Numerical Models for NNP Confinement

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- NNP (Non-neutral Plasma)
- Motivation
- High current ring
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Neutral Plasma

Number of particles in Debye sphere

$n\lambda_D^3 >> 1$

Debye length smaller than size of plasma

$\lambda_D < L$

Observed time scale longer than

$T > 2\pi/\omega_p$

Neutrality -> +=- (quasineutrality)

Non-neutral Plasma

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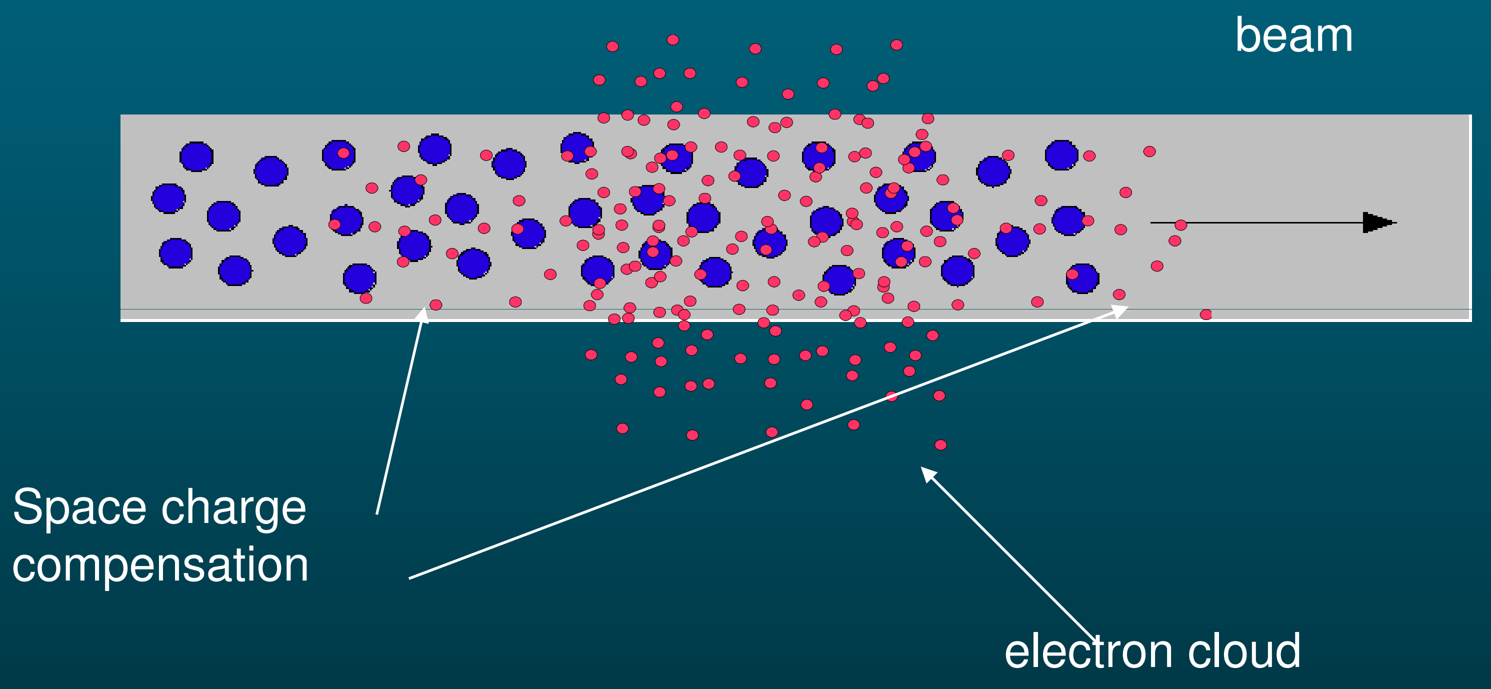
Motivation

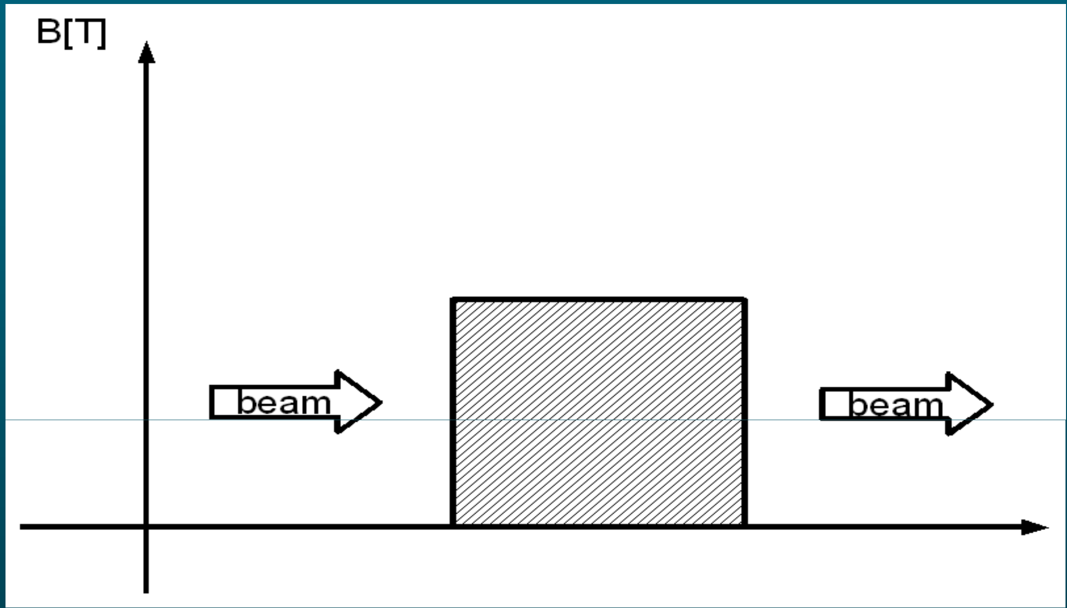
- High current (density) beams Transport ?
  Accelaration?
  Accumulation?
- Space charge compensation
- Interaction with Non-neutral plasma (NNP)
- Using of guiding magnetic fields Drifts
- High current beam projects
  - FRANZ (Frankfurt neutron generator)
  - High current storage ring

Motivation



- **Influence of external fields?**

Solenoid



-Momentum change
-Rotation
-Momentum change

$$H = \frac{(\vec{p} - q\vec{A})^2}{2m} + q\phi$$

$$\vec{p}_{start\perp} = \vec{p}_{sol\perp} + q\vec{A}, \text{ angular momentum and energy conservation}$$

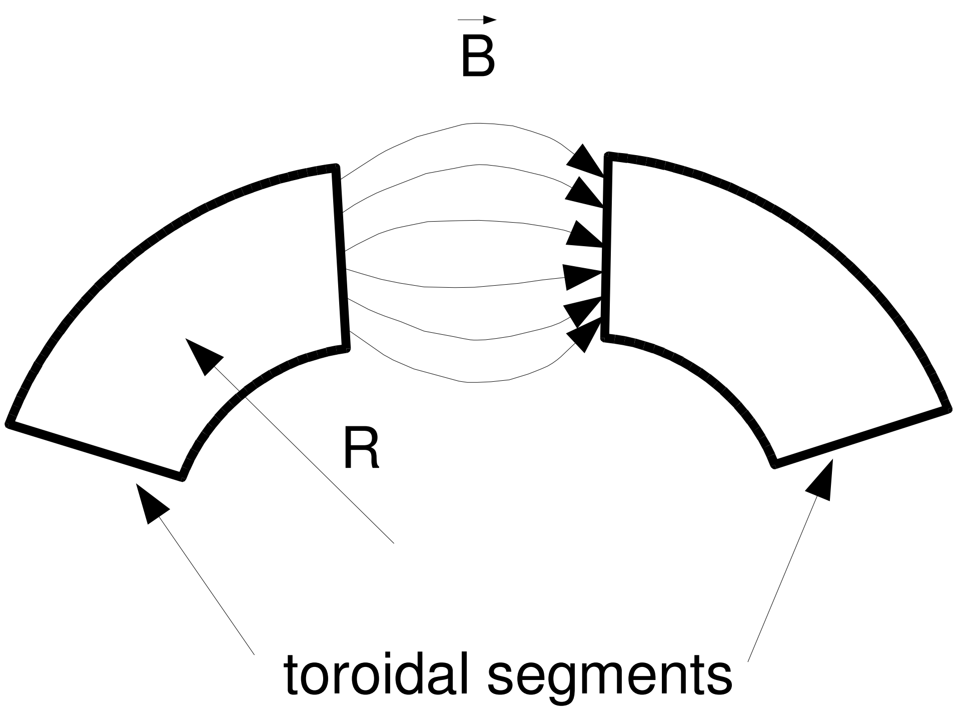
$$\vec{\mathrm{A}} \text{ for hard edge solenoid} = \mathrm{A}_\varphi = \frac{B_0 \cdot r}{2}$$

Toroidal segment

- Effects

  - density variation – electric hoop forces
  - mirror charges
  - centripetal force
  - change of momentum

Toroidal transport - Drifts



- Role of compensation electrons in mirror-like configuration
- Drifts – ExB, centripetal force, grad B
- Different densities

  n_e , n_p and focusing properties – Brillouin flow limit

Magnetic connection of segments

- Magnetic Momentum

$$\mu = \frac{mv_\perp^2}{2B}$$

Higher Orders

$$< \mu >= \mu_0 (1 - \frac{mv_\parallel}{qB} \cdot \vec{b} \cdot \vec{\nabla} \times \vec{b})$$

Conservation

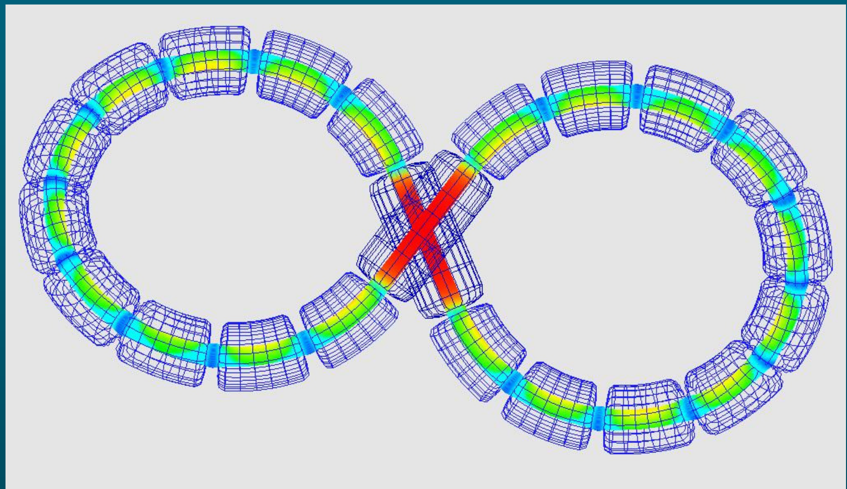
when field change small

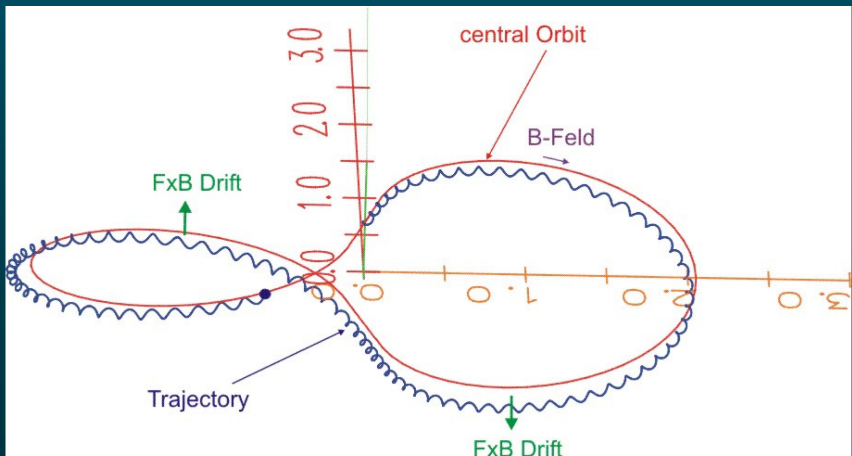
$$(\frac{d}{dt} = \frac{\partial}{\partial t} + v_\parallel \cdot \vec{b} \cdot \nabla) << \Omega$$

For example |B|-Variation 0.3T in 300mm =>

$$\frac{d\vec{B}}{dt} = (\frac{\partial}{\partial t} + v_\parallel \cdot \vec{b} \cdot \vec{\nabla})\vec{B} \sim v_\parallel \cdot \frac{0.3T}{0.3m} = 1.38 \cdot 10^6 \cdot 1 << \Omega \cdot \overline{B} = \frac{q\overline{B}}{m} \cdot \overline{B} = 1.94 \cdot 10^7$$

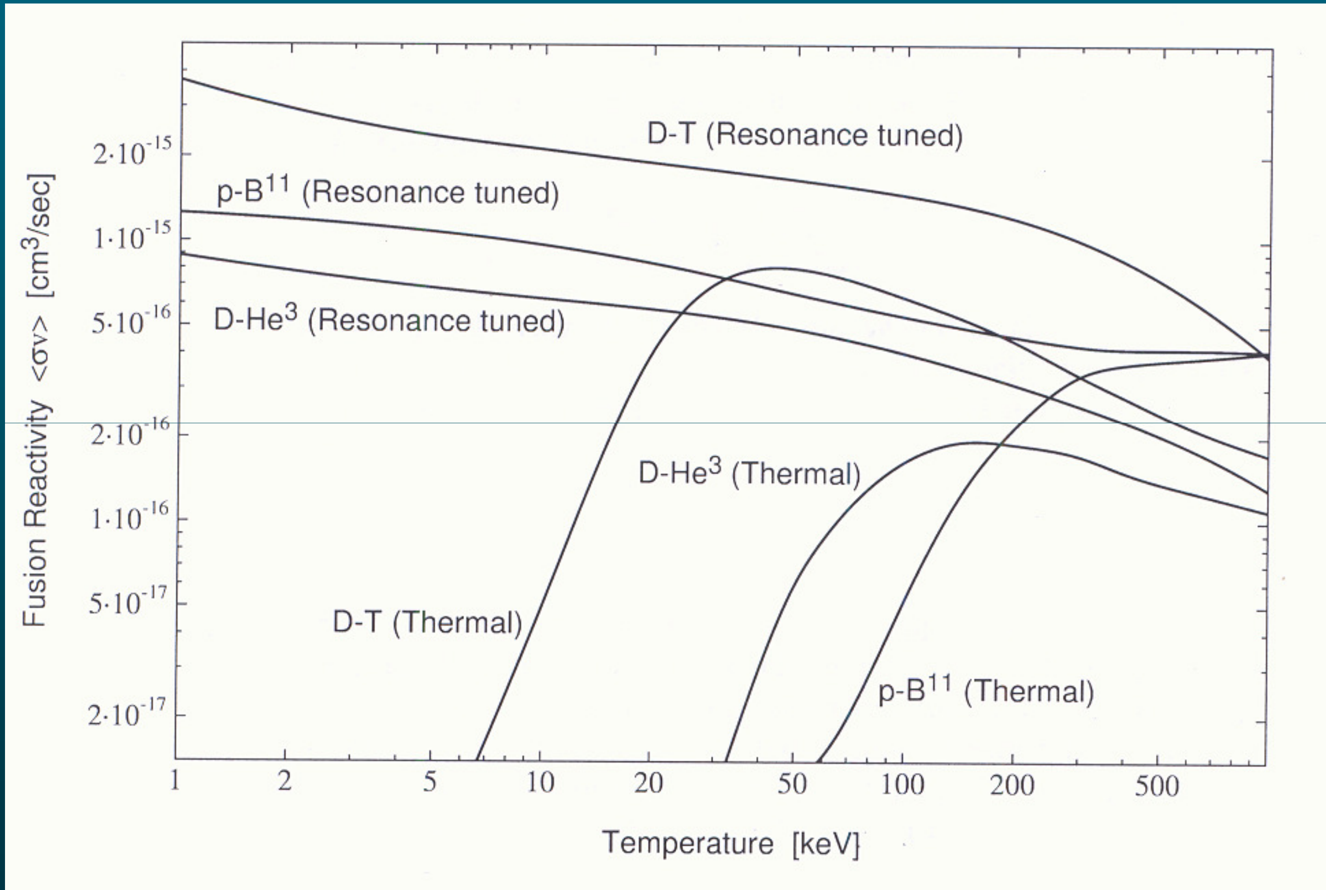
Figure-8 Storage Ring





- **R ~ 1m**
- **r ~ 0.2m**
- **L~10m**
- **22 toroidal segments**
- **h ~ 1m**
- **B ~ 5T**
- **I ~ 10A**

Reactivity of different fusion processes



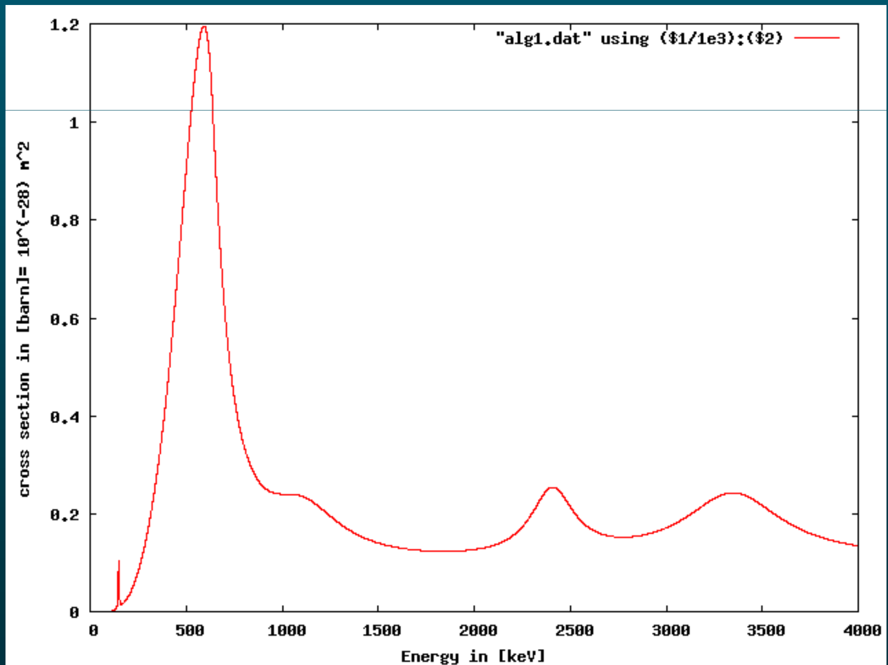
N.Rostoker 1997

Fusion reaction in the ring

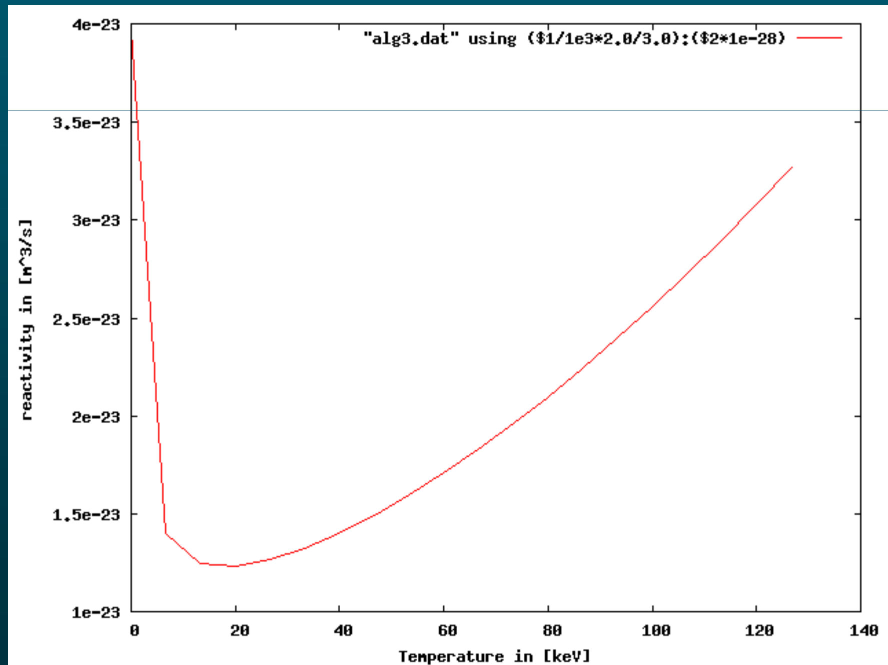
fusion reaction

$^{11}B + p \rightarrow 3\alpha$ (8.7MeV);

fusion cross section $\sigma_{max} \sim 10^{-28}\ m^2$



Reactivity of 150 keV proton beam in dependence from beam temperature



ω_c [s^{-1}] @5T	$4.8 \cdot 10^8$
n_B [m^{-3}]	$6.6 \cdot 10^{16}$
Beam radius a[m]	0.01
Debye length [m]	$3 \cdot 10^{-4}$
ExB rotation time [s]	$5.2 \cdot 10^{-10}$
Ultra high vacuum (n ~ 10^{12} m^{-3} ~ $4 \cdot 10^{-11}$ hPa) Collision time τ_c[s]	12.5
Confinement time in toroidal magnetic field (Crooks 1994)	$\tau \approx \tau_c \cdot (R/\lambda_D)^2$
Confinement time on magnetic surface (Pedersen 2003)	$\tau \approx \tau_c \cdot (a/\lambda_D)^4$

Codes

- **Field mapping – Biot-Savart solver**

(Predictor-Corrector method, Field-line integration –1D information)

- **Frequency decomposition – FFT (for every surface – 1D => 2D)**
- **Reverse mesh design – in new coordinates**

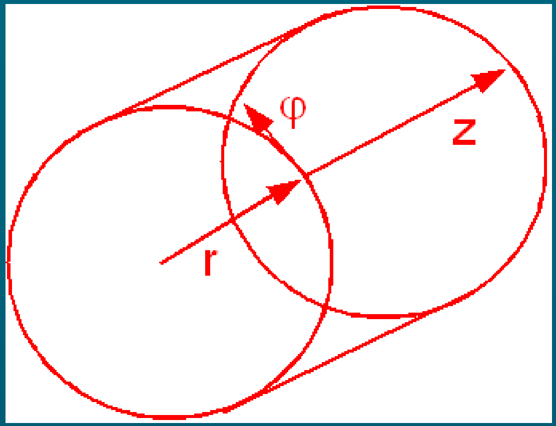
ψ<0,1>, θ<0,2π>, ξ<0,2π>

- **Poisson equation**
- **Guiding center drift motion**

Parallel cluster of CSC (Centre for Scientific Computing)

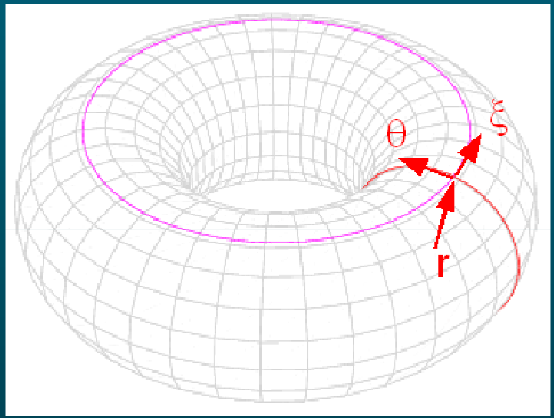
Cylindrical coordinates

r, φ, z



Toroidal coordinates

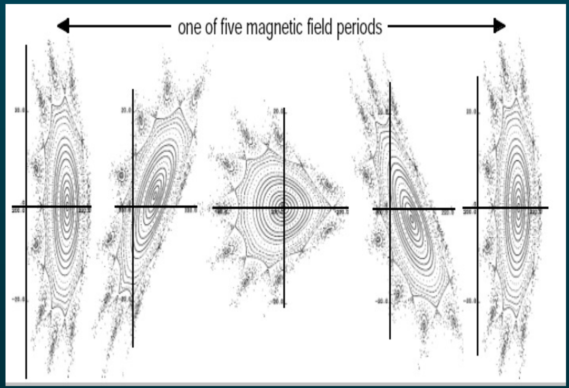
r, θ, ξ



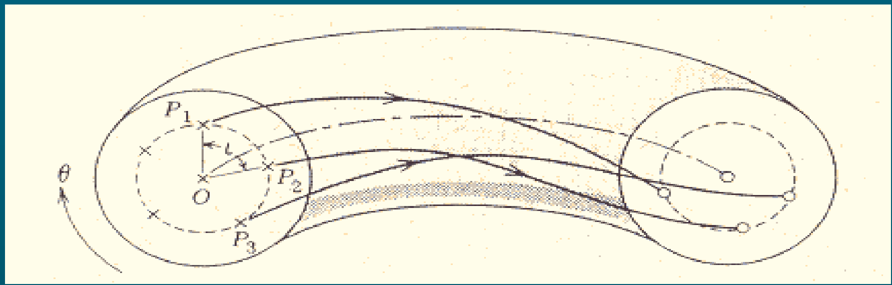
Magnetic coordinates

(Clebsch, Boozer.....)

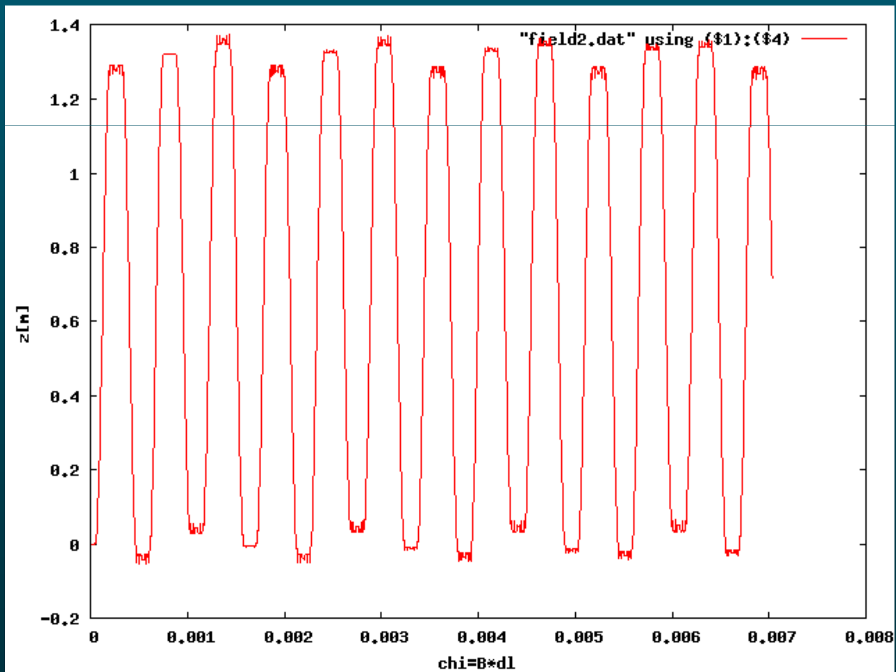
ψ, θ, ξ ψ, α, χ

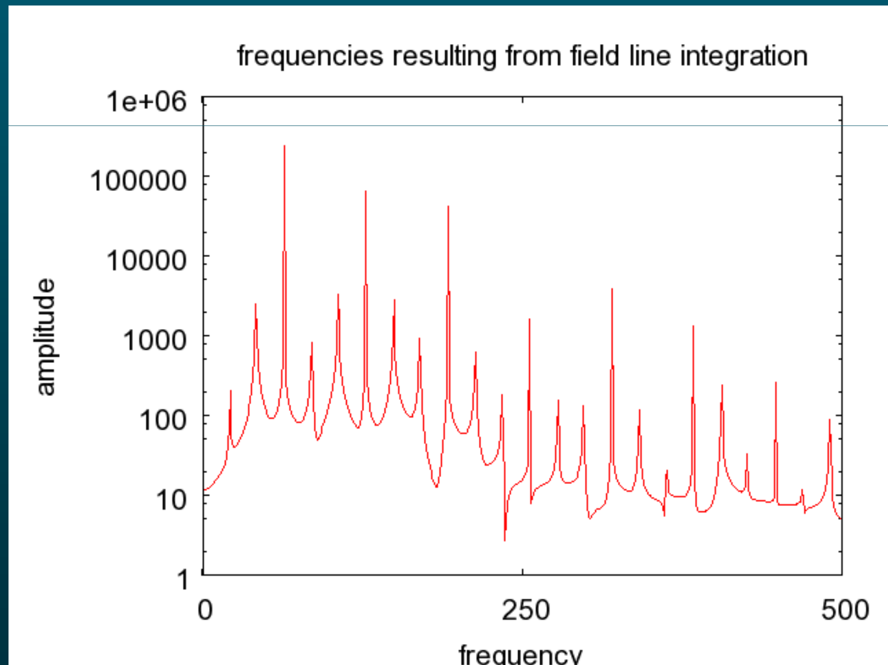


Frequency decomposition – FFT (for every surface – 1D => 2D)



$$\chi = \int B dl$$





Guiding centre equations

$$\frac{d\alpha}{dt} = -\frac{\partial \phi}{\partial \psi} - \left(\frac{1}{e}\mu + \frac{eB}{m}\rho_{\parallel}^{2} \right) \frac{\partial B}{\partial \psi}$$

$$\rho_{\parallel} = \frac{mv_{\parallel}}{eB}$$

$$\frac{d\psi}{dt} = \frac{\partial \phi}{\partial \alpha} + \left(\frac{1}{e}\mu + \frac{eB}{m}\rho_{\parallel}^{2} \right) \frac{\partial B}{\partial \alpha}$$

$$\chi = \int B dl$$

$$\frac{d\chi}{dt} = \left(\frac{eB^{2}}{mc}\rho_{\parallel} \right)$$

$$\frac{d\rho_{\parallel}}{dt} = -\frac{\partial \phi}{\partial \chi} - \left(\frac{1}{e}\mu + \frac{eB}{mc}\rho_{\parallel}^{2} \right) \frac{\partial B}{\partial \chi}$$

Poisson equation

Orthogonal basis

$$h_i = \sqrt{\left(\frac{\partial x}{\partial q_i}\right)^2 + \left(\frac{\partial y}{\partial q_i}\right)^2 + \left(\frac{\partial z}{\partial q_i}\right)^2}$$

$$q = (\psi, \theta, \xi)$$

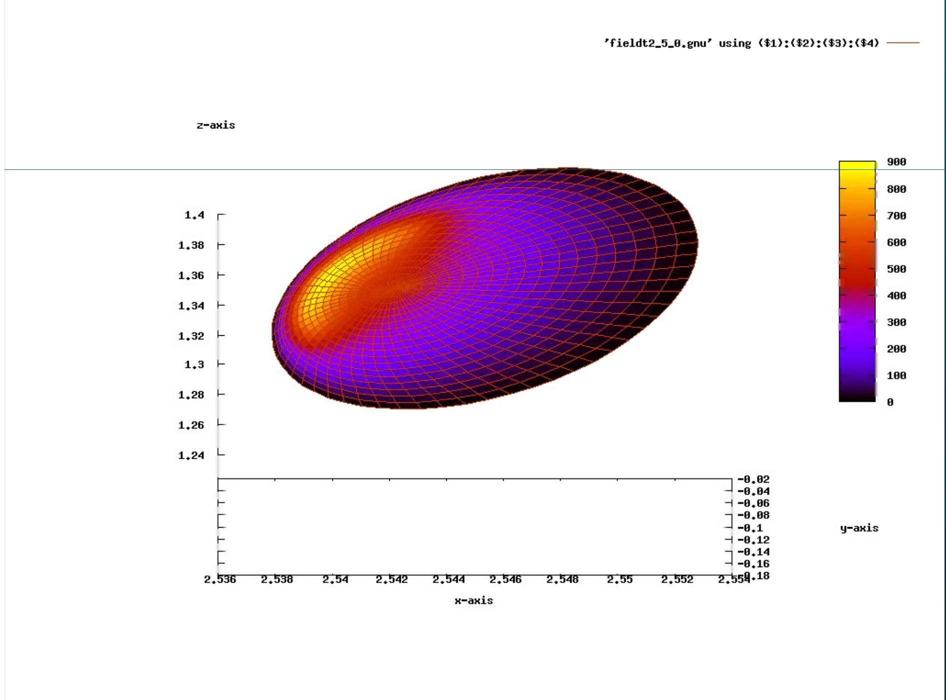
$$\Delta\phi = \frac{1}{h_1 h_2 h_3}\left[\frac{\partial}{\partial\psi}\left(\frac{h_2 h_3}{h_1}\frac{\partial\phi}{\partial\psi}\right) + \frac{\partial}{\partial\theta}\left(\frac{h_1 h_3}{h_2}\frac{\partial\phi}{\partial\theta}\right) + \frac{\partial}{\partial\xi}\left(\frac{h_2 h_1}{h_3}\frac{\partial\phi}{\partial\xi}\right)\right]$$

On axis – integral Gauss law

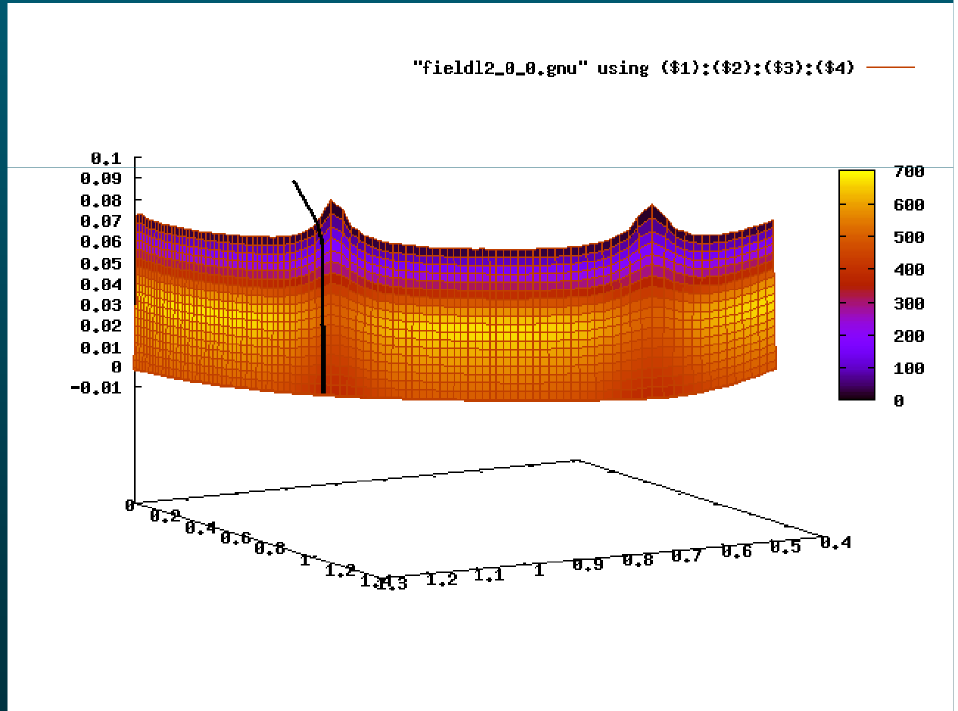
Numerical – iteration method, parallel implementation

Test example

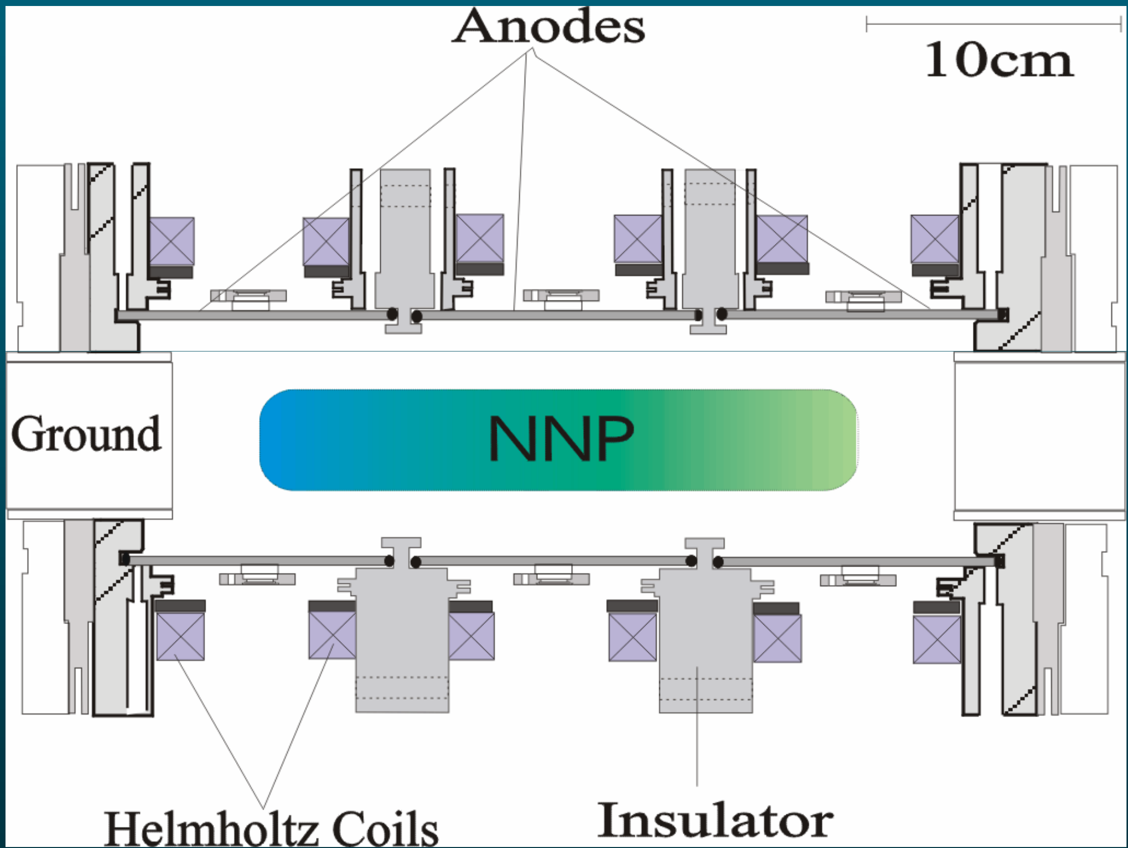
Potential distribution – example for circulating test beam at $\xi=\xi_1$

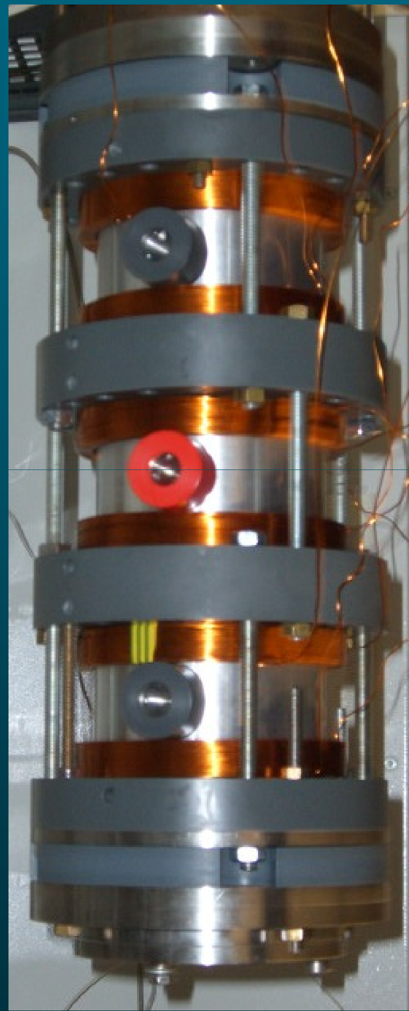


Cut through magnetic structure along ξ, θ plane

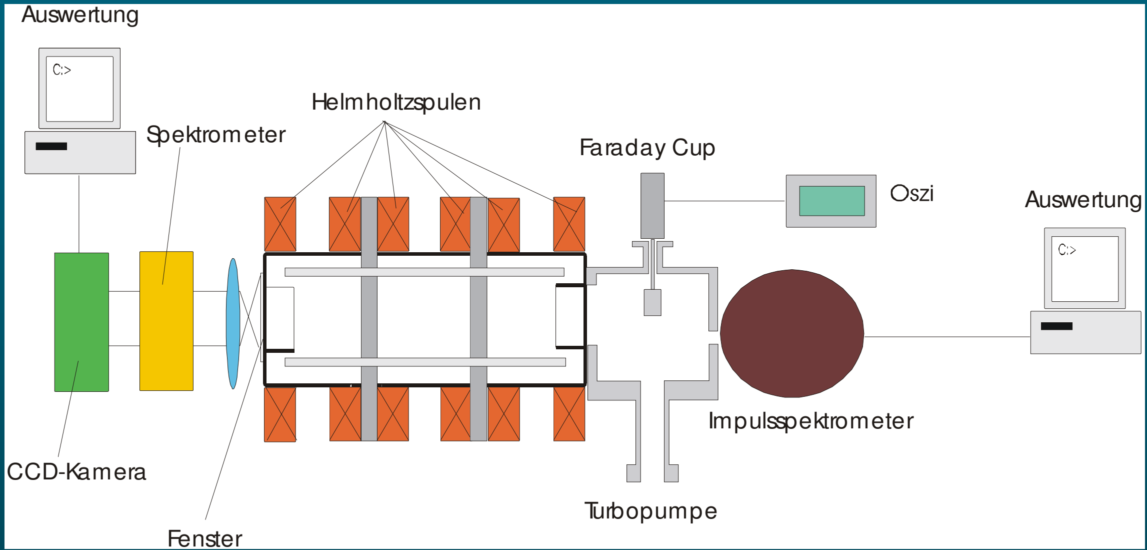


Gabor-Lens





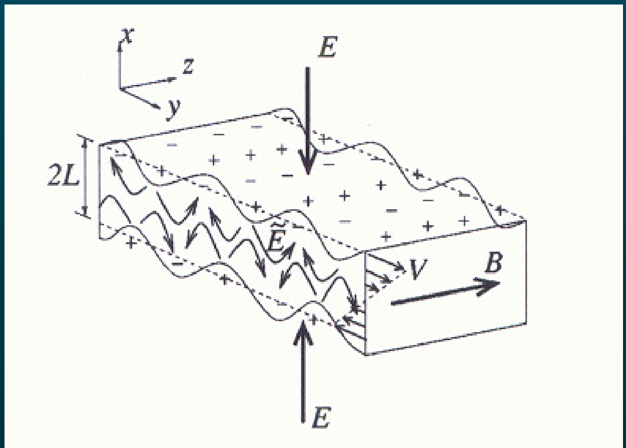
Measurement of n,T profiles



U ~ 5500V
B ~ 0.013T
p ~ 8E-5 mbar

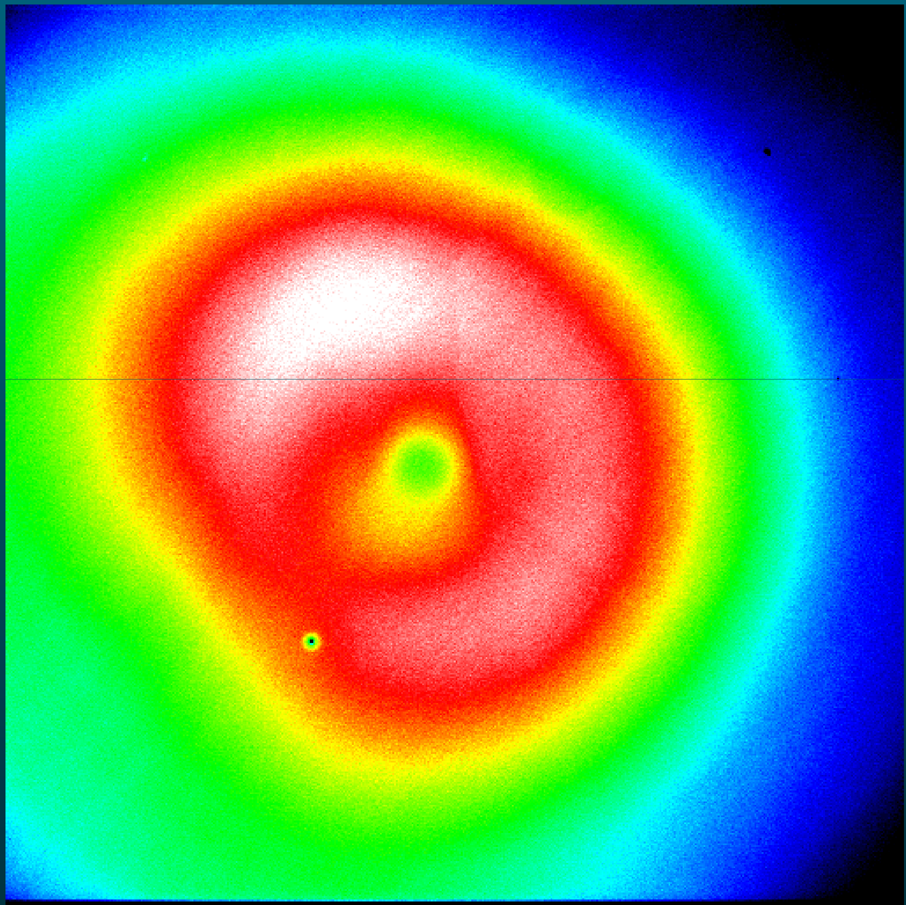
Optical measurements – CCD

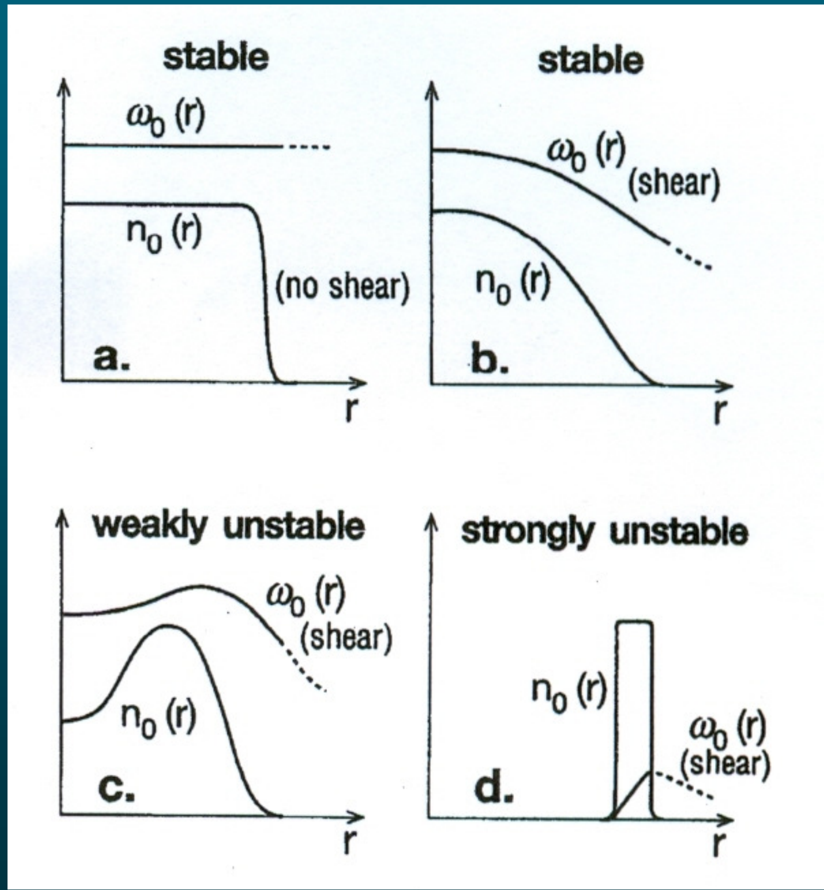
Rest gas ion detection – energy spectrum

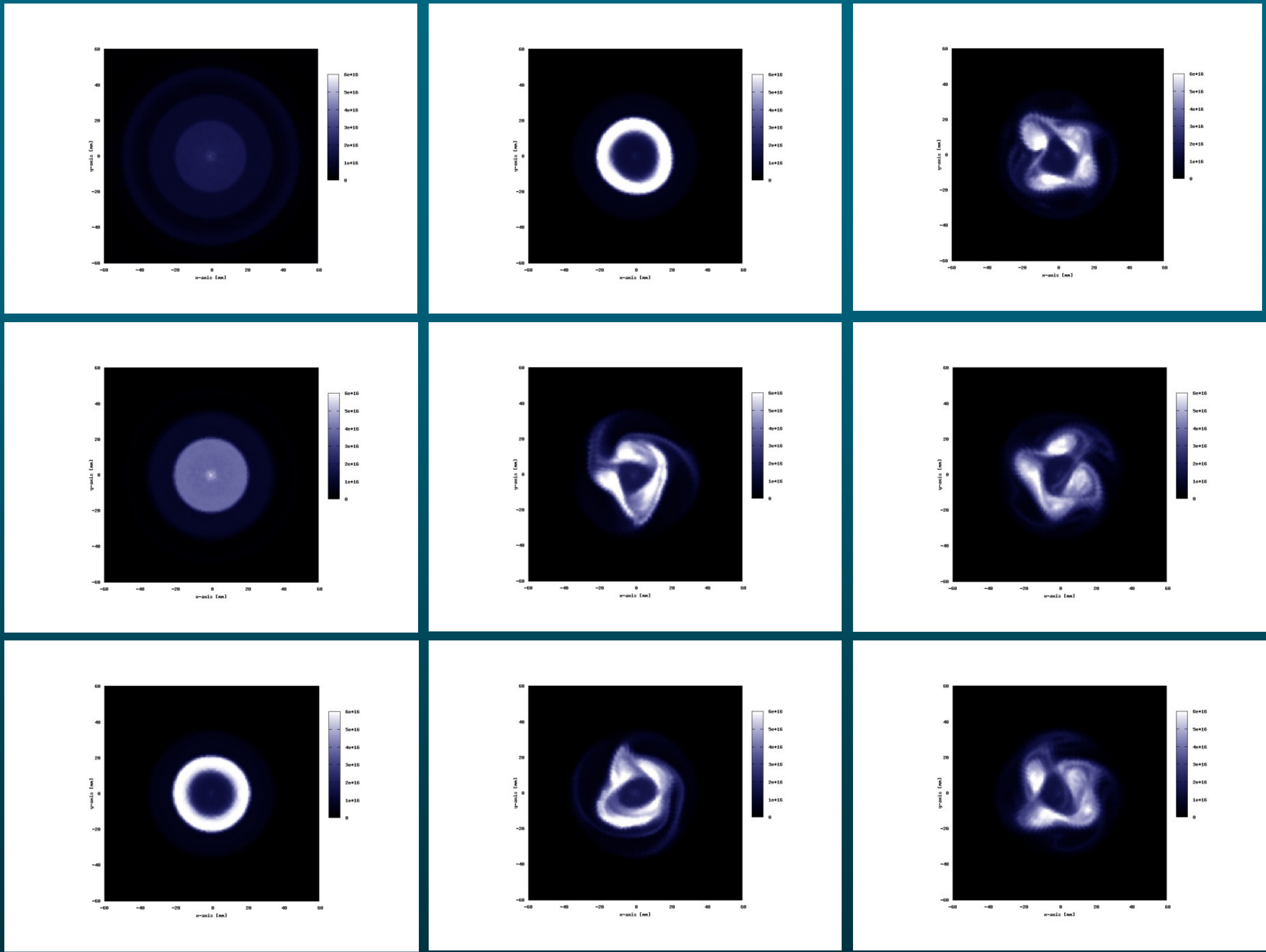


Diocotron instabillity – ExB surface wave
n ~ 10^{14} m^{-3}
Typicall time scale ~ 1μs

Diocotron Instabillity

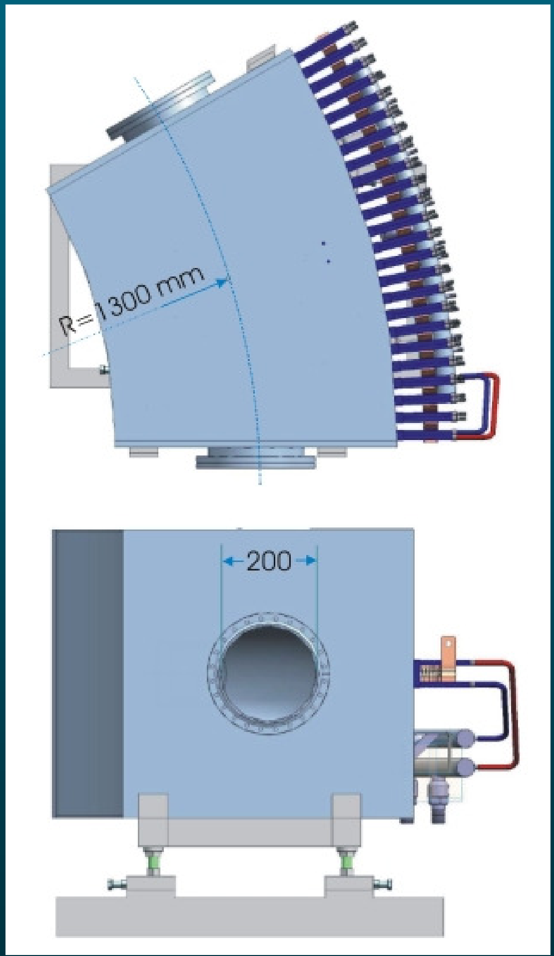






video

Toroidal segments



Parameters

Toroidal magnetic field on axis = 0.6 T

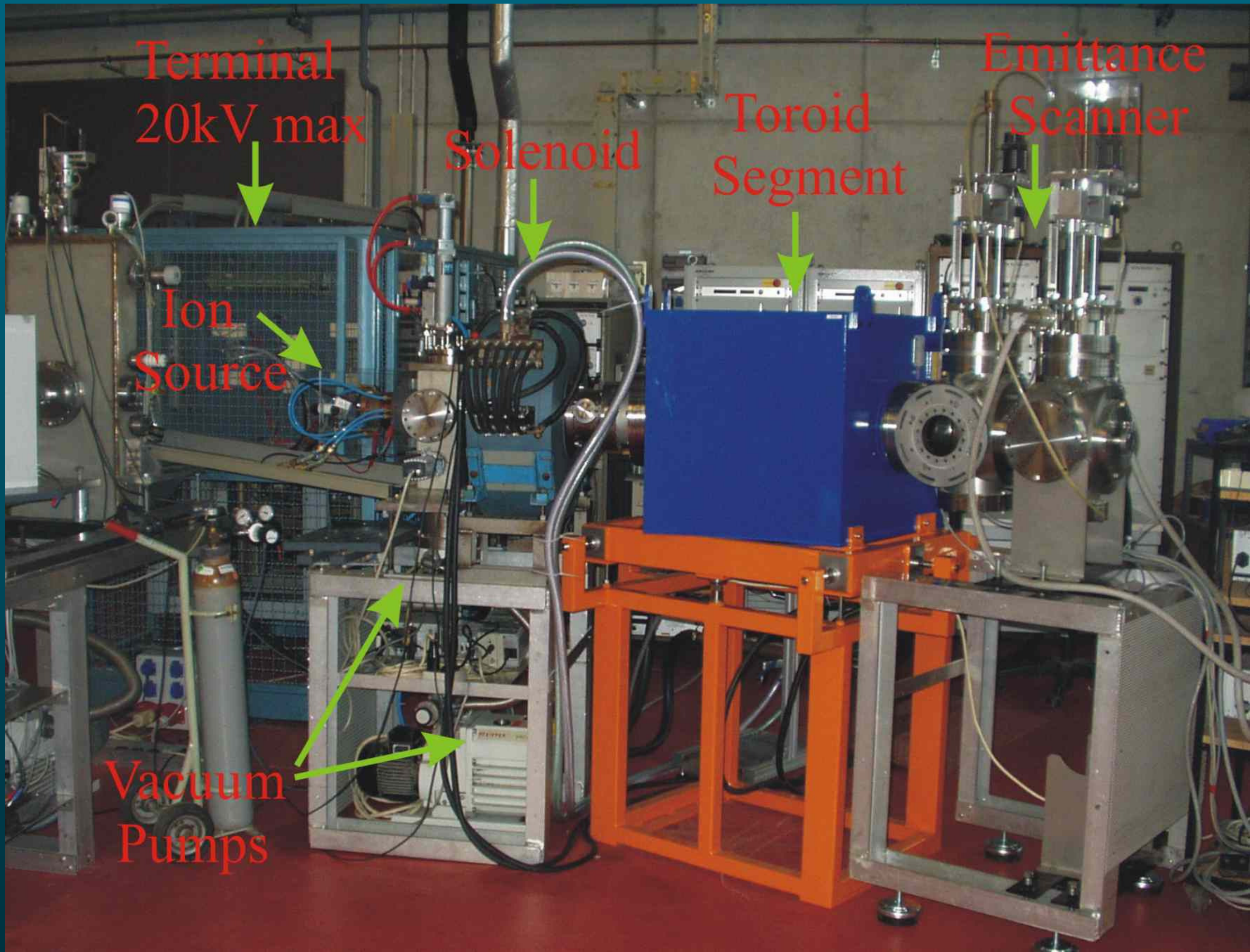
Major Radius = 1300 mm

Minor Radius = 100 mm
Bending angle: 30°,
Axis length: 770 mm

B-Feld max: 0,6 T
Current source: 30 V, 400 A
Water cooling: 6 bar, 20℃
Brillouin-Flow-Limit: 9,5E14 1/m^3
Calculated FxB drift in 1 Segment: ca. 18 mm

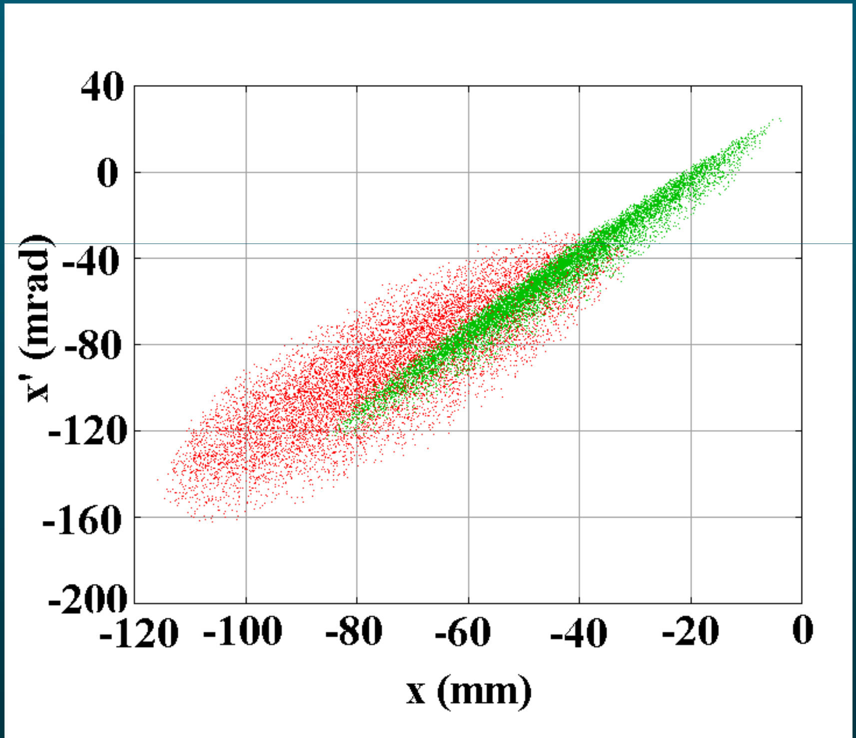
Injection Beam Energy = 20keV max

First transport experiments

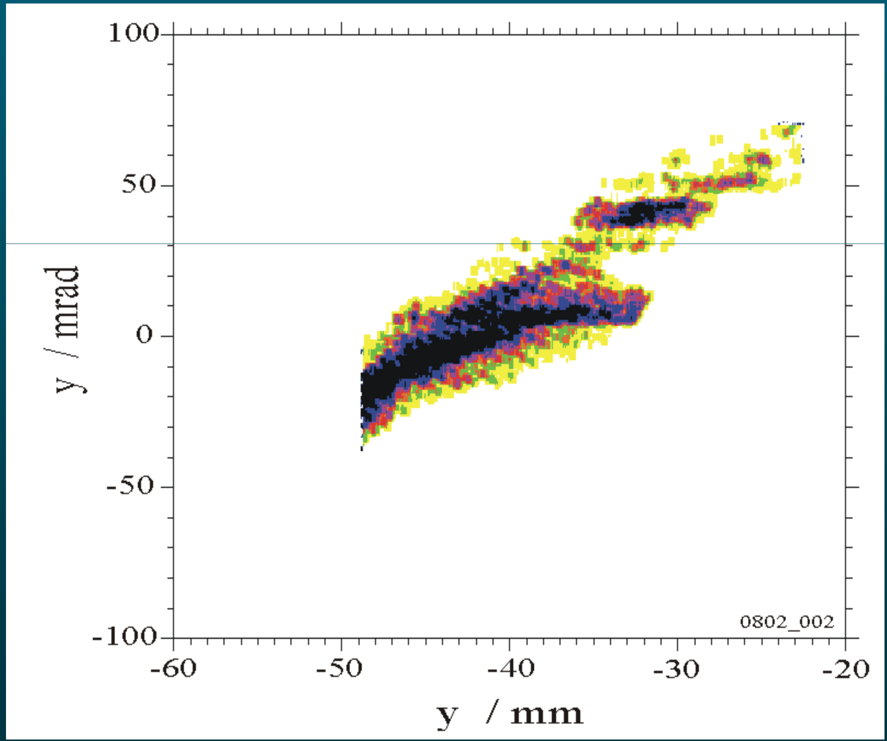


First comparison with experimental data

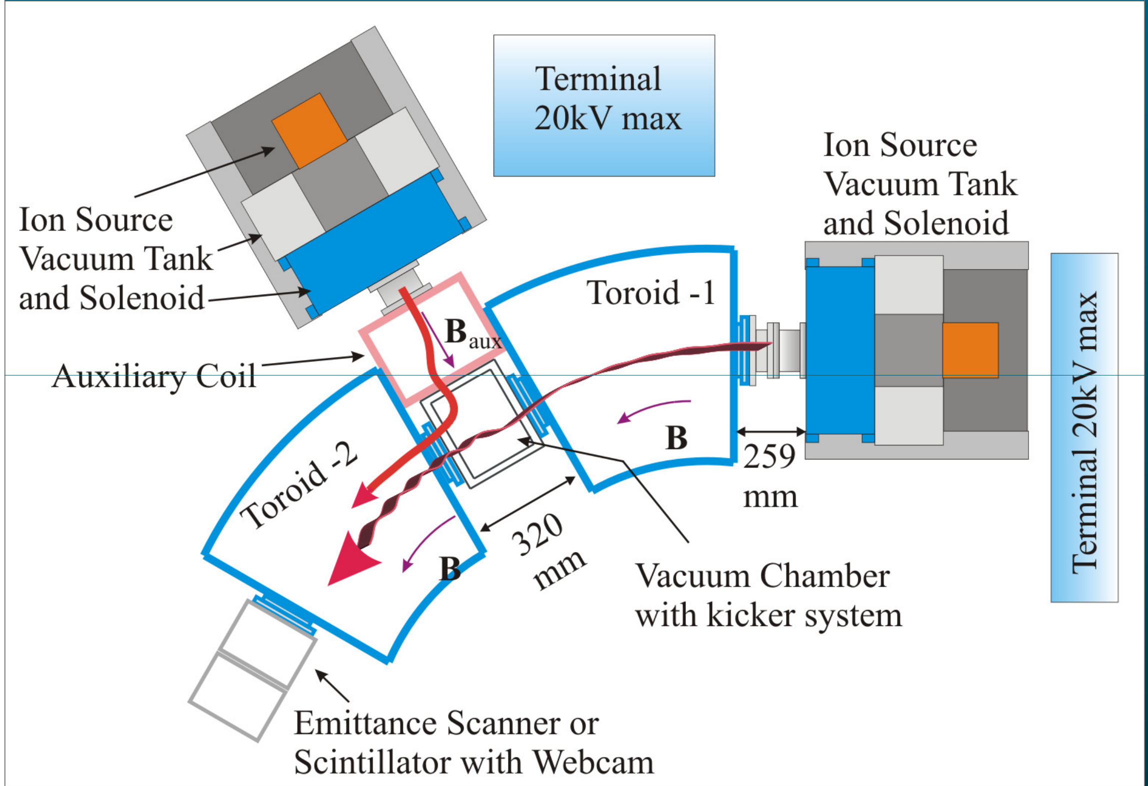
Simulated beam emittance H^+ ,H_3^+



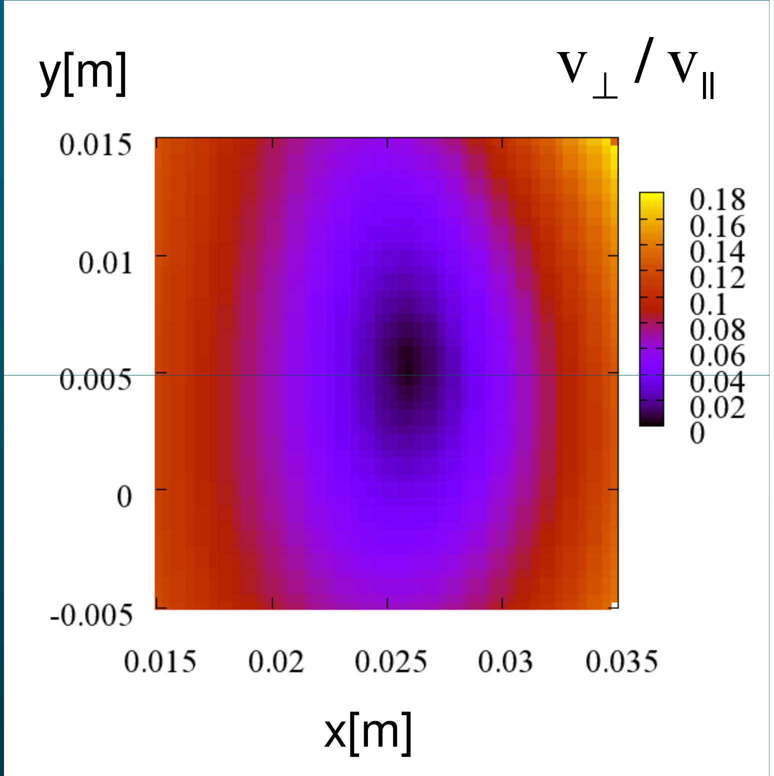
Measured beam emittance



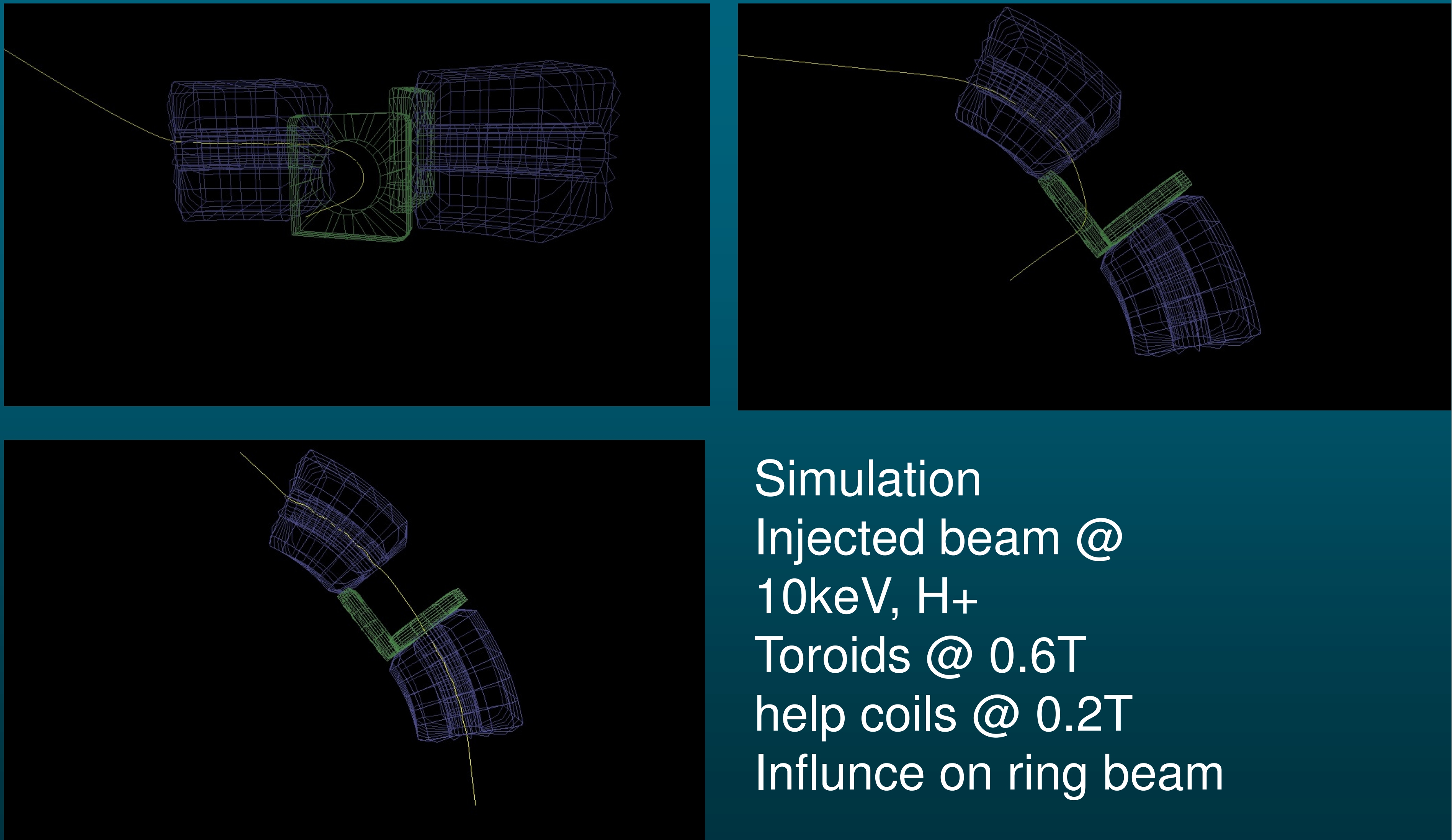
Injection Experiment



Proposed injection experiment



velocity ratio in Toroid-2 according to auxiliary coil entrance



Simulation
Injected beam @
10keV, H+
Toroids @ 0.6T
help coils @ 0.2T
Influnce on ring beam

Summary

- space charge compensation in torodial beam transport
- investigation of beam drift effects
- investigation of beam instabillities
- experimental study of beam injection
- evaluation of numerical simulation with experimental results

NNP Group

M. Droba – Ring Design

N. Joshi – Injection Experiment

O. Meusel – Gabor-Plasma-Lens

K. Schulte – Diagnostic of NNP

L.P.Chau – Bunch Compressor

C.Wiesner – Chopper System