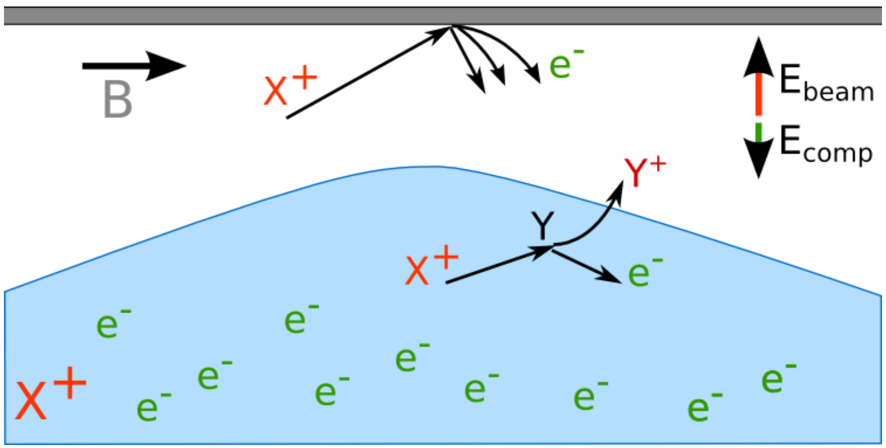
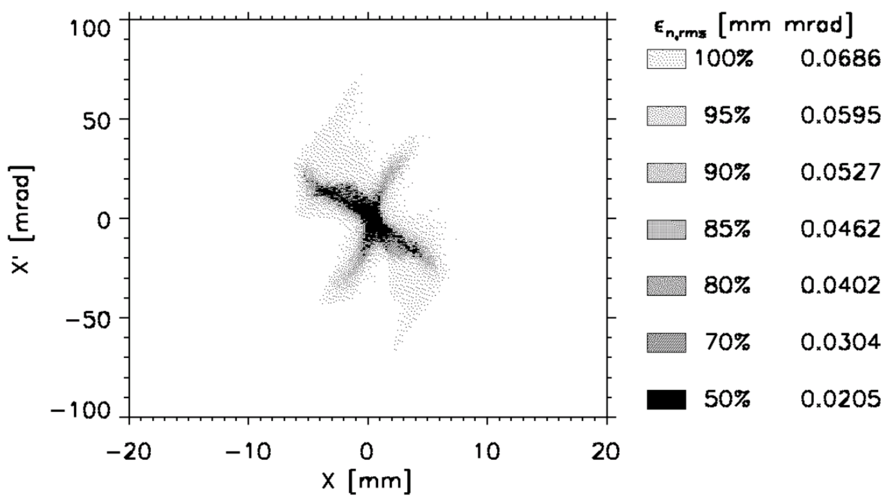
Simulation of Space-Charge Compensation of Proton Beams in Low-Energy Beam Transport

Daniel Noll

Space-Charge Compensation





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

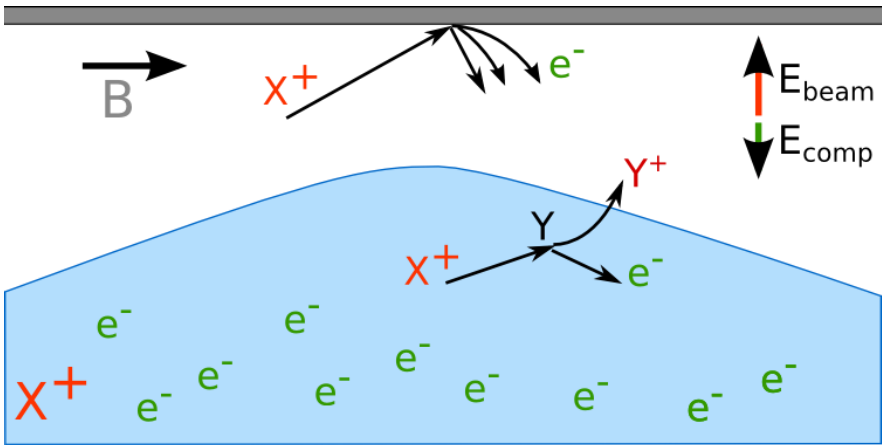
- Accumulation of secondary particles of opposite charge in the beam potential
- "Traditional" treatment: Constant compensation factor

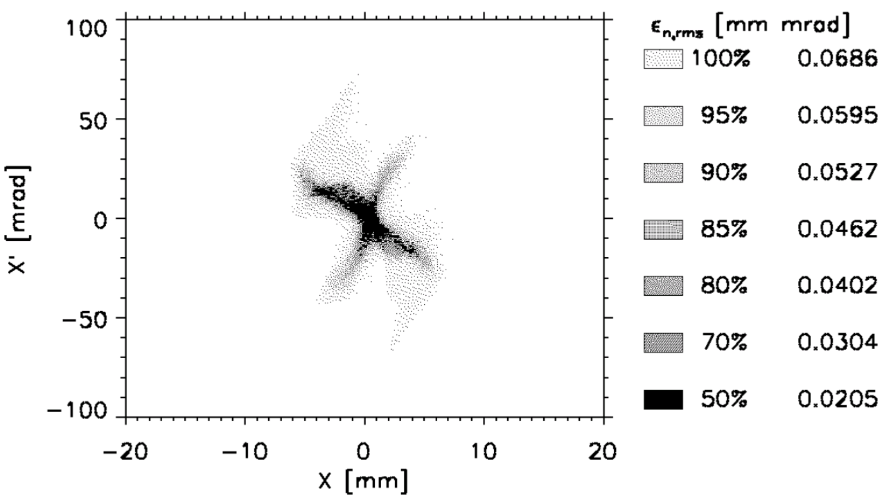
Two options:

- 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

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

120 keV p^+, N_2, p=10^{-5} mbar

- Magnetic fields

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

- Which effects to include?

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

Outline

- Simulation studies on space charge compensation of positive ion beams
  - Particle-in-Cell model
  - Results for a beam drift
  - Comparison with a model of thermalized compensation particles
- Source and low-energy beam transport studies at CERN's Linac 4
  - Introduction
  - Ion source beam extraction studies
  - Influence of space-charge compensation

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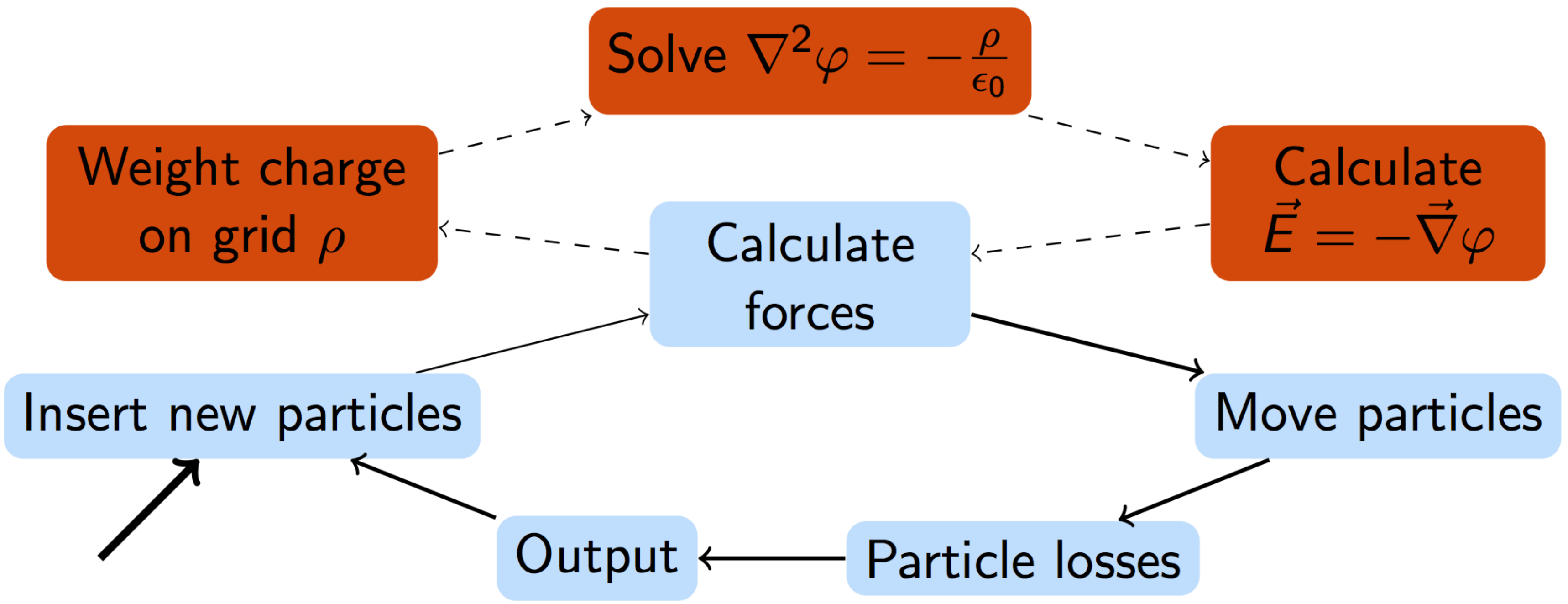
Simulation model

The Particle-in-Cell algorithm



Solution of the Vlasov equation by introducing simulation particles

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m}\frac{\partial f}{\partial q} + qE\frac{\partial f}{\partial p} = 0$$

Code used: *bender* [1]

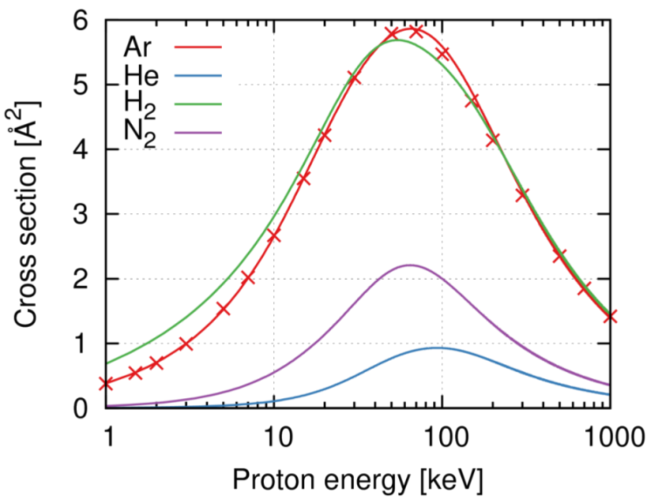
[1] D. Noll, M. Droba, O. Meusel, U. Ratzinger, K. Schulte, C. Wiesner – The Particle-in-Cell Code bender and Its Application to Non-Relativistic Beam Transport, HB2014, WEO4LR02.

Simulation model

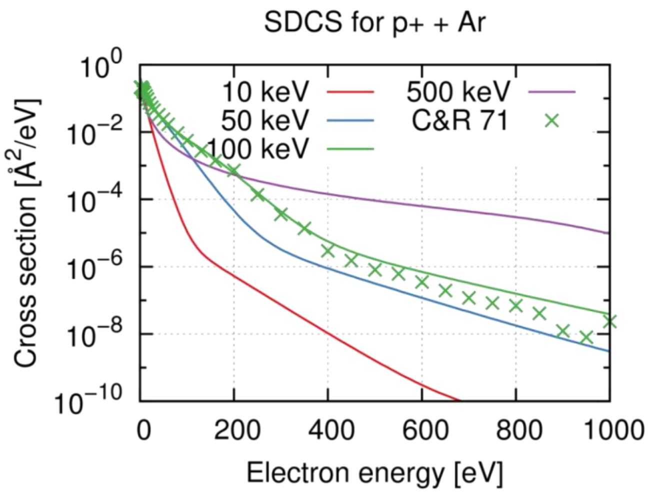
Cross sections

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



$\langle E \rangle \approx 27.5$ eV



Calculation:
- Null collision method [3]
- (Classical) Collision model for energy & momentum conservation

[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.
[3] Vahedi, Surendra – A Monte Carlo Collision Model for the Particle-in-Cell method, Computer Physics Communications (1995).

Space-Charge Compensation

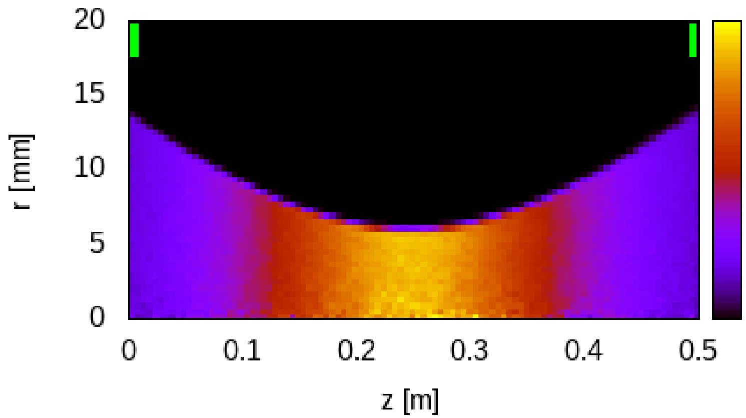
Model system

- Which system to simulate? Should be as simple as possible:
  - Drift section: no magnetic fields
  - No particle losses
  - Argon as residual gas
    - High ionization cross section
    - No dissociation fragments
    - Good data availability

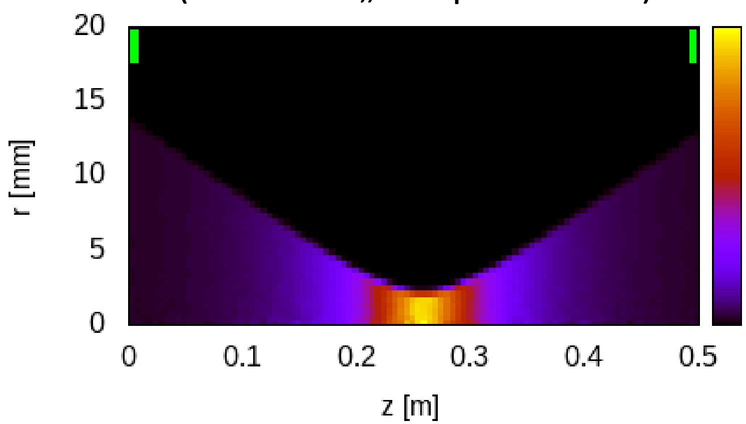
100 mA, 120 keV proton beam
10^{-5} mbar Argon background
-1500 V repeller voltage
ε_{rms} = 25 mm mrad, α=7.4, β=1.89 m

1000 macroparticles per step
0.4 mm mesh resolution
50 ps time step

Proton density without compensation

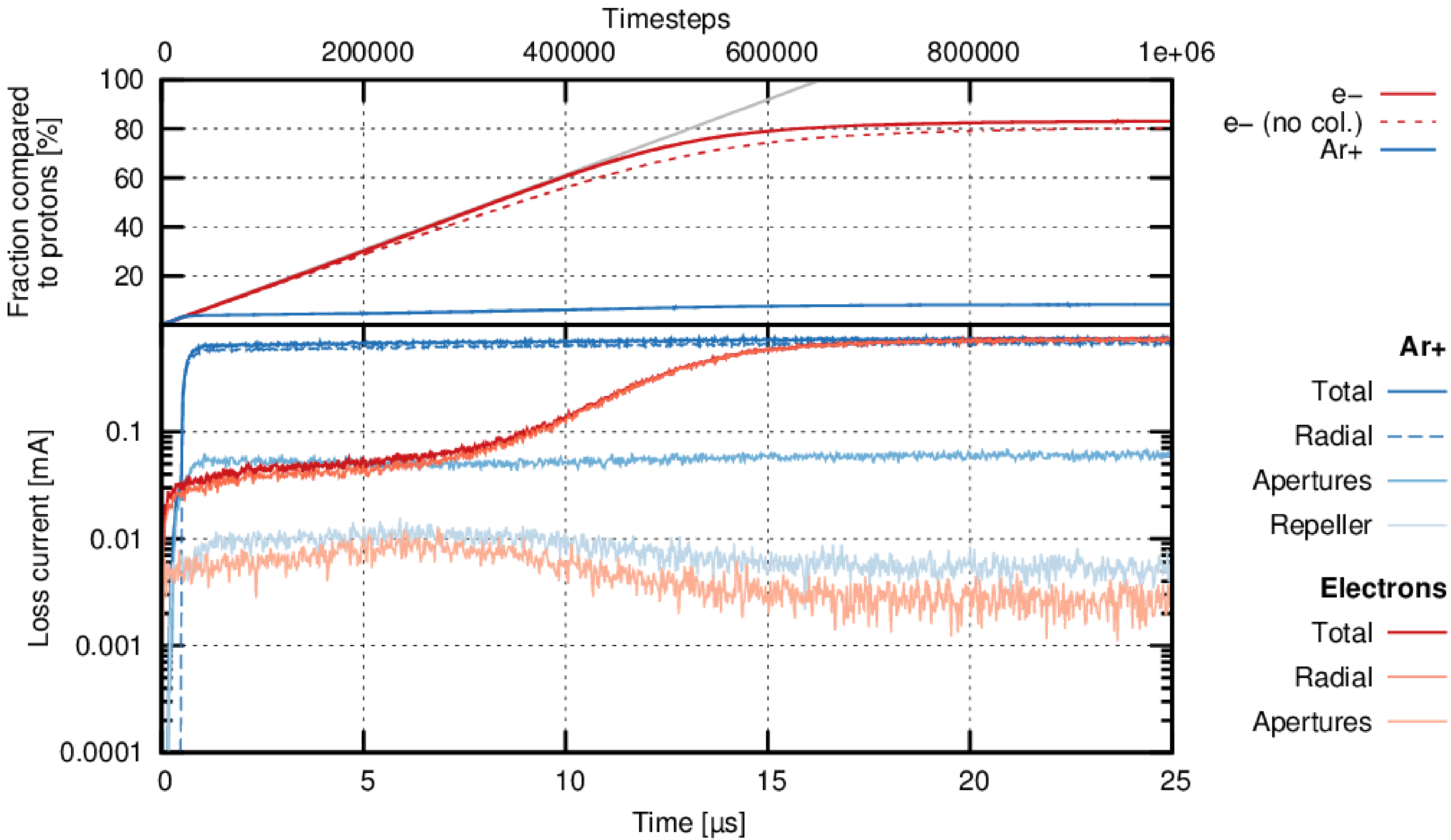


Proton density at 10 mA
(with 90% „compensation“)



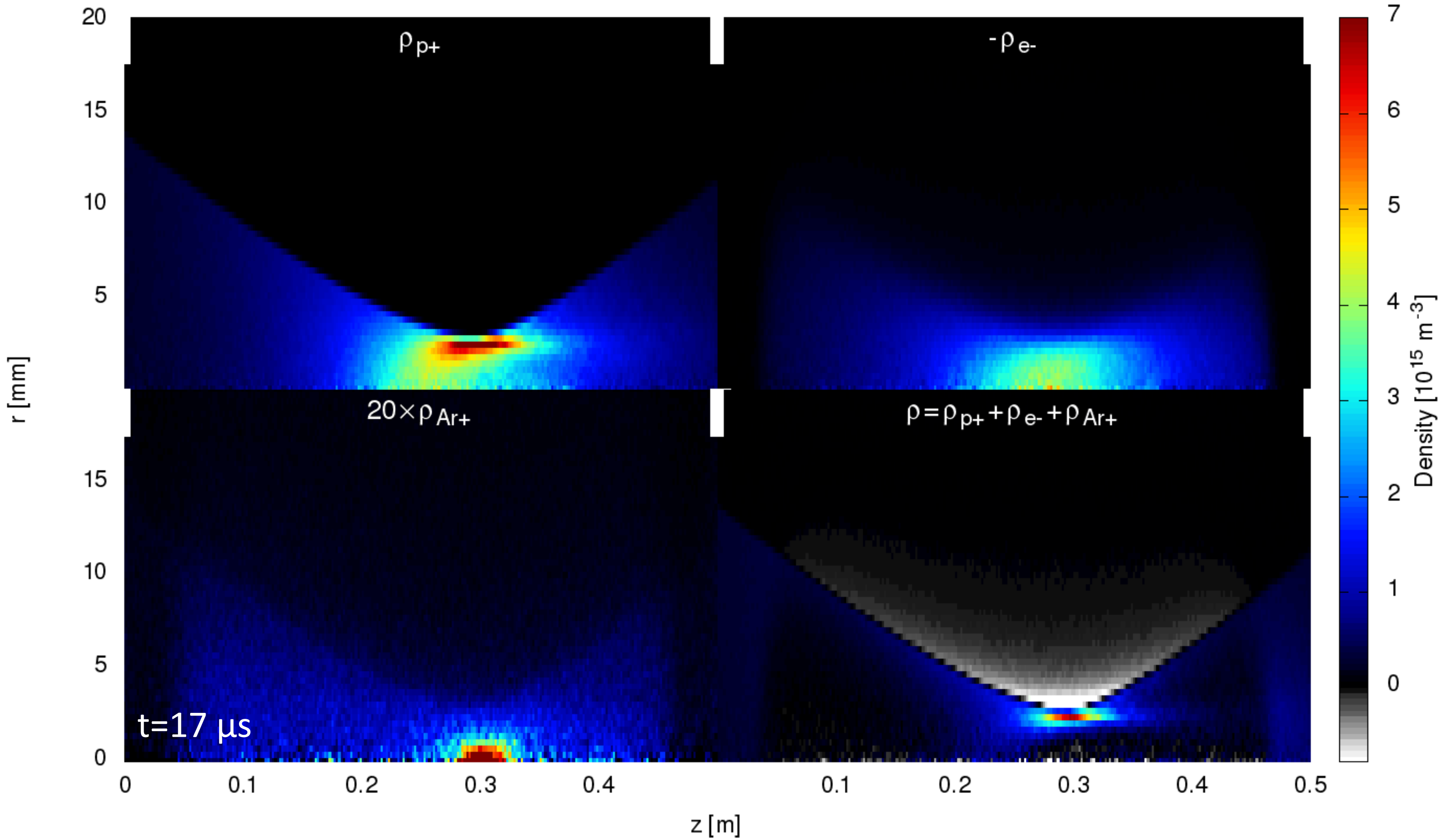
Results for the Drift System

Build-up of compensation



Results for the Drift System

Charge densities



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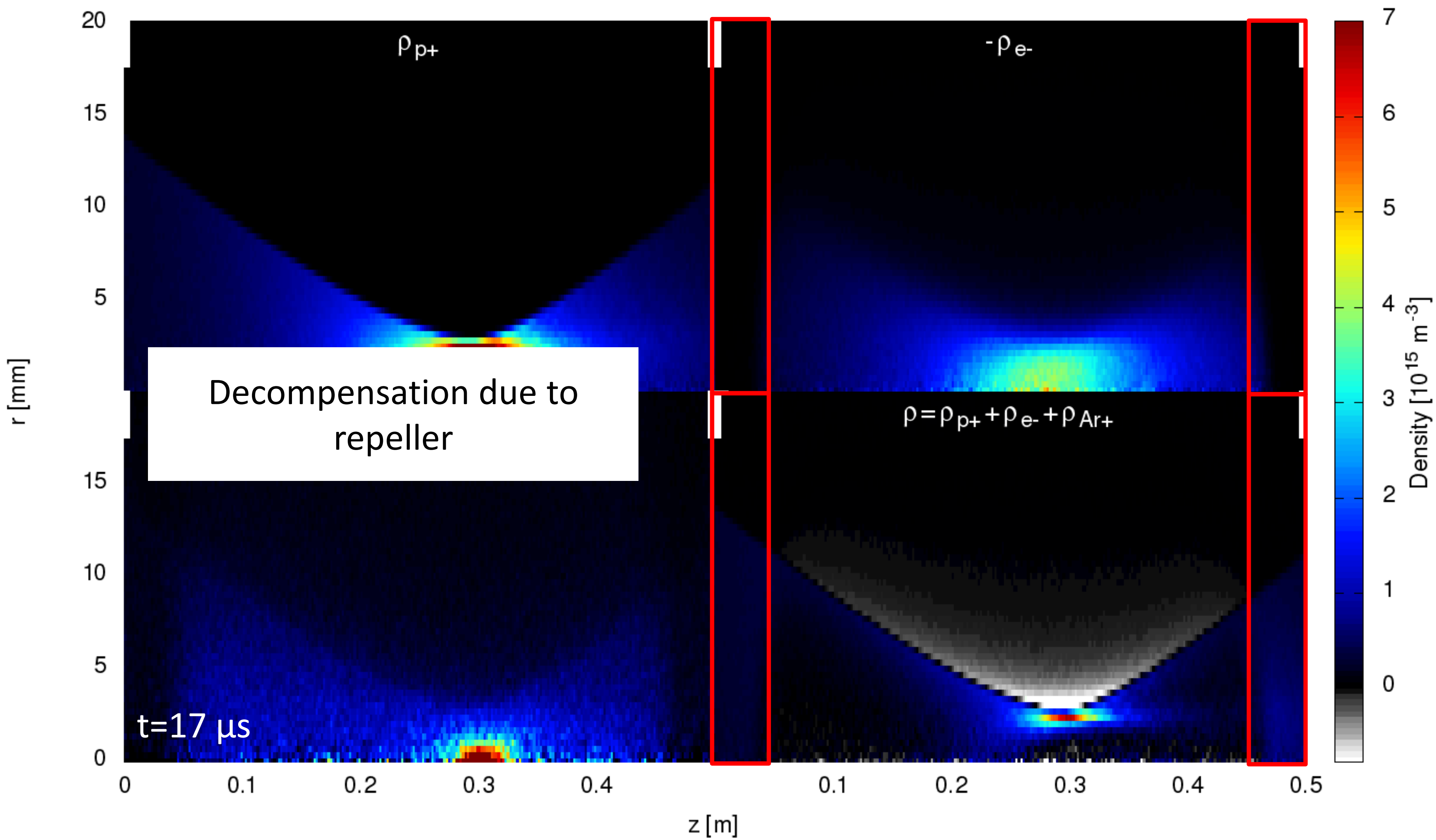

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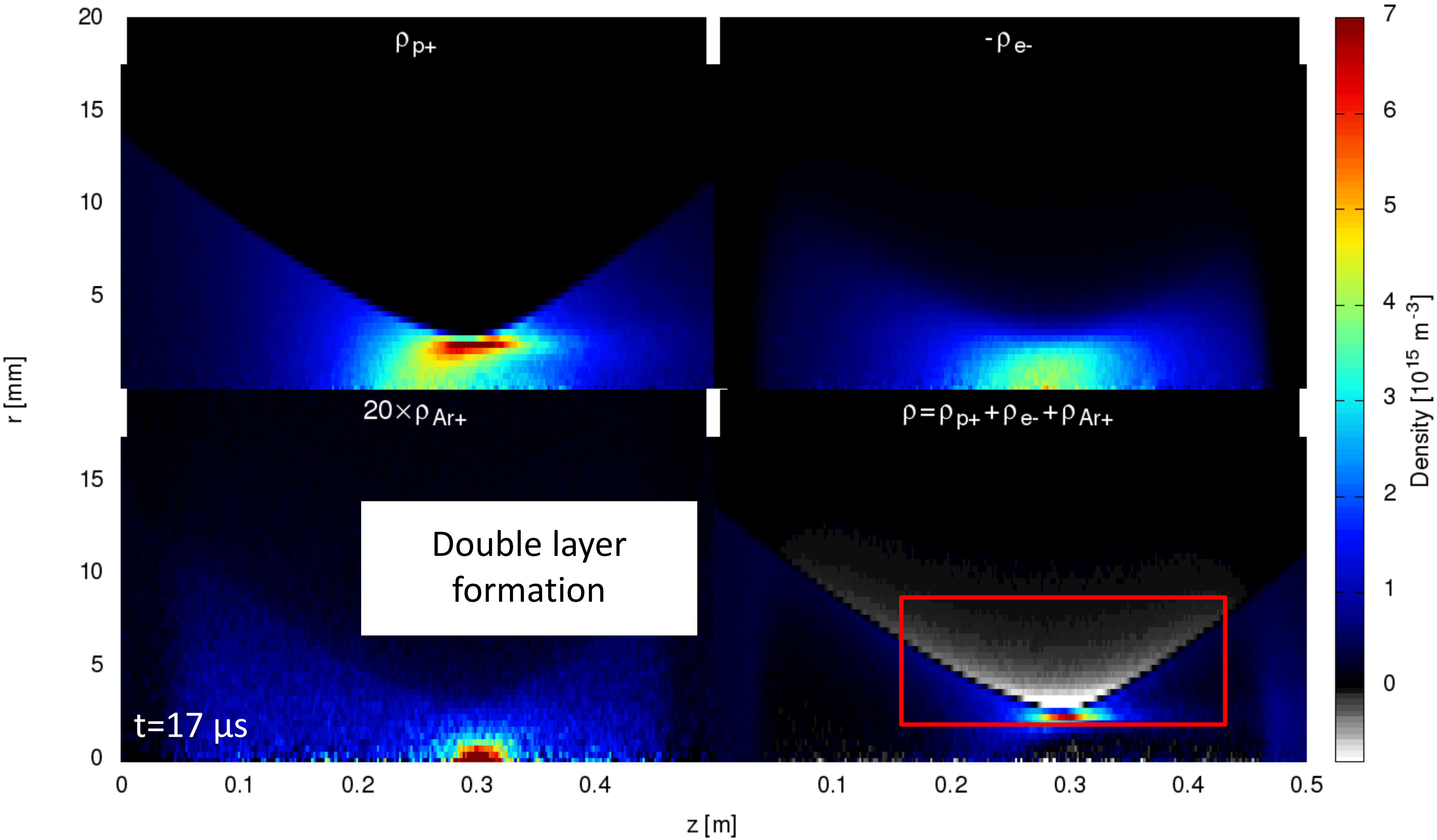

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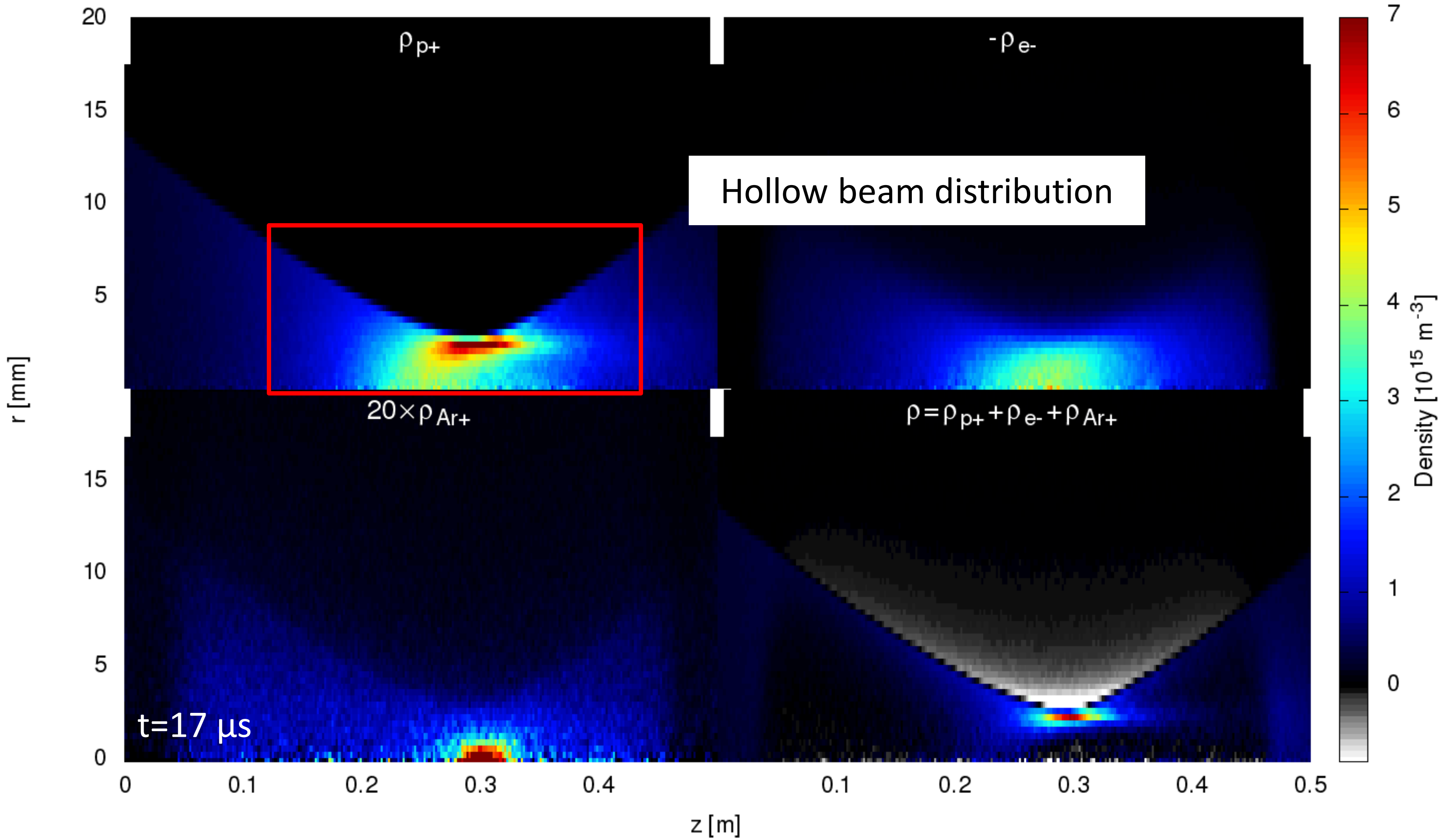
Charge densities



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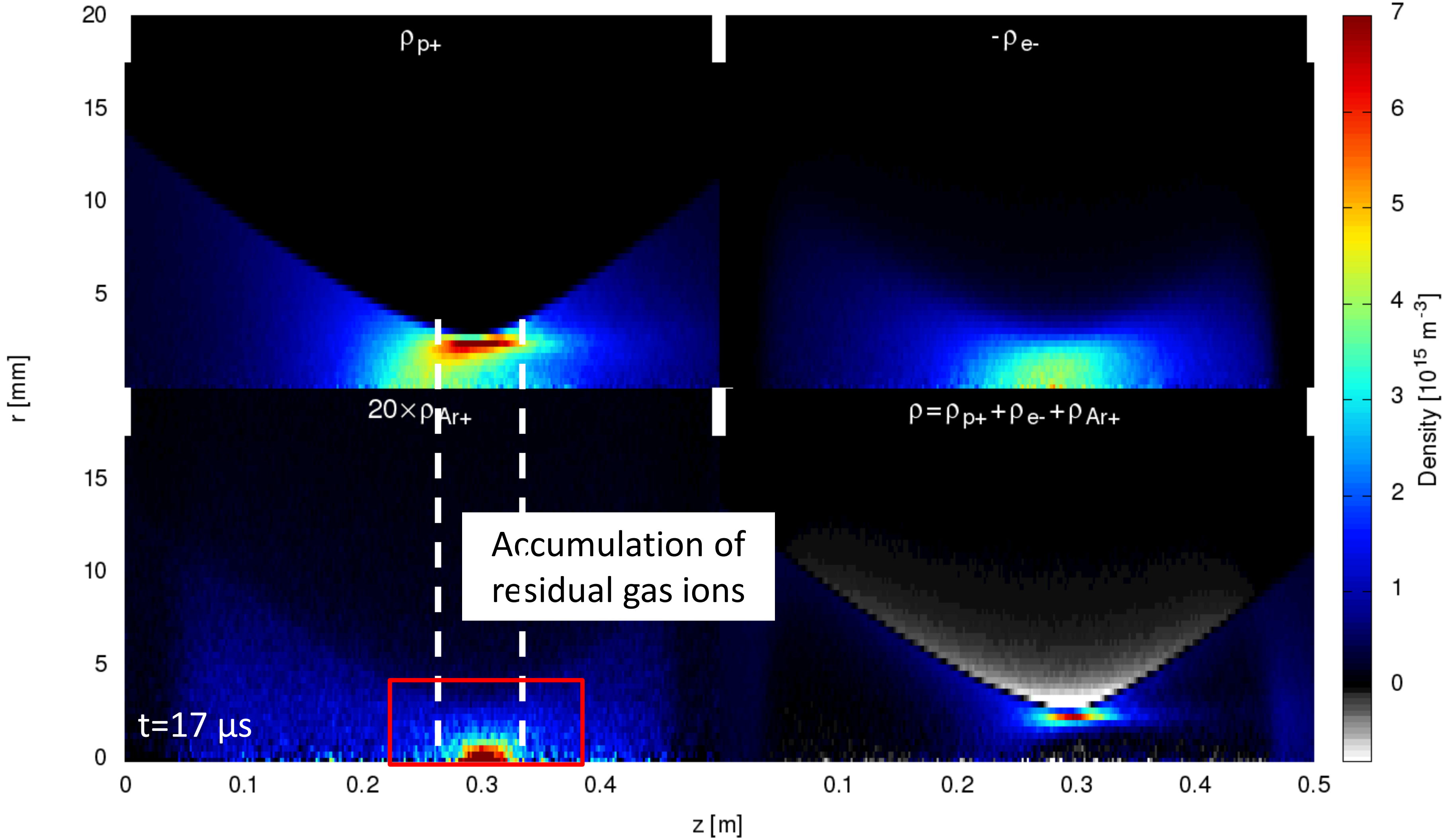
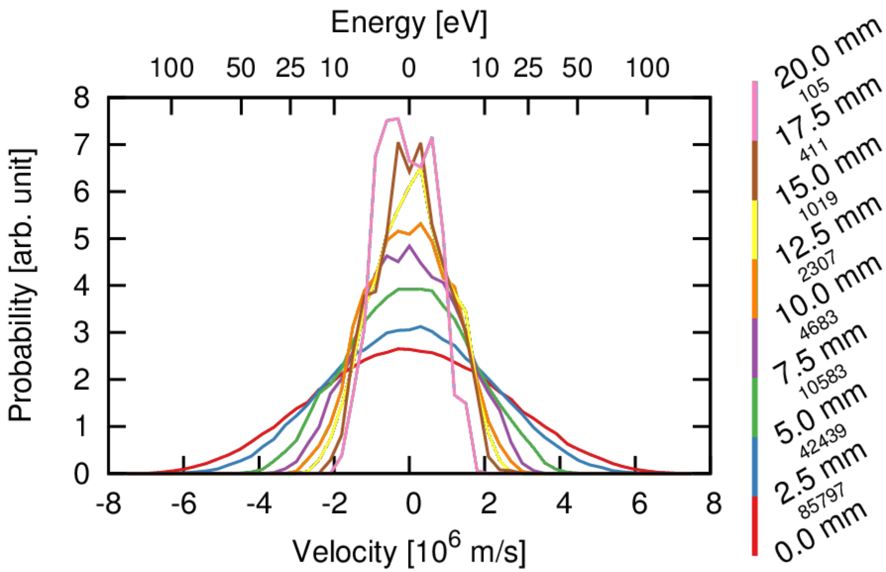
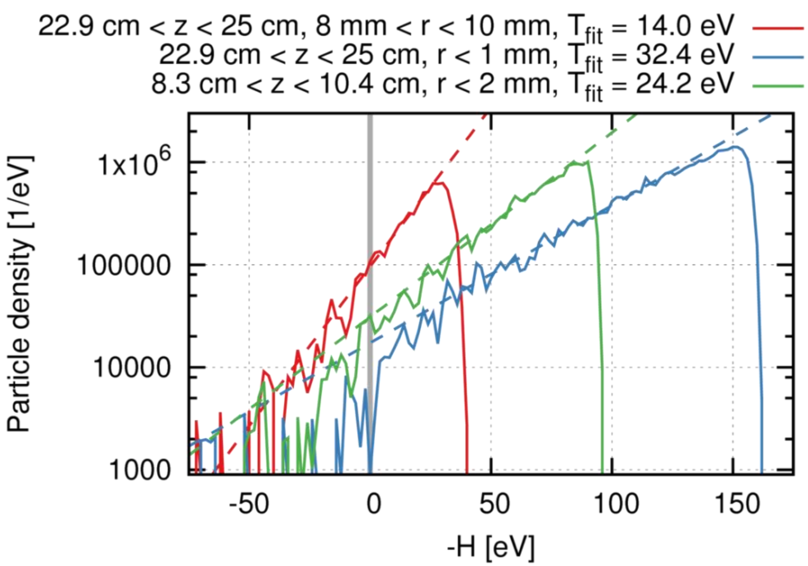


Results for the Drift System

Velocity distribution

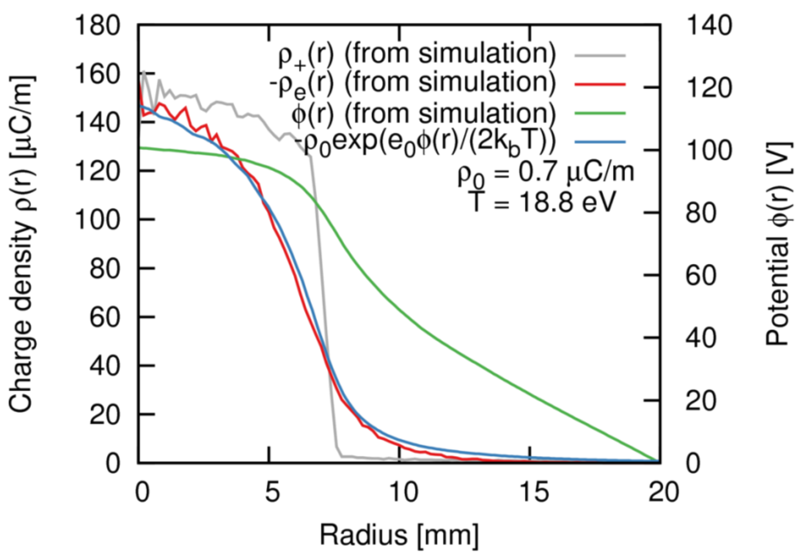




- Gaussian velocity distributions everywhere
  - $T_{x,y} \neq T_z$
  - $T_{x,y} = T_{x,y}(r, z)$
  - Deviation from Gaussians for large radii
  - Remain constant in equilibrium
- Approximately follow a Boltzmann distribution

$$f(\mathbf{r}, \mathbf{p}) = f_0 \exp\left(-\frac{H}{k_\mathrm{b}T}\right)$$

Poisson-Boltzmann Model



- Radial distribution: $f(r) = \widetilde{f_0}\exp(-e\varphi(r)/kT)$
- T, ρ_0 determine distribution
- Compensation electrons behave like a **non-neutral plasma** confined in the beam potential.

If we know T and ρ_0, can we find φ(r), f(r) directly?

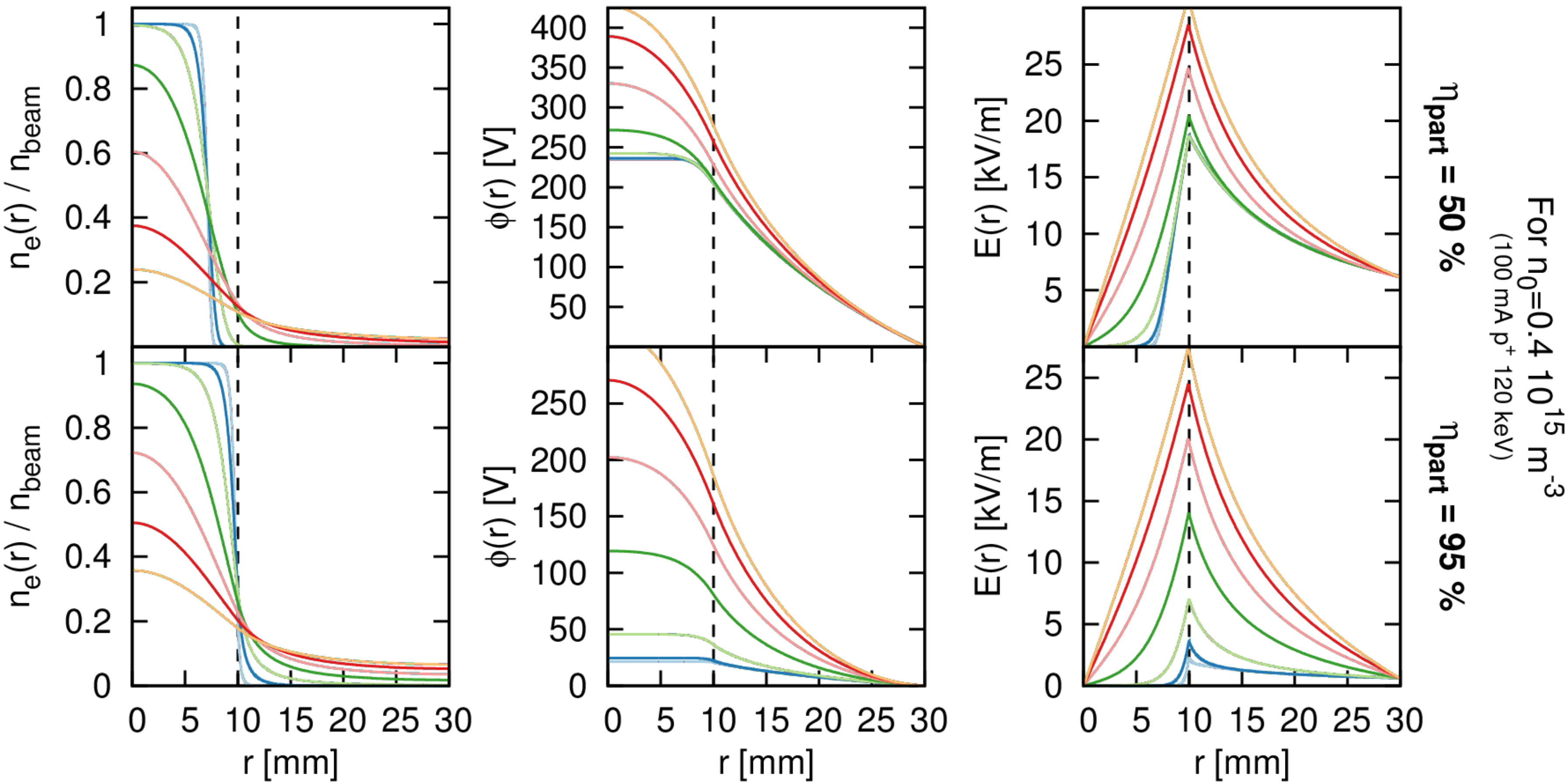
$$f_0 \exp\left(-\frac{\mathbf{p}^2}{2mk_\mathrm{b}T}\right)\exp\left(-\frac{q\left(\varphi_\mathrm{c}(\mathbf{r})+\varphi_\mathrm{ext}(\mathbf{r})\right)}{k_\mathrm{b}T}\right) \qquad \varphi_\mathrm{c}(\mathbf{r})+\varphi_\mathrm{ext}(\mathbf{r})$$

$$\nabla^2\varphi_c(r) = -\frac{q}{\epsilon_0}\int f(\mathbf{r},\mathbf{p})\,\mathrm{d}\mathbf{v} = -\frac{\rho_\mathrm{c}}{\epsilon_0}\exp\left(-\frac{q\varphi(r)}{k_\mathrm{b}T}\right)$$

Poisson-Boltzmann Model

Solutions in r

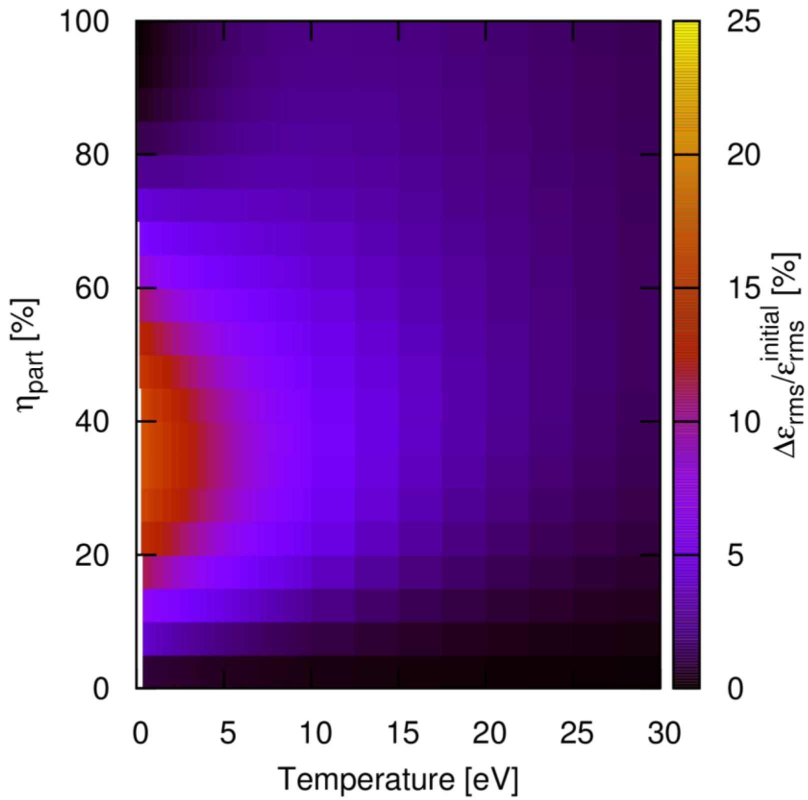
λ_d	0.25 mm	0.50 mm	1.00 mm	2.00 mm	3.00 mm	4.00 mm	5.00 mm
$T(n_0)$	0.5 eV	1.9 eV	7.5 eV	30.0 eV	67.5 eV	120.0 eV	187.4 eV



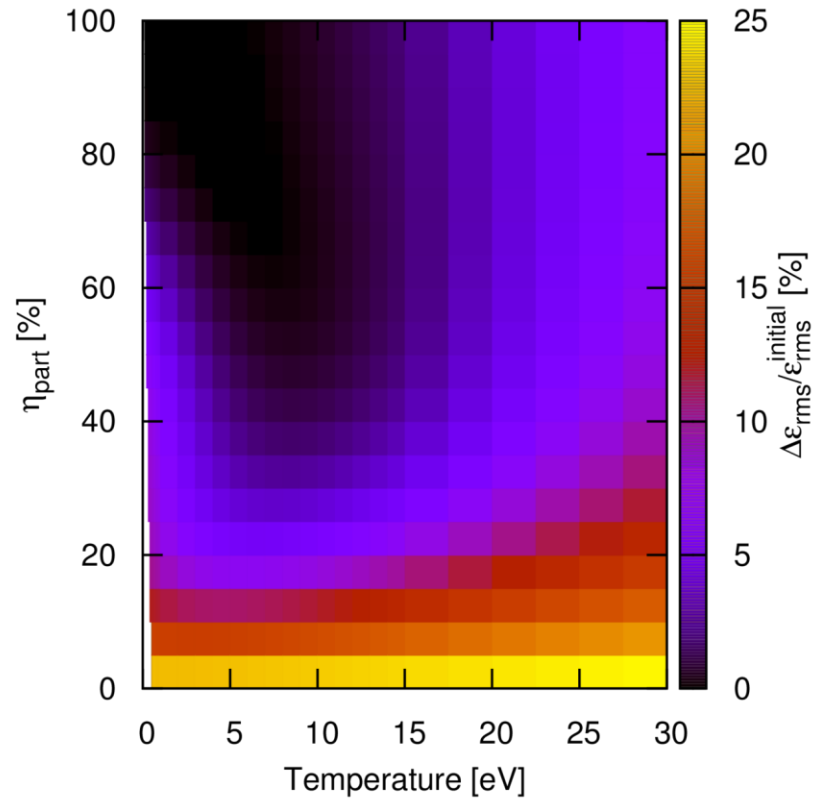
Poisson-Boltzmann Model

Emittance growth

KV distribution



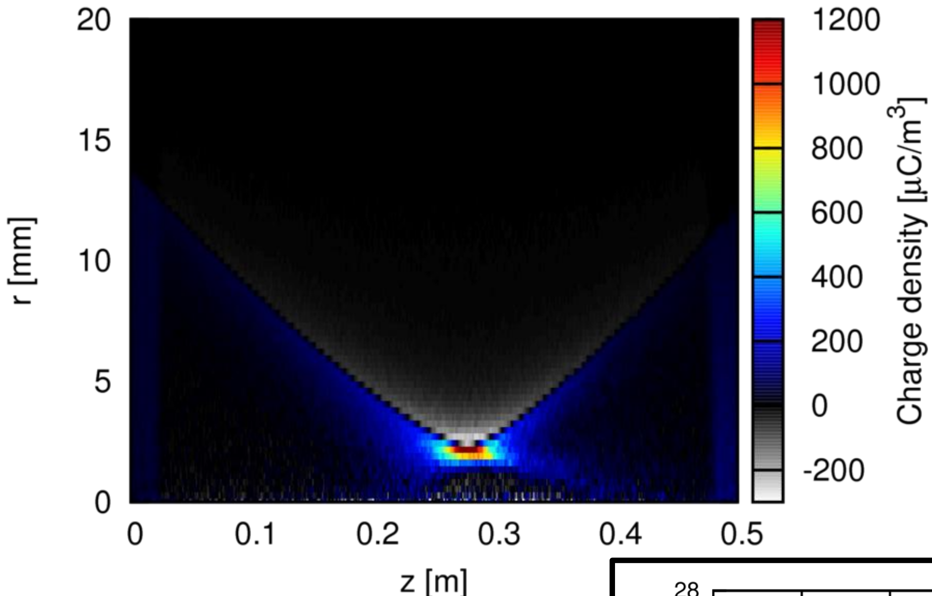
Gaussian distribution

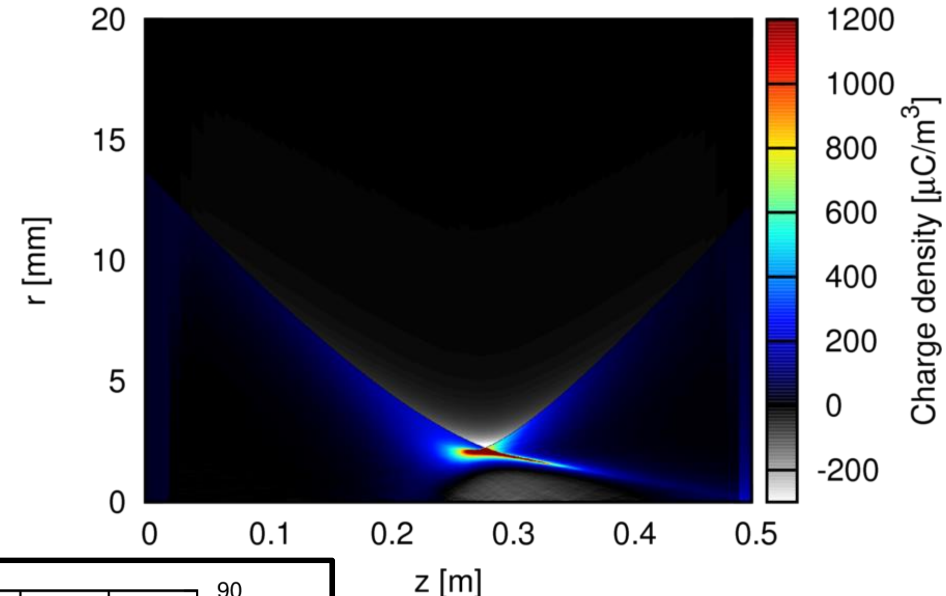


50 cm beam transport, 120 keV, 50 mA

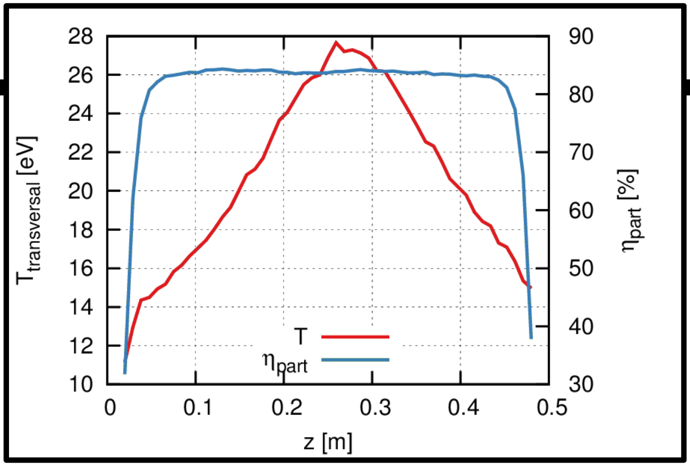
Results for the Drift System

Comparison to bender simulation

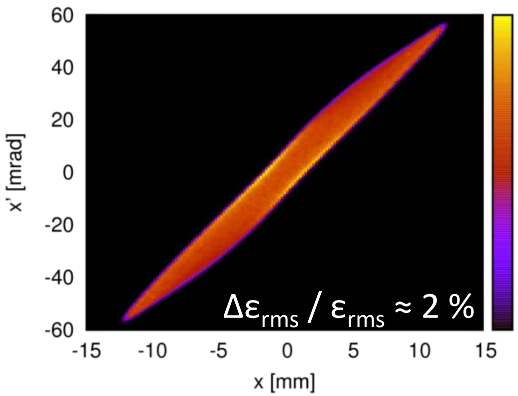


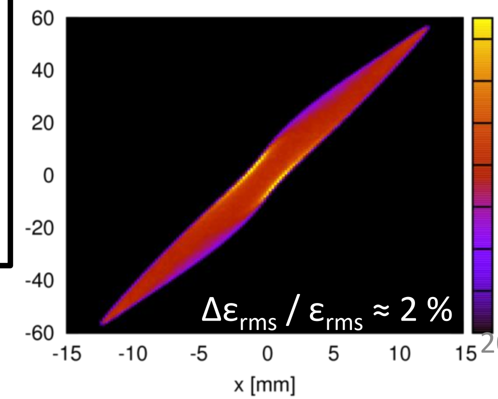


7 days, 24 cores



2 hours, 1 core

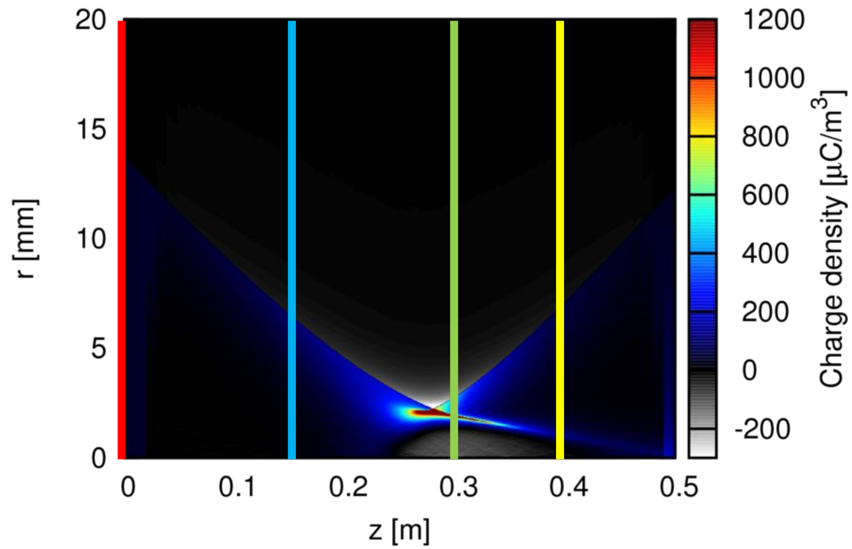


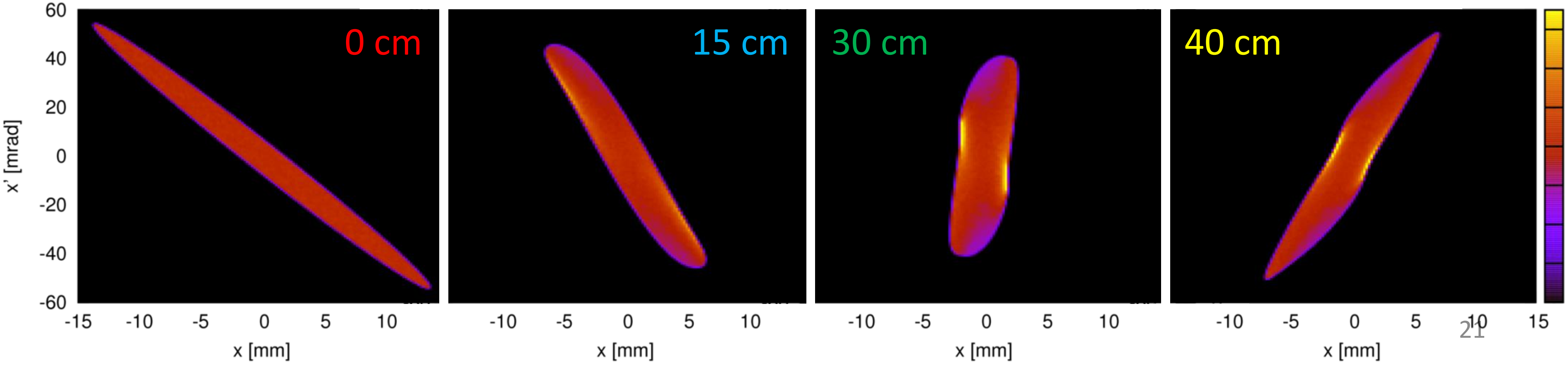


Results for the Drift System

Comparison to bender simulation

- Effects of the radial compensation particle distribution





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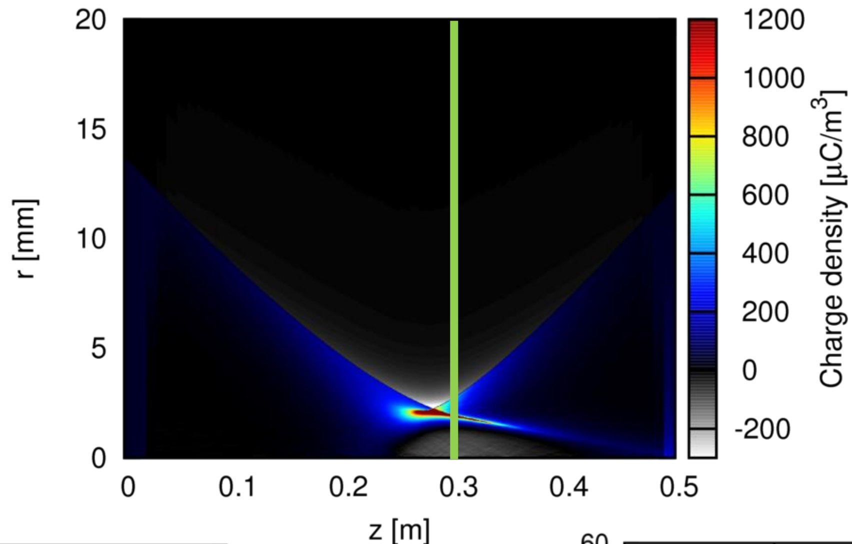
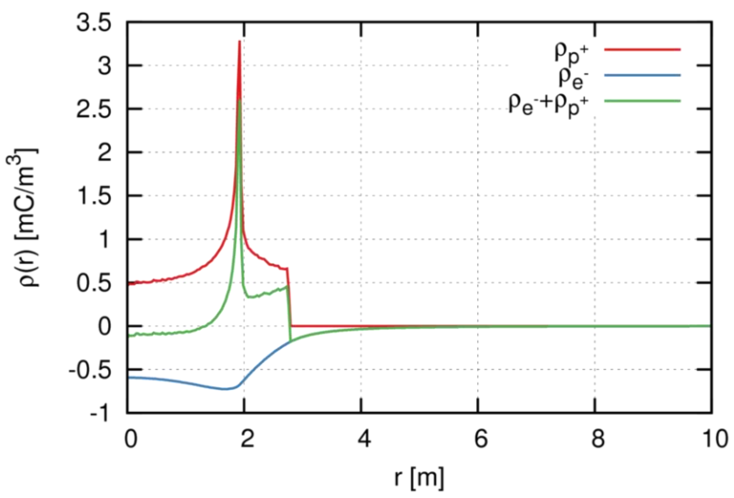
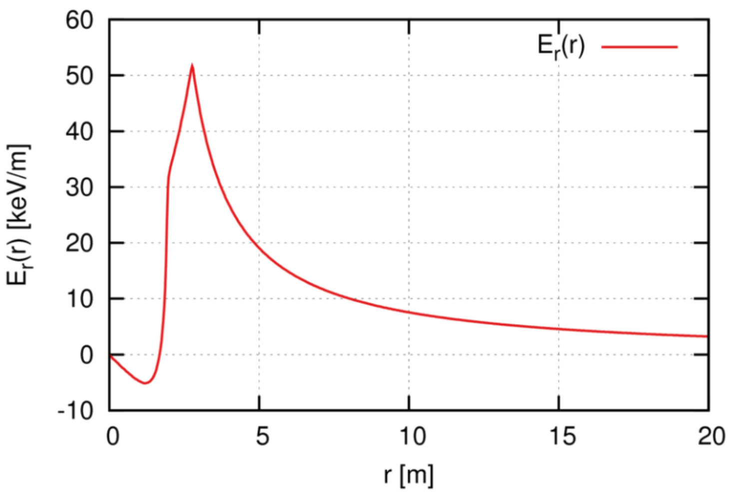


Charge density in r:



Electric field in r:



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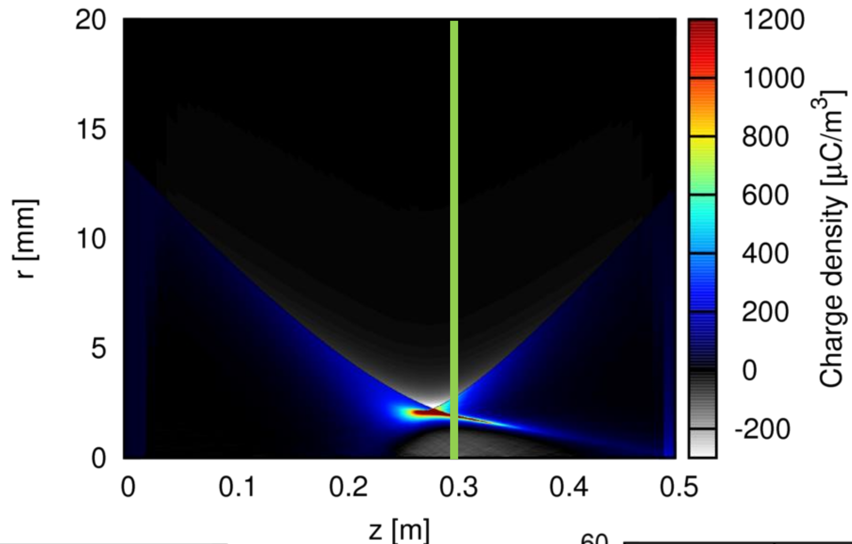
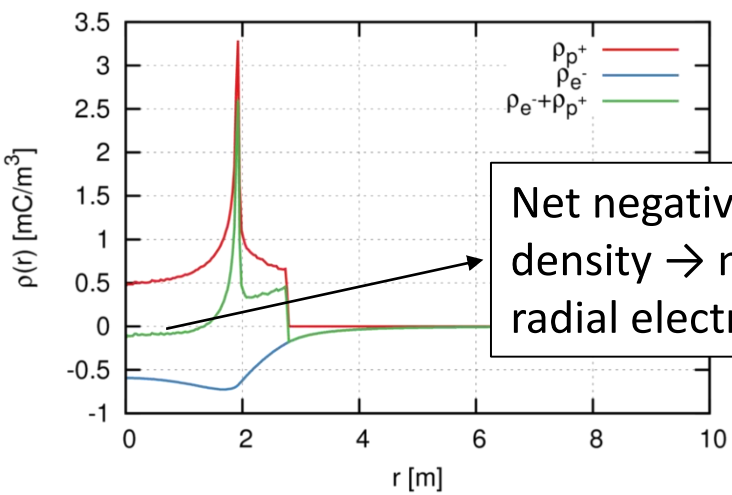
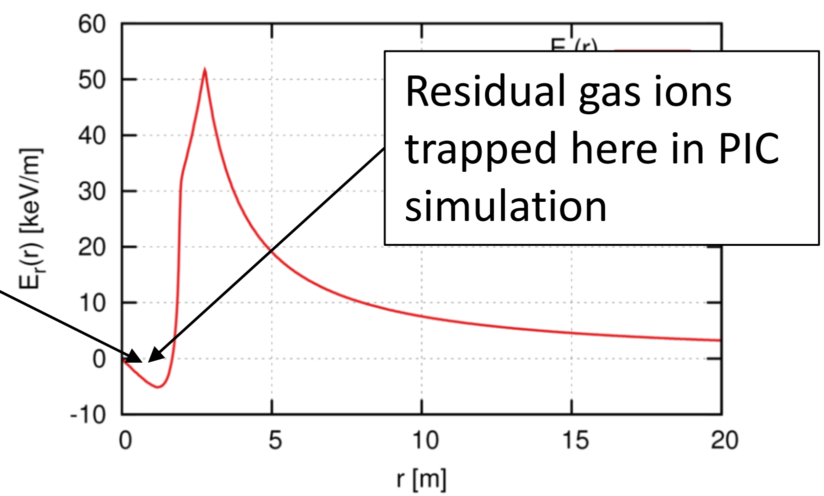


Charge density in r:



Net negative charge density → negative radial electric field

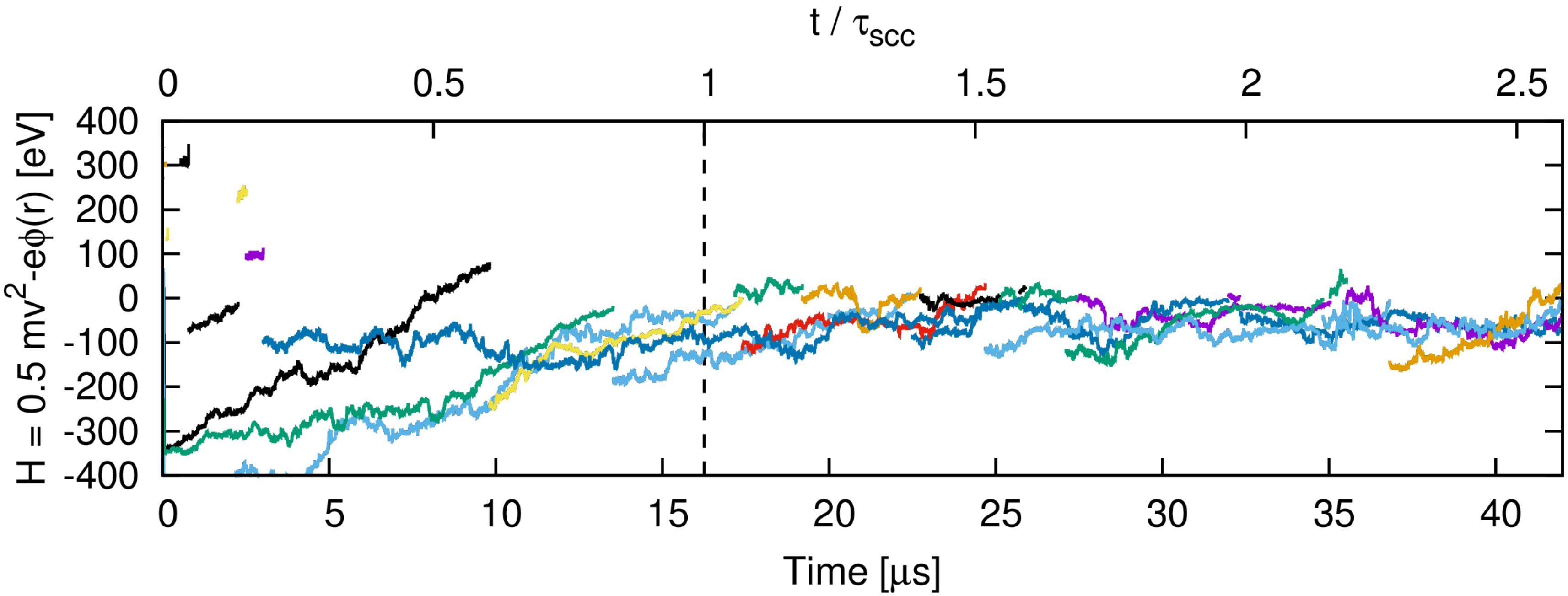
Electric field in r:



Residual gas ions trapped here in PIC simulation

Origin of the Thermalization

- Energy of random electron tracks over time:

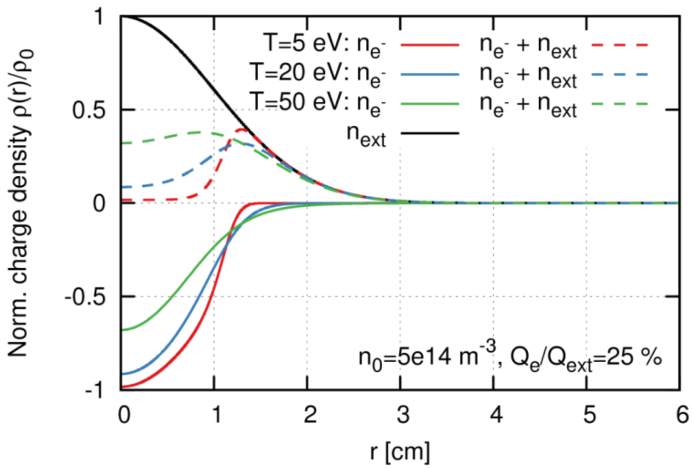


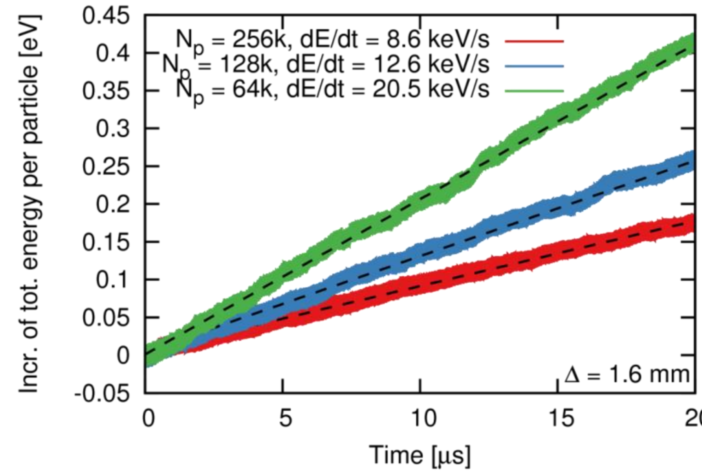
- Random walk until H > 0, then get gradually lost
- Is energy conserved in the simulation?

Origin of the Thermalization

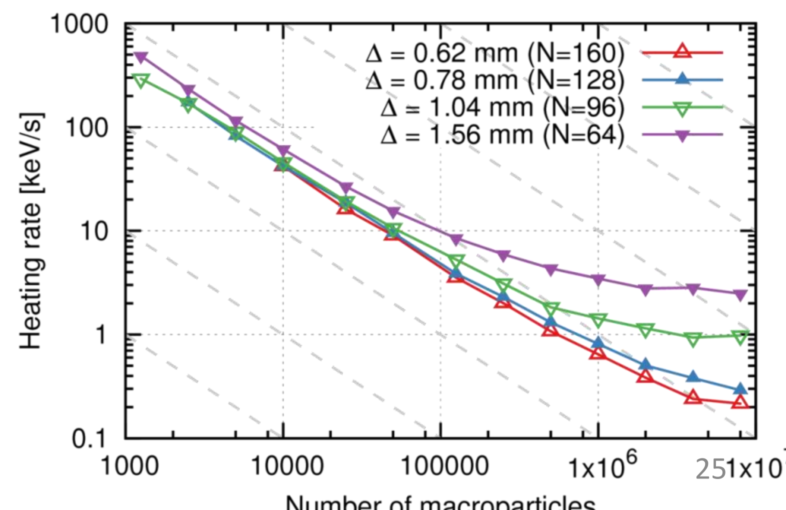
Stochastic heating in a test system

$f(\mathbf{r},\mathbf{p}) = f_0 \exp\left(-\frac{H}{k_\mathrm{b}T}\right)$ is a solution of $\underbrace{\frac{\partial f}{\partial t}}_{=0} + \frac{\mathbf{p}}{m}\frac{\partial f}{\partial q} + qE\frac{\partial f}{\partial p} = 0\,.$





- Stochastic heating [1]:
  - „Error" field with $\overline{\delta E} = 0, \overline{\delta E^2} \neq 0$
    $$\Delta T = T_{i+1} - T_i = \frac{1}{2}\frac{q^2}{m}\overline{\delta E^2}\Delta t^2$$
  - Effect from particle statistics:
    $$|\delta E| \backsim N^{-1/2}$$

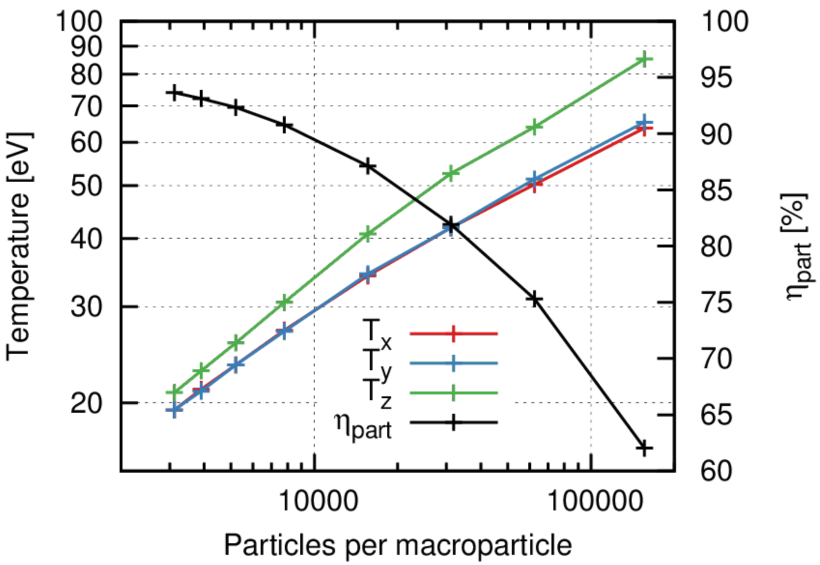


[1] Hockney, Eastwood – Computer Simulation Using Particles, 1989

Origin of the Thermalization

- Dependence on the number of simulation particles
- Temperatures linked to compensation degree
- Not responsible:
  - Secondary electron energy distribution
  - Coulomb collisions

Thermalization



Stochastic heating

↓

Equilibrium due to particle and therefore energy loss

↓

Gaussian distributions of compensation particles & $\eta < 100$ %

- Further indications:
  - 1d simulations show almost no „temperature“
  - Simulation with static beam show lower temperatures

Conclusion

- Space-charge compensation was included in a self-consistent way
  - Electrons follow a Boltzmann distribution
  - The dynamics are completely determined by the plasma nature of the compensation electrons
  - Thermalization is of numerical origin
- Before physical heating processes can be included

$$P_{\text{Heating}} \cong \frac{e^2}{4\pi\varepsilon_0^2 m_e} \frac{n_{\text{beam}} q_{\text{beam}}^2}{v_{\text{beam}}} \ln(\Lambda) \quad [1] \xrightarrow[\text{T=20 eV}]{} \approx 60 \text{ keV/s}$$

numerical effects need to be removed… how?

[1] R. Dölling, Raumladungskompensation driftender intensiver Strahlen niederenergetischer Ionen und Techniken zu ihrer Vermessung, Dissertation, Goethe Universität Frankfurt am Main 1994

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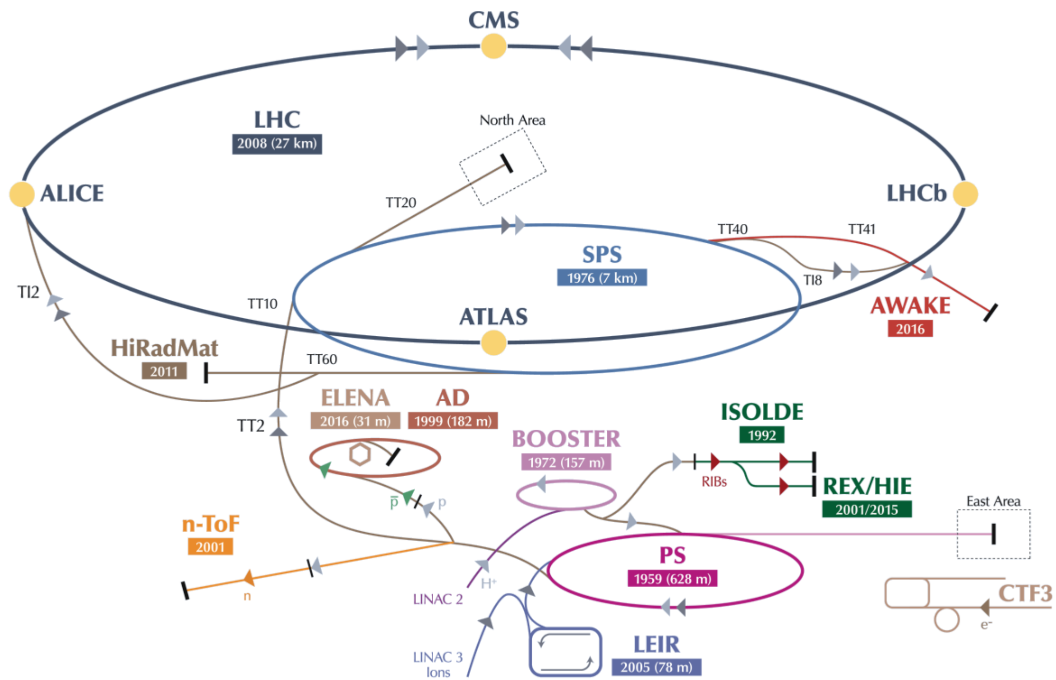
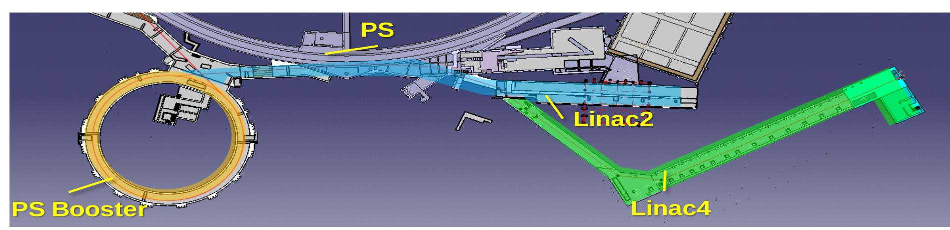
Linac4: A new injector for the CERN proton complex

LINAC2	LINAC4
Protons	H^-
160 mA	40 mA
50 MeV	160 MeV
1 π.mm.mrad	0.4 π.mm.mrad
100 µsec, 1 Hz	400 µsec, 1 Hz
Since 1978	All new components
No longitudinal matching at injection	Fast chopping at 3 MeV Energy painting





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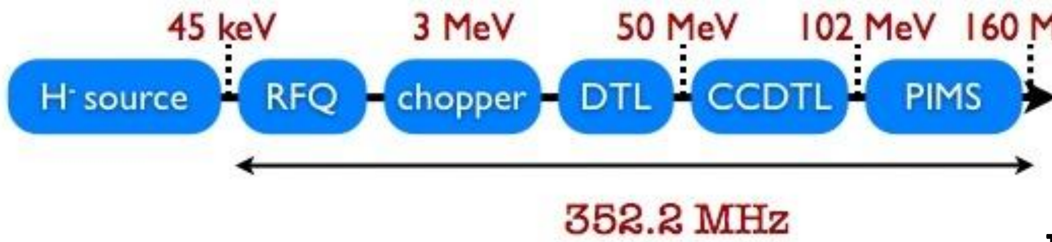
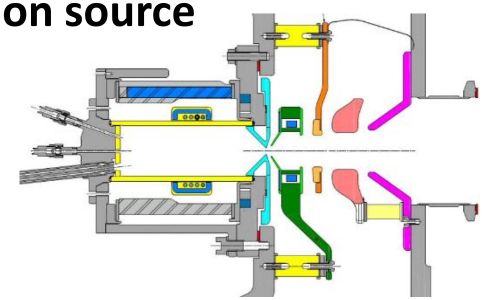


45 keV cesiated H- ion source



π-Mode Structures

12 tanks

Drift Tube Linac

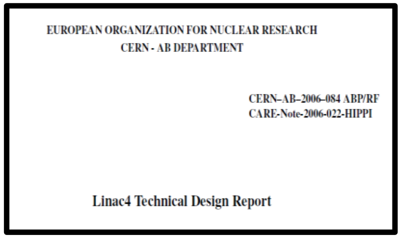
3 tanks

352.2 MHz 4-Vane RFQ

Cell-Coupled DTL

7 modules × 3 cavities

Linac4 from 2000's to 2020


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - AB DEPARTMENT

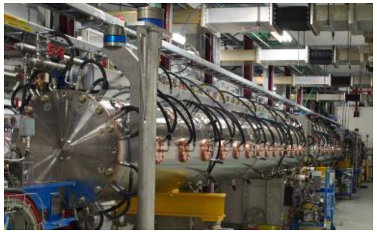
CERN-AB-2006-084 ABP/RF
CARE-Note-2006-022-HIPPI

Linac4 Technical Design Report

2006

2010

2013 – 3 MeV



2015 - 50 MeV

2016 - 160 MeV

Pre-studies → Construction → Installation / Beam commissioning

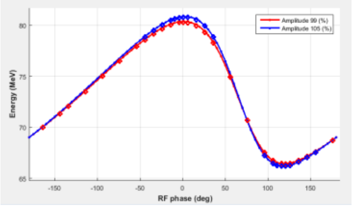
2008

Project approved

2012

2014 - 12 MeV

2016 - 107 MeV



Reliability run

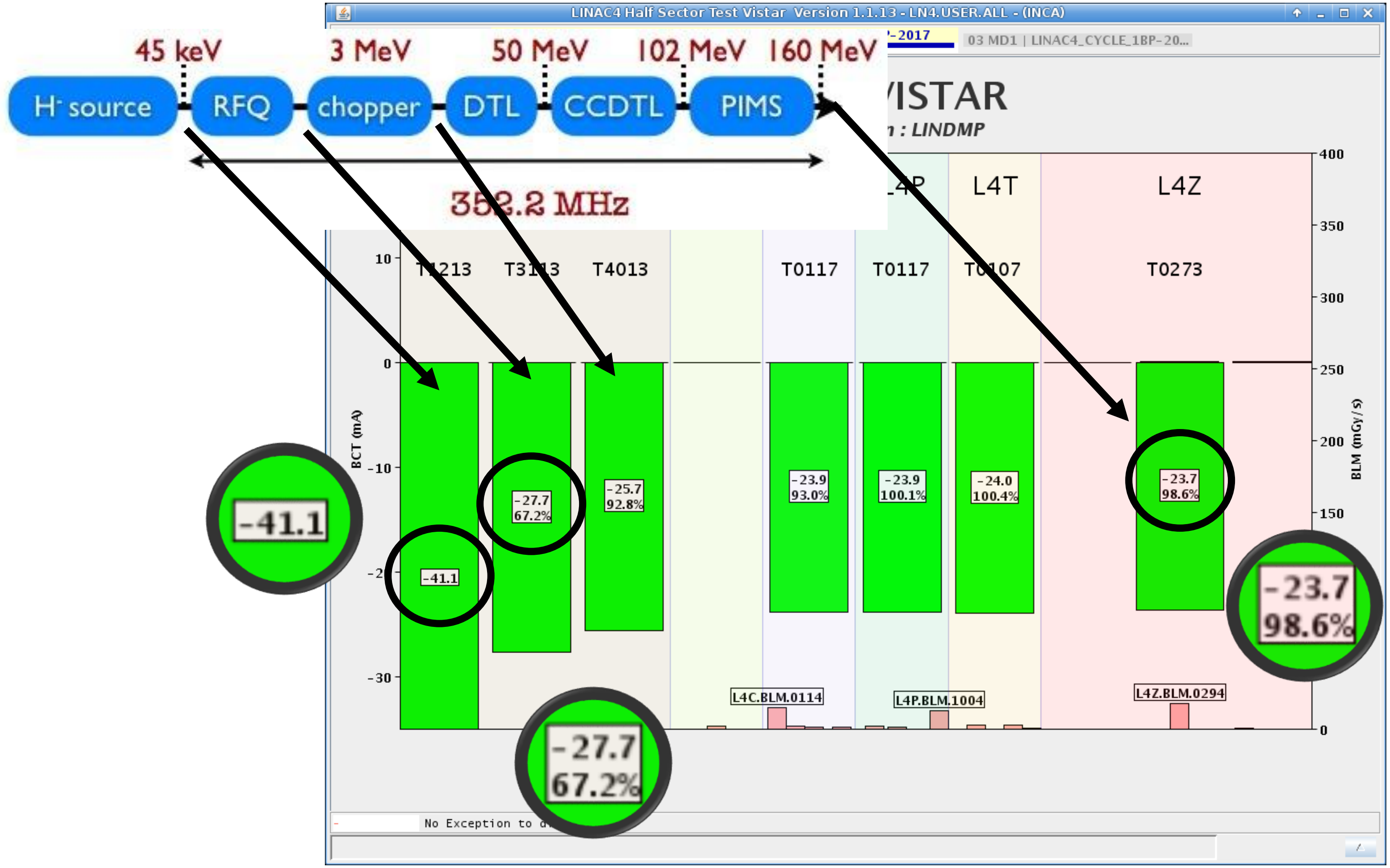
2017

2019

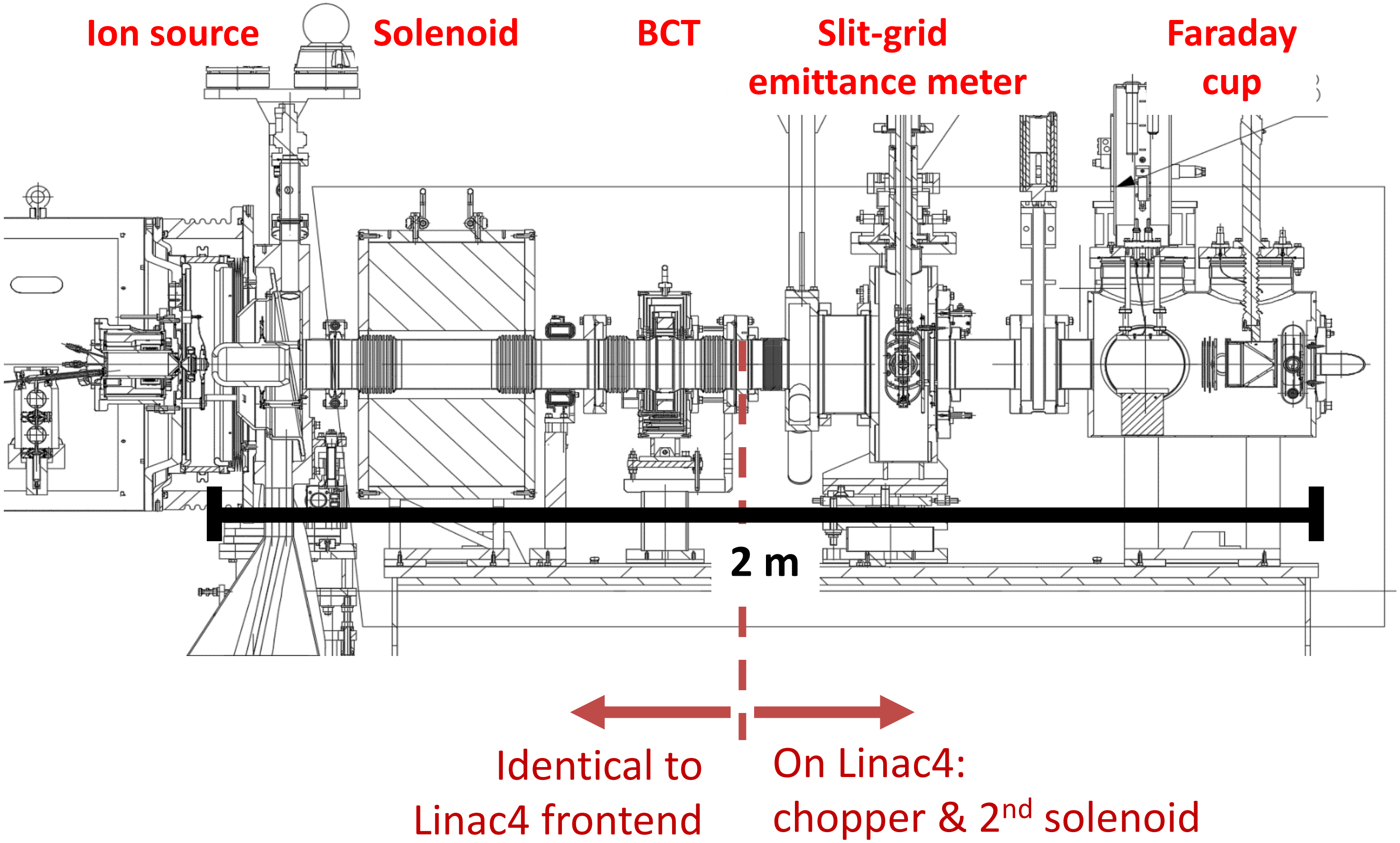
2020

Transfer line installation / Beam commissioning → Connection → Operation

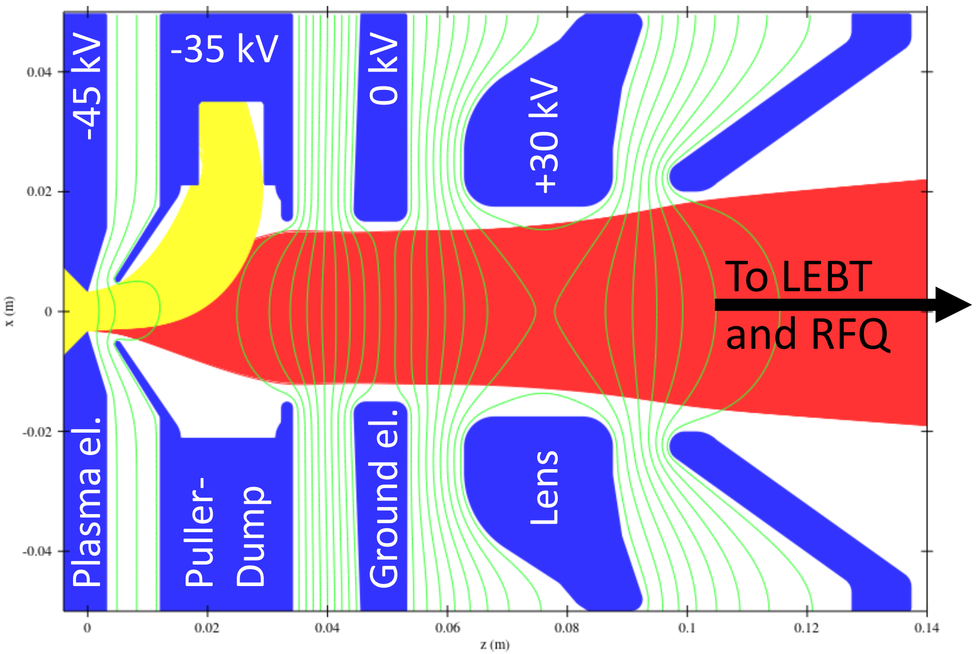
Intensity limitation in the frontend

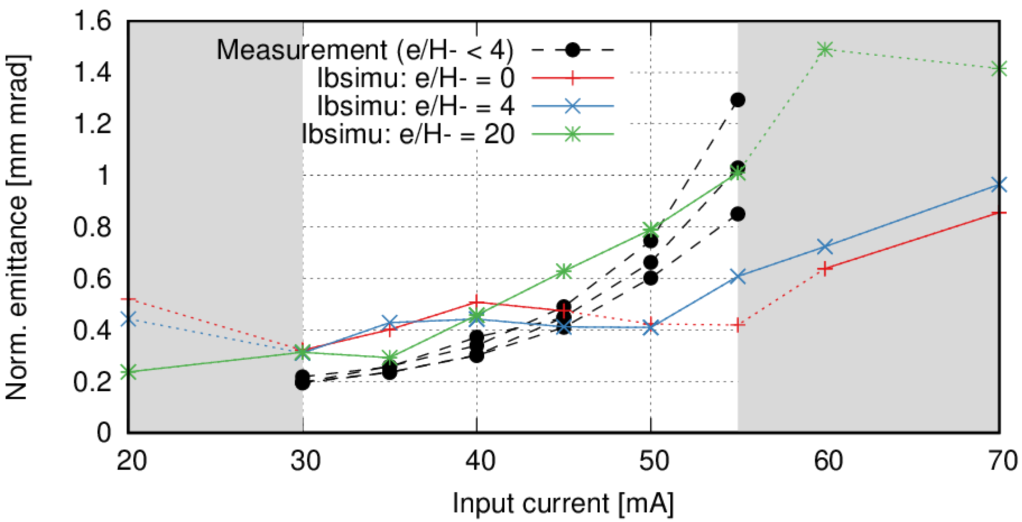


Linac4 ion source test stand



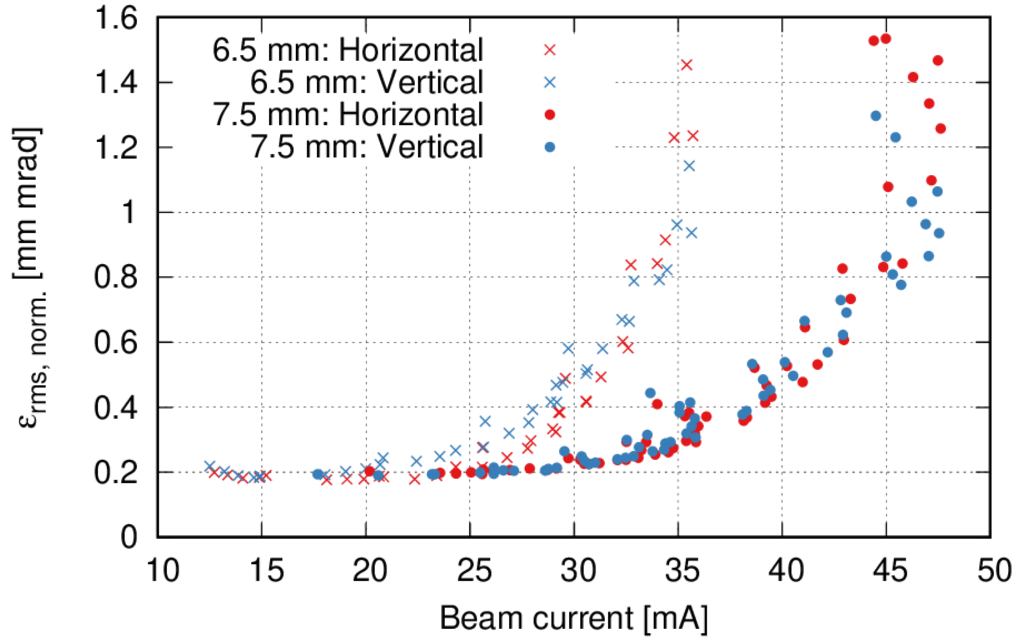
Ion source extraction studies





- Pentode extraction system with electron dump
- Simulation with ibsimu
- Artificially high electron to ion ratio used to match simulation and measurement
  - Determines position of plasma meniscus
  - Points to the end of puller-dump electrode as source of emittance growth

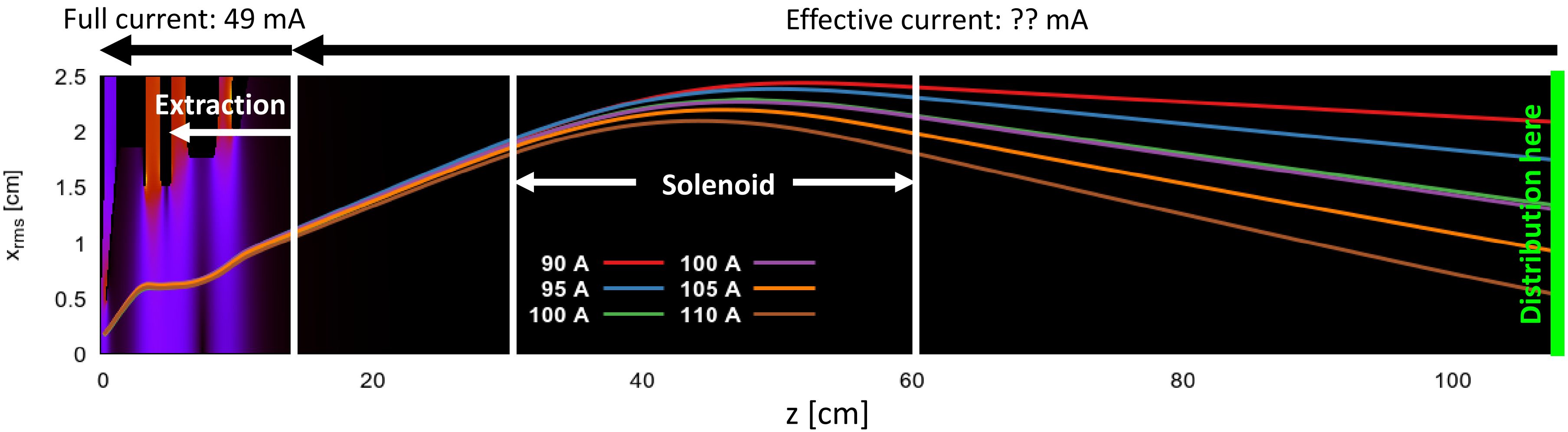
Ion source extraction studies



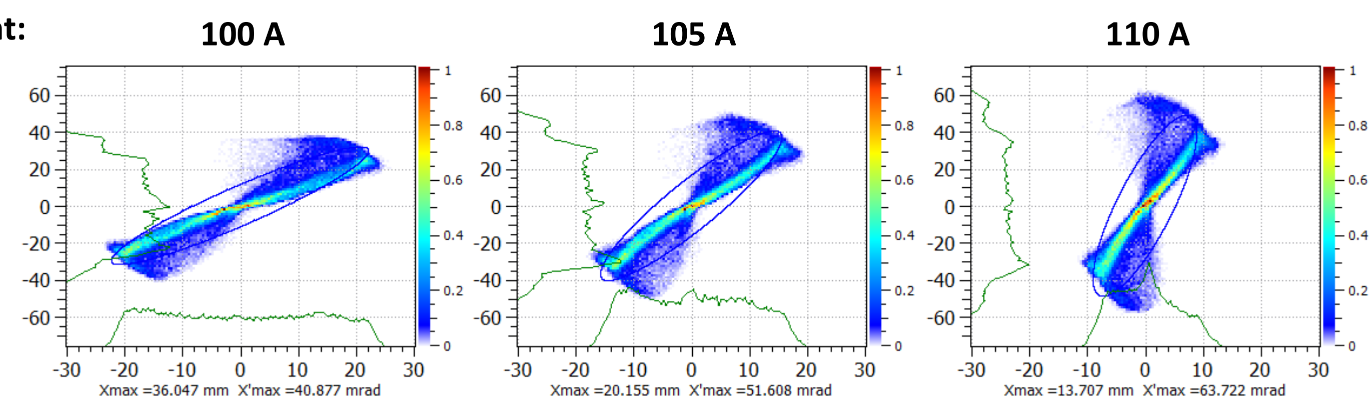
- Simulation predicted emittance improvement for
  - Increased bore diameter
  - Increase in plasma electrode angle
  - Increased extraction field
- Recent measurements in volume mode (without cesium) show improvements in similar range

Beam distributions from measurements

- Emittance measurement backtracked from meter position to extraction end
- Effective beam current is value that provides best match for a scan of the solenoid



Solenoid current:



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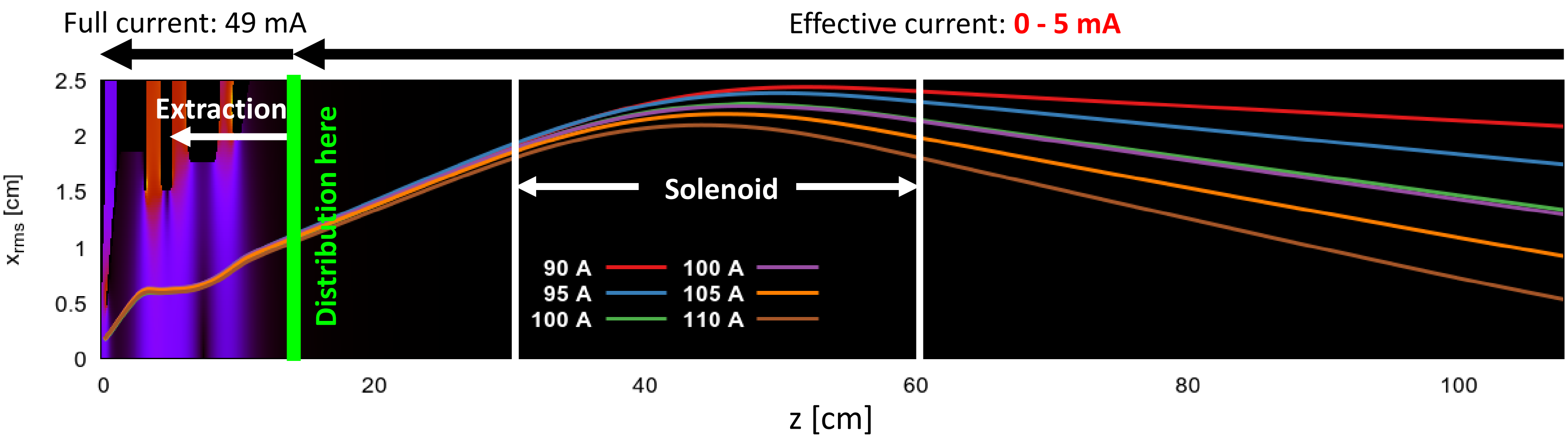
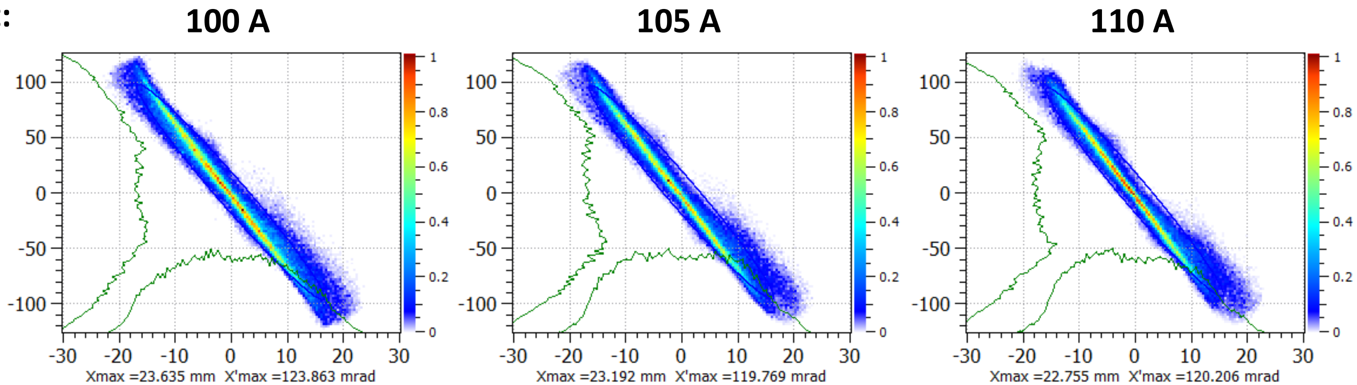


Solenoid current:



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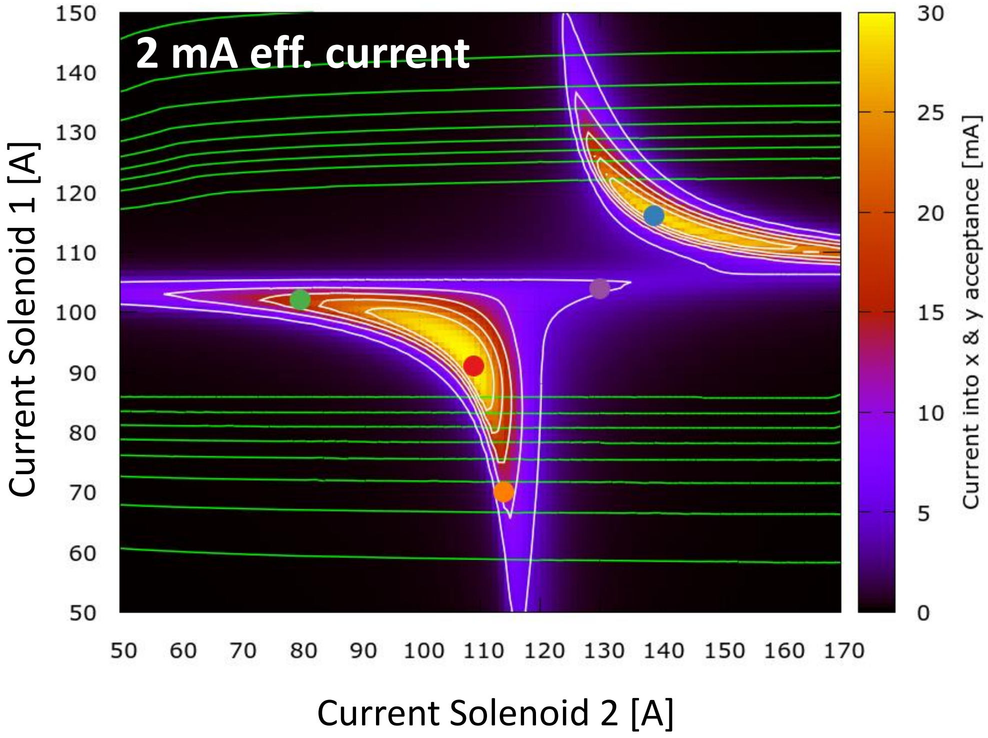
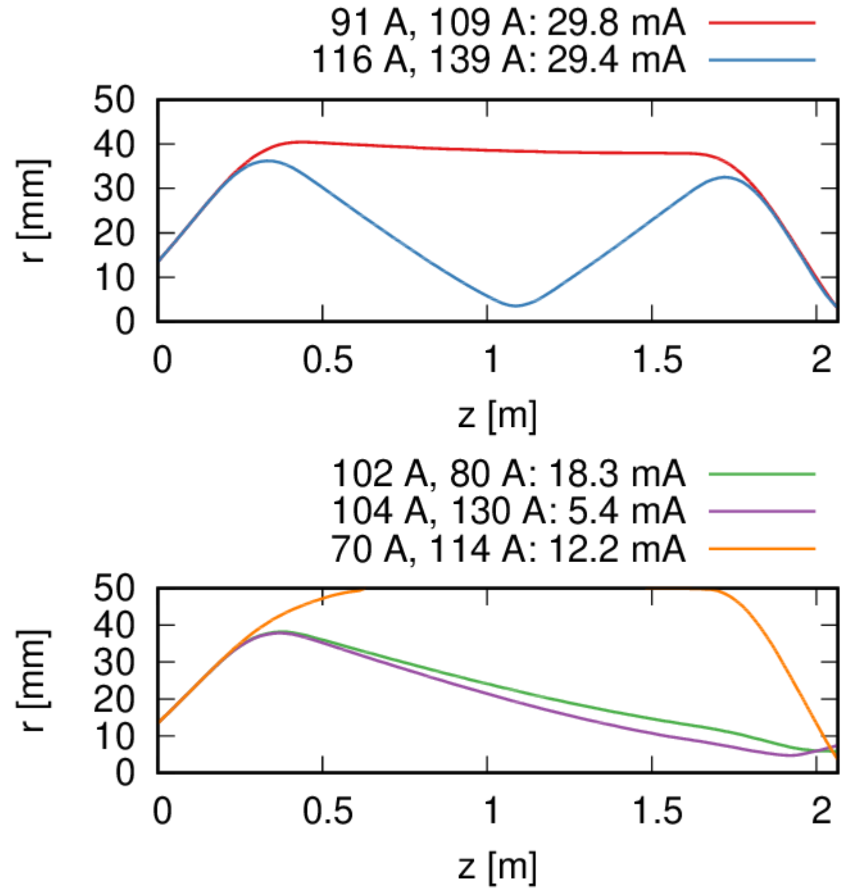
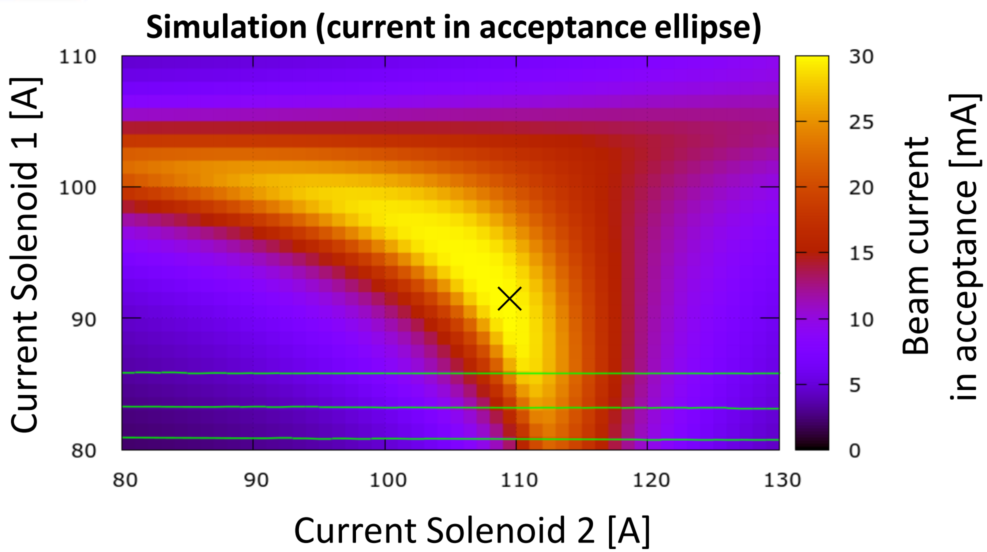
RFQ matching at Linac4

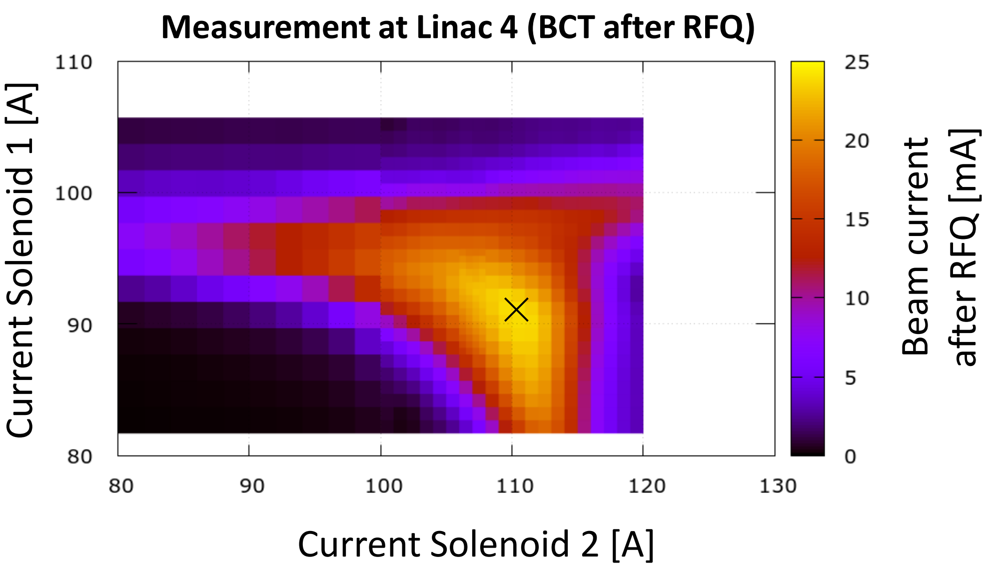
- Matching to the RFQ with determined effective space charge current
- Two possible settings: "normal" and with beam cross over





RFQ matching at Linac4

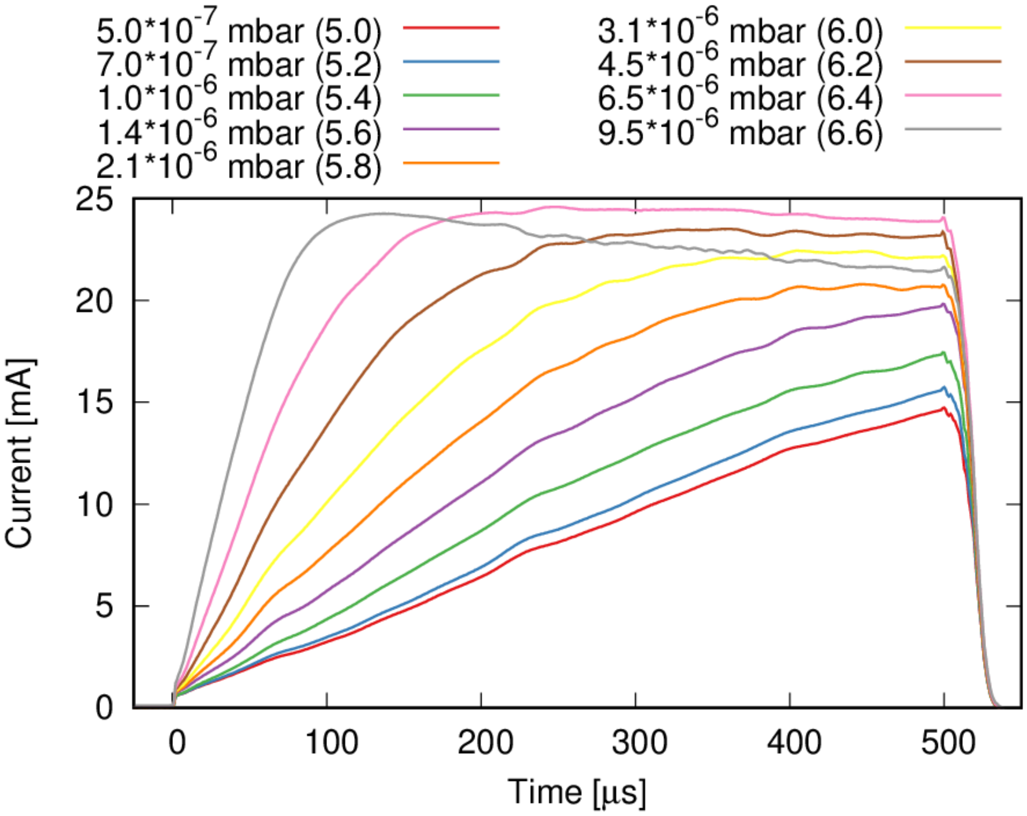




- Optimum from simulation:
  91.0 A, 109 A / 29.8 mA
  measurement:
  91.7 A, 110 A / 24.7 mA
- Measurement also contains effect of steering
- Required optimization of amount of gas injected into the LEBT

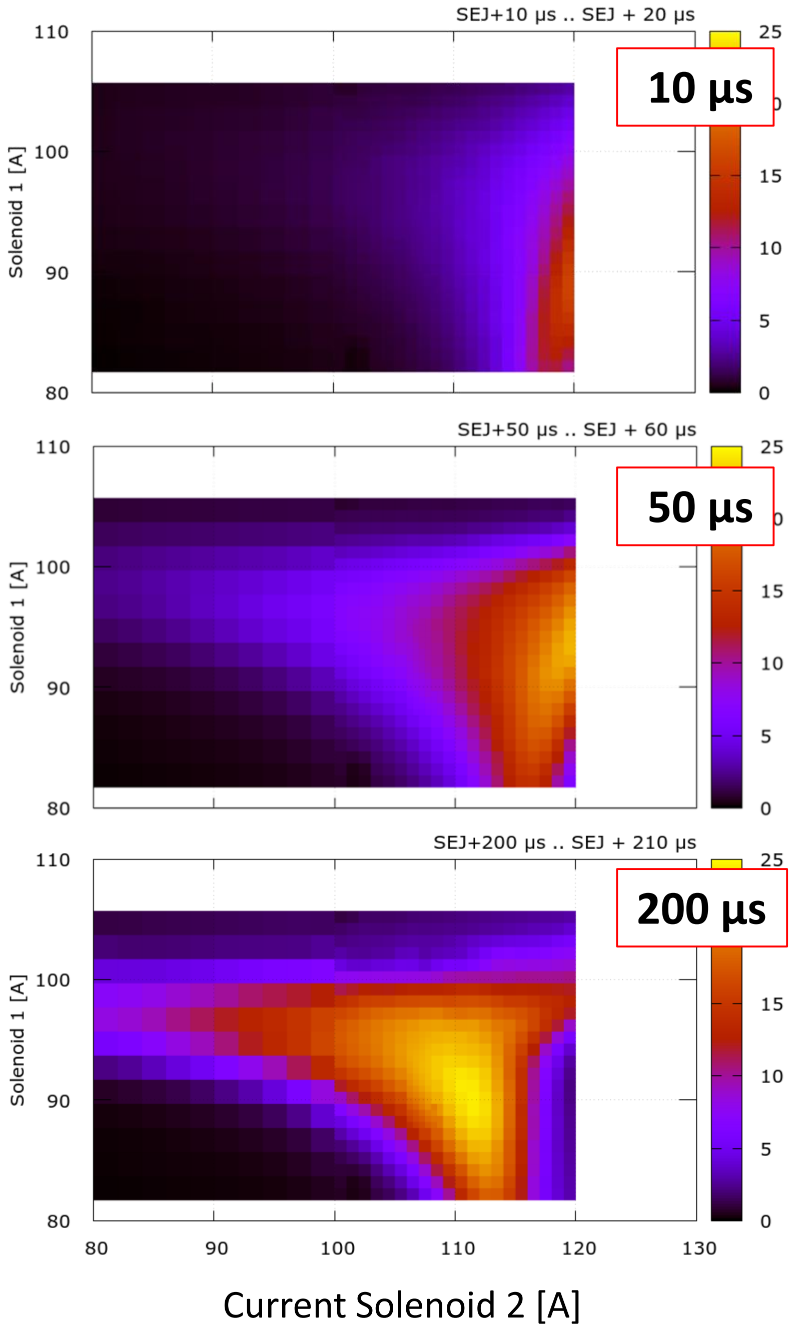
RFQ matching at Linac4

Beam pulse after the RFQ for various LEBT gas pressures

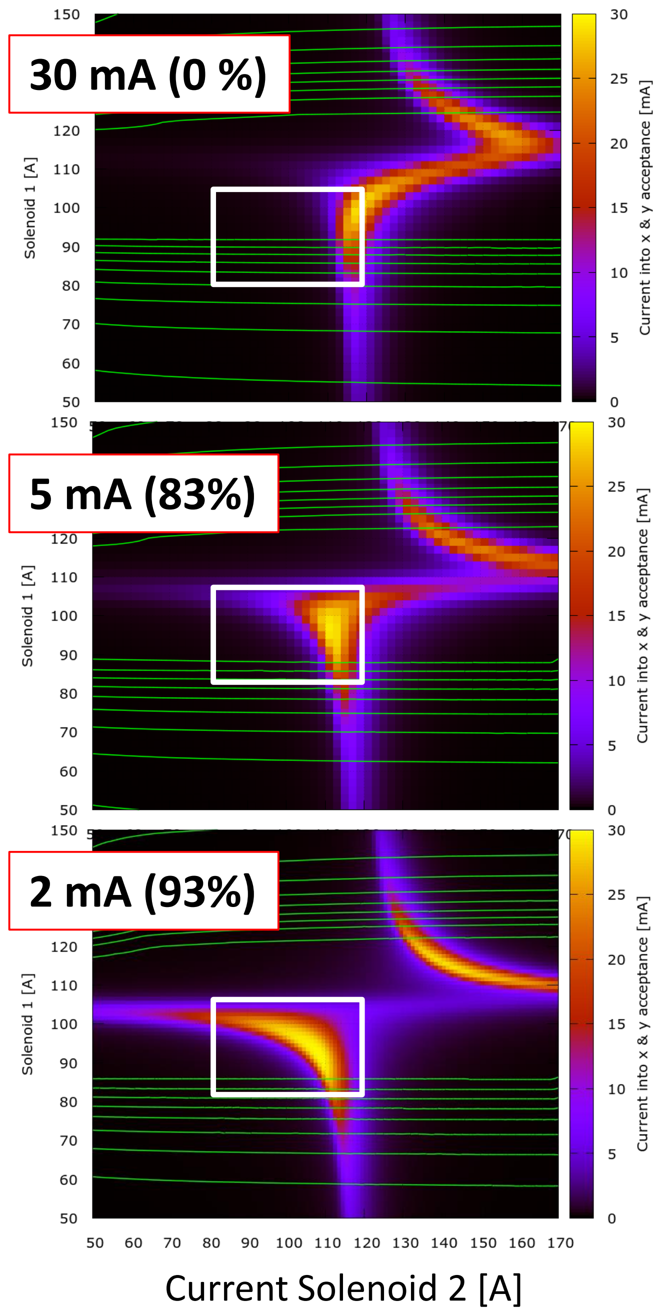


- Optimized for maximum transmission at the end of the pulse
- Estimated space charge compensation time at p=6.5 10^{-6} mbar: 200 µs
- Compensation rise time to be chopped in MEBT
- Decrease of transmission during the pulse at highest measured pressure: overcompensation?

Measurement after RFQ



Simulation with eff. current



Summary

- Linac4 is commissioned and currently tested for reliability
- Pre-injector studies ongoing on the Linac4 test stand
- Matching simulation to measurements made it possible to
  - Predict Linac4 pre-injector performance from measurements at the test stand
  - Find limitations of the present ion source extraction and predict improvements for changed geometries
  - Understand the influence of the compensation build-up on the pulse shape after the RFQ

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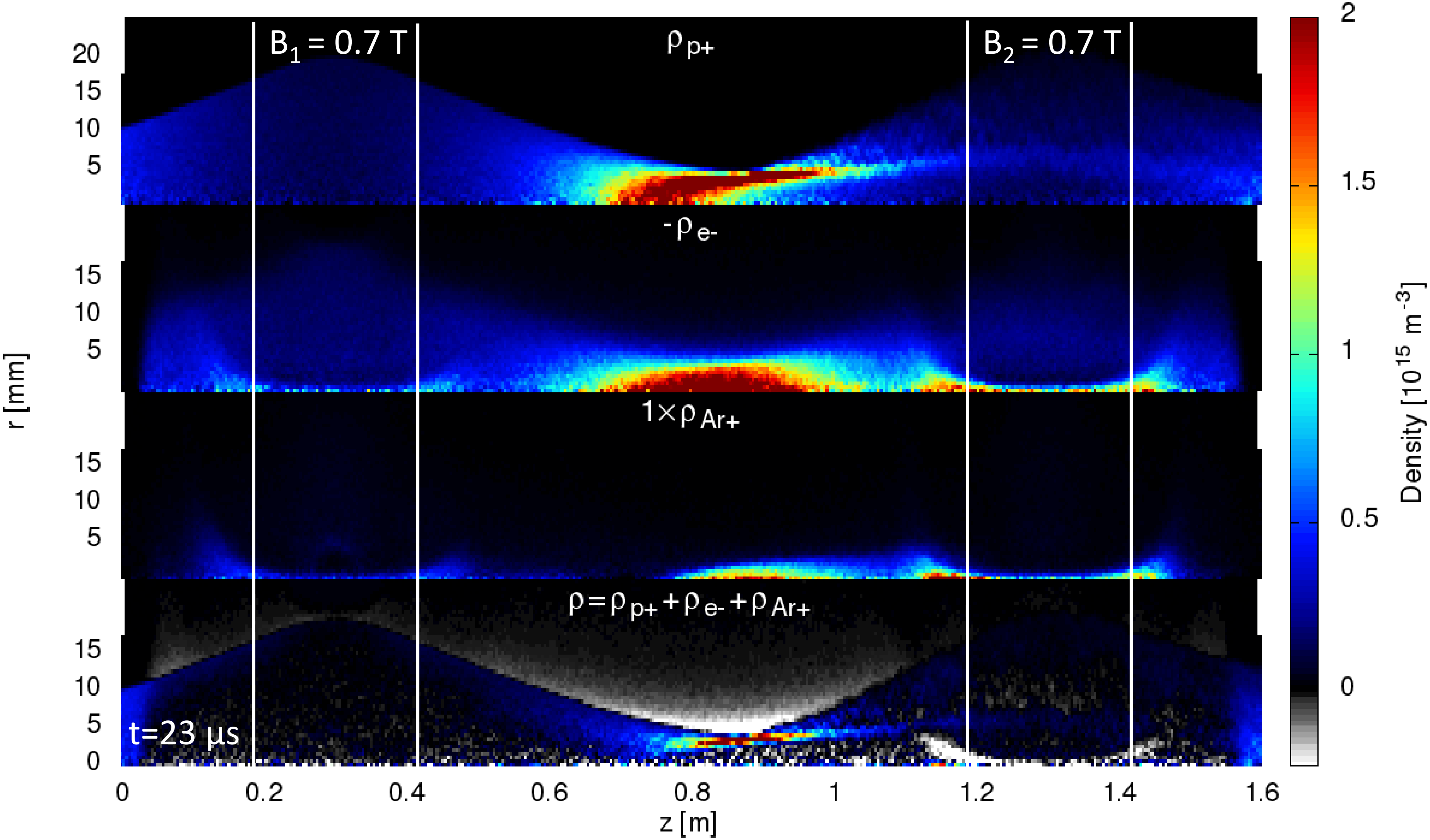
Thank you for your attention!

SCC studies: two solenoid LEBT

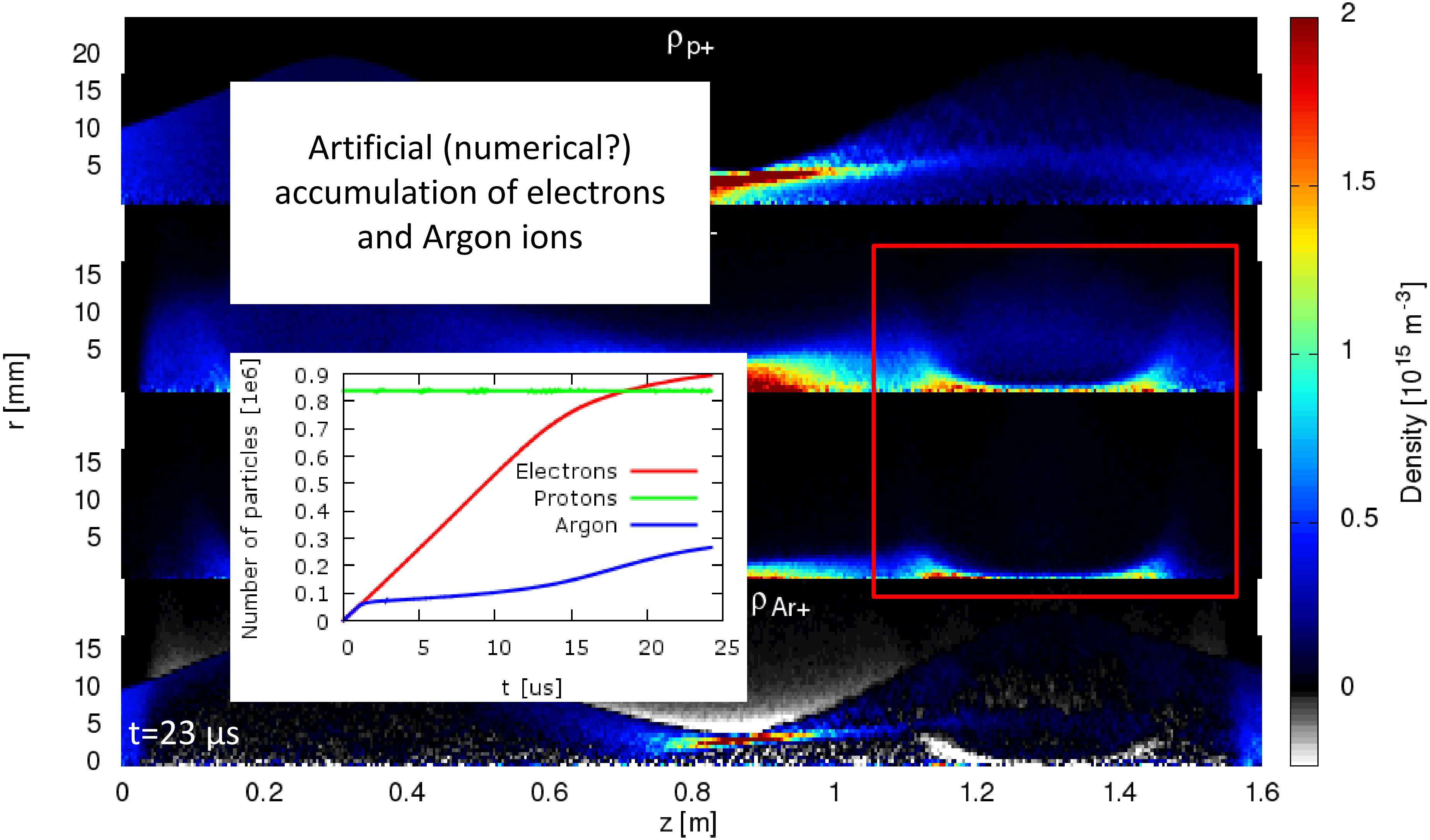
Spatial distribution



SCC studies: two solenoid LEBT

Spatial distribution

Artificial (numerical?) accumulation of electrons and Argon ions



SCC studies: two solenoid LEBT

Spatial distribution