A Review of Superintense Laser-Driven Ion Acceleration (part two)

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Outline of Part Two

A short selection of recent experimental and simulation work mostly oriented to “advanced” schemes of ion acceleration:

- enhanced TNSA in foam-covered and grating targets
  Target Normal Sheath Acceleration (TNSA):

$\Rightarrow$ surface wave coupling in the relativistic regime

- ”Light Sail” radiation pressure acceleration (LS-RPA)

$\Rightarrow$ observation of “fast” scaling in multispecies target

$\Rightarrow$ exploring “unlimited” RPA in 3D simulation

- Collisionless Shock Acceleration (CSA):

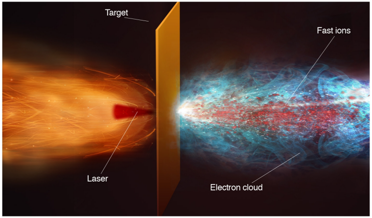
$\Rightarrow$ conditions for monoenergetic acceleration

Open challenges for ion acceleration

- increase maximum energy per nucleon $\mathscr{E}_{\text{max}}$
  - >100 MeV for hadrontherapy
  - >1 GeV for particle physics
- increase efficiency ($> 10\%$ for fast ignition in fusion)
- enable high repetition rate (for medical applications, …)
- achieve monoenergetic spectra
- …

TNSA: enhancing fast electron generation

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

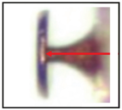


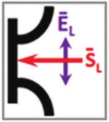
Key issue: increase conversion efficiency of laser energy in fast electrons

A strategy: special targets (mass-reduced, microstructured, low-density, . . .)

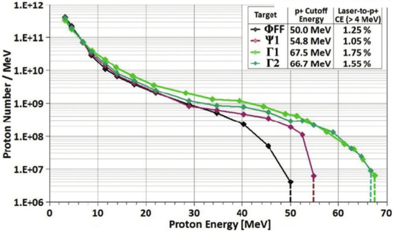
Enhanced TNSA in microcone targets

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





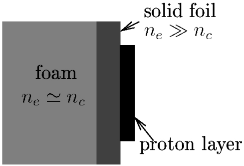
Use of cone target leads to
- effective grazing incidence
$\Longrightarrow$ more efficient fast electron generation
- geometrical collimation of fast electrons ("funnel" effect)



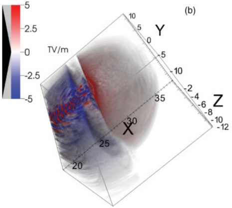
Up to $\mathscr{E}_{\text{max}}$=67.5 MeV protons observed with 80 J pulse energy
New world record in $\mathscr{E}_{\text{max}}$ after LLNL Petawatt experiments
[Snavely et al. PRL **85**, 2945 (2000)]

Enhanced TNSA in foam-covered targets

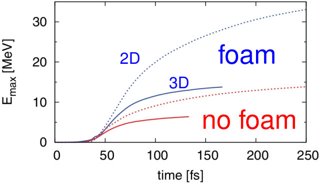
[Sgattoni, Londrillo, Macchi, Passoni, PRE **85**, 036405 (2012)]

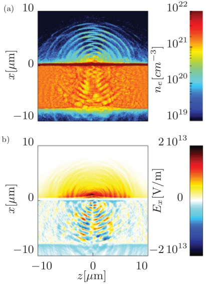


Self-generated channel behaves similar to cone



$\mathscr{E}_{\max}$ doubles with foam up to 15 MeV in 3D simulation with 1 J energy pulse



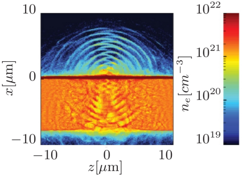


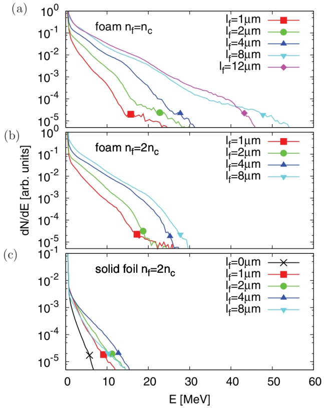
Foam-enhanced fast electron generation

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 $\mathbf{E}$
accelerates electrons
(coupling with
channel walls)



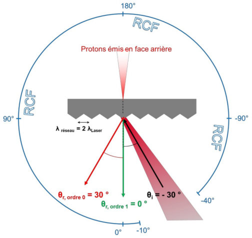


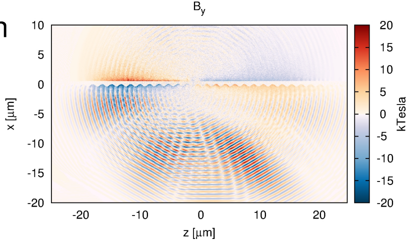
Remarkable similarity with cone-enhanced acceleration

Enhanced absorption in grating targets

Irradiating grating targets at resonant angle (30° for $d = 2\lambda$) leads to surface wave excitation (according to *linear*, *non-relativistic* theory)

- high absorption
- enhanced fast electron generation (with emission at peculiar angles)





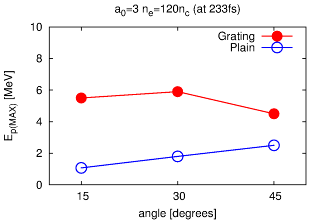
2D PIC simulations by A.Sgattoni

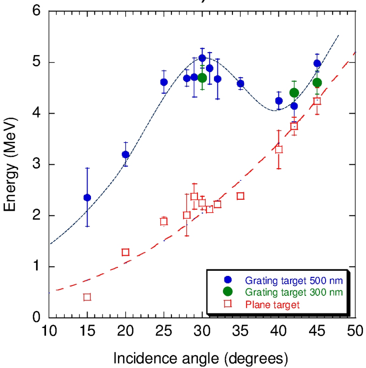
Enhanced proton emission in grating targets

LaserLAB EU experiment at SLIC facility, CEA Saclay (F)
(laser UHI, 28 fs, 5×10^{19} W cm^{-2}, contrast $\sim 10^{-12}$)

Enhancement of $\mathscr{E}_{\text{max}}$ by ~ 2.5X

in a broad aperture around θ_{res}
Fair agreement with 2D simulations

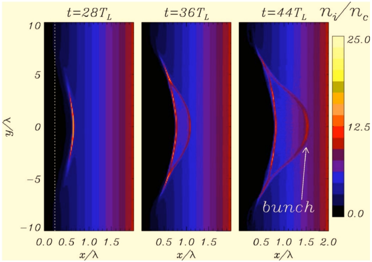




T.Ceccotti, V.Floquet, A.Sgattoni, A.Macchi et al, in preparation

Radiation Pressure Acceleration

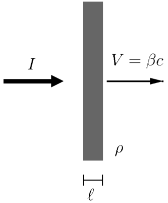
Light pressure effects dominates over TNSA at ultrahigh intensities ($> 10^{23}$ W/cm^{-2}) or when *Circular Polarization* is used (no fast electrons!)



Two RPA regimes:

Hole Boring: thick target, “piston” push of the plasma surface

Light Sail: thin target, whole push of foil

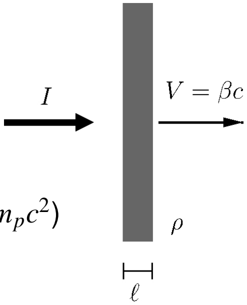


Light Sail "accelerating mirror" model

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

$$\mathscr{F} = 2(\rho\ell)^{-1} \int_0^\infty I(t')dt' \simeq 2I\tau_p/\rho\ell$$

$$E_{\text{ion}}(t) \propto \left(2It/\rho\ell c^2\right)^{1/3} \quad (t \gg \rho\ell c^2/I \,,\, E_{\text{ion}} > m_p c^2)$$



"Dream" features:

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

100% efficiency in the relativistic limit

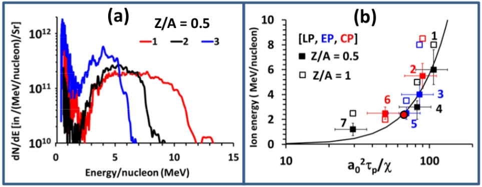
"Perfect" monoenergeticity for "rigid" coherent motion of the foil

Need of ultrathin (nm) foild and ultrahigh contrast pulses

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

RPA-LS: $\mathscr{F}^2$ scaling observed

$\mathscr{E}_{\text{max}} \sim \mathscr{F}^2$ (for $\mathscr{F} \ll 1$)



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

Experiment performed at VULCAN laser, RAL/CLF, UK

S.Kar, K.F.Kakolee, B.Qiao, A.Macchi, M.Borghesi et al.,

Phys. Rev. Lett. **109**, 185006 (2012)

Pushing LS forward: "unlimited" acceleration?

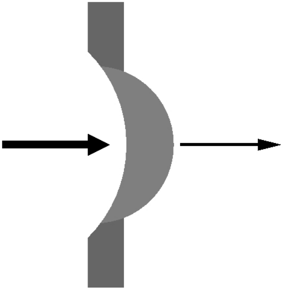
Transverse expansion of the target reduces surface density $\rho\ell$

$\Rightarrow$ "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?



Limitation: relativistic transparency when $a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda}$

Optimal trade-off when $a_0 \simeq \zeta$

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)]
- Radiation Friction (RF) important at $I > 10^{23}$ W cm^{-2} ?

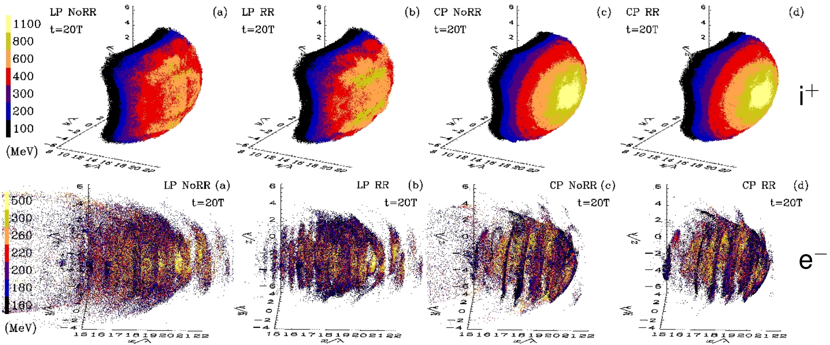
$\Rightarrow$ Address polarization, RF and 3D effects in "unlimited" RPA

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
- Numerical: $1320 \times 896 \times 896$ grid, $\Delta x = \Delta y = \Delta z = \lambda/44$,
  $\Delta t = T/80 = \lambda/80c$, 216 particles per cell (for both e and p),
  1.526×10^{10} in total

Runs performed on 1024 processors (1.7 GBytes each) of IBM-SP6 at CINECA (Italy)

Space-energy distribution in 3D simulations



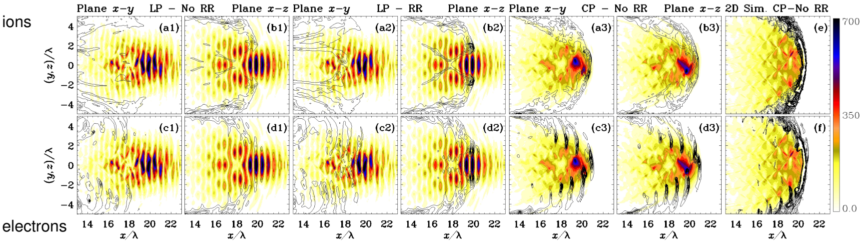
CP: symmetric, collimated ion distribution, weak RF effects

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

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

Pulse self-wrapping by the foil

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



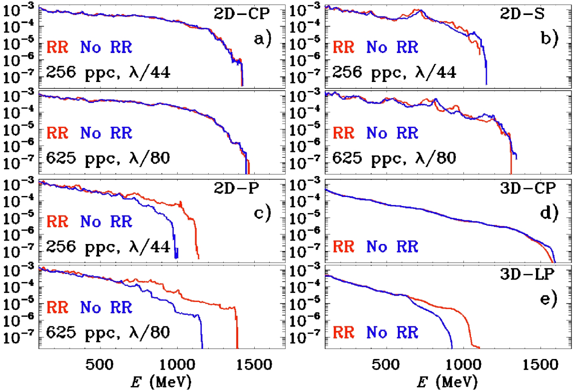
Focusing of the pulse down to $\sim \lambda^3$ volume for CP [see series -3)]

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

Breakthrough in the foil occurs for LP [see series -1)-2)]

Effects of reduced dimensionality and resolution

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



Effects of 2D vs 3D and of limited resolution are evident, but kept below physical effects

The "optimal" CP case is the most robust (but energy is *lower* in 2D vs 3D !)

Unlimited acceleration confirmed (and enforced?)

- 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
- CP optimizes ion acceleration (collimated distribution, negligible RR effects) with respect to LP
- Breaking of the pulse through the foil destroys RPA

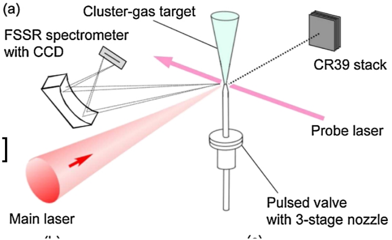
- *Notice, however, that in the transparency regime high-energy ions have been observed*
  (B.M.Hegelich and LANL team, "Break-Out Afterburner" regime – $\mathscr{E}_{\text{max}} > 100$ MeV communicated)

Ion acceleration with gas-jet targets

Interaction with gas jet targets:

- optical fs laser
  with clusters in the jet

[Fukuda et al, PRL **103**, 165002 (2009)]



- CO_2 laser with hydrogen jet:

Hole Boring or Shock Acceleration

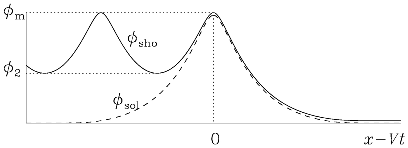
in moderately overdense plasmas ($n_e \gtrsim n_c \simeq 10^{19}$ cm^{-3})

Open issues:

- scaling to >150 MeV for applications?
- energy conversion efficient enough?

Collisionless Shock Acceleration

- Basic idea: a Collisionless Shock Wave of velocity $v_s = Mc_s$ 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: $v_i \simeq 2v_s$ ("moving wall" reflection)
  - Reflected ions are *monoenergetic* if v_s is constant and have multi–MeV energy if $T_e \simeq m_e c^2 \left(\sqrt{1 + a_0^2/2} - 1\right)$

Monoenergetic protons from CO_2 laser-gas interaction

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

Laser: $\lambda = 10\ \mu$m

$I = 6.5 \times 10^{16}$ W cm^{-2}

modulated 100 ps train of 3 ps pulses

Target: H_2 jet, $n_0 \leq \times 4 \times 10^{19}$ cm^{-3}

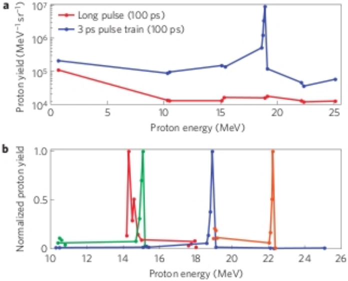


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within the monoenergetic peak was 2.5×10^5. **b**, The details of the energy spectra on four different laser shots with different macropulse structures (number of pulses and a_0 values ranging from 1.5 to 2.5).

Very peaked spectra at ~20 MeV but with low number of ions

Is efficiency of CSA not compatible with monoenergeticity?

More on CO_2 experiments: CSA or RPA?

Monoenergetic acceleration [Palmer et al, PRL **106**, 14801 (2011)] attributed to a "radiation pressure driven shock" using *circular* polarization

But no CSA in the bulk is observed using CP since $T_e \simeq 0$; the mechanism may be "hole boring" ("piston") RPA [Macchi et al, PRL **94**, 165003 (2005); Macchi, Nindrayog, Pegoraro, PRE **85**, 046402 (2012)]

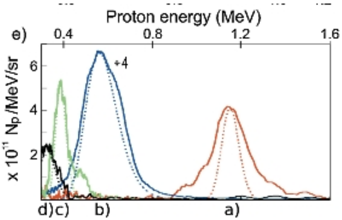


FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{cr}$, (b) $I = 5.5$, $n = 6.1n_{cr}$, (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* be either reflected or not
- Reflected ions are on the tail of the ion distribution ($v_i > v_s - \sqrt{2e\Phi_\mathrm{M}/m_i}$ with Φ_M shock potential barrier)
- Too many ions reflected may lead to shock loading

$\Rightarrow$ shock front slows down and energy spectrum is "chirped" towards low energy

- Search for optimal trade-off ion temperature T_i : energy spread vs. number of ions

CSA with warm ions: 1D simulation - I

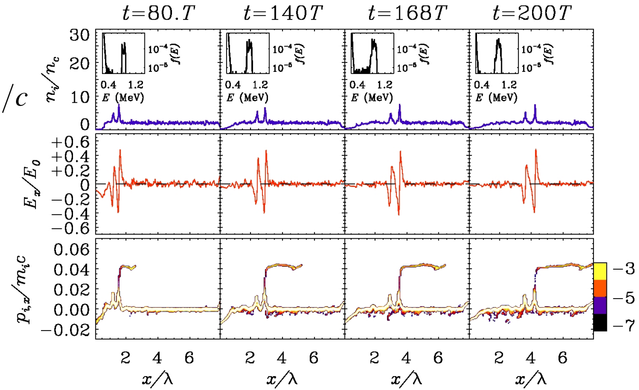
Parameters:

$a_0 = 1$

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

$n_e = 2n_c$

$T_i = 100$ eV



Steady ion reflection produces a narrow energy spectrum

CSA with warm ions: 1D simulation - II

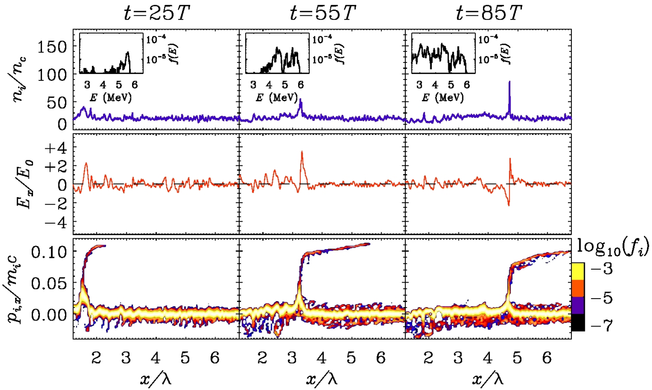
Parameters:

$a_0 = 16$

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

$n_e = 20n_c$

$T_i = 1$ keV

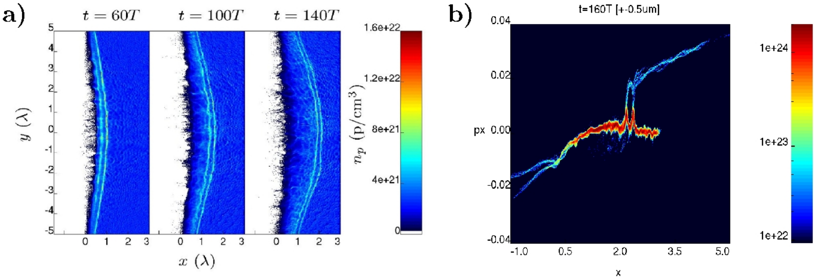


Too high T_i causes shock to slow down and spectrum to broaden

CSA with warm ions: 2D simulation

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

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



Strong “chirping” observed in 2D $\rightarrow$ no monoenergetic spectrum

Spectral broadening related with transverse “rippling”?

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: efficiency and monoenergeticity in CSA seem hardly compatible

  (many reflected ions $\leftrightarrow$ shock loading and spectrum “chirping”)
- Laser and plasma parameters and shock generation dynamics in the experiment by Haberberger et al. are quite different from our simulations but the low efficiency observed seems consistent with above considerations

Conclusions

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

$\longrightarrow$ need to improve spectrum and to check for high repetition rate operation

RPA: Promising for acceleration to >1 GeV (with next term laser facilities)

$\longrightarrow$ 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 some applications

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  - FERMI BlueGene/Q™, PRACE award (project LSAIL – "Large Scale Acceleration of Ions by Lasers")
- Experiments at SLIC facility, CEA Saclay (France) supported by LASERLAB Europe (access project SLIC001693 "Ultrahigh Contrast Laser Interaction with Structured Targets")