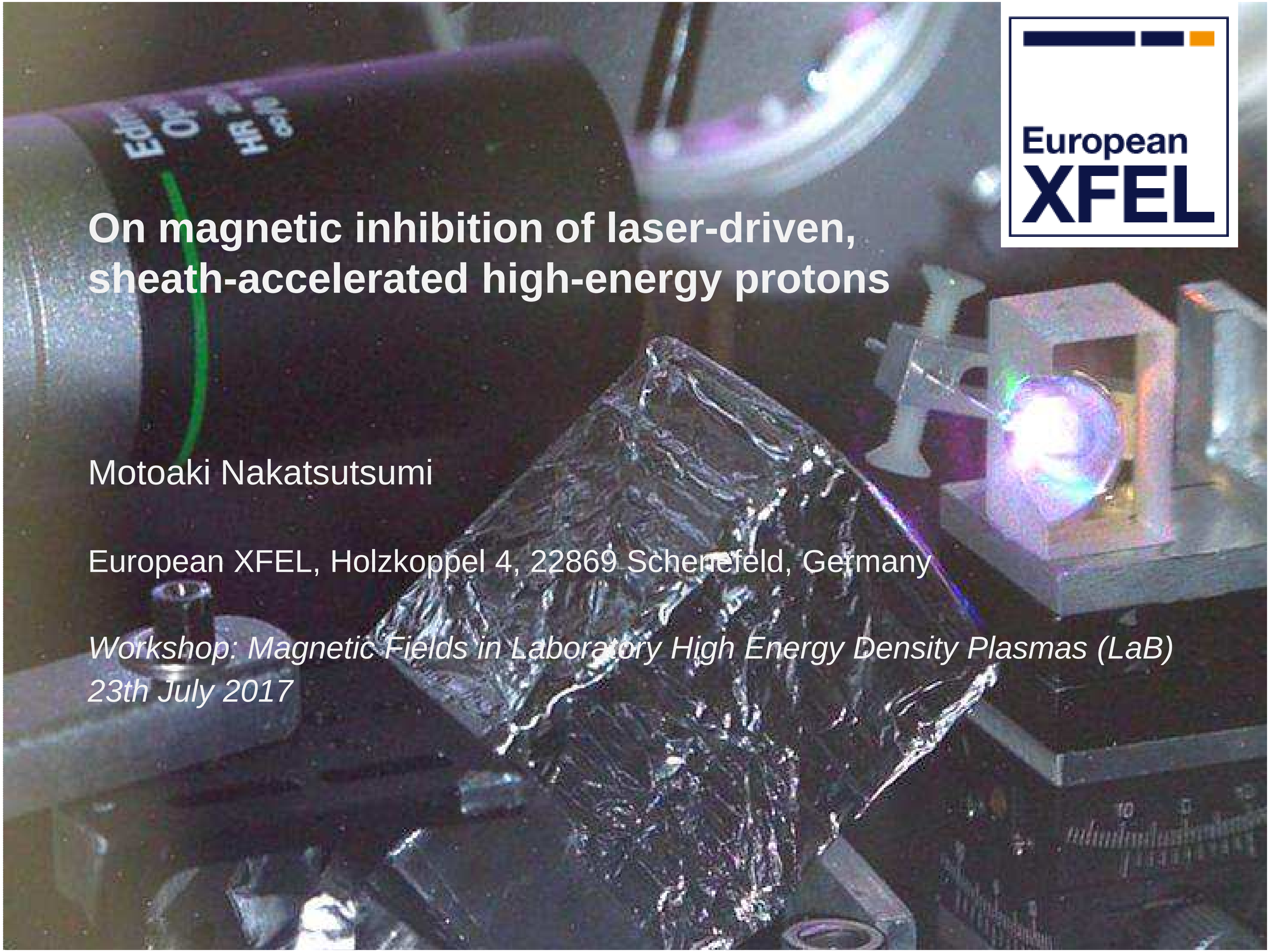

On magnetic inhibition of laser-driven, sheath-accelerated high-energy protons

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Workshop: Magnetic Fields in Laboratory High Energy Density Plasmas (LaB)
23th July 2017

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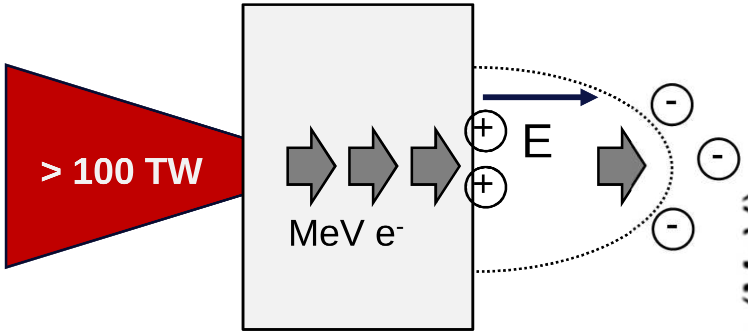
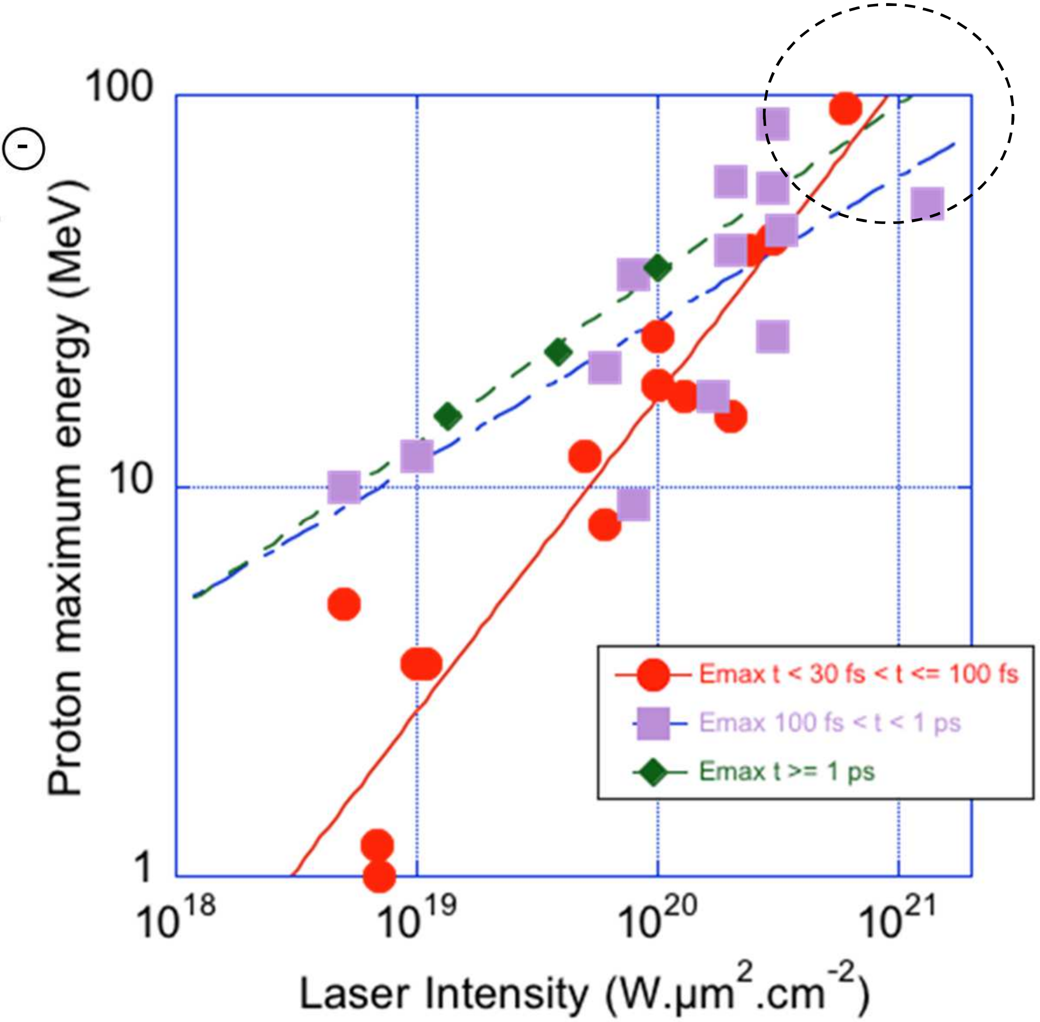
L. Gremillet

Context: laser-based proton acceleration via TNSA



> 100 MeV at > 10^{21} W.µm^2.cm^{-2} ??



Update of
A. Macchi, M. Borghesi, & M. Passoni,
Rev. Mod. Phys. 85, 751-793 (2013).
M, Borghesi, M., et al., Plasma Phys.
Contr. Fusion 50, 124040(2008).

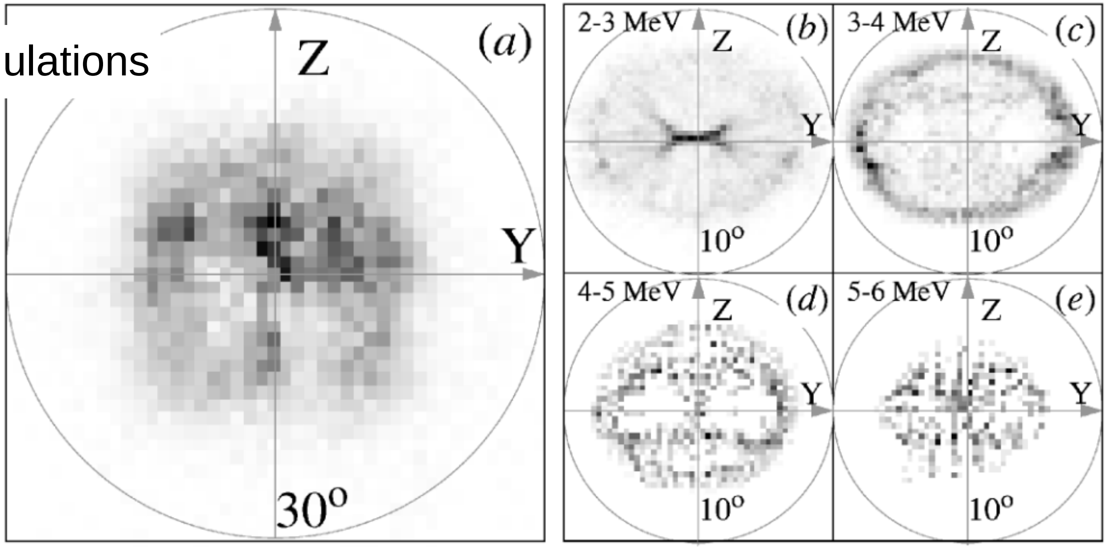
Summary

- **At high intensity (>10^{20} W.cm^{-2}), self-generated magnetostatic fields on the target rear surface may pose a fundamental limit to TNSA.**

- **The B-fields is strong enough (approaching 100 kT or Giga-Gauss at intensity > 10^{21} W/cm^2) to magnetize the sheath electrons and deflect the protons off the accelerating region, hence degrading the energy transfer from the electrons to the protons.**

- **For very short laser pulses (a few tens of fs) the magnetic inhibition effect may be less significant, due to short acceleration time and short plasma expansion, thus particles are less deflected.**

Pioneering work



3D PIC simulations

$I = 10^{19}$ W.µm^2.cm^{-2}

τ = 150 fs

B_{max} ~ 10 MG

FIG. 2. Angular distribution of ions. (a) The ions pushed into the foil at the plasma front surface. (b)–(e) Angular distribution of ions accelerated from the plasma rear surface within the energy intervals: (b) 2–3 MeV; (c) 3–4 MeV; (d) 4–5 MeV; (e) 5–6 MeV.

“Due to self-generated magnetic fields, annular structures protons with radii decreasing as the energy of the ions increases.”

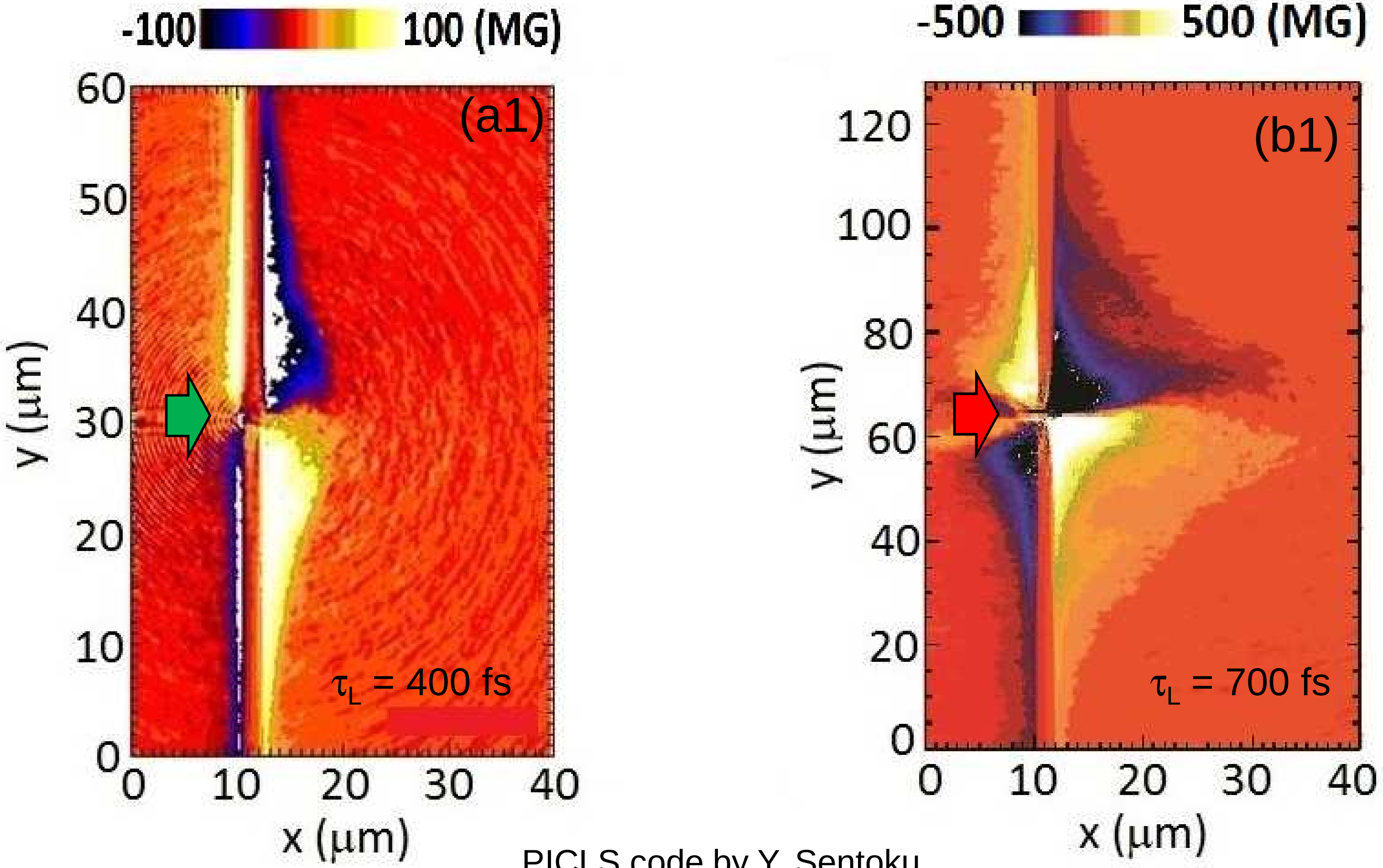
A. Pukhov Phys. Rev. Lett. 86, 3562 (2001)

PIC simulation at high intensity, B-field map

2 µm thick Al target, 100 fs after the peak

$I_L\lambda_L^2 = 6.5 \times 10^{19}$ W.cm^{-2}.µm^2

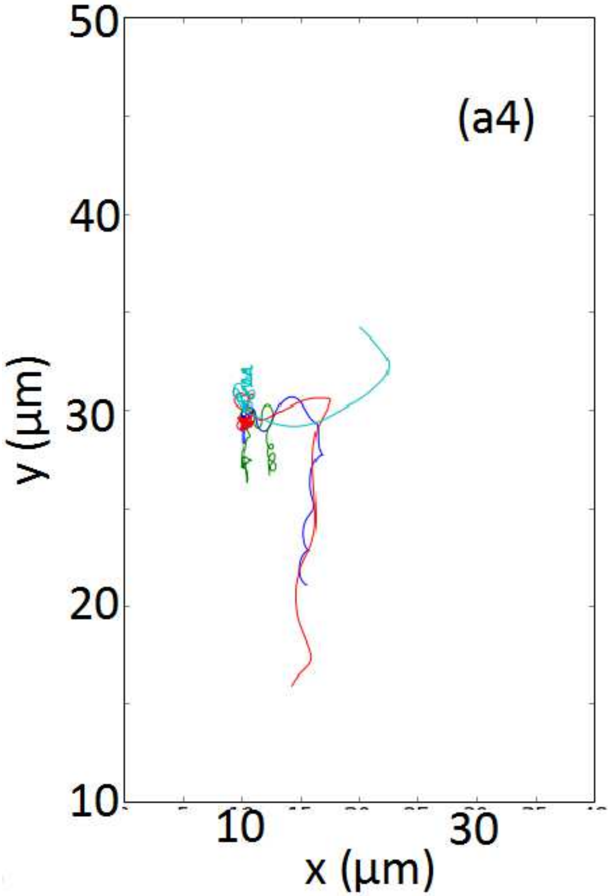
$I_L\lambda_L^2 = 2 \times 10^{21}$ W.cm^{-2}.µm^2



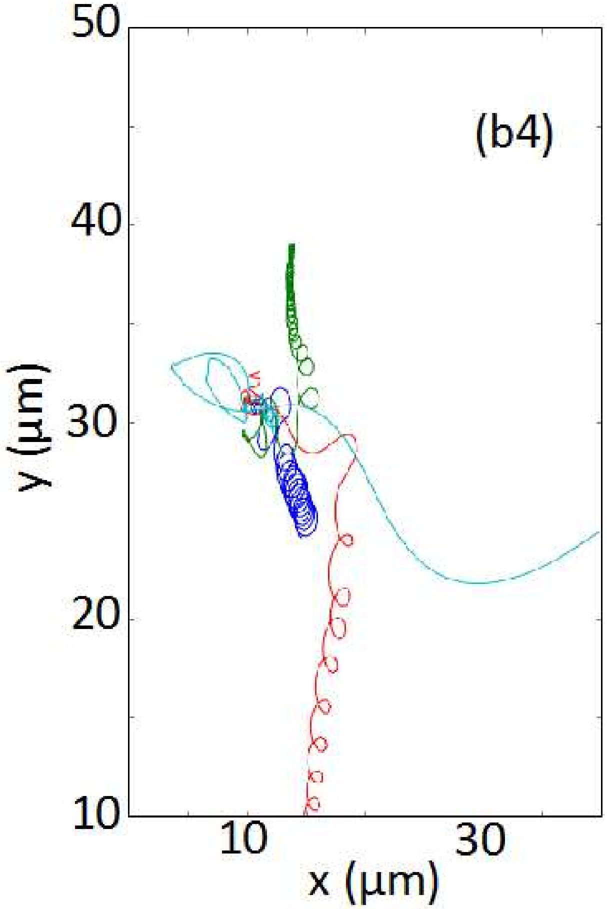
PICLS code by Y. Sentoku

MeV electron trajectories

$I_L\lambda_L^2 = 6.5 \times 10^{19}$ W.cm^{-2}.μm^2

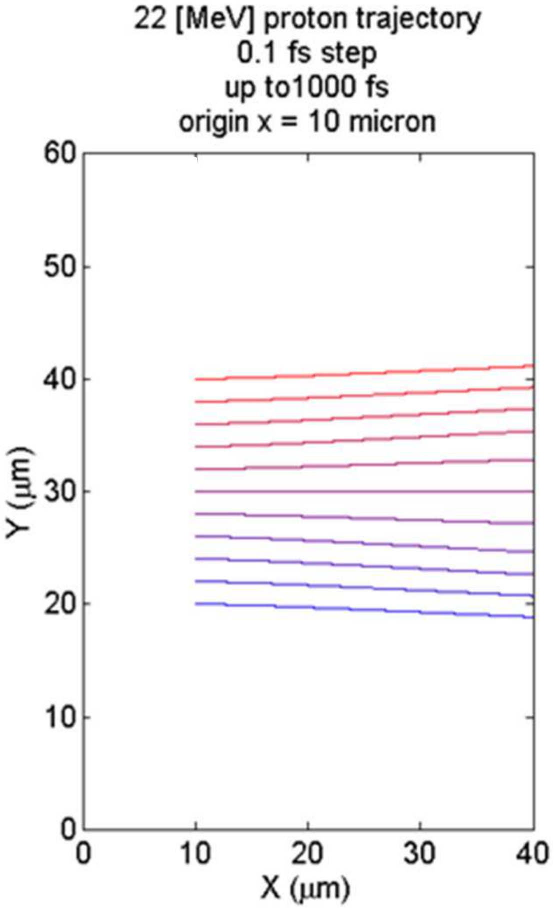


$I_L\lambda_L^2 = 2 \times 10^{21}$ W.cm^{-2}.μm^2

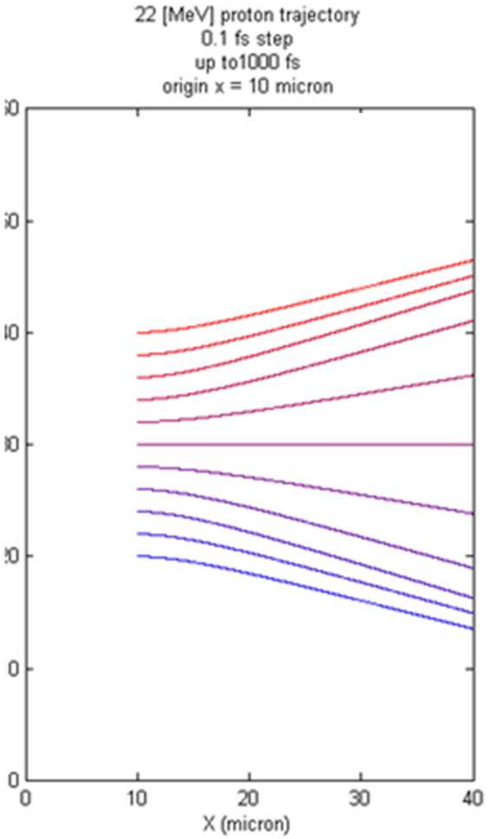


Proton trajectory (E_p = 22 MeV)

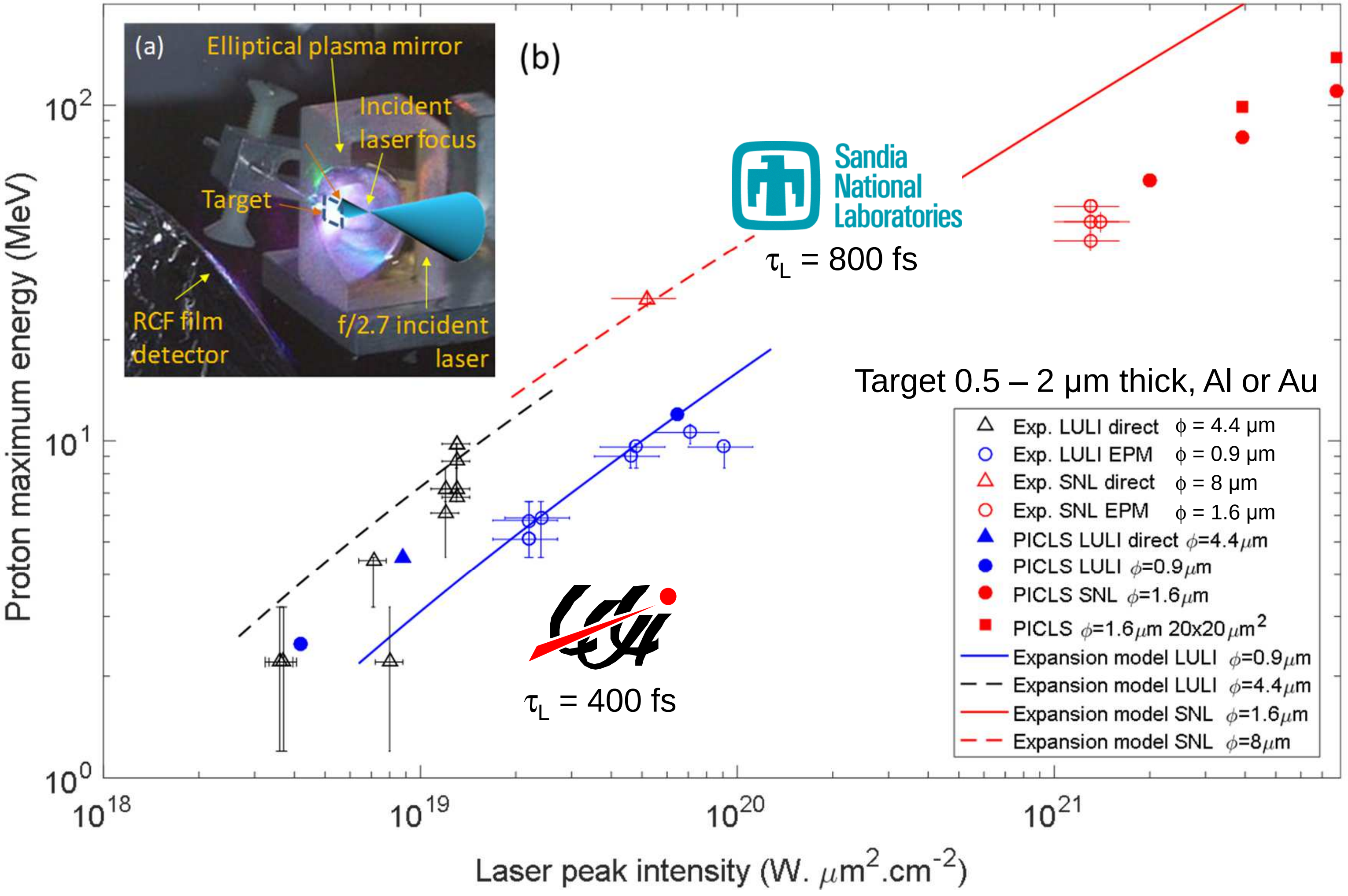
$I_L\lambda_L^2$ = 6.5 x 10^{19} W.cm^{-2}.µm^2



$I_L\lambda_L^2$ = 2 x 10^{21} W.cm^{-2}.µm^2



Experimental results of proton maximum energy



τ_L = 800 fs

Target 0.5 – 2 µm thick, Al or Au

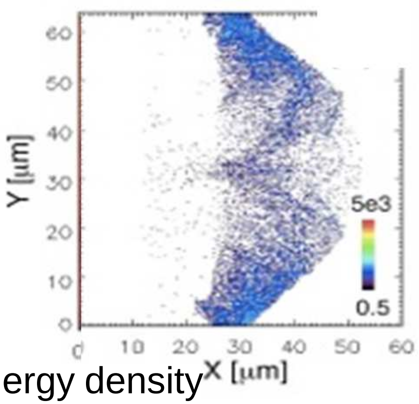
τ_L = 400 fs

1D collisionless expansion model: P. Mora, Phys. Rev. Lett. 90, 185002 (2003).

M. Nakatsutsumi et al., *Under review*

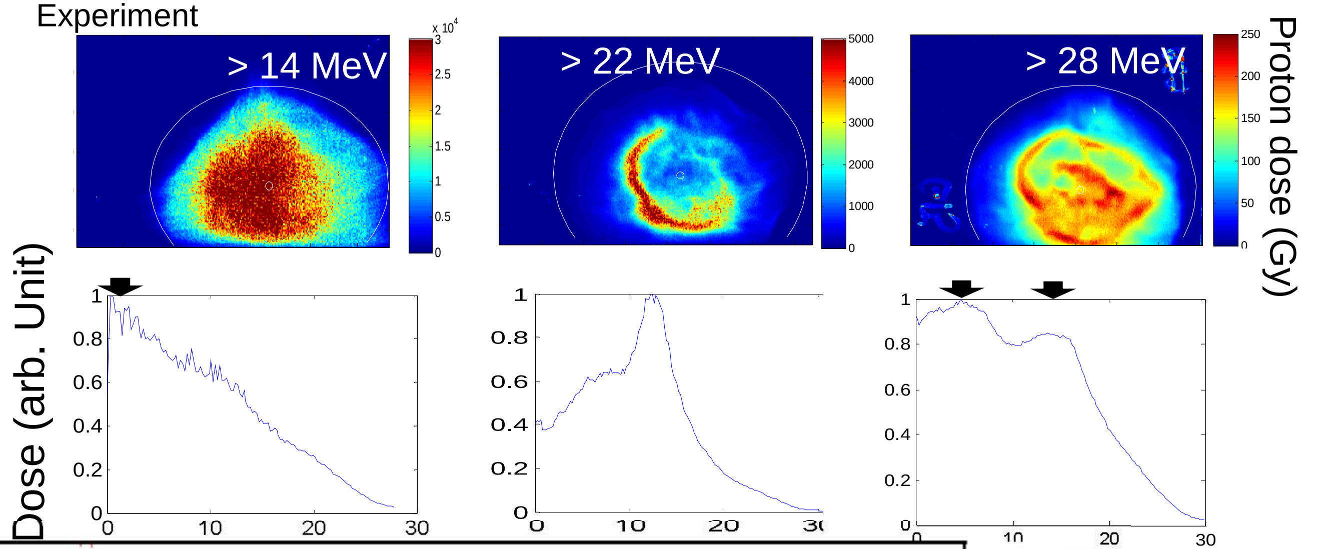
Spatial distribution of accelerated protons shows energy-dependent hollow ring pattern, as suggested by A. Pukhov paper

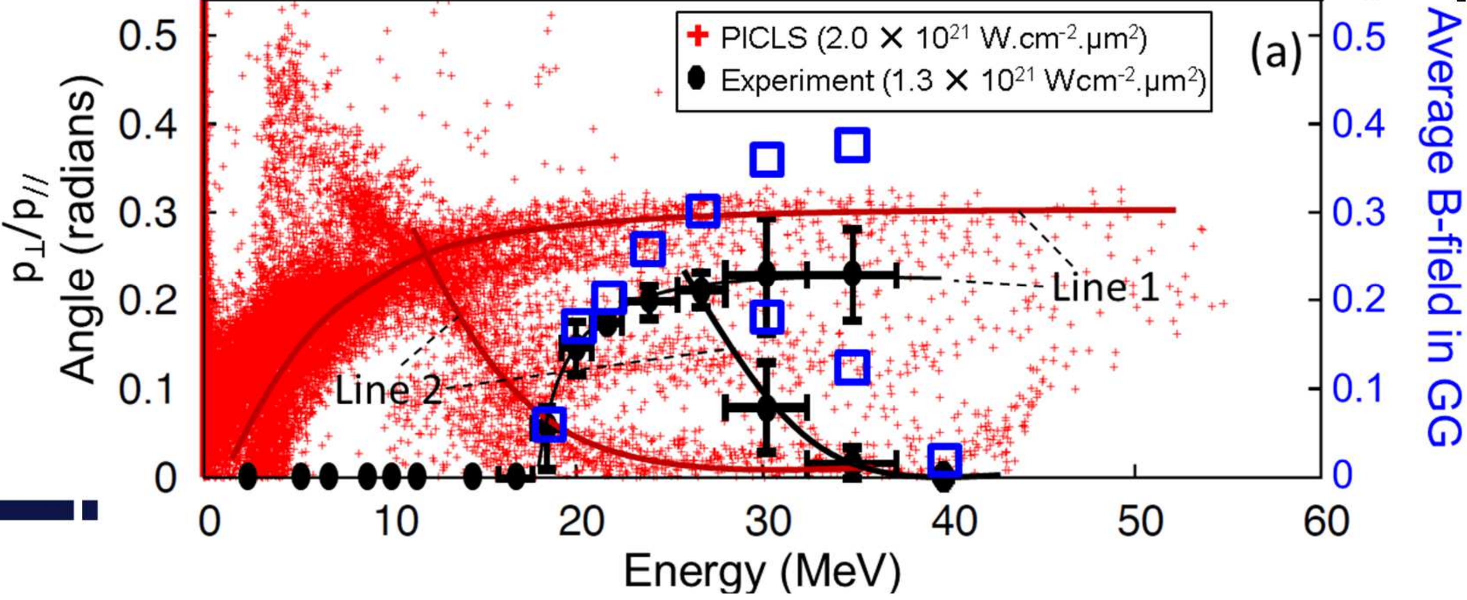
PIC (Y. Sentoku)



p$^+$ energy density

Experiment



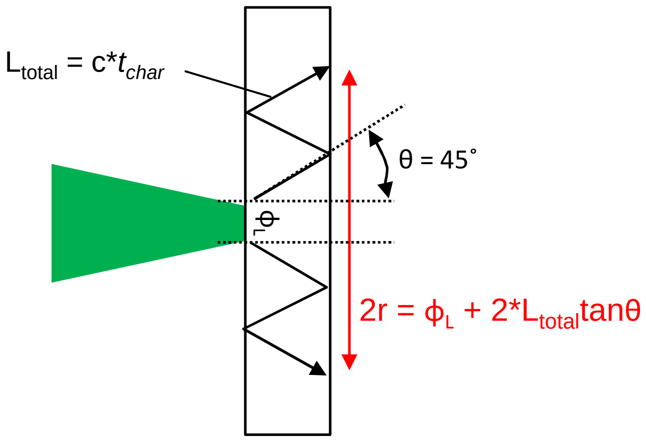


Quantitative assessment of B-field growth and amplitude

Temporal evolution of the B-field (time-dependent Faraday low)

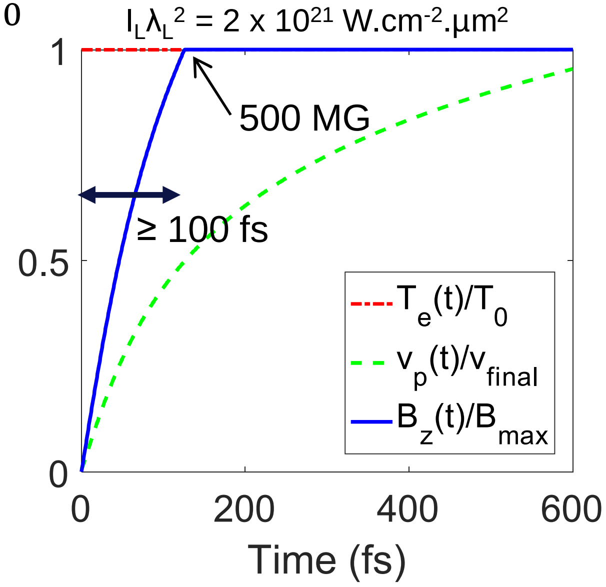
$$\partial B_z/\partial t = \partial E_x/\partial y - \partial E_y/\partial x \sim \partial E_x/\partial y$$

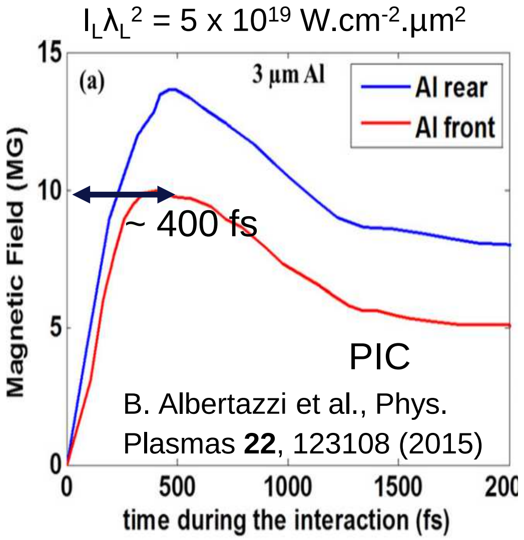
Where E_x, the longitudinal field from self-similar expansion model. Isothermal during the laser pulse.
∂y the transverse gradient of the sheath field, typically ~ 40 μm



An upper limit of B-field when the magnetic and plasma pressures become comparable

$$B_{\max}^2/2\mu_0 \approx n_{h,rear} k_B T_0$$

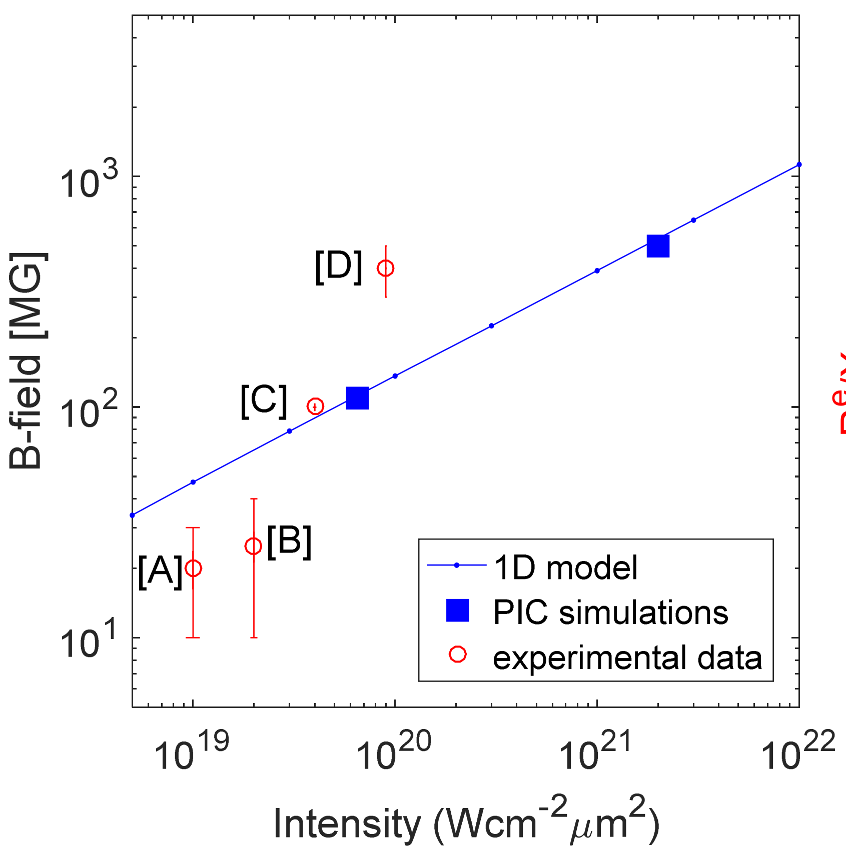

$I_L\lambda_L^2$ = 2 x 10^{21} W.cm^{-2}.μm^2

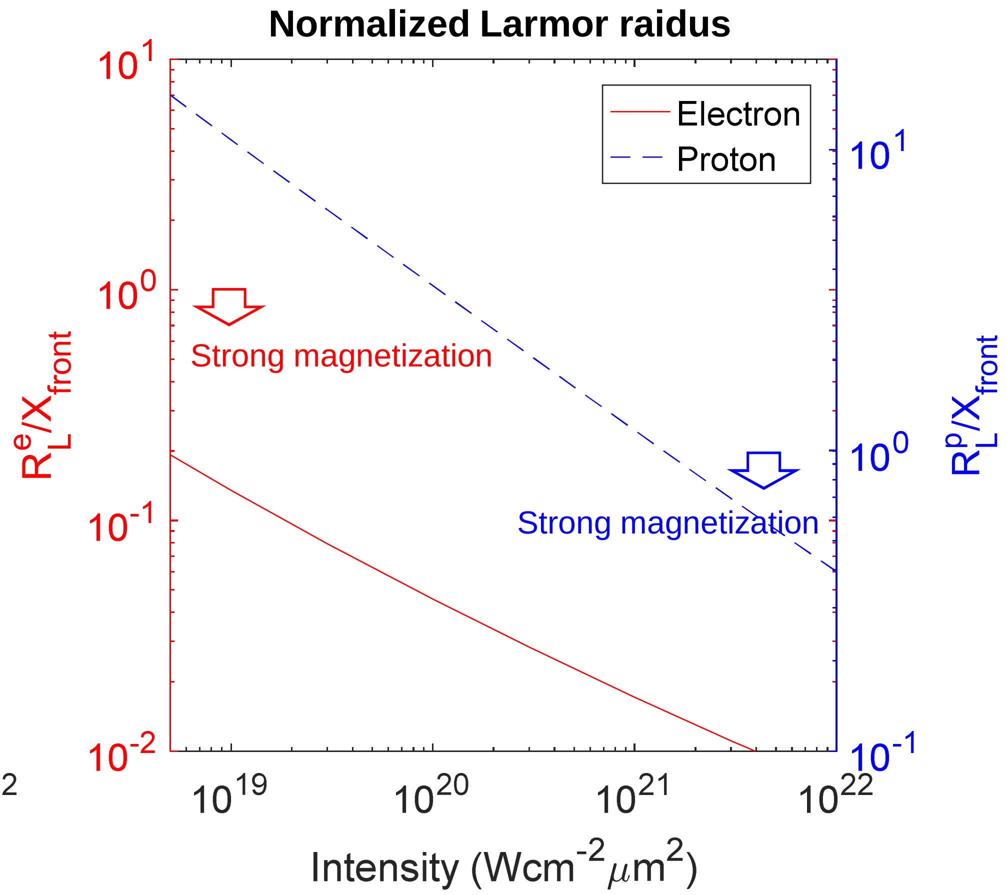

$I_L\lambda_L^2$ = 5 x 10^{19} W.cm^{-2}.μm^2

B. Albertazzi et al., Phys. Plasmas **22**, 123108 (2015)

B-field vs. intensity, normalized Larmor radius for electrons and protons

τ_L = 700 fs, at the laser intensity peak

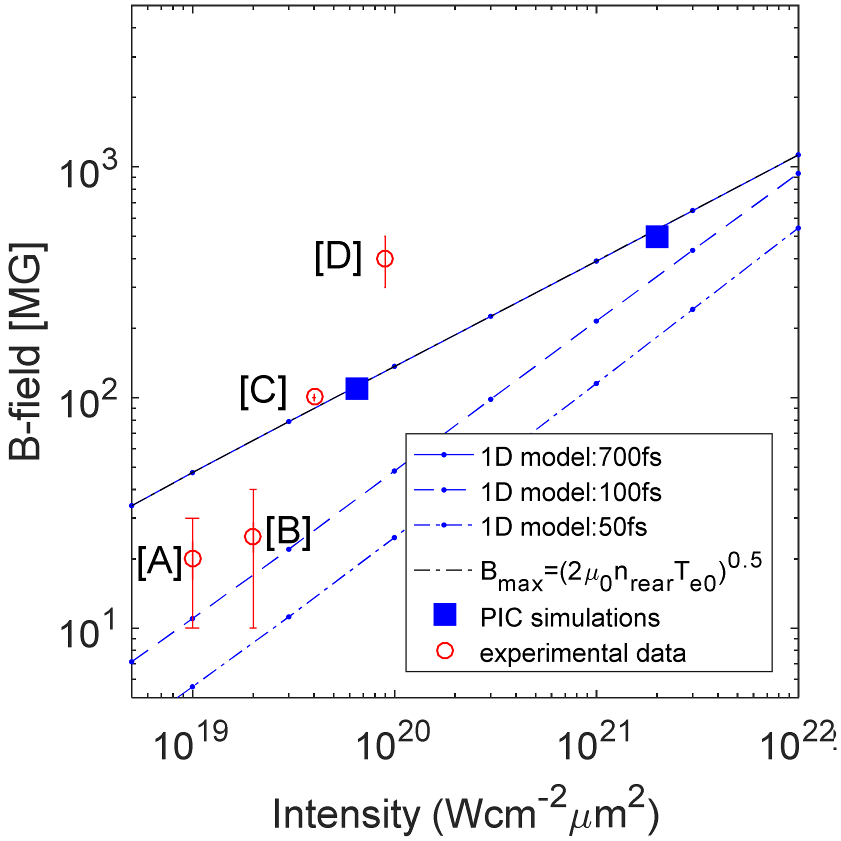




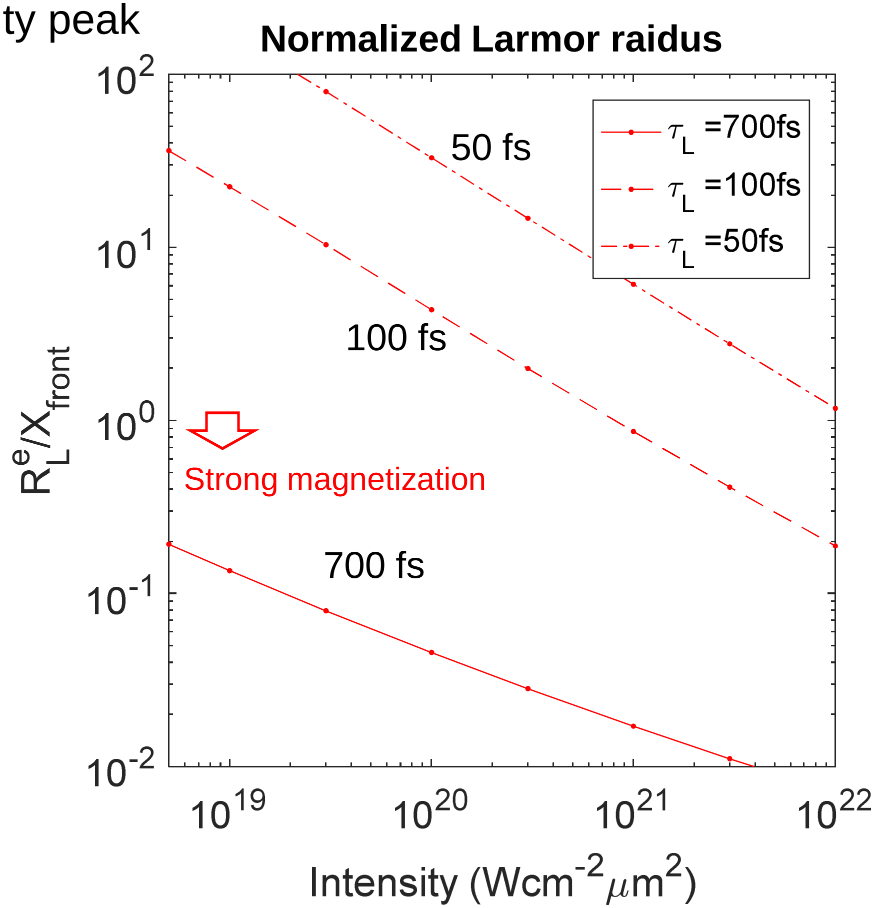
[A] G. Sarri et al., *Phys. Rev. Lett*. **109**, 205002 (2012).
[B] B. Albertazzi et al., *Phys. Plasmas* **22**, 123108 (2015).
[C] W. Schumaker et al., *Phys. Rev. Lett.* **110**, 015003 (2013).
[D] M. Tatarakis et al., *Nature* **415**, 280 (2002).

Dependence on pulse duration

At the laser intensity peak



Normalized Larmor raidus



[A] G. Sarri et al., *Phys. Rev. Lett*. **109**, 205002 (2012).
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