Simulation of Frictional Cooling

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Why a Muon Collider?

- Energies in Electron Colliders are limited due to synchrotron radiation and m_e very small
- $m_\mu \approx 206 \cdot m_e \quad \rightarrow$ much less synchrotron radiation
$$-\Delta E \propto m^{-4}$$
- new frontiers in high energy particle physics
$$E_{cms} = 1 \rightarrow 10 \text{ TeV}$$
- muons are leptons and so are elementary
- know the exact collision energy in contrast to hadrons
- intensive Neutrino factories
- **But:** Muons decay after $2.2\ \mu s$
$\rightarrow$ need more advanced Cooling Techniques

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Muon Collider Scheme

- Protons in the range of $2-30$ GeV produced by a MW accelerator
- impact on metall target (e.g. copper)
- Pions are captured in drift channels with strong (≈ 10 T) magnetic fields
- decay to high energy Muons that have a large spatial and momentum spread
- Muons enter the Section where *Frictional Cooling* is applied
- Phase Rotation and Reacceleration
- a sixdimensional emittance reduction of $O(10^6)$ is concievable

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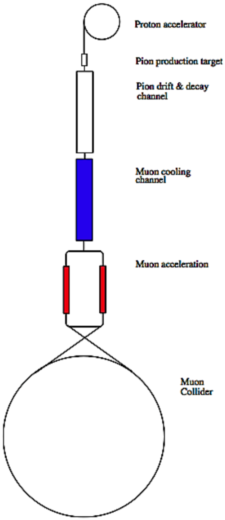

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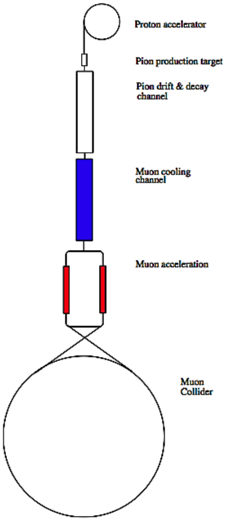

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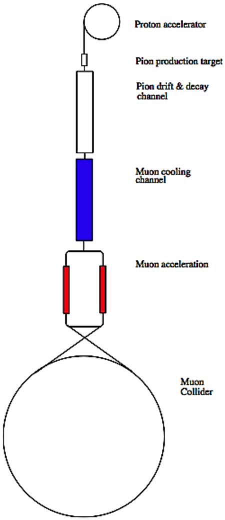

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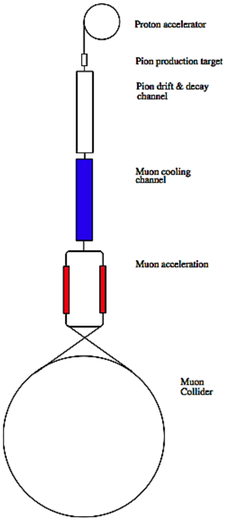

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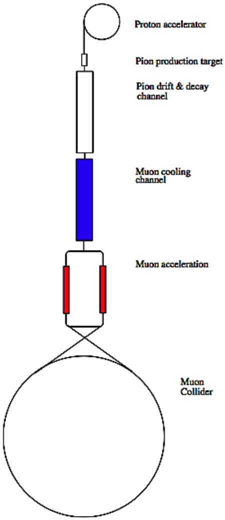

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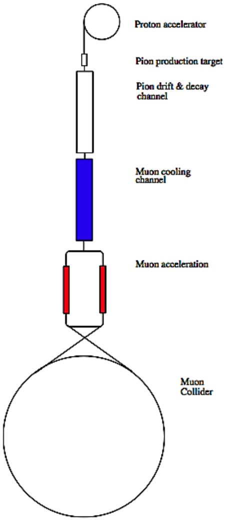

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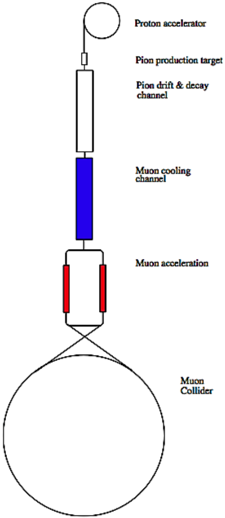

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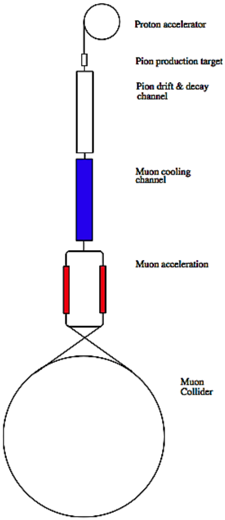

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Frictional Muon Cooling - The idea

- goal is to bring the muons in a region where dT/ds increases with T
  $\rightarrow$ below a few keV (ioniz. peak)
- $dT/ds \propto \mathrm{v}$ where $\mathrm{v} \leq \alpha c$
- applying a constant accelerating force leads to an equilibrium energy
- slow muons speed up, fast ones slow down

  $\rightarrow$ reduction of beam emittance

$$\epsilon = \sigma_x \sigma_{p_x} \sigma_y \sigma_{p_y} \sigma_z \sigma_{p_z} / (\pi m_p c)^3$$

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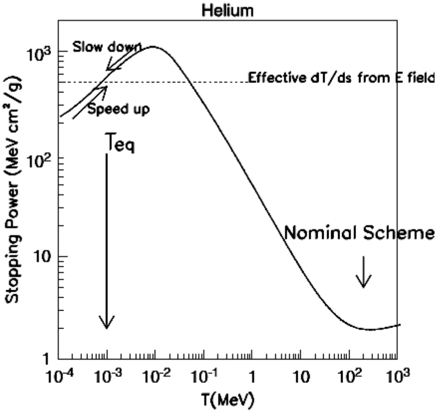

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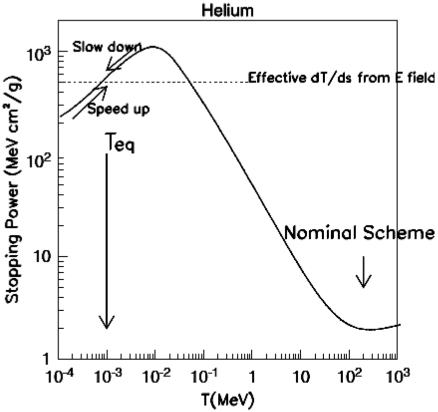

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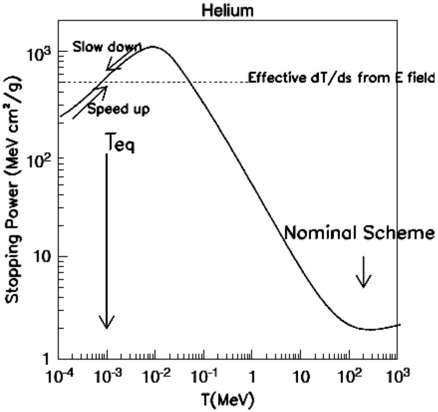

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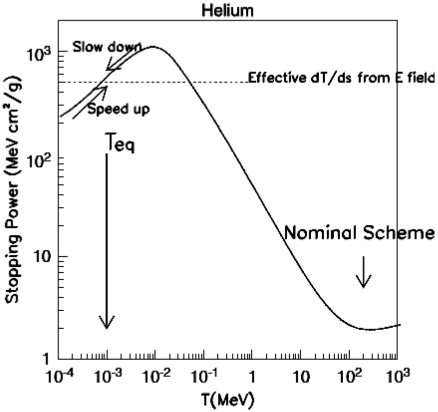

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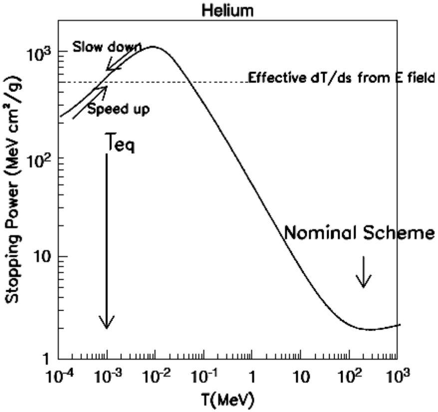

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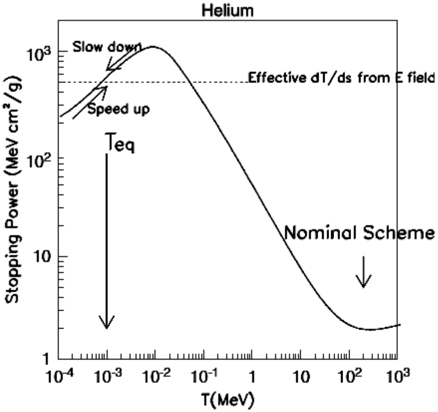

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Frictional Cooling - Protons to prove the principle

- Protons are heavy charged particles
  $\rightarrow$ typical stopping power curve
- loose energy due to *Ionisation, Nuclear Scattering, Excitation* and *Charge Transfer*
- Protons are easy to produce
- they do **not decay**!

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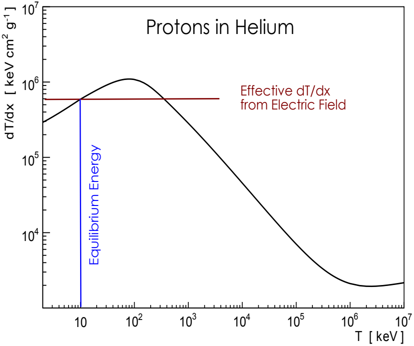

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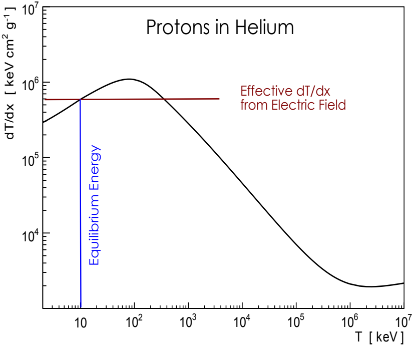

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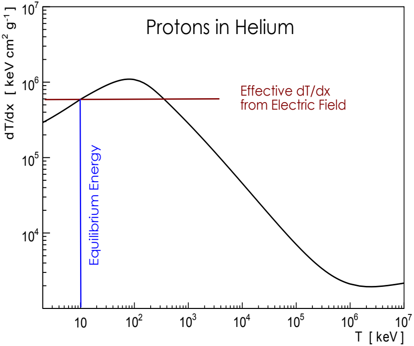

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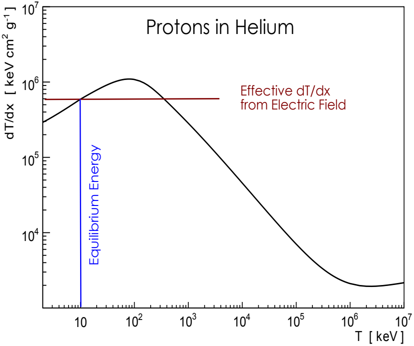

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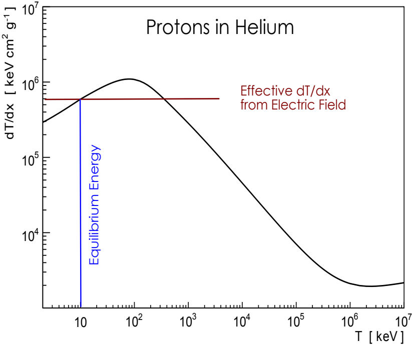

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The Gas cell Construction

- Gas cell is filled with Helium
- the proton source is variable mounted at bottom
- the detector sits on top
- the accelerating grid consists of 21 metal rings which are connected in series by resistors
- on first ring we apply up to 100 kV to provide an almost homogeneous electric field

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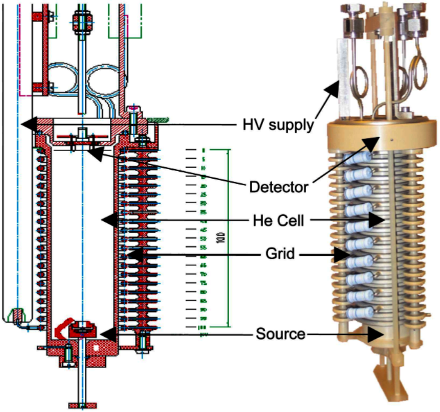

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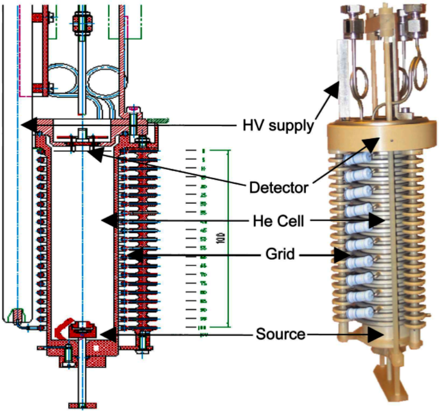

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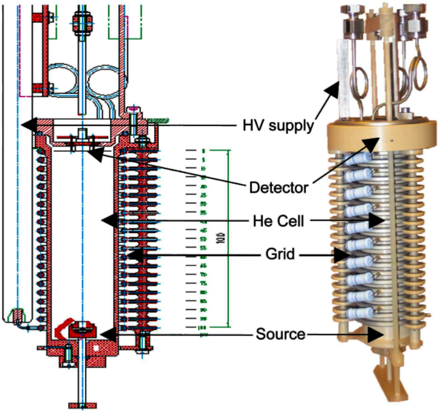

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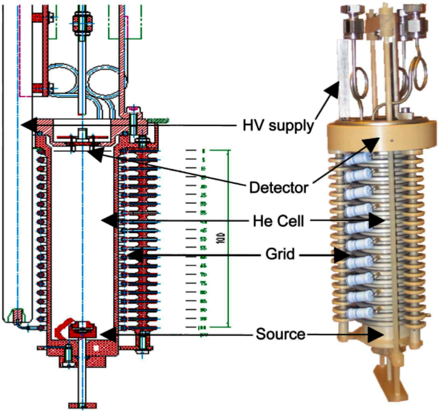

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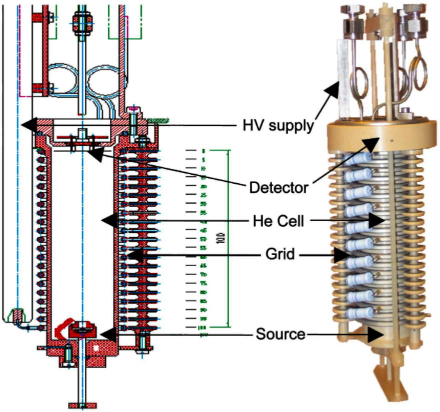

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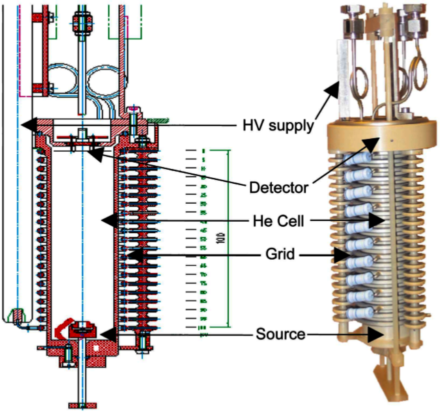

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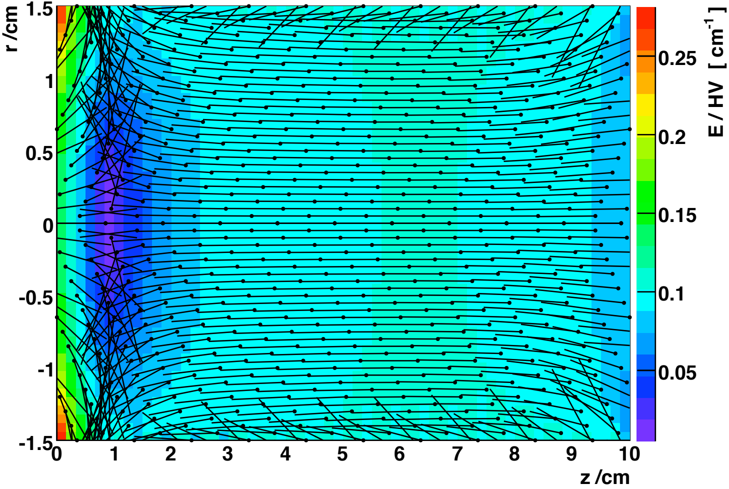

The superconducting magnet

- magnet consists of a superconducting coil with 18.2 cm in length and an inner radius of 5.6 cm
- provides up to 5 Tesla in its center
- the grid including the gas cell is placed insight the magnet

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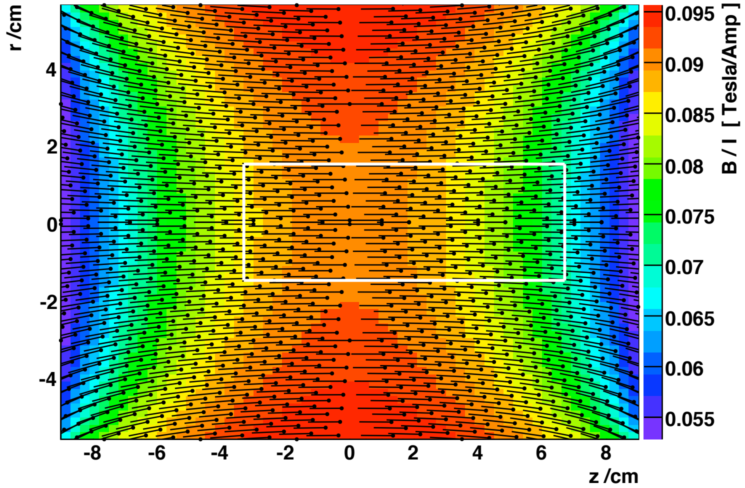

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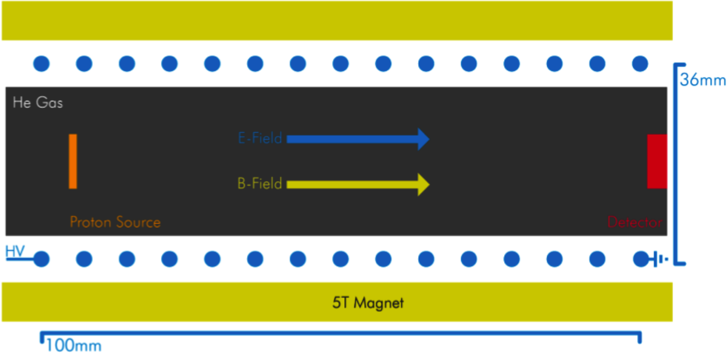

The Geant4 MC Simulation

- The simulation covers all relevant processes
- Classes: *G4MultipleScattering* and *G4hLowEnergyIonisation*
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- Electronic and Nuclear Stopping Power Modells are based on Report 49 (1994) of the International Commission on Radiation Units (ICRU)
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An Ideal Setup

- Simulation of a 50cm x 20cm tube filled with Helium
- Electric and magnetic fields are perfectly homogeneous and parallel aligned
- Do not consider any initial spatial distribution, all Protons start at (0,0,0)

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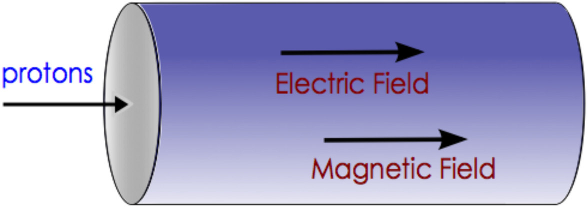

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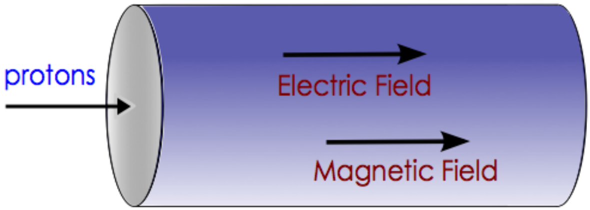

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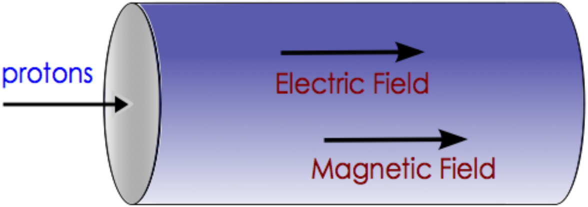

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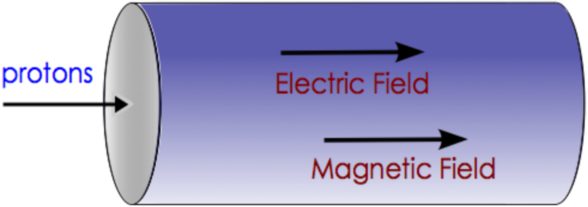

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Single Proton track

- Helium $\rho = 0.01$ mg/cm^3
- E = 6 kV/cm , B = 3 Tesla
- Force on a Proton
  $\mathbf{F} = \mathrm{q}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \frac{\mathrm{dT}}{\mathrm{ds}}\mathbf{v}$
- single nucleus scatters
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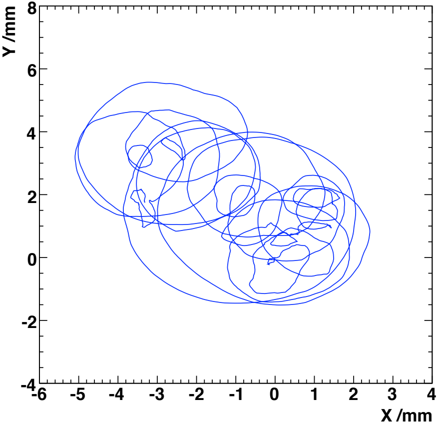

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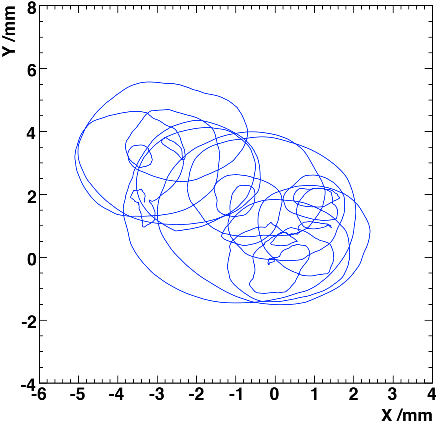

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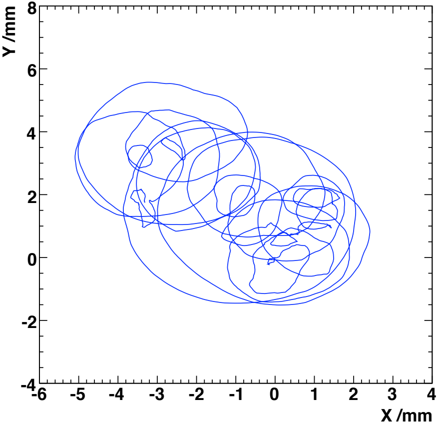

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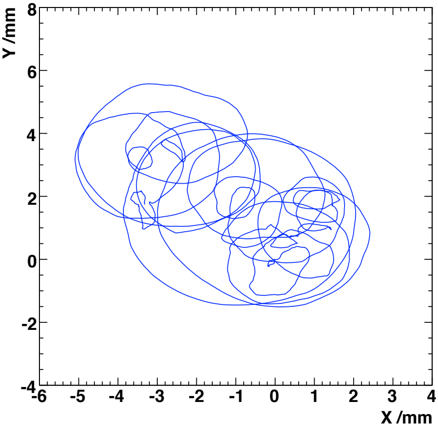

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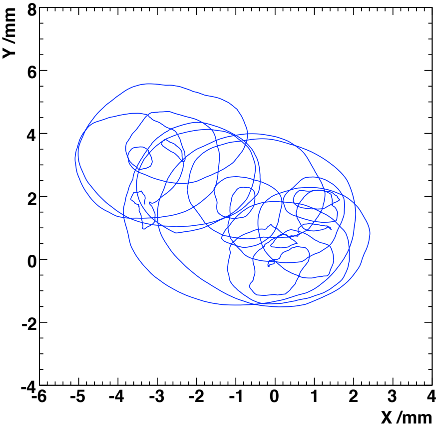

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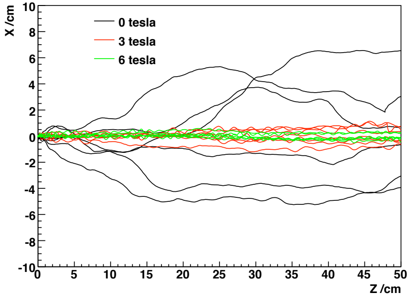

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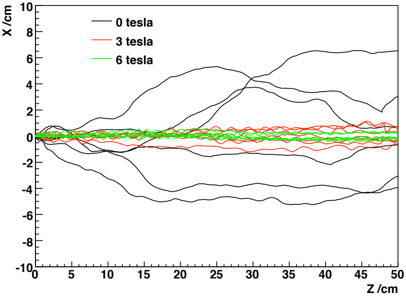

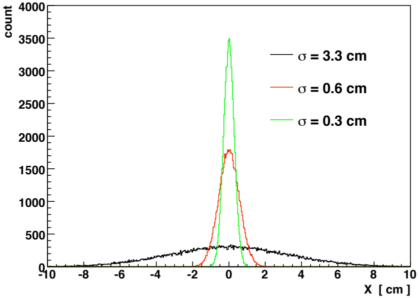

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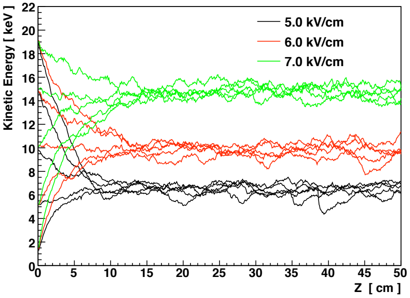

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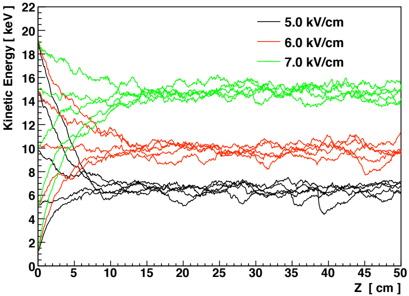

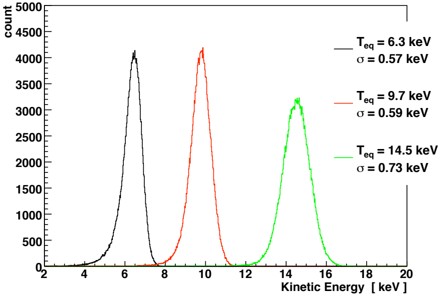

The Equilibrium Energy

- Helium at various densities
- $B = 0$ Tesla
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- straight lines: Simulation
- dots: data from dT/dx curve
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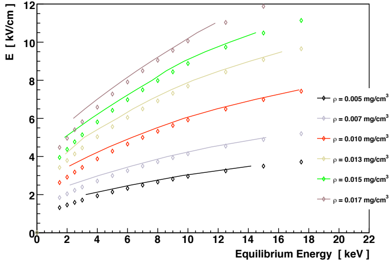

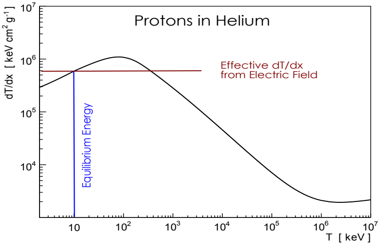

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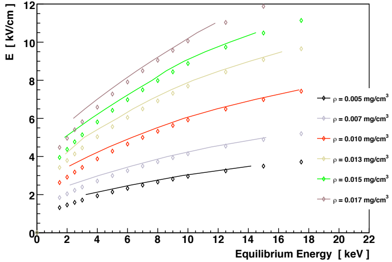

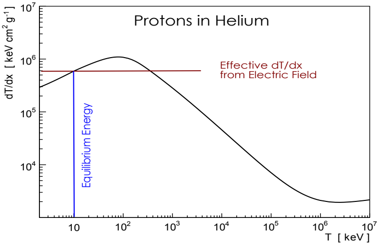

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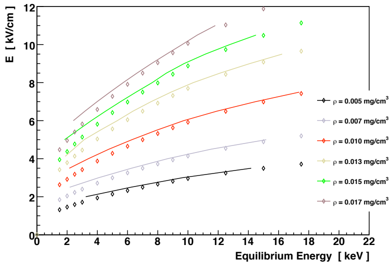

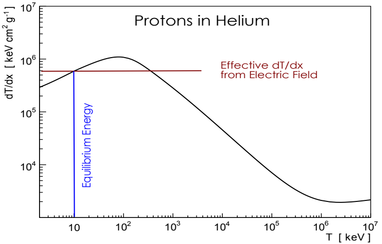

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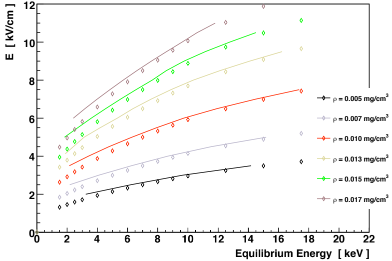

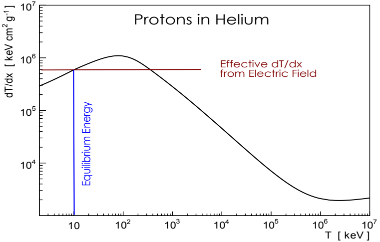

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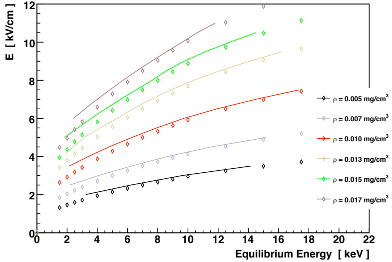

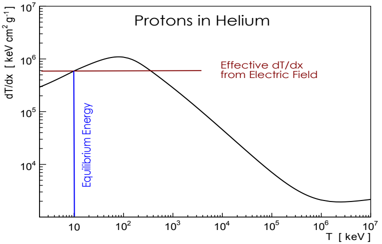

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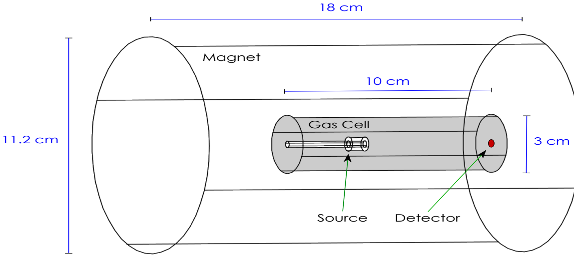

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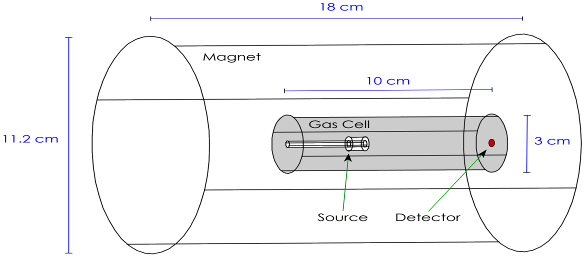

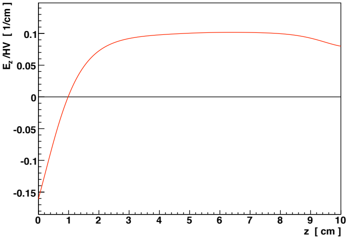

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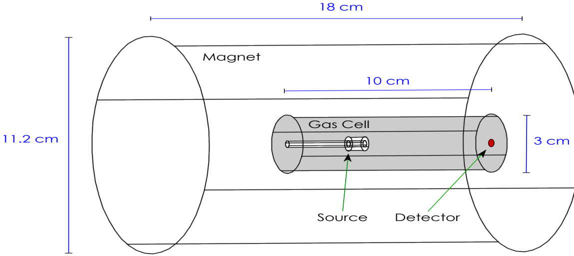

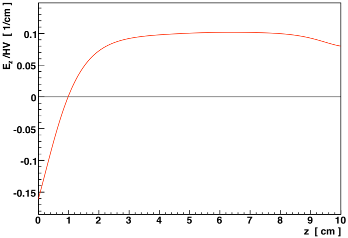

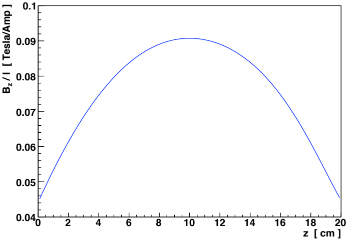

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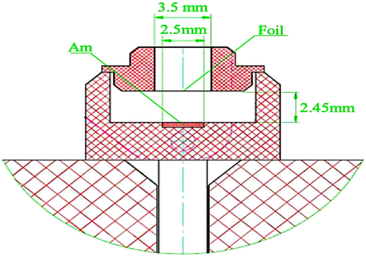

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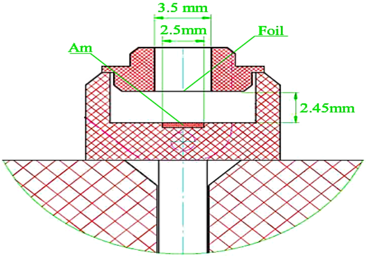

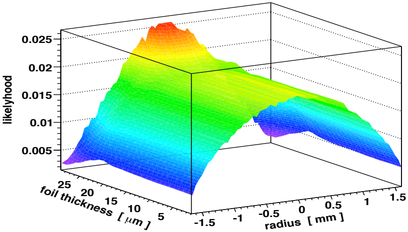

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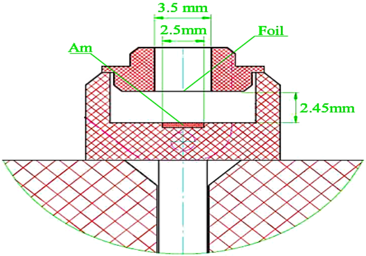

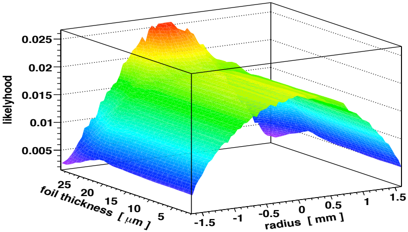

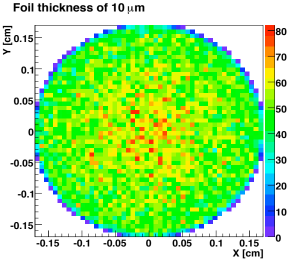

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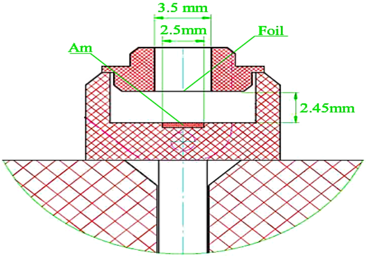
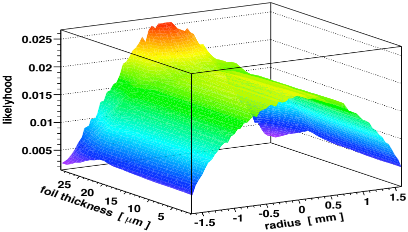
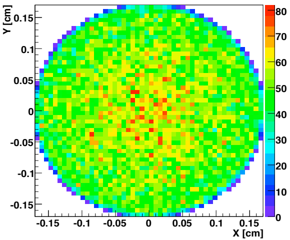
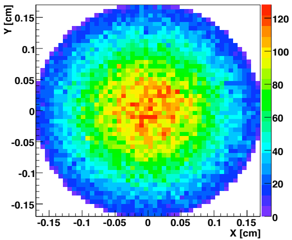




Foil thickness of 10 μm



Foil thickness of 29 μm



A typical run

Conditions

- Helium at a density of $\rho = 0.01$ mg/cm^3 (e.g. at $T = 290$ K and $P = 60$ mbar)
- Highvoltage on first ring $U = 70$ kV
- Current through the coil $I = 50$ A
- Source diameter of 3.4 mm
- Source offset of 3 cm
- Thickness of Mylar foil of 25 μm
- Detector Diameter of 3.4 mm
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- Current through the coil $I = 50$ A
- Source diameter of 3.4 mm
- Source offset of 3 cm
- Thickness of Mylar foil of 25 μm
- Detector Diameter of 3.4 mm
- 1000,000 Protons starting at 20 eV

A typical run - Trajectory Y vs. X

A typical run - Trajectory Y vs. X

(Loading Movie)

A typical run - Trajectory Y vs. Z

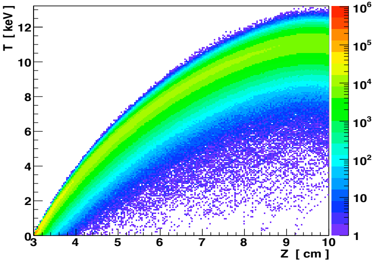
A typical run - Trajectory Y vs. Z

(Loading Movie)

A typical run - Results

A typical run - Results

Evolution >



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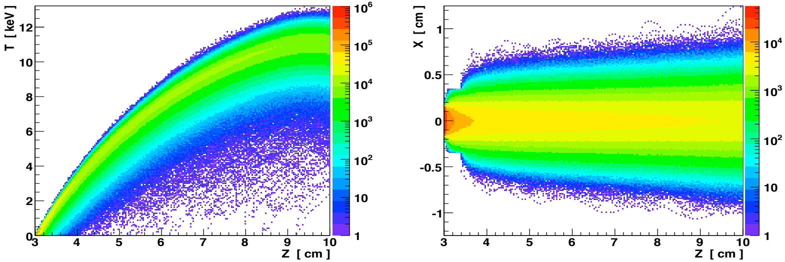

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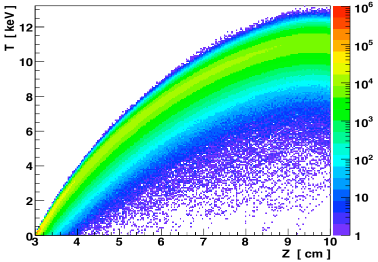
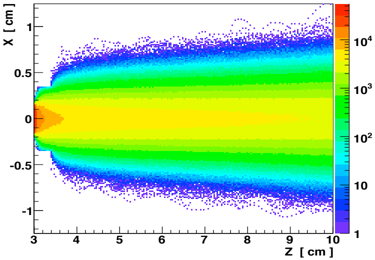
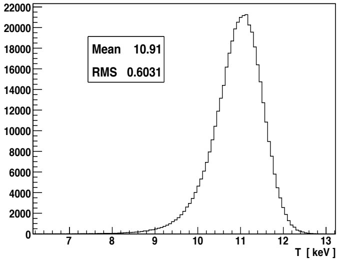




End Plane >



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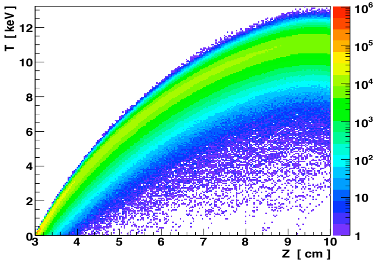

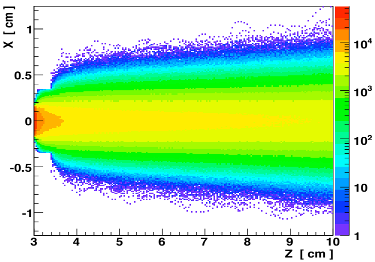

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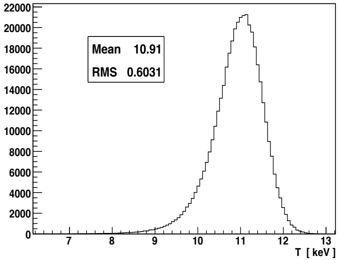
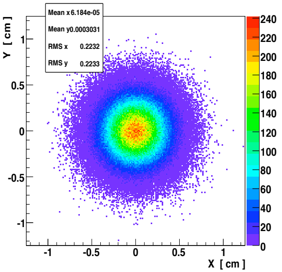




Influence of the electric field

Helium at $\rho = 0.01\ \mathrm{mg/cm^3}$

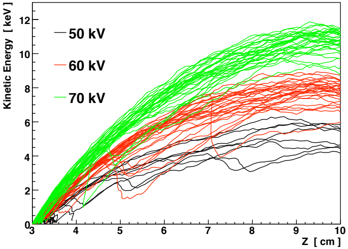
Kinetic Energy vs. Z

- Mean energy depends only on gas density and electric field strength
- Large angle nuclear scatters lead to high energy loss, then reacceleration

Energy distributions

- see again tail to lower energies
- more surviving protons to higher electric fields

Influence of the electric field



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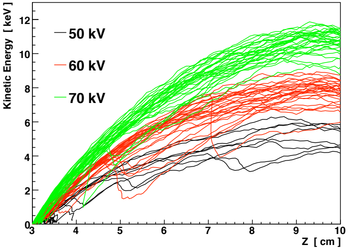

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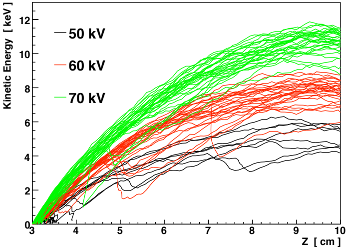

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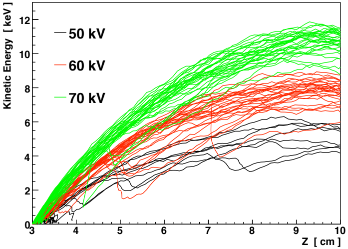

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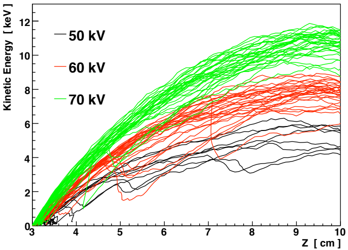

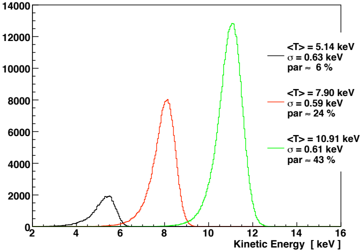

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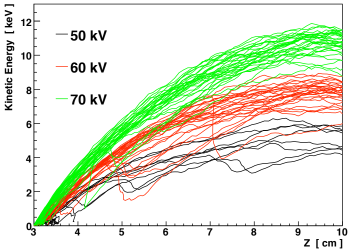

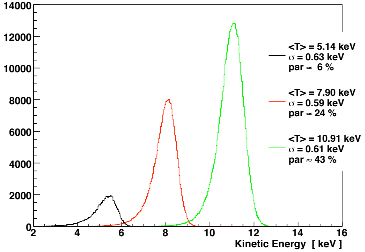

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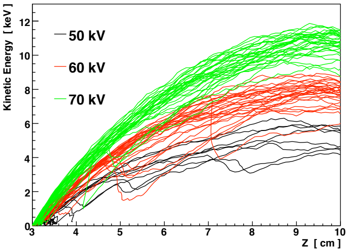

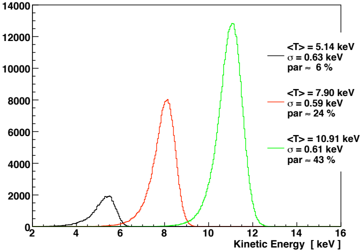

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Mean Energy and Equilibrium

Comparison of Mean Energy and Equilibrium

- from dT/ds curve: $dT/ds = bT^m\rho$ with $b = 2.162 \cdot 10^2$, $m = 0.433$
- from electric field: $E_z = k \cdot HV$ with $k = 0.0973$ cm^{-1}
- Analysis assumptions
  - no nucleus scattering $\Rightarrow$ $v_x = v_y = 0$
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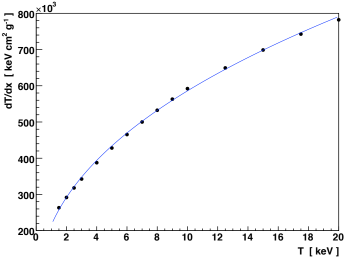

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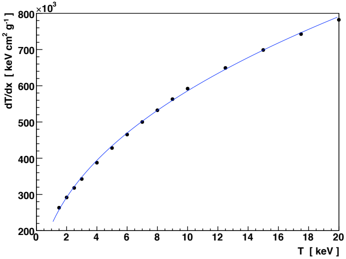

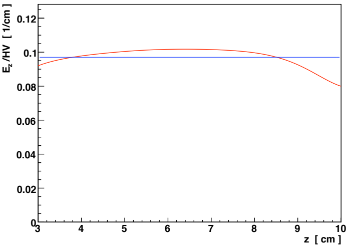

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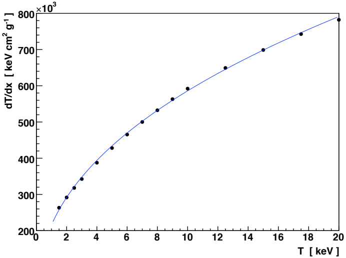

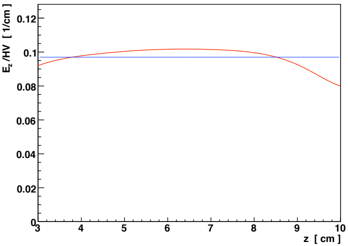

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Equilibrium $\Rightarrow$ Energy Gain balances Energy Loss

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$$\Rightarrow \quad \frac{dT}{dz} = E_z$$

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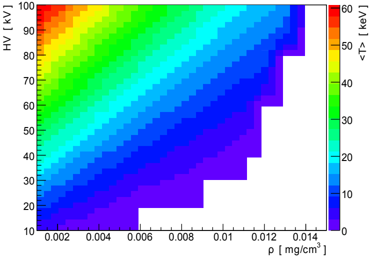

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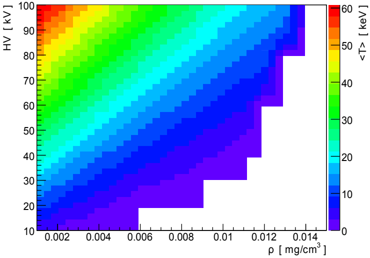

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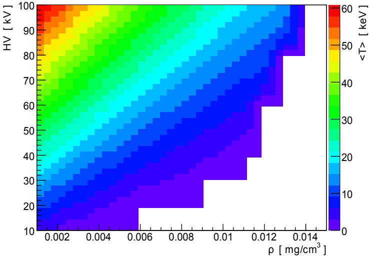

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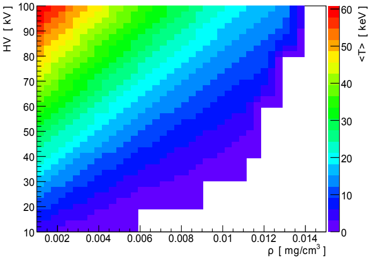
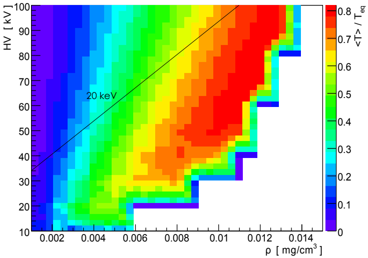




Influence of the magnetic field

$\rho = 0.01 \text{ mg/cm}^3$ and $HV = 70$ kV

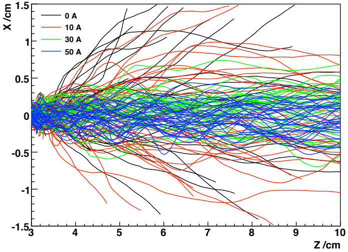
Trajectories

- wavelike movements
- strong collimation to higher fields

Spatial distributions

- σ decreases strongly to higher fields
- number of surviving protons increases with higher field strengths

Influence of the magnetic field



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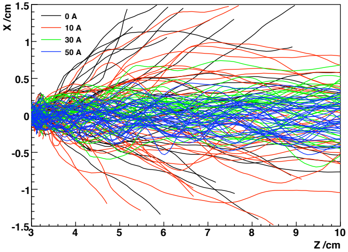

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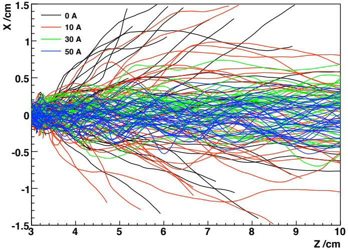

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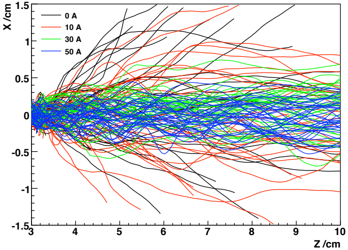

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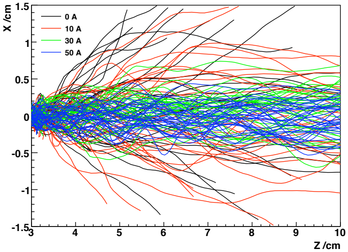

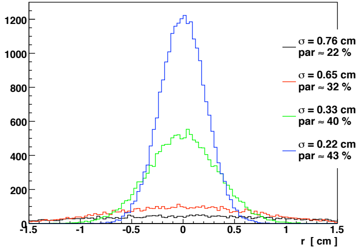

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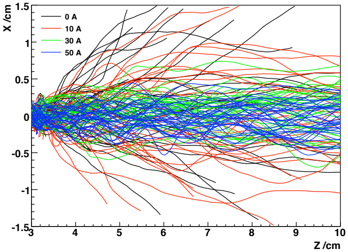

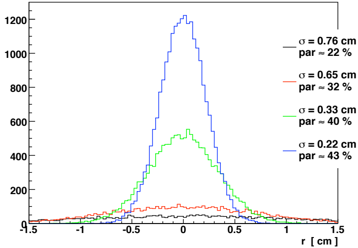

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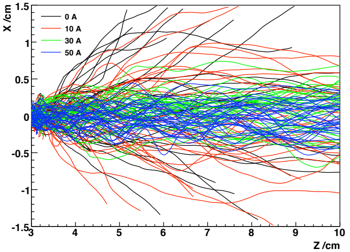

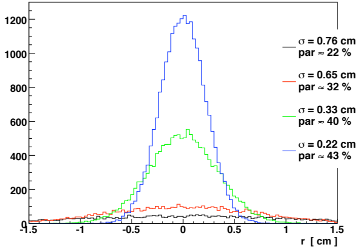

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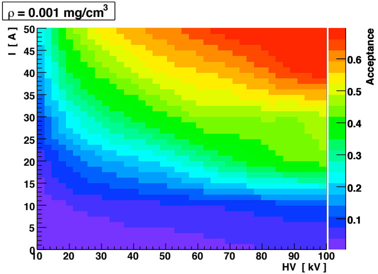

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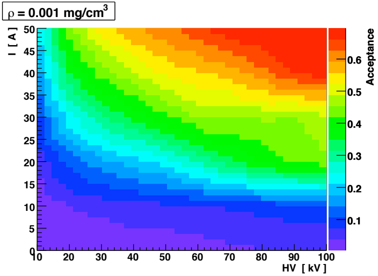

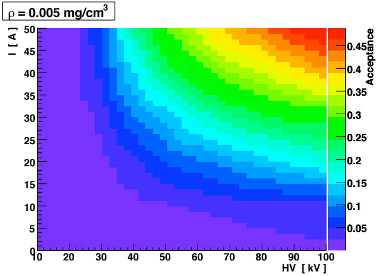

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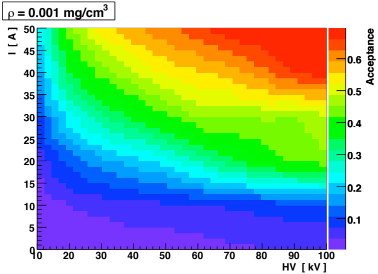

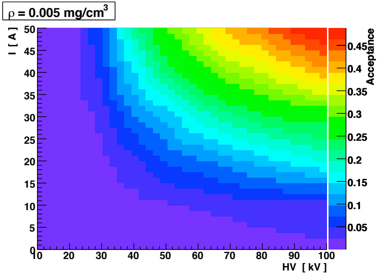

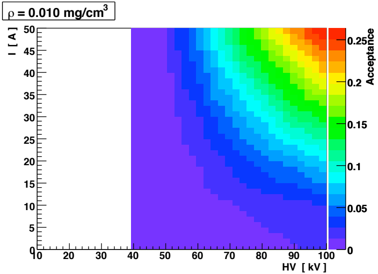

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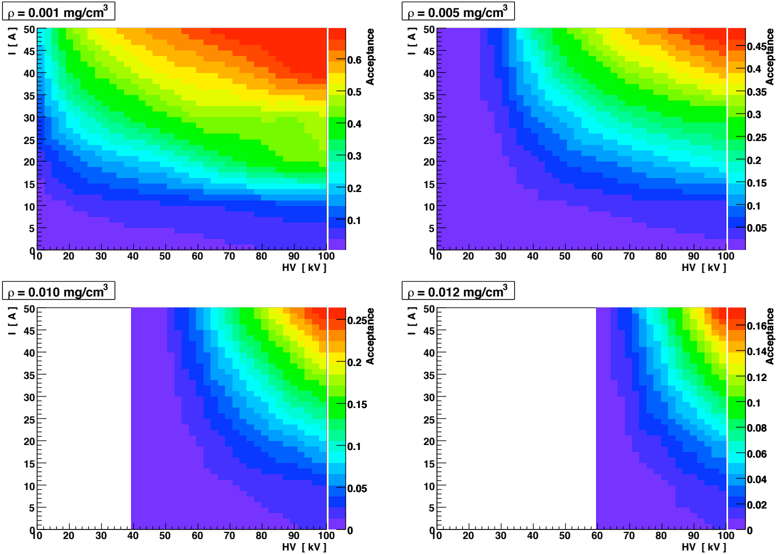

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Conditions

- Gas cell filled with helium, 3cm x 22cm, $\rho = 0.01\ \mathrm{mg/cm^3}$
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- Homogeneous magnetic field at 5 Tesla
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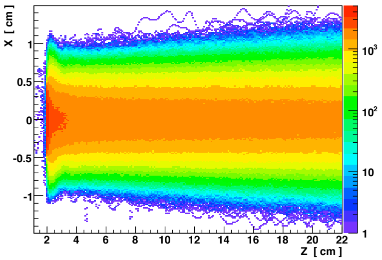

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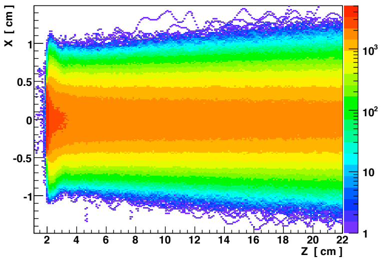

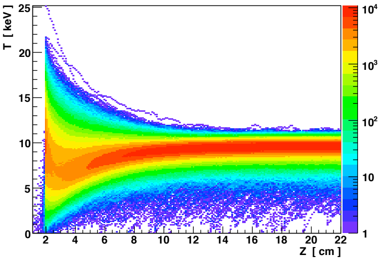

Transversal Emittance

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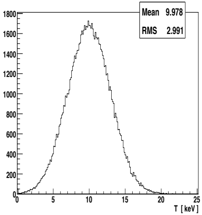

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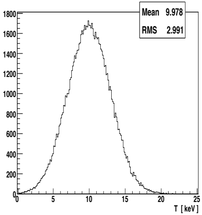

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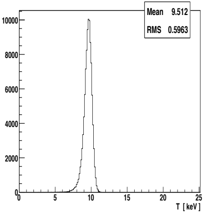

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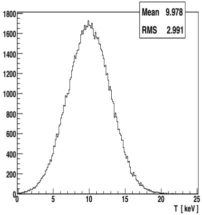

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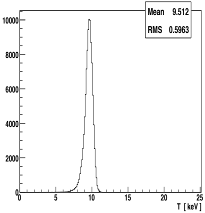

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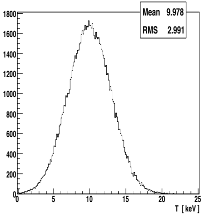

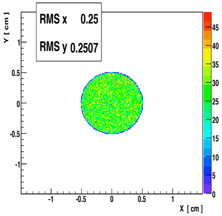

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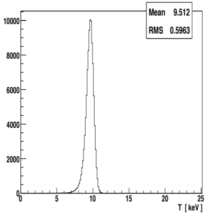

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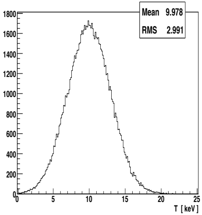

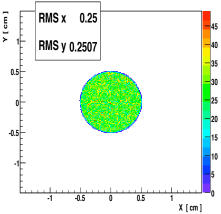

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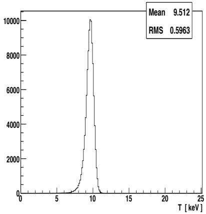

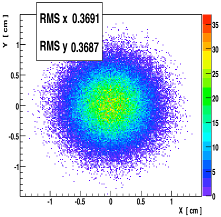

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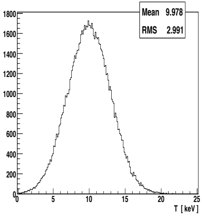

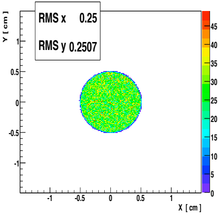

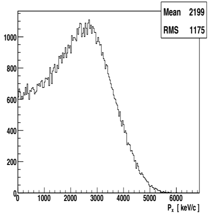

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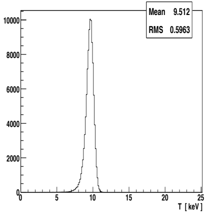

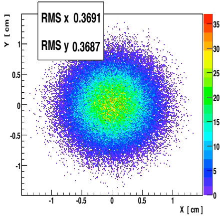

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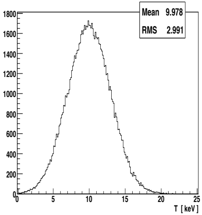

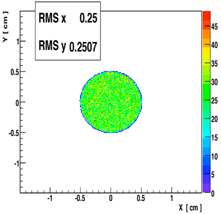

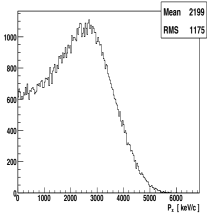

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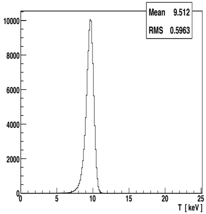

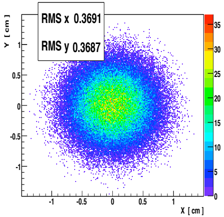

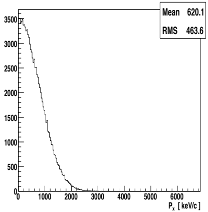

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$$\epsilon_T = \sigma_x \sigma_{p_x} \sigma_y \sigma_{p_y} / (\pi m_p c)^2$$

$$Source: \quad \epsilon_T = 4.4 \cdot 10^{-11} \ (\pi \mathrm{m})^2$$

$$EndPlane: \quad \epsilon_T = 9.3 \cdot 10^{-12} \ (\pi \mathrm{m})^2$$

$\Rightarrow$ **Reduction of Transversal Emittance of approx. one order**

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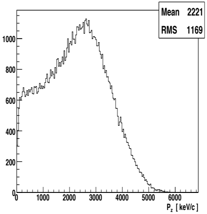

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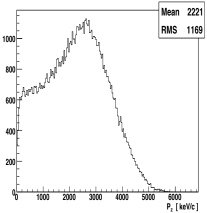

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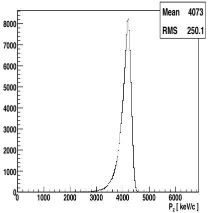

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$$\rightarrow \sigma_z = 2.7 \cdot 10^{-12} \text{ cm}$$

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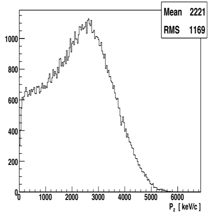

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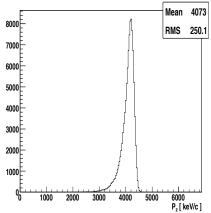

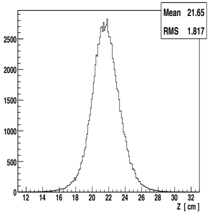

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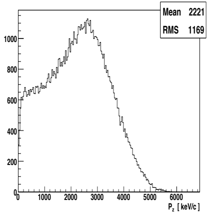

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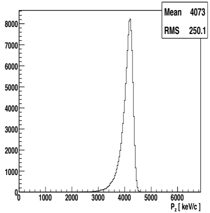

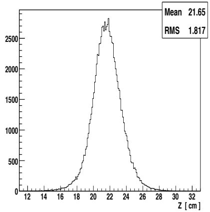

$\Rightarrow$ **No Reduction of Longitudinal Emittance**

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- with a rate of the proton source of $\approx$ 1 kHz we expect good statistics in a reasonable measurement period
- reach mean energies of the protons in a wide and measureable range

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  - Density gradient along the cell
  - other materials that contribute (e.g. nitrogen, water)
  - Detector response
  - Field configurations
- more analysis of simulation results necessary
  - Energy loss
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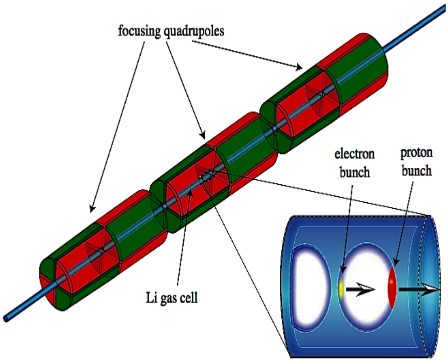
$\Rightarrow$ Comparison of simulation and experiment

$\Rightarrow$ Simulation of a Muon Collider Scheme

Literature

1. Galea, Caldwell, Newburgh , *A frictional cooling demonstration experiment with protons*, Nucl. Instr. and Meth. A, vol. 524, 2004
2. Abramowicz, Caldwell, Galea, Schlenstedt , *A Muon Collider scheme based on Frictional Cooling*, Nucl. Instr. and Meth. A, vol. 546, 2005
3. Daniel E.Greenwald , *Characterization of the Proton Source in the Frictional Cooling Demonstration experiment*, Master Thesis, 2007
4. D.H.Wright *et al.* , *Geant4 9.1 - Physics Reference Manual*, 2007
5. A.Caldwell *et al.* , *Proton Driven Plasma Wakefield Acceleration*, 2008

What is Wakefield Acceleration?



- a driver beam bunch of charged particles propagates through a plasma
- this leads to an oscillation of the plasma electrons $\longrightarrow$ high electric fields which can accelerate a witness beam
- an electron beam of several TeV is conceivable using a PDPWA
- high energies achievable, no synchrotron radiation and small spatial dimensions (linac)
- avoid electrical breakdowns

Wakefield Acceleration - The main issue

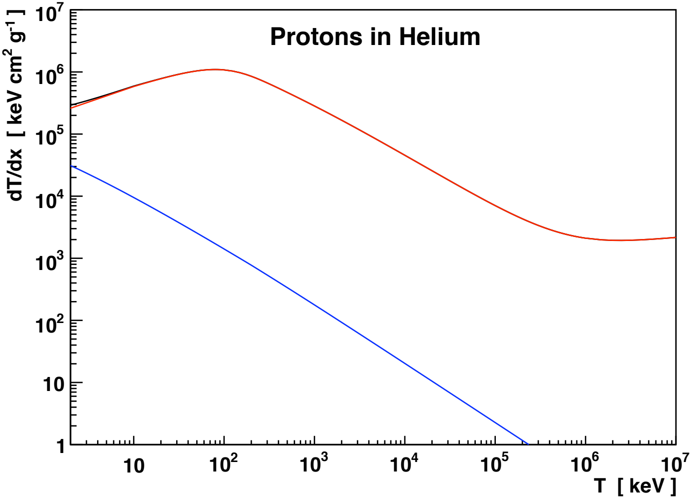
Particle Source $\Rightarrow$ **Frictional Cooling** $\Rightarrow$ Phase Rotation $\Rightarrow$ Plasma Cell

- need driver bunches (e.g. protons) with very high densities and a very small spatial spread
- the gradient reachable by a symmetric driver bunch is limited by

$$E_{max} \propto (N/\sigma_z)^2$$

- to reduce the sixdimensional emittance *Frictional Cooling* might be the promising method
  $\rightarrow$ it could be used for both the driver and the witness as long as they are heavy charged particles
- phase rotation section still a large obstacle

Stopping Power in detail



A typical run - Emittance

- initial emittance is zero in simulation and experiment
- transversal emittance $\epsilon_T = \sigma_x \sigma_{p_x} \sigma_y \sigma_{p_y} / (\pi m_p c)^2$
- longitudinal emittance $\epsilon_L = \sigma_z \sigma_{p_z} / (\pi m_p c)$
- from the simulation we get

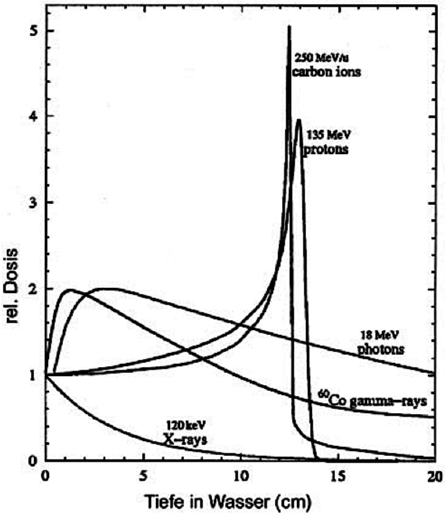
$$\sigma_x = \sigma_y = 2.2 \cdot 10^{-3} \text{ m}$$
$$\sigma_z = 1.6 \cdot 10^{-2} \text{ m}$$

$$\sigma_{p_x} = \sigma_{p_y} = 770.5 \text{ keV/c}$$
$$\sigma_{p_z} = 232.1 \text{ keV/c}$$

$$\Rightarrow \quad \epsilon_T = 3.4 \cdot 10^{-12} \ (\pi \text{m})^2$$
$$\Rightarrow \quad \epsilon_L = 3.9 \cdot 10^{-6} \ (\pi \text{m})$$

$$\Longrightarrow \quad \epsilon = \epsilon_T \epsilon_L = 1.3 \cdot 10^{-17} \ (\pi \text{m})^3$$

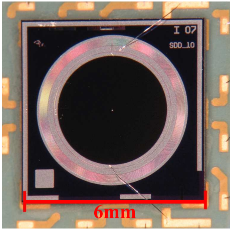
Focussed particle beams in Medicin

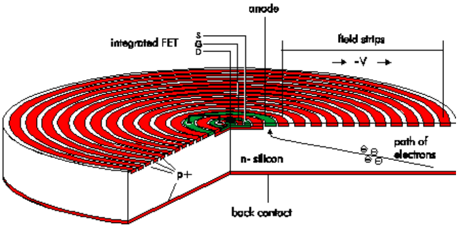


- focussed beams of heavy charged particles (protons, ions) are needed for
  - radiation of tumors
  - assembling of radioisotopes for cancer therapy
- they loose almost all their energy in a single spot (Bragg peak)
- *Frictional Cooling* could help to provide collimated particle beams with in a system of small spatial dimensions

The Silicon drift detector

- SDD was developed by the *MPI Semiconductor Laboratory* (HLL) and built by *PNSensor* (originally for X-rays)
- working at resolutions down to 150 eV in the keV range and a count rate of up to 1 MHz
- 10 mm^2 circular area of 450 μm thick Silicon





Charge Collection Efficiency Curve