HIGH INTENSITY ACCELERATORS FOR ION BEAM FUSION

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Abstract

Pulselac is a compact linear inductive accelerator which uses collective methods of transport to accelerate high power ion beams for inertial fusion applications. A variety of techniques are used to make optimal use of the beams to amplify power. Power multiplication factors (focused beam power density/input pulsed power density) greater than 10^5 may be achieved. The status of Pulselac research and its application to inertial fusion are summarized.

Introduction

The Pulselac Program at Sandia National Laboratories is directed toward the understanding of high current transport in linear ion accelerators. The goal is to utilize the power multiplication capabilities of non-relativistic ion beams to achieve the high power densities necessary for inertial confinement fusion. The limits on ion beam transport set by space charge are greatly alleviated by the use of electron neutralization. Beams with current densities a factor of 10^4 above conventional experience have been generated and post-accelerated. The physical bases of the Pulselac approach have been reviewed in a number of references[1-4]. The emphasis in this paper will be on the type of pulsed power systems needed for ICF accelerators and the role of the beam as a component in the power compression chain.

There are three methods by which a non-relativistic ion beam can be used to increase the power density to a target over that available directly from the pulsed power modulators. The first is area compression, accomplished by focusing. Decreasing the angular divergence of a beam increases its focusibility. The second method, applicable to multi-stage systems, is the utilization of the beam as an energy storage element. Energy is added at medium power and voltage levels and then released quickly when the beam strikes a target. The third option for power multiplication is to decrease the energy release time by decreasing the pulselength of the beam. This can be accomplished by longitudinal velocity bunching following acceleration.

The major goal of Pulselac research is to optimize the power compression properties of the beam to reach fusion parameters without placing excessive demands on the pulsed power modulators. A figure of merit for this process can be defined as the ratio of the beam power density on target to the electromagnetic flux entering the accelerator through the vacuum insulator. Factors as high as 10^5 may be achieved.

The rationale for the high current accelerator approach to ICF is summarized in the next section. Following that, the status of Pulselac research is reviewed. To conclude, parameters are derived for fusion driver accelerators based on present experimental results.

Inertial Fusion Driver Requirements

There has been an increasing interest in the use of ion beams for driving inertial fusion reactions. Ion beams can be generated with relatively high efficiency compared to laser photons, and ions are expected to couple their energy to the target in a predictable manner, even at fusion power densities. An ion beam driver must satisfy a number of requirements for practical pellet ignition. 1) The appropriate power density must be delivered. Presently, it is expected that ignition can be achieved with 1-10 MJ incident on a sub-centimeter diameter spot in less than 20 ns. 2) The beam parameters must be compatible with the reactor chamber design. 3) The beam focal length should be long enough to provide isolation of the final lens from the target. 4) There should be a repetition rate capability (>1 Hz) and a long component lifetime. 5) The conversion efficiency of electrical to beam energy should be better than 25 per cent. 6) The accelerator should have a reasonable capital cost. 7) For engineering feasibility, the driver should have a modular structure.

Design studies have been carried out to determine if conventional accelerator techniques can be extrapolated to fusion parameters as part of the Heavy Ion Fusion Program[5]. Although this approach has considerable technical potential, it is generally concluded that conventional accelerator drivers are too complex and costly to build[6]. An alternate approach is Light Ion Fusion[7]. The idea is to utilize pulsed power technology to generate very high current light ion beams in a single-stage electrostatic accelerator. Although this approach has promise of being simple and inexpensive, there are a number of unsolved problems regarding ion sources, beam focusibility, transport to the target, and component lifetime.

A clear path toward resolving the problems of light ion fusion is to combine multiple-stage acceleration with high current transport physics. There are a number of advantages gained. 1) The lower beam current requirements alleviate demands on the ion source. 2) The beams are more resistant to self-field perturbations, and hence can be focused more accurately. 3) Post-acceleration can reduce the divergence of the beam. This increases the beam brightness and allows a longer focal length to the target. 4) The pulsed power

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14. ABSTRACT
Pulselac is a compact linear inductive accelerator which uses collective methods of transport to accelerate high power ion beams for inertial fusion applications. A variety of techniques are used to make optimal use of the beams to amplify power. Power multiplication factors (focused beam power density/input pulsed power density) greater than 105 may be achieved. The status of Pulselac research and its application to inertial fusion are summarized.

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needed in each stage is small compared to that delivered to an ion diode, minimizing damage to the components.

The advantages of intermediate mass ions compared to light ions[8] are illustrated in the graphs of Fig. 1. In proceeding from H+ to O+, the optimum beam energy for target interaction increases from 2 to 60 MeV (Fig. 1(a)). Thus, electrostatic acceleration is impractical for ions heavier than He+. The current for 100 TW of beam energy drops from 50 MA to less than 2 MA (Fig. 1(b)). The maximum focal length to assure total deposition of the energy in the target rises from 30 cm to 160 cm (Fig. 1(c)). The function F_a in Fig. 1(d) represents the fraction of reactor wall devoted to beam entrance ports. For ions lighter than He+, the entire solid angle surrounding the target must be used. For O+, the fraction is reduced to a few per cent. The factor F_m in Fig. 1(e) indicates the relative stiffness of ion beams in their self magnetic fields. There is an improvement by over four orders of magnitude in the focusibility of O+ compared to H+. Finally, it is shown in Fig. 1(f) that the ion exit velocity has little dependence on species. Thus, longitudinal bunching is a viable option for both light and intermediate mass ions. In general, intermediate mass ions offer a number of technical advantages over light ions for fusion applications. The resulting accelerator systems, discussed in the concluding section, have engineering advantages compared to conventional approaches. They are, in comparison, simple and technologically accessible.

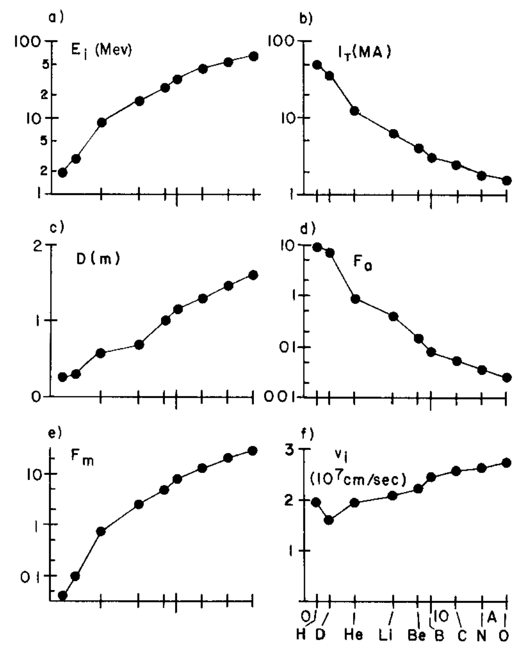

Fig. 1. Scaling of ion beam fusion driver parameters with ion species (Ref. 8).

Pulselac Research

Although present experimental multi-stage ion accelerators are far from the parameters necessary for fusion, a broad understanding of beam physics has been obtained and requisite technology developed in a series of small scale experiments. One activity in the Pulselac Program has been the development of sources to supply neutralizing electrons[9]. The pulsed sources use surface discharge plasmas to provide over 10 A/cm^2 of electrons in a 1 μs pulse. The surface area in the tests was 50 cm^2; the energy required was about 10 mJ/cm^2/pulse. Another area of research has been pulsed high-flux ion sources to supply the injector stage[10]. Considerable progress has been made beyond the simple flashboard sources prevalent in intense ion beam research. The present plasma gun uses gas injection and magnetic acceleration to supply directed velocity plasmas of a number of singly ionized ion species. Equivalent ion fluxes of 50 A/cm^2 of Ne+ have been obtained in a 1 μs pulse.

The injector stage, which accelerates ions from low velocity to 0.1 MeV is the most difficult part of the accelerator since space charge effects are severe. Through the use of a stable magnetically insulating gap geometry, it has been possible to trap electrons in the injector gap to produce ion fluxes a factor of 30 above the Child limit. The Pulselac injector was the first to demonstrate plasma flux control of the gap current and production of beams using independent anode plasma guns. A wide variety of ions have been produced (H+,C+,N+,Ne+) at current levels exceeding 5 kA[11].

Measurements of electron neutralization during propagation between gaps have indicated space charge balance to within 0.2 per cent. Post-acceleration experiments have been carried out in electrostatic systems with 2 gaps[12] and 5 gaps. Transverse focusing of beams was demonstrated by shaping the accelerating fields. The five gap accelerator produced beams of C+ ions exceeding 3 kA at 0.6 MeV with an exit divergence of only 0.7°.

Recent research has centered on Pulselac C, an inductive linear accelerator under development as a technological test bed. A diagram of the injector, one inductive stage, and a focusing chamber is shown in Fig. 2. The

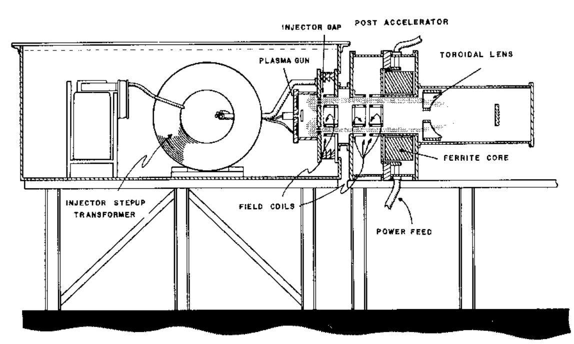

Fig. 2. Pulselac C system with a single inductive cavity.

electrostatic injector is powered by a 120 kV pulse-forming-network. Connections to the anode plasma gun are through a laminated iron core isolation transformer. Beams of over 5 kA of N+ and Ne+ (80 per cent purity) have been generated in 0.5 μs pulses.

The inductive cavity has ferrite cores capable of withstanding 250 kV in a 60 ns pulse. The cavity is driven by an independent pulser connected through commercial high voltage cables. The modulator is a 12.5 Ω water-filled Blumlein line with a gas switch command triggered by a high voltage hydrogen thyratron. Charging of the Blumlein line reverse biases the cores into saturation so that the full flux swing is available. In tests with a magnetically insulated gap with no beam load, the biasing functioned properly, and the cavity supported a 300 KV pulse. Post-acceleration tests are presently underway.

A final focusing toroidal field lens is indicated in Fig. 2. This lens has been built and tested in vacuum. The coils were fabricated using photoetching techniques. This allowed complex field boundaries to be generated to optimize focusing. The 20 element lens (with an 85 per cent transparency) was operated at 14 kG.

A variety of theoretical work on high current accelerators has been performed. This includes studies of ion beam neutralization and transport in vacuum[13,14], the operation of injector gaps with trapped electrons[15], and the longitudinal stability of high current ion beams in inductive LINACs[16]. Recent work has concentrated on longitudinal bunching of beams following acceleration. One approach is to introduce additional cavities that are shunted with an inductive load rather than being driven by a modulator. The beam current drives a positive-negative waveform that slows the beam front and accelerates the rear. The beam will then undergo velocity bunching in a subsequent drift region. Computer simulations indicate that bunching factors of 4 can be obtained, even with non-ideal current waveforms. This process would allow the generation of 10-20 ns beams even though active switching was performed only on a 60 ns time scale. A review of physical studies in the Pulselac Program is currently in preparation[17].

Fusion Driver Accelerators

It is possible, using present Pulselac experimental results and extrapolations from conventional accelerator experience, to derive parameters for fusion driver systems. Two examples will be considered: 1) a near-term experiment, Pulselac D, which would demonstrate required technology and provide a focused beam for first generation ion beam fusion experiments, and 2) a full-scale driver for an ICF power plant.

A diagram of the Pulselac D accelerator is shown in Fig. 3; parameters are listed in the first column of Table 1. The 10 stage accelerator uses ferrite core inductive cavity technology to generate a 100 kA beam. Ferrite cores, which provide a high shunt impedance, are desirable in this application since voltage pulse shaping is essential for the longitudinal confinement and stability of the non-relativistic ions. A detail of a cavity is also shown. The core size is sufficient for a 1 MV, 60 ns pulse. The cores have been arranged to allow radial stacking of voltage in the cavity. Power is supplied from two

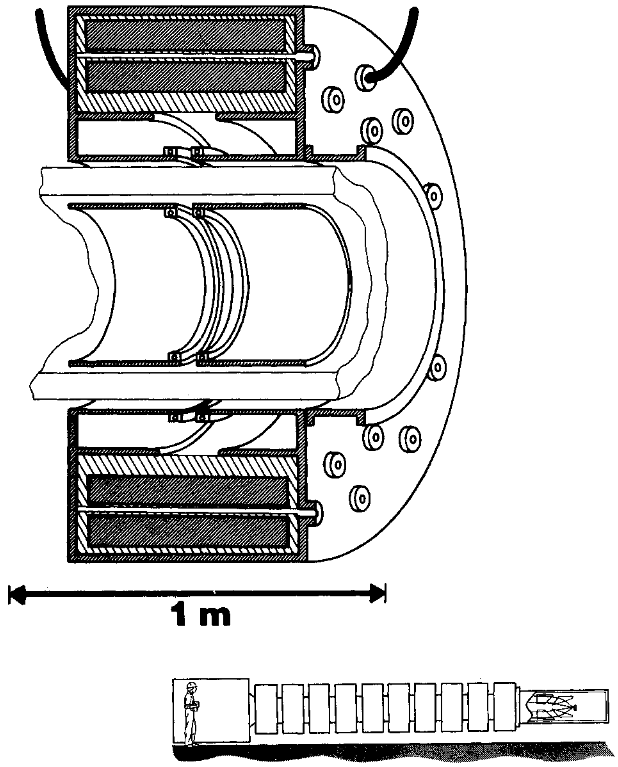

Fig. 3. Pulselac D Accelerator

Table 1. Ion Accelerator Fusion Systems

	Pulselac D	Reactor Driver
Parallel modules	1	6
Total current (before bunching)	100 kA	37 kA
Voltage per stage	1 MV	2 MV
Number of stages	10	75
Beam energy	10 MeV	150 MeV
Bunching factor	1-5	3
Pulselength (before bunching)	60 ns	60 ns
Ion species	He+	Ne+
Drift tube O.D.	60 cm	32 cm
Source ion flux	70 A/cm^2	90 A/cm^2
Injector voltage	0.2 MV	0.2 MV
Injector divergence	1.5°	1.5°
Final beam divergence	0.3°	0.08°
Final lens field	20 kG	7 kG
Final lens focal length	0.5 m	2 m
Focal spot diameter	0.5 cm	0.5 cm
Focused power density	5 TW/cm^2	130 TW/cm^2
Accelerator length	8 m	100 m
Bunching length	3.5 m	20 m

5 Ω , 500 kV modulators switched by low inductance gas-filled spark gaps. The ion He+ is suitable for the 10 MeV final beam energy. The required ion source current density, 70 A/cm^2, has already been achieved[10]. If the beam emittance can be preserved through the accelerator, a final divergence angle of 0.3° may be achieved. An 0.5 m focal length could be accomplished with a 20 kG toroidal field lens. A divergence-limited spot would then have a diameter of 0.5 cm. The power density on target is 5 TW/cm^2; longitudinal bunching may increase this to 15 TW/cm^2. Bunching is initiated in two inductively loaded cavities with a 2 MV voltage swing. Maximum bunching would occur 3.5 m from the cavities. For the accelerating cavity of Fig. 3 the power flow through the insulator is about 35 MW/cm^2. If 15 TW/cm^2 is delivered to the target, the power compression factor is 4 x 10^5. This is a significant increase over the power density supplied directly from the modulators.

Parameters for a fusion driver accelerator are given in the second column of Table 1. The aim in choosing parameters was to provide the necessary power density while de-extrapolating from the experience of Pulselac D in as many areas as possible. The accelerator consists of six parallel modules, each composed of 75 identical cavities. An energy of 2 MJ is delivered to the target at a power density of 130 TW/cm^2. The maximum focal length to a 0.5 cm diameter target is 2 m. A reactor would utilize plasma channel transport[18] for the final propagation through 5 m of reactor vessel environment. It can be shown[8] that, when multiple ionization and improved beam quality are taken into account, the intermediate mass ions can be confined by lower channel currents than light ions. The total length of an accelerator module (including the bunching transport region) is 120 m. A scale drawing of the fusion accelerator is shown in Fig. 4. Even though the accelerating gradient is conservative (1.5 MV/m), the final system is relatively compact.

To conclude, although there is much to be learned in the field of intense ion beam acceleration and transport, experience in the Pulselac Program has been encouraging. Experiments have demonstrated that the physical and technological problems of high current ion accelerators can be addressed and the beam parameters controlled. The Pulselac approach presents a feasible route to inertial confinement fusion based on existing pulsed power devices.

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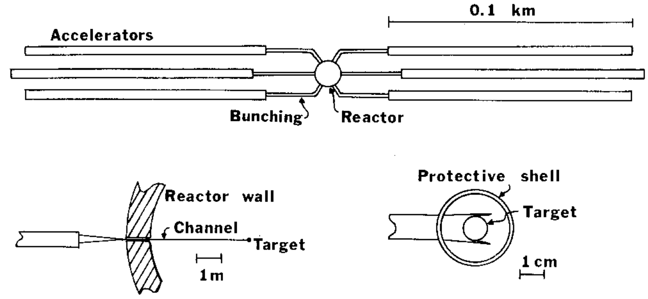

Fig. 4. Scale size of fusion reactor driver ion beam accelerator

References

1. S. Humphries, J.Appl.Phys. 49, 501 (1978).
2. S.Humphries, G.Kuswa, C. Mendel, J.Poukey, IEEE Trans.Nucl.Sci. NS-26, 4220 (1979).
3. S.Humphries, R.Anderson, J.Freeman, T. Lockner, J. Poukey and J.Ramirez in Proc. Conf. Charged Particle Optics (to be published, Nucl. Instr. Methods).
4. S.Humphries, T. Lockner and J.Freeman, IEEE Trans.Nucl.Sci. NS-28, 3410 (1981).
5. See, for instance, R.Arnold, Nature 276, 19 (1978).
6. W.Herrmannsfeldt, 1981 IEEE Conf.Plasma Sci. (IEEE, 81CH1640-2 NPS, 1981), 35.
7. See, for instance, P.Miller, D.Johnson, T. Wright, and G.Kuswa, Comments Plasma Phys. Controlled Fusion 5, 95 (1979).
8. S.Humphries, Comments Plasma Phys. Controlled Fusion 6, 45 (1980).
9. S.Humphries, J.Ramirez and M.Wilde, IEEE Trans.Plasma Sci. PS-8, 517 (1980).
10. S.Humphries, R.Anderson, J.Freeman and J. Greenly, Rev.Sci.Instrum. 52, 162 (1981).
11. T.Lockner, S.Humphries, and J.Ramirez, IEEE Trans.Nucl.Sci. NS-28, 3407 (1981).
12. S.Humphries, J.Freeman, J.Greenly, G.Kuswa, C.Mendel and D.Woodall, J.Appl.Phys. 51, 1876 (1980).
13. J.Poukey and S. Humphries, Appl.Phys.Lett. 33, 122 (1978).
14. S.Humphries, Appl.Phys.Lett. 32, 792 (1978)
15. J.Poukey, S.Humphries and T.Lockner, submitted to Phys. Fluids.
16. S.Humphries, J.Appl.Phys. 51, 2338 (1980).
17. S.Humphries, J.Poukey and T.Lockner, to be published, Applied Charged Particle Optics.
18. P.Miller, R.Butler, M.Cowan, J.Freeman, J. Poukey, T.Wright and G.Yonas, Phys. Rev. Lett. 39, 92 (1977).