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Conceptual design of a permanent ring magnet based helicon plasma source module intended to be used in a large size fusion grade ion source

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ABSTRACT

A conceptual design of a permanent magnet based single driver helicon plasma source module along with its design approach is described in this paper. The module unit is intended to be used in a large size ion source. The conceptual design of the helicon source module has been carried out using a computer code, *HELIC*. The magnetic field topology for the ring magnet is simulated with another code, *BFieldM* and the magnetic field values obtained from the calculation are further used as input in *HELIC* calculation for the conceptual design. The module is conceptualized based on a cylindrical glass vessel to produce plasma of diameter ~50 mm, height ~50 mm. The inner diameter of the permanent ring magnets is also of the same dimension with thickness ~10 mm each, placed slightly above the backplate to maintain the required magnetic field. The simulated results show that for hydrogen gas, expected plasma density can be achieved as high as $\sim10^{12}$–10^{13} cm^{-3} in the proposed helicon source configuration using 1 kW 13.56 MHz RF generator. An experimental setup to characterize a Helicon source module unit, consisting of a cylindrical glass (plasma) chamber along with the vacuum system, RF power supplies, probes and data acquisition system is being installed.

1. Introduction

Helicon plasma sources are very promising plasma sources due to their high ionization efficiency [1]. The physics behind such high efficiency is still a subject of investigation [2]. However, due to having high plasma density ($\sim10^{12}$–10^{13} cm^{-3}; with Argon gas [3,4]) using low RF power (~ few kW), Helicon based plasma sources are used in the fields of plasma processing [3] and space exploration [4]. Helicon waves are a type of whistler waves that can be excited in plasma when the driving frequency of the waves, ω lies in between ion cyclotron frequency Ω_c and electron cyclotron frequency ω_c, i.e. when $\Omega_c \ll \omega_{LH} \ll \omega \ll \omega_c \ll \omega_p$ is satisfied. Here ω_{LH}, ω_p are lower hybrid frequency and plasma frequency respectively.

Institute for Plasma Research (IPR) is engaged and has long term research and development (R&D) programs on fusion related technologies, Neutral Beam Injector (NBI) system is one of them [5]. Large area, high plasma density sources are needed in NBI ion sources [6]. Present day technology relies either on filament based [7] or on inductively coupled plasma (ICP) based ion sources [8], however efficiency of such technologies is low. Due to high ionization efficiency Helicon source configuration would be a promising candidate to explore further in this regard.

In ICP ion sources, RF power is coupled to the plasma through inductive manner and therefore the antenna can be kept outside the plasma. As a result ICP can be considered as electrode-less. Since antenna is not in direct contact with plasma, there is no erosion and less maintenance is expected, which ensures higher machine availability. As a consequence, ITER NBI ion sources are all ICP type [9], and it is expected that future generation NBI sources will be also electrodeless due to the same reason. In an ITER type fusion grade ion source, ~1 MW of RF power is used for plasma production out of which ~880 kW power is removed by the water cooling circuit in the ion source plasma box (without considering accelerator cooling) [10]. High power RF generators of total power ~1 MW are used to create plasma inside the ion source which needs large space in high voltage deck (HV deck) and also correspondingly large cooling system. These are expensive in terms of real equipment cost, running cost and also space. If an alternate efficient electrode less plasma mechanism with minimum interface issues can be identified, it will be beneficial to reduce the overall NBI cost. Due to high ionization efficiency against power input Helicon source with multi-driver configuration [11] would be a promising candidate for a large size ion source, in this regard. Normal helicon sources are based on large electromagnets which need large current

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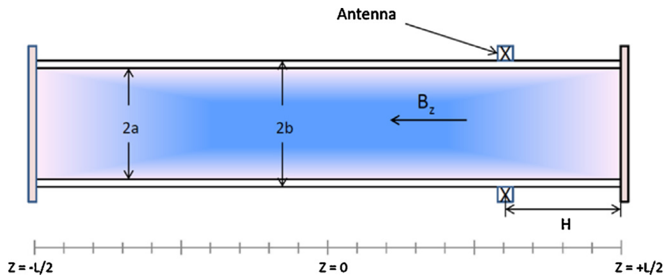

Fig. 1. Geometry of plasma chamber for *HELIC* calculations. "H" indicates the distance of the antenna from the endplate.

power supplies and cooling arrangement; i.e. two major interfaces with auxiliary systems. However, permanent magnet based helicon source is free from these interfaces.

The present work is linked to that above mentioned objective. IPR has initiated a multi-driver based large size Helicon negative ion source R&D program. The program is initiated through a single driver Helicon plasma source having permanent ring magnet for the axial magnetic field. The conceptual design activity is being carried out using two computer codes *HELIC* [12] and *BfieldM* [13]. HELIC computes the power deposition spectra to plasma for a given antenna configuration, magnetic field and geometrical inputs. In Helicon plasma, magnetic field topology inside the source is very important for wave excitation and source operation. Magnetic field distribution due to permanent ring magnets is calculated by *BfieldM* code. The paper describes the conceptual design of a single driver permanent magnet based Helicon plasma source and also its simulated plasma performance for Hydrogen gas using these codes.

It is to be noted that an experimental setup to characterize one Helicon module, consisting of cylindrical glass (plasma) chamber along with the vacuum system, RF power supplies, probes and data acquisition system is being installed in IPR. Later multiple such Helicon modules will be arranged in a desired matrix to build a large size ion source for NBI purpose.

2. Description of "*HELIC*" code [12] and BFieldM code [13]

HELIC is developed by Arnush [12], which is computer program written in C++ language for the design of RF plasma with and without magnetic field through simulation. It predicts the power deposition spectra for given input parameters of plasma density, magnetic field, antenna configuration and geometry in cylindrical symmetry (r,ϕ,z components). Maxwell's equations for a cylindrically symmetric radially non-uniform plasma with the standard cold-plasma dielectric elements is utilized to generate a set of four coupled differential equations for the Fourier transformed variables, assuming cold plasma approximation and corresponding dielectrics. The program solves four coupled radial differential equations for each k_z (wave vector along cylindrical axis or z-axis) to obtain two independent wave equations. By applying the boundary conditions algebraically, these equations are combined. The model assumes that, (i) plasma is cylindrically symmetric, (ii) dc magnetic field is axially uniform, (iii) the program does not take into account the plasma creation through mode of coupling of power from the antenna to the plasma i.e. plasma density value is an input and (iv) it does not consider the plasma transport inside. The basic schematic configuration including antenna and magnetic field direction is shown in Fig. 1. The program computes the following quantities: (a) wave variables: magnitudes, components, and phases of magnetic field—**B**; electric field—**E**; and plasma current density **J** for a given azimuthal wave number m; (b) power spectra: $S(k)\,P(k)$, $P(r)$, $P(z)$, where $k = k_z$. Power terms are estimated based on resistive calculation considering equivalent resistor divider circuit. The term $S(k)$ is the response of the plasma at various k and indicates the relative absorption efficiency of the plasma at each k, normalized to a 1-ampere antenna current; and expressed in ohm-m per ampere. The term $P(k)$ is the relative power absorption or deposition at various k for the given antenna and plasma parameters and expressed in ohm-m. It is the convolution of $S(k)$ and antenna's k spectrum. The term $P(k)$ can also be expressed as $P_{ant}(k)$ considering antenna voltage and current for computation, rather plasma current, as shown in Eq. 1(a) and (b). The term $P(r)$ is the radial profile of power deposition over a given range in z, $P(z)$ is the axial profile of power deposition integrated over cross section; (c) resistive loading $R(n, B)$ for a range of plasma density n_e and axial magnetic field B_0. The detailed of the program methodology and corresponding equations for these parameters and its derivations can be found in [12,14].

The plasma response $S(k)$ and the power delivered to the antenna per unit k are defined as,

$$S(k) = \frac{1}{2}Re\left(\int \underline{\mathbf{E}}.\underline{\mathbf{J}}_{\text{plasma}} d^3r\right) \quad (1)$$

$$P_{\text{ant}}(k) = \frac{1}{2}Re\left(\int \underline{\mathbf{E}} * \underline{\mathbf{J}}_{\text{antenna}}\, d^3r\right). \quad (2)$$

here **E** is the electric field of the wave and **J** is the current density excited in the plasma (1) by an antenna (2) with a spectrum between k_{min} and k_{max}. The total power delivered for a 1 A antenna current is,

$$R_{\text{ant}} = 2\int_{k_{\text{min}}}^{k_{\text{max}}} P_{\text{ant}}(k)\,\text{d}k. \quad (3)$$

In the present context, a single species of singly charged ion is assumed and the total absorbed power is estimated in terms of the wave number, k and is normalized for 1 A antenna current. If the plasma cavity is unbounded (approximated for long plasma column in z-direction—see Fig. 1), a large number of k is possible. Total power can be calculated by integrating and scanning over the range of k with step size dk. The existence of various k is due to the profile of plasma density n_e and the axial magnetic field B_0.The parameter dk is chosen such that the wave is damped within the distance between $z_{\text{min}} = -L/2$ and $z_{\text{max}} = +L/2$, as per the geometry in Fig. 1. It is assumed that the solution repeats with a periodicity $2\pi/\text{d}k$, and the maximum range is defined as, $z_{\text{min}} = -\pi/\text{d}k$, $z_{\text{max}} = +\pi/\text{d}k$. In the code, d$k$ step size is 0.01 m. The limits considered for the range of k are k_{min} and k_{max} and are the input parameters linked to z_{min} and z_{max}.

The radial and axial profiles of deposited power, P_r and P_z, respectively, are also computed as the output from *HELIC*. The user can also specify the type of endplate, insulating or conducting type. For the present case, the design is simulated for a configuration with a conducting endplate. Effect of conducting plate on plasma discharge is discussed in Section 4.

The calculation of the plasma loading is directly related to the power absorbed by the plasma from the antenna. Plasma can be simply approximated as an electrical load in the electrical circuit as shown in Fig. 2.

The power balance among the equivalent resistor divider circuit can be estimated by the equation [15],

$$P_{\text{in}} = P_{\text{rf}}\frac{R_p}{R_c + R_p}. \quad (4)$$

R_p is the plasma resistance and R_c includes all the circuit losses. If $R_c \ll R_p$, then $P_{\text{in}} \sim P_{\text{rf}}$; i.e. most of the power from the RF generator P_{rf}, goes into the plasma P_{in}. Hence, Eq. (4) indicates the