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Performance of positive ion based high power ion source of EAST neutral beam injector

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The positive ion based source with a hot cathode based arc chamber and a tetrode accelerator was employed for a neutral beam injector on the experimental advanced superconducting tokamak (EAST). Four ion sources were developed and each ion source has produced 4 MW @ 80 keV hydrogen beam on the test bed. 100 s long pulse operation with modulated beam has also been tested on the test bed. The accelerator was upgraded from circular shaped to diamond shaped in the latest two ion sources. In the latest campaign of EAST experiment, four ion sources injected more than 4 MW deuterium beam with beam energy of 60 keV into EAST. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4931709]

I. INTRODUCTION

A positive ion based bucket source was developed for a high power neutral beam injector (NBI) on the Experimental Advanced Superconducting Tokamak (EAST).[1,2] According to the design of EAST, two NBI beam lines with total neutral beam power of 8 MW were needed to be installed on the tokamak in tangential injection direction.[3–5] For each beam line, two ion sources were installed parallel.

The ion source is the most precision part of EAST-NBI system. In order to verify the engineering design conforms to the physical design, an ion source test bed was developed. The ion source test bed has also been used to condition the ion source and verify some modification before installing the ion source on the EAST-NBI. So far, four ion sources were developed almost with the same structure. In September 2013, the first beam line with two ion sources was installed on the EAST. In June 2014, a total deuterium beam power of 2.3 MW with beam particles' energy of 60 keV was delivered into the EAST.[6] In May 2015, the beam line with two new ion sources finished the installation on EAST. In June 2015, the two beam lines injected the deuterium beam into the EAST for the first time. A maximum beam power of more than 4 MW was injected to EAST in the latest experimental campaign.

II. ION SOURCE AND CONDITONING RESULTS ON THE TEST BED

On the EAST-NBI, a hot cathode bucket ion source with tetrode accelerator and slit type grids was used. The arc chamber has a length of 650 mm, a width of 260 mm, and a depth of 300 mm. 32 hairpin tungsten filaments with diameter of 1.5 mm supply primary electrons in the arc chamber. The accelerator has the transparence of 60%. The extraction area has the dimensions of 120 mm × 480 mm changed to 110 mm × 480 mm because of the divergence angle which was large than the designed value. The detail parameters can be found in the literatures.[7–9] A picture of arc chamber and the assembled accelerator is shown in Figs. 1 and 2.

There are two methods used on EAST-NBI ion source, one is the arc regulation method[10,11] and other one is the beam modulation method. The arc regulation method exploits the signal of a Langmuir probe to real-time feedback control the operation of arc discharge. The plasma can then be generated much more stable (arc and beam currents do not vary from pulse to pulse). The regulation method consists in modulating the accelerator voltage and suppressor voltage. This method is useful to test the long pulse operation of the source, as required on EAST. The ion source was conditioned on the test bed, using a hydrogen gas for the plasma.[12] The beam power needs to reach 4 MW with beam particles' energy of 80 keV for each of ion source on the test bed. Long pulse operation also needs to be tested. Considering the high power deposited on the calorimeter, the beam was modulated. To verify the long pulse extraction ability of the source, neutral beams were extracted for up to 100 s with a total acceleration energy of 50 keV.[13]

In order to improve the performance of the acceleration system, the first grid of accelerator was changed from circular shape to diamond shape, as shown in Fig. 3. The new plasma grid with diamond shaped rails was used on the third and fourth ion sources: according to the experimental results, the mean arc efficiency was improved from 0.47 A/kW to 0.52 A/kW and the divergence angle decreased from 1.8° to 1.4°, at an optimum beam perveance of 2.3 μperv and 2.75 μperv, respectively.[14] In particular, a smaller divergence angle was much helpful the long pulse operation. In the future, the ion sources with old acceleration system will be upgraded too.

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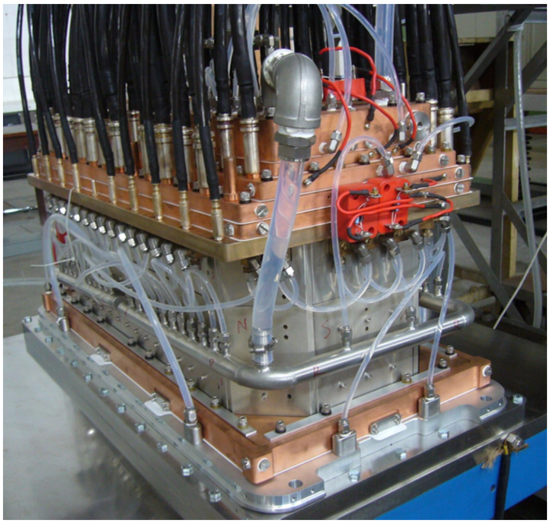

FIG. 1. Outside view of the arc chamber of EAST-NBI ion source.

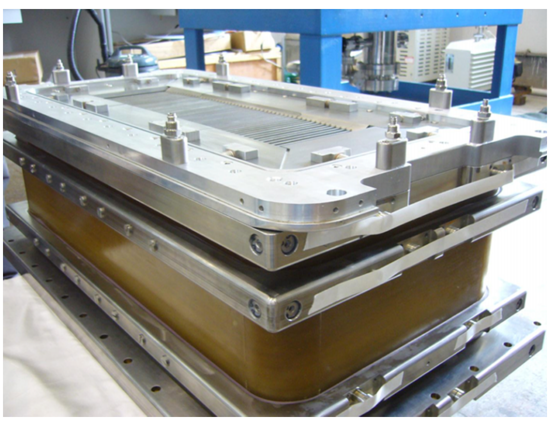

FIG. 2. The accelerator of EAST-NBI ion source.

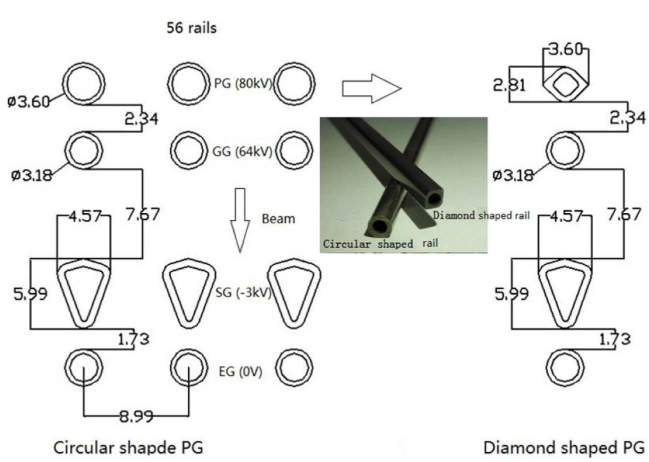

FIG. 3. Improvement of accelerator from circular shaped plasma grid to diamond shaped plasma grid.

III. PERFORMANCE OF ION SOURCE ON EAST-NBI

When installed on the EAST-NBI, the ion sources were operated with deuterium. The total acceleration voltage and the pulse length varied according to the requirements of the EAST operation. The power transmission line was about 100 m, from the power supply building to the NBI in the EAST

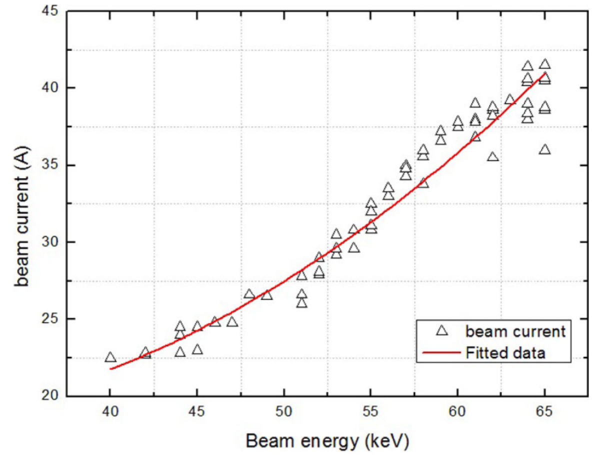

FIG. 4. Beam current as a function of beam total acceleration voltage for operation in deuterium on EAST-NBI.

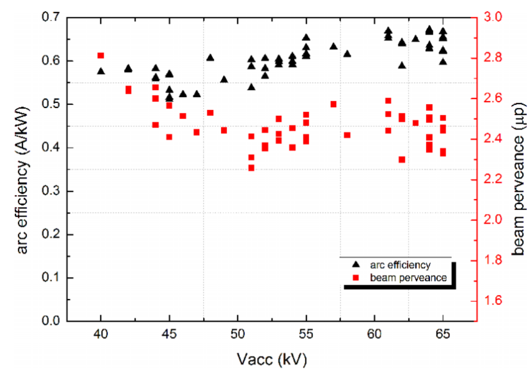

FIG. 5. Arc efficiency and beam perveance as a function of beam acceleration voltage for operation in deuterium on EAST-NBI.

experimental hall. The voltage loss of filament power supply in the transmission line was 2-3 V, which is about 25% of the power supply output. It was the most different when compared with the source on test bed. The highest beam particles' energy achieved on EAST was 65 keV, the maximum pulse length was 22 s with 1 Hz modulation.

The plot in Fig. 4 shows the dependence between the beam current and the beam particles' energy with deuterium gas. The beam current increased from 23 A to 42 A when beam particles' energy increased from 40 keV to 65 keV. Beam current was a little lower compared to the values obtained in hydrogen beams. The arc efficiency was about 0.65 A/kW, higher than in hydrogen beams. The beam perveance was about 2.5 μperv, lower than in hydrogen beams. The experimental results were shown in Fig. 5. The beam profile was measured with the thermocouples installed on the rear side of the calorimeter, the typical results are shown in Fig. 6. The beam particles' energy is 55 keV, the beam divergence angle of left and right ion sources is 1.55° and 1.5°, respectively.

The fractions of ionic species in the beam were measured with the Doppler Shift Spectroscopy (DSS) system. The optic head was installed at the exit of the neutralizer cell. The deuterium beam fractions were measured on the EAST-NBI, the results are shown in Fig. 7 as a function of beam particles' energy. It can be seen that the fraction of accelerated H^+ ions

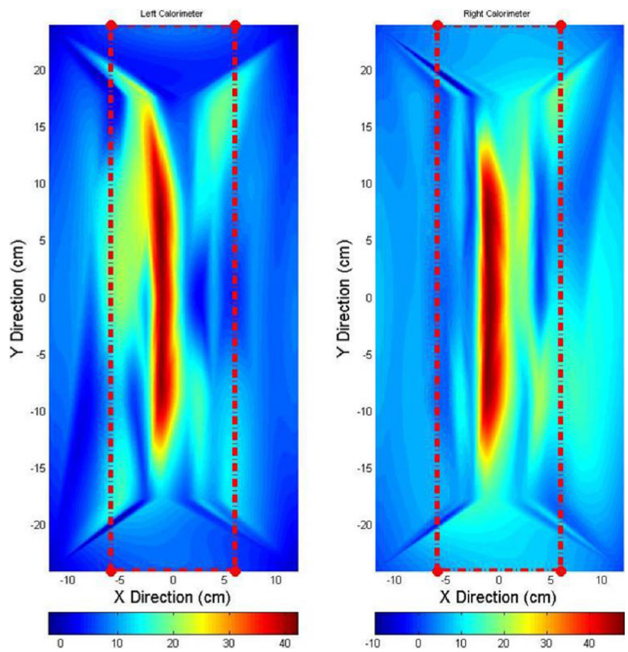

FIG. 6. The beam profile on the calorimeter of two ion sources.

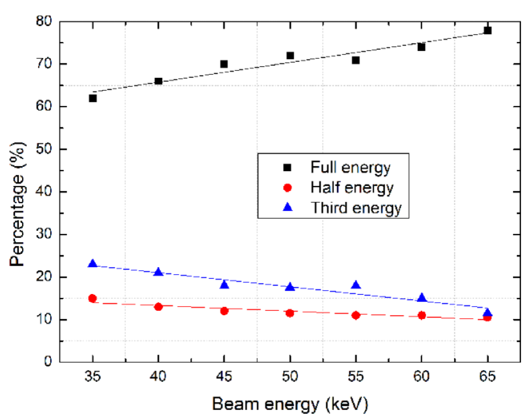

FIG. 7. Deuterium beam species as a function of beam particles' energy.

increased with the beam particles' energy, up to the designed value of 80%.

IV. CONCLUSIONS AND DISCUSSIONS

Four hot cathode bucket ion sources have been developed for the EAST-NBI. Through the upgrade of accelerator, two new ion sources produced beams with lower perveance compared to what was obtained in the old ion sources. All the ion sources were conditioned on the ion source test bed with hydrogen gas. Each ion source can deliver a 4 MW ion beam with beam particles' energy of 80 keV and duration of 100 s (with modulated beam). The beam profile and beam species have also been measured on the test bed. When installed on the EAST-NBI, the ion sources were operated in deuterium. The beam perveance was lower than with the hydrogen beam, but the arc efficiency was higher. So far, the highest beam particles' energy was 60 keV during the EAST experiment. In the future, the ion sources will be further tested, trying to obtain a total acceleration voltage of 80 keV and a pulse length of 100 s also on the EAST-NBI.

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