On the Production, Acceleration and Photo-Neutralization of High Energy and High Current Negative Ions Beam for Magnetic Fusion Applications

Stavros D. Moustaizis[1,#], Paraskevas Lalousis[2] and Kostas Perrakis[1]
[1]*Technical University of Crete, Science Department, 73100 Chania, Crete, Greece*
[2]*Institute of Electronic Structure and Laser, FORTH, Heraklion, Crete, Greece*
[1,2]*Association Euratom-Hellenic Republic*
[#]*moustaiz@yahoo.gr*

Abstract

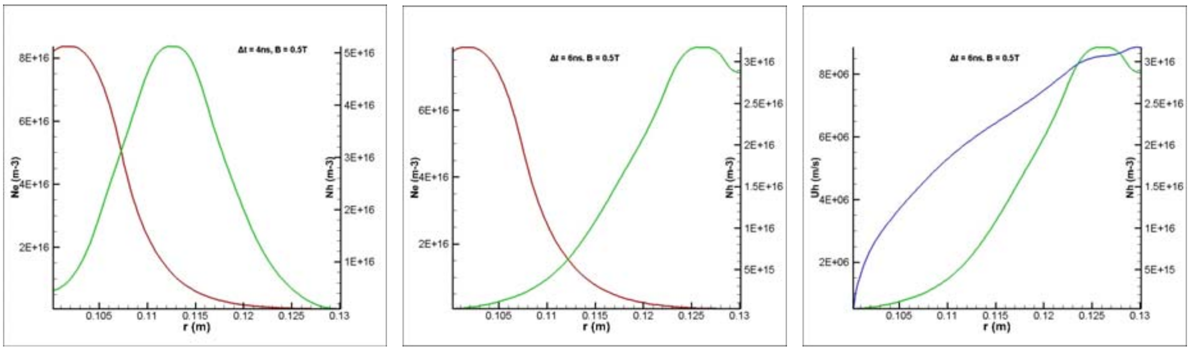
A new scheme and methodology for the production, acceleration and photo-neutralization of negative ion beam (of hydrogen isotopes) for Tokamak Reactor application, is presented. The production of the negative ions is based on ultra-short laser beam interaction with deuterated clusters. The main advantages of the proposed negative ions source are (a) the high density of the produced negative ions and (b) the relatively small volume of production. Such a source can be placed at the end of a pulsed power generator in a magnetically isolated diode operating at 500 kV-1 MV and producing a current of negative ion beam up to 600 A. A highly efficient laser "cavity" neutralizer for negative ion beam photo-detachment, allowing the production of a high current neutral beam and its penetration in the torus of a Tokamak, is proposed for plasma heating. A one dimensional model in cylindrical geometry is being developed which describes the spatio-temporal evolution of negative deuterium ions and electrons in a magnetically isolated diode, which is between two concentric cylinders. A magnetic field parallel to the symmetry axis, and an external electric field between the two concentric cylinders, are applied.

Introduction

The production, acceleration and photo-neutralization of high energy and high current beams of negative ions present an increase interest the last few years due to their potential application as a heating source to Tokamak Reactors and especially for DEMO. In fact experimental results confirm the production of high energy negative ions by ultrashort laser beam interaction with clusters[1], [2], [3], [4], and or plastic surfaces in which the hydrogen was replaced by deuterium. In low pressure hydrogen discharges, significant densities of negative ions[5] can be produced with electron densities up to 10^{12} cm^{-3}. A few decades ago the presence of negative ions has been demonstrated in magnetically insulated transmission lines[6] (MITL) and in magnetically isolated high voltage diodes[7] (MID). The proposed new scheme and methodology for the production of negative ions (H and/ or D) is based on the idea to combine the existing know-how on different scientific areas in order to develop a compact device which will use ultra-short laser – cluster interaction for the negative ion production in a magnetically isolated diode coupled to a pulsed generator capable in order to extract a beam of 1 MeV and 600 A of negative ions. The proposed device will dispose a second laser system with relatively long pulses, nsec or μsec which will be synchronized with the extracted negative ion beam in order to produce a neutral beam using photo-detachment effect. The laser photo-neutralizer presents important improvements, concerning the efficiency, compared to the conventional plasma neutralizer. The magnetic field in the MID is generated using a capacitor bank capable to produce the appropriate current in order to isolate the diode. In such configuration, negative ion beams of hydrogen or deuterium can be extracted with current densities in the range of 1-20 A/cm^2. The magnetic field confines the electron flux in the vicinity of the cathode hence the electrons do not close the gap between anode and cathode. Under these conditions only the negative ions can be accelerated between the cathode and the anode and extracted from the MID. The maximum extracted current depends on various parameters such as the geometrical parameters of the MID, the values of the external applied electric and magnetic fields. The development of a numerical code is necessary in order to simulate the operation of the MID and produce optimized scenarios.

The mathematical model and results

A two fluid, one dimensional code in cylindrical geometry is being developed which describes the spatio-temporal evolution of negative deuterium ions and electrons in a magnetically isolated diode, which is between two concentric cylinders. A magnetic field parallel to the symmetry axis, and an external electric field between the two concentric cylinders, are applied. The model equations include conservation of particles, momentum and energy of electron and negative ions, coupled with Maxwell's equation for the space-charge separation. In the calculations presented here we consider that at time equal zero equal densities of electrons (n_e) and negative ions (n_i) are enclosed between the two concentric cylinders.. We consider the following geometrical parameters: the external radius corresponding to the anode is 13cm and the inner radius is 10cm, corresponding to the cathode. The initial density for electron and negative ions density is 10^{11} cm^{-3} and the external applied voltage between the cathode and the anode of the MID is 1 MV. The values of the external applied magnetic field vary from 0.5 T to 2 T. Fig. 1 shows the spatial distribution of the electron density and ion density at two different time intervals of 4ns and 6 ns (fig.1a and fig. 1b) and the velocity of the negative ions (fig. 1c) in the MID during the operation for an external applied magnetic field up to 0.5 T. The maximum extracted current for this set of parameters is up to 850 A. Similar results we obtain for higher magnetic field up to 2 T but with a relatively lower total extracted current of the order of 550 A.



(a) (b) (c)

Fig.1 shows the spatial distribution of the electron density (in red), the negative ion density (in green) for time intervals of 4ns (a) and 6 ns (b) and the velocity (in blue) of the negative ions after 6 ns (c) of the diode operation.

The Laser photo-Neutralizer

Recent investigations concern the design and the calculation of a double laser system proposed for both the negative ion production and the negative ion neutralization configuration by photo-detachment techniques. The numerical calculations enable to propose a laser ‘cavity’ of approximately 2 m long to neutralize the pulsed negative ion beam of 1 MeV and 600 A. Three different laser systems were considered in order to evaluate their efficiency on the neutralization process of the negative ion beam. The different laser systems concern the Nd:Yag (1,05μm) the Ti:Sapphire (800nm) and the KrF Excimer (248nm) . The efficiencies for the Nd:Yag and the Ti:Sapphire are very close to 98% and the KrF is 37% for the same dimension of the laser neutralizer. The energy of the laser system is up to 25J. The selection of a KrF Excimer laser system is based on existing commercial systems operating at a rep-rate of 1 kHz. The efficiency of the KrF Excimer negative ion neutralizer can be improved by increasing the dimension (the length) of the laser ‘cavity’. Fig.2 show the proposed system composed by the double laser system, the magnetically isolated diode for the production and acceleration of negative ions coupled to Marx Generator and the laser neutralizer in a compact configuration.

Conclusions

The numerical calculations presented show that the separation of the negative ions fluid from the electron fluid occurs approximately 2 nsec after the application of the high voltage in the MID, the extraction of the negative ions is completed after 12 nsec. These results are in good agreement with experiments. During the operation of the MID the electron fluid remains confined by the magnetic field and the gap between the cathode and the anode is closed by the negative ion current. The numerical calculations enable us to evaluate the total extracted current which depends on the value of the external applied magnetic field. The maximum current is 850 A with a pulse duration of 20ns and power for the pulsed negative ion beam up to 1 GW. The proposed photo-neutralizer has an efficiency of 98% which can produce a high power neutral beam for heating applications to Tokamak Reactors, especially for DEMO.

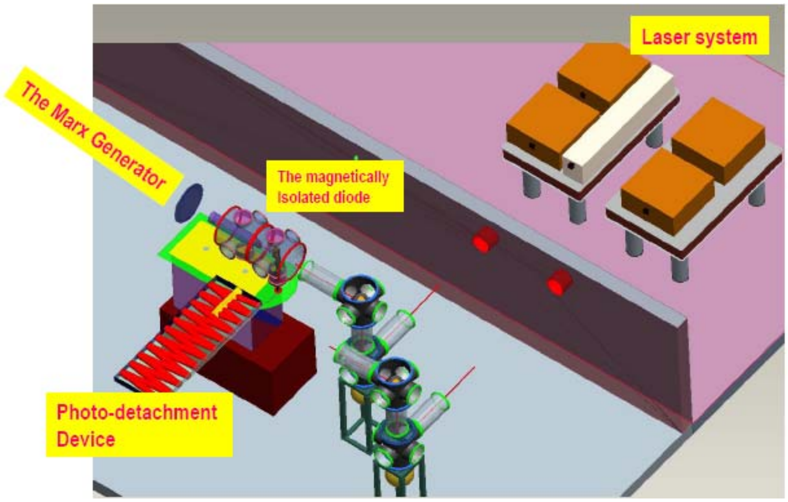


Fig.2 show the proposed device for the production, acceleration of negative ions and photo-neutralization of high energy and high current beams for Tokamak applications

References

1. Ditmire et al., Nature 386, 54, (1997), Ditmire et al., Nature 398, 489-492, (1999)
2. G. Grillon, S.D. Moustaizis, P. Balcou et al., *"Deuterium-Deuterium Dynamics in Low-Density Molecular Cluster Jets by Intense Ultrafast Laser Pulses"*, Phys. Rev. Lett. 89, 065005 (2002) - and P. Balcou,G. Grillon, S. D. Moustaizis et al., *'Neutron Generation by Laser Irradiation of CD4 Clusters'*, AIP Conf. Proc. 611, 244 (2002).
3. S. Ter-Avetisyan et al., Applied Physics Letters 99, 051501, (2011).
4. S. Ter-Avetisyan et al., Review of Scientific Instruments 83, 1 000000-1, (2012).
5. M. Bacal, Volume Production of H- ions in plasma, Physica Scripta 2/2, 467-478 (1982) – and -- M. Bacal et al. '*Volume H- ion Production in Multicusp sources at Ecole Polytechnique'*. Proceedings of the Second European Workshop on the Production and Application of Light Negative Ions. Ecole Polytechnique Palaiseau, March 5-7 (1986) – M. Bacal, '*Extraction of H- Ions from Volume Sources*', Proceedings of the Second European Workshop on the Production and Application of Light Negative Ions. Ecole Polytechnique Palaiseau, March 5-7 (1986).
6. Stinnet and Buttram, J. of Fusion Energy 4, 253 (1983)
7. A. V. Agafonov et al., ' Generation of Intense Flux of Negative Ions, Sov. Phys. JETP 57, 1188, (1983)