Experimental Studies in Mega Ampere Gas embedded Z-pinch with Different Initial Conditions of Preionization

C. Pavez 1, 3), J. Moreno 1, 3), A . Tarifeño 2, 3), A. Clausse 4), and L. Soto 1, 3)
1) Comisión Chilena de Energía Nuclear (CCHEN), Casilla 188-D, Santiago, Chile
2) Universidad de Concepción, Chile
3) Center for Research and Applications in Plasma Physics and Pulsed Power, P^4, Chile
4) CNEA-CONICET and Universidad Nacional del Centro, 7000 Tandil, Argentina

e-mail contact of main author: lsoto@cchen.cl

Abstract. New experimental results of the gas embedded Z-pinch research program of the Chilean Nuclear Energy Commission are presented. Different initial conditions of preionization are studied by using several geometries for the electrodes in combination with a pulsed laser (10ns FWMH at 1064nm). The initial conditions obtained correspond to a hollow plasma column and a coaxial double column. The details of the preionization schemes and the structure of the initial plasma are studied by using a small generator (0.88μF, 30 kV, 140 kA in short circuit, 400J, 300 ns rise time, dI/dt~ $4.6x10^{11}$ A/s). Thus, experiments at mega ampere currents using deuterium as working gas are driven by the SPEED2 generator (4.1 μF equivalent Marx generator capacity, 180 kV, 2.5 MA in short circuit, 70kJ, 400 ns rise time, dI/dt~10^{13} A/s). The diagnostics used are: current derivative and voltage signals, neutron detections using silver activation counters, and 3He proportional counters; scintillators with photomultilier; and optical refractive diagnostics (schlieren, shadowgraphy and interferometry), using a pulsed Nd-YAG laser (8ns FWMH at 532nm). Neutrons have been detected. The stability of the plasma column and the processes of neutron production are discussed.

1. Introduction

New experimental results of the gas embedded Z-pinch research program of the Chilean Nuclear Energy Commission are presented.

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, in Z-Machine in Sandia National Laboratory, USA, ion temperatures in 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 corresponds to a kind of quasi-static Z-pinch. 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], 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 $2\cdot10^{12}$ A/s and the peak current achieves was 150-180kA. The discharges were performed in H_2 and He at 1/3 atmospheres and several preionization schemes were studied [4, 6, 9], showing in some cases a final stage of the pinch with enhanced stability. The aim of this research is studied Z-pinch discharges in deuterium at current of thermonuclear fusion interest, i. e. greater than 1MA with different initial conditions of preionization.

The research program at CCHEN considers different schemes of preionization to be studied by using several geometries for the electrodes in combination with a pulsed laser (10ns FWMH at 1064nm). The initial conditions correspond to a hollow plasma column and a coaxial double column. The details of the preionization schemes and the structure of the initial plasma are studied by using a small generator (0.88 μF, 30 kV, 140 kA in short circuit, 400J, 300 ns rise time, dI/dt~ 4.6×10^{11} A/s). Thus, experiments at mega ampere currents using deuterium as working gas are driven by the SPEED2 generator (4.1 μF equivalent Marx generator capacity, 180 kV, 2.5 MA in short circuit, 70kJ, 400 ns rise time, dI/dt~10^{13} A/s) [5]. In a previous work the modification required in the SPEED2 generator (originally designed to produce plasma focus discharges), in order to produce linear pinches, were discussed and presented [18].

Special interest have been focused to obtain initial 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 ($S=3.87 \times 10^{23} I^4 a N^{-2}$, for a pinch in deuterium. 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 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 ($a_i/a = 8.08 \times 10^8 N^{-1/2}$ for a pinch in deuterium [2-4]). This is consistent with theoretical studies which indicate that the lowest instability growth rate occurs in the neighborhood of a_i/a~0.2 [7, 8].

The diagnostics used are: current derivative and voltage signals, neutron detections using silver activation counters, and 3He proportional counters in charge integrated mode [19]; scintillators with photomultilier; and optical refractive diagnostics (schlieren, shadowgraphy and interferometry), using a pulsed Nd-YAG laser (8ns FWMH at 532nm).

Neutrons were detected. The stability of the plasma column and the processes of neutron production (thermonuclear vs. beam-target) are discussed.

2 Experiments driven by SPEED2 generator.

Discharges through the conical electrodes 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. 1 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. 1 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. 1 show an hollow Z-pinch discharge at early times that produce ionization to the axis of the column while the current is increasing. FIG. 2 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~$2 \times 10^{19} m^{-1}$ and for 305 ns is measured in N_e~$4 \times 10^{19} m^{-1}$. At 305 ns, the mean value for the electron density n_e, is n_e~4×10^{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~1×10^{24} m^{-3}. The density in the singularity at 1-2mm from the cathode can be estimated of the order n_e~4×10^{24} m^{-3}. The density corresponding to the filling pressure (33mbar), is $n_0 = 1.7 \times 10^{24}$ 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 5×10^5 neutrons per shot.

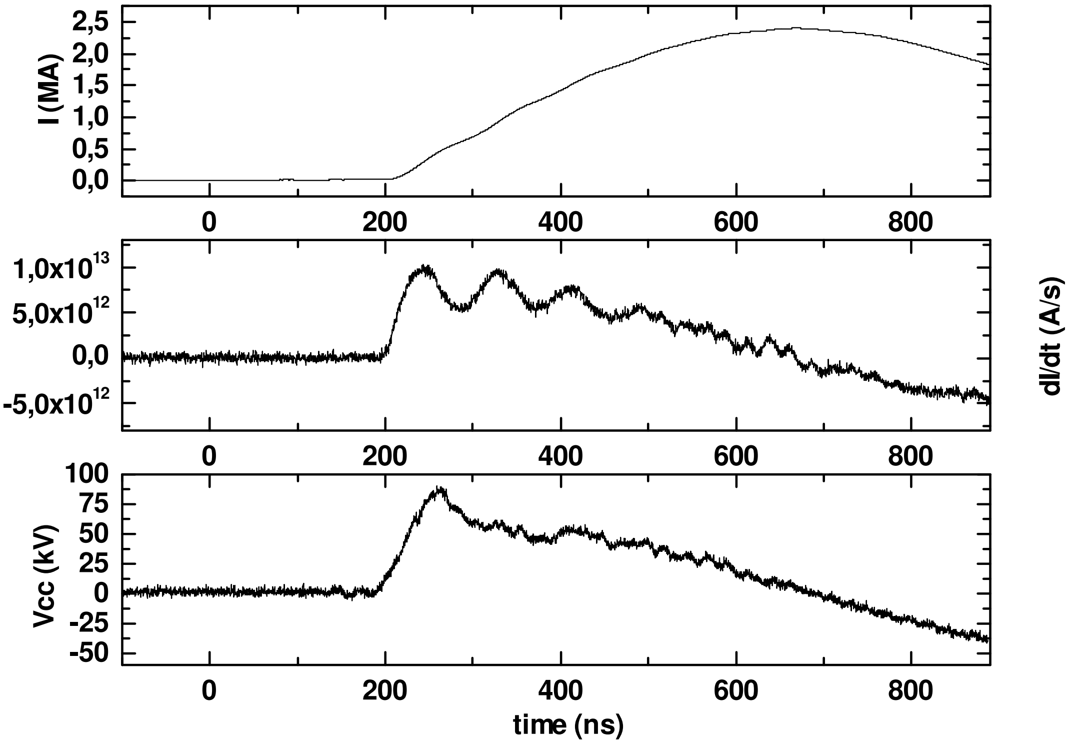

FIG. 1. Electrical signals for a discharge performed in D_2 filling gas, at 33 mbar, with 36 storage Marx modules charged at 30 kV each one, and using the electrode geometry without the laser (secondary) ionization mechanism.

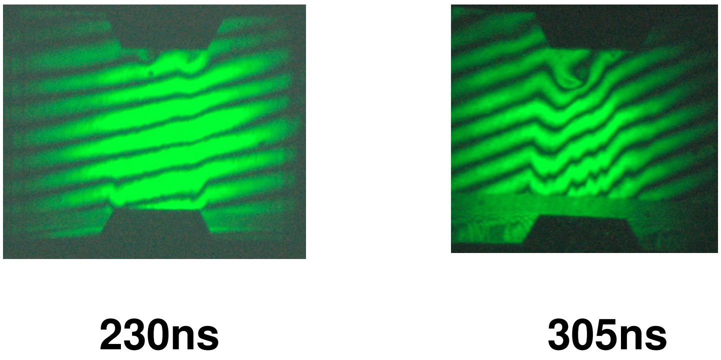

FIG. 2. Interferograms for discharges performed in D_2 filling gas, at 33 mbar, with 36 storage Marx modules charged at 30 kV each one, and using the electrode geometry without the laser (secondary) ionization mechanism. A hollow Z-pinch discharge is produed. The distance between electrodes is 20 mm. The time is measured since the initiation of the discharge.

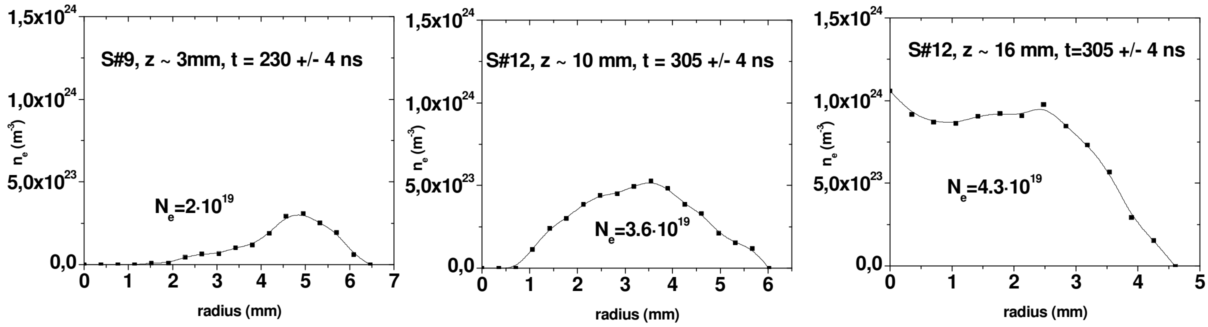

FIG. 3. Density profiles obtained from the interferograms of FIG. 3, z indicates the distance from the anode. The density profile has a hollow structure at 230 ns. At 305 ns the structure is hollowed at 10 mm from the anode but is peaked on the axis near the cathode.

2.1. Discussion

Assuming Bennett equilibrium, the thermonuclear neutron emission rate per unit volume in a Deuterium Z-pinch can be calculated as:

$$\frac{dy_{th}}{dt} = \frac{1}{4} n^2 \langle \sigma v \rangle \tag{5}$$

where n is the deuteron density and $\langle \sigma v \rangle$ is the fusion cross section evaluated at the Bennett temperature , that is [26]:

$$\langle \sigma v \rangle = 3.31\times10^{-23} m^3/s \left(\frac{T_B}{T^*}\right)^{-\frac{2}{3}} \exp\left[\left(\frac{T_B}{T^*}\right)^{-\frac{1}{3}}\right] \tag{6}$$

$$T_B = \frac{1}{k}\frac{\mu_o}{4\pi}\frac{I^2}{N'} \tag{7}$$

N' is the linear ion density, $T^* = 7.65\times10^{10}$ °K, k=1.38×10^{-23} J/°K and $\frac{\mu_o}{4\pi}=10^{-7}$ J/mA^2.

Considering the limit of Pease-Braginskii, the maximum current through the pinch cannot exceed 1.4 MA, n~10^{24} m^{-3}, 3.5mm pinch radius, 20mm pinch length, and numerically integrating Eq. (5) gives a total neutron yield about 10^{10}, which is considerable higher than the measurement. The latter can be explained assuming that the pinch temperature is 9% of the Bennett temperature (~0.7 keV). The measured yield can also be explained assuming that the fusions take place in a hot spot about 0.4 mm diameter, as the observed in the singularity of the second interferogram in FIG. 2 .

3. Experiments driven by a table top generator of hundred of joules.

As a first step, influence of the electrode shape and details of the discharge when using hollow conical electrodes are under study in less complex table top generators. Preliminary studies have been done using a table to generator of 400J. The mean features of this device are: 880nF, 30kV, 140kA, 300J, T/4 ~ 300ns, dI/dt ~ 4.6×10^{11} A/s (FIG. 4.b). Diagnostics used in this experiments are: A Mach-Zender interferometer coupled to a CCD camera and electrical probes for voltage monitoring (resistive divider) and current derivative monitoring (rogowskii coil). In figure 4 a preliminary result at late time is showed. This shot correspond to a D_2 discharges at 33 mbar, 370 J bank energy. The image was taken at a time of 384 ns from the discharge beginning and is close to the current peak. From FIG. 4.c is possible to see an expanding column without the presence of macroscopic instabilities and the appearance of singular regions near the electrodes.

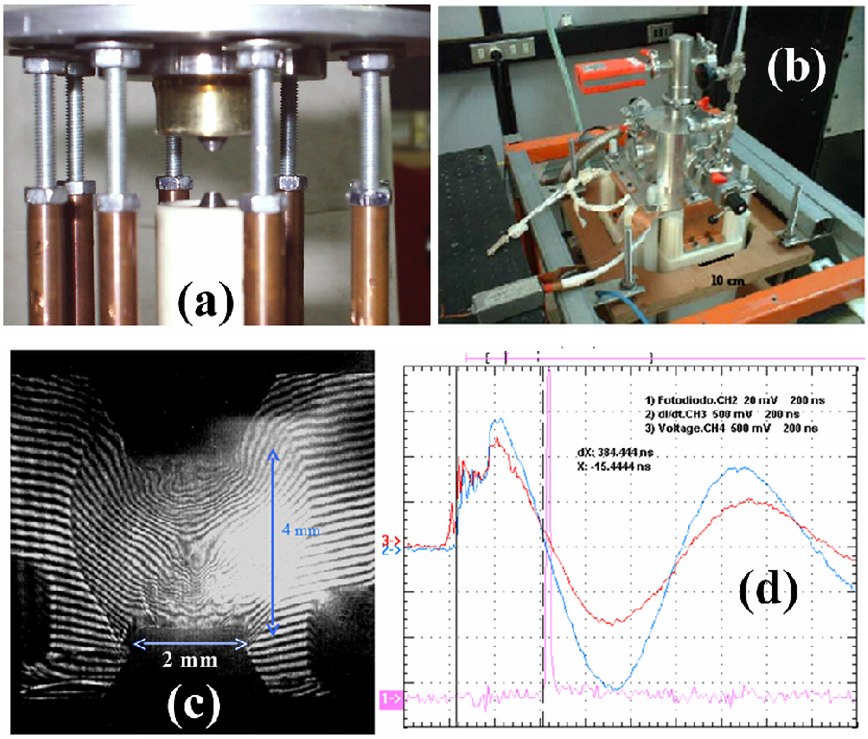

FIG. 4. (a) Electrode configuration (b) PF-400J table top generator (c) and (d) Interferogram and electrical signals for a D_2 discharge at 33 mbar, 370 J bank energy, image time 384 ns from discharge beginning.

4. Conclusions

Suitable initial conditions to safely produce a stable gas embedded Z-pinch driven by the SPEED2 were determined using a 0-D model. A corresponding set of electrodes were designed and constructed in order to produce hollow and double column Z-pinches, which were obtained in discharges at 33mbar Deuterium gas. With the new electrode configuration the SPEED2 generator deliver a peak current of 2.4 MA producing 80 kV in the central collector.

Neutrons pulses were measured in stable plasma columns, which constitute the first experimental evidence of fusion reactions in a gas embedded Z-pinch. The measured line density, $(2\text{-}4)\times 10^{19}\,\mathrm{m}^{-1}$, is consistent with the theoretical calculations using a 0-D model satisfying the finite Larmor-radius stability criterion.

The authors hope that the results presented in this work will encourage other researchers to further study fusion phenomena in Z-pinches. Theoretical [10-11] and experimental evidence indicate 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 should determine optimum conditions for fusion using the double-column preionization scheme, combining the electrodes configuration with laser pulses. A table top generator to driven a gas embedded Z-pinch is being using to study in details the initial conditions and the developed of the plasma column at early times. Furthermore, complementary diagnostics to measure the total current through the plasma should be developed.

8. Acknowledgment

SPEED2 is a donation from Düsseldorf University to CCHEN. Currently, this research is supported by the grant P^4 Project "Center for research and applications in plasma physics and pulsed power technology", PBCT-Chile-ACT26, and a Postdoctoral grant PBCT-Chile-PSD01. A. Tarifeño has a CONICYT doctoral fellowship.

9. References

[1] HAINES, M. G. , et al., Phys. Rev. Lett. **96**, 075003 (2006)
[2] SOTO, L., et al., Phys. Rev. Lett. **72**, 2891 (1994).
[3] SOTO, L., et al., IEEE Trans. Plasma Sci. **24**, 1162 (1998).
[4] SOTO, L., et al., in Proc. Int. Conf. on Plasma Phys. ICPP, 1994, Foz do Iguazú, Brazil, 1994, p. 216.
[5] DECKER, G., et al., Nucl. Instrum. and Methods **A249**, 477 (1986).
[6] SOTO, L. and CLAUSSE, A., Physica Scripta **67**, 77 (2003).
[7] ARBER, T. D., COPPINS, M., and SCHEAFEEL, J., Phys. Rev. Lett. **72**, 2399 (1994)
[8] ARBER, T. D., et al., Phys. Rev. Lett. **74**, 2698 (1995).
[9] PAVEZ, C., et al AIP Conf. Proc. **651**, 233 (2002).
[10] ARBER, T. D., and HOWELL, D. F., Phys. Plasmas **3**, 554 (1996).
[11] HERRERA, J., FEC2004, TH/P2-33 (2004).
[12] WESSEL, F. J., ETLICHER, B., CHOI, P., Phys. Rev. Lett. **69**, 3282 (1992).
[13] VIKHEREV, V., Sov. J. Plasma Phys. 3, 539 (1977).
[14] MILANESE, M., MOROSO, R., POUZO, J., J. Phys. D. Appl. Phys. 31, 85 (1998).
[15] KIES, W., et al., Plasma Sources Sci. Technol. **9**, 279 (2000).
[16] SHUMLAK U., et al., Phys. Rev. Lett. **87** (2001)
[17] HAINES, M.G., and COPPINS, M., Phys. Rev. Lett. **66**, 1462 (1991).
[18] SOTO, L., et al., IC/P7-2, IAEA Fusion Energy Conference, Chengdu, China, October 2006.
[19] MORENO, J. et al., Meas. Sci. and Technol. 19, 087002 (2008).