

A simulation study of a windowless gas stripping room in an E//B neutral particle analyzer

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Abstract

Neutral Particle Analyzer (NPA) is one of the crucial diagnostic devices on Tokamak facilities. Stripping unit is one of the main parts of the NPA. A windowless gas stripping room with two differential pipes is adopted in a parallel direction of electric and magnetic fields (E//B) NPA. The pressure distributions in the stripping chamber are simulated by Ansys Fluent together with MolFlow+. Based on the pressure distributions extracted from the simulation, the stripping efficiency of the E//B NPA is studied with GEANT4. The hadron reaction physics is modified to track the charge state of each particle in a cross section base method in GEANT4. The transmission rates (R) and the stripping efficiencies f_{+1} are examined for the particle energy ranging from 20 to 200 keV at the input pressure (P_0) ranging from 20 to 400 Pa. According to the combined global efficiency, $R \times f_{+1}$, $P_0 = 240$ Pa is obtained as the optimum pressure for the maximum global efficiency in the incident energy range investigated.

Full Text

Preamble

A Simulation Study of a Windowless Gas Stripping Chamber in an E//B Neutral Particle Analyzer

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The Neutral Particle Analyzer (NPA) is one of the crucial diagnostic devices on Tokamak facilities, and the stripping unit constitutes one of its main components. A windowless gas stripping chamber with two differential pipes is adopted for a parallel electric and magnetic fields (E//B) NPA. The pressure distributions in the stripping chamber are simulated using Ansys Fluent together with MolFlow+. Based on the extracted pressure distributions, the stripping efficiency of the E//B NPA is studied with GEANT4. The hadron reaction physics is modified to track the charge state of each particle using a cross-section-based method in GEANT4. The transmission rates (R) and stripping efficiencies $f+1$ are examined for particle energies ranging from 20 to 200 keV at input pressures (P_0) ranging from 20 to 400 Pa. According to the combined global efficiency $R \times f+1$, $P_0 = 240$ Pa is obtained as the optimum pressure for achieving maximum global efficiency across the investigated incident energy range.

Keywords: Neutral particle analyzer, windowless gas stripping chamber, stripping efficiency, Ansys Fluent, MolFlow+, GEANT4

Introduction

The Tokamak is a toroidal device used in nuclear fusion research for magnetic confinement of plasma, providing a platform to test the integrated technologies, materials, and physics regimes necessary for future commercial production of fusion-based electricity [?]. The Neutral Particle Analyzer (NPA) is one of the crucial diagnostic devices on Tokamak facilities, used to determine the bulk ion temperature, isotopic ratio, and fast ion distribution of the plasma by measuring charge-exchange neutral particles escaping from the plasma. Different types of NPAs have been built in Tokamak facilities worldwide [2–13], such as the parallel electric and magnetic fields (E//B) NPA on the Tokamak Fusion Test Reactor (TFTR) [?], the compact neutral particle analyzer (CNPA) on the Wendelstein 7-AS stellarator [?], the low- and high-energy neutral particle analyzers (LENPA and HENPA) on the International Thermonuclear Experimental Reactor (ITER) [?], the solid-state NPA (ssNPA) on the Experimental Advanced Superconducting Tokamak (EAST) [?], and the CP-NPA on the HuanLiuqi-2A (HL-2A) [?].

The stripping unit plays an important role in analyzing neutral particles, except for flux-measurement NPAs such as ssNPA [?]. It provides a region to reionize charge-exchange neutral particles. Based on the state of the stripping material, stripping units can be categorized into two types: stripping foil and gas chamber. When a stripping foil is used in the NPA for low-energy neutrals, an additional accelerating or focusing voltage is required for the secondary ions [?, ?, ?].

A carbon foil with a thickness of 100 \AA is commonly used as the stripping foil. In contrast, a gas chamber requires a differential pumping system when stripping gas is employed. Typically, an integrated target thickness on the order of 10^{16} atoms/cm² for H₂ gas is used in the Joint European Torus (JET) NPA [?], and 10^{15} atoms/cm² for He gas is used in the E//B NPA on TFTR [?].

Energetic particles, also known as fast, superthermal, hot, and high-energy particles, are expected to play a critical role in plasma heating, current drive, momentum transport, energy transfer, and plasma stability [?, ?]. Many experimental and theoretical studies have contributed to this field [16–20] and related areas [21–26] recently. Aiming to study the frontier physics of energetic particles and measure the fuel ratio, a new E//B NPA has been designed for present experimental devices [?]. This E//B NPA is a tandem-type NPA similar to the CNPA built at the Ioffe Physicotechnical Institute, Russia [?]. It will provide mass resolution (H and D resolution) for particles in the energy range of 20 to 200 keV. The magnetic field is designed to be created with a permanent magnet for smaller size and simpler maintenance. The upper limit energy of the E//B NPA is determined from the negative ion source neutral beam heating on the Huanliuqi-2M (HL-2M) device. The lower limit is set to 20 keV because we are interested in fast ions rather than background ions. For more details, we refer to our previous work in Ref. [?].

In this article, the gas stripping chamber of the new E//B NPA is designed and studied. A windowless gas stripping chamber is adopted to avoid replacement of stripping foils and enable easy maintenance in actual operation. The performance of the gas stripping chamber is investigated using Ansys Fluent [?, ?] and MolFlow+ [?], together with GEANT4 [?, ?]. This article is organized as follows: The design and pressure calculation of the gas stripping chamber are presented in Sec. II. The results of GEANT4 simulation and discussions are given in Sec. III. A brief summary is provided in Sec. IV.

II. Design and Pressure Calculation of the Gas Stripping Chamber

The stripping unit is one of the main components of the NPA, where electrons are stripped from escaped neutral particles. A windowless gas stripping chamber is adopted in the design to avoid replacement of stripping foil and enable simple maintenance. To achieve sufficiently high pressure inside the stripping chamber while maintaining high vacuum in the outside vacuum chamber simultaneously, two differential pipes with small flow conductance are used for the stripping chamber. Fig. 1 [Figure 1: see original paper] shows the schematic layout of the stripping chamber. The stripping room (1) with two differential pipes (2) of 36 mm length and 4 mm diameter is placed inside a vacuum chamber (3). Two holes with a diameter of 6 mm (7 and 8) are made on the entrance and exit flanges to limit the beam size and maximize vacuum isolation from the upstream pipe and downstream chamber. H₂ gas is used as the stripping gas

to avoid polluting the Tokamak fuel. It is filled into the stripping room from the top flange (5) of the vacuum chamber through a bellow (4). A mechanical bearing molecular pump with a pumping speed of 340 L/s is used at the bottom of the vacuum chamber together with a gate valve (11) in this work.

The pressure distribution inside the stripping chamber is one of the main concerns of our design. A pressure of dozens of Pa is required in the stripping room to achieve sufficient stripping efficiency for high-energy hydrogen (H) and deuteron (D) atoms. In this pressure region, the gas flow state in the stripping room remains in the viscous-molecular flow regime [?]. The pressure in the gas inlet and bellow is higher than that in the stripping room, while two or three orders of magnitude lower pressure is estimated in the vacuum chamber. The mean free path of gas molecules inside the vacuum chamber is larger than the chamber size, and the motion of gas molecules can be treated as collisionless. The Monte Carlo code MolFlow+ is often used to calculate pressure distributions of collisionless gas in high vacuum systems, but it is not accurate for all gas regions in the gas stripping chamber. Computational fluid dynamics (CFD) software, which includes nonlinear effects of viscous fluid, performs better in high-pressure regions. However, CFD calculations in high vacuum regions show unphysical bumps at corners. Therefore, the gas pressure distribution of the stripping chamber is calculated by combining a CFD software, Ansys Fluent [?, ?], for the viscous region in the bellow, stripping room, and differential pipes, and a Monte Carlo software, MolFlow+ [?], for the low-pressure collisionless region in the vacuum chamber.

Three-dimensional CFD calculations are performed using Ansys Fluent software. The fluid region is established according to the structure of the stripping chamber shown in Fig. 1. The laminar viscous model is adopted in the calculations. A pressure-type gas inlet is defined at the top flange (5) of the vacuum chamber, with the pressure at the gas inlet P_0 ranging from 20 to 400 Pa in steps of 20 Pa in the simulation. Three pressure-type gas outlets are defined at the entrance, exit holes (7 and 8), and the bottom of the gate valve (11). A pressure of 10^{-3} Pa is assumed for all three outlets. Due to the large flow conductance of the two differential pipes (2), small changes in outlet pressure do not affect the pressure distribution in the stripping room. Moreover, the pressure distribution in the vacuum chamber will be replaced with MolFlow+ results. Therefore, a pressure of 10^{-3} Pa at the outlets is used for all Ansys Fluent calculations. Stainless steel is set as the wall material, and room temperature of 300 K is used in the calculations. A typical gas flow rate of 9.97 Pa · L/s is obtained at the bottom of the bellow for an input pressure $P_0 = 100$ Pa.

In the low-pressure region in the vacuum chamber (3) in Fig. 1 and inside the differential pipe (2) at $|z| > 42$ mm, where $z = 0$ is set to the center of the stripping room, the pressure distribution is simulated by MolFlow+ at the same temperature of 300 K. For the MolFlow+ simulation, the outgassing rate adopted is from the Ansys Fluent calculation at $z = \pm 42$ mm inside the differential pipe, 4 mm from the pipe exit. For pumping, it is assumed that

gas molecules are absorbed when they hit the surfaces of the entrance and exit holes (7 and 8), meaning the sticking factor is set to 1 on these surfaces. This results in a pumping speed of 12.4 L/s through the entrance and exit holes. A pumping speed of 340 L/s is set at the bottom of the gate valve (11).

The simulated two-dimensional (2D) pressure distribution at $P_0 = 100$ Pa in the y - z plane at $x = 0$ is shown in Fig. 2 [Figure 2: see original paper] (a). A detailed pressure distribution around the stripping room is shown in Fig. 2 (b) in a magnified scale. The pressure distribution along the beam line is presented in Fig. 2 (c) plotted on a logarithmic scale. Using the two differential pipes in the design, the desired high pressure is achieved inside the stripping room, and a linearly decreasing pressure is observed inside the two differential pipes and the entrance and exit holes. A sharp change in pressure at the entrance of the two differential pipes is observed in the Ansys Fluent calculations, which is not found when MolFlow+ is used to simulate the entire gas region in the stripping chamber.

To evaluate how the pressure distribution changes as the pressure at the gas inlet varies, the pressures at four typical positions are examined for all investigated P_0 values. Fig. 3 [Figure 3: see original paper] shows the pressure inside the stripping room (P_1), at the entrance of the differential pipes (P_2), in the vacuum chamber (P_3), and at the outside surfaces of entrance and exit holes (P_4)—as indicated in Fig. 2 (c)—as a function of the pressure at the gas inlet P_0 . Linear relationships between P_1 , P_2 , P_3 , and P_4 with respect to P_0 are obtained, though slight fluctuations are observed. By using the two differential pipes in the design, more than 500 times lower pressure is achieved in the vacuum chamber compared to that in the stripping room. Through the entrance and exit holes, about one order of magnitude lower pressure is obtained for the upstream pipe and downstream chamber.

The integrated target thickness (nT) is an important quantity for the gas stripping chamber, commonly used to evaluate its efficiency. Since the pressures at the four typical positions are used to construct the pressure distribution in GEANT4 in the next section, a comparison between the exact nT and the nT calculated from the pressure distribution used in GEANT4 is necessary. Fig. 4 [Figure 4: see original paper] shows nT as a function of P_0 for the results of Ansys Fluent and MolFlow+ (solid circles) and that of GEANT4 (open circles). Good agreement is found between them.

III. Results of GEANT4 Simulation and Discussions

Utilizing the obtained P_1 , P_2 , P_3 , and P_4 values, the stripping efficiencies of the stripping room are further studied using GEANT4 [?, ?]. GEANT4 is a toolkit for simulating the passage of particles through matter. It has been applied in various studies, such as our previous investigations of the average neutron detection efficiency for the DETecteur MODulaire de Neutrons detectors (DEMON) [?] and the module test of the Collision Centrality Detector Array

(CCDA) [?], as well as many other studies on electron backscattering [?], the neutron time-of-flight spectrometer system at HL-2M [?], the performance of a large-size CsI detector [?], and so on.

In the GEANT4 simulation, the physics list includes electromagnetic physics [?] and hadronic physics [?], in which ion transportation, electromagnetic, nuclear elastic, and inelastic processes are activated, though some processes may not be used in the actual simulation. Since the integrated target thickness is around 10^{16} atoms/cm², where the scattering probability of incident particles and target atoms is small enough that multiple scattering is negligible, the G4ScreenedNuclearRecoil class [?, ?] is included in the standard electromagnetic physics for incident energies ranging from 10 eV to 100 MeV.

The charge state of H and D atoms is the key variable in this study. However, the original GEANT4 cannot properly handle charge state evolution. To simulate charge state variation, the hadron reaction physics is modified to track the charge state of each particle using a cross-section-based method. By introducing a global charge state variable in the hadron reaction physics, the charge state of H and D is recorded when charge exchange reactions occur in the gas stripping chamber. Many charge exchange cross-section measurements have been performed for H on H₂ gas during the last century [43–53]. Fig. 5 [Figure 5: see original paper] shows the electron loss cross sections of H⁰ ($\sigma_{0,1}$), the electron capture cross sections of H⁺ ($\sigma_{1,0}$), the electron capture cross sections of H⁰ ($\sigma_{0,1}$), and the electron loss cross sections of H⁻ ($\sigma_{1,0}$) on H₂ gas as a function of incident energy (E) in (a), (b), (c), and (d), respectively. Solid circles, solid squares, solid up triangles, solid down triangles, open circles, open squares, and open up triangles represent data from Gealy [?], Stier [?], Barnett [?], Sanders [?], Smith [?], McClure [?], and Van Zyl [?], respectively. Solid curves represent the ORNL recommended cross sections [?, ?]. Since experimental $\sigma_{1,0}$ does not cover the high-energy region above 30 keV, the ORNL recommended cross section for H atoms on H₂ gas is used in the simulation. For a given velocity, the charge exchange cross sections of D on Cs [?] or Rb [?] vapor are the same as those of H. Approximately, the incident energy per nucleon (E/A) of H and D are the same for the investigated energy range when they have the same velocity. Therefore, the charge exchange cross sections of H are also used for D at the same E/A in the simulations.

Simulations are performed for H and D on H₂ gas with incident energy ranging from 20 to 200 keV in steps of 20 keV, and with P₀ ranging from 20 to 400 Pa in steps of 20 Pa. H and D atoms are generated at the entrance hole (7) of the vacuum chamber, corresponding to the z position of -120 mm, and distributed uniformly on the entrance hole surface with a diameter of 6 mm. The momentum direction is assumed parallel to the z-axis. One million events are generated for each run. The energy loss ($\Delta E/E$) of H and D at 20 keV as a function of P₀ is shown in Fig. 6 [Figure 6: see original paper]. A slightly lower energy loss is observed for D because the mass of D is twice that of H, causing less energy loss during collisions. Linear increasing trends are found for both H and D as

P_0 increases. The maximum energy loss for 20 keV H and D is less than 4% for all investigated P_0 values. Compared to the energy resolution of this NPA, the energy loss of H and D after passing through the stripping chamber is small and can be neglected.

Since the diameter of the two differential pipes is smaller than that of the entrance and exit holes, some incident particles will be stopped by the geometry of the stripping chamber. Moreover, due to Coulomb scattering between incident particles and target atoms, some incident particles will be scattered away from their original directions. Therefore, the transmission rate (R) of incident particles is important, especially for low-energy particles that suffer more Coulomb scattering when passing through the stripping chamber. In this study, the transmission rate is defined as the ratio between the number of particles reaching the exit hole (8) after passing through the stripping chamber with H_2 gas ($P_0 > 0$ Pa) and that without gas ($P_0 = 0$ Pa, vacuum). In this way, particle loss caused by the geometry of the stripping chamber is canceled out. Fig. 7 [Figure 7: see original paper] shows the transmission rate as a function of incident energy for $P_0 = 20$ Pa (circles), 100 Pa (squares), and 400 Pa (triangles) in (a), and as a function of P_0 for incident energy $E = 20$ keV (circles), 40 keV (squares), and 100 keV (triangles) in (b). Solid and open symbols represent H and D, respectively. A slight increasing trend is observed for the transmission rate as incident energy increases, but an opposite trend is shown as P_0 increases. The scattering loss is small (less than 3%) for all investigated incident energies and input pressures.

The stripping efficiency in the stripping chamber is evaluated using a charge fraction variable (f) for incident particles after the stripping region. The evolution of charge fractions inside the stripping region is the primary concern of this study. Fig. 8 [Figure 8: see original paper] shows the charge state fraction as a function of z position in the stripping chamber for H and D atoms at 20, 100, and 200 keV. The pressures used in the simulation are those from the results of $P_0 = 100$ Pa as shown in Sec. II. Solid, dashed, and long-dashed curves correspond to the fractions of charge state 0, +1, and -1, respectively. Due to the small cross section of $\sigma_{0,-1}$, the fraction of charge state -1 is less than 2% for H and D at an incident energy of 20 keV and becomes negligible for higher incident energies. The fractions of charge state 0 and +1 show a sharp change starting from z around -40 mm because the stripping room is located at $-46 \text{ mm} < z < 46 \text{ mm}$. Due to the energy dependence of charge exchange cross sections, particles with lower incident energies have smaller saturation thickness for charge fractions. Higher stripping efficiency for particles with larger energies is mainly caused by the sharp decrease of $\sigma_{1,0}$ as incident energy increases.

Figure 9 shows the fraction of charge state +1 (f_1) at $z = 120$ mm as a function of E/A for $P_0 = 20$ Pa (circles), 100 Pa (squares), and 400 Pa (triangles) in (a), and as a function of P_0 for incident energy $E = 20$ keV (circles), 100 keV (squares), and 200 keV (triangles) in (b). Solid and open symbols represent H and D, respectively. As seen in Fig. 9 (a), f_1 increases at lower incident

energies for different P_0 values up to E/A around 100 keV. After reaching the maximum value, f_1 decreases for $P_0 = 20$ Pa, stays flat for $P_0 = 100$ Pa, but keeps slowly increasing for $P_0 = 400$ Pa as E/A increases, indicating that the thickness of stripping gas is insufficient for higher-energy particles at $P_0 = 20$ Pa. No noticeable difference between H and D is observed, indicating that the results can also be applied to neutral Tritium particles when E/A is used. As shown in Fig. 9 (b), the fractions of charge state +1 quickly reach a maximum value and remain at that maximum as P_0 increases at lower E . For larger E , the fractions increase faster at lower P_0 and reach the maximum at a pressure around $P_0 = 240$ Pa.

To verify the GEANT4 results, f_1 is also calculated using the gas integrated target thickness (nT) as:

$$f_{+1} = \frac{\sigma_{01}}{\sigma_{01} + \sigma_{10}} \{1 - \exp[-nT(\sigma_{01} + \sigma_{10})]\}.$$

The σ_{01} and σ_{10} are the stripping (electron loss) and charge exchange (electron capture) cross sections of H(D) and $H^+(D^+)$, respectively. The small amount of particle loss by electron capture of H(D), σ_{0-1} and σ_{-10} , is neglected in Eq. (1). The results are shown in Fig. 10 [Figure 10: see original paper]. The symbols represent the same f_1 values from the GEANT4 simulation in Fig. 9 (b) but plotted as a function of nT , while solid and dashed lines represent those from Eq. (1) for H and D, respectively. Good agreement is found between the calculations and GEANT4 simulations. These good agreements originate from the fact that in the GEANT4 simulation, the evaluation of f_1 is obtained from Monte Carlo sampling of the charge state along the particle track according to the cross sections of σ_{01} , σ_{10} , σ_{0-1} , and σ_{-10} . As mentioned earlier, Eq. (1) uses only part of the cross sections (σ_{01} and σ_{10}), neglecting σ_{0-1} and σ_{-10} since the latter values are orders of magnitude smaller.

To determine the optimum condition, the global efficiency—a combination of transmission rate and fraction of charge state +1, $R \times f_1$ —is further studied. Fig. 11 [Figure 11: see original paper] shows the global efficiency $R \times f_1$ as a function of P_0 for incident energy $E = 20, 100,$ and 200 keV in (a), (b), and (c), and as a function of nT in (d), (e), and (f), respectively. The global efficiency of H and D decreases gradually as pressure P_0 increases for $E = 20$ keV. On the other hand, the global efficiency shows a similar trend to that of f_1 as pressure P_0 increases for $E = 100$ and 200 keV. For pressure $P_0 > 240$ Pa, the global efficiency already becomes flat for all conditions of H and D at incident energy $E \geq 100$ keV. Considering the low temperature of the plasma in HL-2A/M, the number of high-energy particles is orders of magnitude less than that of low-energy particles. Therefore, $P_0 = 240$ Pa is obtained as the optimum pressure for maximum global efficiency across the investigated incident energy range. At this P_0 , the pressure in the vacuum chamber is less than 0.1 Pa, which is within the operating pressure range of the molecular pump. The simulation results would provide a useful guide for actual applications.

IV. Summary

The Neutral Particle Analyzer (NPA) is one of the crucial diagnostic devices on Tokamak facilities. The stripping unit is one of the main components of the NPA. A windowless gas stripping chamber with two differential pipes is adopted to maintain a certain pressure for the parallel electric and magnetic fields (E//B) NPA. The gas pressure distribution of the stripping chamber is calculated by combining a computational fluid dynamics (CFD) software, Ansys Fluent, and a Monte Carlo software, MolFlow+, for the low-pressure collisionless region in the vacuum chamber. The pressure distribution along the beam direction is obtained for different input pressures. A certain high pressure is achieved inside the stripping room, and a linearly decreasing pressure is obtained inside the differential pipes and the entrance and exit holes. More than two orders of magnitude lower pressure is achieved in the vacuum chamber compared to that inside the stripping room.

Based on the pressure distributions calculated by Ansys Fluent and MolFlow+, the stripping efficiency of the stripping chamber for H and D atoms at incident energies ranging from 20 to 200 keV is studied using GEANT4. The energy loss of H and D after passing through the stripping chamber is small and can be neglected for all investigated incident energies and input pressures. The scattering loss of H and D atoms on H₂ gas is studied through the transmission rate (R) of incident atoms. A slight increasing trend is observed for R as incident energy increases, but an opposite trend is shown as input pressure (P₀) increases. The scattering loss is small (less than 3%) for all investigated incident energies and input pressures.

A charge state variable is introduced to track the charge state of particles in the GEANT4 simulation. Adopting the ORNL recommended charge exchange cross sections in modified hadron reaction physics, the charge state of each particle is traced in the simulation. The behavior of charge fractions along the beam direction (z-axis) in the H₂ gas is investigated for E = 20, 100, and 200 keV H and D atoms. The stripping efficiency is obtained as the fraction of charge state +1 at the exit hole of the vacuum chamber (z = 120 mm). After reaching the maximum value, f₁ decreases for P₀ = 20 Pa, stays flat for P₀ = 100 Pa, but keeps slowly increasing for P₀ = 400 Pa as the incident energy per nucleon increases. f₁ quickly reaches a maximum value and remains at that maximum as P₀ increases at lower E. For larger E, the fractions increase faster at lower P₀ and reach the maximum at an input pressure around P₀ = 240 Pa.

According to the combined global efficiency R × f₁, P₀ = 240 Pa is found to be the optimum pressure for maximum global efficiency across the investigated incident energy range. The simulation results would provide a useful guide for actual applications.

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