Optimisation of multi-PW laser-driven proton acceleration in the relativistic transparency regime

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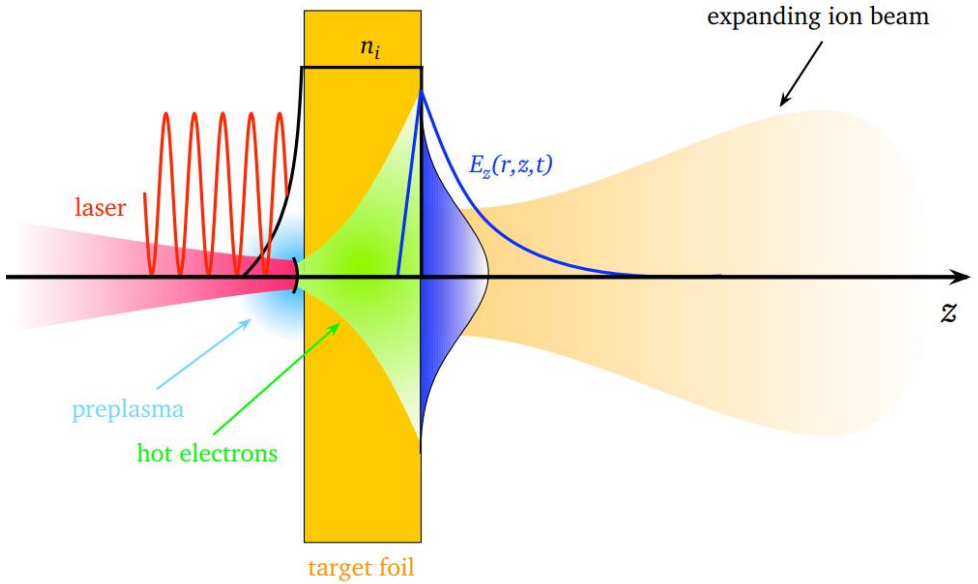
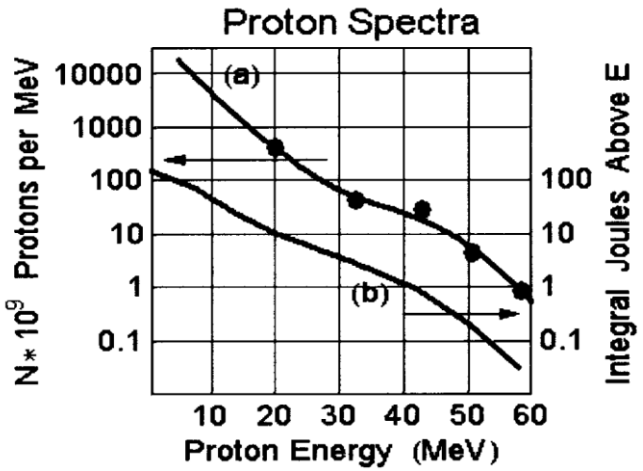
Laser-driven ion acceleration

Properties
- Multi-MeV energies
- Broad energy spectrum
- Ultrashort duration
- High flux
- Divergent
- Small source size

Applications
- Radiography
- Radioisotope generation
- Hadron therapy



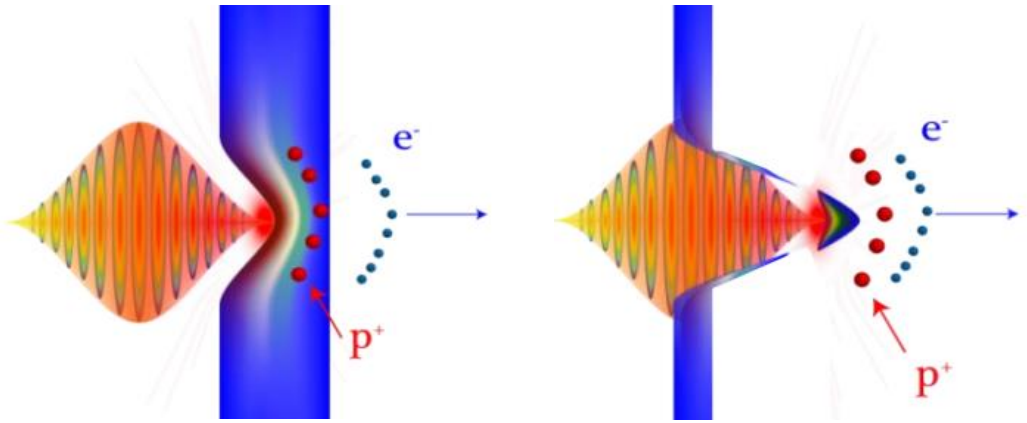
Roth, M., Schollmeier, M. (2013). Ion Acceleration: TNSA. In: McKenna, P. et al. (eds) Laser-Plasma Interactions and Applications. Scottish Graduate Series. Springer, Heidelberg



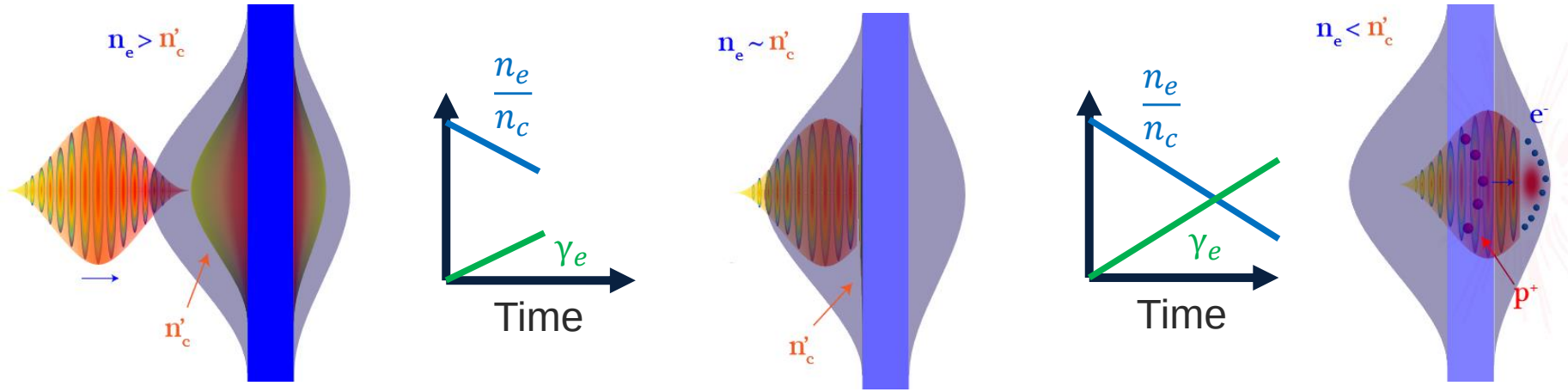
Snavely R A, et al. 2000 Phys. Rev. Lett. 85, 2945

Target normal sheath acceleration (TNSA)
Driven by population of hot electrons refluxing and escaping from the target

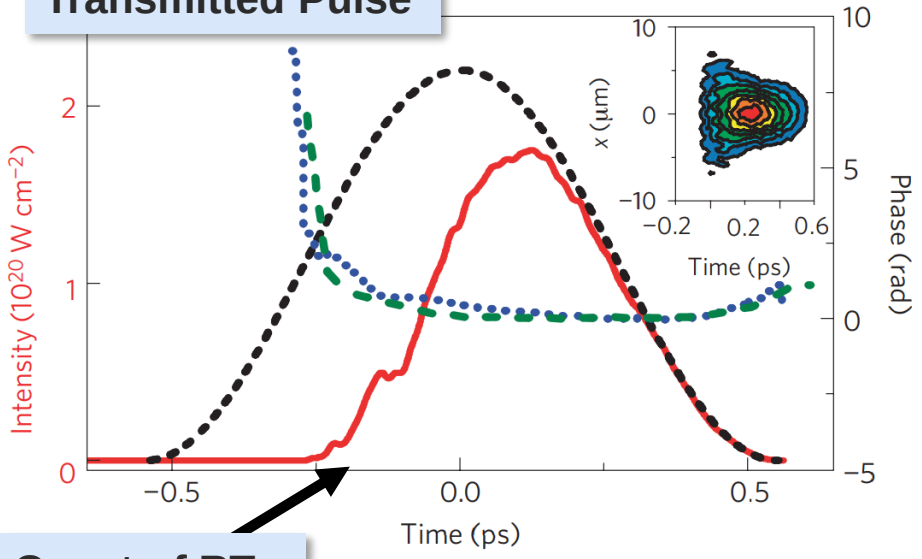
Radiation pressure acceleration (RPA)
Momentum transfer



Relativistic transparency enhanced ion acceleration



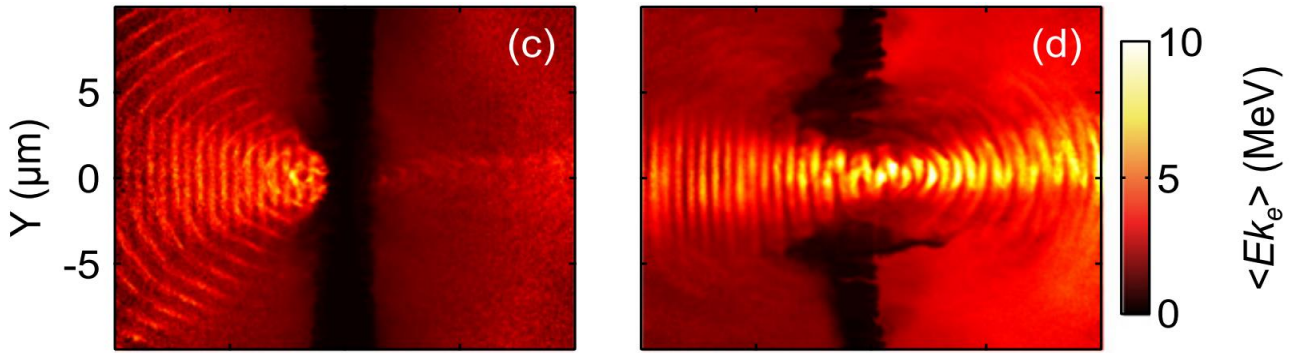
Transmitted Pulse



Onset of RT

Palaniyappan S, et al. 2012 Nat. Phys. 8, 763

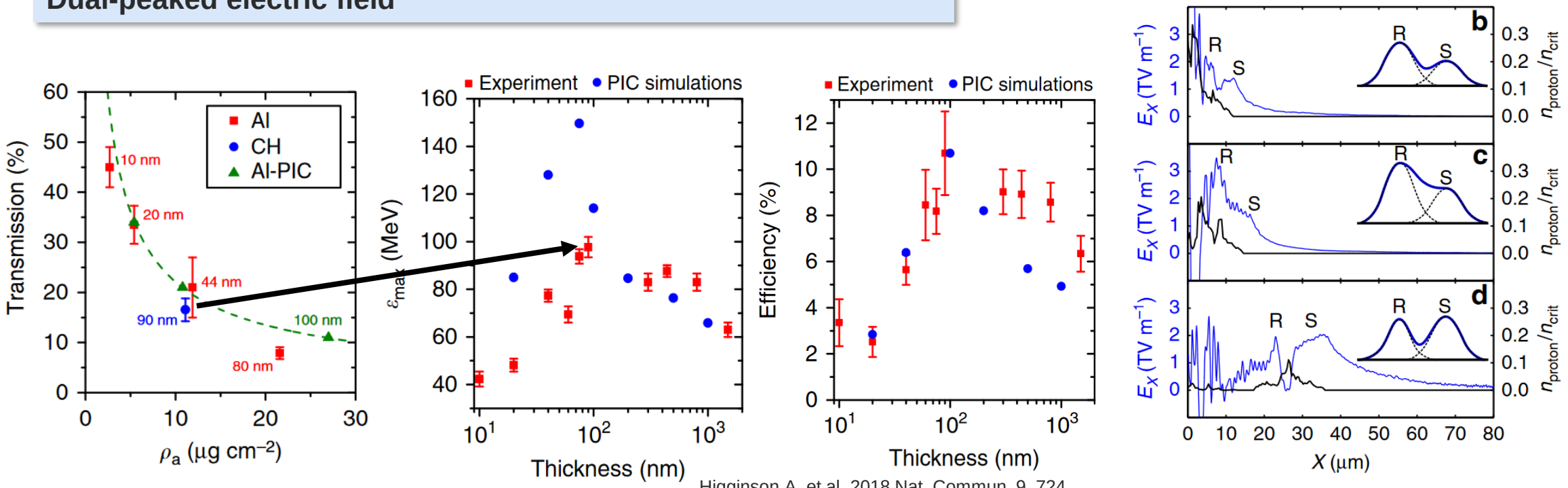
- **Ultrathin foils (≪1 μm)**
- **Target expands and electrons are relativistically heated, when $n_e < \gamma_e n_c$ laser begins to propagate through target**
- **Laser couples energy to electrons within target volume**



Williamson S D R, et al. 2020 New. J. Phys. 22, 053044

Relativistic transparency enhanced ion acceleration

Hybrid RPA-TNSA: Higginson A, et al. 2018 Nat. Commun. 9, 724
Dual-peaked electric field



Higginson A, et al. 2018 Nat. Commun. 9, 724

- **Highest proton energies found in experiment and simulations for targets that become transparent**

Break Out Afterburner (relativistic Buneman instability):

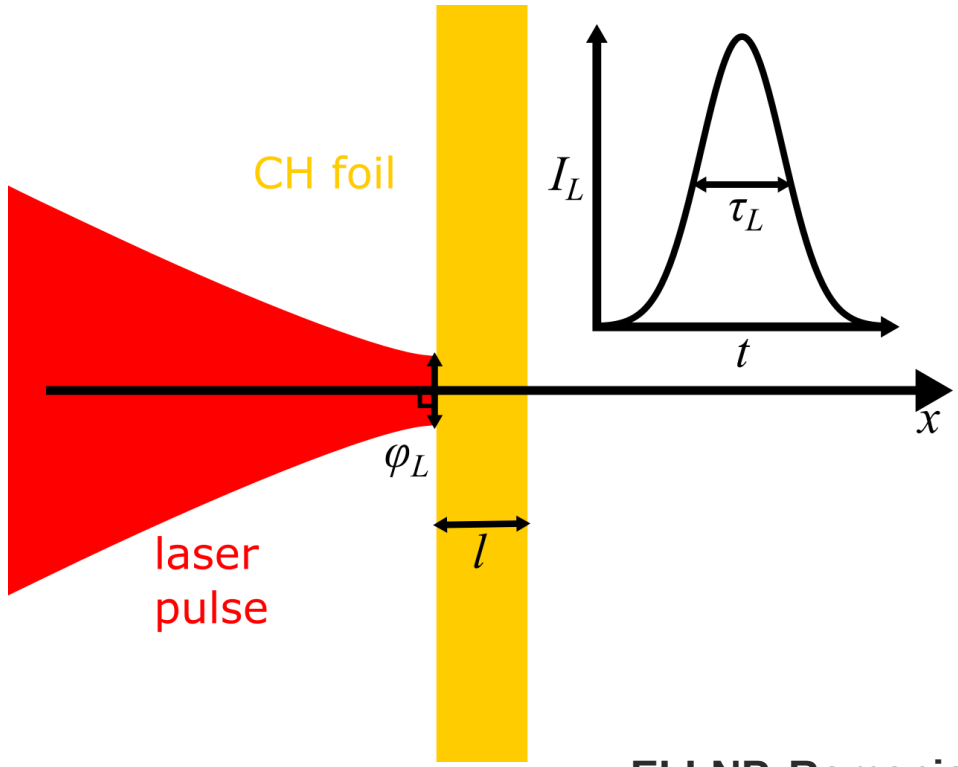
- **Yin L, et al. 2006 Laser Part. Beams 24, 291**
- **Henig A, et al. 2009 Phys. Rev. Lett. 103, 045002**
- **Fernandez J C, et al. 2017 Phys. Plasmas 24, 056702**

Simulation conditions

2D (and 3D) EPOCH particle-in-cell simulations

$\lambda_L = 820$ nm
$\tau_L = 40$ fs
$\varphi_L = 3$ μm
0° AOI
Linearly polarised

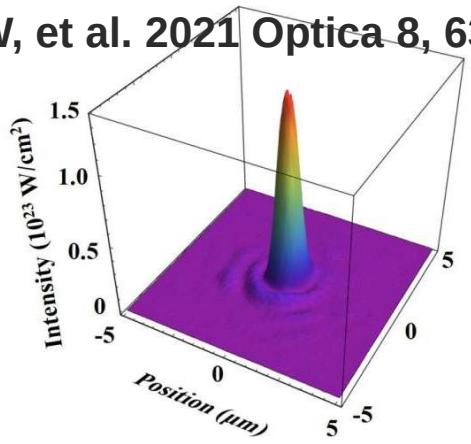
CH target
$n_e = 210 n_c = 3.5 \times 10^{29}$ m^{-3}



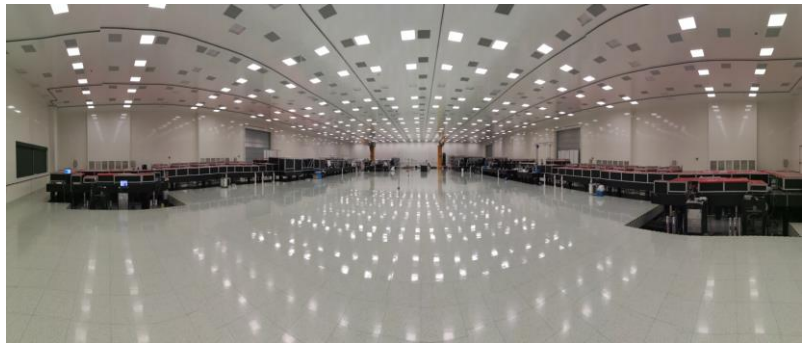
Intensity (W cm^{-2})	a_0
5 x 10^{20}	16
5 x 10^{21}	50
5 x 10^{22}	160
2 x 10^{23}	310

Astra-Gemini, UK
~10^{21} W cm^{-2}

CoReLS, Republic of Korea
10^{23} W cm^{-2} demonstration:
Yoon J W, et al. 2021 Optica 8, 630



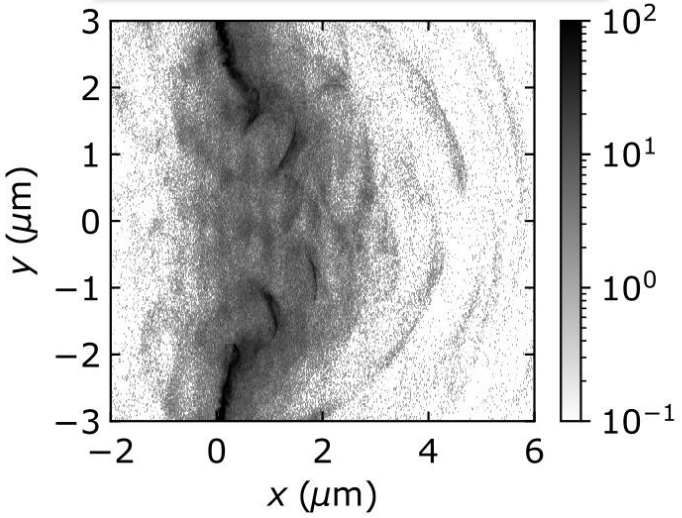
ELI-NP, Romania
~10^{23} W cm^{-2}
10PW demonstration:
Radier C, et al. 2022 HPLSE 10, e21



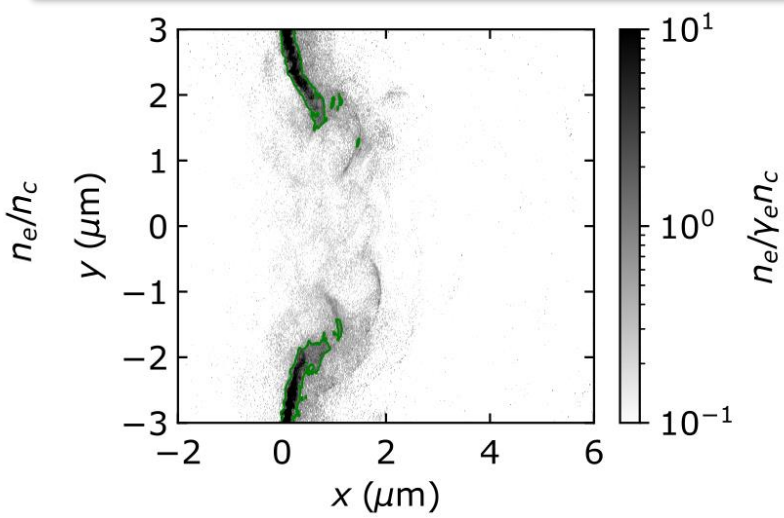
Relativistic transparency in simulations

125nm CH, 5×10^{21} W cm^{-2} ($a_0 = 50$), $t = 17$ fs after pulse peak reaches target

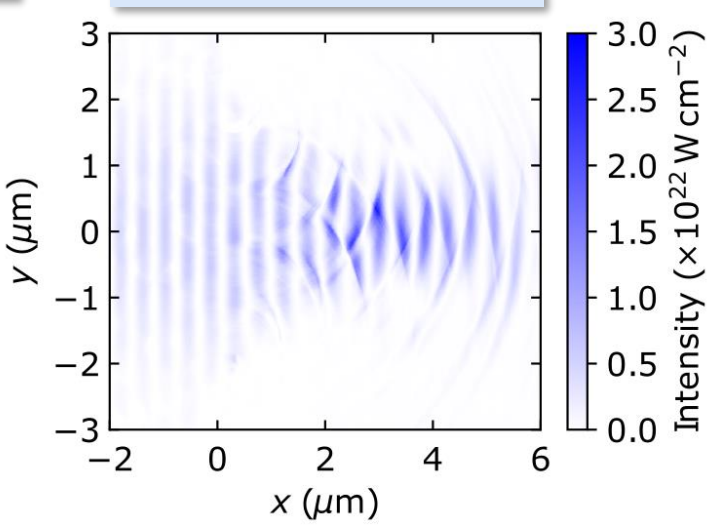
Dense plasma, $n_e > n_c$



Relativistically underdense, $n_e < \gamma_e n_c$

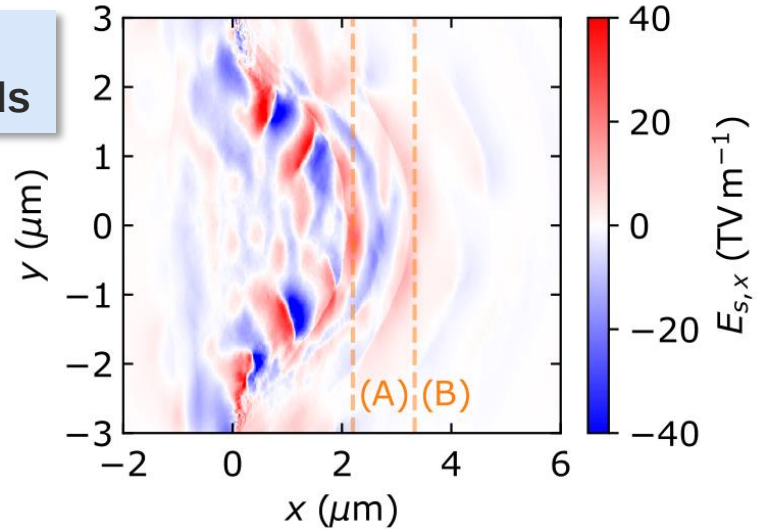


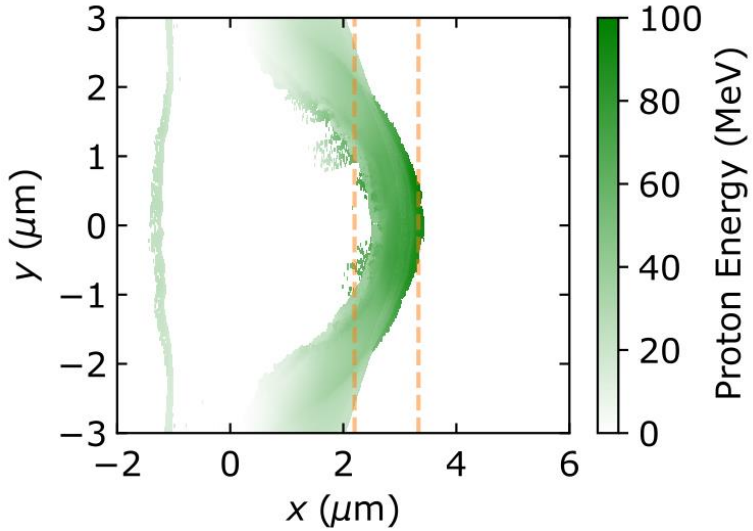
Laser transmission



Laser direction →

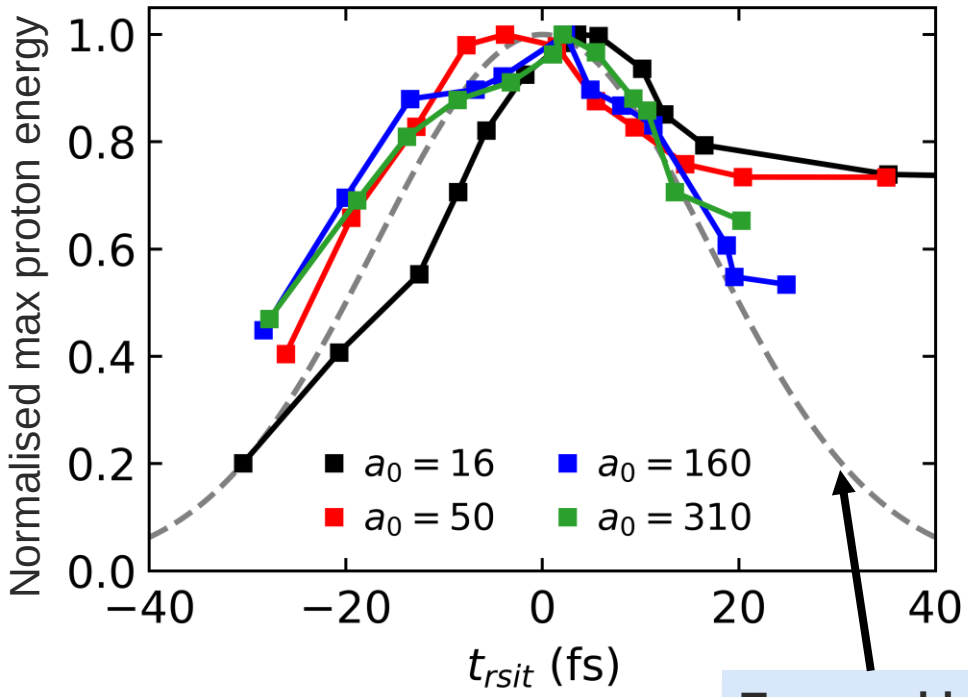
Space charge fields

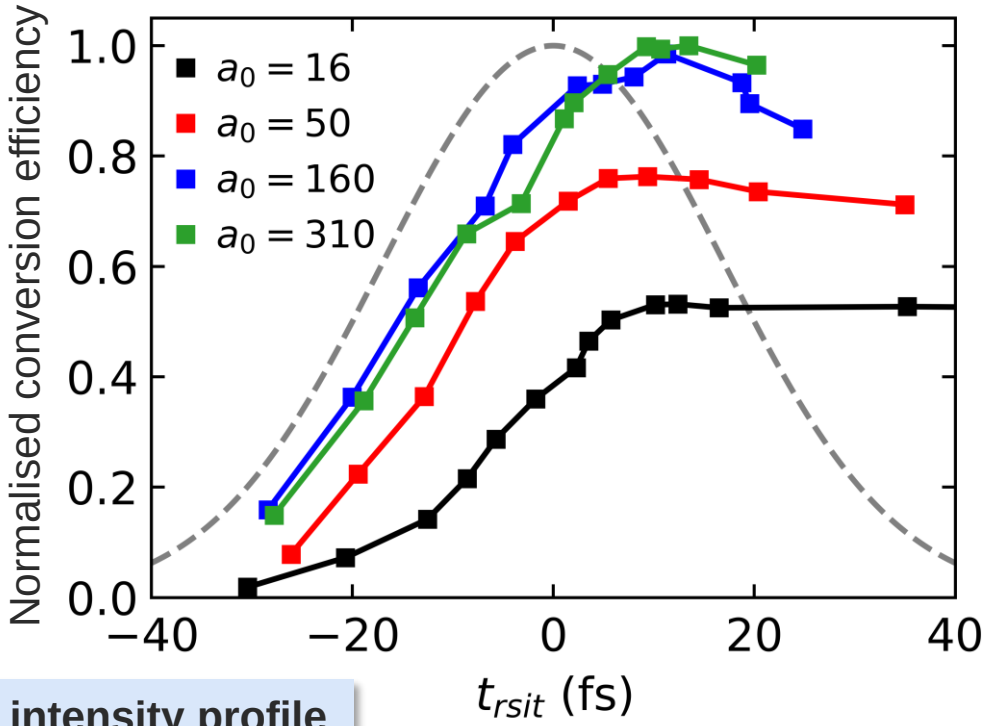




Proton beam

Optimisation of max proton energy with transparency time

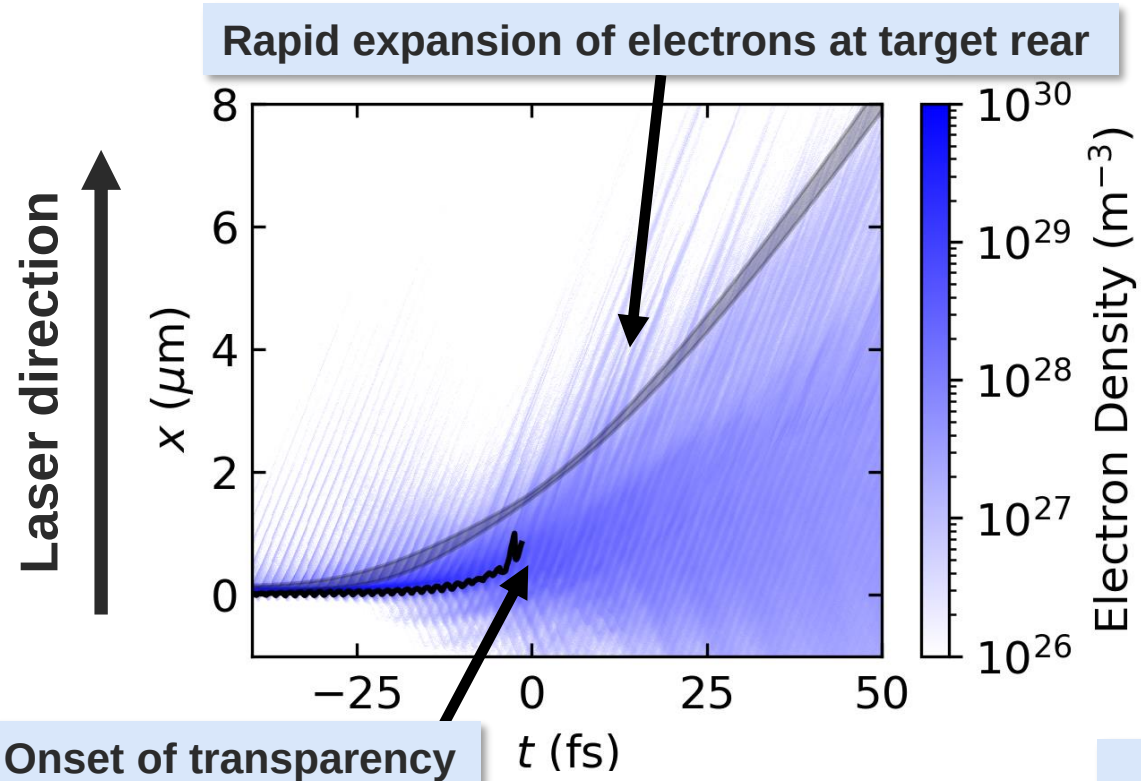


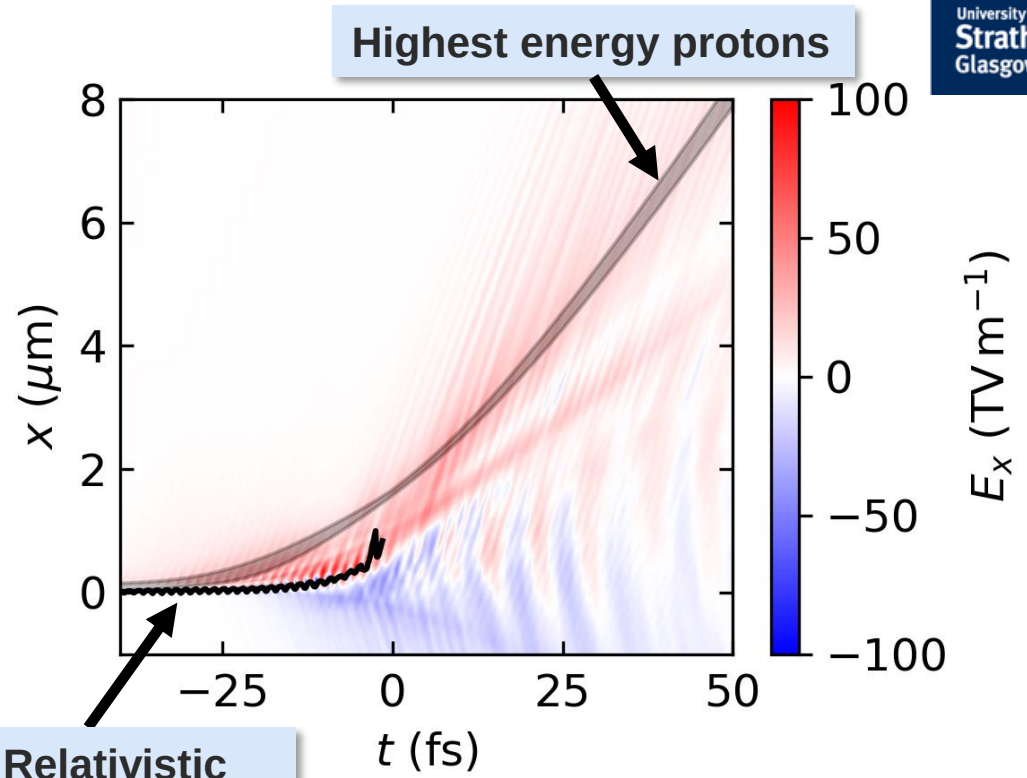


Temporal laser intensity profile

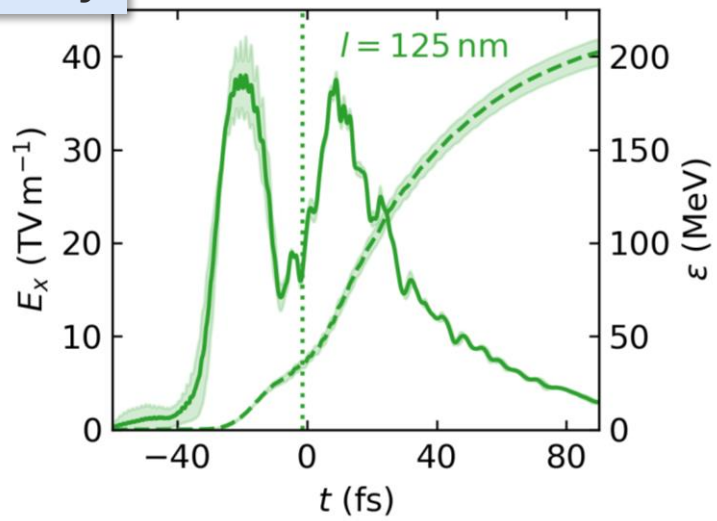
- Transparency time varied by changing target thickness
- Highest proton energies for $t_{rsit} \approx 0$ (onset of transparency to peak of laser pulse) for all intensities considered
- Laser-to-proton energy conversion efficiency highest for transparency ~10 fs after laser peak, and increases with intensity

Optimum case for 5×10^{21} W cm^{-2} ($a_0 = 50$)



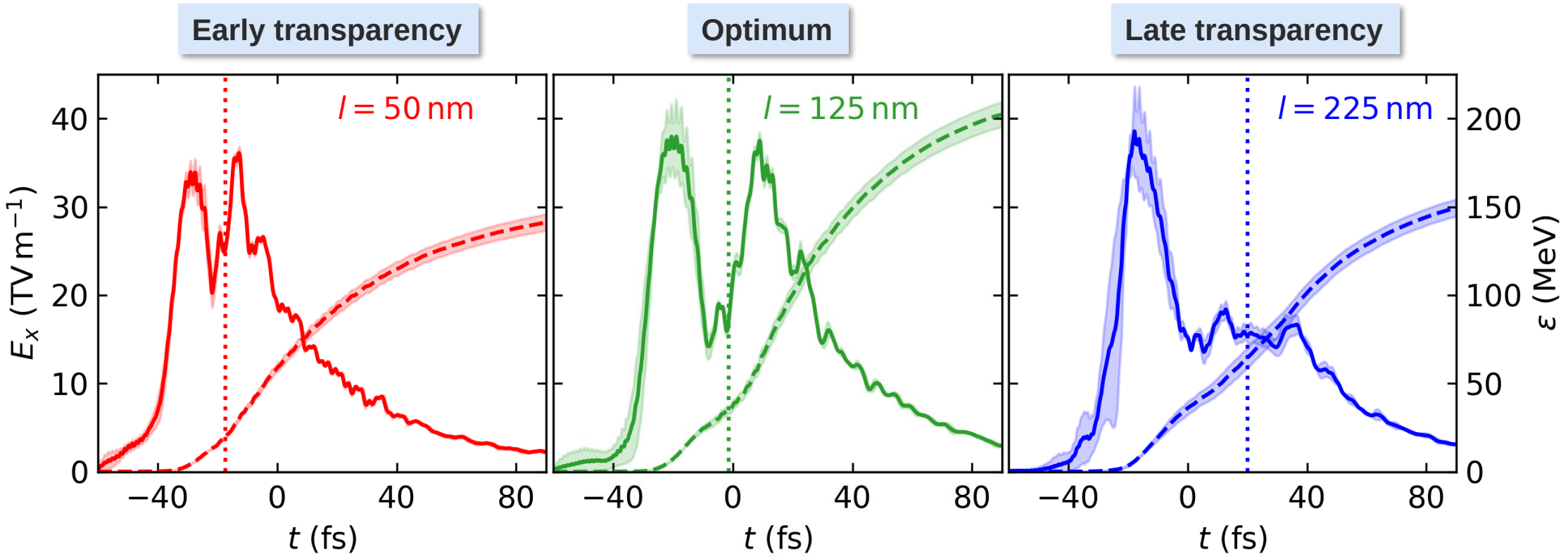


125nm CH target



- Highest energy protons tracked along target normal
- Acceleration dominated by sheath field at target rear
- Blowout of electrons and peak in E_x follows transparency

Comparison to non-optimised conditions

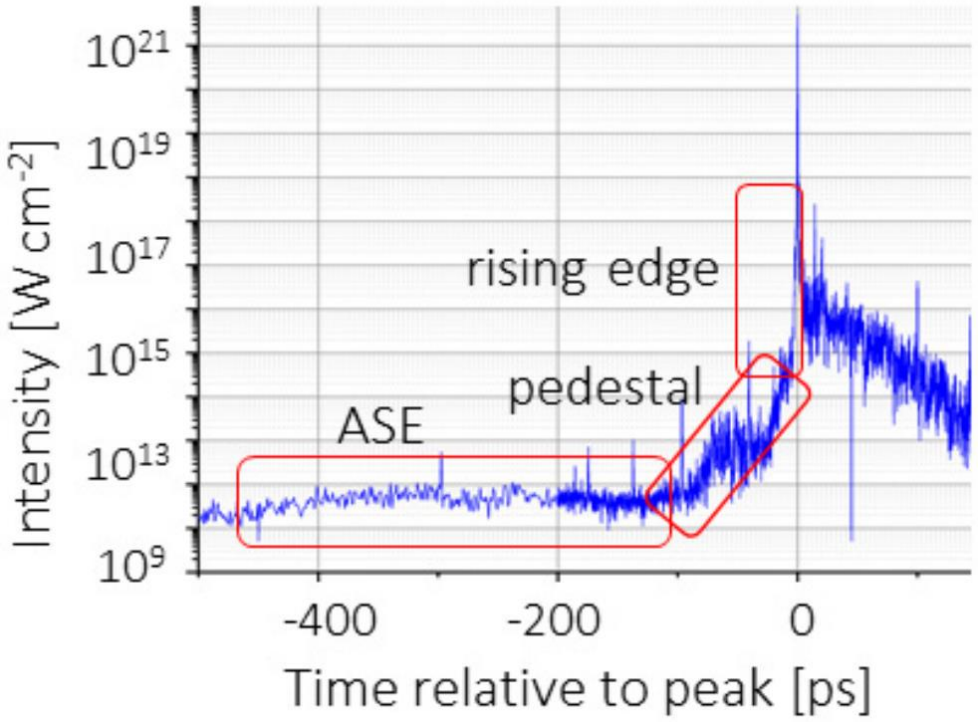


Field strength falls off very quickly

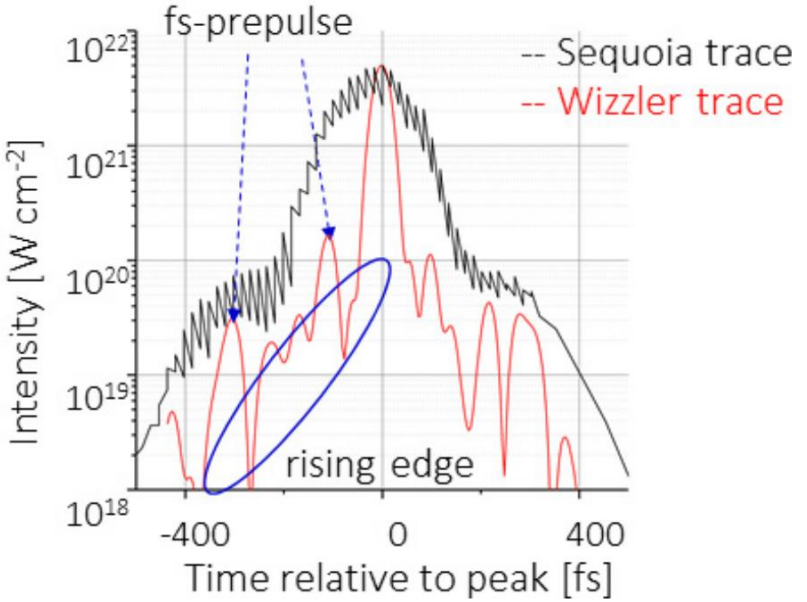
Limited enhancement from transparency

Laser contrast

- **Light arriving before main pulse can pre-expand the target**
- **Needs to be suppressed to avoid destroying ultrathin foils**

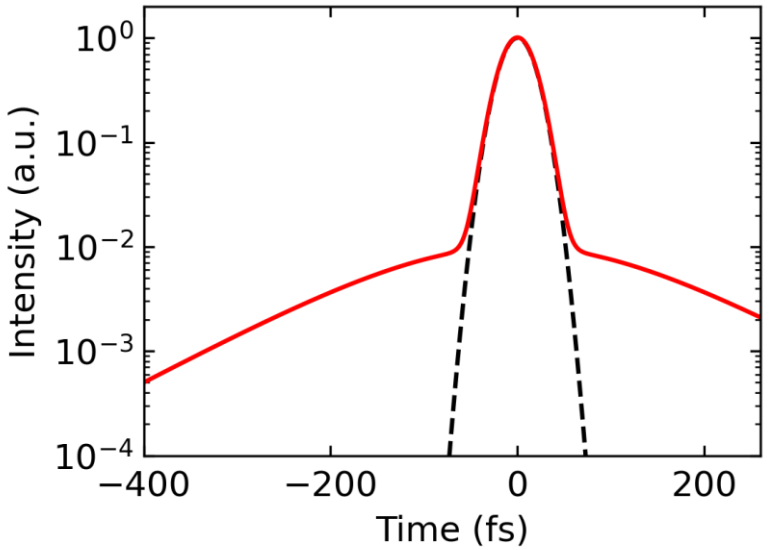


Nishiuchi M, *et al.* 2020 *Phys. Rev. Research* 2, 033081



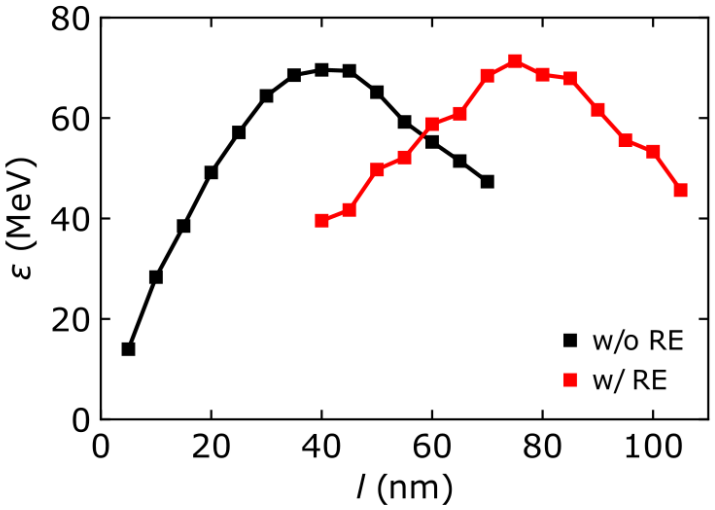
Nishiuchi M, *et al.* 2020 *Phys. Rev. Research* 2, 033081

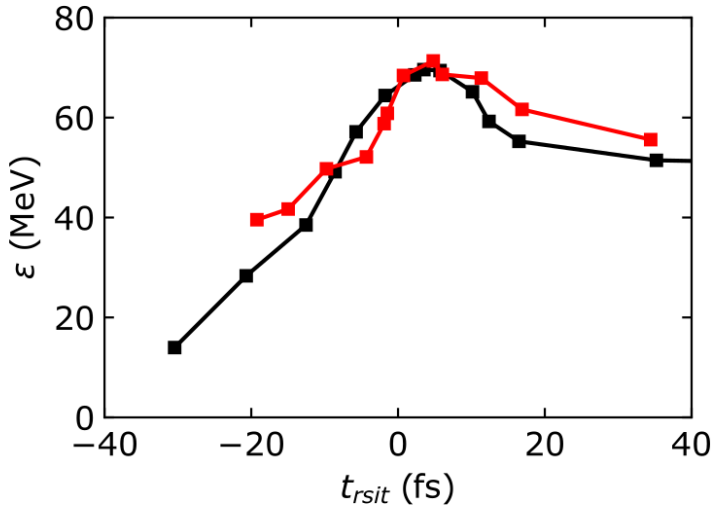
Simulated rising edge profile



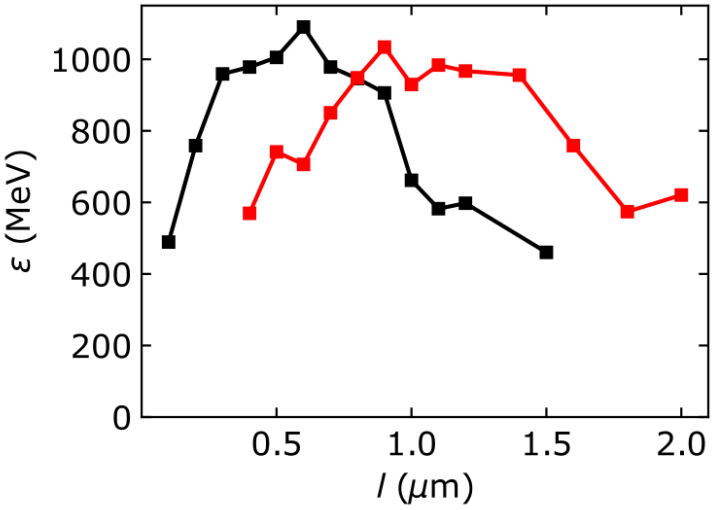
Rising edge contrast

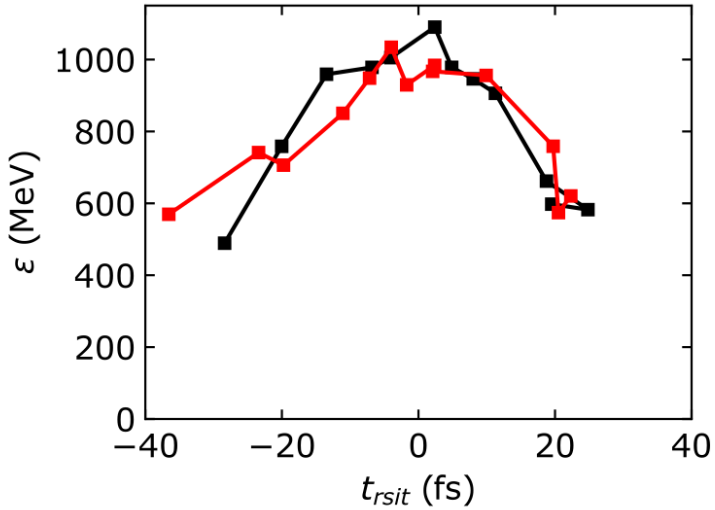
5×10^{20} W cm^{-2}
($a_0 = 16$)





5×10^{22} W cm^{-2}
($a_0 = 160$)





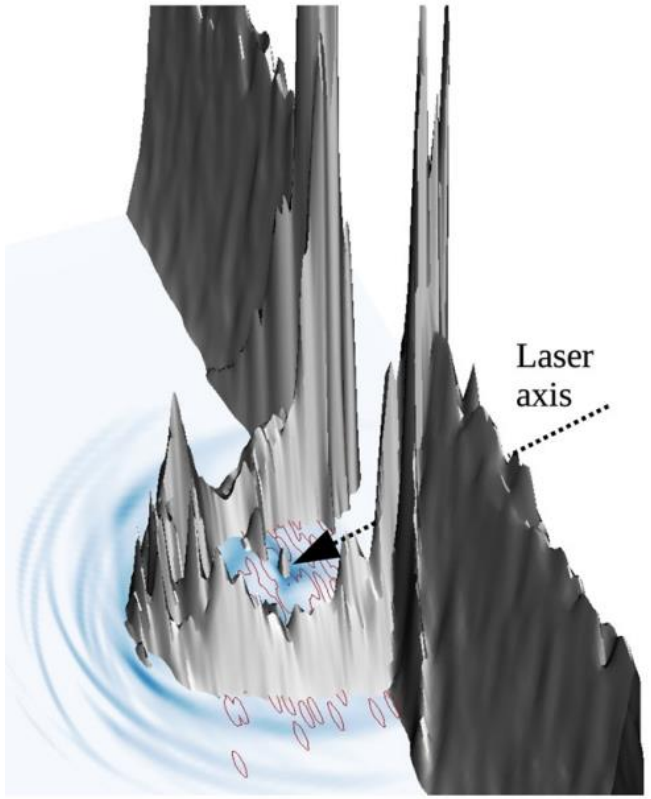
- Increase to optimum target thickness
- Max proton energy does not change

QED effects in laser-solid interactions

- Copious gamma ray production for >10^{23} W cm^{-2}
- Electron-positron pair production important for >10^{24} W cm^{-2}

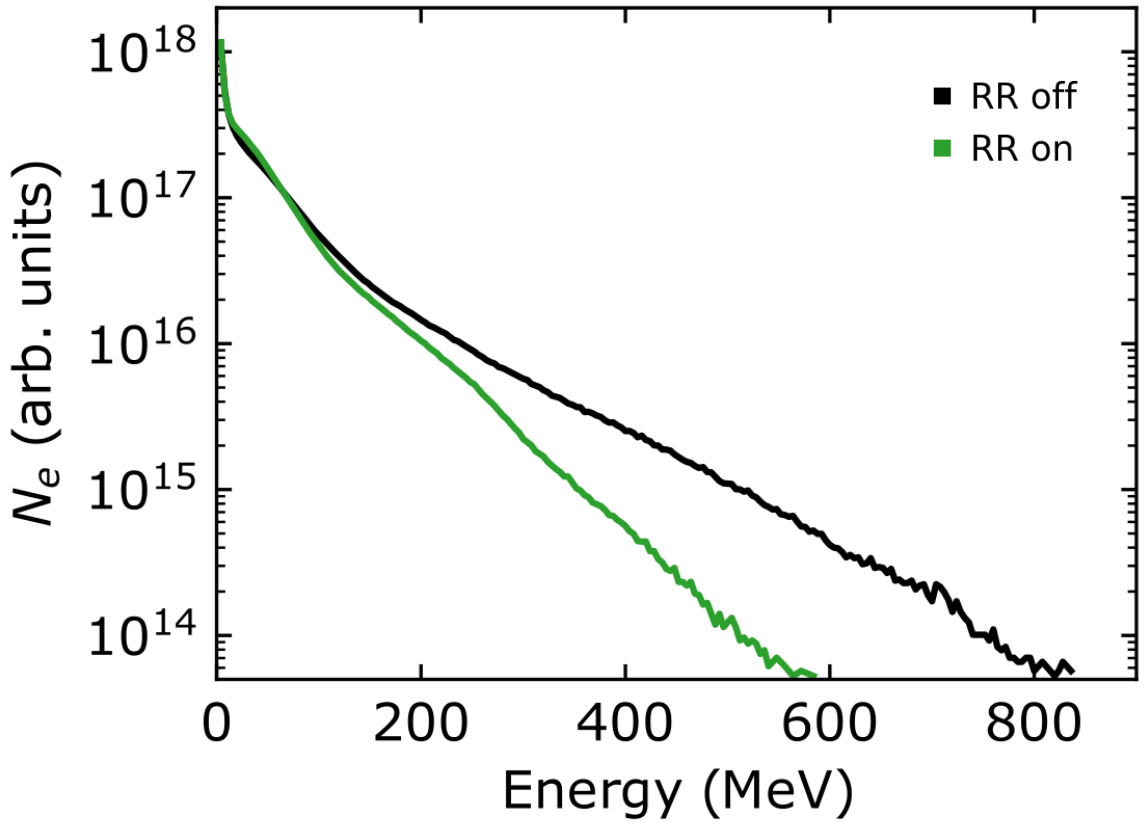
$$e^- + m\gamma_l \rightarrow e^- + \gamma_h$$

- These processes affect the plasma physics



Ridgers C P, *et al.* 2013 *Phys. Plasmas 20*, 056701

Electron spectra at 2×10^{23} W cm^{-2} with and without radiation reaction

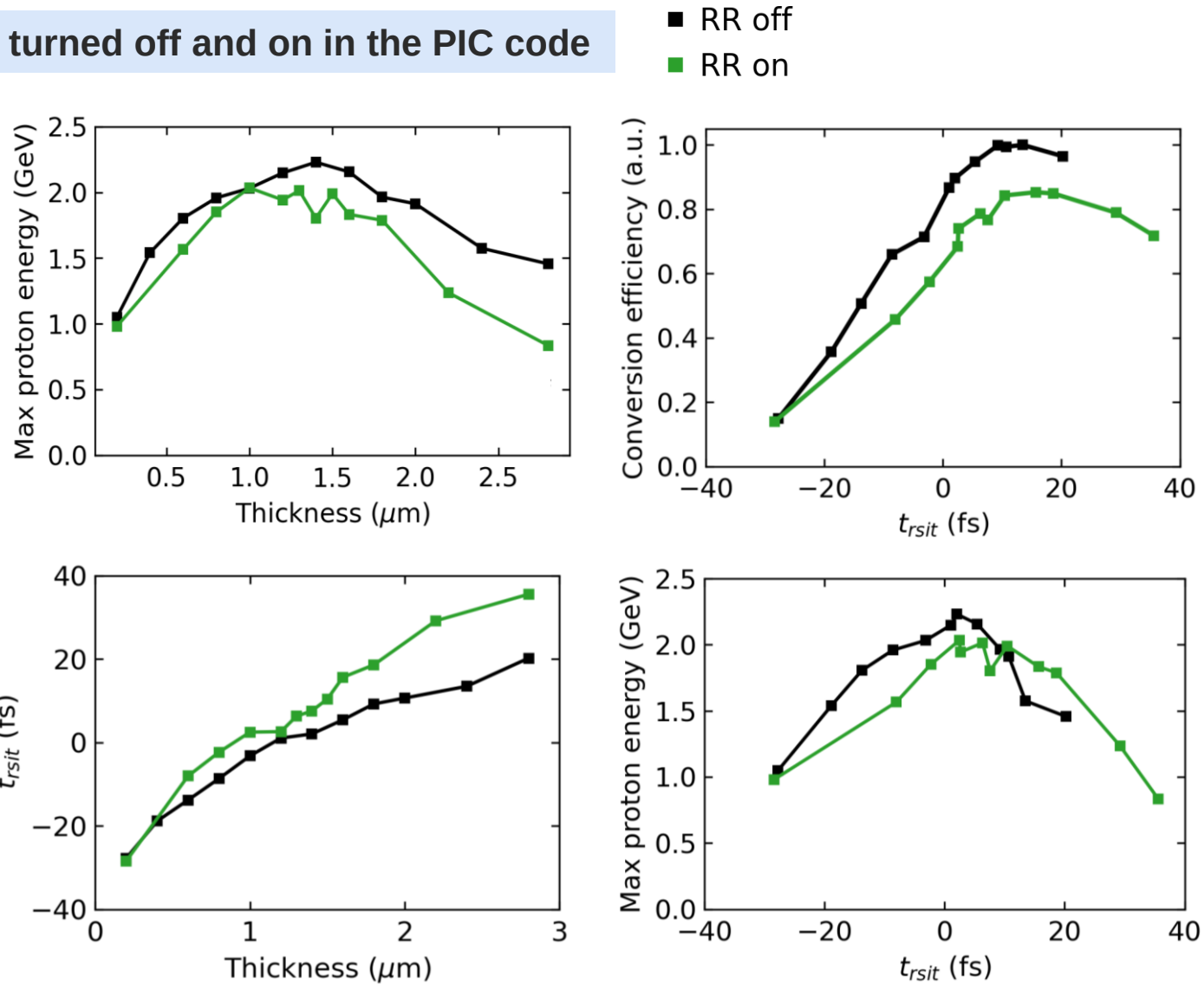


Including radiation reaction (RR)

2×10^{23} W cm^{-2} ($a_0 = 310$)

University of Strathclyde Glasgow

Radiation reaction turned off and on in the PIC code



Lower proton energies

Reduced conversion efficiency

Transparency delayed

Max proton energies still highest for $t_{rsit} \approx 0$

Summary

- Highest proton energies achieved for onset of relativistic transparency to peak of laser pulse for laser intensities from 5×10^{20} W cm^{-2} to 2×10^{23} W cm^{-2}
- Optimum target thickness increases when including laser rising edge but max proton energy at optimum does not change
- Radiation reaction does affect proton acceleration at 2×10^{23} W cm^{-2}: max proton energies reduce, conversion efficiency reduces and relativistic transparency is delayed

Thank you for your attention!

For more information see
J Goodman *et al* 2022 *New J. Phys.* 24 053016

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