Proton energy scaling laws - Generation of above-100-MeV proton beams with Z-Petawatt?

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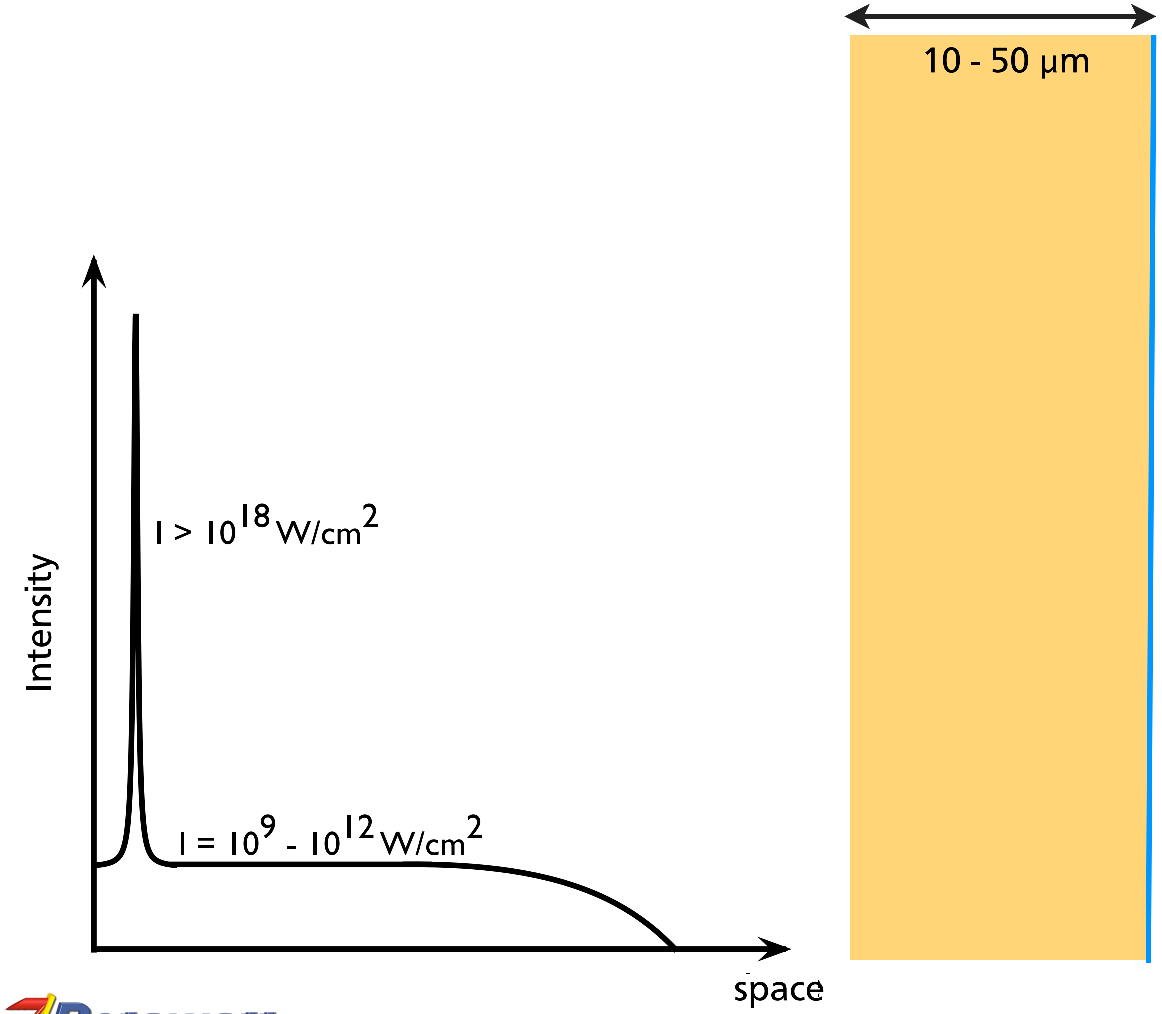
Outline

- Main topic: Investigation of scaling laws and comparison with results from various laser systems
- Introduction: Laser ion acceleration by TNSA
- Scaling law by J. Fuchs *et al*.
- "Optimized" scalings: Energy-enhancement with different laser and different target geometries
- Summary: Can Z-Petawatt accelerate ions up to 100 MeV and more?

Laser ion acceleration:
Target Normal Sheath Acceleration (TNSA)



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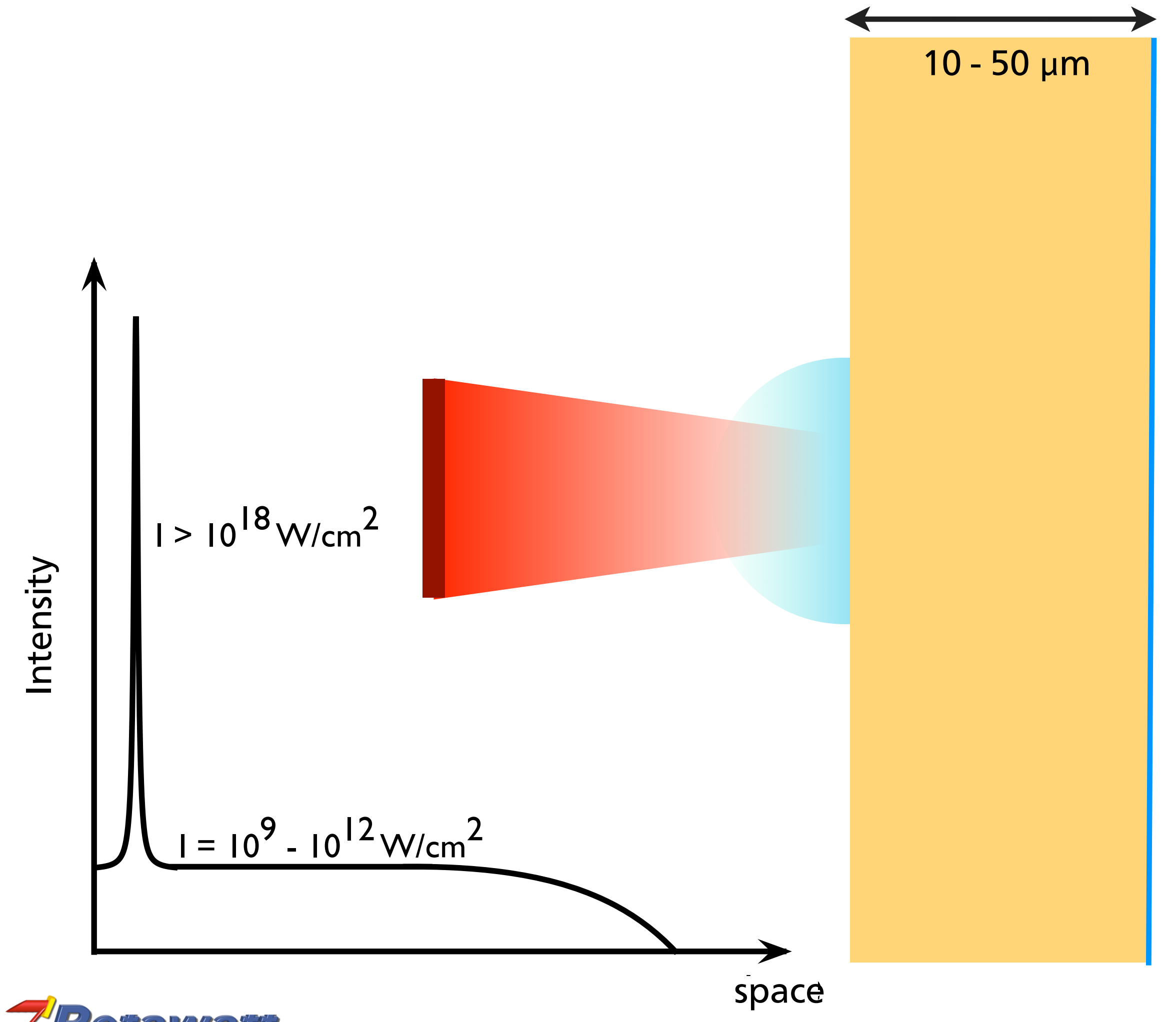
- Laser pulse creates pre-plasma



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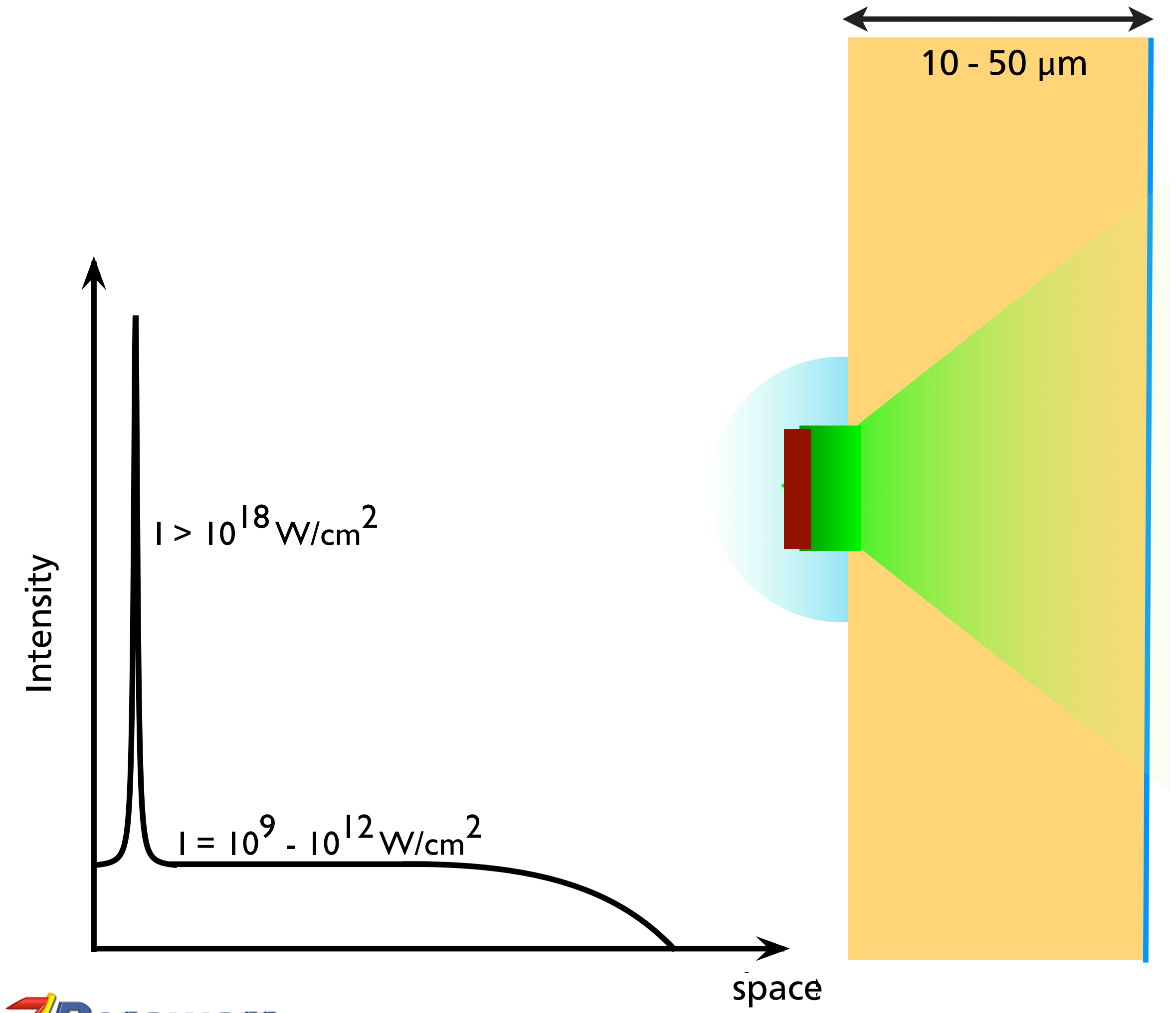

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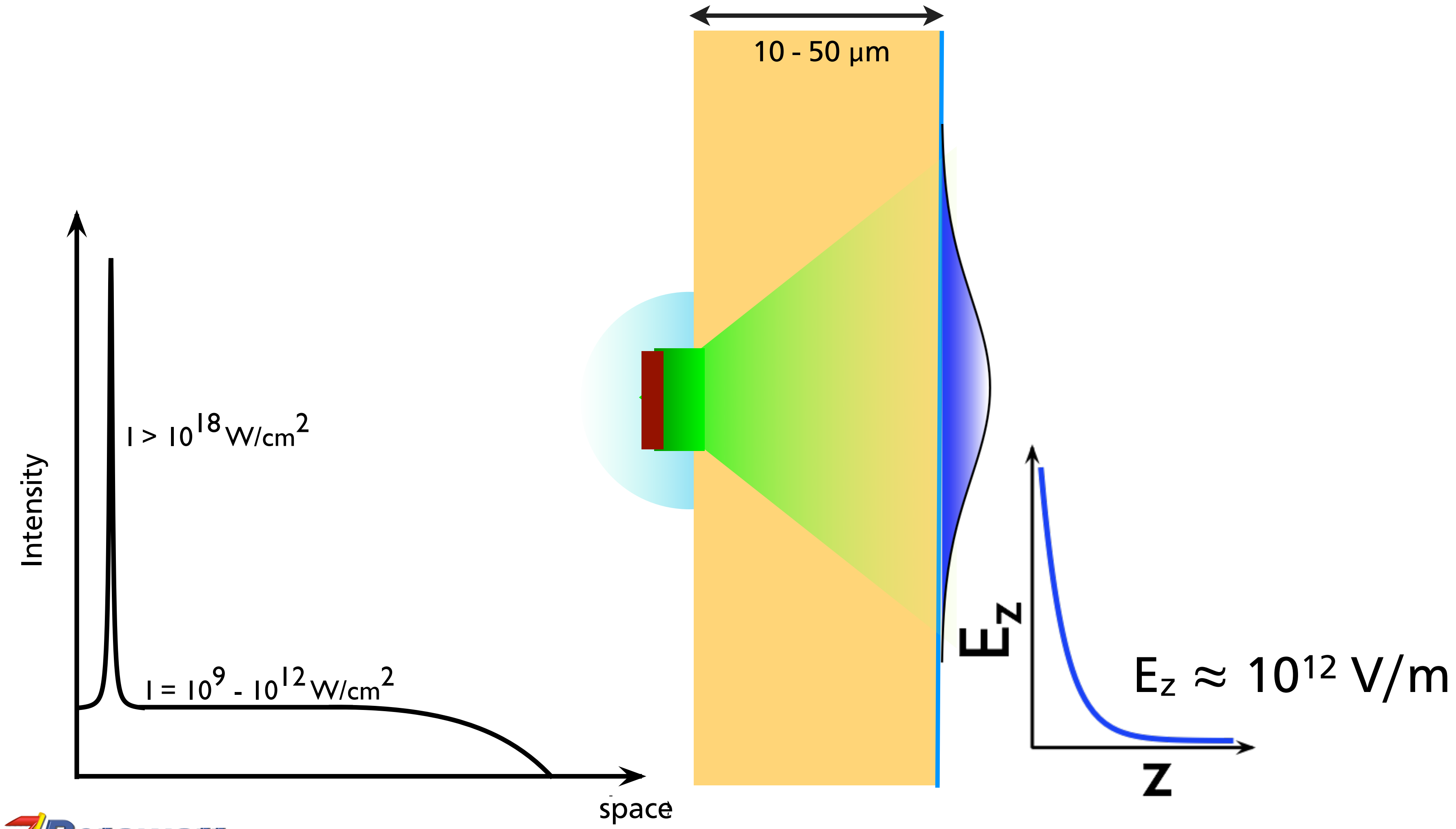

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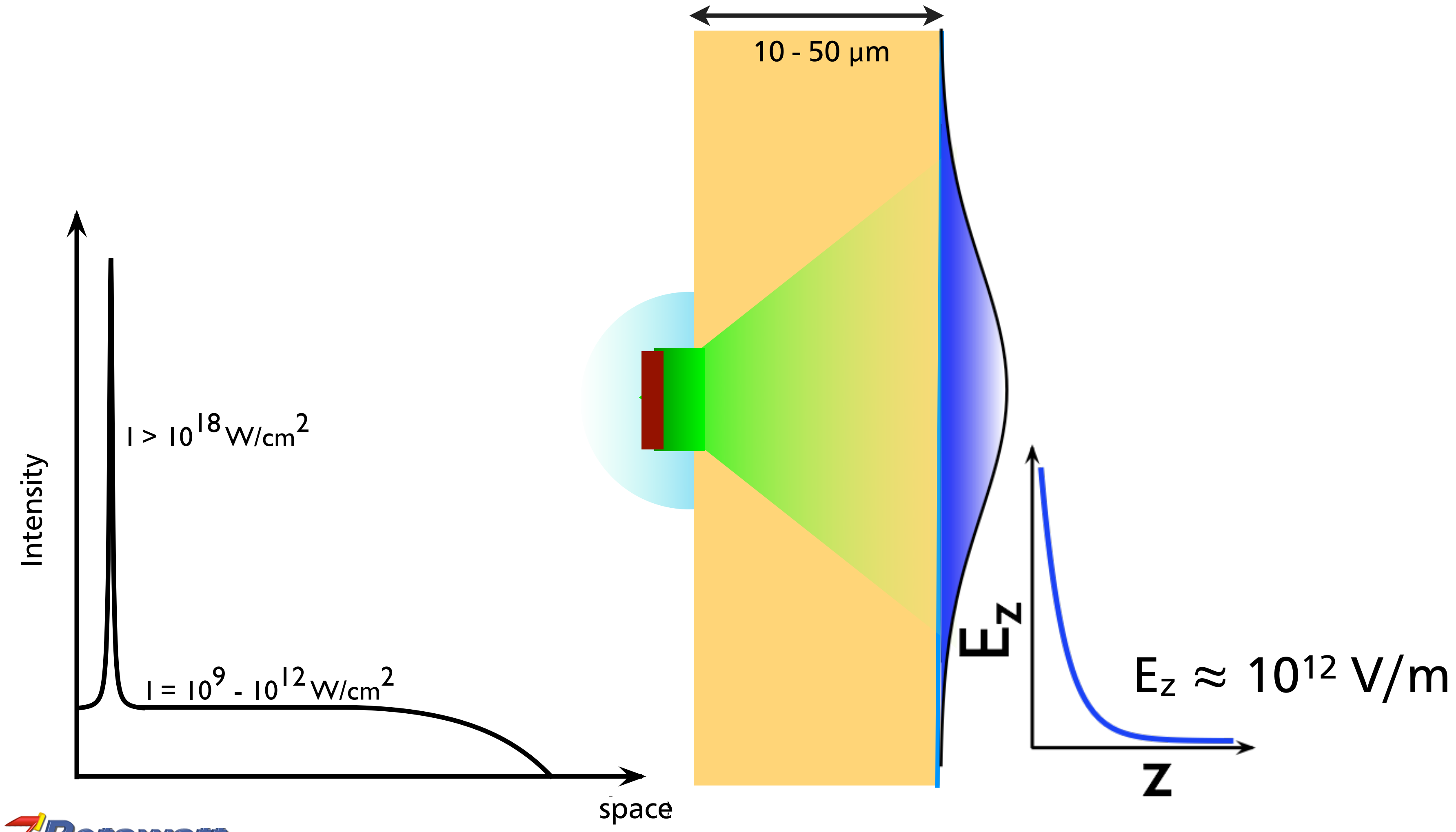

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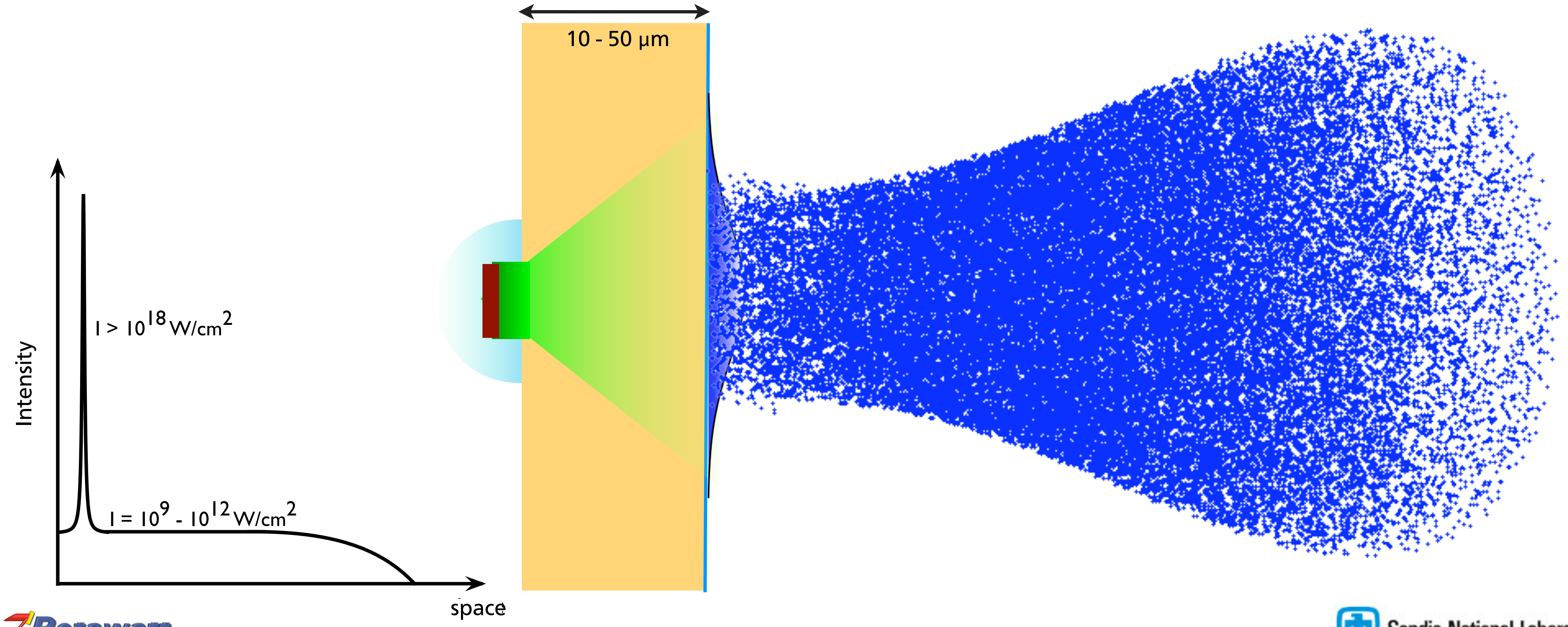

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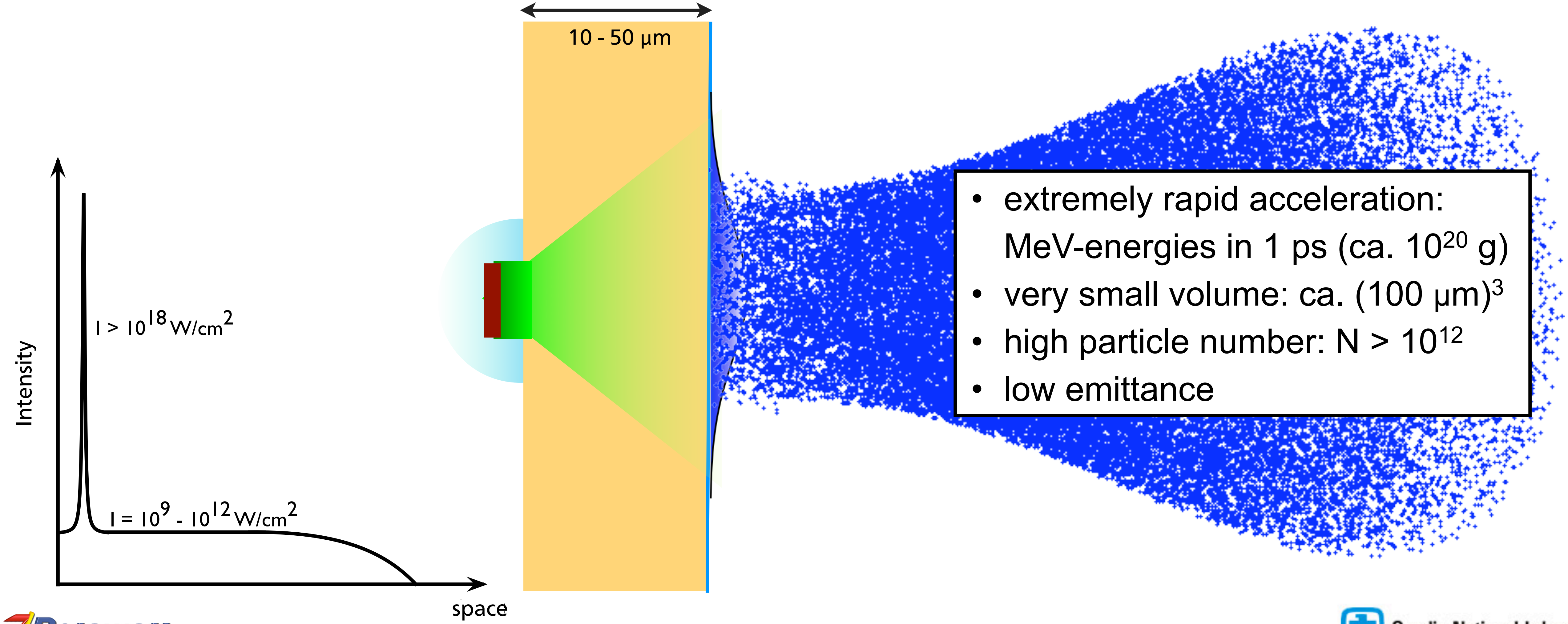


- extremely rapid acceleration: MeV-energies in 1 ps (ca. 10^{20} g)
- very small volume: ca. (100 µm)^3
- high particle number: $N > 10^{12}$
- low emittance

Energy gain in electric field

Laser:

I = 2 x 10^{20} W/cm^2
t_p = 1 ps
10 µm dia. focus

--> E = 150 J

Target:

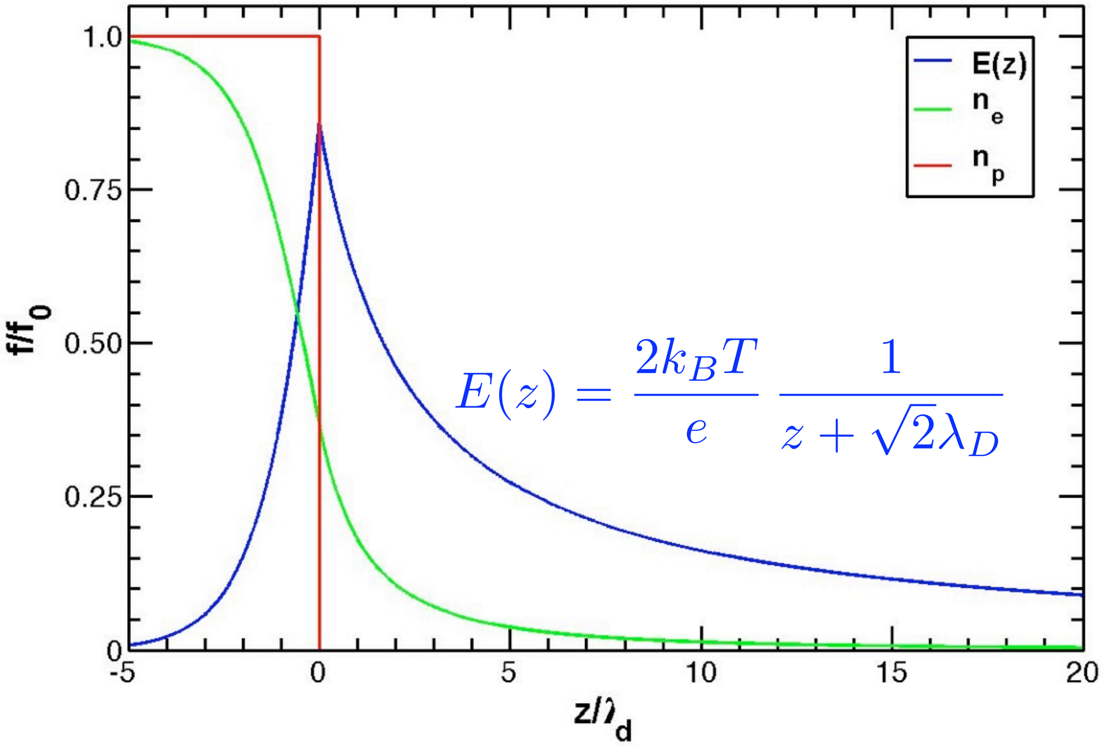
10 µm metal foil

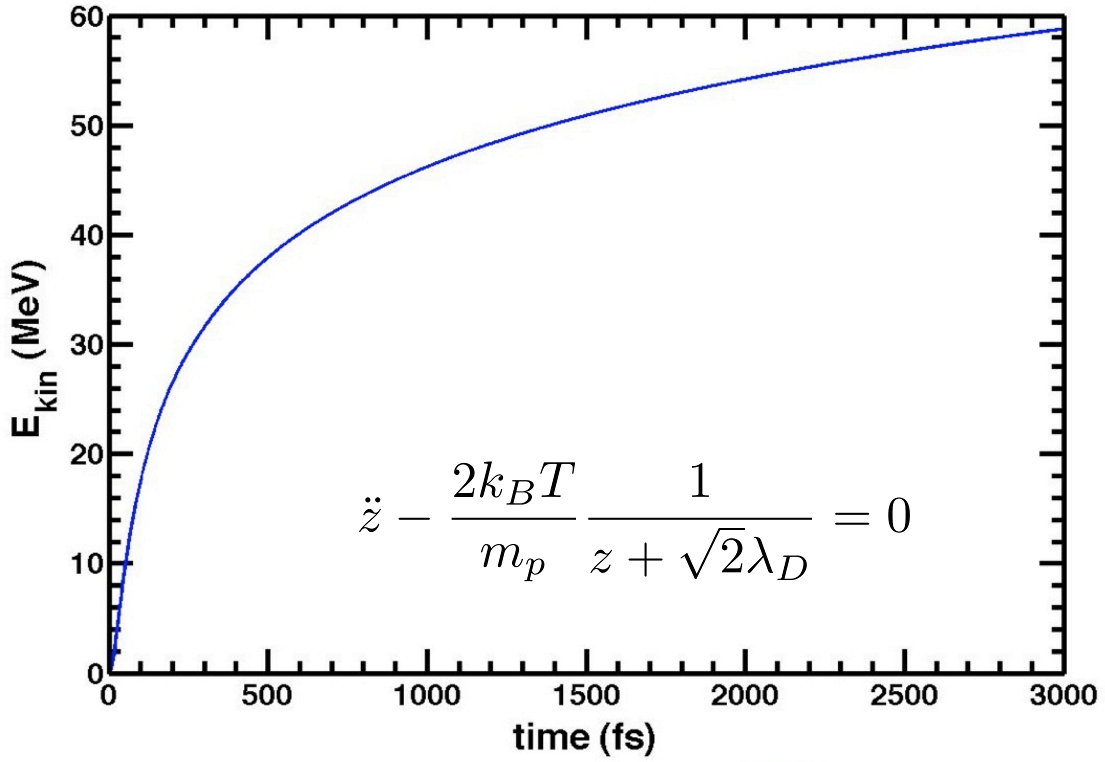
$$k_B T = m_e c^2 \left(\sqrt{1 + \frac{I\lambda^2}{1.37 \times 10^{18}}} - 1 \right) \approx 5\,\mathrm{MeV}$$

$$\lambda_D = 0.56\ \mu m$$

$$E_{\mathrm{max}} \approx 1 \times 10^{13}\,\mathrm{V/m}$$

acceleration time: very long, about 3 ps!!





More realistic: Isothermal expansion

- Mora, PRL **90**, 185002 (2003): isothermal fluid expansion with charge separation
- „Standard model“ of TNSA

$$\frac{\partial n_i}{\partial t} + \frac{\partial (v_i n_i)}{\partial z} = 0 \qquad \frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial z} = -\frac{e}{m_p}\frac{\partial \Phi}{\partial z}$$

$$\varepsilon_0 \frac{\partial^2 \Phi}{\partial z^2} = e\left(n_e(z) - n_i(z)\right) \qquad n_e = n_{e,0} \exp\left(\frac{e\Phi}{k_B T_{\text{hot}}}\right)$$

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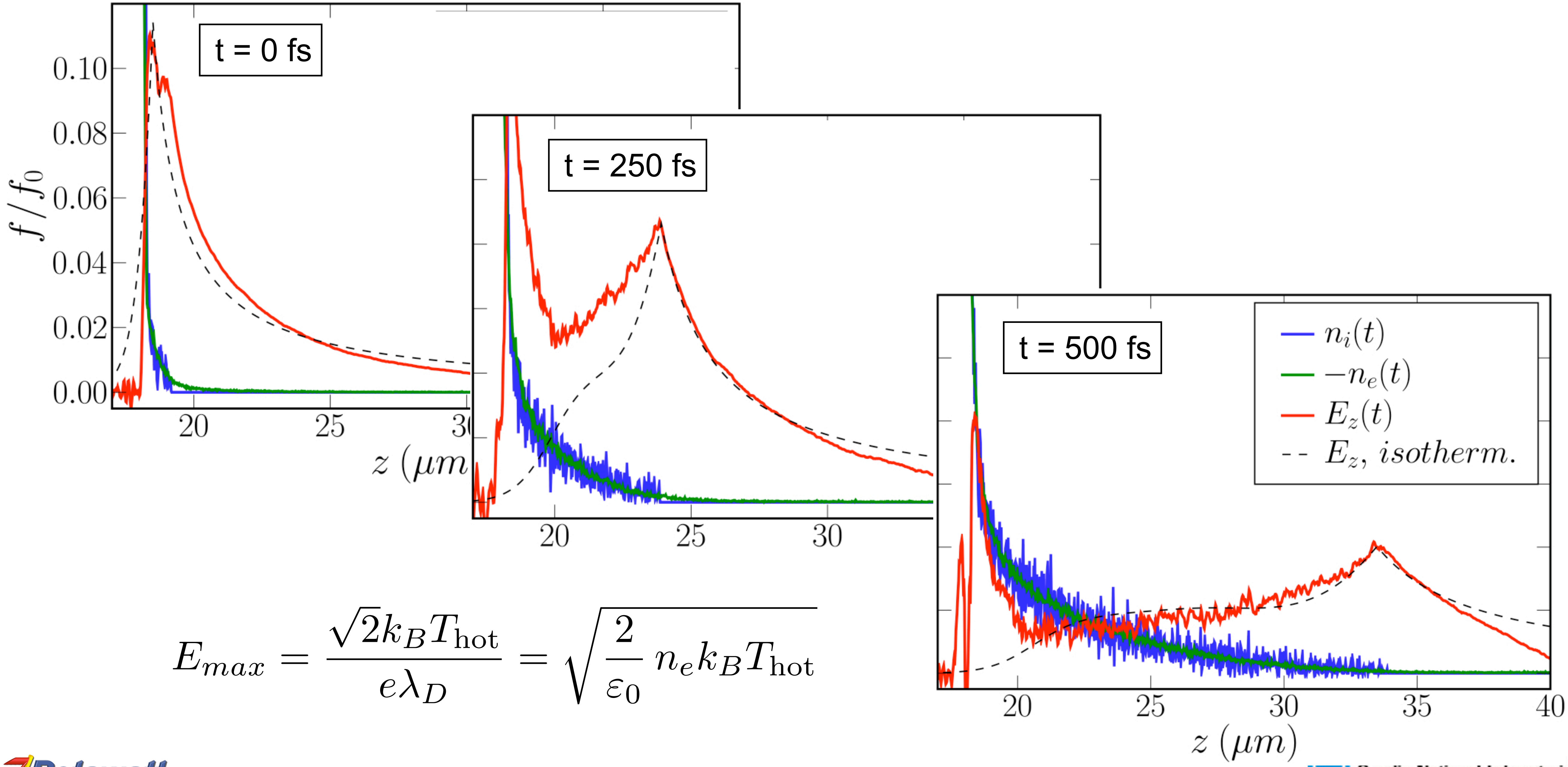
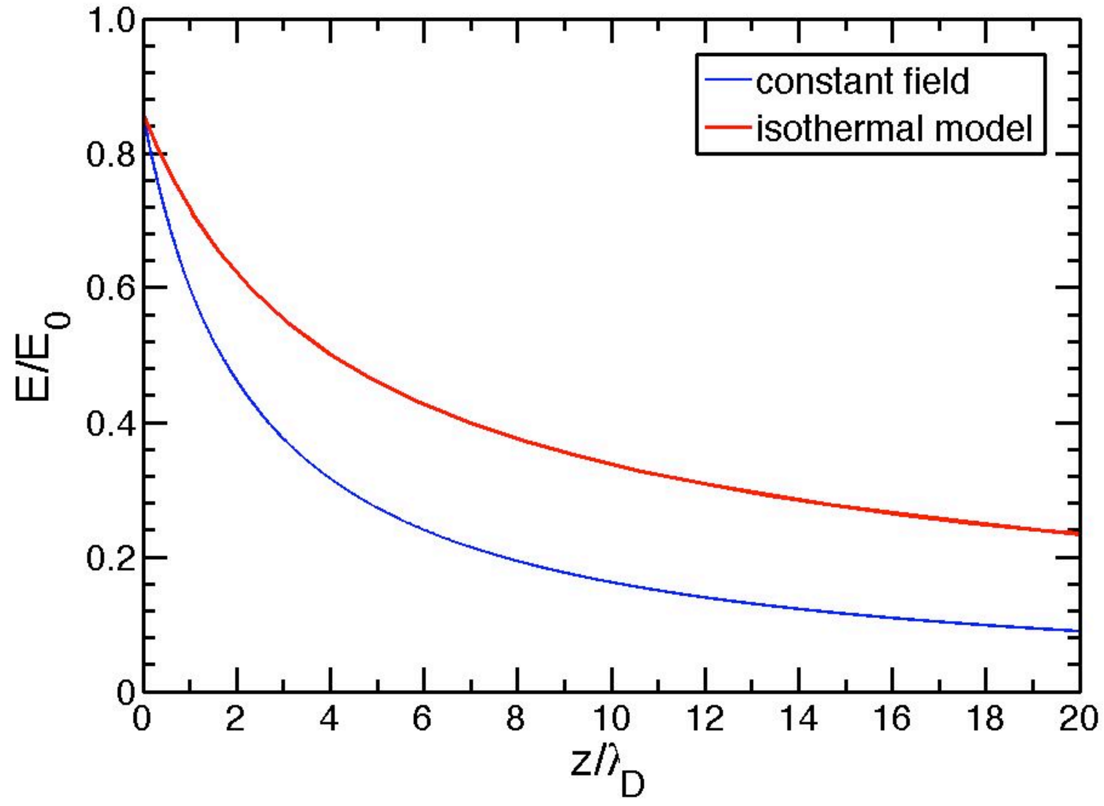
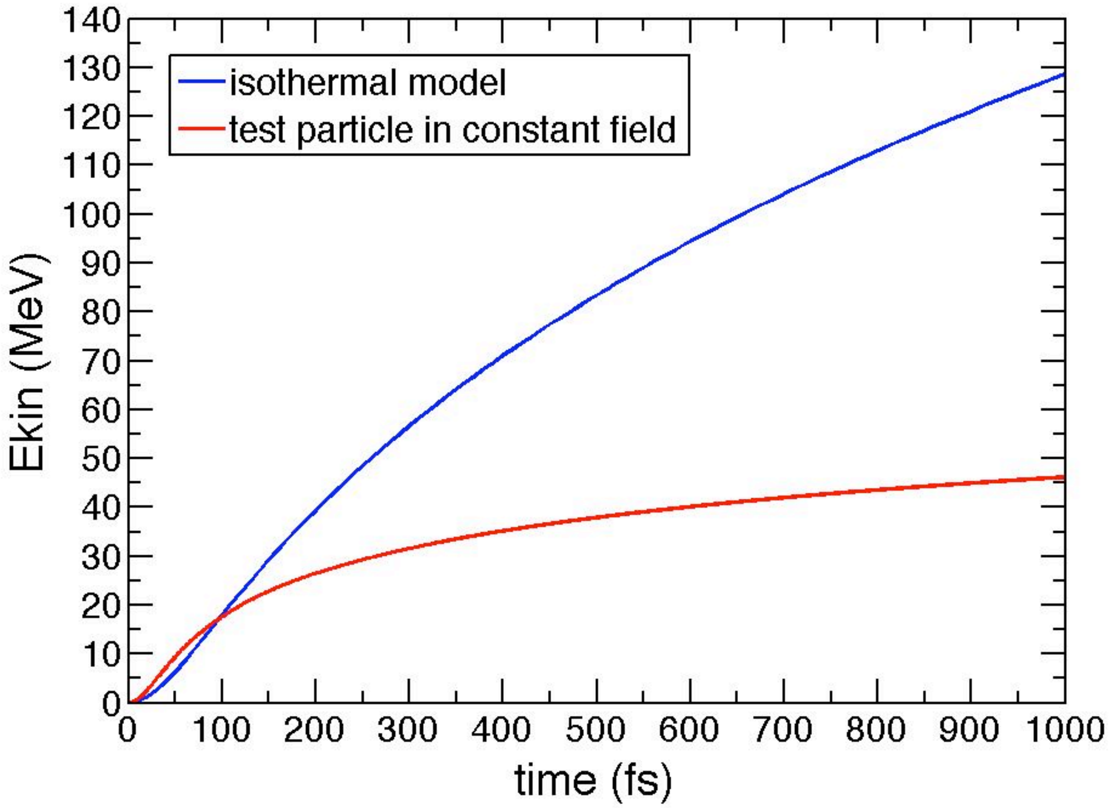


$$E_{max} = \frac{\sqrt{2}k_B T_{\text{hot}}}{e\lambda_D} = \sqrt{\frac{2}{\varepsilon_0}\, n_e k_B T_{\text{hot}}}$$

Energy gain in isothermal model

peak electric field moves with ions -> stronger acceleration





still about 650 fs needed for protons to reach 100 MeV
--> plasma has to stay at temperature for this time

basic model, but good enough for comparison with experimental data

Comparison with experiments: Scaling law

J. Fuchs *et al*., Nature Physics **2**, 48 (2006) and J. Fuchs *et al*., Phys. Plasmas **14**, 053105 (2007) : Isothermal expansion with stopping time

$$\tau_{\mathrm{acc}} = \begin{cases} \left(-6.07 \times 10^{-20} \times (I_L - 2 \times 10^{18}) + 3\right) \times (\tau_L + t_{\mathrm{min}}) & \text{for } I_L \in [2 \times 10^{18}, 3 \times 10^{19}[\ \mathrm{W/cm^2}, \\ 1.3 \times (\tau_L + t_{\mathrm{min}}) & \text{for } I_L \geq 3 \times 10^{19}\ \mathrm{W/cm^2}. \end{cases}$$

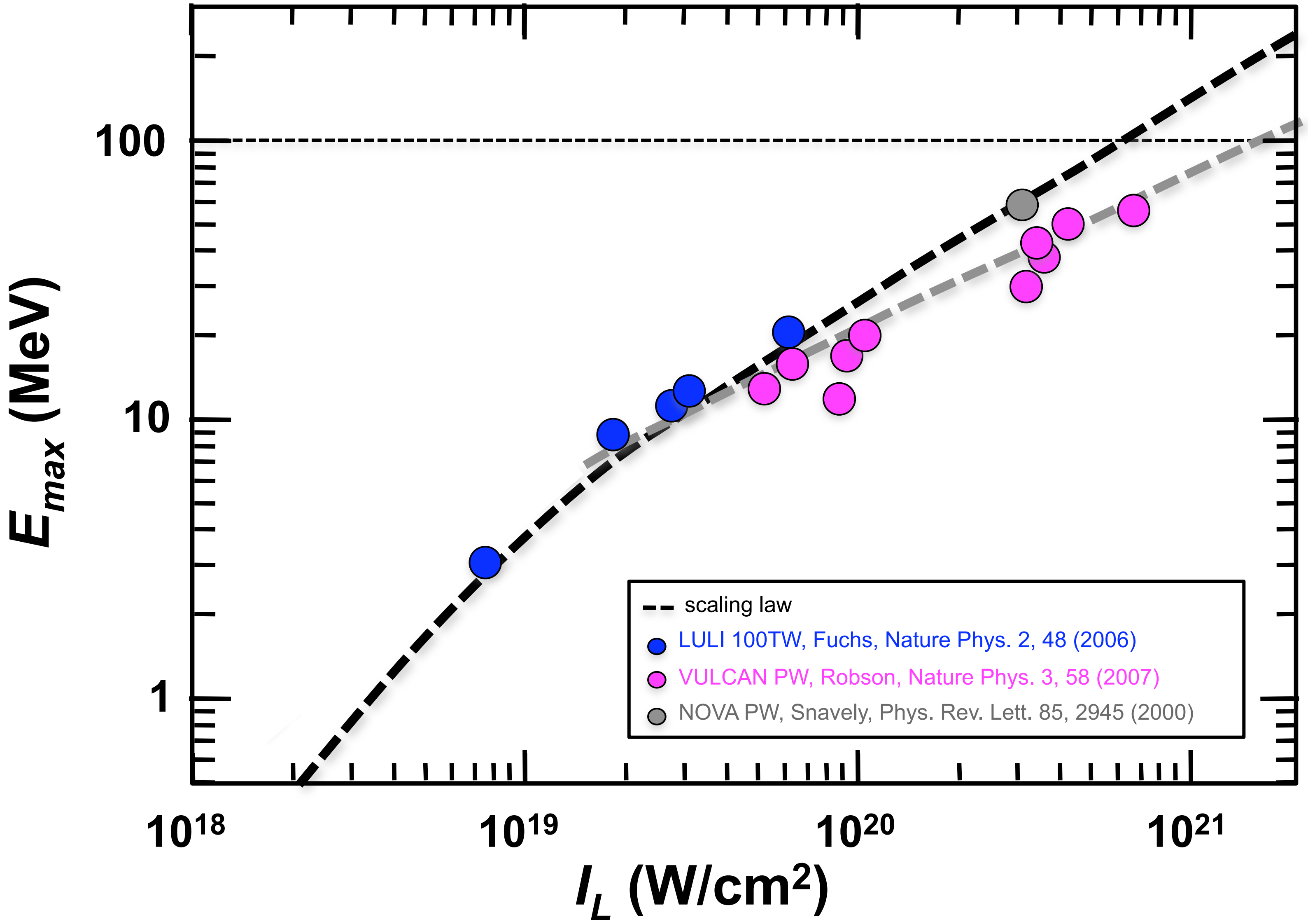
$$E_{\mathrm{max}} = 2T_{\mathrm{hot}}[\ln(t_{\mathrm{p}} + (t_{\mathrm{p}}^2 + 1)^{1/2})]^2$$

$$t_{\mathrm{p}} = \omega_{\mathrm{pi}} t_{\mathrm{acc}} / (2\exp^1)^{1/2}$$

Validity conditions: Similar lasers with t_p = [300 fs, 1 ps], with similar contrasts of about 10^{-6}, metallic targets with d > 10 µm

Comparison with experiments: Scaling law

Parameters:
t_p = 500 fs
focus dia. = 6 μm
25 μm target



E_{max} = 100 MeV:

I = 6 x 10^{20} W/cm^2 E = 84 J or 168 J (50% foc.)
I = 2 x 10^{21} W/cm^2 E = 280 J or 560 J (50% foc.)

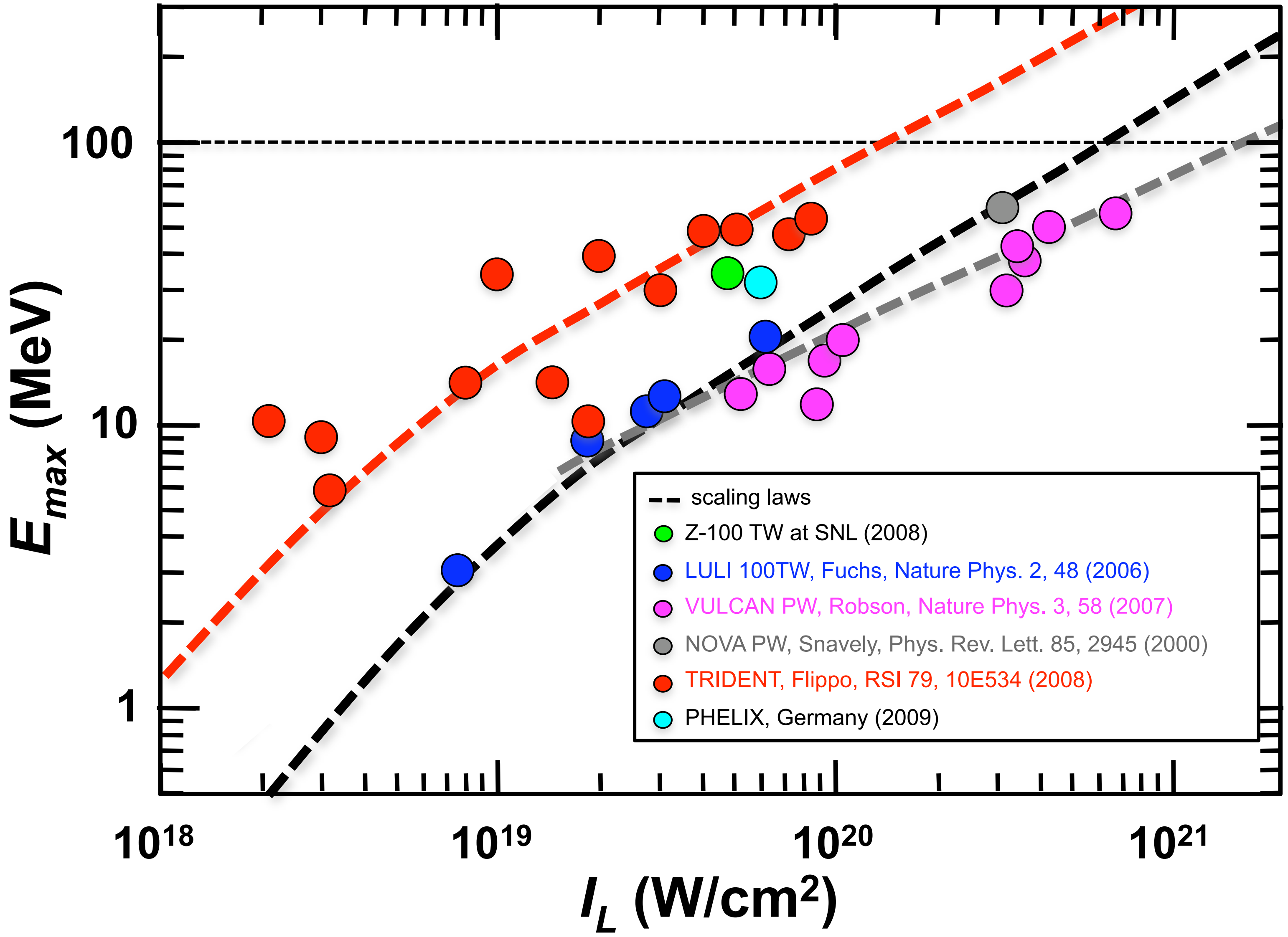
Lasers with longer pulses and larger foci

Parameters:
t_p = 1 ps
focus dia. = 10 μm
target: 10 μm

same scaling law

Result: longer pulses and thinner targets result in higher proton energy:

$$E_{max} \propto k_B T \, \ln\left(\sqrt{n_e}\, \tau_{acc}\right)$$



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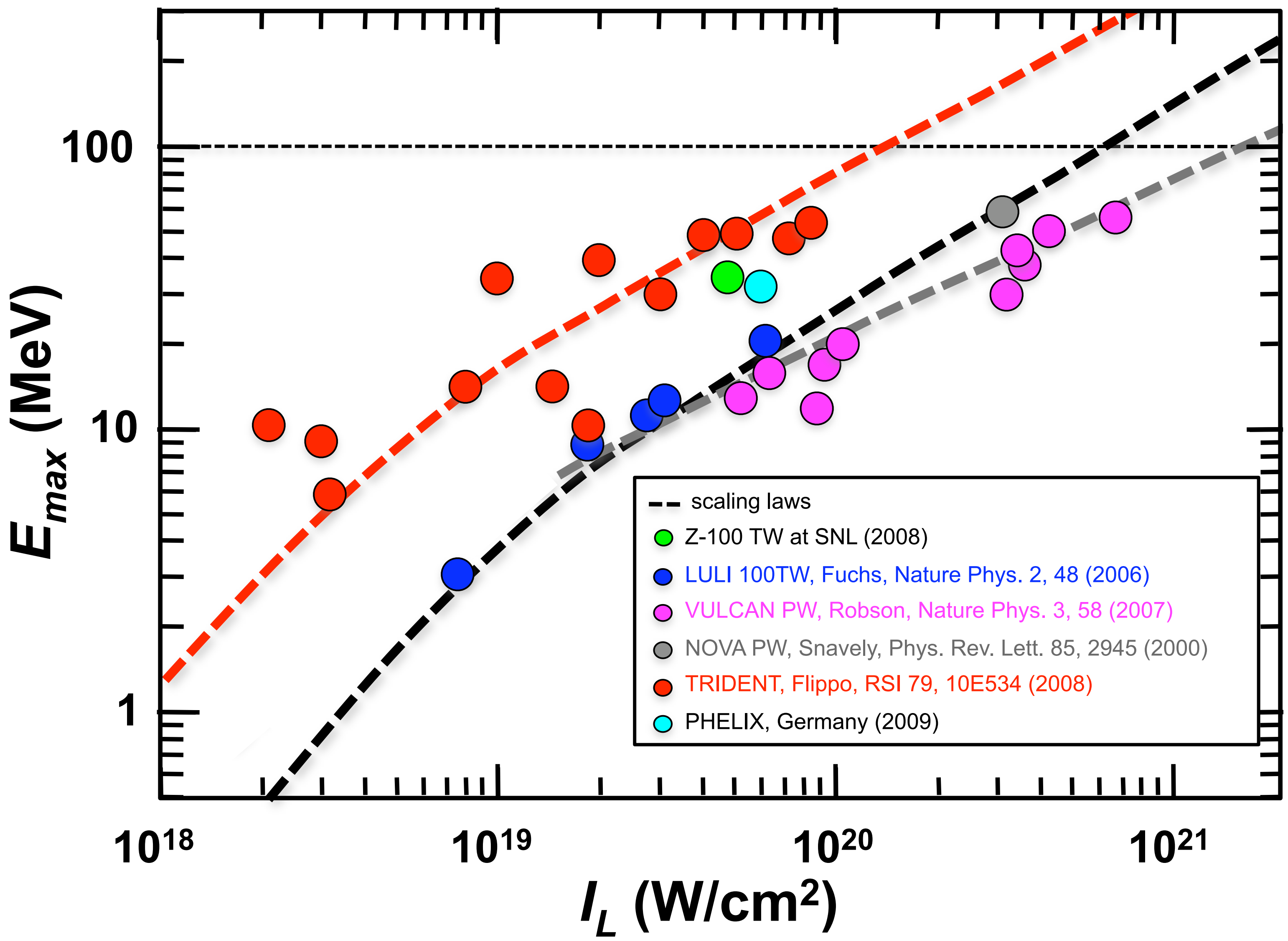


What if the target geometry is changed?

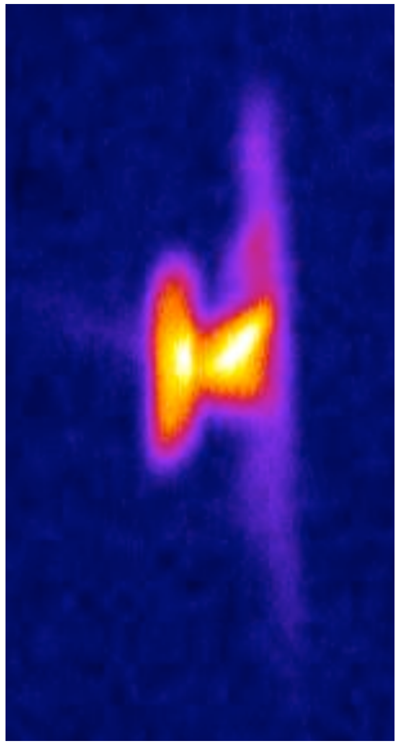
Change of target geometry gets even better results

Experiments at Trident (K. Flippo, S. Gaillard, *et al*., MG, MS): copper Flat Top Cones (FTC)

Trident Shot 21170, 81 Joules and 670 fs: I ~ 4 x 10^{19} W/cm^2

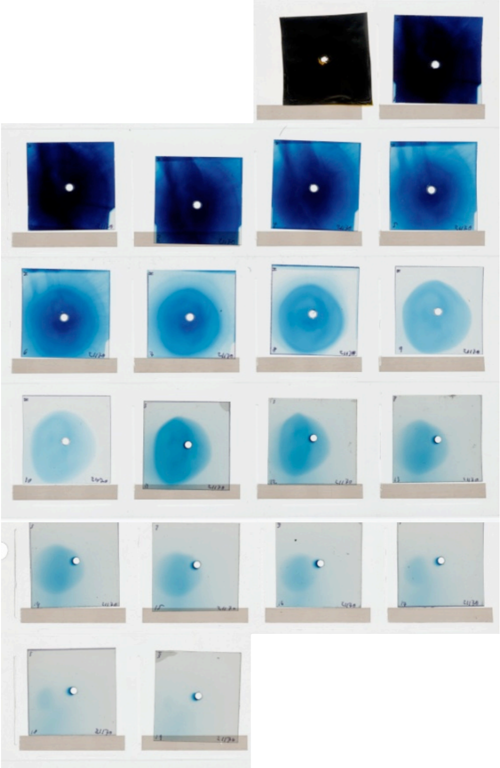
> 65 MeV protons, highest energy protons in the world from laser-ion acceleration

Copper Flat-Top Cone Target Image



Kα shows deep penetration of laser and electrons

preliminary data!

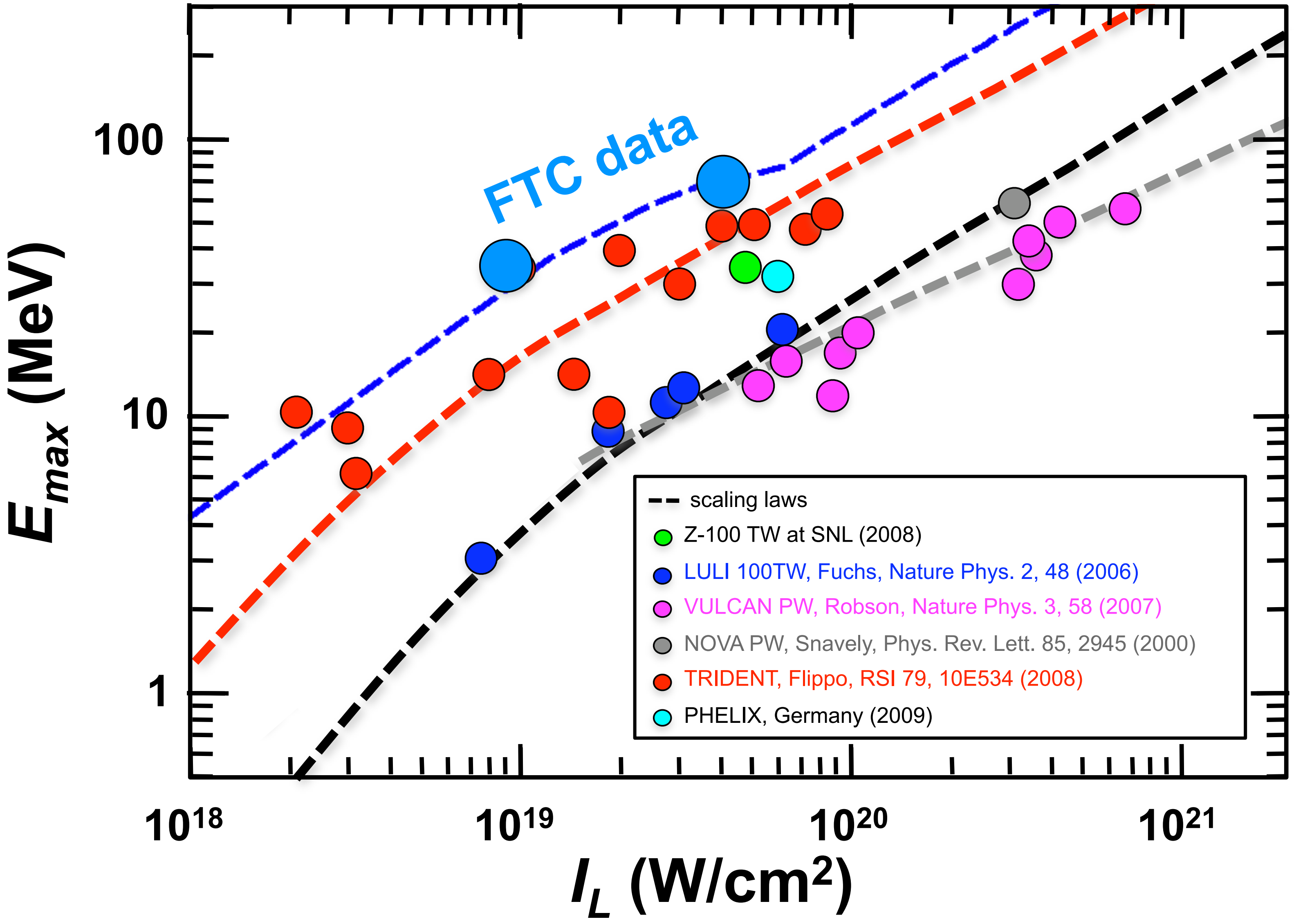


RCF images show a proton beam of > 65 MeV

flat foil: 50 MeV, FTC: 65 MeV
energy increase: 30%

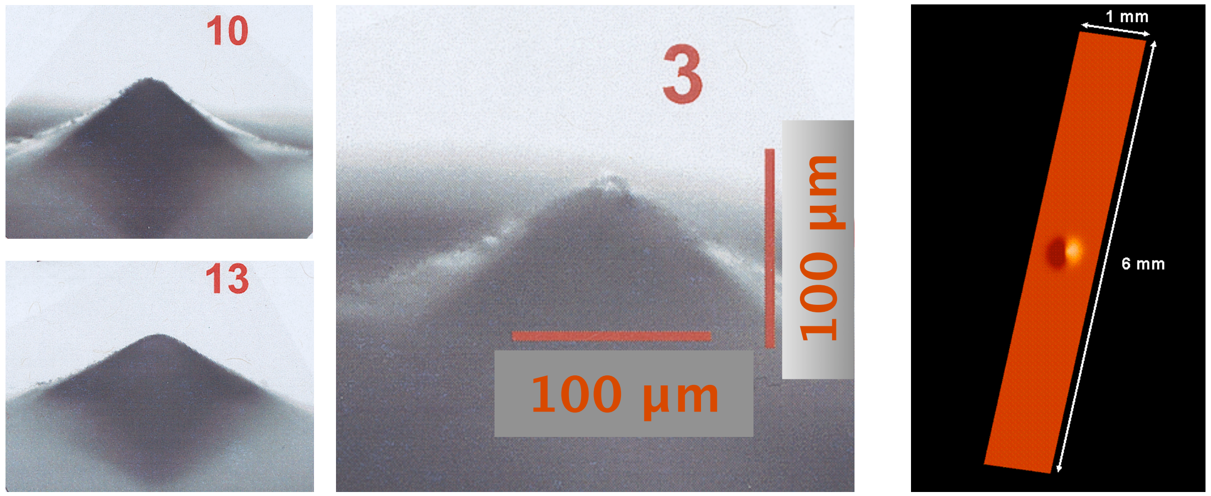
Change of target geometry gets even better results

Scaling law fits, if $f_{abs} = 0.5$ is fixed and kT doubled (more efficient electron heating due to cone-shaped front side, backed up by K-alpha imager data)

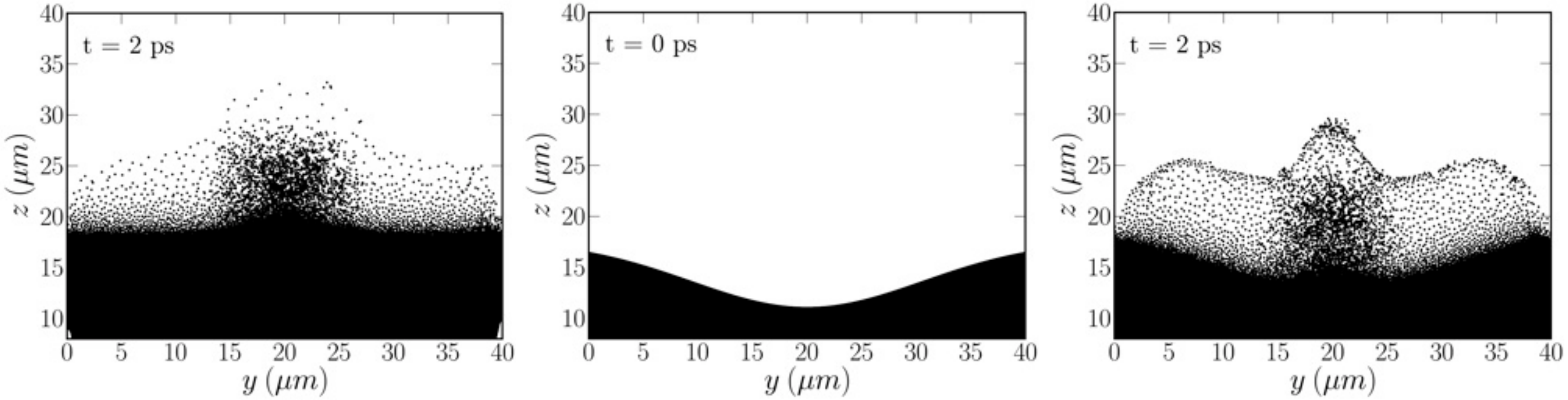


Target geometry II: Curved foils

concave targets lead to slight focusing
-> enhancement of electron density on symmetry axis
-> electric field increase
-> more efficient TNSA



Gaussian shaped foils with about 100 µm width and height have been produced for SNL. Experimental campaign planned this year.



Energy increase seen in 2D-PIC: 20%

Experiment by M. Roth *et al*.: ~30%
(article in preparation)

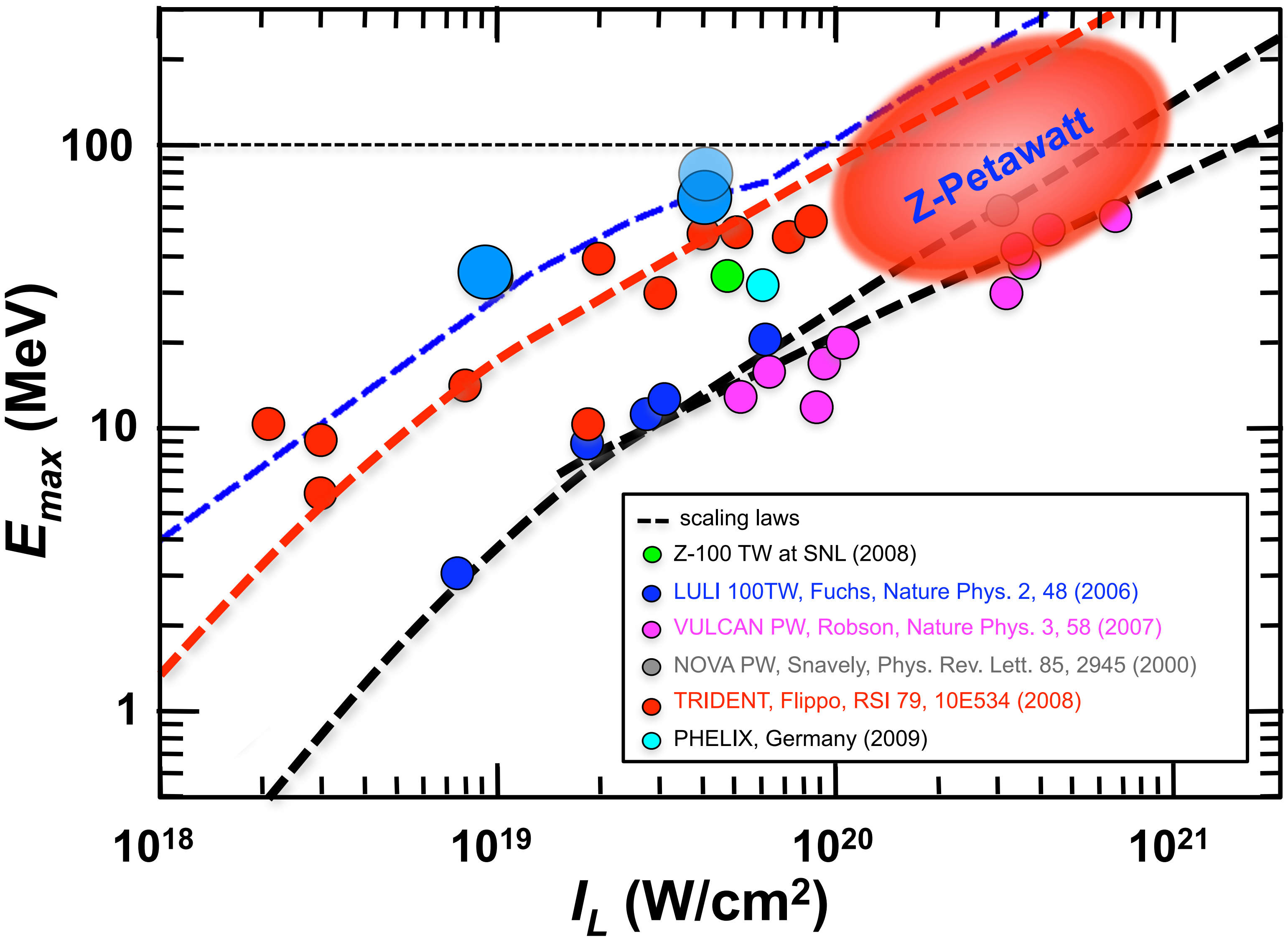
Summary: Can we get there?

Requirements:
- I ~1.3 x 10^{20} W/cm^2
- pulse duration: ~ 1 ps
- 10 µm -> 25 µm targets
- focal spot: 10 µm diameter

--> 100 J in focus or 1.5 J/µm^2
(> 200 J laser energy)

Comparison to simulations:
- J. Davis & G.M. Petrov, Phys. Plasmas **16**, 023105 (2009): similar value:
~2 J/µm^2 (with a 80 fs pulse)

- T. Esirkepov et al., Phys. Rev. Lett. **96**, 105001 (2006):
100 MeV for 10 µm focus, 200 fs pulse, 100 J, 6x10^{20} W/cm^2



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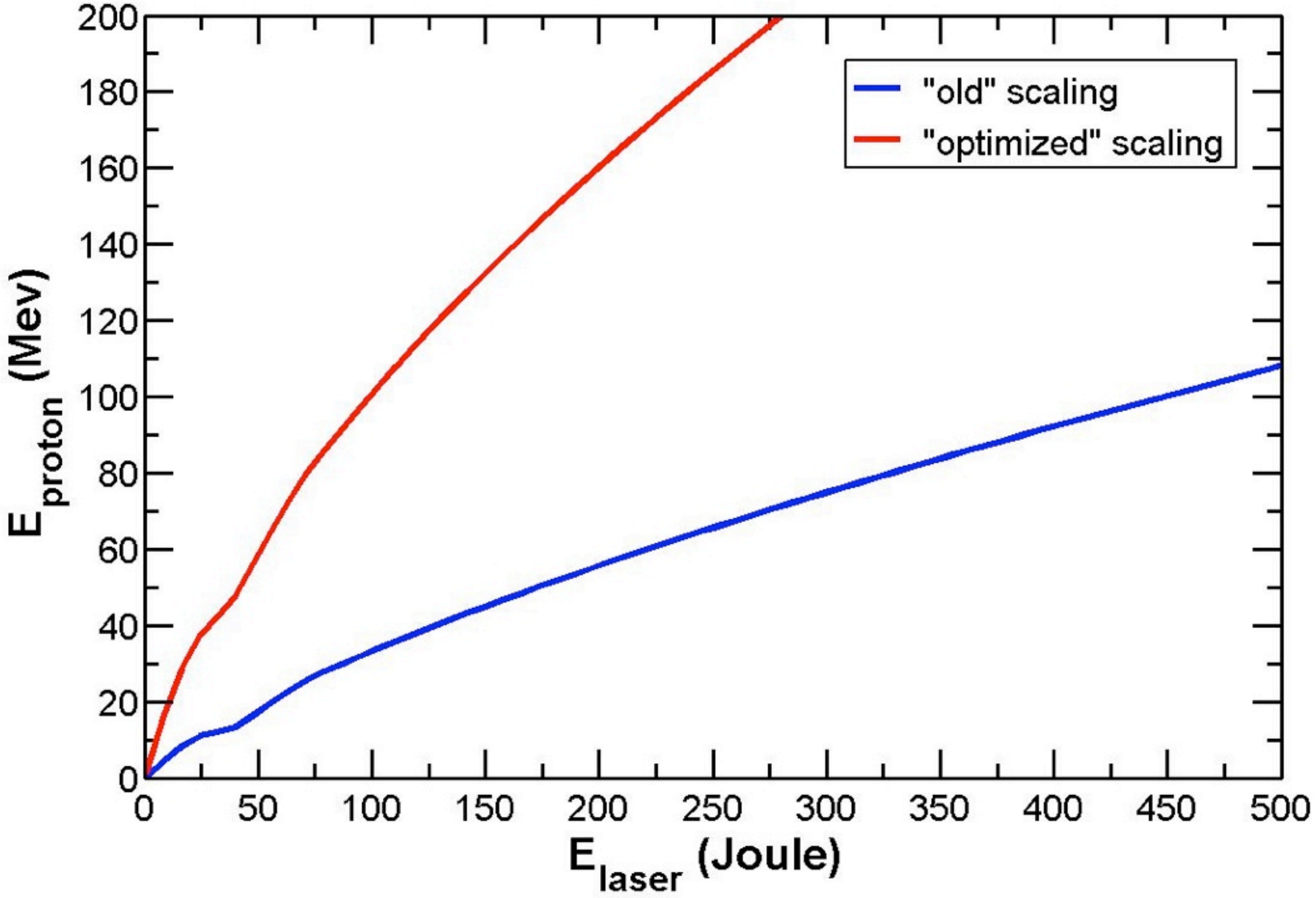

Outlook

Different acceleration schemes:

- Enhanced TNSA / Laser break-out afterburner
  - requires ultra-high contrast (10^{-12} and better) and ultra-thin foils
  - first TNSA, then volumetric heating of bulk when foil becomes transparent
  - First results: E_p = 40 MeV with I = 7 x 10^{19} W/cm^2 (A. Henig *et al*., PRL 103, 045002 (2009))

- Include circular polarization: Radiation pressure acceleration
  - requires ultra-high contrast (10^{-12} and better) and ultra-thin foils
  - experimentally difficult to realize (B-Integral, Plasma mirrors)
  - extremely high intensities are needed for 100 MeV: > 10^{22} W/cm^2 (A.P.L. Robinson, PPCF 51, 024004 (2009))
  - benefit: whole foil is accelerated, quasi-monoenergetic ions