Design and Experiment of a Laser Neutralization Beam Transport Platform for Negative Ion Sources

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Abstract

Neutral beam injection (NBI) serves as a key auxiliary heating method in magnetically confined fusion, with ion beam neutralization being its most critical step. To enhance neutral beam power and extend pulse duration, further exploration of neutralization methods is essential. Theoretically, laser neutralization can exceed 90% efficiency for negative ions, overcoming inherent limitations of gas targets such as efficiency ceilings and high gas load. However, current research remains largely focused on laser desorption diagnostics. To address key technical challenges and advance the practical application of laser neutralization, this study designed and constructed a 30 keV H^- beam transport platform capable of supporting a bow-tie laser cavity. This system enables experimental validation of laser-based H^- neutralization under varied parameters and measure efficiency measurements. Based on the collision mechanisms between H^- ions and laser photons, the factors influencing neutralization efficiency were analyzed in detail using the finite element method. Results indicate that the laser neutralization effect becomes distinguishable only when the beamline vacuum is maintained at or below 1\$×10^{-2}\$ Pa. Furthermore, when neutralization efficiency below 80% is acceptable, the presence of an appropriate amount of background gas can enhance the composite neutralization efficiency. Using a transfer matrix approach with a folding number of n = 4, key parameters of the bow-tie cavity—including incident angle ($_1$), cavity length (L), and beam spot size (w(z))—were optimized for integration with the beam transport platform. Additionally, laser power loss induced by the negative ion beam was estimated to be on the order of ~1 ppm, providing critical input for the design of laser cavity gain. Experimental performance metrics of the beam transport system align well with theoretical predictions, confirming the platform' s reliability. This setup can be further upgraded to support higher H^- beam power, facilitate laser cavity integration, and systematically investigate the effects of various parameters on laser neutralization efficiency.

Full Text

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Neutral beam injection (NBI) serves as a key auxiliary heating method in magnetically confined fusion, with ion beam neutralization being its most critical step. To enhance neutral beam power and extend pulse duration, further exploration of neutralization methods is essential. Theoretically, laser neutralization can exceed 90% efficiency for negative ions, overcoming inherent limitations of gas targets such as efficiency ceilings and high gas load. However, current research remains largely focused on laser desorption diagnostics. To address key technical challenges and advance the practical application of laser neutralization, this study designed and constructed a 30 keV H^- beam transport platform capable of supporting a bow-tie laser cavity. This system enables experimental validation of laser-based H^- neutralization under varied parameters and measurement of efficiency.

Based on the collision mechanisms between H^- ions and laser photons, the factors influencing neutralization efficiency were analyzed in detail using the finite element method. Results indicate that the laser neutralization effect becomes distinguishable only when the beamline vacuum is maintained at or below 1×10^{-2} Pa. Furthermore, when neutralization efficiency below 80% is acceptable, the presence of an appropriate amount of background gas can enhance the composite neutralization efficiency. Using a transfer matrix approach with a folding number of n = 4, key parameters of the bow-tie cavity—including incident angle ($_1$), cavity length (L), and beam spot size (w(z))—were optimized for integration with the beam transport platform. Additionally, laser power loss induced by the negative ion beam was estimated to be on the order of 1 ppm, providing critical input for the design of laser cavity gain. Experimental performance metrics of the beam transport system align well with theoretical predictions, confirming the platform' s reliability. This setup can be further upgraded to support higher H^- beam power, facilitate laser cavity integration, and systematically investigate the effects of various parameters on laser neutralization efficiency.

Keywords: negative ion based neutral beam injection (NNBI); laser neutralization; cavity folding; beam transmission; neutralizing efficiency

INTRODUCTION

Negative ion-based Neutral Beam Injection (NNBI) is one of the effective and widely used techniques in Magnetic Confinement Fusion (MCF) experiments, serving as plasma heating, current drive, and plasma diagnostics. The Experimental Advanced Superconducting Tokamak (EAST) is equipped with two tangential injection heating beam lines for neutral beams with 80 keV@4 MW@100 s, which has achieved steady-state long-pulse high-confinement mode (H-mode) plasma operation at 100 million degrees Celsius for 1066 seconds [1]. International Thermonuclear Experimental Reactor (ITER) is designed to incorporate more than two NBI systems with parameters of 1 MeV@20 MW, using negative ions (H^- or D^-) as the particle source [2, 3]. Meanwhile, the Demonstration Fusion Power Plant (DEMO) is also investigating the role of NBI in fusion power generation [4, 5]. The ion beam neutralization process is the most critical link in a NBI system, with neutralization targets including metal vapor targets, gas targets, plasma targets, and laser targets [6–13].

Currently, the gas target remains the dominant neutralization approach, relying on collisions between the negative ion beam and a co-flowing background gas, which converts the ions into neutral particles. Although the approach is structurally simple and operationally robust, its intrinsic limitations remain essentially non-removable. For example, the neutralization efficiency of gas targets is capped at approximately 60%—a threshold that fails to meet the efficiency demands of auxiliary heating systems for next-generation fusion power plants. Furthermore, increasing the gas target thickness to enhance interaction probability places severe constraints on the vacuum performance of the beam line, as higher gas loads inevitably degrade the ultra-high vacuum environment required for beam transport [6]. Laser neutralization denotes the selective photodetachment of the loosely bound electron from a negative ion (E_{photon} > electron affinity of ions, 0.75 eV for H^-) while keeping the resultant neutral atom below its first-ionization threshold (E_{photon} < first ionization energy, 13.6 eV for H). This method does not introduce new ion or molecular species and can achieve a neutralization efficiency of over 95% theoretically. Moreover, photon-ion collisions induce negligible transverse momentum exchange, leaving the beam divergence essentially unchanged and obviating the need for complex residual-ion bending and recovery optics. Consequently, laser neutralization provides a conceptually straightforward route to upgrade the power, efficiency and duty cycle of next-generation NBI systems. By removing the fundamental constraints of conventional gas-cell neutralizers, it offers a scalable solution that can satisfy the escalating neutral-beam performance requirements of future fusion reactors.

Since Fink first proposed laser neutralization [14–17], it has garnered intense interest within the NBI community [10, 12, 18, 19]. In particular, the rapid progress of magnetic-confinement fusion in recent years has imposed more stringent requirements on beam energy, power, and pulse duration, rendering key technological breakthroughs and practical viability of laser neutralization a central research focus. The group led by A. Simonin in CEA constructed a three-mirror ring cavity with F = 3700 and Q = 900 using fiber lasers, achieving a neutralization fraction exceeding 50% for a 1.2 keV H^- beam—so far the first clear experimental demonstration of laser neutralization [20]. Although this experiment validated the feasibility of laser detachment of H^- ion beams, the beam energy was still too low, and thermal effects together with intracavity optical losses were not fully addressed. For high-power laser cavities, folded resonators remain the mainstream configuration under investigation [21–23]. Nevertheless, several groups are exploring alternative optical-cavity concepts. The team led by A. Fassina in Italy designed an SHG-based pulsed-laser ring cavity that substantially enhances the intracavity optical power, yet at the cost of higher pump-laser power and increased thermo-mechanical instability of the overall optical system [24, 25]. S. S. Popov’ s group in Russia developed an adiabatic-trap cavity. Experimental results demonstrate efficient confinement of the incident laser inside the trap, with intracavity power amplified to 2.1 kW. For H^- and D^- beams below 10 keV, the neutralization efficiency can reach 95%, although this performance critically depends on mirror reflectivity and surface defects, imposing stringent requirements on high-reflectivity optics [26].

Based on the principle of H^- photodetachment, a variable-parameter beamline was designed and implemented for a laser neutralization test platform. Section II systematically introduces the H^--photon collision model and evaluates the key factors influencing neutralization efficiency. Adopting a folded resonator as the baseline architecture, Section III employs Gaussian beam transfer matrices to optimize the optical layout of a bow-tie cavity compatible with the beam transport system. Section IV details the design and integration of the beam-transport platform, including the ion source, differentially pumped vacuum system, deflection magnets, and diagnostic components. Experimental results align well with simulations, verifying the system’ s reliability. Beam transmission and neutralization efficiency are quantitatively analyzed, providing a foundation for subsequent laser-neutralization experiments.

[Figure 1: see original paper] Saturation laser power P_s versus (a) number of crossings n (w_y = 5 mm) and (b) laser spot diameter w (n = 1) for H^- beams of different energies under ideal vacuum.

[Figure 2: see original paper] Total neutralization fraction _(ph+g) for (a) 100 keV and (b) 50 keV H^- beams as a function of background pressure P and laser target thickness D.

II. LASER NEUTRALIZATION EFFICIENCY

Based on the concept of light quanta proposed by Einstein and the confirmation of the Compton effect, the interaction between light and matter can also be interpreted using the classical particle collision model [10, 20, 27]. The collision cross-section is primarily employed to describe the transition of particles between discrete and continuous states—such as photoionization and photodetachment. However, potential nonlinear effects may arise during the transition between discrete states, in which case the collision cross-section fails to fully characterize this process [28]. For a high-energy NBI system based on H$^-$ source, if a 500 keV H$^-$ beam with a beam spot size of 20 mm is considered, laser power of approximately 30 MW is required to achieve 95% neutralization efficiency using a 1064 nm laser—corresponding to a maximum laser amplitude of about 4.243×10^8 V/m. This amplitude is far lower than the threshold for tunneling ionization, confirming that the reaction between the laser and H$^-$ ions remains linear. Based on the particle-particle collision model, the theoretical formula for the laser neutralization efficiency _{ph} can be expressed as:

$$\eta_{ph} = 1 - \exp\left(-\frac{D}{w_x \cdot w_y}\right) = 1 - \exp\left(-\frac{2P}{v_H \cdot h\nu}\right)$$

where D denotes the laser "target thickness" along the ion-beam path (unit: $\mathrm{W \cdot m^{-1}}$); w_x is the laser waist perpendicular to both the ion-beam (x) and laser-propagation (z) directions (unit: m); and L_x = n · w_x gives the total interaction length as the H$^-$ beam crosses the laser beam n times. Provided the circulating power remains in the linear regime, Eq. 1 yields the saturation power P_s given explicitly in Eq. 2. Consequently, a strip-shaped cross-section and low-energy ion beam—i.e., a configuration that maximizes contact area and transit time—permits saturation to be reached at modest laser power, as demonstrated in reduced-scale proof-of-principle experiments.

For a 30 keV H$^-$ beam, the saturation target thickness is about 1.8×10^8 $\mathrm{W \cdot m^{-1}}$, with a 5 mm laser spot translating to 0.8 MW of single-pass laser power—impractical for direct delivery. Folding the interaction n times relaxes the power demand: four passes reduce the required single-pass power to 0.25 MW, as shown in Fig. 1(a). Fig. 1(b) illustrates that widening the laser sheet until the H$^-$ beam is fully embedded increases the interaction volume and reduces the required laser power, though excessive widening dilutes photon flux and diminishes efficiency. An increase in photon flux likewise boosts _{ph}. Experimentally, the H$^-$ beam should therefore be shaped into a narrow ribbon whose height matches the laser waist so that every photon inside the interaction volume contributes to detachment.

The ideal vacuum is unattainable in any real experiment. The total (laser and gas) neutralization yield was therefore recomputed for various background pressures, as shown in Fig. 2. As pressure rises above 1×10^{-2} Pa, gas stripping dominates whenever the laser target thickness D $\leq 1 \times 10^8$ W $\cdot$ m^{-1}, and re-ionization of the freshly created neutrals becomes non-negligible. Consequently, the beamline must be kept below 10^{-2} Pa; otherwise, the gas component masks the laser contribution. If an overall $\geq 80\%$ is not required, a controlled background can slightly boost the combined yield, but the accompanying multiple-scattering growth enlarges beam divergence. To exceed 80%, the only lever is to raise D. Pulsed lasers suffer more from residual gas than CW operation. Hence a narrow-line 1064 nm CW laser is recommended for the test stand.

Under 1064 nm irradiation, laser neutralization drives only the single-channel transition $H^- \rightarrow H^0$. In contrast, gas neutralization involves three species (H^-, H^0, H^+) coupled by six dominant reactions [29]. Fig. 2 shows that above 1×10^{-2} Pa the gas path dominates. We therefore tracked the species evolution at 0.05 Pa and 0.005 Pa, as shown in Fig. 3 [Figure 3: see original paper]. For both CW and pulsed lasers, the H^0 fraction rises rapidly with D and saturates, while H^- decreases monotonically until it drops below the H^+ level. The H^+ fraction stays $< 10\%$, but re-ionization is non-negligible. Without any laser, the gas component alone yields 30% (100 keV) and 40% (50 keV) neutralization at 0.05 Pa, consistent with the total in Fig. 2.

III. FOLDED CAVITY

A. Laser Depletion During Neutralization

Because laser neutralization operates in the single-photon (linear) regime, the power dissipated inside the H^- beam P_{loss} is simply (h $\cdot$ I_B), depending only on the ion current density I_B. For a 100 keV@200 A $\cdot$ m^{-2}@5 mm-diameter H^- beam, 95% neutralization at 1064 nm (1.165 eV) demands 4 MW of circulating laser power. The corresponding in-beam loss is about 18 mW—about 1% of the mirror incomplete reflection loss. Even at the highest envisaged current densities I_B, P_{loss} remains ≤ 1 ppm of the circulating power and is therefore negligible for global laser power budgeting. Yet it must be included when balancing the gain–loss budget of the enhancement cavity.

B. Optical Design of a Bow-Tie Cavity

An external ring resonator suppresses standing-wave and spatial-hole-burning effects while narrowing the linewidth, providing a robust route to single-frequency, high-power laser operation. According to the analysis in Section II, the neutralization efficiency increases linearly with D, and D scales with circulating power P, interaction length (fold number n) and spot size w. A bow-tie cavity (n = 4) is therefore chosen as the laser module for the proposed test stand. Key geometric parameters are the incidence angle $_1$, mirror separations L_1 and L_3, and the curved-mirror radius R_3, as shown in Fig. 4 [Figure 4: see original paper].

Subject to spatial constraints, both $_1$ (0°–45°) and the mirror spacing d should be minimized provided cavity performance is preserved. Using the stability factor I (−1, 1) as criterion, we construct the round-trip matrix M_{rt} ($_1$, L_1, L_3, R_3). Scanning $_1$ = 2°, 10°, 20° and R_3 = 1 m, 4 m, 8 m gives the I (L_1, L_3) maps shown in Fig. 5 [Figure 5: see original paper]. Colored regions are stable, violet corresponds to I → +1, red to I → −1.

For every I, two (L_1, L_3) pairs exist—one on each side of the I = 1 contour (dashed vs solid curves). Parametric surveys show that the dashed branch yields longer cavity lengths and larger spot sizes w, better suited to full-scale NBI systems, whereas the solid branch gives compact geometries preferred for small test benches. Restricting attention to the solid-curve branch, we find that increasing L_1 at fixed L_3 drives the stability factor I toward -1, whereas increasing L_3 at fixed L_1 drives I toward +1 but simultaneously shrinks the allowable L_1 interval. The latter makes alignment and active control more difficult. Consequently, we select (L_1, L_3) pairs that keep I close to -1. Once the curved-mirror radius R_3 is chosen, the entire (I, L_1, L_3) surface is essentially fixed. Larger R_3 widens the stable domain and increases the intracavity spot size w. Reducing $_1$ yields a more compact geometry and slightly narrows the stable region, but its influence is secondary to that of R_3.

Using the parametric data in Fig. 5, we fix $_1$ = 2°, R_3 = 8 m, L_1 (0, 1) m and L_3 (0.05, 0.5) m. Within this domain the stability factor I (0−−1), as shown in Fig. 6(a) [Figure 6: see original paper], so the cavity remains stable. The radius of curvature of the equiphase surface on M_3 shows that larger L_3 shrinks the allowable L_1 range and accelerates mode convergence. The intracavity waist is located between M_3 and M_4, and the spot size w lies between 400 µm and 1000 µm everywhere. With these baseline cavity parameters fixed, the external mode-matching telescope can now be designed and the circulating laser D that intersects the H^- beam evaluated from the cavity gain/loss budget.

IV. LASER NEUTRALIZED BEAM TRANSMISSION PLATFORM

A. Design and Experimentation of Key Components

Based on the parametric analysis of neutralization efficiency, we designed and assembled an ion-beam transport platform dedicated to laser neutralization. Performance simulations and bench tests for key components are presented below.

1. Single-aperture H^- ion Source Taking into account both volume and surface production channels, an inductively-coupled-plasma (ICP) H^- source was developed. The 13.56 MHz RF-driven source is equipped with a three-stage extraction system rated up to 50 keV and side-mounted Cs ovens, as shown in Fig. 7 [Figure 7: see original paper]. At 30 keV and otherwise identical conditions the extracted current is ~1 mA without Cs and reaches 5 mA after Cs conditioning, as detailed in Table 1 .

Table 1. Parameter values of small-size single-hole H⁻ source.

Parameters	Value (test now)	Units
Energy, E		
Intensity, I		
Beam spot size, 2r		
Dispersion angle, _d		
RF Power, P_R		
Discharge gas volume, g_{in}		
Beamline vacuum, P		

2. Beam Size Limitation and Vacuum Distribution The maximum gas flow rate for the beam source discharge is 20 sccm, and the required vacuum level in the beamline section during beam extraction must not exceed 1$×10^{-2}$ Pa. Cryogenic pumps, which typically offer pumping speeds above 10,000 L/s, involve complex installation and exhibit significant vibration, making them unsuitable for compact laser-target beamline systems. Therefore, this system employs large-diameter, high-speed molecular pump sets with high pumping capacity. Based on the vacuum chamber dimensions, the position, pumping speed, and inlet size of the molecular pump set were parametrically optimized. The final configuration features a pump port diameter of 250 mm and a hydrogen pumping speed of 1200 L/s.

Improvements in laser neutralization efficiency are accompanied by an increase in laser target thickness. The beamline chamber, typically a long narrow cylinder, exhibits a vacuum gradient along its axis. This may lead to excessively high vacuum near the beam source electrode, increasing the risk of electrical breakdown and beam divergence. To mitigate this, a limiter is introduced between the beam source and the beamline section. The air domain model of the beam transmission system and the structure of the limiter are shown in Fig. 8 [Figure 8: see original paper].

The dimensions of the limiter baffle not only control the beam size but also influence the vacuum gradient distribution throughout the chamber. Therefore, a parametric analysis was conducted on the relationship between the outlet size and the vacuum level, as shown in Fig. 9 [Figure 9: see original paper]. The beamline vacuum pressure P decreases as the aperture size is reduced. When the aperture dimensions satisfy (r_3, r_4) ≤ (0.02 m, 0.1 m), the vacuum level in the beamline section is below 1$×10^{-2}$ Pa, meeting the beam extraction requirements. At (r_3, r_4) = (0.015 m, 0.05 m), 87% of the ion beam passes through completely, and P reaches approximately 0.005 Pa. With the limiter outlet size set to (r_3, r_4) = (0.02 m, 0.1 m) and a continuous H_2 gas flow of 5 sccm introduced at the beam source inlet, the measured vacuum distribution is shown in Fig. 9. When the gas flow rate is increased to 20 sccm, the average steady-state vacuum in the chamber remains below 0.01 Pa, consistent with simulation results and sufficient for beam extraction under discharge conditions. As the gas flow increases, the pressure difference across the limiter baffle becomes more pronounced, but the system quickly recovers to the static vacuum level after the gas supply is shut off. Further reducing (r_3, r_4) can simultaneously achieve lower P and flatten the beam cross-section profile.

3. Magnetic Field Distribution Considering the structural design and dimensional constraints of the beamline system, a magnetic deflection scheme was adopted in the experimental platform. The core consists of sintered permanent magnets, while the external magnetic circuit yoke is made of industrial soft iron with a permeability of 4000. The schematic of the resulting magnetic deflection structure is provided in Figure 11 [Figure 11: see original paper].

Permanent magnets offer a compact and cost-effective means of deflecting small-scale ion beams, though their fixed magnetic field necessitates precise magnetic circuit design—including optimization of air gaps and relative positioning—to achieve the desired field distribution. To maximize performance, minimize magnet replacement frequency, and accommodate a broader range of ion beam energies, the magnet system was designed according to the following principles: (a) the magnetic flux density B must be sufficient to ensure that all residual charged ions across the full energy range (E_{max}, E_{min}) are captured by the unneutralized ion target; (b) the deflection magnet must be manufacturable within the specified dimensional and magnetic constraints; and (c) the magnetic yoke must effectively confine stray fields to avoid interference with beam transmission.

Assuming a uniform magnetic field B within a region of dimensions (d_x, d_y, d_z) generated by the permanent magnet, the exit displacement l and emission angle _E of ions at different energies can be determined from the Lorentz force law, as shown in Figure 12(a) [Figure 12: see original paper]. It is observed that as d_x increases and d_z decreases, B decreases gradually, while the deflection radius R and exit displacement l increase. Accordingly, the dimensions of the permanent magnet (l_{cx}, l_{cy}, l_{cz}) and magnetic circuit parameters (l_{mt}, l_a, d_y) must be optimized to achieve a suitable B such that l for ions across energy levels remains compatible with the chamber dimensions. To ensure both physical realizability and experimental practicality, the operating range of the magnetic field region was set to d_x (0.1, 0.3) m and d_z (0.1, 0.2) m. Simulations were conducted for three ion beam energies (10 keV, 20 keV, and 30 keV) to evaluate B and l across combinations of (d_x, d_z), presented in Figure 12(b) [Figure 12: see original paper].

The data indicate that under fixed (d_x, d_z, l) conditions, the required flux density follows B_{10keV} < B_{20keV} < B_{30keV}. If a uniform field B = B_{10keV} is applied, the corresponding exit displacements satisfy l_{10keV} < l_{20keV} < l_{30keV}. Contour plots further reveal that different (d_x, d_z) pairs can produce equivalent magnetic effects—though replacing permanent magnets during operation is infeasible. Based on these findings and system layout constraints, an optimal parameter set (d_x, d_z, B) was derived, as summarized in Figure 13 [Figure 13: see original paper]. Considering manufacturability of compact magnets, a configuration with (d_x, d_z) = (0.1 m, 0.2 m) was selected. At the maximum required flux density of 0.1 T in the central region, the exit displacement ranges from 0.3 m to 0.5 m, preventing beam interaction with the magnet structure. At the minimum field strength of 0.05 T, l varies between 0.6 m and 1.0 m, still effectively deflecting H^- ions in the 10-30 keV range onto the target without impinging on the chamber walls.

Among soft magnetic materials, pure iron exhibits the highest permeability and can withstand a maximum B of up to 2 T, making it a common choice for magnetic circuit construction. For a permanent magnet with dimensions (d_x, d_z) = (0.1 m, 0.2 m), Kirchhoff' s law for magnetic circuits indicates that the minimum thickness l_{mtz} of the external yoke should be no less than 2 mm. Parametric simulations were conducted to evaluate the effects of the remanent flux density B_n of the permanent magnet, the relative distance d_y, the air gap thickness l_{ax}, and the yoke thickness l_{mtz}. The resulting distribution of B along the central axis of the beam channel is shown in Figure 14 [Figure 14: see original paper].

When B_n of the permanent magnet ranges between 0.4 T and 0.6 T, B in the central region of the beam channel can be adjusted from 0.05 T to 0.1 T by varying d_y. As d_y increases, B decreases in a manner resembling uniformly decelerated motion, with the B profile becoming sharper and the region of uniform magnetic field contracting. Under consistent conditions, B decreases proportionally with increasing l_{ax}, while the extent of the uniform field region remains largely unchanged. Variations in l_{mtz} have negligible influence on B and do not significantly alter the uniformity of the magnetic field. However, increasing l_{mtz} helps reduce the volumetric magnetic flux density within the yoke, thereby improving magnetic saturation resistance. Based on the above parametric analysis, the main design parameters of the deflection magnet are summarized in Table 2 .

Table 2. Parameter values of the magnetic components.

Symbol	Value	Units
Permanent magnet		
l_{mtx}		
l_{mty}		
l_{mtz}		
l_{az}		
Air gap		
Remanence B_n		

Figure 15 [Figure 15: see original paper] presents the spatial magnetic field distribution of the deflection magnet under the parameters listed in Table 2. Figures 15(a) and 15(c) show the magnetic field distributions on the XOY and XOZ cross-sections, respectively, with contours indicating lines of constant B. The results demonstrate a uniform magnetic field within the beam channel, with the majority of magnetic flux confined inside the yoke. The fringe field is approximately 100 Gs, which is negligible with respect to beam transmission. The central region exhibits B of approximately 0.05 T. Figures 15(b) and 15(d) compare simulated and measured B profiles along selected lines in the XOY and XOZ planes. The measured values at various geometric positions show excellent agreement with simulation results, confirming the accuracy of the measurement methodology. The measured central B is consistently around 0.05 T, indicating that the magnet meets the design requirements and is suitable for deflecting residual ions in the beam transmission test platform.

4. Thermal Stress Distribution The H^- beam generated by the single-aperture ICP source exhibits relatively low power. Beam transmission results indicate that the maximum power density at the limiter is approximately 0.1 W/mm^2. Nevertheless, the thermodynamic performance of beamline components must be considered, and diagnostic measures should be implemented to ensure operational safety. The primary thermal-bearing components in the system are the beam-limiting aperture and the particle beam dump, both fabricated from oxygen-free copper. Based on the vacuum analysis presented in Section IV A 2 and the beam size parameter r, a thermodynamic analysis was conducted for limiters with two aperture configurations—(r_3, r_4) = (15 mm, 50 mm) and (5 mm, 50 mm)—across a range of thicknesses, under a beam exposure time of 10 seconds.

As shown in Fig. 16(a) [Figure 16: see original paper], for thicknesses varying from 2 mm to 15 mm, the maximum equivalent stress in the limiter is approximately 75 MPa, well below the yield strength of oxygen-free copper. The highest stress occurs near the stainless steel mounting bolts. The red asterisks indicate maximum temperature rises of 16.39 K and 9.74 K under steady-state experimental conditions for the two aperture sizes, respectively. The black curve shows that deformation remains below 1%, confirming that the limiter effectively constrains the beam size during operation. To prevent beam divergence from causing spot enlargement beyond the limiter aperture, a 2 mm-thick oxygen-free copper backup plate matching the inner diameter of the chamber was installed behind the limiter. Thermodynamic simulation results confirm the structural reliability of this design, as represented by the three green symbols in Fig. 16(a).

Fig. 16(b) [Figure 16: see original paper] presents the thermal stress results for the beam dump across thicknesses ranging from 1 mm to 5 mm. The maximum temperature rise remains below 42 K throughout this range. To align with the typical accuracy of thermocouples, a 2 mm-thick dump plate was selected for the experimental platform. The temperature distribution under maximum thermal load is illustrated in Fig. 16(c) [Figure 16: see original paper], which informed the placement of thermocouples for experimental monitoring. Additionally, the inset in Fig. 16(b) shows the temperature evolution of the beam dump over time. The temperature returns to near-initial levels after 25 seconds, suggesting that an interval exceeding three times the duration of each experiment (10 s) should be allowed between consecutive runs.

B. Beam Transmission and Neutralization Efficiency

The beam source and beamline components, as designed and analyzed above, were integrated to form the beam transmission system, with a physical assembly shown in Fig. 17 [Figure 17: see original paper]. Beam transmission performance and neutralization efficiency under this system configuration were subsequently calculated, as presented in Fig. 18 [Figure 18: see original paper].

Based on the analysis of beam channel vacuum levels in Section IV A 2, two types of beam-limiting structures with dimensions (r_3, r_4) = (0.015 m, 0.05 m) and (r_3, r_4) = (0.005 m, 0.05 m) were selected, denoted as operating under background gas conditions P_1 and P_2, respectively, corresponding to beamline vacuum levels of 0.01 Pa and 0.005 Pa. As shown in Fig. 18, under vacuum conditions ($P_1 = P_2 = 0$), the laser neutralization efficiency for both aperture configurations matches the theoretical value, confirming the high reliability of the simulation methodology.

In the presence of background gas, the composite neutralization efficiency _(ph+g) increases monotonically with laser D. However, at larger target thicknesses, _(ph+g) remains lower than the laser-only neutralization efficiency _{ph}, indicating that background gas-induced reionization constitutes a non-negligible error source. At smaller laser D, the gas target plays a dominant role, leading to a higher _(ph+g) compared to _{ph}. The transition occurs at approximately 85% efficiency, consistent with the results presented in Fig. 5 in Section II, demonstrating that increasing the laser D is the only means to achieve a neutralization efficiency exceeding 80%.

Under the P_1 and P_2 structural and vacuum configurations, the thermal distributions of the deflected residual H^- and H^+ ion beam spots after the neutralization of a 30keV@5mA@3cm H^- ion beam are shown in Fig. 19 [Figure 19: see original paper]. Under both vacuum conditions, the H^- and H^+ beam profiles exhibit an elongated shape with maximum dimensions of approximately 5 cm × 16 cm, which can be effectively captured by the measurement target. The intensity of the H^- beam decreases gradually with increasing laser target thickness, whereas the H^+ beam shows no significant variation, necessitating higher-sensitivity detection methods. Therefore, the neutralization efficiency can be expressed as _(ph+g) = A_{Target} / (A_H$^-$ + A_H$^+$ + A_{Target}). However, in practice, due to the influence of the gas target and beam divergence, the denominator term (A_H$^-$ + A_H$^+$) is underestimated, leading to an overestimation of the measured neutralization efficiency. Furthermore, negative ions propagate under mutual space-charge repulsion, while neutral particles are unaffected by space-charge effects. As a result, the measured variation in neutral current is greater than that in ion current, causing the actual neutralization efficiency to be lower than the calculated value. These factors must be comprehensively considered in the analysis.

V. CONCLUSION AND PROSPECTS

Negative ion neutralization is a critical process in neutral beam injection heating for magnetic confinement fusion. Laser neutralization offers a promising alternative to conventional gas targets, which are limited to approximately 60% efficiency. This method also reduces vacuum system load and supports long-pulse operation. Current research on laser neutralization is being actively pursued across multiple fusion devices. This study systematically investigated the interaction mechanisms between high-energy H^- ion beams and high-power lasers, analyzing the underlying collision physics and key influencing parameters. Neutralization efficiency and beam composition evolution were evaluated under various laser types and background gas conditions. The results emphasize the necessity of maintaining a beamline vacuum of $\leq 10^{-2}$ Pa to clearly distinguish laser-induced effects from gas-target interactions. Furthermore, when neutralization efficiency below 80% is acceptable, a controlled background gas presence can enhance overall efficiency.

Using Gaussian beam transmission matrices, the optical parameters of a bow-tie cavity were optimized. Under the configuration $_1 = 2°$, $R_3 = 8$ m, L_1 (0, 1) m, and L_3 (0.05, 0.5) m, the beam spot size was maintained within 400–1000 µm. The laser photon depletion caused by the negative ion beam was found to be approximately 1 ppm, which is negligible relative to the laser power but relevant for the design of enhancement cavities. A 30 keV H^- ion beam laser neutralization platform was designed and built, incorporating an ion source, a differentially pumped vacuum system, and a magnetic deflection system. Experimental results consistently aligned with simulations, confirming system reliability and suitability for studying laser neutralization under varied parameters.

To support accurate efficiency measurements in future experiments, the spatial distributions of H^- and H^+ ions were quantitatively analyzed. Incomplete neutralization may lead to underestimation of (A_H^- + A_H^+), highlighting the need for diagnostics with higher precision, broader dynamic range, and compatibility with long-pulse operation. Nevertheless, extended pulse durations may introduce cumulative thermal effects, which warrant careful consideration in experimental planning.

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VI. BIBLIOGRAPHY

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Note: Figure translations are in progress. See original paper for figures.