New ion acceleration mechanisms in relativistic laser-nanotarget interactions

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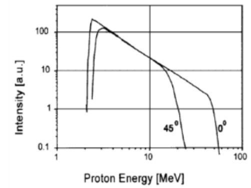
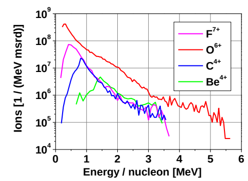
Current status and motivation

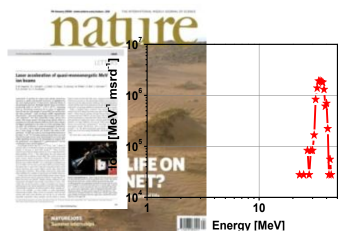
Protons with E ≤ 60MeV
Snavely et al., PRL 85,2945-2948(2000)



Light ions (Z≤10) with
E ≤ 5MeV/amu.
M. Hegelich et al., PRL 89,085002(2002)
Mid-Z ions (10 ≤ Z ≤ 46) with
E ≥ 2MeV/amu.
M. Hegelich et al., PoP 12,056314(2005)

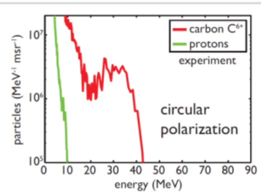


Monoenergetic ions (C^{6+}) 3MeV/amu
M. Hegelich et al., Nature Vol. 439,26,2006



TNSA

Non-Maxwellian ions (C^{6+}) 3MeV/amu
A. Henig et al., PRL 103,245003(2009)



„RPA“

TNSA Limitations:

- Highest Charge-to-Mass ratio is dominantly accelerated and screens the accelerating fields
- Protons from H_2O + hydrocarbons obtain most of the energy
- Target cleaning required for Z > 1 (e.g. heating, ablation, …)
- Energy conversion into high energy ions is very low ~1%
- Maxwellian spectra, 100% energy spread

Ion Fast Ignition
C6+: 450 MeV, ΔE ≤ 10%, CE≥10%

Hadron Therapy
H+: 250 MeV,
C6+: 3-5 GeV, ΔE ≤ 5%, 10Hz

Volumetric interaction with an overdense target : High contrast & energy pulses + free standing nm-targets

Ultrahigh contrast @ ultrahigh intensities

Ultrathin targets require ultrahigh contrast

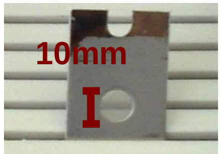
Improvement of laser contrast by 4 - 6 orders of magnitude to ~10^{-11} by short pulse OPA (SPOPA[1]) allows overdense interaction down to 3nm <u>without plasma mirrors</u>

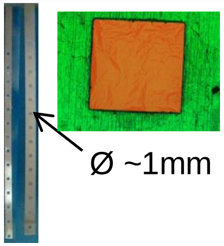
[1]R. Shah, et al., Opt. Lett. **34**, 2273-2275 (2009)

Ultrathin diamond like carbon (DLC) produced at LMU

Robust, free standing (mm), ultrathin (nm) targets with:

Thickness	3 to 60 nm
Bulk density	2.7±0.3 g/cm^3
sp^3 content	~75%
Proton content	<10% (bulk)



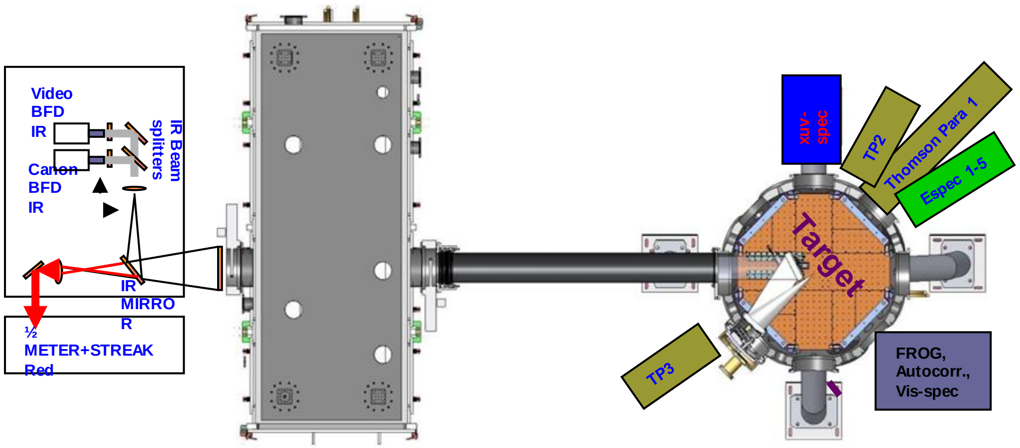


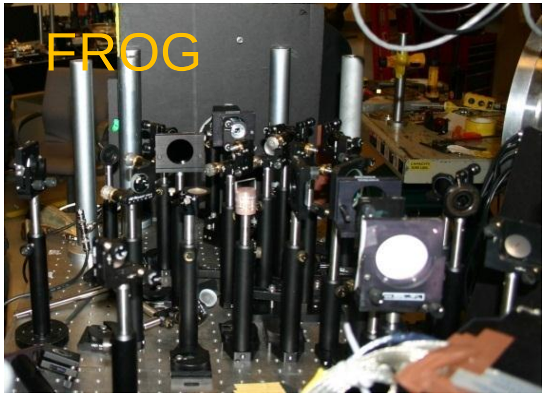
High density & high coupling

- Nanometer foils, aerogels, solid hydrogen,…
- Ion & electron acceleration, transmitted surface harmonics
- BOA, REM,…

$$\frac{n_e}{\gamma\, n_{cr}} \leq 1 < \frac{n_e}{n_{cr}}$$

Typical Experimental Setup & Diagnostics:





Laser parameters:

Energy on target	~80J (@1054nm)
Pulse duration	~500fs
Intensity	~2-5x10^{20}W/cm^2
a_0	~12-19
Polarization	s, CP
OAP Mirror	F/3
Rep. rate:	1 shot / 45 min.
Contrast :	< 5 x 10^{-10} (prepulse)
	< 2 x 10^{-12} (pedestal)
Target thickness	3nm-1000nm

Accumulation of **300+** shots!
(from a „single“ shot laser)

[1]D. Jung, et al., submitted to RSI

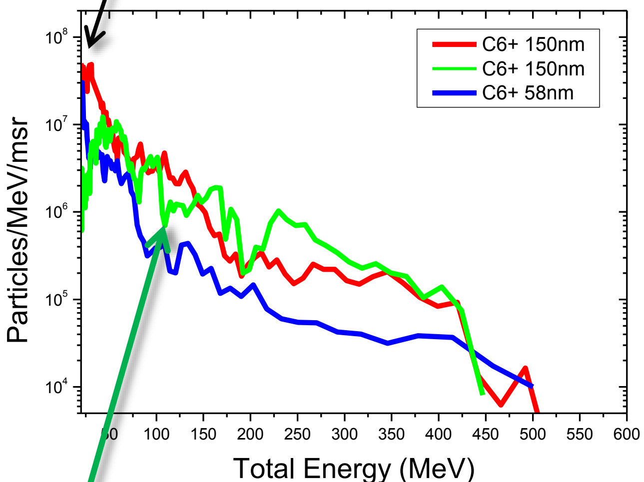
Overcoming TNSA limitations with relativistic laser plasma interaction (BOA[1,2,3,4,5]):

LMU MPQ

We measured laser accelerated protons up to 66MeV and carbon C^{6+} ions up to 42MeV/amu

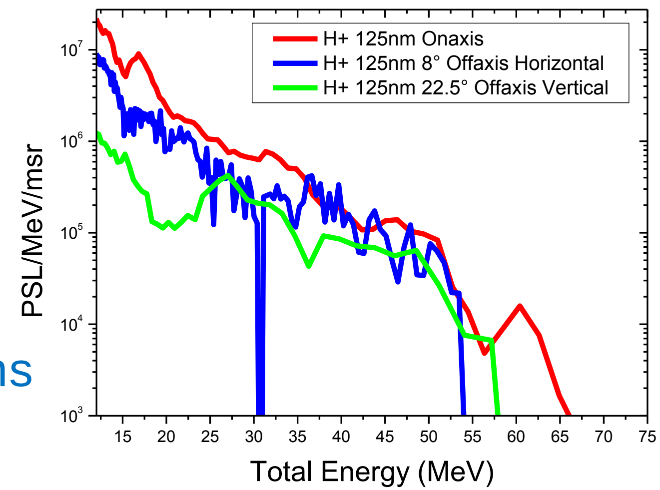
(Previous: H^{+}:60MeV, C^{6+} 5MeV/amu)

Spectrometer low energy cutoff (ranges from 5MeV to 18MeV)



Carbon C^{6+}

Protons



600nJ at 22.5° in $5x10^{-5}$msr → $CE_{20\text{-}300MeV}$ ~8%

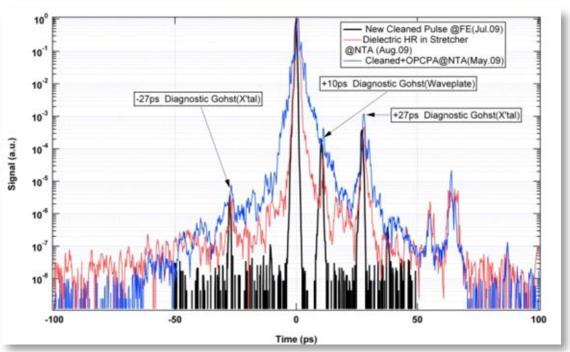
[1] L. Yin, et al., *Laser and Particle Beams 24 (2006), 1–8*
[2] L. Yin, et al., *Phys. Plasmas 14, 056706, (2007).*
[3] B. J. Albright, et al., *Phys. Plasmas 14, 094502 (2007)*
[4] A. Henig, et al., *Phys. Rev. Lett. 103, 045002 (2009)*
[5] B. M. Hegelich, et al., *submitted to Nature Physics (2010)*

Advancing towards (quasi-)monoenergetic spectra:

LMU MPQ

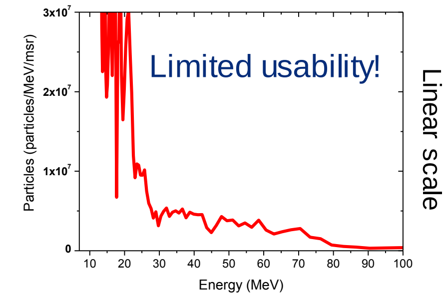
Problems and challenges on experimentally achieving monoenergetic ion spectra predicted by simulations:

- PIC uses idealized laser and target parameters
  - Intensity, energy and pulse duration/shape
  - Contrast, pedestal & prepulse



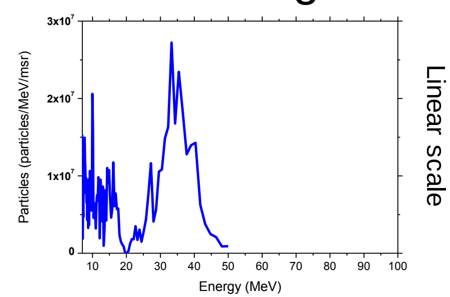
- premature ionization
  target expansion
- target denting
- alter/mix acceleration mechanisms

Exponential



?

Monoenergetic

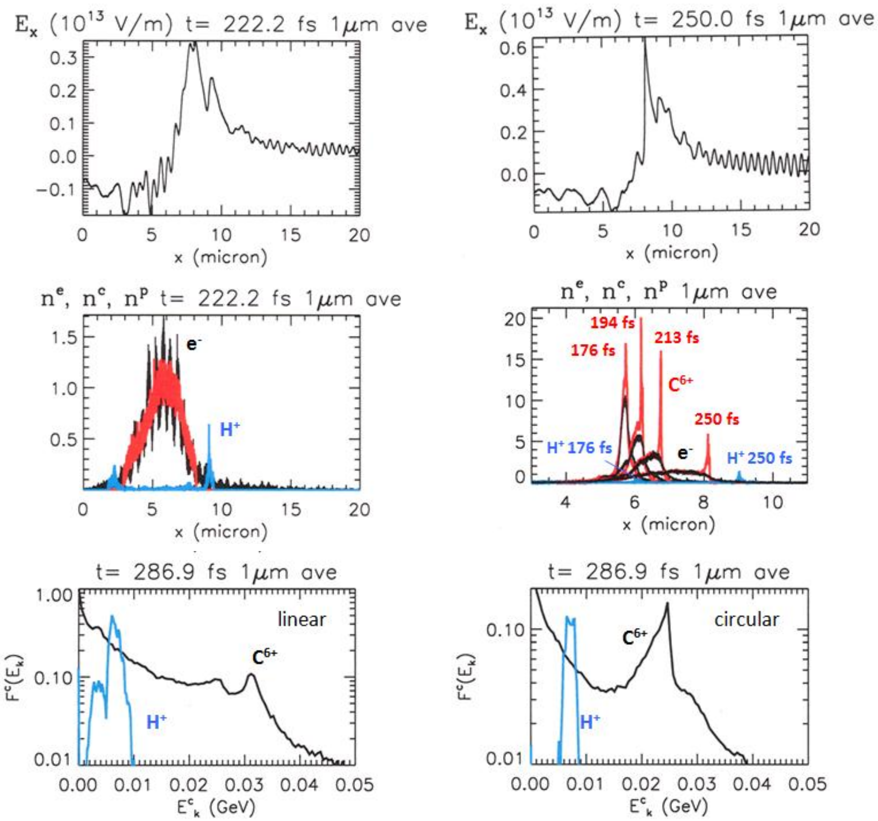


Wide range of applications!
- Ion fast ignition
- Hadron therapy
- …

Monoenergetic spectra using circular polarization:
Ion **S**oliton **W**ave **A**cceleration during relativistic **T**ransparency (SWAT)

High resolution 2D-VPIC simulations revealed new acceleration mechanism ⇨ Ion **S**olitary **W**ave **A**cceleration during relativistic **T**ransparency (SWAT)

Linear P. ⟺ Circular P.



SWAT mechanism basics:

- a pronounced ion density spike forms when the target turns relativistically transparent
- the nonlinear ion density structure propagates across the plasma
- the nonlinear structure is, in fact, an ion soliton, whose properties can be derived analytically[1]

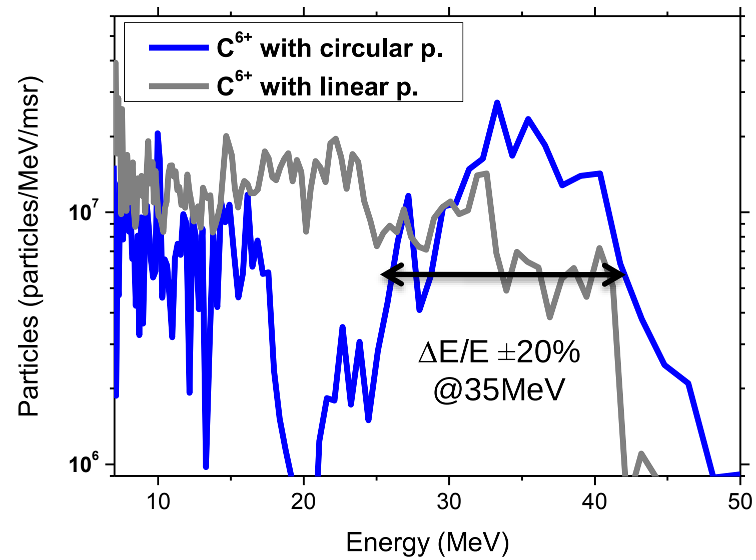
[1]L. Yin, B. J. Albright, et al., to be submitted (PRL)

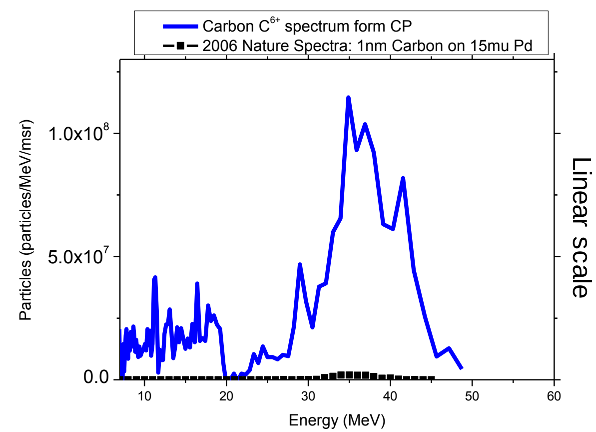
Monoenergetic spectra using circular polarization:
Ion **S**oliton **W**ave **A**cceleration during relativistic **T**ransparency (SWAT)

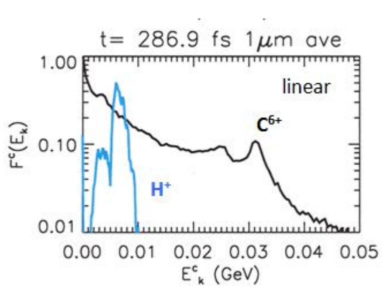
LMU MPQ

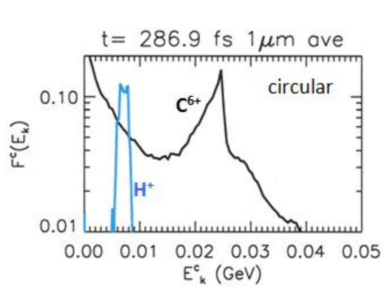
Carbon C^{6+}

- In experiment monoenergetic spectra are generated with CP, exponential spectra with LP
- Peak energy 35MeV (3MeV/nucl.)
- Particle number almost two orders of magnitude higher than previously measuered monoenergetic feature by Hegelich et al., Nature 2006









D. Jung, et al., to be submitted

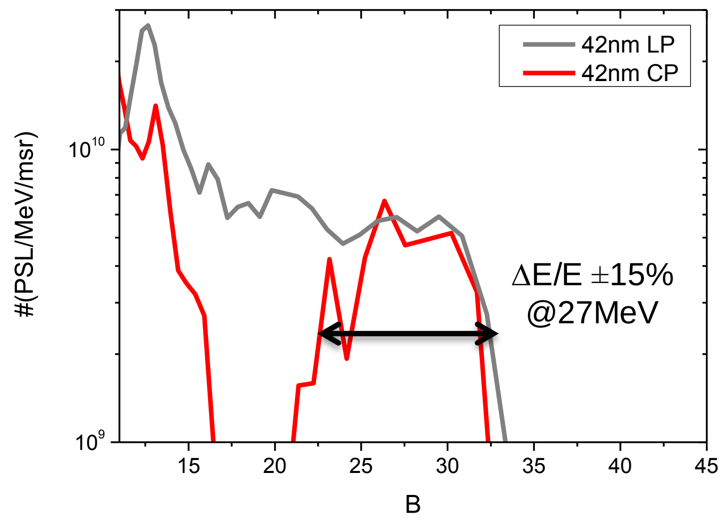
Monoenergetic spectra using circular polarization:

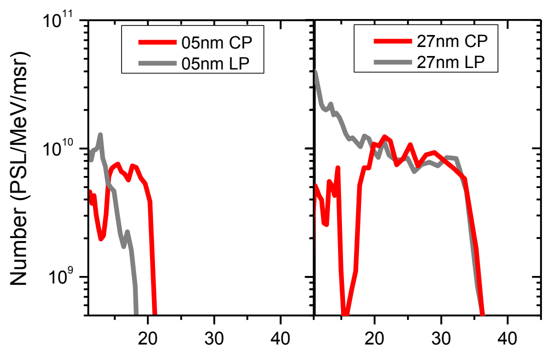
Ion Soliton Wave Acceleration during relativistic Transparency (SWAT)

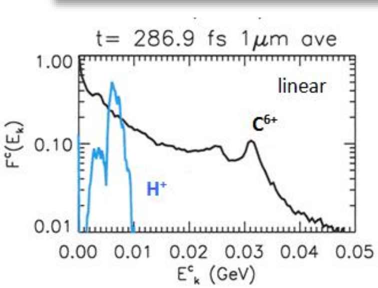
LMU MPQ

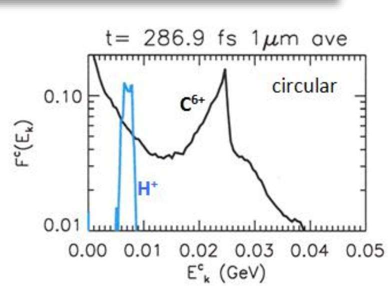
Proton H^+

- Monoenergetic spectra with CP, else exponential spectra
- In simulation soliton only forms for C-ions; protons leave the target too early due to their high q/m ratio
- Peak energy 27MeV/nucl. (C^{6+} at same shot 3MeV/nucl.)
- proton data does not agree well with simulation







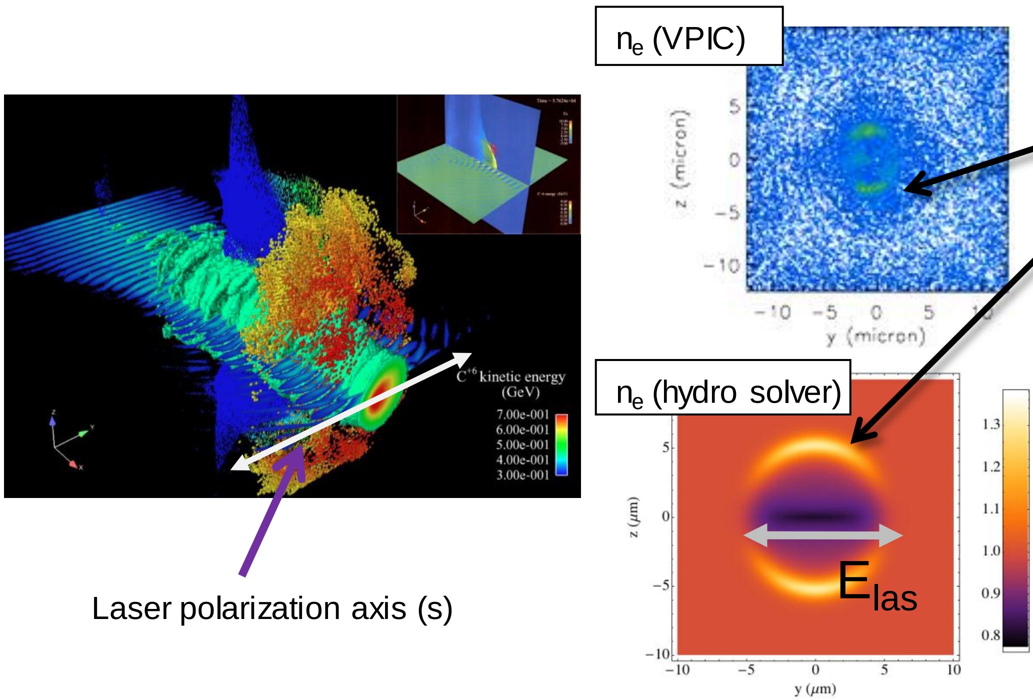


D. Jung, et al., to be submitted

Monoenergetic spectra by angular selection of ions:

Ion lobes from Break-Out Afterburner (BOA)[1]

3D VPIC simulation reveal an angular symmetry of electrons and ions



Ion lobe generation:

- The radial PM force acts differently in parallel vs. perp. directions[1]
- This leads to a pile-up of electrons leading to electron lobes
- Space-charge makes corresponding ion lobes

⇩

strongly anisotropic electric field and angular dependent ion energy spectrum is to be expected:

- Off-axis: dominated by BOA, smooth, localized field
- On-axis: possibly a mixture of BOA (high energy) and other acceleration mechanisms (low energy), strongly varying fields

[1]L. Yin, et al., submitted to PRL(2010)

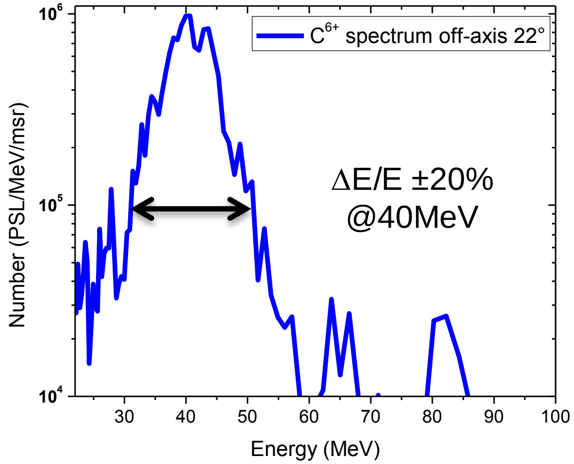
Monoenergetic spectra by angular selection of ions:

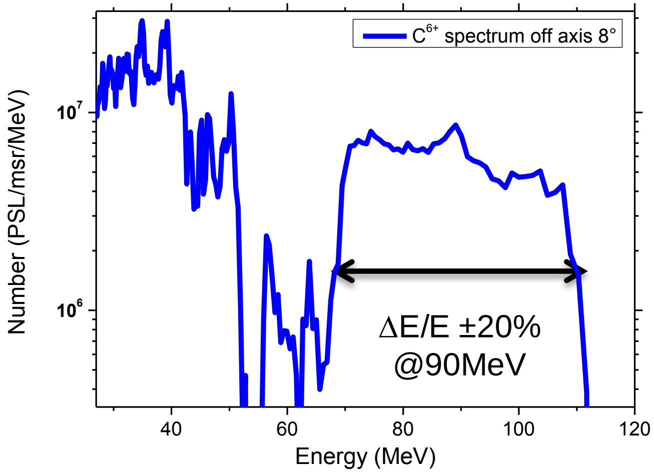
Ion lobes from Break-Out Afterburner (BOA)

Ion spectra measured by up to TPs at 5 different angles (0°, 8°, 22° horizontal and vertical)[1]

C^{6+} spectrum taken off-axis

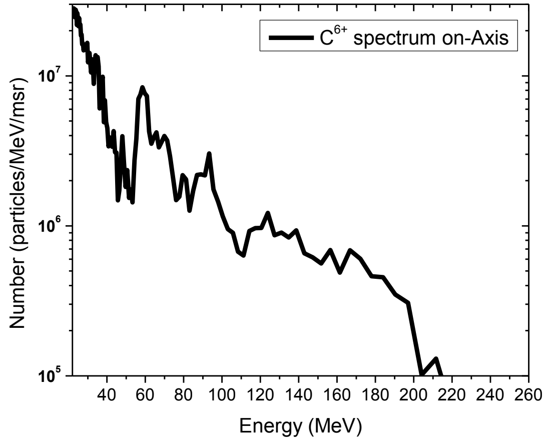
(peaked spectrum)

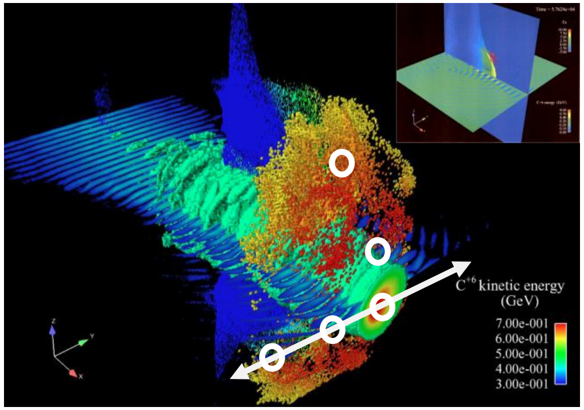




C^{6+} spectrum taken on-axis

(exponentially decaying)





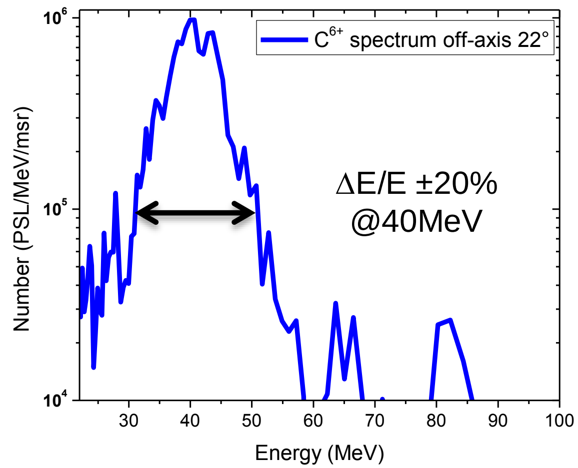
[1]D. Jung, et al., to be submitted

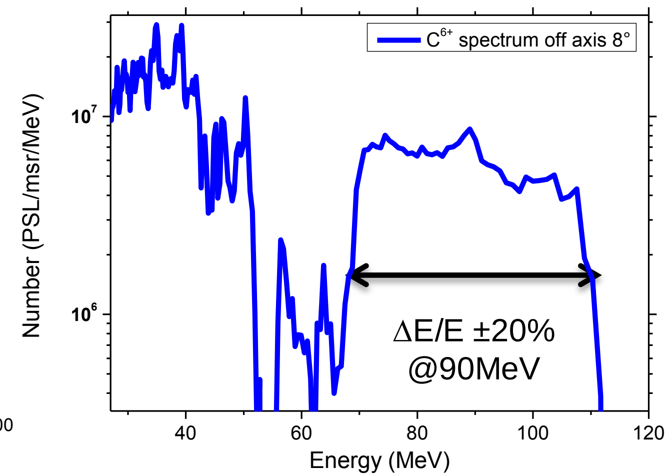
Monoenergetic spectra by angular selection of ions:
Ion lobes from Break-Out Afterburner (BOA)

Ion spectra measured by up to TPs at 5 different angles (0°, 8°, 22° horizontal and vertical)[1]

C^{6+} spectrum taken off-axis

(peaked spectrum)





Future plans:

- F/~1 experiments (2011)
- Use of a **e**lectron/**i**on **w**ide **a**ngle **s**pectrometer (eiWASP[2]) (November 2010)

F/3 OAP:

- Peaked spectra measured at 22°
- "Success" rate ~50%

F/8 OAP:

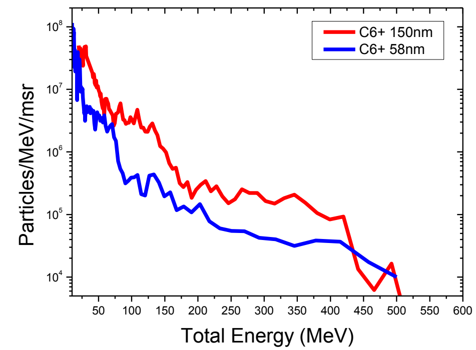
- Peaked spectra measured at 8°
- "Success" rate ~90%

[1,2]D. Jung, et al., to be submitted

Summary

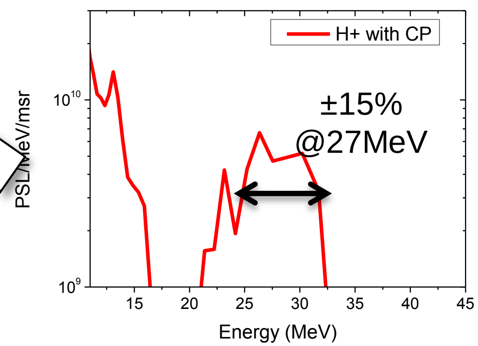
We can overcome TNSA limitations:

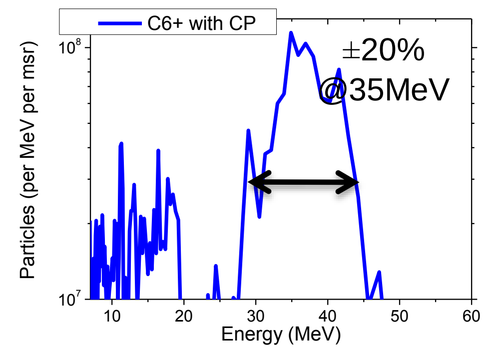
1. Relatvistic transparent laser-plasma interaction (BOA)
   - Increase of low Z ion energies by one order of magnitude



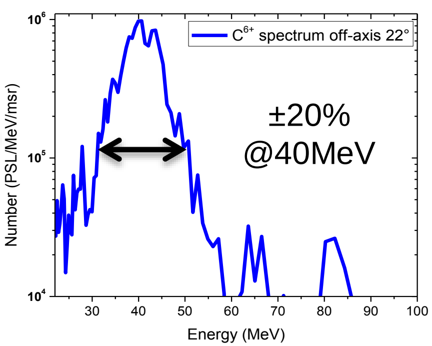
We can manipulate the ion energy spectrum:

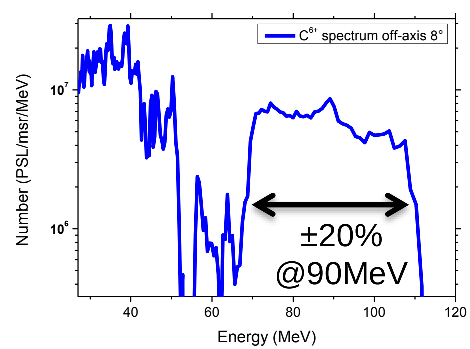
1. <u>Circular polarization</u>
   - protons and carbon ions
   - acceleration of carbon ions by ion soliton





2. <u>Angular selection of ions</u>
   - high energies
   - only carbon ions with DLC targets (pure/rich proton targets planned)





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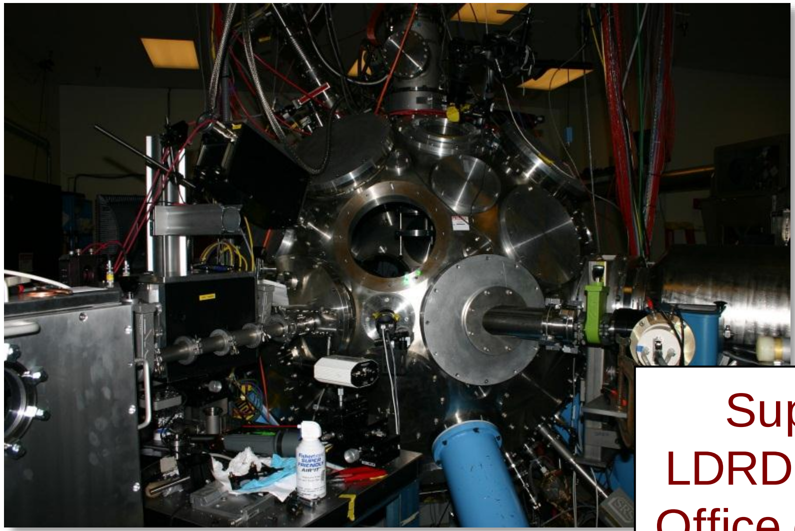

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