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

H-, 5A, 200 keV
I. Introduction

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

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1\(^{\text{st}}\) phase  2\(^{\text{nd}}\) phase

Single driver, 5A, 200keV
I. Introduction

• **Aim in the 1\textsuperscript{st} phase**
  H- beam 5A, energy 200keV, pulse duration 1000s.

• **Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of plasma pulse</td>
<td>1000 s</td>
</tr>
<tr>
<td>Beam energy</td>
<td>200 keV</td>
</tr>
<tr>
<td>Current density</td>
<td>200-300 A/m\textsuperscript{2}</td>
</tr>
<tr>
<td>Extraction area</td>
<td>0.32 m $\times$ 1.6 m</td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>$\sim$10 kV</td>
</tr>
</tbody>
</table>

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 \((\text{multi-physics, modifiable, no meniscus on its own})\)

- **Simplified method for meniscus**
  (boundary between plasma and beam)

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

II. Calculation Model

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

Modules modifiable
(meniscus, …)

Comsol is adopted.

- **Step 1**
  - Axisymmetric model
    - electric factors
    - general rules

- **Step 2**
  - 3D model
    - Electromagnetic field

Emission state, Voltage conditions…
III.A. Meniscus, Current and Voltage

- Electrostatic lens effect

Voltage shapes the beam for fixed distance between grids.

Beam trajectory at $J_H=200\text{A/m}^2$, $V_{EG}=7.8\text{kV}$, $V_{PG}=0$, $V_{GG}=200\text{kV}$
III.A. Meniscus, Current and Voltage

- **Meniscus variation**

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

  $V_{\text{EG}}=7.8 \text{kV}$, ideal convergence

  $V_{\text{EG}}=10 \text{kV}$, defocus at exit

  - nearly flat
  - slightly concave
  - over concave
III.A. Meniscus, Current and Voltage

- Perverance match

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

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

\[
\theta_{\text{rms}} = \sqrt{\frac{1}{N} \sum (\theta_i - \bar{\theta})^2}
\]

\(\theta_i\) - angle of \(i\)th particle; \(\bar{\theta}\) - average angle of all particles; \(N\) - particle total number
III.B. Magnetic Field

- 3D Model

Emission:

Conditions:
- $J_{H_e} = J_e = 200\text{A/m}^2$
- Voltage condition at beam’s minimum angle
  $(V_{PG}=0, V_{EG}=7.8\text{kV}, V_{GG}=200\text{kV})$

Emission:
- Semi-ellipsoid surface
- Particles emitted normal to surface
III.B. Magnetic Field

- 3D Model

Emitter surface

\[ r = r_{PG} \]

\[ d = d_{\text{meniscus}} \]
III.B. Magnetic Field

- Deflection of co-extracted electrons
  Magnet size: 5mm × 6mm × 30mm
  Effective when magnet remanence $B_r > 0.5T$
  (Corresponding to $B_y > 0.03T$
  in the extraction gap.)

Banana-like profile on EG surface

$B_r=0.5T$, max load: 18.2MW/m$^2$
III.B. Magnetic Field

- $H^-$ beam offset

$B_y$ along the beam path
III.B. Magnetic Field

- H⁻ beam offset
  Offset within 1mm
  Angle up to 10mrad

\[ \int B_y \, dz \]

The largest offset.
III.B. Magnetic Field

- $H^-$ beam offset

Blue balls represent $H^-$ ions intercepted with grids.

$B_r = 0.5 \text{T}$

Loss: $1 \sim 6\%$.
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/m² 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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