Transport of laser-accelerated ion beams

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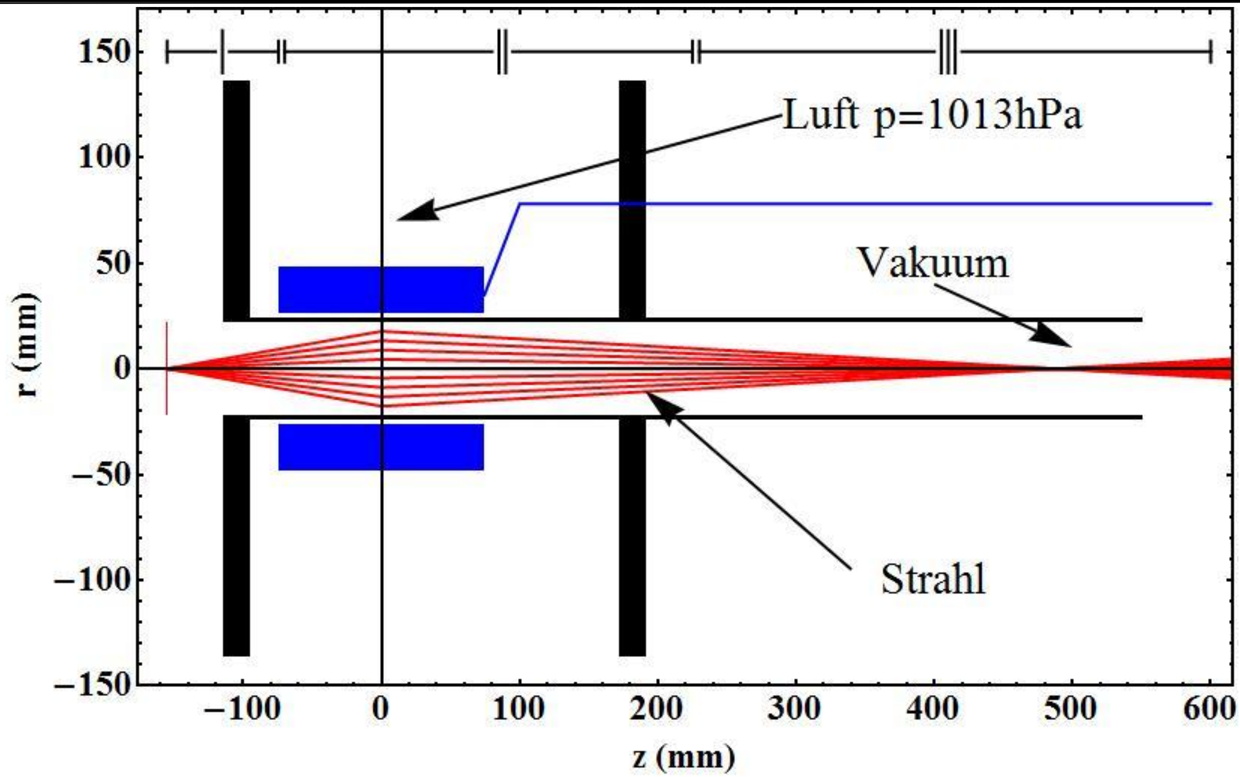


LIGHT-Project

Gesellschaft für Schwerionenforschung mbH, Darmstadt

PHELIX Facility

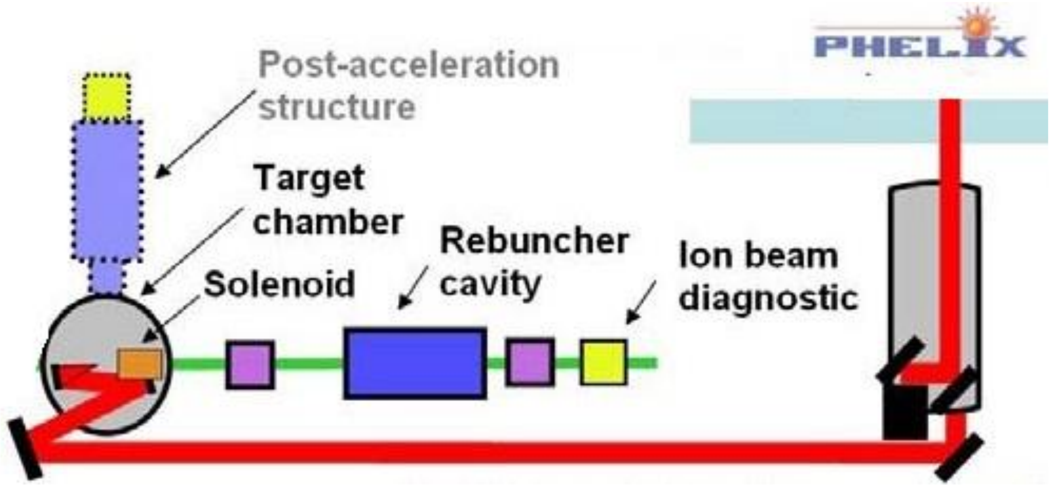
LIGHT – Laser Ion Generation, Handling and Transport

(TU Darmstadt, Uni Frankfurt,

GSI, HHZ Dresden)

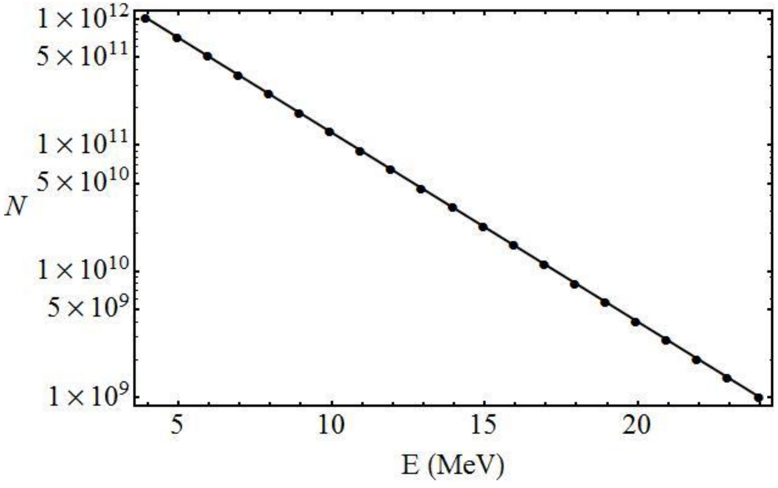
Experimental set-up:

- Laserpulse hits target
- Emission of protons and electrons
- Bunch is focused by solenoid
- Transport and diagnostics



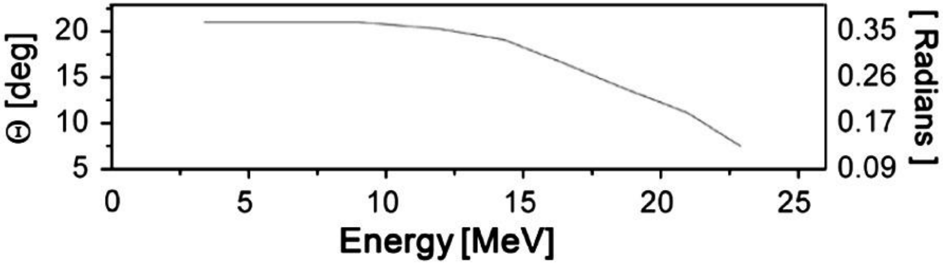
Set-up of the LIGHT-Project

Beam divergence



Emitted Energy spectrum (from measurement)

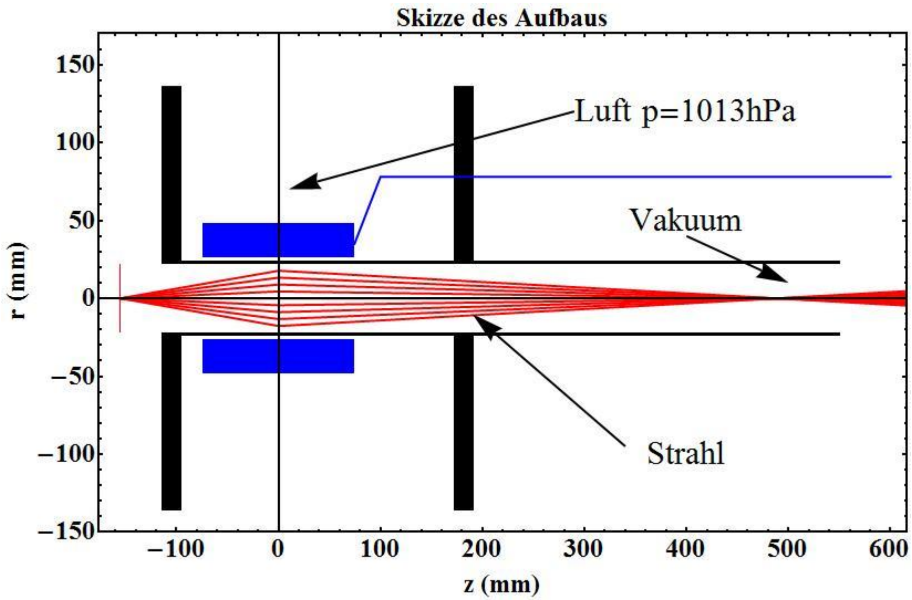
- Laser-accelerated protons exhibit an energy spread
- Beam shows a large divergence angle



Beam divergence after emission as a function of energy (measured)

Collimation and focusing is required to transport the beam through the beam pipe!

CST©-Model beam transport

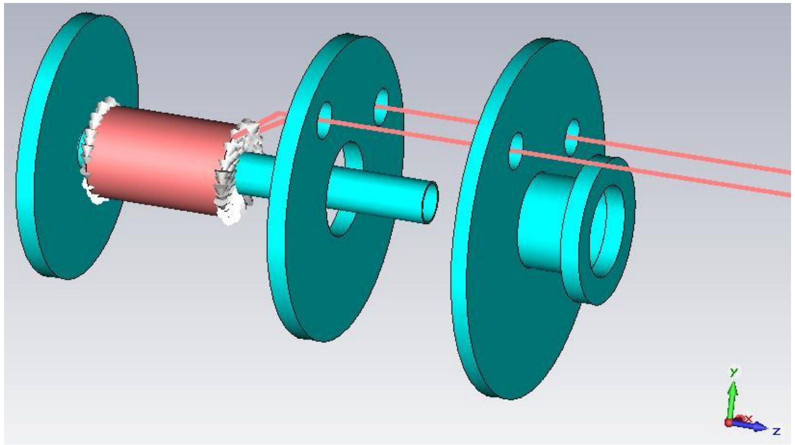


Scetch of the setup

Aim: Focusing of the beam with the pulsed solenoid

Blue: current-carrying parts; coil (thick), supply wires (thin)

Black: Metal parts; Flanges (Thick), beam pipe (thin)



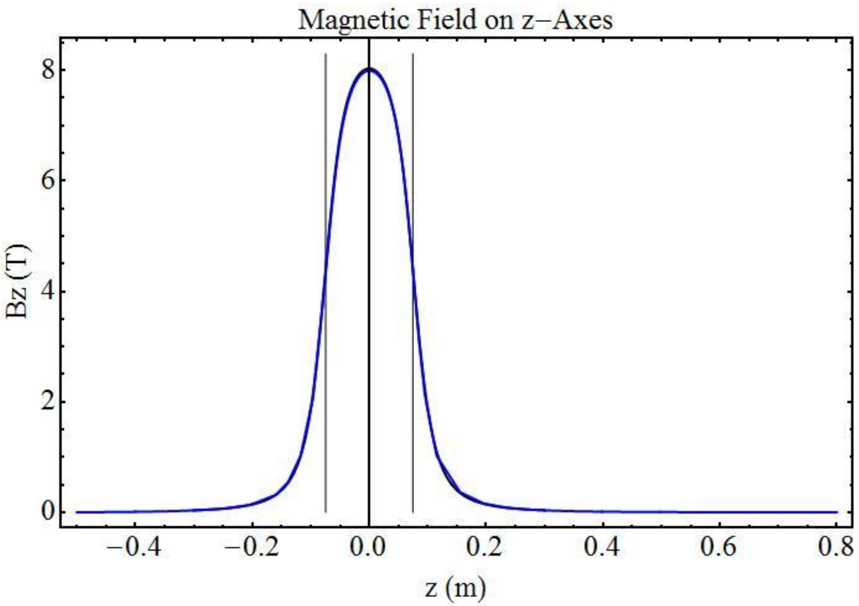
Picture of the CST©-Model

Static magnetic field

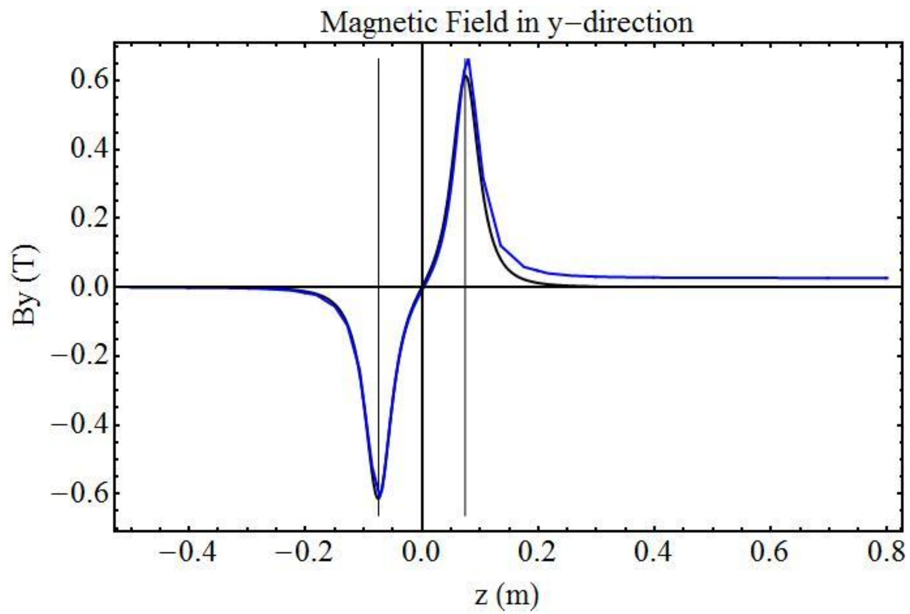
Coil data: $l_{coil} = 150mm$

$\bar{r}_{coil} = 42mm$

$N = 112$



Magnetic field on the z-axes: Simulation (blue line), analytical (black line)



Magnetic field in y-direction, simulated (blue) and analytical (black).

The supply wires lead to a non-vanishing magnetic field in y-direction behind the coil!

Field due to the supply wires analytical

- Treated as infinite line-conductors
- Influence appears behind the flange

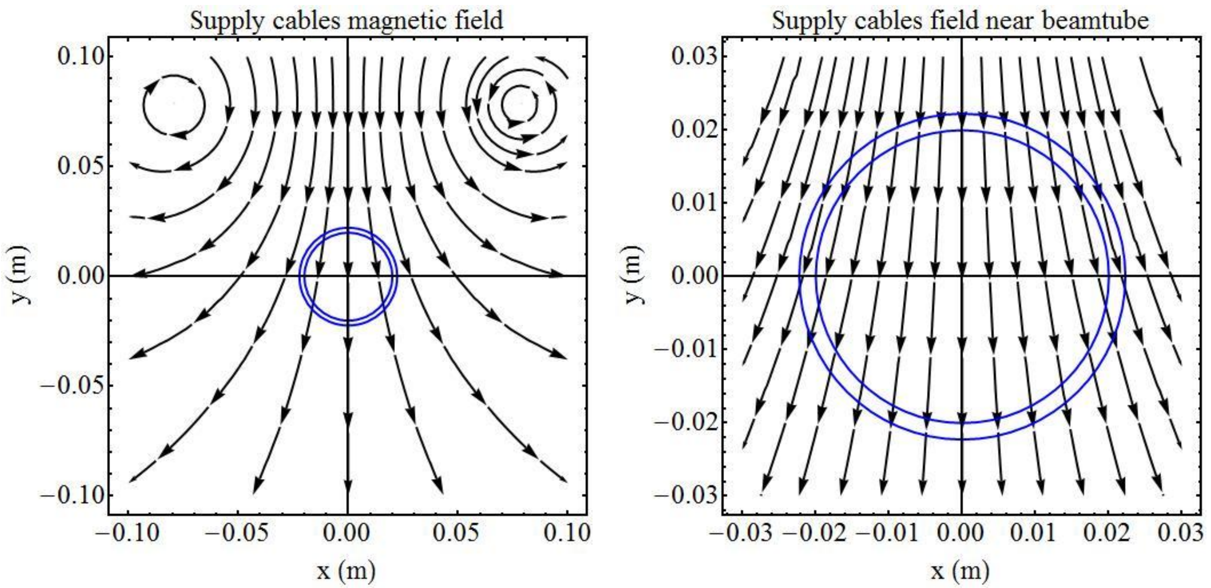
$$I_1(t) = -I_2(t)$$

$$r_1 = r_2 = \sqrt{2}\cdot 78mm$$

$$\phi_1 = \pi/4$$

$$\phi_2 = 3\pi/4$$

$$\vec{B}_{Kabel}(\vec{r},t) = \sum_{k=1}^{2} \frac{\mu_0 I_k(t)}{2\pi} \frac{r\vec{e}_\phi - r_k \vec{e}_{\phi_k}}{r^2 + r_k^2 - 2 r r_k \cos(\phi - \phi_k)}$$



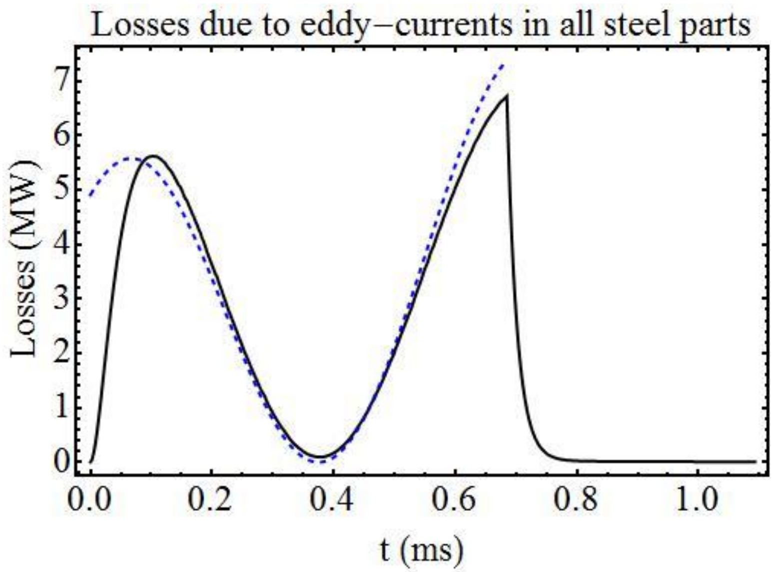
Magnetic field lines due to supply wires. Blue: Beam pipe.

Supply cables field on the z-Axes:

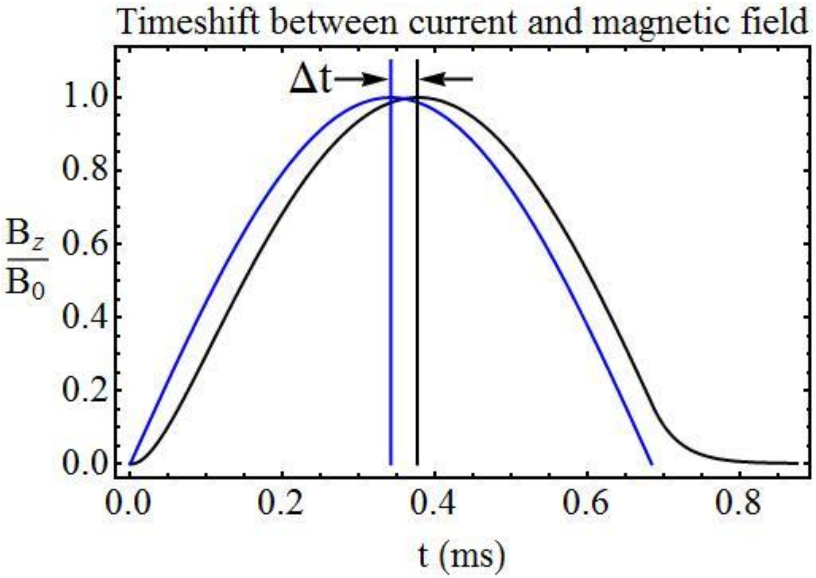
$$\vec{B}_{Kabel}(z=0,\vec{r},t) = \frac{\mu_0 I}{\sqrt{2}\pi r_k}\vec{e}_y$$

Pulsed magnetic field

- Pulsed field B(t) induces eddy-currents in metal parts
- Eddy-currents lead to counter field
- Inductive coupling leads to phase shift and attenuation of the field



Eddy-current losses: Simulation (continuous line), analytical approximation (dashed blue line)



Phase shift due to inductive coupling: Current (blue), magnetic field stregth (black)

Temporal shift: $\Delta t \approx 0{,}04 ms$

$$P_{losses} \propto \left(\frac{\partial \vec{B}(t)}{\partial t} \right)^2$$

Skin-effect in the flanges

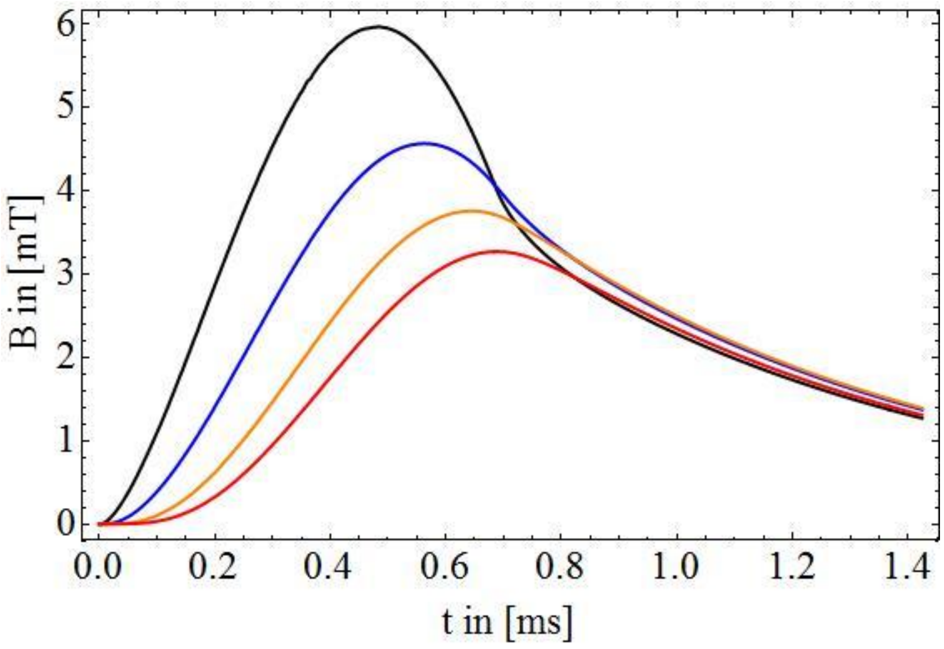
Skin-depth: $d_{skin-effect} = \sqrt{\frac{2}{\mu_0 \mu_r \sigma \omega}} \approx 16{,}7mm$

Flange thickness: $d_{flange} = 20mm$

It holds: $B_z \propto e^{-z/d}$

In addition to that the magnetic field experiences a continuous phase shift φ(z)

The magnetic field of the coil is shielded by the flanges!

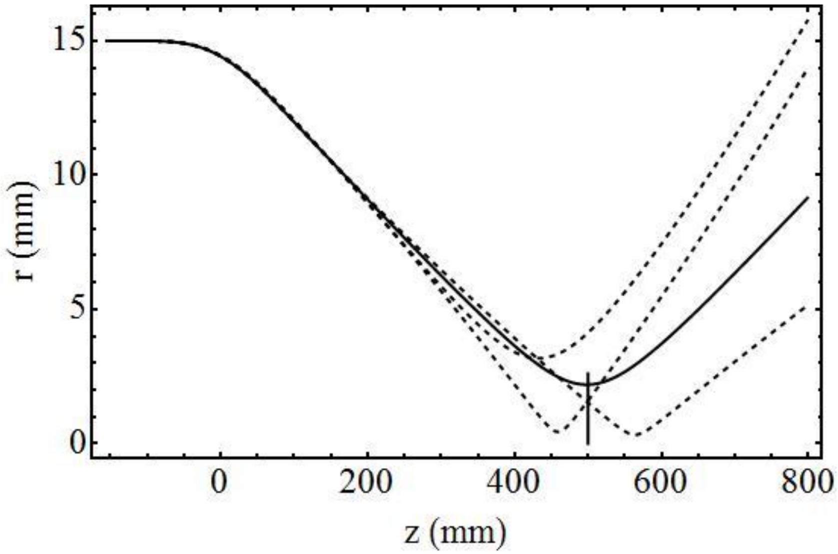


Skin-effect in the flanges of the set-up

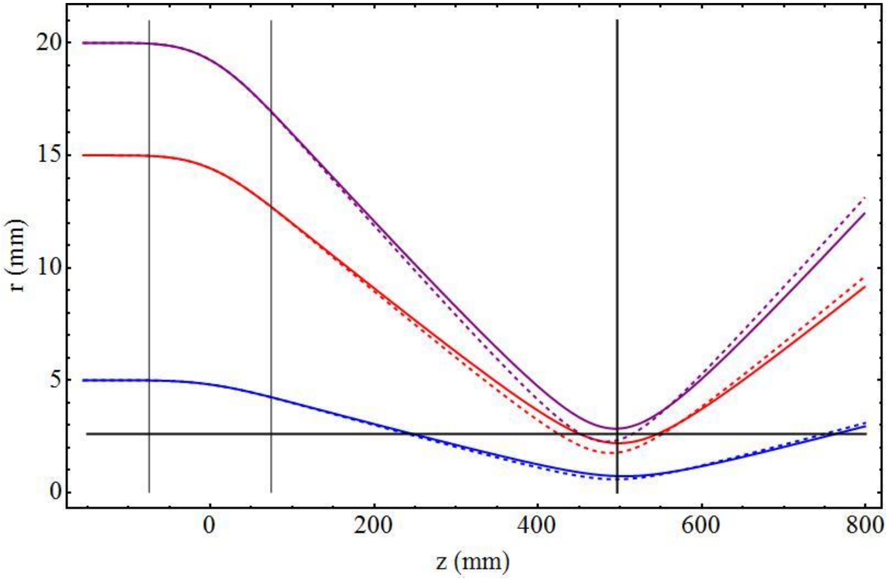
Particle-Tracking with CST Studio©

Focus analytically for the paraxial, laminar case:

$$\frac{1}{f} = \frac{e^2}{4\gamma^2 m_p^2 v_z^2} \int_{-l/2}^{l/2} B^2 dz \quad \Rightarrow \quad f \approx 500mm$$



Particle tracking simulation supply wires.



Beam radius for different initial conditions (coloured lines). The black lines show the radius and position of the analytical determined focus. (without supply wires).

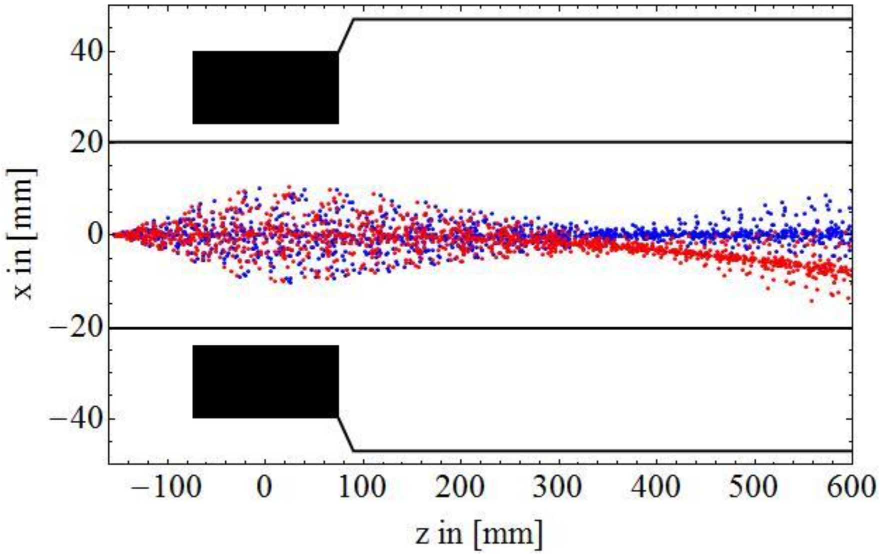
Supply wires effect can **not** be neglected!

Particle-Tracking with CST Studio© and stray field

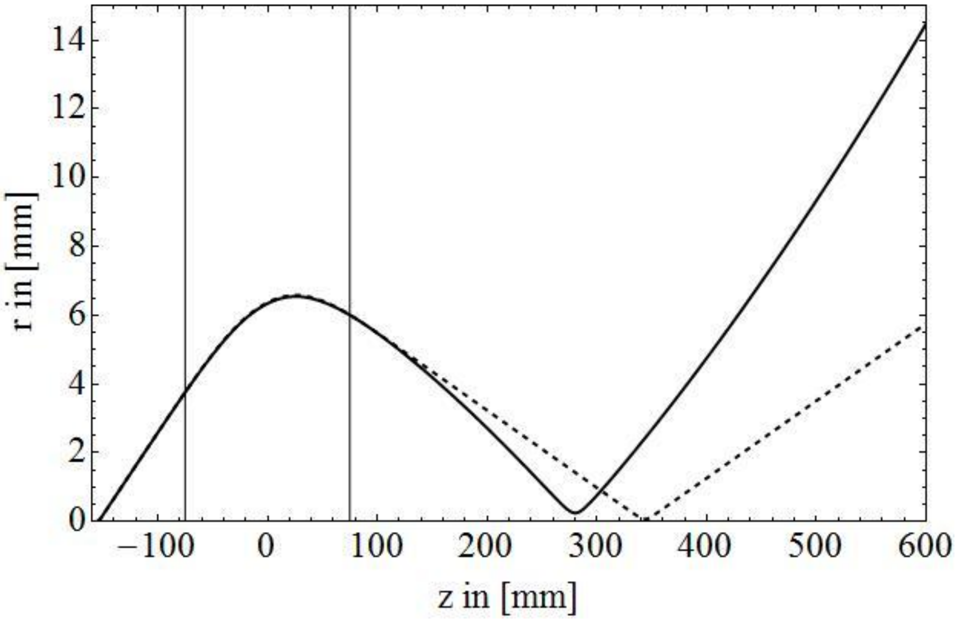
Supply wires field at r=0:

$$\vec{B}_{wire} \approx \frac{\mu_0 I(t)}{\pi r_k}\left(x(z,t)\vec{e}_x - \frac{1}{\sqrt{2}}\vec{e}_y \right)$$

$$r_k = 78mm \quad Wire\ position$$



Particle tracking simulation without (blue) and with (red) supply wires

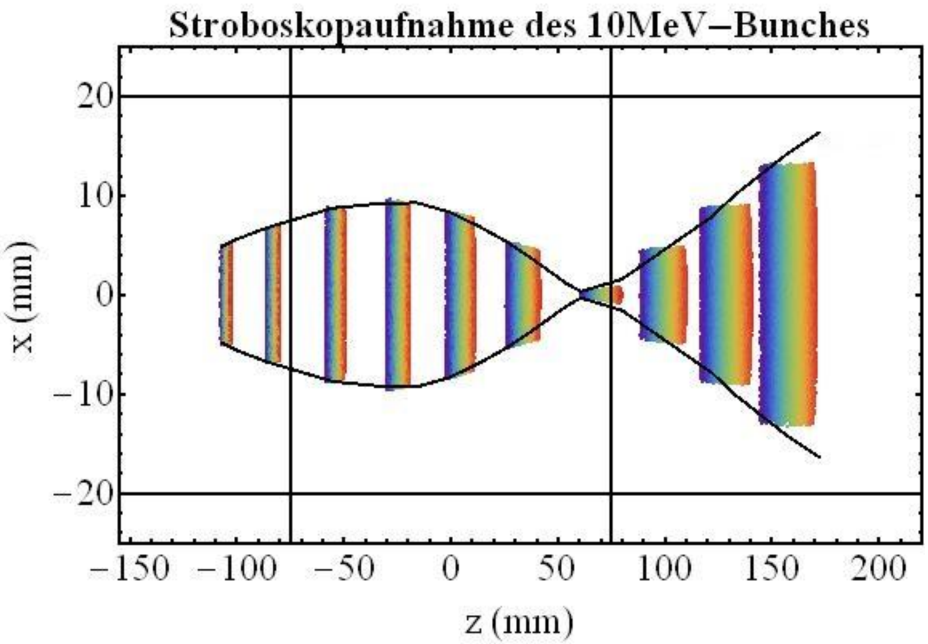


Beam radius without (dashed line) and with (continuous line) supply wires

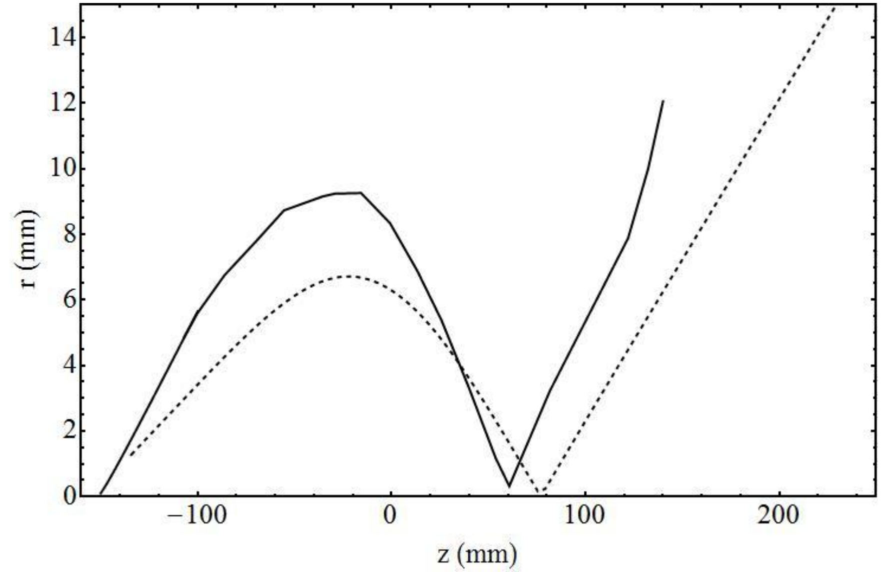
PIC simulation with VORPAL© and space charge

Space charge leads to:

- Increasing divergence
- Broadening of the focus
- Extension of the focue



Stroboscopic recording of the bunch; the colors show different speeds



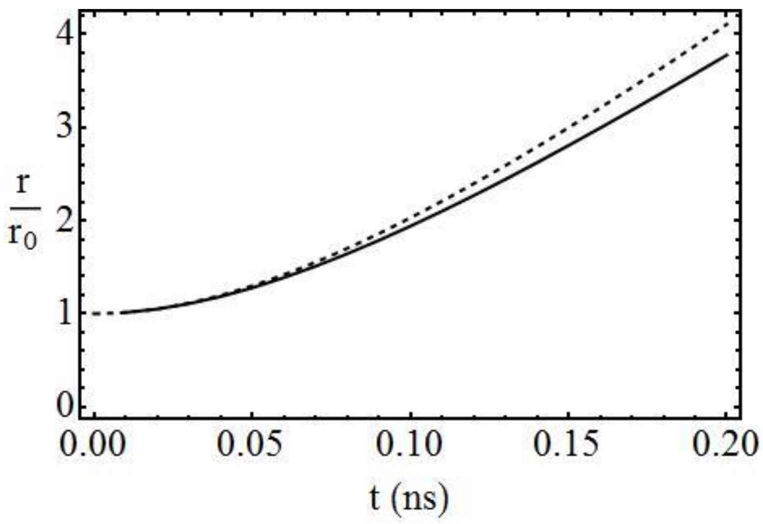
PIC simulation (continuous line) with space charge, Particle tracking (dashed line) without space charge

Simple model for space charge discription

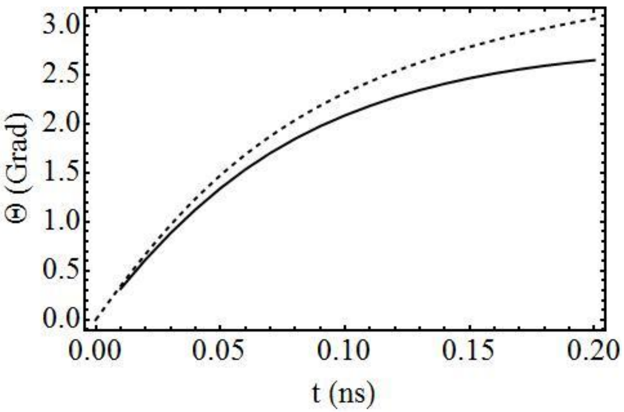
Space charge expansion can be descriped by an envelope equation:

$$\frac{d^2 r}{dt^2} = \frac{N_0 e^2}{2\pi\varepsilon_0 \gamma^3 m_p l_b(t)} \frac{1}{r}$$

With the bunch length: $l_b(t) = l_0 + \Delta v_z t$



PIC simulation: continuous line, analytical: dashed line



Divergence angle; PIC simulation: continuous line, analytical: dashed line

Quasi neutral plasma expansion

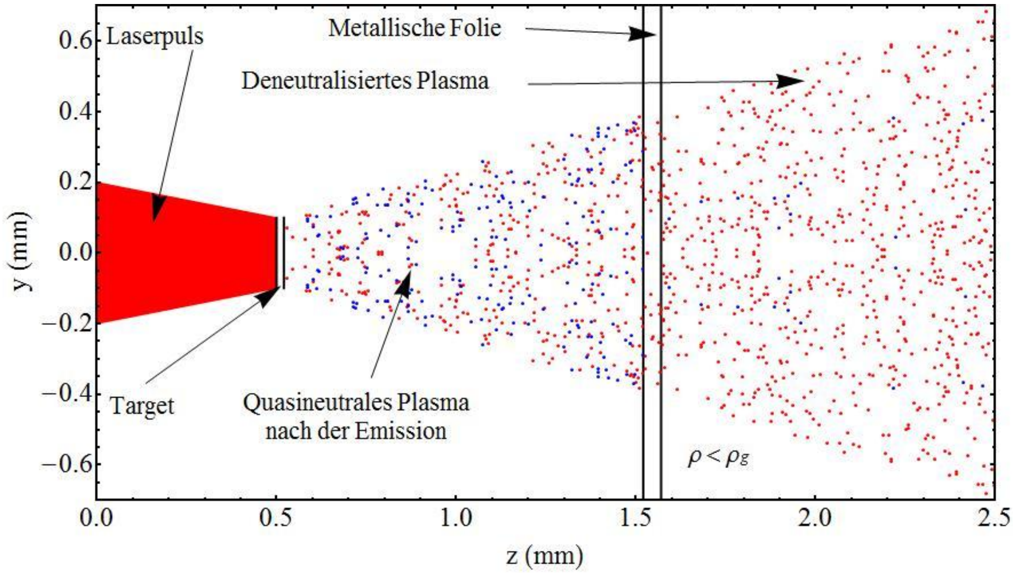
Basics:

- Quasi neutral plasma consisting protons and co-moving electrons
- Expansion without space charge:
  - Longitudinal expansion due to velocity spread: $$l(t) = \Delta v_z t + l_0$$
  - Transversal expansion due to divergence: $$r(t) = v_r t + r_0 = v_z \tan(\theta) t + r_0$$
  - Density decreases: $$\rho(t) \propto \frac{1}{r(t)^2 \pi l(t)}$$

Basic idea:
- At some point, space charge can be neglected
- Neutral expansion to that point followed by **controlled** de-neutralization

Controlled de-neutralization with a thin metal foil

- The quasi neutral plasma hits a thin foil
- Foil absorbs the electrons

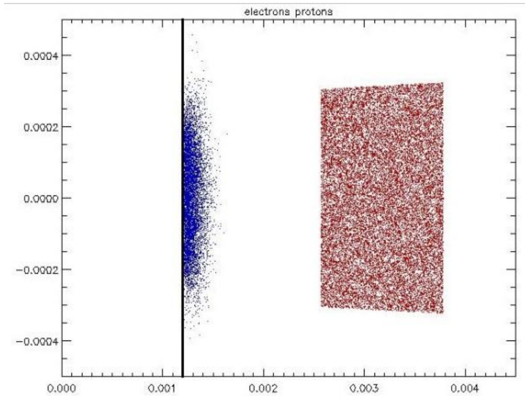


Schematic representation of the deneutralisation set-up

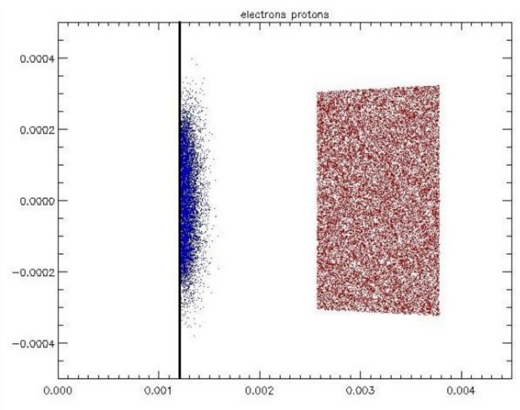
Objectives:

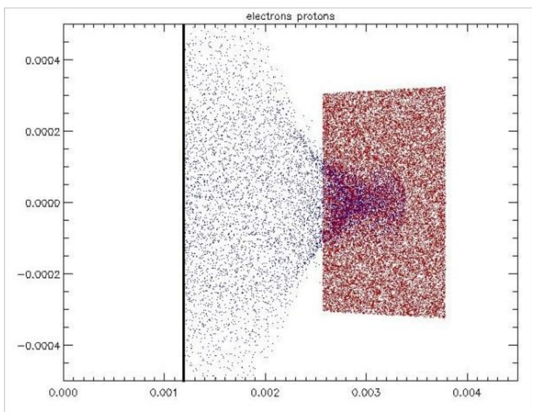
- Emission of secondary electrons due to (Secondary Emission Yield) SEY and due to the electrical field of the protons
  - Dependency on foil material
  - Re-neutralisation depending on proton density
  - Electron train
  - Beam energy loss and scattering

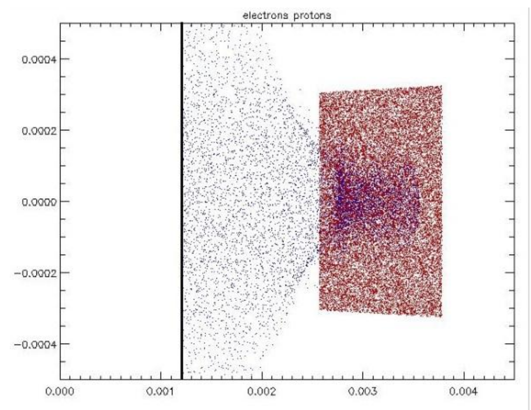
Electron train



- Particle density varies from 10^{17} m^{-3} to 10^{20} m^{-3}
- Bunch expands neutral and is deneutralised by the foil
- Foil emits secondary electrons
- Between 10^{17} m^{-3} and 10^{18} m^{-3} an electron train appears, which partially re-neutralises the bunch







Record of the bunch after the crossing of the foil: The protons are red, the secondary electrons are blue: At some charge density an electron train develops

Summary

•The magnetic field properties of the pulsed solenoid were studied:
- •Stray fields (supply wires)
- •Eddy currents (pulsed field)

•The focusing properties of the set-up were analysed using particle tracking:
- •Influence of stray fields on the proton trajectories
- •Influence of space charge on focusing strength compared to space charge free porpagation

Outlook:

•When (in space and time) can we neglect space charge ?

•Study controlled deneutralisation with a thin metal foil for a beam within the previously worked out conditions:
- •Secondary electron emission and electron train → partial re-neutralisation
- •Electromagnetic effects appearing in the foil and on its boundaries

Thank you for your attention!