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Demonstration of long-pulse acceleration of high power positive ion beam with JT-60 positive ion source in Japan–Korea joint experiment

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ABSTRACT

The long-pulse acceleration of the high-power positive ion beam has been demonstrated with the JT-60 positive ion source in the joint experiment among Japan Atomic Energy Agency (JAEA), Korea Atomic Energy Research Institute (KAERI) and National Fusion Research Institute (NFRI) under the collaboration program for the development of plasma heating and current drive systems. In this joint experiment, the increase of the heat load and the breakdowns induced by the degradation of the beam optics due to the gas accumulation was one of the critical issues for the long-pulse acceleration. As a result of development of the long-pulse operation techniques of the ion source and facilities of the neutral beam test stand in KAERI, 2 MW 100 s beam has been achieved for the first time. The achieved beam performance satisfies the JT-60SA requirement which is designed to be a 1.94 MW ion beam power from an ion source corresponding to total neutral beam power of 20 MW with 24 ion sources. Therefore, it was found that the JT-60 positive ion sources were applicable in the JT-60SA neutral beam injectors. Moreover, because this ion source is planned to be a backup ion source for KSTAR, the operational region and characteristic has been clarified to apply to the KSTAR neutral beam injector.

1. Introduction

A fusion power plant is one of the solutions to realize long-term electric power in future. To achieve steady-state fusion output, heating and current drive systems for fusion plasmas are required to inject the heating power for long-pulse. For this purpose, neutral beam injectors (NBI) have been developed in the world [1–5] as one of candidates for the auxiliary heating and current drive system. Recently, superconducting tokamaks such as JT-60SA [6], KSTAR [7] and EAST [8] have been designed or operated by utilizing long-pulse NBI systems based on the positive hydrogen/deuterium ion sources, where pulse durations of powerful neutral beams are required over 100 s [9,10].

As for JT-60SA, the pulse duration of NBI systems is also planned to extend from 30 s in JT-60U [11] to 100 s with a neutralbeam power of 20–24 MW from 24 positive ion sources and 10 MW from 2 negative ion sources [12]. In order to realize the JT-60SA NBI systems, the power supplies and the beamline components will be upgraded to ensure the 100 s beam injection [13,14]. The ion source which is the most important component for the NBI system also should be developed to extend the pulse duration because the pulse length of the JT-60 positive ion sources has been limited to be 30 s [13].

Therefore, the long-pulse acceleration of the positive hydrogen ion beam over 30 s has been tried by the joint experiment among Japan Atomic Energy Agency (JAEA), Korea Atomic Energy Research Institute (KAERI) and National Fusion Research Institute (NFRI) under the collaboration program for the development of plasma heating and current drive systems [13–15]. This joint experiment aims to demonstrate high-power and long-pulse accelerations with the JT-60 positive ion source for JT-60SA and also KSTAR, because one of the JT-60 positive ion sources is planned to be a backup ion source for KSTAR-NBI.

In this paper, achieved results and developed operation techniques for the long pulse accelerations in the joint experiment are reported.

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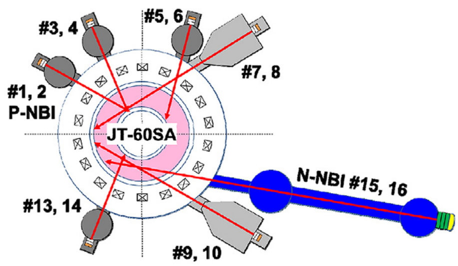

	Specifications	Number of units
P-NBI	85 keV, 20 MW, 100 s	12 units (24 positive ion sources)
N-NBI	500 keV, 10 MW, 100 s	2 units (2 negative ion sources)

Fig. 1. NBI systems in JT-60SA. 12 units of the positive-ion-based NBI (P-NBI) and 2 units of the negative-ion-based NBI (N-NBI) are arranged around the JT-60SA tokamak.

2. JT-60 positive ion source

JT-60SA NBI systems consist of 12 units of the positive-ion-based NBI (P-NBI) and 2 units of the negative-ion-based NBI (N-NBI) [16] as shown in Fig. 1. Each of the P-NBI unit has 2 positive ion sources, therefore totally 24 ion sources will be operated to achieve 20–24 MW neutral beam power for 100 s. Main components of the JT-60SA NBI will be reused, which have been used in JT-60U for 30 years without any big accident [14].

The JT-60 positive ion source was developed in 1980 for the JT-60 NBI [1] as shown in Fig. 2(a). The ion source consists of the bucket-type filament-driven arc chamber and 4 acceleration grids (G1–G4) having 1020 apertures within the extraction area of 12 cm × 27 cm. Considering the heat load distribution to the grids, G1-2 are made of molybdenum as shown in Fig. 2(b) and G3-4 are made of oxygen free copper. Although the ion source was originally designed to accelerate H^+ beams with 75 keV, 35 A for 10 s, by tuning the gap lengths between the acceleration grids, finally 85 keV, 27.5 A D^+ beams were stably available for 30 s in JT-60U operation [11,13]. At this nominal parameter of 85 keV, 27.5 A with the potential ratio of 0.75 between G2 and G1, the measured divergence angle of the D^+ ion beam was about 1 degree, which was consistent with the calculation results as shown in Fig. 2(c).

3. Development of operation techniques of the JT-60 positive ion source for KAERI-NBTS

3.1. Experimental setup

The JT-60 positive ion source was installed to KAERI neutral beam test stand (NBTS) [17], and power supplies were connected to the ion source with the similar circuit to that for JT-60SA as shown in Fig. 3. Hydrogen gas is provided only through the arc chamber for the arc discharge and neutralization of the ion beam due to the limitation of capability of the pumping system without a cryopump. A part of the accelerated ion beam is converted to the neutral beam through the optical multichannel analyzer (OMA) duct and the neutralizer. After the neutralization, the residual ion beams having full, half and a third energies are separated by a bending magnet [18]. In this experiment, due to a low cooling capability of an ion dump, the residual ion beams are deflected with a small deflection angle so as to accept all energy components within the height of the calorimeter. This calorimeter is composed of the hypervapotron array [19] which are arranged in V-shaped with an opening angle of 15 degree. The surface temperature of the calorimeter is measured with an infra-red (IR) camera installed in front of the calorimeter.

3.2. Development of operation techniques for high energy acceleration

Because the operation and the specification of KAERI-NBTS was optimized for the KSTAR ion sources, the operation techniques should be developed in order to fit the characteristic of the JT-60 positive ion source. Fig. 4 shows the typical waveform of the beam acceleration without a pre-arc operation, where V_{acc}, V_{g2} and V_{dec} denote the applied voltage to the 1st, 2nd and 3rd grids G1, G2 and G3. The voltage ratio V_{g2}/V_{acc} was adjusted to be 0.75 which was the nominal operation for the JT-60 positive ion source as shown in Fig. 4(a). After the high-voltages were applied, the beam extraction started at the timing of the arc discharge as shown in Fig. 4(b), where V_{arc} and I_{arc} are the applied voltage and current for an arc discharge. In this experiment, the output of the arc power supply was controlled to keep the arc power constant (Constant-Power mode). The accelerated current is shown in Fig. 4(c) where I_{acc}, I_{g2} and I_{dec} denote the ion beam current, grid current to G2 and G3.

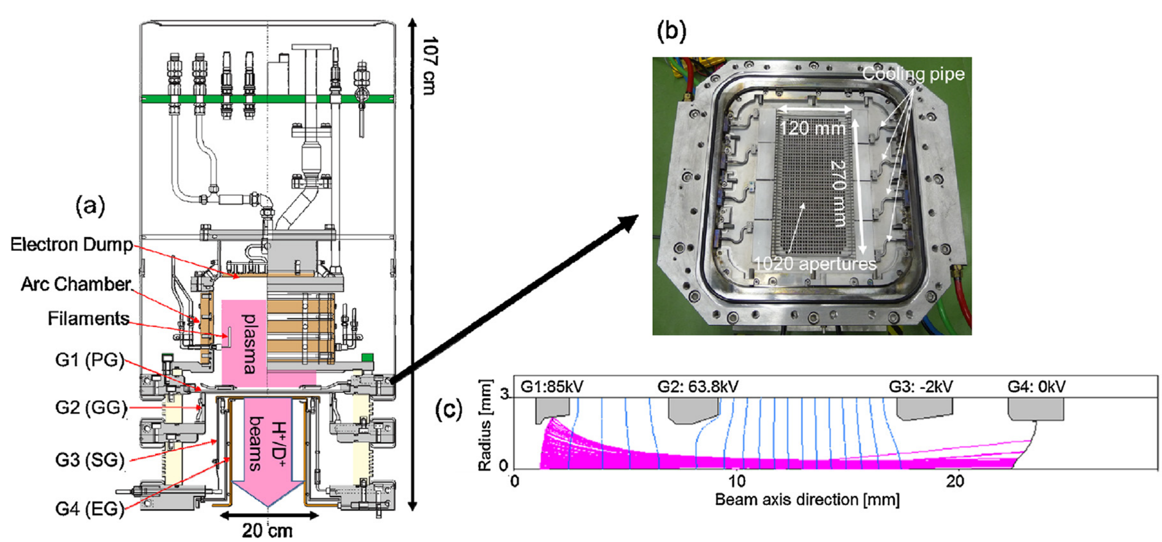

Fig. 2. (a) Schematic view of the JT-60 positive ion source which consists of the arc-discharge chamber, the plasma grid (G1, PG), the gradient grid (G2, GG), the electron suppression grid (G3, SG) and the exit grid (G4, EG). (b) A photograph of the G1 made of molybdenum. (c) Trajectory of 85 keV deuterium ion beam with a beam current of 27.5 A (1550 A/m^2) at the potential ratio G2/G1 of 0.75.