Single Cycle and Exawatt Lasers

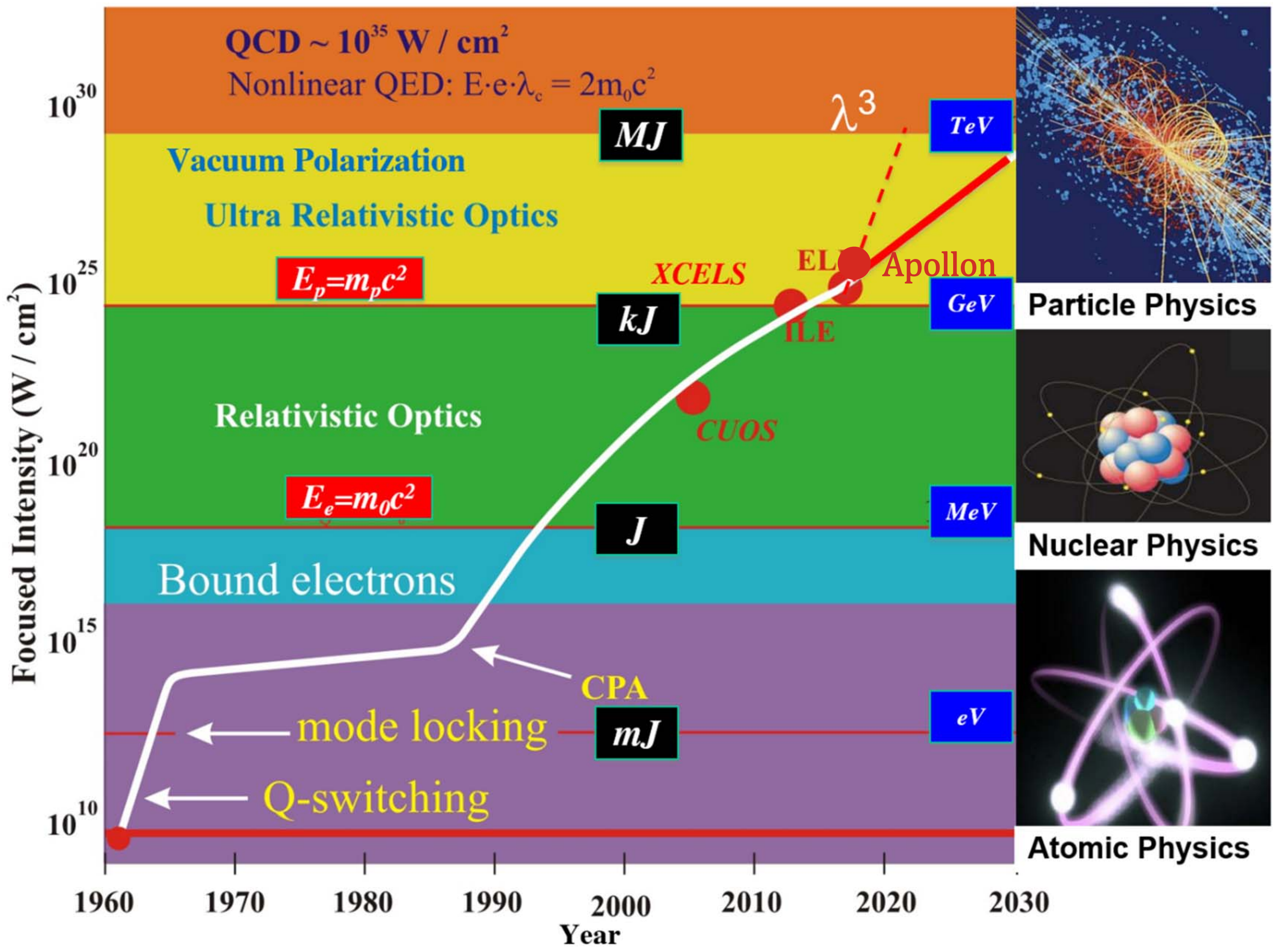
APOLLON FIRE MEETING

Université Paris-Saclay, France

11-12 February 2016

J.A. WHEELER, G. MOUROU, T. TAJIMA

What to DO with a 10-PW Laser ?



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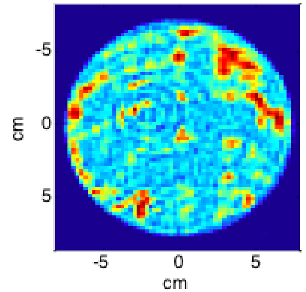
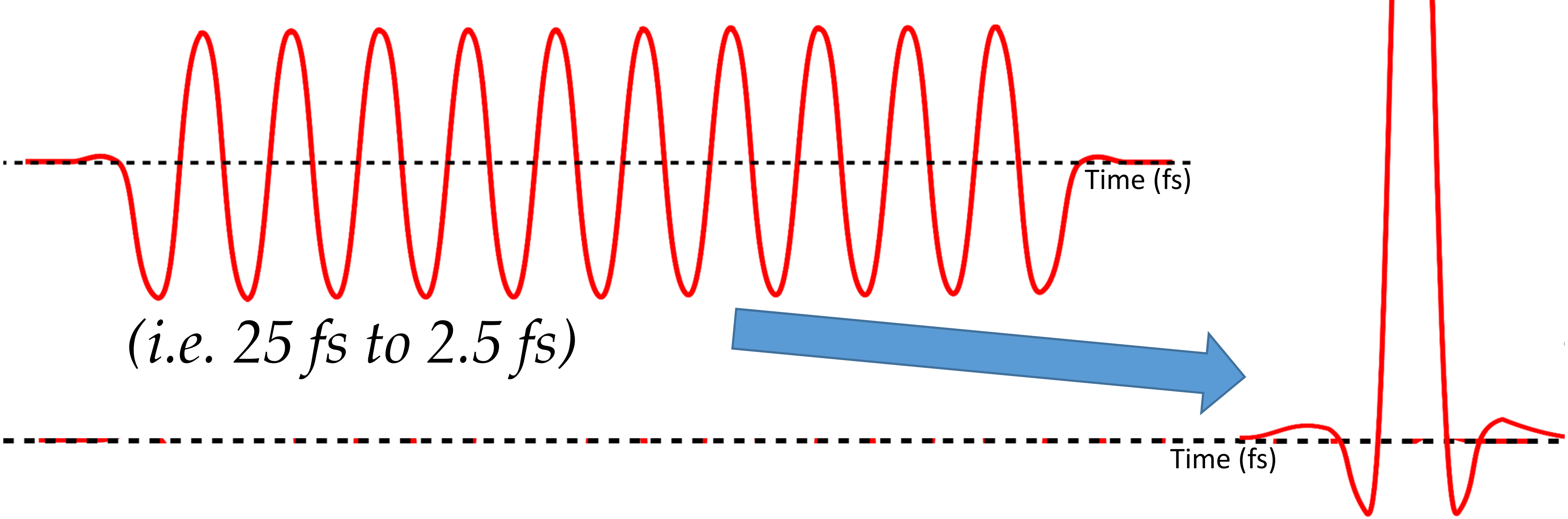
What to DO with a 10-PW Laser ?

Flat-top Spatial Mode
Allows for efficient
Post-Compression of the Pulse!



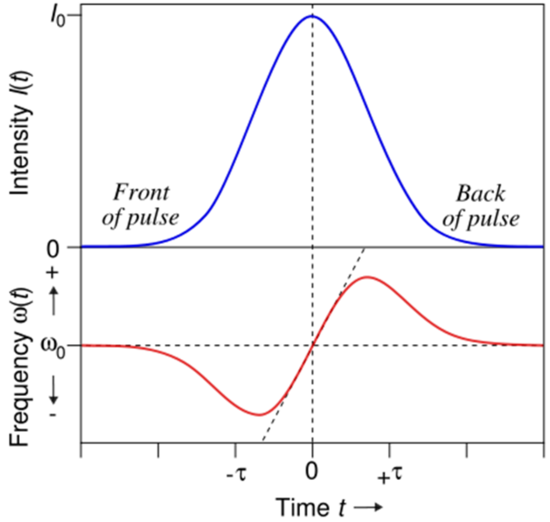


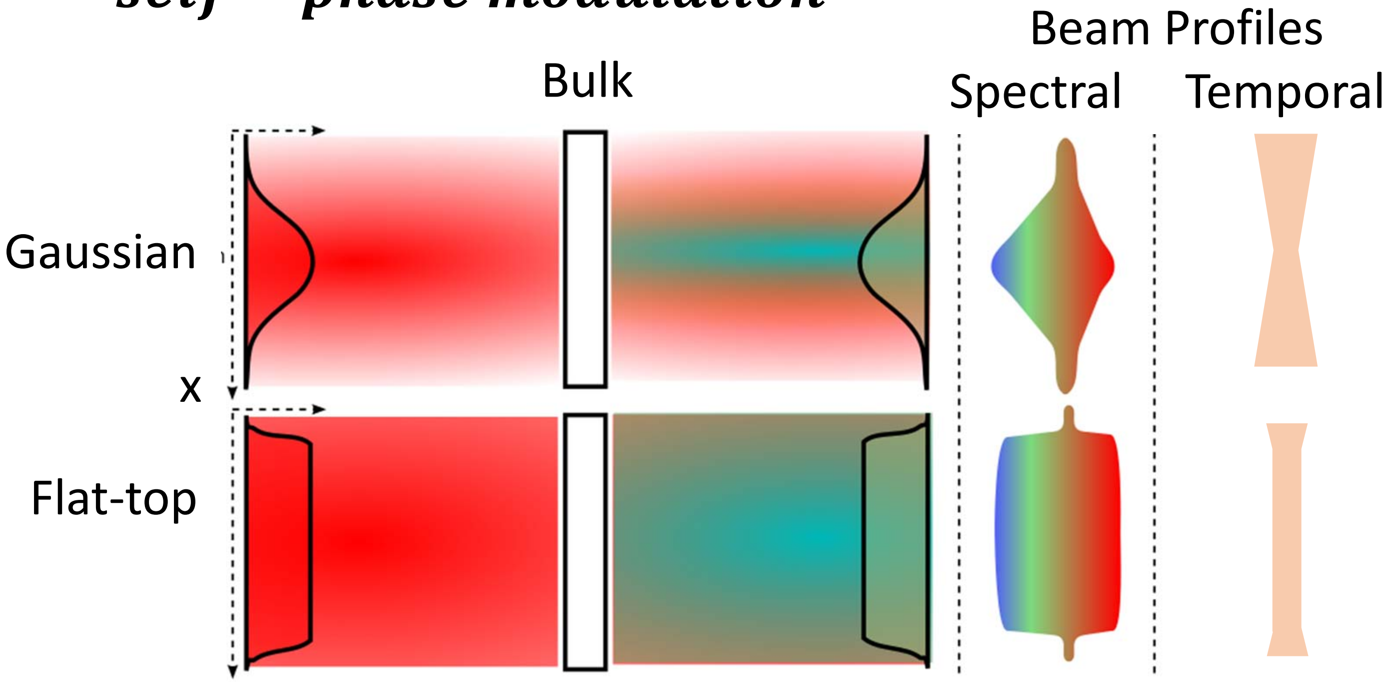
(i.e. 25 fs to 2.5 fs)

Broad Spectra through Self-Phase Modulation (SPM)

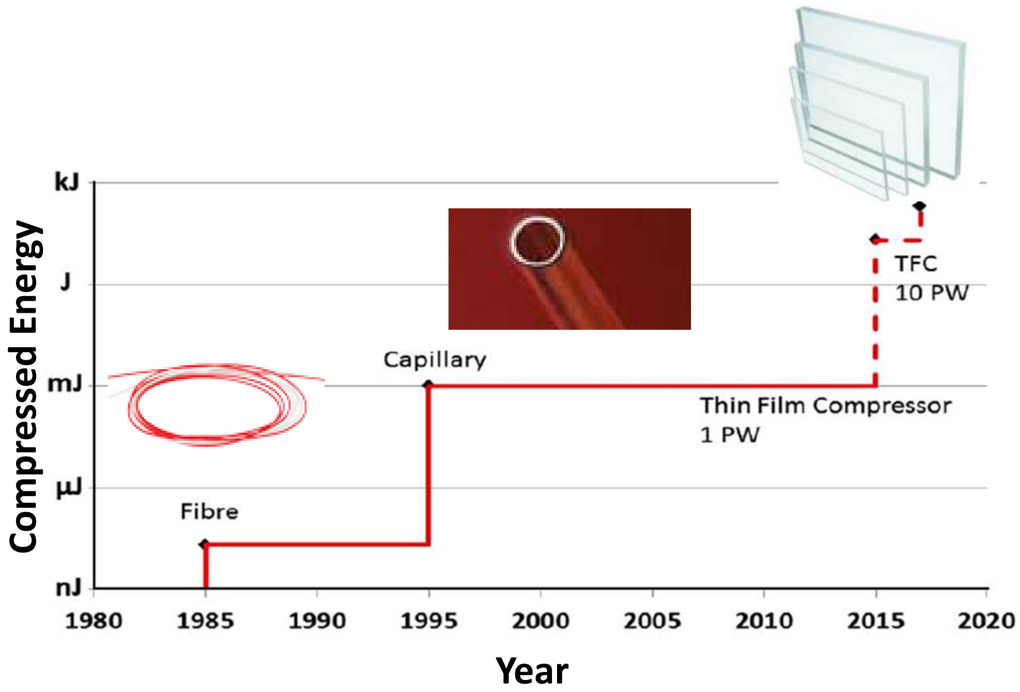
$$\frac{\partial A}{\partial z}+\frac{1}{u}\frac{\partial A}{\partial t}-i\underbrace{\frac{k_2}{2}\frac{\partial^2 A}{\partial t^2}}_{dispersion}-\underbrace{i\gamma_1|A|^2A}_{\boldsymbol{self-phase\ modulation}}+\underbrace{\frac{3\pi\,\chi^{(3)}}{n_o c}\frac{\partial}{\partial t}(|A|^2A)}_{self-steepening}=0$$

SPM





Energy within Single-Cycle Pulses

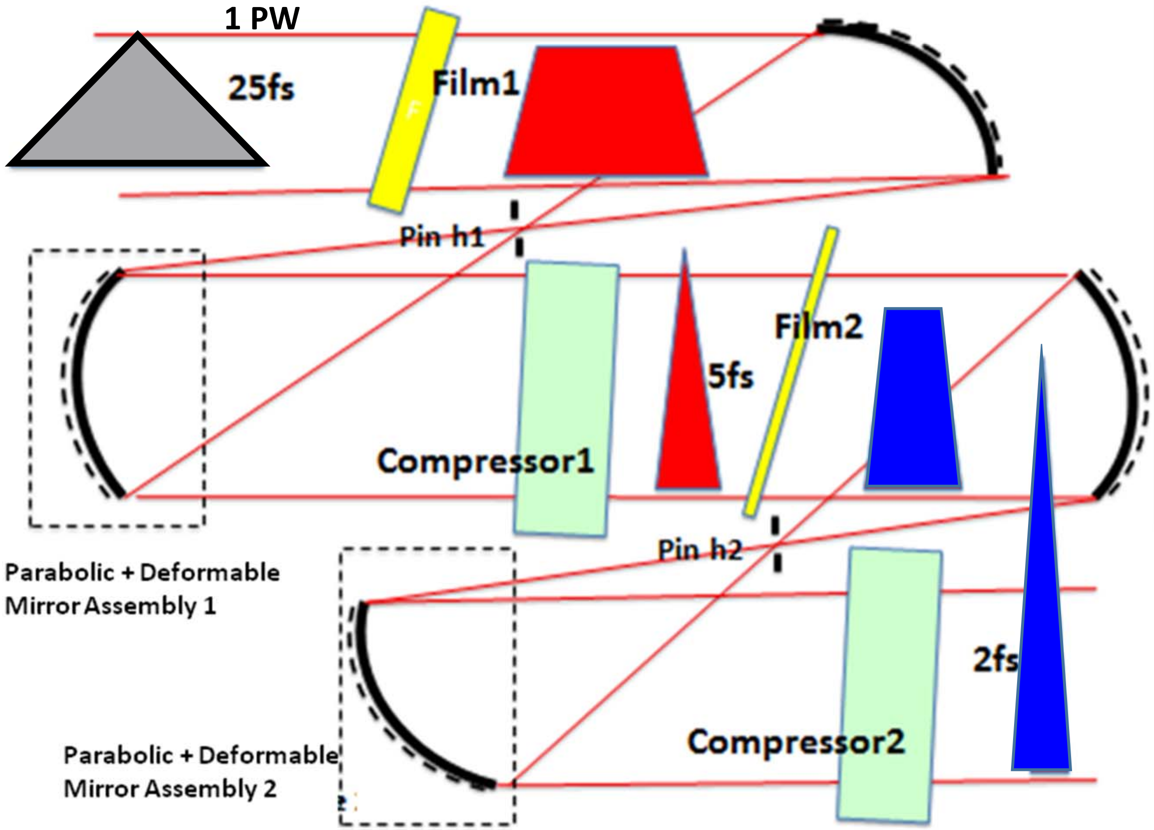


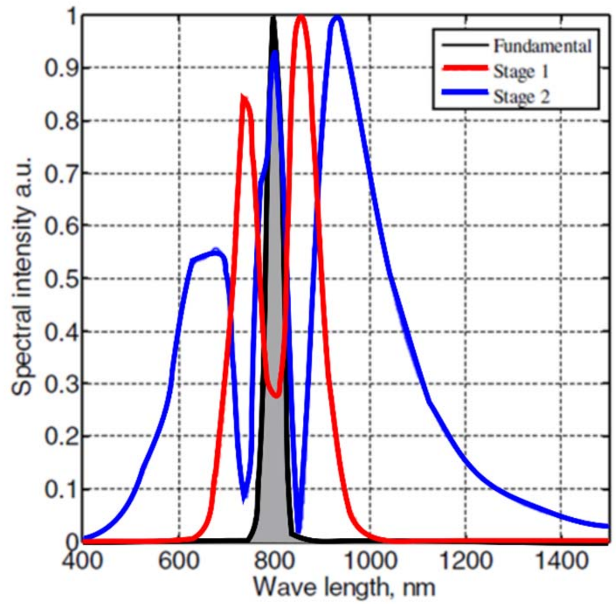
Thin Film Material Requirements

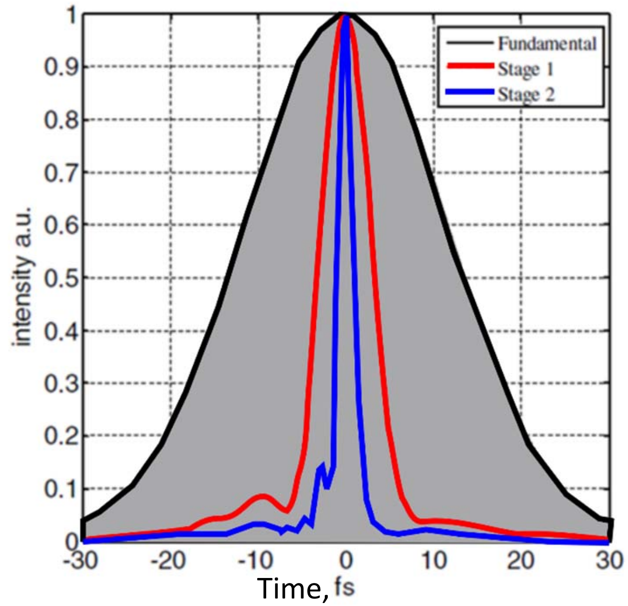
- Appropriate Nonlinear Response:
  - >(5- 8)x10^{-4} cm^2/TW
- Ideal Thickness (<1 mm)
- Large Aperture (>15 cm)
- High Damage Threshold (5 TW/cm^2)
- Low Absorption Losses
- Low Birefringence
- Vacuum Compatibility

- Example Candidates :
  - Cellulose Acetate
  - Polyethylene Terephthalate (PET)
  - Poly(methyl methacrylate) (PMMA)
  - Cyclic Olefin Copolymer (COC)

Thin Film Compression Scheme







Designed based on the CETAL 1-PW laser system.
Mourou G. et al. *Eur. Phys. J. Spec. Top.* **223** 1181–8 (2014)

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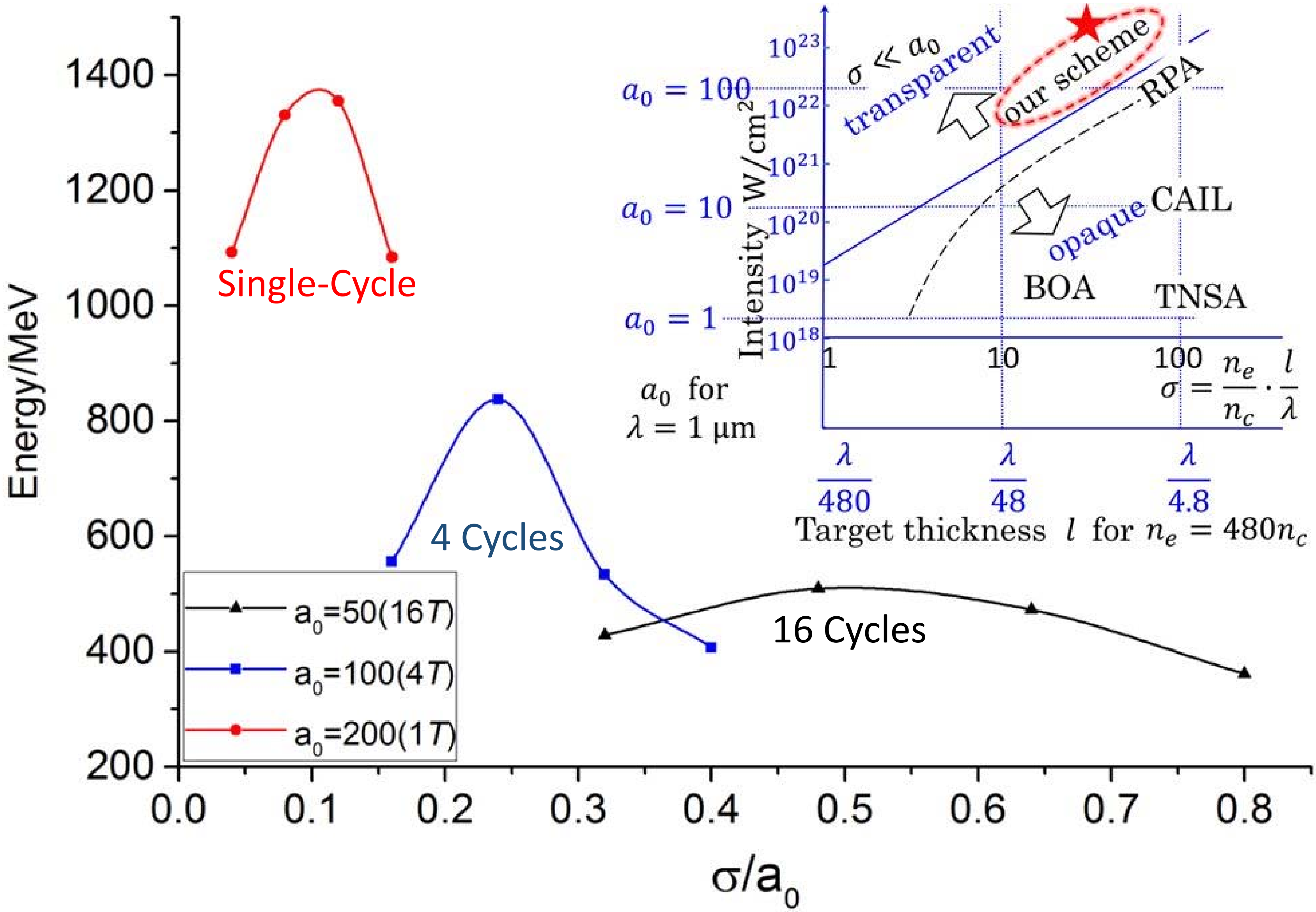
Short Pulse Ion Acceleration



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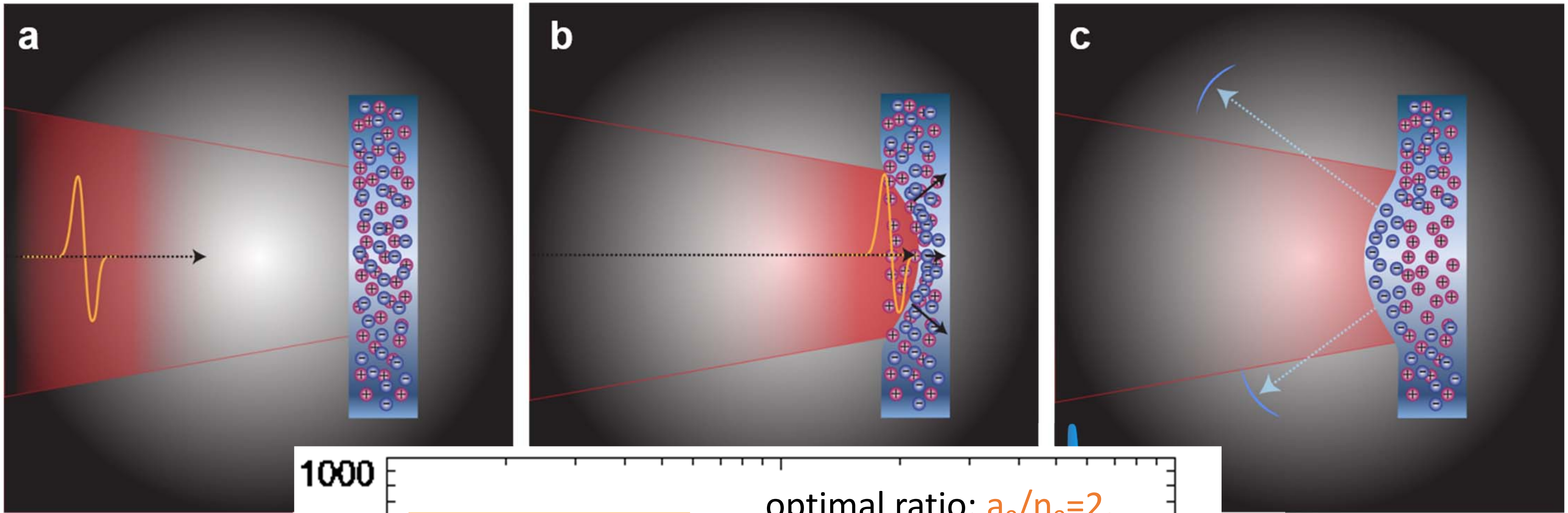
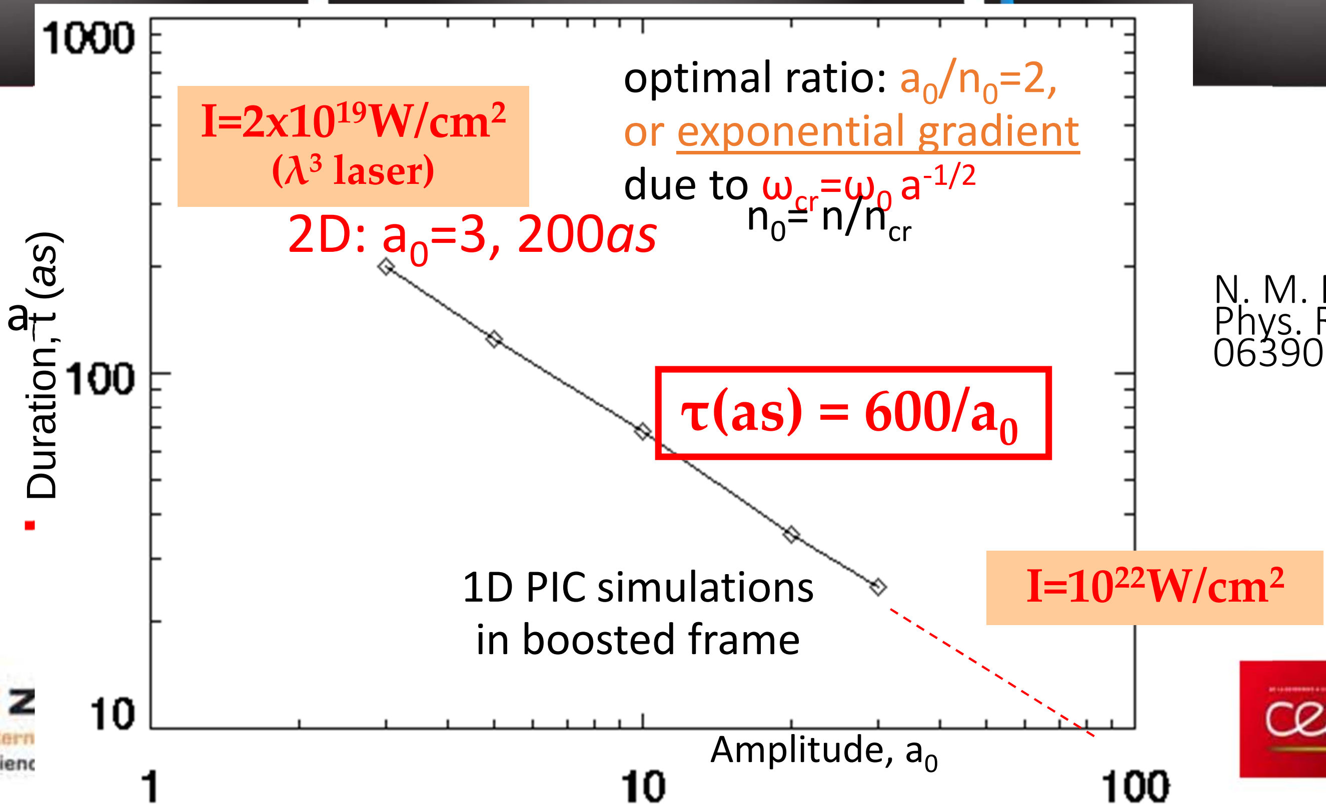
A Single Relativistic Mirror





N. M. Naumova, et al., Phys. Rev. Lett. 92, 063902-1 (2004).

Exawatt is achievable

- 1J in an attosecond (10^{-18}s) is an Exawatt (10^{18}W)
- An attosecond (10^{-18}s) is coherent 10 keV X-rays

Optimistically :

- 1J in a Zeptosecond (10^{-21}s) is a Zetawatt (10^{21}W)
- A Zeptosecond (10^{-21}s) is coherent MeV X-rays

  Giant Laser Acceleration in solid: TeV/cm (CERN on a Dime)
- 1 Zetawatt pulse over a λ^2 spot size yields the Schwinger Intensity: 10^{29} W/cm^2

  Vacuum Physics: Light Turns into Matter and Antimatter

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A Wide Variety of Applications to Motivate Us…

Scientific Applications

- ***High Energy Physics Beyond the Standard Model (TeV/cm)***
- ***Laser Astrophysics and Cosmology (Table Top Cosmos)***
- ***Vacuum Physics: Polarization and Materialization of Light***
- ***Proton/Ion Acceleration***
- ***Hawking Blackhole Radiation***

Societal Applications

- *Transmutation of Nuclear Waste*
- *Under Critical Reactor*
- *Nuclear Pharmacology*
- *Proton Therapy*

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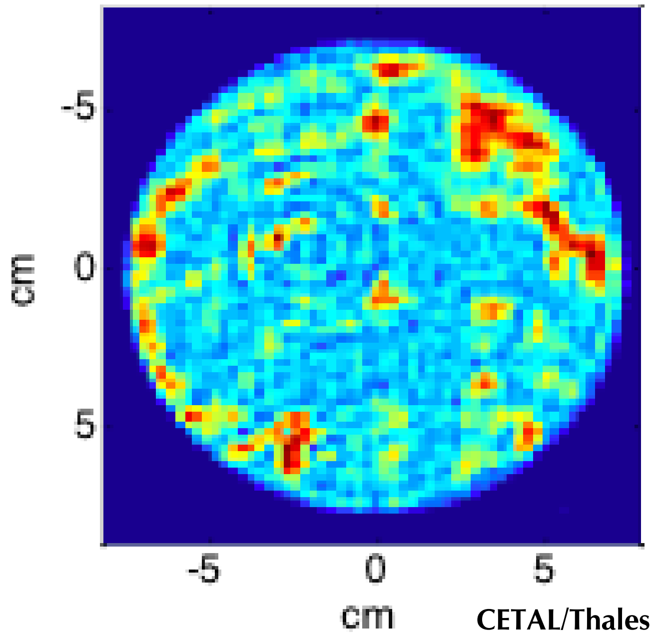
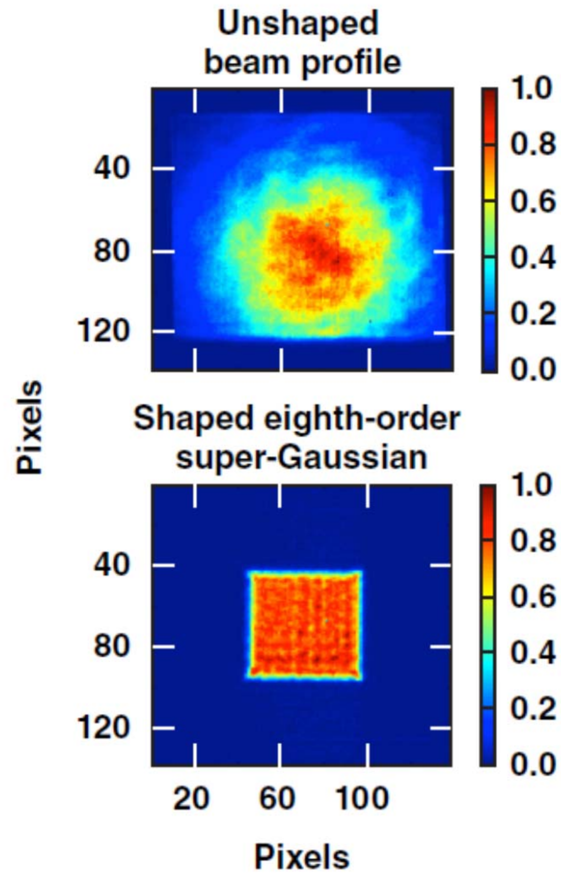
What do we WANT from a 10-PW Laser ?

- ***Flat-top / Uniform Spatial Profile***





- *Short pulses (15 fs is great!)*
- *Spatio-Temporal Diagnostics*
- *CEP Monitor*

S.-W. Bahk, I. A. Begishev, and J. D. Zuegel, Opt. Commun. 333, 45 (2014).

Thank you for your attention

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Thin Film Material Requirements

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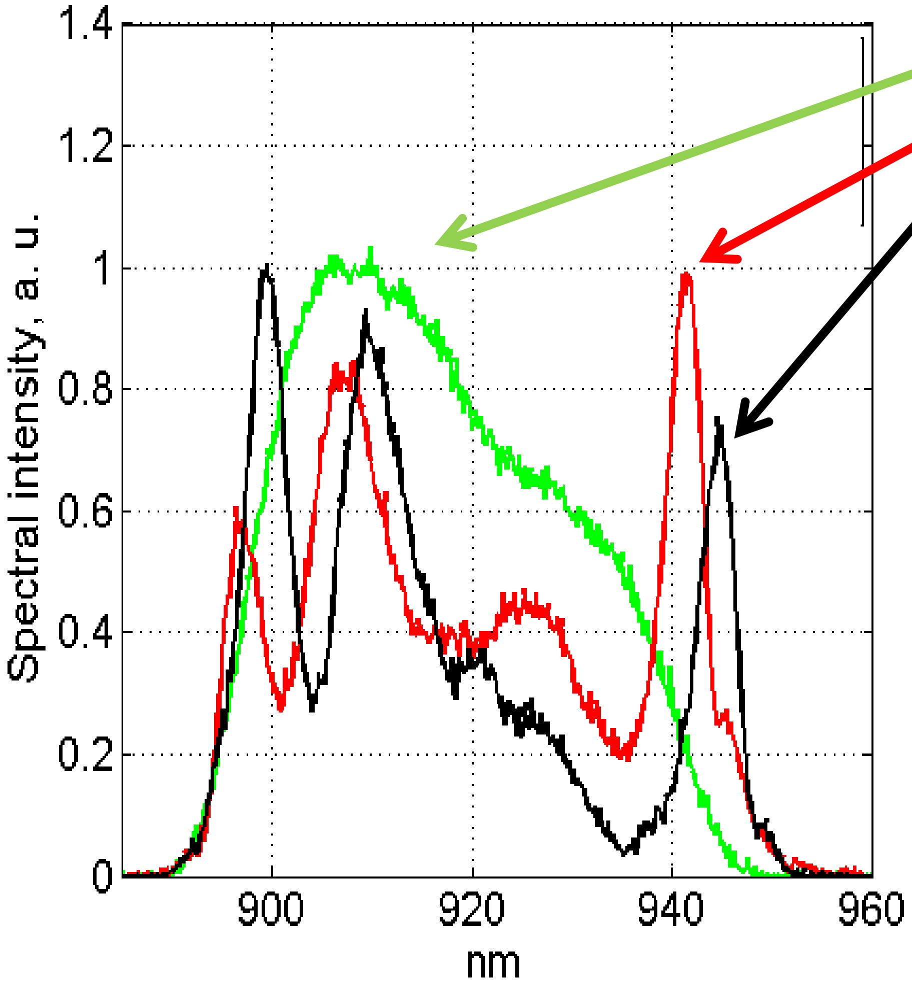
Early Thin Film Demonstration

Polyethylene Terephthalate (PET)



Comparison of spectra of
initial short pulse after:
polyethylene terephthalate (0.7mm)
fused silica (1.7mm).

PEARL laser:

pulse energy 1 mJ,

duration 70 fs,

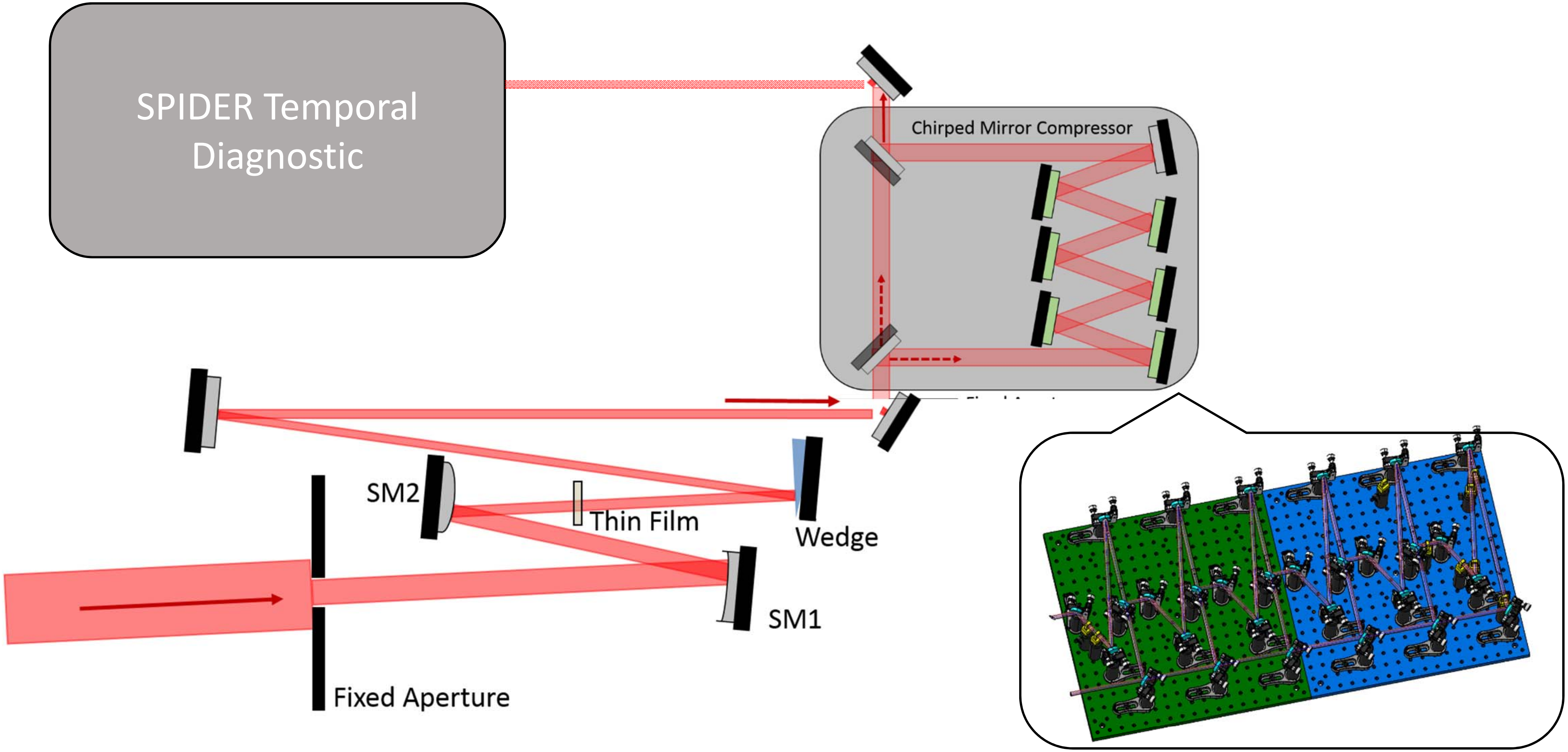
intensity 1.3 TW/cm^2

***Suggests nonlinearity ~ 2x silica.**

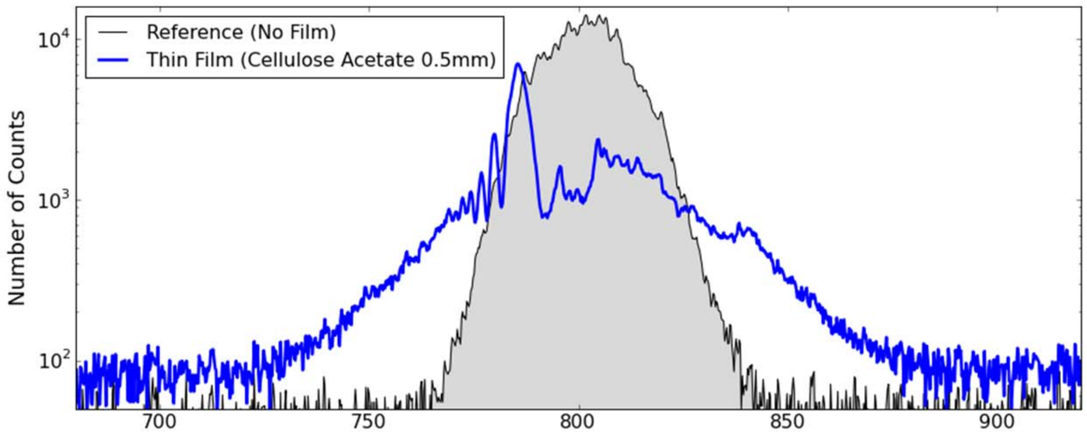
S. Mironov et al., Laser Phys. Lett. 2015.

Initial Experimental Exploration

Preliminary Experiments at TEWALAS laser based at INFLPR, Romania



Initial Results

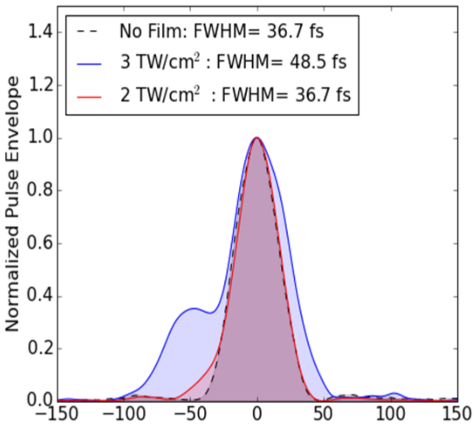


Wavelength [nm]

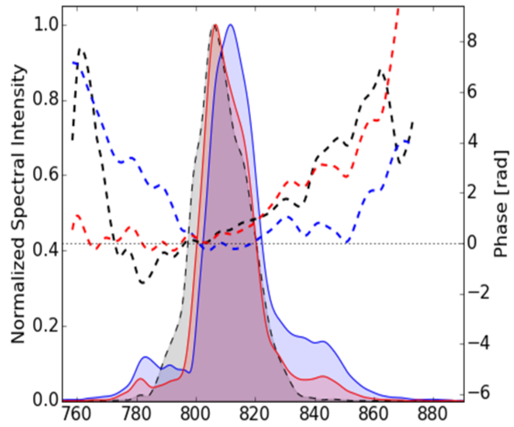
- 0.5 mm film of cellulose acetate
- Intensity of ~ 3 TW/cm^2
- Limited by interaction in air
- B-integral estimated at ~ 3

22 nm FWHM bandwidth (45fs pulse)

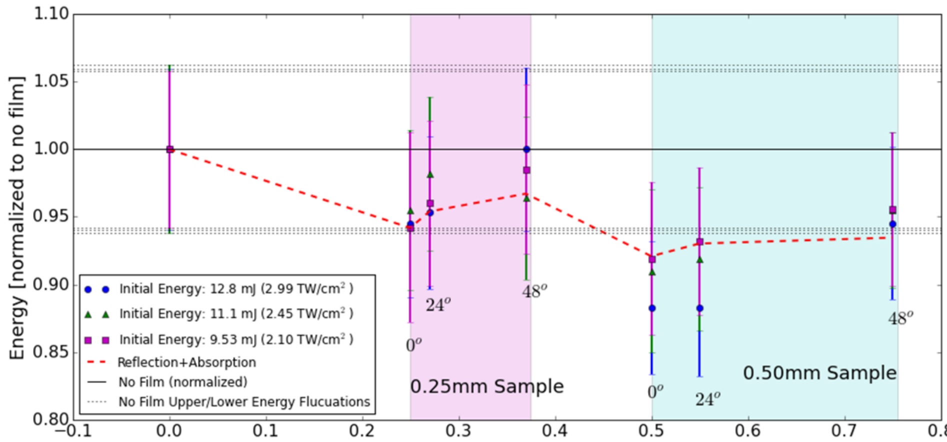
45 nm FWHM bandwidth (22 fs pulse)



Time [fs]



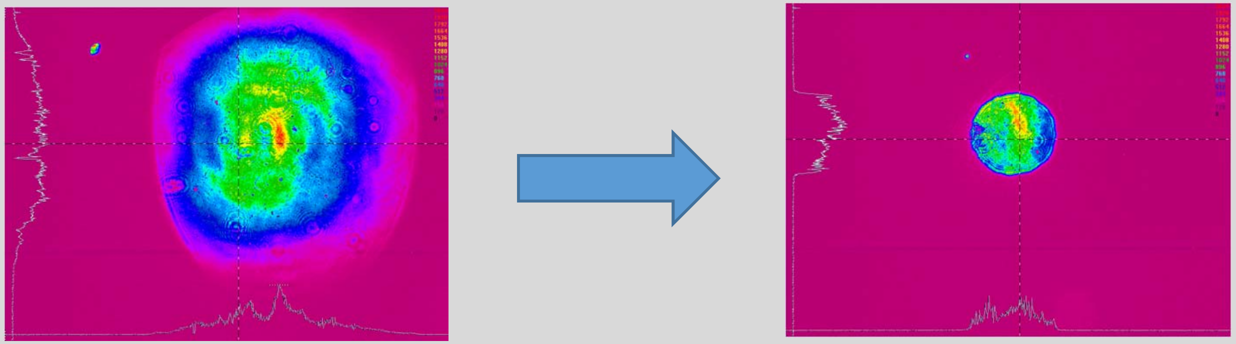
Wavelength [nm]



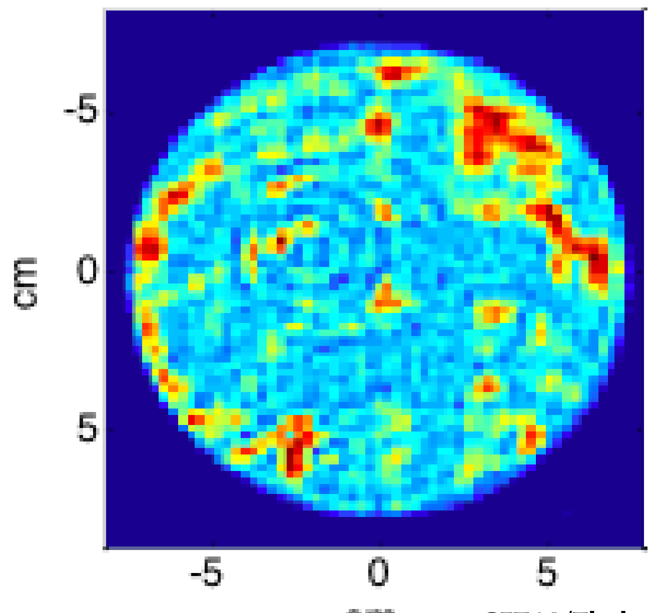
Effective Film Thickness (mm)

The Promise of PW Systems

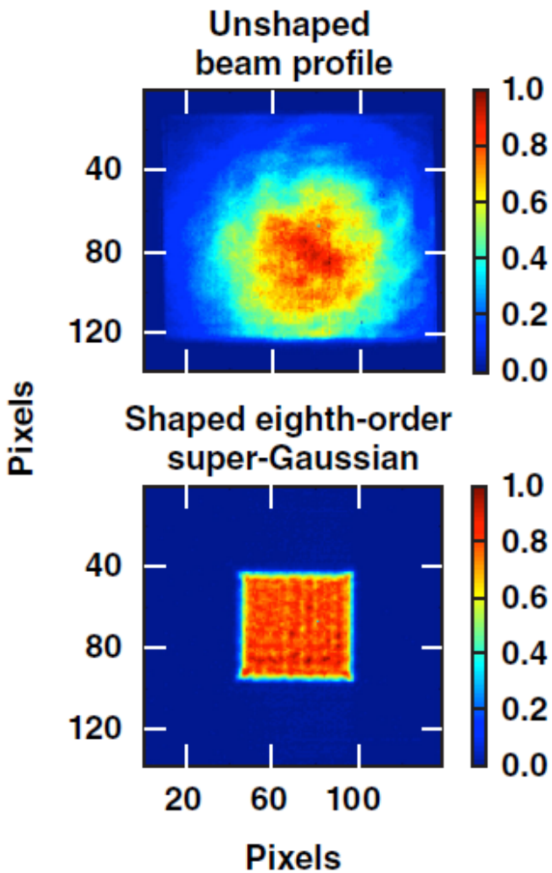
Many laser profiles are less than flat-top



Improved in High Energy Systems



CETAL/Thales



Or/Also Active Control

S.-W. Bahk, I. A. Begishev, and J. D. Zuegel, Opt. Commun. 333, 45 (2014).

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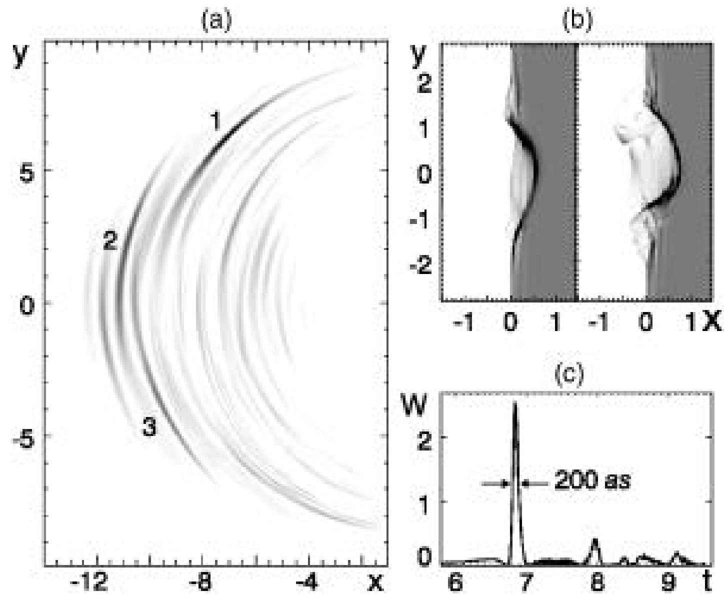
An Exawatt Transition

$$Intensity \propto \frac{E}{\tau(\omega)\,(L(\omega))^2}$$



Phys. Plasmas 12, 056707 (2005)

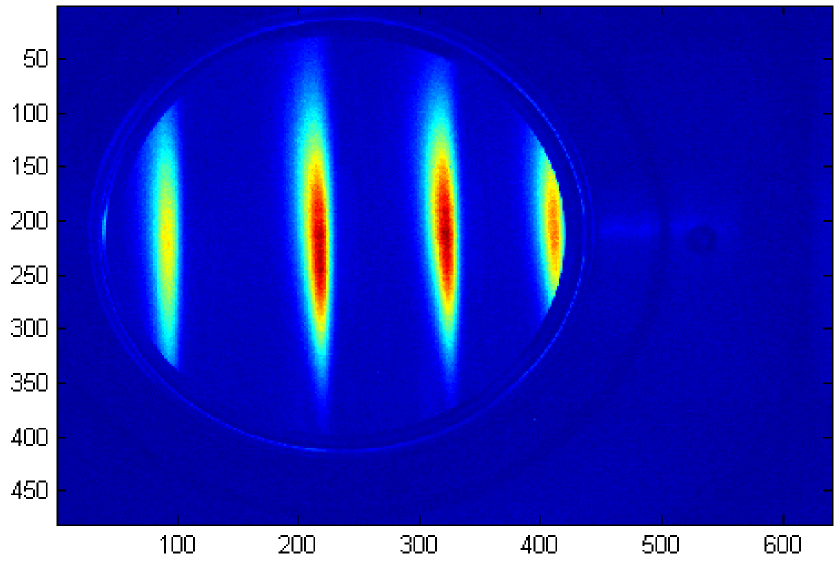
E : *Fixed at input*

L : *Limit dependence on* ω

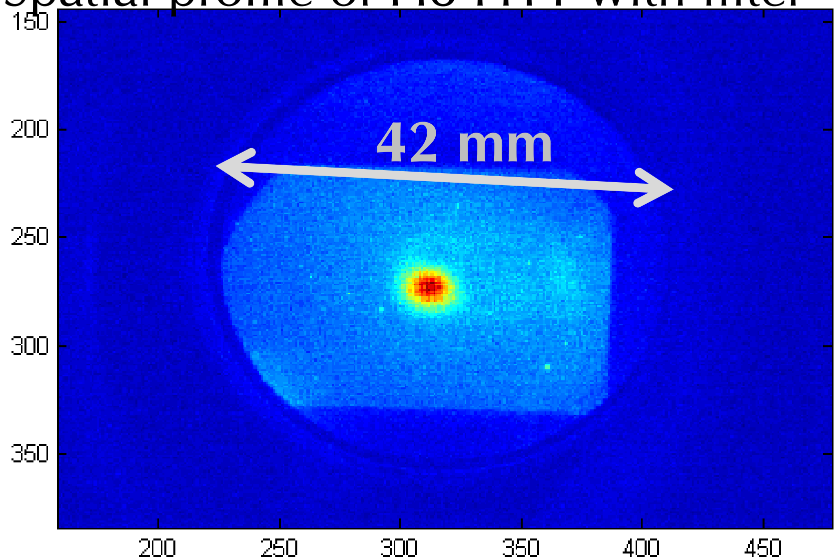
τ : *Limit dependence on* ω

Harmonic Beams from Solid Targets

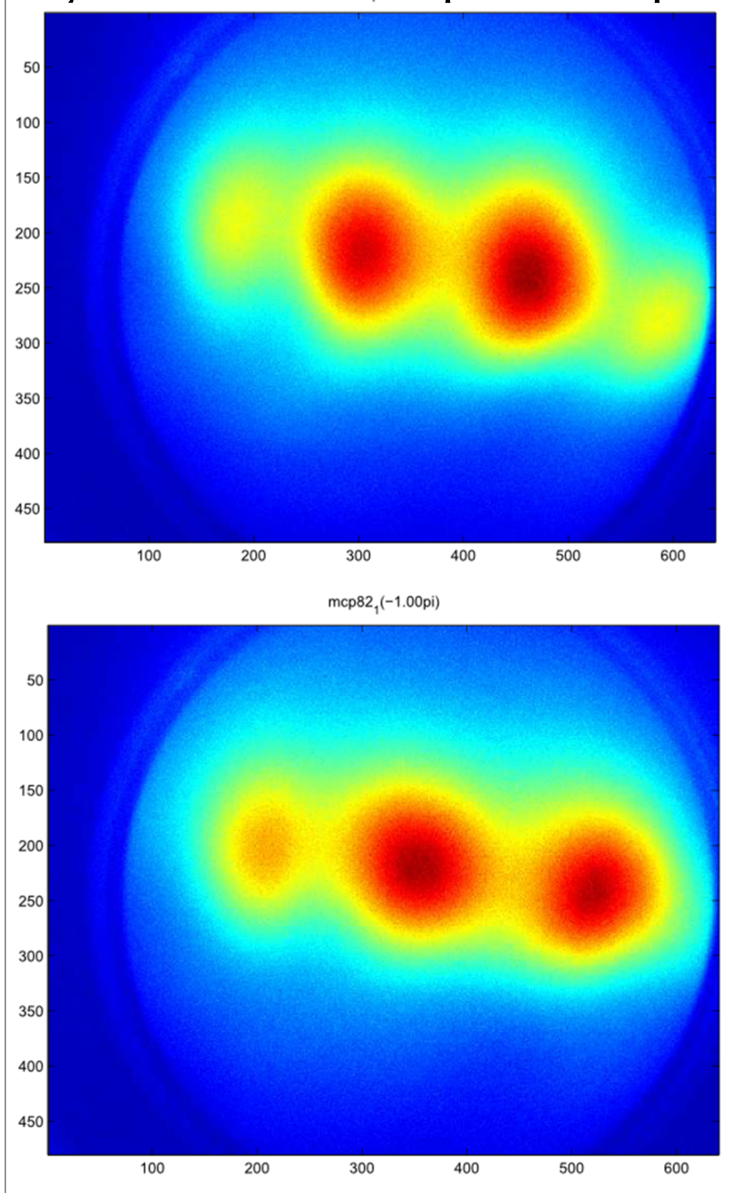
H8-H11 no filter



Spatial profile of H8-H11 with filter



Few-Cycle Beamlets Separated Spatially

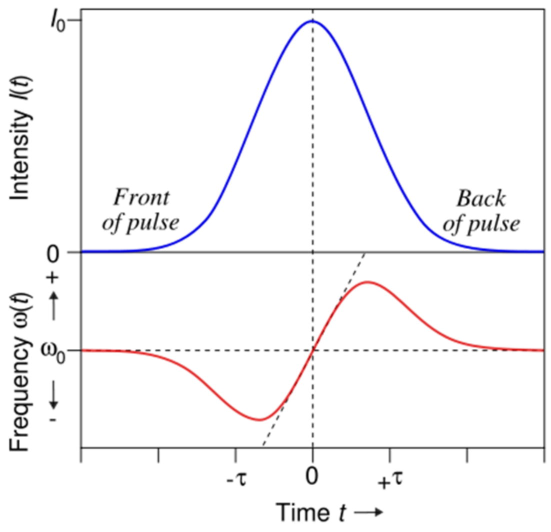


Wheeler et al. *Nat. Photonics* **6** 829–33 (2012)

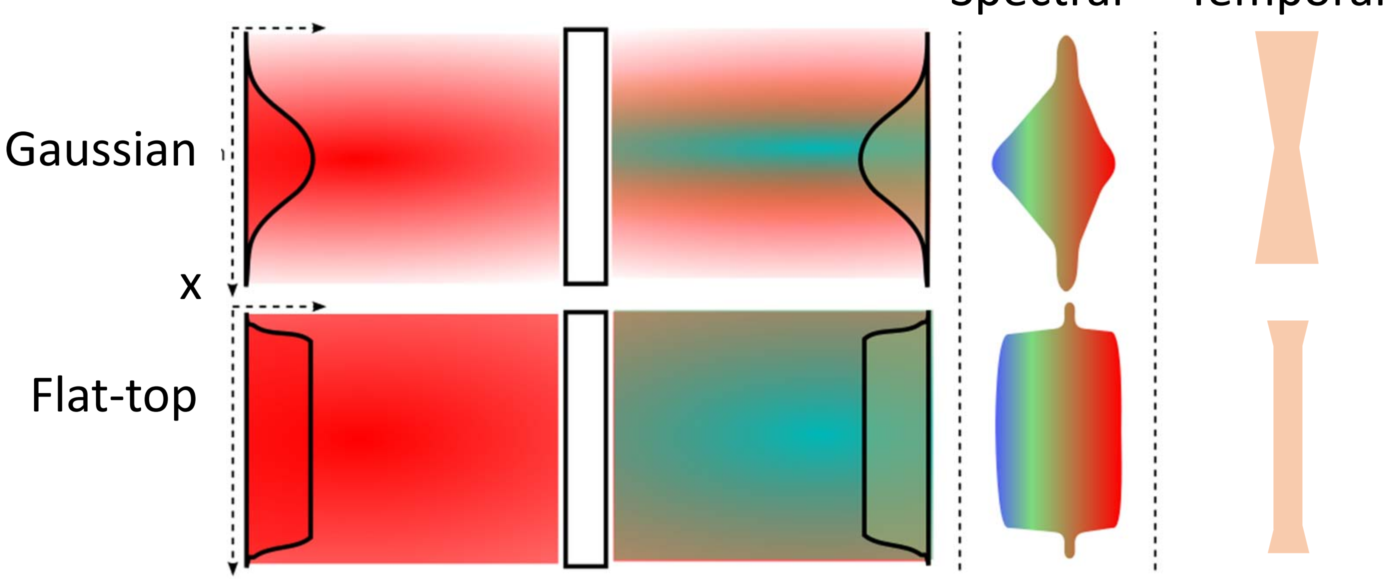
Broad Spectra through Self-Phase Modulation (SPM)

- $n \sim n_o + \frac{1}{2} n_2\, I(x,t)$ — x *dependence : leads to self − focusing*; t dependence: *leads to self − phase modulation*

SPM



Beam Profiles



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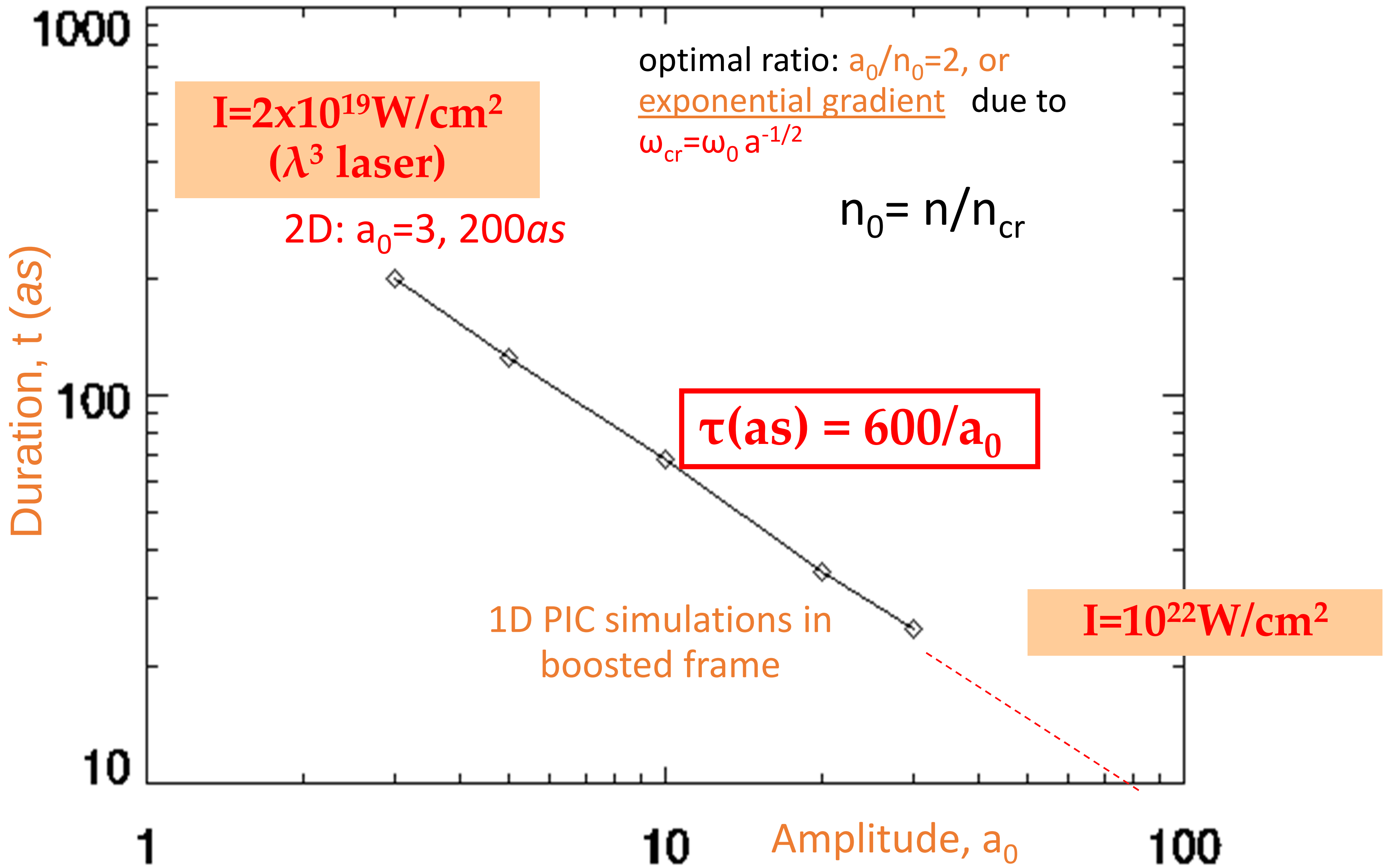
Reflected Pulse Duration



N. M. Naumova, et al., Phys. Rev. Lett. 92, 063902-1 (2004).

Energy within Single-Cycle Pulses