Potential High Gain Target Designs for IFE

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1 Inertial Fusion Energy

In 2010 Nuckolls suggested a novel IFE design which would make use of a density gradient in the assembled fuel to amplify the fusion yield [1]. As an initial concept of this he proposed a design consisting of two different hemispheres with a density step between them. The first hemisphere was based on a typical fast-ignited fuel assembly, with a density of 300 g/cm^3, an areal density of 3 g/cm^2, and a temperature of 10 keV. The other hemisphere was much larger, and consisted of cold fuel at a lower density of 30 g/cm^3 and ρR of 1.4 g/cm^2. The small, high density hemisphere ignites, and the burn then propagates into the cold fuel reservoir provided by the second hemisphere, which has a much larger fuel mass. Simulations performed by Zimmerman and presented in Nuckolls' paper suggest that this reservoir of cold fuel amplifies the yield of the first hemisphere by ten times, and offers an improvement in yield of 2.5 times compared to a full spherically symmetric capsule based on the first hemisphere only.

2 Dual Hemisphere Design

We suggest that a similar idea to Nuckolls' concept could be realised in practice, by placing a high density carbon glide plane between two hemisphere capsules. The hemispheres are kept separate by the glide plane. By applying different pulse sequences to the two hemispheres, an assembly similar to that discussed could be formed at the time of peak compression, and the benefits in yield amplification realised. Such a design could be considered an extreme form of cone-guided fast ignition [5], where the 'cone' (glide plane) has an angle of 180 degrees and the fast ions would be alpha particles which are generated in-situ by fusion reactions in the

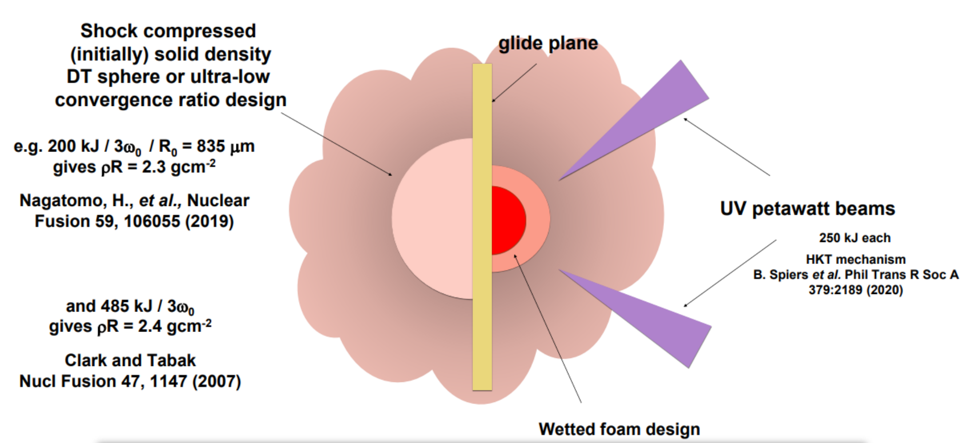

Figure 1: A conceptual design, based upon a shock compressed high mass hemisphere and a fast-ignited wetted foam hemisphere, incorporating previous work from [2], [3] and [4].

high density hemisphere. These propagate through to the cold fuel, after traversing the compressed carbon region separating the two hemispheres. As Nuckolls' paper proposes that this hemisphere is itself ignited by electron-driven fast ignition this would essentially mean using fast ignition (or auxiliary heating [6]) to ignite a small hemisphere, which in turn acts as an ion source to fast-ignite a larger hemisphere. A schematic of such a design is displayed in Figure 1.

Nuckolls discussed the energy requirements that would likely be required for an inertial fusion reactor, and suggested that around a laser energy of ~ 800 kJ would likely be required for reactor to be economically viable - substantially lower than the multi-MJ energies of facilities like the NIF. This is a similar conclusion to more recent work [7], which estimated that a reactor would need to be on the order of 100 MWe in order to be commercially competitive with other energy sources. Based on this, we have considered a design that will operate at 800 kJ, in accordance with Nuckolls' proposal.

3 Experimental Tests

Achieving such an implosion requires a number of preliminary experiments to be performed. Firstly, it is necessary to demonstrate that it is feasible to perform hemisphere implosions on glide planes, and still be able to achieve roughly comparable performance to standard symmetric implosions. Secondly, it is necessary to demonstrate spherical designs corresponding to each of the two hemispheres, at appropriate energy. Thirdly, these spherical designs should then be converted into hemisphere designs, and these tested separately. Finally, the two hemispheres can be brought together (separated by the glide plane) to form a single capsule, with two separate pulse sequences used to produce the required fuel assembly on both hemispheres simultaneously. Each of these stages would require significant amounts of simulation work, along with experiments.

Fortunately, the first of these stages has already been demonstrated at the Sandia National Laboratory, where a hemisphere target was indirectly driven using a gold glide plane [8]. These experiments showed that imploding hemisphere targets on glide planes is feasible, and can be modelled with reasonable accuracy. However the glide plane did affect performance, leading to a more oblate fuel density than suggested by 1D (spherically symmetric simulations), and lower areal fuel densities. It may be possible to reduce the effect of the glide plane through adjustments to the capsule design and laser drive, and this could be explored through simulation work.

4 Wetted Foam Implosions for the First Hemisphere

Possible designs also exist for the two hemispheres. The high density, high temperature hemisphere essentially requires an ignited capsule (with the areal density and temperatures described being above the conventional ignition threshold). We stress here the point of this campaign is to demonstrate the feasibility of this dual-hemisphere approach, and so a non-igniting capsule could be used as a 'proof-of-concept'. For this, we propose a low convergence ratio capsule, as presented in [9] and [10]. Such capsules have been designed with limits on key hydrodynamic parameters (convergence ratio, in-flight aspect ratio and implosion velocity), in order to minimise hydrodynamic instability growth. Maximum intensity is also limited to below the threshold for parametric instability growth. This means that these capsules are expected to experience minimal instability growth, and thus show good agreement with 1D radiation-hydrodynamic simulations. Direct-drive implosions of such capsules at a range of energy scales from [9] and [10] are reproduced in Table 1. For the purposes of demonstrating the dual-hemisphere concept, a low energy Nd:glass third harmonic implosion is sufficient. Given that direct-drive has an efficiency roughly five times higher than indirect-drive, a ~ 150 kJ direct-drive implosion can be estimated as correlating to an 800 kJ indirect-drive one. This would correspond to an implosion between the lowest two energy implosions in [10]. Such a capsule would first need to be simulated in 1D and then 2D, and then experiments performed on this capsule in first spherically symmetric and then hemispherical configurations. As this is not an ignition design, the temperature, areal density, and fusion yield are all significantly lower than in Nuckolls' design.

In the future, this could be augmented or replaced to give ignition or IFE relevant gains. Table 1 also includes implosions at higher energy using different laser architectures (discussed in [10]), which could in future produce hemispheres with gains more relevant to IFE facilities. In particular, the higher energy Argon-Fluoride (ArF) frequency implosions offer gains that, when accounting for the expected ~ 2.5 factor improvement from the hemisphere design, would approach and surpass the gains of 50 expected to be required for an IFE reactor. Alternatively, fast ignition or auxiliary heating could be applied to any of these capsules to improve their performance. Table 2, taken from data in [10], demonstrates the improvement in fusion yield that may be possible through auxiliary heating, where overlapping relativistic electron beams in the capsule hotspot are used to heat the hotspot around the bang-time. Further development of this scheme is required to achieve it in practice, but these early simulations suggest it could significantly improve performance. Finally, if other implosion designs are demonstrated over the coming years that demonstrate high-performance (particularly in light of the recent NIF HYBRID-E result) they could potentially also be used as the basis of the high-density hemisphere.

5 Isochoric Fuel Assembly for the Second Hemisphere

The second hemisphere in Nuckolls design has a density of 30 g/cm^3 and of 1.4 g/cm^2. Such a hemisphere could be based on the work of Clark and Tabak, who demonstrated a self-similar isochoric implosion designed for fast ignition [3]. The 485 kJ direct-drive implosion they presented yielded a significantly higher density of 300 g/cm^3 and of 2.4 g/cm^2, although a slightly lower total fuel mass. However, they also outlined how their methodology could be used to achieve higher densities at higher energies. Given the order of magnitude by which they have surpassed Nuckolls' concept, it is likely it would be possible to design an implosion at low enough energy that continues to satisfy the density requirements using indirect drive. As with the first hemisphere, after simulated design work it would be necessary to perform an experiment to implode such a capsule in a spherically symmetric configuration, before moving on to a hemisphere design.

6 Artificial Intelligence-assisted Simulation Tools

IBM Research has interest in supporting novel approaches to climate change mitigation. This year, IBM and Oxford have started a joint project on integrated simulations for the optimisation of different target designs for IFE. The idea is to use recent developments in cloud computing to visualise outputs of large-scale simulations running simultaneously on different platforms, to account for the different length and time-scales involved. Artificial Intelligence approaches to the optimisation of the fusion output will form the core element of the research. AI and data-driven approaches (e.g. [11]) have to date been used to optimise designs (e.g. [12]), speed up ICF simulation time (e.g. [13]), combine simulation and experiment (e.g. [14]), and finally improve the yield in real experiments (e.g. [15]).

7 Summary

We have discussed the concept of dual-hemisphere implosions as a potential route to reduced drive energies required for IFE. An experiment and simulation campaign designed to test the individual performance of these two hemispheres is proposed. Once the implosion performance of each target has been tested on NIF, we suggest that an capsule can then be assembled consisting of the two hemispheres together separated by the glide plane. This will then point the way forward towards a high gain target for IFE purposes using direct drive. Additional heating, either by fast ignition or by auxiliary heating (possibly by use of multi-kJ petawatt laser pulses generated by beam combiners and plasma amplifiers) also needs to be explored.

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Implosion Type	Nd:glass 3rd harmonic				ArF			Two-colour			
Total laser energy (MJ)	0.10	0.27	0.77	1.71	1.59	1.91	4.55	1.69	2.10	3.12	4.27
3rd harmonic energy (MJ)	0.10	0.27	0.77	1.71	-	-	-	0.92	1.73	2.63	3.80
ArF energy (MJ)	-	-	-	-	1.59	1.91	4.55	0.77	0.37	0.49	0.48
Gain	0.030	0.070	0.19	0.75	10.9	17.3	34.5	4.0	15.5	20.4	30.5
Convergence ratio	15.7	15.7	16.0	15.8	16.0	15.9	14.0	16.0	16.0	16.0	16.0
IFAR	23.4	27.5	29.7	25.1	11.3	10.5	8.5	16.1	20.4	23.8	23.4
Implosion velocity (km/s)	391.4	395.8	399.6	399.6	390.7	398.9	360	391.0	399.9	396.4	391.6
Max 3rd harmonic power (TW)	43	85	173	292	-	-	-	173	292	389	500
Max ArF power (TW)	-	-	-	-	464	572	967	447	755	1006	1292
Pulse 2 switch on time (ns)	1.10	2.20	2.60	3.60	3.90	3.50	2.50	1.95	3.00	2.70	3.50
Pulse 3 switch on time (ns)	3.00	4.60	5.60	7.80	7.10	7.50	8.90	4.35	7.80	7.20	9.10
Pulse 4 switch on time (ns)	3.60	5.50	6.80	9.50	8.85	9.25	10.80	8.05	9.40	9.10	11.10
Laser switch off time (ns)	5.80	8.50	11.00	15.00	11.95	12.25	15.10	12.80	15.30	15.80	18.60
Vapour/liquid boundary (mm)	0.6325	0.8950	1.3050	1.6705	1.072	1.210	1.435	1.230	1.645	1.933	2.210
Liquid/CD boundary (mm)	0.69625	0.976	1.3950	1.8200	1.200	1.340	1.780	1.360	1.818	2.100	2.374
Outer radius (mm)	0.7125	0.9975	1.4250	1.8525	1.2800	1.425	1.8525	1.425	1.8525	2.1375	2.4225
Vapour density (mg/cm^3)	1.35	1.35	1.05	1.00	1.00	1.03	0.60	1.02	1.05	1.00	1.01

Table 1: Simulation parameters for direct-drive wetted foam implosions at both Nd:glass 3rd harmonic and ArF frequencies, along with a two-colour scheme using both frequencies. These results are taken from [9] and [10].

Unheated capsule properties		Yield (kJ) with electron energy deposition of:					
Laser Energy (kJ)	Yield (kJ)	10 kJ	20 kJ	30 kJ	40 kJ	50 kJ	60 kJ
100	3	34	87	140	190	240	270
270	18	87	200	340	500	640	780
770	150	360	690	1100	1500	2000	2400
1700	1300	2800	5300	8300	11000	13000	15000

Table 2: Simulated yield amplification (relative to the yield of the capsule without auxiliary heating) for the four Nd:glass third harmonic capsules from Table 1 when auxiliary heating is applied. Energy is deposited into the electrons over 0.7 ps just before the implosion bang-time. The simulation parameters (i.e. capsule dimensions and laser powers/timings) are unchanged from Table 1. Data taken from [10].