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ABSTRACT

A continuously operated, 1 pps, dense-plasma-focus device capable of delivering a minimum of 10^{15} neutrons per pulse for material testing purposes is described. Moderate scaling from existing results is sufficient to provide 2×10^{13} n/cm^2·s to a suitable target. The average power consumption, which has become a major issue as a result of the energy crisis, is analyzed with respect to other plasma devices and is shown to be highly favorable. A novel approach to the capacitor bank and switch design allowing repetitive operation is discussed.

INTRODUCTION

To produce a practical design for controlled thermonuclear reactors or laser fusion reactors, it is necessary to assume that some structural members will be irradiated by a high flux of 14-MeV neutrons in addition to a "plasma wind" containing gamma rays, x rays, ions, and electrons. We propose to satisfy the neutron requirements for simulation testing of materials with an efficient 1-MJ plasma-focus system designed to deliver one 10^{15} D-T burst per second. The design of the 1-MJ system offers unique solutions to high-voltage, energy-storage, and switching problems for a repetitive system. The full details are given in Lawrence Livermore Laboratory report UCRL-51872 [1]. It is suggested that the technology described can be used to build plasma foci in the multimegajoule range.

Some salient advantages of our sigma Filippov geometry (SFG) simulator are:

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- The plasma focus is unequaled as a laboratory pulsed-neutron source.

- The SFG simulator should be more efficient than other proposed high-energy fusion-reactor simulators because of the approximate E^2 scaling, where E is the stored energy of the plasma focus, and the point-source characteristic. If the energy crisis and the power requirements of alternative systems are to be considered during the next few years, this will be an important factor.

- The goals set for the SFG simulator should be attained without any new fundamental advances in physics. However, considerable research and development (R&D) will be required.

- The R&D program is aimed at utilizing the I^5 scaling to increase yields in the 10^{16} to 10^{17} D-T neutron-per-pulse range.

- The SFG device, like other plasma simulators, provides a realistic environment including gamma rays, x rays, electrons, ions, and neutrons. This plasma wind is not provided by present or proposed beam-target systems.

- The SFG simulator is easier to cool, provides better radiation areas, and has easier access than other plasma-focus devices because of its large electrode surface area and special geometry.

The high efficiency and small source dimension of the SFG simulator are major considerations. Unless extensive improvements are made in the plasma temperature and density in proposed dc and quasi-dc extended-source simulators (e.g., mirror machines, tokomaks, θ pinch), their power requirements will be untenably high.

It is important to note that success of this project depends on straightforward technological extrapolation of well-known plasma-focus and electrical engineering parameters. No increase in yields is assumed for new ideas and/or for better understanding of basic physical principles. However, we suggest that a research effort aimed at the use of higher current will produce higher D-T neutron yields than the 10^{15} per pulse mentioned earlier. We believe that D-T neutron pulses in the 10^{16} to 10^{17} range will be achieved.

ELECTRICAL ENERGY REQUIREMENTS FOR NEUTRON TEST FACILITIES

A major factor in the evaluation of a fusion simulator is its electrical power requirements. All consumers of electrical energy, including national laboratories, are affected by the energy crisis. In the following section we review the energy requirements for plasma-driven devices. The efficiency of accelerator beam-target systems are relatively well known and will not be discussed.

The energy release of 17 MeV caused by 1 D-T fusion is 2.8×10^{-12} J. The energy is carried off by the reaction products: a 14-MeV neutron that does not couple to the reacting plasma and a 3.5-MeV α particle that may be contained in the reacting plasma and thus contribute to plasma heating.

The operating power required by a 14-MeV neutron test facility is given by

$$P = (\phi A/\varepsilon)(2.8 \times 10^{-18}) \text{ megawatts (MW)},$$

where $A = 4\pi R^2 \text{cm}^2$, R is the test volume radius in cm, ϕ is the 14-MeV neutron flux in neutrons/$\text{cm}^2 \cdot \text{s}$, ε is the efficiency defined as the ratio of fusion energy out to electrical energy in, and P is the electric power in megawatts required to operate the facility.

If we assume $\phi = 10^{14}$ n/$\text{cm}^2 \cdot \text{s}$, then

$$P = (A/\varepsilon)(2.8 \times 10^{-4}) \text{ MW}.$$

The initial value of ε for a plasma focus operated at the 1-MJ level will be 2.8×10^{-3}, a value based on common experience.

If the radius R of the test volume is taken as 2 cm, then, for the proposed pulsed-plasma-focus neutron and radiation facility, $A = 50 \text{ cm}^2$. It should be noted that small test samples could be placed closer than 1 cm from the plasma-focus neutron source. The power required to operate the plasma-focus system with $\phi = 10^{14}$ n/$\text{cm}^2 \cdot \text{s}$, $A = 50 \text{ cm}^2$, $\varepsilon = 2.8 \times 10^{-3}$ is $P = 5$ MW assuming no improvements in present system performance.

To estimate operating power requirements of neutron test facilities with various thermonuclear plasma devices, we assume the condition $n\tau = 10^{12}$ at temperature T = 8 kV has been attained. This condition corresponds to a value of $\varepsilon = 0.01$ or 1% of Lawson criterion. A value of ε very much smaller than 0.01 is probably not feasible because it results in large operating power requirements. For the conditions $\phi = 10^{14}$ n/$\text{cm}^2 \cdot \text{s}$, $\varepsilon = 0.01$ and $n\tau = 10^{12}$, the input power requirement P is given by

$$P = (0.028)(A) \text{ MW}.$$

Under these conditions a pulsed-plasma-focus test facility with a test volume surface area of $A = 50 \text{ cm}^2$ would require operating power of 1.4 MW. For comparison, the area of a test facility based on a mirror machine concept has been estimated as $1.26 \times 10^4 \text{ cm}^2$. Thus for T = 8 kV, $n\tau = 10^{12}$ and $\varepsilon = 0.01$, an input operating power of about 350 MW would be required. A neutron test facility for these same conditions based on a linear θ pinch with $A = 1900 \text{ cm}^2$ would require a 53-MW operating power source. It can be seen that the power requirements for CTR device-based test facilities will be large because these low-density systems necessarily occupy large volumes and thus have considerable surface area. Of course, in principle, the power requirements could be reduced by increasing ε, but to achieve the pulsed-plasma-focus power requirement, a CTR device-based facility would have to approach the break-even condition $\varepsilon = 1$. If some of the energy could be recovered through direct conversion of high-energy ions and electrons then these power requirements would be reduced. However, unless near-fusion conditions are achieved, charge exchange between high-energy ions and background gas would reduce the effectiveness of direct conversion.

DESIGN CRITERIA FOR THE SFG REPETITIVE MATERIAL TESTING DEVICE

Required Yield and Rapid Pulsing

The dense plasma focus produces the largest neutron yield per unit plasma volume of any laboratory device now available. For irradiation of materials, however, it suffers from a very poor repetition rate. Present dense plasma-focus devices can be fired only about once every ten minutes. Obviously for the device to be useful for testing purposes a repetition rate of one or more times a second is needed. To accomplish this goal the dense plasma focus must undergo extensive technological modifications. For example, the device itself must be cooled along with the switches and capacitors. The cooling of this device presents stringent engineering problems. However, the designs described in this paper appear to provide adequate cooling for the various components.

Present plasma-focus devices have achieved 1.2×10^{12} D-D neutrons at 420 kJ of stored energy. Figure 1 shows the empirical scaling of D-D neutron yield n versus stored energy E for most of the plasma-focus machines that have been operated. These machines span an energy range of $1\ \text{kJ} < E < 420\ \text{kJ}$ and a voltage range ($E = 1/2\ CV^2$) of $10\ \text{kV} < V < 46\ \text{kV}$. Usually the machines with higher E are designed to have somewhat larger V, but also larger capacitance C and total inductance L. Figure 1 shows an $E^{2.1}$ line drawn through the points. One can see that the scatter of the points about the $E^{2.1}$ line is fairly large, especially for the two lowest E machines, Darmstadt and Hoboken. These various machines have been designed according to the experience and taste of eleven different laboratories; no one parameter was kept constant in these designs. The predicted theoretical scaling according to Filippov and Imshennik [2] gives $N \sim E^{1.9}$ when L increases as C and E increase. This predicted law agrees reasonably well with the $E^{2.1}$ line in Fig. 1 if one considers that the data came from eleven laboratories where the values of C and V were chosen at will.

However, the Bennett-pinch relationship, $I^2 \sim NkT$ and the magnetic energy available being directly proportional to I^2, suggests that the most important factor in directly determining n is I, not V or E, and therefore the scaling of n vs I should be the most meaningful of all scaling relationships. Figure 2 shows n vs I for several of the machines for which we could obtain the appropriate value of peak current. It can be seen that the points lie fairly well upon an $n \sim I^5$ line. Filippov and Imshennik [2] bring forth theoretical arguments stating that when a plasma-focus system remains optimized and L as well as C remain constant, one should expect $N \sim E^{2.43}$ or $n \sim I^{4.9} \sim V^{4.9}$. The agreement of the empirical and theoretical values of the exponent here is fairly good. The two very small Darmstadt and Hoboken plasma-focus devices, which have the same electrode structure, lie considerably above the I^5 line.

We draw attention to the n vs E and n vs V plots by the Darmstadt group, which are reproduced in Fig. 3. The line drawn through the data for this small machine gives $n \sim V^8$ ($\sim I^8$). The implication from the data is that *small machines, with their more* concentrated magnetic fields, are basically superior to the larger machines. Although the data are still scanty, the message seems to be that the best design procedure is to use very high V (several 100 kV), low L (and L_o), and relatively small C to obtain high current. In doing so the designer can perhaps enjoy a scaling law even better than $N \sim I^5$. Figure 4 reproduces Los Alamos n vs V data for a 212-kJ machine showing an $n \sim V^5$ ($\sim I^5$) when the pressure is kept constant and $n \sim E^2$ ($\sim V^4$) for DPF5 and DPF6 when the performance was optimized by changing the pressure.

The SFG plasma focus proposed here is calculated to have a peak current of 7 MA at V = 100 kV and E = 1 MJ. This machine will produce, according to the I^5 scaling, 3×10^{16} D-T neutron per pulse and about 85 kJ in nuclear energy per pulse (17 MeV = 2.8×10^{-12} J per D-T reaction). If the voltage V (and I) are raised by a factor of 3 to V = 300 kV (I = 21 MA), the output is 6.5×10^{16} D-D neutrons per pulse = 6.5×10^{18} D-T neutrons per pulse = 18 MJ per pulse. The nuclear energy released per pulse will thus exceed E (input energy) by a factor of 2.

With the recycling of about 50% of the energy ($\sim E/2$ left in the storage capacitance after each cycle) at 1 pps the average power consumed for the 100-kV, 1-MJ operational level will be 0.5 MW. The average neutron production will be 3×10^{16} n/s, which is an average output power of 85 kW. Thus, on the average it is 17% of break even. The capacitor and the switches of the proposed bank are designed conservatively enough to stand a repetition frequency of more than 1 pps. Therefore, if the user wishes, an average yield of 3×10^{16} D-T n/s can be attained. The capacitor is also designed to operate at V = 300 kV at reduced repetition frequency. The user could then expect about 7×10^{18} neutrons per pulse.

The plasma focus will remain a point source. However, the SFG device proposed by LLL circumvents the well-known window and access problems, which have seriously curtailed the usefulness of the coaxial DPF as a testing device. The decision of the Euratom fusion group to use a Filippov-type, repetitively pulsed plasma focus for material testing was probably founded on similar considerations.

The LLL SFG now being designed will be used for exploratory research work and component testing for the proposed rapid-pulse system. However, when such a testing device is built it must have well-cooled electrical components, remote handling, control systems, high-capacity power supply, tritium-handling facility and about six feet of radiation shielding.

Energy Coupling to Pinch

As stated before, we would like to maximize the current in the machine. Let us assume that the plasma sheet runs down with a constant velocity and that the gun's inductance L_g varies linearly with distance and thus with time. If a constant voltage source V is applied across such a linearly changing inductance, we will obtain a constant current $I = V/\dot{L}$ where $\dot{L} = dL_g/dt$. Thus, maximizing V and minimizing $\dot{L}$ will maximize the current. $\dot{L}$ can be minimized by reducing the gun's inductance and increasing the rundown time. The rundown time can be increased by increasing the gas pressure. However, it has been shown experimentally that rundown time should be less than 3 μs.

If the residual inductance L_B is not zero as assumed earlier, then it will limit the current since in a purely inductive circuit we have $V\tau = L_B I$. Thus reducing L_B and increasing V and τ will increase the current. With these considerations in mind, we designed a high V, low L_B, low $\dot{L}$ system that will maximize the current while keeping the energy reasonably low.

Making a constant-velocity assumption in the SFG, yields $\dot{L} = kv/r$, where v is the sheath velocity, r is the instantaneous radius of the sheath, and k is a constant. A further advantageous modification is to monotonically decrease the electrode spacing in the SFG, thus obtaining an even smaller $\dot{L}$. Figure 5 shows these three basic geometries and their inductance versus time curves.

Figure 6 shows a computer calculation of the proposed capacitor-bank source for these various inductance versus time curves of the load. It is important to realize that the final collapse in the coaxial system really corresponds to the later stage of the Filippov pinch. Thus, the proper comparison of current should be where the SFG radius equals the inside, coaxial gun radius. The corresponding values (I_m) are 6 MA for the coaxial gun and 7.8 MA for the Filippov. The current decrease beyond the maximum current point does not represent a decrease in stored magnetic energy until point B in Fig. 6. After point "B" in time a radial collapse of the current sheath occurs causing a great increase in energy density. However, the rate of work done on the plasma exceeds the rate of energy input from the bank and the total energy in the plasma decreases. During the rundown and the early part of the pinch, flux is conserved. Anomalous resistance (flux destruction) occurs later in the pinch.

The foregoing discussion illustrates some basic operational characteristics of the plasma focus that can be exploited in the SFG we are proposing for material and component testing. This proposed configuration is shown in Fig. 7. Some of the advantages of this system are discussed in the following sections.

Favorable Inductance

As mentioned earlier, in a coaxial gun the increase in inductance in the rundown phase is linear with distance. If the plasma sheet progresses at constant speed, the rate of increase of inductance is constant.

In the Filippov we have a radial rundown. Since the inductance varies with the log of the radius, $\dot{L}$ will vary with r^{-1}. This behavior was shown in Fig. 5. Initially the SFG inductance varies slowly. Hence $\dot{L}$ is small at the time the voltage on the capacitor is largest, allowing for a rapid buildup of current. Close to pinching, $\dot{L}$ eventually becomes very large after the gun has received most of its energy from the capacitor, and therefore it does not affect the energy transport to the gun. A Filippov geometry with monotonically decreasing spacing is also shown. This geometry affords the highest current buildup.

Lower Initial Current Density

A 1-MJ coaxial gun would have a center (anode) electrode about 9 to 10 in. in diameter, whereas a Filippov device of the same energy would be more than three times as large. Thus, the breech current density of the Filippov gun would be about 30% of the coaxial gun for the same energy. This reduced current density will reduce problems of insulator erosion and restrike.

Low Pressure Operation

Low pressure operation has always been associated with a fast collapse and enhanced electron burst in plasma focus machines. One of the characteristics of the Filippov device is its low-pressure operation. In principle the low-inductance SFG system should result in large improvements in current sheet-collapse velocity and the intensity of the electron burst, all of which are enhanced by lower pressure.

Larger Target Area and Plasma-Focus Accessibility

One of the major limitations in utilizing the plasma focus as either a neutron or x-ray testing device is the destructive character of the effluent from the focus, and the difficulty of placing samples near the focus. In the parlance of those interested in testing, this has become known as the "window problem." The SFG has greatly reduced these limitations. Reference to Fig. 7 shows how samples can be placed on either side of the focus in the SFG. We have conducted experiments with rolls of deuterated polyethylene (CD_2) foil where a new surface is exposed on each shot. There are no basic technological problems in producing foils with equal mixtures of CD_2 and CT_2. Metal foils would be useful in those cases where enhanced x rays are desired.

With the 1-m diameter center electrode, samples of various sizes can easily be positioned to within a few centimeters of the focus in a region outside of the discharge chamber, remaining uncontaminated by tritium. Or, for large area irradiations of test reactor wall materials in a realistic plasma environment, the center electrode can be made of the test material and receive the full plasma and x-ray bombardment in addition to the neutron irradiation. At a neutron yield of 3×10^{16} per shot, areas of a few square centimeters can be irradiated to 6×10^{14} n/cm^2 per shot. This presupposes a point neutron source at a distance of 2 cm. At 1 pps, the average neutron flux would then be 6×10^{14} n/cm$^2\cdot$s. If the tests require 10^{14} n/cm$^2\cdot$s, the test sample can be placed 5 cm from the source.

In conclusion, it appears reasonable that a plasma-focus testing facility based on the SFG concept could be developed that would produce $> 10^{16}$ n/s over long periods of time. It appears that only hard work and adequate funds are necessary to reach the goals outlined. A factor of major importance is that no highly uncertain extrapolation of yields or basic physics is required to reach the goals indicated. The problems, while very tough, are primarily technological in nature. It is obvious, however, that a vigorous research program on our present SFG device could well lead to significant improvement in the performance of an actual testing device.

ENERGY SUPPLY (CAPACITOR BANK)

There are several special requirements that must be met by the fast capacitor-bank system. The bank must deliver in a few microseconds 1 MJ of energy at 100 kV at least once per second for upwards of 10^7 shots. A continuously operated 1-MJ, 100-kV, 200-μF, low-inductance (∿5 nh) capacitor bank introduces considerations that are usually neglected in the design of a single-shot capacitor bank such as those used in all of the currently operated plasma-focus machines. The continuous operation at 1 pps requires that component lifetimes be increased by several orders of magnitude. The problem of heat dissipation by the components is now of great importance and must be an integral part of the design. The low-inductance requirement of the design will be difficult to achieve with current techniques, as the volume of the bank will be greater.

To see how all of these considerations are interrelated, let us consider first the high voltage requirement. The maximum permitted electric field between the foils of a capacitor is approximately 160 MV/m (= 4 kV/mil). At this electrical stress, the corona from the sharp edge of the foil carbonizes a path between the edges of the foils in the staggered foil construction normally used. This corona limits the lifetime of the capacitor to about 1000 shots.

With continuous operation at 1 pps, millions of shots will be required. Hence, the capacitor design must use an electric field low enough to eliminate the corona, namely 40 MV/m (= 1 kV/mil).

Since the electrostatic energy density is proportional to the electric field squared, the reduction of the electric field stress in the dielectric from 4 kV/mil to 1 kV/mil will require a 16-fold increase of the volume of the capacitor dielectric to store the same amount of energy.

A small fraction of the energy stored in the capacitor is dissipated as heat in the conducting foils because of the high-discharge currents flowing when the capacitor is discharged. With continuous operation at 1 pps, conventional capacitors would soon succumb to thermal runaway and be destroyed. Obviously the surface-to-volume ratio of the capacitor units must be greatly increased. The question that now confronts the designer is, can such a large high-voltage capacitor with large surface-to-volume ratio be built and still satisfy the low-inductance requirements? The answer is yes. But to achieve this goal the design must utilize new and improved techniques that are not customarily available in conventional capacitor design.

The solution proposed is described in another report [1]. The design utilized an integral approach making the load, transmission line, switch and capacitor a single unit. The design provides a continuous, unobstructed energy flow from capacitor plates to load. The low-source inductance required was achieved by eliminating all possible volumes where the mutual magnetic field could penetrate. The switches proposed are light-activated solid-state devices and represent a breakthrough in longevity and average power handling needed for this application.

A schematic view of the bank system is shown in Fig. 8.

REFERENCES

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2. V. S. IMSHENNIK, N. V. FILIPPOV, and T. I. FILIPPOV, Nucl. Fusion, 13, 929 (1973).

FIGURE CAPTIONS

Fig. 1. Neutron yields n versus E, assembled by H. Rapp with additions by authors of this paper.

Fig. 2. D-T energy output per pulse versus peak current for several machines.

Fig. 3. Neutron yields *n* in relation to capacitor energy E and voltage V. Dashed line represents $\sim V^8 \sim I^8$.

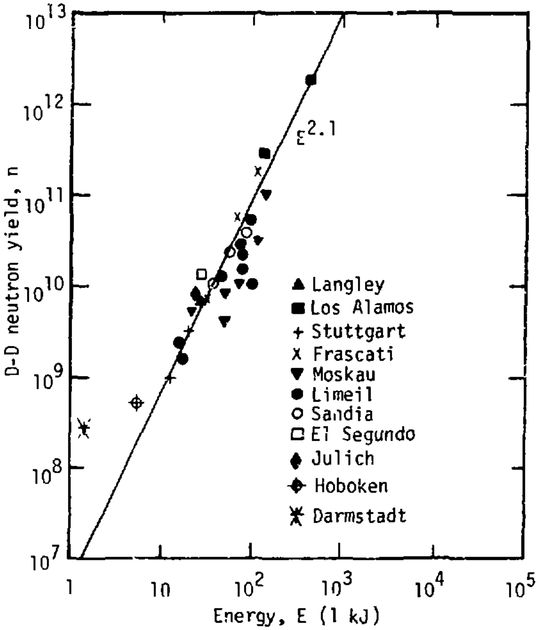
Fig. 4. Los Alamos data for a 212-kJ machine. Line in (a) represents $\sim V^5 \sim I^5$ and lines in (b) represent $\sim E^2 \sim V^4 \sim I^4$.

Fig. 5. Inductance versus time for various geometries

Fig. 6. Calculated load current for various inductance versus time curves of the load.

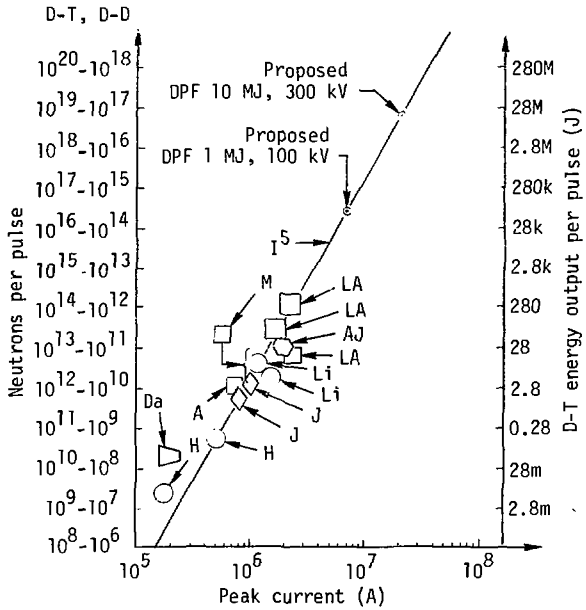
Fig. 7. Sigma Filippov geometry electrode structure showing tungsten-copper alloy feed bars at locations of high current density.

Fig. 8. Schematic of the bank system.



10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
D-D neutron yield, n
$E^{2.1}$
Langley
Los Alamos
Stuttgart
Frascati
Moskau
Limeil
Sandia
El Segundo
Julich
Hoboken
Darmstadt
1
10
10^{2}
10^{3}
10^{4}
10^{5}
Energy, E (1 kJ)

Zucker - Fig. 1


D-T, D-D
Neutrons per pulse
10^{20}-10^{18}
10^{19}-10^{17}
10^{18}-10^{16}
10^{17}-10^{15}
10^{16}-10^{14}
10^{15}-10^{13}
10^{14}-10^{12}
10^{13}-10^{11}
10^{12}-10^{10}
10^{11}-10^{9}
10^{10}-10^{8}
10^{9}-10^{7}
10^{8}-10^{6}
Proposed DPF 10 MJ, 300 kV
Proposed DPF 1 MJ, 100 kV
I^5
M
LA
LA
AJ
LA
Li
Li
J
J
H
H
A
Da
280M
28M
2.8M
280k
28k
2.8k
280
28
2.8
0.28
28m
2.8m
D-T energy output per pulse (J)
10^5
10^6
10^7
10^8
Peak current (A)

Zucker - Fig. 2

Legend

AJ Aerojet Nucleonics: D. Lafferty, D. Gates and K. Hinrichs. 250 kJ, 20 kV, 320 μF.

Da Darmstadt: L. Michel, K. H. Shonbach and H. Fischer, "Neutron Emission From a Small Plasma Focus," Appl. Phys. Lett., 24, 57 (1974). 0.34-1.35 kJ, 10-20 kV, C = 6.7 μF, "zero inductance" 24 nH, circuit frequency 400 kHz, Mather-type gun length 10 cm, diameters 5 and 1.6 cm, hollow center electrode.

H Hoboken: W. H. Bostick, V. Nardi and W. Prior. Electrode structure is identical to that of Darmstadt group. 14-18 kV, C = 6 μF, hollow center electrode. This plasma focus is now in operation at the University of Buenos Aires.

H Hoboken: ∿5 kJ, 45 μF, 14 kV, time-to-current peak 1.8 μs, Mather-type gun, length 14 cm, diameters 10 and 3.4 cm, hollow center electrode.

A^E Aerospace: Bernsteim, Phys. Fluids, 13, 2858 (1970).

J Julich: Cloth. 25 kJ, 40 kV, C = 22.4 μF, center electrode 3 cm long and 6 cm in diam, outer electrode 11 cm in diam.

Li Limeil: A. Bernard et al. Phys. Fluids, 18, 180 (1975). 96 kJ, 40 kV, "stray inductance" 27 nH, 1/4 cycle time 2.5 μs.

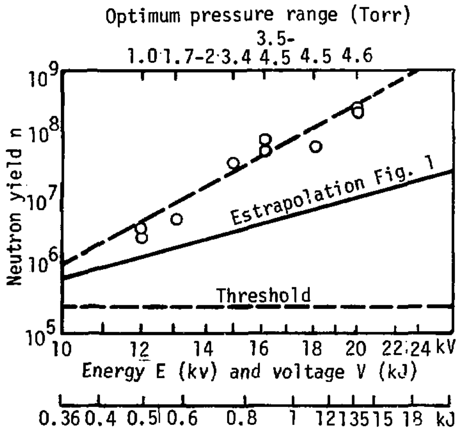
Li Limeil: Proc. International Conference on Energy Storage, Compression and Switching, Torino, Italy (Nov. 1974). Plasma Focus is driven by an explosive generator.

LA Los Alamos: J. Mather, K. D. Ware et al. DPF 6, 420 kJ. See Fig. 4.

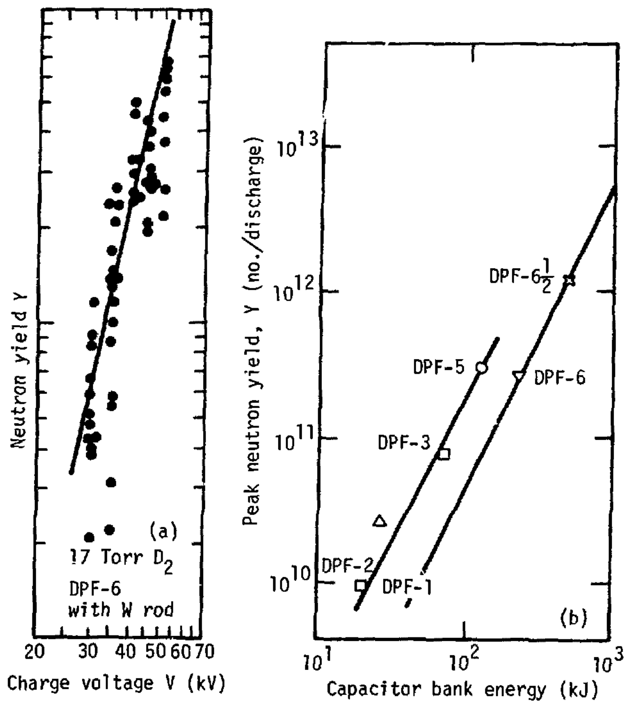
LA Los Alamos: DPF 5, 120 kJ. See Fig. 4.

LA Los Alamos: D. A. Freiwald and J. M. Dowing, "A Survey of a 210 kJ Dense Plasma Focus (DPF 6)," USERDA Rep. LA-5635-MS, Los Alamos Scientific Laboratory (May 1974). See Fig. 4.

M Moscow: Gribkov et al., "$Y \to 10^{10} - 10^{11}$ DD neutrons, I = 1 MA."

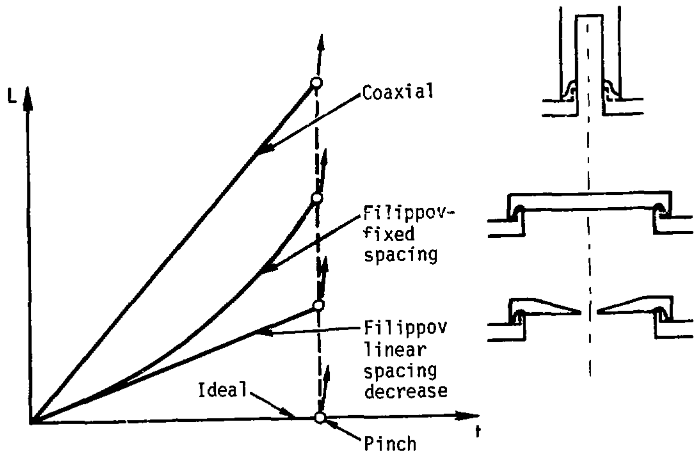

Optimum pressure range (Torr)
3.5-
1.0 1.7-2 3.4 4.5 4.5 4.6
Neutron yield n
10^9
10^8
10^7
10^6
10^5
Estrapolation Fig. 1
Threshold
10 12 14 16 18 20 22 24 kV
Energy E (kv) and voltage V (kJ)
0.36 0.4 0.5 0.6 0.8 1 12 13.5 15 18 kJ

Zucker - Fig. 3

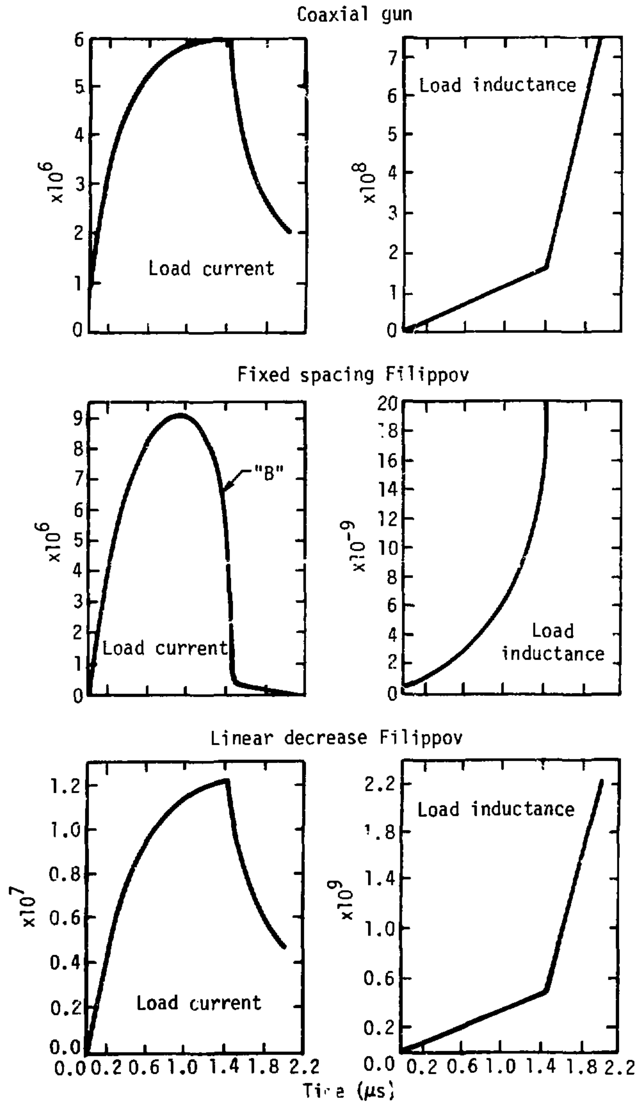


Neutron yield Y
(a)
17 Torr D2
DPF-6
with W rod
20 30 40 50 60 70
Charge voltage V (kV)
Peak neutron yield, Y (no./discharge)
10^13
10^12
10^11
10^10
DPF-6 1/2
DPF-5
DPF-6
DPF-3
DPF-2
DPF-1
(b)
10^1 10^2 10^3
Capacitor bank energy (kJ)

Zucker - Fig. 4

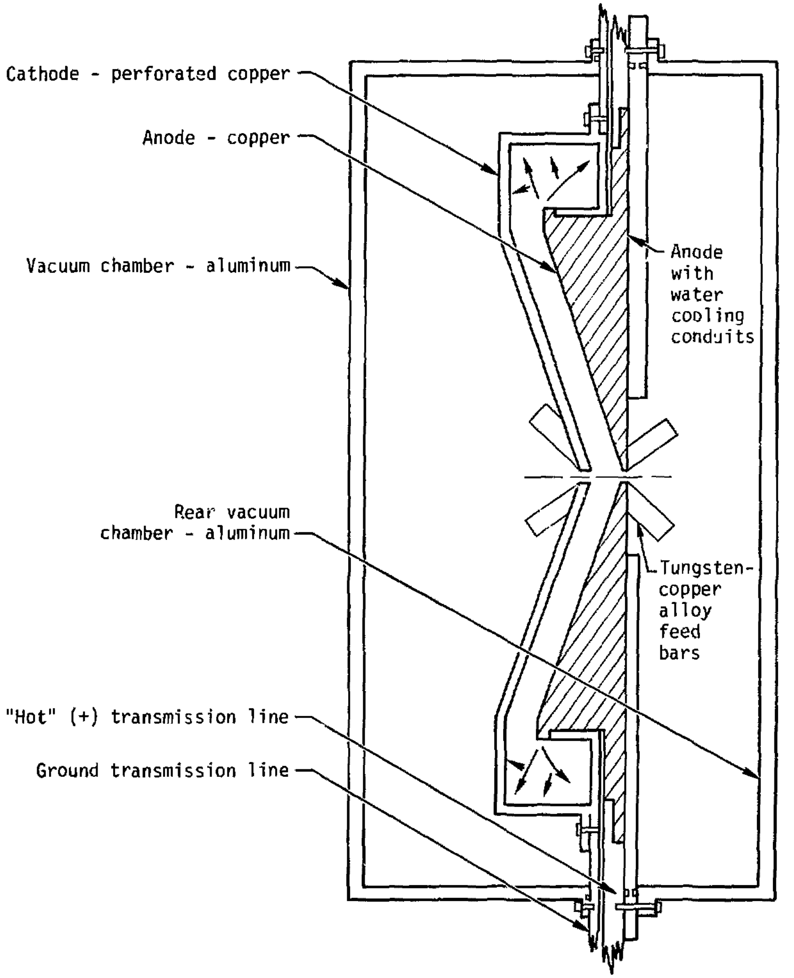

L
Coaxial
Filippov-
fixed
spacing
Filippov
linear
spacing
decrease
Ideal
Pinch
t

Zucker - Fig. 5

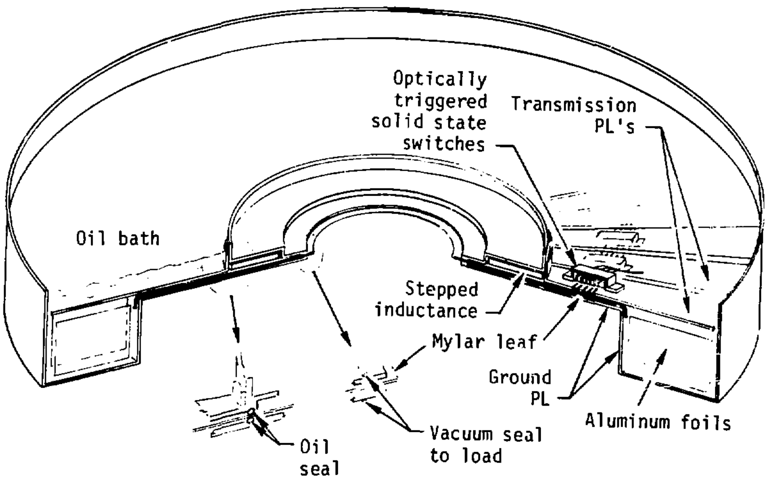


Coaxial gun
Load current
x10^6
Load inductance
x10^8
Fixed spacing Filippov
"B"
Load current
x10^6
Load inductance
x10^-9
Linear decrease Filippov
Load current
x10^7
Load inductance
x10^9
0.0 0.2 0.6 1.0 1.4 1.8 2.2
Time (μs)

Zucker - Fig. 6


Cathode - perforated copper
Anode - copper
Vacuum chamber - aluminum
Anode with water cooling conduits
Rear vacuum chamber - aluminum
Tungsten-copper alloy feed bars
"Hot" (+) transmission line
Ground transmission line

Zucker - Fig. 7


Optically
triggered
solid state
switches
Transmission
PL's
Oil bath
Stepped
inductance
Mylar leaf
Ground
PL
Aluminum foils
Vacuum seal
to load
Oil
seal

Zucker - Fig. 8

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