Numerical investigations on high flux neutron production from a high-current pulsed ion device

K. Perrakis[1,3,[a]], S.D. Moustaizis[1,3], P. Lalousis[2,3]

[1] Technical University of Crete, Lab of Matter Structure and Laser Physics, Chania, Greece

[2] Institute of Electronic Structure and Laser FORTH, Heraklion, Greece

[3] Association Euratom-EuroFusion-Hellenic Republic

[a] e-mail: kperrkis1@isc.tuc.gr

Abstract

High-current pulsed ion accelerators operate on the principle of slow energy storage in the primary accumulator circuit and of fast transfer to the accelerating diode configuration, increasing by many orders of magnitude the current of the generated ion beam. Particular interest exists for the Magnetically Insulated Diode (MID) configurations used for high power generation of negative or positive ion beams. Our previous work [1-3] regarding numerical simulations using 1-D multi-fluid code [4] in cylindrical geometry enable us to investigate both the spatio-temporal evolution of the plasma species in MID configurations and the high power extracted negative ion beam (H^- or D^-). The code allows evaluating the extracted high-current beam for different initial, physical parameters of the MID (externally applied electric and magnetic fields), of the plasma (density, species, temperature) and geometrical parameters. The interaction of high current ion beam with suitable targets enables producing relative high neutron flux for material tests or other industrial applications (e. g. radionuclides of different species). In the present work numerical investigations using the elaborated version of the 1-D multi-fluid code enables to improve the diode operation by studying the spatio-temporal evolution of the ion specie for different initial parameters of the diode in order to optimize the extracted high current. This parametric study allows to increase both the pulse duration of the ion beam up to 0.5 μs - 1 μs and the final extracted current (protons or deuterons) up to 14 kA. The accelerating voltage could vary from 400 keV to 1.2 MeV. The ion source is originated from plasmas formed by ionizing a gas or clusters (by electric discharge or laser beam) close to the diode electrode and feeds the pulse duration of the MID operation, in order to extract the long pulse high current ion beam (typically protons or deuterons). For the neutron production we use the extracted high current deuteron (d) beam to interact with a Be target [^{9}Be (d, n) ^{10}B] which presents a relatively high yield up to $3\text{x}10^{-5}$ n/d, comparing to other targets and with neutron energy spectrum similar to nuclear reactors. The above parameters of the proposed device enable to produce a relatively high neutron flux up 10^{12}–10^{14} n/cm^2 for an operation of several minutes of at a rep. rate of 20 Hz. Alternatively, the use of the proposed high-current deuteron beam with targets implanted with deuterons or ^{3}H (tritium) increase the spectrum of the produced neutrons to energies with interest to test materials for Tokamak blankets.

Introduction

The main objective of our numerical investigations is to describe the operation of a Magnetically Insulated Diode (MID) capable of producing ion beam (positive or negative) pulses of 1.2 MeV peak energy and 14 kA current with duration up to 1 μs. The coupling of the MID with a pulsed power device (e.g. Marx generator), pulsed at 20 Hz could form a compact and low cost machine, capable to produce neutron fluxes up to 10^{12} -10^{14} n/cm^2 within several minutes of operation. The possibility to use MID configuration for negative or positive ion beams, has especially increased interest for activities on Tokamak machines development, such as the plasma heating by high power neutralized beams and radiation tests for blanket materials by using high flux neutrons. Other important potential uses concern medical applications for radioisotope production for PET diagnostic or BNCT therapeutic technique.

The motivation of the present work is based on both the published relevant experiments on high current pulsed devices in the international literature and our previous investigation on the development of a 1-D multi-fluid code in cylindrical geometry describing the operation of a pulsed high power MID for negative ion (protons or deuterons) beam production [1-3]. Indicatively we mention [5-11] a few important experimental results on (a) high current ion beam production of 270 keV energy with duration as long as 4 μs using graphite electrodes, (b) microsecond ion pulses of energy as high as 150 keV with current density in excess of 100 A/cm^2 and (c) ion beams produced in the repetitive mode with 100 keV energy and pulse of 500 ns with rep. rate of 100 Hz (burst mode). The use of the 1-D multi-fluid code enables to extrapolate these values on ion beam production from a MID up to 1.2 MeV energy and 14 kA total extracted current with a pulse duration of 1 μs. The model equations [4,12] of the code (based on a multi-fluid plasma fusion code [13]) include conservation of particles, momentum and energy of the different species coupled with Maxwell's equations for the space charge separation. The code describes the spatio-temporal evolution of electron, positive and (or) negative ions (protons or deuterons) between the diode electrodes and the extracted ion current for different geometrical (inner and outer radius and length of the cylindrical diode and AK gap) and initial physical parameters (density and temperature of the plasma species, applied electric and magnetic field) of the MID.

Numerical results on μs ion beam pulses and discussion

We run the code using initial parameters of operation as shown in Table 1. The code allows to calculate the temporal evolution of the current and the total number of deuterons (or ions) for 1 μs pulse. By modifying any of these initial parameters one can study the MID operation for different applications. We choose the values of Table 1 because most of the experimental high current pulsed power devices from the international literature operate with parameters very close to these. For the aforementioned cylindrical geometry, the formation time of the electrode (cathode or anode) plasma can be increased using an appropriate grid-electrode placed on the inner cylinder of the diode. A high-density volume plasma is formed behind this grid, which penetrates the grid-electrode from where ions are accelerated in the MID configuration. We therefore simulate the plasma generation and reach of equilibrium to extract longer (μs) ion current pulses. Figure 1 shows the spatio-temporal evolution of the particle density

Anode/Cathode (AK) gap	2 cm
Initial electron/ion density	10^{18} m^{-3}
Plasma temperature	a few eV
Plasma thickness	1 mm
Voltage	1 MV
Magnetic field	1.5 T

Table 1: Initial parameters

as well as the rapid rise and establishment of a constant extraction ion current, depending on the initial parameters. Each line of the chart at fig. 1 corresponds to a different snapshot. The line denoted with the blue star corresponds to the particle density at t=2ns and the others are 2 ns apart. This shows that there is a fast (ns) rise time after which the extracted current remains constant, reaching equilibrium. These results are in good agreement with experimental measurements [14].

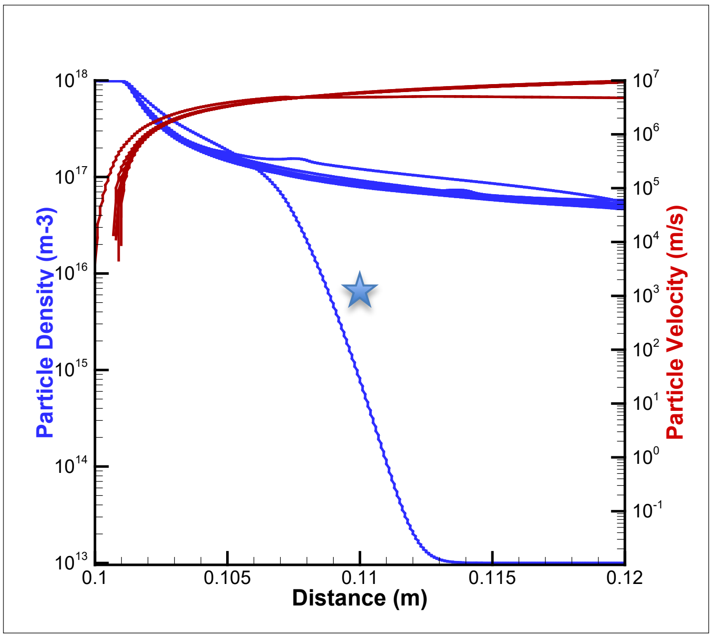

Figure 1: Spatio-temporal evolution of ion density (blue lines) and ion velocity (red lines) in the cylindrical MID AK gap of 2 cm (inner cylinder radius 10 cm and outer cylinder radius 12 cm)

We then perform a study with different values of plasma density, AK gap, accelerating voltage and magnetic field strength to investigate how these parameters affect the extracted current density.

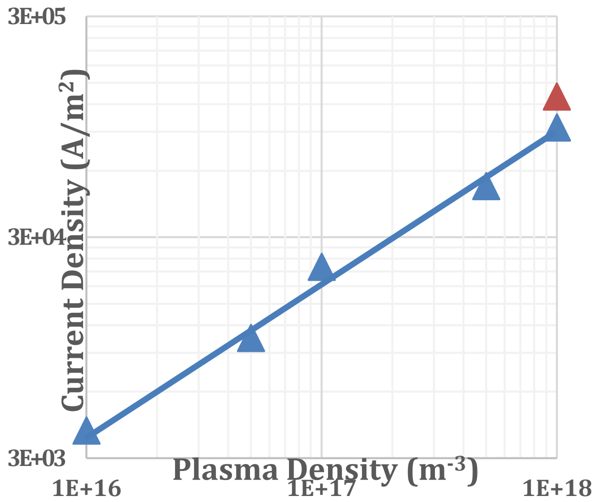

Figure 2: Extracted ion current density versus plasma density.

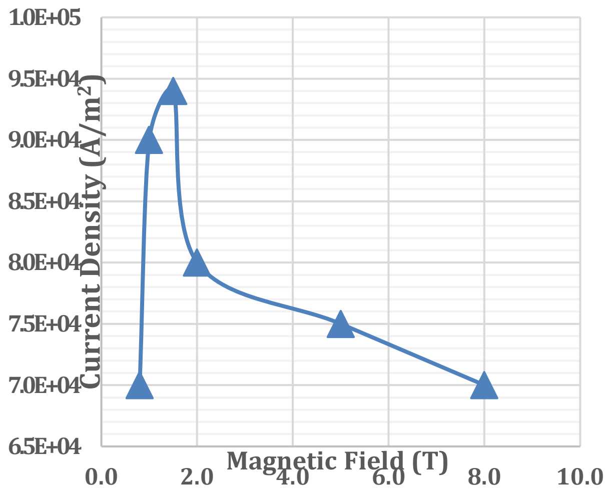

Figure 3: Extracted Ion current density versus Magnetic field

Figures 2 and 3 above show how the current density scales with plasma density and magnetic field at a diode with an AK gap of 2 cm. Evidently, the ion current density scales linearly with the plasma density. We also have data for a smaller AK gap of 1.5 cm (red triangle), showing how a smaller gap increases the current density. Similar ion current density improvement up to 150 kA/m2 may be obtained by modifying two of the main MID parameters, the applied high voltage up to 1.2 MV (instead of 1 MV used with the blue triangles) and the AK gap down to 1.5 cm. Regarding the magnetic field, an optimum range of values for the magnetic field exists, corresponding to 1.5-2 T, for which we achieve the maximum ion current density. This optimum value is due to the formation of a virtual cathode by the electron density distribution which enhances the electric field by effectively modifying the physical distance of the anode-cathode. Too low field will result to inadequate insulation of the diode and subsequent voltage drop, whereas too high field will move the virtual cathode too close to the real electrode.

Conclusion

The obtained results from the use of the 1-D multi-fluid code (~130-150 kA/m^2 ion current density) show that a cylindrical MID is capable to produce 14 kA of ion current with the following parameters: 10 cm radius, 17 cm length (surface ~1000 cm^2), 1 μs pulse duration. This corresponds to a total number of few 10^{17} deuterons. For neutron production we use [15] the extracted high current deuteron (d) beam to interact with a Be target [^{9}Be (d, n) ^{10}B] which presents a relatively high yield up to 3x10^{-5} n/d, comparing to other targets and with neutron energy spectrum similar to nuclear reactors. The above parameters of the proposed device enable to produce a relatively high neutron flux up 10^{12}–10^{14} n/cm^2 for an operation of several minutes at a rep. rate of 20 Hz. Alternatively, the use of the proposed high-current deuteron beam with targets implanted with deuterons or ^{3}H (tritium) increase the spectrum of the produced neutrons to energies with interest to test materials for Tokamak blankets.

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References

1) S. D. Moustaizis, P. Lalousis, K. Perrakis. "On the Production, Acceleration and Photo-Neutralization of High Energy and High Current Negative Ions Beam for Magnetic Fusion Applications.", 39th EPS Conference on Plasma Physics & 16th International Congress on Plasma Physics, Stockholm, Sweden, (2-6 July 2012).
2) S.D. Moustaizis, P.Lalousis, K. Perrakis, J. E. Ducret, J. Larour, and P. Auvray. "Investigations on High Power Neutral Beam Production for Tokamak Applications.", 40th European Physical Society Conference on Plasma Physics, Espoo, Finland, (1—5 July 2013).
3) Moustaizis, S. D., Lalousis, P., Perrakis, K., Auvray, P., Larour, J., Ducret, J. E., & Balcou, P. ICAN: High power neutral beam generation. The European Physical Journal Special Topics, 224(13), 2639-2643 (2015).
4) Lalousis, P., Hora H., First direct electron and ion fluid computation of high electrostatic fields in dense inhomogeneous plasmas withsubsequent nonlinear laser interaction. Laser and Particle Beams, 1(03): p. 22. (1983)
5) C. A. Kapetanakos et. al., Appl. Phys. Letts, 26, 284 (1975)
6) J.B. Greenly, "MID with a Gas-Breakdown Plasma Anode", Cornell Univ Lab of Plasma Studies Rep #315. (1983)
7) J. B. Greenly et al., J. Appl. Physics 63, p. 1972 (1988)
8) M. Ueda et al, "A MID with magnetically controlled gas-breakdown ion source", Laser and Particle Beams , Vol.12 , p. 585 (1994)
9) T. A. Malhom et al., Proc. Of the 9th Int. Conf. on High-Power Particle Beams, Ed. By D. Mosher and G. Cooperstien, p31, Washington USA, May 25-29 (1992).
10) W. A. Noonaqa et al.,"Design and operation of a high pulse rate intense ion beam diode", : Review of Scientific Instruments 66, 3448 (1995)
11) J. B. Greenly et al, "A 1MA, variable rise time pulse generator for high energy density plasma research" Rev. Sci. Instrum. 79, 073501 (2008)
12) P. Lalousis et. al., Plasma Phys. Control. Fusion 50, 085001 (2008)
13) P. Lalousis et. al., Phys. Lett., A377, 885 (2013)
14) P. Auvray, «Hautes tension pulsees commutation haute puissance application aux nouveaux accelerateurs», private communication.
15) Neutron Cross Section, Vol. II, BML-325-ED-3-V-2, Brookhaven National Laboratory, Upton, NY, (1976)