Control of a Laser-Produced Dense Plasma Flow by a Divergent Magnetic Field

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Background and motivation

Advantages of laser ablation plasma:

- Dense plasma produced directly from solid target (high current)
- Plasma ions travels ballistically from a small laser spot (low emittance)

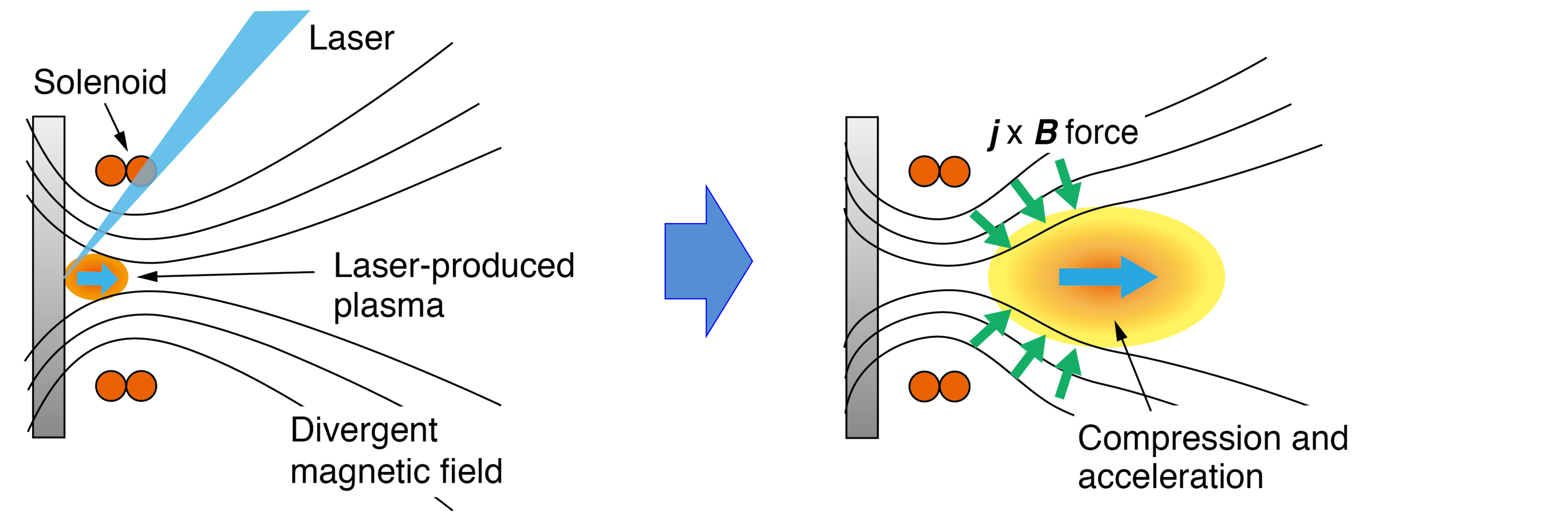
Issues:

- Rapid decrease in ion flux due to three dimensional plasma expansion
- Increase in transverse momentum dispersion caused by magnetic guiding

Question:
Is it possible to control ion directivity and flux by applying a divergent magnetic field to a laser-produced dense plasma flow?

Purpose:
The purpose of this study is to clarify the magnetic nozzle effects on a laser-produced dense plasma flow and evaluate its potential as a method to enhance plasma ion flux without degradation of ion directivity.

Concept of magnetic nozzle control



Lorentz force acting on plasma surface:

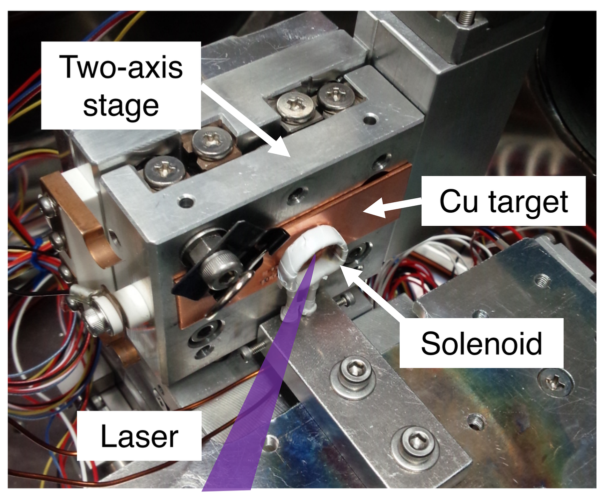
$$\vec{j}\times\vec{B} = -\nabla_{\perp}\left(\frac{B^2}{2\mu}\right)+\frac{B^2}{\mu R_C}\vec{l}_n$$

R_C : Curvature radius of magnetic field line

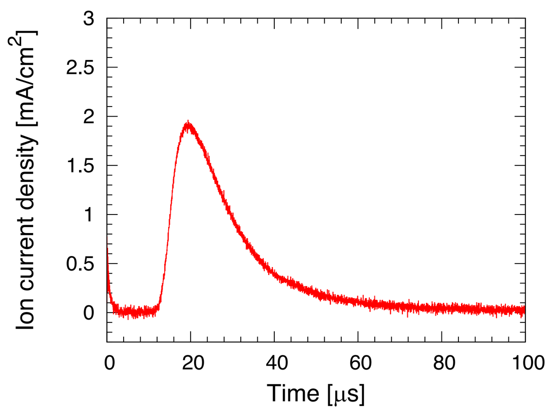
$\vec{l}_n$: Normal vector to the center of curvature

Magnetic pressure — Magnetic tension

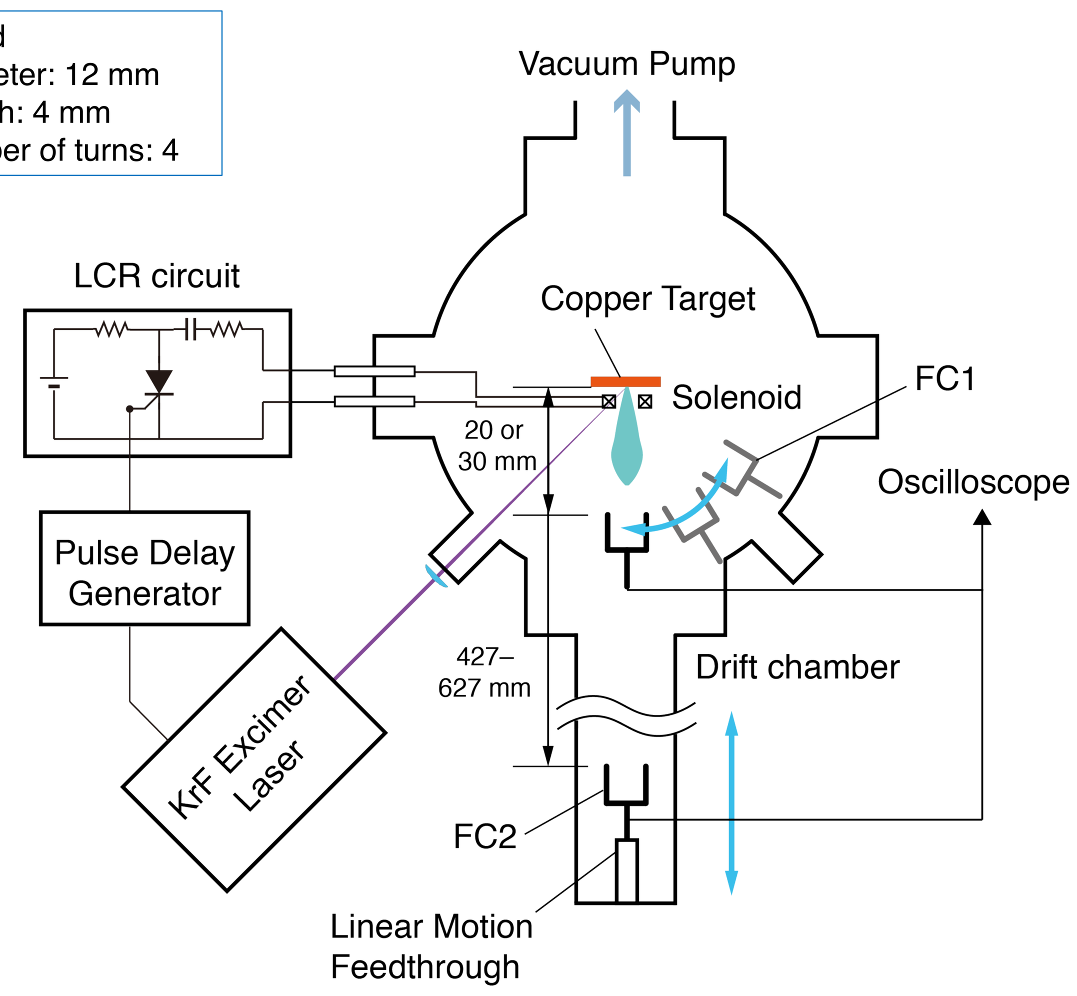
Experimental setup for ion flux measurement

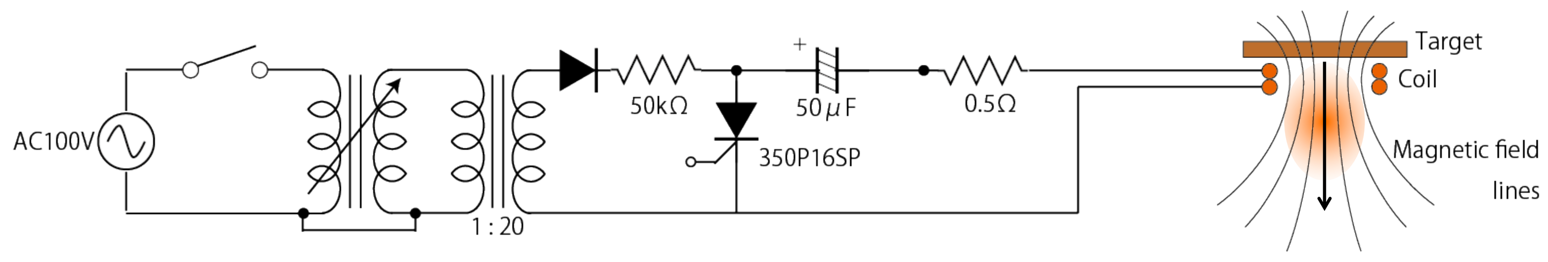


Solenoid
- Diameter: 12 mm
- Length: 4 mm
- Number of turns: 4

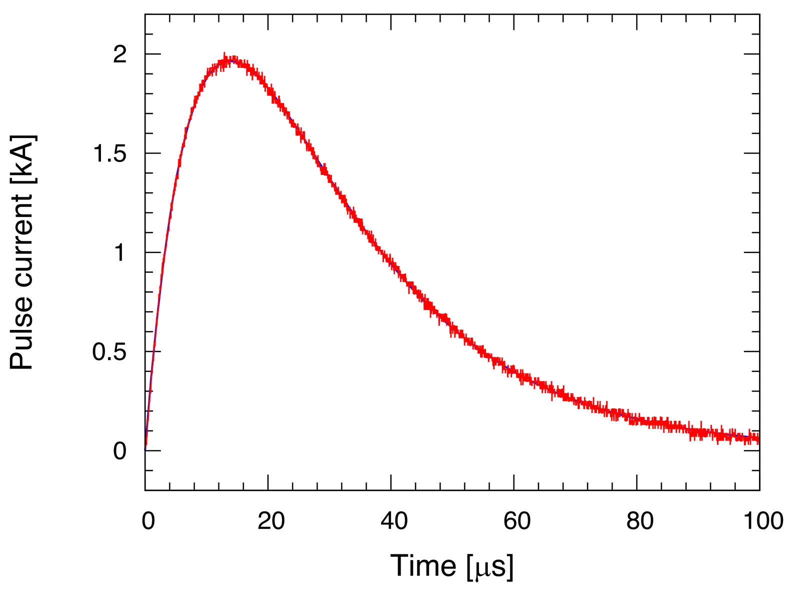


Typical waveform of plasma ion flux

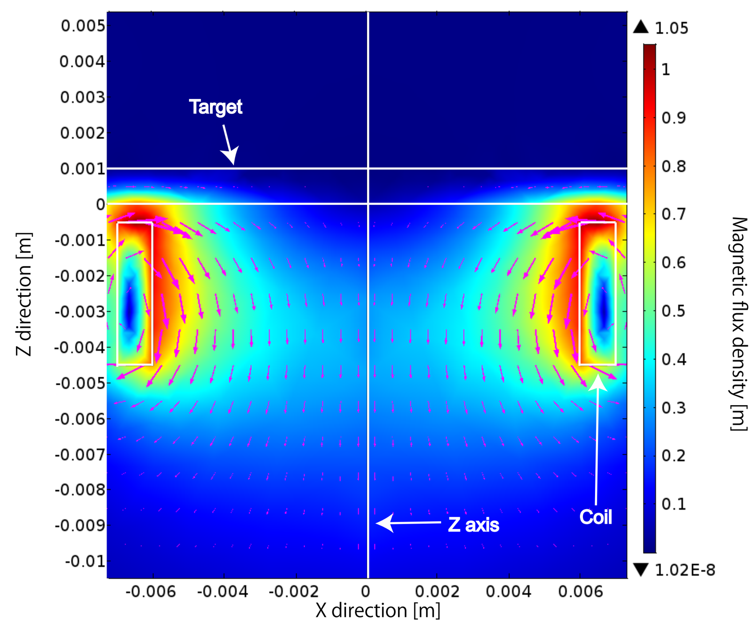




Driving circuit for magnetic field excitation

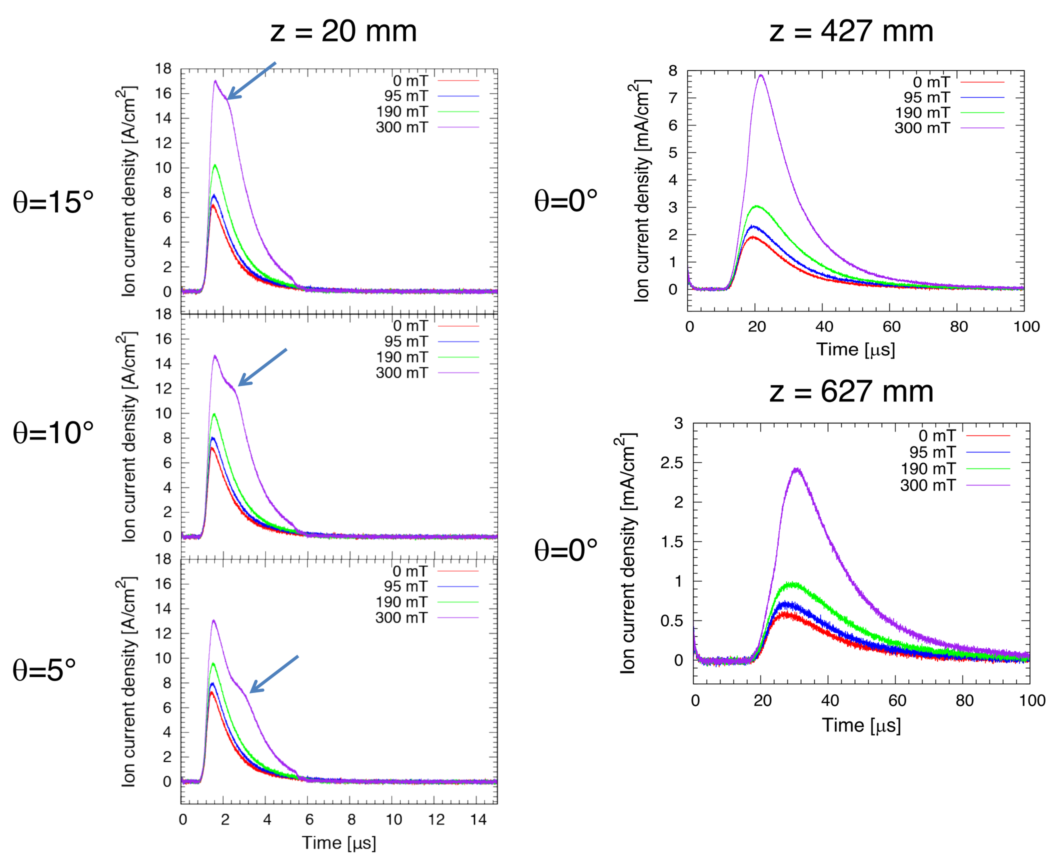


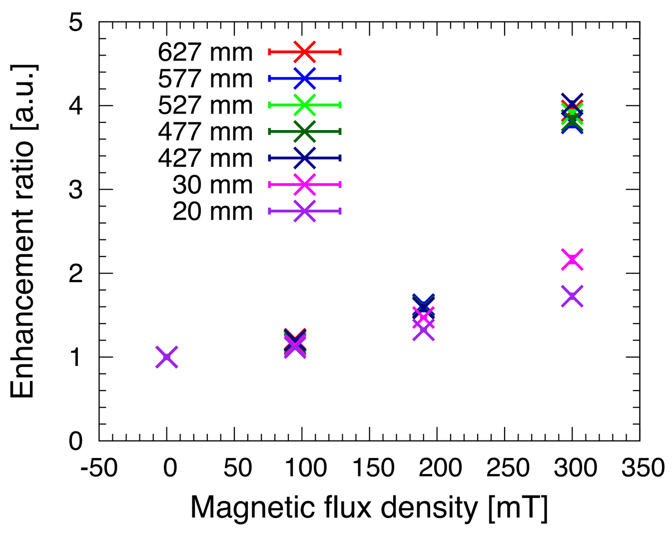
Excitation current waveform



Magnetic flux density distribution at current maximum

Experimental results

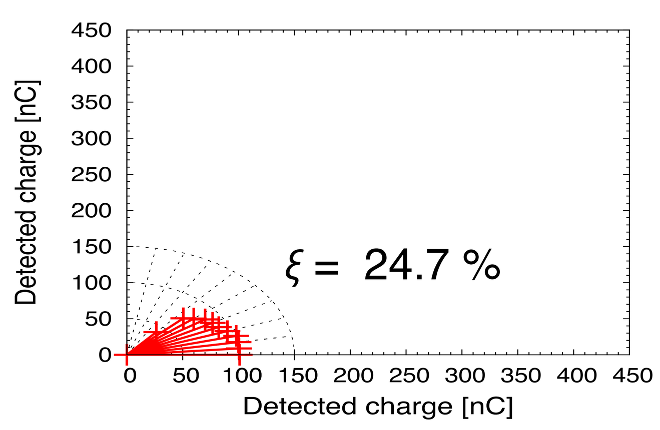
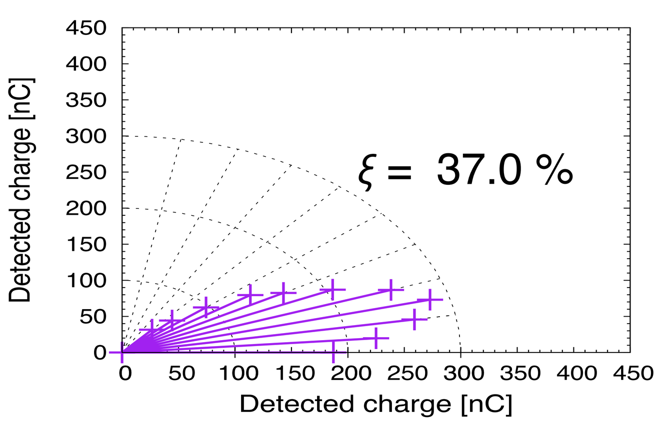
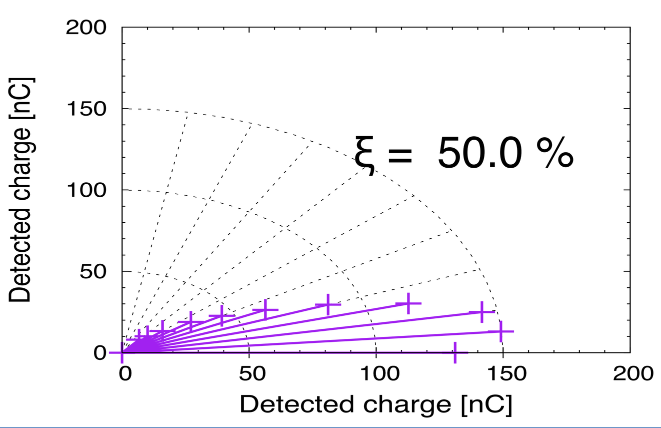




Typical waveform of plasma ion flux

Remarkably large flux enhancement (~4) was observed with B=0.3 T.

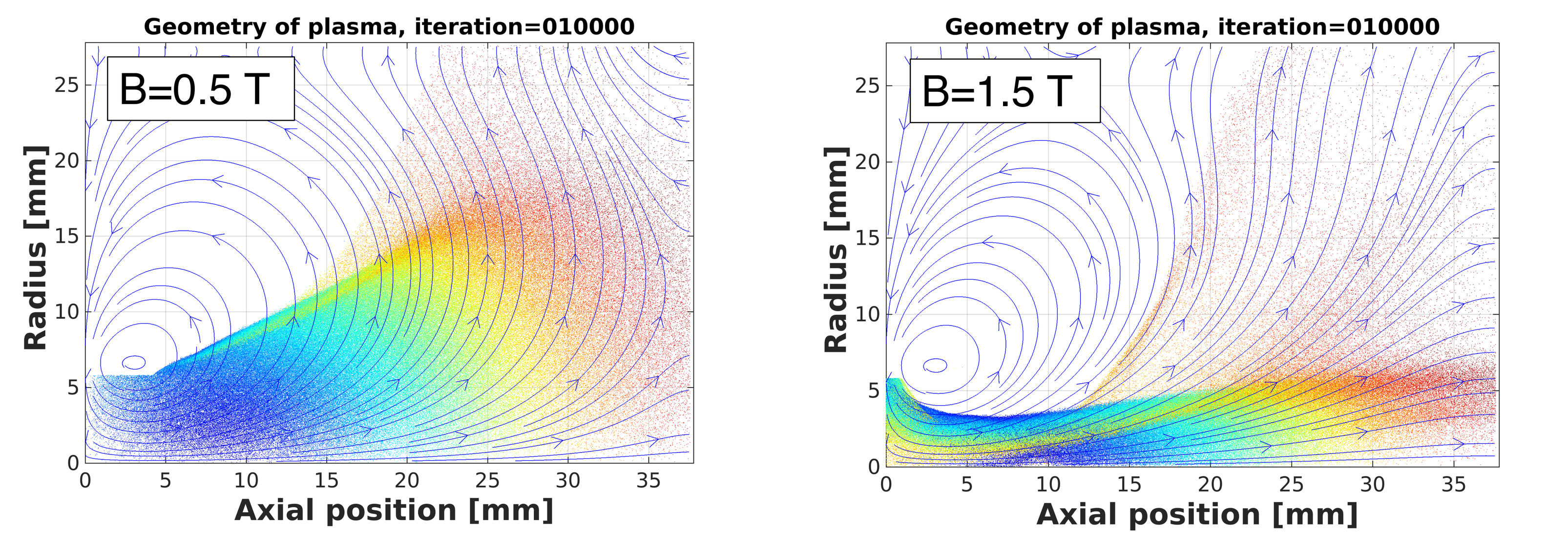
- Compression of plasma core by magnetic pressure
- Focusing of ions in the peripheral part of plasma plume

z	Without magnetic nozzle	With magnetic nozzle
20 mm		
30 mm	**An index for ion directivity:** $\xi \equiv \frac{N_d}{N_t}$ N_d : Total amount of ions observed in a range of 0-20°. N_t : Total amount of ions observed in a range of 0-50°.	

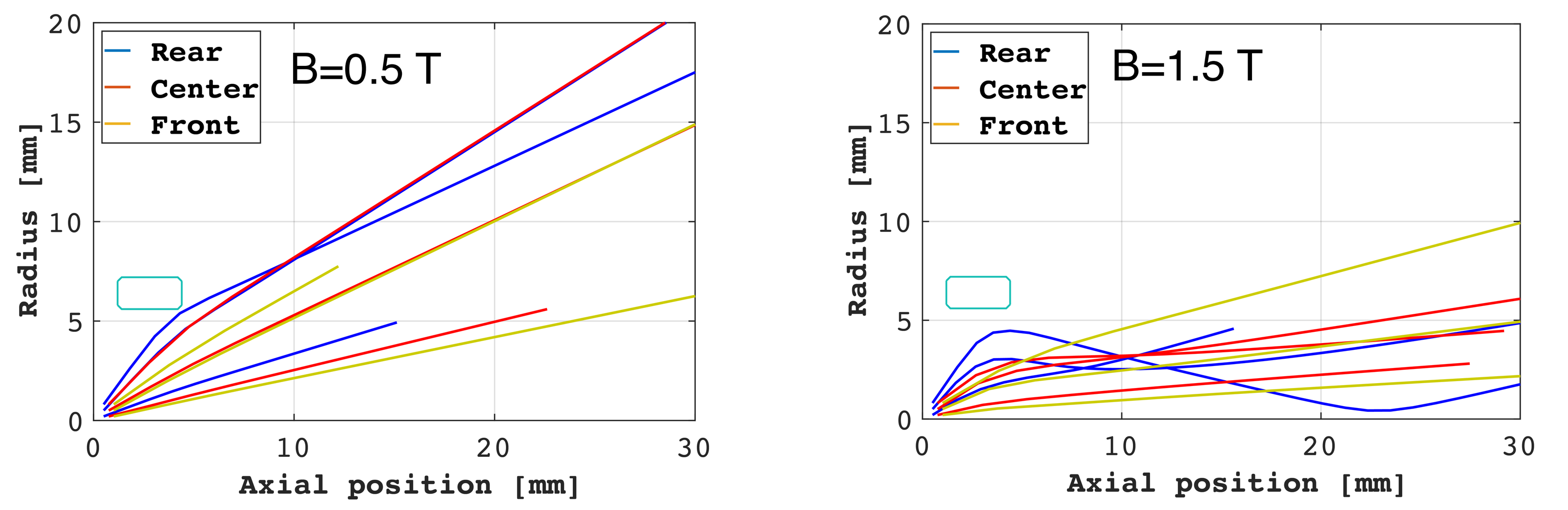
Angular distribution of total ion charge detected by Faraday cup (FC1)

Numerical Analysis

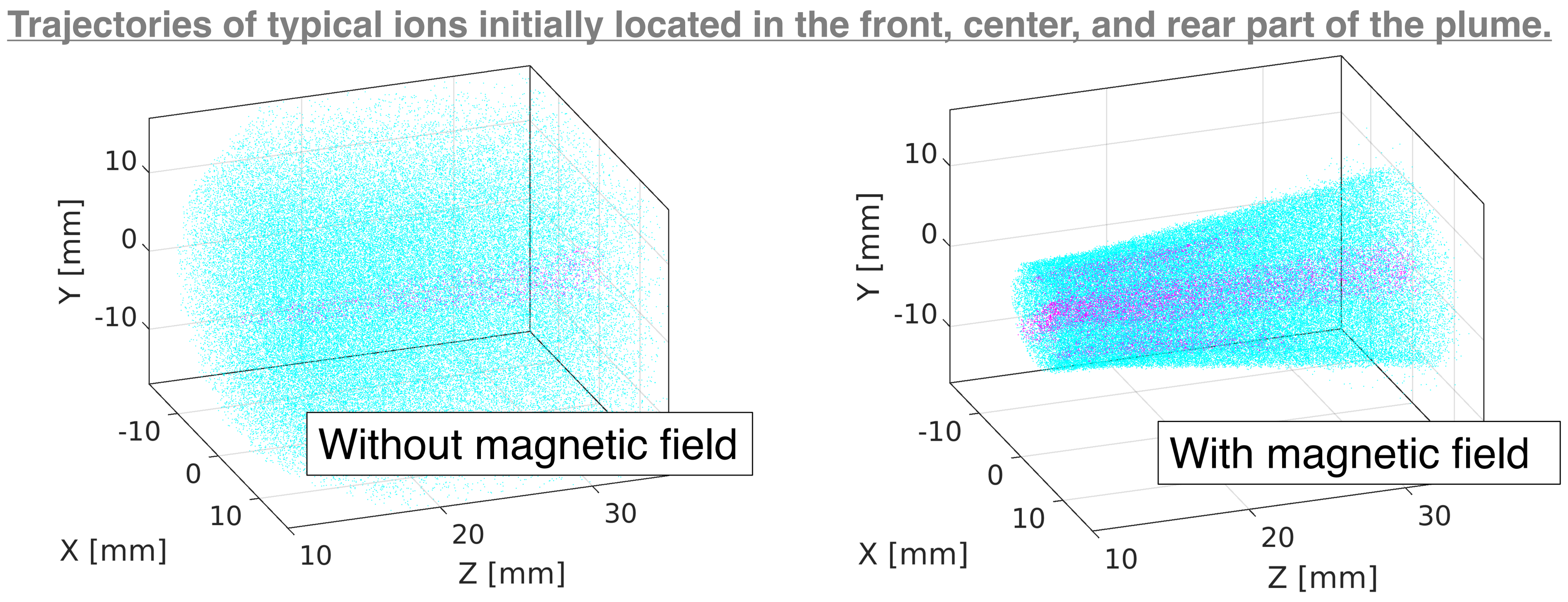
The behavior of a laser-ablation plasma in a divergent magnetic field was investigated also numerically with a 2D hybrid particle-in-cell (Hybrid PIC).



Spatial distributions of ions modulated by a divergent magnetic field.



Trajectories of typical ions initially located in the front, center, and rear part of the plume.



Spatial distributions of ions that are extracted through an extraction hole.

Conclusion

- We proved that the magnetic nozzle can improve the ion directivity of a laser-produced plasma and there are two mechanisms to enhance the plasma ion flux.
- Flux enhancement caused by plasma compression is more preferable because the momentum dispersion in transverse directions becomes minimum.
- Collectively-focused ions may be less useful in extracting low emittance ion beams because their transverse momentums are relatively large.
- However, it may be possible to use a part of focused ions more effectively by optimizing the strength and distribution of the magnetic field.