2nd International Workshop on Proton-Boron Fusion

HB11 ENERGY
LASER BORON FUSION

https://hb11.energy/

The “hybrid” approach to proton-boron inertial fusion

September 5, 2022

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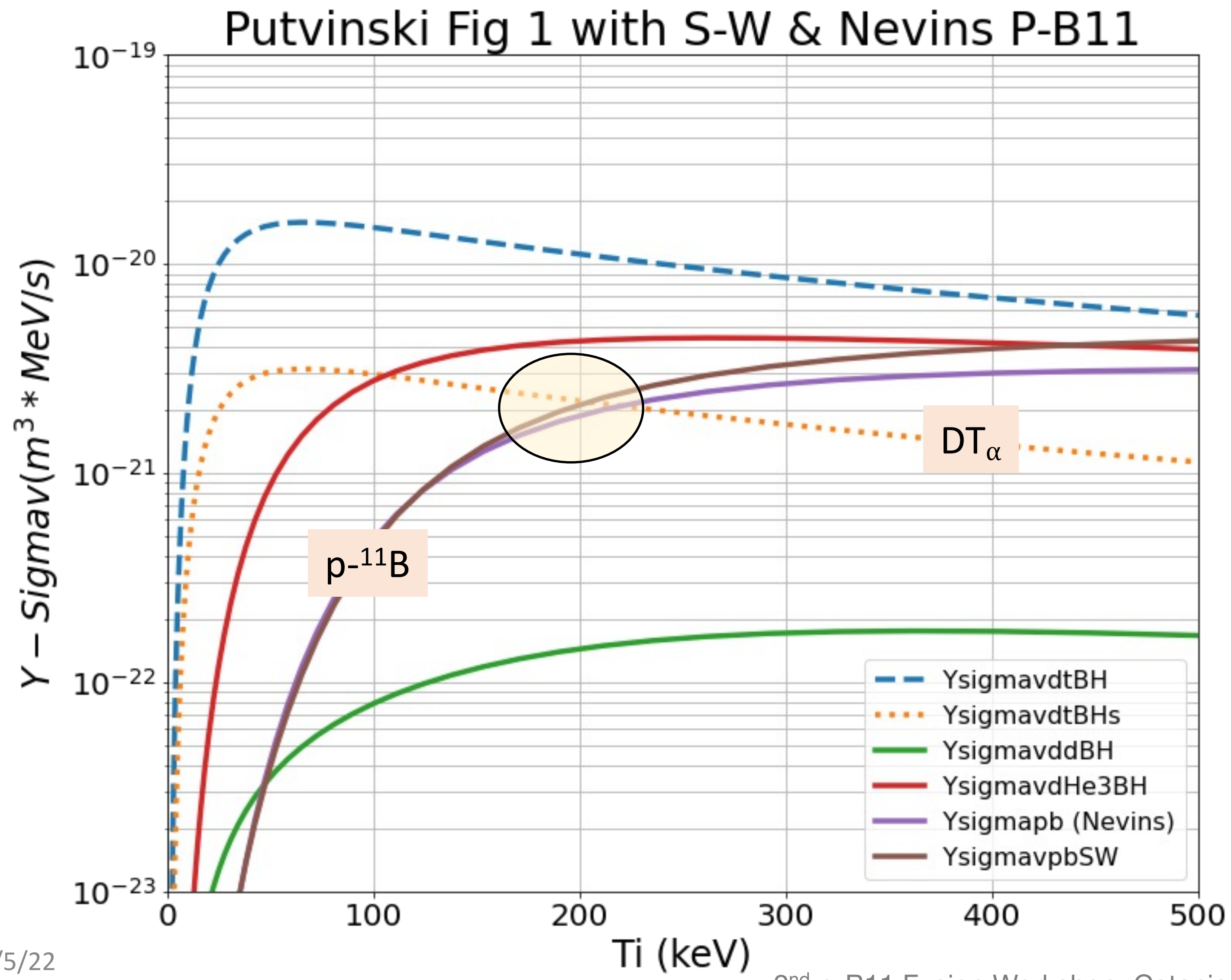
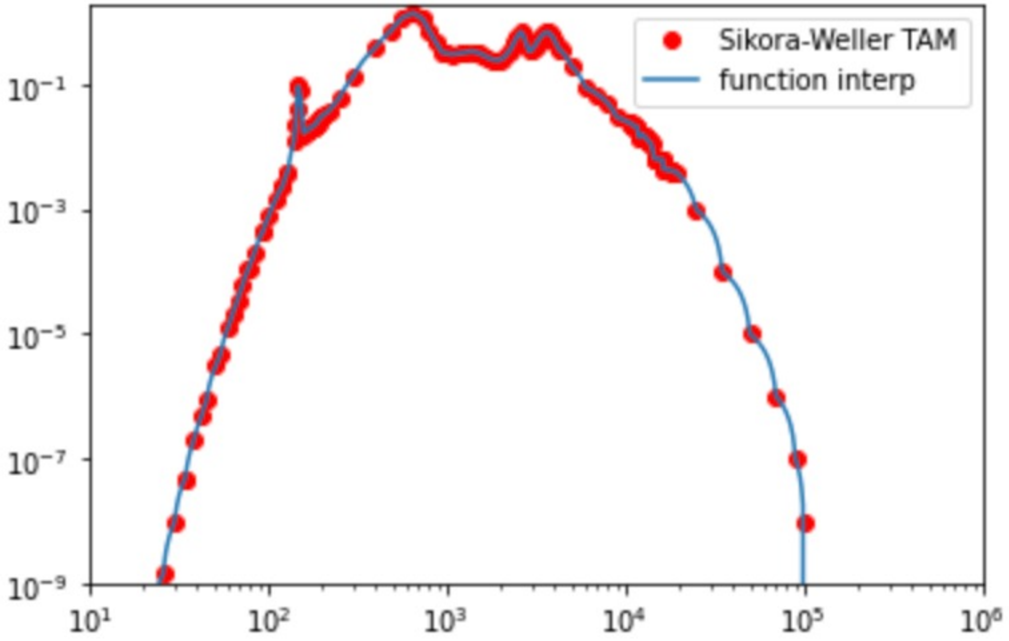
Welch, D.R.[2], Thoma, C.[2], Golovkin, I.E[3]., Campbell, E.M.[4], Hu, S. X.[4], Hegelich, B.M.[5], Labun, L.[5], Batani, D.[6], Belloni, F.[7], Margarone, D.[8]

<u>The Challenge:</u> p-^{11}B reactivity less than DT alpha reactivity below 200 keV





S. V. Putvinski, D. D. Ryutov, and P. N. Yushmanov, "Fusion reactivity of the pB11 plasma revisited," *Nuclear Fusion,* vol. 59, no. 7, p. 076018, 2019

M. H. Sikora and H. R. Weller, "A New Evaluation of the 11B(p,α)αα Reaction Rates," Journal of Fusion Energy, vol. 35, no. 3, pp. 538-543

DT fusion has been researched for decades and ignition has just been achieved – how do we translate this to lower reactivity p-^{11}B?

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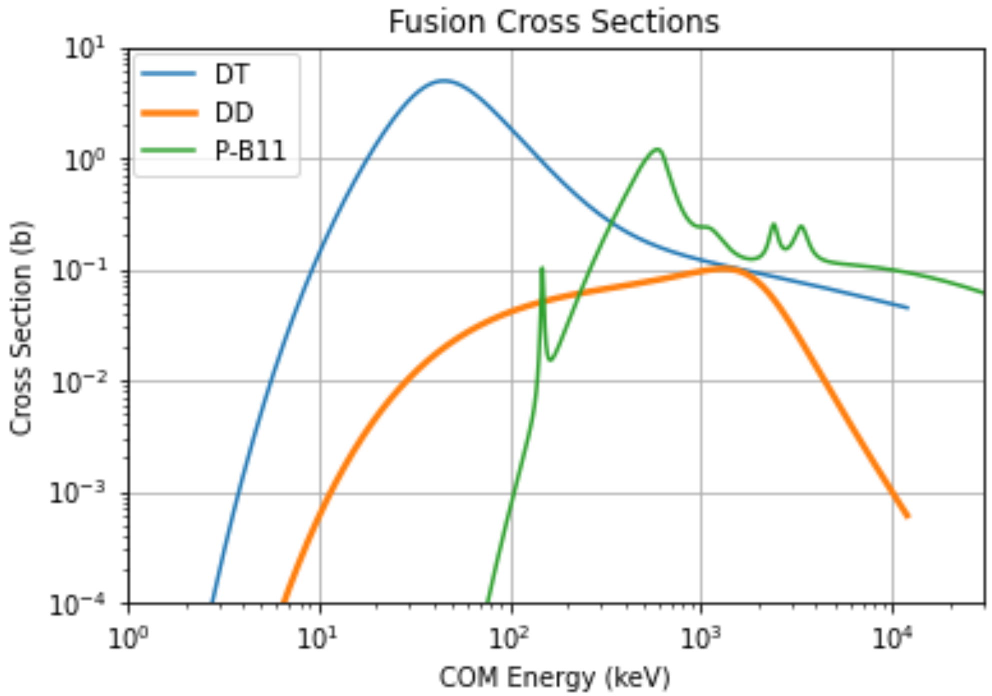
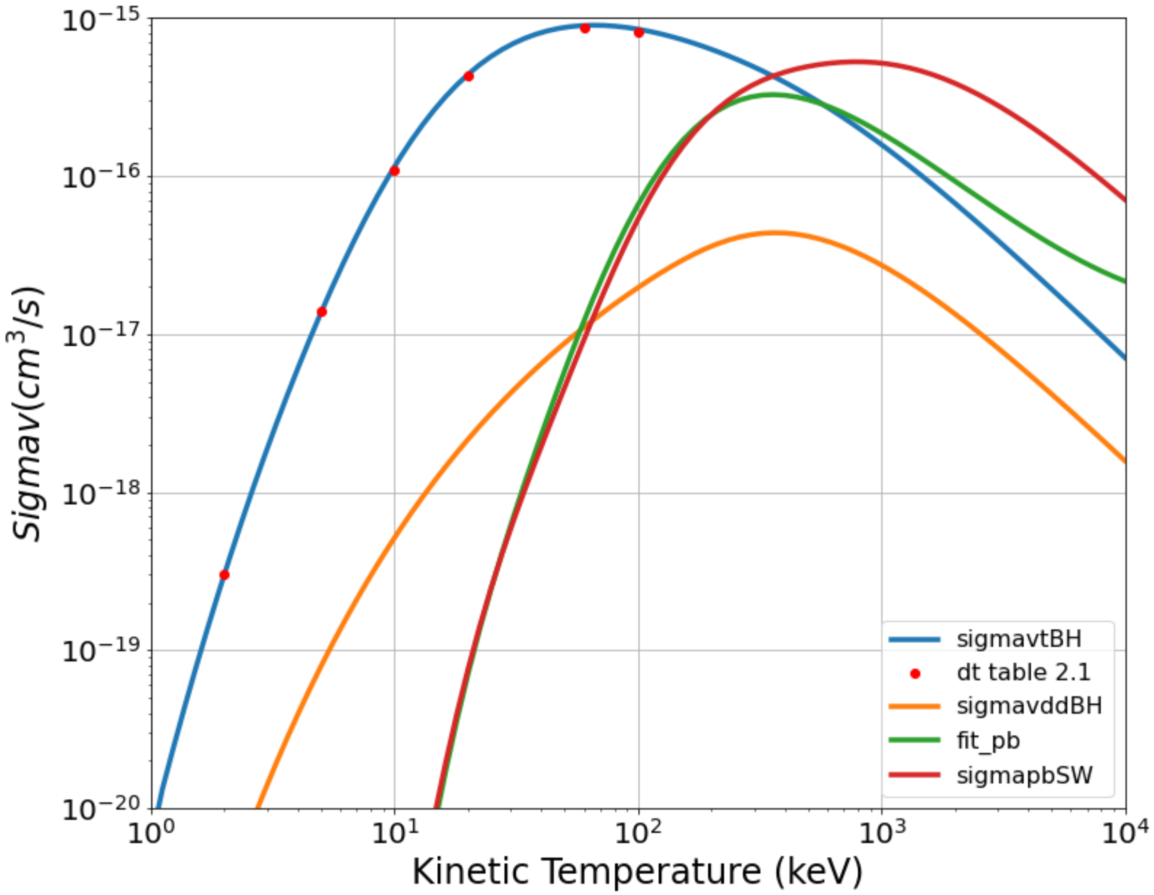


$$P_{fus} = n_p n_b \langle \sigma v \rangle Y$$

$$\langle \sigma v \rangle = \int f_p(v_p) f_b(v_b) \sigma(u) u d^3 v_p d^3 v_b$$



Burning p-^{11}B in equilibrium is likely impractical

J. J. Duderstadt and G. A. Moses, Inertial Confinement Fusion. Wiley, 1982.

Min ρr ~ 50 g/cm^2 @ 400 keV

Larger ρr means larger fuel masses, compressions, yields, & driver energies

Table 2.2 Candidates for Inertial Confinement Fusion Fuels

Fuel Candidate	ρR Requirement (g/cm^2)
$D+T \rightarrow {}^4He+n$	2 to 5
$D+D \rightarrow {}^3He+n$; $D+D \rightarrow T+p$	10 to 20
${}^{11}B+p \rightarrow 3\,{}^4He$	~500

S. Atzeni and J. Meyer-ter Vehn, The Physics of Inertial Fusion: …. 2004.

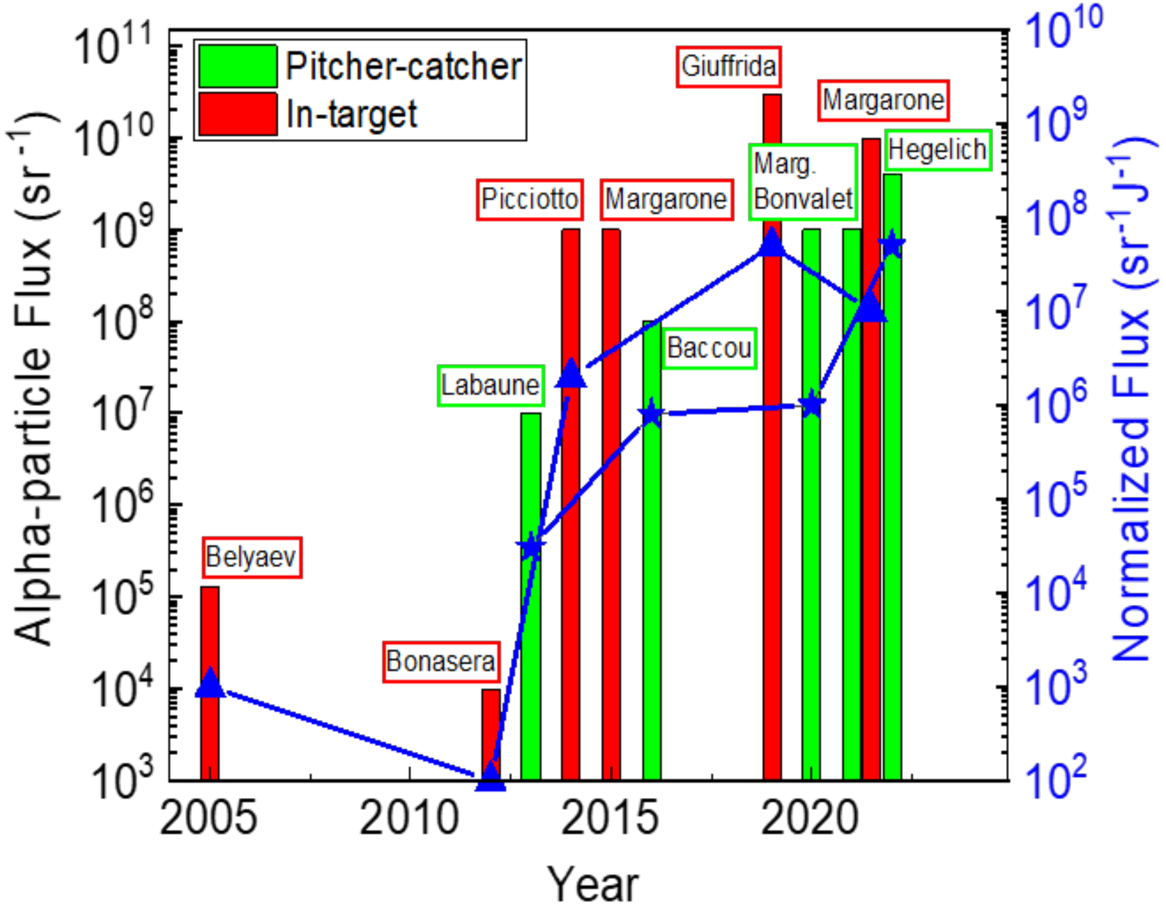
"an ICF reactor cannot be achieved by burning proton-boron mixtures in presently considered ICF concepts".

Table 2.2 Main properties of controlled fusion fuels.

	T_{id} (keV)	H_B^{min} (g/cm^2)	$T(H_B^{min})$ (keV)	Yield (GJ/mg)
DT	4.3	7.3	40	0.337
DD	35	52	500	0.0885
DD (full catalysis)	25	35	500	0.350
D ^{3}He	28	51	38	0.0357
p ^{11}B	—	73	250	0.0697

CPA experiments “seductively successful, but beam fusion reactions do not scale to sufficient gain

Reactions	Range	Slowing down time
$I(E_0) = \int_0^{E_0} \sigma(E) \left(\frac{dE}{dx}\right)^{-1} dE$	$R(E_0) = \int_0^{E_0} \left(\frac{dE}{dx}\right)^{-1} dE$	$\tau(E_0) = \int_0^{E_0} \left(v(E)\frac{dE}{dx}\right)^{-1} dE$

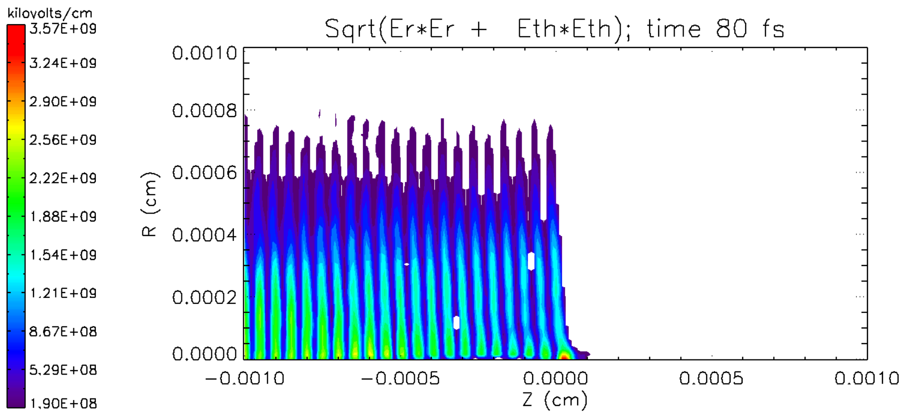


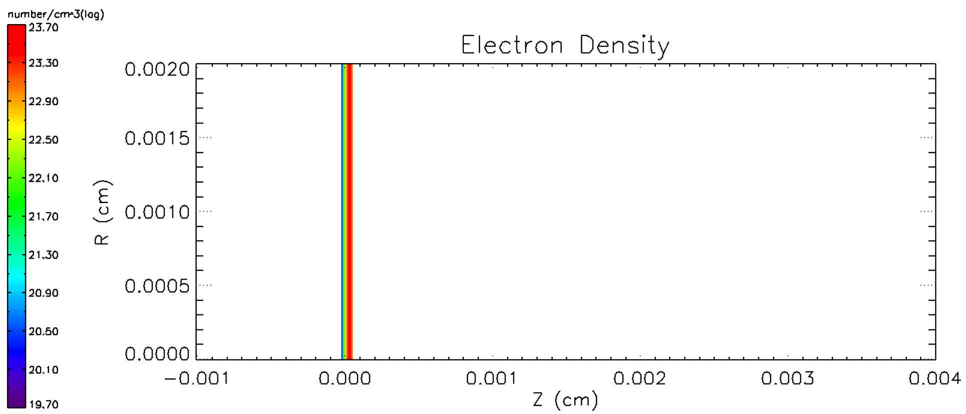
- For 1.4 barn peak cross section, mfp to proton fusion in B = 6.105 cm
- 1 MeV proton range = 12 microns in 1.8 ps - ~ 2.e-4 fusion probability
- Peak cross section @ 660 keV – narrow resonance, negligible < 100 keV
- Calculated thick target yield for 1 MeV in BN @ STP = 6.56e-5
- Proton range can be higher in hot or degenerate plasmas, increasing fusion/elastic scattering ratio

$4x10^{21}$ W/cm^2 laser intensity on thin 0.5 µm thick plastic foil in 3D cylindrical Chicago simulation of UT TPW experiment

Laser: 1 µm wavelength, Linear polarization, 4.85µm FWHM spot, 114 J energy, 147 fs duration, $4.2x10^{21}$ W/cm^2 intensity

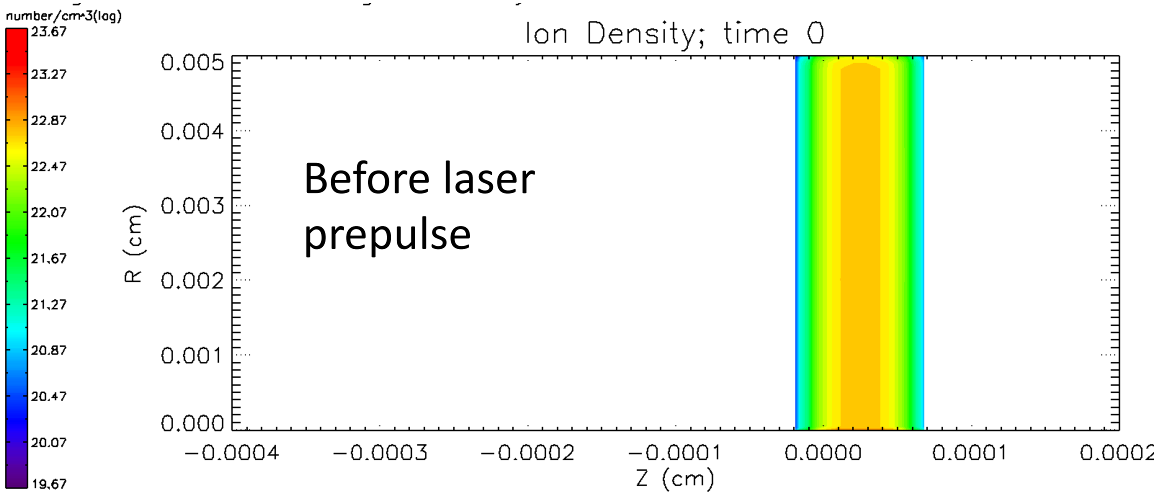
Plasma: 0.5-µm thick CH_2, 0.95 g/cm^3 density, Fixed state, C^{+6}, H^+, 10 eV initial temperature, Binary Scatter between all particles



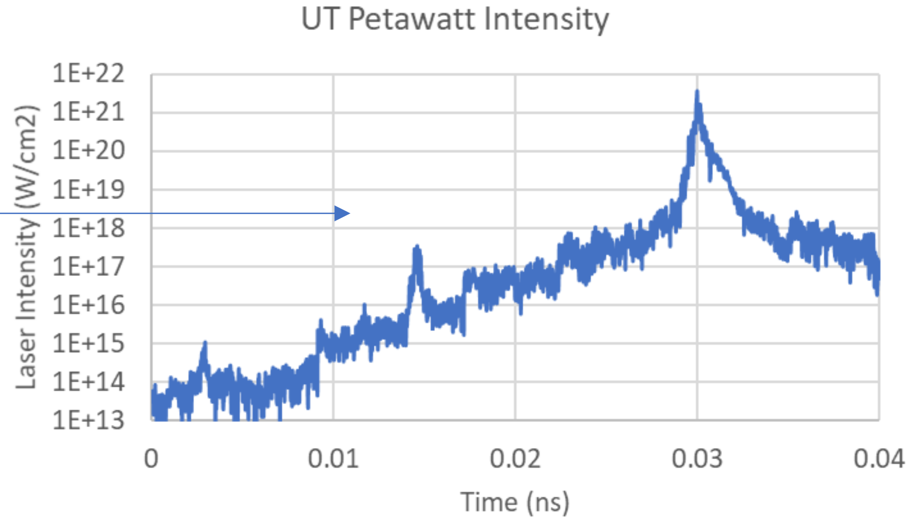


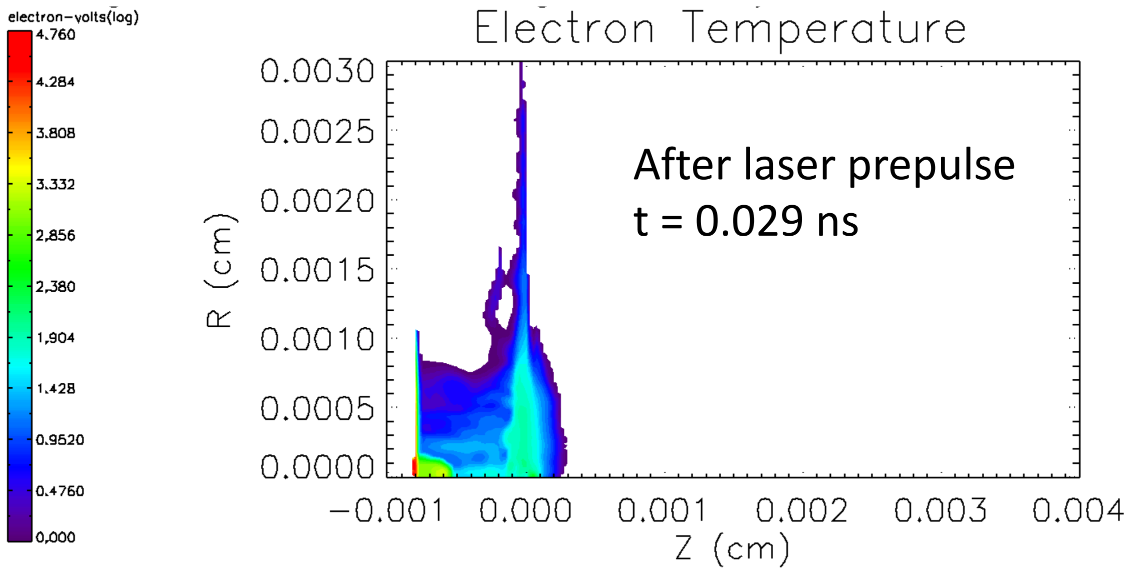
Examine proton production with an initial hydrodynamic simulation with laser foot.

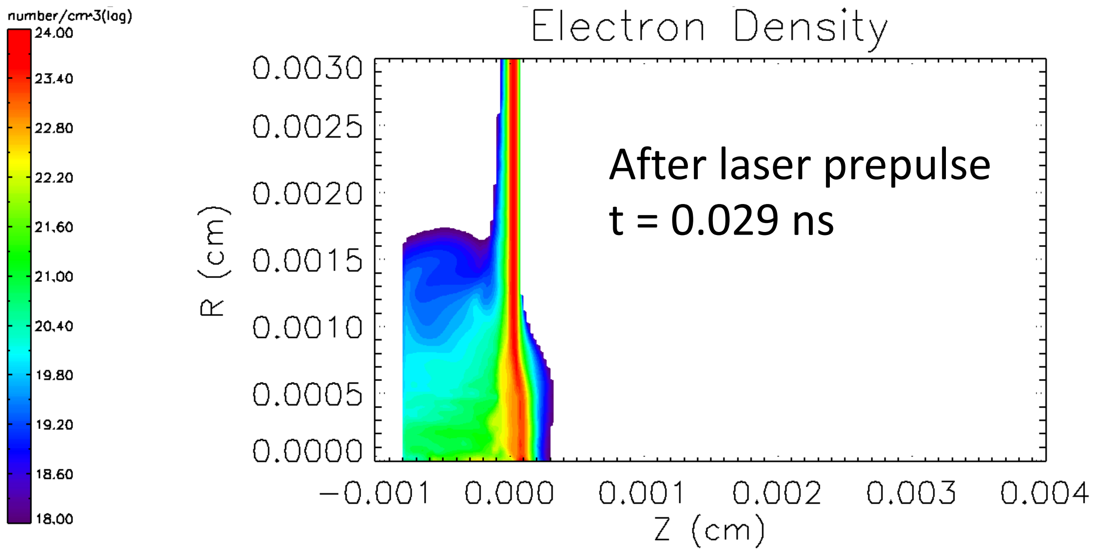
Laser target interaction with simulation of laser contrast from Plasma Mirror shot and expansion of pitcher target.



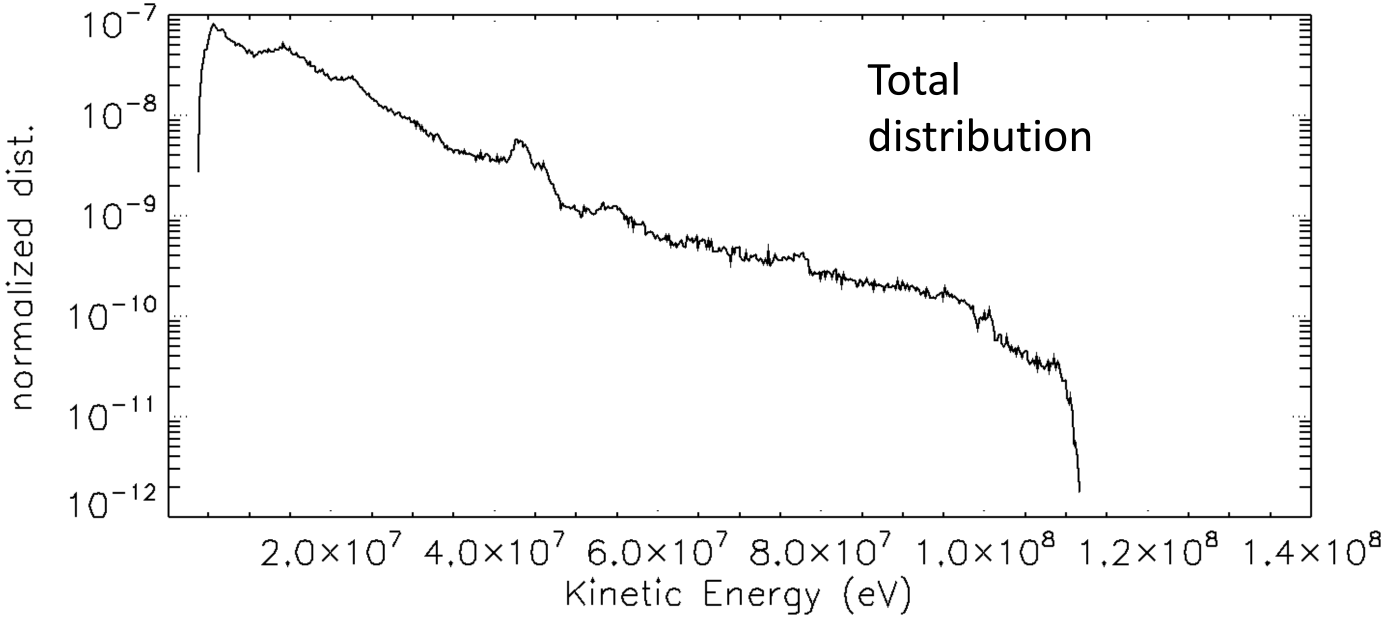
Initial simulation of laser foot impact on target using EOS treatment of plastic and fast photon model.

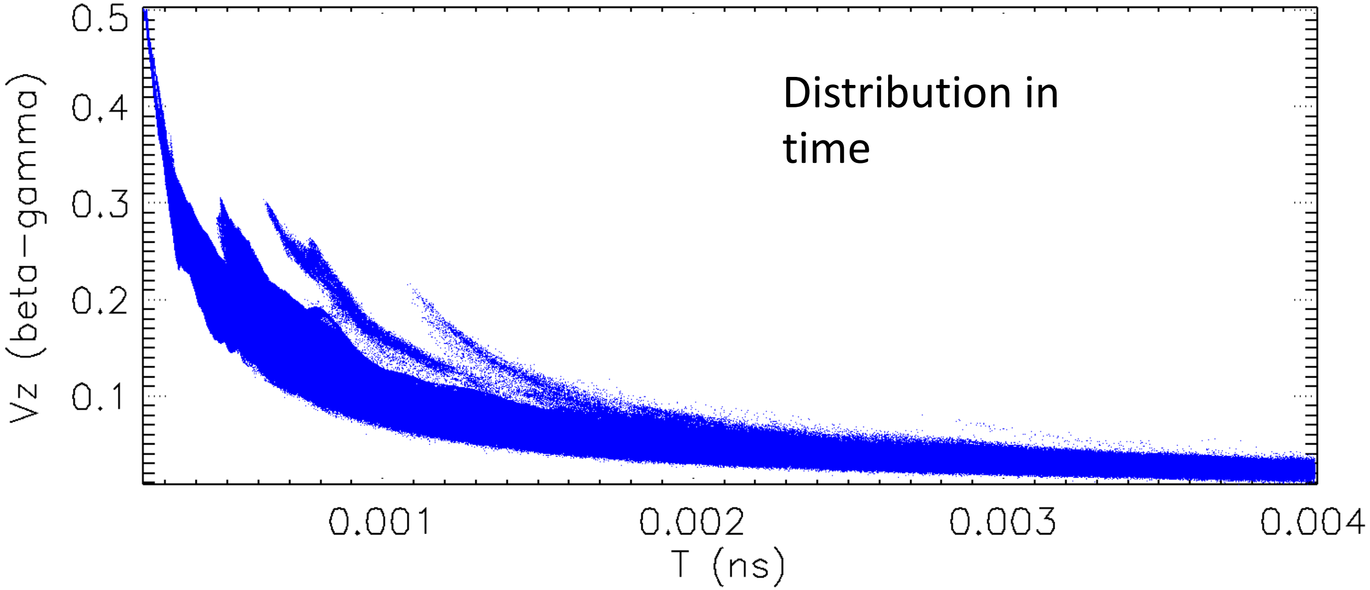






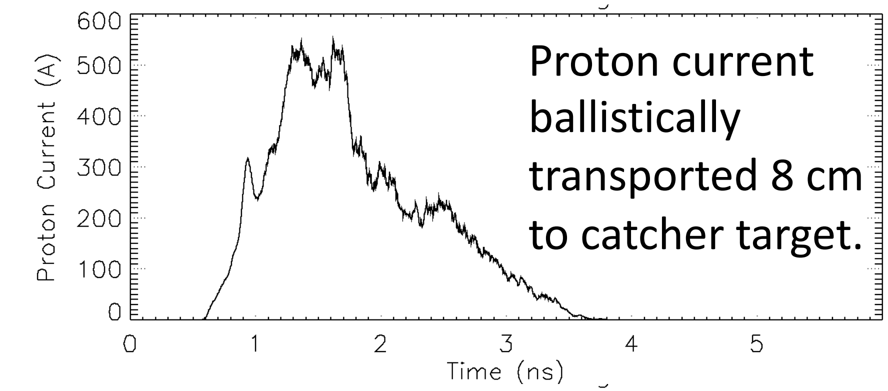
Proton energy spectrum, 115 MeV endpoint.

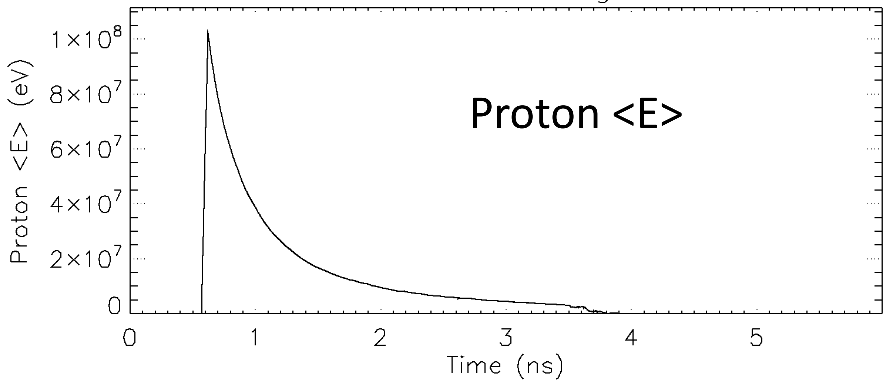


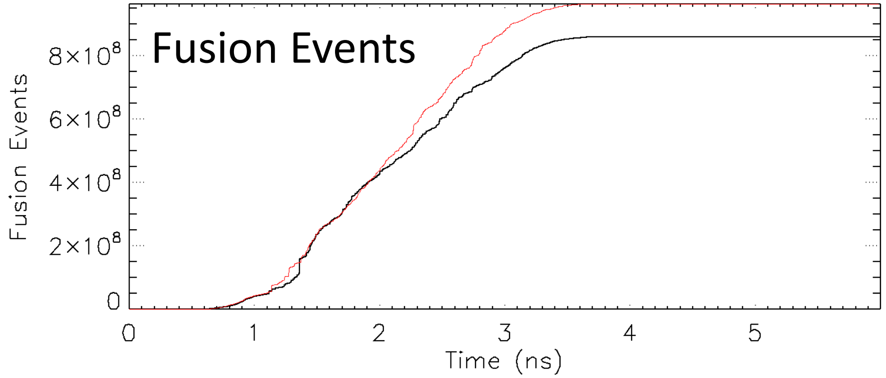


Protons late in time tend to have larger divergence and will miss catcher.

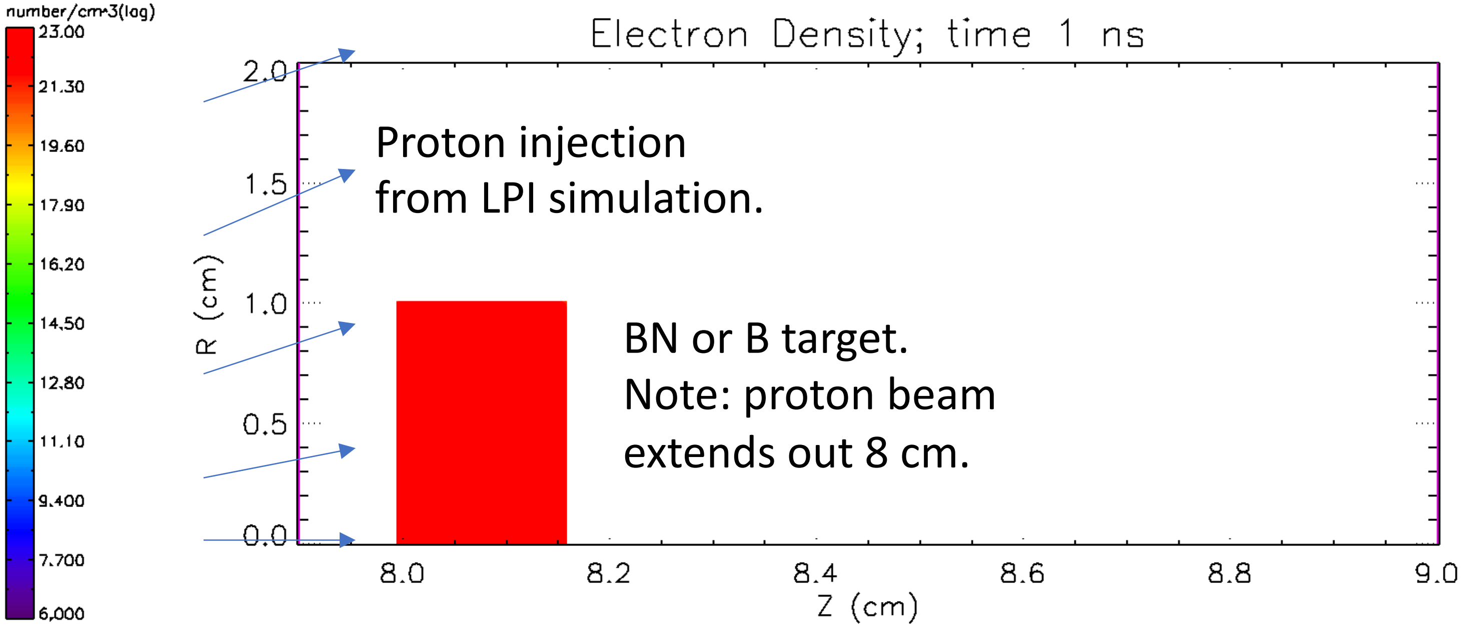
Proton interaction with BN or B cold target: 10^9 fusions.





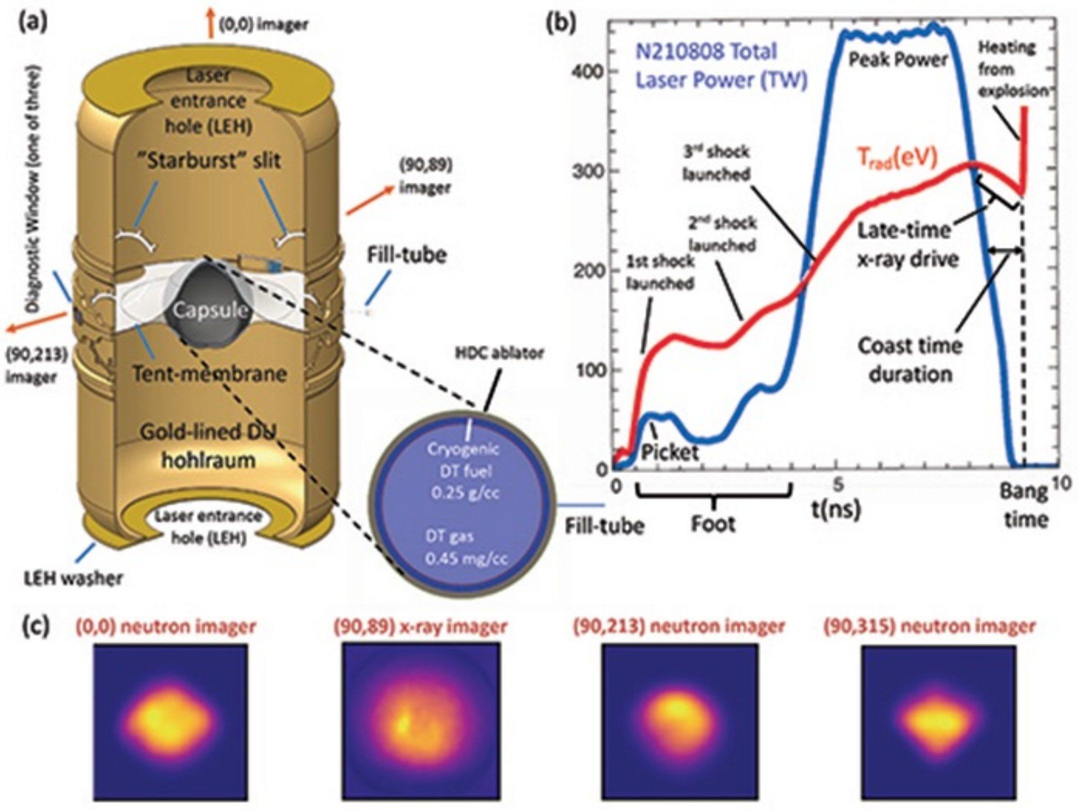


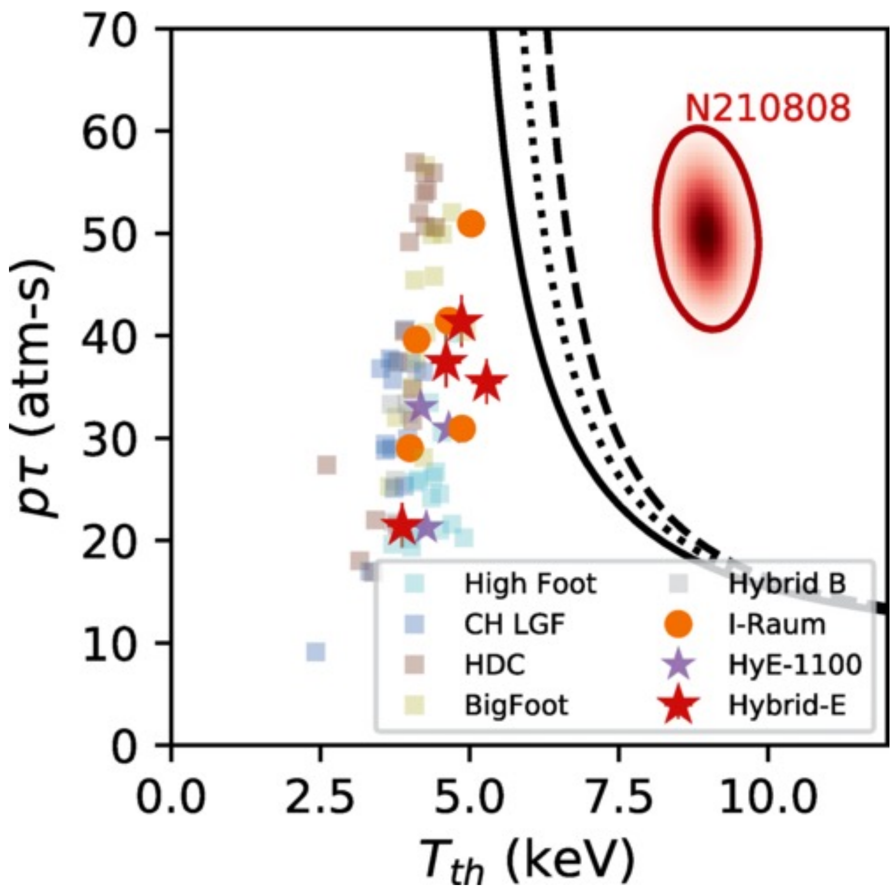
Plasma: 1-cm radius, 1.5 mm thick B_4N
2.1 g/cm^3 density, 0.1 eV temperature
Cold dEdx slowing in B 0.1 eV or
Binary Scatter with fixed state, $N^{+1.8}$, $B^{+1.8}$.



Approaching 10^9 pB11 events.
Cold dE/dx, binary in reasonable agreement.

The success of the National Ignition Campaign has led to renewed excitement, but fusion is hard….

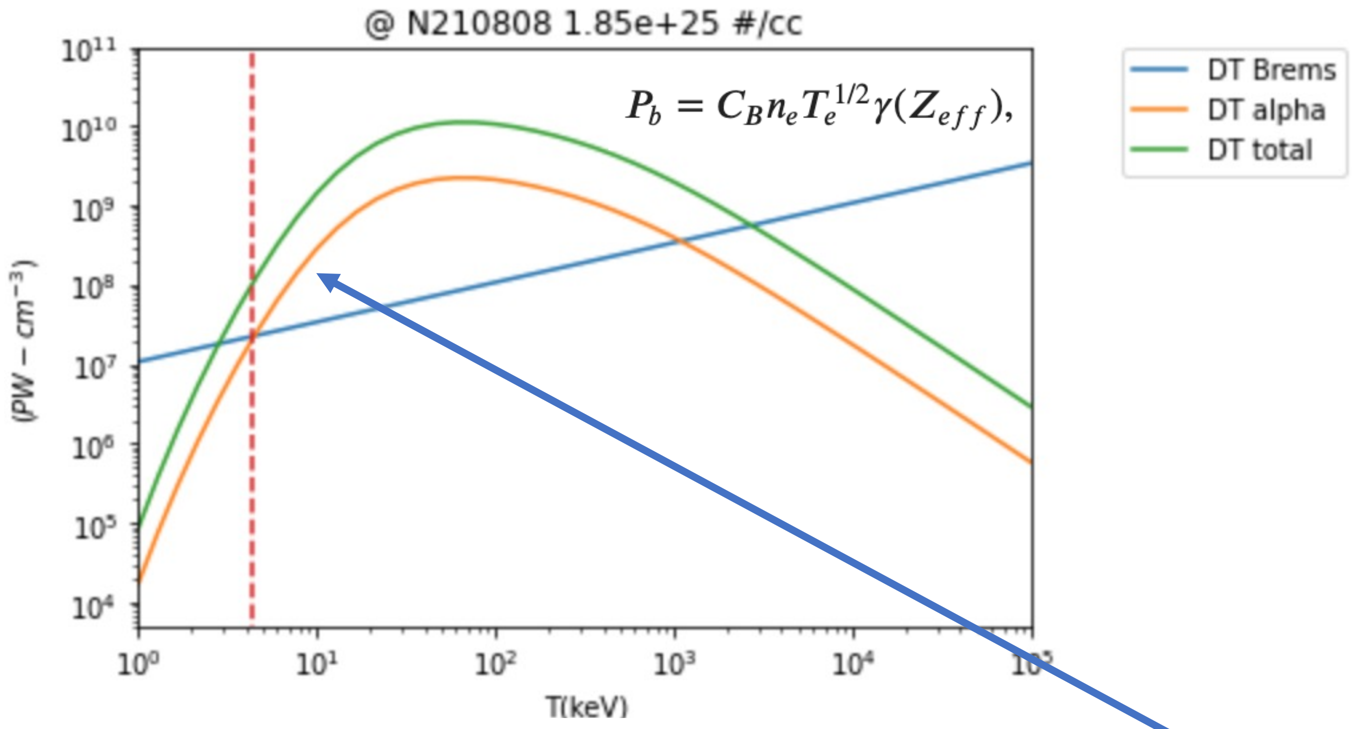


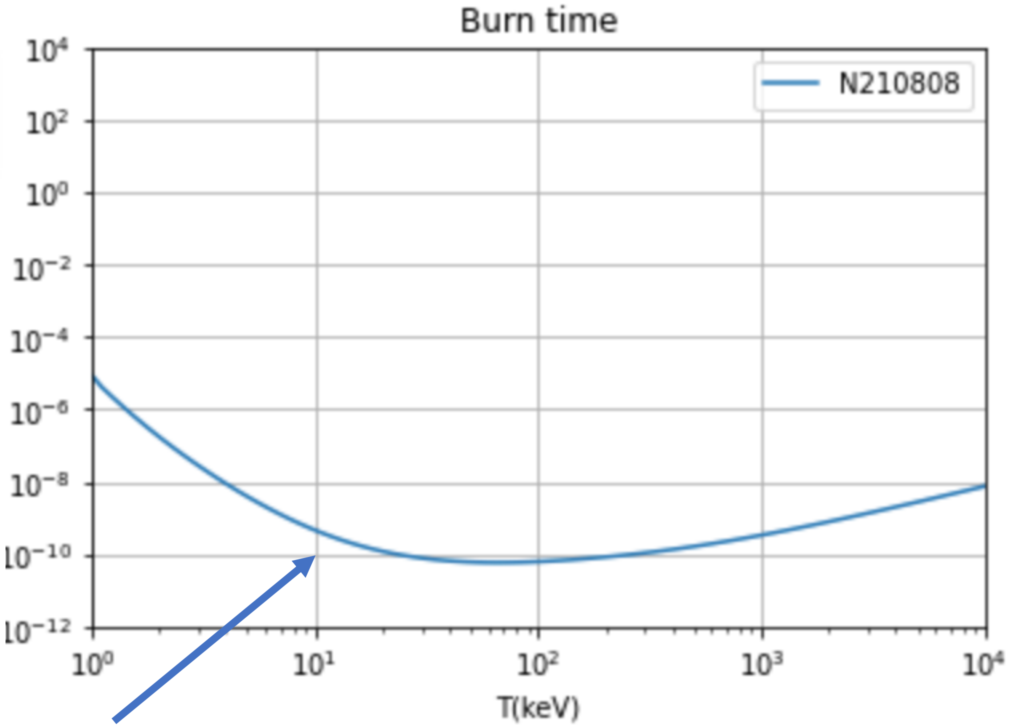


- Zylstra *et al.*, "Experimental achievement and signatures of ignition at the National Ignition Facility," *Physical Review E,* vol. 106, no. 2, p. 025202, 08/08/2022
- A. L. Kritcher et al., "Design of an inertial fusion experiment exceeding the Lawson criterion for ignition," Physical Review E, vol. 106, no. 2, 2022, doi: 10.1103/physreve.106.025201.

T_{ideal} ~4.5 keV

N210808 fusion yield is consistent with DT reactivity and burn time for published conditions





N210808 @ 185e+25 #/cc

$$P_{fus} = n_p n_b \langle \sigma v \rangle Y$$

$$\langle \sigma v \rangle = \int f_p(v_p) f_b(v_b) \sigma(u) u d^3 v_p d^3 v_b$$

$$\tau_{fus} = \frac{1}{\langle \sigma v \rangle n_0}$$

"More than 1,000 authors are included in the Physical Review Letters paper to recognize and acknowledge the many individuals who have worked over many decades to enable this significant advance, which put researchers at the threshold of fusion gain and achieving scientific ignition."

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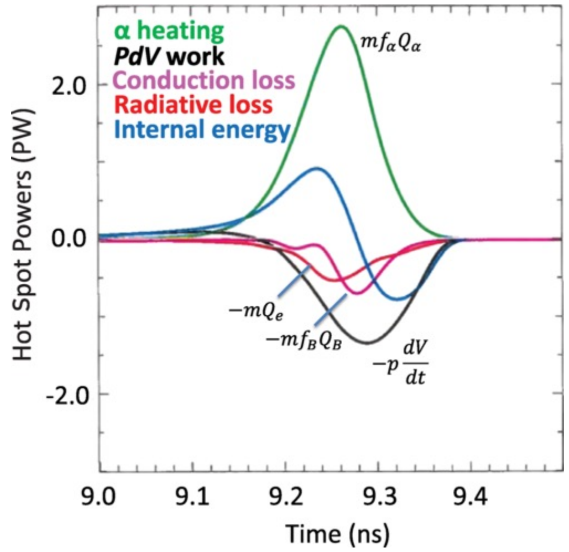
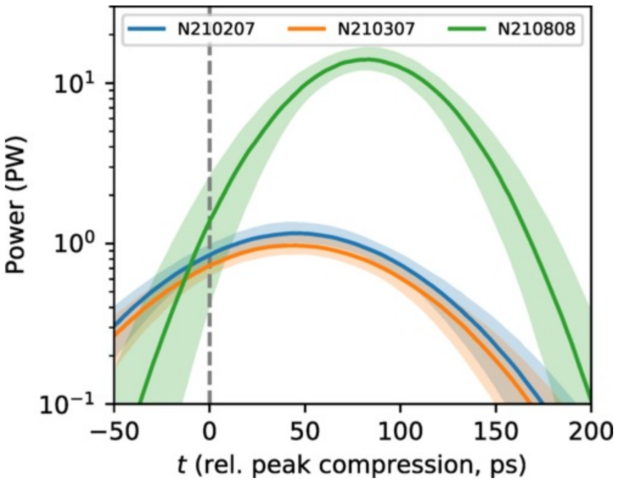
PHYSICAL REVIEW LETTERS **129,** 075001 (2022)

J. M. Mack,[5] A. J. Mackinnon,[2] S. A. MacLaren,[2] A. G. MacPhee,[2] G. R. Magelssen,[5] J. Magoon,[10] R. M. Malone,[6] T. Malsbury,[2] R. Managan,[2] R. Mancini,[30] K. Manes,[2] D. Maney,[2,†] D. Manha,[2] O. M. Mannion,[7] A. M. Manuel,[2] E. Mapoles,[2] G. Mara,[2] T. Marcotte,[1] E. Marin,[1] M. M. Marinak,[2] C. Mariscal,[1] D. A. Mariscal,[2] E. F. Mariscal,[2] E. V. Marley,[2] J. A. Marozas,[10] R. Marquez,[1] C. D. Marshall,[2] F. J. Marshall,[10] M. Marshall,[10] S. Marshall,[16] J. Marticorena,[2] D. Martinez,[2] I. Maslennikov,[2] D. Mason,[2] R. J. Mason,[5] L. Masse,[2,15] W. Massey,[2] P.-E. Masson-Laborde,[15,31] N. D. Masters,[2] D. Mathisen,[2] E. Mathison,[1] J. Matone,[2] M. J. Matthews,[2] C. Mattoon,[2] T. R. Mattsson,[7] K. Matzen,[7] C. W. Mauche,[2] M. Mauldin,[1] T. McAbee,[2] M. McBurney,[2] T. Mccarville,[2] R. L. McCrory Jr.,[10] A. M. McEvoy,[5] C. McGuffey,[1] M. Mcinnis,[1] P. McKenty,[10] M. S. McKinley,[2] J. B. McLeod,[2] A. McPherson,[7] B. Mcquillan,[1,†] M. Meamber,[2] K. D. Meaney,[5] N. B. Meezan,[2] R. Meissner,[2] T. A. Mehlhorn,[7] N. C. Mehta,[2] J. Menapace,[2] F. E. Merrill,[5] B. T. Merritt,[2] E. C. Merritt,[5] D. D. Meyerhofer,[5] S. Mezyk,[2] R. J. Mich,[2] P. A. Michel,[2] D. Milam,[2] C. Miller,[2] D. Miller,[2]



$V_{hotspot}$ = 6.4 ± 0.75 x 10^5 μm^3

15 x 10^3 PW x 100 x 10^{-12} ~ 1.5 MJ
~4 μg DT burned



ICF Indirect Drive Collab. *et al.*, "Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment," *Phys. Rev. Lett.*, vol. 129, no. 7, p. 075001, 08/08/ 2022, doi: 10.1103/PhysRevLett.129.075001.

US DOE held a Basic Research Needs Workshop on IFE & Chairs-Panels-Subpanels are writing a report to establish PRDS for an IFE Program

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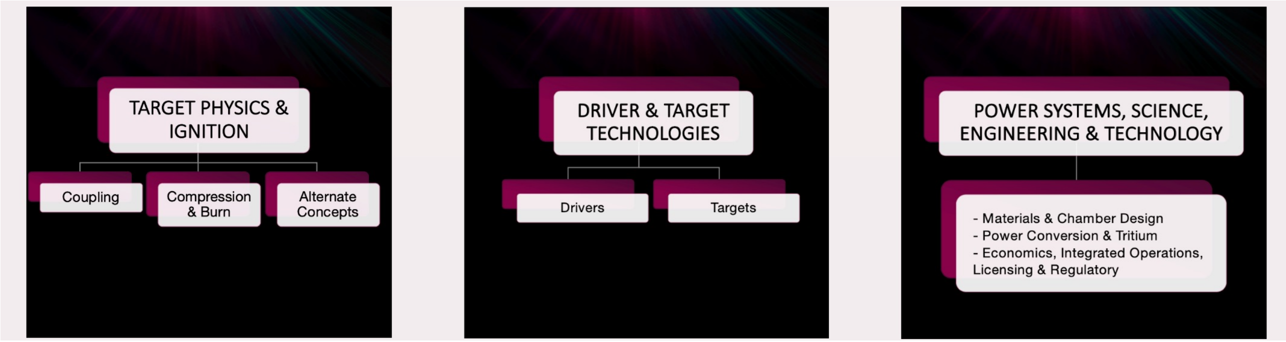
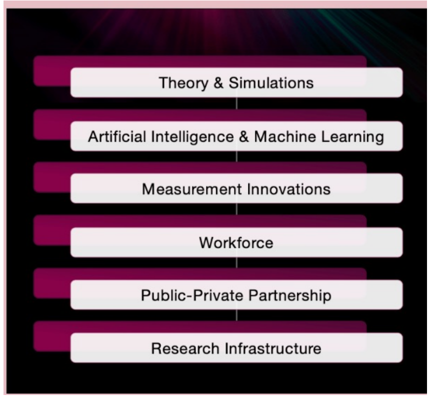


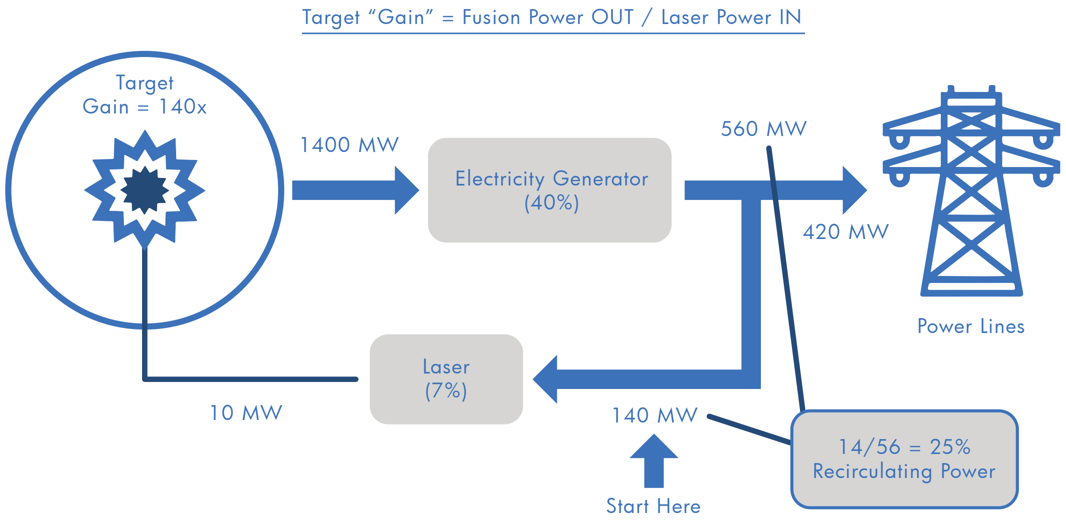


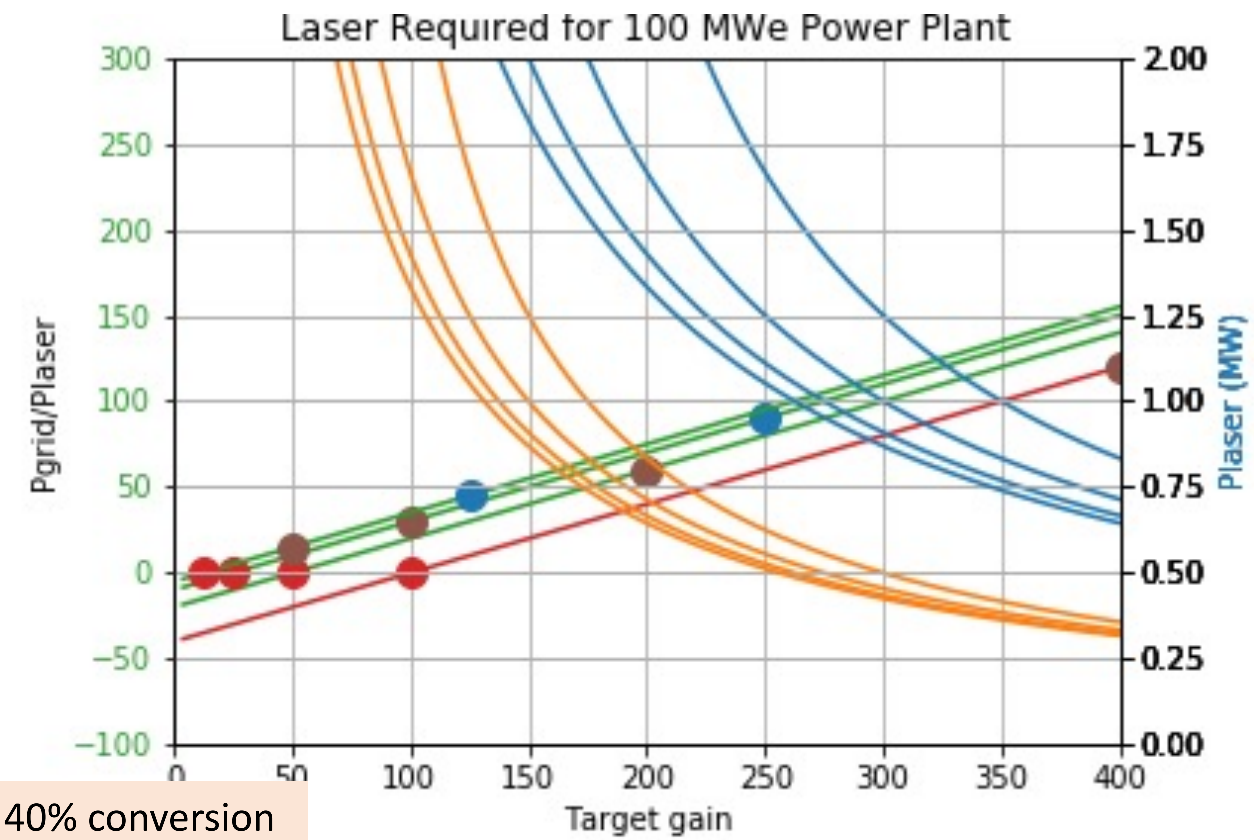
https://events.bizzabo.com/IFEBRN2022/home

- Assess and summarize the status of science and technology for Inertial Fusion Energy (IFE) in the U.S. and abroad.
- Assess enabling science and technologies common to Inertial Confinement Fusion and IFE and define a set of priority research opportunities that address the research and development (R&D) challenges unique to IFE, along with evaluation criteria to assess ongoing progress in an IFE technology development program.
- Assess the maturity and potential of the various IFE concepts toward a path to a viable IFE fusion pilot plant. Use TRL methodology to guide the R&D demonstration of ignition and reactor-level gain for each concept:
  - Demonstration of ignition and reactor-level gain
  - Manufacturing and mass production of reactor-compatible targets
  - Driver technology at reactor-compatible energy, efficiency, and repetition rate
  - Target injection, tracking and engagement at reactor-compatible specifications
  - Chamber design and first wall materials
  - Self-consistency of the proposed concepts regarding an integrated power plant design, to inform the formation of a balanced IFE program
- Identify magnetic fusion energy (MFE) efforts in the United States and abroad that could be leveraged to advance IFE …
- Assess the role of the private sector, including public-private partnerships in a national IFE Program and design of a fusion pilot plant.
  Assessment of IFE research opportunities should span experiments, theory and simulation, artificial Intelligence and machine Learning, diagnostics, drivers, targets, target delivery, integrated plant design, and systems engineering.

The workshop is expected to provide FES with a set of **priority research opportunities (PROs)** that can inform future research efforts in IFE and build a community of next-generation researchers in this area. The findings of this workshop will be summarized in a report that should be submitted to FES within three months after the meeting.

G~200 required for practical fusion powerplant - Target gain set by ICF burn physics

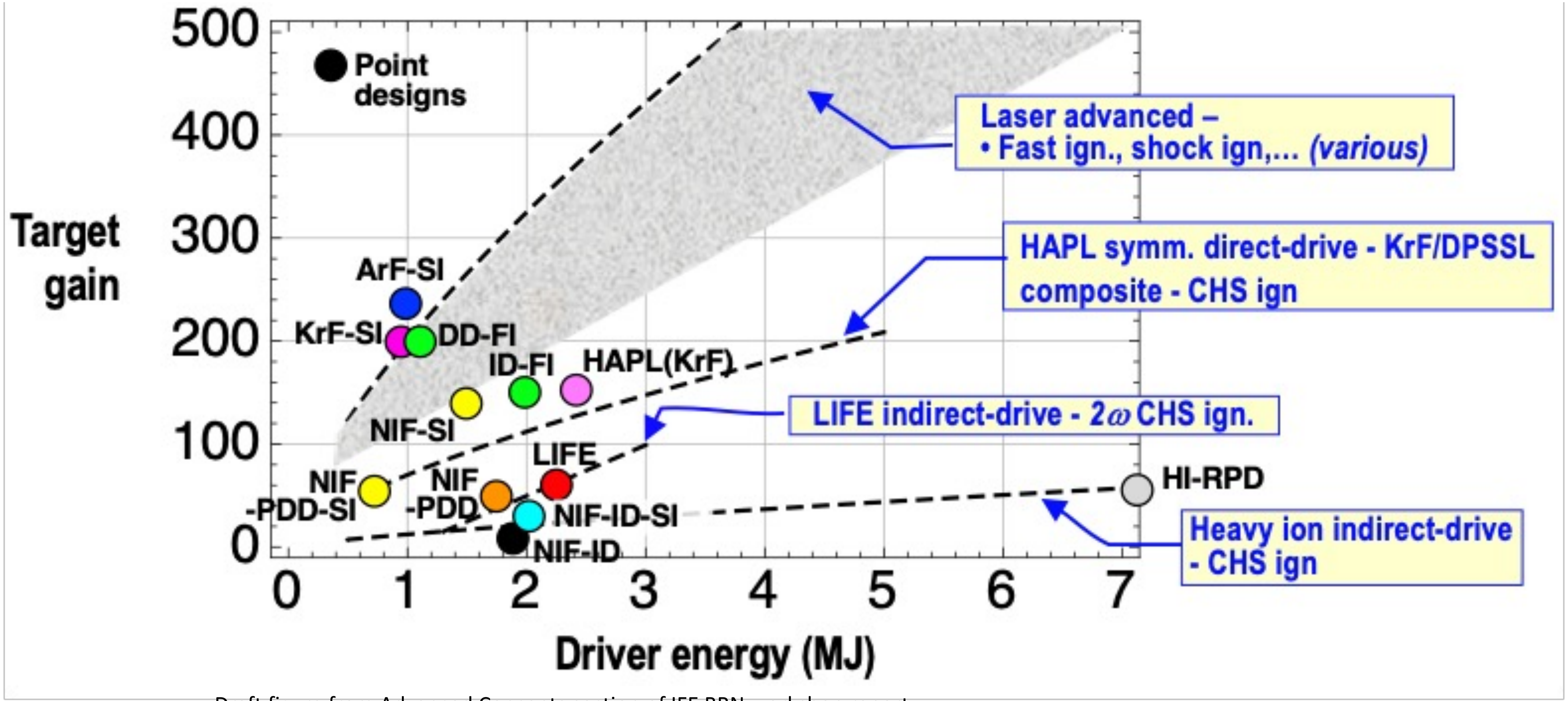




Electrical Power 200 MW requires Thermal Power 500 MW @ 40% conversion
Thermal Energy/pulse = 100 (MJ/pulse) @ 5 Hz
7.e+19 (Reactions/pulse) 2.1e+20 (alphas/pulse)
Boron burnup ~1260 (µg/pulse) > 300 times NIF DT burn

80% electrical conversion efficiency
40% electrical conversion efficiency

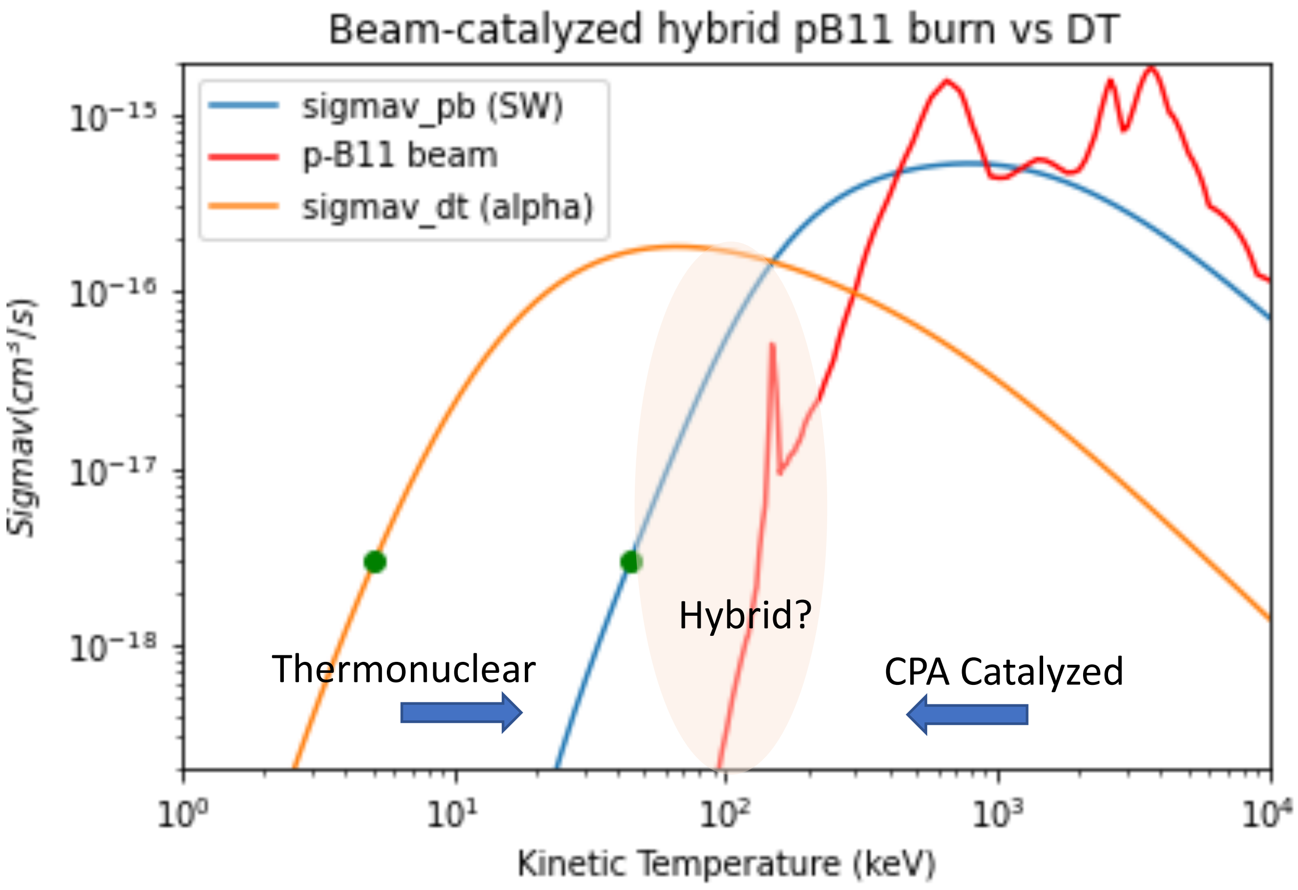
Many ICF target point designs with G > 100 connect to NIF design – we need a credible point design for p-B11

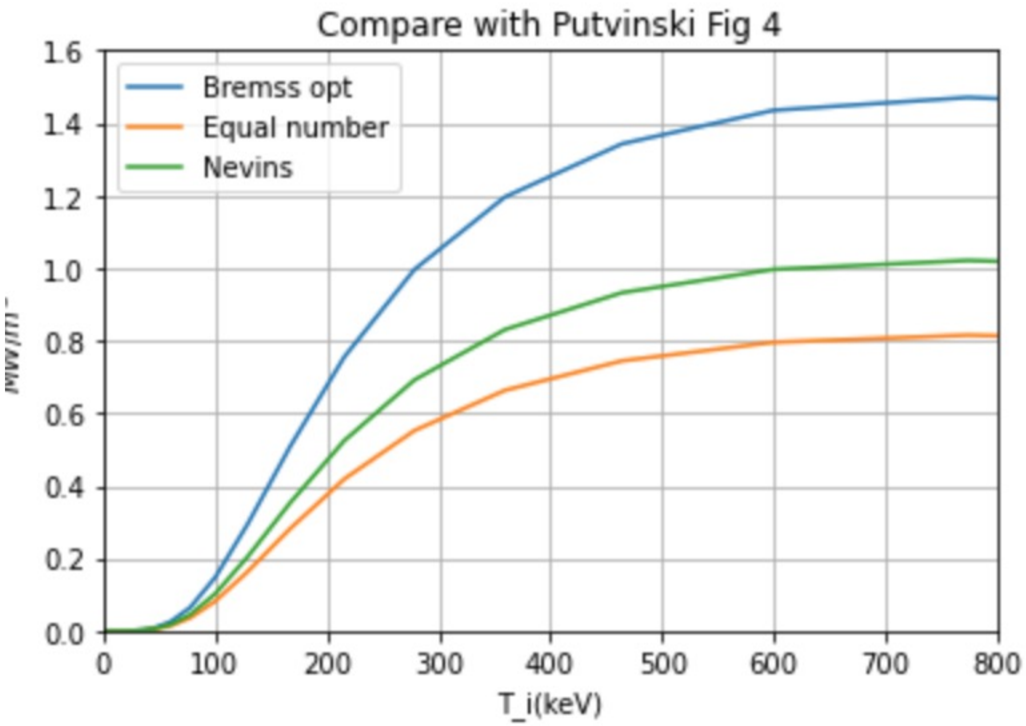


Draft figure from Advanced Concepts section of IFE BRN workshop report

S. W. Haan *et al.*, "Point design targets, specifications, and requirements for the 2010 ignition campaign on the National Ignition Facility," *Physics of Plasmas,* vol. 18, no. 5, p. 051001

The hybrid approach fusion seeks to combine beam-catalyzed & thermonuclear reactions with strong radiation loss control



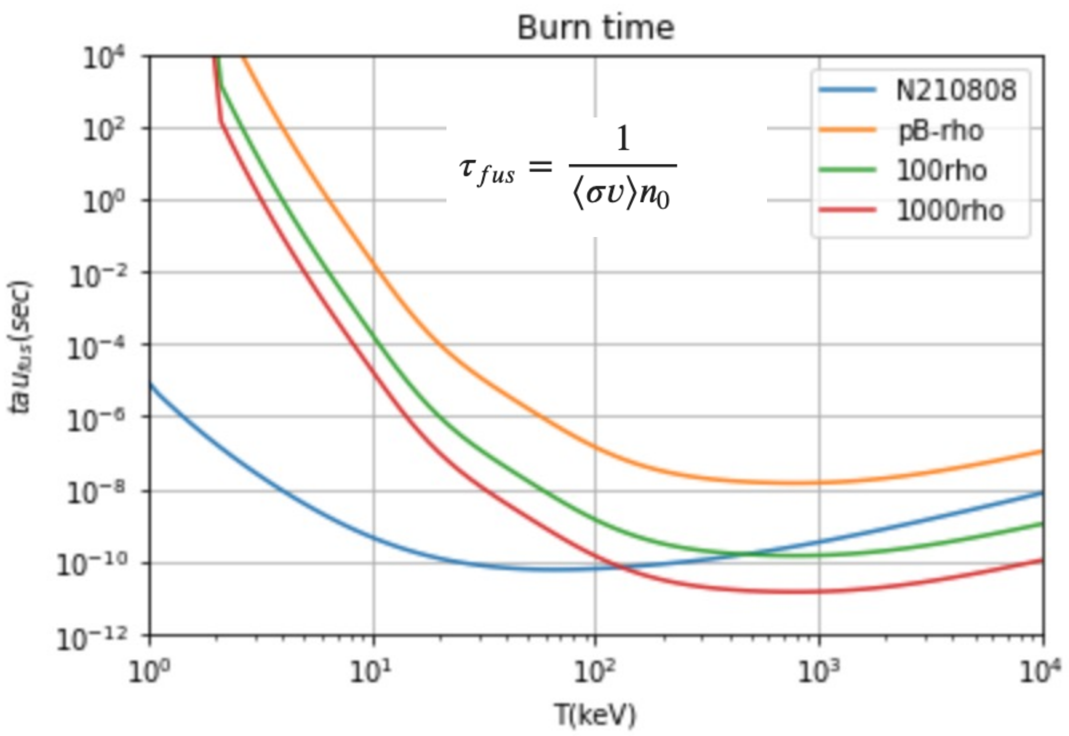


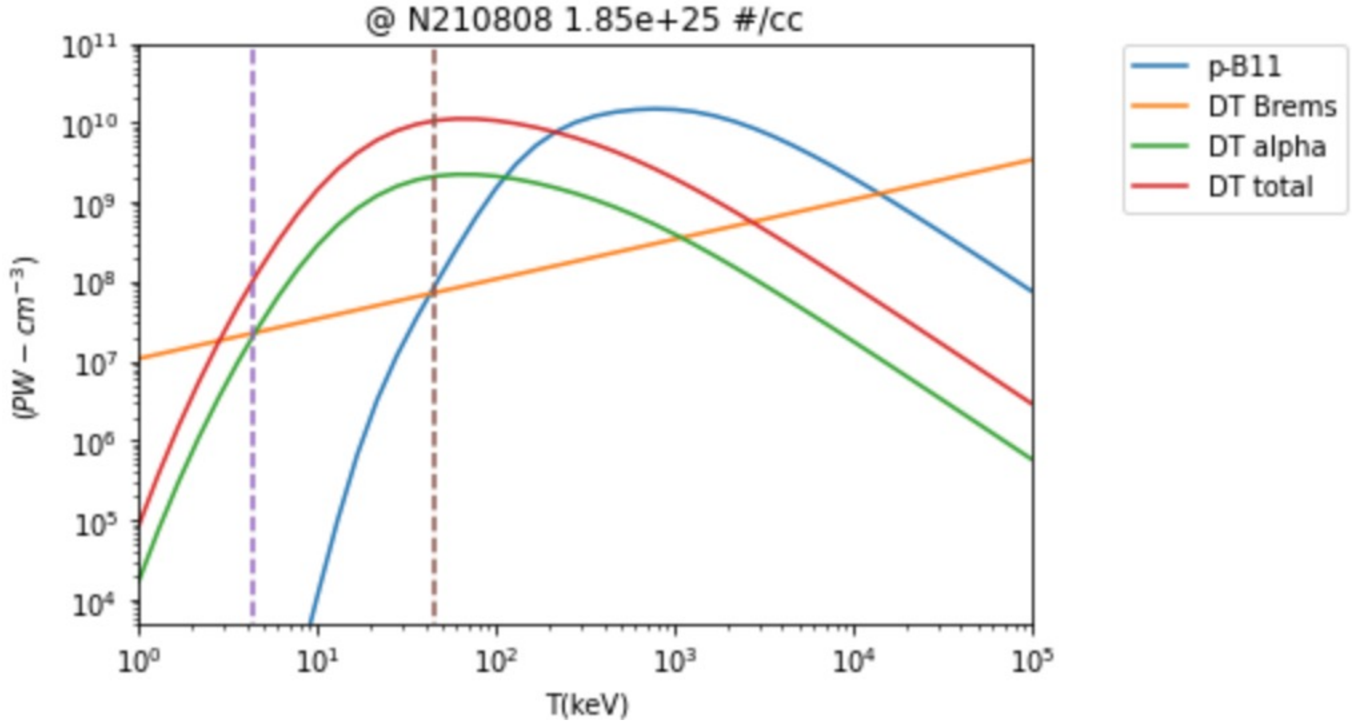
Radiation minimized at 5-H:1-B
Target fabrication challenge…

c.f., J. M. Martinez-Val, S. Eliezer, M. Piera, and G. Velarde, "Fusion burning waves in proton-boron-11 plasmas," *Physics Letters A*, vol. 216, no. 1, pp. 142-152

H. Hora *et al.*, "Road map to clean energy using laser beam ignition of boron-hydrogen fusion," *Laser and Particle Beams*, vol. 35, no. 4, pp. 730-740, 2017

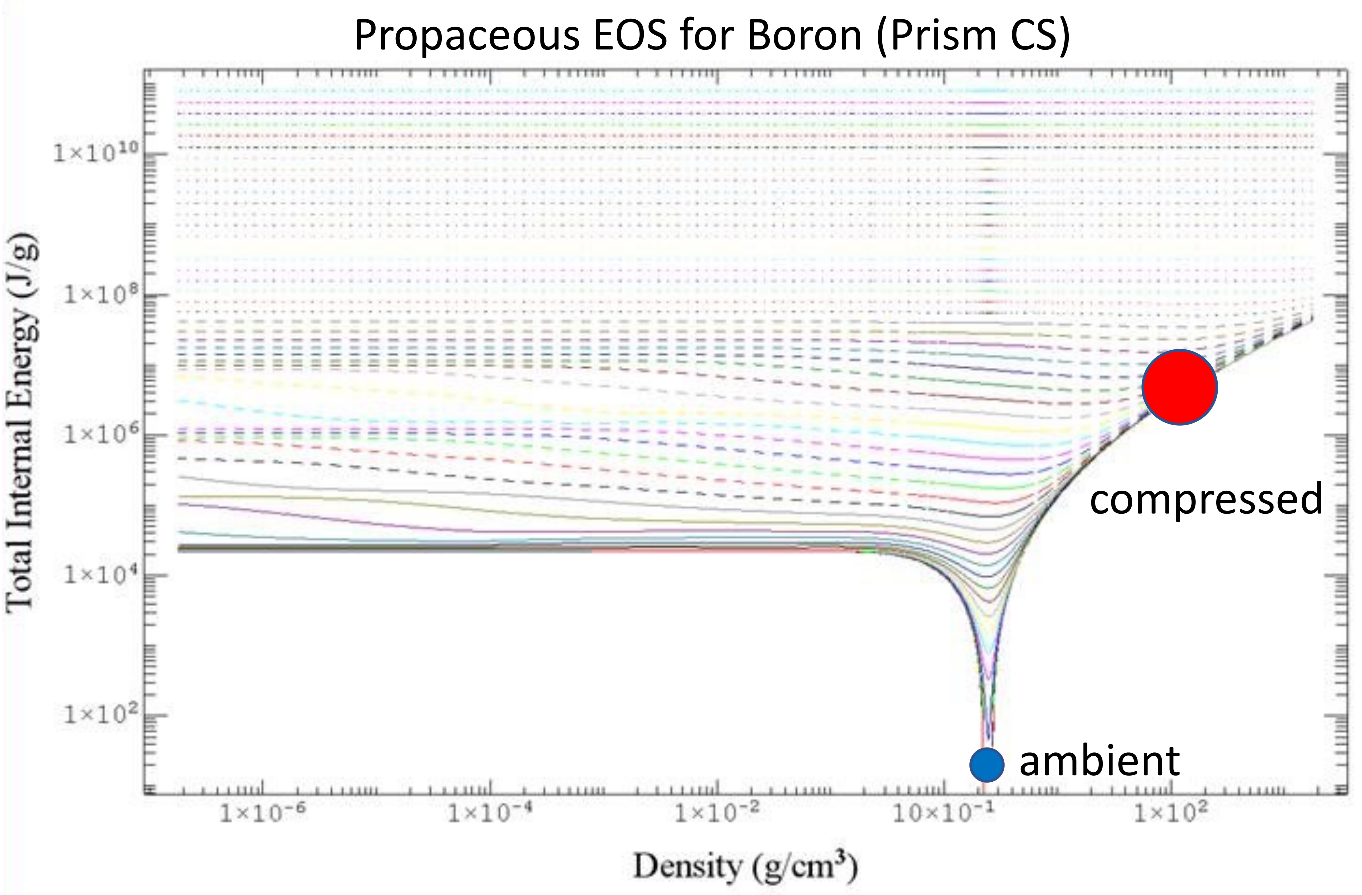
Compression of the fuel is critical to increase reactivity, decrease required burn time, and enable "fast ignition"





To burn 1200 µg/pulse before target disassembly will require strong compression – burn needs to be on ps timescales

Compression increases reactivity & total internal fuel energy, enabling fast ignition & burn wave propagation



Fast ignition scaling for DT fuel

$$E_{ign} = 140\hat{\rho}^{-1.85} kJ$$
$$W_{ign} = 2.6x10^{15}\hat{\rho}^{-1} W$$
$$I_{ign} = 2.4x10^{19}\hat{\rho}^{0.95} W/cm^2$$

Need further research to develop validated EOS for high density p-B materials

New Capabilities in CHICAGO™ enabling HB11 Simulations

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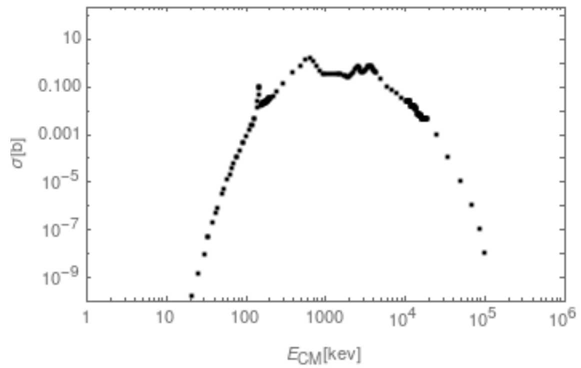
- CHICAGO™ is a relativistic, hybrid/implicit particle-in-cell simulation code.
- Particles have kinetic, multi-fluid, or quasi neutral equations of motion.
- 11B(p,α)αα reaction added to library of fusion reactions. Latest cross-section data from Sikora-Weller[1] used. Full fusion product transport.
- Improvements to Monte-Carlo binary collisions support:
  - relativistic Coulomb scattering,
  - low temperature effects[2],
  - large-angle collisions[3].
  - collisions between kinetic and fluid particle species.

"Avalanche physics"

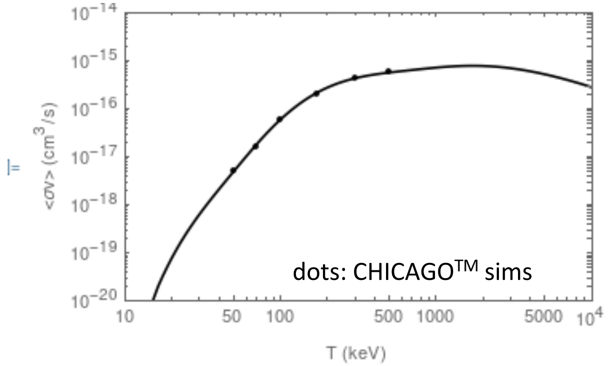
- Improved creation models for kinetic particles with relativistic temperatures (electrons > 100 keV).
- New relativistic bremsstrahlung model based on fitted formulas for power loss vs. electron temperature[4,5].

1. M. H. Sikora, and H. R. Weller, J Fusion Energ. **35**, 538 (2016).
2. F. Perez, et al., Phys. Plasmas **19**, 083104 (2012).
3. D. P. Higginson, J. Comp. Physics **349**, 589 (2017).
4. S. V. Putvinski, D.D. Ryutov, and P.N. Yushmanov, Nucl. Fusion **59**, 076018 (2019).
5. R. Svensson, The Astrophysical Journal **258,** 335 (1982).

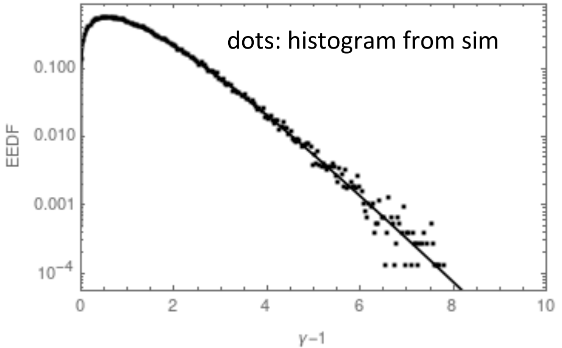
$^{11}B(p,\alpha)\alpha\alpha$ cross-section



$^{11}B(p,\alpha)\alpha\alpha$ reaction rate



Relativistic EEDF at 300 keV



Demonstration of HB11 Burn Window with $T_e \sim T_i/4$

Ion densities:

$$n_p = 5\times10^{24} cm^{-3}$$

$$n_B = 1\times10^{24} cm^{-3}$$

Assume quasi-neutral and fully stripped

$$n_e = n_p + 5n_B = 2n_i = 1\times10^{25} cm^{-3}$$

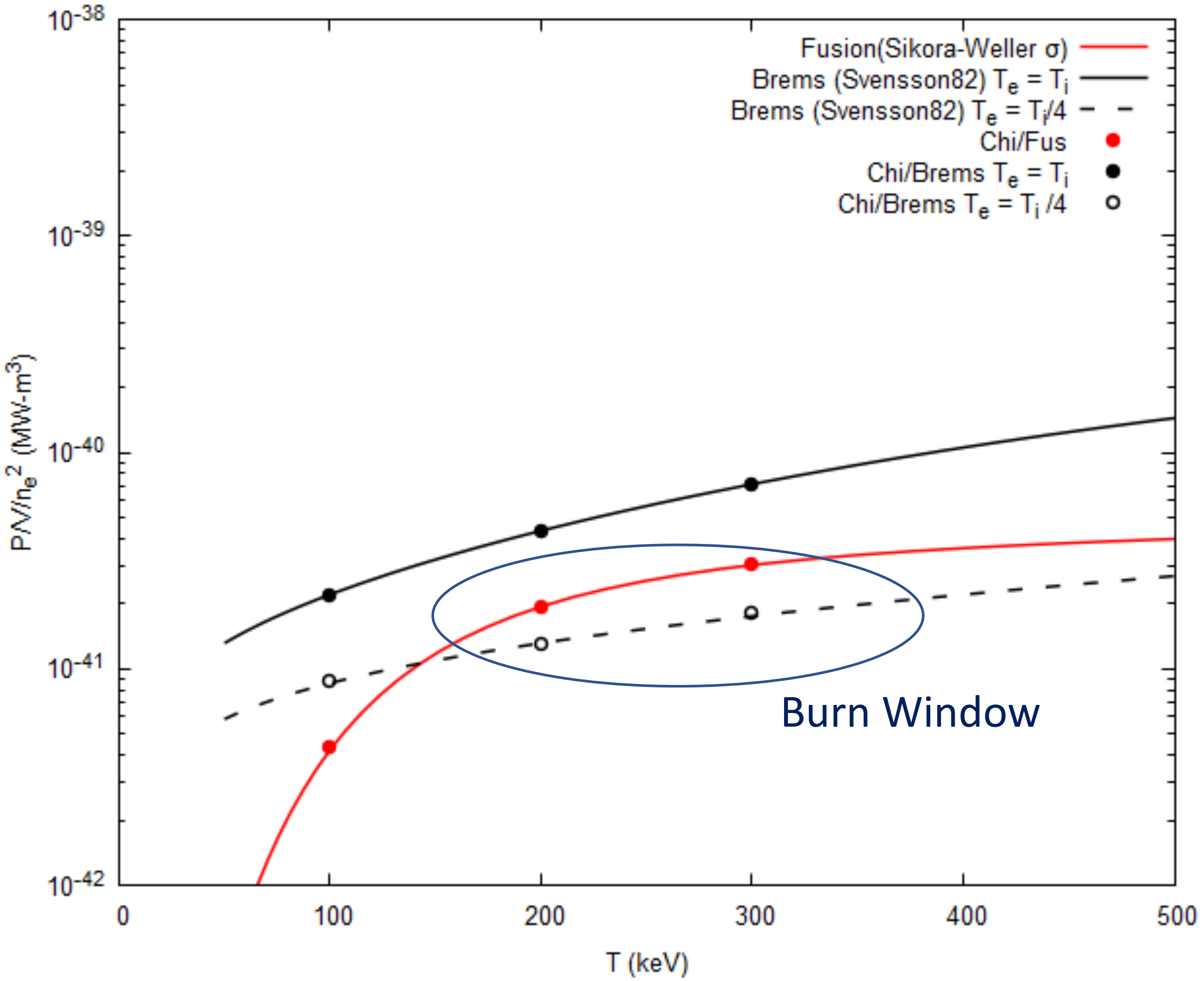
Note:

$$P_{brems} \propto n_e^2$$

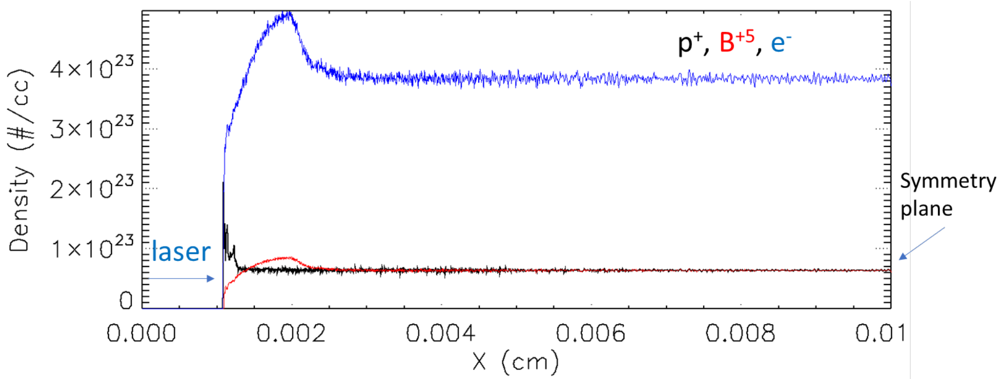
$$P_{fus} \propto n_p n_B = n_e^2 / 20$$

Using Putvinski/Svensson[4,5] Bremsstrahlung formula and Sikora-Weller[1] cross-section.

Fusion power exceeds Bremsstrahlung losses in regime where T_i > 200 keV and $T_e \sim T_i/4$.



Fusion alpha yield scales strongly with intensity up to $4x10^{20}$ W/cm^2 Intensity with 0.25 µm wavelength.*

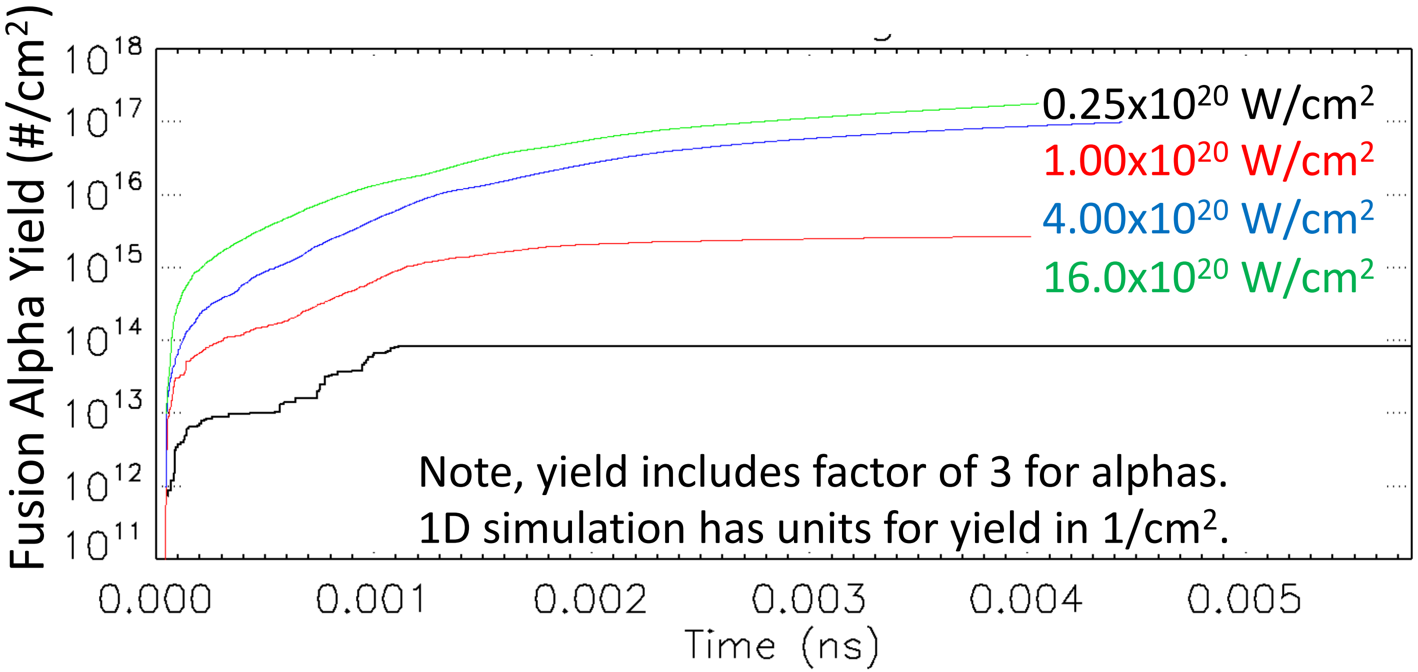


CHICAGO™ setup for 1D illumination of solid HB11 target.

- Two sided illumination due to symmetry BC at .01 cm.
- H^+ B_{11}^{+5} at $6.3x10^{22}$ 1/cc plasma density.
- 0.25--1 µm wavelength, 1-ps pulse, 0.25-$16x10^{20}$ W/cm^2 laser intensity.
- Radiation losses only, no transport.

Simulation uses advanced implicit/hybrid techniques#

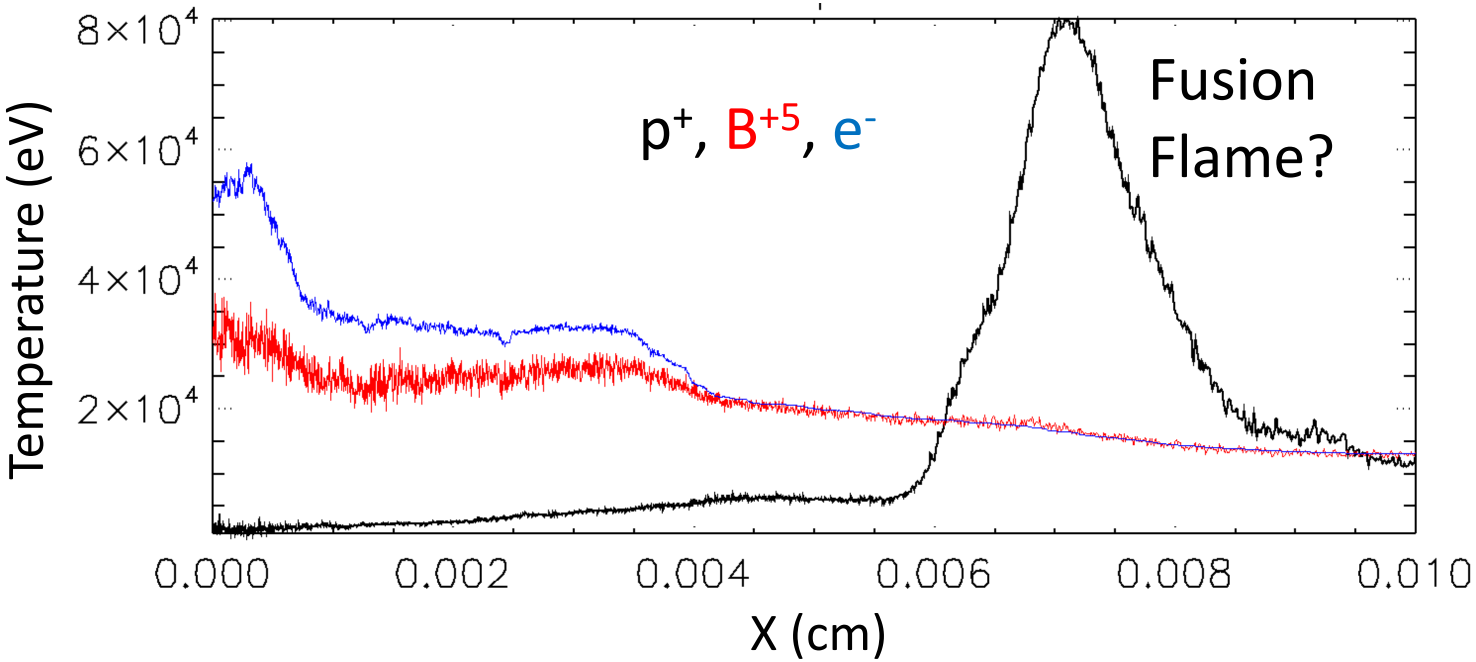
- Magnetic Implicit
- Binary Scatter between all particles.
- Kinetic electrons migrate to fluid after laser shuts off.



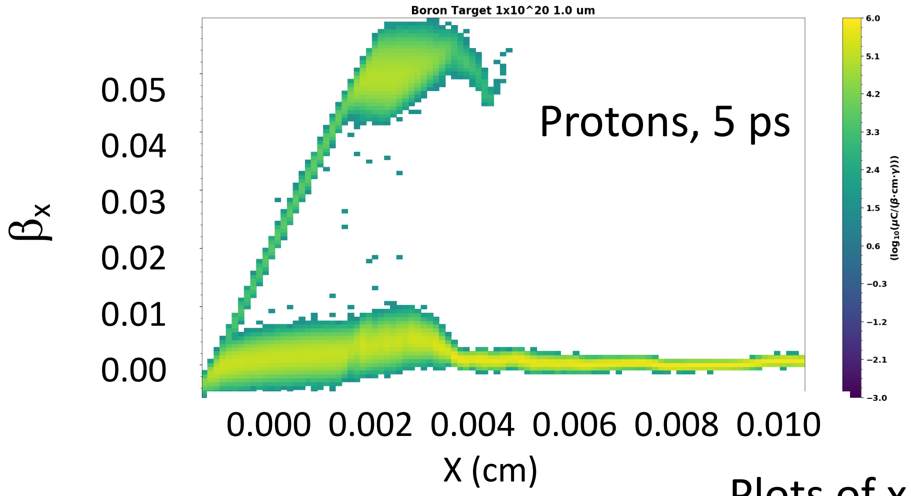
*See P. Lalousis, H. Hora, S. Eliezer, J-M Martinez-Cal, S. Moustaizis, G. H. Miley, and G. Mourou, Phys. Lett. A **377**, 885 (2012).

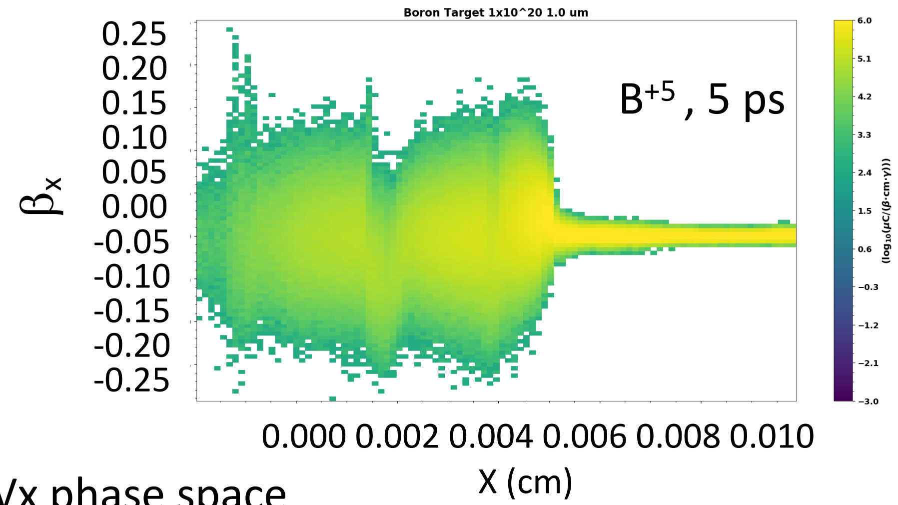
#D. R. Welch, N. Bennett, T. C. Genoni, C. Thoma, and D.V. Rose, *Fast hybrid particle-in-cell technique for pulsed-power accelerators,* Phys. Rev. Accel. Beams **23,** 110401 (2020).

Electron to proton temperature ratio is 0.2 at peak indicating fusion gain exceeds radiation loss.



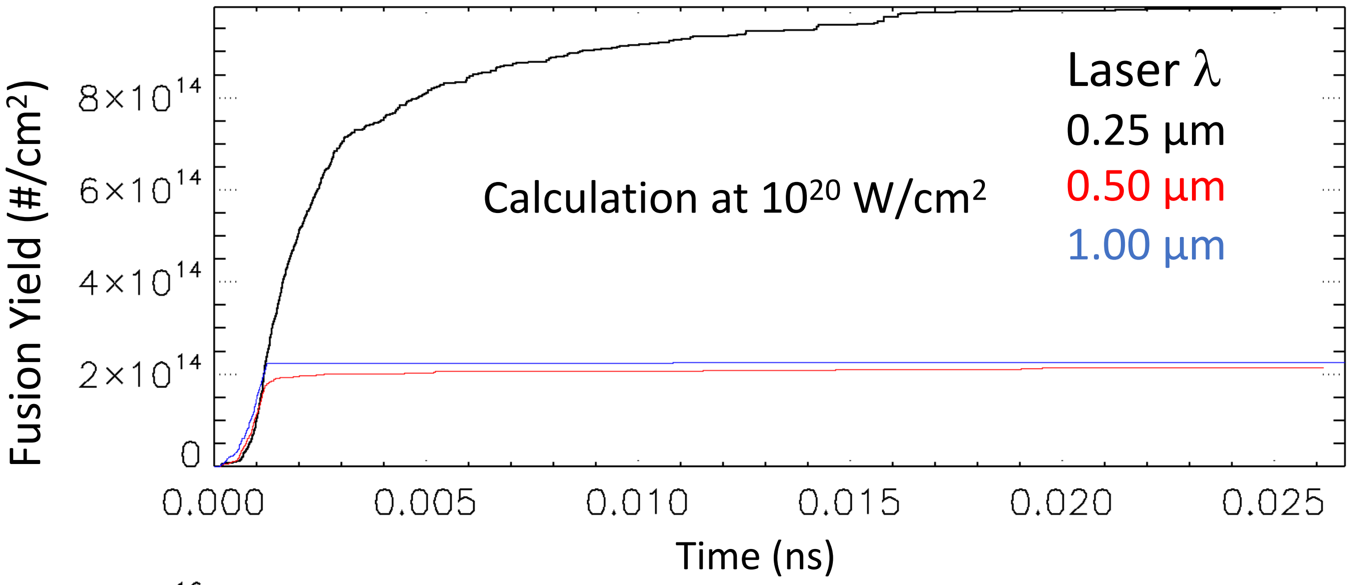
- λ = 0.25 µm, I = 10^{20} W/cm^2.
- Boron and electron temperatures have equilibrated.
- 80 keV proton peak with 16 keV electrons has fusion energy production exceeding radiation losses.
- p^+ beam propagates at .05 *c.*
- Beam persists for 15 ps in target.



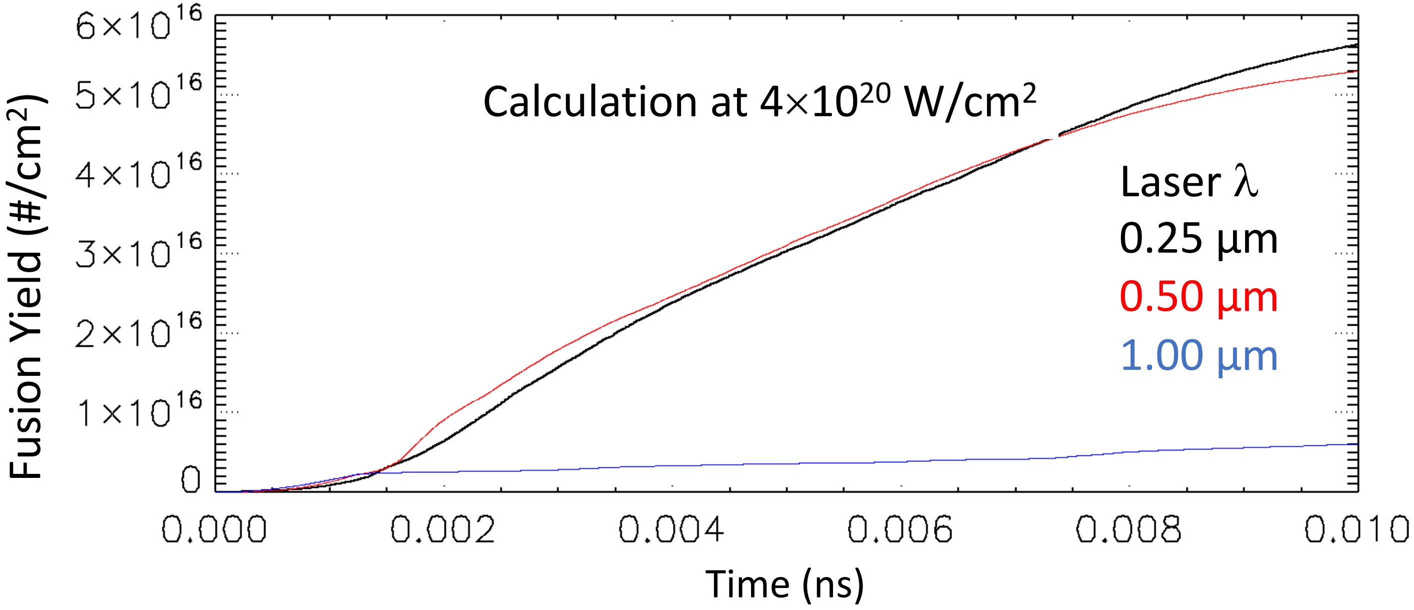


Plots of x-Vx phase space

HB11 yield scaling with laser wavelength indicates smaller wavelength preferable, 0.5 μm feasible.



.25 μm laser outperforms higher wavelengths.

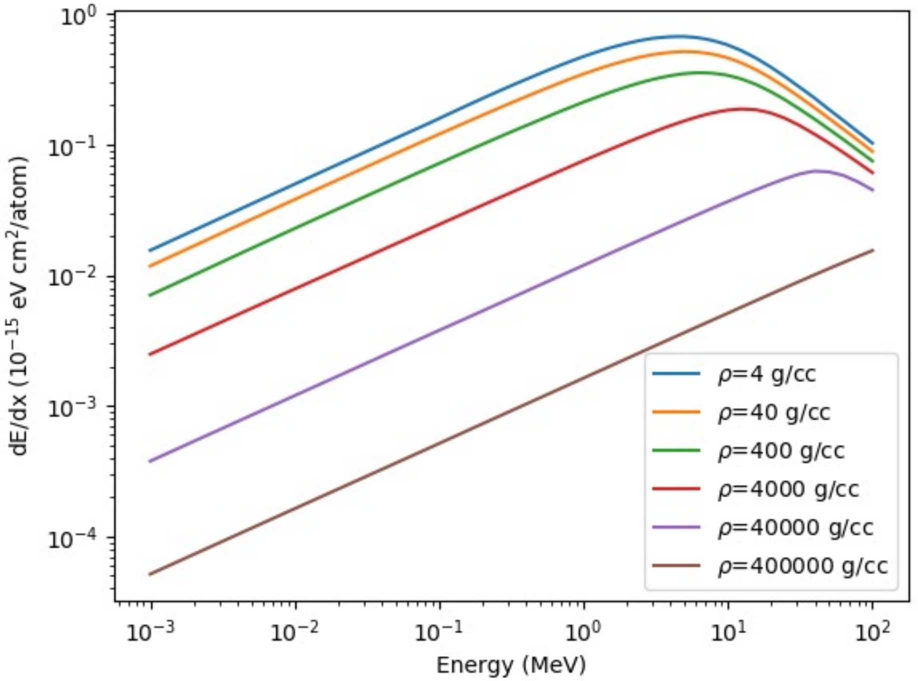


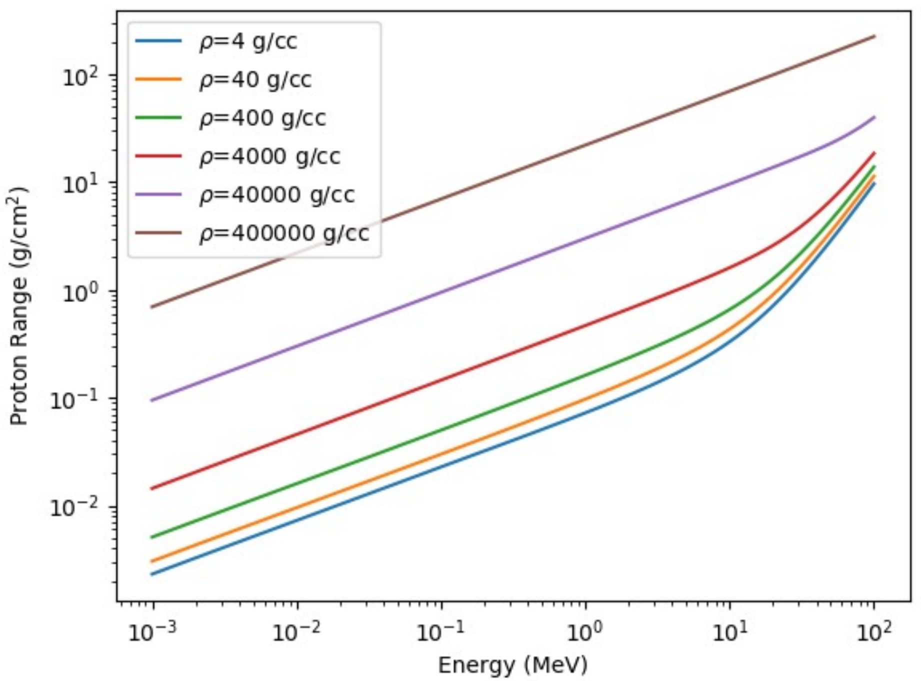
.25--.5 μm lasers have comparable yields.

p-^{11}B burn occurs in an exciting density temperature regime – we need to be careful to include all of the physics

- High density gives smaller log lambda – easier to maintain nonequilibrium
- T_e > 30 keV means more alpha energy to ions than electrons
- Need to track all energy exchanges between energetic species
- Need to have accurate formulation of stopping powers

We are also implementing new density dependence of proton stopping power – shown is boron at T=2 keV





Stopping power decreases as density and degeneracy is increased

This is important for studying the possibility of chain reaction fusion at high densities, e.g., p-^{11}B

The “hybrid” approach to proton-boron inertial fusion

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The Lawson criterion for proton-boron (p-^{11}B) thermonuclear fusion is substantially higher than for deuterium-tritium (DT) because the fusion cross section is lower and peaks at higher ion energies. The Maxwellian averaged p-^{11}B reactivity peaks at several hundred keV, where bremsstrahlung radiation emission may dominate over fusion reactions if electrons and ions are in thermal equilibrium and the losses are unrestricted. Non-equilibrium burn has often been suggested to realize the benefits of this aneutronic reaction, but the predominance of elastic scattering over fusion reactivity makes this difficult to achieve. Ultrashort pulse lasers (USPL) offer new possibilities for initiating non-equilibrium thermonuclear burn and published experiments have measured significant numbers of p-^{11}B alpha particles. However, our analysis shows these alphas are from beam fusion reactions that do not scale to net gain and energy production. Therefore, we are exploring a “hybrid”, fast-ignition-like approach to p-^{11}B where the fuel is imploded to high density and irradiated by protons accelerated by a USPL. We are mapping the burn space using analytic scaling; in a fluid approximation using Helios-CR and a beam deposition/reaction model; and in a hybrid kinetic-fluid approach using Chicago. We will report on ignition and burn in fast ignition-like configurations, accounting for the power balance between heating, fusion, charged particle deposition, bremsstrahlung, thermal conduction, and hydrodynamic expansion as a function of fuel density for both isochoric and isobaric profiles. We will use models that include the effects of density and temperature on the interaction of charged particles in the plasma, including both slowing down and up scattering terms. We will also consider designs that include radiation trapping to reduce losses. Finally, we will discuss options for validating calculations of reactivity in compressed targets on experimental platforms such as Omega-60 and Omega-EP and Gekko and LFEX.