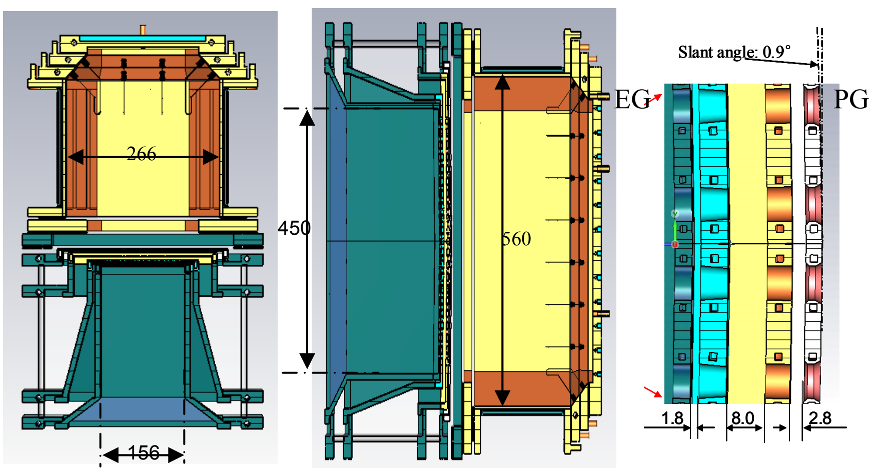
Study of ion beam extraction elements for HL-2M neutral beam injector*

G.Q.Zou, J.Y.Cao, G.J.Lei, H.L.Wei, X.M. Zhang, X.R.Duan.

Southwestern Institute of Physics, Chengdu, China, 610041

1 Introduction

Neutral beam injection is well known as an efficient and promising technique for plasma heating and current drive in magnetic fusion devices. HL-2A Tokamak is currently equipped with two beam lines with nominal power of 3MW at 50keV-60keV beam energy. 1.2MW deuterium beam power has been achieved on the first beam line, and the second beam line with power of 1.5MW-2MW is currently being installed onto the HL-2A Tokamak. At the same time, a completely new tokamak called HL-2M with major radius of 1.78m, minor radius of 0.65m, toroidal magnetic field of 2.2T and plasma current of 2MA is under construction now in Southwestern Institute of Physics of China [1]. For HL-2M Tokamak, the first neutral beam injector (NBI) with beam power of 5MW at 80keV beam energy and beam pulse lengths of 5 seconds is conceptually designed [2]. Therefore a new rectangular magnetic multipole positive ion source with power of 80kv×45A is being designed, shown as Fig.1. 40 lists Cobalt-samarium magnets will be installed around the arc chamber to form a magnetic multipole line cusp filed configuration parallel to the beam axis. The arc chamber wall serves as the anode, and 16 hair-pin shaped tungsten filaments of 1.5mm in diameter are set as the cathode. The ion beam extraction system consists of four grids, called plasma grid (PG), gradient grid (GG), suppressor grid (SG) and ground grid (GG), respectively. Material of the PG is molybdenum, and others are oxygen-free copper. Each grid has 564 apertures of 6.9mm in diameter within an area of 12.8×43.5cm. The grids have been designed to optimize cooling by the use of multiple water-cooling channels arranged between each row of apertures.



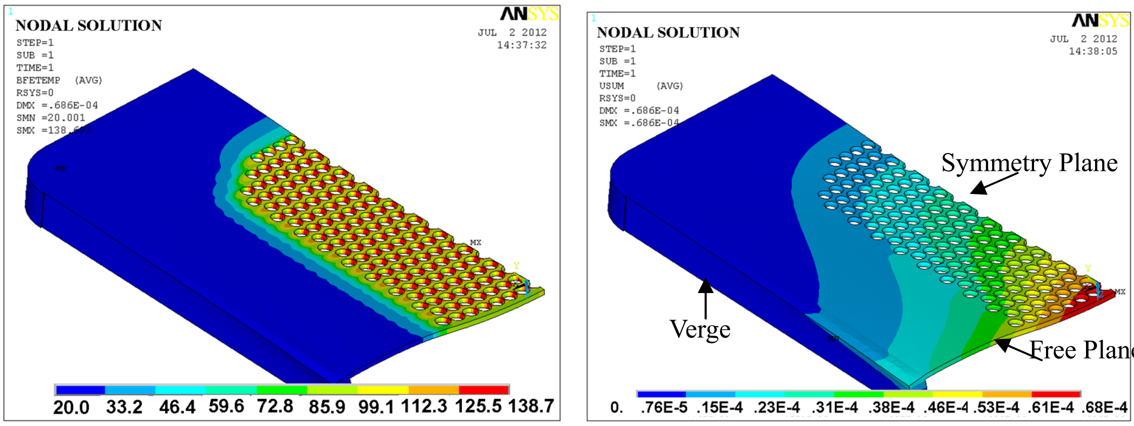
(a)Overlook section (b) Front section (c) Two-stage accelerator

Fig.1 The concept design of 80kV/45A/5s bucket source

* Supported by the National Natural Science Foundation of China under Grants No.**11205052**

2. Thermo-mechanical analysis

The heat dissipation on extraction grids could causes serious problem for long pulse operation. Each grid has received about 2%-3% [3]ion beam power due to direct interception of arc power(for plasma grid), primary ions, back-streaming electrons from neutralizer, bombardment of both secondary electrons, ions produced by ionization, charge exchange of residual gas between the grid spaces and emission from other grid surface. In order to ensure the concept design accommodate the power loads, the thermo-mechanical characteristics of grids were analyzed at different heat loading distribution and different constraint boundaries by software ANSYS. Simulation indicates that heat power distribution affect little on thermal deformation due to thin thickness. and the peak temperature of PG is about 140° and the deformation is 0.07mm, when the heat loading is assumed as large as 2% of the total ion beam power and cooling water velocity is 6m/s. the Maximum von Misses equivalent stress is 0.44GPa close to the yield stress of 0.5GPa, where the boundary is constrained at grid verge surface in all direction and at symmetry plane in x direction. so the temperature maximum of PG need being limited less than 140° for molybdenum. In the same way, the temperature maximum of GG need being limited less than 100° for oxygen-free copper.



(a) Temperature distribution (b) Thermal stress deformation distribution

Fig.2 thermo-mechanical simulation of the 1st electrode

3. Study of ion beam optics

The low beam divergence is required to obtain high injection heating efficiency, so the beam optical properties of the four-grid structure of HL-2M NBI ion source have been studied by a numerical simulation code developed independently [4] and IGUN code [5].Given the ion current density is 0.15A/cm^2, the mass number is 2.0, ion temperature 1.0eV and electron temperature is 5.0eV, the typical ion beam trajectory is shown as Fig.3 for original model in Fig.5. In order to improve the ion beam divergence, the RMS (Root-Mean-Square) divergence angles vs. ion current density are calculated and shown as Fig.4 respectively for four aperture models in Fig.5. According to Fig.4, the RMS divergence angle is lower for the G1_INDIA model and G1_new model. Fig.6 indicates that RMS divergence angles vary with ion current density for 3.45mm and 4.45mm aperture radius of the first grid (i.e. Plasma Grid). It is known that the larger aperture radius increase the transparency, but the divergence increase simultaneity. If the permissible RMS angle is 1°, the maximum ion density is 0.2 A/cm^2 for 4.45mm radius where grid transparency is 41% and 0.24 A/cm^2 for 3.45mm radius where grid transparency is 38%. So the3.45mm radius is optional for the grid design.

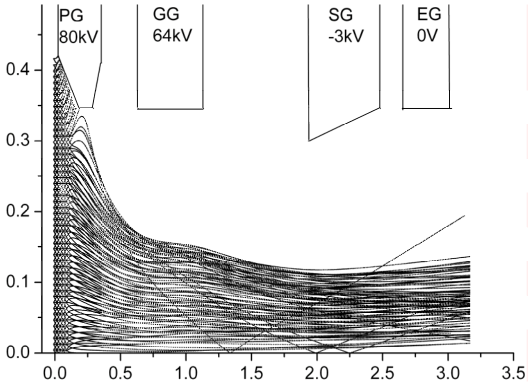


Fig.3 The typical ion beam trajectory

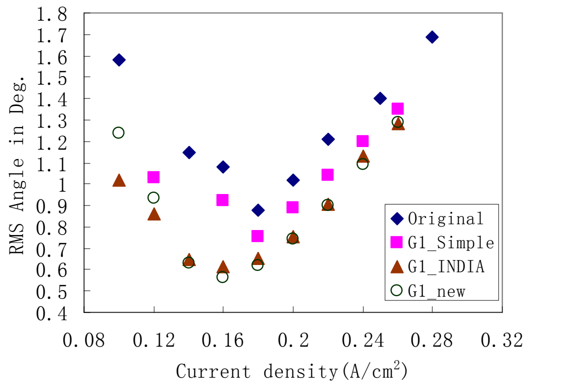


Fig.4 The RMS angle VS ion current density

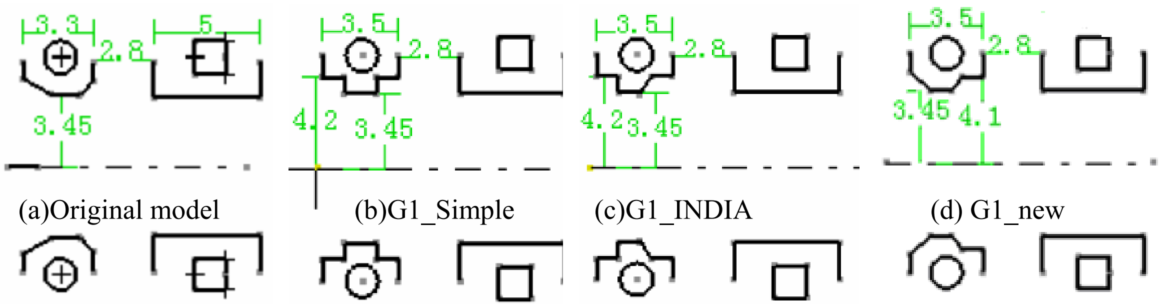


Fig.5 The calculation models of different aperture shape in plasma grid

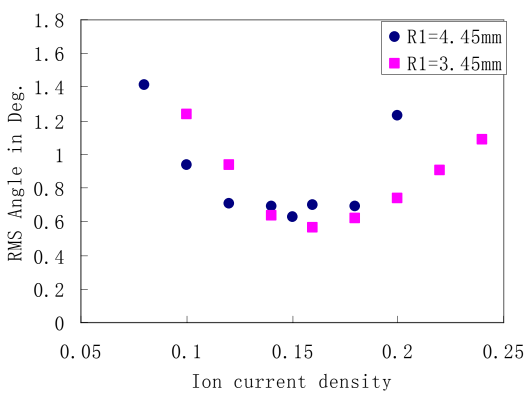


Fig.6 The RMS angle vary with ion current density for different aperture radius

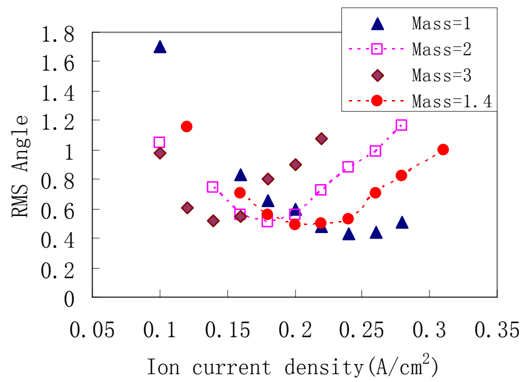


Fig.7 The RMS angle vary with ion current density for different mass number.

The single aperture model of four grids system is shown as Fig8, where the extraction distance is d_1 and acceleration distance is d_2. The field ratio (named as Γ/f, $\Gamma = |V_{GG}-V_{SG}|/|V_{PG}-V_{GG}|$, $f = d_2/d_1$) of acceleration space to extraction space is one very important parameter for ion beam optics of four grids system. The distance between grids is as smaller as possible under conditions of electrical field less than 10kV/mm and the field ratio is larger than 4/3.Given the V_{PG} is 80kV,ion current density is 0.16A/cm^2—0.28A/cm^2, The RMS divergence angles vary with Γ/f shown as Fig.9 (a), where d1 is 2.8mm, d2 is 8mm (named New1 model). Fig.9(a) denotes the divergence angle decreases with Γ/f increasing for a large ion current density, when Γ/f is less than 2.0 for New1 model and NewGAP2 model (d1 is 2.8mm, d2 is 7mm) and less than 2.5 for NewGAP1 model (d1 is 3.8mm, d2 is 7mm). The ion beam optics is also related to ion mass, which is varied with ion species and species ratio shown as Fig.7. The optimum perveance increased with decreasing ion mass. When the allowable RMS (Root-Mean-Square) divergence angle is less than 1.0° and optimum perveance is about 1.06×10^{-9} A $V^{-3/2}$ cm^{-2} for deuterium ion beam. Simulation results indicate that the maximum of ion beam power can reach up to 80kV×50A for deuterium，80kV×65A for hydrogen. The optimized ion source concept design is shown as Fig.8 and the distance between grids is removable taking into account simulation error. The extraction elements can meet the requirements of HL-2M neutral beam injector by next further experimental research.

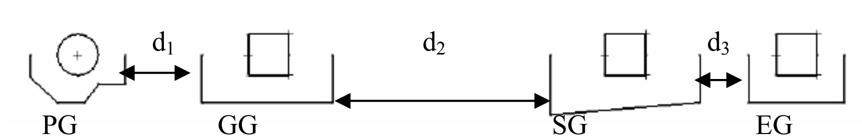


Fig.8 The single aperture model for 80kV 45A 5s ion beam extraction.

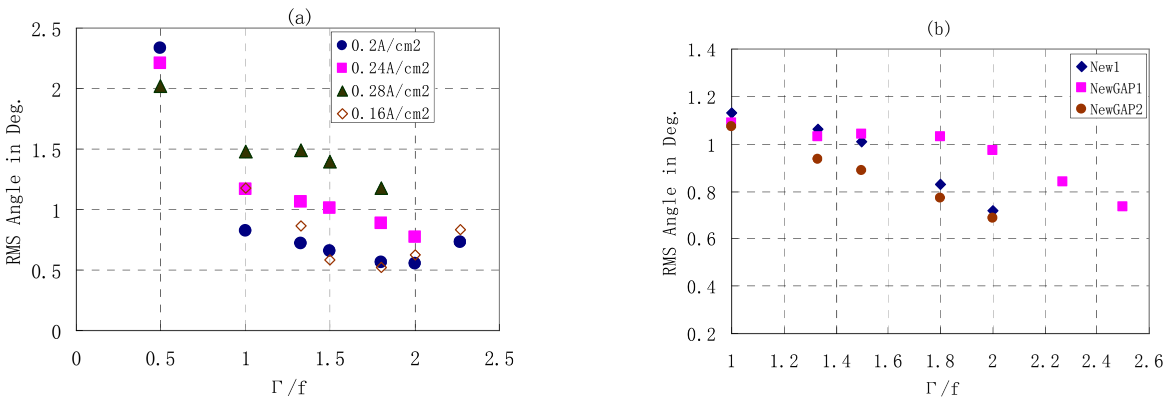


Fig.9 The RMS divergence angles vary with Γ/f , (a) for different ion current density; (b) For different d_2/d_1

Reference

[1] D.Q. Liu et al., 27th Symposium on Fusion Technology, Belgium, Sep. 2012

[2] J.Y. Cao et al., 27th Symposium on Fusion Technology, Belgium, Sep. 2012

[3] H.Horiike et al., Review of Scientific Instruments **50**, 1453(1979).

[4] G.Q.Zou et.al. Review of Scientific Instruments **83**, 073307(2012).

[5] R.Becker, Rev.Sci.Instrum.,**63(4)**, 2756(1992)