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A Pitch-Angle-Resolved PIPS Detector System for D-D Fusion Proton Measurements on the HL-3 Tokamak

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Abstract

A five-channel proton detector(PD) base on Passivated Implanted Planar Silicon(PIPS) detectors has been developed and installed on HL-3 tokamak to measure protons and tritons(tritium ions, $^{\{\{\{3H\}\}}\{+)\}\}$ generated by the d(d,p)t fusion reaction. Featuring tungsten shielding, platinum foils, and optimized collimators for noise suppression, the system design was guided by a self-developed Monte-Carlo code(CFPMC) employing a fourth-order Runge-Kutta method to simulate proton trajectories and optimize detector placement. During the 2024 experimental campaign, initial results confirm the system' s ability to measure proton flux with temporal and pitch-angle resolution during neutral beam injection(NBI) discharges. Clear modulation of proton signals by sawtooth crashes was observed, with distinct responses across different channels, reflecting the sampling of different regions of the plasma relative to the q = 1 surface. The forward source-tracing simulations reproduce the channel-dependent spatial birth distributions in the poloidal plane and yield pitch-angle distributions in good agreement with the experimental measurements. These results demonstrate both the feasibility of the PD diagnostic and the fidelity of the modeling, highlighting the system' s preliminary spatial-resolving capability for D–D fusion protons in HL-3 plasmas. The combined diagnostic-modeling approach offers a promising framework for studying fast-ion redistribution and MHD-induced modulations of fusion reactivity in future HL-3 discharges.

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Full Text

Preamble

A Pitch-Angle-Resolved PIPS Detector System for D-D Fusion Proton Measurements on the HL-3 Tokamak

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A five-channel proton detector (PD) based on Passivated Implanted Planar Silicon (PIPS) detectors has been developed and installed on the HL-3 tokamak to measure protons and tritons (tritium ions, $^3H^+$) generated by the d(d,p)t fusion reaction. Featuring tungsten shielding, platinum foils, and optimized collimators for noise suppression, the system design was guided by a self-developed Monte-Carlo code (CFPMC) employing a fourth-order Runge-Kutta method to simulate proton trajectories and optimize detector placement. During the 2024 experimental campaign, initial results confirmed the system' s ability to measure proton flux with temporal and pitch-angle resolution during neutral beam injection (NBI) discharges. Clear modulation of proton signals by sawtooth crashes was observed, with distinct responses across different channels, reflecting the sampling of different regions of the plasma relative to the q = 1 surface. Forward source-tracing simulations reproduced the channel-dependent spatial birth distributions in the poloidal plane and yielded pitch-angle distributions in good agreement with the experimental measurements. These results demonstrate both the feasibility of the PD diagnostic and the fidelity of the modeling, highlighting the system's preliminary spatial-resolving capability for D–D fusion protons in HL-3 plasmas. The combined diagnostic-modeling approach offers a promising framework for studying fast-ion redistribution and MHD-induced modulations of fusion reactivity in future HL-3 discharges.

Keywords: HL-3 tokamak, D-D fusion protons, Charged fusion products, PIPS detector system, Trajectory simulations, Magnetohydrodynamic (MHD) effects

Introduction

In future ITER-like fusion reactors, charged fusion products—primarily alpha particles from D-T fusion with energies of 3.52 MeV—sustain plasma ignition and must remain well confined until thermalization. Significant losses of these energetic particles (EPs) reduce plasma heating efficiency and, critically, risk material erosion and damage to the first wall [1-3]. Multiple mechanisms can cause EP loss, including first-orbit loss, magnetic field ripple loss, and MHD-driven loss [4]. To date, research reveals that any kind of MHD mode has the potential to result in loss of charged fusion products through either resonant or non-resonant interaction with them [5, 6]. Although most present-day tokamaks, such as HL-3, operate with deuterium fuel, lower plasma currents, and significantly lower fusion yields compared to D-T-fueled ITER-like reactors, measurements of 3.02 MeV protons and 1.01 MeV tritons from D-D fusion reactions offer valuable insights into EP confinement and loss dynamics. For this, a time- and pitch-angle-resolved diagnostic is required (here, the pitch angle is the angle between the particle velocity and the magnetic field), since many MHD activities are characterized by high frequencies and are always correlated with EPs' distribution in phase space [7–9].

Passivated Implanted Planar Silicon (PIPS) detectors combine high energy resolution, fast temporal response, and high intrinsic detection efficiency, making them advantageous over techniques like track-etch detectors [10], activation methods [11, 12], and Faraday cups [13]. However, PIPS detectors also have notable limitations: (1) sensitivity to a broad range of radiation (e.g., visible light, microwaves, X-rays, γ-rays, and low-energy particles), common in tokamaks and often contributing to background noise; (2) limited particle tolerance (typically $< 10^{12}$ neutrons/cm^2, or $< 10^{10}$ protons/cm^2) [14], restricting operational lifetime; (3) a finite particle-handling capacity, confining them to low-flux conditions ($< 10^6$ particles/s) despite their fast response. Faraday cups and track-etch detectors are largely unaffected by high-energy photons and neutrons, but they remain unsuitable for this application. Faraday cups require high ion fluxes to exceed their current measurement threshold (typically 10^{-10} A), which is challenging given the low fusion yield in deuterium-fueled tokamaks, and they lack energy resolution. Track-etch detectors do not provide temporal resolution and require time-consuming data analysis.

Fortunately, on most present-day tokamak devices fueled with deuterium, both the neutron flux and the fusion ion flux are relatively low. This enables the PIPS detectors to have a high chance of surviving within an experimental campaign and without exceeding their counting rate limits through proper collimator aperture design. Signal interference caused by radiation can be largely mitigated through appropriate shielding, collimation, and data processing methods. Given these favorable conditions, PIPS detectors (as well as earlier silicon barrier detectors) have been used to measure charged fusion products from D-D reactions on PLT [15], ASDEX [16], Alcator C-Mod [17], TFTR [18], MAST [19] and MST [20], and recently to detect alpha particles from p^{11}B fusion on LHD [21].

Recently, a pitch-angle-resolved diagnostic based on PIPS detectors has been designed and constructed on the HL-3 tokamak (R_0 = 1.78 m, a = 0.65 m, I < 3 MA, B_0 < 3 T) [22] to measure escaping 3.02 MeV protons and 1.01 MeV tritons from D-D fusion. This system represents the first-stage diagnostic developed for the measurement of charged fusion products. The primary purpose of these systems is to investigate the potential loss behavior of fusion ions under different plasma confinement regimes in HL-3, with particular emphasis on losses induced by MHD activities. The remainder of this paper is organized as follows: Section II describes the simulation, design, hardware configuration, and calibration of the diagnostic; Section III presents the first experimental observations of D-D fusion protons on HL-3, the channel-dependent responses to sawtooth oscillations, and their interpretation through forward Monte-Carlo source-tracing simulations including a comparison between the simulated and measured pitch-angle distributions, while Section IV summarizes the main results and discusses future prospects.

II. Design and Hardware

A. Simulation of Particle Trajectory and Detector Layout

Unlike neutrons, charged fusion products move along curved trajectories in the magnetic field and their loss positions are asymmetric due to curvature and gradient-B drift. To determine the optimal detector placement and collimator orientation, simulations of charged fusion product trajectories and losses were performed. A self-developed Monte-Carlo (MC) code (temporarily named CF-PMC) which employs a fourth-order Runge-Kutta method [23, 24] to solve the equation of motion for charged particles was used in this work. The code follows the full orbits of fusion ions rather than guiding-center trajectories, because under HL-3 magnetic conditions their gyro-radius (more than ten centimeters) is not negligible compared with the minor radius (65 cm) of the device; full-orbit tracking also preserves details such as the incidence angle of ions lost to the first wall. Collision-induced energy change and scattering are not included because, based on preliminary estimates for HL-3 conditions (e.g., 1 MA plasma current, 1.5 T magnetic field), the mean loss time of MeV ions is on the order of tens of microseconds, much shorter than their slowing-down time (on the order of seconds, estimated from the formula described in Ref. [25]), so assuming constant birth energy until loss is a good approximation. The equilibrium magnetic field configuration reconstructed with EFIT (EQDSK file) served as input and the field ripple dependent on the actual layout of the HL-3 toroidal field coils, comprising 20 coils, was considered. In the model, the ripple distribution as a function of poloidal position (R,Z) was obtained from an analytical fit to engineering-calculation data, as described in Refs. [26–28].

A large number of MC particles (representing protons or tritons from D-D reaction) were emitted isotropically within the plasma with their birth weighted by the local fusion reaction rate: d σv + n n σv + σv where σv denotes the fusion reactivity coefficient of the d(d,p)t reaction, either for thermal or fast deuteron populations as indicated by the subscript. The three terms correspond respectively to reactions between thermal–thermal, fast–thermal, and fast–fast D^+ ions. Here, n is the thermal D^+ density and n is the density of fast D^+ ions. In the present work σv is implemented in the code by fitted analytic expressions that are functions of ion temperature (for Maxwellian thermal populations) or of the relative collision energy (for fast/mono-energetic populations) [29, 30], thereby reproducing standard tabulated reactivity/cross-section data. These particles were tracked continuously until they crashed onto the first wall or were confined for a sufficiently long time (>1 ms).

It should be noted that, under typical HL-3 plasma parameters, simulations show that protons produced by fast-ion-induced reactions account for more than 95% of the total yield. Therefore, the contribution from fast D^+ ions is the primary factor to be considered. A typical loss distribution for protons on the HL-3 first wall with plasma current I = 0.7 MA, toroidal magnetic field B_0 = 1.8 T is illustrated in Fig. 1 [Figure 1: see original paper]. In this CFPMC calculation, the core D^+ density is set to $n^+ = 1.8 \times 10^{19}$ m^{-3} and the ion temperature to T = 2.0 keV, both assumed to follow parabolic profiles along the minor radius. The fast D^+ population introduced by NBI is taken as 10% of the thermal ion density, uniformly distributed, and with a monoenergetic value of 50 keV.

The results show that protons are lost in the region below the equatorial plane of the device (Fig. 1a). Accordingly, a location near a port 90 cm (marked as white dash line) below the mid-plane on the lower-field side (LFS) was selected from several candidates to install the detectors. The pitch angles (here defined as the angle between the particle velocity and toroidal magnetic field B) of protons at the time of loss also exhibit a non-uniform distribution, as shown in Fig. 1b. They are concentrated within a relatively narrow range and vary with the poloidal angle. Thus, five detectors were used to cover the peak of pitch-angles and its surrounding region with the orientation of their collimators (as shown by the red dots in Fig. 1b).

The typical trajectories of protons traced backward from the detection positions are shown in Fig. 2 [Figure 2: see original paper]. In these cases, the angle between the projection of the collimator orientation (i.e., the opposite direction of the proton impact velocity) onto the poloidal cross-section and the radial direction was set to 40°, as shown in Fig. 2a. With this angle, the detectors' fields of view avoid direct line-of-sight to both the plasma region and the first wall (as shown in Fig. 2c), thereby minimizing the risk of other particles or radiation entering the detectors either directly or via reflection from the wall. This configuration is a critical noise-reduction strategy in the diagnostic system.

B. Mechanical Structure

Five Ortec TU-014-050-100S PIPS detectors, which are bakeable up to 200 °C, were used in the PD system. This high-temperature tolerance ensures that the detectors can safely withstand the week-long vacuum-vessel baking on HL-3, during which the first-wall temperature reaches approximately 180 °C, without any degradation in performance. Each detector has an effective active sensing surface with a diameter of 8 mm, and a depletion layer thickness of 100 µm (indicated by the "100" in the model number), which is slightly greater than the projected range of 3.02 MeV protons in silicon (94 µm, calculated by the SRIM code [31]). This ensures that the protons can fully deposit their energy within the active layer, while also helping to minimize background noise from hard X-rays and γ-rays. These high-energy photons can lose part of their energy via Compton scattering or the photoelectric effect when passing through the silicon, thereby contributing to noise signals [32].

To provide thermal and radiation shielding, the five detectors were installed inside a mechanical housing made of 5-mm-thick tungsten, as shown in Fig. 3 [Figure 3: see original paper]. This enclosure helps block or attenuate hard X-rays and γ-rays, especially those with energies below 0.5 MeV (based on attenuation data from GSI' s X-ray absorption calculator [33]). The entrance windows of the detectors are aligned with openings in the tungsten housing to allow particle access, while the remaining surfaces are wrapped in polyimide (PI) composite insulation blocks to provide electrical insulation and heat resistance.

A 2-µm-thick platinum (Pt) foil, affixed to a stainless steel ring using vacuum-compatible adhesive, is mounted at the entrance of each detector. The ring is inserted into a PI grooved seat that holds it securely in place; this seat features an annular opening designed to avoid forming a sealed cavity during vacuum pumping. The Pt foil serves to block visible light, microwaves, soft X-rays, and low-energy particles. Laboratory tests confirmed that the detectors are responsive to visible light and microwave signals (in the GHz range), underscoring the necessity of such shielding. According to SRIM simulations, D–D fusion protons and tritons lose 156.1 keV and 393.8 keV of energy in the Pt foil, respectively, while 0.8 MeV ^{3}He ions are completely stopped within the foil.

Tungsten tubes with a length of 4 cm and an inner diameter of 8 mm serve as collimators for the detectors. The angles between the axes of the five collimators and the direction of toroidal magnetic field (B) span the pitch-angle range from 75° ($5\pi/12$ rad) to 135° ($9\pi/12$ rad), distributed at equal intervals of 15° ($\pi/12$ rad), as marked by red dots in Fig. 1b. An aperture cap with an optional hole size is mounted at the front of each collimator to approximately regulate the proton flux reaching the detector, based on the expected plasma conditions of upcoming experimental campaigns. Based on the combination of collimator length and detector active area, the detectors subtend a conical field of view with a half apex angle of about 5.73° for sufficiently small aperture size (e.g., 1 mm diameter). The five PIPS detectors, together with their tungsten housing, collimators and support structure, form the detector head (hereafter referred to as the 'PD head').

The entire PD head is mounted on a stainless steel base, which is electrically insulated from the vessel wall. During installation, the structure can be adjusted to approach the plasma as closely as possible without extending beyond the first wall. The mechanical assembly is connected to the vessel via a stainless steel bellows (rather than directly through the base), which also serves to protect the signal cables. This configuration enables single-point grounding and helps minimize ground loop interference in the PD system. These design features described above—including tungsten shielding, platinum entrance foils, carefully oriented collimators, single-point grounding and coaxial signal transmission—are important steps to effectively mitigate interference noise.

C. Electronics and Data Acquisition System

The weak current signals generated in the detectors are transmitted by coaxial cables (about 1.6 m in length) with PI jackets through a double-ended, floating coaxial feedthrough flange (Accu-Glass 25D-5CX-450) to the preamplifier outside the vacuum vessel. To minimize the distance between the detectors and the preamplifier—and thereby maximize the signal-to-noise ratio—the preamplifier is mounted directly on the air side of the flange. An 8-channel, charge-sensitive Mesytec MSI-8 preamplifier integrated with shaper and timing filter amplifiers has been employed in the PD, capable of handling detector capacitances up to 1000 pF with selectable input polarity and a sensitivity attenuator switch providing a factor of 5 adjustment. The shaping modules, featuring a CR-(RC)^5 filtering network with an integrated passive baseline restorer (ensuring < 100 mV baseline shift at 100 kHz rate for 1 µs shaping), shape the pre-amplified signal into a positive quasi-Gaussian pulse with a selectable FWHM of 1 µs (or 2 µs) and linearly amplify the signal to a maximum output of 10 V (8 V at 50 Ω termination). To avoid saturation under high count-rate conditions, the effective throughput of each detector channel is limited to below 5.0×10^5 particles/s. The dead time of the system is approximately 1 µs, determined primarily by the selected shaping time (FWHM) of the CR-(RC)^5 network, and is therefore consistent with the preamplifier–shaper response characteristics.

The preamplifier is powered and housed within a WIENER NIM Compact 150W crate (12 slots, with 10 free slots available), featuring a compact UEN 04 bin and an integrated front-plug-in UEP15 power supply, which provides the operating voltages for the preamplifier. This crate also accommodates the Mesytec MHV-4 4-channel high-voltage bias supply module, which delivers a bias voltage of about 70 V to the detectors via the preamplifier (with a maximum range of $±$800 V in 12.5 mV steps).

The signals amplified to voltage levels by the preamplifier are transmitted to the data acquisition system about 18 m away via coaxial cables. The data acquisition system includes two 4-channel JYTEK PCIe-JY9815 digitizers with a sampling rate up to 80 MSa/s and a resolution of 14-bit. In practice, a sampling rate of 20 MSa/s conventionally adopted is sufficient to completely record the pulse signals generated by protons/tritons. The digitizers are installed in the PCIe slots of a host computer equipped with 16 GB of memory, which controls the acquisition and uploads the data to the HL-3 diagnostic database.

D. Calibration

Before the detectors were mounted in the HL-3 tokamak, calibration was performed for each channel of the PD system in the laboratory using a low-activity ^{241}Am alpha-particle source. Since air under normal atmospheric pressure strongly scatters alphas and thus affects the accuracy of the calibration, both the detector and the source were placed in a compact, light-tight vacuum chamber with a pressure of 5 Pa, and the source was located at a source-to-detector distance of 2.5 cm. With statistics from a large number of pulse amplitudes and subsequent fitting by three Gaussian functions (representing 85% of decays with energies of 5.486 MeV, 13% with 5.433 MeV and 2% with 5.388 MeV respectively), the calibration result for one of the channels is shown in Fig. 4 [Figure 4: see original paper]. It gives a calibration factor of 1.04 V/MeV, and an energy resolution (the standard deviation of the Gaussian distribution) of 0.157 MeV, or 2.86%.

III. First Measurement of D-D Protons on HL-3

A. PD Raw Data and Signal Characterization

During the winter 2024 experimental campaign, the PD system successfully detected proton signals from D-D fusion reactions on the HL-3 tokamak for the first time. A typical result from shot #8771, acquired with a 4-mm collimator aperture under low-power NBI heating, is presented in Fig. 5 [Figure 5: see original paper]. The main plasma parameters for this discharge were as follows: plasma current I = 300 kA, central toroidal magnetic field $B_0 = 1.2$ T, line-averaged electron density $n = 2.0 \times 10^{19}$ m^{-3}, with a lower single-null divertor configuration. Upon activation of NBI, the PD system recorded a significant number of pulse signals with similar amplitudes (3.8 V). This observation is consistent with the simulation-based prediction that, under HL-3 operating conditions, the majority of D-D fusion protons originate from beam-thermal interactions—i.e., reactions between confined fast D^+ ions (injected by NBI) and background thermal D^+ ions—rather than thermal-thermal reactions.

To further confirm the proton identity of the similar-amplitude pulse signals, a statistical analysis of pulse heights during NBI injection was performed, yielding the histogram shown in Fig. 7 [Figure 7: see original paper]. The histogram reveals an isolated, Gaussian-like peak centered around 3.8 V, attributed to protons from D-D fusion reactions. Additionally, a secondary peak at approximately 0.7 V, attributed to triton signals, is observed, superimposed on a continuous low-amplitude noise background.

Based on the ^{241}Am source calibration (assuming a linear response) described in Section II D, the attenuated proton energies would correspond to pulse heights of 2.98 V and 0.68 V, respectively. However, the observed peak positions deviate from these expectations. As the HL-3 tokamak lacks ion cyclotron resonance frequency (ICRF) heating to accelerate ions, and neutral beam ions (NBI energy 50 keV) cannot produce such high-energy signals, this discrepancy is likely caused by intrinsic differences in the ionization density, range, and charge collection efficiency between the measured ions (protons and tritons) and the alpha particles used for calibration in the detector. Furthermore, it may also arise from (i) energy loss of alpha particles in the relatively thick radioactive coating of the ^{241}Am source and (ii) possible nonlinearity in the response of the preamplifier/shaper.

Despite this deviation, the above peaks at 3.8 V and 0.7 V can still be identified as protons and tritons, respectively, based on the approximate calibration and the exclusion of other particle contributions.

Analysis of extensive PD data across various HL-3 discharges revealed that, although triton signals are sometimes masked by low-amplitude noise, the proton signals consistently remained well above the noise floor and thus could be clearly identified. This robustness enables reliable proton detection even under suboptimal plasma conditions. By setting an appropriate energy window (e.g., 3.3-4.3 V for ch-2 under typical conditions), time-resolved proton count rates can be extracted.

In cases with higher proton flux, where a few pulse pile-up events occur, the upper bound of the energy window can be set higher—according to the actual pulse-height spectrum—to include these piled-up signals in the count rather than discarding them. This enables investigations of fast processes (several ms)—such as MHD-induced effects—that influence local fusion reactivity during discharges. This treatment is justified because, in our system, triton and background-noise pulses are always below the 3.8 V proton peak (Fig. 7). Therefore, considering that double pile-ups dominate (with higher-order pile-ups being much less probable), pulses significantly exceeding the proton peak are most likely produced by proton-triton (or proton-noise) coincidences and, at higher rates, occasional proton-proton pile-up, while triton-noise or noise-noise combinations cannot generate such amplitudes. These pile-up events thus contain at least one proton, and including them improves statistical reliability for fast time-resolved analysis compared with the conventional approach of discarding all pile-up pulses.

When the NBI was switched off, the pulse signals gradually decayed over approximately 60 ms before disappearing, in agreement with the time scales associated with fast ion losses and slowing-down processes. Occasionally, pulses with significantly higher amplitudes than the typical values were observed, attributed to pulse pile-up effects caused by multiple proton events overlapping in time. As evident from Fig. 5c, at the end of the plasma discharge, plasma disruptions induced dense, low-amplitude (<0.7 V) noise signals. These disturbances were effectively distinguished from the proton signals through pulse heights. An expanded view of the raw signal from Fig. 5c is presented in Fig. 6 [Figure 6: see original paper], which displays all data points within the selected time window. A typical single proton pulse (3.8 V) is clearly resolved, accompanied by a neighboring low-amplitude pulse (0.9 V). Such small pulses may originate from triton events or from background noise, and thus cannot be unambiguously identified on a single-pulse basis. The pulses exhibit a quasi-Gaussian waveform, which arises from the shaping effect of the CR-(RC)^5 network.

B. Sawtooth-Modulated Proton Fluxes

Fig. 8 [Figure 8: see original paper] shows a representative case (shot #12269, 1-mm aperture, high-power NBI heating) in which the time evolution of proton flux measured by the PD system reveals clear modulation associated with sawtooth activity. For clarity, in the following discussion the five channels are denoted as ch-1-ch-5, corresponding to pitch angles of 135°, 120°, 105°, 90°, and 75°, respectively (consistent with the labels in Fig. 8, e.g., “ch-2@120°”). Sawtooth crashes are a common type of MHD event occurring near the magnetic surface where the safety factor $q = 1$. These events result in a rapid expulsion of energy and particles—including fast D^+ ions injected by the NBI—from the plasma core [34]. The timings of prominent sawtooth crashes are identified from the core soft X-ray signal [35] and marked with gray vertical lines in the figure.

Distinct responses are observed across PD channels during these events, depending on their pitch-angle coverage. Ch-3 and -4 exhibit clear positive sawtooth patterns, closely resembling the soft X-ray waveform. This indicates that their detected protons predominantly originate from fusion reactions occurring within the $q < 1$ region. In contrast, ch-1 shows an inverse sawtooth response, and ch-5 exhibits a similar but more pronounced trend, suggesting that these channels primarily detect protons generated outside the $q = 1$ surface. Ch-2, with high count rate, does not show a clear sawtooth signature, implying comparable contributions from both inside and outside the core region. These variations also qualitatively reflect differences in the spatial distribution of fusion reactivity.

Because shot #12269 reaches peak count rates of 2×10^5 cps, pulse pile-up becomes non-negligible. By applying the low-flux proton window (3.3–4.3 V) used for shot #8771, the inferred pile-up fraction is found to be 17%-39% across the five channels. Such high pile-up levels highlight the necessity of extending the upper bound of the proton energy window in high-flux cases, ensuring the retention of statistically meaningful proton counts for millisecond-scale analyses of MHD-induced modulation.

C. Monte-Carlo Source Tracing and Comparison with Experiment

To further investigate the spatial origin of the protons detected by each PD channel and to verify the above interpretation, we performed a forward Monte-Carlo (MC) “source-tracing”of ion trajectories using the CFPMC code described in Section II A. In this approach, 10 million MC protons were launched isotropically from the plasma volume with birth weights given by the local D–D fusion reaction rate, and then followed until they were either lost to the first wall or entered a PD collimator. When a proton was judged to enter the acceptance cone of a given channel, its birth (emission) position in the R–Z plane was recorded. The judgment employed the actual geometry of the detector system, including the PD head location in the poloidal plane, its toroidal position relative to the toroidal field coils, the tilt of the detector plane, and the pitch angles and acceptance ranges of each channel. Based on the collimator configuration, the half apex angle of the conical field of view was about 5.73° (as described in Section II B), so that each channel covered its nominal pitch angle $±$5.73°.

Because the detector area is small compared with the first wall, to improve statistics and reduce MC sampling error we also included contributions from toroidally equivalent locations. Specifically, the PD head is positioned midway between two adjacent toroidal field coils within $±$7.5 cm. For each of the 20 such inter-coil regions corresponding to the PD head location, every MC proton lost there was examined to determine whether it would enter the acceptance cone of a given PD channel; if so, its birth position in the R–Z plane was recorded. This procedure is based on the well-established physical property that the ripple field produced by discrete arrangement of toroidal field coils, in turn, causes energetic-particle losses to exhibit a discrete toroidal periodicity matching that of the coils [36]. Plasma parameters used in the simulation were taken, as far as possible, from diagnostics: the electron density profile from Thomson scattering [37], the ion temperature profile from CXRS [38], and the two-dimensional distributions obtained by mapping these one-dimensional profiles onto the EFIT-reconstructed equilibrium magnetic configuration. Because no direct measurement of the absolute fast-ion density is available, the fast-deuteron energy was set by the neutral-beam acceleration voltage and its content was assumed uniform with a mono-energetic distribution at the injection energy. Although this simplification affects the absolute fusion rate, its impact on the relative spatial distribution is minor and thus provides a qualitative estimate of the proton source regions.

Fig. 9 [Figure 9: see original paper] presents the simulated poloidal birth distributions of protons detected by each channel for shot #12269 at 1400 ms (T_{0} = 2.1 keV, $n_{0} = 2.1 \times 10^{19}$ m^{-3}, NBI energy E = 47.5 keV, total NBI power P = 2.8 MW, assumed fast-ion fraction n /n = 3.5%). The source regions appear as vertically elongated, with finite radial width, slightly curved bands in the RZ plane, extended primarily along the Z direction rather than forming flux-surface-symmetric rings. Quantitatively, the centroids of the simulated birth positions shift from the high-field side (HFS) toward the low-field side (LFS) from ch-1 to ch-4 (R 1.68 → 1.94 m), while each band typically spans 0.8–0.9 m in Z and 0.4–0.5 m in R (10–90% intervals). This vertical elongation reflects the PD channels' effective vertical sight lines: the collimator geometry causes the detectors to sample fusion reactions distributed along a vertically oriented cone of acceptance. The observed curvature and radial offset of the bands probably arise from guiding-center drifts (curvature and B drifts), finite gyroradius effects of the fusion protons, and the local magnetic geometry (EFIT equilibrium) combined with the collimator pointing (pitch-angle coverage).

In effect, each PD channel samples the fusion reactivity along a particular line of sight oriented roughly in the vertical (Z) direction, thereby providing information on the underlying fast-D^{+} ion distribution. The relation between these source bands and the q = 1 surface (marked by the magenta curve), whose location was determined from the inversion of the sawtooth signals in each channel as identified by the electron cyclotron emission (ECE) diagnostic [39], explains the different sawtooth responses observed in Fig. 8: channels sampling predominantly inside q = 1 (e.g., ch-3 and ch-4) show positive sawtooth signatures, whereas those dominated by protons born outside q = 1 (ch-1 and ch-5) display inverse or weaker responses, and ch-2 shows mixed behavior. Quantitatively, the fractions of simulated protons originating inside the q = 1 surface for ch-1 through ch-5 are 1.6%, 25.0%, 33.2%, 17.3%, and 0.36%, respectively, consistent with the qualitative interpretation above.

To further validate the interpretation of Fig. 9, the simulated proton flux incident on the PD head for shot #12269 at 1400 ms is compared with the corresponding experimental measurements, as shown in Fig. 10 [Figure 10: see original paper]. The simulation yields a continuous distribution of proton loss flux versus pitch angle (0–180°) at the PD location, obtained by counting all protons striking the detector region with velocity directions near 40° of the horizontal (i.e., matching the nominal viewing geometry of the PD array). In contrast, the experimental data provide discrete pitch angle points corresponding to the five PD channels. Nevertheless, the measured points closely follow the simulated distribution, exhibiting striking agreement in overall shape and relative magnitude.

The simulation reproduces the characteristic variation of detected flux with pitch angle covering the five PD channels. Minor spikes visible on the simulated curve are attributable to statistical fluctuations inherent to the Monte-Carlo procedure: even with 10 million launched protons, finite sampling in each small angular bin produces residual noise. Nevertheless, the experimental points fall systematically within the envelope of the simulation, confirming that the PD system is correctly sampling the expected pitch-angle distribution of D–D fusion protons under these discharge conditions.

The close agreement between simulation and experiment strongly supports both the feasibility of the PD diagnostic and the fidelity of the forward MC trajectory modeling. Despite the complex trajectories of charged fusion products—affected by gyromotion, magnetic drifts, and field ripple—the combination of pitch-angle-resolved measurements with forward MC simulations provides preliminary evidence of the PD system' s spatial-resolving capability for D–D fusion protons and greatly improves the interpretation of MHD-induced modulations of fast-ion-driven fusion reactivity in HL-3 plasmas.

Realizing the full potential of this approach will require continued integration with detailed and accurate numerical modeling. Under present HL-3 conditions, where D–D fusion reactions are predominantly driven by neutral-beam-injected fast D^+ ions, such measurements also offer a new window on the spatial distribution of fast ions themselves. Looking ahead, applying this combined diagnostic–modeling method to more complicated scenarios—such as during MHD activity, fishbone instability, or other fast-ion redistribution events—will enable time-resolved interpretation of fusion reactivity and disentangling of spatial and temporal effects in the measured signals.

Compared with conventional neutron cameras, which are typically bulky, expensive, and have limited detection efficiency for neutrons, the PD system—thanks to its simple structure, compact size, low cost, and near-100% detection efficiency for charged particles—provides a complementary and potentially valuable tool for monitoring fusion reactions in deuterium-fueled plasmas.

IV. Summary and Outlook

This paper reports on a five-channel proton detector (PD) system based on passivated implanted planar silicon (PIPS) detectors, which has been constructed on the HL-3 tokamak for the first-time measurement of charged fusion products from D–D reactions. The system incorporates multiple noise-suppression strategies, including a tungsten-shielded housing, carefully oriented collimators that avoid direct plasma sightlines, Pt foils to block electromagnetic background, and fully coaxial signal transmission to minimize electromagnetic and ground-loop interference. Laboratory calibration using a ^{241}Am α source established the energy response of each channel.

During 2024 experimental campaigns, the system successfully captured characteristic proton signals under NBI conditions and enabled time-resolved analysis of fusion reactivity, including distinct channel-dependent responses to sawtooth oscillations that reflect different sampling regions relative to the q = 1 surface. Forward source-tracing simulations performed with our self-developed Monte-Carlo code (CFPMC) reproduced the channel-dependent spatial birth distributions in the R–Z plane and yielded pitch-angle distributions in good qualitative agreement with the experimental measurements.

These results demonstrate not only the capability of the PD system to provide temporal and pitch-angle-resolved fusion product measurements, but also the fidelity of the modeling and its value for interpreting MHD-induced modulations of fusion reactivity in deuterium-fueled plasmas.

This diagnostic marks the first-stage implementation of charged fusion-product measurements on HL-3, focusing on D–D fusion protons. With increasing fusion power, future efforts will extend to developing diamond-detector systems with enhanced radiation tolerance and improved time resolution to enable the detection of both protons and alpha particles under more demanding conditions. In parallel, optimizing the collimator geometry and further refining the CFPMC model—including more realistic fast-ion source distributions and magnetic perturbations—will be essential for improving spatial resolution, reducing modeling uncertainties, and enabling more accurate inference of core plasma conditions.

In addition, an upgraded electronics chain with significantly shorter shaping times (<100 ns) is being planned. Such fast shaping will substantially reduce the pile-up probability under high-flux conditions and thereby improve the statistical quality of time-resolved proton measurements. This enhancement will be particularly important for studies of rapid MHD-induced modulation and transient fast-ion behavior.

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