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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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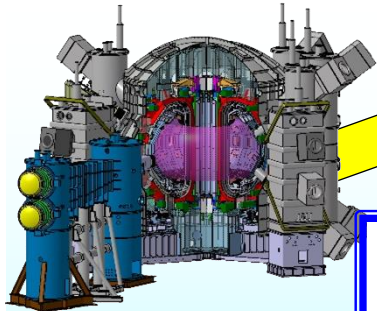
1. Introduction

Activities for fusion reactor

Framework toward nuclear fusion plant in Japan

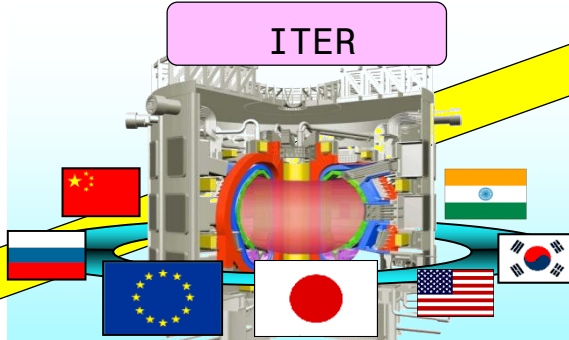
Broader approach

JT-60SA



ITER project

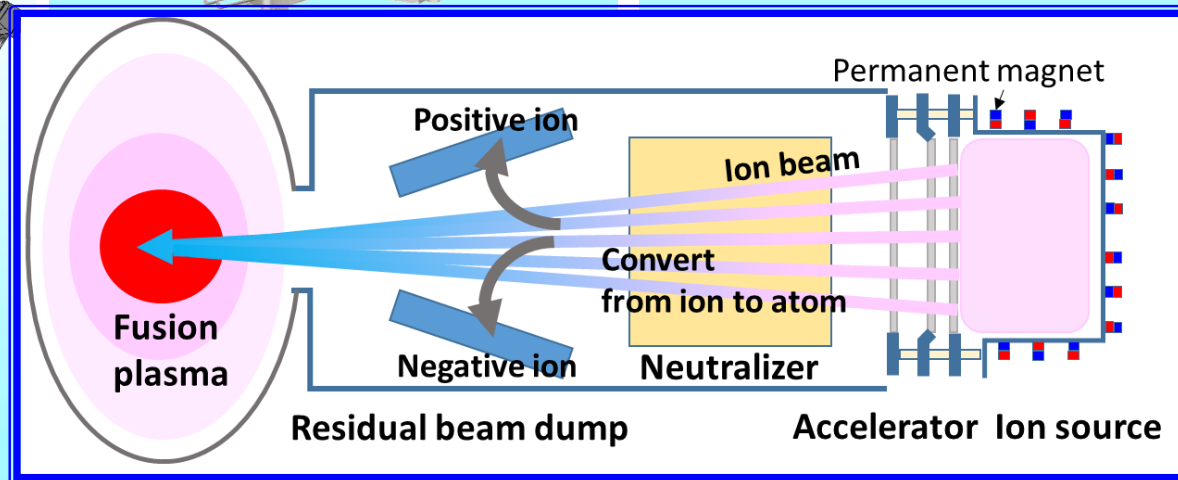
ITER



DEMO



Plant

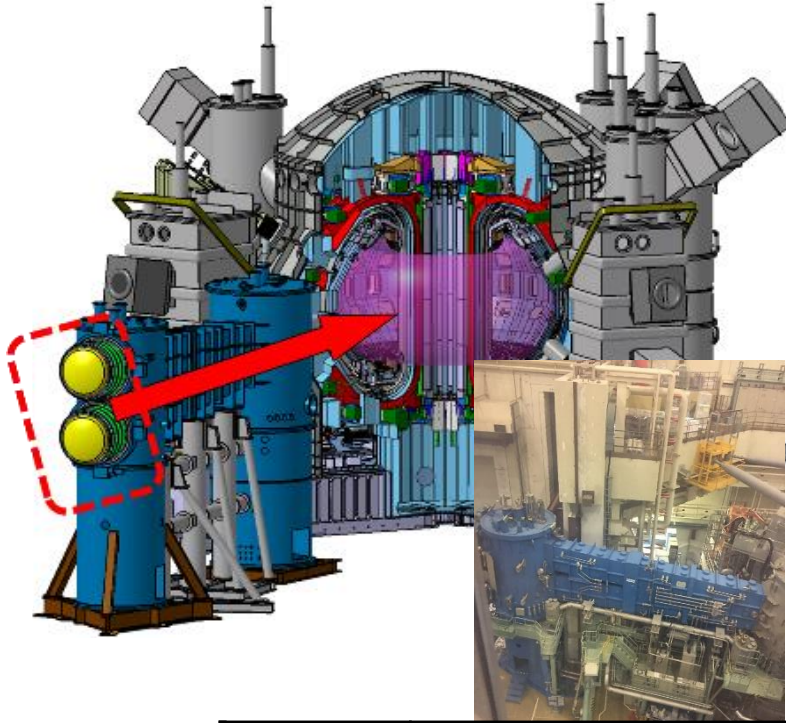


Neutral beam injector(NBI) is one of key components for heating (up to several hundred million degrees) & current drive of fusion plasma.

Our missions for fusion reactors

JT-60SA

Negative-ion-based NBs(10 MW)
12 positive-ion-based NBs(24 MW)

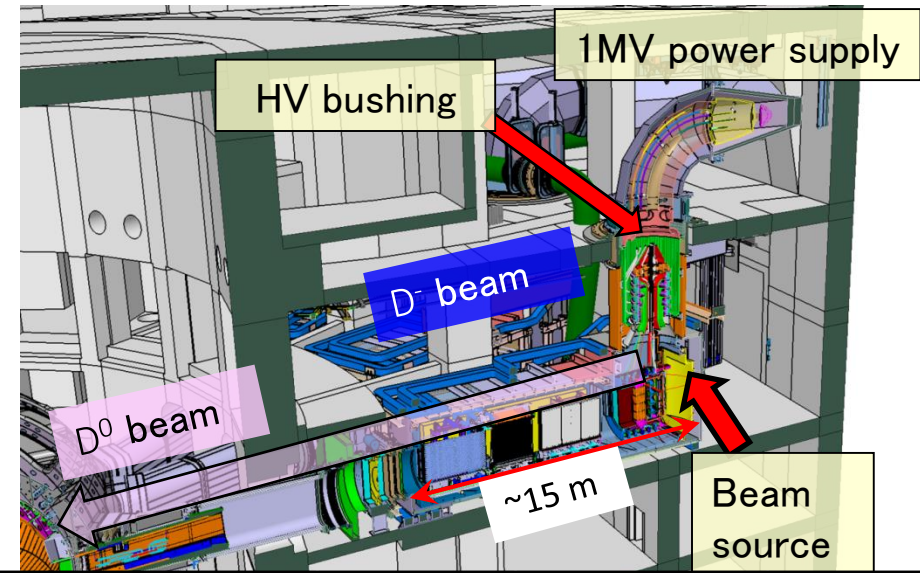


ITER project

Three negative-ion-based NBs
(NB test facility and two NBs)

Japanese procurement :

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



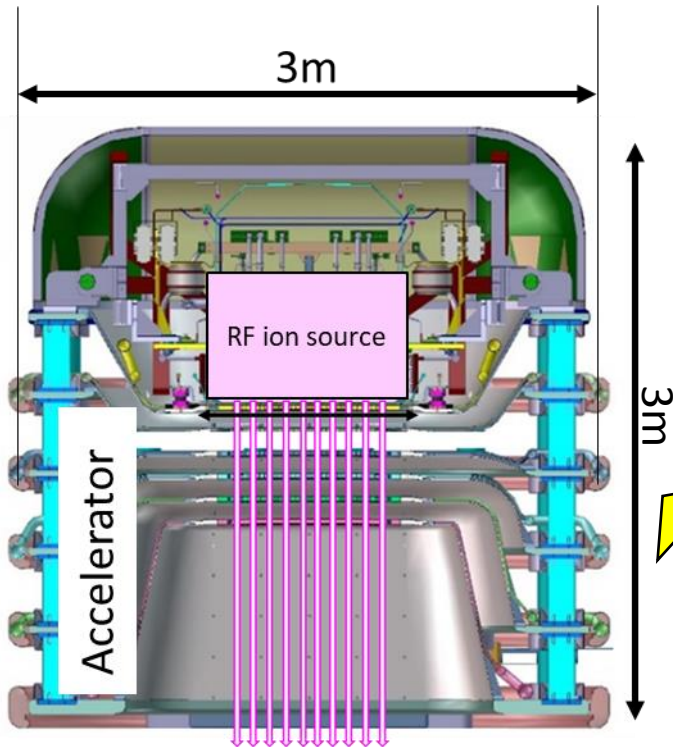
	60SA target	Energy, current and pulse have been achieved independently.			Next target	ITER target	Achievement	Today's topics	Next target
Energy (MeV)	0.5	0.5	0.01	0.01	0.5	1	1	1	1

High energy and short pulse (a few seconds) beams have been achieved.
Next target is high energy and long pulse beams.

ITER accelerator

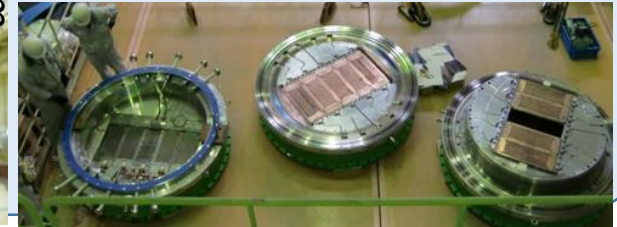
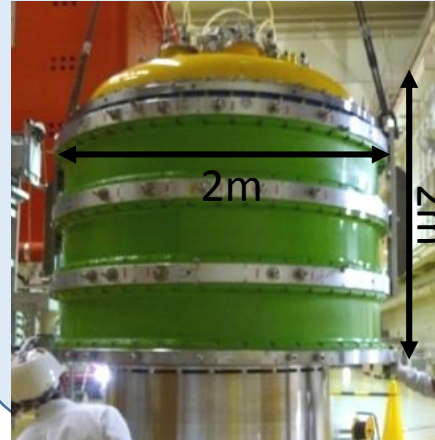
(1 MeV, 40 A (200 A/m²), 3600 s)

- Five-stage (1MV)
- Large grid with multi aperture (1280)
- Large grid support



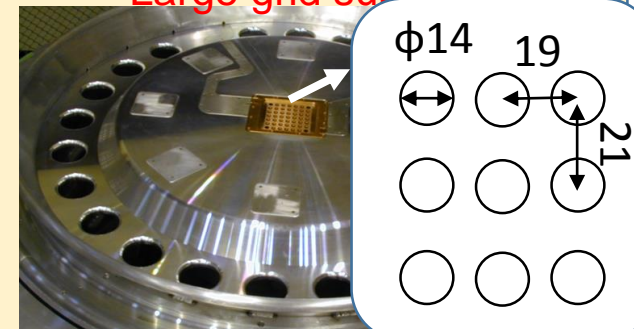
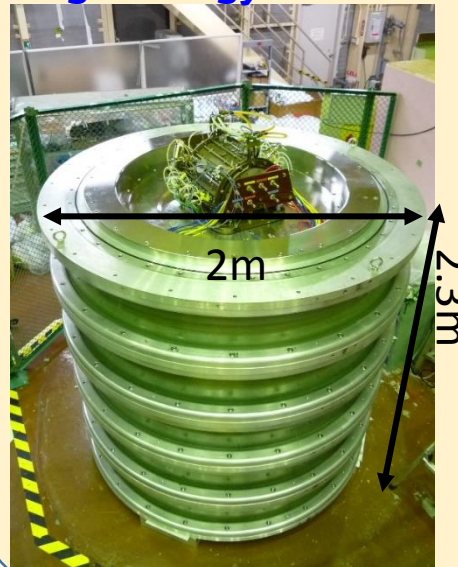
High current beam acceleration in JT-60SA (0.5 MeV, 22 A (130 A/m²), 100 s)

- 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)

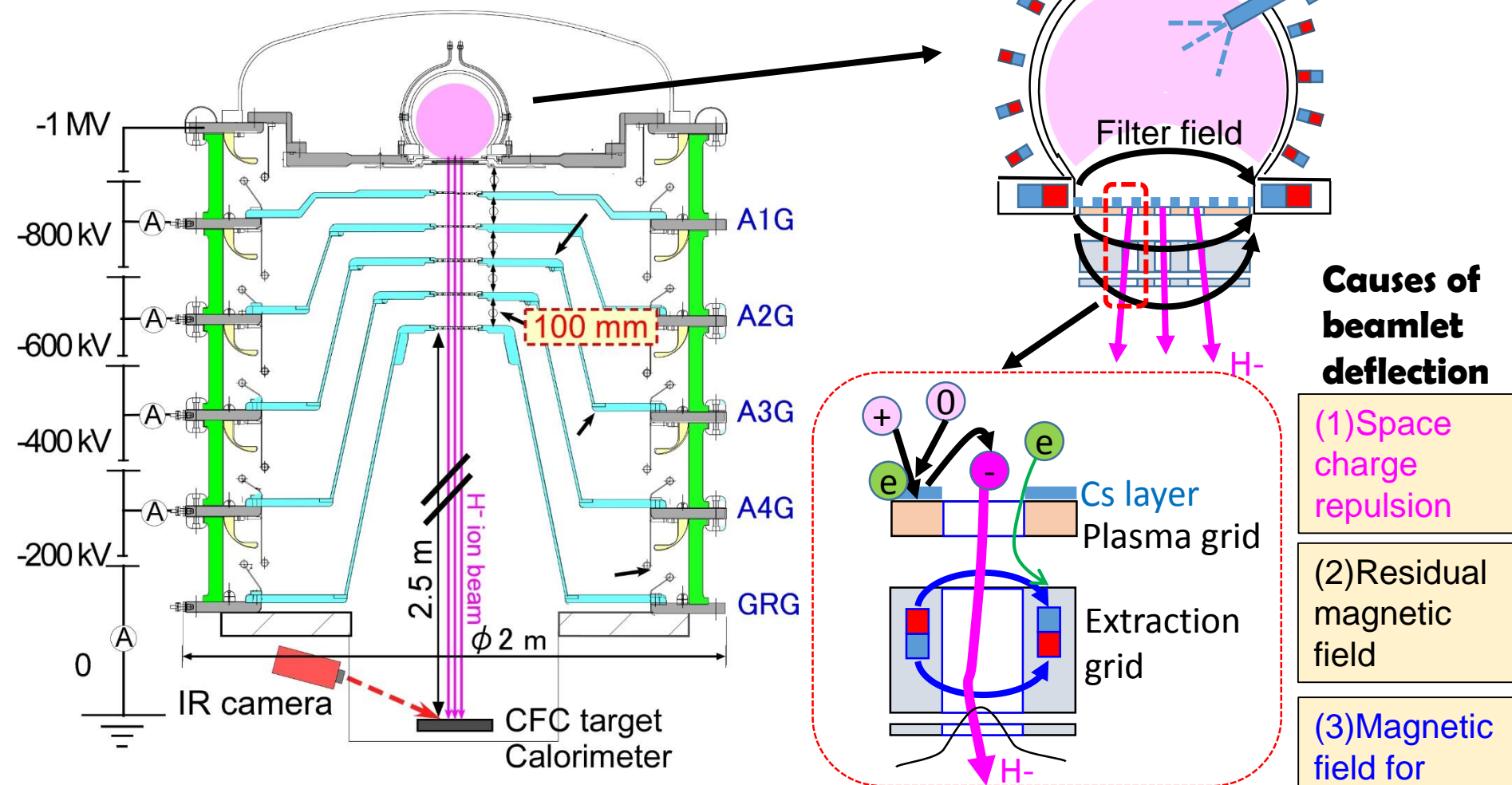
- Five-stage (1MV)
- Small grid, but multi-aperture (9-15)
- Large grid support



2. Long pulse beam experiments of 1MeV beams

Experimental setup of MeV accelerator

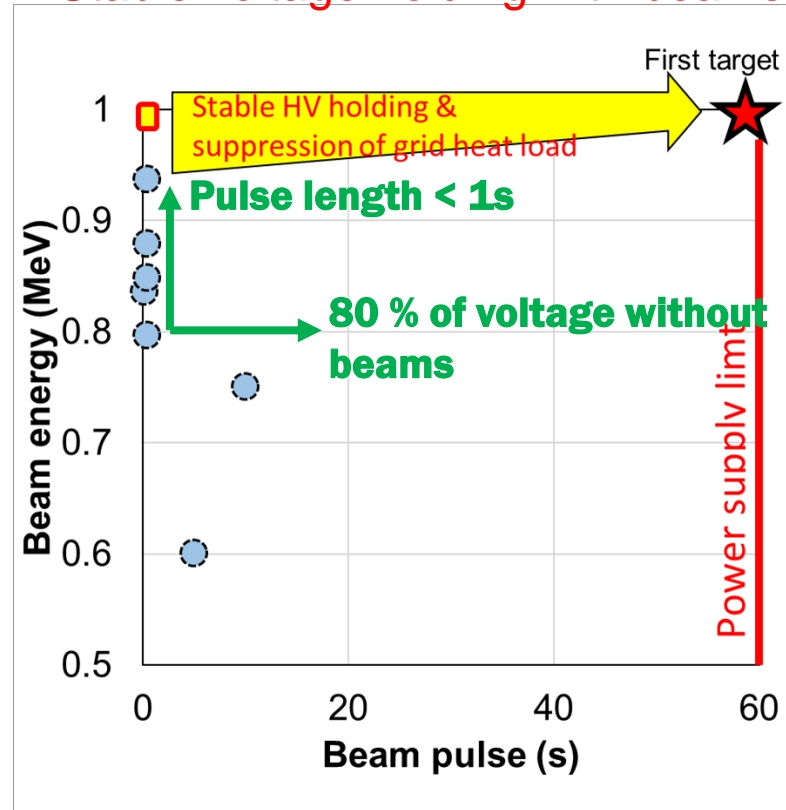
First target: 1MeV, 200A/m² H⁻ for 60s beams



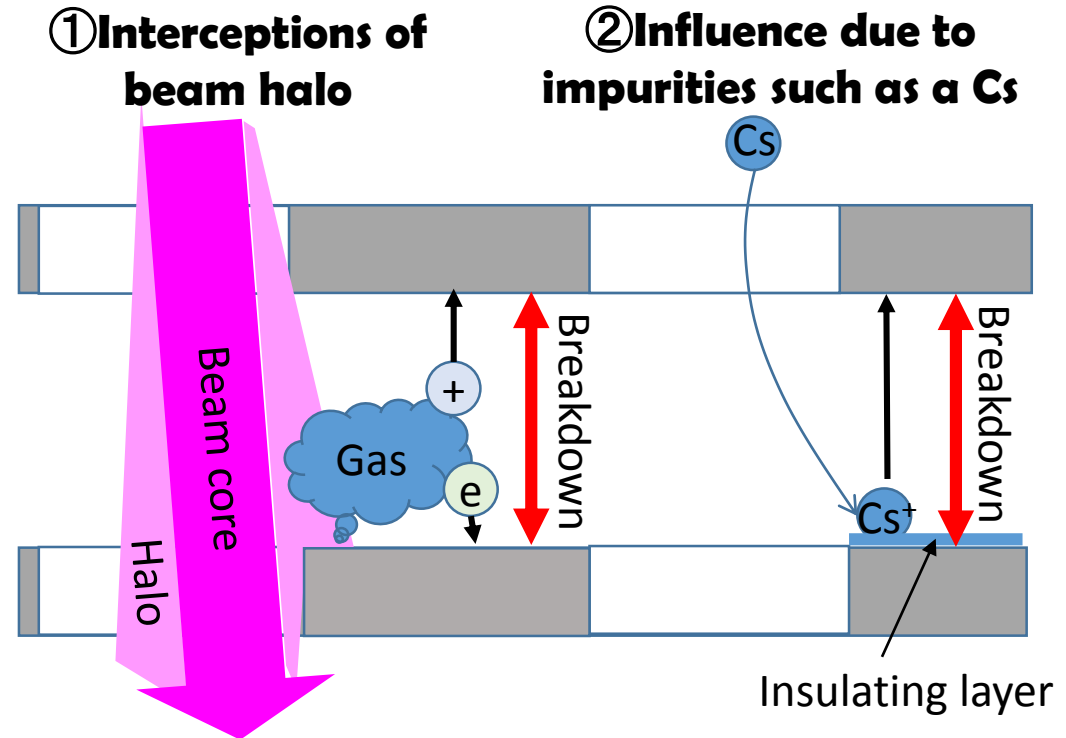
Initially, the beamlet deflection due to (1)(3) have been compensated. As the result, 1MeV beams was sustained for 0.4 s (2011).

Issues for stable high power long pulse beam

- Without beams, 1MV has been sustained stably more than 1hour. **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



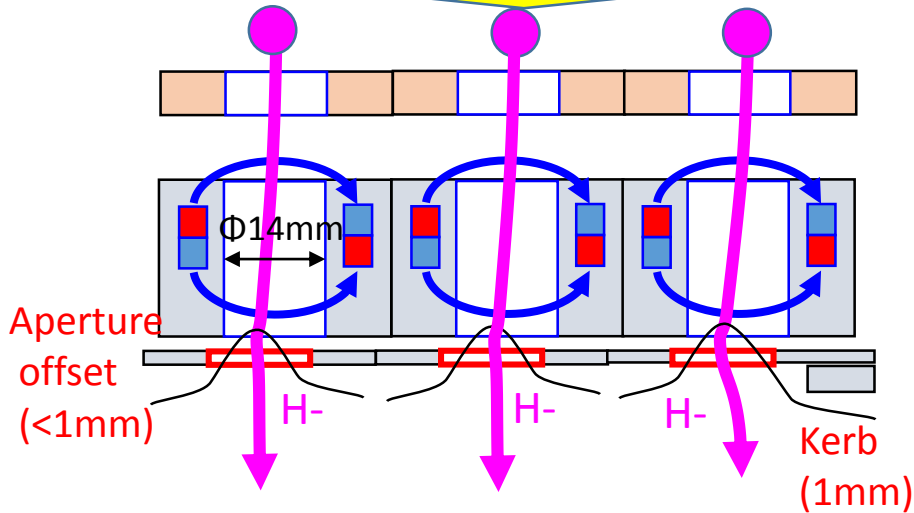
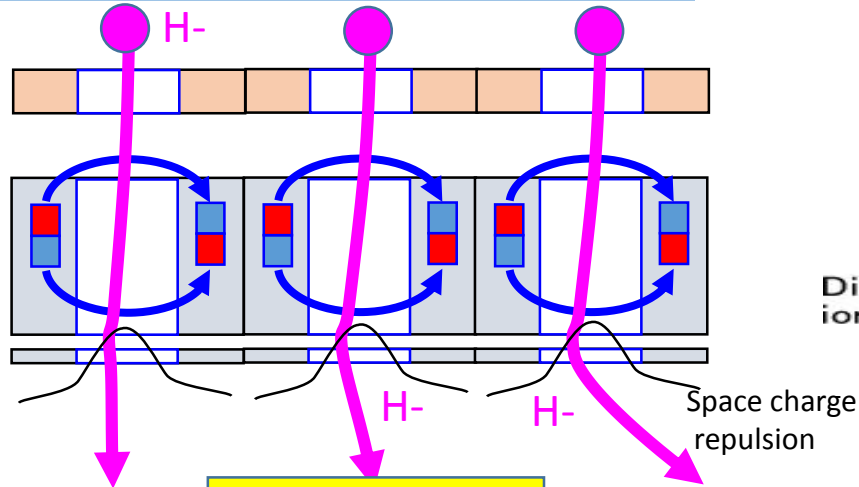
(1) Reduction of grid heat load to suppress case ①

(2) Voltage holding with the margin of 20 % considering influence of outgas and impurities (①②)

Lon pulse beam acceleration

(1) Suppression of grid heat load

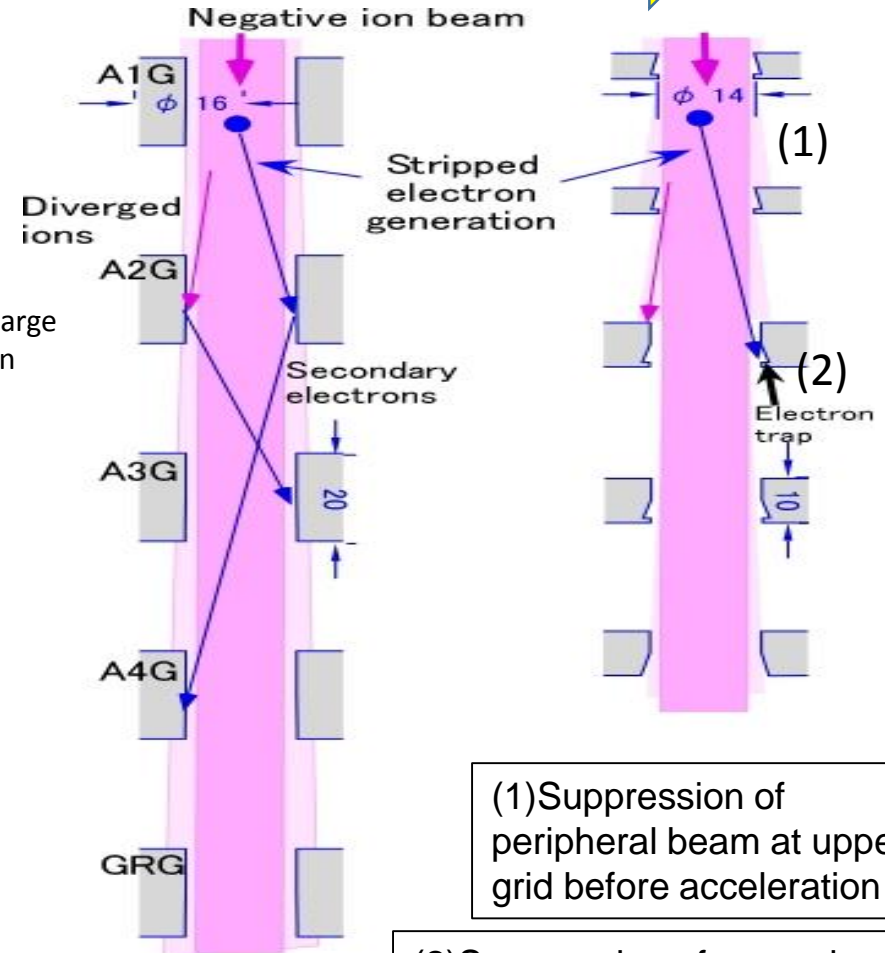
Compensation of beam deflections using precise 3D beam analysis.



Beamlet deflection $< \pm 1 \text{ mrad}$ (ITER requirement)

Modification of grid aperture

Optimization



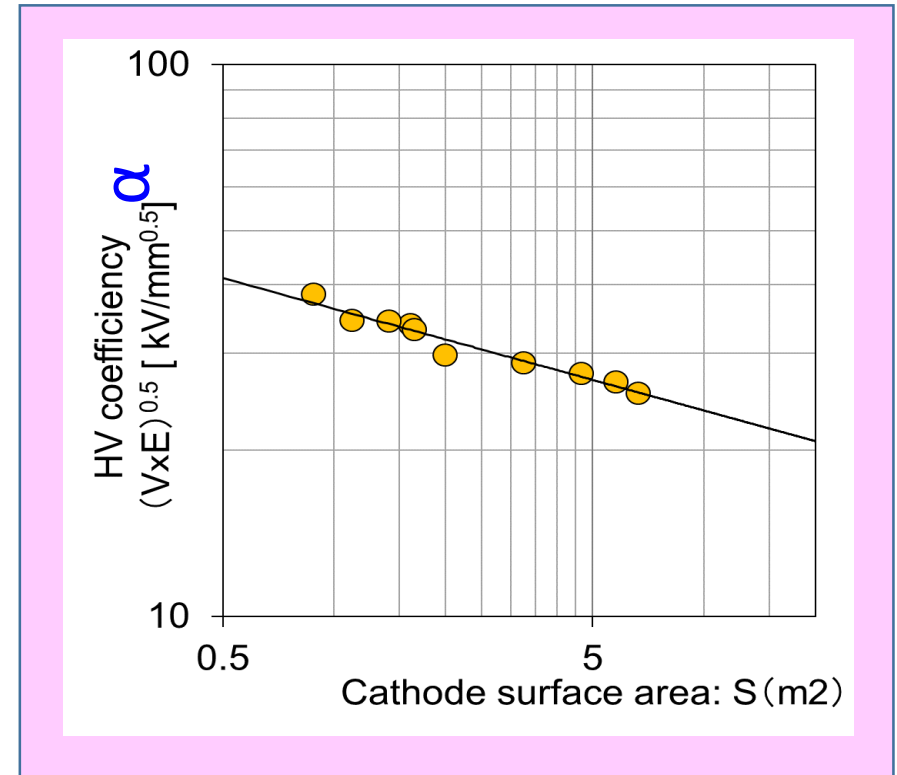
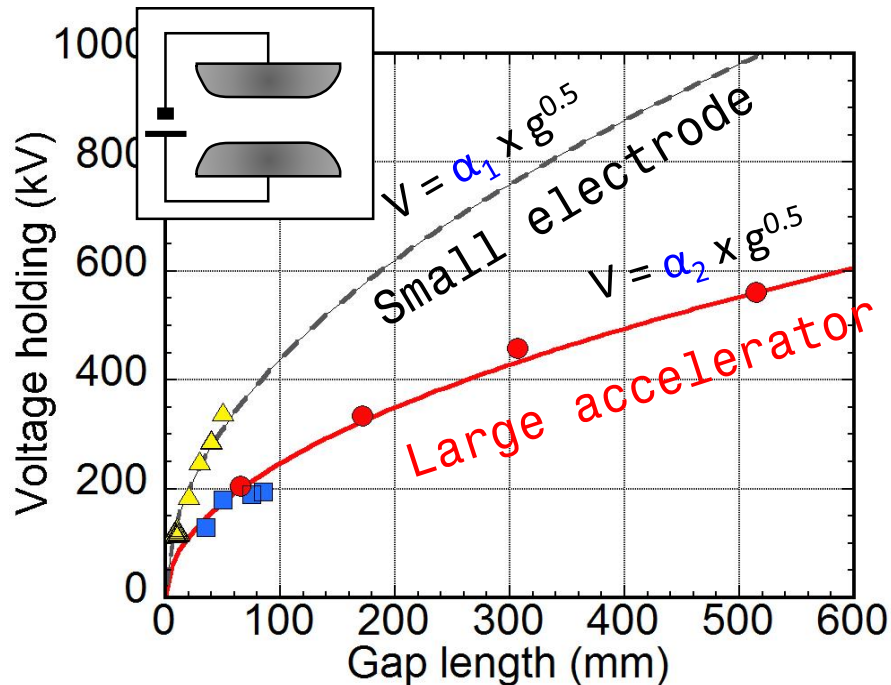
(1) Suppression of peripheral beam at upper grid before acceleration

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

(2) Stable high voltage holding

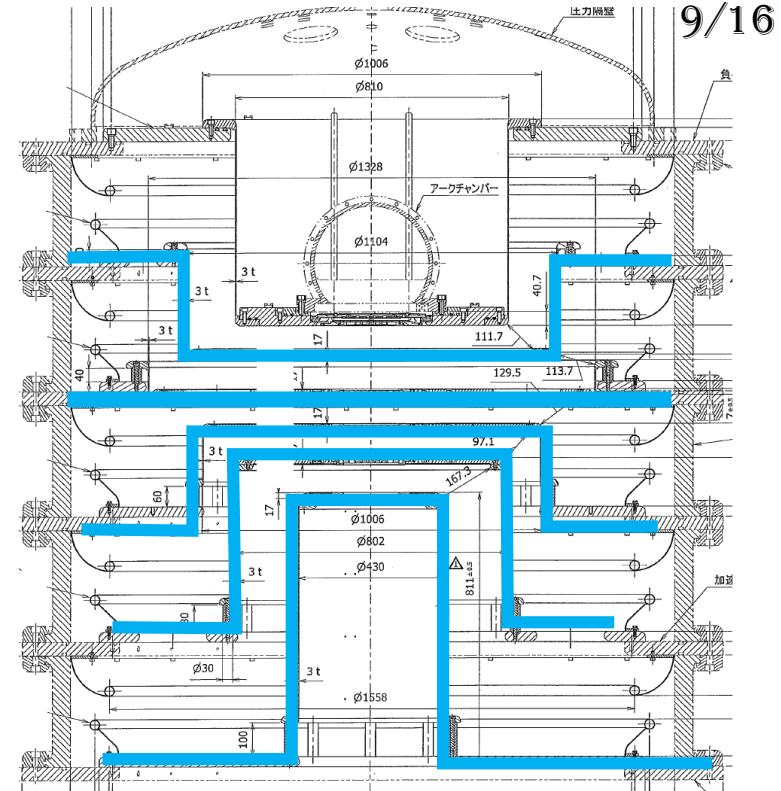
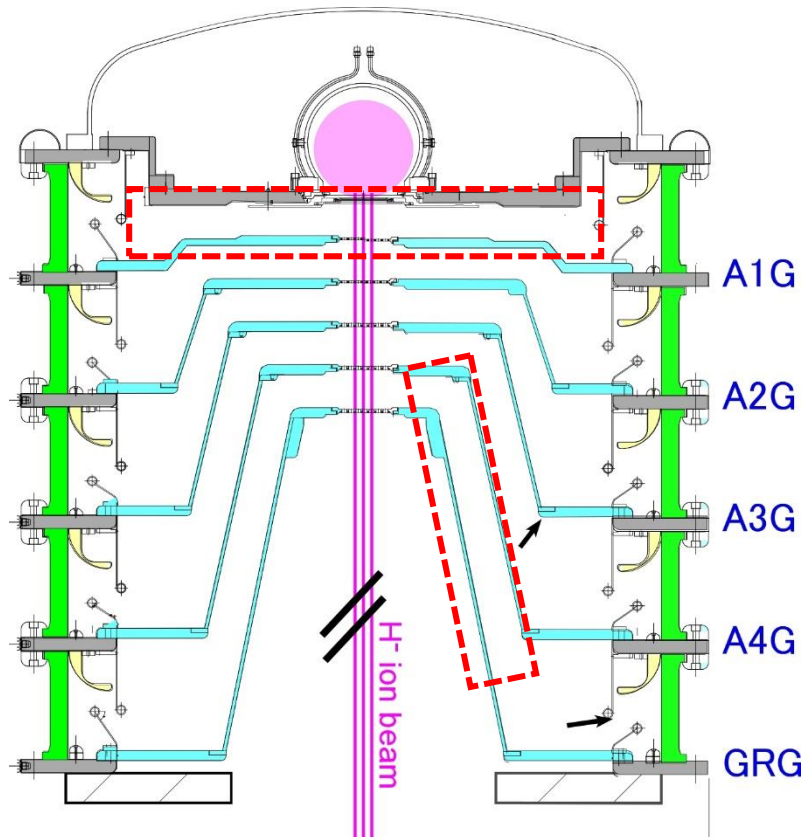
Previous: Gap between metals had been designed only considering electric field strength on the metal surface.

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



Critical parts :

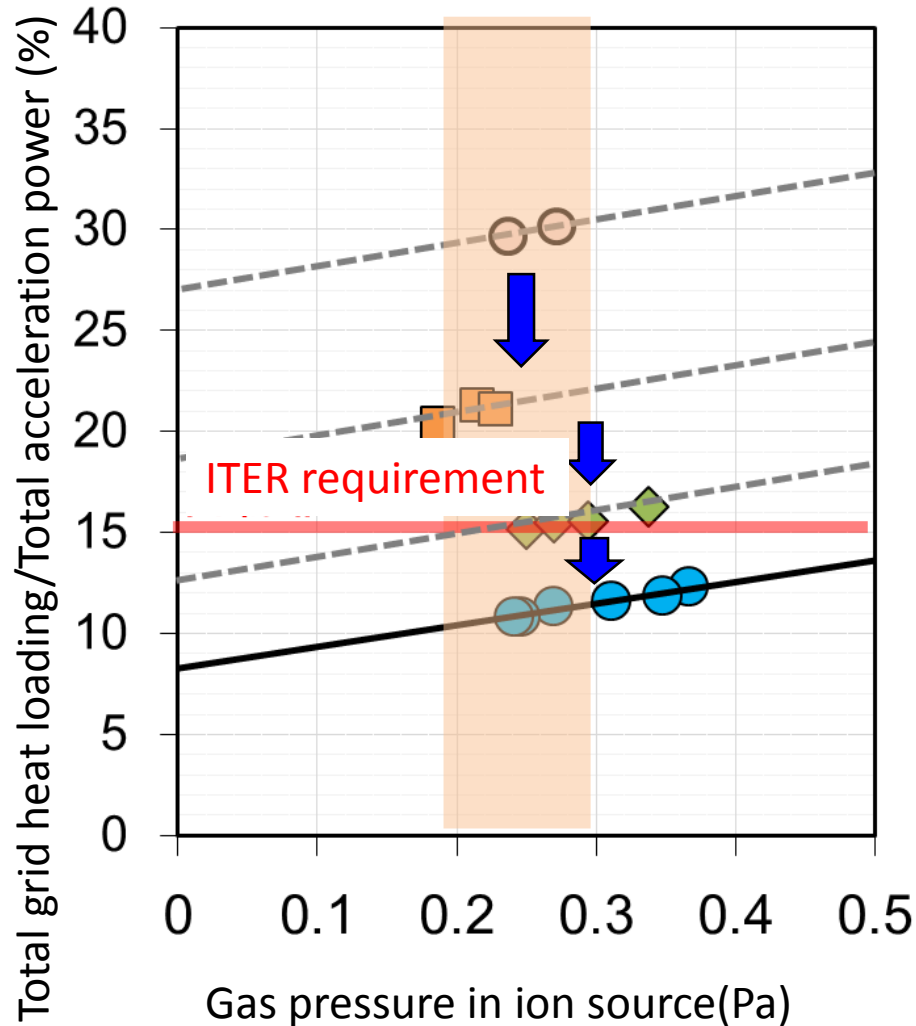
Large planer grid (A1G) and large cylindrical (A4G)

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 %.

Grid support configuration was modified to get sufficient HV holding.



Original grid loading melts the grid

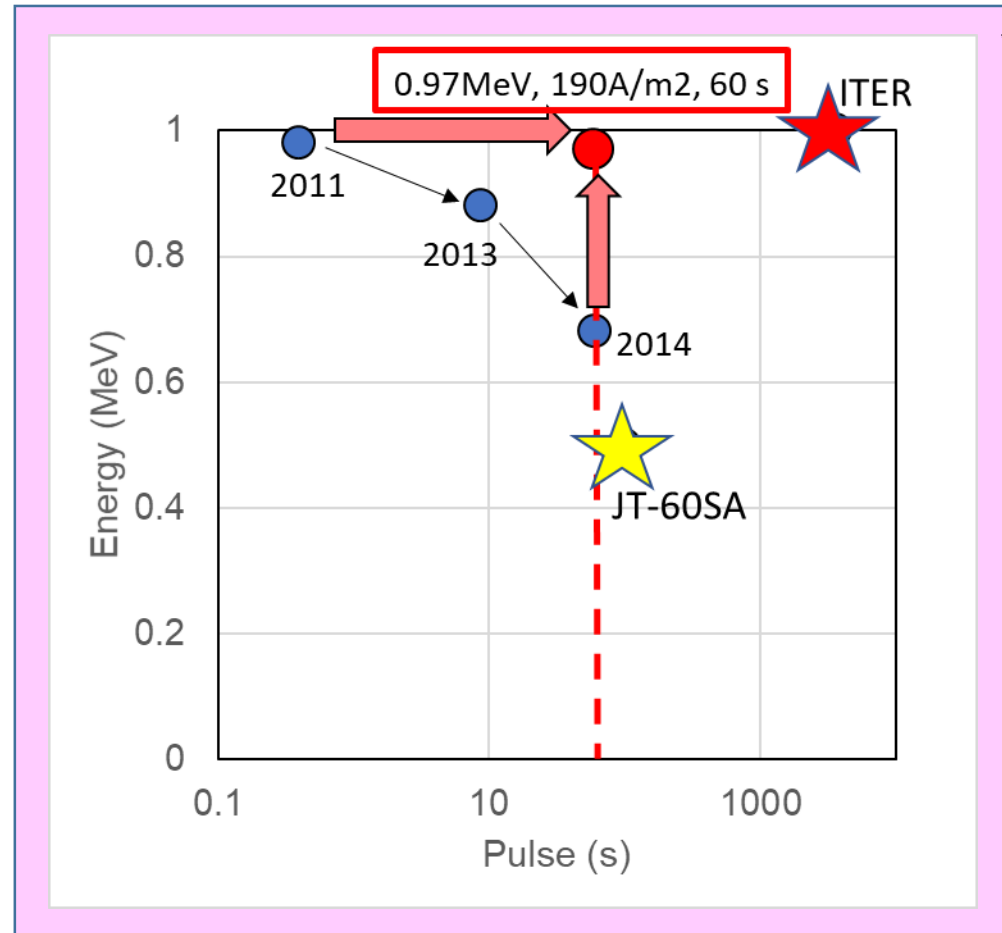
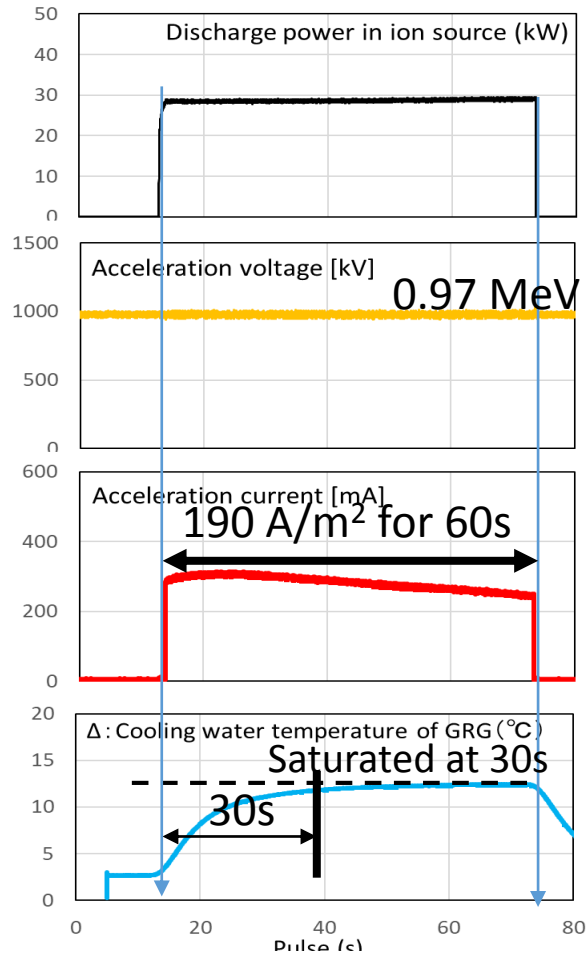
Compensation of beam deflections due to (1) space charge repulsion and (3) magnetic field for electron removal
→ 1MeV, 0.4s

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

Pulse lengths was extended step by step.

Long pulse operation of beams



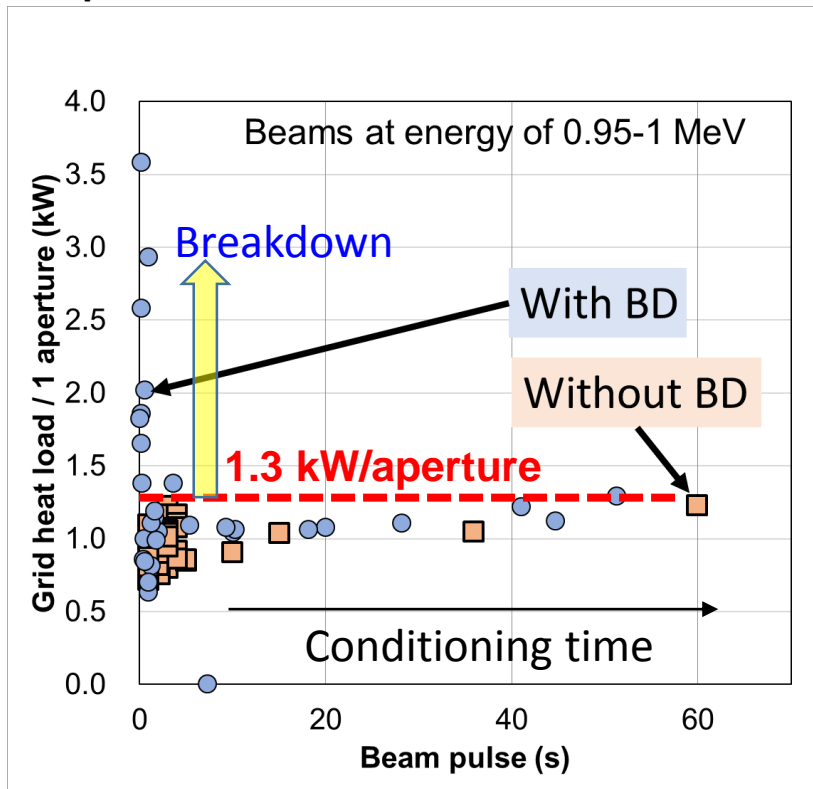
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**Pulse length with 1MeV beam was extended from $< 1 \text{ s}$ to 60 s (PS limit).
There are no limitations to extend the pulse length under this condition.**

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).

Acceptable grid heat load for voltage holding



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 1.3kW/aperture → Breakdown

★ Less than 1.3 kW/aperture →

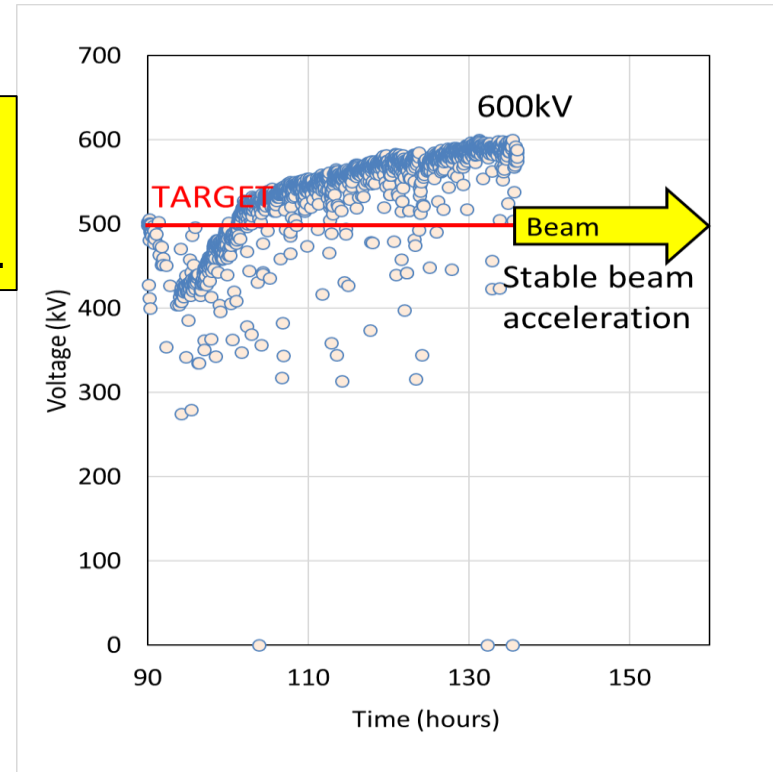
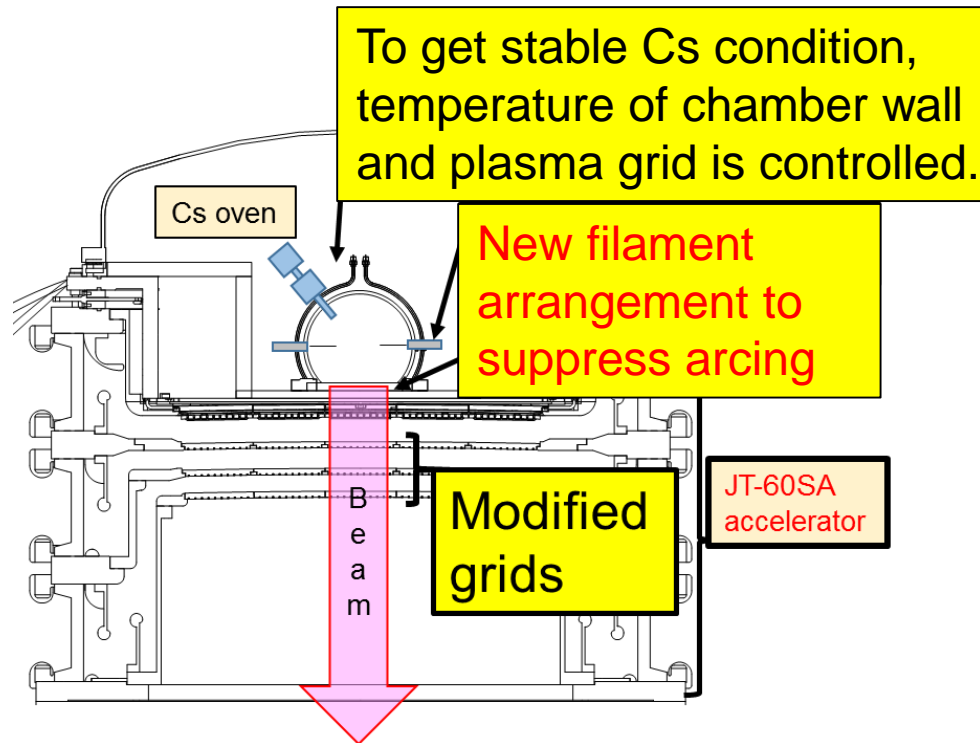
Non remarkable differences in grid heat load between BD or No-BD cases.

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).



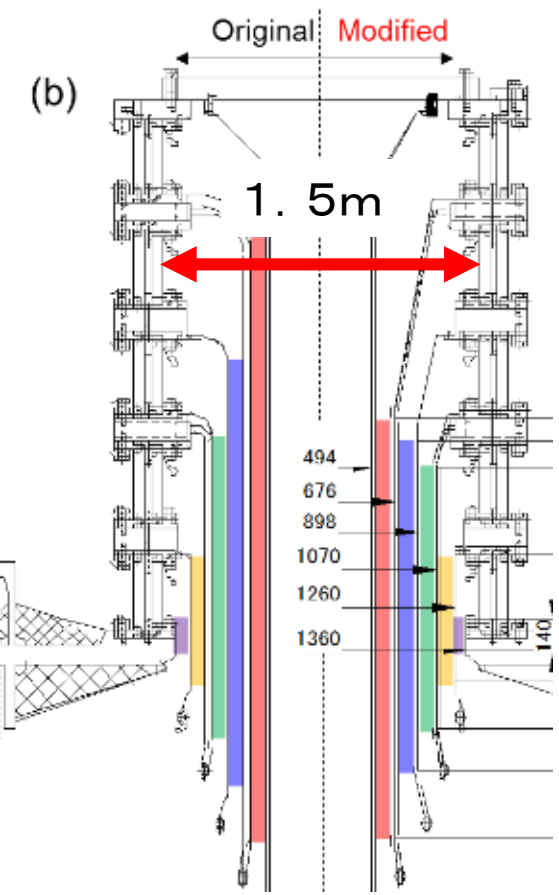
After conditioning of 600 kV with the margin of 20%, the beam was stably operated at 500keV. Now, the beam current is increasing to the target value.

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 m²)



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.

1MV power supply for 1MeV accelerator (NBTF site)

1. Testing power supply
2. Transmission line1
3. Transmission line2
4. DCG5 (0.2MV)
5. DCG4 (0.4MV)
6. DCG3 (0.6MV)
7. DCG2 (0.8MV)
8. DCG1 (1MV)
9. 1MV insulating transformer

10. DC filter
11. Transmission line3
12. High voltage deck2
13. Short circuit devise
14. Dummy load
15. HV bushing

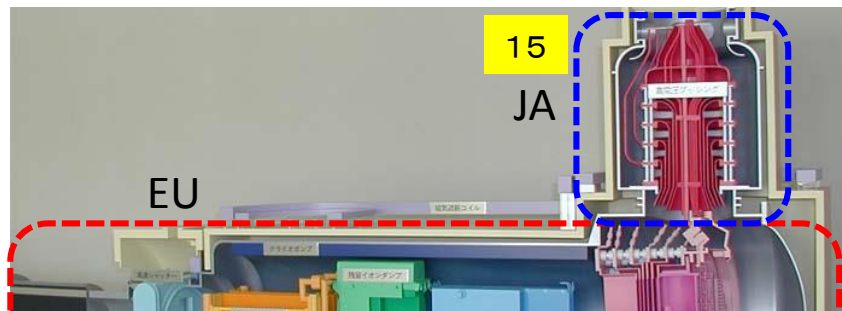
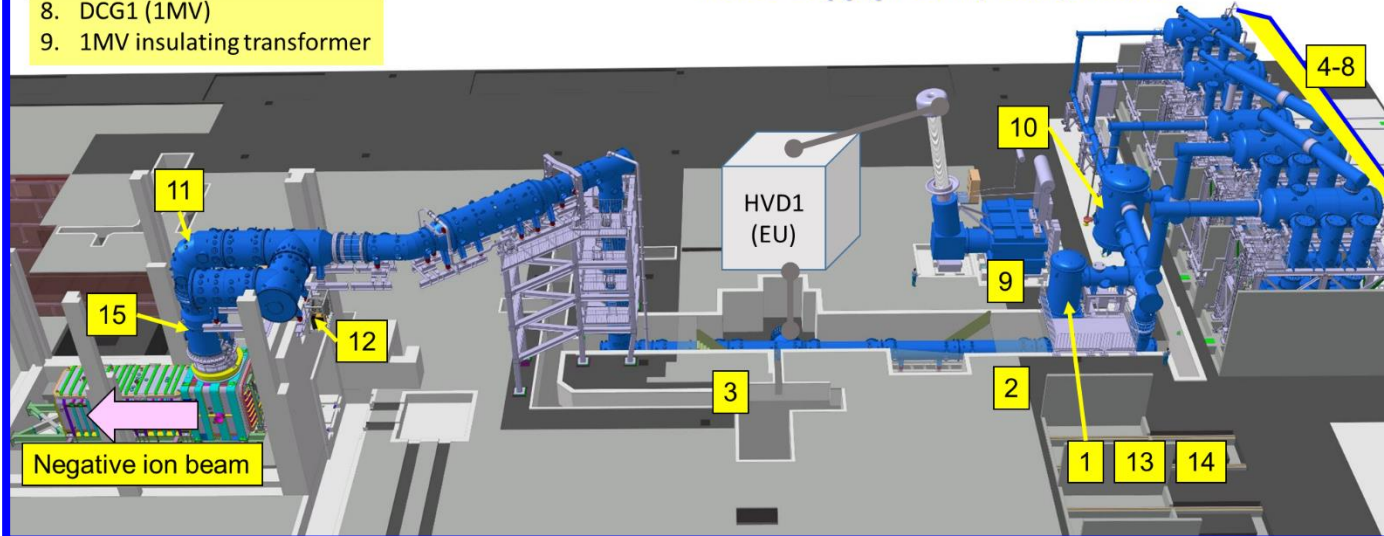
NBTF in Italy :

ITER Neutral Beam Injection system test facility

イーター中性粒子入射装置 実機試験施設

D- ion beam : 1MeV, 40 A, 3600 s

Power supply : 1MV, 60 A, 3600 s



**Installation: Transformer 100%, Transmission line 90% completed.
Integrated test will be started in 2018.**

4. Summary

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- 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.