Investigations on Transport and Storage of High Ion Beam Intensities

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Disputation

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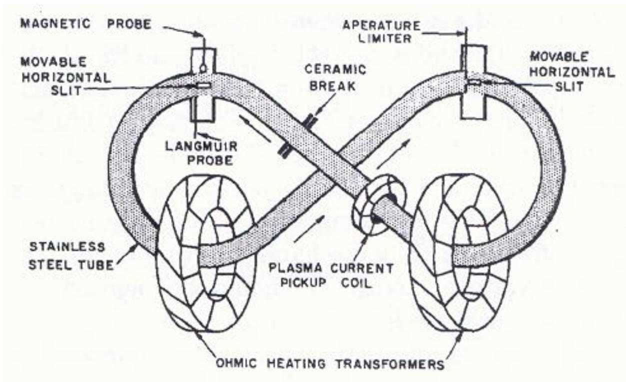
- Motivation
- Simulation of beam transport
- Experimental results
- Conclusions

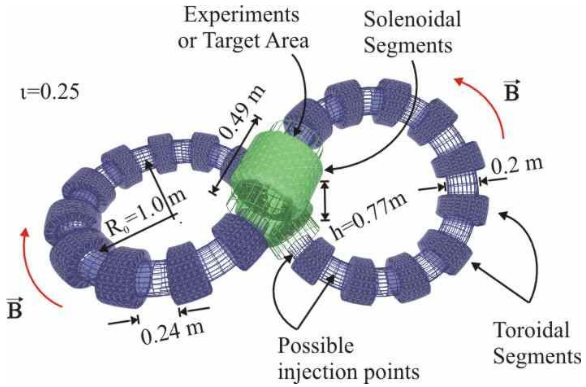
Motivation

Stellarator (Project Matterhorn 1960's) Los Alamos



- Neutral Plasma
- kT = 1-10 *keV*
- Current = up to *MA*
- Confinement time = ~*ms*
- Thermal fusion

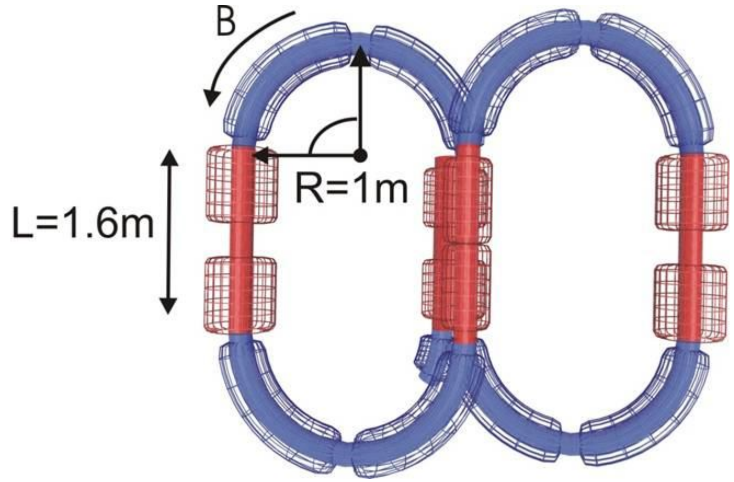
Storage Ring (early study) Frankfurt

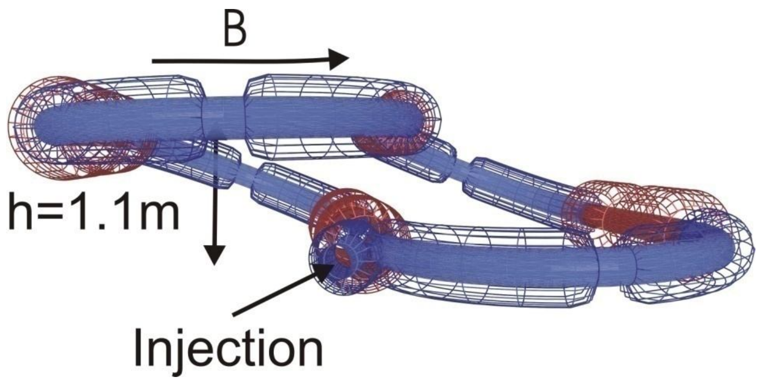


- Non-Neutral Plasma
- p_z main component
- Current = few 10 *A*
- Confinement time = ~1 *s*
- Atomic physics experiments, beam-beam collision, low energy experiments

Proposal at IAP Frankfurt

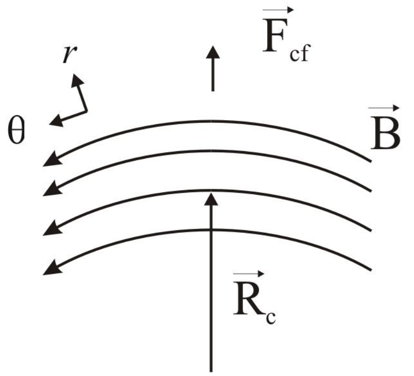
- Low energy and high current storage
  - High space charge
  - Injected Proton beams 200 *mA* @150 *keV*, multiturn injection
- Longitudinal magnetic fields as guiding force
  - No force free region (drift without external fields)
  - Higher transverse momentum acceptance
  - B = about 5 *T*
- Beam Dynamics
  - Inhomogeneous curved magnetic fields – drift motion
  - Injection - to bring charged particles from field free region into the strong fields



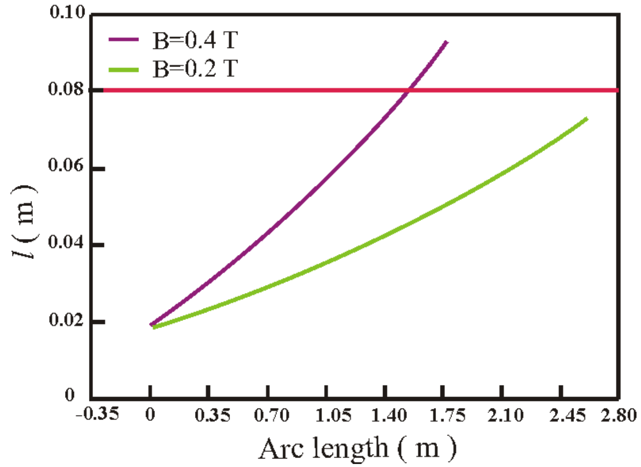


Why figure-8

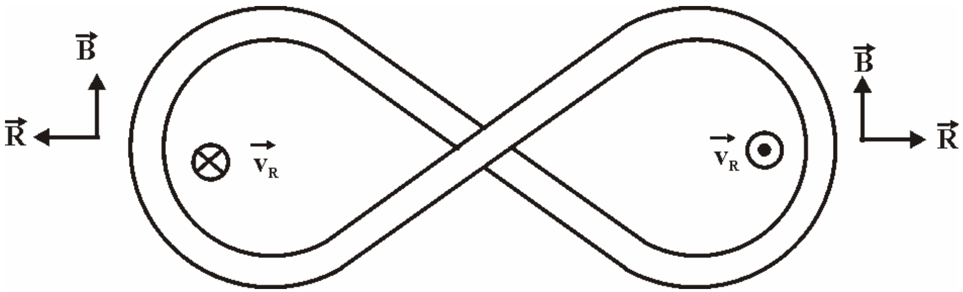
Curvature Drift => Beam losses

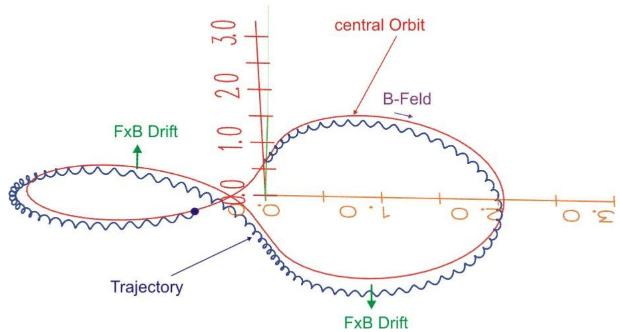


$$v_{R\times B} = \frac{mv_{\parallel}^{2}}{qB^{2}} \frac{\vec{R}\times\vec{B}}{R^{2}}$$



Solution => twist gives compensation in either part



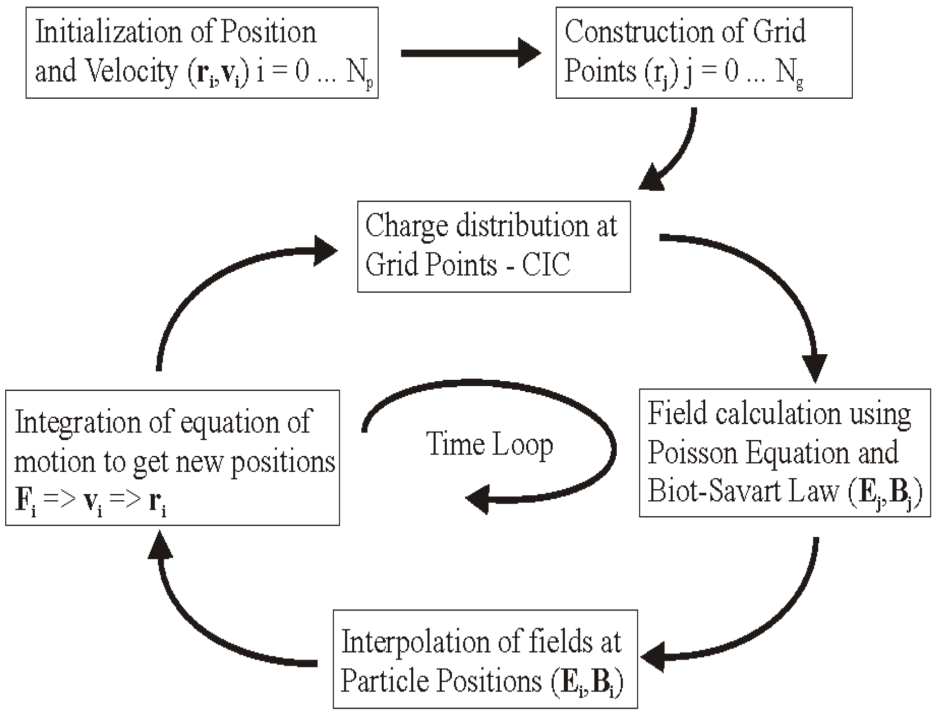


Numerical model for beam simulations

Initial Distribution
- Homogeneous distribution
- External (Measured)

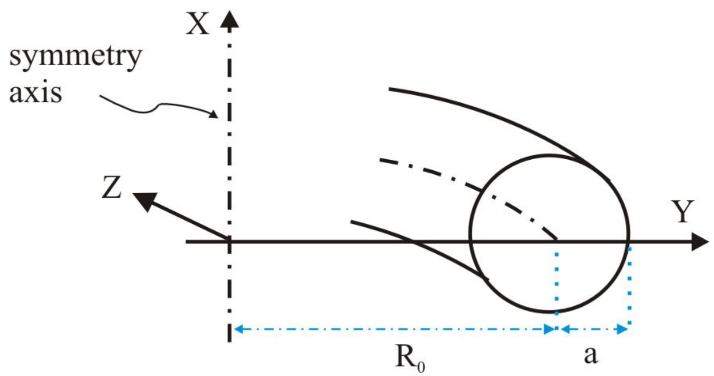
Grid geometry
- Toroidal, Cartesian, and Cylindrical mesh

PIC method
- Second order charge distribution
- Multi-species, multi-particles simulations



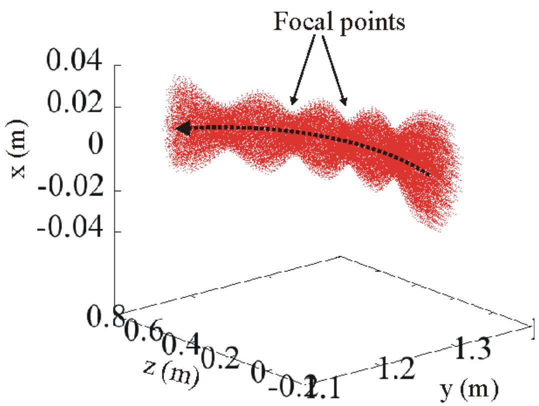
Poisson solver
- Poisson solver in toroidal coordinates
- Arbitrary boundary conditions to define electrode
- Matrix solved with iterative methods

Proton beam transport in curved fields

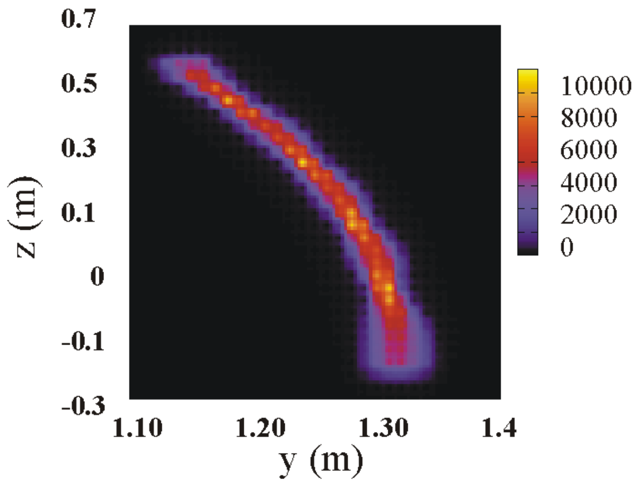


Example :
10*keV* proton beam injected into 30 degree toroid at 0.6 *T*.
Vertical drift results in about 15 mm

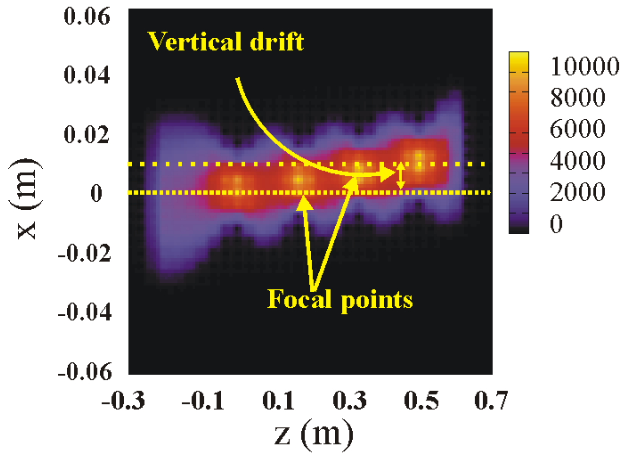
3d view



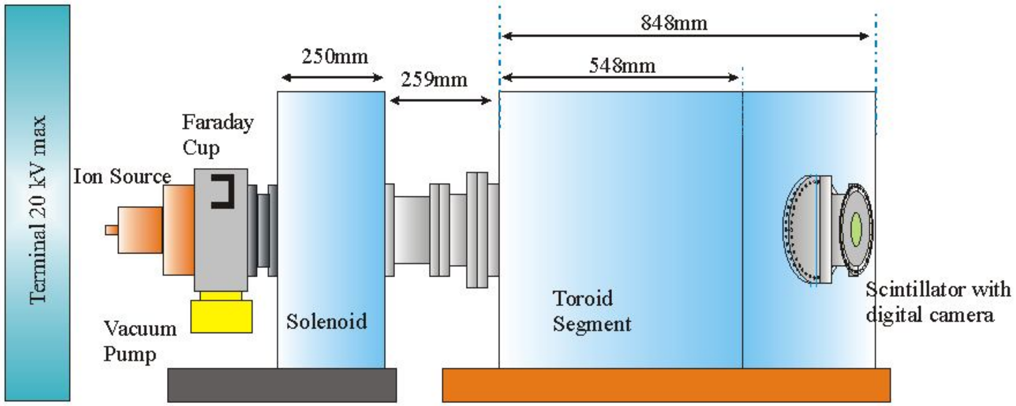
y-z projection

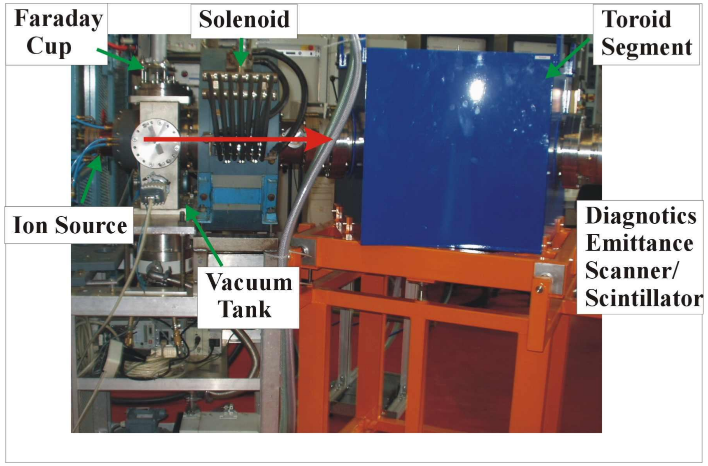


x-z projection



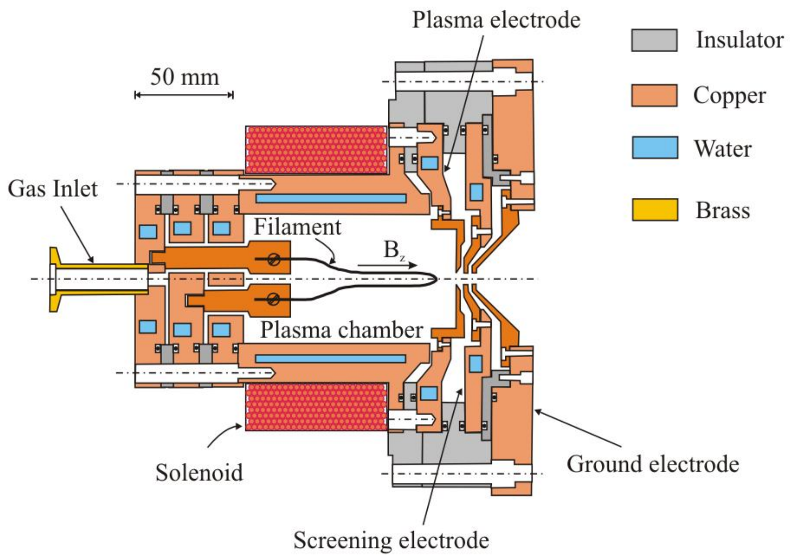
Experiments





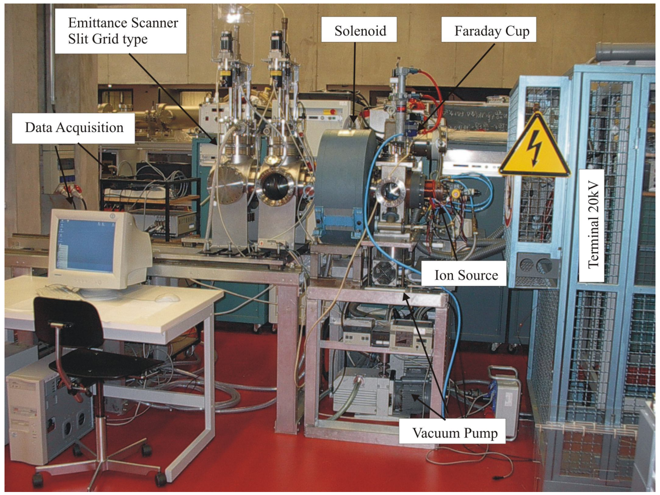
- Injector: HV terminal, volume type ion source, solenoid
- Transport through single segment with toroidal magnetic field
- Diagnostics: Phosphor screen (*P20*) and digital camera
- Scaled down experiments with respect to energy and magnetic field

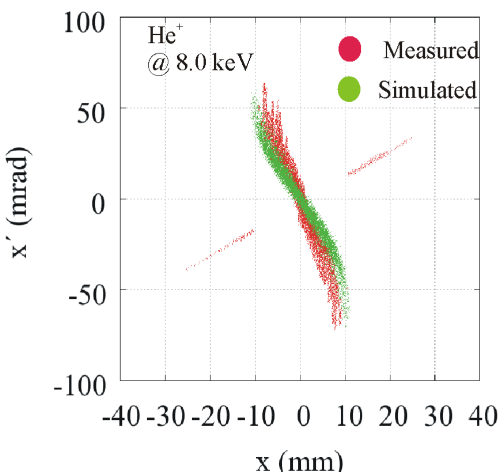
Beam Matching: Source and Solenoid



Type	hot filament volume type
Extraction system	triode
Ion Specie	$He^+, composite(H^+, H_2^+, H_3^+)$
Energy	$20\ keV max$
H^+ max	$\sim 45\% \Longrightarrow 2.8\ mA\ @\ 10\ keV$
H_2^+ max	$\sim 91\% \Longrightarrow 2.84\ mA\ @\ 10\ keV$
H_3^+ max	$\sim 95\% \Longrightarrow 3.05\ mA\ @\ 10\ keV$
He^+ max	$2.0\ mA\ @\ 10\ keV$

Perveance (~10^{-3}) of ion beam in the same order
=> comparable space charge forces for 5*T* ring





Phase-Space measurements from source

↓

Simulations transport through solenoid (LINTRA)

↓

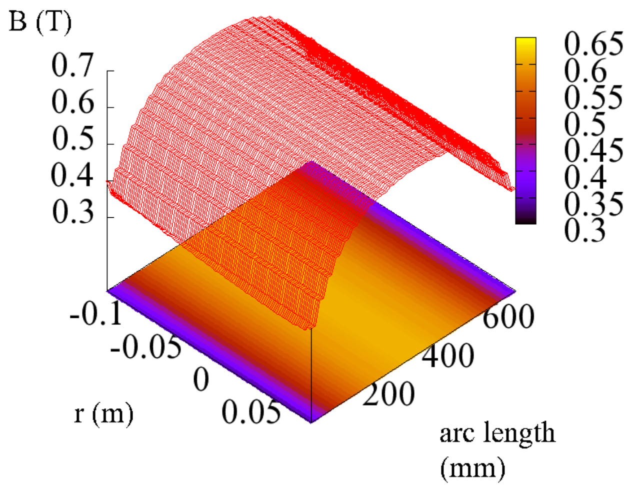
Comparison with experiments

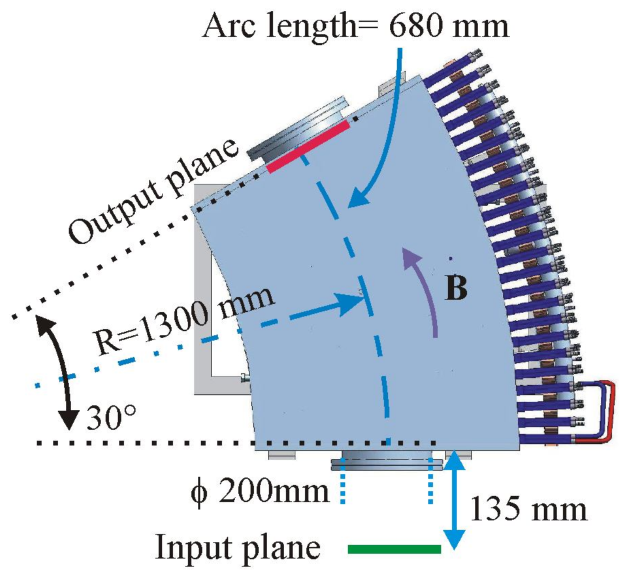
↓

Calculation of phase-space for injection into toroid

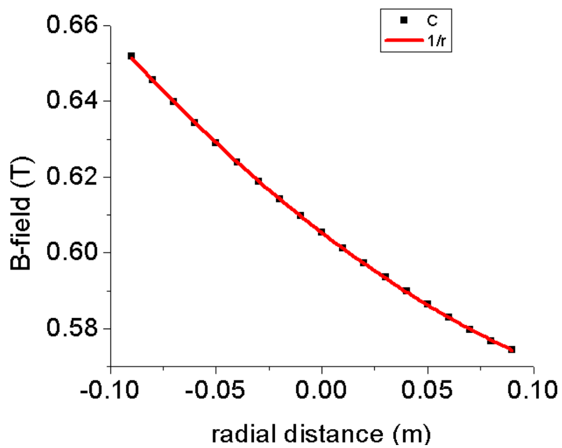
Toroidal segment

Maximum field 0.6*T* @ 480*A*

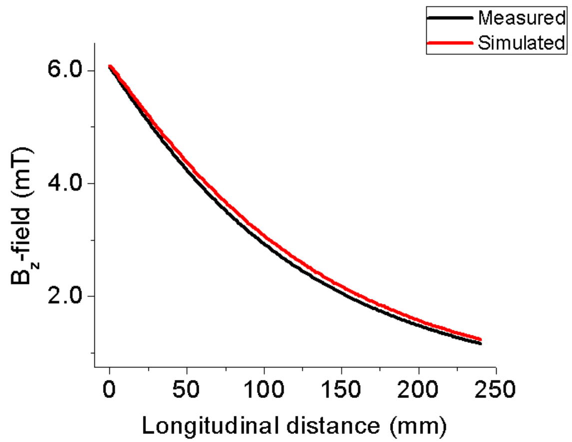




Field gradient~ 0.4T/m

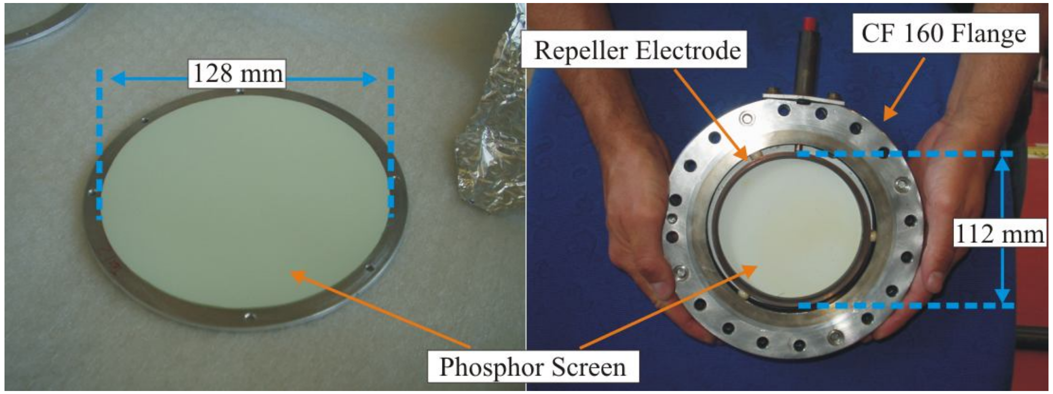


Fringe field comparison at lower current



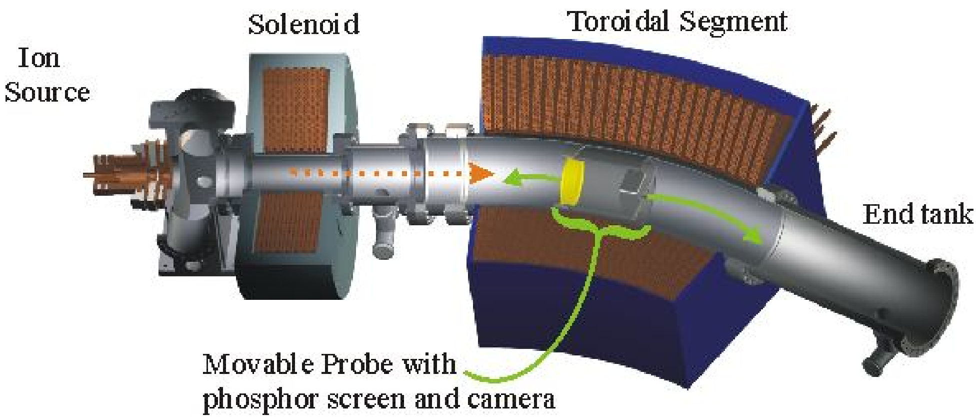
Optical diagnostics

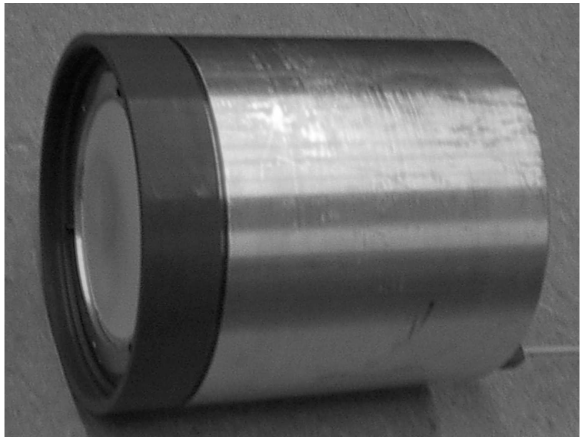
Fixed detector technique



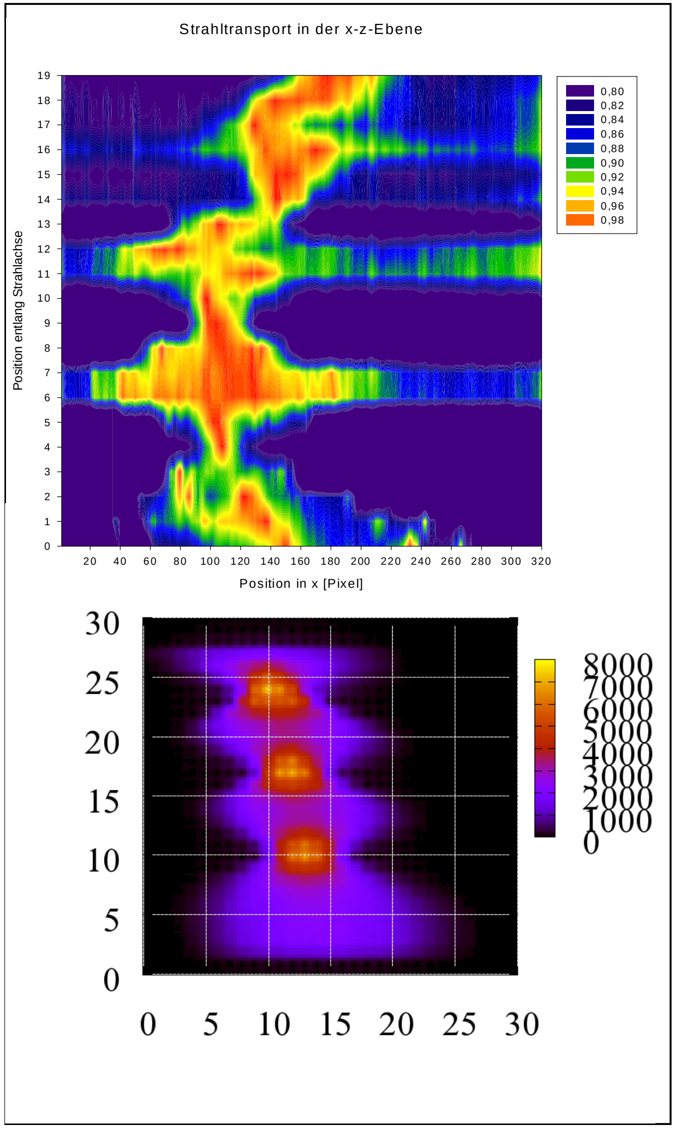
- Phosphor screen *P20*
- Max power 1 *W/cm²*
- Repeller electrode 1.2*kV* max
- Digital camera (WCam 300)

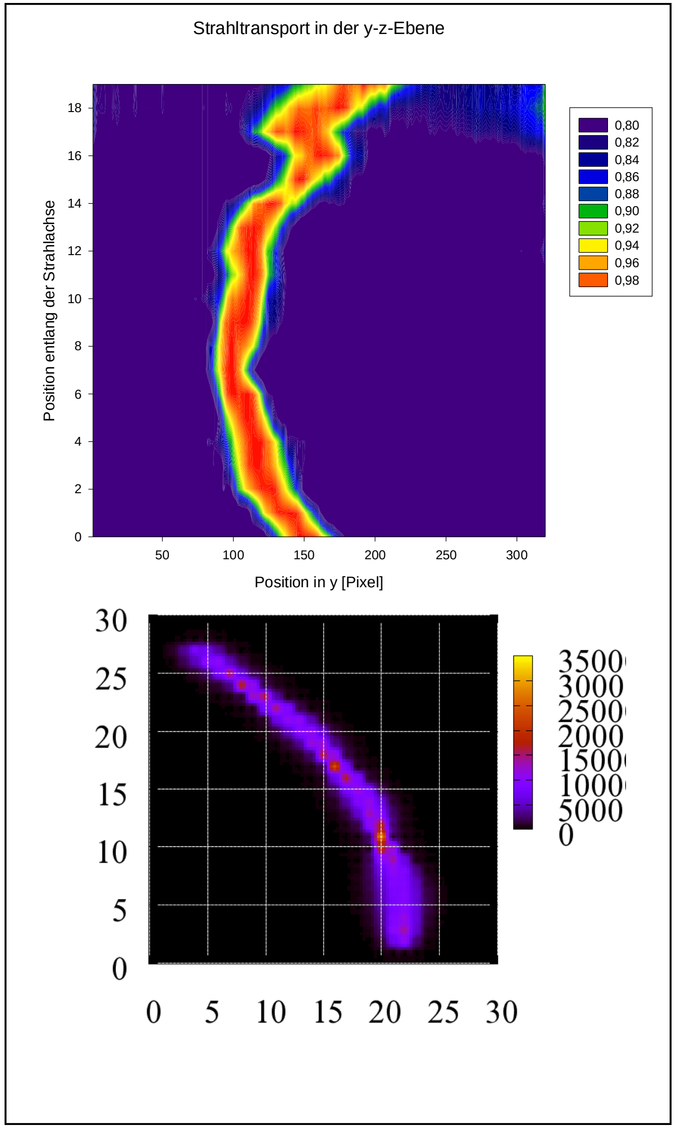
Movable detector technique





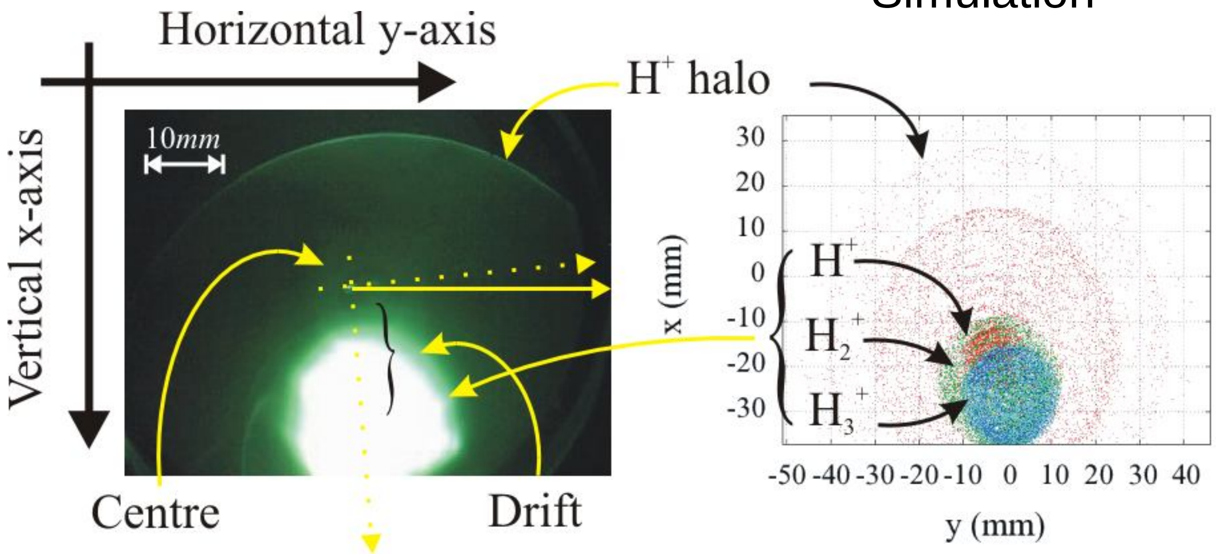
He-beam reference





Composite proton beam

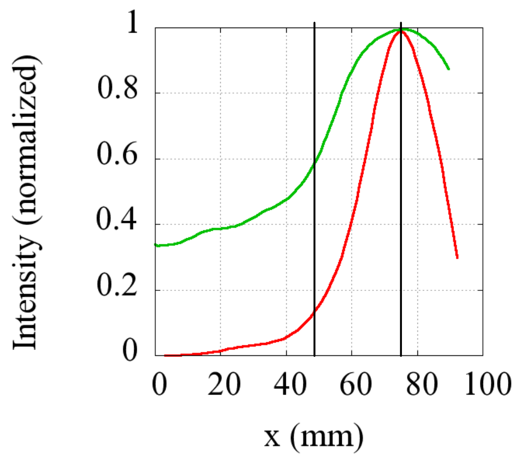
Measurements Simulation



An example of a composite proton beam @8 *keV* ~2.0 *mA*

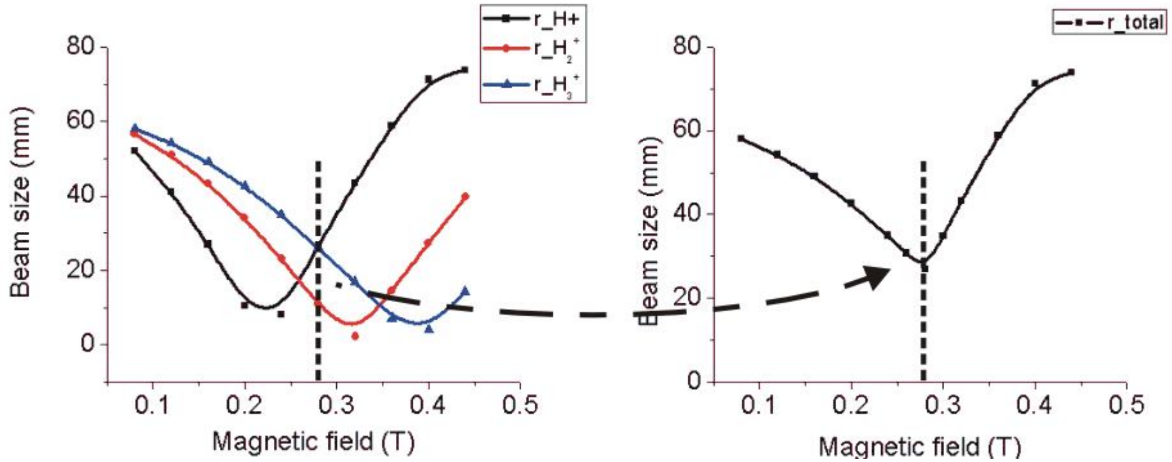
Measurements

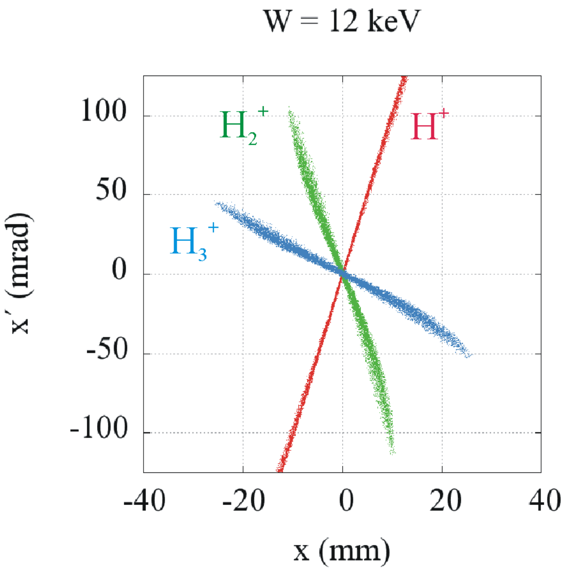
Simulation

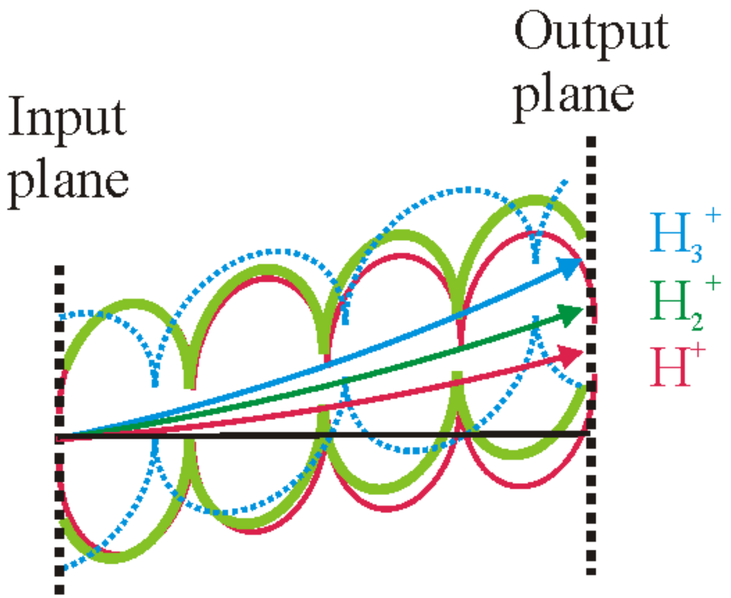


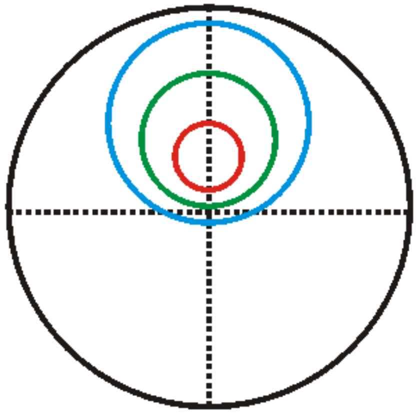
- Magnetic field in opposite direction hence curvature drift downward
- Image processing code was written
- Drift, beam size were compared directly with simulation

Composite beam transport







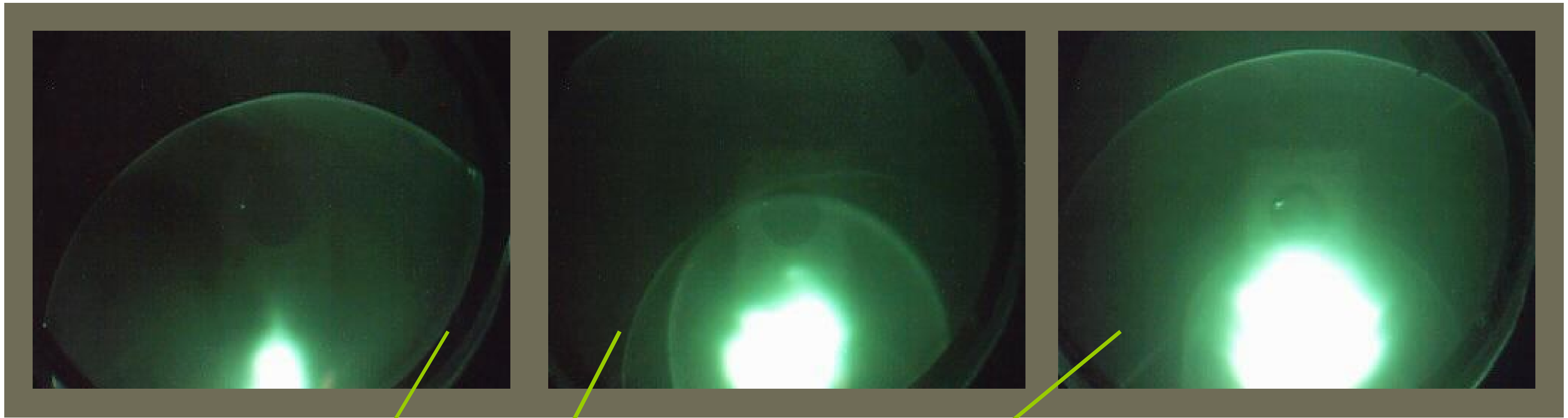


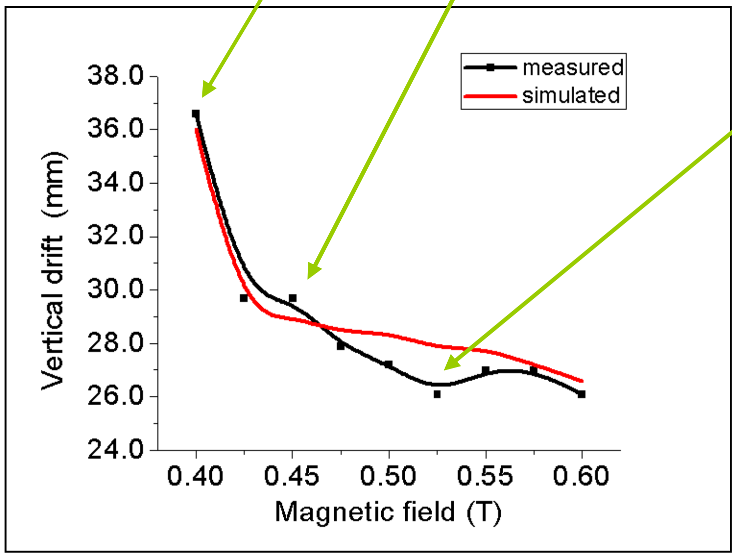
Multispecies

Simulation

Phase synchronization

Drift measurement and comparison

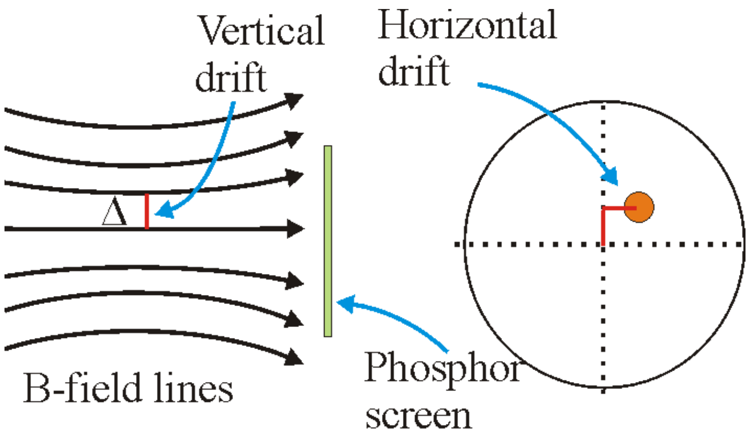


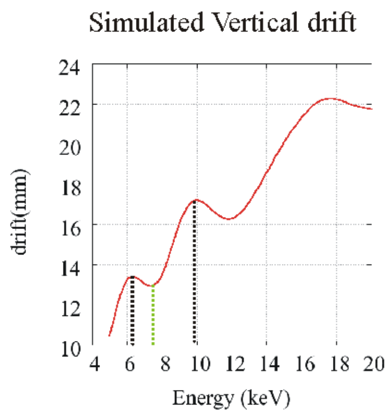


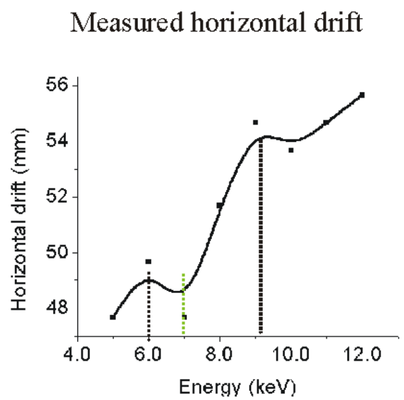
Experimental setup

Additional Effects

Effect of fringing fields : coupling between planes

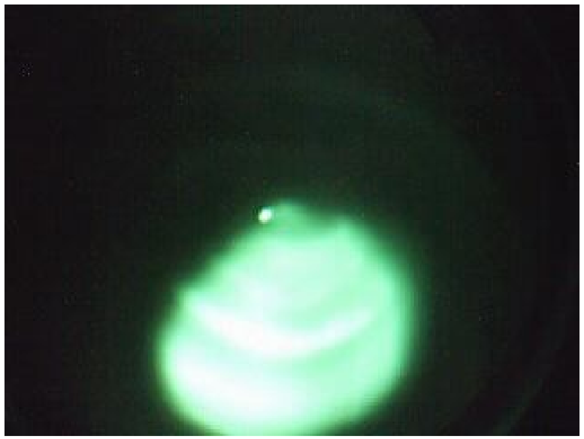




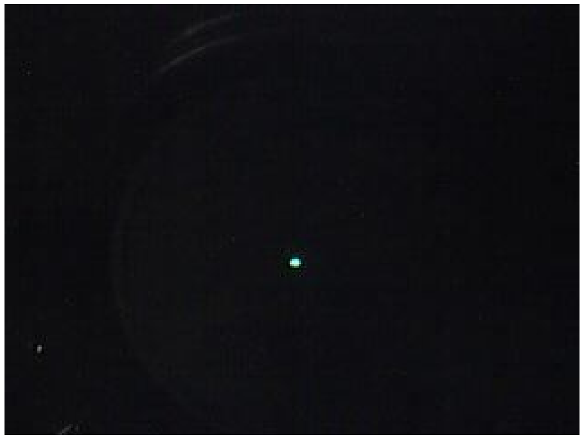


Proton beam @10keV in magnetic field of B=0.6T

Proton beam



Electron beam @3keV

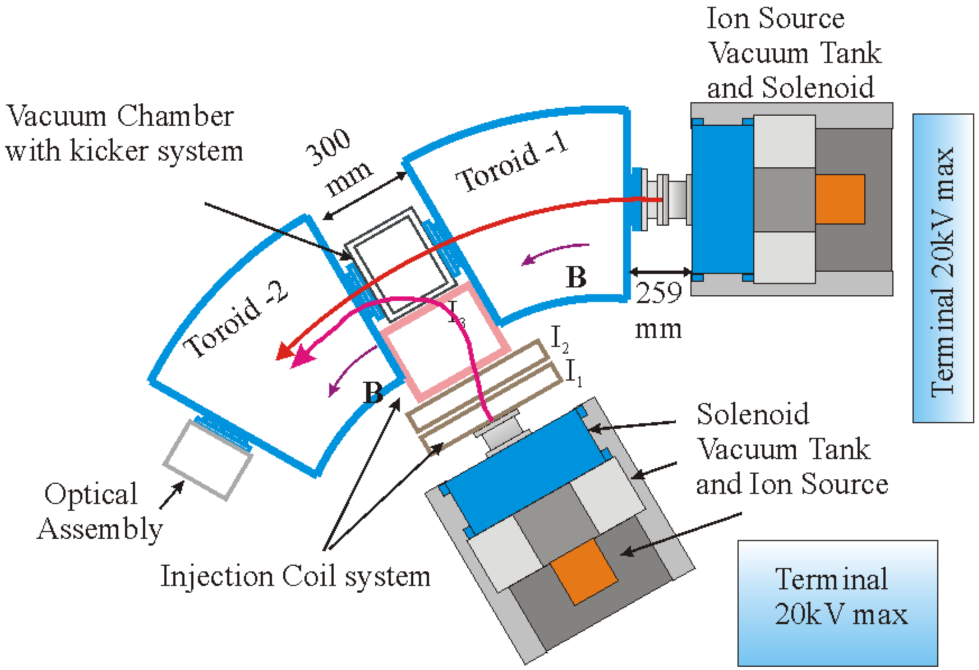


Drift due to electrons about 0.3 *mm* => This gives magnetic centre

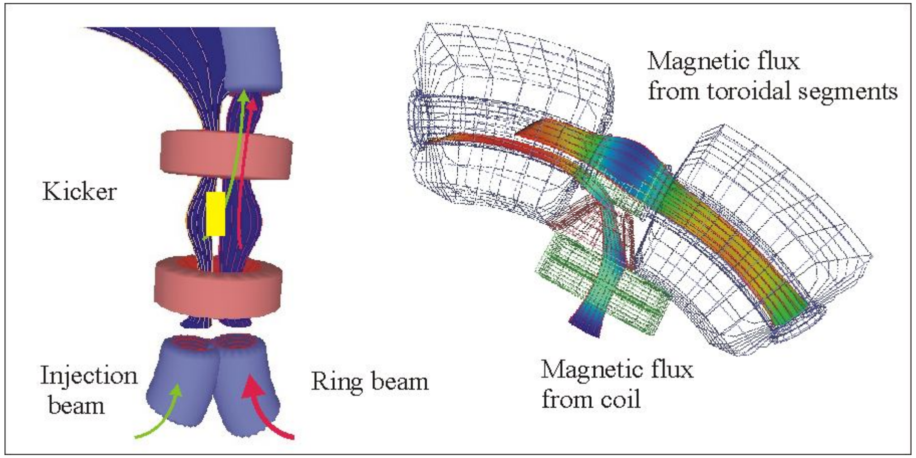
Injection system

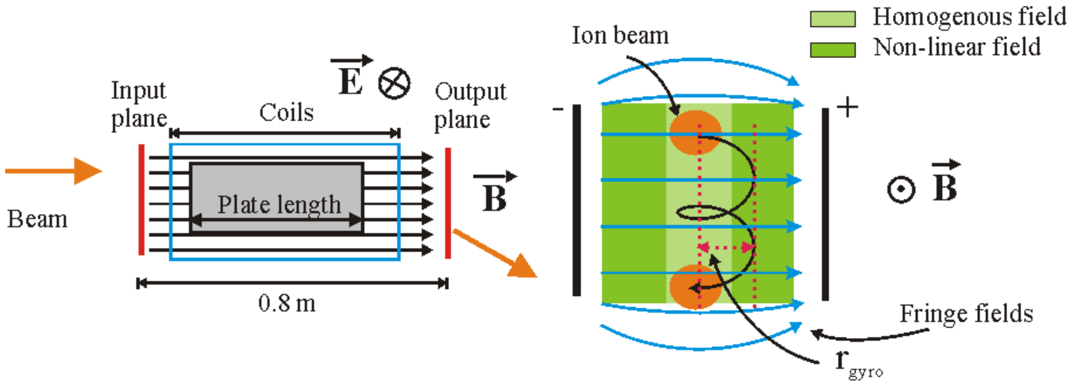
Simulation of beam dynamics in toroid → Comparison shows acceptable tolerance → Injection system that can be realized practically

Experiments of beam transport in toroid → Comparison shows acceptable tolerance



Kicker

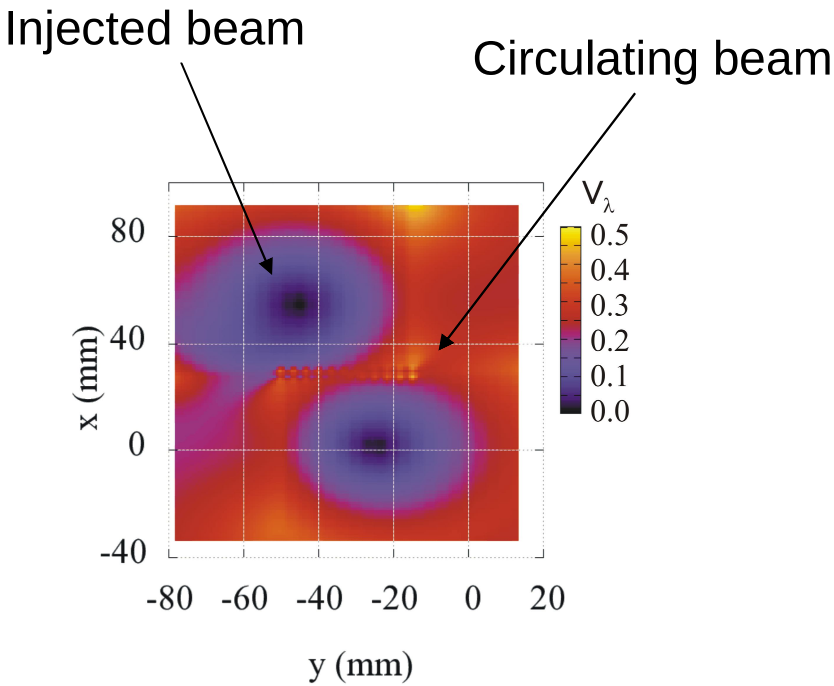


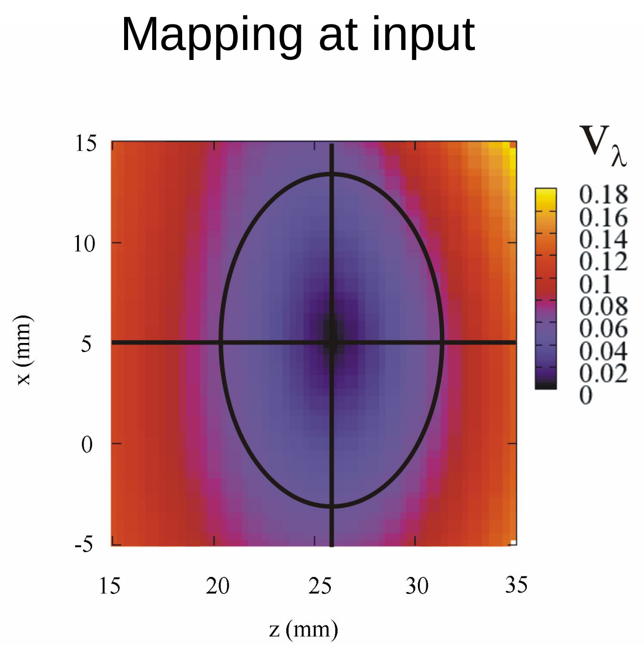


- The injected beam is moved from auxiliary field lines to main lines using kicker
- The injection scheme for lower scale experiments is based on the same principle that can be used for complete ring
- Unshielded segments help providing larger space, in principle the distance between two segments should be much less than the aperture

For ring: Kicker plates will be installed in straight sector 1.4m long
@150keV single rotation about 2.3 microseconds
Multiturn like system to be used

Simulated two beams for experiments



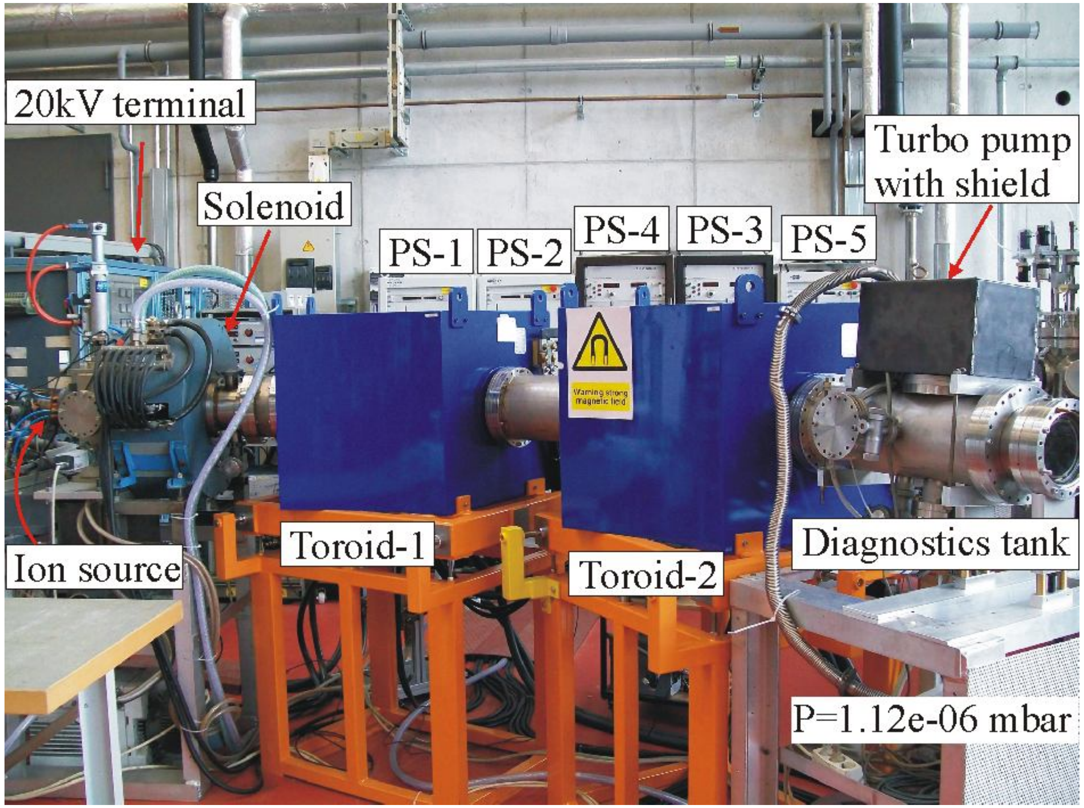


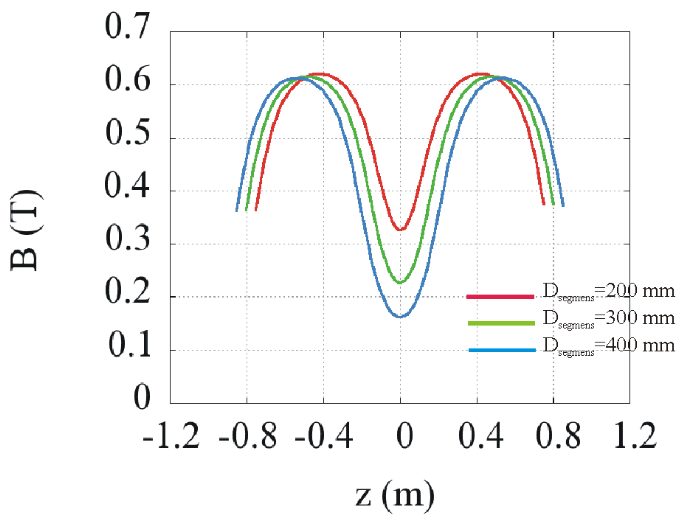
• Figure on the left shows injected and circulating beam with two segments coupled with 0.6*T* field and separation distance 300*mm*

• Figure on the right shows mapping at input plane indicating at least a beam with diameter 10mm can be injected

• Mapping parameter velocity ratio = $(v_{\perp}/v_{\parallel})_B$

Coupling of two segments





- The coupling between two segments will be investigated with beam at different distances
- 300 mm is reasonable distance for injection experiments as predicted by simulations

- The segments can be arranged with S-shape to compensate drift
- Electron trapping will be investigated using this setup

Conclusions

- The ion beam transport in toroidal like magnetic field was investigated
- A simulation code was developed
  - Space charge
  - toroidal and other coordinate systems
  - Multi-specie,multiparticle
  - Arbitrary boundary conditions
- Experiments were carried out
  - Ion source was constructed and characterized
  - Designed injector fulfills the experimental requirements
  - Development of beam diagnostic techniques in strong fields
- Numerical model was successfully compared with experimental data
- An optimized injection system was designed using the developed simulation tool

Thank you

- Prof. Ratzinger
- Prof. Schempp and comittee members
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