High power long pulse beams for ITER and JT-60SA

Achievement of
1 MeV beam accelerations for 60 s toward high power NBIs

1. Introduction
2. Long pulse beam experiments
3. Recent activities
4. Summary

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1. Introduction
Activities for fusion reactor

Framework toward nuclear fusion plant in Japan

Neutral beam injector (NBI) is one of key components for heating (up to several hundred million degrees) & current drive of fusion plasma.
Our missions for fusion reactors

**JT-60SA**
- Negative-ion-based NBIs (10 MW)
- 12 positive-ion-based NBIs (24 MW)

**ITER project**
- Three negative-ion-based NBIs (NB test facility and two NBIs)

Japanese procurement:
- Three 1 MV power supplies and HV bushings
- One 1MeV accelerators

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<th>ITER target</th>
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**High energy and short pulse (a few seconds) beams have been achieved.**

**Next target is high energy and long pulse beams.**
To realize the accelerator for high power NBIs

**ITER accelerator**
(1 MeV, 40 A (200 A/m²), 3600 s)
- Five-stage (1 MV)
- Large grid with multi-aperture (1280)
- Large grid support

**High current beam acceleration in JT-60SA**
(0.5 MeV, 22 A (130 A/m², 100 s)
- Three-stage (0.5 MV)
- Large grid with multi-aperture (1024)
- Large grid support

**High energy beam acceleration in MeV accelerator**
(1 MeV, 0.5 A (200 A/m², 60 s)
- Five-stage (1 MV)
- Small grid, but multi-aperture (9-15)
- Large grid support
2. Long pulse beam experiments of 1MeV beams
Experimental setup of MeV accelerator

First target: 1MeV, 200A/m² H- for 60s beams

Initially, the beamlet deflection due to (1)(3) have been compensated. As the result, 1MeV beams was sustained for 0.4 s (2011).
Issues for stable high power long pulse beam

Without beams, 1MV has been sustained stably more than 1 hour. However,
- Pulse length with 1MeV beams has been limited less than 1 s due to breakdowns.
- Stable voltage holding with beams is around 80% of voltage holding without beams.

**Possible causes of breakdown**

1. Interceptions of beam halo
2. Influence due to impurities such as Cs

**Graphs:**
- Stable HV holding & suppression of grid heat load
- Pulse length < 1s
- Power supply limit

**Possible solutions:**

1. Reduction of grid heat load to suppress case
2. Voltage holding with the margin of 20% considering influence of outgas and impurities (①②)
(1) Suppression of grid heat load

Compensation of beam deflections using precise 3D beam analysis.

Modification of grid aperture

Optimization

(1) Suppression of peripheral beam at upper grid before acceleration

(2) Suppression of secondary electrons due to thinner grid.

Aperture offset (<1mm)

Kerb (1mm)

Space charge repulsion

Beamlet deflection < ±1 mrad (ITER requirement)
(2) Stable high voltage holding

**Previous:** Gap between metals had been designed only considering electric field strength on the metal surface.

**Progress:** Voltage holding varies with not only electric field also surface area. Voltage holdings were investigated experimentally as a function of surface area.

Experimental scaling to design large accelerator with large grid and large support system is established.
Improvement of voltage holding

Grid support configuration was modified to get sufficient HV holding.

Critical parts:
- Large planer grid (A1G) and large cylindrical (A4G)

Possible voltage holding: 1 MV

Grid support structure was modified according to the experimental scaling.

Possible voltage holding: 1.2 MV
Including the margin of 20%
Pulse lengths was extended step by step.

Reduction of grid heat load

Original grid loading melts the grid

Compensation of beam deflections due to (1) space charge repulsion and (3) magnetic field for electron removal
→ 1MeV, 0.4s

Additional compensation of beam deflections due to (2) filter field and aperture modification
→ 0.9MeV, 9s, 0.7MeV, 60s

More tuning of compensation of beam deflections, and modification of grid support to have voltage holding with the margin of 20%.
→ 0.97MeV, 60s
Long pulse operation of beams

Pulse length with 1MeV beam was extended from < 1 s to 60 s (PS limit). There are no limitations to extend the pulse length under this condition. Based on this results, the power supply was modified to demonstrate 1MeV beam for 1000 s.

Poster Tu_50; J. Hiratsuka, Experimental validation of grid heat loadings in the five-stage accelerator with the ITER-relevant gap lengths.)
Investigation: Voltage holding with beams

This acceptable grid heat load for voltage holding

Grid heat load for grid melt.

As the further study:
-Breakdown probability with beams considering outgas and Cs is to be examined.

☆ Over 1.3 kW/aperture → Breakdown
★ Less than 1.3 kW/aperture →
Non remarkable differences in grid heat load between BD or No-BD cases.
The pulse length was gradually extended with conditioning time.
3. Recent activities
Toward longer beam pulse over 100 s

As the first test campaign after the power supply modification up to 1000s, integration test for 500 keV, 130A/m² for 100 s (target value of JT-60SA).

To get stable Cs condition, temperature of chamber wall and plasma grid is controlled.

New filament arrangement to suppress arcing

After conditioning of 600 kV with the margin of 20%, the beam was stably operated at 500keV. Now, the beam current is increasing to the target value.

*Poster Tu_48 M. Ichikawa, High power and long pulse negative ion production by suppressing of arcing for JT-60SA*
Development of large grid: HV bushing for ITER NBI

Critical components for ITER NBI to feed 1MV with water/gas/signal cables to accelerator:
Boundary between 0.6MPa gas and vacuum, and 1MV vacuum insulation

Surface area (5 m$^2$)

1MV was sustained stably and repeatedly during three days test period.

Delivered to the NBTF site (RFX).

This is the first components for 1MV vacuum insulation for the ITER procurement.
Realization of this critical component contributes to the realize the vacuum insulation technology required for the ITER NBI.
Installation: Transformer 100%, Transmission line 90% completed. Integrated test will be started in 2018.
4. Summary

- R&Ds for the high power NBI system concentrates to long pulse beam production.
- To stable voltage holding, the grid heat load due to the beam interception on the grid was reduced, and the experimental scaling of voltage holding was established to design the accelerator with sufficient voltage holding.
- Beam acceleration test for ITER, pulse length of 1MeV beam was successfully extended from $>1$ s to 60 s (PS limit).
- There are not remarkable limitations to extend the pulse. For 1000s-class beam for ITER, the further long pulse test is ongoing.

- In parallel, other high voltage components for ITER have been developed and delivered to the NBTF site / Italy. The installation work is going well under collaboration with RFX colleagues.