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Multivariate scaling of maximum proton energy in intense laser driven ion acceleration

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High-energy ion generation using intense laser lights has been studied to realize compact ion sources for applications such as proton radiography and cancer therapy. Target Normal Sheath Acceleration (TNSA), one of the acceleration mechanisms of ions, is a controllable method that can produce ions with a small emittance without being affected strongly by the plasma instabilities.

To obtain higher energy protons, a number of theoretical, numerical, and experimental studies have been conducted on the dependence of the maximum acceleration energy of protons E_{max} on experimental conditions, e.g., laser intensity I_{L}, pulse length τ_{L}, spot diameter W, target density ϱ, and thickness L. As shown in Fig. 1, so far these studies have been performed with single variable scaling for experimental data, Particle-In-Cell (PIC) simulations, and TNSA models. They have predicted E_{max} of several hundred MeV by increasing the laser intensity over 10^{20} W/cm^2, but it has not been demonstrated. Since not all the physics is included in the simulations and the theoretical models, it is difficult to sufficiently capture the high-intensity laser-plasma interaction with these conventional approaches.

We propose a different pathway, namely, the multivariate regression analysis using Bayesian inference in combination with experimental data and 1D PIC simulations, as illustrated in Fig. 1.[1] We derived the scaling from the experimental parameters or physical quantities such as hot electron temperature T_{h} and density n_{h} measured from 1D PIC simulations. In particular, we add two additional effects of the prepulse rising time τ_{pre} and small spot size of ultra-intense lasers l_{ex}/W, which is the ratio of the electron's excursion length l_{ex} to the spot diameter W, and derive a new scaling as

$$E_{max}(\text{MeV}) = 152.1\left(I_{20}\lambda_{\mu\text{m}}^2\right)^{1.01}\left(\frac{\tau_L}{10T_L}\right)^{0.51} \times\left(\frac{\rho}{\rho_{\text{Al}}}\frac{L}{1\mu\text{m}}\right)^{-0.56}\left(\frac{W}{10\mu\text{m}}\right)^{0.61} \times\left(\frac{\tau_L+\tau_{\text{pre}}}{\tau_L}\right)^{-0.48}\left(\frac{W+2l_{\text{ex}}}{W}\right)^{-1.42} \quad (1).$$

This model provides good predictions even for laser intensities over 10^{20} W/cm^2 (see Fig. 2).

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References

[1] Y. Takagi *et al*, Phys. Rev. Res. **3**, 043140 (2021)

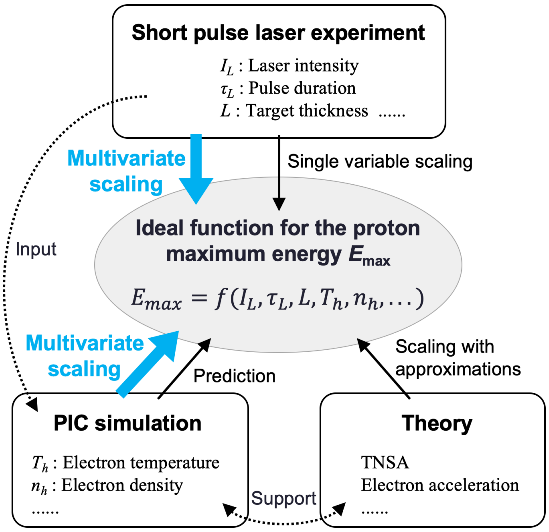

FIG. 1. Conventional approaches and the proposed approach (blue) for the prediction of the laser-driven ion acceleration.

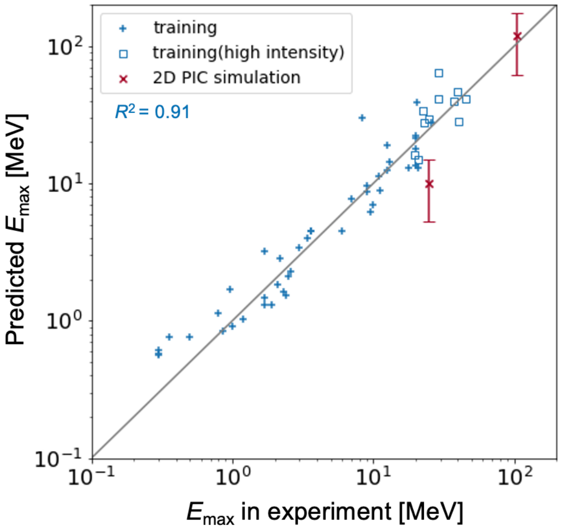

FIG. 2. Prediction for the maximum proton energy E_{max} by Eq. (1). The blue pluses and squares are the training data. Red crosses are validations using 2D PIC simulations. Here R^2 is the coefficient of determination