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# INSTRUMENTATION FOR A PROTOTYPE FUSION PROPULSION SYSTEM

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*Abstract*

A prototype colliding beam accelerator has been fabricated for the study of a fusion-based propulsion concept for interplanetary exploration. The purpose of this prototype is to demonstrate collider luminosities commensurate with the requirements of this application. While fusion fuels such as p/Li7 and He3/He3 would generate the required thrust characteristics, this prototype currently employs deuterium. Because neutrons are produced via DD fusion with a peak cross section of 0.1 barns, even modest initial luminosities yield event rates suitable for real-time measurements and lifetime monitoring. The proposed luminosity monitor is based on neutron moderation and absorption and subsequent gamma-ray detection. Sodium chloride serves as the moderator, with most neutrons absorbed by chlorine-35 nuclei having a thermal neutron absorption cross section of 43.6 barns. The collider is a linear device employing electrostatic axial confinement and radial focusing. A combination of destructive and nondestructive sensors are employed to monitor various beam parameters such as intensity, energy spectrum, transverse tunes and halo density distribution.

## TERRESTIAL APPARATUS

The fusion reactor architecture used in the proposed propulsion system [1] consists of an electrostatic charged particle trap [2-4] that brings two ion beams into collision with equal and opposite momentum. The terrestrial prototype apparatus utilizes deuteron beams confined both radially and axially by an array of electrostatic electrodes. A picture of the apparatus exterior is displayed in Fig. 1. The dark spots along the side of the white tube are the vacuum electrical feedthroughs to each electrode. Visible on the left side are vacuum pumps and related equipment along with vacuum feedthroughs to a Faraday cup.

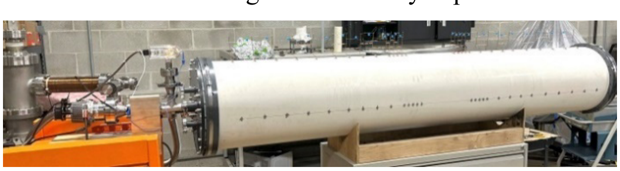

Figure 1: Picture of the prototype fusion propulsion apparatus used to understand and improve luminosity performance.

The internal geometry of the collider, along with the axial potential, are illustrated in Fig. 2. The radial aperture of the electrodes increases linearly with distance from the central collision region. On one side of the array is the deuteron ion source, while on the opposite side is a set of destructive beam instrumentation such as the Faraday cup.

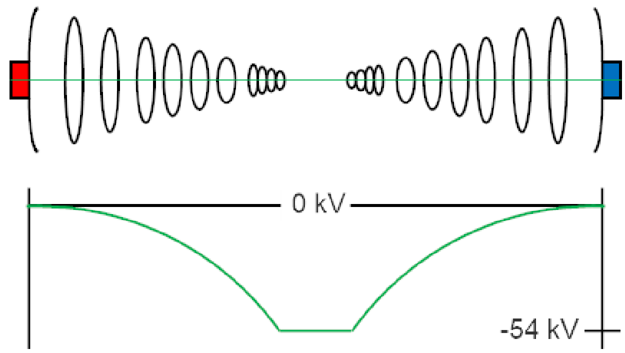


Figure 2: Illustration of the electrostatic electrode array of the fusion collider (top) and the axial potential (bottom).

The axial potential is imposed by applying specific voltages to each electrode in the array. Maintaining even axial symmetry about the center, networks of resistors and capacitors pictured in Fig. 3 are used to distribute the appropriate electrode voltages from a single high-voltage power supply. While the end electrodes are set to zero volts to simplify instrumentation connections, the central collision region is set to an axial potential of -54 kV.

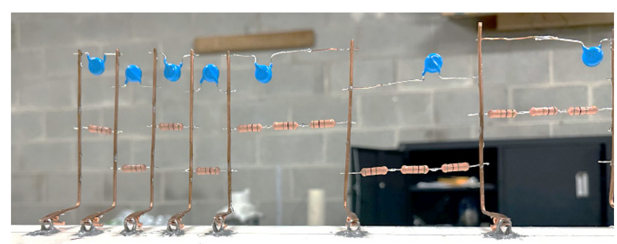

Figure 3: Picture of a portion of the network of resistors and capacitors used to set the voltages of the individual electrodes.

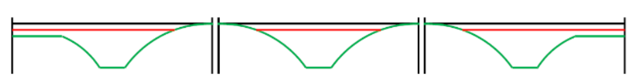

Figure 4: Illustrations of beam injection (left), storage (center), and extraction (right) via modification of the axial potential. The total (kinetic plus potential) energy of the beam is indicated with the red line.

Beam injection and extraction is accomplished with high-speed high-voltage switches that lower the axial potential during each of these events. Illustrations of these operations are sketched in Fig. 4. This enables deuteron injection from ion source on the left side with finite kinetic energy. Before bouncing back to the left side, the axial potential is returned to the storage configuration in the center (and shown in Fig. 2). Arbitrary beam collision kinetic energies less than 54 keV are achievable.

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## LUMINOSITY MONITOR

Since the purpose of this prototype apparatus is to study luminosity in this unique collider architecture, the luminosity monitor is of particular interest. In order to achieve radial focusing, the quadratic axial potential that provides axial ion confinement generates bounce (revolution) frequencies that depend strongly on deuteron kinetic energy at the collision point. Therefore, the deuterons from the single ion source quickly decohere axially into a continuous beam that collides with itself. This produces symmetric collisions with beam kinetic energy of up to 54 keV. The DD fusion cross section as a function of deuteron beam kinetic energy is graphed in Fig. 5. At a kinetic energy of approximately 50 keV the neutron production cross section is approximately one third of the peak value.

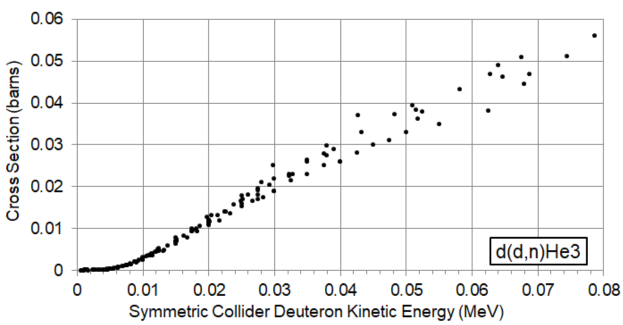


Figure 5: Low energy cross section for DD neutron production. The peak DD fusion cross section is 0.1 barns.

Neutrons emanating from these fusion reactions have an energy of approximately 2.5 MeV. One means to efficiently detect them is to moderate them to thermal energies and then absorb them in nuclei that subsequently emit readily detectable gamma-rays. These gamma-rays are then counted with large-area ionization chambers.

For a luminosity of $1\text{x}10^{27}$ $\text{cm}^{-2}$ $\text{s}^{-1}$, a cross section of 0.3 barns produces a neutron production rate of 30 Hz. With an overall detection efficiency of 3%, a counting rate of 1 Hz is achievable. While such low luminosities are probable in the early days of collider operations, it is anticipated that luminosities several orders of magnitude higher are achievable. A candidate monitor in proximity to the prototype fusion collider is sketched in Fig. 6.

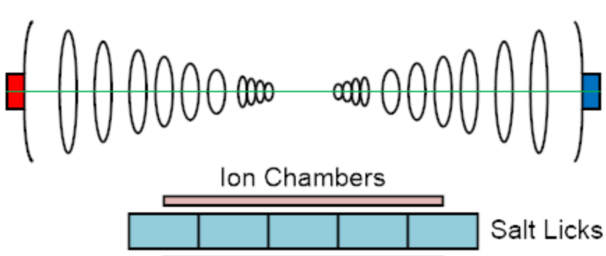


Figure 6: Top view configuration of the luminosity monitor with respect to the fusion collider apparatus.

As luminosity increases and counts begin to overlap, the monitor can be moved radially away from the apparatus to reduce geometric capture efficiency. The large-area ionization chambers will also be replaced with segmented detectors to further avoid event overlap. The large-area ionization chambers have already been tested in a horizontal configuration with cosmic rays.

Figure 7: Luminosity monitor utilizing sodium chloride blocks (commercially available salt licks) and a 2 ft. x 4 ft. large-area ionization chamber on either side.

A convenient material for the neutron moderator/absorber is sodium chloride. While sodium has a thermal neutron absorption cross section of 0.525 barns, chlorine-35 has a radiative cross section of 43.6 barns. The resultant chlorine-36 has a beta-decay half-life of 300,000 years. Chlorine-35 has a natural abundance of 75.8%, whereas the remaining chlorine-37 has a relatively small thermal neutron cross section of 0.433 barns. Hence most absorbed neutrons generate detectable gamma-rays. Figure 7 is a picture of the luminosity monitor fabricated for this project.

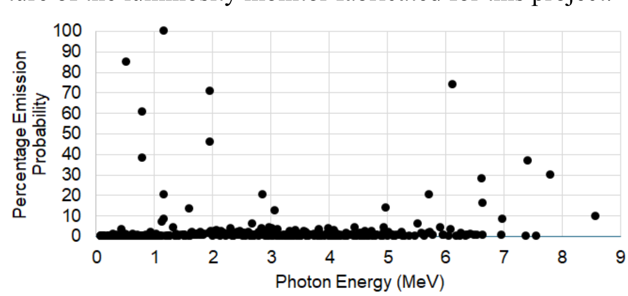


Figure 8: Radiative neutron capture gamma-ray spectrum measured from chlorine-35. For each gamma-ray energy the corresponding emission probability is graphed.

The 2.5 MeV neutrons tend to stop near the center of the salt licks. Upon neutron absorption, chlorine-35 emits a gamma spectrum graphed in Fig. 8. Note that these photons are of sufficient energy to escape from the center of the salt licks and register counts in the ionization chambers.

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## BEAM CURRENT

The number of deuterons stored in the collider is another parameter that is measured. Upon injection and before complete decoherence of that initial current pulse, an AC-coupled central tube between the innermost electrodes on either side of the collision point intercepts the image charge of the deuterons within the tube. With a bounce (revolution) frequency of approximately 1 MHz, this initial coherent current modulation has a fundamental frequency of roughly 2 MHz. Capacitive coupling from the detection tube through high voltage capacitors transmits this beam signal to a digital oscilloscope.

Once full decoherence occurs, there is no longer a net beam current to detect. Not even a DC current monitor is effective. Schottky signals [5] are a nondestructive possibility once sufficient resources and time become available. In the meantime, pulsed extraction into the Faraday cup has been implemented.

## RADIAL TUNE

The axial potential in Fig. 2 generates a radial focusing force F within the quadratic regions on either side of the apparatus. The transition from the quadratic to constant axial potential on either side of the collision region generates a axially narrow but strong defocusing force D. The collision region acts as a drift L. Given that the beam spends much less time under the defocussing force than slowing and reversing course in the quadratic region, overall radial confinement is possible.

Assuming axial symmetry, the Twiss parameter $\alpha^*$ is zero at the center. For a half-bounce starting at the center, the deuterons witness a LDFDL lattice. Analyzing this lattice with matrices assuming stepwise continuous radial elements yields a kinetic energy island of stability graphed in Fig. 9.

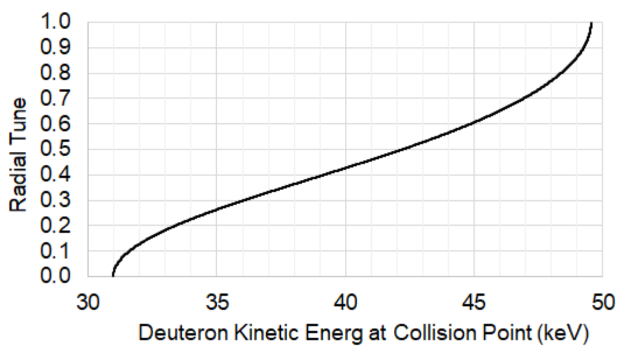


Figure 9: Calculated radial tune assuming stepwise continuous radial elements.

During injection radial misalignment of the deuteron ion source with respect to the collider lattice will induce coherent beam oscillations that are measured with a split-tube beam position detector. This signal will be observable until the beam current distribution decoheres into a DC current of zero.

After decoherence, a transfer function [6] approach to radial (betatron) tune monitoring is planned. As sketched in Fig. 10, a network analyzer drives the beam radially and simultaneously monitors the resultant radial beam deviation. Knowing the radial phase advance θ between the kicker and the radial position monitor, the erosion of deuterons due to radial tune resonance is directly observable.

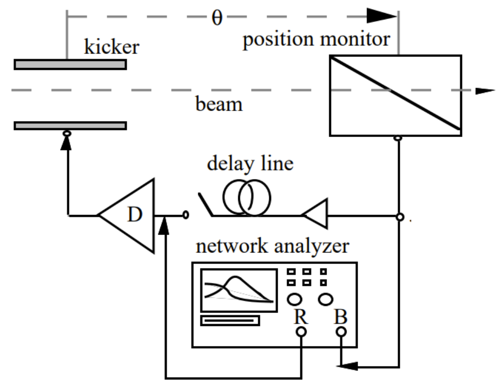


Figure 10: Electronic used to measure the radial transfer function of the stored deuteron beam.

## CONCLUSION

A prototype colliding beam accelerator has been designed and fabricated for the study of a fusion-based propulsion concept for interplanetary exploration. The purpose of this terrestrial prototype is to demonstrate collider luminosities commensurate with the requirements of this application. DD fusion generating neutrons enables real time monitoring of the luminosity. Other instrumentation such as a capacitive pickup and Faraday cup have been installed. Given that the radial (betatron) tune is an important measure of the energy aperture of the collider, a split-ring beam position sensor and radial kicker have been designed and are being fabricated. Deuteron storage is anticipated in the next month.

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