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GENERATION OF PARTICLE BEAMS IN A 340 kJ PLASMA FOCUS WITH GAS INJECTION BY A FAST VALVE

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Abstract

A fast valve injects gas transiently near the insulator in order to optimize pressures separately for breakdown and beam generation. On a different machine without gas injection the interaction of the ion beam with targets of variable thicknesses can be used to diagnose the beam.

1. INTRODUCTION

It has been reported previously /1/ that beams of electrons and ions in the megaampere range are generated in a plasma focus electrical discharge powered by a 340 kJ capacitor bank. The compression of the plasma sheath, in which microinstabilities lead to an anomalously high resistance, is followed by the beam phase with the simultaneous emission of electrons towards the anode and ions in the opposite direction. It has been observed experimentally that to increase the plasma resistance (to values close to one ohm) and consequently the power of the beams the hydrogen or deuterium pressure in the chamber must be 1 Torr or below. Compression of the sheath and beam generation occur at the anode end. On the contrary initial breakdown takes place near the insulator at the breech end of the gun and other experiments have clearly indicated that too low fill pressures prevent the formation of a uniform sheath. With the same pressure in the whole chamber a compromise has to be found between the requirements of both phases of the discharge. Such a compromise has been more and more difficult to reach in machines with banks of energy above 100 kJ.

In order to optimize separately breakdown and beam generation it has been designed and built a fast annular valve which ejects gas puffs through 48 holes (as many holes as bars of the squirrel cage constituting the cathode) near the insulator. At valve opening one obtains transiently extra pressure in the breakdown zone depending on pressure in the valve volume (0.5 to 3 bars), injectors size and delay between valve opening and bank firing. Before valve opening the whole chamber is filled statically at pressures (0.1 - 1 Torr) most favorable for beam generation. The plasma discharge then takes place in a non-uniform but practically static gas due to its short duration (3 - 4 μs).

2. EXPERIMENTAL ARRANGEMENT

The Mather-type plasma focus gun is shown in Fig. 1 with main dimensions. The capacitor bank delivers 340 kJ at 40 kV. The electrodes are in copper and the 150 mm long insulator in pyrex.

In its principle /2/ the valve is given a high initial velocity by the shock of a soft iron hammer attracted inside a 1.4 mH magnetic coil. The coil is powered by a 333 µF at voltage between 1 and 5 kV. The delay between the start of the coil current and the valve opening is 5 ms at 3.5 kV with jitter less than 50 µs. Pressure risetime measured with a piezoelectric gauge is less than 100 µs close to insulator.

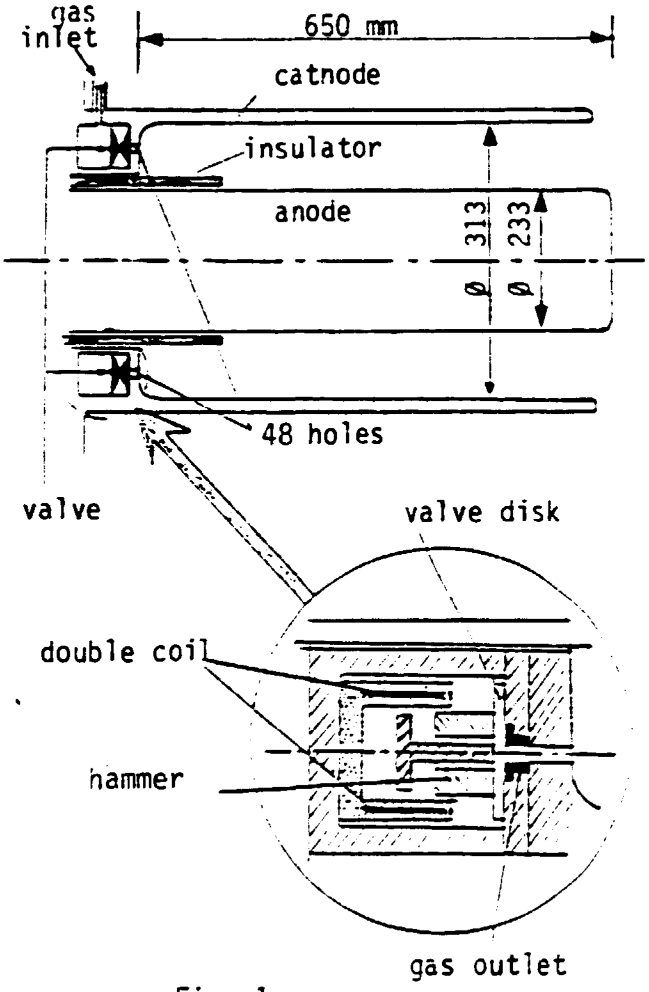

Fig. 1

On the same chamber we have used a mechanical device with a "lock-chamber" which allows to change the anode end at will without breaking the vacuum. A similar arrangement allows to place targets easily in front of the anode (Fig. 2). It is also possible to use such a target as a close cathode instead of a virtual cathode inside the plasma. With these two automated devices one can readily modify parameters of the discharge – anode end, cathode end, or target – and make no alteration in the vacuum. Conditioning discharges are no longer necessary, and the experimental study of the best geometry for efficient beam generation can be done.

3. OPERATION WITH THE FAST VALVE

The valve has been used mainly in the low pressure régimes to study the particle beams.

Approximately 100 low pressure discharges have been done with CD_2 or FLi solid targets and in most (80 %) the interaction of the ion beam with the target is clearly visible and the neutron yield is large. With the same machine but without gas injection by the fast valve the discharges used to be very erratic. An example of a series of successive discharges is shown

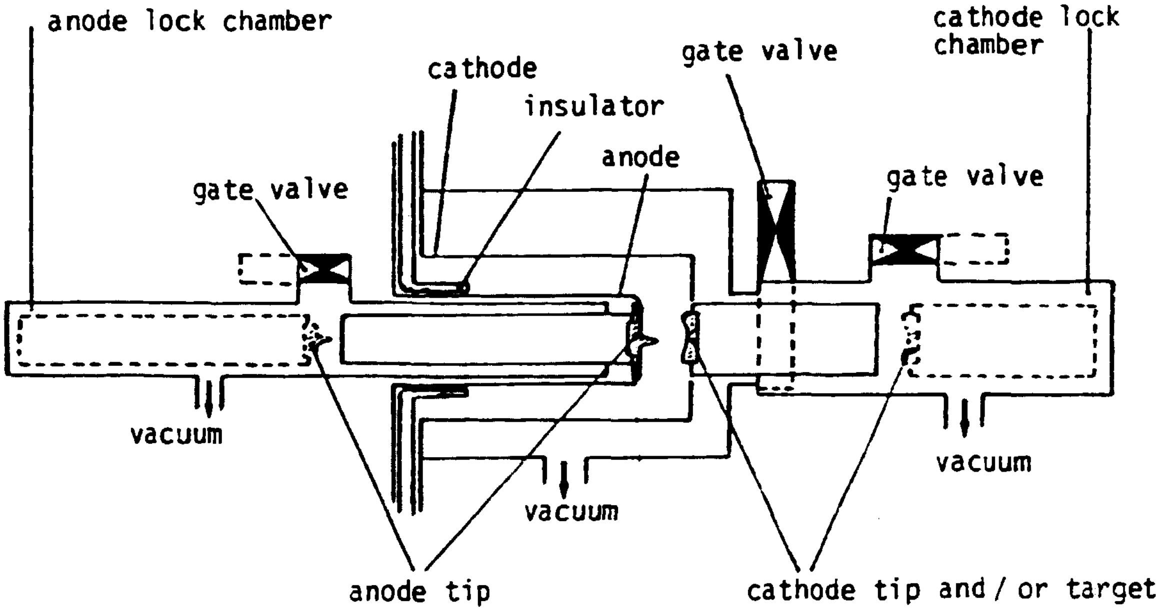

Fig. 2

in Fig. 3 at 1 Torr deuterium initial pressure and with a solid target placed 25 mm off the anode : the recorded signals are X-rays and neutrons measured 6.5 m from the source. The oscillograms show that the X-rays are followed after time of flight by 13.2 and 10.8 MeV neutrons of the ^{7}Li (d,n) ^{8}Be reaction, then by 2.45 MeV neutrons of the d,D reaction in gas.

The fast valve makes possible to operate the discharge properly down to very low initial pressures, such as 0.15 Torr deuterium : overvoltages and X-rays are very large and the neutron yield is relatively weak (10^{10} neutrons) when no solid target is used. With a target overvoltages and X-rays are the same but the neutron yield is increased by a large factor (5 to 15 according to target size).

The X-ray emission is also analysed by a scintillator (NE 111) coupled to a photodiode placed 60 cm from the source ; photocurrents of 5 Amps with risetime less than 1.5 ns are recorded. An example is shown in Fig. 4 with the anode voltage measured near the insulator by a resistive divider. From previous X-ray spectrum determination it is concluded that 300 Joules of X-rays above 10 keV are radiated in all directions.

The electrical singularity in the voltage waveform (Fig. 4 a) occurs 3.2 µs after initial breakdown which correspond to a mean velocity of the current sheath larger than 2×10^7 cm s^{-1} compared to 1.2×10^7 cm s^{-1} at 1 Torr.

Operation at 0.15 Torr is very recent and requires further study. Still the following values can be given :

a) the neutron yield of the deuterium plasma or gas (no solid target) is close to 10^{10} (measured at 45° from axis).

b) the neutron yield increases strongly when a solid CD_2 target is placed 25 mm off the anode tip. The neutron yield emitted from the target reaches 8×10^{10} for a 10 mm diam. target and 1.5×10^{11} for a 40 mm diam. target.

c) when the target is made from FLi fewer neutrons are emitted with a maximum of 2×10^{10} for a 20 mm diam. target.

d) from the curves versus energy of nuclear cross sections and relative stopping power of lithium and deuterium it is concluded that the mean energy of the deuteron beam is less than 500 keV ; otherwise FLi targets would emit more neutrons that CD_2 targets.

e) assuming a mean deuteron energy of 500 keV one calculates from interaction with CD_2 lower estimates for the deuteron beam : the energy is 5.6 kJ ; the duration is 50 ns corresponding to 220 kA and 0.1 TW ; the current density accounting for 8.10^{10} neutrons from a 10 mm diam. target is 150 $kA.cm^{-2}$.

In fact it is clearly an oversimplification to assume the beam monoenergetic as will be shown in next section.

4. METAL FOIL HEATING BY DEUTERON BEAMS

On a smaller machine working at 200 kJ in the conventional mode without gas injection the first experiments of heating thin metallic targets by the plasma focus ion beam have been started /3/. Aluminium targets are placed 30 mm from the anode at 45° angle with the beam axis (Fig. 5). Radiation from the forward side (the one hit by the beam) and the backward side are measured by two X-ray

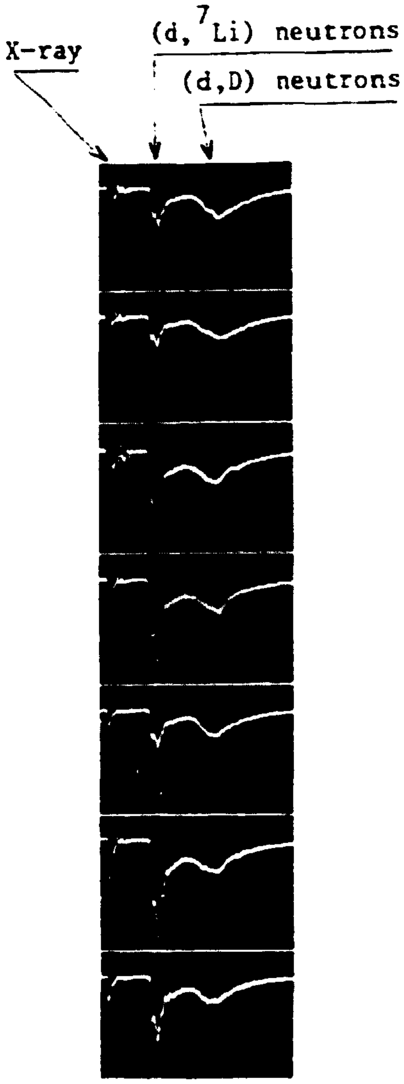

Fig. 3

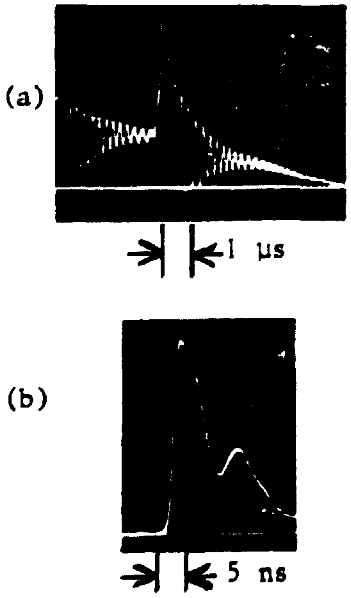

Fig.4 Typical waveforms of (a) the voltage and (b) the hard X-ray emission

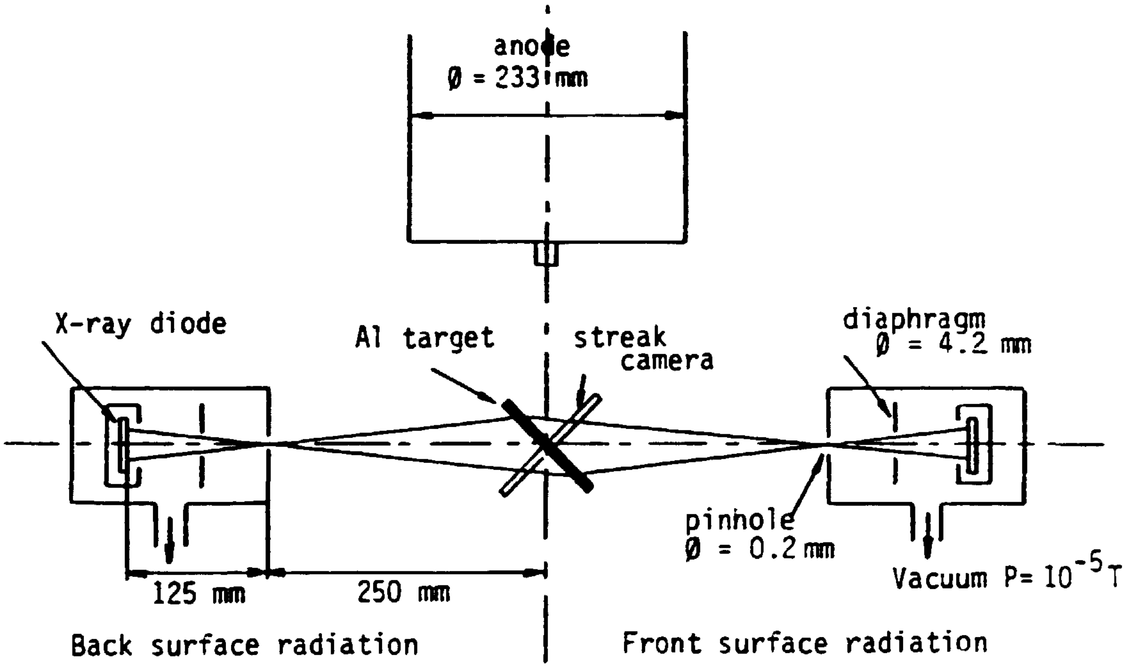

Fig. 5

diodes under vacuum (better than 10^{-5} Torr) located behind a 200 μ diam. pinhole. The target area hit by the beam is determined by a Kα pinhole camera which looks at the 1.5 keV Kα line of aluminium /4-5/. The expansion velocity of the plasma luminous front is recorded by a streak camera (Fig.5) the slit of which is perpendicular to the target plane. Fig. 6 shows the picture from the Kα camera when the discharge is operated at 4 Torr fill pressure. There is uniform interaction in a 10 mm diam. area. At 1 Torr the area is similar ($\lesssim$ 10 mm) but there is less uniformity. Fig. 7 shows the streak camera picture and X-ray signals from both sides for a 9 μ thick aluminium target.

Assuming blackbody radiation and knowing the surface hit by the ion beam it is possible to calculate the target temperature /6/. Without target the diode voltage is less than 100 mV which allows to determine temperature larger than 8 eV.

At 1 Torr fill pressure, for which beam power is larger, aluminium thicknesses between 0.75 and 12 μm have been used. The main results are as follows :

- forward side temperature is between 10 and 15 eV (average is 12 eV for 20 discharges)
- backward side temperature is not different from the latter for thicknesses between 0.75 and 1.4 μm ; it is smaller than 10 eV for thicknesses between 3 and 9 μm and smaller than 8 eV beyond.
- there is correlation between front velocities of the forward and backward

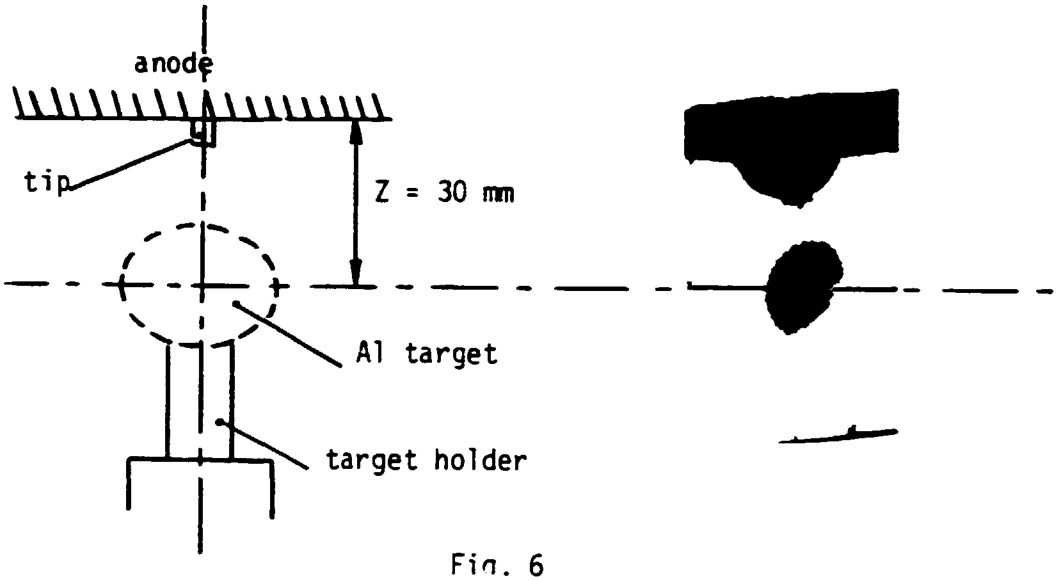

Fig. 6

sides and their respective temperatures. The velocity is 6×10^{6} cm.s^{-1} for T = 12 eV, while it is 2×10^{6} cm.s^{-1} for T = 10 eV.

All these measurements are consistent with an essentially two component ion beam : the first has a deposition range of about 1 μm which corresponds to 80 keV mean deuteron energy, the second has a deposition range of about 9 μm which corresponds to 1 MeV mean energy.

The total energies of the beam actually deposited in the target have been calculated by comparing experimental data with results from a numerical code /7/. The code determines the temperature reached by a foil heated uniformly in volume and time, accounting for hydrodynamics and radiation. It is seen in Fig. 7 that the X-ray diode signal risetime is generally between 15 and 30 ns and that it is almost simultaneous with the hard X-ray signal emitted when the electron beam strikes the anode. The X-ray duration is considered equal to the deposition time. The code is then used to determine the energy deposition that accounts for the measured temperature. The 80 keV ion beam thus deposits 2.6 MJ.g^{-1} corresponding to an incident beam of 700 Joules.cm^{-2} on approximately 1 cm^{2}. The 1 MeV ion beam deposits 0.4 MJ.g^{-1} with beam energy density 1 kJ.cm^{-2} on the same surface.

Supporting the relevance of the calculation to describe the ion-target interaction one notes that expansion velocities measured with the streak camera are in good agreement with those computed from the code.

5. CONCLUSION

Operation with a fast valve injecting extra pressure near the insulator has proved successful even in the low pressure régimes in which the discharge behaviour used to be erratic. Certainly this added degree of freedom in the system would be welcome to operate the machines with large banks, at

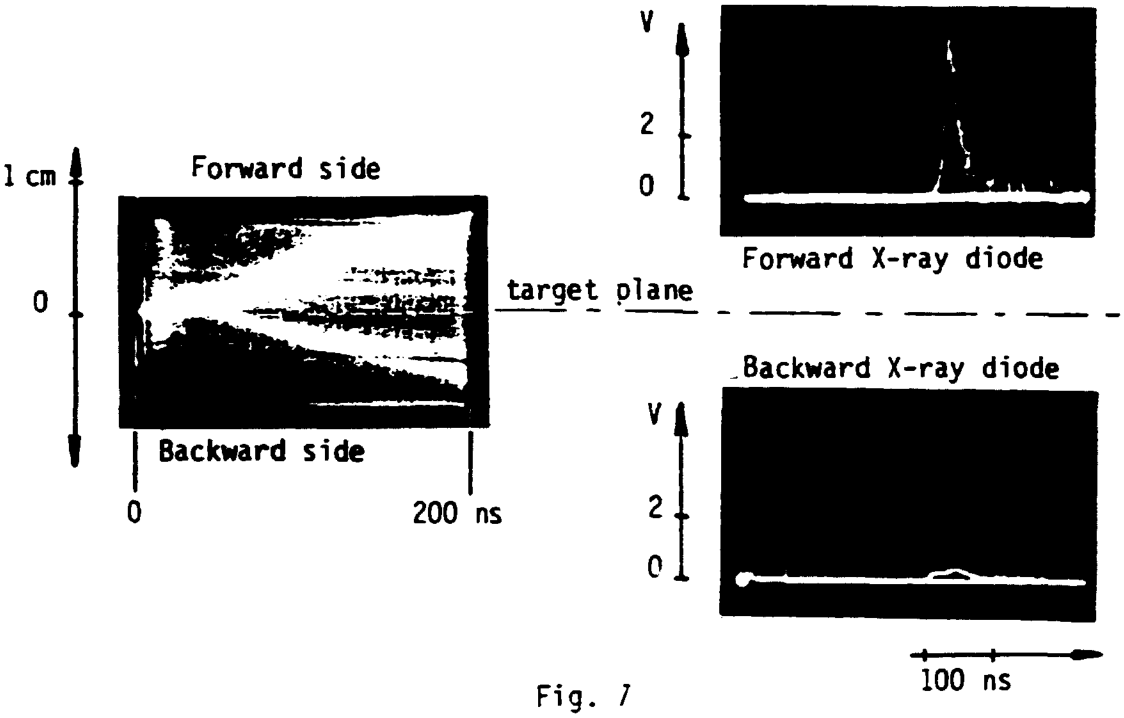

Fig. 7

Frascati for instance, in which full energy cannot be delivered to the plasma. It makes now quite possible to couple multimegajoule banks to plasma focus machines.

With the 340 kJ bank in Limeil the machine has worked correctly at the very low pressure of 0.15 Torr deuterium. At this régime further optimization is possible. One notices in particular that the plasma sheath reaches the anode end before the current is maximum. Also further optimization of the anode and cathode tips (the diode geometry) could now be done with the two mechanical arrangements that allow easy changes without reconditioning of the machine.

Work done with thin metallic targets shows that even the lower energy ion component is a beam directed away from the anode. Estimates of both ion components have been deduced by fitting measurements of the foil temperatures with calculations which take into account hydrodynamics and radiation.

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