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European fusion target work

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Abstract

Target concepts developed in the context of the HIDIF project (Heavy Ion Driven Inertial Fusion) are presented. Target design has evolved, from the beginning of the study in 1993, in parallel with the evolution of accelerator parameters. Two different phases can be distinguished: (a) up to 1998 the goal was just demonstration of ignition with heavy ions, (b) from 1998 target and driver are being upgraded to high-gain designs able to be used for energy production. Analytical models and numerical tools developed in this context are summarized, and future research directions are discussed. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the middle of the 1990s a collaboration of European laboratories and university groups aimed at Heavy Ion Driven Inertial Fusion (HIDIF) was established. In an early phase (1993–1998), the study was oriented towards the conceptual goal of ignition, i.e. a facility providing

just enough energy to ignite a minimum quantity of DT [1].

These studies lead to the conclusion that the driver parameters were unfavorable for a low-gain ignition facility. Although drive energy decreases with pellet gain, drive power (the dominant factor determining the heavy ion driver) is essentially independent of gain. An upgrade of the ignition facility to an energy production concept was undertaken in 1998.

From the beginning of the studies, it appears clear that only indirectly driven targets can meet the characteristics of the HIDIF driver. The evaluation of such targets requires the simultaneous consideration of a large number of factors, and the use of sophisticated numerical and

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analytical tools. The authors have developed and applied for this purpose a wide spectrum of codes, including radiation hydrodynamics in 1D and 2D geometries, and view factor codes in 2D and 3D.

2. Ignition targets (1993–1998)

All these designs were developed around a fusion capsule identical to one of the capsules proposed for the NIF project [2]. With 1.19 mm of external radius, a Be shell as ablator, and loaded with 0.2 mg of DT fuel, this capsule can be driven with a relatively moderate radiation temperature: 250 eV with a 80 eV foot. An optimally shaped radiation pulse produces its implosion to thermonuclear conditions in 16 ns and around 10 MJ of yield. The capsule is located inside a cavity whose walls, made of high-Z materials (typically Au) confine thermal radiation. Ion beams penetrate into the cavity through the walls and dump its energy on the converters. In turn the converters emit thermal radiation to the cavity walls, where it is absorbed and reemitted again. This process generates a nicely isotropic radiation field that produces a quasi-uniform capsule illumination and implosion. Nevertheless, the uniformity requirements are so strong (of the order of 1% peak-to-valley), that the placement of the converters and the shape of the cavity have to be carefully studied and controlled in order to maximize the homogeneity of the radiation flux on the capsule surface. In addition, internal shields are needed to avoid direct impingement of ion beams and to control radiation fluxes.

The reference driver parameters considered at that epoch were 10 GeV Bi^+ ions, focussed in a spot radius of 1.7 mm, with a total energy up to 4.5 MJ, and a 4 ns FWHM pulse duration. Fig. 1 shows the geometrical arrangement of cavity, capsule, converters and shields for the four designs considered below.

2.1. Octopus

Octopus is Composed of a cylindrical cavity irradiated by eight clusters of beams impinging on eight converters [3]. The converter material is

imbedded into tube like structures to maintain its expansion as close to 1D flow as possible. Converter dynamics has been modeled by the 1D three temperatures code DEIRA [4], and flux uniformity in the capsule by the view factor codes VF2 [5] (in 2D geometry), and HOLCON [6] (in 3D geometry). The needed beam energy is about 4.1 MJ with a focal spot radius of 1.65 mm. This value is relatively large due to the fact that the energy used to heat up converter material scales with the number of converters.

2.2. Spanish

All beam energy is concentrated into only two cylindrical converters [7]. Due to the packing of final focusing elements in the walls of the vacuum chamber, incidence angle of beams goes from 0° to 30° . This fact has several implications: (a) not all beam energy can be stopped by the converter material, a substantial part is dumped on the walls, (b) a thick end-shield is needed to protect the capsule, (c) due to this shield, converters have to radiate through their lateral surface, and radiation have to be canalized to the capsule through the annular aperture between shields and cavity walls, (d) this configuration allows converters to expand laterally, pushing converter material outside the beam path, (e) all these facts imply a degradation of efficiency that have to be compensated by reducing target dimensions to their limit.

The analysis of such configuration can be only afforded by 2D radiation hydrodynamics simulations. The lagrangian code MULTI2D [8] has been used for this purpose.

- (a) Converter Au doping, wall thickness, converter length, etc. were optimized in the sense of obtaining a maximum circulating radiation flux for a given incident power.
- (b) Radiation temperature near the capsule was monitored in the simulations, and arrival time of the beams adjusted until the nominal temperature profile (validated with 1D runs of code MULTI1D [9]) was reasonably reproduced. This requires an input energy of 3 MJ, for a focal spot radius of 2.1 mm.

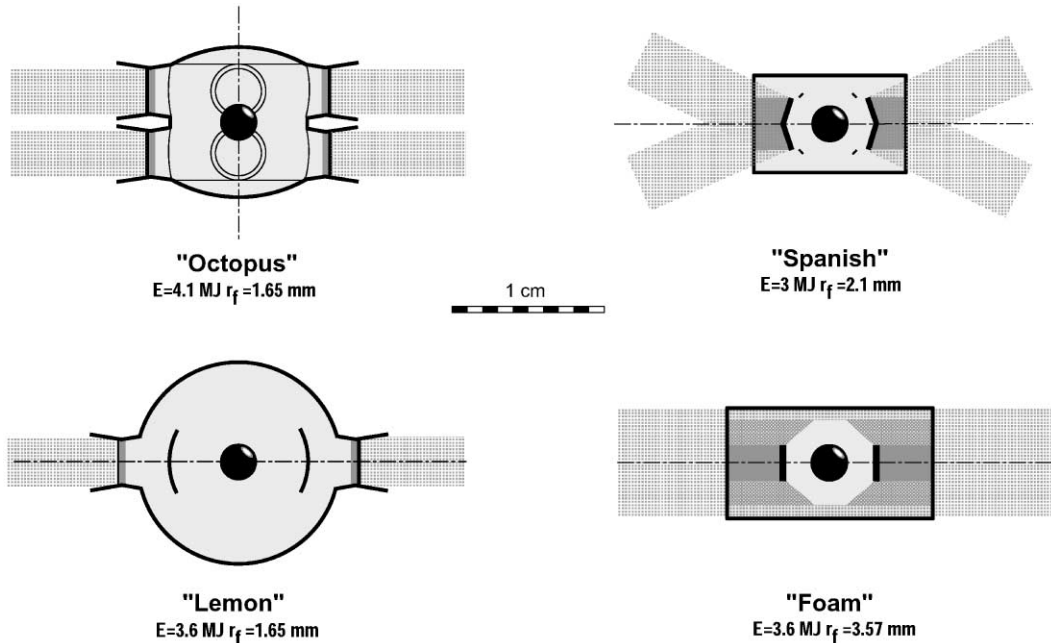


Fig. 1. Geometric arrangement of the four ignition targets discussed in the text. All targets, except Octopus, have a horizontal symmetry axis. Octopus has eight converters, four are in the front/back of the section showed.

- (c) Uniformity of the implosion was defined in terms of distortion of the DT-Ablator interface. Legendre mode 2 was eliminated by adjusting the aspect ratio of the cavity, and mode 4 by locating two thin ($1.35 \mu\text{m}$) Au rings over the capsule at polar angle 45° . Residual non-uniformity was reduced to less than 1% RMS.
- (d) Present 2D simulations can only follow capsule evolution up to the moment when the capsule radius is about 1/4 of initial. Although the level of time-integrated symmetry suggests that ignition is feasible [2], the effect of time dependences in the uniformity has not been evaluated.

2.3. Lemon

This design is an advance on earlier publications by the Livermore group [10]. It has two converters similar to the ones in Octopus. Two shields are situated or located in-between the converters, to avoid direct irradiation of the capsule from the

converters. The size and position of shields are adjusted so as to suppress mode 2 asymmetry on the capsule and maximize energy transfer. This optimization has been carried by using the 2D-view factor code VF2. In comparison with Octopus, ignition energy was on the one hand, reduced by using less converter material, but on the other hand, increased due to the larger distance between radiation source and capsule. The final result is 3.6 MJ for a focal spot of radius of 1.65 mm.

2.4. Foam

In this cylindrical, two side-irradiated target, low-density (foam) converter material fills almost entirely the cavity [11]. This is inconvenient from the point of view of mass to be heated (proportional to converter diameter), but has several advantages: (a) more direct and efficient energy transfer than in the above designs, (b) the shape, density and composition of foam can be used to control radiation flux symmetry, (c) larger focal spots relax driver design. This target has been

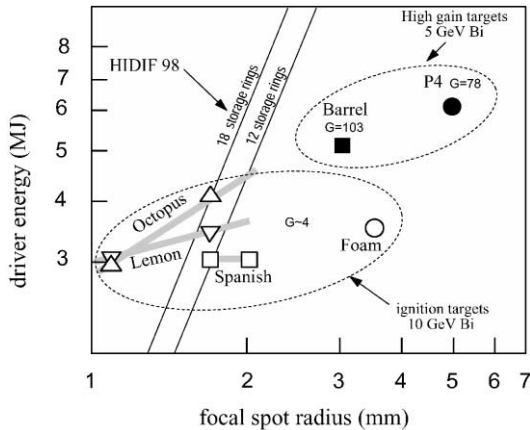


Fig. 2. Summary of target characteristics. Lines show the HIDIF'98 driver scaling for two options differing in the number of storage rings.

simulated by the eulerian computer code SARA2D. Preliminary results give an ignition threshold of 3.6 MJ with the quite large focal spot radius of 3.57 mm.

2.5. Summary of ignition targets

The performances of the four targets have been summarized in Fig. 2. Energy and focal spot size characterize each target. The inclined lines represent HIDIF driver scaling (assuming spot size \propto emittance^{0.4} and emittance \propto stored energy) [1]. Better targets are on the right side of these lines.

No direct comparison between designs is possible because: (a) not all the targets have been optimized up to the same degree, (b) different modeling and codes have been used. The last point affects specially the *lemon* and *octopus* targets, whose performances have been evaluated by means of view factor codes. Due to the lack of hydrodynamic expansion and time dependent geometry, these calculations tend to underestimate the coupling efficiency.

3. High gain targets (1998–2000)

From 1998 the upgrade of the HIDIF driver from an ignition facility to an energy production

plant has been considered. The ignition target studies indicate that high gain can be reached with a modest increase of energy. On the other hand, accelerator studies show that lower energy ions (5 GeV Bi⁺) can also be considered. In this case, a larger focus radius of the order from 3 to 5 mm has to be acceptable. This value is comparable to the target size; thus localized converter concepts used in almost all ignition targets must be excluded now. Fig. 3 shows the two concepts studied up to now.

3.1. Barrel

The fusion capsule is located in the center of a cylindrical hohlraum [12]. The central part of each base is a thick shield that protects the capsule from direct impingement of ions and ion fragments. Beams with elliptical cross-section enter into the cavity through the annular part of the wall surrounding these shields, and deposit their energy, both in the entrance window, and in the inner surface of the walls. This geometric arrangement is quite similar to the distributed radiator concept proposed by the Livermore group [13]. The use of the high-Z material of the walls to convert ion energy to X-rays (instead of low-Z materials) has advantages and disadvantages. Gold has lower stopping power than beryllium and, although its heat capacity is lower, the energy required to heat up gold is about a 50% higher. However, the sound velocity in gold is considerably lower than in beryllium ($\approx 1/2$) and, consequently, the hydrodynamic expansion is reduced. The possibility of using, as converter, a beryllium layer covering the internal side of the walls has been reported in Ref. [14].

This target uses an specifically designed capsule [15] slightly larger than the one referenced in Ref. [10] (2.69 mm versus 2.33 mm of radius), yielding around 450 MJ, and using a lower radiation temperature: 220 eV instead of 260 eV. The in-flight-aspect-ratio (45) is larger, but of the same order of magnitude as the one in the NIF capsules. Detailed multigroup simulations taking into account angular dependence of the radiation field have been carried on by using the code SARA-1D [16]. An optimum doping of the ablator material has been found: beryllium with 0.2% of

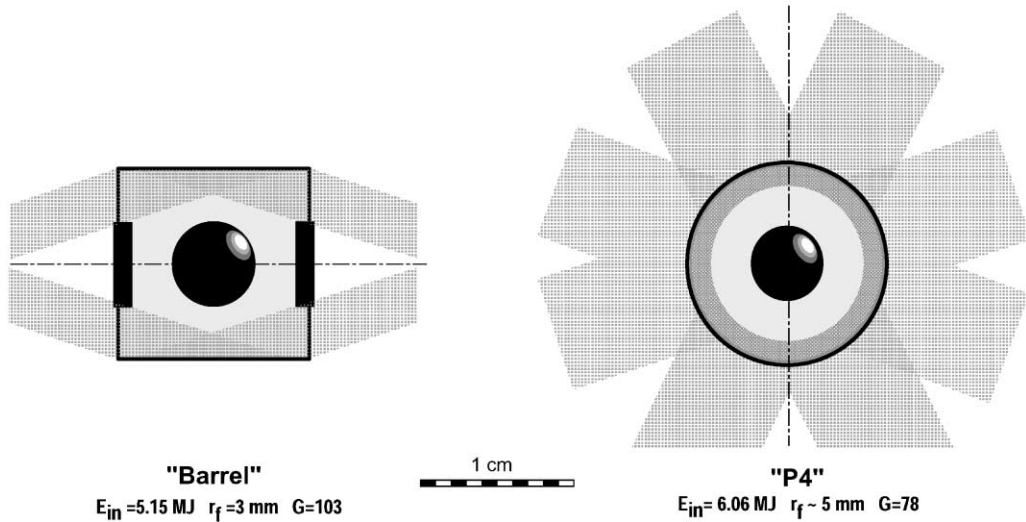


Fig. 3. High-gain targets. Barrel has a horizontal symmetry axis, whereas P4 is quasi-spherical.

copper (in atoms). Code MULTI2D was used to simulate the complete target, and to study the following aspects:

3.1.1. Coupling efficiency

A simple model of the cavity has been developed. Both the power used to heat up the material inside the cavity (converters, shields, capsule, with a total thermal capacity α), and the power need to drive a thermal wave into the walls (surface S , specific heat c , conductivity kT^n) can be modeled by

$$\Phi = Sc \frac{d}{dt}(T_R L) + \alpha \frac{dT_R}{dt}, \quad \frac{kT_R^{n+1}}{n+1} = \frac{c}{2} \frac{d}{dt}(T_R L^2)$$

with T_R being the radiation temperature, Φ the beam power, and L the instantaneous depth of the wave. Effective values for the parameters S , c , k , n and α are obtained by adjusting the behavior of the model to 2D simulation results. Once fixed, this set of parameters characterizes the cavity, and allows obtain $T_R(t)$ when $\Phi(t)$ is given, without the need to perform expensive 2D simulations.

3.1.2. Pulse shape

Basic temporal profile of beam is assumed to have an inverted parabola shape with total duration τ . Several beam lines (4 groups) are assumed to arrive

to the target at different times. The above model, together with 1D simulations, allows to fix the energies and delay of each line by automatic optimization of the gain, by using either the downhill simplex or the simulated annealing methods [17]. High gain (>100) can be obtained with relatively long pulses $\tau \approx 20$ ns (peak power ≈ 350 TW).

The sensitivity to pulse shape has been determined by imposing random perturbation of the beam lines in timing and energy. The average gain decreases to one half when the variance of perturbation is 5%.

3.1.3. Implosion symmetry

As in Spanish target, the time integrated asymmetry Legendre modes 2 and 4 can be controlled by adjusting two appropriate target parameters. (See Fig. 4) We choose: (a) cavity length, and (b) nominal position of the beam focus. Several iterations are needed to cancel simultaneously both modes. Higher number modes have lower values and cannot be distinguished clearly from the numerical noise in the simulations.

3.1.4. Sensitivity to focusing

Fig. 4 also shows that a ± 0.25 mm deviation of parameter H from its nominal value will produce a

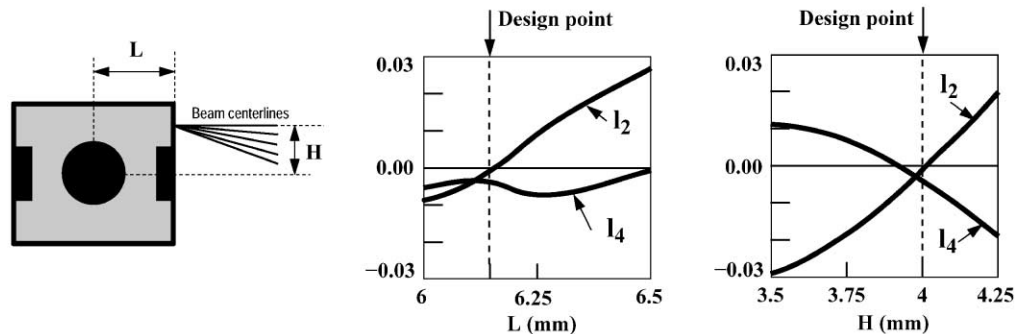


Fig. 4. Legendre coefficients 2 and 4 of time integrated non-uniformity as a function of target length and focus position.

non-uniformity of about 1% in the implosion, the maximum considered tolerable. This means that beam pointing has to be less than 5 arcsec for a reactor chamber of 10 m of radius!

3.2. P4

This is a quasi-spherical configuration [18]. The capsule is inside a spherical layered shell (Li-foam + solid-Be + Au-foil) that acts both as converter and as radiation container. The capsule parameters are given in Ref. [10]. 1D simulations with code DEIRA allowed to optimize the energy coupling to the capsule maintaining a low stagnation pressure in the collision of the imploding shell against the expanding capsule ablator. The 1D gain is 78.

Beam lines are arranged into angle cones of $\pm 20^\circ$, $\pm 60^\circ$ with respect to the horizontal plane, corresponding to the zeros of the fourth Legendre polynomial P_4 . Using an appropriate power ratio between both cones, the low asymmetry modes ($l < 8$) can be suppressed. The residual non-uniformity have been calculated by the code VF2 to be less than 1% PTV. This target is simple and efficient but requires the steering of ion beam lines at considerable angles with respect to the horizontal plane. As in the targets described in Sections 2.1 and 2.3, the estimates of uniformity on the capsule obtained without hydrodynamic calculations can be misleading [19]. A 2D or 3D simulation will be needed to correctly evaluate the degree of symmetry.

4. Conclusions

A wide range of target configurations, compatible with presently considered HIDIF parameters, appears to be possible. A more detailed description of beam characteristics is needed to select an optimum target. In particular the following parameters have to be specified:

- Time and transversal profiles of the beam.
- Precision in power, timing and pointing.
- Cost and efficiency of the driver as a function of ion energy, focusing radius, pulse power and duration.
- Penalty cost associated with each different irradiation scheme.

Although a considerable progress in the understanding of heavy-ion fusion has resulted from the HIDIF project, several physical aspects have been not yet considered in our studies:

- Influence of time dependent asymmetries on capsule performance.
- Accurate evaluation of target constrains due to the Rayleigh–Taylor and Richtmyer–Meshkov short wavelength instabilities [20].
- 3D hydrodynamics aspects.
- Fully integrated simulations.

The inclusion of these points will require substantial improvements of our computer codes and models in the coming years.

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