



**Beam Propagation, Target Performance, and
Cavity Conditions for the LIBRA-SP Conceptual
Power Plant Design: Annual Report for Calendar
Year 1995**

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G.L. Kulcinski, J.J. MacFarlane, E.A. Mogahed, G.A. Moses,
R.R. Peterson, M.E. Sawan, I.N. Sviatoslavsky, P. Wang**

December 1995

UWFDM-975

***FUSION TECHNOLOGY INSTITUTE
UNIVERSITY OF WISCONSIN
MADISON WISCONSIN***

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UWFDM-975

(also FPA-95-2).

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1. Current Status of PERIT Unit Design

1.1. Introduction

The LIBRA (Light Ion Beam ReActor) concept has been developed over the past decade into the premier commercial power reactor for light ions. The original LIBRA [1] design relied on channel transport of Li ions to a generic target. This was followed by a study (LIBRA-LiTE) [2] using ballistic transport of ions to a similar target. In 1994, the concept of self-pinched beams was developed into a preliminary blanket design for the LIBRA-SP [3-5] reactor. All of these designs have shown that commercial fusion power plants using light ion beam drivers can be economically and technically competitive with other ICF approaches (e.g., lasers and heavy ion beams) as well as comparing favorably to magnetic confinement approaches. However, there were several issues left unresolved in these designs at the end of 1994 and in calendar year 1995, the emphasis has been on resolving some of those issues.

The specific statement of work (SOW) on the LIBRA-SP reactor design for the CY 1995 is given below.

- A. Calculate the MHD stability of the self-pinched beam.
- B. Scope out the nature of the beam overlap problem.
- C. Assess the capability of the IPROP code (developed by SNL) for application to LIBRA-SP.
- D. Design a light ion beam driven target using recently declassified information.
- E. Calculate the implosion conditions and output of the light ion beam target.
- F. Optimize the PERIT concept with respect to establishing favorable beam propagation conditions.
- G. Write an end of period report.

Each of the topics in the SOW will be addressed in the subsequent chapters and verification of the calculations performed for this contract will hopefully be partially accomplished by experiments at SNL in the near future.

References for Section 1

1. B. Badger et al., “LIBRA – A Light Ion Beam Fusion Conceptual Reactor Design,” University of Wisconsin Fusion Technology Institute Report, UWFD-800 (revised Feb. 1990).
2. B. Badger et al., “LIBRA-LiTE – A Commercial Light Ion Fusion Power Plant,” University of Wisconsin Fusion Technology Institute Report UWFD-880 and Fusion Power Report FPA-91-4 (1991).
3. G. L. Kulcinski, et al., “Evolution of Light Ion Driven Fusion Power Plants Leading to the LIBRA-SP Design,” *Fusion Technology* **26**, 849 (1994).
4. B. Badger et al., “LIBRA-SP – A Light Ion Fusion Power Reactor Design Study Utilizing a Self-Pinched Mode of Ion Propagation,” University of Wisconsin Fusion Technology Institute Report UWFD-982 (June 1995).
5. E. A. Mogahed, et al., “A Novel First Wall Protection Scheme for Ion Beam ICF Reactors,” to be published in the 16th IEEE/NPSS Symp. on Fusion Engineering, Sept. 30–Oct. 5, 1995.

2. Modeling of Ion Beam Transport

The 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. A self-pinched transport system is depicted in Figure 2.1. The advantages of self-pinched transport include:

- No lasers for guiding the beams,
- No magnets inside the target chamber,
- High efficiency,
- Transport in bendable narrow tubes is allowed in the region of the PERITs.

There are several issues that need to be addressed in considering the use of self-pinched channels in the LIBRA-SP power plant concept. These include:

- **Background Gas Requirements.** The choice of target chamber fill gas will affect the behavior of the self-pinched channel through neutralization and emittance growth due to scattering.
- **Magnetohydrodynamic Stability.** The MHD stability of the channels is essential to high transport efficiency and beam directionality.
- **Neutralization.** The self-pinched transport concept depends on the proper amount of neutralization of the beam to produce the correct net current in the channel. The current will then create azimuthal magnetic fields of the right strength to confine ions in the desired size channel.
- **Transport Efficiency.** One of the main potential advantages of self-pinched channels is the transport efficiency. Ion energy losses from collisions and beam particle losses due to the lack of proper magnetic confinement at the beam head are identified as potential major contributors to efficiency losses.

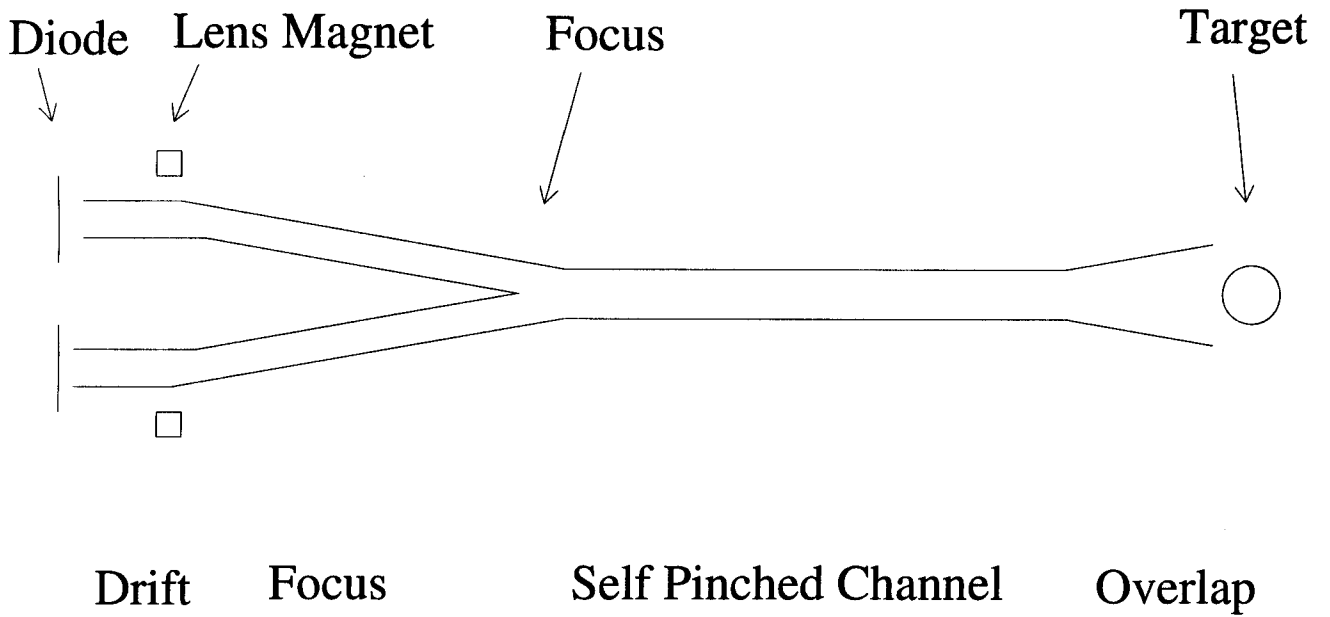


Figure 2.1. Schematic picture of an ion beam transport system using self-pinched transport.

- **Overlap Near Target.** Near the target, magnetic fields from neighboring channels begin to interfere. These lead to a loss of magnetic confinement of the beam.

2.1. Chantran Code

To address these issues in a systematic way that will aid in the design of a self-pinch transport system for LIBRA-SP, a computer code has been written. This code, called Chantran, follows the beam from the diodes through a drift section, a ballistic focus, channel transport, and to the target. It calculates the divergence of the beam due to scattering as it grows along the transport length. It also calculates the beam area including effects of focusing and beam spreading in the overlap region. It finds the beam current density and then the heating of the background gas along the transport. Finally, it determines the conductivity of the background gas in the channel.

2.1.1. Code Description

The Chantran code is a major modification to the Scatball code [1]. It is written in Fortran 77 and queries the user for all of the parameters of the transport system. As in Scatball, the microdivergence of the beam is calculated by adding scattering contributions in quadrature:

$$\theta_\mu(z) = (\theta_{\mu o}^2 + \theta_{scat}^2(z))^{1/2}. \quad (2.1)$$

Here, z is the axial distance from the diode. $\theta_{\mu o}$ is the initial microdivergence of the beam and $\theta_{scat}(z)$ is the growth in microdivergence integrated to axial position z . The initial microdivergence from the diode is an input parameter provided by the user. The contributions from scattering are assumed to be due to Coulomb collisions:

$$\theta_{scat}^2(z) = \frac{2.68 \times 10^{-36} n_q z Z_g^4 \log(210 Z_g^{-1/3})}{\gamma^2 A_g^2 m_p^2 v_{ion}^4}. \quad (2.2)$$

Here, n_q is the density of ions in the background gas in cm^{-3} , which consists of atoms of atomic mass A_g in amu, and nuclear charge Z_g in electron charges. m_p is the mass of a proton in g, γ is the standard relativistic mass parameter, and v_{ion} is the velocity of beam ions in cm/s . The size of the beam is calculated by methods particular to each section of the

transport. In the drift and channel regions of the transport, the beam is assumed to have a radius that increases only due to microdivergence:

$$r_{beam}(z) = R_{diode} + \delta x_{\perp}(z). \quad (2.3)$$

R_{diode} is the outer radius of the anode of the diode and $\delta x_{\perp}(z)$ is the transverse spreading of the beam due to microdivergence:

$$\delta x_{\perp}(z) = \frac{2}{3}\theta_{\mu}(z)z \left(1 + \left[\frac{\theta_{\mu i}^2}{\theta_{scat}^2} \frac{1 - (\theta_{\mu i}^2)^{1/2}}{\theta_{\mu}(z)} \right] \right). \quad (2.4)$$

In the focus region, geometrical focusing is combined with divergence spreading:

$$r_{beam}(z) = \frac{R_{diode}}{F}(z - z_{focus}) + \delta x_{\perp}(z). \quad (2.5)$$

In the channel overlap region, the beam spreads at the same angle it was focused at and divergence spreading is added:

$$r_{beam}(z) = \frac{R_{diode}}{F}(z - z_{overlap}) + \delta x_{\perp}(z). \quad (2.6)$$

Here, F is the focal length of the ballistic focusing lens magnet, z_{focus} is the axial position of the geometrical focus of the magnet, and $z_{overlap}$ is the axial position of the start of the overlap region, where the magnetic fields of adjacent channels begin to interfere with each other.

The beam heats the channel gas via ion energy loss. The deposition of beam energy in the gas is calculated with a form of the Bethe model [2] at high particle energy and with the Lindhard model [3] at low energy. That is:

$$\left(\frac{dE}{dx} \right)_{Bethe} = \left(\frac{\omega_p q_{ion} e}{v_{ion}} \right)^2 \left[\ln \frac{2m_e v_{ion}^2}{\bar{\Phi}_2 (1 - v_{ion}^2/c^2)} - \left(\frac{v_{ion}}{c} \right)^2 \right] \quad (2.7)$$

for ion velocities greater than the orbital velocity of electrons in the target atom, and

$$\left(\frac{dE}{dx} \right)_{LS} = (3.84 \times 10^{18} \text{ keV cm}^{-1}) n_g \frac{q_{ion}^{7/6} Z_g^*}{[q_{ion}^{2/3} 1 + (Z_g^*)^{2/3}]^{2/3}} \left(\frac{E_{ion}}{A_{ion}} \right) \quad (2.8)$$

for ion velocities below the orbital velocity of electrons in the target atom. $\bar{\Phi}_2$ is the average ionization potential and Z_g^* is the average screened nuclear charge of the background plasma.

The electron plasma frequency is ω_p , m_e the electron mass in g, e the electron charge in esu, and q_{ion} the charge on a beam ion in units of e . The beam ions have an energy E_{ion} and an atomic mass A_{ion} .

The ionization state of the background gas is calculated with a Saha model [4]. This assumes an equilibrium plasma, which is in doubt because electrons may be removed from inner gas atom orbitals leaving the atoms in a non-equilibrium state and the electrons in a non-Maxwellian distribution. It is hoped that the equation-of-state is not greatly in error, though it is clear that this model is unacceptable for calculation of the opacity. The energy density ϵ is calculated with an ideal gas model:

$$\epsilon = (1 + Z_g^*)n_g k_B T_e, \quad (2.9)$$

where T_e is the electron temperature (which is assumed equal to the ion temperature in the background gas) and k_B is Boltzmann's constant. Using the energy density determined from the ion deposition and this equation-of-state, Chantran determines the temperature of the background gas. From the temperature, the conductivity is calculated;

$$\sigma(1/s) = \frac{2.533 \times 10^8 Z n(\text{cm}^{-3})}{cf_{Spitzer} + cf_{e-n}}, \quad (2.10)$$

where the Spitzer collision frequency is

$$cf_{Spitzer}(1/s) = 8.6 \times 10^{-7} n_{ion}(\text{cm}^{-3}) \ln \Lambda Z \times (1 + Z) \frac{1}{T_e^{1.5}(\text{eV})}, \quad (2.11)$$

and the electron - neutral collision frequency is

$$cf_{e-n}(1/s) = 2.514 \times 10^{-8} n_{neut}(\text{cm}^{-3}) T_e^{0.5}(\text{eV}). \quad (2.12)$$

Here, $\ln \Lambda$ is the standard Coulomb logarithm and n_{neut} is the density of neutral atoms.

2.1.2. Model for Erosion of Beam Head

The head of the beam moves into un-ionized background gas. There are few free electrons available for neutralization of the beam and the ion beam current is well below the nominal levels. There are no confining magnetic fields frozen into the channel plasma, as

is the case farther back in the beam. For all of these reasons, the head of the beam is not confined to the self-pinched channel in the same manner as the rest of the beam.

Because the rate at which the head of the beam is lost is very complicated to calculate, we have scaled results from the IPROP code [13]. The beam loses the head at the rate of

$$\tau_e(ns) = \frac{L_{beam}}{400 \text{ cm}} \frac{I_{net}}{50 \text{ kA}}, \quad (2.13)$$

where τ_e is the part of the beam in ns lost out of the total pulse width while the beam moves L_{beam} cm for a net beam current of I_{net} kA.

I_{net} , the net current in a self-pinched channel, is set by the requirement that the ions in the beam are confined by the azimuthal magnetic field that is generated by the current itself. Chantran uses the following relation [6] for the net current:

$$I_{net} = 0.5 \left(\frac{R_{diode} \theta_\mu}{r_{chan}} \right)^2 I_A. \quad (2.14)$$

2.1.3. Model for Beam Overlap

Near the target the beams are geometrically forced to be close enough to each other that the magnetic fields from adjacent channels interfere. The ions are then no longer confined and they begin to spread at the angles they achieve in the betatron orbits. Here, we assume that the angle that the betatron orbits make with the propagation of the channels is the angle reached from focusing by the magnetic lenses plus the growth due to scattering in the channel and overlap regions.

The position where the channels begin to overlap is determined geometrically. Figures 2.1.1 and 2.1.2 show the geometry. The N_{chan} channels each have a radius of R_{chan} . A fraction, Ω_{unirr} , of the total solid angle seen by the target is assumed to contain no ion beams. In totally symmetric irradiation, Ω_{unirr} is zero. In the irradiated fraction of solid angle, the beams are assumed to have a packing fraction of F_{pack} . This is determined by how the beams are arranged and how close the beams can get before they interfere, as shown in

Self Pinched Channel

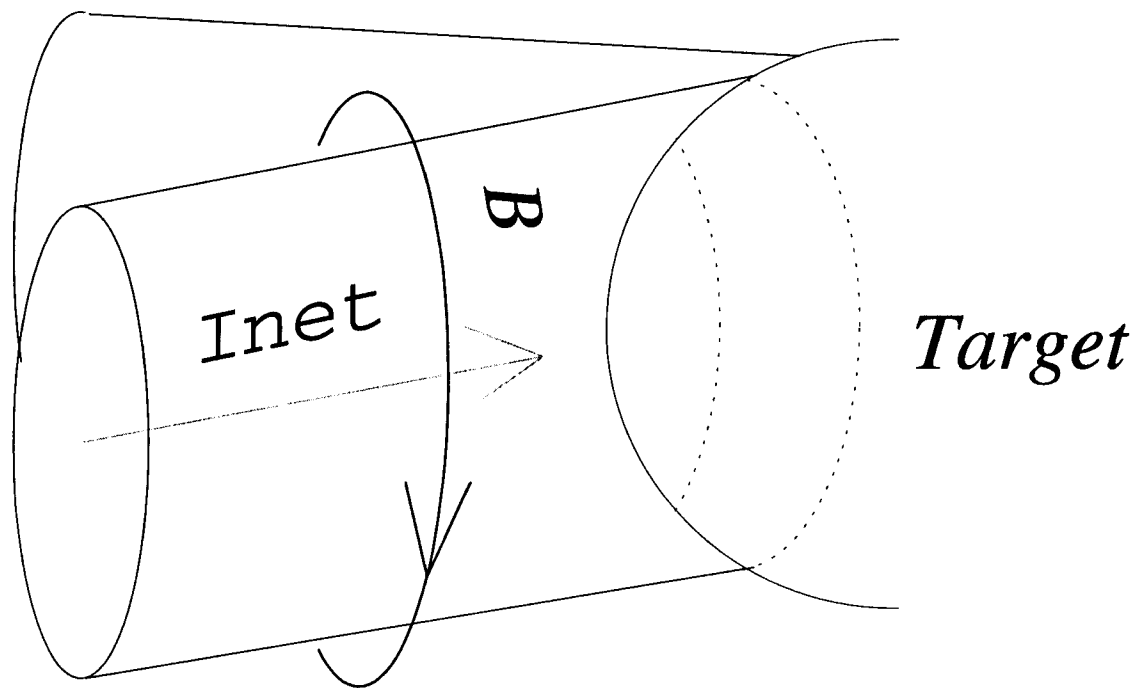


Figure 2.1.1. Schematic picture of the overlap of beams near the target.

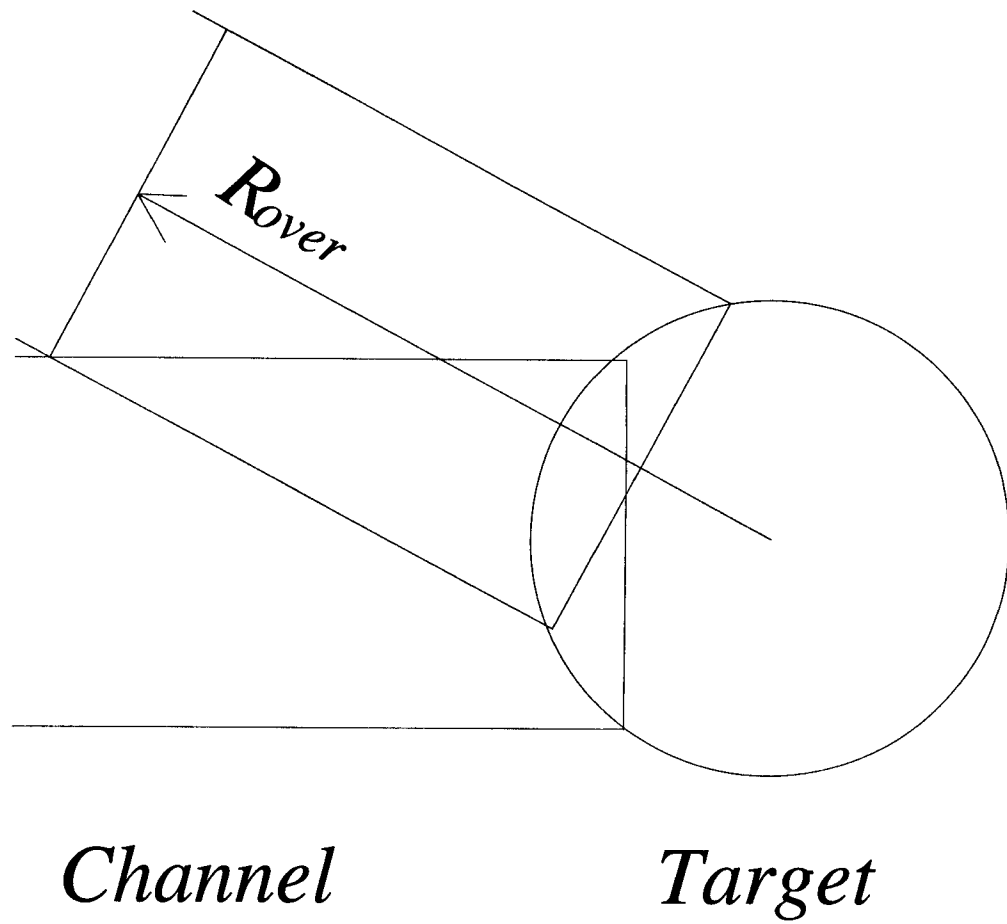


Figure 2.1.2. Schematic picture of the overlap of beams near the target. Overhead view, showing position of overlap radius.

Figure 2.1.2. These considerations lead to the overlap radius;

$$r_{over} = \frac{R_{chan} N_{chan}^{1/2}}{2(1 - \Omega_{unirr})^{1/2} F_{pack}^{1/2}}, \quad (2.15)$$

where r_{over} is the distance from the center of the target to where the overlap begins. In this analysis, the main and prepulse beams are assumed to have the same R_{chan} and Ω_{unirr} , and all beams sum to N_{chan} with a packing fraction of F_{pack} . z_{over} is the position of the target minus r_{over} .

In the overlap region, it is assumed that the ions move ballistically, that is, after they reach the overlap region, the magnetic fields are instantly set to zero and the ions move in whatever direction they were at that time. It is also assumed that there is sufficient neutralization that beam expansion due to space charge is not an issue. With these assumptions, one can use Equation 2.6.

2.1.4. Code Runs for LIBRA-SP

The Chantran computer code has been used to simulate the behavior of the self-pinch channels in LIBRA-SP. The parameters used in the simulations are shown in Table 2.1.1. The results are summarized in Table 2.1.2. Details of the simulations are shown in Figures 2.1.3 through 2.1.11, where various parameters are plotted versus the distance from the anode of the diode. The radius of the beam envelope is seen to start at the outer radius of the diode's anode and then be focused to a radius of about 0.6 cm, where it remains while in self-pinch transport. Once the overlap position is reached, the beam radius is seen to increase. This is all shown in Figure 2.1.3 for both the main and prepulse beams; the corresponding beam cross sectional areas are shown in Figure 2.1.4. The prepulse beam begins more narrow because the low power and energy requirements lead to a smaller diode, but the channels are about the same for main and prepulse, because the channel radius is determined by the microdivergence and the focal length which are similar for the two types of beams. After the beams overlap, the ions spread at the same angle at which they were focused plus any additional effects due to growth in microdivergence. The microdivergence is shown in Figure 2.1.5, where it is seen that the prepulse beams become more divergent

Table 2.1.1. Parameters for LIBRA-SP Self-Pinched Channels

	Main Pulse	Prepulse
Ion species	Lithium	Lithium
Ion energy (MeV)	30	20
Background gas species	Helium	Helium
Background gas density (cm^{-3})	7×10^{15}	7×10^{15}
Number of beams	12	12
Anode outer radius (cm)	15.593	11.27
Anode inner radius (cm)	10.0	10.0
Total ion power on target (TW)	480	26
Total ion energy on target (MJ)	6.7	1.02
Ion power leaving each anode (TW)	20.8	2.54
Ion energy leaving each anode (MJ)	0.832	0.102
Pulse width at each anode (ns)	40	40
Bunching factor	2.594	1.0
Drift length (cm)	50	50
Focal length (cm)	150	150
Distance from anode to target (cm)	1152	1152
Target radius (cm)	0.7	0.7
Fraction of target area not irradiated	0	0
Microdivergence at anode (mrad)	4	4
Anode current density (A/cm^2)	1500	1500

Table 2.1.2. Results for LIBRA-SP Self-Pinched Transport

	Main Pulse	Prepulse
Microdivergence at target (mrad)	4.053	4.119
Neutralization at target end of channel	.978	.866
Pulse width at target (ns)	14.0	39.2
Overlap radius (cm)	1.96	1.96
Overlap efficiency	.74	.85
Channel transport efficiency	.905	.979
Net efficiency	.670	.835

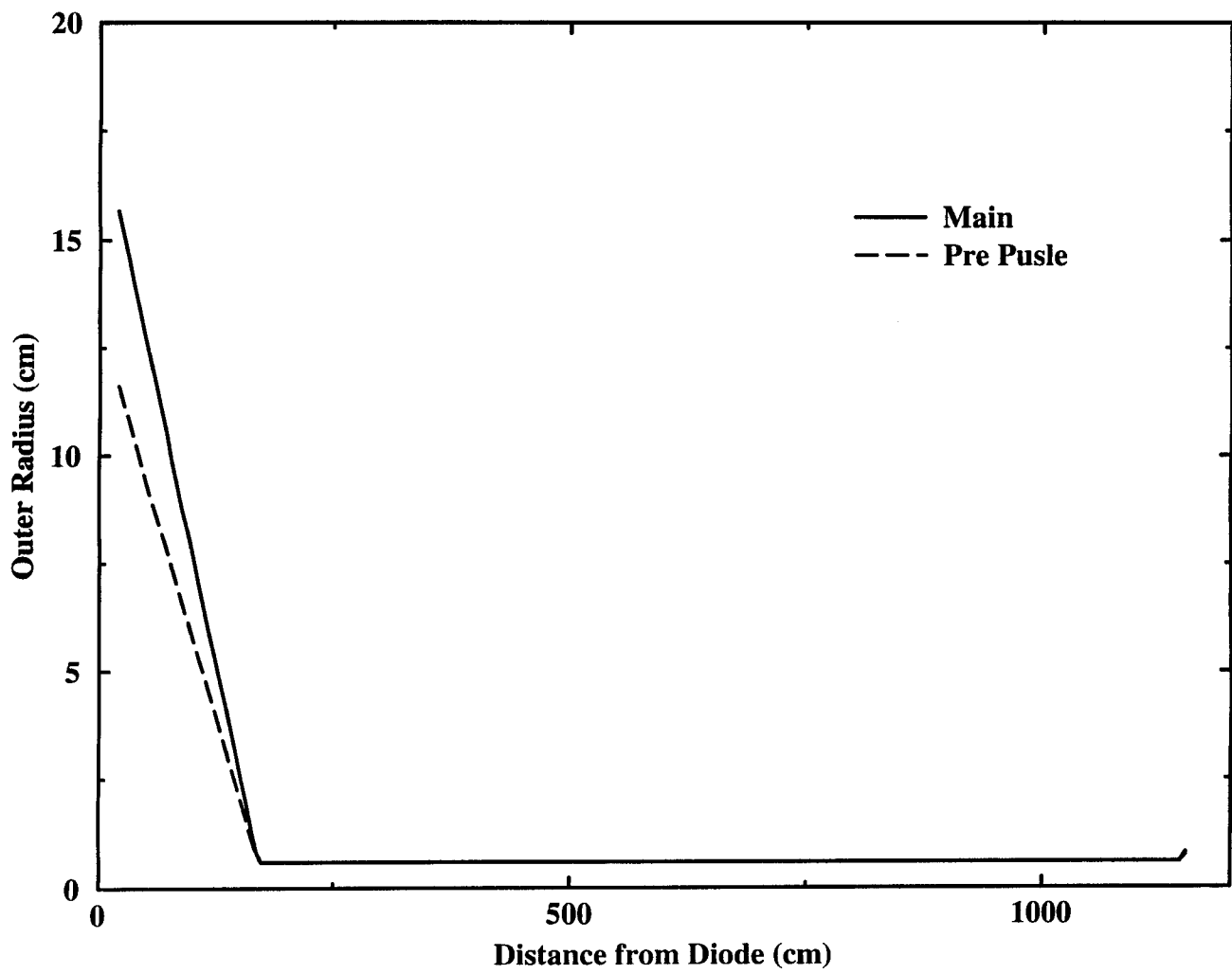


Figure 2.1.3. Outer radius of beam envelope versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

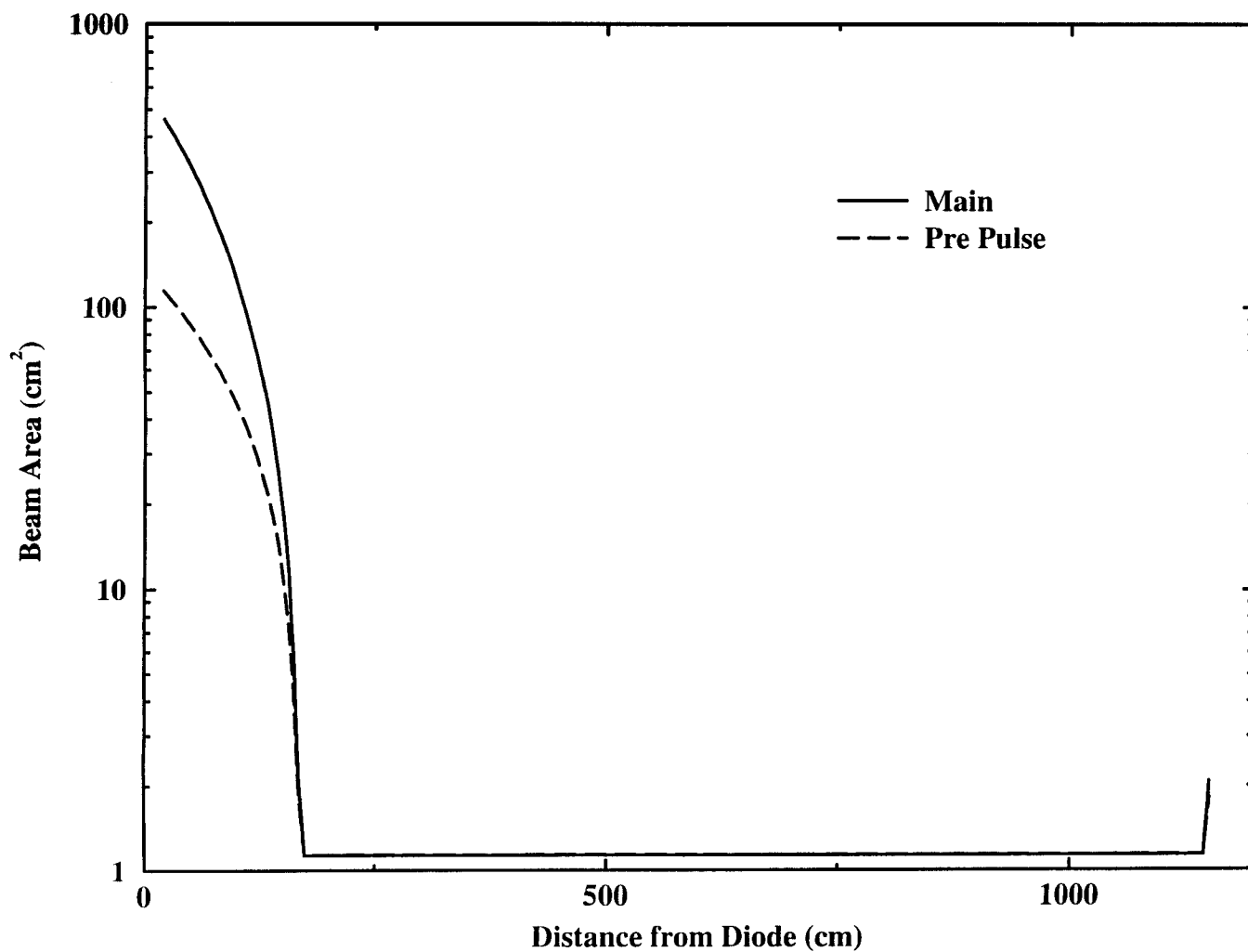


Figure 2.1.4. Cross sectional area of beam envelope versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

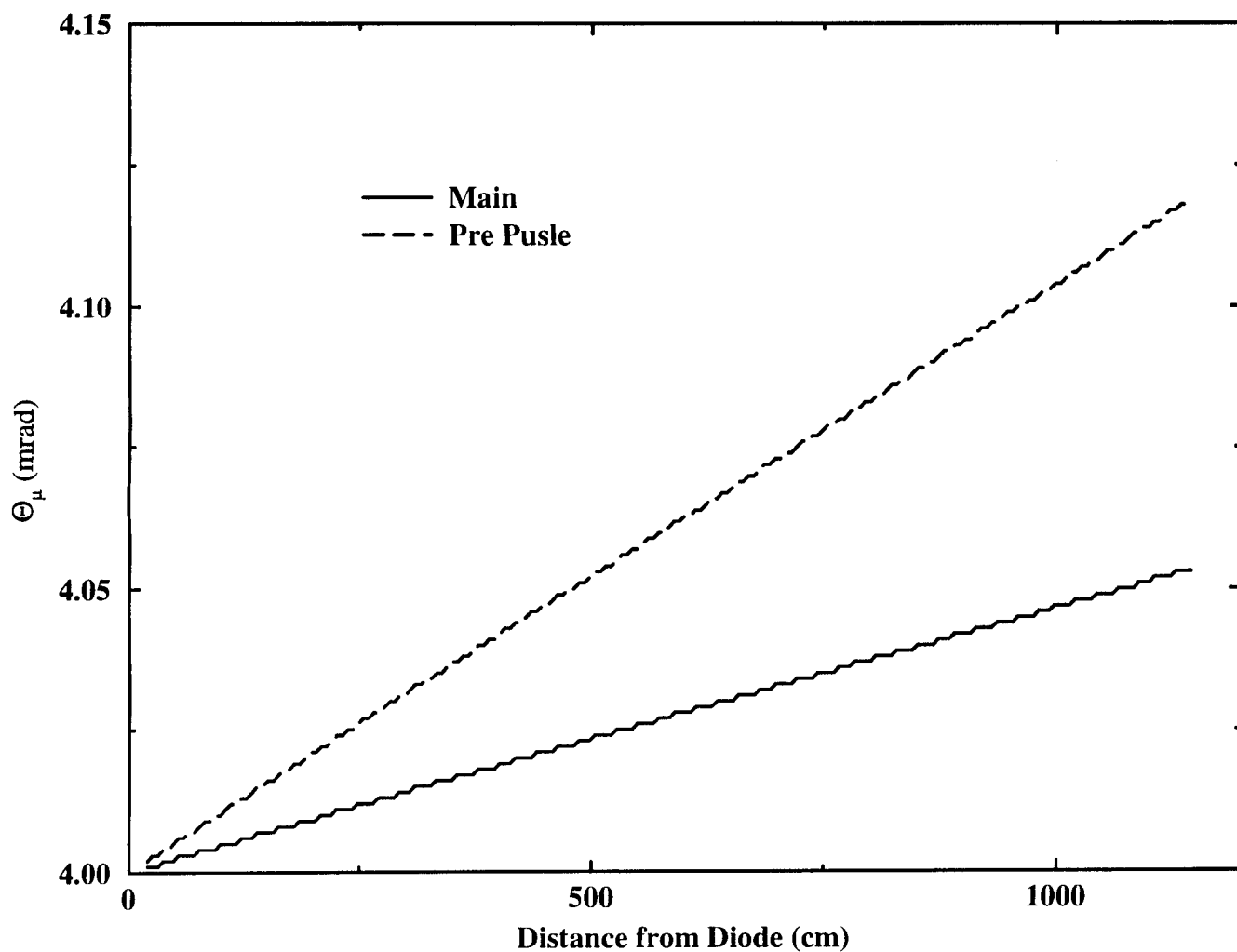


Figure 2.1.5. Microdivergence versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

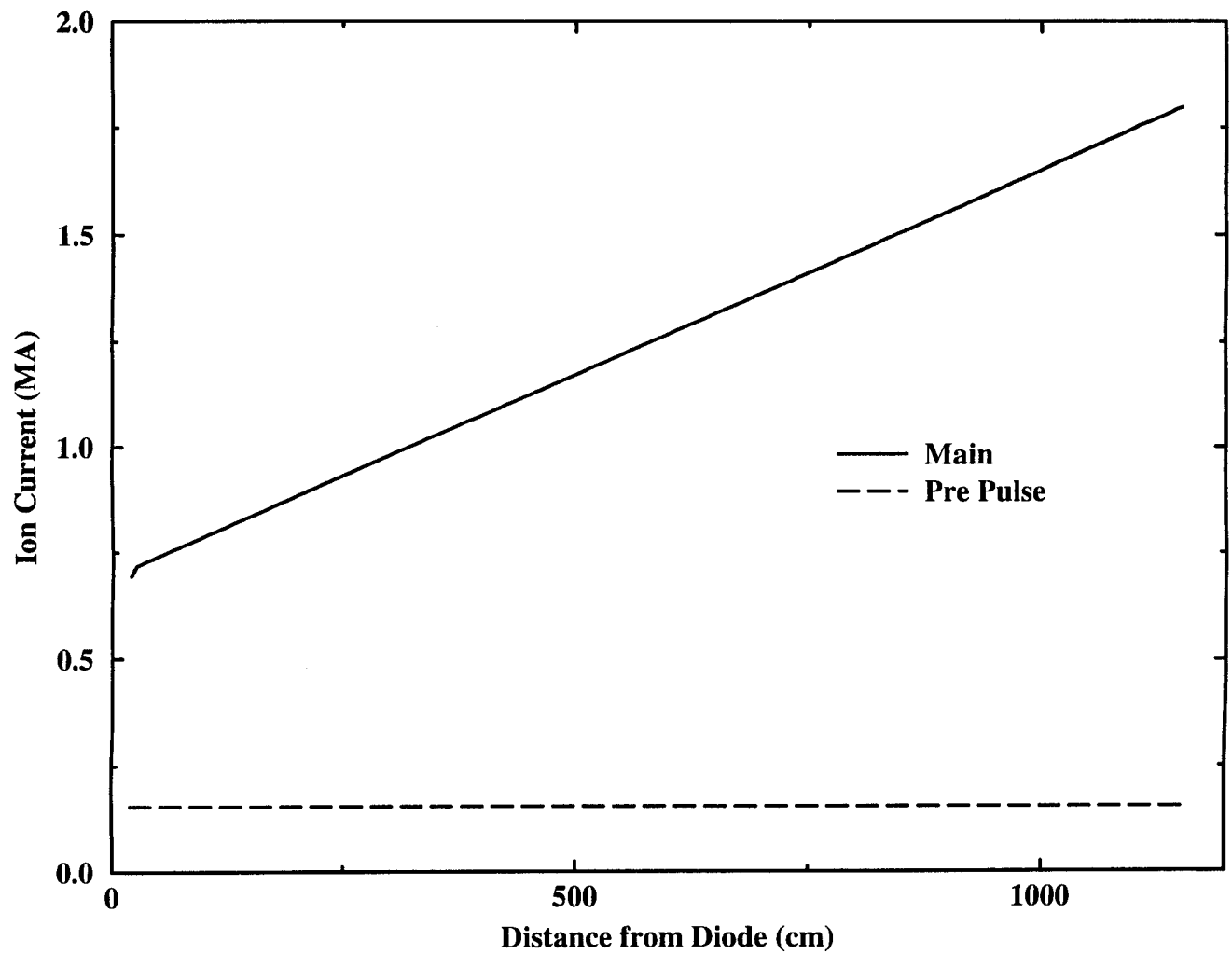


Figure 2.1.6. Ion current versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

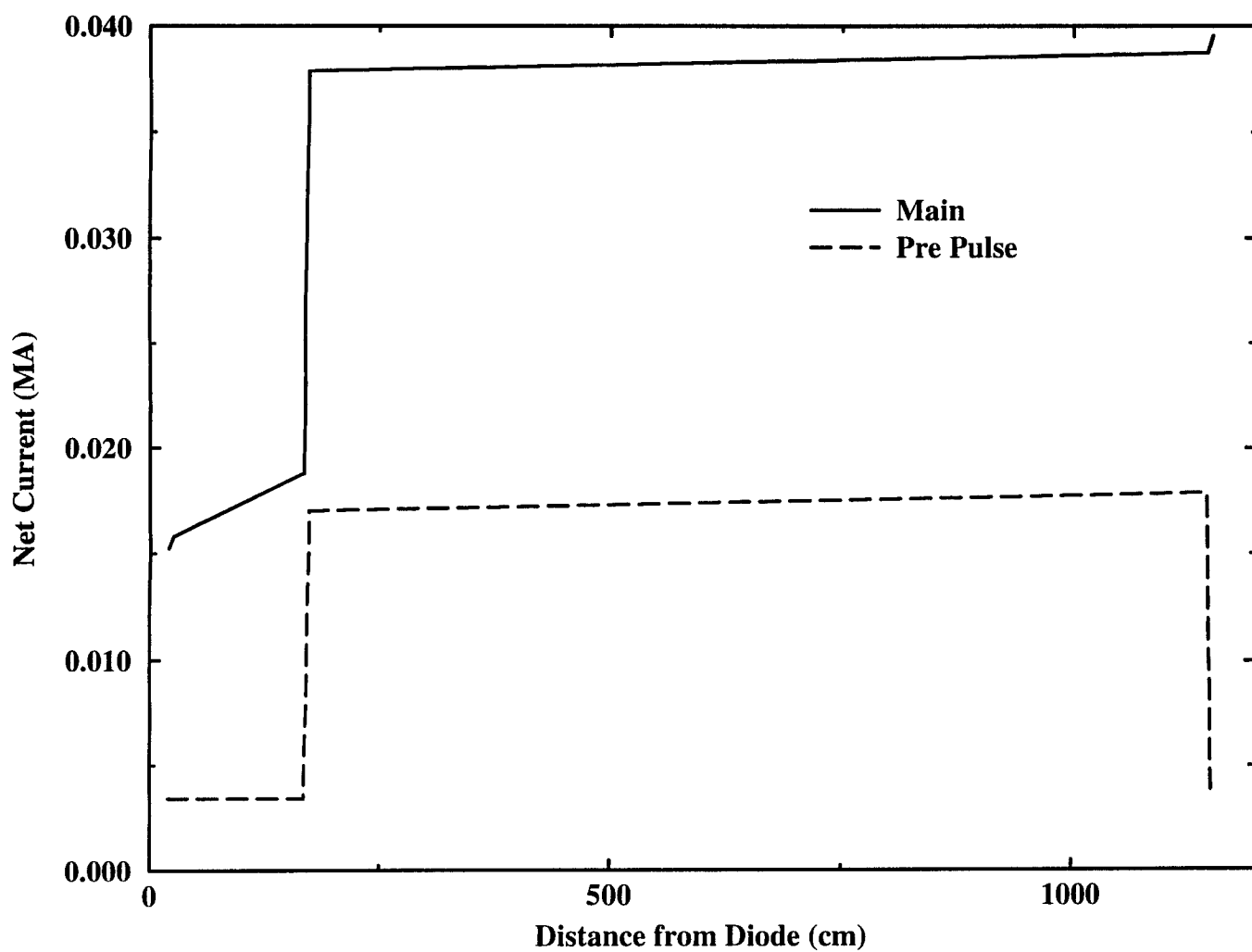


Figure 2.1.7. Net current versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

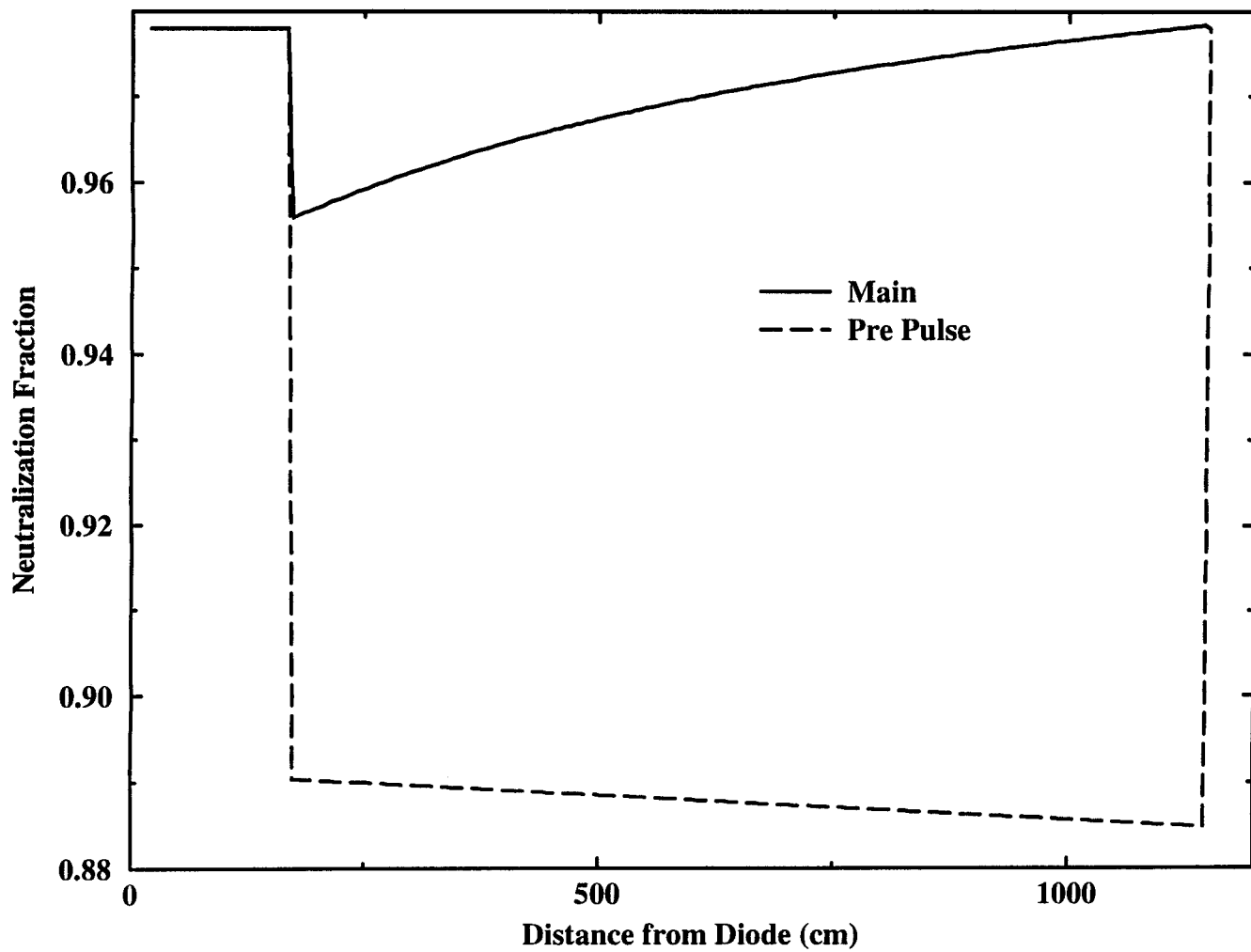


Figure 2.1.8. Neutralization fraction versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

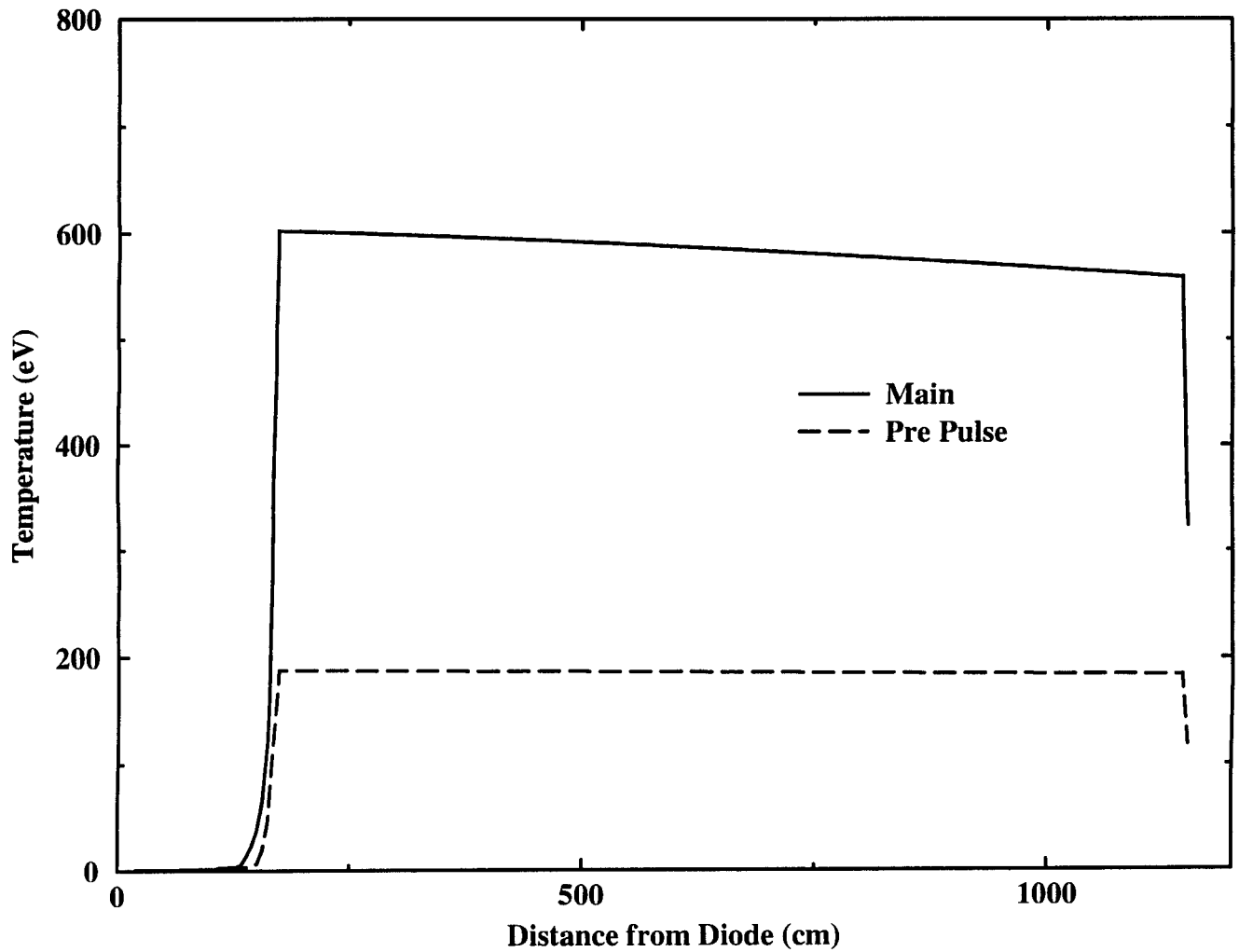


Figure 2.1.9. Background gas temperature in self-pinched channel versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

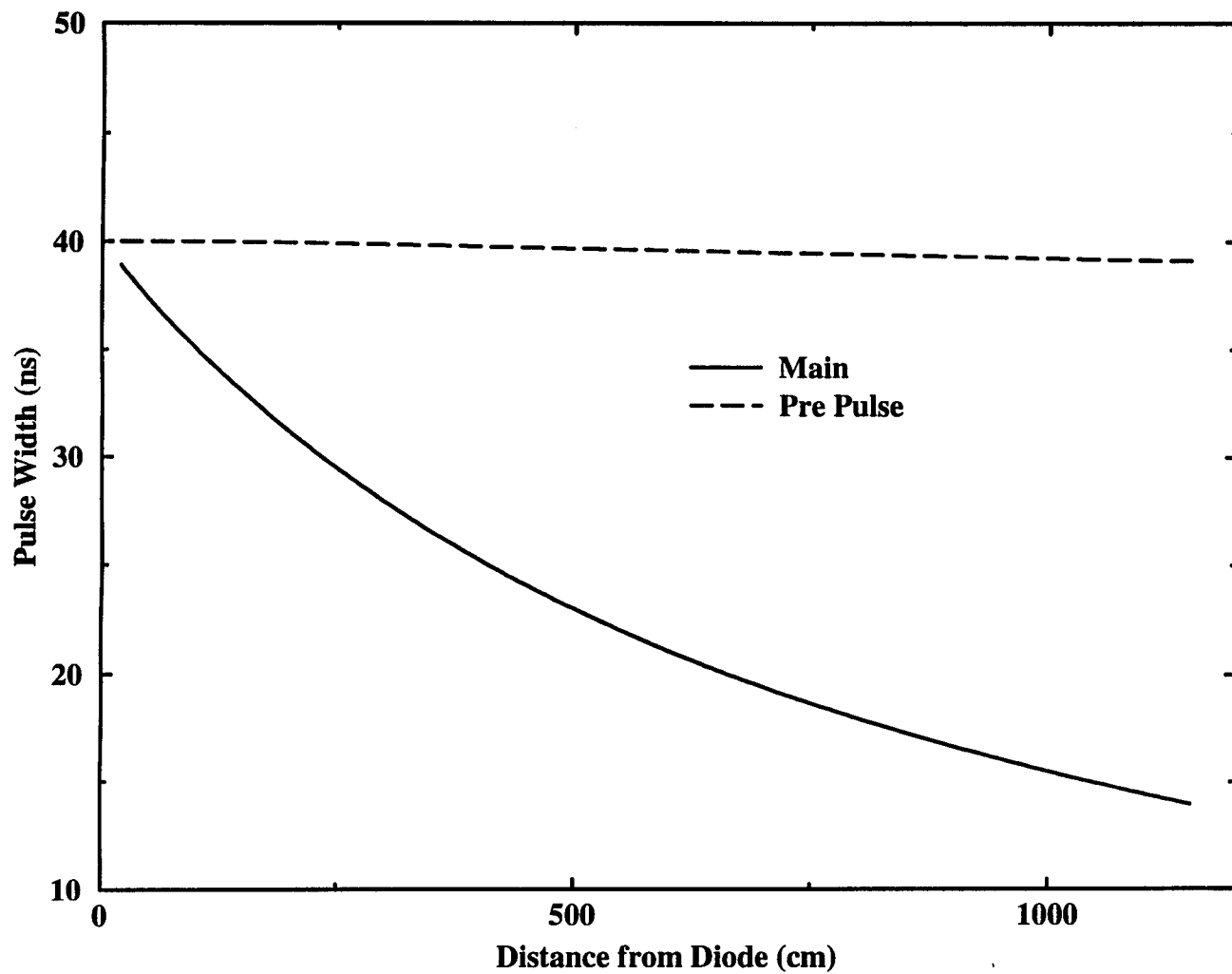


Figure 2.1.10. Pulse width versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

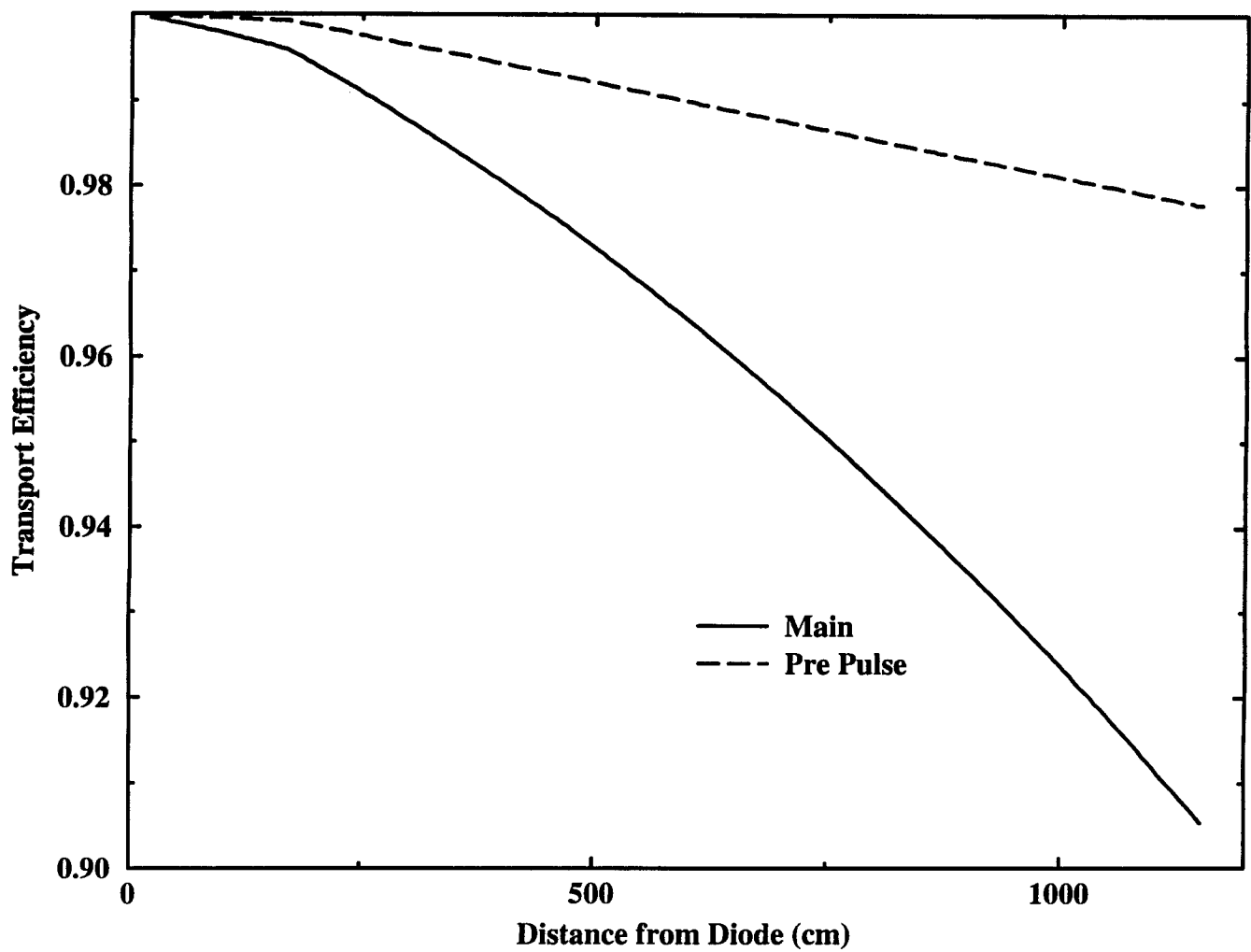


Figure 2.1.11. Transport efficiency versus distance from diode for LIBRA-SP main and prepulse beams. Calculated by Chantran computer code.

due to scattering because of lower beam energy, but that the microdivergence only grows by a small amount because of the low background gas density. The overlap position is the same for the two types of beams because the channel radius and all of the other geometrical parameters are the same for both. The angle at which the ions spread is greater for the main beams because the anode radius had to be larger and this leads to more ions missing the target. We assume that the density of ions is always uniform across the beam area and this leads to 26% of the ions in the main beam that reach the end of the channel missing the target and 15% for the prepulse beams.

The ion current in each beam, shown in Figure 2.1.6, increases as the main beams move down the channel because of time-of-flight bunching. The prepulsed beam is not bunched as the current is about constant. The net current is set by Equation 2.14. The main beam requires a higher net current because R_{diode} is larger. Therefore, the required neutralization fraction, shown in Figure 2.1.8, is much lower for the prepulse beam. The neutralization in the focus and overlap regions is fixed at about 0.98. A better calculation of the neutralization needs to be done at some point with IPROP or some other code. The ion and electron currents heat the background gas to the temperatures shown in Figure 2.1.9, where the higher currents in the main beams lead to higher temperatures.

The pulse widths are shown in Figure 2.1.10. The prepulse beams have an almost constant pulse width because there is no bunching and the erosion of the beam is small because of the low net current. The main beams experience significant erosion and bunching producing a pulse width at the target of 14 ns. Erosion also reduces the transport efficiency, shown in Figure 2.1.11, where the main beams are seen to be 90% efficient to the end of the channel. Combining this with the 74% overlap efficiency leads to a 67% net transport efficiency. The prepulse beams are much more efficient because of lower erosion and higher overlap efficiency. The net efficiency of the prepulse beams is 84%.

The beam parameters in this study have changed significantly since the previous report [12]. The channels are much longer (1152 cm versus 550 cm), which leads to more erosion of the beam head and lower transport efficiency. The peak beam power required on

target was much higher (480 TW compared to 300 TW), which also leads to more erosion because of higher beam current. Also the higher power requires larger radius anodes in the main diodes (15.593 cm versus 14.1 cm) which means that the angle of injection of ions into the channel is higher, which in turn leads to lower overlap efficiency. The overall effect of these changes is to lower the net transport efficiency for the main beams from 90% to 67%.

2.2. MHD Stability

Any current carrying discharge, such as self-pinched ion beam channels, is susceptible to magnetohydrodynamic instabilities. The two most common are sausage modes, where the plasma is displaced in an azimuthally symmetric manner ($m = 0$, where the displacement is proportional to $e^{im\phi}$, ϕ being the azimuthal angle), and kink modes with $m = 1$. The two modes are depicted in Figure 2.2.1. Kink modes are potentially most damaging to self-pinched transport because they change the direction of the beams. At issue is how fast the modes grow. The current is only on for 10's of ns, so the instabilities must have e-folding times less than a few ns for the instabilities to be a problem. In contrast, preformed plasma channels have a current lasting microseconds, so that damaging e-folding times can be much larger, and therefore, more easily achieved.

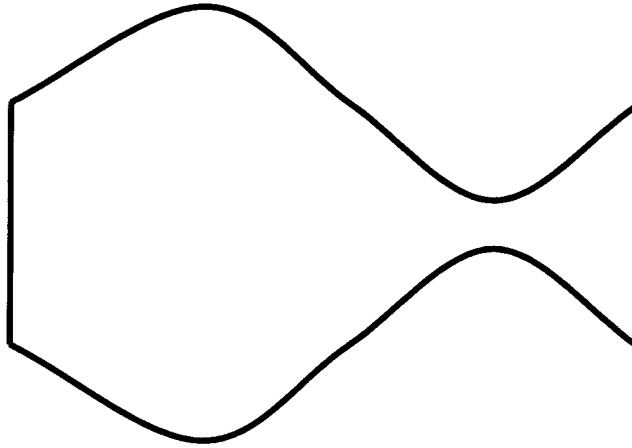
2.2.1. Stability Model

MHD instabilities have been known to exist in z-pinches for a very long time. A stability criterion based on the energy principle [7] can predict when a z-pinch is susceptible to MHD instabilities. The equilibrium relation for z-pinches of all modes is

$$\frac{dp}{dr} + \frac{B_\theta}{\mu_o r} \frac{d}{dr}(r B_\theta) = 0 . \quad (2.16)$$

Here, p is the pressure of the gas in the channel, B_θ is the azimuthal magnetic field, and μ_o is the permeability of free space. For $m = 0$, the energy principle states that for the plasma to be stable against MHD modes, perturbations in the plasma must not reduce the total

Sausage Mode



Kink Mode

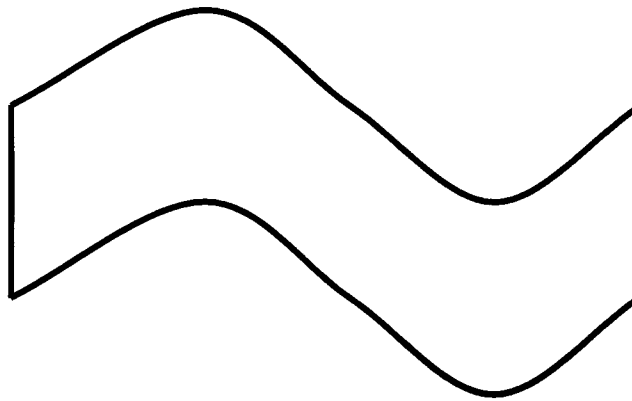


Figure 2.2.1. Schematic pictures of sausage and kink MHD modes.

energy in the plasma. For $m = 0$ perturbations, this reduces to

$$\frac{r \frac{dp}{dr}}{p} < \frac{2\gamma \frac{B_\theta^2}{\mu_o}}{\gamma p + \frac{B_\theta^2}{\mu_o}}. \quad (2.17)$$

This condition is generally difficult to meet, so z-pinches are almost always unstable against $m = 0$ sausage modes. Experimentally, sausage mode have been seen in z-pinches. For $m \neq 0$, the stability criterion becomes,

$$2r \frac{dp}{dr} + \frac{m^2 B_\theta^2}{\mu_o} > 0. \quad (2.18)$$

This can be rewritten as,

$$\frac{\frac{d}{dr}(r B_\theta^2)}{B_\theta^2} < m^2 - 1. \quad (2.19)$$

For $m = 1$, $\frac{d}{dr}(r B_\theta^2)$ must be negative for stability. In self-pinched channels, the peak magnetic field is reached near the channel radius. Therefore the part of the plasma inside the channel radius is kink unstable. For $m \geq 2$, the z-pinch is almost always stable.

The growth rate for $m = 0$ and 1 MHD instabilities in self-pinched channels must now be estimated. In the energy principle approach to MHD, the time dependence of the instability is governed by the momentum equation for a perturbed displacement of the plasma, ξ ,

$$\rho \frac{\partial^2 \vec{\xi}}{\partial t^2} = \vec{F}(\vec{\xi}); \quad (2.20)$$

$\vec{F}(\vec{\xi})$ is the force operator,

$$\vec{F}(\vec{\xi}) = \frac{1}{\mu_o} (\vec{\nabla} x \vec{Q}) x \vec{B} + \frac{1}{\mu_o} (\vec{\nabla} x \vec{B}) x \vec{Q} + \vec{\nabla} (\vec{\xi} \cdot \vec{\nabla} p + \gamma p \vec{\nabla} \cdot \vec{\xi}). \quad (2.21)$$

Here, $\vec{Q} \equiv \vec{\nabla} x (\vec{\xi} x \vec{B})$. The temporal behavior of $\vec{\xi}$ is taken to be $\propto e^{-i\omega t}$, which leads to a relation for ω ,

$$-\rho \omega^2 \vec{\xi} = \vec{F}(\vec{\xi}). \quad (2.22)$$

If ω^2 is negative, then it is minus the square of the growth rate. In the z-pinch geometry, $\vec{B}$ is only in the azimuthal direction, and $\vec{Q} = \frac{im B_{theta}}{r} (\xi_r \hat{r} + \xi_z \hat{z})$. The solution of Equation 2.22 is rather difficult to perform analytically because there are many terms resulting from the

cross products. Once a solution is obtained, there is some worry that the growth rate will be an overestimate because the assumptions of ideal MHD are not valid. Experiments of fiber pinches [8, 9, 10] have shown that the MHD growth rates are anomalously below the predicted values. Computational results for fiber pinches show that the sausage mode grows at about the time it takes an Alfvén wave to transit a pinch [11],

$$\vec{\xi} = \vec{\xi}_o e^{\gamma t}, \quad (2.23)$$

where,

$$\gamma = v_A / r_{chan} = \frac{B_{theta}}{(4\pi n_{ion} m_{ion})^{1/2} r_{chan}} \quad (2.24)$$

2.2.2. Stability of LIBRA-SP

There is not enough information at this time to calculate the growth rate for MHD sausage and kink modes in LIBRA-SP self-pinch channels using Equation 2.22. To do an accurate calculation, one needs the pressure and magnetic field profiles to calculate all of the terms in $\vec{F}$. Even if these are available, Equation 2.22 is only strictly valid for ideal MHD. So, we suggest that a full computer simulation be eventually performed. For now, Equation 2.24 will be used. In the future, computer simulations will be performed with the Zeus 2-D MHD hydrodynamics code and with the IPROP code (if possible).

The growth of MHD instabilities has been estimated using Equation 2.24. The parameters for transport are shown in Table 2.2.1. The channel parameters are the most recent estimates for the LIBRA-SP main and prepulse channels [12]. The growth factor is the multiplier on an initial perturbation seen at the end of the pulse. The 1.74 and 1.40 growth factors mean that a small initial perturbation will remain small.

2.3. IPROP Code

IPROP is a hybrid particle-in-cell (PIC) computer code in three dimensions [13], though two-dimensional boundary conditions are required. Magnetic and electric fields are calculated in three dimensions and ion transport is calculated in a PIC model. The ions are assumed to have a constant charge state (no charge exchange). Plasma electrons are modeled

Table 2.2.1. MHD Instability Growth for LIBRA-SP Self-Pinched Channels

	Main Pulse	Prepulse
r_{chan} (cm)	0.6	0.6
I_{net} (kA)	30.7	18.5
B_{theta} (gauss)	1.02×10^4	0.617×10^4
n_{ion} (cm ⁻³)	7×10^{15}	7×10^{15}
v_A (cm/s)	1.87×10^7	1.13×10^7
γ (s ⁻¹)	3.11×10^7	1.88×10^7
τ_{pulse} (ns)	40	40
Growth factor	3.47	2.12

with thermal fluid and high energy macroparticle contributions. Electrons with energies greater than 100 eV are transported with a PIC model, while less energetic electrons are transported as a fluid. Electron populations are calculated including contributions from ion impact ionization, avalanche and recombination. There is currently no radiation in IPROP.

There is currently an effort to add to the capabilities of IPROP. The atomic physics modeling is being expanded in a collaboration between Dale Welch of Mission Research and scientists at the University of Wisconsin. These improvements should allow IPROP to calculate radiation emission and charge exchange in the beam ions. Radiation emission is needed in LIBRA-SP self-pinched transport simulations because the temperature of the channels becomes very high (several 100's of eV). The code may also be ported to a parallel computer that would allow LIBRA-SP problems to be run.

IPROP could eventually be useful in the study of several issues related to LIBRA-SP channels. The MHD stability of channels can be simulated with IPROP once it is running on a sufficiently fast computer. The calculation of neutralization is possible once radiation emission is included. Charge exchange is probably not important in LIBRA-SP channels, but it would be important to the transport of heavy ions in self-pinched channels. It is not clear whether it is practical to use IPROP to study the beam overlap problem because of the three dimensional nature of the problem, though there is some effort to find a way to use the code for this. No definitive recommendation can be made at this time.

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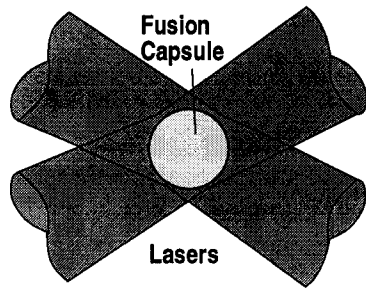
3. Target Performance

3.1. Introduction

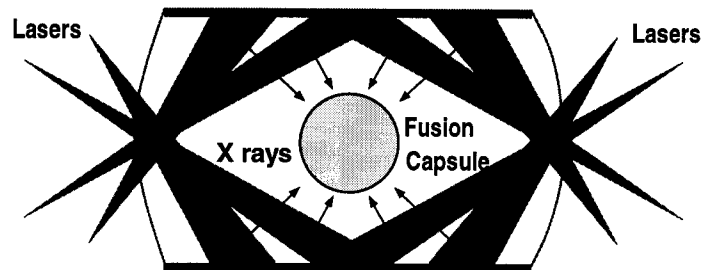
In this section, the results from BUCKY-1 [1] radiation-hydrodynamics simulations of the implosion, fusion burn, and breakup of the LIBRA-SP target are presented. The results presented here should be considered preliminary, since, at the time of publication, the total fusion yield of the target has reached only 320 MJ (as compared to 589 MJ envisioned for the LIBRA-SP reactor design [2]). It is expected that a yield of 500–600 MJ will be readily achieved with a modest amount of additional target design work [3]. It is important to note, however, that these calculations represent the first *non-classified* detailed radiation-hydrodynamics simulations of the implosion and burn of a high-gain ICF target irradiated by an intense Li ion beam. This has become possible because of recent significant changes in the classification guidelines for ICF [4].

The LIBRA-SP target is based on the “indirect-drive” concept in contrast to the direct drive approach commonly used with laser driven targets (see Fig. 3.1.1). The light ion indirect drive concept is also different than the indirect drive concepts for lasers and heavy ion beams (see Fig. 3.1.1). In the light ion approach, the x-ray driven ICF capsule is embedded within a spherical foam-filled hohlraum. The Li ions penetrate the hohlraum wall (or radiation case) and deposit the bulk of their energy in a low density CH foam, which converts the ion beam energy into x-rays that have a high enough energy to freely traverse the foam. This radiation, in turn, bathes the fusion capsule and provides the drive for the capsule implosion. Details of this target concept, together with descriptions of recent proof-of-principle experiments for light ion-driven hohlraums and x-ray pulse-shaping techniques, have been presented elsewhere [5,6].

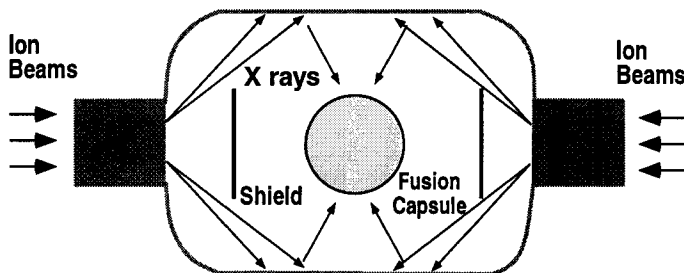
In this report, the BUCKY-1 simulations of the implosion, burn, and breakup of the LIBRA-SP target are discussed. Section 3.2 describes the target design and Li beam parameters used in the simulation. Here, the major features of the physics models in BUCKY-1 are summarized. In Section 3.3, results for the implosion and fusion burn phases



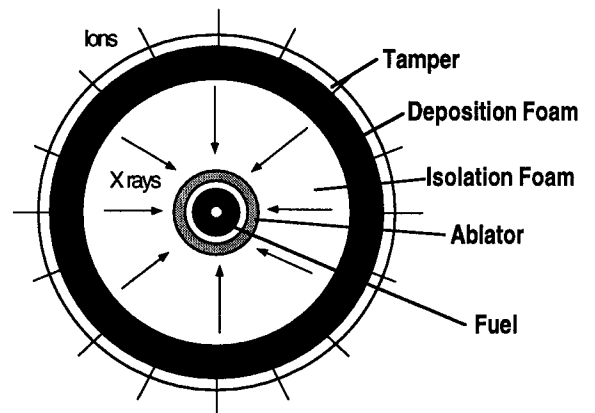
Direct Drive Lasers



Indirect Drive Lasers



Indirect Drive Heavy Ions



Indirect Drive Light Ions

Figure 3.1.1. Comparison of ICF targets for laser, light ion, and heavy ion drivers.

are discussed, while predictions for the target debris and x-ray spectra are given in Section 3.4. Calculations of the neutron spectra are presented in Section 3.5.

3.2. Target Design

The LIBRA-SP light ion beam reactor design utilizes: 20–30 MeV Li ions generated by pulse-power accelerators; self-pinch transport [7,8]; foam-filled, spherical indirect-drive targets; and 24 Li beams (12 prepulse and 12 full power) [2]. Figure 3.2.1 shows the initial target configuration for the 320 MJ target used in the BUCKY-1 simulations described below. The final 589 MJ target might alter the details of the design. The outer radius of the hohlraum target is 7.015 mm and the Au radiation case is a thin solid layer with a thickness of 15 μm . Between the Au case and the capsule ($2.55 \text{ mm} < r < 7.00 \text{ mm}$) is a low density (15 mg/cc) CH foam. It is possible that the final target might use Pb instead of Au but this change will have little effect on the target implosion and yield.

The CH foam is divided into a “deposition” region, where the Li beam deposits the bulk of its energy, and an “isolation” region. It is expected [3] that deviations from spherical symmetry due to the finite number of Li beams will be smoothed out at the capsule surface as radiation burns through the isolation region. The outer part of the capsule is composed of a 247 μm -thick polycarbonate ($\text{C}_{16}\text{H}_{14}\text{O}_3$) ablator, surrounded by a 33 μm -thick CF_2 x-ray pulse-shaping layer. The purpose of the pulse-shaping layer is to tailor the propagation of shocks so that multiple shocks arrive simultaneously at the inner surface of the capsule. Inside the ablator is the DT fuel, which is composed of a solid 271 μm -thick DT shell and a low density DT vapor. In the present simulations, the DT mass is 2.47 mg. This will be increased in future simulations to achieve the desired yield of nearly 600 MJ.

The evolution of the Li beam power on target used in the radiation-hydrodynamics simulation is shown in Figure 3.2.2. It is composed of a 38 ns, 20 MeV, low power (26 TW) “foot”, followed by a 14 ns, 30 MeV, high power (480 TW) main pulse. The low power and high power portions of the pulse are supplied by separate beams (12 each) in the LIBRA-SP design.

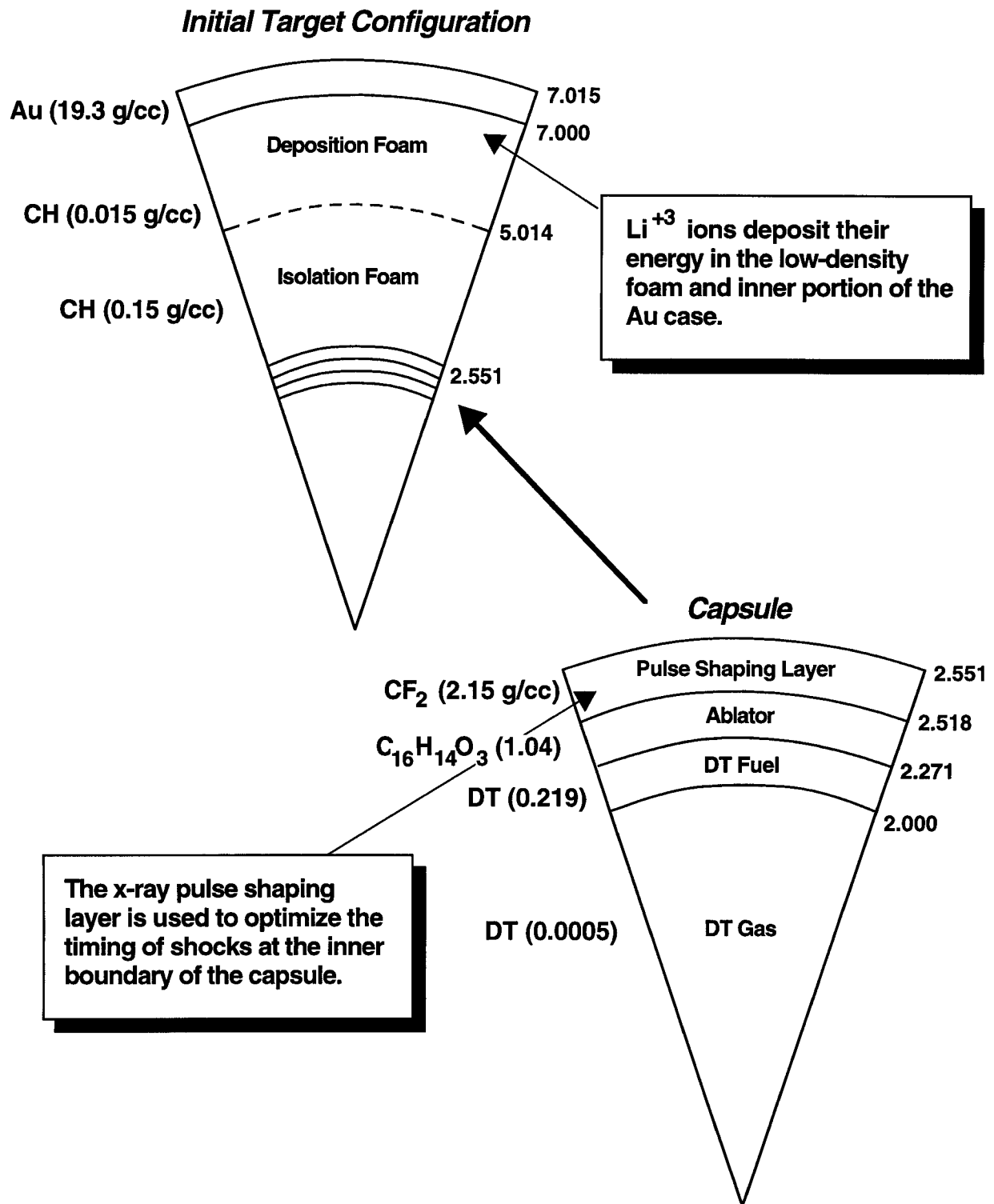


Figure 3.2.1. Initial target configuration used in the LIBRA-SP target implosion simulations.

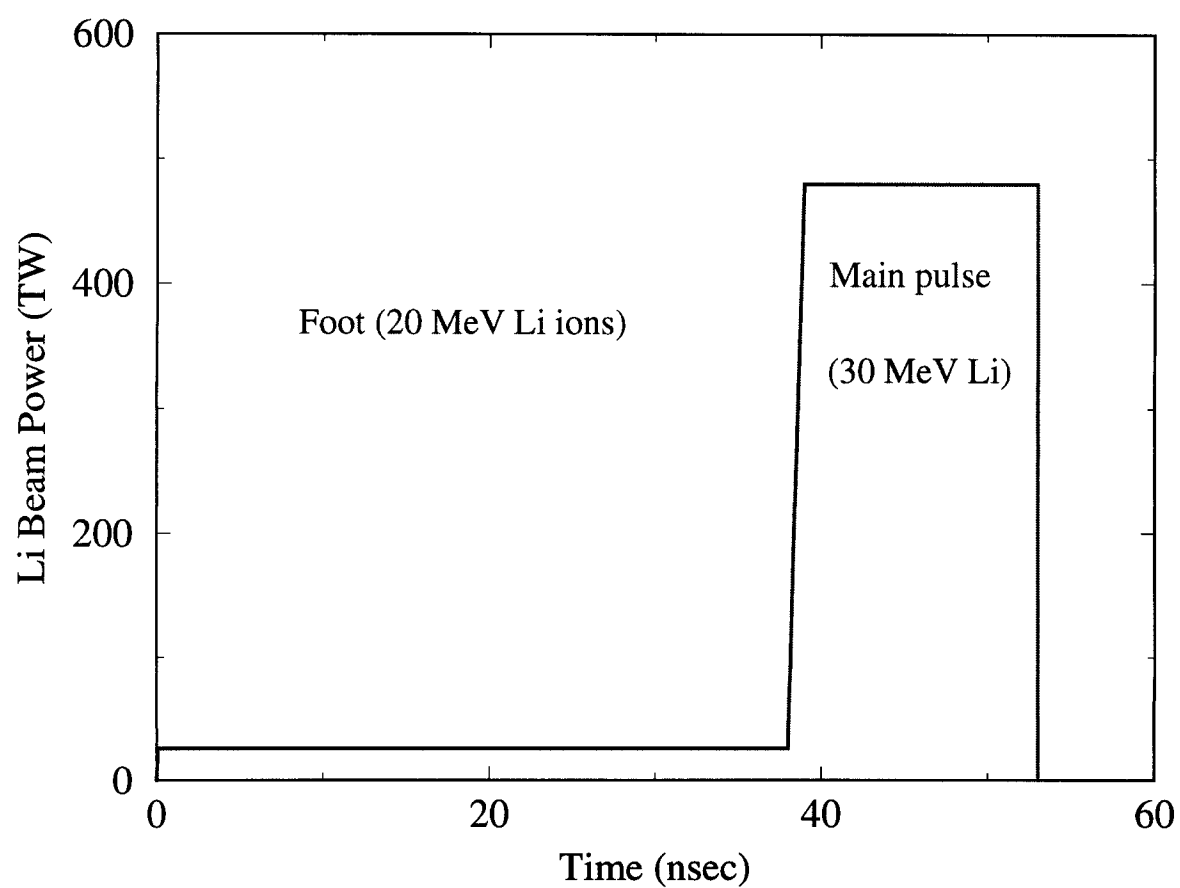


Figure 3.2.2. Li beam power incident on target in LIBRA-SP target simulation.

The beam parameters and initial target configuration discussed above are the main input to the BUCKY-1 calculation. BUCKY-1 [1] is a 1-D (planar, cylindrical, or spherical) Lagrangian radiation-hydrodynamics code which has been used to simulate a variety of high energy density plasma physics phenomena relevant to ICF. It solves the single fluid equation of motion with pressure contributions from ions, electrons, radiation, and fast charged particles. Energy conservation equations are solved for both ions and electrons ($T_e \neq T_i$). Thermal conduction for each species is treated using Spitzer conductivities, with the electron conduction being flux-limited. In the calculations described below, a multigroup diffusion model was used to transport radiation. A total of 100 frequency groups was used, with a finer mesh used near 0.4–1.2 keV to resolve the C, O, and F K-edges in the x-ray pulse shaping layer and ablators. Equation of state data from SESAME [9] tables were used, while multigroup opacity data were computed using EOSOPA [10]. EOSOPA uses a detailed configuration accounting model for low-Z materials, while an unresolved transition array (UTA) model is used for high-Z material (e.g., Au).

Li beam ion energy deposition was computed using a classical stopping power model based on Mehlhorn [11]. Here, the Lindhard model is used at low projectile velocities, while the Bethe model is used at high energies. Fusion burn is computed for DT reactions, with the charged particle reaction products transported and slowed using a time-dependent particle tracking algorithm [12].

3.3. Simulation of the Target Implosion and Fusion Burn

Results from the simulation of the LIBRA-SP target implosion are shown in Figures 3.3.1–3.3.5. Figure 3.3.1 shows the radiation temperature in the CH foam (i.e., the hohlraum temperature) as a function of time. During the foot of the pulse, the radiation temperature rises slowly to approximately $T_R = 125$ eV. When the main power pulse from the Li beam turns on at $t = 38$ ns, the radiation temperature rises quickly to above 250 eV, and reaches a peak of $T_R \approx 280$ eV. Because the x-rays tend to have long mean free paths in the CH foam, the radiation temperature is essentially uniform (spatially) in the foam.

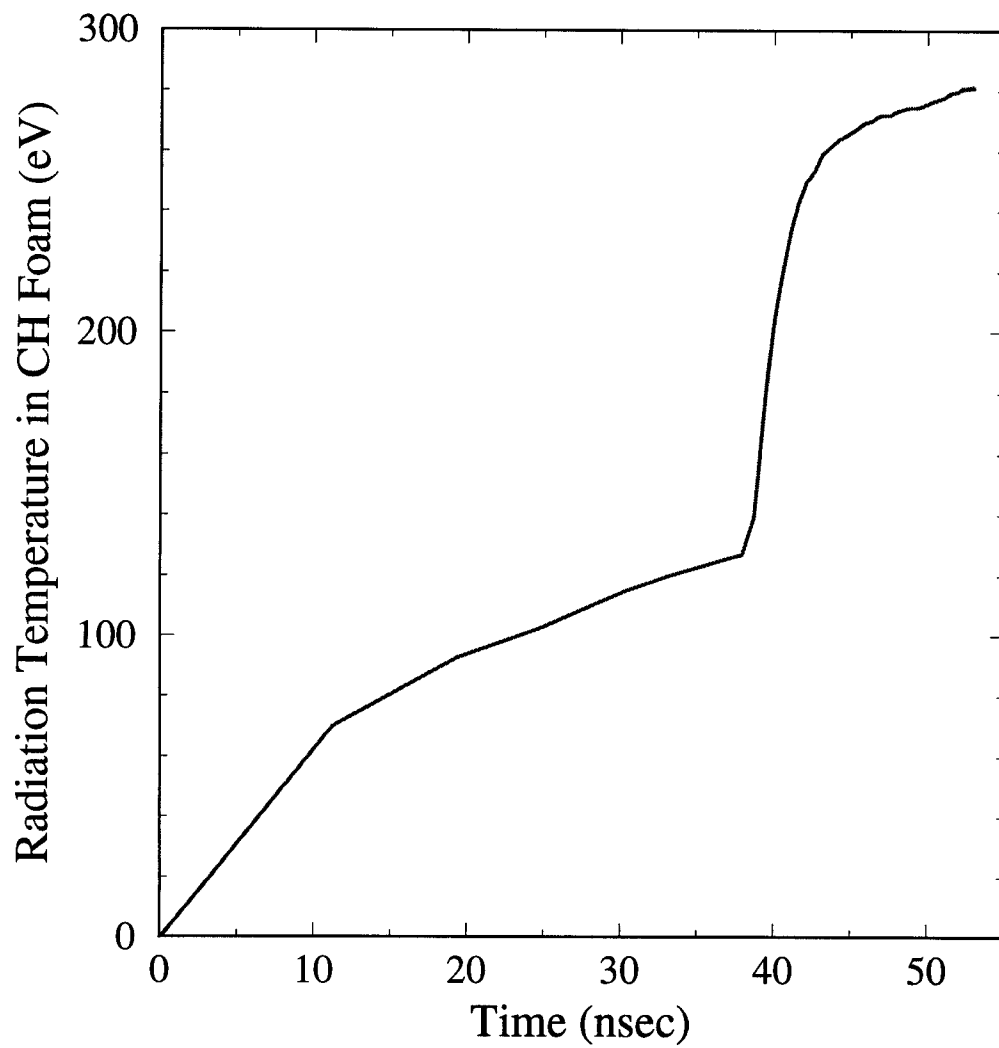


Figure 3.3.1. Hohlraum radiation temperature versus time.

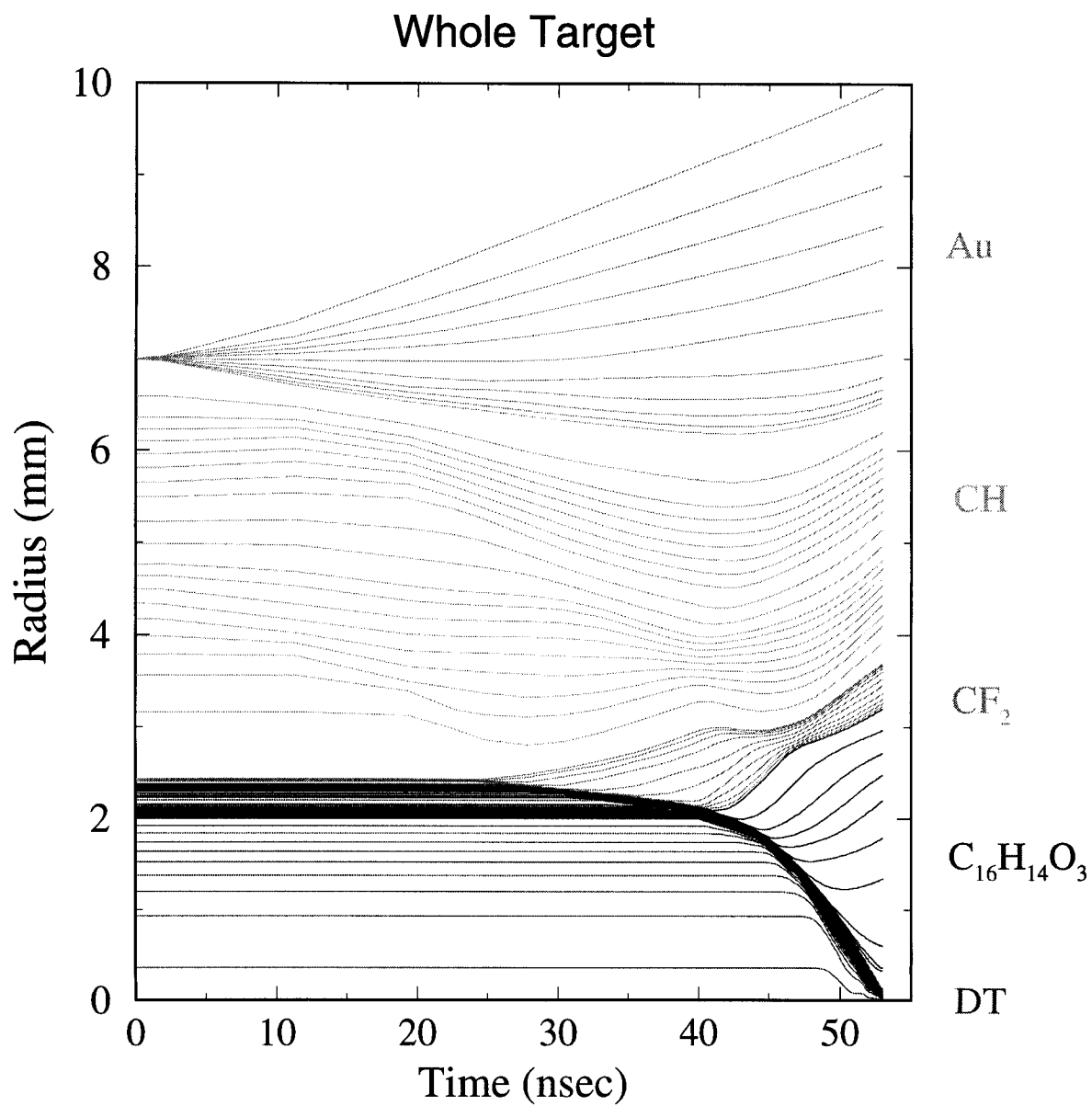


Figure 3.3.2. Lagrangian zone positions versus time.

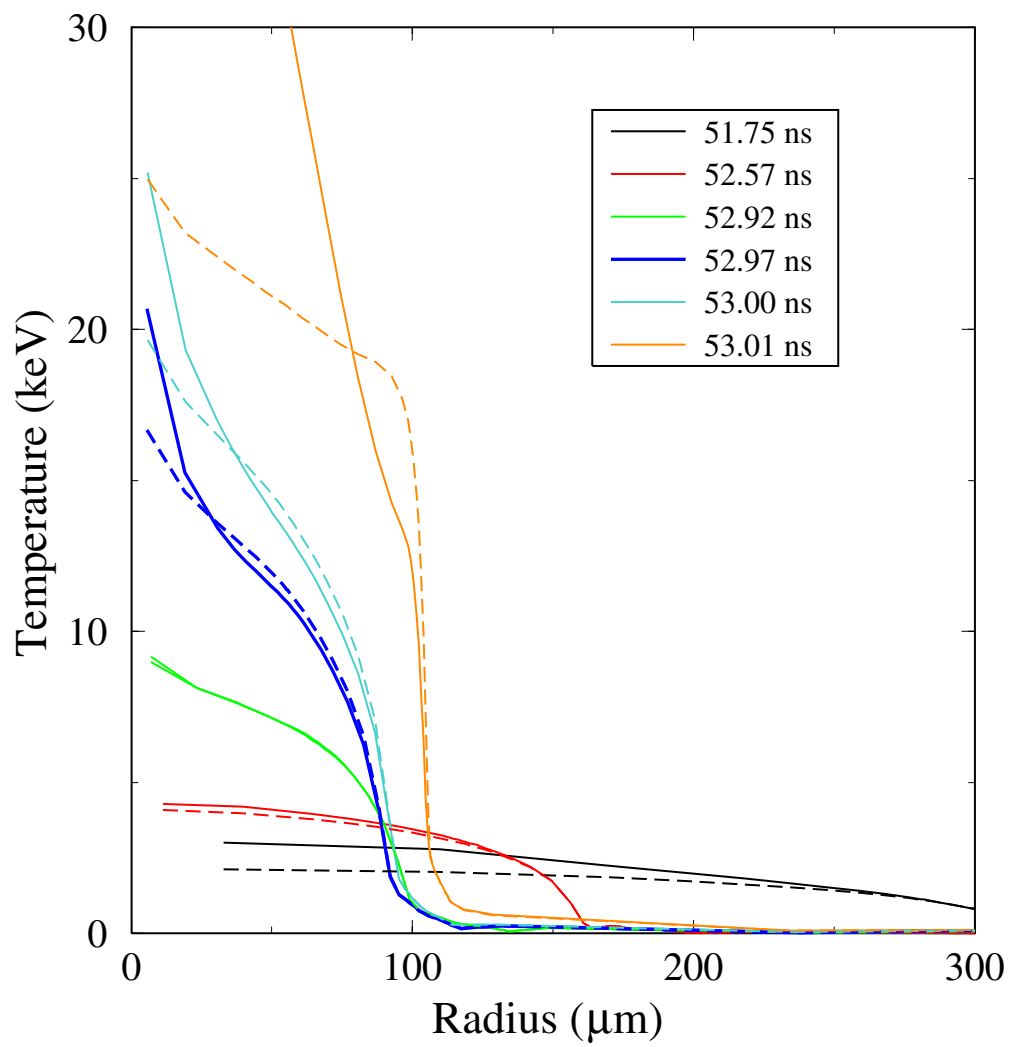


Figure 3.3.3. Electron (dashed curves) and ion (solid curves) temperatures in the capsule region at several simulation times near the time of ignition.

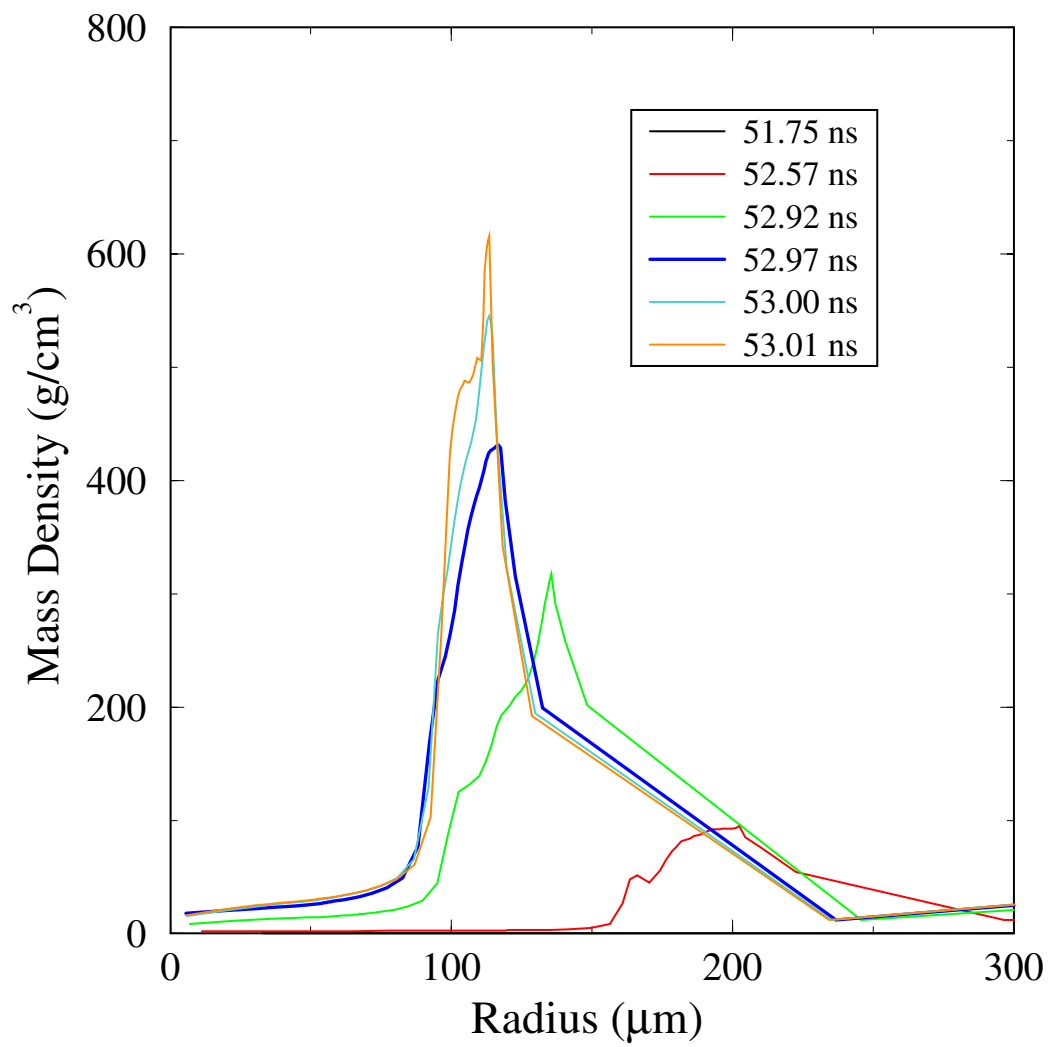


Figure 3.3.4. Mass densities in the capsule region at several simulation times near the time of ignition.

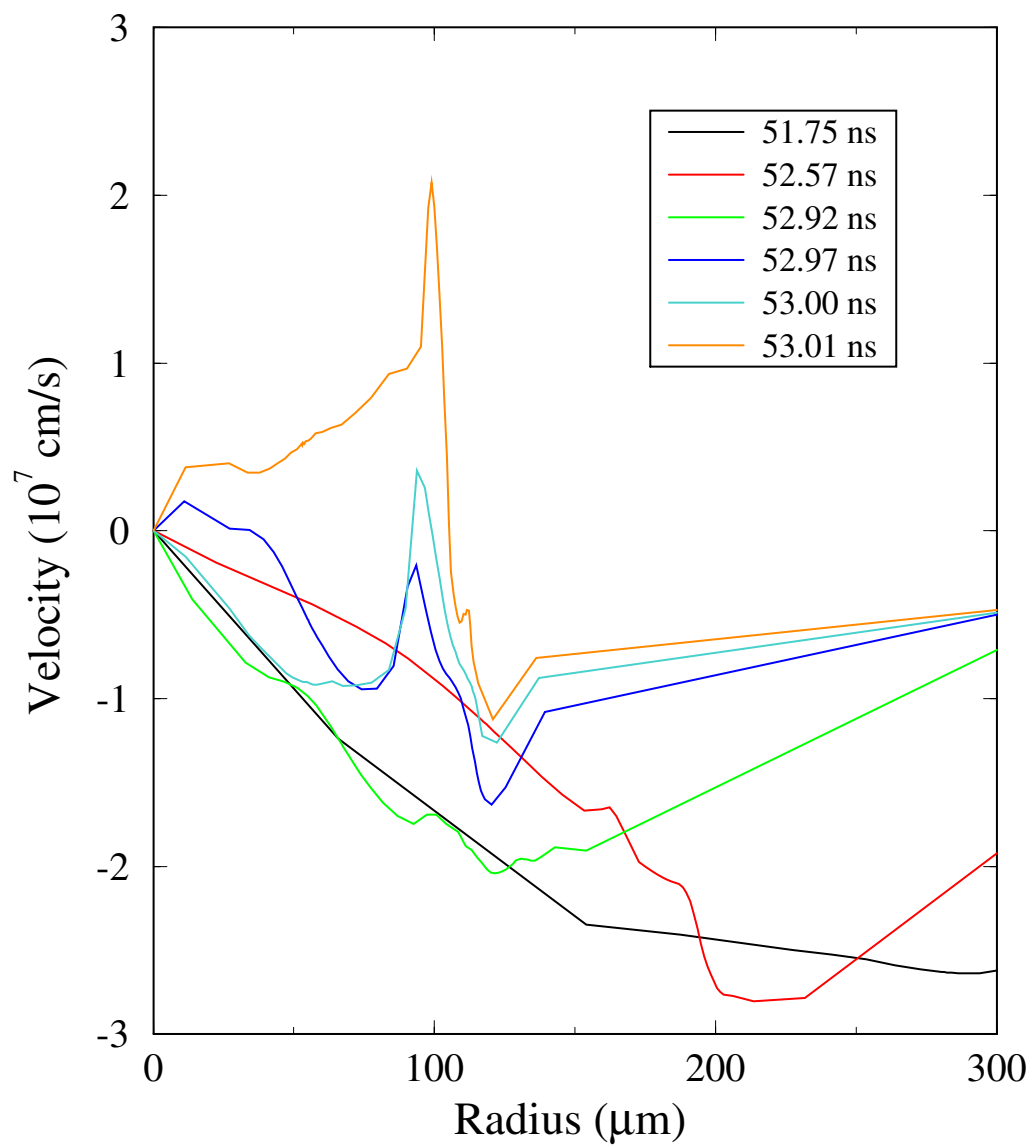


Figure 3.3.5. Fluid velocities in the capsule region at several simulation times near the time of ignition.

Figure 3.3.2 shows the positions of the zone boundaries as a function of time. Since BUCKY-1 is a Lagrangian code, the zone boundaries track the fluid motion within the target. The simulation predicts that the thickness of the CH foam remains fairly constant over time. Thus, the Au case does not move very far inward toward the capsule. This is beneficial because maintaining a large case-to-capsule ratio allows for better symmetry of the radiation field on the capsule surface throughout the implosion. Figure 3.3.2 also shows the rapid inward acceleration of the DT fuel region between 40 and 53 ns. “Ignition” is achieved at 52.97 ns in the simulation (here, ignition is loosely defined as the time at which the “hot spot” — the region where $T_{\text{ion}} > 5$ keV — achieves a $(\rho R)_{\text{hot}}$ of 0.25 g/cm^2). The maximum total fuel ρR achieved in this simulation was 2.3 g/cm^2 .

Figures 3.3.3 through 3.3.5 show temperature, density, and fluid velocity distributions at several simulation times near the time of ignition. The electron and ion temperatures are represented in Figure 3.3.3 by the dashed and solid curves, respectively. The hot spot is seen to be contained within a radius of about $100 \mu\text{m}$. As the DT burn proceeds the temperatures increase rapidly, with the rise in ion temperatures outpacing that of the electrons.

Fuel densities during the implosion phase peak at approximately 600 g/cm^3 . Note that the highest densities are achieved in the outer regions of the DT fuel at this time. Densities in the central hot spot are $\approx 20 - 30 \text{ g/cm}^3$. Figure 3.3.5 shows that the maximum implosion velocities are $\approx 3 \times 10^7 \text{ cm/s}$ (note that $v < 0$ indicates an inward-moving fluid).

Results for the fusion burn phase of the BUCKY-1 simulation are shown in Figure 3.3.6, which shows the total DT yield as a function of time. (Results for the neutron spectrum are discussed in Section 3.5.) The total fusion yield in this simulation was 322 MJ and is achieved with a 38% burnup fraction of the DT fuel. Thus, the target gain attained in the present simulation is approximately 40. It is important to note, however, that additional “fine-tuning” of the target design is expected to lead to a significantly higher yield [3].

The results described in this section should *not* be taken to be those of the optimum LIBRA target design, but instead should be viewed as preliminary results. It is also worth emphasizing that the simulations performed for the LIBRA light ion fusion target

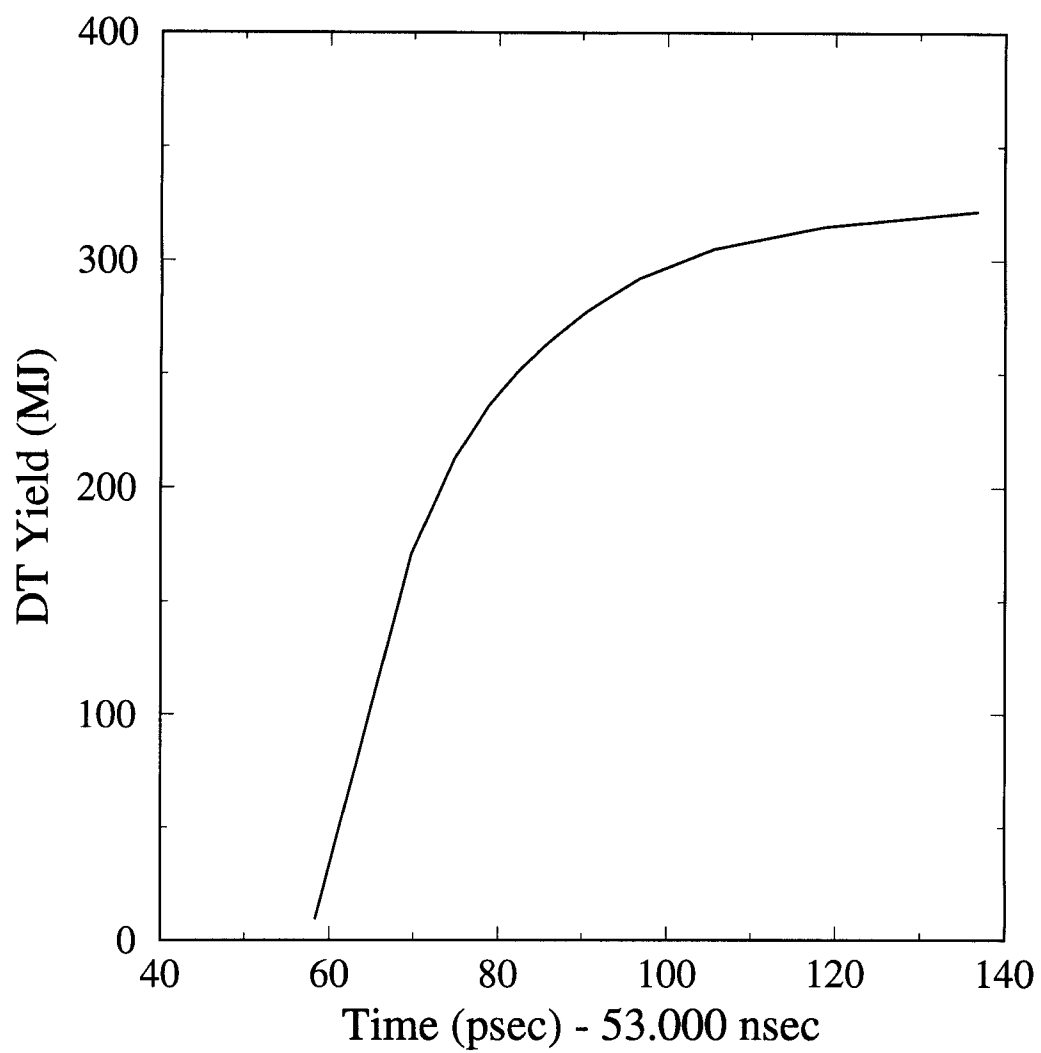


Figure 3.3.6. Total fusion yield as a function of time.

using BUCKY-1 do not in any way conflict with any classification guidelines of the U.S. Department of Energy. This is a result of the recent change in the classification guidelines for ICF research [4].

3.4. Simulation of Target Breakup and Energy Release

In this section, results are presented which describe the partitioning of energy during the target breakup, or explosion, phase. It is worth noting that results are qualitatively similar to those obtained [13] in previous simulations using the PHD-IV code [12]. However, there are several important differences in the simulations. First, the explosion and fusion burn proceeds from realistic temperature and density distributions at the time of ignition (see Figs. 3.3.3 and 3.3.4). In the previous PHD-IV simulations, the “imploded” target was divided into several isothermal, isochoric regions to initiate the calculation. Second, neutron deposition in the target is accounted for in the current simulations using an escape probability model [14,1], whereas it was not previously modeled in PHD-IV simulations. Third, the total energy released from the target in the current simulation is 323 MJ (vs. 589 MJ in the PHD-IV simulation). This is simply due to the fact that the current target design needs to be “fine tuned” to obtain a larger yield.

Results for the target breakup phase are shown in Figures 3.4.1 through 3.4.4. Figure 3.4.1 shows the energy partitioning between kinetic (hydrodynamic) energy, the internal energy of electrons and ions, and the x-ray radiation lost from the target. The time is given with respect to the time the Li beam starts to irradiate the target (recall that the time of ignition occurs at $t = 52.97$ ns; see Section 3.3). At early times in the explosion phase ($t \approx 53 - 55$ ns), most of the non-neutronic energy is in the form of kinetic energy. Most of this is contained in the DT region which expands at velocities of a few $\times 10^8$ cm/s. As the inner part of the target collides with the Au case at $t \approx 55$ ns, a significant fraction of the energy from the target is lost in the form of x-rays. By the end of the simulation, approximately 80 MJ (or 25% of the target yield) of x-ray radiation escapes the target. Figure 3.4.2 shows the Lagrangian zone boundary positions as a function of time. Here, a strong shock is seen to be propagating radially outward as the DT fuel rapidly expands. The

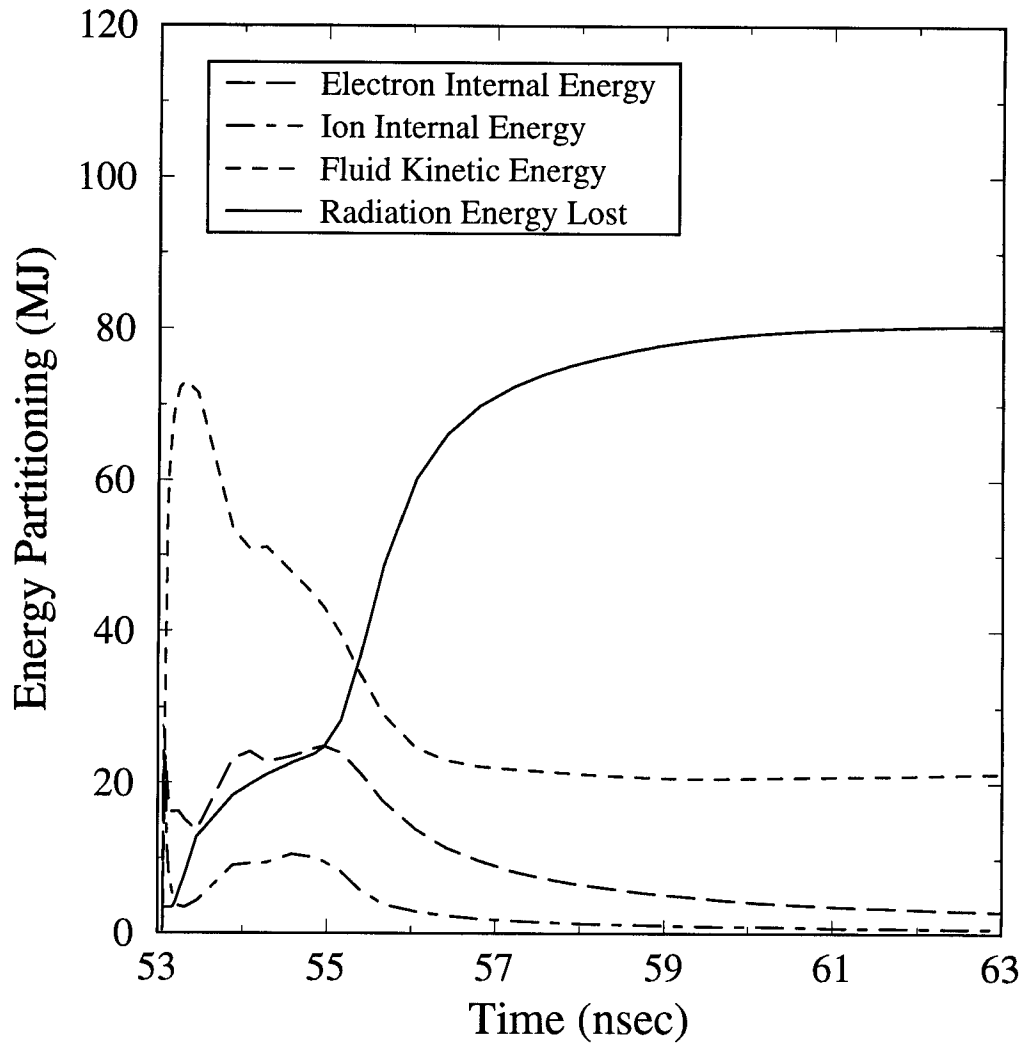


Figure 3.4.1. Time-dependence of energy partitioning between kinetic energy, ion and electron internal energy, and radiation energy lost.

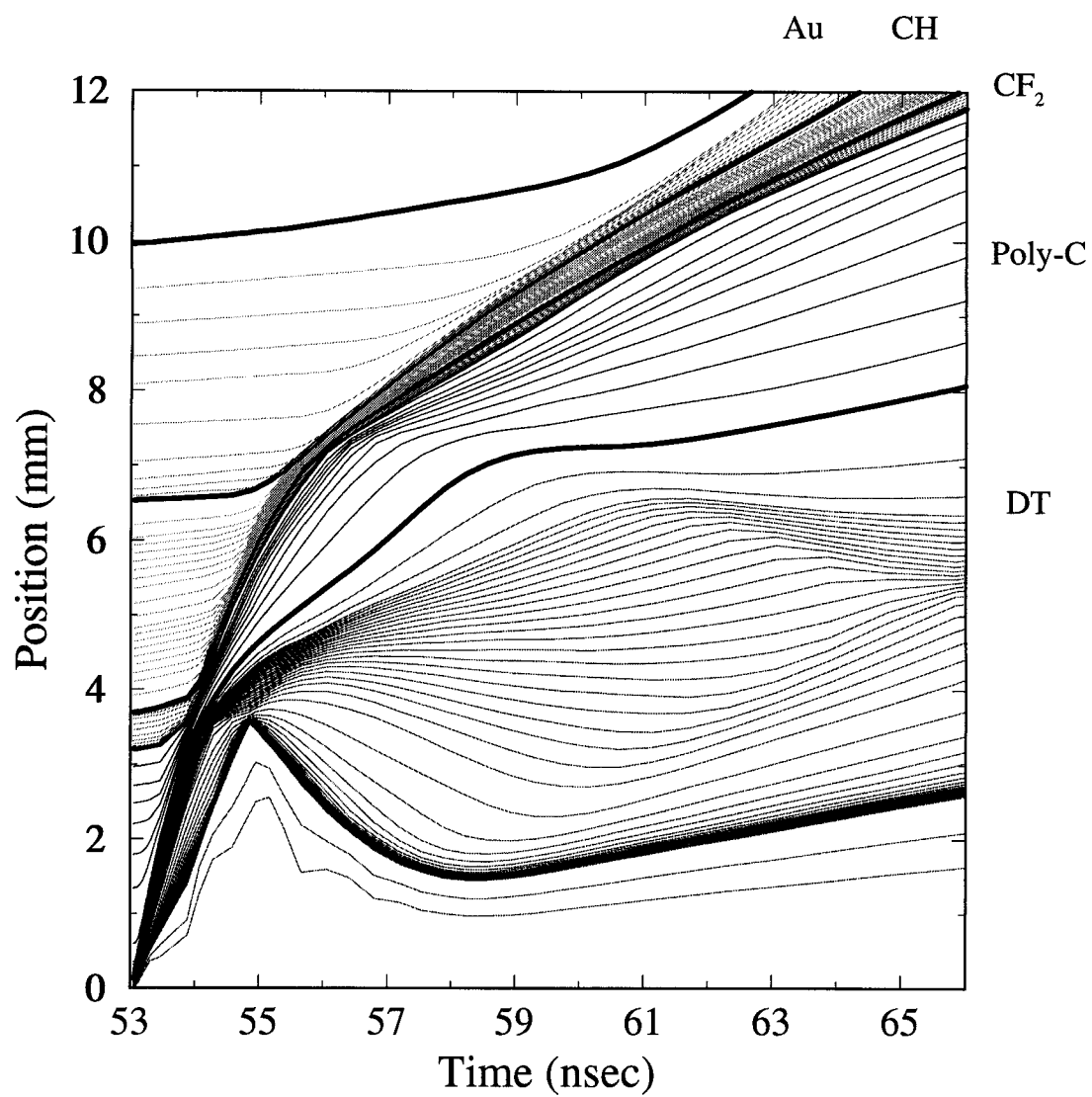


Figure 3.4.2. Time-dependence of Lagrangian zone boundaries during target breakup phase.

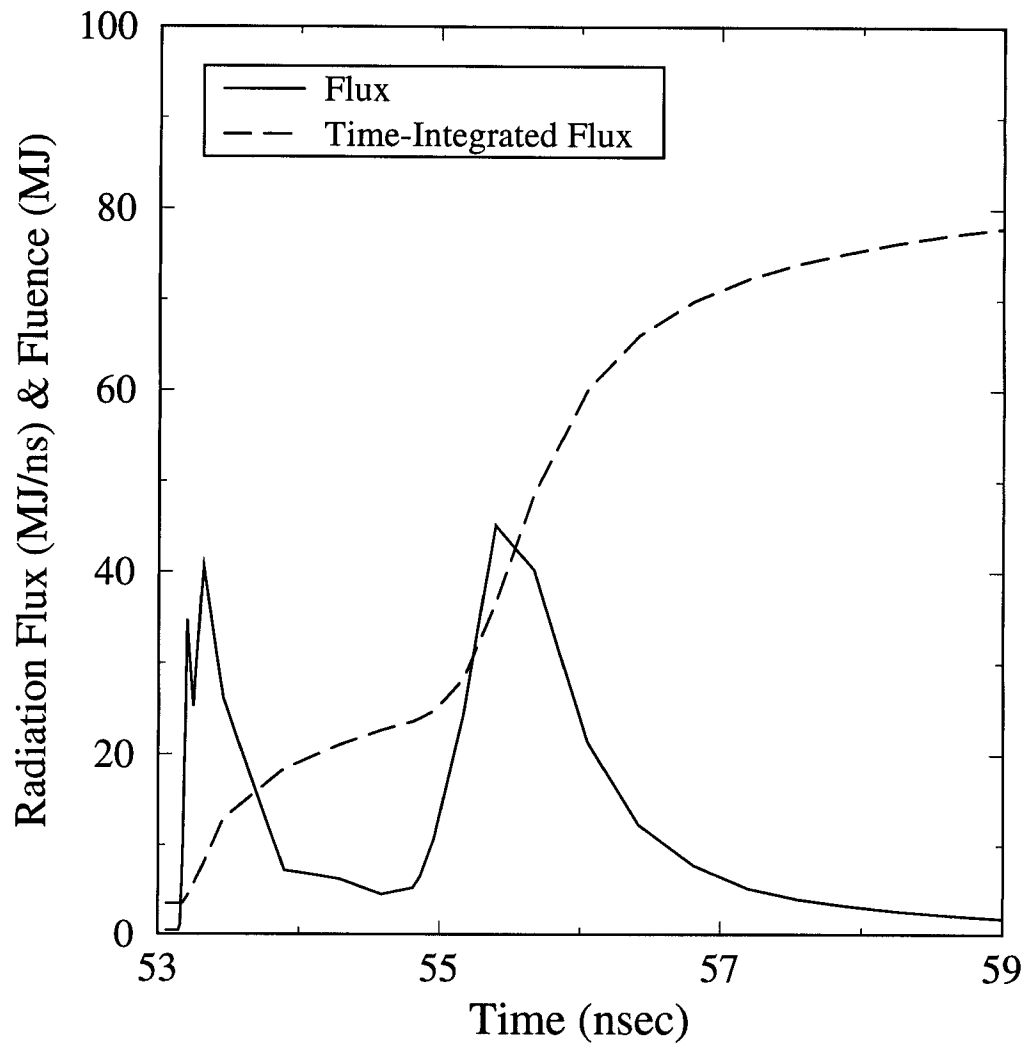


Figure 3.4.3. Time-dependent and time-integrated radiation power emitted by the target.

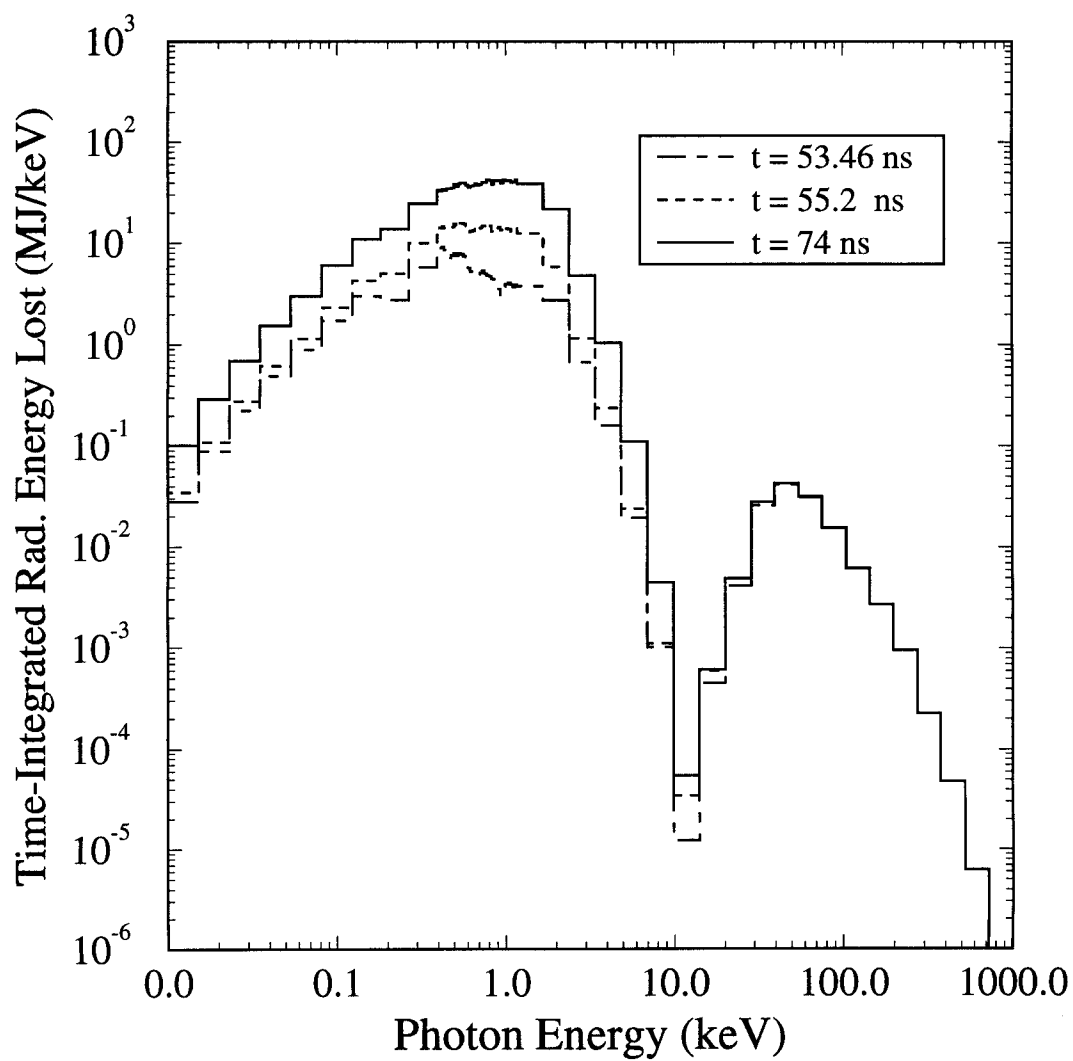


Figure 3.4.4. Time-integrated spectra of radiation emitted from the target at several simulation times.

DT and ablator are seen to collide with the CH foam at $t \approx 55$ ns, which later collides with the Au case at $t \approx 55$ ns. As the inner material collides with the Au case it slows significantly, converting kinetic energy into internal energy, which subsequently radiates away. At the end of the simulation, 22 MJ, or about 7% of the total target yield, remains in the form of kinetic energy in the debris.

The time dependence of the x-ray emission flux escaping the target is shown in Figure 3.4.3. Just after the fusion burn phase a burst of x-rays is released in the form of relatively hard x-rays. The curve for the time-integrated flux (dashed) shows that about 20 MJ is released at this time. Time-integrated x-ray spectra are shown in Figure 3.4.4. Note that virtually all of the hard x-ray emission ($h\nu > 20$ keV) occurs within the first 0.5 ns after the burn ($t \leq 53.5$ ns). A second burst of x-rays occurs at $t \approx 55 - 57$ ns. This is due to softer x-rays emitted by the Au case.

To summarize, an “end-to-end” simulation of the LIBRA light ion reactor target using the BUCKY-1 code has been performed. The calculation is based on an indirect-drive, spherical target design which utilizes a low-density CH foam between the capsule and the high-Z case. The polycarbonate ablator is surrounded with a thin CF_2 shell (x-ray pulse shaping layer) to tailor the propagation of shocks in the capsule. Using a simple Li beam profile, with a low power foot and a high power main pulse, the evolution of the target is followed through its 3 critical phases: implosion, fusion burn, and breakup. Using the present target design, the total yield was 323 MJ for a Li beam with 7.9 MJ on target, thus giving a gain of 41. It is anticipated [3] that with slight modifications to the target design a yield of 500–600 MJ will be achieved. It is emphasized again that because of changes in the U.S. Department of Energy classification guidelines, detailed simulations of ICF targets can now be carried out on a routine basis. Because BUCKY-1 is an unclassified code, it is felt that the above calculations represent a significant step forward in this area.

3.5. Target Neutronics

The initial split of energy from a single DT fusion reaction is one 14.1 MeV neutron and one 3.5 MeV alpha particle. In an inertial confinement fusion reactor, the DT fuel is

heated and compressed to extremely high densities before it ignites. Therefore, neutron/fuel interactions cannot be neglected. This results in significant softening of the neutron spectrum as a result of elastic and inelastic collisions with the target constituent materials. In addition, neutron multiplication in the target occurs as a result of (n,2n) and (n,3n) reactions and gamma photons are produced. The energy deposited by the neutrons and gamma photons heats the target and ultimately takes the form of radiated x-rays from the hot plasma and expanding ionic debris.

Neutronics calculations have been performed for the LIBRA-SP target using the one-dimensional discrete ordinates code ONEDANT [15]. The neutronics calculations performed previously for the LIBRA-SP target used a single configuration at ignition [16]. However, the target hydrodynamics calculations indicate that the target configuration changes during the burn. The target configuration and zone densities were used at five time intervals during the burn to perform 5 neutronics calculations. The results were combined weighted by the percentage of the yield produced in each time interval to determine the overall target neutronics parameters. Table 3.5.1 gives the target parameters used in the neutronics calculations for each time interval. The calculations were performed using spherical geometry and 46 neutron - 21 gamma group cross section data based on the FENDL-1 nuclear data evaluation [17]. A uniform 14.1 MeV neutron source was used in the compressed DT fuel zone.

The total energy deposition in the target per DT fusion is given in Table 3.5.2 for the different time intervals. The table also includes the number of neutrons emitted from the target per DT fusion. It is clear that due to the reduction in the DT density during the final stages of the burn, the energy deposition decreases significantly and the neutron multiplication decreases. In addition, the neutron spectrum gets harder in the final stages of the burn. For example, 97.3% of the emitted neutrons per fusion are uncollided 14.1 MeV neutrons in time interval 5 compared to only 65% in time interval 1. The overall target neutronics parameters are discussed below.

Table 3.5.1. Target Data During Burn

Time Interval % of Yield	1 53.11%	2 20.19%	3 8.69%	4 8.69%	5 9.32%
R-H Simulation Time (psec) Start at - 53.00 nsec	58-70	70-79	79-86	86-97	97-137
Outer Radius (cm)					
DT	0.014484	0.016336	0.019931	0.024317	0.037875
CH polycarbonate	0.32033	0.32038	0.32045	0.32052	0.32082
CF ₂	0.36943	0.36948	0.36956	0.36965	0.36997
CH foam	0.65321	0.65324	0.65328	0.65334	0.65352
Au	0.99602	0.99606	0.99611	0.99617	0.99636
Average Density (g/cm ³)					
DT	194.06	135.26	74.48	41.01	10.85
CH polycarbonate	0.1017	0.1016	0.1016	0.1015	0.1014
CF ₂	0.0699	0.0699	0.0699	0.0698	0.0696
CH foam	0.0213	0.0213	0.0213	0.0213	0.0213
Au	0.0400	0.0400	0.0400	0.0400	0.0400

Due to (n,2n) and (n,3n) reactions occurring in the target, a total of 1.039 neutrons are emitted from the target for each DT fusion reaction. These neutrons carry a total energy of 12.72 MeV implying that the average energy of neutrons emitted from the target is 12.24 MeV. It is interesting to note that only 73.4% of the neutrons emitted from the target are uncollided 14.1 MeV neutrons. For each DT fusion reaction, 0.0006 gamma photons are emitted from the target with an average energy of 1.57 MeV. The energy spectra of neutrons

Table 3.5.2. Target Neutronics Results for Time Intervals During Burn

Time Interval	1	2	3	4	5
Nuclear energy deposition (MeV/DT fusion)	1.706	1.1795	0.6409	0.3504	0.0942
Neutrons emitted from target (n/DT fusion)	1.053	1.038	1.022	1.012	1.003

Table 3.5.3. Energy Partitioning from LIBRA-SP Target

Fusion energy	17.6 MeV/DT fusion
Energy carried by neutrons	12.72 MeV/DT fusion (72.2%)
Energy carried by gamma photons	0.001 MeV/DT fusion (0.006%)
Energy carried by x-rays and debris	4.74 MeV/DT fusion (26.9%)
Energy lost in endoergic reactions	0.14 MeV/DT fusion (0.8%)

and gamma photons emitted from the LIBRA-SP target are shown in Figs. 3.5.1 and 3.5.2, respectively.

The total energy deposited by neutrons and gamma photons in the target was calculated to be 1.24 MeV per DT fusion. Almost all of the gamma ray energy is deposited in the DT fuel zone. This is a direct result of the relatively large ρR value for the DT fuel region. When the 3.5 MeV energy carried by the alpha particle emerging from the fusion reaction is added, a total energy of 4.74 MeV per DT fusion is found to be carried by x-rays and target debris following the microexplosion. Performing an energy balance for the target indicates that 0.14 MeV of energy is lost in endoergic reactions per DT fusion. The detailed partitioning of the energy produced from the target is listed in Table 3.5.3.

The neutronics calculations performed here assumed uniform densities in the different zones with a uniform fusion source in the DT fuel zone. Future improvement to the target neutronics calculations will include modeling the detailed spatial variation of density as obtained from the target hydrodynamics calculations for each time interval during the burn. In addition, the spatial distribution of the fusion source will be represented by the fusion power density distribution obtained from the target calculations.

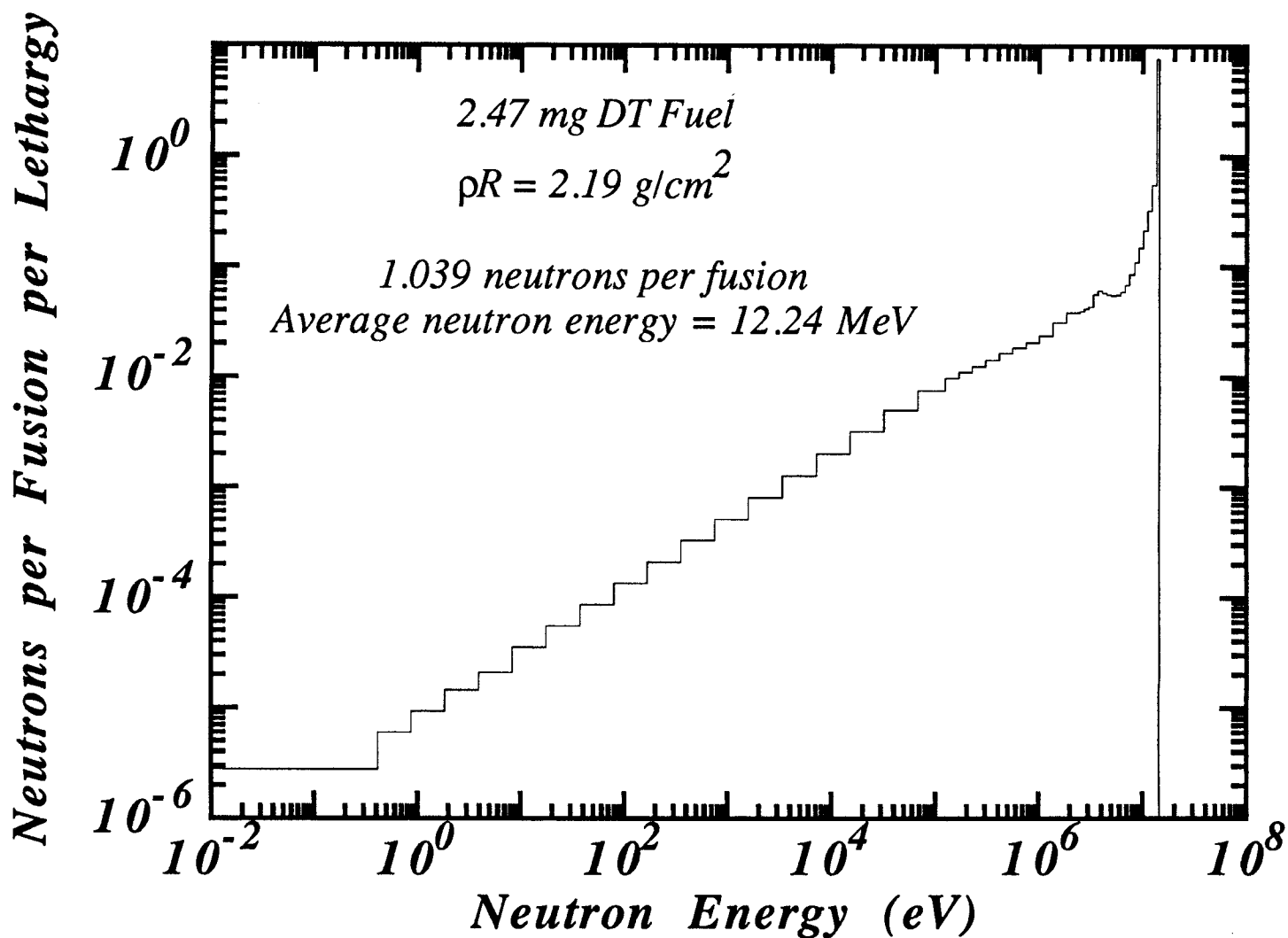


Figure 3.5.1. Energy spectrum of neutrons emitted from the LIBRA-SP target.

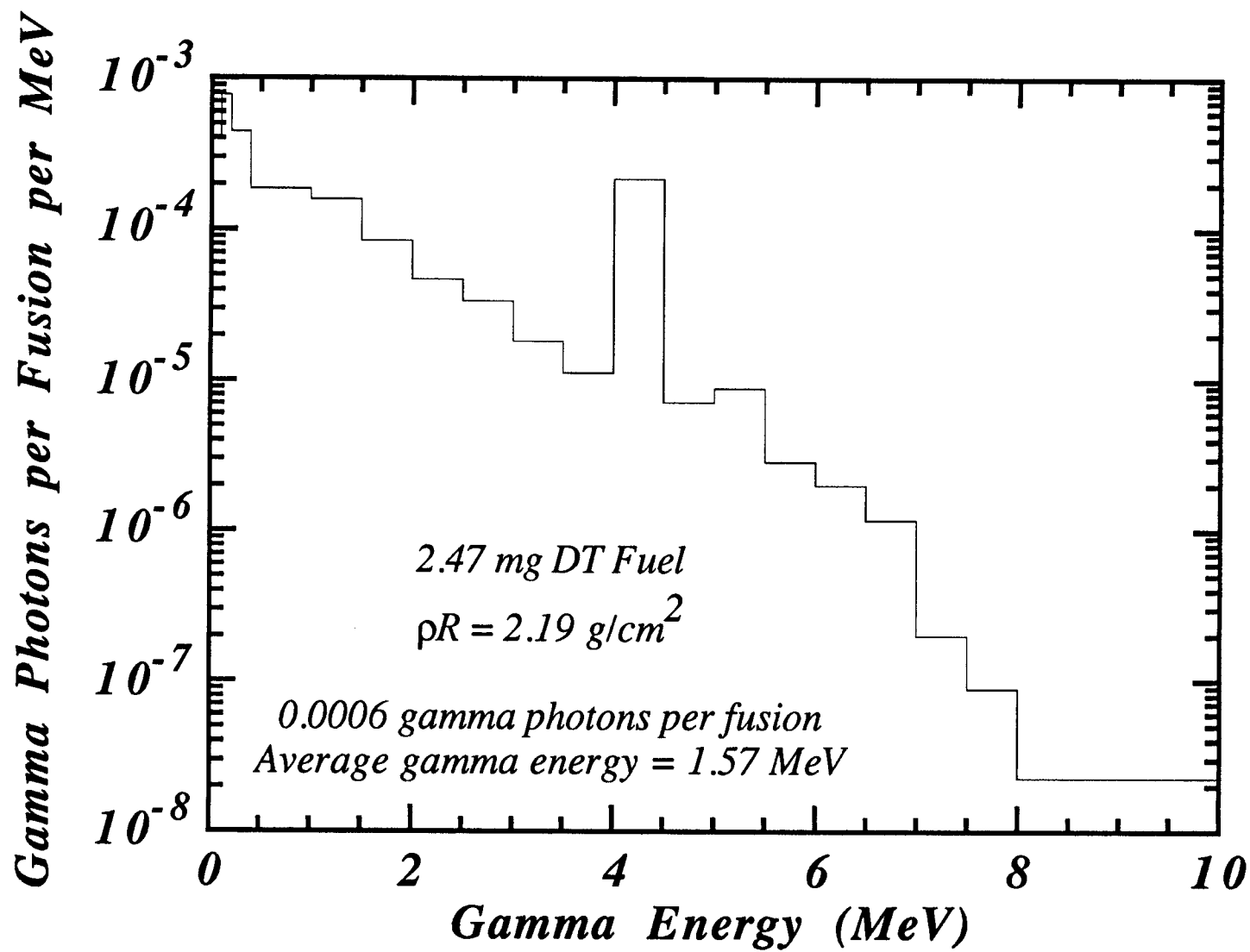


Figure 3.5.2. Energy spectrum of gamma photons emitted from LIBRA-SP target.

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4. Current Status of PERIT Unit Design

4.1. Introduction

LIBRA-SP is a conceptual design study of an inertially confined fusion power reactor utilizing self-pinched light ion beams. There are 24 ion beams altogether which are arranged around the reactor cavity to assure optimum distribution of the ion beams on the target. The ion beams are distributed around the midplane and at 53° conical angle planes from the horizontal. Figure 4.1.1 is a cross sectional view of the reaction chamber.

4.2. Mechanical Layout of PERIT Units

The reaction chamber is an upright cylinder with an inverted conical roof resembling a mushroom, and a pool floor. The vertical sides of the cylinder are occupied with a blanket zone consisting of many perforated rigid ferritic steel tubes with a packing fraction of about 50% through which the breeding/cooling material, liquid lead-lithium, flows. This blanket zone, besides breeding T_2 and converting neutronic energy to thermal energy, also provides protection to the reflector/vacuum chamber so as to make it a lifetime component. The radius to the first row of tubes is 4.0 m, the thickness of the blanket zone is 1.25 m and the length of the tubes is 10.6 m in two segments of 5.3 m each. The tubes are called PERIT (PErforated RIgid Tube) units and are made of the HT-9 ferritic steel alloy. The idea behind the concept is to make the tubes rigid and robust so they can withstand shock. The tubes are perforated to permit a jet fan spray which maintains a very thin liquid sheet which acts as a first protection surface. In this way, the tubes are assured of having a continuously wetted metallic first surface due to splashing of the thin liquid metal sheet on the PERIT units between every target microexplosion. Figure 4.2.1 shows a set of three PERIT units with the sheets of fan spray completely shadowing the PERIT units.

There are two rows of 7 and 8 cm diameter PERIT units arranged at 14 cm between centerlines in the circumferential direction as well as between rows. These front tubes are configured to totally shadow the rear zone, and the spaces between the rows are determined from dynamic motion considerations. The rear tubes are 15 cm in diameter and there are 7 rows of them. Their sole function is to contain and transport the PbLi which moderates

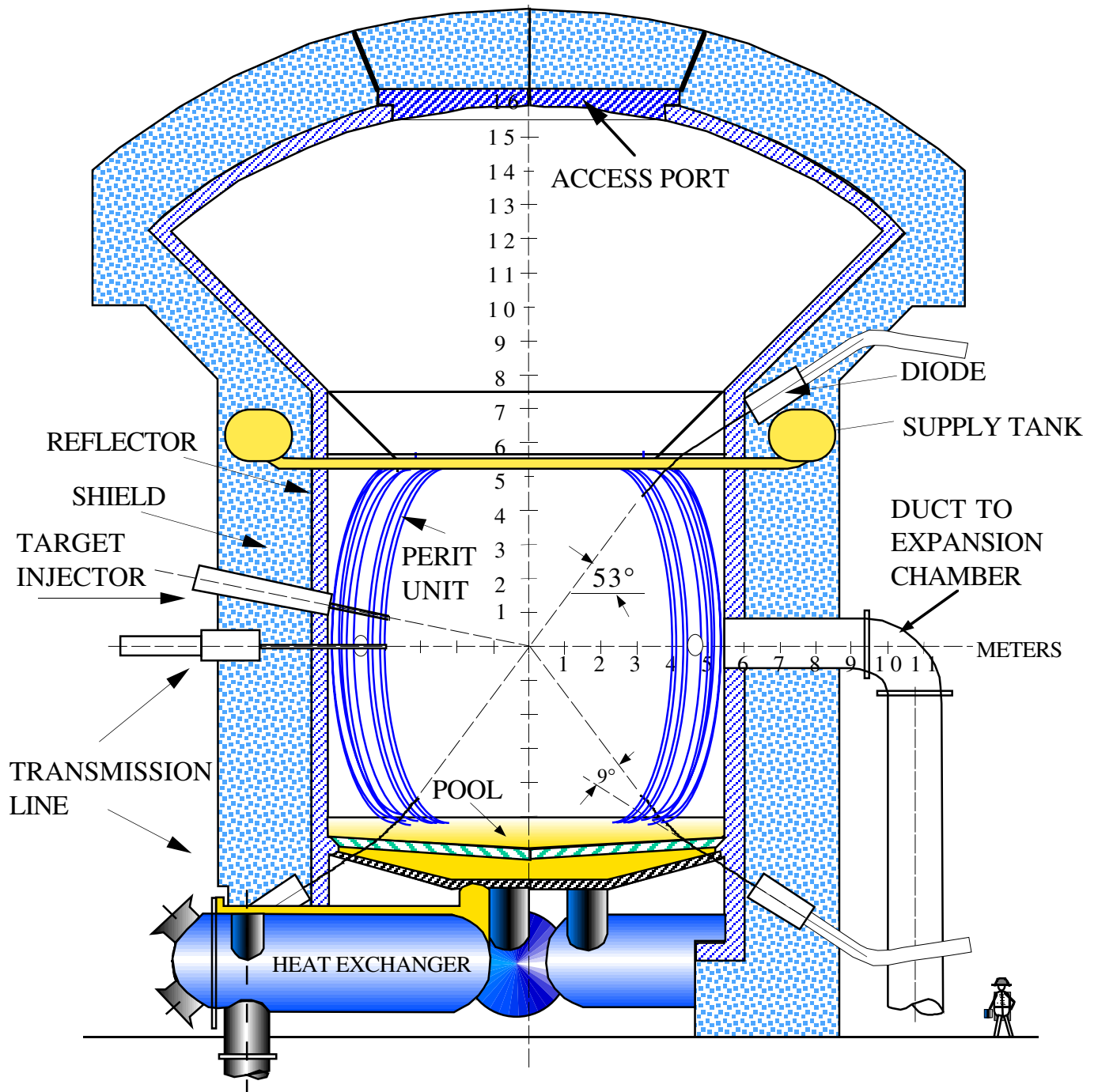


Figure 4.1.1. Vertical cross-sectional view of the reactor chamber.

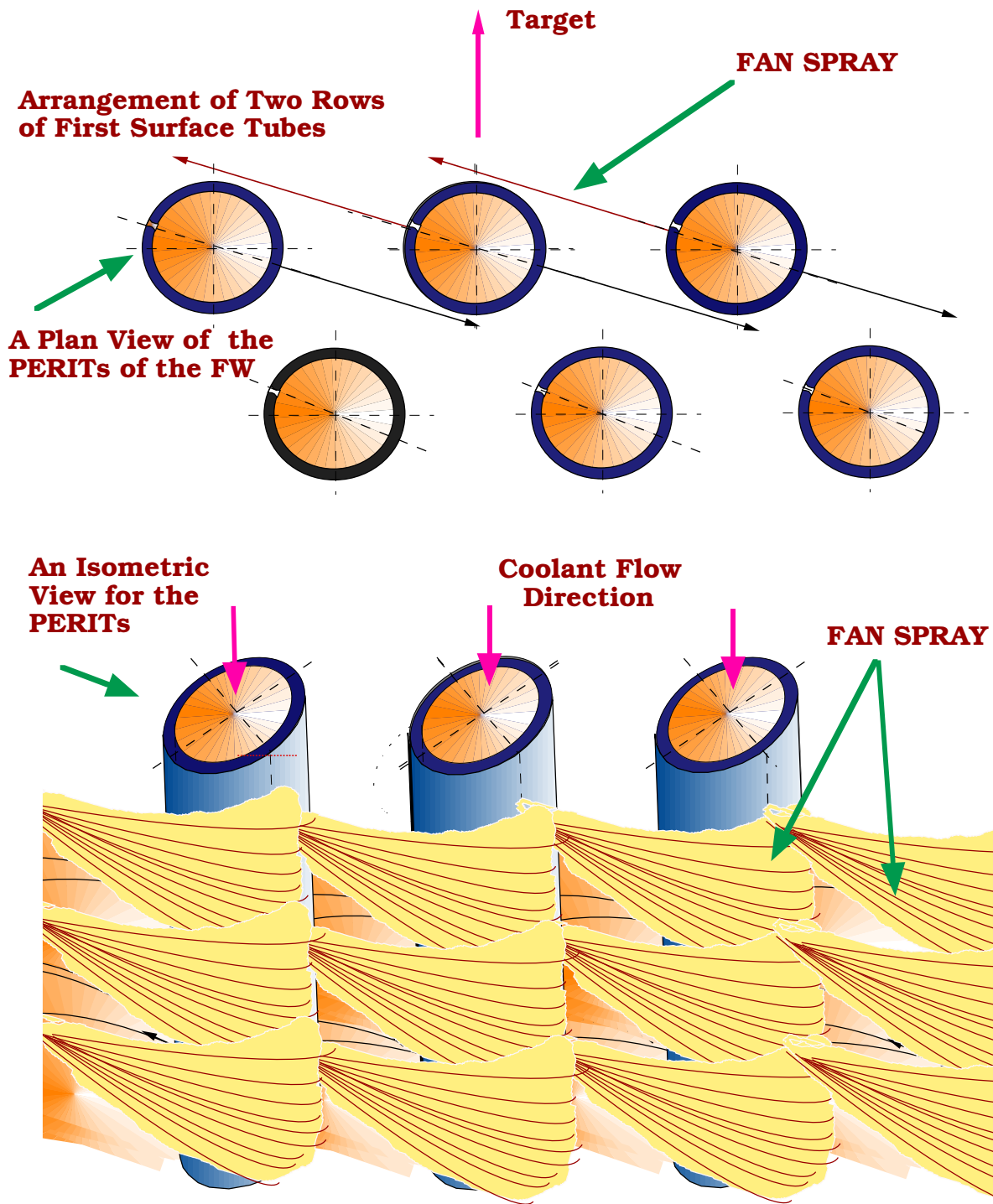


Figure 4.2.1. A set of three PERIT units with the sheets of fan spray completely shadowing the PERIT units.

neutrons and breeds T_2 . Behind the blanket is a 50 cm thick HT-9 ferritic steel reflector which is also the vacuum boundary. Finally, the whole chamber is surrounded by a steel reinforced concrete shield which varies in thickness but is nominally 2.7 m. Figure 4.1.1 also shows the 6 large evacuated tubes located behind the shield/blanket zone at the chamber midplane which lead to an expansion tank situated below the reaction chamber. The function of this tank is to provide volume for the vapor to expand into, following each shot. As the vapor flows into the expansion tank it exchanges heat with the PERIT units, and the vapor is cooled by virtue of an isentropic expansion. Vacuum pumps which are attached to the expansion tank then evacuate the noncondensable species in preparation for the next shot. The chamber roof is not protected with PERIT units and for this reason is removed to a distance of 16 m from the target, also making it a lifetime component. The roof with its integral shield is designed to be removed to provide access during internal reactor chamber component maintenance. Since the roof will be cooled, it also will condense vapor and have a wetted surface which will be vaporized after each shot. Another function of the mushroom shape is to protect the side walls which are shadowed by the PERIT units and to provide additional volume in the chamber for the vapor to expand into.

4.3. Accommodation of Beam Tubes Within PERIT Units

The ion beam guide tube has to reach the first surface and must be aimed at the center of the reactor cavity. Fortunately, the ion beam guide tube can be curved and still function properly. Approximately a 10° turning angle (through a distance of about 3 m) is used in this design. A local modification and rearrangement of the blanket and first surface tubes is needed to accommodate the penetration of the ion beam guide tube without sacrificing the shielding. A set of smaller tubes, 8 cm in diameter, are used in the region of the penetration to replace the original tubes (15 cm in diameter) to facilitate the required coverage and to avoid neutron streaming. Figure 4.3.1 is a horizontal cross-sectional view of a sector of the reactor chamber at midplane. It also shows the distribution of PERIT units in the shield/blanket zone. Figures 4.1.1 and 4.3.1 show also the local rearrangement of the tubes to accommodate the penetration of the curved ion beam guide tube.

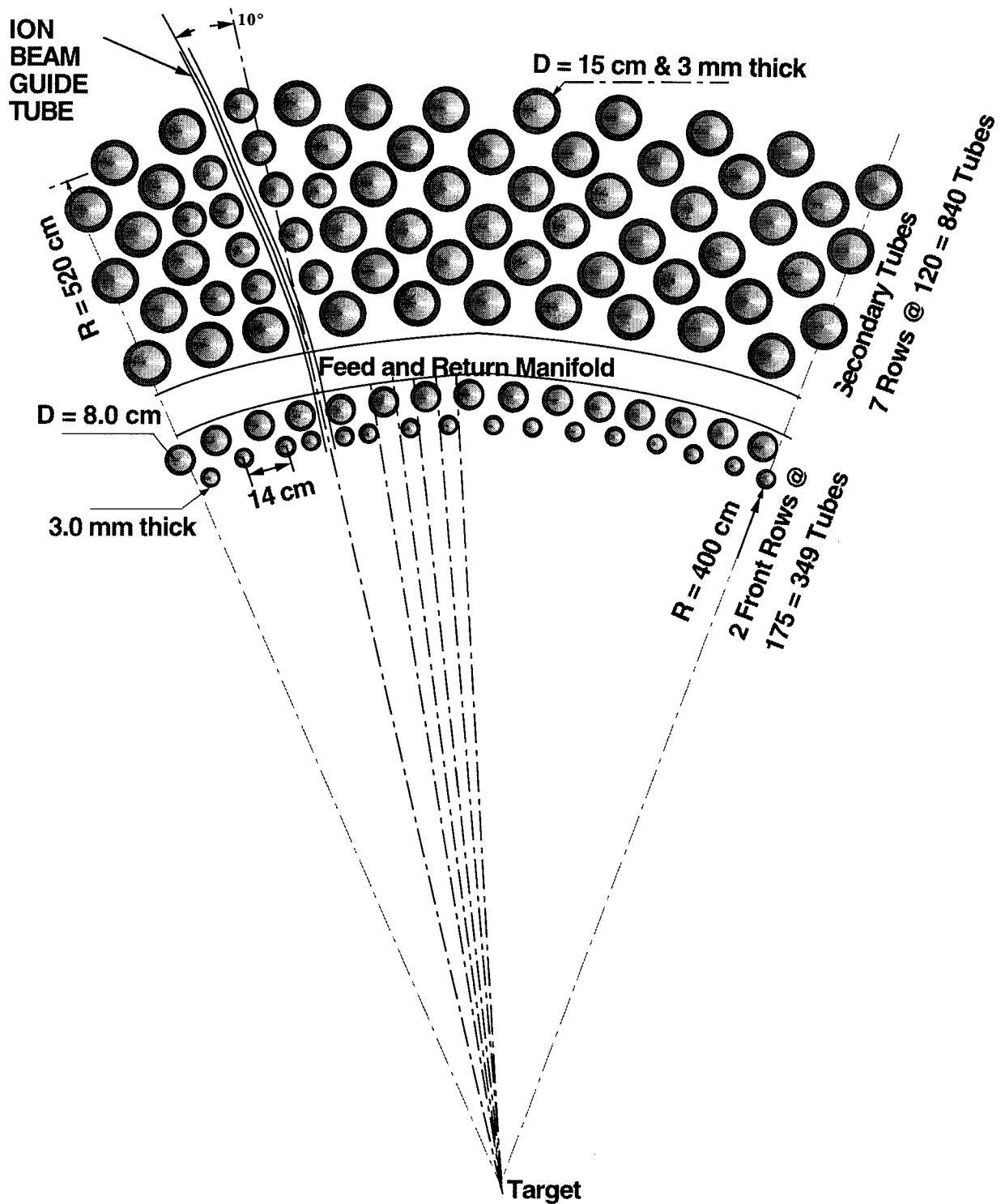


Figure 4.3.1. Horizontal cross-sectional view of a sector of the reactor chamber at midplane.

4.4. Beam Tube Stabilization and Control

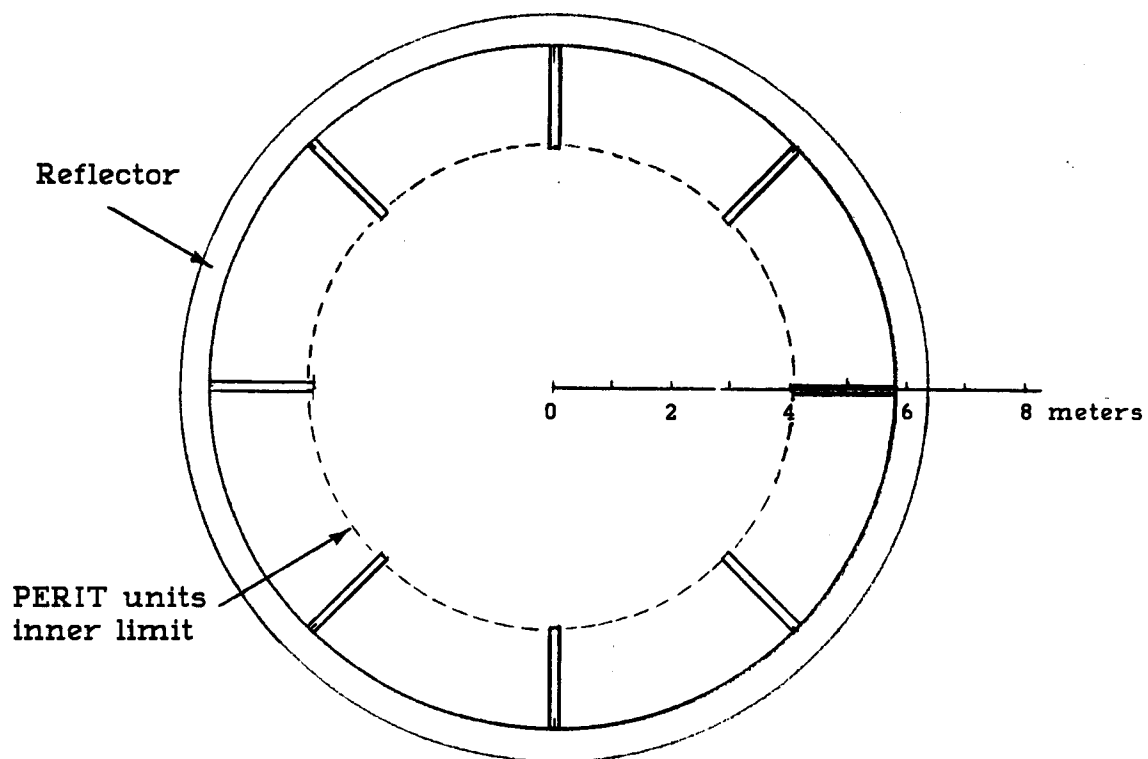
4.4.1. Introduction

The beams in LIBRA-SP are propagated to the target in the so-called self-pinch mode where the net electric current of the beams provides the azimuthal magnetic fields that confine the ions to the channels. Guide tubes are used to aim the beams at the target and for this reason, these tubes, which confine the beam with image charges, must be precisely aimed. A major advantage of this scheme is that the beam tubes can accommodate some large bend radii, and thus prevent primary neutrons from finding a direct path to the diode.

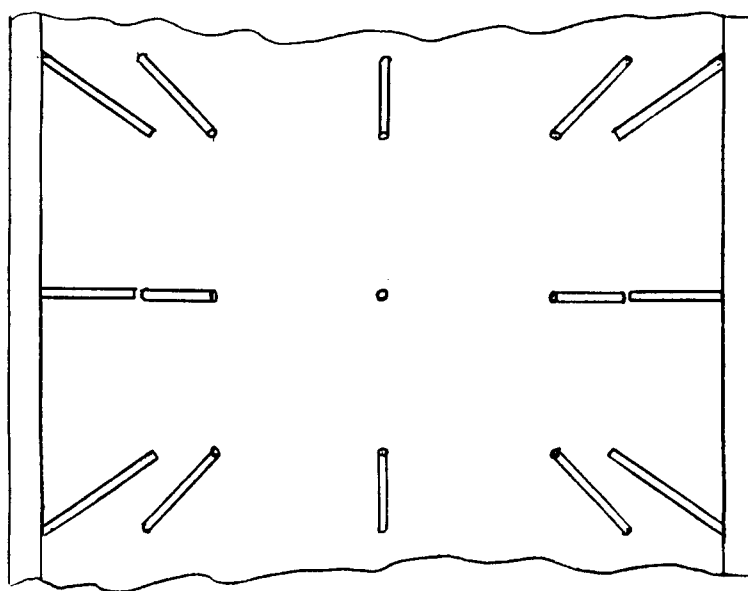
4.4.2. Description

Figure 4.1.1 is a side view of the LIBRA-SP chamber. LIBRA-SP has 24 beams aimed at the target, 12 of which are pre-pulse beams and 12 main pulse beams. The pre-pulse beams each deliver 1.2 MJ and the main pulse beams, 6 MJ to the target, respectively. Figure 4.4.1 is a schematic of the top view and side view of the beams. The beams are divided into three groups, one at the midplane and one each at the upper and lower ends of the cylindrical reaction chamber. As shown in the figure, the beam tubes appear by themselves. In the actual case, they are surrounded by the PERIT units made of solid ferritic steel which constitute the first wall (FW) and the blanket. The PERIT units carry lithium lead ($\text{Li}_{17}\text{Pb}_{83}$) from the top of the chamber to the bottom, capturing the neutrons, converting their energy into heat and breeding tritium (T_2). The front PERIT units are equipped with small nozzles along each side which spray liquid jets in the form of vertical fans. These fans overlap and provide a continuous film of protection in front of the tubes for intercepting target x-rays and target debris. Because the PERIT units are subjected to impulses from the target explosions, they vibrate. For the chosen reactor parameters, the rep-rate is 3.88 Hz. At this rep-rate the front PERIT units are deflected approximately one centimeter at their midspan.

Because the beam tubes act like gun barrels for aiming the beams at the target, they must remain stationary during reactor operation. For this reason, the beam tubes cannot be



Top View of Beam Tubes



Side View of Beam Tubes

Figure 4.4.1. Top and side views of beam tubes.

in contact with the PERIT units or their support structure. Figure 4.3.1 shows how a bend in the beam tube can be accommodated without sacrificing tube protection. In this section we explore possible support schemes for the beam tubes.

4.4.3. Beam Tubes Support

There are five basic requirements in the support scheme for the beam tubes, which are:

1. The beam tubes should be supported independently of the PERIT units or any of their support structure.
2. The beam tubes must be rigid enough so that any vibrations would be small enough in order not to adversely affect beam delivery.
3. The beam tubes should be capable of remote alignment during reactor shutdown.
4. The beam tubes must be cooled.
5. The support scheme must be compatible with PERIT unit maintenance.

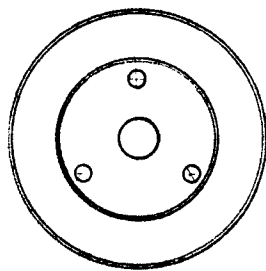
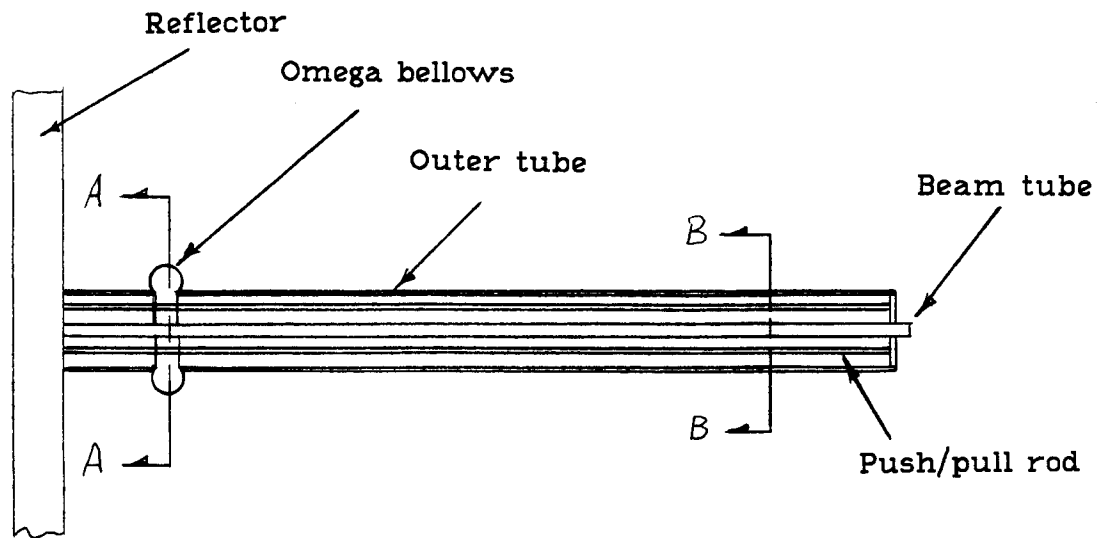
Two schemes have been evaluated and one has been selected for further development. The first scheme entailed the construction of rings which connected all the beams at any elevation. Thus a ring would circumvent the inside of the chamber connecting the 8 beam tubes on the upper level. Similar rings would be used for the middle and lower levels. It was found that it would be impossible to place such a ring without interfering with the PERIT units or part of their support structure. Furthermore, making the tubes remotely alignable was also difficult.

The support scheme that seems to satisfy all the listed requirements is one where each beam tube is self supporting, and is attached to a rigid structure, in this case the reflector. The scheme calls for two concentric tubes, the inner tube being the beam tube, and the outer tube acting as the support and stiffening member. The beam tube itself is flexible enough as to be capable of minor deflections. The outer tube will be very stiff, but will be equipped with a single turn omega bellows to make it adjustable. On the inside, between the outer and the inner tubes will be three rods on an equilateral triangle configuration. The rods will be remotely driven from behind the reflector, providing a three point adjusting mechanism capable of covering a complete range of adjustments. The annular space between the tubes can have LiPb pumped through it to provide cooling and damping. Figure 4.4.2 shows the beam tube support scheme. The figure shows the beam tube as being straight. In the actual case, the beam tubes will be curved $\sim 10^\circ$ in order to avoid neutron streaming. The adjustment rods will have guides along the length of the beam tube to keep them from bending.

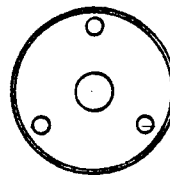
4.4.4. Remote Adjustment

Laser and heavy ion beam proponents claim that they can do on-line manipulation of the beam as they track a target on its trajectory through the chamber. This is not possible in the case of LIBRA-SP. Thus, the beam tubes have to be adjusted while the reactor is down, and the beam tubes must stay aligned between adjustments. In the previous section it was described how the end of the beam tube can be adjusted for proper aiming on the target and the mechanism for these adjustments is explained below.

When the reactor is down, a special spherical target built in a configuration of a calorimeter is positioned on a stem in the center of the chamber. The precise location will be the point at which all the beams will be aimed and this represents the exact location where the target will be imploded. Each beam can now be fired individually at a small fraction of its power and the reading from the target calorimeter noted. A computer then instructs the beam tube adjustment mechanism to make a correction. The process is repeated until



Section A-A
enlarged



Section B-B
enlarged

Figure 4.4.2. Support and alignment scheme for beam tubes.

the beam delivery is maximized on the calorimeter. Each beam will undergo the same kind of adjustment separately until all the beams are aligned. The use of fast computers should make this kind of task relatively easy and rapid. The whole process of beam tube adjustment may only take less than one hour.

4.4.5. Results and Conclusions

The scheme for supporting the beam tubes satisfies the five requirements listed above. The tubes are attached to the reflector wall which is for all practical purposes an immovable object. The outer tube stiffness, in spite of the adjusting omega bellows, can be made high enough to give the required stability. The impulses on the tubes will be head-on, providing no force to initiate sideways motion. The coolant in the outer annular region provides cooling for the tubes and the adjustment rods, and also aids in damping. A rather simple and fundamental method for covering all the degrees of freedom is provided with the three point adjustment scheme. An adjustment of the beam tubes by a radial distance of 1 cm at the end of the tube in all directions can be easily achieved. A method has been proposed for aligning the beam tubes onto a dummy target calorimeter using computer directions based on the output of the calorimeter. Additional analysis will be needed to determine the effect of the bends and work will be required for an engineering design with dimensions based on a complete analysis.

4.5. Mechanical Response of the PERIT Units

It is expected that the first two rows of PERIT units will be subjected to the radial impulse load from the blast wave. The primary response of the tubes will be a radial displacement (or planar displacement), however, it has been shown that the tubes could begin to “whirl” under certain operating conditions [1, 2]. If three-dimensional motion were to take place, it is assumed that the maximum displacement would not be greater than the maximum planar displacement. The pressure load is assumed to be uniformly distributed over the length of the tube and is applied at the rep-rate of the reactor. Since the flow velocity of the fluid is low, the effects of the moving liquid through a vibrating tube are

neglected and the fluid is considered stationary. Stationary fluid in a tube adds mass to the system without changing the flexural rigidity of the tube. Characterizing the planar motion and the resulting stresses in the PERIT units is essential for a credible design and is the focus of this section.

The mechanical response of a PERIT unit was modeled by modifying Euler's beam equation. The general equation describing the motion of a tube under sequential impulse loading can be expressed as

$$EI \frac{\partial^4 y}{\partial x^4} + \gamma \frac{\partial^2 y}{\partial t^2} + \kappa \frac{\partial y}{\partial t} = 2RI_p \sum_{n=0}^{n\tau_{imp} \leq t} \delta(t - n\tau_{imp})$$

$$\begin{aligned} y &= \text{radial displacement coordinate} \\ x &= \text{spatial coordinate} \\ t &= \text{time} \\ E &= \text{modulus of elasticity of the tube} \\ I &= \text{area moment of inertia of the tube} \\ \gamma &= \text{mass per unit length of the tube including fluid} \\ \kappa &= \text{coefficient of viscous damping per unit length} \\ \delta &= \text{Dirac delta function} \\ R &= \text{outer radius of the tube} \\ I_p &= \text{impulse pressure} \\ \tau_{imp} &= \text{impulse period.} \end{aligned}$$

The homogeneous solution using separation of variables is given by:

$$\begin{aligned} y_h(x, t) &= \sum_{i=1}^{\infty} Q_i(t) \phi_i(x) \\ \phi_i(x) &= \text{orthogonal mode shape that satisfies the boundary conditions} \\ Q_i(t) &= e^{-\zeta_i \omega_i t} [A_i \sin((\omega_d)_i t) + B_i \cos((\omega_d)_i t)] \\ (\omega_d)_i &= \omega_i \sqrt{1 - \zeta_i^2} \\ \omega_i &= \left(\frac{\lambda_i}{L} \right)^2 \sqrt{\frac{EI}{\gamma}} \end{aligned}$$

where ζ_i represents the equivalent modal damping factor, L is the length of the tube, λ_i is the separation constant prescribed by the boundary conditions and A_i and B_i are constants determined by initial conditions. For this problem, the homogeneous solution represents the

motion of the tube before the sequential impulses. If the tube is initially at rest, then the homogeneous solution is equal to zero, i.e., $A_i = B_i = 0$.

Variation of parameters can be used to find the particular solution. Consequently, a solution of the following form is assumed:

$$y_p(x, t) = \sum_{i=1}^{\infty} T_i(t) \phi_i(x)$$

where $Q_i(t)$ has been replaced by an unknown function $T_i(t)$. Inserting the assumed solution in the governing equation and using the orthogonality property of the shape functions and the integration property of the delta function, it can be shown that

$$T_i(t) = \frac{2RD_i}{\gamma C(\omega_d)_i} q_i(t)$$

$$q_i(t) = \sum_{n=0}^{n\tau_{imp} \leq t} e^{-\zeta_i \omega_i(t-n\tau_{imp})} \sin [(\omega_d)_i t - (\omega_d)_i n\tau_{imp}]$$

where

$$C = \int_0^L \phi_i^2(x) dx$$

$$D_i = \int_0^L I_p(x) \phi_i(x) dx .$$

$I_p(x)$ represents the distribution of the pressure load along the span of the tube. In this study, the pressure load is distributed uniformly over the length of the tube, therefore $I_p(x) = I_p$, a constant.

Combining the above results, the general solution for the displacement of the beam starting from rest is given by

$$y(x, t) = \frac{2R}{\gamma C} \sum_{i=1}^{\infty} \frac{D_i}{(\omega_d)_i} \phi_i(x) q_i(t) .$$

By examining the time function $q_i(t)$, one observes that each impulse starts a free vibration solution and the total response is the superposition of all the free vibrations. As time progresses, a free vibration solution is diminished by damping, so only the most recent impulses or corresponding free vibration solutions contribute to the tube's response.

In a beam, the bending stress, σ , is equal to

$$\sigma(x, t) = Ec \frac{\partial^2 y}{\partial x^2}$$

where c is the perpendicular distance from the tube's neutral axes to the point of interest. Then the general expression for the bending stress in the beam driven by sequential impulses is given by

$$\sigma(x, t) = \frac{2REc}{\gamma C} \sum_{i=1}^{\infty} \frac{D_i}{(\omega_d)_i} \frac{d^2 \phi_i(x)}{dx^2} q_i(t).$$

Values for the equivalent modal damping factor, ζ_i , are determined using Rayleigh damping. Rayleigh damping combines viscous damping (the retarding force proportional to velocity) and structural damping (energy loss per cycle proportional to the square of the strain amplitude) [3, 4]. Values for the equivalent modal damping factor can be found using

$$\zeta_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2}$$

where α is the damping constant for viscous damping and β is the damping constant for structural damping. For this application, the PERIT units are vibrating in a vacuum so the viscous damping constant was set equal to zero, i.e., $\alpha = 0$. At low stress levels the damping factor for steel is about 0.5%. Therefore, the value of the structural damping constant, β , was set such that the damping factor for the fundamental mode was equal to 0.5%.

The above displacement and stress solutions were derived for arbitrary boundary conditions. To date, two different end conditions have been examined, i.e., pinned-pinned and clamped-clamped. Because of the generality of the derivation, other more complicated boundary conditions can be studied by using their associated shape functions. The following orthogonal shape functions for a pinned-pinned and clamped-clamped beam are found in reference [5] (for convenience the integration constants have been included).

Pinned-Pinned Beam:

$$\phi_i(x) = \sin \frac{\lambda_i x}{L}$$

$$\lambda_i = i\pi$$

$$C = \int_0^L \phi_i^2(x) dx = \frac{L}{2}$$

$$D_i = \int_0^L I_p(x) \phi_i(x) dx = \begin{cases} 0 & \text{for even } i \\ \frac{2I_p L}{\lambda_i} & \text{for odd } i \end{cases}$$

Clamped-Clamped Beam:

$$\phi_i(x) = \cosh \frac{\lambda_i x}{L} - \cos \frac{\lambda_i x}{L} - \alpha_i \left(\sinh \frac{\lambda_i x}{L} - \sin \frac{\lambda_i x}{L} \right)$$

$$\alpha_i = \frac{\cosh \lambda_i - \cos \lambda_i}{\sinh \lambda_i - \sin \lambda_i}$$

$$\cos \lambda_i \cosh \lambda_i = 1$$

$$C = L$$

$$D_i = \begin{cases} 0 & \text{for even } i \\ \frac{4\alpha_i I_p L}{\lambda_i} & \text{for odd } i \end{cases}$$

Notice that because D_i is zero for even i , the even modes will not contribute to the total displacement or the stress. The reason for this is that the even or anti-symmetric modes are not excited by the uniform or symmetric pressure load. For a system with non-symmetric boundary conditions or non-symmetric pressure loading, all modes will contribute to the modal solution.

The above solutions give the displacement and stress of a PERIT unit starting from rest and driven by periodic impulses of constant magnitude. Other situations can be easily studied by making small changes in the general solutions. By varying the impulse period, t_{imp} , the effect of non-periodic impulses can be studied; this will occur during the startup of the reactor. By skipping a term in the time summation, $q_i(x)$, the effect of a missed target can be analyzed. Also the consequences of pressure loads of different magnitudes or distributions can be examined by changing $I_p(x)$.

For the proposed LIBRA-SP cavity, a number of the PERIT design parameters have been set by power requirements and heat transfer requirements, e.g., using HT-9 as the tube material and LiPb as the liquid metal. Table 4.5.1 lists the system parameters that have

Table 4.5.1. PERIT System Parameters

Tube outer diameter	7 cm
Tube thickness	3 mm
Tube length	5.3 m
Impulse (I_p)	71 Pa-s
Rep rate	3.88 Hz
Density of LiPb	9440 kg/m ³
Density of HT-9	7625 kg/m ³
Damping of the fundamental mode	0.5%
Elastic modulus of HT-9 (E)	163 GPa
Yield strength at 625°C	250 MPa

been used to calculate the mechanical response. The magnitude of the impulse load was calculated at 71 Pa-s, so calculations were performed using impulse loads of 50 Pa-s, 71 Pa-s and 100 Pa-s. The results scale linearly so the displacements and stresses can be easily determined for any impulse magnitude.

The length of the tubes remained as a design parameter to be optimized. Parametric studies were performed to determine the necessary length to preclude resonant conditions and minimize the radial displacement and bending stress. Figure 4.5.1 shows the midspan displacement amplitude as a function of the impulse frequency (or rep-rate) for a pinned-pinned tube of length 5.3 m. A maximum allowable displacement of 3.5 cm, to prevent tube interference, has also been noted on the figure. For a rep-rate of 3.88 Hz, the absolute displacement of the tube is well below the allowable deflection. The corresponding midspan bending stresses are given in Fig. 4.5.2 with the yield strength of the material [6] indicated. Both figures illustrate the frequencies or rep-rates associated with resonant conditions, i.e., the peaks in the response curves. The large peak in the center of the figures is the fundamental frequency of the system and the peaks to the left are overtones of the fundamental frequency. The smaller peaks (bumps) on the right side of the figures are the overtones of the second natural frequency. The large rise on the far right of the figures is in the region where the rep-rate of the reactor is much larger than the fundamental frequency

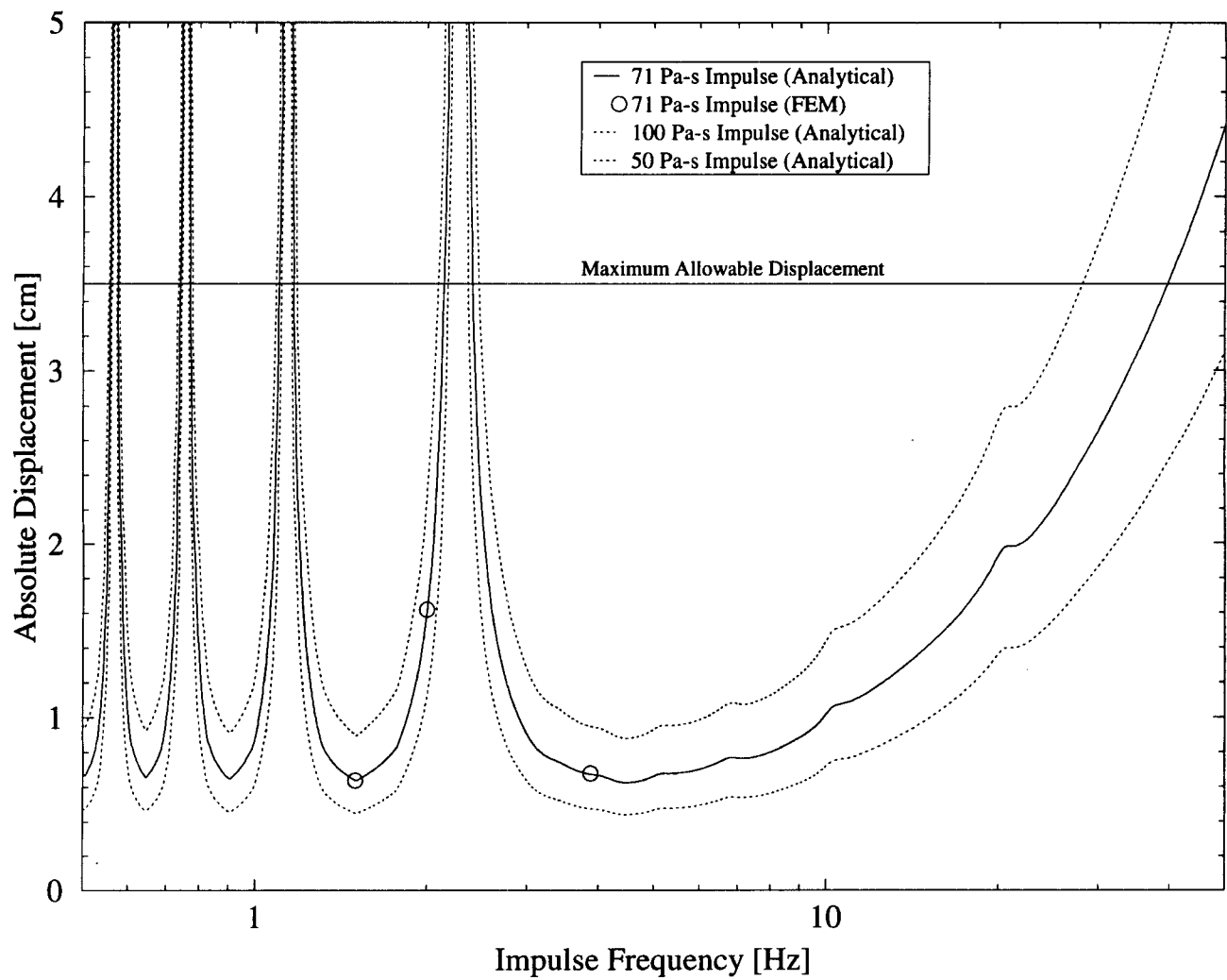


Figure 4.5.1. Maximum midspan displacement of the pinned-pinned PERIT unit as a function of impulse frequency.

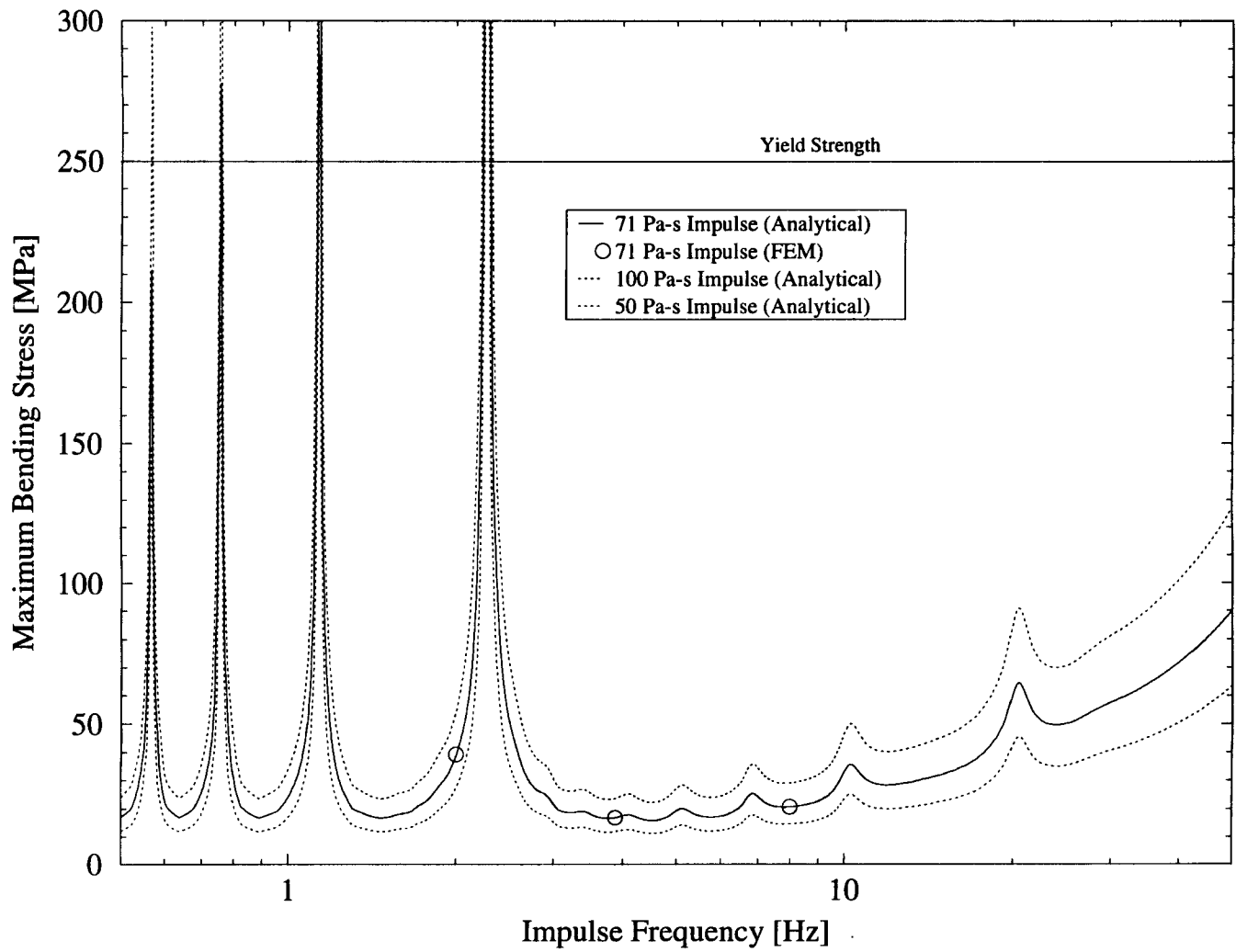


Figure 4.5.2. Maximum midspan bending stress of the pinned-pinned PERIT unit as a function of impulse frequency.

of the tube. In this region the tube does not have a chance to recover (return to equilibrium) between impulses. Repeated impulses will force the tube to diverge from the equilibrium position in a “static” like manner. All of the above characteristics (peaks) would effectively shift as the length of the tube changes. Therefore, it is imperative to design the free span of the tube at approximately 5.3 m in order to ensure that the reactor’s operating rep-rate, 3.88 Hz, does not coincide with the resonant peaks.

Throughout the above analysis of the PERIT units, the dynamic effects of fluid moving through a vibrating tube have been neglected. Although the velocity of the fluid is low, 4 m/s, the density of LiPb is quite high and therefore might significantly change the computed natural frequencies of the tube. The exact solution for the fundamental frequency of a tube with internal fluid flow is reported in [7]. For the proposed PERIT design, the LiPb velocity of 4 m/s will decrease the PERITs’ fundamental frequency by 1.4%. Therefore, the assumption that dynamic effects can be neglected and the internal fluid can be modelled as a stationary mass is legitimate.

To verify the analytical solution, a finite element model of a PERIT unit under sequential impulse loading was constructed using the commercially available finite element package ANSYS. Beam elements were used to model the tube and the internal fluid flow was modeled by added mass. The sequential impulses were simulated by applying a uniform pressure, normal to the surface of the beam for short durations (much smaller than the beam’s fundamental frequency). The area under the pressure pulse is equal to the magnitude of the impulse, I_p . Figure 4.5.3 compares the analytical and the finite element solutions for the midspan displacement of a PERIT unit. Figure 4.5.4 compares the midspan bending stress. These figures indicate that the two solution methods are in full agreement.

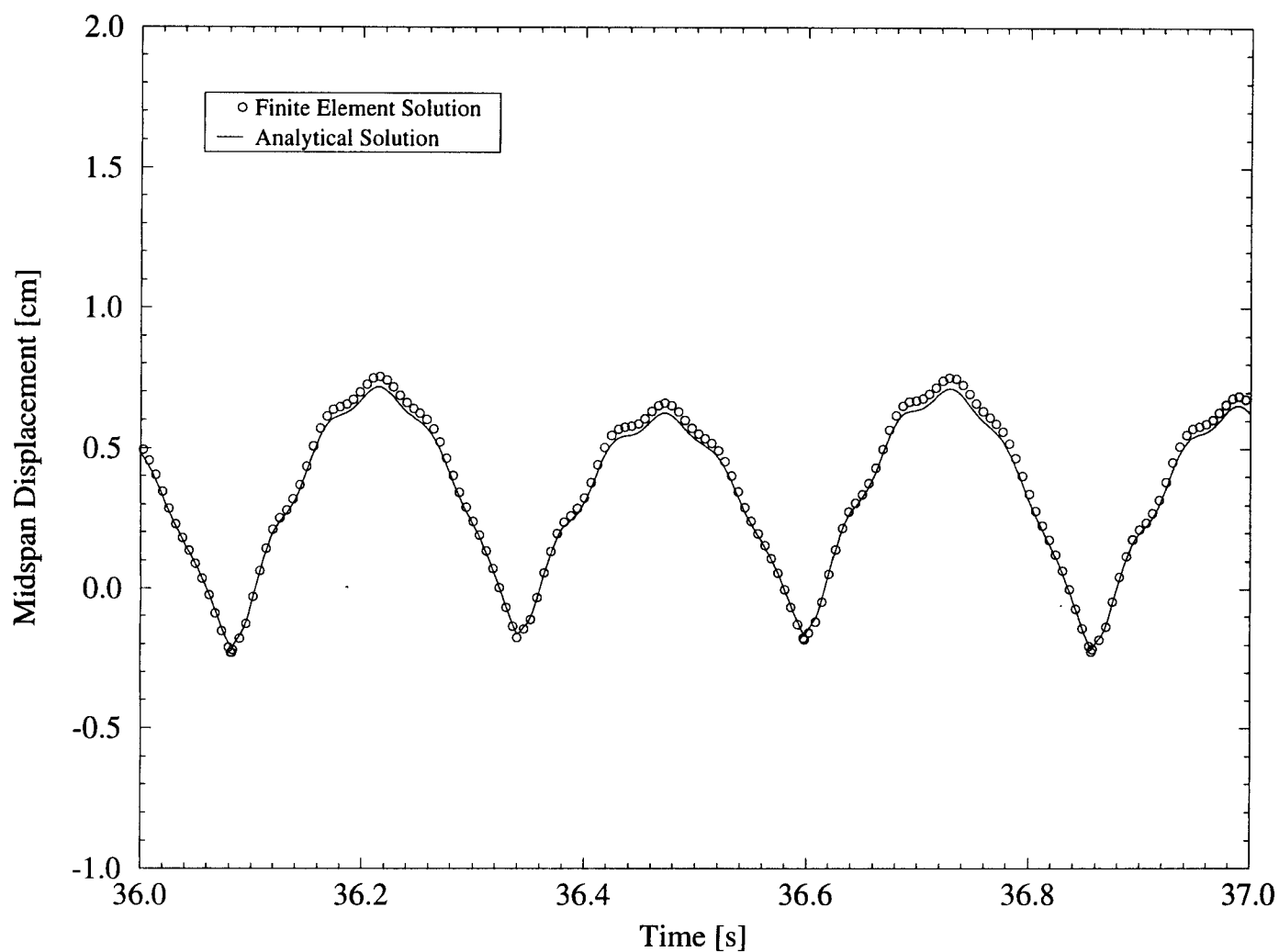


Figure 4.5.3. Midspan displacement vs. time of the pinned-pinned PERIT unit driven at a rep-rate of 3.88 Hz.

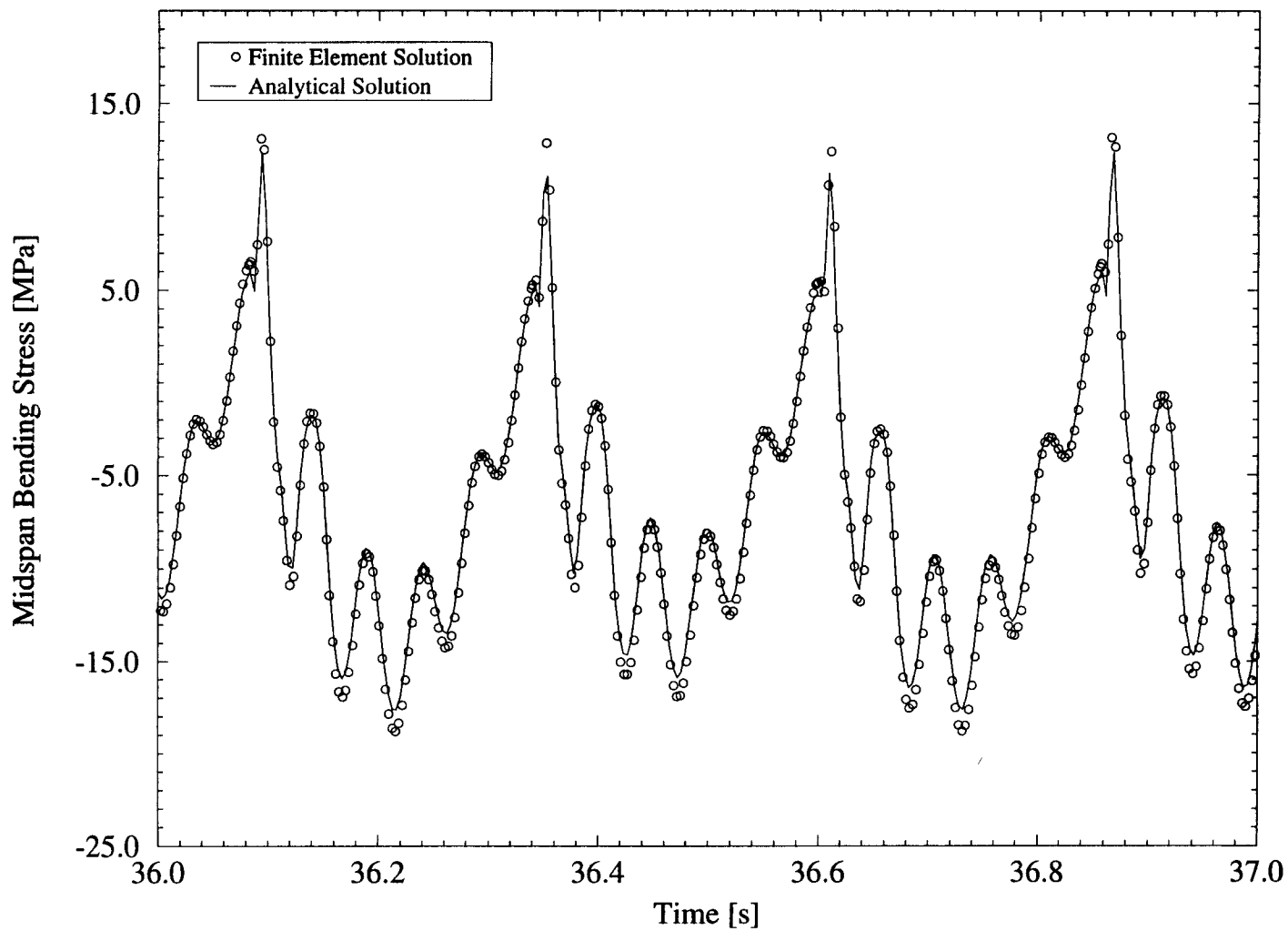


Figure 4.5.4. Midspan bending stress vs. time of the pinned-pinned PERIT unit driven at a rep-rate of 3.88 Hz.

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5. Conclusions and Recommendations

5.1. Conclusions

The use of self-propagation schemes for light ions has allowed designers to remove the final focusing magnets from inside the chamber that were required by ballistically focused ions. This ion propagation mechanism greatly simplifies the reaction chamber design and should result in a more robust and long lasting cavity design. The credibility of the propagation scheme can be demonstrated on existing or modified facilities. If such confirmation occurs, then one of the main obstacles to economical power generation from light ions will have been removed.

The MHD analysis shows that the growth factors for the main and prepulse LIBRA-SP beams (over the 40 ns beam pulse) are only 3.47 and 2.12 respectively. This small growth factor means that small perturbations will remain small during the critical period of the pulse and the present beam design is credible.

The effect of overlapping beams on the number of ions that reach the target has been studied with the Chantran code (specially developed for this contract) revealing that 26% of the ions in the main pulse are lost compared to $\approx 15\%$ of those from the prepulse beam. The loss rates are higher than previously thought but it is felt that the present models may be too conservative and overpredict the loss fraction. Also, the latest target design requires a much higher beam power, which also makes the overlap losses much greater. Therefore, the IPROP code (developed by Mission Research Corp.) has been investigated as a more realistic predictor of overlap losses. It was determined that before any drastic changes in the designs are made, the same overlap calculation for LIBRA-SP beams needs to be repeated with the IPROP code and compared to the Chantran results. This will require collaboration with scientists at Mission Research Corporation and such an avenue is being pursued.

In combination with increased ion losses from beam overlap along with increased power on required by more realistic target designs and longer beam propagation lengths, the overall transport efficiency has dropped from our previous assumption of 90% to a calculated value of 67% for the main pulse beams (83.5% for the prepulse beams). When this is factored

into the overall driver efficiency (wall-plug to diode efficiency times the transport efficiency), a $\approx 10\%$ increase in recirculating power is required. This will amount to a 2-3% drop in net power which can be compensated for by increasing the rep-rate from 3.88 Hz to ≈ 4.0 Hz.

Recent declassification of target designs in the U.S. has allowed the LIBRA team to more correctly describe the geometry, mass, and manufacturing requirements for LIB targets. The more detailed target designs also allow more accurate description of the target debris, x-rays, and neutrons. The goal yield from the LIBRA-SP target is 589 MJ and during CY-95, a design which yields 323 MJ was analyzed with the BUCKY-1 code. It was found that the relatively simple prepulse and main beam totaling 7.9 MJ and a peak power of 480 TW could produce the proper time structured x-ray pulse to the fuel capsule to achieve a gain of over 40. With a minimal amount of continued target optimization, a 589 MJ target configuration should be available.

Aside from detailed target output spectra that have been calculated, the most important advance made during CY95 is the ability of scientists in the field to use unclassified codes (e.g., BUCKY-1) to design robust light ion targets which can convert simple ion beam pulses to an internally time tailored, x-ray pulse on a fuel target. Once the experience gained from the current optimization studies is assimilated, relatively rapid turn-around can be expected for future target designs.

The 24 ion beams (8 prepulse and 16 main pulse) have been repositioned to irradiate the target at 53° from the horizontal instead of the 45° previously used. This was easily accommodated in the present cavity design.

The use of solid perforated tubes (PERIT units) in place of flexible INPORT units removes the need for pre-tension on the tubes to avoid interference during pulsing. The fact the tubes are rigid allows them to be curved resulting in a more uniform heat flux to the units. Credible design of the ion beam entrance ports has allowed us to develop more detailed shield configurations to shield the final diodes. The tubes that guide the beam from the diode to the target are slightly bent (at a 10° angle) in the horizontal plane and 9° in the vertical plane in order to reduce the neutron streaming to the diode. This has been done by

changing the size of some of the PERIT units close to the chamber wall. If such a concept is substantiated by actual experiments at SNL or Karlsruhe, then another impediment to commercial power will have been removed.

A mechanism for supporting and aligning the tubes that guide the ions to the target has been proposed. Because of the current cavity design, the alignment adjustments need to be done when the reactor is down and the beam guidance tubes must be robust enough to maintain that alignment during the operation of the reactor.

Specific analysis of pinned-pinned PERIT units reveals that at the proposed rep-rate of 3.88 Hz, the maximum midplane displacement is slightly more than 0.6 cm which is a factor of 6 below the maximum allowable displacement. The maximum midplane stress is slightly less than 20 MPa which is more than a factor of 10 below the yield strength of the PERIT units. The current design reveals a broad minimum in the neighborhood of 4 ± 1 Hz so that the rep-rate can be used as a mechanism to compensate for abnormal operating conditions.

The overall progress during CY95 has been very encouraging to the prospects for safe, clean, and economical electrical power from light ion beam driven fusion targets. Continued advances in this field could allow light ion beams to emerge as the leading contender to drive ICF targets in the future.

5.2. Recommendations

As a follow-up to the significant progress made in 1995, there are a few issues that still remain to be examined in the future. First, the inclusion of the IPROP code in the analysis of the overall beam transport efficiency of LIBRA-SP would be extremely valuable. Integration of this code with Chantran and others that have been developed for the ICF program over the past 20 years will enable the LIBRA team to develop more credible designs with less human resources.

Second, the use of BUCKY-1 to calculate the light ion target performance under reactor conditions has allowed us to be more quantitative about the design margin available

in the LIBRA class of reactors. The final optimizations need to be made to field a ≈ 600 MJ target and the results need to be published in high visibility refereed journals.

Third, now that the time and spatially dependent ρR values are available, a detailed calculation of the neutron and x-ray spectra emanating from the target should be completed. This will have a very large impact on first wall design and the ultimate lifetime of structural components. It will also have an impact on the radioactivity induced in the first wall.

Finally, it may be time to consider the concept of a light ion “NIF” ignition facility from the standpoint of physics, technological, cost, and environmental requirements. Past conclusions by the ICF community that a heavy ion driven “NIF” is the most attractive option are probably no longer true given the rapid progress in light ion physics and technology. A relatively low level effort in this area, based on experience with past LIBRA designs could yield very favorable results.

Acknowledgement

The authors wish to acknowledge helpful technical discussions with Dr. R. Olson of Sandia National Laboratory and Dr. D. R. Welch of Mission Research Corp. in Albuquerque, NM. Support for this work has been provided by the Institut für Neutronen Physik und Reactortechnik of the Forschungszentrum Karlsruhe.

Appendix

A Novel First Wall Protection Scheme for Ion Beam ICF Reactors

**To be published in Proceedings of the 16th IEEE/NPSS Symposium
on Fusion Engineering, 1–5 October 1995, Champaign, IL**

A Novel First Wall Protection Scheme for Ion Beam ICF Reactors

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ABSTRACT AND INTRODUCTION

A novel scheme of first wall protection for ion beam driven inertial confinement fusion reactors is presented. LIBRA-SP utilizes a self-pinch ion beam transport and is intended as a 1000 MWe power reactor. LIBRA-SP uses rigid HT-9 ferritic steel tubes called PERIT (perforated rigid tubes) units. These tubes are equipped with tiny nozzles on either side which spray vertical fans of liquid metal, overlapping each other such that the first two rows of tubes are completely shadowed from the target emanations. The target generated X rays accelerate the LiPb spray through the rapid vaporization of the surface facing the target. Simulations of the behavior of the spray with the BUCKY computer code show that the spray remains intact and is still at liquid density when it hits the PERIT units producing a peak pressure on the PERITS of several GPa, and a total impulsive loading of 72 Pa-s. The spray that is vaporized by the X rays blows into the center of the target chamber intercepting the target debris ions. The first row of tubes in the blanket carry the brunt of the radial impulsive load, which is applied at the reactor repetition rate. A code has been developed for determining the transient and steady state response of the tubes containing the liquid metal, driven by sequential pulses for specific boundary conditions. Maximum steady state deflections and bending stresses as a function of the rep-rate are calculated and used to optimize the length of the PERIT units for avoiding resonant conditions. The cylindrical portion of the chamber is covered by a blanket of rigid steel tubes at a packing fraction of 50%. Only the front two rows of tubes are equipped with the spray nozzles. These tubes are at a radius of 4 m and the radius of the reflector, which is the vacuum boundary is 5.2 m.

II. OVERALL DESIGN

In LIBRA-SP there are 24 ion beams altogether. Fig. 1 is a cross sectional view of the reaction chamber. The vertical sides of the chamber contain a blanket zone consisting of many perforated rigid ferritic steel tubes with a packing fraction of about 50% through which the breeding/cooling material, liquid lead-lithium, flows. This blanket zone, besides breeding T_2 and converting neutronic energy to thermal energy, also provides protection to the reflector/vacuum chamber so as to make it a lifetime component. The length of the first row tubes is 10.4 m in two segments of 5.2 m each between supports. The tubes are rigid so they can withstand

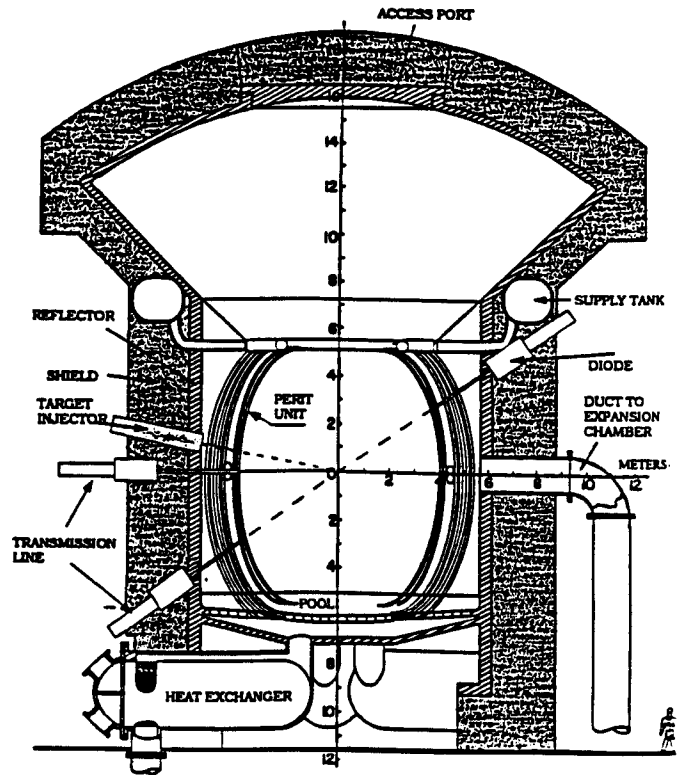


Fig. 1. Cross-sectional view of the reactor chamber.

shocks, and are perforated so they can maintain a wetted surface through the jet fan spray. There are two rows of 7 and 8 cm diameter PERIT units arranged at 14 cm between centerlines at midplane in the circumferential direction as well as between rows. The front tubes totally shadow the rear zone. There are 7 rows of HT-9 rear tubes, 15 cm in diameter, Fig. 2. They transport the PbLi which moderates neutrons and breeds T_2 . Behind the blanket is a 50 cm thick HT-9 ferritic steel reflector which is also the vacuum boundary. The whole chamber is surrounded by a steel reinforced concrete shield nominally 2.7 m in thickness.

Fig. 1 also shows vacuum tubes located behind the shield/blanket zone at the chamber midplane which lead to an expansion tank situated below the reaction chamber. Vapor flows into the expansion tank following a shot, exchanging heat with the PERIT units, and cooling by isentropic expansion. Vacuum pumps attached to the expansion tank evacuate the noncondensable species in preparation for the next shot.

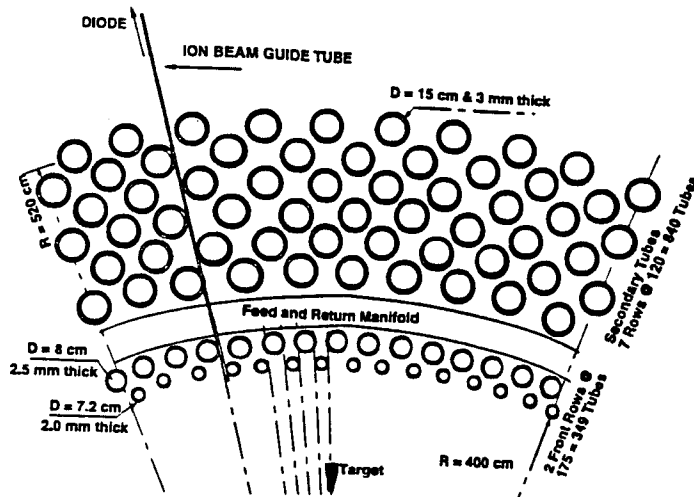


Fig. 2. The distribution of PERIT units and the shield/blanket zone.

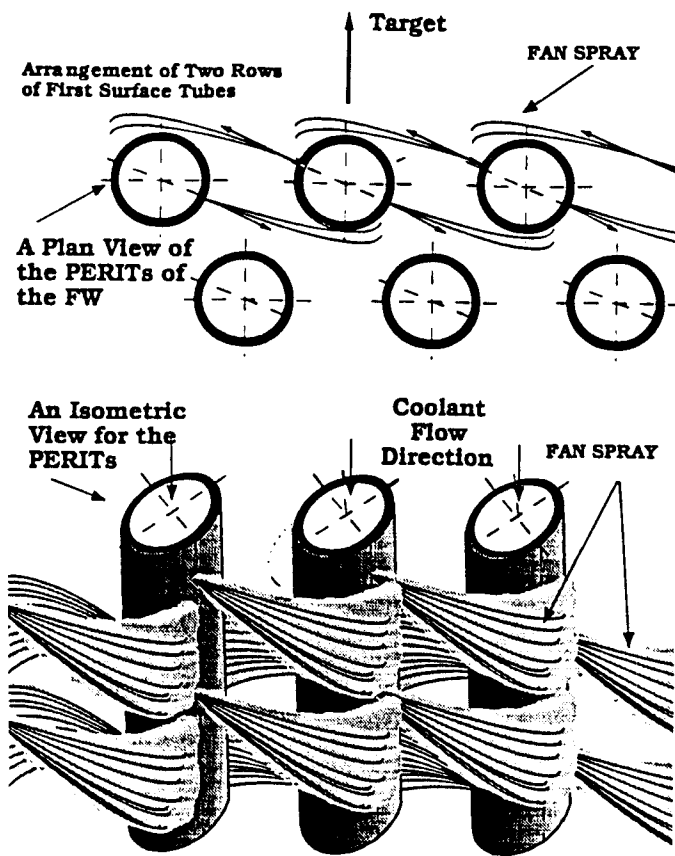


Fig. 3. First surface protection by fan sheet spray

The chamber roof is unprotected with PERIT units 16 m from the target, also making it a lifetime component. The roof and its integral shield are removable providing access for chamber maintenance. Since the roof will be cooled, it also will condense vapor and have a wetted surface which will be vaporized after each shot. Another function of the mushroom shape is to protect the side walls which are shadowed by the PERIT units and to provide additional volume in the chamber for the vapor to expand into.

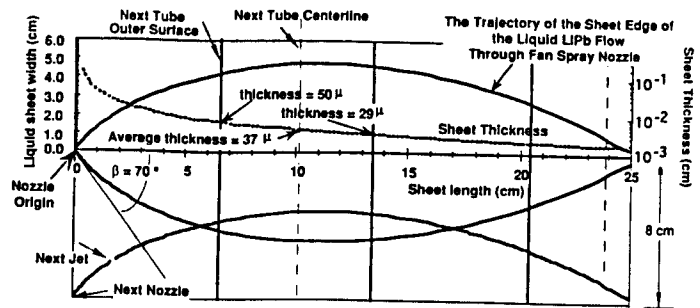


Fig. 4. The fan spray jet trajectory.

The coolant feed pumps only supply the liquid metal to the open liquid tank at the top of each segment group. The liquid metal flows under the gravity effect down the coolant tubes and through the perforations. Fig. 3 is a view of three of the PERIT units showing these fan sheet sprays. The PbLi coolant enters the reactor at 370°C and exits at an average temperature of 500°C and collects in the bottom pool. The collected PbLi drains through a perforated plate into a sump leading to the intermediate heat exchangers (IHx) located in the base of the chamber. In the IHx the PbLi exchanges heat with liquid PbLi, which is pumped to a steam generator. A fraction of the PbLi flow is diverted to a T₂ removal system.

III. FIRST SURFACE PROTECTION

A. Recent Work and Discussion

LIBRA-SP uses solid coolant tubes for the first surface, blanket and shield to improve the performance of the target chamber.

1) *Formation of liquid sheets.* In this work, our attention will be concentrated on flat liquid sheets. Taylor [4] explains the principles of liquid sheets formation. In practice, in the fan sheet nozzle, two streams of liquid are made to impinge behind an orifice by specially designed approach passages and a sheet is formed in a plane perpendicular to the plane of the streams. The principle is illustrated in Fig. 4(a), which shows liquid flowing through a rectangular orifice formed at the end of the rectangular tube. A flat sheet is produced as the liquid freely spreads through the orifice limited only by the side walls. A commercial nozzle is shown in Fig. 4(b). It is designed on this principle, made of ceramic material and contains a rectangular orifice which is produced by the interpenetration of two rectangular slots.

In the absence of surface tension, the edges of the sheet would travel in straight lines from the orifice so that a sector of a circle would be formed. However, as a result of surface tension, the edges contract and a curved boundary is produced as the sheet develops beyond the orifice. Liquid at the edge moves along the curved boundary, and later becomes disturbed and disintegrates [4]. The breakdown of the edges is

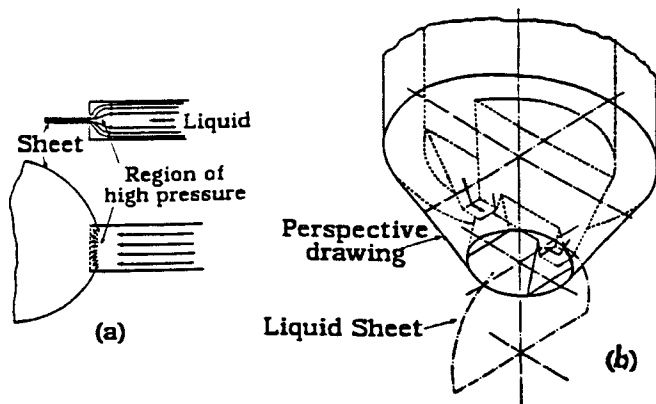


Fig. 5. Sketch of mechanism of flow through fan sheet nozzle.

restrained by viscosity. At higher injection velocities the contraction is less pronounced, and the placid sheet eventually becomes ruffled, and experiences violent oscillations due to a flag-like instability caused by the reaction of the surrounding gas with the sheet. In our case where the surrounding gas is at very low pressure these flag-like instability is less likely to occur.

2) *Analysis of flow in sheets.* In order to examine the nature of the fluid stream lines in a fan sheet, investigators [4,5] have used photographs of jets containing aluminum particles. Measurements from successive photographs with different conditions indicate that the stream velocity is constant along the sheet and its absolute value depends only on the differential injection pressure.

G. I. Taylor [4] and N. Dombrowski, et al. [5] analyzed this problem and the latter reached an approximate expression for the trajectory, and obtained an expression for the sheet thickness (see Ref. 6 for detailed analysis). The calculations are performed to design the nozzle needed to produce a satisfactory liquid metal sheet for LIBRA-SP. Fig. 5 shows the trajectory of the sheet edge of the liquid PbLi for a 5 mm times 1.5 mm fan spray nozzle. Fig. 5 also shows the sheet thickness distribution along the jet with an average value of 37 μm . To get full coverage for the PERIT every consecutive sheet must overlap. The required overlap gives the distance between each consecutive nozzle to be 8 cm.

From the structural dynamics (fatigue) point of view, it is better to have the perforations as close as possible to the bending plane (less stress concentration). Then, the direction of the jet is chosen to make the sheet 1.0 mm away from the surface of the next PERIT. Exactly on the opposite side of the PERIT there is another system of perforations but staggered 4.0 cm in the vertical direction to complete the coverage of the cavity first surface. The mechanical advantage of having both perforations on the opposite sides is that the lateral jet reaction is canceled.

IV. MECHANICAL RESPONSE

A. Interaction of Target Emanations with Spray

The deposition of target x rays and debris ions in the spray causes an explosive expansion of the region of the spray facing the target. This blows a small amount of vapor into the middle of the chamber, drives a shock through the spray, and accelerates the bulk of the spray toward the PERITs. The BUCKY computer code has been used to study these phenomena in the LIBRA-SP target chamber [6].

The results of a BUCKY simulation of the reaction of the spray to the target is summarized in Table I. The $\text{Pb}_{83}\text{Li}_{17}$ spray is initially 40 μm thick and at a temperature of 600°C. In this simulation, one can see that the spray mostly remains intact and placing the PERITs very close to the spray loses very little information since the spray will coast at a constant speed until it strikes the PERITs. In the simulation the spray collides with the PERITs at 0.8 μs , so the spray is moving at about 1.8×10^4 cm/s. At the time of collision, the pressure on the PERITs quickly rises to about 11 GPa. The spray begins to disperse after the collision. A total impulsive pressure of 71 Pa-s is applied of the whole pulse. A shock is initially driven through the spray by the rapid deposition of target energy. The shock reaches the back of the spray at about 0.07 μs , so the average shock speed is about 5.7×10^4 cm/s. About 1.15 mg/cm² of the spray are blown in to the middle of the target chamber [6].

Table I
Summary of BUCKY Simulation of Spray Behavior

Initial spray thickness	40 μm
Spray velocity	1.8×10^4 cm/s
Shock velocity	5.7×10^4 cm/s
Peak pressure on PERITs	11 GPa
Impulsive pressure on PERITs	71 Pa-s
Mass blown into chamber	1.15 mg/cm ²

B. Mechanical Response of the PERIT Units

It is expected that the first two rows of PERIT units will be subjected to the radial impulse load from the blast wave. The primary response of the tube will be a radial displacement (or planar displacement), however, it has been shown that the tubes could begin to "whirl" under certain operating conditions [7,8]. If three-dimensional motion were to take place, it is assumed that the maximum displacement would not be greater than the maximum planar displacement. Characterizing the planar motion and the resulting stresses in the PERIT units is the focus of this section.

The general equation of motion describing the mechanical response of a PERIT unit under sequential impulse loading can be found in [6]. A modal solution of the equation of motion for arbitrary boundary conditions is also given. In the

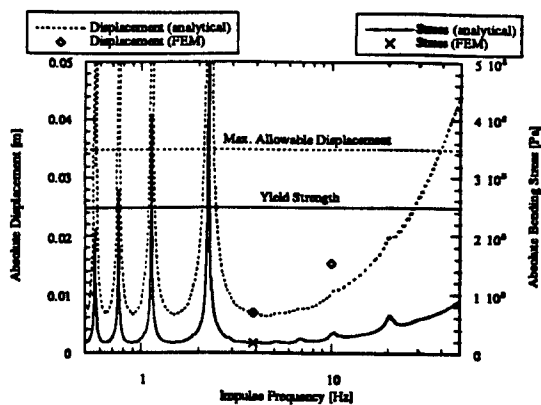


Fig. 6. Maximum radial displacement and maximum normal stress of clamped-clamped PERET units.

above derivation the following assumptions were made. The pressure load is assumed to be uniformly distributed over the length of the tube, impulsive and is applied at the rep rate of the reactor. In the previous section the magnitude of the impulse load was calculated at 71 Pa-s. The results scale linearly so the displacements and stresses can be easily determined for any impulse magnitude. Since the flow velocity of the LiPb is small, the effects of moving liquid within the tube can be neglected and the fluid considered stationary. Stationary fluid in a tube adds mass to the system without change the flexural rigidity of the tube. Rayleigh damping was used to model internal structural damping; external viscous damping was neglected. The damping ratio of the fundamental natural frequency set at 0.5%. For this study two different end conditions were examined; pinned-pinned and clamped-clamped. Because of the generality of the modal solution, other more complicated boundary conditions can be studied by using their associated orthogonal shape functions. A finite element model of a PERIT unit under sequential impulse loading was also constructed using the commercially available program ANSYS®. The finite element model confirms the results from the modal solution.

For the proposed LIBRA-SP cavity, a number of the PERIT design parameters have been set by power requirements and heat transfer requirements, e.g., using HT-9 as the tube material and LiPb as the liquid metal. The length of the tubes remained as a design parameter to be optimized. Parametric studies were performed to determine the necessary length to preclude resonant conditions and minimize the radial displacements and bending stresses. Fig. 6 shows the midspan displacement amplitude as a function of the impulse frequency (or rep rate) for a pinned-pinned tube of length 5.3 m. A maximum allowable displacement of 3.5 cm, to prevent tube interference, has been noted on the figure. For a rep rate of 3.88 Hz, the absolute displacement of the tube is well below the allowable. Fig. 6 also shows the corresponding midspan bending stresses with the yield strength of the material [9] marked as shown. This figure illustrates the frequencies or

rep rates associated with resonant conditions, i.e., the peaks in the response curves. The large peak in the center of the figure is the fundamental frequency of the system and the peaks to the left are overtones of the fundamental frequency. These peaks would effectively shift if as the length of the tube changes. Therefore, it is necessary to establish the free span of the tube at approximately 5.3 m to place the reactor's operating rep rate away from the resonant peaks.

ACKNOWLEDGMENT

Support for this work was provided by the U. S. Department of Energy.

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