accepted for Vacuum **83**, No. 0, 1 – 6 (2009) / **DOI** 10.1016/j.vacuum.2008.05.020

Comparison of the Ioffe neutral particle analyser with the Princeton analyser on the Mega Amp Spherical Tokamak

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Received 14 December 2007, revised 11 March 2008, accepted 13 March 2008

Key words Fusion plasma, Ion temperature, MAST, Neutral particle analyser

Abstract Charge exchange-neutral particle analysis (CX-NPA) will be applied for determining the ion temperature in the stellarator Wendelstein 7-X (W7-X), which is under construction, now, at the Max-Planck-Institute of Plasma Physics Greifswald, Germany. Three ACORD-type analysers and one compact analyser (CNPA) are foreseen for the active NPA diagnostics at W7-X, i.e. NPA in combination with a 60 keV neutral beam injector, thus enabling locally resolved CX-NPA measurements. For an intermediate period the CNPA is now installed on the Mega Amp Spherical Tokamak (MAST) in Culham Science Centre, UK. The arrangement of the CNPA on MAST and results of energy spectra of plasma ions in MAST are presented. They are in a good agreement with measurements by the Princeton particle analyser.

1 Introduction

The experimental set-up for the measurement of charge-exchange hydrogen atoms emitted from a tokamak or stellarator plasma is mainly influenced by the residual magnetic stray field at the local position of the energy analyser and by the spatial conditions. The latter often may require the application of small-sized analysers such as the considered Compact Analyser for Neutral Particle Diagnostics (CNPA). That is of about half the size compared to the 24 channel E||B analyser of type ACORD-24. Both analyser types have been developed by the IOFFE Physico-Technical Institute of the Russian Academy of Sciences, St. Petersburg (IOFFE Institute). Because of the interruption of operation between the shut down of the stellarator W7-AS in the Max-Planck-Institute for Plasma Physics Garching and the start of the stellarator W7-X in the Institute for Plasma Physics in Greifswald, the CNPA has been installed at the Mega Amp Spherical Tokamak in the meantime. Prospective applications of CNPA enable a set-up of multi-chord analysers with locally higher resolved measurements of the ion temperatures of core and edge plasmas by using smaller analyser and therefore a larger number of them. In the short period of application of the CNPA analyser on the stellarator Wendelstein 7-AS in 2002 a comparison of the properties of this CNPA with those of the well approved ACORD-type analyser could not completely be carried out. Therefore, the CNPA was tested on MAST, now, with the intention of comparing its results with those of the Princeton analyser installed on MAST for several years. The CNPA in combination with three ACORD-type analyser is foreseen for measuring the core and edge plasma temperatures in W7-X simultaneously at four positions. Furthermore, future CNPA, using a thin diamond-like foil for stripping of hydrogen atoms, are intended to replace successively conventional ACORD analyser with stripping in nitrogen gas cells. A step by step replacement of the ACORD analyser gives the possibility to increase the number of analyser in the NPA set-up from 4 to 7 analyser, which increases the local resolution of ion temperature profiles.

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2 Experimental conditions at MAST and W7-X

A number of features at MAST and W7-X are expected to be similar, e.g., the residual magnetic stray fields are of the same order of magnitude in both devices. At present, at MAST the influence of neutrons on the neutral particle analyser (NPA) is less by one order of magnitude. But, after upgrading and operating with increased beam heating power the influence of neutrons will be comparable to the expected values of W7-X (about 10^{15} neutrons/s). The ion temperatures in the core plasma of W7-X are expected to reach 5 - 10 keV, those of MAST up to about 2 keV. The positions of the Princeton analyser, of the CNPA on MAST and their lines of sight are shown in Fig. 1. The distance of the CNPA to the MAST vessel was short (≈ 0.5 m). Thus, the analyser was located in an area with rather strong magnetic stray field of about 20 mT. However, the Hall probe measurements performed during MAST operation showed that the value of magnetic induction inside the CNPA is negligible and the analyser was able to operate without additional magnetic shield. The functional principles of the Princeton analyser are explained in Ref. [1]. A schematic drawing of the CNPA is shown in Fig. 2. Details are published in Ref. [2]. The CNPA was designed to measure the absolute energy distribution of H and D neutral fluxes emitted by plasma in the energy range 0.8 - 80 keV (H) and 0.8 - 40 keV (D). The fluxes are measured simultaneously, with a mass-rejection $\geq 10^3$. The specific features of the CNPA are:

(a) stripping off the neutrals by use of thin (100) diamond-like carbon (DLC) foil,
(b) acceleration (+ 5 kV) of the secondary ions after stripping,
(c) $E \| B$ analysis of the ions in non-uniform E and B fields, providing two-dimensional focusing,
(d) using of strong NdFeB permanent magnets instead of the conventional electromagnets.

The CNPA is further characterised by a small weight, low dimensions and lower requirements to the pumping system.

3 First experiments of CNPA at MAST

The very first experiments with the CNPA on MAST showed that the high pressure between the tokamak wall and the plasma boundary does not permit to run the analyser without an additional pumping system of its own. Fig.3 shows the correlation between the noise in one of the CNPA channels and the signal of fast ion gauge during the MAST plasma discharge. It seems that the gas inflow from the plasma in the MAST device during the operation was at a very high level, which excites the noise (≈ 0.5 kHz) in CNPA channels. During the CNPA commissioning the noise caused by gas inflow was eliminated by pumping of the CNPA during MAST operation.

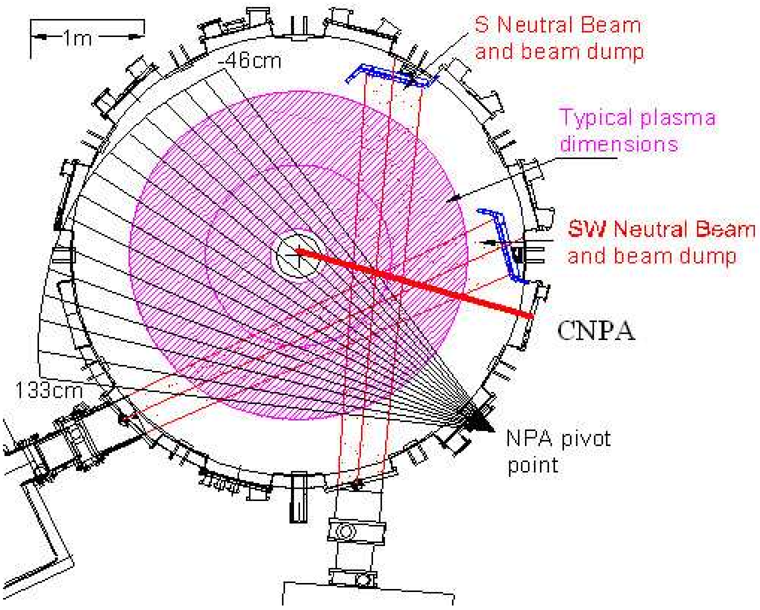

Fig. 1 Diagram of the set-up of the CNPA at MAST.

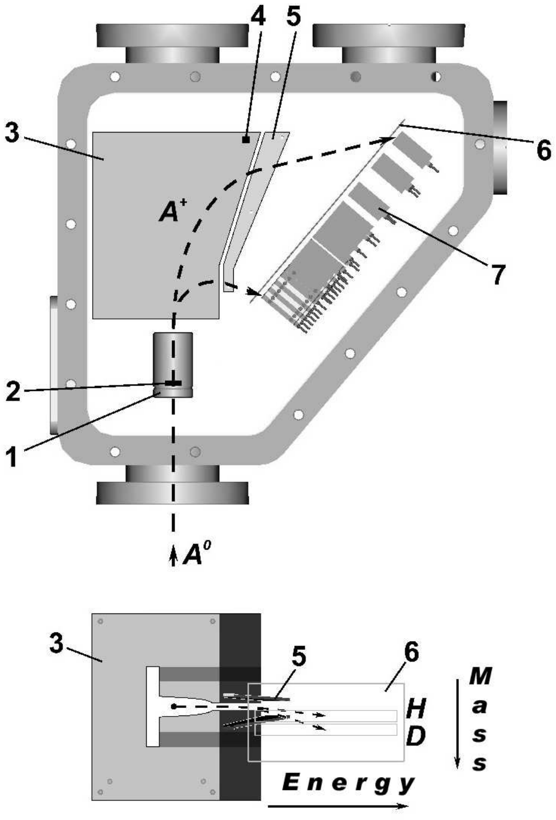

Fig. 2 Diagram of the compact neutral particle analyser: 1 – stripping/acceleration unit, 2 - DLC stripping foil, 3 – analysing magnet, 4 – Hall probe, 5 – analysing electrostatic condenser, 6 - shielding mask at the entrance to the detector array, 7 – detectors.

Since the CNPA was installed close to the plasma device without any neutron shielding, a test of the influence of neutron irradiation on analyser detectors was performed. Fig.3 shows that the level of the counting rate of the detectors caused by neutron flux was about 20 kHz when the total neutron yield of MAST was $\approx$ 7x10^{13} neutrons/s. At the same time the level of neutron noise induced in the Princeton NPA is also about 20 kHz though the CNPA was closer to the MAST-torus. This is probably due to the close positional relationship of the analysers and the neutral beam injectors.

As seen from Fig.4, the particle signal at thermal energies (E $\approx$ 1.7 keV) is weak and the CNPA channel represents generally the neutron induced noise. The Signal-to-Noise (s/n) ratio reaches a maximal value of $\approx$ 0.5 at the middle of Neutral Beam Injection (NBI) phase and the extraction of particle signal from the total signal seems to be problematic. On the other hand the signal of slowing down beam-particles is high at high energies (E $\approx$ 28 keV). The s/n-ratio is about 5 - 10 and neutron noise can be neglected in the total signal. Later on, the problem of weak particle signals at thermal energies was partly solved by the enlargement of the CNPA aperture, which increased the s/n-ratio by factor of 4.

The first experiments with the CNPA at MAST were carried out with deuterium injection into a deuterium plasma.

4 Comparison to the Princeton Analyser

After the commissioning of the CNPA at MAST a cross test of CNPA and the Princeton NPA was performed. The results of this test are shown in Fig.5 and Fig. 6. The comparison of counting rates of CNPA and the Princeton NPA rates is shown in Fig. 5. The Princeton NPA was working in a special gated regime [3], which permitted to measure the neutron induced noise between the gates. As can be seen the level of the counting rate and its behavior are similar for both analyser. The charge exchange spectra (CX-spectra) obtained during NBI by both

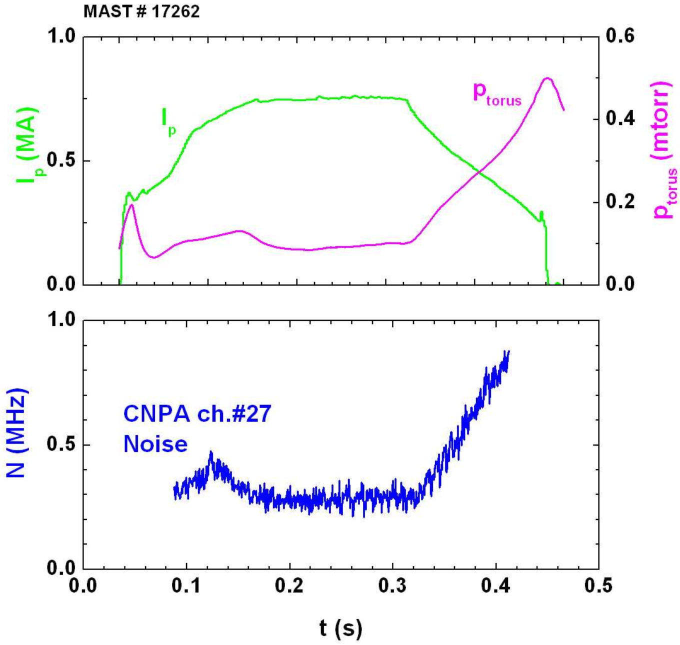

Fig. 3 Operation of CNPA without additional pumping system. The noise in analyser channels is caused by gas inflow from MAST-plasma. I_p - plasma current. p_{torus} - pressure near MAST wall. N - noise in CNPA detector.

instruments are shown in Fig.6. This comparison shows a satisfactory agreement between the CNPA and the Princeton NPA data at thermal energies (0 – 2 x 10^4 eV) as well as at high energies (above 2 x 10^4 eV). In Fig.7

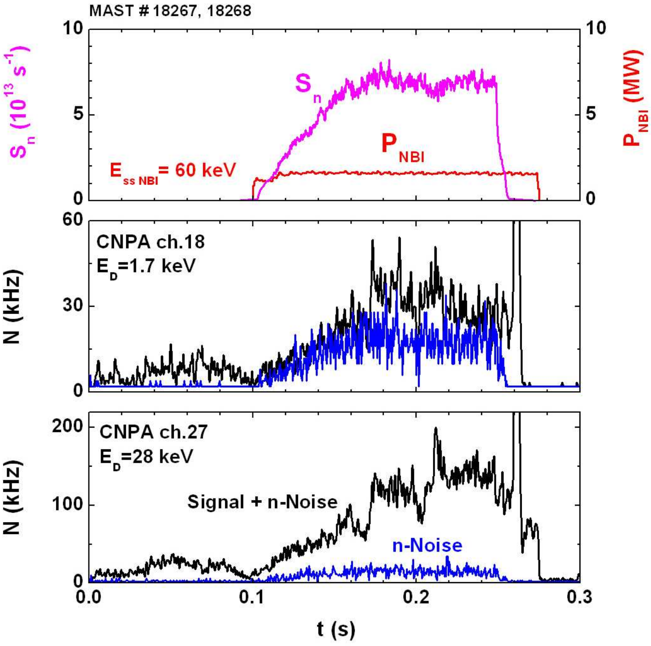

Fig. 4 Influence of neutron irradiation on CNPA detectors. S_n - tokamak total neutron yield. P_{NBI} - neutral beam power. N - counting rate of CNPA detectors. Blue lines – neutron induced noise. Black lines - total signal (neutron induced noise together with CX particle signal).

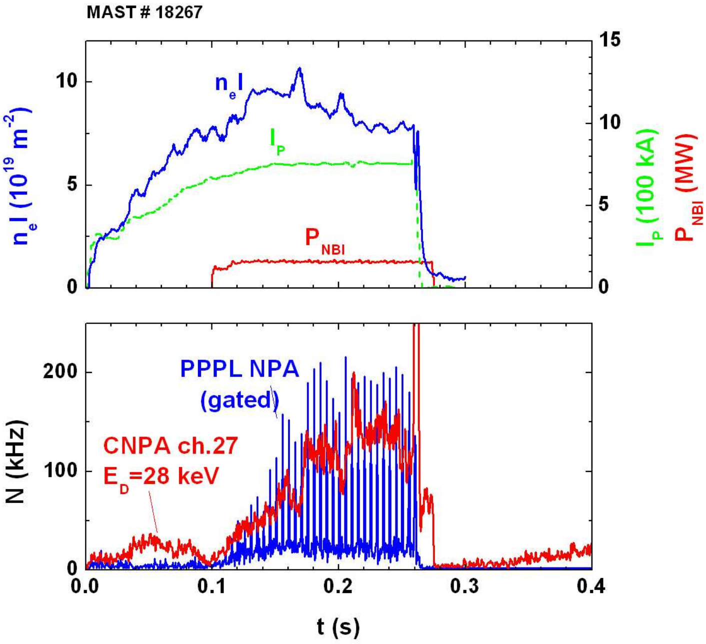

Fig. 5 The comparison of CNPA and Princeton NPA channel counting rates during NBI experiment on MAST. The Princeton NPA was operated in a gated regime permitted to measure the neutron induced noise between the gates. n_{el} - electron line density. I_P - plasma current. P_{NBI} - neutral beam power. N - counting rates of CNPA and Princeton NPA detectors.

the decay of the hydrogen flux in dependence on the energy for a NBI heated MAST discharge is shown. The evaluation of the slope in the thermal range from about 0.6 keV up to 5 keV yields an ion temperature of about 800 eV for the discharge 18696 at 200 ms after igniting the MAST discharge.

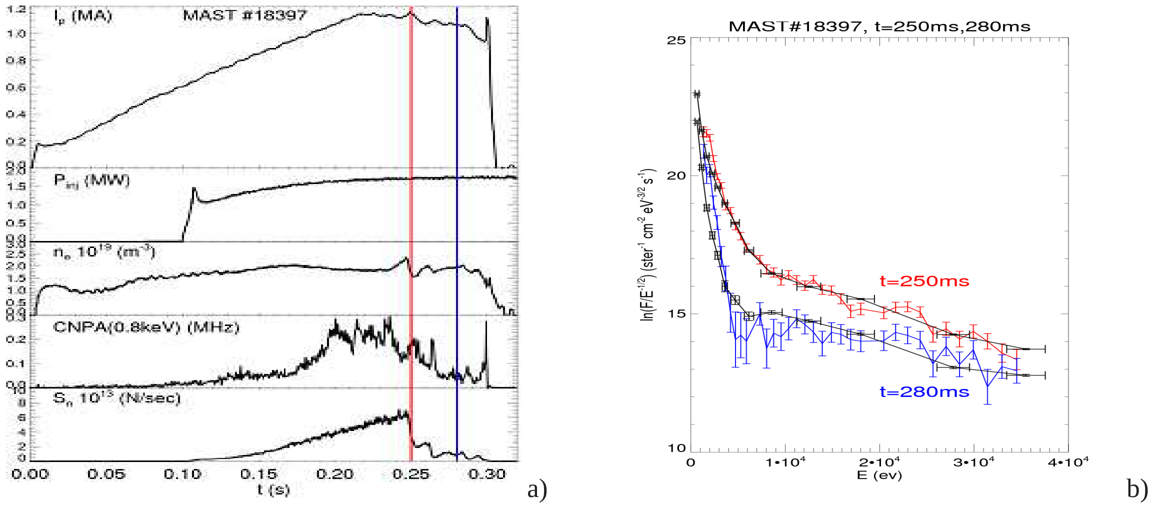

Fig. 6 Cross-calibration test of CNPA and Princeton NPA during NBI experiment on MAST. **a)** Plasma parameter traces: I_P - plasma current, P_{NBI} - neutral beam power, n_{el} - electron line density, S_N - total neutron yield. **b)** NPA charge exchange spectra of Deuterium atoms measured with the CNPA (black) and the Princeton NPA (red and blue for t=250 ms and t=280ms, respectively).

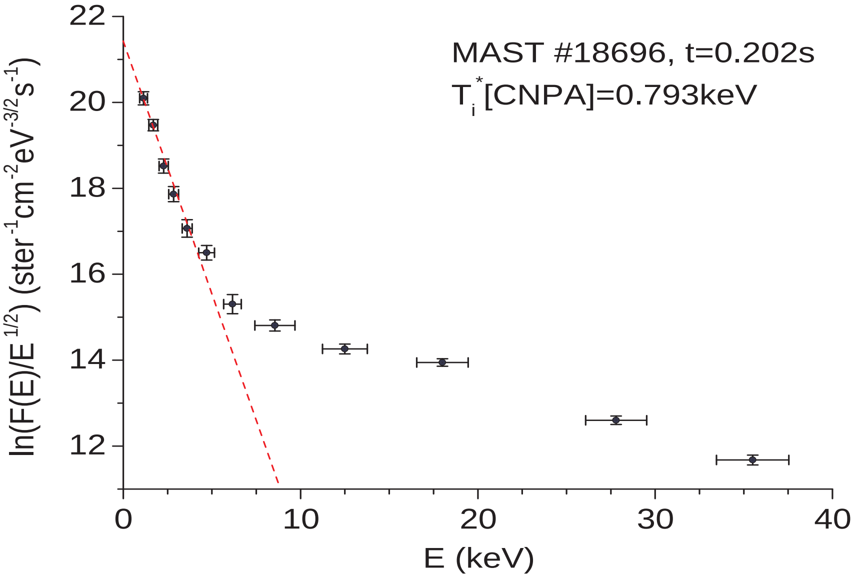

Fig. 7 Decay of hydrogen flux with the energy for a NBI heated MAST discharge. Fluxes at energies above 5 keV result from the slowing down spectrum of particles injected by NBI.

5 Conclusions

First results of the compact neutral particle energy analyser CNPA show promising results with respect to further applications on ion diagnostics of core and edge plasmas of MAST. They are in a good agreement with results of the Princeton analyser. In order to improve the signal/noise relation, the CNPA should be separated from the MAST vacuum chamber and should be permanently pumped by its own. A systematic study of CNPA properties and its comparison with results of charge exchange recombination spectroscopy will be done in the near future.

6 Acknowledgements

The authors thank the MAST Team for providing the plasma and supporting the NPA diagnostics. The work was partly founded by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities.

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