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COMPACT SOURCES FOR ENERGETIC PARTICLE-BEAM GENERATION*

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Summary

A compact plasma source for energetic particle beam generation that is compatible with inductive energy storage systems is described. The plasma production and beam generation phases are separated into independently controlled functions in order to provide additional flexibility for improving the effeciency of beam production. Several experiments that suggest possible plasma sources and mechanisms for beam production are also discussed. Using this technique in conjunction with the Suzy II 0.5 megajoule bank at NRL, it appears possible to obtain megampere beams with particle energies in MeV range.

I. Introduction

Several methods have been developed for generating high current electron beams with relativistic energy in a range of 100 to 10,000 keV in conjunction with heating of inertially confined fusion pellets,[1] simulation programs,[2] excitation of laser media[3] and for production of intense microwaves.[4] Most commonly, these methods use cold[1] or thermionically emitting diodes,[5] fast z-pinch plasma[6,7] or dense plasma focus (DPF)[8] to produce electron beams with current densities that in some cases can exceed 10^6 A/cm^2. A common feature of most of these methods is the presence of plasma in the accelerating anode-cathode gap region that is needed to produce high current density beams. Such plasma is formed at both electrode surfaces even in field-emission diodes where, as in other types of sources, it is also associated with the formation of large currents of ions.[9,10]

The main interest in generating intense electron and ion beams is in depositing them on a suitable (fusion) target. Because the pulser beam current capacity is limited, modular beam sources are used, requiring transport channels to be formed and integrated with the particle source, i.e., connecting the source and the target. For example, electron beam injection into high density plasma channels has been used to combine outputs of several generators onto a single target surface.[11] Similarly, a thoroughly analyzed method for generating, focusing and transporting ion beams which includes pulse time compression has also been worked out and many of its aspects tested at hundreds of kA level.[10] The logistics problems associated with the power density limitations of existing pulsers may be reduced by using higher density storage and a compact beam-producing source. High energy density inductive storage systems, with large energy capability, have the potential of being developed for use as high power pulsers;[12] thus, the study of an inherently compact beam source compatible with such storage systems is of interest.

The efficiency of production of particle beams varies broadly. Typically, in applications at high power level (multi-terawatt), of interest to fusion, the efficiency (ratio of beam energy to generator stored energy) is in the range of 30% for conventional field emission diodes and less than 5% for dense plasma focus devices. The different efficiencies are not a result of the distinct beam generating mechanisms, but because of different methods of the plasma formation, e.g., a substantial amount of pulser energy is used in the plasma run-down phase in DPF devices.[8] When the pulse time is reduced to that common for high power field emitting diodes (typically, 100 nsec) the beam production efficiency is also high, as was shown in experiments using exploded wires to generate the plasma in the diode region.[6] Although the beam formation times are mechanism dependent, in practice they tend to be the same in many of the approaches--of the order of 10-100 nsec -- because of rapid plasma closure short circuiting the anode-cathode gap in diodes and, for example, short inductive (L/R) times in DPF devices.

In this paper a concept combining the attractive features of inductive storage with the compact nature of plasma sources for particle beam production is described. We review some experiments which suggest such plasma sources and extrapolate to possible beam parameters attainable with the Suzy II 0.5 megajoule bank at NRL.

II. Compact Plasma Source of Particle Beams

A. General Description

As discussed in the next section, in many experiments particle beams are obtained from plasma sources.[6-8,13-15] The DPF[8] and z-pinch[6,7] use magnetic fields generated by the discharge current to sufficiently compress the plasma in order to generate either an inductive (rate of change of load inductance, dL/dt or, alternatively, rate of current interruption, L(dI/dt)) or resistive (onset of instability) voltage which serves as the beam accelerating voltage. Limits on the range of beam current densities, pulse lengths, and particle energies depend on the plasma conditions which eventually manifest themselves in the generation of the beam. For example, in DPF devices the plasma conditions for beam generation may be adversely affected by poor compression resulting from excessive front thickness, voltage restrikes behind the compression front and effects of the electrode plasma.

Recent experimental results[15,16] suggest that the functions of assembling the plasma for beam production and the actual beam production can be separated into independently controlled functions. This methodology may provide a more efficient means of generating internal beams. Illustrated in Fig. 1 is one possible way to accomplish this separation. Initially, current, I_o, in a coaxial cavity is set up to generate the azimuthal field. The plasma is injected into the field free region ($B_\theta = 0$) from a separate source, e.g., a coaxial plasma gun, and is initially not disturbed by the current flow. If the cavity current return paths are fuses, as indicated in Fig. 1, it is easy to arrange for the heating of the fuses by the current to cause precisely timed vaporization, rapidly raising their resistance. The rapid change in azimuthal magnetic flux caused by the increased resistance generates a voltage pulse across the plasma leading to an axial induced field, $E_z \sim dB_\theta/dt$, across the plasma column. The current flow is transferred to the plasma column and a linear discharge established.

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*Work supported by the Office of Naval Research

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **JUN 1981**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Compact Sources For Energetic Particle-Beam Generation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory Washington, DC 20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

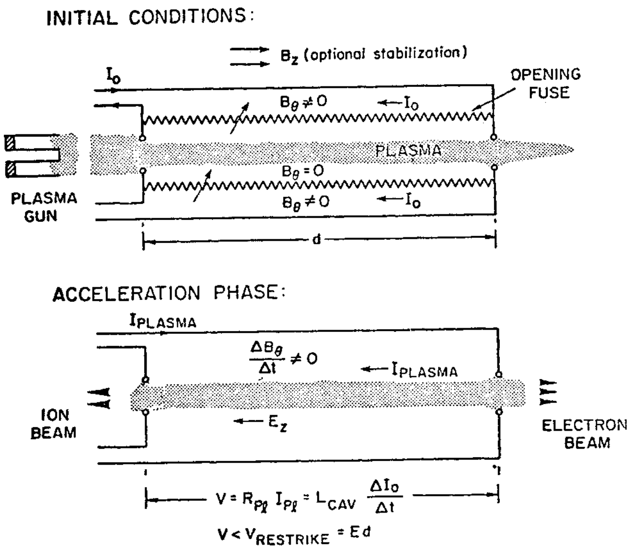

Fig. 1. Schematic representation of inductively driven plasma source of particle beams.

The actual beam generation mechanism is not depicted in Fig. 1 because one concludes from the experimental and theoretical evidence in the literature that this mechanism is not well understood and may be different for different types of experiments and plasma conditions as discussed in Section III.

B. Design Considerations

Efficient coupling of power from the inductive store to the plasma for conversion into particle beam energy requires a minimum amount of inductance between the output opening switch and the plasma column. That is, the cavity in Figure 1 sould be constructed so that the fuses are as close to a plasma column as possible. Low cavity inductance is also consistent with production of pulses with short duration required by many experiments.[1] In addition, the fuse shown in Fig. 1 must be able to withstand the inductive voltage that may in some cases be generated by plasma response to the current flow shunted through it by opening of the fuses. Studies of inductive switching have shown that sub-megajoule storage systems can provide megavolt output pulses with risetimes of about 100 nsec.[17] In these studies output pulses of up to 1.4 MV have been obtained using fuses as multi-stage opening elements.

The ability of such fuses to withstand inductive voltages generated by the plasma load, in those cases where the plasma response to current flow excites mechanisms which interrupt the inductor current, has been studied in detail.[18] Fuses exploded in air are best suited for this application because they can generate inductive fields of 10-20 kV/cm and, furthermore, have very high recovery (20 kV/cm) capability during the period when plasma response to the commutated current can be expected to occur.

The rapid current transfer ability of the opening fuses is determined by the transfer time,

$$T = IL_{cav}/V \quad , \qquad (1)$$

where L_{cav} is the cavity inductance associated with the volume inside the cylinder defined by the wire fuse array and plasma shown in Fig. 1, I is the current in the plasma, and V is the inductive voltage across the plasma generated by the fuse array. Because the value of L_{cav} increases linearly with the cavity length, the induced and recovery electric fields should be as high as possible. A specific example of the storage and plasma system is described in the last section.

III. Brief Review of Some Relevant Experiments

Many experiments are described in the literature in which particle beams have been generated from plasma sources. There are at least two (not totally unrelated) modes in which the plasma can act as a particle-beam source that depend on the plasma density. We therefore make a somewhat arbitrary, but convenient, division in low density, $n \leqslant 10^{14}$ cm^{-3}, and high density, $n > 10^{14}$ cm^{-3}, experiments.

The low density experiments include turbulent heating experiments,[13] plasma erosion switches[16] and plasma filled diodes[15] and other low density linear discharges.[14,19,20] A common feature in all these experiments is an interruption of the discharge current associated with a plasma sheath broadening usually at the negative electrode and the generation of a beam (or beams) of particles across the sheath. The sheath broadening has been studied theoretically[21] and in some cases has been associated with ion-acoustic turbulence[22] or other microturbulence.[19,20] The experiment proposed in the preceding section is expected to operate this regime if the injected plasma is of low enough density. This may be accomplished by timing the fuse opening (Fig. 1) to coincide with the presence of the low density tail of gun produced plasma between the electrodes.

Included in the high density experiments are the high density z-pinch,[6,7,23] vacuum spark,[7] and DPF[8,24]. Associated with these experiments is a rapid pinching (m=0) of the plasma which interrupts the current flow in the system and allows large voltages to be developed from the release of the stored magnetic energy. The voltage is not necessarily generated near an electrode and may be $\geqslant$ 10 times higher than the applied voltage. The actual beam formation mechanism may, however, be very similar to that discussed in connection with the lower density experiments; the plasma on either side of the pinch forming virtual electrodes. The proposed experiment may also operate in this regime if the fuses open rapidly and a m=0 instability occurs.

IV. Estimate of Possible Beam Parameters and Conclusion

The Suzy II facility at NRL when used with a typical 1 μH inductor provides a capacitively driven inductive store of $\frac{1}{2}$ LI^2 = 0.5 MJ. It generates ~ 1 MA in a risetime $(\pi/2\sqrt{LC}$, where C = 240 μf) of $\simeq$ 15 μsec. If we assume a coaxial plasma cavity of 50-cm length and ratio of fuse radius to plasma radius of 3, L_{cav} ~ 100 nH. If we further assume the wire fuses open in 100 nsec, Eq. (1) gives the voltage generated across the fuse, V $\simeq$ 1 MV. Thus, in an extreme case where all the system current is transferred to the beam and the 1 MV is maintained across the accelerating region, beam voltages of ~ 1MV and currents of ~ 1 MA may be produced. For cases where the plasma load rapidly becomes highly resistive (because of some pinch phenomenon) the current in the system will be interrupted and voltages > 1 MV will be induced. Under these circumstances voltage standoff capability of the fuses and storage system will dominate the efficiency of the configuration.

In conclusion, we have described a compact plasma source for energetic particle beams that is compatable with inductive storage. Many experiments in which particle beams were produced provide the motivation for this source. Estimates based on the Suzy II bank at NRL indicate that beams of ~ 1 MA at ~ 1 MV may be possible.

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