Analytical Estimates of Proton Acceleration in Laser-produced Turbulent Plasma

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Abstract

With the advent of high power lasers, new opportunities have opened up for simulating astrophysical processes in the laboratory. We show that 2nd-order Fermi acceleration can be directly investigated at the National Ignition Facility, Livermore. This requires measuring the momentum-space diffusion of 3 MeV protons produced within a turbulent plasma generated by a laser. Treating Fermi acceleration as a biased diffusion process, we show analytically that a measurable broadening of the initial proton distribution is then expected for particles exiting the plasma.

Motivation

In 1912 Viktor Hess concluded the existance of cosmic radiation after a series of baloon flights to measure ionization as a function of altitude. Radiation can rip out electrons from their atoms (ionization) and so the existance of this radiation can be inferred from a measurment of ionization.
Following the detection of the existence, many properties of cosmic rays were measured. One of them being the energy, which can be very high, orders of magnitude higher than what is currently achievable in particle accelerators like CERN. One natural question to ask concerns the acceleration mechanism.

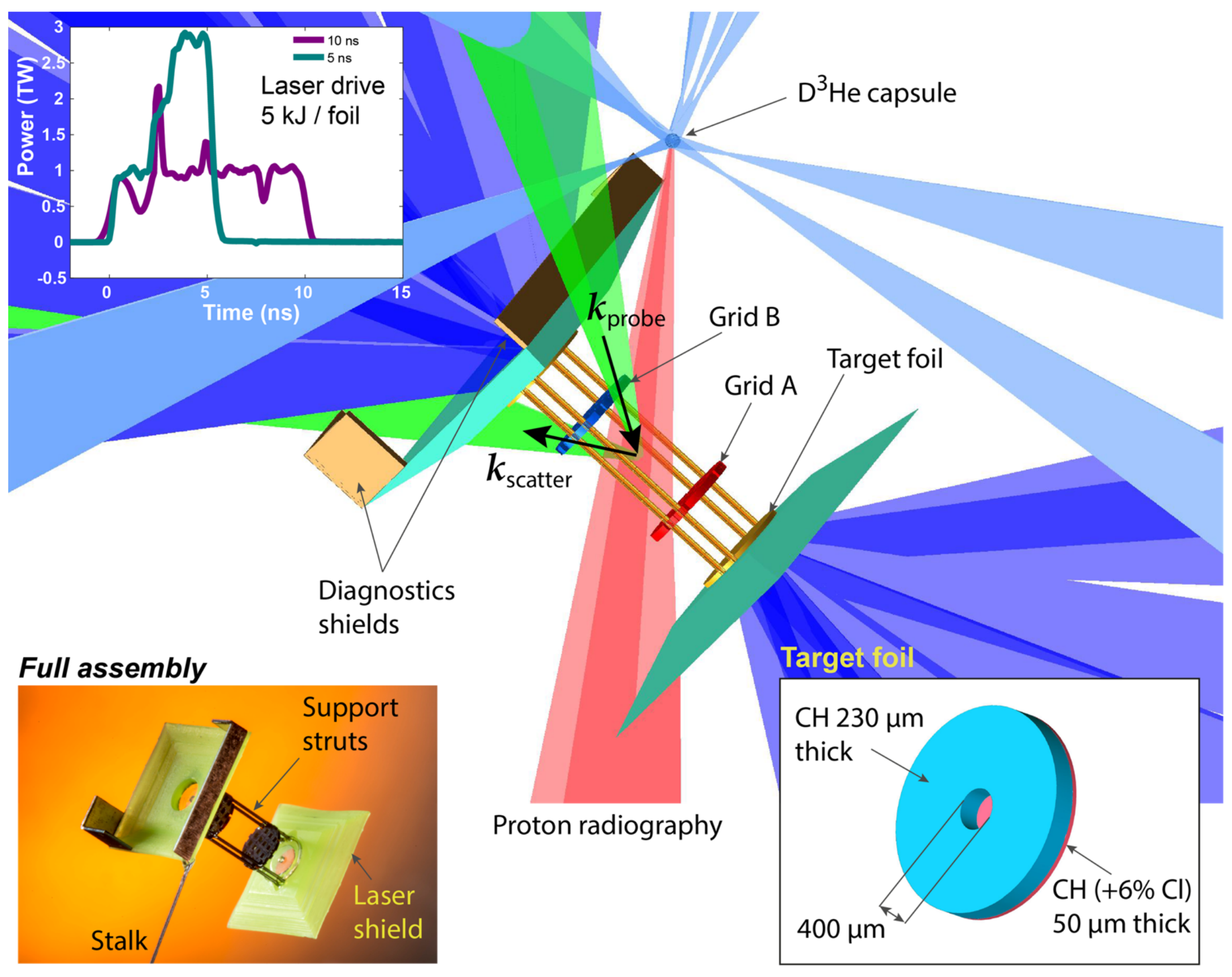
→ Second-order Fermi acceleration

This can be investigated in laboratory experiments due to a scale invariance in the equations describing these systems. By proper scaling, a laboratory plasma will exhibit similar behavior as the astrophysical counterpart.

→ Laboratory Astrophysics

Experimental Design

Two essential ingredients for second-order Fermi acceleration are turbulent motion and magnetic fields. The TDYNO platform was designed to investigate the turbulent dynamo (Tzeferacos, 2018). This effect leads to the amplification of magnetic fields and the appearance of strong, turbulent magnetic fields, which can be used to investigate Fermi acceleration.
Two Plasma jets are produced and subsequently guided through two grids which are rotated relative to each other.



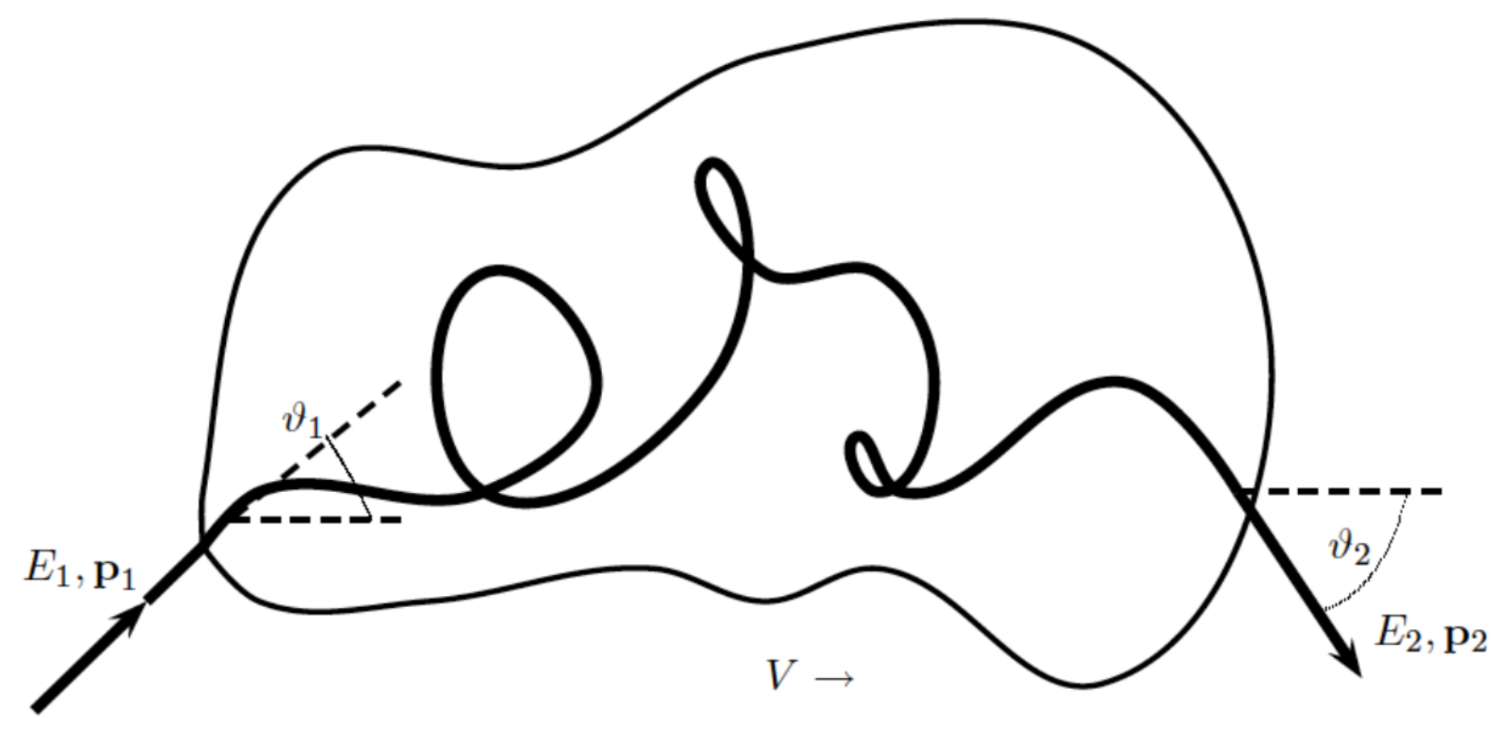
(Tzeferacos, 2018)

These dissect the jets into 'fingers' which then collide and form a turbulent region in which the dynamo operates and strong magnetic fields are produced. Protons in this region will experience stochastic acceleration.
By a combination of past experiments and numerical simulations one can infer a set of parameters describing the plasma in this experiment as given in the table below.

Parameter	Measured OMEGA values	Scaled NIF values
RMS magnetic field	0.12 MG	**1.2-4 MG**
Temperature	450 eV	700 eV
Electron/Ion density	~10^{20}/cm^3	~7 · 10^{20}/cm^3
RMS turbulent velocity	150 km/s	600 km/s
Plasma beta	125	13.7
Reynolds Number	370	**~1200**
Magnetic Reynolds Number	870	**~20000**

Second-order Fermi acceleration

Fast particles collide with magnetised 'clouds' (Fermi, 1949) gaining or loosing energy for head-on or overtaking collisions, respectively. The process leads to ***stochastic acceleration*** with energy gain second order in V/c.



Kachelries (arXiv:0801.4376)

$$E_1' = \gamma E_1 (1 - \beta \cos\theta_1)$$

with $\beta = V/c$

and $\gamma = 1/\sqrt{1-\beta^2}$

Performing angle averages under consideration of the collision rate which is proportional to the relative velocity between the scattering agents

$$\langle \cos\theta_2' \rangle = 0 \text{ and } \langle \cos\theta_1 \rangle = \frac{\int \cos\theta_1 \frac{dn}{d\Omega_1} d\Omega_1}{\int \frac{dn}{d\Omega_1} d\Omega_1} \sim -\beta$$

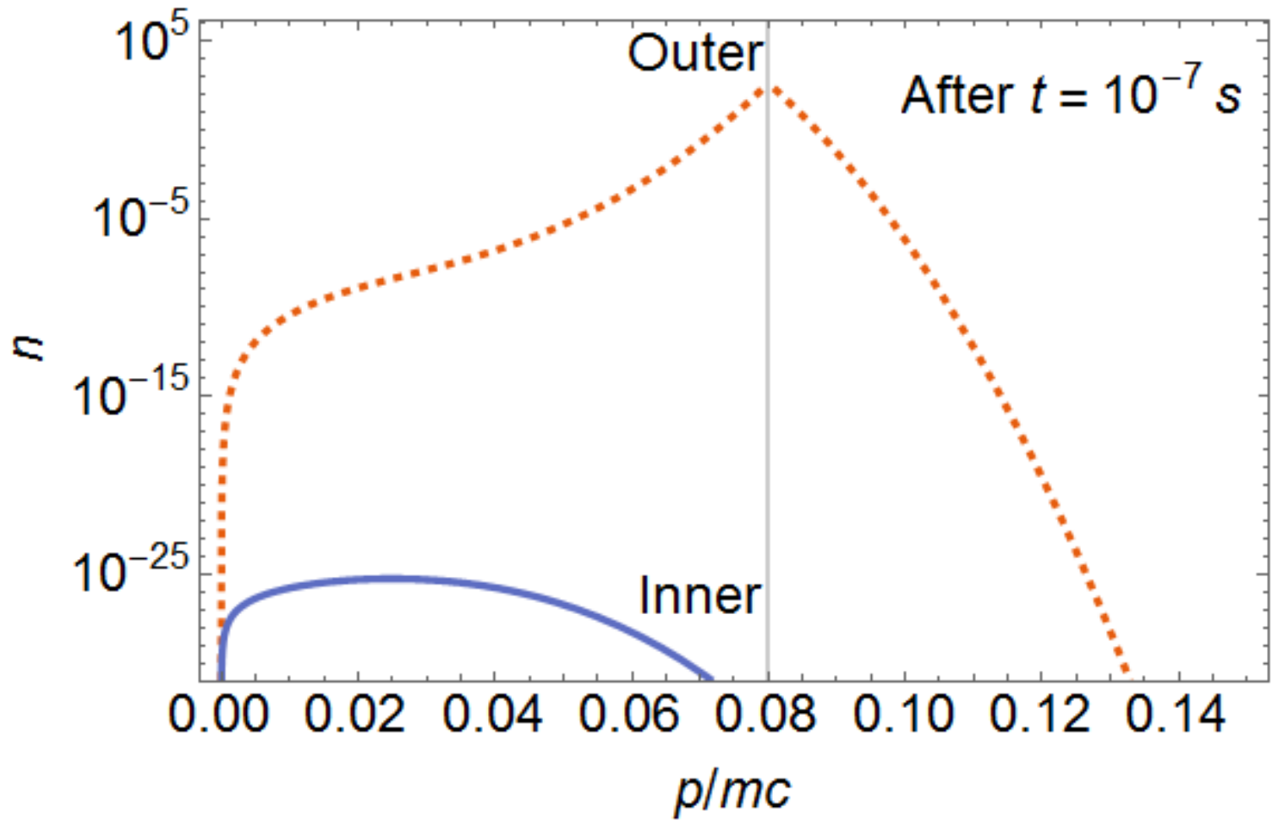
This leads to an energy gain after many encounters which is given by

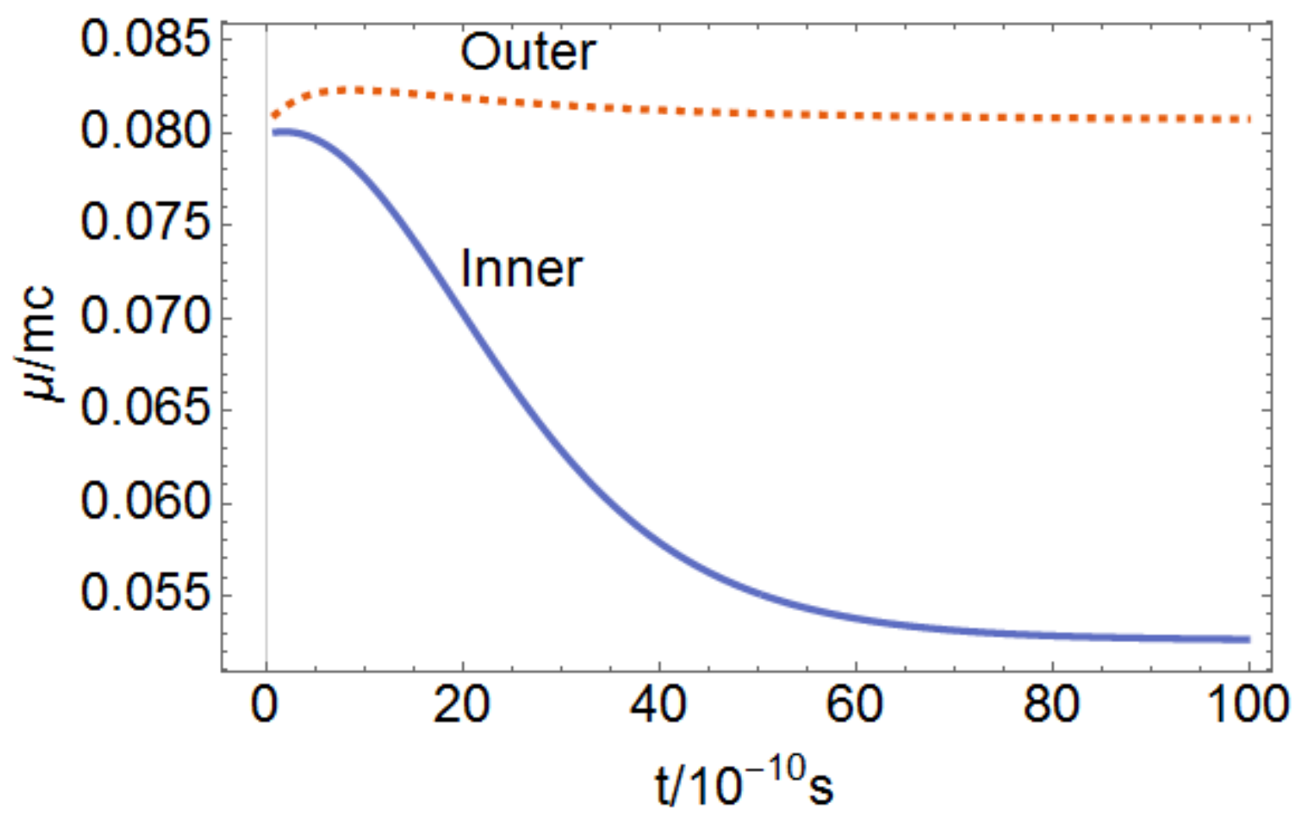
$$\left\langle \frac{E_2 - E_1}{E_1} \right\rangle = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2' - \beta^2 \cos\theta_1 \cos\theta_2'}{1-\beta^2} - 1 \sim \beta^2$$

It has later been found that for example MHD turbulence can provide the scattering centres. (Sturrock 1966, Kulsrud and Ferrari 1971)

Estimated Effect

The diffusion equation can be solved exactly (Mertsch, 2011) and the resulting spectrum is shown below.





The mean momentum of the proton spectrum is shifted by

$$\Delta\mu_E \sim 10 - 200\ keV$$

depending on the actual magnetic field.
Also the FWHM of the distribution is increased by

$$\Delta E_{FWHM} \sim 0.24 - 1.2\ MeV.$$

A threshold value for the detection of this effect is set by additional effects leading to a broader spectrum. One significant effect is the imprint of the turbulent motion on the fusion proton spectrum prior to acceleration.

$$\Delta E_{Threshold} \sim 300\ keV$$

References:
Beyer et. al. 2018, arXiv:1808.04356
Kachelries, 2008, arXiv:0801.4376
Mertsch, 2011, Journal of Cosmology and Astroparticle Physics 12, 010
Ostrowski, 1997, Astroparticle Phys. 6, 271
Tzeferacos, 2018, Nature Communications 9, 591
Fermi, 1949, Phys. Rev. 75, 1169
Kulsrud, 1995, Phys. of Plasmas 2 (5), 1735

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