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A photodiode-based neutral particle bolometer for characterizing charge-exchanged fast-ion behavior[a)]

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A neutral particle bolometer (NPB) has been designed and implemented on Tri Alpha Energy's C-2 device in order to spatially and temporally resolve the charge-exchange losses of fast-ion populations originating from neutral beam injection into field-reversed configuration plasmas. This instrument employs a silicon photodiode as the detection device with an integrated tungsten filter coating to reduce sensitivity to light radiation. Here we discuss the technical aspects and calibration of the NPB, and report typical NPB measurement results of wall recycling effects on fast-ion losses.
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I. INTRODUCTION

The field-reversed configuration (FRC) experiment at Tri Alpha Energy aims to extend the confinement and stability of an FRC in part with the use of neutral beam injection (NBI).[1–3] Up to six neutral beams ($E = 20\,\mathrm{keV}$, 40 A, each) are used to inject fast ions confined in betatron (axis-encircling) orbits near the separatrix. Such ions are predicted to improve FRC stability and transport.[4–6]

Fast ions in FRCs are highly non-local since the betatron orbits extend from inside the field null to outside the separatrix, sampling large changes in neutral density, plasma density, and magnetic field. This results in rich fast-ion dynamics and motivates a spatially and temporally resolved study of fast-ion transport, particularly charge-exchange losses. We have designed a neutral particle bolometer (NPB) to measure fast-neutral flux resulting from charge-exchanged fast ions.

We chose a silicon photodiode for the detector because it is compact and easily configured for multichannel use. Photodiodes have been used with pulsed height analysis (PHA) methods for the express purpose of obtaining time resolved energy spectra of fast neutrals on stellarators[7–9] and a spherical tokamak.[10] However, present PHA techniques do not meet the time resolution (few μs) or minimum cutoff energy requirements ($<$10 keV) of the C-2 experiment. Photodiodes have also been used in current mode to infer fast-neutral bolometry.[11] In this paper we report direct measurements of fast-neutral flux using a photodiode in current mode.

II. DESIGN CONSIDERATIONS

In the C-2 experiment, neutral beams inject fast ions perpendicular to the symmetry axis and at various locations, generating betatron orbits with a rich pitch-angle distribution (see Fig. 1). To address this, we designed the NPB with a linear channel array on a rotatable flange allowing radially or axially resolved measurements.

The photodiodes used in the NPB are sensitive to both fast ions and light (visible to x-ray). In order to attenuate photon energies in the visible to EUV range we chose a tungsten filter coating for its low transmittance up to ∼80 eV, according to available transmittance data.[12,13] Using this data and the Stopping and Range of Ions in Matter (SRIM) code[14] we determined that a 40 nm coating should provide sufficient attenuation of photons and remain sensitive to neutrals with energy $>$5 keV, for the possible detection of the $E/3$ component of neutral beam injected fast ions.

III. TECHNICAL DESCRIPTION

The photodiode is a linear array of sixteen 2 mm × 5 mm pixels (IRD AXUV16ELG[15]). A 4 nm of titanium is applied to the photodiode surface to provide an adhesion surface for the tungsten layer. Also, a 1 μm aluminum coating is applied between each element to prevent photons and particles that strike the inter-element regions from polluting signals produced by the detector elements.

An enclosure houses the detector, positions the aperture, has a black oxide treatment to reduce light reflection, and can pivot ±15°. The aperture is 500 μm in diameter and located about 6 cm from the face of the photodiode array. The assembly mounts to a 6 in. conflat flange. Figure 2 shows a rendering of the NPB with side panel removed.

Each photodiode channel has a single gain stage transimpedance amplifier (250 kA/V) with a rise-time $\lesssim$1 μs. A single circuit board incorporates sixteen amplifier channels and supplies 10 V reverse bias to the photodiode array. The circuit board and two lithium-ion batteries are contained in an aluminum enclosure (about 10 cm × 10 cm × 10 cm) attached directly to the DB25 feedthrough on the 6 in. flange. Signals are transmitted to a data acquisition cabinet and digitized at 500 ks/s.

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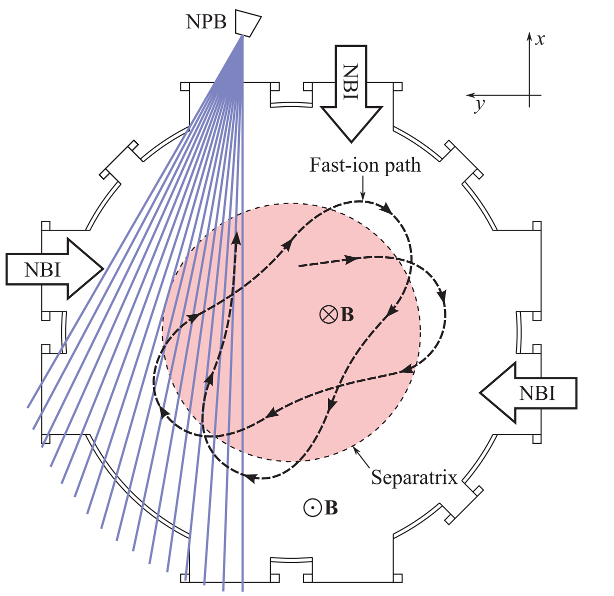

FIG. 1. Illustration of NPB view chords, the C-2 vessel, and a fast-ion betatron orbit shortly after FRC formation ($\sim t > 0$ ms).

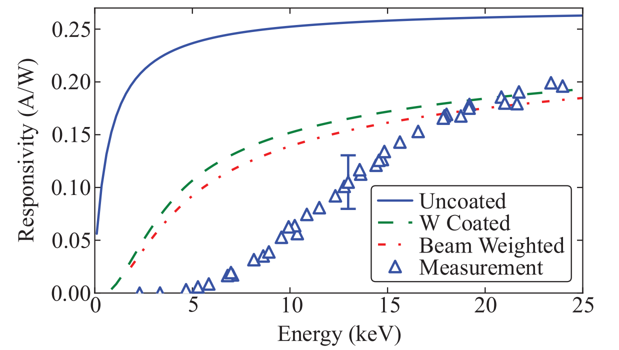

FIG. 3. Responsivity of an AXUV16ELG photodiode to fast neutrals. Also shown is the responsivity for a tungsten coated photodiode and calibration measurements.

We did not seek a precise responsivity to photons over a broad spectrum. However, we determined the filter's general attenuation in the visible by illuminating a coated photodiode with a uniform light source and comparing the response to that of an identically situated uncoated photodiode and found about a 20 × attenuation. We assume transmittance data remains accurate for energies above the visible.

IV. CALIBRATION

We measured the effective responsivity of a tungsten coated photodiode pixel by exposing it to an NBI with $<4^\circ$ divergence and normalizing the response to that of a similarly exposed $LiNbO_3$ pyro-bolometer.[16] We repeated measurements for several beam energies between 2 keV and 25 keV and the results are shown in Fig. 3. Also shown for comparison are the empirical responsivity of an uncoated photodiode (Eq. (5) from Ref. 17), the expected effective responsivity (determined from SRIM and the uncoated responsivity), and the expected responsivity with neutral beam energy components considered. Imprecise knowledge of the neutral beam current fractions or inaccurate filter thickness cannot explain the discrepancy between the expected responsivity and the measurement. Plausible explanations include: (a) an instance of the photodiode may differ in response from Ref. 17; (b) the photodiode may have been damaged during the calibration procedure; (c) issues regarding the application of the filter coating. We plan to calibrate with a separate ion-source to help resolve this discrepancy.

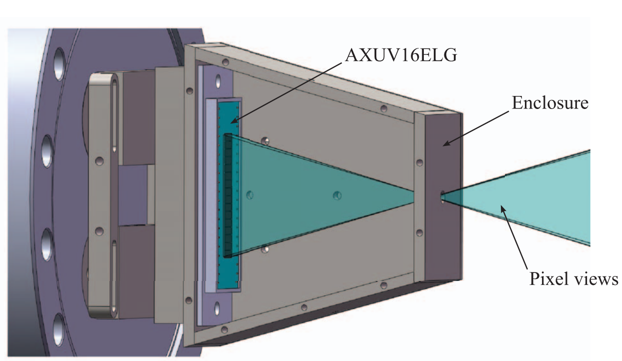

FIG. 2. Rendering of the NPB device with side panel removed.

V. EXPERIMENTAL RESULTS AND DISCUSSION

We have installed NPB devices at various locations on C-2. An illustration of the view chords for one NPB is shown in Fig. 1. The radii of tangency of the view chords range between 15 cm and 65 cm and are oriented opposing the ion diamagnetic direction to capture escaping fast neutrals. Initially we installed two oppositely oriented NPBs to determine the contribution of light emissions to the signal and found it to be $\lesssim 10\%$. Presently, the light signal baseline is obtained by terminating neutral beams early (at $t = 0$).

Figure 4 shows for a typical shot the spatially averaged NPB signal, the neutral beam shine-through, and

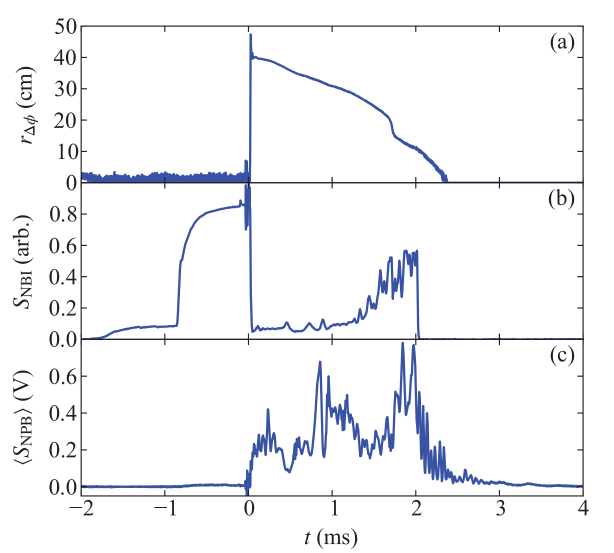

FIG. 4. Typical signal traces for the excluded flux radius (a), neutral beam shine-through (b), and spatial average NPB signal (c). The FRC is formed at $\sim t = 0$ ms, and NBI is engaged between -1.8 ms $\leq t \leq 2.0$ ms (Shot 18760).

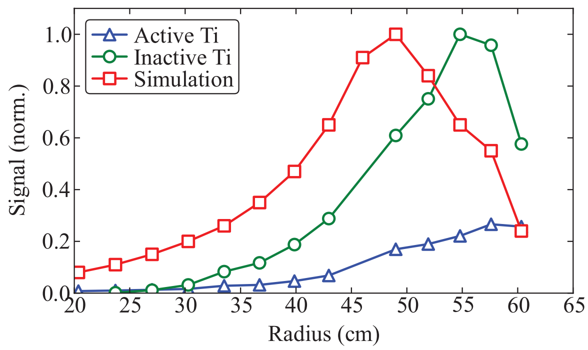

FIG. 5. Normalized NPB signal as a function of view-chord radius, with and without active titanium gettering. Also shown is a simulated fast neutral flux profile.

excluded flux radius (approximate separatrix radius). The shine-through trace shows NBI reaching full power at $t \simeq -0.5$ ms and terminating at $t = 2$ ms. The FRC forms in the confinement chamber at $t \simeq 0.03$ ms, capturing a significant fraction of the neutral beam, as evidenced by reduced shine-through signal. Shine-through gradually increases as the FRC shrinks in length and radius. We observe fast-neutral flux while trapped fast ions are present.

The AXUV16ELG photodiodes are capable of long lifetimes for exposure to photons[18] and ions.[19] We estimate the effective lifetime of an NPB detector to be about 30 000 shots, which is about twice the age of presently commissioned detectors, so some degradation is expected. However, since changes to C-2 conditions preclude direct signal comparison between old and new shots, a deliberate longevity study is planned.

We performed an experiment to determine the effectiveness of titanium gettering in reducing background neutral gas. Figure 5 shows the signal amplitudes from an NPB as a function of radius (averaged over an ensemble of shots and between $0.2\,\text{ms} \leq t \leq 0.3\,\text{ms}$) for conditions with and without active titanium gettering. Also shown is a fast neutral flux profile calculated by Monte-Carlo simulation with wall recycling coefficient of one. The data show a $\sim 5 \times$ reduction in fast-neutral flux in the outer channels, suggesting that background neutral density was reduced. Others also determined independently that titanium gettering reduced neutral density in C-2 with D_α and multi-chord interferometer measurements.[20]

In an equilibrium model, the NPB signal is proportional to the following expression:

$$S_{\mathrm{NPB}} \propto n^* \nu_{\mathrm{cx}} \propto \frac{I_{\mathrm{NB}}}{\nu_{\mathrm{cx}} + \nu_{\mathrm{x}}} \nu_{\mathrm{cx}} \,, \tag{1}$$

where n^* is the trapped fast-ion density, I_{NB} is the captured neutral beam current, ν_{cx} is the charge-exchange rate of fast ions ($\propto$ neutral density), and ν_{x} is the sum of all other fast-ion loss rates, e.g., classical slowing down and diffusion. Equation (1) indicates that the NPB signal should be insensitive to changes in neutral density for $\nu_{\mathrm{cx}} \gg \nu_{\mathrm{x}}$, so we also conclude that charge-exchange is not the dominant loss mechanism for fast ions.

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