

## Experimental study on the gas stripping chamber of an E/B neutral particle analyzer

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### Abstract

Stripping unit plays an important role in the neutral particle analyzer (NPA). An updated gas stripping unit was constructed for the newly designed E//B NPA. The pressures at the gas inlet ( $P_0$ ) and the vacuum chamber ( $P_3$ ) were measured with the working gas of  $H_2$ , and the pressure distribution inside the gas stripping room was calculated using Ansys Fluent with the measured  $P_0$  and  $P_3$  as the boundary conditions. The stripping efficiency of the stripping unit is then simulated using Geant4 Monte Carlo code for H and D particles. The pressure  $P_0 = 40$  Pa, which is four times less than that in previous design and corresponds to a thickness of  $1.27 \times 10^{17}$  atoms/cm<sup>2</sup>, is obtained as the optimum working pressure for the updated stripping unit. A 50 kV electron cyclotron resonance (ECR) ion source platform has been designed and constructed for the E//B NPA calibration, and its performance was measured. Utilizing the ECR ion source platform, the efficiency of the stripping unit was measured in an inverse experiment with proton beams. The current ratio of the measurements with and without  $H_2$  gas are compared with those of Geant4 simulation. Good agreements of the overall trend between the experiment and the simulation are found. The large deviation at the incident energy below 20 keV could be the scattering effect of low energy protons, where the accuracy breaks down in the single scattering physics involved in the Geant4 simulations. {After the scattering corrections observed in the reverse experiments, more accurate stripping efficiencies for H and D atoms in the energy range of 20-200 keV are obtained and the global efficiency reaches the maximum values of 95.0% for H atoms and 78.9% for D atoms at 200 keV.

## Full Text

### Preamble

#### Experimental Study on the Gas Stripping Chamber of an E//B Neutral Particle Analyzer

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The stripping unit plays a crucial role in neutral particle analyzers (NPAs). An updated gas stripping unit has been constructed for a newly designed E//B NPA. Pressure measurements were conducted at the gas inlet ( $P_0$ ) and vacuum chamber ( $P_3$ ) using  $H_2$  as the working gas, and the pressure distribution inside the gas stripping chamber was calculated using Ansys Fluent with the measured  $P_0$  and  $P_3$  values as boundary conditions. The stripping efficiency of the unit was then simulated using Geant4 Monte Carlo code for hydrogen and deuterium particles. An optimal working pressure of  $P_0 = 40$  Pa was determined for the updated stripping unit, which is four times lower than that in the previous design and corresponds to a thickness of  $1.27 \times 10^{17}$  atoms/cm<sup>2</sup>. A 50 kV electron cyclotron resonance (ECR) ion source platform has been designed and constructed for E//B NPA calibration, and its performance has been characterized. Utilizing this platform, the stripping unit efficiency was measured in inverse experiments with proton beams. The current ratios measured with and without  $H_2$  gas were compared with Geant4 simulation results, showing good overall agreement in trend. The large deviation observed at incident energies below 20 keV is attributed to scattering effects of low-energy protons, where the accuracy of the single-scattering physics employed in Geant4 simulations breaks down. After applying scattering corrections based on the reverse experiments, more accurate stripping efficiencies for H and D atoms were obtained in the energy range of 20–200 keV, with maximum global efficiencies reaching 95.0% for H atoms and 78.9% for D atoms at 200 keV.

**Keywords:** NPA, gas-stripping, ECR ion source, stripping efficiency, Geant4

## 1 Introduction

The tokamak is a magnetic confinement fusion device for controllable fusion experiments. The interaction between shear Alfvén waves and energetic particles plays an important role in high-temperature plasma confinement and steady-state operation in tokamaks [1–11]. Numerous diagnostic devices have been developed to study fusion plasma and energetic particles, including microwave diagnostics [12–14], soft x-ray diagnostics [15–17], neutron diagnostics [18–25], visible/infrared cameras [26–29], neutral particle analyzers (NPAs) [30–37], and others. NPAs are particularly important for providing energy spectra, which constitute key information for frontier physics of energetic particles [4–7, 40–42]. By measuring charge-exchange neutral particles escaping from the plasma, NPAs enable determination of bulk ion temperature, isotopic ratio, and fast ion distribution.

Since the world's first NPA was developed in 1960 [30], numerous NPAs have been designed and constructed worldwide [31–39, 43–50]. For example, the compact NPA (CNPA) developed for Wendelstein 7-AS stellarator offers the advantage of simultaneous analysis for hydrogen (0.8–80 keV) and deuterium (0.8–40 keV) in a more compact structure (169 mm × 302 mm × 326 mm, weight: 42.5 kg). The NPA system on the International Thermonuclear Experimental Reactor (ITER) includes a high-energy NPA to measure D and T atoms in the ranges of 0.11–1.4 MeV and 0.16–2.2 MeV, respectively, and a low-energy NPA for the thermal energy range of 10–200 keV for all hydrogen isotopes [32, 50].

Typically, an NPA consists of three main components: a stripping unit, an analyzing unit, and a detecting unit. The stripping unit re-ionizes neutral particles via charge-exchange reactions with the stripping material. The energy and/or mass of the re-ionized particles are then identified by magnetic and/or electric fields and recorded by the detecting unit. Various ion detectors have been employed in NPAs, including micro-channel plates [35, 52–55], channel electron multipliers [33, 37, 56], CsI [31, 32, 39, 57, 58] and LYSO scintillators [38, 59, 60], diamond-like detectors [61, 62], and others. The stripping material can be either a stripping foil or stripping gas. When a solid foil is used for low-energy neutrals, an additional accelerating or focusing voltage is often required for secondary ions [31–33]. A carbon foil with a thickness of 100 Å is commonly employed. In contrast, a gas chamber requires a differential pumping system. Typical integrated target thicknesses are on the order of  $10^{16}$  atoms/cm<sup>2</sup> for H<sub>2</sub> gas in the JET NPA [46] and  $10^{15}$  atoms/cm<sup>2</sup> for He gas in the E//B NPA on TFTR [35]. This low-pressure operation is necessary to maintain reasonably high vacuum during tokamak operation but results in rather low stripping efficiency.

A new NPA with parallel electric and magnetic fields (E//B) for studying frontier physics of energetic particles is currently under development [63, 64]. A gas stripping chamber filled with H<sub>2</sub> as the working gas was adopted as the stripping unit in this E//B NPA. In our previous work [64], we presented simulated

pressure distributions inside the stripping chamber using Ansys Fluent [65, 66] together with MolFlow+ [67], and calculated stripping efficiencies for H and D atoms passing through the unit using Geant4 [68, 69] simulation code. This article presents experimental investigation of pressure distributions inside an updated stripping chamber—a further optimized version of the design in Refs. [64, 70]—and ion beam tests of the stripping unit on a newly constructed 50 kV electron cyclotron resonance (ECR) ion source platform at Sichuan University.

This article is organized as follows: Section 2 presents the experimental investigation of pressure distribution inside the stripping chamber. Section 3 describes the newly constructed 50 kV ECR ion source platform and its performance. Section 4 presents ion beam tests of the stripping unit. A brief summary is given in Section 5.

## 2 Pressure Distribution and Stripping Efficiency of the Stripping Unit

A prototype design of the gas stripping chamber was presented in our previous work [64, 70], featuring a stripping chamber 54 mm in length with two differential pipes of 4 mm inner diameter. The pressure distribution was calculated using Ansys Fluent [65] and MolFlow+ [67], assuming constant pumping speed for the outlet surface. However, after constructing the unit, we found that the molecular pump's pumping speed decreases when pressure exceeds a certain value, resulting in higher vacuum chamber pressure than predicted. Therefore, the stripping chamber structure was modified to reduce vacuum chamber pressure. An updated stripping chamber with 84 mm length and differential pipes of 2 mm inner diameter was constructed. [Figure 1: see original paper] shows a cross-sectional view of the updated gas stripping chamber.

[Figure 2: see original paper] shows a photograph of the updated stripping unit. A Faraday cup (FC) located in the downstream vacuum chamber was integrated with the stripping unit to measure incident beam current. A needle valve and electromagnetic valve controlled by a proportional-integral-derivative (PID) regulator were connected to the gas inlet flange to maintain stable  $H_2$  gas flow. Two Pfeiffer diaphragm vacuum gauges (CMR362 and CMR365) measured pressures at the gas inlet ( $P_0$ ) and vacuum chamber ( $P_3$ ), respectively. Using these measured pressures as boundary conditions in Ansys Fluent, the pressure distribution inside the stripping chamber was obtained.

Employing the experimentally measured  $P_3$  value in Ansys Fluent calculations yields more precise predictions of pressure distribution. [Figure 3: see original paper] shows a typical two-dimensional (2D) pressure distribution for  $P_0 = 40$  Pa in the central plane ( $Z = 0$  mm) of the stripping chamber (a) and the pressure distribution along the path of incident neutral particles ( $Y = 0$  mm and  $Z = 0$  mm) for  $P_0 = 40$  Pa (b). With the reduced inner diameter of differential pipes in the updated unit, higher pressure inside the stripping chamber is expected for a given  $P_0$ . As shown in Figure 3: see original paper, a constant pressure of

approximately 31 Pa is achieved at the chamber center—more than three times that of the previous design [64]. Linearly decreasing pressures are also obtained inside the differential pipes.

Pressures at the stripping chamber center ( $P_1$ ) and at the inner ends of differential pipes ( $P_2$ ) were extracted and plotted with  $P_3$  as functions of inlet pressure  $P_0$  in [Figure 4: see original paper].  $P_1$  shows a linear increasing trend with  $P_0$ , while  $P_2$  and  $P_3$  exhibit slight nonlinear behavior, likely due to pumping speed variations at different  $P_0$  values. The Geant4 [68, 69] Monte Carlo code was applied to simulate the global stripping efficiency ( $R \times f_1$ , where  $R$  represents the transmission rate of the stripping chamber and  $f_1$  represents the fraction of +1 charge state at the exit hole) of an earlier stripping unit version. With increased stripping gas thickness in the updated unit, a lower  $P_0$  value is required to achieve the same global stripping efficiency.

As shown in [Figure 5: see original paper], global efficiency increases with gas inlet pressure  $P_0$  and reaches a maximum at approximately  $P_0 = 40$  Pa for the maximum designed energy (200 keV) in the updated unit. The pressure  $P_0 = 40$  Pa, which is four times lower than in the previous design [64] and corresponds to a thickness of  $1.27 \times 10^{17}$  atoms/cm<sup>2</sup>, is determined as the optimum working pressure for the updated stripping unit.

In our previous work [64, 70], an optimum  $P_0$  of 200 Pa was obtained. The simulations employed charge exchange cross sections from the ORNL recommended data set [71], including electron capture and loss cross sections for  $H^0$ , electron capture cross sections for  $H^+$ , and electron loss cross sections for  $H^-$ . Using these cross sections at a given energy, stripping efficiency can be calculated via a simple equation without scattering correction, as shown in Eq. (1) of Ref. [64]. By modifying the structure and pressure distribution in the code to match the updated unit,  $R \times f_1$  values were obtained. [Figure 5: see original paper] shows  $R \times f_1$  as a function of gas inlet pressure  $P_0$  for H and D atoms at incident energies of 20, 100, and 200 keV in (a), (b), and (c), respectively. With the increased stripping chamber length, the optimum  $P_0$  is reduced to 40 Pa.

### 3 The 50 kV ECR Ion Source Platform

To calibrate the E//B NPA, a new 50 kV ECR ion source platform with a compact permanent magnet ECR ion source and 30° dipole magnet was designed and constructed at Sichuan University. The platform generally consists of an ECR ion source, dipole magnet, FC, vacuum system, and water cooling system. [Figure 6: see original paper] shows a photograph of the 50 kV ECR ion source platform.

As shown in [Figure 7: see original paper], a more compact 2.45 GHz single-charge-state ECR ion source was developed for the platform, modified from the design in Ref. [72]. The source body has an outer diameter of 50 mm. The magnetic field is produced by a single NdFeB permanent magnet ring. The plasma chamber has a diameter of 30 mm and length of 30 mm. The suppressor

and shield electrodes used in Ref. [72] were removed. The plasma aperture and extraction aperture diameters were reduced to 3 mm and 5 mm, respectively. A newly designed spherical antenna head, which increases plasma density in the chamber by approximately 10%, was implemented. The ceramic insulator tube length was increased to 120 mm to sustain 50 kV extraction voltage. The high-voltage power supply exhibits 0.1% voltage drift over time and temperature during operation. Microwave power is supplied from the high-voltage platform and coupled into the plasma chamber via coaxial cable and antenna. An isolation transformer rated for 80 kV isolation with 1 kVA power supplies the microwave generator. A needle valve with  $10^{-9}$  Pa · L · s<sup>-1</sup> leakage rate controls working gas inlet flow. Energy spread caused by plasma instabilities was measured using a retarding field energy analyzer, yielding a maximum spread of less than 5 eV.

A dipole magnet with 30° deflection angle, 250 mm deflection radius, 40 mm gap, and 70 mm width was installed, capable of analyzing 50 keV He<sup>+</sup> particles from the ECR source. As shown in the schematic diagram in [Figure 8: see original paper], the ECR ion source and dipole magnet are connected to vacuum chamber (A). Another vacuum chamber (B) is located downstream of the dipole magnet. Two identical molecular pumps with 700 L/s (N<sub>2</sub>) pumping speed are mounted on both chambers to maintain high vacuum. A 5 mm diameter collimator between chamber A and the dipole magnet reduces beam spot size, achieving typical spots less than 15 mm in diameter for 20 keV proton beams at the terminal flange. An FC with 2 cm entrance diameter in chamber B measures beam intensity. A temperature-controlled deionized water cooling system cools the ion source and dipole magnet.

The 50 kV ECR ion source platform performance was characterized using 99.999% purity H<sub>2</sub> as working gas. Beam current was measured by the FC in chamber B with the suppressor electrode biased to -300 V to suppress secondary electrons. [Figure 9: see original paper] shows typical beam current as a function of magnetic current for extraction voltages of 5, 10, 20, and 40 kV in (a), (b), (c), and (d), respectively. Three major peaks from right to left correspond to H<sup>+</sup>, H<sub>2</sub><sup>+</sup>, and H<sub>3</sub><sup>+</sup>, respectively. Two small peaks at low magnetic current are breakup H<sup>+</sup> events from H<sub>2</sub><sup>+</sup> (right) and H<sub>3</sub><sup>+</sup> (left). A small peak between the largest H<sup>+</sup> and H<sub>2</sub><sup>+</sup> peaks appears at 20 kV extraction voltage, representing breakup H<sub>2</sub><sup>+</sup> from H<sub>3</sub><sup>+</sup>. Similar small yields are found at other extraction voltages, causing differences in charged particle yield shown in [Figure 9: see original paper]. Further optimization of charged particle composition is needed for actual applications.

Charged particle intensity dependence on microwave power was measured under constant gas inlet flow at 5 kV extraction voltage. Gas flow was monitored by pressure in chamber B, maintaining  $P_B = 3.44 \times 10^{-4}$  Pa throughout measurements. [Figure 10: see original paper] shows total, H<sup>+</sup>, H<sub>2</sub><sup>+</sup>, and H<sub>3</sub><sup>+</sup> currents as functions of microwave power. Total current increases dramatically

as microwave power rises from 53 W to 146 W, consistent with Ref. [72].  $\text{H}^+$  and  $\text{H}_2^+$  fractions increase with microwave power, while  $\text{H}_3^+$  shows a decreasing trend above 120 W. This may be explained by increasing electron density with microwave power [73], producing more  $\text{H}^+$  and  $\text{H}_2^+$  while reducing  $\text{H}_3^+$  fraction.

The dependence of charged particle intensity on gas inlet flow was also measured at fixed 95 W microwave power and 5 kV extraction voltage. [Figure 11: see original paper] shows total,  $\text{H}^+$ ,  $\text{H}_2^+$ , and  $\text{H}_3^+$  currents as functions of PB. Total current increases rapidly, reaching maximum at  $\text{PB} = 5.27 \times 10^{-4}$  Pa, then decreases slowly.  $\text{H}^+$  intensity changes smoothly, peaking at the same PB value.  $\text{H}_2^+$  intensity peaks at lower pressure ( $\text{PB} = 3.7 \times 10^{-4}$  Pa), while  $\text{H}_3^+$  dominates at  $\text{PB} > 5 \times 10^{-4}$  Pa. Notably, comparable beam intensities of  $\text{H}_2^+$  and  $\text{H}_3^+$  are found across all microwave powers, as shown in [Figure 10: see original paper]. Even higher  $\text{H}_3^+$  fractions ( $>90\%$ ) occur at increased gas inlet flow, as shown in [Figure 11: see original paper].

Large  $\text{H}_3^+$  fractions were reported for pulse-type ECR ion sources [74] but never previously for DC-mode ECR sources. As shown in Refs. [74, 75], higher working gas pressure and lower microwave power in ECR sources produce more  $\text{H}_3^+$  ions. The extremely large  $\text{H}_3^+$  fraction in our 50 kV platform may result from the small discharge chamber and extraction aperture, leading to higher pressure in the discharge chamber. This has significant implications for intense  $\text{H}_3^+$  beam applications.

## 4 The Experimental Test of the Gas Stripping Unit

Calibration of the gas stripping unit is crucial for NPA performance. Since neutral particles are difficult to handle as incident particles for precise measurement, direct verification of simulated results is challenging in the laboratory. However, because stripping cross sections from neutrals to ions and capture cross sections from ions to neutrals are comparable at a given energy [64], verification can be performed in reverse using ion beams.

Reverse experiments were conducted on the 50 kV ECR ion source platform. [Figure 12: see original paper] shows the experimental setup schematic. Proton beams with energies of 5, 10, 20, 30, and 40 keV were delivered to the stripping unit entrance window. After charge exchange processes in the  $\text{H}_2$ -filled stripping chamber, the total current of remaining charged particles was measured by the downstream FC. A digital current integrator (ORTEC 439) measured FC current, with output pulses recorded by a CAEN DT5724B digitizer. Beam current without  $\text{H}_2$  gas was measured before and after each run as reference. Experiments were performed at three gas inlet pressures:  $P_0 = 20, 30,$  and  $40$  Pa for each proton energy.

In the experiment, each ORTEC 439 pulse corresponds to  $10^{-10}$  C. [Figure 13: see original paper] shows FC current versus recording time for 20 keV incident protons. Solid circles, solid down triangles, and open squares correspond to vacuum conditions at the beginning, middle, and end of 20 keV measurements.

Solid squares, solid up triangles, and open circles represent measurements with  $\text{H}_2$  gas at  $P_0 = 40, 30,$  and  $20$  Pa, respectively. Solid lines are linear fits. A slight decreasing trend of less than 0.5% over the entire recording time is observed for vacuum measurements, indicating stable long-term ECR source operation. Vacuum measurements before and after  $\text{H}_2$  runs provide good beam intensity references.

Current ratios between measurements with and without (vacuum)  $\text{H}_2$  gas were obtained from FC current ratios. Linear fits of vacuum measurements were used to extrapolate beam currents for  $\text{H}_2$  measurements. [Figure 14: see original paper] shows current ratio versus proton energy ( $E_p$ ) for  $P_0 = 20$  (solid triangles), 30 (solid squares), and 40 Pa (solid circles), with Geant4 simulations for comparison. The ratio increases rapidly with  $E_p$  above 10 keV and flattens below 10 keV, consistent with electron removal cross section ( $\sigma_{0,1}$ ) trends from Ref. [71]. Geant4 simulations reproduce this overall trend. Notable deviations between simulation and experiment occur for  $E_p \leq 20$  keV. Geant4 simulations yield nearly identical results for a given  $E_p$  across the three  $P_0$  values, likely due to breakdown of single-scattering physics accuracy below 20 keV employed in Geant4. Note that the E//B NPA's designed energy range is 20–200 keV, where scattering effects are small above 30 keV.

Scattering effects observed in reverse experiments for low-energy ( $E \leq 30$  keV) protons were used to correct stripping efficiencies from Geant4 simulations. Results are presented in [Figure 15: see original paper]. Global stripping efficiency for H and D gradually increases from 20 to 200 keV, reaching maximum values of 95.0% for H atoms and 78.9% for D atoms at 200 keV. These results demonstrate excellent stripping capability of the updated chamber for H and D atoms in the 20–200 keV range at  $P_0 = 40$  Pa.

## 5 Summary

An updated stripping unit for the newly designed E//B NPA was constructed. The relationship between vacuum chamber pressure ( $P_3$ ) and gas inlet pressure ( $P_0$ ) was measured. Using measured  $P_0$  and  $P_3$  as Ansys Fluent boundary conditions, pressure distributions inside the stripping chamber were obtained. Stripping efficiency was simulated using Geant4 Monte Carlo code. With the stripping chamber length increased from 54 mm to 84 mm and differential pipe inner radius reduced from 4 mm to 2 mm, the center pressure ( $P_1$ ) is more than three times higher than in the previous design, yielding an optimal  $P_0 = 40$  Pa—one quarter of the previous value—corresponding to  $1.27 \times 10^{17}$  atoms/cm<sup>2</sup> thickness.

A 50 kV ECR ion source platform was designed and constructed for E//B NPA calibration at Sichuan University. A more compact 2.45 GHz single-charge ECR ion source was developed, capable of providing  $\text{H}^+$ ,  $\text{H}_2^+$ , and  $\text{H}_3^+$  beams below 50 keV. Platform performance was characterized with  $\text{H}_2$  working gas, providing useful guidance for future applications.

Stripping efficiency was investigated in reverse experiments on the 50 kV platform. Proton beams at 5, 10, 20, 30, and 40 keV were delivered to the H<sub>2</sub>-filled stripping unit at P<sub>0</sub> = 20, 30, and 40 Pa. Beam current was measured by the downstream FC. Current ratios with and without H<sub>2</sub> gas were compared with Geant4 simulations, showing good trend agreement. Large deviations below 20 keV are attributed to low-energy proton scattering effects in Geant4's single-scattering physics. After scattering corrections, more precise stripping efficiencies were obtained, reaching maximum global efficiencies of 95.0% for H atoms and 78.9% for D atoms at 200 keV.

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