To be published: Proc. 12h Int. Conf. on High Power Particle Beams, Haifa, Israel, (1998).

The Prospect for Fusion Energy with Light Ions

T.A. Mehlhorn, R.G. Adams, J.E. Bailey, M.E. Cuneo, M.P. Desjarlais, A. Filuk, D.L. Hanson, D.J. Johnson, C.L. Olson, T.D. Pointon, S.A. Slutz, R.A. Vesey, D.R. Welch*, D.F. Wenger
Sandia National Laboratories, Albuquerque, New Mexico, 87185-1186
*Mission Research Corporation, Albuquerque, New Mexico, 87106

Abstract

Intense ion beams may be the best option for an Inertial Fusion Energy (IFE) driver. While light ions may be the long-term pulsed power approach to IFE, the current economic climate is such that there is no urgency in developing fusion energy sources. Research on light ion beams at Sandia will be suspended at the end of this fiscal year in favor of z-pinches studying ICF target physics, high yield fusion, and stewardship issues. We document the status of light ion research and our understanding of the feasibility of scaling light ions to IFE.

BACKGROUND

The primary focus of the Pulsed Power Fusion Program at Sandia National Laboratories since 1980 has been the development of intense beams of light ions for driving high yield fusion within the U.S. Department of Energy's (DOE) Inertial Confinement Fusion (ICF) Program. The funding for this effort came from the Defense Programs portion of DOE. However, progress in light ion beam physics and technology has been disappointingly slow, especially in comparison with Sandia's recent dramatic success in radiation generation using pulsed-power-driven z-pinches. The status of light ion fusion research has recently been thoroughly documented in Ref. 1. Sandia has made the decision that research on light ion beams at Sandia will be suspended this year in favor of z-pinches studying ICF target physics, high yield fusion, and stockpile stewardship issues.

Intense ion beams may still be the best option for an Inertial Fusion Energy (IFE) driver, however, the current economic climate is such that there is no urgency in developing fusion energy sources. The goal of Sandia's closeout activities this year is to perform critical proof-of-principle scaling experiments, study the scaling of the results to high yield requirements, and document the prospect of light ions for IFE in anticipation of a future expansion of DOE's IFE program.

LIGHT IONS FOR IFE

In a two-stage light ion accelerator module for IFE the divergence obtained in the first stage (injector), the divergence reduction through post-acceleration in the second stage, and the divergence that the transport system can tolerate are interdependent. Our most mature light ion concept calls for a high-contrast (10:1 ratio) shaped power pulse with a peak on-target power of ~700 TW and total on-target energy of ~14 MJ. The on-target power is supplied by twenty individual beams providing a "foot" pulse (5.4 TW each for 60 ns) and twelve beams comprising the main pulse (50 TW each for 20 ns) which, together with an internal pulse shaping technique, drive a nearly isentropic implosion of the fusion capsule [2]. The absorbed capsule energy in this design is 1.4 MJ and the peak radiation drive temperature is 260 eV. The predicted target yield exceeds 500 MJ.

Each beam is generated by a two-stage, applied-B extraction ion diode. Ballistic transport to the target requires a 6 mrad beam divergence while self-pinched transport

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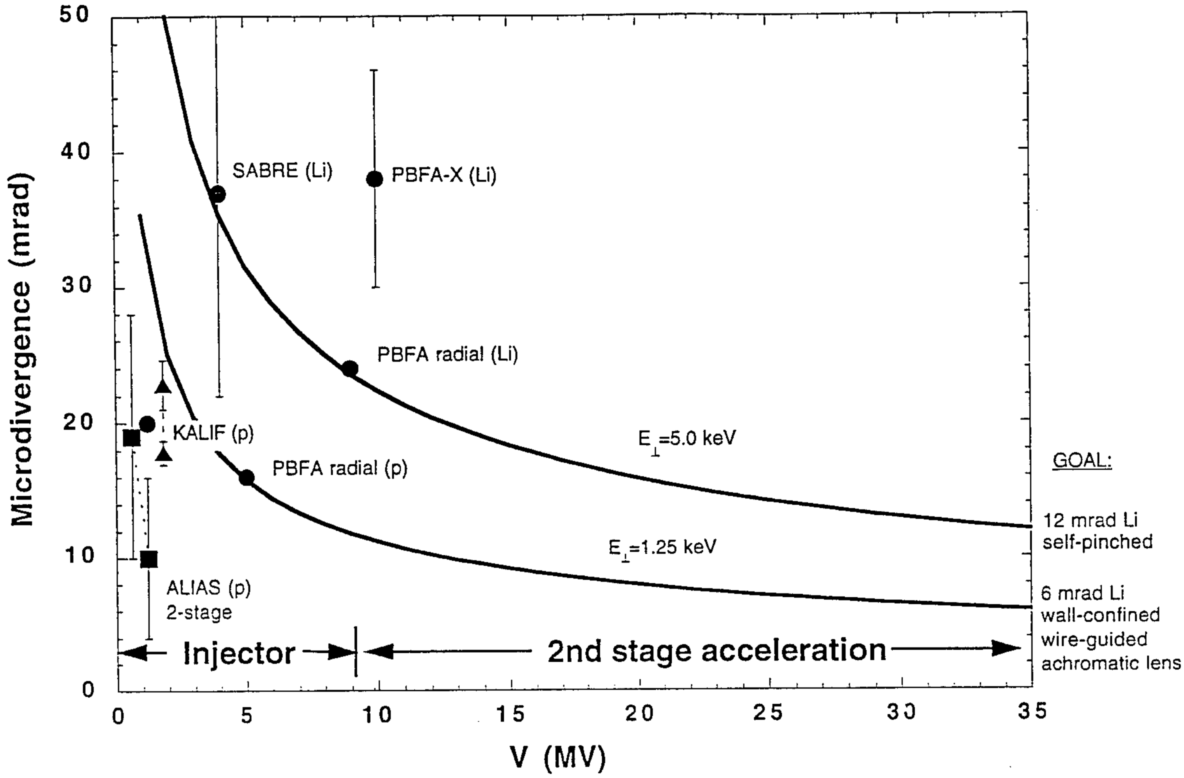

Figure 1: Ion beam microdivergence versus ion beam energy showing divergence reduction with two-stage acceleration at constant transverse energy.

could allow the divergence constraint to be relaxed to 12 mrad for a four meter standoff distance. The interrelation of divergence between injector, second-stage, and transport system is demonstrated in Figure 1.

Our IFE concept calls for (1) an injector with a lithium beam divergence of ≤24 mrad at 9 MeV, (2) two-stage diode operation at constant transverse temperature so the ion divergence is reduced to ≤12 mrad at 35 MeV and the power is doubled through time-of-flight bunching, and (3) self-pinched transport that will accept divergences up to 12 mrad. The 12 mrad and 6 mrad divergences correspond to transverse ion energies of 5.0 keV and 1.25 keV at 35 MeV, respectively. This factor of four in transverse energy emphasizes the importance of developing self-pinched transport. Following curves of constant transverse energy on Figure 1, we require a first stage injector with a transverse energy of 1.25 to 5 keV (12-24 mrad) at 9 MeV. Post-acceleration of the beam at constant normalized emittance from 9 to 35 MeV then achieves the required beam divergence. The operating parameters for the present baseline 2-stage IFE diode using lithium ions are summarized in Table 1. These parameters define the goals for intense light ion beam development.

Ion species	Li^{+1}
Peak voltage	35 MeV (9+26 MeV)
Peak ion current	1 MA
Ion power (@ diode)	25 TW
Bunching factor	2
Ion power (@ target)	50 TW
Energy	1 MJ/beam
Ion beam divergence	6 mrad (lens transport)
	6-12 mrad (self-pinched transport)
Standoff distance	4 meters

TABLE 1. IFE lithium two-stage ion diode parameters

CURRENT KEY ISSUES

The four key issues that are currently most important in determining the viability of light ions for IFE are: 1) developing a bright ion source, 2) operating a non-protonic diode in the diocotron mode, 3) generating a beam with a sufficiently stable impedance to allow time of flight bunching, and 4) testing the self-pinched transport concept.

An IFE diode will require an ion source that is capable of producing 1-2 kA/cm^2 of the desired ion species with an intrinsic source divergence of ≤10 mrad over areas of 500-1000 cm^2. Recent work at Sandia has suggested that a lithium-dominated plasma with n≥ 10^{17} cm^{-2}, and an expansion velocity of ~1-2 cm/μs can be produced with a YAG laser fluence of 0.5 J/cm^2 incident on a LiAg thin film [3]. However, contaminant species have been observed, and they will need to be controlled through electrode cleaning techniques or by in-situ lithium deposition. The issue of surface contamination is very serious for ion sources. Assuming a 1 kA/cm^2 current density for 50 ns, the ion beam draws a charge density of ~3x10^{14} ions/cm^2 from the anode surface. Since each monolayer of surface contaminants has a density of ~3x10^{15} cm^{-2}, contaminants can overwhelm the desired ion species. The subject of surface contaminants and electrode conditioning techniques is discussed in detail in Ref. 4.

Ion beam divergence is the ratio of the ion momentum transverse and parallel to the beam direction. Beam divergence can come from the ion source, nonuniformities, and transport-related processes. Electromagnetic instabilities in the virtual cathode of an applied-B ion diode can also cause ion beam divergence. QUICKSILVER simulations show that the high frequency diocotron mode causes acceptable divergence, while the low frequency ion mode causes unacceptably large divergence. The ion mode also enhances electron loss to the anode [5]. Strong magnetic insulation, uniform ion emission, and limited current enhancement are predicted to minimize ion beam divergence by sustaining diode operation in the diocotron mode. Non-linear saturation calculations for the diocotron instability [6] give the scaling:

$$\theta_d = \kappa B_0(d + x_0)\sqrt{\frac{q}{MV}} \qquad (1)$$

where B_0 is the amplitude of the applied magnetic field, d is the mechanical anode-cathode gap, x_0 is the recession distance of the gas-cell behind the cathode tip, q/M is the ion charge-to-mass ratio, and V is the diode voltage. Since Eq. 1 is inversely proportional to the square root of the ion mass, the diocotron divergences for lithium are 38% less than the proton values. While experiments at Sandia and FZK have shown diocotron-level divergence with protons, it is essential that operation of an applied-B diode in the diocotron mode be demonstrated for non-protonic ions.

IFE-equivalent divergences for lithium beams on the SABRE accelerator are ~17 and 37 mrad at 4 MeV (1.25 keV and 5.0 keV transverse energies, respectively, see Fig. 1). Diocotron divergences of ≤10 mrad are predicted for SABRE. Adding this in quadrature with a 10 mrad source divergence gives a total divergence of ≤15 mrad. The goal of Sandia's ongoing SABRE experiments is to reduce beam divergence to 15±5 mrad divergence at 4 MeV.

Light ion IFE is predicated on doubling the ion power on target by time-of-flight bunching from the diode to the target. This requires a rising diode impedance. Further, the bunched pulse length is set by the hydrodynamic acceptance time of the ICF target. This sets the initial ion beam pulse length and places further constraints on the diode impedance. Recent experiments at Cornell [7] and simulations [8] and experiments [9] at Sandia have shown that an axial current load can significantly improve the impedance stability of an applied-B ion diode by limiting beam current enhancement.

Finally, self-pinched transport experiments are being performed on the GAMBLE-II accelerator at the Naval Research Laboratories. Successful demonstration of the principles of self-pinched transport would provide an attractive IFE option that relaxes the divergence requirement of the injected beam from 6 to 12 mrad.

SABRE RESULTS

We are integrating a laser-produced ion source, high magnetic insulation, and removal of surface contaminants on the closeout beam generation experiments on the SABRE accelerator. The goal of these experiments is to demonstrate an active lithium ion source and study lithium beam divergence and impedance scaling. Progress to date, includes [9]:

- Reduction of proton contamination at laser fluence ≤0.4 J/cm^2 by a factor of 10-20 (to ≤100 A/cm^2) with discharge cleaning and strong insulation
- Earlier turn-on of the ion beam by 20 ns
- Stable beam impedance where the beam enhancement is ≤3.5 for 46 ns and $J/J_{CL} \leq 1$ for 26 ns.
- Stable radial uniformity in agreement with Atheta magnetic field design tools
- Improved azimuthal uniformity
- A well-behaved, non-protonic, space-charge-limited beam that may allow study of EM-induced divergence scaling.

PRESENT DAY LIMITATIONS

The most serious technical limitation for light ion IFE is the lack of an adequate ion source. For example, the recent SABRE experiments show that the laser ion source is producing a beam dominated by contaminant ions heavier than lithium. A magnetic spectrometer and Thomson parabola indicate the dominant contaminant is oxygen. Apparently this is due to oxide layers on the lithium surface. Whereas it is possible to diagnose the divergence of a 4-5 MeV lithium beam, the extremely short range of 4-5 MeV oxygen ions makes measurement difficult. We are investigating the possibility of avoiding the oxide contamination problem by using an in-situ lithium coating system [9]. In-situ deposition on cryogenic anodes has produced high purity proton, nitrogen, methane and neon beams [10]. We expect that depositing a fresh lithium coating on an anode in a diode with a low base pressure (<10^{-7} torr) and then firing the accelerator within 30 seconds should avoid the oxide contamination problem.

Another serious limitation is that our particle-in-cell simulation codes can not handle the anode and cathode plasmas that form in ion diodes and strongly influence the beam generation physics. A hybrid modeling capability that can study the interaction between electrode plasmas, the electron sheath, and the ion beam is essential to understanding applied-B ion diodes.

ACKNOWLEDGEMENTS

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. This paper is dedicated to the memory of Alex Filuk.

REFERENCES

[1] T.A. Mehlhorn, IEEE Trans Plasma Sci **25** (1997) pp. 1336-1356.

[2] R.E. Olson, et al., Proc. 15th IEEE Symp. Fusion Eng., (1993) pp.189-193.

[3] A.B. Filuk, 1997 IEEE ICOPS, p121..

[4] M.E. Cuneo, et al., IEEE Trans. Plasma Sci., **25** (1997) pp. 229-251

[5] R.A. Vesey, et al., to be published.

[6] T.D. Pointon, et al., Phys. Plasmas **1** (1994) pp. 429-443.

[7] J.B. Greenly, et al, Bull Am. Phys. Soc. **42** (1997) pp. 1846.

[8] R.A. Vesey, et al, Bull Am. Phys. Soc. **42** (1997) pp. 1846.

[9] M.E. Cuneo, et al., private communication.

[10] D.L. Hanson, et al., J. Appl. Phys. **70** (1991) pp. 2926-2937.

Report Number (14) SAND--98-1397C
CONF-980603--

Publ. Date (11) 1998
Sponsor Code (18) DOE/DP, XF
UC Category (19) UC-700, DOE/ER

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