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A Lower Cost Development Path for Heavy Ion Fusion

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SUMMARY

If two features of the inertial fusion process are exploited successfully, they can lead to significantly lower costs for demonstrating the feasibility of commercial electric power production from this source of energy. First, fusion capsule ignition and burn physics is independent of reaction chamber size and hydrodynamically-equivalent capsules can be designed to perform at small yield, exactly as they do at large yield. This means that an integrated test of all power plant components and feasibility tests of various reaction chamber concepts can be done at much smaller sizes (about 1-2 m first wall radius) and much lower powers (tens of MWs) than magnetic fusion development facilities such as ITER. Second, the driver, which is the most expensive component of currently conceived IFE development facilities, can be used to support more than one experiment target chamber/reactor (simultaneously and/or sequentially). These two factors lead to lower development facility costs, modular facilities, and the planning flexibility to spread costs over time or do several things in parallel and thus shorten the total time needed for development of Inertial Fusion Energy (IFE). In this paper we describe the general feature of a heavy ion fusion development plan that takes advantage of upgradable accelerators and the ability to test chambers and reactor systems at small scale in order to reduce development time and costs.

1.0 OVERVIEW OF THE HEAVY ION FUSION DEVELOPMENT PATH

Following up on earlier work [1], the Lawrence Livermore National Laboratory (LLNL) has been conducting a study of lower cost development scenarios for heavy ion driven IFE. As envisioned here and illustrated in Fig. 1, the demonstration of heavy ion fusion would require the construction of the following facilities: a National Ignition Facility (NIF), driven by a laser, to demonstrate target ignition and gain; in parallel with this, both the Induction Linac Systems Experiments (ILSE) and an Intermediate Driver Facility (IDF); an Integrated Test Facility (ITF); and a Demonstration Power Plant (DPP). An upgradable driver would be used for the IDF, ITF, and DPP.

This year we have been focusing on the objectives and design aspects of the ITF. It is the key to a low cost and rapid IFE development program. The ITF is the first facility to integrate all the major subsystems required for an inertial fusion power plant including the driver, target production and injection systems, and reactor systems (chamber, blanket, heat removal, tritium recovery, etc.).

Development Required Prior to the ITF

It is assumed that, before the ITF is built, three avenues of development concerned with target physics, driver scaling, and reactor technology will have produced positive results.

First, the NIF, with a laser driver, will have ignited targets and produced energy gains of up to 10. Other NIF target experiments will have studied energy transport in laser targets designed to simulate certain aspects of heavy ion targets in order to estimate the minimum ion energy required to ignite a target with ions. NIF experiments can also study the target manufacturing tolerances required for mass production.

Second, the driver development program will have demonstrated that an ion driver can be built with the required beam performance, high-pulse rate capability, and low-cost characteristics necessary. ILSE will address emittance growth and beam transport issues. ILSE will test concepts for all necessary beam manipulations (beam merging, bending, compression, and focusing) at significant scale. ILSE may also investigate recirculating induction accelerator (RIA) issues. The IDF that follows ILSE will prove that an affordable driver can be built and operated as expected. It will be an end-to-end test of a 100-400 kJ driver. The IDF will provide an engineering demonstration of longitudinal instability control, give the first beam/target physics experiments with a heavy ion driver, provide validation of engineering performance, and give high confidence for the design of the ITF driver.

Third, a reactor technology program, using the above and other existing facilities will have demonstrated certain reactor technologies. These will include target injection and tracking, beam steering, and reactor/driver interface systems. Using the output of ignited targets, NIF experiments will be able to characterize radiation, shock, and debris effects on various first wall candidates and on driver/reactor interface systems providing the data necessary to design multiple pulse experiments for the ITF.

The Integrated Test Facility

The ITF, illustrated schematically in Fig. 2, is the key to a low cost and rapid IFE development program. The ITF will be designed with an upgradable heavy ion driver whose initial energy will be just above the threshold for ignition. In fact, the ITF driver could simply be an upgrade of the IDF. Multiple experimental chambers are envisioned, operating in parallel if the minimum time development program is desired. Initial

experiments will demonstrate the first ignition with an ion driver using a fixed-position, minimal-ignition, low-yield target. Following experiments will ignite a target "on the fly." Next, multiple-shot, low-yield experiments will be done in a burst mode to determine the pulse rate achievable in various reaction chamber concepts. Finally, longer duration experiments will demonstrate steady thermal power production and removal. With low yield targets, even these last experiments can be done at estimated power levels of 50 to 100 MW_t. Targets for these burst-mode tests would be initially produced in a batch mode. As the technology for continuous manufacture improved and the need for longer duration tests grew, this technology would be incorporated into the experiments.

At this point, the ITF will have met all the objectives of a Pilot Plant [2], which are to

- 1) Demonstrate proof-of-principle of a new technology;
- 2) Integrate, for the first time, all required systems together at some scale;
- 3) Establish, at low cost and small scale, the technical feasibility of the concept; and
- 4) Demonstrate that the technological steps to a DPP will primarily consist of scaling up from the Pilot Plant.

Demonstration Power Plant

In parallel with the ITF chamber experiments and prior to the DPP, experiments will be done to improve target gain to that necessary for an ηG (driver efficiency-gain product) large enough to reduce the driver power requirement to an acceptably low value (typically $\eta G > 10$). These will be done in a separate, low pulse rate (i.e., a single shot) chamber with a fixed target position but capable of higher yield. Achieving this goal may

require that the driver energy be increased over that initially required for ignition and minimal gain. This is the reason for requiring an upgradable driver design.

If, however, the required ηG can be achieved with the ITF driver, and if the long duration, low power chamber tests are successful, an integrated, larger scale reactor could be added to the ITF driver. The power level and size of this reactor would be chosen appropriate for the last demonstrations before the first commercial plant. At this time, the ITF would *de facto* become the DPP without actually building a new separate large facility.

A DPP addresses the issues of reliability, establishes scalability from a Pilot plant, and is large enough that the step to the first commercial plant (the Prototype Plant) leaves no question about scalability. The DPP demonstrates licensibility, public acceptability, and cost viability [2].

Potential for Low Cost Development

There are several critical issues for the development path outlined above and the ability to keep the development costs as low as possible. Three such questions are: 1) How well can target experiments using a laser driver on the NIF and beam deposition experiments on the IDF determine the minimum drive energy and beam characteristics necessary for ignition of ion targets? 2) Can an affordable, upgradable ion driver with the appropriate characteristics be designed? 3) How small can the burst-mode test chambers be made and still accurately determine the pulse rate capabilities of the various chamber concepts?

The first question is beyond the scope of the present study. This paper will concentrate on the second and third questions. We have been studying the design of both

linear and recirculating induction accelerator (RIA) drivers [3] that can be upgraded in energy. We also examine the phenomenology determining chamber pulse rate and how it scales with chamber size and target yield.

2.0 UPGRADABLE HEAVY ION DRIVERS

A key to the low cost develop path for heavy ion fusion is the ability to upgrade a single driver and use it for several development facilities. In this section, we discuss options for upgrading both RIAs and Linacs. Based on current estimates of target gain, the driver for the ITF will have to deliver 1-2 MJ to the target depending on the ion that is used and the spot size that can be achieved. If targets could be designed to give net gain for driver energies of less than 1 MJ, the scale-up from the IDF to the ITF may be much less than considered here. Also, we currently estimate that about 4 MJ will be required for the DPP. This estimate depends on current projections for target gain, driver efficiency, and the ability of chambers to operate at high rep-rate. Developments in any or all of these areas could lead to changes in the driver energy required for the DPP.

Upgrading RIAs

Two possible approaches to upgrading an RIA are compared in Table 1. (The Heavy Ion Fusion Group at LLNL has also proposed other upgrade options which are not presented here.) The "D-path" is a three phase approach. The first phase is a 200 kJ, two-ring, four-beam IDF. To be used for target interaction experiments, the output beam with a pulse duration of 2.6 μ s, would have to be compressed in a linear drift compression section. To upgrade this IDF to a 2-MJ ITF driver, a third, four-beam ring

with an energy gain of 10 is added. The output pulse duration for the ITF driver is 250 ns, so less pulse compression would be needed than for the IDF.

To upgrade the ITF driver to 4 MJ, the entire 2-MJ driver is duplicated with the exception of common support facilities. If, based on the results of target physics experiments with the ITF driver, it is projected that less than a factor of two increase in driver energy is needed for the DPP, a linac section could be added to the RIA to increase the beam energy to the required value. If high enough target gain and driver efficiency are achieved with the 2-MJ ITF driver, no additional upgrade would be needed.

The estimated direct capital costs for the three stages of the D-path are given in Table 1. There is a relatively high buy-in cost for the IDF compared to the cost of the ITF driver. Two major factors contribute to this: 1) there are many fixed costs (e.g., the injector) that must be included at any energy, and 2) the cost of the pulse compression section for the IDF adds about \$60 M to the IDF cost while no additional components are needed when upgrading to the ITF driver. The cost of the 4-MJ DPP driver will be nearly double the cost of the ITF driver since almost the entire driver is duplicated.

The second option listed in Table 1 is the "C-Path" (named after the C-Design described in Ref. 3). The C-path is a two phase approach for upgrading a RIA. In this case, the first phase IDF also uses a two-ring, four-beam approach, but it would be larger, on the order of 10% of the final DPP driver energy. In the example of a 4-MJ DPP driver, the IDF would be 400 kJ. The IDF would be upgraded in a single step to a driver that would serve as the driver for both the ITF and DPP. This approach has a higher cost for the IDF and ITF, but the overall cost to provide 4 MJ is less than the three phase, D-path.

Upgrading Linacs

For an upgradable linac, the IDF and ITF are simply the first segments of the final DPP driver. Typical parameters for a sequence of a 200-kJ IDF, 2-MJ ITF, and 4-MJ DPP driver are listed in Table 2. The IDF would be only a couple hundred meters long. The output pulse duration at 500 ns would require a relatively short (~35 m) pulse compression section to do target material interaction experiments. Upgrading to 2 MJ would require adding a 2.3 km accelerator section. The final 2 MJ would require an additional 2.4 km.

We are still examining options for the site layout for the IDF, ITF, and DPP. It would be desirable to have the experimental facilities (test chamber, etc..) at the same location, especially for the ITF and DPP. This would require that segments of the longer drivers be turned and/or folded back to deliver the beams to the same location. This is not seen as a problem since beam turning will be required for two-sided target drive and for final focusing in any case.

The estimated direct capital costs are based on a 12-beam driver with singly charged Xe ions. Note that these cost estimates are not totally self-consistent with the RIA costs given in Table 1. Also, Lawrence Berkeley Laboratory (LBL) has recently proposed using higher acceleration gradients than we assumed, which would reduce the length of the 4 MJ driver from 4.9 to 3.7 km.

Unlike the RIA, which tends to upgrade in quantum of energy, the linac can add energy in small increments. Thus, the size of the DPP driver can be selected based on the results of the ITF experiments (both target physics and chamber rep-rate), and only the required amount of additional energy (if any) will be added.

3.0 SCALING CHAMBER DESIGNS

Fusion capsule ignition and burn physics are independent of reaction chamber size, and hydrodynamically equivalent capsules can be designed to perform at small yield, exactly as they do at large yield. This means that an integrated test of all power plant components and feasibility tests of various reaction chamber concepts can be done at much smaller sizes (about 1-2 m first wall radius) and much lower powers (tens of MWs) than magnetic fusion development facilities such as ITER. In this section we discuss some important considerations when scaling chamber to do simulations at low yield.

X-ray and Debris Effects in Scaled Chambers

Some of the most important effects in an IFE chamber are related to the intense energy deposition by x rays and target debris. The sudden vaporization of a thin (10's of μm) layer of the first surface causes an impulsive pressure load on the underlying material. The vaporized material fills the center of the chamber with a hot plasma that re-radiates and vaporizes more material. As this vapor cools, it condenses, and the vapor density in the chamber returns to a level that is low enough to allow the beams to propagate through the chamber for the next pulse. Understanding and being able to predict the chamber dynamics are the key to determining the maximum possible rep-rate for the chamber design, which in turn can affect the overall plant economics.

A series of CONRAD [4] calculations were carried out to examine key response functions for both full size chambers (i.e, for future commercial power plants) and small chambers characteristic of what we envision for the ITF. These calculations were conducted for three representative chamber types: HYLIFE-II [5], which features a thick

liquid (FLIBE) wall blanket; Osiris [6], which has a Flibe-filled, porous-fabric blanket; and Cascade [7], which has a flowing granular blanket (the innermost layer is carbon). The inner radius of the ITF blankets was set so that total x-ray and debris fluence per shot (J/cm^2) was the same as for the full size designs .

A summary of some key results is given in Table 3. In all cases, the thickness of material vaporized by x rays, debris, and re-radiated energy is about the same in the ITF and full size chambers. Peak pressures and impulsive loads are also very close. Although not shown here, the time dependent features of plasma temperature, radiation temperature, etc., demonstrate similar characteristics.

The final parameter listed in Table 3 is the vapor energy per unit volume within the first wall at the end of the calculation ($6 \mu\text{s}$ in these cases). This parameter is related to the pressure in the vapor and is important for the long-term mechanical response of the blanket and chamber structures to the pressure pulse. It will also affect the rate at which vapor blows through the HYLIFE-II jets and the rate at which hot Flibe vapor will be driven into the condensing pool at the bottom of the Osiris chamber.

The J/cm^3 scales $Y^{1/2}$ since the energy in the vapor is proportional to the yield, while the volume scales as R^3 , which is proportional to $Y^{3/2}$ when the first surface fluence constant is held constant.

$$\frac{E}{V} \approx \frac{Y}{R^3} \approx \frac{Y}{Y^{3/2}} \approx \frac{1}{Y^{1/2}}$$

For a 30 MJ ITF, the yield is down by a factor of 12-14 (for chamber designs we considered) and the E/V is about a factor of 3-4 higher in the small chambers. More calculations are needed to determine if a factor of 3-4 gives an acceptable simulation. We

note, however, that it will be possible in the ITF to gradually reduce the yield (by reducing the driver energy or modifying target design) and observe changes in chamber response as the first wall fluence (J/cm^2) is reduced below the values for a full scale chamber while the E/V moves closer to the value for the full size chamber. These experiments should provide enough information to allow designers to scale the results to the DPP size chamber.

Another factor to be considered in the chamber response to x rays and debris is that at very low target gain, the driver energy increases the fraction of the yield that is in x-rays and debris. This is illustrated in Fig. 3. The x-ray and debris yield of the capsule is assumed fixed at $\sim 24\%$. At high gains, the contribution of the beam energy is minimal, but as the gain approaches 1, the contribution is very large. This will be important for designs where the combination of neutrons and short range energy effects are both important; HYLIFE-II is an example.

Neutron Effects in Scaled Chambers

We have also examined how neutron energy deposition profiles change as a function of yield. Again, the inner radii of the blankets were scaled as $Y^{1/2}$. Results are shown for HYLIFE-II in Fig. 4. The exponential fall-off through the blankets is similar at all yields. The specific energy deposition (J/g), however, decreases with decreasing yield, and the fall-off is greatest for the innermost zones of the blanket. This is basically a geometric effect. To first order, a fixed fraction of the neutron energy will be deposited in a given thickness (ΔR) of the blanket. Therefore, as the yield approaches zero, the energy deposited in a fixed thickness approaches zero, while the volume of that blanket region approaches the volume of a sphere of thickness ΔR . Therefore, the effect is most

pronounced for chamber designs that have very small inner radius for the full-scale chambers.

While the J/g in the innermost zone of a low yield HYLIFE-II ITF chamber may be a factor of two lower than for the full size chamber, it is still higher than the 10 J/g needed to break up the Flibe jets. Therefore, the gross effects of jet break-up will still be observed at yields of 10's of MJ.

4.0 SCALING HEAT TRANSFER COMPONENTS.

As previously discussed, the ITF will also conduct long duration tests to examine the heat transfer and transport characteristics of the designs. These tests must be conducted at a power level that allows scale-up to DPP-size heat transfer system (HTS) components. Figure 5 illustrates one possible scenario for rolling back HTS component sizes of a commercial plant to determine what would be needed in the DPP and ITF. In this example, we assume that the commercial plant has a thermal power of 2800 MWt and has four parallel heat transfer loops supplying steam to the turbine. The DPP will only have to demonstrate a single loop and only at about 1/3 scale in power. Therefore, the DPP will operate at a power of ~230 MWt. The DPP chamber will only handle 1/12 the power of a commercial chamber. This reduced power could be obtained with somewhat lower yield targets and lower rep-rate so that each of these parameters is closer than 1/12 to the full scale plant parameters. For example, the full-scale Osiris operates at 430 MJ at 4.6 Hz. An Osiris DPP could operate at 150 - 200 MJ and 1.5 - 1 HZ for the power test. It would still be possible to do burst-mode tests at the full 4.6 Hz, but it would not be necessary to have HTS components capable of handling the higher power.

The ITF would also only test a single heat transfer loop, but at a 1/3 scale of the DPP. For this particular example, the ITF power level would be about 75 MWt. With yields of 20 to 30 MJ, this would require rep-rates of ~ 3 Hz. Again, burst-mode experiments at higher rep-rates would already have demonstrated the rep-rated capabilities of the designs. Figure 6 shows an Osiris chamber scaled to a yield of 20 MJ and thermal power of 100 MWt. The outer diameter of the vacuum vessel is only 2 m.

5.0 CONCLUSIONS

LLNL, in conjunction with LBL, industry, and university participants, has been investigating low-cost development paths of heavy ion fusion power. One of the key factors in minimizing development costs is the ability to use an upgradable driver for several development facilities. We have shown how both recirculating and linear induction accelerators can be upgraded from the IDF to drivers for the ITF and Demo. Since the driver is expected to be the major cost item, at least for the IDF and ITF, this will result in significant savings. In addition, critical chamber phenomenology (e.g., vaporization and condensation dynamics) can be tested with low yield targets using very compact chamber designs. A single ITF can test several different chamber concepts, a possibility that is unique to IFE. Less than 100 MW will be required to test heat transfer equipment. This power level is based on reasonable assumptions about component capacity scale-up between each successive facilities; the power is not determined by the ignition physics as in MFE.

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Table 1. Comparison of Two Options for Upgrading RIA Drivers

D-Path Option	IDF	ITF	DPP
Energy, MJ	0.2	2	4
Efficiency, %	8	27	27
L/M/H ring Diameter, m	180 / 210	180 / 210 / 490	180 / 210 / 490
Final Ion Energy, GeV	0.71	7.1	7.1
Final Beam Current, A	28	280	280
Final Pulse Duration, ns	2590	250	250
Approx. Direct Cost, \$M	230	+ 140	+ <370

C-Path Option	IDF	ITF / DPP
Energy, MJ	0.4	4
Efficiency, %	11	32
L/M/H Ring Diameter, m	250 / 260	250 / 260 / 620
Final Ion Energy, GeV	1.1	11
Final Beam Current, A	37	370
Final Pulse Duration, ns	2590	250
Approx. Direct Cost, \$M	290	+ 190

Table 2. Parameters for an Upgradable Linac Driver

	IDF	ITF	DEMO
Energy, MJ	0.2	2	4
Efficiency, %	20	22	23
Acc. Length, km	0.22	2.5	4.9
Final Ion Energy, GeV	0.16	2.1	4.1
Final Beam Current, A	160	570	810
Final Pulse Duration, ns	500	140	100
Approx. Direct Cost, \$M	100	+ 310	+ 280

Table 3. Results of CONRAD Chamber Dynamics Calculations.

Scale	Cascade		HYLIFE-II		Osiris	
	Reactor	ITF	Reactor	ITF	Reactor	ITF
Yield (MJ)	375	31.5	350	31.5	430	31.5
First Surface Radius (cm)	310	86.2	50	14.4	350	90.9
X-ray and Debris (J/cm^2)	93	93	3340	3340	56	56
Ablated Thickness (μm)	2.9	3.1	200	190	20	18
Peak Pressure (GPa)	17	17	90	200	30	28
Impulsive Pressure (Pa-s)	32	31	1900	1700	120	100
Re-radiation to Surf. (J/cm^2)	2.4	0.6	1100	1300	9.5	4.8
Cavity E/V (J/cm^3)	0.6	2.5	120	390	0.5	2.0

FIGURE CAPTIONS

- Fig. 1. Schematic of a heavy ion fusion development plan. Target physics, driver, and reactor technology will all be needed to build an ITF.
- Fig. 2. Schematic of the Integrated Test Facility. The ITF can be built in modules that can operate in parallel or series.
- Fig. 3. X-ray and debris energy fraction versus target gain. The driver energy heats the target materials, which increases the x-ray and debris fraction at low gain.
- Fig. 4. Neutron energy deposition profiles in HYLIFE-II blankets for different yields. The inner radius scales as the square root of yield.
- Fig. 5. The size of the heat transfer system components to be tested in the ITF is set by scale-up requirements to the DPP and commercial size power plant.
- Fig. 6. Example of a small ITF test chamber. This version of Osiris is scaled for a target yield of 20 MJ and a power of 100 MWt.

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FIG. 1

FIG. 2

Fig. 3

FIG. 5

DEMOM

FIG. 6

Power Plant

Four full scale heat transfer loops (~700 MW/loop)
Full scale chamber (~2800 MW)
Generates electric power

DEMO

One HT loop at 1/3 scale (~ 230 MW)
Chamber at 1/12 scale (~ 230 MW)
Generates electric power

ITF

One HT loop at 1/9 scale (~ 75 MW)
Chamber at 1/36 scale (~ 75 MW)
Electric power generation optional

END

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