PROCEEDINGS OF SCIENCE

First results from the Neutral Particle Analyzer on the COMPASS tokamak

K. Mitosinkova[1]
Institute of plasma physics ASCR, Department of Surface and Plasma Science Charles University
Prague, Czech Republic
E-mail: `mitosinkova@ipp.cas.cz`

A. Melnik
Ioffe Institute
St. Petersburg, Russia
E-mail: `another.author@pos.it`

M. Tomes
Institute of plasma physics ASCR, Department of Surface and Plasma Science Charles University
Prague, Czech Republic
E-mail: `tomes@ipp.cas.cz`

J. Stöckel
Institute of plasma physics ASCR
Prague, Czech Republic
E-mail: `stockel@ipp.cas.cz`

F. Janky
Institute of plasma physics ASCR, Department of Surface and Plasma Science Charles University
Prague, Czech Republic
E-mail: filip.`janky.work@gmail.com`

M. Komm
Institute of plasma physics ASCR
Prague, Czech Republic
E-mail: `komm@ipp.cas.cz`

M. Imrisek
Institute of plasma physics ASCR, Department of Surface and Plasma Science Charles University
Prague, Czech Republic
E-mail: `imrisek@ipp.cas.cz`

PoS(ECPD2015)074

---

[1] Speaker

P. Hacek
Institute of plasma physics ASCR, Department of Surface and Plasma Science Charles University Prague, Czech Republic
E-mail: `phacek@ipp.cas.cz`

J. Varju
Institute of plasma physics ASCR, Department of Surface and Plasma Science Charles University Prague, Czech Republic
E-mail: `varju@ipp.cas.cz`

V. Weinzettl
Institute of plasma physics ASCR, Department of Surface and Plasma Science Charles University Prague, Czech Republic
E-mail: `vwei@ipp.cas.cz`

The Neutral Particle Analyzer (NPA) for the COMPASS tokamak was recently upgraded and absolutely calibrated in the Ioffe Institute, St. Petersburg. NPA allows simultaneous measurements of the energy spectra of fast hydrogen and deuterium atoms and determination of the ion temperature. Energy spectra of the neutral fluxes are measured by NPA in Ohmic as well as in the NBI heated plasmas. The measured ion temperature in L-mode plasmas varies in the range of 300-500 eV. After the L-H transition, the ion temperature increases by $\Delta T_i \approx 250$ eV. A relatively high temporal resolution of the NPA data acquisition system allows study of fast transient phenomena, such as the Edge Localized Mode and sawtooth oscillation.

Comparative measurement of T_i in the plasma core given by NPA and at the plasma edge using Retarding Field Analyzer is also reported.

First EPs Conference on Plasma Diagnostics - 1st ECPD
14-17 April 2015,
Villa Mondragone , Frascati (Rome) Italy

Introduction

Passive analysis of energy spectra of charge exchange neutral atoms escaping from plasma has been applied to measure the ion temperature since early phase of the tokamak research [1]. Nowadays, this diagnostic technique is exploited worldwide. The COMPASS tokamak was recently equipped with the Neutral Particle Analyzer (NPA), ACORD-24, which was developed and absolutely calibrated in the Ioffe Institute St. Petersburg [2]. The analyzer has 24 energy channels for simultaneous measurement of energy spectra of fast hydrogen and deuterium atoms (each measured by 12 energy channels).

This paper describes main principle of NPA, and its arrangement on the COMPASS tokamak. Temporal evolution of the central ion temperature during L and H-mode discharges is reported. By exploiting a relatively fast temporal resolution of the ACORD-24 and its data acquisition system (50 – 1000 μs), we present first measurements of transient phenomena observed on the COMPASS tokamak: decay time of fast ions generated by the Neutral Beam Injection (NBI) and temporal evolution of fast neutral flux during Edge Localized Modes (ELMs) and sawtooth instabilities. During selected L-mode discharges, the ion temperature was also directly measured at the plasma edge by the Retarding Field Analyzer (RFA) and compared with NPA data.

Principles of measurements with NPA

NPA measures the energy spectrum of the flux of fast neutral atoms escaping from plasma. The ion temperature can be deduced from the obtained energy spectra thanks to the fact that detected neutrals are born from plasma ions due to CX process without significant changes of their energy.

The analyzer ACORD-24 is schematically depicted in Figure 1.

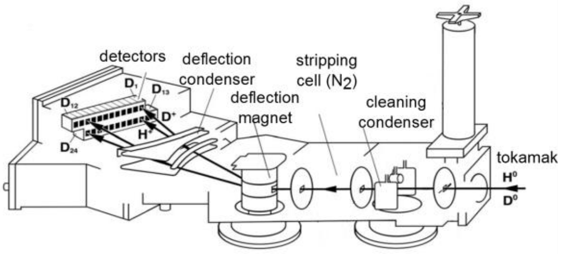

Figure 1: Scheme of the ACORD-24 [2].

The entrance slit of NPA selects a narrow flux of particles escaping the tokamak vessel. Any charged particles are removed from this collimated flow by the cleaning condenser. The beam of neutrals is then ionized by stripping collisions in a chamber filled by nitrogen up to $p \approx 5 \times 10^{-2}$ Pa. The resulting secondary ions are sorted according to their momentum and energy in the magnetic and electric fields. The ions are detected by two rows of 12 channeltrons operating in the counting regime. The available temporal resolution of the counter is from 50 up to 1000 μs. The energy range of the analyzer can be set from 0.25 keV up to 70 keV for hydrogen and from 0.3 keV up to 50 keV for deuterium atoms.

Experimental results

Presented data have been obtained during several experimental campaigns on the COMPASS tokamak ($R = 0.56$ m, $a = 0.2$ m, $B_T = 1\text{-}2.1$ T, $I_p < 400$ kA, and the pulse length up to 0.5 s) [3]. Measurements with NPA discussed in this contribution were performed with D-shaped deuterim plasmas. COMPASS is equipped with two Neutral Beam Injectors (NBI) for additional plasma heating. The deuterium beam energy is E_{NBI} = 40 keV and the beam power $P_{NBI} = 2 \times 300$ kW. Experimental set up is depicted in Figure 2.

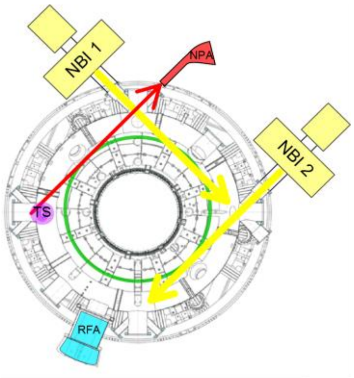

Figure 2: The COMPASS tokamak as seen from the top. Toroidal position of the ACORD-24 (red), two Neutral beam injectors (yellow), the Retarding Field Analyzer (blue) and Thomson scattering system (pink) are marked.

The line-of-sight of the neutral particle analyzer is oriented tangentially to the central circumference defined by the major radius. The retarding field analyzer measures the radial profiles of the ion temperature in the scrape of layer. The electron temperature profile is measured by High – resolution Thomson scattering system [4].

Figure 3 shows an example of a recorded energy spectrum of the neutral flux.

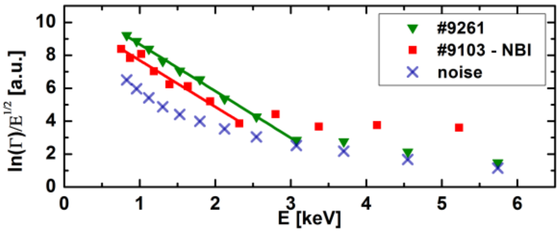

Figure 3: Energy spectra of the neutral flux in deuterium plasmas in Ohmic (#9261) and NBI heated discharges (#9103). Formation of the high energy tail of the spectrum (NBI heated discharge - red symbols) is apparent.

The ion temperature is usually determined from the slope of the spectrum in the energy range of ~ 0.7 – 3 keV, i.e. in the energy range 2 – 7 times higher than the expected ion temperature. In ohmic discharges, the energy spectrum tail (E > 3 keV) is just slightly above the instrumental noise, and therefore not interpreted.

At sufficiently low plasma densities ($n_e < 3 \times 10^{19}$ m^{-3}), the measured slope corresponds to the central ion temperature. With increasing plasma density, the plasma transparency for neutral particles drops. The measured T_i then corresponds to region exterior of the plasma center. Corrections of this phenomenon can be performed only by numerical simulations. At present, such simulations were performed by using the numerical code DOUBLE [5] just assuming parabolic profiles of the electron density and temperature. Figure 4 shows result of these numerical simulations.

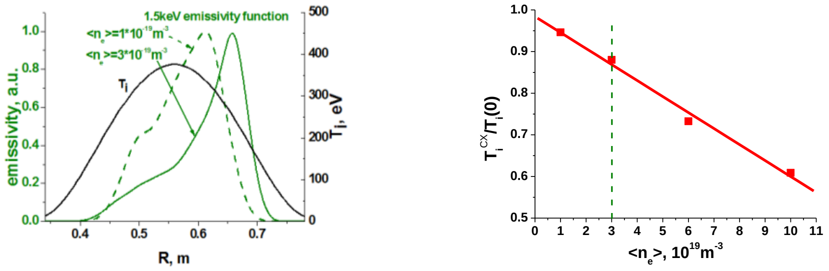

Figure 4: Left - the emissivity function of fast neutrals (E = 1.5 keV) at two values of the line average density. Right – the correction factor versus the line average density.

It is seen that the fast neutral atoms are emitted outside of the central region of the plasma column. The resulting correction factor $c_{corr} = T_i^{CX}/T_i(0)$, used in this contribution for correction of the measured temperature T_i^{CX} , is $c_{corr} = -0.038n_e + 0.988$ where n_e is the line avarage density (in 10^{19} m^{-3}).

1.1 Ion heating in the H-mode discharge

Temporal evolution of the ion temperature in the discharge with transition from L- to H-mode is shown in Figure 5. The L-H transition is identified by a sharp drop of the D_α spectral line intensity. The L-H transition, occurring in this particular discharge at t = 1080 ms, is accompanied by increase of the plasma density.

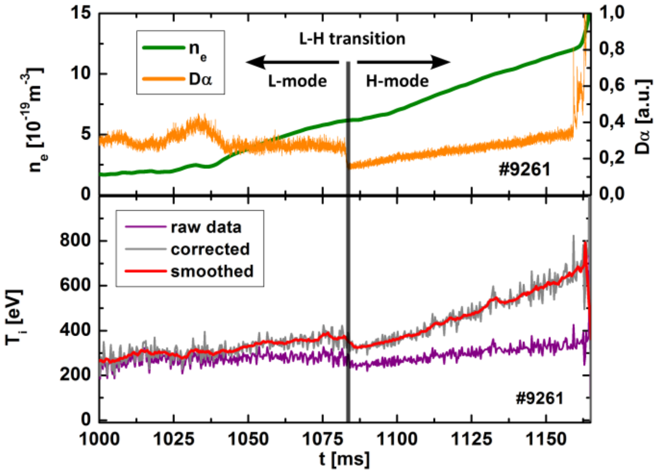

Figure 5: Top panel: Temporal evolution of the line averaged density and the intensity of D_α line in the discharge #9261. Bottom panel: the corresponding ion temperature determined from the slope of energy spectrum (violet line) and the central T_i corrected assuming the parabolic profiles of T_e, T_i and n_e (gray and red lines).

The bottom panel in Figure 5 displays the evolution of the ion temperature. The central ion temperature in the L-mode phase of the discharge (T_i (L-mode) = 315 eV) agrees reasonably with the Artsimovich formula derived for circular plasmas [6]

$$T_i\,(0) = 60\sqrt[3]{I_p B_t R^2 \langle n_e \rangle}\,\frac{1}{\sqrt{A_i}} \qquad [\text{eV, kA, T, m, } 10^{19}\ \text{m}^{-3}] \qquad (1)$$

According (1), the central ion temperature (for $n_e = 3 \times 10^{19}$ m^{-3}, I_p = 240 kA B_t = 1.15 $A_i = 2$) is ~320 eV.

Due to the increase of the plasma density in the H-mode phase, the corrected central ion temperature is increasing up to ~ 700 eV, being comparable with the central electron temperature. However, more modelling is required to interpret correctly the fast neutral spectra and obtain more realistic profiles of temperature and density in H-mode discharges.

1.2 Deacy time of fast ion flux

As is seen in Figure 3, a high energy tail is formed during the NBI injection. Ionized beam atoms, captured by magnetic field, are slowed down mainly by collisions with plasma electrons. After several circumnavigations around the torus, the ions can be neutralized again, and consequently registered by NPA. When NBI is switched off the neutral flux decays exponentially as demonstrated in Figure 6.

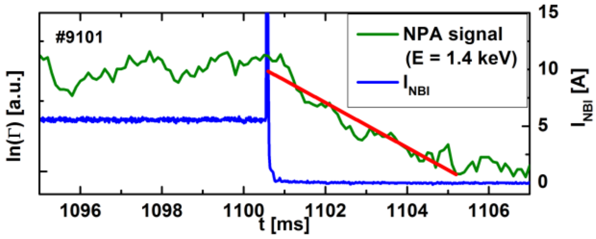

Figure 6: Temporal evolution of the neutral flux with energy 1.4 keV and the NBI beam current in the shot #9101. The NBI heating is switched off at t = 1100.5 ms and the neutral flux starts to decay exponentially as marked by the red line. At the same time, the line average density is $n_e \approx 9.4 \times 10^{19} m^{-3}$, and the line average electron temperature is $T_e \approx 540$ eV.

From the fit of the linearly decreasing part of the signal in logarithmic scale (red line in Figure 6) the decay time of the ions within the given energy range $\Gamma(E) \sim \exp(-t/\tau(E_i))$ can be determined.

Figure 7 shows the dependence of the ion decay time on ion energy for several discharges with the NBI heating.

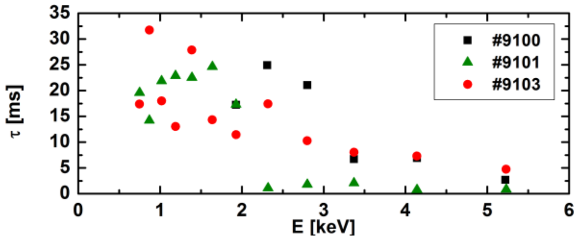

Figure 7: Dependence of the ion decay time on energy (L-mode, D-shaped plasma, $I_p \approx 200$ kA). At the time of the NBI switching off, shots #9100 and #9103 have similar electron density $n_e \approx 7 \times 10^{19}$ m^{-3}, 6×10^{19} m^{-3} respectively. In the shot #9101 the electron density was $n_e \approx 9.4 \times 10^{19}$ m^{-3}.

The ion decay time is around 20 ms for energies corresponding to bulk of the ion energy distribution function (< 2 – 3 keV). This value is comparable with the global energy confinement time on COMPASS determined from diamagnetic measurements. For energies E > 3 keV, the flux of neutral atoms decays noticeably faster, in particular at high densities, as expected from expression for the slowing down time of fast ions, $t_{sc} \sim T_e^{3/2}/n_e$ [7].

1.3 Fast transient phenomena observed by NPA

The NPA temporal resolution allows observation of fast transient phenomena. Figure 8 shows a temporal evolution of the signal of a single energy channel in ELMy H-mode discharge.

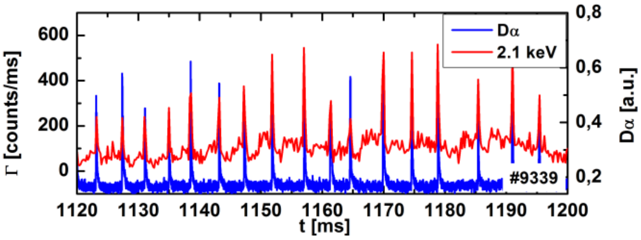

Figure 8: Evolution of counts measured by one channel (E = 2.1 keV) with temporal resolution 0.2 ms during ELMy H-mode discharge (#9339, NBI 1 on).

It can be observed that the Edge Localized Mode (ELM) instabilities accompanying H-mode are well resolved. In discharges with NBI heating, the ELMs are pronounced on all energy channels. In Ohmic H-mode, the ELMs are visible only on low energy channels (E < 3 keV). Note also the increasing counting rate before the ELMs.

Figure 9 displays another example of transient phenomena seen by NPA. The sawtooth instability is visible on the SXR signal.

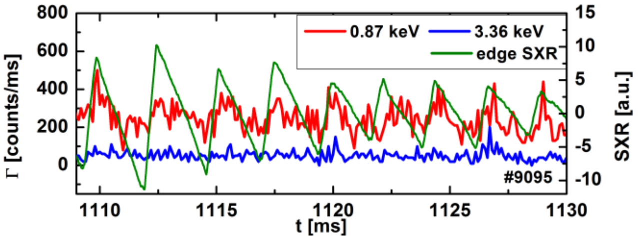

Figure 9: Temporal evolution of signals of two NPA channels (0.87 keV and 3.36 keV) with SXR signal (channel SXR_A_24) in Ohmic discharge #9095 (I_p = 260 kA, n_e = 8.7 × 10^{19} m^{-3}).

It is seen that sawteeth cause oscillations at low energy channels of NPA, E < 2keV. It should be noted that the sawtooth oscillations are observed at NBI heating also on high energy channels of NPA [8].

1.4 Comparison of ion and electron temperatures

Lala Recently, the Retarding Field Analyzer for measurement of the ion temperature in the scrape off layer was installed on the reciprocating manipulator. This allows simultaneous measurements of the central and edge ion temperatures. Comparison of these two quantities for D-shaped, L-mode discharge with electron temperature profile measured by Thomson scattering system is plotted in Figure 10.

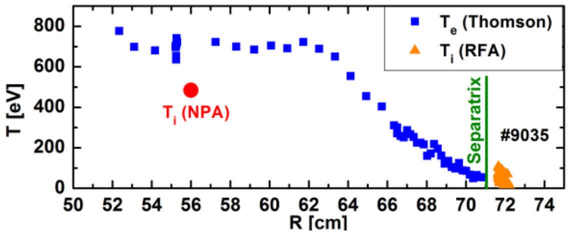

Figure 10: The central ion temperature (corrected data for the electron density measured by NPA), the edge ion temperature (measured by RFA) and the radial profile of the electron temperature in L-mode ohmic discharge (#9035) are compared. The line average electron density is 5 × 10^{19} m^{-3}.

The ion temperature is about two times lower than the electron temperature in the plasma core. At the plasma edge they have comparable values.

Conclusion

The main aim of the NPA installation on the COMPASS tokamak was to measure the energy distribution of fast neutral flux and consequently the ion temperature. First measurements with the ACORD-24 demonstrate that the central ion temperature in low density L-mode discharges is about 300 - 400 eV, which is ~ 3 times less than the central electron temperature. After L-H transition the central ion temperature increases. At the end of the H-mode phase it is about two times higher compared to T_i at the beginning. However, more precise interpretation of the energy spectra at densities $> 3 \times 10^{19}$ m^{-3} is required. Simulations of energy spectra by the numerical code DOUBLE are now underway.

It has been also demonstrated that NPA equipped with fast data acquisition, is capable to study transient phenomena on COMPASS, such as ELMs or sawtooth instabilities. In NBI heating discharges, the ion decay time and its dependence on plasma parameters is determined, which can be useful for understanding of plasma interaction with NBI particles. We also succeed to measure simultaneously T_i in the plasma core and in the SOL. The central ion temperature is lower than the electron temperature in the plasma core and similar in the edge.

It is clear that more systematic measurements are required in future to improve statistics of NPA data.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
The work was partly supported by the Ministry of Education, Youth, and Sports CR project #LM2011021.
Part of the research is supported by the grant of the Czech Science Foundation project 15-10723S.

References

[1] V.V. Afrosimov, Method of investigation of the flux of atoms emitted by a plasma, Sov. Phys. – Technical Physics **5** (1961) 1378

[2] http://www.ioffe.rssi.ru/ACPL/npd/npa01.htm

[3] R. Panek, O. Bilykova, V. Fuchs, M. Hron, P. Chraska, P. Pavlo, J. Stockel, J. Urban, V. Weinzettl, J. Zajac and F. Zacek, *Reinstallation of the COMPASS-D Tokamak in IPP ASCR*, Czechoslovak Journal of Physics, Vol. 56 (2006), Suppl. B, B125

[4] P. Bilková, M. Aftanas, P. Bohm, V. Weinzettl, D. Sestak, R. Melich, J. Stockel, R. Scannell, Walsh, *Design of new Thomson scattering diagnostic system on COMPASS tokamak,* Nuclear Instruments & Methods in Physics Research, Sec. A 623 2 (2010) 656

[5] Ch. Schlatter, Reconstruction of ion temperature profiles from single chord NPA measurements on the TCV tokamak, Plasma Phys. Control. Fusion, **48** (2006) 1765

[6] LA Artsimovich, *Tokamak devices*, Nuclear Fusion, **12** (1972) 21

[7] J. Wesson, *Tokamaks*. 3rd ed. New York: Oxford University Press, 2004. 764 p. ISBN 0198509227

[8] A. D. Melnik, *Study of fast ion losses during NBI heating on Globus-M tokamak, Proc.* 40th EPS Conference on Plasma Physics, Berlin, 2013, P