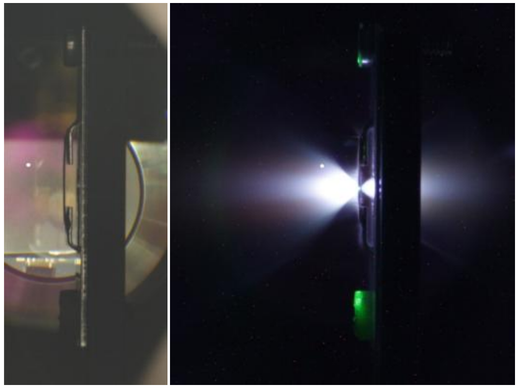
Capture laser-accelerated proton beams: Experiment and Simulations

TECHNISCHE UNIVERSITÄT DARMSTADT

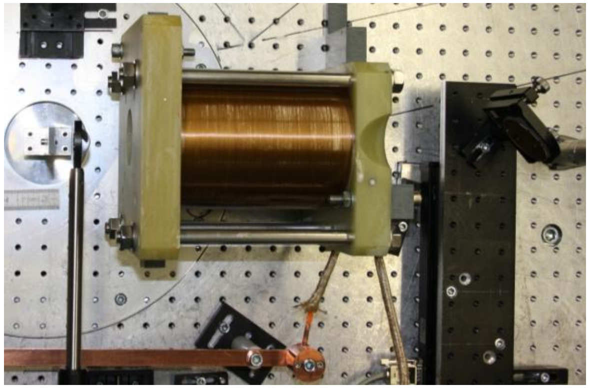
Frank Nürnberg

Knut Harres, Simon Busold, Oliver Deppert, Prof. Markus Roth .... *TUD*
Trevor Burris, Tom Cowan .... FZD
Dave P. Grote, Alex Friedman, B. Grant Logan .... LBNL/LLNL



Phelix laser
GSI

Au 26 µm,
72 J @ 500 fs

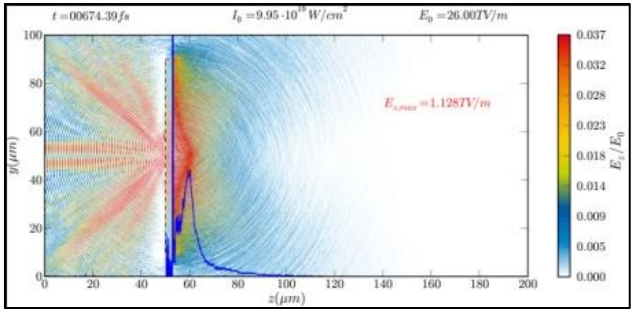


Pulsed solenoid
FZR

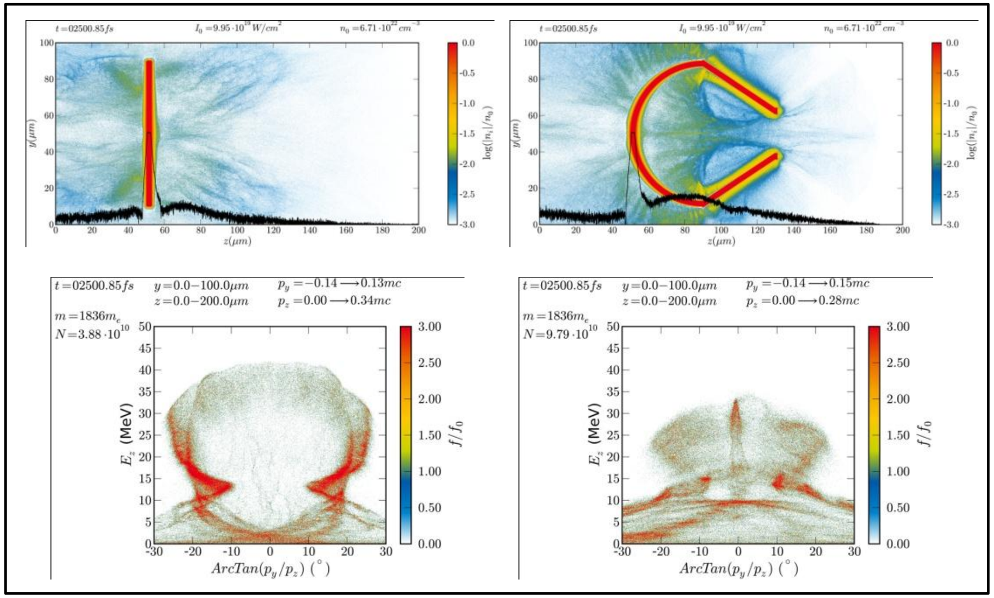
12 kV, 9.32 kA
7,51 T

Plasma Simulation Code

- **General understanding** of ion acceleration mechanisms
- **Studies** of different absorption mechanisms: Vacuum-Heating vs. ponderomotive acceleration, impact on electron and ion spectrum
- **Complex target** geometries: divergence reduction



- **Why PSC:**
  - of of the most efficient and powerful PIC codes
  - Fortran90, MPI (up to 360 CPUs)
  - Open source, collaboration with H. Ruhl
  - source code well documented and commented, easy implementation of self-developed modules
  - Monte-Carlo collisions module implemented
  - empiric models for field and collision ionisation implemented



- **alternative:**
  - EPOCH openSource PIC Project: http://ccpforge.cse.rl.ac.uk/projects/epoch/
  - Promissing futher developement of PSC
- **ToDo:**
  - Output of PSC as input for Warp transport simulations

Warp suite of simulation codes

- Developed to study **high current ion beams** (heavy-ion driven ICF).
- High current beams necessary for a driver
  → **space-charge forces** dominate over thermal forces (and mag. self-fields at low v).
  → analysis of beam dynamics needs to include the **electrostatic self-fields** of the beam.
- Warp combines the **PIC** technique (Lorentz equation of motion to advance macro-particles (simulation particles) in time) with a description of the accelerator "**lattice**" of elements. The effects of the **space-charge** is included by a global solution of **Poisson's equation**, giving the electrostatic potential, at each timestep.

Each time step goes through the following pattern:

1.) **Charge** of macro-particles is deposited onto **mesh**.

2.) **Charge density** is calculated via trilinear interpolation of **macro-particles** onto **mesh**.

3.) Electrostatic potential is calculated from charge density by solving **Poisson**'s equation.

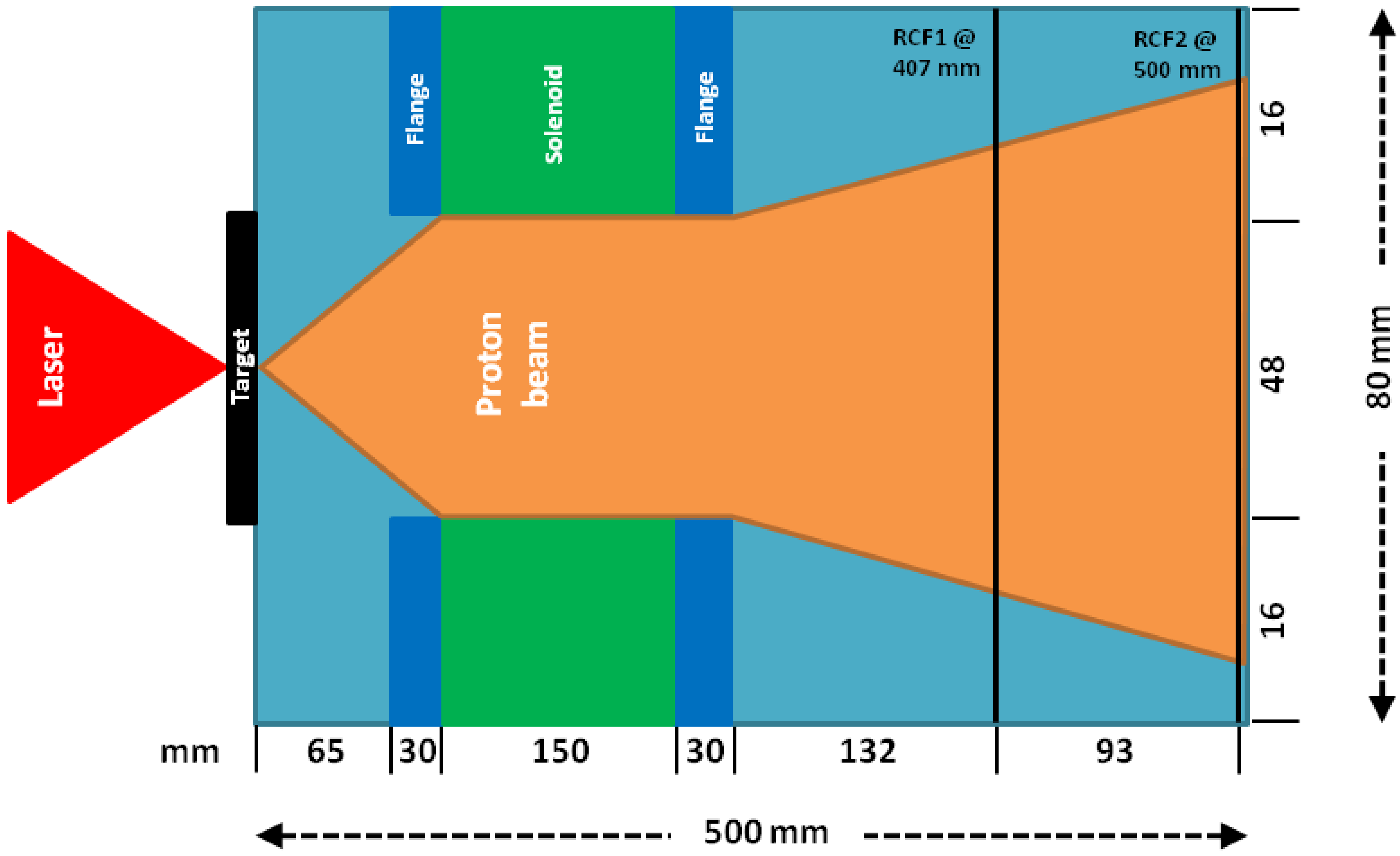
4.) **Electric fields** are interpolated from mesh to macro-particles.

5.) **Velocities and positions** of macro-particles are advanced.

- Macro-particles are advanced in time using a combination of the "**leap frog**" and "**isochronous leap frog**" methods.

Setup: experiment and simulation

TECHNISCHE UNIVERSITÄT DARMSTADT



RCF imaging spectroscopy

F. Nürnberg *et al.*, Rev. Sci. Instrum. **80**, 033301 (2009)

TECHNISCHE UNIVERSITÄT DARMSTADT

- Source size
- Envelope divergence
- Transverse emittance
- spectrum

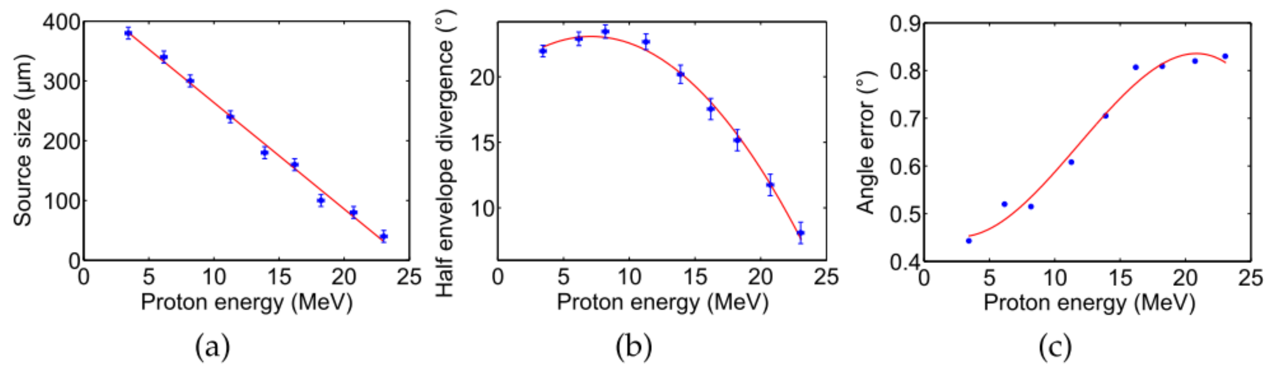
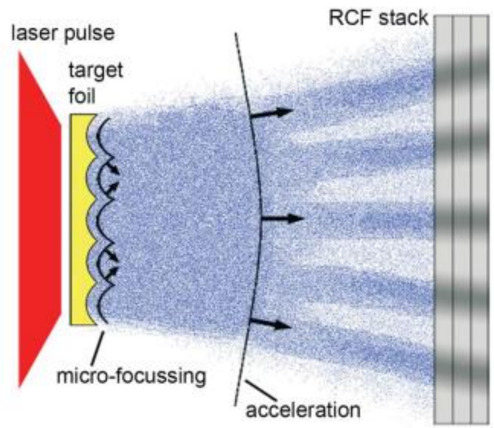
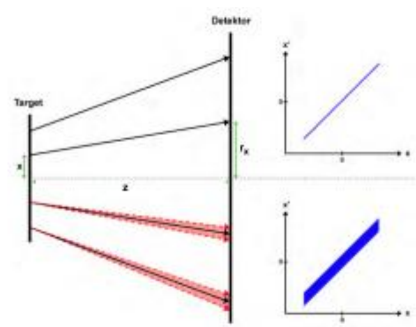
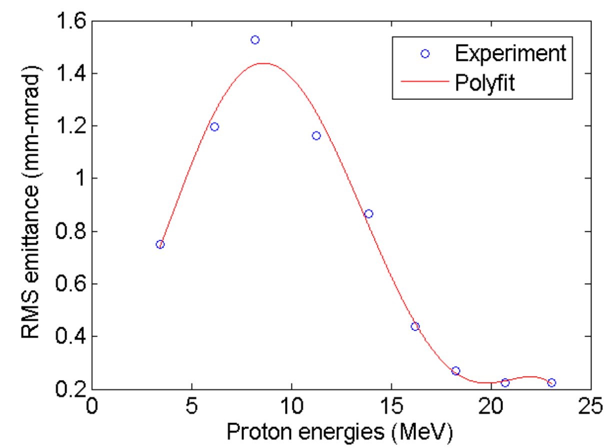


Figure 3: Proton beam parameters of the Phelix shot 18 for the Warp particle loader: experimental data (•) and polynomial fits (—) of the source size (a), the envelope divergence (b) and the angle error for the transverse beam emittance (c).







Electrons & Solenoidal magnetic field

TECHNISCHE UNIVERSITÄT DARMSTADT

Co-moving electrons:

- $v_p = v_e$
- $[3.42\ \text{MeV}, 23.04\ \text{MeV}]_p \rightarrow [1.87\ \text{keV}, 12.54\ \text{keV}]_e$
- same beam parameters as protons, but different inital x/y-positions to avoid same emission point

Quasi-neutral beam expansion

P. Mora, „Plasma expansion into vacuum“, Phys. Rev. Lett. 90, 185002 (2003)

→ no cold electron background

→ no hot electrons

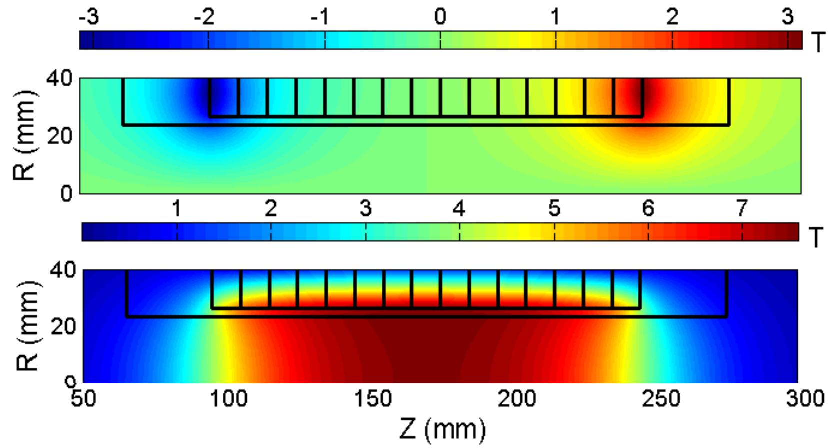
→ absorbing boundary condition at z=0

Solenoidal magneticfield

$B_{0,max} = 7.51\ \text{T}$ - $B_{r,max} = \pm 3.11\ \text{T}$

B field at target position:

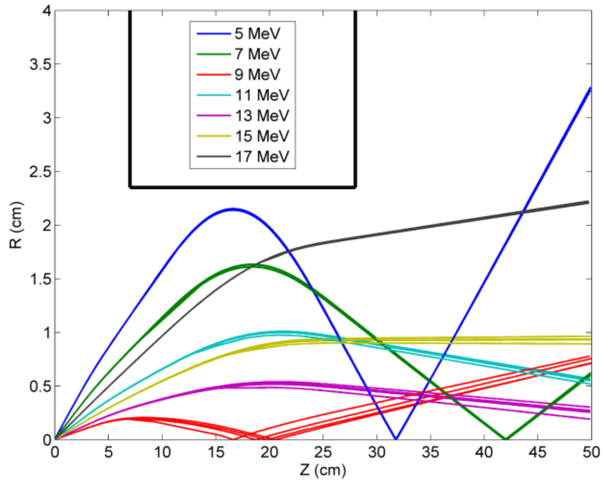
$B_{z,max} = 105\ \text{mT}$ - $B_{r,max} = 0.25\ \text{mT}$



Plasma and simulation criteria

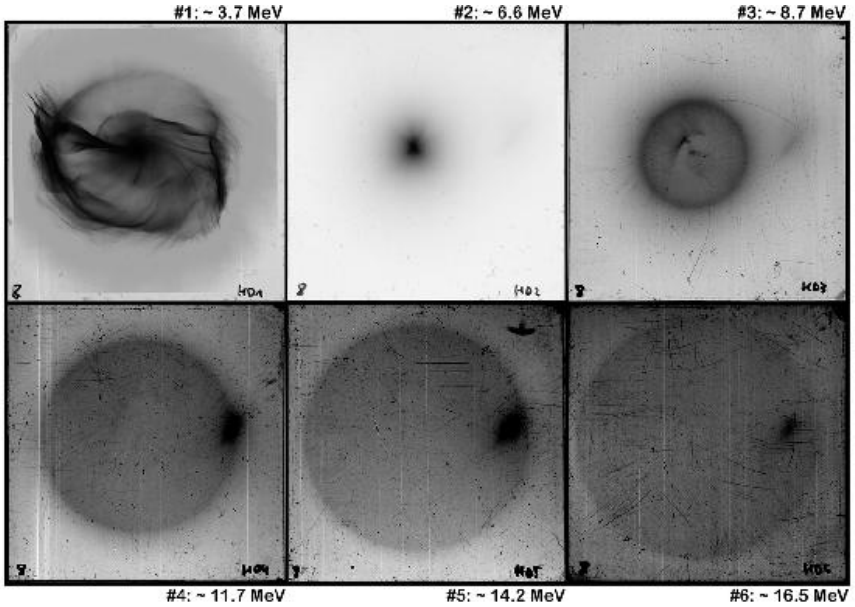
TECHNISCHE UNIVERSITÄT DARMSTADT

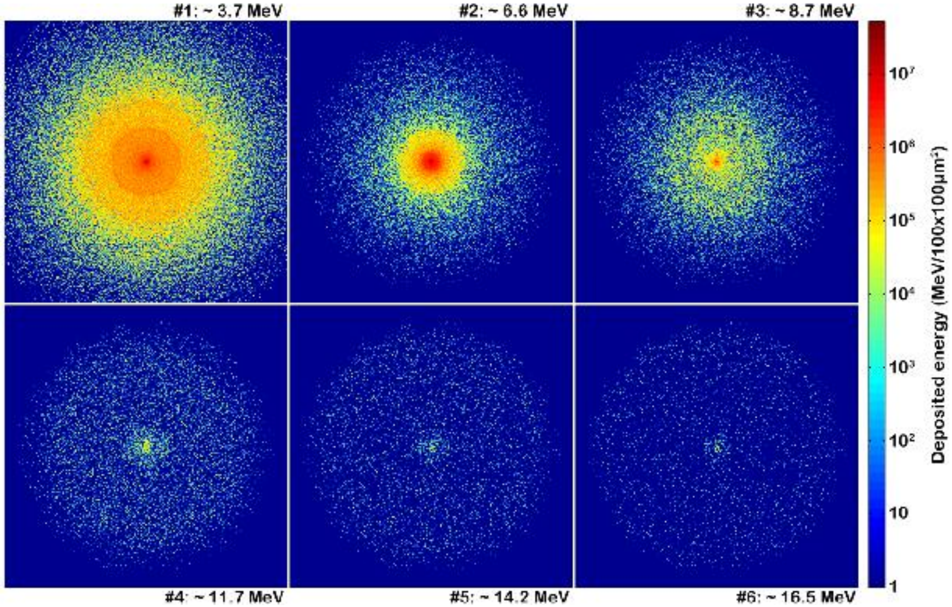
- Resolving **plasma frequency**: $\omega_p \cdot \Delta t < 1$
  → Volume source because of n_e
  → Δt = 75 fs (680 steps = 51 ps), Δt = 1 ps (21000 steps)
- **Courant criterion**:
  → Δt = 75 fs: $\Delta s(E_{p,max})$ = 5 µm, $\Delta s(E_e$=300 keV) = 17 µm
  → Δt = 1 ps: $\Delta s(E_{p,max})$ = 65 µm , $\Delta s(E_e$=300 keV) = 232 µm
- **Debye length**
  → grid
  → convergence check:
  1000/500/250/100 µm
- **Warp RZ** with absorbing/Dirichlet boundary conditions



Comparison

Experiment & Simulation



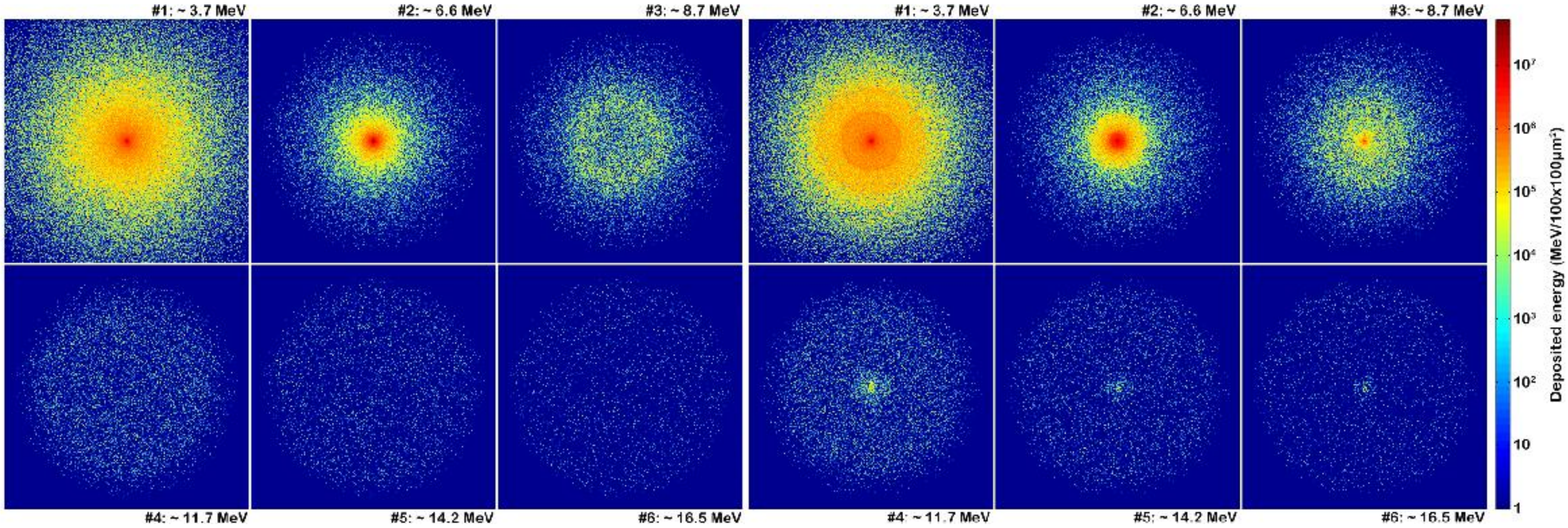


Film size: 2.5 inch x 2.5 inch

Gafchromic radiochromic film type HD-810

Space-charge effect

TECHNISCHE UNIVERSITÄT DARMSTADT

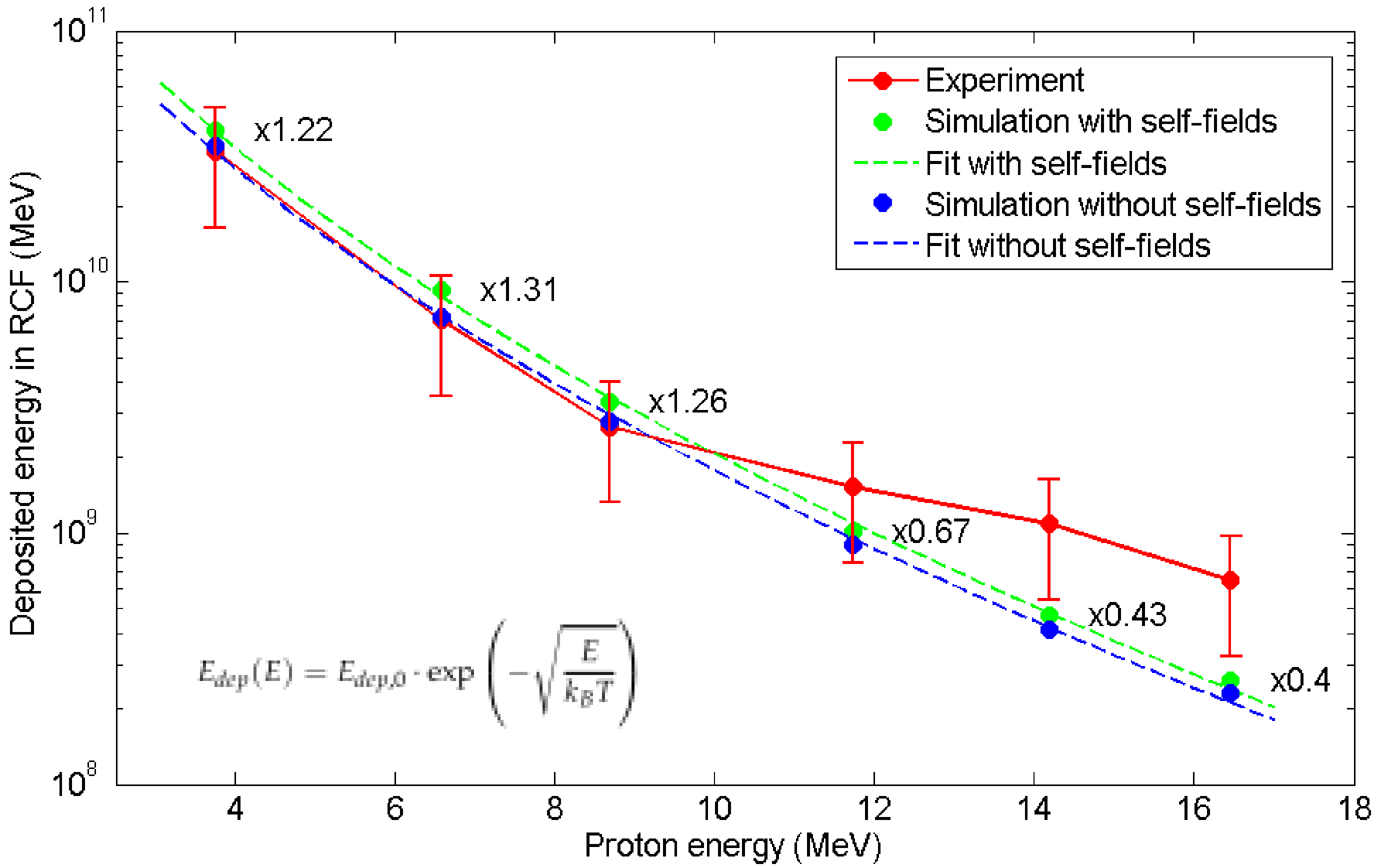


Field solver **off**

Field solver **on**

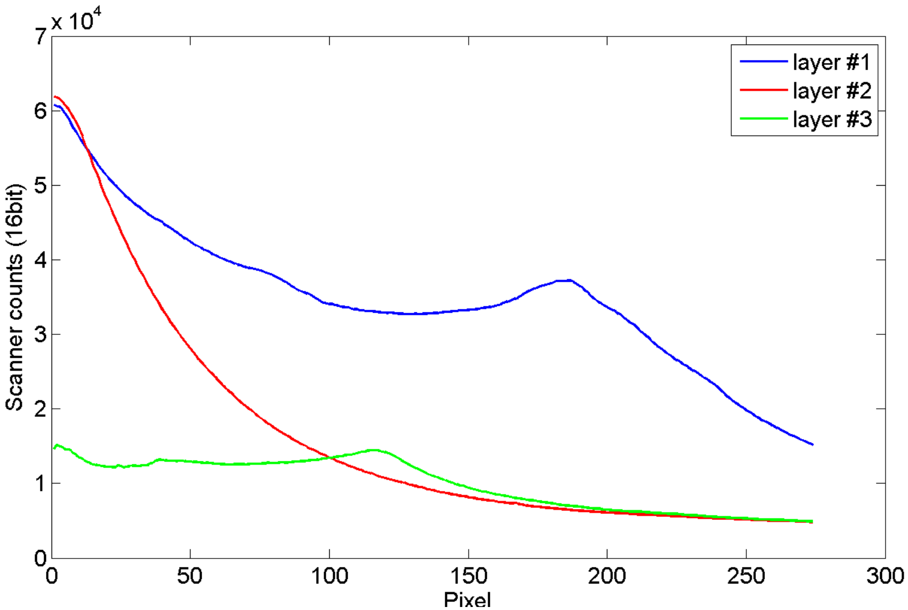
Comparison

Experiment & Simulation

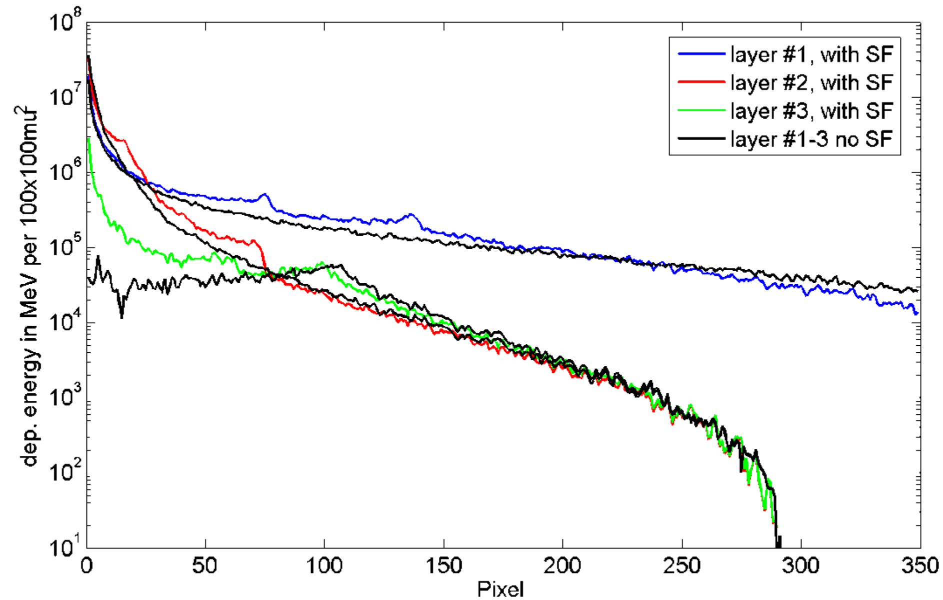


Comparison

Experiment & Simulation



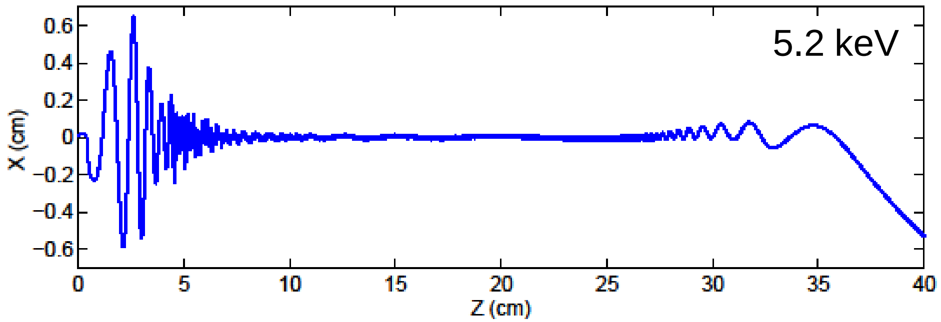
Radial line-outs **experiment**

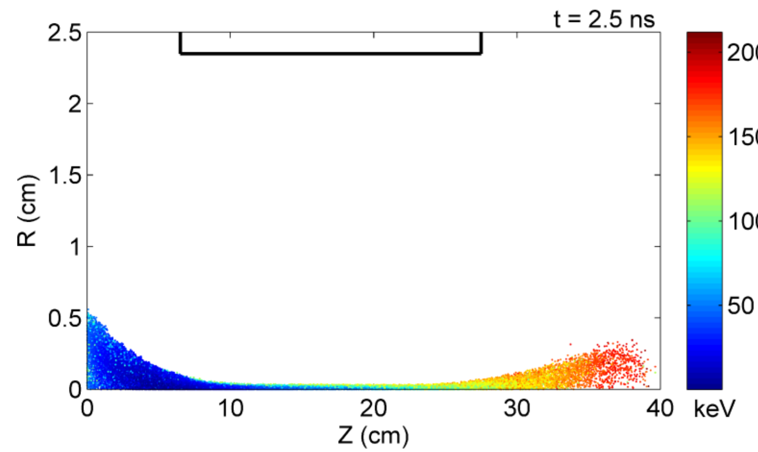


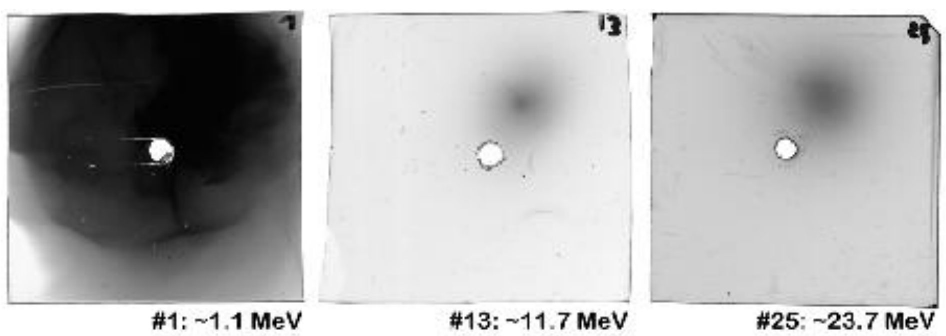
Radial line-outs **simulations**

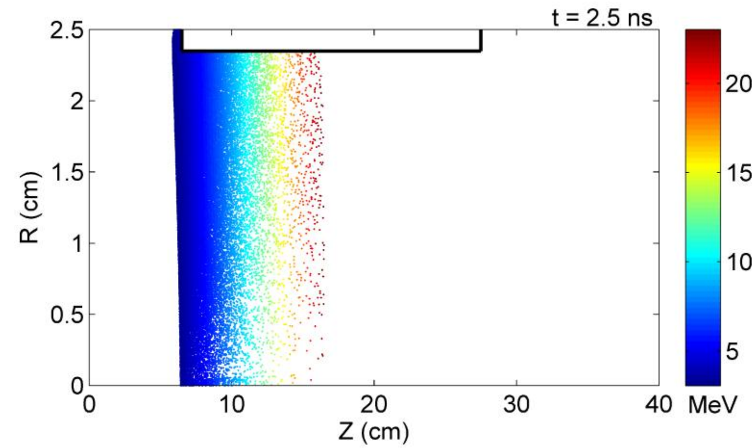
Magnetic field effect on electrons

TECHNISCHE UNIVERSITÄT DARMSTADT





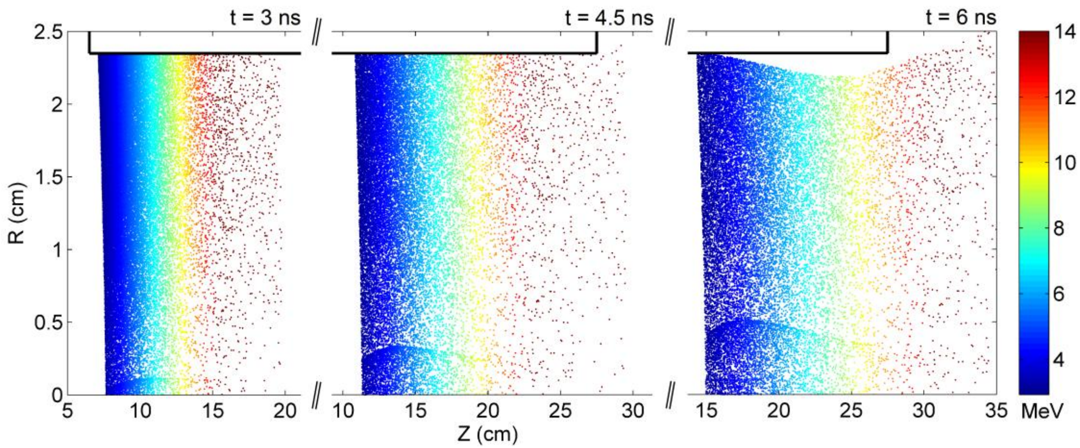


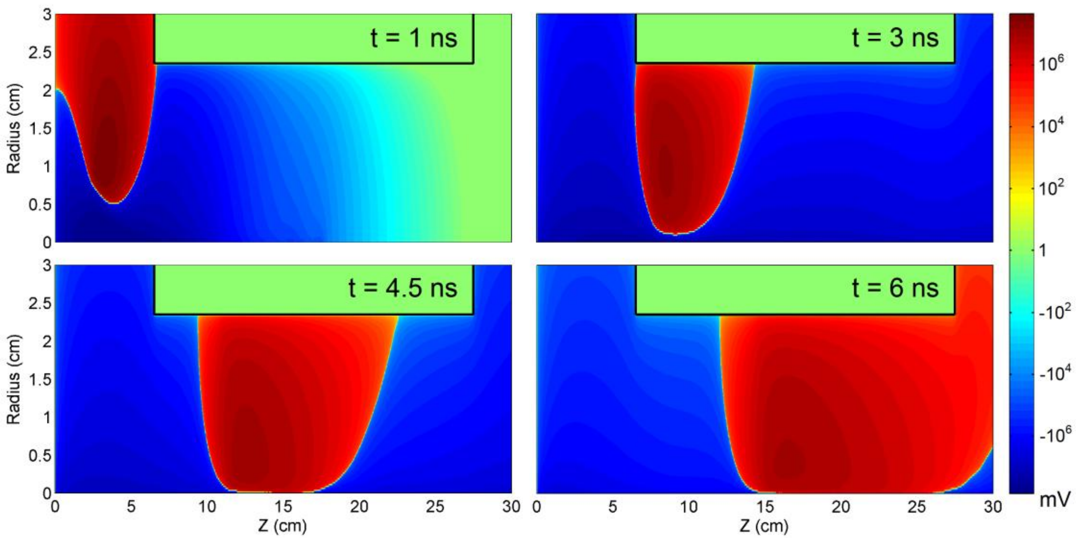


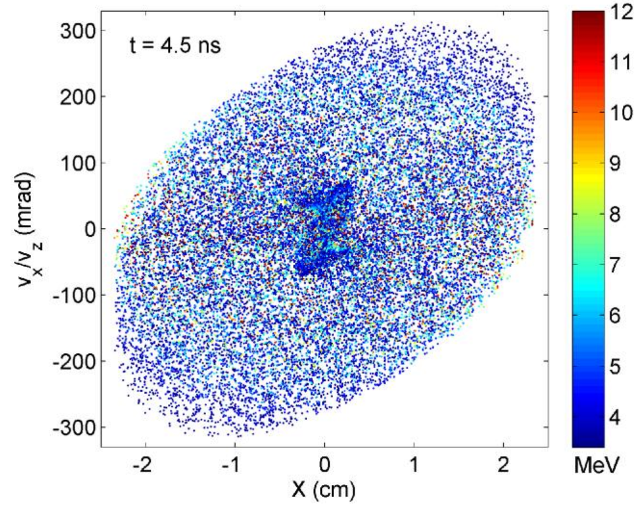
Casino simulation: 2 MeV electron

Magnetic field effect on protons

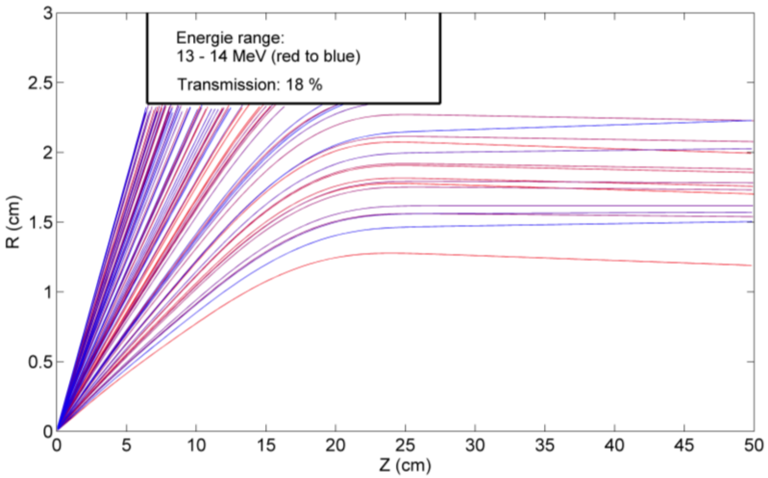
TECHNISCHE UNIVERSITÄT DARMSTADT

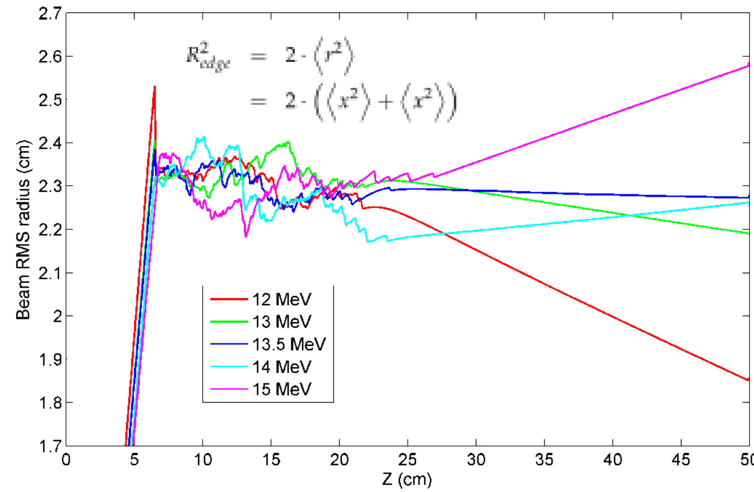


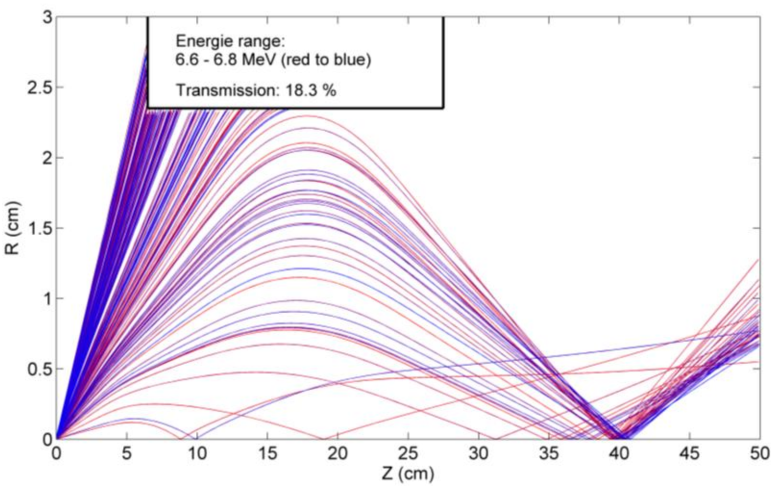


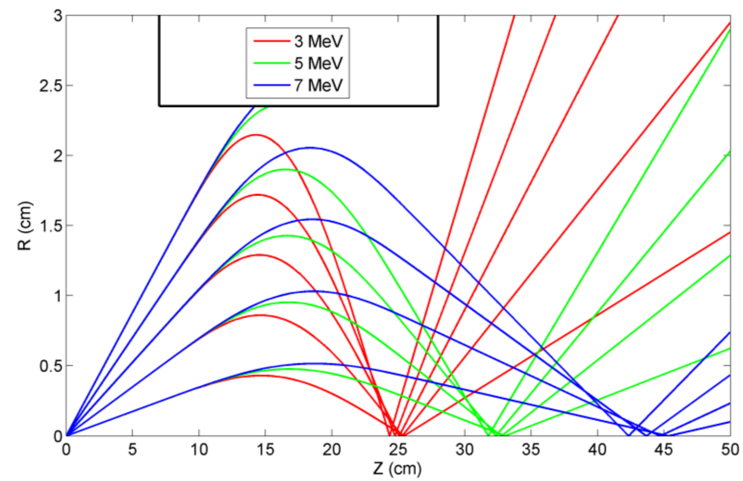


Collimation & Focussing









Initial particle number: 1.85×10^{12} protons

Overall proton loss: 74.8%

Collimation
Transmission 18%
→ 2.99×10^9 p+
(ΔE = 1 MeV)

Focussing
Transmission 18.3%
→ 8.42×10^9 p+
(ΔE = 200 keV)

Conclusion & Outlook

- Warp modified for quasi-neutral beam expansion
- Magnetic field effect -> space-charge effect
- Comparison experiment – simulation
- Collimation: 2.99×10^9 p+ (ΔE = 1 MeV)
- Focussing: 8.42×10^9 p+ (ΔE = 200 keV)

- Source modifications
- PSC output as Warp input
- Stronger effect: solenoid abberations – space-charge
- Optimization experiment