Heavy Ion Targets

Presented at the 19th Symposium on Heavy Ion Inertial Fusion

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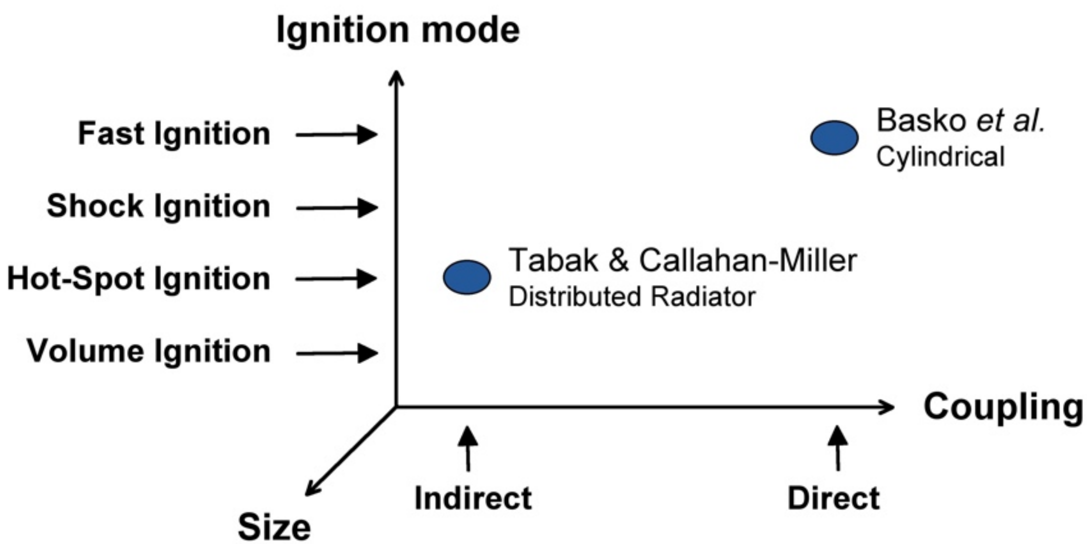
Target options fill a large 3-D space.



- **Increasing size ⇒ more energy, higher G, easier phase space**
- **Indirect → Direct ⇒ better coupling, harder alignment and beam smoothness**
- **Hot Spot → Fast ⇒ harder phase space and/or higher kinetic energy**

Different classes of targets have different programmatic implications.

- For indirect drive with hot-spot ignition, the NIF experiments are highly relevant. The physics of radiation production is different, but this physics has been tested to about 60 eV using light ions. If NIF is successful with indirect drive, it will be a huge programmatic advantage for ion indirect drive -- and vice versa.

- Although beam quality (and probably illumination geometry) are more demanding for direct drive with hot-spot ignition, the power, energy, and focal spot requirements are comparable to those of indirect drive. It seems likely that a machine designed for either could explore both. Shock ignition?

- In contrast, accelerators for fast ignition appear to be very different than those for hot-spot ignition. Moreover, accelerators for direct-drive fast ignition may not be suitable for indirect drive fast ignition.

- Choosing between fast ignition and other options is a critical issue.

Targets that separate compression and ignition (fast ignition, shock ignition) can, in principle, achieve high gain at low driver energy.

- **Assumptions about accelerators and beam physics strongly influence both gain and required driver energy.**

- **Fast ignition requires the deposition of ~ 10^9 J/g in a mass of fuel having characteristic "size" ≥ 0.3 g/cm^2 (an alpha range in hot DT fuel).**

- **Two cylindrical examples ($m = \pi r^2 R$)**
  r = 50 μ, R = 0.6 g/cm^2 ⇒ 50 kJ and r = 200 μ, R = 3 g/cm^2 ⇒ 4 MJ
  Similar arguments apply to compression.

- **Laser target designs, taken at face value, currently show better performance than ion target designs, e.g., Schmitt *et al*. G ~ 100 @ 250 kJ compared to Basko *et al*. G ~ 100 @ ≈ 7 MJ. Why?**

- **Almost everyone believes that high kinetic energy (> 50 GeV heavy ions) is needed to have a chance of getting the required radius and pulse duration ⇒large range ⇒ large ignition and compression energies.**

- **Assumed requirements such as using the same ion energy and beam geometry for compression and ignition may demand more driver energy.**

- **Are such additional requirements advantages or disadvantages?**

Fast ignition magnifies the importance of some traditional ion target issues.

- **Electrons: Simulations often use Maxwellian $dN/dT = 2N[T/(\pi\Theta^3)]^{1/2}\ exp(-T/\Theta)$. Binary collisions give $dN/dT \propto 1/T^{2}$, $T_{min} \le T \le T_{max} = 2\ m_e(\beta\gamma)^2$. For typical parameters $T_{min} \sim 10$ eV and $T_{max} \approx 1$ MeV. Note that binary collisions give equal integrated electron energy per decade. For $\Theta = 100$ eV, binary collisions give orders of magnitude more energy above say 100 keV. Does it matter?**

    - **At 100 keV, $R_e \approx 0.017$ g/cm^2. At 1 MeV, $R_e \approx 0.5$ g/cm^2 in low Z.**

    - **Hydrodynamics: In solid density (1 g/cm^3), >10% of the beam energy, at the beginning of the range, is transferred to electrons that can penetrate 0.2 to 5 mm. If one is trying to focus to say 1 mm, this effect appears significant, even if one considers multiple scattering.**

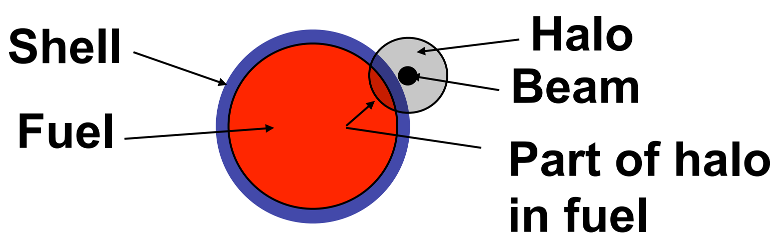
    - **Preheat is important if specific energy deposition in DT $\ge$ 100 J/mg ($\sim\varepsilon_F$). Simulations indicate that it requires ~ 100 kJ/mg to begin fuel compression $\Rightarrow$ ~ 0.1% of beam energy transported to fuel is a problem.**

- **Photons: Excitation by hot electrons, excitation by incident ions, and excitation of incident ions produce high energy photons not included in simple models. What do they do?**

Fast ignition magnifies the importance of some traditional ion target issues (continued).

- **Nuclear Reactions: Cross sections roughly geometric in HIF regime; σ = 2.2 b for Pb $\Rightarrow$ $\sigma \approx$ 2.2 b in DT $\Rightarrow$ Reaction Length = 1.9 g/cm^2 ; Range 3.8 g/cm^2 for 75 GeV $\Rightarrow$ 86% react. If mitigated by stopping all but the last 0.6 g/cm^2 (2 α ranges) in high-Z stuff, 27% react $\Rightarrow$ Simple range-energy is optimistic.**

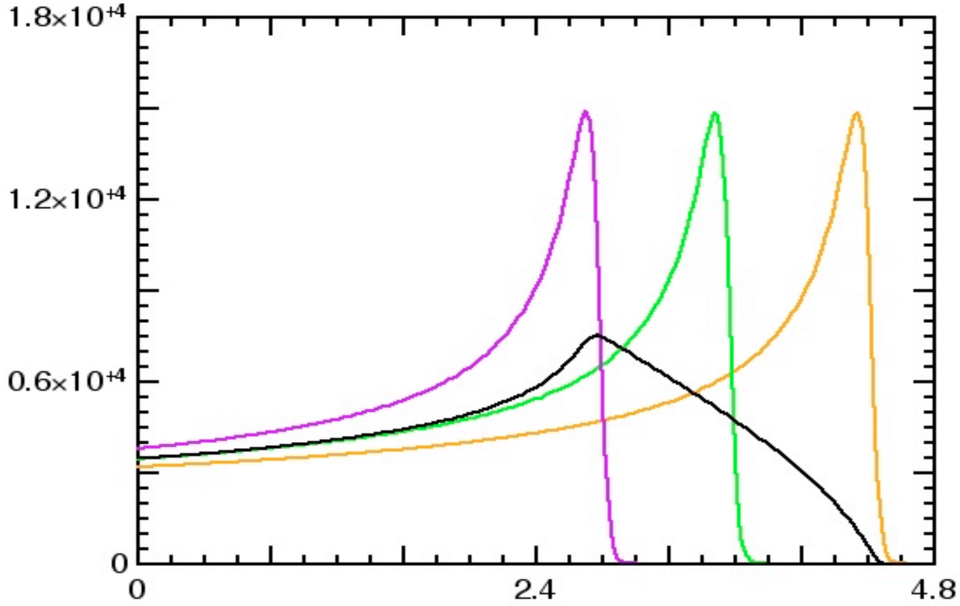
- **The "edge" of a beam is often approximated by 2 x rms. For a Gaussian spot 13.5% of energy lies outside 2σ. Experience shows that there is often a broad, Non-Gaussian halo. If even 1% of the beam energy were in such a halo, it would cause preheat (without some kind of mitigation).**



As drawn, ~ 10% of halo would preheat fuel -- enough to be of concern.

Fast ignition magnifies the importance of some traditional ion target issues (continued).

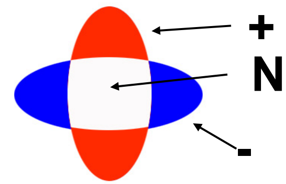
• The effects of energy spread on target gain were addressed in the 1980s. Consider an energy spread $\delta T/T = 10^{-4}$ before longitudinal compression. At this point the pulse duration is roughly 100 ns $\Rightarrow$ $\delta T/T$ = 10% @ 100 ps .



The colored curves (energy deposition vs. g/cm^2) are for 18, 20, and 22 GeV rubidium in hot DT. The black curve integrates over the energy spread. It shows a significant reduction in the Bragg peak used for ignition. This effect adds to straggling which is not included in all simulations.

Accelerator issues are challenging.

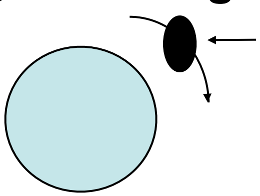
- **Even with non-Liouvillian schemes, the phase-space constraints for fast ignition are formidable. Moreover, there are issues with these schemes.**

  - **Opposite charge schemes:** 

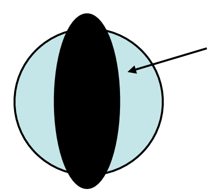
Simulated?

  - **Telescoping:** $x'' = -k^2(p)x$; **no space charge.**
$x'' = -k^2(p)x + CEx/(p\beta)$; **with space charge where electric field E = E(t).**
The space charge forces can also be funny:  **Simulated?**

- **In general, beam foci are astigmatic. The astigmatism and the transverse profile, including the beam radius, are likely time-dependent.**



Rotation leads to an m = 2 asymmetry.



What does a beam like this do to polar or spherical direct drive?

- **The beam centroids wobble. The current estimate in the IBEAM code is ~ 200 μ; marginal for indirect drive, likely fatal for the other options.**

Fast ignition magnifies the importance of some traditional beam physics issues.

• Consider neutralized focusing in the chamber. Assume $r = 100\ \mu$, $\tau = 100$ ps, 1 MJ, 20 GeV, A > 80 $\Rightarrow$ ion density ~ 5×10^{17} cm^{-3} $\Rightarrow$ plasma density ~ 5×10^{18} cm^{-3}. Since $\sigma > 10^{-18}$ cm^2, the beam is stripped, say +20 $\Rightarrow$ plasma density ~ 10^{20} cm^{-3} (> atmospheric density).

• At this density scattering destroys focus and nuclear reactions make a substantial halo.

• The Faltens issue: If there is high density in the chamber, how does one maintain vacuum in the beam lines? Loss of even one electron is fatal.

• The Tidman issue: Residual, non-reproducible magnetic fields in chamber plasma (perhaps $\nabla n \times \nabla T$) deflect the stripped beam. For example, a field of 1 Gauss could deflect the beam more than 100 μ.

• For intense beams all the other traditional issues (e.g., filamentation) must be revisited.

Outline/Summary

- **Ion targets can be classified according to their mode of implosion and their mode of ignition. Most target classes currently being studied already existed at the first HIF workshop 36 years ago, but there has been an explosion of different designs in the various classes.**

- **Target design cannot be separated from accelerator considerations. A target doesn't make sense unless an accelerator can drive it.**

- **Choosing the correct target-accelerator option is a critical issue -- particularly the choice between fast ignition and other options.**

- **Many of the questions about the various options are clear. Enough is known and the tools are available to answer many of these questions now.**