Progress in Z-pinch research driven by the mega-ampere device SPEED2

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Abstract.
Several pinch configurations have being studied at the Chilean Nuclear Energy Commission using the SPEED2 generator: plasma focus, gas embedded z-pinch and wire arrays. SPEED2 is a generator based on Marx technology (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). Currently the device is being operated at 70kJ stored energy producing a peak current of 2.4 MA in short circuit. In this work results related to studies in gas embedded z-pinch in deuterium and studies in wire arrays are presented.

Keywords: z-pinch, gas embedded z-pinch, compressional z-pinch, double column z-pinch, wire arrays.
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INTRODUCTION

Z-pinch experiments relevant to fusion studies require generators capable of achieving currents up to some MA in hundreds of nanoseconds. At present, studies on wire arrays are being carried out in various laboratories (Sandia, USA; Triniti-Kurchatov, Russian Federation; Imperial College, UK, for example). The soft x rays emitted from metallic plasmas produced in wire arrays are studied in order to be used as illumination source for inertial confinement experiments. In Sandia, in the Z-Machine, discharges over ~200 wires of ~10-20μm diameter are produced with 20MA. A current of the order of 100kA per wire is established.

SPEED2 is a generator based on Marx technology (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). Currently the device is being operated at CCHEN at 70kJ stored energy producing a peak current of 2.4 MA in short circuit. Thus, the generator is suitable to produce wire arrays discharges over ~ 20 wires. Then, on one hand, in order to produce a metallic pinch plasma radiating soft x-ray for studies relevant to inertial confinement, a 0-D model was used to design wire arrays suitable to be driven by SPEED2. On the other hand, studies on z-pinch stability are being carried out in gas embedded z-pinch at MA current driven by the SPEED2 generators.

WIRE ARRAYS

In order to calculate the number and the diameter of wires, and the initial radius of an array, a simple 0-D model for the dynamics of a liner was used, considering the electrical features of the SPEED2 generator. Using the results of the 0-D model, electrodes of 28mm diameter were constructed to be used with arrays of 18, 18μm tungsten wires. The following diagnostics have been implemented and will be applied in the near future to the wire array discharge: current derivative and voltage signals, pin diodes, time integrated x-ray pinhole camera and time resolved four frame MCP pinhole camera.

GAS EMBEDDED Z-PINCH

Experiments in gas-embedded Z-pinches were carried out in Chile some years ago [1-3], 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 [1-3]. In particular the most interesting results were obtained in a double column pinch. This configuration used a pre-ionization scheme based on a combination of an annular micro-discharge followed by a laser pulse. This scheme produces a double column pinch 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 rise (150ns) and achieves 180kA. The aim of this research is to study a double column pinch at currents of thermonuclear interest, i. e. greater than 1MA. The SPEED2 generator is being used with this purpose.

The SPEED2 was originally designed as a device with an impedance of the order of the pinch impedance for plasma focus discharges (~100 mΩ) [7]. The impedance of the device does not allow to drive a narrow pinch, like a fiber pinch or a conventional gas embedded Z-pinch; at early times the voltage on the load could be increased by a factor of two destroying the central collector of the SPEED2 generator . Therefore a study using a 0-D model was applied to find the initial conditions needed to produce a gas embedded z-pinch suitable to be driven safely by the SPEED2 generator. In addition only the solutions that could results in a z-pinch with enhanced stability were selected. In fact, it has been theoretically conjectured that there is a threshold for the stabilization due to resistive effects, corresponding to a Lundquist number S~100 ($S=3.87 \times 10^{23} I^4 a N^{-2}$, for a pinch in deuterium [4]). 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 stages in the discharges studied experimentally [1-3], it is apparent that they are resistive at early stages. In addition, for the particular case of a double column pinch, which presents 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 at later stages ($a_i/a = 8.08 \times 10^8 N^{-1/2}$ for a pinch in deuterium [1-4]). This is consistent with theoretical studies which indicate that the region of minimum instability for pinch discharges is in the neighborhood of $a_i/a \sim 0.2$ [5, 6].

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 around a_i/a around 0.1-0.2, i.e. for values of the line density N of the order of $6.5 \times 10^{19} m^{-1}$ - $1.6 \times 10^{19} m^{-1}$.

A set of results obtained with the 0-D model, that fit the conditions explained above, show the following range for the initial conditions: charging voltage of +/-30kV, initial radius a_0 = 2-5mm, filling pressure p=33mbar of deuterium, and plasma length h=10-20mm. Then, the electrodes from the plasma focus configuration of SPEED2 were modified in order to produce a double column linear Z-pinch when assisted by a pulsed laser. Figure 1a) shows the electrodes configuration to produce a double column pinch. The laser produces 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 photomultipliers; and interferograms using a pulse Nd-YAG laser (8ns FWMH at 532nm). Figure 1b) shows the layout of experiments and diagnostics.

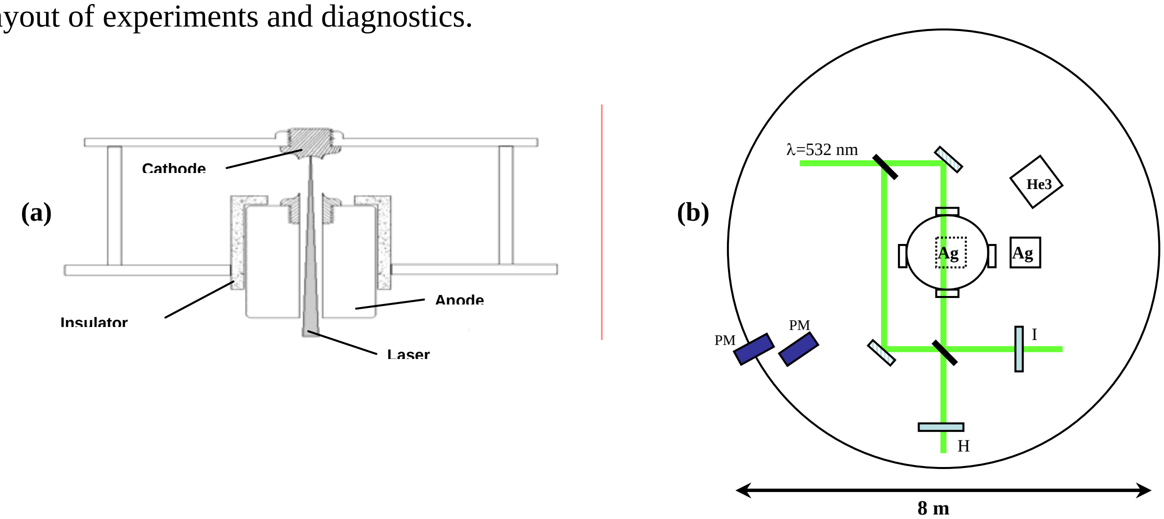
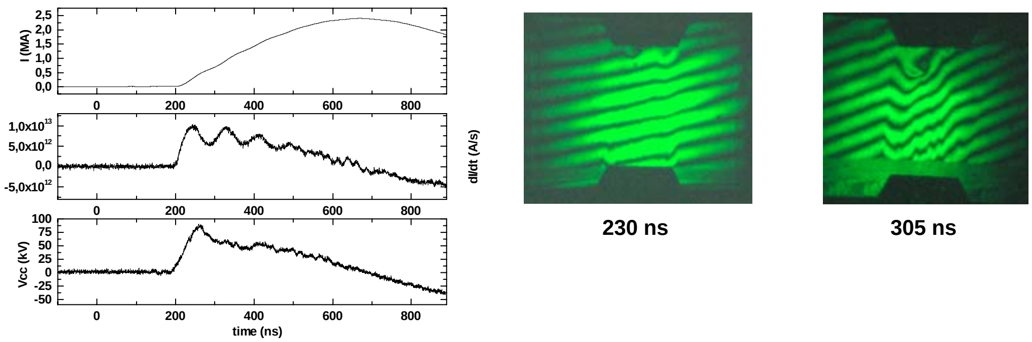


Figure 1. a) Electrodes configuration. b) Layout of the experiment and diagnostics. Discharge chamber at center. Ag: 2 silver activation counter (axial and radial); PM: 2 radial scintillator-photomultiplier; I and H, interferogram and hologram obtained from Mach-Zehnder interferometry.

Discharges through the conical electrodes described in figure 1a) were performed with a pulsed laser focused onto the cathode and without laser. In both cases no damages in the SPEED2 generator was observed. Preliminary diagnostics of discharges without the laser pulse for secondary preionization were performed. Figure 2a) 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. Figure 2b) shows a sequence of two interferograms for such kind of discharges. A hollow Z-pinch discharge is produced. The last interferogram is 95 ns before the peak current.



(a) (b)

Figure 2. a) 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 without the laser (secondary) ionization mechanism. b) interferograms.

The interferograms of figure 2b) show a hollow Z-pinch discharge at early times which produces ionization on the axis of the column while the current is increasing. Figure 3 shows density profiles obtained from the interferograms.

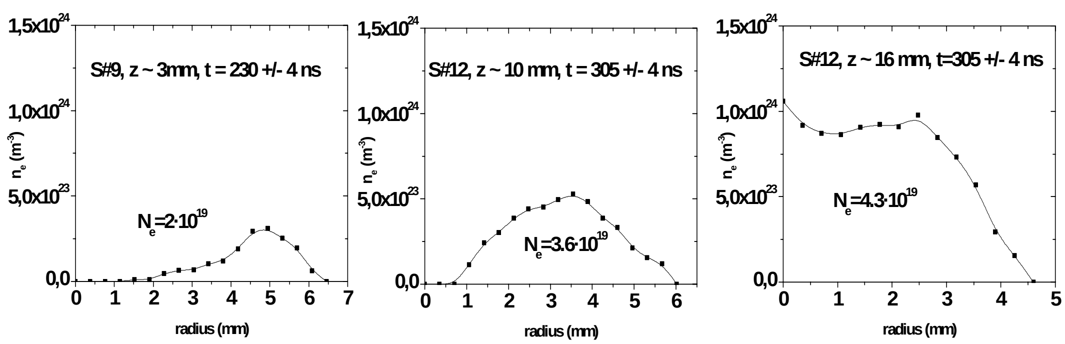


Figure 3. Density profiles obtained from the interferograms of fig. 2b), z indicates the distance from the anode. The density profile has a hollow structure at 230 ns. At 305 ns the structure is hollowed at 10 mm from the anode but is peaked on the axis near the cathode.

From the interferogram at 230 ns the number of electrons per unit length N_e, is measured as $N_e \sim 2x10^{19} m^{-1}$ and for 305 ns it is found to be $N_e \sim 4x10^{19} m^{-1}$. 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 to be of the order of $n_e \sim 4x10^{24}$ m^{-3}. The density corresponding to the filling pressure (33mbar), is $n_0 = 1.7x10^{24}$ m^{-3}. Thus, from these rough estimates it is possible to suggest that the plasma has been compressed near the cathode.

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

DISCUSSION AND CONCLUSIONS

In summary, on one hand, electrodes and diagnostics for studies in wire arrays using the SPEED2 generator were constructed and implemented. Experiments will be carried out in the near future. On the other hand, initial conditions to produce a gas embedded Z-pinch suitable to 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. 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 feasibility and security to use the SPEED2 generator in configurations different to that of a plasma focus, for which it was originally devised. In this new electrode configuration, the SPEED2 generator delivers a maximum current of ~2.4 MA and produces a voltage, at the central collector, of ~80 kV. An apparently stable plasma column was obtained and neutrons were detected. The line density measured, $(2\text{-}4)x10^{19}m^{-1}$ corresponds to that expected from the 0-D model and is consistent with finite Larmor radius stability effects. These preliminary results are interesting enough to motivate further experiments. There are both, theoretical and experimental evidence indicating that composite coaxial pinches (plasma on wire, plasma focus plus gas puffed, sheared flow on z-pinch, double column gas embedded z-pinch) are more stable than single column pinches. In the near future, experiments including the double column preionization scheme, combining the electrodes configuration with a pulse laser onto the cathode will be carried out. In addition a complementary diagnostics to measure the total current through the plasma should be developed.

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