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Characterization of neutral particle fluxes from ICWC and ECWC plasmas in the TOMAS facility

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Abstract

Electron- (ECWC) and ion- (ICWC) cyclotron wall conditioning are essential means for controlled fusion to modify the surface state of plasma-facing components in order to reduce impurity generation and fuel accumulation in the wall. Development of ECWC and ICWC requires characterization of neutral particle fluxes generated in discharges, because neutrals enhance the homogeneity of the conditioning, which may contribute to remote or shadowed areas, especially in the presence of a permanent magnetic field (e.g. W7-X, ITER). A time-of-flight neutral particle analyzer (ToF-NPA) with 4.07 m flight distance is employed to measure time- and energy-resolved low energetic (<1 keV) neutral particle distributions. The ToF-NPA setup tested at the EXTRAP T2R reversed field pinch was installed at the TOMAS toroidal plasma facility to determine low energy neutral particle fluxes while investigating the impact of the gas pressure in the instrument and compatibility with low count rates during EC- and ICWC discharges. TOMAS has a major radius of 0.78 m and provides various plasma operation conditions: toroidal magnetic field up to 0.12 T, EC frequency 2.45 GHz with the power of 0.6–6 kW, IC frequency of 10–50 MHz with the power of up to 6 kW. Early results on the characterization of three phases (EC only, EC + IC, and IC only) of hydrogen discharges demonstrate: (i) the low energy (10–725 eV) neutrals distribution has been determined by the NPA system, (ii) the mixed EC + IC phase produces the highest population of neutral particles, while the EC only provides one order of magnitude lower rate, (iii) the neutrals produced in IC only have higher average energy (28 eV) than EC only (7 eV) and EC + IC (16 eV).

1. Introduction

Wall conditioning in magnetic fusion devices was introduced to enhance plasma performance by controlling plasma-wall interaction (PWI) processes [1–3]. The aim is to provide effective means to modify the surface state of plasma-facing components (PFC) in order to reduce impurity generation and fuel accumulation in the wall. Besides control of the discharge conditions it is used to assist plasma start-up, to recover after disruptions, intentional vents (at shutdowns) and accidents involving air or water leaks. The currently employed conditioning techniques are baking [4], glow discharge cleaning (GDC) in hydrogen, deuterium or helium [5], deposition of low-Z (Li, B, C, Si) thin films (200–600 nm) by evaporation [6–8], plasma-assisted procedures [9–13], pellet injection [14–16] and plasma operation with ion- (ICWC) [3, 17–20] or electron-cyclotron (ECWC) [21–24] generation systems. In ITER (in Latin: The Way) conventional direct current GDC or plasma-based thin film deposition would be unstable in the presence of the strong magnetic field generated by superconducting coils [25]. Therefore, methods such as ICWC and ECWC are required. Both of them are



included in the ITER Research Plan, in particular, ICWC is included in the functional requirement of the ion cyclotron heating and current drive system.

ICWC discharge, operated under the toroidal magnetic field in tokamaks and stellarators, is based on a low temperature ion cyclotron range of frequencies (ICRF) plasma. The impact of ICWC on the removal of codeposited layers [26–30] and isotopic exchange for fuel removal [17–20] has been studied. Low energetic neutrals (tens of eV to a few keV) are generated through charge exchange (CX) reactions of ions with background neutrals, which significantly enhances the homogeneity of the conditioning, as the ion flux distribution is particularly affected by the strong magnetic fields [17–19]. ECWC discharge, similarly operated with a magnetic field in tokamaks, is based on electron heating, typically by gyrotrons operated in the 84–170 GHz range [30]. At present there are no published results on measurements of neutral particle fluxes in ECWC discharges. One may expect that the distinct plasma production schemes of ECWC and ICWC induce differences in particle fluxes to the wall but quantitative data are still needed. Therefore, to better assess the applicability of the EC- and ICWC for removal of hydrogen isotopes and co-deposited layers, the determination of neutral particle fluxes is one of the necessary steps towards the ultimate goal: preparation of wall conditioning scenarios applicable under permanent magnetic field.

The focus of this work has been on two main points: (i) testing of the time-of-flight neutral particle analyzer (ToF-NPA) and measurement of fluxes in the EXTRAP T2R reversed field pinch at the KTH Royal Institute of Technology; (ii) characterization of neutral particle fluxes generated in the TOMAS (TOroidal MAgnetic System) at the Forschungszentrum Jülich (FZJ). Both devices have full metal wall and, this feature makes them highly relevant for the characterization of neutrals in the IC-/ECWC development for future experiments, including ITER. The overall aim was to set-up the system and to determine the impact of operation parameters on the flux and the energy distribution of neutral particles in discharges performed in hydrogen.

2. Experiments

2.1. Time-of-flight neutral particle analyzer

The determination of particle fluxes in the IC/EC discharges requires the application of ToF-NPA [31–37]. The ToF-NPA method allows measuring the time- and energy-resolved neutral particle distribution, and it is especially beneficial to determine the low energy (<1 keV) neutral particle flux. A schematic drawing of the setup is shown in figure 1. Photons and neutral particles from the plasma enter the tube (i.e. flight path), pass the chopper and then reach to the detector: Hamamatsu Photonics R595. The chopper has two disks: a fixed and a rotating one. The fixed disk has a diameter of 250 mm with two slits 180 degree apart. One slit, serving as collimator for photons and neutrals from the plasma, is connected to the tube from the vessel through the DN 40 CF porthole at one side while the other side is connected to the flight tube. The opposite slit, providing for a laser triggered signal, connects to porthole windows on both sides. The rotating disk has a diameter of 240 mm and 20 slits with an angular separation of 18 degree. The slit has a rectangular shape: 0.15 mm width and 40 mm height. The rotation speed can be controlled up to 20000 rpm. The maximum gating time, i.e. the period from the start to the end of the slits overlap, is 1.8 μ s, and the average opening time of the slits, is about 0.7 μ s at the maximum chopper speed which is usually used. When the slits are overlapped the particles can pass the chopper, thus only 0.48% of the flux from the plasma can pass the chopper thus corresponding to the open/close time ratio 0.7 μ s/ 150 μ s. The closing time between the two consecutive slit openings is about 150 μ s. The closing time is the time resolution of the NPA detector. The particles travel a total of 4.07 m after chopper including the 3 m long flight tube, diameter 100 mm. Inside of tube, there are twelve donut-shaped disks (25 cm apart) with an inner diameter of 35 mm and 1 mm thick to prevent the arrival to the detector of stray light and particles internally reflected in the tube. Photons arrive in the detector immediately when the slit is open while neutral particles arrive after that. The impacting photons and neutrals raise the voltage when they hit the photomultiplier tube of the detector. The voltage is converted to the recorded signal through a pre-amplifier (Hamamatsu C9999-01) and a digitizer. The time difference between recording the photons (or reference laser signal) and neutral particles defines the arrival

Parameter	Experimental information
Major Radius	124 cm
Minor Radius	18.3 cm
Base Pressure of chamber	$1 imes10^{-6}\mathrm{Pa}$
Base Pressure of ToF tube	$1 imes10^{-5}\mathrm{Pa}$
Operation Pressure of chamber	$2 imes10^{-1}\mathrm{Pa}$
Operation Pressure of ToF tube	$1-7 imes10^{-3}\mathrm{Pa}$
B toroidal	0.2–0.3 T
Plasma current	80–100 kA
Electron density	$0.5 - 1.0 \times 10^{13} \mathrm{cm}^{-3}$
Electron temperature	200–400 eV
Ion temperature	400–600 eV
Discharge duration	up to 0.10 s
Typical fueling gas	Hydrogen

Table 1. Technical and plasma parameters in Extrap T2R.

Table 2. Technical parameters of TOMAS andapproximate operation window in EC and ICWCdischarges.

Parameter	Value
Volume	1.1 m ³
Major Radius	78 cm
Minor Radius	26 cm
Base pressure	$2.5 imes 10^{-6} \mathrm{Pa}$
Operation pressure	$0.5-5 imes 10^{-2} \mathrm{Pa}$
IC frequency	10-50 MHz
IC power	up to 6.0 kW
EC frequency	2.45 GHz
EC power	0.6–6.0 kW
Electron density in ICRF	$1-25 \times 10^9 {\rm cm}^{-3}$
Electron density in ECR	$5-50 \times 10^9 {\rm cm}^{-3}$
Electron temperature in ICRF	5–50 eV
Electron temperature in ECR	1–25 eV for H
B toroidal	up to 125 mT

time. Then, the kinetic energy of particle is calculated with the assumed mass when the only one type of gas is used in the discharge.

2.2. Experiments at extrap T2R

The Extrap T2R reversed field pinch parameters and plasma characteristics are presented in table 1, while details on the operation parameters and wall components have been published earlier in [38–40]. The signal of neutrals could only be detected during a few intervals, and its intensity varies within one order of magnitude, thus indicating that the neutral particle signal was for most of the time within the noise level. This clearly shows the need for signal integration over a large number of cycles to ensure sufficient statistics and collecting a representative energy spectrum of particles. The test of the diagnostic setup was performed in 45 plasma discharges fueled with hydrogen. The data were recorded for 32 ms in each discharge with a 3 MHz sampling frequency using a 12 bit transient recorder Joerger TR612/3 equipped with 128 Ksample of memory; other details of the setup are in [35].

2.3. Experiments at TOMAS

ICWC and ECWC experiments carried out in tokamaks (TEXTOR [17–19, 27, 29], JET [18–20], ToreSupra [18, 19], ASDEX Upgrade [17–19, 28]) serve as a test of principle. The results have encouraged the continuation of efforts towards the development of ICWC/ECWC conditioning techniques. However, the availability of experimental sessions in fusion devices has been always limited, whereas the development requires a large number of tests to assess the most promising procedures. The exact number of the needed tests with different antenna settings, power, and frequency of cycles is not possible to define at this stage; it is most probably in the range of several hundreds. To complement the work on medium and large size devices, experimental opportunities are offered at the TOMAS plasma device operated at FZJ for the development and testing of



Figure 2. Overview of the TOMAS facility with the installed ToF-NPA.



various wall conditioning methods [41–43]. TOMAS with a stainless-steel vacuum vessel has high flexibility of operation in terms of pressure, pumping speed, magnetic field and RF frequency. In addition, possibilities of running long conditioning campaigns under magnetic field make this device unique. Technical details regarding the approximate operation window are compiled in table 2. The system is equipped with the Wendelstein 7-X prototype DC glow discharge graphite anode which can be operated with its maximum voltage of 1.5 kV and current of 6 A, electron cyclotron resonance heating (ECRH) which can generate continuous wave operation, and newly developed ICRF antenna to generate energetic ions. For RF conditioning in plasmas of low density and low temperature it also has a set of dedicated diagnostics including ToF-NPA system, as shown in figure 2. That system equipped with a new detector was transferred from KTH to FZJ and then fitted with two new turbomolecular pumps and a laser for the additional recording of the chopper open timing. The system allows for measurements of neutral particle fluxes to PFCs in different gas fueling (H, D, He) and different types of plasma to resolve the energy distribution of neutrals in the energy range from 10 to 1000 eV. Details of the upgraded TOMAS and its auxiliary systems and diagnostics are described in [44].

As shown in figure 3, neutral fluxes in TOMAS were studied during 6 s long plasma pulses comprising three phases: the first with only EC plasma for 2 s, followed by a mixed 2 s phase with EC and IC plasma, and the last phase with 2 s of only IC plasma. 20 pulses were repeated under the same conditions, corresponding to the total operation time of 120 s in each experimental series.

The NPA data are recorded by the CAEN DT5790 Dual Digital Acquisition System which allows for data collection at 250 MS s⁻¹ with a bandwidth of up to 125 MHz. Pulse processing is performed during the data collection to detect, events above a preset trigger level for noise subtraction. The signal-to-noise ratio is fairly high showing very clear photon or neutral particle events. The experimental result is a set of numerical data of timing and gate-time of the detected signal. Other phenomena are also present, e.g. background radiation, but they are rare and can be determined by operating the detector with the closed gate valve to the machine.

3. Results and discussion

3.1. Results from EXTRAP T2R

A graph in figure 4(a) shows two types of signals recorded by the ToF-NPA system: (i) pronounced features of photons (circles) with periodic pattern; (ii) weaker traces related to neutrals (reversed triangles). Figure 4(b) shows the integrated NPA data within 448 ms corresponding to fourteen discharges (#26377–26379, #26383–26393) of the same condition. By identifying the photon peak, the data can be divided into sub-sections between photon peaks. The timing of each photon peak is the reference point for the determination of the arrival



time of neutrals, i.e. the difference between the photon and the neutral signal. Counting the detected neutral particles arriving at a given time is the basis for the arrival time distribution (ATD). When such a clear photon signal is visible, the arrival time can be calculated from the photon peak timing without an additional trigger signal from a laser, see figure 1. In the 10–60 μ s range neutral signals show a distribution corresponding to CX hydrogen neutral particles in the 25–865 eV energy range. The majority of the flux (around 97%) is fitted to the Maxwell-Boltzmann distribution of 5 eV average energy, while remaining 3% is fitted to about 500 eV. The detailed process of conversion is described in next sections.

3.2. Results from TOMAS

3.2.1. Data analysis

Figure 5(a) shows an example of both NPA and laser signals recorded by an oscilloscope during 6 ms. The photon peaks are recorded at the same timing as the laser shot, while the neutral particle peaks are recorded between the laser signals. Fewer photon peaks were detected, since the photon flux in the TOMAS plasma is lower than that in Extrap T2R. Therefore, an external light source is required to compensate for the missing photon peak and to provide the time reference signal. The average number of detected neutral particle signals is 1.65 per 10 ms in EC + IC mix phase with 20 sccm (standard cubic centimetre per minute) H₂ flow. The lower rate of neutral events can be compensated for by a longer pulse duration and, consequently, longer data collection time, which is possible in TOMAS. A continuous wave laser in front of a separate viewport of the chopper and a photodiode behind it have been used, as shown in figure 1. Hence, two signal lists are recorded in two separate channels: timing and gate signal for plasma related to events detected in NPA by channel 0, and timing of the laser pulses by channel 1. These two lists are then sorted by time. The arrival time for a plasma event is then calculated as the difference to the timing of a respective laser pulse.

Two series of experiments were performed in the hydrogen plasma under toroidal magnetic field of 125 mT, IC frequency of 25 MHz and the EC and IC power of 2 kW and 1 kW, respectively. The difference between the series was the gas feed rate: $35 \text{ sccm} (1.46 \times 10^{19} \text{ H}_2/\text{s})$ in the first series and 20 sccm ($8.36 \times 10^{18} \text{ H}_2/\text{s}$) in another. Data for around 8×10^5 cycles under the same experimental conditions were recorded and then processed to obtain an integrated spectrum. In figure 5(b) from 0 to 10 μ s is an integrated photon peak, while above 10 μ s, there is an ATD of neutrals particles. One may perceive that the EC operation yields only very few neutral particles reaching the detector, while EC + IC phase and IC phase have relatively similar number of neutral particles. The results with a corresponding energy conversion are presented in section 3.2.4.



|--|

Energy (eV)	ZBL	KrC	Moliere	Nakagawa- Yamamura	Average
10	4.59	0.81	0.62	37.29	10.83
50	17.71	6.58	4.74	47.08	19.02
100	26.93	11.7	9.23	51.85	24.93
300	44.82	26.41	22.11	60.18	38.38
1000	64.00	49.66	44.33	71.00	57.25

3.2.2. Passing probability

When neutrals pass the tube between the vacuum vessel to the chopper, they may be scattered depending on their energy and the gas pressure in the torus. To assess the effect of scattering on the measured energy distributions, the passing probability was calculated by the binary collision simulation program SDTrimSP 5.00 [45] which is a proper tool for calculating collisions in low-density gaseous media, i.e. under vacuum. The obtained values show some variations because the different interaction models [46–49] lead to different results. The results show that, at higher pressure hydrogen pressure, e.g. 2.0×10^{-2} Pa, a significant number of particles are scattered in the 81 cm long tube before reaching the chopper.

For instance, in the case of 100 eV particles at this pressure, calculations with the ZBL (Ziegler-Biersack-Littmark) potential indicate that 27% of the population arrives at the detector through the ToF system. Other potentials provide different results: KrC (12%), Moliere (9%), and Nakagawa-Yamamura (52%). In this study, the average is used, since it is hard to be decided unambiguously which potential model provides the closest results with experiment [50]. Therefore, the average is 25% in given conditions thus meaning that if the 2.37 particles per second are detected, then the actual number of particles is 9.51 particles per second. The passing probabilities in the relevant energy range (10–1000 eV) are simulated, as shown in table 3. The energy distribution results are accordingly corrected. In summary, the resulting value for 100 eV particles is about four





Fable 4	Experimental	results in each	nhase at TOMAS
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Gas flow	Phase	Neutral flux $(10^{15} \mathrm{H^0 cm^{-2} s^{-1}})$	$n_e(10^9 cm^{-3})$	Neutrals temperature (eV)	T _e (eV)
20 sccm	EC	0.11	5.5-40	12	2–9
	EC + IC	1.11	8.1-40	15	4-18
	IC	0.24	1.4-10	32	7–36
35 sccm	EC	0.06	1.0-27	7	1-7
	EC + IC	0.50	7.5–28	16	3-17
	IC	0.23	2.0–12	28	5-23

times higher than the number of detected ones, while it is even ten times higher in the 10 eV energy range. It is stressed, however, that despite scattering, particles preserve more than 99.6% of their energy. Finally, for the ToF tube which is under high vacuum (1.0×10^{-5} Pa) it is found that more than 99%, particles can pass, even those of low energy.

3.2.3. Detection efficiency

The differential flux of neutral particles can be determined from the detected number of particles, N(E) [33]:

$$\frac{\mathrm{d}\Gamma(\mathrm{E})}{\mathrm{d}\mathrm{E} \ \mathrm{d}\Omega} = \frac{\mathrm{N}(\mathrm{E})}{\delta(\mathrm{E})\mathrm{A}_{\mathrm{s}}\mathrm{d}\Omega \ \mathrm{d}\mathrm{E} \ \mathrm{t}_{\mathrm{m}}}$$

where δ (E) is the detector efficiency including the probability of incoming neutral particles to generate at least one secondary electron at the detector dynode, and the probability of secondary electrons producing output pulses, A_s is the slit area (=0.15 × 35.6 mm²), d Ω is the solid angle of detector from the vessel wall (=4.82 µSr), dE is the relevant energy interval, t_m is the effective measuring time which is the opening ratio of chopper slits during the 1 s (=1 s × 4.77 × 10⁻³). The efficiency δ (E) data for a Cu-Be detector have been taken from [32, 33]. Geometrical and systematic errors such as finite gating time, measurement error of distance, small variation on the slit distance, and fluctuations on the motor of chopper, may result in an error of 25%.

3.2.4. Energy analysis

Figure 6 shows the differential flux of hydrogen monoatomic neutrals in three operation phases, and the corresponding fitting line with the Maxwellian energy distribution. The differential flux is a result of a series of calculations: (i) the arrival time of neutrals is converted into the energy, (ii) the results of all discharges are binned for each of the different heating phases in the energy histogram, (iii) the number of detected particles of each energy interval is divided by the total plasma time, (iv) passing probability correction is applied, (v) the detection efficiency is applied to the number of detected particles per second.

The total fluxes of neutral particles shown in table 4 are the integrated differential fluxes in the 10–725 eV energy range and in 4π geometry. Such energy interval has been decided for two following reasons. Below 10 eV there are only very few particles detected in the 90–140 μ s window of ATD, while the detector efficiency under 10 eV is not reliably determined. Above 725 eV, i.e. in the region corresponding to less than 11 μ s on the ATD scale, there is a tail of the photon signal distribution. Therefore, it is hard to distinguish in that range signals attributed



to neutrals, see figure 5(b) as reference. The density (n_e) and temperature (T_e) of electron in table 4 are the results of the triple probe measurement [45] which was done simultaneously with ToF-NPA in the same series of discharges. The variation of results is depend on the radial position of the plasma; detailed probe results will be reported in a separately.

The mixed EC + IC phase produces a higher neutral particle flux than the other phases. The total flux under the 20 sccm gas flow is $1.11 \times 10^{15} \,\text{H}^{0} \,\text{cm}^{-2} \,\text{s}^{-1}$, while in the IC-only phase it is about 5 times lower and, in the EC it is even one order of magnitude lower. The differential fluxes are fitted to the Maxwellian energy distribution. The probability density of each energy interval is multiplied by the total flux of each phase. As shown in figure 6, the experimental results of EC is fitted with two lines: 7 eV of Maxwellian distribution with 94% of total flux (solid line), and 30 eV with 6% of population (dashed line). The EC + IC and IC results agree with the 16 and 28 eV of particle energy distribution, respectively. Although at the same IC power and frequency, the EC + IC phase is characterized by a lower mean neutral energy than IC alone. This may be associated with the lower temperature caused by the increase of electron density at the EC + IC phase. These results are consistent with previous data obtained with a Langmuir probe [20].

At a reduced gas flow one observes a higher fraction of neutrals at higher energy, as shown in figure 7. The difference is related to the gas feed, i.e. hydrogen flow rate: 35 and 20 sccm, respectively. Again, it points to the impact of density and temperature. The reduction of the gas feed has resulted in a lower plasma density and, as a consequence, led to the rise of particles energy.

4. Concluding remarks and Outlook

Following the refurbishment and upgrade of TOMAS [44] essential experimental systems, such as ToF-NPA, have been brought to operation in order to progress the development of wall conditioning under permanent magnetic field. The major contributions of this work are: (i) the complete test of the NPA functionality (both in EXTRAP T2R and TOMAS); (ii) the determination of low energy (10–725 eV) neutral particle flux; and (iii) the assessment of the neutral distribution under the different conditions with respect to the IC and EC operation, and gas flow. The effective generation of energetic neutrals occurs under IC and combined application of IC and EC, while EC alone is not sufficient for that purpose. The reduction of gas flow increases the neutral particle flux and energy. The experimentally obtained neutral particle distribution corrected by the passing probability and the detection efficiency fits with the Maxwell-Boltzmann distribution in the low energy range (10–300 eV). The application of an auxiliary laser pulse has been identified as crucial for the discrimination of photon and particle signals thus enhancing the reliability of data acquisition and interpretation in TOMAS.

In further studies exposures of pre-characterised samples made of wall materials earlier used in fusion devices will be carried out. Post exposure surface analyses will allow for the assessment the fuel removal efficiency. This will serve for the optimization of operation conditions and, eventually, for the elaboration of wall conditioning strategy in machines with superconducting magnets.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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