Collisionless shock acceleration in near-critical and underdense plasmas

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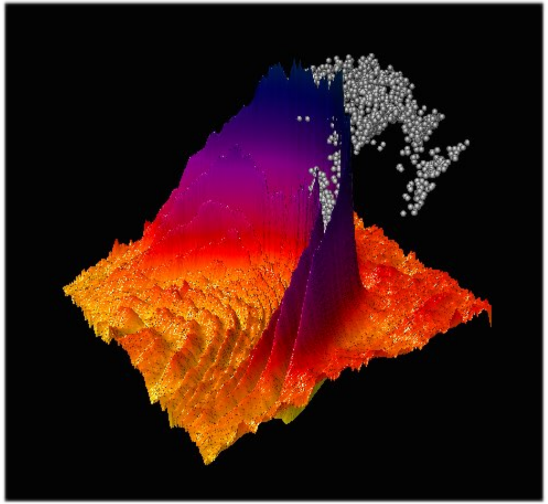


Acknowledgements

Work in collaboration with
F. Fiúza (SLAC, Menlo Park, CA),
A. Stockem (Ruhr-Universitat Bochum, Bochum, Germany),
P. Antici (Univeristà di Roma La Sapienza, Rome, Italy),
E. d'Humières (CELIA, Bordeaux, France),
S. Chen, J. Fuchs (LULI, Palaiseau, France),
R. Fonseca and **L.O. Silva** (IST, Lisbon, Portugal).

Simulation results obtained at
IST cluster (IST, Lisbon), SuperMUC (LRZ, Garching),
Juqueen (JSC, Julich) and Marconi (CINECA, Casalecchio di Reno)

Shock acceleration:
a possible route towards a table-top accelerator?

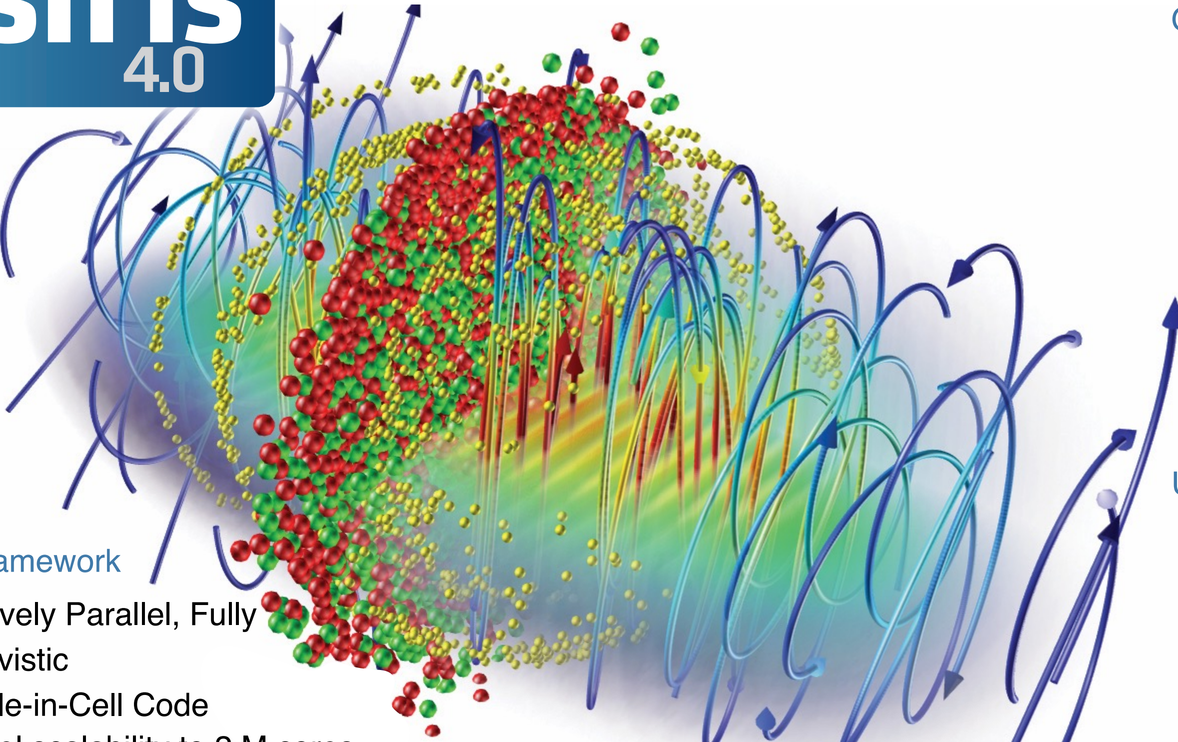
Shock acceleration has been demonstrated with critical targets

How shocks are generated?

What are the optimal conditions for ion acceleration?

D. Haberberger et al., Nat. Phys., 8, 95 (2012).

Committed to open science



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended physics/simulation models

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:

http://epp.tecnico.ulisboa.pt/osiris

Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

How to drive an electrostatic shock: 2D simulation setup

Laser parameters

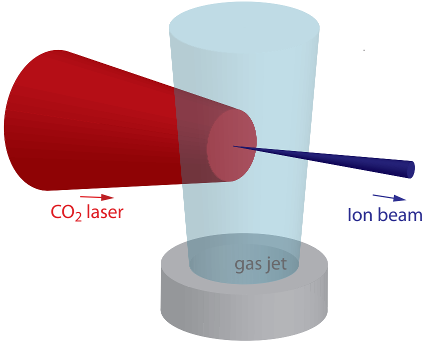
$I = 9 * 10^{16}$ W/cm^2
$\lambda_0 = 10$ µm
$a_0 = 2.5$
$\tau = 14$ ps $= 2640\ \omega_p^{-1}$
p - polarized

Plasma parameters

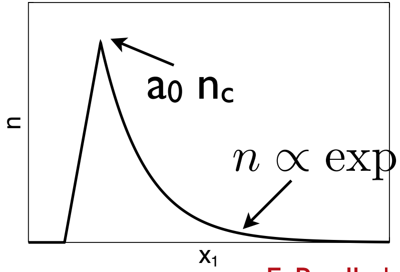
$L_x = 4000$ µm
$L_y = 200$ µm
$L_g = 200$ µm
$n_c = 10^{19}$ pp/cm^3
$m_i/m_e = 1836$

Simulation parameters

$L_x = 2500 * 120\ (c/\omega_p)^2$
$\Delta x = \Delta y = 0.25\ (c/\omega_p)$
$\Delta t = 0.2\ \omega_p^{-1}$
#ppc = 8 * 8
cubic interpolation



Longitudinal density profile



$$n \propto \exp\left(-\frac{x_1}{L_g}\right)$$

Intense heating and density steepening lead to the shock generation

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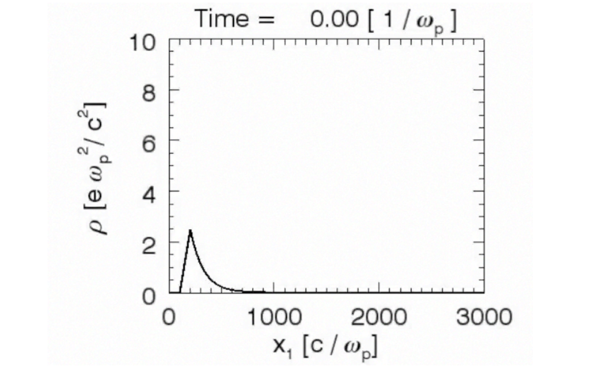
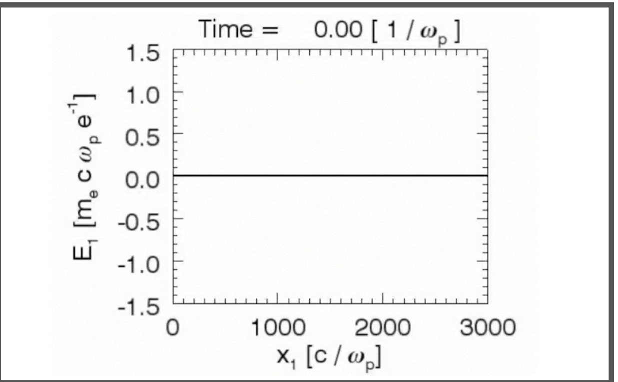
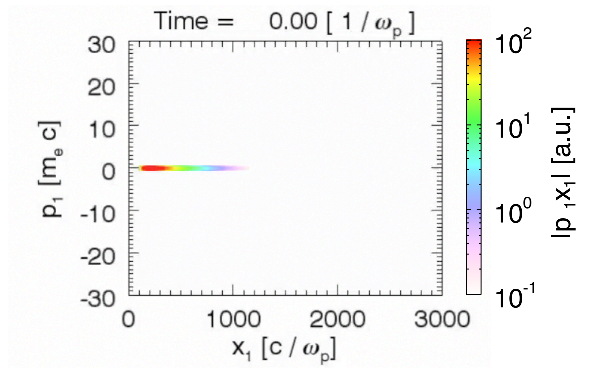
Ion density



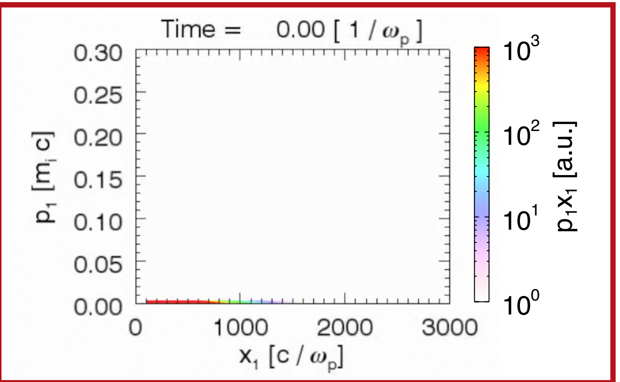
Electric field



e^- phase space



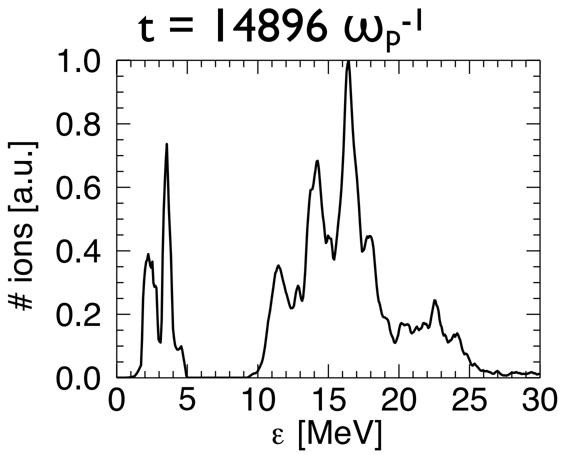
p^+ phase space



F. Fiúza, A. Stockem, E. Boella et al., Phys. Rev. Lett. 109, 215001 (2012).

Quasi-monoenergetic beam is obtained in tailored near-critical density plasmas

p^+ energy spectrum



ε = 16 MeV

$\Delta\varepsilon/\varepsilon$ = 15%

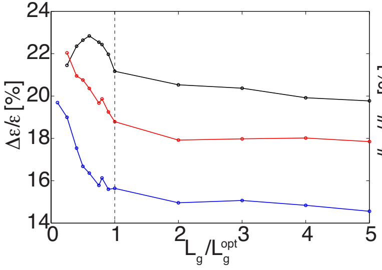
Q_{beam}/Q_{up} = 10%

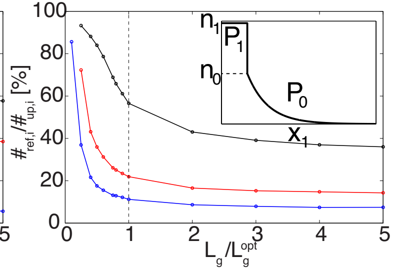
Requirements on the spatial scale of the rear plasma to achieve high-quality ions have been identified

Theoretical prediction on L_g^{opt}

Uniform shock velocity	Uniform ion reflection	Symmetric expansion	
$L_{\mathrm{target}} < \lambda_0 \sqrt{\frac{m_i}{m_e}}$	$L_g > \frac{2c_{s0}^2}{v_s c}\lambda_0 \sqrt{\frac{m_i}{m_e}}$	$L_{\mathrm{target}} \leq 2L_g$	$L_g^{\mathrm{opt}} \simeq \frac{\pi c}{\omega_{pi}}$

1D parameter scan in simplified setup confirms theoretical prediction on L_g^{opt}





T_{e0} = 0.08 MeV
T_{e0} = 0.2 MeV
T_{e0} = 0.5 MeV

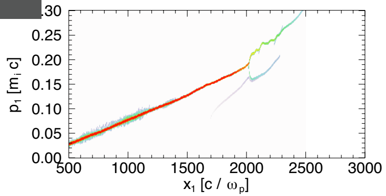
Shock driven by a density discontinuity; simulations performed with the shell algorithm (E. Boella et al., Comput. Phys. Commun. 224, 136 (2018).)

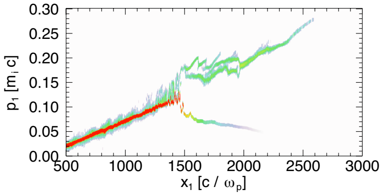
E. Boella et al., Plasma Phys. Contr. F. 60, 035010 (2018).

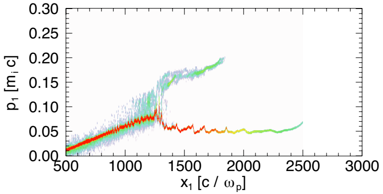
Optimal conditions for a quasi-monochromatic beam have been confirmed by 2D simulations of laser-driven shocks

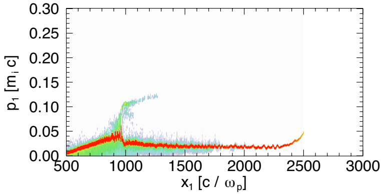
L_g^{opt} minimizes energy spread maximising the fraction of reflected ions

	$L_g = L_g^{opt}/2$	$L_g = L_g^{opt}$	$L_g = 2\ L_g^{opt}$	$L_g = 4\ L_g^{opt}$
ε_{avg} [MeV]	25	16	2.1	0.5
$\Delta\varepsilon/\varepsilon_{avg}$ [%]	30%	15%	15%	15%
Q_{beam}/Q_{up} [%]	80%	10%	0.04%	0.03%



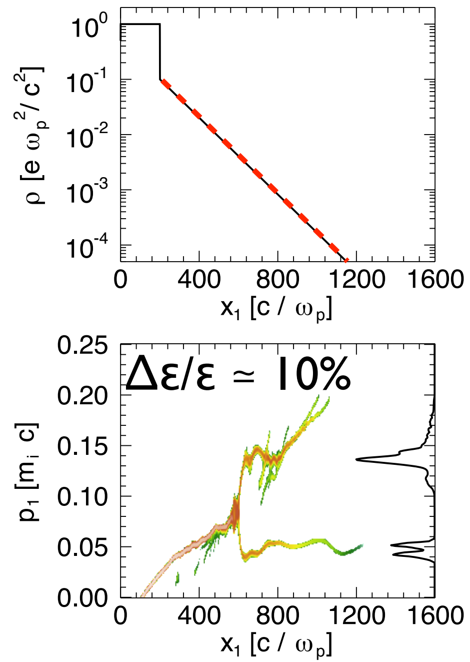




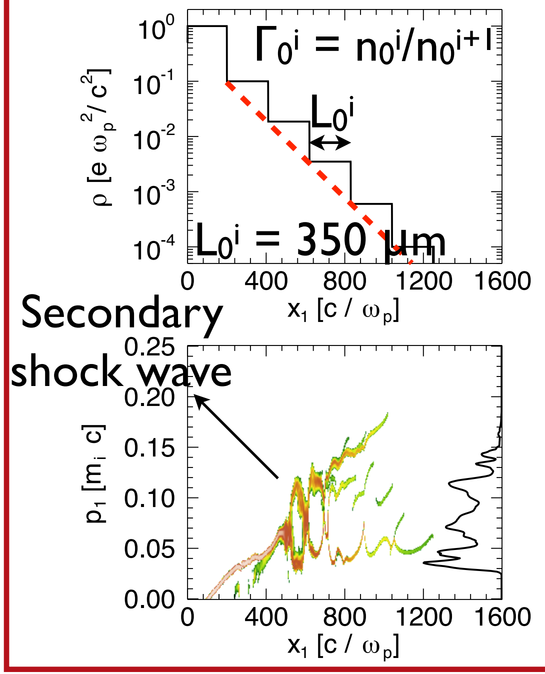


Engineering exponentially decaying profile with multi-layer plasmas

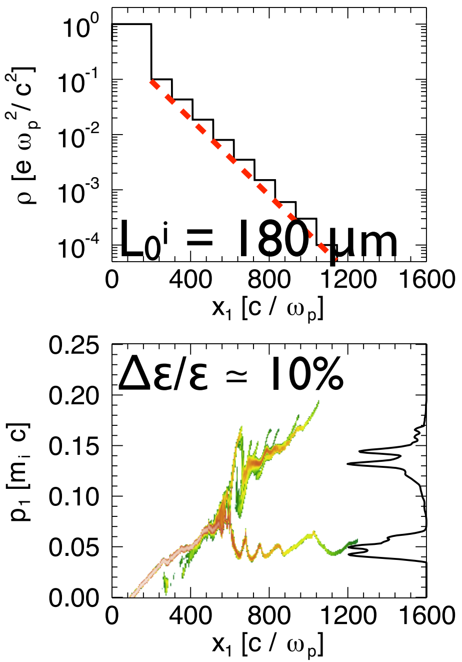
Exponential profile



$\Gamma_0^i = 5.4$



$\Gamma_0^i = 2.3$



E. Boella et al., Plasma Phys. Contr. F. 60, 035010 (2018).

In underdense plasmas with long plasma gradients shock is due to ion overtakings

3D simulation setup

$I = 10^{20}$ W/cm^2

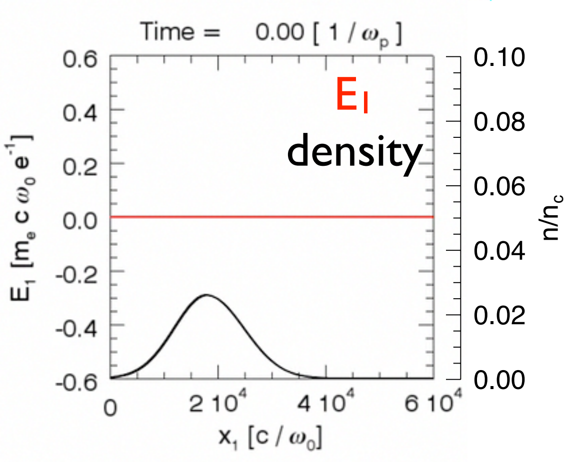
$\lambda_0 = 1.054$ µm

$a_0 = 8.959$

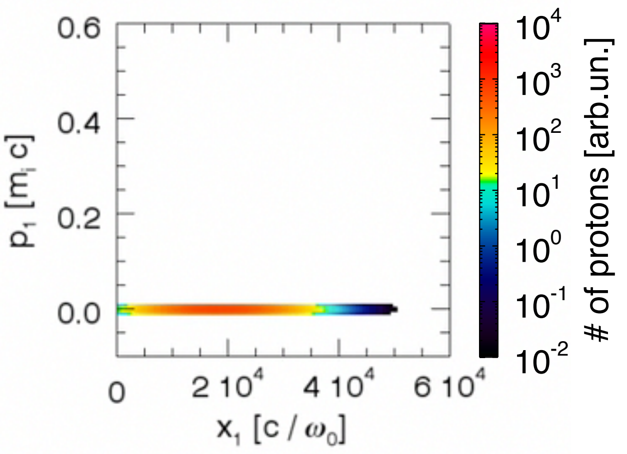
$\tau = 700$ fs $= 1252\ \omega_0^{-1}$

p - polarization

Electric field and density



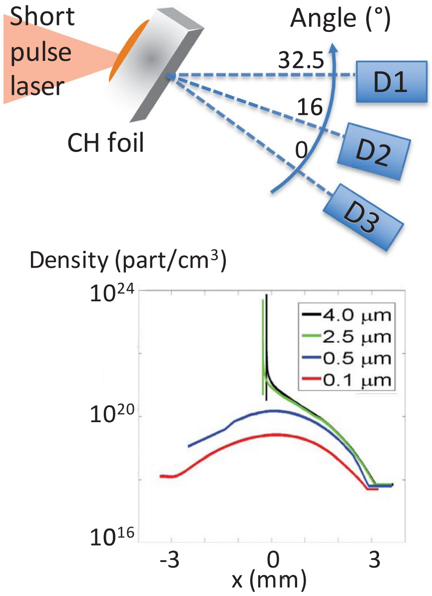
Longitudinal p+ phase space



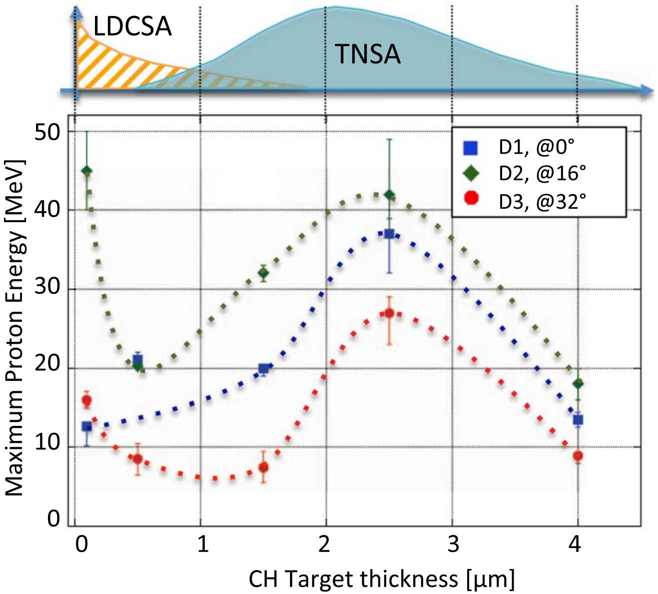
P. Antici, E. Boella et al., Sci. Rep. 7, 16463 (2017).

Experimental proof of Low Density Collisionless Shock Acceleration (LDCSA)

Experimental setup



p⁺ cut-off energy vs initial target thickness

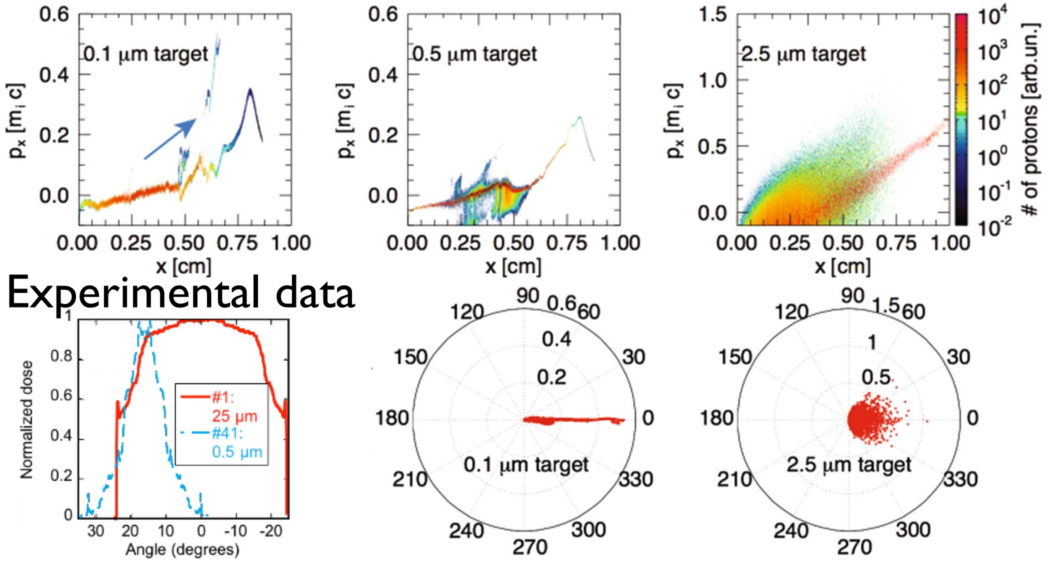


P. Antici, E. Boella et al., Sci. Rep. 7, 16463 (2017).

Simulations show that LDCSA is very effective in exploded thin targets

LDCSA accelerates ions with lower divergence compared to TNSA

Results @ t = 33.7 ps



P. Antici, E. Boella et al., Sci. Rep. 7, 16463 (2017).

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Summary

Shocks in near-critical density plasmas

Requirements for accelerating a good quality ion beam have been identified and verified in simulations.

A new engineered multi-layer configuration has been proposed and tested, showing that it will lead to a high quality ion beam.

Shocks in underdense plasmas

Low density collisionless shock acceleration has been demonstrated in laboratory and confirmed by numerical simulations.

The maximum proton energy is as high as in TNSA under the same conditions, but the beam presents a lower divergence.

For more exciting numerical and experimental work on laser-driven ion acceleration please check L. Gizzi's poster on Wednesday