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

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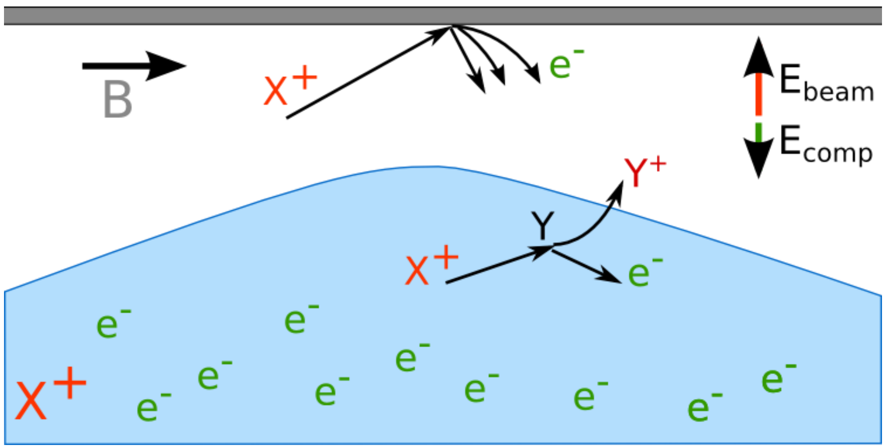
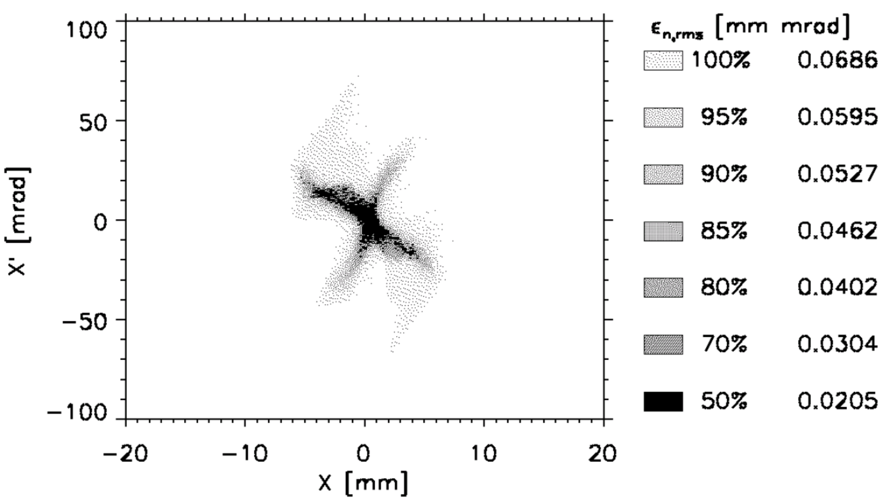
Space charge compensation





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

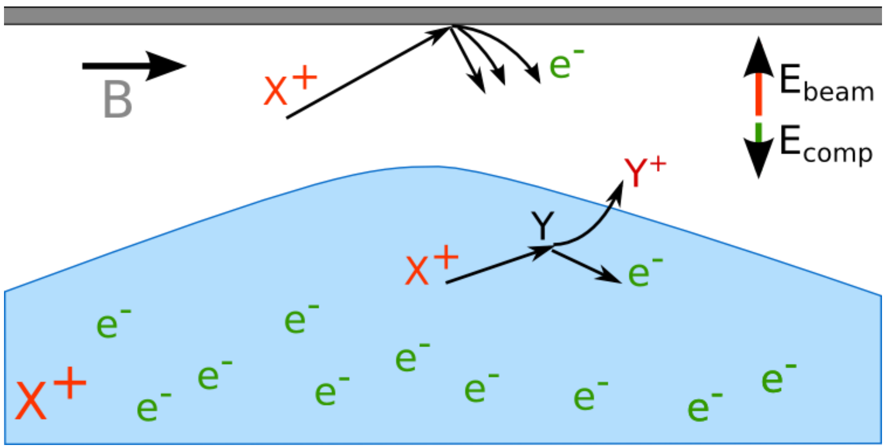
- Accumulation of secondary particles in the beam potential
- "Traditional" treatment: Constant compensation factor

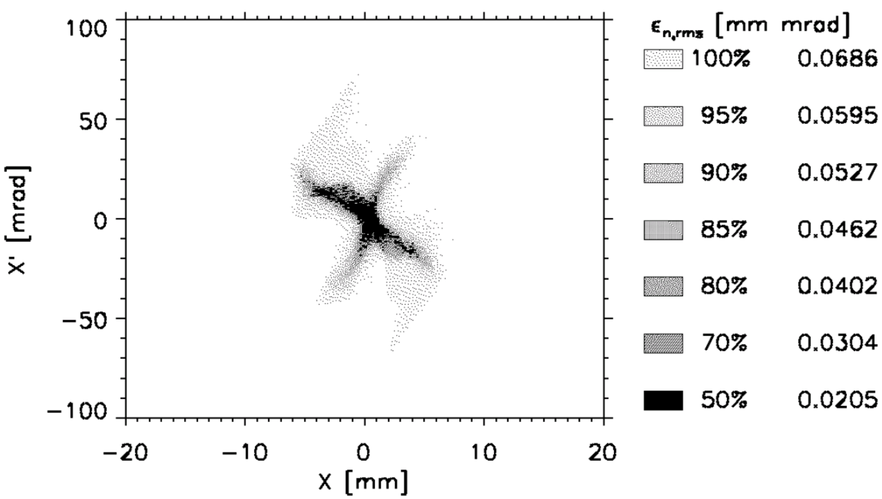
Two options:

- 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

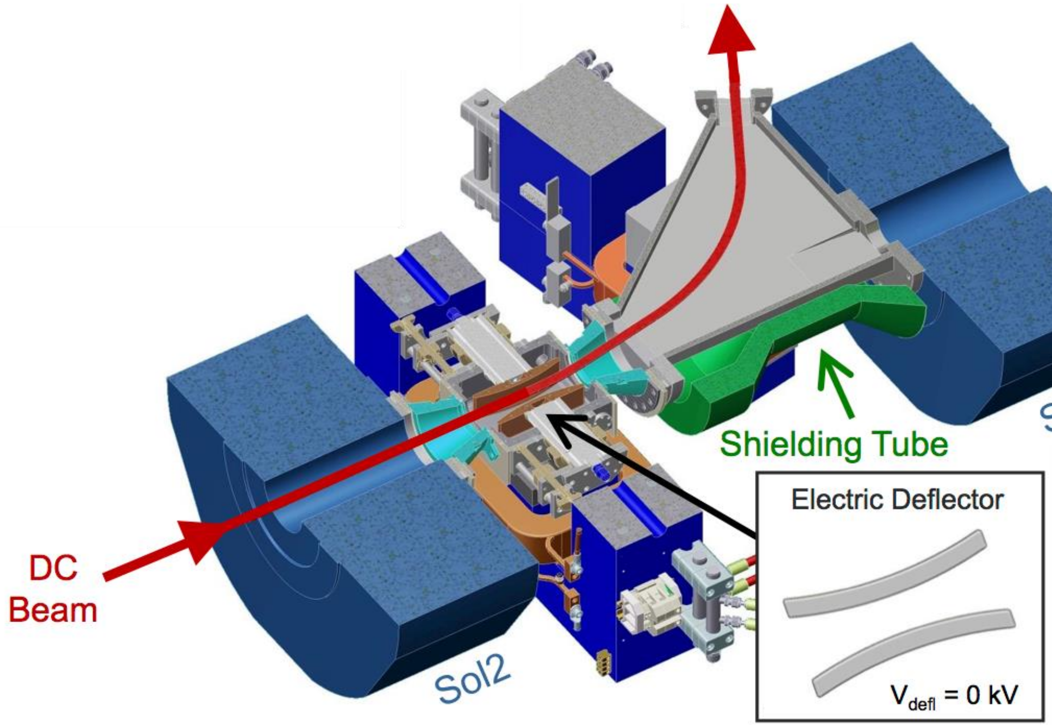
$$t_{\text{cyclotron}} = \frac{2\pi m}{qB} = 71\ ps, \ \ B = 0.5\ T$$

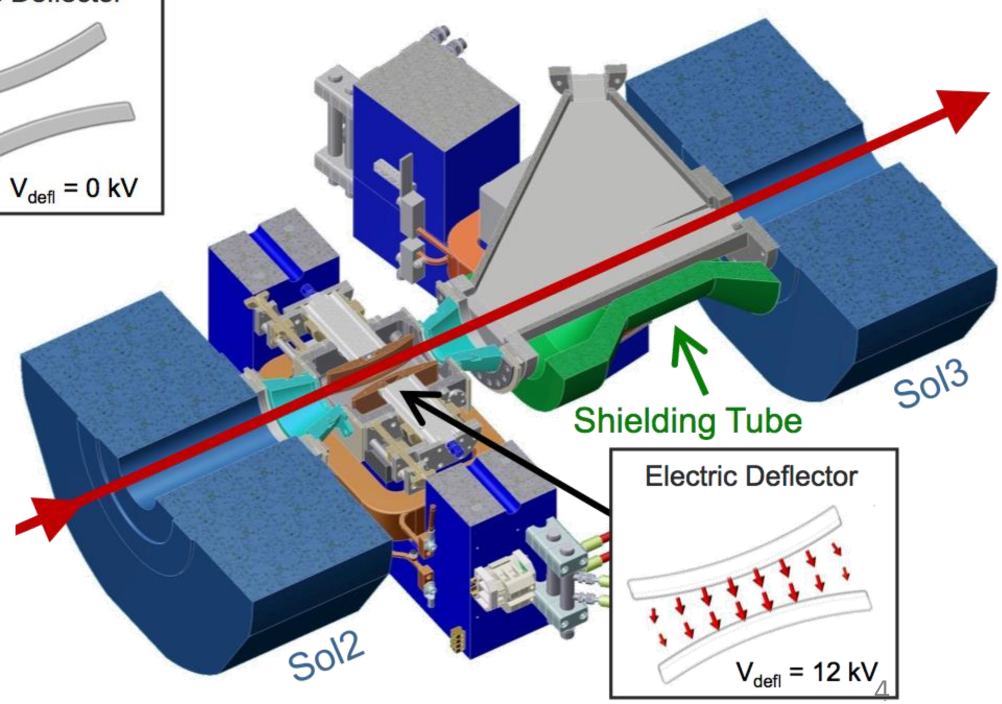
- What is the “correct” physics?

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

FRANZ E×B chopper [1]

- Provides short proton pulses at 250 kHz for the future Frankfurt neutron source facility [2]
- High space charge forces for produced proton pulse





(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

Overview

- Motivation
- 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

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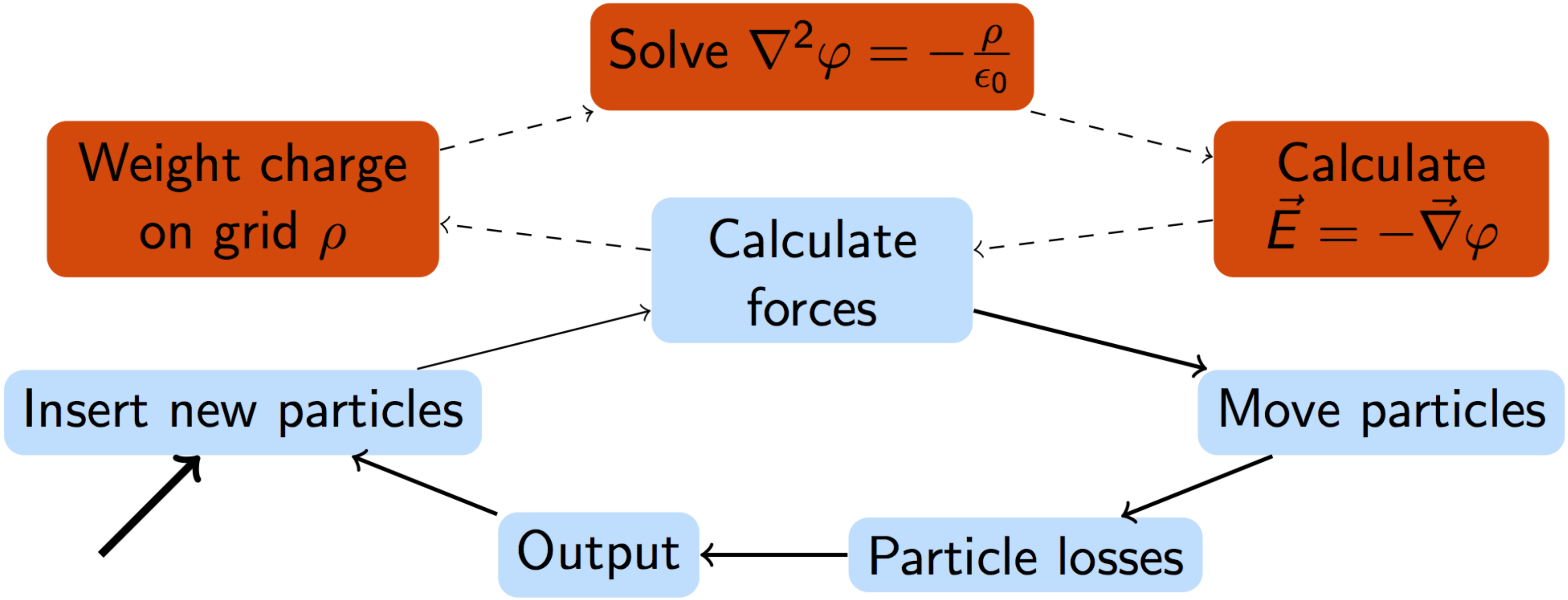
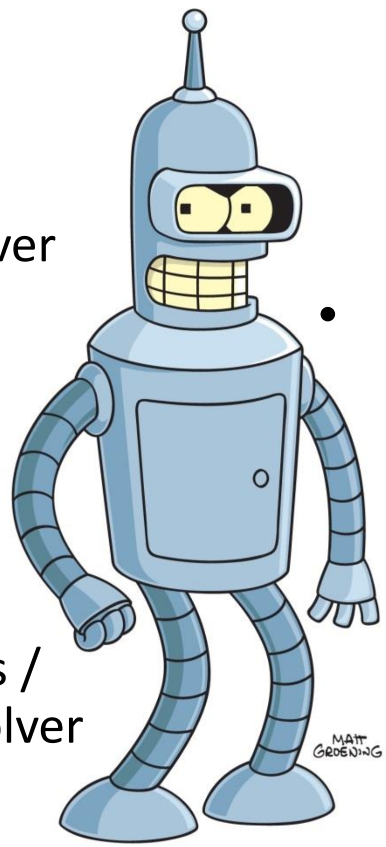
The Particle-in-Cell method



The Particle-in-Cell code bender

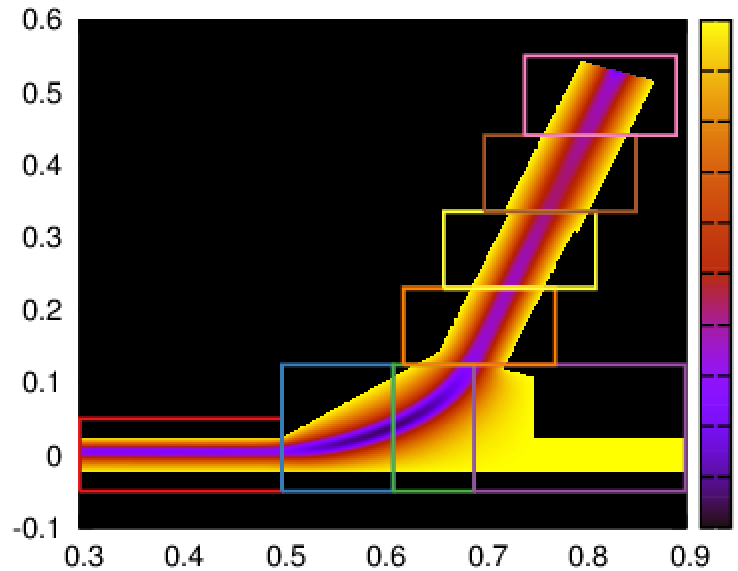
- Written in C++
- Parallelized using MPI
- Input in XML-style format
- Multiple species
- Fields from:
  - Multipole expansion
  - Solenoid field models
  - Biot-Savart / Laplace solver
  - CST / Opera import
- Geometric objects:
  - Primitive objects: Plane, Pipe, Plates, …
  - STL import
  - Usable for particle losses / boundaries in Poisson solver
- Mover algorithms:
  - Velocity Verlet, RK4, Symplectic Euler
- Configurable output:
  - Particle distributions
  - Fields / Space charge potential
  - Particle tracking
  - Particle losses
- Flexible geometric positioning using “coordinate systems”:
  - Translation, Rotation, Scaling
  - Comoving



Bending unit 22 “Bender”
TV series “Futurama“

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 system matrix using PetSc [1]

3D fast fourier solver:

- Rectangular equidistant grid
- Neumann & Dirichlet boundaries
- Distributed in z
- Implementation 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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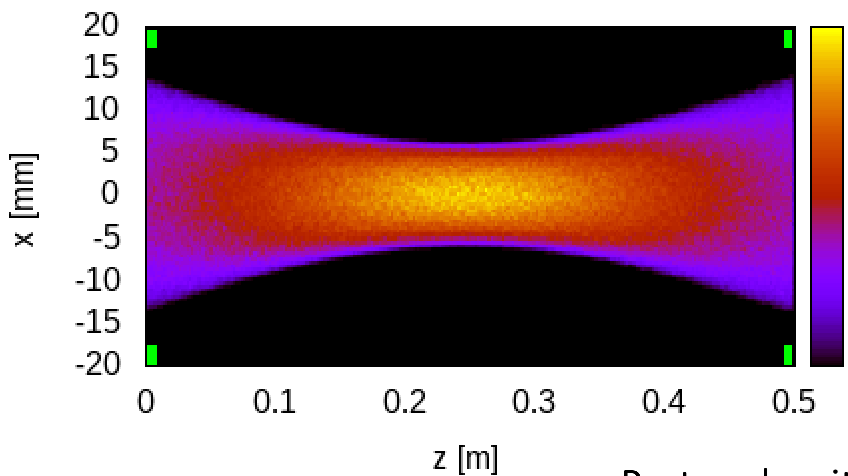
SCC studies: drift system

Investigated systems

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

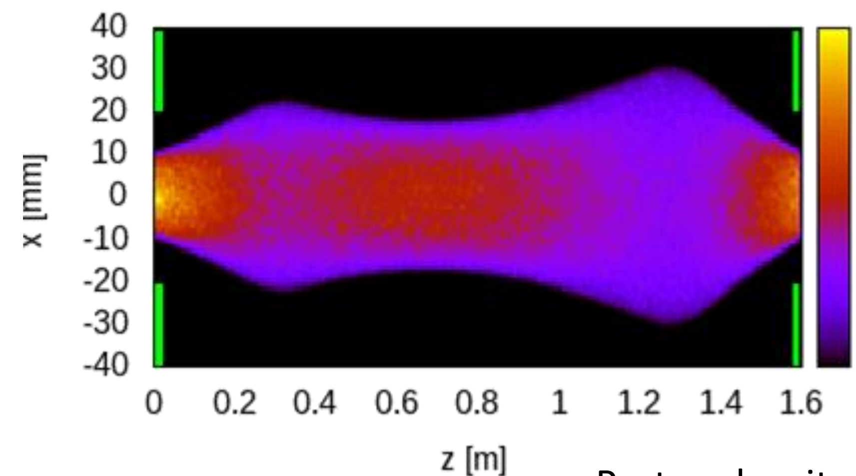
Drift (50 cm)



Proton density

- Matched to achieve zero losses
- Δt = 25 ps, 1 mm grid spacing
- Runtime usually ≈ 1 day using rz solver

Two-solenoid LEBT section



Proton density

- 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 collisions via Null-collision method
- Isotropic distribution of secondary electrons assumed

Cross-section models implemented in the code:

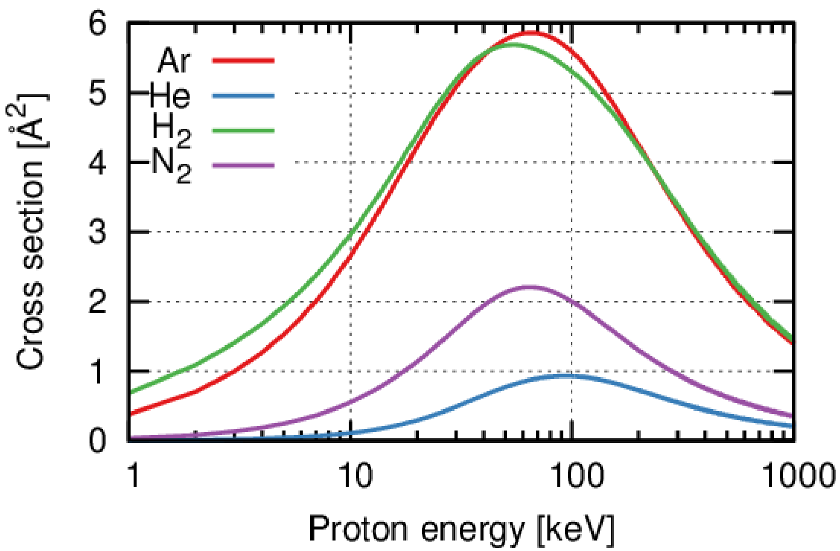
Proton impact ionization:

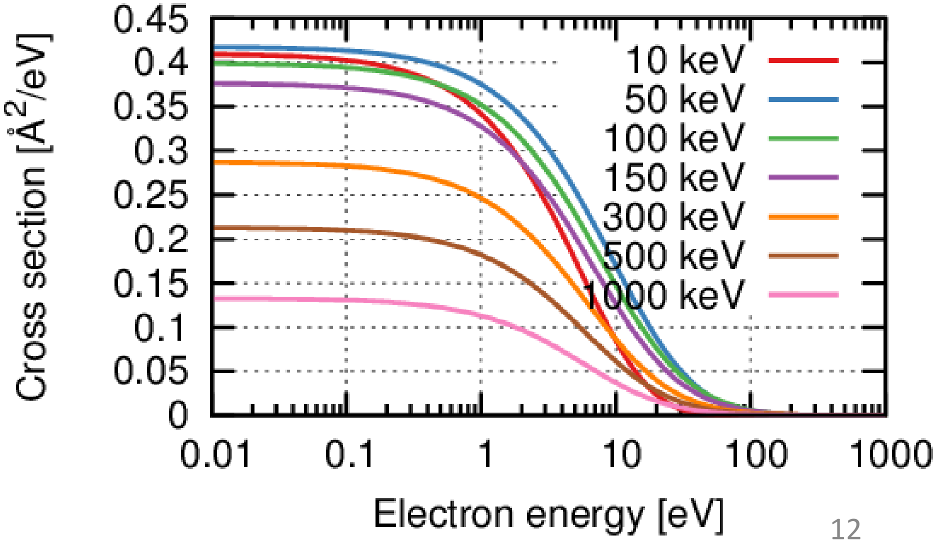
- Model from Rudd et al. [1]
- Single differential cross section fitted to 6 datasets from different authors
- Accurate to ≈ 10-15 %

Electron impact ionization:

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

Cross sections



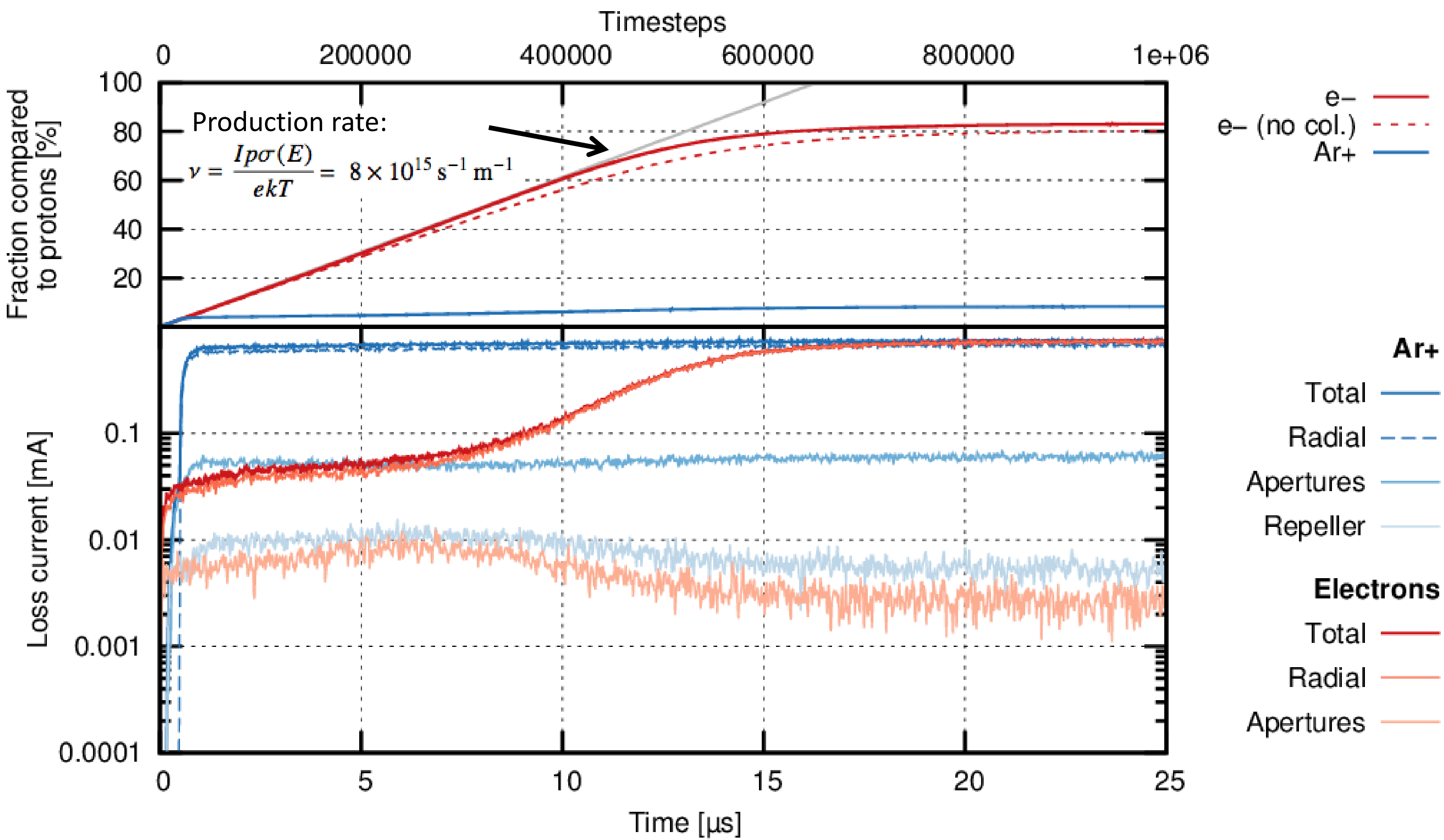


[1] Rudd, Kim, Madison, Gay - Electron production in proton collisions with atoms and molecules: energy distributions, Rev. Mod. Phys. 64, 441-490 (1992)

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

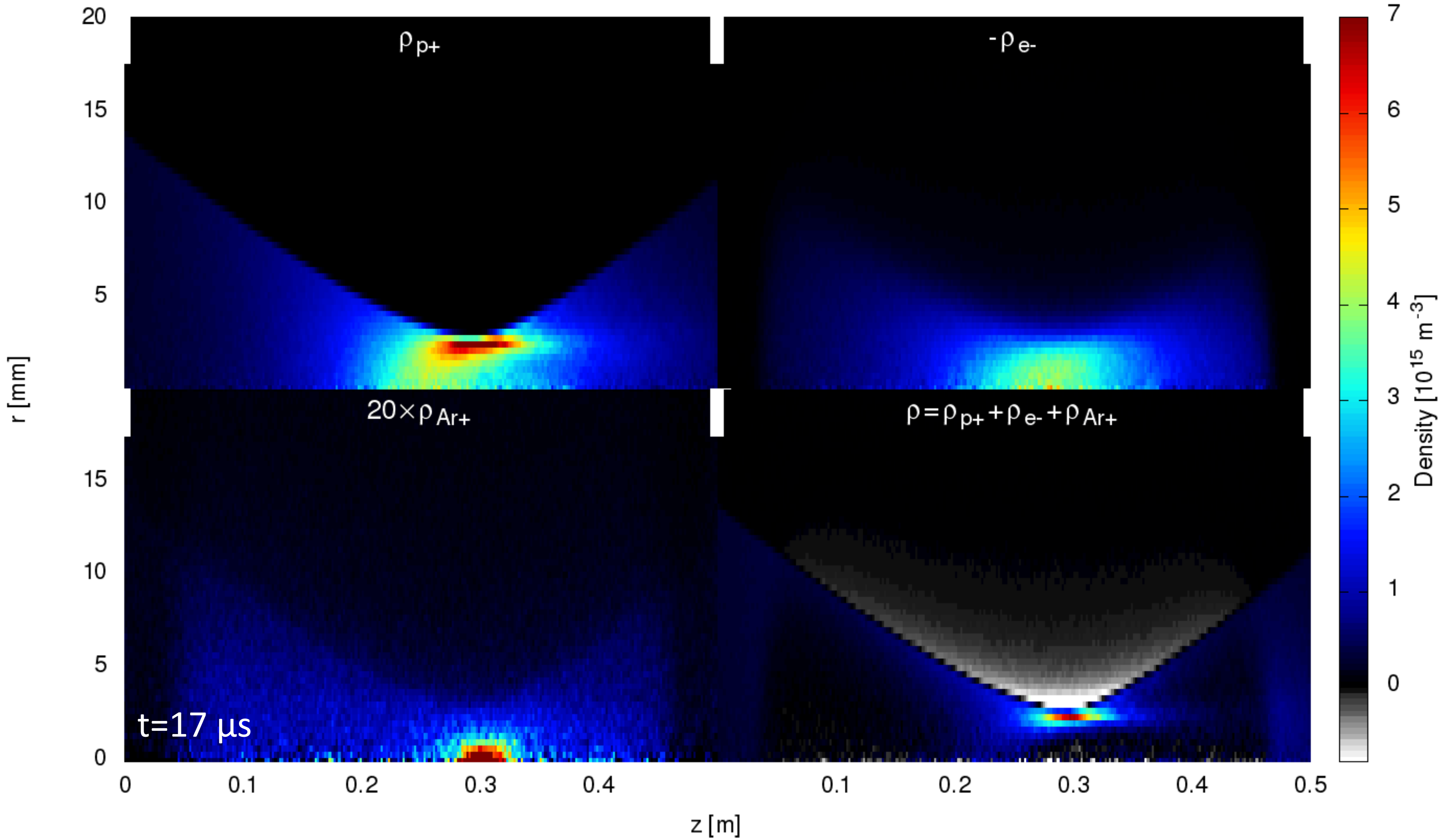
SCC studies: drift system

Compensation build-up



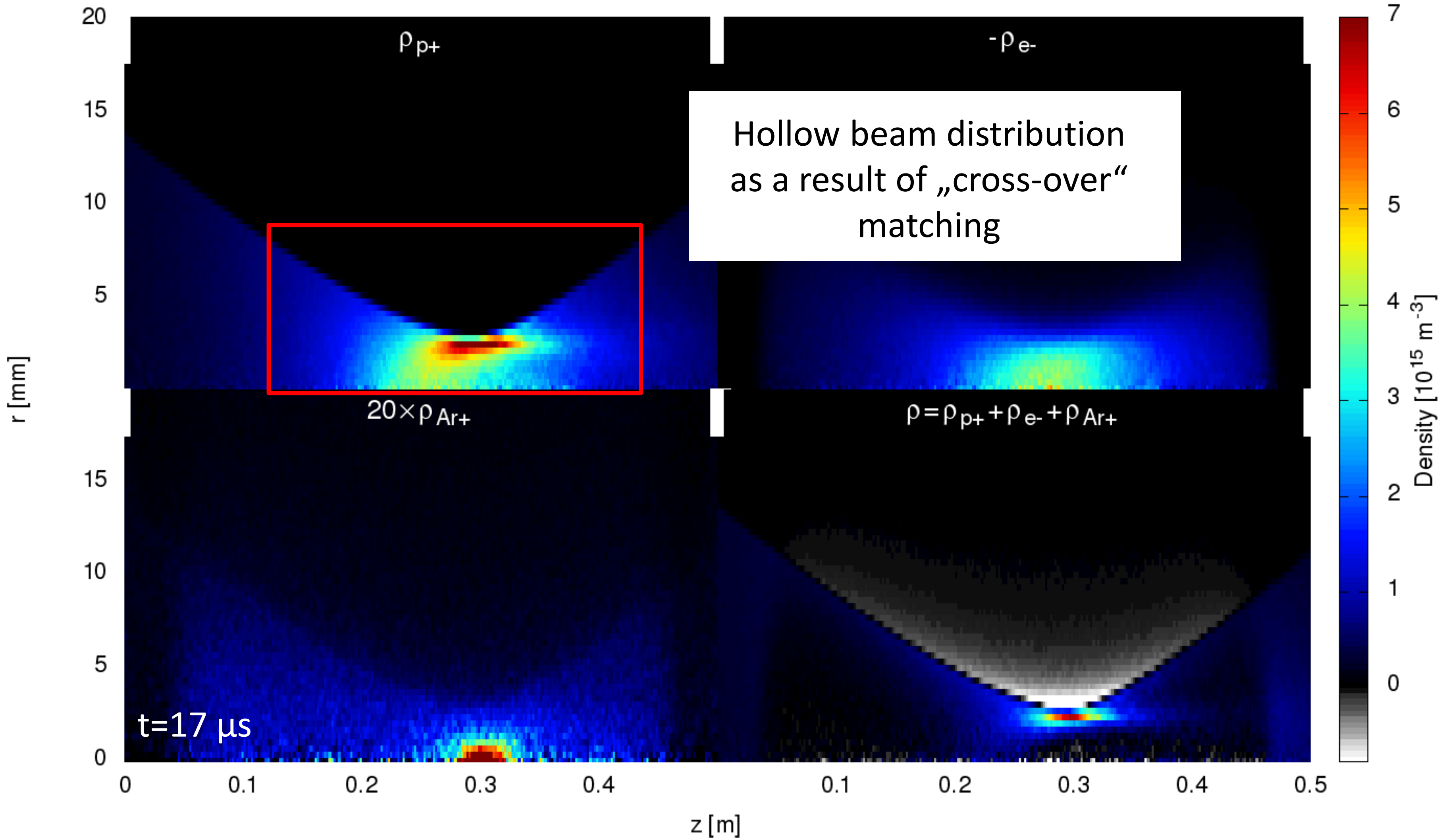
SCC studies: drift system

Spatial distribution



SCC studies: drift system

Spatial distribution



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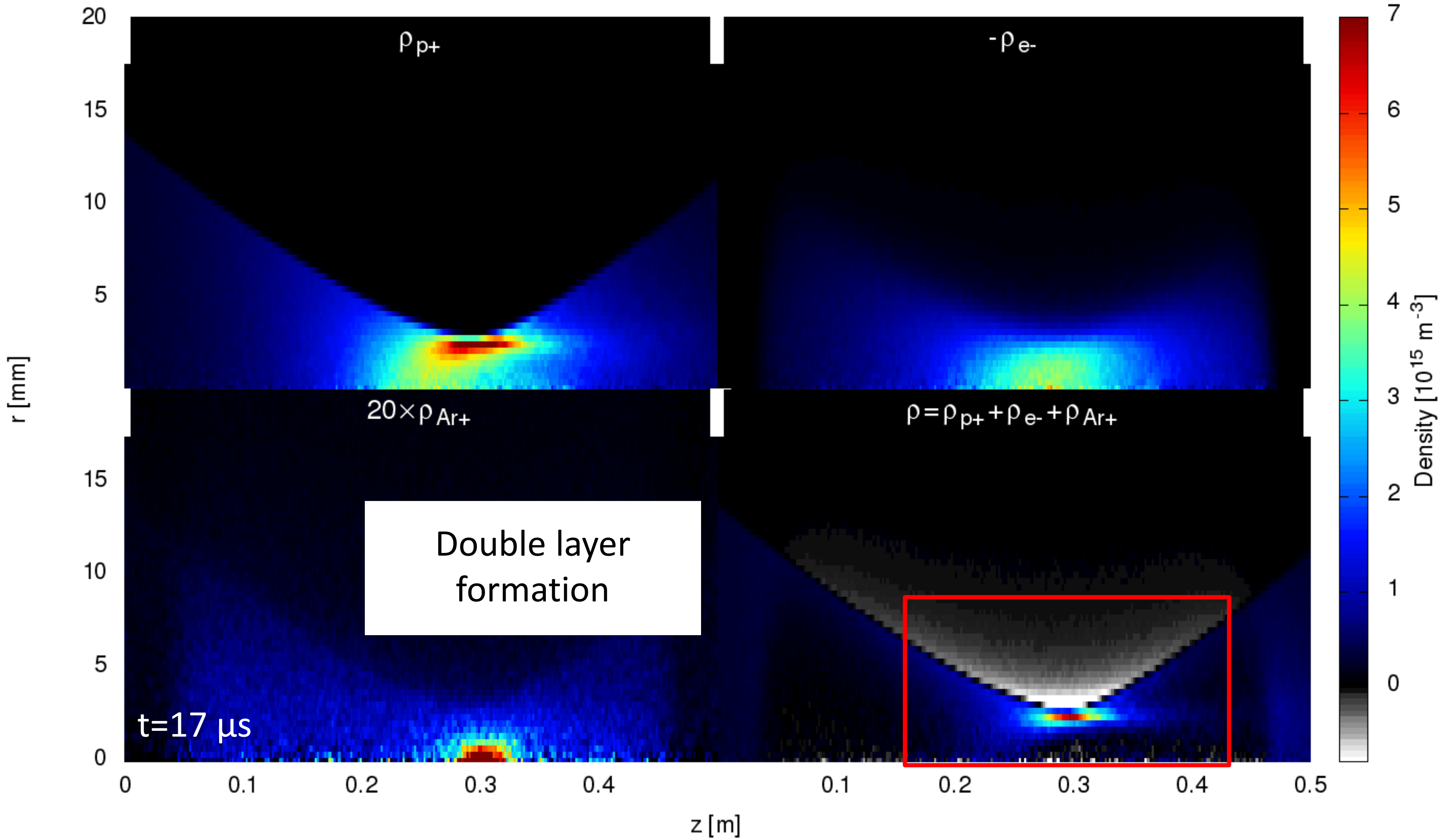
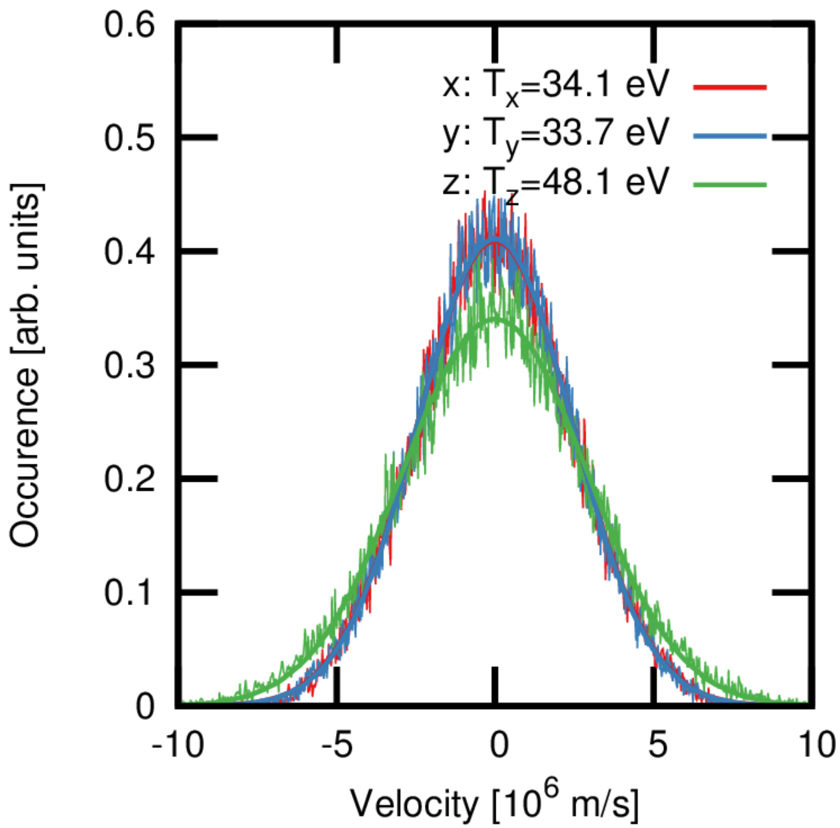


SCC studies: drift system

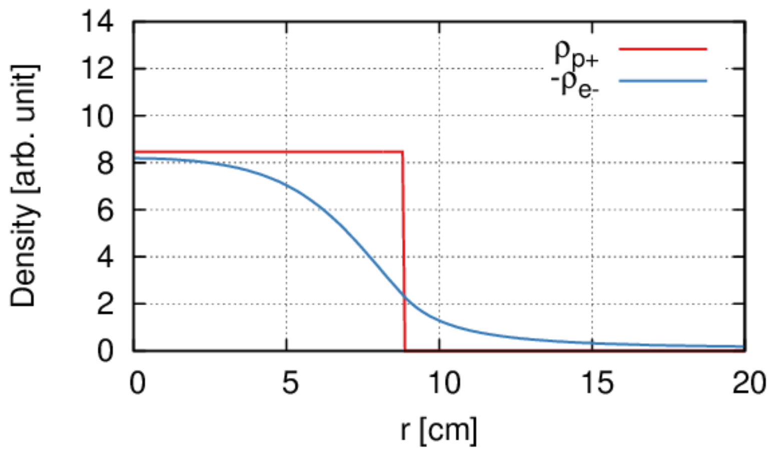
Energy distribution

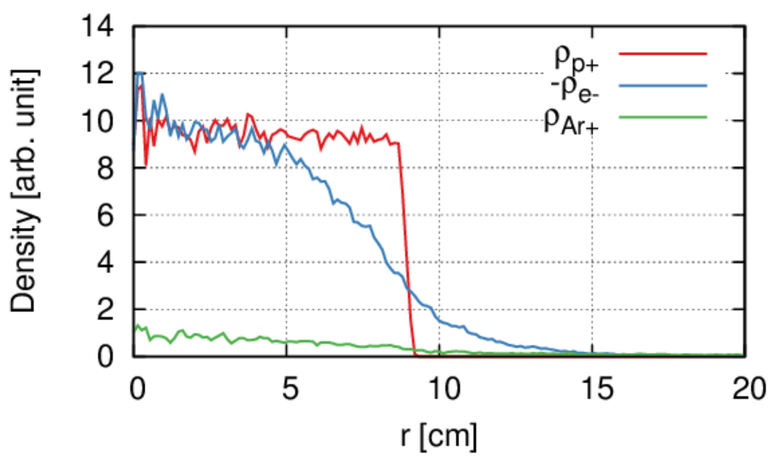


- Thermal velocity distribution
  - $T_{x,y} \neq T_z$
  - Temperatures not constant along beam axis
- Non-neutral plasma
  - $n_e \approx 3.9 \cdot 10^{15}$ m^{-3}
  - $\lambda_d \approx 0.7$ mm < r_{beam}
  - $\ln \Lambda \approx 16.6$
  - $\omega_p \approx 3.5$ GHz

SCC studies: drift system

Spatial distribution





η_{comp}=90.6 %, T=22.9 eV

- Poisson-Boltzmann equation for electrons (1d)

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

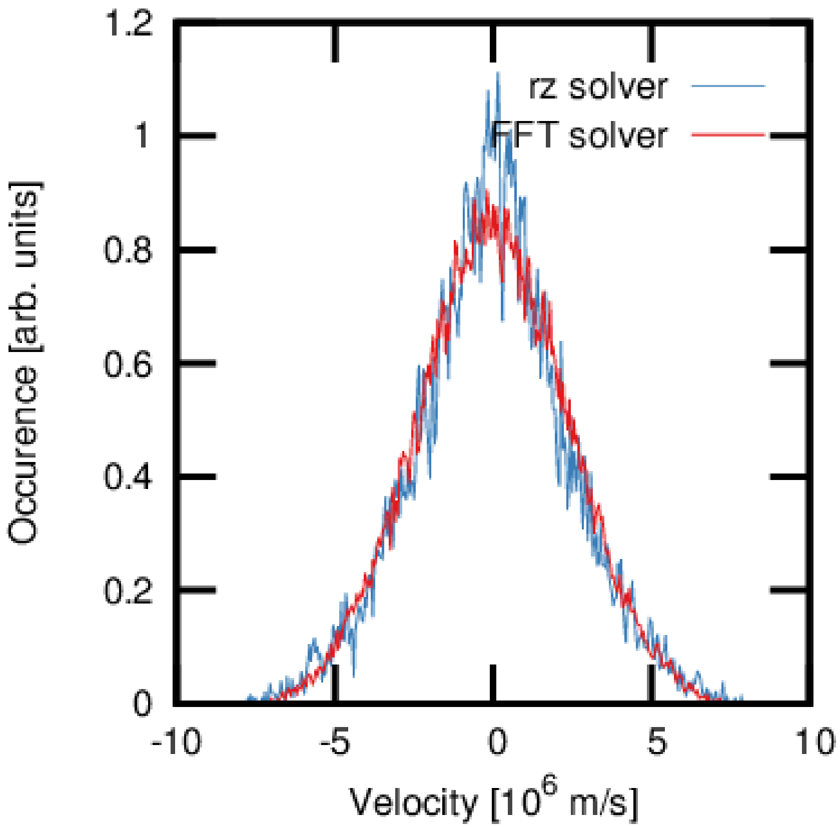
- Normalization condition

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

- Even for “100%” compensation, for $T_e > 0$, some space charge forces remain…
- Future work: Implementation in 2d code *tralitrala*, free parameters T, η_{comp}

SCC studies: drift system

Energy distribution



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

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

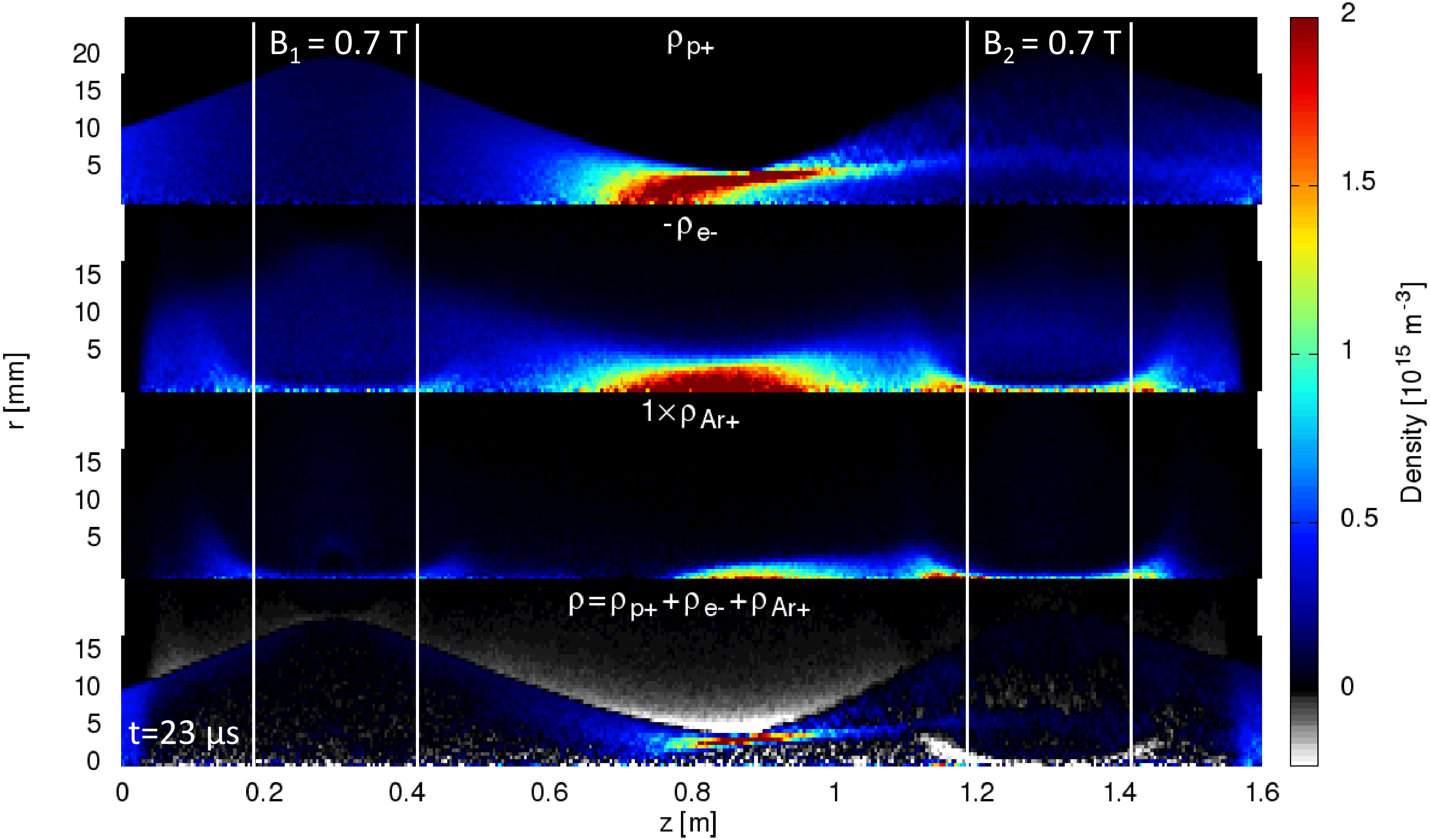
- Simulation:
  - Thermal distribution after ≈ microsecond
  - Influence of solver geometry (but almost none on macroparticle number, grid resolution…)

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)

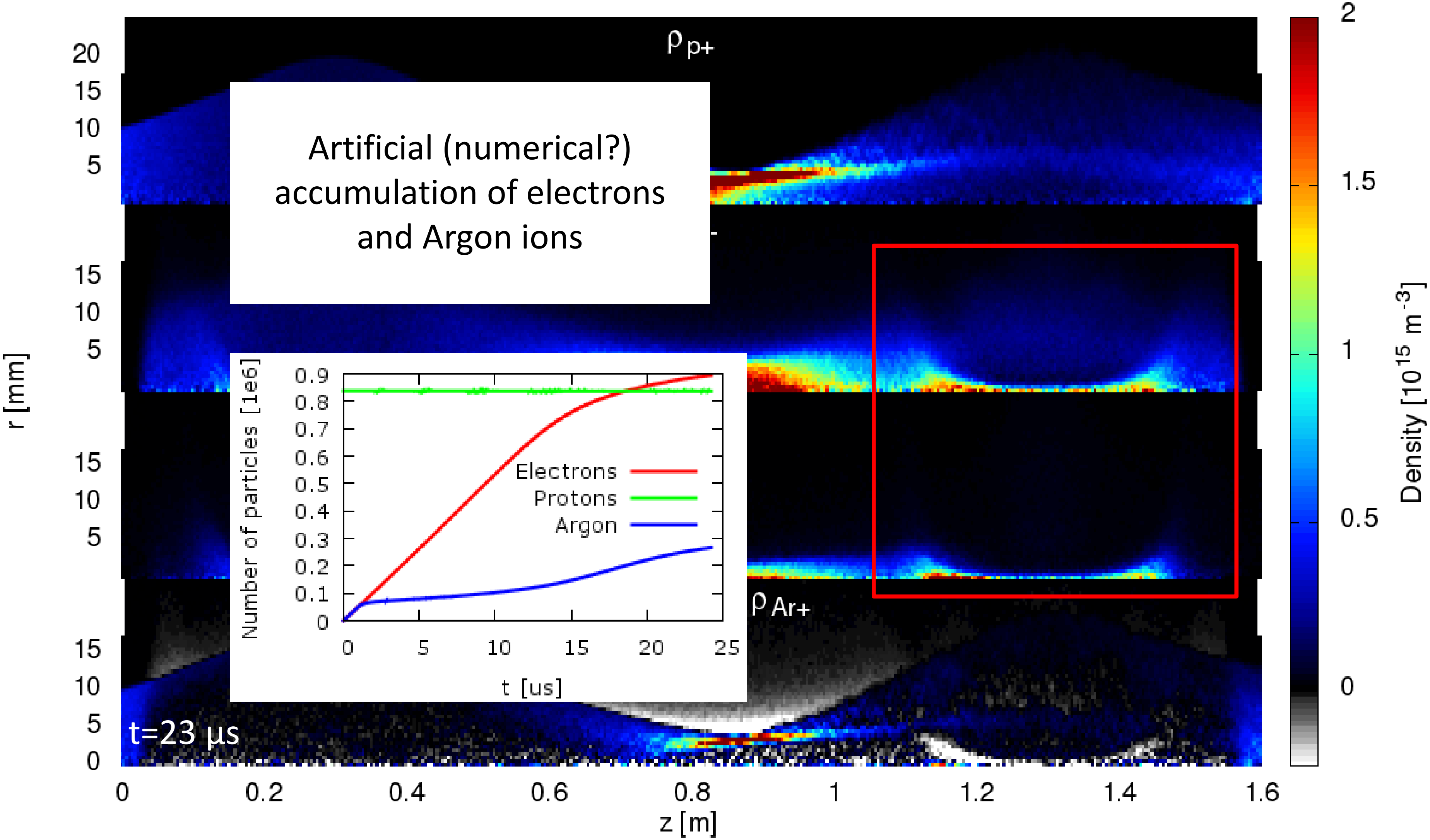
SCC studies: two solenoid LEBT

Spatial distribution



SCC studies: two solenoid LEBT

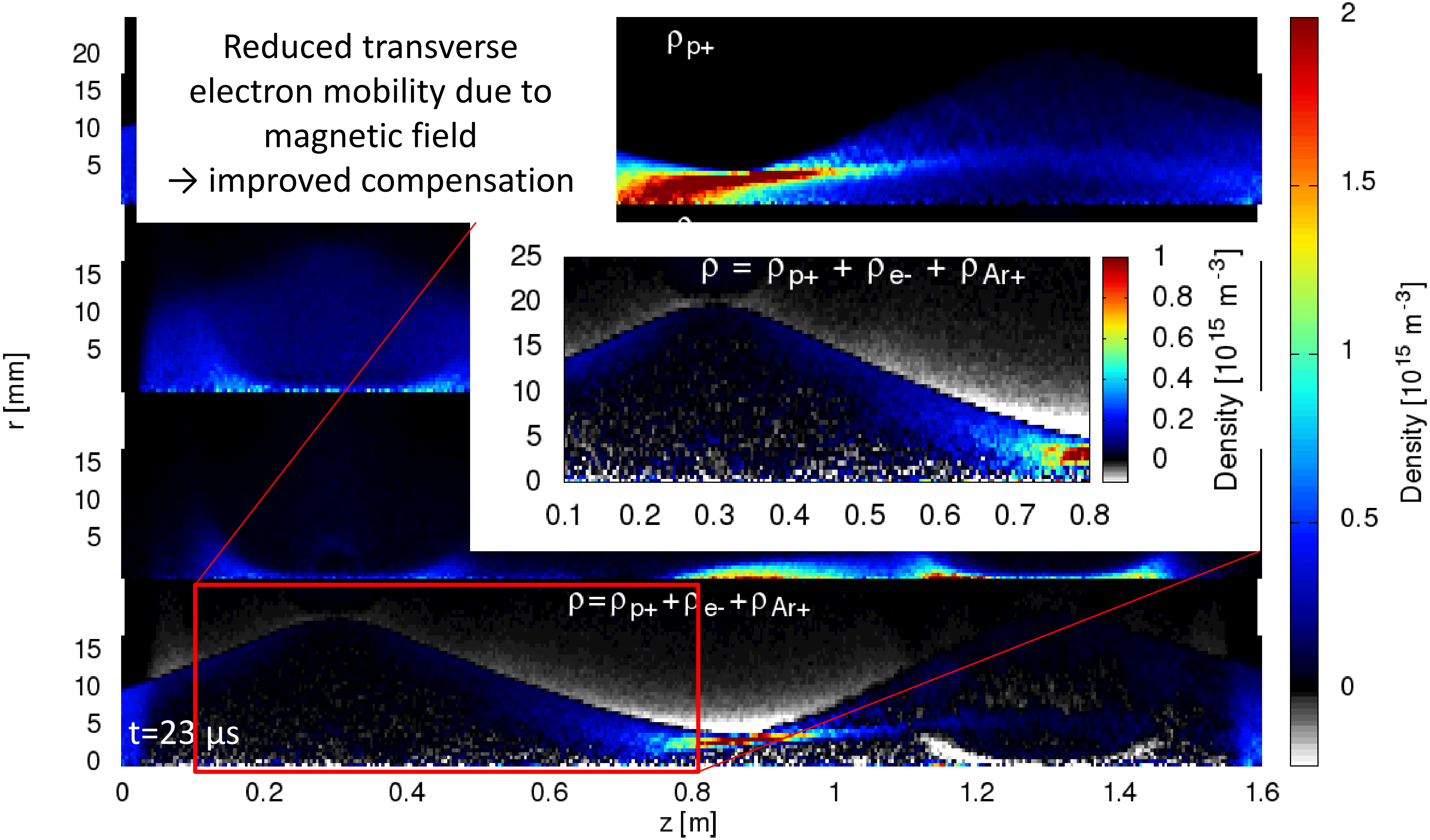
Spatial distribution



SCC studies: two solenoid LEBT

Spatial distribution

Reduced transverse electron mobility due to magnetic field
→ improved compensation



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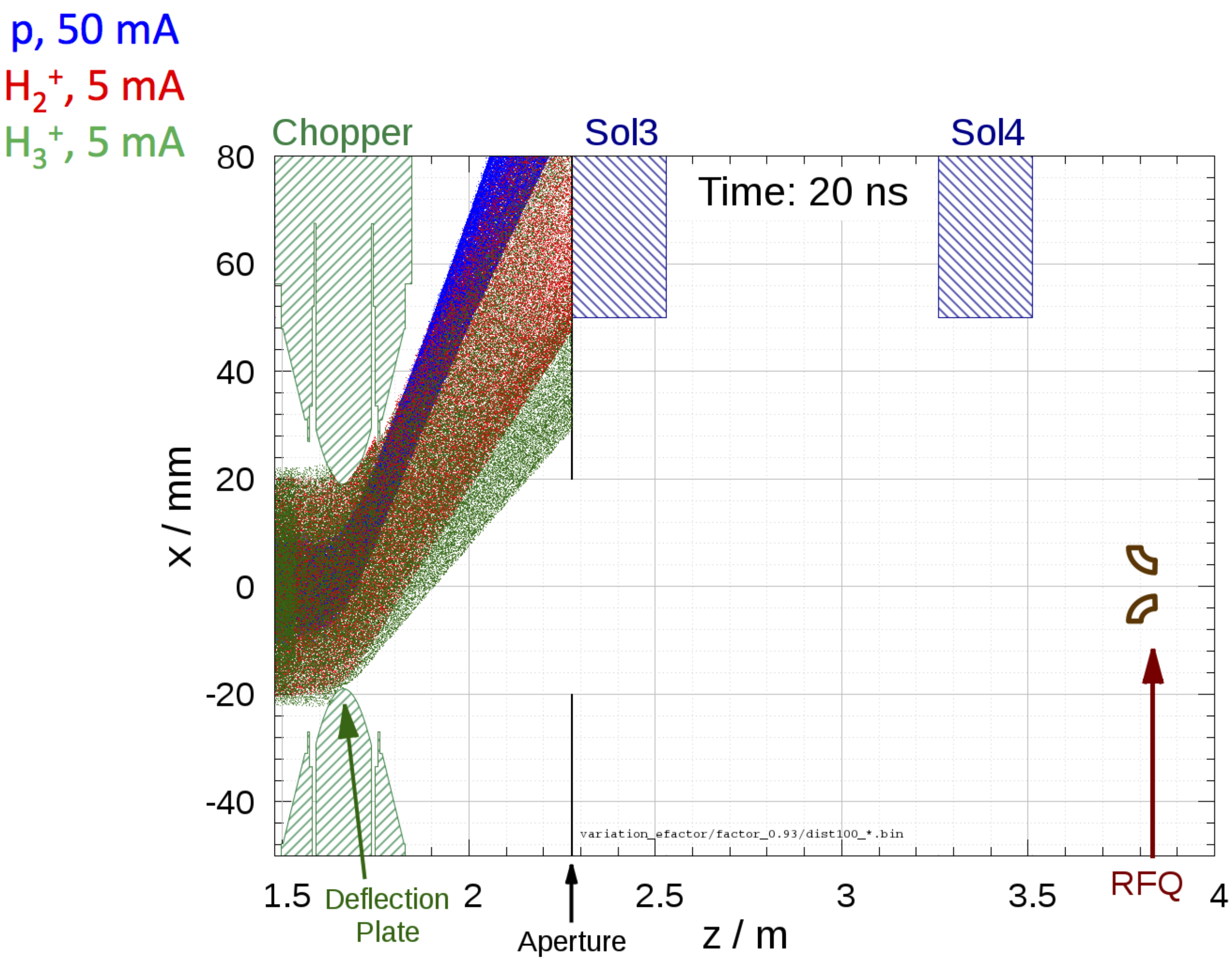
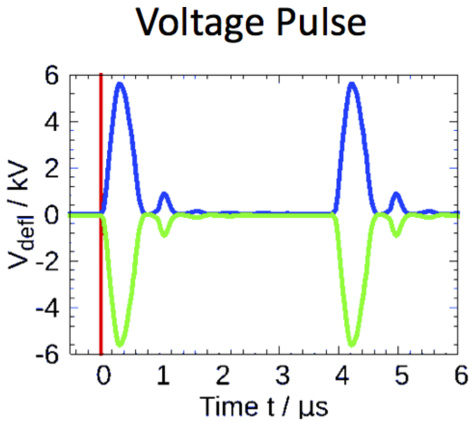
FRANZ E×B chopper

Pulse forming



Input:

- Field maps from CST Magnetostatic Solver
- Matched beam distribution
- Measured voltage pulse

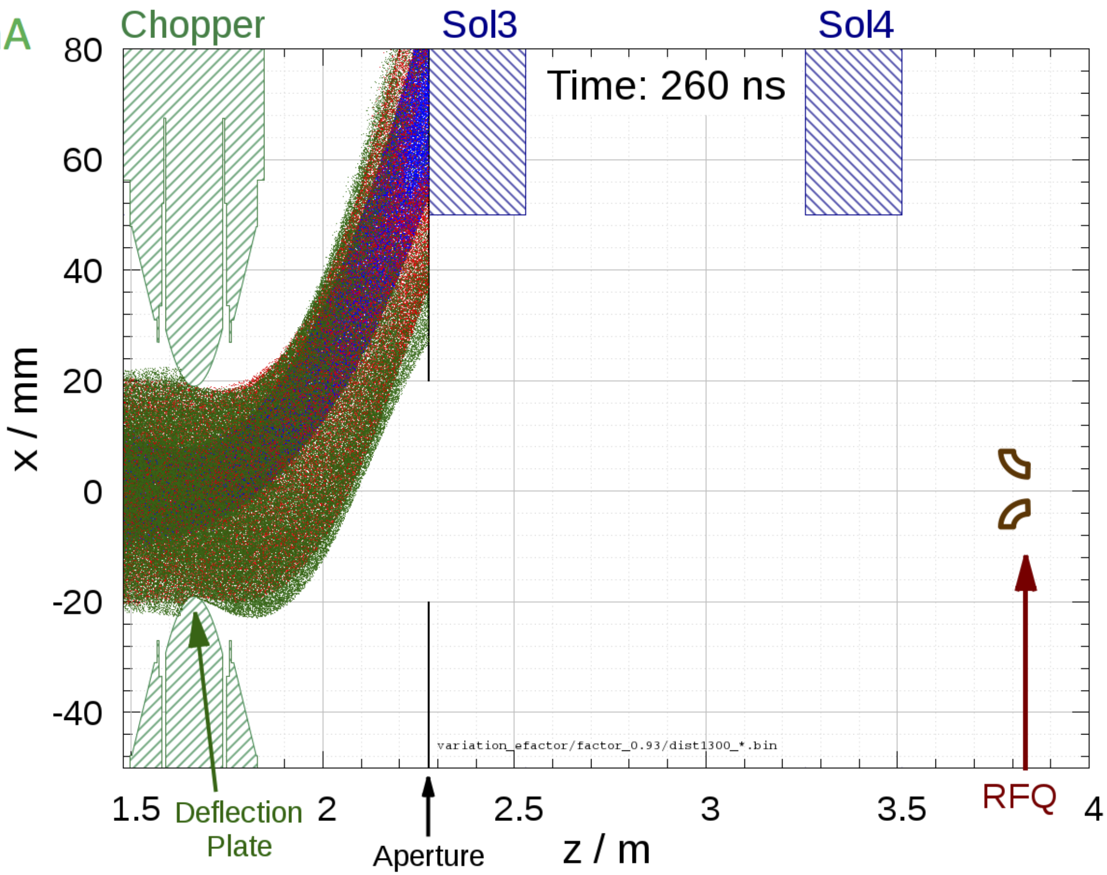


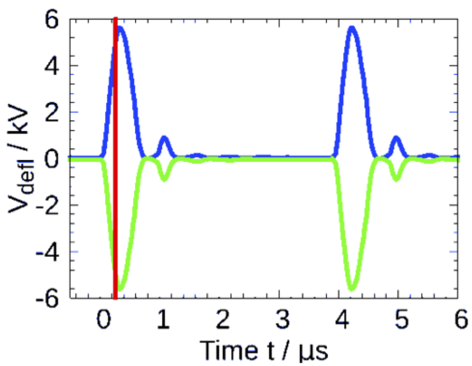
Plot by C. Wiesner

FRANZ E×B chopper

Pulse forming

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





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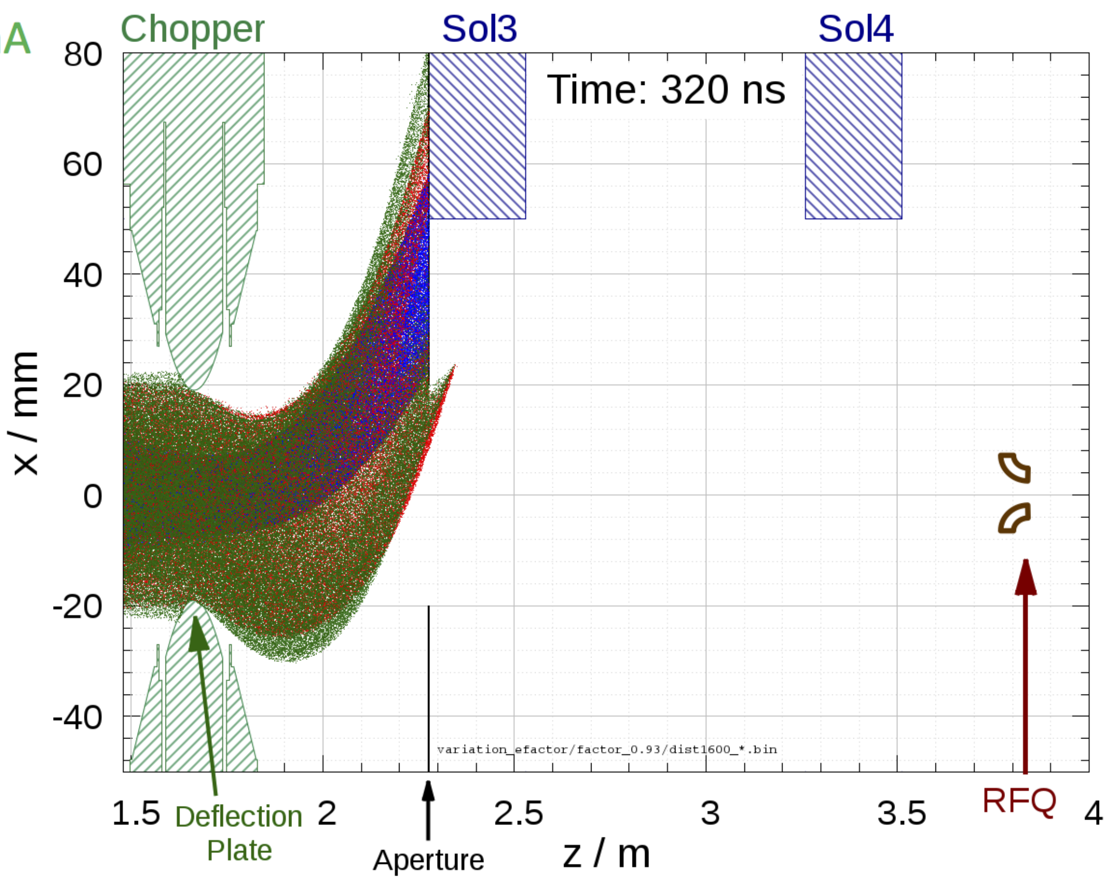
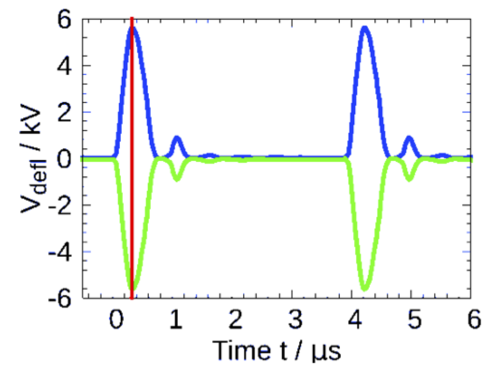


Voltage Pulse



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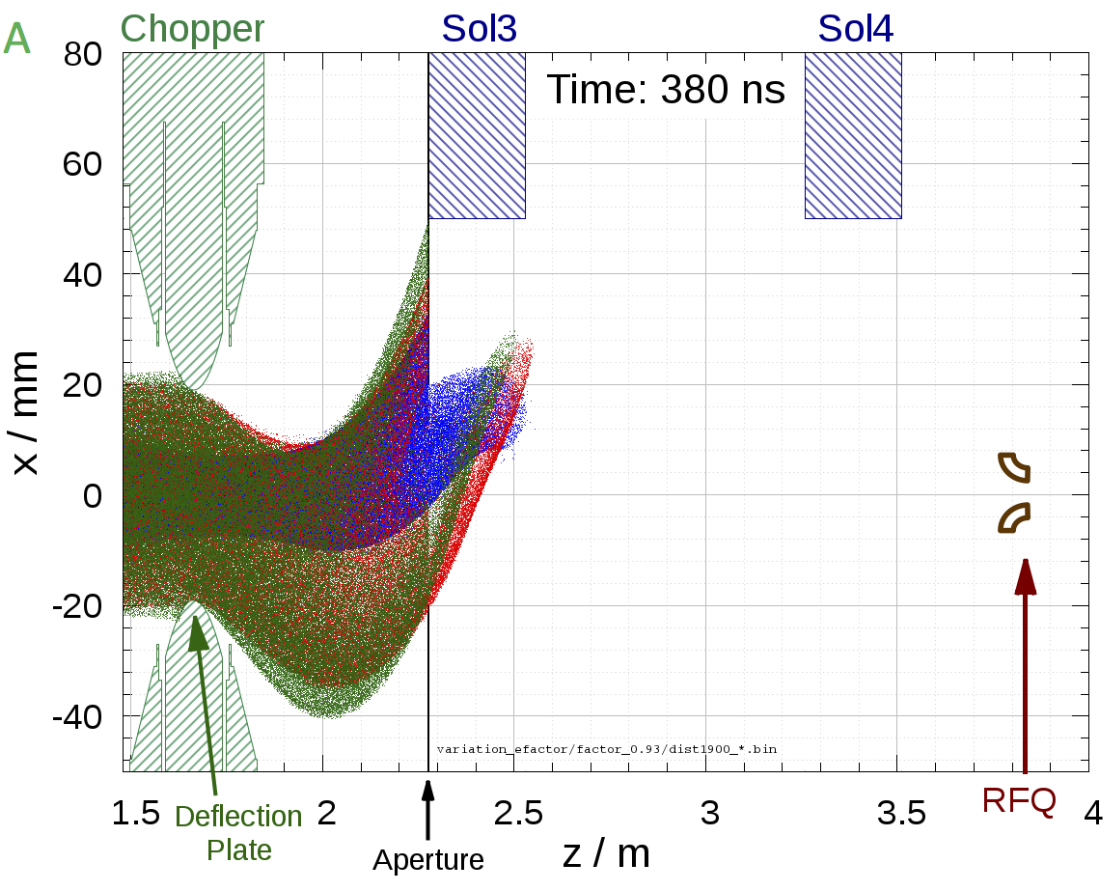

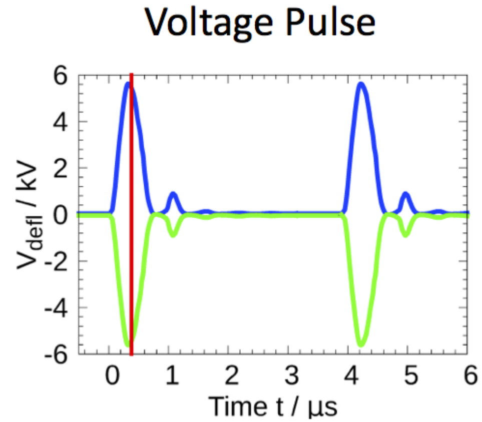

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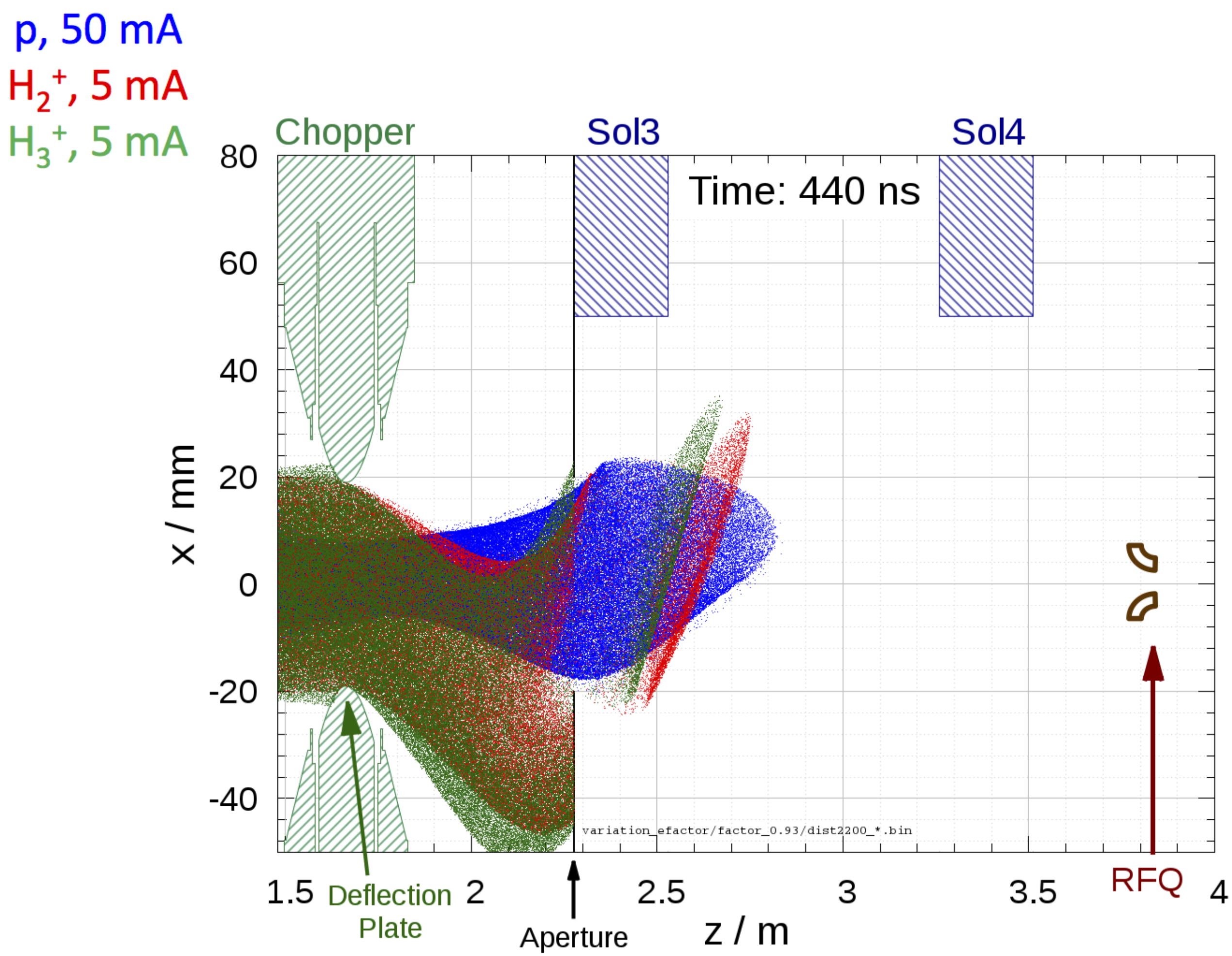

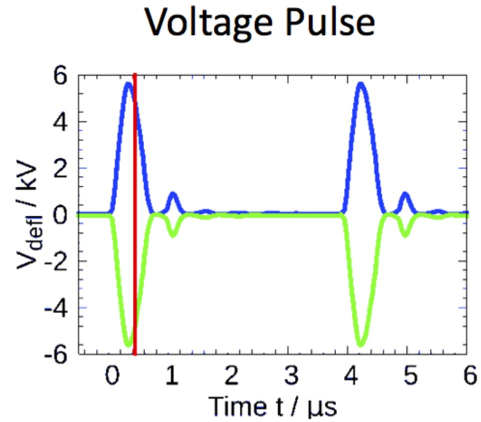

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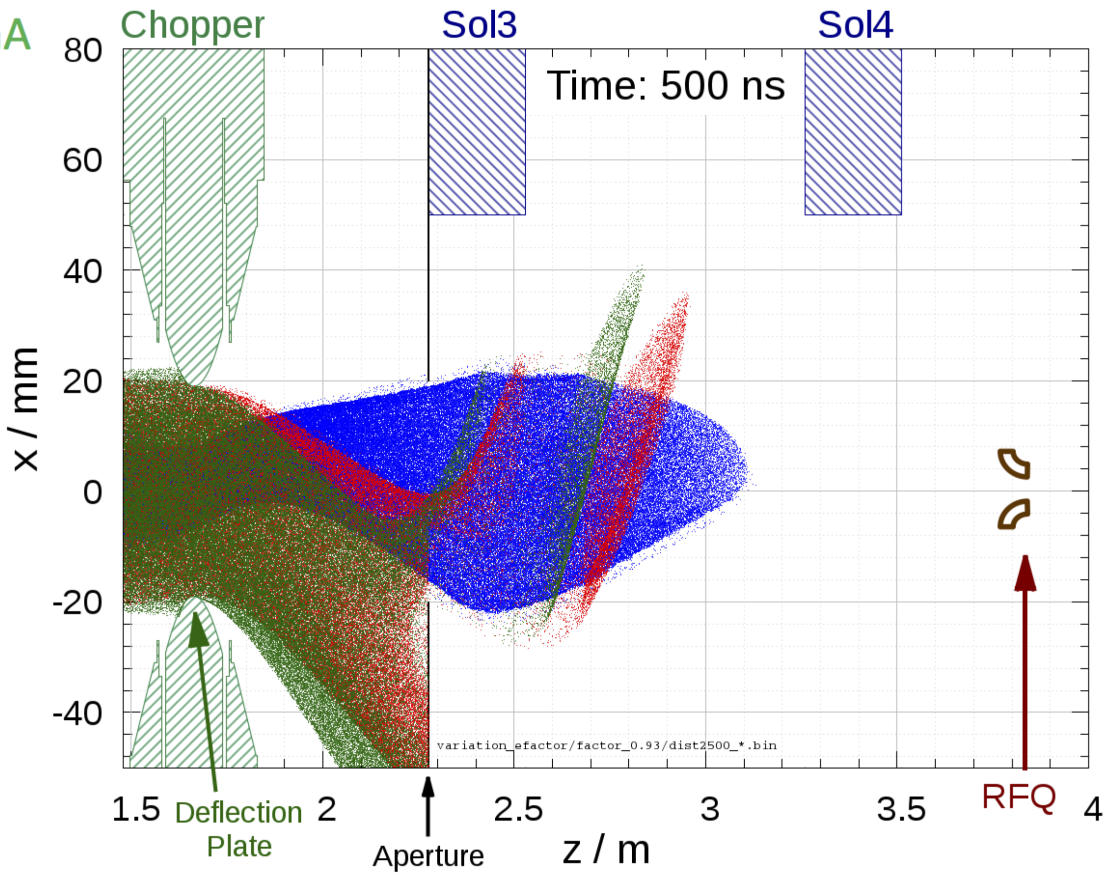

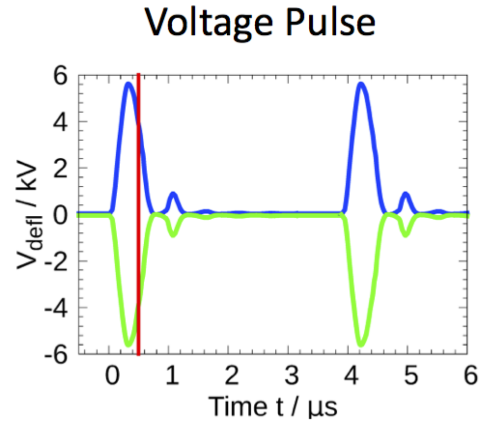

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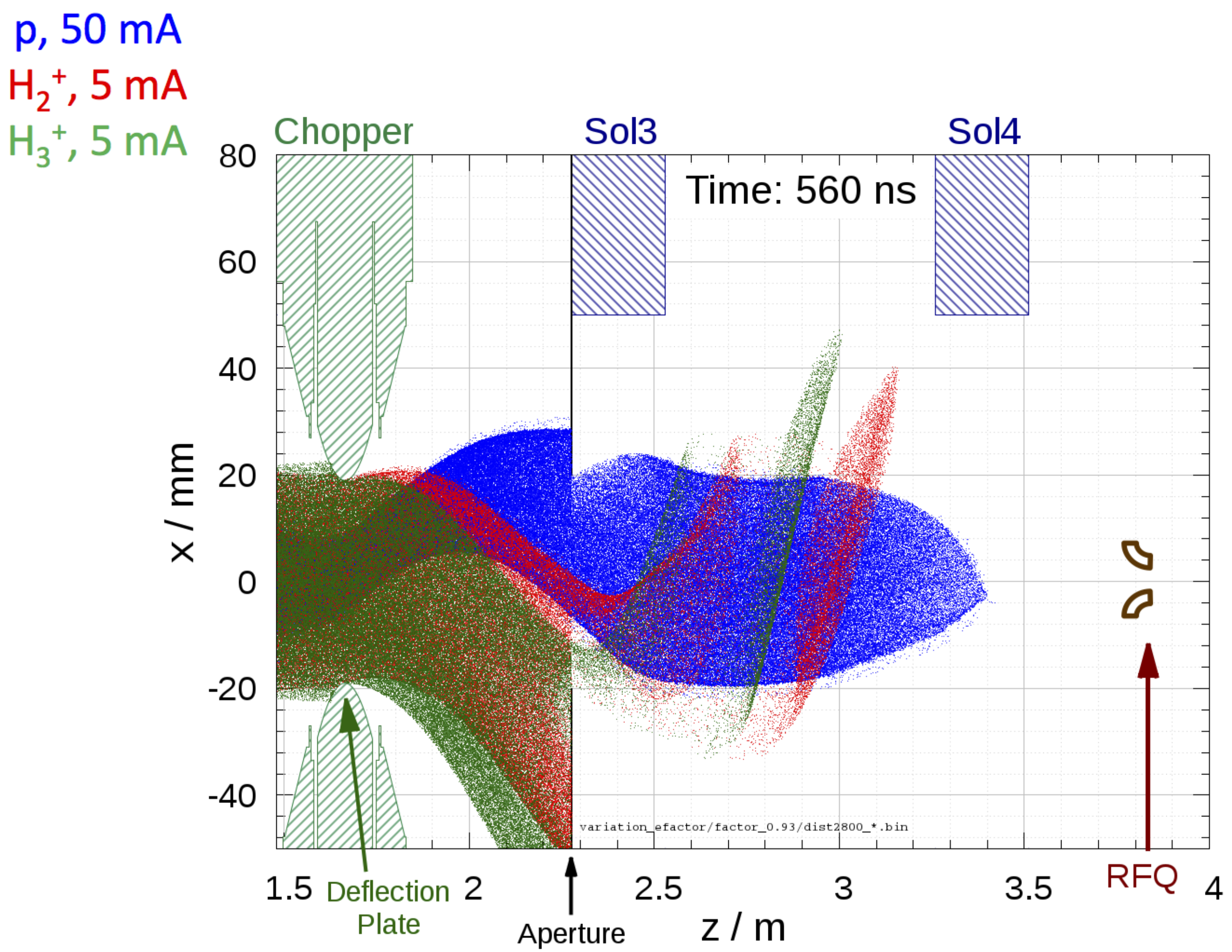

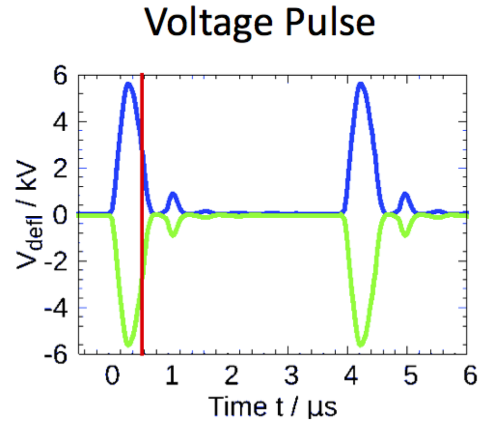

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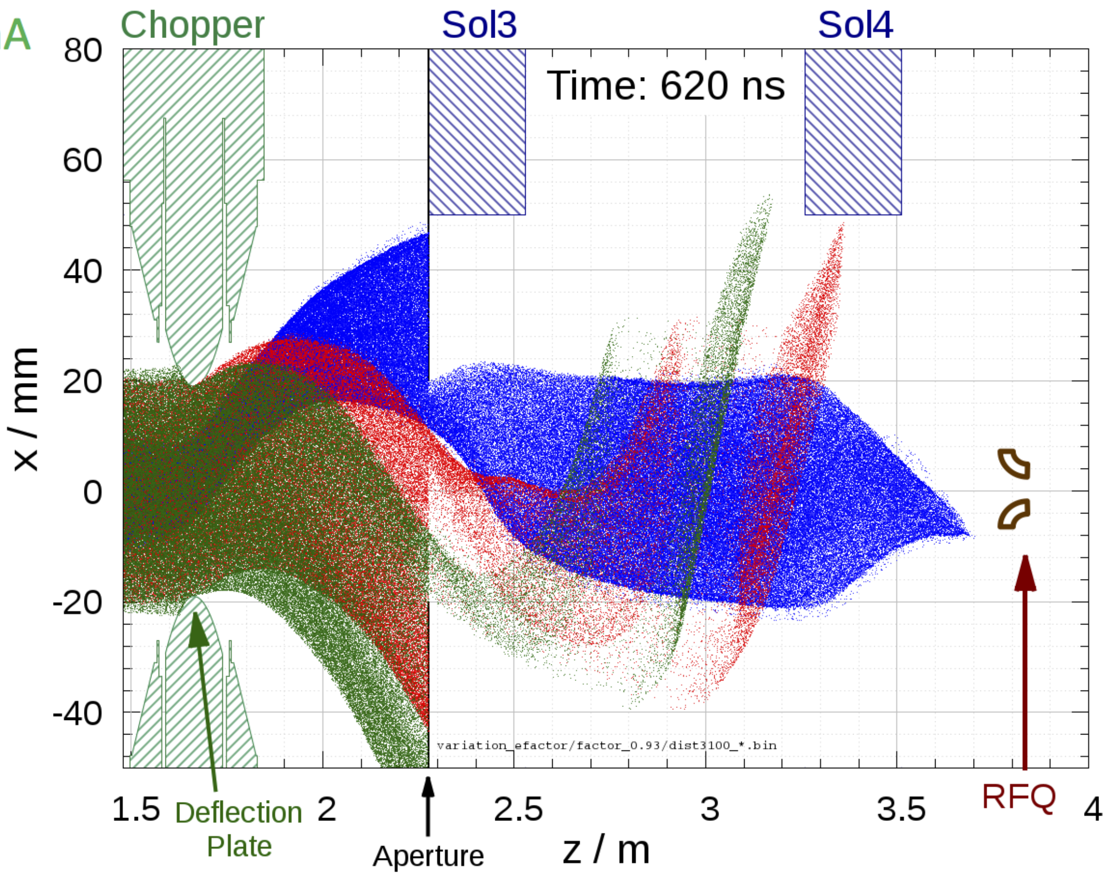

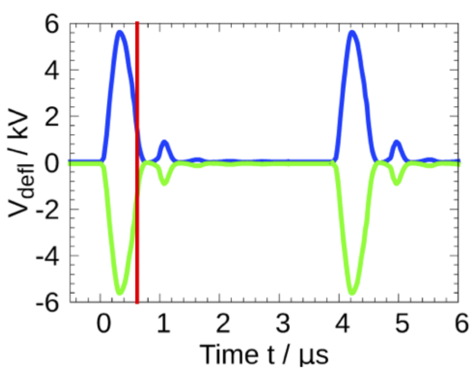

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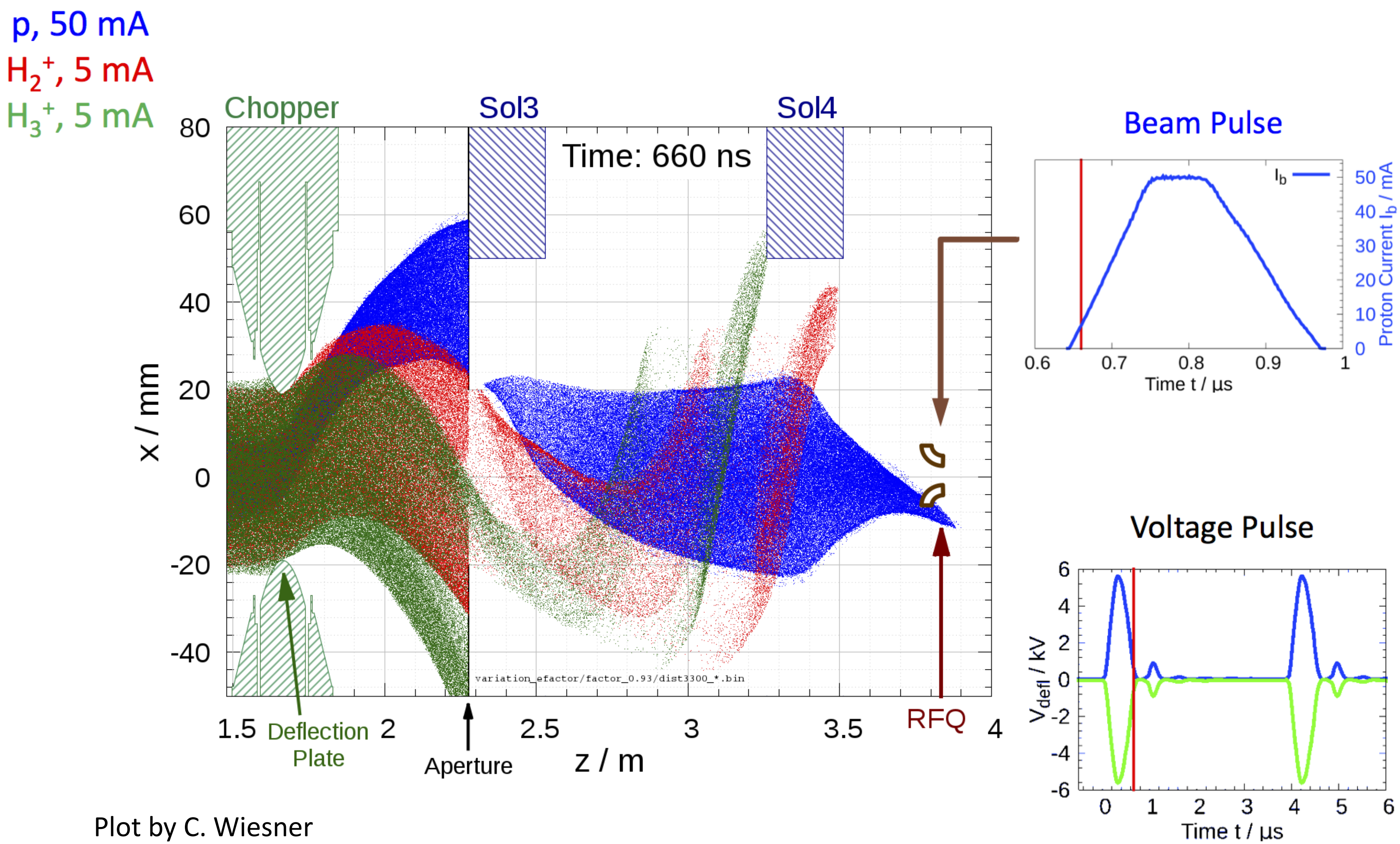

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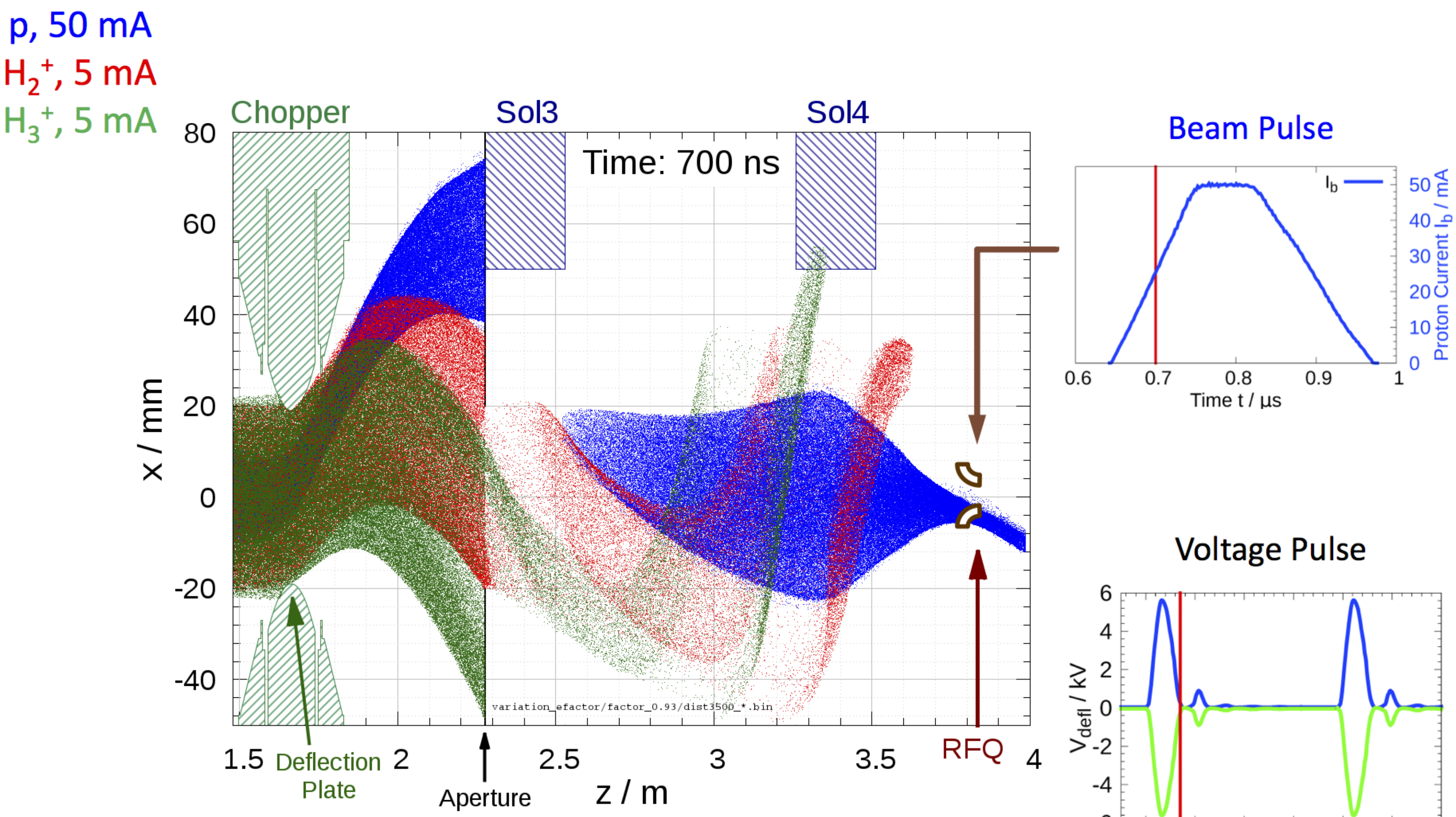

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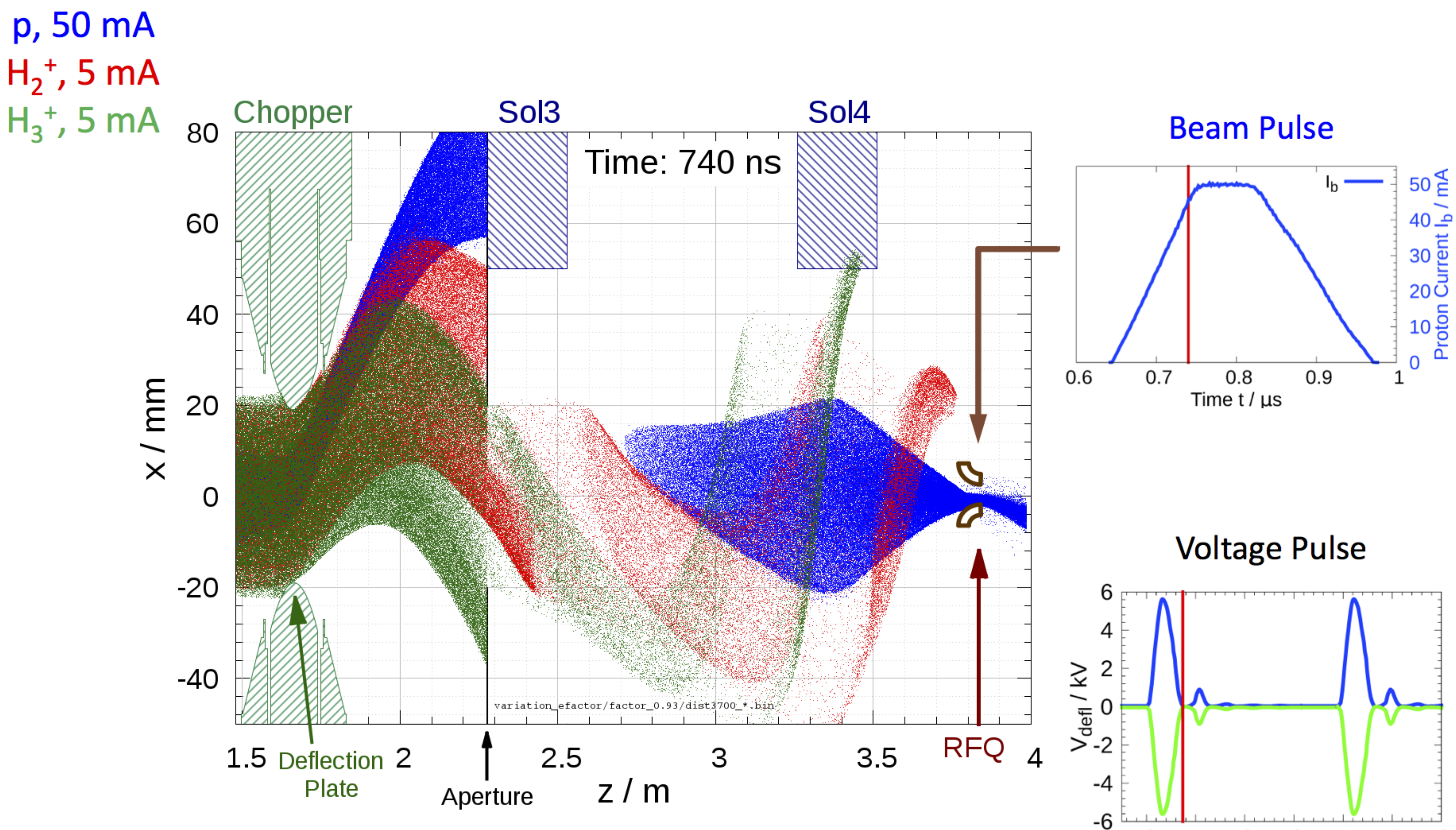

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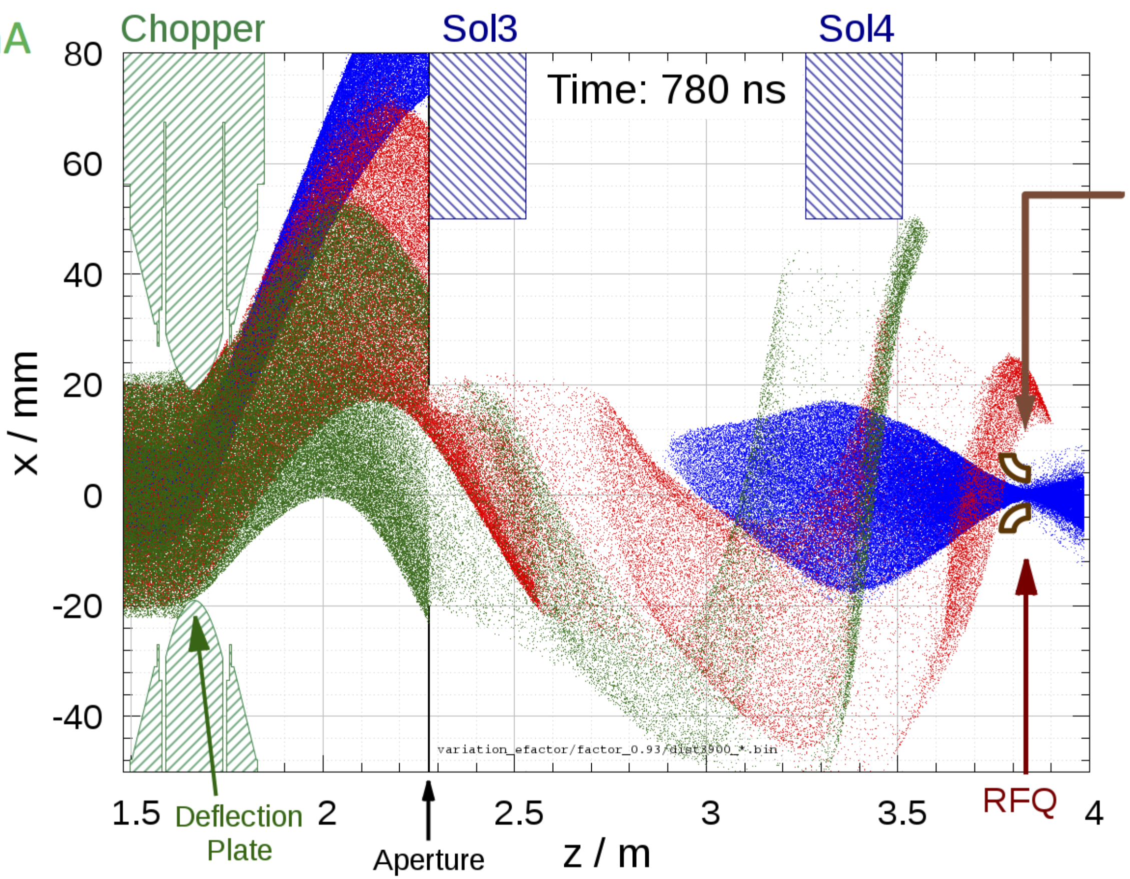
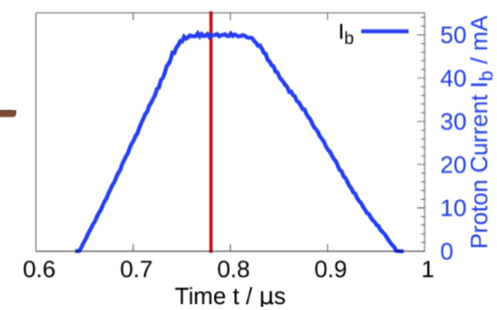
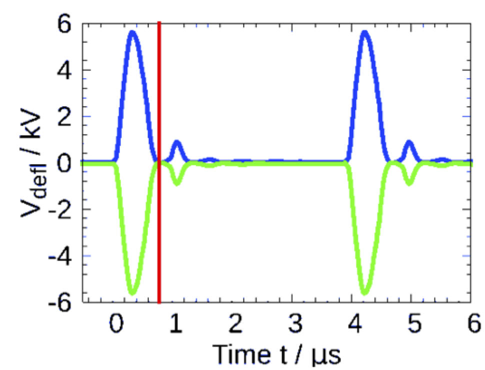


Beam Pulse

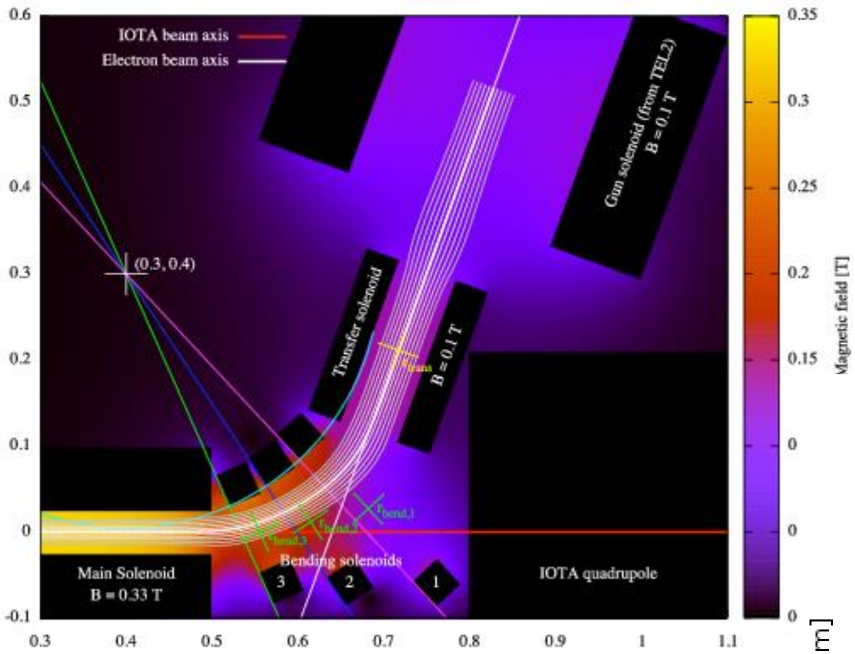


Voltage Pulse



Plot by C. Wiesner

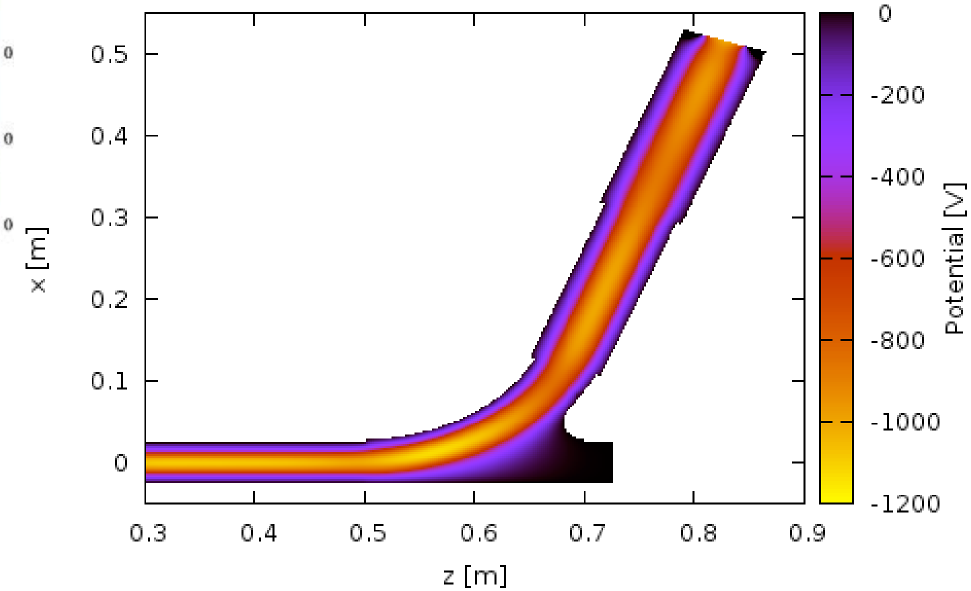
Electron lens for IOTA



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 processors, 0.5 mm, 1e7 particles

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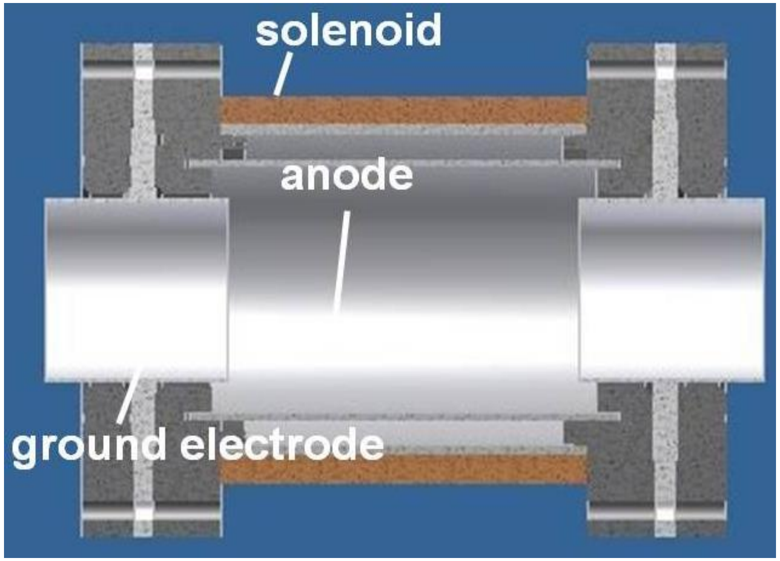
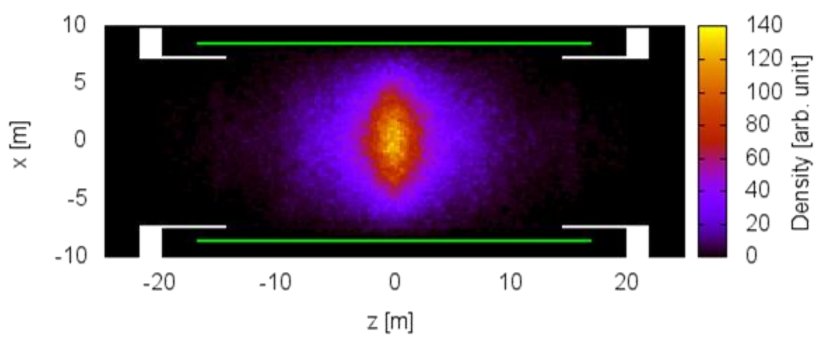
- Outlook and conclusion

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…

More about plasma measurements on Gabor lenses: Talk by K. Schulte on Thursday

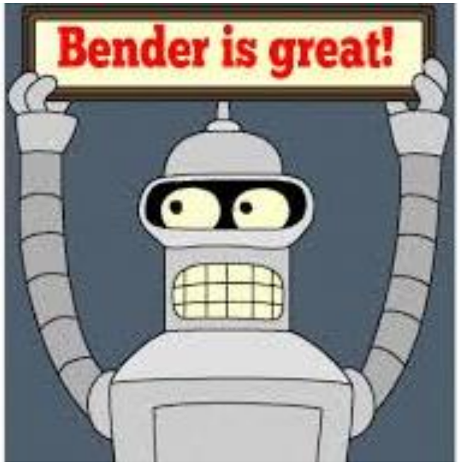
Conclusion and outlook

- 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? Recombination?)
  - Comparison to measurements done at FRANZ

Thank you for your attention!

Open questions:

- What is the source of the thermal distribution in the simulation? Is it numerical or is it physical?
- If numerical, how can the algorithm be modified to provide “correct“ equilibration times?
- Which process is missing to stop the spurious growth in the presence of magnetic field?



In the name of the Frankfurt NNP group:
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