Summary of IFE-target working group

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Target design may be considered a continuum in a multi-dimensional parameter space. One classification scheme (by R. Bangerter) views any particular target as falling in a three dimensional space having three continually varying parameters: 1. degree of direct drive vs. indirect drive; 2. scale of target; and 3. the mode of ignition (whereby hot-spot ignition requires the highest value of the central adiabat just before ignition, and fast ignition requires a low central adiabat, with shock ignition somewhere in between). As one goes from indirect drive to direct drive, there is better coupling but harder alignment and beam smoothness requirements. As one increases the target scale and focal spot requirement of the target (keeping the type of drive and mode of ignition fixed), phase space requirements are eased and there is a potential for higher gain, and lower repetition rate, but the driver energy requirement increases. As one proceeds from hot spot ignition to fast ignition, the pulse duration and spot radius goes down, increasing phase space density requirements or increasing ion energy, but the amount of compressibility also goes down, favoring more stable targets.

I. Basic description of target classes

For the purpose of the workshop and this report, we focused on four examples in the parameter space for which there has been recent work: 1. Cylindrical hohlraum indirect drive targets; 2. Spherical targets; 3. X-targets (one-sided illumination, quasi-spherical compression); and 4. Direct drive with cylindrical compression. Figure 1 summarizes these targets, summarizing features and issues. Table 1 gives some examples of parameters for these classes of targets, and Figure 2 shows possible ions and ion energies that would have a suitable range for these various targets.

<u>1. Cylindrical hohlraum targets</u> include "distributed radiator" targets [1], and their close relatives the "closely coupled target" [2] and the "hybrid" target [3,4]. These are perhaps the most mature of the targets, with existing integrated 2D designs, having gains ranging from 60-130 for 3-7 MJ input energy, depending on the specific design. Further, the basic ablation physics of the capsule, and symmetry studies that can be carried over from lasers to ions will be studied on NIF. They also naturally require a two-sided geometry, with a limited range in the total cone angle of the ion beams, a feature that allows thick liquid wall protection. However, the drive efficiency (i.e. the ratio of beam energy to kinetic energy of the fuel in the capsule) is lower than direct drive schemes, because indirect drive requires the additional energy needed to heat the converter material to a temperature that can produce copious x-rays. The lower gains then translate to high required driver energies. The "distributed radiator" family of point designs of indirect drive targets, so far, require two separate ion energies for the pre pulse and the main pulse, as the target heating during the prepulse creates a plasma in the hohlraum, requiring a more penetrating ion during the main pulse to maintain a nearly uniform radiation illumination on the capsule. [1,2]. As discussed below, having dual ion energies is not a fundamental requirement of hohlraum targets, but may impose an energy penalty. Beam spot radii are in the range 2-5 mm, and the ignition pulse duration is ~10 ns.

2. For the case of <u>spherical targets</u> the ion beam converters are spherically distributed around the DT fuel [5 - 11]. A tamper (using high density material) can surround the capsule and increases the coupling efficiency. However, the tamper also absorbs beam energy before the ions reach the

converter, offsetting some of the increased coupling efficiency. But the tamper also allows ions of higher range to illuminate the target, easing phase space requirements on the accelerator. Since the targets are layered spheres they are relatively simple to fabricate. They have high gains and many have been designed with single ion-kinetic-energies (~2-10 GeV) [5-11].
Optimum ion species and energy are still under investigation. One-dimensional designs correspond to four-pi beam illumination, not preferred for the IFE application because of chamber complexity considerations. Two-sided (polar) geometry is the goal but has yet to be established. The simulation machinery for creating polar geometry has recently been developed for laser targets and will soon be applied to ion targets. The stability of tamped spherical targets has yet to be confirmed in 3D simulations, and in general suffers from sensitivity to beam inhomogeneities and pointing errors in the focal plane. However, this may be alleviated by inclusion of radiating layers in the target construction, creating direct drive/indirect drive hybrids. Spherical targets exemplify the possible continuum between direct and indirect drive targets, as the amount of radiative smoothing can be greatly varied depending on the design. These targets, especially those closer to direct drive, are more sensitive to beam inhomogeneity and pointing accuracy than indirect drive targets with a larger case-to-capsule ratio. Another technique that can limit Rayleigh-Taylor (RT) instability is the application of so-called "wobblers" whereby the beam rapidly rotates in a circle about a central point, thus averaging the intensity variations, and lowering the total gain of the RT instability. Wobblers are being constructed and will be tested at the FAIR facility in Germany on cylindrical targets designed for high energy density physics studies, the so-called Laboratory Planetary Science targets (LAPLAS) [12]. (Some smoothing of the beam distribution will arise from inevitable natural “wobbling” of the beam in the accelerator.) Finally, shock ignition is an option that can be applied to spherical targets, and has the potential for creating high gain options for these targets. The decreased pulse duration requires higher phase space density for the driver however. Beam spot radii are ~2 mm, and the ignition pulse duration is ~0.5 ns.

3. The X-target [13] gets its name because the outer case (a metallic tamper) can be described roughly as a surface of revolution, formed by rotating about the horizontal axis passing through the center of an X. This creates a solid target with quasi-spherical symmetry, but with two cones removed from the sphere. The case is filled with outer shells of "propellant" such as aluminum, and DT fuel interior to the propellant. The ion beams illuminate the target from one side only, deposit their energy volumetrically in the propellant or the DT, and assemble fuel with a sequence of two quasi-spherical shocks. A final short igniter pulse provides the spark to ignite the assembled DT fuel. X-targets are inherently one-sided drive and have high coupling efficiencies, reduced stability issues associated with the low compression ratio, and a potential for high yields (~GJ) and high gains. The high gains require high densities under the quasi-3D compression. The target has a high range and thus requires higher ion kinetic energies. High power and small focal spot beams (< 1mm) are needed for fast ignition. The driver concepts for these schemes are, at this point, immature. Beam spot radii are ~0.2 mm, and the ignition pulse duration is ~0.2 ns.

4. The final target class examined by our target group was direct drive with cylindrical compression. An example for this class is a design created by Russian investigators [14]. This target has also been designed as inherently one-sided illumination geometry. As direct drive targets they have high coupling efficiencies. Since they are in cylindrical geometry they would have relatively low gain, but as a fast ignition target, the gain can be high, and this compensates for the effect of geometry. As with the X-target they have high range and so can accommodate high ion kinetic energies. The fast ignition pulse requires high power, and a small focal spot, that requires high phase space density in the accelerator. The driver concept for this target is at this point immature. Beam spot radii are ~0.05 mm, and the ignition pulse duration is ~0.2 ns.

Fusion Power Corporation has adopted this type of target for its high yield heavy ion fusion power plant design. The Russian target required 7.5 MJ, and had a yield of 750 MJ (for a gain of 100). The Fusion Power Corporation goal for the cylindrical target was to increase the required pulse energy to 20 MJ, and require a gain of 500 for a 10 GJ yield.
They propose replacing the 100 GeV Pt^+ ion beam with 20 GeV Xe^+, and Sn^+ compression beams and 13 GeV Pb^+ and Bi^+ ignitor beams. The single-sided illumination for the fast ignition pulse is replaced with two-sided illumination. with the stopping distance matched to the compressed fuel in order to ignite the minimum mass defined by the rho-R criterion. Target simulations need to be carried out to validate the zero order design.

II. Specific comments on the directions for investigation for the various target classes:
Axisymmetric hohlraums: Should be investigated in more detail, because of relevance to NIF experiments (both physics and timeliness). The ion driver intensity profile was originally based on laser-based intensity profiles. Specific pulse shapes optimized for ion drivers should be explored. One sided hohlraums also could be promising.
•Hybrid: There were two issues with the hybrid target: 1. a small acceptance cone angle in the original design. The cone angle could be increased; the large spot radius may be consistent with a 20 degree bundle. 2. The design was numerically less robust than the distributed radiator.
•Distributed radiator target/close coupled target: Larger cone angle, more robust than hybrid, but also needs more scaling work. (Beyond the single parameter scaling previously carried out based on a spot radius that scaled with pulse energy but with fixed ion range.)
Tamped spherical targets: show promise for high gain and acceptable spot size. There is a research need to explore spectrum between radiation drive and direct drive. There is also an opportunity to explore possibility of shock ignition and to create polar drive versions. Stability calculations should also be carried out.
X-target: shows promise for high gain, high yield, one-sided illumination, and higher ranges. The target requires complete stability calculations (including Rayleigh Taylor and Kelvin Helmholtz) and evaluation of the precision requirements of the ignitor pulse. The high yield version of X-target may be a match to FPC requirements.
Cylindrical target: In ref [14] one sided illumination was used for the compression beam and with the other side used for the igniter. This target also was of high yield and required higher ion ranges. The stability of cylindrical targets has been studied for the upcoming LAPLAS experiment [12] at the FAIR project, but at lower compression ratios than is needed for inertial fusion energy production. The FPC adaptation of the ITEP target [14] (with ten times yield) needs simulation.

There are some issues that are common to all targets: Stability issues (to varying degrees for the various targets); Chemical issues: compatibility of mixtures, opacities of mixtures;
Activation issues of high-Z material; Fabrication costs (normalized to yield);
Tritium inventory for each target; Alignment tolerances and tolerances for beam intensity variations for each target; (note that spherical tolerances will be different than cylindrical tolerances); Injection issues for each target (ion targets have advantages because they are closed; capsules insulated from target environment)

III. Specific IFE Target Questions
What is a figure of merit for accelerator difficulty for different targets?
A necessary (but not sufficient) requirement that must be met by the driver is that the required phase space density at the target must be less than the achievable phase space density at the injector. This has been recognized since the earliest HIF symposia in the 70's. (See, e.g. [16]). The target requires a particular pulse energy E, supplied in a pulse duration Δt, spot radius r_{spot}, and with contstraints on the cone angle θ. The final emittance and chromatic aberrations limit

(among other factors) the spot radius. The 6D phase space density dN/dU_6 required by the target, assuming equal contributions to the spot radius from chromatic aberrations and emittance, can be expressed as (see e.g. [17]):

$$\left.\frac{dN}{dU_6}\right|_{\text{target}} = \frac{2^{3/2}\alpha_1^{1/2} d\ E}{\left[(\gamma-1)^3(\gamma+1)^2/\gamma\right] n_{beams} m^4 c^6 \theta r_{spot}^3 \Delta t}$$

Here, α_1 is a constant of the focusing system (~ 16), d is the final focal length (~ 6 m), m is the ion mass, γ is the ion relativistic factor, n_{beams} is the total number of ion beams, and c is the speed of light.

The phase space density produced at the injector (assuming space charge limited flow, breakdown limited diode voltage, a ratio of beam radius to diode gap of 1/4, and source temperature limited emittance; see [17] for details) is:

$$\left.\frac{dN}{dU_6}\right|_{injector} = \frac{\pi\varepsilon_0}{2^{1/2}9}\left(\frac{V_0}{m^3 q^3}\right)^{1/2} \frac{1}{kT_{source}(\Delta p_z/p_z)(1\ \ cm)^2 \alpha_{\text{B}}},$$

where $\alpha_{\text{b}} = (V_0/100\text{ kV})^2$ for V_0 <100 kV and $\alpha_{\text{b}} = (V_0/100\text{ kV})^4$ for V_0 >100 kV. Here $\Delta p_z/p_z$ is the fractional momentum spread at the injector exit, q is the charge state of the ion, kT_{source} is the ion source temperature, and V_0 is the injector diode voltage.

Note that the ratio of the target requirement to the injector phase space density is proportional to $Eq^{3/2}/([(\gamma-1)^3(\gamma+1)^2/\gamma]\theta r_{\text{spot}}^3\ \Delta t\ m^{5/2} n_{beams})$. For non-relativistic beams this ratio is proportional to $1/\beta^6$ where β is the ion velocity/c. Thus, from the phase space density point of view, constraints are eased as one goes to larger number of beams, higher ion velocity, larger spot radius, longer pulse duration, larger focusing angle, higher ion mass, and lower ion charge state. The ratio should be much less than unity to allow for inevitable phase space dilution from injector to target.

What near-term surrogate experiments can be done (e.g on NIF, OMEGA etc) to elucidate HI target physics needs?

NIF: laser-driven and heavy-ion driven indirect drive targets have the same implosion physics.
 Also share the coupling efficiency issues of X-ray hohlraum wall losses, hohlraum wall motion and radiation transport.

FAIR/GSI: LAPLAS (cylindrical implosions)
 X-Target (quasi-spherical implosions)/Cylindrical implosions
 Radiation converter physics

Z-machine (Sandia): X-Target (quasi-spherical implosions)/Cylindrical implosions

NIF/Omega/GEKKO: Rugby laser configurations for closely coupled
 ion analog targets
 Fuel/propellant scraping against high-Z material in a cone geometry

NDCX-II/GSI:
 Ion-coupling experiments (creating weak shocks in planar targets)
 Examine tamper shock/Bragg-peak shock generation with tamped foils
 Pulse shaping (to test flexibility of accelerator to accommodate some target designs)

How realistic is it to assume that targets with a single ion kinetic energy can be designed? What is the research required that would demonstrate it to be practical?

For cylindrical hohlraums: it appears that a single-energy-target could be designed at some energy or yield penalty. (Time dependent symmetry is the issue, as target heating changes ion range over the course of the pulse); Tamped spherical targets historically have only required a

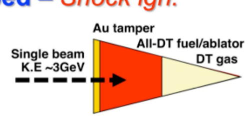
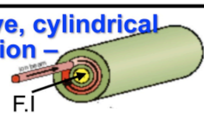
single ion energy; For tamped spherical targets with shock ignition, some study is required to see if shock ignition is consistent with a single ion energy;
For the X-target or Cylindrical target, a single ion energy for the target was chosen by design.

The hohlraum target designs and beam power profiles were derived by demanding the same temperature versus time profile in the hohlraum as were developed for laser hohlraum targets. This might have forced some beam current (vs time) features and constraints that aren't fundamental requirements (eg: the 90-TW, 6.5-ns high intensity feature that precedes the relatively long 20-TW power level at the front of the pulse for the RPD target). Can the group clarify or add to this?

The accelerator constraints were not part of the original design of the pulse shape. This is an area that would benefit by revisiting.

When should the goals of the Heavy Ion Driver Implosion Experiment (HIDIX) be specified?
The target group recommends that the specific goals of the HIDIX facility should be specified in the near term. The Integrated Research Experiment (IRE) design from Snowmass-2002 should drive HIDIX for both direct and indirect drive targets

Summary and Conclusions
We have reviewed a number of promising examples of HIF targets. The down select time is at least five years away, so no promising targets should be eliminated at this time. An important point is that heavy ion targets now cover a wider range of target design classes that may use existing heavy ion accelerator technologies. This feature provides for flexibility of HIF chamber and accelerator choices. Also, the target work requires close iteration and coordination among other elements of the power plant (e.g. chamber and accelerator). We believe all the target classes deserve increased attention.

	Features	Issues
Indirect drive – HS ign. 	• Integrated 2D designs exist • Ablation/burn physics on NIF • Natural two-sided geometry	• Lower drive efficiency • Lower gains, high driver energies
Direct drive X-target – Fast ign. 	• Inherent one-sided drive • High coupling efficiencies • Reduced stability issues • Potential for high yields (~GJ) and gains	• High gains require high densities under quasi-3D compression • Higher ion kinetic energies • High power, small focal spot beams needed for fast ignition • Driver concepts immature
Direct (+indirect) drive, tamped – Shock ign. 	• High coupling efficiencies (tamped ablation) • Simple targets • High gains consistent with low ion-kinetic-energies (~2-10GeV)	• Optimum ion species and energy • Two-sided (polar) geometry to be established** • High power beams needed for shock ignition • Stability to be confirmed
Direct drive, cylindrical compression – Fast ign. 	• Inherent one-sided drive • High coupling efficiencies • Simple targets	• Low gains, high driver energies • High ion kinetic energies • High power. small focal spot beams needed for fast ignition • Driver concepts immature • No U.S target design interest

**Will leverage present NIF PDD studies

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Figure 1. The features and issues of the main classes of targets that were the focus of the working group.

	Hybrid		Distributed Radiator (RPD)		Tamped Direct Drive		X-Target		Cylind. ITEP [FPC] Target		Spherical Hohlraum	
	Foot	Main	Foot	Main	Compressor	Shock	Compressor	Ignitor	Compressor	Ignitor	Pre	Main
Energy (in pulse) (MJ)	1.7	5	2.7	4.9	2	1	1	2	7.1 [20]	0.4	1	3
Pulse duration (ns)	7	11	6.5	9.3	20	0.5	20	0.2	75 [75]	0.2	20	10
Beam radius (mm)	3.8 x 5.4	3.8 x 5.4	1.8 x 4.1	1.8 x 4.1	1.9	2.2	0.5	0.2	0.5 [0.05]	0.05	3	3
Ion range (g/cm^2)	0.031	0.049	0.034	0.042	0.038	0.038	2	2	4 [7]	4 [1]	0.15	0.15
Target acceptance angle (deg)	0 to 6	0 to 12	0 to 20	0 to 20	20 degree goal		0 to 20 degree		0 [2]	0 [2]	4 Pi	4 Pi
Illumination geometry	Two-sided		Two-sided		Two-sided		One-sided		Two-sided [Two-sided]		Spherical	
Target gain	55		68		100?		400		100 [500?]		50 - 100	
Avg. Req. Beam Power for 1 GW net electric (MW)[1]	56.0		43.8		28.4		6.6		28.4 [5.3]		63 - 28	
Rep rate for 1 GW net electric power (Hz)[1]	8.4		5.8		9.5		2.2		3.8 [0.3]		16 - 7	
(Example ion mass) (amu)	207	207	209	209	200.59	200.59	207	207	207 [130]	207 [200]	207	207
(Example ion energy) (GeV)	3	4.5	3.3	4	3.5	3.5	63	63	100 [20]	100 [13.5]	8	8
(Example charge in pulse) (mC)	0.57	1.11	0.82	1.23	0.57	0.29	0.02	0.03	0.07 [1.0]	.004 [0.07]	0.13	0.38
(Example current in pulse) (kA)	81.0	101.0	125.9	131.7	28.6	571.4	0.8	158.7	0.9 [13]	20 [37]	6.3	37.5

Table 1. Examples of target requirements for various classes of targets.
Hybrid target parameters from ref. [3]; Distributed radiator (Robust Point Design) parameters from refs [2,15]; Tamped direct drive [20]; X-Target [13]; Cylind. ITEP represents cylindrical direct drive, fast ignition target parameters obtained from ref. [18, 14]. FPC parameters in brackets represent Fusion Power Corporation parameters from ref. [19]; Spherical hohlraum [21].
[1.] Assumptions on beam power requirement: Net_electric_power = 1 GW; Thermal-to-electric efficiency = 0.35; Blanket multiplier =1.1; Accelerator efficiency =0.3; Formulae used: Beam_power= Net_electric_power /(target_gain x blanket_multiplier x thermal-to-electric-efficiency - 1/accelerator-efficiency); rep rate = Average beam_power/Pulse_energy

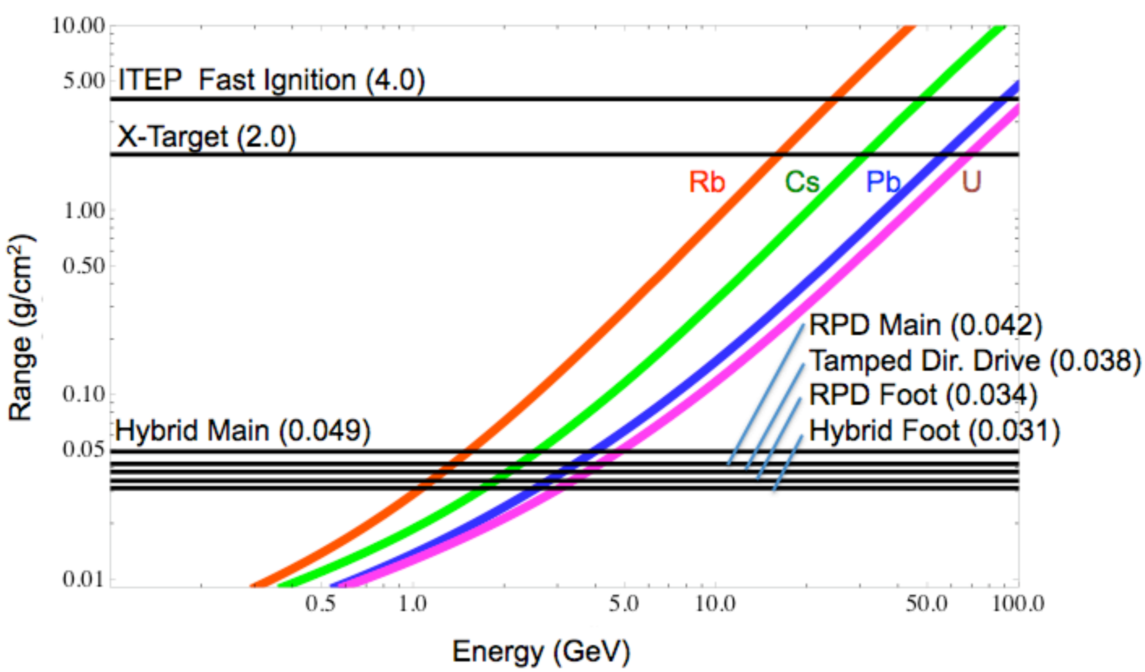

Figure 2. Range as a function of ion energy and ion mass.

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