Ion acceleration and beam quality preservation of structured targets using PetaWatt-class lasers via Hole- Boring Radiation Pressure Acceleration

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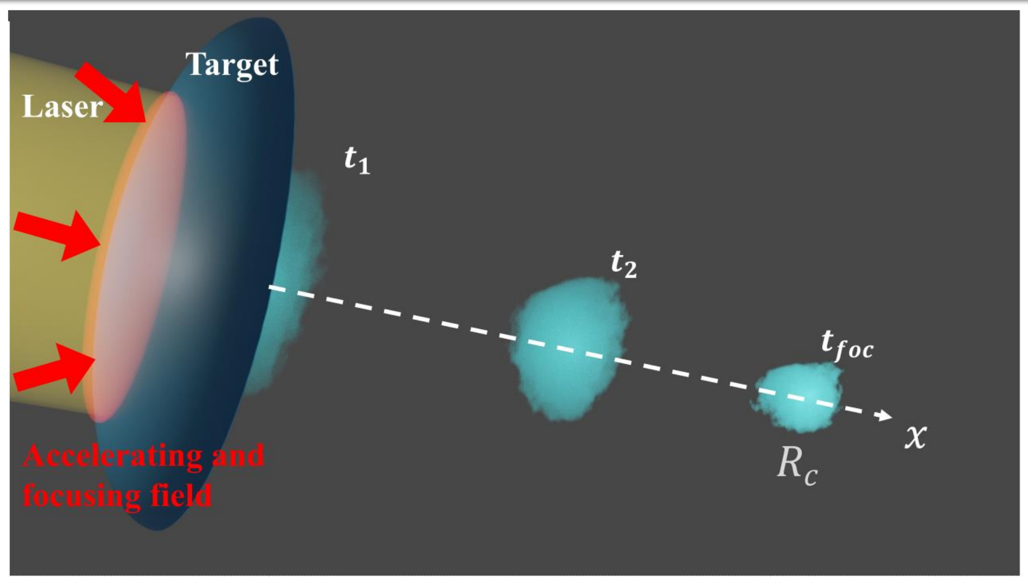
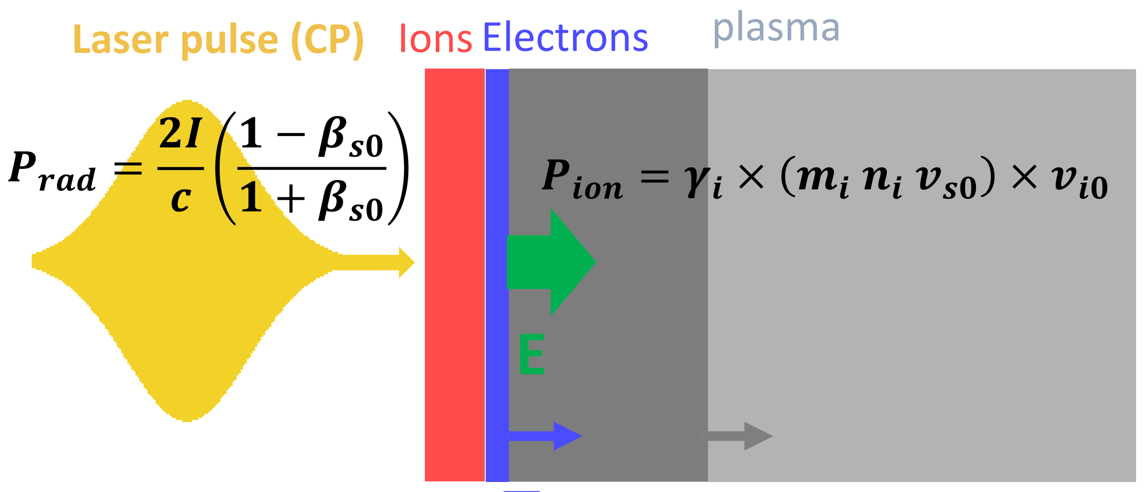
Introduction to Converging Laser Ion Accelerators (CLIA) [1]



- High-power laser impinging on an overdense target can generate a monoenergetic ion flux via Hole-Boring Radiation Pressure Acceleration (HB-RPA) mechanism[2].
- HB-RPA accelerates the ions perpendicular to the front surface
- Curved front surface shape + HB-RPA= converging monoenergetic flow of ions!

Hole-Boring Radiation Pressure Acceleration (HB-RPA)

HB-RPA = Momentum balance between photon and outgoing ion momentum flux



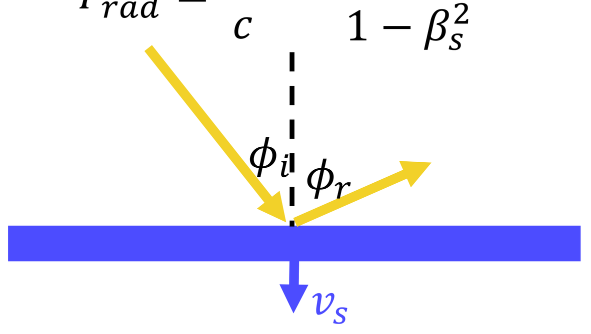
$$P_{rad} = \frac{2I}{c}\left(\frac{1-\beta_{s0}}{1+\beta_{s0}}\right) \qquad P_{ion} = \gamma_i \times (m_i n_i v_{s0}) \times v_{i0}$$

$$v_{s0} = c\beta_{s0} = c\frac{\sqrt{\Theta}}{1+\sqrt{\Theta}}, \quad v_{i0} = \frac{2v_{s0}}{1+\beta_{s0}^2}, \quad \Theta = \frac{I}{\rho c^3}$$

- Laser "snow-plows" a continuous flux of ions at the laser-plasma interface moving with v_{s0}
- "Fresh" plasma accelerated every instant to same velocity v_{i0}

HB-RPA at non-normal incidence: reflection off a relativistic moving mirror

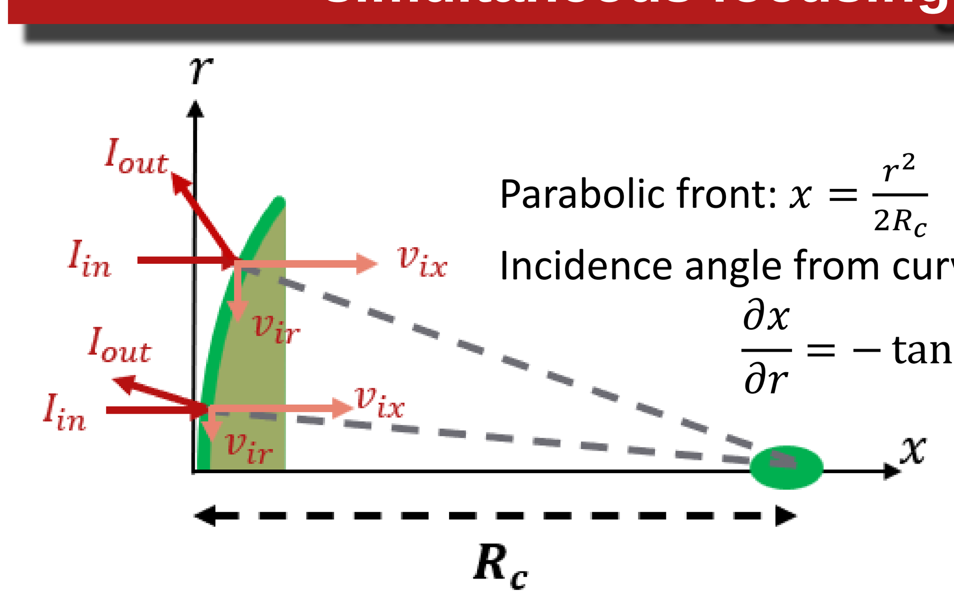
$$P_{rad} = \frac{2I}{c}\frac{(\cos\phi_i - \beta_s)^2}{1-\beta_s^2}$$



$$v_{s0} \to v_s = v_{s0}\cos\phi_i$$
$$v_{i0} \to v_i = \frac{2v_{s0}}{1+\beta_{s0}^2}$$

- Radiation pressure/ion acceleration direction is still perpendicular to the front surface

Parabolic front surface =simultaneous focusing



Parabolic front: $x = \frac{r^2}{2R_c}$

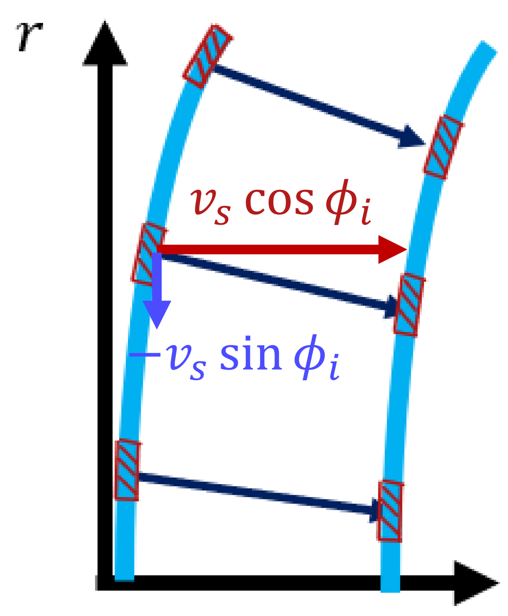
Incidence angle from curvature $\frac{\partial x}{\partial r} = -\tan\phi_i$

$$v_{ix} = v_i\cos\phi_i, \quad v_{ir} = -v_i\sin\phi_i \xrightarrow[\phi_i \sim \frac{r}{R_c}]{r \ll R_c} v_{ix} \sim v_i, \quad v_{ir} \sim -\frac{v_i r}{R_c}$$

$$t_{foc}(r) = \frac{r}{v_{ir}} \sim \frac{R_c}{v_i}, x_{foc} = t_{foc}(r)v_i \sim R_c$$

Monoenergetic ions focus simultaneously on time t_{foc} to focal point $x_{foc} = R_c$

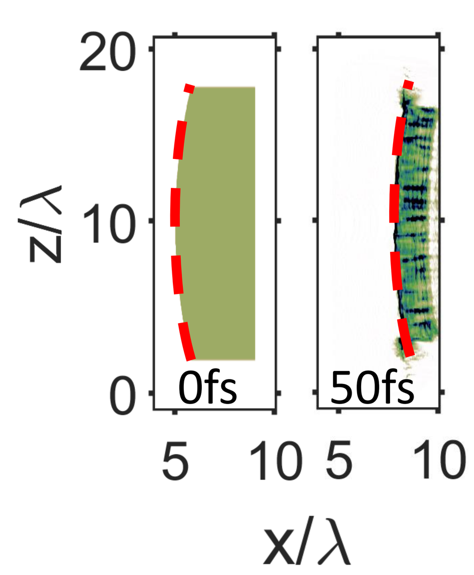
Analytic description of surface evolution



$$\frac{dx(r,t)}{dt} = v_{s0}(r) = \frac{\sqrt{\Theta(r)}}{1+\sqrt{\Theta(r)}}$$
$$\Theta(r) = \frac{I(r)}{\rho c^3}$$

If the laser transverse intensity profile is known, surface evolution can be analytically calculated

1. Plane laser (very large spot size): surface shape preservation over several microns

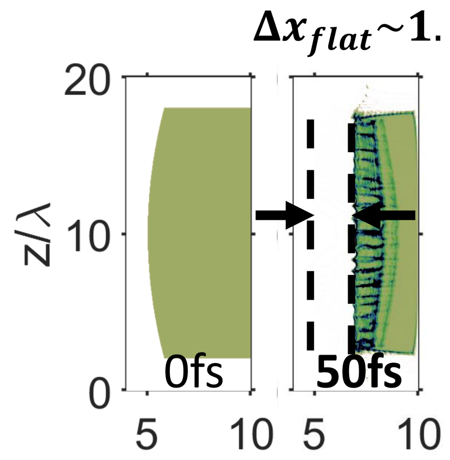


$$\Theta(r) \to \Theta, v_{s0}(r) \to v_{s0}$$
$$x(r,t) = x(r,0) + v_{s0}t$$

Persistence of converging surface shape enables acceleration and focusing of high-charge high-flux ion beams to the same focal length

2. Gaussian laser: surface curvature flattening

$\Delta x_{flat} \sim 1.9\mu m$



$$x = \frac{r^2}{2R_c} + \frac{\sqrt{\Theta}\exp(-r^2/\sigma^2)}{1+\sqrt{\Theta}\exp(-r^2/\sigma^2)}t$$

$$\frac{\partial x(t)}{\partial r} = 0 \quad \sigma = 11.2\mu m, R_c = 40\mu m, \Theta = 0.025$$

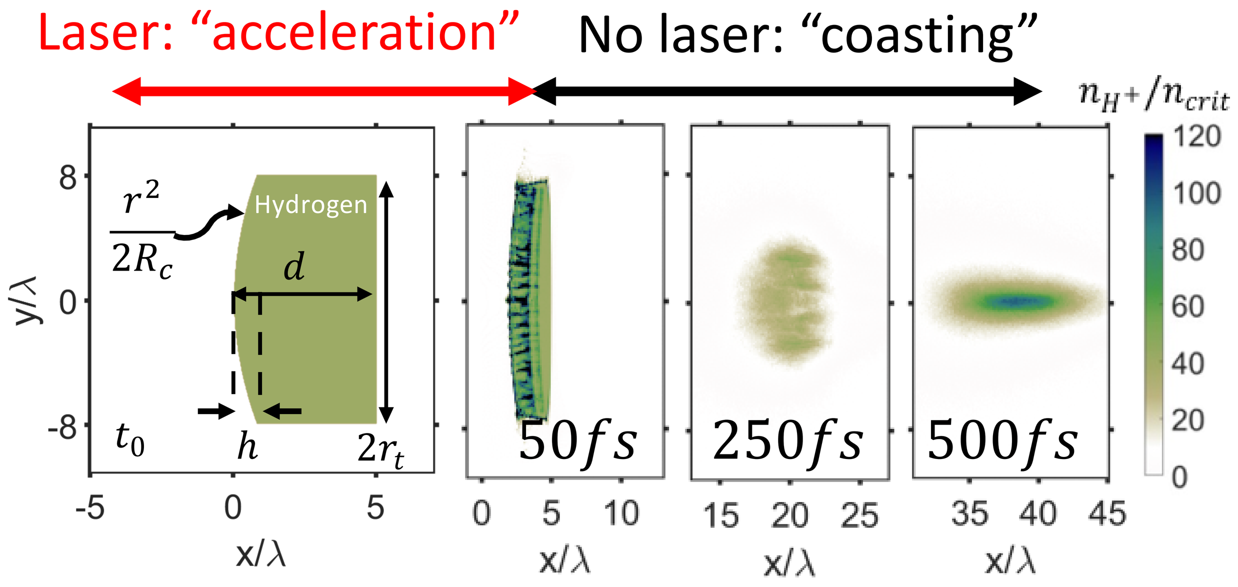
$$t_{flat} = \frac{\sigma^2(1+\sqrt{\Theta})^2}{2c\sqrt{\Theta}R_c} \sim 45fs,$$
$$x_{flat} = v_{s0}t_{flip} \sim 1.8\mu m$$

Analytical estimate agrees well with first-principles PIC results!

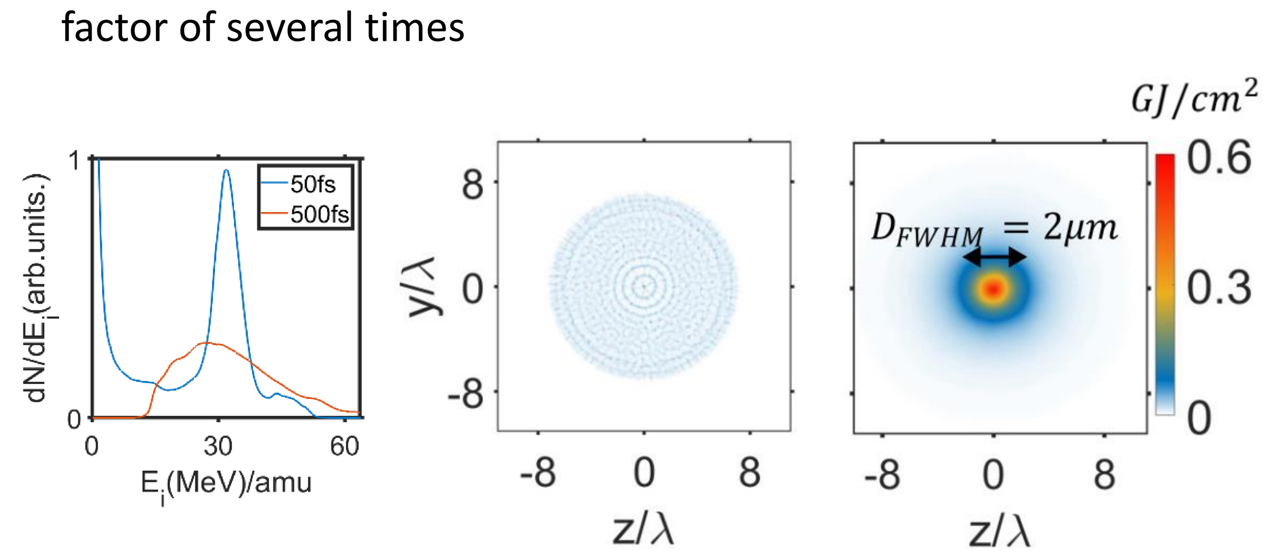
3D PIC simulations of CLIA

3D Full PIC (Smilei) parameters
Cryogenic hydrogen target: $\rho \sim 0.1 g/cm^3$
$R_c = 40\mu m, d = 5\mu m, r_t = 8\mu m$
Laser: $\lambda = 1\mu m$,10PW(on target), 40fs(400J), CP

Laser: "acceleration" No laser: "coasting"

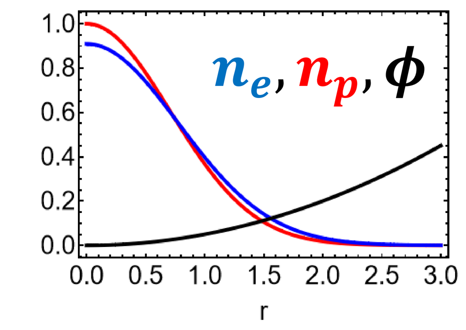


- ion beams accelerated via HB-RPA mechanism during the acceleration stage
- The accelerated ions co-propagate with electron population neutralizing them during the coasting stage, contracting by factor of several times



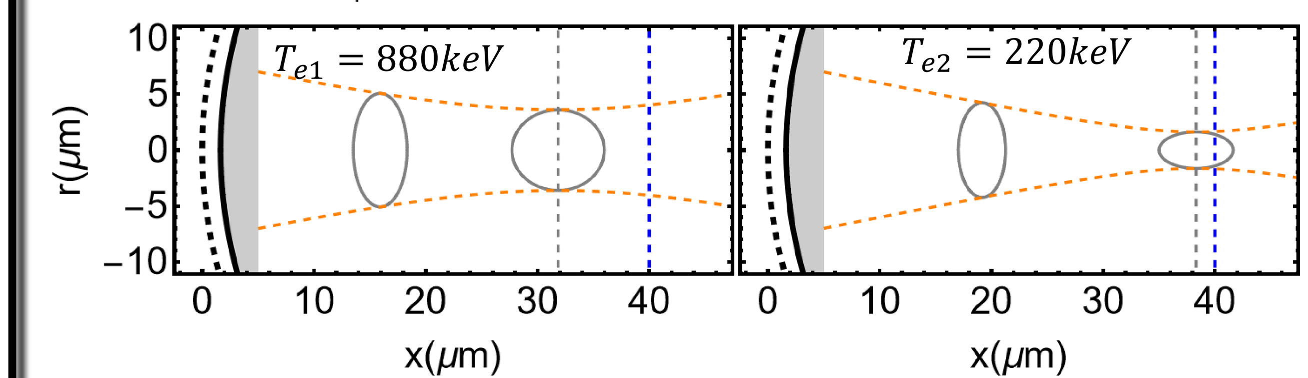
- Monoenergetic ion beam spectra deteriorates significantly during coasting stage
- Ion beam focusing leads to more than an order of magnitude flux increase, acquiring $O(GJ/cm^2)$ energy flux

Coasting stage= competition between focusing and ion diffusion[3]



$$\phi(r) \propto r^2, c_{ion} \sim \sqrt{\frac{Z}{m_i}T_e}$$

Hot electrons cause ion diffusion, countering the ion focusing



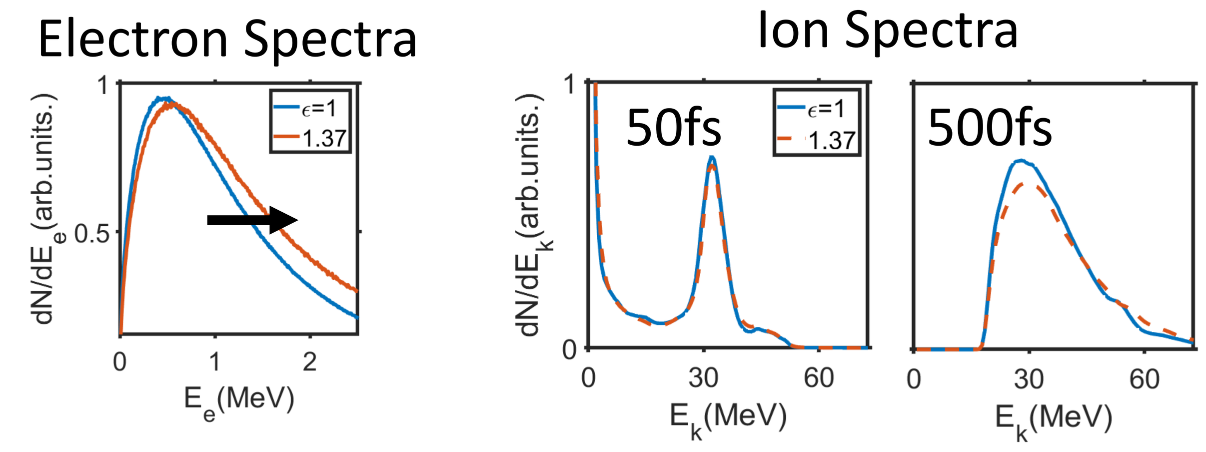
Colder electrons= better focus (and less energy spread)

Beam quality modification: laser polarization, target structure, and target composition

Elliptically polarized laser =beam quality degradation

$$\epsilon = \frac{E_z}{E_y} = 1(Circular), 1.37(Elliptical)$$

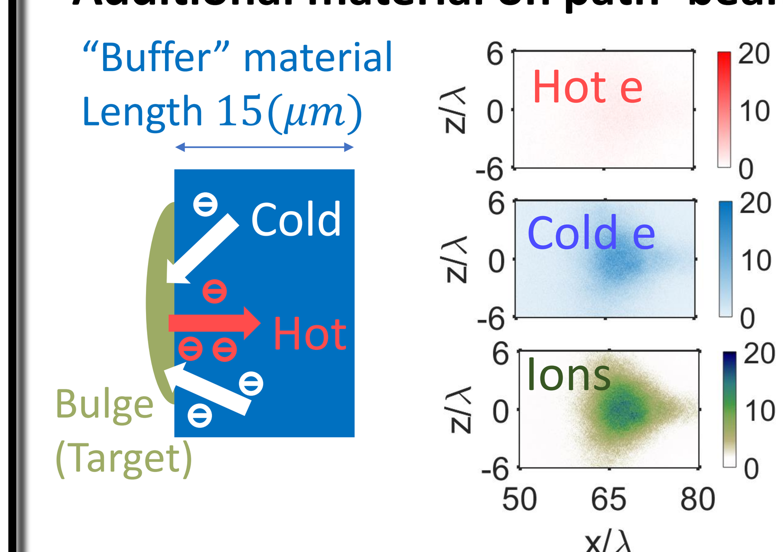
Electron Spectra Ion Spectra



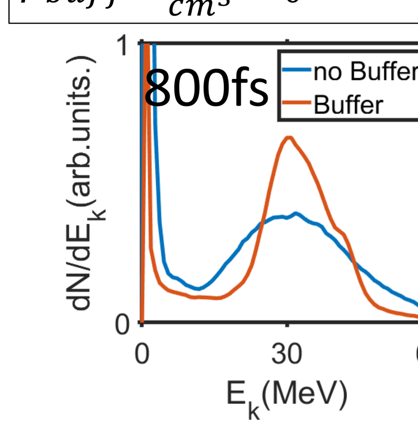
- Acceleration not significantly affected by polarization
- JxB electron heating = ion spectra degradation in coasting

Additional material on path=beam quality improvement

"Buffer" material Length $15(\mu m)$

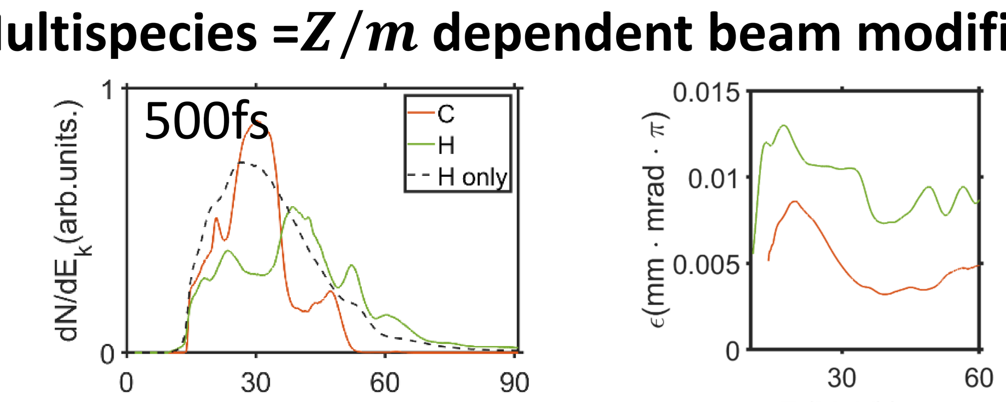


2D PIC, $R_c = 60, \rho \sim \frac{0.1g}{cm^3}$, $\rho_{buff} \sim \frac{0.2g}{cm^3}, a_0 = 43$



- Target hot electrons replaced by cold buffer electrons
- Ion spectra drastically improved for target with buffer due to reduced ion diffusion during coasting

Multispecies =Z/m dependent beam modification



- For multispecies target, higher Z/m ions interact more strongly with the hot electrons and are further accelerated
- This comes at the expense of beam emittance increase

Summary

- Parabolic front surface + HB-RPA = monoenergetic multispecies focused ion beams
- Analytic theory describes acceleration and surface evolution
- O(GJ/cm^2) energy flux at arbitrary focal length achieved
- Post-acceleration ("coasting" stage) governed by ion diffusion mediated by hot electrons
- Three ways to control coasting stage: laser polarization, buffer, and multispecies target

References

[1]Kim et al, arXiv:2310.08432
[2] Naumova et al, PRL 102 025002(2009), Robinson et al, PPCF 51 024004 (2009)
[3] Dorozhkina et al, PRL 81 13 (1998),

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