High-Power Ion Beam Characteristics of a Magnetic Multi-Pole Line-Cusp Ion Source for the HL-2A Tokomak

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(Received 16 February 2009)

A circular magnetic multi-pole line-cusp ion source with a nominal 45 keV 25 A hydrogen ion beam is developed for the neutral beam injector of the HL-2A tokomak. At present, this bucket ion source can produce a 40 keV 20 A hydrogen ion beam for less than 100 ms on a test bed, and a 35 keV 13 A ion beam for 300 ms on the injector of the HL-2A tokomak. The $1/e$ half-width of the ion beam power profile is about 6.0 $\pm$ 0.2 cm at the position of 3.26 m downstream from ion source, and the corresponding divergence degree is nearly 1.1. The optimum perveance matched conditions were obtained experimentally, and were in good agreement with the values from experiential equation of Uhlemann et al. The maximum of optimum perveance reached $2.2 \times 10^{-6}$ A/V$^{1.5}$ for 38 keV beam energy. An ion beam with above 60% H$^+$ species fraction can be achieved, which was measured by $H_{\alpha}$ light Doppler shift spectroscopy. According to research results, a neutral beam with a total power of more than 0.6 MW was successfully injected into the plasma of the HL-2A Tokomak in 2008.

PACS: 29. 27. Fh, 29. 27. Ac, 29. 25. Ni

Neutral beam injection (NBI) is widely recognized to be one of the most powerful and effective methods for heating plasma on a large variety of fusion devices. An ion source for a neutral beam injector must be capable of producing a high-current beam at high energy with small divergence, and the plasma density in the ion source must be sufficiently high and uniform. The magnetic multi-pole line-cusp ion source was investigated in plasma confinement by Mackenzie et al. and was shown to fulfill all the requirements of NBI systems at JT-60U[2] and LHD et al fusion devices.

In order to meet the requirements of the HL-2A NBI system, a circular magnetic multi-pole line-cusp ion source with 45 keV, 25 A nominal hydrogen ion beam was developed at the Southwestern Institute of Physics (SWIP) and the schematic figure is shown in Fig. 1. The arc chamber is a water-cooled stainless-steel cylinder 260 mm in diameter, 4 mm thick and 240 mm long. The chamber wall serving as an anode is surrounded by Co-Sm permanent magnets, which are arranged to form a 36-pole line cusp field parallel to the beam axis at the sidewall and an 18-pole field at the back plate. The magnetic field strength is less than 17 G within the region of 174 mm in diameter near the plasma grid. Nine hair-pin-shaped tungsten filaments of 1.5 mm in diameter and 15 cm length are attached to the water-cooled holders on the back plate of the arc chamber. These filaments required 5–6 s to reach operating conditions. The accelerator in the 174 mm diameter extraction area is an accel-decel system which consists of three oxygen-free copper grids called plasma, suppressor and ground grid. The plasma grid has 313 apertures in 6.89 mm diameter and 3.46 mm thickness, which was connected to the arc chamber via a resistance. The apertures in the suppressor and ground grid are 5.20 mm in diameter. The gap distance between the plasma grid and the suppressor is 7.09 mm and another gap is 1.51 mm.

![Fig. 1. Schematic diagram of the positive ion source in the HL-2A NBI system.](image-url)