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Review of Dense Plasma Focus Technology for Intense and Directional Neutron Sources

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Abstract

We believe the Dense Plasma Focus (DPF) has possible applications as a unique high intensity neutron source when compared with conventional accelerator-driven neutron generators or ^{252}Cf isotope-based sources. We see two possible opportunities where DPF devices could have a major impact as an alternate radiological source in comparison with conventional technology in terms of average and especially peak neutron output, and also directional neutron emission via ~100 MV/m plasma-based acceleration gradients. Here, we briefly review DPF technology and compare it to conventional neutron generators, and present our two research prospects.

Device Description

The DPF is a compact plasma device comprised primarily of a coaxial head or gun for generating a unique class of intense z-pinch plasmas. A moderate to high-power pulse forming network (PFN) initiates the plasma and drives the pinch effect. The coaxial gun itself is physically small; the electrodes typically have sizes on the order of ~10 cm and the total size of the system is normally dominated by the PFN. While physically and operationally simple, these devices have been studied for over ~40 years worldwide as possible fusion reactors and intense neutron machines, and yet have still to be fully understood and characterized. The DPF has been shown to be a copious source of pulsed x-rays, ion and electron beams, and neutrons [1-32]. Acceleration gradients of ~100 MV/m due to non-linear processes have also been observed in these plasmas. The physics behind the rather remarkable intensities and beam energies obtained in the pinch remains obtuse. Although the mechanisms of plasma formation, beam creation, and neutron production are not completely understood, significant amount of empirical, experimental, and modeling information is available to guide the design of DPF neutron sources [e.g. 33-35]. Table 1 summarizes the parameters of several DPF devices compared to some conventional accelerator and isotope based neutron sources and shows that they are not only competitive, but in some cases superior in their output.

In typical DPF operation, illustrated in Figure 1, plasma current sheets in a coaxial configuration or gun are first formed from flashover breakdown along insulator surfaces on the inner electrode and accelerated forward through **J** x **B** forces. A fill gas at the Torr level is normally used. At the end of the coaxial gun, the sheets expand and collide to form a ~cm long high density (n_e~10^{19}-10^{20}/cc, T_e~1-10 keV) z-pinch plasma on the tip of the inner electrode. In this region, the z-pinch is typically confined for ~100 ns and intense x-rays, ion, and electron beams are generated through a complex combination of non-linear instabilities and other mechanisms that result in effective acceleration gradients of ~100 MV/m. Axial ion beams from the anode with energies in the hundreds of keV to MeV range have been observed in numerous experiments [9-12, 15-16, 18, 22-24, 26], especially during low pressure operation. Abundant high-energy neutrons can be emitted through thermonuclear, beam-gas, and beam-beam fusion reactions in the pinch if deuterium and/or tritium is used as the filling gas [1-6, 9, 14, 18, 24-29, 31]. Depending on the device and operating parameters, the axial neutron emission can be up to four

times greater than the radial emission [1, 4, 25]. The D-D neutron output from 10^4 to 10^{12} per ~100 ns pulse, corresponding to peak neutron outputs of ~10^{11} to 10^{19}/s, was found to conservatively scale with the pinch current to the fourth power in a range of devices powered by PFNs typically involving high voltage capacitors delivering ~100 J to ~MJ. The scaling basis is shown in Figure 1. The emitted D-D neutron energy spectra can have a wide spread; for example, energies up to ~4 MeV for axially forward neutrons were detected in a 27 kJ device [5].

Table 1: Summary of parameters for some DPF devices compared to conventional sources

Device	Average D-D n output (n/s)	Peak D-D n output (n/s)	Rep rate (Hz)	Max neutron energy[1] (MeV)	Neutron Directionality	Size w/PFN or equivalent
125 J DPF [27]	~>10^6	2×10^{13} (~50 ns)	>1.0*	~2.5-3	1 to 4 x axial/radial[2]	~portable tool chest
6 kJ DPF [28]	3×10^8	3×10^{15} (~100 ns)	~1	~3-4	1 to 4 x axial/radial[2]	~large tool chest
126 kJ DPF [2]	2×10^{10}-2×10^{11}	2×10^{18} (~100 ns)	~0.1-1.0*	~5-6	1 to 4 x axial/radial[2]	~Small office*
RFQ	~10^{10}	10^{12} (~100 μs)	100	~7	~45 deg Cone	~Small office
Neutron tube w/ Penning source[3]	~10^6	~10^9 (~10μs)	100	~2.5-2.8	Little	~large tool chest
^{252}Cf	~10^6 to ~10^9 (SF)	na	na	~5	None	<palm

[1]Estimated for ~10 x falloff from axial peak for DPF, based on available beam and/or neutron data
*Estimated to be feasible   [2]Typical ratios for DPF   [3]ATC N-250   (SF): spontaneous fission spectrum (see Smith 57 and/or Bowman 62)
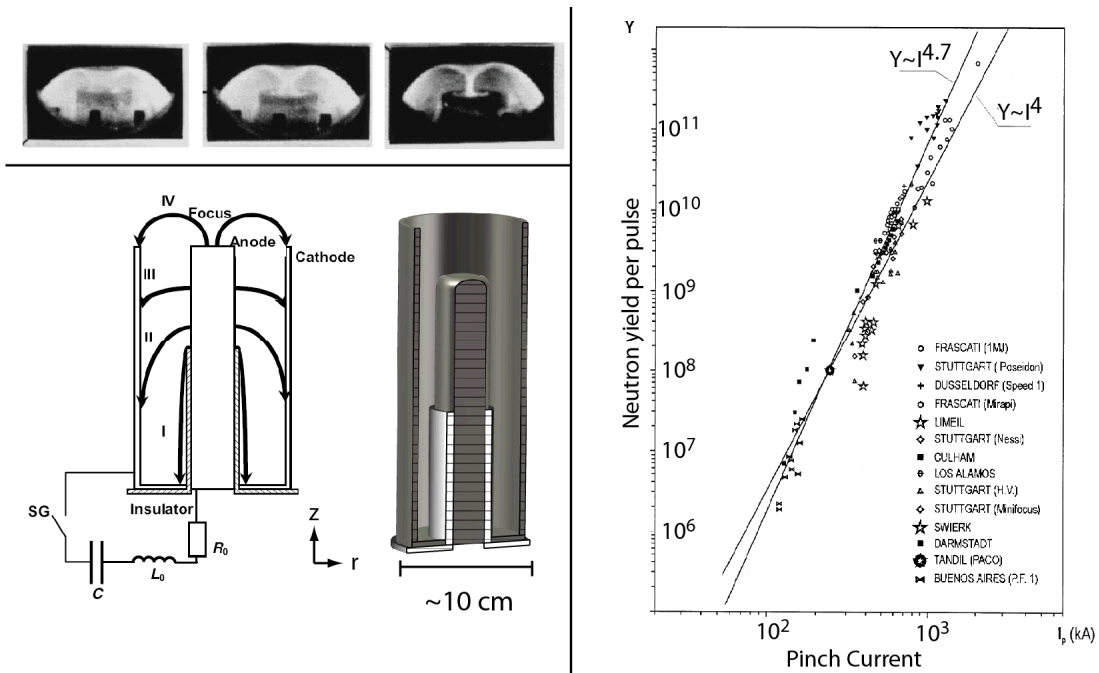

Figure 1 Left) Schematic of a dense plasma focus and its mode of operation. For reference, the axial direction refers to the z-axis. The photographs on top show the formation of the plasma from flashover of the insulator (I), followed by the sheet propagation (II, III) through collapse of the current sheets to form the pinch (IV). Right) Scaling of neutron yield per pulse for the D-D reaction as a function of DPF pinch current. [1, Pouzo, Soto]

As An Alternative Neutron Source

Straightforward engineering development of the DPF for field application would readily lead to a mobile DPF neutron source with significantly higher peak and average neutron output (and energy) compared with more conventional accelerator-driven sources. Recent work in Italy [28] has already demonstrated a semi-mobile deuterium 6 kJ plasma focus operating at 3×10^8 n/s using a repetition rate of 1 Hz, giving a peak neutron output exceeding ~10^{15} n/s. Hundreds of

successful shots per day were performed to test the reliability and repeatability of this device. The authors believe that given the research-oriented design of their PFN, conventional optimization of it for mobility would make their device readily portable. Another candidate is the significantly more compact 125 J device chargeable by a tractor battery [27] which demonstrated output up to $\sim 10^6$ n per 50 ns pulse giving a peak neutron intensity of $\sim 2 \times 10^{13}$ n/s. The neutron output of this smaller device is favorably above the neutron-pinch current scaling law. Existing DPF machines with their PFN have thus shown average neutron outputs up to a two orders of magnitude greater than conventional neutron generators based on Penning sources of approximately the same size, and peak neutron output up to six orders of magnitude larger. This is partly because the non-linear beam acceleration in the pinch region leads to higher energy ions which are much closer to the peak of the D(d,n) cross section. Also, as mentioned, the neutron output can be axially favored. Compared with isotope sources of similar output, the advantages of the DPF are compelling in terms of possibly reduced shielding, source radioactivity, and pulsing capability. We therefore believe that an optimized mobile DPF source based on demonstrated experimental results could meet or exceed the performance of available source technologies, especially in interrogation schemes that favor extremely short pulses or high peak and average neutron output. If the device could be optimized to deliver greater currents of high energy ions, larger semi-mobile DPFs at $\sim 10^{11}$ n/s output could be favorable for various schemes, such as significantly shortening irradiation time for cargo interrogation.

As An Advanced Accelerator Technology

Another intriguing opportunity is the possibility of optimizing axial beam production in a DPF for providing MeV beams for a compact directional neutron source and other applications. This work would attempt to better understand and take advantage of the DPF's demonstrated ~ 100 MV/m acceleration gradients. Generating higher energy ions allows more directional neutrons to be created via the kinematics of the D-D reaction, or through threshold kinematic reactions like p-Li if a near mono-energetic proton beam can be produced just above threshold energies. The majority of work done so far has been primarily for neutron optimization in the pinch, not necessarily ion beam production and acceleration. Experimentally, on smaller devices with capacitor energies in the kJ regime, the measured axial ions have energies in the low hundreds of keV range [11, 24, 26]. On larger devices with capacitor energies in the 10-100 kJ range, such as the Livermore DPF, $\sim 10^{14}$ ions with energies greater than 330 keV were detected for each pulse. Roughly 10^{12} of those ions had energies greater than 5 MeV. These measured ion beam data for the Livermore device and the device configuration are shown in Figure 2.
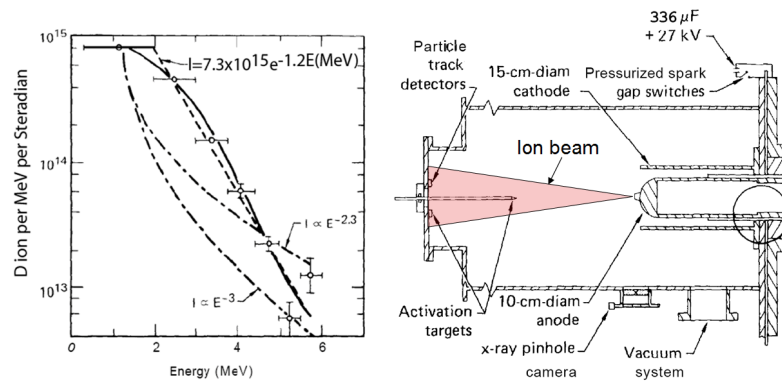

Figure 2) Axial beam spectrum from the Livermore DPF and the associated experimental geometry [10]. The device operated in the late seventies. [2]

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Incorporating a deuterated target into the Livermore device to better utilize these MeV level deuterons could have resulted in an additional $\sim 10^7$-10^8 forward directed neutrons per pulse**.** For this ion beam optimization approach, we propose first modeling and understanding in detail the DPF formation, beam creation, acceleration and collisional processes in order to numerically optimize the DPF for MeV level axial beam production and to examine if and how more qausi-mono-energetic beams can be created. Modeling could be approached through a linked series of circuit, magneto-hydrodynamic and particle-in-cell simulations [32, 36-42] to provide insight into the inner workings of the pinch which could not be performed in detail 20-30 years ago due to computational resource limitations. This simulation approach combined with today's computational power would allow us to study more complex scenarios, such as stacking of multiple DPFs with hollow electrodes for a multi-stage plasma based accelerator. If significant amount of MeV level beams could be produced from a DPF at the $\sim$kJ power supply level, a truly ultra-compact and portable directional neutron source should be possible. In addition to compact directional neutron production, remarkable opportunities for accelerator technology exist if the DPF can be used as the basis for a $\sim$100 MV/m plasma accelerator.

Conclusion

The DPF thus holds significant promise for compact neutron sources compared with conventional technology. Mobile sources with peak neutron outputs exceeding $\sim 10^{15}$ n/s should be feasible with some engineering development. Successful optimization of the DPF for axial beam production could allow intense directional neutron sources utilizing plasma-based accelerating gradients of $\sim$100 MV/m.

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