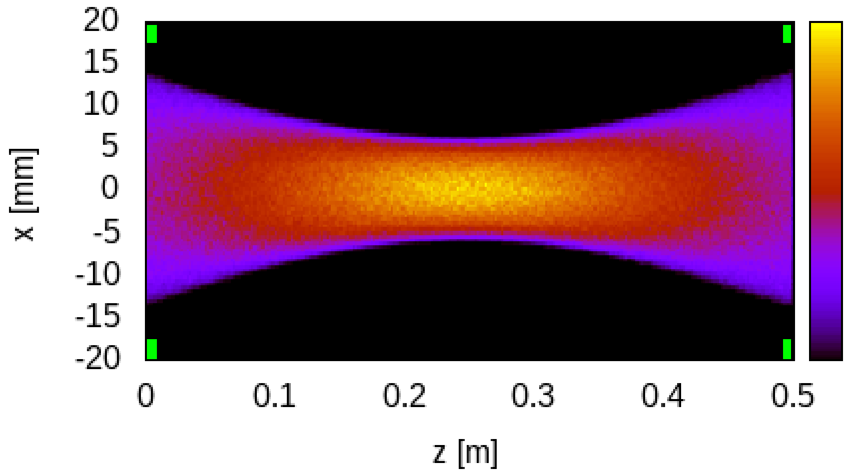
SCC studies: drift system

Investigated systems

- 120 keV, 100 mA proton beam, KV distribution
- Homogenous gas background: Argon, $p=10^{-3}$ Pa
- Repeller electrodes at -1500 V

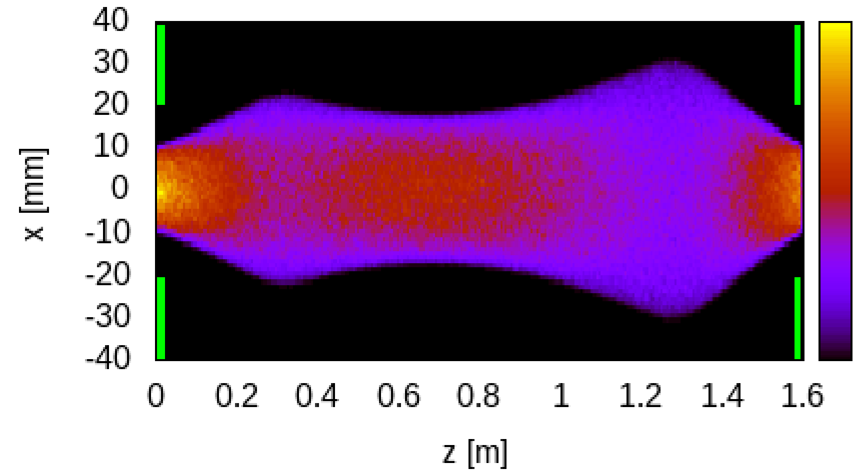
Drift (50 cm)



- Matched to achieve zero losses
- Δt = 25 ps, 1 mm grid spacing

- Runtime usually ≈ 1 day using rz solver

Two-solenoid LEBT section



- Multiple matching scenarios, B ≈ 0.7 T
- Δt = 2 ps, 1 mm grid spacing, subcycling of electrons
- Runtime ≈ 1 month using rz solver

SCC studies: drift system

- Ionizing collision via Null-collision method
- Cross-section models implemented in the code
- Isotropic distribution of secondary electron assumed

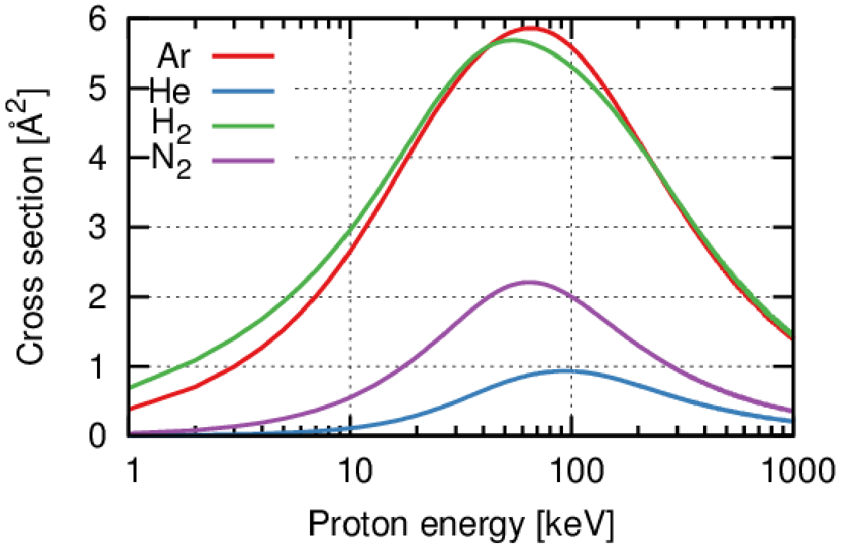
Proton impact ionization:

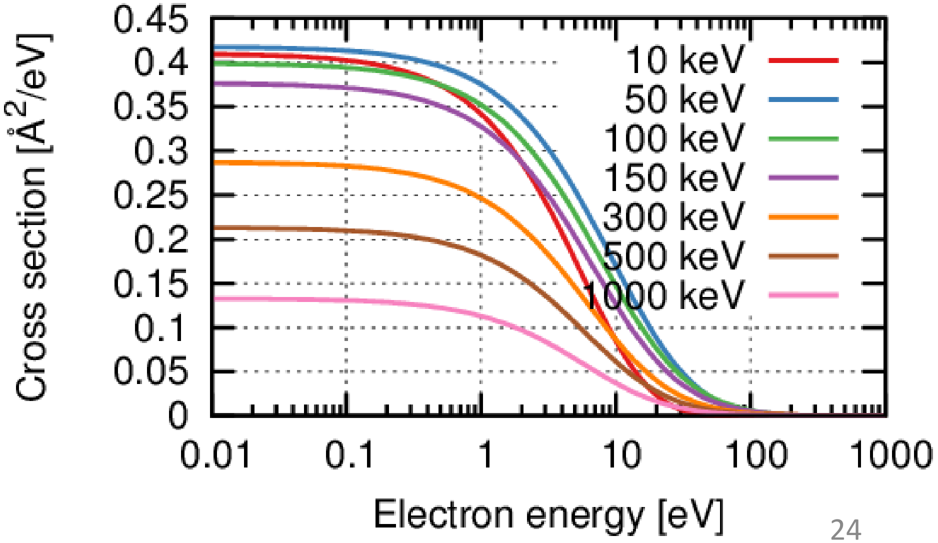
- Model from Rudd et al. [1]
- Single-differential cross section fitted to 6 datasets from different authors
- Accurate to ≈ 10-15 %

Electron impact ionization:

- Binary-Encounter Bethe model
- Single differential cross section
- Theoretical model

Cross sections



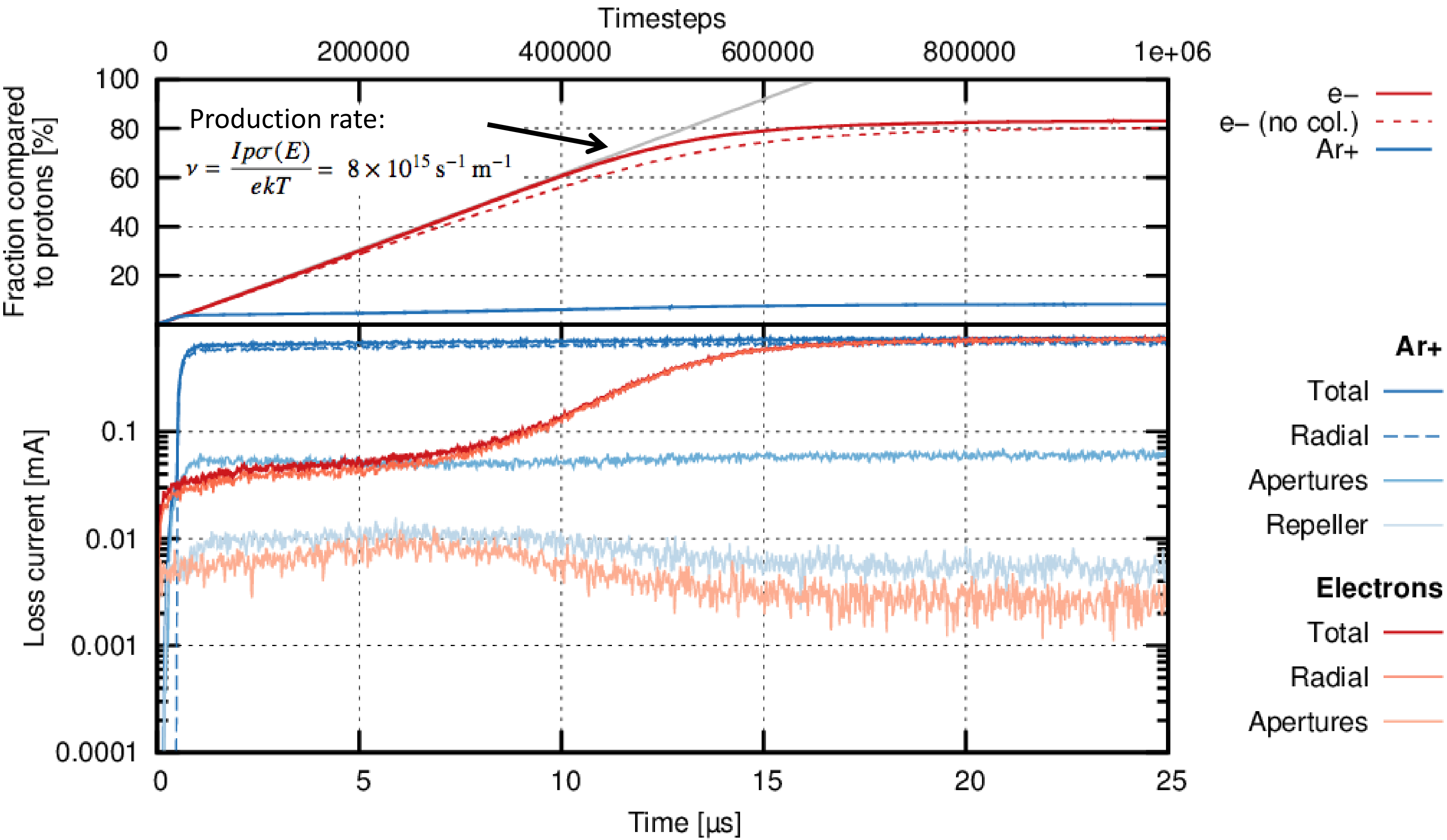


[1] Rudd, Kim, Madison, Gay - Electron production in proton collisions with atoms and molecules: energy distributions, Rev. Mod. Phys. 64, 441-490 (1992)

[2] Kim, Rudd – Binary-Encounter-Dipole Model for Electron-Impact Ionization, Physical Review A, 50(5), 3954.

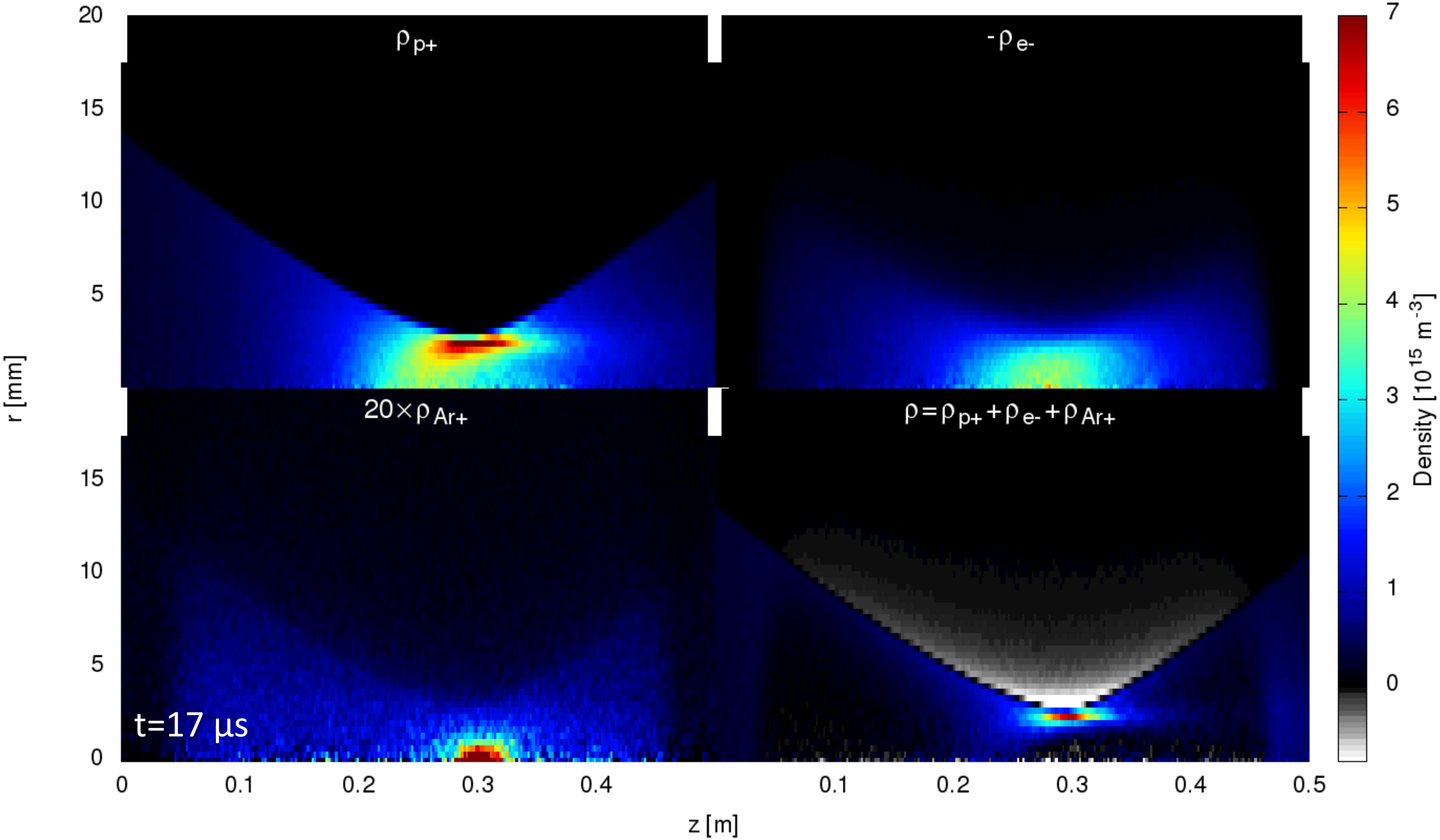
SCC studies: drift system

Compensation built-up



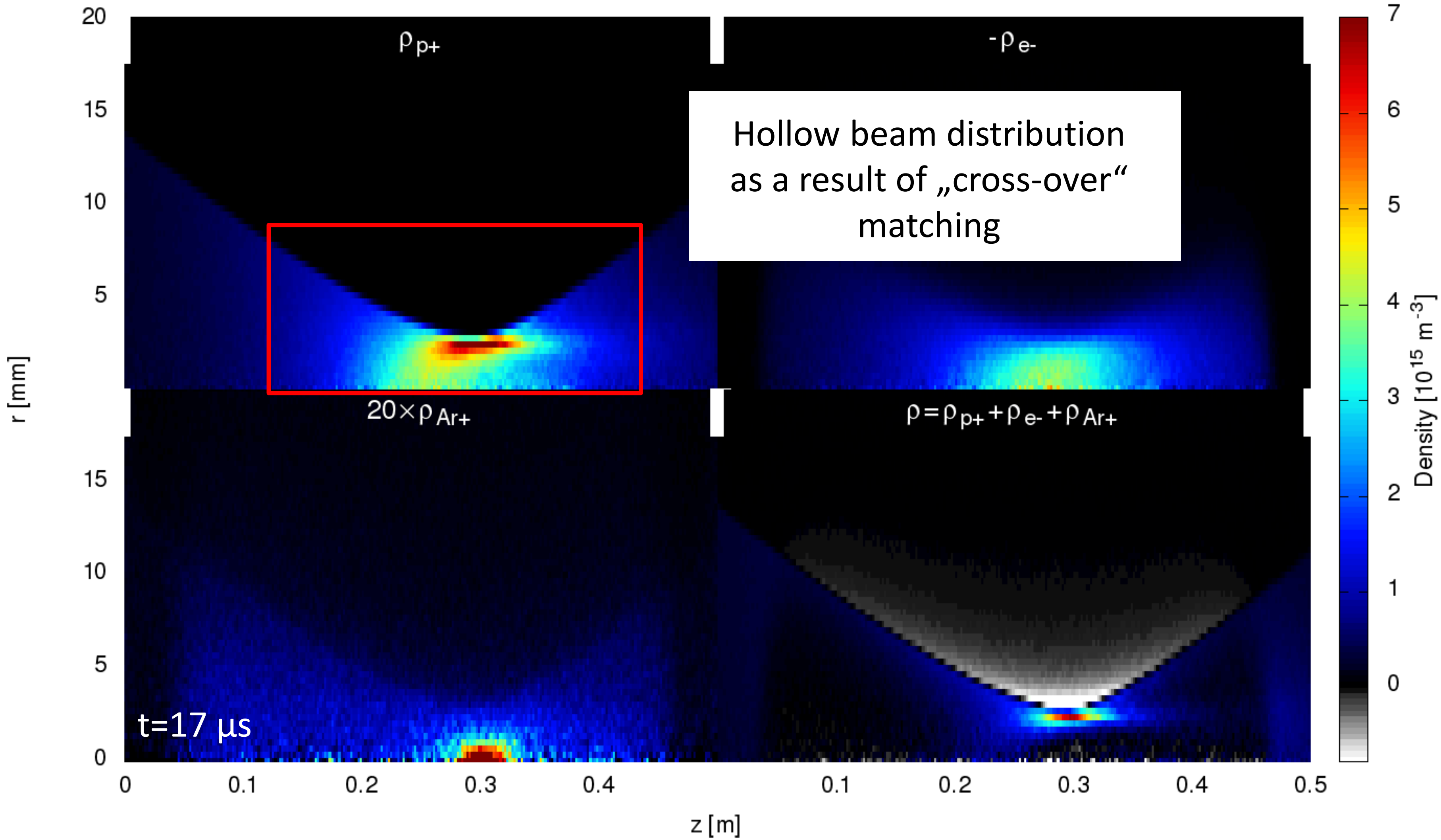
SCC studies: drift system

Spatial distribution



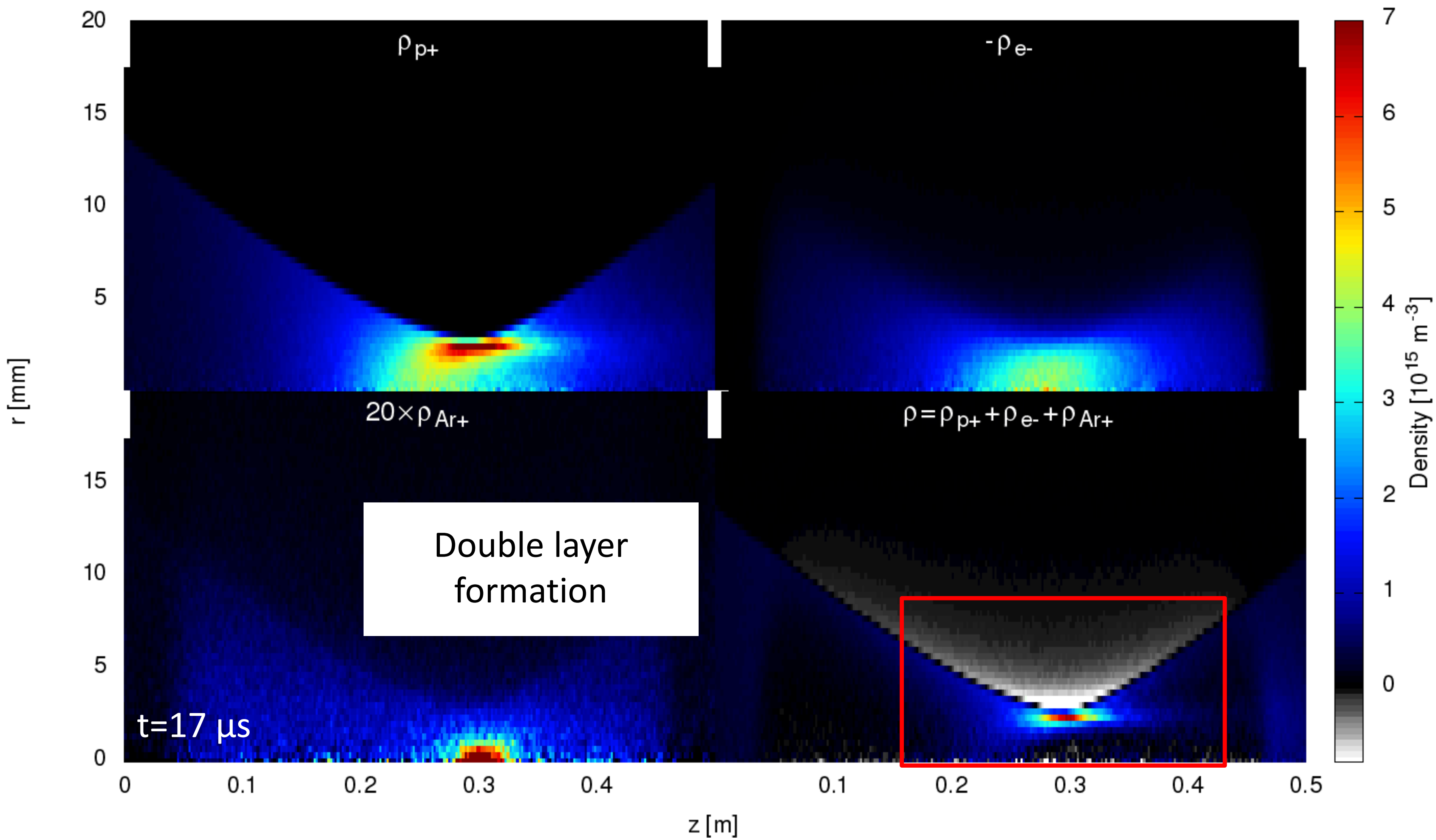
SCC studies: drift system

Spatial distribution



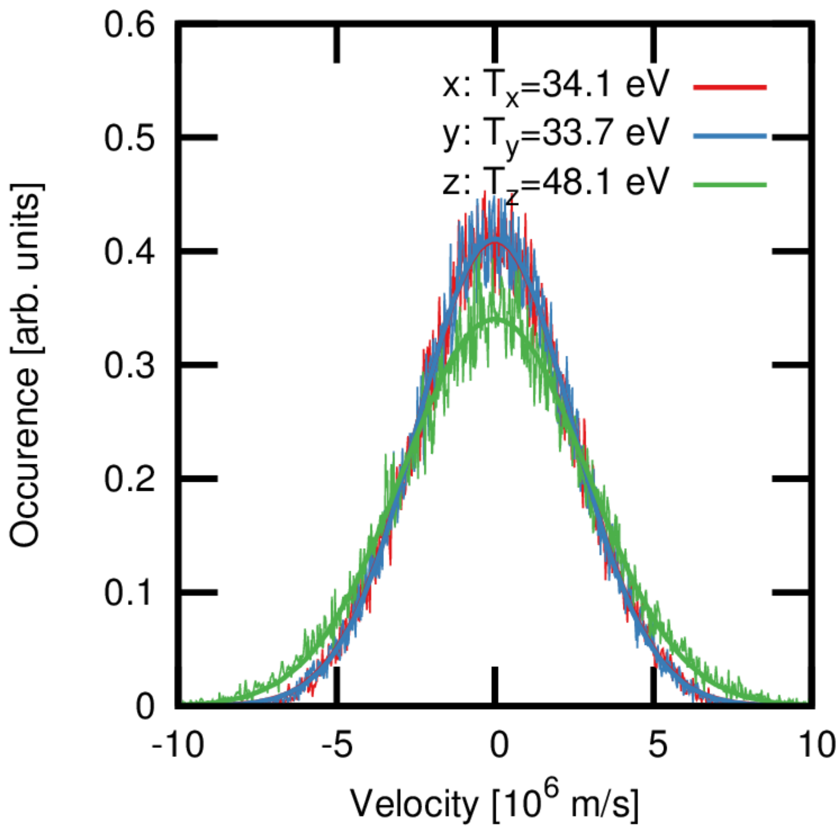
SCC studies: drift system

Spatial distribution



SCC studies: drift system

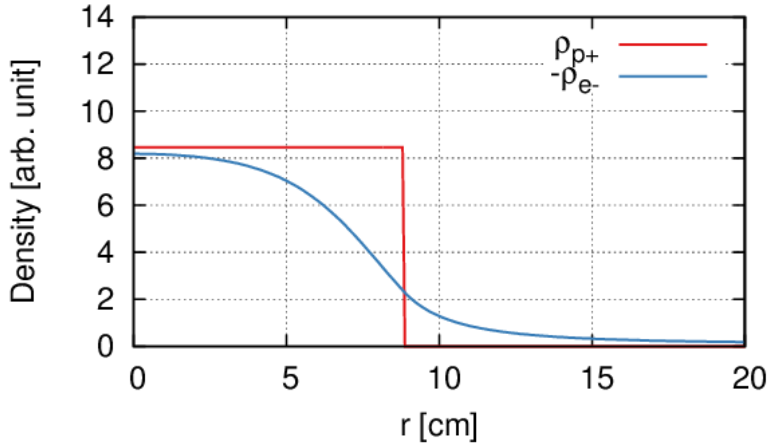
Energy distribution

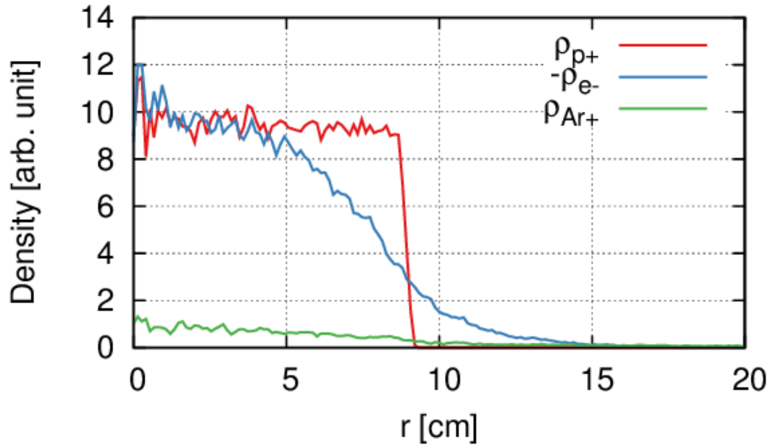


- Thermal velocity distribution
  - $T_{x,y} \neq T_z$
  - Temperatures not constant along beam axis
- Non-neutral plasma?
  - $n_e \approx 3.9 \cdot 10^{15}\ m^{-3}$
  - $\lambda_d \approx 0.7$ mm $< r_{beam}$
  - $\ln \Lambda \approx 16.6$
  - $\omega_p \approx 3.5$ GHz

SCC studies: drift system

Spatial distribution





η_{comp}=90.6 %, T=22.9 eV

- Poisson-Boltzmann equation for electrons

$$\frac{1}{r}\frac{\partial}{\partial r}(r\varphi(r)) = -\frac{\rho_{\text{beam}}(r)}{\varepsilon_0} - \frac{\rho_0}{\varepsilon_0}\exp\left\{-\frac{e\varphi(r)}{kT}\right\}$$

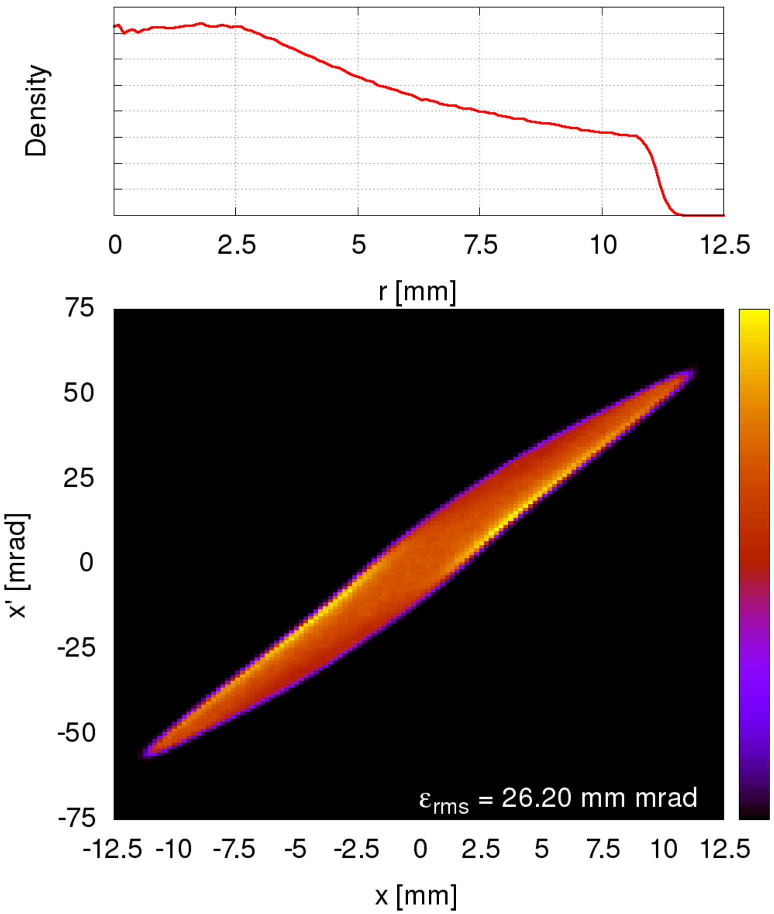
- Normalization condition

$$\int_0^R \mathrm{d}r\, r\, \rho_{\text{beam}}(r) = \rho_0 \eta_{\text{comp}} \int_0^R \mathrm{d}r\, r \exp\left\{-\frac{e\varphi(r)}{kT}\right\}$$

- Future work: Implementation in 2d code *tralitrala*, free parameters T, η_{comp}

SCC studies: drift system

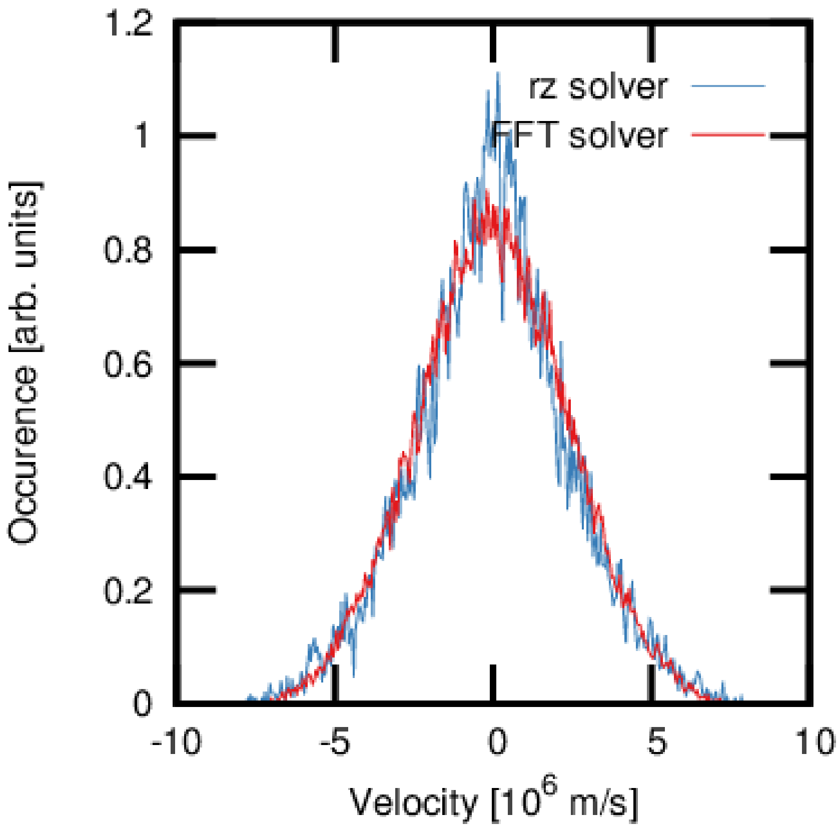
Influence on the beam



- Even for "100%" compensation, for $T_e > 0$, some space charge forces remain...

SCC studies: drift system

Energy distribution



- Remaining question:
  Which process leads to thermal distribution?
- Physical system:
  - Thermalization time due to Coulomb collisions [1]:

$$\tau_{ee} = 3\pi(2\pi)^{1/2}\frac{\epsilon_0^2(kT)^{3/2}}{n_e e^4 m^{1/2}\ln\Lambda} \approx 0.5\,\mathrm{ms}$$

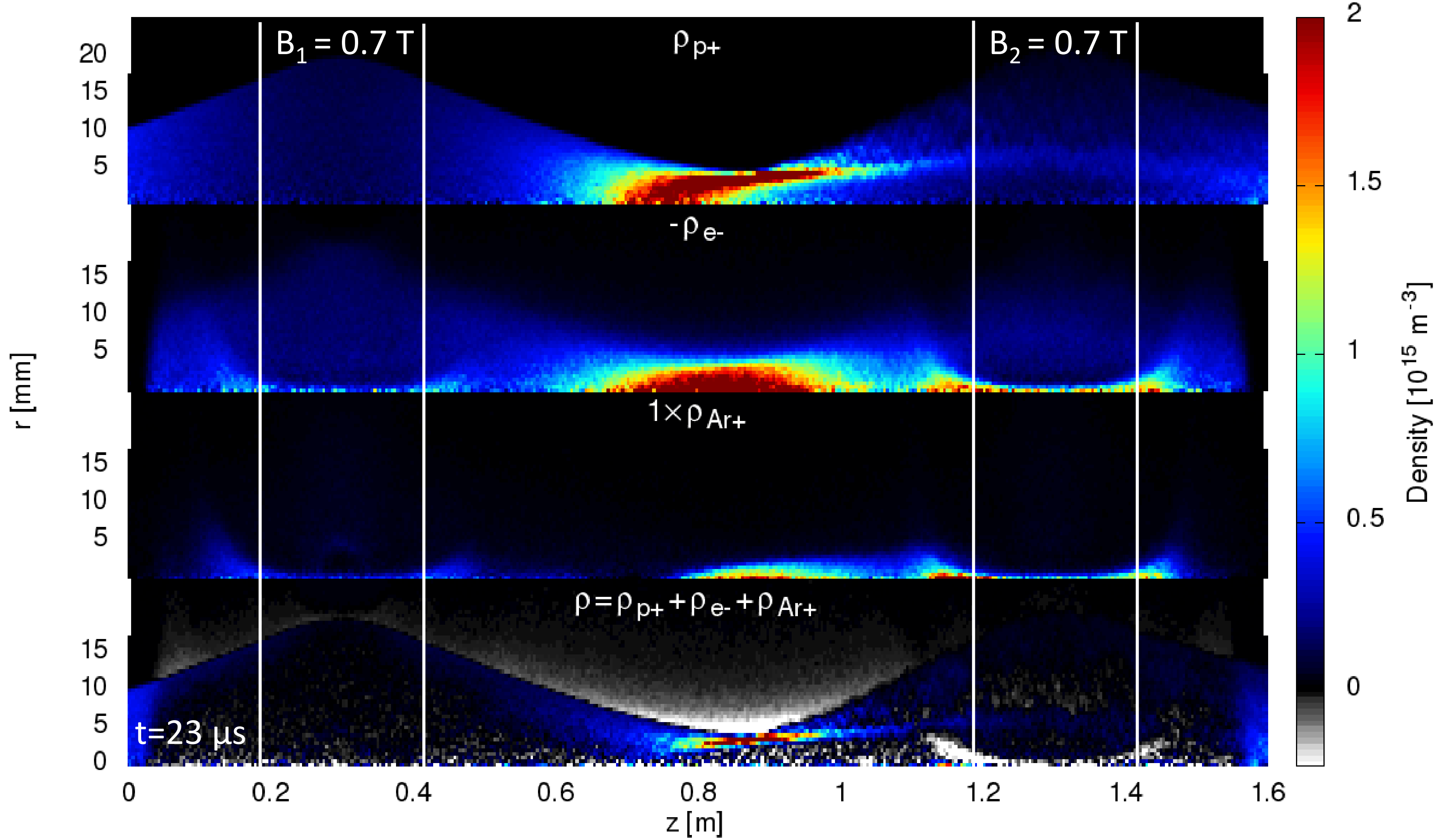
- Simulation:
  - Thermal distribution after ≈ microsecond
  - Influence of solver geometry (but almost none on macroparticle number, grid resolution…)

Open Question: Which process produces thermal distribution in the simulation?

[1] Goldston, R.J., Rutherford P.H., Introduction to Plasma Physics, Institute of Physics Pub. (1995)

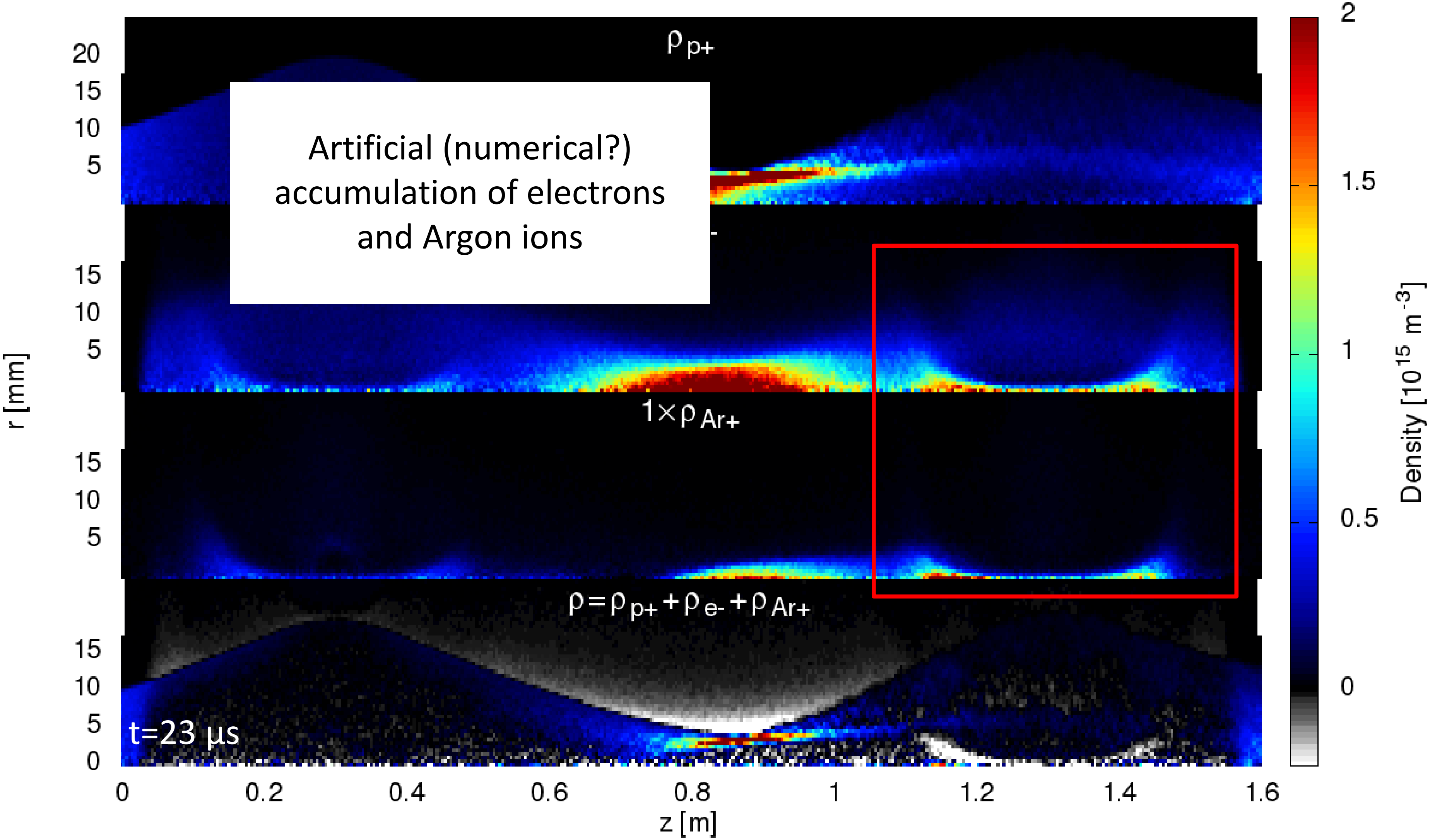
SCC studies: two solenoid LEBT

Spatial distribution



SCC studies: two solenoid LEBT

Spatial distribution



SCC studies: two solenoid LEBT

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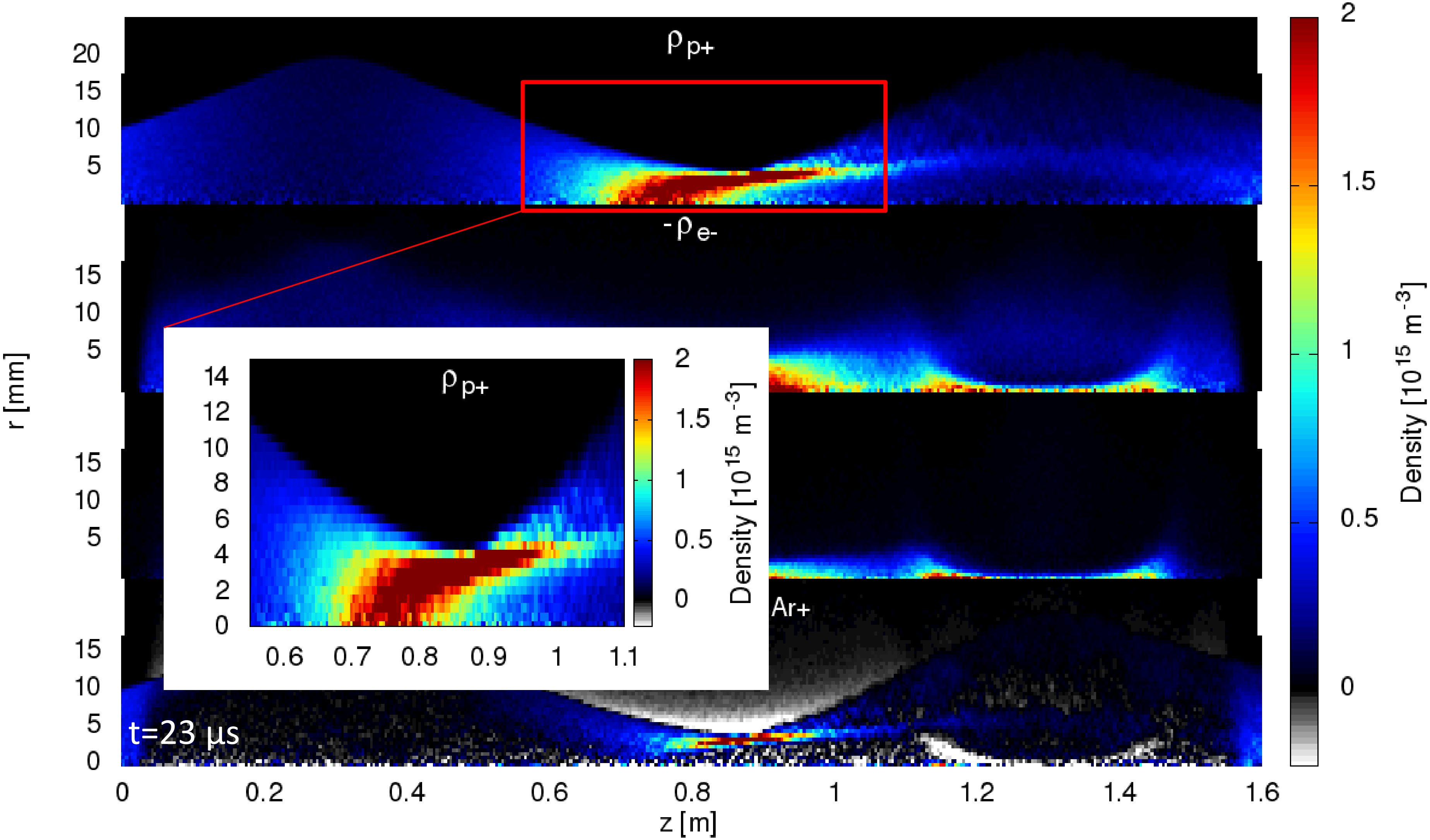

SCC studies: two solenoid LEBT

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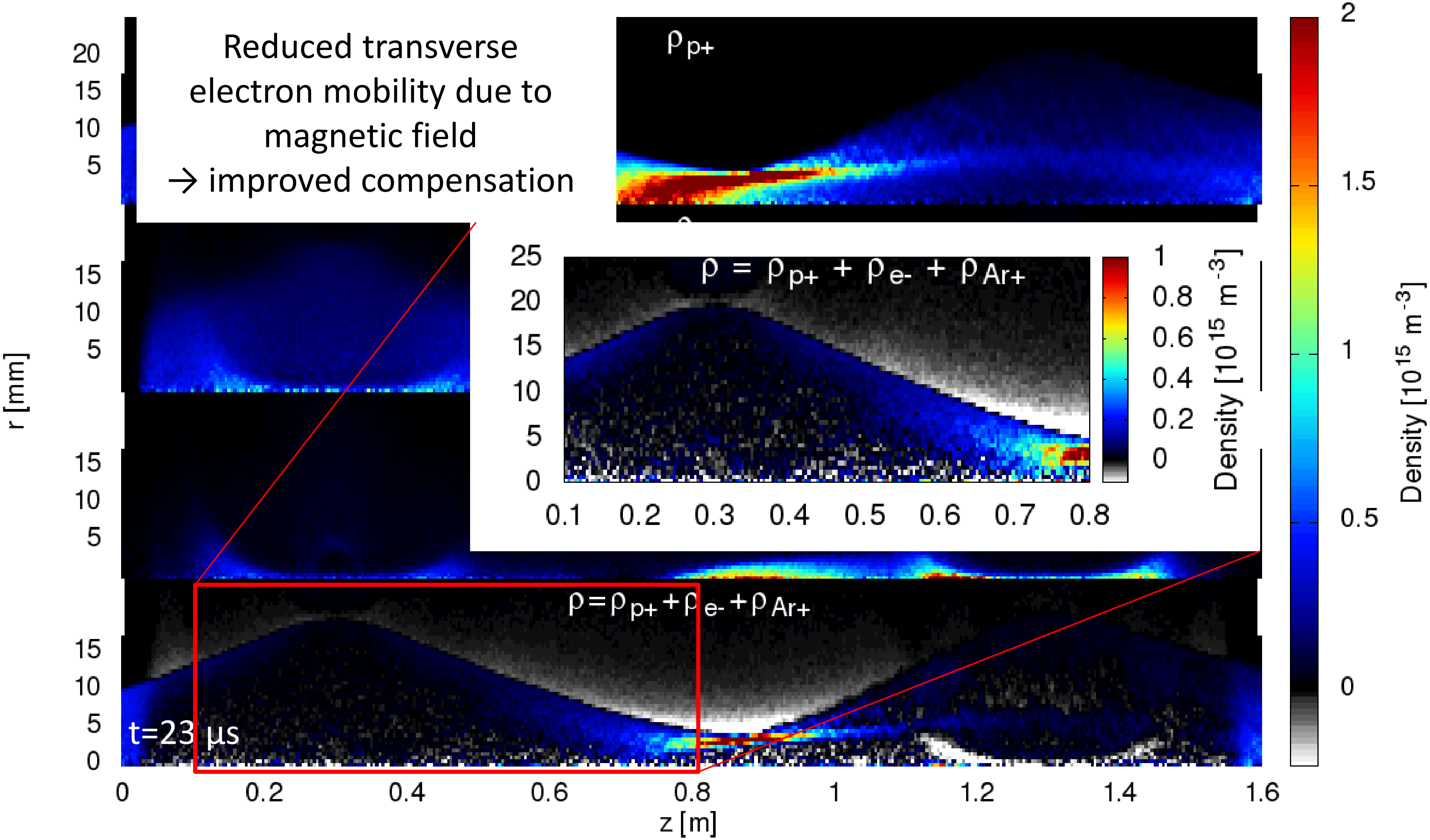

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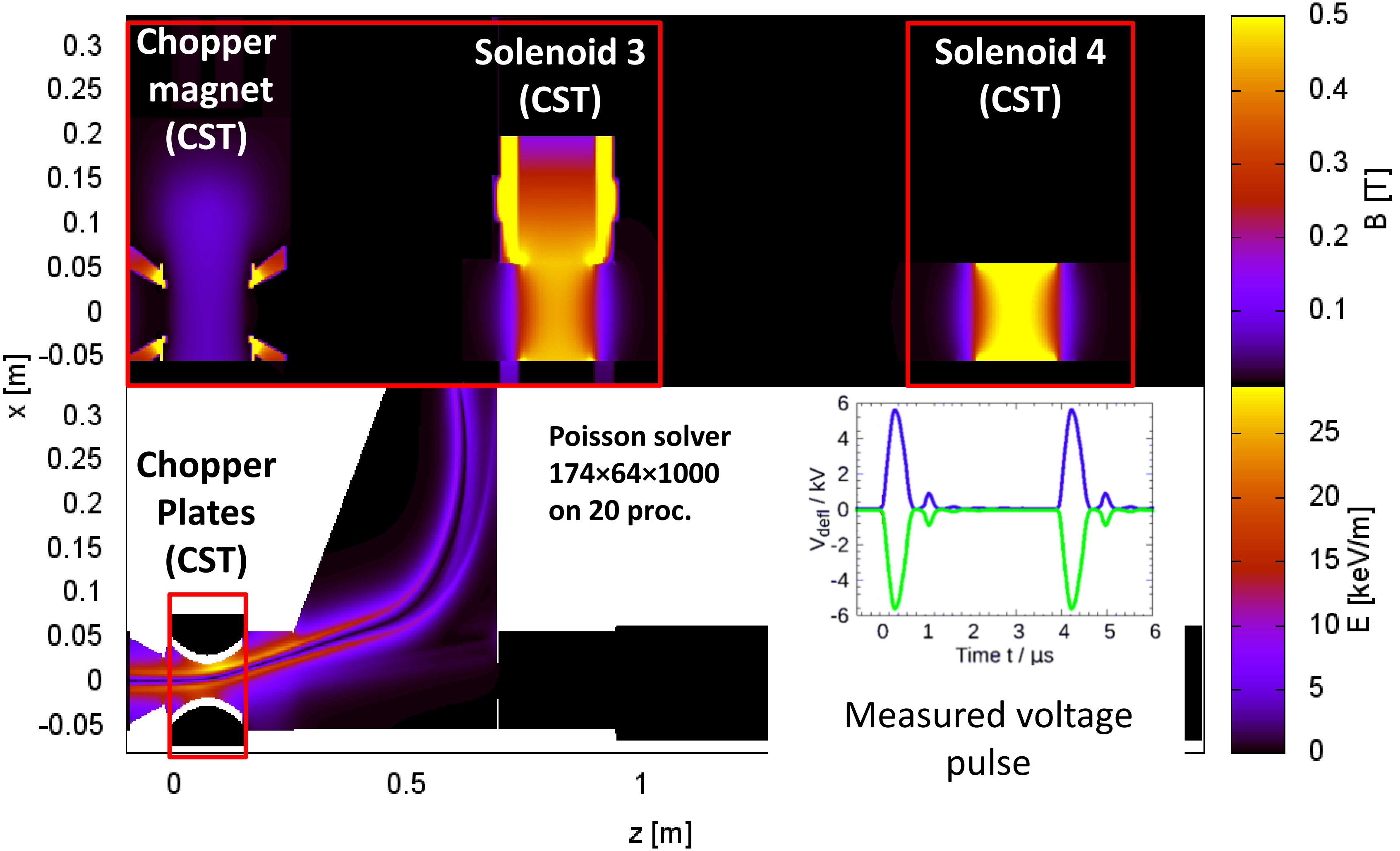
FRANZ E×B chopper

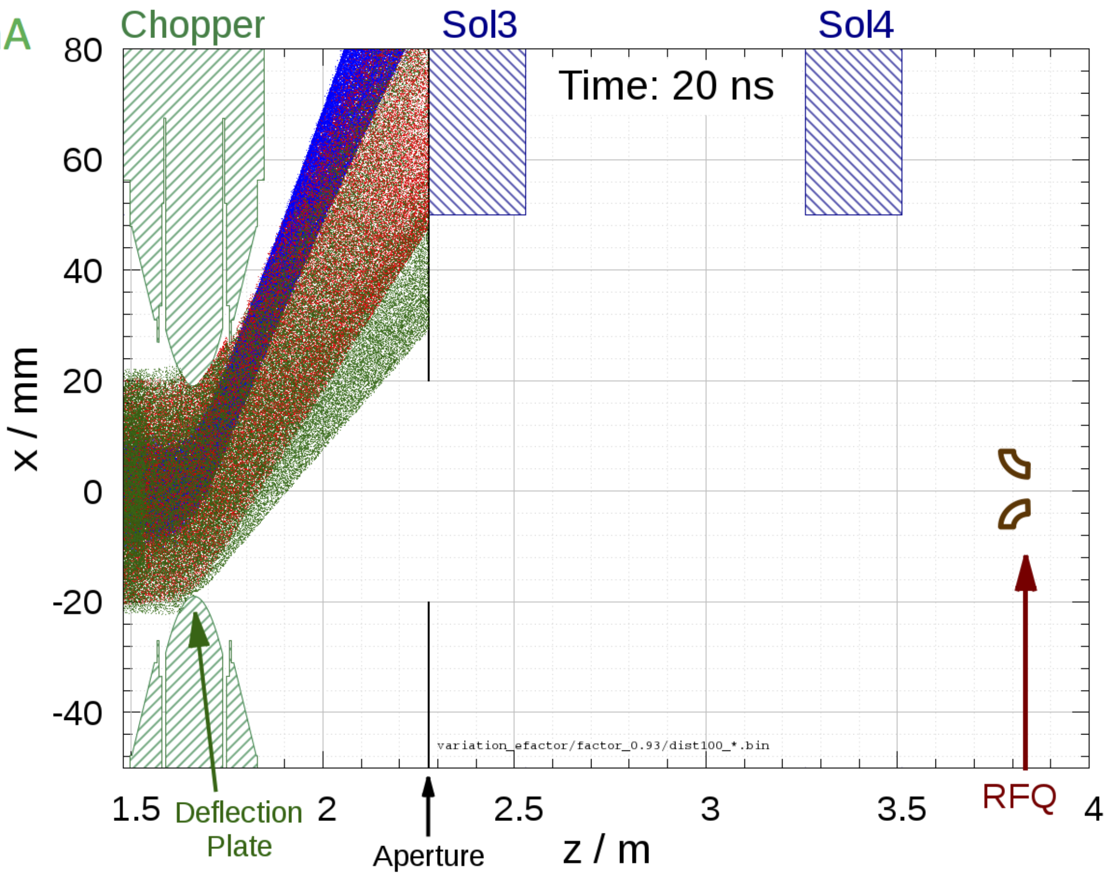
Simulation input

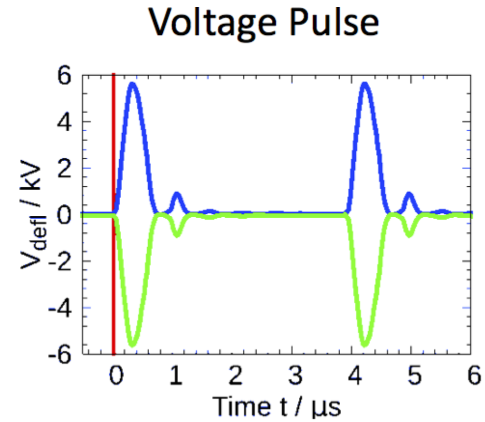


FRANZ E×B chopper

Pulse forming

p, 50 mA
H_2^+, 5 mA
H_3^+, 5 mA





Plot by C. Wiesner

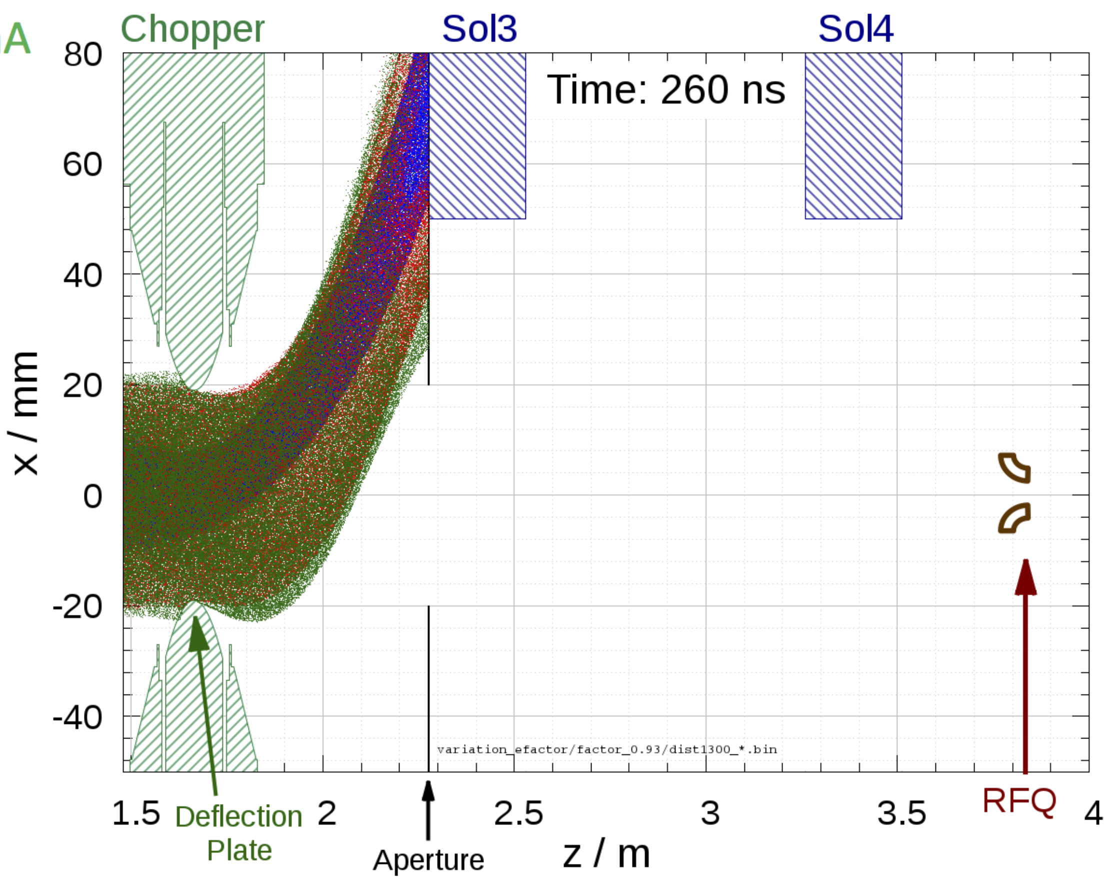
FRANZ E×B chopper

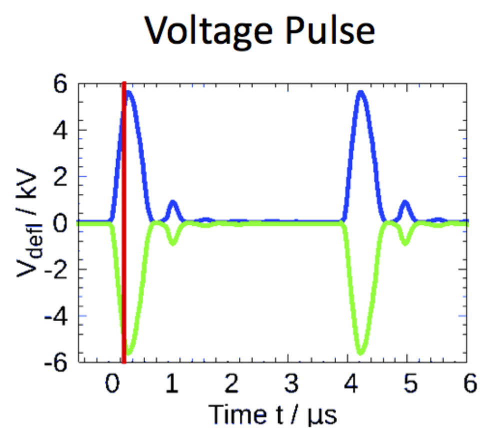
Pulse forming

p, 50 mA

H_2^+, 5 mA

H_3^+, 5 mA





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FRANZ E×B chopper

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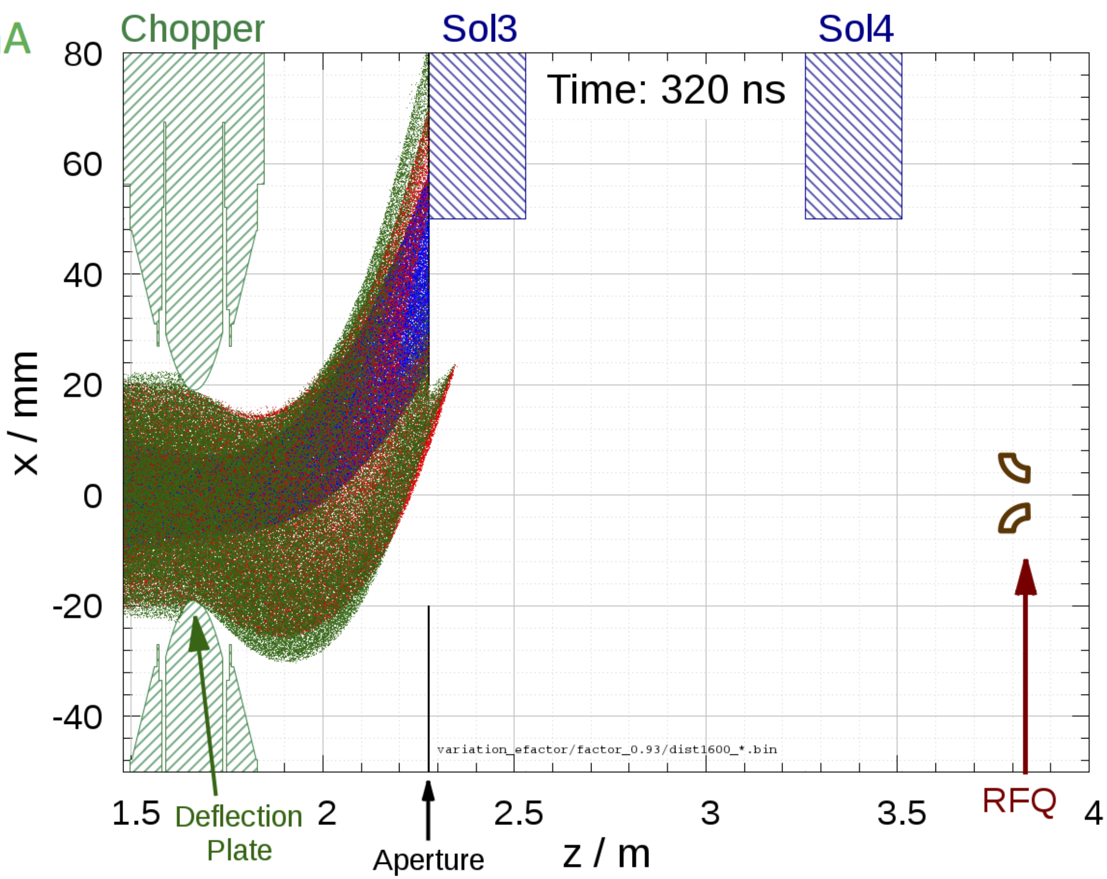

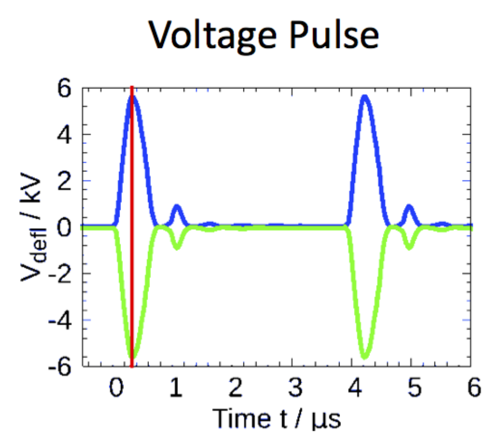

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FRANZ E×B chopper

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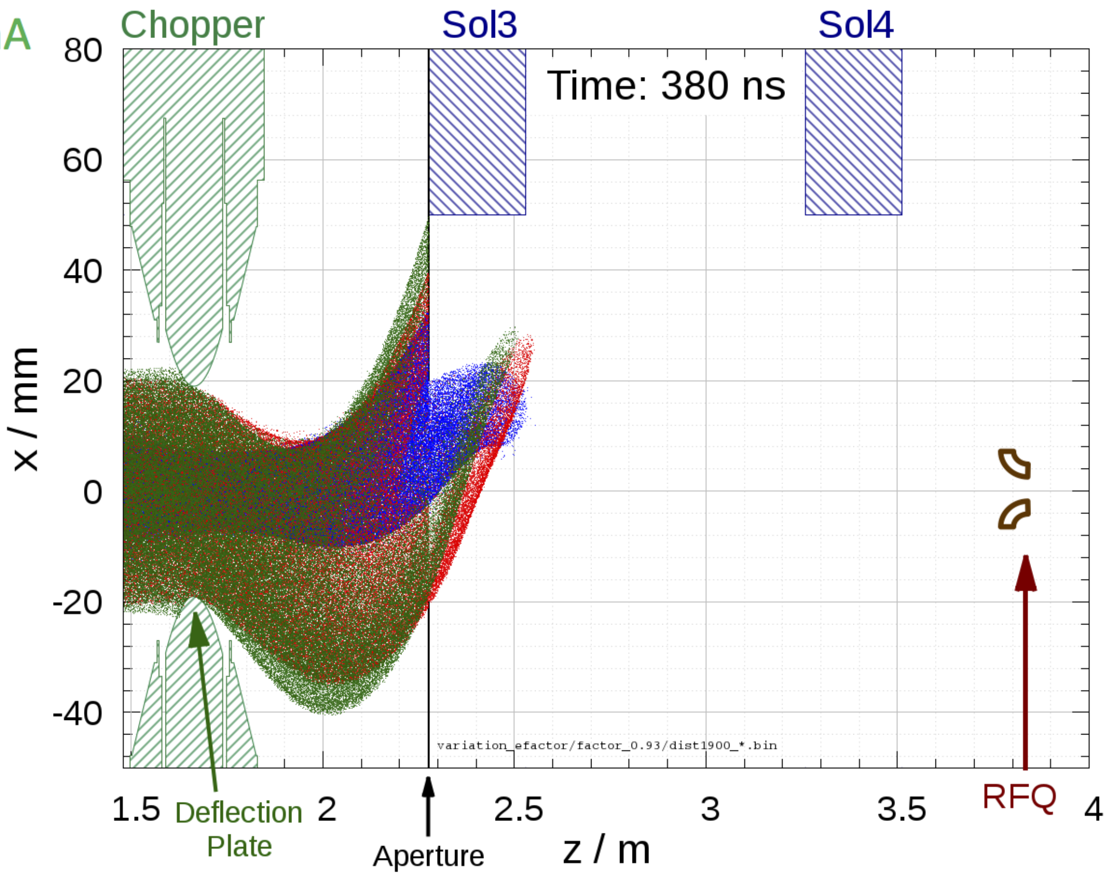
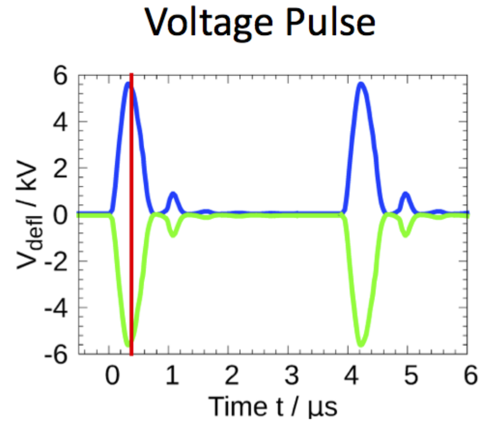
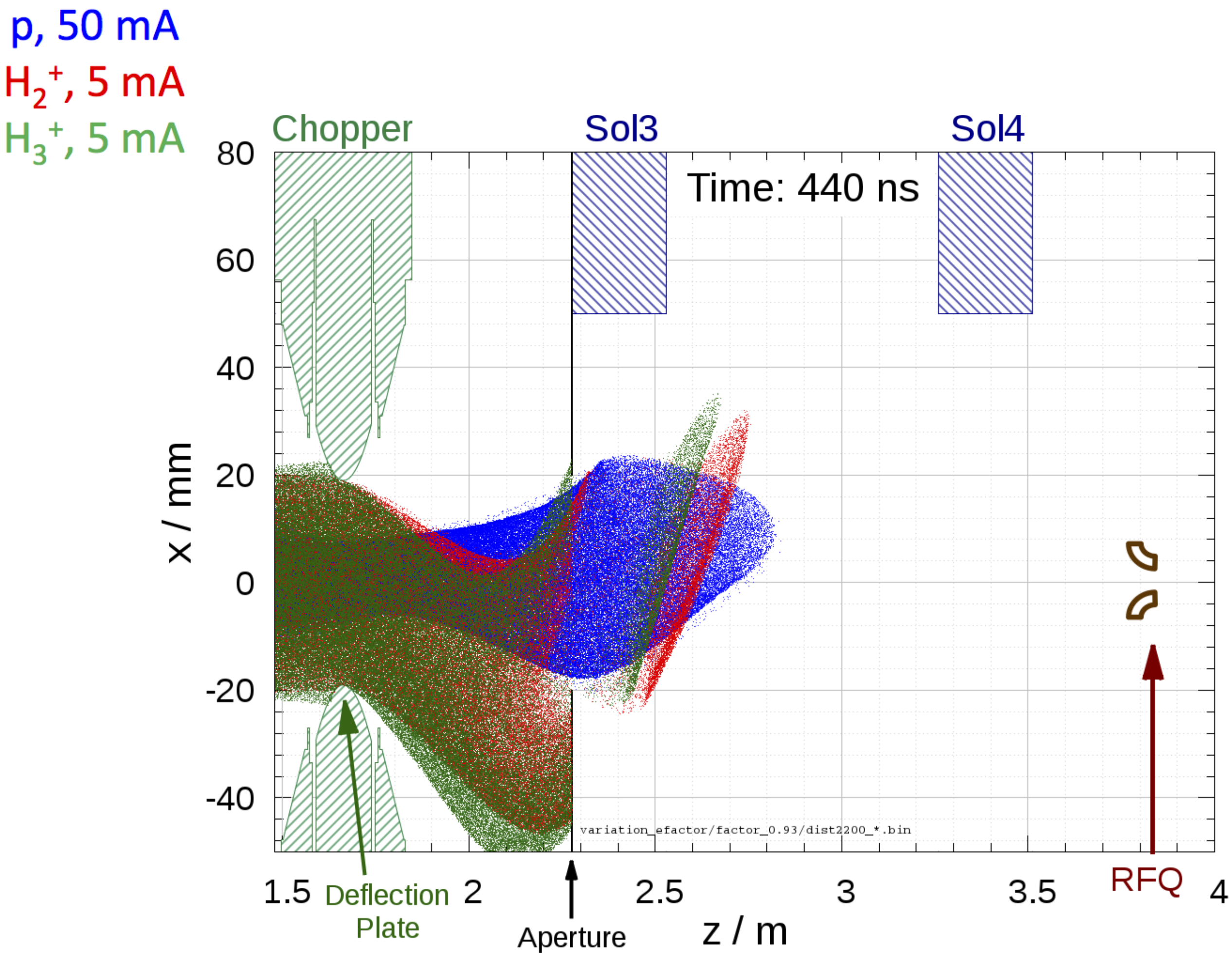


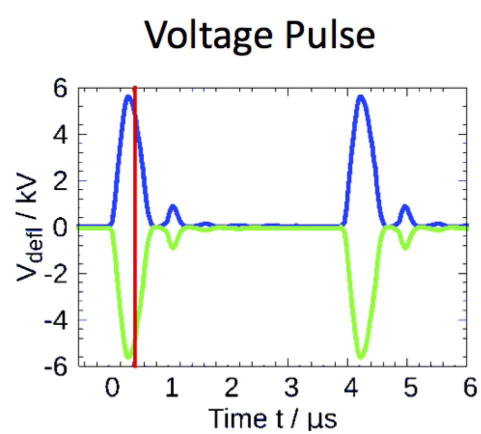


Plot by C. Wiesner

FRANZ E×B chopper

Pulse forming





Plot by C. Wiesner

FRANZ E×B chopper

Pulse forming

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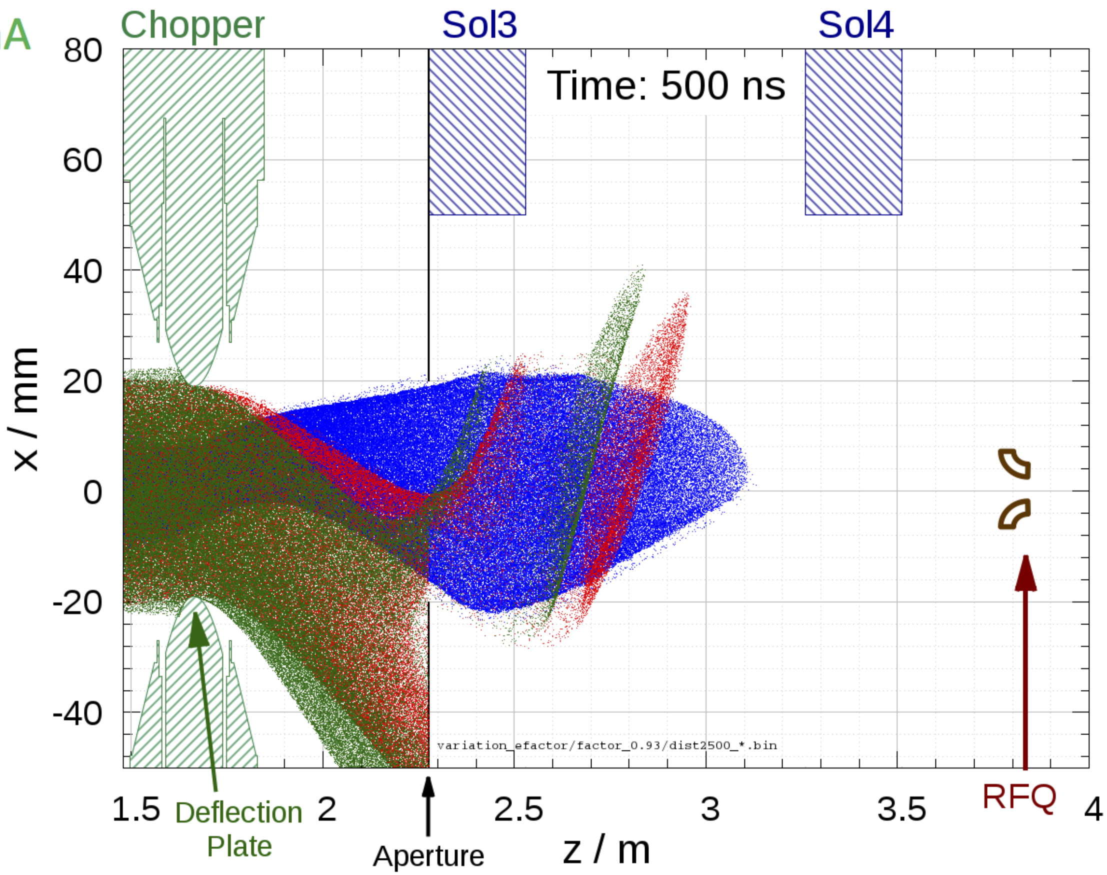
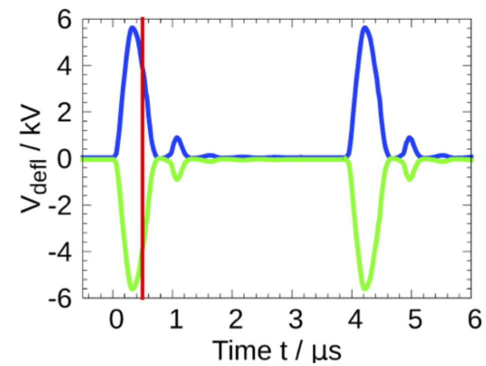
H_2^+, 5 mA

H_3^+, 5 mA



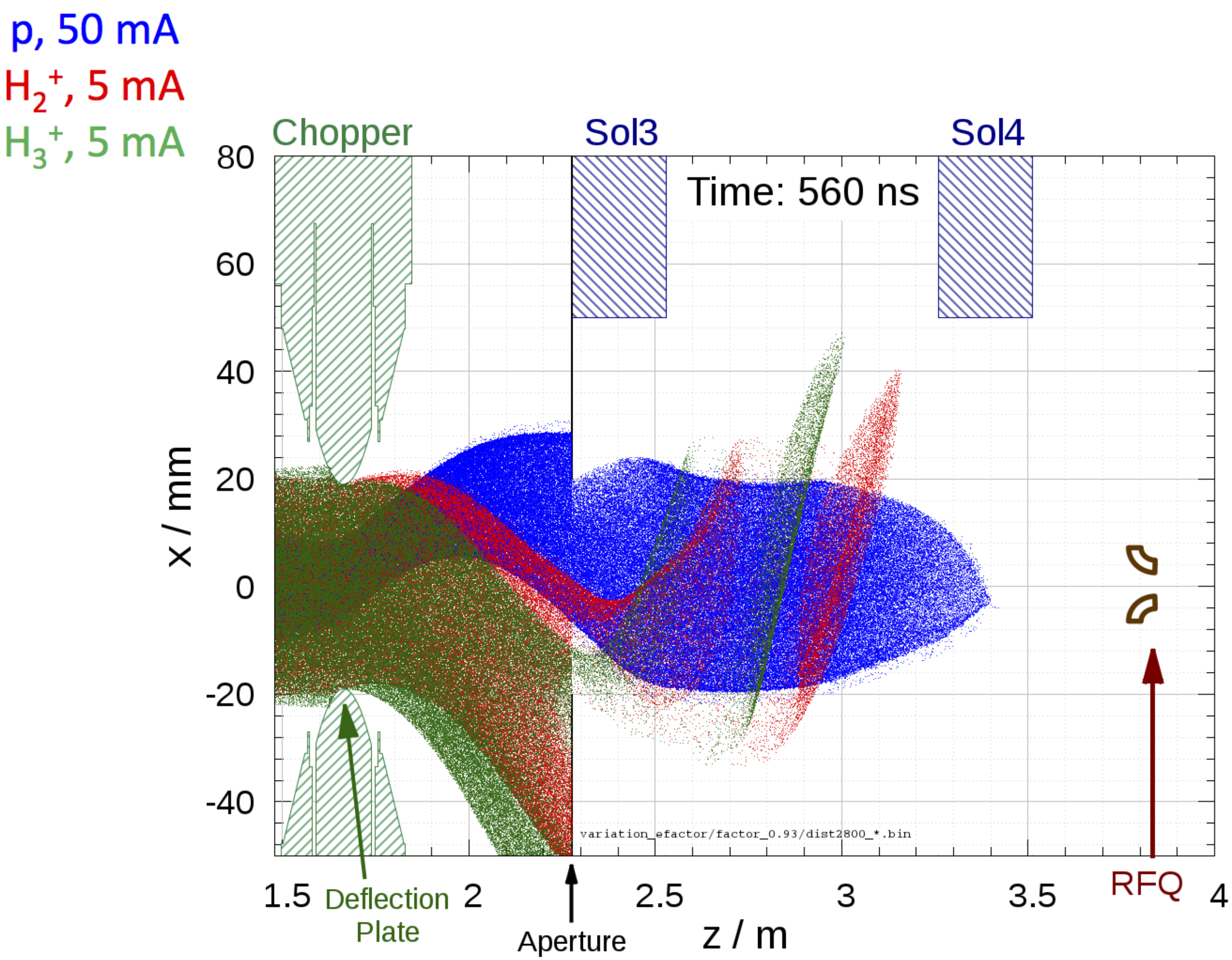
Voltage Pulse

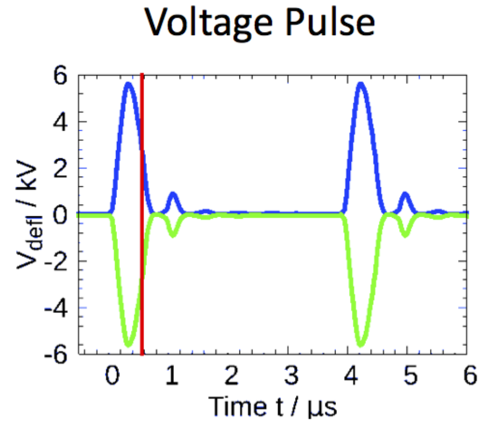


Plot by C. Wiesner

FRANZ E×B chopper

Pulse forming



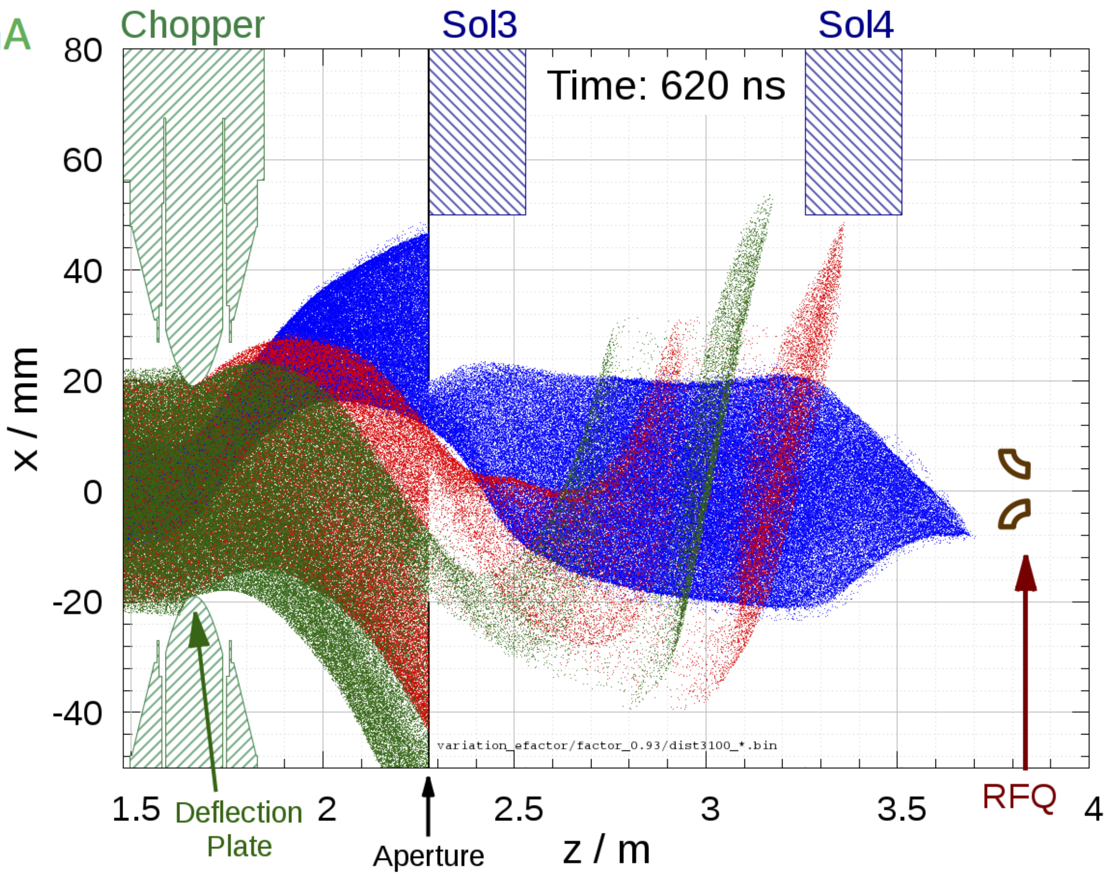


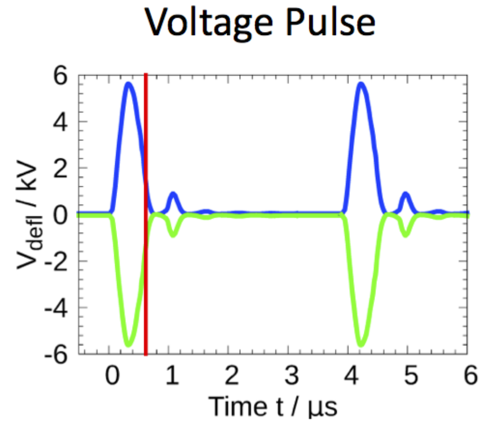
Plot by C. Wiesner

FRANZ E×B chopper

Pulse forming

p, 50 mA
H_2^+, 5 mA
H_3^+, 5 mA

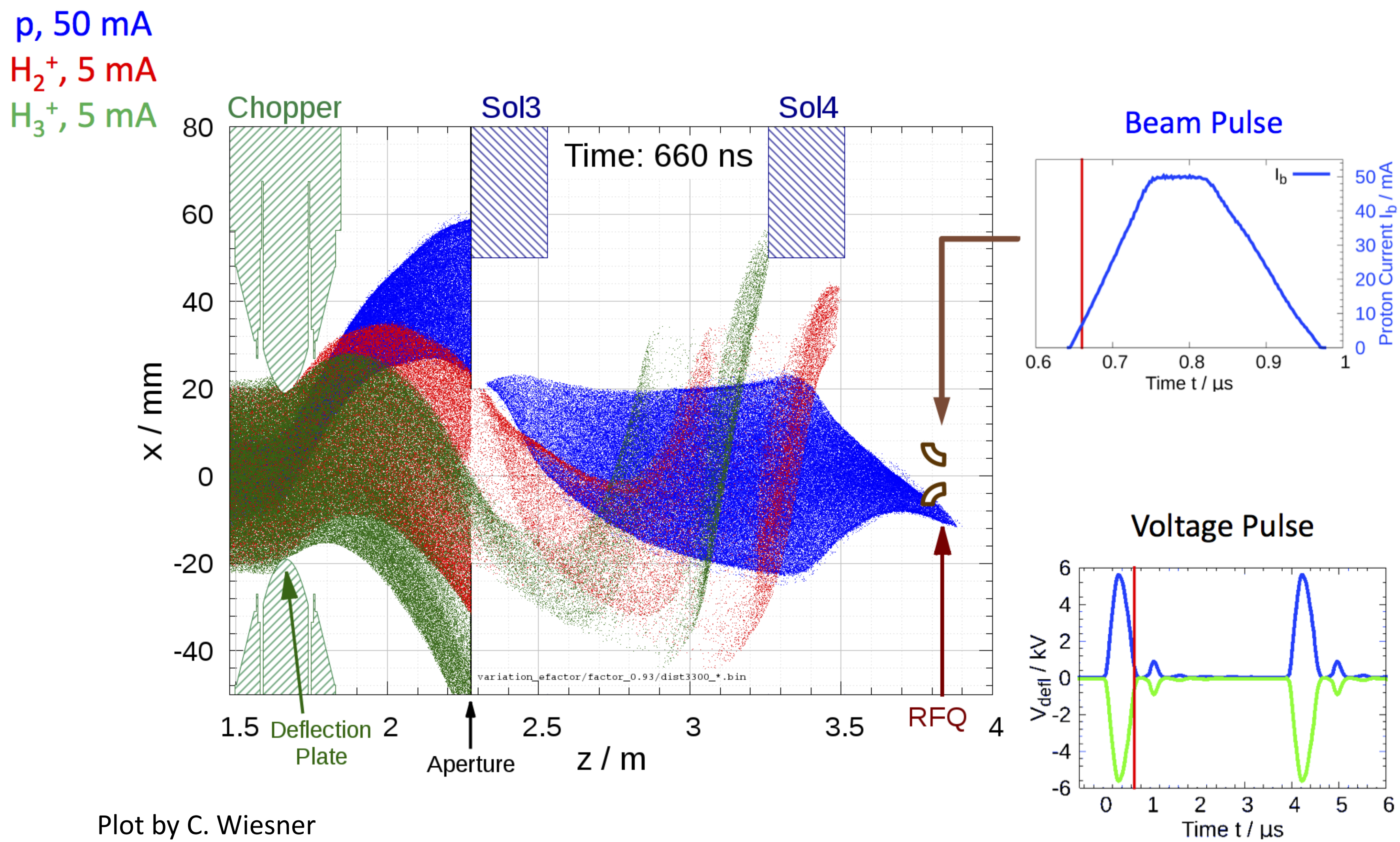




Plot by C. Wiesner

FRANZ E×B chopper

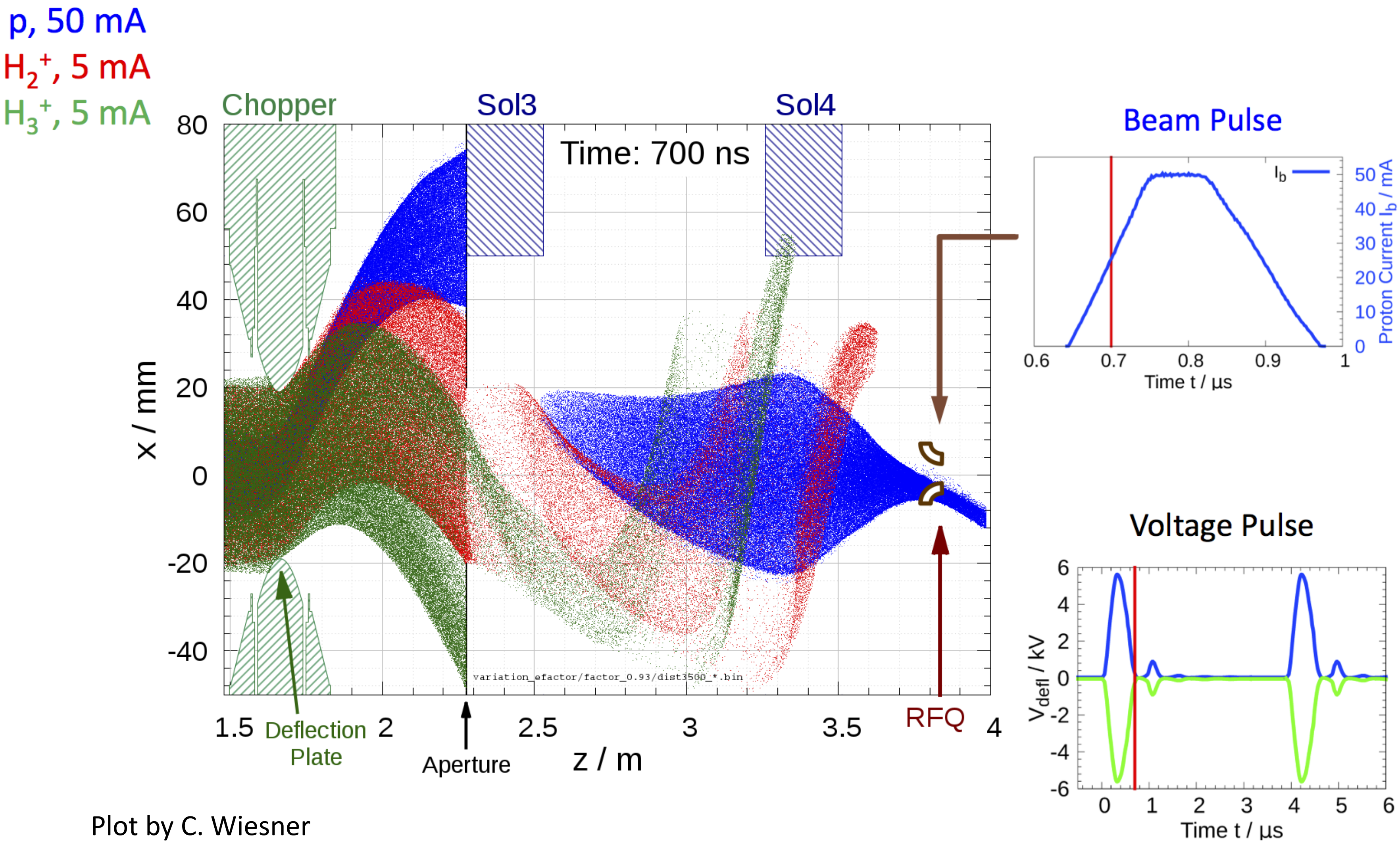
Pulse forming



Plot by C. Wiesner

FRANZ E×B chopper

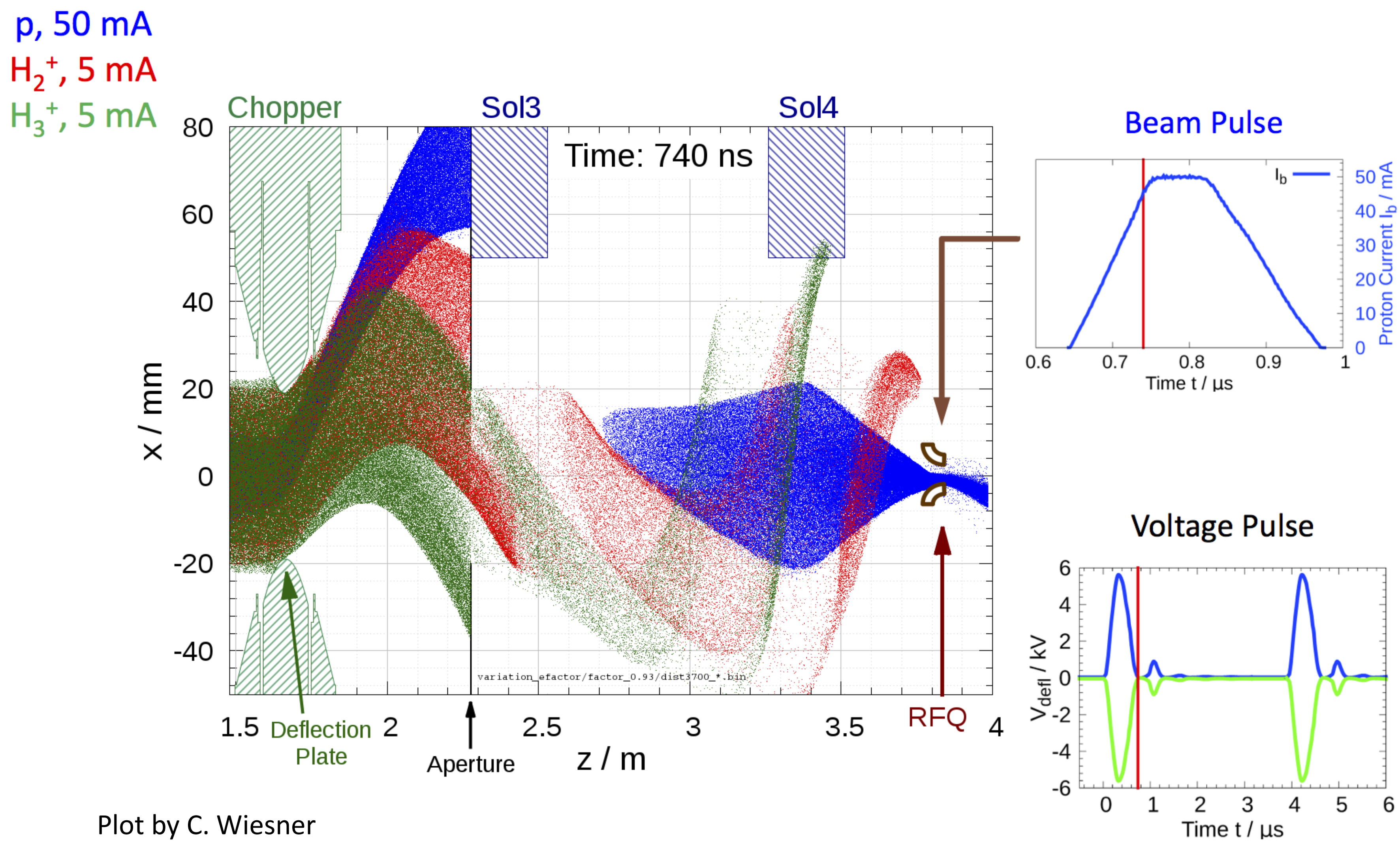
Pulse forming



Plot by C. Wiesner

FRANZ E×B chopper

Pulse forming

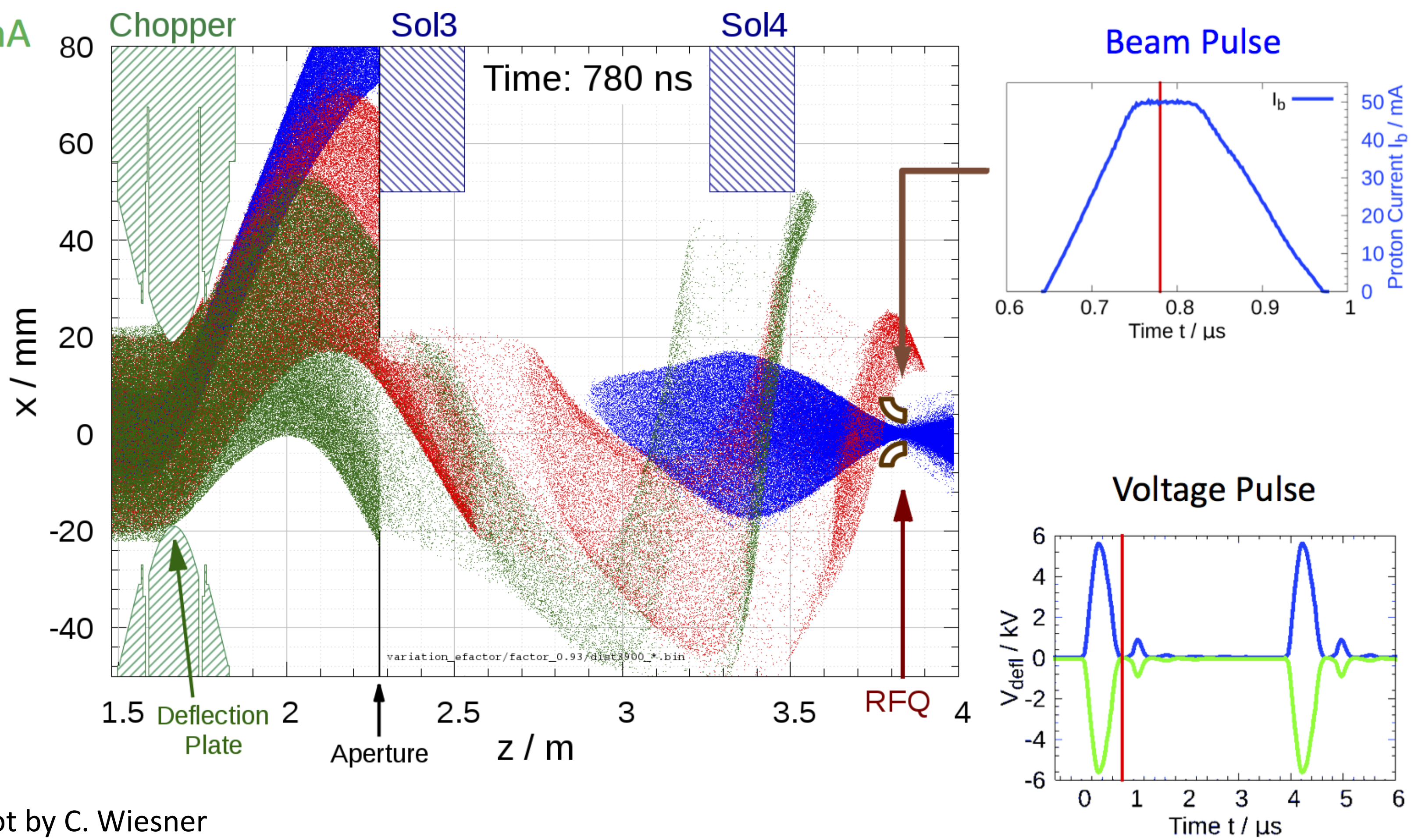


Plot by C. Wiesner

FRANZ E×B chopper

Pulse forming

p, 50 mA
H_2^+, 5 mA
H_3^+, 5 mA



Plot by C. Wiesner

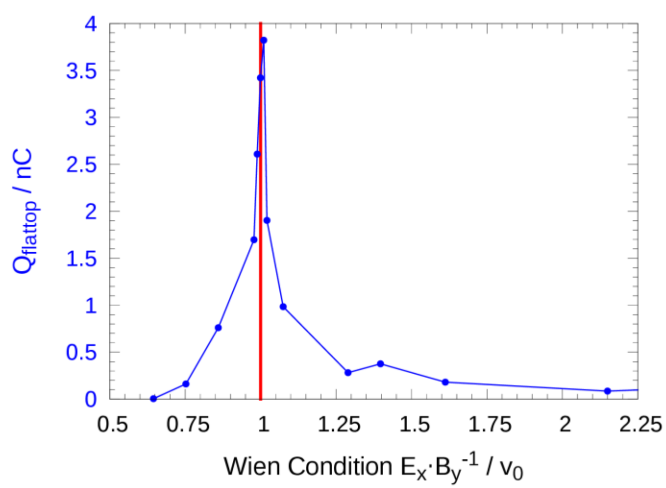
FRANZ E×B chopper

Comparison with measurements

- Measurement of charge in flat top, $Q_{flattop}$
- Constant magnetic field, sweep over voltage

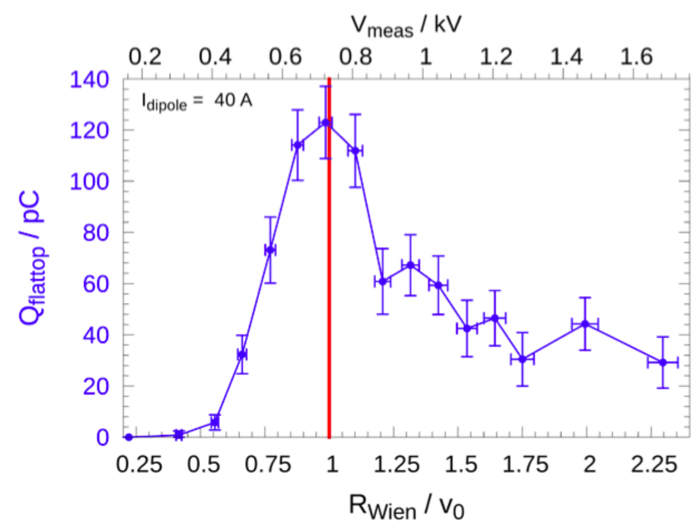
$$R_{\text{Wien}} = \frac{\int E_x \, \mathrm{d}z \cdot f_{\text{tof}}}{\int B_y \, \mathrm{d}z}$$

Simulation



p+, 120 keV, 20 mm aperture

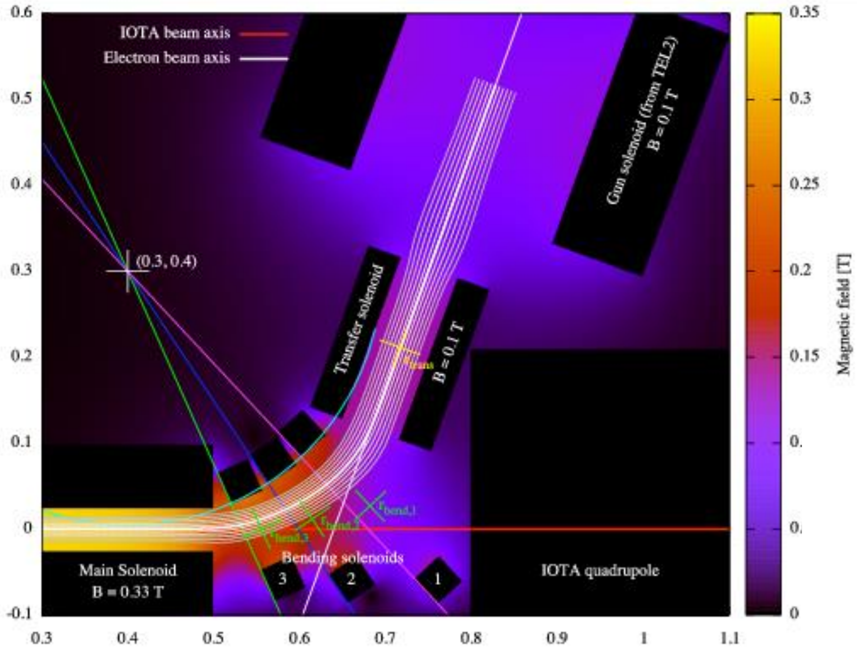
Measurement



He^{+}, 14 keV, 50 mm aperture

Courtesy of C. Wiesner

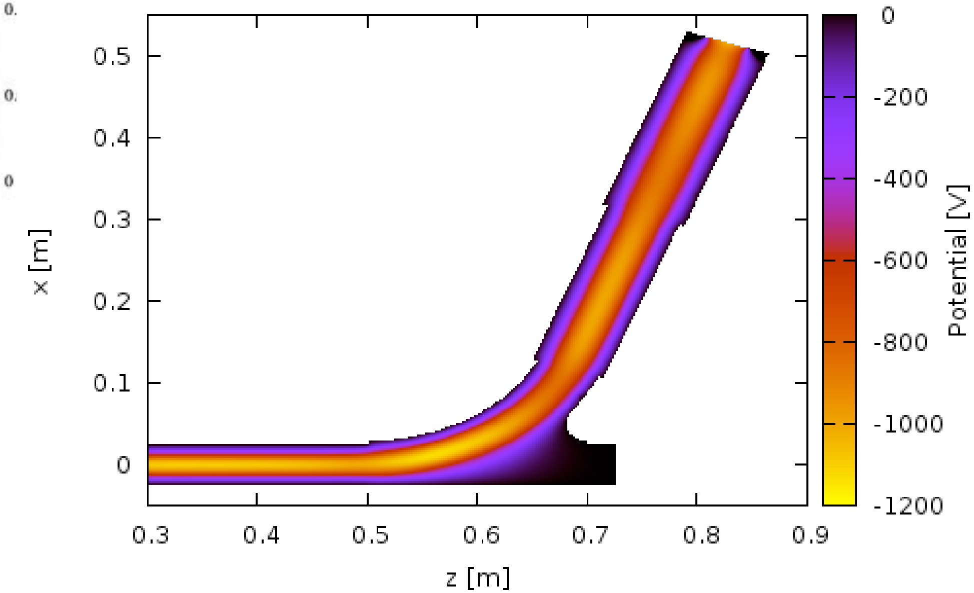
Electron lens for IOTA



Initial bend design of the electron lens

- Bender used for investigation of
  - Particle drifts in bend sections
  - Influence of space charge

- Electron lens for non-linear optics in the Integrable Optics Test Accelerator @ ASTA
- Parameters for McMillan case
  E = 5 keV, I = 1.7 A

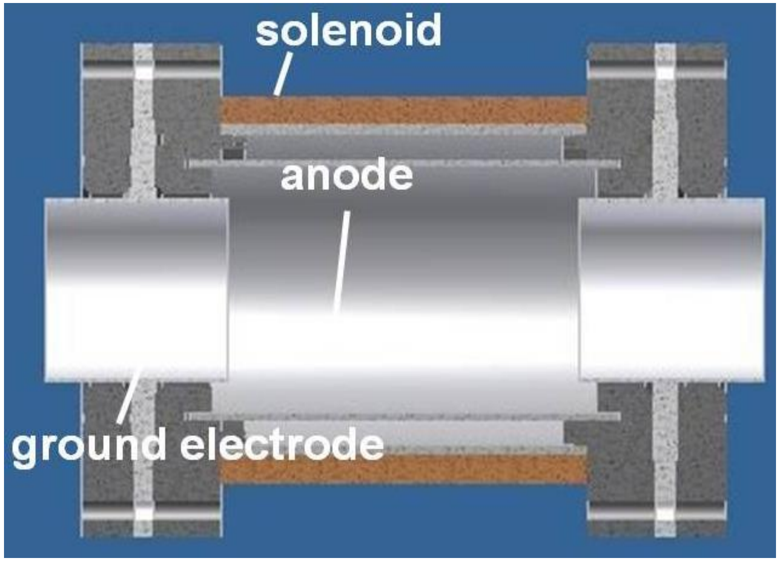


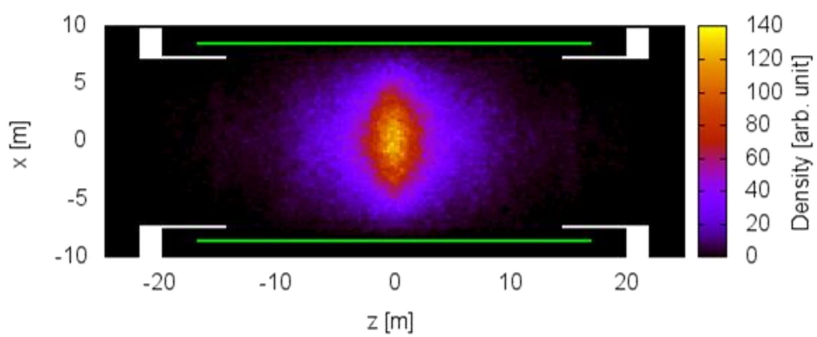
Space charge simulation on cluster TEV
192 processor, 0.5 mm, 1e7 particles

Overview

- Accelerator physics at IAP Frankfurt
- Motivation for a new code
- Structure of the code *bender*
- Simulation of space-charge compensation
  - Drift sections
  - Compensation in the presence of solenoidal magnetic fields
- Other applications of the code
  - E×B chopper at the Frankfurt Neutron Source (FRANZ)
  - Electron lenses for IOTA at Fermilab
- Outlook and conclusion

Gabor lens





State of the plasma column after 140 µs, U=9.8 kV, B=10.8 mT, 1e-3 Pa Ar+

- Electron trap
  - Longitudinal magnetic field for transversal confinement
  - Potential well for longitudinal confinement
- Can be used to focus ion beams…
  or investigate the properties of the confined plasma
- Simulations using bender are under way…

Conclusion and outlook

- A new electrostatic, parallel Particle-in-Cell code has been developed
- It has been used to
  - Investigate space charge compensation in simple model low-energy beam transport sections
  - Understand the pulse shaping in the FRANZ E×B chopper
- Future work will include
  - Better understand the thermalisation process of the plasma of compensation electrons
  - Include additional effects required for modeling the compensation process (charge exchange? Atomic excitation?)
  - Comparison to measurements done at FRANZ

Thank you for your attention!

In the name of the Frankfurt NNP group:
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M. Schwarz, O. Payir, J. Wagner, C. Wiesner, K. Zerbe