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Development of an integrated energetic neutral particle measurement system on experimental advanced full superconducting tokamak[a)]

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Full function integrated, compact silicon photodiode based solid state neutral particle analyzers (ssNPA) have been developed for energetic particle (EP) relevant studies on the Experimental Advanced Superconducting Tokamak (EAST). The ssNPAs will be mostly operated in advanced current mode with a few channels to be operated in conventional pulse-counting mode, aiming to simultaneously achieve individually proved ultra-fast temporal, spatial, and spectral resolution capabilities. The design details together with considerations on EAST specific engineering realities and physics requirements are presented. The system, including a group of single detectors on two vertical ports and two 16-channel arrays on a horizontal port, can provide both active and passive charge exchange measurements. ssNPA detectors, with variable thickness of ultra thin tungsten dominated foils directly deposited on the front surface, are specially fabricated and utilized to achieve about 22 keV energy resolution for deuterium particle detection. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4886431]

I. INTRODUCTION

Compact solid state neutral particle analyzers with capabilities of ultra-fast temporal, spatial, and spectral resolution based on absolute extreme ultraviolet (AXUV) silicon photodiode[1] have been developed on the tokamaks DIII-D,[2] National Spherical Torus Experiment (NSTX[3,4]), and Alcator C-Mod,[5] as well as the large field reversed configuration (FRC[6]) facility.

ssNPA in traditional counting mode was initially tested on NSTX[3,4] and followed by C-Mod;[5] it provided good spatial resolution together with a coarse spectral resolution of about 10–20 keV. With the success of a DIII-D three-channel near-vertical-view current mode ssNPA,[2] the apertures on existing NSTX array were expanded to increase the particle influx and directly foil-deposited AXUV arrays were also employed for FRC neutral particle bolometry.[6]

ssNPA arrays operated in current mode on the DIII-D and NSTX tokamaks have typically 5 cm spatial resolution with both active and passive charge exchange (CX) measurement capability. Compared with conventional pulse-counting NPAs, current-mode operation sacrifices energy resolution to obtain economical, high-bandwidth, pitch-angle resolved measurements. Directly deposited ultra-thin foils on the DIII-D detector surface block stray photons below the energy of 1 keV and also set a low energy threshold of about 25 keV for deuterium particle detection. Oscillations in neutral flux produced by high frequency magnetohydrodynamics instabilities up to ∼150 kHz have been detected on DIII-D with this technique.

As an international extension and full-function integration, advanced ssNPA diagnostics making full use of intrinsic measurement capabilities have been developed and implemented on the EAST superconducting tokamak. In this article, the system design considerations are presented in Sec. II. Final setup and potential operational modes are shown in Sec. III. Present status and future plans are given in Sec. IV.

II. CONSIDERATIONS FOR SYSTEM DESIGN

A. EAST current status and EP's role

EAST, formerly known as HT-7U,[7] is the world's first non-circular cross-section full superconducting tokamak. Significant progress, on both the technological and physical fronts towards high-performance long-pulse plasma discharges, has been achieved in recent years.[8,9] Aggressive upgrade plans have been established and will enhance EAST operation and research capabilities drastically in the near future.

The tokamak, with major radius ∼1.85 m and minor radius ∼0.45 m, can provide an experiment platform up to 4 T toroidal field and 1.5 MA, 1000 s plasma current, for double null and single null divertor configuration with a variety of wall conditions, control, and a combination of auxiliary heating and current drive. The current 4 MW low hybrid current drive (LHCD) and 6 MW ion cyclotron resonant heating (ICRH) will be upgraded to 10 and 12 MW, respectively. For 2014 campaign, one 50–80 keV 4 MW neutral beam injection (NBI) system has been successfully bench-tested and ready for plasma experiment. Another 4 MW NBI and a new 4 MW electron cyclotron resonant heating (ECRH) systems are scheduled to be installed later this year.

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Measurement and experiment on energetic particle, both confined and lost part, are critical to the success of EAST. With ∼34 MW auxiliary heating and current drive capability, energetic particle population will be notably increased, as well as the occurrence of EP related instabilities, loss, and redistribution behavior. ssNPA with temporal, spatial, and energy resolution capabilities is ideal measurement technology to be implemented.

B. Primary design considerations

1. EAST physics requirements

Besides the fusion reactions, the location, spectrum, and their evolutions of ICRH energetic ion tail are of top interest. The new NBI system will provide the EP source as well as a probe for passive and active charge exchange measurement. With these in mind, a full-function integrated ssNPA diagnostic package, with the ability to cover a wide energy spectrum range while keeping the fast temporal and fine spatial resolution, for long pulse operation capability (>100 s) is desirable.

2. Relevant EAST engineering and operational realities

The complex superconducting environment and the facility operational realities are the main issues for the EAST ssNPA design. Typical factors and considerations are briefly listed in Table I.

It has proven extremely difficult to satisfy all of the design criteria in light of the restrictions summarized above. As a compromise, a system has been designed and implemented to get the most important data and experience from EAST 2014 campaign.

TABLE I. Typical EAST engineering and operational realities.

Facility engineering and operational realities	Considerations in ssNPA design
Long vacuum port (vertical ∼4 m, horizontal ∼1 m)	Limited access and blocking of view Accurate alignment and calibration In-vacuum electronics to minimize noise
Very limited usable ports	Port sharing, diagnostic view interference, require compact design
Closed tile on dome zone	Specific small hole punch through tungsten tile
Vacuum baking up to 250 °C	Material selection and active detector cooling
Boronization, lithium evaporation and during-shot wall coating	Shutter, instant on/off capability
ICRH energetic tail	Resonance layer, boundary view-chord required, pulse height analysis
NBI and its future upgrade	Active and passive CX measurement Current mode
X and gamma rays	Need to be effectively blocked/subtracted
Background subtraction	Beam modulation Reference channel
Long pulse plasmas	Dedicated data acquisition
Upgrade of nearly every-subsystem before 2014 campaign	Limited time and engineering support available
Future facility upgrade	Economical and flexible ssNPA, potential extension/upgrade

III. FINAL SETUP AND OPERATION MODES

A. ssNPA detector design

Detectors and filter material are carefully selected, based on DIII-D experience,[2] SRIM code[10] simulations, and X-ray data.[11] With similar foil deposition techniques as in Refs. 2 and 6, a new package of special AXUV detectors (AXUV20HS1 and AXUV16ELG) with ultra-thin Tungsten (W) foil directly deposited on the detector entrance-window has been designed and fabricated.

Detectors with W dominated foil of thickness 100, 200, 300, and 400 nm provide the low detection threshold for deuterium around 22.0, 45.6, 70.3, and 96.0 keV. As a heavy element metal, these W foils will block X-ray below 0.87, 2.55, 3.15, and 3.55 keV. Deuterium, hydrogen, and helium's projected ranges in W and aluminium (Al) are shown in Figure 1(a), while X-ray attenuation lengths are compared in Figure 1(b). It is obvious that W is superior to a light material such as Al when the ssNPA filter must operate in a harsh X-ray background, e.g., wave heating plasmas. The neutron damage and surface contamination on silicon photodiodes require that regular detectors' change is necessary at least every other year.

B. Horizontal ssNPA arrays

Figure 2 illustrates the top view of the EAST torus, including two horizontal ssNPA arrays with 100 nm W filtered AXUV16ELG and their fields of view, the first and second NBI beam-lines, and the B-up port location for one of the vertical ssNPA groups. One of the two arrays will benefit from the NBI for active CX measurement, while the other one with an opposite view faces clockwise for passive CX.

An UHV compatible linear motion feedthrough with 12 inch maximum axial travel capability is employed for accurate detector positioning. During extreme wall-conditioning

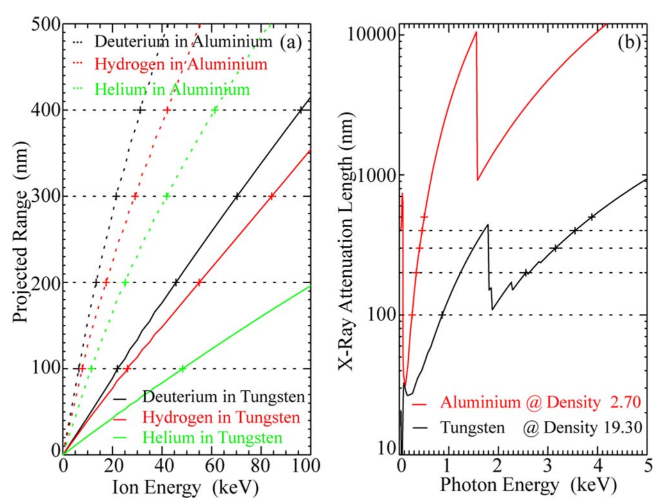

FIG. 1. Ion projected range from SRIM calculation (a) and X-ray transmission length (b) in tungsten (W) and aluminium (Al) foil.

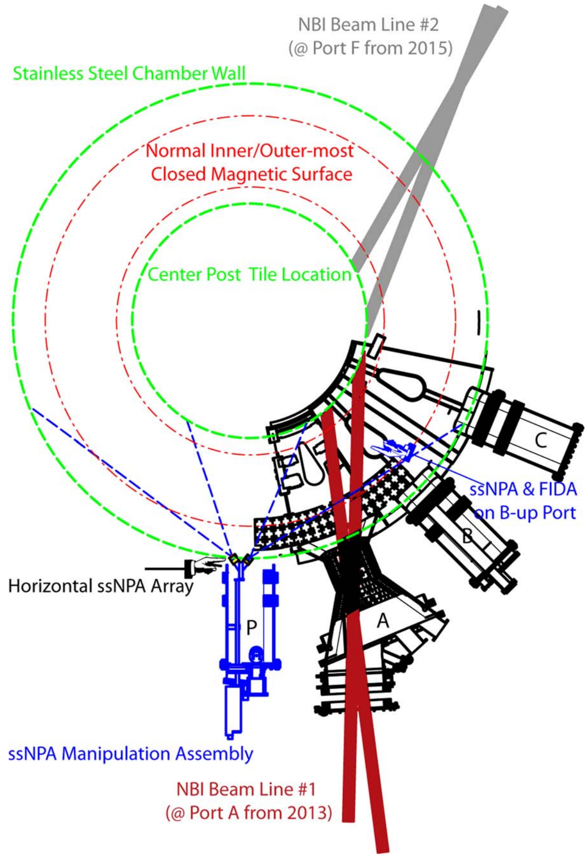

FIG. 2. NBI footprint locations and ssNPA field of view.

such as vacuum baking and intensive lithium-powder dropping, the detector will be actively retracted from harsh place. For considerations of safety and space saving, shutter and active cooling components are skipped temporarily.

C. Group of vertical ssNPA single detectors

Individual AXUV20HS1 detectors (unfiltered and filtered with 100/200/300/400 nm W) are selected for two groups of vertical ssNPAs, partly because of the extremely limited access from long vertical port, narrow space shared with fast ion Dα (FIDA)[12] and resonant magnetic perturbation (RMP) coil leads, and the newly installed W tiles in upper diverter region.

As shown in Figure 3, 5 channels on B-up port intersect with the beam footprint, while 4 nearby channels and 7 channels on N-up port miss the beam. Sixteen pieces of 0.5 m long stainless steel guiding tube together with collimation apertures on both ends are equipped. Flexible combination of these channels with different foil-deposited detectors will simultaneously provide fast temporal, fine spatial, and coarse spectrum resolution of EP information for NBI (both active and passive CX) as well as ICRH plasmas.

D. Operational modes considerations

All channels (except two mentioned below) will be operated in advanced current mode, for fast time resolution measurement by employing EAST general fast data acquisition

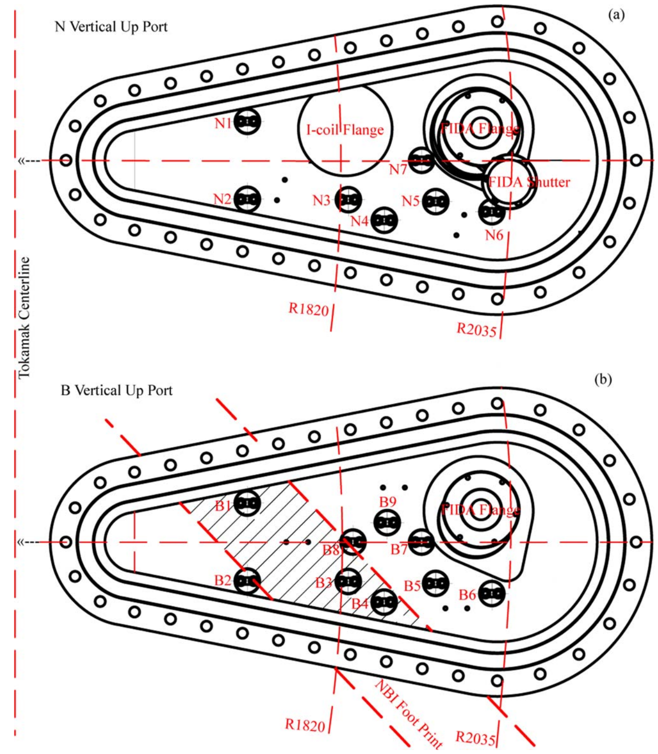

FIG. 3. Locations of individual vertical ssNPA detectors.

system at sampling rate of 250–500 kHz. Two vertical channels with 10 μm collimation aperture and 100 nm W-filtered detectors can be used for up to MeV ICRF energetic ion tails study by conventional counting mode. Both hardware and software pulse height analysis (PHA) methods will be applied. The spectrum from PHA in counting mode will be cross-checked with spectrum obtained from different filters in current mode.

Background subtraction for active CX channels can be achieved by (1) NBI beam modulation and (2) detection of the signals from reference channels at similar radial location. The efficiency of method (2) on horizontal ssNPA arrays will be studied.

IV. PRESENT STATUS AND FUTURE PLAN

The recent EAST upgrades open up a whole new range of opportunities for interesting EP experiments. The new integrated ssNPA systems on EAST are evolving based on the experiences gained through the successful implementation of their predecessors, with some considerations on EAST specific stricter engineering realities and physics requirements.

At the time of writing, all detectors and relevant in-vessel components have been successfully fabricated and installed in EAST. Fields of view and collimation have been briefly tested and 5 commercial transimpedance amplifiers are ready. Upon the completion of other specifically designed amplifiers fabrication and benchtest,[13] cable routing and data acquisition (DAQ) system hookup, this integrated ssNPA package will enter its commissioning phase on EAST 2014 campaign, undergo a series of *in situ* tests and valuable data are expected thereafter.

For system performance improvement, there are a few challenges lie ahead, e.g., a dedicated DAQ system is scheduled for 100 s scale data acquisition at ∼500 kHz sampling rate; a better solution needs to be devised for detector protection from heat and contamination.

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[1] See http://optodiode.com/products.html#IRD-UV-Photodiodes for more information about AXUV silicon photodiode.

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