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The optimal injection energy for beam-driven proton–boron fusion lies above the 675 keV resonance

Oleg Agamalov

olegagamalov@gmail.com

Independent Researcher

Short Report

Keywords: proton–boron fusion, beam-driven fusion, injection energy optimization, slowing-down, non-thermal reactivity, aneutronic fusion

Posted Date: October 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11085294/v1

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Additional Declarations: No competing interests reported.

Abstract

Every non-thermal proton–boron-11 scheme now pursued places its fast ions at the 675 keV resonance of the ¹¹B(p,3α) cross section. The rate coefficient, however, is the product σ(E) v(E), and because the relative velocity grows as the square root of energy, the true maximum of the rate coefficient lies at 3.7 MeV. While this theoretical displacement governs ignition, a driven device is governed by a different, practically accessible quantity: the fusion yield integrated over the slowing-down history of the fast ion, weighted by the energy invested. We evaluate this engineering gain per unit injected energy analytically. We find that the optimum injection energy for a beam-driven device is 0.85 MeV, which is a little above the resonance but far below the 3.7 MeV kinematic ceiling. Injecting protons at 0.85 MeV rather than at the widely targeted 675 keV resonance raises the beam-driven gain per unit energy invested by 25 per cent. This improvement requires no new physics, no new confinement scheme, and no change of magnetic configuration — only a higher injector voltage.

1. Introduction

Proton–boron-11 fuel is attractive because the primary reaction, p + ¹¹B $\rightarrow$ 3 α + 8.7 MeV, produces no primary neutrons [1, 2]. Against this stands a Lawson requirement roughly two orders of magnitude more demanding than for D–T [3]. The classical assessments concluded that the balance does not close [4–6]. The question has been reopened by relaxing the Maxwellian assumption [7–9], and several privately funded programmes now pursue the fuel using non-thermal schemes [10, 11].

These approaches share a single premise. The p–¹¹B cross section carries a pronounced resonance at a laboratory proton energy of 675 keV, and a distribution that places ions preferentially there — such as a neutral beam — is expected to sample that resonance more effectively than a thermal population. That enhancement is what converts a marginal or negative power balance into an ignited one, and the 675 keV resonance is, without exception, the target energy across the field.

However, the rate of fusion depends not on the cross section σ alone, but on the rate coefficient σv. Because the relative velocity v grows with energy, the maximum of the product lies above the maximum of the cross section. Evaluated on the cross sections of Sikora and Weller [13], the global maximum of σv sits at a proton energy near 3.7 MeV.

While the 3.7 MeV kinematic ceiling is of theoretical interest for ignition, it is too high in energy to be practically accessible for beam-driven devices, as establishing a population there demands immense drive power [7]. A driven device is instead governed by the fusion yield integrated over the slowing-down history of the fast ions. This Brief Communication demonstrates that the practically important optimum for a beam-driven device lies at 0.85 MeV, and that injecting there rather than at the resonance yields a 25 per cent gain in fusion energy per unit energy invested.

2. The slowing-down integral

A fast ion injected at laboratory energy E_0 slows on the background electrons and makes reactions all the way down. What matters is not the instantaneous rate coefficient at the injection energy, but its integral over the slowing-down history, weighted by the time spent at each energy.

In the regime where the fast proton velocity is much smaller than the electron thermal velocity ($v_f \ll v_{te}$), the energy loss rate on the electrons is $dE/dt = -2E/\tau_{se}$, where τ_{se} is the Spitzer slowing-down time:

$$\tau_{se} = \frac{3(2\pi)^{3/2}\epsilon_0^2 m_p m_e v_{te}^3}{n_e Z_p^2 e^4 \ln\Lambda_e}$$

1

where ϵ_0 is the vacuum permittivity, m_p and m_e are the proton and electron masses, n_e is the electron density, Z_p is the proton charge number, e is the elementary charge, $\ln\Lambda_e$ is the Coulomb logarithm, and v_{te} is the electron thermal speed.

The fusion yield per injected proton is the integral of the reaction rate over the slowing-down time. The engineering gain of the beam, $Q(E_0)$, is the total fusion energy produced divided by the energy invested in the injected particle. Substituting the electron-drag power loss, the gain per unit energy invested is proportional to:

$$Q(E_0) \propto \frac{1}{E_0}\int_0^{E_0} \frac{\sigma(E)\,v(E)}{E}\,dE$$

2

where E is the kinetic energy, and $\sigma(E)\,v(E)$ is the reaction-rate coefficient.

The $1/E$ weighting penalizes high injection energy twice over: the ion costs more to make, and it spends the early part of its life in the shallow region between 1 and 3 MeV where the cross section is small.

3. The 0.85 MeV optimum

We evaluate Eq. (2) using the analytic fit of Tentori and Belloni [15] for center-of-mass energies above 0.668 MeV, and the low-energy parameterisation of Becker et al. [14] below that, joined by a linear bridge.

Table 1 evaluates the integral of Eq. (2). The optimum lies at 0.85 MeV, a little above the resonance and far below the 3.7 MeV theoretical maximum of σv.

Table 1
Beam-driven gain per unit injected energy, Eq. (2), normalized to its maximum.

E_0 **(MeV)**	$Q\left(E_0\right)/Q_{max}$
0.50	0.43
0.675	0.80
0.85	1.00
1.20	0.88
2.00	0.69
3.60	0.60

As shown in Table 1, injecting at 0.85 MeV rather than at the 675 keV resonance raises the beam-driven gain by 25 per cent (1.00 vs 0.80).

Equation (2) treats the slowing-down time, and with it the Coulomb logarithm, as independent of the fast-ion energy. Allowing $\ln\Lambda_e$ to drift across the whole slowing-down range moves the optimum by less than one per cent, and the gain stays within 3 per cent of its maximum between 0.77 and 0.96 MeV. The optimum is therefore a plateau rather than a sharp point.

4. Practical implications

The field currently injects at, or below, 675 keV because that is where the cross section peaks. However, as demonstrated by Eq. (2), the true figure of merit for a beam-driven device is 25 per cent larger at 0.85 MeV than at 0.675 MeV.

That improvement requires no new physics, no new confinement regime, and no change of magnetic configuration — only a higher injector voltage. It is an immediately available gain for any driven proton-boron system.

Furthermore, targeting the 3.6–3.7 MeV global maximum of σv is highly inefficient for a driven device. As Table 1 shows, despite the instantaneous rate coefficient being higher at 3.6 MeV, the beam-driven gain $Q\left(E_0\right)$ there is 40 per cent worse than at the 0.85 MeV optimum, because of the massive initial energy investment and the long transit through the cross-section valley.

5. Conclusions

The engineering gain of a beam-driven proton–boron device is optimized at an injection energy of 0.85 MeV, not at the 675 keV resonance on which every current scheme is built. The result follows from the

fusion yield integrated over the slowing-down history of a fast proton. Injecting at 0.85 MeV rather than at the resonance raises the gain per unit energy invested by 25 per cent. This represents a substantial, practically accessible improvement for the development of proton–boron fusion as a driven system.

Declarations

Author declarations

The author has no conflicts to disclose.

Author Contribution

Oleg Agamalov is the sole author of this paper

Data availability

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.22139230.

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Figures

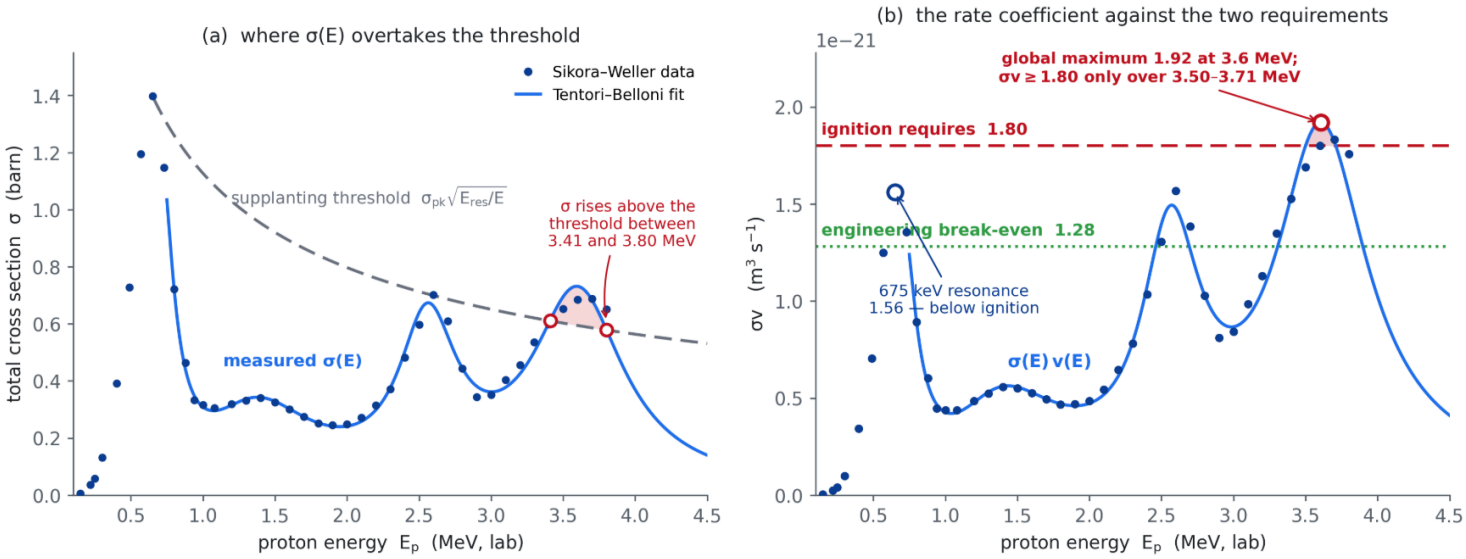


Figure 1

(a) The total cross section evaluated from the tabulated Legendre coefficients. (b) The reaction-rate coefficient σv. While the cross section sharply peaks at the 675 keV resonance, the increasing relative velocity shifts the maximum of the rate coefficient to 3.7 MeV.