Foil-less plasma-filled diode for HPM generator

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Abstract. Plasma-filled diode regarded as perspective source of electron beam feeding HPM generator of GW power level, comparing to conventional explosive emission vacuum diode. Electron beam generation occurs in plasma double layer, where plasma boundary plays as an anode. It allows cancelling the usage of anode foils or grids in HPM generators with the virtual cathode, which could limit its life time to few shots. The presence of ions in the e-beam drift space could raise the limiting current for a drift space, but it could affect to microwave generation also. Sectioned plasma-filled diode with beam current of about 100 kA, electron beam energy of about 0.5 MV and beam current density of 1-10 kA/cm^2 was realized. Cylindrical transport channel with the diameter of 200 mm and the length of about 30 cm was attached to the diode. Beam current measurements in a drift space were performed. Computer simulations of electron beam transport with the presence of ions were carried out with the 2.5D axisymmetric version of PiC-code KARAT. Obtained results would help optimizing electrodynamic system of HPM generator subjected to the presence of ions.

1. Introduction

An increasing of HPM generators output power requires increasing in the feeding electron beam power and its current density. So, the plasma-filled diode looks as a good candidate to use in the HPM generators. The presence of plasma in the accelerating diode gap removes the charge current limitation. This allows an increasing of an electron beam power by one or two order comparing to the vacuum diode with the same accelerating voltage. Low impedance pulsed power generator, such as linear transformer driver (LTD) [1], could be utilized efficiently to feed these diodes [2]. The usage of a plasma-filled diode gives another benefit which is an absence of anode meshes or foils in HPM generators with the virtual cathode (vircators). These foils limiting the gigawatt level vircators operation time to a few shots [3, 4].

There are few tasks to be investigated and solved then using plasma-filled diode in HPM generators. The main one is beam transport conditions and formation of virtual cathode (VC) in presence of ions, as the electron beam tends to contract by self-magnetic fields. Plasma-filled diode with voltage of about 0.5 MV, beam current of about 100 kV and its density of 1-10 kA/cm^2 was realized for further microwave applications. It was attached directly to cylindrical drift channel with no anode mesh in between. Current evolution in drift space was measured in experiment. Numerical modelling of electron beam transportation with the presence of ions by the 2.5D symmetric version of Particle-in-Cell (PiC) code KARAT [5] shown good agreement with experimental results giving a base for further development and optimization of electrodynamic system of HPM generator.

2. Experiment

Plasma-filled diode was fed by LTD with six sections connected in series. Equivalent capacitance was 53 nF, inductance was 260 nH, stored energy was 7.8 kJ with sections charging voltage of 90 kV. Experiment setup arrangement represented on Figure 1. Diode was split to six separate sections to decrease beam current self focusing, as magnetic field of section defined by its current instead of full diode current. The diameter of anode hollow (1) for each section was 38 mm. Every section has the cylindrical cathode (2) of 12 mm diameter made of stainless steel. Cathodes were placed on diameter of 80 mm. Drift channel (3) with diameter of 200 mm and length of 290 mm was attached to the sectioned diode.
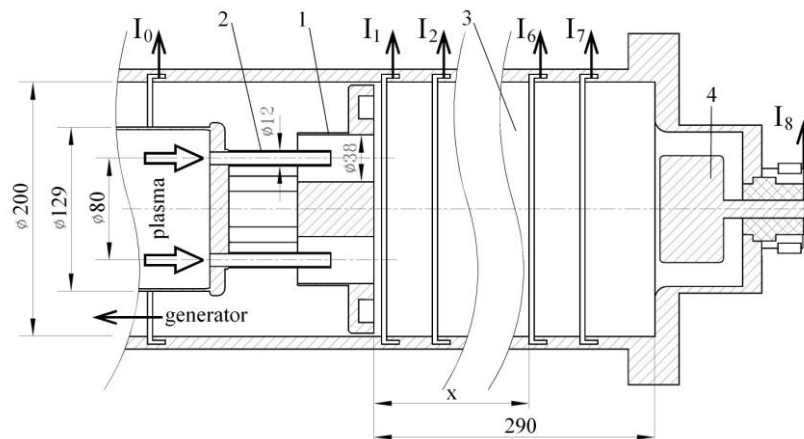

Figure 1. Experimental arrangement: 1 – anode, 2 – cathode, 3 – drift channel, 4 – electron beam collector

Six capillary plasma guns used for plasma generation in diode. Dielectric material of plasma guns was polyethylene. The diameter of capillar was 1.3 mm and its length was 15 mm. Guns were placed into the cathodes (2) and injected plasma towards to the drift channel (3). Guns were fed by separated pulse generator with capacitance of 40 nF and charging voltage of 80 kV. The current for a single gun was of 1.5 kA, first half-wave duration was of 800 ns. LTD pulse to the diode was delayed for time t_d from plasma gun generator to change plasma density in the diode.

The full diode current I_0 was measured by the inductive sensor. The output LTD voltage was measured by the active resistive voltage divider. Diode voltage was calculated taking into account inductive voltage drop on the section between the LTD output voltage sensor and the cathode. Beam currents I_1-I_8 in the drift channel (3) at different distances x from the anode (1) were measured by inductive sensors spaced by the 40 mm step. Collector with diameter of 84 mm was loaded by resistive shunt for collector current measurements.

The time delay t_d between the main LTD pulse and the pulse of the plasma generator defines the plasma-filled diode operation and conditions of beam transportation in the drift channel (3). Figure 2 represents waveforms of diode current and voltage as well as beam current in the drift channel at different lengths x from the anode for t_d=0.7 and 1.0 μs. High voltage stage of electron beam generation in the diode foreran by low impedance stage with impedance much lower than the LTD's one, then the voltage at the diode gap is small and the current close to the short circuit one. At the low impedance stage all current goes through the anode (1) with no current through the drift channel (3). After that diode impedance increases forming the voltage pulse of 450 kV and electron beam is generated with a current going through the drift channel.
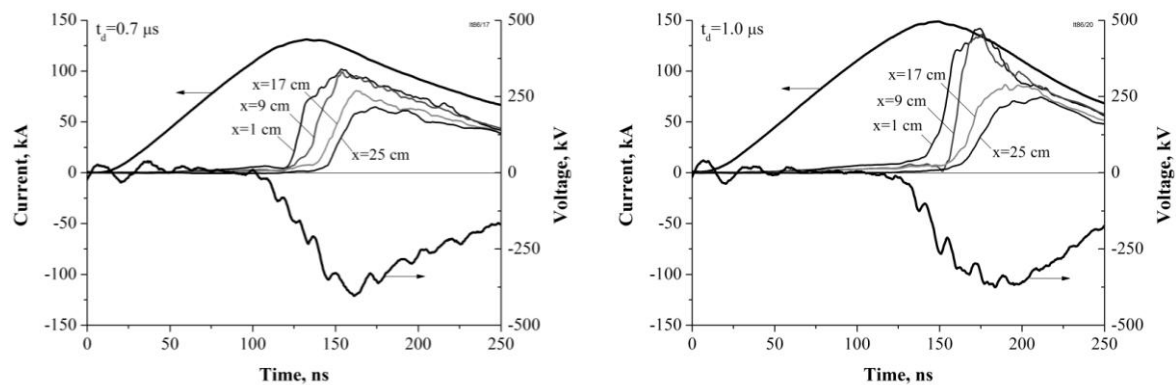
Figure 2. Plasma-filled diode voltage and current waveforms for t_d=0.7 and 1.0 μs. Beam currents in the drift channel at distances x=1,9,17,25 cm from the anode

For t_d=0.7 μs current at low impedance stage was of 130 kA. Electron beam current with amplitude of 100 kA and rise front duration of about 20 ns went to x=9 cm without losses. Near the right end of the drift channel beam current amplitude dropped almost twice. With increasing t_d to 1 μs current at low impedance stage was increased to 150 kA. Beam current at distance x=9 cm increased to about 130 kA with the same loss rate for a bigger distances.

3. Numerical modelling

Numerical experiment by PiC method recognised as powerful tool in research of plasma and dense particle beams. Modelling of drift channel was carried out by symmetric 2.5D version of code KARAT. The goal of this modelling was to obtain qualitative demonstration of processes in the drift channel of experimental setup.

The electron beam was injected through the left wall with the shape similar to the experimental one (Fig.3). Plasma was modelled by the PIC plasma consisting of electron and proton macroparticles. The electron beam particles were injected with the energy corresponded to the experimental voltage pulse. The current of injected beam were equal to the total LTD current. The PIC plasma particles were injected with the energy of 3 eV. The pre-ionized area was used to simulate a delay between the plasma generator pulse and the main LTD pulse.
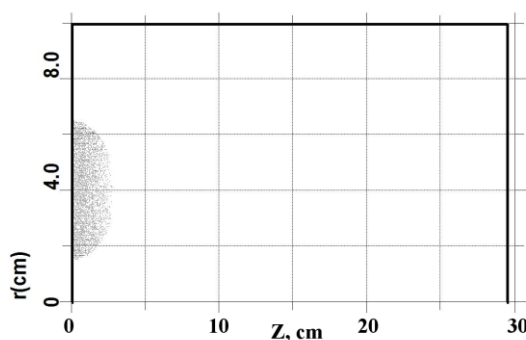

Figure 3. Layout for numerical modelling by 2.5D PiC code KARAT using electron beam and PIC electron-proton plasma injection

The transported current for this geometry without PIC plasma was limited to about 15 kA. We were rising the PIC plasma density from one numerical experiment to another. The transporting beam current with the amplitudes similar to the experimental one were obtained at PIC plasma density of

5×10^{13} cm^{-3}. The waveforms of passed current at different crossections of the drift channel are shown at Figure 4.

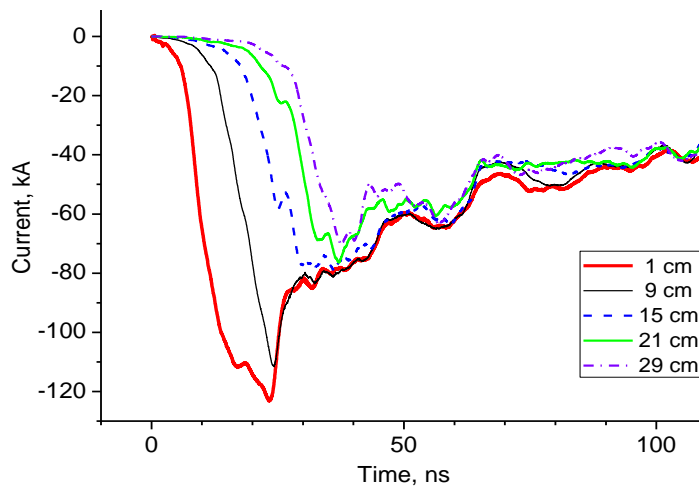**Figure 4.** Result of numerical modelling by 2.5D PiC code KARAT
with PIC electron-proton plasma (n=5×10^{13} cm^{-3}). Transporting current
at different distances

The electron transportation channel was formed in the drift space of 30 cm length in less than 40 ns, as the low-energetic protons were accelerated by the virtual cathode formed by the electron beam close to the injection area. Figure 5 demonstrates distributions of electrons and protons in real and phase spaces at 50 ns from the beginning of voltage pulse, describing the "stable" stage.
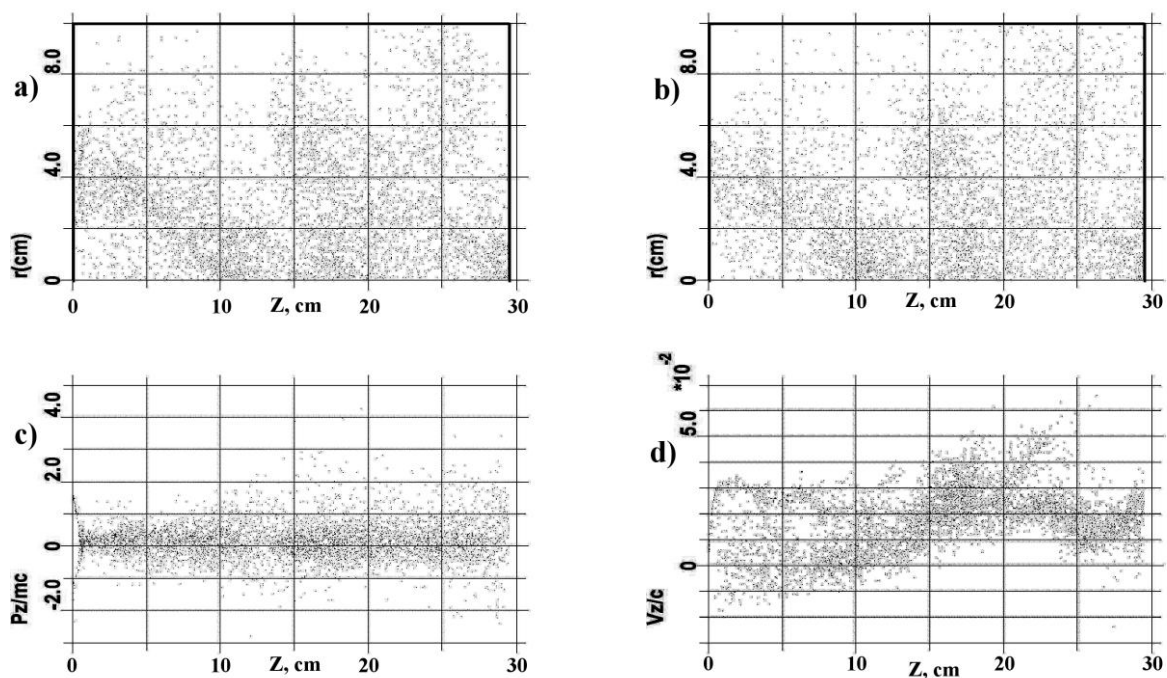

Figure 5. The distributions of electrons (on the left – **a** and **c**) and protons (on the right – **b** and **d**) in real (top) and phase (bottom) spaces at 50 ns from the beginning of voltage pulse

The electrons and protons has similar space distribution (the upper images in Figure 5). The electron and proton beams that are hollow initially pinching at the 10 cm distance. Then they are spreading but the most part of particles reaching the collector is within the radius of 40 mm. Distributions of longitudinal momentum of electrons and velocity of protons are represented in the lower images of Figure 5. The electron beam injected in the drift channel forms the virtual cathode just near the injection area and there is the two counter stream state of electron beam behind the VC. The longitudinal component of the velocity of electrons is well below the one corresponding to the starting energy. The protons injected with low energy are efficiently accelerated by the VC to the energies similar to the starting energy of the electrons. The proton beam surprisingly forms virtual anode about the centre of the drift channel with two counter streams before it and the downstream behind. There are some protons in the downstream beam with the energies above the starting energy of electrons.

4. Conclusion

Sectioned plasma-filled diode with beam current of about 100 kA, electron beam energy of about 0.5 MV and beam current density of 1-10 kA/cm^2 was realized within this work. This diode is proposed to feed a HPM generator with the virtual cathode, allowing to obsolete foils in its design.

The results of the numerical modelling of electron beam transportation with the presence of ions by the 2.5D symmetric version of PiC code KARAT are in good agreement with experiment, giving us powerful tool for further design and optimization of a vircator. It demonstrated the complicated dynamic of partially compensated beam. The presence of virtual cathode allows the protons to fill in the drift channel in a short time.

A possible electromagnetic structure of vircator with the plasma-filled diode should not use long transportation channel as it might be a reason of great losses of microwave energy. A possible changes in the electromagnetic structure due to the presence of dense plasma should be also taken into account.

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