Investigations on High Power Neutral Beam Production for Tokamak Applications

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Abstract

The development of a two fluid, one dimensional code in cylindrical geometry enables to study and describe the spatio-temporal evolution of negative hydrogen (or deuterium) ions and electrons in a magnetically insulated diode. The code is applied to test experimental data from the international literature on pulsed power devices producing high voltage and high current negative ion beams in order to investigate the physical processes of the acceleration and the extraction of the beam. The numerical results of the code are in good agreement with the experimental data using the appropriate physical and the geometrical parameters of the devices. These investigations allow to propose a new scheme for the production of a high power (~100MW) neutral beam, based on different well established technologies such as: (a) the production of negative ions by ultra-short laser beam interaction with clusters, (b) the coupling of a magnetically insulated diode with a pulsed power device capable to extract high current (200 A) and high energy (1 MeV) negative ion beam and (c) laser based photodetachment techniques for beam neutralization. The proposed scheme has applications to Tokamak reactors.

Introduction

The need for efficient plasma heating is one of the keys to achieve fusion in devices such ITER and DEMO. Neutral beams are getting more attention lately because they can fulfil these goals, development is in progres on standard as well as alternative techniques for negative ion beam production and neutralization. This paper is concerned with the study of a Magnetically Insulated Diode (MID) as an alternative technique for the production, acceleration, and extraction of a high power negative ion beam. Since the early eighties there are a sufficient number of experiments (about ten) on high current density and high voltage negative ion beam production using pulsed power generators, coupled with MIDs. By selecting the geometrical and physical parameters from experiments performed world-wide on high power negative ion beam production, we investigate comparisons with the results of a 2-fluid, 1-D numerical code we have developed and select appropriate parameters for custom applications. These experimental results are in good agreement with the numerical results from our code are in good agreement and are presented hereafter. These successful investigations enables us to propose, in the near future, an alternative high power negative ion beam for ITER/DEMO application. Previous experimental results[1], [2], [3], confirmed by recent experimental data[4] show that negative ion densities up to 10^{12} cm^{-3} can be produced by ultra-short laser beam interaction with clusters. This technique can be elaborated in order to be used to fuel the cathode of a MID.

Discussion

The MID principle of operation requires the presence of a strong pulsed magnetic field in ored to trap the electrons close to the cathode and to extract the negative ions. Our previous experimental work on pulsed magnetic devices[5] showed that we can generate magnetic field using a capacitor bank coupled with a surface switch up to 30 T. These values are more than enough for the specifications for the MID we describe. To simulate the electron and negative ion spatio-temporal evolution inside the diode, a numerical code was developed. The code treats the cathode plasma as a two fluid system, with electrons and negative ions enclosed between two concentric cylinders, polarized at a high voltage and are generated on the surface of the inner cylinder. In adition, an initial uniform magnetic field is applied parralel to the symmetry axis. The code computes the conservation equations, continuity momentum and energy, of the two species, as well as the interactions with the electric and magnetic fields. The main bibliography concerning research and results on the pulsed power devices coupled with MIDs, along with corresponding data and results are shown in Table 1. All configurations are for a diode with anode-cathode gap of few centimeters, using an external magnetic field of few teslas. From the existing experimental data (see the bibliography corresponding to table I) it is evident that high negative ion current density can be accelerated and be extracted from the diode. We used our 2-fluid, 1-D numerical code to simulate the operation of these MIDs. Our results are in good agreement with the experimental ones from the references in Table 1. We also operate the code using several other parameters to investigate the influence each one has on the extracted negative ion current. In Figure 1 we have kept all parameters constant (AK gap = 3 cm, electron density = 10^{11} cm^{-3}, voltage = 1MV, beam area = 25 cm^2) and only varying the magnetic field strength. We can see that there is an optimum B value that maximizes the ion current. This value is about 1.5 times the critical magnetic field (obtained from the gyroradius of the electron), as indicated from experiments[1]. Figure 2 shows the dependence of the ion density on the extracted current, and there is a rather linear correlation between these two parameters. From table 1 we can also conclude that we can reach negative hydrogen densities of 10^{14} cm^{-3} formed from a dense and relatively hot plasma. There have been experiments confirming that such a plasma can be formed from laser-cluster interaction techniques.

Source	Electron density (cm^{-3})	Voltage (keV)	Ion current density J (A/cm^2)	Ion current I (kA)	Diode geometry	Diode area (cm^2)
Stinnett & Buttram[7]	10^{14}-10^{18}	1000-4000	100-300*	600*	Planar	1400*
Agafonov et al. [8]	10^{15}	500-700	13	2	Cylindrical	60-120
Papadichev et al. [9]	0,7x 10^{16}	40-150	200	2	Cylindrical	60-120
Pushkarev et al. [10]	10^{14}	150-200	20-150	1.6-12	Planar	80
Pushkarev et al. [6]	N/A	200-250	20-40	2-4	Planar	100
Rej et al [11]	N/A	100	100	50	N/A	300
Xin et al [12]	N/A	250	300	30	Cylindrical	96
Park & Wurden [13]	10^{14}	100-125	25	2	N/A	400

Table 1. Important parameters from MID bibliography. *Estimations, N/A Non Available

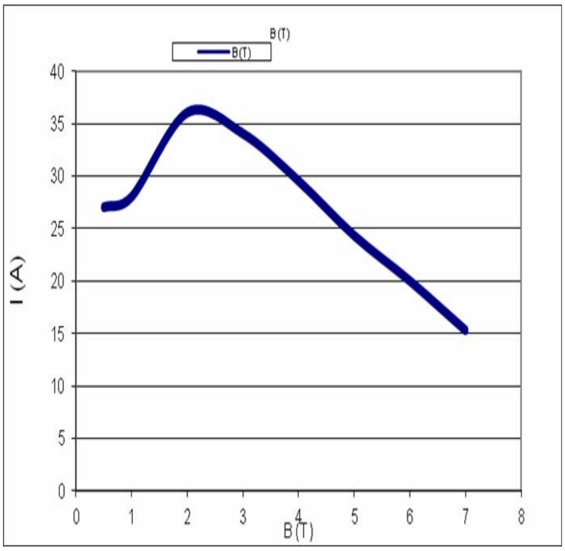

Fig.1: The ion current extracted from the MID versus the magnetic field B.

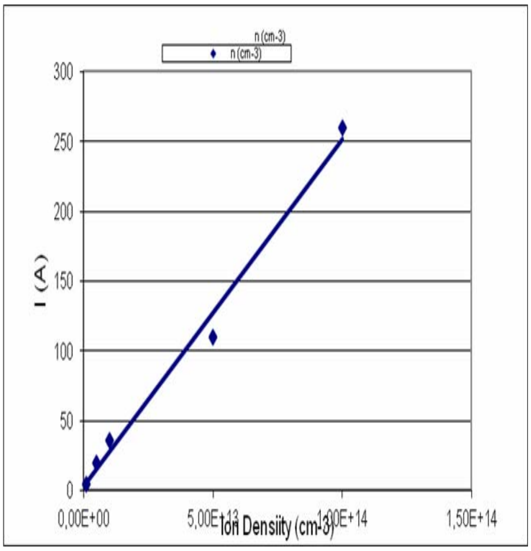

Fig.2: The ion current I versus the ion density inside the diode.

Note that in our tests, the numerical code simulates the initial ion and electron density which is then left to evolve, so once the extraction of the ions is completed, the procedure stops. For the practical continuous pulsed operation of the MID, the code can be configured with an appropriate ion density source term and can simulate the MID operation for different electron and negative ion densities.

Conclusions

For the first time the development of a 2-fluid, 1-D numerical code allows to describe the operation of MID for high power negative ion extraction from a MID and to compare with experimental results from the international bibliography. The good aggreement between the results from the code and experimental results enables to apply the code to simulate the MID operation for different geometrical and physical parameters. The coupling of the MID with a pulsed power generator operating at 1 MeV with pulse duration of μsec, an initial H^- density of 10^{16} cm^{-3} on the cathode, a cathode surface of 25 cm^2 and an applied magnetic field[5] of 2T, can generate a negative hydrogen beam of 100 MW with rep-rate of 100 Hz. In the proposed alternative device for high power neutral beam production, a double laser system will be considered: an ultra-short (fs) laser can be used for the negative ion production by laser-cluster interaction[1], [2], [3[, [4] with densities up 10^{12} cm^{-3} inside the diode, while a longer pulse (μs) laser beam with energy of 25 J can be used for the photo-neutralization. The integration of these techniques in a unique device can provide a new alternative high power Neutral Beam method for heating needs of Tokamak reactors.

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