MAGNETIC RECONNECTION · LASER-DRIVEN ANEUTRONIC FUSION

Reconnection-Driven Non-Thermal Proton Acceleration to p–^{11}B Fusion Energies at Joule-Class Laser Energy

When field topology does the work bulk heating cannot — a ring-geometry hybrid-PIC study

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MOTIVATION

Two regimes of laser-driven fusion — and a gap between them

kJ

Facility-scale (kJ–MJ)

- NIF, OMEGA, Apollon, PHELIX, LFEX
- Record p–^{11}B yield ≈ 10^{10} α/sr at ≈ 500 J coupled
- Absolute yield — but high capital cost, low repetition rate

↓

≤J

Tabletop petawatt (≤ few J)

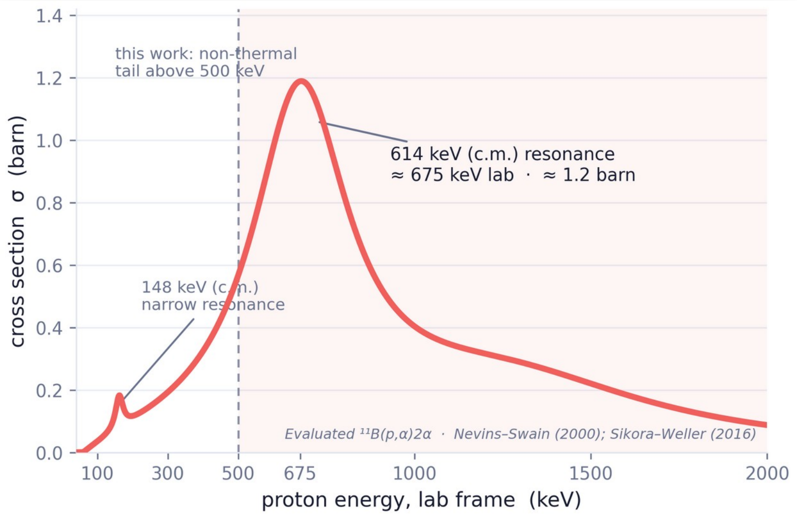
- TARANIS, PALS, university-scale short-pulse
- High rep-rate, sub-$M, room-scale deployment
- Per-shot yield too low for breakeven — advantages unexploited

This work: engineer the field topology, not the energy — eight-spot ring reconnection at 5 J coupled.

p–^{11}B: clean fuel, but gated by a hard reaction threshold

$p + {}^{11}B \rightarrow 3\alpha + 8.68$ MeV

- All products charged — no neutrons
- Fuel abundant, inexpensive, solid-storable
- Attractive, decades-pursued aneutronic route

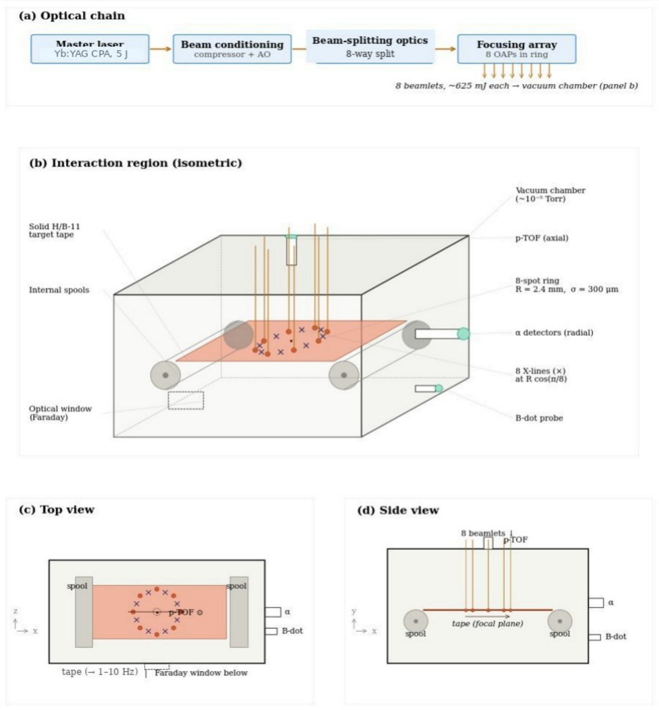


The obstacle

- (p,α) threshold ≈ 500 keV, peak ≈ 675 keV
- Bremsstrahlung (Rider; Nevins–Swain) forecloses a steady-state bulk-thermal route

No tractable bulk-thermal route to 500 keV → the suprathermal tail must be populated non-thermally.

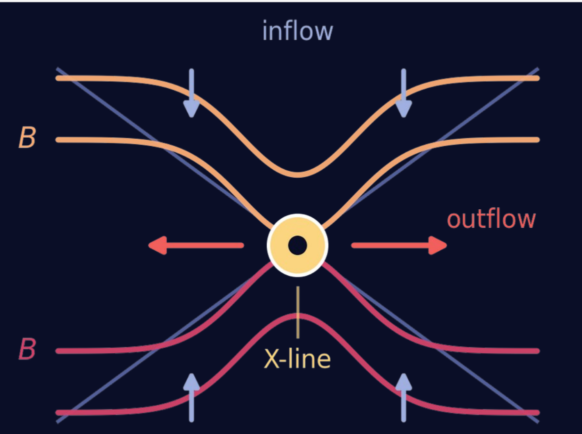
What the experiment looks like



From one 5 J master to eight converging beamlets

- 5 J cryogenic Yb:YAG CPA master → beam conditioning → 8-way split → array of 8 off-axis parabolas.
- Eight beamlets (~625 mJ each) onto a solid H / B-11 target tape on internal spools.
- 8-spot ring R = 2.4 mm, σ = 300 μm; eight X-lines at R·cos(π/8) = 2.217 mm.
- Diagnostics: α detectors (radial), p-TOF (axial), B-dot probe, Faraday window.
- mm-scale interaction region in a ~10^{-5} Torr chamber; spooled tape supports 1–10 Hz operation.

The mechanism — and that the laboratory already shows it accelerates particles



Anti-parallel field annihilates at an X-line; the out-of-plane reconnection E-field accelerates particles directly.

WHAT RECONNECTION DELIVERS

- Magnetic energy → flow, heat, and a non-thermal particle tail.
- Direct acceleration by the out-of-plane reconnection E-field.
- The lab's two-plume mechanism — here tiled eightfold, converged.

MEASURED IN THE LABORATORY

First laser-driven reconnection

Anti-parallel Biermann fields, ~100–1000 T (MG-scale), meet and reconnect — Nilson et al., PRL 2006.

Reconnection accelerates a non-thermal tail

Electrons measured to 50–70 keV (Chien 2023); non-thermal ions in laser-plasma PIC (Totorica & Fiuza 2020).

Already proven in space: reconnection drives ions far past these energies in solar flares and substorms — the lab just hasn't reached p–^{11}B proton energies this way yet (those have come via TNSA beam-target: Belyaev 2005, Margarone 2022). This ring's sustained, cyclic reconnection opens a path to that same multi-pass (Fermi) acceleration.

THE CENTRAL ARGUMENT

Every reaction is reconnection-driven by construction

12–46 eV

Max bulk-thermal energy per ion at 5 J coupled (100% efficiency, transparent σ-volume bound)

327 keV

Equilibrium proton E_{95} — a characteristic energy of a non-thermal distribution, not a Maxwellian temperature

~10^4×

Gap — 327 keV sits 7,000–27,000× above the thermal floor

A purely thermal hydrogenated boron–nitride plasma — carbon, hydrogen, boron-11 and nitrogen — at 5 J produces zero p–^{11}B fusion. Thermal-floor baseline is zero, independent of any modeling choice.

METHODS

2D-XZ guide-field hybrid-PIC, with no external drive

1 Code & model

WarpX (AMReX 26.04), hybrid-PIC. Ions fully kinetic; electrons a quasi-neutral resistive fluid ($\eta = 9.69\times10^{-8}$ Ω·m).

2 Fuel

Idealized hydrogenated boron–nitride. Base $n = 5\times10^{24}$ m^{-3}; n_H = 1.63n, n_B11 = n.

3 Seed field

85 T Harris By, alternating polarity at the eight midplanes. Plasma β = 13.7 (warm, thermal-dominated).

4 No external Jy

Supporting current is self-consistent from particle drift → reported gain is reconnection-driven only.

WHY THIS CONFIGURATION — FIDELITY vs COMPUTE

Harris-sheet seed

Force-balanced Harris sheets — magnetic ↔ thermal pressure — give the canonical, analytic reconnection start state at the eight alternating-By midplanes.

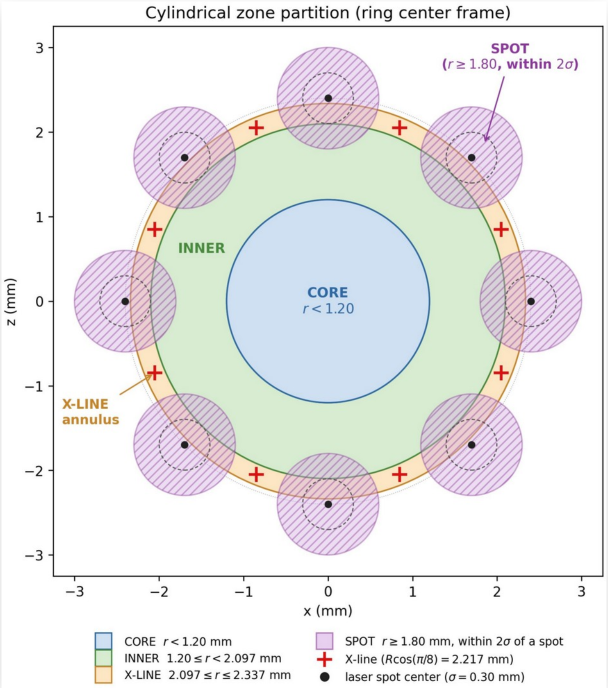
Hybrid-PIC trade-off

Kinetic ions carry the acceleration; fluid electrons drop the fast electron scales, reaching the 10 ps–1 ns reconnection window full PIC can't afford.

Cloud H100 ladder

$256^2/512^2/1024^2$ at matched ~15 ps cadence over 1153 ps, run on cloud NVIDIA H100 GPUs — the throughput behind the ultrafine convergence ladder.

Simulation geometry and the four-zone partition



Simulation geometry

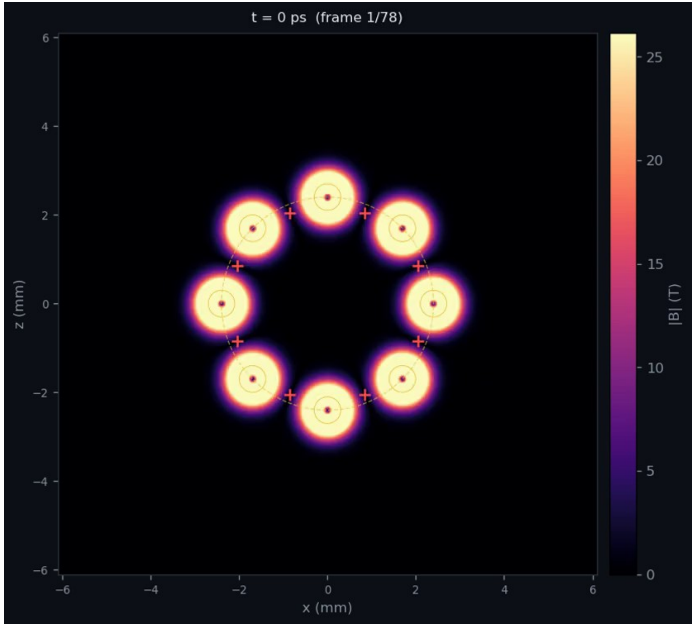
- 2D Cartesian X–Z, fully periodic; domain ≈ 6.1 × 6.1 mm (60 proton skin depths).
- Eight laser spots on a ring — R = 2.4 mm, σ = 300 μm.
- X-lines form at R·cos(π/8) = 2.217 mm; 85 T Harris seed, β = 13.7.

Where each population lives

- CORE (r < 1.20 mm) — the convergence target the eight outflows feed.
- INNER (1.20–2.097 mm) — the reconnection-energized interior.
- X-LINE annulus (2.097–2.337 mm) — brackets the eight X-lines at 2.217 mm.
- SPOT (r ≥ 1.80 mm, within 2σ) — laser spots, bulk-thermal deposition dominates.

First-transit accounting: each zone’s f(E,t) folds through the (p,α) cross-section; every proton counted once, before any boundary wrap — the conservative G_FT floor.

Reconnection onsets by ~15 ps and recurs in cycles; |B| collapses ~75% and stays down



LD 512² ultrafine · |B| (T) animation over 0–1153 ps · "+" marks the eight X-lines · plays in PowerPoint

~15 ps

Onset — the first X-line reconnects and bright inward outflow fingers appear

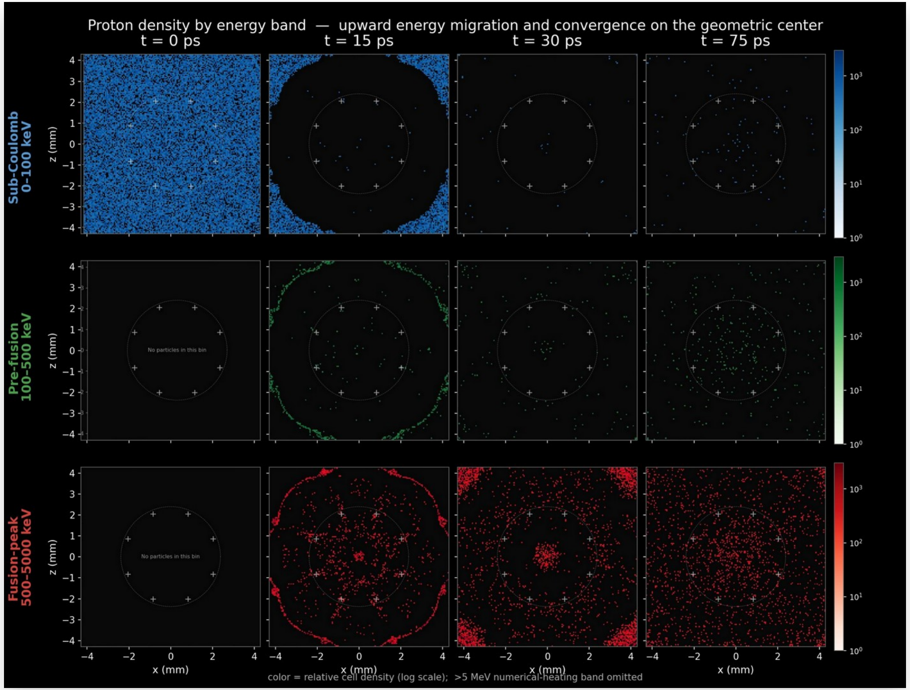
~35 ps cadence

Then recurs in cycles — events at 15, 52, 67, 97, 127, 195, 225 ps — not a one-shot decay

74.8%, sustained

Seed-relative |B| collapse (51.6→21.4 T; grid-independent 74.8/74.8/75.8%); stays down to 1153 ps

Fusion-grade protons appear and converge on the center



Reading down

upward energy migration — the cold sub-Coulomb band drains as the 500–5000 keV fusion-grade band fills.

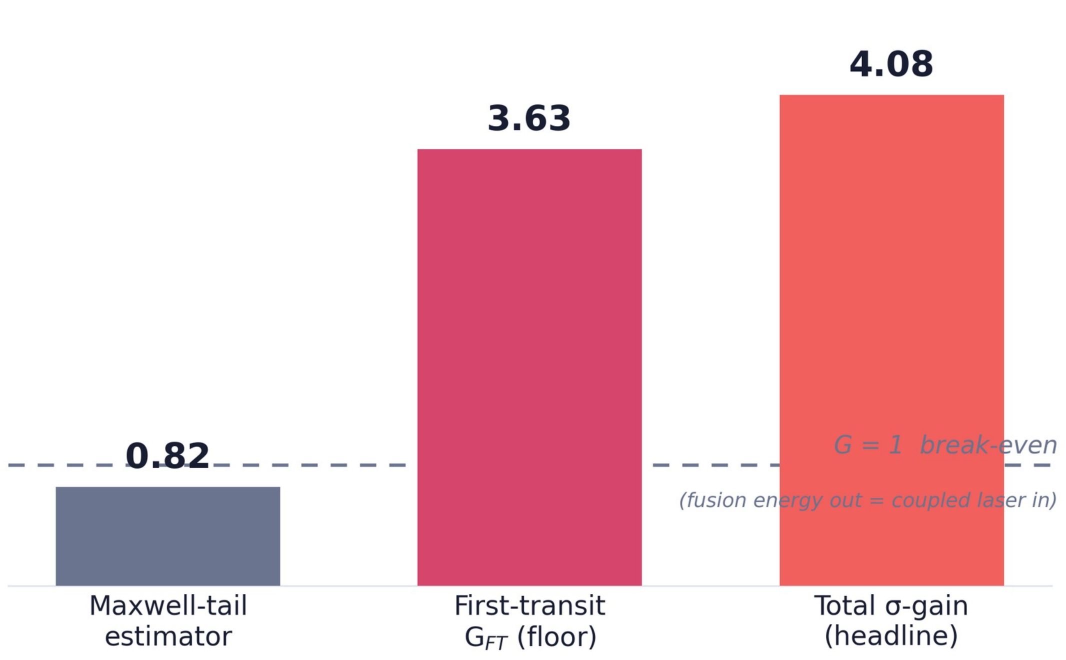
Reading across

the fusion-grade population converges on the geometric center — empty at t = 0, an eight-fold ring with a central concentration by 15–30 ps.

The spatial signature of reconnection-driven energization.

HEADLINE RESULT

σ-weighted total gain G_tot = 4.08 at 5 J coupled



5.0×

two estimators on the SAME reconnection-driven non-thermal distribution — a methodology metric, not a thermal / non-reconnection channel

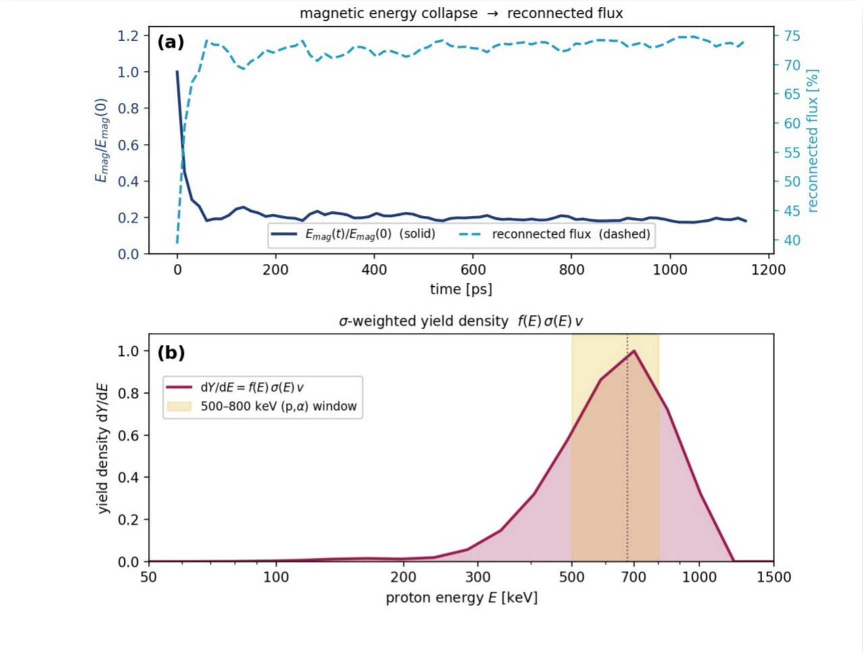
23% / 77%

direct reconnection event / non-thermal relaxation — stable to 1 pt across resolutions

8.8×10^{12} – 4.4×10^{13}

alphas per shot (bracketed reporting convention)

Magnetic free energy collapses, then feeds the fusion window



LD 512² · (a) E_mag(t)/E_mag(0) and reconnected-flux fraction · (b) σ-weighted yield density

Reading the chain

- (a) Magnetic free energy decays to ~20% of its initial value and stays there — no rebound — while the reconnected-flux fraction rises to ~70% and holds.
- The energy-side view of the same 74.8% seed-relative |B| collapse (energy ∝ $|B|^2$).
- (b) The resulting σ-weighted yield density peaks squarely in the 500–800 keV (p,α) window — right where the reactions occur.

Why σ-weighted integrated yield, not peak-instant E_{95}

1

The cross-section is slowly varying

(p,α) varies slowly across 500–800 keV, so the integrated yield is robust to whether the diagnostic samples at a peak-E_{95} instant or between peaks — unlike peak-instant statistics, which depend on cadence vs the natural-cycle Nyquist limit.

2

The integrated quantities converge

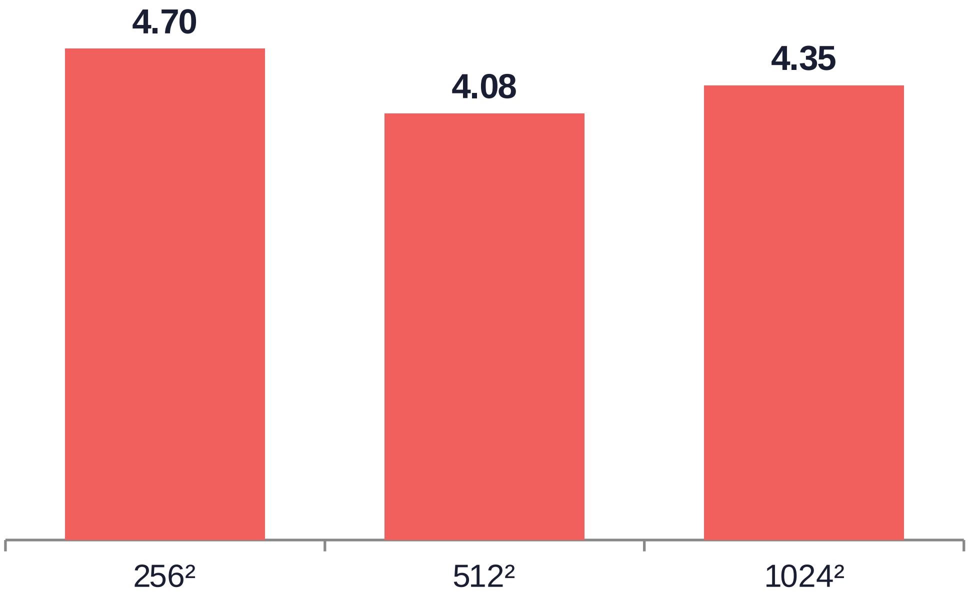
σ-integrated fixed-window observables are grid-converged (~12%; decomposition to 1 pt). Peak-instant statistics shift unpredictably with which timestep happens to bracket the cycle peak.

3

It matches the literature

The laser-driven reconnection-fusion literature reports integrated yields and enhancement factors — adopting the same metric makes cross-comparison direct.

Grid-converged across a 16× change in cell count



Total σ-weighted gain over the common 0–1153 ps window — within ~12%, non-monotonic

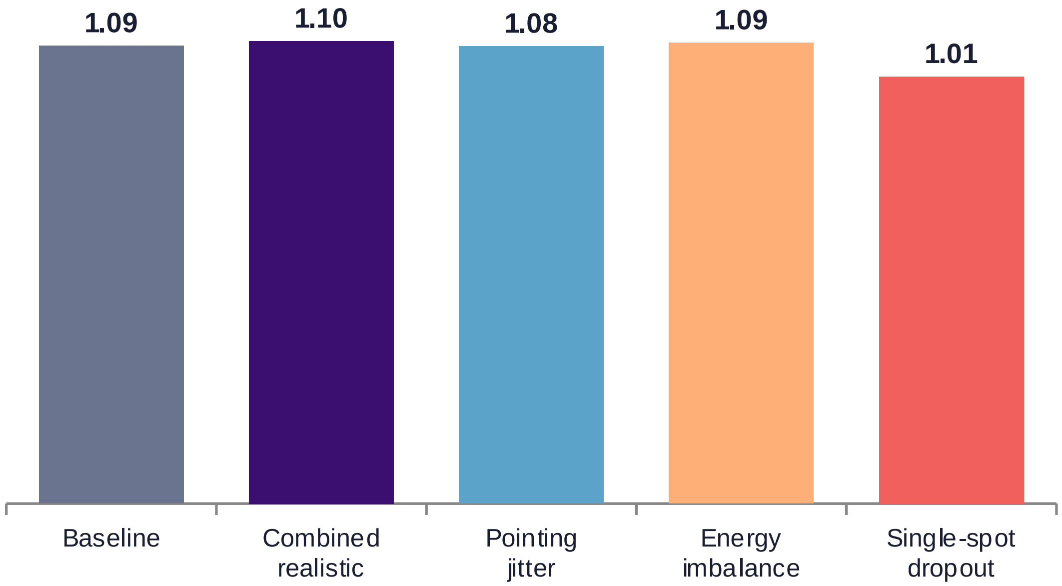
Grid-independent observables

- Direct / relaxation split ≈ 23% / 77% (±1 pt)
- Seed-relative B-collapse 74.8 / 74.8 / 75.8%
- Maxwellian estimator 0.82 (matched duration)

On the first-transit floor

G_FT rises with resolution (2.02 / 3.63 / 7.98) because t_cut lengthens — it is **window-dependent by construction**. Reported as a conservative lower bound, not a convergence observable.

Yield is invariant under realistic beam imperfections



CV = 1.97%

coefficient of variation of G_FT across the envelope

- Envelope: pointing jitter 5–150 µm, energy imbalance 5–10%, single-spot dropout, and all three combined.
- Combined-realistic reproduces baseline to within 1%.
- Only dropout exceeds 1% (−6.8%) — within normal shot-to-shot variation.

σ-weighted first-transit gain at the fixed t = 300 ps pre-wrap time (13-run envelope)

Why a wide closed ring keeps draining where a tight cluster corks

✓ The ring advantage

- Converts independent two-spot events into one system with predictable X-lines and a guaranteed convergence point.
- Eight inward jets superpose at the center — the spatial signature of preferential energization, distinct from bulk heating.
- Sustained, cyclic collapse: the ultrafine record shows recurring events at ~35 ps cadence, not a one-shot decay — a path to multi-pass (Fermi-type) acceleration.

! Where tight clusters cork

- Bolaños et al. (2023): three adjacent sites cork — inner outflows pile into a small shared volume (centroid ~0.66 mm from each vertex), stalling reconnection mid-cycle.
- Distance, not spacing: the ring center sits $R \approx 2.2$ mm from every X-line — ~3× farther — so each X-line drains before back-pressure builds.
- Angle: at 45° neighboring jets are near co-directional vs the triangle's head-on 120° — less interference. σ-gain robust (<2%) even with a hemisphere removed.

Empirically the ring re-forms reconnection in cycles where a tight triangle settles to one stalled state; a matched 2-/3-/8-site scan at fixed parameters is the clean test (follow-up).

OPERATING WINDOW

A reconnection threshold between 51 and 85 T

Driver class	Seed (T)	β	B-collapse	Reconnects ?
Q-switched Nd:YAG	45	48.9	−301% (grew)	No
Yb-fiber MOPA	51	38.1	−93% (grew)	No
Hybrid Yb:fiber / Nd:YAG (ref.)	85	13.7	+72%	Yes
Hybrid Yb:fiber / Nd:YAG	120	6.9	+68%	Yes
ps Nd:YAG	361	0.76	+68%	Yes*

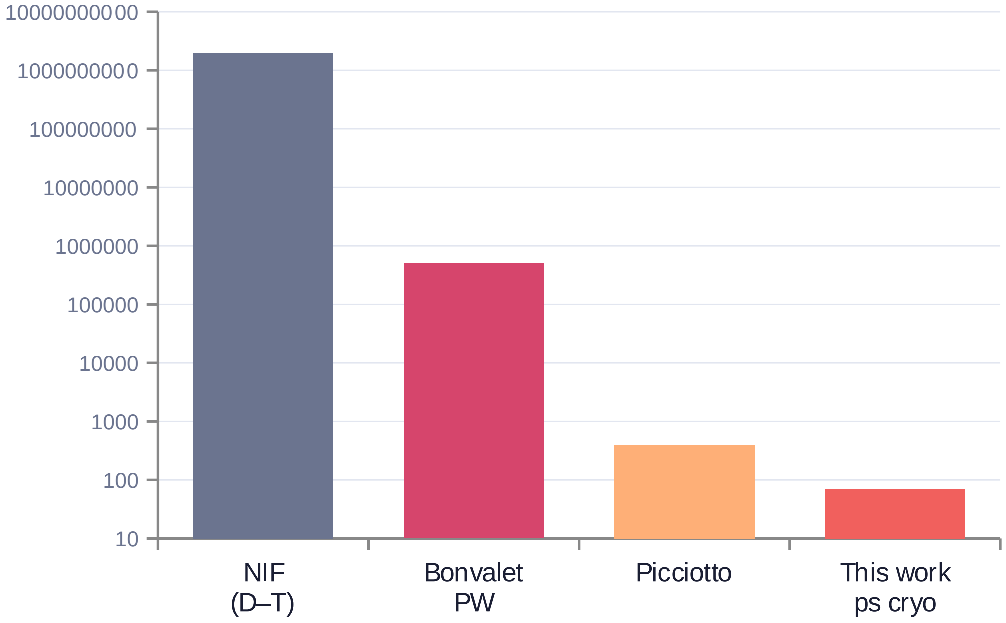
≥ 85 T
lobe field annihilates — reconnection drives yield

45–51 T
field grows monotonically — drive-dominated, no reconnection

**361 T reconnects but at β = 0.76, where 256^2 numerical heating makes its absolute gain a scaling check only.*

Above the floor, yield is set by the fraction of flux annihilated, not absolute seed.

Why 5 J and kHz repetition change the deployment economics



Wall-plug electrical energy per shot (log scale) — ~70 J for the ps cryo Yb:YAG class

~7,000×

hardware-and-scale wall-plug advantage per shot over PW p–^{11}B — robust to spec-sheet verification, no simulation needed

3–5 orders

per-joule yield above TNSA campaigns (conservative isotropic assumption)

~1 kHz

rep rate for the joule-class cryo Yb:YAG CPA class. Facility ICF and PW p–^{11}B shots fire hours apart — here, time-averaged output = yield/shot × rep rate, the lever current approaches lack.

Per-α advantage up to ~10^7× is simulation-conditional — to be established by experimental validation.

From 2D to 3D: published studies say the yield should survive — our 3D run is follow-up

Fast rate is not a 2D artifact

The normalized rate of order 0.1 is set by a force balance at the MHD scale, largely insensitive to the dissipation mechanism (Liu et al.).

Energy-conversion time survives

In matched 2D / 3D kinetic layers the energy-conversion timescale stays very close to the 2D value (Daughton et al.).

Closest geometry agrees within ~2×

For parallel flux ropes merging via coalescence — our multi-site analog — 3D matches 2D within a factor ~2; drift-kink governs the departure (Sauppe & Daughton). We adopt the conservative 2× bound.

3D coheres, not fragments

3D organizes multiple reconnection sites into a single coherent diffusion region — the behavior the ring assumes.

These are other groups' 3D results, not a 3D run of this geometry. Our own 3D simulation is the required follow-up; the planned pilot measures the drift-kink correction directly.

What this does — and does not — claim

2D-XZ reduction

3D effects (drift-kink of the X-lines) bounded to ≈ 2× longer reconnection timescale by the kinetic-reconnection literature.

Hybrid-PIC numerical heating

Generates an unphysical >1 MeV tail; the σ-weighted metric de-weights it. >10 MeV spectrum and α kinematics deferred to full-PIC.

First-transit G_FT

Window-dependent by construction; reported as a conservative lower bound, not a converged value.

Single operating point

Collisionless, low-density; one (n, B-seed) point. Density / field dependence is follow-up work.

No net energy gain claimed

Seed-to-intensity mapping is an order-of-magnitude scaling; loss channels (radiation, disassembly) not modeled.

VALIDATION PATH

Two tracks — and the experiment is very attainable

S Simulation track

- Full-PIC cross-validation of the >1 MeV bulk distribution.
- 3D hybrid-PIC pilot — out-of-plane tilts and X-line kink.
- Cross-code check (OSIRIS / EPOCH / SMILEI).

Compute-gated; tractable in the current code base.

E Experimental track

attainable today

- CLPU Vega II (6 J / 30 fs, ≤10 Hz) already matches 5 J coupled; a ps driver matches the seed directly.
- PROBONO partners (ELI, PALS, Catania, Bordeaux, QUB) share the methodology.
- Signature: eight X-line emission pattern · ToF non-thermal tail >500 keV on the convergence axis · α yield in the projected range.

No petawatt or megajoule facility required — room-scale, joule-class hardware already in operation can run the first test.

SUMMARY

Conclusions

1. An eight-spot ring reconnection geometry drives protons to p–^{11}B fusion energies non-thermally at only 5 J coupled.
2. Headline G_tot = 4.08 (conservative floor G_FT = 3.63), grid-converged within ~12%; the thermal-floor baseline is zero.
3. Yield is robust to realistic beam imperfections (CV < 2%); a reconnection threshold sits between 51 and 85 T.
4. Compounded hardware-and-scale accessibility ≈ 7,000× per shot over petawatt-class p–^{11}B campaigns — validation within reach of present-day, room-scale hardware.

4.08 total σ-gain	**3.63** G_FT floor	**~75%** B-collapse	**5 J** coupled

OPEN TO COLLABORATION

Compute-gated extensions

- Full-PIC validation of the >1 MeV bulk proton distribution
- 3D hybrid-PIC pilot — out-of-plane tilts and X-line kink
- Fine-cadence (3.7 ps) f(E,t) campaign
- (n, B-seed) parameter sweeps toward the Li et al. limit
- Cross-code validation (OSIRIS / EPOCH / SMILEI)

Openly archived

Code, data & WarpX container · with checksums

Simulation results · v1.2.2
10.5281/zenodo.20528212

Analysis & code suite
10.5281/zenodo.20540413

Runtime container · v1.2.2
10.5281/zenodo.20541777

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