Beam Extraction and Optics of the 200keV Beam Accelerator for Neutral Beam Injection in China

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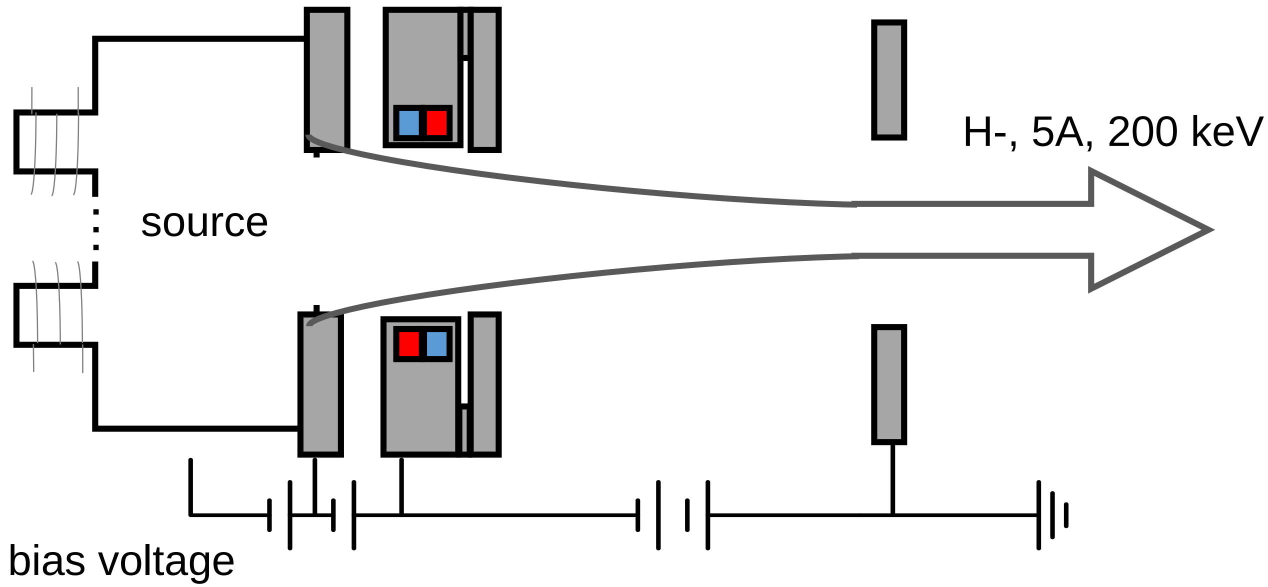
I. Introduction

CFETR N-NBI:
China Fusion Engineering Test Reactor
Negative-ion-based Neutral Beam Injection

CFETR NNBI source
single-stage beam accelerator



I. Introduction

CFETR N-NBI:
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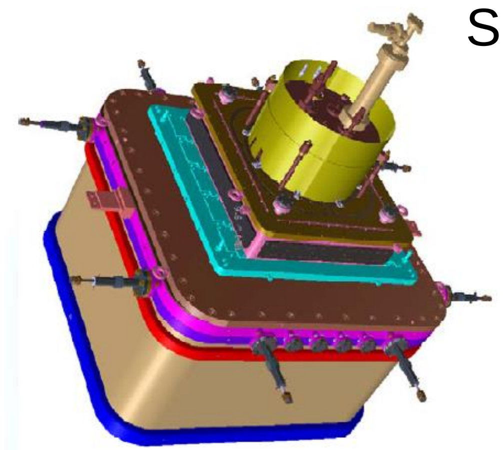
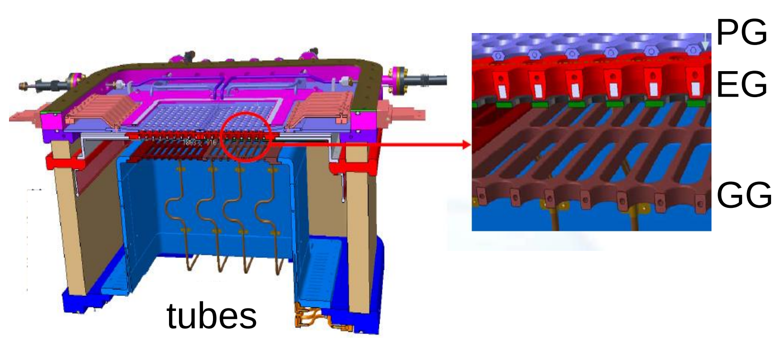
Negative-ion-based Neutral Beam Injection

CFETR NNBI source
single-stage beam accelerator

1st phase 2nd phase

Single driver, 5A, 200keV





I. Introduction

- Aim in the 1st phase

  H- beam 5A, energy 200keV, pulse duration 1000s.

- Parameters

Duration of plasma pulse	1000 s
Beam energy	200 keV
Current density	200-300 A/m^2
Extraction area	0.32 m × 1.6 m
Extraction voltage	~10 kV

272 apertures on each grid, extraction aperture diameter 7 mm.

Molybdenum for PG and copper for the others.

I. Introduction

Estimation of Beam Optics.

(Factors in beam extraction and transport.)

In this work:

Single beamlet model, electromagnetic effects.

1. **Meniscus, Current and Voltage**

   Meniscus calculated with a simplified method in Comsol Multiphysics, sensitivity to current and extraction voltage.

   Influence on beam divergence.

2. **Deflection Magnets**

   Effect for co-extracted electrons deflection.

   Influence on ion beam.

II. Calculation Model

- Numerical tool

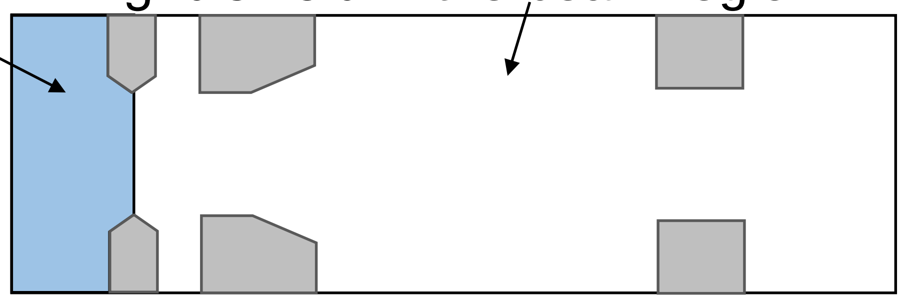
  Comsol Multiphysics (multi-physics, modifiable, no meniscus on its own)

- Simplified method for meniscus

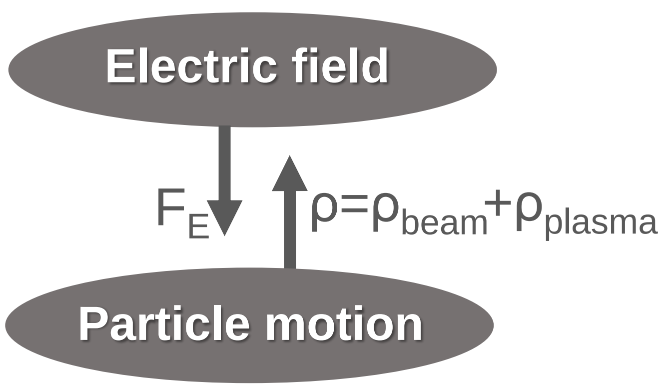
  (boundary between plasma and beam)

grid's field in the beam region

Quasi-neutral charge density in the plasma



Input: geometry, particle property, current density, and grid voltage.

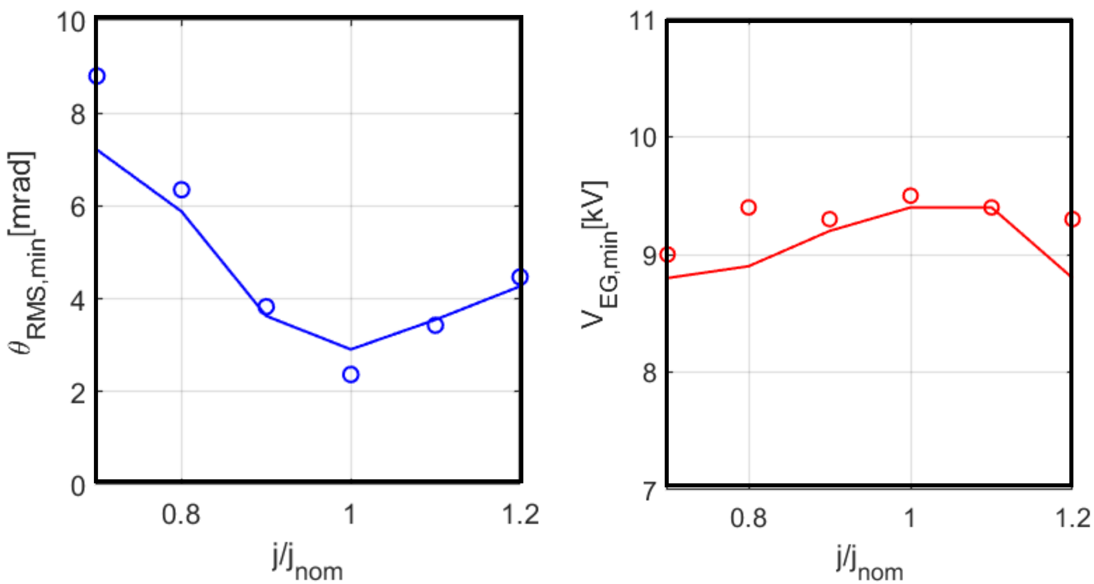


Iteration of electric field calculation and particle tracing.

II. Calculation Model

- Results agreement

The single beamlet case in Ref.[1]:



-dot: data from [1], SLACCAD
-line: calculated by Comsol with meniscus

(Both programs with axisymmetric model.)

Current limitation

[1] Agostinetti, P., et al., Physics and engineering design of the accelerator and electron dump for SPIDER. Nuclear Fusion, 2011

II. Calculation Model

Multi-physics factors in beam transport
(electromagnetics, particle tracing, collisions, mechanics, thermodynamics…)

Modules modifiable
(meniscus, …)

→ Comsol is adopted.

Emission state,
Voltage conditions…

Step 1

Axisymmetric model

- electric factors
- general rules

Step 2

3D model

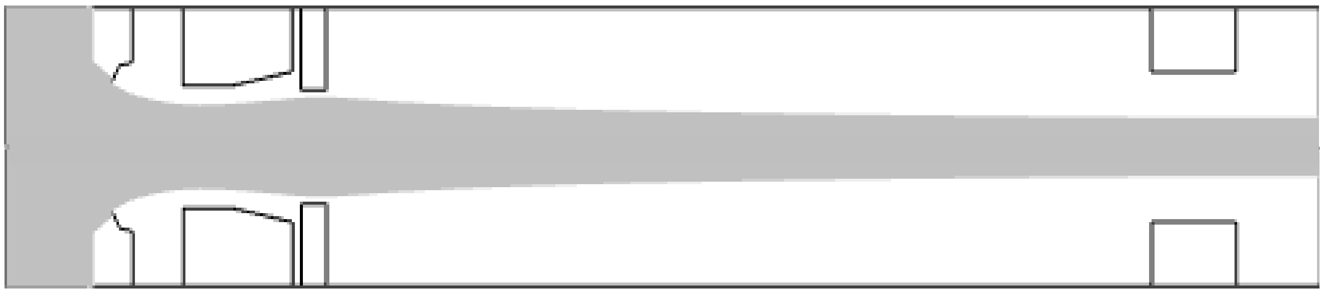
- Electromagnetic field

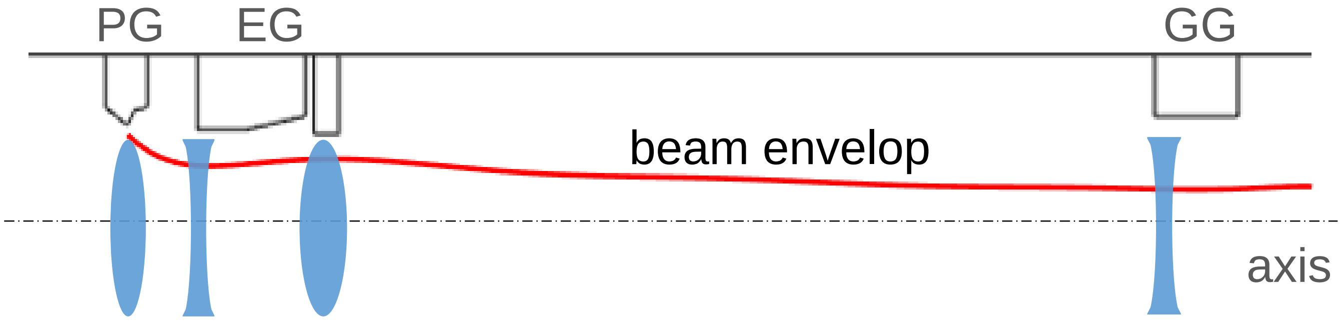
III.A. Meniscus, Current and Voltage

- Electrostatic lens effect

  Voltage shapes the beam for fixed distance between grids.

Beam trajectory at J_{H-}=200A/m^2, V_{EG}=7.8kV V_{PG}=0, V_{GG}=200kV

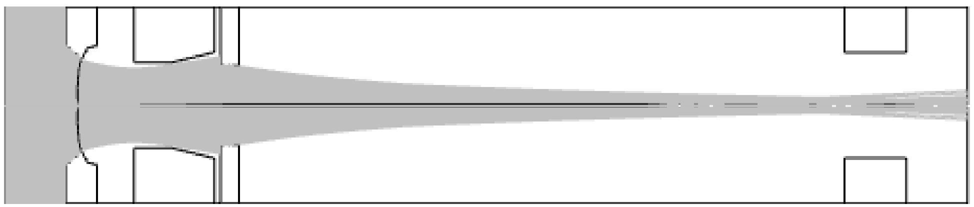


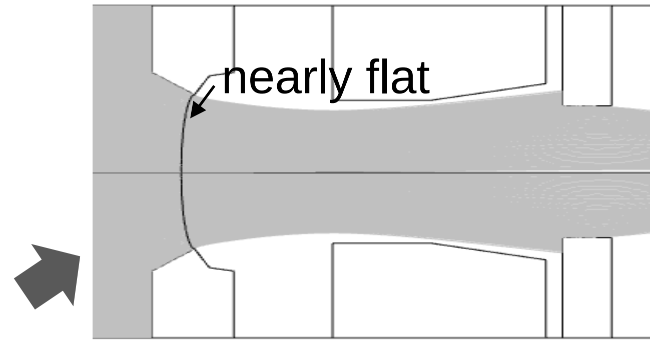


III.A. Meniscus, Current and Voltage

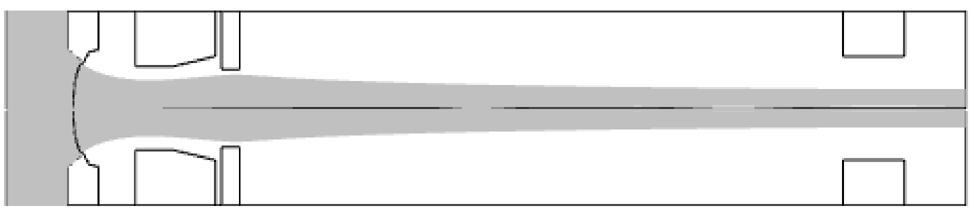
- Meniscus variation

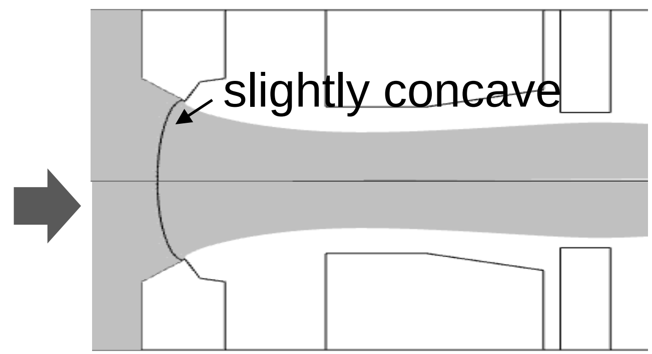
200A/m^2, V_{EG}=6kV, over-focus at exit



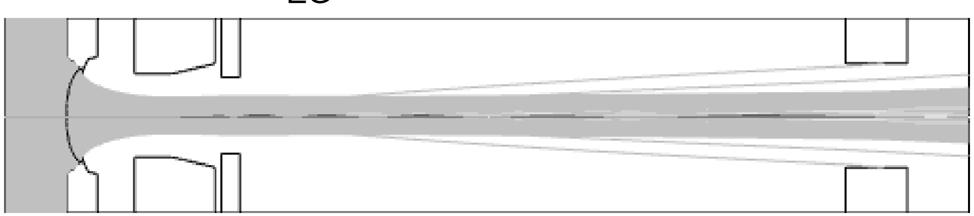


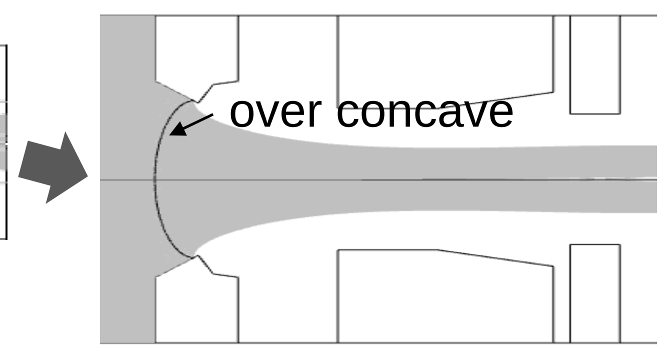
V_{EG}=7.8kV, ideal convergence





V_{EG}=10kV, defocus at exit

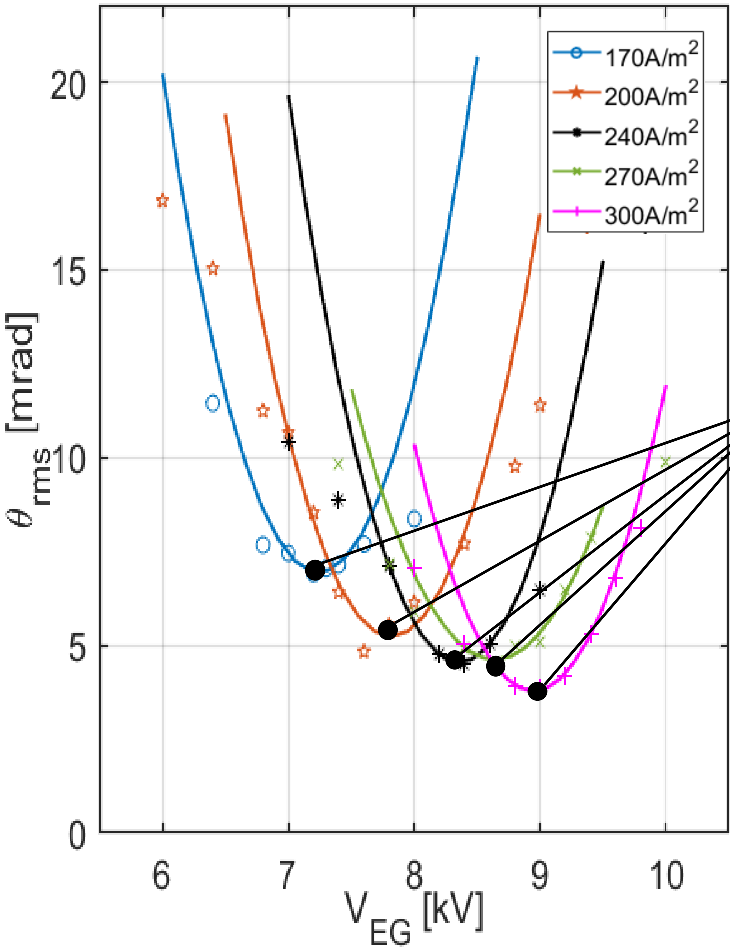




III.A. Meniscus, Current and Voltage

- Perveance match

-dots: original data -lines: fitted curve



Density[A/m²]	J_{H-}=170	J_{H-}=200	J_{H-}=240	J_{H-}=270	J_{H-}=300
Current I_{H-} [mA]	30.1	35	39	43	47
Optimal voltage U_0 [kV]	7.1	7.8	8.4	8.8	9
Perveance P_0 [$A\cdot V^{-3/2}\times 10^{-8}$]	5.0	5.1	5.1	5.2	5.5

✓ The optimal perveance is about $5\times 10^{-8} A\cdot V^{-3/2}$.

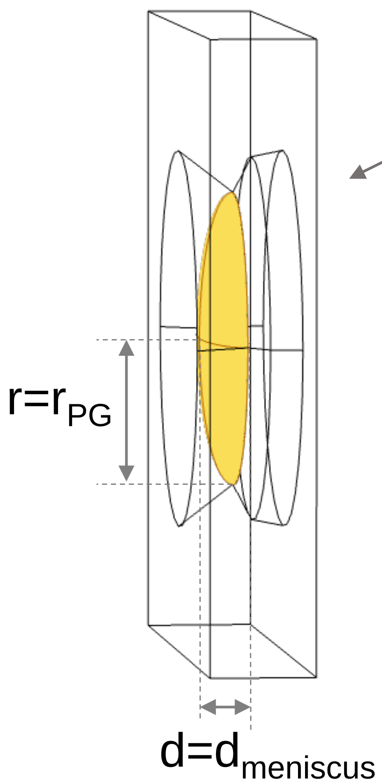
✓ Modify the extraction voltage to adjust beam angle to demand.

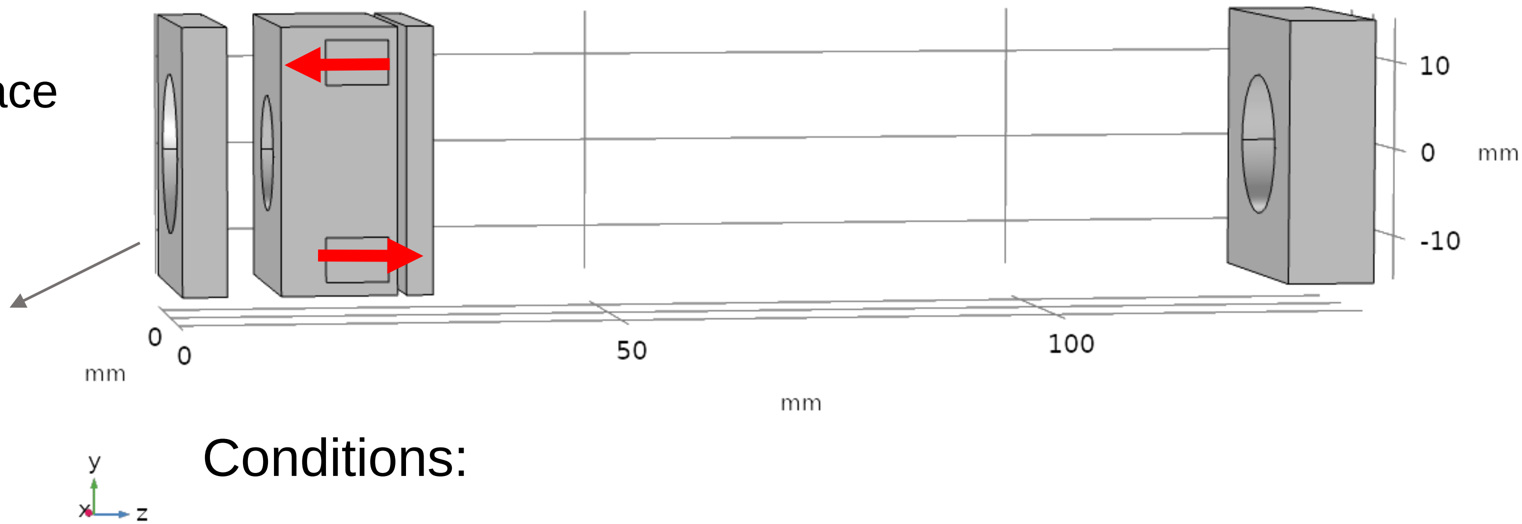
($\theta_{rms} = \sqrt{\sum(\theta_i - \bar{\theta})^2 / N}$ θ_i -angle of *ith* particle; $\bar{\theta}$ -average angle of all particles; *N*- particle total number)

III.B. Magnetic Field

- 3D Model

Emitter surface





Conditions:

✓ $J_{H-}=J_e=200A/m^2$

✓ Voltage condition at beam's minimum angle
($V_{PG}=0$, $V_{EG}=7.8kV$, $V_{GG}=200kV$)

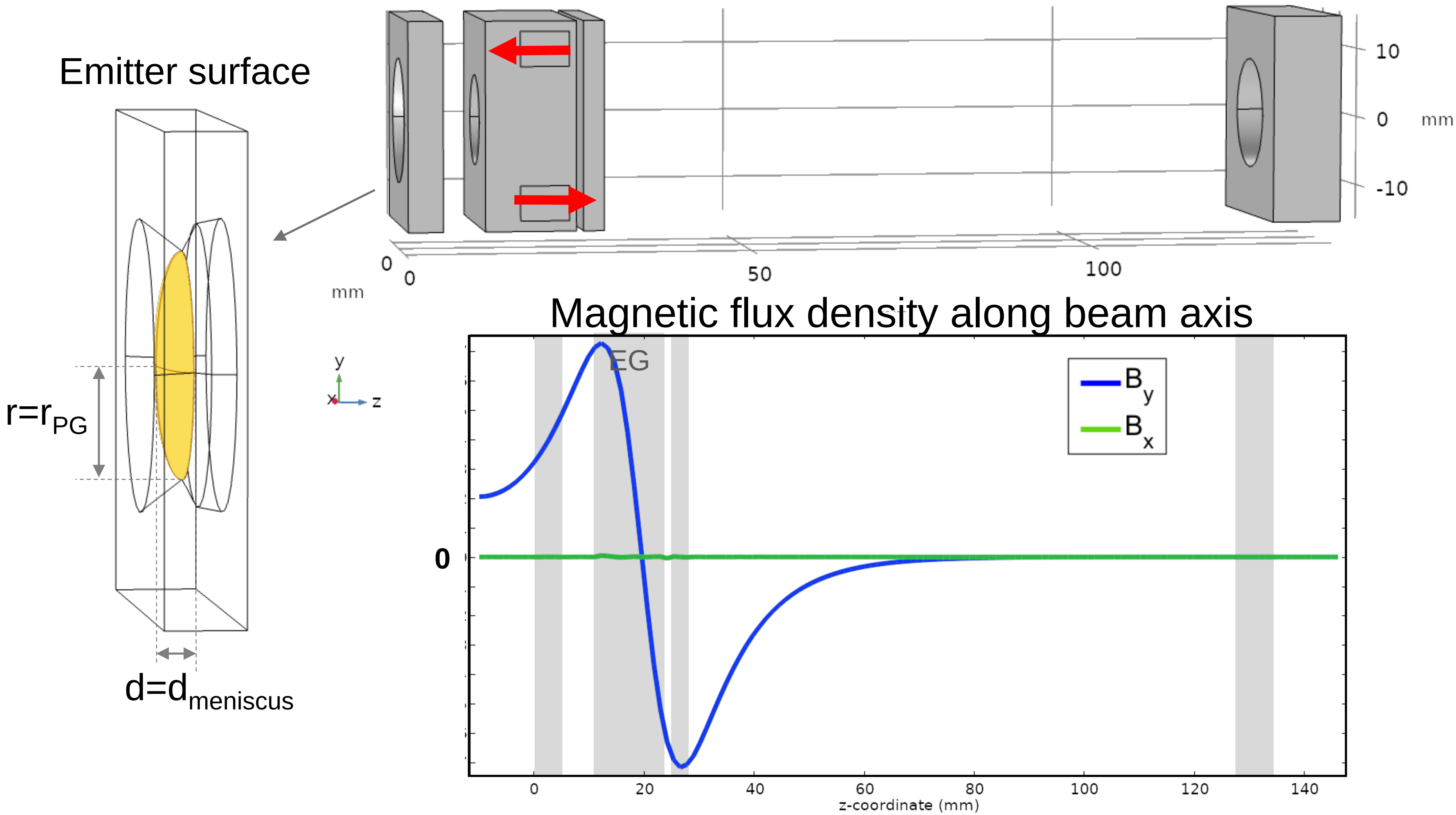
Emission:

✓ Semi-ellipsoid surface

✓ Particles emitted normal to surface

III.B. Magnetic Field

- 3D Model



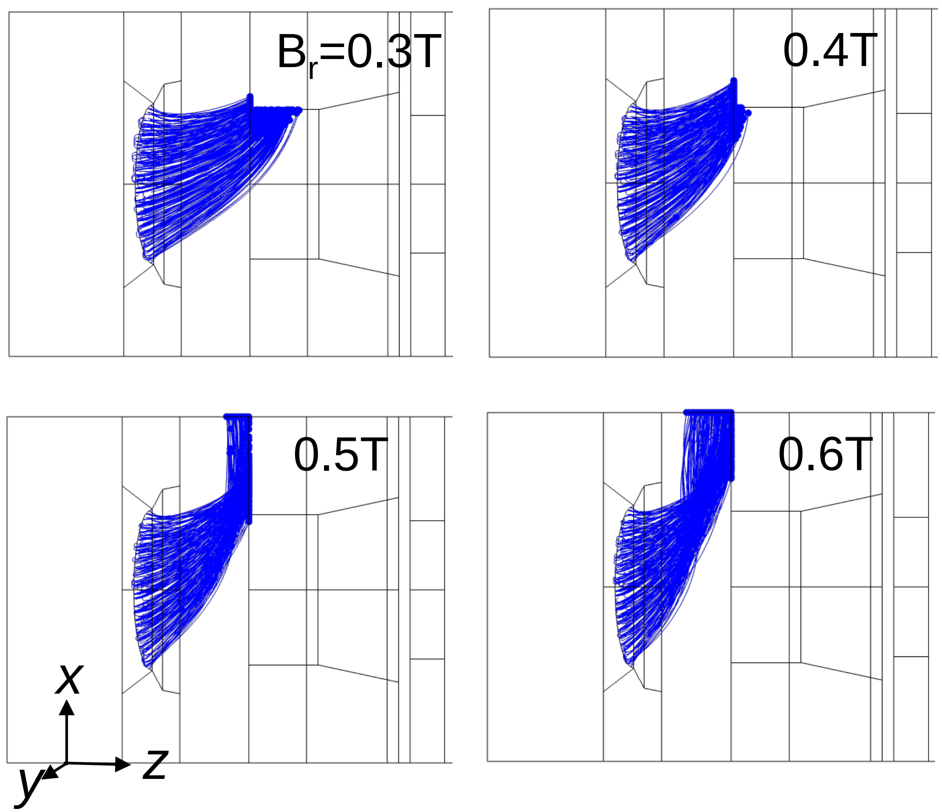
III.B. Magnetic Field

- Deflection of co-extracted electrons

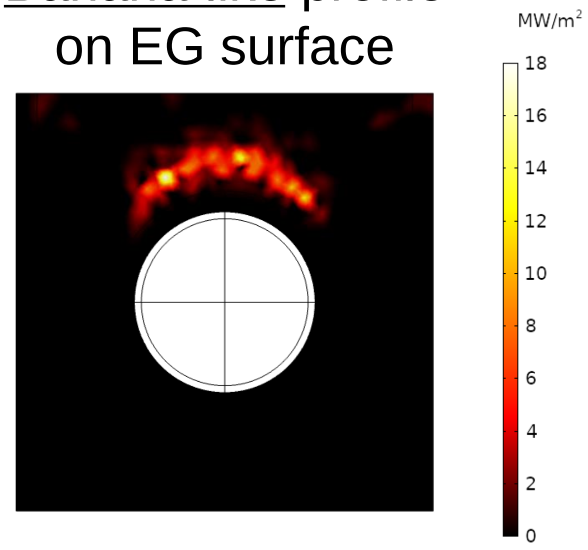
Magnet size: 5mm × 6mm × 30mm

Effective when magnet remanence <u>B_r>0.5T</u>

(Corresponding to B_y >0.03T in the extraction gap.)



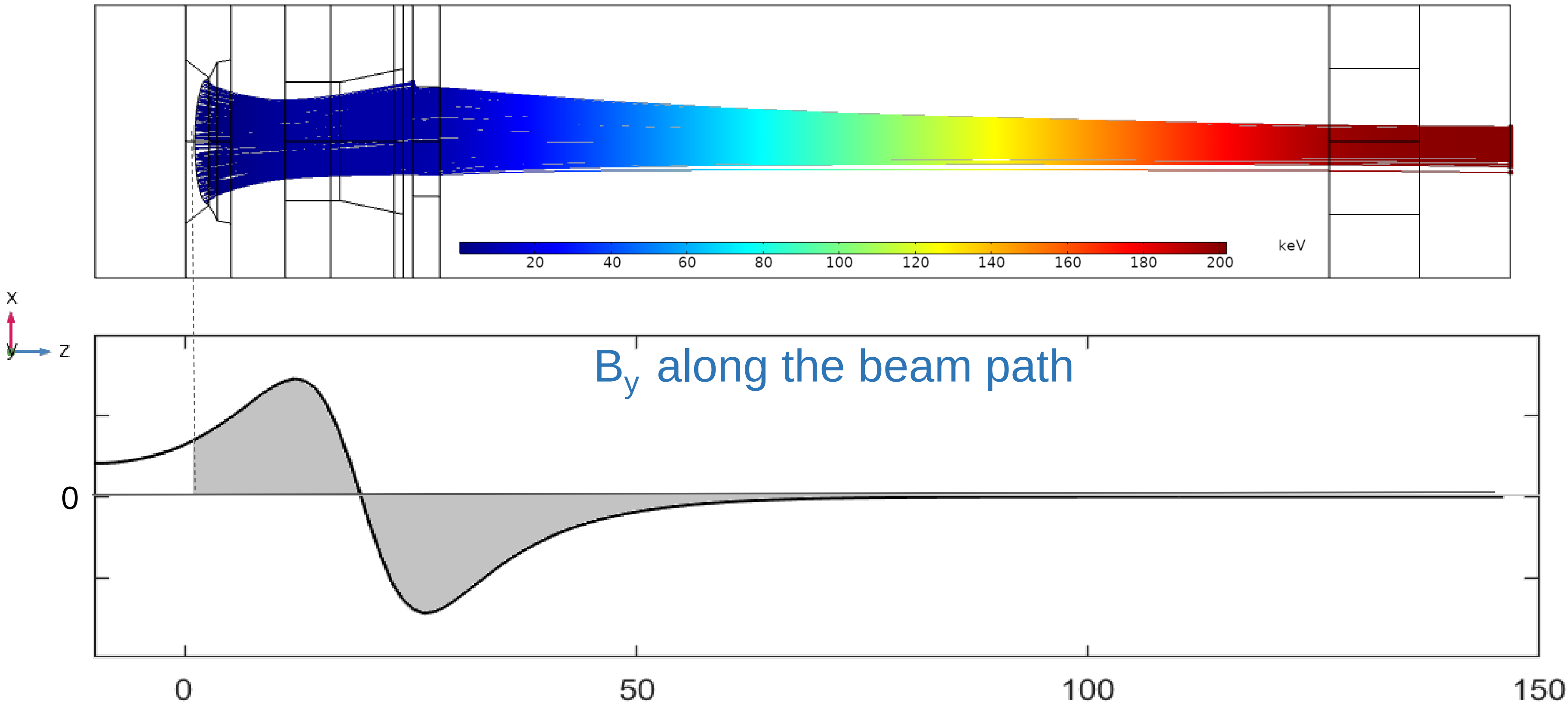
<u>Banana-like</u> profile on EG surface



B_r=0.5T, max load: 18.2MW/m^2

III.B. Magnetic Field

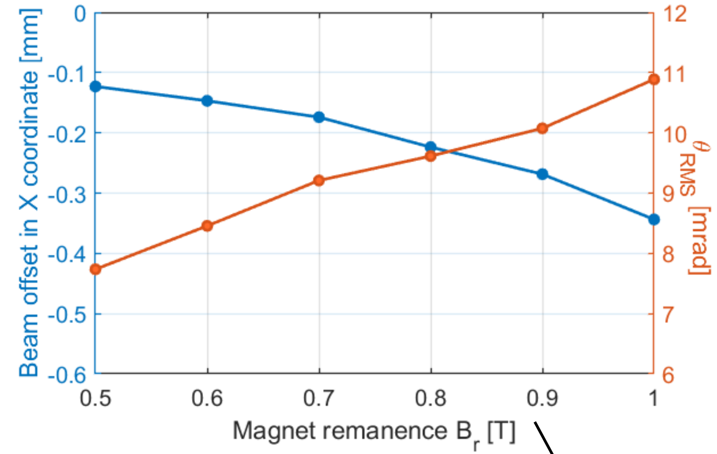
- H^- beam offset

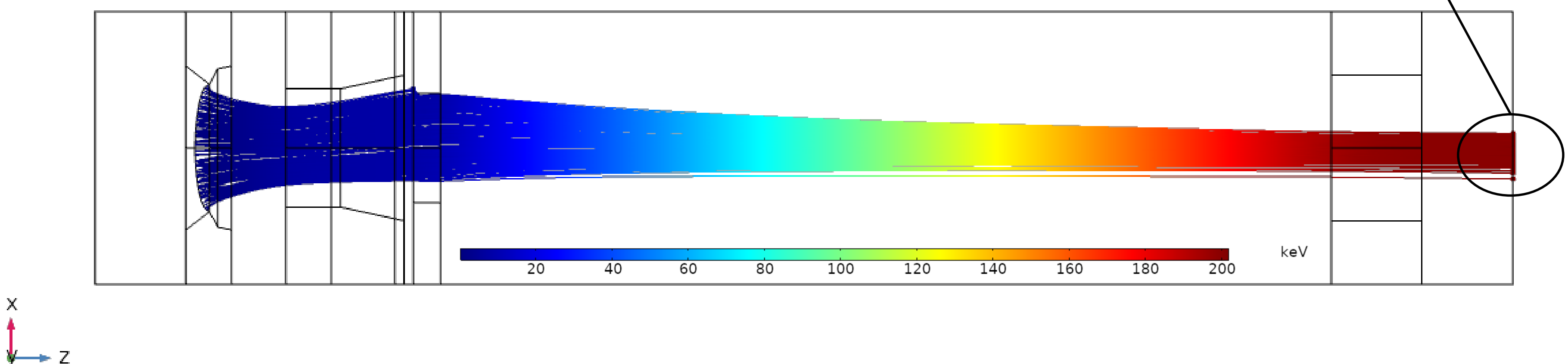


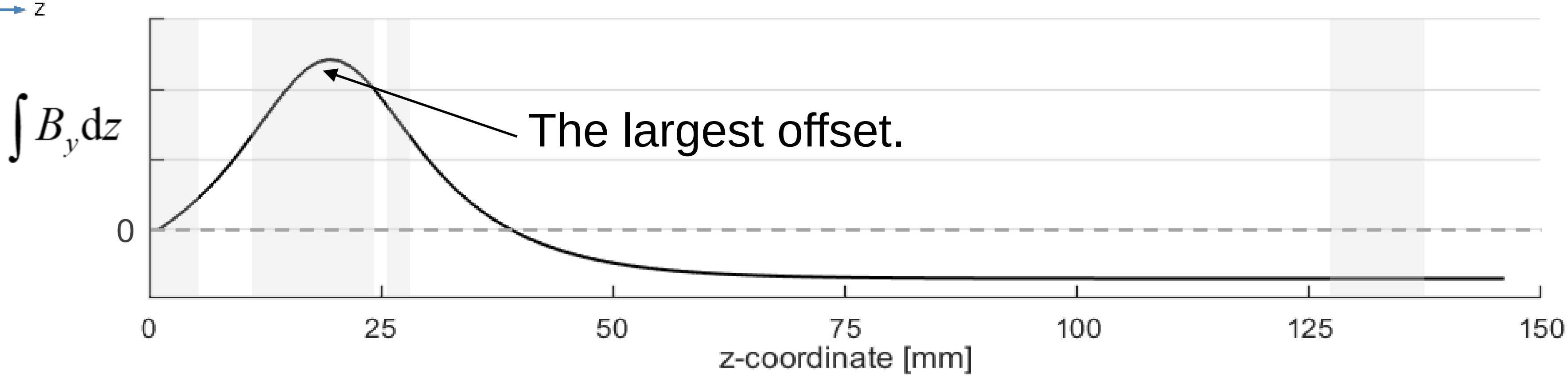
III.B. Magnetic Field

- H^- beam offset

Offset within 1mm
Angle up to 10mrad

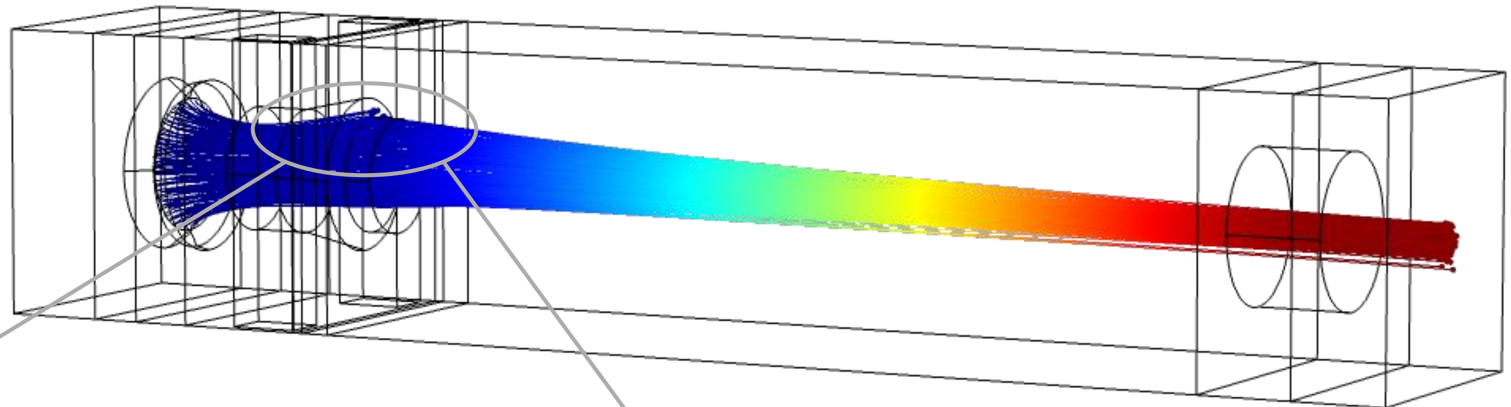


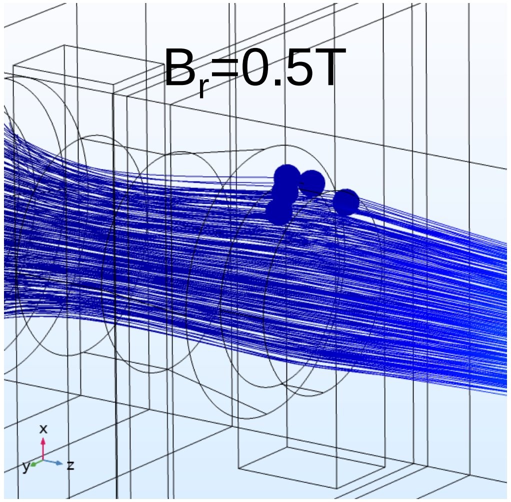




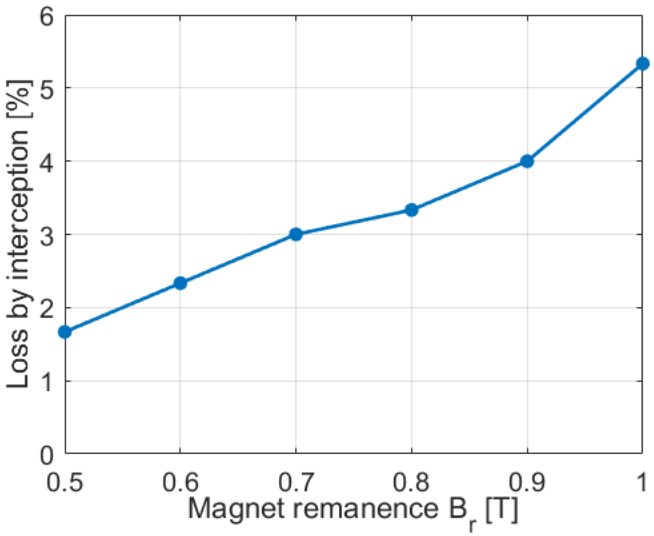
III.B. Magnetic Field

- H^- beam offset





Blue balls represent H- ions intercepted with grids.



loss 1~6%.

IV. Conclusion

1. Meniscus is calculated self-consistently with Comsol in the axisymmetric case.
2. Electromagnetic effects on single beamlet optic of the CFETR NNBI 200keV accelerator is investigated.
   - The system follows Child's Law to a first approximation. 7.8kV is capable for extraction of 200A/m^2 current density, beam divergence angle 5mrad within limit.
   - Deflection magnets are effective for B_y>0.03T in the gap. For less electrons running into neighbor aperture, B_y<0.07T is also recommended.
   - With no compensation, beam offset less than 1mm. Divergence up to 10mrad. Ions lost on grid in 1~6%.

Future plans:

- Further development for 3D meniscus and more accurate plasma model
- Influence of beam halo and stray particles
- Compensation for beam offset

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