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Abstract

Inertial electrostatic confinement is a method for achieving fusion of light nuclei wherein ions are injected into a spherically symmetric system of concentric electrodes. The electrostatic field accelerates ions to energies sufficient to overcome Coulomb repulsion and achieve nuclear fusion. The most commonly used fusion fuels are deuterium-deuterium (D-D) and deuterium-tritium (D-T). Both reactions result in the production of fast neutrons with distinct energies. Neutron production rates are therefore proportional to fusion reaction rates in fusion reactors burning D-D or D-T fuel, and neutron detectors are integral to fusion research. Because both reactions are possible with both fuel gas mixtures, two neutron species will be present in the neutron flux from reactors fueled by either. Richer data can therefore be collected from reactors fueled by either mixture if the contributions from both fusion reactions to the overall reaction rate can be determined. We present progress made toward a low-cost neutron time of flight spectrometer capable of measuring neutron production rate and neutron energy distribution, thereby enabling quantification of the D-D, D-T, and combined reaction rates for D-D or D-T fueled fusion reactors.

Background

i. Nuclear Fusion

The energy released from the fusion of hydrogen isotopes, illustrated in Figure 1, is on the order of MeV. Per reaction, this is six orders of magnitude more energy than is released from the combustion of methane. Moreover, no greenhouse gases are produced through nuclear fusion.

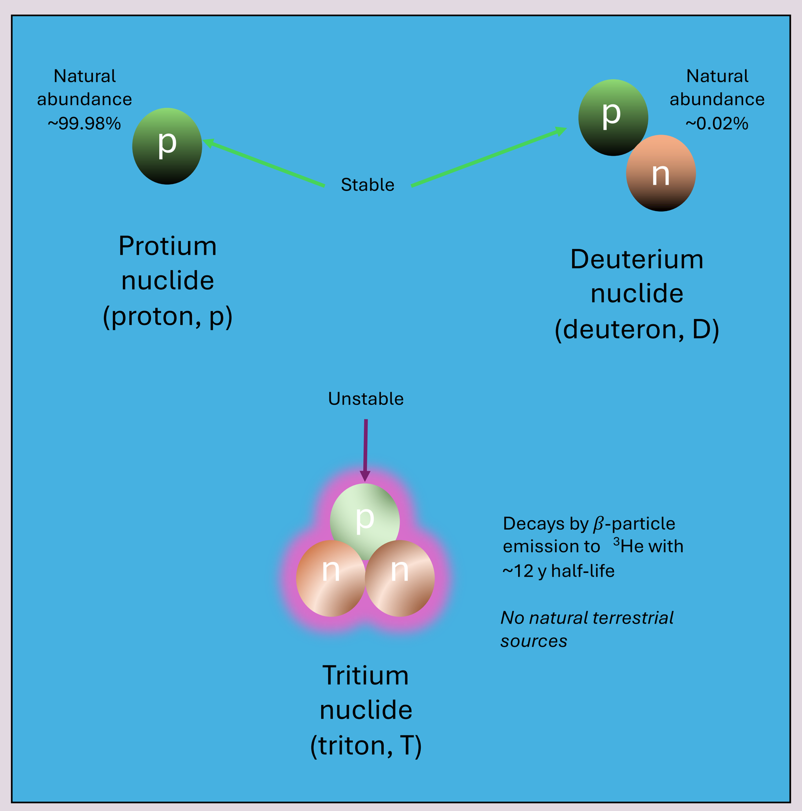

Figure 1: Schematic representation of nuclides of three hydrogen isotopes, i.e., protium, deuterium, and tritium. Unlike protium and deuterium, tritium does not occur naturally, but can be created artificially through nuclear reactions. Fusion reactions can occur between all three nuclides.

Fusion occurs only if two nuclei are brought within ~10^{-15} m of each other—the approximate effective range of the strong nuclear force. Outside of this range, Coulomb repulsion dominates. As such, initiating fusion requires a large amount of energy, but fusion plasmas can "burn" or become self-sustaining, and confining these hot plasmas presents numerous challenges.

ii. Inertial Electrostatic Confinement

IEC was conceptualized by Lavrent'ev in the 1950s, and further developed in the 1960s by Farnsworth [1]. IEC relies on the application of large, axially symmetric electrostatic fields to accelerate nuclei to energies around 100 keV. IEC reactors or fusors, as shown in Figures 2 and 3, are compact and, compared to more popular confinement methods, are simple and inexpensive to build in. As such, IEC can be seen as a democratizing force in fusion research, opening the field to a wider community of researchers.

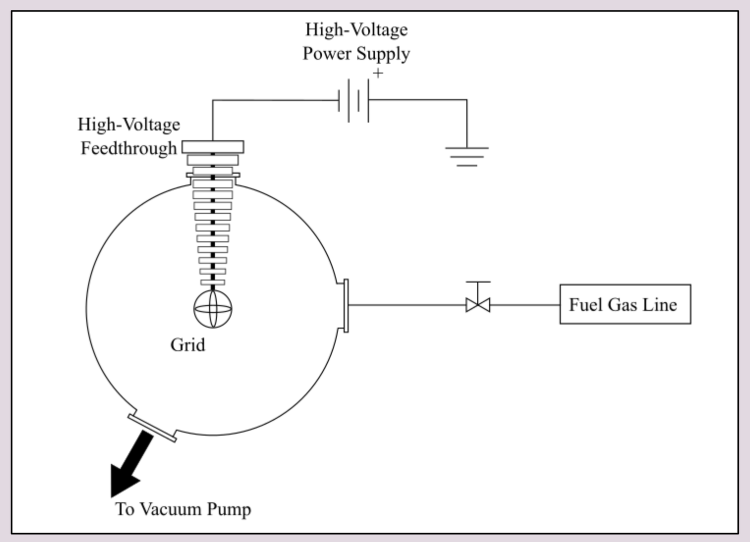

Figure 2: simplified schematic representation of a gridded, plasma discharge type IEC reactor. Negative high voltage between grid and chamber wall ionizes fuel gas by plasma discharge, accelerating ions inward where fusion can occur.

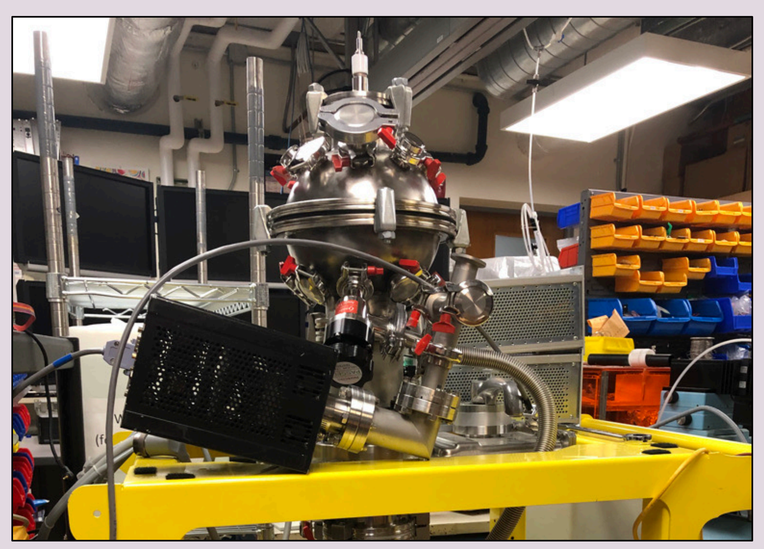

Figure 3: One of the fusors operated by the Sánchez group. The spherical chamber features symmetrically-placed ports for the attachment of ion sources or a variety of instrumentation. Ion sources can improve reactor efficiency by reducing operating pressures,

iii. D-D fusion, D-T fusion, and the diagnostic importance of fast neutrons

This work focuses on deuterium (D-D) fusion, which branches two ways with roughly equal probability, as illustrated in Figure 4. One branch yields tritium, which can undergo deuterium-tritium (D-T) fusion. Because both D-D and D-T reactions yield fast neutrons (2.45 MeV for D-D and 14.05 MeV for D-T), the total fusion reaction rate is proportional to the neutron production rate in a deuterium fueled IEC reactor.

Fast neutron detection typically involves observing effects from secondary reactions caused by elastic neutron scattering. Proton recoil in a hydrogenous scintillator material, for instance, will cause a light pulse that can be converted into a measurable current pulse with a photomultiplier tube (PMT).

iv. Time of Flight Method

Time of flight (TOF) is an established method for determining the energy of fast neutrons based on two sequential detections along its path [2]. The speed of an object that travels a

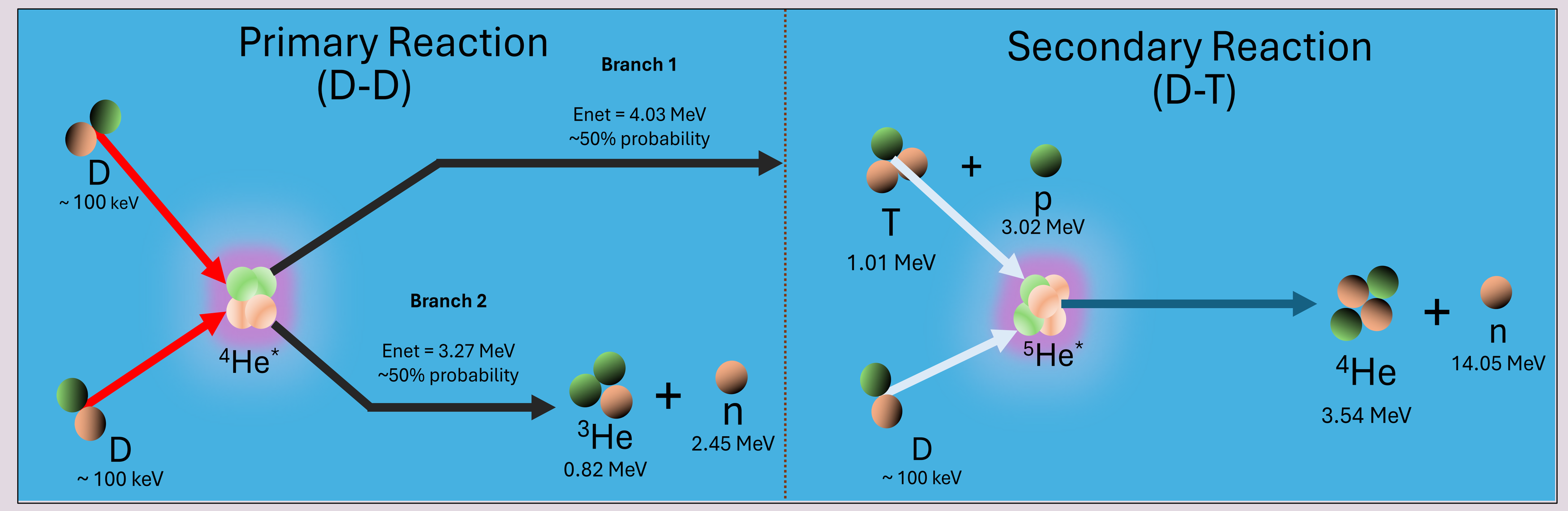

Figure 3: Diagram illustrating approximately 50/50 branching of the D-D fusion reaction (left). Branch 1 is aneutronic, yielding a triton and a fast proton. The second reaction pathway is neutronic, yielding a helium-3 nuclide and a 2.45 MeV neutron. Tritium produced in the first D-D fusion branch have fusion-relevant energies and can undergo secondary D-T reactions with deuterium nuclides in the chamber (right). This reaction does not branch.

distance Δx in time interval Δt, in the absence of external forces, is given by:

$$v = \frac{\Delta x}{\Delta t} \quad (1).$$

Assuming the object's mass m is known, we can then calculate its kinetic energy in MeV:

$$E_k = \left(3.121 \times 10^{12}\, \frac{\text{MeV}}{\text{J}}\right) mv^2 \quad (2).$$

Historically, low source flux and technological limitations have meant fast neutron TOF required path lengths of several meters for sufficient energy resolution [2]. Modern time-to-digital converter (TDC) chips, such as the Texas Instruments (TI) TDC7201 [3], are capable of measuring time differences down to 0.250 ns with ~55 ps time resolution. While commonly used in LIDAR or laser range finding applications, this sensitivity is more than sufficient to detect neutrons with energies in excess of 20 MeV by TOF with path lengths of a few centimeters.

Project Goals

The primary aim of this work is to construct a compact, low-cost instrument capable of simultaneously measuring neutron production rates and neutron energy distribution of deuterium fueled IEC fusion reactors. Neutron energy will be determined using a TOF method incorporating two scintillator-PMT pairs and a TDC7201 integrated circuit.

The instrument concept and general experimental setup are illustrated in Figure 4, and a block diagram of the electronic systems is shown in Figure 5.

The TDC7201 determines neutron TOF as time between START and STOP pulses:

$$\Delta t = (t_{STOP} - t_{START}) \quad (3).$$

This is used in conjunction with known scintillator separation and neutron mass to calculate neutron velocity and energy according to Equations (1) and (2).

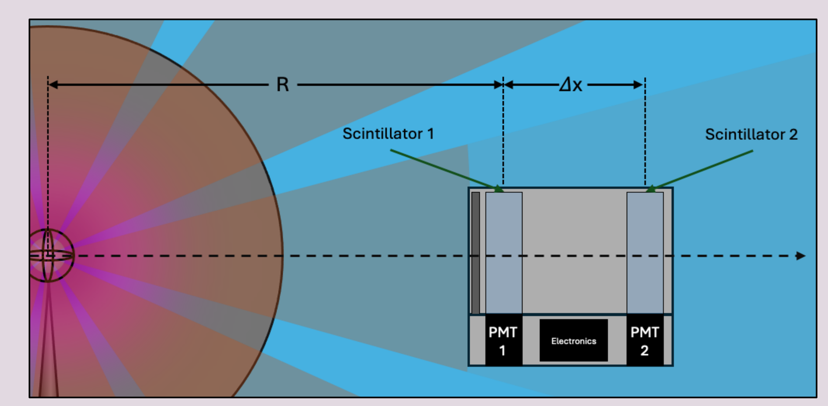

Figure 4: Basic setup for fast neutron TOF spectrometer. The device is placed with the front face of the first scintillator a distance R from the center of the fusor (i.e., origin) such that a ray drawn from the origin is normal to both scintillator surfaces..

Design Considerations

To detect D-T neutrons, our instrument requires a minimum path length of just 1.3 cm. Increased scintillator separation increases the instrument's maximum measurable energy, but also reduces the probability of a detection, which in the context of this work, means one neutron causing a scintillation in both scintillators. Increased scintillator thickness makes a single fast neutron detection more likely, but also increases multiple scattering which could render it undetectable by our definition. As such, optimal scintillator geometry and separation remain to be determined. Optimization of these and other parameters will be accomplished with simulations using GEANT4 software [6].

Progress and Outlook

Software libraries interfacing the MSP430 and TDC7201 have been written. An alternative TDC7201 breakout was designed as a less-costly backup in case of damage to the original device, and pulse conditioning circuits

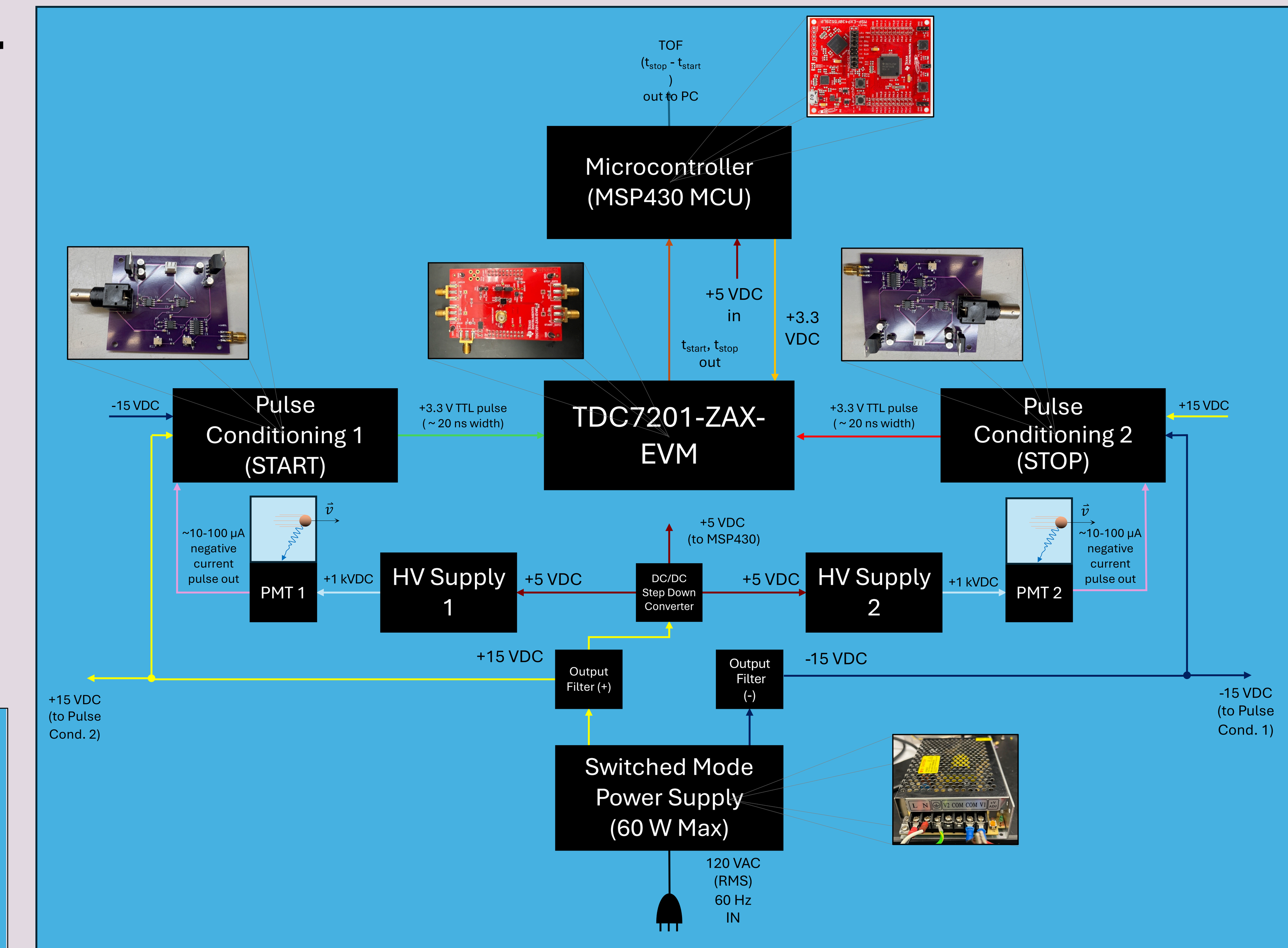

Figure 5: Block diagram of the electronic systems of the fast neutron TOF spectrometer. A START or STOP signal begins at the corresponding scintillator as a light pulse. This is first converted to a small (microampere) negative current pulse by a PMT, and the current pulse is processed by a pulse conditioning stage. Finally, a 3.3 V TTL pulse is sent from the pulse conditioning stage to the TDC7201 to either start or stop a TOF measurement.

have been designed, built, and tested. A suitable power supply for the instrument's electronics, high voltage PMT power supplies [5], and materials for device enclosure have been acquired. Prototype output filters to reduce noise from the power supply have been designed and tested.

Near term goals for the project include finalizing output filters and interconnects between stages; continuing work on GEANT4 simulations to aid in above-mentioned parameter optimizations; selecting scintillator material and PMTs; constructing and testing scintillator/PMT pairs; finalizing device layout in Fusion360; and building the instrument. Once the instrument is built, it can be calibrated in collaboration with Reed College's Research Reactor, whose has fast neutron sources with energies relevant to our research are available for such purposes.

An initial device will serve as a proof of concept that, if successful, will directly impact IEC fusion research at not only at Portland State University, but among the fusion and nuclear research communities in general. The fast neutron TOF spectrometer described above will perform the work of multiple instruments for a fraction of the cost, enabling budget-conscious fusion researchers to gain insight into the operation of their reactors. The concept, once proven, could for instance be extended to multiple devices placed at different locations around an IEC reactor to measure spatial distribution of neutronic reactions in the chamber, in addition to raw counts and neutron energy. Additionally, by using the device described herein in conjunction with raster scanning or a similar method, it is possible in principle to build images of a fast neutron source, provided sufficient source flux.

Acknowledgements

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In loving memory of Chicken

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