Study on the Key Technologies Involved in the Laser Neutralisation of Negative Ion Source

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Abstract

- Based on the collision model, the influence of background vacuum on laser neutralization efficiency was investigated. When the neutralization efficiency does not need to be higher than 80%, the presence of a certain amount of background gas can improve the recombination neutralization efficiency.
- The H^- beam transmission platform with a maximum energy of 50 keV was designed and constructed. The experimental performance indicators are in good agreement with the theoretical design, and further upgrades can be used to verify the systematization of laser neutralization and parameter variable studies.
- Based on the designed H^- beam transmission platform, the optical configuration parameters of the folded ring cavity were designed, including the incident angle, cavity length, and spot size at various locations, providing a design basis for the integration of the laser module.

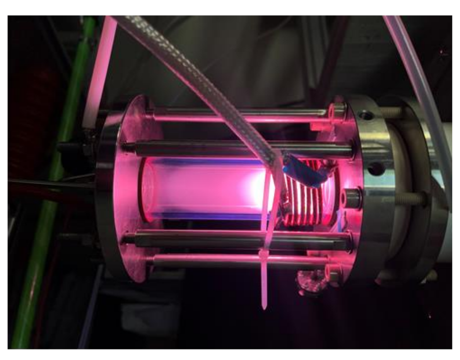
Background

- 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 ion beam neutralization process is crucial in a NBI system. Neutralization targets include metal vapor, gas, plasma, and laser targets. Currently, gas targets are dominant, relying on collisions to produce neutrals. However, this method has a maximum efficiency of around 60%, which is insufficient for next-generation fusion reactors. Higher gas densities also degrade vacuum quality and impair beam transmission.
- In 1984, Fink first proposed laser neutralization. Laser neutralization uses photons to detach the extra electron from H^- without ionizing the atom. It can theoretically achieve over 95% efficiency, introduces no additional gas or ion species, and causes 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 NBI systems.

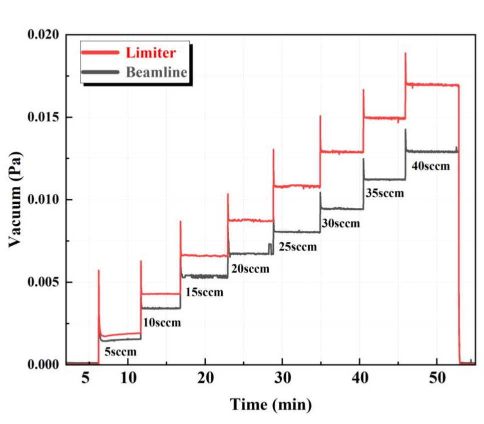
Laser Neutralized Beam Transmission Platform

- Based on the particle collision model and the finite element calculation method, the parameters affecting the neutralization efficiency, including background gas density, beam cross-section shape, and laser folding times, were systematically analyzed. On this basis, an ion beam transport platform for laser neutralization was designed and built, with the maximum H^- ion beam energy reaching 50 keV. The main components include a vacuum gradient distribution chamber, beam size limiter, deflecting magnet, and beam diagnostic device. The test results are consistent with the performance simulation results, confirming the reliability of the platform.

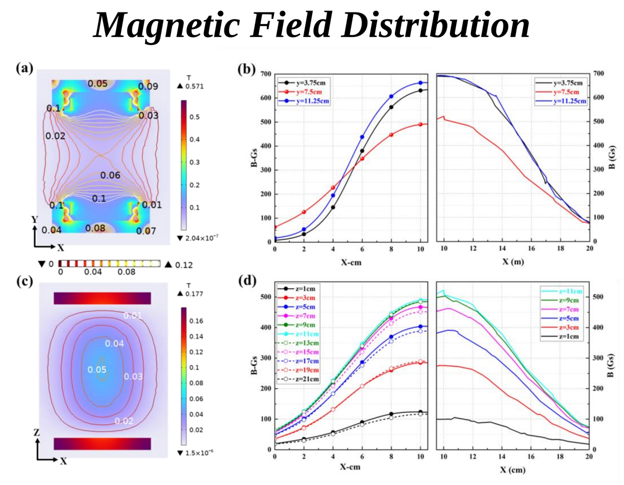
Single-aperture ICP H^- Source

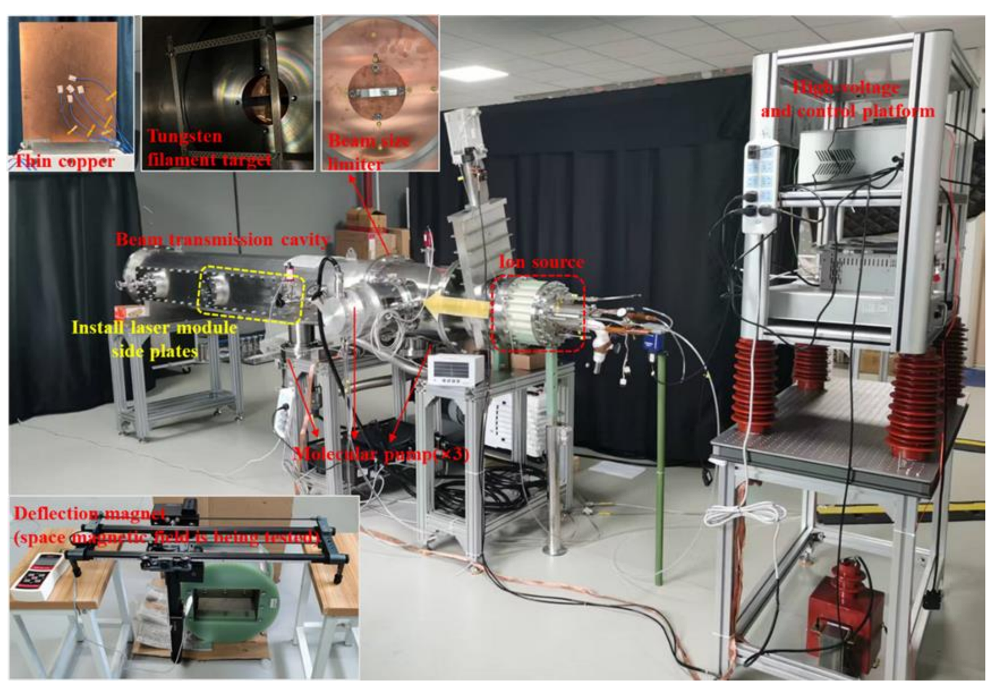


Beam Vacuum Distribution

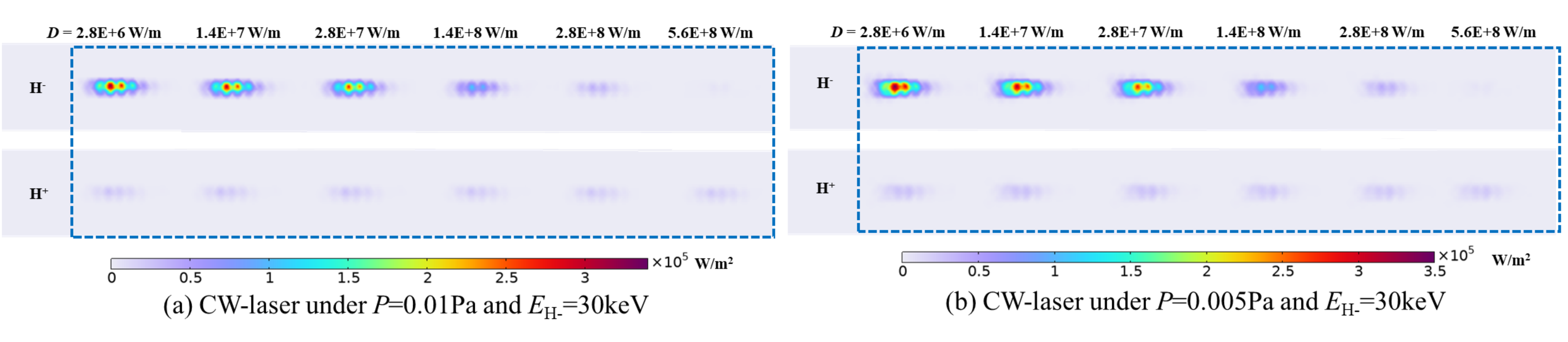


Magnetic Field Distribution





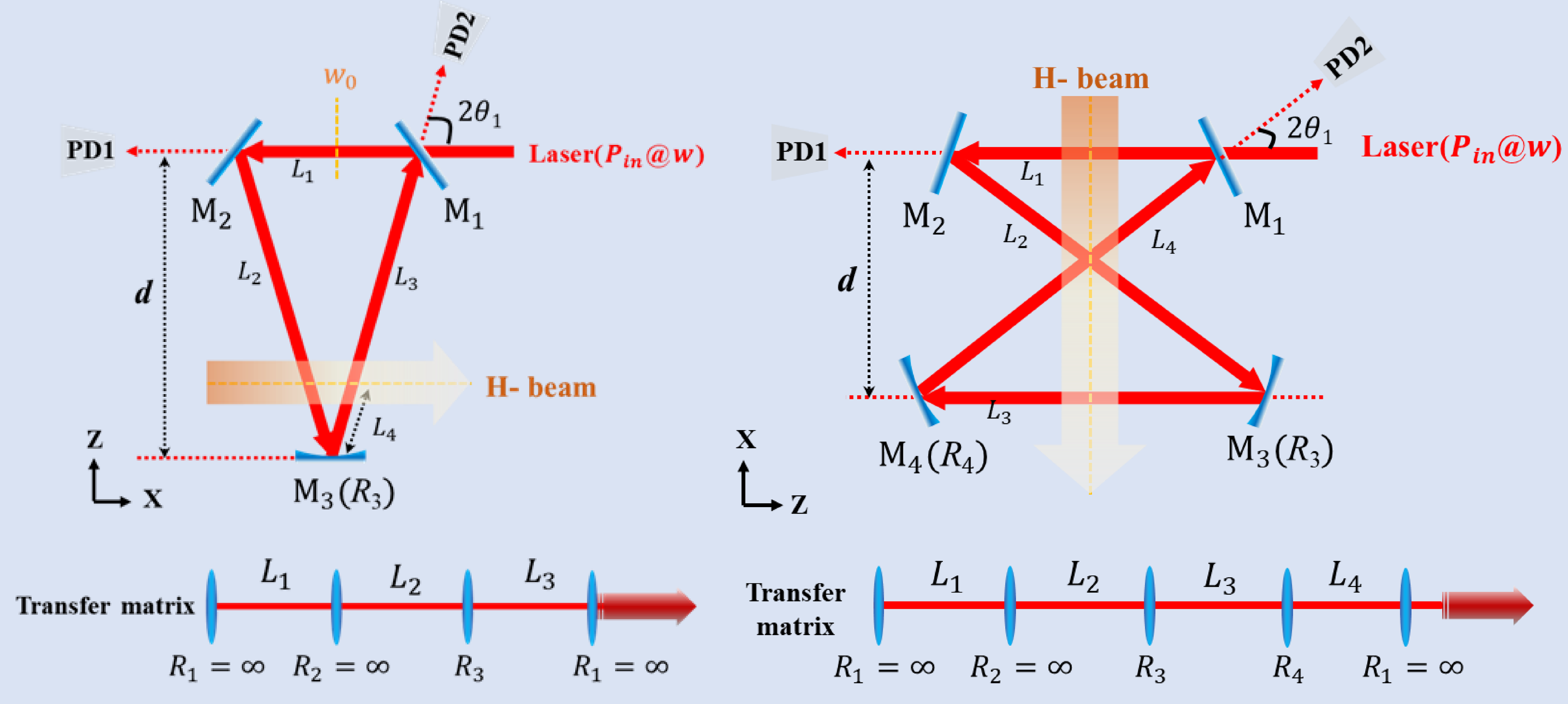
Laser-neutralization beam-transport test platform



Thermal distribution of deflected ion beam spots under different laser target thicknesses D and beam background vacuum level P

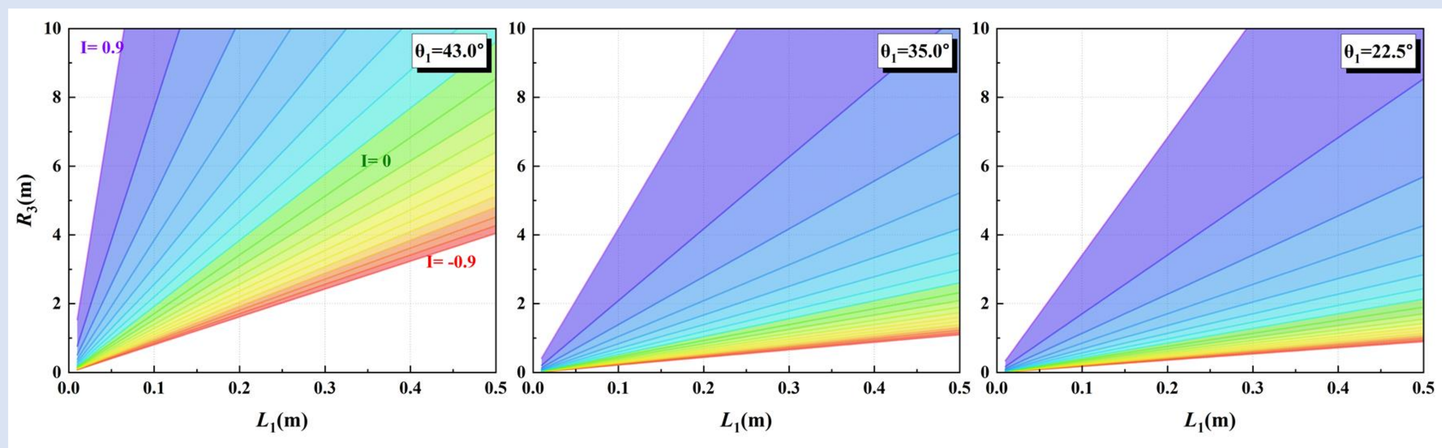
Folding Cavity Topology

- The photon-negative ion collision cross-section is very small (10^{-21} m²), requiring extremely high laser power. Long-pulse high-power laser operation can cause significant photothermal effects on mirrors, limiting the cavity enhancement factor and potentially damaging components. Additionally, the interaction volume increases with the laser target thickness, posing a challenge to system stability.
- To meet the laser cavity requirements for laser neutralization (stability *I*, spot size, and power), we analyzes the laser transmission and optical path parameters of folded ring cavities (n=3,4) using the paraxial optical transmission matrix. The numerical results allow for quick and flexible cavity configuration adjustments. These findings can be extended to more complex and larger cavities, providing a theoretical basis for tabletop experiments and practical laser neutralization systems.

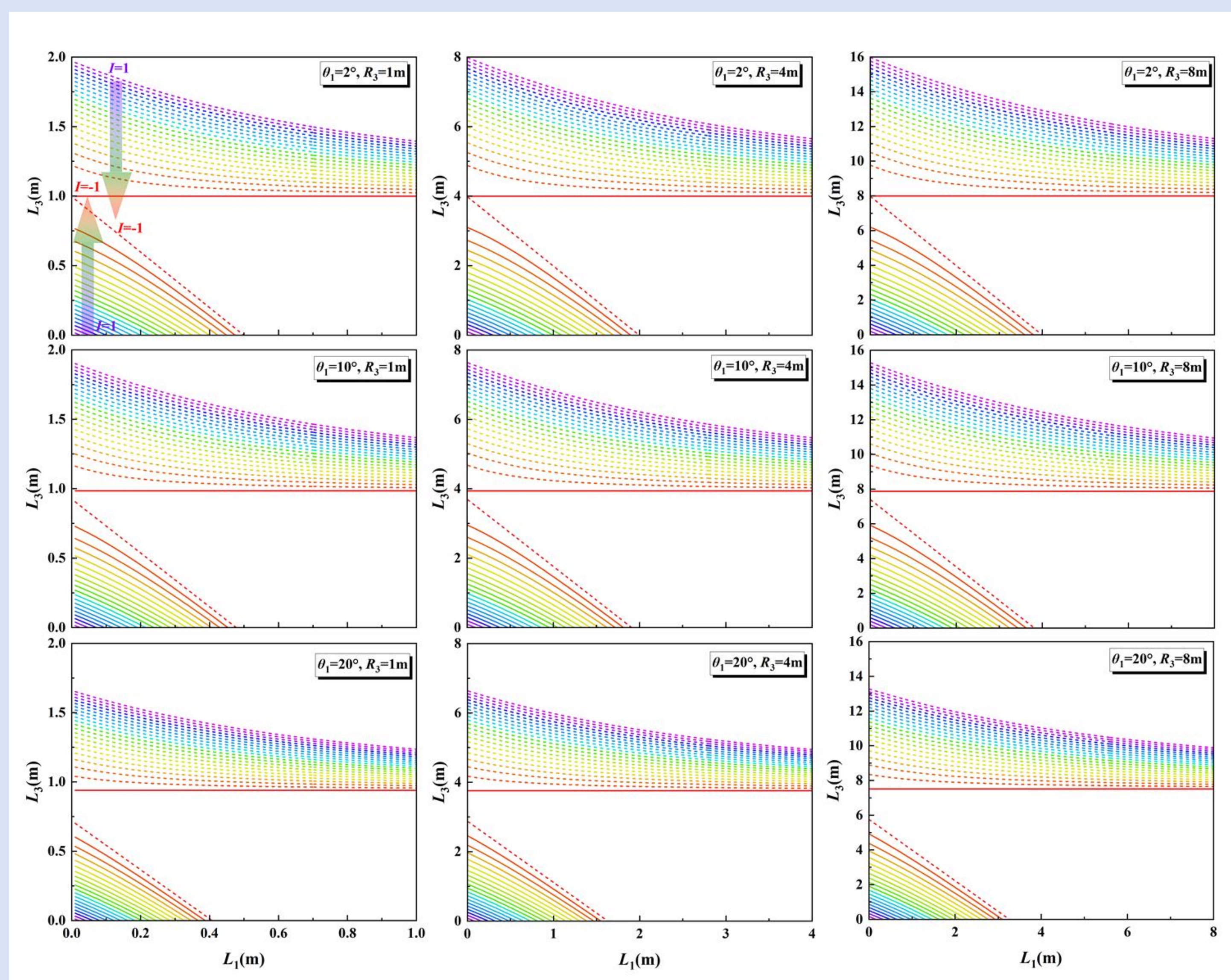


Ray-trace schematic of the triangular ring cavity and bow-tie ring cavity

Stability factor I (L_1, R_3) for fixed θ_1 about triangular ring cavity



Stability factor I (L_1, L_3) for fixed (θ_1, R_3) about bow-tie ring cavity



CONCLUSION

- An H^- beam transport platform with a maximum energy of 50 keV was designed and built, and the experimental performance matched the theoretical design well.
- The topological structural parameters of the folded ring cavity were designed, and the calculation method can quickly derive the incidence angle, cavity length, and spot sizes at various locations.
- The ring cavity module was further assembled onto the beam transport platform, which can be used to verify the feasibility of laser neutralization and conduct systematic studies on parameter variations.

ACKNOWLEDGEMENTS

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