Can two ultra-intense laser pulses accelerate protons better than one with the same total energy?

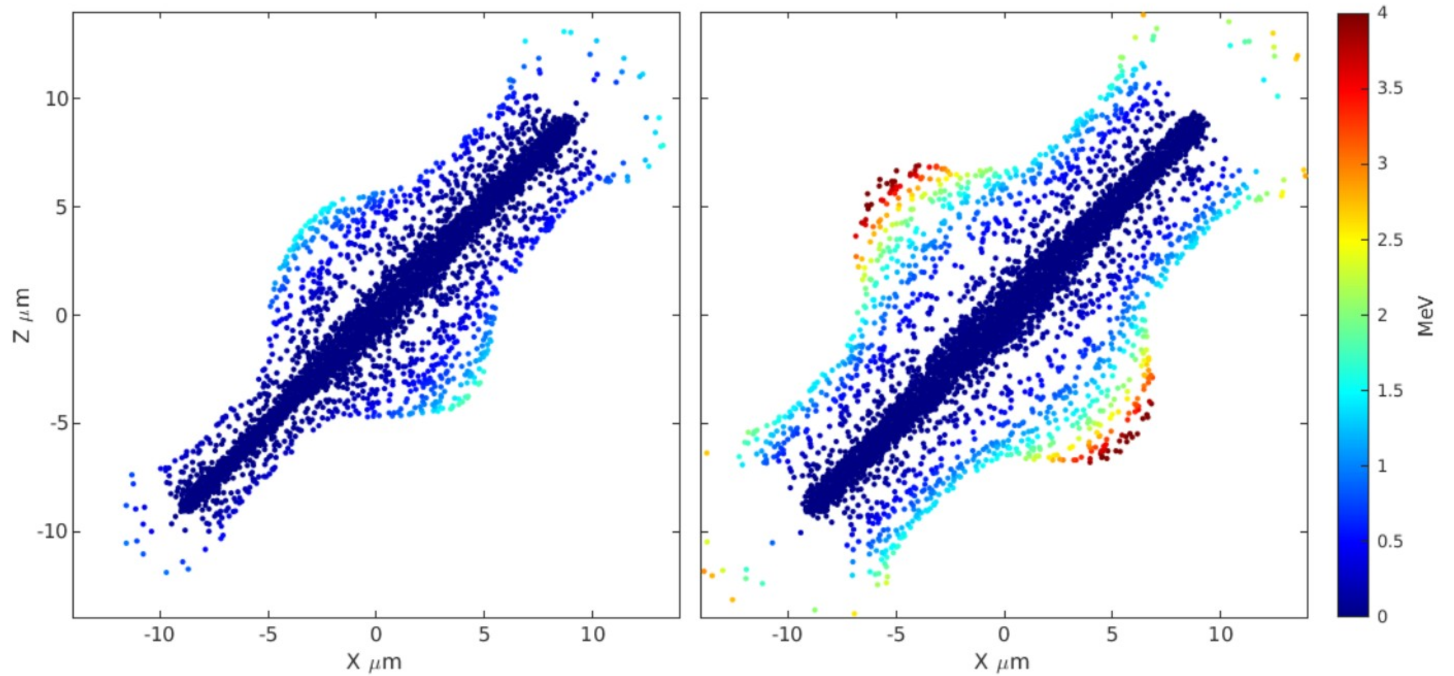

FIG. 4. (left panel) Proton energy 450 fs after pulse for single pulse. (right panel) Proton energy 450 fs after pulse for double pulse.

Chris Orban

Ohio State University (OSU)

PHYSICS

Physics of Plasmas ARTICLE scitation.org/journal/php

Particle-in-cell modeling of a potential demonstration experiment for double pulse enhanced target normal sheath acceleration

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Nashad Rahman,[1] Joseph R. Smith,[1,2,3] Gregory K. Ngirmang,[4,5] and Chris Orban[1,a)]

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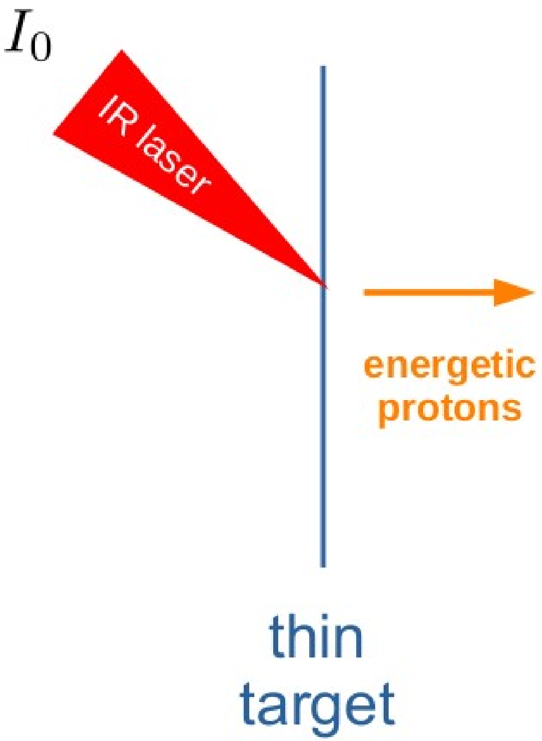
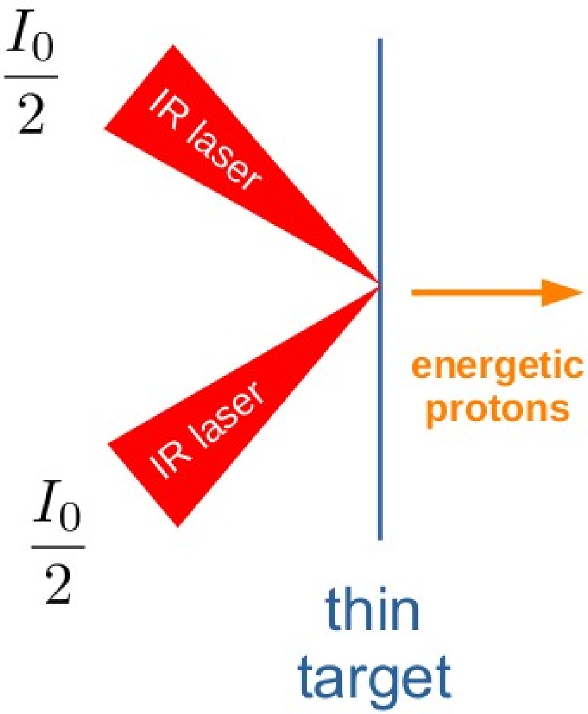
ABSTRACT

Ultra-intense lasers are a promising source of energetic ions for various applications. An interesting approach described in Ferri *et al.* [Commun. Phys. **2**, 40 (2019)] argues from particle-in-cell simulations that using two laser pulses of half energy (half intensity) arriving with close to 45° angle of incidence is significantly more effective at accelerating ions than one pulse at full energy (full intensity). For a variety of reasons, at the time of this writing, there has not yet been a true experimental confirmation of this enhancement. In this paper, we perform 2D particle-in-cell simulations to examine if a millijoule class, 5×10^{18} W cm^{-2} peak intensity laser system could be used for such a demonstration experiment. Laser systems in this class can operate at a kHz rate which should be helpful for addressing some of the challenges of performing this experiment. Despite investigating a 3.5 times lower intensity than Ferri *et al.* [Commun. Phys. **2**, 40 (2019)] did, we find that the double pulse approach enhances the peak proton energy and the energy conversion to protons by a factor of about three compared to a single laser pulse with the same total laser energy. We also comment on the nature of the enhancement and describe simulations that examine how the enhancement may depend on the spatial or temporal alignment of the two pulses.

TNSA



Double Pulse Enhanced TNSA



(not my idea!)

Previous studies

ARTICLE

https://doi.org/10.1038/s42005-019-0140-x OPEN

Enhanced target normal sheath acceleration using colliding laser pulses

J. Ferri[1], E. Siminos[2] & T. Fülöp[1]

Laser-solid interaction can lead to the acceleration of protons to tens of MeV. Here, we show that a strong enhancement of this acceleration can be achieved by splitting the laser pulse to two parts of equal energy and opposite incidence angles. Through the use of two- and three-dimensional Particle-In-Cell simulations, we find that the multi-pulse interaction leads to a standing wave pattern at the front side of the target, with an enhanced electric field and a substantial modification of the hot electron generation process. This in turn leads to significant improvement of the proton spectra, with an almost doubling of the accelerated proton energy and five-fold enhancement of the number of protons. The proposed scheme is robust with respect to incidence angles for the laser pulses, providing flexibility to the scheme, which should facilitate its experimental implementation.

(Ferri et al 2019)

(Ferri et al 2020)

Effects of oblique incidence and colliding pulses on laser-driven proton acceleration from relativistically transparent ultrathin targets

J. Ferri[1,†], E. Siminos[2], L. Gremillet[3,4] and T. Fülöp[1]

[1]Department of Physics, Chalmers University of Technology, SE-41296 Göteborg, Sweden

[2]Department of Physics, University of Gothenburg, SE-41296 Göteborg, Sweden

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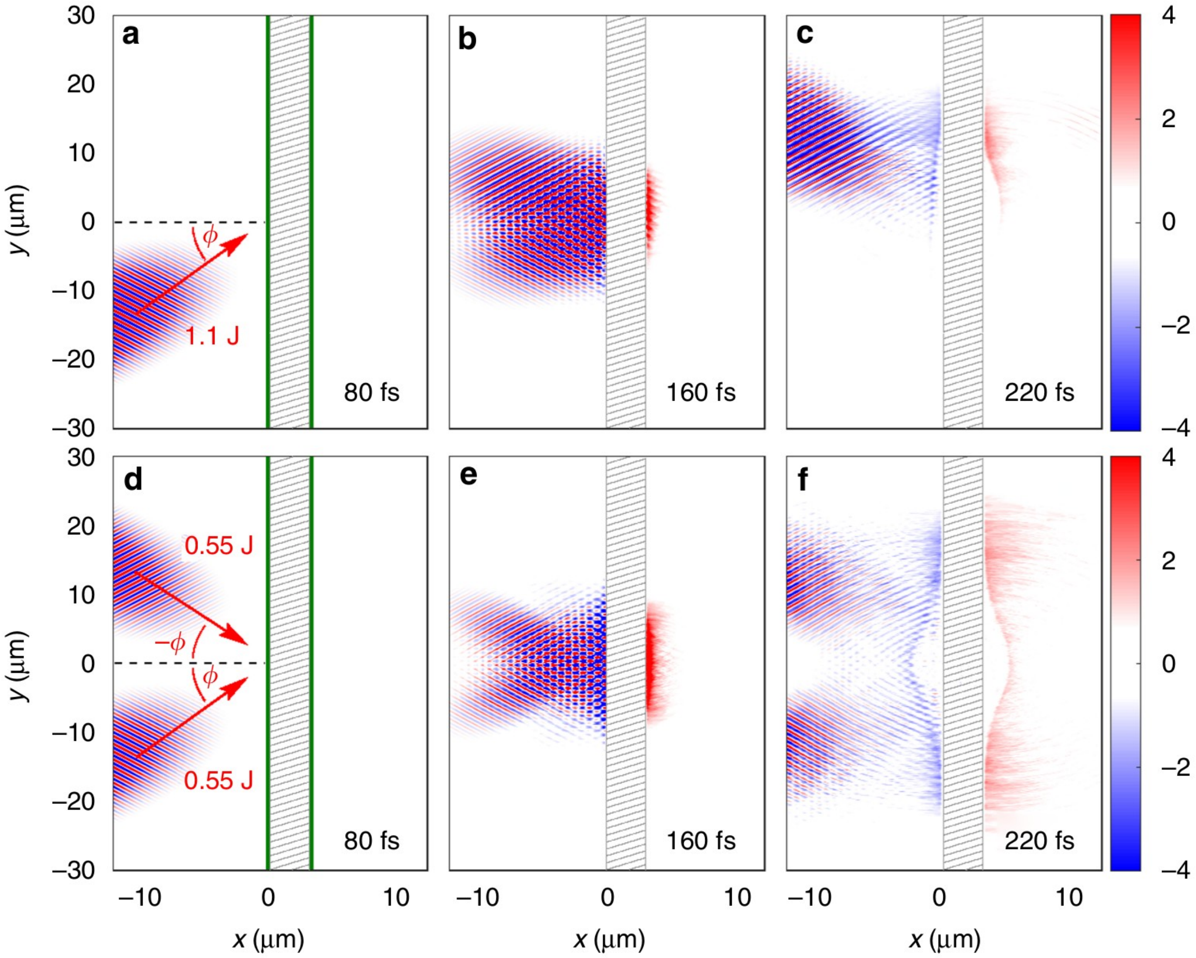
(Received 1 April 2020; revised 13 July 2020; accepted 14 July 2020)

The use of ultrathin solid foils offers optimal conditions for accelerating protons to high energies from laser–matter interactions. When the target is thin enough that relativistic self-induced transparency sets in, all of the target electrons get heated to high energies by the laser, which maximizes the accelerating electric field and therefore the final ion energy. In this work, we first investigate how ion acceleration by ultraintense femtosecond laser pulses in transparent CH_2 solid foils is modified when turning from normal to oblique (45°) incidence. Due to stronger electron heating, we find that higher proton energies can be obtained at oblique incidence but in thinner optimum targets. We then show that proton acceleration can be further improved by splitting the laser pulse into two half-pulses focused at opposite incidence angles. An increase by ∼30 % in the maximum proton energy and by a factor of ∼4 in the high-energy proton charge is reported compared to the reference case of a single normally incident pulse.

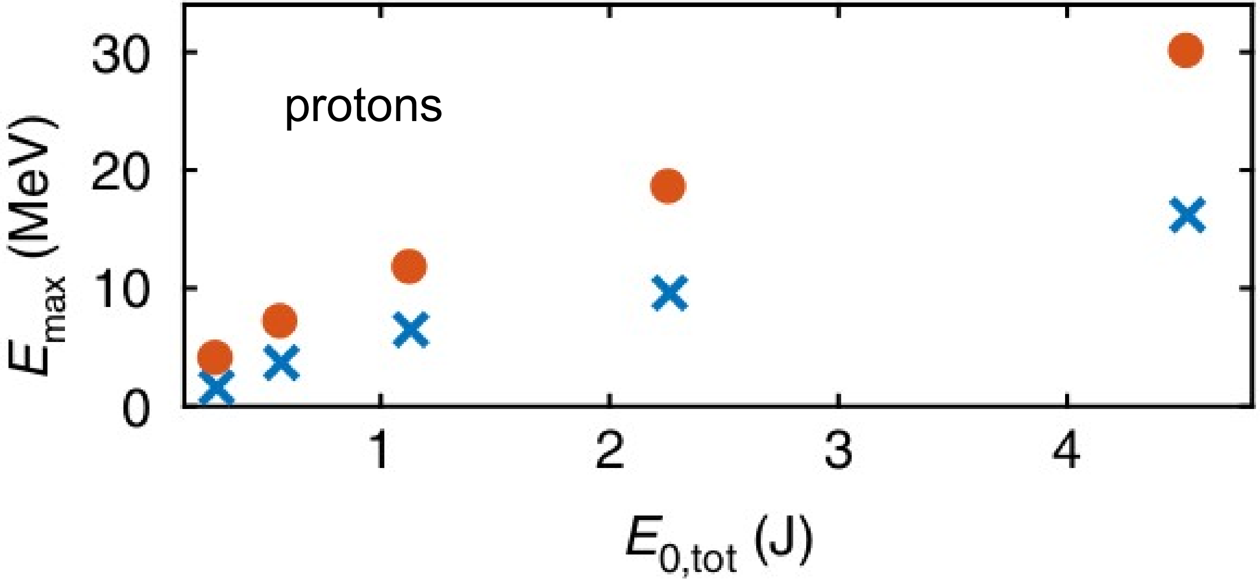


ARTICLE

https://doi.org/10.1038/s42005-019-0140-x OPEN

Enhanced target normal sheath acceleration using colliding laser pulses

J. Ferri[1], E. Siminos[2] & T. Fülöp[1]



ARTICLE
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Enhanced target normal sheath acceleration using colliding laser pulses

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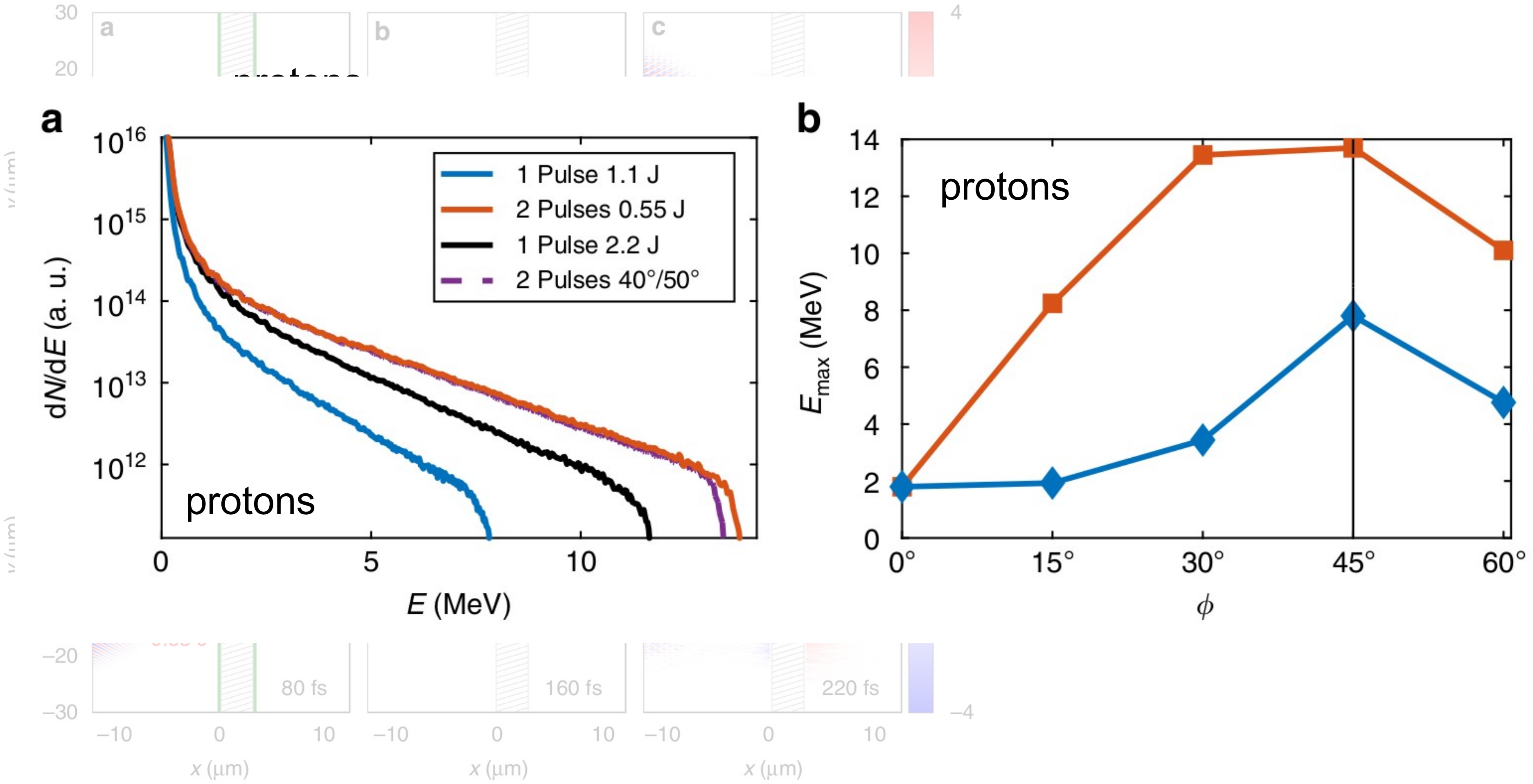

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OPEN

Enhanced target normal sheath acceleration using colliding laser pulses

J. Ferri[1], E. Siminos[2] & T. Fülöp[1]

nature COMMUNICATIONS

Enhancing laser beam performance by interfering intense laser beamlets

A. Morace[1], N. Iwata[1], Y. Sentoku[1], K. Mima[1], Y. Arikawa[1], A. Yogo[1], A. Andreev[2,3], S. Tosaki[1], X. Vaisseau[1], Y. Abe[1], S. Kojima[1], S. Sakata[1], M. Hata[1], S. Lee[1], K. Matsuo[1], N. Kamitsukasa[1], T. Norimatsu[1], J. Kawanaka[1], S. Tokita[1], N. Miyanaga[1], H. Shiraga[1], Y. Sakawa[1], M. Nakai[1], H. Nishimura[1], H. Azechi[1], S. Fujioka[1] & R. Kodama[1]

Increasing the laser energy absorption into energetic particle beams represents a long-standing quest in intense laser-plasma physics. During the interaction with matter, part of the laser energy is converted into relativistic electron beams, which are the origin of secondary sources of energetic ions, γ-rays and neutrons. Here we experimentally demonstrate that using multiple coherent laser beamlets spatially and temporally overlapped, thus producing an interference pattern in the laser focus, significantly improves the laser energy conversion efficiency into hot electrons, compared to one beam with the same energy and nominal intensity as the four beamlets combined. Two-dimensional particle-in-cell simulations support the experimental results, suggesting that beamlet interference pattern induces a periodical shaping of the critical density, ultimately playing a key-role in enhancing the laser-to-electron energy conversion efficiency. This method is rather insensitive to laser pulse contrast and duration, making this approach robust and suitable to many existing facilities.

Total energy: 270 J
Pulse duration: 1.5 ps

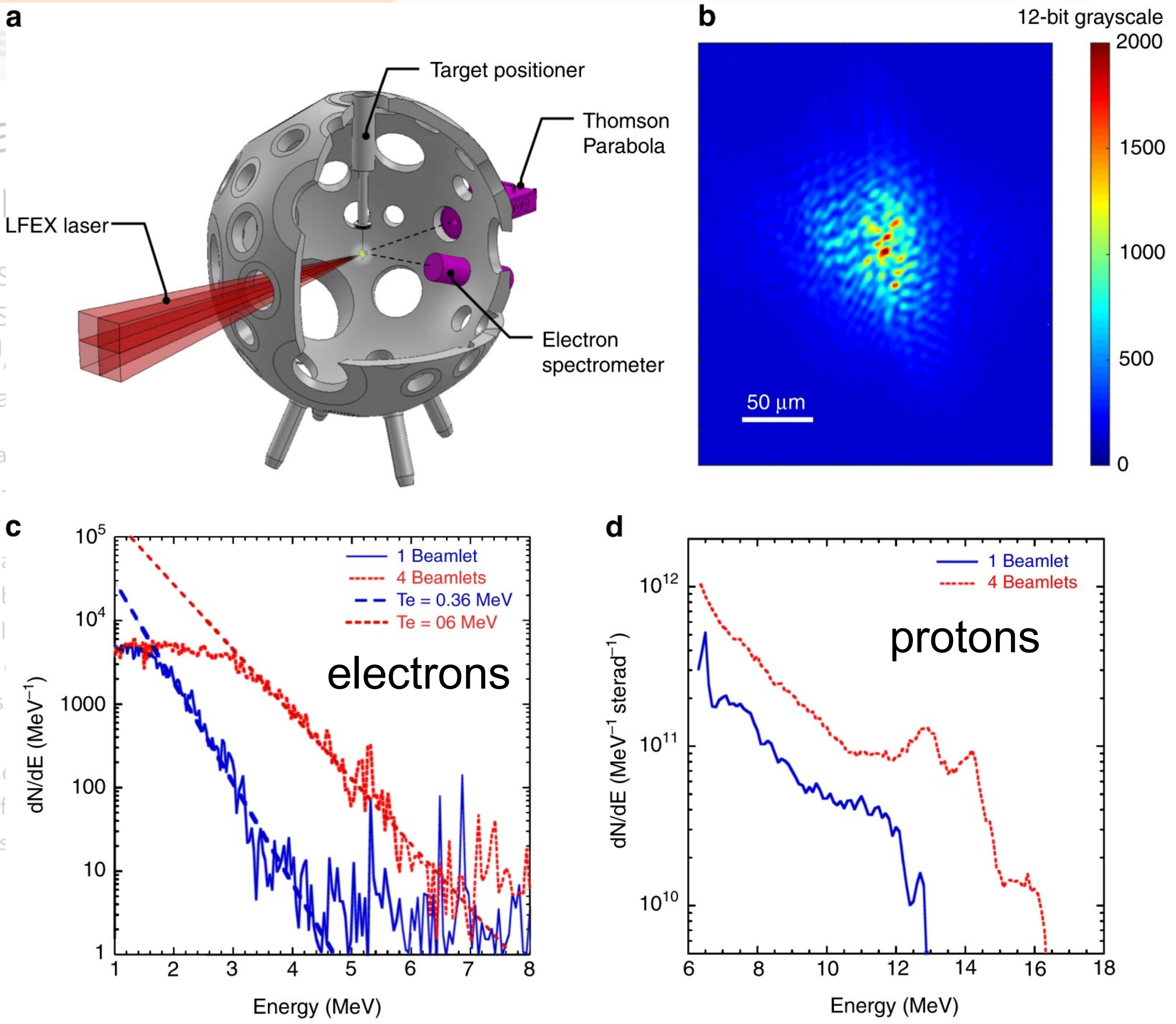
(Morace et al 2019)

nature COMMUNICATIONS

Enhancing la
intense laser

A. Morace[1], N. Iwata[1], Y. S
Y. Abe [1], S. Kojima [1], S
J. Kawanaka [1], S. Tokita[1],
S. Fujioka [1] & R. Kodama

Increasing the laser energy a
standing quest in intense laser-
laser energy is converted into
sources of energetic ions, γ-ra
using multiple coherent laser b
an interference pattern in the l
efficiency into hot electrons,
intensity as the four beamlets
port the experimental results,
odical shaping of the critical de
electron energy conversion eff
trast and duration, making this



(Morace et al 2019)

IOP Publishing | International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion 60 (2020) 076019 (9pp) https://doi.org/10.1088/1741-4326/ab91f9

Energetic deuterium-ion beams and neutron source driven by multiple-laser interaction with pitcher-catcher target

X.R. Jiang[1], F.Q. Shao[1], D.B. Zou[1,2], M.Y. Yu[2], L.X. Hu[1], X.Y. Guo[2], T.W. Huang[2], H. Zhang[2], S.Z Wu[2], G.B. Zhang[1], T.P. Yu[1], Y. Yin[1], H.B. Zhuo[2] and C.T. Zhou[2,3]

[1] Department of Physics, National University of Defense Technology, Changsha 410073, China
[2] Center for Advanced Material Diagnostic Technology, College of Engineering Physics, Shenzhen Technology University, Shenzhen 518118, China
[3] College of Applied Technology, Shenzhen University, Shenzhen 518060, China

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Published 16 June 2020

Abstract
Multiple lasers interacting with a deuterated (D) pitcher-catcher target and neutron generation are investigated using two-dimensional hybrid particle-in-cell and Monte Carlo simulations. It is found that when multiple laser pulses are focused on the front surface of the pitcher layer, D^+ ion acceleration by target normal sheath acceleration (TNSA) is enhanced by the interfering overlapped light fields and the resulting periodic target-surface structure. With three laser pulses each of 4.5×10^{19} W cm^{-2} intensity, 33 fs duration and ~160 mJ energy, focusing at suitable angles on the pitcher layer, one can obtain 15 MeV D^+ ions and ~25% laser-to-D^+ ions energy conversion efficiency. As the resulting high-energy-density D^+ ions bombard the catcher layer, D-D fusion reactions are triggered. About 3.6×10^7 neutrons can be produced, with the maximum neutron production rate as high as 3.1×10^{36} m^{-3}s^{-1}, almost an order of magnitude higher than that from a single laser of the same total energy.

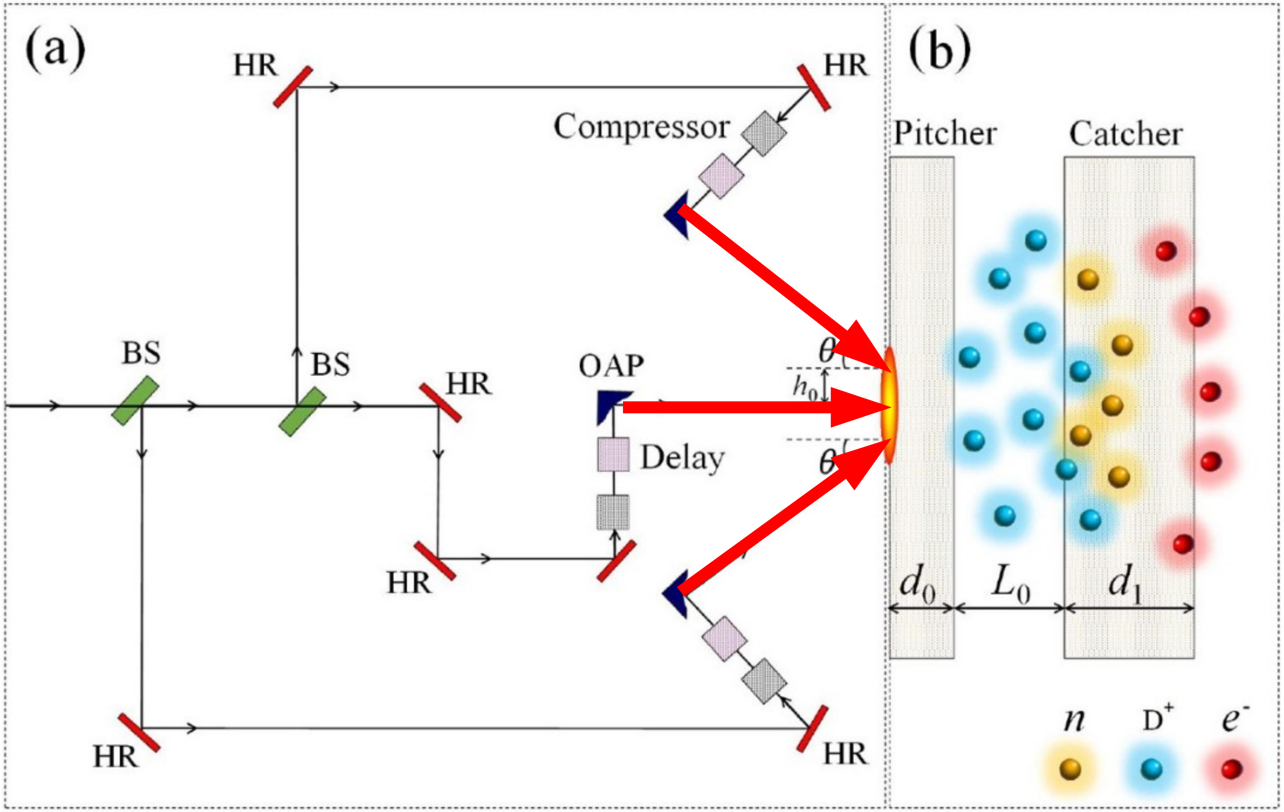
Note:
This is a simulation study

IOP Publishing | International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion 60 (2020) 076019 (9pp) https://doi.org/10.1088/1741-4326/ab91f9

Energetic deuterium-ion beams and neutron source driven by

Three Laser Pulses!

interaction with



X.R. Jiang[1], F.Q. Shao[1], D.B. Zou
H. Zhang[2], S.Z Wu[2], G.B. Zhang[1],

[1] Department of Physics, National University of
[2] Center for Advanced Material Diagnostic Tech
Technology University, Shenzhen 518118, Chin
[3] College of Applied Technology, Shenzhen Un

E-mail: debinzou@nudt.edu.cn and zcangtao@

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Abstract

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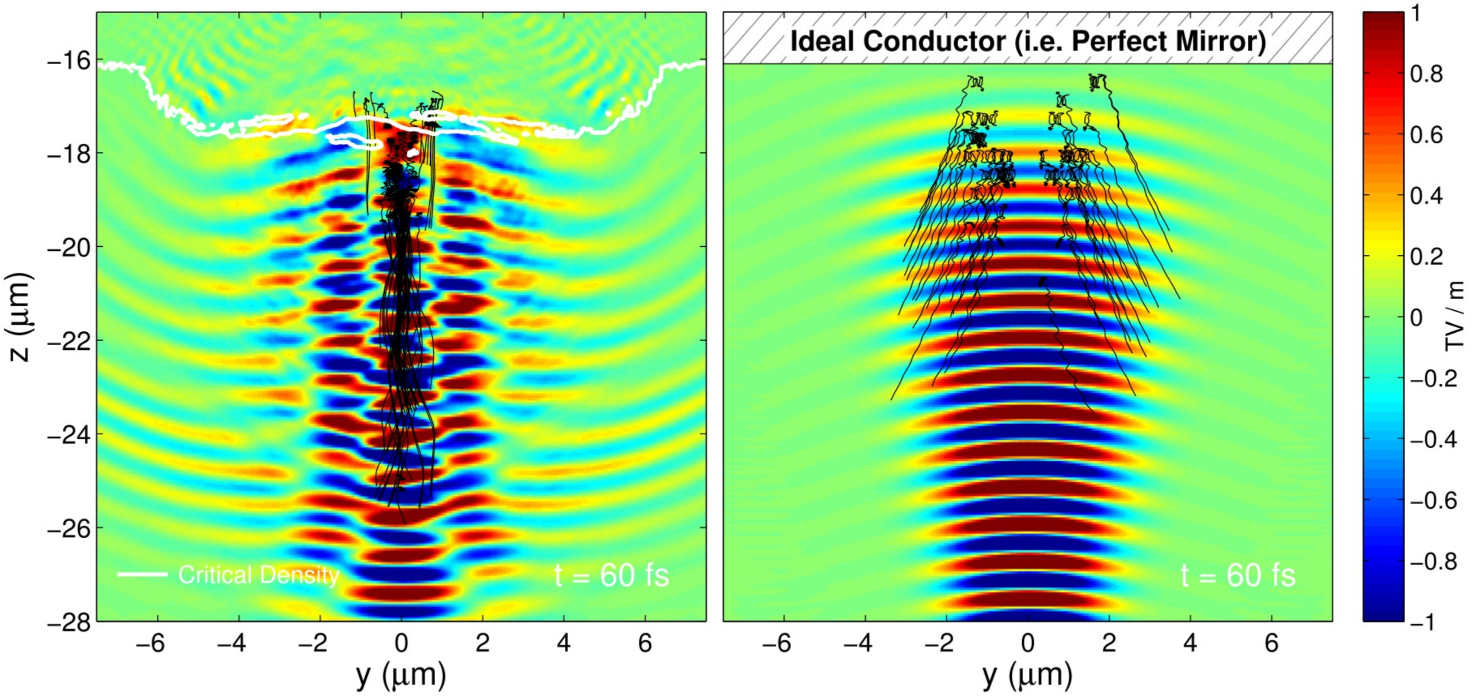
maximum neutron production rate as high as 3.1×10^{36} m^{-3}s^{-1}, almost an order of magnitude
higher than that from a single laser of the same total energy.

The Literature

- Mostly simulation studies
- Enhancements of ***both*** peak proton energy and numbers of protons
- One experiment (LFEX)
  - Angle was small, timescale was picosecond
  - Authors argue that the enhancement relates to hole boring of beamlets
- **No experimental study with short pulse (<< ps) and large angle**
- Aside: Some similarities to Raymond et al 2018 (UMich)

My interest / expertise

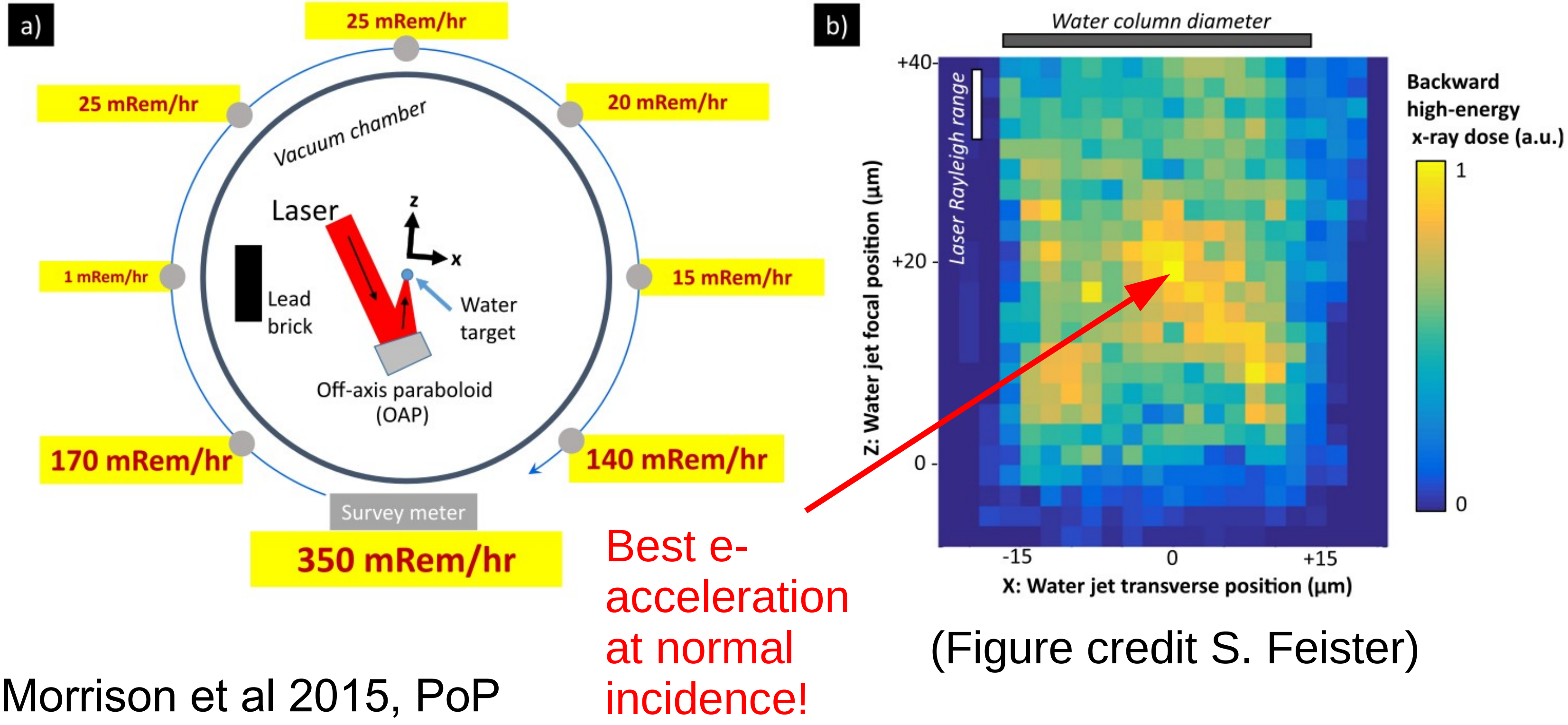
Much of my prior research has involved constructive interference of laser fields (esp. normal incidence)



Orban et al 2015, PoP

My interest / expertise

Much of my prior research has involved constructive interference of laser fields (esp. normal incidence)



Morrison et al 2015, PoP

(Figure credit S. Feister)

My interest / expertise

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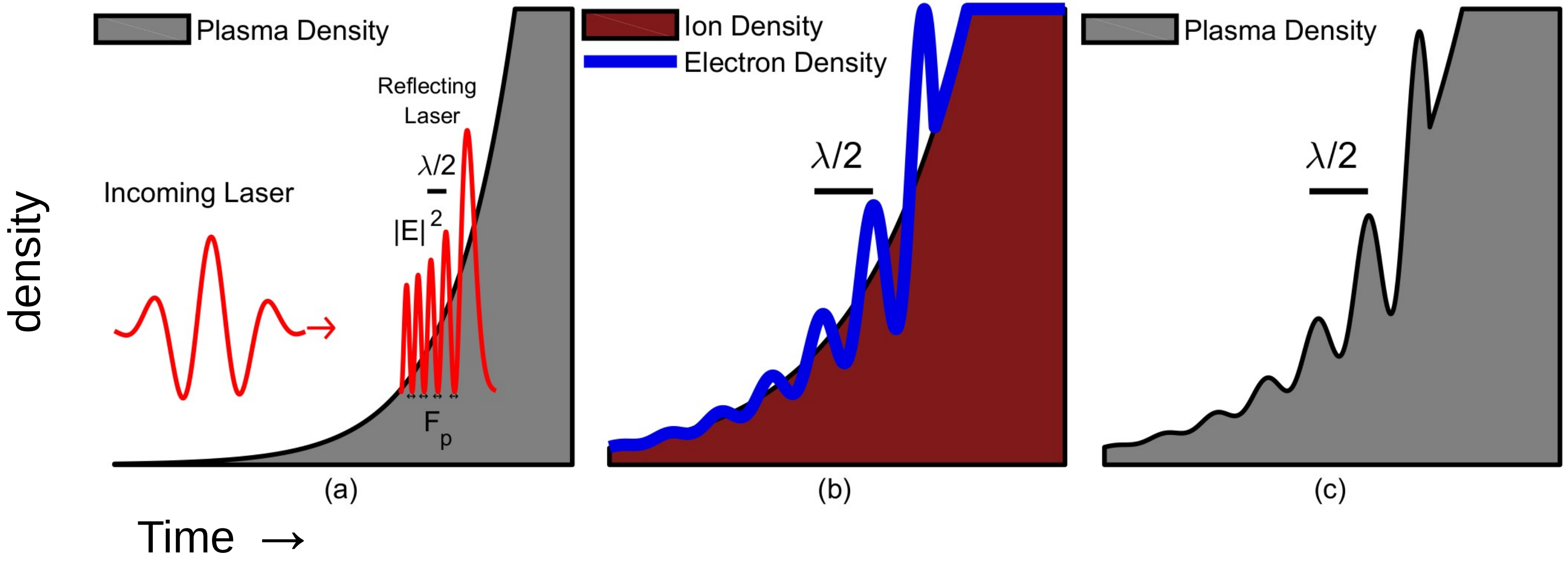

Smith & Orban et al 2019, PoP

My interest / expertise

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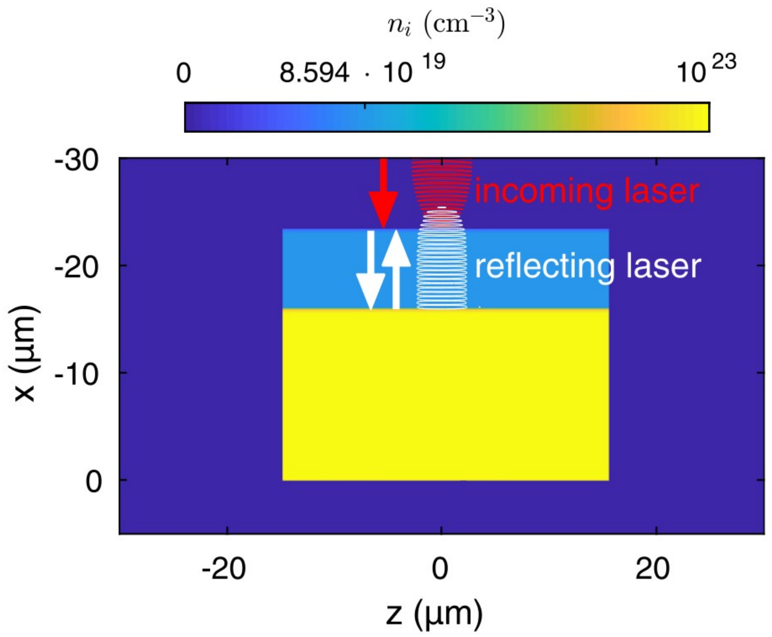

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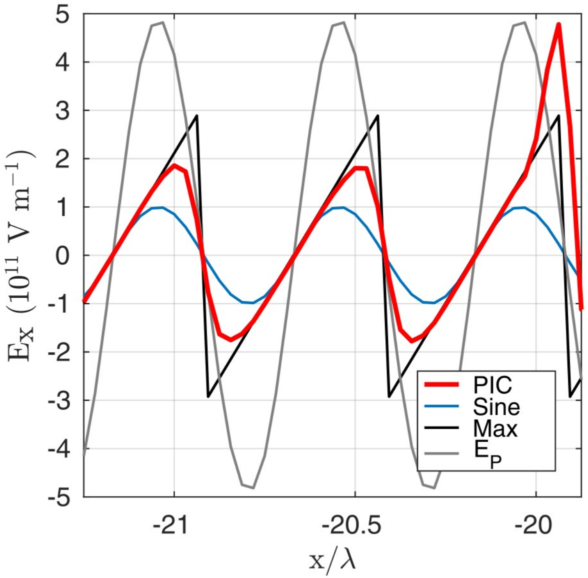
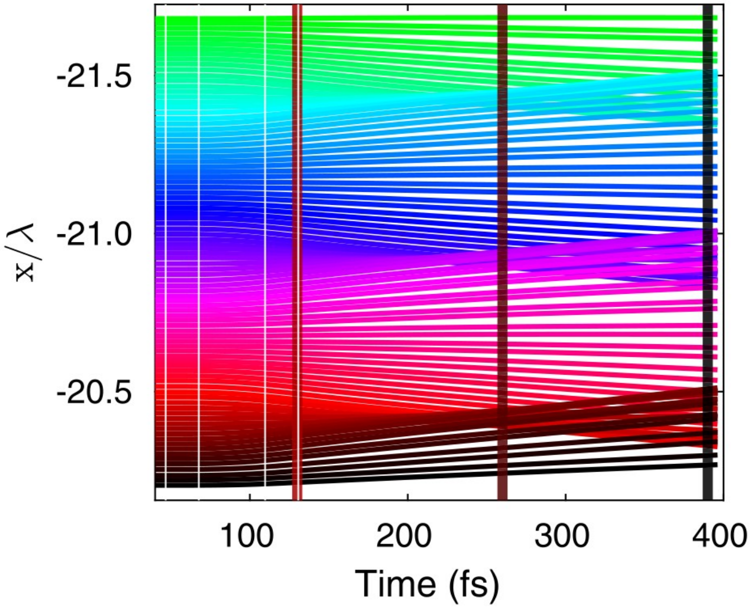
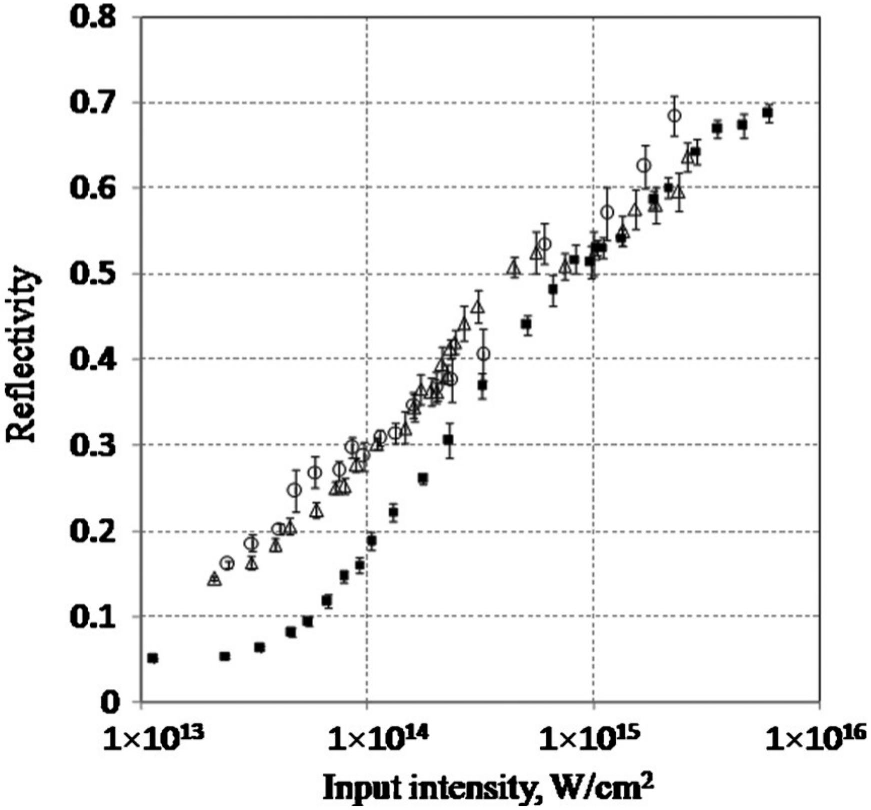


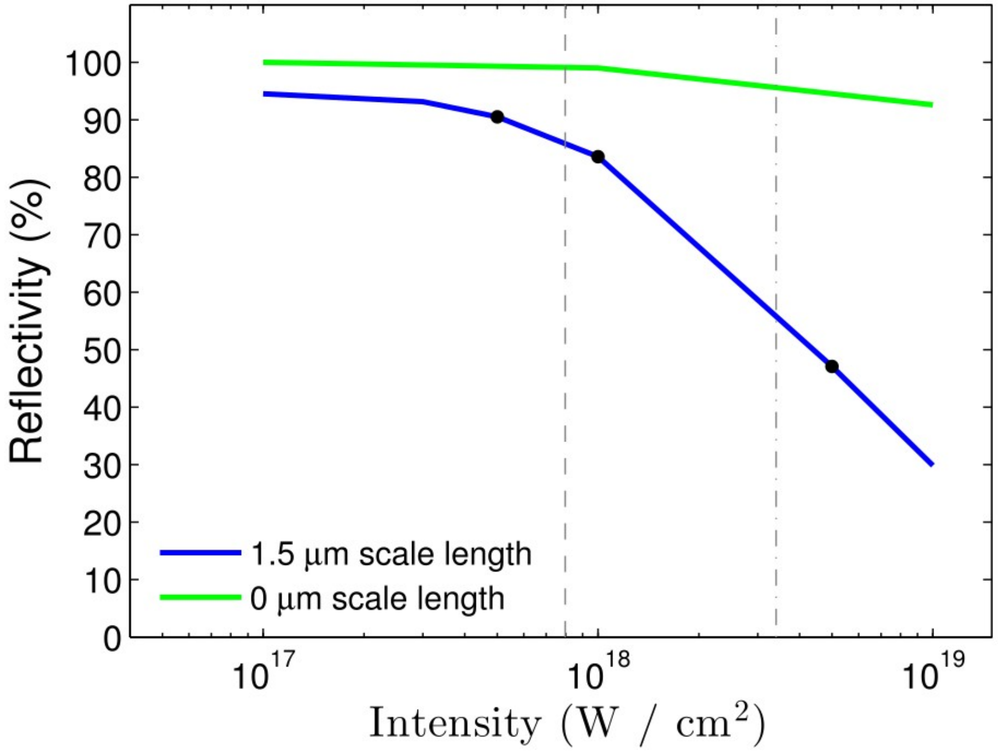


Smith & Orban et al 2019, PoP

Reflectivity matters!



(from Panaseko et al 2010)



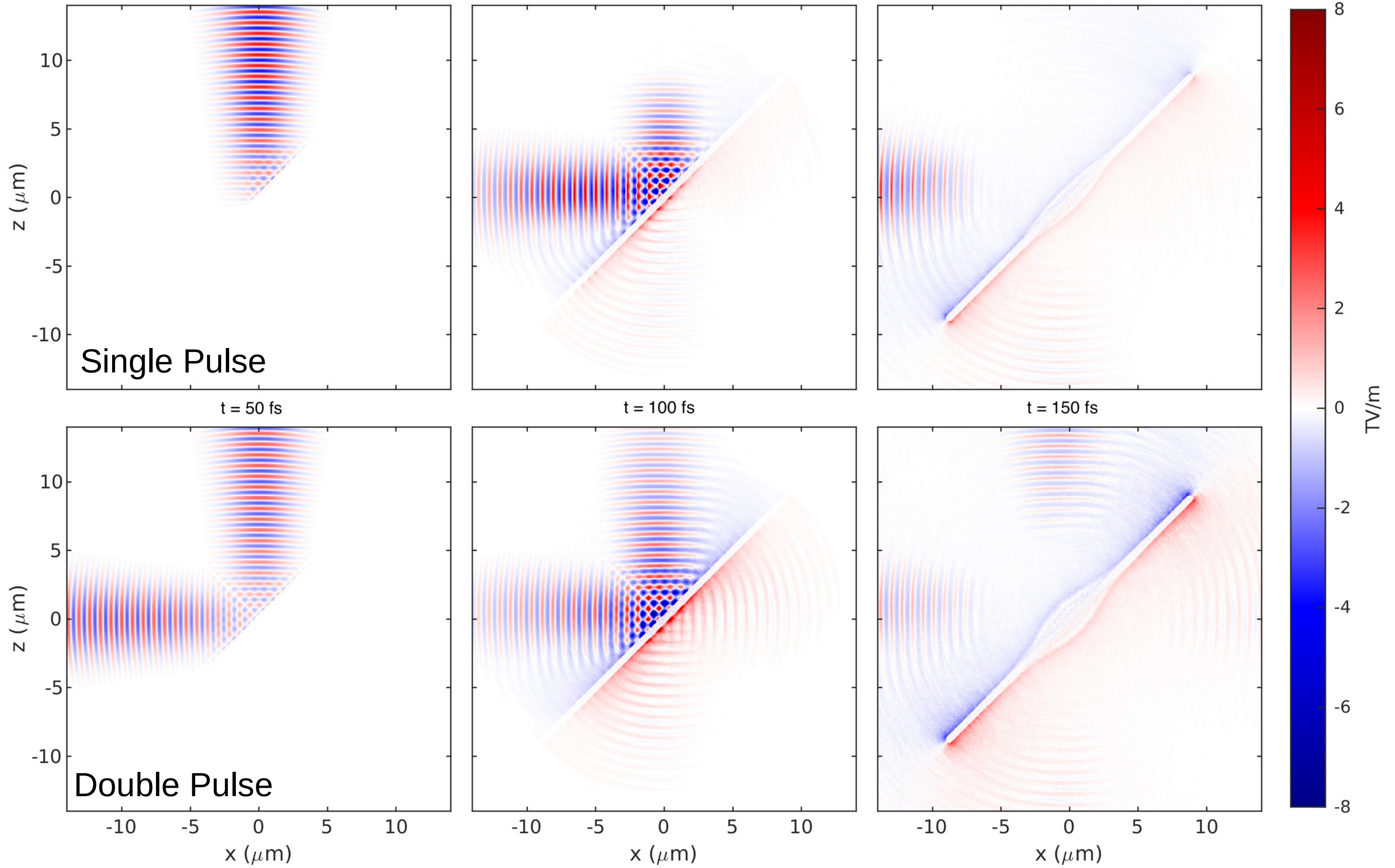
(from Orban et al 2015)

Questions in Rahman et al 2021

- What is the absorption?
  - Conversion efficiency from laser to electrons
- What is the energy transfer to protons?
  - Conversion efficiency from electrons to protons
- Does this work at lower intensities than Ferri et al have considered?
  - Lower intensity experiments are easier to perform!

2D3v PIC simulation results from Rahman et al 2021

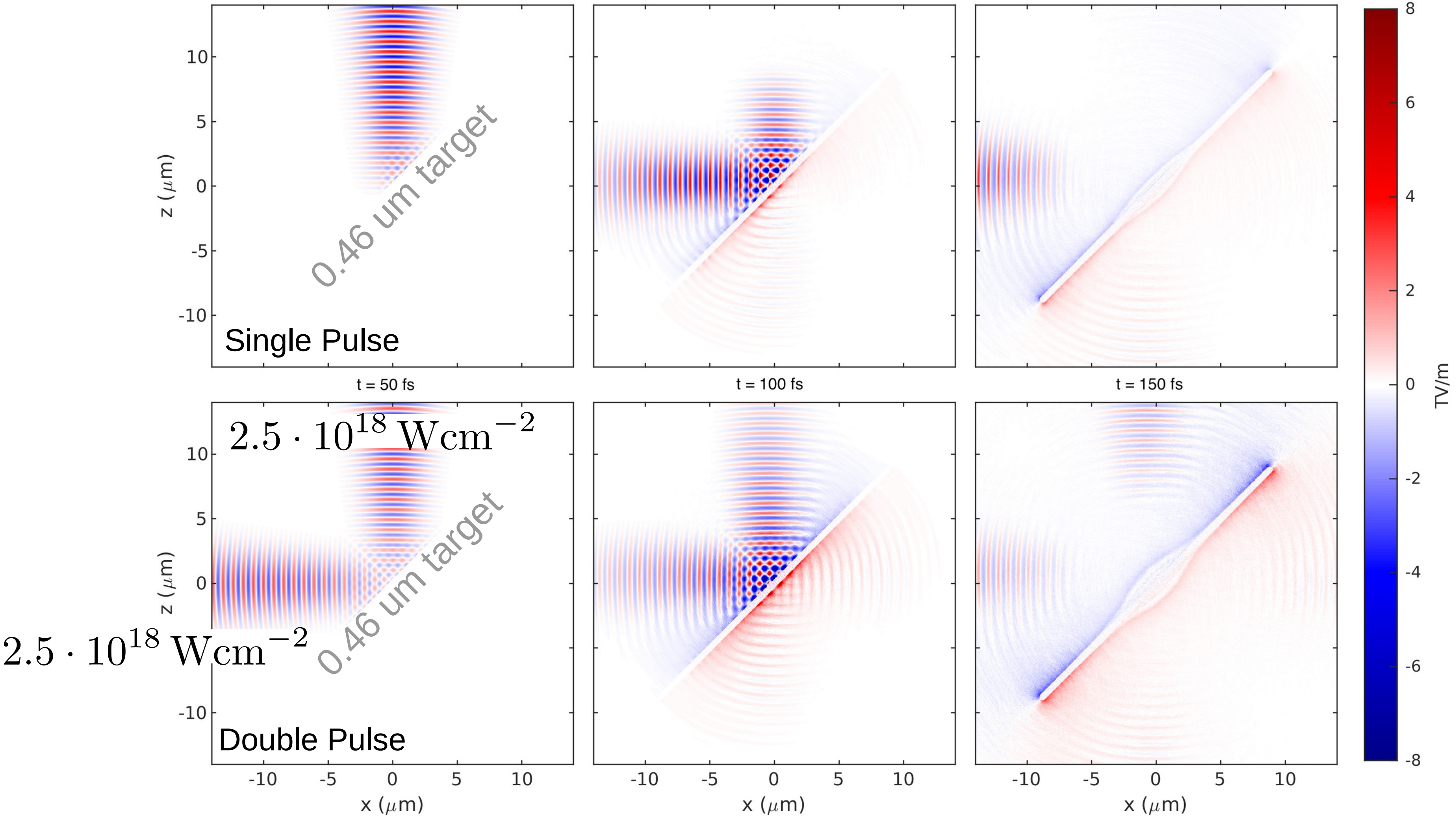
Electric Fields



2D3v PIC simulation results from Rahman et al 2021

Electric Fields

$5 \cdot 10^{18}\ \mathrm{Wcm}^{-2}$



2D3v PIC simulation results from Rahman et al 2021

Position vs Proton Energy

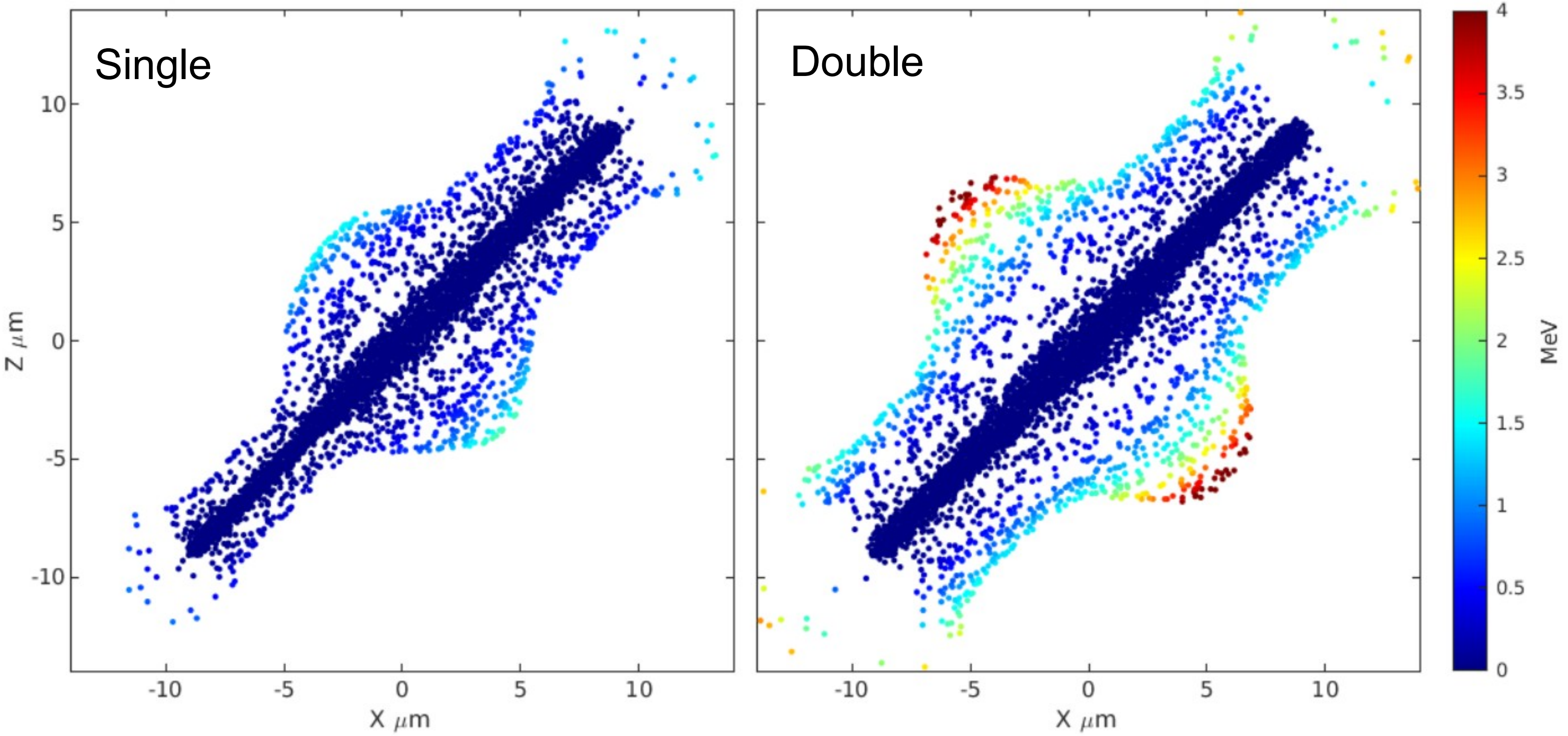
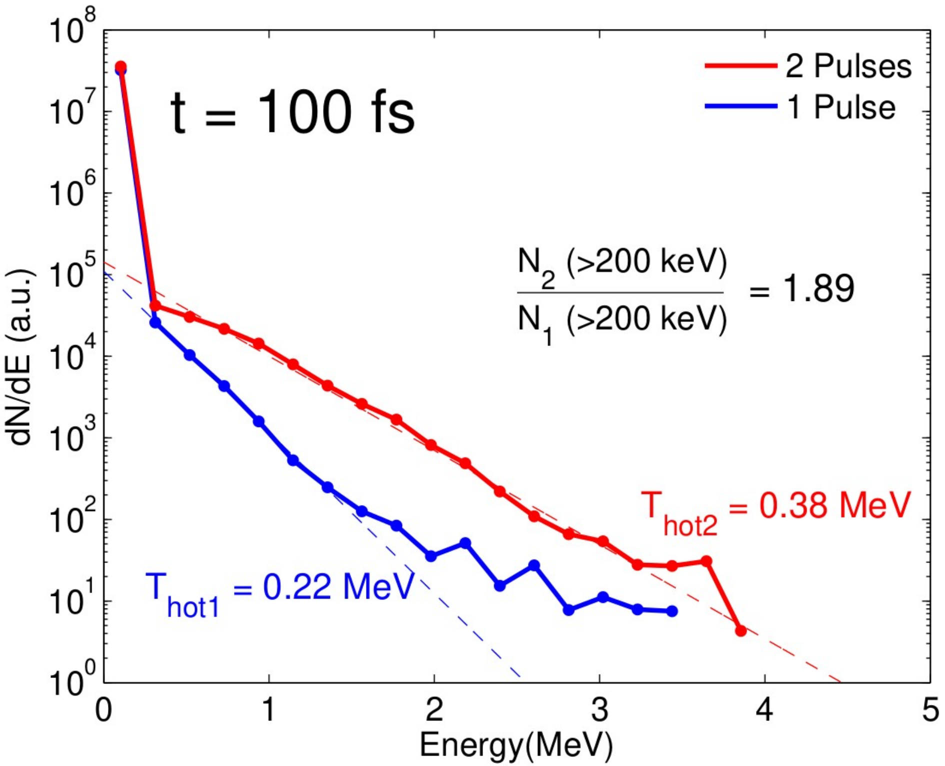


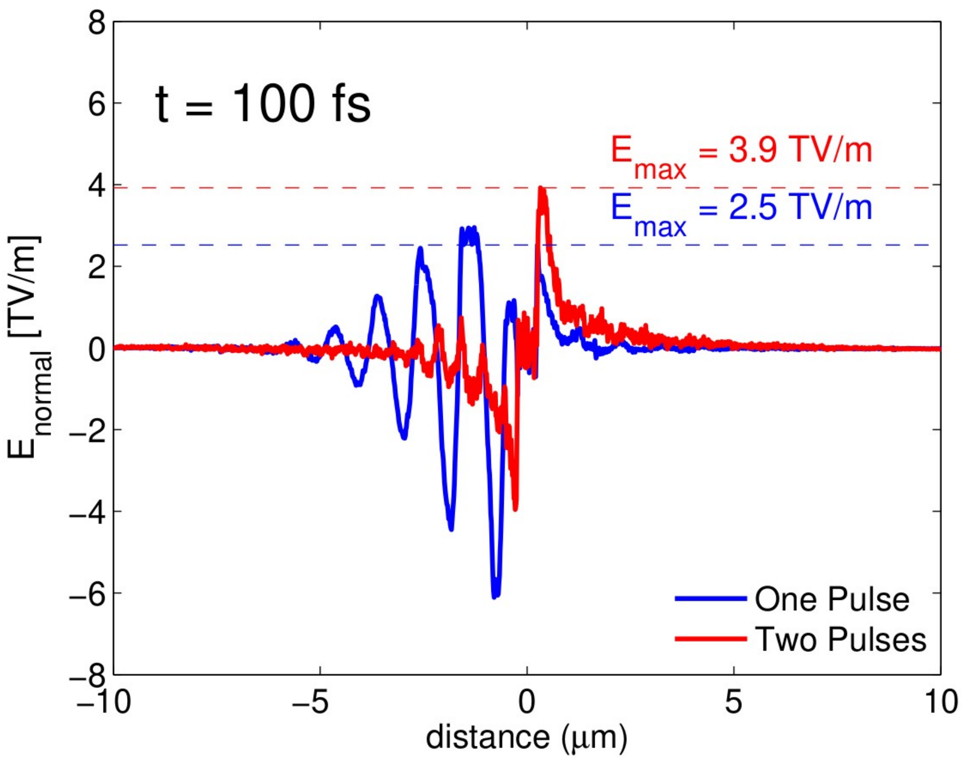
FIG. 4. (left panel) Proton energy 450 fs after pulse for single pulse. (right panel) Proton energy 450 fs after pulse for double pulse.

2D3v PIC simulation results from Rahman et al 2021

Electron Energy Distribution



Electric Field Lineout



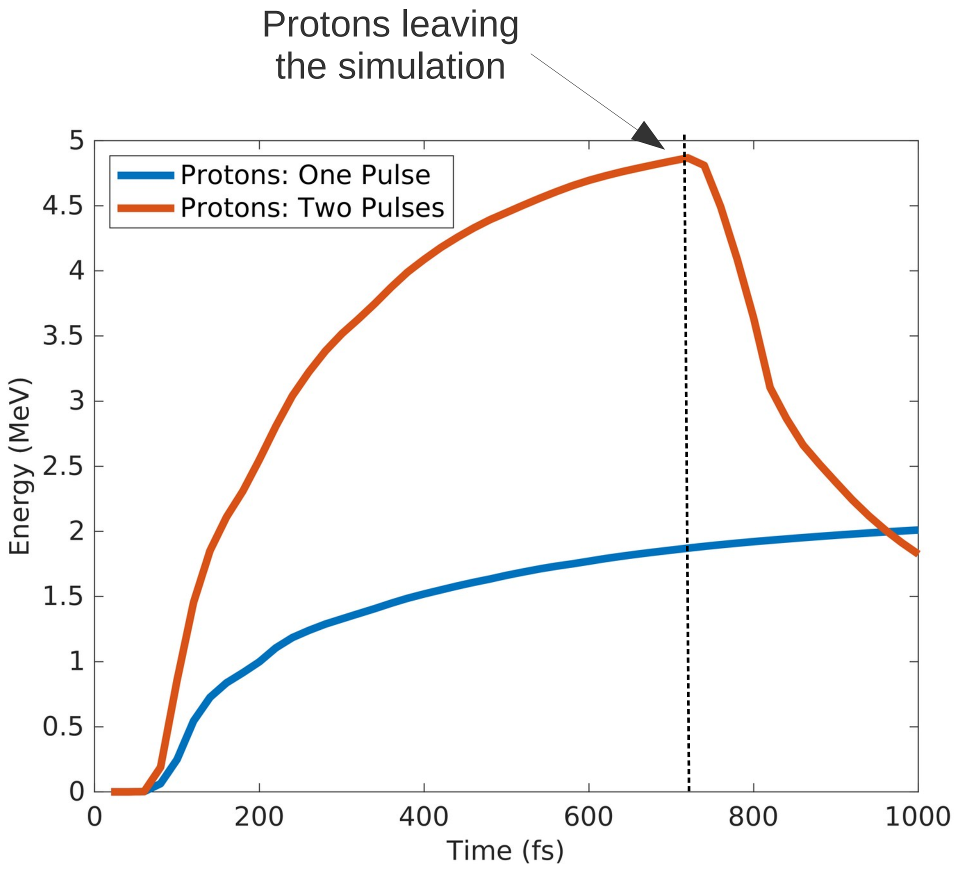
According to TNSA theory: $$E_{\max} \sim \frac{k_B T_{\text{hot}}}{e\lambda_D} \sim \sqrt{n_{\text{hot}} k_B T_{\text{hot}}}$$

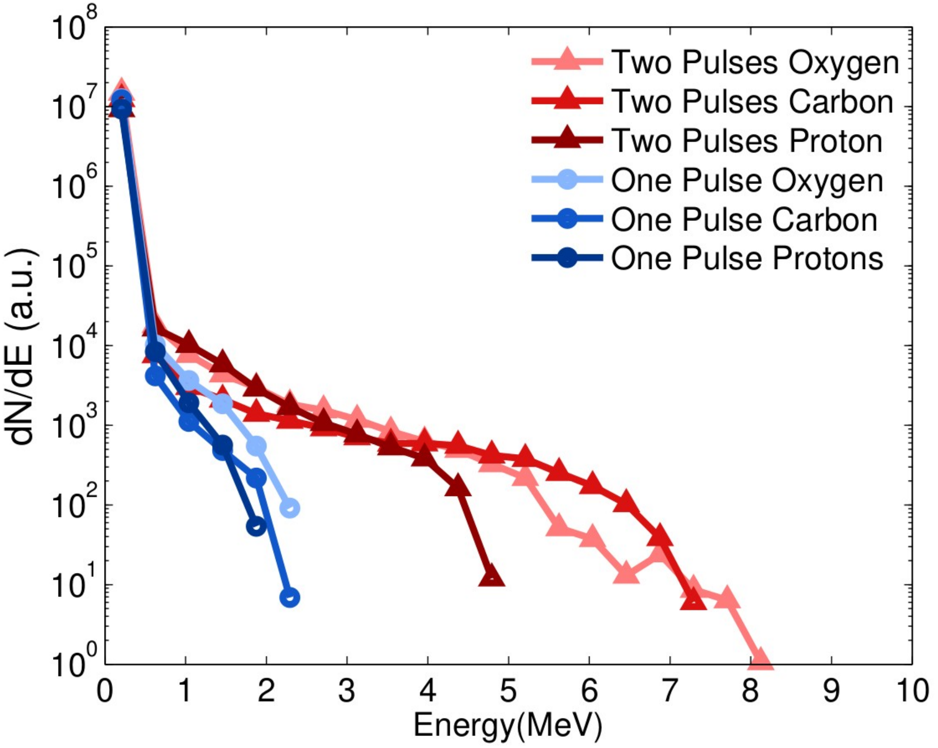
$$\frac{E_{\max,2}}{E_{\max,1}} = \sqrt{\frac{n_2(> 200\, keV)}{n_1(> 200\, keV)} \cdot \frac{T_{\text{hot}2}}{T_{\text{hot},1}}} \approx 2$$

Observed: $$\frac{E_{\max,2}}{E_{\max,1}} \approx 1.5$$

Closer to 1.5 for lower energy thresholds

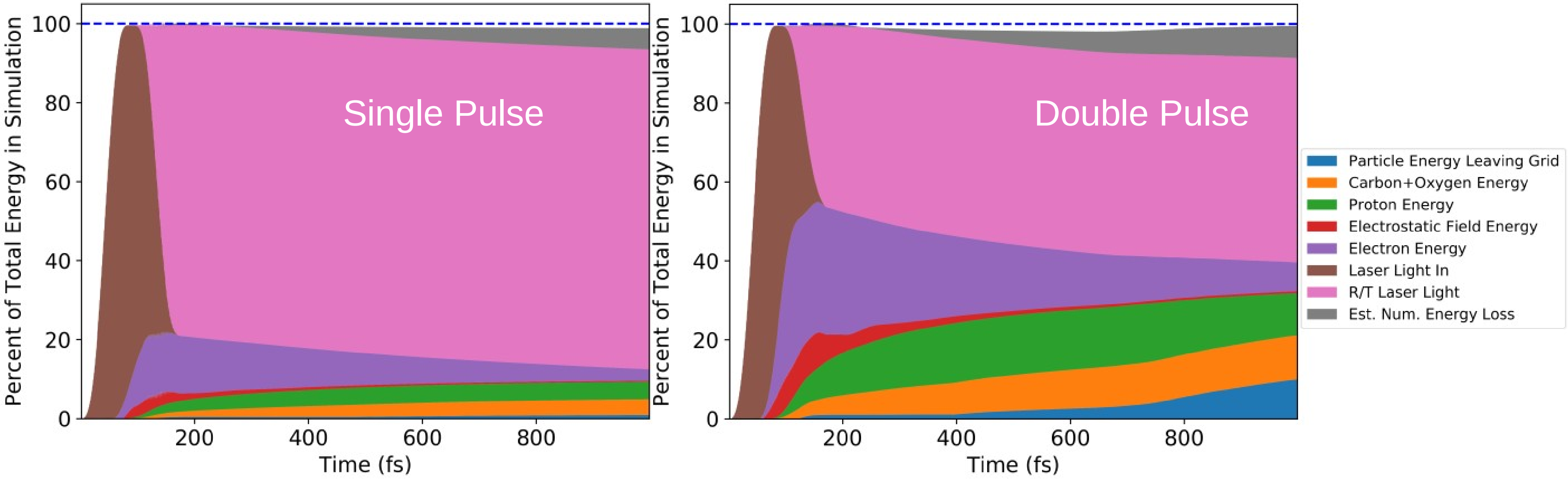
2D3v PIC simulation results from Rahman et al 2021





Why?!

2D3v PIC simulation results from Rahman et al 2021

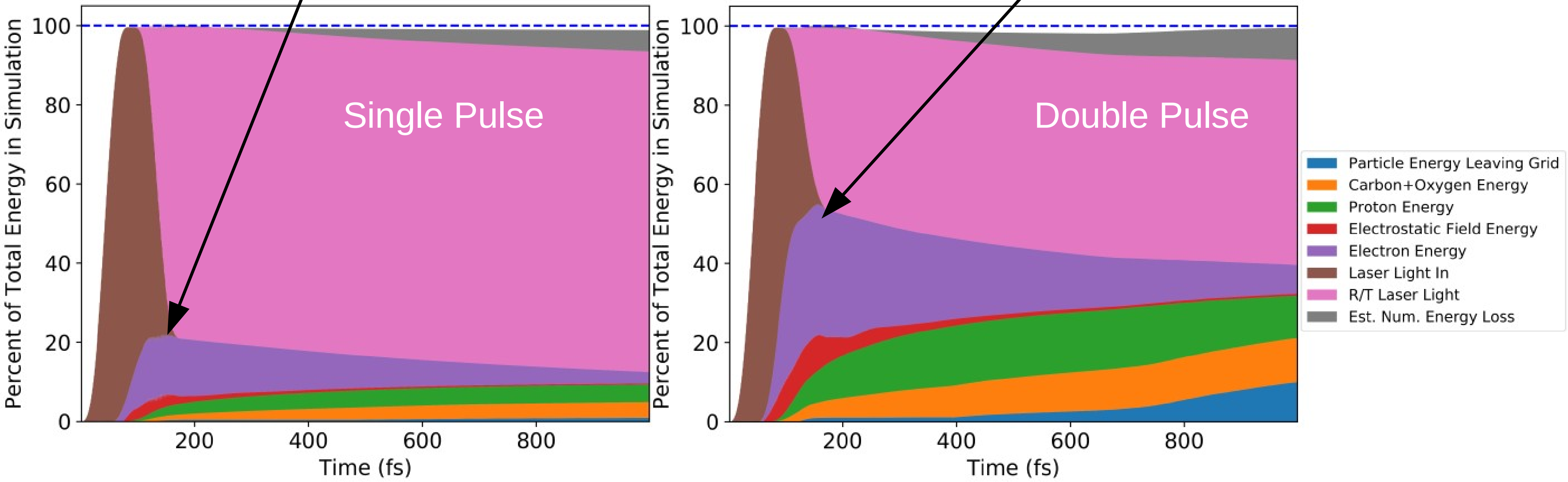


Note: Laser Pulse was 42 fs FWHM

2D3v PIC simulation results from Rahman et al 2021

21% Absorption

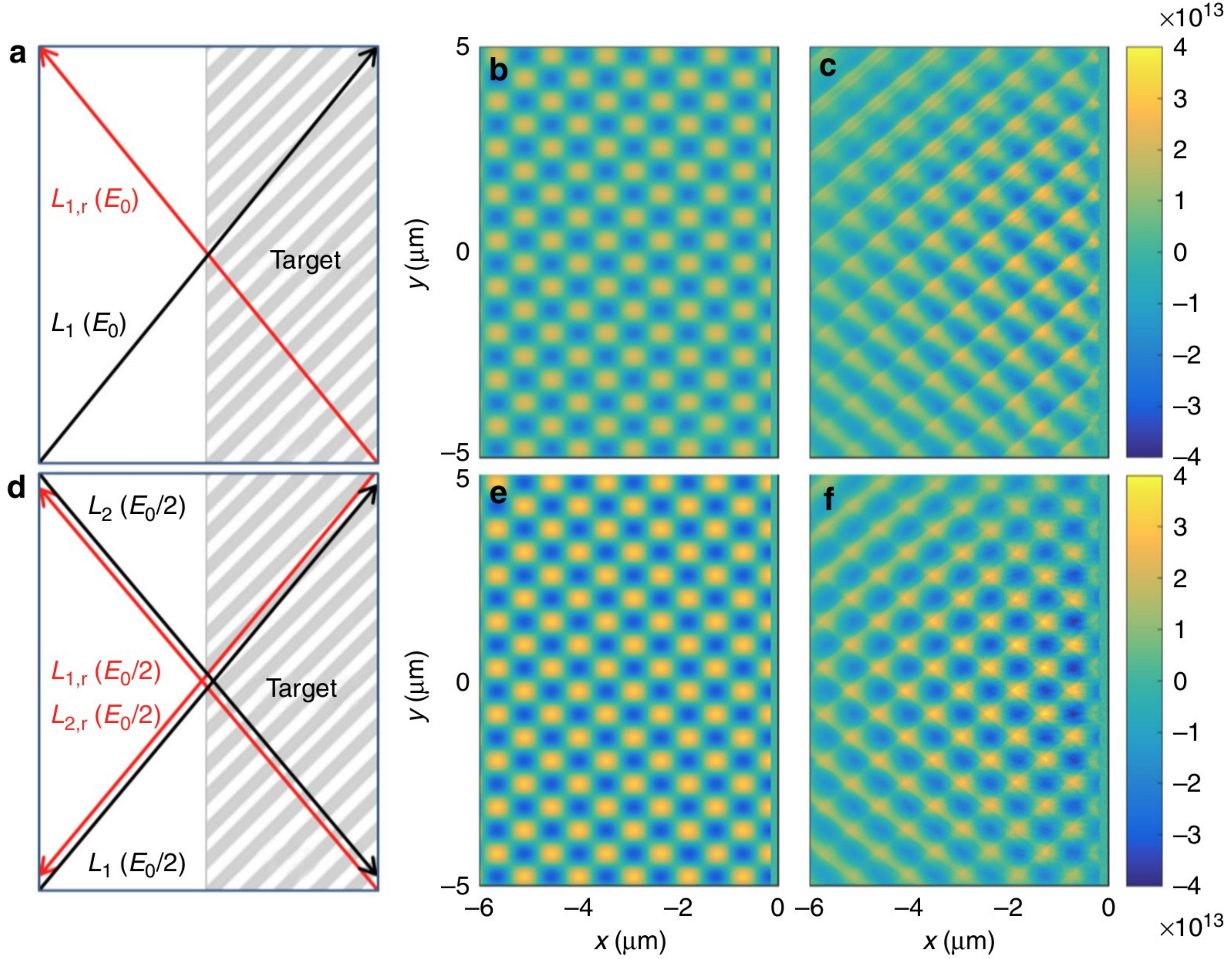
53% Absorption!



Note: Laser Pulse was 42 fs FWHM

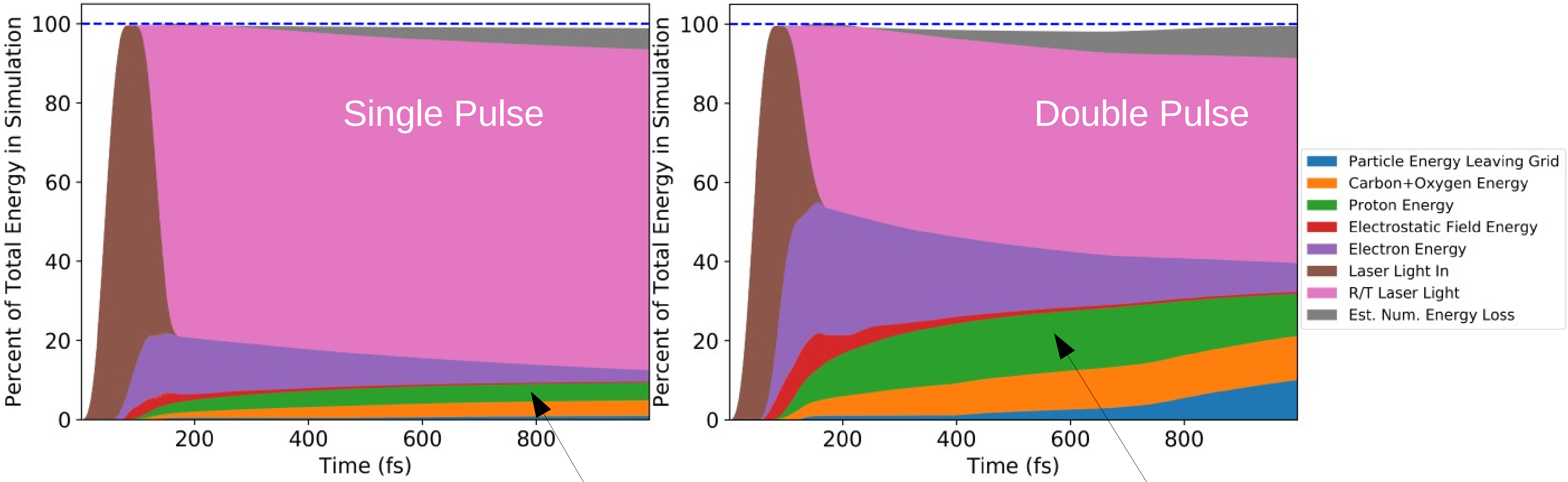
Why 2x absorption?

- The short answer is constructive interference
- Long answer:
  - You do get constructive interference for the single pulse reflecting off a boundary
  - Ferri et al 2019 shows that you get still higher E fields with the double pulse reflecting



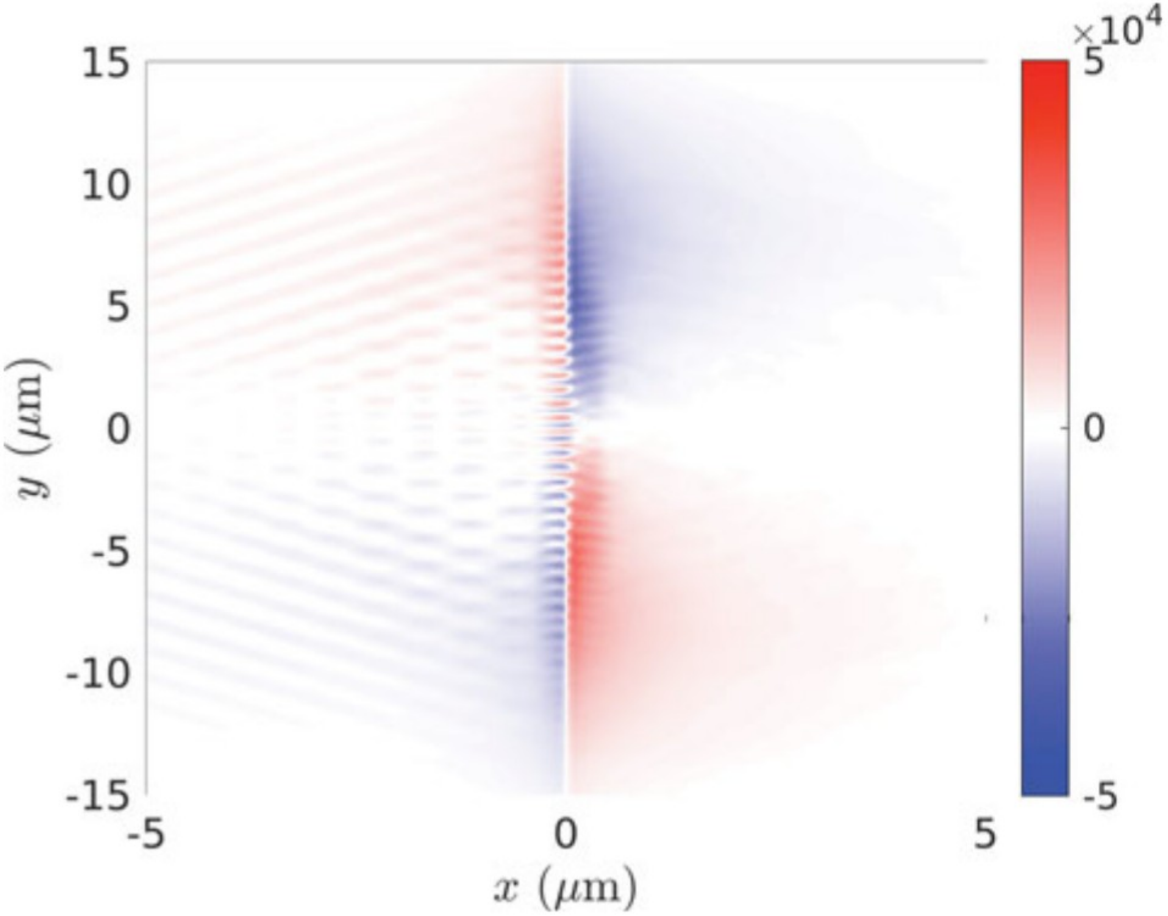
From Ferri et al 2019

2D3v PIC simulation results from Rahman et al 2021



28% of e- energy transferred to protons

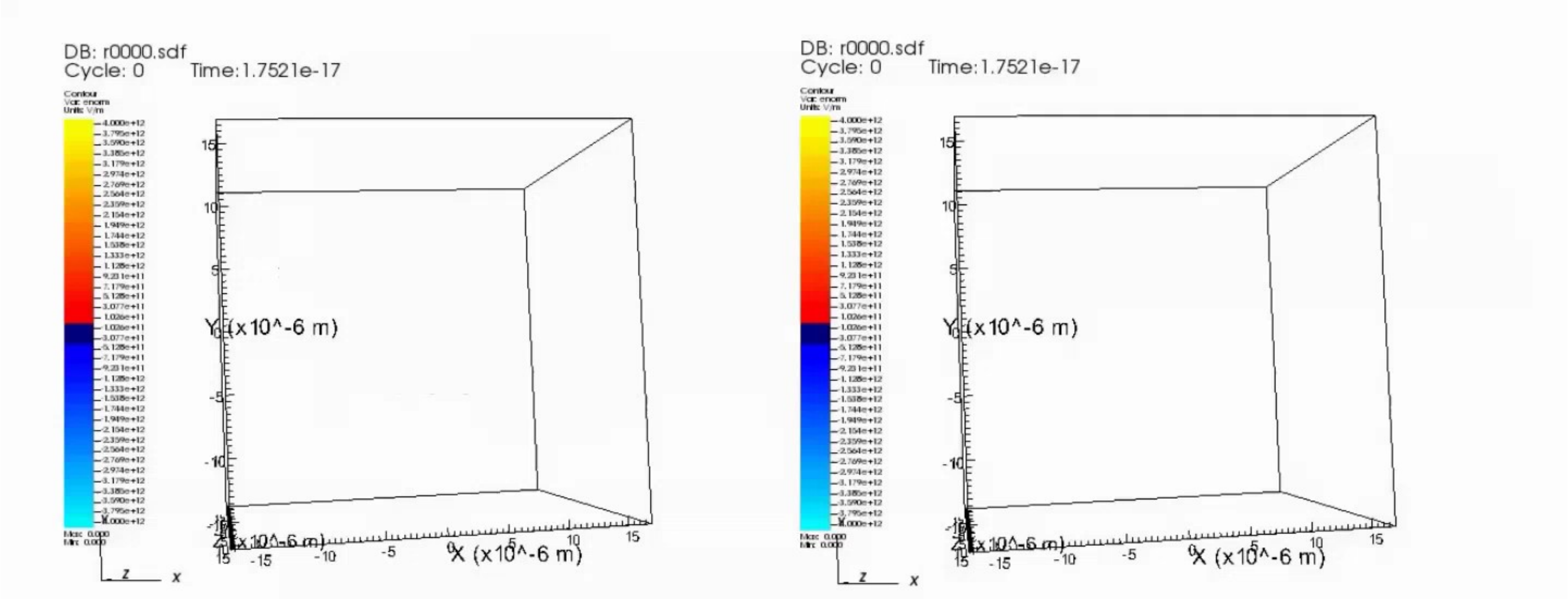
43% of e- energy transferred to protons



From Ferri et al 2020

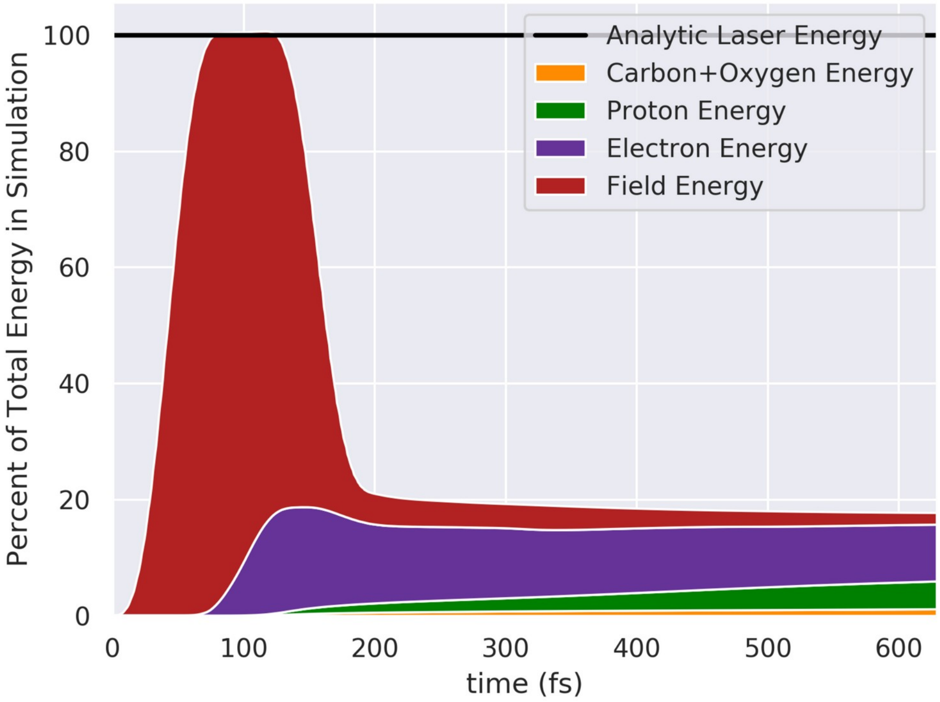
From Oropeza et al in prep.

3D PIC sims (from Ricky Oropeza's DPP poster)

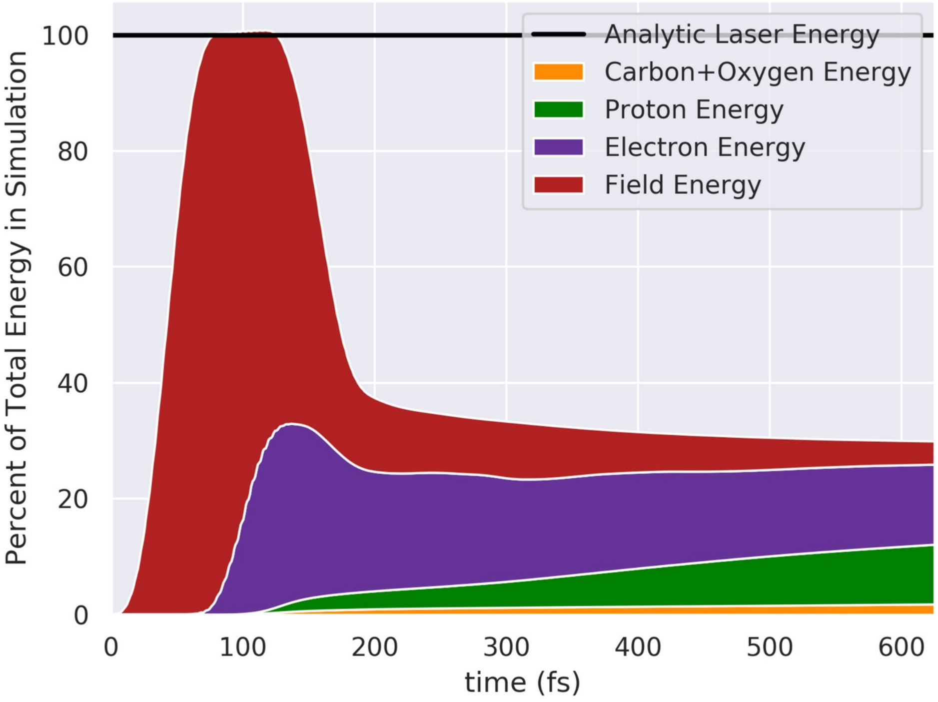


3D PIC sims (from Ricky Oropeza's DPP poster)

Single pulse



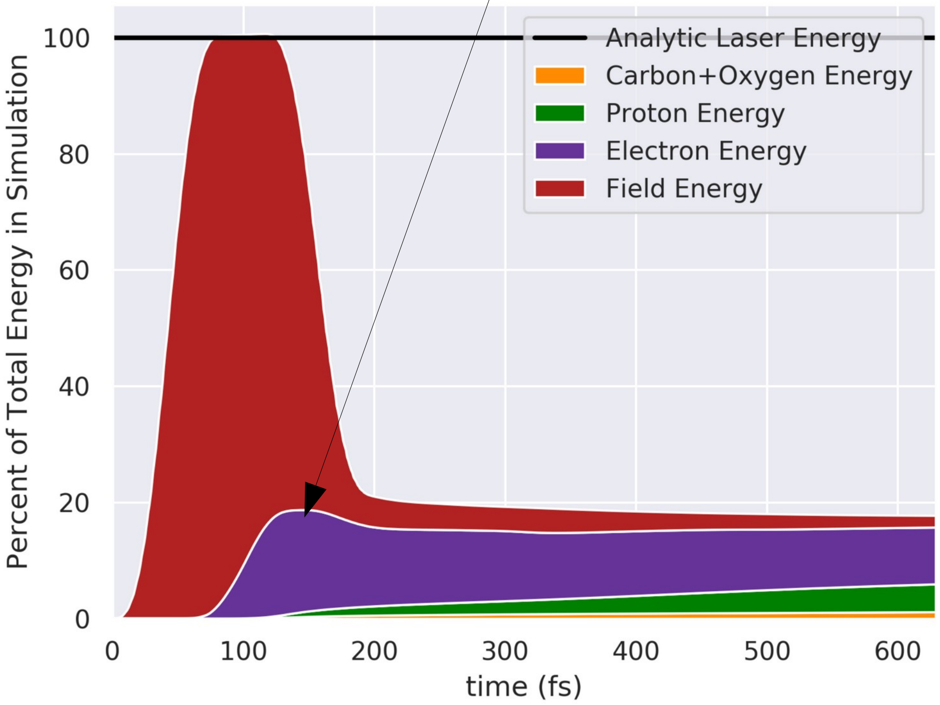
Double pulse



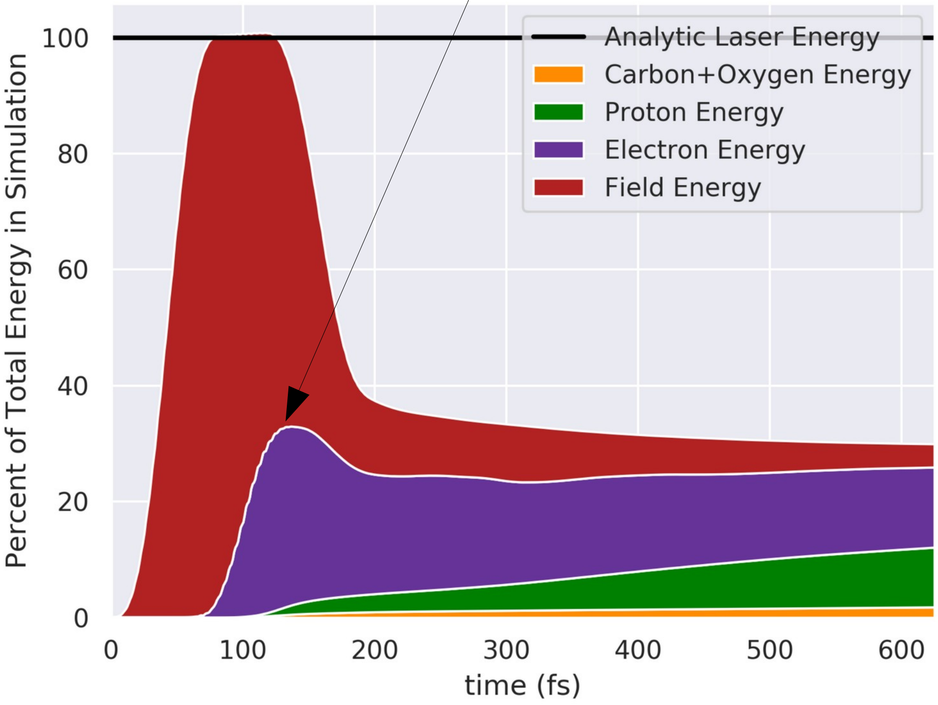
3D PIC sims (from Ricky Oropeza's DPP poster)

19% Absorption

33% Absorption!



Single pulse

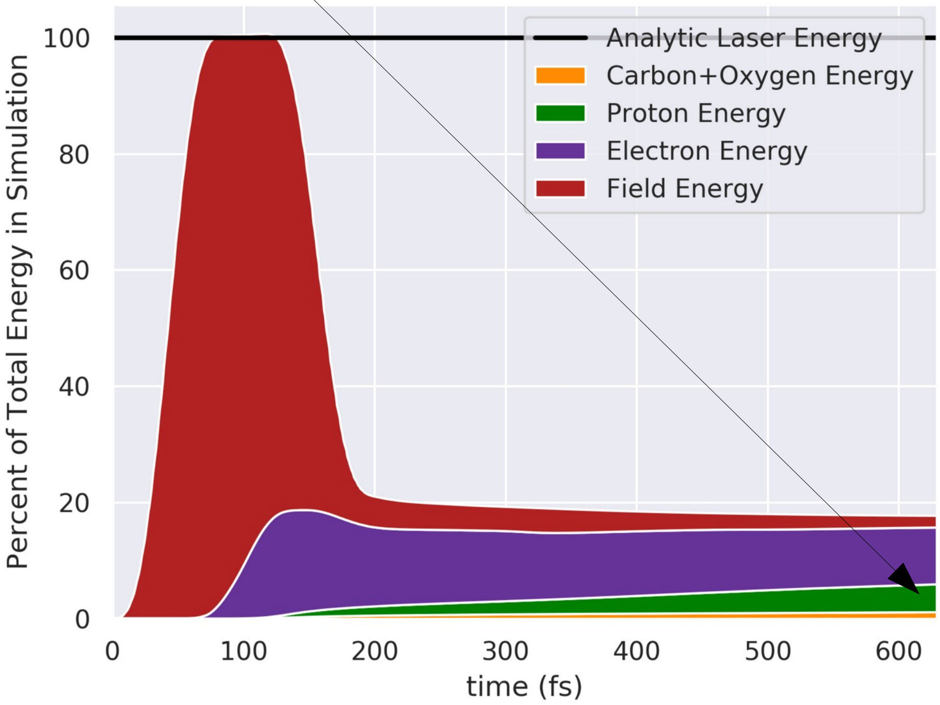


Double pulse

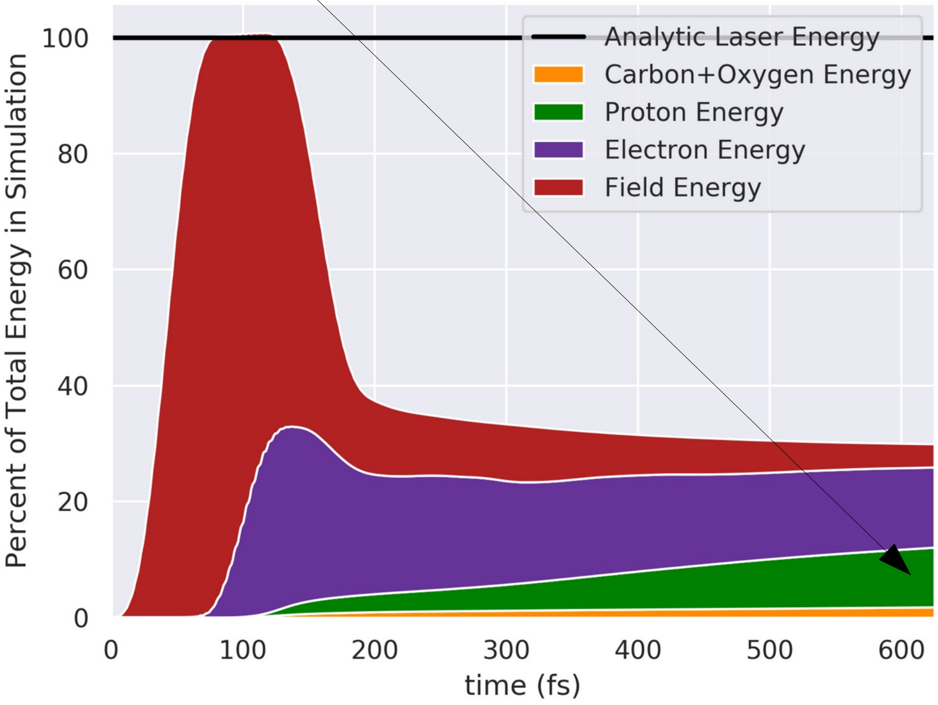
3D PIC sims (from Ricky Oropeza's DPP poster)

26% of e- energy transferred to protons

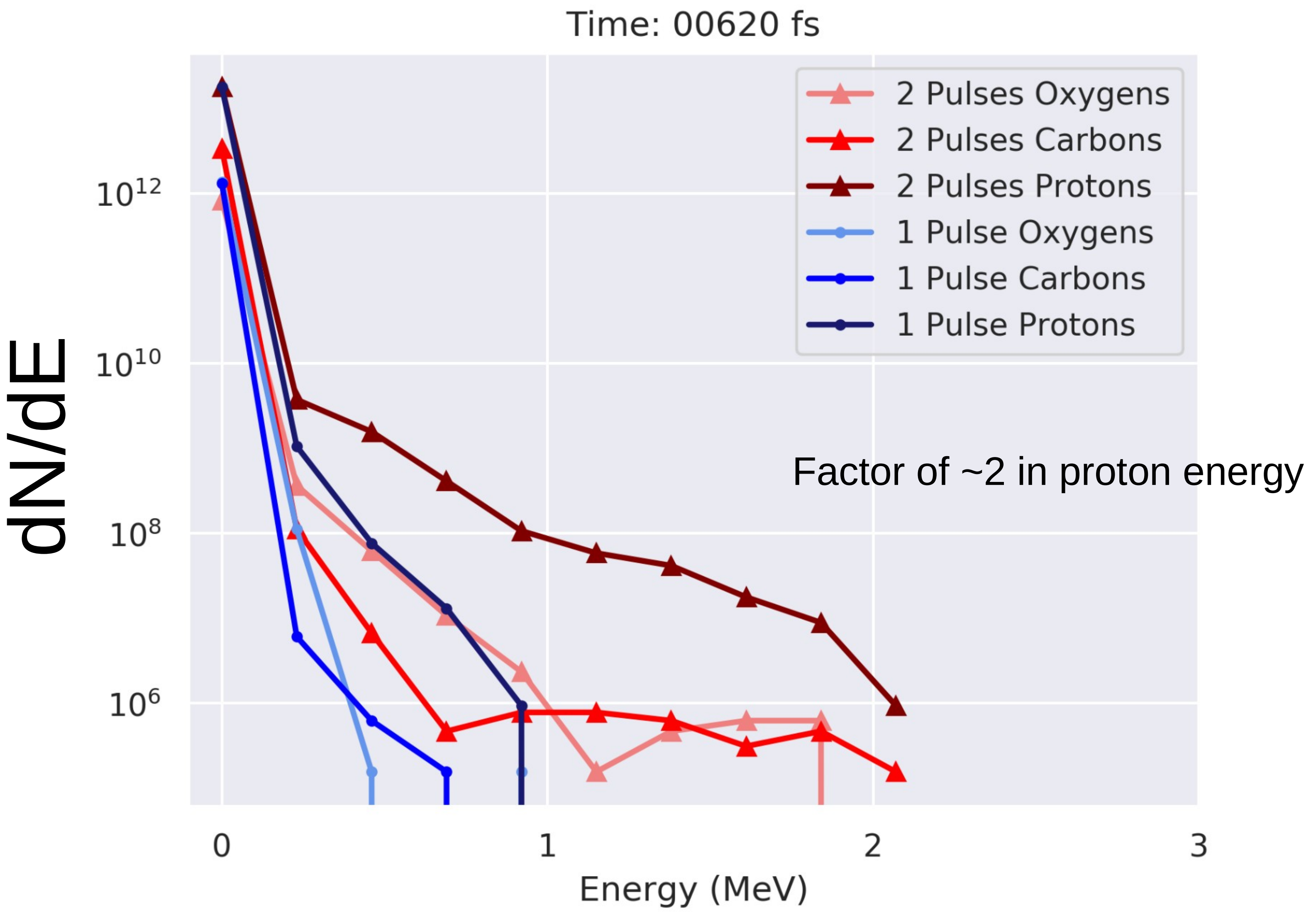
36% of e- energy transferred to protons



Single pulse



Double pulse

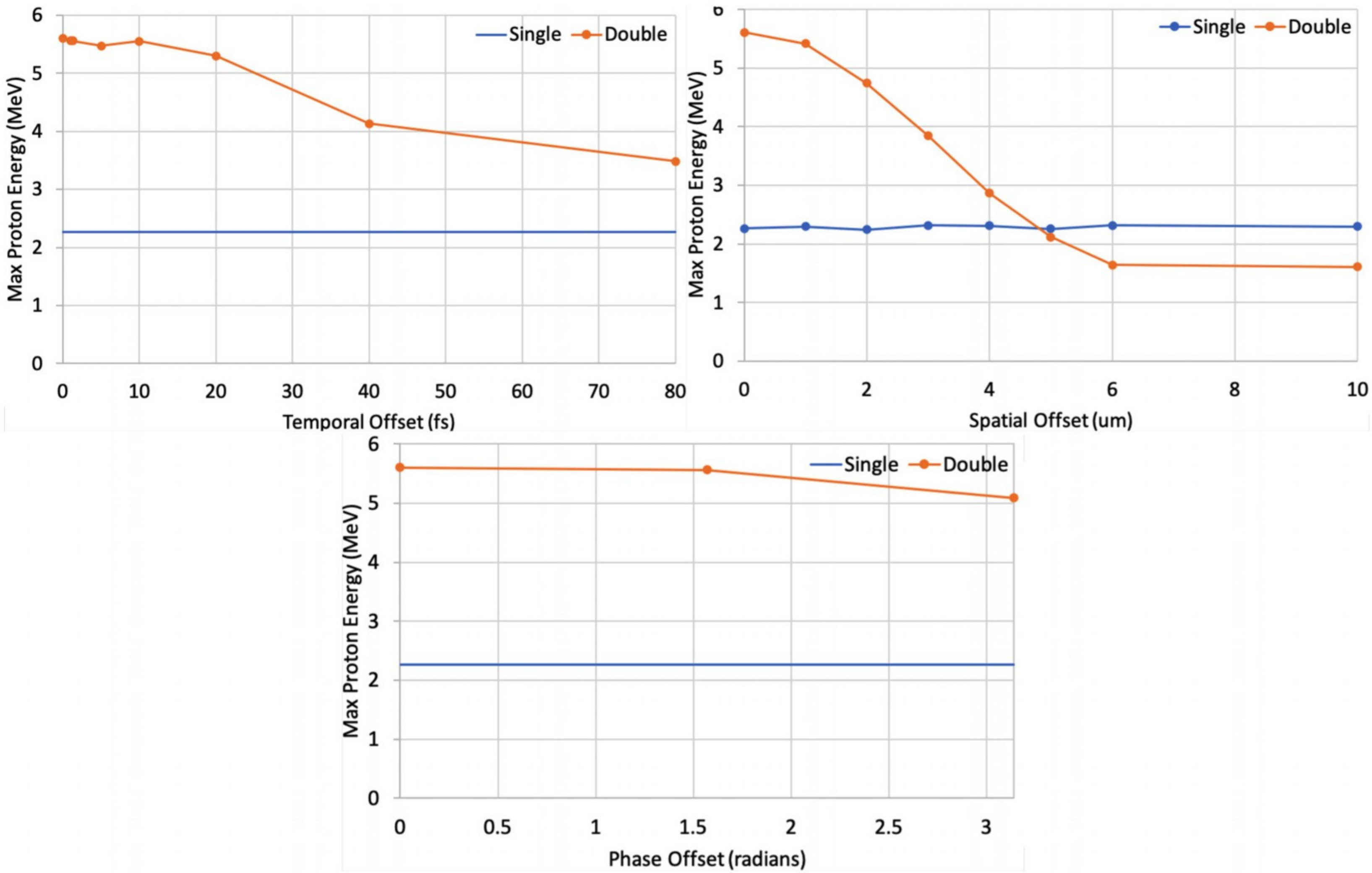


Time: 00620 fs
dN/dE
10^12
10^10
10^8
10^6
0
1
2
3
Energy (MeV)
2 Pulses Oxygens
2 Pulses Carbons
2 Pulses Protons
1 Pulse Oxygens
1 Pulse Carbons
1 Pulse Protons
Factor of ~2 in proton energy

Experimental Considerations

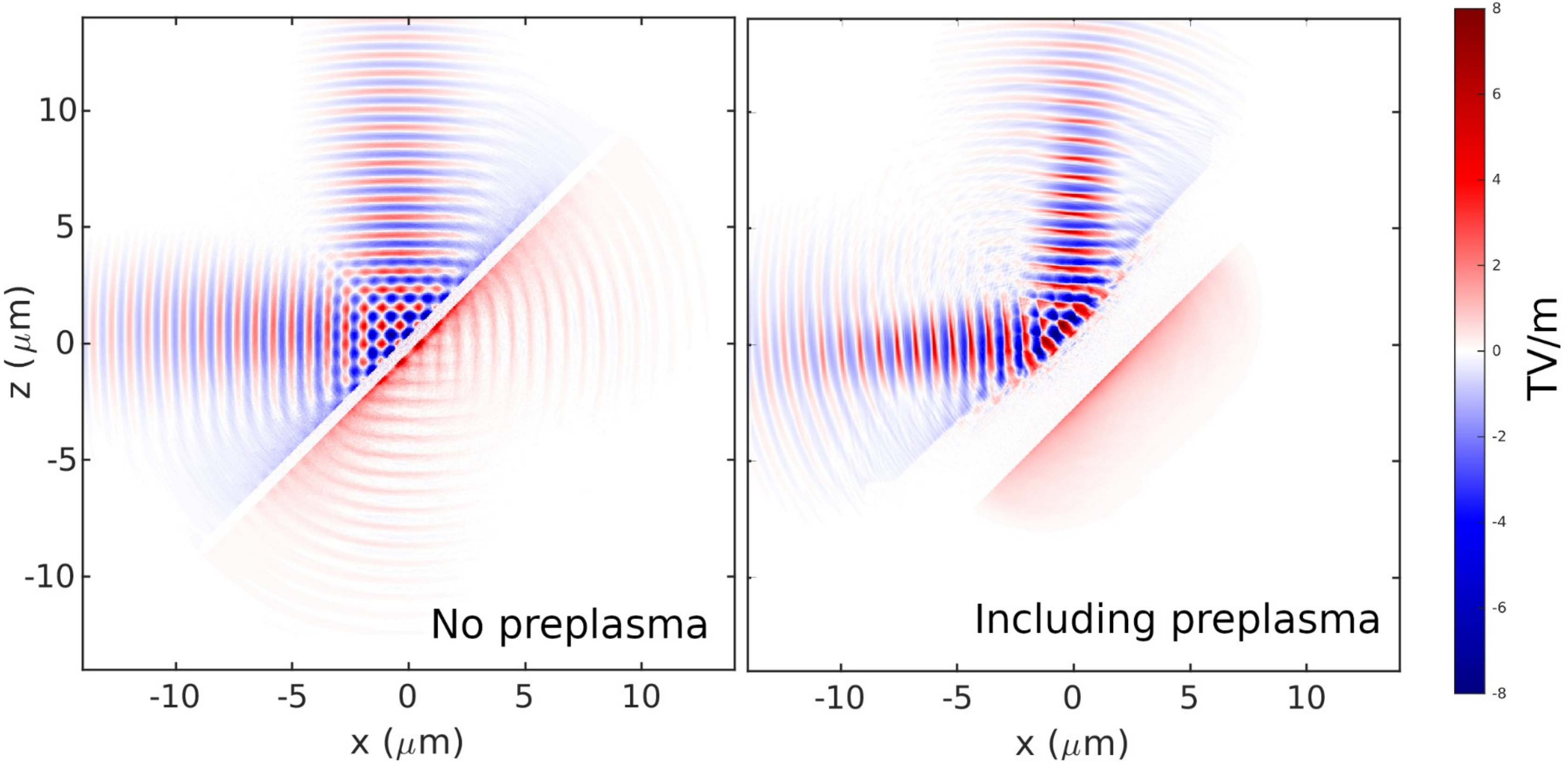
Experimental Considerations

- Spatial overlap & shot-to-shot jitter
- Temporal overlap
- Pre-pulse

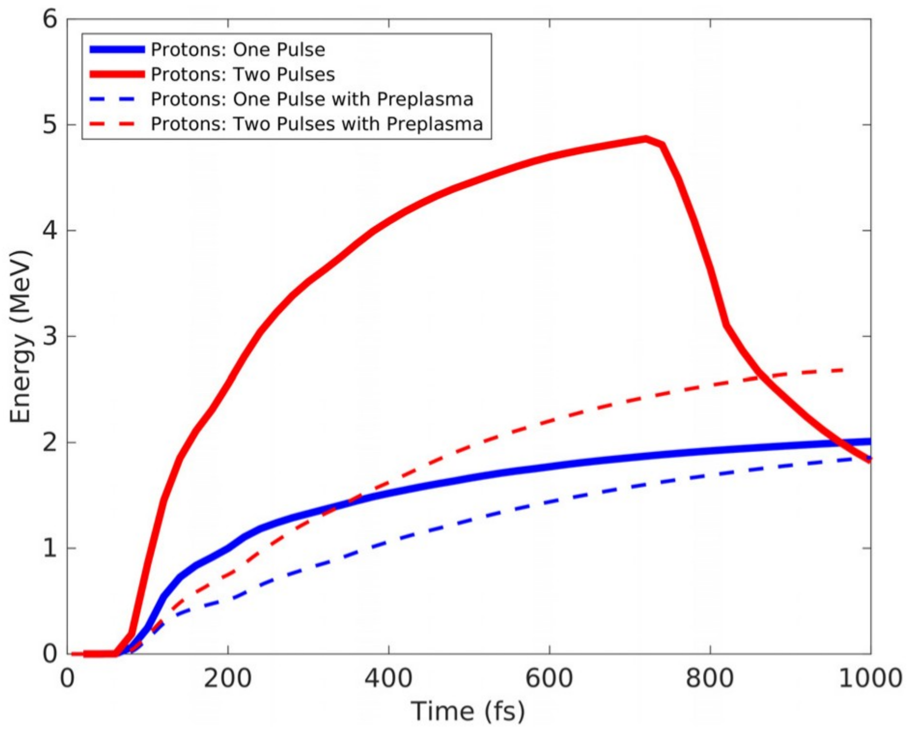


from Rahman et al 2021

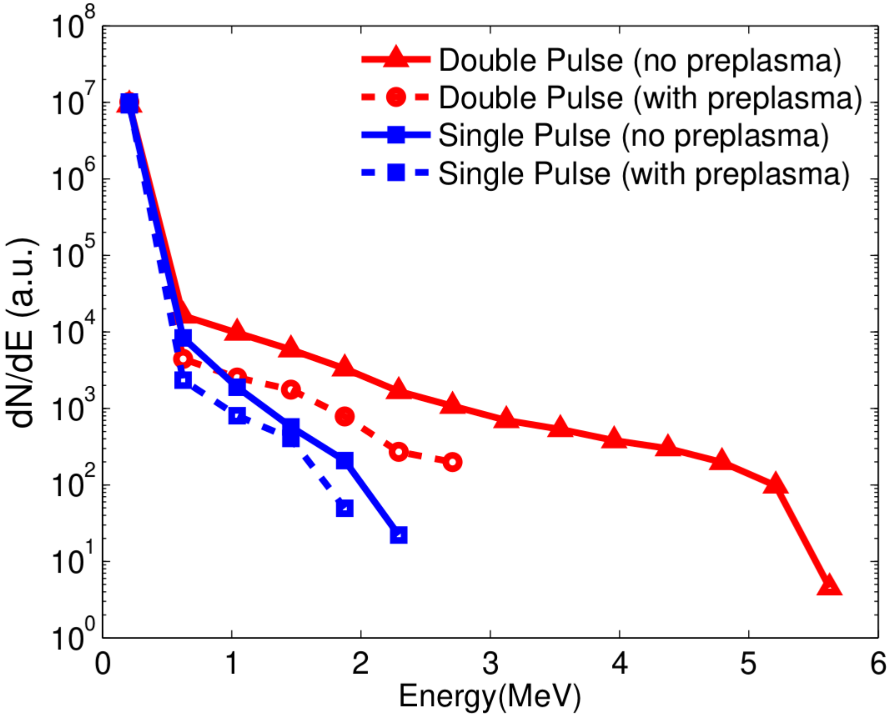
Preplasma Results



Preplasma Results :(



(Rahman et al 2021)



(Unpublished work, same sims)

Upshot #1

- Constructive interference produces higher effective intensity
  - Ferri et al 2019 explain ~2 increase in intensity
- Reflectivity is the ~same but more energy is absorbed because of higher intensity
- The effective reflectivity of the entire interaction is therefore reduced, and more energy absorbed

Upshot #2

- Electrons transfer higher % of energy to protons and ions in double pulse sims
  - Unclear why: quasi-static magnetic fields?
- This combined with enhanced absorption makes two half intensity pulses better than one pulse with ***twice*** the intensity and energy!

Summary

- Double pulse enhanced TNSA is a promising method for accelerating protons
- Enhanced absorption and e- to ion energy transfer are both key to the effect
- The absorption remains high in 3D PIC sims
- Sensitive to pre-plasma

Future work

- We received an NSF/DOE grant to pursue double pulse enhanced TNSA experiments and theory
- Experiments at Wright Patt and eventually LaserNetUS
- The grant also includes a machine learning effort to control proton acceleration (single pulse)
- We do have postdoc $$ so let me know if interested!

Acknowledgements

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