X-ray Free Electron Laser Driven Fast Ignition

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X-RAY FREE ELECTRON LASER ENHANCED NUCLEAR FUSION CROSS SECTIONS

Upgrades at the Linac Coherent Light Source (LCLS) will allow the testing of theories that predict increased quantum-mechanical tunneling probabilities of nuclear fusion reactions [1-3]. The existing experimental capabilities together with possible future upgrades such as the Double Bunch X-ray Free Electron Laser (DBXFEL) are poised to demonstrate electric field-assisted nuclear fusion enhancements and to determine the dependence on the electric field strength and frequency. The present LCLS X-ray beam routinely delivers 80 GW with 3-4 mJ energy at 8 keV photon energies. In contrast to optical lasers, X-ray Free Electron laser beams can be focused to a 10 nm focal spot thus producing intensities of 10^{23} W cm^{-2} and an electric field strength in excess of $E_{XFEL} = 10^{14}$ V/m for which dynamical nuclear fusion assistance has been predicted to occur [1-3]. Future upgrades will further allow increases in the electric field strength by a factor of 20 to 100 due to the higher photon flux and improved X-ray focusing. These capabilities will thus open up detailed future studies of nuclear fusion cross section enhancements. Finally, a dedicated undulator and possible improvements in beam quality suggest future XFEL intensities of 10^{24} W cm^{-2} producing field strengths well above $E_{XFEL} = 10^{15}$ V/m directly deforming the nuclear potential barrier and affecting the tunneling probability.

Figure 1 shows a schematic of the nuclear potential that is distorted by a strong electric field. For this case, the Coulomb barrier is reduced leading to a significantly enhanced tunneling probability. Besides the obvious static field case, dynamically varying field can further enhance tunneling.

Many concepts for Inertial Fusion Energy (IFE) rely on hot spot formation and assembly of nuclear fuel. Within this approach, nuclear fusion reactions are first initiated within the hot spot volume producing fusion yield and energetic fusion reaction nuclei that stop and deposit their kinetic energy within the cold and dense nuclear fuel. At sufficiently large fusion reactivities and densities, simulations and experiments on the NIF show that a nuclear burn wave will be launched into the nuclear fuel burning significant fractions and resulting into net energy gain.

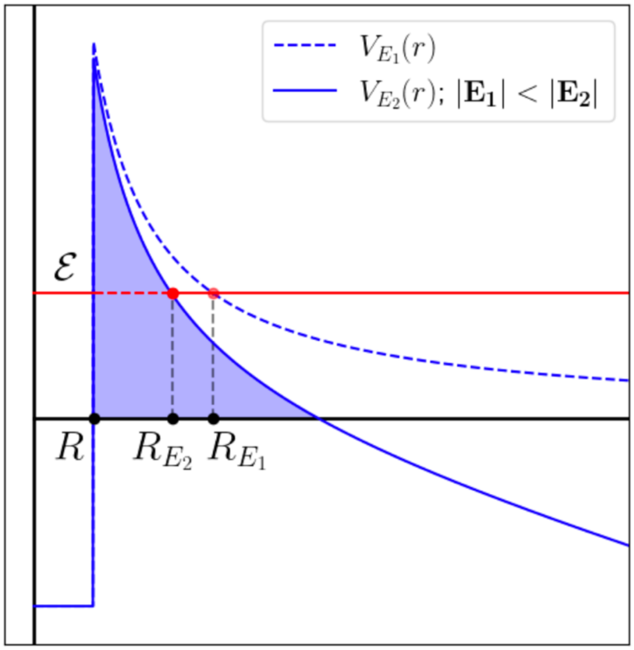

Figure 1. Schematic of a distorted nuclear potential through by a strong electric field, adopted from Ref. [1].

In some advanced schemes presently pursued within the Inertial Confinement Fusion (ICF) approach to ignition, a hot spot forms in the center of a spherical implosion surrounded by deuterium-tritium fuel that is compressed near an isentropic implosion trajectory reaching ion densities of $N_i = 10^{26}$ cm^{-3}. Recent experiments on the National Ignition Facility (NIF) have converted > 70 % of the driver energy into fusion energy [3-6]. In addition, alternative fast ignition concepts are being pursued that use high-power short-pulse lasers or laser-produced proton beams to produce a hot spot in near isobarically compressed matter [7].

Consequently, bringing enhanced fusion cross sections to inertial fusion energy research can open up the field to more advantageous hot spot formation physics and has the potential to pave the way for future advances using smaller fusion drivers or the usage of advanced fusion fuels. The latter is particularly attractive if the need of radioactive nuclear fuel, i.e., tritium, and the requirements for breeding can be avoided.

One of the early successes of quantum mechanics was Gamow's derivation of the α–decay rate [8] via tunneling of the α–particle through the nuclear potential and thus explaining the Geiger-Nuttal law [9]. Building on this result we can evaluate tunneling in the inverse direction arriving at the familiar expression for the nuclear fusion cross section

$$\sigma(\epsilon) = \frac{S(\epsilon)}{\epsilon}\exp(-\sqrt{\epsilon_G/\epsilon}), \qquad (1)$$

with ε being the center-of-mass energy, *S* the slowly varying astrophysical *S*–factor, and the Gamow energy, $\epsilon_G = (\pi\alpha_f Z_1 Z_2)^2 2m_r c^2$ Here, α_f is the fine structure constant, m_r is the reduced mass of the two fusion nuclei, and *c* is the speed of light.

Theory further suggests that the addition of a dynamical time-varying electric field can drastically enhance the tunneling probability. In a possible Ansatz, the barrier transparency T in Eq (1) can be replaced via:

$$\mathcal{T} = \exp(-\sqrt{\epsilon_G/\epsilon}) \rightarrow \exp(-\sqrt{\epsilon_G/(\epsilon + h\nu)}). \qquad (2)$$

In Ref. [2], for ε = 1 keV and an X-ray laser energy of 10 keV, the authors estimate an enhancement factor of 10 orders of magnitude. Obviously, higher X-ray energies are already available at X-ray laser facilities. Although DBXFEL pulses are relatively short and predicted to deliver 15 fs long pulses at ≤ 10 keV it is important to scale to higher photon energies to deliver a field whose time variation is of the order of the tunneling time; in this case, tunneling enhancements have been predicted for field strength of order $E_{XFEL} = 10^{13}$ V/m [10].

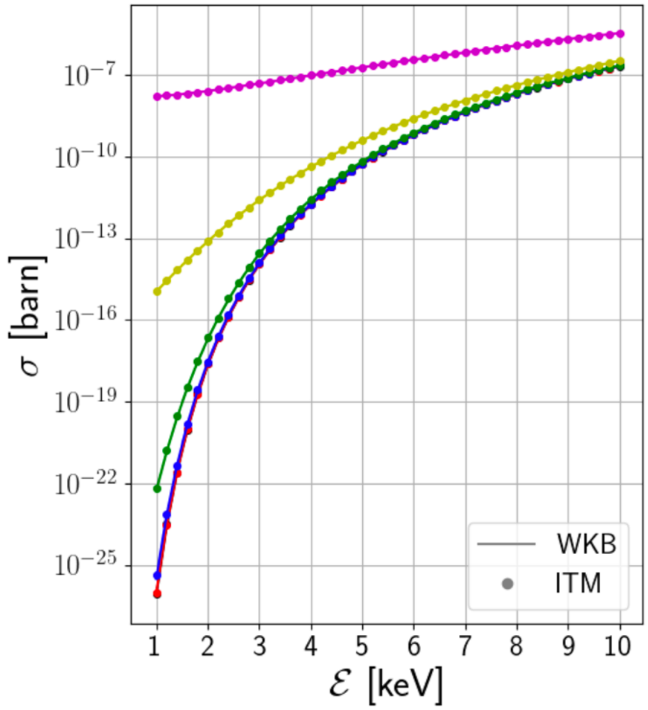

Figure 2. Example of fusion cross section enhancement for D-^{3}He fusion through by a strong electric field, adopted from Ref. [1]. In the case of static fields shown here, we observe agreement with the WKB and the Imaginary Time Method (ITM). The colors denote field strength from 10^{13} V/m (red) to 10^{17} V/m (purple). Ref. [1] provides a thorough presentation for various fusion processes and the challenges for calculations of dynamically varying electric fields.

Current theoretical work on this subject is challenging because established theoretical methods are applicable only in a very narrow regime of interest for experiments. Figure 2 shows an example of theoretical calculations of fusion cross section enhancement for D ^{3}He. The case for DT is very similar to the results shown in Fig. 2 [1].

From this analysis we arrive at the following conclusion for a Basic Research Need: **We will need to experimentally explore fusion tunneling enhancement though electric fields, validate theoretical predictions, and find suitable parameters that will enable Inertial Fusion Energy.**

As a first step, we would require a direct observation of nuclear fusion enhancement. It could make use of a dense target that delivers hydrogen isotopes to an XFEL focus. Cryogenic deuterium jets [11, 12] and room-temperature heavy water jets [13, 14] have recently been successfully fielded in laser and XFEL facilities. They have the advantage to allow experiments at high repetition rates and have already demonstrated predictable neutron yields in short-pulse laser facilities. Experiments suggest neutron production rates of 10^6 neutrons/joule [15, 16].

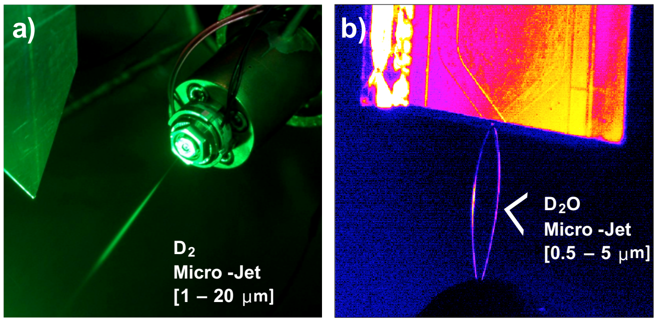

Figure 3. Examples of jet targets suitable for testing tunneling enhancement in heavy hydrogen isotopes at X-ray Free Electron Lasers. (left) A cryogenic deuterium jet has been demonstrated at 120 Hz in LCLS experiments with a target thickness in the range of 1μm to 20μm. (Right) Room temperature heavy water jets have been demonstrated at 380 Hz in LCLS experiments with a target thickness in the range of 0.5μm to 5μm.

A possible experimental study would use a 100 mJ short pulse laser to heat the target to 1 keV temperatures. Here, our scaling suggest that we would produce a thermal neutron signal of 10^5 neutrons. Further, assuming a 5μm cylindrical jet at liquid densities of 5×10^{22} cm^{-3} and an XFEL spot of 100 nm provides a volume of $V = 5\times10^{-14}$ cm^{-3} and a maximum number of 10^9 fusion reactions that are easily detectable. In the same geometry, a 10 nm XFEL focus would allow 10^7 fusion reactions, again easily detectable.

A detailed experimental test of fusion cross section enhancements will include the following studies:

1) Perform absolute neutron yield measurements and quantify the tunneling enhancement by comparing experiments with and without the electric field of the XFEL. These studies will need to provide data to estimate the pre-factor in Eq. (1) in the presence of the electric field of the XFEL.

2) Perform measurements by scaling the electric field of the XFEL by varying the total photon flux and focusing; assess the regime of direct potential deformation.

3) Perform measurements by tuning the photon energy to validate the scaling laws for dynamical assistance. Here, the advantage of tune-ability of XFELs and future increases of the photon energy to 25 keV (accessible now at LCLS) and potentially up to 70 keV in the longer term can provide significant insight into tunneling processes.

4) An assessment will need to be made to explore opportunities for nuclear burn wave launch from a small initial volume determined by the XFEL focal spot.

This work was supported by U.S. Department of Energy, Fusion Energy Sciences under FWP100182.

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