Exploiting relativistic nonlinearities in near-critical density plasmas for laser driven ion acceleration

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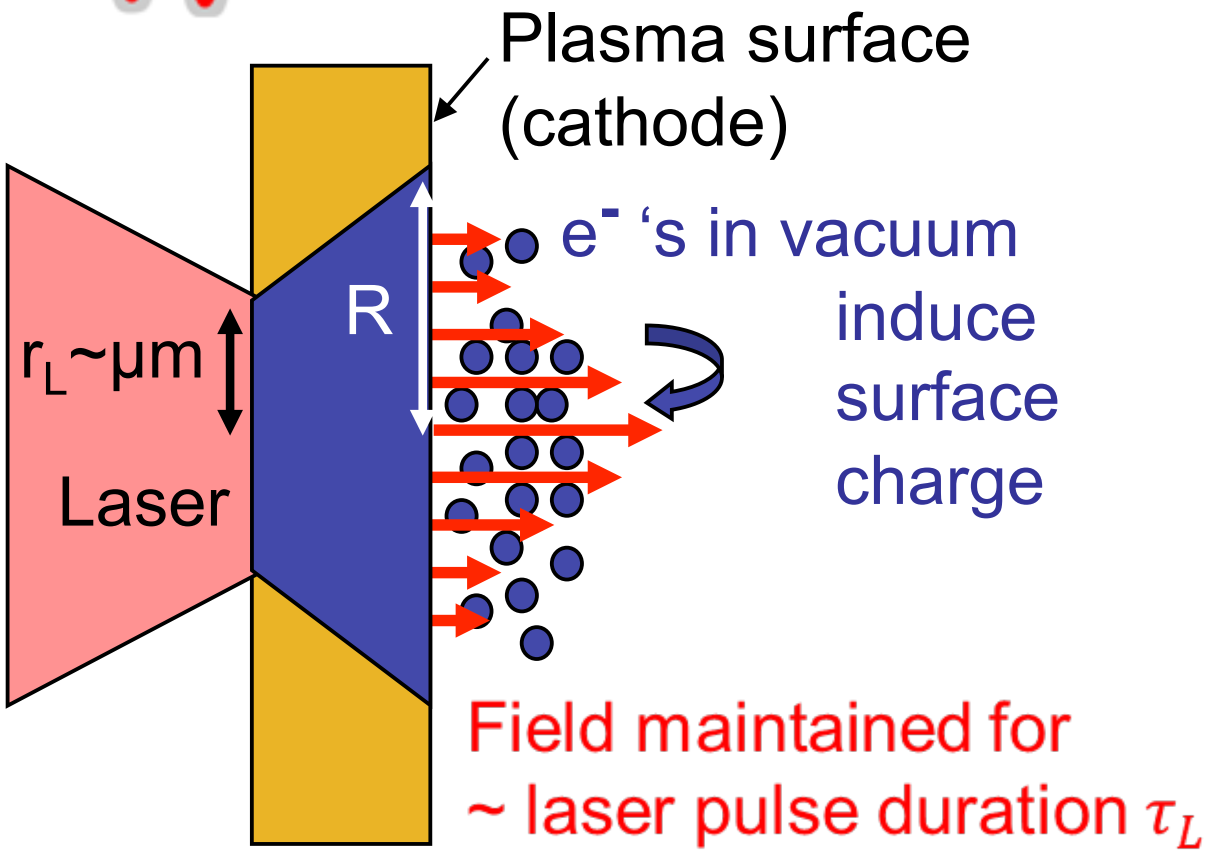
TNSA (Target Normal Sheath Acceleration)



- opaque targets (μm thick)
- hot electrons generate quasi-static E-field (TV/m)
- ions are accelerated from the back surface (MeV/u)

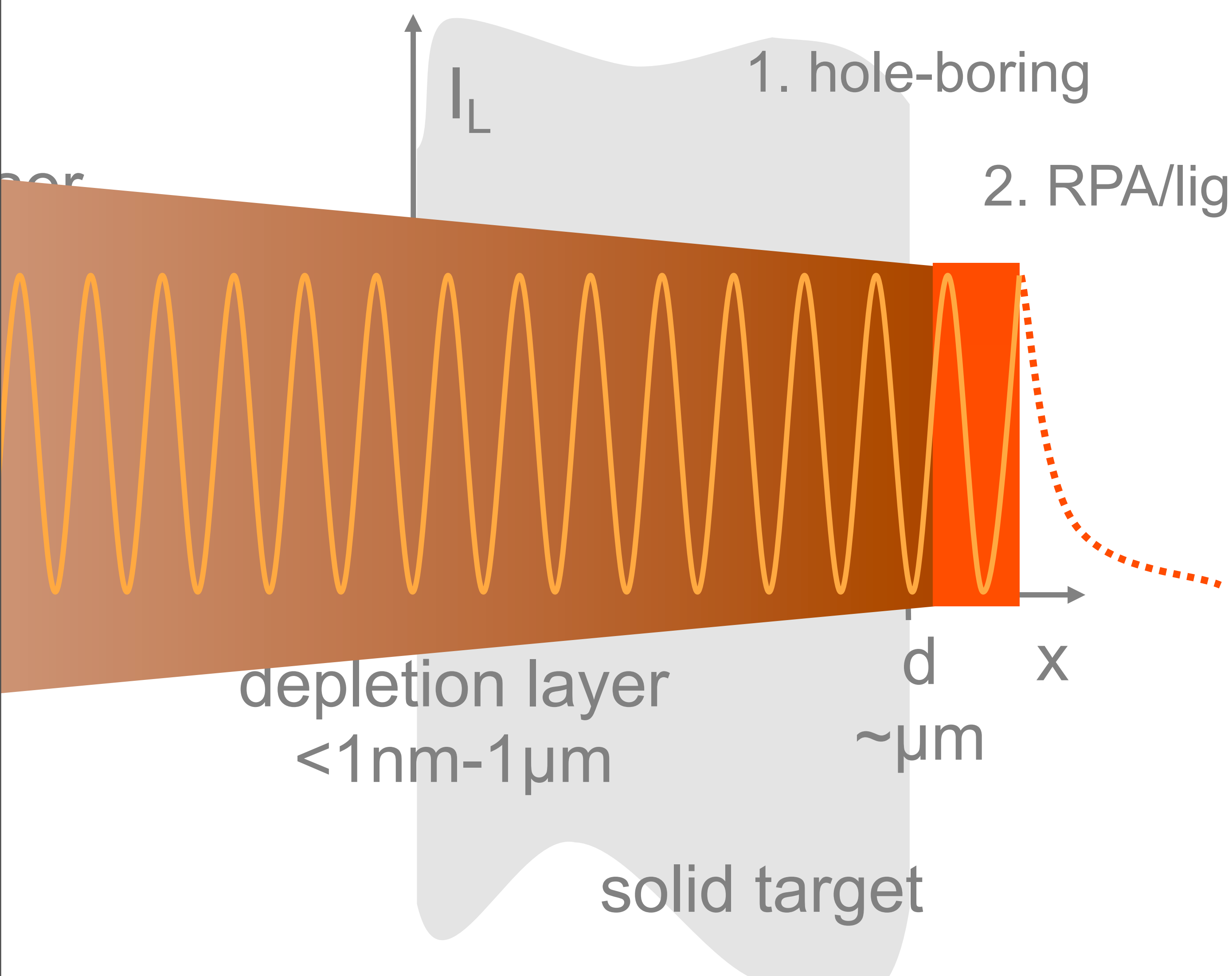
But:

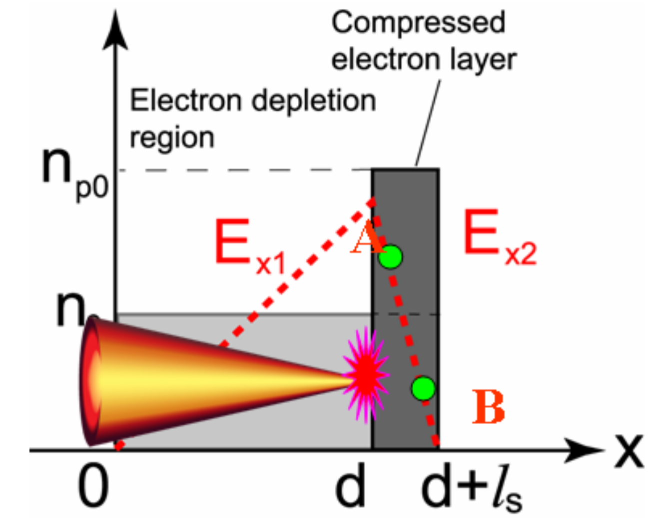
- energy transfers to electrons directly and ions got energy from electron
- exponential spectrum (possibly peaked spectrum)
- large angular divergence (can be ~10's degrees)
- light ions preference (mostly proton)

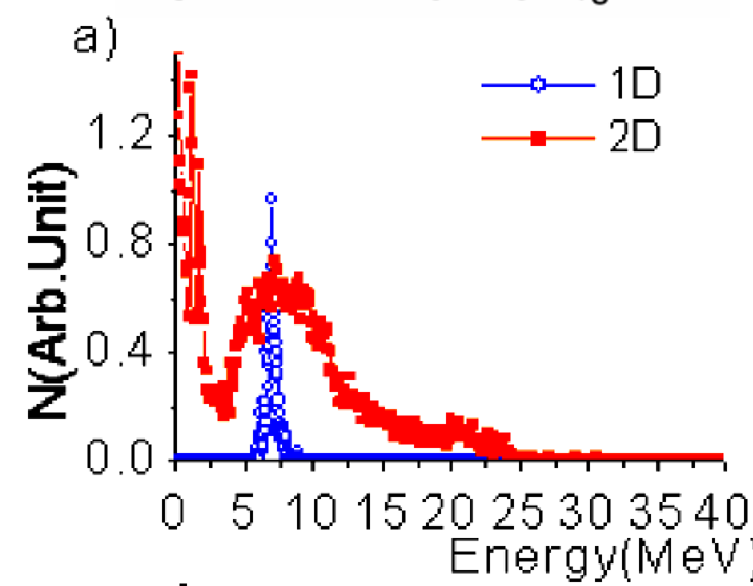
RPA (Radiation Pressure Acceleration)

key to success: suppression of electron heating

Requests: high intensity and steep rising edge







- direct acceleration
- high conversion efficiency
- mono-energetic spectrum
- benefit for heavy ions (same velocity for all the ion species)

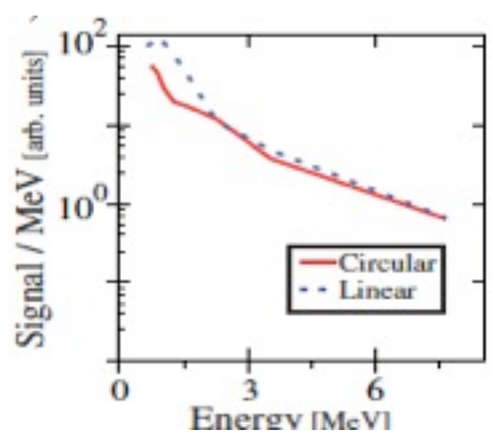
T. Esirkepov *et al*, PRL. **92**, 175003 (2004);
O. Klimo *et al*, PRST AB **11**, 031301 (2008)
A.P.L. Robinson *et al*, NJP **10**, 013021 (2008)
X.Q. Yan *et al*, PRL **100**, 135003 (2008)

Experimental requirements, RPA

Typical experimental setup

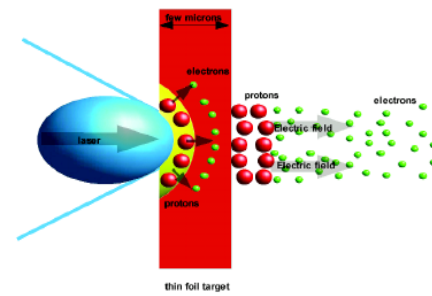
CP laser pulses

electron heating
target pre-expansion...



Dollar, et al. PRL 108, 2012

nm thin foil, thickness

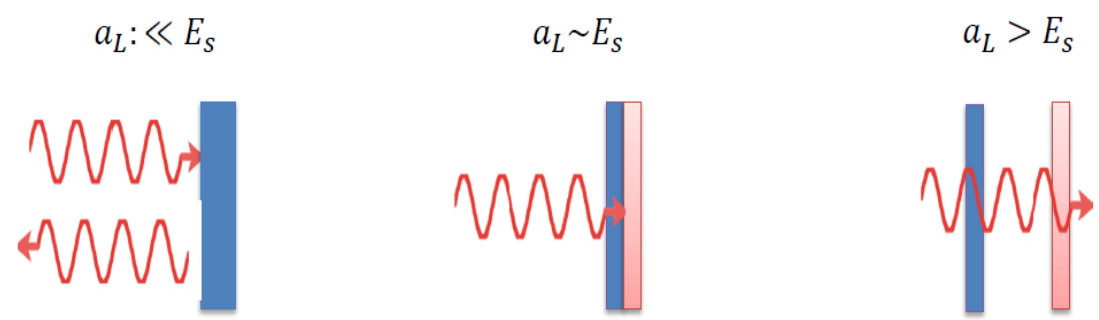


Laser Field

$$a_L = \frac{eE_L}{mc\omega}$$

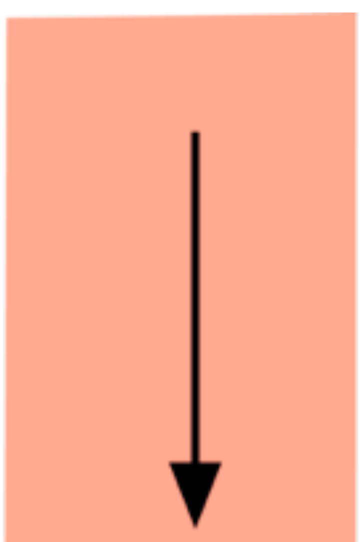
Maximum Coulomb Field in a Thin Foil

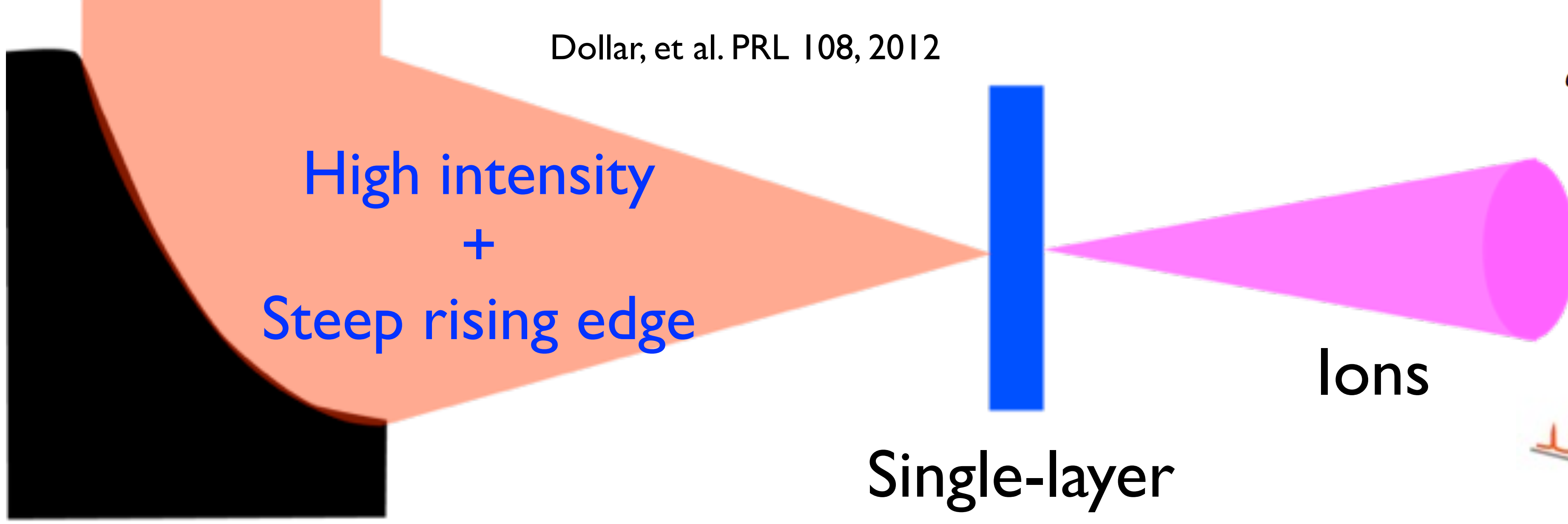
$$E_s \sim \frac{n_e}{n_c} \cdot \frac{d}{\lambda}$$



$d \sim 5 - 10\ nm$

$d < 5\ nm$

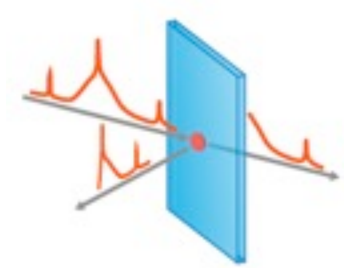




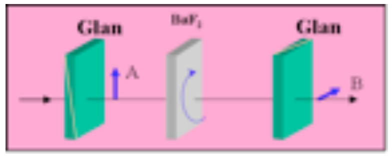
Off-axis parabolic mirror

Single-layer nm thin foil

Additional pulse cleaning setup

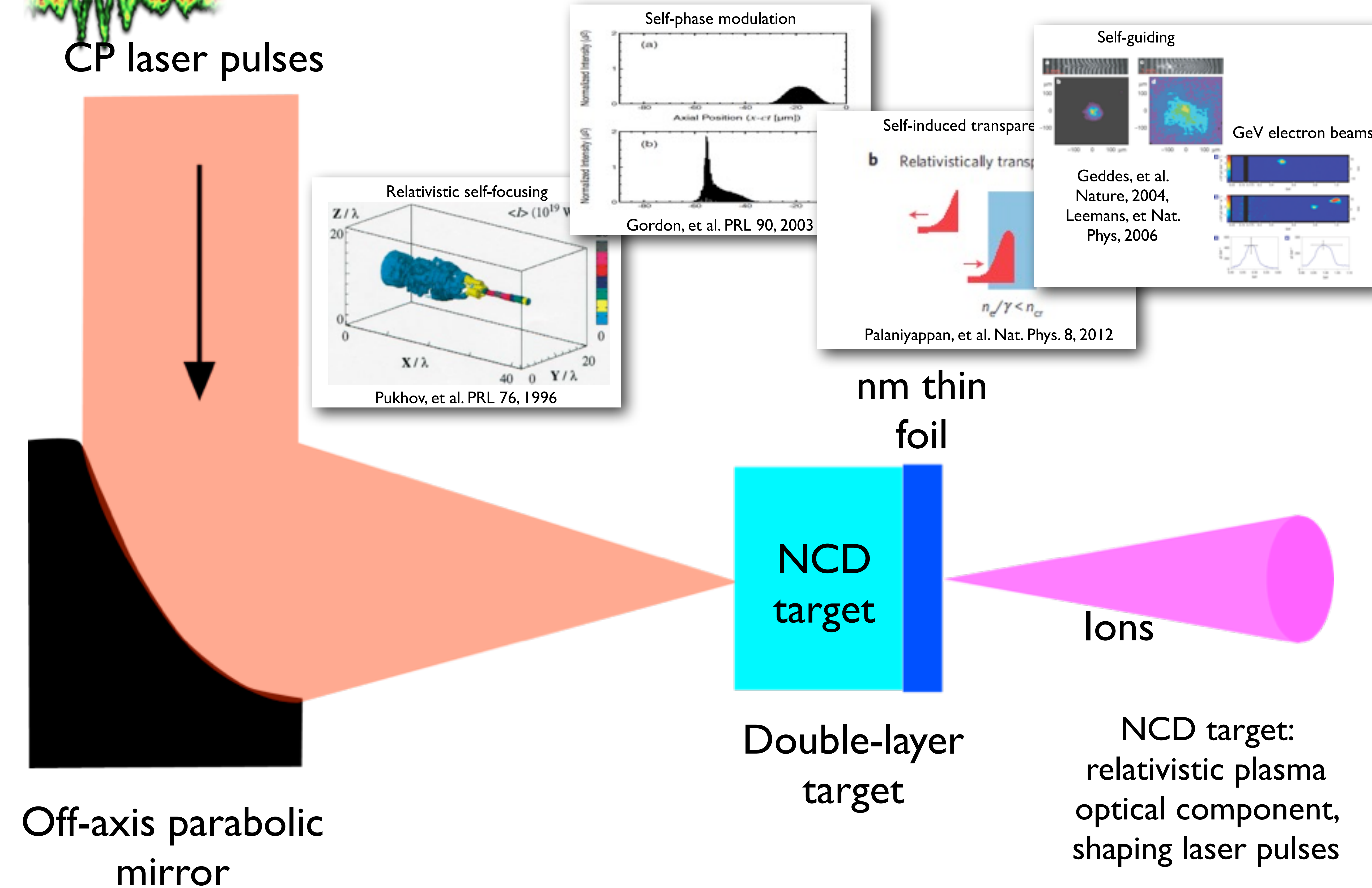


PM



XPW

Exploiting nonlinearities for ion acceleration



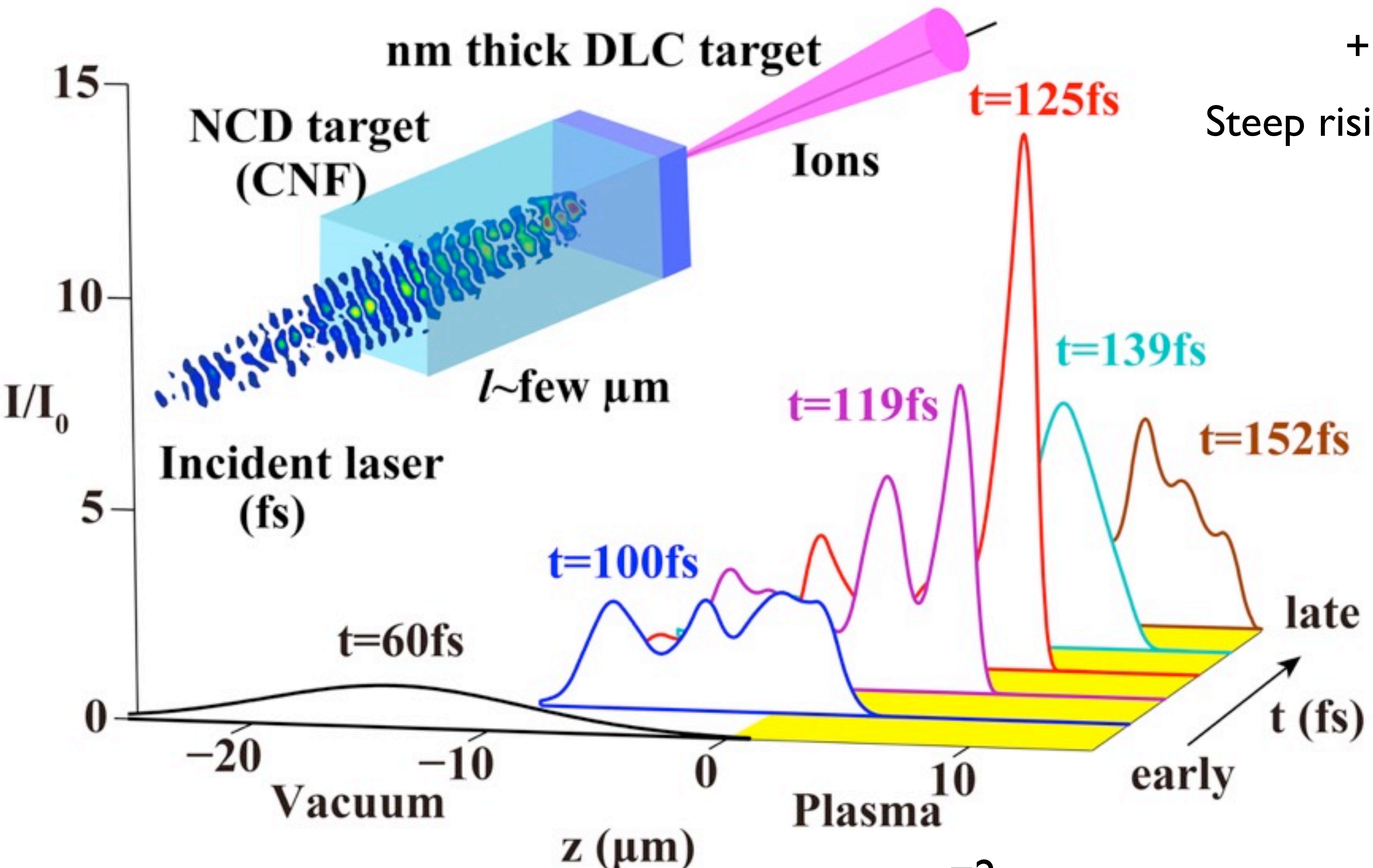
Exploiting nonlinearities for ion acceleration

3D PIC simulation

Higher laser intensity

+

Steep rising edge



$n_e=2n_c$

Suitable target parameters

MPQ LMU www.attoworld.de

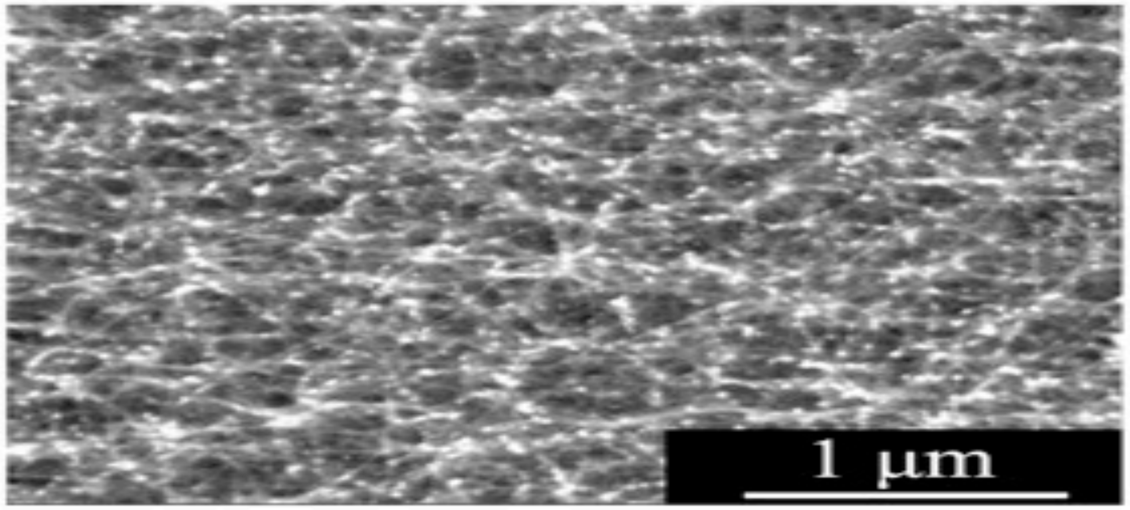
Self-focusing in Plasma

	Theoretical estimation	$n_e = 10^{-2} n_c$ $a_0 = 10$	$n_e = 1 n_c$ $a_0 = 10$
Refractive index (η)	$(1 - n_e / \gamma n_c)^{1/2}$	0.9993	**0.93**
Self-focus length (*f*)	$D_L \cdot (n_c a_0 / n_e)^{1/2}$	32 D_L	**3 D_L**
Self-focus size (r_{FWHM})	$0.37 \lambda_L \cdot (n_c a_0 / n_e)^{1/2}$	10 μm	**1 μm**

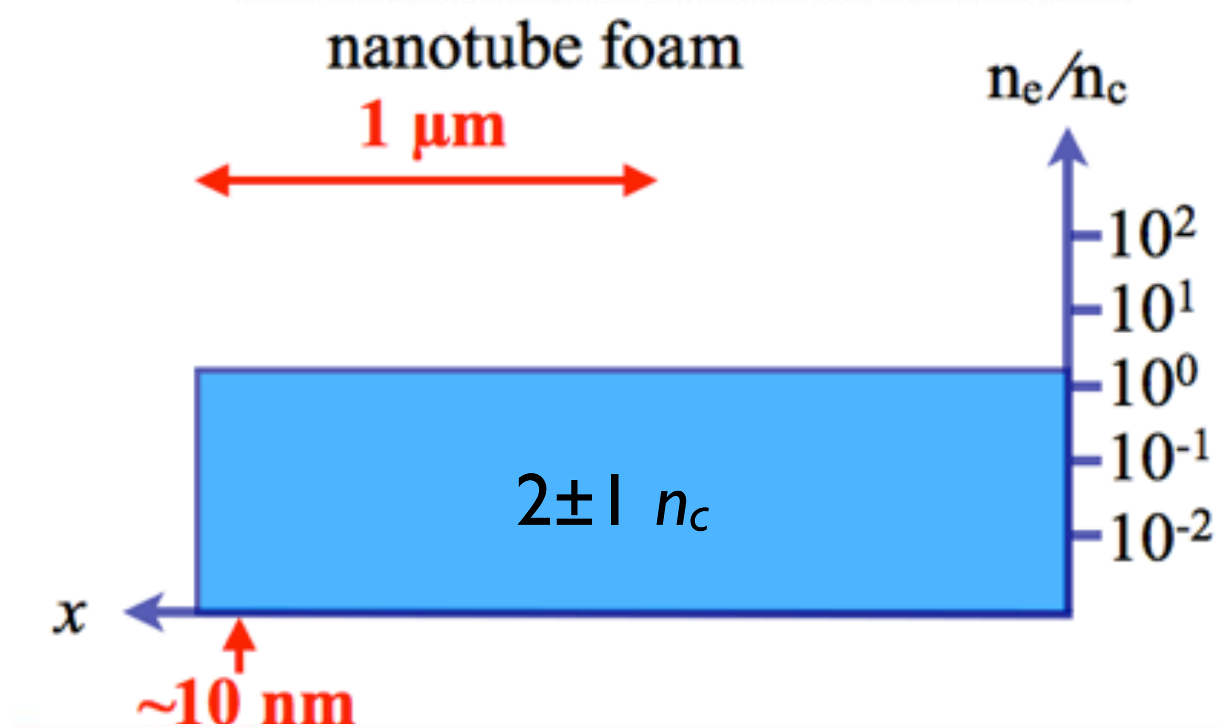
- Strongest self-focusing occurs in near-critical density regime
- Characteristic lengths on μm-scale

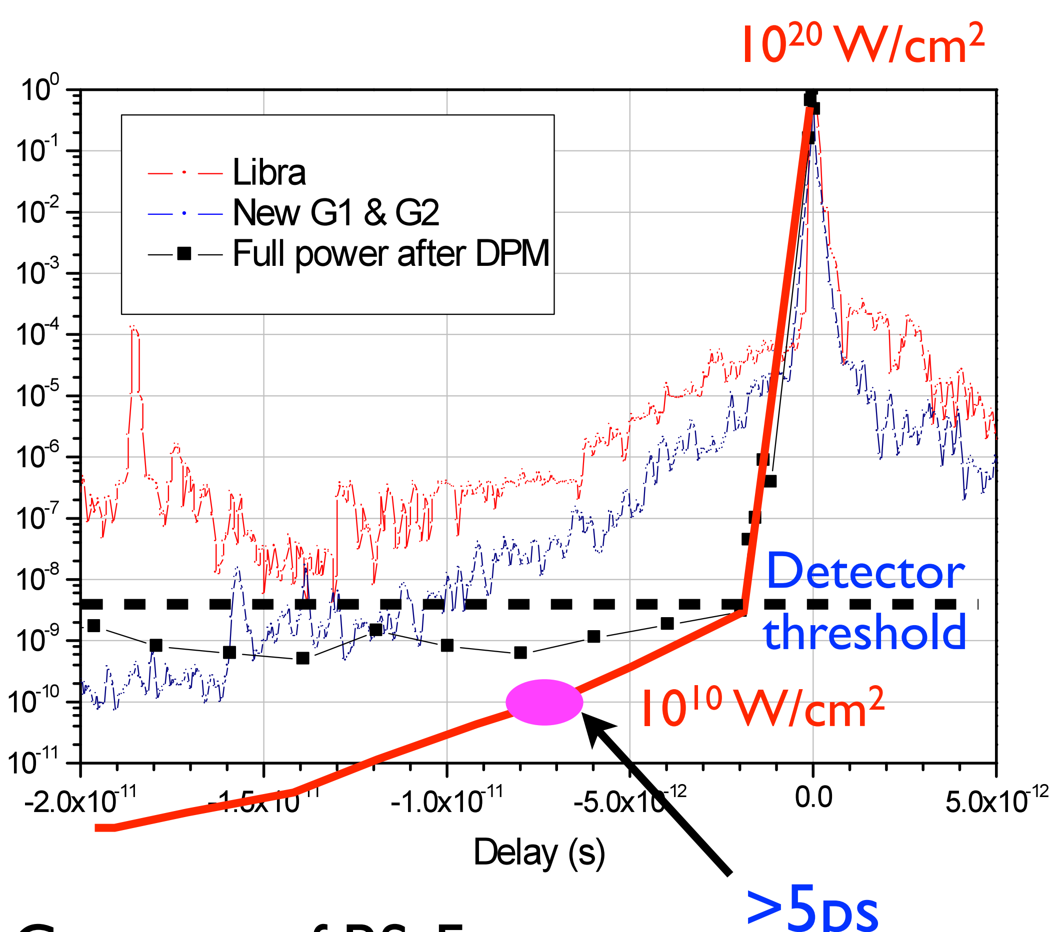
Experimental challenge: uniform NCD target with a few μm thickness

Carbon nanotube foam (CNF)



SEM image

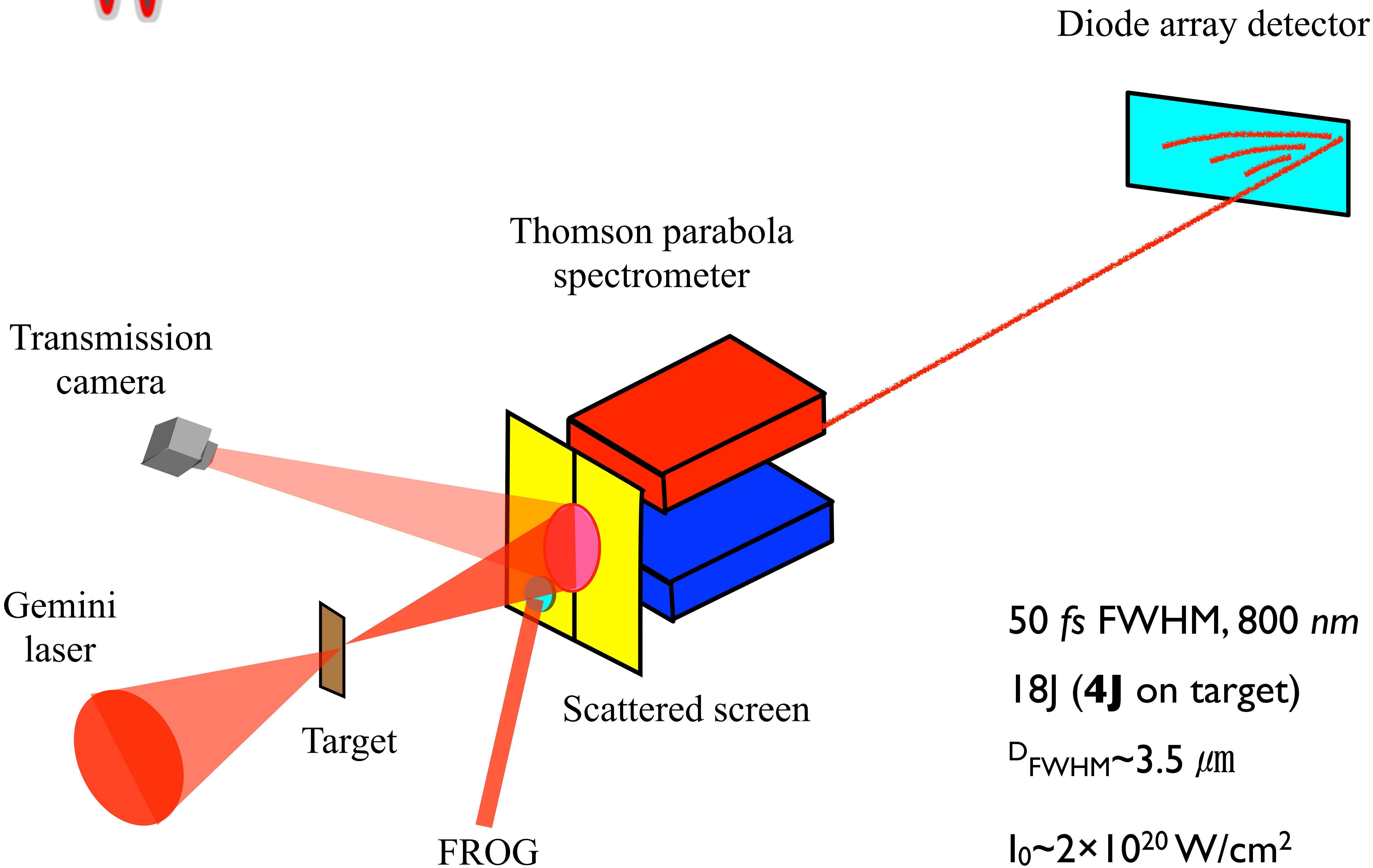




Courtesy of P.S. Foster

- Homogeneous on µm-scale
- Thickness below 1 µm
- Initial density of 2±1 n_c
- Sharp boundary, uniform plasma
- Directly deposit on DLC foils

Experimental set-up @ Gemini



50 *fs* FWHM, 800 *nm*

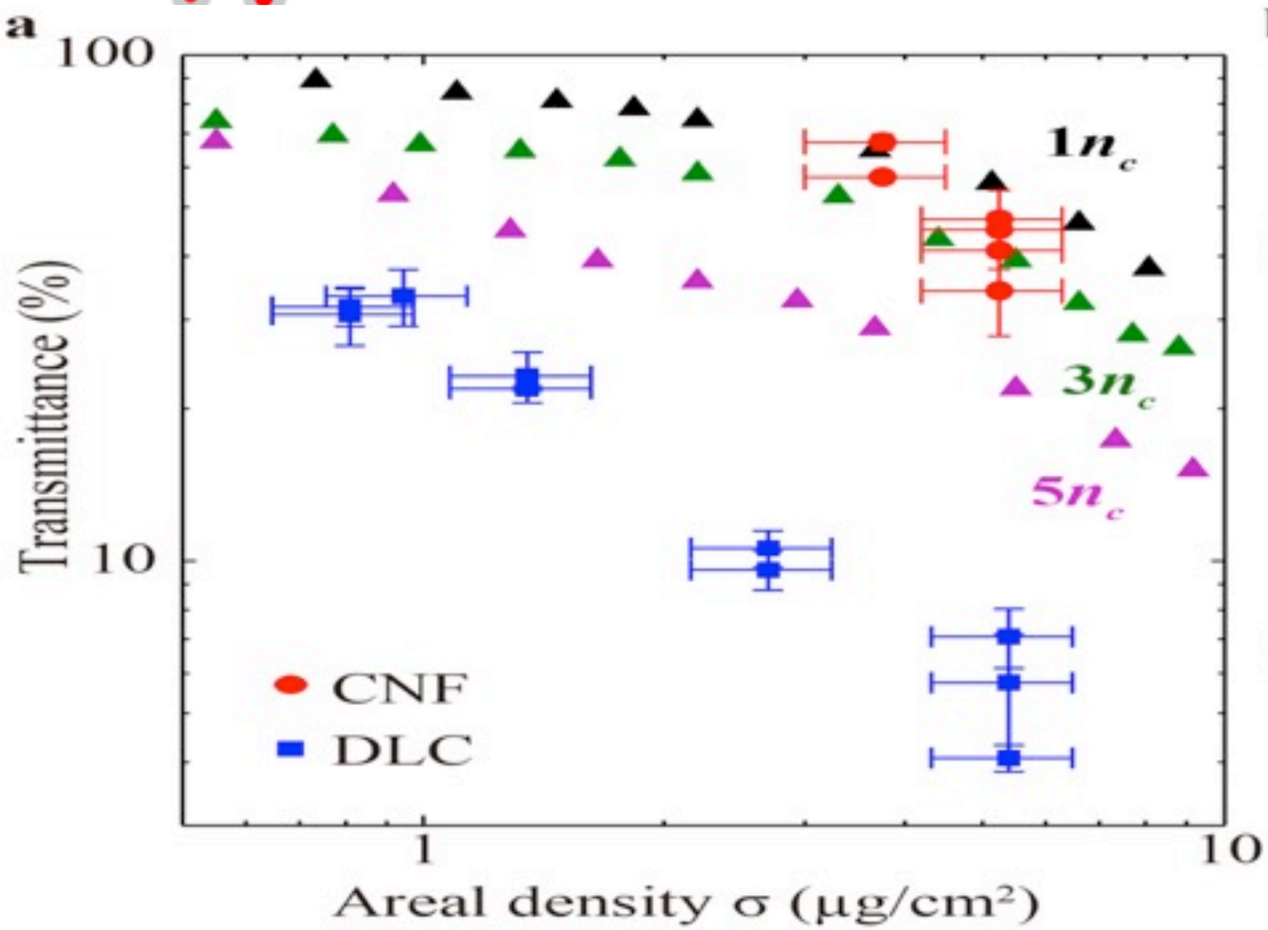
18J (**4J** on target)

D_{FWHM}~3.5 μm

I_0~2×10^{20} W/cm^2

MPQ LMU www.attoworld.de

Performance of CNF

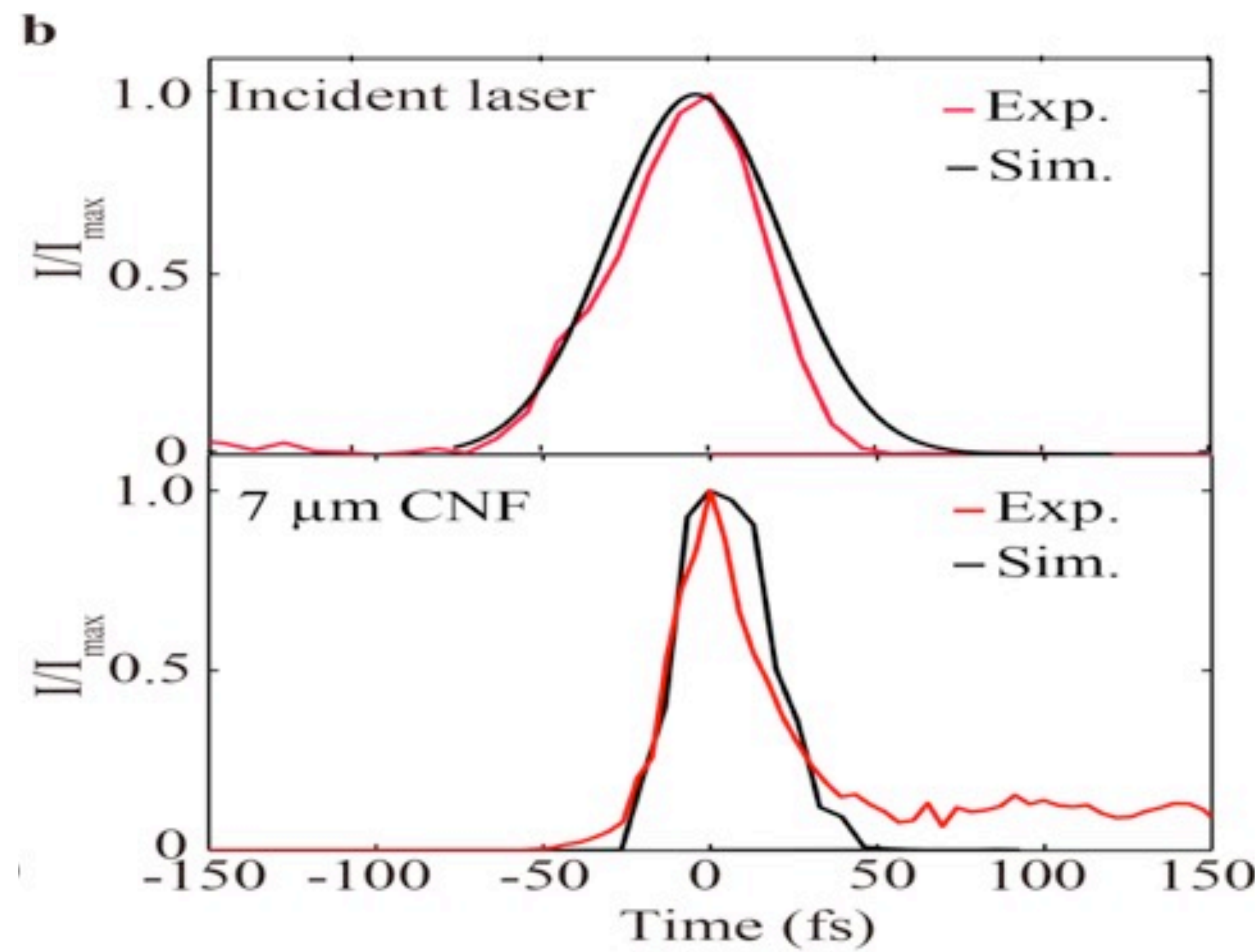


Near-critical density regime:
1-3 n_c (3D PIC simulation)

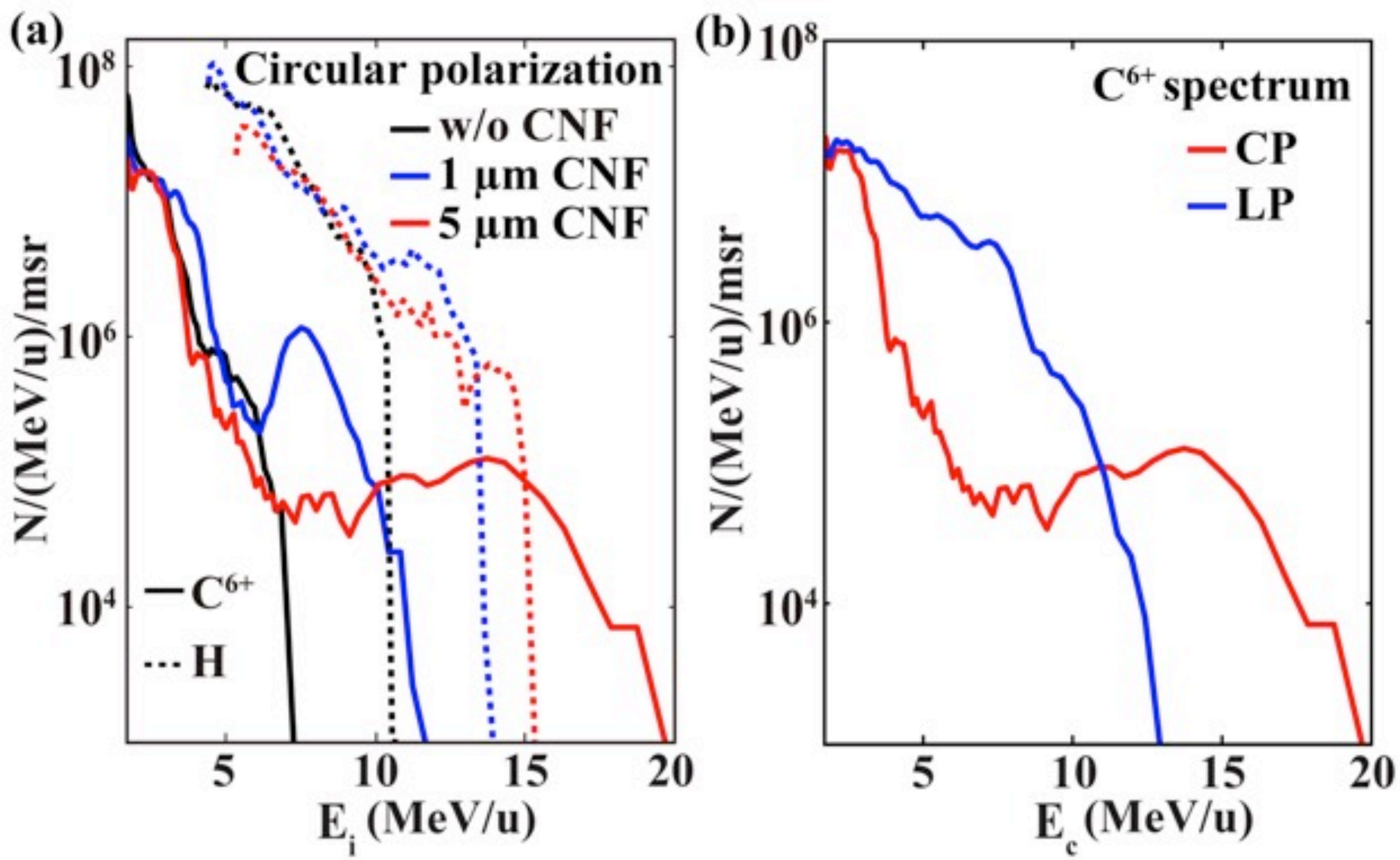
Initial density:

2±1 n_c (production process)

Observation of pulse steepening



Experimental results



Enhancement on ion energy

Maximum proton:

1.5×

10 MeV → 15 MeV

Maximum C^{6+}:

2.7×

88 MeV → 236 MeV

Peaked C^{6+}:

2.7×

60 MeV → 165 MeV

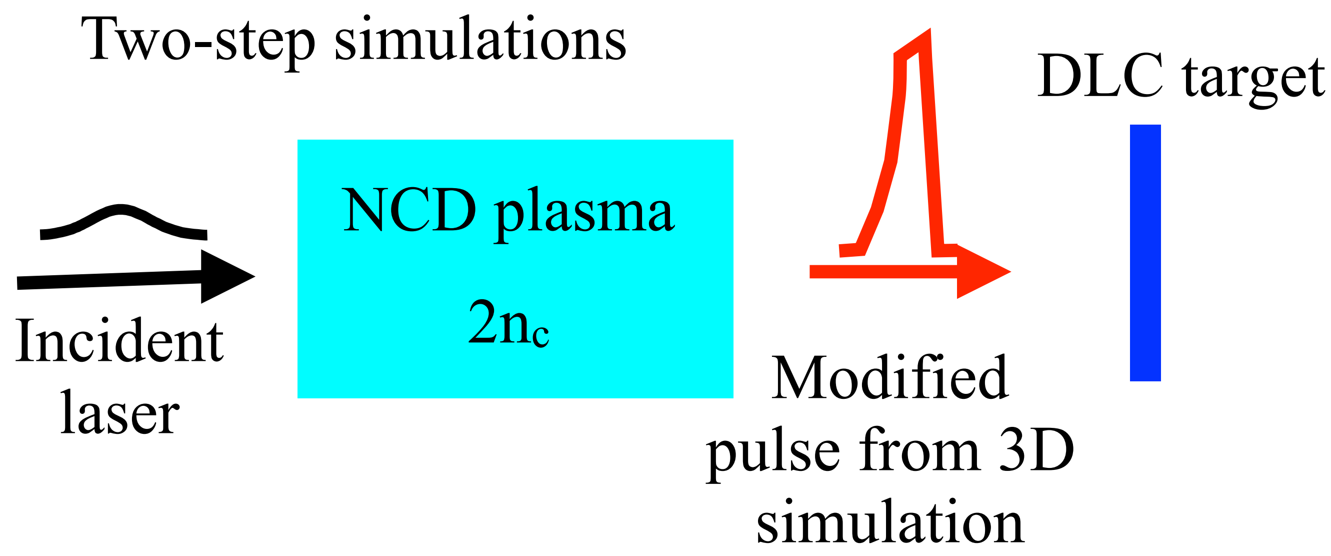
CP:

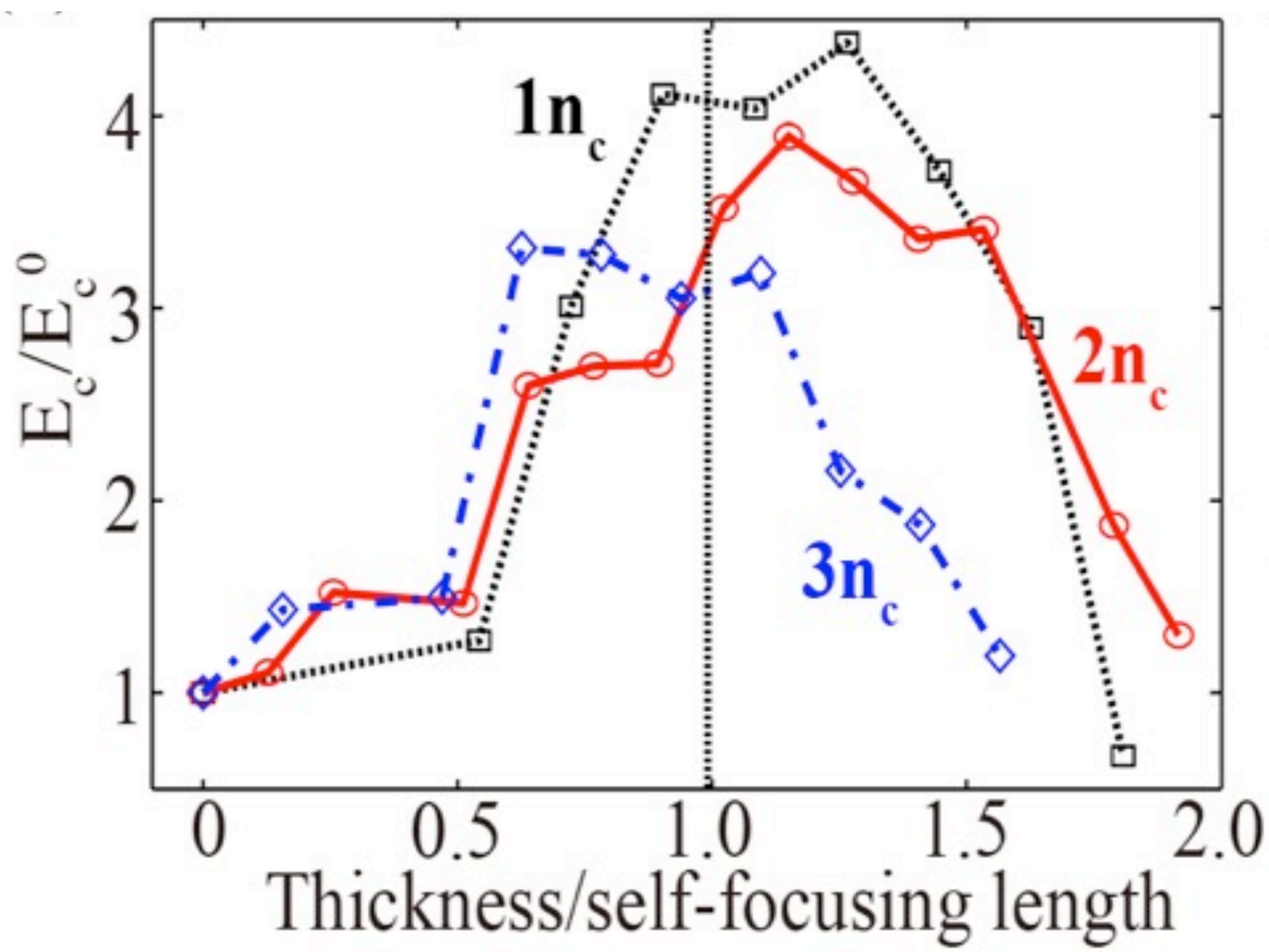
- Energy increases with CNF thickness
- Preferential for carbon ions
- Non-exponential C^{6+} spectra
- Comparable velocity for both species

Compared to LP:

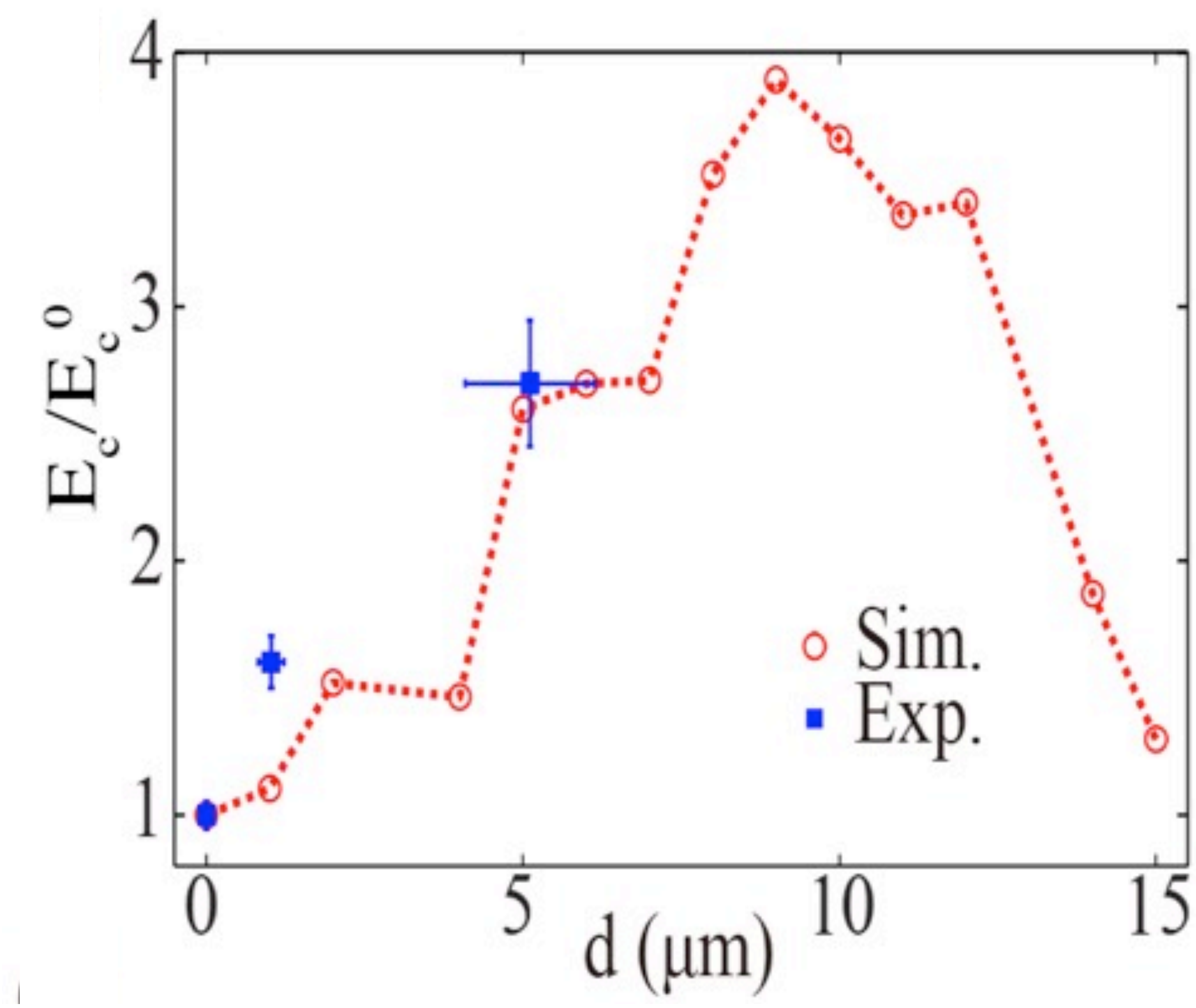
- Preferential for carbon ions
- Non-exponential C^{6+} spectra
- Comparable velocity for both species

3D PIC simulation @ CP



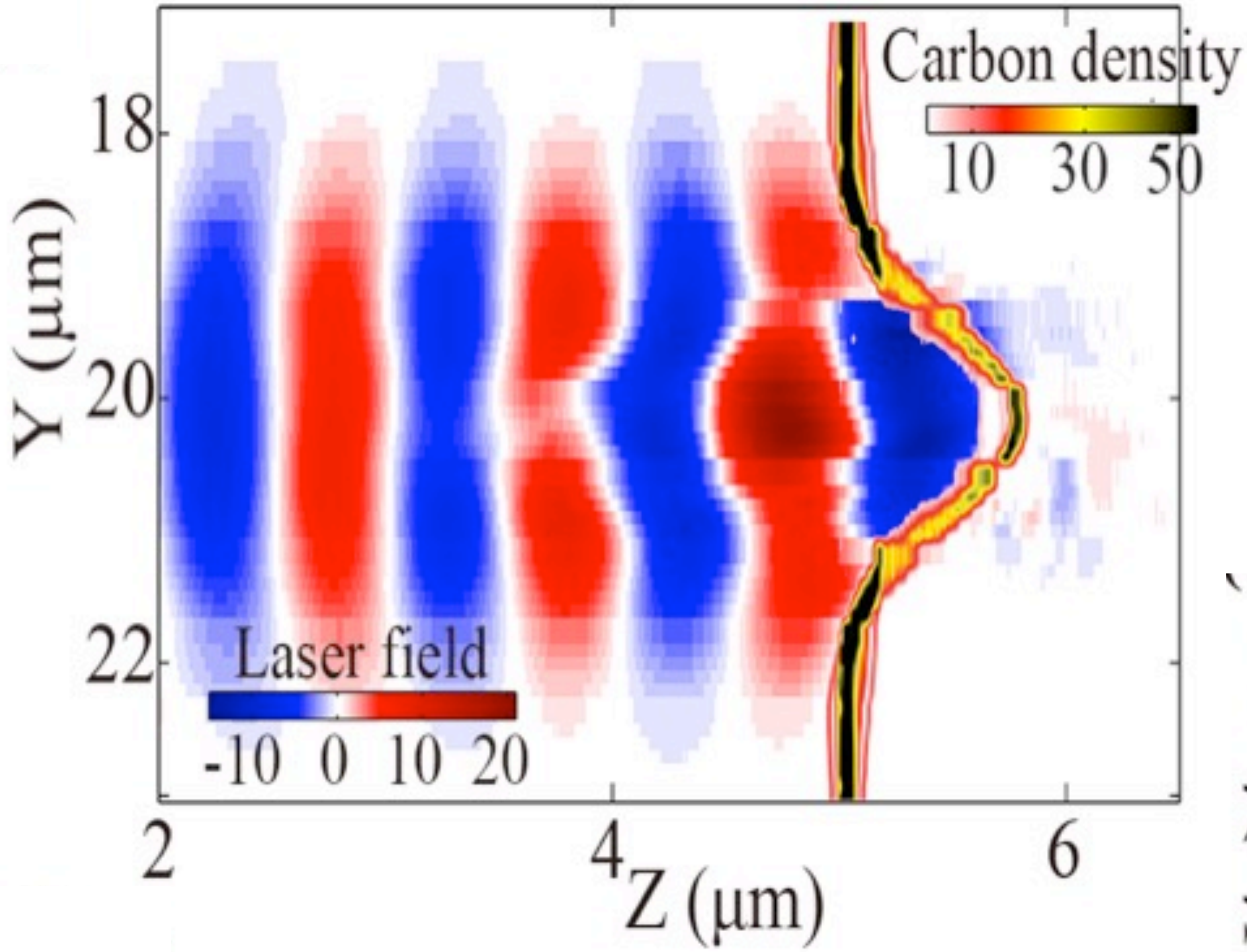


$$f \approx D_L \cdot (n_c a_0 / n_e)^{1/2}$$

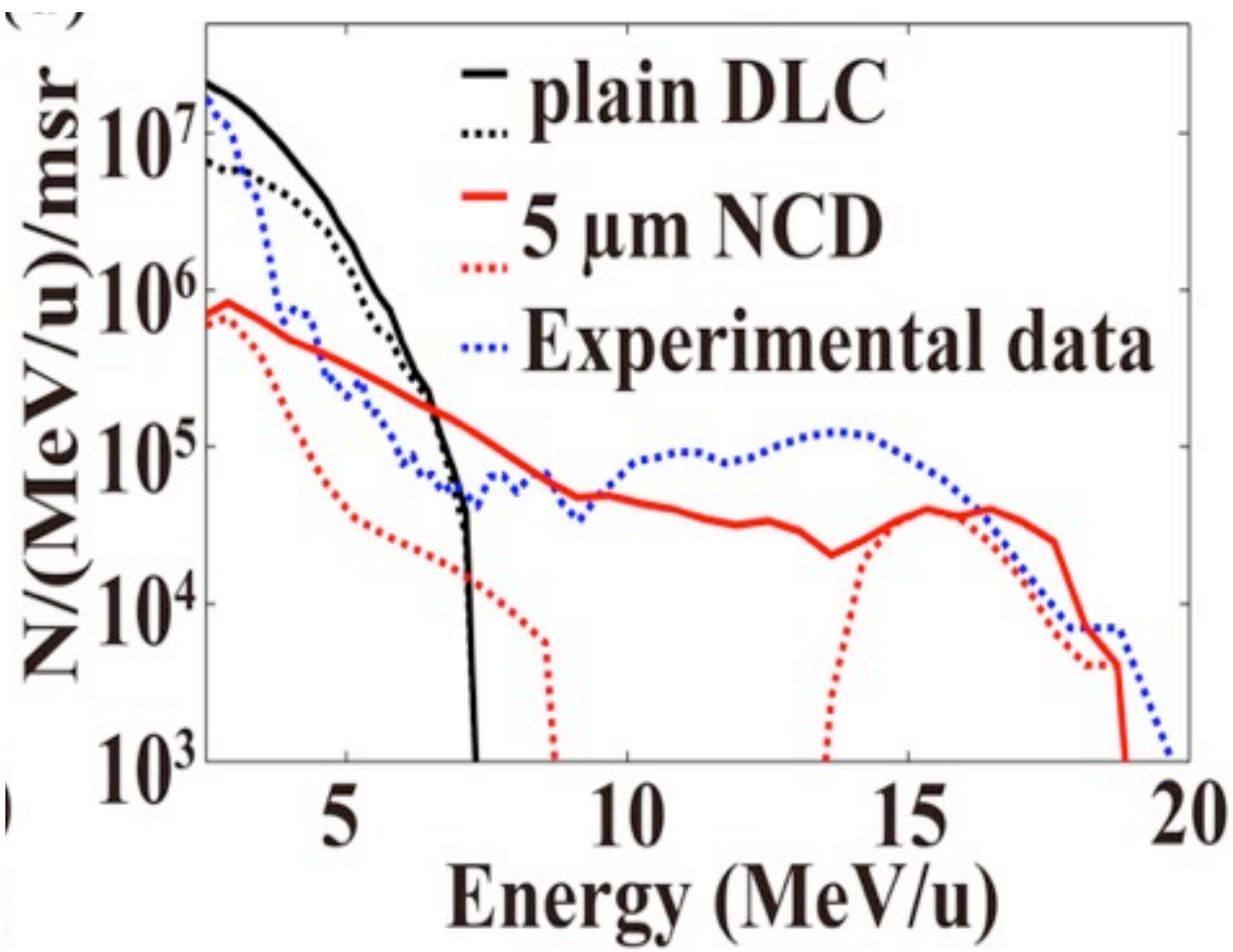


- Maximum energy increase with NCD thickness
- Primarily due to self-focusing

3D PIC simulation @ CP



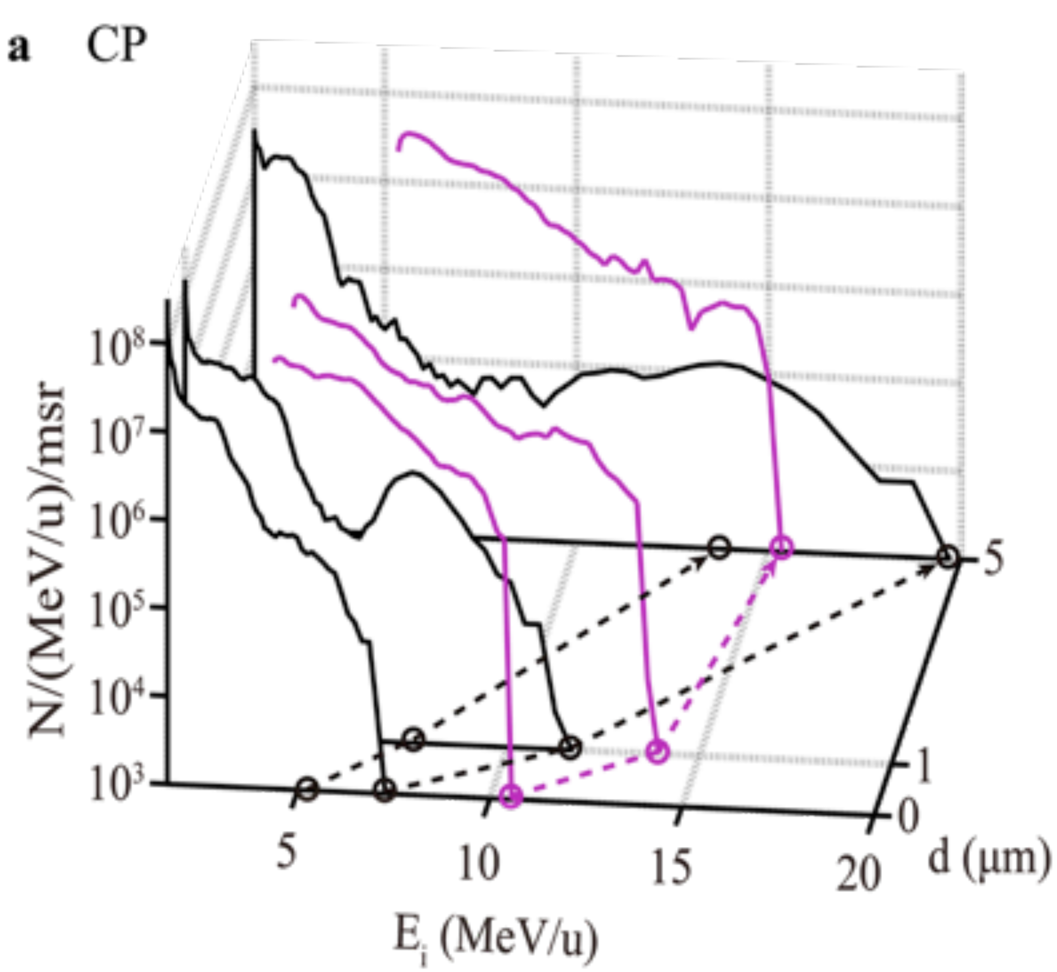
- whole target is accelerated forward
- resembles the laser intensity profile
- high reflectivity, few-percent transmission



- non-exponential spectrum
- high energy peak original from rear surface within focal volume

Consisting with Macchi *et al*, PRL. **103**, (2009);

Increased RPA contribution

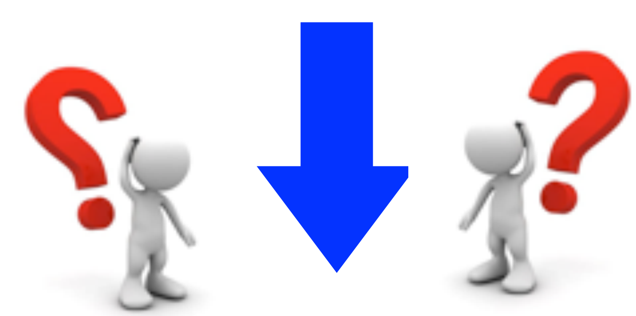


J.H. Bin, et al. PRL, 115, 064801 (2015)

- Strong energy enhance for carbon ions
- Non-exponential carbon spectra
- Similar velocities for both species

An increased RPA contribution (a transition to RPA) due to the increased laser intensity and better contrast

Proof-of-principle experiment



deliverable technology

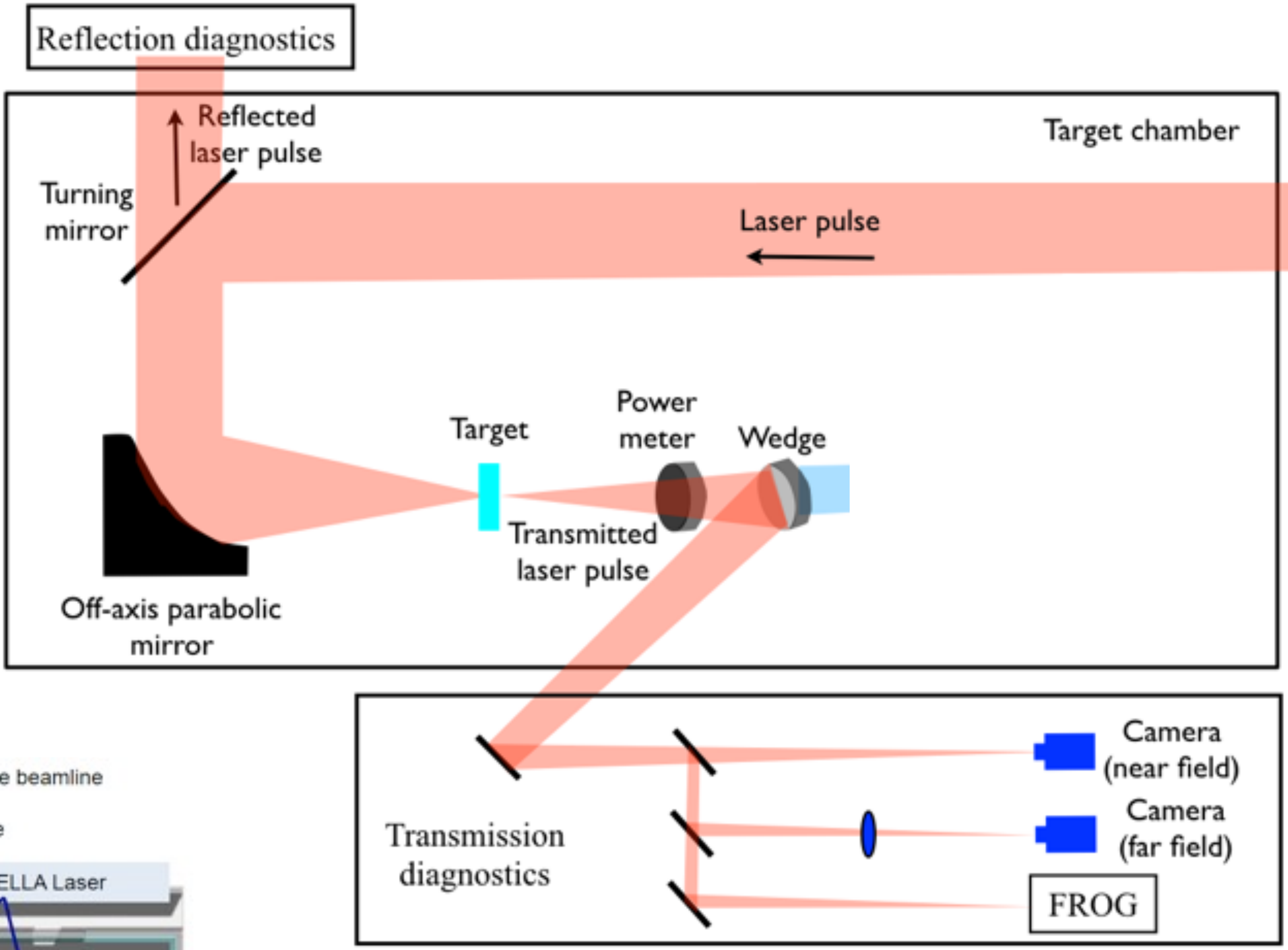
Potential developments on BELLA

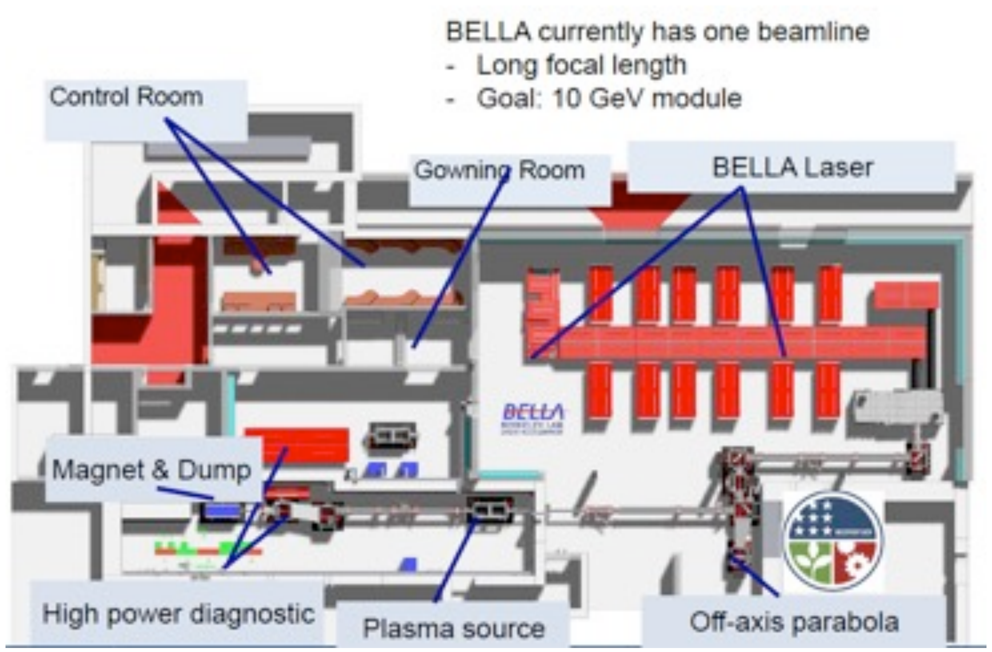
Part 1

30 *fs* FWHM, 40J

D_{FWHM}~55 μm (long focusing, ~f/60)

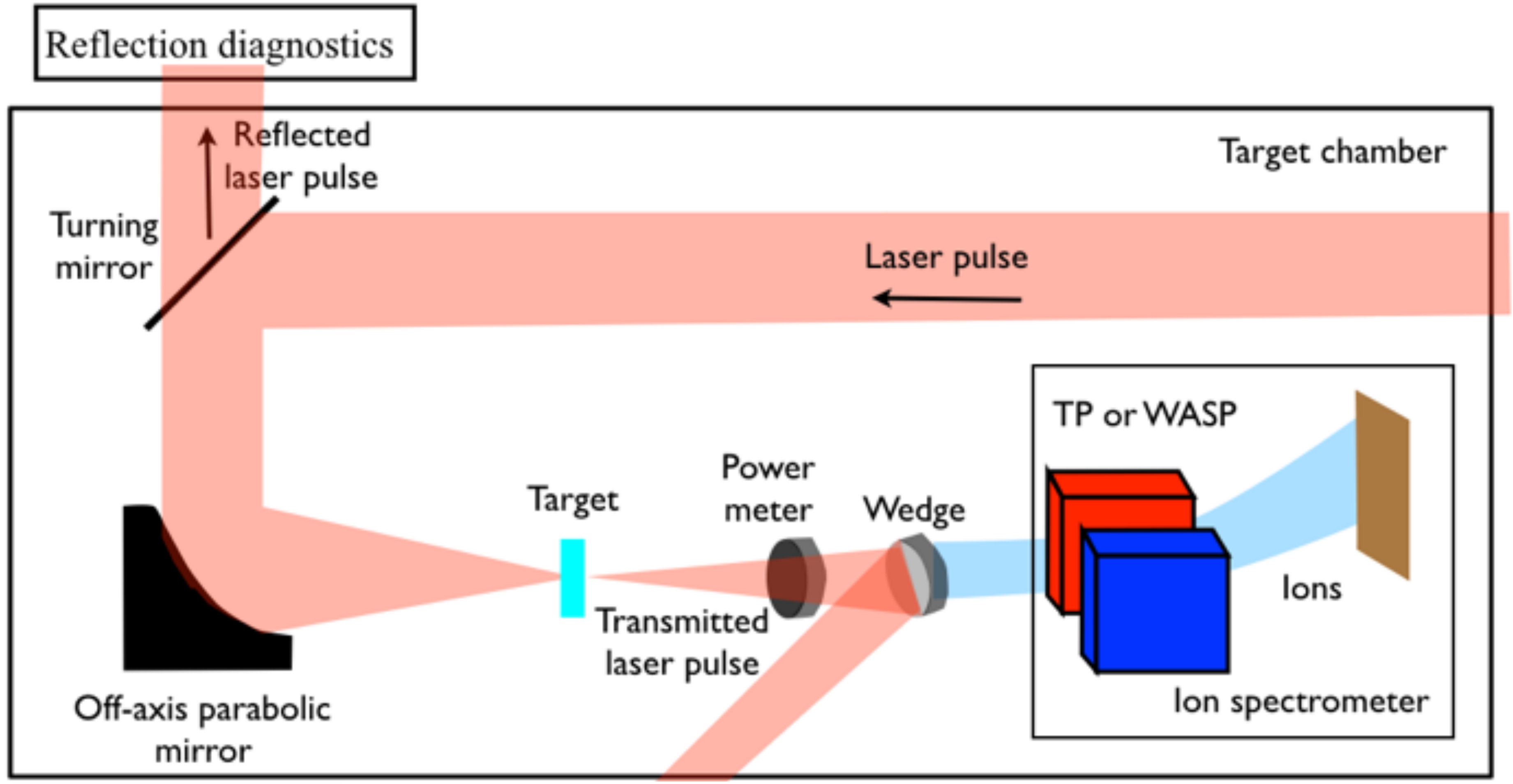
$I_0 \sim 1.5\times10^{19}$ W/cm^2





- Novel NCD target design (gas-jet, foam, CNF)
- Detailed studies of nonlinear dynamics (Target and laser parameters.)

Potential developments on BELLA

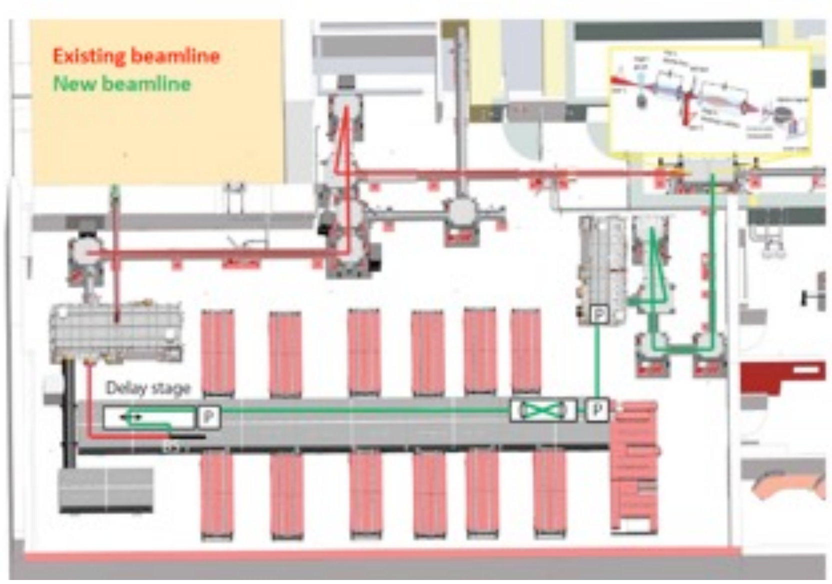


Part 2

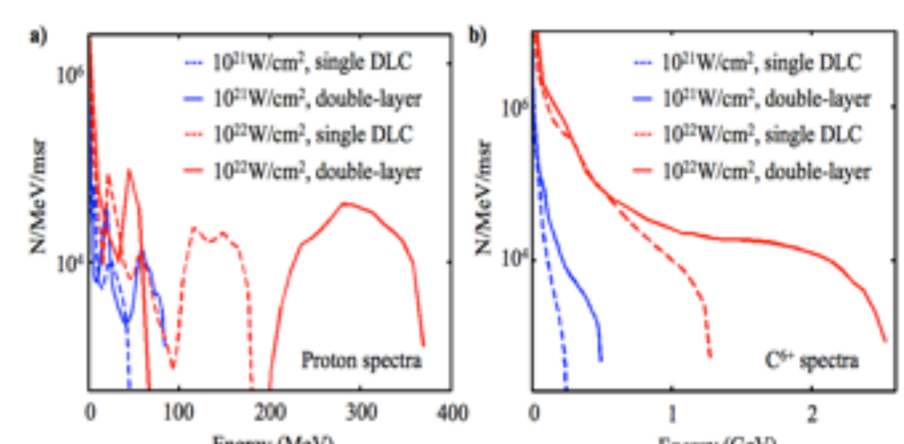
30 *fs* FWHM, 40J

D_{FWHM}~5 μm (short focusing)

$I_0 \sim 2\times10^{21}$ W/cm^2



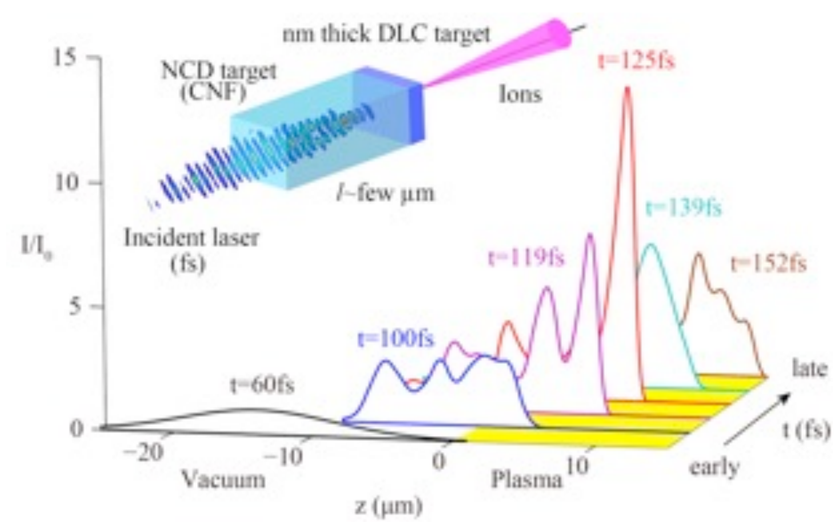
- Ion acceleration based on double-layer target configuration
- GeV carbon beams

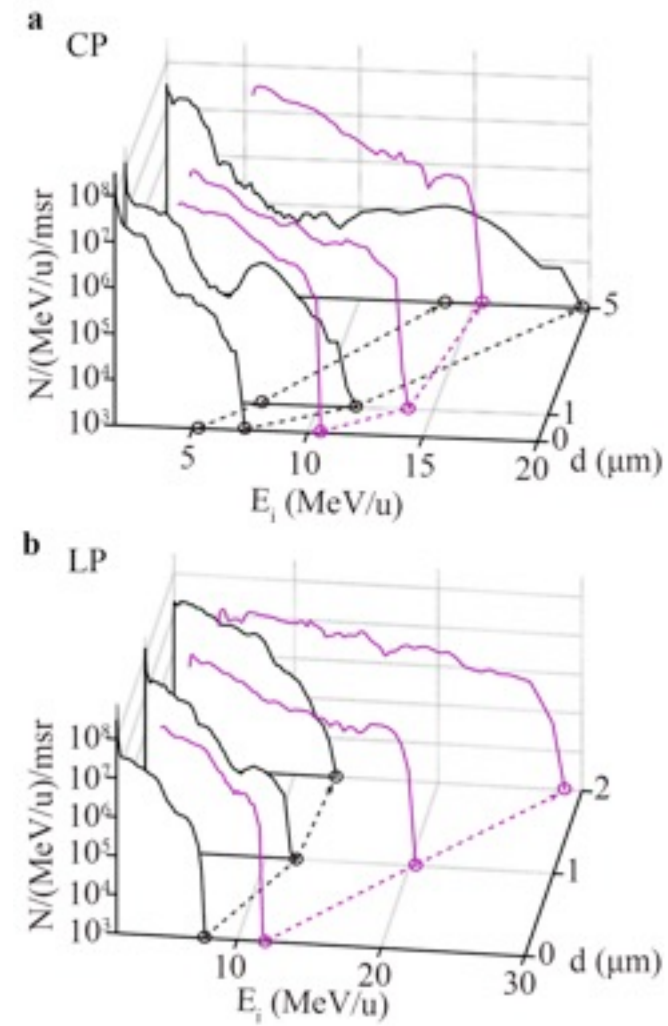


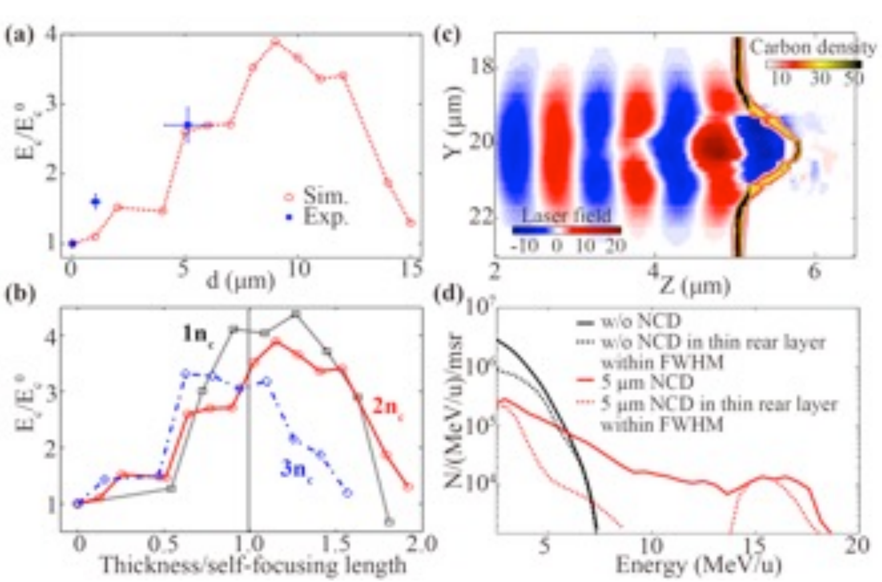
Summary

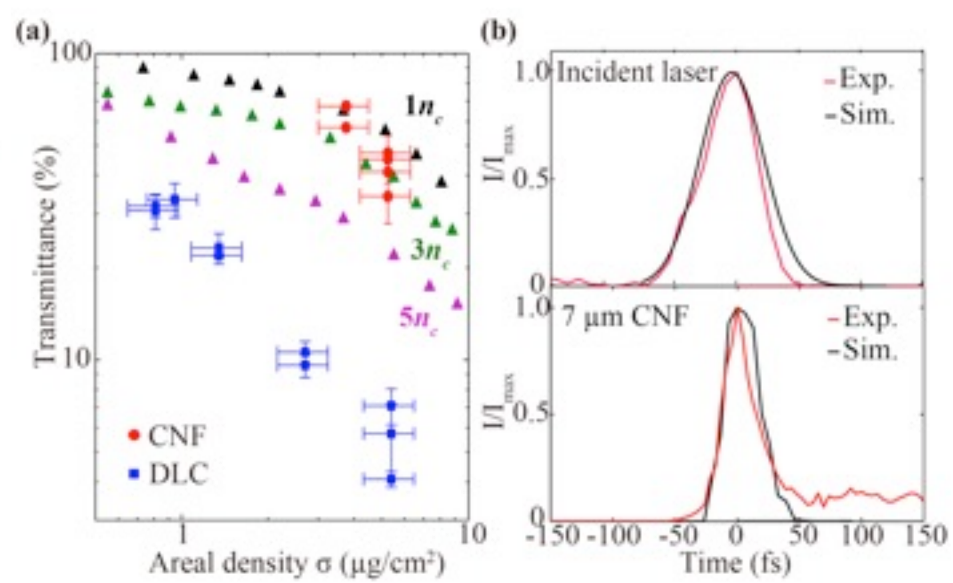
Summary:

- Demonstrate the feasibility of exploiting relativistic nonlinearities in NCD plasmas for ion acceleration
- First 'proof-of-principle' application for laser-driven ion acceleration (~3 times increase in ion energy, a transition to RPA process)
- Driving it from proof-of-principle stage to a phase that is closer to actual deliverable technology









Many thanks to my colleagues...

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Thank you!