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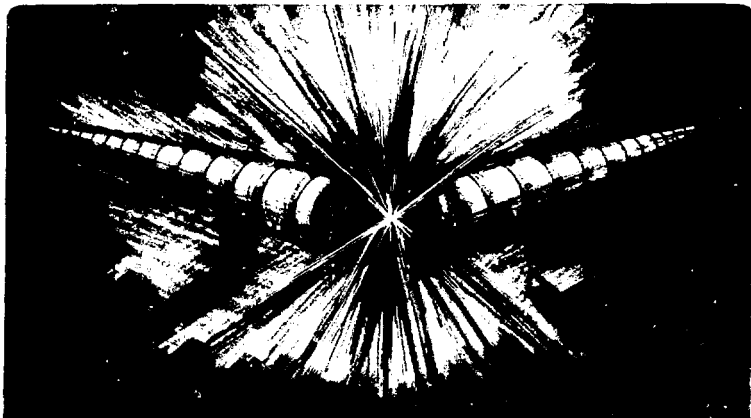
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CONFINEMENT FUSION

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INTRODUCTION

During the past few years the possibility of using intense ion beams to ignite a pellet of fusion fuel has looked increasingly promising. Ion beams ranging in mass from protons up to uranium have been investigated and several machines have been built at different laboratories to investigate the required technology. Light ion drivers are based on the use of high current, high voltage diodes arranged around a central target. These devices have the necessary power and energy to initiate fusion burn but suffer from the inability to transport stably the necessary huge beam currents over long distances to a small target. Heavy ion drivers are based either on the radio-frequency linac or the induction linac. Because heavy ions have a much shorter range than light ions of the same energy, one is able to raise the beam voltage by a factor of one-thousand and lower the current correspondingly. The expected parameters for a fusion driver will be delineated and the present state of development of the technology for the candidate ion beam drivers will be described in light of these desiderata.

ENERGY PRODUCTION VIA INERTIAL CONFINEMENT FUSION

For inertial confinement fusion (ICF) to lead to net energy production one must as a minimum:

1. Compress the D-T fuel from its initial density to about 10^3 times liquid density.
2. Heat the fuel to $T > 20$ keV. If one were to achieve complete burn of 1 mg of D-T fuel this would yield 350 MJ, the equivalent of 1/10 ton of TNT.

To carry out the compression one surrounds the fuel by concentric shells of material chosen such that the driver energy is absorbed in the outer shell and the ablation of this shell drives the fuel inward. Many schemes can be examined with multiple shell targets to "push" and "tamp" the fuel. Computer calculation of the hydrodynamics of these targets produce gain curves for ion drivers. Such a set of curves calculated by Bangert^{1,2} is shown in Fig. 1. To achieve a gain of 100 it would seem wise to arrange for an input energy of 2 - 10 MJ.

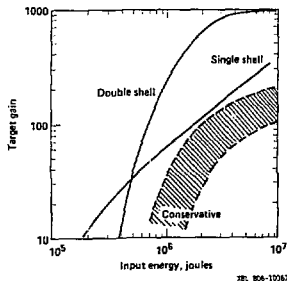


Fig. 1 - Gain curve for ion driver inertial confinement fusion calculated by Bangert

If the drivers to be considered we will only concern ourselves with those using ion beams. These are divided into two classes - those using light ions, based on neutralized beam transport and those based on heavy ions using conventional accelerator technology and charged particle transport.

To examine the relative merits of light and heavy ions one must examine the range - energy curve in view of the requirement that in order to generate the implosion one must deposit at least 20 MJ/gm in a thin layer on the surface of a pellet of radius about 1 mm. Thus,

$$W = \frac{Q}{2\pi r^2 R} > 20 \frac{\text{MJ}}{\text{gm}}$$

with Q = total beam energy = $I\tau V$ in MJ

$I\tau$ = beam charge

V = beam voltage = kinetic energy/charge state of ion

r = pellet radius in cm. ²

R = particle range in g/cm

Using this relation and range curves calculated by Bangert for particles in dense Pb plasma we can calculate the curves shown in Fig. 2. The four heavy curves show the results of this calculation for protons, carbon, cesium and uranium ion beams. Above the curves one has a sufficiently short range that the target will tend to implode rather than explode. In all cases the total beam energy must be greater than 1 MJ in order to get a significant pellet gain. It is clear that light ions must push to very high currents (tens of MA at a few MV) while heavy ions can do the job at several GV and tens of kA. Also indicated on the curve is the location in this parameter space of the present major ion driver programs. These will be described in the following sections beginning with the driver requirements shown in Table 1.

Table 1: Driver Requirements for Power Production

- Energy - 1 to 10 MJ
- Power - 100 to 600 TW
- Pulse shape - Control needed
- Efficiency x gain > 10
- Focusing - to a few mm at 5 to 10 m
- Reliability - > 80 percent on-time
- Lifetime - 30 years
- Rep rate - 1 to 10/sec
- Cost - (a few) $\times 10^8$ \$/GW of electrical output

The energy requirement has been discussed already. The power and pulse shaping arise in order to deposit this energy in a time short compared to the time for the hydrodynamic disassembly of the pellet.

A minimum efficiency-times-gain product requirement arises from trying to keep the recirculating power in the plant small in order to make the cost of power economically reasonable. This can be readily seen from the following argument. To produce a beam energy, Q , a driver of efficiency, η , requires Q/η input energy. If the electric power generators are taken to be 33 percent efficient, and the pellet gain is G , then the output energy is $QG/3$. Requiring the recirculating power to be small implies that $\eta G > 3$ eg. $\eta G \sim 10$. If we are limited to $G = 100$ this requires that $\eta > 10$ percent. For laser drivers, with $\eta < 10$ percent, the acceptable G must be higher whereas, because accelerators have a higher η , G can be lower. The rep rate arises from the requirement that the plant produce $\sim 1 \text{ MW}$ from a pellet burn in the reactor which would not damage the structure in an unreasonably short time (less than several years).

We will now examine the different drivers and then indicate their relative promise in meeting those criteria.

HEAVY ION DRIVERS

1. RF Linac

The RF linac is the driver most familiar to the accelerator community. The technology needs no description here except to point out the driver scenario and the areas of uncertainty. The program is being carried out principally at Argonne National Laboratory (ANL)³ with strong contributions from

Brookhaven National Laboratory (Meqalac) and Los Alamos Scientific Laboratory (rf quadrupoles).

The basic problem is to develop a high current beam from a low current rf linac by transverse and longitudinal beam manipulations. The scheme proposed for a 1 MJ driver involves funneling current from a tree of linacs and then amplifying the current by a further large factor by multistep stacking of the beam in both transverse phase planes in a storage ring followed by further bunching after single turn extraction. The main question here is whether the complex beam manipulations required cause sufficient dilution of the emittance that the final focussing of the beam onto the pellet is badly compromised.

The present program at ANL is directed towards an investigation of the low β part of the machine using a multi-aperture Xe source on a 1.5 MV Dynamitron high voltage source. The beam will be injected into a 12.5 MHz Wideroe Linac and then matched into a 25 MHz Wideroe Linac and further accelerated. The main aim here is to examine the experimental difficulties and emittance dilution involved in the funneling scheme. A new feature to be examined is the longitudinal phase-space matching as the beam is transferred from one linac to another one operating at a different frequency. In the future the ANL program is proposing to build a Beam Development Facility, (BDF) which will involve adding a storage ring at the output of the 25 MHz linac to examine the stacking and extraction in the storage ring. The parameters of this facility are indicated as BDF on Figure 2.

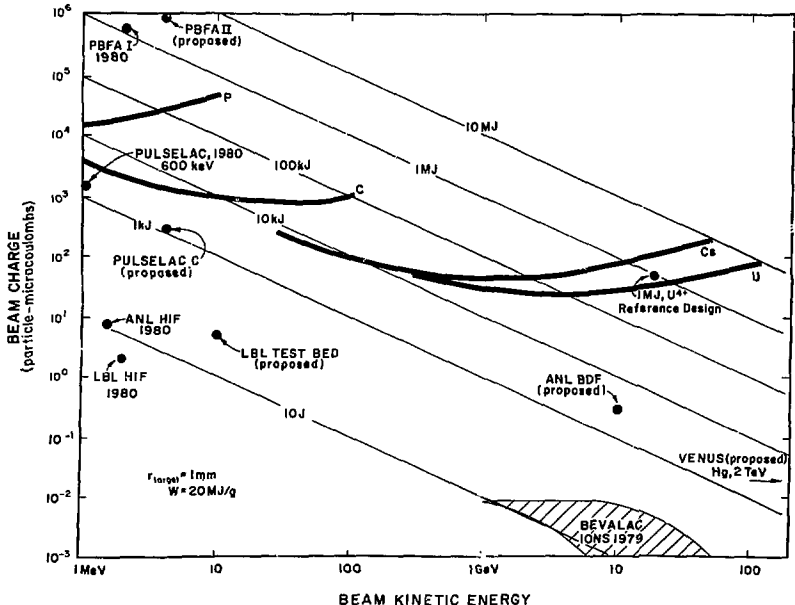


Figure 2 - Ion beam fusion driver road map

2. Induction Linac

The induction linac is probably less familiar having only been used up to now to accelerate high current (1-100 kA) electron beams. The accelerating modules are non-resonant, consisting of large toroids of ferromagnetic material driven by pulsed modulators. A schematic representation of such a machine is shown in Fig. 3. The modules can be viewed as single turn transformers in which the drive line is the primary and the particle beam is the secondary. This driver program is being pursued principally at Lawrence Berkeley Laboratory (LBL).⁴ In this system, in a 1MJ driver the entire bunch of charge is accelerated in a single pass from the source to the end of the accelerator through a large beam pipe. The stacking in both transverse phase planes is accomplished right at the source by using a very large emitting area. Next, by ramping the voltage pulses in a number of the earlier modules, a compression process is begun such that the pulse-duration becomes shorter and the current is amplified continually along the length of the accelerator. To be reasonably efficient, the induction linac operates just below the maximum current that can be stably transported, so the design requires a precise knowledge of the space-charge limit.

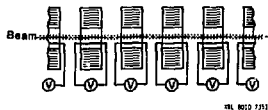


Fig. 3 - Schematic representation of an induction linac

Being a pulsed power device the induction linac is inherently adapted to high current, short pulse operation. Although the manipulations are fewer and the residence times in the accelerator are less than in the rf linac storage ring approach, there are, likewise, questions to be answered of whether the space charge limited beam transport will lead to possibly unforeseen emittance growth or instability. The present LBL program is involved with the low beta end of such an induction linac and is centered around a 2 MV, 1A Cs injector. The next stage of the program envisions the construction of a modest Cs ion induction linac (10 MV, 5A) to examine the questions of transport stability and emittance growth in such a structure and, above all, demonstration of current amplification during acceleration in a satisfactory way. This device is indicated as LBL Test Bed (proposed) on Fig. 2.

LIGHT ION DRIVERS

Light ion drivers differ from heavy ion drivers principally in that they make use of schemes to neutralize the particle beams. The main effort in this area is at Sandia Laboratories in Albuquerque with supporting research principally at the Naval Research Laboratory and Cornell University. A comprehensive review of this entire field has recently been given by Humphries.⁵

1. PBFA

PBFA I (Particle Beam Fusion Accelerator) is presently in operation at Sandia Laboratories Albuquerque (SAN).⁶ It consists of 36 Marx generators and pulse forming networks each pulsed to 2 MV and delivering 400 kA, 40 ns pulses. This system delivers its energy to a cylindrical diode array at the center, the total delivered energy to a target being 1MJ.

The diode makes use of a magnetic field perpendicular to the beam direction produced by external coils to prevent electrons from crossing the diode gap. Otherwise, most of the current would appear in the electron beam. A schematic diagram showing this principle is shown in Fig. 4. The cathode is designed to be fairly transparent to the ions.

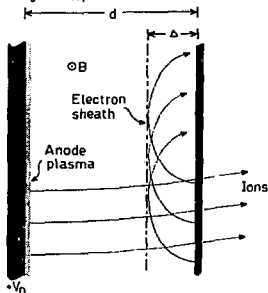


Fig. 4 - Schematic representation of a magnetically insulated ion diode (courtesy of S. Humphries, Jr.)

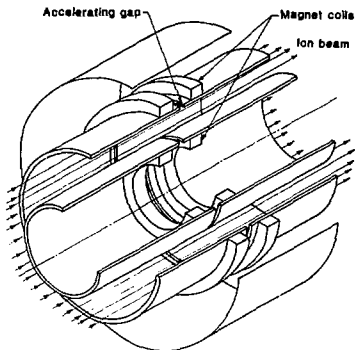
Because these beams cannot be contained by achievable magnetic or electric fields one must neutralize them via transport in strongly ionized plasma channels using a vaporized wire or a laser pulse. The main difficulty here is to hit reliably and repetitively a mm size target in a 10m diameter vessel with these beams. Targets of several cm diameter are presently being used. At present PBFA II is being planned - it will have 72 beams of 4 MV each, thus raising the total beam energy to 4 MJ. These devices are indicated in Fig. 2 as PBFA I and PBFA II.

2. Pulselac

Pulselac, a device also presently being developed at Sandia Laboratories, Albuquerque,⁷ couples neutralized beam transport with induction acceleration. The aim of this device is to bring about the ion acceleration in several stages rather than in a single stage as in PBFA. This might lead to less stringent demands on the switches and pulse forming networks. The transport is brought about via the collective focussing effect of injected cold electrons. Magnetic insulation must be used at the accelerating gaps to prevent the electrons from shorting out the accelerating field. A schematic diagram of a Pulselac gap is shown in Fig. 5. The inner and outer coils are driven such that the main component of the B field is in the radial direction. The beam is in the annular space between the inner and outer coils. The accelerating potential is applied across the gaps in the tubes by an induction module. At present Pulselac B is operating at a final beam voltage of 600 keV of carbon at 3 kA. The carbon beam is produced by a plasma gun which is also magnetically insulated from the accelerator section.

This is a promising technology in that it can accelerate somewhat heavier ions than PBFA in a more gradual way such that the demands on the switches and pulse forming network are much less stringent. At present, however, the beams are not of sufficiently low emittance that they could hit a 1 mm pellet in a reactor chamber, and repetition rate capability has not

been demonstrated. On Fig. 2 is shown the relevant point for the present Pulsefac B as well as the future Pulsefac C which will have a 4 MeV, 5kA beam of carbon in a 50 ns pulse.



PULSEFAC ACCELERATING MODULE

Schematic

ITE 6010-730

Fig. 5 - Schematic representation of a Pulsefac gap

SUMMARY

A representation of the state of ion driver technology is shown in Table II. As in any such superficial treatment there are some subjective conclusions but the clear generalization is that the light ion machines have the necessary power and energy but lack rep rate and reliability. The heavy ion drivers, on the other hand, are based on developed accelerator technology which is demonstrated to be of high rep rate and reliability, but is still not at the required energy or power levels.

ACKNOWLEDGMENT

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Parameter	Driver			
	PBFA	Pulsefac	R F Linac	Induction Linac
Energy	☺	☆	☆	☆
Power	☺	☆		☆
Pulse Shape	☆	☆		
Efficiency - Gain Product	☆	☆	☆	☆
Focusing onto pBFC			☆	☆
Emittance Growth	N. A.			
Rep. rate			☺	☺
Lifetime			☺	☺
Reliability			☺	☺

Legend	
☺	Goal substantially achieved.
☆	Goal a likely extrapolation from existing hardware.
□	More "experimentation" required.

ION BEAM DRIVER COMPARISON

ITE 6010-731

TABLE II