



Harnessing The Power Of Light To Drive Nuclear Fusion

Background

Nuclear fusion has long been under investigation. With global warming and climate change being pressing issues that need immediate addressing, the search for clean, sustainable energy sources continues. Nuclear fusion presents a tantalising alternative with the potential to solve the “trilemma” of energy sources: It is clean, safe and abundant, combining the high power of nuclear energy with the safety profile of renewables.

So why are we not using it yet? Currently, a massive amount of energy is required to start a nuclear fusion reaction, often exceeding the amount of energy gained and resulting in a negative energy balance. That means the reaction does not produce enough energy to keep itself going and grinds to a halt instead.

“Traditional” nuclear fusion uses tritium as a fuel, which is very rare in natural occurrence, and releases high-energy neutrons, making engineering of nuclear reactors extremely challenging.

Ignition of a fusion reaction can be attempted in different ways: Magnetic confinement fusion and inertial confinement fusion. For successful ignition – i.e. a fusion reaction with a positive energy balance – reactions need to fulfill the Lawson Criterion. Temperature, density and confinement time of the plasma need to be high enough for the atomic nuclei to fuse and release energy in the form of fast-moving particles.

In magnetic confinement fusion, a strong magnetic field is used to confine and compress plasma, often in combination with an additional heat source. In inertial confinement fusion, high-power lasers are shot at a small fuel pellet, ablating the outer layer of the pellet and creating an enormous inward force that produces a central hot spot in which the fusion reaction begins.

Beams with Orbital Angular Momentum

The paradigm of the Vortex-4-Fusion project is that structured light – specifically beams carrying Orbital Angular Momentum (OAM) – has the potential to lower the requirements for induction of fusion. Studies have shown that applying a magnetic field to inertial confinement fusion reactions can increase the hot-spot temperature and yield by 15-30%, providing a crucial step towards fulfilling the Lawson Criterion. So far, only externally generated fields have been applied, requiring a complex set-up. V4F will provide a simple and elegant solution to solve complexity-related issues: OAM laser pulses are capable of generating strong magnetic fields in plasma, acting as an intrinsic source of magnetic fields.

The theory is simple: Use OAM beams, and inertial confinement fusion will be easier to trigger. In practice, there is a significant hurdle: generating high-power OAM beams. Current approaches rely on bulk optical elements and are plagued by various shortcomings, such as low laser-induced damage thresholds and low conversion efficiency. By introducing V4F’s proprietary helical tapered fiber technology, we aim to overcome these issues and abolish the need for bulk optical elements, enabling direct generation of high-order OAM beams with short pulses. These pulses subsequently need to be amplified to Tera-Watt level to reach the beam intensity required to ignite a fusion reaction. We believe that V4F can achieve this ambitious goal, demonstrating for the first time how the use of OAM beams in nuclear fusion can lower the threshold for ignition.

So far, we have been able to identify optimal parameters of helical fiber amplifiers and undertaken first demonstrations of power-scaling of pulsed OAM beams and are now actively working towards first plasma amplification experiments.



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Proton-Boron Fusion

In parallel with the exploration of OAM beams, V4F pursues a pathway to simplify the engineering of fusion reactors by substituting conventional tritium fuels with boranes. The high-energy neutrons produced as a by-product of fusion reactions using tritium pose a significant challenge for reactor engineering as they can cause radiation damage to materials, and neutron activation can create radioactive isotopes. Proton-boron fusion has previously been suggested as an alternative pathway as the fusion reaction does not generate neutrons as a by-product.

While the concept of proton-boron fusion is not new, several unresolved questions are hindering practical execution. Most notably, the optimal laser requirements to induce inertial confinement fusion remain to be identified, and there is a significant lack in understanding the ideal fuel. V4F aims to address these open questions by pioneering a new class of fusion fuels: boranes, molecules consisting of only boron and hydrogen atoms. We will systematically study various targets to identify the key determinants for successful fusion, thus pioneering new principles for proton-boron fusion.

To date, initial experiments have demonstrated that proton-boron fusion using boranes can achieve alpha-particle yields in the same order of magnitude as current record rates observed. Systematical assessment of a range of boranes has allowed us to identify important determinants for the interaction of laser beams with the target.



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Final Proof-of-Concept

By the end of the project, it is our ambition to execute a key proof-of-principle experiment demonstrating that the use of TW-level OAM beams can generate record-high yields of alpha particles. Such result will constitute the first practical evidence for our hypothesis, indicating that using OAM beams in inertial confinement fusion to induce proton-boron fusion reactions has the potential to lower the ignition threshold as well as the demands on reactor engineering – both will be significant steps in turning nuclear fusion as sustainable energy source from a future vision into a realistic opportunity. At the same time, demonstrating direct OAM beam generation in a tapered fiber with ring-shaped core will overcome key obstacles in optics that hinder the widespread use of OAM beams by eliminating the need for bulk optical elements.

The V4F Consortium



 <https://www.v4f.eu/>

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