# IMPROVING LASER-DRIVEN PROTON BEAM DIVERGENCE AND UNIFORMITY BY USING SELF-GENERATED EM MULTIPOLES IN CHANNEL-SHAPED TARGETS


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## INTRODUCTION

Improving the angular properties of laser-accelerated ion beams is essential for advancing the applicability of laser-driven ion sources. This work builds on comprehensive **2D and 3D PIC study [1], [2]** of advanced plastic target designs (flat and curved foils with a range of rear-side channel geometries (see Fig. 1)) aimed at reducing proton beam divergence while preserving high energies and particle numbers. The parametric study identifies **a flat foil with straight cylindrical channel (6μm) as the most effective configuration** (i.e. Fig.1 (f)).

The channel structure generates a long-lasting transverse electric field and, importantly, induces a distinctive electromagnetic field topology within the guiding cylinder. These **self-generated fields** include a magnetic quadrupole with a pronounced octupole component - an effect analogous to conventional multipole magnets. The resulting field configuration substantially **reduces proton beam divergence and improves spatial uniformity across a broad energy interval**. A realistic scenario was also modelled by including **prepulse-generated preplasma** in the optimal channel target design, enabling direct comparison between ideal and experimental laser conditions. Additional investigations address **the influence of linear polarization direction** on ion beam characteristics.

These findings demonstrate that structured channel targets can act as passive beam-conditioning elements, offering a promising route toward controllable and application-ready laser-driven proton beams.

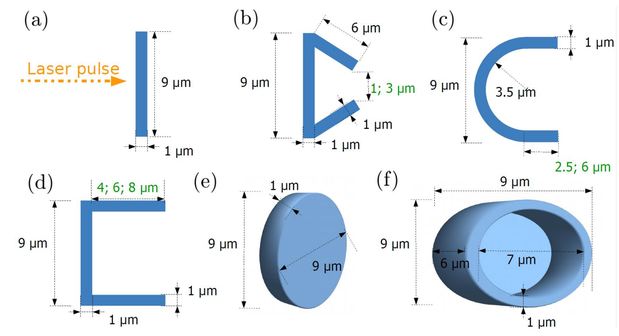


*Figure 1: Advanced plastic target designs simulated by 2D PIC (a)-(d) or by 3D PIC (e)-(f) code EPOCH.*

## FORMATION OF SELF-GENERATED MAGNETIC MULTIPOLE

The resulting magnetic field resembles a **multipole magnet**, specifically a **quadrupole with a strong octupole component**. This multipole B-field originates from the collective motion of laser-accelerated electrons, particularly their organized transport along the channel walls (confined by the geometry and forming structured current loops). These currents generate transverse magnetic field components (primarily $B_y$ and $B_z$), which combine to produce a radial magnetic field. Unlike in flat targets - where electron motion is disorganized and fields rapidly decay - this structured electron motion leads to a well-defined magnetic configuration within the channel. The quadrupole component focuses particles in one transverse plane while defocusing in the perpendicular one, thereby introducing anisotropic beam shaping. The octupole component, which naturally appears as a higher-order harmonic due to imperfections and asymmetries, contributes to improving beam uniformity by smoothing spatial variations. This combination explains both the observed reduction in divergence (up to 80%) and the enhanced homogeneity of the particle beam (up to 30%).

*For numerical comparison:* the magnetic field integral for the channel target starts at **0.217 T·m**, peaks at **0.368 T·m**, then decreases to **0.098 T·m** by the end; ELIMAIA beamline quadrupoles have **10 T/m over 70 mm → 0.084 T·m,** PMQs have **100 T/m over 36 mm → 0.291 T·m**, [3], [4]. This means that the channel-target field integral exceeds that of the ELIMAIA quadrupoles throughout the acceleration process.

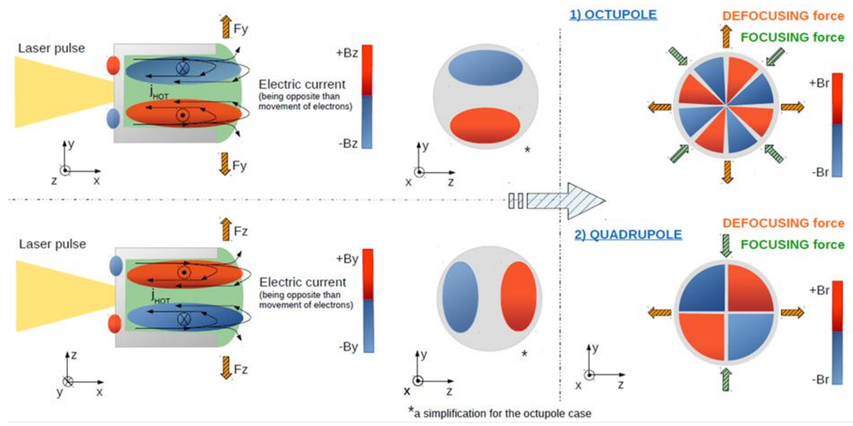


*Figure 2: Schematic sketch of the establishment of magnetic field components driven by electron motion (current loops), and of the magnetic multipoles creation in all planes.*

## DE/FOCUSING ELECTRIC FIELD AND JOINT EM FIELDS EFFECT

The focusing effect in channel targets originates from transverse electric fields ($E_y$, $E_z$). In the channel case, these fields maintain a focusing orientation, whereas in the flat foil they reverse after a few tens of fs. In the flat foil, the fields switch to defocusing, pushing protons away from the laser axis and increasing beam divergence.

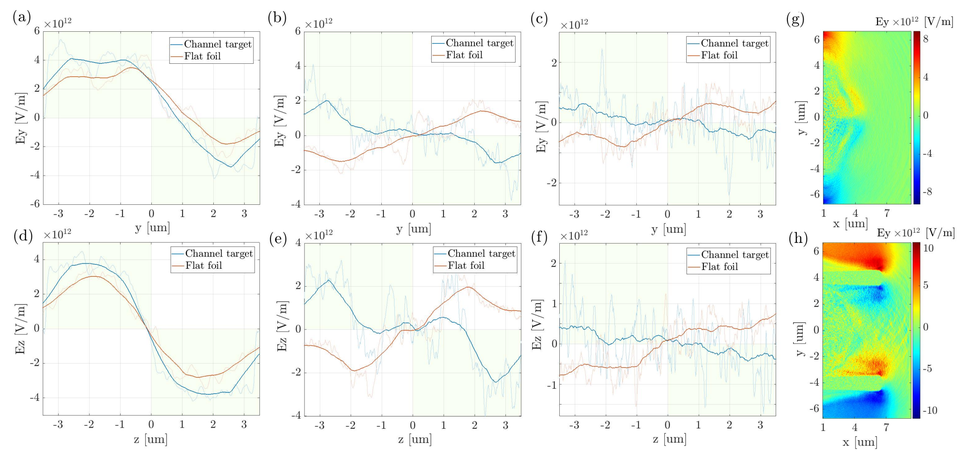


*Figure 5: Demonstration of the opposite orientation establishment of electric field components $E_y$ and $E_z$ at 30 fs ((a), (d)), at 90 fs ((b), (e)) and at 120 fs ((c), (f)). Focusing regions for ions are highlighted in green, defocusing regions in white. Graphs (g) and (h) show $E_y$ in the plane x−y at 90 fs for the flat and the channel target, respectively.*

The influence of electric and magnetic fields on particle divergence was analysed as a function of proton energy. Two energy intervals, **5–15 MeV** and **35–45 MeV**, show the strongest divergence suppression, reaching up to **~80%** in the favorable plane. The angular spread is both plane- and energy-dependent, since fields act differently on ions of different energies, and magnetic multipoles, although symmetric, can produce asymmetric focusing effects (e.g. quadrupoles).

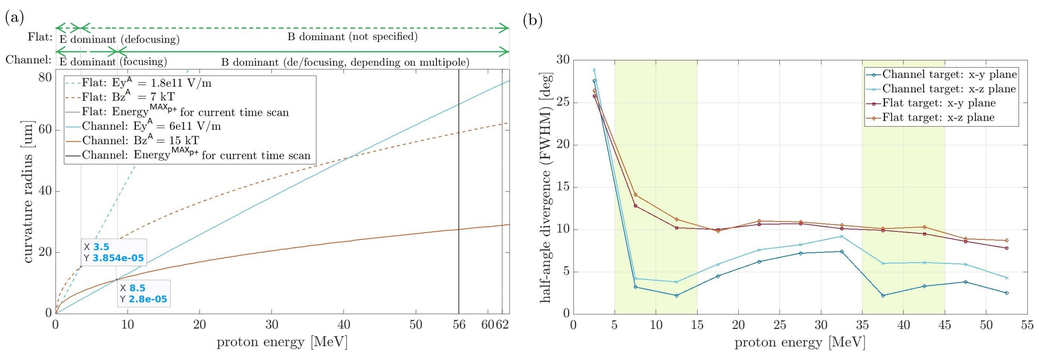


*Figure 6: Comparison of E- and of B-field impact on the proton beam divergence for the channel and the flat target at the end of 3D simulations: (a) the dependence of electric and magnetic curvature radius in x-y plane (taken from electric and magnetic rigidity) on a particular energy of the reference proton (moving along x−axis); the nature of the radius (de/focusing) is shown above the graph for both fields; (b) half-angle proton beam divergence (FWHM) in both x-y and x-z planes inferred from 3D PIC simulations and analyzed separately for energy intervals of 5 MeV width up to 55 MeV.*

An important advantage of reducing divergence directly by target shaping is improved matching to the entrance aperture of beamline transport systems. For example, in the ELIMED section of the ELIMAIA beamline, about **36%** of protons (>10 MeV) from a flat foil would be clipped when entering the transport system, compared to only **9%** in the case of the channel target.

## POLARIZATION DIRECTION: IMPACT ON BEAM DIVERGENCE AND SHAPE

Laser polarization strongly affects proton beam shape and divergence through its influence on electron dynamics and the resulting EM fields. Previous RT target studies showed that linearly polarized pulses produce a diffraction structure and a double-lobed proton beam perpendicular to the polarization direction [5], [6], caused by electron expulsion from high-field regions along the polarization axis [6]. In our simulations, the target does not fully reach the relativistic transparency (RT) regime, although a partially transmitted pulse still interacts with the rear side. As a result, the diffraction pattern is absent and the proton beam elongates along the polarization direction instead. This is linked to the transmitted pulse propagating in a $TE_{01}$ mode, which modifies transverse electric fields [2]. Polarization changes proton divergence moderately (~10%), mainly for lower-energy protons, while the central narrow filament remains unaffected. Overall, polarization primarily modifies the strength & orientation of transverse electric fields (see Fig. 7).

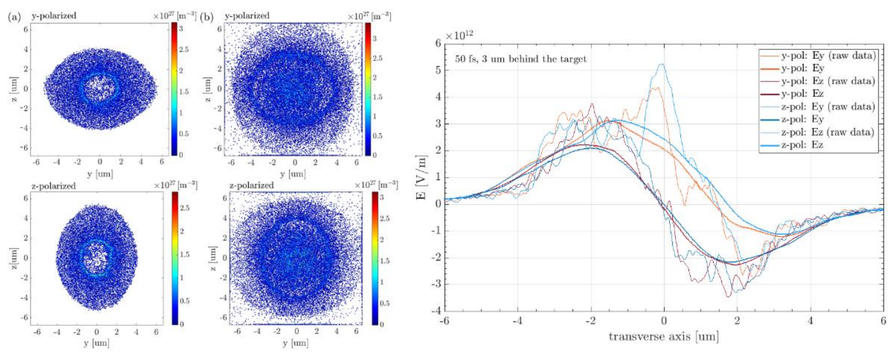


*Figure 7: Left: Density plots comparison of the proton beam cross sections in the case of the reference flat target interacting with y- or z−linearly polarized laser pulse at (a) 180 fs or at (b) 270 fs. Right: Comparison of 1D profiles of transverse focusing electric field components plotted along corresponding axes, i.e., Ey−y and Ez−z, for linearly y− and z−polarized laser pulses, respectively.*

## NON-IDEAL LASER CONTRAST: PREPLASMA IMPACT

The impact of preplasma, generated by a realistic laser prepulse ($I_p = 10^{11}$ W/cm$^2$, duration 0.5 ns), was studied using additional 2D PIC simulations with input from MHD modeling. The results show that preplasma leads to a temporary increase in laser intensity due to self-focusing, causing a slight rise in maximum proton energy (due to the higher accelerating $E_x$ field resulting from a 55% increase in electron temperature) and a flatter energy spectrum due to enhanced front-side acceleration. At the same time, a modest increase in divergence is observed due to the larger angular spread of hot electrons generated in the preplasma (though at relatively low intensity to be effective [7]). No other accelerating mechanisms have been observed. Overall, the channel target design appears reasonably robust against weak prepulses.

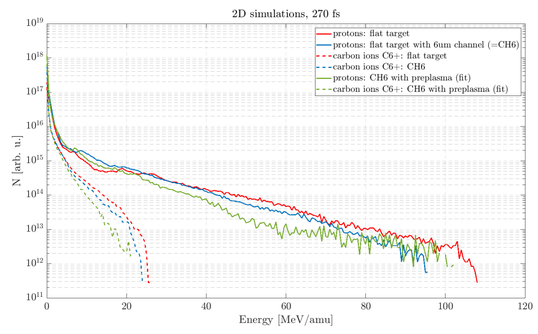


*Figure 8: Comparative preplasma study: energy spectra of protons (solid lines) and carbon ions (dashed lines) taken at the end of 2D PIC simulations, i.e., at 270 fs after the start of laser-target interaction.*

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