Bulk ion acceleration from ultrathin foils in PW-class interactions on the ASTRA GEMINI laser

A-SAIL
ADVANCED STRATEGIES FOR ACCELERATING IONS WITH LASERS

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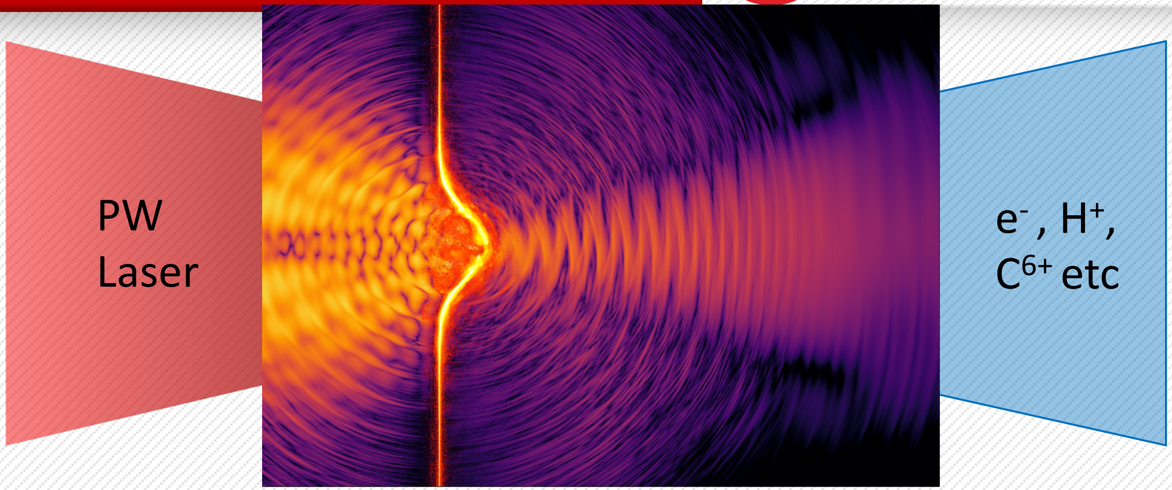
Outline

- Laser-driven ion acceleration from ultrathin foils: Radiation Pressure Acceleration (RPA)
- Experiments on ASTRA-GEMINI
  - Past – Previous work. Polarization dependence of RPA
  - Current:
    - Intensity dependent optimum thickness for RPA
    - Multi-Species Effects
    - Species dependent RPA – PIC simulations

Ion Acceleration – RPA

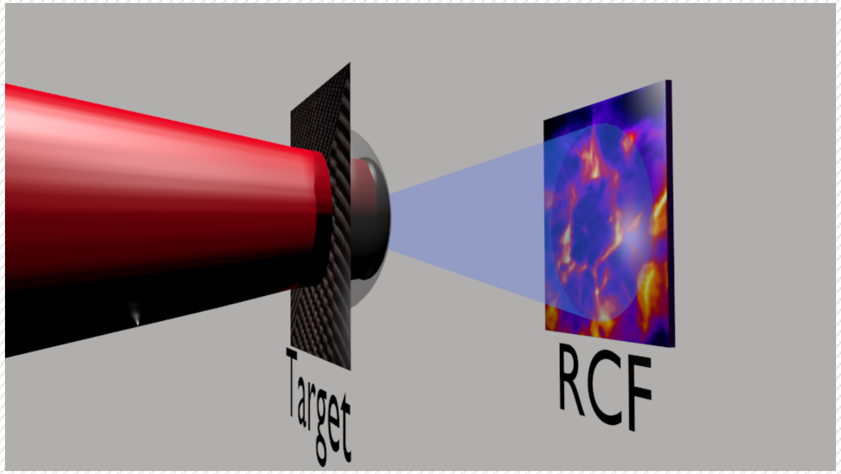
Why RPA?

- Desirable Scaling with Intensity
    - $E_{LS} \propto I^2$
    - $E_{HB} \propto I$
- Potential for quasi mono-energetic spectrum
- Bulk Ion acceleration – heavy ions e.g. C^{6+}



Drawbacks

- Low areal density – Ultra-thin foils / low density foams required
- Ultra-high contrast needed – limited by transparency effects



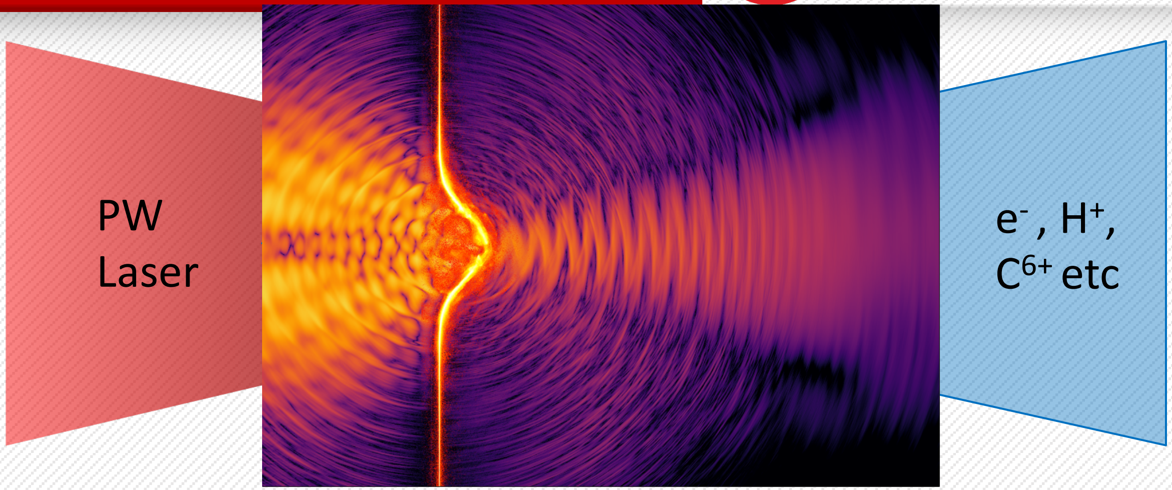
Ion Acceleration – RPA

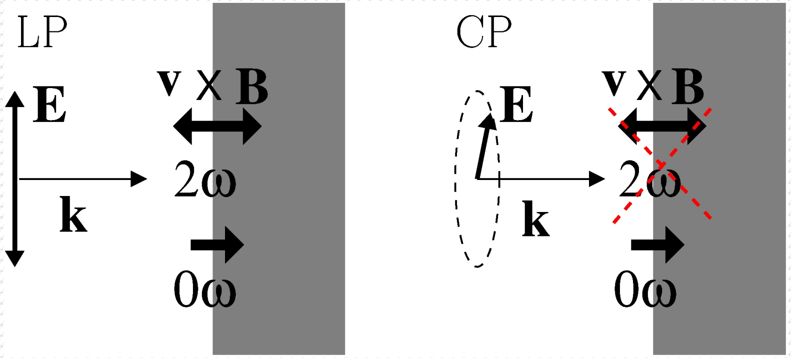
Accessing the RPA regime

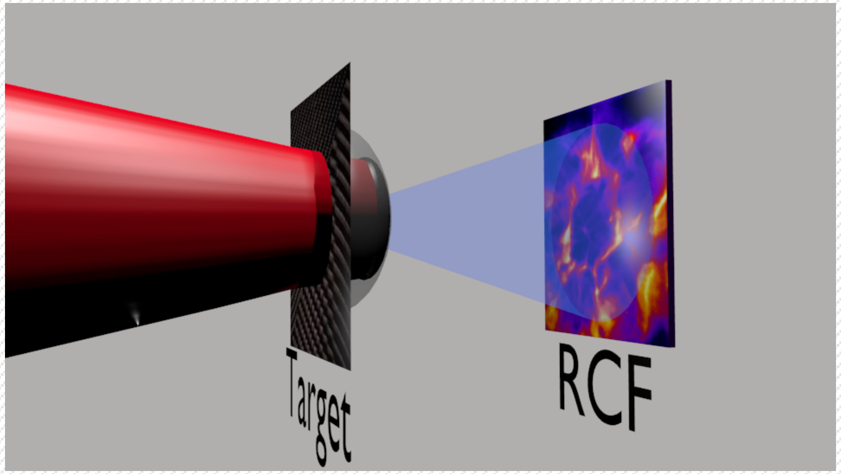
- $a_0 = \pi \frac{n_e}{n_c} \frac{\ell}{\lambda} = \zeta$

For amorphous carbon foils $\rho \approx 350 n_c$ hence $\ell \approx 10nm$

- Use of circular polarisation (CP) – Reduces electron heating by removing oscillating $\boldsymbol{J} \times \boldsymbol{B}$ term



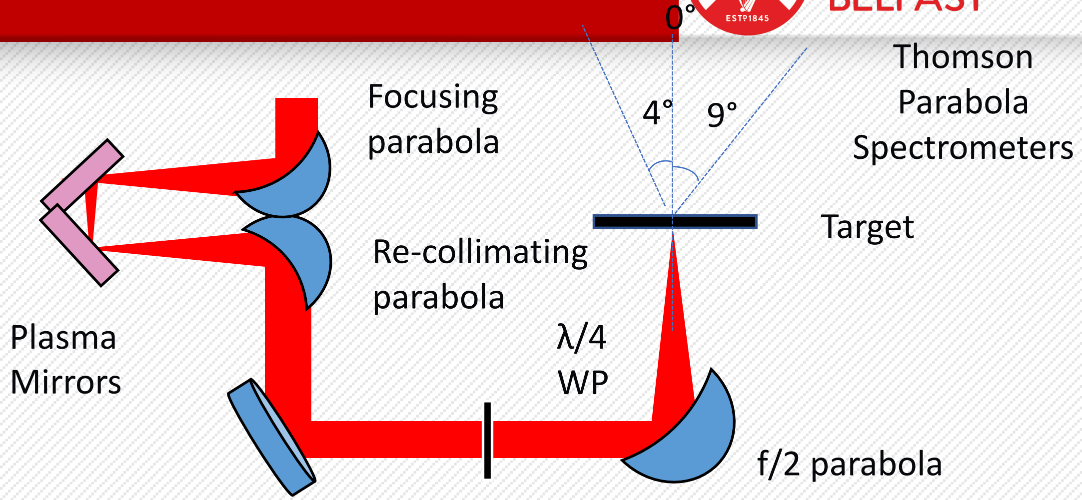


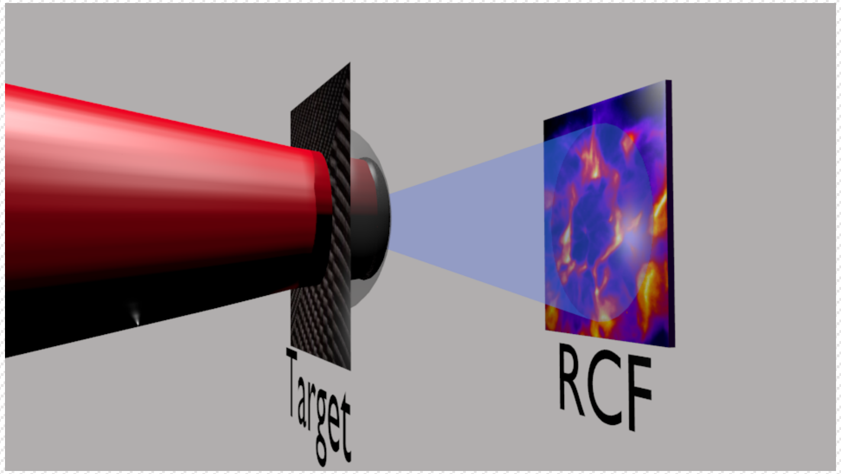


ASTRA - GEMINI

- CLF – RAL UK

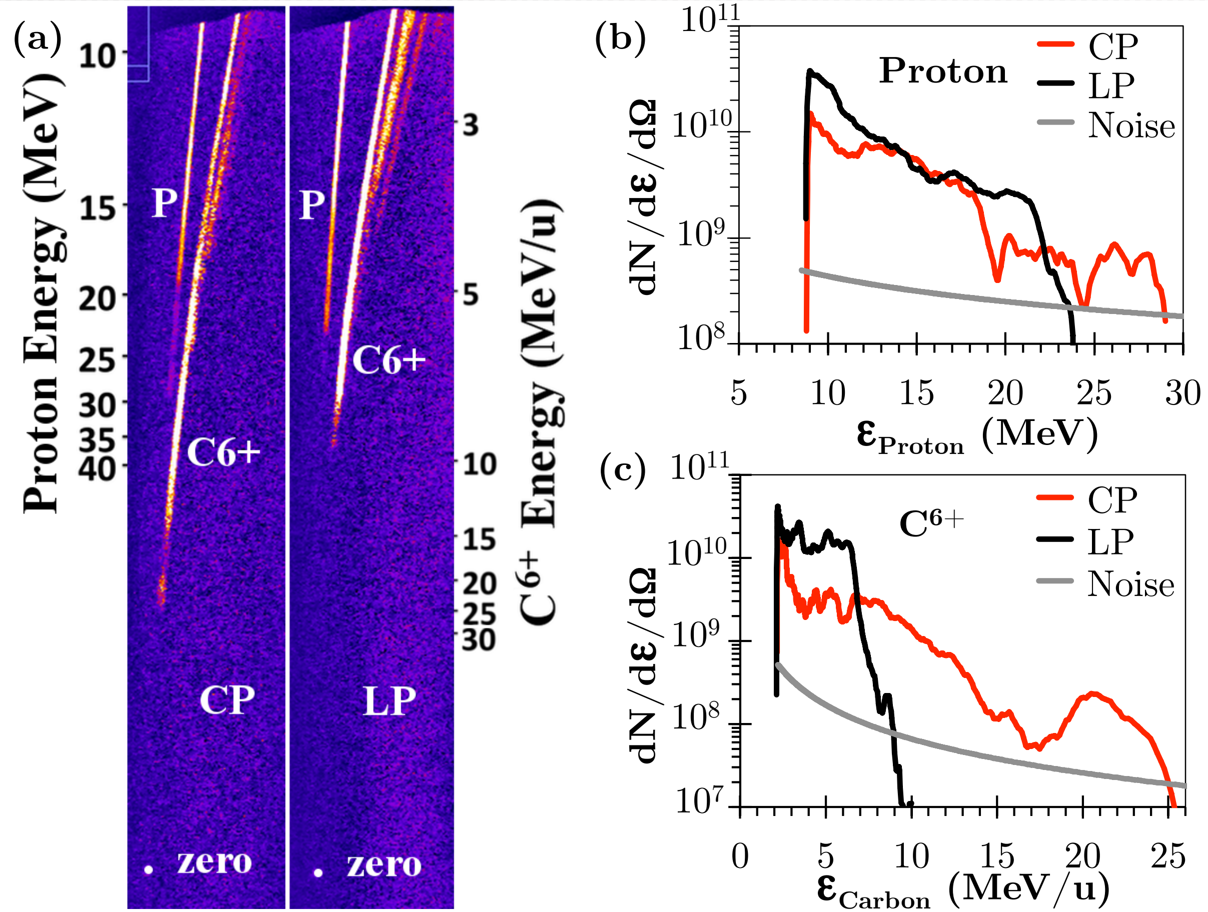
Central Wavelength	800nm
Pulse Length	40fs FWHM
Contrast	10^{12} (After DPM)
Energy on Target	6J
Intensity	$5x10^{20}W/cm^2$





Polarisation Dependence RPA - 2013

- Higher ion energies shown for CP – vs linearly polarised (LP)
- Particularly C^{6+} - evidence of bulk acceleration



C. Scullion *et al*, Phys. Rev. Lett., **119**, 054801 (2017)

[1]A. Macchi, S. Veghini and F. Pagoraro PRL 103, 085003 (2009)
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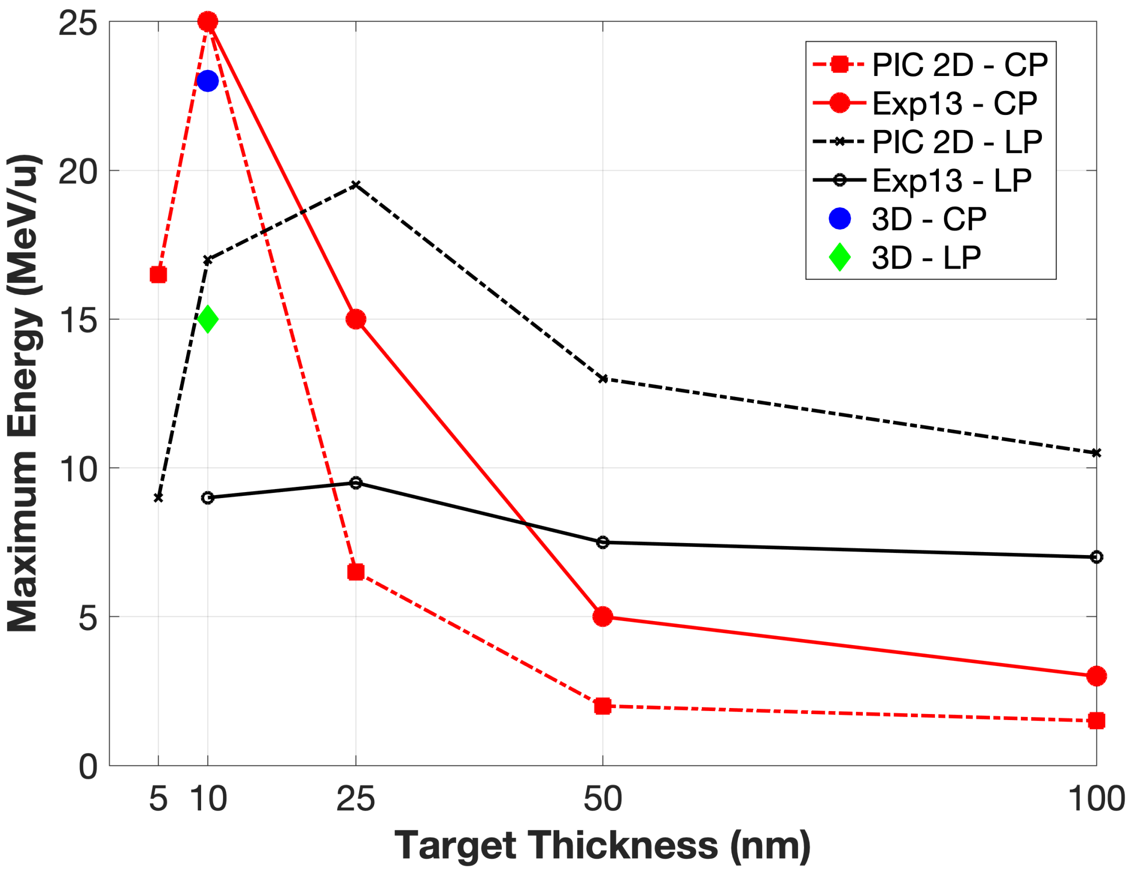

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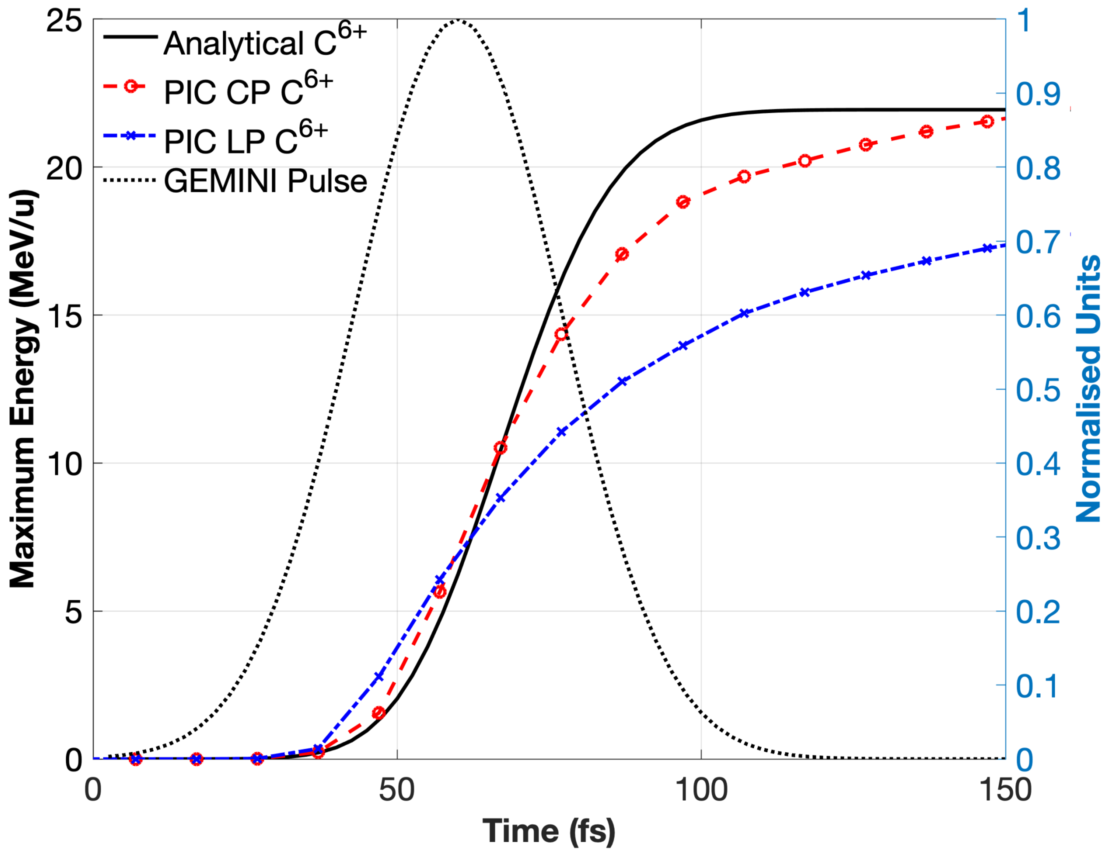
- Particularly C^{6+} - evidence of bulk acceleration
- Good agreement with 2D/3D simulations
- LP target becomes transparent much earlier, reduces bulk ion acceleration
- Energy gain for CP follows the expected energy evolution for LS for a gaussian pulse for longer than LP

$$\beta = \frac{v}{c} \qquad \beta_{LS} = \frac{(1+\epsilon)^2 - 1}{(1+\epsilon)^2 + 1} \qquad \epsilon = \frac{2\mathcal{F}(t)}{\rho l c^2}$$



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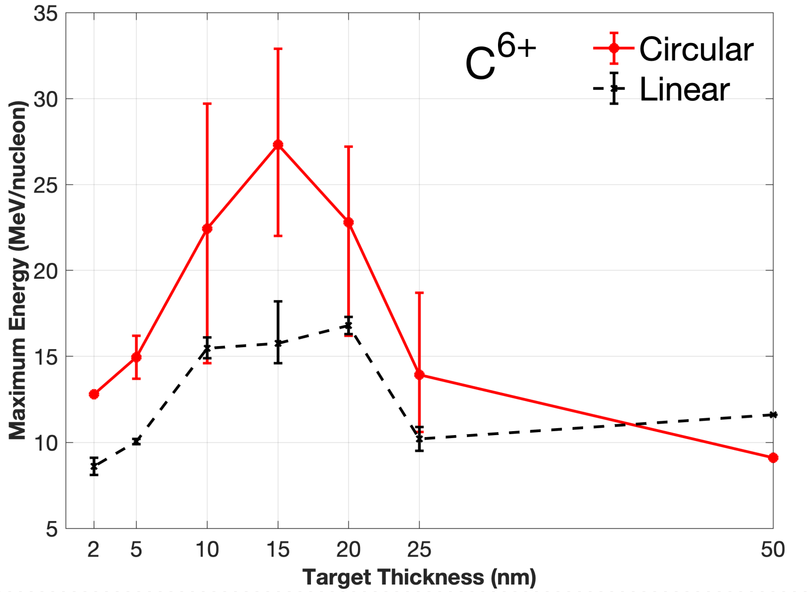
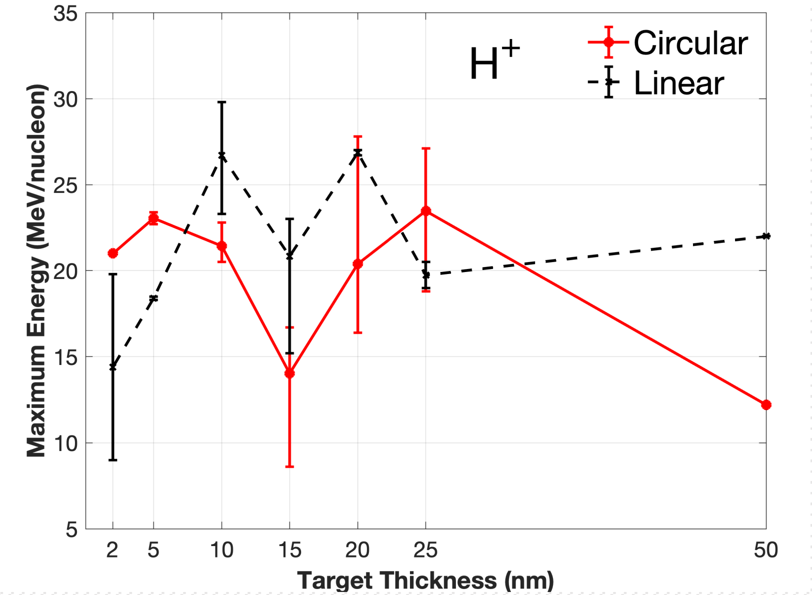
Optimum Thickness - 2017

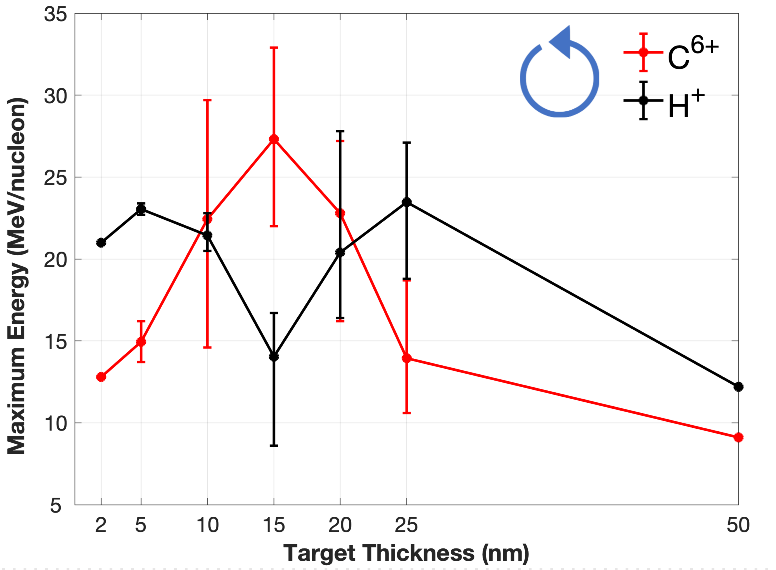
- Presence of an optimum thickness (15nm) for RPA (33MeV/n – 400MeV)
- C^{6+} Energies decrease < 15nm since target goes transparent earlier in the pulse
- Proton energies do not follow the same trend with thickness





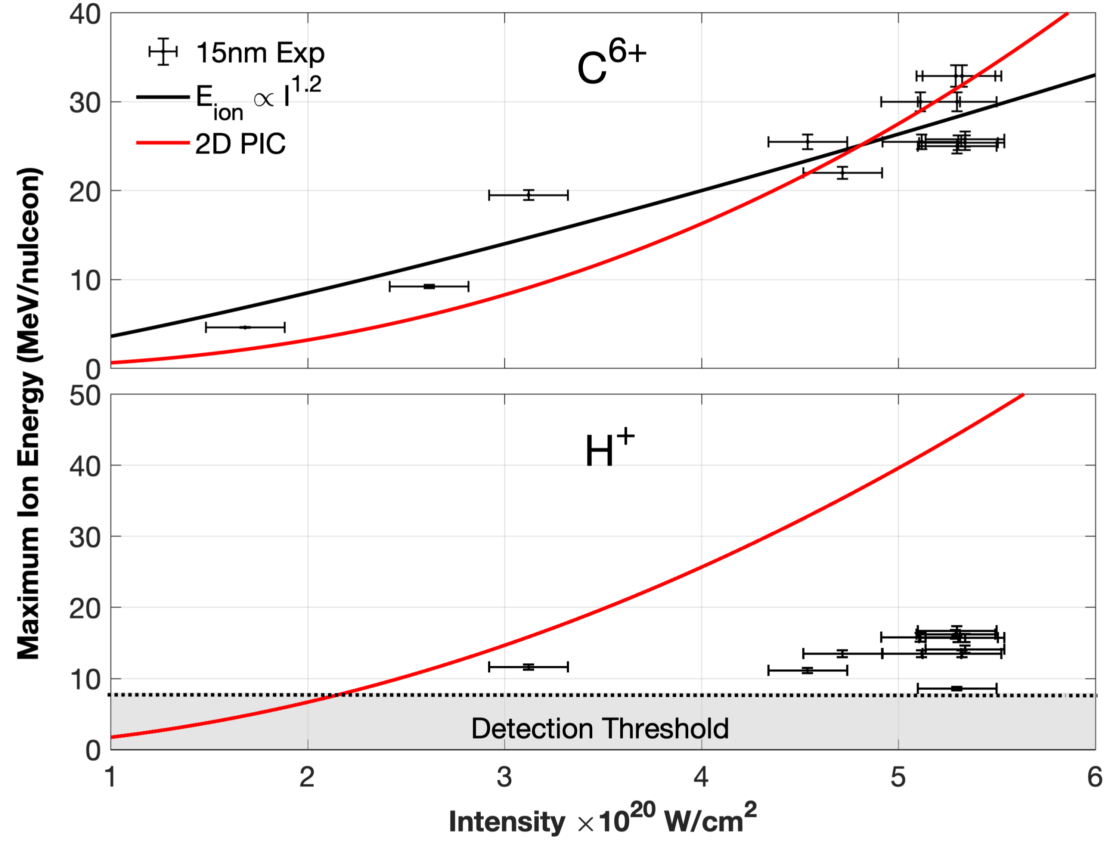
Optimum Thickness - 2017

- Protons (q/m = 1) are usually accelerated over C^{6+} (q/m = ½) in the presence of a sheath field
- RPA should present similar energies per nucleon for the species
- Optimum thickness for C^{6+} produces a local minimum in proton energies
- They increase again as the target goes transparent earlier
- 15nm > analytical prediction (10nm)



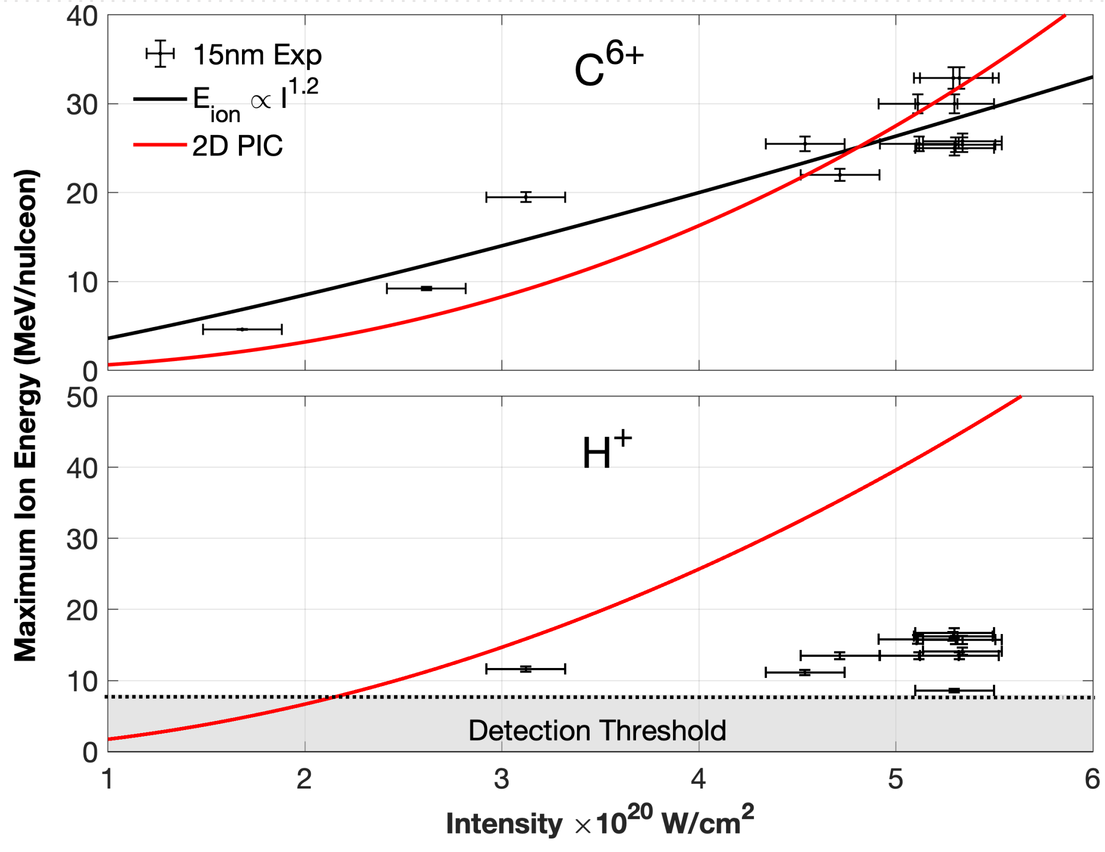
Intensity Scaling - 2017

- Intensity (energy) scan shows another huge difference in the acceleration of the 2 species
- Comparing optimum thickness between PIC (10nm) and experiment (15nm).



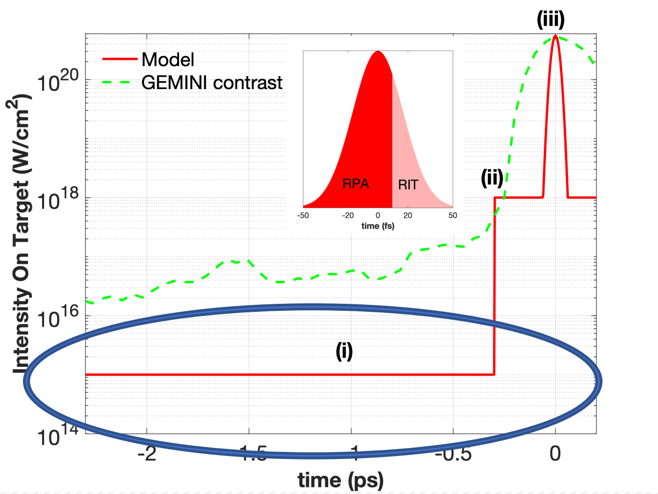
Intensity Scaling - 2017

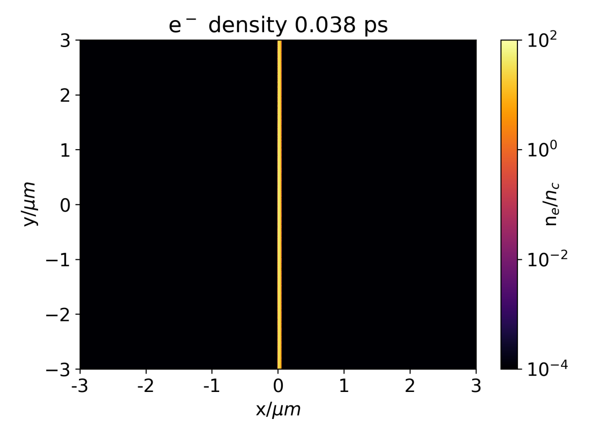
- Intensity (energy) scan shows another huge difference in the acceleration of the 2 species
- Comparing optimum thickness between PIC (10nm) and experiment (15nm).
- Simple 2D PIC overestimates C^{6+} scaling compared to experiment $I^2 \rightarrow I^{1.2}$ due to later onset of transparency – Still RPA regime
- Simple 2D PIC does not account for the difference in the species
- Independent of proton concentration/location

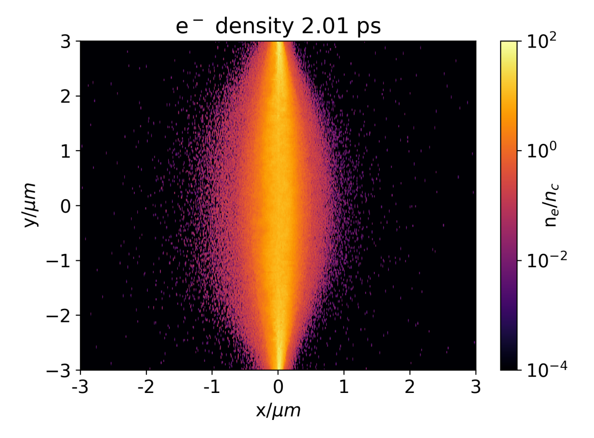


RPA - PIC

- Considering laser pedestal and rising edge after plasma mirrors
- Plasma mirrors activated a few ps before the pulse, target begins to expand.

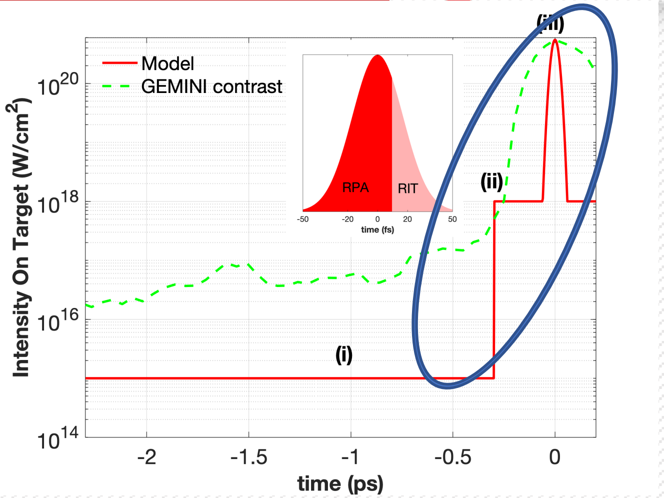


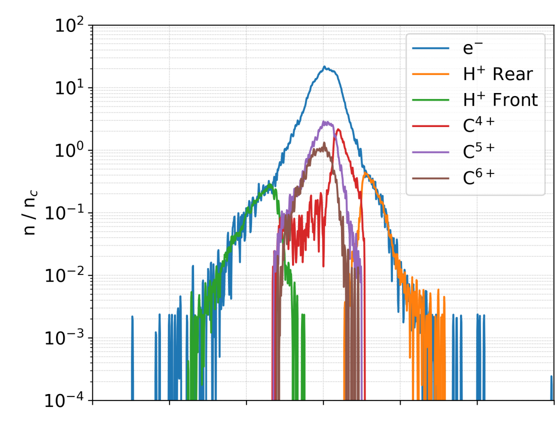


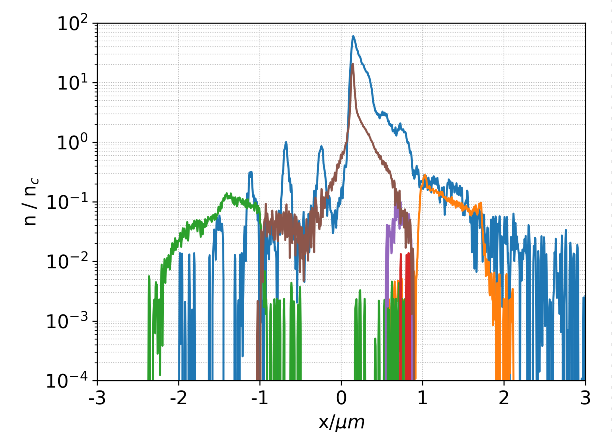


RPA - PIC

- Considering laser pedestal and rising edge after plasma mirrors
- Plasma mirrors activated a few ps before the pulse, target begins to expand.
- Parts of the target become underdense
- Target recompresses during the rising edge of the pulse
- ‘Overdense areal density’ decreases

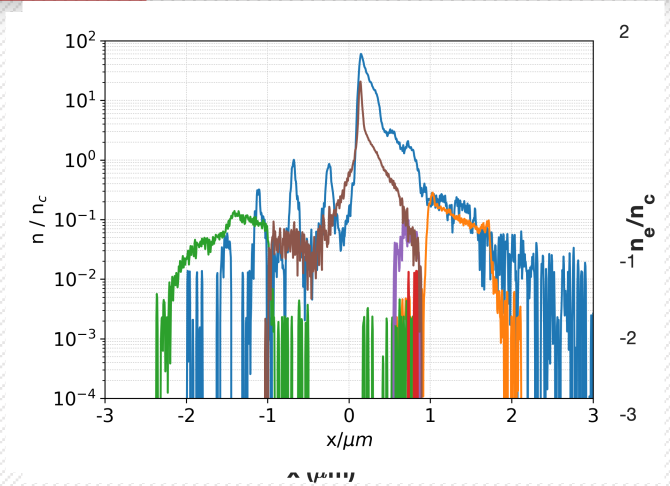


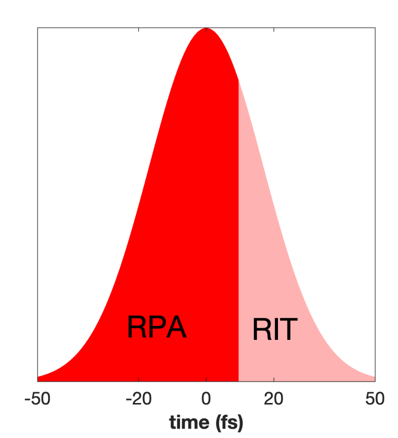


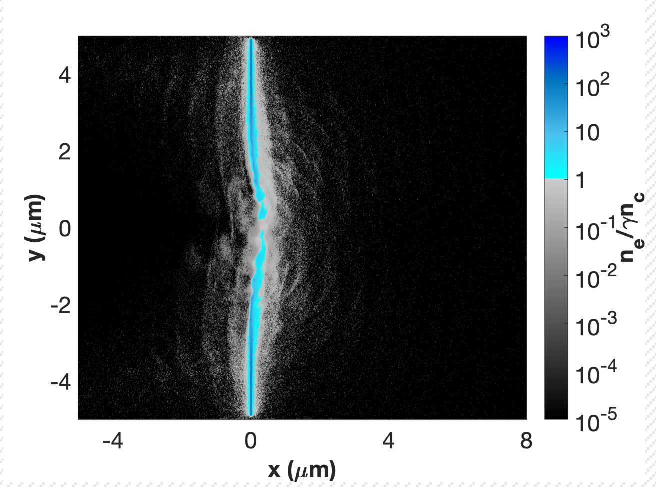


Multi-species acceleration

- Protons are mostly accelerated by the plasma expansion (few MeV) / sheath effects
- Carbon is initially accelerated by RPA
- Target (optimum thickness) goes transparent just after the peak of the pulse as the density drops
- RPA shuts off , enhanced acceleration takes place with transparency effects
- Followed by sheath effects

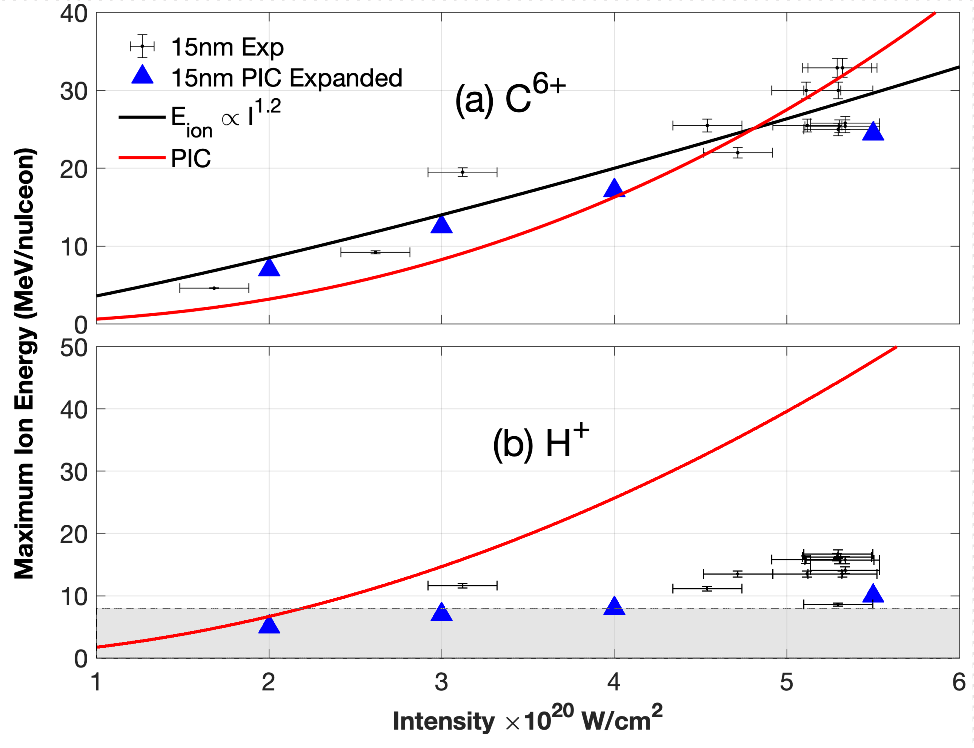






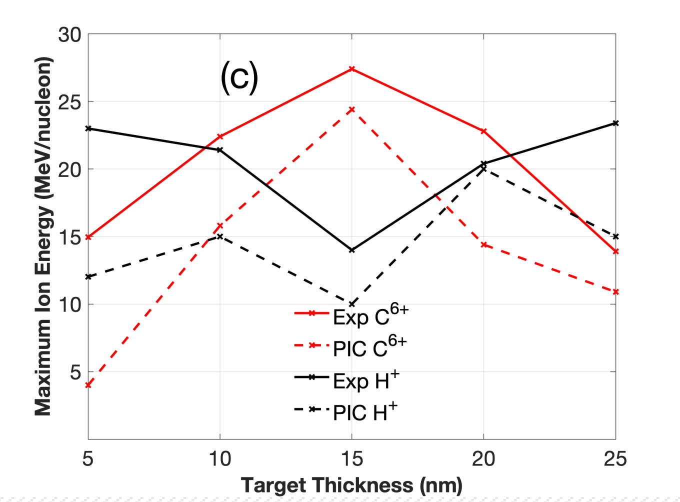
Multi-species scaling

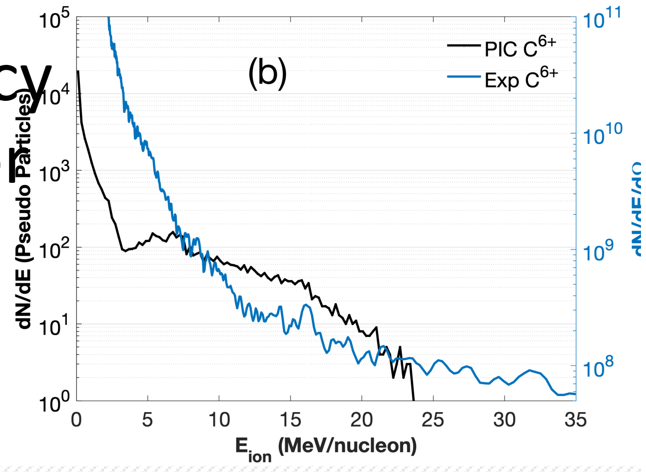
- Running an intensity scan shows the different scaling of carbon vs protons
- Carbon scaling indicates RPA (early shut off due to transparency)
- Protons scaling similar to sheath effects acceleration

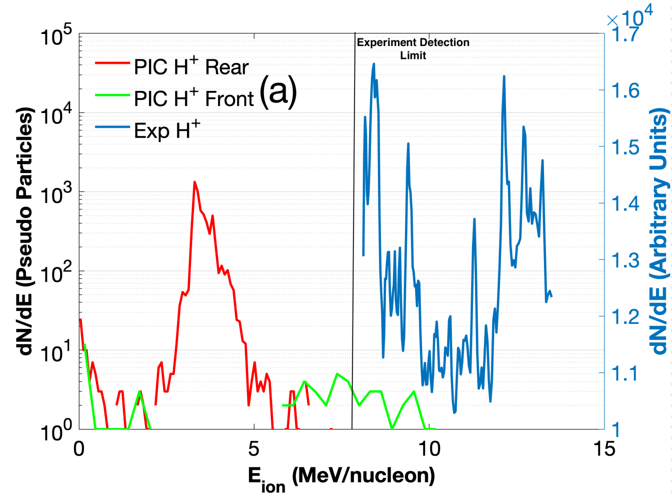


PIC thickness scan

- Plasma temperature increases for thinner targets - thick targets have a smaller separation between carbon and protons
- Optimal thickness means carbon gets greater acceleration over protons
- <15nm, earlier onset of transparency reduces carbon acceleration in favor of protons
- Results in dip in optimum thickness

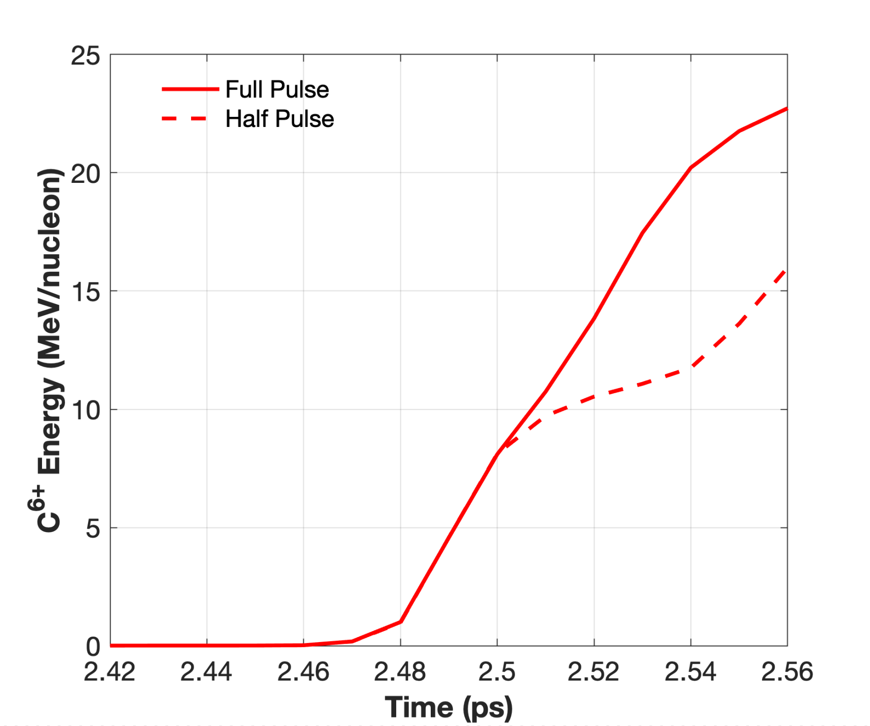






Acceleration contributions

- Cutting the pulse at different points allows a determination of which mechanisms dominate
- 70% comes from RPA and subsequent sheath effects
- 30% contribution from transparency
- Measurement still under investigation!



Summary

- Demonstrated the effect of polarization on the transition to LS acceleration (25MeV/u carbon)
- Demonstration of (intensity dependent) optimum thickness for RPA – 15nm, producing 33MeV/u carbon
- Contribution of RPA to species dependent ion acceleration – ion energy scaling depends on the species
  - Carbon accelerated in RPA regime, protons accelerated in the expansion/sheath acceleration regime

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- LuLi – L. Romagnani
- CLF – N. Booth, G. G. Scott and D. Neely
- Pisa – A. Macchi

Thanks for listening!

Supplementary Slides

Future Scaling

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- Increasing the intensity to 1PW regime will result in an increase in optimal thickness – energy scaling reduces to linear
- Optimum thickness will only scale $I^{1/2}$: still in the ultra-thin range
- Increased pedestal level likely to have more of an effect in this regime

$$L_{optimum} = \frac{a_0}{\pi}\frac{n_{crit}}{n_e}\lambda \qquad a_0 \propto \sqrt{I}$$

$$E_{max} \propto \left(\frac{a_0^2 \tau_p}{\chi}\right)^2 \qquad \chi = \frac{\rho L_{optimum}}{\lambda m_p n_c}$$