Methods of Beam Emittance Measurements of High Power Negative Ion Beams for NBIs

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High power negative ion beam for NBIs

**JT-60SA**

0.5 MeV, 22 A (130 A/m²) for 100s from three stage-multi aperture beam source

**ITER project**

1 MeV, 40 A (200 A/m²) for 3600 s from five stage and multi aperture beam source
MeV ion source Test Facility (MTF) in QST

The test facility is developing the ion beam accelerator for the ITER NBI system.

**ITER REQUIREMENTS:**
- Beam Energy: 1 MeV
- Beam Current: 40 A
- Current Density: 200 A/m² (D⁻)
- Pulse Length: 3600 s

**MTF specification**
- Beam Energy: 1 MeV
- Beam Current: 1 A
- Current Density: 200 A/m² (H⁻)
- Pulse Length: > 1000 s
Recent issues and solutions

**Negative ion production**

Degradation of current for long pulse

→ Temperature control of chamber wall to suppress excess Cs deposition from wall to plasma grid (Dr. Yoshida (P1-09))

**Negative ion acceleration**

High power loading on acceleration grids due to beam deflection by magnetic field and space charge repulsion → Compensated

Insufficient voltage holding capability of large accelerator → Construction of experimental scaling to design large grid with multi apertures

Beam acceleration up to 60 s has been achieved.

Beam acceleration over 100 s is now on-going.
Recent results

Result of five stage accelerator in 2015

- Discharge power in ion source (kW)
- Acceleration voltage [kV]
- Acceleration current [mA]: 190 A/m² for 60s
- Δ: Cooling water temperature of GRG (°C)

Saturated at 30s

0.97 MeV

Long pulse tests over 100 s is now in progress.

However, precise study for this kind of high dense and large beams has not been performed yet.

Recent result using JT-60SA three stage accelerator

- Discharge power (kW)
- Acceleration voltage (kV)
- Camber wall temperature < 60°C
- Acceleration current density (A/m²)

0.5 MeV

For 100s

Δ cooling water temperature of GRG
Beam Diagnostics

for 1 MeV High current density Beams

Common Measurement Methods:

Slit-and-Collector Method

Faraday cups and wire scanners.

Things to consider:
- electrical noise (i.e. secondary electrons)
- sensitivity/resolution

Imaging methods

Fluorescence due to particle beams.

Things to consider:
- lifetime of scintillator screens
Thermal Measurement of Beam Emittance

Target Material

A one-dimensional carbon fiber composite (CFC) target is selected to measure the high power beam.

- **High heat resistance**
  (Melting Point: 2000ºC)
- **Good machining properties**
- **Low axial thermal conductivity**
- **Imaging form of measurement**

Low axial conductivity reduces the overestimation of the beam size.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Expansion Coefficient (linear)</th>
<th>Melting Point (ºC)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (J/kg K)</th>
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<tbody>
<tr>
<td>1D-CFC</td>
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<td>2000</td>
<td>1660</td>
<td>1140</td>
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<tr>
<td>Cu</td>
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<td>1085</td>
<td>8960</td>
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<td>W</td>
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<td>3410</td>
<td>19600</td>
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<td>Mo</td>
<td>5</td>
<td>2623</td>
<td>10188</td>
<td>277.1</td>
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Thermal Measurement of Beam Emittance

Target Material

Previous thermal images that captured the beam footprint of a 1 MeV negative ion beam exhibited a Gaussian profile with the beam power density averaging to 200 MW/m².

Calculation of a Gaussian profile beam
Total Beam Power Density in 1D

Beam Divergence: 5 mrad
Drift distance: 2.3 m
Aperture diameter: 14 mm

Spatial contour of the Gaussian beam

Peak Temp will be as high as 1400 MW/m²

Material Parameters:
- Thickness / Dimensions
- Exposure time
- Thermal Expansion

The exposure time of the beam to the CFC target will be limited when reproducing the beam footprint.
Operation of the 1 MeV Negative Ion Beam

The negative ions formed from a cesium seeded vacuum arc ion source are extracted to a multi-aperture multi-grid acceleration system.

Current measured in the accelerator

Timing sequence for operation
Operation of the 1 MeV Negative Ion Beam

Beam Profile

The multiple beamlet profiles of a 900 keV negative hydrogen ion beam was observed through the thermal images on the CFC target.

Temperature progression in the central part

0.2 sec

Thermal Imaging
Sampling Rate: 120 Hz
Beam Pulse: 0.2 sec

Broadening of the beam footprint at longer exposure times.

Tune to the stable beam operation
Operation of the 1 MeV Negative Ion Beam

Beam Profile

Thermal images show the multiple beamlets.

Noise from the background temperature in the images were reduced.

Displacement on the beamlet alignment

Possible reasons:

- Initial particle trajectories upon extraction
- Non-uniformity in the beam initializing phase
Operation of the 1 MeV Negative Ion Beam

Beam Profile

At 900 keV, the observed beamlet diameters became concentrated.

Increasing the beam energy also increased the temperature in the thermal images.

This relation is important for image analysis.

Intensity response determines the reliability of the beam emittance experiment.

Sample measurement for Beam Emittance

Pepper-pot plane

Analysis plane

<table>
<thead>
<tr>
<th>Vac (keV)</th>
<th>Parc (kW)</th>
<th>Vext (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>24</td>
<td>3.7</td>
</tr>
<tr>
<td>800</td>
<td>34</td>
<td>4.3</td>
</tr>
<tr>
<td>900</td>
<td>43</td>
<td>4.8</td>
</tr>
</tbody>
</table>

• Some parameters for beam optics
Diagnostics for 1 MeV Negative Ion Beam

Beam Emittance Application

**Main Concerns:**

**Temperature Range of the Measurement**

- **Material Deformation**
  - Beam pulse
  - $T_{\text{max}}$

- **Acceptable Range**
  - Material limit
  - Interlock

**Phases of the Beam**

- Tuning the measurement to match the stable beam phase
  - Initializing Phase
  - STABLE BEAM
  - Emittance pattern

**$H^-$ Ion Beam Current**

- Time

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Diagnostics for 1 MeV Negative Ion Beam

Measurement Schemes

To assure that the measured beam is stable, the ion source will operate continuously.

Beam selection scheme is necessary for long H- beam pulses.

90° rotation can allow the open the beam path.

Possible mechanisms for continuous beam monitoring.
Summary

1 MeV High Power Beam
High Beam Power Densities

Thermal Beam Emittance Measurement Method
1D – Carbon-Fiber Composite

Challenge for Beam Diagnostics:
High voltage components of the accelerator
High temperature heat loading
(Long) Beam Pulse Operation

Advantages:
Imaging form of measurement
CFC has a high heat resistance
Measurement schemes are possible

Beam diagnostics of the 1MeV H⁻ beam is possible with the thermal beam emittance measurement. This method is being developed specifically for ITER class beams for NBI systems.
Thank you for your attention