2025 Introduction to Plasma and Fusion Course

Laser-Driven Particle Acceleration & Advanced Light Sources

Franklin Dollar

UCI University of California, Irvine

About Me

Dry Creek Rancheria Band of Pomo Indians
Sonoma County, California

Cal

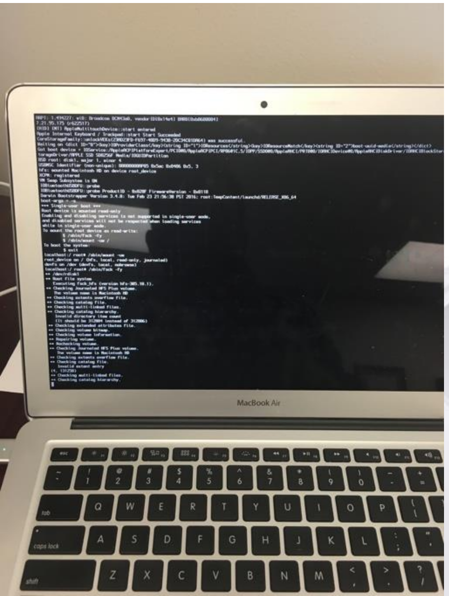
MICHIGAN

JILA
NIST CU

UC

UCI University of California, Irvine

Computers



Computers

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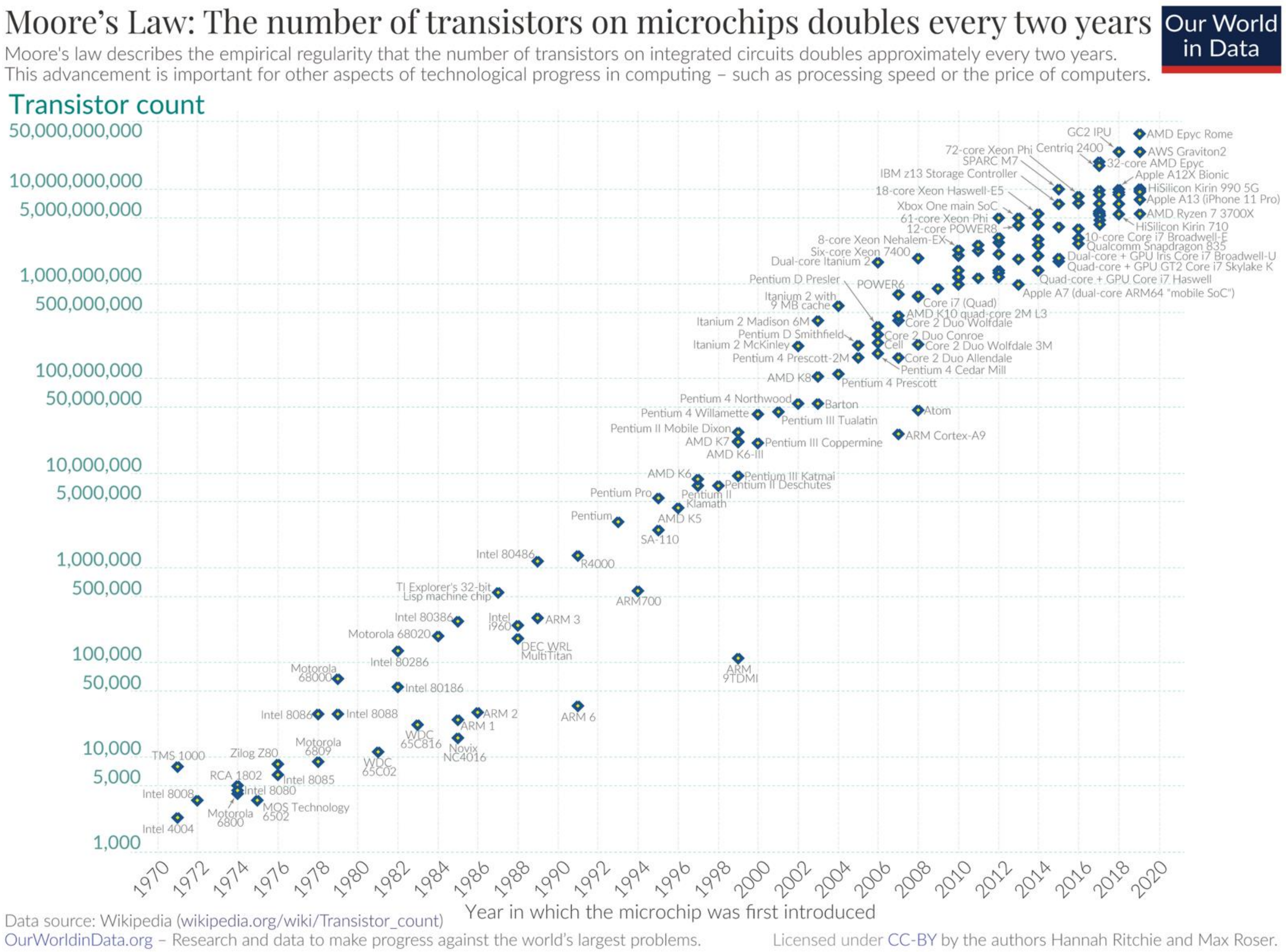
https://en.wikipedia.org/wiki/Computer_(occupation)

Moore’s Law



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https://en.wikipedia.org/wiki/Moore%27s_law

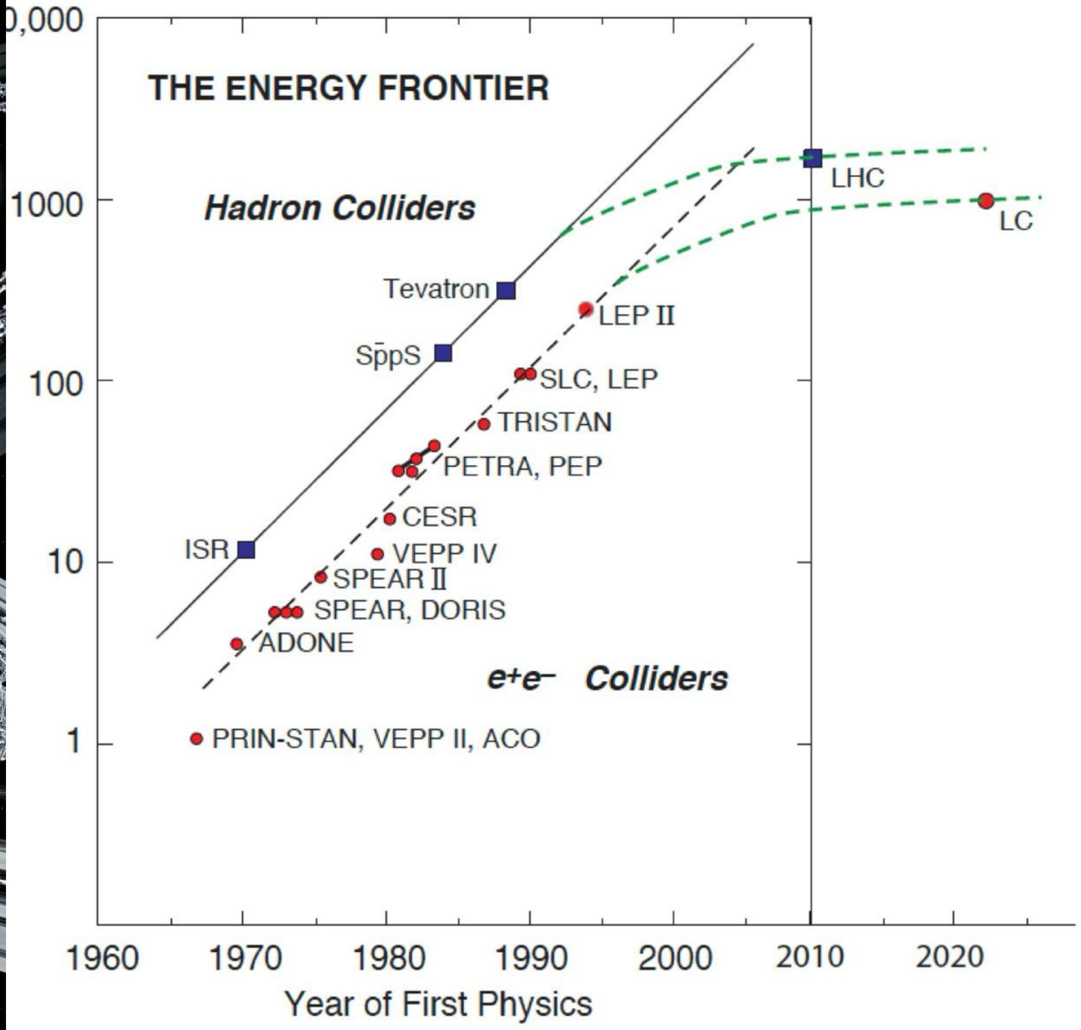
Gordon E. Moore, Cramming more components onto integrated circuits. (1965)

“However, the inexorable progress towards smaller chips may be nearing its limit. Physicists reckon that below 0.1 micron - a size which would be reached around 2005 - significant problems could arise from the unusual phenomena known as "quantum effects", in which individual electrons can tunnel through solid barriers.”

C. Arthur, The Independent, 1996

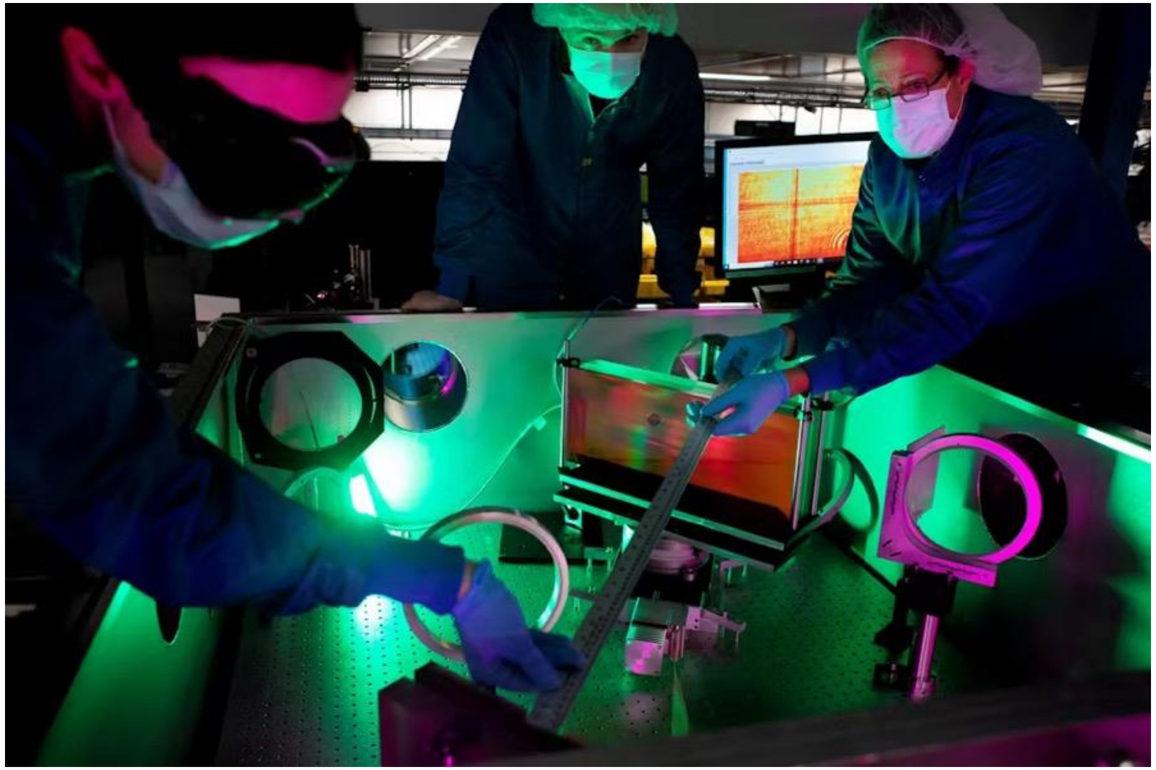
"The technology has a habit of moving immovable barriers. Somehow, we always get past these problems."

C. Hoggar, Texas Instruments

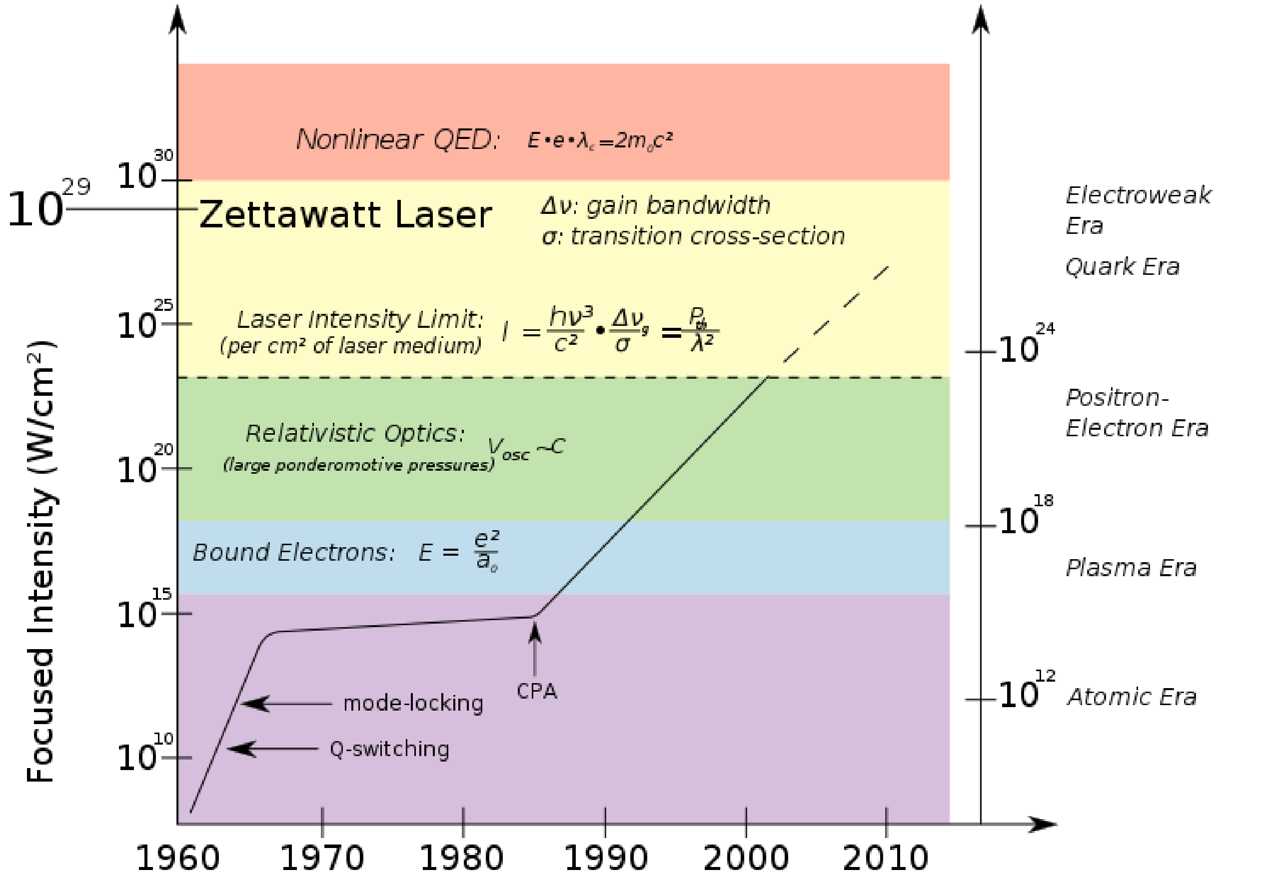


2010). Current and Future Developments in Accelerator Facilities.

Dawn of the laser empire



CPA enables relativistic intensities



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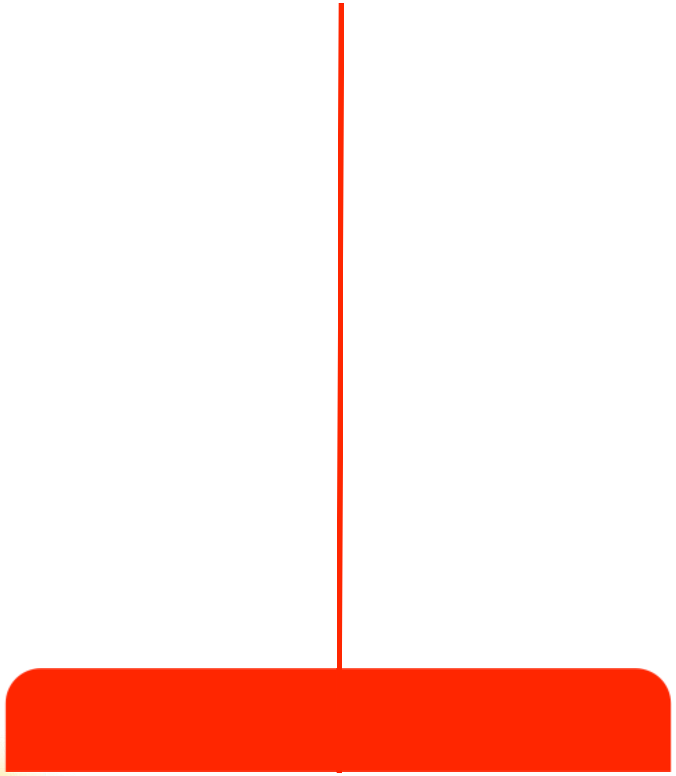
G. Mourou, et al., Mod. Phys. 78, 309 (2006)

Ultrafast Lasers



1 TW focused to 10 um

> 3 teraVolts per meter

electron quiver velocity of 10^8 ms^{-1}

1 mJ in 1 second = 1 milliwatt
1 mJ in 1 femtosecond = 1 terawatt

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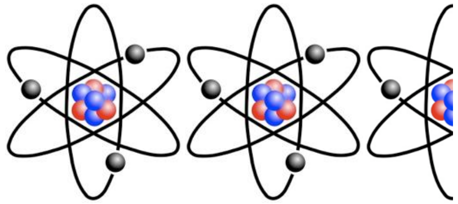
Ultrafast

Short pulse lasers have pulse durations of >100 femtoseconds

1 femtosecond is one millionth of a billionth of a second (10^{-15} s)

Space shuttle max speed = 17,500 mph

Travels 8 angstroms in 100 fs



2.5x size of Carbon atom

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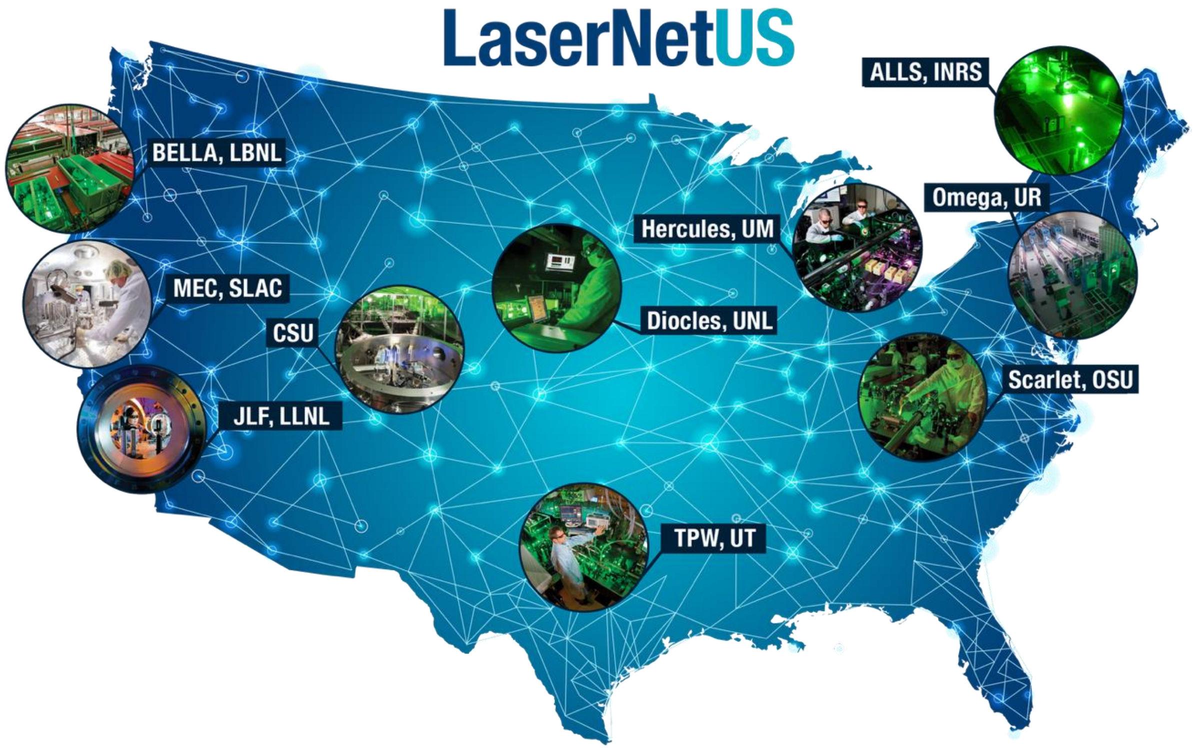
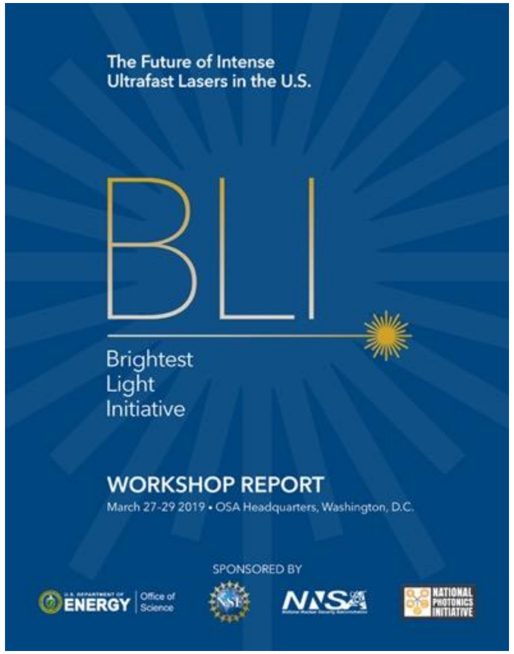
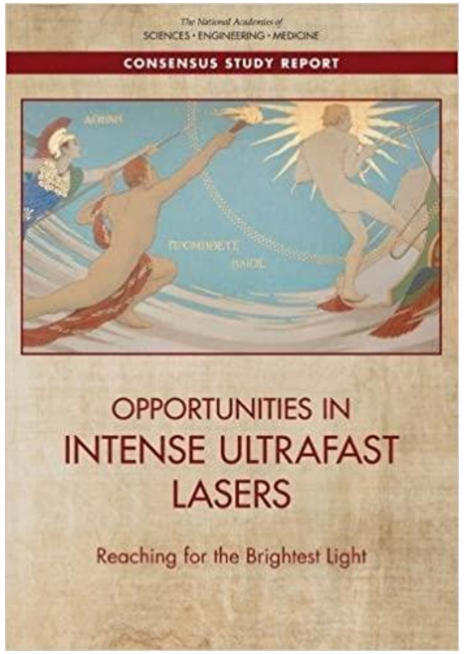
Laser Power

- 1 Terawatt = a trillion Watts
- United States power capacity ~1 teraw

Laser Revolution







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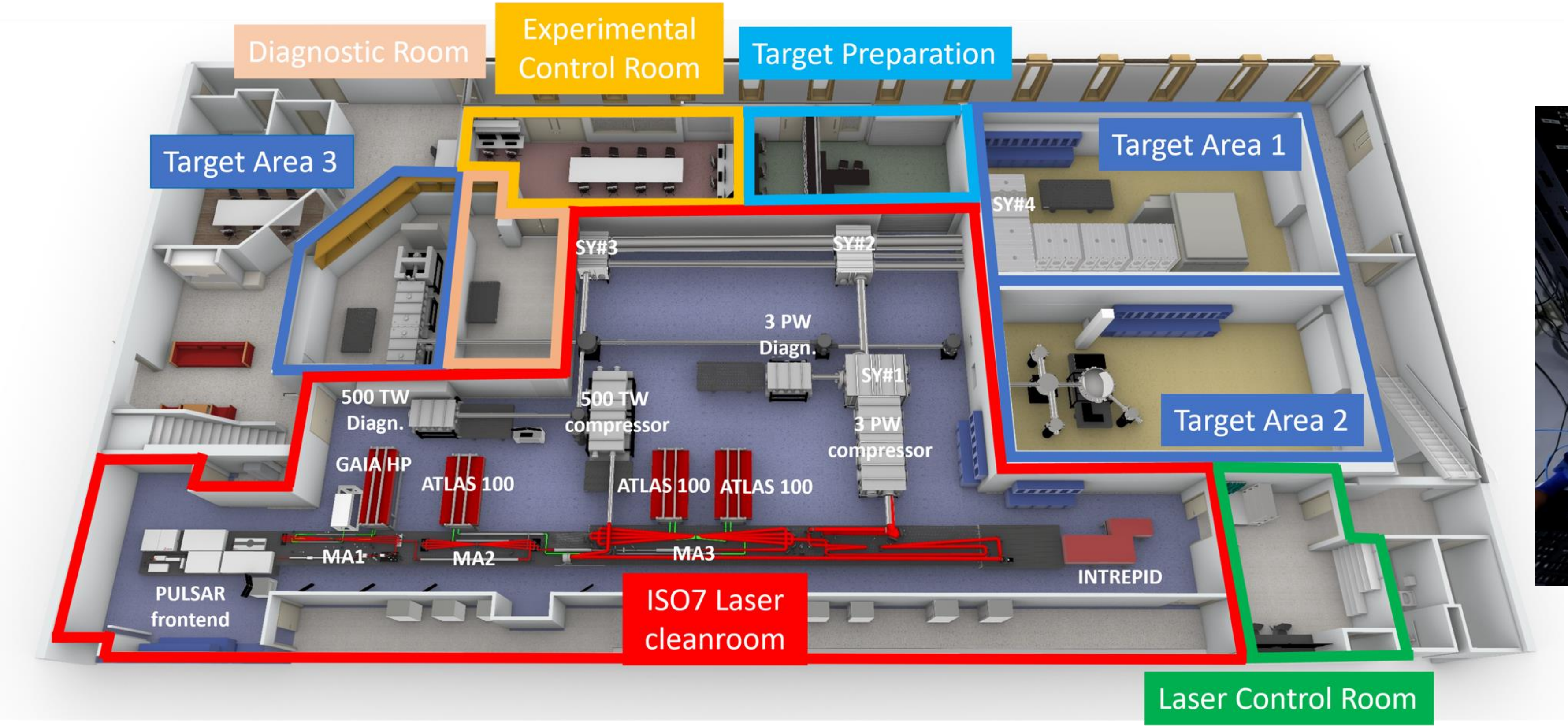
Petawatt Powers



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Light and plasma

- The index of refraction for light is given by

$$n(\omega) = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

$$\omega_p = \sqrt{\frac{n_e e_c^2}{\epsilon_0 m_e}}$$

$$n_{crit} = \frac{\epsilon_0 m_e}{e_c^2} \omega^2$$

Underdense interactions

Laser Wakefield Acceleration

V. Flores

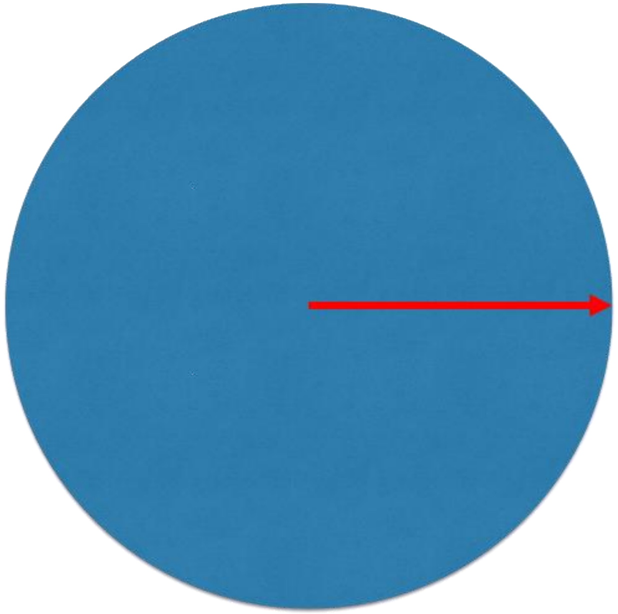
University of California, Irvine

$$F_{Pond} = -\frac{e_c^2}{4m_e\omega_0^2}\nabla|E_0|^2$$

Laser Wakefield Acceleration

Bubble size

$$\Delta v = \frac{L_d}{c} = \frac{\lambda_p}{2}$$

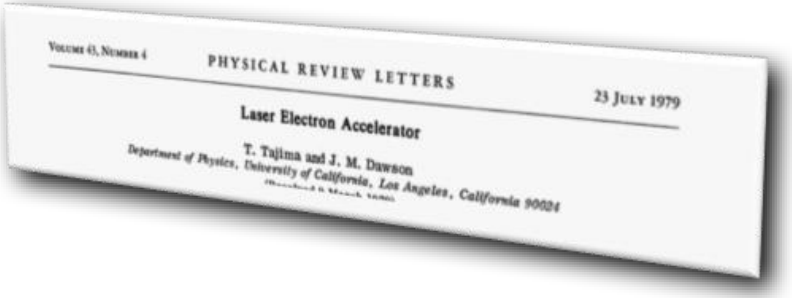


Implications

- Short duration
- Wavebreaking
- Dephasing

Laser Wakefield Progress

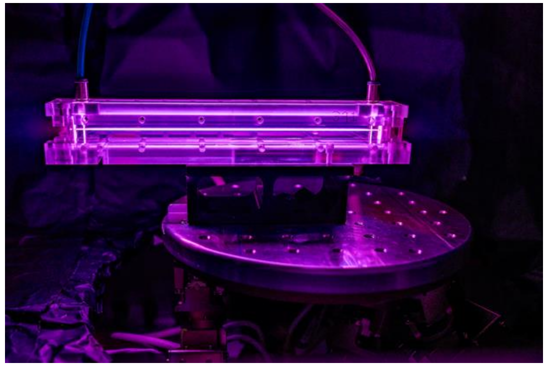
- First described by simulations!
  - 1979 Tajima & Dawson
  - Predicted 100 GeV/meter
- Proof of principle experiments in 90s
- First "monoenergetic beams" in 2000s
- Current petawatt lasers can exceed 10 GeV


Volume 43, Number 4 PHYSICAL REVIEW LETTERS 23 July 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024


BELLA

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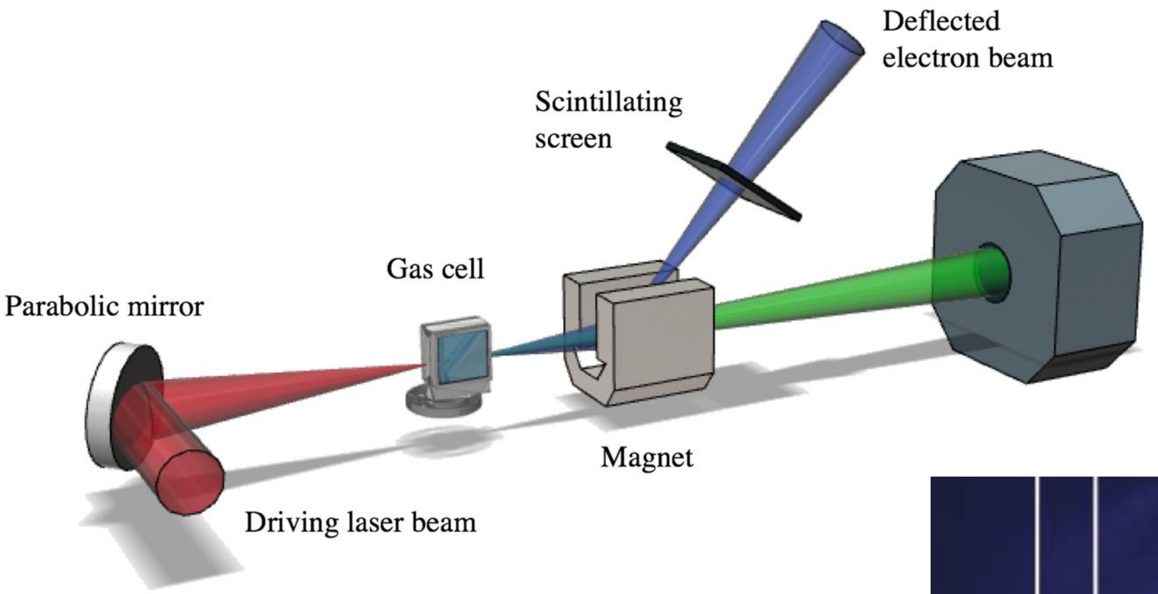
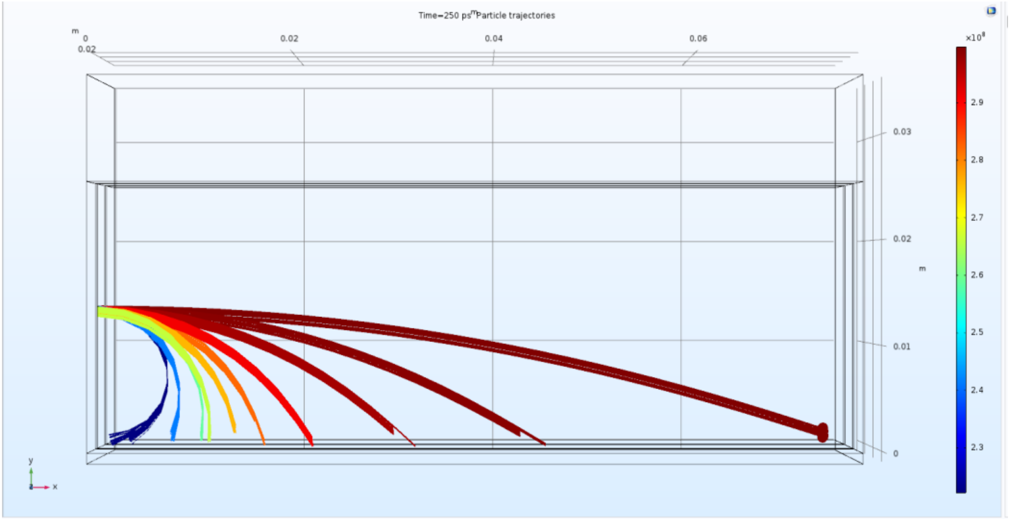
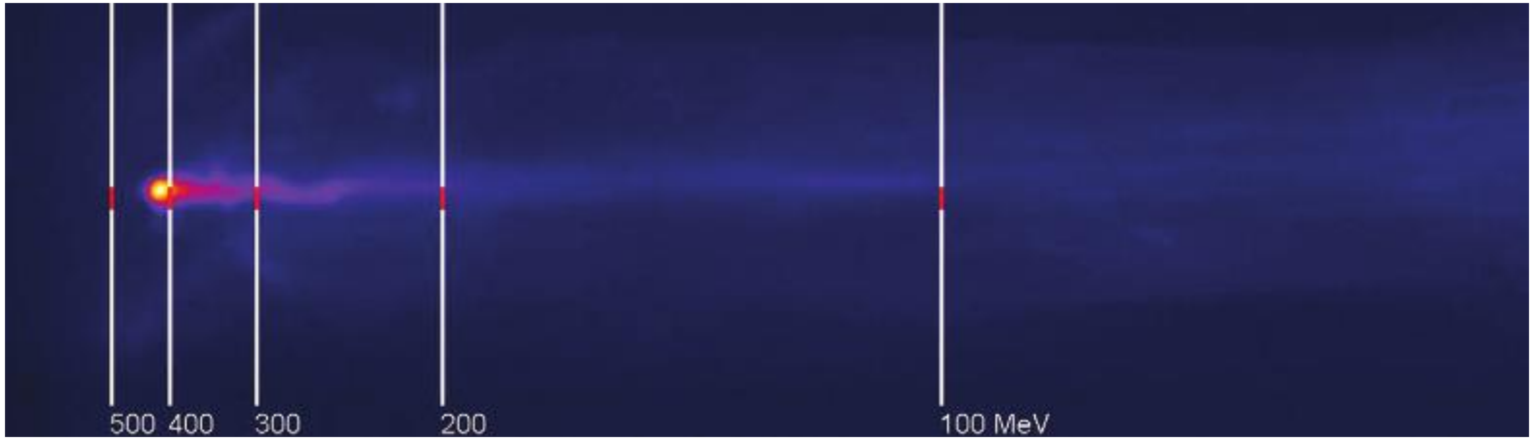
Laser Wakefield Acceleration

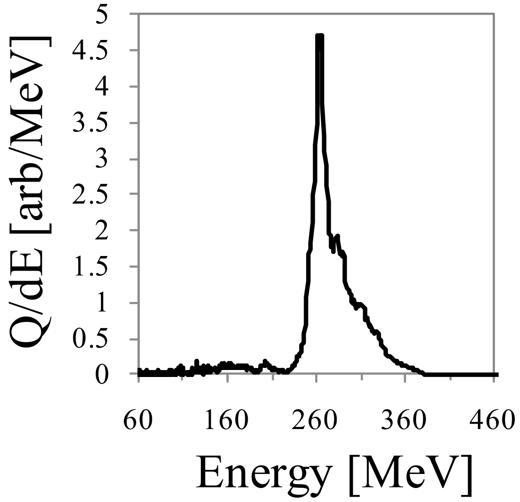


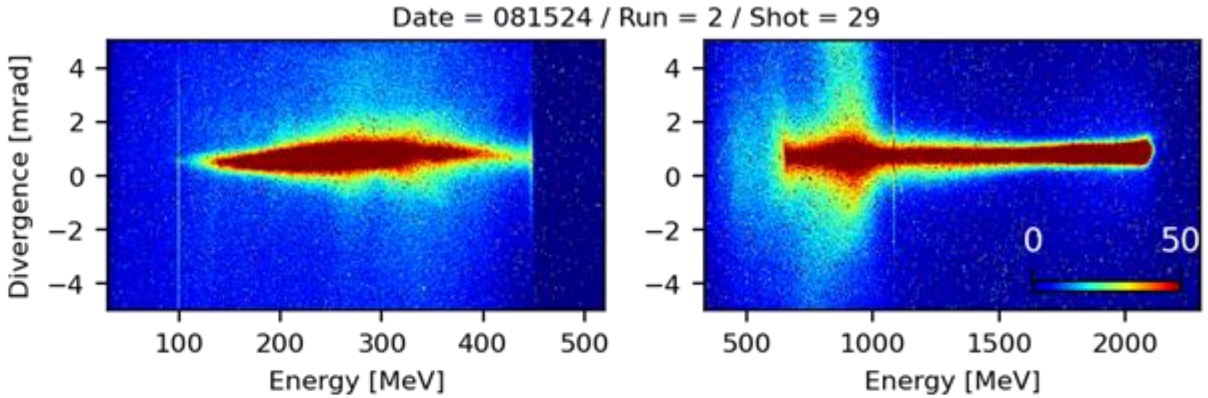


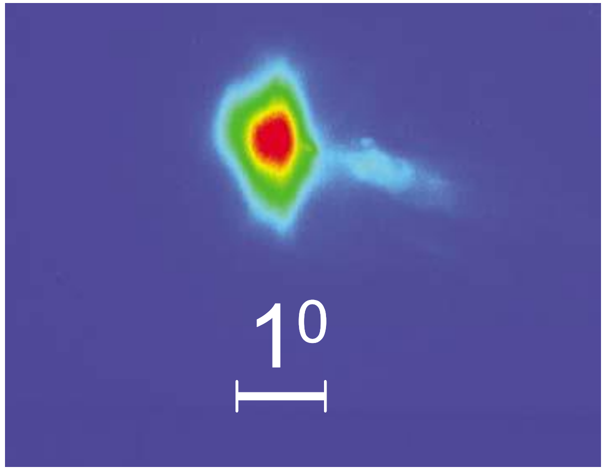


Electron Properties

- 1% Energy spread
- <15 fs bunch duration
- <10 mrad divergence
- >0.5 π mm mrad transverse emittance
- ~nanocoulomb charge







[C. McGuffey, et al., Phys Plasm. 2012, C McGuffey, et al., Phys. Plasm. 2018]

Making X-rays

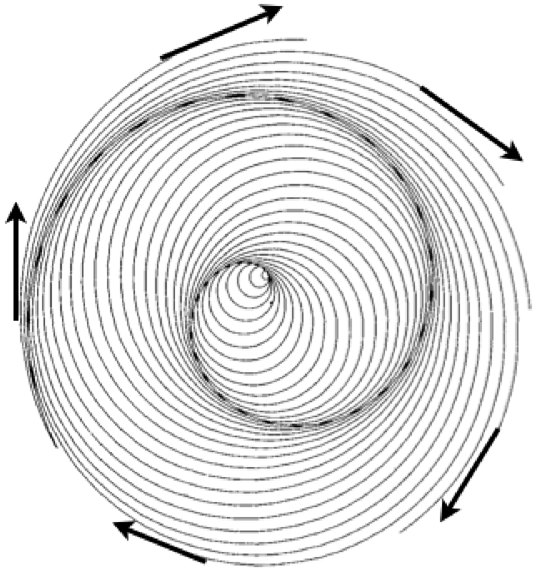
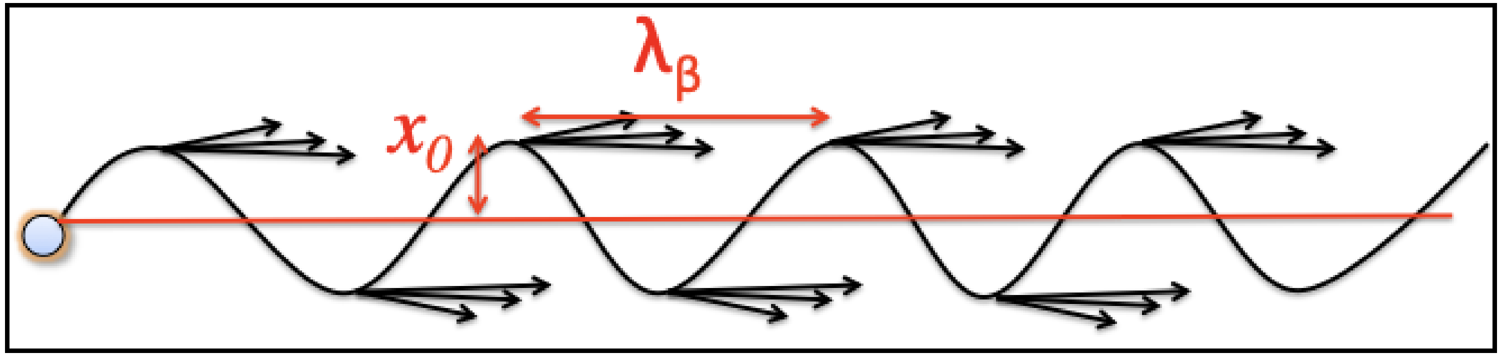


FIG. 6. Electric field lines for a charge moving at tangential speed $\beta = 0.95$ on a circular path centered on the ×.

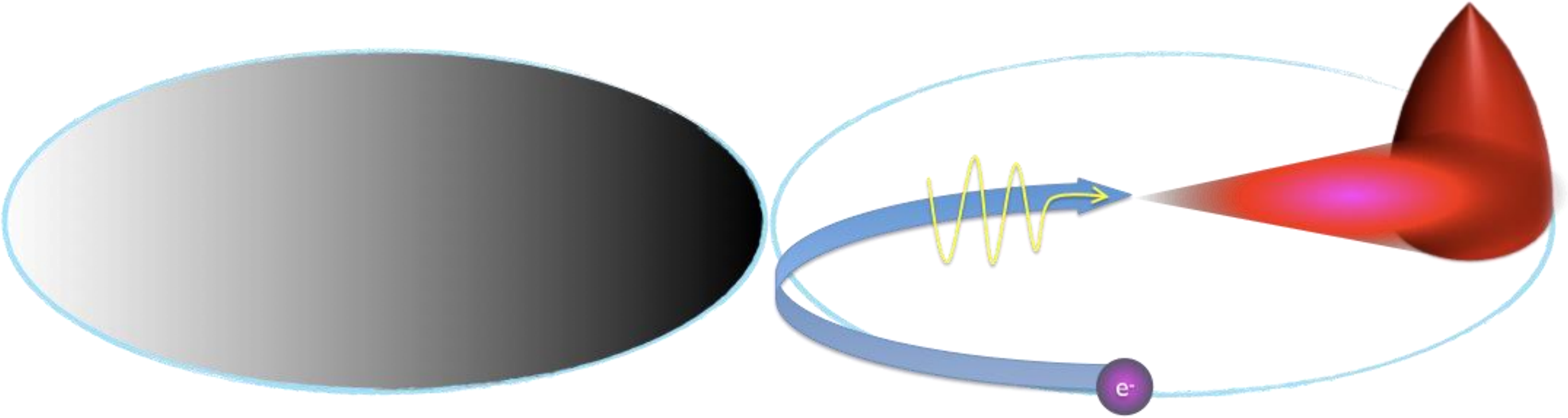
R Tsien Am. J. Phys., (1972)

$$\lambda = {\lambda_u}/{2\gamma^2}$$

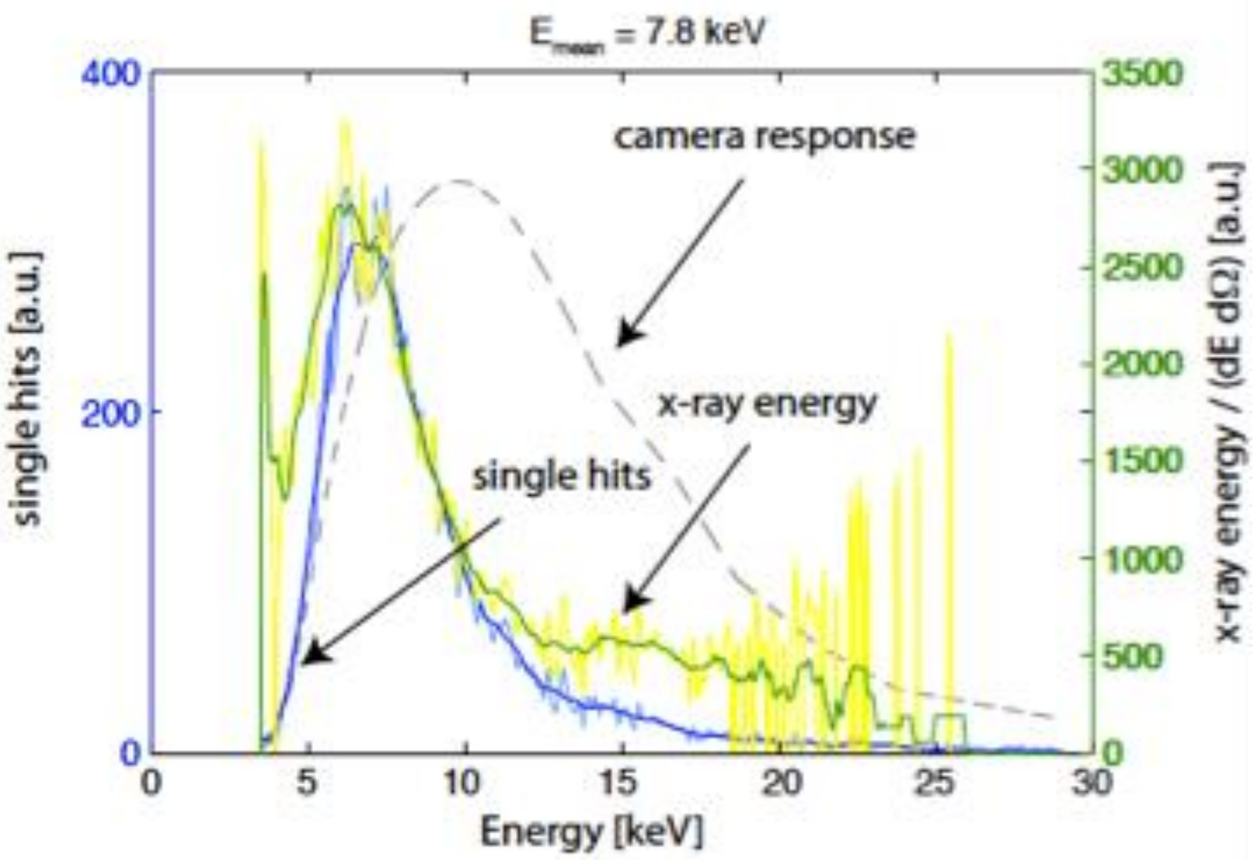


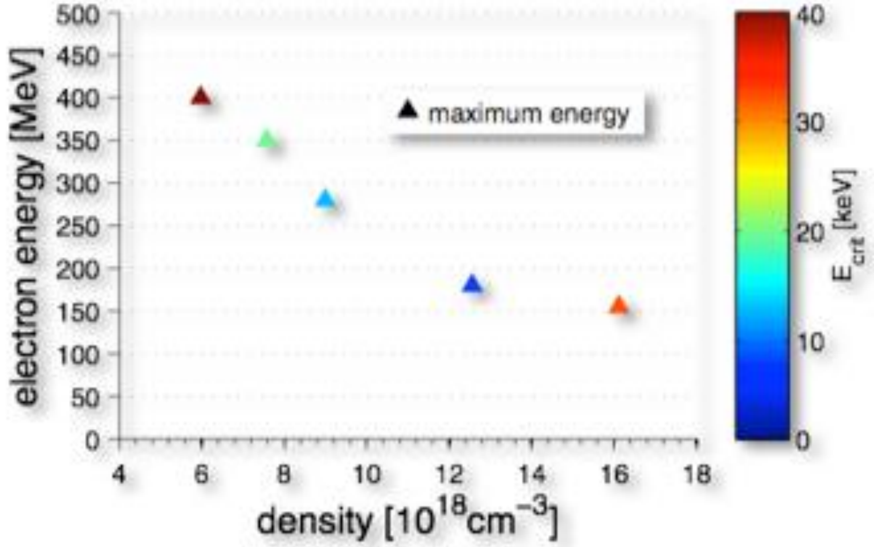
Wikipedia

Plasma Undulators



Betatron Spectrum





- E_{crit} tunable from 5 - 40 KeV
- average electron and x-ray data for many shots

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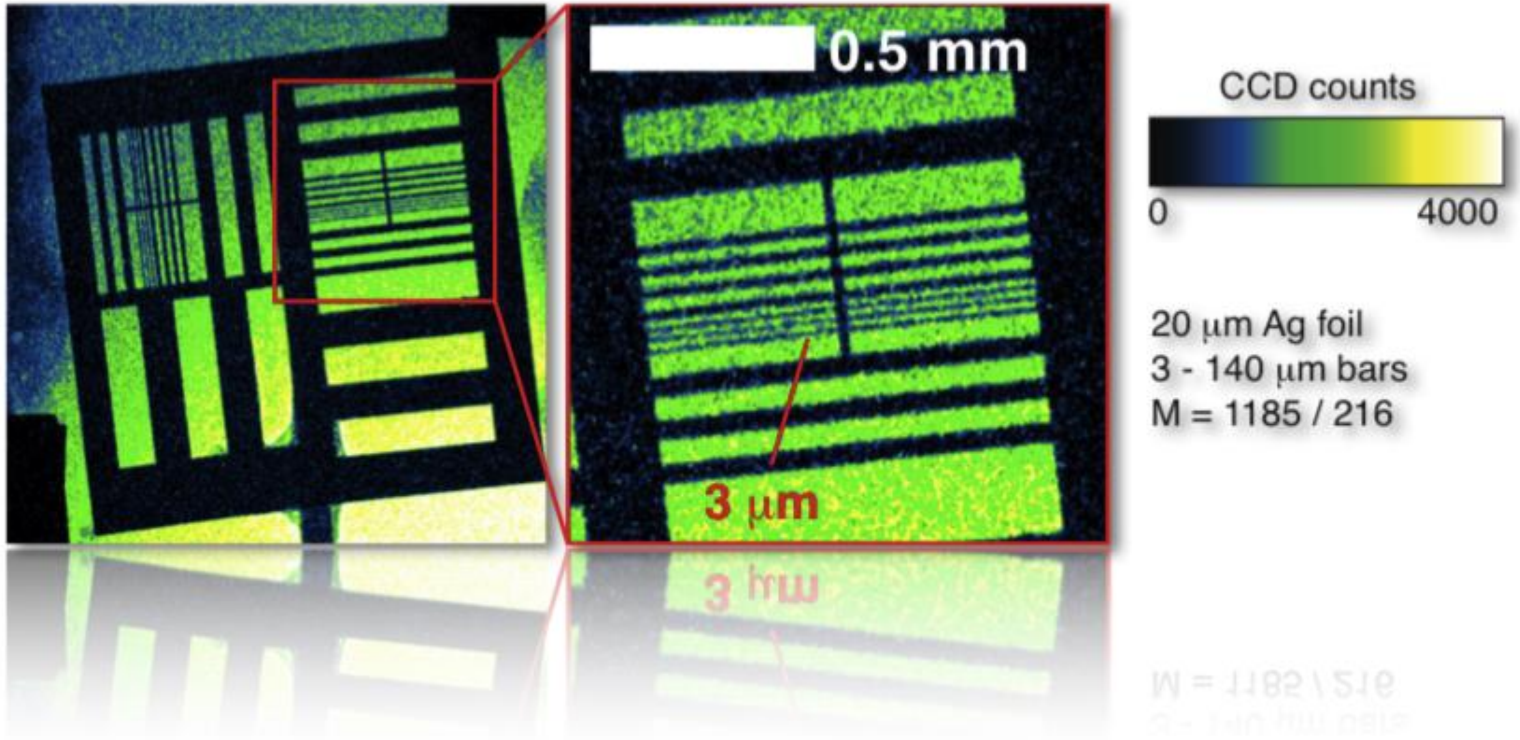
[S. Kneip, et al., Nat. Phys. 2010, S. Kneip, et al., App. Phys. Lett. 2011 , C McGuffey, et al., Phys. Plasm. 2018]

X-ray Properties



- x-ray radiographs
- single shot on CCD
- x-rays resolve 3-5 µm objects
- x-ray source size ~ µm

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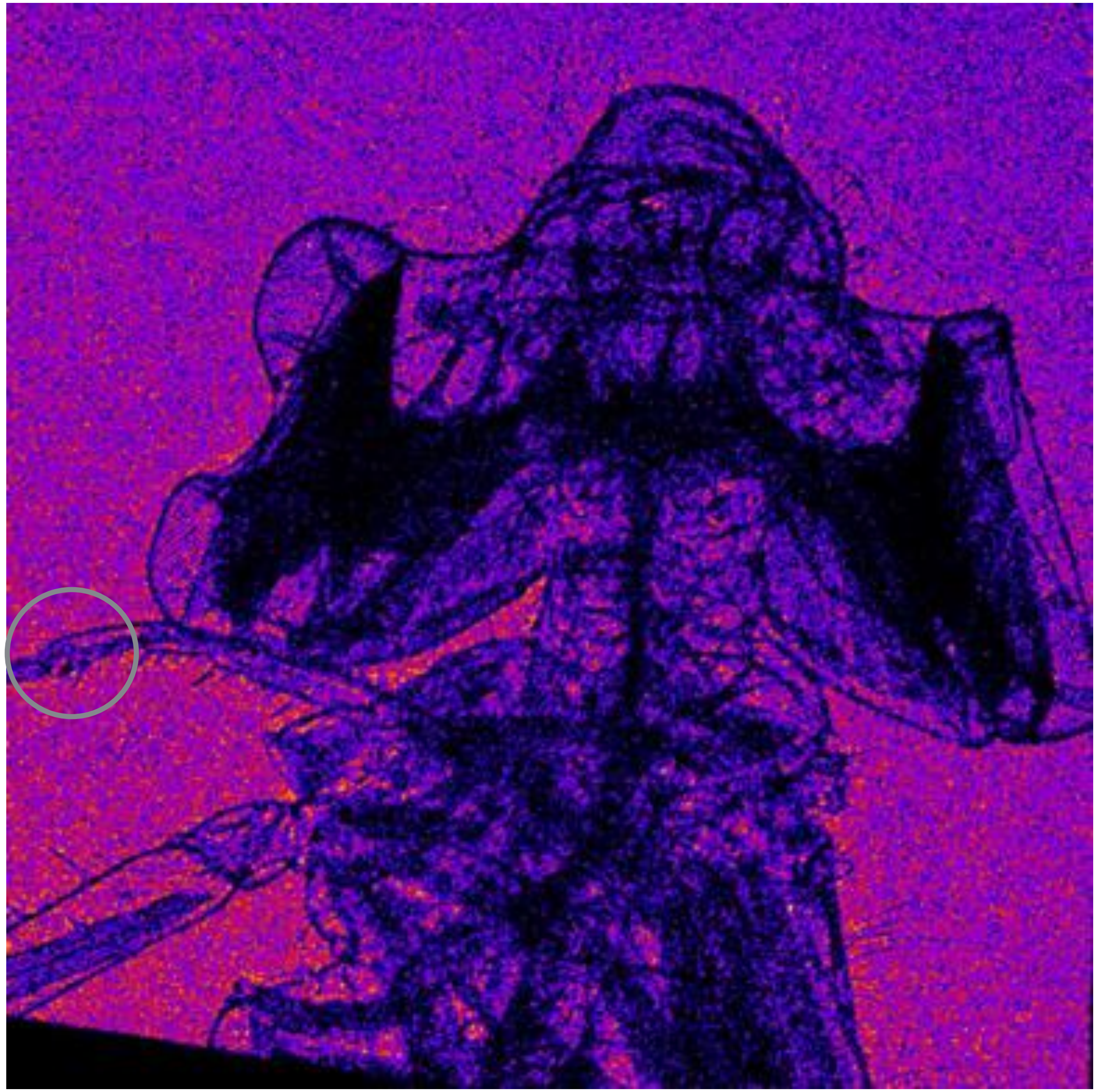
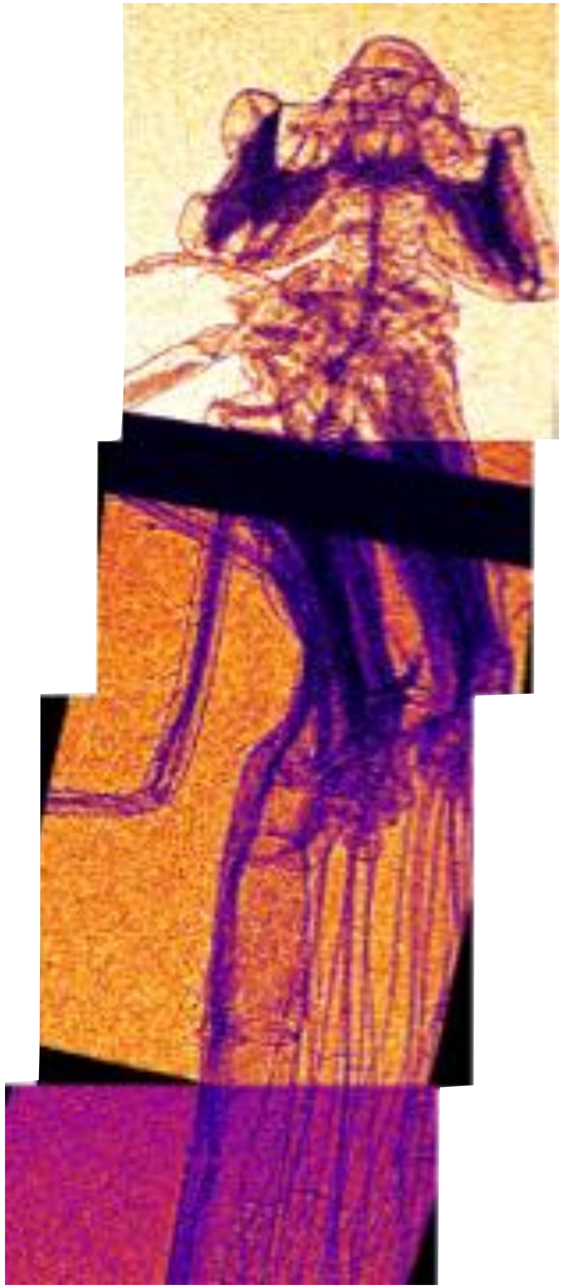
[S. Kneip, et al., Nat. Phot. (2010)]

X-ray Phase Contrast Imaging





[S. Kneip, et al., App. Phys. Lett. 2011]

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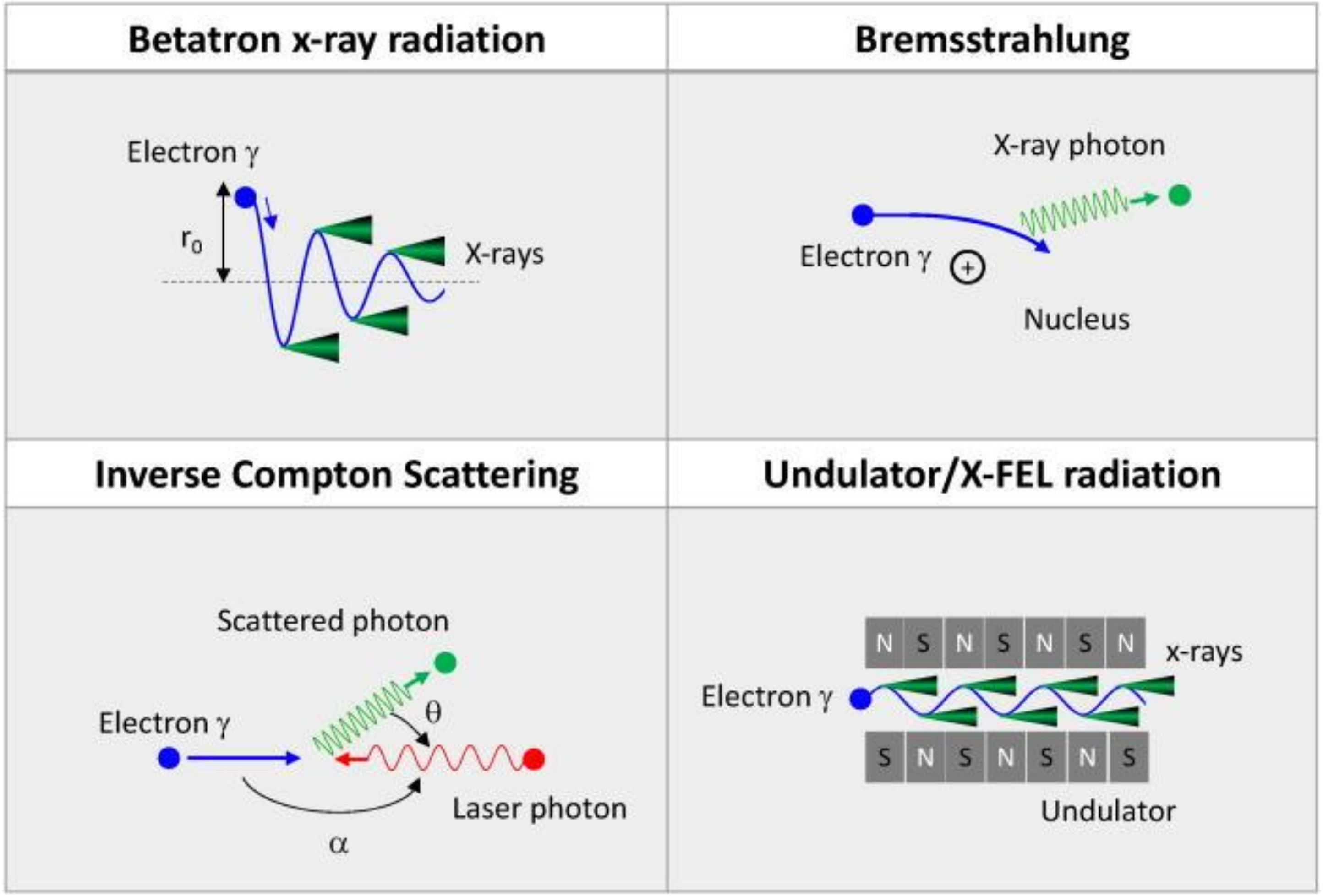
Other x-ray sources



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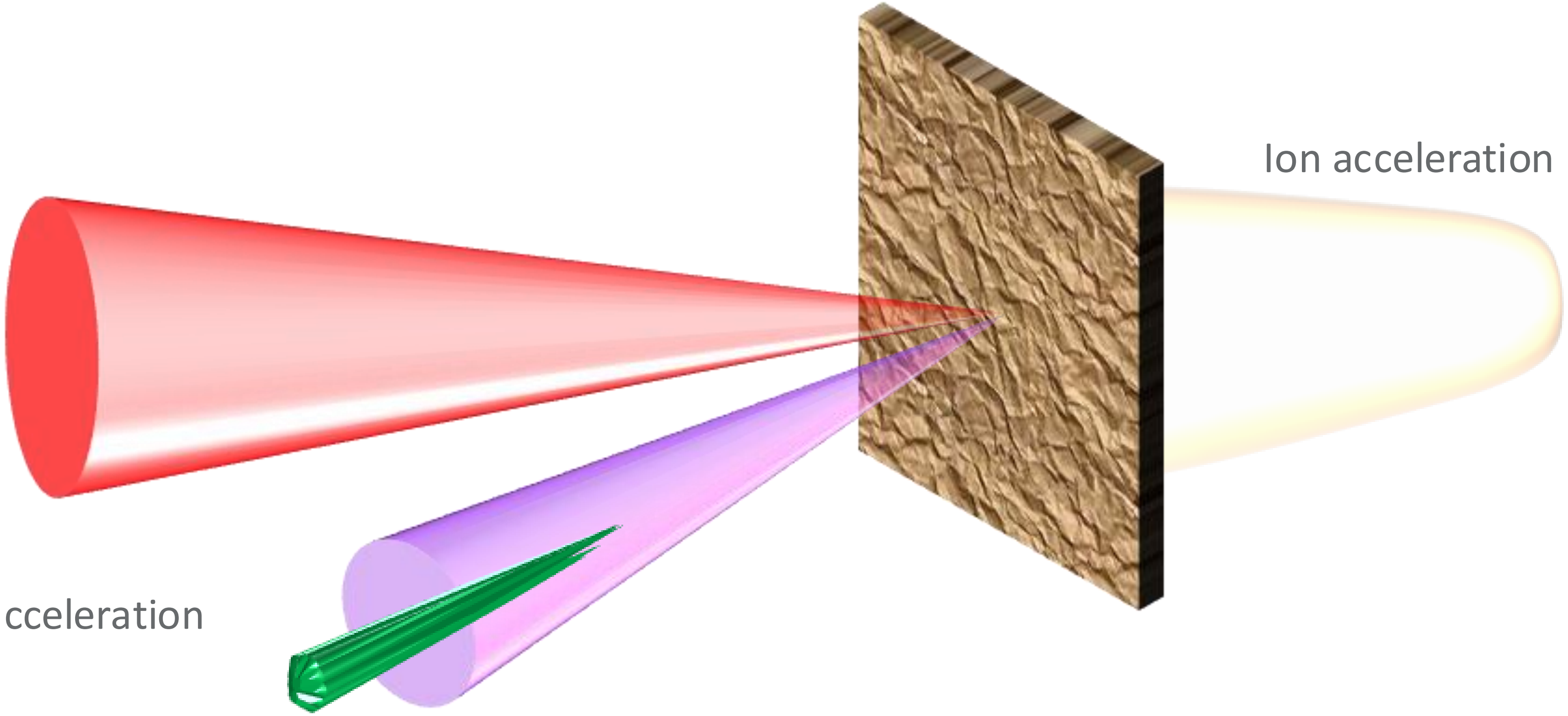
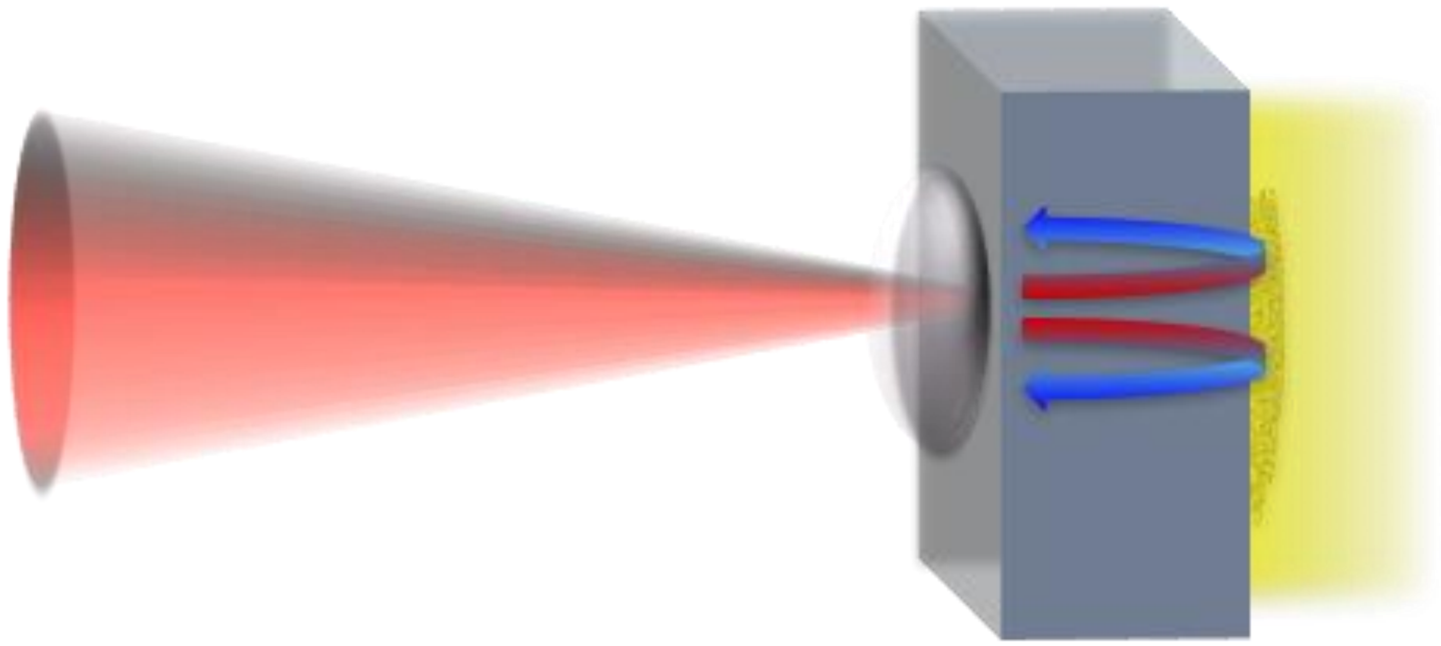
F. Albert. Phys. Plasmas 30, 050902 (2023)

Overdense interactions

Short pulse lasers and overdense plasmas



Target Normal Sheath Acceleration



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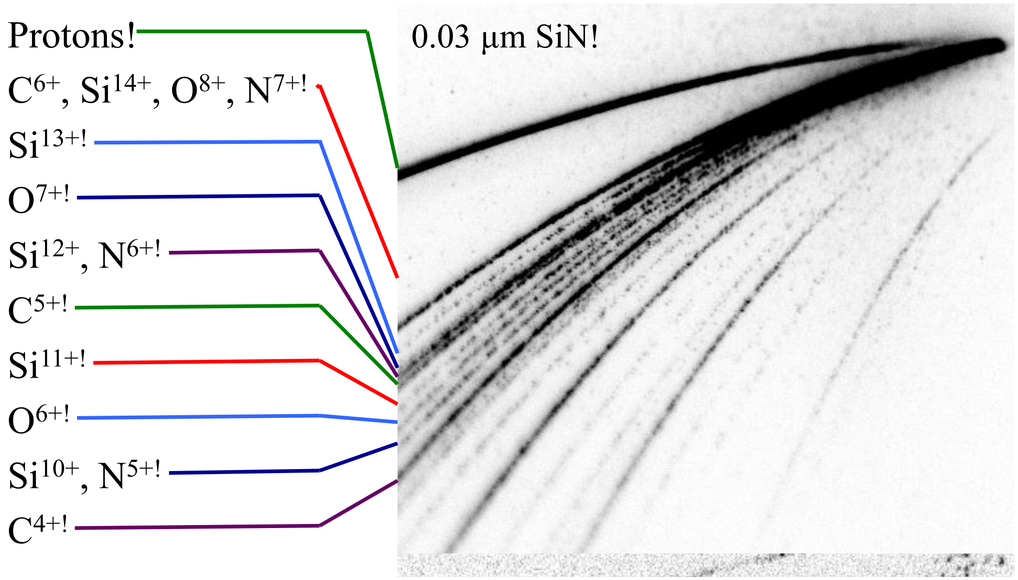
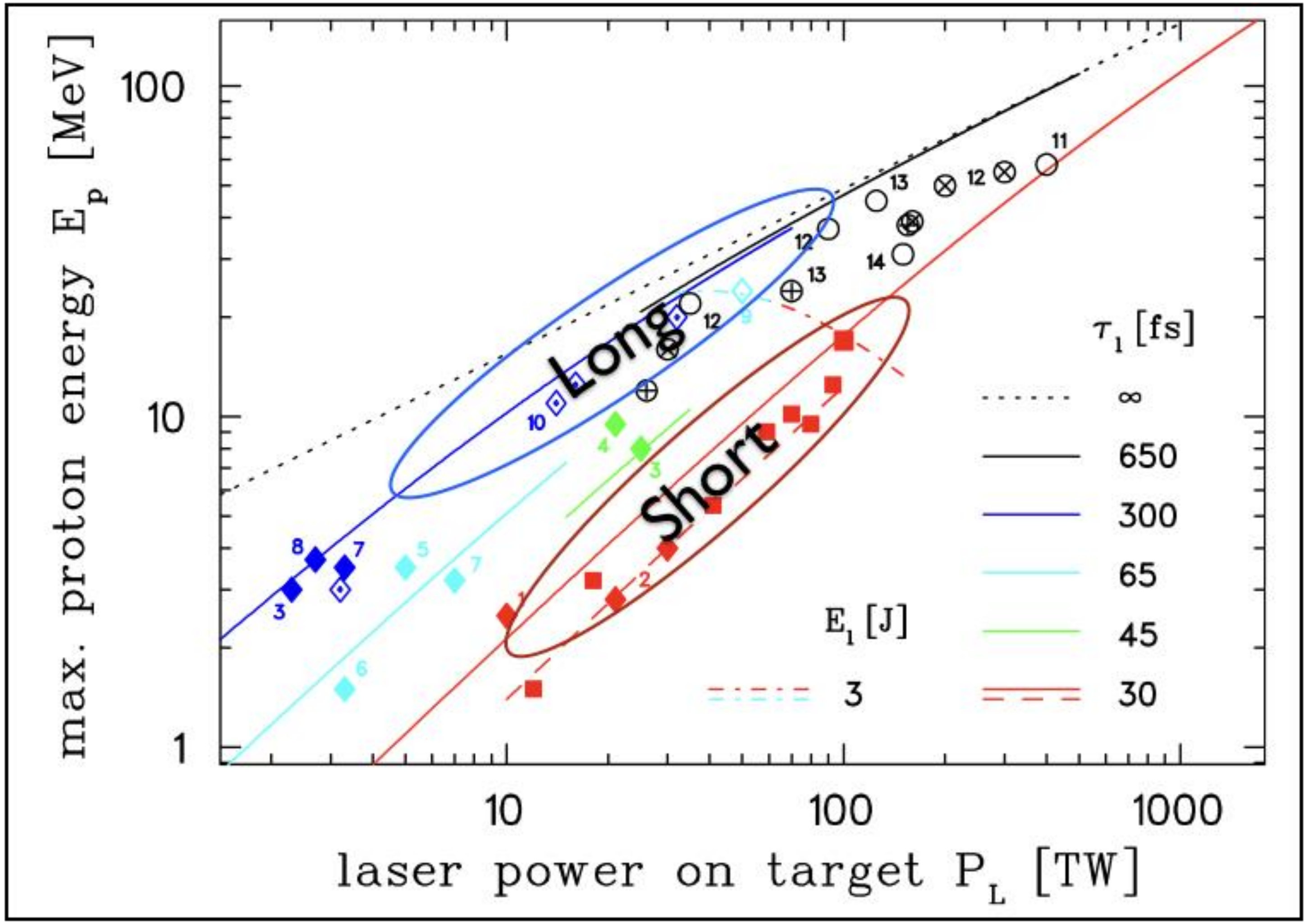
Target Normal Sheath Acceleration

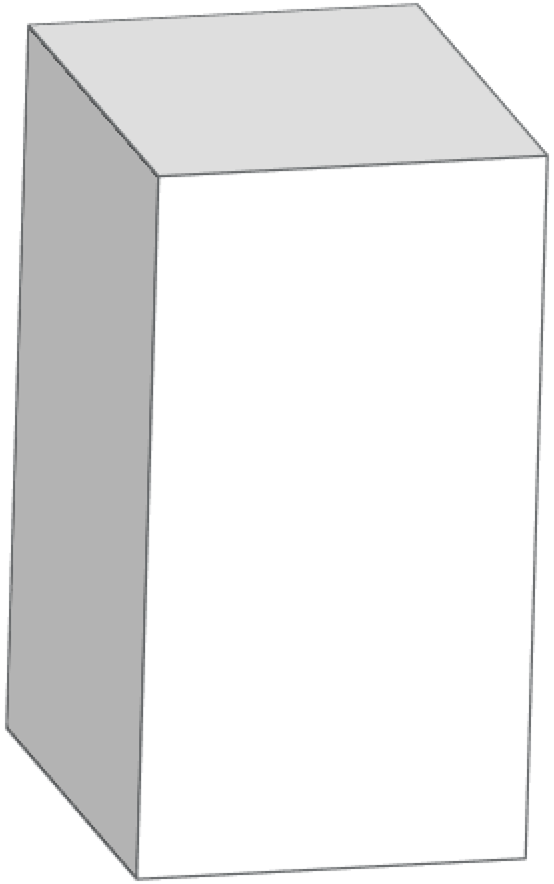


[F. Dollar, et al., Phys. Plasm. 2013]



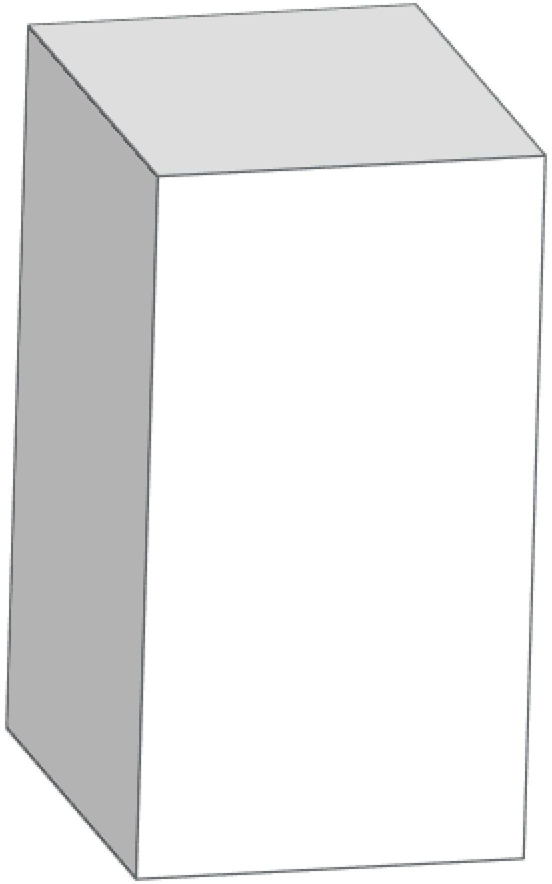
K Zeil et al 2010 New J. Phys. 12 045015

Relativistically Induced Transparency



$$n_{crit} = \frac{\epsilon_0 \gamma m_e}{e_c^2} \omega^2$$

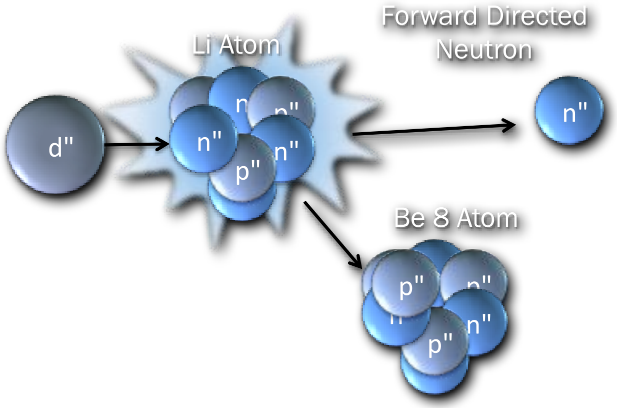
Laser Driven Neutron Sources



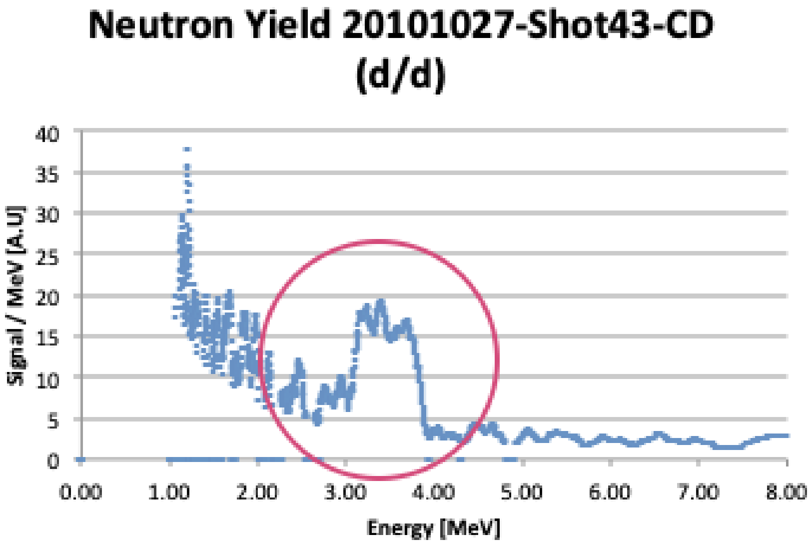
$$ {}_1^1p + {}_3^7Li \rightarrow {}_4^7Be + {}_0^1n \qquad Q = -1.64MeV $$

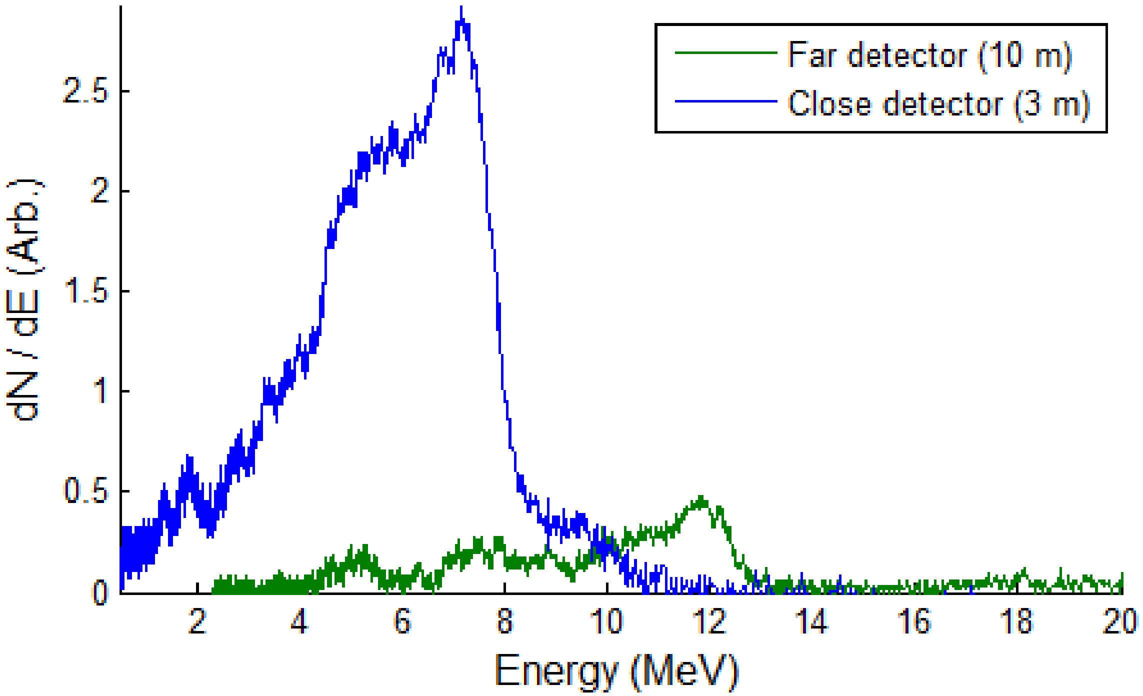
$$ {}_1^2d + {}_3^7Li \rightarrow {}_4^8Be + {}_0^1n \qquad Q = 15.03MeV $$

$$ {}_1^2d + {}_1^2d \rightarrow {}_2^3He + {}_0^1n \qquad Q = 3.27MeV $$



Neutron Time-of-flight





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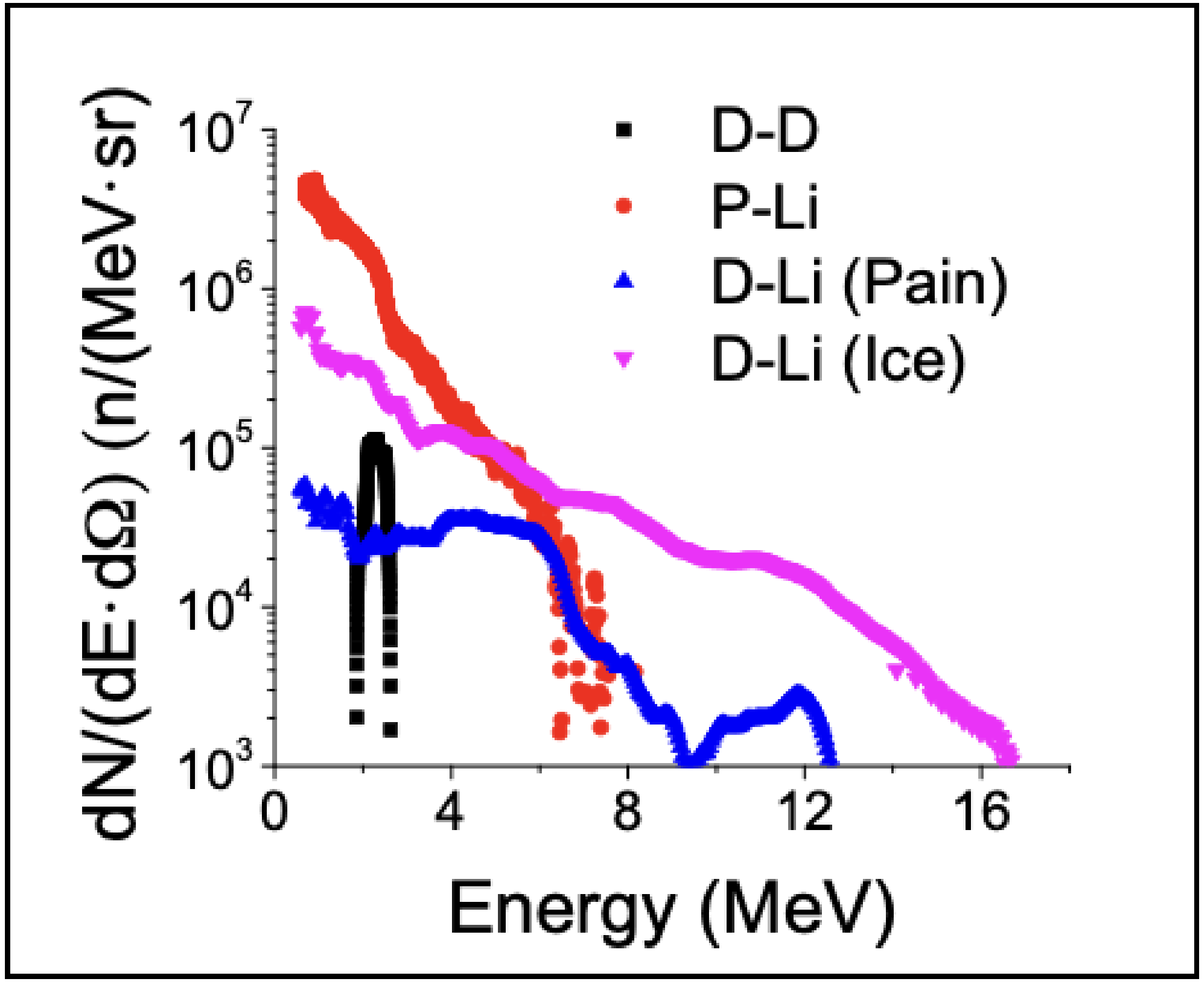
[C. Zulick, et al., App. Phys. Lett. 2013]

Neutrons on ice



[A. Maksimchuk, et al., App. Phys. Lett. 2013]

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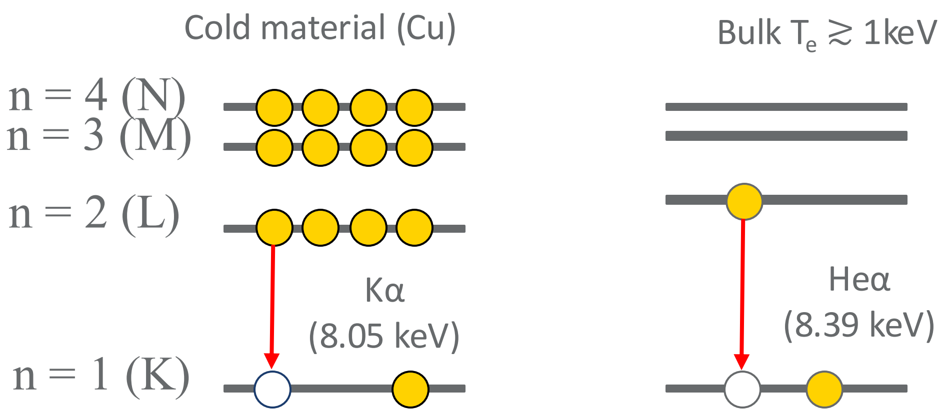
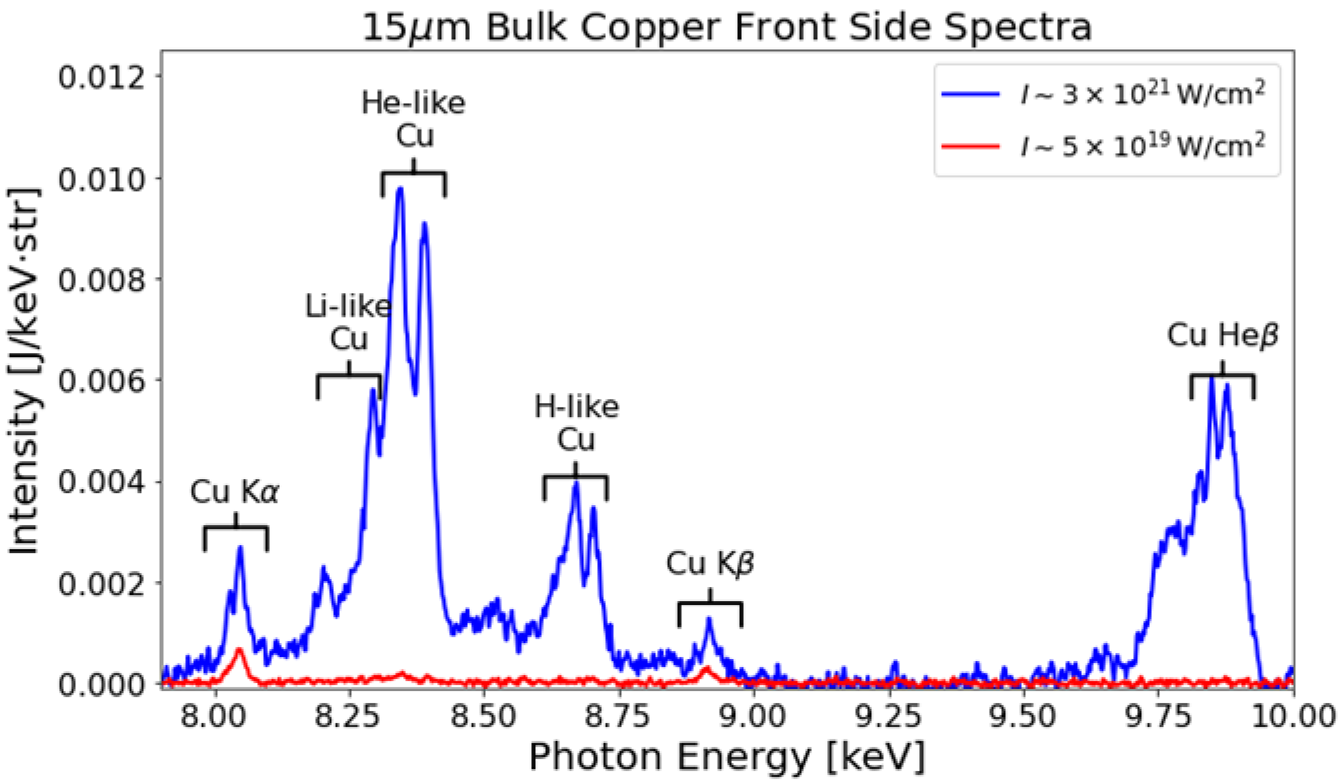
Plasma emission





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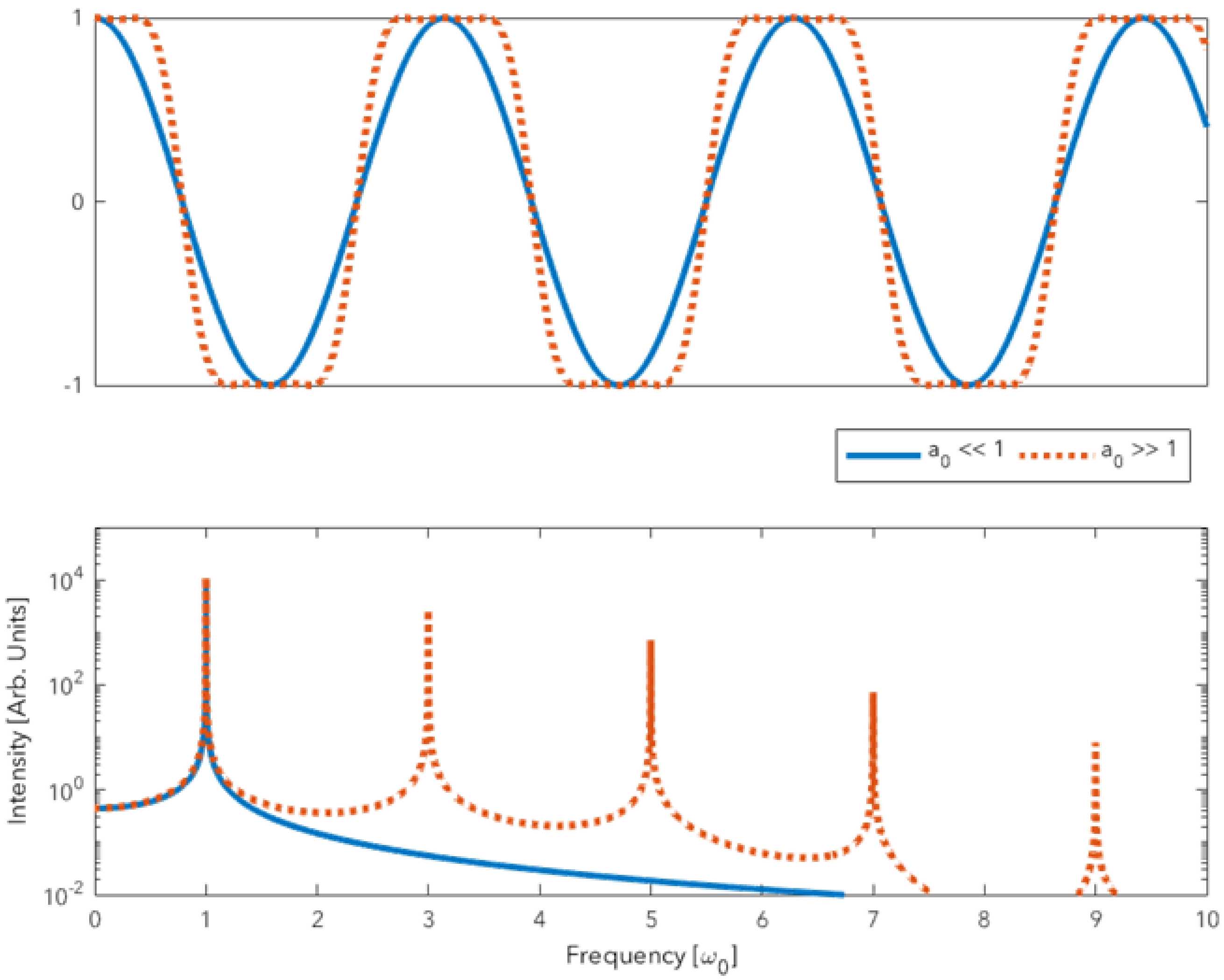
N. Beier, Thesis 2021

ROM

- High order harmonic generation from aharmonic surface motion
- Low intensities via Coherent Wake Emission
- High intensities via Relativistic oscillating mirror



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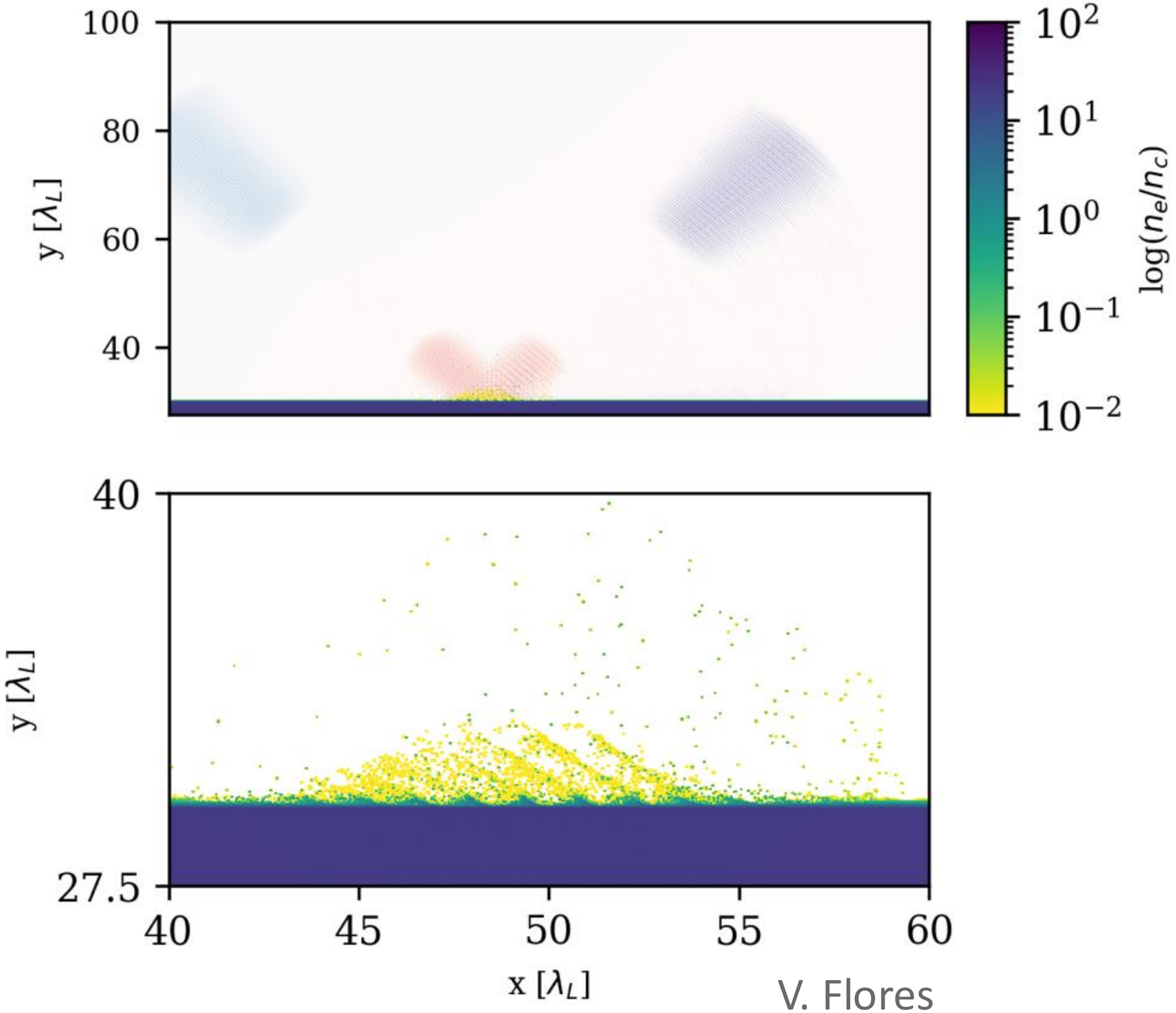
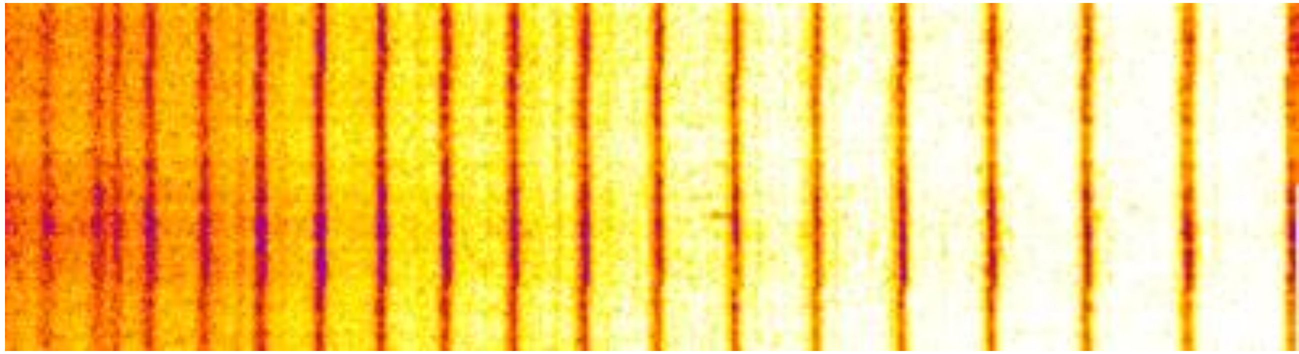
High Harmonic Generation

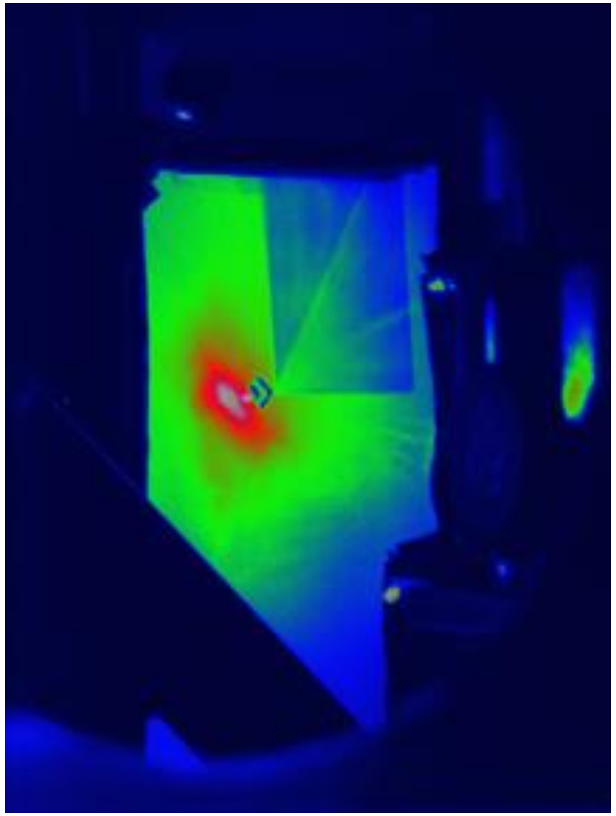


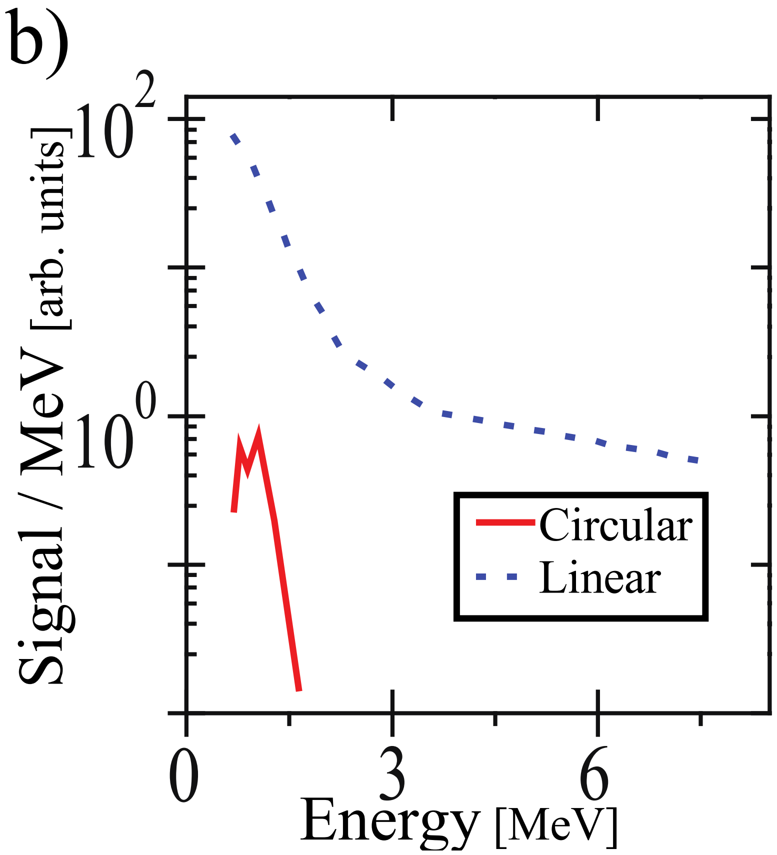
V. Flores

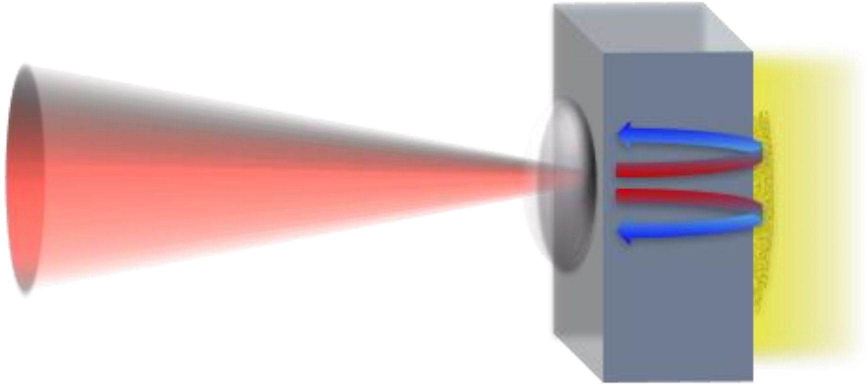


F. Dollar, et al., PRL **110**, 175002 (2013)

Laser solid electron sources







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[F. Dollar, et al., Phys. Plasm. 2013]

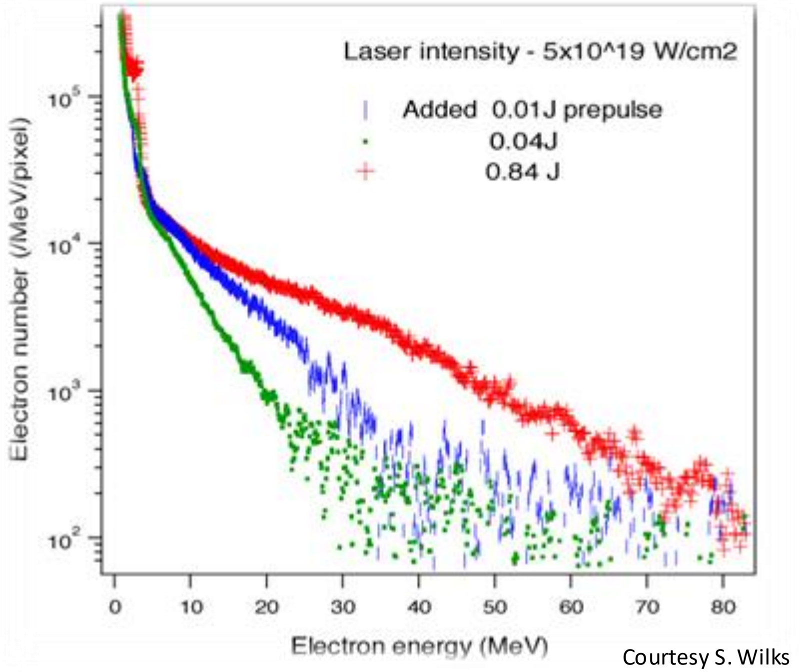
Experiments

Titan Laser Facility @ LLNL

1 micron wavelength

Up to 400 J

<10 picoseconds



Courtesy S. Wilks

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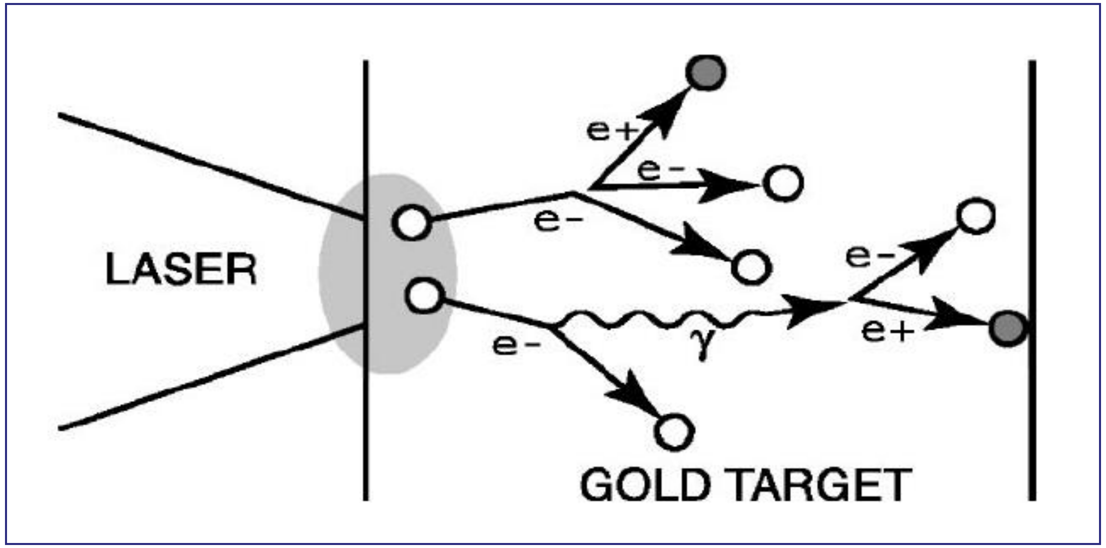
Pair Production

1. Direct (Trident) pair production

   $e^- + Z \rightarrow 2e^- + e^+ + Z$

   $(Z:$ nucleus)



2. Indirect (Bethe-Heitler) pair production:

   $e^- + Z \rightarrow \gamma + e^- + Z$

   $\gamma + Z \rightarrow e^- + e^+ + Z$

   (γ: Bremsstrahlung)

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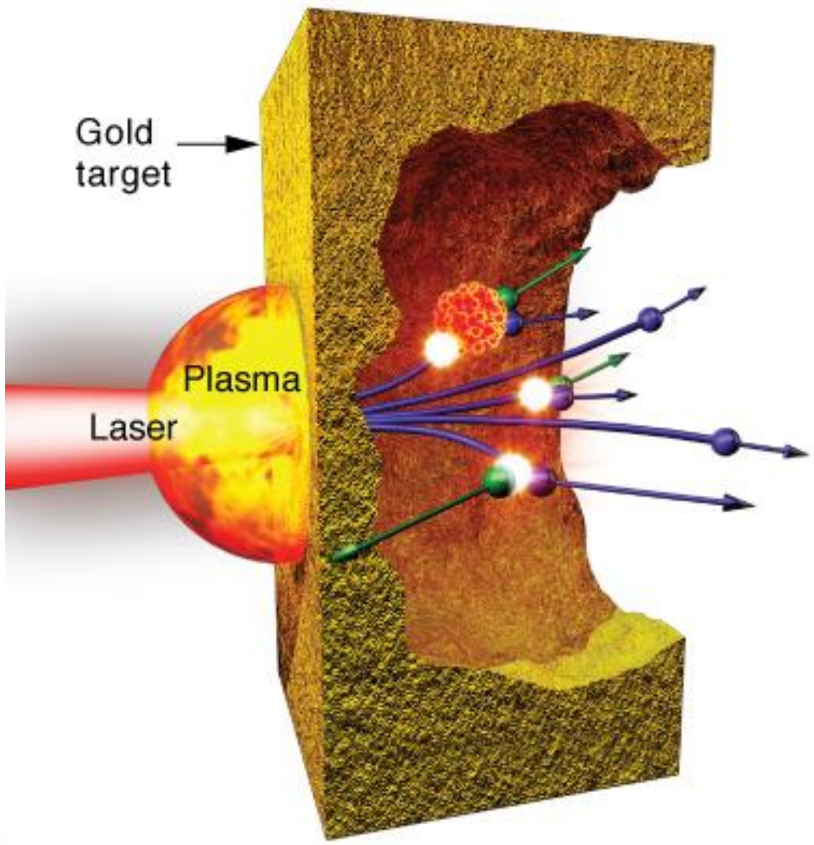
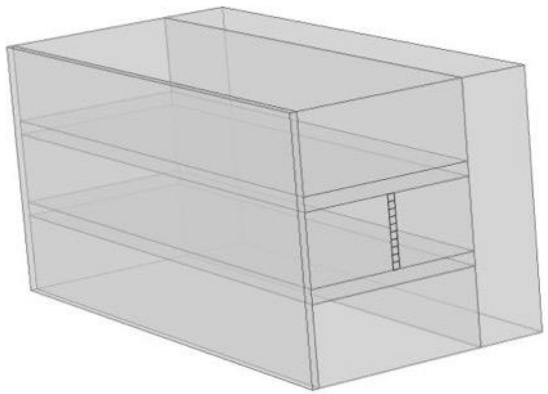
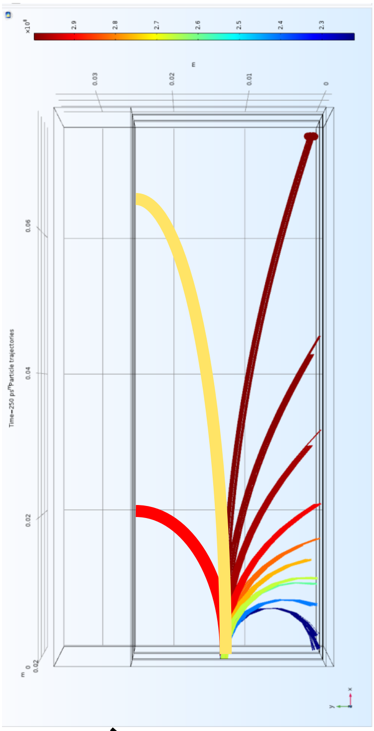
Positron Measurements



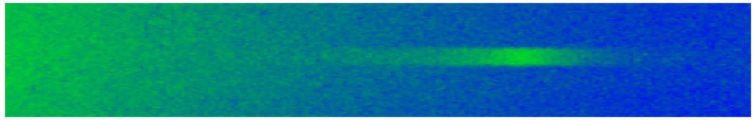
Electron Proton Positron Spectrometer

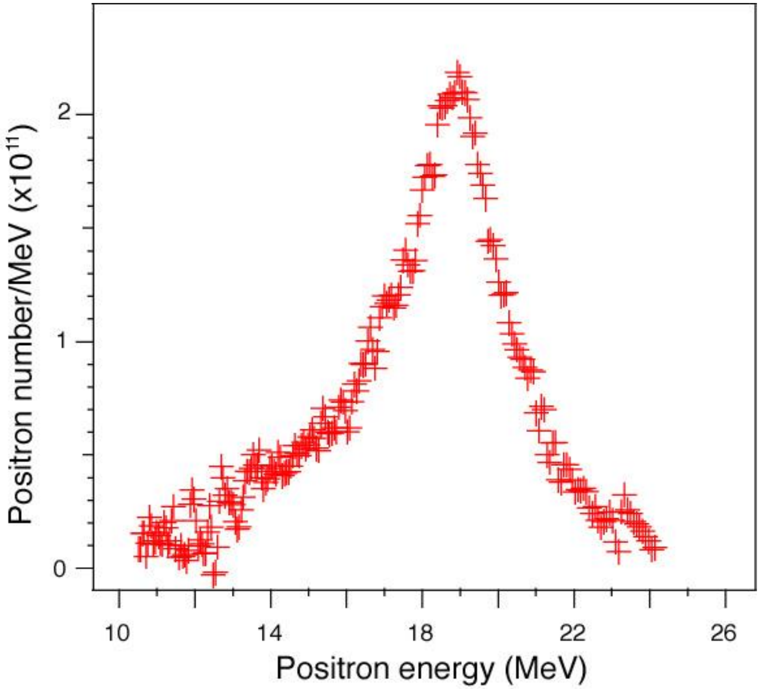


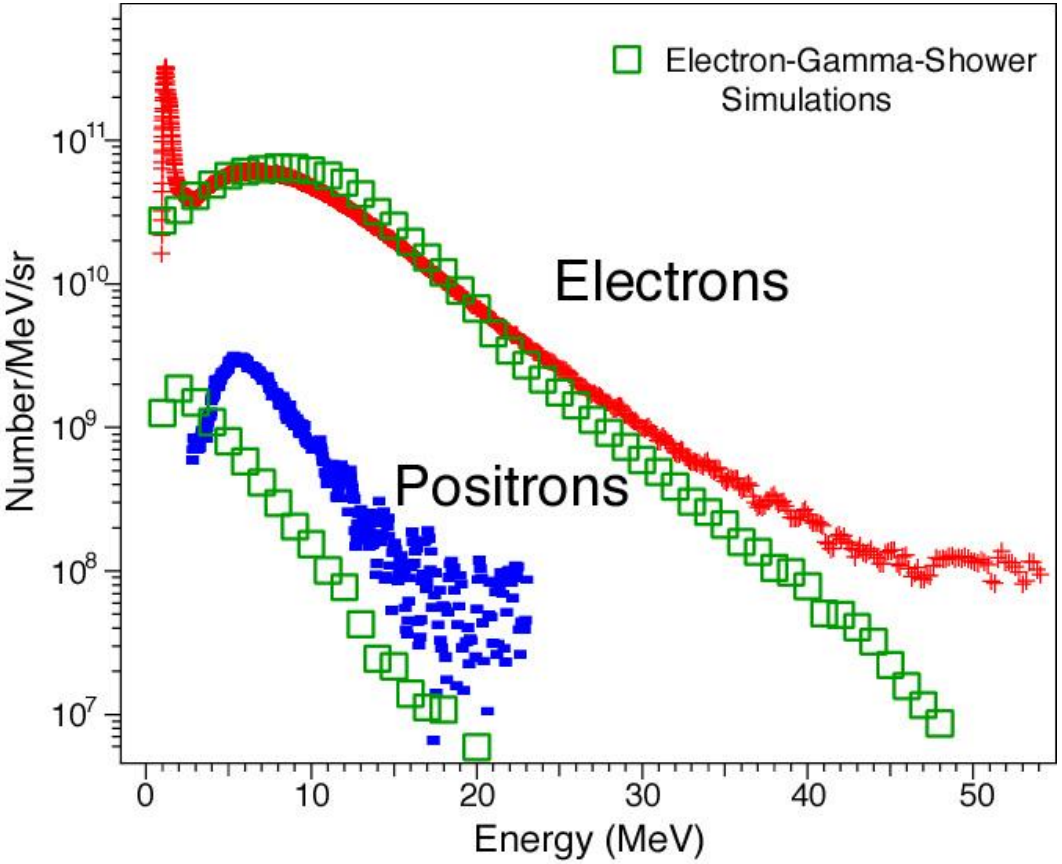


$$\vec{F}_{Lorentz} = e_c\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Positron Measurments







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[H. Chen, et al., HEDP 2011]

Conclusion

- High intensity lasers are powerful drivers of particle accelerators and advanced light sources
- In the underdense regime, multi-GeV electron accelerators have been demonstrated
- Bright x-ray sources with energies ranging from tens to thousands of eV have been demonstrated
- Tunable sources of electrons, ions, x-rays, neutrons, and positrons are capable