R&D on a High Energy Accelerator and a Large Negative Ion Source for ITER

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Abstract. The R&D of a 1 MeV accelerator and a large negative ion source has been carried out at Japan Atomic Energy Research Institute (JAERI) for the ITER NB system. The R&D is in progress at present toward: 1) 1 MeV acceleration of H^- ion beams at the ITER relevant current density of 200 A/m^2, and 2) improvement of uniform negative ion production over wide extraction area in large negative ion sources. Recently, H^- ion beams of 1 MeV, 140 mA level have been generated with a substantial beam current density (100 A/m^2). In the uniformity study, it has been clarified that electron temperature in the ion extraction region is locally high (> 1 eV), which resulted in destruction of negative ions at a high reaction rate. Interception of fast electrons leaking through a transverse magnetic field called "magnetic filter" has been found effective to lower the local electron temperature, followed by an improvement of negative ion beam profile.

1. Introduction

In the present ITER design [1], two neutral beam (NB) systems are to be installed together with radio frequency systems, to achieve $Q \geq 10$. ITER plans installation of the third NB system in the latter half of the operation, to demonstrate steady state operation at $Q \geq 5$ with the NB on-/off-axis current drive. The design value of the beam energy was decided to 1 MeV from trade off between the current drive efficiency and shinethrough of the beam at the plasma lamp-up phase. And then the NB output power of 16.5 MW is required at 1 MeV for the plasma heating and current drive. Having constrains in neutralization efficiency of gas cell ($\leq$ 60 %) and relatively low beam transmission efficiency ($\approx$ 90%) etc., overall efficiency of the ITER NB system is estimated to be $\approx$ 40%. And hence, the beam source (ion source and accelerator) is required to generate negative ion (D^-) beams of 40 A, as the primary beam of NB. In addition, due to limitation in available space for the NB system, the negative ion beam is to be generated at high current density of 200 A/m^2.

In conventional accelerators in universities and industries, insulation gas such as SF_6 is widely used for insulation of MV class high voltage. However, the design and R&D done in EDA revealed that the insulation gas is not applicable in radiation environment of the ITER NB system due to radiation induced conductivity (RIC) [2, 3] in the gas and consequent heat dissipation of about 1 MW [4]. Thus the present ITER NB design adopts vacuum insulation all around/inside the accelerator for the insulation of 1 MV high voltage. This also required a challenging R&D for the voltage holding of accelerator, before the beam acceleration. In fact, it took years to achieve stable voltage holding in the vacuum insulated accelerator at JAERI.

There has been no attempt in the world to accelerate even ampere class charged particle beams up to the energy of MeV range. Thus the accelerator design requires robust development. Since the beginning of EDA, JAERI has developed such high power accelerators toward demonstration of 1 A class H^- ion beam acceleration at the current density of 200 A/m^2 up to 1 MeV as a "Proof-of-Principle" of the ITER accelerator.

In the meantime, both existing negative-ion based NB systems in JT-60U and Large Helical Device

(LHD) reported high heat load in the beamline and subsequent loss of NB injection power. They claimed that this was caused by non-uniform distribution of negative ion intensity in the large negative ion sources. They have tuned local input power of the filament and arc discharge over the wide extraction area [5, 6], and found that the uniformity of negative ion beam was improved. However, the recovery of the local negative ion current was not enough, and moreover, it has not been cleared yet the physical mechanism how the negative ion density decreased locally in the wide extraction area. Further improvement of the negative ion uniformity is essential for the ITER NB system, since the ITER ion source design is based on that of the JT-60U.

At the previous conference of this series, achievements of 1 MV vacuum insulation in the accelerator and H^- ion production at low gas pressure (300 A/m^2 H^- at 0.1 Pa) were reported [7]. In this paper, the progress of 1) acceleration of high current density H^- ions up to MeV range energy, and 2) improvement of uniform negative ion production in large negative ion sources, is reported. In the end of this paper we summarize the status of the R&D, and future program planned for the ITER construction phase.

2. 1 MeV accelerator development

2.1 Vacuum insulated accelerator

The vacuum insulated accelerator developed at JAERI is shown in FIG. 1. The accelerator and power supply are contained in a SF_6 gas tank at the pressure of 0.6 MPa. The vacuum boundary that insolates the main structure of accelerator (acceleration grids and its support structures) from the SF_6 gas is a FRP (fiber reinforced epoxy) insulator column consisting of a stack of 5 FRP insulator rings. The dimensions of each ring are 1.8 m in diameter and 0.33 m in height, and hence, the overall size of the FRP insulator column is 1.8 m in diameter and 1.9 m in height.

The accelerator of the ITER NB system is surrounded with vacuum gap all round for high voltage insulation. To simulate the ITER geometry as much as possible, the FRP insulator column is utilized as a bushing, and the accelerator main structure is inserted in the FRP insulator column that is under vacuum [8]. As shown in the cross sectional view of FIG. 1, there is a vacuum gap of 50 mm all around the accelerator main structure to the FRP insulator column. The acceleration grids and their support structures are suspended via post insulators made of Al_2O_3 ceramic from a flange on the top the accelerator (-1 MV potential). Only the parts crossing the vacuum gap are metal rods (10 mm dia.,

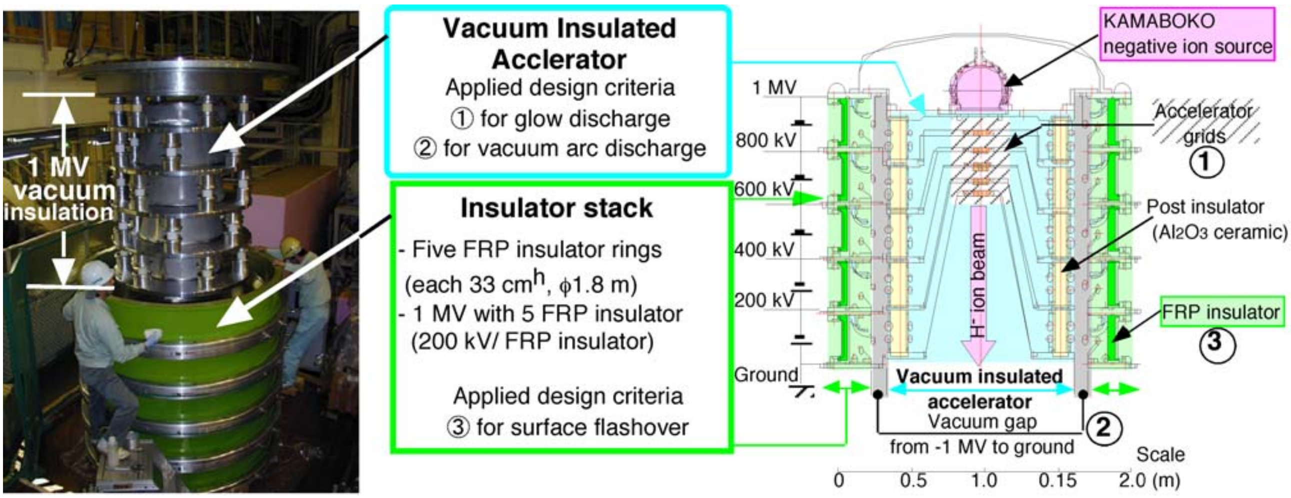

FIG.1 JAERI vacuum insulated accelerator.

stainless steel) to apply electric potential to each acceleration grid. Thus the accelerator main structure is geometrically isolated from the FRP insulator column, and the applied high voltage is totally insulated in vacuum.

The KAMABOKO negative ion source [7, 9] is mounted on the top flange at –1 MV. The H^- ions produced in the source are extracted through 49 apertures drilled in the first grid facing to the ion source plasma (plasma grid) in the array of 7 x 7. In the present experiment, the beams were extracted through 3 x 3 or 5 x 5 apertures by covering other apertures with a mask plate, aiming at high current density relevant to the ITER requirement. The extracted H^- ions are directly injected into the accelerator, without mass separation, focusing and vacuum pumping. The H^- ions are accelerated progressively with potential applied to each acceleration grid, to increase its energy every 200 keV in each acceleration gap between grids.

Following features were included in the vacuum insulation design of the JAERI vacuum insulated accelerator:

1) The vacuum gap between the accelerator main structure and the FRP insulator column allows direct line of sight from –1 MV to the ground (in distance ≈ 1.8 m). The insulation design was considered for this gap extrapolating a conventional "Clump theory" to high voltage and long gap region [10].
2) The hydrogen gas fed in the ion source is pumped down through the accelerator. And hence, pressure in the accelerator is in the range of 0.05 ~ 0.2 Pa during the operation. This is the pressure range not only the vacuum arc discharge but also glow discharge could occur. The gas pressure distribution in the accelerator was analyzed with a three-dimensional Monte-Carlo code [11] and insulation distances were designed so as to prevent the glow discharge.
3) To avoid surface flashover along the insulator, electric field concentration at the negative side triple junction was reduced to very low level of 1.2 kV/mm [12].

As a result, the accelerator sustained the rated voltage of 1 MV for 8,500 s continuously without breakdown.

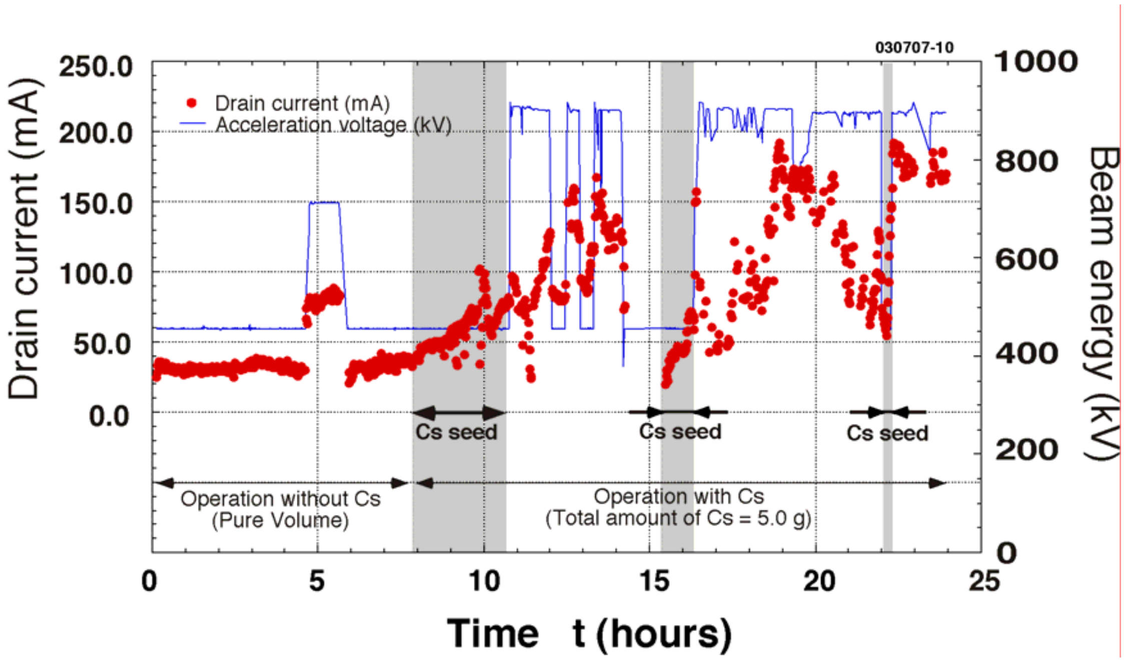

FIG.2 A time record of acceleration test, voltage and current evolution with Cs seeding.

2.2 Acceleration of 1 MeV, high current density H⁻ ion beams

After the success in the stable voltage holding of 1 MV, acceleration test was started for demonstration of 1 MeV, high current density H⁻ ion beam. A time evolution of accelerator operation is shown in FIG. 2 as an example to show how the acceleration test has been carried out. Typically, it takes 30 hours to condition the accelerator to achieve 1 MV voltage holding (without beams) after assembly. Then the ion source operation was tested at low current (≈30 mA) and voltage (≈ 450 kV) level ($0 \le t \le 8$ h). Cesium oven was heated ($8 \text{ h} \le t \le 10.6$ h) to enhance surface production of negative ions in the source, subsequently the H⁻ ion current increased ($8 \text{ h} \le t \le 13$ h). After confirmation of enough current enhancement (≈ 200 mA at t = 22 h), the acceleration voltage was increased to 900 kV. As shown in the figure ($t \ge 16.3$ h), the accelerator operated very stable, and also the H⁻ ion current was stable at the high current level after t = 22 h.

Thus no degradation of the voltage holding capability has been observed even by the Cs seeding and with the beam acceleration of ≈200 mA (drain current) at the acceleration voltage of ≈ 1 MV. Such stable voltage holding is essential in the accelerator operation, first of all, to tune the negative ion production by seeding cesium slowly into the negative ion source. The H⁻ ion beams of this level have been obtained several hundred shots stably. In several experimental campaigns number of filaments, operation pressure in the source, and magnetic filter strength (see section 3) have been optimized to achieve acceleration of H⁻ ion beam at higher current density.

FIG. 3 shows progress of the beam energy and accelerated H⁻ ion current density achieved in the vacuum insulated accelerator test. Until the voltage holding was improved, typical beam energy was only the level of ≤ 700 keV and the beam current density was very low (< 10 A/m²). As soon as the accelerator capability was improved to sustain MV level high voltage, the beam current density increased step by step, according to the progress of source tuning under Cs seeded condition and high power operations. So far, we have succeeded in acceleration of 140 mA H⁻ ion beam up to 800 keV at the current density of 100 A/m². The achieved current density is in a substantial level as a high current accelerator, hoever, it is still a half of the ITER requirement.

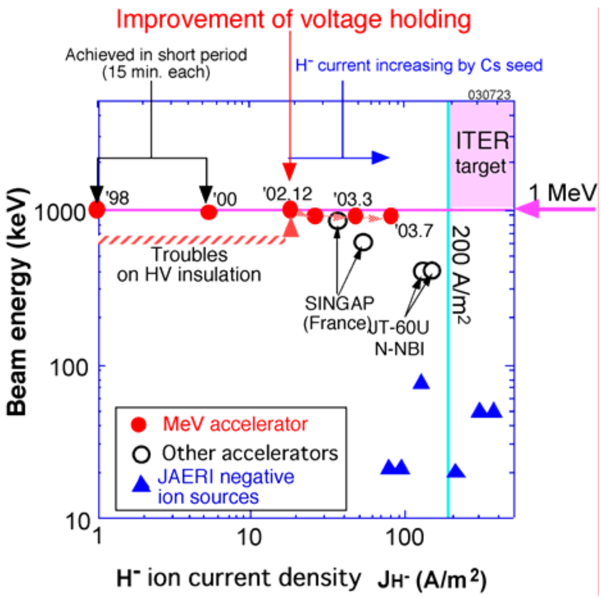

FIG. 3 A summary of MeV accelerator progress, the H⁻ ion current density is increasing after the improvement of voltage holding.

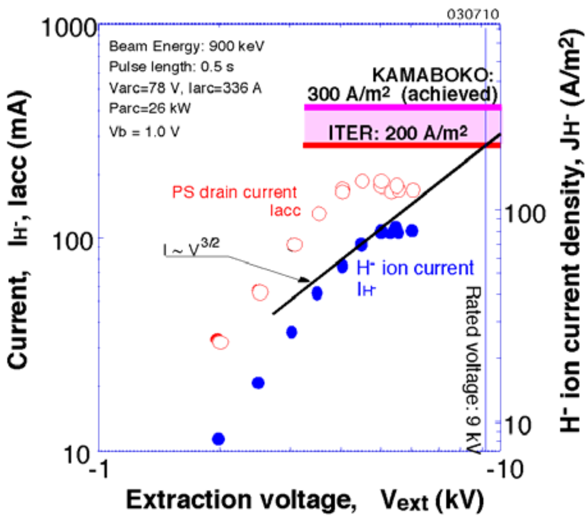

FIG. 4 The H⁻ current as a function of extraction voltage. Beam energy: 900 keV.

Typical beam parameters obtained for both with and without cesium are as follows:

- 1 MeV, 70 mA (18 A/m^2) for 1.0 s (without Cs)
- 900 keV, 110 mA (80 A/m^2) for 0.5 s (with Cs)
- 800 keV, 140 mA (100 A/m^2) for 0.5 s (with Cs)

Note that the pulse lengths were limited by heat handling capability of the beam dump. The beam dump is to be replaced to a new one with swirl tubes to receive high heat load of 160 MW/m^2 (normal to the beam incident) in the case of 1 MeV, 200 A/m^2 H^- ion beams for seconds.

FIG. 4 shows H^- ion beam current (I_{H^-}) as a function of extraction voltage (V_{ext}) at the beam energy of 900 keV. Since the current density was still lower than the design value (200 A/m^2), some of extracted ions were lost in the accelerator due to direct interception of diverging beam. The H^- ion current increased rapidly as the extraction voltage because of less direct interception at higher V_{ext} and resulted in higher current. The H^- ion current increased according to $I_{H^-} \sim V_{ext}^{3/2}$ (Child-Langmuir law) in the extraction voltage of 3.5 kV $\leq V_{ext} \leq$ 5 kV, and then saturated to the current of 110 mA (H^- ion current density: 80 A/m^2) [13]. Note that space charge of co-extracted electrons is negligible under Cs seeded source operation. And hence, the saturation of the current indicates that the ions near the plasma grid aperture are all extracted (emission limit).

Since the KAMABOKO source itself has already demonstrated H^- ion production of 300 A/m^2 (at the beam energy of 50 keV) [7], the current density of ITER requirement (200 A/m^2) is to be achieved by seeding more Cs and further source tuning, with the total H^- ion current of ampere level.

3. Uniformity of Negative Ion Production

The negative ion destruction reaction, $H^- + e \rightarrow H^0 + 2e$, has a large cross section at higher electron temperature (T_e > 1 eV). For example, the cross section increases ~5 times larger only with the temperature increase from 1 eV to 2 eV. To lower the electron temperature in the volume where the negative ions are produced, the negative ion source is divided into two regions, namely, driver region and extraction region, by a transverse magnetic field called "magnetic filter". In the driver region, arc

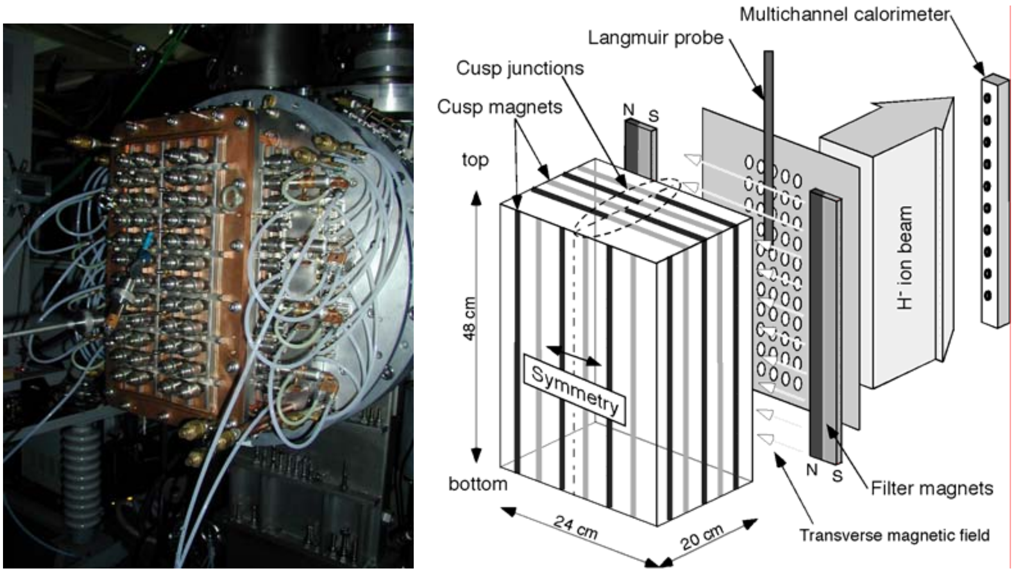

FIG. 5 The 10 ampere negative ion source (left) and its magnetic configuration(right).

discharge is fired with fast electrons emitted from filaments. On the contrary, the extraction region is filled with low electron temperature plasma diffused through the magnetic filter. By increasing the magnetic filter strength, the electron temperature is kept to $T_e \leq 1$ eV in negative ion sources to suppress destruction of negative ions minimizing the electron detachment reaction.

However, the electron temperature in the extraction region has not been confirmed in the large source of JT-60U negative-ion based NB system, due to difficulty of probe access to the source. And hence, we have measured the plasma parameters and beam profile in the JAERI 10 ampere negative ion source [14]. FIG. 5 shows the 10 ampere negative ion source and schematic of the measurements. The 10 ampere negative ion source has a similar magnetic configuration to that of JT-60U large source. A unique feature of the JAERI negative ion sources is in the arrangement of cusp magnets, which is right-left symmetry to form a continuous field line with the filter magnets. Whilst this arrangement forms a “junction” of the cusp magnetic field on the top and bottom plate of the source.

Langmuir probes were inserted and scanned in the extraction region from top and bottom of the source. In the meantime, the beam profile in the vertical direction was measured using a multichannel calorimeter. Typical results are shown in FIG. 6. The result revealed strong gradient in electron temperature (T_e, open circles) even with uniform filter field, and it reached ~5 eV at the bottom of the ion source. The H^- ion beam intensity was lower at the bottom. This suggests that the high T_e is one of the reasons of local reduction in the H^- ion current.

To lower the local electron temperature, strength of magnetic filter field was increasing to 130% of the original at the bottom half of the source as shown in (a) of FIG.6. According to the reduction of T_e, (closed circles in (c)) the beam intensity was increased at the bottom (d). Thus it is important to achieve low electron temperature uniformly in the wide extraction region for uniform H^- ion production.

A careful analysis of magnetic configuration and primary electron trajectory indicated possible leakage path of the fast electrons through the cusp junction (See FIG. 5) from the driver region to the extraction region [15]. To identify the leakage path of fast electrons, a Molybdenum plate of 50 mm x 50 mm was inserted in the source to intercept the leaking fast electron. A reduction of T_e followed by the recovery of H^- ion current was also observed when the plate was placed at center of the bottom source wall (FIG. 6), where the cusp junction was located. Thus the physics mechanism of local H^- ion reduction could be due to the leakage of fast electrons through the cusp junction.

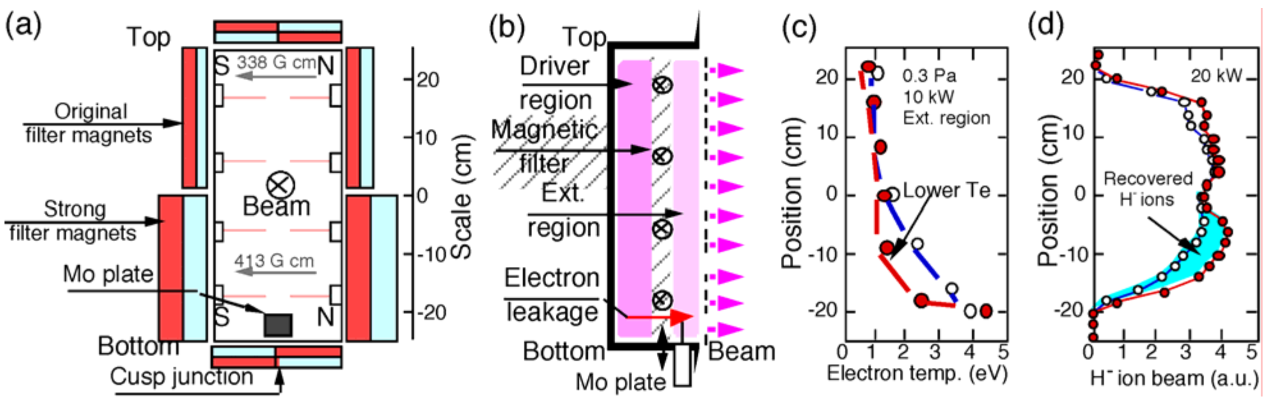

FIG.6 A change of electron temperature and H^- ion current recovery. (a) The source plan view with the filter magnet configuration, (b) the source side view, and variation of (c) electron temperature, and (d) H^- ion beam intensity, before (open circles) and after (close circles) filter field enhancement.

4. Summary and Future Plan

The R&D for the ITER NB system have been progressed at JAERI as follows:

1) After success in stable voltage holding of 1 MV in the vacuum insulated accelerator, H^- ion acceleration test has been carried out for demonstration of high current density H^- ion beams at 1 MeV level beam energy. So far, the H^- ion beams of 1 MeV, 140 mA level have been generated with a substantial beam current density of 100 A/m^2.
2) Negative ion uniformity issue has been studied in the JAERI 10 ampere negative ion source. By a detailed measurement of ion source plasma and H^- ion beam spatial distribution, it was found that electron temperature in the ion extraction region are locally high (> 1 eV), which presumably resulted in destruction of negative ions at a high reaction rate. Interception of fast electrons leaking through a transverse magnetic field called "magnetic filter" has found effective to lower the local electron temperature, followed by an improvement of negative ion beam profile.

In the accelerator development, although the achieved current density is still a half of the ITER requirement, the beams of this level have been obtained stably for more than several hundreds shots. The ITER requirement of current density will be achieved by further tuning of the KAMABOKO source operation. The uniformity study in a large negative ion source showed a possible physics mechanism of the local reduction in negative ions. Development of countermeasures is in progress to achieve uniform negative ion production over wide extraction area.

FIG. 8 summarizes R&D status of the large negative ion source and the 1 MeV accelerator, together with the capability of existing test facilities in JAERI. Both R&D is approaching to the ITER requirement. However, it is obvious that the R&D reaches earlier to the envelope of the existing test facility. In particular, there is a large difference in the current of 1 MeV accelerators between the R&D (≤1 A) and in the ITER requirement (40 A). For this the world NB experts have proposed construction of a full-scale testbed for the ITER NB system, to be followed by an integration test of high current, 1 MeV negative ion beams. With the progress of R&D at present, discussion on the full-scale testbed for the ITER NB system has been started among interested parties.

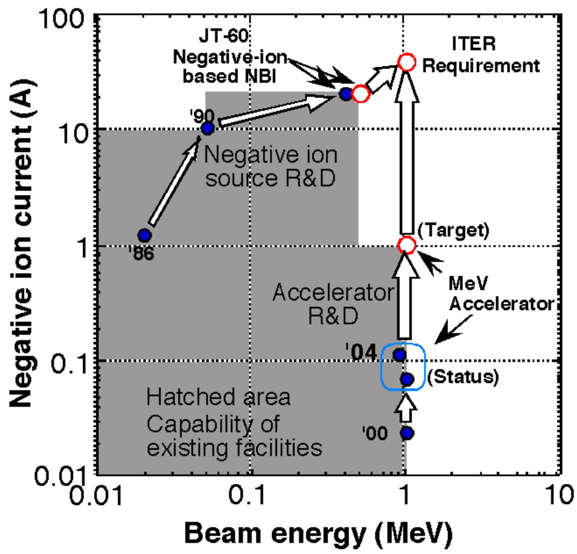

FIG. 8 A summary of R&D status on the negative ion sources and accelerators for ITER NB system. The hatched area indicates the capability of test facilities at JAERI.

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