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First Measurements of High-Energy Charge-Exchange Neutrals Using Compact Neutral Particle Analyser in TJ-II Stellarator

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Compact Neutral Particle Analyzer

A Compact Neutral Particle Analyser (CNPA) [1], developed by the A. F. Ioffe Physical-Technical Institute, has been installed on TJ-II. The TJ-II is a 4-period, low magnetic shear, stellarator device with average minor radius ≤0.22 m and major radius of 1.5 m that was designed for exploring a wide range of magnetic configurations [2]. To date, central electron densities and temperatures up to 1.7×10^{19} m^{-3} and 2 keV respectively have been achieved in plasmas created and maintained by electron cyclotron resonance heating (ECRH) (f=53.2 GHz tuned to 2nd harmonic, P_{ECRH} ≤600 kW, X-mode polarization). Recently, operation has commenced on one of two neutral beam injectors (NBI) each of which will produce ≤300 ms pulses of neutral hydrogen accelerated to ≤40 keV to provide up to 1.2 MW of additional heating.

The CNPA is an energy and mass spectrometer of reduced size. Significant reductions in the spectrometer size and weight were achieved by replacing the standard stripping chamber (where incoming neutrals are stripped using gas) with a 50 Å diamond-like carbon foil, and by using a permanent high-field NdFeB magnet, rather than traditional electromagnets, to generate the required analysing magnetic fields. This CNPA was specially designed for the TJ-II for studying, in the energy range 0.95 to 43 keV (16 energy channels), the high-energy tails in the distribution function of escaped NBI H^0 atoms. It is now

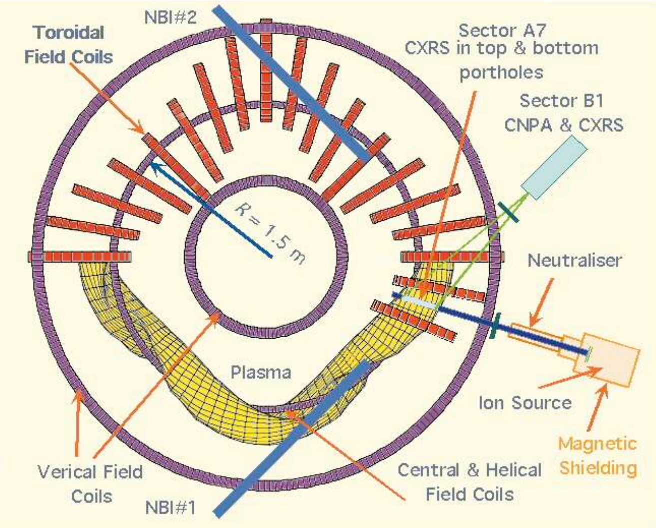

Figure 1. Schematic view of the TJ-II with both NBI injectors indicated (only NBI#1 is currently in operation). The positions of the CNPA and the DNBI are shown.

installed in a tangential viewing porthole so that its line-of-sight, which is almost tangential to the magnetic axis, also traverses the beam path of a recently installed diagnostic neutral beam injector [3]. See Fig. 1.

The CNPA was designed with the standard E||B set-up. Neutrals born in the plasma as a consequence of charge-exchange interactions involving protons and neutrals can escape without undergoing further interactions and may reach the carbon stripping foil of the CNPA where they are ionised. These ions then pass an accelerator where they are focussed and accelerated before entering the permanent magnet region. In this section they are deviated in proportion to their momentum. Next, they pass through the analysing condenser, located at the magnet exit. In this way only ions can reach the detectors and background light is blocked. Finally, the particles are collected in 16 different channeltrons (by Dr. Sjuts Optotechnik GmbH, Goettingen, Germany) where each channeltron corresponds to a specific energy range. These channeltrons have a maximum detection rate of 1 MHz. In addition, the analyser is absolutely calibrated, so absolute fluxes can be deduced from the analyser. Note: the detection efficiency of these 16 channeltrons varies with incident ion from $3.43 \cdot 10^{-4}$ to 0.125 for the energy range covered while the width $\Delta E/E$ of the channel windows changes from 57% to 6.5%.

Electronics and Data Acquisition System

The CNPA installed in TJ-II is equipped with a specially developed electronics system consisting of two individual modules (190 × 190 × 70 mm in size). The first (a HV module) supplies the voltages needed for the acceleration and deflection systems. It is also used as an interface for the Hall probe connection. This module is based on three HV blocks (by Spellman Co., type MM10P1.5/24/S) and provides +5.0 kV to the accelerator and ±5.0 kV to the analysing condenser. Finally, the channeltron detectors have a 2.5 kV high voltage supply.

The second module (a Control Module) is designed to detect the preliminary processed signals from the channeltron outputs, as well as to store and transmit data from the 16 counting channels. The accumulation of the data produced by the counting channels is performed in time intervals that are identical to those generated by a built-in time generator. The data collected is transferred to a personal computer using an Ethernet channel. Each counting channel contains two 16-bit counters, one of which is operating in a storage regime, while simultaneously the second one is operating in data output mode. Hence, by changing the time window (from 8.68 μs to 0.569 s) the system dead-time can be set to zero. Finally, there are two window modes. Now, in the case of storage fill in an internal buffer memory (64 kb), 2048 time-windows are available while in the regime of continuous storage-data to the external Ethernet channel, 65535 time-windows are available. The maximum frequency of input signals is 30 MHz.

Experimental results

The main purpose of the TJ-II CNPA is to study the behaviour of NBI ions. For this the analyser was installed in a tangential port that faces one of the NBI injectors (Fig. 1). It is mounted on a support structure that permits scans of the plasma to be made in both the vertical and horizontal directions. Also, the CNPA does not require its own high-vacuum pumping system (as there is no gas sources in the analyzer) and is directly coupled to the TJ-II vacuum chamber using flexible bellows.

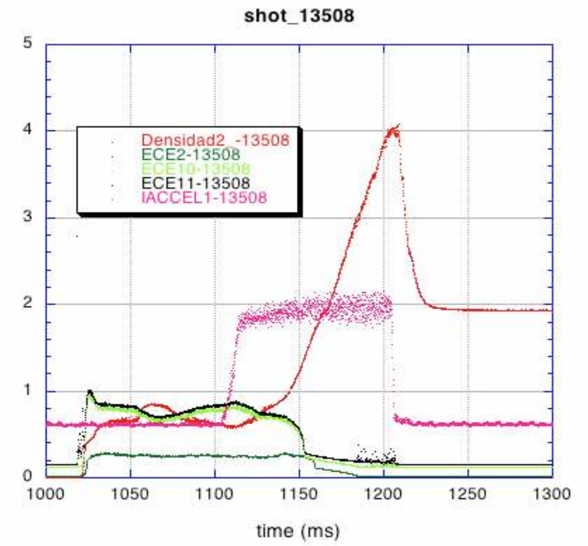

Figure 2. Plasma parameters along shot #13508 showing the temporal behavior of density (Densidad2, in $10^{19}m^{-3}$), central ECE channels (ECE10 and ECE11, in keV), a periphery ECE channel (ECE2, in keV) and NBI injection (IACCEL1, a.u.). Gyrotrons heating occurs all along the discharge.

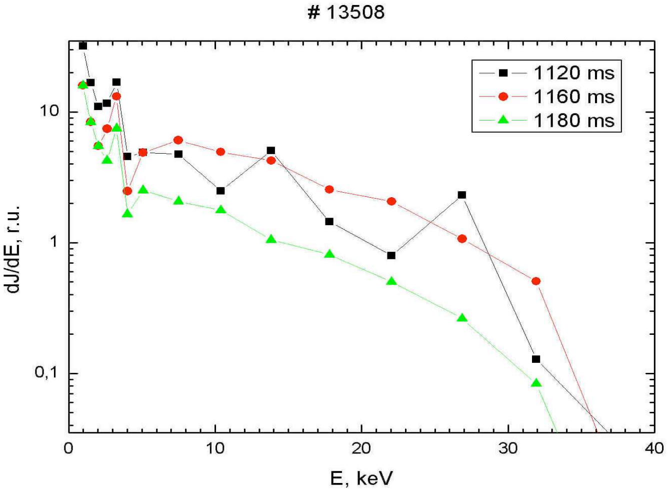

Figure 3: The energy spectra of detected escaping NBI H^0 particles for three different time intervals during discharge #13508.

Plasmas in the TJ-II were created and maintained using two 200 kW gyrotrons. During the NBI heating experiments plasmas were created in hydrogen and heating H^0 neutrals were injected at 28 keV. Figure 2 shows the temporal evolution of selected plasma parameters during these experiments: *i.e.*, NBI current, electron density (n_e) and temperature (T_e). Next, spectra of detected high-energy neutrals are plotted in Fig. 3 for three different time interval during a single TJ-II discharge: the first time interval corresponds to the start of the NBI pulse, the second to 30 ms after the NBI start and the third to the end of the NBI pulse. It should be noted that at the start of the NBI injection there exist peaks in the channels corresponding to the beam energy (28 keV) and half-energy (14 keV). The following time interval (1160 ms) corresponds to a period when the plasma electron density is increasing while the electron temperature is decreasing (see Fig. 2). In this interval the slowing down time of the ions is approximately two orders of magnitude lower than that at the start of NBI injection. The fast ion slowing down time is calculated here using (see ref. [5]),

$$\tau_{sd} = 6.3 \cdot 10^{14} \frac{A_f T_e^{1.5}}{Z_f^2 n_e \ln \Lambda_e}, \qquad (1)$$

where A_f is ion atomic weight, T_e is electron temperature (in eV), n_e is electron density (in m^{-3}), $ln\Lambda_e$ is the Coulomb logarithm, and Z_f is ion charge. The third period corresponds to an interval when the density is near its maximum for this discharge and the electron temperature has fallen further. In this interval the absolute ion spectrum is reduced at all energies as the plasma encountered by the ions is colder and the charge-exchange reactions become less probable.

Conclusions

A new dedicated Compact Neutral Particle Analyser has been installed on the TJ-II device. This diagnostic is devoted to study the high-energy tails during Neutral Beam Injection heating. The first measurements obtained with this diagnostic have been presented and they reveal that the energy spectra of escaping NBI particles are different at the start and end of NBI discharges. At the start of such heating pulses the two peaks are seen in the spectra. These correspond to the full and half energies of the injected NBI neutrals. As the discharge continues, these peaks disappear due to an increase in the number of slowed ions and a straight line fit can be made to the energy logarithmic spectrum. This might indicate a change in the slowing down time during NBI pulses.

Acknowledgements

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[1] F.V. Chernyshev et al. 30th EPS Conference on Contr. Fus. And Plasma Phys. Vol. **27A** (2003) P-4.71 and F.V. Chernyshev et al. Instruments and Experimental Techniques, **47**, 2, 2004, 214-220

[2] E. Ascasibar *et al.*, Fusion Eng. Des. **56-57** (2001) 145.

[3] K.J. McCarthy *et al.*, Rev. Sci. Instrum. **75** (2004) 3499.

[4] M. Liniers et al. Proc. 31st EPS Conference on Contr. Fus. And Plasma Phys. Vol. **28G** (ECA) (Mulhoulse EPS) P4-183 (2004)

[5] R. Koch Fusion Science and Technology **45(2T)** (2004) 183