Low and High Temperature Non-Thermonuclear Fusion Approaches to Energy Production

A Response to
DE-FOA-0002499 RFI on Nonconventional Fusion Approaches and Energy Applications

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Abstract

We are responding to the RFI points A1, A2 and A3. We appreciate the need for a high density, high power, environmentally-benign and carbon-neutral power system. Although fusion has been considered for over 70 years, the nearly intractable means of maintaining a hydrogen plasma at temperatures exceeding the center of the Sun increasingly delays not only commercialization but even the scientific breakeven point. As a recent JASON report notes, the world-wide energy grid is moving towards decentralization which is counter to the large tokamak fusion devices necessary given their underdense plasmas.

NASA has spent several years understanding and developing Lattice Confinement Fusion as an alternative to thermonuclear fusion by exploring many means of loading and triggering fusion reactions in deuterated metal lattices. Triggering has run the gamut from bremsstrahlung-initiated photo-neutrons to the role of electron screening in assisting these reactions. Electron screening may be responsible for both nuclear effects in deuterium pumped metals as well as fast neutrons observed from electrolytically driven cathodes. Electron screened fusion rate enhancement has been observed by others, including the Lawrence Berkeley National Laboratory.

NASA's need for deep space power drove this research with a goal of a ten-year lifetime for a multi-kW_e power system. Previous NASA studies have explored the use of fusion systems for nuclear thermal propulsion[1] for manned spaceflight to the outer planets. Despite these designated uses, small-scale terrestrial power applications as well as medical isotope production are possible once scaling is achieved. ARPA-E can contribute to the Nation's Green Energy mandates by funding research in this field that builds on condensed matter nuclear science findings by the US Navy and NASA.

The Need

There is a need for a decentralized, non-CO_2 emitting, base-load capable power system. The most likely CO_2-free power source, fission reactors which until the advent of Small Modular Reactors (SMD), tended toward GW_e sizes. Even 50 MW_e fission reactors require large sites due to safety concerns, and both fission reactor types have long regulatory and construction build times resulting in high initial costs. They have long term fission waste storage, special nuclear material regulations as well as perennial air and water radioactive waste leakage issues.

The Problem

Unlike nuclear fission, fusion is expected to primarily result in relatively short-lived activation of the fusion reactor due to neutron capture. However, the fusion reaction with DT fusion has the highest cross-section and the lowest energy threshold. First, 2/3 of the energy appears as 2.45 and 14.1 MeV neutrons which require significant shielding ultimately leading to activation. Second, each of these neutrons needs to be captured to breed additional tritium, which itself is an environmental hazard though with a 12.7 year half-life and a less than two-week biological half-life. Third, in order to maintain a plasma at over 5 keV, or 55 million degrees K, three methods have been devised, with various modifications; magnetic confinement (MCF), inertial confinement (ICF), and combined magnetic-inertial confinement (MIF)[2].

Each of these approaches follows the Lawson criteria[3], better expressed as the Fusion Triple Product, or $nT\tau_E$ where n=plasma density, T=plasma temperature and τ_E = energy confinement time. All have demonstrated plasma temperatures of several keV. MCF provides seconds of confinement time, but due to the Greenwald Limit[4], has an underdense plasma (10^{14} ions/cm^3). ICF provides high density plasma (10^{26} ions/cm^3) but is confined for only nanoseconds. MIF, ($< 10^{23}$ ions/cm^3) favored by some of the ARPA-E fusion initiatives and reviewed by the JASON[2], attempts to maintain the plasma density slightly longer than ICF, but with modest densities.

An Alternative: Lattice Confinement Fusion

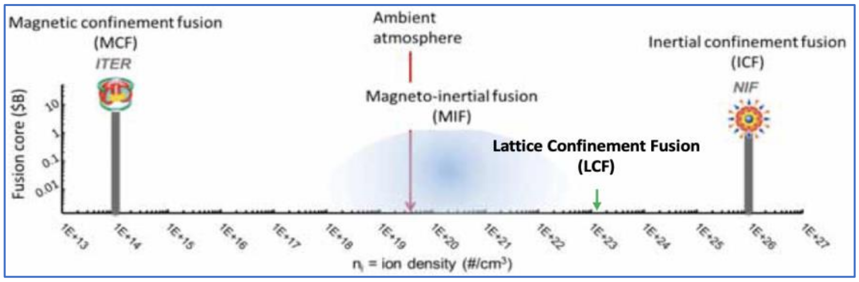
Electron Screening: In 1954, Saltpeter considered electron screening as a factor in fusion and various astrophysical processes[5] which remained unexplained for decades.[6] Beginning in the 1980s, astrophysical observations and laboratory experiments with metal lattices[7] concluded that the electron screening potential, U_e, that translates as an effective deuteron kinetic energy, drastically increases fusion rates:

> …the astrophysical S(E)-factor and the reaction rate of the nuclear reactions responsible for the burning of such elements [Li, Be and B] must be measured and evaluated at ultra-low energies (between 0 and 10 keV)… In this review we will report the details of these experimental measurements and the results in terms of S(E)-factor, reaction rate and electron screening potential.[8]

Lawrence Berkeley National Laboratory (LBNL) used plasma discharge to both load and trigger DD fusion and observed increased fusion rates of 1000 x at deuteron center-of-mass kinetic energies as low as 1.25 keV using plasma loading of deuterons into palladium[9]. They attributed this increased fusion rate to electron screening. With the cross section of bare deuterium nuclei fusion in the neutron channel being 33 μb at 6.3 keV in the center of the mass frame, electron screening is estimated to increase that cross section to 33 mb as shown in the LBNL plasma experiments.

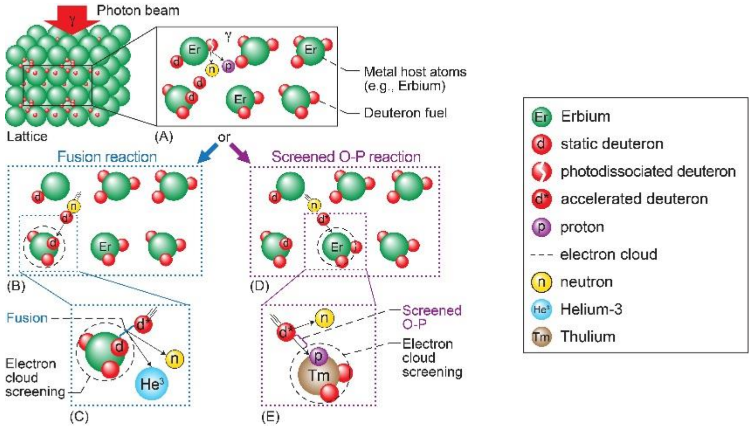
Electron screening does not occur in MCF due to the low plasma density and has not been addressed in ICF. ICF uses low-Z elements in both direct and indirect drive targets to prevent fast electrons from pre-heating the target. The exception is the use of gold and other materials to prevent ponderomotive electron acceleration in the incident laser beam. However, electron screening in lattices allows a *locally hot, globally cold* high-density plasma.

High Fuel Density: The electron-screened deuterated metal lattice approaches a deuteron density of 10^{23} ions/cm^3 as shown in the figure[10] at the right. This deuteron fuel density vastly exceeds MCF (tokamak,10^{14} ions/cm^3), MIF ($< 10^{23}$ ions/cm^3), and approaches ICF core-collapse



densities (10^{26} ions/cm^3). However, unlike sub-microsecond ICF core compression, the screened lattice indefinitely confines the fuel at high density.

There are several means of loading metal lattices with high density deuterium including electrolytic, gas, plasma, glow discharge and others. Similarly, there are multiple ways of triggering a screened lattice to induce Lattice Confinement Fusion[11] (LCF). NASA revealed a means of triggering nuclear fusion (LCF) also utilizing electron screening. The results are published in the Elsevier journal, *Physical Review C*. The theoretical paper, "Nuclear fusion reactions in deuterated metals," describes the mechanisms, and the companion paper, "Novel nuclear reactions observed in bremsstrahlung-irradiated deuterated metals," presents experimental results. During the experiments, nuclear reactions were triggered between deuterium nuclei—or more specifically, deuterons—that are confined in a metal lattice as fuel held at ambient temperature, thus creating a locally hot, globally cold high-density plasma approaching 10^{23} ions/cm^3. The resulting LCF process is illustrated in the figure to the left. Part (A) in the figure shows a lattice of erbium loaded with deuterium. Upon irradiation with a photon beam, a deuteron dissociates, and the neutron and proton are ejected. The neutron collides with a deuteron, accelerating it as an energetic "d*" as seen in (B) and (D). The "d*" induces either screened fusion (C) or screened Oppenheimer-Phillips (O-P) stripping reactions (E). In (C), the energetic "d*" collides with a static deuteron "d" in the lattice, and they fuse together. This fusion reaction releases either a neutron and helium-3 (shown) or a proton and tritium. These fusion products may also react in subsequent nuclear reactions, releasing more energy. In (E), a proton is stripped from an energetic "d*" and is captured by an erbium (Er) atom, which is then converted to a different element, thulium (Tm). If the neutron instead is captured by Er, a new isotope of Er is formed (not shown).



The NASA experiments were repeatable and exhibited fusion gain via either deuteron stripping reactions or boosted fusion reactions resulting in primary 2.45 MeV fusion neutrons, and 4 and 5 MeV boosted neutrons. NASA triggered these high energy reactions with a 2.9 MeV beam. It is anticipated that even higher reaction rates and secondary and tertiary nuclear processes would occur with higher incident beam energies. Though the NASA experiments used photoneutrons to initiate the process, other neutron sources can also be used to initiate the fusion events, coupling to work with NAVY researchers.

Szpak and Mosier-Boss of the US Navy SPAWAR patented an electrochemical means of driving anomalous nuclear reactions[12]. Their co-deposition technique simultaneously plates out Pd and deuterons resulting in a slightly strained, fractal reaction surface, neutron source. The co-deposition protocol[13] has been successfully used for 30 years with government, institute, and university laboratories from 14 countries publishing over 60 peer-reviewed co-deposition papers. Hundreds of successful experiments have established its reliability and reproducibility producing fast neutrons[14,15], excess power[16] and transmutation[17]. Both reliability and repeatability are necessary to demonstrate and probe a scientific phenomenon leading to power scaling and a deployable technology.

Scaling

The US Navy SPAWAR conducted a hybrid fusion-fast-fission experiment. This experiment used Pd/D co-deposition to both load, trigger, and sustain the observed reactions for over 24 hours. They observed a high neutron flux (10^6 neutrons/sec) with an average energy of 6.4 MeV from a deuterated natural uranium cathode.[18] Using 38 mg of natural deuterated uranium, 3.4×10^{10} fissions/cm^3/s were produced compared to a compact highly enriched uranium (HEU) fission reactor where 3×10^{10} fissions/s is one watt.

The aforementioned bremsstrahlung initiated fusion reactions also demonstrated possible fusion gain either from deuteron stripping reactions or boosted fusion reactions resulting in primary 2.45 MeV fusion neutrons, and 4 and 5 MeV boosted neutrons. NASA explored multiple methods of triggering fusion reactions. The deuteron energies ranged from an average 64 keV kinetic energy with bremsstrahlung radiation to eV in gas cycled and electrolysis experiments. However, the goal must be at least 10 times the required input energy vs the thermal energy with a delta T over the background exceeding 250 °C for efficient electrical conversion. An alternative is to use direct conversion of charged particles whose energies have been directly measured.[19]

Unknowns

Although the phenomena have been well demonstrated and documented across a variety of deuterated materials, as evidenced by excess power, transmutation products, fast neutrons, protons and alphas, it is not well understood. The triggering and loading mechanisms are repeatable. However, the operating lifetimes are not yet known. The best materials need to be identified both for power density and operational lifetime. Additional Los Alamos National Laboratory MCNP modeling, augmented with code developed for ITER[20] and NASA analyses[21] will assist with understanding and scaling these reactions. There are several theories that explain the experimental data including electron screening, phonon nuclear coupling, deuteron stripping, and nuclear magnetic effects. It is worth noting that the lack of a comprehensive theory does not obviate the data: experimental data and theory work hand in hand.

Path Forward

NASA GRC and NSWC Dahlgren cooperated under an Interagency Agreement[22] for Condensed Matter Nuclear Reactions using and analyzing materials from co-deposition with a GEC Space Act Agreement and a JWK NCRADA. ARPA-E support could leverage thirty years of existing research across agencies with non-Government involvement to better understand and scale lattice confinement fusion to commercially useful levels.

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[10] “Lattice Confinement Fusion (LCF)” is overlaid on the JASON report[2] Figure 1, page 3, taken from P. McGrath, ARPA-E.

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