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

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Abstract

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Full Text

Preamble

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Abstract

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 generated by the d(d,p)t fusion reaction. The system features tungsten shielding, platinum foils, and optimized collimators for noise suppression, with detector placement guided by Monte-Carlo simulations of numerous ion trajectories. 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, revealing fusion reactivity modulation by magnetohydrodynamic (MHD) events.

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

1 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]. Research to date 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 [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. A pitch-angle-resolved diagnostic is required because MHD activity is characterized by high frequencies and is always correlated with EPs' distribution in phase space.

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, activation methods, and Faraday cups. 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) [7], which affects lifetime; and (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 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 PIPS detectors to survive within an experimental campaign 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 [8], ASDEX [9], Alcator C-Mod [10], TFTR [11], MAST [12] and MST [13], and recently to detect α particles from $p^{11}B$ fusion on LHD [14].

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) [15] 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 charged fusion product measurements. The primary purpose 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 2 describes the simulation, design, hardware configuration, and calibration of the diagnostic; Section 3 presents the first experimental observations and related analysis; and Section 4 summarizes the main results and discusses future prospects.

2.1 Simulation of particle trajectory and detectors layout

Unlike neutrons, charged fusion products move along curved trajectories in the magnetic field and their loss positions are asymmetric due to curvature and B drift. To determine optimal detector placement and collimator orientation, simulations of charged fusion product trajectories and losses were performed. A self-developed Monte-Carlo (MC) code employing a 4th-order Runge-Kutta method to solve the equation of motion for charged particles was used. 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 was considered.

A large number of MC particles (representing protons or tritons from D-D reactions) were emitted isotropically within the plasma with birth weighting by the local fusion reaction rate: [illegible] where σv denotes the fusion reactivity 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_d is the thermal D^+ density and n_{fast} is the density of fast D^+ ions. These particles were tracked continuously until they crashed onto the first wall or were confined for a sufficiently long time (>1 ms). Under typical HL-3 plasma parameters, fast-ion-induced reactions account for more than 95% of the total yield in simulations, so contribution from fast D^+ ions is the primary factor to consider.

A typical loss distribution for protons on the HL-3 first wall with plasma current I =0.7 MA and toroidal magnetic field B_0=1.8 T is illustrated in Fig. 1. Protons are lost in the region below the equatorial plane of the device (Fig. 1(a)). Based on this, a location near a port ~90 cm below the mid-plane on the low-field side (marked by a white dashed line) was selected from several candidates for detector installation. The pitch angles (defined as the angle between particle velocity and toroidal magnetic field B) of protons at the time of loss also exhibit a non-uniform distribution, as shown in Fig. 1(b). They are concentrated within a relatively narrow range and vary with poloidal angle. Thus, five detectors were used to cover the peak of pitch angles and its surrounding region, with collimator orientations as shown by the red dots in Fig. 1(b).

Fig. 1. Simulated loss distribution for 3.02 MeV protons on the HL-3 first wall: (a) as a function of toroidal angle (ϕ) and poloidal angle ( ) in the device coordinate system, (b) as a function of poloidal angle and pitch angle. The white dashed line indicates the position of a lower port, where the first wall has an opening and detectors will be located. The red dots represent the orientation of the center axes of the collimators for the planned detectors.

Typical proton trajectories traced backward from the detection positions are shown in Fig. 2. In these cases, the angle between the projection of the collimator orientation (i.e., the opposite direction of proton impact velocity) onto the poloidal cross-section and the radial direction was set to 40°, as shown in Fig. 2(a). With this angle, the detectors' fields of view avoid direct line-of-sight to both the plasma region and the first wall (Fig. 2(c) [Figure 2: see original paper]), 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.

Fig. 2 [Figure 2: see original paper]. Example simulated trajectories of protons reaching the detectors. (a) Projection onto the poloidal cross-section of the HL-3 vessel; (b) corresponding 3D view of the trajectories shown in (a), with consistent color identification; (c) illustration of the view fields of the collimators to be installed.

2.2 Mechanical structure

Five Ortec TU-014-050-100S PIPS detectors, bakeable up to 200 °C, were used in the PD system. Each detector has a depletion layer thickness of 100 m (indicated by the "100" in the model number), which is slightly greater than the projected range of 3.02 MeV protons in silicon (~94 m, calculated by SRIM). This ensures protons fully deposit their energy within the active layer while minimizing background noise from hard X-rays and γ-rays, which can lose energy via Compton scattering or the photoelectric effect when passing through silicon.

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. This enclosure blocks or attenuates 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 [16]). The entrance windows of the detectors align with openings in the tungsten housing to allow particle access, while remaining surfaces are wrapped in polyimide (PI) composite insulation blocks for electrical insulation and heat resistance.

Fig. 3. Structural configuration of the PD system. (a) Schematic of the integrated mechanical housing with thermal and radiation shielding. (b) Exploded view of a single detection channel illustrating the PIPS detector assembly, insulation components, Pt foil and collimation structure.

A 2 m-thick platinum (Pt) foil, affixed to a stainless steel ring using vacuum-compatible adhesive, is mounted at the entrance of each detector. The ring inserts into a PI grooved seat that holds it securely; this seat features an annular opening designed to avoid forming a sealed cavity during vacuum pumping. The Pt foil blocks visible light, microwaves, soft X-rays, and low-energy particles. Laboratory tests confirmed 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.

Tungsten tubes 4 cm long with an inner diameter of 8 mm serve as collimators. The angles between the axes of the five collimators and the 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 ($\pi/12$ rad), as marked by green dots in Fig. 1(b). An aperture cap with optional hole size mounts at the front of each collimator to regulate proton flux based on expected plasma conditions.

The entire tungsten housing mounts on a stainless steel base 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 connects to the vessel via a stainless steel bellows (rather than directly through the base), which also protects signal cables. This configuration enables single-point grounding and minimizes ground loop interference. These design features—including tungsten shielding, platinum entrance foils, carefully oriented collimators, single-point grounding, and coaxial signal transmission—effectively mitigate interference noise.

2.3 Preamplifier

Weak current signals generated in the detectors are transmitted by coaxial cables (~1.6 m 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 distance between detectors and preamplifier—and thereby maximize signal-to-noise ratio—the preamplifier mounts 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. The shaping modules convert pre-amplified signals into quasi-Gaussian pulses with FWHM of ~1 s (or 2 s, selectable) and linearly amplify them to volt-level amplitudes. A NIM chassis powers the preamplifier, and its high-voltage power supply module provides a bias voltage of ~70 V for the detectors.

2.4 Digitizer

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

2.5 Calibration

Before mounting detectors in the HL-3 tokamak, each PD channel was calibrated in the laboratory using a low-activity ^{241}Am alpha-particle source, chosen because no calibration facility provides low-flux ($<10^5$ protons/s) $>$3 MeV monoenergetic protons. Since air at atmospheric pressure strongly scatters alphas and affects calibration accuracy, both detector and source were placed in a compact, light-tight vacuum chamber at ~5 Pa pressure with a source-to-detector distance of ~2.5 cm. Using statistics from a large number of pulse amplitudes and subsequent fitting with three Gaussian functions (representing 85% of decays at 5.486 MeV, 13% at 5.433 MeV, and 2% at 5.388 MeV), the calibration result for one channel is shown in Fig. 4. This yields a calibration factor of 1.04 V/MeV and an energy resolution (standard deviation of the Gaussian distribution) of 0.157 MeV, or 2.86%.

Fig. 4. Energy calibration result of one PD channel using a ^{241}Am α source. The measured pulse-height histogram (dots) was fitted with three Gaussian components (solid, dashed, and dotted blue lines) corresponding to three α decay energies. The derived calibration factor is 1.04 V/MeV, with an energy resolution of 0.157 MeV (σ).

3 First observation of D-D protons on HL-3

During the winter 2024 experimental campaign, the PD system successfully detected proton signals from D-D fusion reactions on HL-3 for the first time. In preparation for increased NBI power planned for the spring 2025 campaign, the collimator aperture was adjusted from 4 mm to 1 mm during the experimental hiatus to mitigate excessive proton flux and prevent signal pile-up.

A typical result from shot #8771 is presented in Fig. 5. Main plasma parameters were: plasma current I =300 kA, central toroidal magnetic field B $_0$=1.2 T, line-averaged electron density n =2.0$×10^{19}$ m^{-3}, with a lower single-null divertor configuration.

Upon NBI activation, the PD system recorded numerous pulse signals with similar amplitudes (~3.8 V). This is consistent with simulation-based predictions that, under HL-3 operating conditions, most D-D fusion protons originate from beam-thermal interactions—reactions between confined fast D^+ ions (injected by NBI) and background thermal D^+ ions—rather than thermal-thermal reactions. When NBI switched off, pulse signals gradually decayed over ~60 ms before disappearing, consistent with fast ion loss and slowing-down timescales. Occasionally, pulses with significantly higher amplitudes were observed, attributed to pile-up effects from multiple proton events overlapping in time. As evident in Fig. 5(c), plasma disruptions at the end of the discharge induced dense, low-amplitude (<0.7 V) noise signals, which were effectively distinguished from proton signals by pulse height.

Fig. 5 [Figure 5: see original paper]. Time evolution of (a) plasma current, (b) neutral beam injection (NBI) power and (c) raw signal data from the PD system for HL-3 shot #8771, showing proton events from fast D^+ ion-induced D–D fusion reactions. Due to the high sampling rate, one out of every 100 points is plotted in (c) for clarity.

To confirm the proton identity of these signals, a statistical analysis of pulse heights during NBI injection was performed, yielding the histogram in Fig. 6. This reveals an isolated, Gaussian-like peak centered at ~3.8 V, attributed to D-D fusion protons, and a secondary peak at ~0.7 V, attributed to triton signals, superimposed on a continuous low-amplitude noise background. Based on the ^{241}Am source calibration (assuming linear response) described in Section 2.5, attenuated proton (~2.86 MeV) and triton (~0.65 MeV) signals were expected at 2.98 V and 0.65 V, respectively. However, observed peak positions deviate from these expectations. Since HL-3 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 likely arises from significant differences in ionization density, range, and charge collection efficiency between measured ions (protons and tritons) and calibration alpha particles. Despite this deviation, peaks at 3.8 V and 0.7 V can still be identified as protons and tritons based on approximate calibration and exclusion of other particle contributions.

Fig. 6. Pulse height spectrum of channel-2 during NBI injection in shot #8771. The histogram shows a prominent peak around 3.8 V attributed to D–D fusion protons and a secondary peak near 0.7 V attributed to tritons, superimposed on a low-amplitude noise background. The red dashed line indicates the approximate boundary between triton signals and the noise region.

Analysis of extensive PD data across various HL-3 discharges revealed that, although triton signals are sometimes masked by low-amplitude noise, proton signals consistently remain well above the noise floor and can 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 pulse pile-up occurs, the upper bound can be set higher—according to the actual pulse-height spectrum—to include piled-up signals rather than discard them, enabling investigation of fast processes (~several 10 ms) such as MHD-induced effects that influence local fusion reactivity.

Fig. 7 shows a representative case (shot #12269) where the time evolution of proton flux measured by the PD system reveals clear modulation associated with sawtooth activity. For clarity, the five channels are denoted ch-1–ch-5, corresponding to pitch angles of 135°, 120°, 105°, 90°, and 75°, respectively (consistent with labels in Fig. 7, e.g., "ch-2@120°"). Sawtooth crashes are common MHD events occurring near the magnetic surface where the safety factor q=1, resulting in rapid expulsion of energy and particles—including fast D^+ ions injected by NBI—from the plasma core. Prominent sawtooth crash timings identified from the core soft X-ray signal are marked with gray vertical lines.

Distinct responses appear across PD channels during these events, depending on pitch-angle coverage. Ch-3 and ch-4 exhibit clear positive sawtooth patterns, closely resembling the soft X-ray waveform, indicating their detected protons predominantly originate from fusion reactions within the $q<1$ region. In contrast, ch-1 shows an inverse sawtooth response, while ch-5 exhibits a similar but more pronounced trend, suggesting these channels primarily detect protons generated outside the q=1 surface. Ch-2, with high count rate, shows no clear sawtooth signature, implying comparable contributions from both inside and outside the core region. These variations qualitatively reflect differences in the spatial distribution of fusion reactivity.

Fig. 7 [Figure 7: see original paper]. Time evolution of (a) proton flux measured by five PD channels with different pitch angles, (b) core soft X-ray emission, and (c) neutron flux during shot #12269. Gray vertical lines mark prominent sawtooth crash timings. The five channels (ch-1–ch-5) correspond to pitch angles of 135°, 120°, 105°, 90°, and 75°, respectively.

These results demonstrate that, despite complex trajectories of charged fusion products such as high-energy protons—affected by gyromotion, magnetic drifts, and magnetic field ripples—pitch-angle-resolved measurements can probe the spatial distribution and temporal evolution of fusion reactivity inside the plasma. Realizing this potential requires further integration with detailed numerical modeling. Moreover, since D–D fusion reactions under present HL-3 conditions are predominantly driven by fast deuterons injected via NBI, such measurements may also offer insights into fast ion spatial distribution. Compared with conventional neutron cameras—which are typically bulky, expensive, and have limited neutron detection efficiency—the PD system, with its simple structure, compact size, low cost, and near-100% detection efficiency for charged particles, provides a backup and potentially valuable approach for monitoring fusion reactions.

4 Summary and outlook

This paper reports that a five-channel proton detector (PD) system based on passivated implanted planar silicon (PIPS) detectors has been constructed on the HL-3 tokamak for 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 experimental campaigns, the system successfully captured characteristic proton signals and enabled time-resolved analysis of fusion reactivity, including modulation by MHD events such as sawtooth crashes. These results demonstrate the PD system' s capability to provide temporal and pitch-angle-resolved fusion product measurements and offer new insights into fusion reactivity dynamics in deuterium-fueled plasmas. This first-stage diagnostic marks the initial implementation of charged fusion product measurements on HL-3, focusing on D–D fusion protons. With increasing fusion power, future efforts will focus on developing diamond detector systems with enhanced radiation tolerance and improved time resolution to enable detection of both protons and alpha particles under more demanding conditions. In parallel, optimizing collimator geometry and incorporating advanced numerical modeling will be essential for improving spatial resolution and enabling more accurate inference of core plasma conditions.

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Note: Figure translations are in progress. See original paper for figures.