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Compact solid-state neutral particle analyzer in current mode[a)]

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Abstract. Solid state neutral particle analyzer (ssNPA) arrays are operated in current mode on the DIII-D tokamak and the National Spherical Torus eXperiment (NSTX). Compared with conventional pulse-counting NPAs, current-mode operation sacrifices energy resolution to obtain economical, high-bandwidth, pitch-angle resolved measurements. With the success from a new three-channel near-vertical-view current mode ssNPA on DIII-D, the apertures on an existing array on NSTX were expanded to increase the particle influx. The sightlines of both arrays intersect heating beams, enabling both active and passive charge exchange (CX) measurements. The spatial resolution at beam intersection is typically 5cm on both devices. Directly deposited ultra-thin foils on the detector surface block stray photons below the energy of 1keV and also set low energy threshold about 25keV for deuterium particle detection. Oscillations in neutral flux produced by high frequency MHD instabilities are readily detected.

I. INTRODUCTION

The neutral particle analyzer (NPA), introduced in the early 1960s initially as an ion temperature diagnostic, has evolved through the years to meet new demands in fusion plasma research. It is based on charge exchange (CX) process whereby an ion gains an electron from a background atom to get neutralized and ceases to be confined by the magnetic field; NPA measures the lost neutrals and their distribution to deduce the ion energies, plasma temperature and their profile. As shown in a recent review paper[1] and some contemporary publications[2-5], a variety of NPAs have been developed based on different neutral re-ionization techniques and spectrometer designs, including electrostatic, E//B and time-of-flight spectrometers. These conventional NPA systems are well understood but are relatively complex, bulky and expensive. For example, traditional neutral re-ionization utilizes either conventional gas stripping cell with differential vacuum pumping, an ultrathin carbon foil with high-transparency metallic mesh, or a diamond-like carbon stripping foil.

Natural diamond detectors (NDD)[6,7], developed by Troitsk Institute for Innovating and Fusion Research in Russia (TRINITI), have been applied on tokamaks like TFTR, JET, NSTX, JT-60U and on the Large Helical Device (LHD). The compact size and convenience of NDDs make them an attractive alternative to traditional NPA technologies. Recently, compact NPA system based on absolute extreme ultraviolet (AXUV) silicon photodiode[8] has been demonstrated on NSTX[9,10] and successfully applied on Alcator C-Mod[11]. Silicon detectors are cheaper and more sensitive than diamond detectors but have poorer radiation resistance. The advantages of AXUV detectors (solid state, UHV compatibility, high carrier collection efficiency, fast response, compact size, low cost) make them an appealing option for multi-channel, high resolution (in time, space, and energy) NPA applications, for both passive and active measurements.

Recent rapid progress on energetic particle studies at DIII-D and other fusion research facilities[12,13] requires reliable measurements of fast neutral particles and their distribution with hundred kHz frequency-resolution and centimeter level spatial-resolution. The ssNPA in counting mode for pulse height analysis (PHA), provides good spatial resolution, moderate energy (~10keV) and time resolution (~10ms). However, none of them has ever been operated in current mode, which has the intrinsic potential for very high time resolved measurement and spatial resolution at the ion orbit radius scale.

In this article, details of the first-time application of the AXUV diode based ssNPA system in current mode are presented. The system design and diagnostic setup are shown in Sec. II. In Sec. III, experimental results on DIII-D and NSTX are reported. Finally, a brief summary and future plan are given in Sec. IV.

II. DIAGNOSTIC SETUP AND DESCRIPTION

A. Basic design considerations

The new ssNPA array was designed as a replacement for a mothballed compact electrostatic NPA[14] diagnostic and complements for existing neutron counters and scintillators[15] (for volume averaged fusion products), fast ion Dα (FIDA)[16] (confined ions) and beam ion loss detector (BILD)[17] (lost fast ions) diagnostics. NPA diagnostics have better velocity-space resolution than other confined fast-ion diagnostics, so they provide unique physics information about the mechanism of wave-particle resonances and transport. Figure 1 demonstrates a typical NPA weight function in velocity and configuration space for an SSNPA channel operated in current mode. The narrow pitch-angle resolution due to the near-perpendicular view of the diagnostic implies that only trapped ions contribute to the signal. Spatially, both injected (active) neutrals in the core and edge (passive) neutrals contribute to the signal.

As in Ref. [9-11], an AXUV diode was exploited on DIII-D. With numerical estimations on a variety of factors like geometric

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allowance and vacuum requirements, neutral attenuation and signal level, noise suppression and radiation damage, detectors with directly deposited ultra-thin foil on the front surface based on module AXUV63HS1 are manufactured by International Radiation Detectors, Inc.[8] for DIII-D specific application. Their characteristic parameters are: 63 mm^2 effective area, 20nA dark current, 2ns risetime with -150V bias; the deposited foils on the detector surface consists of 6nm Ti, 100 nm W, and 20 nm C. The deposited foil is more robust than a free-standing ultra-thin foil. The foil i) provides neutral re-ionization; ii) blocks stray photons below the energy of 1keV; and iii) sets a low energy threshold of ~25keV for deuterium particle detection.

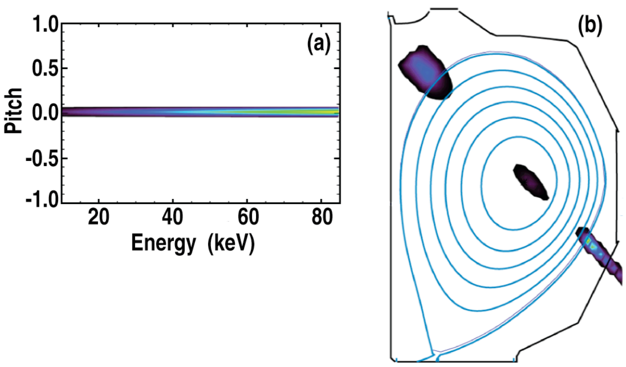

FIG. 1. The current mode ssNPA diagnostics retains excellent pitch resolution. Weight function in (a) velocity space, (b) configuration-space.

B. ssNPA system description

On DIII-D, a new three-channel ssNPA array was installed. As shown in Fig. 2, and Fig. 1(b), the ssNPA system shares a 10" flange at 225 R-1 port with scintillator based fast ion loss detector (FILD)[18]. The three near-vertical viewing chords of the DIII-D array intersect the centerline of the closest near-tangential 210R neutral beam at major radii of 1.50, 1.65, and 1.83m. Each of the independent ssNPA channels is collimated with about 254 mm long 10 mm inner diameter guiding tube with threaded-on aperture at the front end. This aperture together with the other one just in front of the detector controls the particle influx.

Noise suppression and instrument safety are included in the design. The detector sits on AXUV100CS ceramic socket, which is supported by stainless steel support structure. Two standard standoffs hold them to the 2-3/4" BNC floating coaxial feedthrough. For high voltage isolation, a ceramic break is used between the guiding tube and detector cup. Signals are fed into current amplifier via a short BNC cable and then transferred to DAQ system with typical sampling rate of 1MHz. For detector protection during vacuum baking with potential temperature of 400^{o}C, active air-cooling and thermal couple are attached.

III. PRELIMINARY OPERATING RESULTS

The system on DIII-D started to produce valuable signals in the 2009 experiment campaign, during which the innermost channel are blocked to provide a background reference. Figure 3 illustrates the typical correlation between signals of the ssNPA and the 201R active beam: two unblocked channels of the ssNPA did work in active CX mode. The differences between the signal amplitude are consistent with the prediction from the beam attenuation. The 3rd channel was unblocked during the 2010 vent because the noise background from that channel was ignorable. Active signals in a recent experiment show that the number of trapped ions depends on the angle of beam injection.[19]

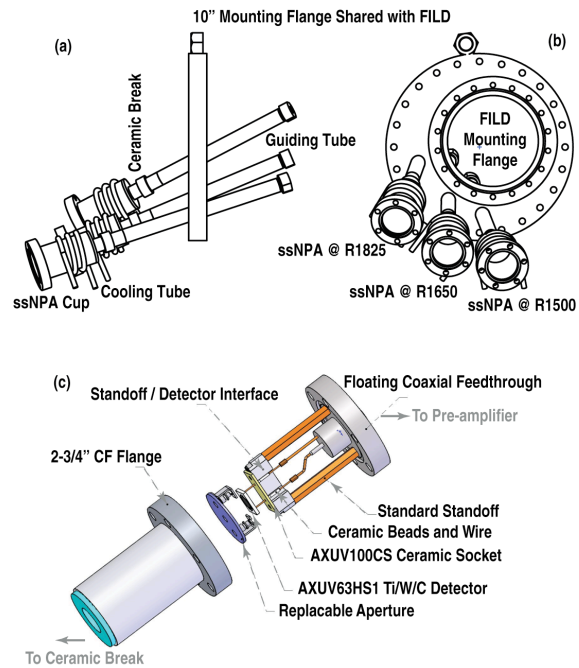

FIG. 2. CAD drawing for 3-channel DIII-D ssNPA system. (a)(b) geometric arrangement (c) ssNPA detector head assembly.

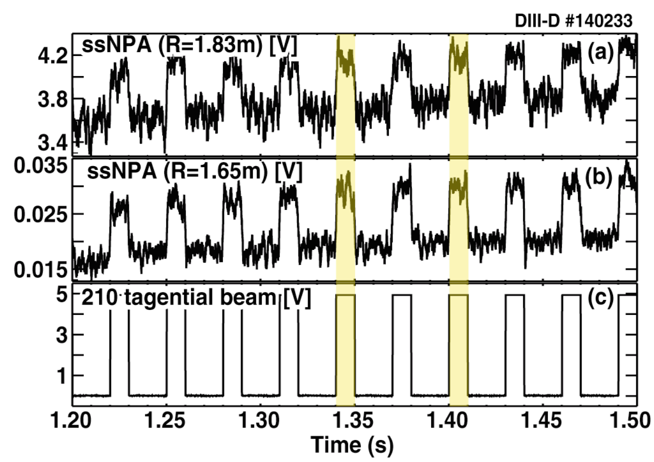

FIG. 3. DIII-D ssNPA system works in active CX mode.

The system's functionality in passive CX mode is well demonstrated by sub-millisecond scale fast time response of ssNPA to high frequency MHD instabilities, without active neutral beam. During so-called off-axis fishbones, where modes are driven by energetic trapped particles at the fast-ion precession frequency, significant burst signals are readily detected on ssNPA as well as other energetic fast ion measurements.[20]

After the successful DIII-D ssNPA tests, the 4-channel array existing on NSTX[9,10] was adapted to current mode operation, using 25 mm^2 AXUV sensors and extended apertures. The neutral particle influx was increased by a factor of ~7000, allowing sampling rates >1MHz. With some modifications, similar ideas are provided to the Tri-Alpha Energy Inc. as a collaboration research on the field reversed configurations (FRC) machine.[21]

Some results from NSTX are shown in Figs. 4 and 5. Autopower spectra from a mid-plane Mirnov probe and the ssNPA at R=0.9 m (Fig. 4) shows that the ssNPA detects Energetic Particle Modes (EPM) correlated oscillations at the frequency of up to about 70kHz. The oscillations are absent when the diagnostic gate valve is closed. Figure 5 details the measurements during a single EPM burst. A sequence of peaks in phase with Mirnov oscillations is captured by the ssNPA. Peaks first appear in the outermost channel (most tangential) with structure likely due to contributions from spatially separated sources of neutrals (beam, edge).

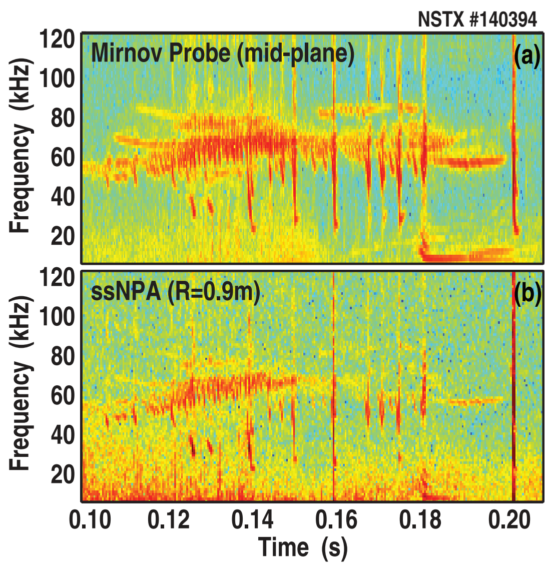

FIG. 4. Spectrogram of signal measured by a Mirnov probe (top) and one ssNPA view line (bottom) in a NSTX H-mode discharge.

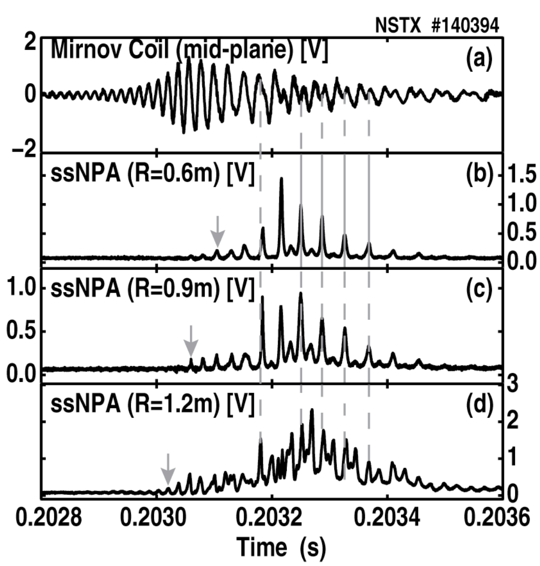

FIG. 5. Time traces of ssNPA measurements during a strongly chirping EPM mode on NSTX, for different tangency radii R=0.6, 0.9 and 1.2m. The signal from a Mirnov coil (top) provides a reference for the phase of the magnetic perturbation.

IV. SUMMARY AND FUTURE PLAN

Three (four) channels of a new type ssNPA in current operation mode have been successfully tested on the DIII-D (NSTX) tokamaks. Both active and passive CX measurements have been achieved at about 5cm spatial resolution. About 70 kHz oscillations in neutral flux from high frequency MHD instability are readily detected. This study has paved the way for a simple, compact, economical, but robust and reliable approach for diagnosing fast particles with high temporal, spatial, and pitch angle resolution.

Some further study on improvement of the bandwidth and signal to noise ratio will be performed. For future energetic particle relevant experiments, an ssNPA system with more channels in current mode will be developed.

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