Design and Experimentation with 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, the 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 (θ_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

Preamble

Design and Experimentation with a Laser Neutralization Beam Transport Platform for Negative Ion Sources∗ Hui-Hui Hong,1, 2 Li-Zhen Liang,1 Bin Li,1, 2 Hao-Zhi Zhang,1, 2 Qian-Xu Wang,1, 2 Fang Wang,1, 2 Yue Yun,1, 2 Hao-Ran Xie,1, 2 and Yuan-Lai Xie1, † 1Institute of Plasma Physics, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei, 230031, China 2University of Science and Technology of China, Hefei, 230026, China 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% ef- ficiency 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, the study designed and constructed a 30 keV H− beam transport platform capable of supporting a bow-tie laser cavity. This system enables ex- perimental 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. Fur- thermore, 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 crit- ical 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; neu- tralizing 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 Ex- perimental 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 [1–6], marking significant progress toward fu- sion engineering [7]. The Comprehensive Research Facil- ity for Fusion Technology (CRAFT) includes a negative ion- based neutral beam injection (NNBI) system designed to de- liver a beam energy of 200–400 keV, a neutral power of 2 MW, and a pulse duration of 100 s [8, 9]. Key achievements have been experimentally demonstrated, including the extrac- tion and acceleration of high-energy, high-current, uniform large-area negative ion beams [10–12], a stable gas target ef- ficiency of approximately 60% [13] , the effective removal of residual ions via electrostatic deflection, and the entire beam ∗ Supported by the Comprehensive Research Facility for Fusion Technology Program of China under Contract No. 2018-000052-73-01-001228. † Corresponding author, Yuan-Lai Xie, laurrence@ipp.ac.cn transport process [14–17]. International Thermonuclear Ex- perimental 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 [18, 19].

Meanwhile, the Demonstration Fusion Power Plant (DEMO) is also investigating the role of NBI in fusion power genera- tion [20, 21]. The ion beam neutralization process is the most critical link in a NBI system, with neutralization targets in- cluding metal vapor targets, gas targets, plasma targets, and laser targets [22–29]. Currently, gas targets are the dominant neutralization method, relying on collisions between negative ions and background gas to produce neutrals. While simple and robust, this approach has inherent limitations that efficiency is capped near 60%, insufficient for next-generation fusion reactors, and higher gas densities compromise beam- line vacuum quality, impairing beam transmission [22]. Laser neutralization, in contrast, uses photons with energy between the electron affinity of H− (0.75 eV) and its ionization thresh- old (13.6 eV) to detach the extra electron without ionizing the resulting atom. Theoretically achieving over 95% effi- ciency, it introduces no additional gas load or ion species and induces negligible beam divergence. This eliminates the need for complex ion recovery systems and offers a scalable path toward higher power, efficiency, and duty cycle in future neu- tral beam injection systems.

Since Fink first proposed laser neutralization [30, 31], it has garnered intense interest within the NBI community [26, In particular, the rapid progress of magnetic- 28, 32, 33]. confinement fusion in recent years has imposed more strin- gent requirements on beam energy, power, and pulse dura- tion, 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 finesse 3700 and enhancement factor 900 using fiber lasers, achieving a neutralization fraction exceed- ing 50% for a 1.2 keV H− beam—so far the first clear exper- imental demonstration of laser neutralization [34]. Although this experiment validated the feasibility of laser detachment of H− ion beams, the beam energy was still too low, and ther- mal effects together with intracavity optical losses were not fully addressed. For high-power laser cavities, folded res- onators remain the mainstream configuration under investiga- tion [35-37]. Nevertheless, several groups are exploring al- ternative 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 [38, 39].

S. S. Popov’ s group in Russia developed an adiabatic-trap cavity. Experimental results demonstrate efficient confine- ment 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 [40]. The Tsinghua University accelerator team has achieved stable 500 kW infrared laser output in a high-finesse (35,000) enhancement cavity, advancing high- power laser–radiation interaction and modulation and paving the way for future MW-scale systems [41–45]. The NBI team at ASIPP has demonstrated world-class performance in long- pulse, high-current-density (>200 A/m2) H− ion extraction and megawatt-level neutral beam injection. However, the 60% efficiency limit of gas targets during long-pulse oper- ation limits power scaling and places strain on the cryogenic vacuum system. Laser neutralization is therefore critical for enhancing NBI performance, and a dedicated roadmap has been established [46].

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 em- ploys 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, differen- tially pumped vacuum system, deflection magnets, and diag- nostic components. Experimental results align well with sim- ulations, verifying the system’ s reliability. Beam transmission and neutralization efficiency are quantitatively analyzed, providing a foundation for subsequent laser-neutralization ex- periments.

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 [26, 34, 47]. The collision cross-section is primarily employed to describe the transition of particles between dis-

> crete and continuous states—such as photoionization and photodetachment. However, potential nonlinear effects may arise during the transition between dis- crete states.

In such cases, the collision cross-section fails to fully characterize this process [48-51]. The H− beam in the NBI system is a high-energy negative hydrogen ion beam composed of one proton and two electrons.

It can achieve a significant momentum change when interacting with high laser field. However, due to the relatively large mass of H− ions and the enormous difference between the laser fre- quency and the plasma frequency, the effect of the pondero- motive force, which characterizes the nonlinear effect, is negligible. 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 re- quired to achieve 95% neutralization efficiency using a 1064 nm laser —corresponding to a maximum laser amplitude of about 4.243 × 108 V/m. This amplitude is far lower than the threshold for tunneling ionization, confirming that the reac- tion between the laser and H− ions remains linear. Based on the particle-particle collision model, the theoretical formula for the laser neutralization efficiency ηph and saturation laser power Ps can be expressed as: (cid:34) ηph = 1 − exp (cid:34) = 1 − exp (cid:114) 2 (cid:114) 2 υH− · hν (cid:35) (cid:35) υH− · hν , D = (cid:114) π υH− · wy (wx · wy) In Eq. (1), P denotes the required laser power (unit: W); D denotes the laser "target thickness" along the ion-beam path (unit: W/m); wx is the laser waist perpendicular to both the ion-beam (x) and laser-propagation (z) directions (unit: m); υH− represents the forward velocity of the H− ion beam (unit: m/s); hν stands for the single-photon energy (unit: J), and Lx = n · wx gives the total interaction length as the H− beam crosses the laser beam n times. Provided the cir- culating power remains in the linear regime, Eq. (1) yields the saturation power Ps given explicitly in Eq. (2). Con- sequently, 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. Fig. 1 [Figure 1: see original paper] summarises the corresponding parameter for the ideal-vacuum neutralization efficiency obtained under these assumptions.

Fig. 1. Under vacuum conditions, (a) the relationship between the required laser power P and laser wavelength λ as well as neutral- ization efficiency for H− beams with different energies EH− ; the saturated laser power PS varies with (b) the number of beam cross- ings n (wy = 5 mm) and (c) the beam spot diameter w (n = 1).

For the high-energy NBI, assuming that the beam spot size of H− ions is dH− = 20 mm, the relationship between laser power P and H− ion beam energy EH− , laser wavelength λ as well as neutralization efficiency is illustrated in Fig. 1(a).

It can be seen from the figure that for a 500 keV H− beam, a minimum laser power of 30 MW is required to achieve a neutralization efficiency of 95% with a single laser beam of 1064 nm.

In practical NBI devices, the extraction surface is sufficiently large, so a single laser beam cannot achieve full coverage of the H— beam spot, thus an additional laser array layout is required on the cross-section of the H— beam spot. For a 30 keV H— beam, the saturation target thickness is about 1.8 × 108 W • m-1, with a 5 mm laser spot translating to 0.8 MW of single-pass laser power—impractical for direct delivery.

Fig. 1(b) demonstrates that the saturated laser power PS required for the H— ion beam in the energy range of 30-200 keV decreases exponentially with an increase in the num- ber of laser beam foldings n (the interaction n times). For in- stance, four foldings ($n = 4$) can reduce PS from 0.8 MW to

0.25 MW, as indicated by the blue line in Fig. 1(b). Fig. 1(c)

shows that, under the same ion beam conditions, expanding the cross-sectional size w of the laser beam spot to fully en- close the H— ion beam within the laser flux region is equiv- alent to increasing the laser power required for the neutral- ization process, thereby enhancing the laser neutralization ef- ficiency. Experimentally, the H— beam should therefore be shaped into blade-shaped beam 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.

Further analytical investigations were conducted on the neu- tralization process in the presence of background gas. As illustrated in Fig. 2 [Figure 2: see original paper], the combined neutralization efficiency ηph+g was calculated under different vacuum levels PV . With the increase of background gas density, gas-neutralization gradually dominates, especially under the conditions of low laser target thickness D and vacuum level PV > 10−2 Pa. For example, as can be seen from the upper panels of Figs. 2(a) and (b), for 50 keV (100 keV) H— beams, when $D \leq 2 \times$

108 W/m ($\leq 3 \times$ 108 W/m), ηph+g under PV > 0.01 Pa

is higher than that under PV < 0.01 Pa. Under such cir- cumstances, further increasing D yields a negligible improve- ment in neutralization efficiency. Consequently, the beamline must be kept below 10−2 Pa; otherwise the gas component masks the laser contribution. In "turning disadvantages into advantages", if the neutralization efficiency is not re- quired to exceed 80% under certain experimental conditions, the presence of background gas with an appropriate density is conducive to enhancing ηph+g and can simultaneously com- pensate for the beam divergence induced by space-charge ef- fects. Nevertheless, it should not be overlooked that an exces- sively high background gas density will lead to an increase in beam divergence. It can also be observed from Fig. 2 that the only approach to achieve a neutralization efficiency exceed- ing 60% (the theoretical limit of gas targets) is to increase the laser target thickness.

The lower panels of Figs. 2(a) and (b) demonstrate the ηph+g under pulsed laser irradiation. Under the identical conditions of background vacuum, laser target thickness and ion beam parameters, the neutralization efficiency induced by continuous-wave (CW) lasers is higher than that induced by pulsed lasers (PL), being approximately a factor of (the duty cycle)1/2, and it is more significantly affected by the back- ground vacuum level. Although the peak power density of pulsed lasers can more easily meet the demand of MW/cm2, the duty cycle directly affects the power fluctuation of neutral beam injection. Therefore, it is practically recommended to adopt a narrow-linewidth CW laser operating at 1064 nm.

Under 1064 nm irradiation, laser neutralization drives only the single-channel transition H− → H0. In contrast, gas neu- tralization involves three species (H−, H0, H+) coupled by six dominant reactions [52, 53]. 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 H0 fraction rises rapidly with D and saturates, while H− decreases monotoni- cally until it drops below the H+ level. The H+ fraction stays III. FOLDED CAVITY A. Laser Depletion During Neutralization Because laser neutralization operates in the single-photon (linear) regime, the laser power dissipated inside the H− beam Ploss is simply as (hν · IB/e), depending only on the ion current density IB. For a 100 keV@200 A · m-2@5 mm-diameter H− beam, 95% neutralization at 1064 nm (1.165 eV) demands 4 MW of circulating laser power. The corre- sponding in-beam loss is about 18 mW—about 1 % of the mirror incomplete reflection loss. Even at the highest envisaged current densities IB, the photodetachment loss remains at the magnitude of 1 ppm, which is negligible compared with the global laser power budgeting. Yet it must be included when balancing the gain-loss budget of the enhancement cav- An external ring resonator can effectively suppress the standing-wave effect and spatial hole-burning effect inside the cavity while narrowing the linewidth, providing a robust route to single-frequency, high-power laser operation.Owing to differences in experimental conditions and the manufactur- ing technology level of cavity mirrors, the main sources of loss—apart from the photodetachment loss in the neutraliza- tion process—include the incomplete reflection loss of high- reflectivity mirrors and intrinsic intracavity losses (i.e., mir- ror scattering, absorption, and round-trip losses), which can be characterized via the resonance mechanism. In a typical empty-cavity configuration, the mode stability can be deter- mined using matrix optics, which will be elaborated on in the next section. When the intracavity mode is matched with the incident laser, the loss is dominated by mirror absorption and scattering. Otherwise, the loss is mainly induced by mir- ror transmission. For high-reflectivity mirrors, the scattering loss is generally less than 10 ppm, the absorption loss is typi- cally below 1 ppm, and the transmission loss is usually under 10 ppm. In particular, the transmission loss of the input cou- pler may be relatively high, approximately 100 ppm. In addi- tion, the geometric deflection loss increases with the number of reflections. After a finite number of round trips between the two mirrors, the light will inevitably escape from the cav- ity. Assuming that the laser propagates in a resonator with cavity length L and transverse dimension dM , if the cavity mirrors form a small angle β, the corresponding geometric loss $\delta\beta$ is approximately (cid:112)βL/2dM .

B. Optical Design of a Bow-Tie Cavity Based on the theoretical analysis presented in Section II, the laser neutralization efficiency is positively correlated with the laser target thickness D, while D is closely associated with the laser power P , interaction length along the H− beam transport trajectory (the number of beam foldings n), and spot size w.

Increasing n is equivalent to increasing the laser target thickness and reducing the incident laser power per beam Fig. 2. Total neutralisation fraction η(ph+g) for (a) 100 keV and (b) 50 keV H− beams as a function of background pressure P and laser target thickness D.

Fig. 3. Evolution of beam species during neutralization for (a) 100 keV and (b) 50 keV H− beams at 0.05 Pa and 0.005 Pa background pressures as a function of laser target thickness D. < 10%, but re-ionisation is non-negligible. Without any laser, the gas component alone yields 30% (100 keV) and 40% (50 keV) neutralisation at 0.05 Pa, consistent with the total η in Fig. 2. path. The F-P cavity can be employed for n = 1, the three- mirror cavity for n = 2, and the bow-tie cavity as illustrated in the Fig. 4 [Figure 4: see original paper] below for n = 4, where the H− beam can pass through the laser beam four times. According to Section III A, a higher value of n will increase the cavity loss. It is thus con- ceivable to add multiple bow-tie cavities along the H− beam transport trajectory, which corresponds to interaction times that are integer multiples of four. 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 L1 and L3, and the curved-mirror radius R3, see Fig. 4. makes alignment and active control more difficult. Conse- quently, we select (L1, L3) pairs that keep I close to -1. Once the curved-mirror radius R3 is chosen, the entire (I, L1, L3) surface is essentially fixed. Larger R3 widens the stable do- main and increases the intracavity spot size w. Reducing $ $1 yields a more compact geometry and slightly narrows the sta- ble region, but its influence is secondary to that of R3.

Fig. 4. Ray-trace schematic of the bow-tie ring cavity.

Subject to spatial constraints, both $ 1(0°–45°)*andthemirrorspacingdshouldbeminimizedprovidedcav−ityperformanceispreserved.AcyclictransfermatrixMrt*($1, L1, L3, R3) is constructed with the input coupler M1 as the reference plane. Based on the eigenmode transforma- tion of stable resonators, the relationships between the param- eters can be derived, as shown in Eq. (3) and Eq. (4).

Mrt = (cid:19) (cid:18)A B (cid:18)1 0 (cid:18) 1 (cid:19) (cid:18)1 L4 (cid:19) (cid:18) 1 −1/f3 1 (cid:19) (cid:18)1 L2 (cid:19) (cid:19) (cid:18)1 L3 −1/f4 1 (cid:19) (cid:18)1 L1 (cid:19) (cid:18)1 0 (cid:20) 1 (cid:21)2 (A + D) (cid:19) Scanning \$ \$1 = 2, 10°, 20° and R3 = 1 m, 4 m, 8 m gives the I (L1, L3) maps shown in Fig. 6 [Figure 6: see original paper]. Coloured regions are stable, violet corresponds to I → +1, red to I → −1. For every I, two (L1, L3) 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 L1 at fixed L3 drives the stability factor I toward -1, whereas increasing L3 at fixed L1 drives I toward +1 but simultaneously shrinks the allowable L1 interval. The latter Fig. 5 [Figure 5: see original paper]. With \$ $1 = 2andR3 = 8mfixed : (a)stabilityfactorI, (b)intracavitywaistw'$ \$ 0 (mid-plane between M3-M4), (c) spot sizes w1 (M1) and w3 (M3), and (d) wave-front curvature R′ 3 on M3 as functions of (L3, L1).

Combined with the parametric analysis results presented in Fig. 5, the incident angle was set as \$ \$1 = 2 ∘ , R3 = 8 m, L1 (0, 1) m and L3 (0.05, 0.5) m. The parameter con- figuration of the resonator satisfying the requirements of this paper was thus determined, as illustrated in Fig. 5. Fig. 5(a) depicts the variation of the resonator stability factor I for dif- ferent (L1, L3) combinations. All results fall within the range of 0–1, indicating that the resonator remains stable when L1 is in the range of (0–1) m and L3 is within (0.05-0.5) m.

The curvature radius of the equiphase surface R′ 3 on mirror M3 demonstrates that: the smaller the value of L3, the wider the adjustable range of L1, and R′ 3 decreases accordingly to a value close to R3/2. Conversely, R′ 3 approaches the set value of R3, meaning that the eigenmode is more readily achieved, as shown in Fig. 5(d). Figs. 5(b) and (c) show the variation of the laser spot size w(z) at different positions inside the res- onator. As L1 and L3 increase, w at all positions increases from a minimum of 400 µm to approximately 1000 µm. The growth rate of w3 on cavity mirror M3 is higher than that of w1 on cavity mirror M1, with the laser waist located between M3 and M4. 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.

Fig. 6. Stability factor I (L1, L3) for \$ \$1 = 2, 10°, 20° and R3 = 1 m, 4 m, 8 m.

IV. LASER NEUTRALIZED BEAM TRANSMISSION PLATFORM

1. Single-aperture H— ion Source

A. Design and Experimentation of Key Components Based on the parametric analysis of neutralization effi- ciency, we designed and assembled an ion-beam transport platform dedicated to laser neutralization. Performance simu- lations and bench tests for key components are presented. H− ions are generated via radiofrequency (RF) discharge. After undergoing extraction, filtering, and acceleration, they inter- act with photons to become neutral particles. Subsequently, the particles are deflected by a magnetic field and separated into H−, H+, and H0 beams. All of which are striking on the receiver, generating electric current and heat. The laser conditions in the interaction zone are derived from the cal- culation results presented in Chapter 3. The particle beam transport, collision, electromagnetic interaction, and thermal analysis are fully coupled, and the results are obtained simul- taneously by means of finite element modeling.

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 30 keV and side-mounted Cs ovens.Fig. 7 Figure 7: see original paper shows a cross-sectional view of the entire beam source structure excluding the insulating housing. H− ions are generated in the discharge chamber, extracted Fig. 7(b) presents an enlarged schematic diagram of the three-stage electrode structure in Fig. 7(a), where three pairs of filtering and correction magnets are integrated into the design. Figs. 7(c) and (d) display the overall structural drawing and the actual photograph, respectively. At 30 keV and otherwise identical conditions the extracted current is sta- ble ~0.14 mA, as detailed in Table 1 .

Fig. 7. ICP H− source: (a) cross-section drawing; (b)three-electrode size; (c)overall structure drawing; (d)the actual object.

Table 1. Parameter values of small-size single-hole H− source Fig. 8 [Figure 8: see original paper]. Air domain model of the beam system and limiter structure.

Parameters Energy, E Beam current, I Beam spot size, 2r Beam divergence, θd RF Power, PRF Units Value mA 0.14 mrad 20 W 200 Beam source gas flux, gm sccm 10 Beamline vacuum, Pv tion 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 (r3, r4) ≤ (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 (r3, r4) = (0.015 m, 0.05 m), 87% of the ion beam passes through completely, and P reaches approximately 0.005 Pa.

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 beam- line 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 em- ploys large-diameter, high-speed molecular pump sets with high pumping capacity. Based on the vacuum chamber di- mensions, the position, pumping speed, and inlet size of the molecular pump set were parametrically optimized. The fi- nal 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 in- crease in laser target thickness. The beamline chamber, typi- cally 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 break- down and beam divergence. To mitigate this, a limiter is in- troduced 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.

The dimensions of the limiter baffle not only control the beam size but also influence the vacuum gradient distribu- Fig. 9. Pumping test results of the beam transmission platform.

With the limiter outlet size set to (r3, r4) = (0.02 m, 0.1 m) and a continuous H2 gas flow of 5 sccm introduced at the beam source inlet, the measured vacuum distribution is shown in Fig. 10 [Figure 10: see original paper]. When the gas flow rate is increased to 20 sccm, the average steady-state vacuum in the chamber remains be- low 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 baf- fle becomes more pronounced, but the system quickly recov- ers to the static vacuum level after the gas supply is shut off.

Further reducing (r3, r4) can simultaneously achieve lower P and flatten the beam cross-section profile.

Fig. 11 [Figure 11: see original paper]. Schematic of the magnetic deflection structure. flection magnet must be manufacturable within the specified dimensional and magnetic constraints; and (c) the magnetic yoke must effectively confine stray fields to avoid interfer- ence with beam transmission.

Fig. 10. Pumping test results of the beam transmission platform

3. Magnetic Field Distribution

The outlet diameter of the H— beam source GG is approx- imately 20 mm, and the aperture of the restrictor is no more than 10 cm. Accordingly, the diameter of the vacuum cham- ber is set to 400 mm. Given that neither the H— beam size nor the chamber size is excessively large, the vacuum chamber features a high pumping speed, which facilitates the replace- ment of equipment components. Therefore, the experimental platform adopts magnetic deflection instead of more sophis- ticated electrostatic deflectors and electromagnets. 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 Fig. 11.

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 perfor- mance, minimize magnet replacement frequency, and accom- modate a broader range of ion beam energies, the magnet sys- tem 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 (Emax, Emin) are captured by the unneutralized ion target; (b) the de- Fig. 12 [Figure 12: see original paper]. The influence of the uniform magnetic field size (dx, dz) on (a) magnetic induction intensity B (T) —green surface, exit distance l (m) —golden surface and deflection radius RH— (m) —purple surface for EH— = 30 keV; (b) on magnetic induction intensity B (T), exit distance l (m) —purple surface for different EH— [In (b), the 30 keV, 20 keV, and 10 keV cases are represented by the green, red, and golden surfaces, respectively.].

Assuming a uniform magnetic field B within a region of dimensions (dx, dy, dz) generated by the permanent mag- net, the exit displacement l and emission angle θE of ions at different energies can be determined from the Lorentz force It is observed that as dx in- law, as shown in Fig. 12(a). creases and dz decreases, B decreases gradually, while the deflection radius R and exit displacement l increase. Accord- ingly, the dimensions of the permanent magnet (lcx, lcy, lcz) and magnetic circuit parameters (lmt, la, dy) must be opti- mized to achieve a suitable B such that l for ions across en- ergy levels remains compatible with the chamber dimensions.

To ensure both physical realizability and experimental prac- ticality, the operating range of the magnetic field region was set to dx (0.1, 0.3) m and dz (0.1, 0.2) m. Simula- tions were conducted for three ion beam energies (10 keV, 20 keV, and 30 keV) to evaluate B and l across combina- tions of (dx, dz), presented in Fig. 12(b). The data indicate that under fixed (dx, dz, l) conditions, the required flux den- sity follows B10keV < B20keV < B30keV. If a uniform field B = B10keV is applied, the corresponding exit displacements satisfy l10keV < l20keV < l30keV. Contour plots further reveal that different (dx, dz) pairs can produce equivalent magnetic magnetic field. However, increasing lmtz helps reduce the volumetric magnetic flux density within the yoke, thereby im- proving magnetic saturation resistance. Based on the above parametric analysis, the main design parameters of the de- flection magnet are summarized in Table. 2. effects—though replacing permanent magnets during opera- tion is infeasible. Based on these findings and system layout constraints, an optimal parameter set (dx, dz, B) was derived, as summarized in Fig. 13 [Figure 13: see original paper]. Considering manufacturability of compact magnets, a configuration with (dx, dz) = (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.

Fig. 13. Ion exit distance l by maximum B for different values (dx, 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 con- struction. For a permanent magnet with dimensions (dx, dz) = (0.1 m, 0.2 m), Kirchhoff' s law for magnetic circuits indi- cates that the minimum thickness lmtz of the external yoke should be no less than 2 mm. Parametric simulations were conducted to evaluate the effects of the remanent flux density Bn of the permanent magnet, the relative distance dy, the air gap thickness lax, and the yoke thickness lmtz. The resulting distribution of B along the central axis of the beam channel is shown in Fig. 14 [Figure 14: see original paper].

When Bn 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 dy. As dy in- creases, B decreases in a manner resembling uniformly de- celerated motion, with the B profile becoming sharper and the region of uniform magnetic field contracting. Under con- sistent conditions, B decreases proportionally with increas- ing lax, while the extent of the uniform field region remains largely unchanged. Variations in lmtz have negligible influ- ence on B and do not significantly alter the uniformity of the Fig. 14. Variation of the magnetic flux density B along the central axis with respect to Bn, dy, lax, and lmtz.

Fig. 15 [Figure 15: see original paper] presents the spatial magnetic field distribution of the deflection magnet under the parameters listed in Table.2.

Figs. 15(a) and (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 uni- form magnetic field within the beam channel, with the major- ity of magnetic flux confined inside the yoke. The magnetic field strength is approximately 0.05 T in the central region and about 100 Gs at the edges. The beam transport results indicate that it exerts no influence on the composite beam.

However, it may cause premature deflection of charged ions, thereby increasing scattering. The left panels of Figs. 15(b) and (d) present the test results at different positions in the XOY and XOZ cross-sections, respectively. The magnetic Table 2 . Main parameters of the deflection magnet Permanent magnet Symbol lcx lcy Unit m m Value 0.2 0.02 lmtx lmty lmtz lax Air gap Remanent flux density Fig. 15. Spatial magnetic field distribution of the deflection magnet: (a) Surface magnetic field distribution on the XOY plane; (b) Comparison between simulated and measured line field profiles on the XOY plane; (c) and (d) for XOZ plane field intensity B at symmetric geometric positions is nearly identical and is also in excellent agreement with the corre- sponding simulation values shown in the right panels, which verifies the accuracy of the testing method. The experimental test results also demonstrate that the magnetic field strength in the central region is 0.05 T and that at the edges is less than

100 Gs (20 Gs), confirming that the magnet meets the de-

sign requirements and is suitable for deflecting residual ions in this beam transport test platform.

4. Thermal Stress Distribution

The H— beam generated by the single-aperture ICP source exhibits relatively low power. Beam transmission results indi- cate that the maximum power density at the limiter is approx- imately 0.1 W/mm2. Nevertheless, the thermodynamic per- formance of beamline components must be considered, and diagnostic measures should be implemented to ensure opera- tional 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 —(r3, r4) = (15 mm, 50 mm) and (5 mm, 50 mm)—across a range of thick- nesses, under a beam exposure time of 10 seconds. As shown in Fig. 16 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 condi- tions 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 opera- tion. To prevent beam divergence from causing spot enlarge- ment beyond the limiter aperture, a 2 mm-thick oxygen-free copper backup plate matching the inner diameter of the cham- ber was installed behind the limiter. Thermodynamic simula- tion results confirm the structural reliability of this design, as represented by the three green symbols in Fig. 16(a).

Fig. 16(b) 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 experi- mental platform. The temperature distribution under maxi- Fig. 16. Thermal stress analysis: (a) the ion beam aperture limiter, (b) the rectangular target plate under varying thicknesses, (c) temperature distribution of the 2 mm-thick rectangular target plate. Inset in (b) shows the dynamic temperature variation over time for the 2 mm-thick target plate. mum thermal load is illustrated in Fig. 16(c), 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 re- turns to near-initial levels after 25 seconds, suggesting that an interval exceeding three times the duration of each experi- ment (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 trans- mission system, with a physical assembly shown in Fig. 18 [Figure 18: see original paper].

The inlet flow rate of H2 is regulated by a mass flow controller (MFC). After being ionized in the discharge chamber and ac- celerated by the PG-EG-GG module, the ions pass through the gate valve and restrictor in sequence. The yellow box de- notes the optical enhancement cavity module to be installed in future upgrades. Subsequently, the ion beam is deflected by the bending magnet and then detected by beam diagnostic equipment, including a tungsten wire target, a copper target, and a Faraday cup. A total of three turbomolecular pumps are equipped on the platform: two are mounted on both sides of the restrictor chamber, and one is installed directly beneath the beamline chamber. The radiofrequency (RF) power gen- erator, RF coupler, extraction power supply, and acceleration power supply are all placed on the high-voltage platform. The entire system is controlled by dedicated software to ensure the safety and standardization of experimental operation and pro- cedures.

Fig. 17 [Figure 17: see original paper]. Composite neutralization efficiency ηph+g under different vacuum levels PV and laser target thicknesses D.

Based on the component test results of the platform and the performance parameters of the H− beam presented in Sec- tion. IV A, a fully coupled finite element simulation was per- formed for the neutralization efficiency of the platform, incor- porating the neutralization process, electromagnetism, ther- mal effects, and beam transport. The results are illustrated in Fig. 17.

Based on the test results of the vacuum level presented in Section. IV A 2, two types of beam size limiting struc- tures were selected, with (r3, r4) = (0.015 m, 0.05 m) and (r3, r4) = (0.005 m, 0.05 m). The background gas vacuum conditions are denoted by PV 1 and PV 2, respectively, 0.01 Pa and 0.005 Pa, as showed in Fig. 9. It can be seen from Fig. 17 that in a vacuum environment (PV 1 = PV 2 = 0), the neu- Fig. 18. Laser-neutralization beam-transport test platform. tralization efficiencies of the two limiting aperture structures are consistent with the theoretical values, which reflects the credibility of the simulation method. The combined neutral- ization efficiency ηph+g and the net laser neutralization effi- ciency ηph under the two background vacuum levels show lit- tle difference, both increasing monotonically with the rise of laser target thickness. However, when the laser target thick- ness D exceeds a certain "turning point" , the combined neu- tralization efficiency ηph+g becomes lower than which with- out background gas. This indicates that the re-ionization induced by background gas cannot be neglected as a source of error, when the H0 beam intensity is sufficiently high. For example, under CW-laser irradiation, this "turning point" is approximately 2 × 108 W/m, at which the neutralization effi- ciency is about 85%. When the laser target thickness is less than the "turning point" , the gas target dominates, resulting in the combined neutralization efficiency ηph+g being higher than the net laser neutralization efficiency ηph. Moreover, this competitive effect of the gas target becomes more pronounced with increasing PV , which is consistent with the conclusions presented in Fig. 6 of Section. III B. This demonstrates that the only approach to achieve a neutralization efficiency ex- ceeding 80% is to increase the laser target thickness.

Considering the limiting aperture structures under the PV 1 and PV 2, the thermal distribution of the deflected residual H− and H+ ion beam spots is illustrated in Fig. 19 [Figure 19: see original paper] , where the H− ion beam with parameters of 30 keV@5 mA@3 cm after the GG electrode undergoes CW-laser neutralization. Under the Fig. 19. Thermal distribution of residual ion beams (H− and H+) of the 30 keV@5 mA@3 cm H− ion beam under different laser target thicknesses D and limiting aperture configurations.. combined effects of the restrictor, space-charge effect, beam divergence, and magnetic field deflection, the ion beam spots exhibit an elongated shape. For the two limiting aperture con- figurations, the maximum sizes of the H− and H+ beam spots are approximately (5 cm\$×\$16 cm), which can all be effectively captured by the diagnostic target. The H− beam spot size de- creases gradually with increasing D. In contrast, the varia- tion in the H+ beam spot size is negligible, necessitating the adoption of a more sensitive measurement method. There- fore, the combined neutralization efficiency can be expressed as ηph+g = ATarget/(AH− + AH+ + ATarget). Owing to the impacts of re-ionization and beam divergence, the numera- tor ATarget is underestimated, resulting in a lower measured value of the ηph+g. In addition, negative ions propagate un- der the influence of space-charge repulsion, whereas neutral particles are unaffected by space-charge effects. The mea- sured variation in neutral current is larger than that in ion current, leading to the actual neutralization efficiency being higher than the calculated value, which should be compre- hensively considered in data interpretation.

V. CONCLUSION AND PROSPECTS Negative ion neutralization is a critical process in neu- tral beam injection heating for magnetic confinement fusion.

Laser neutralization offers a promising alternative to conven- tional 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 fu- sion devices. This study systematically investigated the inter- action 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 em- phasize the necessity of maintaining a beamline vacuum of ≤ 10−2 Pa to clearly distinguish laser-induced effects from gas-target interactions. Furthermore, when neutralization ef- ficiency 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 ◦ , [1] Xie Y, Hu C, Liu S, et al. Long pulse operation of neutral beam injector on EAST tokamak. Fusion Engineering and Design, 2023, 193: 113744. DOI:10.1016/j.fusengdes.2023.113744 [2] Hu C, Xie Y, et al. Overview of Development Status for EAST- NBI System. Plasma Science & Technology, 2015, 17(10): 1029–1035. DOI:10.1088/1009-0630/17/10/02 [3] Tao L, Hu C, Xie Y, et al. Thermodynamic analysis and simu- lation for gas baffle entrance collimator of EAST-NBI system based on thermo-fluid coupled method. Nuclear Science and Techniques, 2018, 29: 98. DOI:10.1007/s41365-018-0374-4 [4] Xu Y, Li X, Hu C, et al. Analysis of heat trans- fer capacity of electron dump on EAST-NBI. Nuclear Techniques, 2016, 39(10): 100602. DOI:10.11889/j.0253- 3219.2016.hjs.39.100602 [5] Chen Y, Ji J, Hu C, et al. Activation and shutdown dose-rate analyses for the EAST NBI test facility. Nuclear Science and R3 = 8 m, L1 (0, 1) m, and L3 (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. Based on the theoretical analysis presented above, a beam transport platform based on laser neutralization for 30 keV H− ion beams was designed and constructed, consist- ing of key beamline components including the beam source, vacuum system, and magnetic deflection unit. The compo- nent performance test results are consistent with the paramet- ric calculation outcomes, which verifies the reliability of the H− beam transport system. The stable transmission of H− beams and the accurate diagnostic methods implemented on this test platform provide a crucial reference for subsequent verification of the feasibility of laser neutralization under dif- ferent H− beam parameters, practical measurement of η, and analysis of measurement uncertainty after the integration of the laser module.

To support accurate efficiency measurements in future ex- periments, the spatial distributions of H− and H+ ions were quantitatively analyzed. Incomplete neutralization may lead to underestimation of (AH− + AH+), 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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Note: Figure translations are in progress. See original paper for figures.