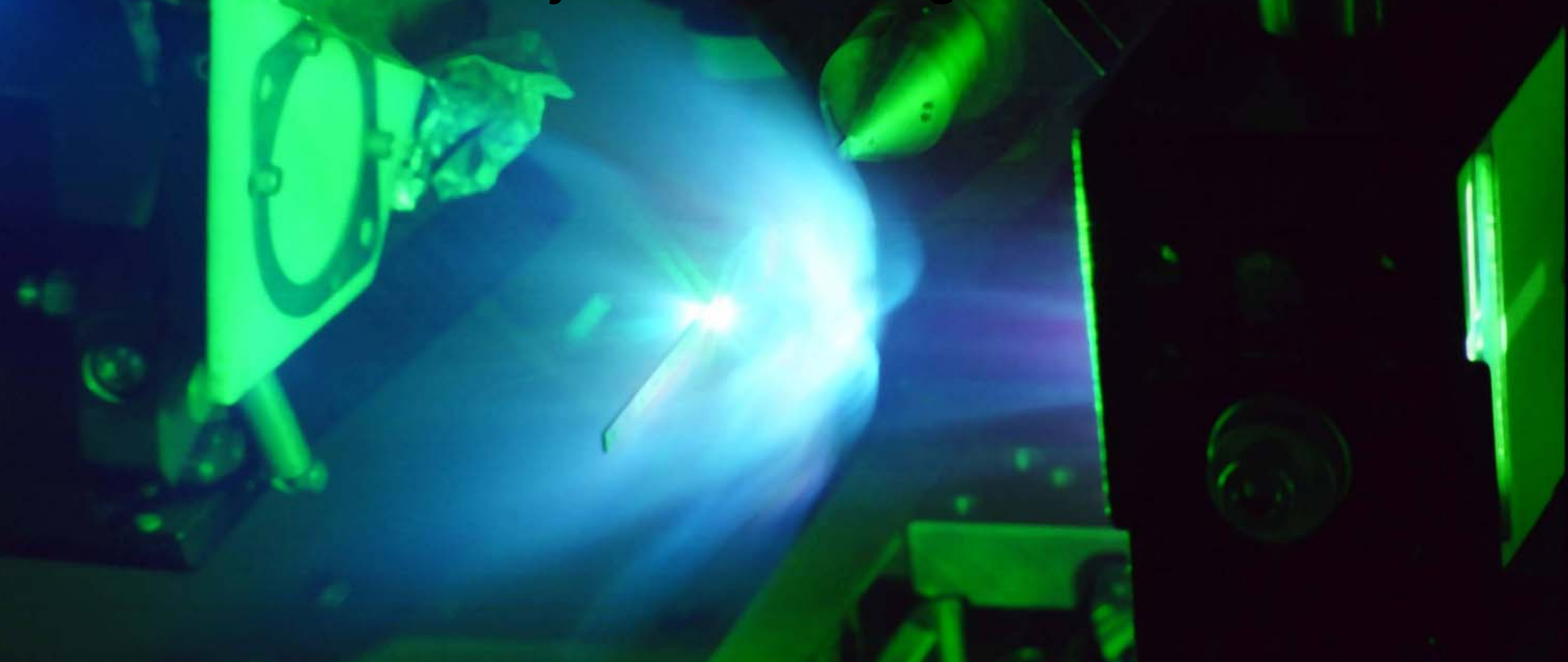
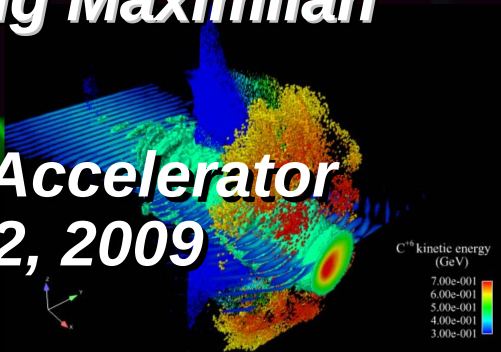
“Towards GeV laser-driven ion acceleration“

Björn Manuel Hegelich



Los Alamos National Laboratory & Ludwig Maximilan Universität München

International Conference on Heavy Ion Accelerator Technology, Venice, Italy, June 8-12, 2009



hegelich@lanl.gov

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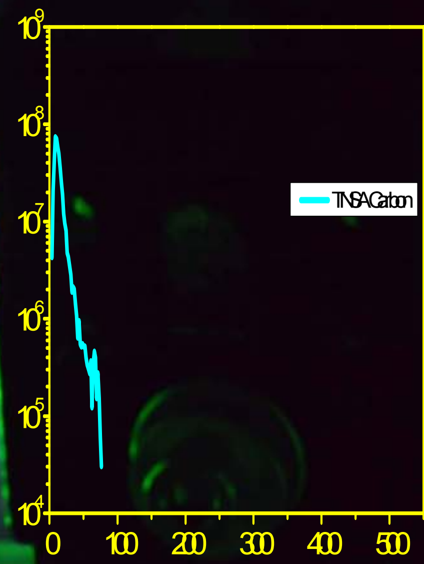

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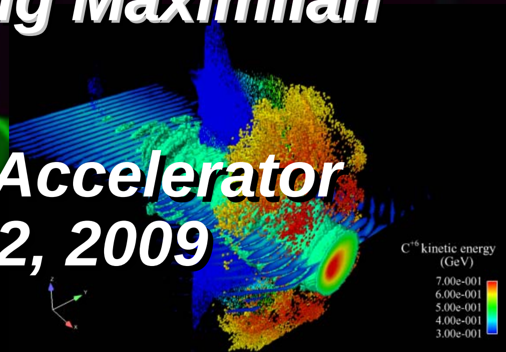

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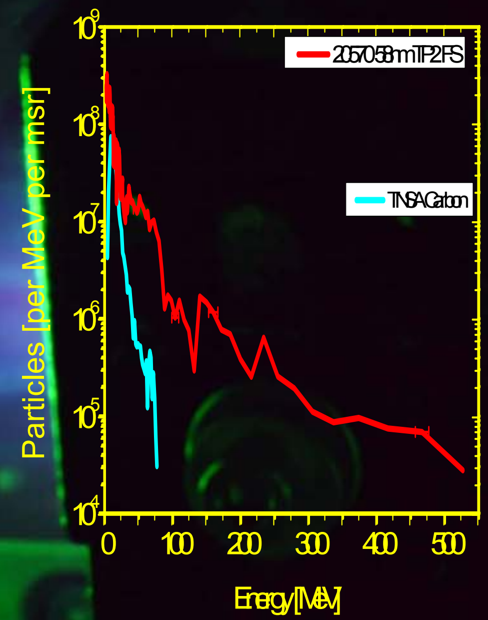

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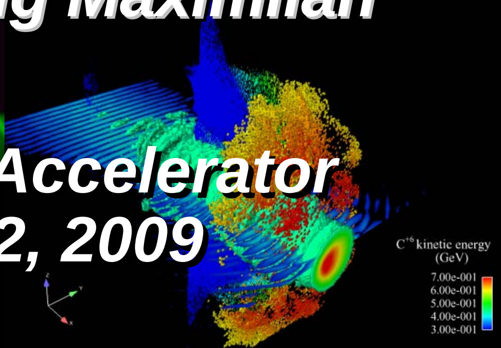

International Conference on Heavy Ion Accelerator Technology, Venice, Italy, June 8-12, 2009

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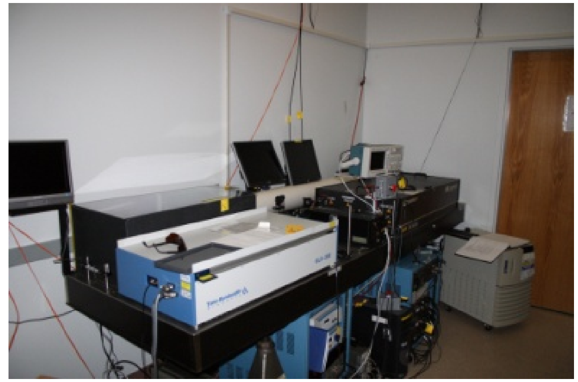
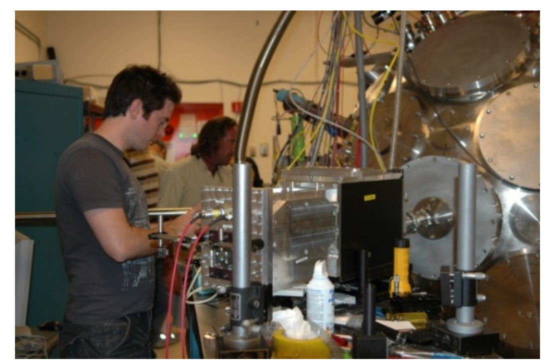
Outline:

- Laser-driven ion acceleration: Motivation & Current status
- Paradigm shift:
  ultrahigh contrast enables use of ultrathin targets
  $\Rightarrow$ ultrathin targets enable new acceleration mechanisms
- A new acceleration mechanisms: Break-Out Afterburner Acceleration (BOA)
  - Theoretical Concept, Simulations
  - First experimental demonstration of BOA:
    - >0.5 GeV carbon at ~100J Trident laser, Los Alamos
    - >70 MeV carbon at 0.7J Ti:Saph laser at MBI, Berlin
  - Reduced Analytical Model
- Summary

The Los Alamos Trident Laser Facility

200 TW, 100J, 500fs, 1 shot/h shortpulse + 2x 500J, 1ns longpulse beams





3 beamlines, 3 target areas:

A + B: 100ps – 6µs, 80-1000J (532nm)

- Full temporal pulse shaping

- C-Beam: 500fs, 125J, 250 TW (1054nm)

Intensity: 5×10^{20} W/cm^2

- Rep. rate: 1 shot / 45 min.
- AODF (spectral control), adaptive optics
- Complete suite of laser diagnostics on each shot (Energy, pulse length, pre-pulse, spectrum, far field, near field)
- Contrast: Old frontend: $\sim 10^{-7}$
  New frontend: $< 5 \times 10^{-10}$ (prepulse)
  $< 2 \times 10^{-12}$ (pedestal)

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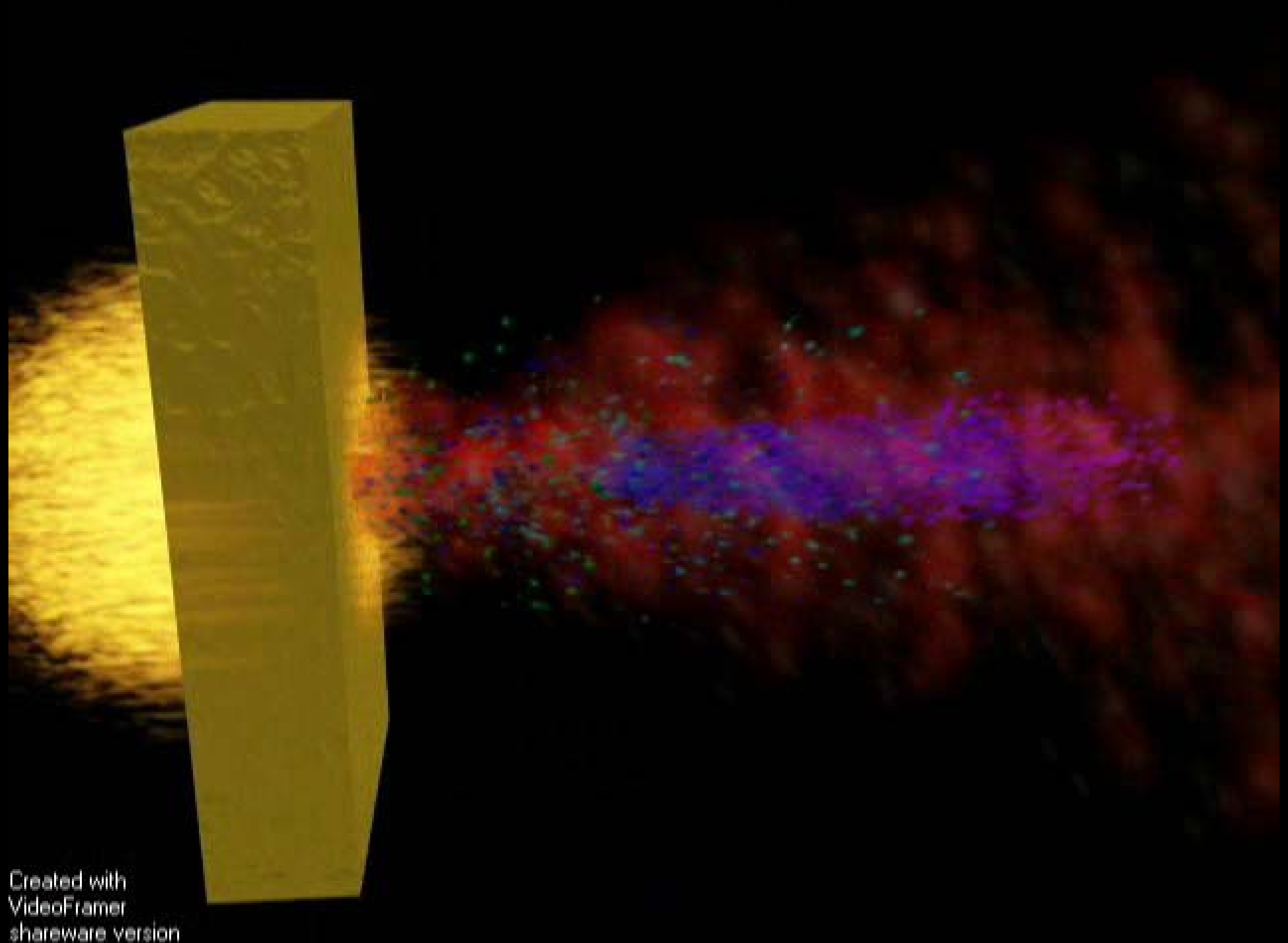
Current status of laser-ion acceleration

A laser pulse accelerates e^- through the target. The e^- set up a TV/m E-field at the rear surface, ionizing and accelerating atoms to MeV/u :

Target Normal Sheath Acceleration (TNSA):



Legend:

e-, C1+, C2+, C3+, C4+

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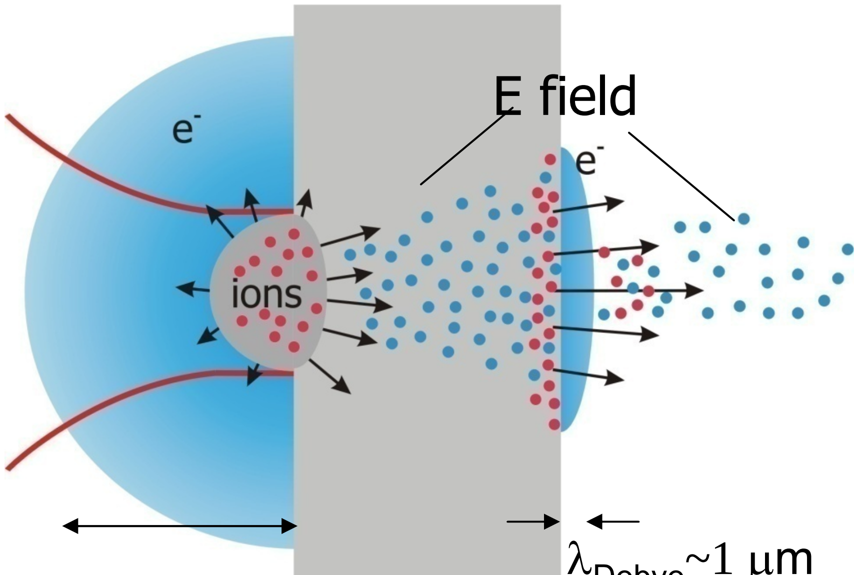
Target Normal Sheath Acceleration (TNSA):

Accelerates ions from the rear surface of ~μm foils in laser directions

The TNSA mechanism:
laser electron acceleration → charge separation → quasi static electric field → ion acceleration



λ_{Debye}~100 μm

λ_{Debye}~1 μm
T_e ~ MeV
E ~TV/m

Advantages of laser-driven ion beams:

- Shorter pulse duration [1]
  <ps vs. >ns
- Smaller longitudinal emittance [1]
  10^{-6} eVs vs. 1 eVs (CERN SPS)
- Smaller transverse emittance [2]
  <0.001πmm-mrad vs. 1 πmm-mrad (CERN SPS)
- High beam currents [1]
  kA – MA vs. μA-mA

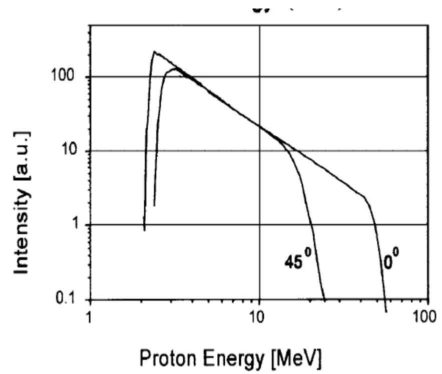
---

[1] Hegelich et al., Nature **439** (2006) p441
[2] Cowan *et al.*, PRL **92** (2004) 204801

TNSA ion acceleration:

No significant increase in particle energies since first demonstrations.

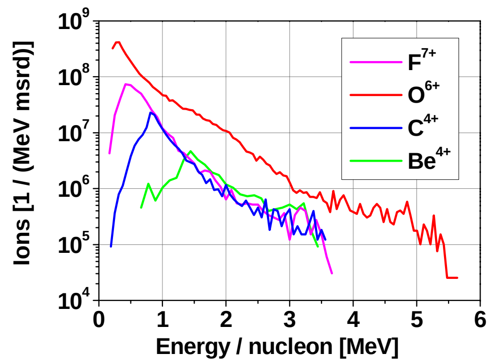
Protons with E ≤ 60 MeV.



Snavely et al. PRL 2000

Light ions (Z ≤ 10) with E ≤ 5 MeV/amu.

Mid-Z ions (10 ≤ Z ≤ 46) with E ≥ 2 MeV/amu.




VOLUME 89, NUMBER 8 PHYSICAL REVIEW LETTERS 19 AUGUST 2002

MeV Ion Jets from Short-Pulse-Laser Interaction with Thin Foils

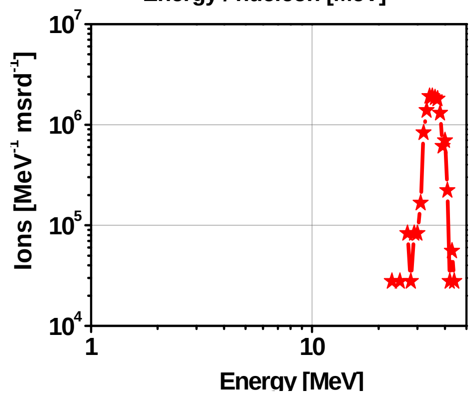
M. Hegelich,[1,2] S. Karsch,[1,2] G. Pretzler,[1,2] D. Habs,[2] K. Witte,[1] W. Guenther,[3] M. Allen,[4] A. Blazevic,[5] J. Fuchs,[6] J. C. Gauthier,[6] M. Geissel,[5] P. Audebert,[6] T. Cowan,[4] and M. Roth[5]
[1]MPI für Quantenoptik, 85748 Garching, Germany
[2]Universität München, 85748 Garching, Germany
[3]Universität Siegen, 57068 Siegen, Germany


PHYSICS OF PLASMAS 12,

Spectral properties of laser-accelerated mid-*Z* MeV/u ion beams[a)]

B. M. Hegelich, B. Albright, P. Audebert, A. Blazevic, E. Brambrink, J. Cobble, T. Cowan, J. Fuchs, J. C. Gauthier, C. Gautier, M. Geissel, D. Habs, R. Johnson, S. Karsch, A. Kemp, S. Letzring, M. Roth, U. Schramm, J. Schreiber, K. J. Witte, and J. C. Fernández
[1]Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Mono-energetic ions (carbon) 3 MeV/amu



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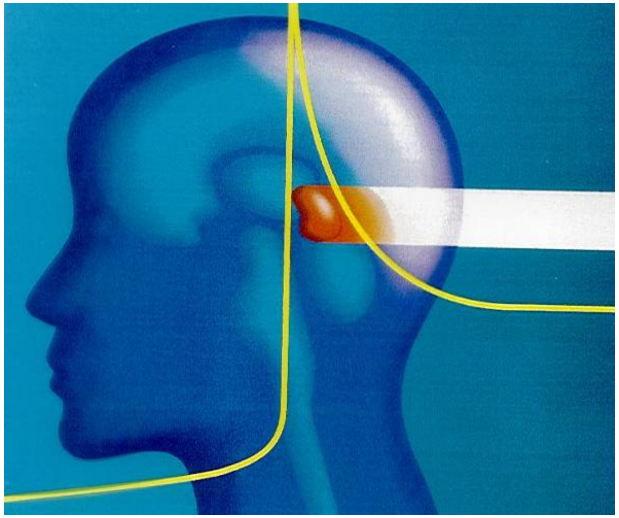
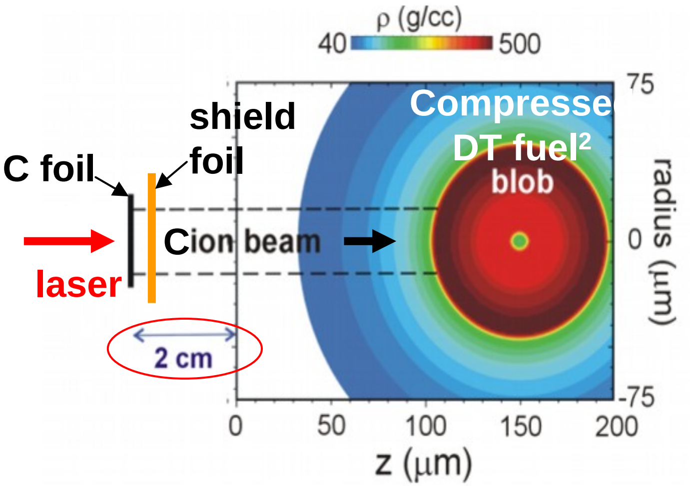
Potential Applications of Laser-driven Ions:

Hadron Therapy and Ion-driven Fast Ignition require GeV-class particle energies

Hadron therapy



Ion-driven Fast Ignition (IFI)



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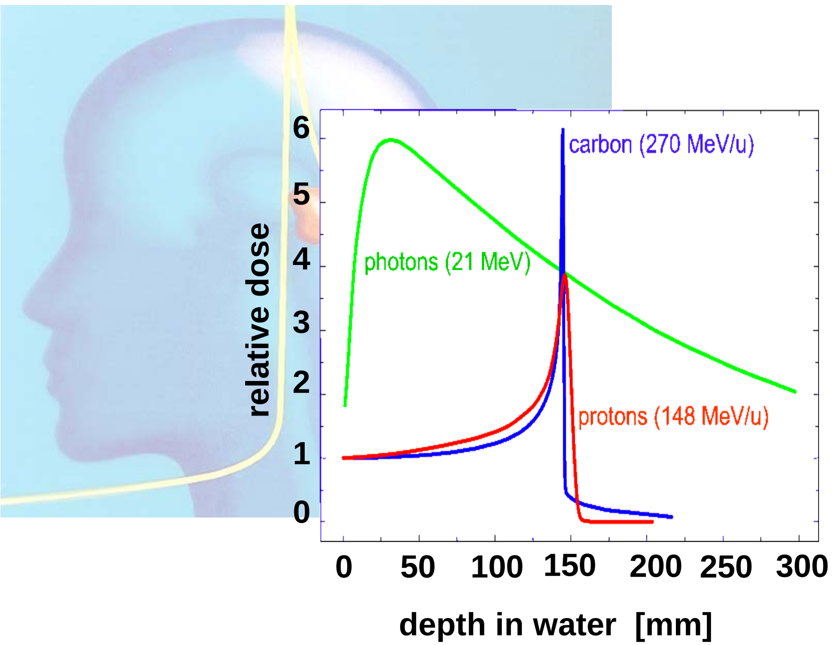

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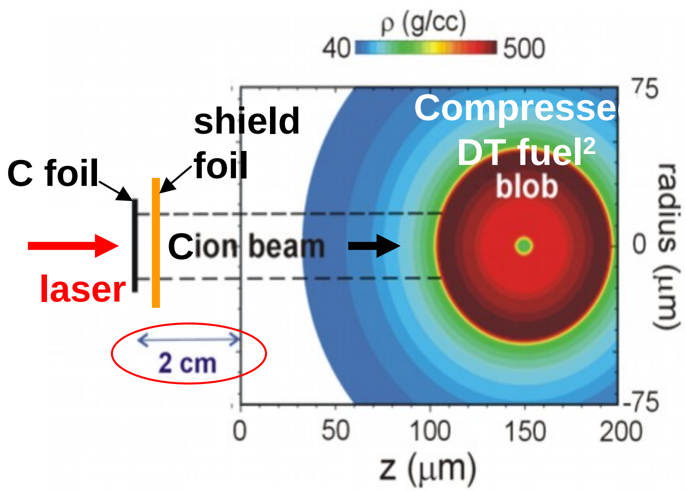

- Hadron therapy
- requires:
- 150 – 250 MeV protons
- 2-4 GeV carbon ions

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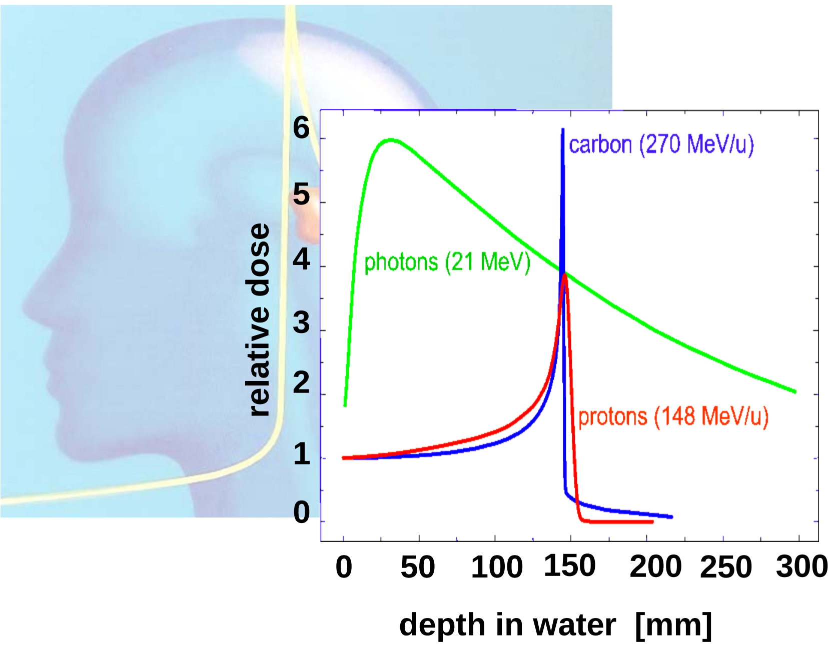
Hadron therapy



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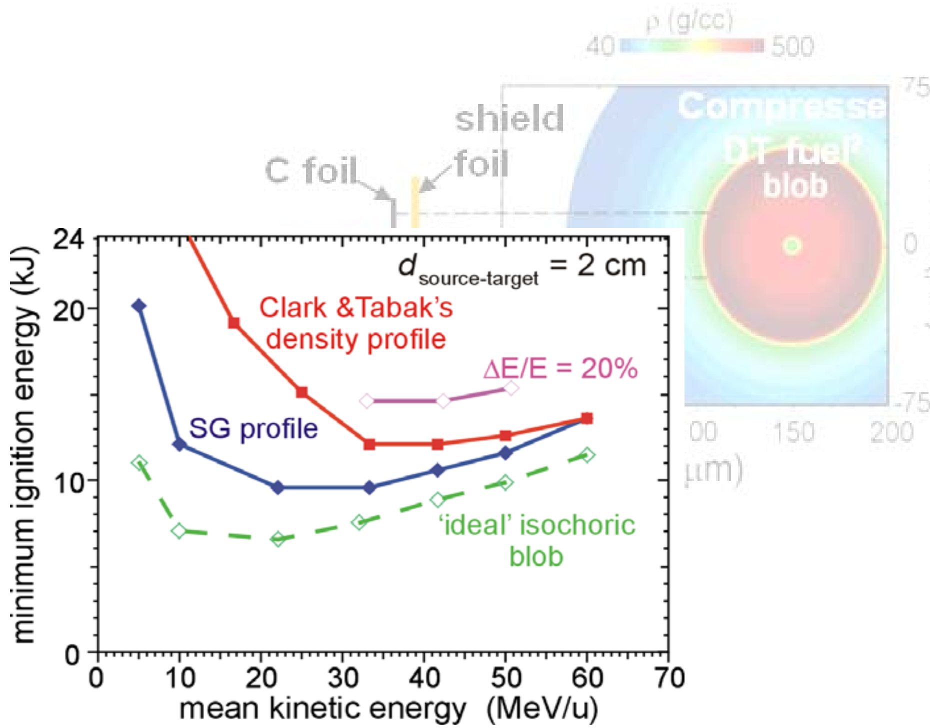


- Hadron therapy
- requires:
- 150 – 250 MeV protons
- 2-4 GeV carbon ions

Beam Ion	Energy (MeV)	Number of Ions	Laser Irrad. (W/cm^2)
Protons	7 – 19	10^{16}	~ 10^{20}
C^{6+}	**400-480**	10^{14}	~ 10^{21}

Potential Applications of Laser-driven Ions:

Advanced Accelerators: Injecting into SIS-18?

To inject into SIS-18 or similar:*

* I. Hofmann, priv. comm.

- 10^{12} ions / sec
- 30-70 MeV/amu
- ΔE~1-2%

Not promising with Phelix type system at 1 shot per hour

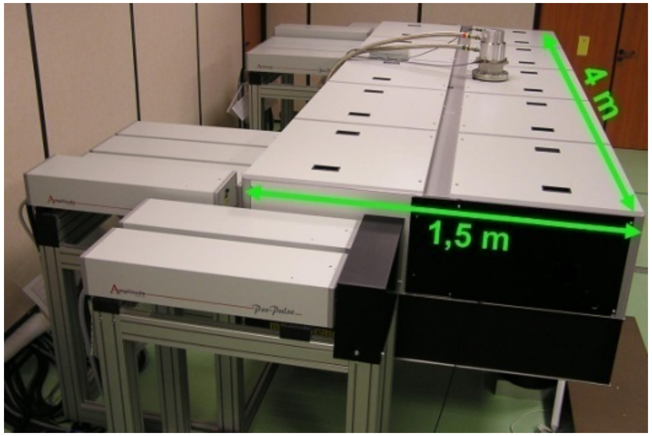
BUT

@ 100Hz: 10^{10} ions per shot

@ 50MeV: 80mJ per bunch

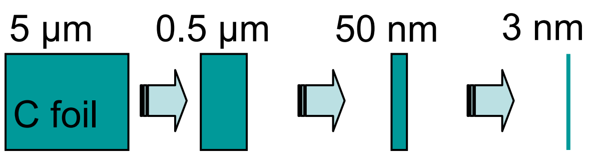
@ 1% CE: 8J laser

FEASIBLE



Nanoscale targets

Enable GeV ion energies at achievable laser intensities of I ~ 10^{21} W/cm²




GeV laser ion acceleration from ultrathin targets:
The laser break-out afterburner

L. YIN, B. J. ALBRIGHT, B. M. HEGELICH, and J. C. FERNANDEZ

Enhanced TNSA: Thinner targets enable higher ion energies:

1.LLNL: Enhancement of Proton Acceleration by Hot-Electron Recirculation in Thin Foils Irradiated by Ultraintense Laser Pulses. A. MacKinnon, et al., **PRL 88**, (2002)

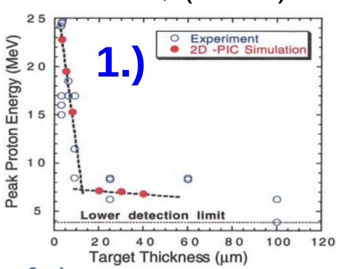
2.LULI: Ion acceleration using high-contrast ultra-intense lasers, J. Fuchs et al., **J. Phys. IV France 133** (2006) 1151–1153

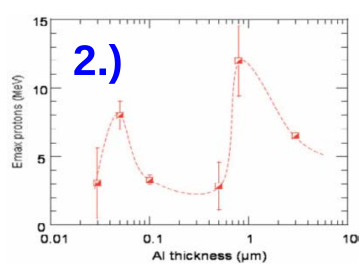
Break-Out Afterburner (BOA): Matching of laser and target parameters enables additional energy transfer via relativistic Buneman instability:

3.LANL: GeV laser ion acceleration from ultrathin targets: The laser break-out afterburner, L. Yin, et al., **Laser and Particle Beams 24** (2006), 1–8

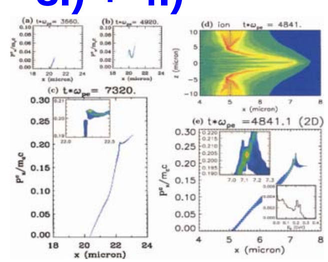
4.LANL: Monoenergetic and GeV ion acceleration from the laser break-outafterburner using ultrathin targets, L. Yin, et al., **PoP 14**, 056706, (2007).

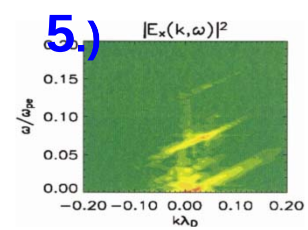
5.LANL: Relativistic Buneman instability in the laser breakout afterburner, B. J. Albright, et al., **PoP 14**, 094502, (2007)





3.) + 4.)



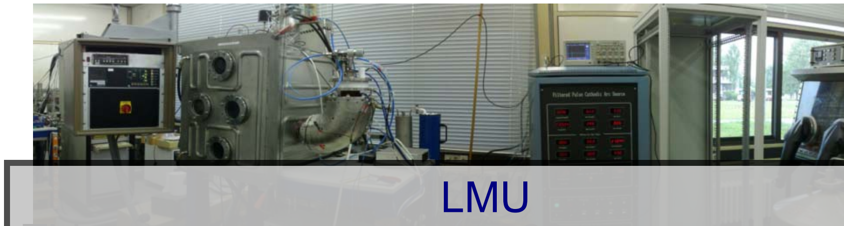


Experimental Realization

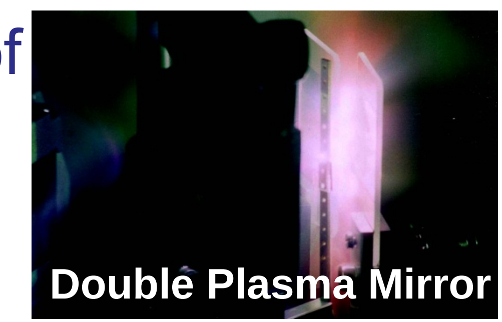
Ultrathin, nm-scale, robust, free standing targets & ultrahigh contrast

The experimental use of ultrathin targets required two major developments:

- Robust, free standing (mm), ultrathin (nm) targets
- Improvement of laser contrast by 4 - 6 orders of magnitude from 10^{-6} to $\sim 10^{-11}$



	LMU
Thickness	3 to 60 nm
Bulk density	2.7±0.3 g/cm^3
sp^3 content	>75%
Roughness	~2 nm
Damage Threshold	10^{11} W/cm^2 @ 500 fs 10^8 W/cm^2 @ 1.2 ns
Atomic composition	<10% protons (bulk), proton layer on top



Double Plasma Mirror

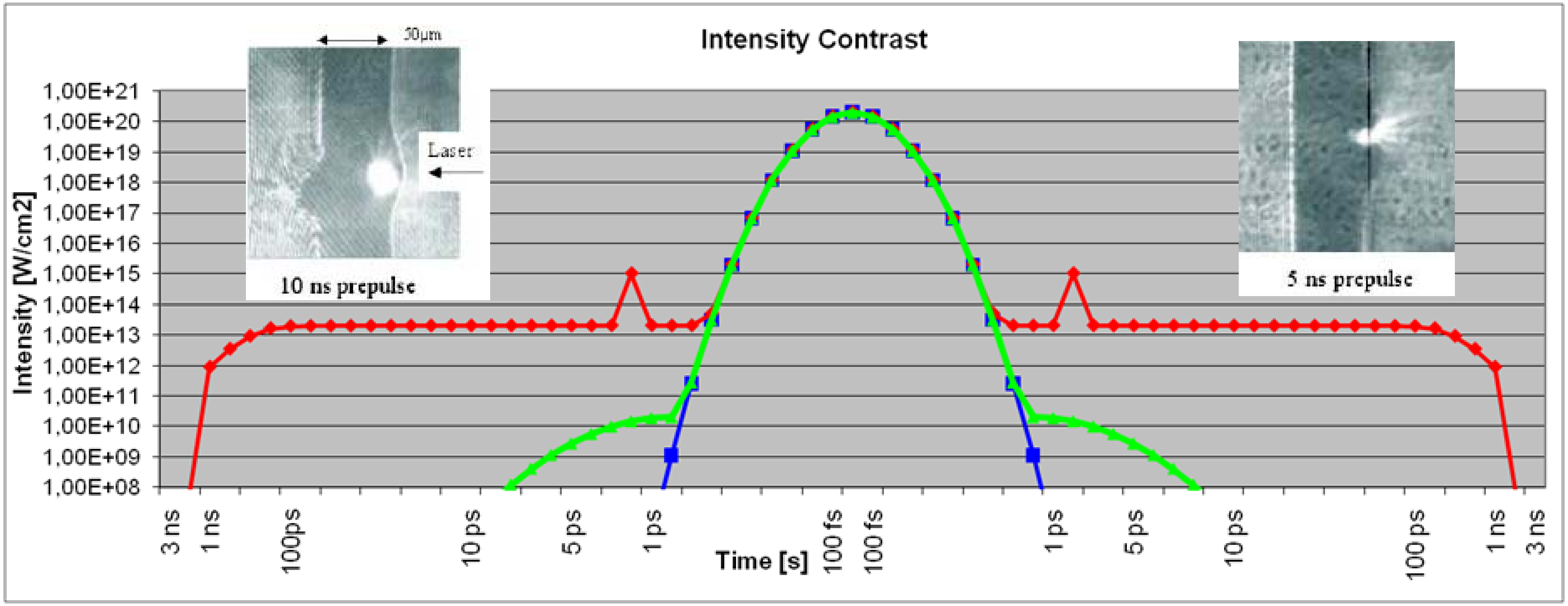
New High-Contrast OPA Trident Laser Front End

High-contrast (<10^{-10} @ 5ps) is needed to shoot ~40nm targets without shot breakout before the main pulse:

Starting point:

- Current contrast: <10^{-7} @ 1ns
- V_s~7 nm/ps ⇒ 40nm/5.7ps

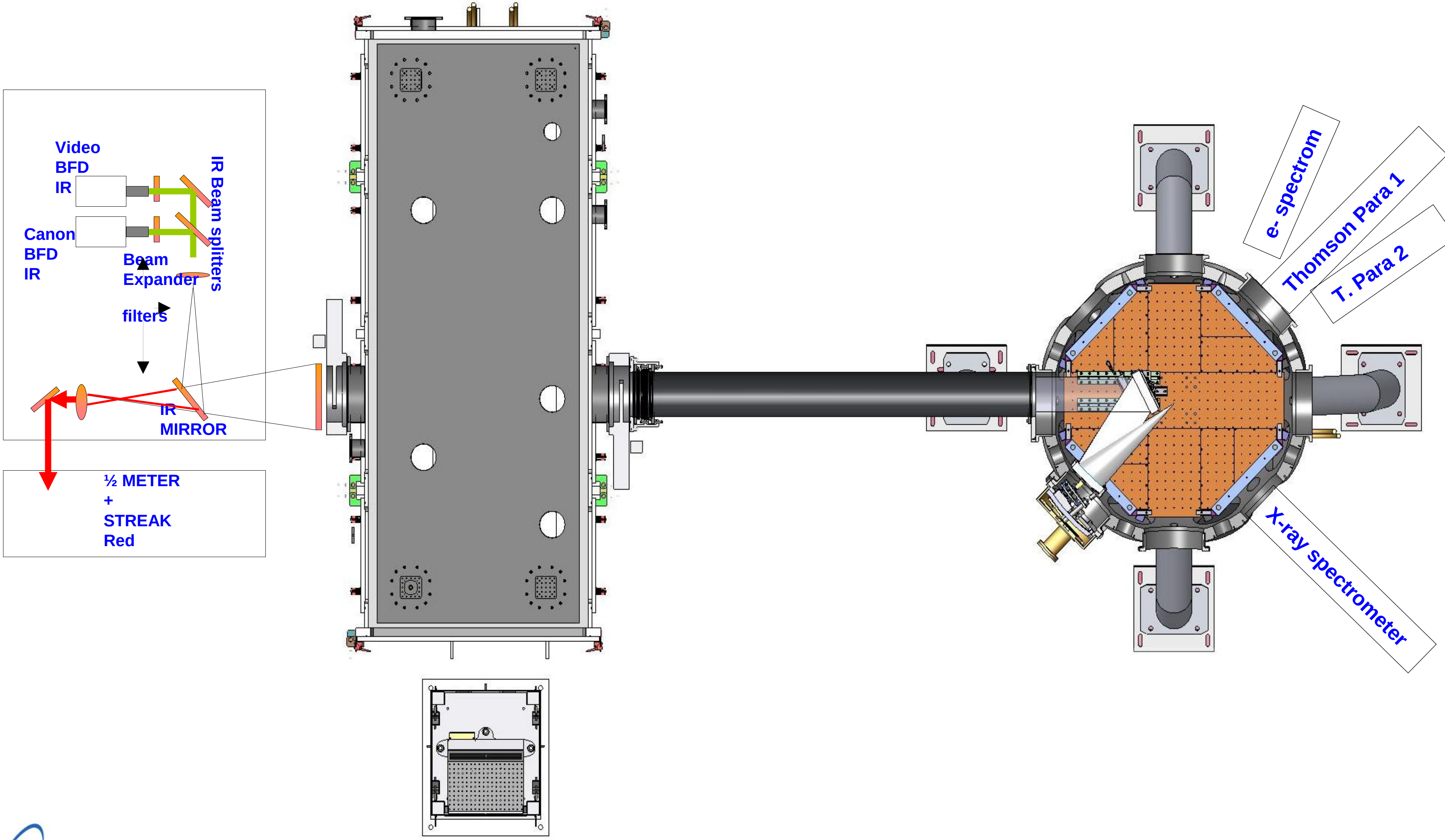
Goals:
Intensity contrast of <10^{-10} @ 5ps on target



Energetic ions generated by laser pulses: A detailed study on target properties; M. Roth, M. Hegelich, et al.
PRST – AB, Vol. 5, 061301, 2002

High-temporal contrast using low-gain optical parametric amplification; R. Shah, M. Hegelich, et al.
Accepted for publication, Opt. Lett. 2009

Experimental Setup: F/3 OAP, 2 Thomson parabola ion spectr., e-spectr., Full-Aperture Backscatter (FABS), x-ray spectrom.



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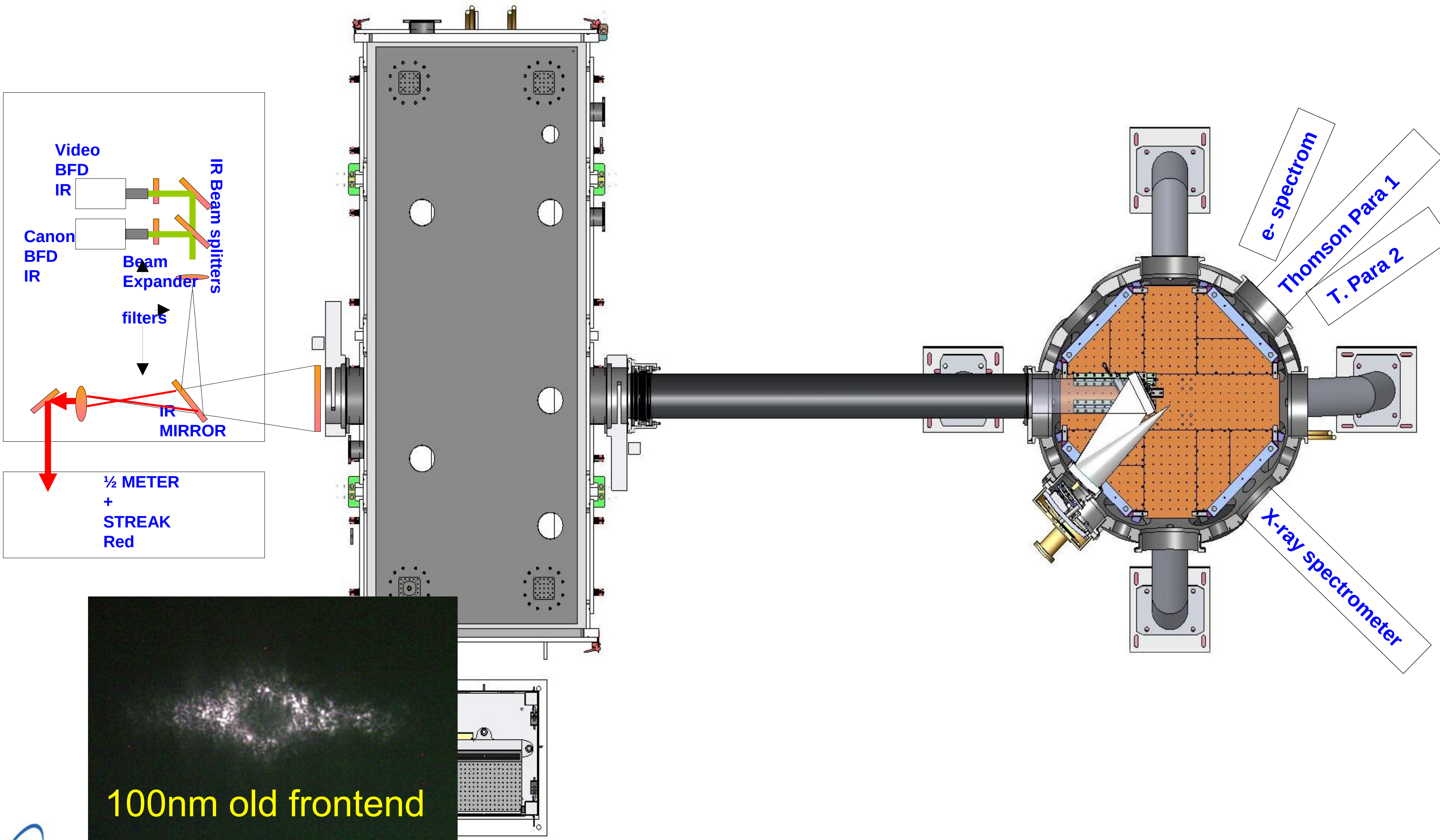

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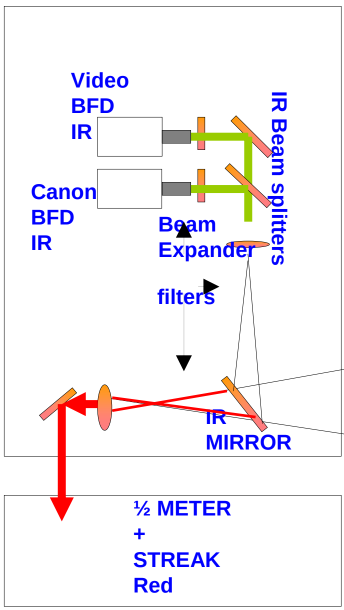

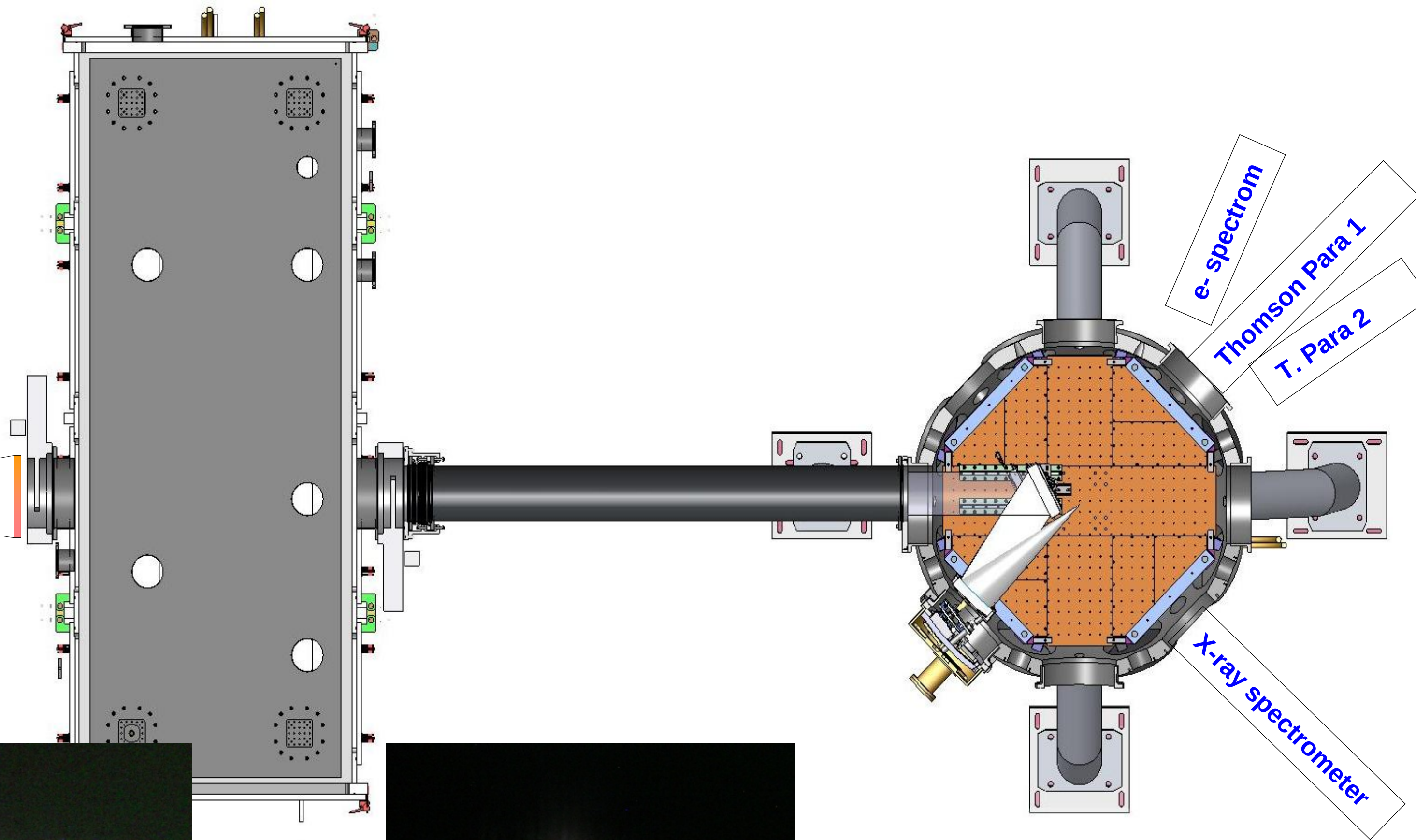

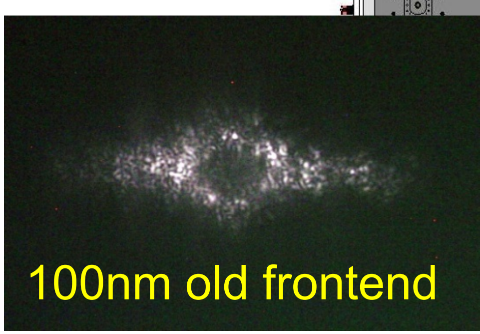

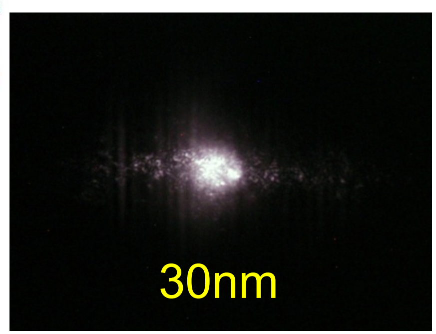

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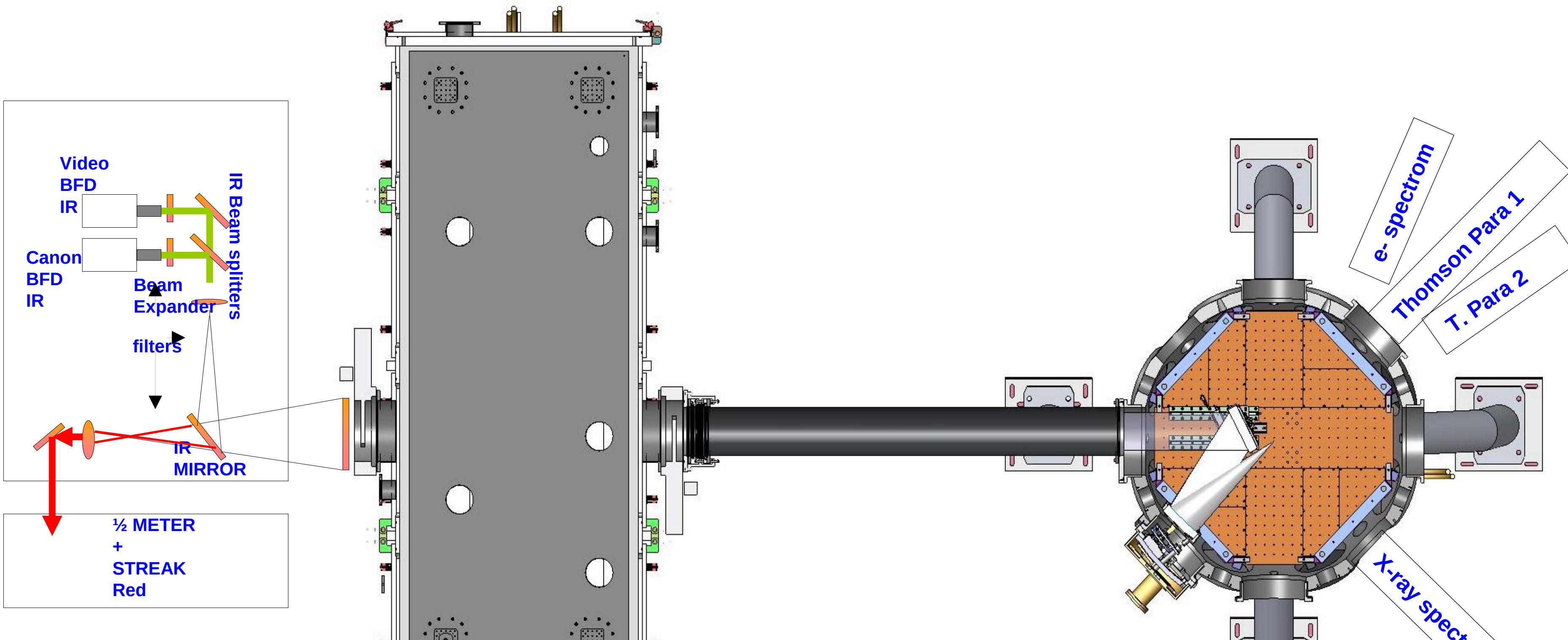
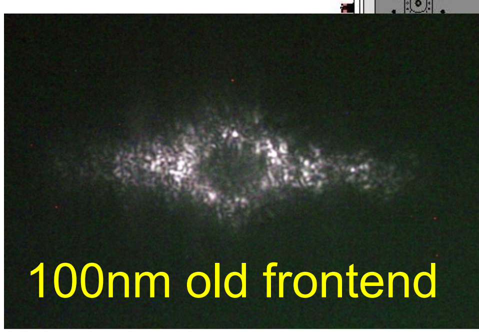
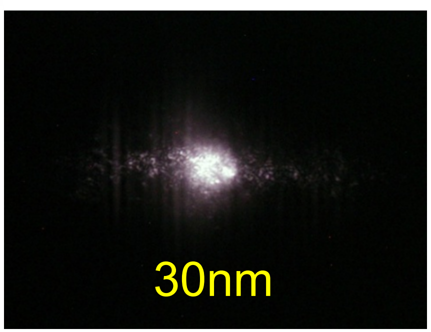
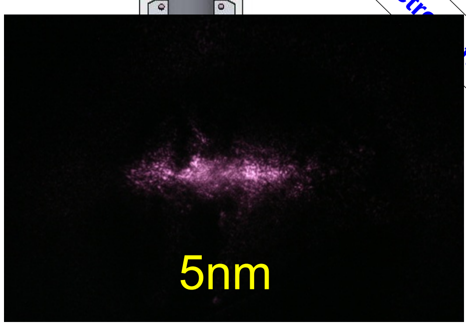


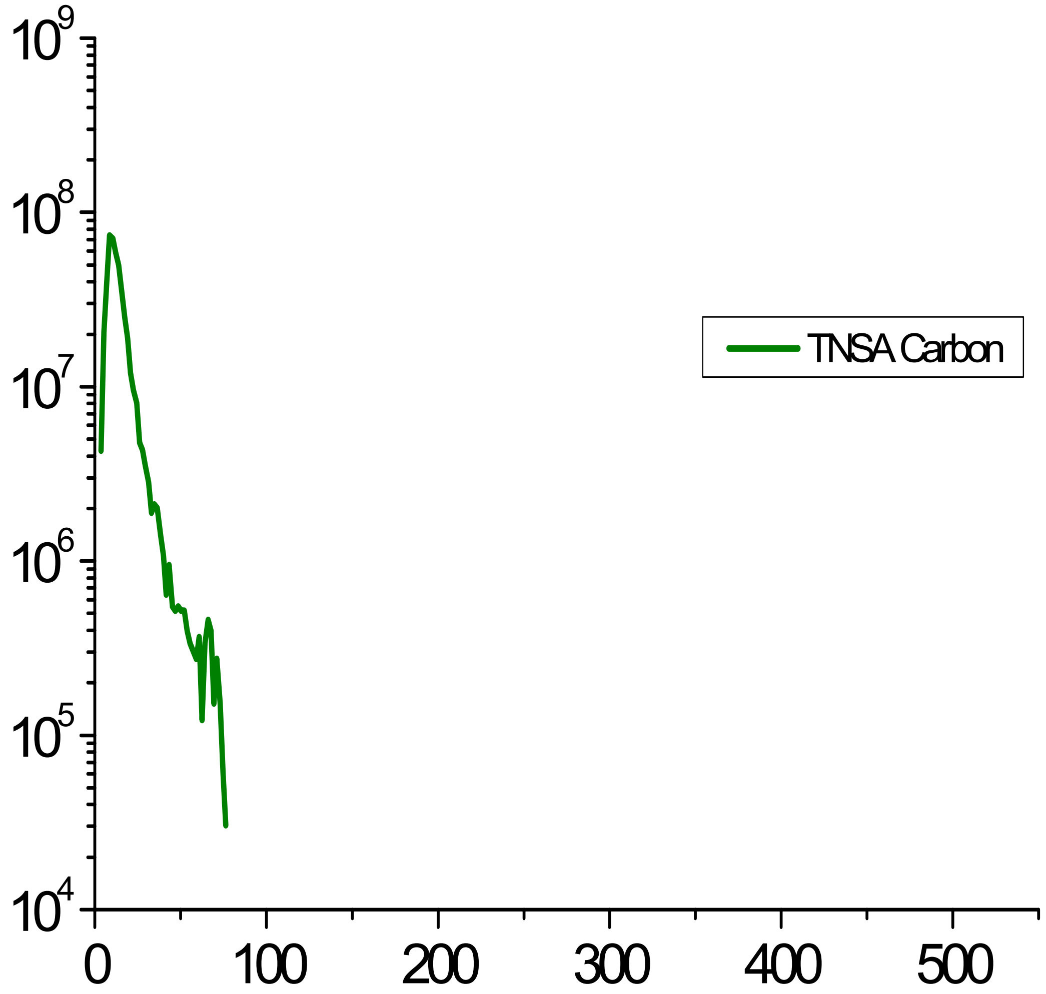






1st Demonstration of Break-Out Afterburner:

Shot #20570, 58nm DLC foil, E_{target} = 90.1J, t=540fs, I = $2x10^{20}$ W/cm²



- Compared to 75 MeV from TNSA (scaling a measured 30J spectra with [Hegelich, M. et al., Phys. Plasmas, 12, 056314 (2005).]

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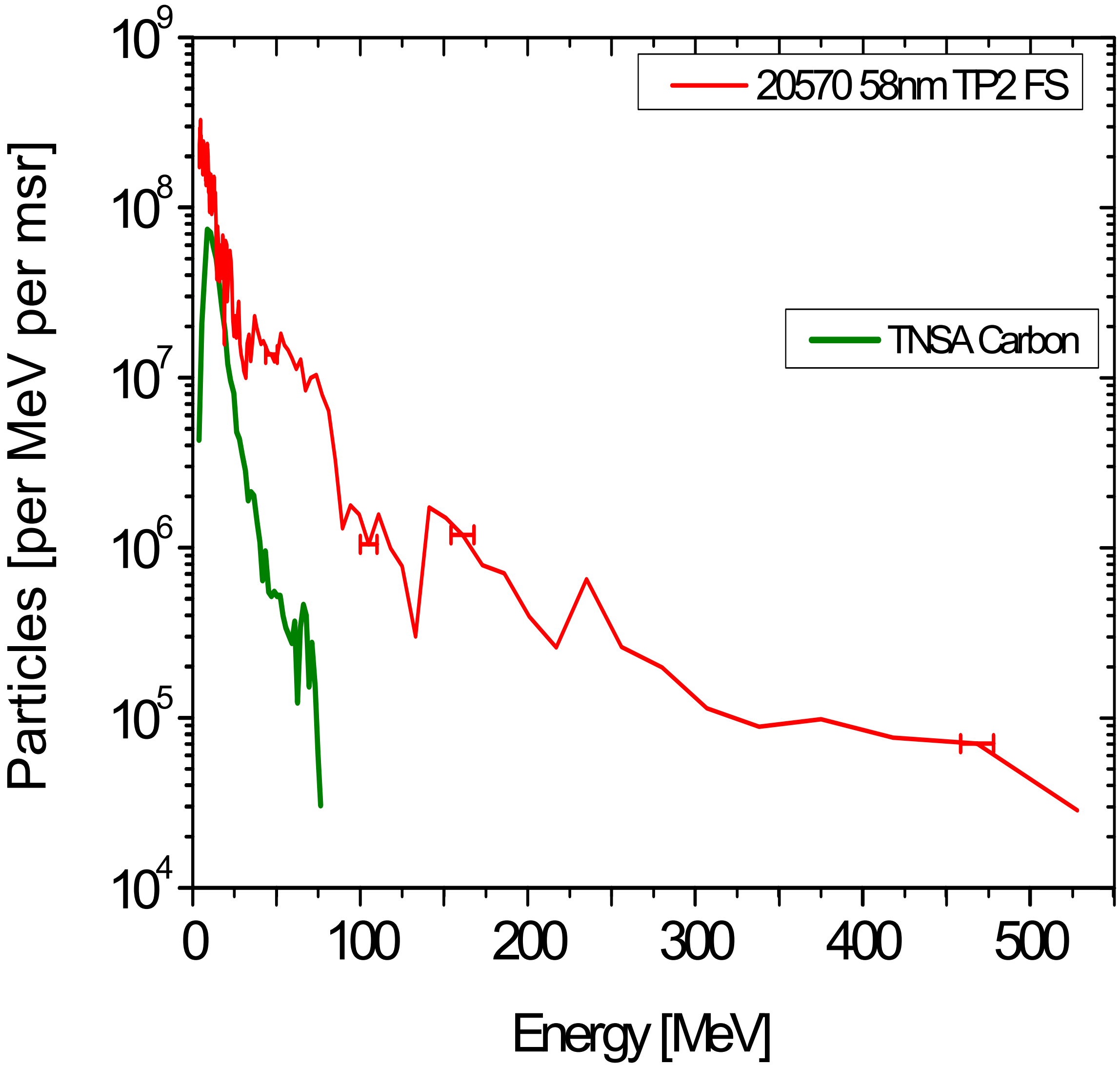

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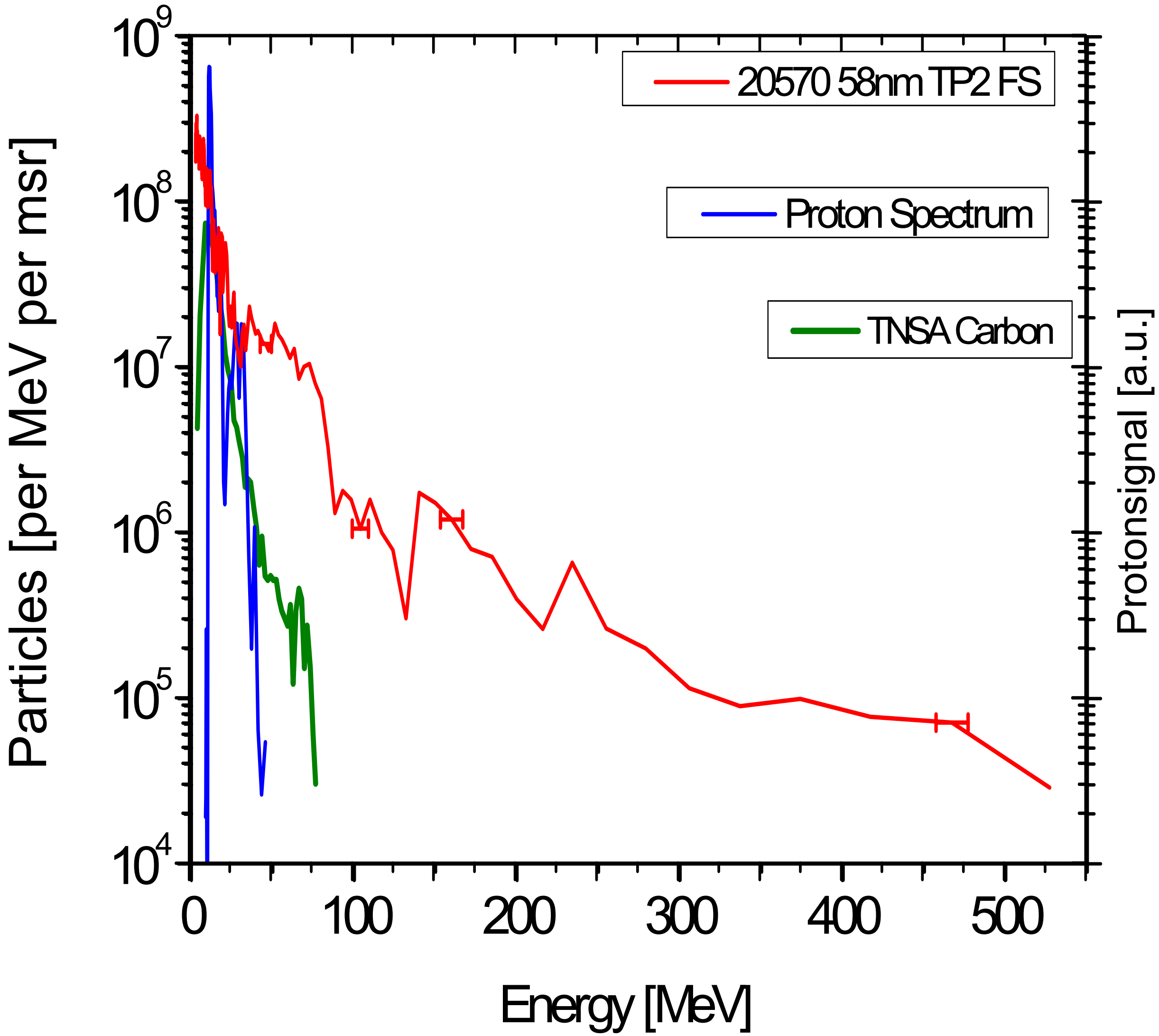

- Compared to 75 MeV from TNSA (scaling a measured 30J spectra with [Hegelich, M. et al., Phys. Plasmas, 12, 056314 (2005).]
- >500 MeV Carbon 6+
- Protons on shot have same velocity
- First demonstration of BOA acceleration

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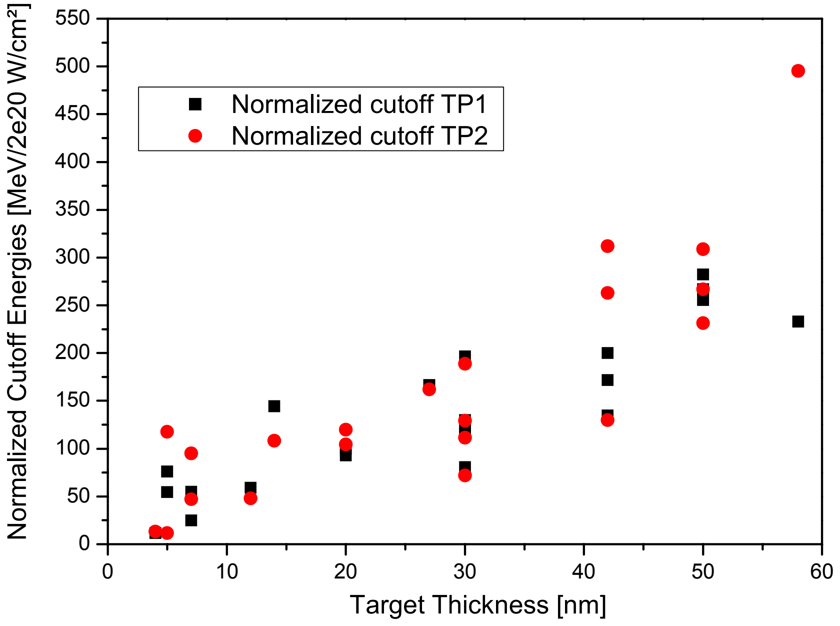
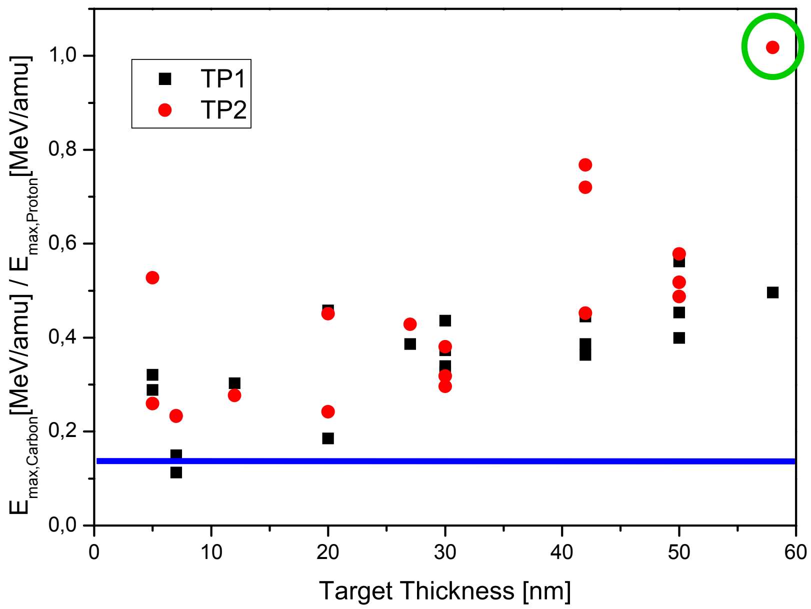
Experimental Results: Cutoff energies

Carbon ion reach same velocity as protons



Best shot at 58nm:
0.525 GeV C6+ cutoff energy



Theoretical C/p limit for TNSA is 0.5
best observed TNSA ratio 0.16
Simulation prediction for BOA is 1.0
Hegelich et al., PRL 89, 85002 (2002)

Ion acceleration from nm-targets:
MPQ/LMU – MBI collaboration

Max-Born-Institut

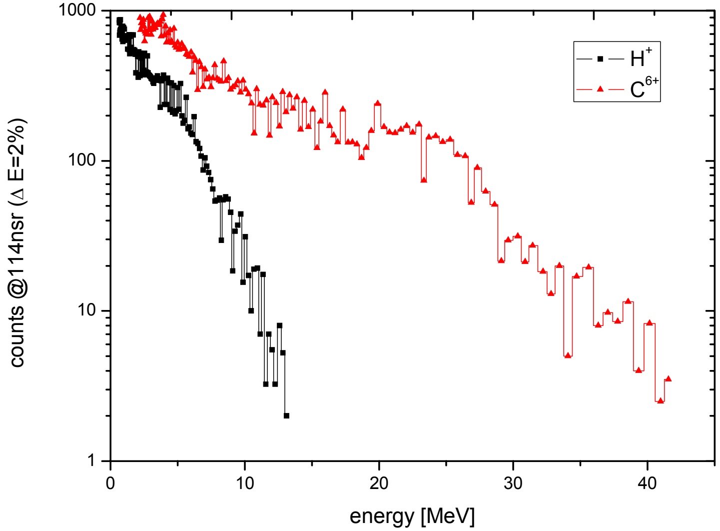
2-weeks experiment in November 2008:

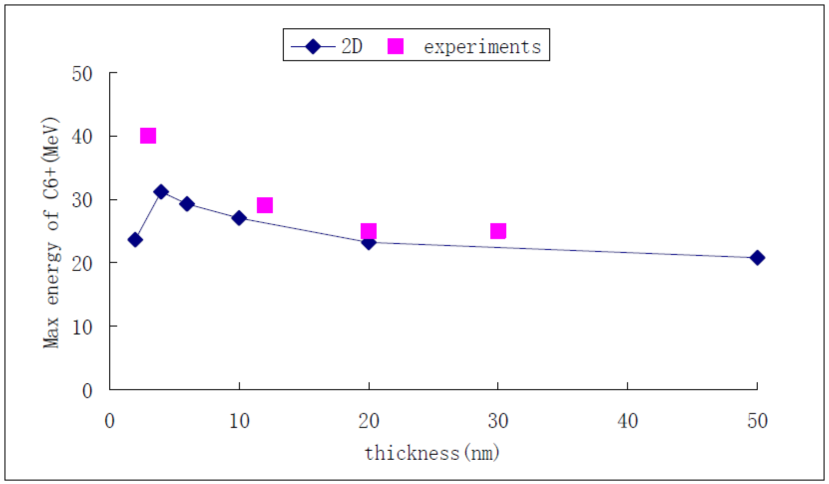
A. Henig, D. Kiefer, D. Jung, X. Yan, D. Habs, M. Hegelich (LMU)

S. Steinke, T. Sokollik, M. Schnürer, P. Nickles (MBI)

- **10Hz Ti:Sapphire laser system: 700 mJ, 45 fs, 3 x 10^{19} W/cm²**
- **double plasma mirror for contrast enhancement**
- **DLC-foils of thickness 50nm down to sub-5nm (shot at normal incidence)**

Ion spectra observed from sub-5nm target at linear polarization:





Last experiments in March/April 09 got >70 MeV carbon

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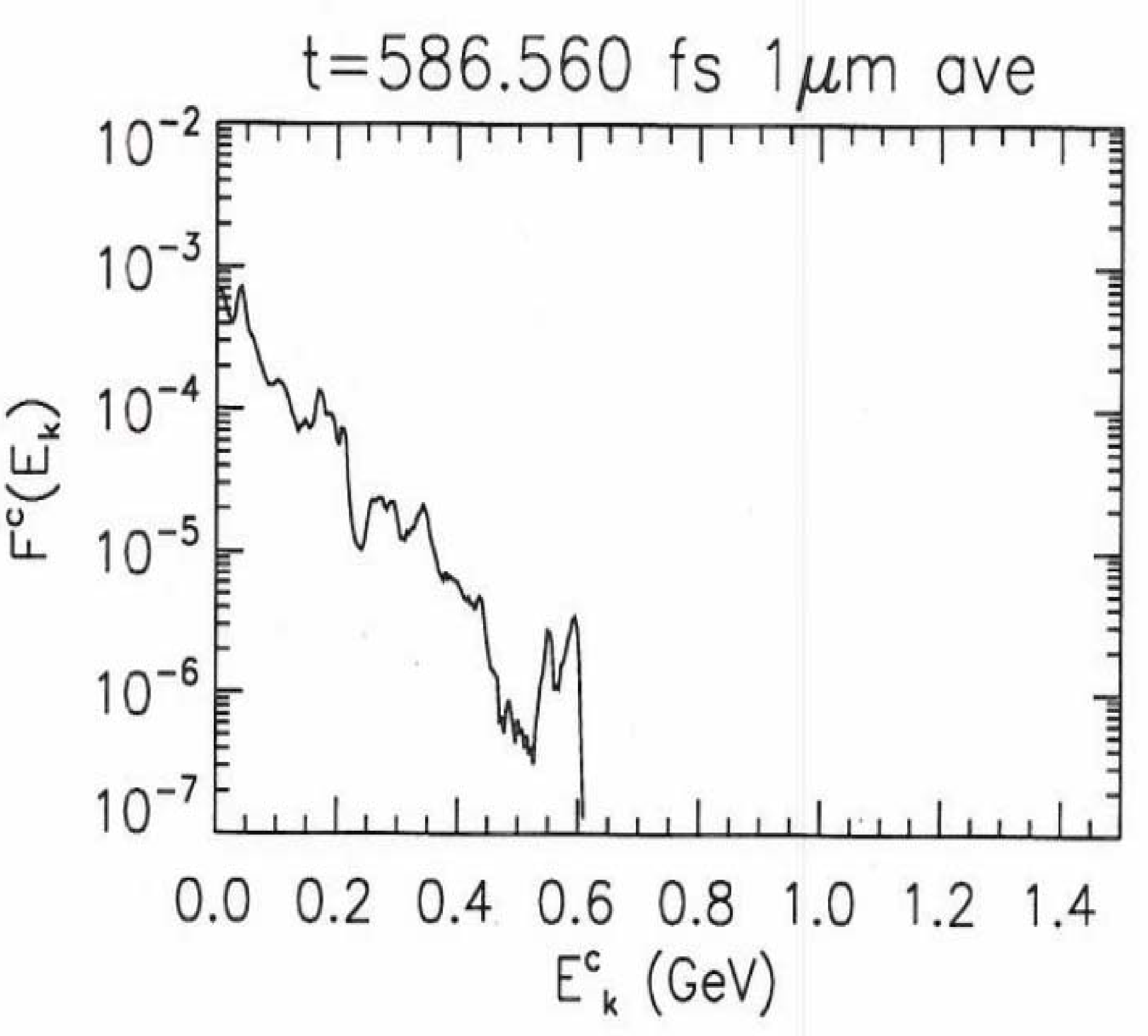
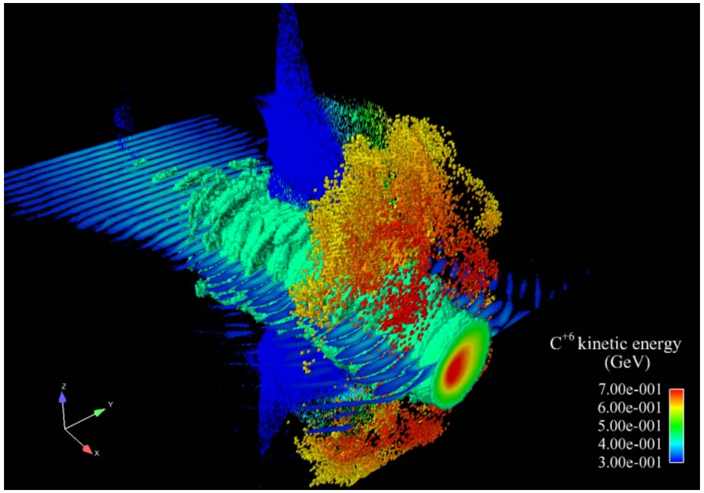
Simulations

- **Ion energy and spectra qualitatively and quantitatively well reproduced**
- **Angular anisotropy reproduced: 2D and 3D effects!**
- **Main acceleration is due to co-moving (with carbon ions) electric field and happens between the times of relativistic and classic transparency (BOA)**
- **Plasma frequency analysis suggest kinetic instability (Buneman-like) as cause of the E-field**
- **~80% of the energy gain happens in BOA phase**

VPIC Simulation:
2D simulation of 58nm target shows good agreement





Roadrunner base system
25x25x20 µm
Target: 58nm DLC
n = $821n_{cr}$ (2.8 g/cc)
I=5e20 W/cm², t=540fs FWHM
14 x 10^9 cells
21 x 10^9 particles
4096 processors

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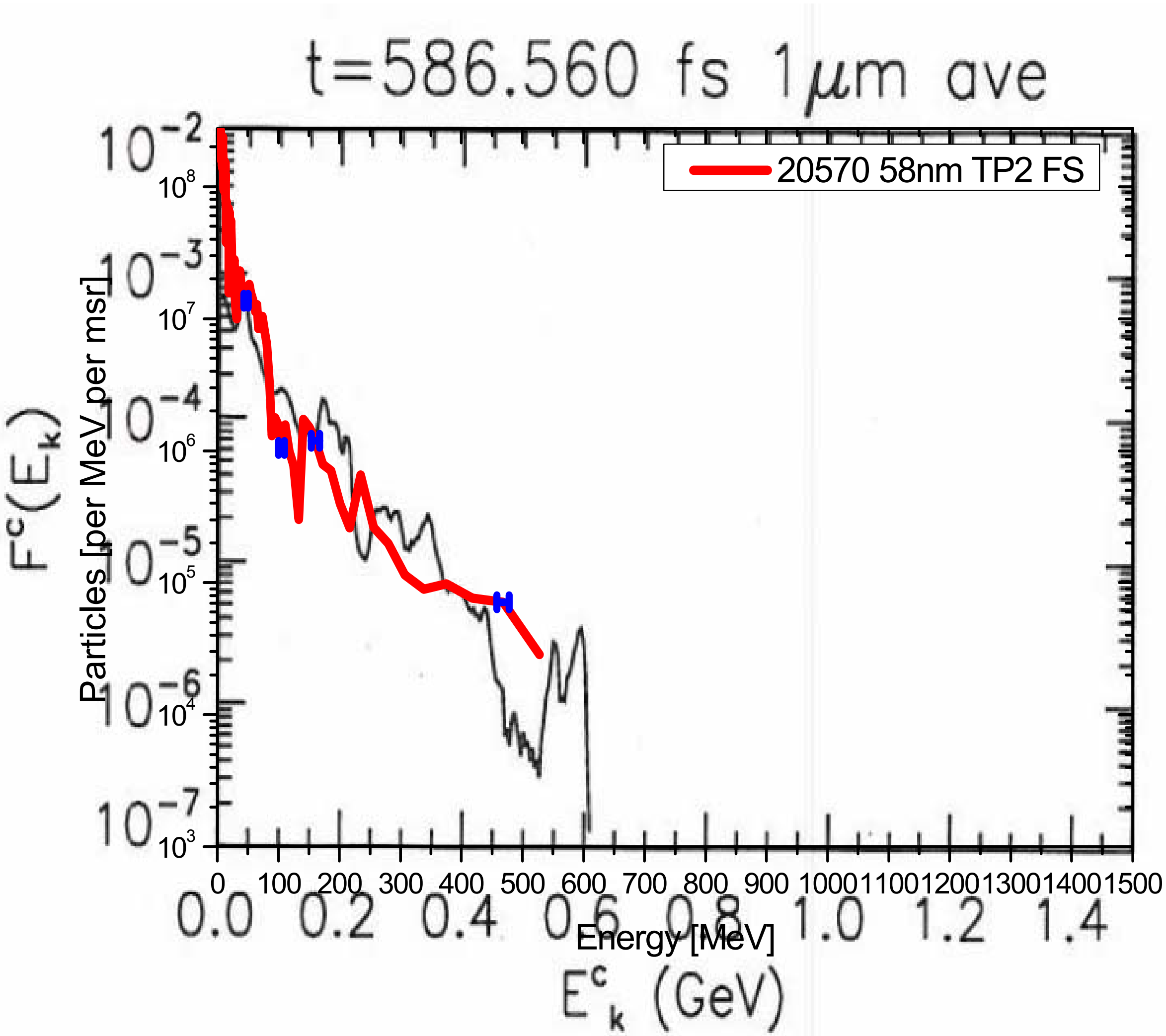

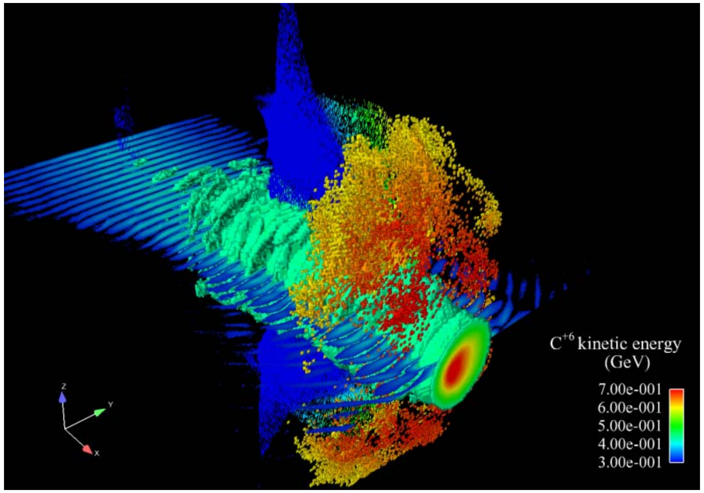

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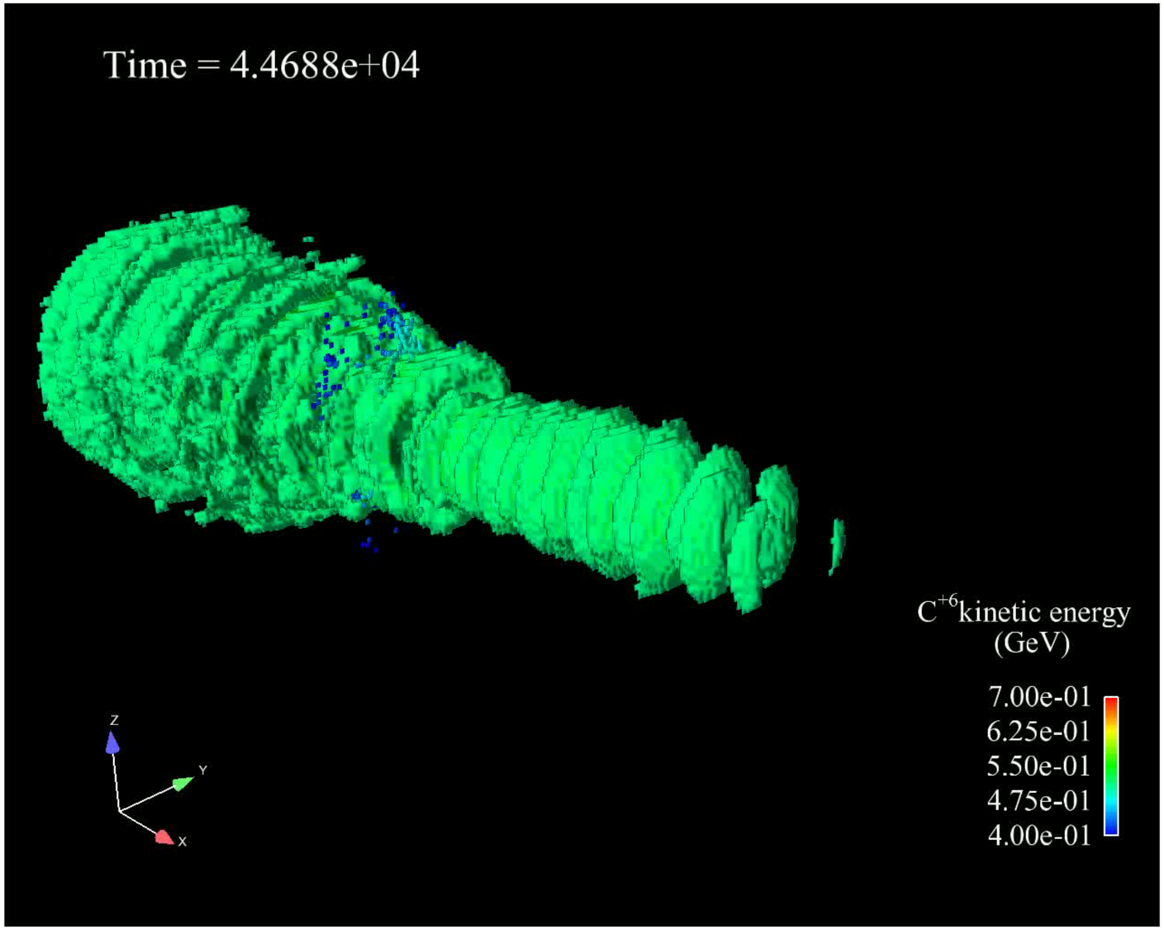
3D VPIC: simulation of the BOA

highest energies are observed out of polarization plane, slightly off-axis

Horizontal Polarization, 60nm C, I0 = 6 x 10^{20} W/cm², 540 fs pulse

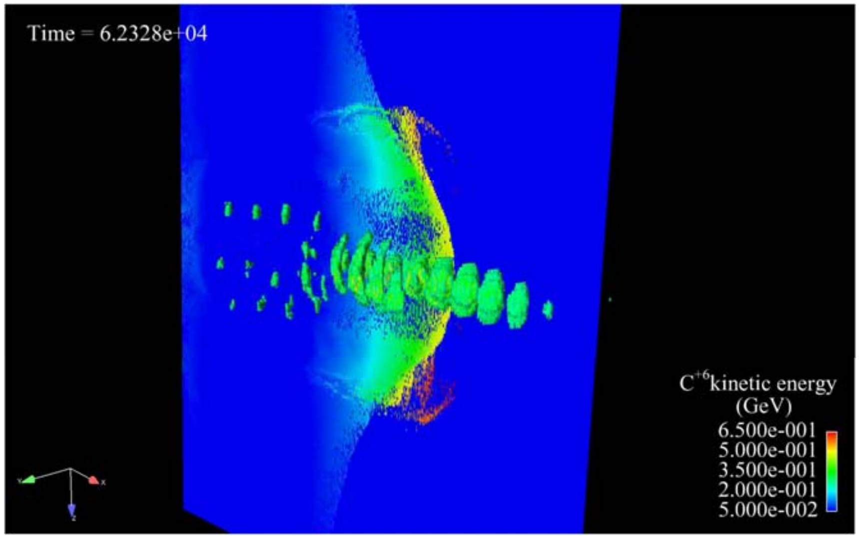
Our largest simulation to date on ion acceleration (run on Roadrunner base system):

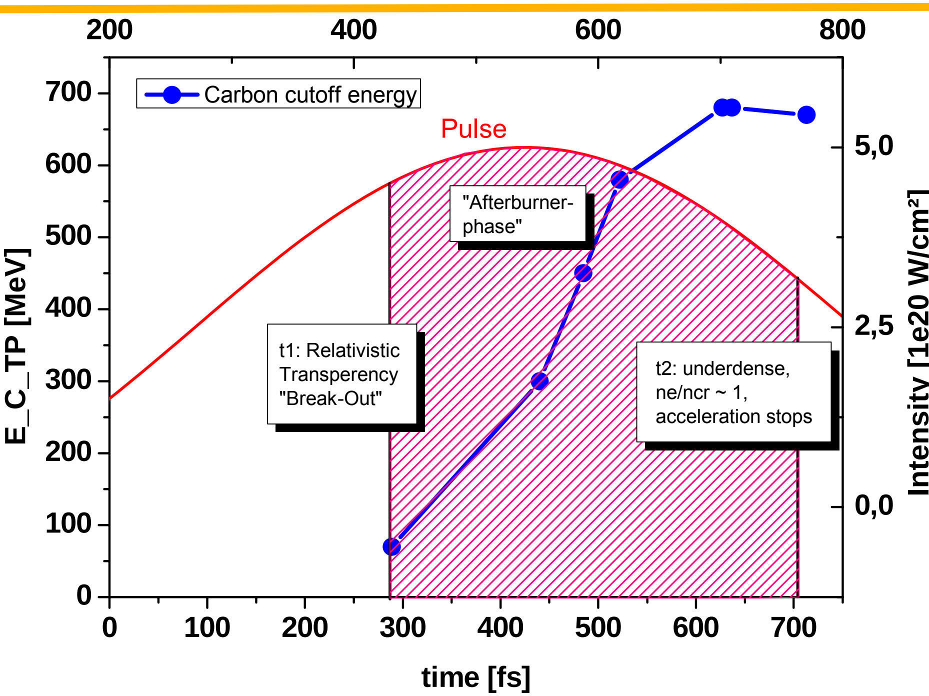
- Physical domain 25x25x20 μm w. solid target density
  14×10^9 cells, 21 x 10^9 particles, 4096 processors
- Contrasting with sim. size at the time of the proposal:
  0.5×10^9 cells, 2.2×10^9 particles, 510 processors
- 3D visualization using EnSight server-of-servers mode enables viewing, analysis of very large (multiple-TB) data sets.



Simulation Results: Acceleration Dynamic

~80% of the carbon acceleration happens during BOA phase





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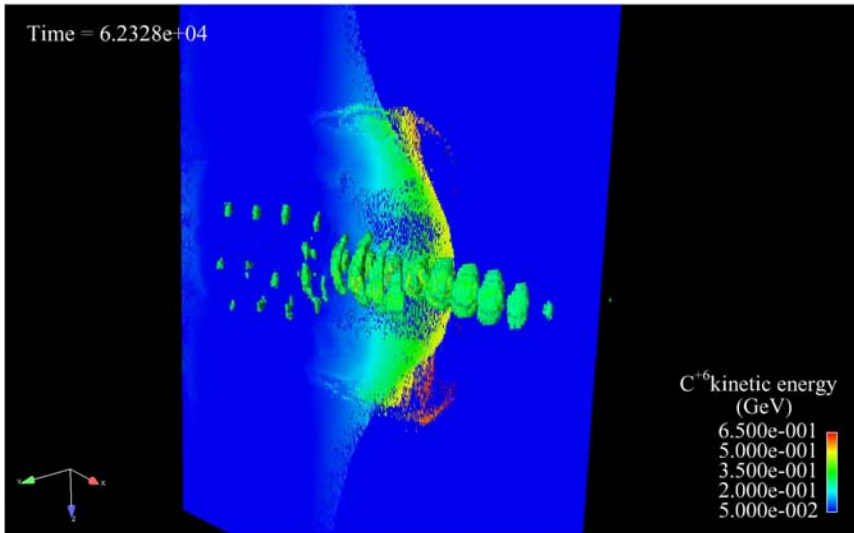

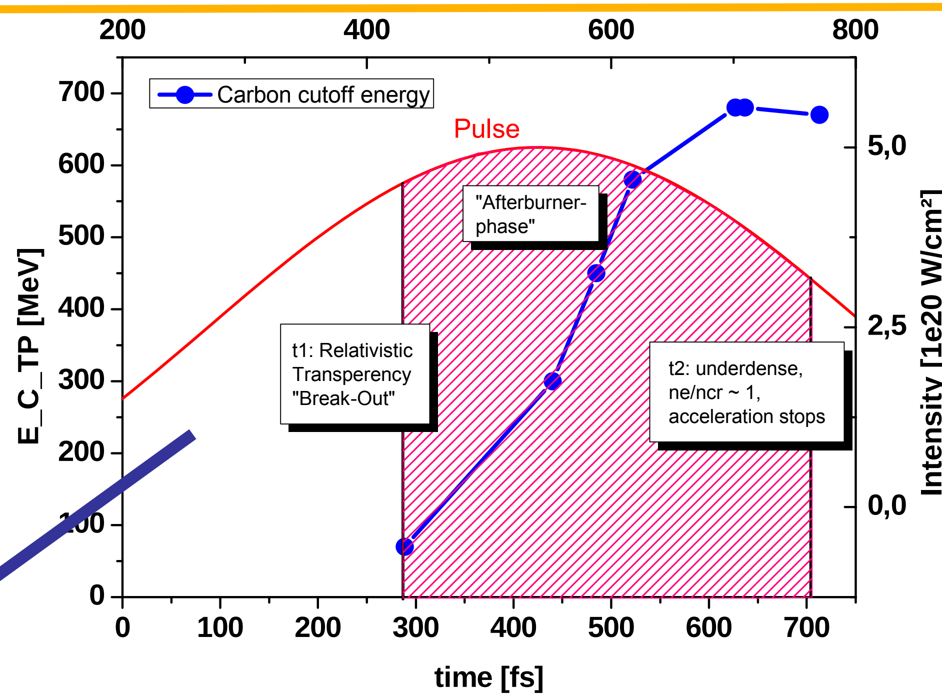

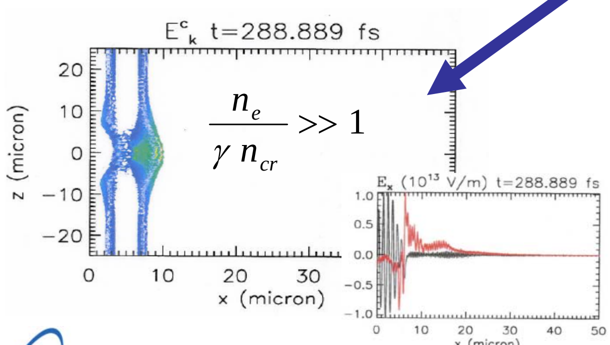

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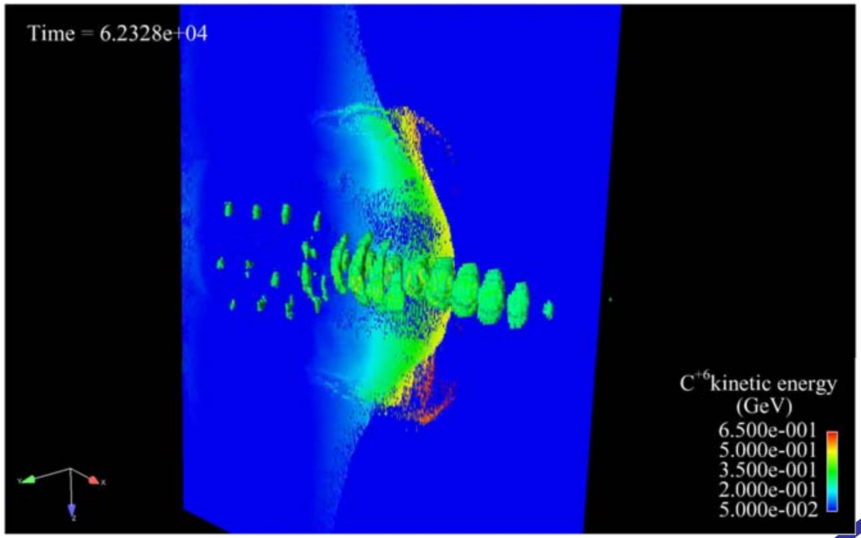

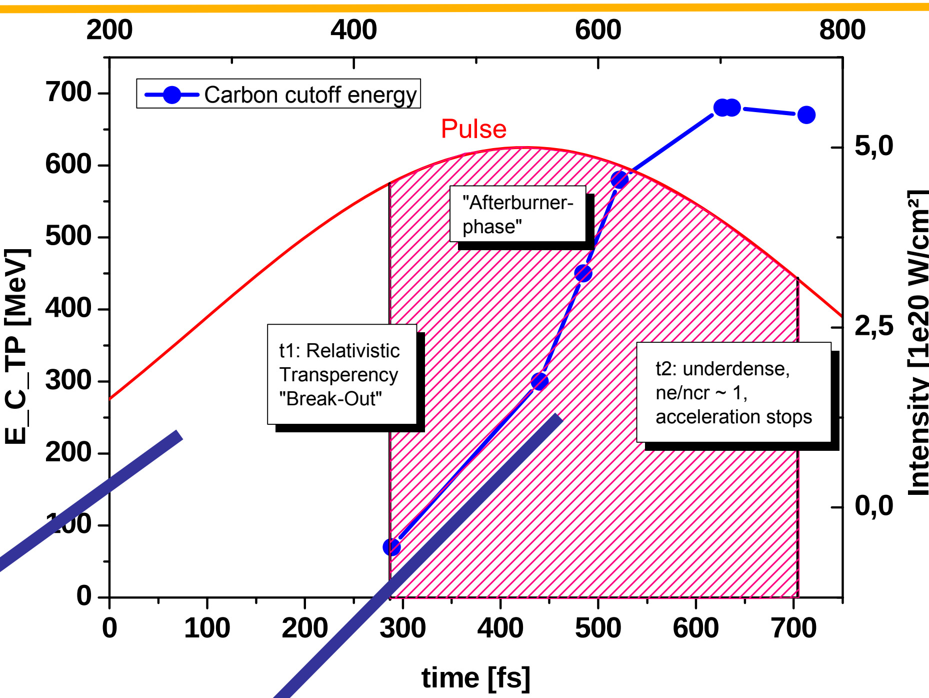

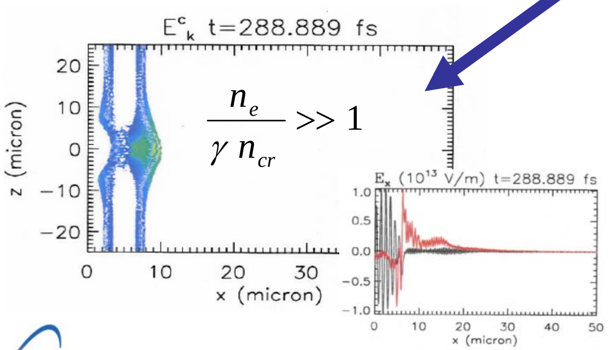

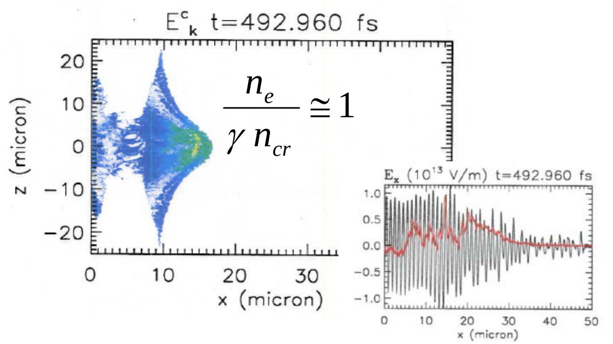

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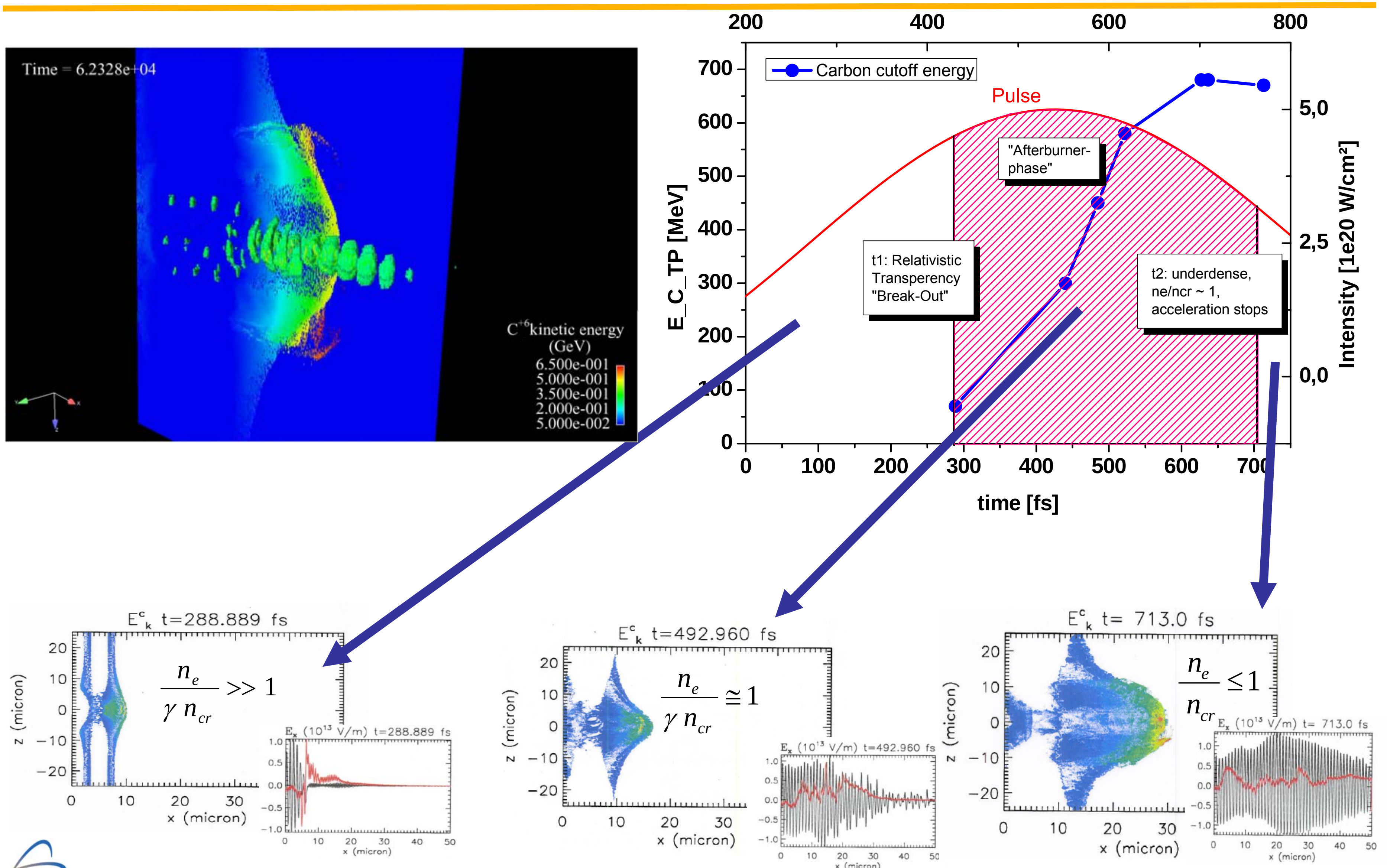

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Theory

- **Analytical model* reproduces existing data**
- **Analytical model showed predictive capability**
- **Allows design of experiments w/o having to rely on massive parallel simulations**

* Yan, Tashima, Hegelich **(Subm. to New Journ. Physics (arXiv:0904.1466)**

Theory:

HYT- model (Subm. to New Journ. Physics (arXiv:0904.1466))

$\mathcal{E}_{sum} = \mathcal{E}_{max,i} + \mathcal{E}_{max,BOA}$

$$\varepsilon_{\max,i}(t_1) = (2\alpha+1)Q\overline{E}_0(t_1)((1+\omega t_1)^{1/2\alpha+1} - 1)$$

$$\overline{E}_0(t_1) = m_e c^2 \int_0^{t_1} (\sqrt{T(t')a^2(t')+1} - 1)\frac{dt'}{t_1}$$

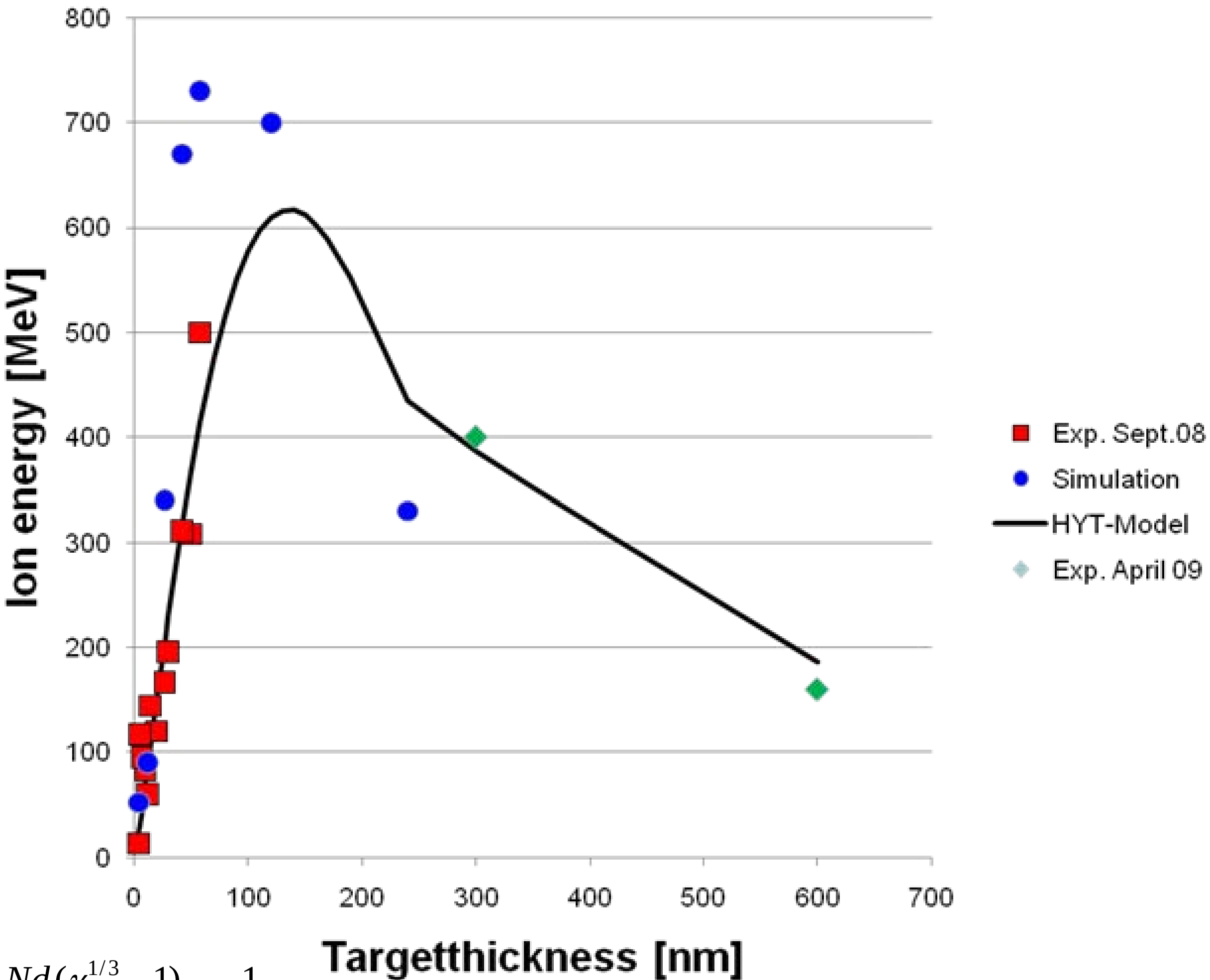
$$\varepsilon_{\max,i,BOA} = (2\alpha+1)Q\overline{E}_0((1+\omega(t_2-t_1))^{1/2\alpha+1} - 1)$$

t_1 : $n_e/\gamma n_{cr} \sim 1$

$$t_1 = \left(\frac{M}{m}\frac{3N^2d^2}{q_i\omega_0^2c^2a_0^3}\right)^{1/4} = \left(\frac{12}{q_i\pi^2}\frac{M}{m}\frac{N^2d^2}{a_0^3}\frac{\tau^2}{c^2}\right)^{1/4}$$

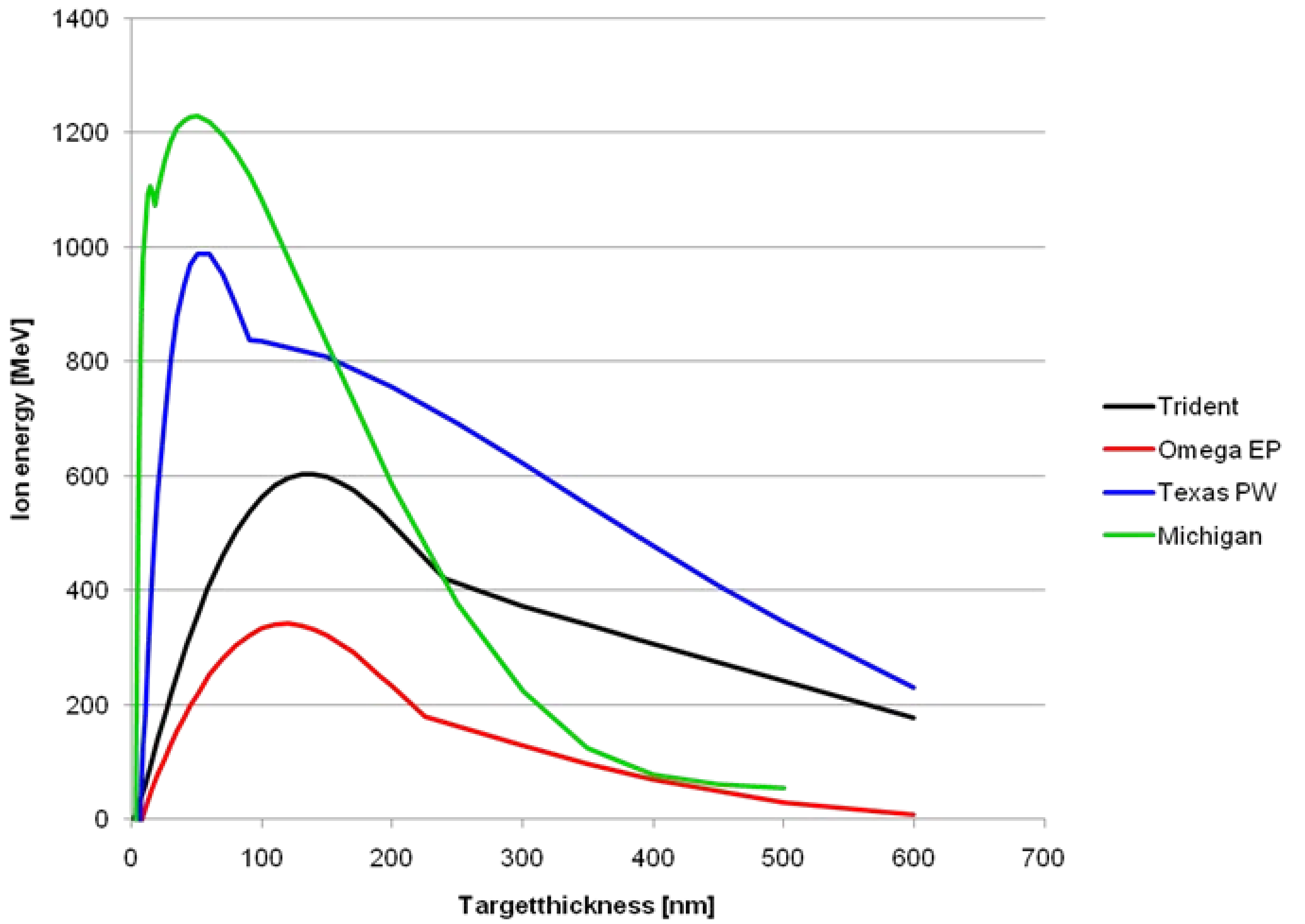
$t_2 = t_1 + \Delta t$: $n_e/n_{cr} \sim 1$

$$\Delta t = \frac{x_2 - x_1}{C_{s,\max}}\frac{1}{\sin(\omega t_1)} = \frac{x_1(\gamma^{1/3}-1)}{C_s}\frac{1}{\sin(\omega t_1)} = \frac{Nd(\gamma^{1/3}-1)}{\gamma C_s}\frac{1}{\sin(\omega t_1)}$$



Outlook

new lasersystems will reach > GeV



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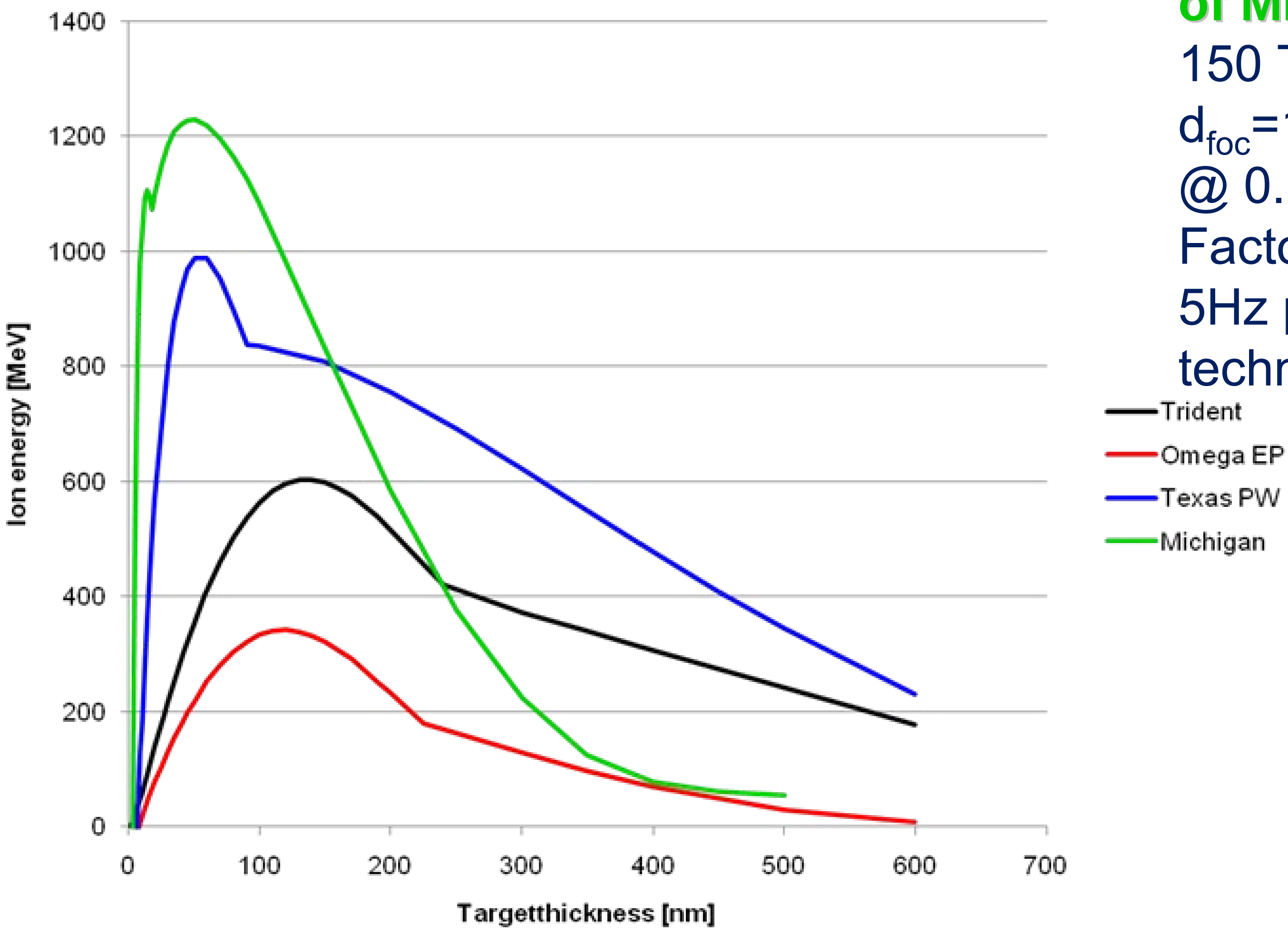

Hercules Laser @ Univ. of Michigan:
150 TW, 30fs, 5J,
d_{foc}=1µm, 1×10^{22}W/cm²,
@ 0.1 Hz
Factor 5 larger system at 5Hz possible with current technology for ~$10M

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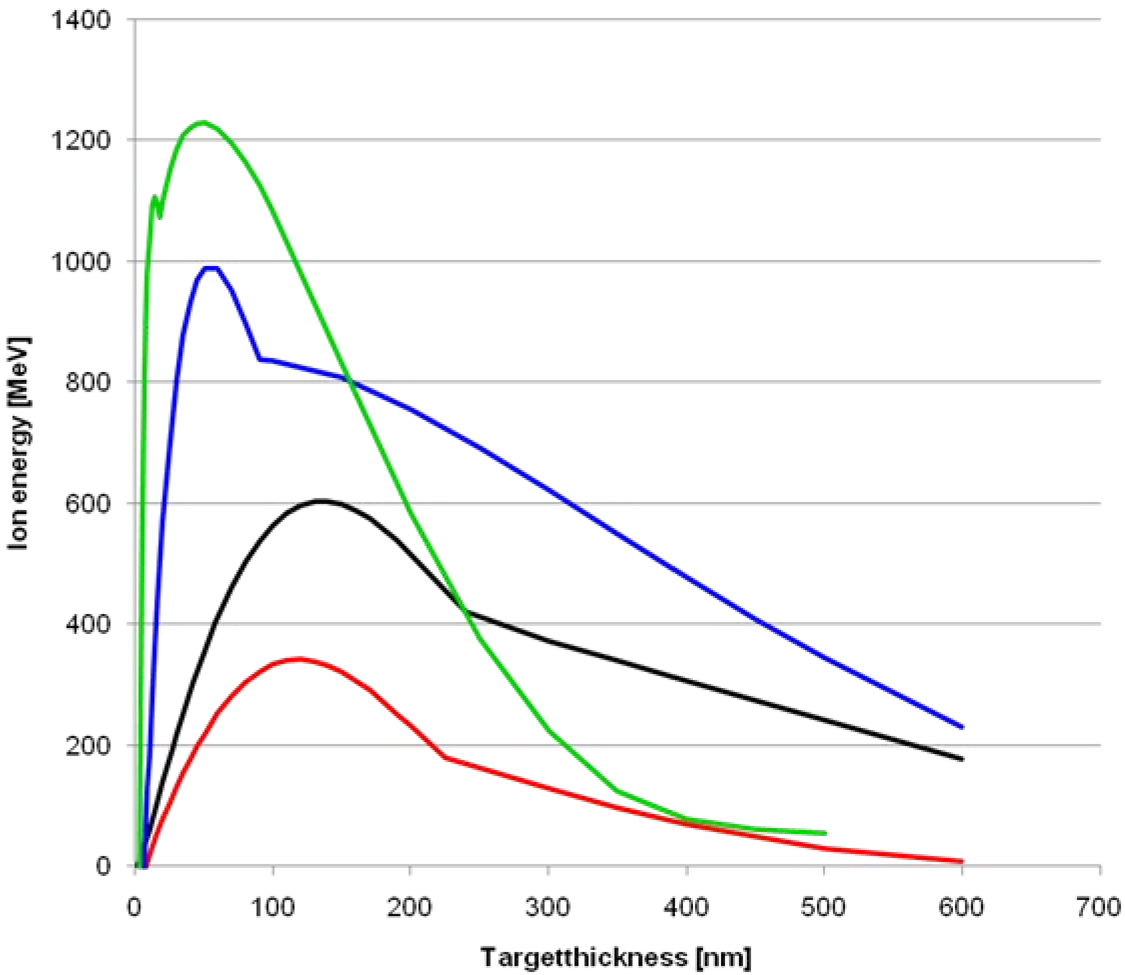

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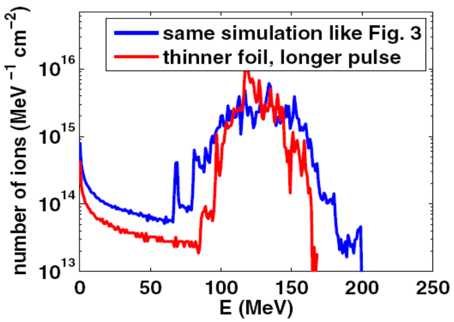
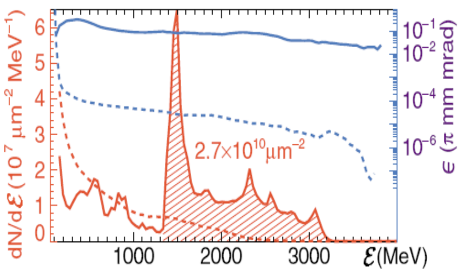
Fast rise time of laser pulse (~15fs) enables lower ΔE/E

- Simulations show more mono-energetic spectra for fast-rise time (square pulses)





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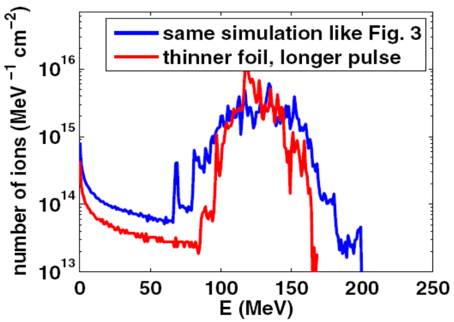

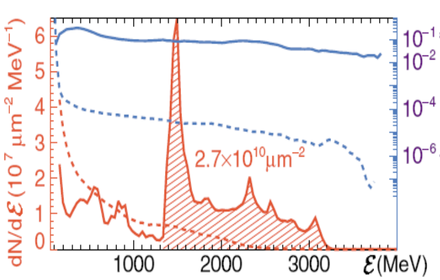

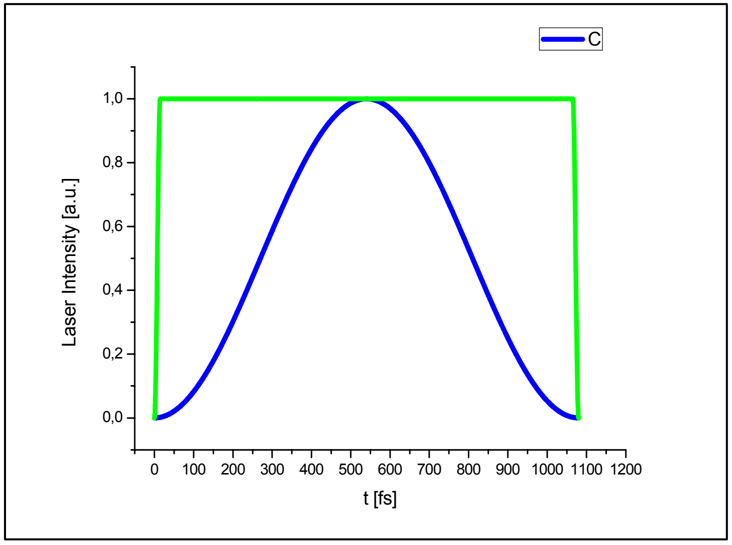

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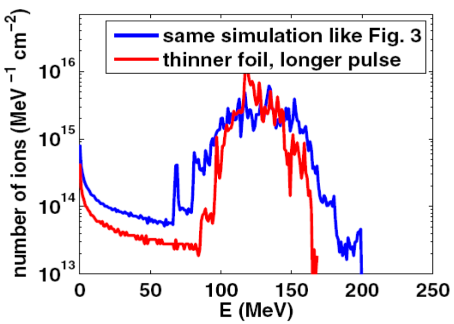

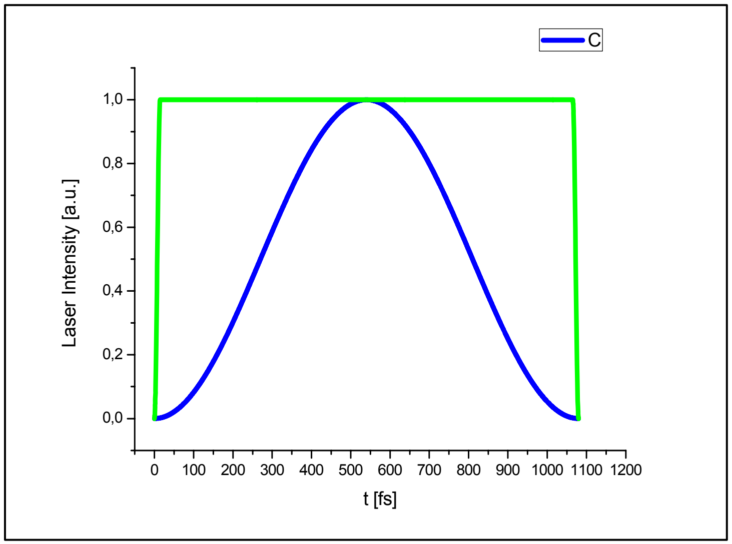

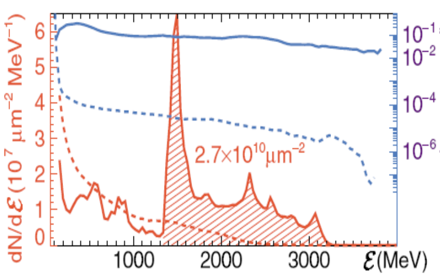

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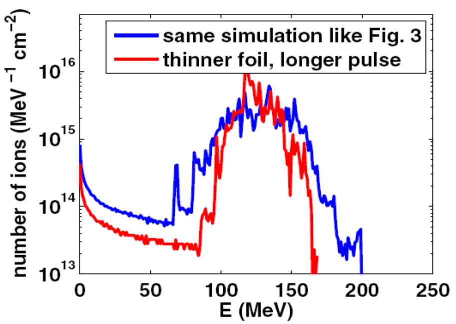

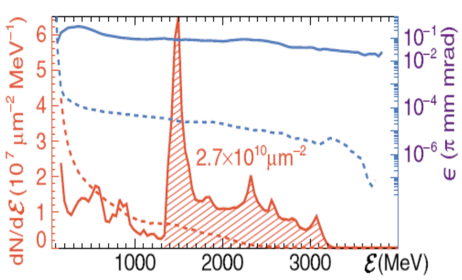

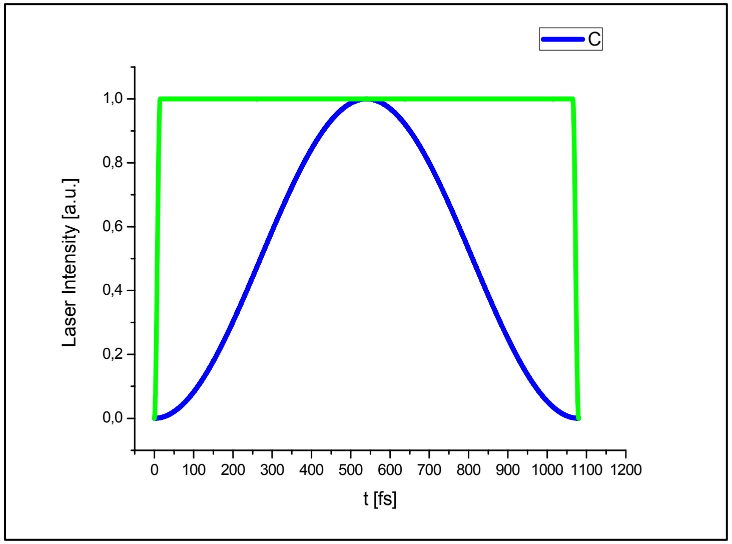

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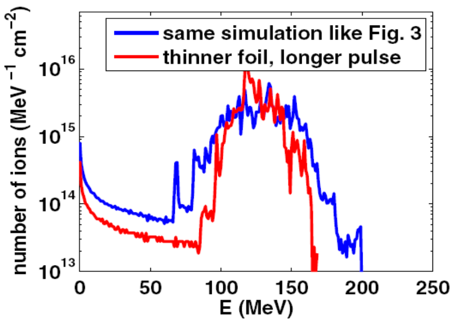

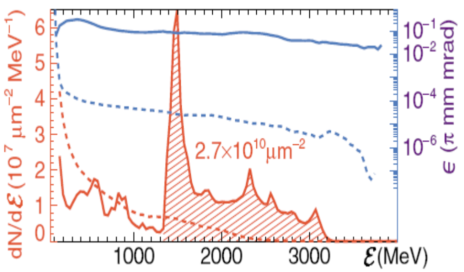

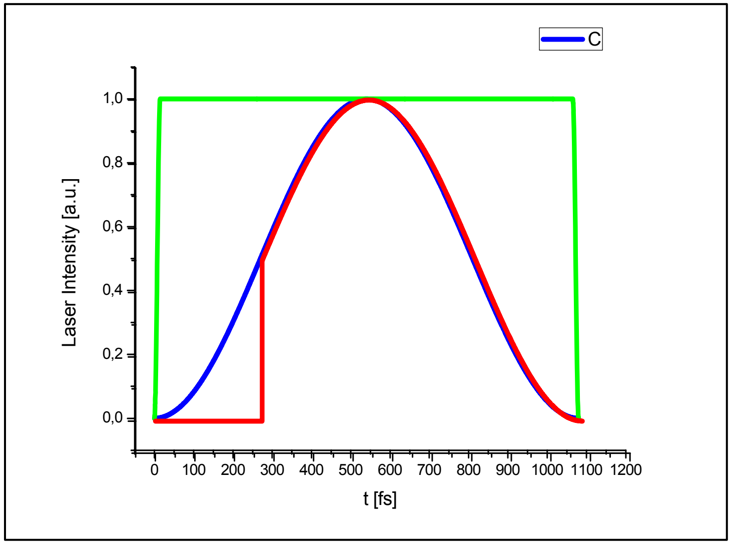

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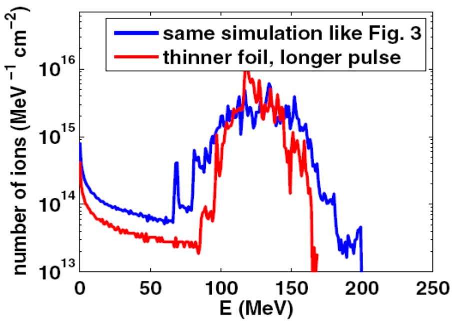
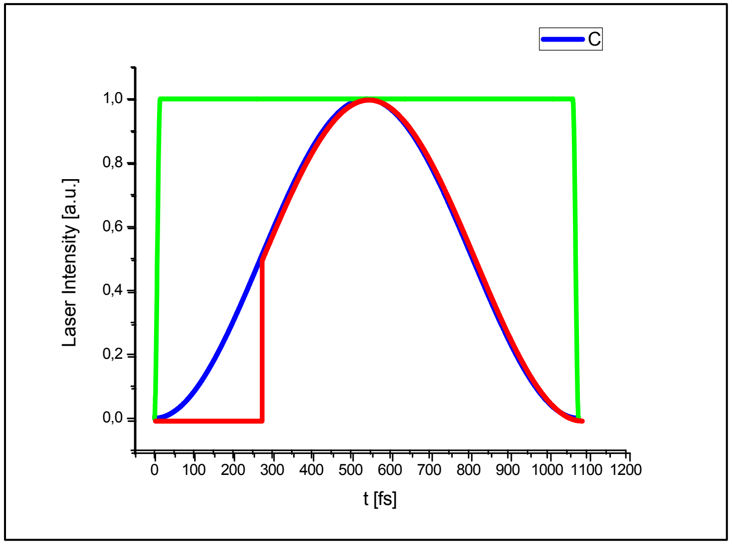
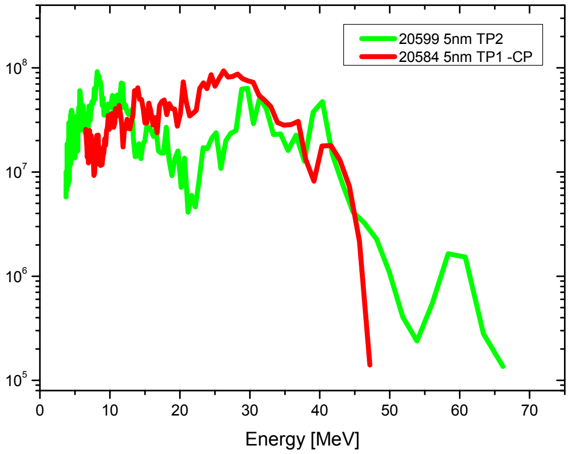
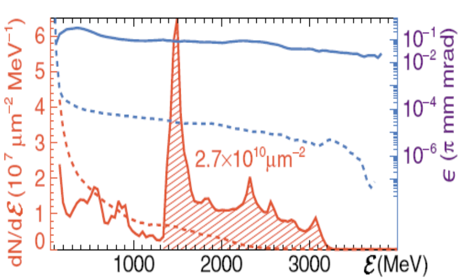




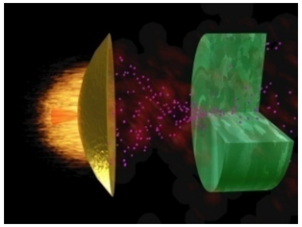


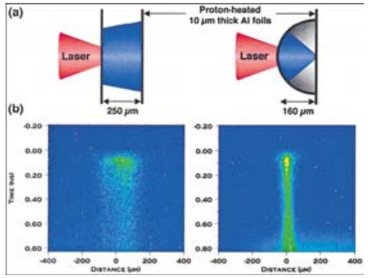


Challenges – Beam Divergence:

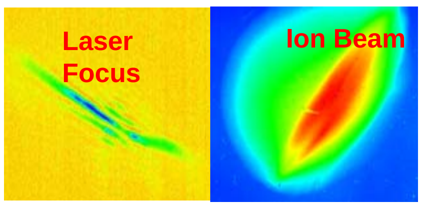
A lot of progress has been made in understanding and control

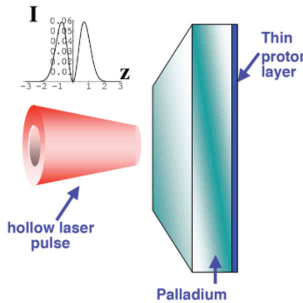
By shaped targets:

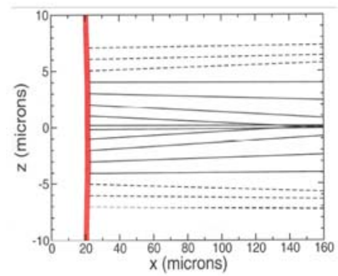




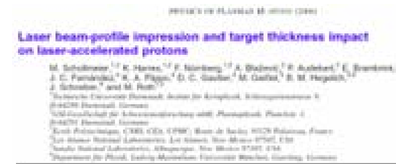
By shaped laser focus:







LANL, Yin, Hegelich et al. (2005)


Laser beam-profile impression and target thickness impact on laser-accelerated protons

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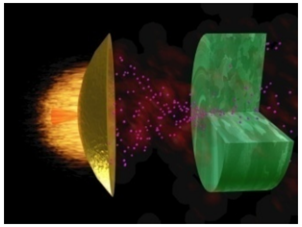

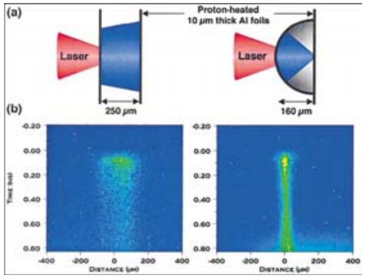

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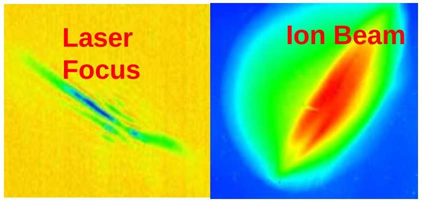

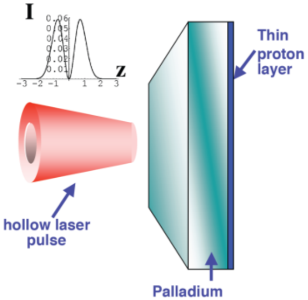

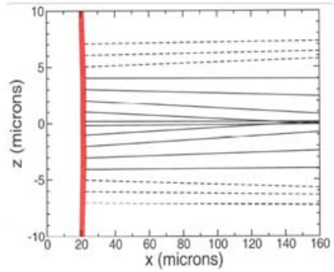

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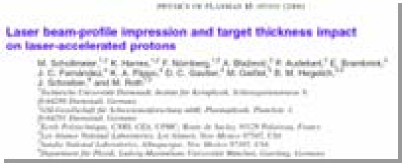
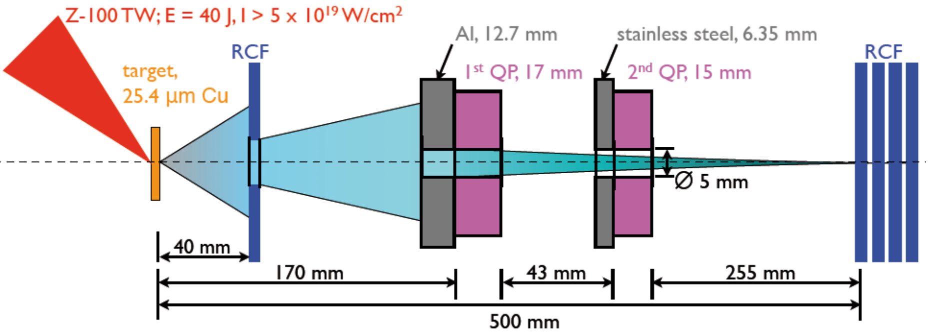
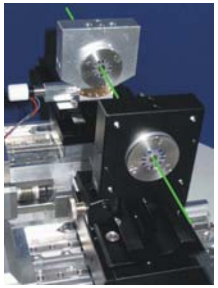
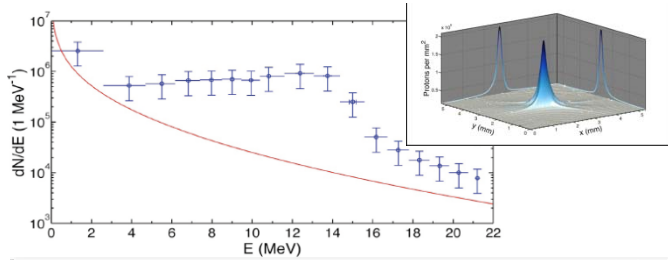

Laser beam-profile impression and target thickness impact on laser-accelerated protons

By magnetic lenses:



T. Eichner *et al.*, Phys. Rev. ST AB 10, (2007)






PRL 101, 055004 (2008) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2008

Controlled Transport and Focusing of Laser-Accelerated Protons with Miniature Magnetic Devices

M. Schollmeier, S. Becker, M. Geißel, K. A. Flippo, A. Blažević, S. A. Gaillard, D. C. Gautier, F. Grüner, K. Harres, M. Kimmel, F. Nürnberg, P. Rambo, U. Schramm, J. Schreiber, J. Schütrumpf, J. Schwarz, N. A. Tahir, B. Atherton, D. Habs, B. M. Hegelich, and M. Roth

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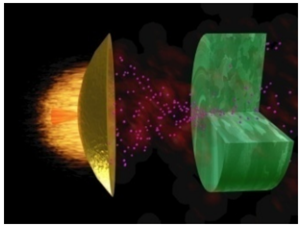
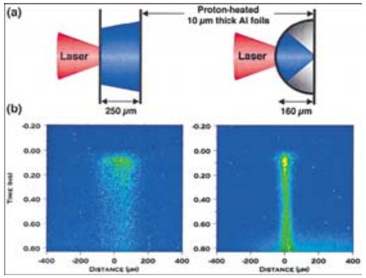
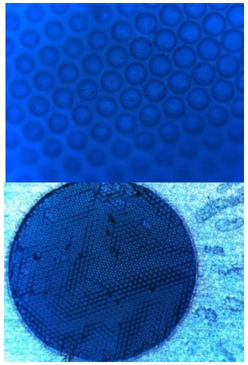


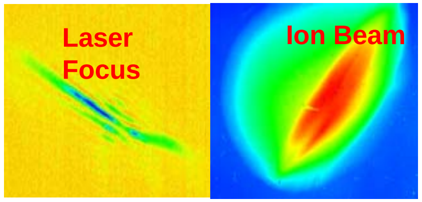


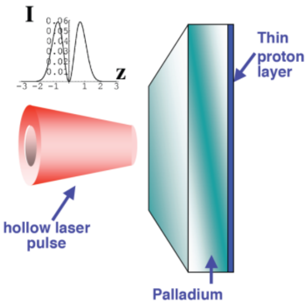


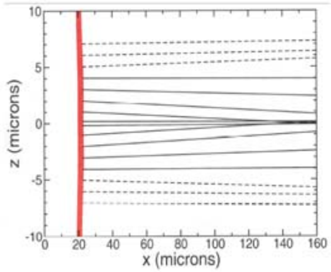
15nm DLC target with micro-hemis:
R=42μm, d=20μm
Mounted over 1mm hole

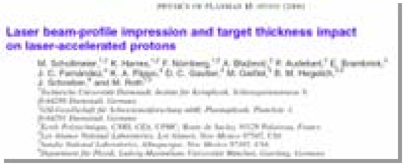
LANL, Yin, Hegelich et al. (2005)

By shaped laser focus:



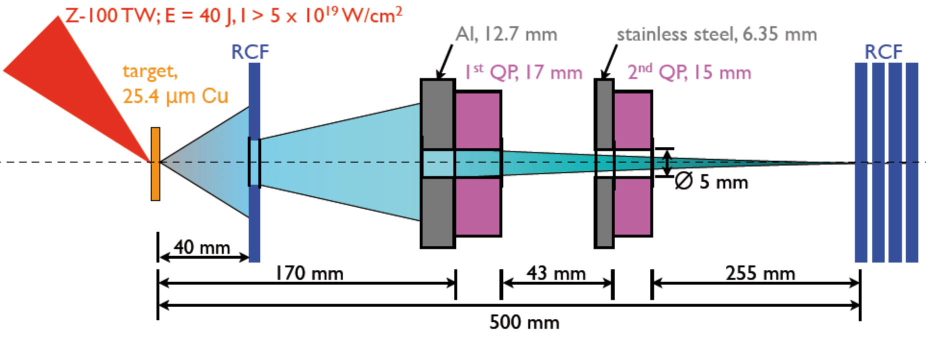




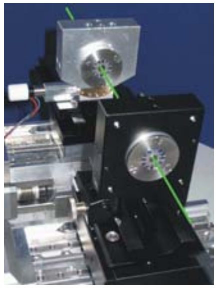


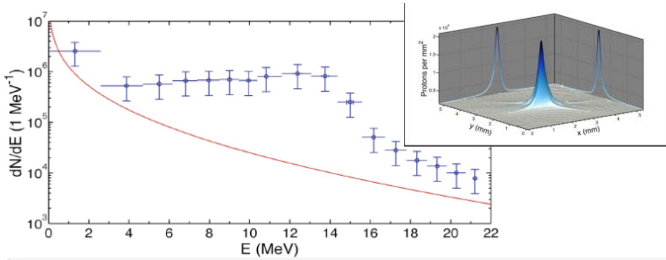
Laser beam-profile impression and target thickness impact on laser-accelerated protons

By magnetic lenses:



T. Eichner *et al.*, Phys. Rev. ST AB 10, (2007)





Controlled Transport and Focusing of Laser-Accelerated Protons with Miniature Magnetic Devices

PHYSICAL REVIEW LETTERS

Los Alamos NATIONAL LABORATORY EST. 1943

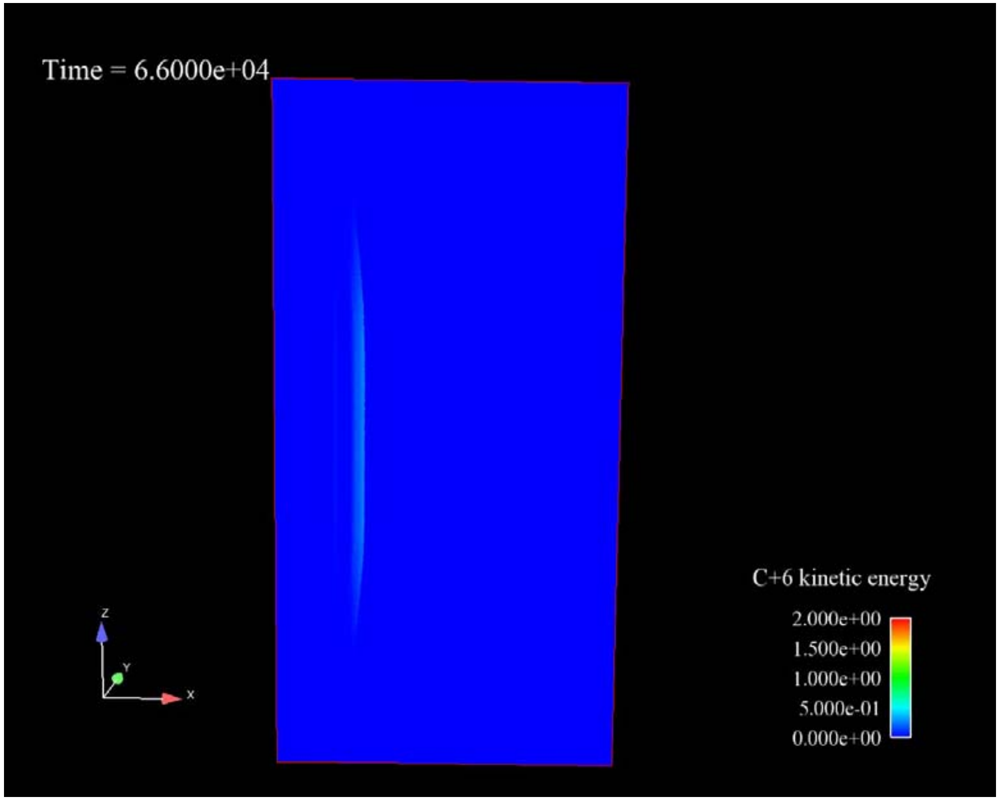
Trident

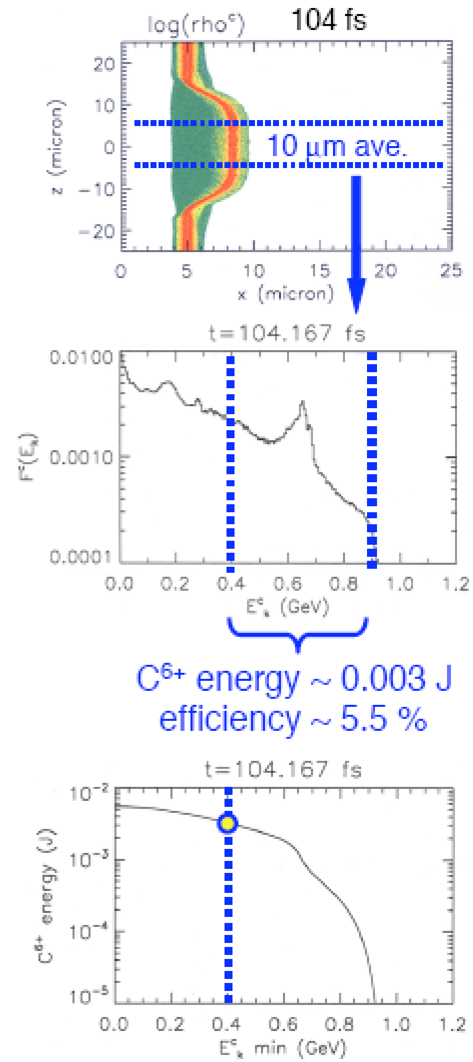
LMU

BOA: Laser Pulse Shaping

enables spectral and directional control and higher conversion efficiency

- I(t) = I0(t)exp[-(r2/2w2)6]
- w =10 microns (spot size larger)
- I0(t) short rise to 10^{21} W/cm²
- ne/ncr = 939





- Collimated C+6 ion beam
- GeV cabon ions
- Quasi-monoenergetic C6+ > 600 MeV
- 10 µm ave: 0.003 J in ions > 400 MeV, conversion efficiency ~ 5.5 %
- 50 µm ave: 0.006 J in ions > 400 MeV, conversion efficiency ~ 11 %

Summary

- Combination of nm-scale targets and ultrahigh contrast pulses leads to a paradigm shift in relativistic laser-matter interaction.
- We have demonstrated the production and integration of nm-scale targets and ultraclean pulses.
- They enable new particle acceleration mechanisms (BOA, RPA).
- First demonstration of BOA with carbon energies up to 0.5 GeV is promising for applications like IFI and hadron therapy:
- IFI energies reached with modest laser, much smaller than a real FI laser
- Experiments at small Ti:Sa laser at MBI also show enhanced acceleration
- Full 3D PIC simulation on Roadrunner are in excellent agreement and allow design of future experiments

Thank you for your attention!

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Theory:

Hegelich-Yan-Tashima model: calculating times t_1 and t_2

t_1 is 1D until $x \sim r_0$:

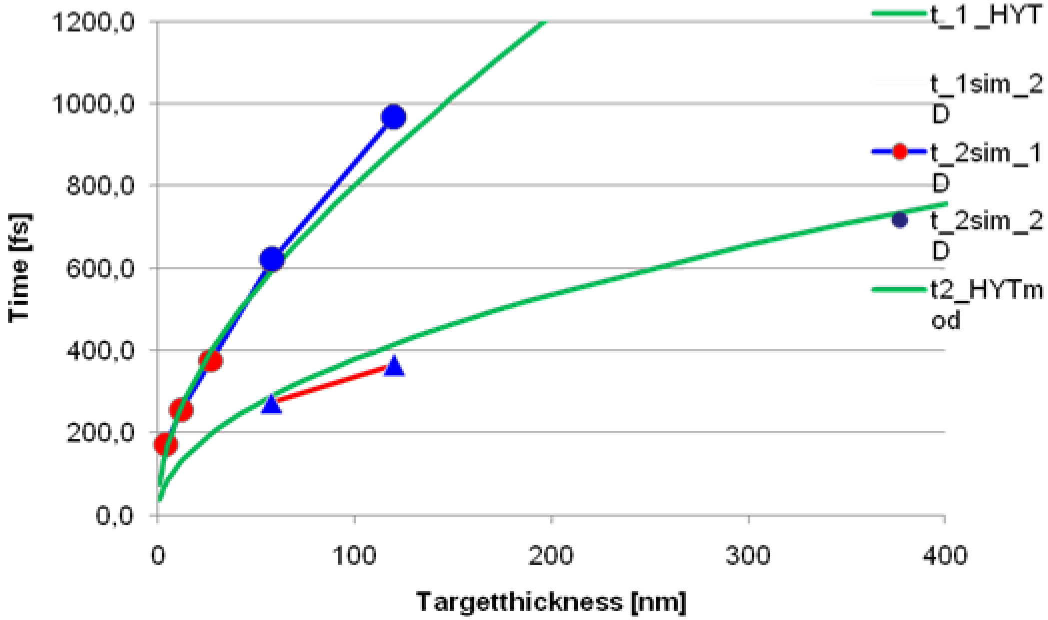
$$\frac{dp}{dt} = \frac{\phi}{r_0} = \frac{\phi_0\sqrt{a_0^2+1}}{r_0}\sin^2(\omega_0 t)$$

$$x\,dx = \frac{q_i\phi_0\sqrt{a_0^2+1}}{M}\left(t - \frac{1}{2\omega_0}\sin(2\omega_0 t)\right)$$

$$x_1^2 - d^2 = \frac{m}{M}\frac{q_i c^2\sqrt{a_0^2+1}}{3}\omega_0^2 t_1^4$$

$$x_1 = Nd/\gamma = Nd/\sqrt{a_0^2+1},\ x_1 >> d$$

$$t_1 = \left(\frac{M}{m}\frac{3N^2d^2}{q_i\omega_0^2c^2a_0^3}\right)^{1/4} = \left(\frac{12}{q_i\pi^2}\frac{M}{m}\frac{N^2d^2}{a_0^3}\frac{\tau^2}{c^2}\right)^{1/4}$$



$t_2 = t_1 + \Delta t$: 3D sphere isotropic expansion:

$$dt = \frac{dx}{C_s(t)} = \frac{dx}{C_{s,\max}\sin(\omega t)}$$

$$\Delta t = \frac{x_2 - x_1}{C_{s,\max}}\frac{1}{\sin(\omega t_1)} = \frac{x_1(\gamma^{1/3}-1)}{C_s}\frac{1}{\sin(\omega t_1)} = \frac{Nd(\gamma^{1/3}-1)}{\gamma C_s}\frac{1}{\sin(\omega t_1)}$$

Theory:

HYT-model: calculating the maximum energy

$$\mathrm{E}_{\max} = \left(2\alpha(t_1)+1\right)\phi_{e-}(t_1)\left(\left(1+\omega t_1\right)^{1/2\alpha(t_1)+1}-1\right)$$
$$+\left(2\alpha(t_1)+1\right)\phi_{Pt}(t_1)\left(\left(1+\omega t_1\right)^{1/2\alpha(t_1)+1}-1\right)$$
$$+\left(2\alpha(t_2)+1\right)\phi_{BOA}(t_{2-1})\left(\left(1+\omega t_{2-1}\right)^{1/2\alpha(t_{2-1})+1}-1\right)$$

$$\phi_{e-} = m_e c^2 \sqrt{(1-T(t_1))\sqrt{2}\langle a(t_1)\rangle + 1}$$

$$\phi_{Pt} = m_e c^2 \sqrt{(T(t_1))\, a(t_1)^2 + 1}$$

$$\phi_{BOA} = m_e c^2 \sqrt{(1-T(t_2))\langle a(t_2-t_1)\rangle^2 + 1}$$

t_{e-} = t_1 until relativistic transperency
t_{Pt-} = t_1 until relativistic transperency
t_{BOA} = t_2-t_1

$$a_0^2 = \frac{I_0 \lambda^2}{1.37\times 10^{18}}$$

$$\sigma = \frac{n_e}{n_{cr}}\frac{d}{\lambda}$$

$$T = \frac{1}{1+\pi^2 \dfrac{\sigma^2}{a(t)^2}}$$