A Modular Three-Stage Fusion Framework for Future Applications

Mamuka Molashkhia
Zugdidi Public School No. 2, Zugdidi, Georgia

May 1, 2025

Abstract

Fusion energy offers a sustainable, clean energy source with applications on Earth and in space. This paper presents a modular three-stage fusion framework designed to achieve self-sustaining, aneutronic energy production with minimal external inputs. By integrating fuel production, intermediate energy generation, and main power output into a feedback loop, the system leverages deuterium-deuterium (D-D), deuterium-helium-3 (D-He-3), and proton-boron-11 (p-B-11) fusion processes. Computational simulations, implemented via a Python-based calculator, assess the framework's feasibility across modern, near-future, and theoretical maximum scenarios. While current technology yields a net energy deficit, near-future advancements enable positive energy output, with theoretical limits suggesting significant potential. This framework outlines a scalable path for fusion energy, identifying key technological challenges for future research.

1 Introduction

Fusion energy, the process powering stars, fuses light atomic nuclei to release vast energy, providing a clean alternative to fossil fuels and fission-based power [1]. Unlike conventional sources, fusion emits no greenhouse gases and, in aneutronic reactions, minimal radioactive waste [2]. Its potential spans terrestrial grids and extraterrestrial habitats, such as lunar bases or deep-space missions, where energy autonomy is vital [3]. However, fusion demands immense energy inputs to achieve the requisite temperatures and pressures, often exceeding outputs with current technology [4].

Dominant fusion research focuses on tokamaks and inertial confinement fusion (ICF) using deuterium-tritium (D-T) fuels [5, 6]. These systems, while advanced, require large infrastructures and external power. Aneutronic fusion, utilizing helium-3 or boron-11, reduces neutron emissions but demands higher ignition temperatures [7, 8]. This paper proposes a modular three-stage fusion framework that interlinks distinct fusion processes into a self-sustaining cycle, minimizing external resource reliance and enhancing adaptability for diverse applications.

2 Conceptual Framework

The framework comprises three interdependent stages, forming a scalable cycle adaptable to technological progress.

2.1 Stage 1: Fuel Production

This stage generates helium-3 via deuterium-deuterium (D-D) fusion [9]. Small-scale reactors, such as inertial electrostatic confinement (IEC) or Polywell designs, produce helium-3 despite low efficiencies [10]. Operating intermittently, Stage 1 stockpiles fuel for subsequent stages.

2.2 Stage 2: Intermediate Energy Generation

Stage 2 employs deuterium-helium-3 (D-He-3) fusion in a field-reversed configuration (FRC) reactor, yielding high-energy protons with minimal neutrons [11]. Requiring small helium-3 quantities, it bridges to Stage 3 by producing protons for ignition.

2.3 Stage 3: Main Power Generation

Stage 3 utilizes proton-boron-11 (p-B-11) fusion, an aneutronic process, for primary energy output [7]. Laser-compressed boron pellets, ignited by Stage 2 protons, aim for net energy gain. The system's innovation is its feedback loop: Stage 3 energy powers Stage 1, producing helium-3 for Stage 2, which generates protons for Stage 3, reducing external fuel dependency.

3 Technical Analysis

This section quantifies the framework's energy performance, focusing on Stage 3 and its reliance on Stages 1 and 2. The total net electrical energy is:

$$E_{\text{total}} = E_{\text{stage 3}} - E_{\text{grid}} \tag{1}$$

where $E_{\text{stage 3}}$ is Stage 3's net electrical output, and E_{grid} is the external energy input.

3.1 Stage 3 Energy Calculations

Stage 3's net electrical energy is:

$$E_{stage3} = E_{stage3output} - (E_{ProtonBeam} + E_{Laser})$$

Where:

$$E_{stage3output} = N_{fuel} \times f_{burn} \times E_{fusion} \times \epsilon_{thermal}$$

Symbols	Description	Units
$\boldsymbol{N_{fuel}}$	number of ^{11}B ions	Particles
$\boldsymbol{f_{burn}}$	the percentage of fuel that reacts in the fusion reaction	Decimals
$\boldsymbol{E_{fusion}}$	the energy we get per fusion reaction	Joules
$\boldsymbol{\epsilon_{thermal}}$	Efficiency of converting to useful electricity	Decimals

$$E_{ProtonBeam} = \frac{N_{proton} \times T_{proton} \times 1.602 \times 10^{-19}}{\epsilon_{driver}}$$

Symbols	Description	Units
$\boldsymbol{E_{ProtonBeam}}$	Energy for the proton beam	Joules
$\boldsymbol{N_{proton}}$	Required amount of protons	Particles
$\boldsymbol{T_{proton}}$	Energy/temperature of protons	eV
$\boldsymbol{\epsilon_{driver}}$	Efficiency of the proton beam	decimals

$$E_{laser} = \frac{\frac{3}{2} \times N_{fuel} \times K_B \times (\Delta T)}{\epsilon_{laser}}$$

Symbols	Description	Units
$\boldsymbol{N_{fuel}}$	Number of ions in the fuel	particles
$\boldsymbol{K_B}$	Boltzmann's constant	1.380649×10−23 J/K
$\boldsymbol{\Delta T}$	Difference between the desired temperature and the starting temperature	Kelvin(K)
$\boldsymbol{\epsilon_{laser}}$	Laser to plasma coupling, or the efficiency of delivering energy via the laser	decimals

3.2 Grid Energy Input

Grid energy includes ignition and sustainment costs:

$$E_{\text{grid}} = E_{\text{ignition1}} + E_{\text{sustain1}} + E_{\text{ignition2}} \tag{6}$$

Ignition energy for Stages 1 and 2, corrected for accuracy, is:

$$E_{ignition1-2} = n \times V \times (\frac{3}{2} \times K_B \times T + E_{ion})$$

(7)

Where

Symbols	Description	Units
$\boldsymbol{n}$	Deuterium ion density	m^{-3}
$\boldsymbol{V}$	Plasma volume	m^3
K_B	Boltzmann constant	1.380649×10−23 J/K
$\boldsymbol{T}$	Plasma temperature	Kelvin, or eV
$\boldsymbol{E_{ion}}$	Ionization energy per particle	J

Stage 1 sustainment energy is:

$$E_{sustain1} = (P_{magnet} + P_{ElectronInjection} - P_{fusion}) \times t_{operation} \tag{8}$$

Where:

$$P_{magnet} = \frac{B^2 \times V}{2\mu_o \times \epsilon_{magnet}}$$

Symbols	Description	Units
$\boldsymbol{P_{magnet}}$	Power for magnetic confinement	W
B	Magnetic field strength	T
$\boldsymbol{V}$	Plasma volume	m^3
$\boldsymbol{\mu_o}$	Permeability of free space	$4\pi \times 10^{-7}$ H/m
$\boldsymbol{\epsilon_{magnet}}$	Magnet efficiency	decimals

$$P_{elec} = I_e \times V_e$$

Symbols	Description	Units
$\boldsymbol{P_{elec}}$	Power for electron injection	W
$\boldsymbol{I_e}$	Electron current	A
$\boldsymbol{V_e}$	Electron drive voltage	V

$$P_{fusion} = \frac{1}{2} \times n^2 \times \langle \sigma v \rangle \times E_{fusion} \times V$$

Symbols	Description	Units
$\boldsymbol{P_{fusion}}$	Power produced by D-D fusion, which reduces external input.	W
$\boldsymbol{n}$	Deuterium ion density	m^{-3}
$\boldsymbol{\langle \sigma v \rangle}$	D-D fusion reactivity. Temperature dependent	m^3/s
$\boldsymbol{E_{fusion}}$	Energy per D-D fusion reaction	eV
$\boldsymbol{V}$	Plasma volume	m^3

. Operation time, corrected from $\frac{1}{18}$ to $\frac{1}{4}$ based on D-D branching ratios, is:

$$t_{operation} = \frac{N_{Helium-3}}{\frac{1}{4} \times n^2 \times \langle \sigma v \rangle \times V} \tag{12}$$

3.3 Helium-3 Requirements

Helium-3 mass for Stage 2, driving Stage 3 ignition, is:

$$m = \frac{E_{Stage2Output}}{E_{PerGram} \times Q}$$

where Q is Stage 2's Q-value, and $E_{\text{per gram He3}} = 5.87 \times 10^{11}$ J/g.

4 Computational Results

A Python-based fusion energy calculator (available in supplementary materials) simulated the framework using modern, near-future, and maximum theoretical parameters.

4.1 Modern Values

With current technology:

- Stage-3 net energy: -0.445MJ
- Grid energy input: 0.444MJ

- Total net energy: -0.889MJ
- He-3 required: 0.574μg
- Stage 1 operation time: 0.459s

Negative output reflects current inefficiencies.

4.2 Near-Future Values

With moderate advancements:

- Stage-3 net energy: 248.597MJ
- Grid energy input: 110.601MJ
- Total net energy: 137.996MJ
- He-3 required: 192.013μg
- Stage 1 operation time: 0.001s

Positive output suggests near-term viability.

4.3 Maximum Theoretical Values

Under optimal conditions:

- Stage-3 net energy: $1{,}348{,}028.754$MJ
- Grid energy input: $524{,}767.712$MJ
- Total net energy: $823{,}261.042$MJ
- He-3 required: $413{,}264.589\mu$g
- Stage 1 operation time: ≈ 0s

This highlights the framework's potential with advanced technology.

5 Applications and Challenges

The framework promises scalable, clean energy for Earth and autonomous power for space habitats [1, 3]. Challenges include:

- **Helium-3 Production**: Low-efficiency IEC reactors require design improvements [10].
- **Energy Transfer**: Proton and energy delivery across stages demands precision [14].
- **Technology**: High-efficiency lasers, superconductors, and materials are critical [13].

6 Conclusion

This modular three-stage fusion framework offers a theoretical path to self-sustaining, aneutronic energy production. While currently unfeasible, simulations indicate viability with near-future advancements, with significant potential under theoretical maxima. Continued research into reactor efficiency and inter-stage energy transfer is essential to realize fusion's promise.

References

[1] Katoch, G., et al. (2025). Fusion energy: A sustainable pathway to meeting future global energy demands. *Discover Sustainability*, 6, 221.

[2] National Academies of Sciences, Engineering, and Medicine. (2021). *Bringing fusion to the U.S. grid*. The National Academies Press.

[3] Meschini, S., et al. (2023). Review of commercial nuclear fusion projects. *Frontiers in Energy Research*, 11, 1157394.

[4] Wurzel, S. E., & Hsu, S. C. (2022). Progress toward fusion energy breakeven and gain. *Physics of Plasmas*, 29(6), 062103.

[5] Wesson, J. (2011). *Tokamaks* (4th ed.). Oxford University Press.

[6] Lindl, J. D., et al. (2004). The physics basis for ignition using indirect-drive ICF targets. *Physics of Plasmas*, 11(2), 339–491.

[7] Magee, R. M., et al. (2023). First measurements of p-11B fusion in a magnetically confined plasma. *Nature Communications*, 14, 955.

[8] Cai, J., et al. (2022). A study of the requirements of p-11B fusion reactor by tokamak system code. *Fusion Science and Technology*, 78(1), 149–163.

[9] Mahdavi, M., & Koohrokhi, T. (2010). Simultaneous catalytic regime of tritium and helium-3 in D-D fusion. *Pramana - Journal of Physics*, 74, 377–390.

[10] Wulfkühler, J.-P., et al. (2024). A systematic approach to modelling geometries of IEC fusion devices. *Scientific Reports*, 14, 2261.

[11] Helion Energy. (2023). How does Helion generate electricity? *Helion Energy FAQs*.

[12] Freidberg, J. P. (2007). *Plasma physics and fusion energy*. Cambridge University Press.

[13] Batani, D. (2024). Inertial confinement fusion: Recent results and perspectives. *EPJ Web of Conferences*, 310, 00013.

[14] National Research Council. (2013). *Assessment of inertial confinement fusion targets*. The National Academies Press.

7 Appendix

Provided here are the values taken for the computational model, as well as the link to the python tool.

7.1 Modern values

Parameter	Value	Units	Explanation
Mass of B-11 fuel	0.001	g	Small-scale experimental runs
Burn-up fraction	0.01	Decimal	Low due to current fusion challenges
Thermal efficiency	0.3	Decimal	Typical for modern power plants
Proton driver efficiency	0.2	Decimal	Current particle accelerator efficiency
Temperature rise **Laser coupling efficiency**	1×10^{7} 0.1	K Decimal	Needed for fusion initiation Standard for inertial confinement
Number of protons in beam **Ion density** **Plasma volume**	1×10^{18} 1×10^{21} 0.01	Particles m^{-3} m^{3}	Feasible for small experiments Common in magnetic confinement Small experimental reactors
Stage 1 ignition temperature **Stage 2 ignition temperature** **Ionization energy (Stage 1)** **Ionization energy (Stage 2)** **ReactivityMagnetic field$\langle\sigma v\rangle$ for D-D**	1×10^{8} 2×10^{8} 2×10^{-18} 2×10^{-18} 1×10^{-22}	K K J J m^3/s T	Approximate for deuterium Same as Stage 1 At moderate temperatures Current superconducting magnets
Magnet efficiency	0.8	Decimal	Reasonable for today's systems
Electron current	100	A	Standard for auxiliary heating
Electron drive voltage **Stage-2 Q-value**	1×10^{4} 0.5	V Unitless	Typical for electron injection Below breakeven, current limits

7.2 Near-Future Values

Parameter	Value	Units	Explanation
Mass of B-11 fuel	0.1	g	Larger fuel for sustained experiments
Burn-up fraction	0.1	Decimal	Better confinement and drivers
Thermal efficiency	0.4	Decimal	Improved heat transfer systems
Proton driver efficiency	0.4	Decimal	Advances in accelerators
Temperature rise **Laser coupling efficiency**	5×10^{7} 0.2	K Decimal	Higher temps for better reaction rates Improved laser-plasma interaction
Number of protons in beam **Ion density** **Plasma volume**	1×10^{20} 5×10^{21} 1	Particles m^{-3} m^{3}	Larger beams for more energy Denser plasmas for fusion Medium-sized reactors
Stage 1 ignition temperature **Stage 2 ignition temperature** **Ionization energy (Stage 1)** **Ionization energy (Stage 2)** **ReactivityMagnetic field$\langle\sigma v\rangle$ for D-D**	5×10^{8} 1×10^{9} 2×10^{-18} 2×10^{-18} 5×10^{-21} 10	K K J J m^{3}/s T	Higher for improved reactivity Even higher for Stage 2 Unchanged Unchanged At higher temperatures Stronger fields with advanced magnets
Magnet efficiency	0.9	Decimal	Improved magnet designs
Electron current	1000	A	Higher currents for heating
Electron drive voltage **Stage-2 Q-value**	5×10^{4} 2	V Unitless	More effective injection Above breakeven, net energy gain

7.2.1 Required Advancements for Near-future

- High-temperature superconductors
- Improved laser systems
- Advanced plasma diagnostics and control
- Efficient particle accelerators
- Better heat transfer materials

7.3 Maximum Theoretical Values

Parameter	Value	Units	Explanation
Mass of B-11 fuel	100	g	
Burn-up fraction	0.3	Decimal	Near max for p-11B fusion
Thermal efficiency	0.6	Decimal	Upper limit for energy conversion
Proton driver efficiency	0.7	Decimal	Highly efficient accelerators
Temperature rise **Laser coupling efficiency**	1×10^{8} 0.5	K Decimal	Optimal reaction rates Near-perfect energy transfer
Number of protons in beam **Ion density** **Plasma volume**	1×10^{22} 1×10^{23} 100	Particles m^{-3} m^{3}	Massive beams for high output Ultra-dense plasmas Large reactor volumes
Stage 1 ignition temperature **Stage 2 ignition temperature** **Ionization energy (Stage 1)** **Ionization energy (Stage 2)** **ReactivityMagnetic field$\langle \sigma v \rangle$ for D-D**	1×10^{9} 2×10^{9} 1×10^{-18} 1×10^{-18} 1×10^{-20} 20	K K J J m^{3}/s T	Very high for D-D fusion Even higher for Stage 2 Lower due to advanced techniques At extremely high temperatures Exceptionally strong fields
Magnet efficiency	0.95	Decimal	Near-ideal performance
Electron current **Electron drive voltage** **Stage-2 Q-value**	1×10^{4} 1×10^{5} 10	A V Unitless	Very high currents for heating Maximum feasible voltage High gain, highly efficient system

7.3.1 Required Advances For Maximum Theoretical Values

- Breakthroughs in plasma confinement
- Ultra-efficient laser/particle beams
- Advanced materials
- AI-driven plasma control

Link to the python tool:

https://gist.github.com/mamukicha/cf57c287f4e91f0ab4d5e6fa801e5e3c