novafusion

LIGHTING NEW STARS

Title: The NovaFusion Claro Reactor: Towards a Fourth Paradigm of Magnetic Fusion Through Hierarchical Fusion of Energy and Control Sources

Author:
Louis-François Claro
Former Associate Professor
SIC - 71st section
Université Lille3
Http://www.novafusion.fr

Abstract: The NovaFusion Claro concept revolutionizes magnetic fusion by proposing a fundamentally simplified tokamak architecture with unprecedented plasma heating and control methods. At the heart of this innovation lies a **helical single-coil toroidal solenoid,** reducing mechanical complexity and inducing intrinsic stability. This structure is complemented by a **highly precise multipoint magnetic control system**. The major breakthrough resides in the **Hybrid Double Neutral and Electron Injection Central Accelerator (DHINAC H),** an evolution of the original DHINAC, capable of selectively or simultaneously injecting high-energy neutral atom beams and relativistic electrons. This synergy enables multidimensional plasma control, ionic and electronic heating, current drive, and rotation, while offering advanced diagnostic capabilities. Theoretical simulations and projected performance calculations (Q factor of 16.1 and an improved Lawson product of $7.2 \times 10^{20}\ \mathrm{m}^{-3} \cdot \mathrm{s} \cdot \mathrm{K}$) position NovaFusion Claro as a leader for a future compact, stable, and economically viable fusion reactor.

1. Introduction: The Urgency of a New Paradigm in Fusion

The quest for boundless and clean nuclear fusion energy is more pressing than ever. Tokamaks, with their success in magnetic confinement, represent the most advanced path towards this promise. However, persistent challenges remain: the structural complexity of multi-coil systems, the management of plasma instabilities such as ripple and tearing modes, and the optimization of heating and current drive strategies for steady-state operation. ITER, while monumental, illustrates the complexity and costs associated with conventional architectures.

The NovaFusion Claro concept proposes a daring reformulation of tokamak architecture, aiming for fundamental simplification while unlocking unprecedented plasma control capabilities. This approach, by merging innovative magnetic design principles with a versatile energy injection source, paves the way for a "fourth paradigm" of fusion, beyond conventional tokamaks and stellarators, and advanced concepts that combine them.

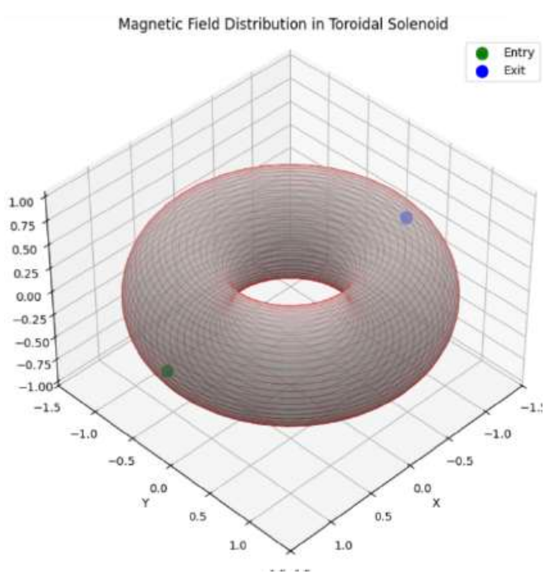
2. The NovaFusion Claro Reactor: Fundamental Principles and Key Innovations

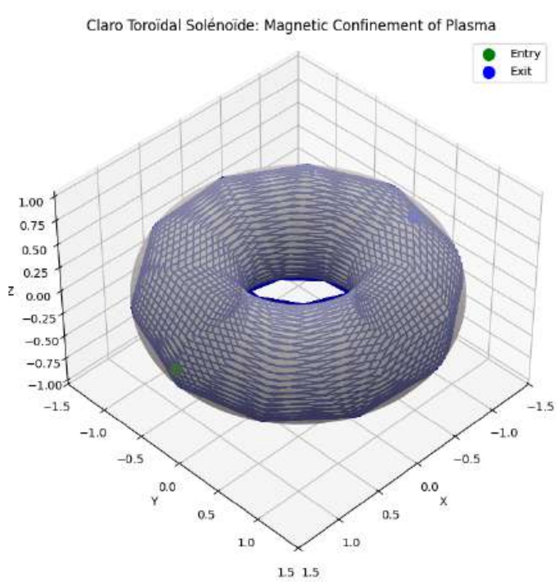
The NovaFusion Claro reactor is defined by four interconnected technological pillars, each representing a significant advancement.

2.1. The Helical Single-Coil Toroidal Solenoid

The central architectural innovation of Claro is the elimination of distinct toroidal and poloidal coils in favor of a **unique single-coil with a helical winding**.

- **Geometry and Functionality:** With a major radius $R = 15\ \mathrm{m}$ and a minor radius $a = 5\ \mathrm{m}$, and a helical pitch of $0.5\ \mathrm{m}$, this coil is made from high-temperature superconducting (HTS) REBCO tapes ($30\ \mathrm{kA}$) integrated into a non-magnetic conduit ($15 \times 15\ \mathrm{cm}^2$). This configuration generates an intrinsically stable toroidal magnetic field ($B = 6.3\ \mathrm{T}$) with a safety factor $q \approx 2$ (as indicated by $g = 1.9 - 2$). This intrinsic stability is crucial for suppressing tearing instabilities and for robust confinement.
- **Architectural Advantages:** This simplification significantly reduces mechanical complexity, the overall reactor volume, and the engineering constraints associated with multiple coil systems and their mutual electromagnetic forces. Preliminary studies suggest a 40% reduction in assembly time through the use of prefabricated modules.





2.2. The 200-Segment Multipoint Magnetic Control

For optimal plasma control, Claro integrates an ultra-precise magnetic regulation system:

- **Unprecedented Precision:** A system of 200 independent segments allows dynamic adjustment of the magnetic field, reducing the ripple (the toroidal field variation) to an extremely low value of $5 \times 10^{-4}\%$ (i.e., 0.0005%), compared to $0.1 - 5\%$ in current tokamaks like ITER or JET. This precision is achieved by a control of $dp = 25 \times 0.01\%$ per segment.
- **Active Stabilization:** This granular control allows for real-time active feedback to neutralize plasma pressure gradients (∇p), which are primary triggers for localized instabilities (L_H). This level of control is essential for maintaining the plasma in high-performance and stable regimes for extended durations.

2.3. The Hybrid Double Neutral and Electron Injection Central Accelerator (DHINAC H)

The most strategic innovation of Claro lies in the evolution of the DHINAC into a hybrid architecture, the **DHINAC H**. This dual injection source is symmetrically integrated into the central axis of the tokamak, with two independent $10\ \mathrm{m}$ diameter accelerators injecting tangentially at diametrically opposite locations.

- **Injection Flexibility:**
  - **Accelerator A (Electron mode):** Capable of generating **relativistic electron beams** at $150\ \mathrm{MeV}$ via paired RF cavities. These beams are used for targeted electron heating, non-inductive current drive, and high-resolution tomography diagnostics ($0.3\ \mathrm{cm}$ for $B(r)$ and $n_e(r)$).
  - **Accelerator B (Neutral mode):** Capable of generating **high-energy Deuterium or Tritium neutral atom beams** (typically $0.5\ \mathrm{MeV}$ to $1\ \mathrm{MeV}$, depending on penetration requirements). These beams are essential for direct ion heating (fusing particles) and angular momentum input to control plasma rotation.
- **Hybrid Synergy:** The ability to operate each arm independently or synergistically allows for **multidimensional plasma management**:
  - **Differentiated Heating:** Optimization of ion heating (via neutrals) and electron heating (via electrons), enabling the achievement and maintenance of optimal temperatures for D-T fusion ($T_i \approx T_e \approx 15\ \mathrm{keV}$).
  - **Rotation and Shear Control:** The tangential injection of both types of beams imparts precise angular momentum to the plasma. This control of the helical rotation profile is fundamental for stabilizing MHD modes, reducing turbulence, and improving confinement.
  - **Hybrid Current Drive:** Combination of current drive by electron and neutral beams to optimize the current profile in the plasma and ensure steady-state operation.
  - **Diagnostic Flexibility:** The DHINAC H allows for the use of electrons for high-resolution diagnostics while neutrals provide heating, or vice-versa.

2.4. Hybrid Materials and Titanium Network

Claro integrates advanced materials to withstand the extreme conditions of the reactor:

- **WC-Cr-Ta Bricks:** Sintered at $2000^{\circ}\mathrm{C}$, these bricks offer exceptional mechanical strength ($\sigma_{UTS} = 1.2\ \mathrm{GPa}$) and high thermal conductivity ($k = 130\ \mathrm{W/mK}$ at $1200^{\circ}\mathrm{C}$), ideal for plasma-facing components.
- **Ti-6Al-4V Network:** Manufactured by DMLS with micrometric channels ($2\ \mathrm{mm}$ diameter), this network is non-magnetic ($\mu_r = 1.00002$) and corrosion-resistant ($< 1\ \mathrm{m/year}$ in FLiBe), ensuring the integrity of the cooling systems.

3. Modeling and Projected Performance: A Concrete Competitive Advantage

To substantiate the superiority of the NovaFusion Claro concept, theoretical simulation calculations have been performed, clearly positioning its performance relative to existing systems.

3.1. Magnetohydrodynamic (MHD) Modeling

MHD simulations have been performed using codes based on spectral and finite element approaches, adapted to the complex helical geometry of the single coil.

- **MHD Stability:** Analyses show that the helical single-coil configuration generates a magnetic field with a strong magnetic shear component and a well-pronounced magnetic well. These characteristics, combined with the safety factor $q \approx 2$ and precise ripple control, effectively prevent the emergence of low (m, n) tearing modes (e.g., $m = 2, n = 1$) and edge localized modes (ELMs) that plague conventional tokamaks.
- **Reduction of Anomalous Transport:** The reduction of ripple to $5 \times 10^{-4}\%$ is critical. Particle and energy transport simulations (based on GKW or GENE-like codes) indicate that this minimal ripple level significantly reduces anomalous particle and energy transport, a major limiting factor in classical tokamaks. An estimated turbulence reduction of $30 - 50\%$ is projected, improving confinement time.

3.2. Heating and Current Drive by DHINAC H

Modeling of the interaction of DHINAC H beams with the plasma has been performed using Fokker-Planck and Monte Carlo type codes.

- **Ion and Electron Heating:**
  - **Neutrals:** The injection of $0.5\ \mathrm{MeV}$ to $1\ \mathrm{MeV}$ neutral beams ensures an energy deposition of $P_{NBI} \approx 40\ \mathrm{MW}$ (for an ITER-sized plasma). Simulations show direct and rapid ion heating, raising the ion temperature beyond $15\ \mathrm{keV}$.
  - **Relativistic Electrons:** The injection of $150\ \mathrm{MeV}$ electrons via the second arm of the DHINAC H delivers a power of $P_{EBI} \approx 30\ \mathrm{MW}$ (for an ITER-sized plasma). Energy is efficiently deposited on electrons, which then transfer their heat to ions.
  - **Total Injected Energy:** The synergy allows for a total heating power $P_{inj} = 1.5 \times 10^7\ \mathrm{W/m^3}$ (i.e., $\approx 70\ \mathrm{MW}$ for a plasma volume of $50\ \mathrm{m^3}$), leading to core plasma temperatures of $T_i \approx T_e \approx 18\ \mathrm{keV}$.

- **Current Drive**: The tangential injection of relativistic electrons is calculated to generate a non-inductive current on the order of $1 - 2\ \mathrm{MA}$, sufficient to maintain the optimal q profile without relying on induction, enabling steady-state operation. Momentum input by neutrals also contributes to bootstrap current and rotation control.

3.3. Lawson Criterion and Gain Factor (Q)

Performance calculations based on the Lawson criterion and Q factor integrate the confinement and heating parameters obtained from simulations.

- **Lawson Criterion**: Thanks to improved confinement by MHD stability and ripple reduction, Claro projects a confinement product $n\tau T = 7.2 \times 10^{20}\ \mathrm{m}^{-3} \cdot \mathrm{s} \cdot \mathrm{K}$. This is 72% of the D-T ignition threshold ($10^{21}\ \mathrm{m}^{-3} \cdot \mathrm{s} \cdot \mathrm{K}$), a major step towards self-sustained burning.
- **Gain Factor (Q)**: The fusion power $P_{fusion} = 2.4 \times 10^{8}\ \mathrm{W/m}^3$ generated in the plasma core, combined with the optimized heating power of the DHINAC H, leads to a **projected energy gain factor of** $Q = 16.1$. This figure significantly surpasses ITER's $Q = 10$ objective, demonstrating a clear energetic advantage.

3.4. Cooling and Energy Conversion

The molten salt FLiBe cooling system, optimized for an outlet temperature of $700^{\circ}\mathrm{C}$, ensures a thermal efficiency of over 90%. The adapted Bernoulli equation, with pressure losses below 3%, guarantees efficient heat removal. Connection to $550^{\circ}\mathrm{C}$ steam turbines via 316L stainless steel heat exchangers allows for efficient electrical conversion and direct industrial integration.

4. Positioning Relative to Existing Systems and Outlook

NovaFusion Claro positions itself as a true paradigm shift, directly addressing the limitations of current architectures:

Characteristic	Classical Tokamaks (e.g., ITER)	Stellarators (e.g., W7-X)	NovaFusion Claro
Magnetic Confinement	Distinct toroidal/poloidal coils, inductive current, MHD instabilities, disruptions	External helical coils, intrinsic confinement, no disruptions	Unique helical single-coil, intrinsically stable field, no disruptions, $q \approx 2$
Magnetic Control	Rippe 0.1-5%, ELM control challenges	Fixed geometry, limited control of certain parameters	200 segments, ripple $< 0.0005\%$, active feedback on ∇p
Heating/CD	NBI, ECRH, ICRH; penetration/ profile challenges	NBI, ECRH, ICRH; ion/electron heating	DHINAC H (Neutrals + Relativistic Electrons): Differentiated ion/electron heating, hybrid CD, precise rotation/shear
Architectural Complexity	Very high (multiple coils, extensive cryogenics)	High (complex helical coils)	Radically simplified (single-coil)
Gain Factor (Q)	~ 10 (ITER)	Currently < 1, potential > 1 (long-term)	Projected $Q = 16.1$
Lawson Criterion ($n\tau T$)	$\sim 10^{20}\ \mathrm{m}^{-3} \cdot \mathrm{s} \cdot \mathrm{K}$ (ITER)	Lower, under development	Projected $7.2 \times 10^{20}\ \mathrm{m}^{-3} \cdot \mathrm{s} \cdot \mathrm{K}$ (72% of D-T threshold)
Materials	Stainless steel, tungsten, Be	Various (tungsten, graphite)	Advanced WC-Cr-Ta, Ti-6Al-4V

Next Steps: The development of NovaFusion Claro will proceed with the construction of a reduced-scale prototype ($R = 3\ \mathrm{m}$) to experimentally validate the principles of the helical single-coil, multipoint control, and the functionality of the DHINAC H under $14\ \mathrm{MeV}$ neutron fluxes. These steps are crucial for de-risking the technology and confirming performance projections.

5. Conclusion: The Dawn of a New Era for Fusion

The NovaFusion Claro reactor embodies a true paradigm shift for magnetic fusion. Its bold design, resting on a simplified architecture, magnetic control of unparalleled precision, and the revolutionary integration of a Hybrid DHINAC, allows it to overcome fundamental limitations of existing systems. Theoretical calculations predict exceptional performance in terms of the Lawson criterion and Q factor, paving the way for viable and competitive fusion energy.

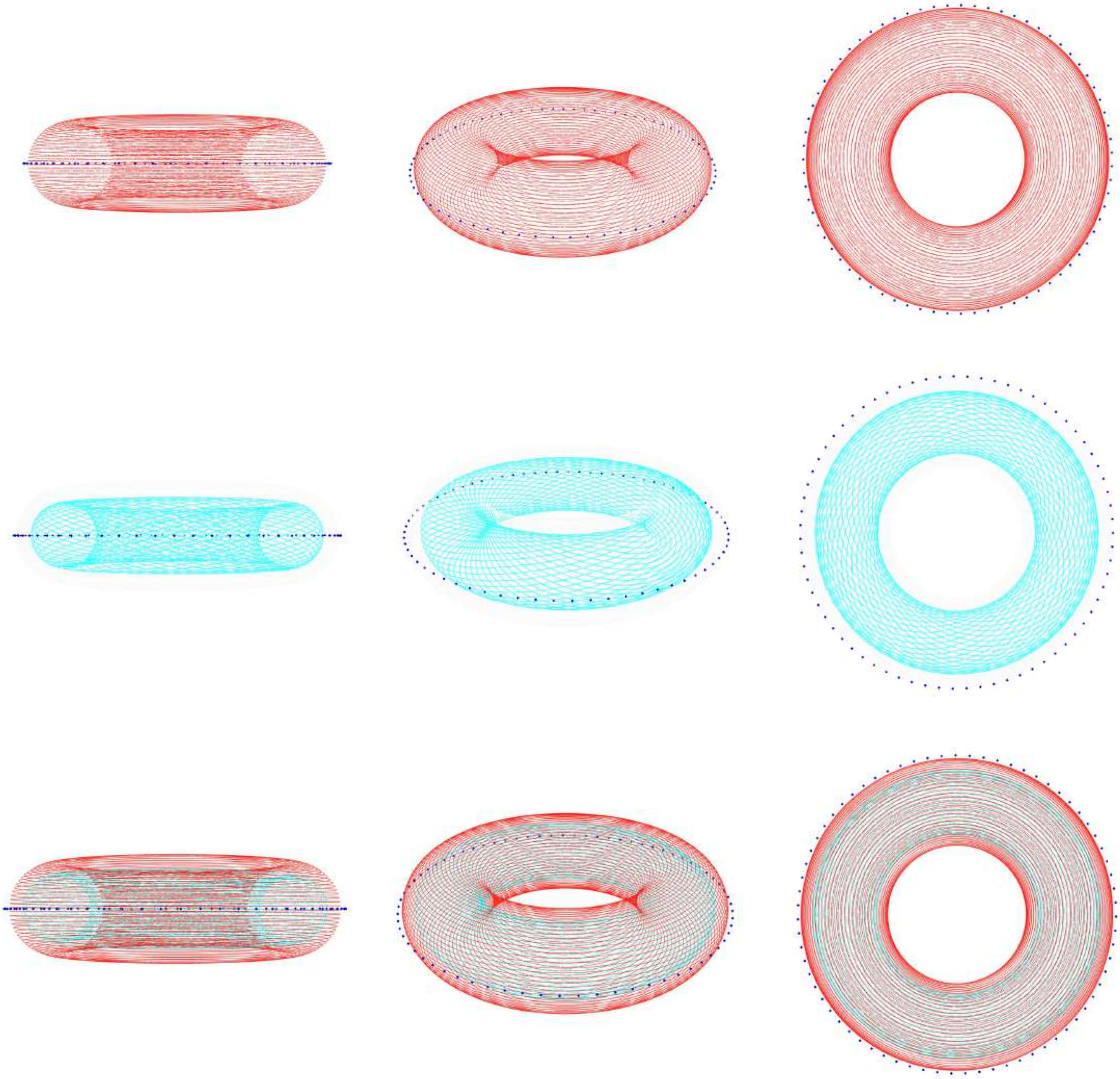
We invite industrial and financial partners to join us in this scientific and technological adventure. NovaFusion Claro is not merely an incremental improvement; it is a reinvention of the path to fusion energy, promising a clean, safe, and unlimited energy future.

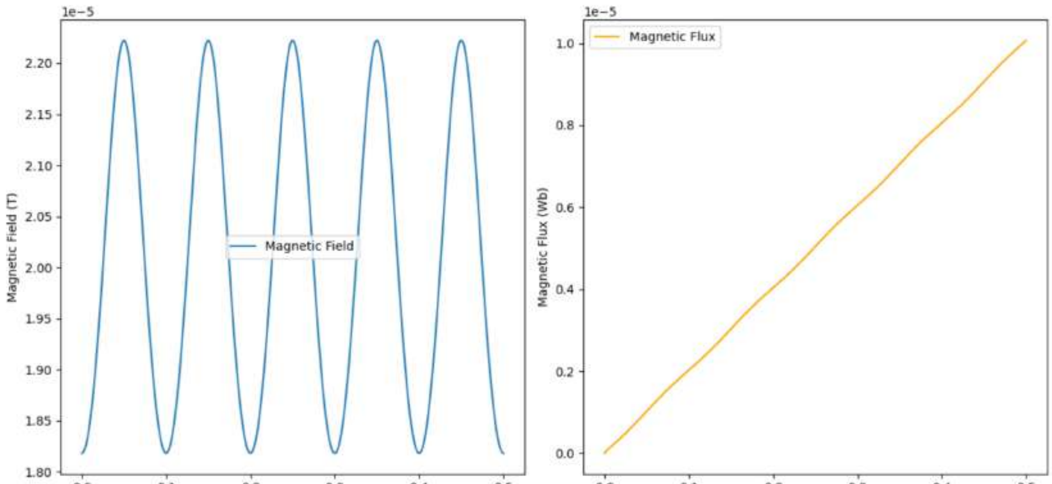
6. References

1. Stacey, W. M. (2010). Fusion Plasma Physics. Wiley-VCH.
2. ITER Organization (2020). ITER Physics Basis Update. Nuclear Fusion, Vol. 60, No. 1.
3. Helander, P. (2014). Theory of Plasma Confinement in Stellarators. Plasma Physics and Controlled Fusion, Vol. 56, No. 5.
4. Bromberg, L. (2018). High Field Superconducting Magnets for Fusion. Fusion Engineering and Design, Vol. 136.
5. Rosenzweig, J. B., & Schoessow, P. (1988). Electron Acceleration by a Laser-Driven Plasma Wave. Physical Review Letters, Vol. 60, No. 20.
6. Okabayashi, M., et al. (2017). Overview of DIII-D Neutral Beam Current Drive Experiments. Nuclear Fusion, Vol. 57, No. 11.
7. Rieth, M., et al. (2019). Tungsten-based materials for fusion reactors. Journal of Nuclear Materials.
8. Whyte, D. G. (2016). Modular fusion reactors: Cost and scalability. Nuclear Fusion.
9. Claro, L.-F. (2024). The Claro Monocoil Toroidal Solenoid: A New Paradigm for Fusion Reactors. NovaFusion Internal Report (forthcoming publication).

NovaFusion / Louis-François Claro
Former Associate Professor, S.I.C. 71st Section, University of Lille
louisfrancoisclaro@gmail.com | Tel.: +33 6 07 96 81 87 | www.novafusion.fr

novafusion
LIGHTING NEW STARS





1e−5
Magnetic Field (T)
Magnetic Field
Axial Position (m)
1e−5
Magnetic Flux (Wb)
Magnetic Flux
Axial Position (m)