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Ion Acceleration in Superintense Laser Interaction with Ultrathin Targets

INO-CNR
Istituto Nazionale di Ottica

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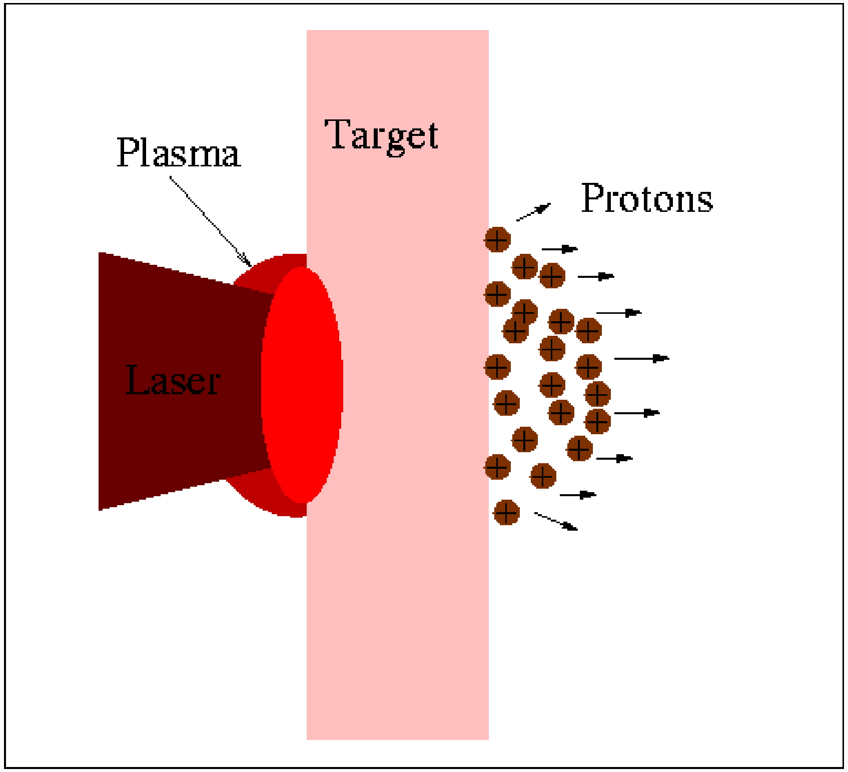
TEN YEARS OF ION ACCELERATION



Protons from Metallic targets observed in 2000 by three experimental groups

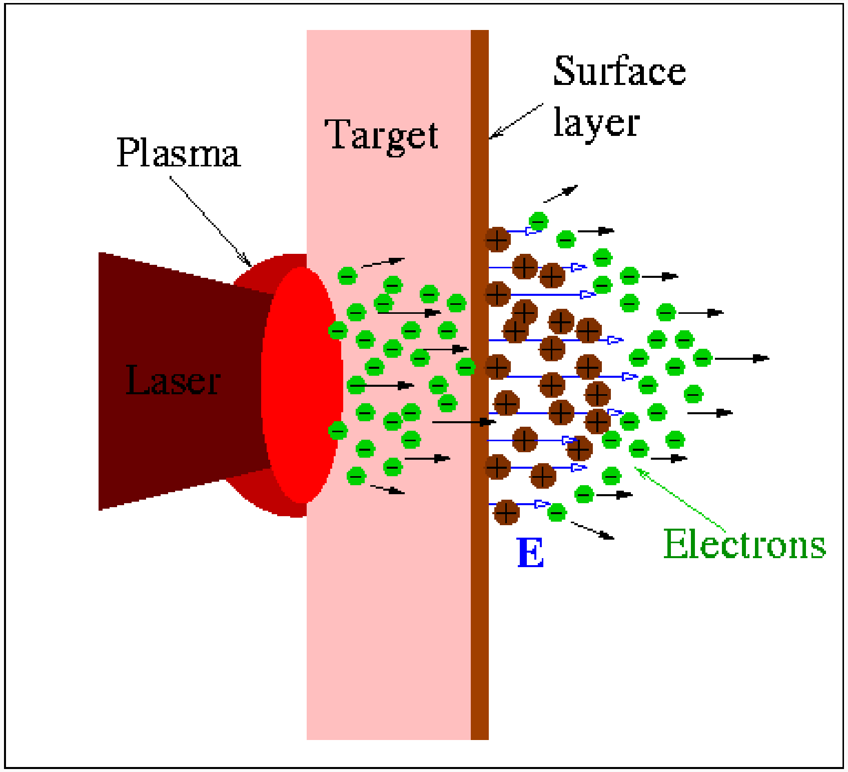
[Clark et al, PRL **84** (2000) 670;
Maksimchuk et al, *ibid.*, 4108;
Snavely et al, PRL **85** (2000) 2945 (*)]

- **high number** (up to 10^{14})
- **good collimation**
- **ultra-low emittance** (4×10^{-3} mm mrad)
- maximum energy and efficiency observed (*):
  58 MeV , **12% of laser energy**@ I=3 x 10^{20} W/cm^2

TARGET NORMAL SHEATH ACCELERATION

TNSA physical mechanism: acceleration in space-charge electric fields generated at the rear surface by escaping high-energy ("fast") electrons

[S. Wilks et al, Phys. Plasmas **8** (2001) 542]



Connection with the "classic" problems of sheath dynamics and plasma expansion into vacuum

Protons originate from impurities: TNSA of heavier ions can be achieved by target engineering

APPLICATIONS AND CHALLENGES

Foreseen applications:
- Ignitor or diagnostic beam in Inertial Confinement Fusion
- Oncological hadrontherapy & isotope production in Medicine
- Probing of laser-plasma interactions

Challenging tasks:
- Reaching >150MeV/A : scaling at higher intensities?
- Improve and control proton/ion beam properties (monoenergeticity, collimation, repetition rate, ...)
- Reaching relativistic ion regimes (>1 GeV/A); what happens at ultrahigh intensities? (ELI project: intensities up to 10^{26} W/cm^2)

RUNNING PROJECTS ON ION ACCELERATION

FIRB “Futuro in Ricerca” project SULDIS
(“SUperintense Laser-Driven Ion Sources”) 2010/14
National coordinator: Matteo Passoni (Politecnico Milano)
Local coordinator: AM

Italian SuperComputing Resource Allocation (ISCRA)
project TOFUSEX at CINECA (Bologna)
(“TOwards Full-scale Simulations of laser-plasma EXperiments)
Principal Investigator: AM
Collaborators: G.Turchetti, P.Londrillo, A.Sgattoni (Bologna)

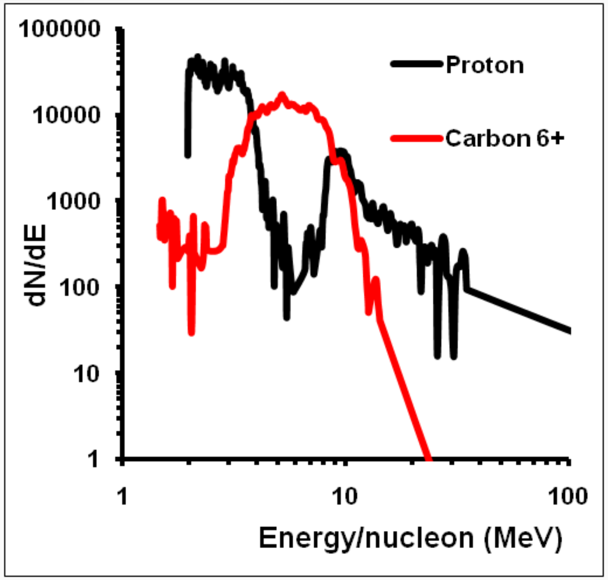
ULTRATHIN TARGETS (1-100 nm)

Advantages:
- Concentration of laser pulse energy in small volume: higher electron temperature → higher ion energy?
- Significant (or even dominant) effect of direct Radiation Pressure Acceleration (RPA)

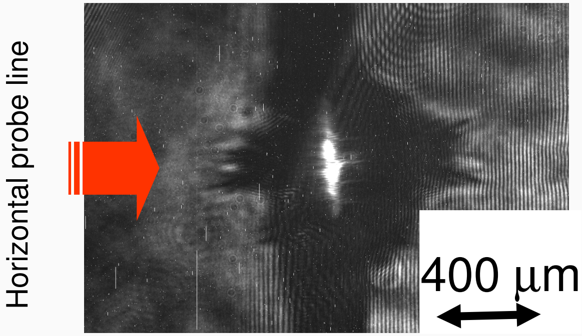
Possible to use thanks to:
- advanced target manufacturing (e.g. Diamond-Like Carbon foils)
- pulse cleaning techniques (e.g. plasma mirrors) to generate prepulse-free ultrashort pulses avoiding early target disruption

TWO-SPECIES ION ACCELERATION

Target: thin (0.1-1 μm) **Cu** foil
with **C** and **H** impurities
Laser pulse: 1ps, up to 3×10^{20} W/cm^2
various polarizations



Modulated, "complementary" spectra for **C** and **H** (**H dip** at **C peak**)



Time Approx. +600 ps

Collimated plasma jet
observed via interferometry

Data from VULCAN-TAP@RAL, UK (S.Kar)

2D SIMULATIONS FOR THE EXPERIMENT

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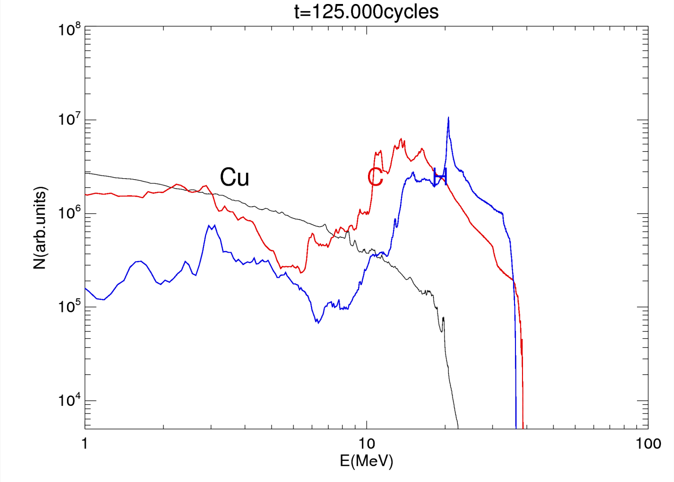
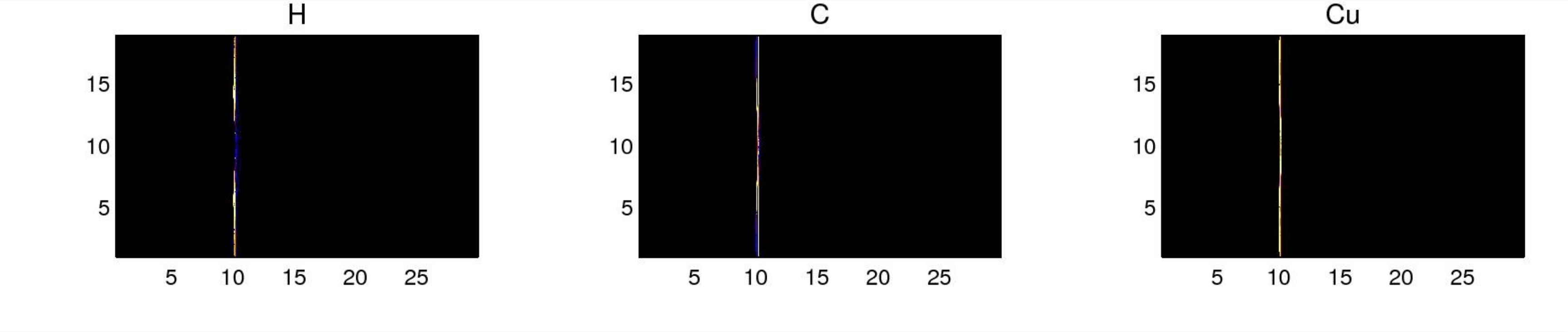
Target:0.1μm **Cu** foil with 10nm **CH** layers
electron density 10^{23} cm^{-3}
Laser pulse: 0.5ps, 1.4 X 10^{20} W/cm^2
linear polarization



The scaled down model problem qualitatively reproduces the experiment

t= 25 cycles



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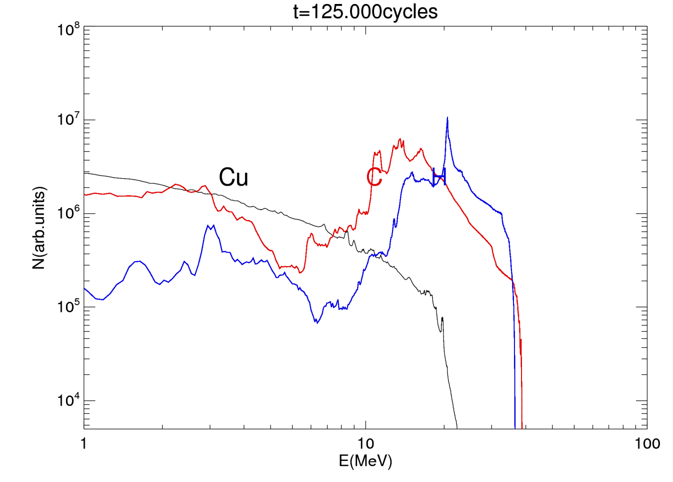

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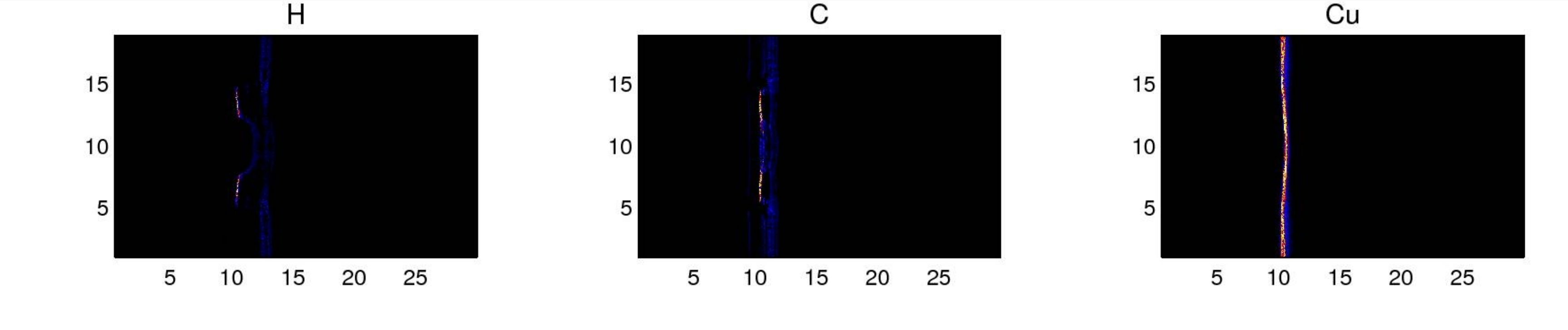
t= 50 cycles



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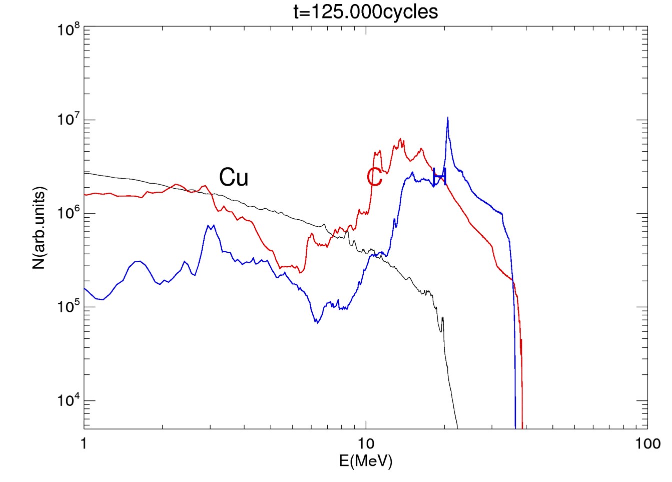
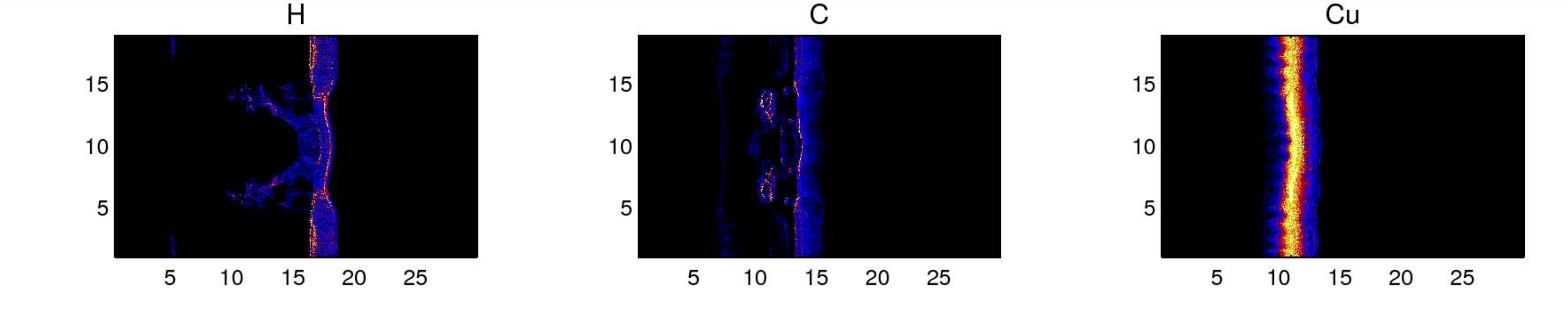


The scaled down model problem qualitatively reproduces the experiment

t= 75 cycles



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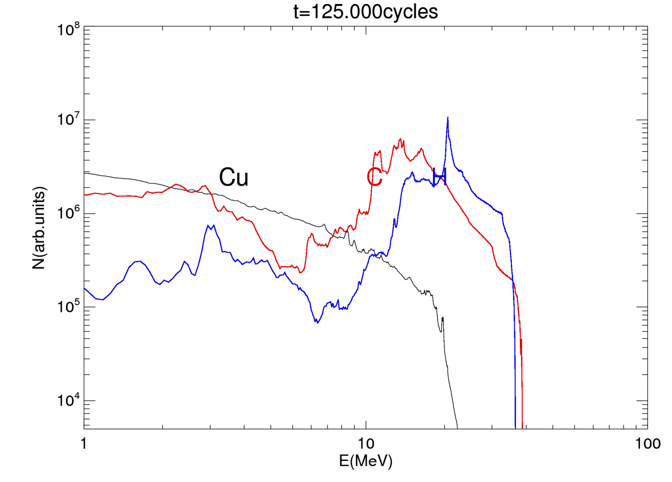
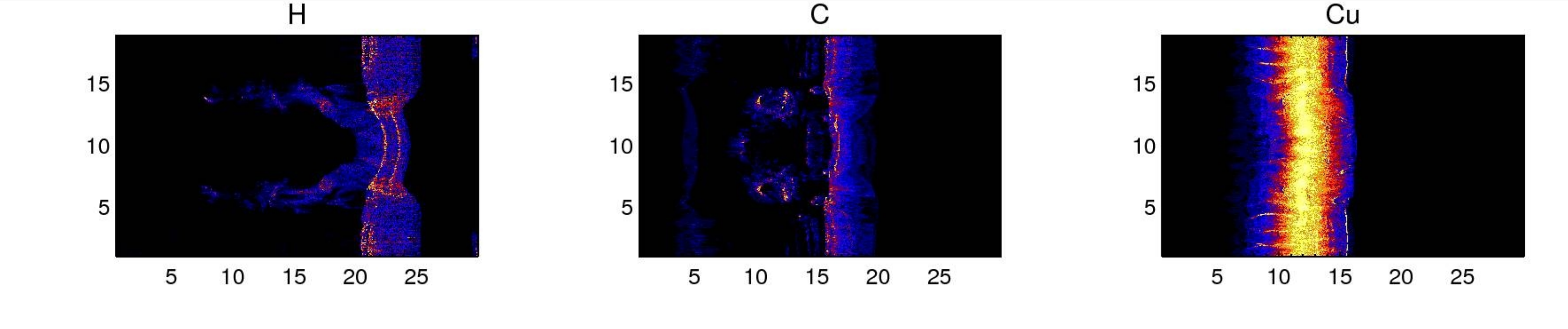


The scaled down model problem qualitatively reproduces the experiment

t=100 cycles



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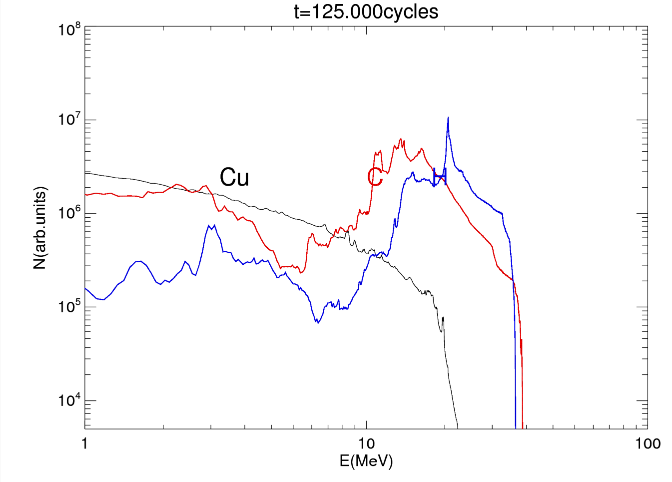
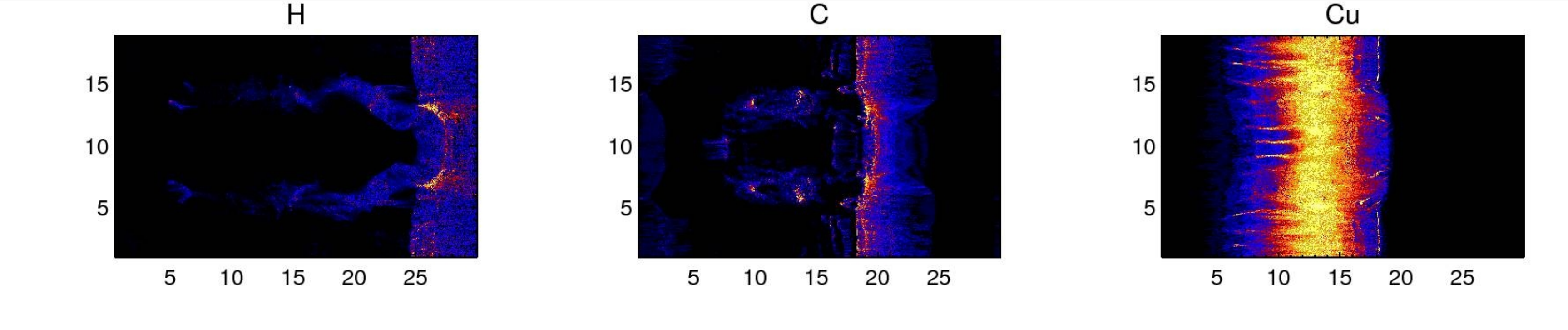


The scaled down model problem qualitatively reproduces the experiment

t=125 cycles



THEORY (WORK IN PROGRESS)

Extension of the classic model of plasma expansion in vacuum to a multispecies plasma predicts the formation of shock fronts due to spatial separation between light and heavy species and formation of spectral peaks and dips.

[see e.g. Kemp & Ruhl, PoP **12** (2005) 033105; Tikhonchuk et al, PPCF **47** (2005) B869]

Possible additional effects in this experiment characterized by unprecedented intensity and ultrathin substrate target:

- nearly full relativistic electron population
- instabilities (two-stream, Buneman) in the blow-off plasma
- significant boost by radiation pressure acceleration (RPA)

[see e.g. Kar et al, PRL **100** (2008) 225004]

TWO RPA-BASED VISIONS (1966 - 2010)

22 NATURE JULY 2, 1966 Vol. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

By Prof. G. MARX
Institute of Theoretical Physics, Roland Eötvös University, Budapest

PRL 104, 135003 (2010) PHYSICAL REVIEW LETTERS week ending 2 APRIL 2010

Unlimited Ion Acceleration by Radiation Pressure

S. V. Bulanov,[1,*] E. Yu. Echkina,[2] T. Zh. Esirkepov,[1] I. N. Inovenkov,[2] M. Kando,[1] F. Pegoraro,[3] and G. Korn[4]
[1]*Kansai Photon Science Institute, JAEA, Kizugawa, Kyoto 619-0215, Japan*
[2]*CMC, Moscow State University, Moscow 119899, Russia*
[3]*Physics Department, University of Pisa and CNISM, Pisa 56127, Italy*
[4]*Max Plank Institute of Quantum Optics, Garching 85748, Germany*
(Received 18 November 2009; published 2 April 2010)

INTERSTELLAR TRAVEL (1966)

to α-Centauri

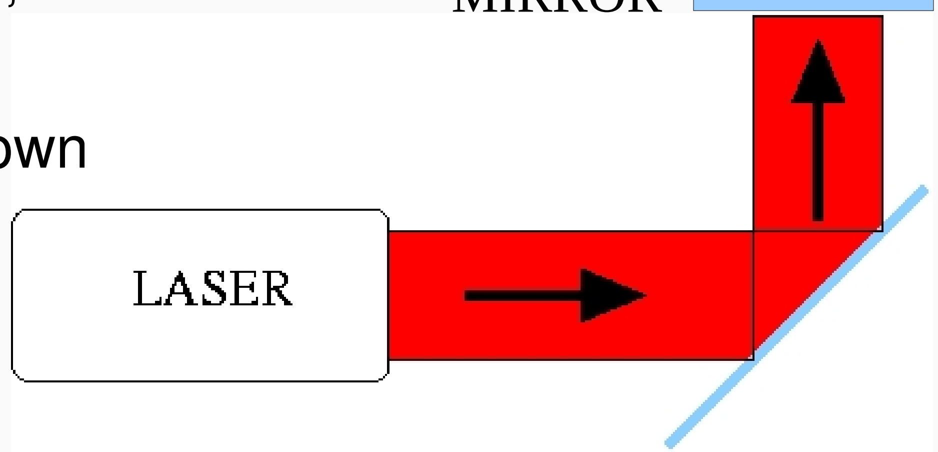
22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL L

By PROF. G. MARX

Institute of Theoretical Physics, Roland Eötvös University, Budapest

Using the "Light Sail" model, i.e. a perfect mirror boosted by Radiation Pressure, it is shown that acceleration efficiency is 100% as $V \rightarrow c$

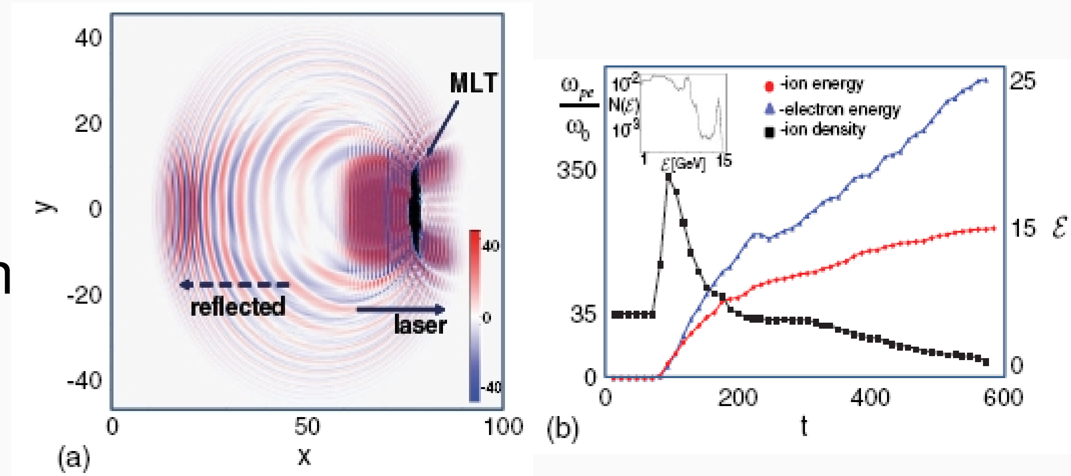


ULTRA-RELATIVISTIC IONS (2010)

Simulations at

$I \geq 10^{23}\ \mathrm{W/cm^2}$

suggest thin foil acceleration up to GeV/A energies



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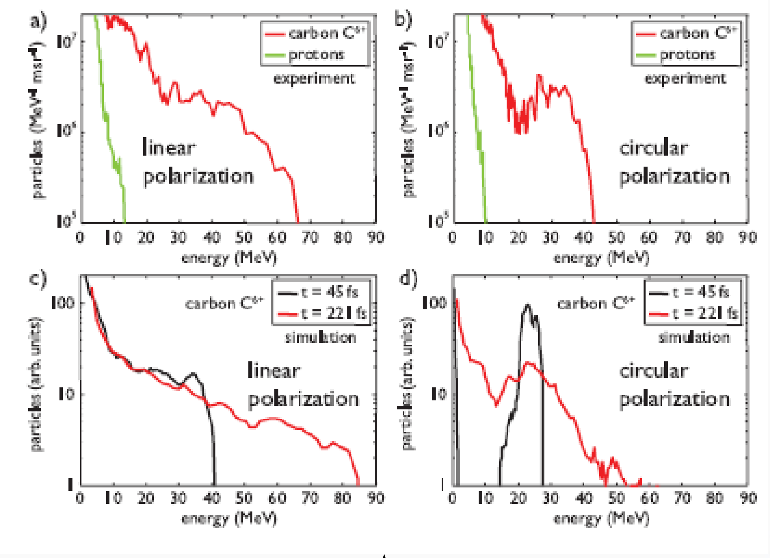
RPA WITH CIRCULAR POLARIZATION

Using CP and normal incidence fast electron generation is strongly suppressed, making radiation pressure dominant even at intensities lower than

Early study in “thick” targets:
Macchi et al, PRL **94** (2005) 165003

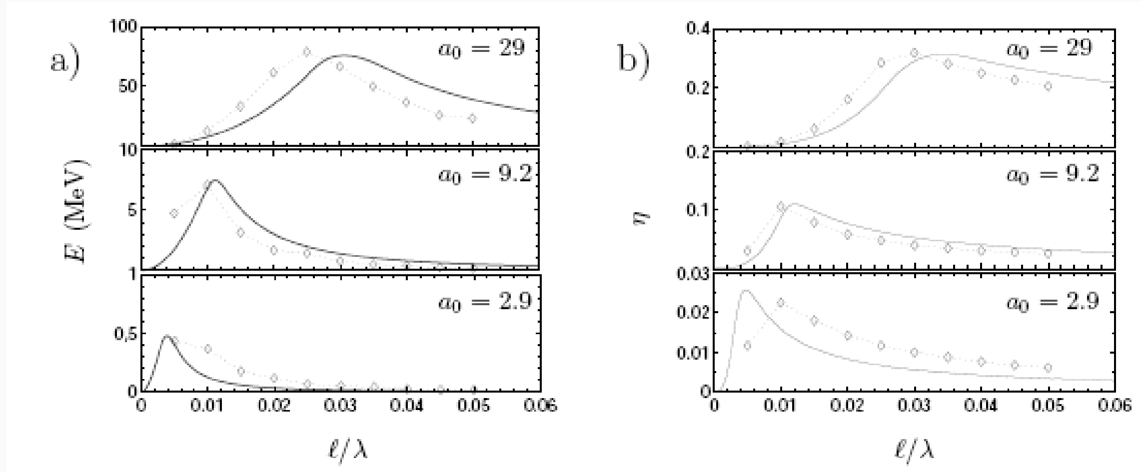
Proposal of CP-RPA of ultrathin foils for efficient and monoenergetic acceleration:
Zhang et al, PoP **14** (2007) 073101
Robinson et al, NJP **10** (2008) 013201;
Klimo et al, PRST-AB **11** (2008) 031301.

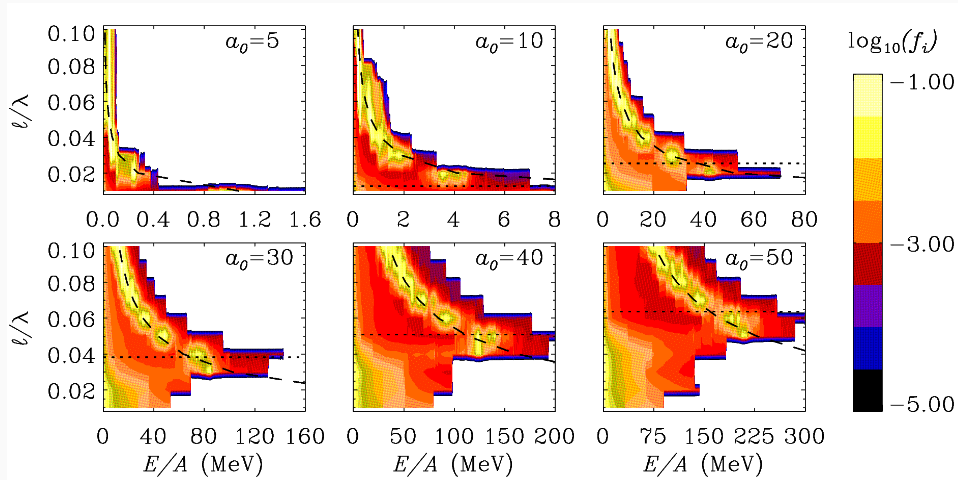


First experimental study reported:
Henig et al, PRL **103** (2009) 245003

CP-RPA SIMULATIONS: 1D

Peak ion energy (a)
efficiency (b)
& energy spectra (c)
vs. laser pulse intensity and thickness:
very good agreement of analytical model with results of PIC simulations accounting for kinetic effects



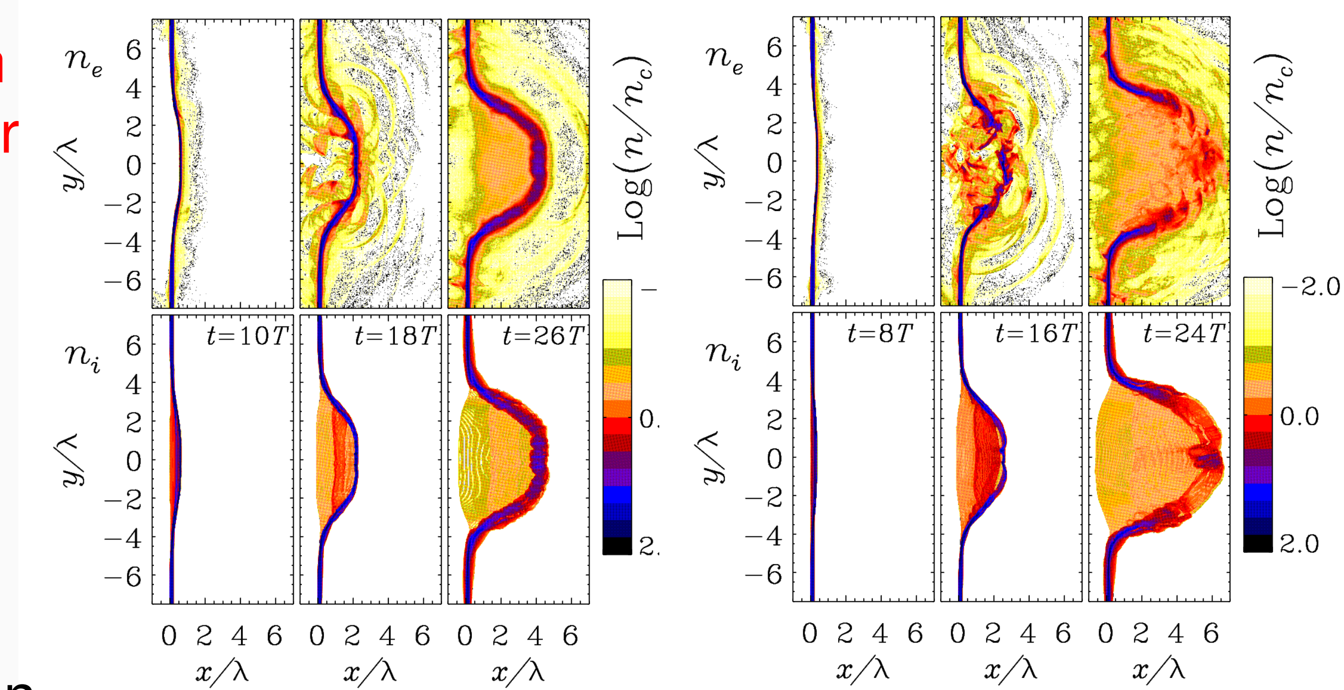


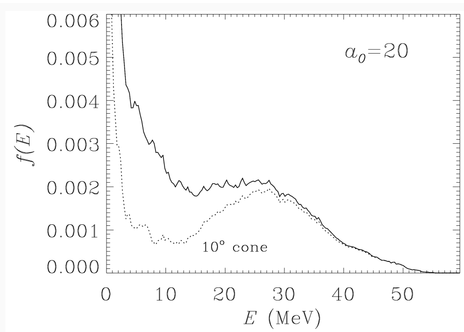
Macchi et al,
PRL **103** (2009) 085003;
New J. Phys. **12** (2010) 045013.

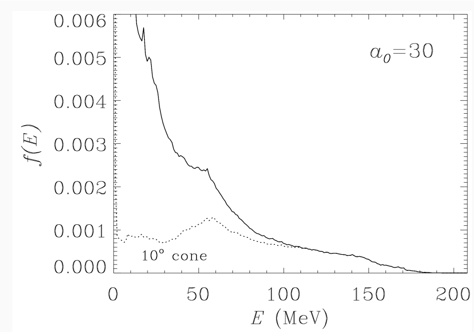
CP-RPA SIMULATIONS: 2D

Stronger electron heating and lower "penetration" threshold with respect to 1D: ion spectrum broadens and monoenergetic peak tends to disappear as seen in experiment

Macchi et al, New J. Phys. **12** (2010) 045013.



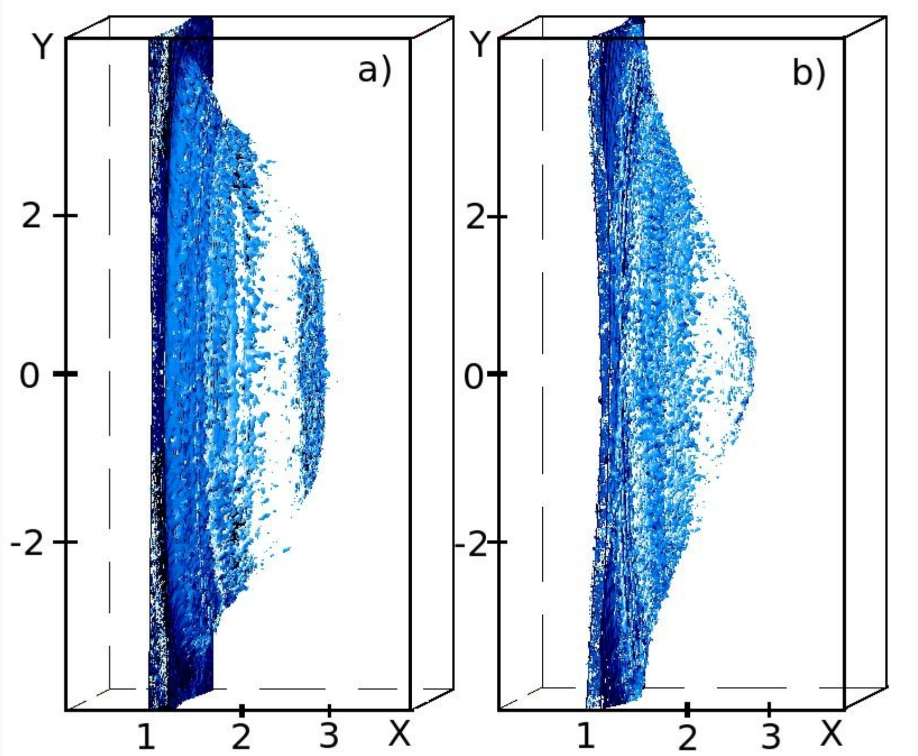




CP-RPA SIMULATIONS: 3D

3D simulations
left: Supergaussian spot profile
right: Gaussian

Note that only in 3D angular momentum conservation is taken into account



Simulation set-up:
- 320 X 1050 X 1050 grid, 80 points per wavelength
- 27 particles per cell, ~1.5X10^9 in total
- 182 PEs, ~360 Gbytes load

Lyseykina, Borghesi, Macchi, Tuveri, PPCF **50** (2008) 124033

RADIATION FRICTION EFFECTS

Motivation: Radiation Reaction (RR) aka Radiation Friction is important for ultra-relativistic particles in EM fields and is thus expected to play a strong role in next generation experiments at ultra-high intensities.

The typical intensity for relevant RR effects is estimated to be $\sim 10^{23}$ W/cm^2 . This corresponds, to the foreseen regime of RPA dominance (for Linear Polarization)
[Esirkepov et al, PRL **92** (2004) 175003]

Our approach: inclusion of Landau-Lifshitz RR force in PIC simulations (plus suitable approximations)
[M.Tamburini, F.Pegoraro, A. Di Piazza, C.H.Keitel, A.Macchi, preprint arxiv:1008.1685]

RADIATION REACTION MODELING

EoM with
Landau-Lifshitz force
in non-covariant notation

(Landau & Lifshitz,
The Classical Theory of Fields, par. 76)

$$
\begin{aligned}
\frac{d\mathbf{p}}{dt} &= -e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) \\
&\quad -e\tau_0\left[\gamma\left(\frac{d\mathbf{E}}{dt} + \frac{\mathbf{v}}{c}\times\frac{d\mathbf{B}}{dt}\right)\right. \\
&\quad -\frac{e}{m_e c}\left(\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\times\mathbf{B}\right) + \left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\mathbf{E} \\
&\quad \left.-\gamma^2\frac{e}{m_e c}\left(\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2 - \left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right)\mathbf{v}\right] \\
\tau_0 &= \frac{2e^2}{3m_e c^3}
\end{aligned}
$$

Numerical implementation benchmarked with the exact solution in a plane wave
[A.Di Piazza, Lett.Math.Phys. **83** (2008) 305]

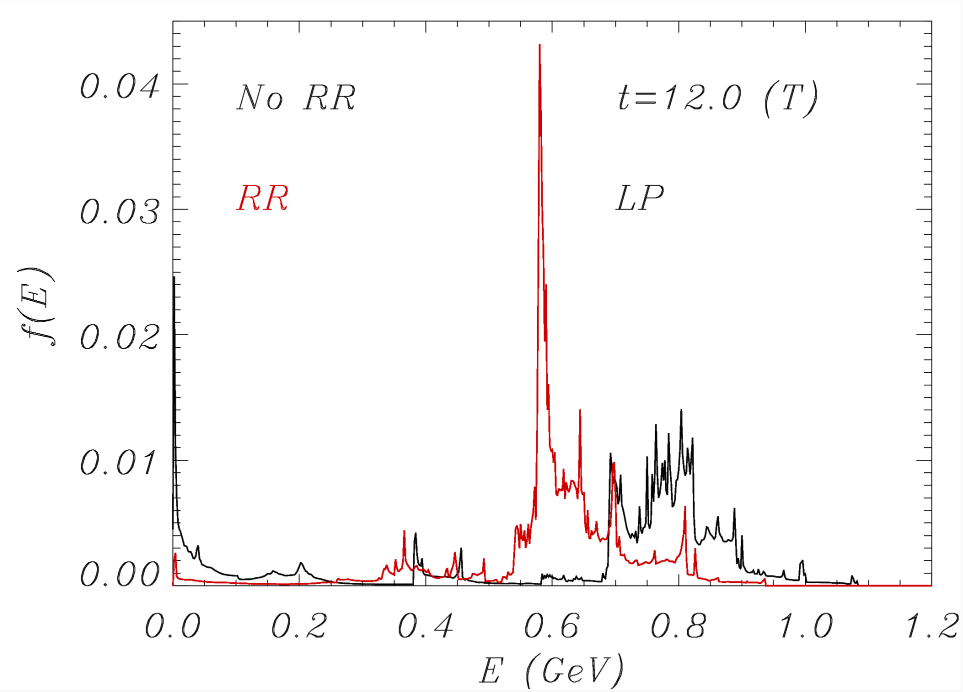
RR EFFECTS ON ION SPECTRA – II (CP)

RP-dominated regime: 2.3×10^{23} W/cm^2, 11 cycles pulse

1 um foil, $100n_c$, circular polarization

Negligible RR effects on ion spectrum!

Higher energy than in LP case



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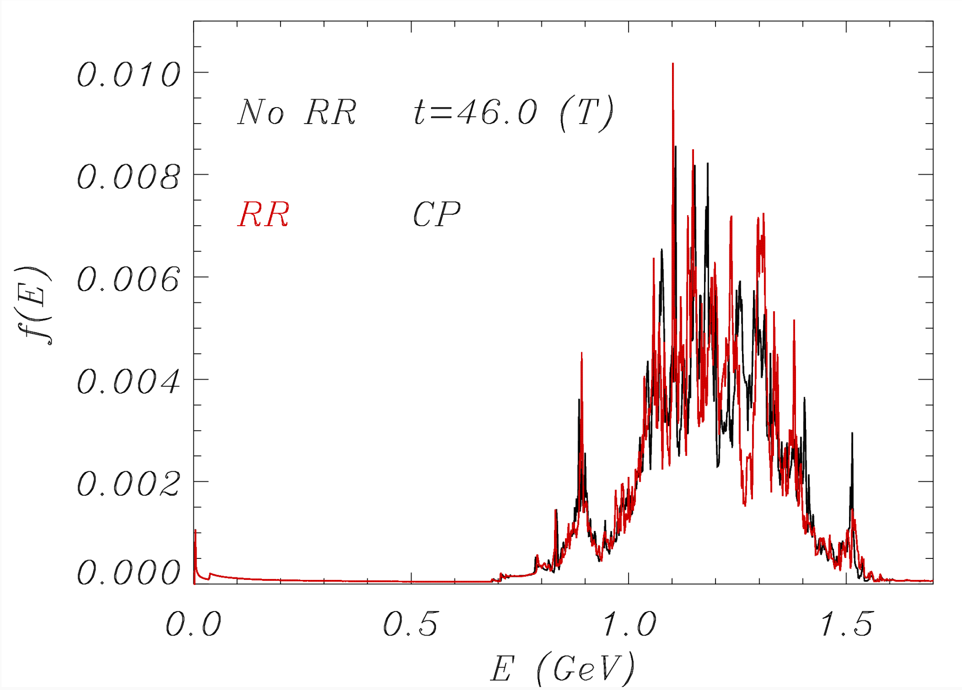


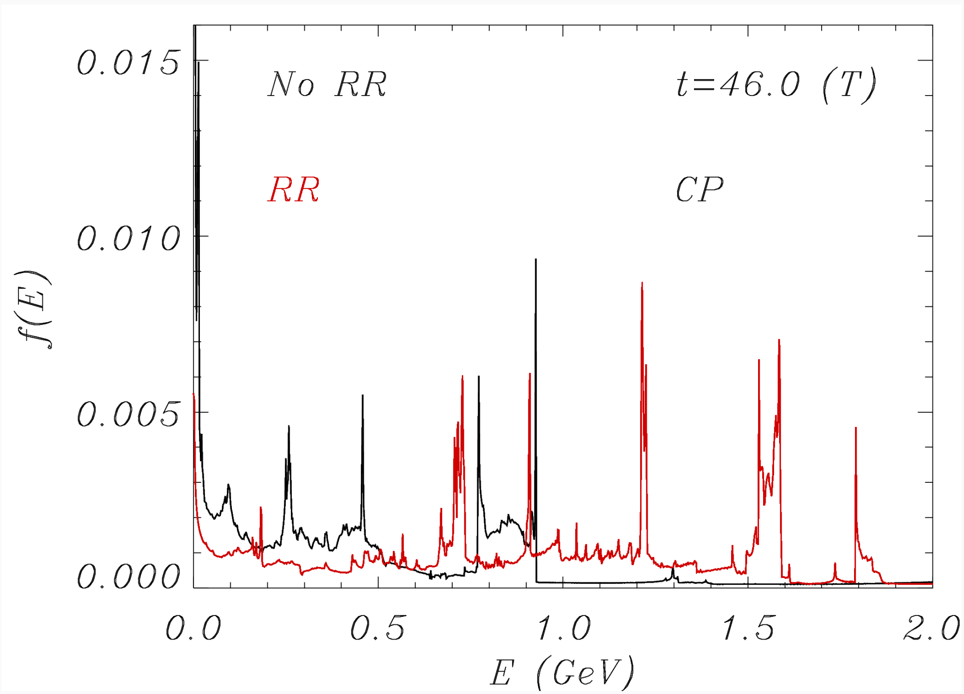
RR EFFECTS ON ION SPECTRA – III (CP)

RP-dominated regime: 2.3×10^{23} W/cm^2 , 11 cycles pulse

0.3 um foil, 100n_c , circular polarization

The pulse penetrates through the foil due to “relativistic” Self-Induced Transparency

RR effects are now important for CP and *increase* the ion energy, but the regime is *not* optimal for ion acceleration



CONCLUSIONS

- Impressive amount of experimental research on laser ion acceleration in the last 10 years
- Theory and simulation are able to support and promote experimental activities and developments
- Combining progress in laser systems (higher intensities, (cleaner) pulses with target engineering (ultrathin foils, structured/multispecies targets ...) offers new perspectives
- Increase of Supercomputing power allows more realistic, closer to experimental simulations

Lots of work remain to be done anyway...