Ballistic Focus Light Ion Beams for an Inertial Confinement Fusion Reactor

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Abstract

The issues of ion beam transport are studied in the context of the LIBRA-LiTE reactor study. LIBRA-LiTE is a 1000 MWe power plant design consistent with ballistic ion focusing. The ion beam energy must be divided between many beams to provide proper illumination symmetry. The needs to keep the total beam energy low and the intensity at the required level lead to constraints on the transport system, particularly, a high degree of bunching and a low microdivergence. This paper will describe arguments leading to an operating point for light ion ICF with ballistic focusing. Calculations of heating of the background gas by the ion beams and the subsequent increase in the electrical conductivity of the gas will be presented. This is an important issue to the stability of the ion beam.

Introduction

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, to keep the focusing magnets as far as possible from the target, the focal spot at the target is large. Target ignition requires a beam intensity above some minimum value, which in this work has been 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. To achieve proper symmetry and pulse shaping, the pulse on the target includes a main pulse with 90% of the energy in 24 beams and a pre-pulse supplied by 6 beams. The SCATBALL computer code has been used to verify the ability of the ion beam transport system to provide the proper target conditions. This is done within the context of the LIBRA-LiTE [1-4] reactor study that uses ballistic ion beam transport in a concept that produces 1000 MW of electrical power.

LIBRA-LiTE Ion Beam Transport System

The LIBRA-LiTE ion beam transport system consists of extractor diodes, drift regions, solenoidal lens magnets, and focus regions. The ions propagate out of the diodes, across the drift regions, to the focusing lens magnets in hollow cylindrical beams. The width of the cylindrical shell to which the beams are confined thickens during transport due to scattering of beam ions by the background gas and due to microdivergence. Microdivergence is determined in the diode. We have neglected microdivergence growth due to plasma instabilities during transport. The beam radius, which is initially equal to the diode outer radius, increases due to this spreading. The bore radius of the focusing lens magnet must be large enough to contain the beam. The beams are focused onto the target by the lens magnets. The focal spot size, which must be no larger than the target, is affected by microdivergence and scattering during transport between the magnets and the target.

The focusing lens magnets are designed to focus cylindrical ion beams to a target. The magnet operates by using B_r fields that exist near the ends of the solenoid to convert some of the axial ion beam velocity, v_z, into azimuthal velocity, v_θ. The axial magnetic field then acts against the v_θ to give the ions a focusing force and a radial velocity, v_r. As the ions move out of the solenoid, they once again encounter a B_r, but in the opposite direction, which removes the azimuthal motion. Conservation of canonical angular momentum requires that the ion beam has the same angular momentum on both sides of the magnet, which we assume to be zero far from the magnets. In the presence of the magnetic field, the canonical angular momentum is $m\vec{v} + q\vec{A}/c$. In a solenoid, $\vec{A}$ is azimuthal, so $\vec{v}$ has an azimuthal component in the opposite direction while there is a finite vector potential, $\vec{A}$. It is important that the ion beam has no angular momentum at the target, or it will not focus to a spot.

The design parameters for the ion transport systems for LIBRA [5] and LIBRA-LiTE are shown in Table I. LIBRA is a reactor design using ion transport in pre-formed plasma channels. A background gas of 3.55×10^{16} cm^{-3} of helium is assumed to be present throughout the entire beam transport system of LIBRA-LiTE. Some method of isolating the diode from the gas will be required. Because LIBRA-LiTE uses liquid lithium target chamber protection, there will be some impurity of lithium vapor, but we do not expect it to affect beam transport. The microdivergence is chosen to be 4.0 mrad as a base case. Though this would require great advances in diode technology, it only requires a source plasma temperature below about 500 eV. The 7.14 cm radius beam spreads to 9.0 cm at the lens magnets. The 470 cm drift length between the diodes and the magnets allows the diodes to be placed outside of the target chamber and allows distance for time of flight bunching and gas isolation equipment. The magnets have a focal length measured from the magnet center to the target of 230 cm. The magnets have an average field of 1.2 tesla and a length of 50 cm, which is required to focus a 30 MeV lithium beam. The main beams will be focused to a 0.95 cm radius spot.

SCATBALL Computer Code

The SCATBALL code has been used to study the transport of ions from the diodes, through the focusing magnets to the target. This code calculates the envelope for the ion beam. This includes the effects of scattering by the background gas, spreading from microdivergence, focusing by the lens magnets and time-of-flight bunching of the ion beam. These properties are all calculated using

Table I. LIBRA-LiTE and LIBRA Ion Beam Parameters

	LIBRA-LiTE	LIBRA
Transport Method	Ballistic	Channels
Gas Species	Helium	Helium
Gas Density (cm^{-3})	3.55×10^{16}	3.55×10^{18}
Total Transport Length (m)	7.0	7.3
Focal Length (m)	2.3	0.7
Drift Length (m)	4.7	6.6
Beam Microdivergence (mrad)	4.0	6.0
Ion Species	30 MeV Lithium	30 MeV Lithium
Max. Source Plasma Temperature (eV)	480	1080
Energy From Each Main Diode (MJ)	0.375	0.375
Number of Main Beams	24	16
Transport Efficiency (%)	62.5	60.0
Main Pulse Energy on Target (MJ)	5.63	3.6
Pulse Width at Diode (ns)	40	40
Bunching Factor	11.8	4
Pulse Width on Target (ns)	3.4	10
Main Pulse Power on Target (TW)	1656	360
Focal Spot Radius (cm)	0.95	0.47
Peak Intensity on Target (TW/cm^2)	127	127
Peak Current Density on Target (MA/cm^2)	4.23	4.23
Current Density on Diode Anode (kA/cm^2)	5.0	2.0
Diode Anode Area (cm^2)	62.6	157
Diode Outer Radius (cm)	25.773	7.14
Diode Inner Radius (cm)	25.385	1.0

analytic formulae [6]. In addition, the heating of the background gas by the ions is calculated numerically.

Results

SCATBALL has been used to study the effects of microdivergence on the transport parameters. The microdivergence caused by the diodes is one of the greatest uncertainties in light ion fusion. Light ion fusion with ballistic focusing will probably not be credible for microdivergences greater than about 6 mrad. This is demonstrated by using the SCATBALL code to calculate the required energy on target in the main pulse to obtain 127 TW/cm^2 with a 11.8 bunching factor. This bunching factor has been chosen for LIBRA-LiTE and is slightly more than the achievable bunching predicted for the pulse power system designed for LIBRA [4]. A greater bunching factor is probably not credible. This value has been chosen to minimize the required energy on target. For a distance between the target and the center of the magnets of 230 cm, one obtains the plot shown in Fig. 1. Here, the energy on target in the main pulse is plotted against microdivergence. Based on this, a microdivergence of 4 mrad has been chosen, which provides 127 TW/cm^2 in a 3.4 ns main pulse containing 5.4 MJ on a 1 cm radius target. The near term microdivergence goals are approximately 15 mrad on PBFA-II with lithium. The distance between the first surface of the focusing lens magnets and the target has been studied as a function of microdivergence for the same target parameters and 5.4 MJ in the main pulse. This is shown in Fig. 2 along with the average neutron wall loading on the surface of the 50 cm long magnets for a 1000 MW$_e$ power plant versus microdivergence. The magnets are 50 cm long and the focal length is measured from the center of the magnet.

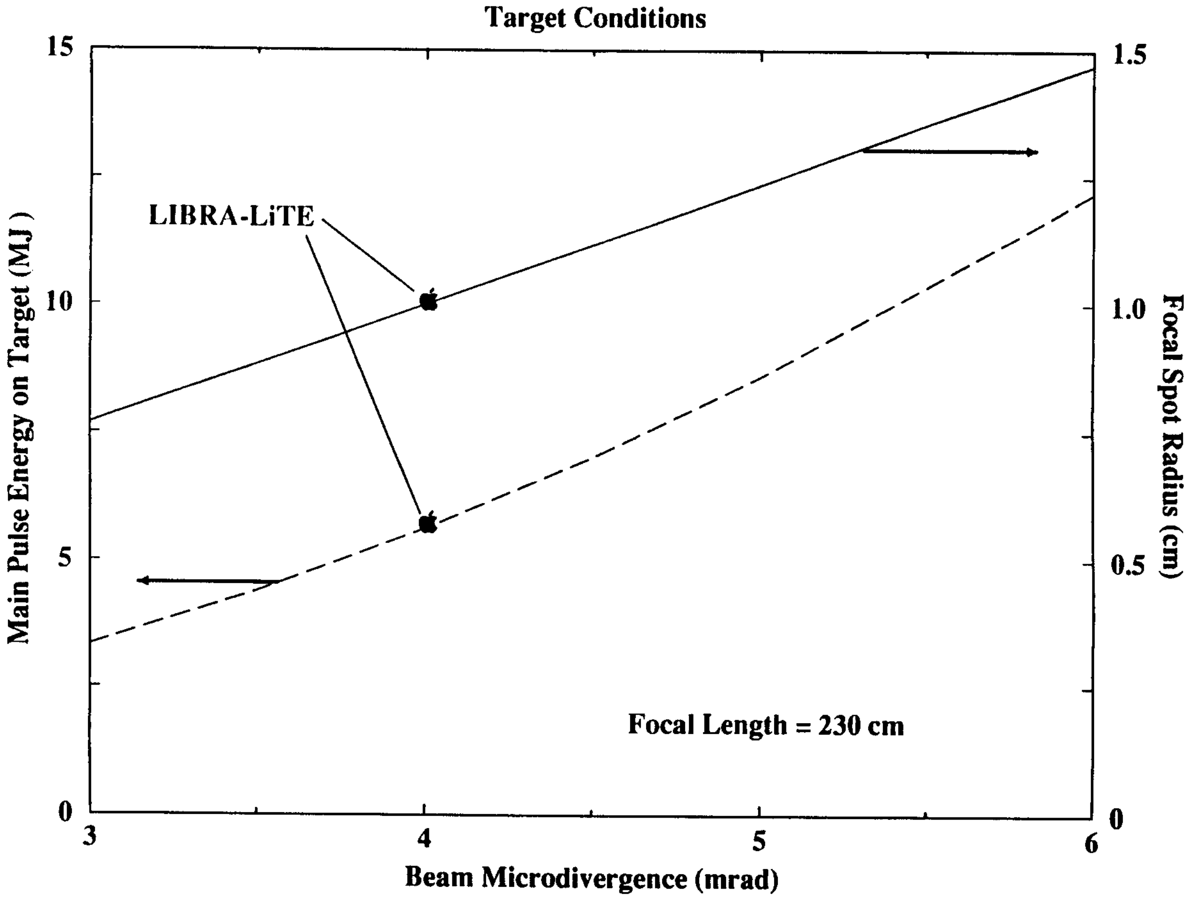

Figure 1. Required energy on target in the main pulse and the focal spot radius versus ion beam microdivergence. The focal length for the focusing magnet is 230 cm. The pulse width on target is 3.4 ns and 127 TW/cm^2 are assumed required for ignition.

The heating of the target chamber gas by the ion beams has been considered. It is thought that filamentation instabilities can be avoided if the electrical conductivity of the gas is greater than 10^{14} s^{-1}. The SCATBALL code has been used to calculate the conductivity of the gas. The gas is heated by ion beam energy deposition. As the background gas temperature increases, the gas ionizes and the conductivity increases. Electron collisions dominate the conductivity, so electron temperature increases lead to higher conductivity. The conductivity at the head of each beam is very low. Therefore the leading edge of the beam is subject to the instability. The breakdown process in the head of the beam is very complicated because the low conductivity and the large time rate of change of the current density allow large electromagnetic fields to be generated. These fields are thought to initiate electron avalanche. This process is not considered in SCATBALL. After the avalanche breakdown is complete, the conductivity is still below the required value but ion beam heating and ohmic heating by the return current continues. This is included in SCATBALL. The conductivity at the lens magnet for a main pulse beam at the tail end of the beam is 1.59×10^{14} s^{-1}.

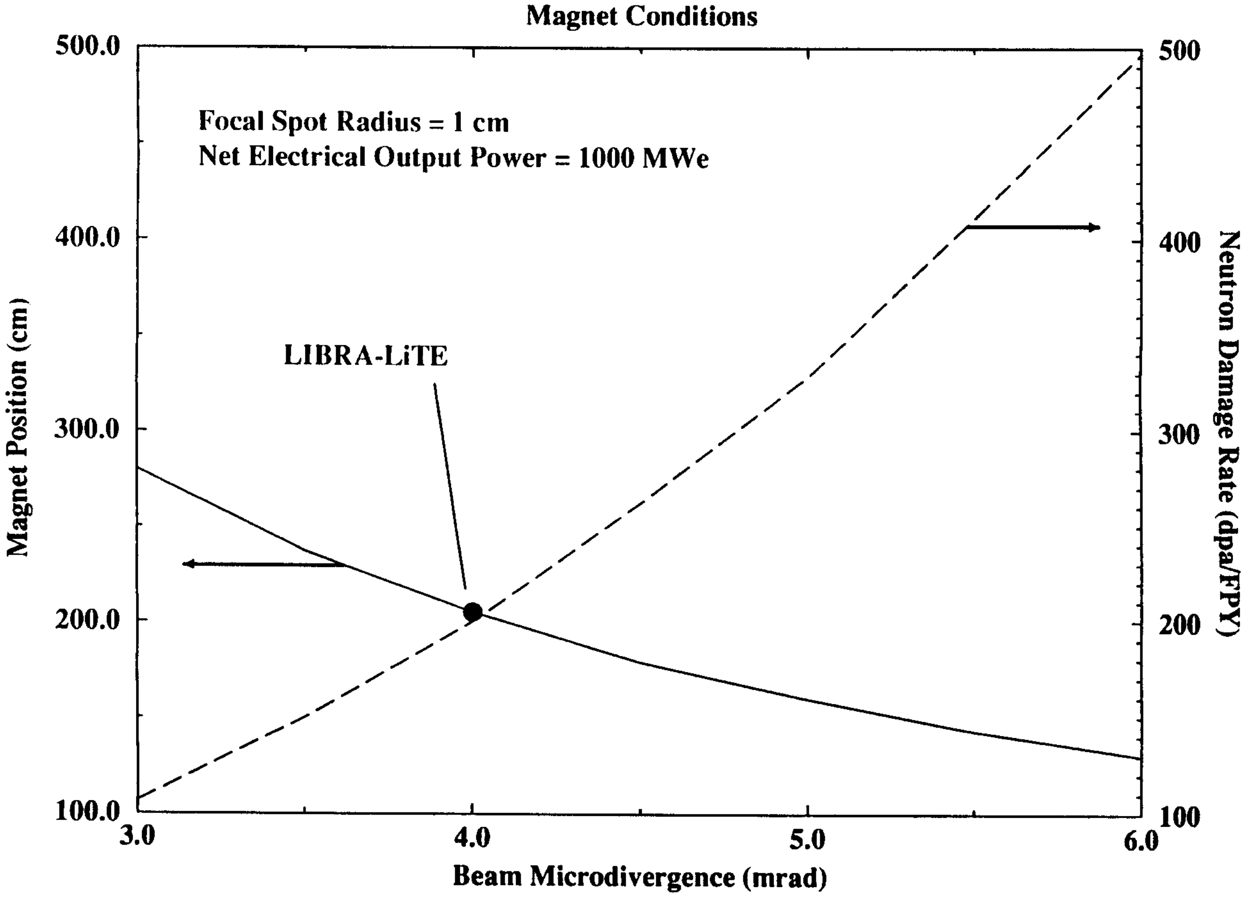

Figure 2. Distance from target to front of magnet and neutron damage rate in front surface of magnet versus microdivergence. The magnet is assumed to be made of TZM and to be 50 cm long. The focal spot radius is 1 cm. The net electrical output power is taken to be 1000 MWe.

Conclusions

Ballistic focusing limits in the LIBRA–LiTE reactor have forced a compromise between focal spot radius, magnet stand-off distance, driver energy, bunching, and beam microdivergence. The driver energy has a great effect on the cost of construction and the cost of produced electricity so the system has been designed to minimize driver energy at the costs of very high bunching, a high nuclear damage rate in the magnets, and a low beam microdivergence. The high bunching requires a very well-programmed voltage waveform on the diodes. The high damage rate in the magnets means that they must be replaced frequently. This will have an effect on the availability of the power plant. The 4 mrad microdivergence is roughly one third of the lowest currently achieved, and so requires significant advances in diode technology. These considerations show that ballistic transport light ion fusion is economically viable if advances are made in diode performance.

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