LIBRA-SP, A Commercial Fusion Reactor Based on Near Term Technology

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Wang

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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E. A. Mogahed, R. R. Peterson, M. E. Sawan, I. N. Sviatoslavsky, P. Wang
Fusion Technology Institute
University of Wisconsin-Madison
Madison, WI 53706-1687 U.S.A.
(608) 263-2308

ABSTRACT

The design of a 1,000 MWe light ion driven fusion power plant is given. Considerable progress has been made in analyzing the target performance and its impact on the cavity design. Recent declassification actions in the U.S. have resulted in more detailed calculations that reveal a somewhat lower gain ($\approx$70) compared to those gains previously assumed (80–100). Methods to recover that more conservative gain from other parts of the reactor design include more efficient beam transport and higher conversion efficiencies to electricity.

I. INTRODUCTION

LIBRA-SP is the third in the LIBRA series of light ion driven commercial fusion electrical power plant designs (previous designs were LIBRA,[1] LIBRA-LiTE,[2] and an early version of LIBRA-SP[3]). All 3 reactors use the current HELIA technology[4] to generate 20–30 MeV Li ions which are delivered to a DT target in the center of the reactor chamber. However, the transport mechanism in each of the reactors varies from channels in LIBRA, to the ballistic mode in LIBRA-LiTE, and finally to the more efficient self-pinch (SP) mode in LIBRA-SP.

The LIBRA-LiTE and LIBRA-SP power plants were both designed for 1,000 MWe (net) in order to allow comparisons to other magnetic and inertial fusion power plant designs. The recent declassification of ICF target concepts[5] has allowed the LIBRA team to develop a more realistic target design[6] which, in turn, has allowed more realistic neutron, photon, and debris environments to be assessed. However, the new targets show slightly lower gains than those assumed in the first two studies and this essentially balances the higher efficiency transport scheme in LIBRA-SP.

II. OVERALL REACTOR DESIGN

A schematic of the LIBRA-SP target chamber is shown in Fig. 1 and the key operating parameters are given in Table I. Other papers in this conference cover the target design,[6] cavity design,[7–9] neutronics,[10] and environmental and safety issues.[11] In addition, recent reports cover more detail on the beam transport and cavity response to the thermonuclear energy release in the chamber.[12–13]

There are 3 key differences between the LIBRA-SP design and the previous LIBRA designs:

- Self-pinched ion beam transport to the target
- More credible target design and yield calculations
- A new method for protecting the first wall from the target debris and neutrons.

The highlights of each of these areas will be given here and the reader is referred to other reports[1–3, 6–11] for more detailed information.

III. ION BEAM TRANSPORT

The ion beams in LIBRA-SP are transported to the target in self-pinched channels. The channels are formed by the portion of the ion beam current that is not neutralized by the background gas. The net current in the beam forms an azimuthal magnetic field, which confines the ion beams. The advantages of self-pinched transport include:

TABLE I

System Parameters for LIBRA, LIBRA-LiTE, and LIBRA-SP

Parameter	Units	LIBRA	LIBRA-LiTE	LIBRA-SP	LIBRA-SP
Net electrical power	MWe	332	1,000	1,000	1,000
Year published		1990	1991	1994	1996
Accelerator technology		HELIA	HELIA	HELIA	HELIA
Ion beam transport		Channel	Ballistic	Self-pinched	Self-pinched
Number of beams		18	30	24	24
Energy on target	MJ	4	6	7.2	7.8
Target gain		80 (assumed)	100 (assumed)	82 (calculated)	71 (calculated)
Rep rate	Hz	3	4	3.9	4.2
DT fusion power	MW	960	2,394	2,285	2,318
Total thermal power (incl. n mult., beam, etc.)	MW	1,163	2,778	2,781	2,820
Coolant/breeder		PbLi	Li	PbLi	PbLi
Tritium breeding ratio		.36	1.41	1.48	1.48
Damage to steel chamber	dpa/FPY	6.7	5	3.9	4.2
Thermal efficiency	%	38	44	43	43
Gross electrical power	MWe	442	1,222	1,196	1,213
Unit direct costs (1995$)	$/kWe	2,710	1,960	1,612	1,867

TABLE II

Selected Ion Beam Parameters for Self-Pinched Transport in LIBRA-SP

Parameter	Prepulse	Main Pulse
	Input	
Ion species	Li	Li
Ion energy (MeV)	20	30
Background gas	He	He
Background gas density (cm^{-3})	7×10^{15}	7×10^{15}
No. of beams	12	12
Total ion power on target (TW)	26	480
Total ion energy on target (MJ)	1.02	6.7
Pulse width at anode (ns)	40	40
Bunching factor	1.0	2.6
Distance anode to target-m	11.52	11.52
Microdivergence @ anode (mrad)	4	4
	Calculated	
Microdivergence at target (mrad)	4.119	4.053
Neutralization at the end of the target	0.866	0.978
Pulse width at the target (ns)	39.2	14.0
Overlap radius (cm)	1.96	1.96
Overlap efficiency (%)	85	74
Channel transport efficiency (%)	98	91
Net transport efficiency (%)	83.5	67

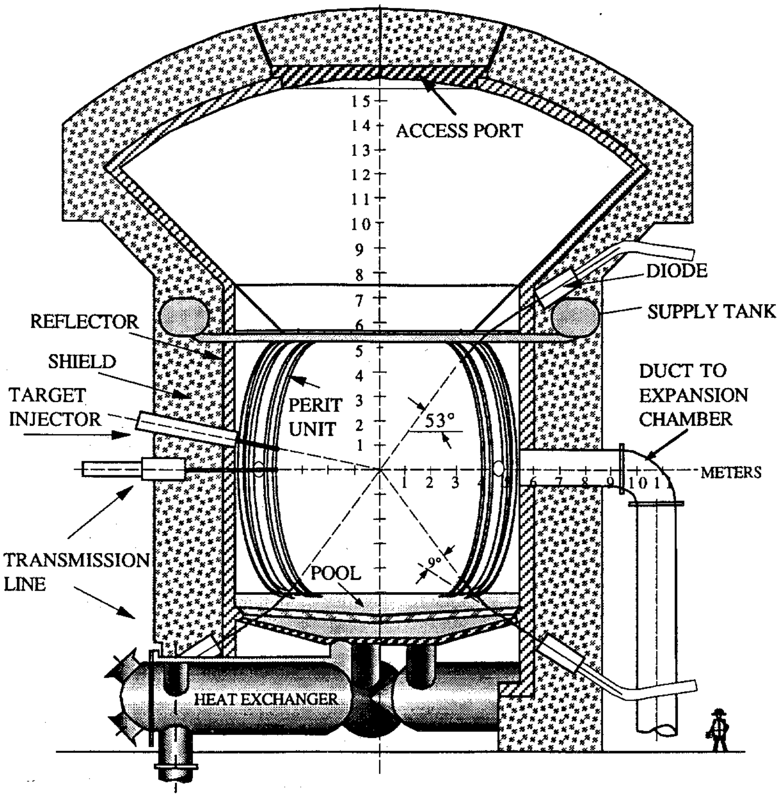

Fig. 1. Power plant schematic for LIBRA-SP.

- No lasers for guiding the beams
- No magnets inside the target chamber
- High efficiency
- Transport in bendable narrow tubes allows the use of the PERIT design.[7]

The main issues addressed in the present study include: background gas required, magnetohydrodynamic stability, neutralization, and transport efficiency. The results of this work are displayed in Table II for both the 12 prepulse and 12 main driver beams.

IV. TARGET DESIGN

The target for LIBRA-SP is an X-ray driven DT filled capsule embedded in a spherical foam-filled hohlraum. The initial and "final" configuration of the target is shown in Fig. 2.[6] Calculations using the BUCKY–1[14] code show that imploding this target with 7.75 MJ of 20–30 MeV Li ions can give a gain of 71 and a yield of 552 MJ. Other details of the target calculation[6] reveal the following energy partitioning from the target in Fig. 2:

- Neutrons–69.8%
- γ rays–0.07%
- X-rays–22%
- Debris ions–6%
- Endoergic loss–2.1%.

For the first time in the unclassified literature we were able to obtain a realistic time dependent neutron flux calculation from a commercial ICF target. The details are reported elsewhere,[6] but one of the general results from this work is shown in Fig. 3. It can be seen that the neutron spectrum starts out much harder at the beginning of the burn and is "softened" considerably by the end of the burn. To the degree that transmutation products interact with the point defects generated by the energetic neutrons (there will be a high rate of n, α reactions at the beginning of the burn and a lower number at the end), such temporal variations will have to be included in future theoretical analyses of materials in ICF power plants.

V. PROTECTION OF THE FIRST WALL

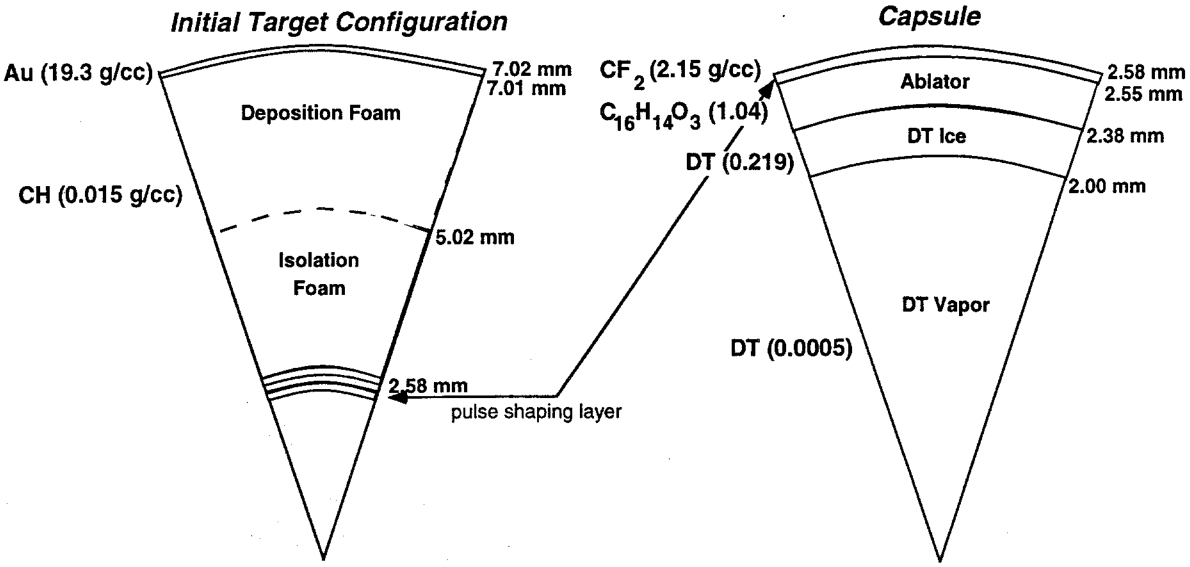

Fig. 2. Schematic of the LIBRA-SP target before (left) and after (right) the TN burn.[6]

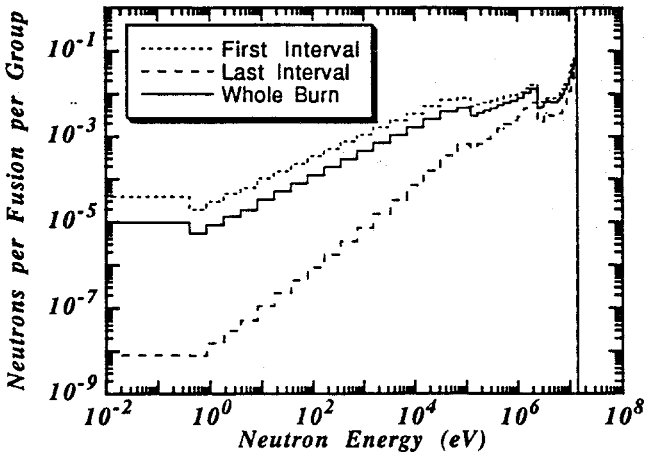

Fig. 3. Neutronic energy spectrum (standard 46 group structure) as a function of time in the LIBRA-SP target (Fig. 2).[10]

The method for protecting the first wall (FW) of LIBRA-SP from the target debris, X-rays, and neutrons is quite different than in earlier designs. Instead of using the woven SiC or HT-9 INPORT units filled with $Pb_{83}Li_{17}$, a new concept, called PERIT's, is used.[7] The PERIT concept uses a combination of Pb-Li spray with liquid Pb-Li in solid steel tubes to protect the "permanent" reactor vessel walls. It allows a more rigid protection scheme to be built and may even allow smaller overall cavity designs.

VI. POWER CYCLE

Figure 4 displays the overall power flow in the LIBRA-SP design. The recirculating power fraction is 18% and the largest components are the power to the drivers (138 MWe) and the pumping power needed for the circulation of the heavy PbLi coolant/breeder through the reactor (70 MWe). A conservative 43% conversion of the energy in the 500°C PbLi coolant could be improved with more aggressive topping/bottoming cycles but the overall cost of such conversion equipment may not pay for the added complexity (increased conversion efficiency).

VII. CONCLUSION

The design of light ion driven fusion reactors continues to provide more insights into and confidence in the use of this technology to generate electricity in the 21st century. The LIBRA-SP design is the latest in this progression. Recent declassification actions allow scientists and engineers to make more realistic unclassified calculations with respect to gain and target spectra. It also allows more realistic beam power input profiles to be calculated which, in turn, should give the fusion community more confidence in the driver design. Finally, the increasing level of information available to universities and industry resulting from recent experimental programs in the national laboratories will insure a broader level of participation in the development of this important source of energy.

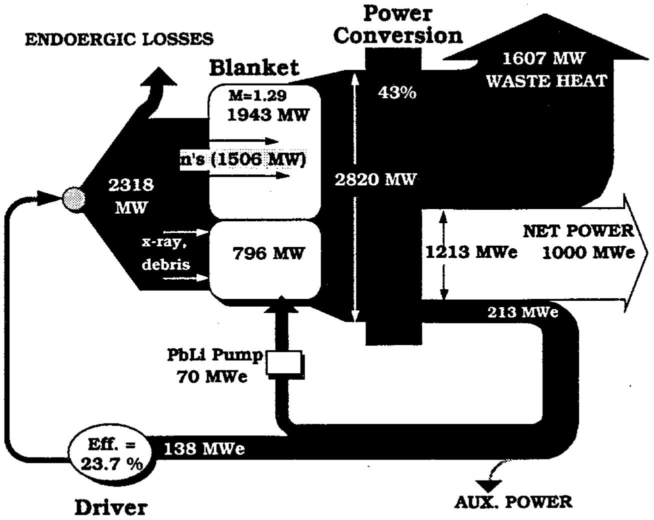

Fig. 4. Power cycle flow diagram for LIBRA-SP.

ACKNOWLEDGMENT

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