Experimental Studies in a Gas Embedded Z-pinch Operating at Mega Amperes Currents

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Abstract. A gas embedded Z-pinch has been implemented using the SPEED2 generator (4.1 μF equivalent Marx generator capacity, 300 kV, 4 MA in short circuit, 187 kJ, 400 ns rise time, dI/dt~10^{13} A/s). Initial conditions to produce a gas embedded Z-pinch suitable of be driven by the SPEED2 and with enhanced stability by means of resistive effects and by finite Larmor radius effects were obtained using a 0-D model. Thus, electrodes were constructed in order to obtain a double column Z-pinch and a hollow discharge. Experiments were carried out in deuterium at mega amperes currents. The diagnostics used are: current derivative and voltage signals, neutron detections using silver activation counters, and ^{3}He detectors; scintillators with photomultiplier; and interferograms using a pulse Nd-YAG laser (8ns FWMH at 532nm). Optical diagnostics show an apparently stable plasma column and a density of 10^{24}m^{-3} was obtained on the axis at 300ns since the initiation of the discharge. Neutrons have been detected in the ^{3}He detectors.

1. Introduction

The foundational aim of Z-pinch discharges were the thermonuclear fusion. Several configurations that produce Z-pinch have been studied in the last five decades. Instabilities disrupt the plasma column limiting the heating of the plasma. However, recently in Z-Machine in Sandia National Laboratory, USA, ion temperatures of the order of 200keV have been measured in a wire array Z-pinch [1].

Gas-embedded Z-pinches are produced by discharges in dense gases at near atmospheric pressure, and it correspond to a kind of quasi-static Z-pinch. Due the fact that in gas embedded Z-pinches intense X- rays or particles beam (neutrons, ions and electrons) have not been measured, practically the gas embedded Z-pinch is not being studied by the Z-pinch community. However, a gas embedded Z-pinch is a useful object for experimental studies of dynamics and stability in pinches. Changing the filling pressure and electrodes configuration, different initial conditions and different stability regimes can be studied.

Experiments in gas-embedded Z-pinches were carried out in Chile some years ago [2-4, 9], driven by a small pulse power generator, a Marx bank (400 kV) coupled to a water transmission line (1.5 Ω, 300kV, 120ns double transit time). The current rate was approximately $2 \cdot 10^{12}$ A/s and the peak current achieved was 150-180kA. The discharges were performed in H_2 and He at 1/3 atmospheres and several preionization schemes were studied [4]. In particular the most interesting results were obtained in a double column pinch. This configuration use a pre-ionization scheme based on a combination of an annular micro-discharge followed by a laser pulse. This scheme produces a double column at the early stage that coalesces into a single plasma column at 60ns, showing again a period of enhanced stability with no MHD instabilities developing during the current rising (150ns) and achives 180kA. The aim of this research is study a double column pinch in deuterium at current of thermonuclear fusion interest, i. e. greater than 1MA. The SPEED2 generator will be used with this purpose.

2. SPEED2 generator

SPEED2 is a generator based on Marx technology and was designed in the University of Düsseldorf [5]. The special design produces a device with an impedance of the order of the pinch impedance (~100 mΩ) for plasma focus discharges. Thus it is more efficient in the transference of energy to the plasma. The SPEED2 consists on 40 +/- Marx modules connected in parallel. Each module has 6 capacitors (50kV, 0.625 μF, 20nH) and 3 spark gaps, so the pulse power generator SPEED2 is a medium energy and large current device (SPEED2: 4.1 μF equivalent Marx generator capacity, 300 kV, 4 MA in short circuit, 187 kJ, 400 ns rise time, dI/dt~10^{13} A/s) [5]. The SPEED2 is currently in Chile at the CCHEN. It arrived in May 2001 from Düsseldorf University, Germany, and it is in operation since January 2002, becoming the most powerful and highest energy device for dense transient plasma in the Southern Hemisphere. The impedance of the device does not allow drive a narrow pinch, like a fiber pinch or a conventional gas embedded z-pinch. Therefore a study using a 0-D model was applied to find the initial conditions to produce gas embedded z-pinch suitable to be driven by SPEED2 generator.

3. Requirements to protect the generator

For the plasma driven stage the SPEED2 was simulated by means of a RLC circuit (with C=4.1μF, L=20nH, R~0). For a charging voltage of the marx of +/-V_1, an equivalent charging voltage $V_0=6V_1$ is used to charge the equivalent capacitor of C=4.1μF. The equations of electrical circuit are solved numerically coupled to the 0-D model used in reference [6]. In order to protect the generator the experiments must be restricted to the results that produce initial peak voltage on the plasma less or equal than $V_0=6V_1$.

4. Stability requirements

Additional requirements are used to select the initial conditions for experiments, i. e. conditions to produce a Z-pinch with enhanced stability. It has been theoretically conjectured that there is a threshold for the stabilization due to resistive effects, corresponding to Lundquist number S~100 ($S=3.87\times10^{23}I^4aN^{-2}$, for a pinch in deuterium) [17]. Experimentally, it has been observed that for Z-pinch discharges with a substantially lower value of S, no instabilities appear. From the values of S, obtained at early stage in discharges studied experimentally [2-4], it is apparent that they are resistive at early stages [3]. In addition for the particular case of a double column pinch, which present enhanced stability, the value observed for the ratio between Larmor radius a_i, over pinch radius a, was a_i/a~0.1 to 0.2 ($a_i/a = 8.08\times10^8 N^{-1/2}$ for a pinch in deuterium [2-4]). This is consistent with theoretical studies which indicate that the region of minimum instability for pinch discharges is in the neighbourhood of a_i/a~0.2 [7, 8].

Based on experimental observations in a double column pinch, it would appear that the pinch could be maintained stable if it crosses over the S~100 boundary with a value of a_i/a around 0.1-0.2, i.e. for values of the line density N of the order of $6.5\times10^{19}m^{-1}$ - $1.6\times10^{19}m^{-1}$.

5. Experiments and diagnostics

A set of results obtained with the 0-D model, that fit with the conditions explained above shown the following range for the initial conditions: V_0=180kV (V_1=30kV), a_0=2-5mm, p=33mbar of deuterium, and h=10-20mm.

The electrodes from the plasma focus configuration were modified in order to produce a double column linear Z-pinch when is assisted by a pulsed laser. Figure 1 shows the electrodes configuration to produce a double column pinch. The laser produce a secondary mechanism of ionization in order to produce a double column pinch. Without laser a hollow Z-pinch is expected.

The diagnostics used are: current derivative and voltage signals, neutron detections using silver activation counters, and ^{3}He detectors; scintillators with photomultiplier; and interferograms using a pulse Nd-YAG laser (8ns FWMH at 532nm). Figure 2 shows the layout of experiments and diagnostics.

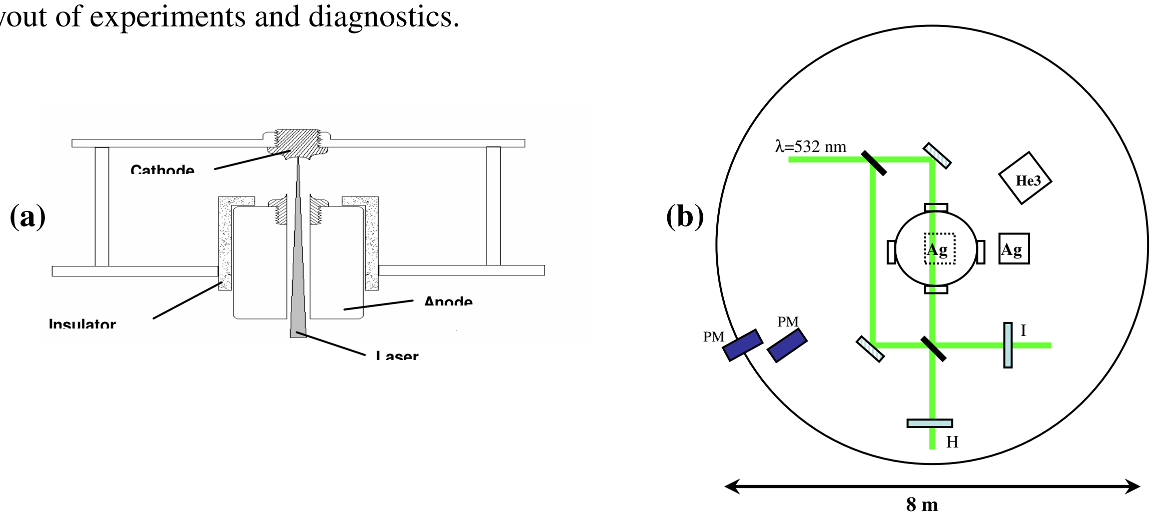

FIG. 1. a) Electrodes configuration. b) Layout of the experiment and diagnostics. Discharge chamber at center. Ag: 2 silver activation counter (axial and radial); PM: 2 radial scintillator-photomultiplier; I and H, interferogram and hologram obtained from a Mach-Zehnder interferometry.

6. Results

Discharges through the conical electrodes described in FIG. 1 were performed with a pulsed laser focused onto the cathode and without laser. In both cases no damages in the SPEED2 generator were observed. Preliminary diagnostics of discharges without the laser pulse for secondary preionization were performed. FIG. 2 shows the voltage, discharge current and the current derivative signals corresponding to a discharge performed in D_2 filling gas, at 33 mbar, with 36 storage Marx modules charged at 30 kV each one, using the electrode geometry combined without the laser (secondary) ionization mechanism. The distance between electrodes was 20 mm. FIG. 3 shows a sequence of 2 interferograms for such kind of discharges. A hollow Z-pinch discharge is produced. The last interferogram is 95 ns before the peak current.

The interferograms of the FIG. 3 show an hollow Z-pinch discharge at early times that produce ionization to the axis of the column while the current is increasing. FIG. 4 shows density profiles obtained from the interferograms. From the interferogram at 230 ns the number of electron per unit length N_e, is measured in $N_e \sim 2x10^{19} m^{-1}$ and for 305 ns is measured in $N_e \sim 4x10^{19} m^{-1}$. At 305 ns, the mean value for the electron density n_e, is $n_e \sim 4x10^{23}$ m^{-3} between the electrodes, and at 4mm from the cathode the maximum density on the pinch axis is of the order of $n_e \sim 1x10^{24}$ m^{-3}. The density in the singularity at 1-2mm from the cathode can be estimated of the order $n_e \sim 4x10^{24}$ m^{-3}. The density corresponding to the filling pressure (33mbar), is $n_0 = 1.7x10^{24}$ m^{-3}. Thus, from these roughly estimations it is possible suggest that the plasma have been compressed near the cathode.

For these experiments the scintillators with photomultiplier and the silver activation counters did not detect signals, however the ^{3}He detector recorded signals in several discharges that correspond to a pulse of a $5x10^5$ neutrons per shot.

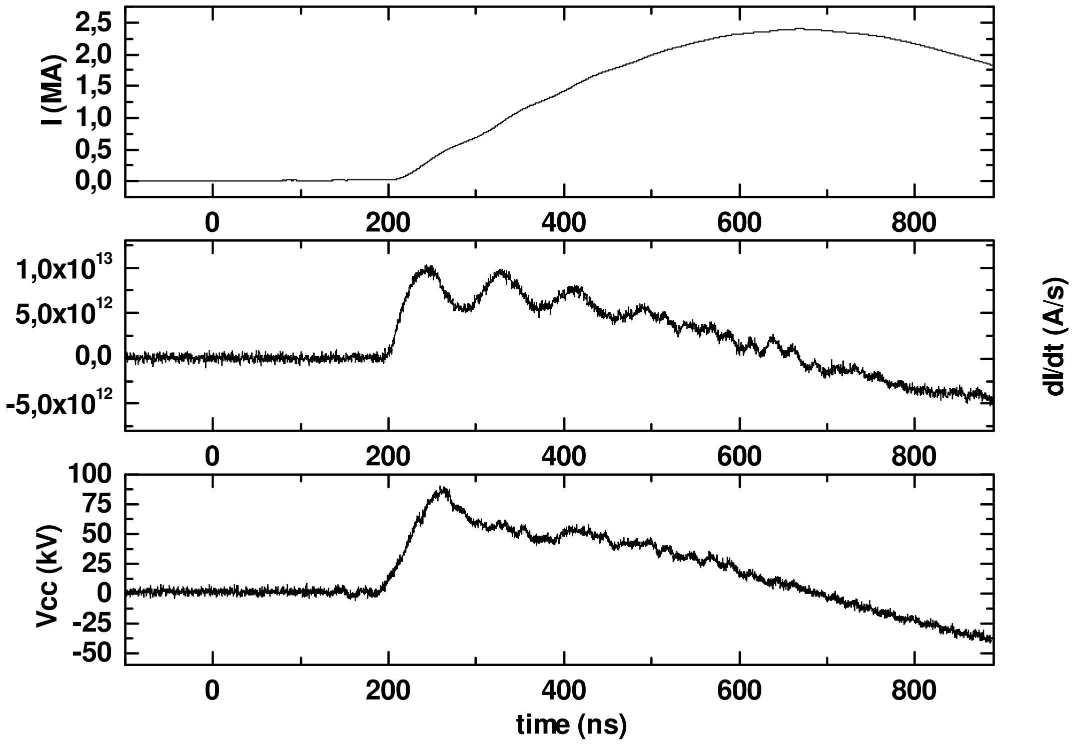

FIG. 2. Electrical signals for a discharge performed in D_2 filling gas, at 33 mbar, with 36 storage Marx modules charged at 30 kV each one, and using the electrode geometry combined with the laser (secondary) ionization mechanism.

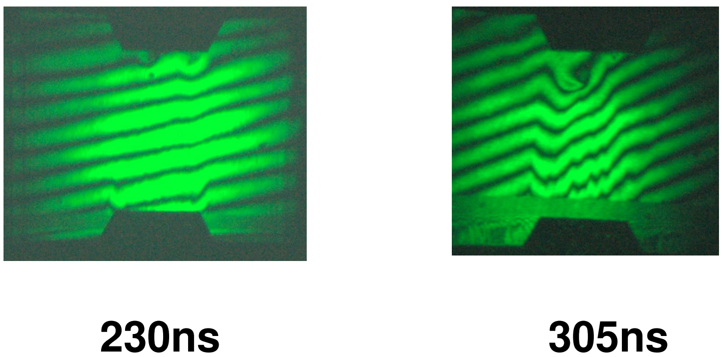

FIG. 3. Interferograms for discharges performed in D_2 filling gas, at 33 mbar, with 36 storage Marx modules charged at 30 kV each one, and using the electrode geometry without the laser (secondary) ionization mechanism. A hollow Z-pinch discharge is produed. The distance between electrodes is 20 mm. The time is measured since the initiation of the discharge.

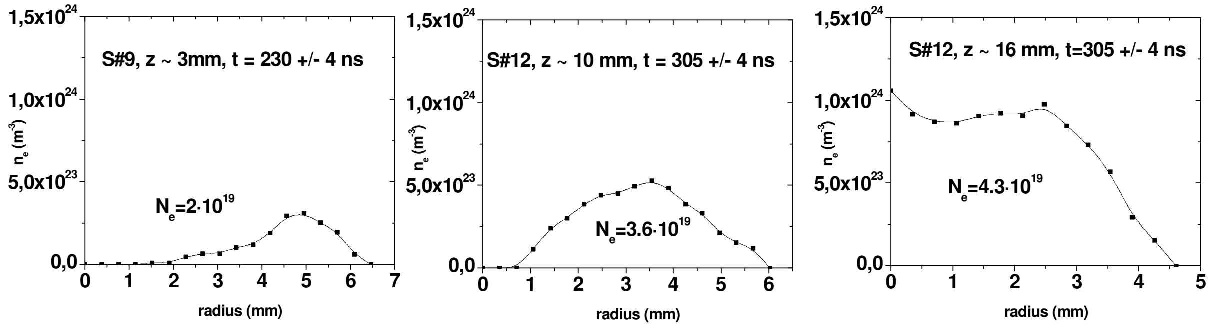

FIG. 4. Density profiles obtained from the interferograms of FIG. 3, z indicates the distance from the anode. The density profile has a hollow structure at 230 ns. At 305 ns the structure is hollowed at 10 mm from the anode but is peaked on the axis near the cathode.

7. Discussion and conclusions

In summary, initial conditions to produce a gas embedded Z-pinch suitable of be driven by the SPEED2 and with enhanced stability by means of resistive effects and by finite Larmor radius effects were obtained using a 0-D model. Thus, electrodes were constructed in order to obtain a double column Z-pinch and an hollow discharge. Thus, experiments in a gas embedded Z-pinch using D_2 as filling gas at 33mbar were performed using the SPEED2 generator. Preliminary results using a hollow discharge at early times were presented. The electrodes configuration scheme used shows feasibilities and security in order to use the SPEED2 generator in a configuration different to a plasma focus, that corresponds to the original design. In this new electrode configuration, the SPEED2 generator delivery ~2.4 MA of maximum current and produce a voltage, in the central collector, of ~80 kV. An apparently stable plasma column was obtained and neutrons were detected. The line density measured, $(2\text{-}4)\text{x}10^{19}\text{m}^{-1}$ corresponds to the expected from the 0-D model and is consistent with finite Larmor radius stability effects. These preliminary results are enoughly interesting to motive further experiments. There are both, theoretical [10, 11] and experimental evidence indicating that composite coaxial pinches (plasma on wire [12], plasma focus plus gas puffed [13-15], sheared flow on z-pinch [16], double column gas embedded z-pinch [2-4]) are more stable than single column pinches. Future experiments include the double column preionization scheme, combining the electrodes configuration with a pulse laser onto the cathode. In addition a complementary diagnostics to measure the total current through the plasma should be developed.

8. Acknowledgment

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9. References

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