

Title: EXPLOSIVE FLUX COMPRESSION: 50 YEARS OF LOS ALAMOS  
ACTIVITIES

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## Explosive Flux Compression: 50 Years of Los Alamos Activities

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### Abstract

Los Alamos flux compression activities are surveyed, mainly through references in view of space limitations. However, two plasma physics programs done with Sandia National Laboratory are discussed in more detail.

### I Introduction

In this section, we briefly outline major Los Alamos (LANL) flux compression activities. More detailed discussions are given of two programs done with Sandia National Laboratories, (SNL) intermittently from 1966 to 1973. Use of flux compression generators (FCG's) to power  $\theta$ -pinches is discussed in Sect. II. The "Birdseed" program, in which 150-200 kJ of neon plasma was injected into the ionosphere, is discussed in Sect. III, together with plans for a more energetic system. The first open description of the Los Alamos objectives was published in [1]. Items featured were the use of the high magnetic fields made at Los Alamos to compress D-T plasmas to make large neutron bursts, for solid-state investigations, and to accelerate matter, topics that remain relevant today. Later, unclassified Los Alamos activities were surveyed at the first Megagauss Conference (1965), [2]. The next Megagauss Conference took place in 1979 [3]. Other activities between these conferences included high field solid-state and isentropic compression experiments. Component development included construction of megavolt transformers and FCG improvements, as with the plate generator. FCG uses as power supplies for railguns, the plasma focus, laser generation, e-beam machines and soft X-ray generators are described in later Megagauss Conference Proceedings, as is the development of high current opening switches. A collaborative flux compression program with Los Alamos and Russian scientists from Arzamas-16 began in 1993, and included Magnetized Target Fusion and high field experiments that have been surveyed in [4] and also reported at MG VII (whose Proceedings are in press). Little of our solid-state work has appeared in the Megagauss Proceedings. However, surveys appear in [5,6,7]. More recent work has been done in the "Dirac" shot series where scientists from the USA and several other countries have collaborated on high field experiments using Russian MC-1 high field generators and Los Alamos strip generators. Various aspects of this program are treated at this conference and at the preceding MG VII Conference.

### II. Explosive-driven $\theta$ -pinch experiments

A.  $\theta$ -pinch liner implosion experiments. Early experiments [2a,c,8] at Los Alamos to apply explosively driven flux compression (MG fields) to high temperature plasmas were exploratory, and involved creating a fast theta pinch

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inside a thin, implodable cylindrical  $\theta$ -coil. Parameters were chosen to achieve MG fields with systems then available at Los Alamos, and used early  $\theta$ -pinch data (Scylla I, Scylla III) [9,10]. Implosion of the plasma/magnetic system was started using high T high  $\beta$  plasma confined by the axial magnetic field.

In these experiments, a good diagnostic neutron signal verified that the initial plasma was in place as expected, and gave a measure of the plasma behavior vs. time during the explosive driven phase. Fundamental problems existed. Plasma confinement in the short coil (~25 cm)  $\theta$ -pinches available for the firing point was limited to 2-3  $\mu$ sec due to end-loss, flute instabilities [8,10,11] and to field asymmetries [2c]. In 1966, a new  $\theta$ -pinch (Scyllacita) with a faster capacitor bank was used to create the initial plasma [8]. A new side-fed coil implosion system eliminated field asymmetries. Since the basic plasma confinement time limitation with the short  $\theta$ -coil (~3 $\mu$ s) remained, as did the quenching effect of the imploding discharge tube, we did not pursue this approach beyond one Scyllacita shot. However, the goal of achieving fusion with MG fields in imploding liners remains valid today. We suggest developing a technique, such as an FRC [12], to inject, at the proper time, an initial high-beta plasma axially into a clean, resistive liner implosion system [2c] for explosive compression to 4 MG or greater. For good confinement, the implosion system length should probably be increased to a half meter or more.

**B. The explosive generator powered  $\theta$ -pinch.** In 1967, Los Alamos and Sandia Laboratories collaborated in a series of generator powered  $\theta$ -pinch experiments using Sandia generators {13,14,15,16}. Two sizes of helical generators were used: the Model 106 generator (5# of PBX 9404 explosive) and the larger Model 169 (17# of PBX 9404 explosive). Exploding wire fuses were used to sharpen the pulses to drive the  $\theta$ -pinch coils. The  $\theta$ -coils were switched in when the voltage across the fuses reached preselected voltages. The initial plasma was created by first putting a few kG bias field,  $-B_z$ , in the coil, then passing a linear z-current through the deuterium to preionize it, and finally applying the main drive field to heat and compress the plasma.

Nine shots were fired, five with the Model 106 generator and four with the Model 169. Table I of Ref [16] lists conditions for each shot. The preionized plasma was created inside a 2 mm wall Pyrex or quartz discharge tube with a 40 kA linear current discharge (from a 7.5  $\mu$ F, 15 kV bank) which was shorted out after a half-cycle to eliminate axial current before switching in the generator.

Discharge tube conditioning for each shot involved warm-up  $\theta$ -pinch shots with an auxiliary capacitor bank [14,15,16]. The generator-powered  $\theta$ -pinch shot was then fired, complete with preionization, bias field and diagnostics, within 30-60 minutes of the last warm-up shot. Results of the nine generator driven pinch shots are also given in Table I, [16]. Time resolved neutron yields, measuring plasma behavior, have been reported [14,15,16,17]. The shot series demonstrated the importance of reverse bias field, tube conditioning, preionization, and particularly the initial voltage,  $V_0$ , applied to the preionized plasma. Good diagnostic neutron yields were obtained on 7 of the 9 shots. Results for shots 8 and 9 are shown in Fig 1, which gives the time history of the applied magnetic field ( $B_z$ ) and the resulting neutron yield rate for each shot. The highest neutron yield ( $1.4 \times 10^6$ ) occurred when all drive parameters were at optimum. The maximum neutron yield rate per unit coil length was comparable

to or better than those for laboratory theta pinches worldwide [18]. In 1968, the Frascati group conducted five generator-driven  $\theta$ -pinch shots with at least one neutron yield ( $5 \times 10^7$ ) [19], supporting our demonstration of the feasibility [14,15,16] of generator-driven  $\theta$ -pinches.

C. Predictions with a  $\theta$ -pinch scaling model. A  $\theta$ -pinch scaling model was developed [20] using a simple computer code and used to calculate plasma radius, temperature, density, neutron yields and radiation rates for a large variety of short-coil ( $\sim 25$  cm) Los Alamos  $\theta$ -pinches (1963-1978). The one-dimensional model assumes that  $V_0$  drive voltage, reverse field cancellation, and adiabatic compression may be separated. End-losses are neglected for  $2\mu\text{s}$ . A  $\beta=1$  plasma and perfect conductivity are assumed during compression. The code assumes adiabatic compression ( $T \sim B^{4/3}$ ) and used a radiation loss rate  $\sim n_e n_i T_e^{1/2}$  during the compression phase. The code contained a single scaling constant,  $K$ , which successfully correlated results from Scylla III, Scyllacita and Scylla IA.. It then successfully correlated the results of the 1967 explosive generator shot series.

In the 1970s, a dedicated theta pinch, Scyllar, was used at Los Alamos to study plasma radiation, opacities, and atomic properties in high temperature plasmas.[21,22]. The code [20] was used to compare Scyllar results at higher densities ( $>10^{17}/\text{cc}$ ) than used previously ( $\sim 10^{16}/\text{cc}$ ). Comparisons with experiment were generally good [20].

In the mid 1970s, high-current plate generators were developed extensively at Los Alamos.[17,23]. These generators are fast and can generate multi- MA currents at terawatt levels. Using a typical plate generator performance [17], a calculated [20] field vs. time dependence for a  $\theta$ -coil (25.4 cm long, 7.6 cm i.d.) is shown in Fig 2.  $V_0$  is about 50 kV, and  $B_z$  rises from 0 to 900 kG in 2  $\mu\text{s}$ . With a 50 mT  $D_2$  fill, the code predicts a fusion (10 keV) neutron yield of  $\sim 3 \times 10^{11}$  which could be increased to  $\sim 3 \times 10^{15}$  by using a DT mixture and extending the coil length to one meter. With a fill of 1.0 torr  $D_2$ , seeded with a high Z species, a final temperature of 1.0 keV (Fig.2) at a density of  $10^{19}/\text{cm}^3$  is

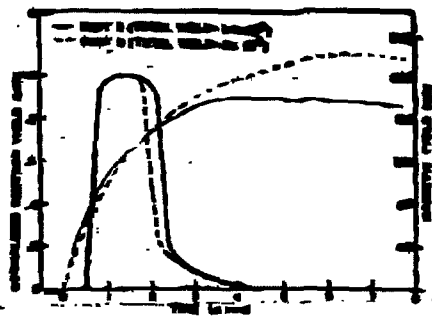


Fig. 1 Magnetic field and relative neutron yield rate vs. time for two  $\theta$ -pinch shots using Model 169 generator.

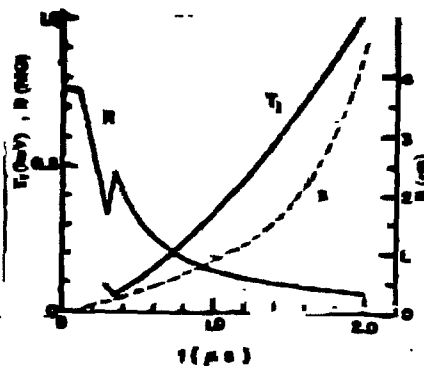


Fig. 2.  $B$  vs.  $t$  in  $\theta$ -coil ( $L=25$  cm, i.d.=7.6 cm) calculated from plate generator data. Plasma temperature and radius vs  $t$  are predicted from scaling code.  $D_2$  fill, 1.0 torr; bias field, 2 kG

predicted. If seeded with selected high-Z elements, as with Scyllar [21,22], such plasmas would allow studies of atomic processes and opacities at temperatures and densities much higher than those obtained in the laboratory, making possible unique regimes for comparison of spectral observations with theory.

### III The Birdseed Program

The initial goal of the Birdseed Program was to inject neon plasma into the ionosphere to study its interaction with ionospheric matter and magnetic fields. It was hoped that at least 100 kJ of plasma could be injected, with average directed velocity of 100 km/s or greater. Program planning began in 1967. It was decided that the plasma would be produced by a Marshall plasma gun [24] and that the system would be launched in a Sandia Laboratory STRYPI rocket. The gun would be fired when the rocket reached the ionosphere (approximately 220-240 km altitude). The STRYPI payload was of order 500 kg, of which somewhat more than 200 kg were available for the power supply. An FCG system system was selected to power the plasma gun to meet weight and volume restrictions. All system components were designed to be compatible with the planned payload layout and to meet the STRYPI acceleration demands. Figure 3 shows the placement of the major components. These consisted of a capacitor bank, the initial energy source; a Mark V booster generator; the Model 169 output generator; a ballast load and the plasma gun. Switching of components into the system was done with detonator closing switches. Neon gas was first injected into the plasma gun from a storage plenum by means of a detonator actuated valve. The capacitor bank (~15 kJ, charged mainly during flight by a battery powered DC-DC converter) was fired next to energize the Mark V generator (~400  $\mu$  H), which then delivered 60 to 75 kJ to the Model 169 generator. This generator was then fired, first into the ballast load B, and subsequently also into the plasma gun. Tests at the Los Alamos Firing Site showed that this system delivered 300-350 kJ to the gun, with about 60 % of the energy going into the directed plasma. Diagnostics showed that for a typical shot, plasma velocities varied from 50 to 250 km/s, with mean velocities in the range of 90-110 km/s. The program culminated in three successful shots at the Barking Sands Facility in Kauai, Hawaii, two in 1970 (Birdseed I), the third in 1971 (Birdseed II). A summary of the generator-gun development program through Birdseed I can be found in [25], while discussions of the diagnostics employed are available in [26,27]. The system engineering development is treated in [28], and a general description of the STRYPI rocket is given in [29].

Planning for Birdseed III began in late 1970. The system was to be launched in a STRYPI rocket, but was to deliver ten times the plasma energy, thus calling for major changes in the plasma gun and the power supply.

Plasma gun. Birdseed plasma spectra showed appreciable contaminants from gun components which did not appear in lower energy laboratory tests. Consequently, a new gun was designed [30], but not tested, that was expected to generate the required plasma and to withstand the substantially larger required currents. The inner electrode diameter was increased from 6.35 to 30 cm, the outer electrode diameter from 15.24 to 50 cm the length from 100 to 150 cm.

Power supply The power supply was required to deliver a total of about 5 MJ, 3.5 MJ to the gun. It would consist of a single, helical generator. Initial flux

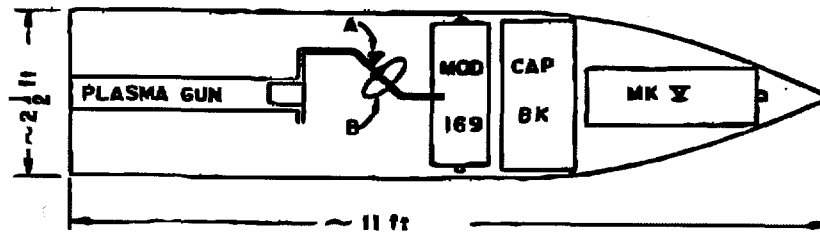


Figure 3. Location of major system components in STRYPI payload. Ballast load B carries all the current until plasma gun is switched into circuit by detonator switch A.

would be supplied by a superconducting coil. A full-scale helical generator was built and tested with satisfactory results, as were acceleration test results on the stator. A NbTi superconducting scaled down coil was built. Acceleration tests [31] showed that it would withstand the rocket accelerations without going normal. The coil was then tested in an explosive shot, where it supplied the initial flux for a scaled down helical generator, with satisfactory results [32]. There was also some concern that the coil might go normal during launch as the system swept by the steel rocket launch structure. Calculations [33] indicated that a few sheets of magnetic shielding around the coil would solve this problem if it indeed existed

**Summary:** These experiments demonstrated the feasibility of using FCG's to power  $\theta$ -pinches and plasma guns for physics, fusion and space applications.

**Dedication.** The authors dedicate this paper to the memory of their colleague and friend, Robert S. (Bob) Caird who passed away on March 27, 1997. Bob was a pioneer in magnetic flux compression, and shared coauthorship with us on the first paper published in the Megagauss Conference series.

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\* We note with sadness the loss of our colleague in the Birdseed program, John Marshall, who passed away on October 21, 1997.