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# MECHANICAL DESIGN ASPECTS OF THE LIBRA-SP LIGHT ION BEAM DRIVEN ICF POWER REACTOR

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## ABSTRACT

LIBRA-SP is a 1000 MWe light ion beam driven inertial confinement fusion power reactor design study which utilizes a self-pinched mode for propagating ions to the target. It is driven by 7.2 MJ of 30 MeV Li ions of which 1.2 MJ is in prepulse and 6 MJ in the main pulse. There are 24 ion beams in a three tier geometry of 8 beams each. The chamber is an upright cylinder with a LiPb pool in the bottom and a flared extended roof. The blanket zone consists of solid ferritic steel tubes at a 50% packing fraction containing LiPb breeding material. The LiPb empties into the bottom pool and then flows through heat exchangers in the base of the reactor. The two front rows of tubes are called PERIT units (PErforated RIgid Tubes) and are at a distance of 4 m from the target. The front row has nozzles on its sides which spray vertical fans of liquid completely shadowing the tubes with a thin layer of liquid lithium lead and protecting them from x-rays and target debris. The deposition of the x-rays and debris ions in the liquid layer causes an explosive expansion which blows a small amount of vapor into the middle of the chamber, drives a shock through the liquid spray, and accelerates the bulk of the spray toward the PERITS. A computer code BUCKY[1] is used to study these phenomena. The PERIT units, which are divided into upper and lower halves, each 5.3 m long, receive a 71 Pa-s impulse at 3.9 Hz rep-rate, have a maximum displacement of 0.8 cm and reach a maximum bending stress of 13 MPa. Beam tubes which guide the beams in the self-pinched mode are curved to avoid neutron streaming to the diodes and to avoid making contact with the PERIT units. A method for supporting these beam tubes and remotely aligning them on target will be discussed.

## I. INTRODUCTION

The LIBRA (Light Ion Beam ReActor) series of studies has been evolving since the mid-1980s and has gone through several iterations primarily driven by the mode of beam propagation. The beam transport evolution went from laser beam channel formed ion path to the target, to a ballistic mode of transport, and finally to the self-pinched mode utilized in LIBRA-SP. In this mode, the channels are formed by the portion of the ion beam current that is not neutralized by the background gas. Thus, the net current in the beam forms an azimuthal magnetic field which confines the ions in a self-pinched configuration. There are several advantages to this mode; no laser guide beam needed, no magnets inside the target chamber and high transport efficiency. Another aspect which is useful in this mode is that the beams can be bent to follow narrow tubes, thus making it possible to penetrate the blanket region and mitigating the problem of neutron streaming to the diodes.

Another innovation which is being developed for LIBRA-SP is the PERIT (PErforated RIgid Tubes) concept of first wall (FW) protection. In this scheme, the front rows are composed of solid metallic tubes which have nozzles built into the sides capable of spraying vertical fans of liquid lithium lead, completely shadowing the exposed areas of the blanket. This spray intercepts the x-rays and ion debris emanating from the target and protects the blanket components from intense pulses of energy deposition. The computer code BUCKY[1] has been used to study the resulting vapor and shock dynamics, and determine the impulse that the front tubes have to deal with in a steady state mode at the reactor repetition rate.

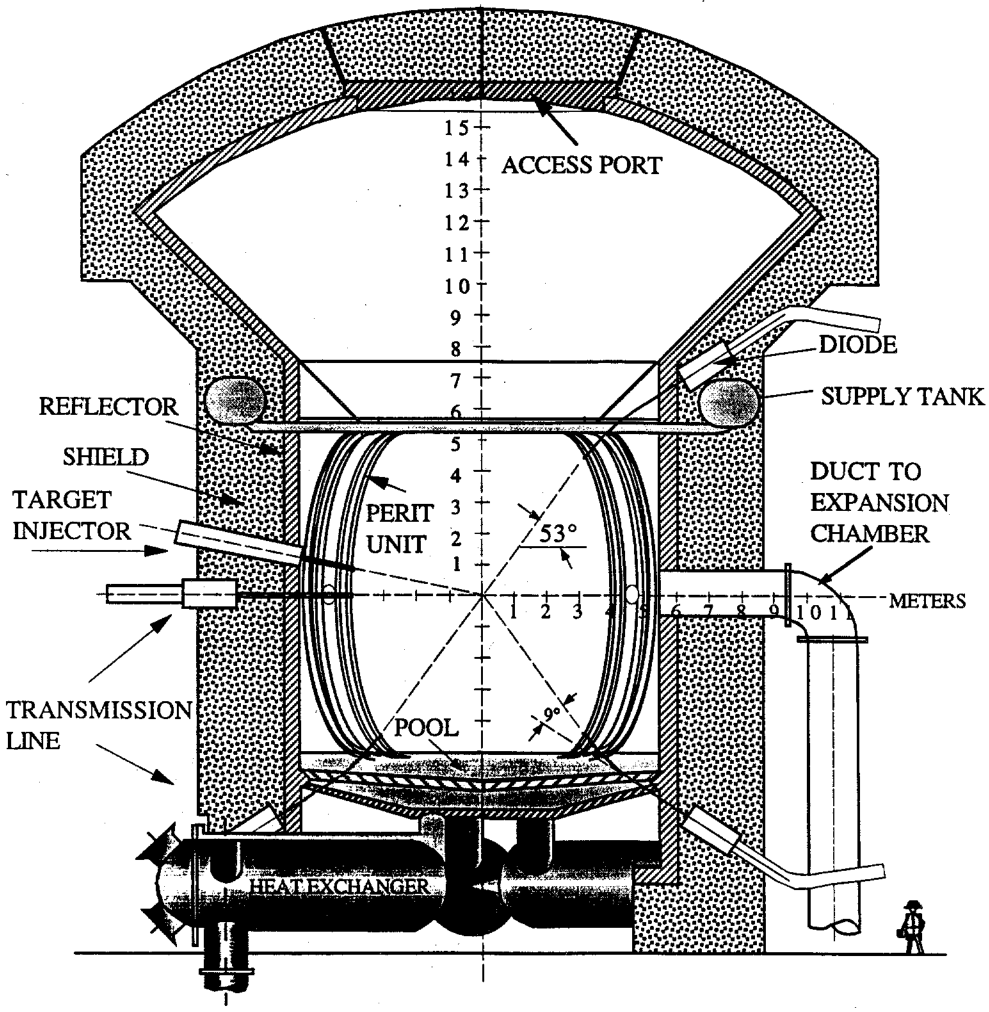

Fig. 1. Cross-sectional view of the reactor chamber.

## II. OVERALL REACTOR CHAMBER DESCRIPTION

Figure 1 is a cross-section of the LIBRA-SP reactor chamber. There are 24 ion beams in the reactor divided into a three tier geometry of 8 beams each. The beam tubes in the figure are shown curved to mitigate neutron streaming to the diodes. The energy on target is 7.2 MJ from 30 MeV Li ions, of which 1.2 MJ are used for prepulse. The active chamber is an upright cylinder 10 m high, has a LiPb pool in the bottom and a flared extended spherical roof. When the extended roof and the lower part of the chamber below the pool are included, the chamber height is 30 m. The vertical sides of the active chamber contain a blanket zone consisting of rigid HT-9 (ferritic steel) tubes, 15.6 cm OD at a 50% fill fraction. These tubes, which are shown curved in Fig. 1 to conform to the spherical target blast, transport LiPb which cools the chamber and breeds $T_2$. Another function of the blanket is to provide protection for the 50 cm thick ferritic steel reflector which is a lifetime component of the chamber and acts as a vacuum boundary. The two front rows of tubes, called PERIT units, are at a radius of 4 m from the chamber center and are 7.4 cm and 8.5 cm OD, respectively. The front row of PERIT units is equipped with special nozzles down the sides which spray overlapping vertical fans of liquid, completely shadowing the tubes from the x-rays and ions emanating from the target. 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. Since the roof will be cooled, it will always condense vapor in the form of a wetted surface, which will evaporate after each shot. A pool of LiPb in the bottom of the chamber protects the lower structures and provides adequate shielding so as to make them lifetime

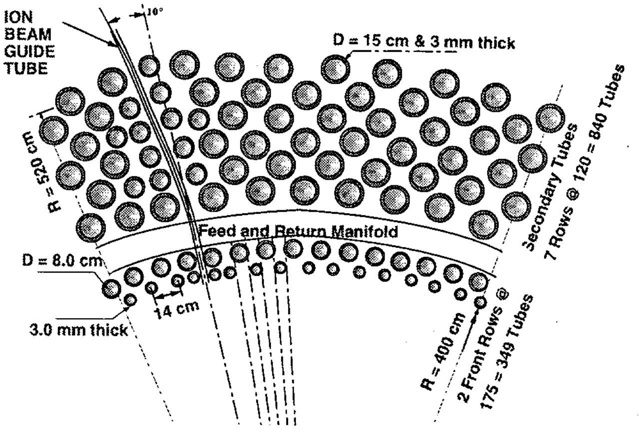

Fig. 2. The distribution of PERIT units and the shield/blanket zone.

components. The chamber is surrounded by a steel reinforced concrete biological shield nominally 2.7 m thick. Coolant is supplied to the free surface tanks located near the start of the flared roof. From there the coolant flows by gravity through the PERITS and through the blanket tubes, ending up in the bottom pool. The pool drains through a perforated plate into a sump leading to three intermediate heat exchangers (IHX) located in the base of the chamber. The thermal hydraulics for this chamber are discussed in a companion paper[2] in these proceedings.

## III. PROTECTION FROM THE TARGET BLAST

Two forms of protection are needed in an ICF reactor against the target blast. The first is a means of mitigating the effects of x-rays and ion debris on the components in direct view of the blast, and the second is shielding components from neutron effects. PERIT units perform the first means, but play no role in the second. The neutronics of the chamber is covered in a companion paper in these proceedings.[3]

Figure 2 is a midplane cross section of a segment of the reactor chamber showing the two rows of PERIT units and the larger secondary tubes which constitute the blanket. Figure 3 is a top view and side view of three PERIT units. The side view in Fig. 3 shows the overlapping vertical fan sprays jetting from the front row of tubes and the top view shows the direction of the spray. These figures show how the overlapping spray fans completely shadow the structural components of the blanket. The x-rays and ion debris are intercepted by this thin layer of liquid LiPb and thus do not deposit their energy directly onto the tubes. Instead, some of the liquid evaporates and causes an explosive expansion, which blows a small amount of vapor toward the chamber center, driving a shock through the liquid spray and accelerating the bulk of the spray into the PERIT units. The spray remains mostly intact as it undergoes this process. This delayed and attenuated impulse, when it arrives at the PERIT units, produces a reduced impact on these units. The hydrodynamic motion and energy transport in a fluid code BUCKY,[1] which uses one-dimensional Lagrangian mesh to model the processes, is used to study the phenomenon. Target x-rays and ion debris are applied as time-dependent sources from one side of the mesh. Equation of state and opacities for high temperature plasmas are provided using calculations which have detailed atomic models.[4] The results of the target simulations on the slab geometry are then normalized to provide the proper fluence and flux per unit area at the surface of the PERITs. It turns out that the velocity with which the spray is driven into the PERITs is $1.8 \times 10^4$ cm/s, the shock wave velocity is $5.7 \times 10^4$ cm/s, the peak pressure on the PERITs is 11 GPa and the impulse pressure is 71 Pa-s. This information is then used to determine the mechanical response of the PERIT units.

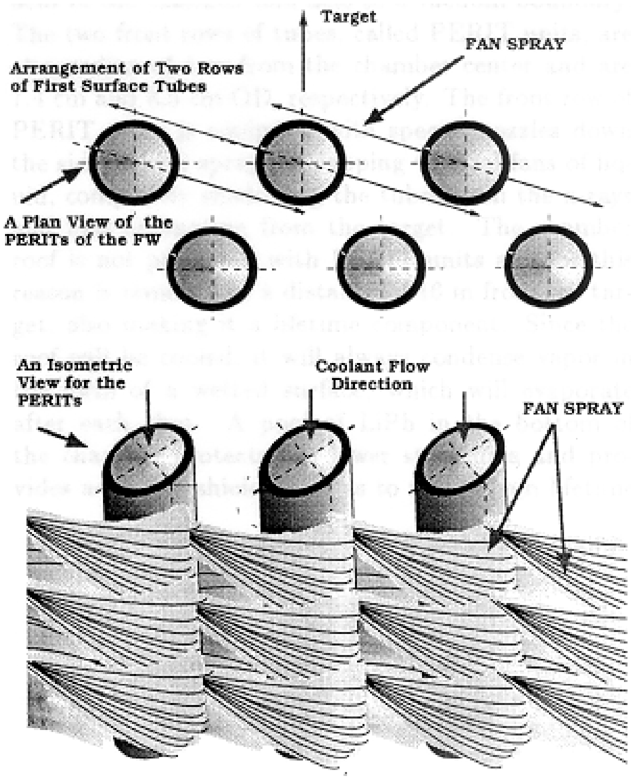

Fig. 3. First surface protection by fan sheet spray.

## IV. DYNAMIC RESPONSE OF THE PERIT UNITS

Analysis of the dynamic response of the PERIT units is very important to determine stresses, fatigue and the geometric spacing needed to allow for displacement of the tubes during steady state operation at the prescribed frequency. The first two rows of PERIT units will be subjected to the 71 Pa-s impulsive pressure following each target explosion and their primary response will be a radial planar displacement. Under certain operating conditions the tubes can perform a "whirl"; however, it is assumed that these gyrations will not exceed the radial displacements of the planar kind.

A detailed description of the equation of motion for the tubes and a modal solution of the equation for arbitrary boundary conditions can be found in Ref. 5. It is assumed that the pressure is applied uniformly over the length of the tubes and the effects of the moving liquid are neglected because of the low velocity. The fluid adds mass to the tubes but has no effect on the rigidity. Rayleigh damping was used to model internal structural damping and external viscous damping was neglected. The damping ratio of the fundamental natural frequency was set at 0.5% and two boundary conditions have been examined: pinned-pinned and clamped-clamped. In the analysis some of the parameters were set to satisfy neutronics and heat transfer requirements, but within certain limits, the length of the tube remained as a design parameter to be optimized. Figure 4 shows the results of the parametric studies to determine the necessary tube length in order to avoid resonant conditions and minimize deflections and bending stresses. The figure shows the midspan radial deflection of the front row of PERITs as a function of reactor rep-rate for a pinned-pinned tube of 5.3 m length. The maximum allowable displacement of 3.5 cm set by interference considerations and the yield strength of 250 MPa for HT-9 at 550°C are shown on the graph. At the reactor rep-rate of 3.88 Hz, the absolute displacement of the tube midspan of 0.8 cm is well below the allowable limit. The maximum bending stress is 13 MPa leaving a healthy margin relative to the yield strength of HT-9 at 550°C. The datapoints on the curve were obtained with a finite element model used to verify the results of the modal solution. The figure shows the frequencies at which resonant conditions dominate. The largest peak occurs at the fundamental frequency and the peaks to the left are harmonics. A change in the length of the tubes will shift the peaks. This is one of the advantages of rigid tubes, their length will not change with time.

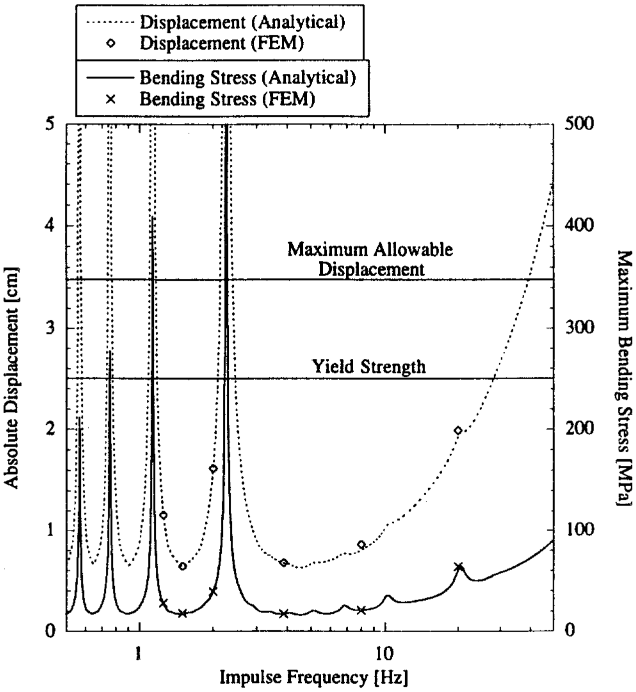

Fig. 4. Maximum steady state midspan displacement and bending stress of a pinned-pinned PERIT unit.

## V. BEAM TUBE SUPPORT AND ALIGNMENT

The five basic requirements in the support scheme for the beam tubes are: they should be supported independently from the PERIT units; the supports must be rigid to minimize displacements; the beam tubes must be cooled; they should be capable of remote alignment and they should be compatible with PERIT unit maintenance. Several schemes have been investigated and one has been selected that comes the closest to satisfying these requirements.

Figures 1 and 2 show how the beam tubes are bent to avoid interference with the PERIT units and to avoid neutrons streaming to the diodes. Figure 5 shows the support scheme for the beam tubes. In this support scheme there are two concentric tubes, an inner tube which is the beam conduit and an outer tube which is the stiffener and support member. The outer tube is attached rigidly to the reflector and is equipped with a stiff omega bellows while the inner tube is flexible enough to permit minor deflections. In the annular space between the tubes there will be three rods spaced on an equilateral triangle with LiPb coolant circulating around them. The rods will be remotely driven from behind the reflector, providing a three point adjustment capability such that the guide tube end can be manipulated over the whole range of

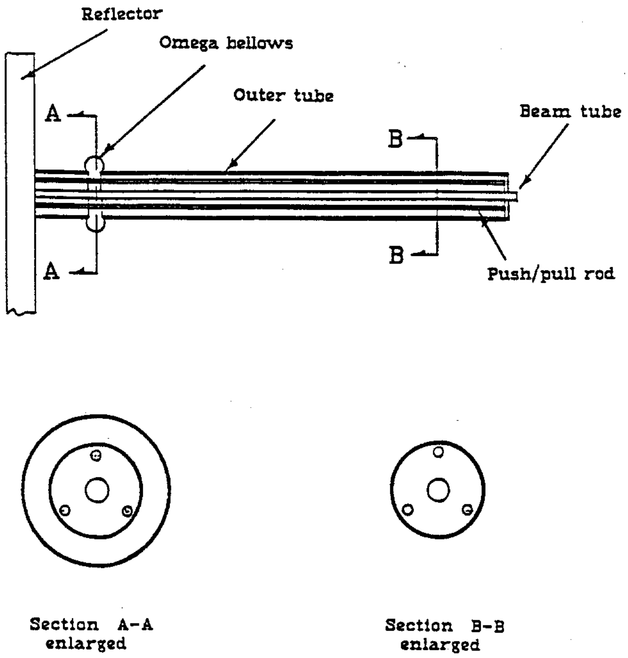

Fig. 5. Support and alignment scheme for beam guide tubes.

possibilities. Once the beam leaves the guide tube it follows a straight trajectory to the target. Ultimately, it is the aiming of the guide tubes which determines how accurately the beams converge on the target.

Alignment of the beams during periodic shutdown is crucial to the operation of the reactor, and for this reason a remote method for performing the adjustment has been devised. In this method, a spherical target, the same size as a regular target, but built as a calorimeter is inserted on a stem in the center of the chamber. Each beam is then fired individually at a small fraction of its power and a computer controls the beam tube adjustment to maximize the reading on the calorimeter. The process is repeated until all the beam tubes are aligned. Since there can be no active control of the beams during the target delivery, this scheme depends on the target being at the precise center of the chamber when the beams are fired. It also means that the beam tubes cannot deviate from their adjusted locations by more than a fraction of a percent. Stability of this support scheme and the dynamic response of the beam guide tubes is yet to be investigated.

## VI. SUMMARY AND CONCLUSIONS

A new method for first surface protection in ion beam driven inertial confinement fusion reactors is presented. This method depends on the use of rigid steel tubes which spray vertical fans of liquid LiPb and totally shadow the structural components of the blanket from target emanations. The use of rigid tubes eliminates the problem of the earlier flexible tubes which could elongate with time and thus deviate from the prescribed design parameters. A method is presented for supporting the ion beam tubes which guide the self-pinched beams through the blanket. Since active beam adjustment during operation is not possible, a scheme is presented for remotely aiming the beams during reactor shutdown. The combination of a new self-pinched mode of beam transport, the new first surface protection and the beam tube support and adjustment capability has considerably enhanced the attractiveness of ion beam driven inertial fusion power reactors.

## ACKNOWLEDGEMENT

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