Compact Ion Beam System for Fusion Demonstration

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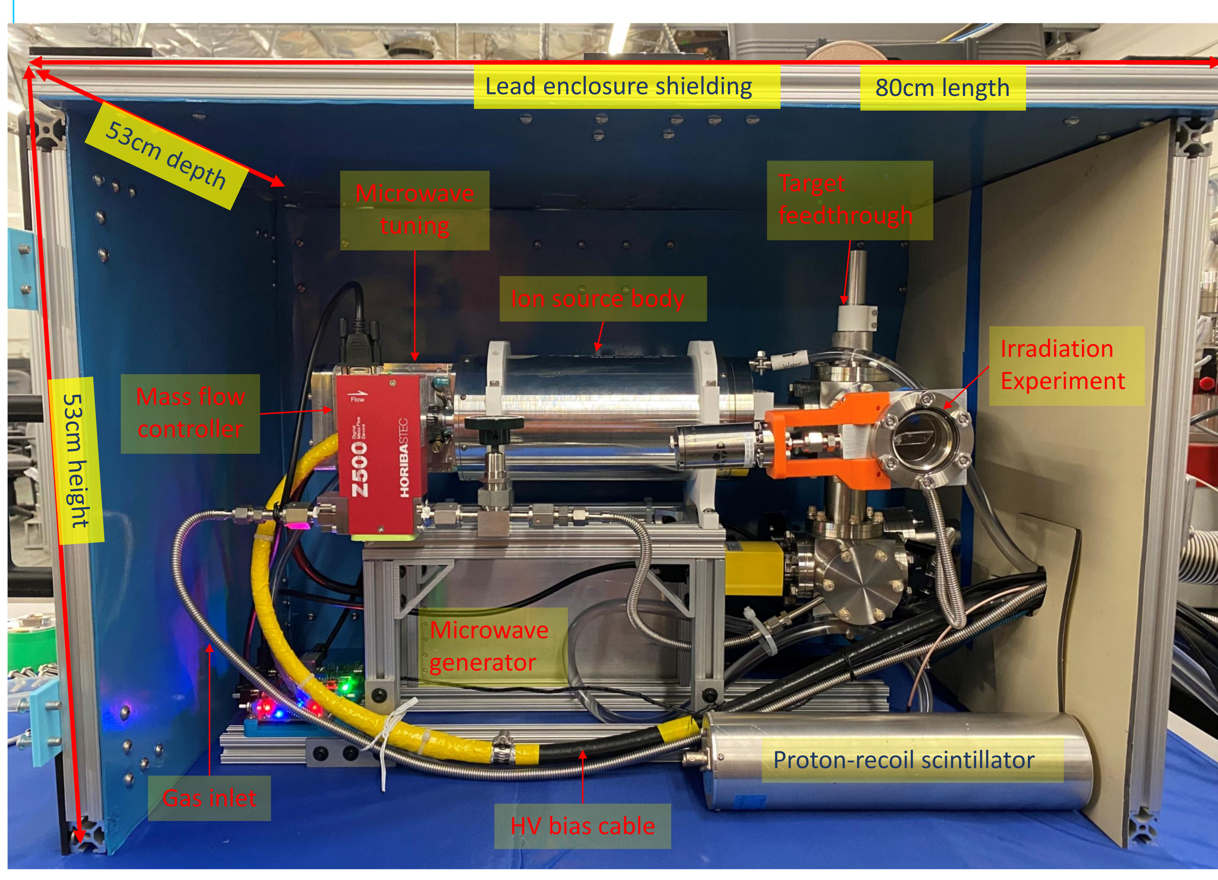
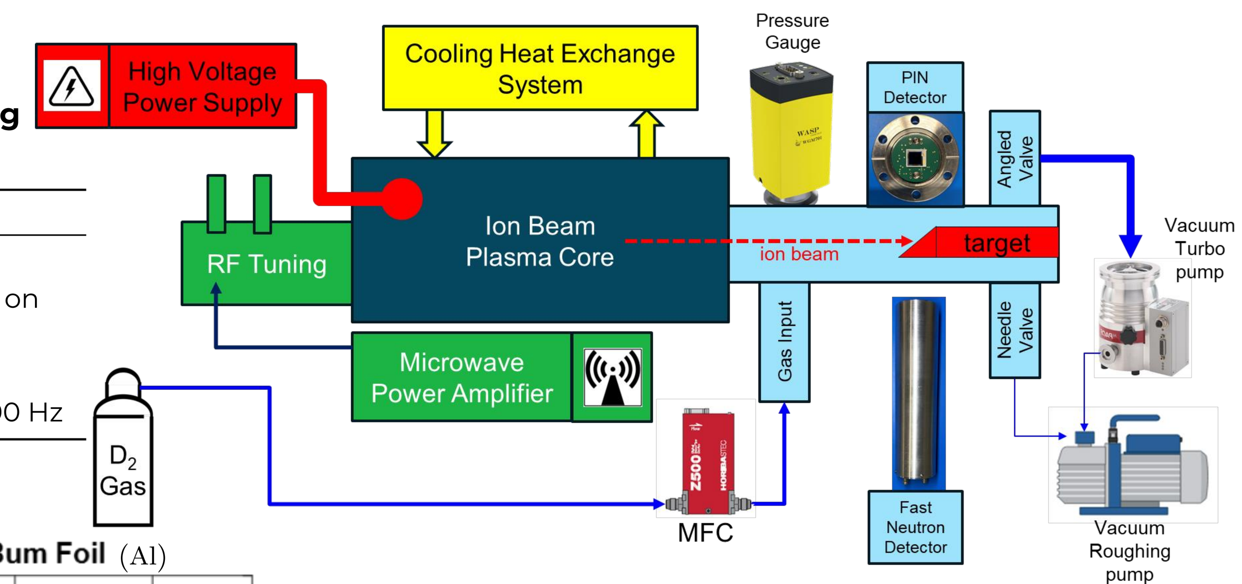
Abstract

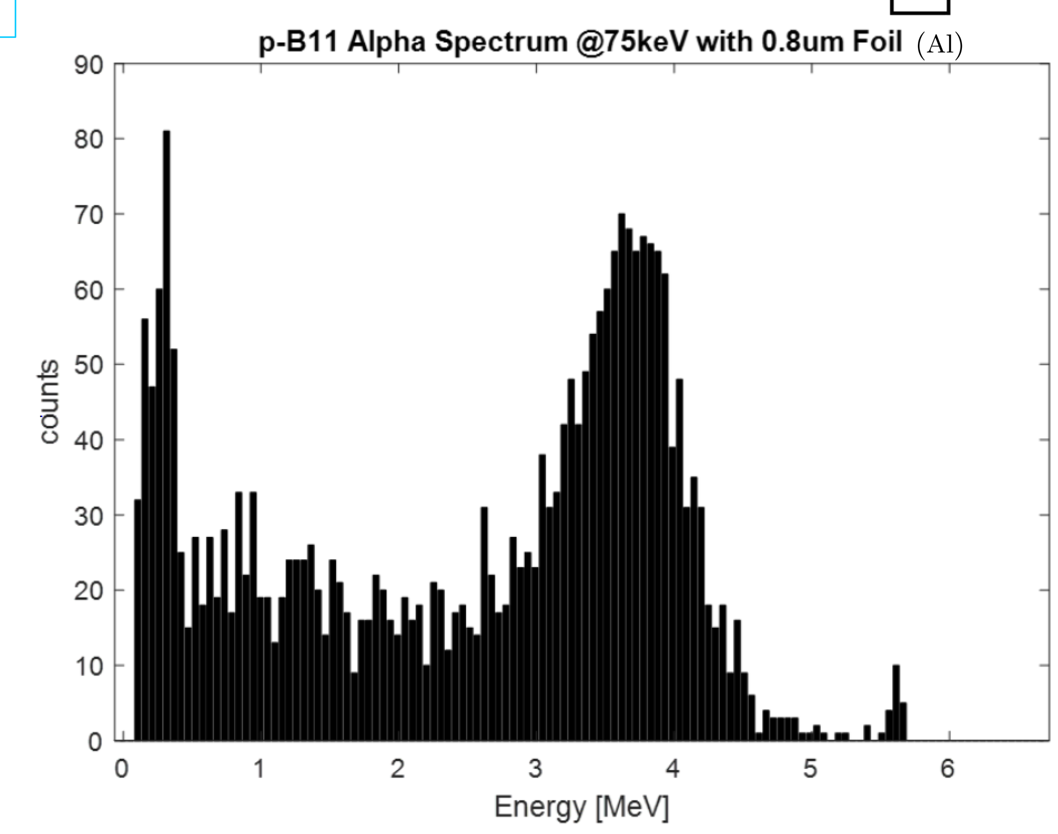
We demonstrate a compact ion beam device capable of accelerating H^+ and D^+ ions up to 75 keV energy, onto a solid target, with sufficient beam current to study fusion reactions. The ion beam system uses a microwave driven plasma source to generate ions that are accelerated to high energy with a DC acceleration structure. The plasma source is driven by pulsed microwaves from a solid-state RF amplifier, which is impedance matched to the plasma source chamber at the ISM band frequency (2.4–2.5 GHz). The plasma chamber is held at high positive DC potential and is isolated from the impedance matching structure (at ground potential) by a dielectric-filled gap. To facilitate the use of high-energy-particle detectors near the target, the plasma chamber is biased to a high positive voltage, while the target remains grounded. A target loaded with deuterium is used to study D-D fusion and a B_4C or LaB_6 target is used to study p-^{11}B fusion. Detectors include solid-state charged particle detectors and a scintillation fast neutron detector. The complete ion beam system can fit on a laboratory table and is a versatile R&D platform and a useful tool for teaching undergraduate and graduate students about the physics of fusion.

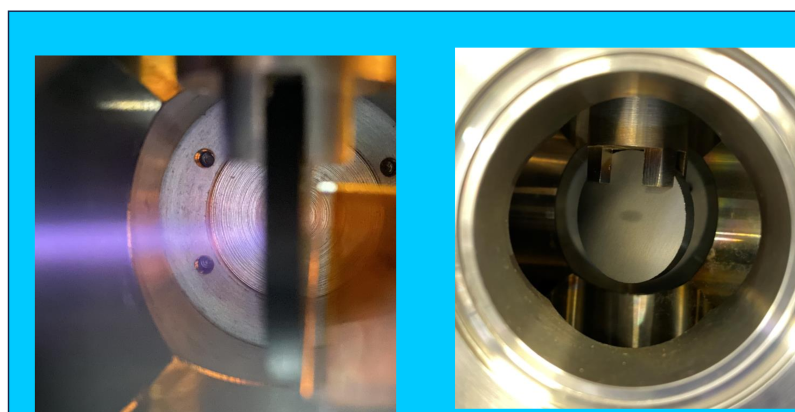


Example power consumption in various operating modes, excluding power for vacuum pumps.

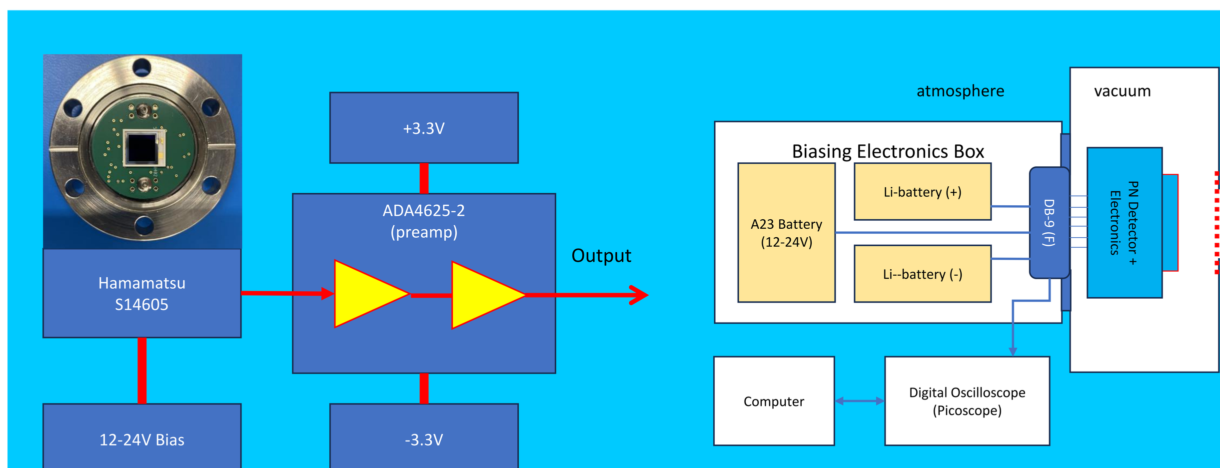
mode	power (W)	conditions
idle	5.4	control systems only
standby	52.5	chiller, MW source, HV supply all on
beam ready	79.2	HV 30 kV, 0 A
beam on	97.2	HV: 30 kV, 0.0208 mA; MW: 5% 100 Hz

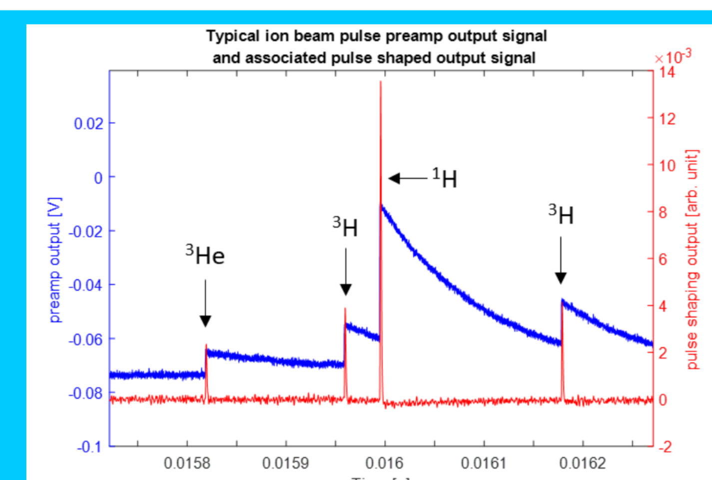






At around 3 mTorr pressure, the drift region is about the length of the mean free path for the beam ions. The beam spot size ~2.3 mm @ 75keV as shown in the images above.



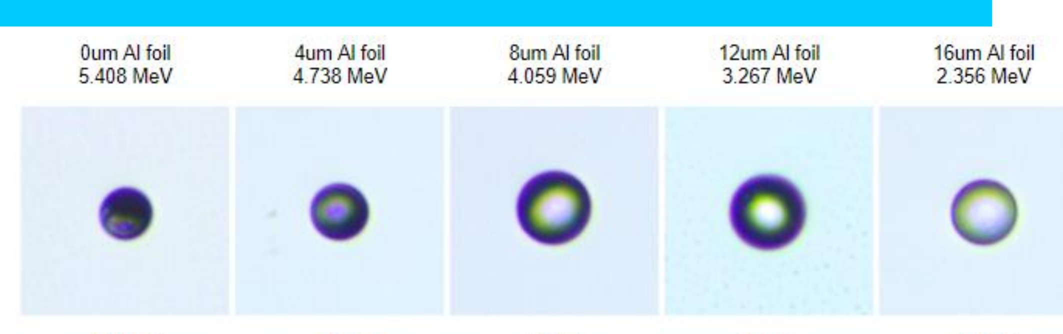


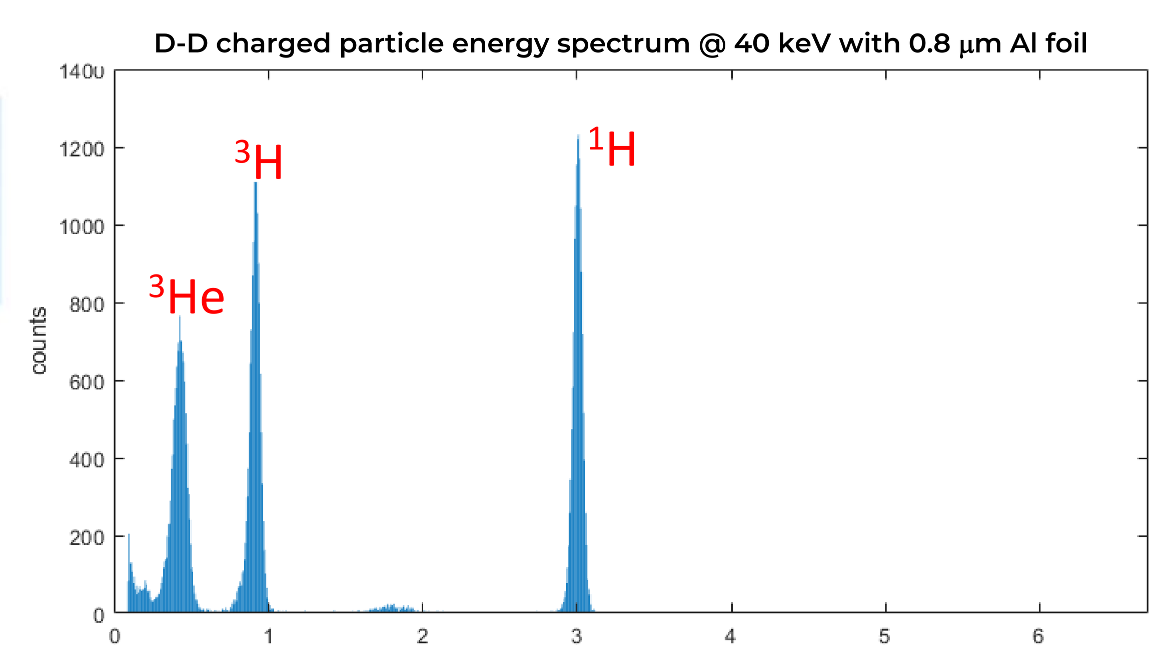
PIN detector (Hamamatsu S14605) used to observe charged particles from the D-D reaction. We used a dual JFET op amp as the charge sensitive preamp and batteries to provide stable power for the detection circuit. The blue curve shows the raw preamp signal, the red curve shows the digitally filtered signal. The signal height is proportional to the energy of the particle.

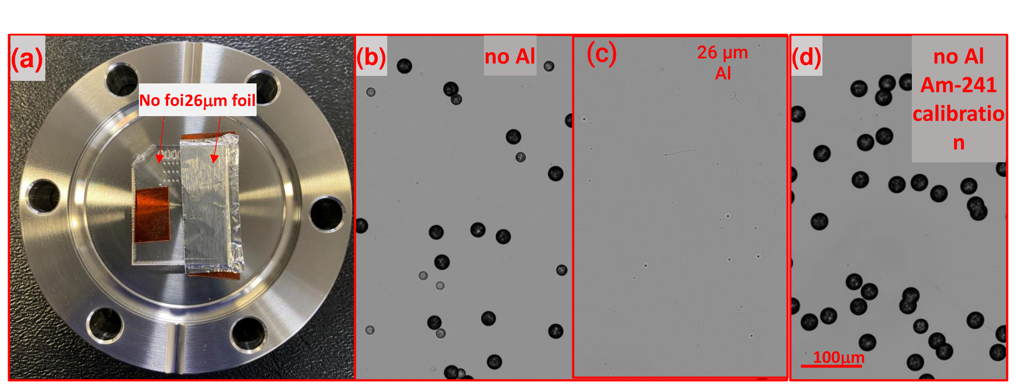
Proton-boron (p-^{11}B) and deuterium-deuterium (D-D) reactions are examples of the fundamental fusion reactions that can be demonstrated using the Alpha-E system. This benchtop accelerator can, thus, serve as a primary standard for detector calibration.

Silicon diode type detectors are susceptible to interference from light and RF. Polymer detectors, such as CR-39, are not susceptible to electromagnetic radiation, but there can be distortion of the surface from heat or from large particles that may not be of interest. Both of these types of detectors are, therefore, often shielded from the experimental system by a thin layer of materials like Al foil or mylar. These shielding materials shift the apparent energies of the detected particles. Measurements using the Alpha-E fusion products as a standard helps account for these shifts and broadening.

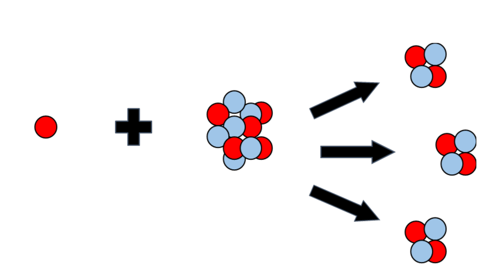
CR-39 track dimensions vary with the energy of the incident particle and with etching conditions. Such variations, however, are neither linear nor single-valued. The diameter, for example has a maximum value for alpha particles at around 4 MeV for a given set of etch conditions, as shown in the images to the right.



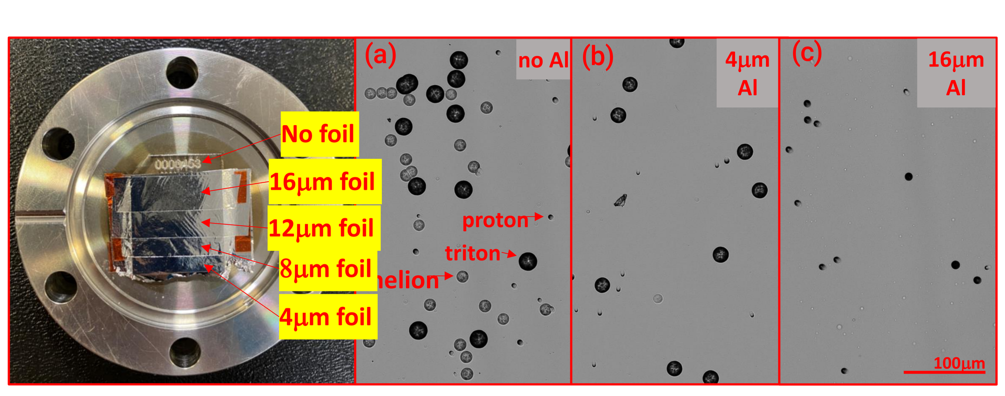




CR-39 nuclear track detector showing alpha particle tracks from
(b) p-^{11}B reaction with no Al foil, coupon show a distribution of radii
(c) p-^{11}B reaction with 26 μm Al foil (no alpha particle tracks are visible)
(d) ^{241}Am calibration with no Al foil (single radius of tracks)
p-^{11}B beam conditions: 75keV/0.05mA(avg.), 5% duty, 3.3mTorr, 20 min. irradiation, CR-39 located ~4.4cm from source.

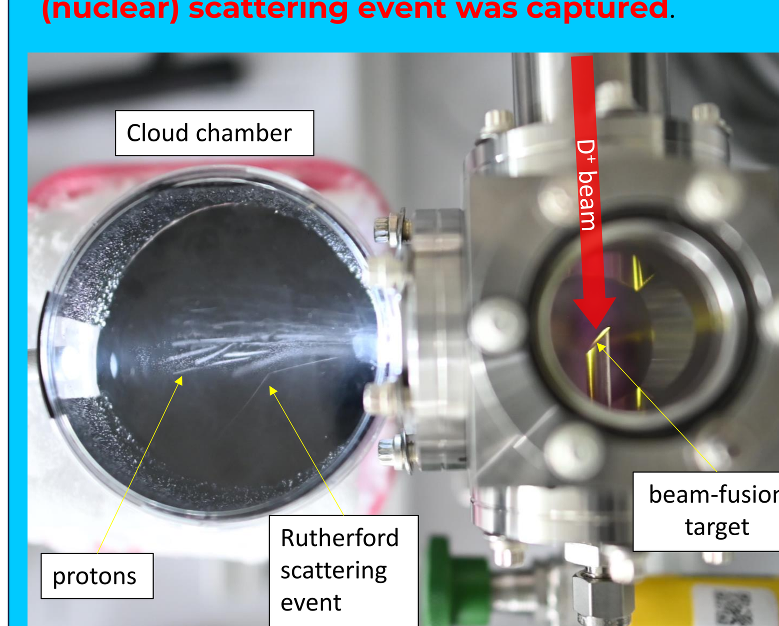


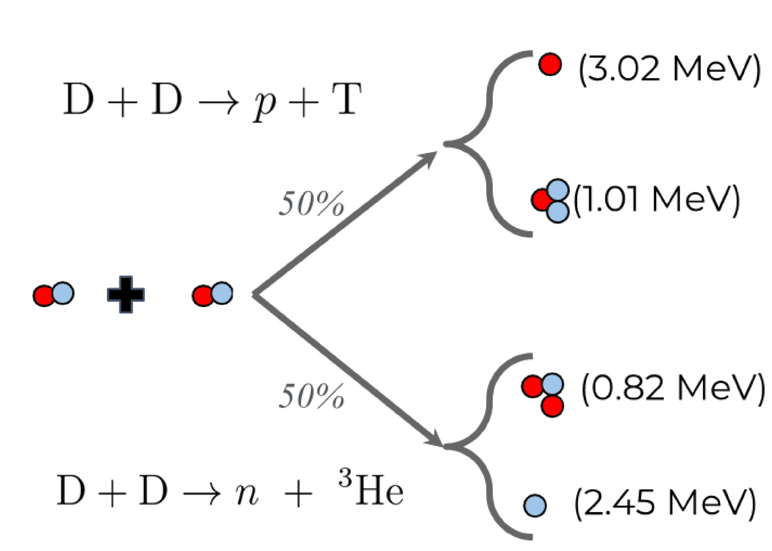
$$p + {}^{11}B \rightarrow 3\alpha$$



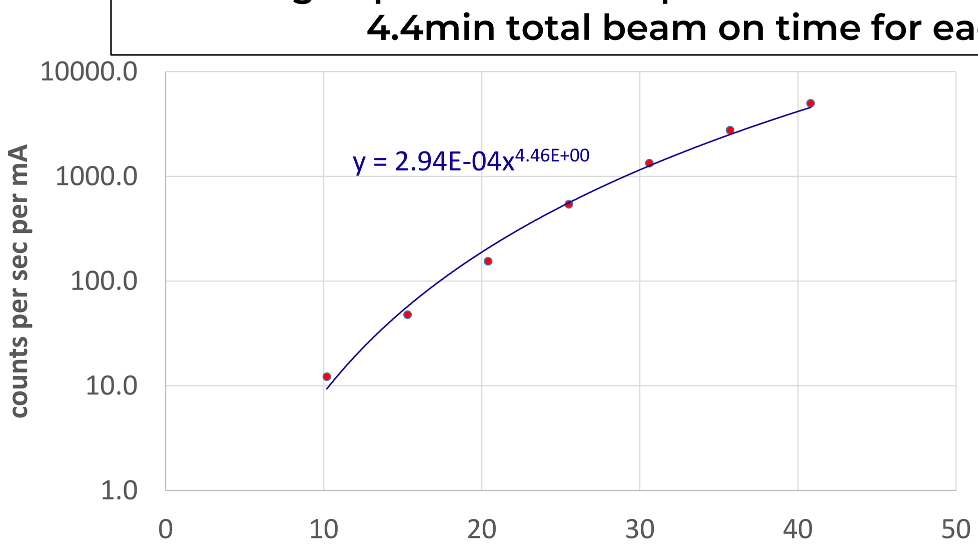
CR-39 nuclear track detector with different thickness of Al foils to block off different particles from the D-D reaction
(a) With no aluminum foil, all 3 particles (^{1}H, ^{3}H, ^{3}He) are visible
(b) With 4um Al foil, ^{3}He are blocked. Only (^{1}H, ^{3}H) are visible.
(c) With 16um Al foil, only ^{1}H are visible.
D-D beam conditions: 30keV/0.03mA(avg.), 5% duty, 3.3mTorr, 10 min. irradiation, CR-39 located ~4.4cm from source.

Cloud chamber mounted outside of the vacuum chamber to visualize proton tracks from the D-D reaction. A thin window is used to separate the vacuum from atmospheric pressure while allowing protons to penetrate into the cloud chamber. In the left image, a rare **Rutherford (nuclear) scattering event was captured**.



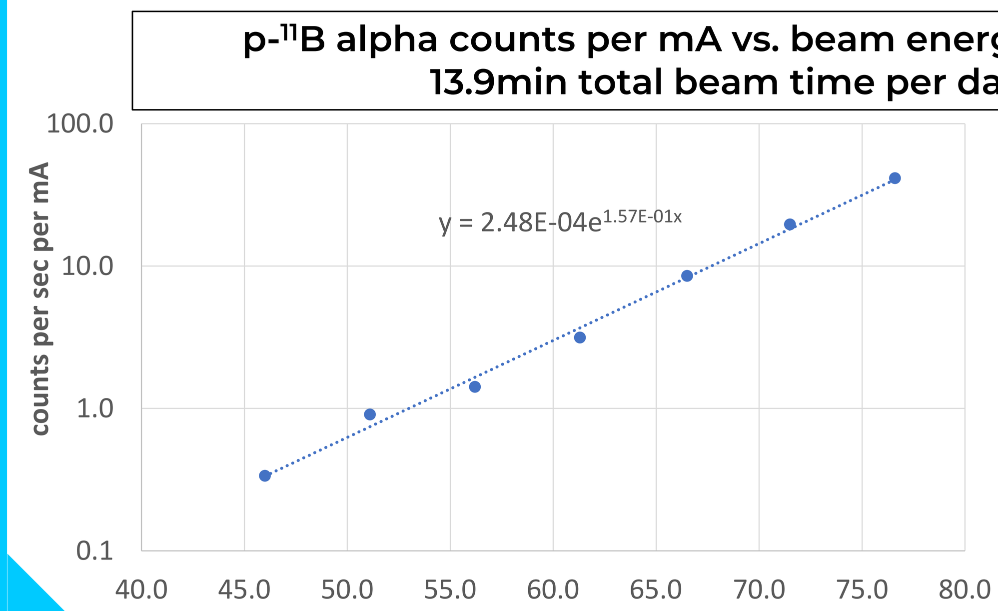


D-D charged particle counts per mA vs. beam energy @ 3Hz, 5% duty, 4.4min total beam on time for each voltage



E [kV]	Yield (cps)	Current [mA]	DD_Yield /mA	Yield
10.2	0.34	0.0277	12.2	90
15.3	1.40	0.0293	47.6	372
20.4	4.64	0.0301	154.2	1238
25.5	15.83	0.0293	540.1	4220
30.6	42.21	0.0316	1335.6	11255
35.7	89.42	0.0324	2760.0	23846
40.8	164.85	0.0331	4980.5	43961

p-^{11}B alpha counts per mA vs. beam energy @ 3Hz, 5% duty, 13.9min total beam time per data point



E [kV]	Yield (cps)	Current [mA]	pB_Yield /mA	Yield
46.0	0.013	0.0393	0.3	11
51.1	0.038	0.0424	0.9	32
56.2	0.060	0.0424	1.4	50
61.3	0.143	0.0455	3.1	119
66.5	0.392	0.046	8.5	327
71.5	0.920	0.047	19.6	767
76.6	1.980	0.0478	41.4	1650

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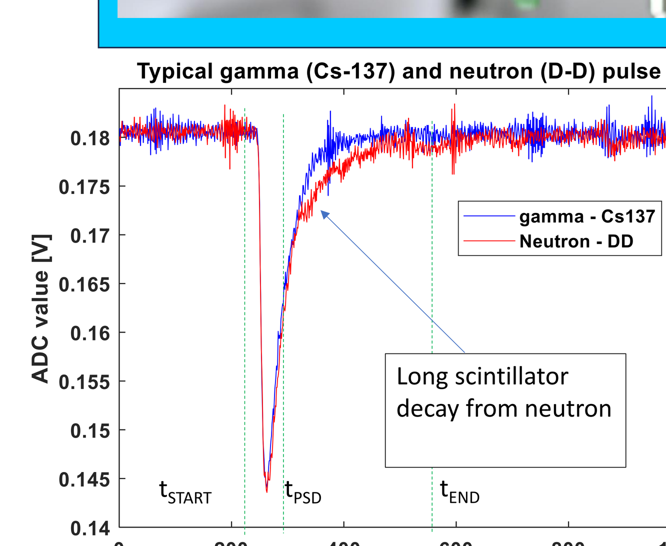

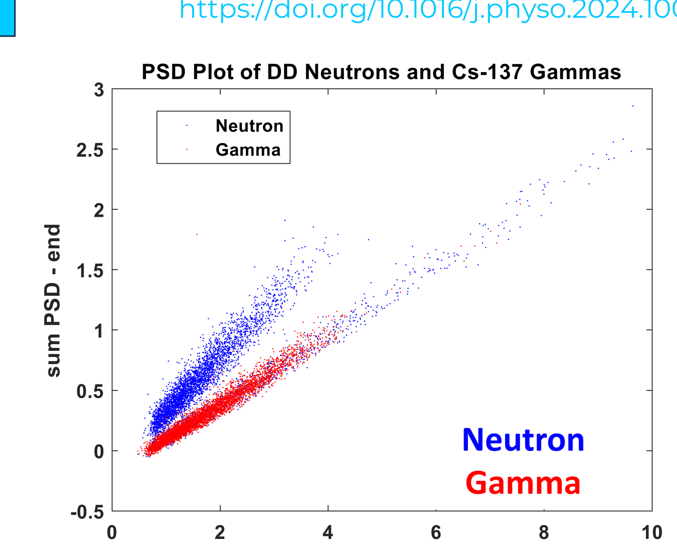

A proton-recoil scintillator is used to detect fast neutrons. The detector is also sensitive to gamma photons. These two classes of signals can be distinguished using pulse shape discrimination (PSD). The ratio of a partial integral to a total integral can be used to separate the signals based on the differences in decay rate observed in the scintillator response waveform.