- IFSA2025 –

GeV Proton Generation at Moderate Intensities via an Energy-Matched Double-Pulse Scheme in Micronozzle Acceleration

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Although GeV-class proton beams have already been demonstrated numerically by the micro-nozzle acceleration (MNA) scheme using laser intensities on the order of 10^{22} W/cm²[1], such extreme conditions remain challenging for many facilities. In this work, we introduce an innovative energy-matched double-pulse approach that operates at moderate intensities while still achieving GeV proton beams.

In our scheme, the total laser energy is divided into two pulses: a short, high-intensity pre-pulse and a longer main pulse. The pre-pulse (with a 2 μm focal spot and 30 fs FWHM) is designed to provide initial momentum to protons within the hydrogen rod embedded in the micro-nozzle, effectively "priming" the target. Following this, the main pulse (with a 10 μm focal spot and 100 fs FWHM) irradiates the entire micro-nozzle target, generating a strong, persistent electrostatic field that further accelerates the pre-energized protons. By rigorously matching the total energy using the relation $E=I\times SpotArea\times\tau$, we ensure that both the single-pulse and double-pulse configurations share an identical energy budget.

Particle-in-cell simulations reveal that with an optimal delay of approximately 20 fs between the pulses and a pre-pulse intensity 3–4 times that of the main pulse (while keeping the pre-pulse below 10^{22} W/cm^2), the double-pulse scheme nearly doubles the maximum proton energy compared to the single-pulse case. Furthermore, the double-pulse configuration produces a more collimated proton beam with significantly reduced divergence.

These results indicate that our double-pulse strategy not only offers a practical pathway to achieving GeV proton beams at moderate intensities but also enhances beam quality, thereby providing crucial insights for optimizing laser parameters in future experimental implementations of laser–plasma ion acceleration.

References

[1] Generation of Giga-electron-volt Proton Beams by Micronozzle Acceleration. M. Murakami