Light Ion Fusion Target Development Facility Preliminary Design

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February 1985

UWFDM-627

Presented at the Sixth Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, 3-7 March 1985; Fusion Technology 8, 1895-1900 (July 1985).

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ABSTRACT

The Light Ion Fusion Target Development Facility (TDF) is expected to test approximately ten targets per day having yields in the 50 to 800 MJ range. This large number of high yield microexplosions creates design problems in the TDF that are not present in PBFA-I and PBFA-II. The TDF would be the first light ion facility where radioactivity in the target debris and induced in the facility itself constitute a biological hazard. It must have a first wall and a target diagnostics package that can survive repeated mechanical and thermal pulses from the target microexplosions. In addition, the repetition rate is much higher than for present day light ion beam drivers. A preliminary conceptual design for the TDF including a reaction chamber, biological shield, target diagnostics package and driver that addresses these and other problems is presented.

INTRODUCTION

The Light Ion Fusion Target Development Facility (TDF) is proposed to test ten fusion targets per day with yields from 50 to 800 MJ, over a period of five years. The basic philosophy is to provide a driver capable of supplying 5 to 10 MJ of ion energy over a span of 10 to 15 ns on target, so that target designers can have excess energy available and work downwards in energy and upwards in gain. The large number of high yield shots that would occur in the TDF make it very different from the experiments that precede it (PBFA-I and II). The unique areas of concern include first wall fatigue and erosion, fusion neutron induced radioactivity, survival of a target diagnostics package for many shots and reliable performance of the driver and diodes over many shots.

The preliminary design includes features that are meant to address these problems. These design features are (1) a woven high temperature ceramic thermal liner to protect the first wall from the heat pulse of the fireball and to trap the radioactive target debris for periodic removal, (2) a first wall designed to withstand the fatigue induced by the shock of the blast wave according to conservative ASME code predictions, (3) a similar thermal shield and thick plate on the target diagnostics package to protect the instruments inside for 50 shots, and (4) a borated water radiation shield and remote maintenance procedures that allow operation and periodic removal and replacement of the thermal liner in the presence of the induced radioactivity. A preliminary design for a light ion beam driver that is capable of supplying up to 10 MJ of ion energy is also included.

TARGET DEVELOPMENT FACILITY DESIGN

The TDF is depicted in Fig. 1. The reaction chamber sits under 3 meters of water shield and inside the Target Chamber Access Room (TCAR). Each of these serve as biological shields to the radioactivity induced in the reaction chamber and as tritium barriers. The TCAR has a polar crane which is separate from the crane system for the rest of the facility, to avoid extremely long crane spans. Equipment would be moved into and out from the TCAR through an air tight door that is not shown. The target injector is accessed from the TCAR operating floor and the target chamber is accessed through a service port that is normally filled with water.

The TDF driver, Fig. 2, relies to a large extent upon the direct extension of pulsed power technology utilized in PBFA-II. Conventional Marx generators will be used for prime energy storage and intermediate storage and pulse forming will be done in water. Synchronization of the different lines will be done with laser triggered gas switches and a vacuum voltage adder will be employed. Magnetically insulated transmission lines (MITL's) and plasma erosion opening switches (PEOS's) will be used in the design. The magnetic switching technology developed for PBFA-II will be extended for use in

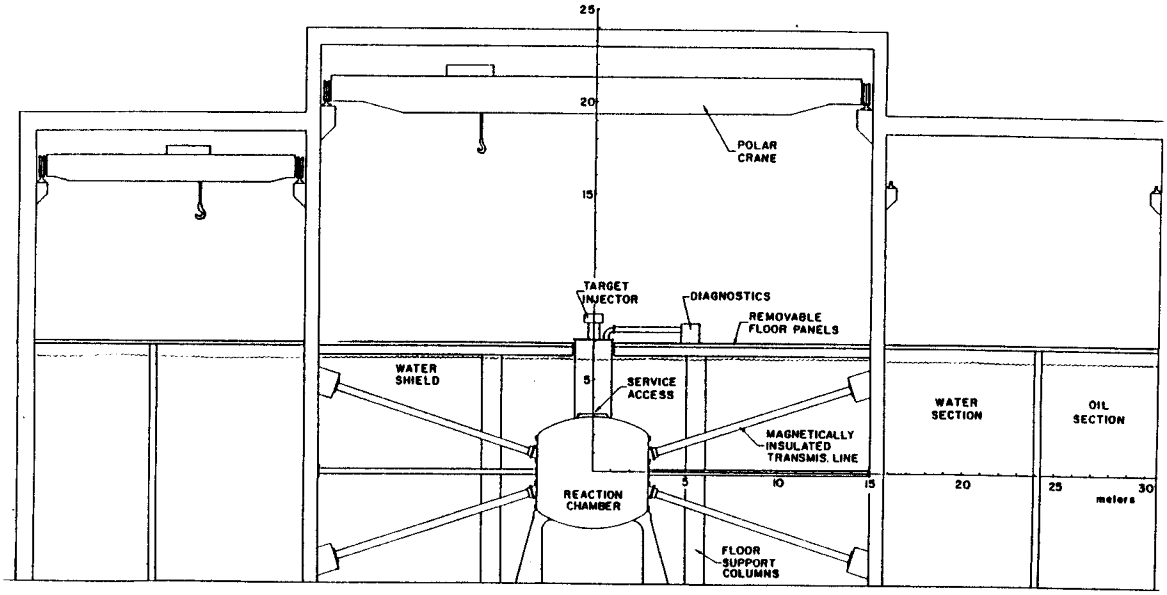

Fig. 1. Overall View of Target Development Facility.

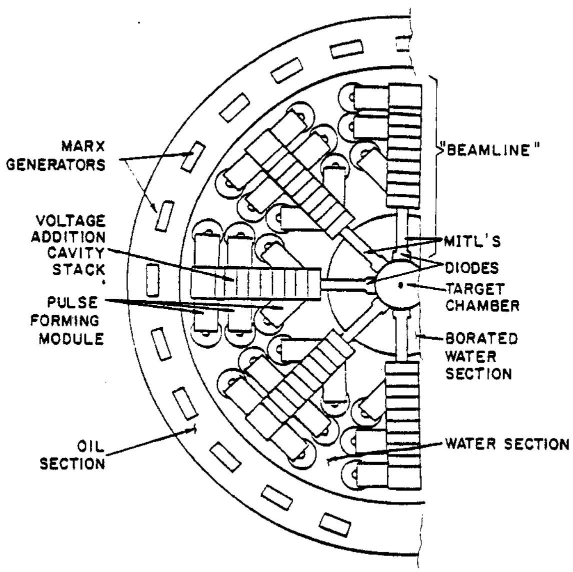

Fig. 2. Overhead View of the Pulsed Power Driver.

the TDF nontriggered switching. Parameters for the TDF driver are given in Table I.

Table I. TDF Driver Parameters

Marx Voltage	10 MV
Energy per Marx	2.4 MJ
Number of Marxes	24
Number of PFL's	48
PFL Output	360 KJ/module
Energy to Diodes	14 MJ
Diode Efficiency	80%
Pulse Compression in Channels	2
Channel Efficiency	80%
Final Pulse Width	15 ns
Energy on Target	7-8 MJ

Up to 58 MJ can be put into the prime energy store. Thus the overall efficiency from the wall plug to the diodes is about 25% so that about 56 MJ must be put into prime storage. Each of the 8 lines contains three 10 MV Marx generators for prime storage, each with 2.4 MJ. The Marx generators feed into first coaxial PFL's terminated with the metglas magnetic switches and then into the second smaller PFL's, which are also terminated with magnetic switches. Here the energy flows into the voltage adders and then into the MITL's. At the end of the MITL's, and, possibly within the voltage adder, PEOS's compress the pulse to 30 ns and feed the energy into the ion diodes.

The ion diodes must be able to survive many shots. Since they are assumed to be 80% efficient and each receives 1.75 MJ from the pulsed power lines, 440 KJ must be dissipated in each diode on each shot. Much of this energy will be in the form of energetic electrons in the region close to the anode. The electrons and the x-rays that they emit will be mainly directed onto the anode. Liquid metal anode surfaces such as lithium offer the possibility of dissipating this heat load. The details and analysis of such a diode await further study.

Each of the 8 diodes focus their ions onto preformed plasma channels that bring the ions the final 3.5 meters to the target. The diodes are designed with a ratio of their radii to their focal lengths of about 0.1. It has been found that, if the beam ions are 30 MeV Li, a divergence of 0.1 radians is close to an optimum for propagation of the beam in the plasma channels. It is assumed that the energy loss in the channels is 25%, putting 7 to 8 MJ of energy to the target end of the channels. It is not yet known how much of this energy reaches the target itself. During their transit of the channel, the beam pulses are compressed to 15 ns, giving a total power at the end of the channels of about 500 TW.

The reaction chamber with a thermal shield and the in-vessel diagnostics package are shown in Fig. 3. Parameters for the reaction chamber are listed in Table II. The first wall of the reaction chamber has been designed according to ASME Boiler and Pressure Vessel Code fatigue lifetime guidelines to withstand the mechanical loads of 15,000 target microexplosions of 200 MJ nominal yield.[1] The wall design consists of a cylindrical shell with external reinforcing rings. Fatigue lifetime estimates including weld strength degradation have been made for both Al-6061-T6 and 2-1/4 Cr-1 Mo steel walls. This represents an improvement over previously reported work where the effects of welds were not included.[2] The maximum overpressure experienced by the wall was estimated using the MFFIRE radiation hydrodynamics code for microexplosions in 13.6 torr of nitrogen gas in the chamber[3] (0.64 MPa for a 200 MJ microexplosion). This overpressure value was used along with the detailed pulse shape to determine the fatigue lifetime of walls of varying thickness. This fatigue lifetime analysis was also done for an overpressure value of twice this best estimate to account for uncertainties in the hydrodynamics calculations. These results are summarized in Table III. In addition to the 15,000 shots at 200 MJ there is the potential of testing a limited number of very high yield targets in the 800 MJ range. The wall thickness required to accommodate 200 of these additional very high yield shots is also given in Table III. While the steel wall can be designed to easily manage these 800 MJ shots, the aluminum wall cannot meet ASME code guidelines for any reasonable thickness. This is due to the severe penalty taken for strength degradation due to welds in aluminum.

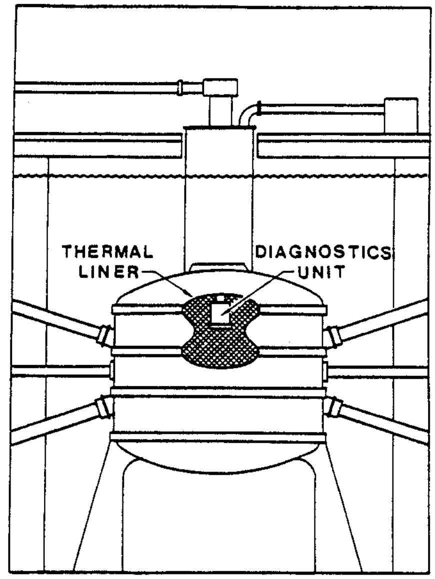

Fig. 3. Reaction Chamber with Thermal Liner and Diagnostics Package.

In order to prohibit thermal damage to the first wall due to the pulse of heat from the target generated blast wave and to allow the first wall mechanical response to be computed using room temperature properties, a thermal shield of the high temperature woven ceramic NEXTEL is attached to the inside surface of the target chamber.[4] This material has a melting point of 2073 K and a thermal conductivity of 5.1×10^{-4} W/cm-K. In order to be conservative, the thermal pulse is treated as an instantaneous surface load containing all of the non-neutronic energy released by the target. A finite difference heat transfer computer code is then used to find the time dependent temperature profiles in the NEXTEL liner. For the nominal design parameters, the maximum temperature reached in the liner is 1500 K. The heat capacity of the liner is sufficient to reduce the heat transfer to the metal first wall to a negligible level. With one hour between shots the whole system returns to room temperature before the next microexplosion.

The response of preformed plasma channels to the target explosion generated microfireball is important to the design of the reaction chamber to determine whether the channel focuses the microexplosion energy onto the wall or diodes. Hydrodynamics simulations have been used to determine the axial and radial behavior of the channel-microfireball system. It has been found that the radial heat transfer out of the channel is an important energy loss for the axial propagation of the fireball but that radial expansion is too slow to affect the axial heat transfer.[5]

Table II. Target Development Facility Chamber Parameters

Target	
Nominal Target Yield	200 MJ
No. of Nominal Yield Shots per Day	10
Maximum Target Yield	800 MJ
No. of High Yield Shots Over Service Lifetime	200
Target Chamber	
Target Chamber Diameter	6 m
Target Chamber Height	6 m
Wall Material	Al 6061 2-1/4 Cr-1 Mo steel
Wall Thickness	14.8 cm (Al)* 4.7 cm (steel)
Liner Material	NEXTEL
Liner Thickness	1 cm
Gas Type	Nitrogen
Gas Density	2.25×10^{-5} g/cm^3
Fatigue Lifetime	15,000 shots
Service Lifetime	5 years
Radiation Dose at Outside Edge of 1st Wall 1 wk After Shutdown	1.5 rems/hr (Al) 35.4 rems/hr (steel)
Shielding	Borated Water
Diagnostics Package	
Distance from Target	1 m
Length of Package	1 m
Diameter	30 cm
Thermal Protection Material	NEXTEL
Thermal Protection Thickness	2 cm
Front Plate Thickness	5 cm

*No extra 800 MJ shots allowed for Al.

Table III. First Wall Thickness for Welded Al and Steel Walls

	Al 6061	2-1/4 Cr-1 Mo
15,000/200 MJ shots		
Best est. ΔP (0.64 MPa)	7.0	3.0
2 x best est. ΔP (1.28 Mpa)	14.8	3.5
200 Additional 800 MJ shots		
Best est. ΔP (2.96 MPa)	---	3.0
2 x best est. ΔP (5.92 MPa)	---	4.7

Much of the energy in the channel after the explosion is due to ion beam heating of the channel during propagation of the ion beam from the diode to the target.

The TDF chamber will experience a neutron fluence of 4.8×10^7 n/cm^2 over its lifetime. This is not large enough to pose radiation damage concerns; however, the radioactivity induced in the structure of the facility and in the target debris poses a serious obstacle to hands-on maintenance. In order to analyze the problem of radioactivity, neutronics, activation and photonics calculations have been carried out to determine the biological dose rate at various points in the facility.[6] Calculations have been completed for targets made of Au tampers with plastic pushers and W tampers with BeO_2 pushers and first walls made of Al 6061 and 2-1/4 Cr-1 Mo steel. Shields of borated water and concrete have been considered as have temporary lead shields that would be inserted before maintenance is attempted. In all cases, the doses are calculated for 1 full power year of operation which contains 3120 shots.

These calculations have shown that the condensable target debris can be an important part of the dose rate inside the reaction chamber. At 1 week following shutdown the activated Au represents a dose rate of 15 rem/hr while the Al first wall contributes only 4.3 rem/hr inside the first wall surface. Other combinations of first wall material and target constituents lead to different results. Therefore, periodic removal of the thermal liner, which will catch the condensable target debris, can significantly lower the dose rates. The dose rates outside the chamber depend mainly on the choice of first wall material. At 1 day after shutdown, a wall made of the Al alloy has a higher dose than the steel, 361 rem/hr as compared to 38 rem/hr. After a few days the situation is reversed. The dose rate 1 week after shutdown at the outside surface of the wall is 1.5 rem/hr for Al and 35.4 rem/hr for steel. On the operating floor of the TCAR the dose rate is 11 mrem/hr for the Al chamber design and 23 mrem/hr for the steel chamber at shutdown. One day after shutdown these values are reduced to 0.31 mrem/hr and 2.3×10^{-4} mrem/hr, respectively.

A diagnostics package[8] placed as close as possible to the exploding targets will allow diagnostics to be exposed to very high instantaneous fluxes of neutrons and gamma rays, Fig. 3. Of course this means that the surface of the package facing the target will encounter very high heat fluxes and shock pressures. A design goal of 50 shots before change-out of the diagnostics package will allow it to reside in the chamber for a week of operation. Evaporation calculations indicate that a 2 cm thick pad of NEXTEL will protect the package for 50 shots. At 1 meter from the target a 30 cm diameter face plate of Al or steel must be 5 cm thick to avoid yielding under the 20 MPa overpressure.

The thermal protection pad and steel plate severely alter the target spectra. The gamma flux inside the diagnostics package is 100 times greater than the incident flux due to neutron interactions in the face plate and first wall. It may be possible to put small thin spots in the thermal pad and steel plate that would allow purer target spectra to reach the diagnostics but this has not been analyzed.

Maintenance problems pertaining to the reaction chamber have been examined. Remote removal and replacement of the thermal liner is a crucial item. The liner may have trapped large amounts of radioactive target debris in its fabric during the operation of the facility. An umbrella type device has been designed that could be used to insert the liner and press it up against the wall. The liner could be held on the wall with a metal "velcro" that could be fastened with pressure and removed with pulling by the umbrella. The liner would be put into and removed from the chamber via the service access. Once the used liner has been removed from the service access, it will be held in the TCAR. The TCAR is shielded and provides an additional tritium barrier and is shown in Fig. 1. While the used liner is in the TCAR it will be compacted and put into a shielded capsule in which it can be transported to a suitable disposal facility.

Rapid access to the diodes located at the outside of the first wall is essential for such a test facility. To access the diodes, the water shield must be lowered and a lead shield installed between the first wall and maintenance personnel. This lead shield must be 12 cm thick to reduce the dose rate to 2.4 mrem/hr at shutdown for the steel chamber and 22 cm thick to reduce it to this level for the aluminum chamber.[6] A detailed diode maintenance procedure awaits further definition of the diode design. Unless the diodes can be constructed from very low activation materials, they will likely produce dose rates, on contact, that are comparable to the first wall. As a completely different alternative, a permanent concrete shield of 250 cm thickness would reduce the dose rate to this same value at the edge of the shield.

The cost of the reaction chamber vessel has been estimated for the point design for walls made of both steel and aluminum. The Al 6061 first wall is somewhat more expensive than the 2-1/4 Cr-1 Mo steel at 6.1 M$ compared to 3.3 M$. These costs are broken down in Table IV. One can see that the fabrication costs make aluminum more costly even though the material costs are higher for steel. For either case, the costs are small compared to that of the whole facility. The costs of the thermal liner are as yet unknown.

CONCLUSIONS

Preliminary conceptual design studies of the light ion fusion target development facility have led to four viable target chamber and shielding combinations. A conservative design of the target chamber first wall that greatly reduces the number of welds over previous designs and conforms to the fatigue lifetime criteria of the ASME Code has been completed for both Al-6061-T6 and 2-1/4 Cr-1 Mo steel. Both designs are acceptable for 15,000 shots at 200 MJ. However, should additional 800 MJ shots be desired, only the steel design can accommodate these higher stresses without yielding. Activation and radiological dose calculations have been done for both wall designs including the accumulation of condensable target debris on the inner surface of the first wall. For times less than 1 week the aluminum structure has a much higher dose rate than the steel structure. At 1 week this situation reverses as the aluminum activation products decay. This leads to the conclusion that a steel structure is more suitable for a test facility where access is required in less than 1 week after shutdown. If one could allow a 1 month cool-down time following shutdown then the aluminum structure would permit limited hands-on maintenance. A 3 meter water shield provides adequate biological shielding for personnel access to the operations floor above the chamber.

An 8 beam pulsed power driver has been designed to provide 14 MJ to the diodes in a 30 ns pulse. The technology of this pulsed power machine is based upon modest extrapolation from PBFA-II technology. Bunching in the channel reduces the pulse length to 15 ns. It is assumed that about half of this energy reaches the target although this awaits further detailed analysis. It is expected that 7-10 MJ of energy is adequate to achieve a starting point from

Table IV. Target Chamber Costs

	Al 6061	2-1/4 Cr-1 Mo
Wall Thickness (cm)	14.8	3.5
Volume (cm^3)*	4.33×10^7	9.99×10^6
Density (g/cm^{-3})	2.7	7.75
Mass of Wall (kg)	1.17×10^5	7.74×10^4
Unit Bulk Cost ($/kg)	1.8	18
Cost of Materials in First Wall ($)	2.1×10^5	1.4×10^6
Unit Fabrication Cost ($/kg)	50	25
Fabrication Cost for First Wall ($)	5.9×10^6	1.9×10^6
Total First Wall Cost ($)	6.1×10^6	3.3×10^6

*Hemispherical caps and support structure included.

which target designers can work towards high gains with reduced on target energies.

A target diagnostics package placed 1 meter from the target can be designed to withstand 50 200 MJ shots using a 2 cm NEXTEL heat shield and a 5 cm thick steel plate as the face plate. The gamma flux within the package is 100 times greater than the unattenuated target flux due to neutron interactions in the package and the first wall.

ACKNOWLEDGEMENT

This work has been supported under contract to Sandia National Laboratory and the U.S. Department of Energy.

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4. NEXTEL is the trade name for 3M's high temperature ceramic fibers made from 62% Al_2O_3, 14% B_2O_3, and 24% SiO_2.

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