Status and Trends in Laser-Plasma Acceleration of Ions

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Main coworkers for this talk

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T. V.Liseykina[4], P. Londrillo[5], S. Kar[6], M. Borghesi[6],
T. Ceccotti[7], V. Floquet[7], M. Passoni[3], F. Pegoraro[1,2]

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[2]CNR/INO, Pisa, Italy
[3]Dipartimento di Energia, Politecnico di Milano, Milan, Italy
[4]Institut fuer Physik, Universitaet Rostock, Germany
[5]INAF and INFN, Bologna, Italy
[6]Center for Plasma Physics, Queen’s University of Belfast, UK
[7]CEA/DSM/IRAMIS/SPAM/PHI, Saclay, France
[*]presently at MPI-K, Heidelberg, Germany

Outline of the talk

A short selection of recent experimental results and of our group's theoretical and simulation work loosely related to such experiments, on the following mechanisms:

- Radiation Pressure Acceleration (RPA)

$\Rightarrow$ exploring "unlimited" RPA in 3D

- Collisional Shock Acceleration (CSA):

$\Rightarrow$ conditions for monoenergetic acceleration

- Target Normal Sheath Acceleration (TNSA):

$\Rightarrow$ enhanced TNSA in foam-covered and grating targets

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Reviews of ion acceleration

A. Macchi, M. Borghesi, M. Passoni,
Superintense Laser-Plasma Ion Acceleration,
Rev. Mod. Phys. (2012), submitted.

H. Daido, M. Nishiuchi, A. S. Pirozhkov,
Review of laser-driven ion sources and their applications,
Rep. Prog. Phys. **75**, 056401 (2012).

Basic concepts of laser-driven ion acceleration - I

Target Normal Sheath Acceleration (TNSA):
targets: thin **solid** foil
Mechanism:
generation of *fast* electrons
creating a sheath at the target rear
So far the most studied
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Open issues:
-scaling to >150 MeV for applications?
- suitable for high repetition rate?

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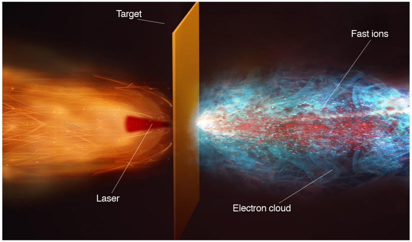

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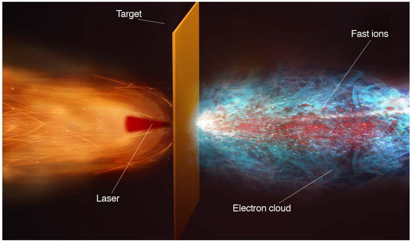

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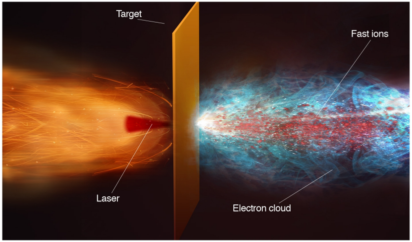

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"Light Sail" acceleration
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Radiation Pressure Acceleration (RPA)
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Very attractive for scaling
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Open issues:
- ultrahigh contrast to preserve foil
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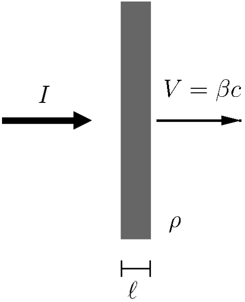

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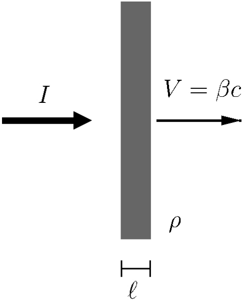

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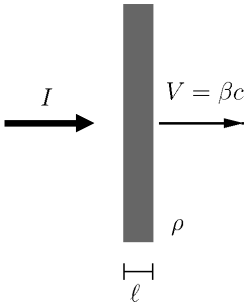

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Interaction with gas jet targets:

- optical fs laser
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[Fukuda et al, PRL **103**, 165002 (2009)]

- CO_2 laser with hydrogen jet:

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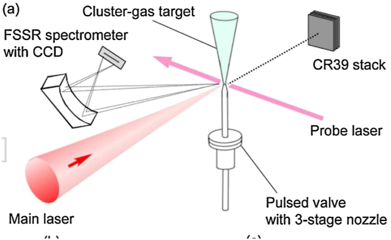

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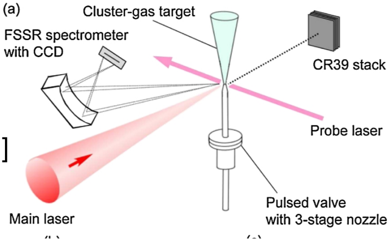

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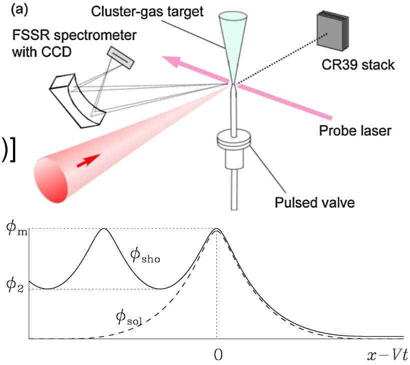

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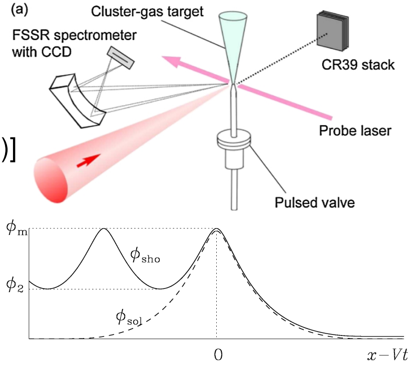

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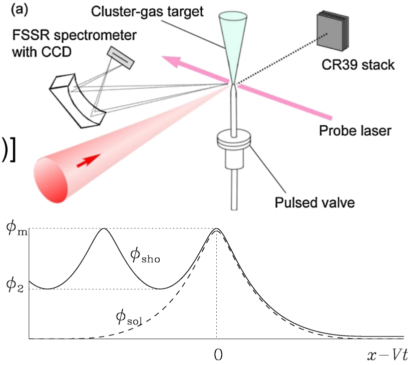

RPA of thin foils: Light Sail model

$$E_{\text{ion}}(t) \simeq \left(2It/\rho\ell c^2\right)^{1/3} \quad (t \to \infty)$$

$$E_{\max} \simeq m_p c^2 \mathscr{F}^2/(2(\mathscr{F}+1))$$

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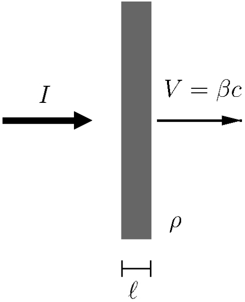

"Dream" features:

Favorable scaling with laser pulse fluence $\mathscr{F}$

100% efficiency in the relativistic limit

"Perfect" monoenergeticity for "rigid" coherent motion of the foil

Limits: "slow" energy gain, foil transparency and deformation

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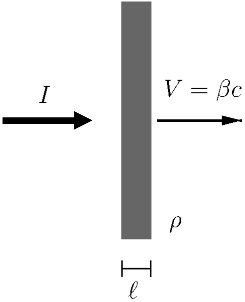

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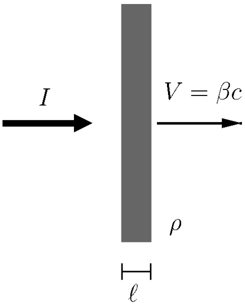

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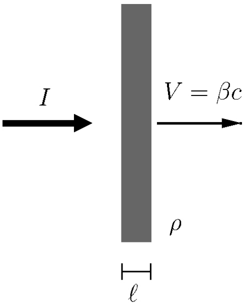

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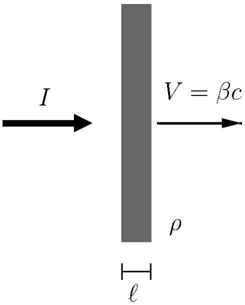

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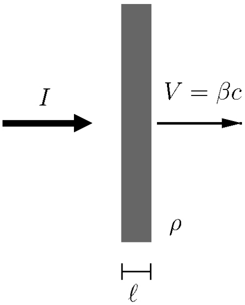

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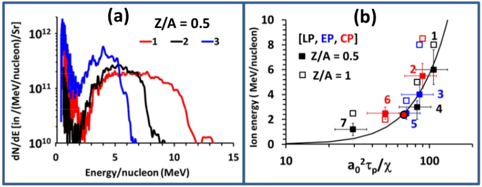

Laser pulse: $t_p \simeq 800\ fs$
3×10^{20} W cm^{-2}
$\sim 10^9$ contrast
Target: $\sim 0.1\ \mu$m metal foil
Multispecies ($Z/A = 1, 1/2$) peak observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Almost no laser polarization dependence observed

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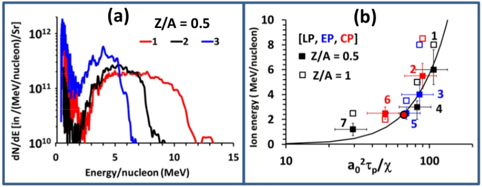

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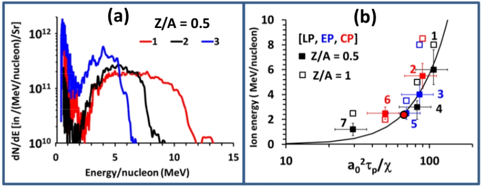

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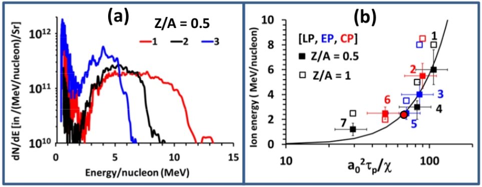

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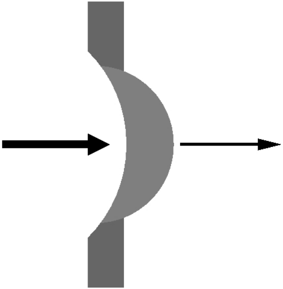
Transverse expansion of the target reduces surface density $\rho\ell$

$\Rightarrow$ "unlimited" acceleration possible at the expense of the number of ions

[Bulanov et al, PRL **104**, 135003 (2010)]

"Faster" gain $E_{\text{ion}}(t) \simeq \left(2It/\rho\ell c^2\right)^{3/5}$ predicted

Route to relativistic (>GeV) ions?



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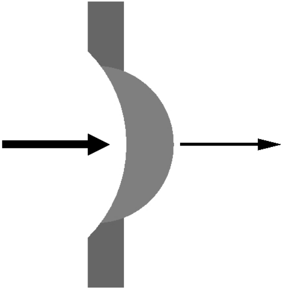

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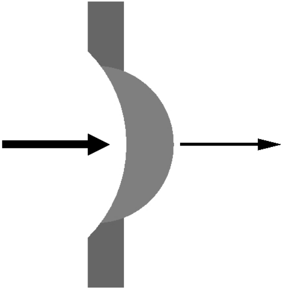

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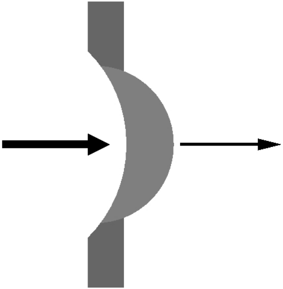

Open issues: polarization, geometry, radiation friction

- Early 3D simulation demonstration of RPA [Esirkepov et al, PRL **92**, 175003 (2004)] at $I > 10^{23}$ W cm^{-2} suggests polarization is inessential
- Unlimited acceleration later demonstrated by 2D simulation and circular polarization (CP) [Bulanov et al, PRL **104**, 135003 (2010)]
- Several studies (after [Macchi et al, PRL **94**, 165003 (2005)]) suggested use of Circular Polarization (CP) for RPA at $I = 10^{18} - 10^{21}$ W cm^{-2}; but also Linear Polarization (LP) may work [Qiao et al, PRL **108**, 115002 (2012)]
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$\Rightarrow$ Address polarization, RF and 3D effects in "unlimited" RPA

Open issues: polarization, geometry, radiation friction

- Early 3D simulation demonstration of RPA [Esirkepov et al, PRL **92**, 175003 (2004)] at $I > 10^{23}$ W cm^{-2} suggests polarization is inessential
- Unlimited acceleration later demonstrated by 2D simulation and circular polarization (CP) [Bulanov et al, PRL **104**, 135003 (2010)]
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Set-up of 3D RPA simulations

- Laser pulse: $(9T) \times (10\lambda)^2$ (FWHM) $[T = \lambda/c]$
  $\sin^2 \times$Gaussian shape, $a_0 = 280$ (198) for LP (CP),
  $\lambda = 0.8$ μm ($I = 1.7 \times 10^{23}$ W cm^{-2})
- Plasma: $\ell = 1\lambda$, $n_0 = 64n_c$, $Z = A = 1$
  Note: $a_0 \simeq \zeta = \pi(n_e/n_c)(\ell/\lambda)$
- RF included via Landau-Lifshitz force
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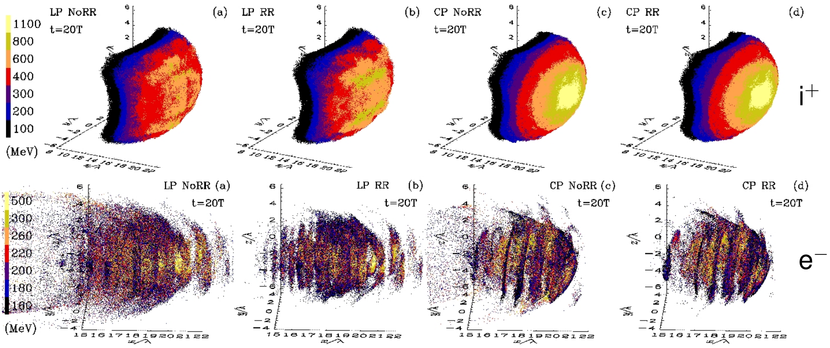
Space-energy distribution in 3D simulations



CP: symmetric, collimated ion distribution, weak RF effects

LP: asymmetric two-lobe ion distribution, strong RF effects

[Tamburini, Liseykina, Pegoraro, Macchi, PRE **85**, 016407 (2012)]

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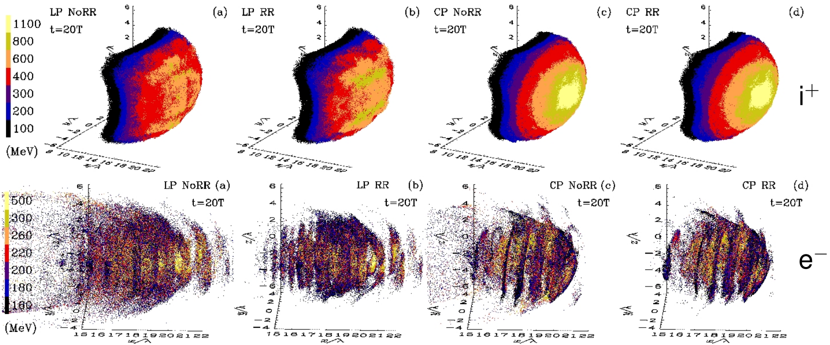

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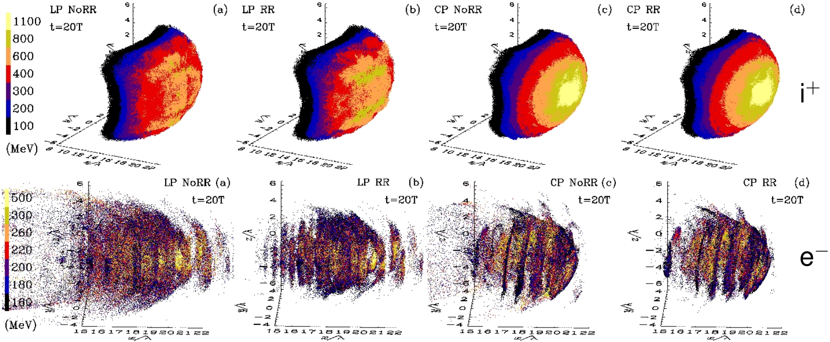

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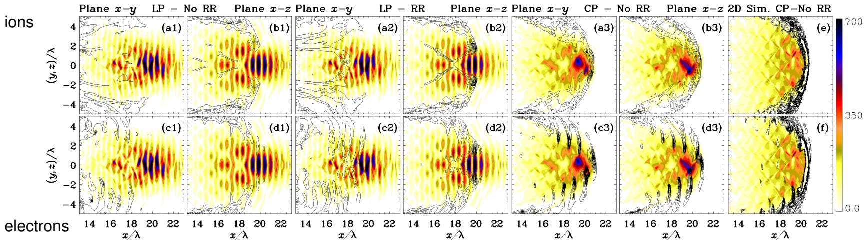
Pulse self-wrapping by the foil

Sections of 3D fields [a1)-d3)] vs 2D simulations [e)-f)]



Focusing of the pulse down to $\sim \lambda^3$ volume for CP [see series -3)]

“Wrapping” and focusing effects are weaker in 2D vs 3D [see e)-f)]

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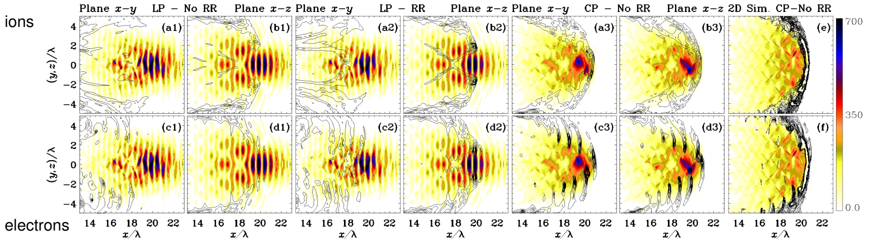

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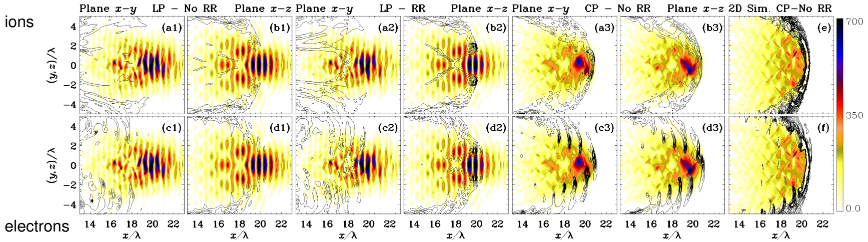

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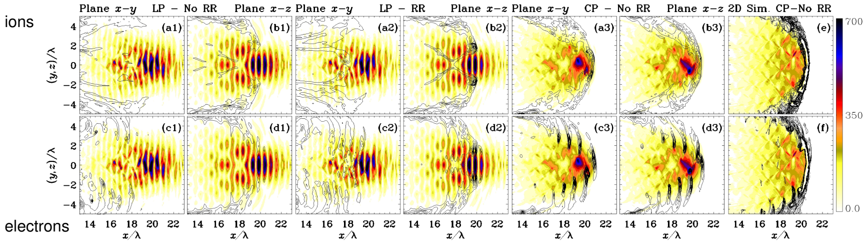

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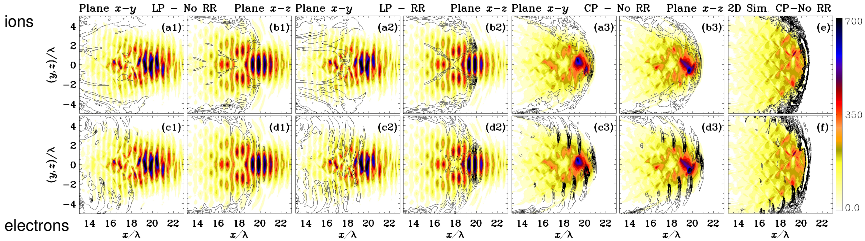

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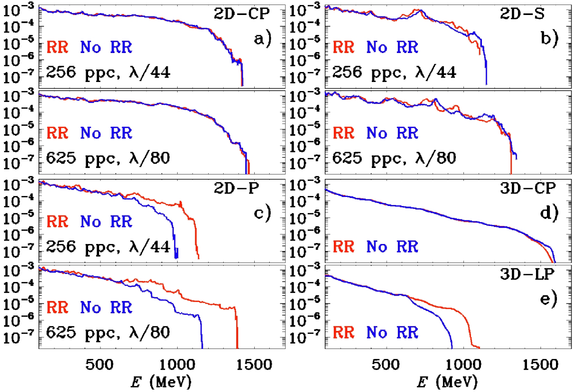
Comparison of 3D ion spectra with 2D results (both S and P for LP) for both the same and higher resolution



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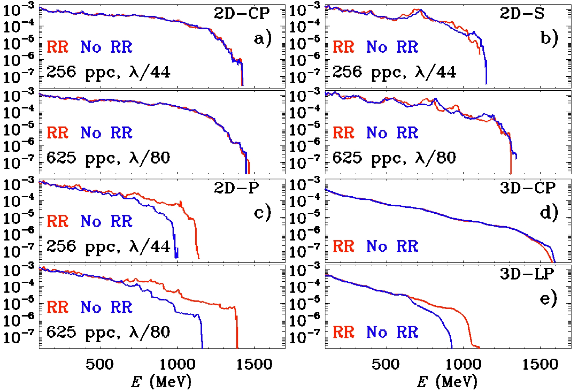

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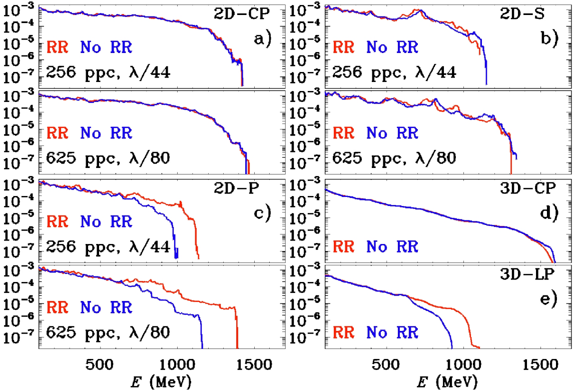

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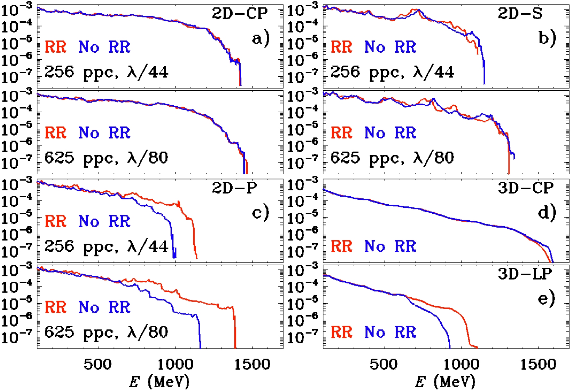

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- For CP: the energy cut-off corresponds to ions on axis and is *higher* in 3D than in 2D/1D

  1: more efficient rarefaction by transverse expansion

  2: increase of energy density on axis by pulse self-wrapping
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- Notice, however, that in the transparency regime high-energy ions have been observed (B.M.Hegelich and LANL team)

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- Basic idea: a Collisionless Shock Wave of velocity $\upsilon_s = Mc_s$ with $M > 1$ ($c_s = \sqrt{ZT_e/Am_p}$) is driven into an overdense plasma by either piston-like push of radiation pressure or "suprathermal" pressure of fast electrons
- Ion acceleration occurs in the plasma bulk by *reflection* from the shock front: $\upsilon_i \simeq 2\upsilon_s$ ("moving wall" reflection)
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Monoenergetic protons from CO_2 laser-gas interaction

[Haberberger et al,
Nat. Phys. **8**, 95 (2012)]

Laser: $\lambda = 10\ \mu$m
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modulated 100 ps train
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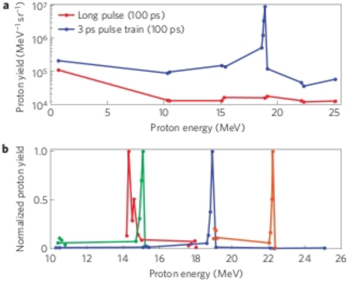
Target: H_2 jet, $n_0 \leq \times 4 \times 10^{19}$ cm^{-3}



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Very peaked spectra at $\sim$20 MeV
but with low number of ions

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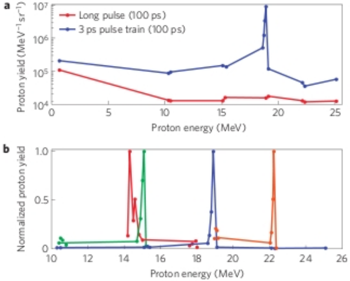

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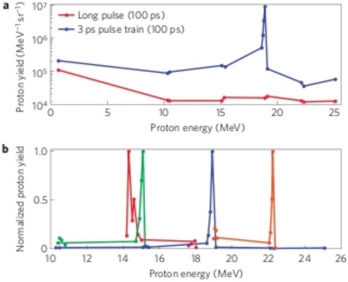

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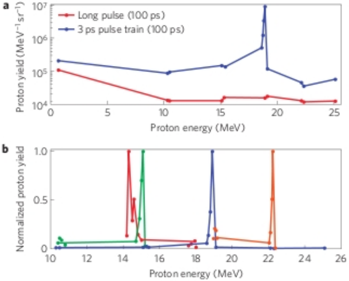

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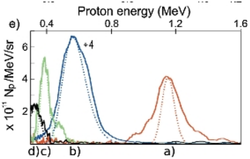

FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{cr}$, (b) $I = 5.5$, $n = 6.1n_{cr}$, (c) $I = 5.9$, $n = 7.6n_{cr}$, (d) $I = 5.7$, $n = 8.0n_{cr}$ (I in units of 10^{15} W cm^{-2}). (e) Background subtracted (solid lines) and also corrected (dashed lines) spectra. Heights of corrected spectra adjusted to match those of raw lineouts. Lineout corresponding to (b) reduced 4× to fit on the same scale.

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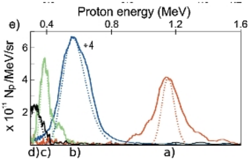
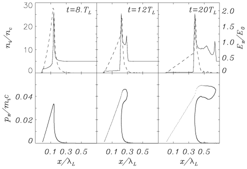


FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{cr}$, (b) $I = 5.5$, $n = 6.1n_{cr}$, (c) $I = 5.9$, $n = 7.6n_{cr}$, (d) $I = 5.7$, $n = 8.0n_{cr}$ (I in units of 10^{15} W cm^{-2}). (e) Background subtracted (solid lines) and also corrected (dashed lines) spectra. Heights of corrected spectra adjusted to match those of raw lineouts. Lineout corresponding to (b) reduced 4× to fit on the same scale.



Hints from Collisionless Shocks theory

[Tidman & Krall, *Shock Waves in Collisionless Plasmas* (Wiley, 1971)]

- Ion reflection may *not* form at all in the absence of reflected ions
- Background ions *must* have some energy spread otherwise they would *all* either reflected or not
- Reflected ions are on the tail of the ion distribution ($v_i > v_s - \sqrt{2e\Phi_{\rm M}/m_i}$ with $\Phi_{\rm M}$ shock potential barrier)
- Too many ions reflected may lead to shock loading

$\Rightarrow$ shock front slows down and monoenergeticity is lost

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CSA with warm ions: 1D simulation - I

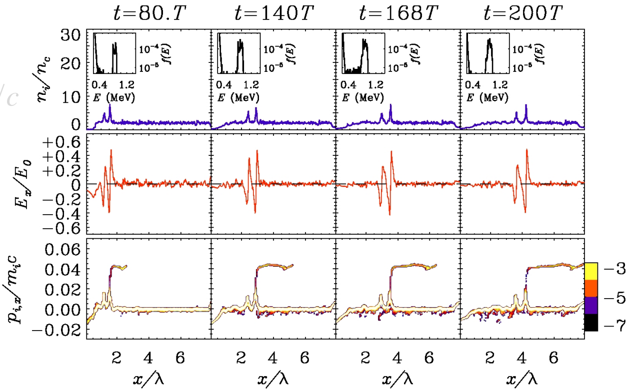
Parameters:

$a_0 = 1$

$\tau_p = 4T = 4\lambda/c$

$n_e = 2n_c$

$T_i = 100$ eV



Steady ion reflection produces a narrow energy spectrum

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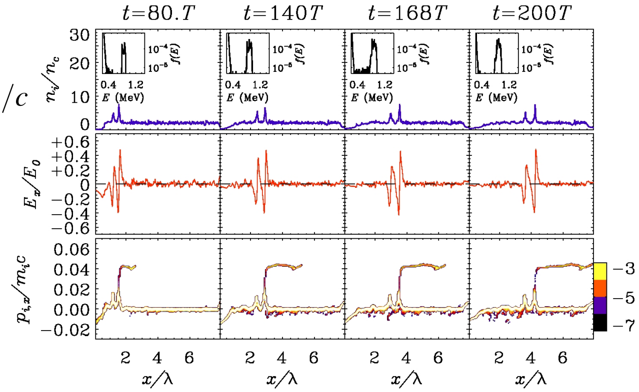

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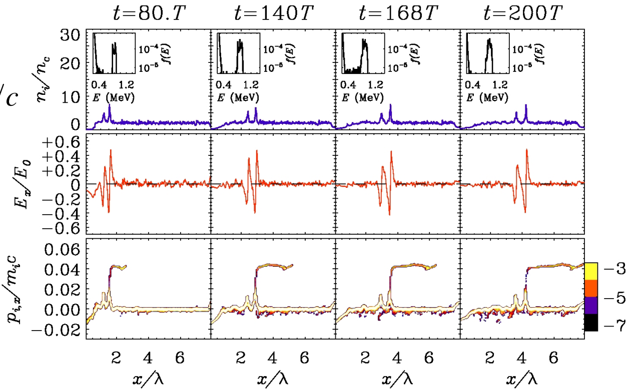

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CSA with warm ions: 1D simulation - II

Parameters:

$a_0 = 16$

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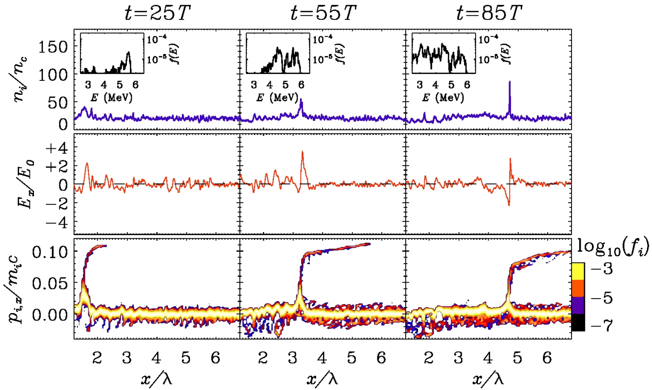

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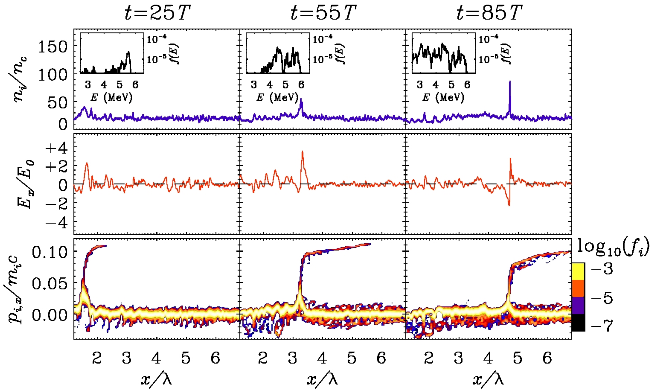

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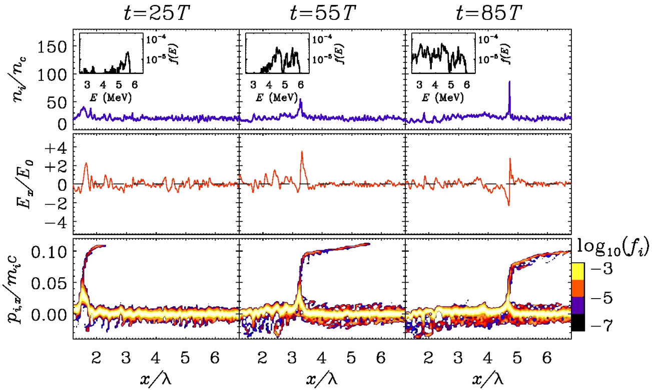

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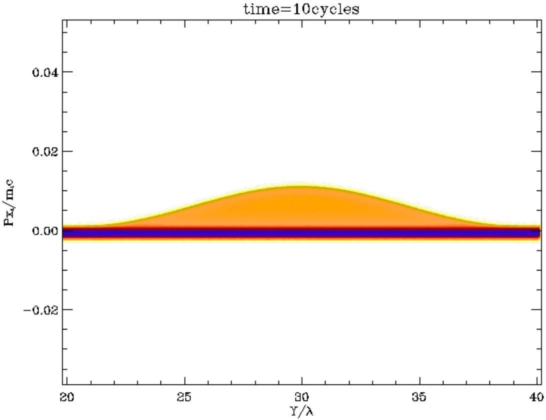
CSA with warm ions: 2D simulation (preliminary)

2D PIC simulation
laser pulse: $\tau_p = 45T$, $a_0 = 1$, $w = 5\lambda$
target: $n_e = 2n_c$, $T_i = 100$ eV, $Z/A = 1$

Same parameters as 1D (on axis) except lower resolution
($\Delta x = \lambda/100$, 100 part/cell)

CSA with warm ions: 2D simulation (preliminary)



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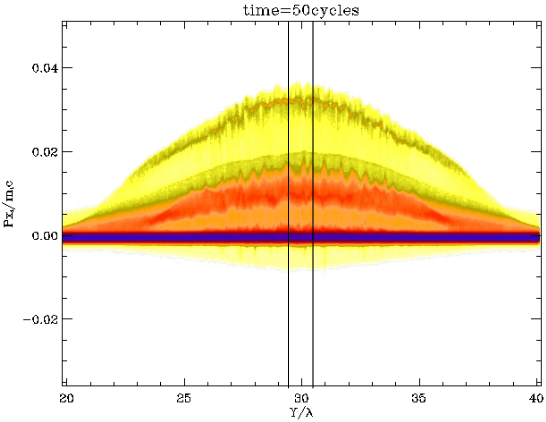

Ion spectrum near axis $29.4\lambda < y < 30.6\lambda$

Development of transverse "ripples"

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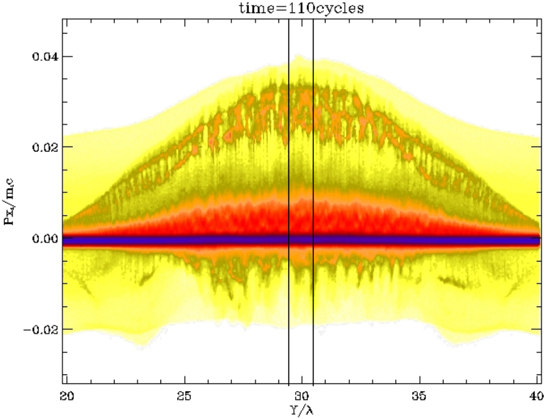

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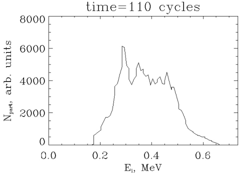

Reflected ions spectrum is much broader than in 1D

Promises and open issues with CSA

- Use of both gas laser and gas target is very suitable for high repetition rate
- Further theoretical investigation needed to understand shock front rippling and conditions for monoenergetic acceleration in 2D/3D
- More general issue: is it possible to have *both* efficiency and monoenergeticity in CSA?

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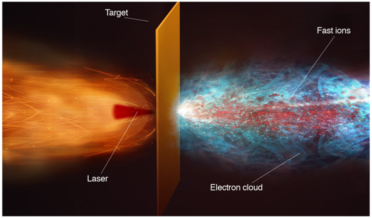
TNSA is driven by *fast* electrons generated at the *front* surface of solid targets

Key issue: increase conversion efficiency of laser energy in fast electrons



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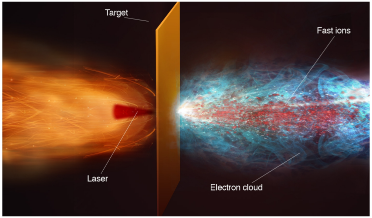

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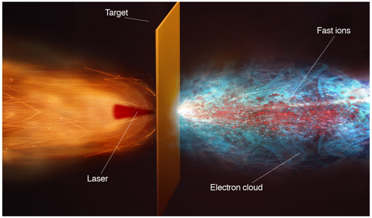

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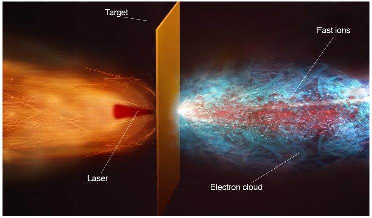

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Enhanced TNSA in microcone targets

[Gaillard et al, Phys.Plasmas **18**, 056710 (2011)]
Experiment at TRIDENT, LANL (USA)

Use of cone target leads to
- effective grazing incidence
$\Longrightarrow$ more efficient
fast electron generation
- geometrical collimation of
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Up to 67.5 MeV protons observed with 80 J pulse energy

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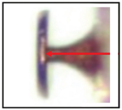

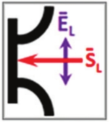

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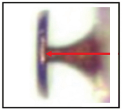

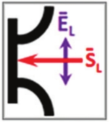

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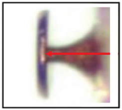

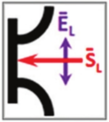

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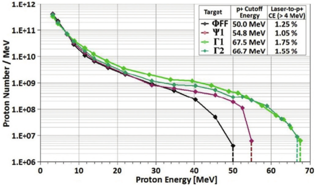

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Self-generated channel
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$\mathscr{E}_{\text{max}}$ doubles with foam
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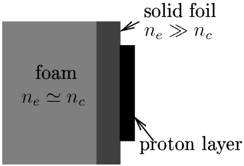

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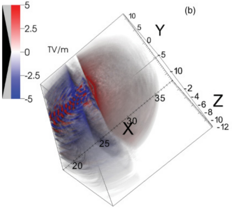

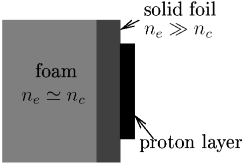

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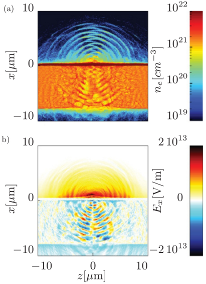

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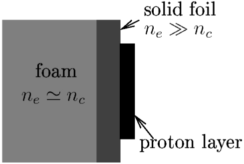

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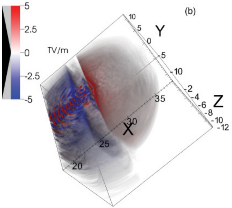

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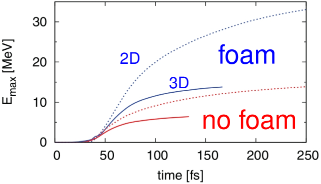

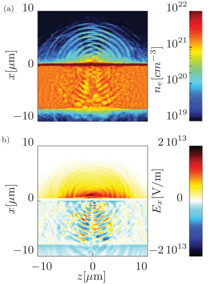

Foam-enhanced fast electron generation

2D parametric simulations:

Optimal foam mass density $n_e\ell$ exists
to enhance fast electron generation

fast electron temperature $T_f \gtrsim 3T_p$
where $T_p = m_e c^2 \left(\sqrt{1 + a_0^2/2} - 1\right)$

P-component of $\mathbf{E}$
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Remarkable similarity with cone-enhanced acceleration

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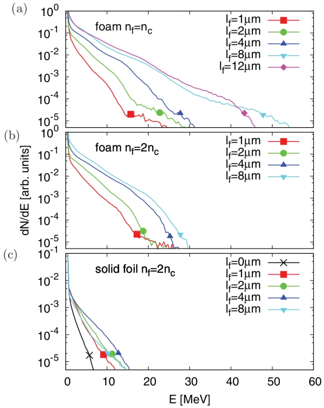

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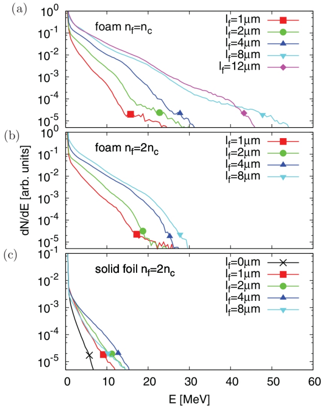

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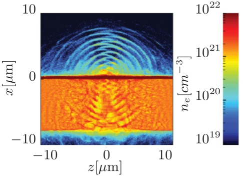

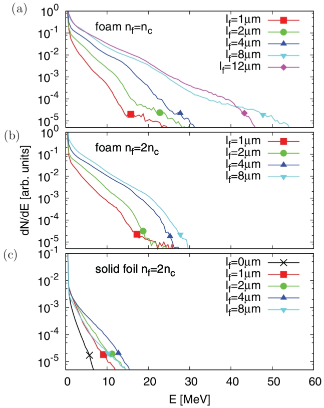

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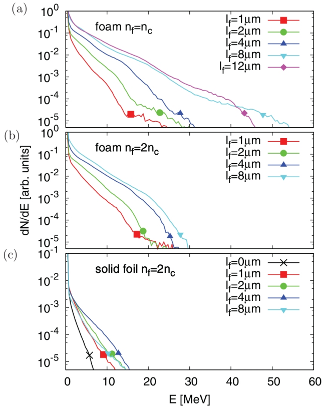

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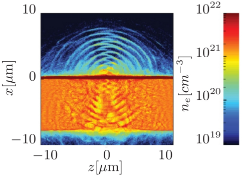

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Enhanced absorption in grating targets

Irradiating grating targets at resonant angle
(30° for $d = 2\lambda$)
leads to resonant
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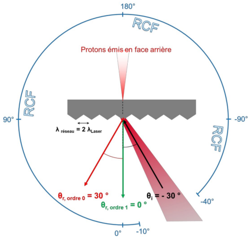
- high absorption
- enhanced fast electron generation
  (with emission at peculiar angles

2D PIC simulations by A.Sgattoni

Enhanced absorption in grating targets



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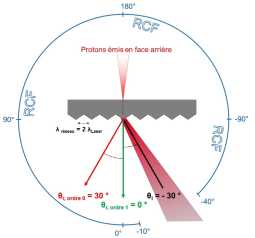

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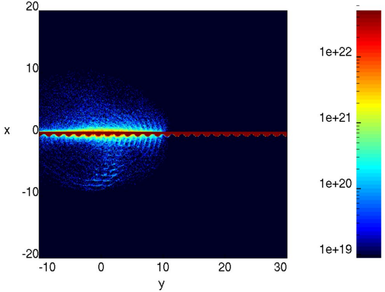

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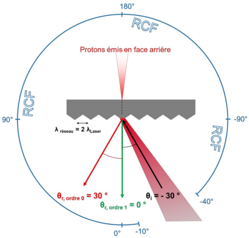

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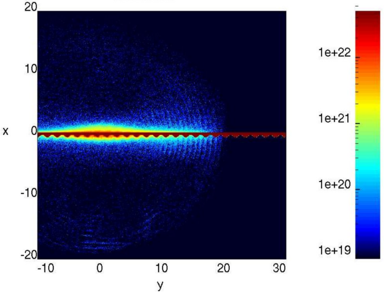

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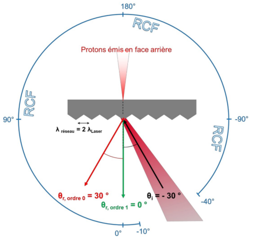

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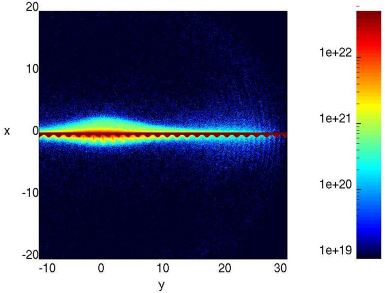

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(laser UHI, 28 fs, 5×10^{19} W cm^{-2}, contrast $\sim 10^{-12}$)

Enhancement of proton
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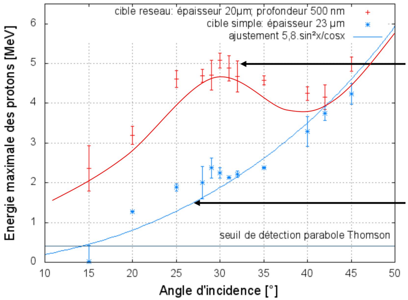

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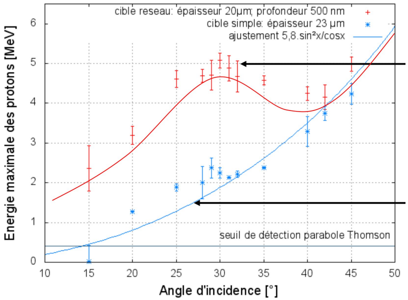

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$\longrightarrow$ need to improve spectrum, increase acceleration length, ...

CSA: Attractive because of monoenergetic spectra and for gas-based scheme at high repetition

$\longrightarrow$ may be not efficient enough for applications

TNSA: Most tested mechanism, structured targets (foams, gratings, ...) may increase energy and efficiency

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Acknowledgments

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