Research on the energy loss increase of intense proton beams in plasma

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Bethe's theory[1]

The energy loss of a single ion in matter, in cgs units, reads,

$$-\frac{dE}{dx}=\frac{4\pi e^4 Z_{eff}^2}{m_e v_p^2}\left[\sum_k n_{bek}\ln\left(\frac{2m_e v_p^2}{I_k}\right)+G\left(\frac{v_p}{v_{th}}\right)n_{fe}\ln\left(\frac{2m_e v_p^2}{\hbar\omega_p}\right)\right].$$

e:	the elementary charge;	n_{bek}:	bound electron density;
Z_{eff}:	particle effective charge;	n_{fe}:	free electron density;
m_e:	electron mass;	I_k:	ionization energy of bound electron;
v_p:	particle velocity;	ω_p:	plasma frequency;
v_{th}:	plasma thermal velocity;	G:	Chandrasekhar function.

McCorkle's theory [2]

Considering the beam-density effect, the energy loss of a ion beam with a density of n_b is

$$S_b=S_0\left[1+\int_0^\infty g(r/a)4\pi r^2 n_b dr\right]$$
$$=S_0\left(1+2\pi n_b a^3/3\right)$$
$$=S_0\left(1+N_c\right),$$

where S_0 is the energy loss of a single ion, $g(r/a)$ is an interference term

$$g(r/a)=\begin{cases}1/2, r\le a\\ 0, r>a\end{cases}$$

and a equals v_p/ω_p.

[1] H. Bethe, Ann. Phys. (Leipzig) 5, 325-400 (1930).
[2] R. A. McCorkle and G. J. Iafrate, Phys. Rev. Lett. 39, 1263-1266 (1977).
[3] J. Ren, Z. Deng, W. Qi, B. Chen, *et al.*, Nat. Commun. 11, 5157 (2020).

Simulation and experiment

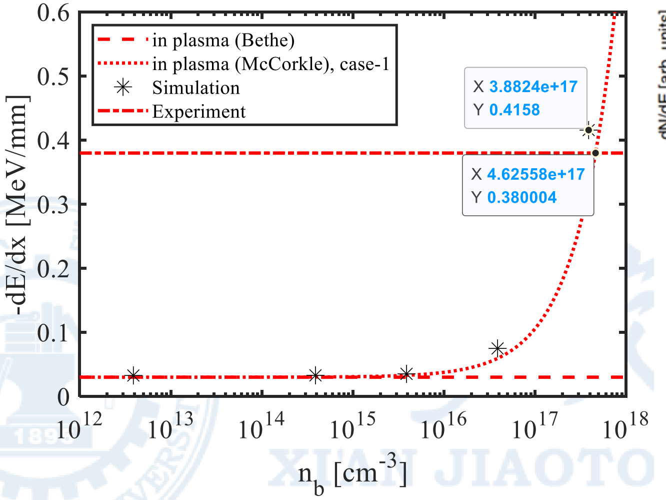

Fig. 1 The stopping power as a function of beam density.

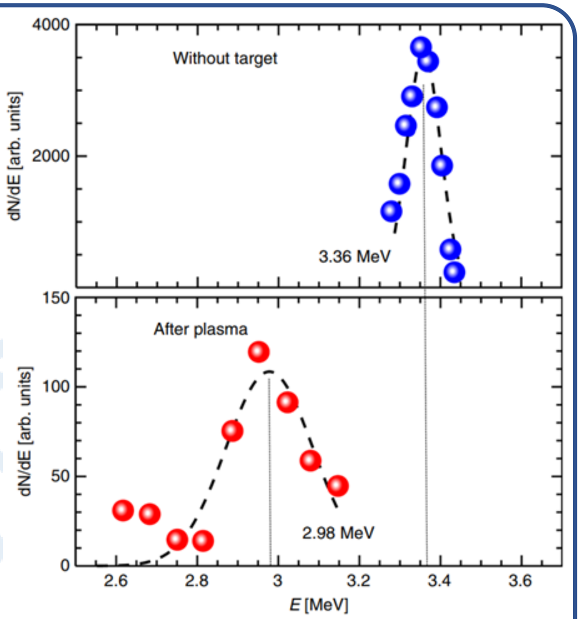

Fig. 2 The energy spectra of the initial injected proton beam (without target) and that passing though the plasma target. [3]

Conclusion

- The stopping power is proportional to a well-defined number of beam particles that interact coherently.
- PIC simulation results agree with the beam-density effect theory.
- In experiment, the stopping enhancement of intense proton beam in plasma can reach one order of magnitude compared with individual ion stopping models.

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Appendix

Injected proton beam	Beam length	1 ps
	Beam radius	0.5 mm
	Energy	3.36 MeV (FWHM of 0.06 MeV)
	Density	4×10^{12}-10^{17} /cm^3
	Current	1.6×10^{3}-10^{8} A/cm^2
$C_9H_{16}O_8$ plasma	Density	2 mg/cm^3
	Length	1 mm
	e^- density	4×10^{20} /cm^3
	Temperature	17 eV
	Ionization state	$C^{3.8+}H^{0.98+}O^{4.5+}$

Case-1: $a = v_p / \sqrt{4\pi n_e e^2 / m_e}$

Case-2: $a = v_p / \sqrt{4\pi n_{ve} e^2 / m_e}$

n_{ve} ---- valence electron density