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Design and simulation of NBI heating system using high dense helicon plasma source for Damavand Tokamak

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ABSTRACT

A neutral beam injection system by using standard COMSOL software is designed and simulated for plasma heating of small size Damavand tokamak. In context of theoretical model, the needed heat power for plasma heating of this tokamak to the specified temperature is estimated. The number of particles per second, power and energy of the neutral beam which is needed to reach the intended heat power are calculated. Based on these parameters, all sections of the neutral beam injection system such as the plasma source, the extractor, the accelerator, the neutralizer and the charge particles deflector system, are designed and simulated. A dense helicon plasma source, with nonuniform magnetic field configuration, is employed as a plasma source of the device. This helicon plasma source is designed and simulated according to the estimated parameters. Considering the beam optics and space-charge effects, an ion extractor system is simulated and designed for this device. This extractor system can extract an ion beam with current about 7.5 A. The simulation results show that a neutral beam with energy 4.45 KeV and particle current about 6.6 particle per second can be obtained from our designed NBI system. This neutral beam can heat the electrons of plasma to temperature 300 eV and ions to 150 eV. On the other hand, the results of the simulation indicate that our designed neutralizer system could neutralize about 90.58 percent of the initial input ions. In this context, the proper parameters (the neutral beam energy and power) of the NBI systems are calculated for heating of the electrons and ions of the plasma to temperature 1000 eV and 500 eV, respectively.

1. Introduction

Neutral beam injection system is used for plasma heating in the many tokomak devices. This system is known as a successful plasma heating approach in the magnetic confinement devices such as tokamaks [1–3].

A neutral beam injection system with power 2–4 MW and energy of beam 50-80KeV is used in the EAST Tokamak [4–6]. The KSTAR has a neutral beam injection (NBI) system in power 8 MW and beam energy 120 keV [7]. In the same way, TCV, Globus, MAST, COMPASS and NSTX have NBI systems with powers 1–3 MW, 0.5–0.7 MW, 0.53 MW, 0.6 MW and 5 MW and beam energies 20–35 keV, 30kev, 30 keV, 40 keV and 80 keV respectively [8–13]. The neutral beam injection system can be used as a powerful diagnostic system for measurement of some of the tokomak fundamental parameters such as ion and electron temperature, safety factor, impurity concentration, and etc. [14].

The neutral beam injection systems consist of different sections. The most important part of the NBI system is Ion source. The sources such as inductively coupled plasma sources (ICP), capacitively coupled plasma sources (CCP), plasmatron ion sources, the ion sources which are based on the heating by filament and the helicon plasma sources can be used as ion source in the NBI systems [15–21]. Among different plasma sources, the helicon plasma sources, due to producing a dense plasma with density of order $10^{19} m^{-3}$ under low pressure, are interesting assets and used in accelerators, materials processing, propulsion and ion sources [22–27]. The helicon plasma sources are proper candidates for extraction and production of ions and can be used as powerful ion sources in the neutral beam injection systems [28–30].

In this regard, Shunjiro and his coworkers have studied the applications of the dense helicon plasma sources experimentally [31]. Using Langmuir probe, the electron temperature and density of a helicon plasma system were measured by Chen, who has investigated the influence of the static magnetic field and collisions on the electron current in this system [32]. Melazzi has compared the effects of the different antenna in the helicon plasma sources [33]. The governing mechanism on the helicon plasmas and the mechanism of wave

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generation are analyzed by Chen [34].

A novel high efficiency antenna for helicon plasma source is designed and proposed in our previous work [35]. This new configuration of antenna has increased the absorption power and helicon plasma density in comparison to the common antenna.

On the other side, Choe and his coworkers have used four helicon plasma sources for achieving an ion current about 10 A, in the neutral beam injection system of the VEST device [36]. The researchers in the Demo project have employed the helicon plasma source as an ion source for developing of the neutral beam injection system [37–40]. The helicon plasma source as an ion source for NBI system in the ITER project is an interesting asset studied by scientists of this project [39,40]. As mentioned above, the neutral beam injection systems include different sections; a plasma source, an extractor and an accelerator, a neutralizer and an ion deflector. The helicon plasma sources can produce a plasma with high density in low pressure, then these systems can be used as high density plasma source and high density ion source in NBI systems. In this article, we try to design and simulate a neutral beam injection system, using a helicon plasma source, for our small size Damavand Tokamak which is operating in Atomic energy organization of Iran [41]. Using a standard COMSOL software, all sections of the device; the helicon plasma source, the extractor, the electrostatic ion accelerator, the neutralizer, and the chamber of the neutral beam injection system, are designed and simulated. The cross section of all reactions; ionization interactions, recombination, excitations, charge exchanges, elastic and inelastic collisions in range of 0.1 eV to 100KeV are considered in our simulation.

In context of a theoretical model and according to the parameters of the mentioned tokamak, our calculations indicate that for heating the electrons to temperature 300 eV and ions to temperature 150 eV, in this Tokamak device, an ion beam with a current of 7.18 A and the energy of 4.45 keV is needed.

Based on the value of needed ion beam current and equation of the ion-saturation current density, we can estimate plasma density and electron temperature of the plasma source. In this regard, a plasma with density of $7.35 \times 10^{18}\,m^{-3}$ and temperature of 3.1 eV is needed for generating this ion beam. Therefore, a helicon plasma source with nonuniform magnetic field configuration, for producing this dense plasma, is designed and simulated. An electrostatic array of extractor and accelerator is designed and simulated for extraction and acceleration of ions. On the other side, the beam optics play a vital role in design of the extractor system [42–44]. The beam optics is a function of several beam parameters [42–44] such as, beam perveance, beam brightness, space charge effects, beam divergence, electron and ion temperature, and geometry of electrodes [45–48].

In this work, at first, an extractor system with single aperture grid is considered. Using child Langmuir equation, ideal current of the ion beam is estimated. At the following, effects of the beam optics on the beam current, for single aperture grid, is studied and analyzed. In addition, influence of some restrictions, which are due to space charge effects, are estimated and applied on the beam current. In respect to all of these effects, the beam current of a single aperture grid extractor is calculated. Since influence of neighboring beams on optics of each other are assumed insignificant, beam optics calculations of single aperture grid can be used in multi aperture grids calculations. According to calculated beam current of the single aperture grid, we estimate number of apertures of extractor grids.

According to our analysis and calculations, for reach to proper ion beam current in our work, we need three helicon plasma sources and three extractor systems which can extractor ion beam with energy of 4.45kev and beam current of 2.5 A, approximately.

In this context, we must use a neutralizer chamber in $2.5 \times 10^{19}\,m^{-3}$ density and 0.5mTorr pressure for neutralizing the mentioned ion beam in the proposed NBI system. Results of our simulation and calculation show that the proposed NBI system can generate a neutral beam with power 28.3KW and energy 4.45KeV for plasma heating (heating of electrons to temperature 300 eV and ions to temperature 150 eV) of the mentioned tokamak. In context of these calculations and simulations, the electrons and ions of the plasma are heated to temperature 1000 eV and 500 eV, in the several temperature steps. The proper parameters (the neutral beam energy and power) of the NBI systems are calculated and simulated for each step.

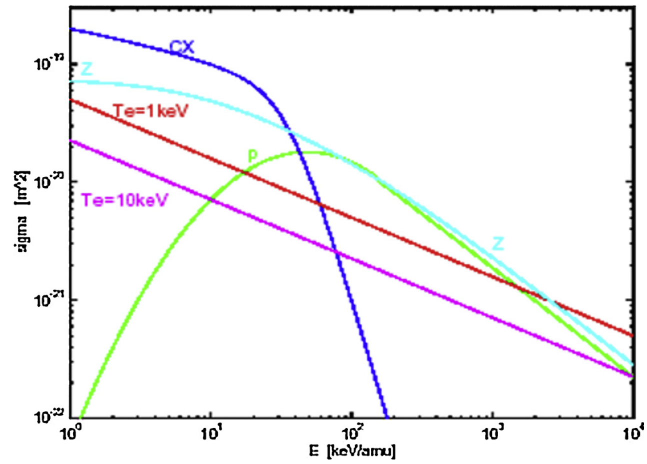

Fig. 1. The Ionization Cross Sections.

In Section II, the basic theory of the work is represented. Section III deals with design and simulation of NBI system for the mentioned tokamak. The work is concluded in Sec IV.

2. Theory

In all tokamaks the primary heating is supplied via Ohmic heating by central solenoid. However, auxiliary heating systems are used to reach the proper heat for fusion reactions. The neutral beam injection and radio frequency heating systems are two common ways for plasma heating in tokamaks [49,50].

The neutral beam injection systems include a plasma source, an extractor, an accelerator, a neutralizer and a charge particles deflector system. In this heating system: first, plasma with proper density is generated by a plasma source; second, ions are extracted by an extractor from the plasma source and accelerated to a proper energy by an accelerator system, and then for charge exchanging, the accelerated ion beam is transmitted through the neutralizer system. In the neutralizer, some of the ions are neutralized and some others are deflected by a charge deflector system. The neutral particles transmit in a straight line, without bending by magnetic fields, they can reach to plasma and lead to plasma heating. In this approach, in addition to the plasma current increment, the neutral beam energy is transferred to the plasma by collision of the beam particles with ions and electrons of the plasma.

The ion source of the NBI system includes a plasma source and an extractor system. Various plasma sources such as helicon sources, inductively coupled plasma sources (ICP), capacitively coupled plasma sources (CCP), plasmatron sources and electron bombardment source, have been used for generation and extraction of ions [21,22,33,34].

Because of the ability of generating dense plasma in low pressure and with a low temperature, the helicon plasma source is one of the important and applicable sources [24]. A helicon plasma source consists of static magnetic field, vacuum chamber, antenna, RF generator and an injection gas system. In helicon plasma sources, the radio frequency wave is launched between the two magnetic coils. The helicon wave causes ionization of neutral injected gas and dense plasma is generated in low pressure [24]. The magnetic and electric field components of the helicon waves are derived by solving the Maxwell Equations and the particle motion equation self consistently in cylindrical coordinate system. The dispersion relation of the helicon wave is