Generation of Monoenergetic Protons by Laser Acceleration of Multi-Ion Foils with Polarization Switch

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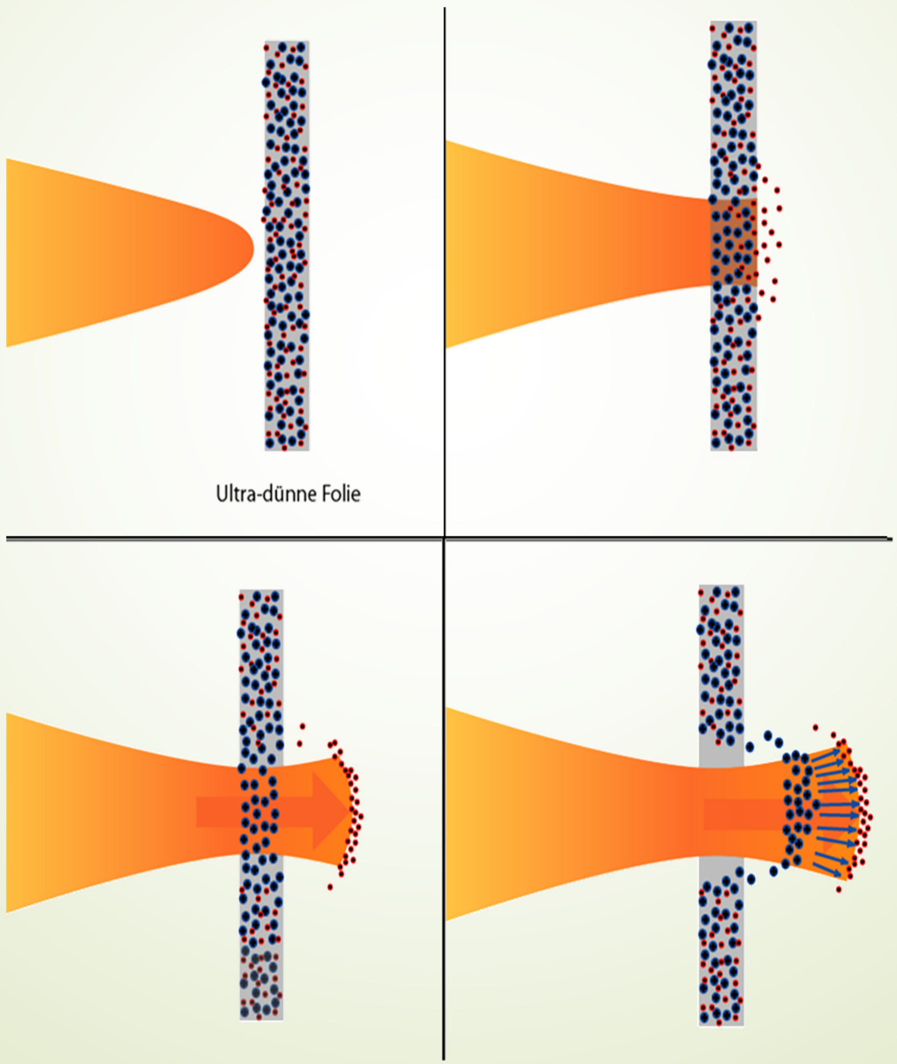
Outline

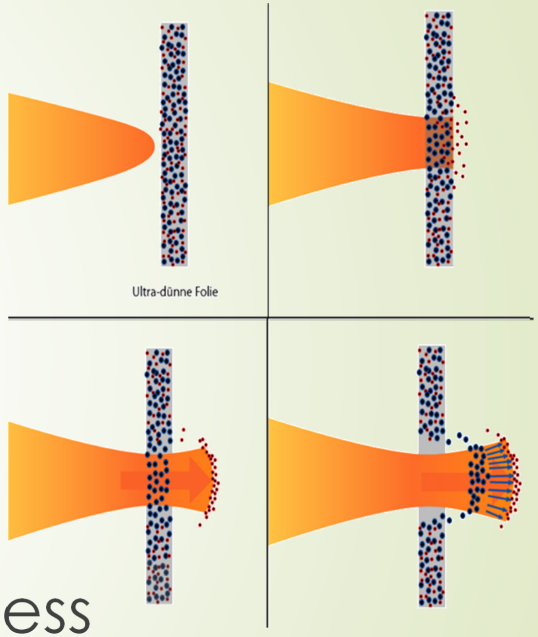
- Generation of monoenergetic ions to MeV level – laser radiation pressure acceleration
- Extended acceleration using multi-ion foils – a two-stage acceleration scheme combining radiation pressure and Coulomb repulsion
- Further acceleration with laser profile design – switch of laser polarization during acceleration

Radiation Pressure Acceleration



Robinson et al. 2008
Klimo et al. 2008
Yan et al. 2008
M. Schnürer *et al.*, 2012

Radiation Pressure Acceleration of Quasi-monoenergetic Hadrons



- Requirements:
  - Circularly polarized laser
    - Avoiding electric oscillation and 2nd harmonics
  - High contrast ratio (> 10^9)
    - Minimizing pre-pulse
  - Ultra-thin optimal target thickness
    - Stable ion trapping of double-layer structure
- Advantage
  - Monoenergetic ion spectra with high energy

Robinson et al. 2008
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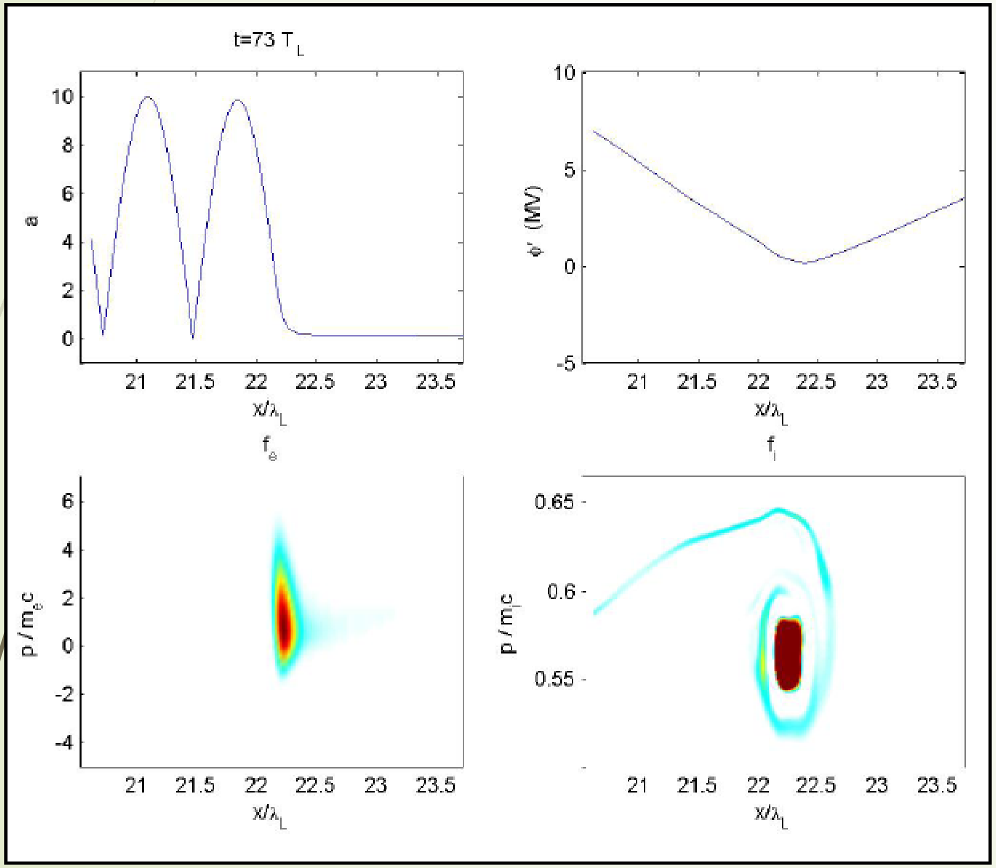
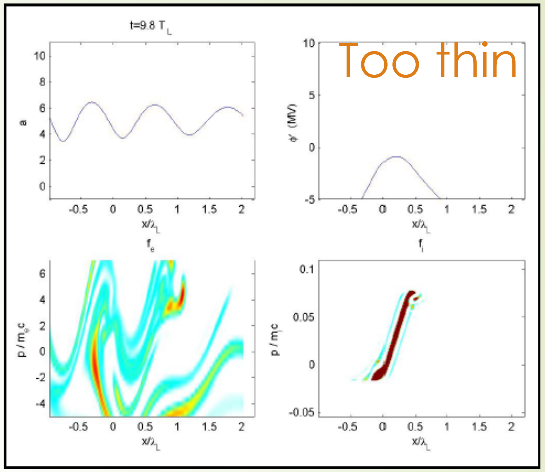
1D Vlasov-Maxwell Simulation

Simulation optimal width $l_0 = 0.2\ \lambda_L$



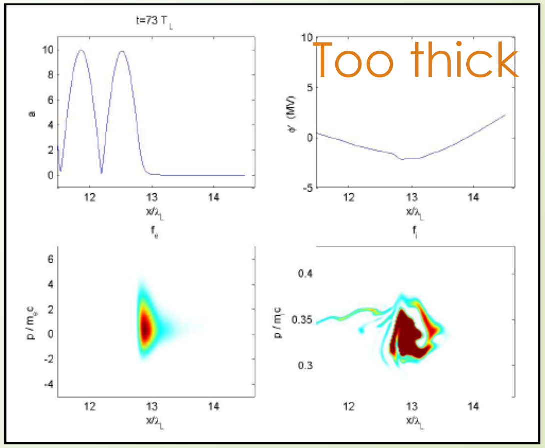
Optimal thickness, stable ion trapping

Simulation half the optimal width $l_0 = 0.1\ \lambda_L$



Laser burns through. Poor acceleration

Simulation twice the optimal width $l_0 = 0.4\ \lambda_L$



Wider energy spread, less acceleration

B. Eliasson, C.S. Liu, X. Shao, R.Z. Sagdeev, P.K. Shukla, New J. Phys. **11**, 073006 (2009)

Rayleigh-Taylor Instability (RTI) and Induced Transparency

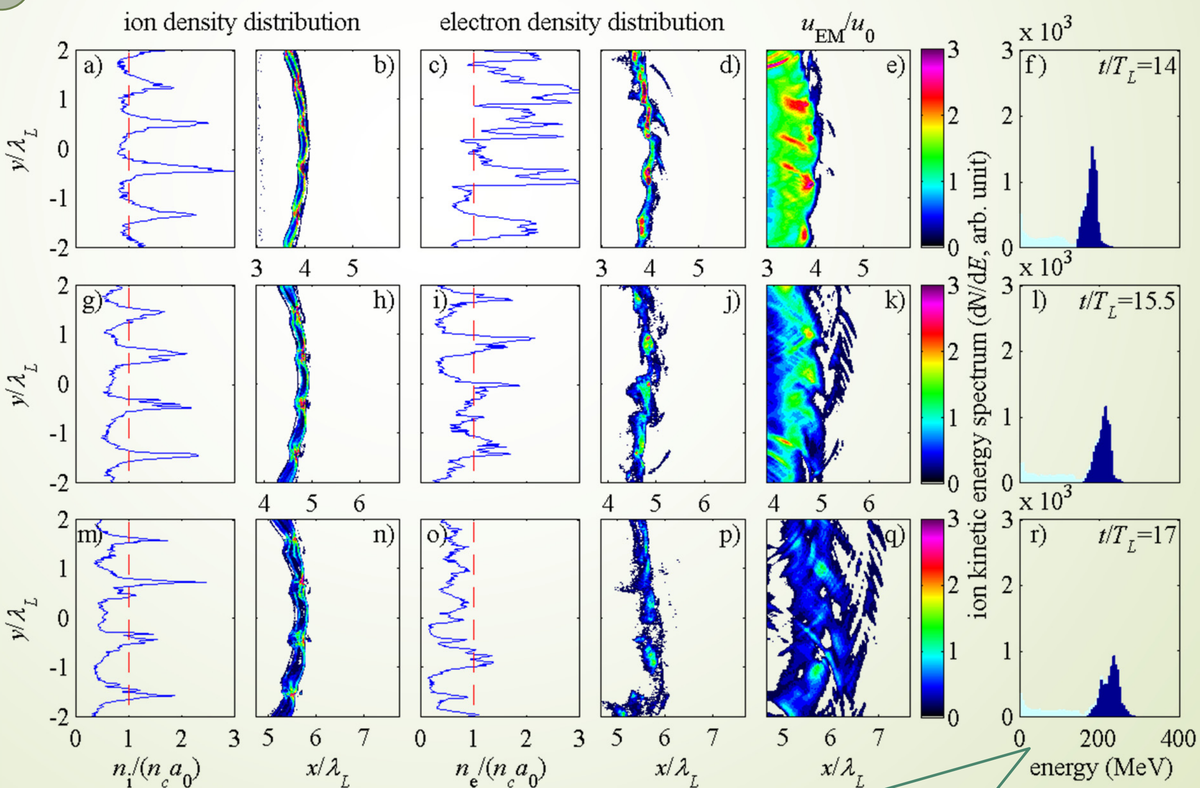
a_0 = 25
n_{e0} = 41.7n_{cr}
l_0 = 0.2λ_L

Proton density | **Electron density** | **EM energy density** | **Proton energy spectra**

t = 14T_L

t = 15.5T_L

t = 17T_L



Losing Monoenergetic Property

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Multi-Ion Foils – Significantly Enhanced Proton Energy due to Longer Acceleration time

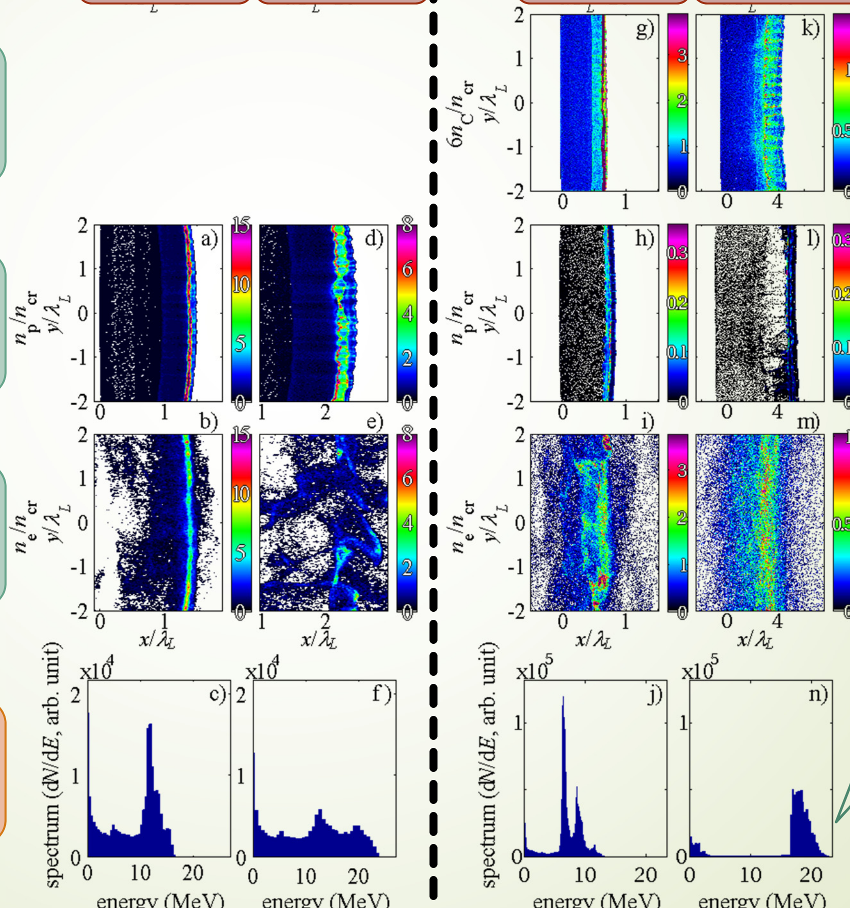
t = 15 | *t* = 20 | *t* = 20 | *t* = 40

Carbon density

Proton density

Electron density

Proton energy



Hydrogen foil | **Multi-ion foil**

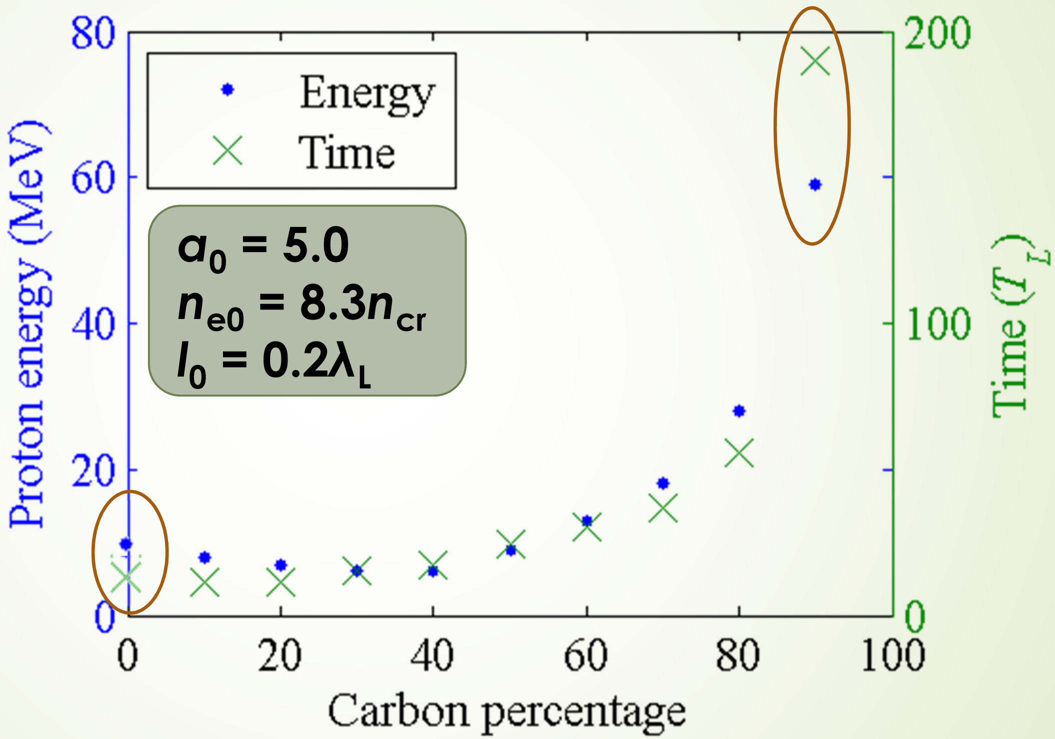
Longer acceleration time

Greater mono-energy

a_0 = 5.0
n_{e0} = 8.3n_{cr}
l_0 = 0.2λ_L

T.-C. Liu *et al.*, New J. Phys. **15**, 025026 (2013)

Scaling of Monoenergetic Proton with Different Carbon Concentration



- Compared with pure hydrogen foil:
  - Proton energy is **6x** as much.
  - Acceleration time is **10x** extended.

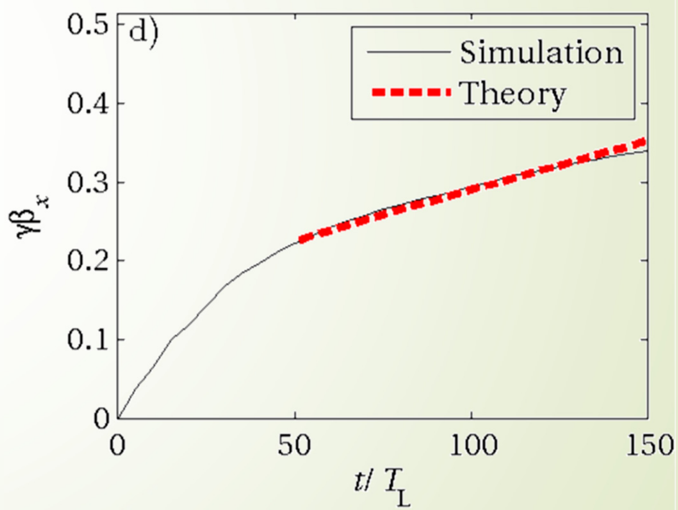
1D Theoretical Model of Proton by Carbon Repulsion Shielded by Electrons

- Assuming protons as a test charge, the Poisson equation

$$\frac{d^2\phi}{dx^2} = \frac{en_0}{\varepsilon_0}\exp\left(\frac{e\phi}{k_B T_e}\right)$$

can be solved to obtain the equation of motion as

$$\begin{cases} \dfrac{dx_p}{dt} = v_p \\ \dfrac{d(\gamma_p v_p)}{dt} = \dfrac{eE_x}{m_p} = \dfrac{e\sigma_{net}}{2\varepsilon_0 m_p}\coth\dfrac{(x_p - v_C t)e\sigma_{net}}{4\varepsilon_0 k_B T} \end{cases}$$



- Good agreement is achieved.

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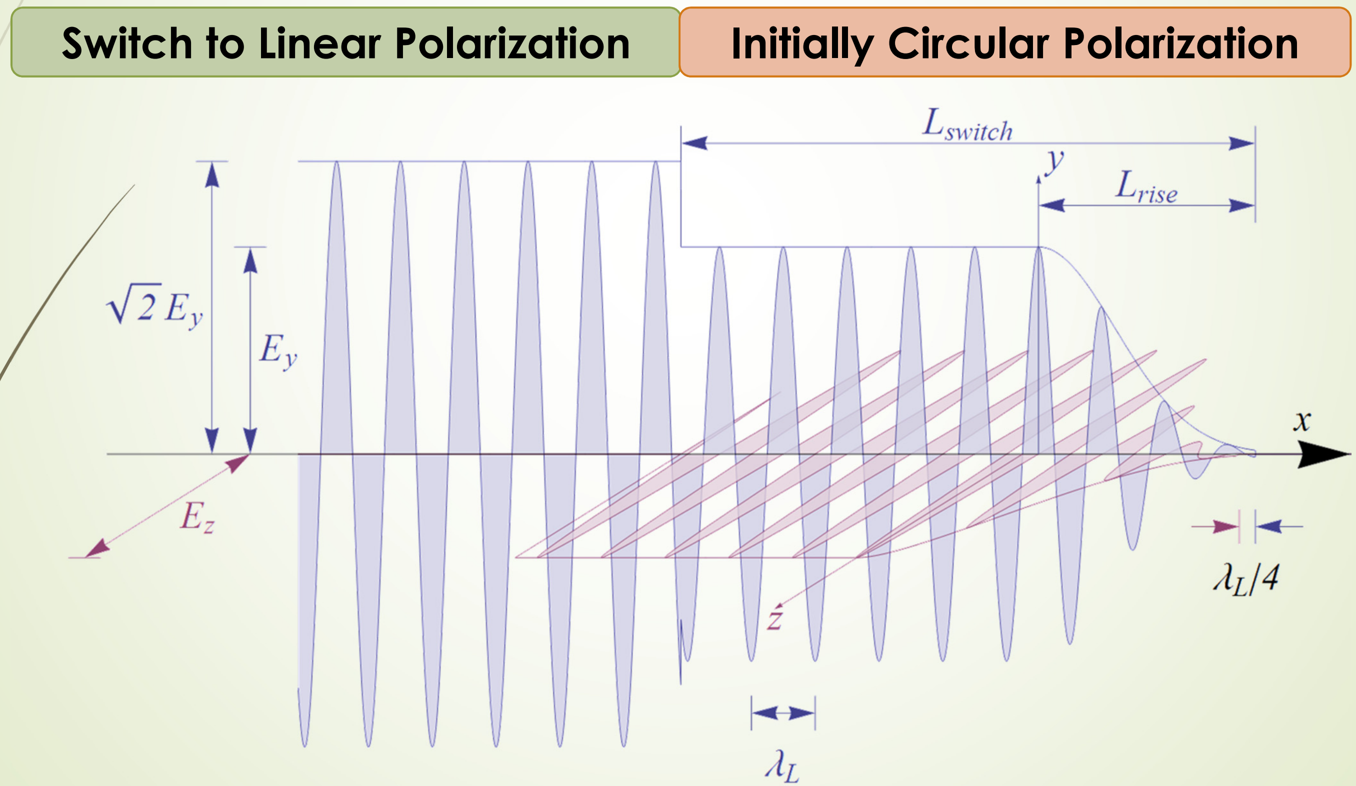
Further Improvement

- Since the **electron temperature** plays an important rule in deciding the shielding effect of Coulomb repulsion due to carbon ions, increasing it could slow down the returning electrons and boost the acceleration.
- **Linear polarized wave** – unwanted heating effect in radiation pressure acceleration now could be an advantage after transparency.

Polarization Switch – Simulation Setup



Comparison and Analysis – Electron Temperature

$a_0 = 5.0$
$n_{e0} = 8.3 n_{cr}$
$l_0 = 0.2\lambda_L$

With Switch

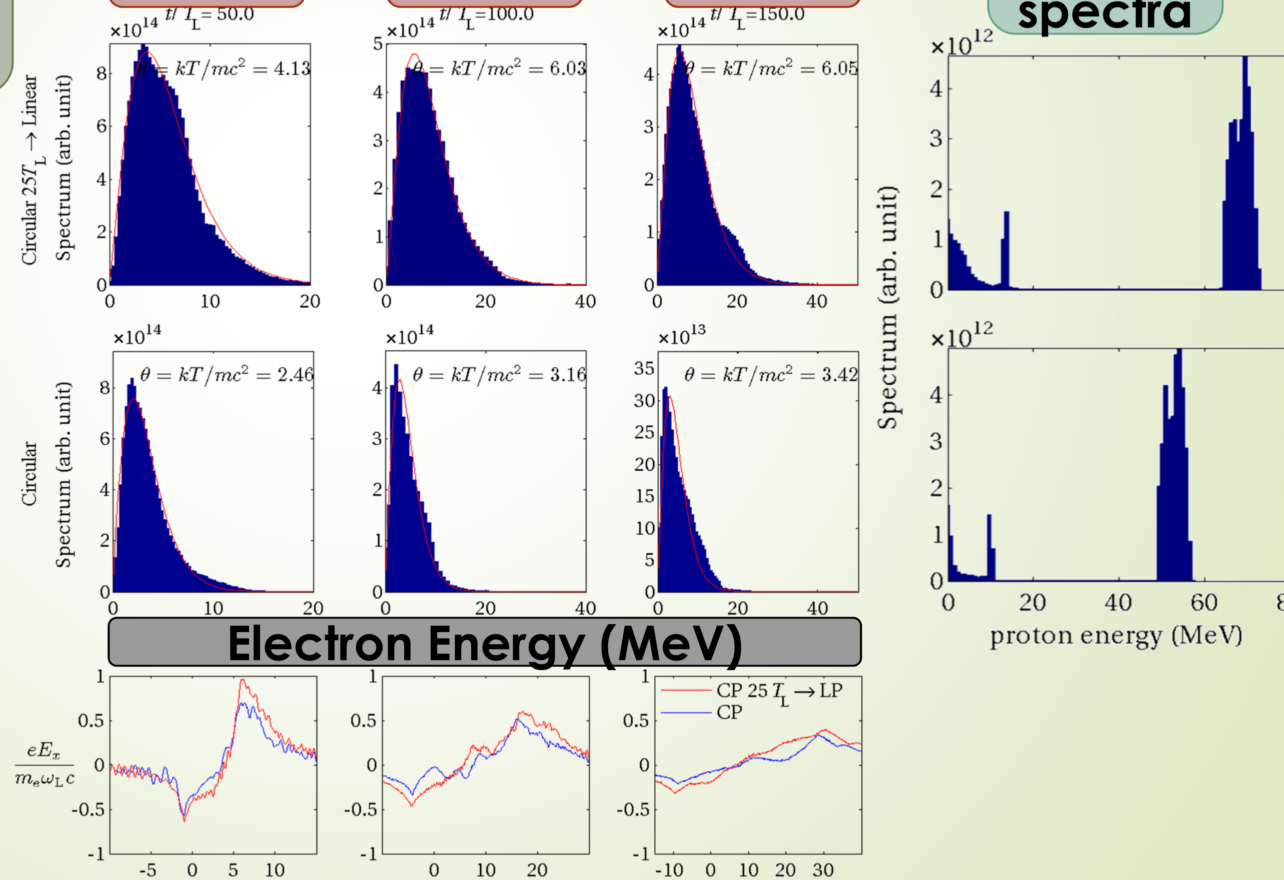
Electron Temperature in COM Frame

Without Switch

Electrostatic Field

t = 50 | **t = 100** | **t = 150**

Proton energy spectra

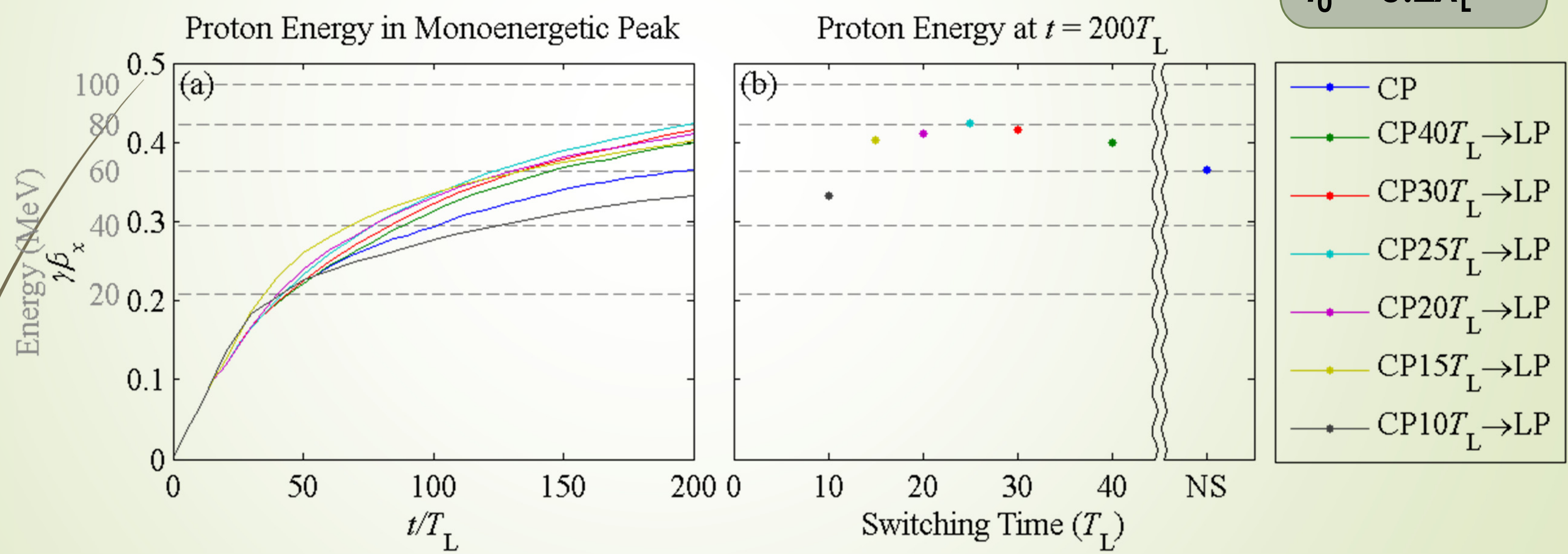


Electron Energy (MeV)

x / λ_L

33% Boost in Monoenergy with Optimal Switching Time

$a_0 = 5.0$
$n_{e0} = 8.3n_{cr}$
$l_0 = 0.2\lambda_L$



Conclusion

- Laser radiation pressure is useful in not only accelerating the proton mono-energetically, but also splitting the proton and carbon ion layers.
- Shielded repulsion can accelerate the protons stably and be modeled with good agreement.
- Switching the polarization increases the electron temperature after transparency and can significantly boost the obtainable energy.

Thank you!

Questions?