Ion acceleration with high intensity lasers

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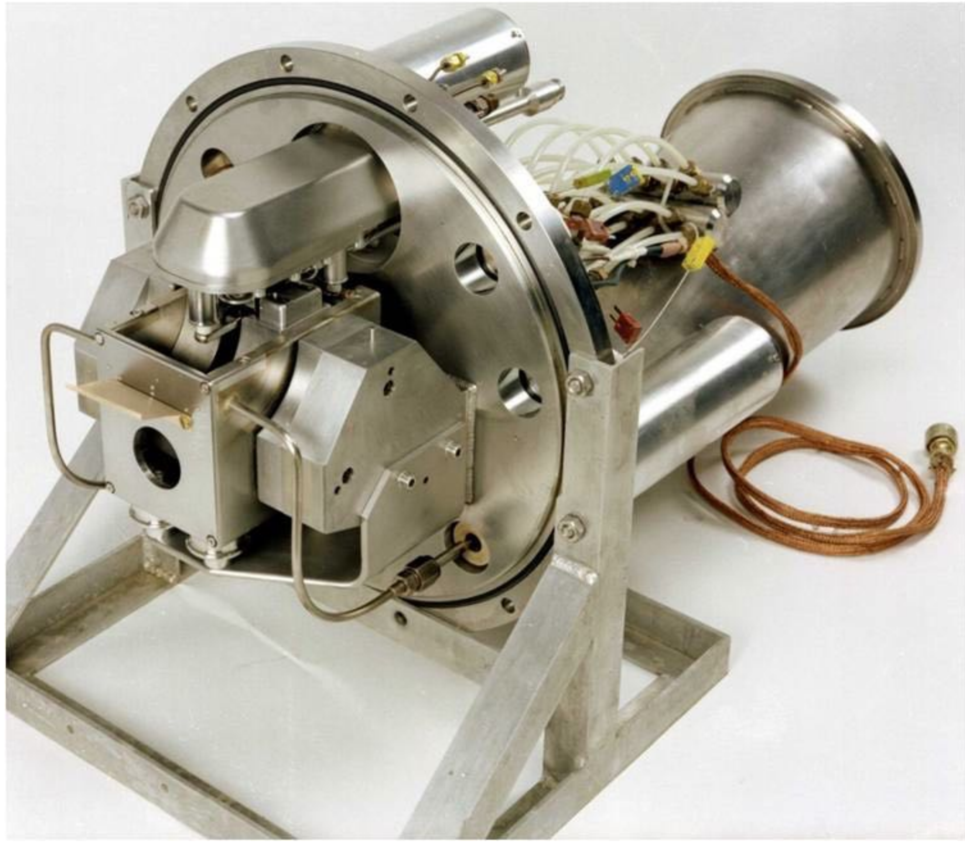
17th November 2020

Ion sources



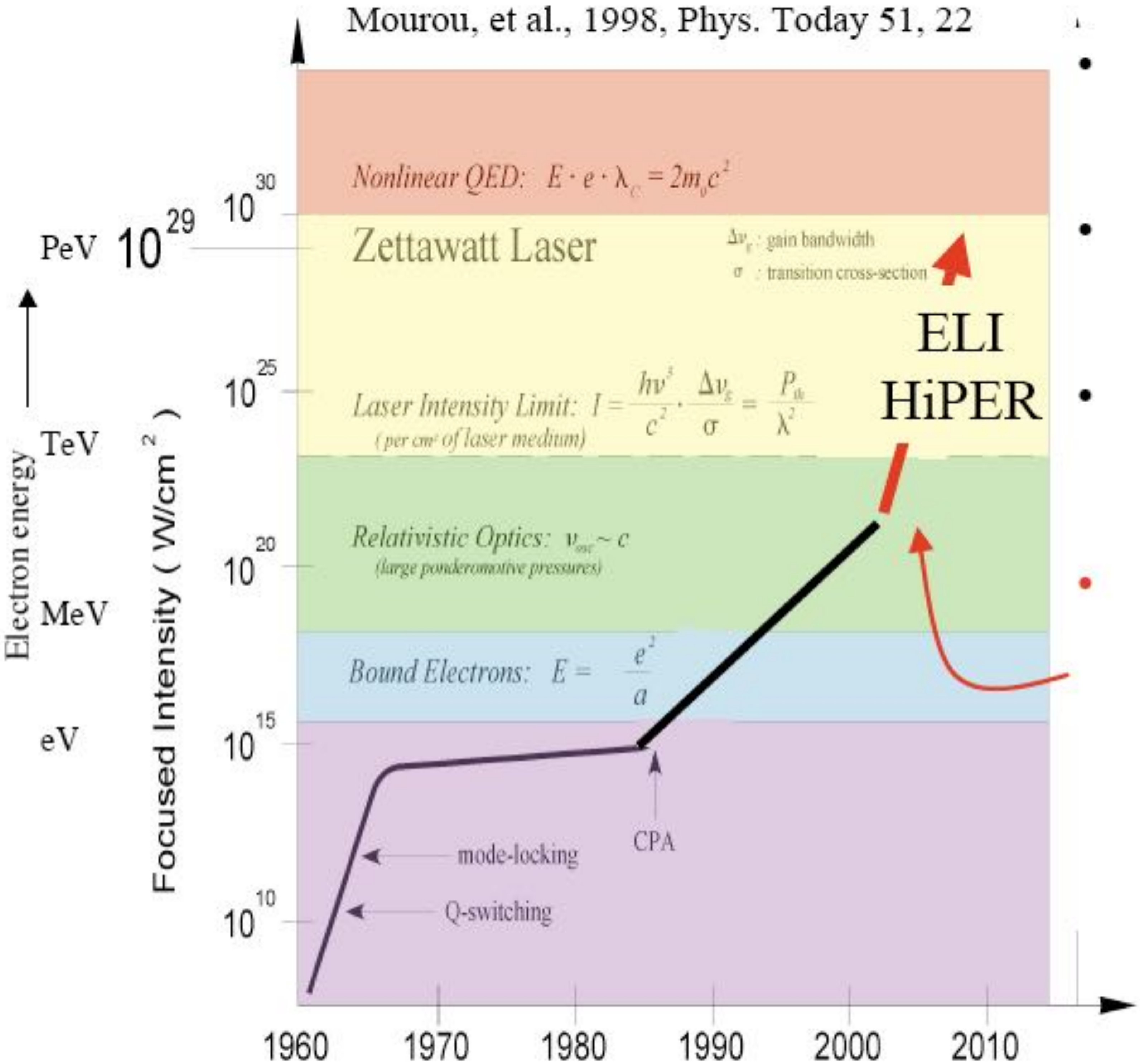
http://www.isis.stfc.ac.uk/about-isis/how-isis-works---in-depth4371.html

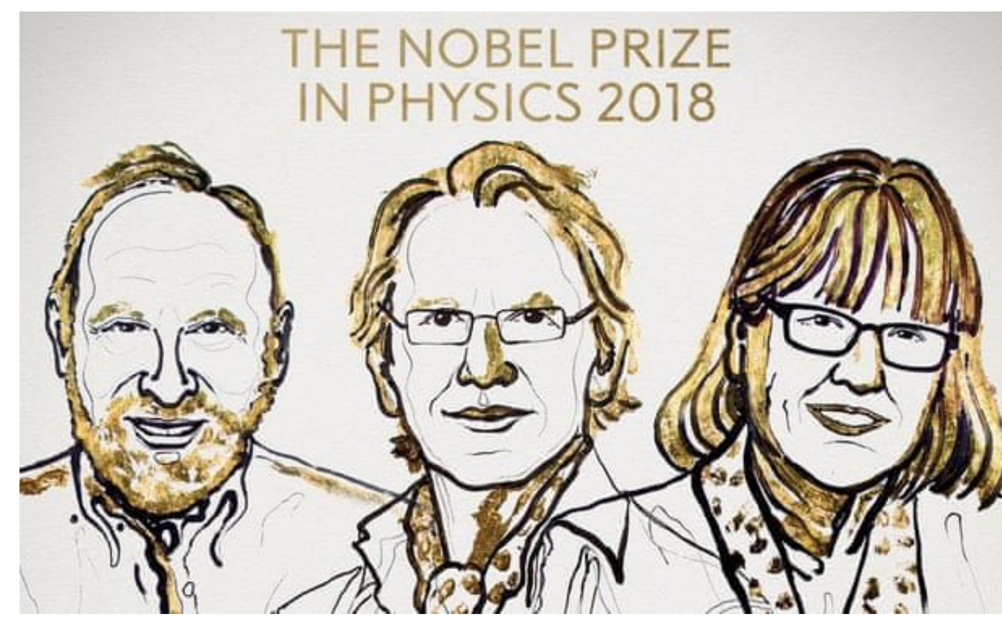
Based on thermal plasmas:

Plus:
- reliable
- long lifetime

Cons:
- low-energy (need acceleration)
- long pulses (need compression)

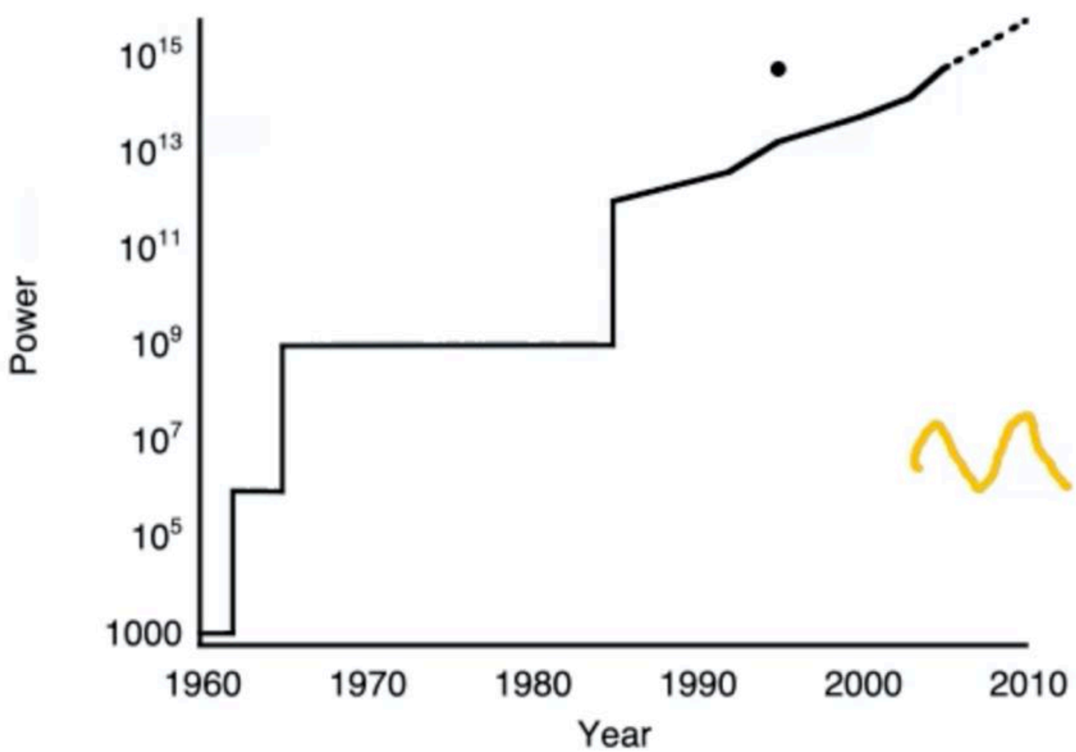
High Intensity Lasers





High intensity lasers

The evolution of Power of small diameter laser systems



vulcan PW, 400 J in 400 fs

$P \sim \frac{\cancel{400}}{\cancel{400}\cdot 10^{-15}} \sim 10^{15}\,W = 1\,PW$

Focussed to $(10\,\mu m)^2 - 10^{-10}\,m$

$\text{Intensity} \sim \frac{I}{A} \sim \frac{10^{15}}{10^{-10}} \sim 10^{25}\,W$

$I \sim |\underline{E}\times\underline{H}| \sim \frac{1}{2}\varepsilon_0 E^2 \cdot c$

$\Rightarrow E = (2\mu_0 c)^{1/2} I^{1/2} \simeq 30\, I^{1/2}$

$= 30 \times 3 \times 10^{12}$

$= 10^{14}\,Vm^{-1}.$

$E_{RF} \propto 10^{8}\,Vm^{-1}.$

Motion of charge in laser field

$$\underline{F} = \frac{d\underline{p}}{dt} = -e(\underline{E} + \underline{v} \times \underline{B})$$

(ignore $\underline{B}$), $\underline{E} = E_x \cos(kz - \omega t)\,\hat{i}$, $\underline{E} = -\frac{\partial \underline{A}}{\partial t}$.

$$\frac{\partial p_x}{\partial t} = e\frac{\partial A_x}{\partial t} \Rightarrow p_x = eA = a\,mc$$

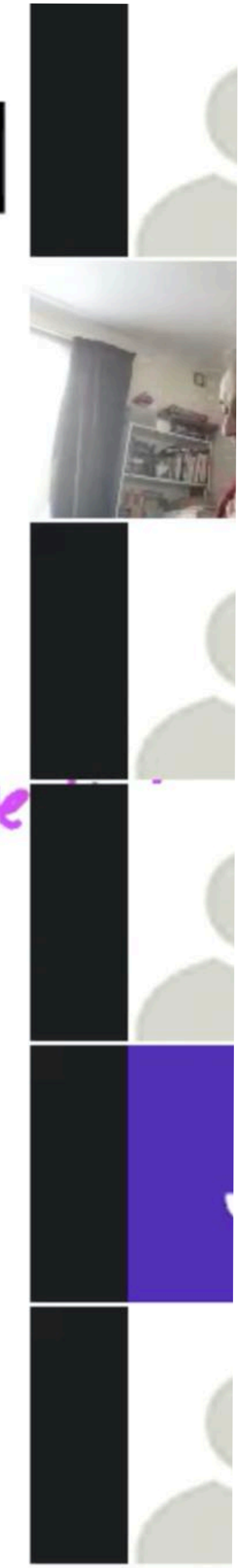
↑ normalised vector pote

$$a = \frac{eA}{mc} \Rightarrow a_0 = \frac{eE}{m\omega c}$$

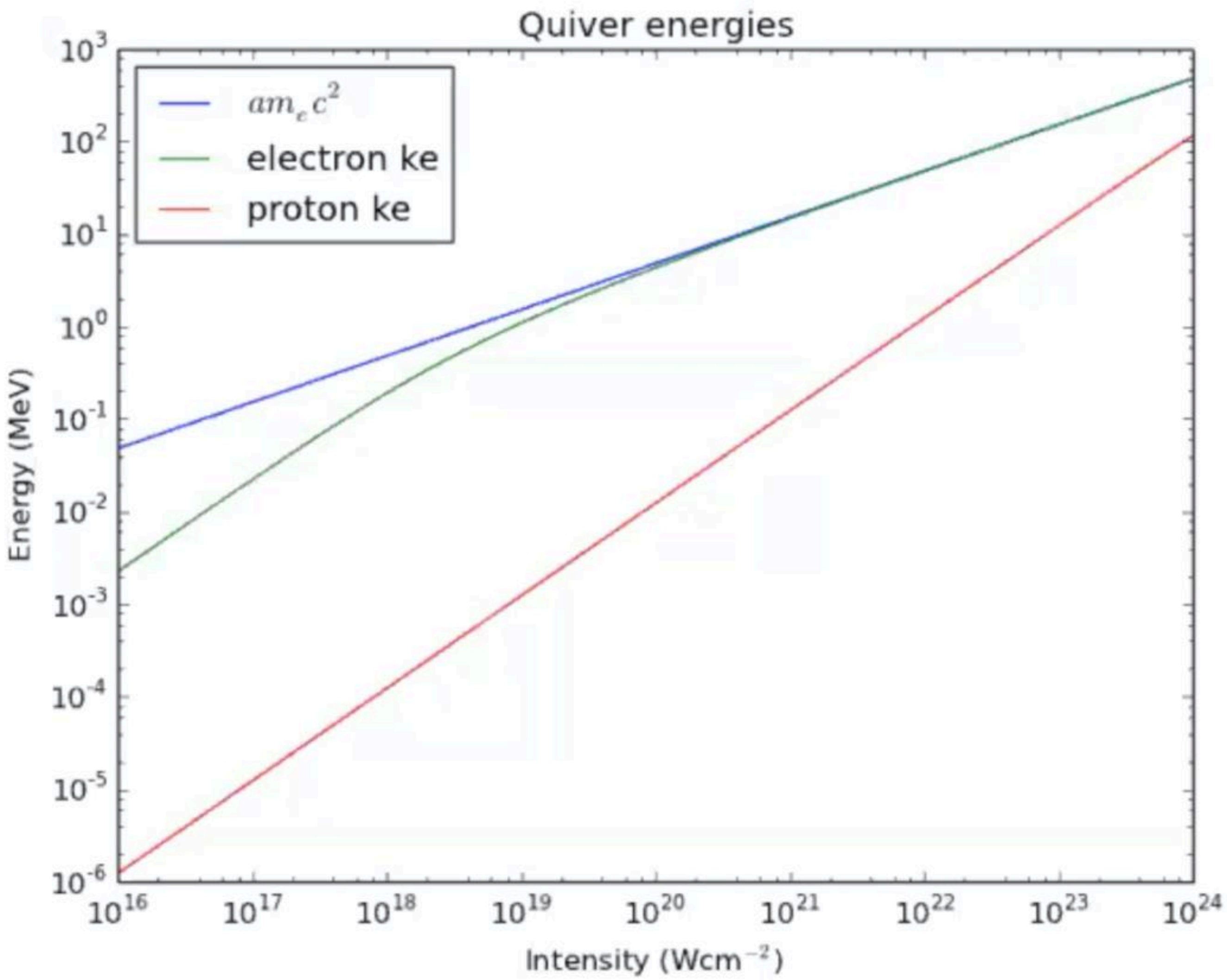
(normalised momentum)

$$a_0 \simeq 0.855\,(I_{22}\lambda_{\mu}^{2})$$

↑ $10^{22}\ \mathrm{Wm^{-2}}$ μm



Quiver energies



$$E^2 = c^2 \underbrace{p^2}_{\sim a^2 m^2 c^2} + m^2 c^4$$

$$= m^2 c^4 (1 + a^2)$$

$$K_e = m c^2 (1 + a^2)^{1/2} - mc^2$$

for small a,

$$\approx mc^2 (\cancel{1} + \tfrac{1}{2} a^2) - \cancel{mc^2}$$

$$\approx \tfrac{1}{2} mc^2 a^2$$

$(= \tfrac{1}{2} m$

$a \approx v/$

quiver

$$K_i \approx Mc^2 \sqrt{1 + \left(\frac{m}{M}\right) a^2} - Mc^2$$

need $a \sim > 2000\times$ to get the same energy

Motion of charge in laser field

(From Faraday's law $\nabla \times \mathbf{E} = \dot{\mathbf{B}} \rightarrow \mathbf{B} = \hat{\mathbf{j}}(kE_x/\omega)\cos(kz - \omega t)$).
In vacuum this implies $\mathbf{B} = \hat{\mathbf{j}} B_y \cos(kz - \omega t)$, where $E_x = cB_y$.

Now particle motion including B-field becomes:

$$
\begin{aligned}
m\dot{v}_x &= -eE_x \cos(kz - \omega t) \\
m\dot{v}_y &= 0 \\
m\dot{v}_z &= -ev_x B_y \cos(kz - \omega t)
\end{aligned}
$$

(NB we ignored $B_y \times v_z$ force on v_x, assuming 2nd order small).

Again $v_x = -a_0 c \sin(kz - \omega t)$ but now,

$$
\begin{aligned}
\dot{v}_z &= (ea_0 cE_x/mc)\sin(kz - \omega t)\cos(kz - \omega t) \\
&= (a_0^2 c\omega/2)\sin 2(kz - \omega t)
\end{aligned}
$$

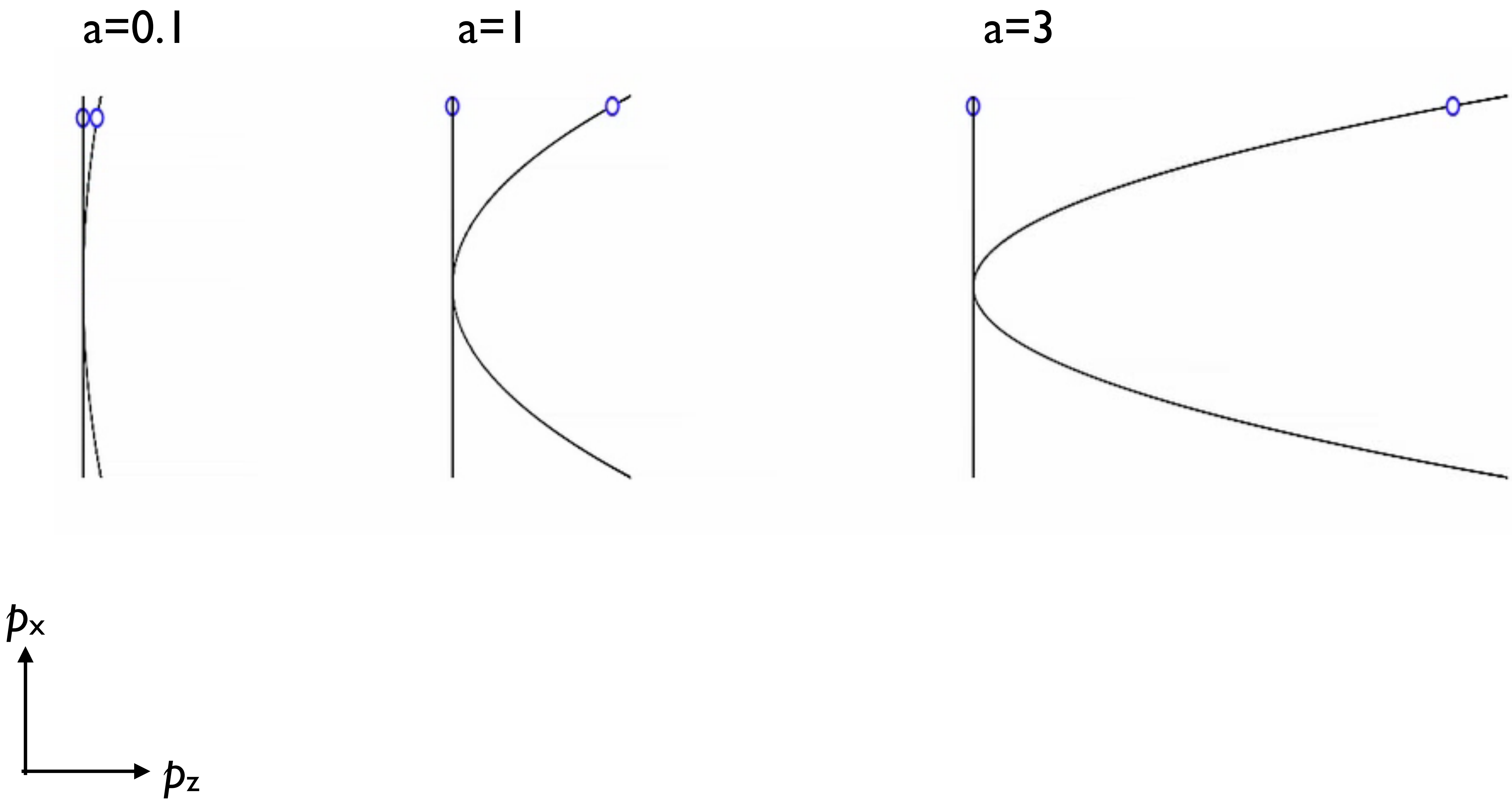
So, $v_z = -(a_0^2 c/4)\cos 2(kz - \omega t) + k$

If particle starts with $v_x = 0, v_z = 0$, then $k = (a_0^2 c/4)$, so

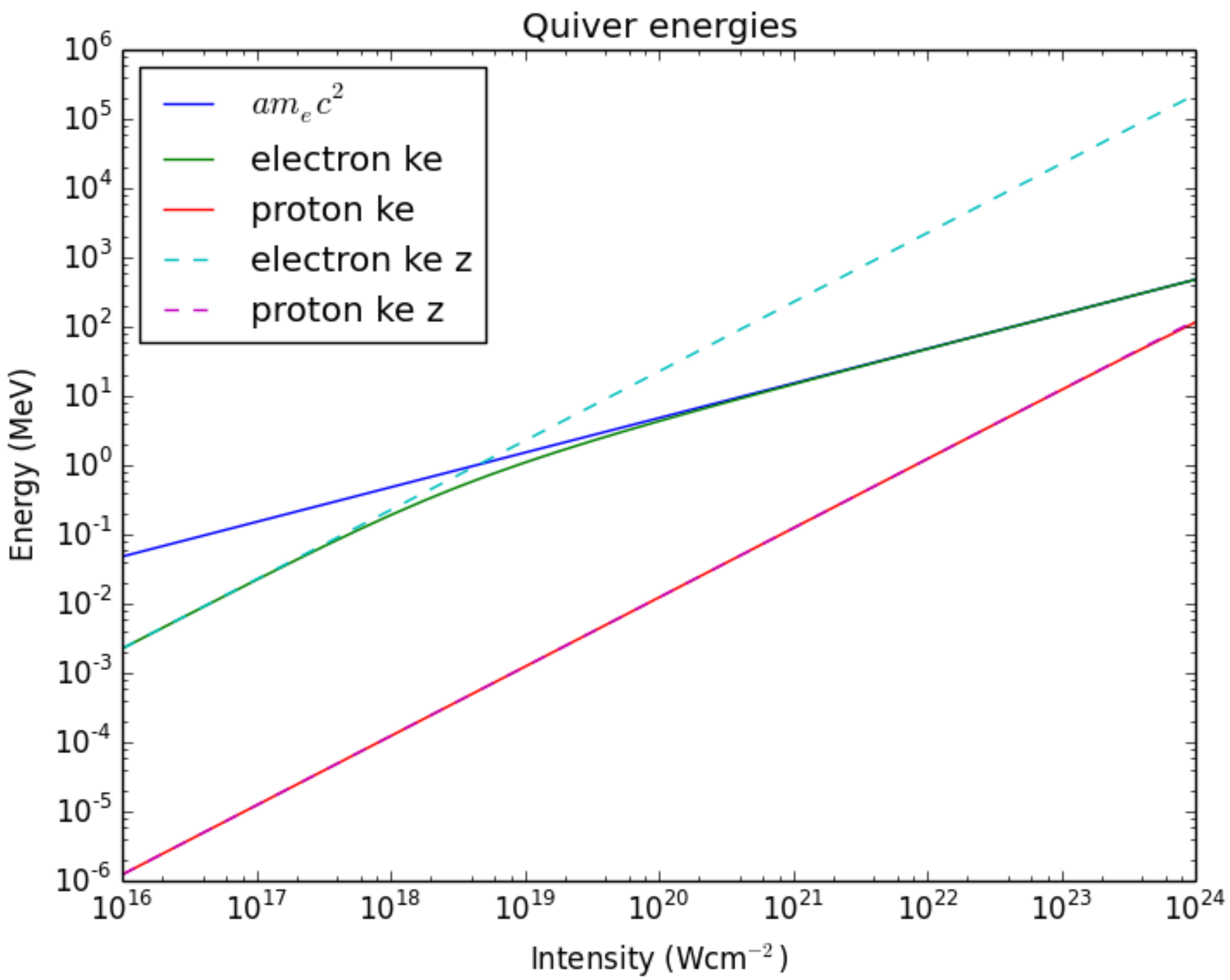
$$
v_z = (a_0^2 c/4)(1 - \cos 2(kz - \omega t)) = (a_0^2 c/2)(\sin^2(kz - \omega t))
$$

Note these are parabolic tracks with $v_z = v_x^2/2$, and that the larger the transverse velocity (and thus a_0), so the larger the longitudinal acceleration.

Some phase space trajectories



Quiver velocities



Now, $p_x = a\,mc$ and $p_z = \frac{1}{2}a^2 mc$

So $\mathcal{E} = \sqrt{m^2c^4 + c^2{p_x}^2 + c^2{p_z}^2}$

$$= mc^2\sqrt{1 + a^2 + \tfrac{1}{4}a^4} = mc^2(1 + \tfrac{1}{2}a^2)$$

So $K_e = \mathcal{E} - mc^2 = \frac{1}{2}a^2mc^2$

For $v \ll c$, $K_e \approx \frac{1}{2}m{v_x}^2$ as before (so x motion has most of the energy).

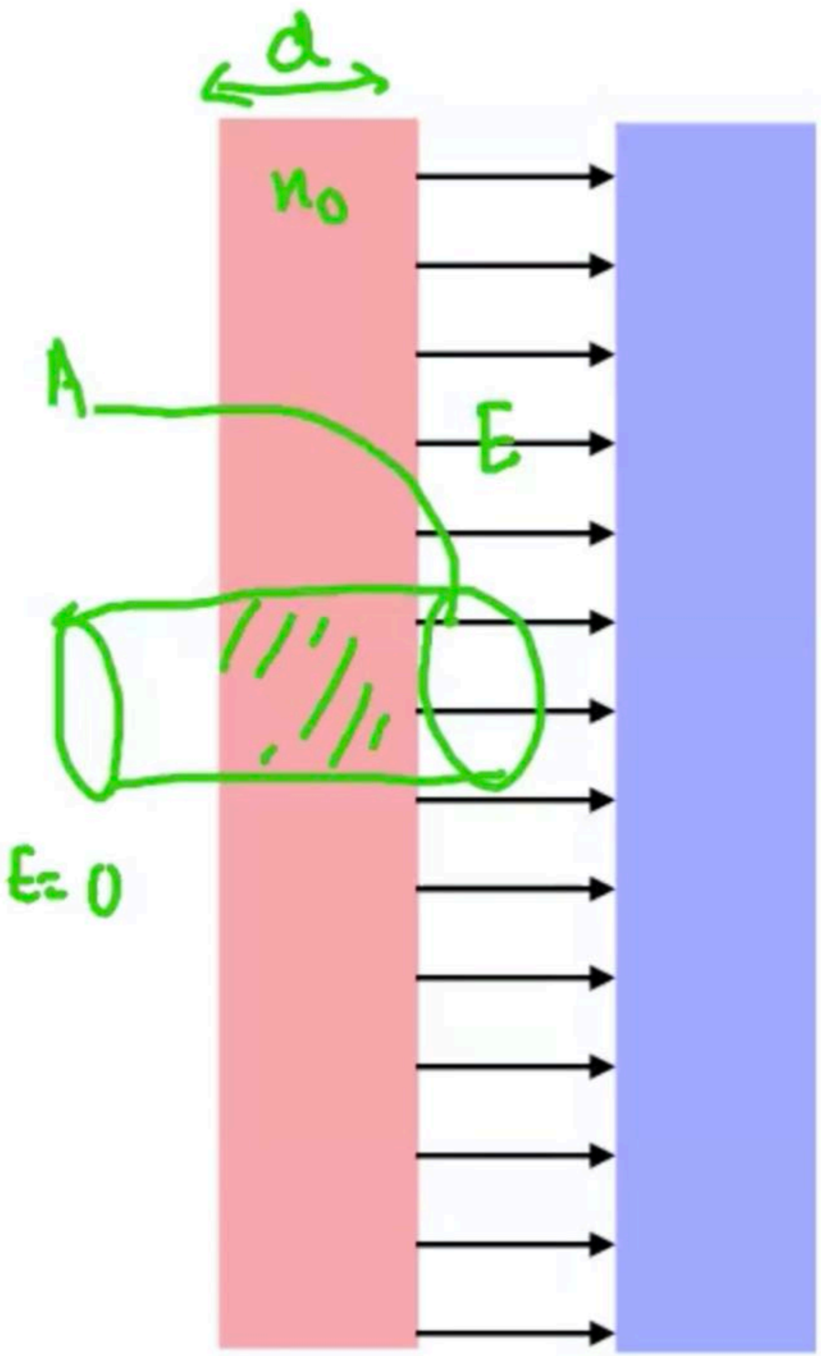
Similarly for ions:

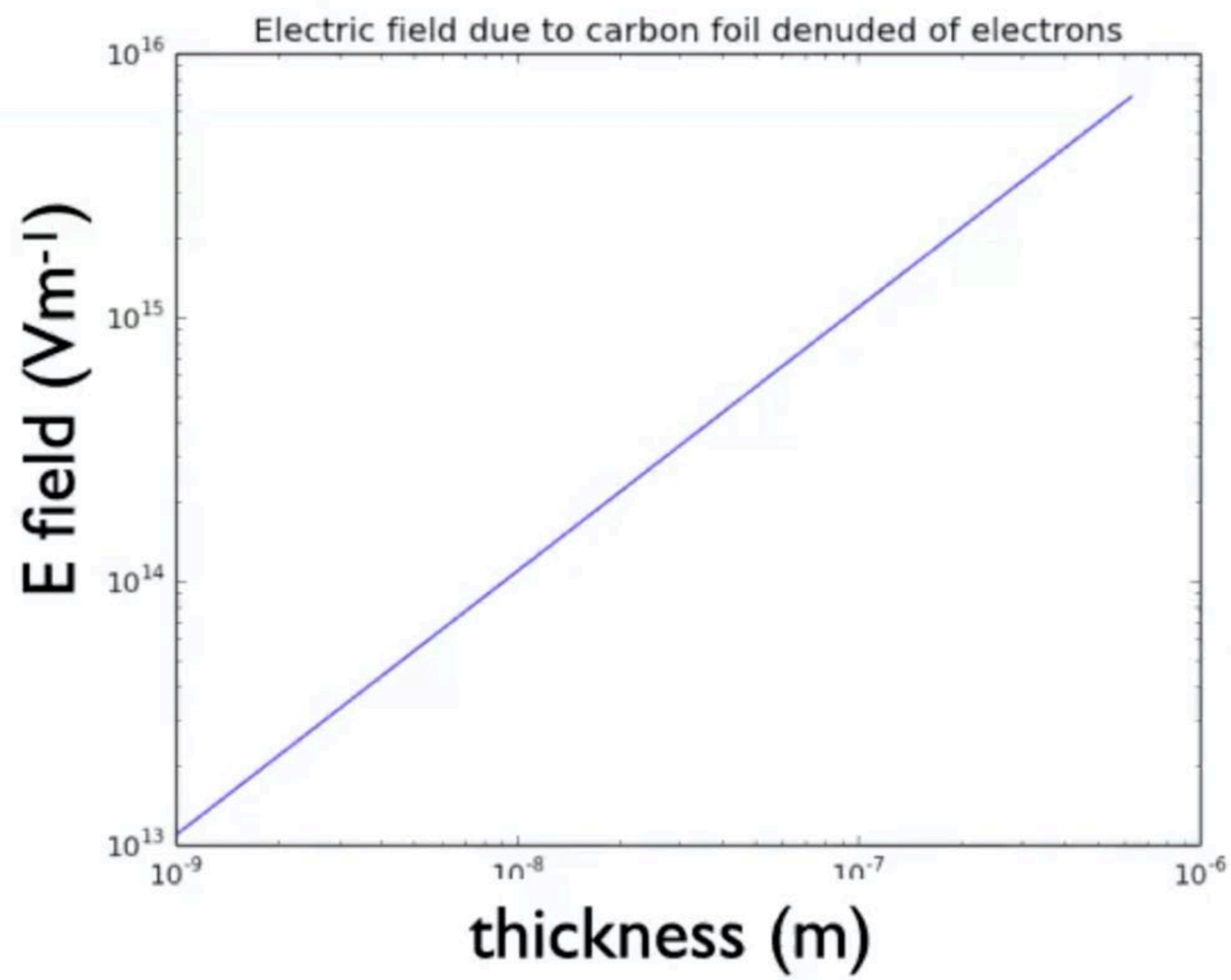
So $K_i = \frac{1}{2}(m/M)^2a^2Mc^2$

Foils

$$\varepsilon_0 E \cancel{A} = n_0 e \cancel{A} d$$

$$E = \frac{n_0 e d}{\varepsilon_0}$$





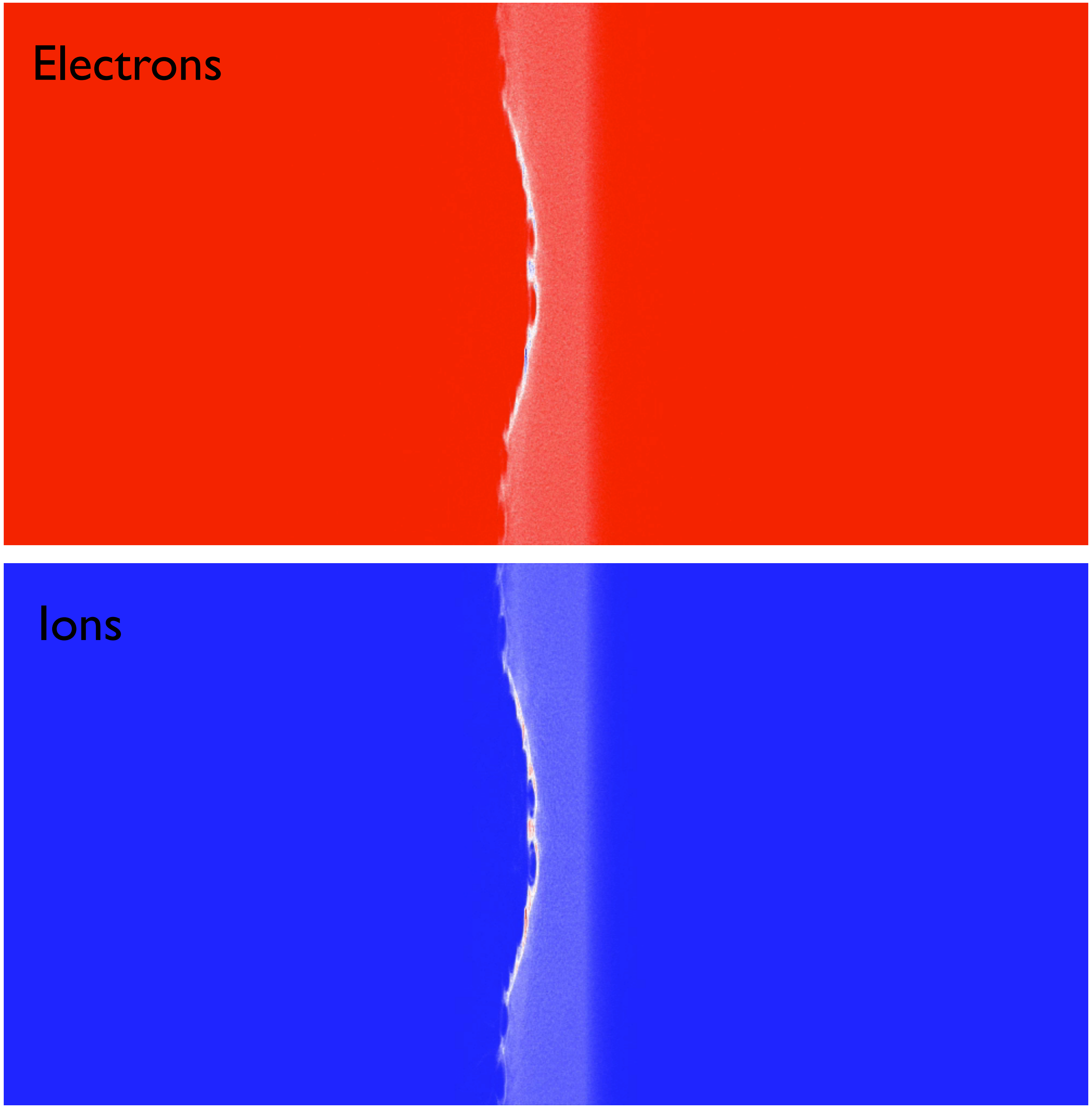
High-intensity laser-solid interact

$$\cancel{\tfrac{1}{2}}\varepsilon_0 \cancel{E}^2 = \cancel{\tfrac{1}{2}} m c^2 a^2 n_e = \cancel{\tfrac{1}{2}} \cancel{m} \cancel{c^2} \frac{e^2 \cancel{E}^2}{m^2 \omega^2 \cancel{c^2}} n_e$$

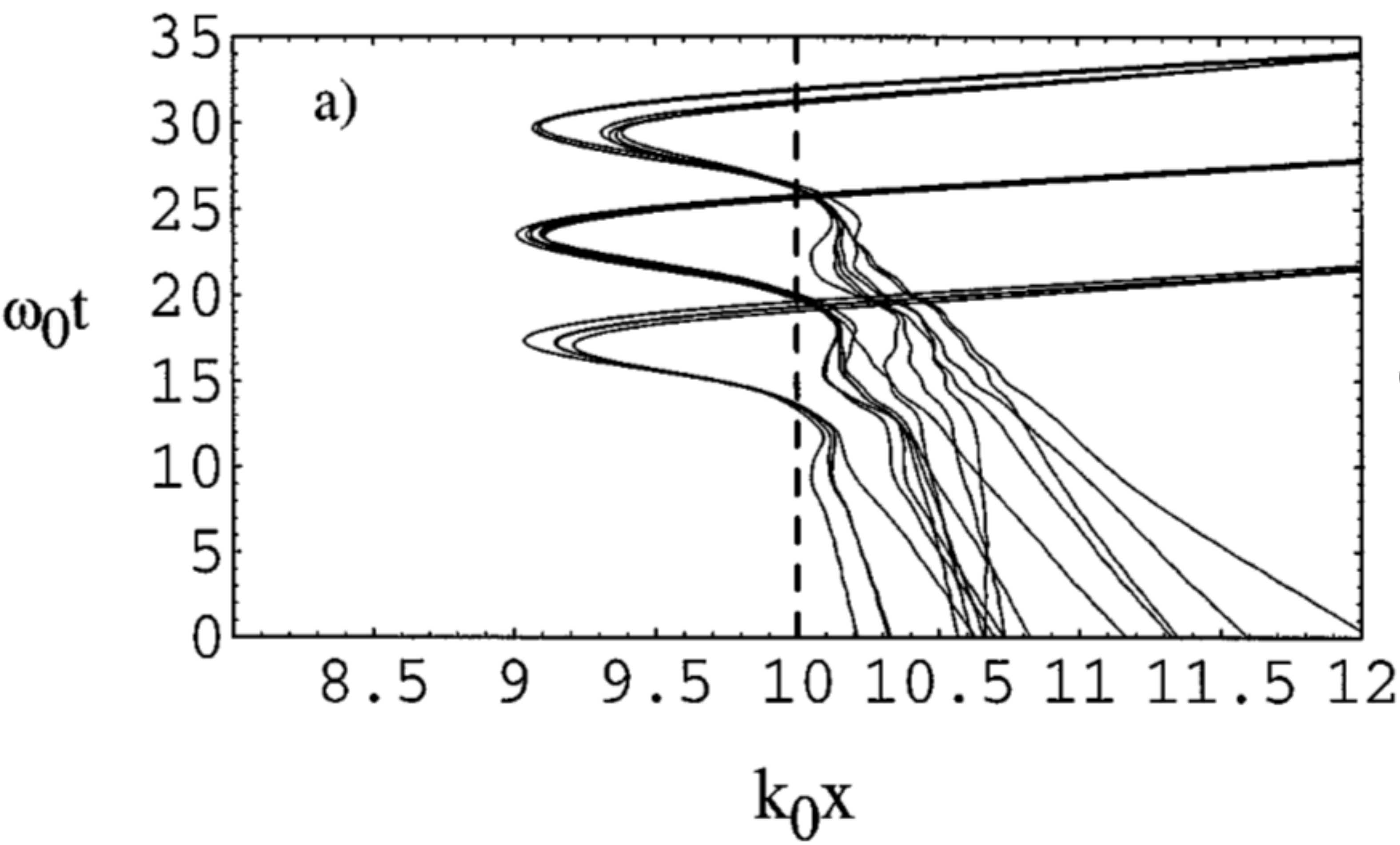
$$\Rightarrow \quad n_{cr} = \frac{\varepsilon_0 m \omega^2}{e^2} \qquad \text{(critical density)}$$

$$n_{cr} \sim 10^{27}$$

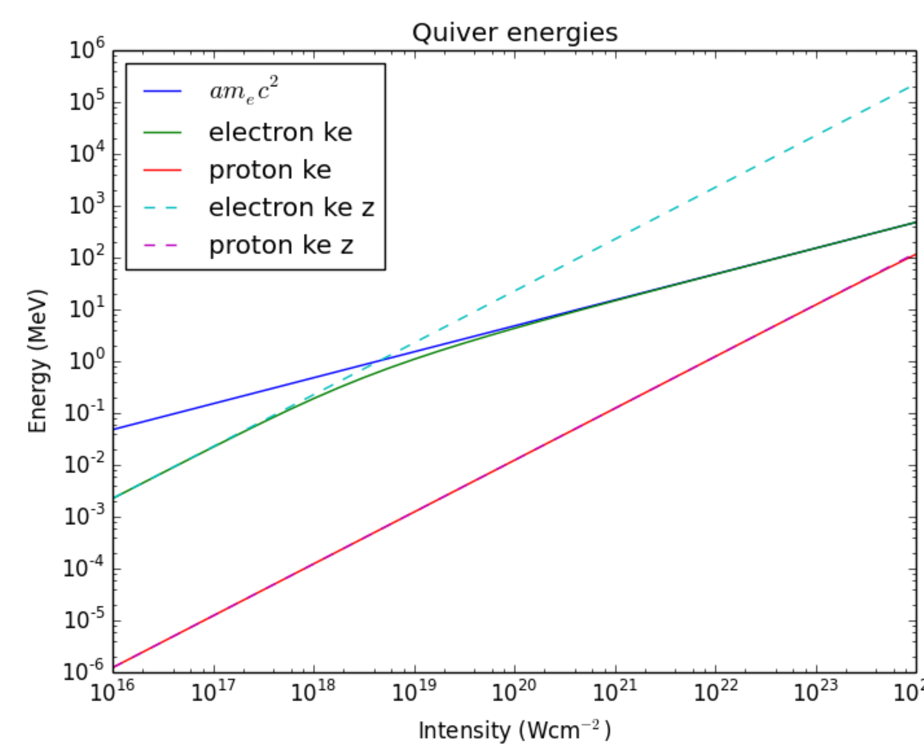
Solid interaction simulation



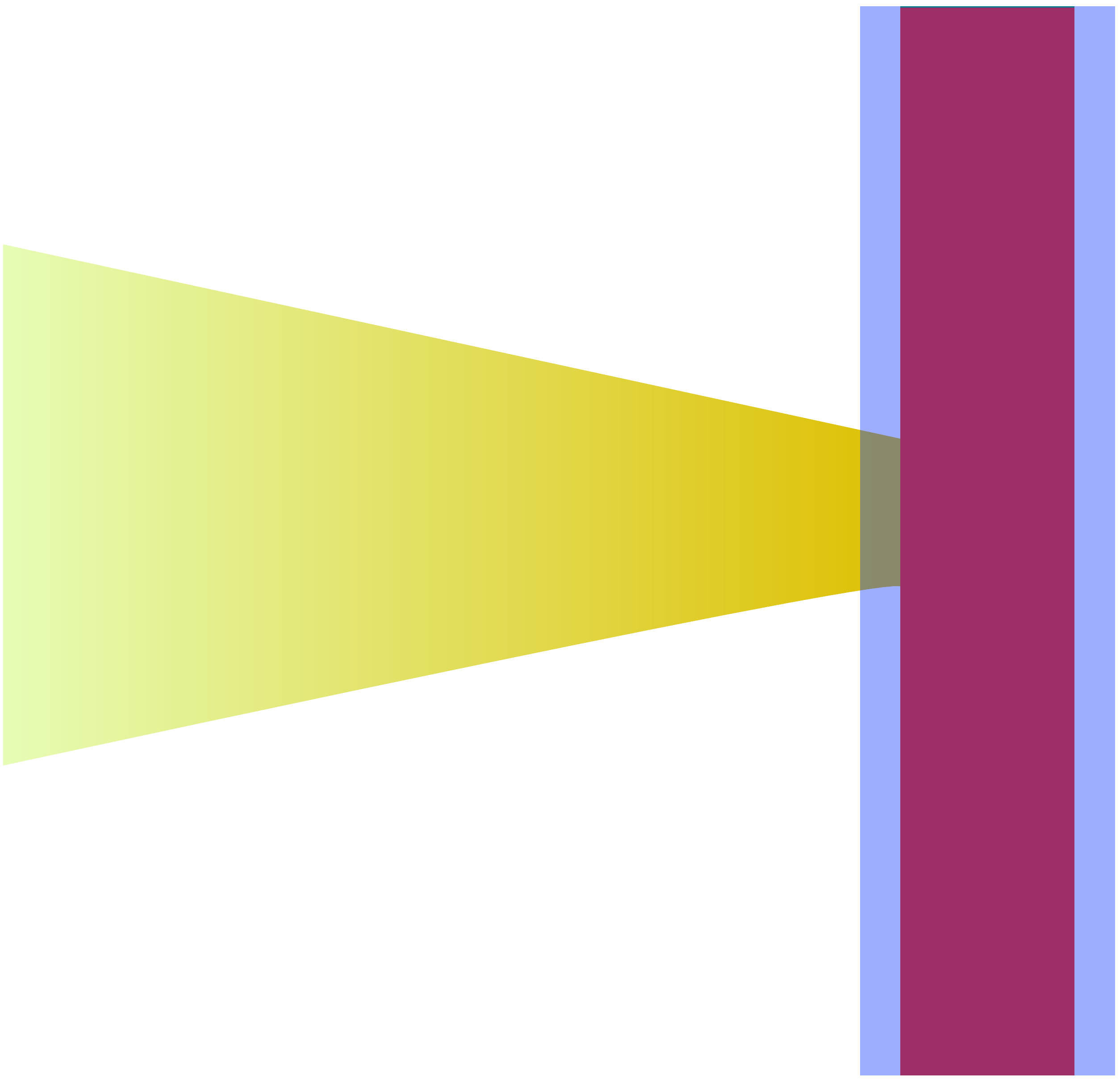
Laser absorption at high intensity: vacuum heating



Brunel (vacuum) heating
(see for example Gibbon & Bell 1992)



Sheath acceleration



Energies ~ $\alpha k_B T_e \sim \alpha^* m_e c^2 (I\lambda^2)^{1/2}$

Laser generated ion beams I: sheath acceleration

Poisson eq^{n} $\frac{\partial^2 \phi}{\partial x^2} = \frac{e n_h}{\epsilon_0}$

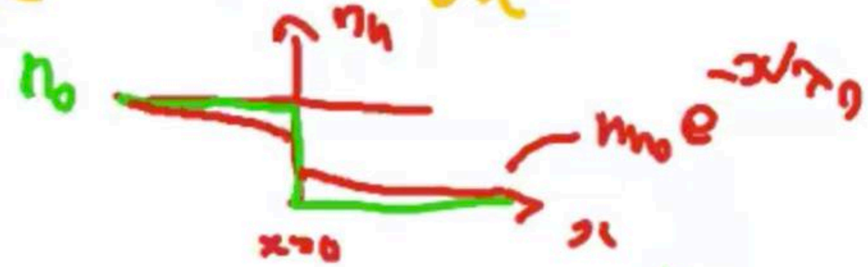
$n_h = n_{h_0} e^{e\phi/k_B T}$

$\simeq n_{h_0}\left(1 + \frac{e\phi}{k_B T}\right)$

$\frac{k_B T}{n_{h_0} e} \frac{\partial^2 n_h}{\partial x^2} = \frac{\partial^2 \phi}{\partial x^2}$

$\Rightarrow \frac{\partial^2 n_h}{\partial x^2} - \overbrace{\left(\frac{n_{h_0} e^2}{\epsilon_0 k_B T}\right)}^{\sim 1/\lambda_D^2} = 0$

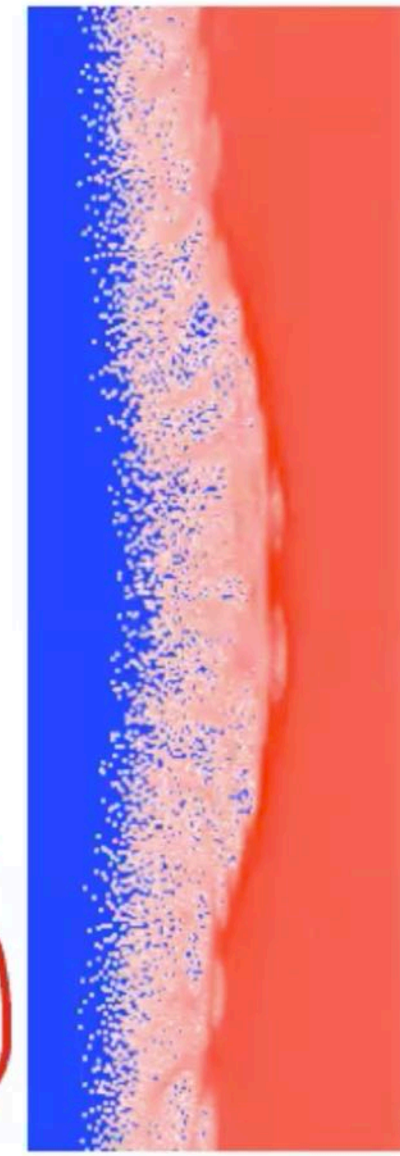
$n_h(x) = n_{h_0} \exp\left(-x/\lambda_D\right)$

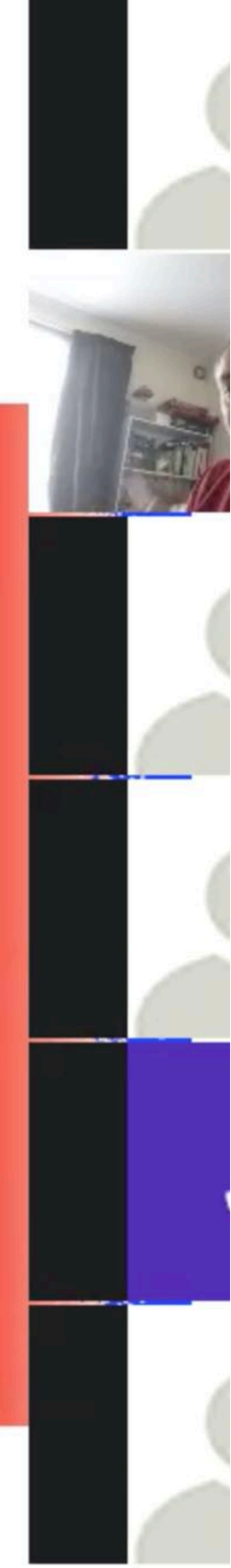


So energy gain $Ze\Delta\phi = Ze\left(n_h(0) - n_h(\infty)\right)$

$= Z\cancel{e} \cdot \frac{k_B T}{\cancel{n_{h_0}}\cancel{e}} \cdot \left(\cancel{n_{h_0}} \overset{=1}{e^{(0)}} - \cancel{n_{h_0}} \overset{=0}{e^{(-\infty)}}\right)$

$= Z k_B T_e$





Sheath acceleration

The motion of the sheath is determined by the continuity and force equation for the ions:

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(n_i v_i) = 0$$
$$\frac{\partial v_i}{\partial t} + \frac{v_i \partial v_i}{\partial x} = \frac{Ze}{M}E$$

The sheath field can be calculated by balance with the hot electron pressure gradient,

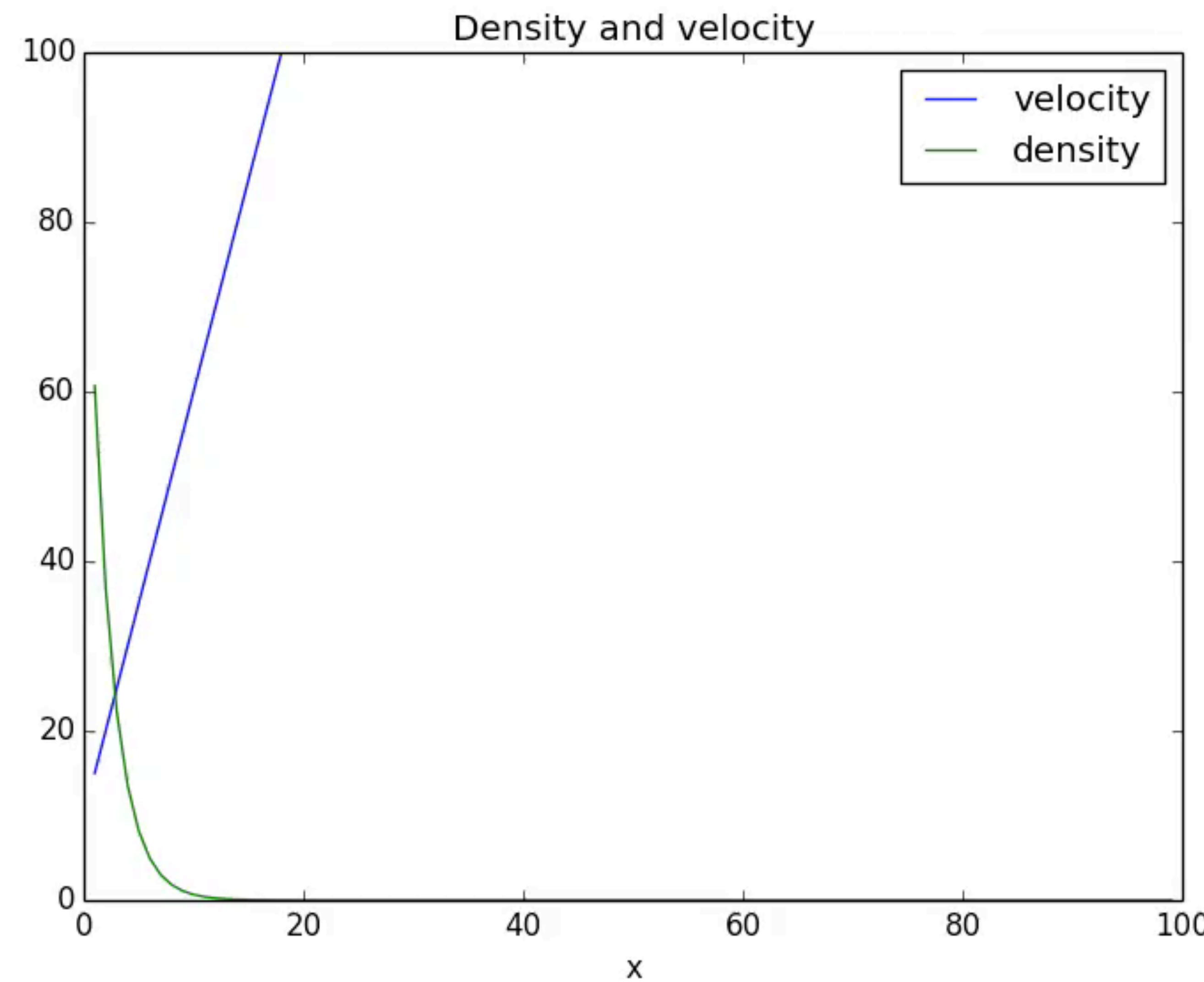
$$n_h e E = -\frac{\partial P_h}{\partial x} = -k_B T \frac{\partial n_h}{\partial x}$$

Substituting for E in the equation of motion and assuming quasi-neutrality $n_h \simeq Z n_i$,

$$\frac{\partial v_i}{\partial t} + \frac{v_i \partial v_i}{\partial x} = -\frac{ZT_h}{M}\frac{1}{n_h}\frac{\partial n_h}{\partial x} = -c_s^2 \frac{1}{n_i}\frac{\partial n_i}{\partial x}$$

where the ion expansion speed $c_s = (ZT_h/M)^{1/2}$. There is a self-similar solution, found by using substitution $\xi = x/t$.

$$v_i = c_s + x/t$$
$$n_i = n_0 \exp(-x/c_s t)$$



Sheath Acceleration 2

This 1D solution gives infinite energies (with infinite spread). But acceleration will stop when inverse density scale length equals the local Debye length (so becoming neutral).

$$L_n = \left| \frac{n_i}{\partial n_i / \partial x} \right| = c_s t_f = \lambda_d(x_f)$$

$$\text{where} \qquad \lambda_d(x_f) \equiv \left(\frac{\epsilon_0 k_B T}{Z n_f(x_f) e^2} \right)^{1/2} = \frac{c_s}{\omega_{pi0}} \left(\frac{n_0}{n_f} \right)^{1/2}$$

Using the self-similar solutions,

$$\begin{aligned} v_{max} &= c_s + \ln \left(\frac{n_0}{n_f(x_f)} \right) \\ &= c_s + \ln \left(\omega_{pi0} \frac{\lambda_D(x_f)}{c_s} \right)^2 \\ &= c_s [1 + 2 \ln (\omega_{pi0} t_f)] = \alpha c_s \end{aligned}$$

α thus accounts for the front expansion. So final ion energy is

$$W_{max} = \frac{1}{2} M v_{max}^2 = \alpha^2 k_B T / 2$$

Typically α is only of the order of a few.

First experiments

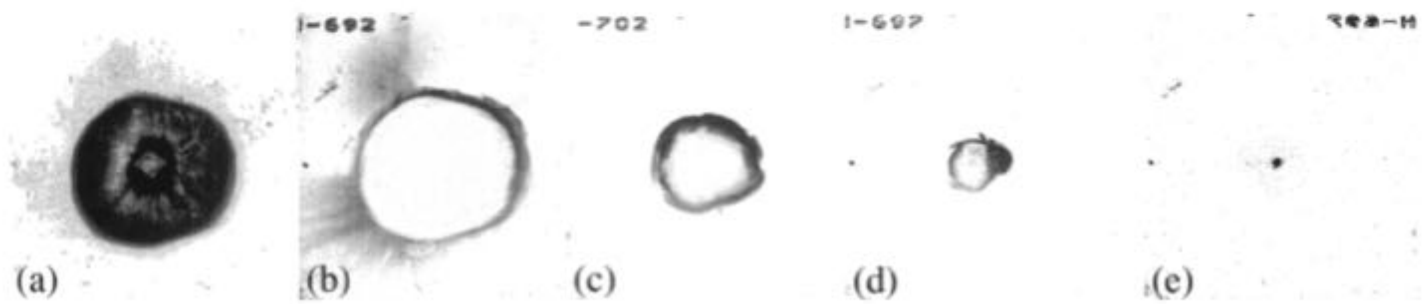


FIG. 1. Ring structure observed on RCF/CR39 "sandwich" track detectors: (a) radiochromic film (front surface); (b) tracks on CR39 from 3 MeV protons; (c) 8.9 MeV, (d) 11.6 MeV, (e) 17.6 MeV protons (track detectors were 5 cm × 5 cm × 0.75 mm thick).

Clark, E.L. et al., 2000. Measurements of energetic proton transport through magnetized plasma from intense laser interactions with solids. Physical Review Letters, 84, p.670.

Snavely, R.A. et al., 2000. Intense high-energy proton beams from Petawatt-laser irradiation of solids. Physical Review Letters, 85(14), p.2945.

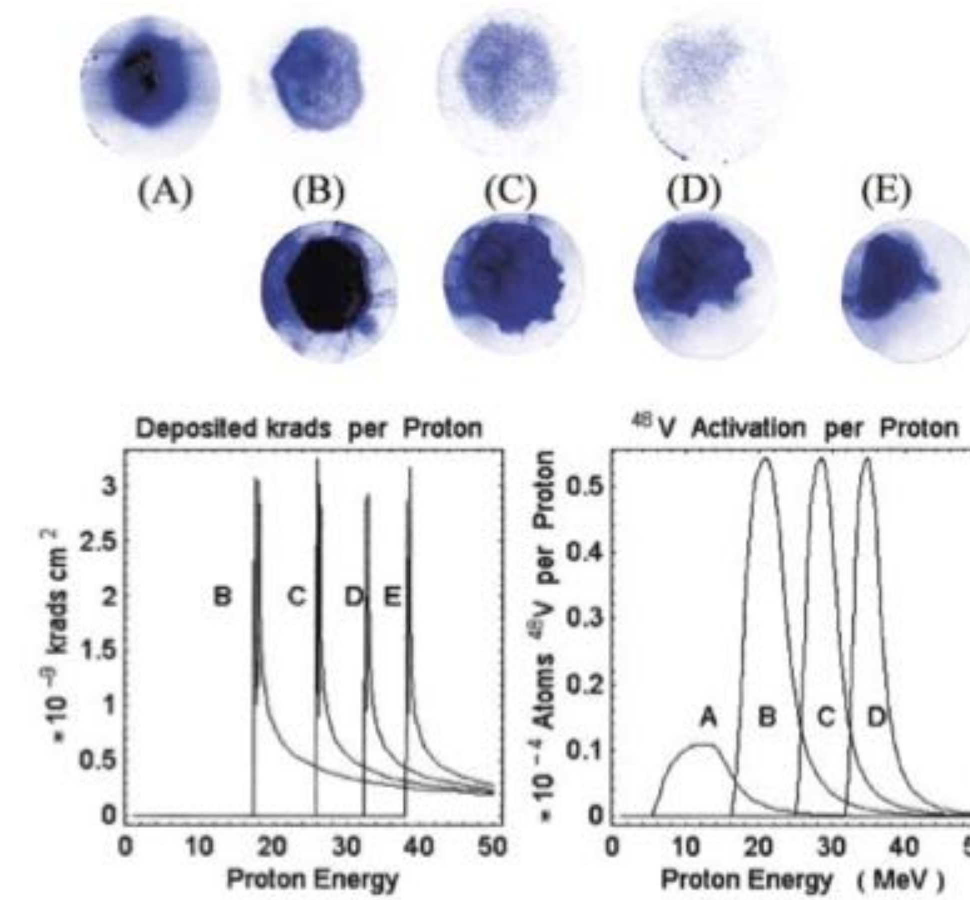


FIG. 2 (color). Data for a normal incidence 445 J shot on 100 μm CH from the Ti nuclear activation and RC film detector described later in the text: Ti foil autoradiographs (top row) and RC film images (middle row). The plots show Monte Carlo modeling of (below left) the RC film detector response in krads cm^2 per proton normally incident in the film layers; the nuclear activation response (below right) of the Ti layers to protons through the successive filter layers of the detector.

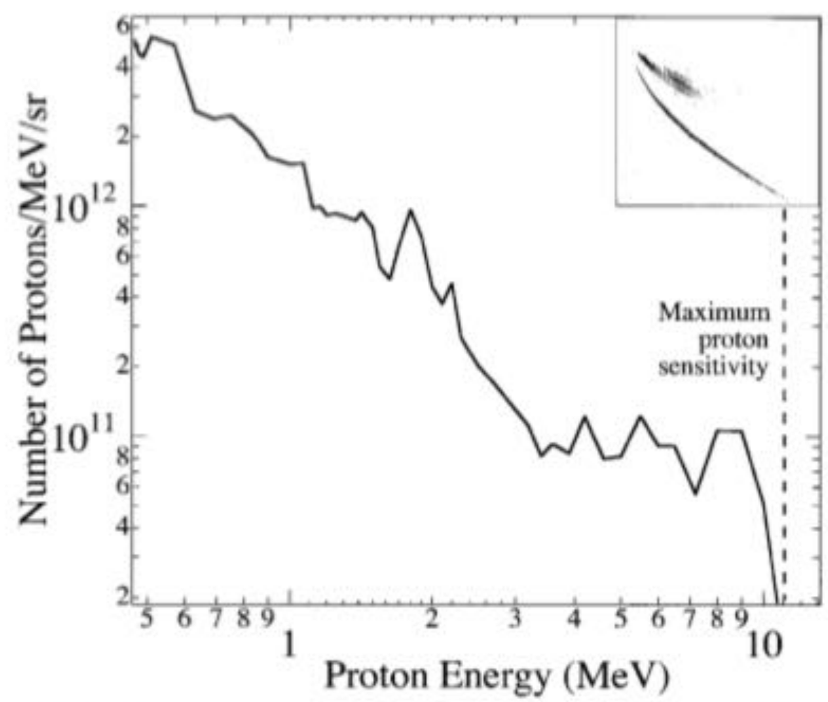
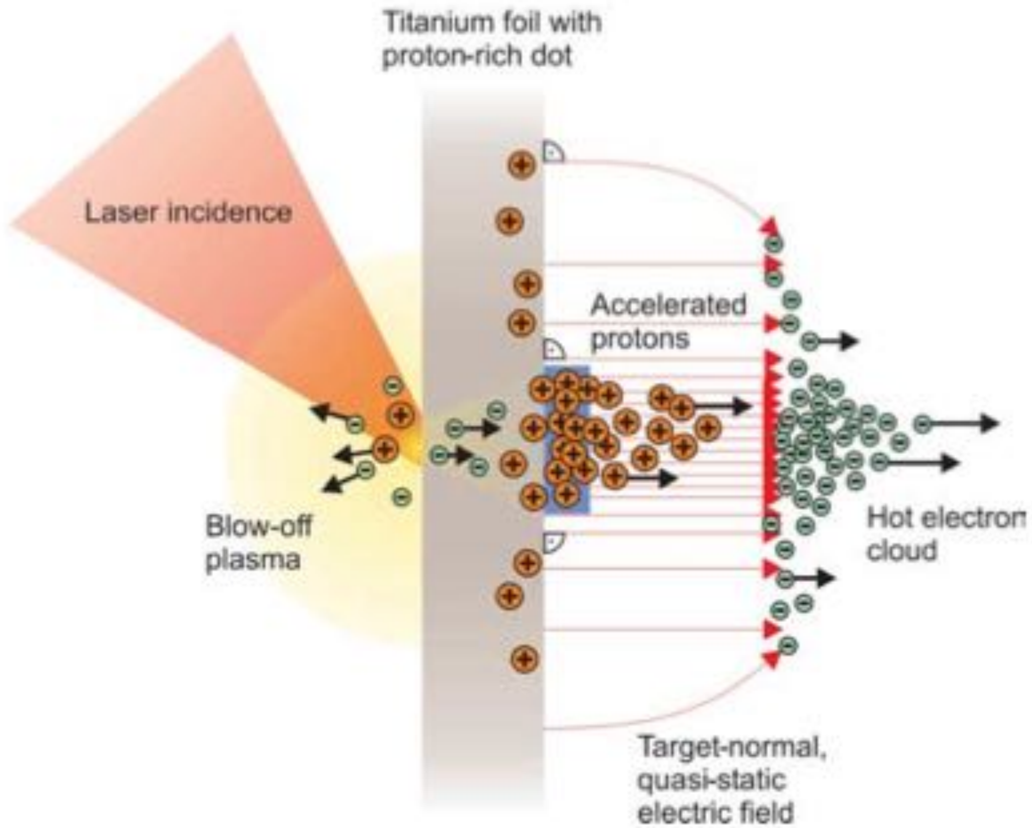


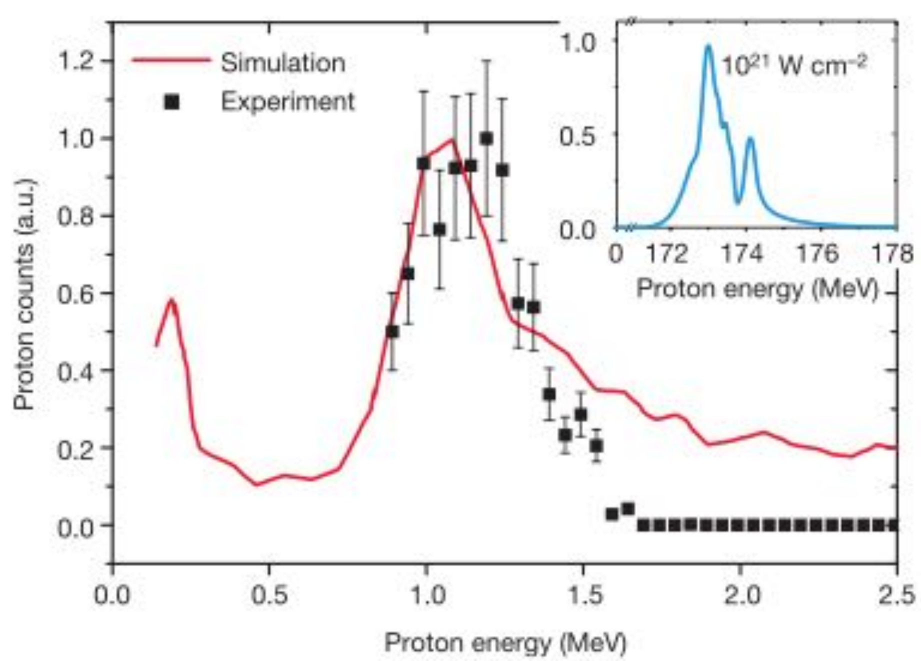
FIG. 3. Proton spectrum indicating multiple peaks and a flattening of the spectrum at ~4 MeV. Data from the Thomson parabola is inset.

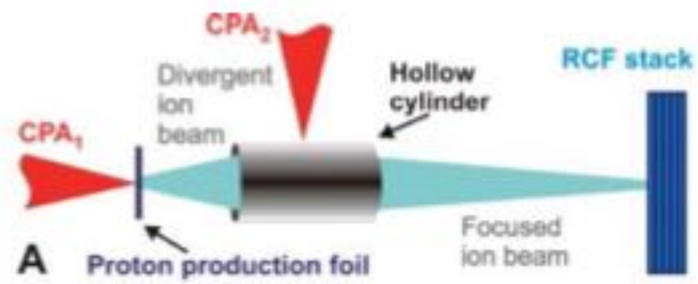
Clark, E.L. et al., 2000. Energetic heavy-Ion and proton generation from ultraintense laser-plasma interactions with solids. Physical Review Letters, 85(8), p.1654.

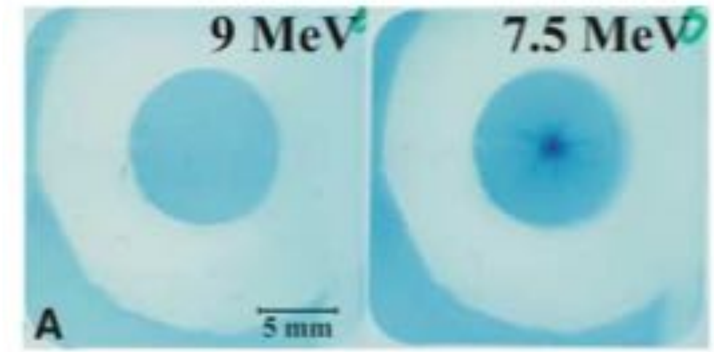
Improvements



Schwoerer, H. et al., 2006. Laser-plasma acceleration of quasi-monoenergetic protons from microstructured targets. Nature, 439(7075), pp.445–8.





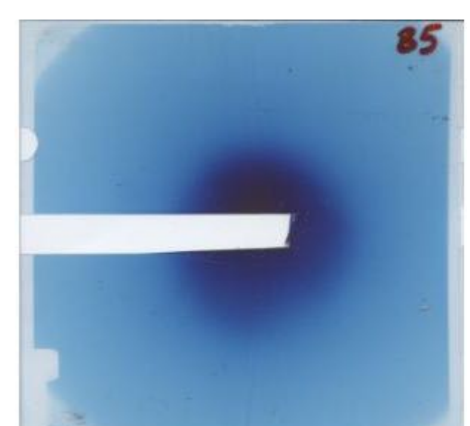


Toncian, T. et al., 2006. Ultrafast laser-driven microlens to focus and energy-select mega-electron volt protons. Science (New York, N.Y.), 312(5772), pp.410–3.

C. Palmer, Unpublished.

Radiochromic film:

- dose dependent radiation detector.
- proton beam profiles for different energies.



Commonly observed beam structure – smooth.

Pros and cons

- Extremely high accelerating fields means:

  short pulse

  low emittance

  compact size

  high charge

- Disadvantages:

  Large energy spread

  Poor energy scaling ($T_{hot} \propto (I\lambda^2)^{1/2}$)

  Multiple ion species (especially impurities)

Hole-boring acceleration

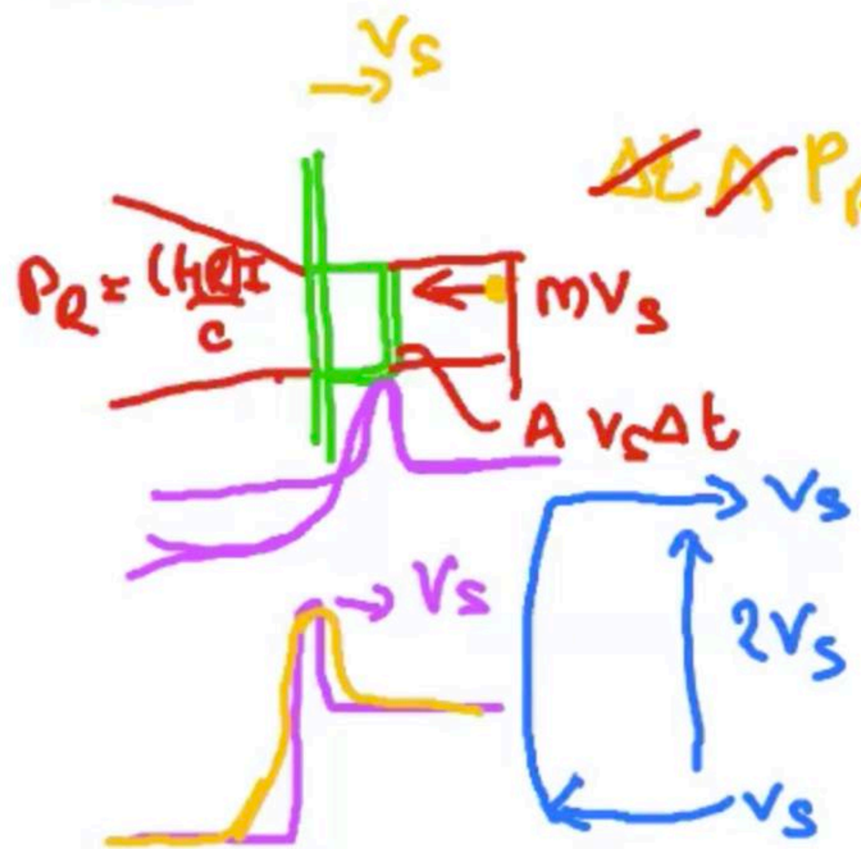
$$N_{ph} = n_{ph} \cdot c\Delta\tau \cdot A$$

$$\mathcal{E} = n_{ph} \cdot c\tau \, A \, \hbar\omega$$

$$I = n_{ph} \, c \, \hbar\omega$$

$$F = \Delta p / \Delta t$$
$$= N_{ph} \cdot \Delta p / \Delta t$$
$$= n_{ph} \cdot c \cancel{\Delta t} \, A / \cancel{\Delta t} \times (1+R)\hbar k$$

$$P_{rad} = \frac{F}{A} = (1+R)\hbar k \, n_{ph} \, c$$
$$= (1+R) \, I/c$$

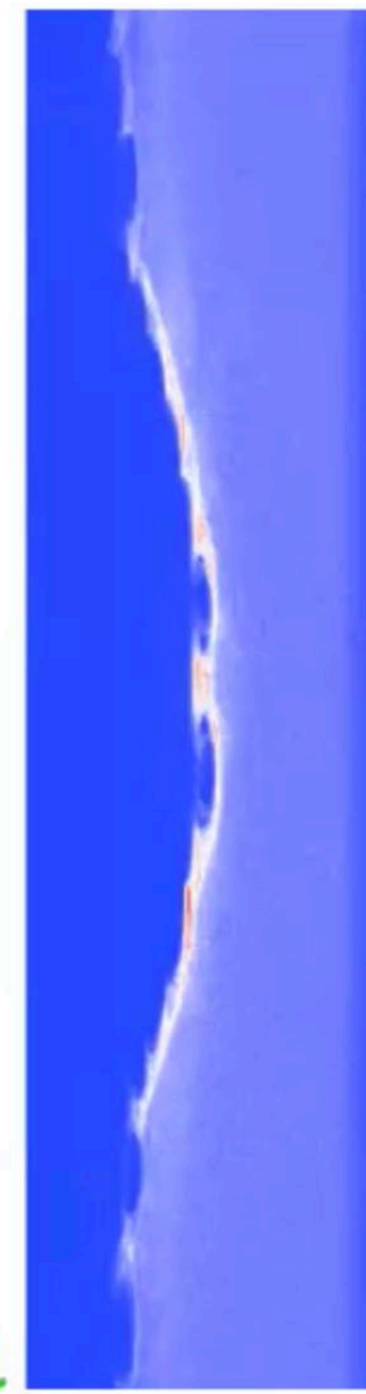


$$\cancel{\Delta t} \cancel{A} P_R = v_s \cancel{\Delta t} \cancel{A} \cdot m_i v_s \cdot n_0$$

$$v_s^2 = \frac{I (1+R)}{m_i n_0 c}$$

$$\mathcal{E} = \frac{1}{2} m (2v_s)^2 = \frac{4I}{nc}$$

$$\mathcal{E} = 1\,\mathrm{MeV}, \rightsquigarrow n_e \sim 10^{28}\,\mathrm{m}^{-3}$$
$$I \sim 10^{20}\,\mathrm{W m}^{-2}$$



Gas targets

- Less susceptible to impurities
- Less susceptible to prepulse effects
- Potentially single species, in particular, protons
- Easy to operate at high rep-rate

Downsides:

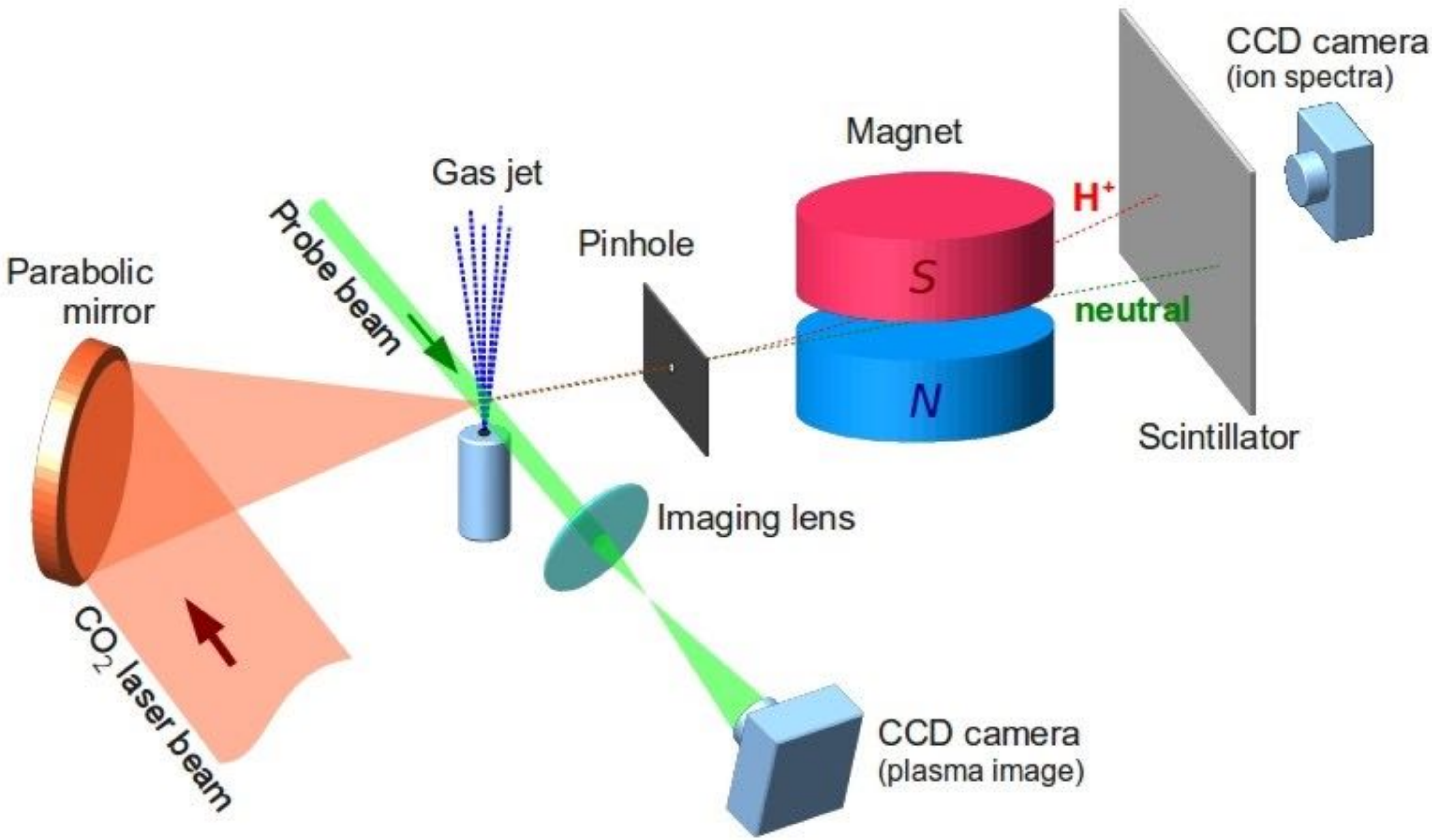
- most efficient at critical density, $n_{cr} = 10^{21}$ cm^{-3} for $\lambda = 1$ μm.
  - difficult to obtain in a gas jet.
  - but $n_e = 10^{19}$ cm^{-3} possible, why not use long λ?

Motivation for CO2 experiments

Difficulties:

- High $I\lambda^2$ for a given intensity → good for sheath acceleration but bad for RPA
  - ➡ Use circular polarisation
- Ideally short pulse
  - ➡ new techniques can produce pulse train of pulses < 10 ps
  - ➡ but train of pulses produced
- Reproducibility a problem for gas lasers

Set-up


CCD camera
(ion spectra)
Magnet
Gas jet
Probe beam
Pinhole
Parabolic
mirror
H+
S
neutral
N
Scintillator
Imaging lens
CO2 laser beam
CCD camera
(plasma image)

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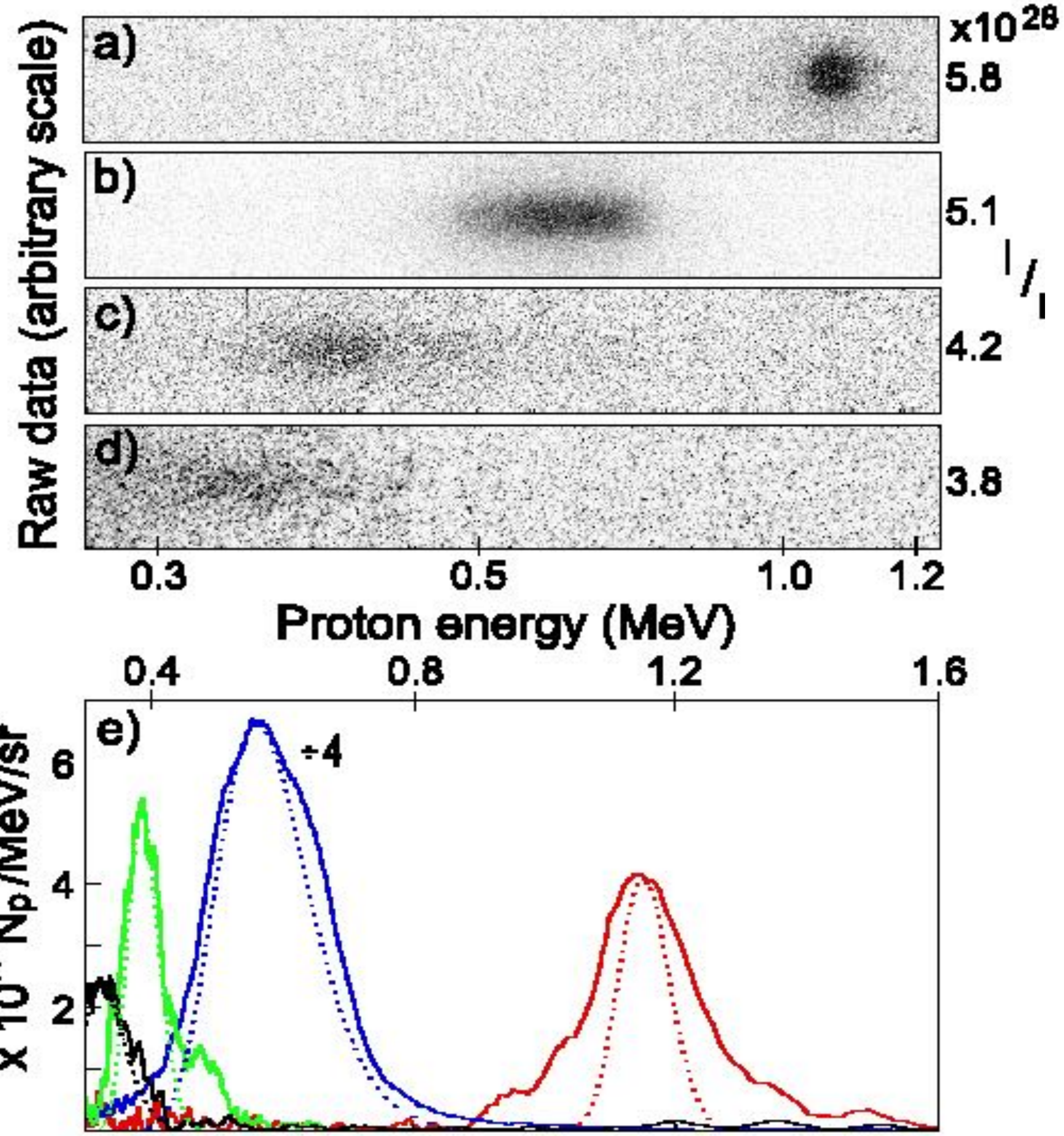
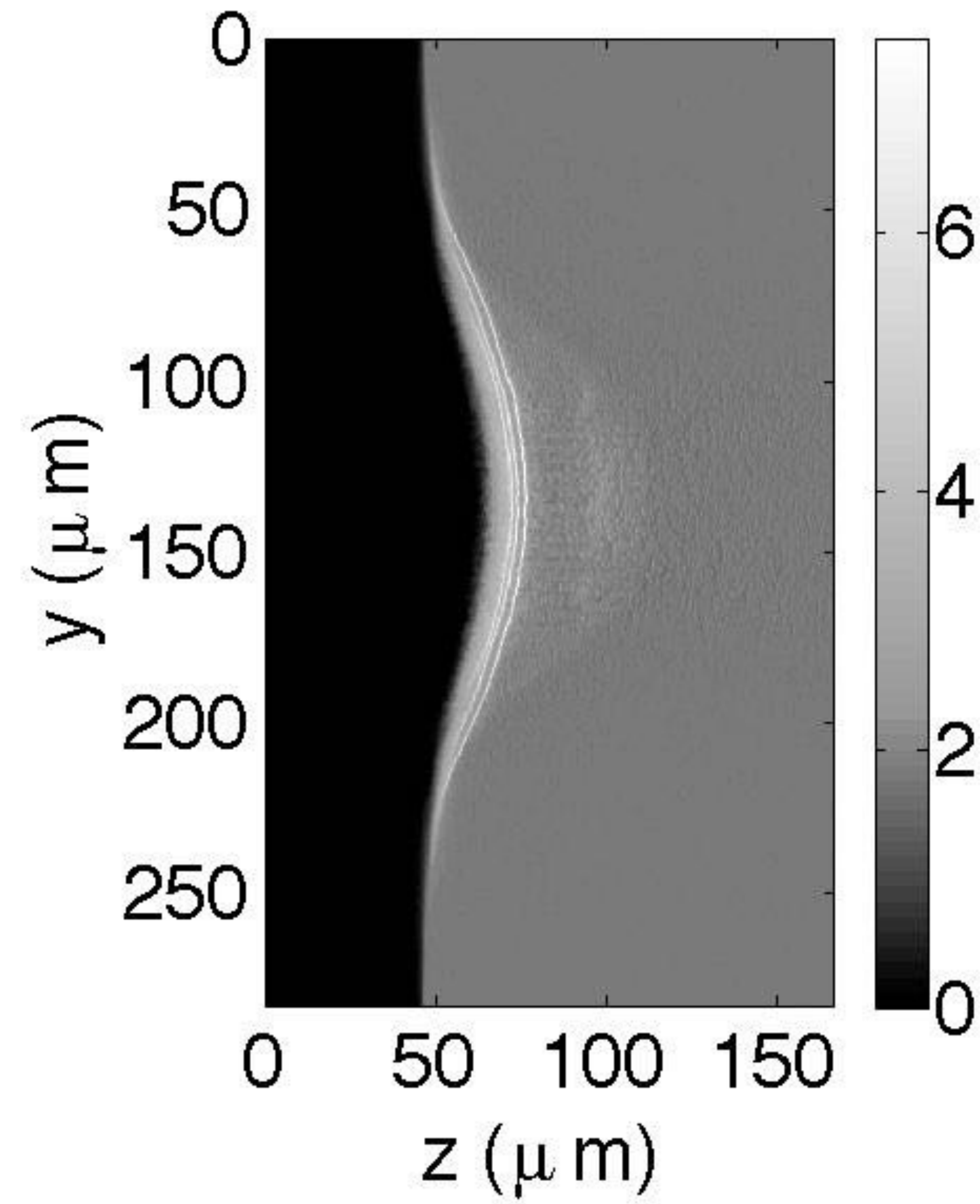
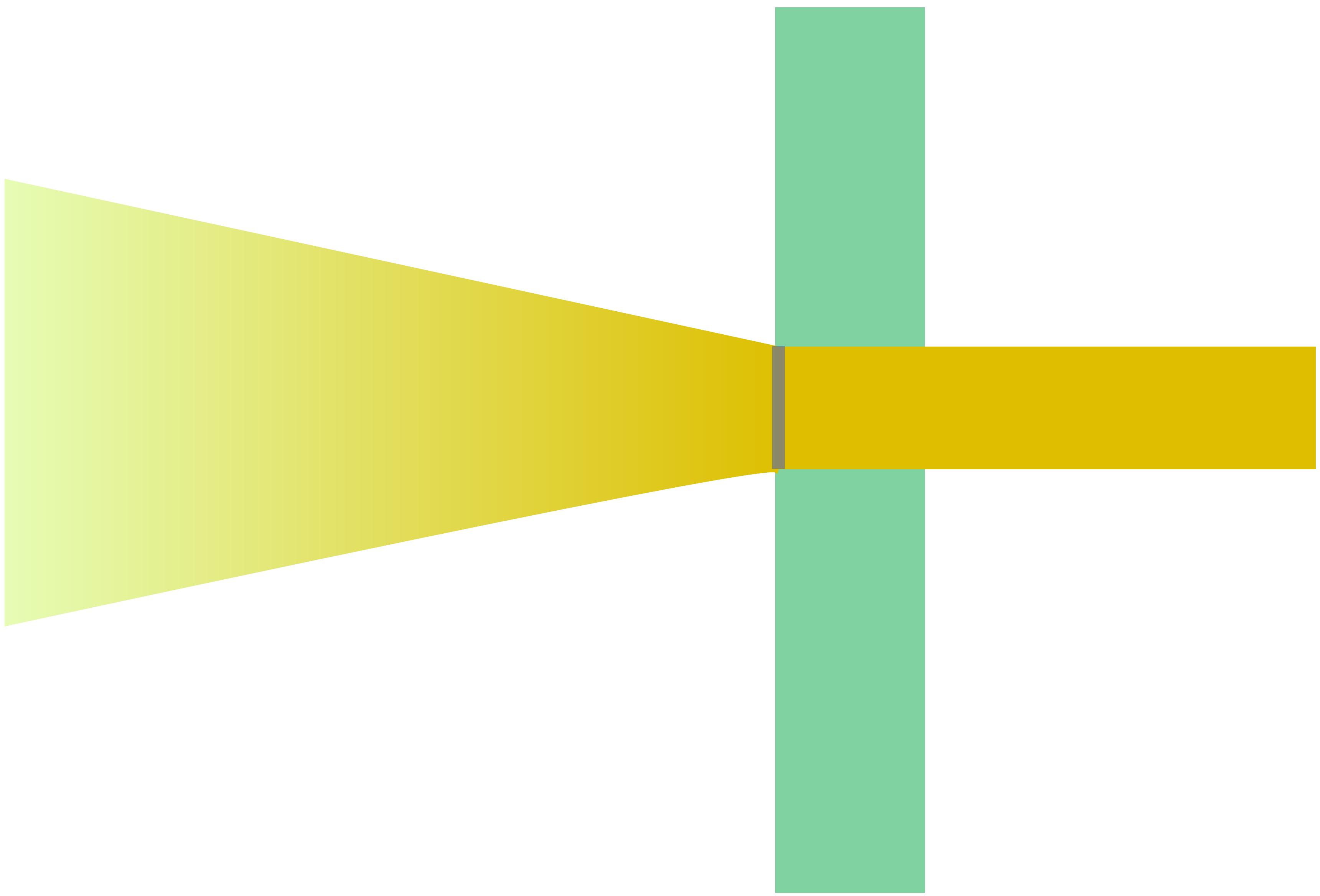
NARROW ENERGY SPREAD PROTON BEAMS





Palmer, Charlotte A. J., N. P. Dover, I. Pogorelsky, M. Babzien, G. I. Dudnikova, M. Ispiriyan, M. N. Polyanskiy, et al. “Monoenergetic Proton Beams Accelerated by a Radiation Pressure Driven Shock.” Physical Review Letters 106 (2011)

light-sail acceleration

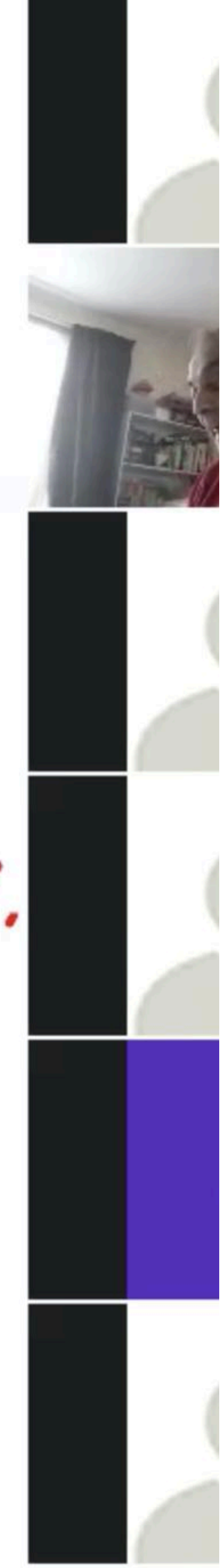


Light Sail Acceleration – Simple model

$$\xi = \left(\frac{2I^2}{m_i n_i e^2}\right) I^2 \qquad \xi \propto I^2$$

parameters Gemini $\xi \approx 10^{-10}$ J

$\approx$ ~~10~~ 1 GeV.



Optimum size

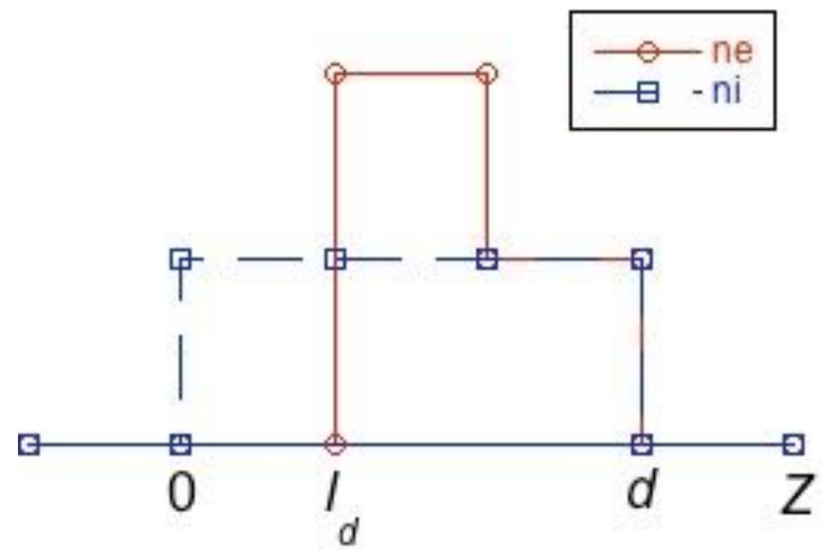
$$v_i = \frac{(1+R)\tau}{m_i n_i d} \frac{I_L}{c}$$

Velocity gained by ions **proportional to I_L**, compared to $I_L^{1/2}$ for hole-boring

• naively looks like thinner target means higher energy, but if too thin all electrons depleted from foil

•Hence, there is a **minimum thickness l_d** under which the electrons are ripped off and the target 'Coulomb explodes', can be rewritten:

$$d_{opt} = a_0 n_e$$



• where d is in units of (c/ω_p) and n_e in units of (n_{cr})

• for $I \approx 10^{20}$ Wcm^{-2}, $d_{opt} \approx 5$ nm

[1]A. Macchi et al., C.R. Physique 10(2009)
[2]A. Robinson et al., New Journal of Physics 10 (2008)

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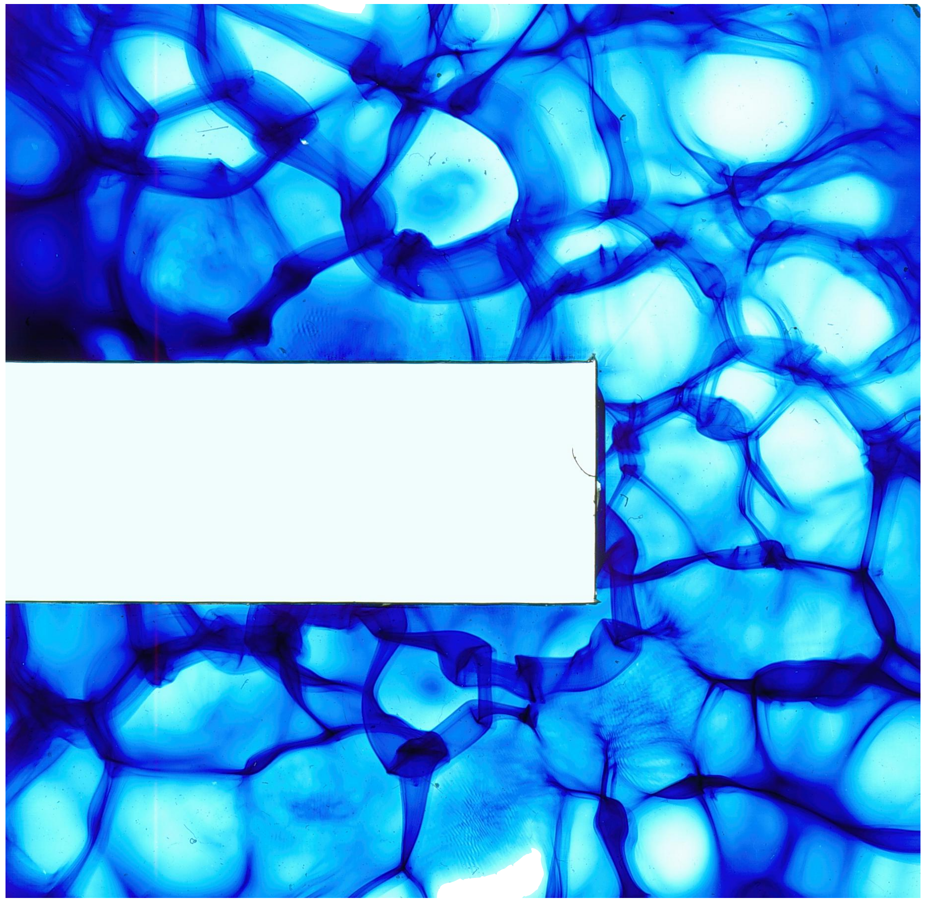
STRUCTURED BEAMS



- Assuming laminar ion flow to estimate the size of the acceleration region.
  - < focal spot diameter (7μm) ⟶ structure > 0.6μm

Solid interaction simulation