MEC

Study of Proton-Boron Fusion Burn Driven by Short Pulse Lasers

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ABSTRACT

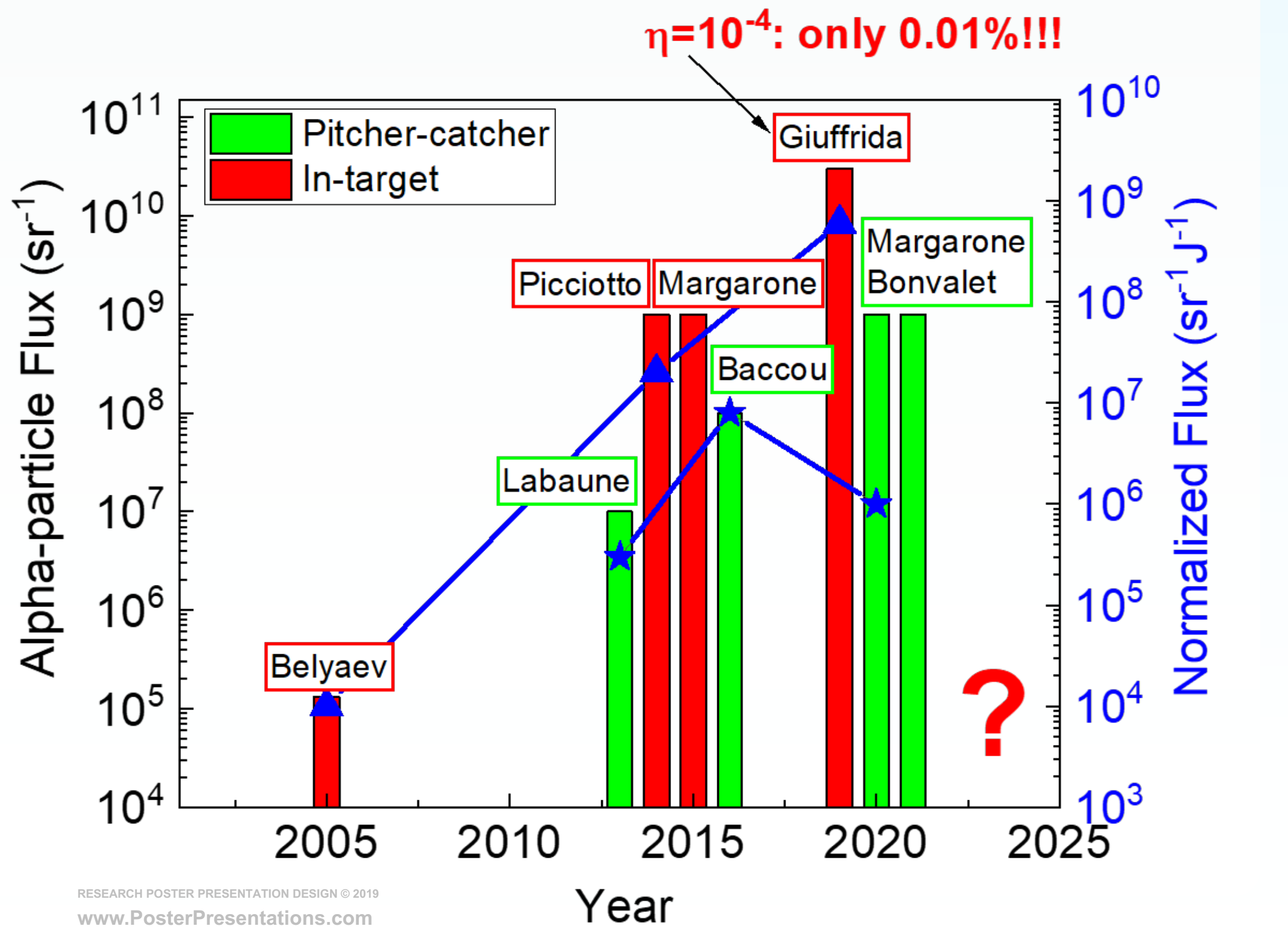
The p-B11 advanced fusion fuel is an attractive alternative to D-T fusion in that its fuels are stable (non-radioactive) and its fusion products are aneutronic charged particles, enabling the possibility of higher efficiency direct energy conversion. Since 2005, a series of "pitcher-catcher" experiments in Russia, France, the Czech Republic, Japan, and the US have shown substantial alpha yields from the p-B11 reaction driven by short pulse lasers. Our analysis of these experiments shows that the magnitude of the alpha particle yields is consistent with their generation via beam fusion reactions by laser accelerated protons slowing down and reacting with boron nuclei. Further, when the boron plasmas are sufficiently hot to decrease the proton stopping power, the fusion yields have been increased by up to an order of magnitude. However, beam fusion reactions do not scale to net gain and energy production. A recent paper has revisited the fusion reactivity of a pB11 plasma in a magnetic containment device based on new cross section measurements and an accounting of kinetic effects and found a net increase of ~30%, which makes the necessary conditions for achieving ignition possible to be satisfied. We will present the initial results of our study of proton-boron fusion burn driven by short pulse lasers using these new cross sections, as well as a hybrid kinetic-fluid approach to calculating the implosion, burn, and expansion physics of an IFE target. We will quantify the possibility of 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 via isochoric models and rad-hydro simulations. 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.

Fusion is hard – can we find a regime in burn space where p-^{11}B has high gain?

- Fusion reactivity must exceed losses (conduction, Bremss, expansion etc)
- CPA intensities create fast electrons & ions – hybrid kinetic-fluid model required
- Reactivity scales with density – compression (isochoric) can boost yield
- Managing the energetic proton spectrum is a key (Fokker-Planck)
- Developing computational point design for HB11 targets

CPA-driven experiments "seductively" successful

- High energy protons generated by charged particle acceleration via ultra-short pulse lasers (USPL) have been observed to produced numerous alpha particles when striking boron-containing targets via the p-B11 reaction. This figure shows the maximum yield by year for various lasers.
- Most experiments use a "pitcher-catcher" geometry where the protons are generated from a thin foil (pitcher) and undergo beam fusion reactions in the catcher.

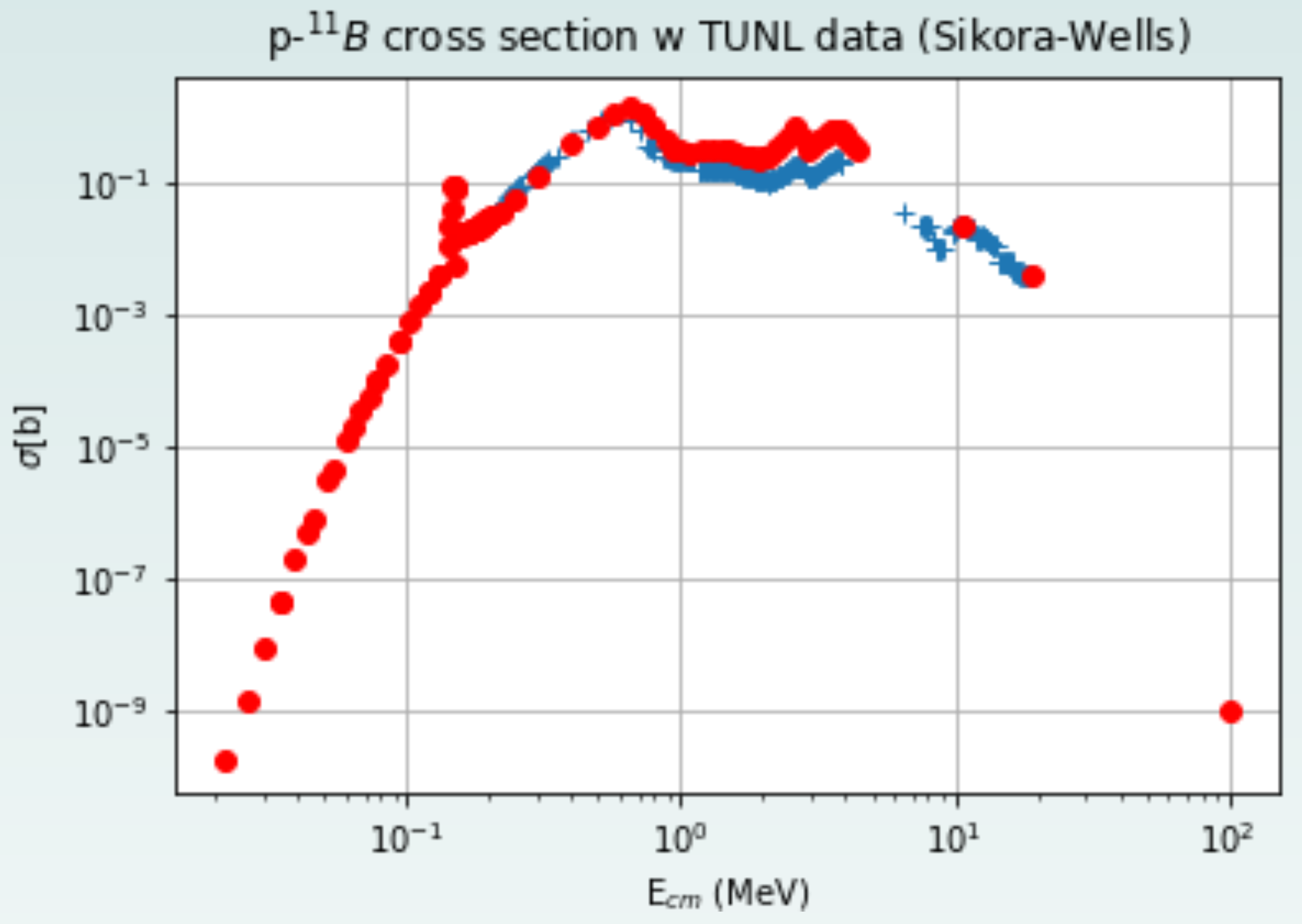


But beam fusion reactions don't scale to high yield

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

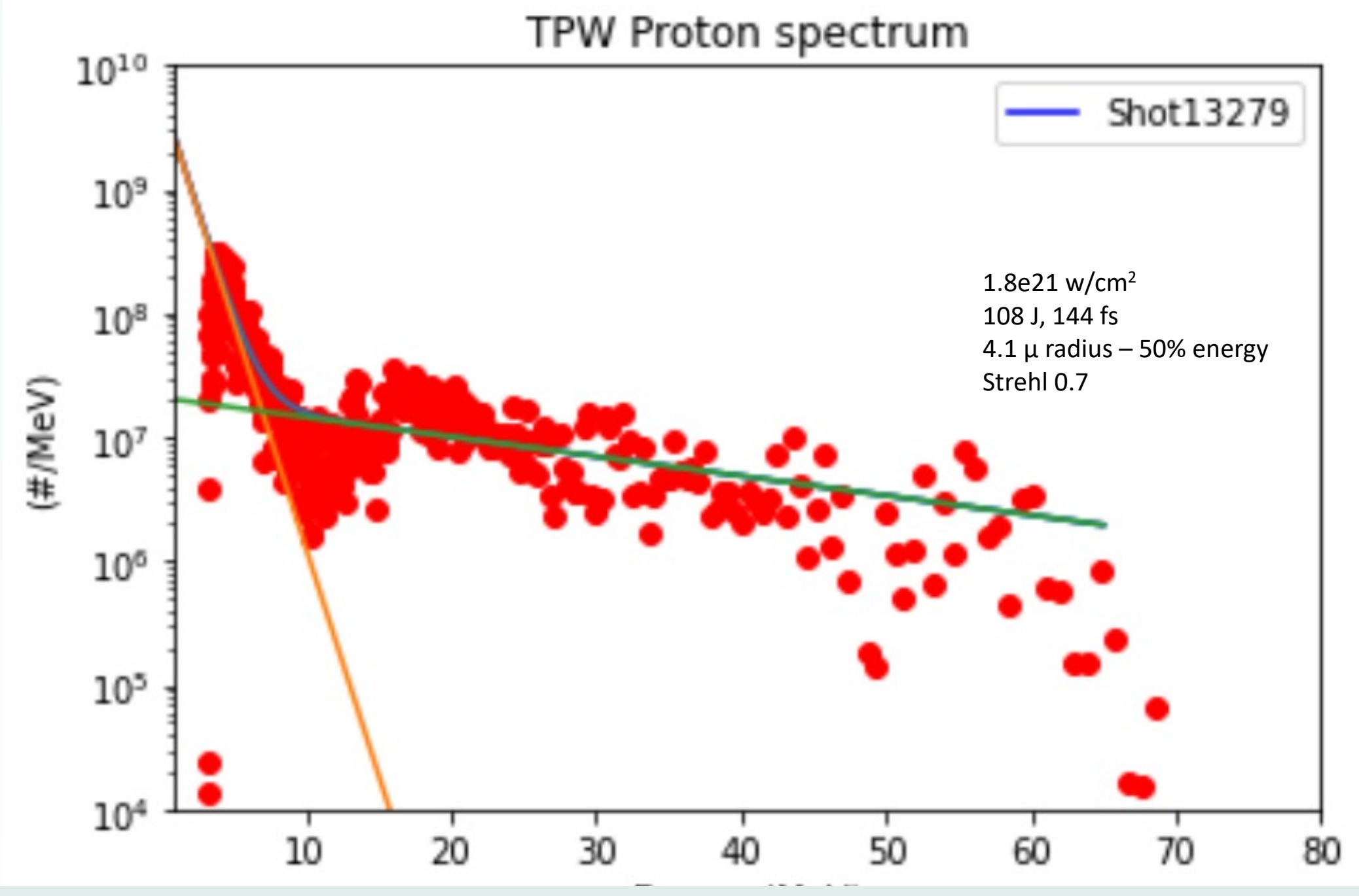
- For 1.4 barn peak cross section, mfp to proton fusion in B = 6.105 cm
- 1 MeV proton range = 12 microns in 1.8 ps - ~ 2.e-4 fusion probability
- Peak cross section @ 660 keV – narrow resonance, negligible < 100 keV
- Calculated thick target yield for 1 MeV in BN @ STP = 6.56e-5
- Proton range can be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

TUNL cross section higher in MeV regime



- All analysis of published experiments have used Nevins cross section (blue) – recent Sikora-Weller measurement gives higher cross section in the MeV regime, where the protons from USPL accelerations start
- Higher cross section appears to explains higher yields, not avalanche

Texas PW data shows typical bi-Maxwellian shape



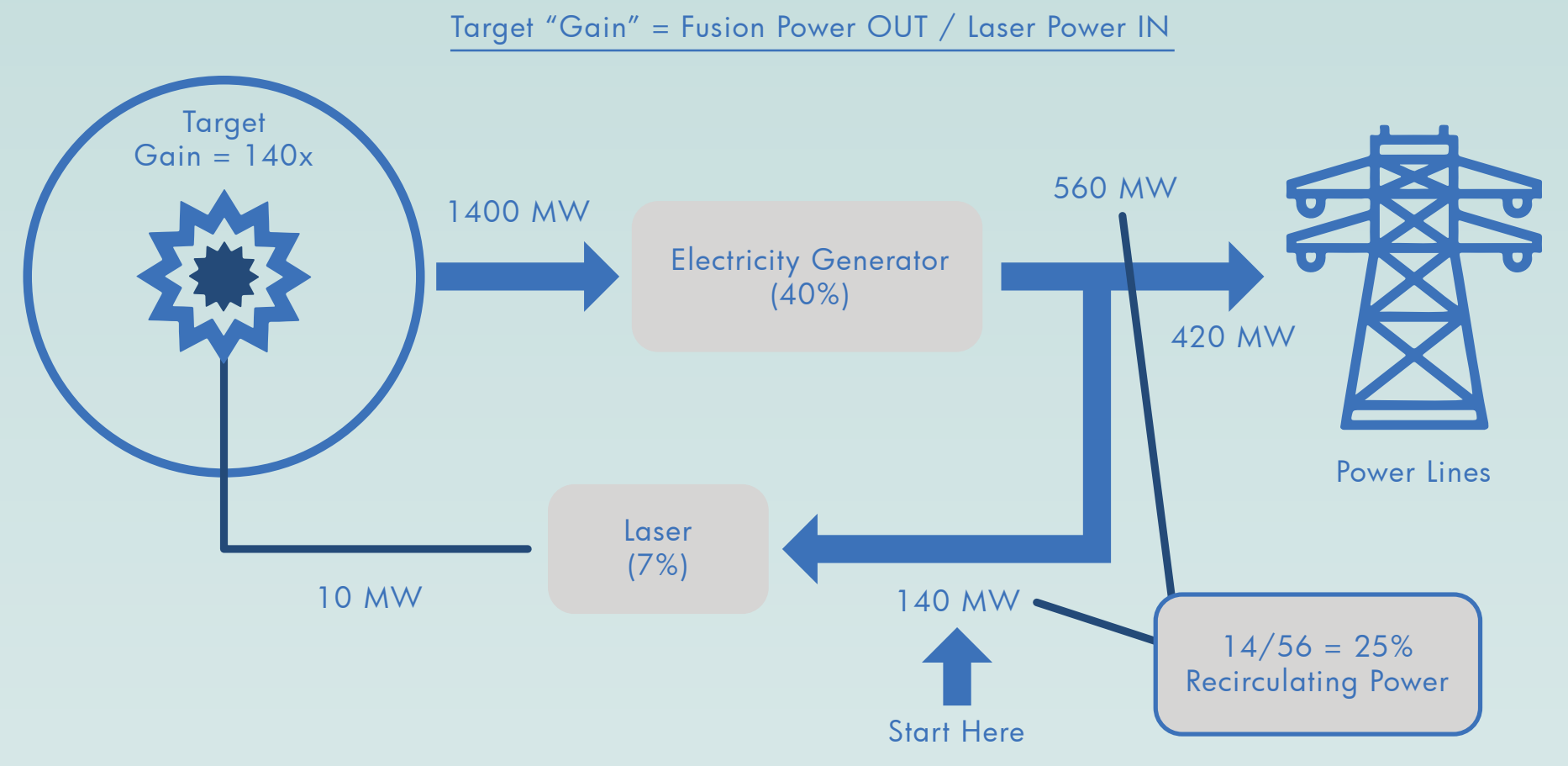
- Total yield calculated by convolving cross section over proton spectrum
- Table shows ~equal contributions from "hard" & "soft" components
- C11 reactions can provide nuclear activation cross check

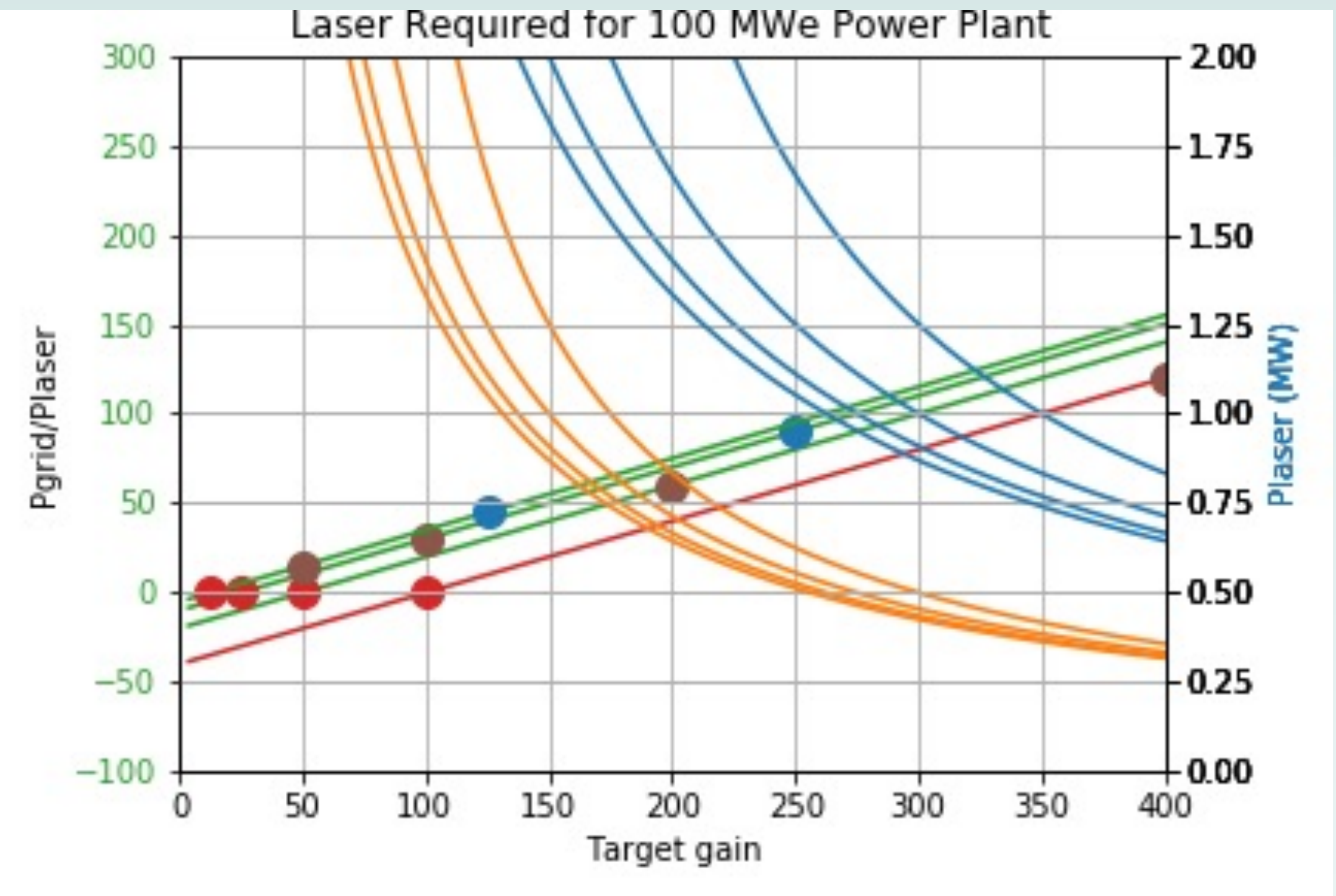
$$\frac{dN}{dE} \approx A_{soft}e^{-E/T_{soft}} + A_{hard}e^{-E/T_{hard}}$$

	Total	Hard	Soft
Protons	7.30E+09	5.50E+08	6.75E+09
Proton Energy (J)	3.72E-03	2.43E-03	1.29E-03
pB11 reactions	1.70E+06	8.51E+05	8.38E+05
C11 reactions	2.50E+06		

Requirements for a power plant: fusion is an "energy amplifier"

@ 5 Hz rep rate, yield/pulse = 280 MJ; Laser energy in = 2 MJ/pulse





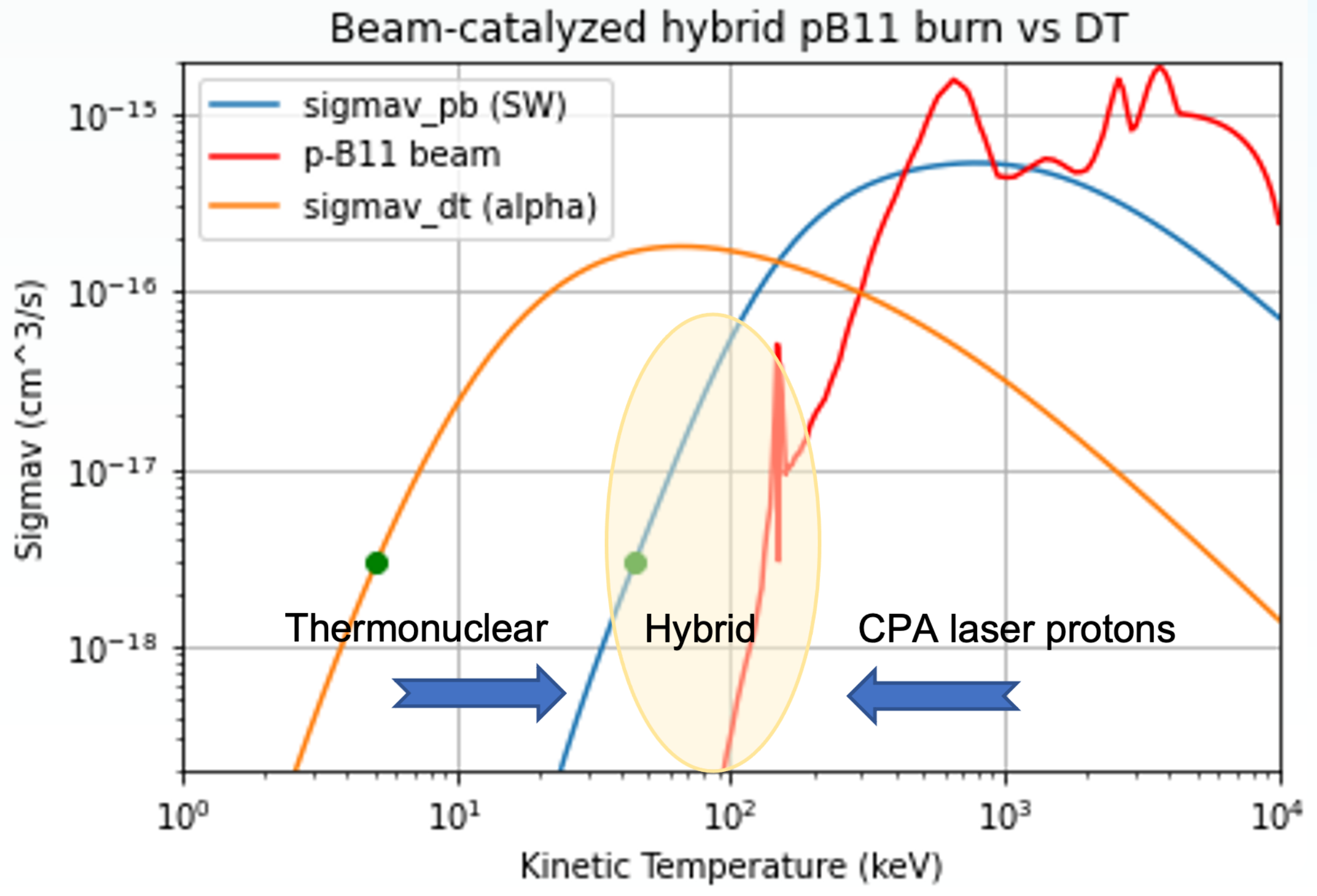
This figure demonstrates the central importance of target gain in the techno-economic viability of an HB11 powerplant. The straight lines show the P_grid/P_laser ratio as a function of gain. The blue and orange curves show the required laser power to generate 100 MWe for conversion efficiency of 0.4 and 0.8 (direct conversion of charged particles). We see that Gains >= 100 are required for economic power production.

Maxwellian averaged fusion reactivity

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

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

- Thermonuclear fusion scales with n^2 => use isochoric compression
- Beam fusion scales with n_beam X n_fuel
- "Hybrid" burn regime: non-equilibrium "fast ignition" + beam fusion (FI*)
- "Lift" high energy proton tail via up-scattering (Fokker-Planck)



Target design & burn physics issues for study

- DT ignition @ ~ 5 keV; p-B11 has same reactivity @ `~45 keV
- P-B11 less reactive, but alphas have same range & deposit 2.5x E/fusion
- Ideal ignition balances fusion production & radiation loss rates
- Can hi-Z radiation-trapping layers enable p-B11 ignition & gain?
- DT fast ignition @ >= 100 g/cc – what is required for FI* with p-B11?
- What ρr is required for p-B11 & how does burnup fraction scale with ρr?
  - 280 MJ/pulse = 3.525 mg of 11B burned/pulse
  - Need propagating burn – can't rely solely on driver energy
  - For 10% burnup fraction – solid sphere radius ~ 1.5 mm

Managing energetic proton spectrum may be key

- Thermonuclear burn occurs @ high energy tail – how to maximize?
- Can CPA proton fusion energy & collisions catalyze propagating burn?
- "Lift" high energy proton tail via up-scattering & nuclear reactions
- Need Fokker-Planck model for beam and thermonuclear species
- Include relativistic effects, ala Putvinsi, et al.

UPCOMING SIMULATIONS:

HELIOS-CR has pB-11 reactivity & beam fusion module to study burn space

Chicago (Voss) will be used to study multi-species burn kinetics

Diagnostics & Future Experiments

- Nuclear diagnostics can help provide insights into distributions
- Nuclear diagnostics augment particle diagnostics (CR-39, TP, etc)
- Future experiments to clarify physics and validate models include:
  - High repetition rate VEGA laser of CLPU in Spain
  - Experiment at Omega EP (planar geometry)
  - Expt @ Gekko/LFEX (cylindrical geometry with B-field)
  - Experiment at Omega (spherical geometry / implosion)
- Additional/complementary experiments:
  - Experiments at PALS
  - Experiment at Hilase
  - Measuring EOS of boron / boron nitride

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