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Abstract

Ballistic propagation of ions in a light ion Inertial Confinement Fusion (ICF) reactor has potential advantages over propagation using plasma channels, but it requires that focusing magnets be close to the target. Ballistic transport is simpler and potentially more efficient, but limits on the ion microdivergence make a small focal spot and a large focal length simultaneously impossible. Target ignition requires a beam intensity above some minimum value, assumed to be 127 TW/cm^2. To achieve this intensity, one adjusts the total beam energy, the positions of the focusing magnets, the microdivergence of the ion beam, and the time of flight bunching of the beam. LIBRA-LiTE is a 1000 MWe power plant design consistent with ballistic ion focusing, where these parameters have been optimized.

Introduction

LIBRA-LiTE [1-3] is a 1000 MWe power plant conceptual design using light ion beam driven inertial fusion. A schematic picture of the LIBRA-LiTE target chamber is shown in Fig. 1. LIBRA-LiTE differs from the LIBRA design [4] in the electrical power level, the ion transport system, and the target chamber design. The general parameters are shown for both designs in Table I. Both designs use 127 TW/cm^2 of 30 MeV Li ions to drive the fusion target. Both designs use liquid metal first surface protection. The same liquid metal is used as breeding blanket material when confined in porous woven INPORT [5] units. LIBRA uses lithium-lead eutectic, LIBRA-LiTE, lithium. LIBRA uses plasma channels to propagate the ion beams, while LIBRA-LiTE uses ballistic propagation with focusing magnets near to the target. The LIBRA concept required electrical insulation magnets to prevent breakdown between the channels and the chamber structures. Finally, the target chamber roof was fabric wetted with liquid metal in LIBRA, but is a dry dome in LIBRA-LiTE. The LIBRA-LiTE roof of the target chamber is a large dome that is far enough away from the target that it needs no liquid metal coating for protection from target x rays and that neutron damage occurs slowly enough for the roof to be, along with the target chamber walls, a lifetime component. The target chamber and the 30 driver modules fit in a single large building.

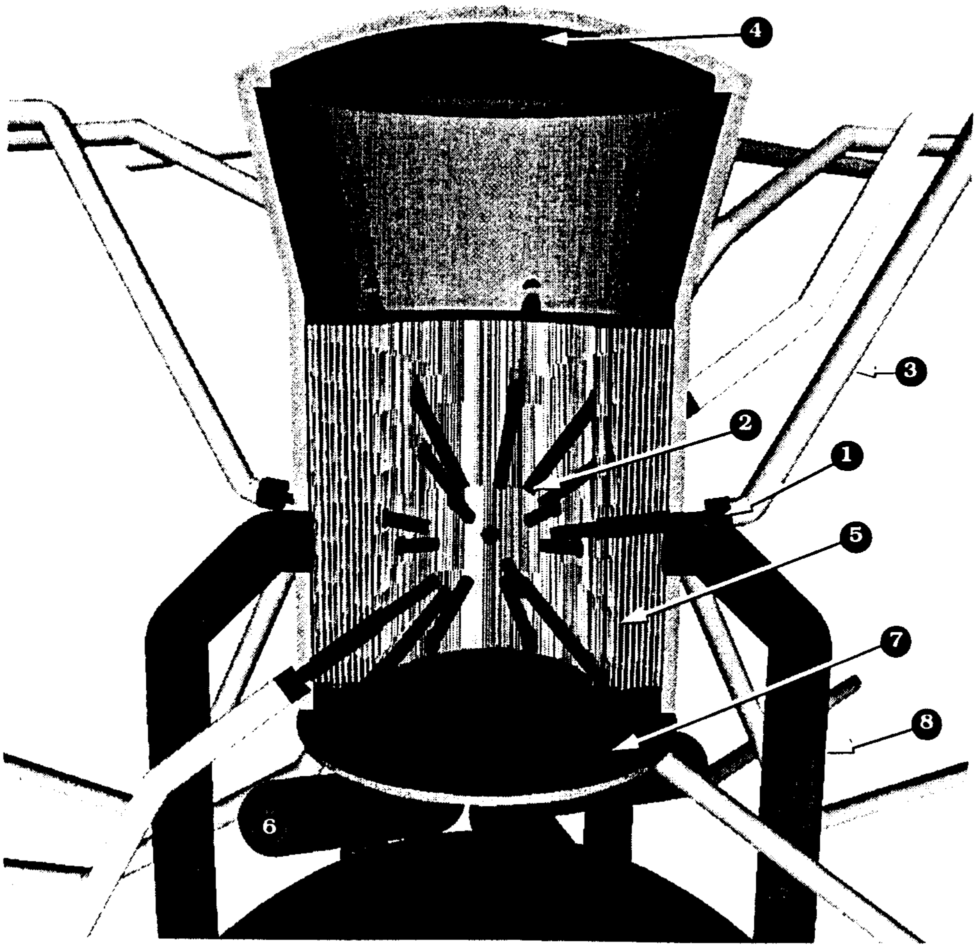

Figure 1. Schematic Picture of LIBRA-LiTE Target Chamber. (1) Diode, (2) Focusing Magnet, (3) Magnetically Insulated Transmission Line, (4) Chamber Roof, (5) INPORTs, (6) Heat Exchanger, (7) Bottom Plate, (8) Vacuum Line.

The choice of ballistic ion propagation in LIBRA-LiTE dictates some important features of the target chamber design. Ballistic propagation requires focusing magnets, each with a surface that faces and is near to the target microexplosion. Ballistic propagation also dictates that the gas density in the target chamber at the time of beam propagation be high enough to insure current and charge neutralization but low enough to not excessively scatter the beam. The focusing magnets in LIBRA-LiTE use liquid metal conductor in a metal case to avoid radiation damage to solid conductor. The tritium breeding blanket uses this same liquid metal, flowing in woven porous tubes. To protect solid surfaces from the target x rays, the blanket tubes and the focusing magnets are coated with this liquid metal. We have done neutronics calculations to determine the lifetime of the metallic case and the frequency at which it must be replaced. The optimum density for the gas in the target chamber has been determined with calculations with the SCATBALL code and has been found to be too low to absorb target x rays and ions before they reach the focusing magnets and INPORTs.

Table I. LIBRA-LiTE and LIBRA Parameters

	LIBRA	LIBRA-LiTE
General		
Net Power (MWe)	331	1000
Rep Rate (Hz)	3	3.9
Thermal Power (MW)	1161	2710
Gross Thermal Eff. (%)	38	44
Gross Power (MWe)	441	1192
Recirculating Power Fraction (%)	25	16.1
ηG	18.8	18
Availability (%)	75	75
Cost of Electricity (mills/kWh)	97	43
Driver		
Pulsed Power Type	Helia	Helia
Number of Beams	18	30
Beam Ion	30 MeV Li	30 Mev Li
Transport Method	channel	ballistic
Transport Length from Magnet (m)	3.3	2.05
Peak In Current/Diode (MA)	0.3	0.313
Bunching Factor	4.0	11.8
Peak Power on Target (TW)	400	1588
Pulsed Power Efficiency (%)	37.6	37.6
Transport Efficiency (%)	62.5	60.0
Net Driver Efficiency (%)	23.5	22.6
Target		
Ion Energy on Target (MJ)	4	6
Target Radius (cm)	0.5	1.0
Target Gain	80	100
Target Yield (MJ)	320	600
X-ray and Ion Yield (MJ)	95.4	179
Neutron Yield (MJ)	217	407
Chamber and Blanket		
Coolant/Breeder	PbLi	Li
Distance to INPORTs (m)	3.0	3.45
Mass Vaporized/Shot (kg)	8	5.2
Peak Pressure on INPORTs (GPa)	100	4.6
Pressure Impulse on INPORTs (Pa-s)	125	103
Peak Pressure on Magnets (GPa)	100	7.3
Pressure Impulse on Magnets (Pa-s)	125	188
Tritium Breeding Ratio	1.4	1.4
Vessel Life (FPY)	30	30
INPORT Life (FPY)	1.5	2.2
Magnet Life (FPY)	1.5	.75

Light Ion Driver and Beam Propagation

The pulsed power portion of the driver is essentially the same in LIBRA-LiTE as in LIBRA. Thirty modules with inductive voltage adders driven by magnetically switched water lines and step-up transformers provide roughly 30 MV, 40 ns shaped pulses on 30 diodes at a rate of 3.9 Hz. The number of modules has been increased from the 18 of LIBRA to provide better symmetry and more credible target performance. The pulses are carefully ramped in voltage to provide time-of-flight bunching of the beam. The total energy provided to all driver modules is 26.6 MJ, of which 6 MJ reach the target for a net driver and transport efficiency of 22.6%. We have assumed that the pulsed power efficiency is the same as in LIBRA, or 37.6%, that the ion production efficiency is 80%, and that the ion propagation efficiency is 75%. The last two efficiencies are consistent with LMF parameters [6].

Ballistic propagation of ions in a light ion fusion reactor has potential advantages over propagation using plasma channels, but it requires that focusing magnets be close to the target. Ballistic transport is simpler than channel transport and avoids the problem of electrical breakdown between the plasma channels and the target chamber structure. However, to keep the focusing magnets required for ballistic transport as far as possible from the target, the focal spot at the target is large, which leads to a large required driver energy. Target ignition requires a beam intensity above some minimum value, which we have taken to be 127 TW/cm^2. To achieve this intensity, one adjusts the total beam energy, the positions of the focusing magnets, the microdivergence of the ion beam, and the time of flight bunching of the beam.

We have used the SCATBALL computer code to verify the ability of the ion beam transport system to provide the proper target conditions. SCATBALL is a computer code written at the University of Wisconsin to study the passage of a ballistically focused ion beam through a gas. The code calculates the envelope of the beam as a function of position. It includes the effects of initial microdivergence, scattering by a background gas and a foil (if one is present), and magnets. The envelope calculation is based on an analytic formulation [7]. SCATBALL also calculates the heating of the background gas by the ion beam. Heating of the background gas by the beam is an important issue because the gas must have a high conductivity for the beam to be stable. We have performed calculations for 30 MeV Li ions and a 1 torr background gas of Li vapor with no foils intersecting the beam. This calculation predicts that the conductivity of the gas becomes sufficiently high.

Because the electrical resistance of any solid conductor in the focusing magnet would increase rapidly due to radiation effects, flowing lithium was selected as a conductor [8]. The magnet needs a center bore radius of 9 cm and a length average magnetic field product of 60 T-cm. The magnet is a 50 cm long five-turn solendoid. The current density in the present design is 10.1 MA/m^2, leading to a power loss of 2.1 MW per magnet. Nuclear heating, MHD effects on the flow, and front surface heating have all been assessed. We estimate that the magnets will survive 1 calendar year.

Target Chamber Analysis

The target microexplosion releases x rays, neutrons and ion debris that deposit in the target chamber vapors and structures. We have assumed that the energy partitioning and the emitted spectra are the same as for the ion beam target designed by Bangerter [9]. The x rays deposit in the liquid Li film on the INPORTs and the magnets. A portion of the Li film is rapidly vaporized by the x rays and the debris ions are deposited in that vapor and in the original Li vapor in the target chamber.

To analyze the behavior of the target chamber gases and vapors, we have used the CONRAD computer code [10]. CONRAD is a one-dimensional Lagrangian radiation-hydrodynamics computer code. Radiation transport is calculated with 20 group radiation diffusion and time-dependent target x-ray and ion deposition is included. The code includes calculation of vaporization and recondensation of materials from an outer wall and heat transfer through the wall. CONRAD simulations have been carried out for vaporization over materials from the surface of the INPORTs and the focusing magnets. The simulations have shown that a shock wave is launched in the vaporized Li that leads to a very high peak pressure imposed on the remaining liquid at the vapor/liquid interface. The peak pressure is several GPa, which is certainly high enough to force a shock into the liquid. We have not yet considered the propagation of the shock in the liquid. The impulses on the INPORTs and magnets will be used to consider the mechanical response of these structures and to allow the design of structures with acceptable lifetimes.

Neutronics analysis has been performed for LIBRA-LiTE by performing several one-dimensional spherical geometry calculations. The discrete ordinates code ONEDANT [11] was utilized along with 30 neutron-12 gamma group cross section data based on the ENDF/B-V evaluation. A point source is used at the center of the chamber emitting neutrons and gamma photons with the LIBRA target spectrum [4]. The target spectrum takes into account neutron multiplication, spectrum softening and gamma generation resulting from the interaction of the fusion neutrons with the dense target material. The results were normalized to a 600 MJ yield and a repetition rate of 3.9 Hz.

Conclusion

We have designed and analyzed the LIBRA-LiTE ballistic ion propagation power plant. We have extended the life of the focusing magnets but using a liquid lithium conductor and by placing them as far as possible from the target. The placement of the magnets requires low diode microdivergence and a high beam bunching ratio to avoid a very high driver energy. We have done neutronic and vaporization analysis for the target chamber.

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