Chirped standing wave acceleration (CSWA)
A controllable laser-driven ion accelerator

F. Mackenroth, A. Gonoskov, M. Marklund
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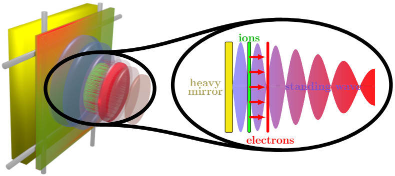
Berkeley, January 20th 2016



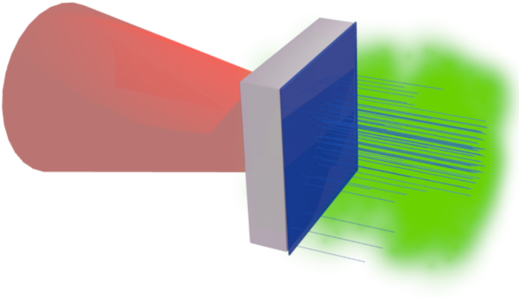
arXiv:1601.03967

Outline

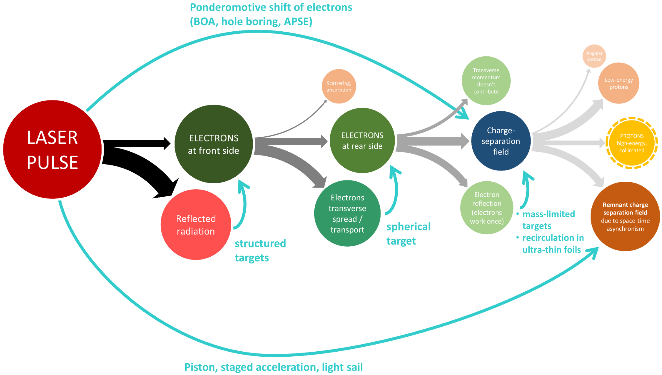
Laser acceleration of ions

Motivation

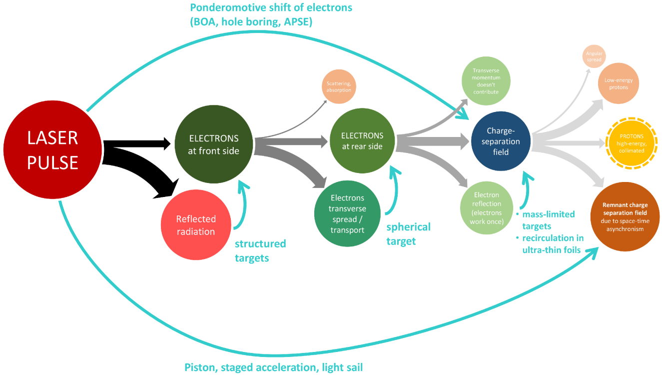
Ions acceleration via charge separation due to thermal expansion (TNSA)



Motivation


Ponderomotive shift of electrons
(BOA, hole boring, APSE)
LASER PULSE
ELECTRONS at front side
Reflected radiation
structured targets
Scattering, absorption
ELECTRONS at rear side
Electrons transverse spread / transport
spherical target
Transverse momentum doesn't contribute
Charge-separation field
Electron reflection (electrons work once)
• mass-limited targets
• recirculation in ultra-thin foils
Angular spread
Low-energy protons
PROTONS high-energy, collimated
Remnant charge separation field due to space-time asynchronism
Piston, staged acceleration, light sail

Motivation

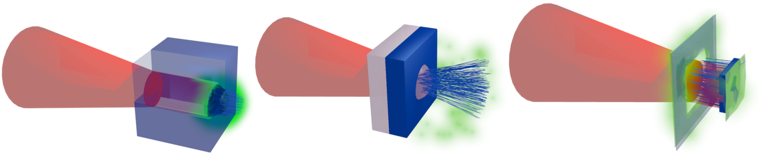


Problems of TNSA:

- energy transfer efficiency decreased by intermediate steps
- high laser intensities affect ions directly
  (TNSA mechanism altered)
- limited control

Non-thermal ion acceleration schemes

Ions acceleration schemes beyond TNSA (selection)



hole boring Coulomb explosion light sail (laser piston)

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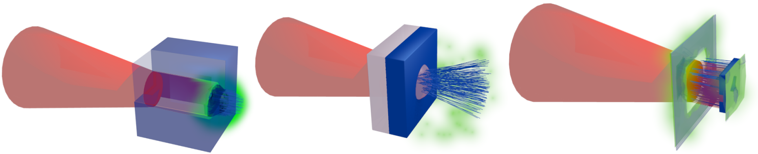


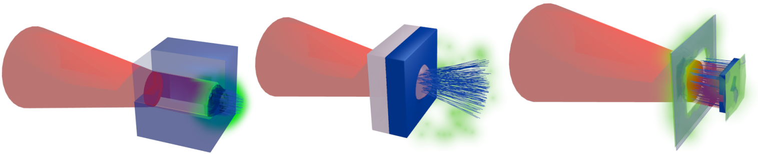
hole boring   Coulomb explosion   light sail (laser piston)

Problems of ion acceleration:

- HB: laser-solid **interface unstable**
- CE: complex targets, limited spectral control
- LS: formation of **plasma instabilities**

Non-thermal ion acceleration schemes

Ions acceleration schemes beyond TNSA (selection)



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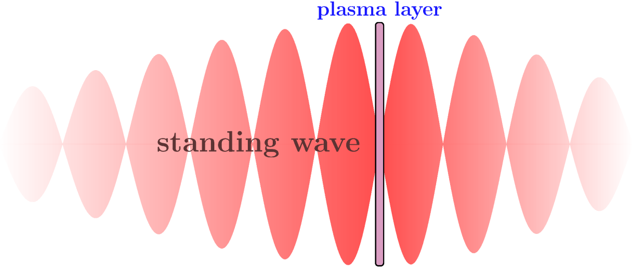
Chirped standing wave acceleration (CSWA)

Chirped standing wave acceleration

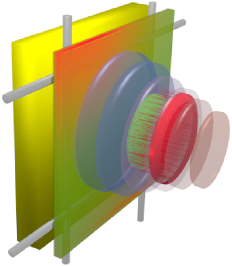
Basic idea



- stabilize **accelerated** layer from both sides:
  - electrons steered by **standing wave**
  - ions follow charge separation

Chirped standing wave acceleration

Basic setup



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- construct by reflecting a laser pulse from a mirror
  rel. self-induced transparency (RSIT) of thin layer: single pulse
  - electrons trapped at break-through
  - ponderomotive force allows field rectification

Chirped standing wave acceleration

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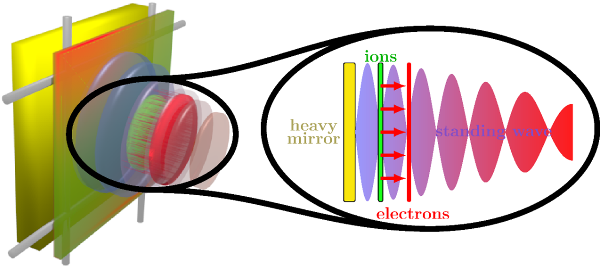

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Chirped standing wave acceleration

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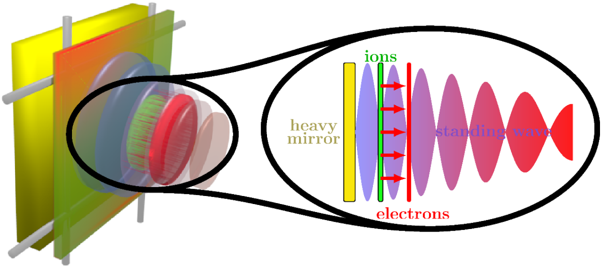

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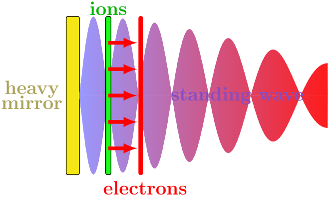
Analytical model

Chirped standing wave acceleration

Ions accelerated by **sheath field** (approx. 1D)

$$p_{\text{ion}} = 2\pi e^2 \sigma \tau_{\text{acc}}$$



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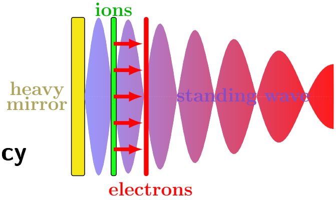
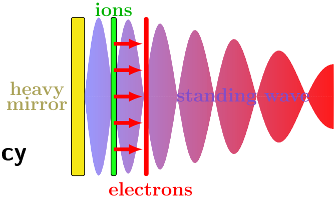


Standing wave through **relativistic transparency**

$$\frac{E\left(\frac{\tau_{acc}}{2}\right)}{E_{rel}} =: a_0\left(\frac{\tau_{acc}}{2}\right) = \pi\frac{\sigma}{\sigma_{cr}}$$

$$E_{rel} = \frac{m_e c\omega_0}{e} \quad , \quad \sigma_{cr} = n_{cr}\lambda_0 = \frac{m_e c\omega_0}{2e^2}$$

Chirped standing wave acceleration



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Chirped pulse field for bandwidth $\Delta\omega_0 = 4\log 2/\tau_0$ (τ_0: pulse duration)

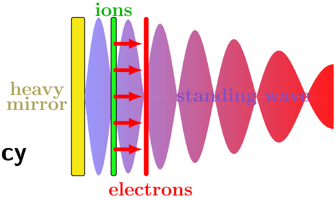
$$E(\eta) = \frac{E_0}{\left(1+\mathcal{C}^2\right)^{-1/4}} e^{-(\Delta\omega_0(\mathcal{C})\eta)^2 + i\Sigma(\eta)}$$

pulse energy (spectrum) conserved

$$\Sigma(\eta) = \omega_0\eta + \mathcal{C}\left[\left(\Delta\omega_0(\mathcal{C})\,\eta\right)^2 + \frac{2\omega_0^2\log 2}{\Delta\omega_0^2}\right] + \frac{\text{atg}\mathcal{C}}{2}$$

$$\Delta\omega_0(\mathcal{C}) = \frac{\Delta\omega_0}{\sqrt{8\log 2\left(1+\mathcal{C}^2\right)}}$$

Chirped standing wave acceleration



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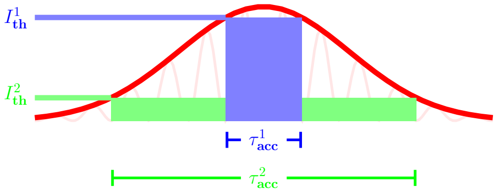
$$\Delta\omega_0(\mathcal{C}) = \frac{\Delta\omega_0}{\sqrt{8\log 2\,(1+\mathcal{C}^2)}}$$

Chirped standing wave acceleration

Acceleration time determined by σ



From relativistic transparency (neglect oscillating phase structure)

$$p_{\text{ion}} = 2e^2 \underbrace{\frac{a_0}{\left(1+\mathcal{C}^2\right)^{-1/4}}}_{\text{field rectified}} \underbrace{e^{-\left(\Delta\omega_0(\mathcal{C})\frac{\tau_{\text{acc}}}{2}\right)^2}\tau_{\text{acc}}}_{\text{optimize for } \tau_{\text{acc}}}$$

$$\tau_{\text{acc}}^{\text{opt}} = \frac{\sqrt{2}}{\Delta\omega_0\left(\mathcal{C}\right)} \approx 0.85\,\tau_0\left(\mathcal{C}\right)$$

Chirped standing wave acceleration

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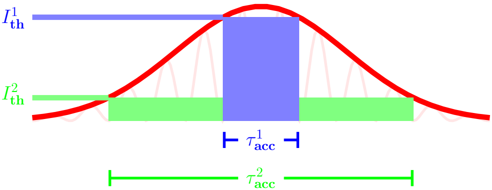

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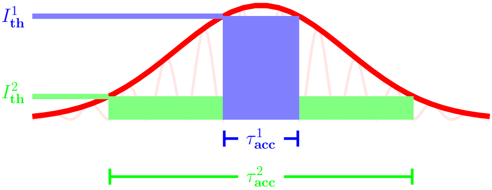
$$\sigma^{\text{opt}} = \frac{a_0 e^{-\frac{1}{2}}}{\pi\left(1+\mathcal{C}^2\right)^{1/4}}\sigma_{\text{cr}}$$

Chirped standing wave acceleration

Acceleration time determined by σ



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$$p^{\text{opt}}_{\text{ion}} \approx 4 m_e c \frac{\omega_0}{\Delta\omega_0} a_0 \left(1+\mathcal{C}^2\right)^{1/4}$$

Simulation

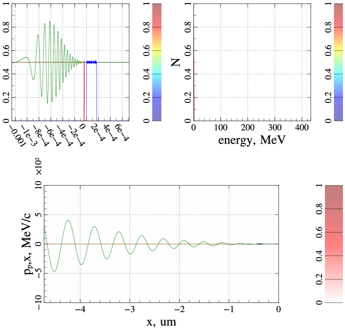
Simulation results

Demonstrate CSWA's feasibility

- 1D PIC simulation (PICADOR)
- thin plasma layer - high resolution (16000 cells, 100 ppc)
- available laser parameters

Example:

$$\varepsilon_L = 20\,\text{J}$$
$$\lambda_0 = 800\,\text{nm}$$
$$r_{spot} = 5\,\mu\text{m}$$
$$\Delta\omega_0 = 0.5\omega_0$$
$$\mathcal{C} = -7$$
$$\tau_0(C) \approx 7.5\,\text{fs}$$
$$\boldsymbol{a_0 \approx 40}$$



t = 7.8 fs

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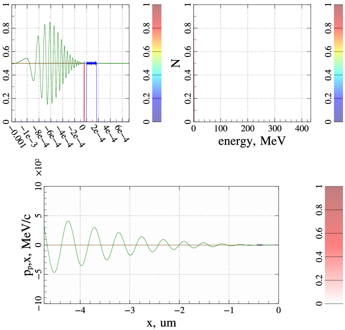

t = 7.8 fs

- monochromatic ion spectrum
- $> 10^{10}$ particles ($\sim$ nC)

Simulation results

Demonstrate CSWA's flexibility

- explore CSWA's capabilities
- tune previous example only in chirp & bandwidth
- shorter pulse, higher a_0

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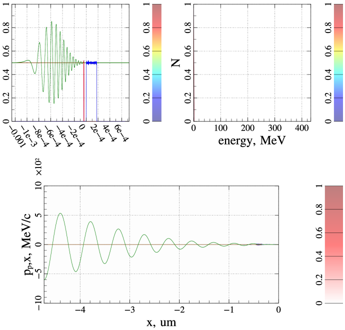
$$\tau_0\,(\mathcal{C}) \approx 6.5\,\mathrm{fs}$$
$$\boldsymbol{a_0} \approx \mathbf{43}$$



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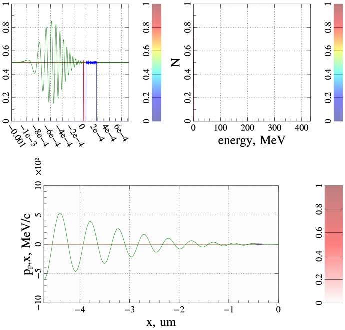

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- higher ion energies
  no spectral peak
- less stable regime

Parameter scan

Scan CSWA's wide range of applicability

$\lambda_0 = 800\,\mathrm{nm}$
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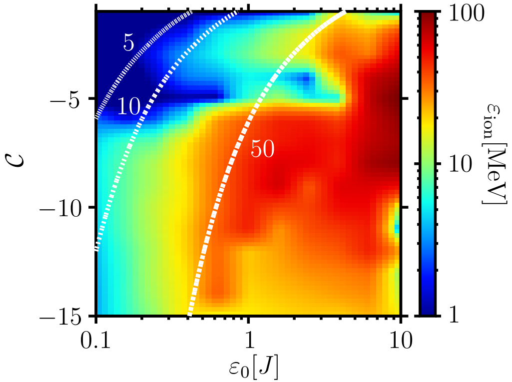


arXiv:1601.03967

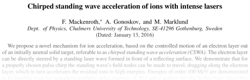
- up to 100 MeV ion energies
- compares well with analytical prediction $p_{ion} \sim a_0 \left(1 + \mathcal{C}^2\right)^{-1/4}$
- decrease of optimal chirp value $\mathcal{C}$

Summary & Outlook

Summary CSWA

"**C**hirped **S**tanding **W**ave **A**cceleration"

- stable high-quality ion beams: monochromatic, collimated, high-charge
- favorable energy scaling
- refined chirp model for temporal control
- reference: arXiv:1601.03967


Chirped standing wave acceleration of ions with intense lasers

F. Mackenroth,* A. Gonoskov, and M. Marklund
Dept. of Physics, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
(Dated: January 13, 2016)

We propose a novel mechanism for ion acceleration, based on the controlled motion of an electron layer out of an initially neutral solid target, referable to as *chirped standing wave acceleration (CSWA)*. The electron layer can be directly steered by a standing laser wave formed in front of a reflecting surface. We demonstrate that for a properly chosen pulse chirp the standing wave's field nodes can be made to travel, dragging along the electron layer, which in turn accelerates the residual ions to high energies. Energies of order 100 MeV are demonstrated

Tasks

- optimization of high-energy regime
- analyze locked standing wave acceleration stage
  transition to light-sail
- experimental campaign

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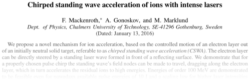

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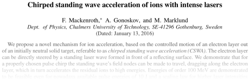

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Thank you

Backup

Chirp model

Modeling a laser pulse chirp

Base model on temporal delay of frequency components

Original pulse duration τ_0, frequency ω_0, unchirped, plane wave $\boldsymbol{E}(\eta) = \boldsymbol{E}_0\psi(\eta)$:

$$\psi(\eta) = e^{-4\log 2\left(\frac{\eta}{\tau_0}\right)^2 + i\omega_0\eta},$$

Modeling a laser pulse chirp

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Fourier transform

$$\sigma(\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} d\eta\ \mathrm{e}^{-4\log 2\left(\frac{\eta}{\tau_0}\right)^2 + i(\omega_0-\omega)\eta} = \sqrt{\frac{\tau_0^2 c^2}{8\log 2}}\mathrm{e}^{-\left(\frac{\tau_0(\omega_0-\omega)}{4\sqrt{\log 2}}\right)^2}$$

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Chirp

$$\sigma_C(\omega) = \sigma(\omega)\mathrm{e}^{-i\delta\Psi(\omega)}$$

$$\delta\Psi(\omega) = \mathcal{C}\left(\frac{\tau_0}{4\sqrt{\log 2}}\right)^2 \omega\left(\omega - 2\omega_0\right)$$

Assumption: **Linear phase shift**

Chirped pulse model

Back-transformation

$$\psi(\eta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega \sqrt{\frac{\tau_0^2 c^2}{8 \log 2}} e^{-\left(\frac{\tau_0(\omega_0-\omega)}{4\sqrt{\log 2}}\right)^2} e^{-i\mathcal{C}\left(\frac{\tau_0}{4\sqrt{\log 2}}\right)^2 \omega(\omega-2\omega_0)+i\omega\eta}$$

Resulting pulse model

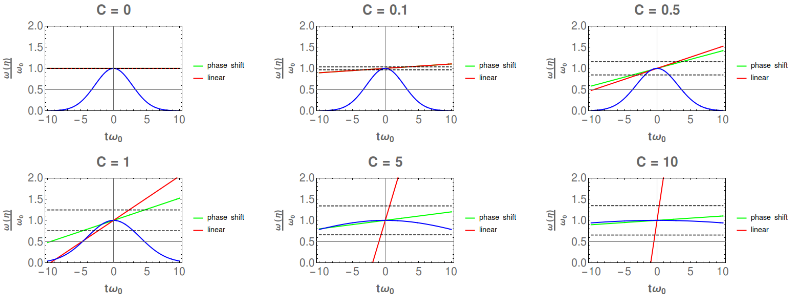
$$\psi_{\mathcal{C},I}(\eta) = \frac{1}{\sqrt{1+i\mathcal{C}}} e^{-\frac{4\log 2\left(\frac{\eta}{\tau_0}\right)^2}{(1+\mathcal{C}^2)}} e^{i\left(\omega_0\eta + \frac{4\log 2}{\tau_0^2(1+\mathcal{C}^2)}\mathcal{C}\eta^2 + \left(\frac{\tau_0\omega_0}{4\sqrt{\log 2}}\right)^2\mathcal{C}\right)}$$

Conclusions

amplitude	$E(\eta=0)$	$\propto E_0\left(1+\mathcal{C}^2\right)^{-\frac{1}{4}}$
duration	τ	$\propto \tau_0\sqrt{1+\mathcal{C}^2}$
frequency	$\omega(\eta)$	$= \omega_0 + \frac{8\log 2}{\tau_0^2(1+\mathcal{C}^2)}\mathcal{C}\eta$
spectral width	$\Delta\omega =$	$\begin{cases} \frac{8\log 2}{\tau_0}\mathcal{C} & \text{for } \mathcal{C} \ll 1 \\ \frac{8\log 2}{\tau_0} & \text{for } \mathcal{C} \gg 1 \end{cases}$ bandwidth limit

Chirped pulse model

Comparison of **phase shift** to **linear** chirp model
$\lambda_0 = 800$ nm, $\tau_0 = 10$ fs (4 cycles)



- symmetric for negative chirp
- $\omega(\eta) = 0$ unphysical
- critical chirp for linear approximation $\mathcal{C} = 1$

Chirped standing wave acceleration

Optimal areal thickness (for ion energy gain)

$$\sigma^{\mathrm{opt}} = \frac{a_0 e^{-\frac{1}{2}}}{\pi\left(1+\mathcal{C}^2\right)^{1/4}}\sigma_{\mathrm{cr}}$$

Chirped standing wave acceleration

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Final ion momentum

$$p_{\rm ion}^{\rm opt} \approx 4 m_e c \frac{\omega_0}{\Delta\omega_0} a_0 \left(1 + \mathcal{C}^2\right)^{1/4}$$

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Final ion momentum

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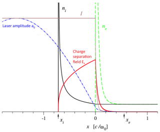
Match (non-relativistic) ion velocity to propagation speed of field nodes

$$v_{\mathrm{node}} = 2\pi c \frac{\Delta\omega_0^2(\mathcal{C})}{\omega^2(t)}\mathcal{C}$$

Optimal chirp parameter

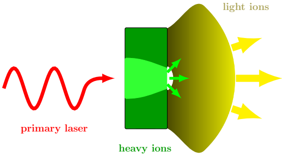
$$\mathcal{C}^{\mathrm{opt}} \approx \left(\frac{m_p}{m_e}\frac{\pi}{16 a_0 \log 2}\frac{\Delta\omega_0}{\omega_0}\right)^{2/3} \sim a_0^{-2/3}$$

HI Acceleration mechanisms - 1D models



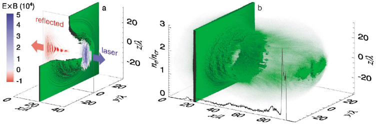
hole boring:

- electrons pushed into target
- charge separation field
- thick, overdense target



Coulomb explosion:

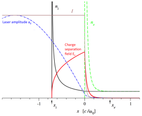
- two-species target
- all electrons expelled
- Coulomb field acceleration



light sail:

- light pressure acceleration
- susceptible to plasma instabilities

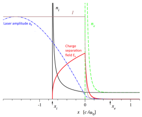
Limitations of acceleration schemes - *Discussion*

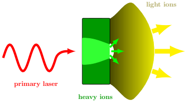


hole boring:

- no transverse electron motion
- coupling accelerated ions into vacuum
- number estimate of accelerated particles

Limitations of acceleration schemes - *Discussion*





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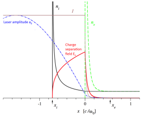
Coulomb explosion:

- instantaneously no electrons in target
- undeformed electron-free region
- no ponderomotive force on electrons

Limitations of acceleration schemes - *Discussion*



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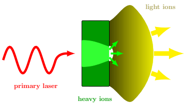

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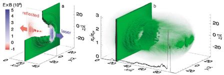
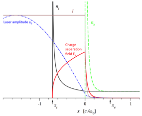


light sail:

- non-flat sail surface
- 2D/3D-effects blow out particles
- total reflection assumed from start

Limitations of acceleration schemes - *Discussion*



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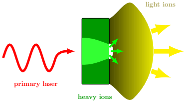

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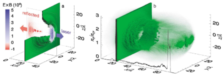

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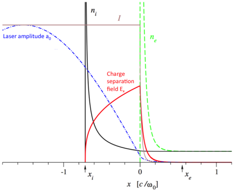
⇒ **Complete, quantify and overcome listed obstacles**

Hole Boring acceleration (Thanks to Chris)

A kind of radiation pressure acceleration in an overdense, thick target



from Schlegel et al., Phys. Plasmas 16, 083103 (2009).

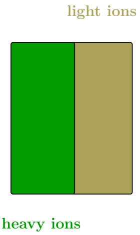
Working principle:

- Laser pulse piles up thin electron spike
- Charge separation field pulls up an ion spike
- Electron & ion spikes form propagating electrostatic shock

The maximum kinetic ion energy (lab frame)

$$\varepsilon_{HB} = m_p c^2 \frac{2\Xi}{1 + 2\sqrt{\Xi}} \; ; \; \Xi = \frac{I_L}{m_p n_0 c^3}$$

Coulomb Explosion acceleration



Working principle:

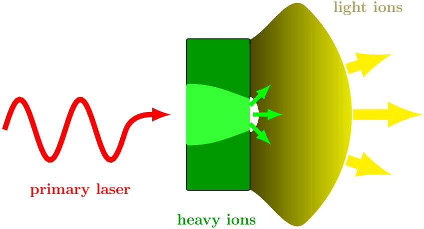
- Two-layered target: heavy and light ions
- Laser expels electrons, heavy ions stay at rest
- Coulomb repulsion accelerates light ions

Accelerating field & ion energy

$$E_{CE} = 2\pi n_0 Ze\ell$$

$$\varepsilon_{CE} = eE_{CE}\frac{w_0}{2}$$

Coulomb Explosion acceleration



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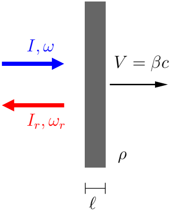
Light Sail acceleration (Thanks to Jens)

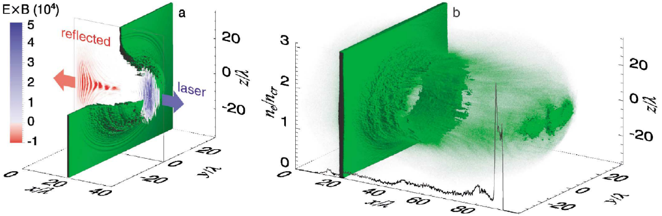


from A. Macchi, arXiv 1403.6273 (2014).

Working principle:

- Thin foil, perpendicular incidence
- $P_{rad} \overset{!}{>} P_{therm}$!

Light Sail acceleration (Thanks to Jens)



from Esirkepov et al., Phys. Rev. Lett. 92, 175003 (2004).

Working principle:

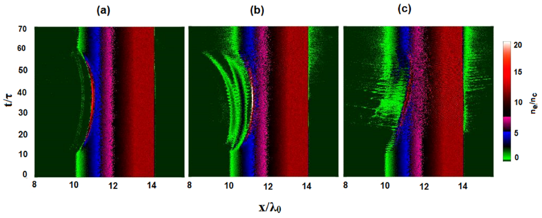
- Thin foil, perpendicular incidence
- $P_{rad} \overset{!}{>} P_{therm}$!
- Decreased target density: Higher energies, less accelerated ions

Coupled kinetic equations

$$\frac{d(\gamma V)}{dt} = \frac{2}{\sigma c} I_L \left(t - \frac{x}{c}\right) \frac{1 - \frac{v}{c}}{1 + \frac{v}{c}} \; ; \; \frac{dx}{dt} = v$$

Chirped break-out afterburner

- influence of pulse chirps rarely studied
- recently, e.g., studied in TNSA
  $\Rightarrow$ two-fold increased electron heating rate



from E. Yazdani et al., J. Appl. Phys. 116, 103302 (2014).

- electron density spike
  $\Rightarrow$ employ for HI acceleration schemes