Radiation Pressure Dominated Acceleration of Ions

and Electrons

Dr. Sven Steinke

Max Born Institute, Berlin

steinke@mbi-berlin.de

Collaborations

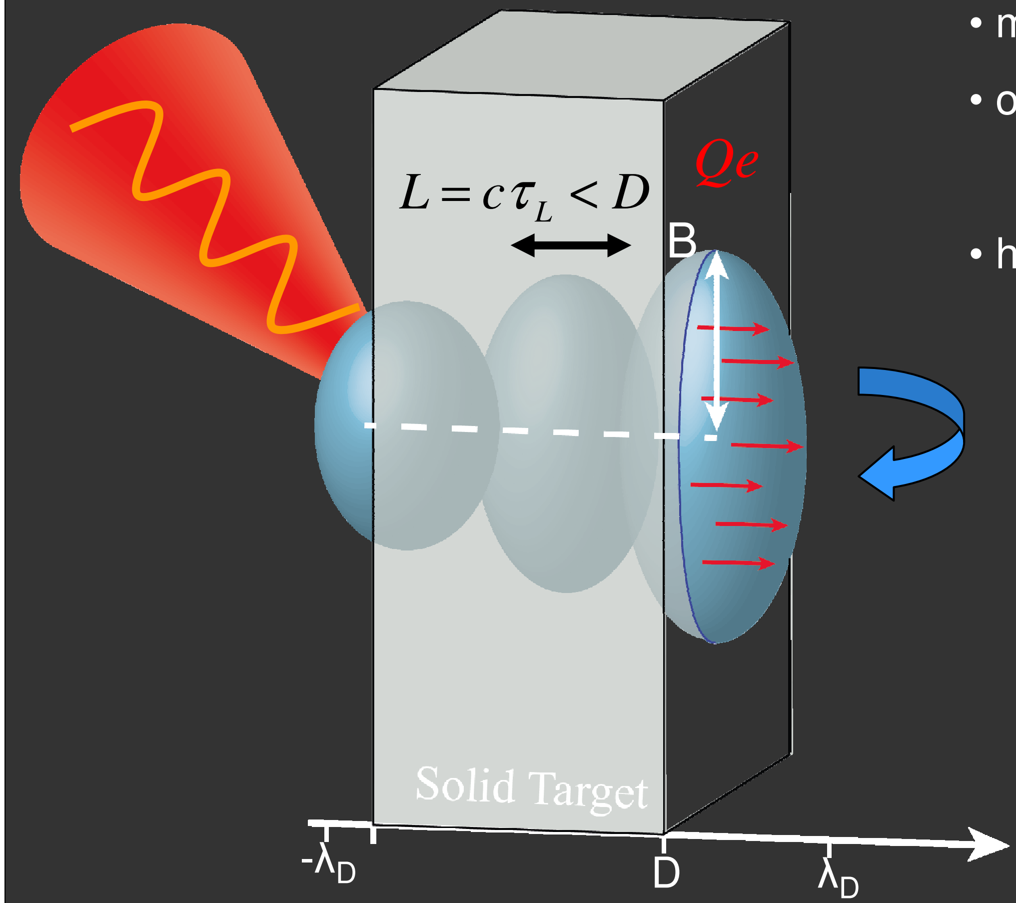
S. Steinke[1], M. Schnürer[1], T. Sokollik[1], P.V. Nickles[1],
A.A. Andreev[1,6]
and W. Sandner[1]

A. Henig[2,3], R. Hörlein[2], D. Kiefer[2,3]
T. Tajima[3,4], X. Q. Yan[2,5], J. Schreiber[2,7],
D. Jung[3,8], M. Hegelich[8], J. Meyer-ter-Vehn[2] and D. Habs[2,3]

[1]Max-Born-Institute for Nonlinear Optics and Short Pulse Spectroscopy
[2]Max-Planck-Institut f. Quantenoptik, Garching
[3]Fakultät f. Physik, LMU München
[4]Photomedical Research Center, JAEA, Kyoto, Japan
[5]State Key Lab of Nuclear physics and technology, Peking University
[6]Institute for Laser Physics, St. Petersburg
[7]Imperial College, London
[8]Los Alamos National Lab

Target Normal Sheath Acceleration (TNSA)

$$T_{hot} \approx \phi_p = m_e c^2 (\sqrt{1+a_0^2} - 1), \quad a_0 = eE_0 / m_e \omega c$$



J. Schreiber et al., PRL **97**, 045005 (2006).

- Induced surface charge → Electric field
- most electrons are forced to turn around @ λ_D
- only electrons with $\varepsilon > \varepsilon_\infty$ can leave the potential

$$\varepsilon_\infty = Qe^2 / (2\pi\varepsilon_0 B)$$

- hot electrons outside the target

$$Q \sim 2\lambda_D N_e / L$$

E_{sheath} ~ TV/m – ionizes and accelerates the ions

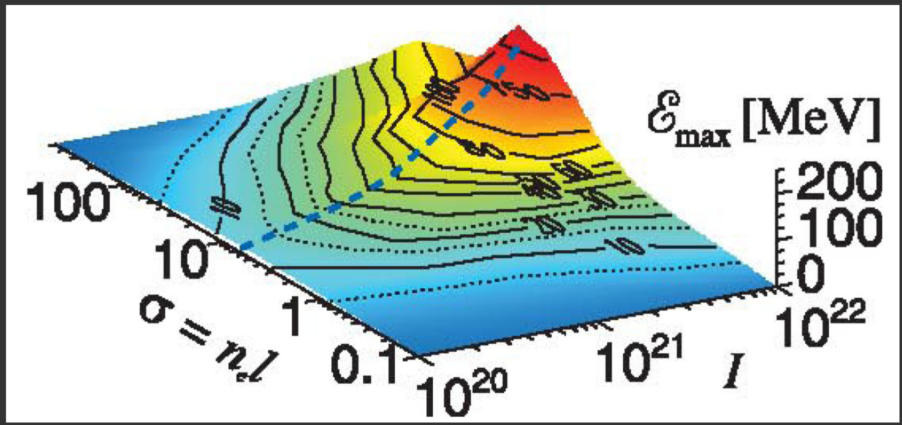
dependence on target thickness only due to divergence of electrons

S.C. Wilks et al., PRL. ***69****, 1383 (1992).*
P. Mora, PRL ***90****, 185002 (2003).*
J. Fuchs et al., Nat. Phys. ***2****, 48 (2006).*

Transparency Regime

Esirkepov et al., PRL ***96****, 105001 (2006)*

Multiparametric 2D-PIC Simulation



Empirical law for optimum areal density:

$$(\sigma = n_e D)$$

$$\sigma_{opt} / n_c \lambda \approx 3 + 0.4 (I / I_0)^{1/2}$$

$$I_0 = 1.368 \times 10^{18} \times (\mu m / \lambda)^2$$

$\sigma < \sigma_{opt}$:

- the plasma becomes increasingly transparent, electrons are detached from the ions (→electron break out)

$\sigma > \sigma_{opt}$:

- no maximum displacement of all electrons within the focal volume

scaling: $E_{max} \sim \sqrt{I} \sim a_0$, $\quad a_0 = \frac{eE_0}{m_e \omega c}$

some numbers:

$$I = 5 \times 10^{19} W / cm^2$$

$$n_e / n_c = 500, \lambda = 810 nm$$

$$\Rightarrow D_{opt} \approx 8nm \leq \delta_\lambda$$

Coherent Acceleration of Ions by Laser (CAIL)

- target becomes transparent if $D \leq 8$nm

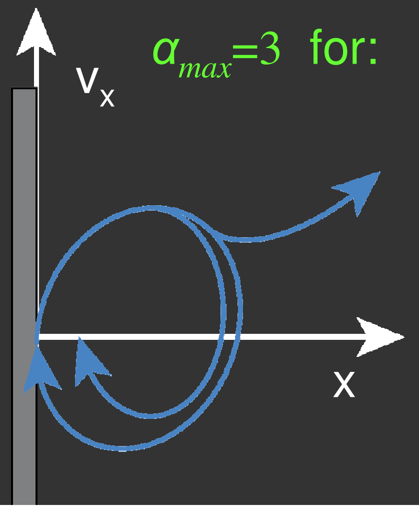
→ transmitted laser preserves electron forward momentum → coherent motion

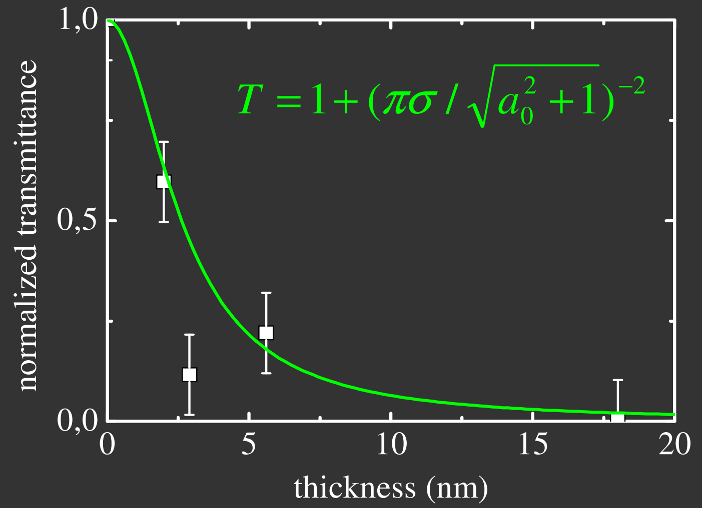
- forward current density *J(ε)* changes from exponential to power law dependence:

$$J(\varepsilon) = -J_0(1-\varepsilon/\varepsilon_0)^{\alpha}$$

coherence parameter:

$\alpha_{max}=3$ for: $\sigma_{opt}/n_c\lambda \approx a_0$





<u>Prevention of adiabatic acceleration:</u>

- electron “reflexing” or “blow-out”
- high thermal component of electron energy (→ collisionless adsorption)

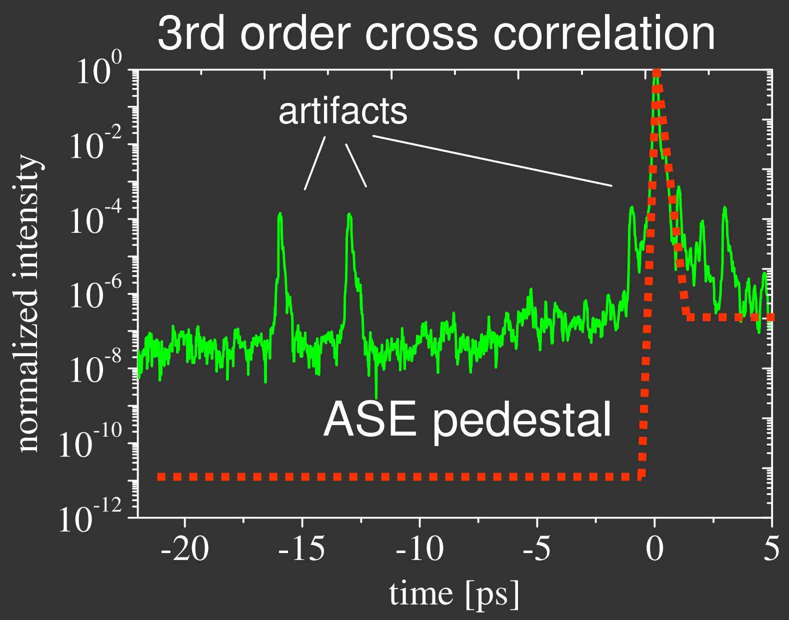
→ Ion energy enhancement:

$$E = (2\alpha+1)E_0$$

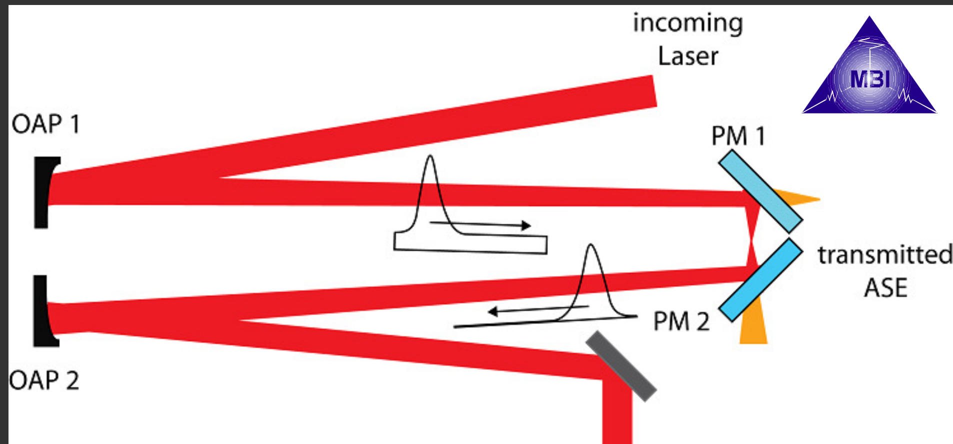
T. Tajima et al. RAST ***2****, 201 (2009).*
X. Q. Yan et al., App. Phys. B, ***98*** *(2009).*
S. Steinke et al., LPB ***28****, 215 (2010).*

How to access this Regime?

Requirements



energy throughput: ~60%:
→ 0.7J @ 45fs → I= 5 x 10^{19} W/cm²; a_0=5



Andreev, Steinke et al. POP **16**, *9 (2009)*

<u>DLC Properties</u>
- thickness 3 nm - 60 nm
- bulk density (2.7±0.3) g/cm³ (75 % sp3)
- damage threshold: 10^{11} W/cm² @ 500 fs, 10^8 W/cm² @ 1.2 ns

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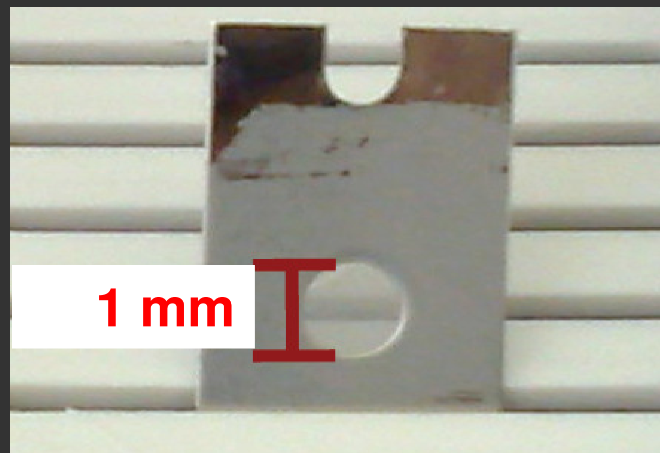
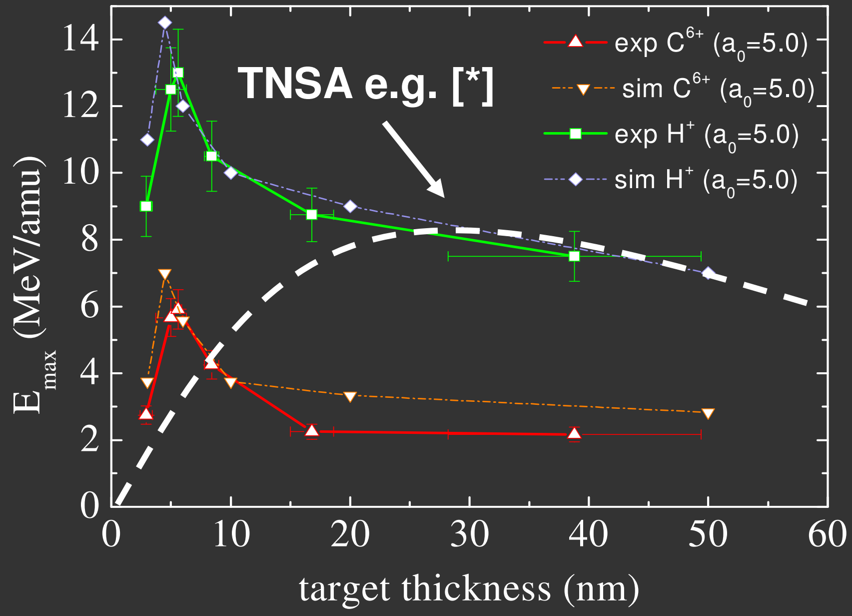


Results (linear polarization)

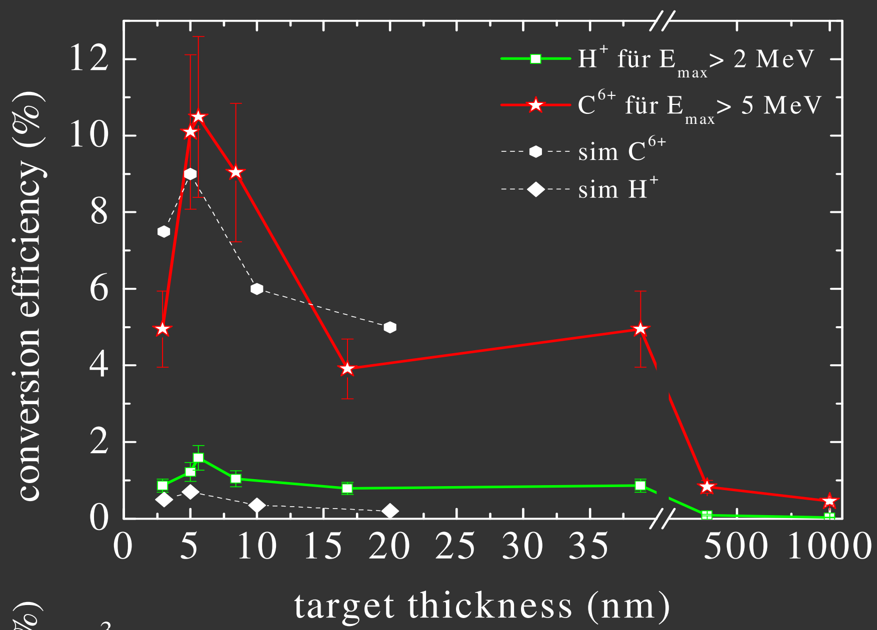


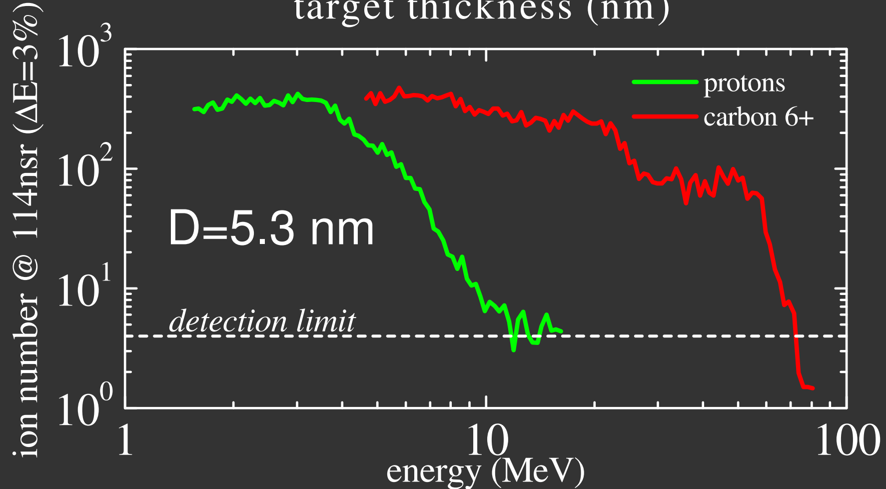
[*] A.A. Andreev *et al.* , *PRL* ***101***, 155002 (2008)

5.3nm DLC (a_0=5):

- **13 MeV** Protons
- **71 MeV** C^{6+} Ions
- maximum @ 5.3nm

→ $\sigma_{opt} / n_c \lambda \sim a_0$





S. Steinke, A. Henig *et al.* *LPB* **28**, 215 (2010)

Radiation Pressure Acceleration (RPA)

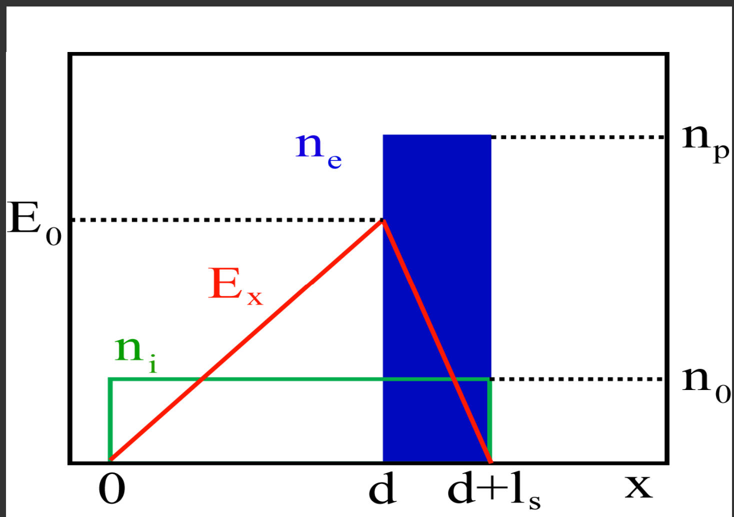
Aim: Gradual acceleration

→ Reduce absorption

Method: Circular Polarization:
Lorentz force: $\mathbf{F}_L = e(\mathbf{E}_L + $ ~~$\mathbf{v}_e \times \mathbf{B}_L$~~$)$

→ Suppression of 2**ω**-electron heating

Macchi *et al.*, PRL 2005 and 2009



• electrons pile up

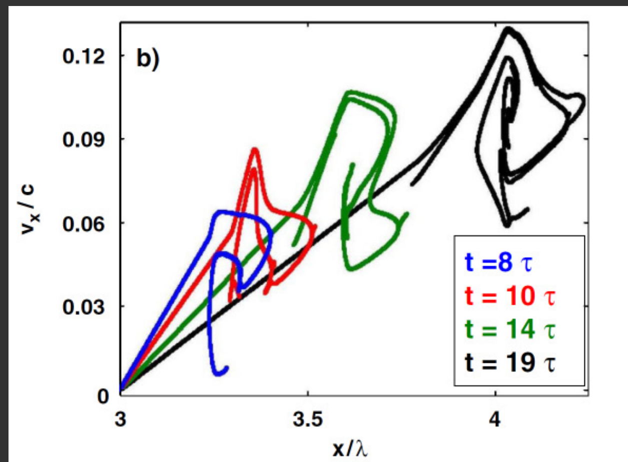
→ electron depletion layer left behind

• E_x balances F_P at any time, i.e.

$$P_{rad} = 2I/c \approx P_{es} = (en_0 d)^2/2$$

$$\Rightarrow \sigma_{opt}/n_c\lambda \approx a_0$$

• all ions in ($d<x<d+l_s$) reach ($d+l_s$) at the same time by cyclic RPA

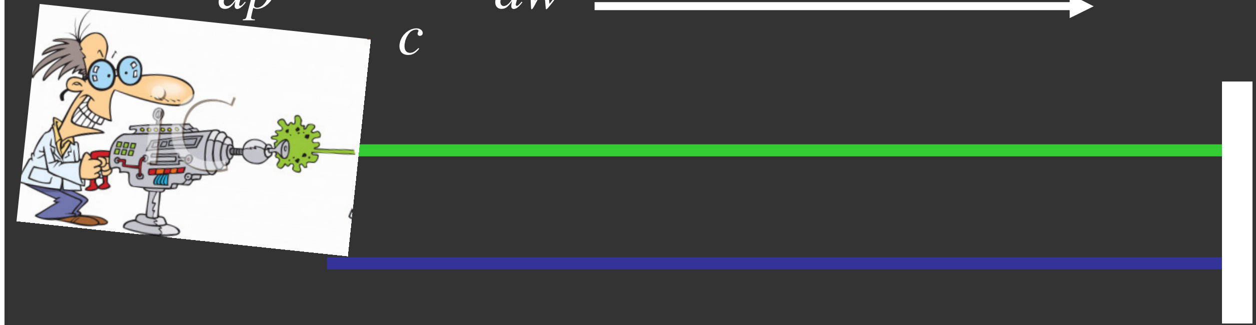


Klimo *et al.*, PRST **11**, 14 (2008)

$$dp = \frac{2I(w)}{c} dw$$

Doppler-Shift →

$$dp = \frac{2I(w)}{c} \gamma(1-\beta) dw$$



↓ Proper Time Interval

$$dp = \frac{2I(w)}{c} \frac{1-\beta}{1+\beta} d\tau$$

Pascal's law: $dp = \rho a(dD)$

← Doppler-Shift

$$\frac{d}{d\tau}(\gamma\beta) = \frac{2I(w)}{\rho D c^2} \frac{1-\beta}{1+\beta}$$

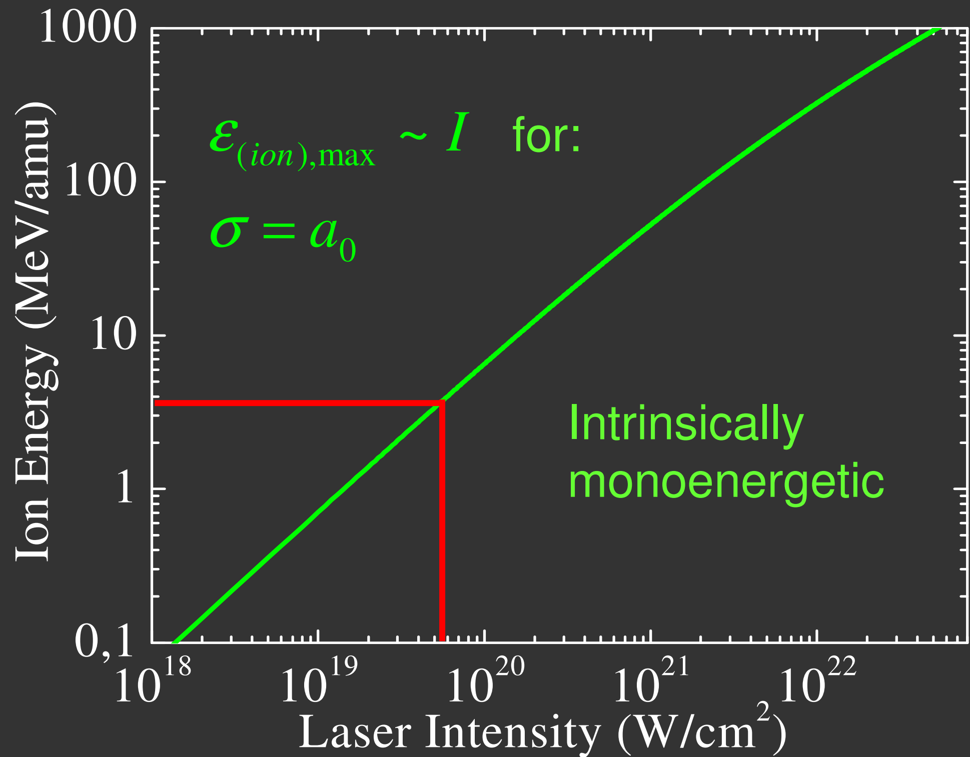
↓ Integration

Final velocity:

$$\beta_f = \frac{(1-E)^2 - 1}{(1+E)^2 + 1}$$

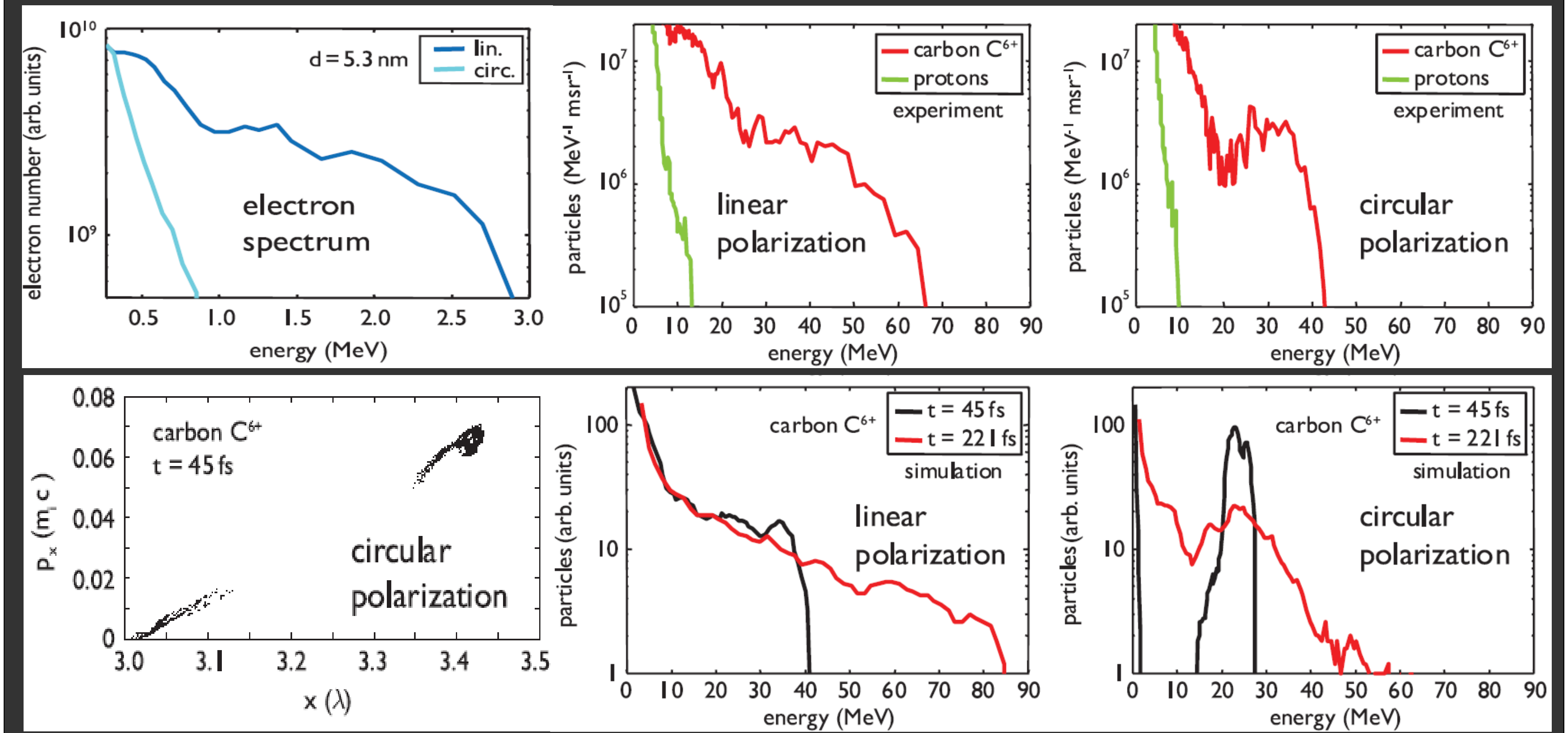
total laser energy output: $E = \frac{2F}{\rho D c^2}$

with fluence: $F = \int_0^w I(w) dw$



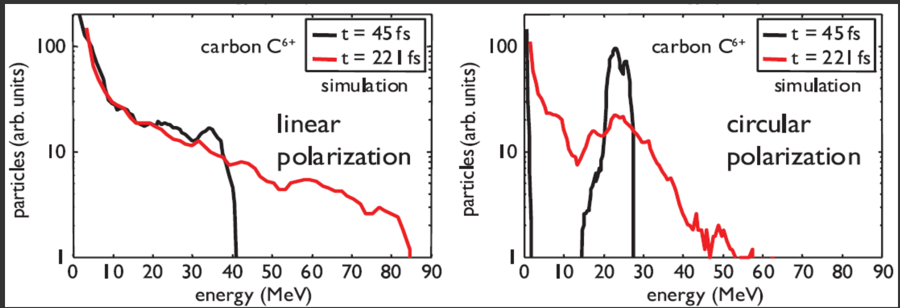
Peak in C^{6+} Spectrum

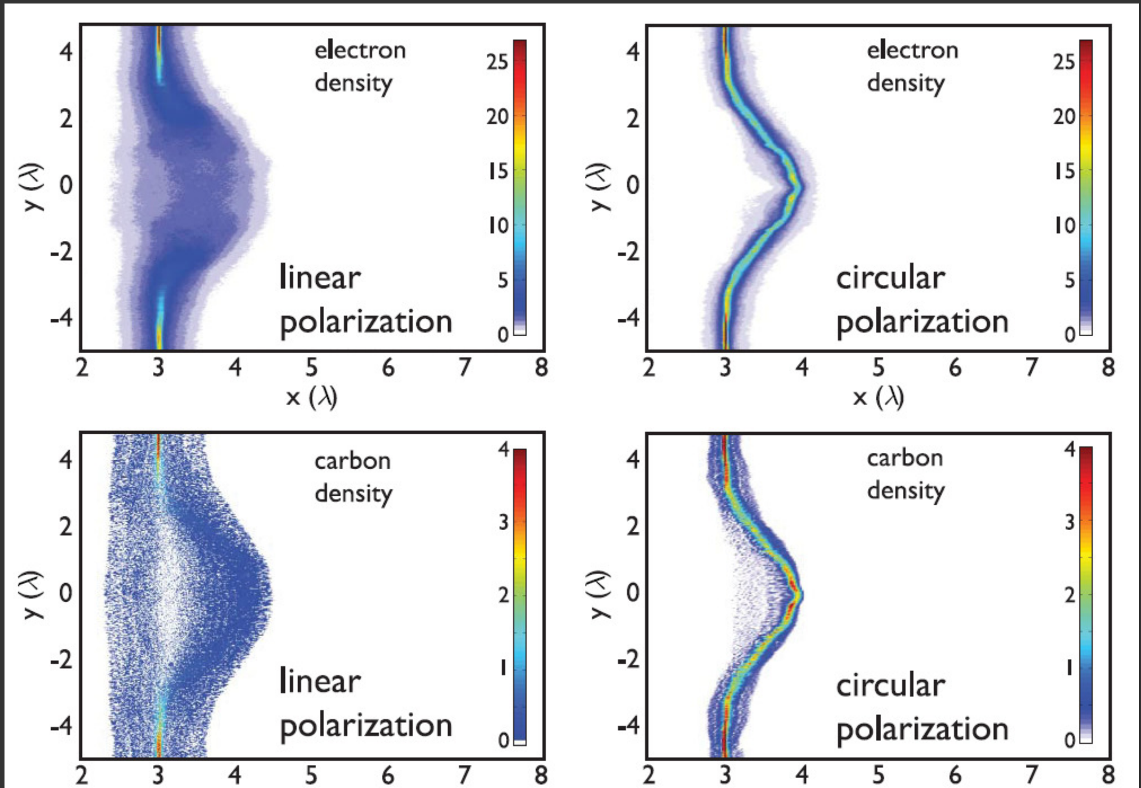
At the optimum thickness (D=5.3nm)



*A. Henig, S. Steinke, et al. PRL, **103**, 245003 (2009)*

2D-PIC Simulation





A. Henig, S. Steinke, *et al.* PRL, **103**, 245003 (2009)

Circular Polarization:

- ballistic acceleration of the whole target volume
- target movement results in E-field oscillations perpendicular to (moved) target surface

→ Electron heating

→ Peak dissolves in time

Conclusion

Departure from thermal TNSA towards collective, gradual acceleration

Prerequisites:

- ultra-high contrast laser pulses (Double-Plasma-Mirror)
- ultra-thin target foils (Diamond-Like-Carbon)

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Laser Transparency Regime

Coherent Acceleration of Ions by Laser

- Ion Energy Enhancement: 2 times (13MeV) for protons and 20 times for carbon ions (70 MeV)
- Very high conversion efficiency: 10% for carbon ions and 1.6% for protons

Radiation Pressure Acceleration

- narrowed carbon energy spectra: centered around 30 MeV
- Promising scaling: maximum ion energy proportional to laser intensity