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ANALYSIS OF BEAM OPTICS FOR A HIGH POWER ION SOURCE*

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Abstract

The high power ion source is the key parts of neutral beam injector. Generally speaking, the beam power should matching the extraction voltage for a given accelerator. In order to get higher beam power with lower beam extraction voltage, the beam optics of accelerator was analyzed based on the structure of EAST-NBI tetrode accelerator. The beam optics of a tetrode accelerator and a new designed three-electrode accelerator was analyzed with beam energy of 50 keV. The results shown that, the two types of accelerator can get high beam perveance (4.6μp) with lower beam divergence angle compare to the EAST-NBI accelerator (2.8 μp). And the tetrode accelerator can gets lower beam divergence angle compare to the three-electrode accelerator, but the electric field between two electrode is much higher than three-electrode accelerator. The results can help for the ion source design of high power ion source.

INTRODUCTION

The Experimental Advanced Superconducting Tokamak (EAST) is the first fully superconducting tokamak in the world. It aims at the long-pulse operation (1000s) to study the physics and engineering questions of steady-state operation for controlled nuclear fusion sciences[1]. High auxiliary heating power was needed to support the physical research of EAST. So, a Neutral Beam Injection (NBI) system was designed and developed in the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) for the EAST plasma heating and current driving[2-5].

The EAST-NBI system consist two ion sources, which has the same structure and designed parameters. According to the physical requirements of the EAST, a hot cathode multi-cusp ion source with four stage accelerator girds was employed for the EAST-NBI since the year of 2010. In September of 2013, one beam line with two ion sources are installed on the EAST and high power neutral beam of 2MW were injected into EAST in July of 2014. In the same year, other beam line with two modified accelerator with diamond plasma grids were installed on the EAST and it was contributed in the next campaign experiment of the EAST in 2015. The parameters of NBI can be achieved was mainly decided by the performance of ion source. In order to achieve high beam power with lower beam energy, the beam optics of a new designed accelerator based on the EAST-NBI accelerator was analyzed.

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THE HIGH POWER ION SOURCE OF EAST-NBI

The hot cathode bucket ion source with tetrode accelerator was employed on the EAST-NBI system[6-7]. The ion source contains a plasma generator and a tetrode accelerator. The plasma generator has a rectangle cross section arc chamber with the dimension of 650 mm × 260 mm × 300 mm (W×L×H). In the top side, 32 pure tungsten filaments with diameter of 1.6 mm are installed near the back electron plate, which was used to provide sufficient primary electrons. The accelerator is a multiple slit type. It has a high transparence of 60%. Each layer of accelerator grid has 64 rails, which made of molybdenum and has cavity structure. The cooling water runs through the inner of rails, so, it has good performance of heating remove. The schematic map of ion source is shown in Figure 1. The cross-sectional picture of accelerator is shown in Figure 2. The designed beam energy of ion source is 50-80 keV, beam power is 2-4 MW. The beam cross section is 120mm×480mm and can be changed. The designed divergence angle in X direction is 0.6 degree and Y direction is 1.2 degree.

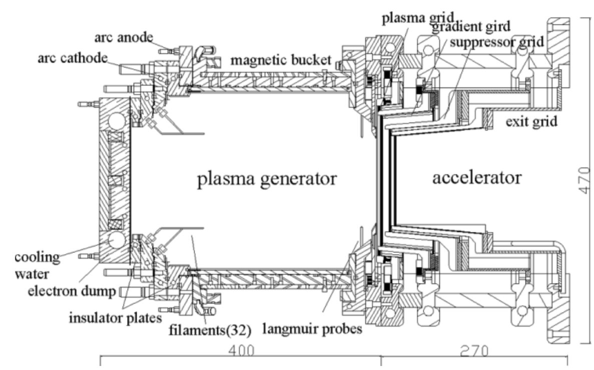

Figure 1: Schematic of high current ion source.

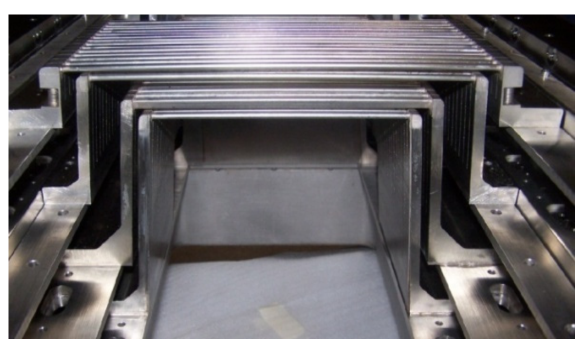

Figure 2: Cross sectional picture of accelerator with four stages of grids.

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ACCELERATOR MODIFICATION BACKGROUND

When the neutral beam injected into the EAST plasma, the beam energy should matching the EAST plasma density to heating the core plamsa. For the ion source, the extracted beam current also should matching the extraction voltage (beam energy), thus, the beam power can not change with given beam energy. In order to achieve high beam power with lower beam energy, the ion source should be modificated.

The accelerator of EAST-NBI has a four stage electrode grids, which are plasma grid (PG), gradient grid (GG), suppressor grid (SG) and exit grid (EG). The schematic map of accelerator is shown in Figure 3. The extracted ion current I_E can be calculated by equation (1)[8].

$$I_E = \frac{4\varepsilon_0}{9}\sqrt{2\eta}\frac{V^{3/2}}{d^2} \tag{1}$$

When ε_0 is the permittivity of vacuum, $\eta = q/m_i$, d is the distance between two extraction grids, V is the extraction voltage.

In order to increase the extracted ions, the distance between grids should be decreased, which is shown in Figure 3.

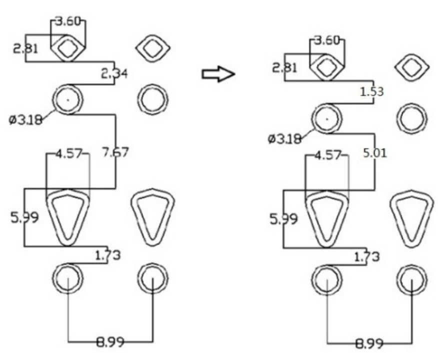

Figure 3: Schematic map of original and modified accelerator for the high current ion source.

THE SIMULATION MODE OF ACCELERATOR FOR EAST-NBI

The prototype draw of accelerator is shown in Figure 4. The thickness of PG, GG, SG and EG are t1, t2, t3 and t4, respectively. The distance between PG and GG, GG and SG, SG and EG are d1, d2 and d3, respectively. The half-gap of rails of each layer are a1, a2, a3 and a4. The a1 = 2.7mm, a2 = 2.9 mm, a3 = 2.26 mm, a4 = 2.9 mm, d3 = 1.73 are not changed during the simulation.

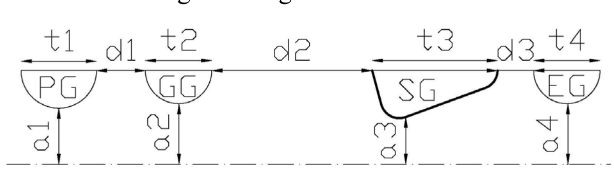

Figure 4: The simulation prototype of accelerator.

SIMULATION RESULTS WITH MODIFIED TETRODE ACCELERATOR

The optics of the accelerator was simulated with the EAST-NBI accelerator[9,10] and the modified accelerator. The voltage applied on the GG is 80% of the voltage on PG. The voltage applied on SG is -2.5 kV. The beam perveance (perv = $A/V^{3/2} \times 10^6$, A: beam current [A], V: applied beam voltage [V]) and the beam divergence angle are two important parameters to estimate the beam optics. The simulation parameters and the results were shown in table 1. The divegence angle was analyzed with different beam perveance and extracted ion density, which shown in Figure 5 and Figure 6.

It can be seen that, the modified accelerator can got high optimum beam perveance of 4.6 μp compare with the original structure of accelerator (2.8 μp). The beam power can be increased about 62%. The beam divegence angle is 0.8 degree and almost keep no change. The extraced ion density is increased from 0.11 A/cm^2 to 0.18 A/cm^2 and also acceptable by the plasma generator. But the maximum electric field is 123 kV/cm compare to the original accelerator of 88 kV/cm. It may has the high risk of beam break down and may not good for the stable beam extraction.

Table 1: Simulation Results of Tetrode Accelerator with 50 keV Beam Energy

Item	Used in ASIPP	Modified
d1	2.34 mm	1.53 mm
d2	7.67 mm	5.01 mm
d3	1.73 mm	1.73 mm
Optimum beam perveance	2.8 μp	4.6 μp
Ion density at optimum beam perveance	0.11 A/cm^2	0.18 A/cm^2
Divergence angle	0.8 degree	0.8 degree
Maximum electric field	88 kV/cm	123 kV/cm

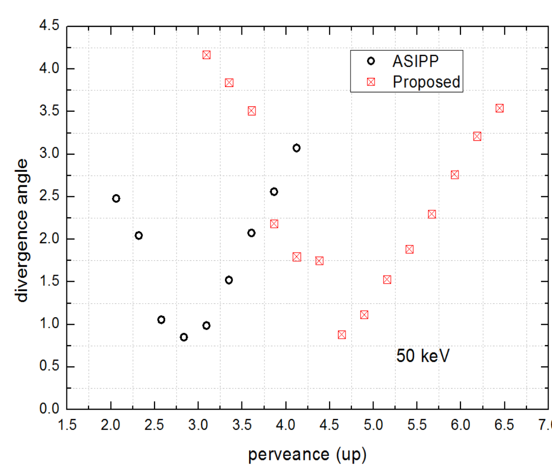

Figure 5: Divergence angle as a function of beam perveance with 50keV beam energy.

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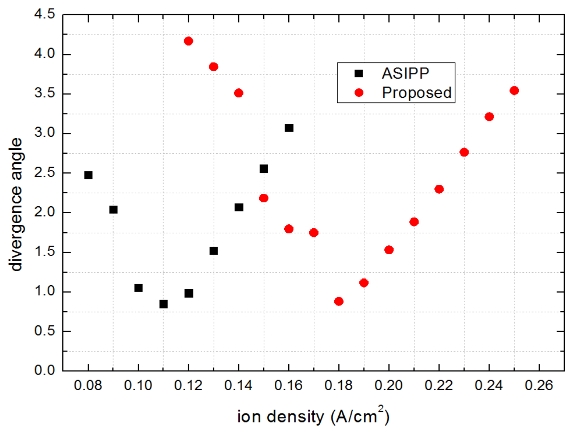

Figure 6: Divergence angle as a function of ion density with two type of accelerator.

SIMULATON RESULTS WITH THREE-ELECTROD ACCELERATOR

Consider the beam energy is 50 keV, a three-electrod accelerator was designed, which is PG, SG and EG. In order to extract high beam current, the distance between PG and SG was estimated according to the original and modified tetrode accelrator, which is during 52.5 × 1.53/10 = 8.02 mm to 52.5×2.43/10 = 12.76 mm. The beam optics was simulated with different parameters which listed in Table 2. The divergence angle, extracted ion density and the optimum beam pervance was analized and shown in Table 2 too.

It can be seen that, the divergence angle is much larger (about two times) compare to the tetrode accelerator, more beam will losed during the beam transmission channel. The beam perveance is about 3.6 μp with the lowest divergence angle (1.55 degree) and is lower than the modified tetrode accelerator. The ion extraction density is from 1.3 A/cm2 to 1.9 A/cm2 when the beam divergence angle close to 1.6 degree, which also acceptable. The maximum electric field is 68.82 kV/cm with the optimum beam perveance. It was much lower compare to the tetrode accelerator (88-123 kV/cm).

Table 2: Simulation Results of Three-electrod Accelerator with 50 KeV Beam Energy

D1 mm	D2 mm	Ion density A/cm^2	Optimum beam perveance μp	Divergence angle	Maximum field kV/cm
7.75	1.73	0.28	7.2	2.45	106.86
8.75	1.73	0.25	6.44	2.29	98.16
9.75	1.73	0.25	6.44	2.11	90.42
10.75	1.73	0.21	5.41	1.63	84.04
11.75	1.73	0.19	4.89	1.6	77.59
12.75	1.73	0.17	4.38	1.58	73.21
13.75	1.73	0.14	3.61	1.55	68.82
14.75	1.73	0.13	3.35	1.58	64.96

DISCUSSIONS AND CONCLUSIONS

The ion optics of modified tetrode accelerator and designed three-electrod accelerator were simulated with beam energy of 50 keV for the high current extraction. The minimum divergence angle of 0.8 degree is almost the same compare with the original accelerator. The optimum perveance increased from 2.8 μp to 4.6 μp. The ion density is increased from 0.11 A/cm^2 to 0.18 A/cm^2. But the maximum electric field is 123 kV/cm and the accelerator has the risk of break down. The minimum divergence angle is about 1.6 degree for the three-electrod accelerator. The optimum beam perveance is about 3.6 μp, and the ion density is also acceptable for the original plamsa generator. The maximum electric field is 68.82 kV/cm and much lower than the original accelerator.

The results shown that, the modified accelerator can achieve high beam power. But the divergence angle of three-electrod accelerator is large and the maximum electric field of modified tetrode accelerator is very high. A new ion source with modified tetrode accelerator was assembled and will be tested soon. The simulation results can help for the design and optimization of high curent ion source.

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