GENERATING HIGH-BRIGHTNESS LIGHT ION BEAMS FOR INERTIAL FUSION ENERGY

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Abstract

Light ion beams may be the best option for an Inertial Fusion Energy (IFE) driver from the standpoint of efficiency, standoff, rep-rate operation and cost. This approach uses high-energy-density pulsed power to efficiently accelerate ions in one or two stages at fields of 0.5 to 1.0 GV/m to produce a medium energy (30 MeV), high-current (1 MA) beam of light ions, such as lithium. Ion beams provide the ability for medium distance transport (4 m) of the ions to the target, and standoff of the driver from high-yield implosions. Rep-rate operation of high current ion sources has also been demonstrated for industrial applications and could be applied to IFE. Although these factors make light ions the best long-term pulsed-power approach to IFE, light-ion research at Sandia is being suspended this year in favor of a Z-pinch-driven approach which has an excellent opportunity to rapidly achieve the U.S. Department of Energy sponsor's goal of high-yield fusion. This paper will summarize the status and most recent results of the light-ion beam program at Sandia National Laboratories (SNL), and document the prospects for light-ion IFE driver development.

1. INTRODUCTION

The generation of high current density ion beams with applied-B ion diodes showed promise in the late-1980's as an efficient, rep-ratable, focusable driver for inertial confinement fusion (ICF). In the light-ion fusion approach, beam generation and acceleration are done in one or two, short, closely-coupled regions at high accelerating gradients (0.5 - 1 GV/m) which are well above electron emission thresholds. These devices therefore require the use of several Tesla insulating magnetic fields to restrict motion of an electron sheath [1] which fills the anode-cathode (AK) gaps of order 1-3 cm, while accelerating lithium ions to generate 200 - 700 A/cm^2, 4 - 12 MeV beams on the PBFA-II, SABRE and PBFA-X accelerators at SNL. Lithium ion beams have been used to heat hohlraums to 58±4 eV on PBFA-II [2]. However, meeting the IFE driver requirements for high-brightness Li+ beams has been more technically challenging than initially thought. IFE driver-scaling issues are strongly affected by the ion beam power brightness, $B \approx P/\theta^2$, where P and θ are the ion power density and divergence respectively. An ion beam power brightness of about 0.3 GW/cm^2/mrad^2 scales conservatively to IFE requirements (600 TW delivered to a target in 10 ns) [3]. A baseline approach to this brightness involves production of a Li+ current density of 1 kA/cm^2 with a divergence of $\leq$ 20 mrad at $\approx$ 8 MeV for 20 ns in the first-stage (injector-stage) of a two-stage system. Post-acceleration of this beam at $\approx$ 22 MeV in a second stage would give about a 10 mrad beam at 30 MeV, assuming no emittance growth during post-acceleration [4], which meets the requirements for self-pinched transport [5].

Flashover sources have produced proton beams at > 1 kA/cm^2 at 17 - 20 mrad on several diodes [6,7,8], showing that it is possible to achieve both these parameters simultaneously. The results of the non-protonic experiments to date have been limited by higher beam divergence (20 - 40 mrad), lower Li+ current density (< 700 A/cm^2), and poor impedance behavior that would not couple well to a second-stage. These experiments used so called “passive” ion sources which produce nonuniform beams with large source divergence and result in electron thermal and stimulated desorption and ionization of surface and bulk hydrocarbon contamination which limits ion beam purity and causes impedance collapse [9,10]. The main problems appear to be extending an initial period of stable, acceptably low-divergence operation while simultaneously producing a high enough non-protonic current density for 20 ns.

Experimental and theoretical work over the last 6 years shows that high-brightness beams meeting the requirements for an IFE-injector could be possible, but require the simultaneous integration of at least four key conditions. These key conditions are: 1) rigorous vacuum cleaning techniques for control of undesired anode, cathode, and ion source plasma formation from electrode contaminants to control impurity ions and impedance collapse; 2) carefully tailored insulating magnetic field geometry for radially uniform beam generation; 3) high magnetic fields and other techniques to control the electron sheath and the onset of a high divergence electromagnetic instability that couples strongly to the ion beam; and 4) a pre-formed (“active”), pure, uniform lithium plasma for improved beam uniformity and low source divergence which is compatible with the above electron-sheath control techniques. These four conditions have never been simultaneously present in any intense non-protonic ion beam experiment, but we have demonstrated the effectiveness of each condition in experimental tests. A major advance in our understanding is that these conditions are synergistic and tightly-linked. We have brought these four key technologies and the underlying physics understanding together on the SABRE accelerator.

2.0 ELECTRODE CONTAMINANT CLEANING TECHNIQUES

Applied-B diodes use electric fields far above cathode plasma formation thresholds to generate intense ion beams. Energy is also deposited in anode surfaces by several mechanisms. Plasmas therefore form on anode and cathode surfaces from surface contaminants [9]. These plasmas impact impedance history, ion beam purity, uniformity and divergence. We mitigate the impact of these plasmas with cleaning techniques: reactive discharges, heating, improved base pressures, gold electrode coatings, cryogenically-cooled cathodes, hardware conditioning and others [10]. We have increased the voltage pulse width at the accelerating gap by a factor of 2 to 4, up to the width of the accelerator input pulse. This is an entry level requirement to sustain high energy and brightness ion beams. In addition to impedance collapse, production of non-Li+ contaminant ions have dominated the purity of the Li beam. Li+ current density from the passive LiF ion source has been increased by a factor of 2 with the use of cleaning techniques in three different ion diode geometries on SABRE and PBFA-X [10]. Other beneficial effects from mitigation of anode and cathode plasmas are reduction of diode electron loss and beam contaminants, and an increase in ion efficiency, power, and energy. Cleaning is also critical for the production of pure, pre-formed, Li-plasma sources and is discussed in section 5.0.

3.0 TAILORED MAGNETIC FIELD PROFILES

A carefully tailored insulating B-field and diode geometry is required to control the time-dependent radial beam uniformity [6,7,10]. A radially non-uniform beam can generate both source and wave-induced divergence as demonstrated by Quicksilver 3-D electromagnetic PIC simulations (see section 4.0) [11,12]. Beam profile control requires balancing the ion current enhancement from the electron spatial distribution and the effect of ion-feedback on electron sheath dynamics as a function of radius [12]. Anode and cathode plasmas also have a strong effect on the field profile for uniform beam production. The production of radially uniform beams has raised the ion production efficiency of extraction diodes from 20-30% to 50-80%. This control has recently resulted in a reduction of proton divergence from 26 mrad to 17 mrad [7]. A simultaneous reduction in fluctuations on the ion beam current density was also observed, possibly due to a reduction in wave-particle coupling. The combination of cleaning and uniform field profiles (e.g. key conditions 1 and 2) has increased the lithium current density and energy a factor of 4 from 125 to 500 A/cm^2 on SABRE (see Table I).

4.0 ELECTRON SHEATH AND ION BEAM ENHANCEMENT CONTROL TECHNIQUES

The electron sheath distribution across the acceleration gap influences the ion beam current enhancement above the space-charge-limit and also affects the growth-rate of electromagnetic instabilities which can couple to the beam and cause divergence. Quicksilver simulations show a high-frequency instability at low enhancement (diocotron mode) that produces < 10 mrad of ion beam divergence. One important reason to use a non-protonic ion (e.g. Li+) is that the divergence produced by wave-particle coupling in the diocotron limit is predicted to scale with sqrt(q/A) [13]. Once the electron sheath fully spans the vacuum gap, and ion beam enhancement exceeds 5-6, simulations show a transition to a low-frequency instability (ion mode) that produces large divergence, in excess of 30 mrad. This picture of wave-particle divergence growth has received strong experimental support [14,15], although some differences exist between experimentally measured electron and ion density profiles and Quicksilver predictions. SABRE results clearly show that current density fluctuations are consistent with a wave-particle coupling mechanism. High B-fields are predicted to control the charged-particle dynamics which can decrease the growth-rate and wave-particle coupling that produce divergence, by limiting charge injection rate into the AK gap.

Axial current flow is another technique to effectively control the electron sheath and ion beam enhancement and has recently been demonstrated both at Cornell University [16] and at SNL. In the SNL implementation, a small area electron beam diode on the axis of the ion diode (axial electron beam load or AEL) draws of order 25-50% of the diode current, shunting charge in parallel that would fill the AK gap. The time-integrated divergence of the ion beam with the passive LiF source is reduced from 39±8 mrad to 20±8 mrad, and the current density fluctuation level, electron loss and impurity generation are reduced. Accounting for the reduction of Li beam power by 40%, the beam brightness increased by a factor of 2. Quicksilver simulations also show a reduction of wave-particle induced divergence, fluctuations, and electron loss as on-axis current is increased.

5.0 PRE-FORMED NON-PROTONIC SOURCE

Previous work has shown that as much as half of the divergence of the LiF Li+ ion source (in quadrature) is dominated by the source [17], and that the source uniformity is poor. The generation of high brightness ion beams requires a uniform pre-formed anode plasma to improve uniformity and lower source divergence, and to be compatible with the above electron sheath control techniques (e.g. high B-fields which shut off passive sources). We have concentrated on Li+ ion sources for two reasons: 1) Li has a large second ionization energy so that production of only a single charge state in the plasma might be possible, and 2) the Li energy for coupling to an ICF target is readily achievable with current pulsed-power technology. Previous laser source experiments which required plasma formation over ≥ 500 cm^2 used a 10-20 MW/cm^2 evaporation laser with LiAg Li-bearing thin-films which produced non-uniform plasma and ion beam, and large source divergence. Small-scale experiments have shown that average Nd:Yag laser irradiances > 30 MW/cm^2 can generate non-uniform plasmas, while irradiances > 75 MW/cm^2 will give uniform plasma generation from LiAg films when illuminating at angles of 70° from normal [18]. A 90 J, 15 ns, Nd:Yag laser was developed that provides about 25-40 MW/cm^2 average irradiance over the 70 cm^2 anode areas at the SABRE accelerator. These experiments are discussed in section 6.0.

The effort to generate a pre-formed, pure Li anode plasma source for ion fusion has, in-part been dominated by the inevitable surface oxides that form when loading lithium-bearing films, and operating at pressures of ≈ 5e-5 Torr. IFE injector beam inventory requirements are equivalent to about 0.1 monolayers (ml) of Li+ ions. Since a single ionized ml can supply the entire beam inventory, control of contaminants is critical [9]. For example, we have measured more than 30 ml of hydrogen desorbed from LiAg films by the laser at 90 MW/cm^2 [18] which is reduced by a factor of 10-15 with discharge cleaning. These hydrocarbon and oxygen contaminants have quickly come to dominate the desired Li+ beam in all previous pre-formed source experiments on SABRE, PBFA-II, and PBFA-X.

6.0 PARTIAL INTEGRATION

With laser-produced sources, we have for the first time produced a pre-formed plasma layer on the anode with LiAg films. Reactive discharges and high magnetic fields were required to reduce the proton contamination in this beam (by sputtering away a LiOH layer) to a 10% level, but the heavy particle current produced from a Li_2O layer (e.g. O+, etc.) dominated the Li+ current, which was also only about 10%. This source layer is also locally nonuniform because of inadequate laser fluence to turn-on the entire anode area, and large laser nonuniformity, so source divergence could be significant. Further improvement in laser uniformity and power density is critical to achieve the best integrated performance. Nevertheless, this partial integration of the four key conditions has resulted in: 1) the first intense beam from a pre-formed source with a well-behaved, dominant, non-protonic particle current density of 400 A/cm^2, 2) a 20 ns earlier turn-on of ion current, and 3) the best impedance history that we have ever produced with an enhancement below 4 and no impedance collapse for up to 45 ns. This impedance history may be acceptable to drive the 2nd stage of a two-stage system. We have also observed that the pre-formed source layer is modified by the arrival of the power pulse at the diode and the electron sheath at the anode. Li ion source purity is still a very difficult issue. An in-situ Li deposition system for rapid anode coating, coupled with a large-area cryogenic differential-pumping system for base pressures of 7e-8 Torr has been developed and would allow a clean Li surface to be deposited just prior to the laser and accelerator firing. We have also produced a carbon beam with only about 20% proton contamination with minimal cleaning, although there is a carbon ion charge-state spread in the extracted beam.

7.0 CONCLUSIONS

There is no question that this is quite challenging plasma physics. The enormous potential payoff of accelerating particles in one or two steps at fields of 0.5 to 1 GV/m *still* makes this a worthwhile candidate for fusion. The lack of appreciation for the dominant role of the ion source, the treatment of ion sources as an engineering development issue, and the fundamentally difficult surface physics of producing a lithium source at 5e-5 Torr over areas of up to 1000 cm^2 has greatly hindered progress in the past. In addition, it was extremely difficult to develop a systematic approach to these issues on the large scale, low-shot-rate (60 shots/year) PBFA-II facility with reduced access for diagnostics.

We have pursued a physics-based development of extraction ion diodes for application to IFE-drivers on the SABRE accelerator at 150 - 200 shots/year since 1992. Significant progress has been made on accelerator-diode coupling, high-power, efficient extraction diode design, anode and cathode plasma and impedance collapse mitigation, divergence physics and control, and pre-formed ion sources in this 6 year period. For comparison, we may define a figure of merit (FOM) for an IFE injector brightness as $FOM=J\ (A/cm^2)*\tau(ns)/\theta(mrad)^2$ where J is the non-protonic current density, θ is the divergence at peak ion power, and τ is the usable pulse lengh ($\tau \approx 20$ ns is required for the main pulse, 40 ns for the foot pulse[3]). Table I shows that successively improved integration of the four key conditions has produced non-protonic beams on the SABRE accelerator with a FOM that has increased by about an order of magnitude from 0.8 to 7.3 since the first Li beam experiments in 1993. Table I also gives Li beam results from the PBFA-II experiments with a FOM of ≈ 18 at 9 MeV [14], which scales to about 12 at the 4 MeV SABRE level. An entry-level IFE injector requires a FOM>50 at 8 MeV which scales to about 23 at 4 MeV. The bold figures in Table I show where injector requirements have been met. Partial integration has produced a current density which scales to those required with a stable pulsewidth which meets requirements for both the main and foot beams. Divergence requirements were met on the PBFA-II diode which had improved beam uniformity compared to SABRE. This analysis implies beams that are within a factor of 3 to 5 of IFE-injector requirements. Divergence must be reduced by 40% to meet this goal.

Table I. Injector FOM Performance for Non-Protonic Beams

Parameter	SABRE @ 4 MV						PBFA-II		IFE Requirem.	
							4 MV[3]	9 MV	4 MV[3]	8 MV
Key Conditions[1]	none	1	2	1, 2	2, 3b	1,2,3a/b,4a	2[4]		1,2,3,4	
J (A/cm^2)	125	250	300	500	180	**400**[2]	450	700	**450**	1000
θ (mrad)	30-50		30-50		15-30	33	**22**		**20**	
τ (ns)	10		10-15		15	**20/40**	10-15		**20/40**	
FOM	0.8	1.6	2.4	3.9	5.3	7.3	11.7	17.5	23	50
Circa	1993	1994	1995	1995	1997	1998	1995			

1. Key Conditions-1:electrode cleaning, 2:uniform B-profiles, 3:electron sheath control/3a. high-B, 3b. axial load, 4:source layer/4a. pre-formed, 4b. uniform, 4c. pure
2. Not Li, but non-protonic, all other current densities quoted are Li. Error estimate on current density is ±15%.
3. PBFA-II and IFE injector current densities scaled by $V^{3/2}/d^2$ for comparison with SABRE at 4 MeV, 1.2 cm gap.
4. The uniformity for the PBFA-II radial ion diode was significantly better than for the SABRE extraction ion diode.

The production of bright ion beams requires care in diode alignment, source purity and plasma control, laser uniformity and power density, and B-field profile and magnitude. We have not achieved the level of integration of these issues hoped for prior to program suspension, and yet partial integration has resulted in some significant improvements. We have discovered nothing to show that achieving the requisite beam divergence and current density is fundamentally impossible. The recent work on the SABRE accelerator, particularly the demonstration of non-protonic ion sources with well-behaved impedance histories, forms a strong basis for further engineering and physics development for a light ion driver for IFE. Pre-formed sources allow a fundamentally new regime of diode performance to be accessed. Further progress could be made in the important areas: plasma source formation and purity, beam and source uniformity, and divergence-reduction physics, with a focused, multi-year, physics-based program at universities, on small-scale development facilities and on accelerators. Ion source/acceleration schemes for appropriate charge states of other candidate ions such as B, C, N, O should also be developed. Relevant IFE-scale injector and post-acceleration physics could be pursued on the existing SABRE and HERMES-III accelerators should a serious nationally-funded effort to develop IFE drivers be desired. Light-ion diodes also offer high-current space-charge dominated beams suitable for a physics-based modeling of the issues in heavy ion fusion final transport.

ACKNOWLEDGMENTS

The authors wish to thank Dr. D. L. Cook, and Dr. J. P. Quintenz for enthusiastic support of this research. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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