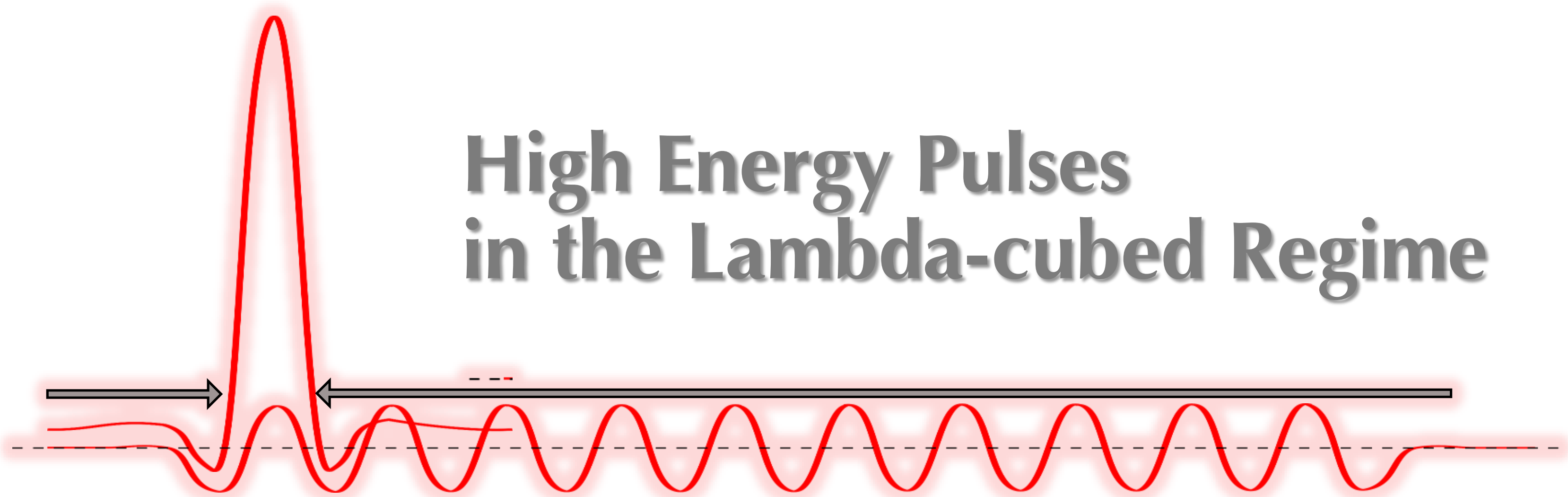
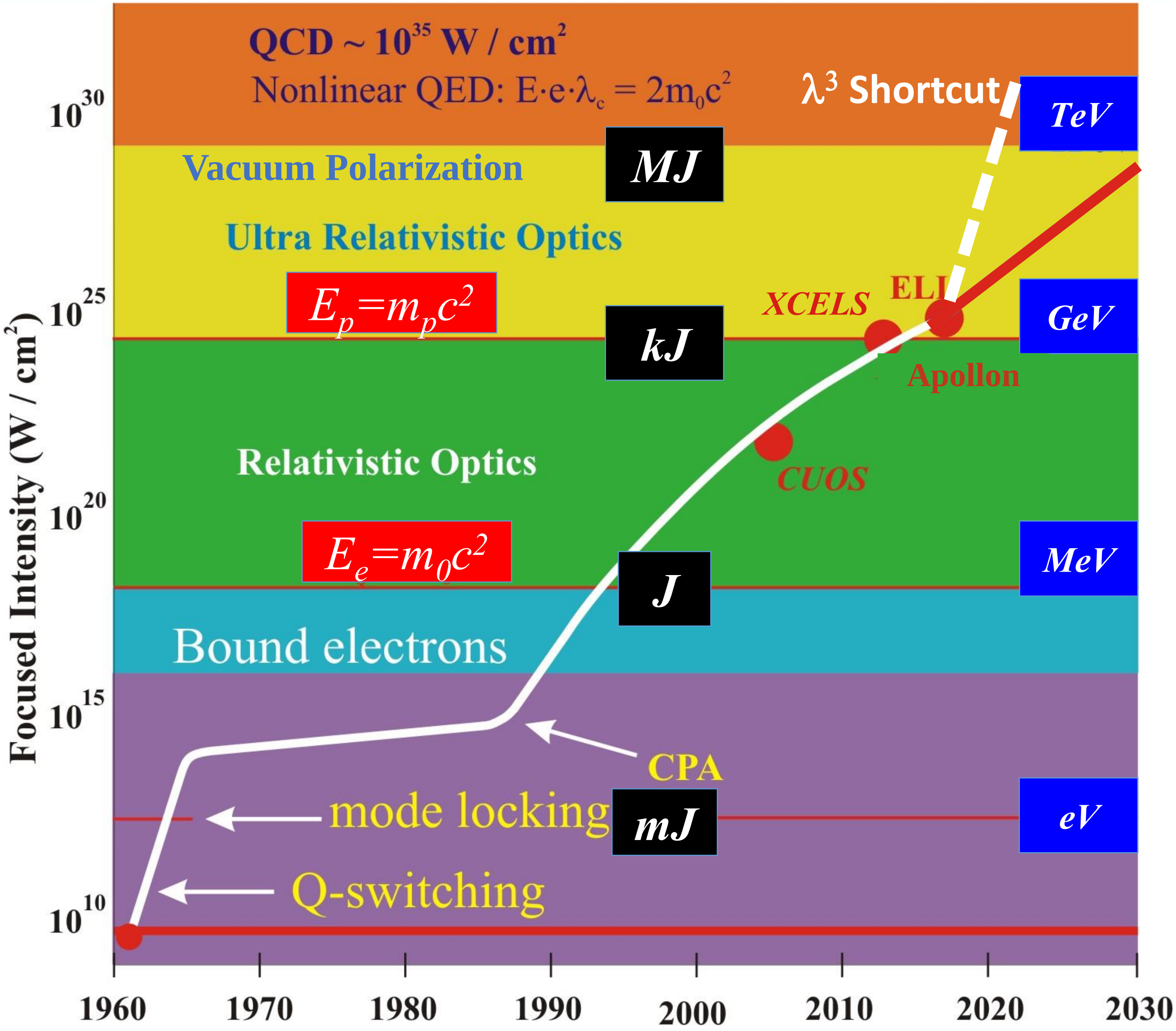
04 April 2017



High Energy Pulses in the Lambda-cubed Regime

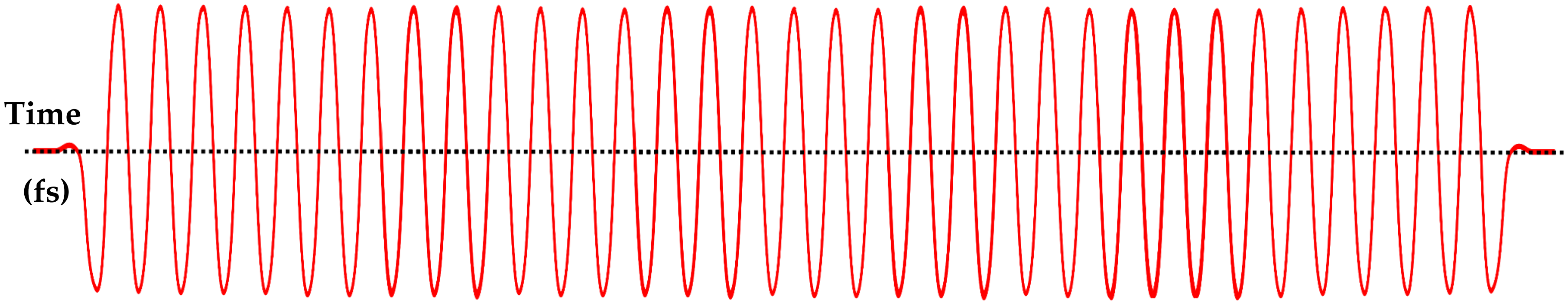
Jonathan WHEELER *(IZEST, Ecole Polytechnique; IFIN-HH, ELI-NP)*
Gérard MOUROU *(IZEST, Ecole Polytechnique)*
Toshi TAJIMA *(IZEST, UCI)*
Sergey MIRONOV *(IAP-RAS)*
Rémy GONIN *(IZEST, Ecole Polytechnique; U.Paris-sud, Orsay)*

Pulse Compression: A Boost to Intensity Enhancement

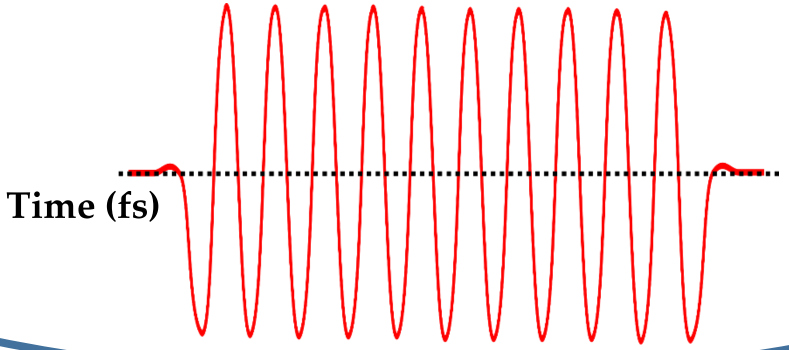


Two Compression Regimes dependent on Initial Pulse

Long Pulse (*i.e.* 50 fs to 500 fs) --> Peak Power Enhancement



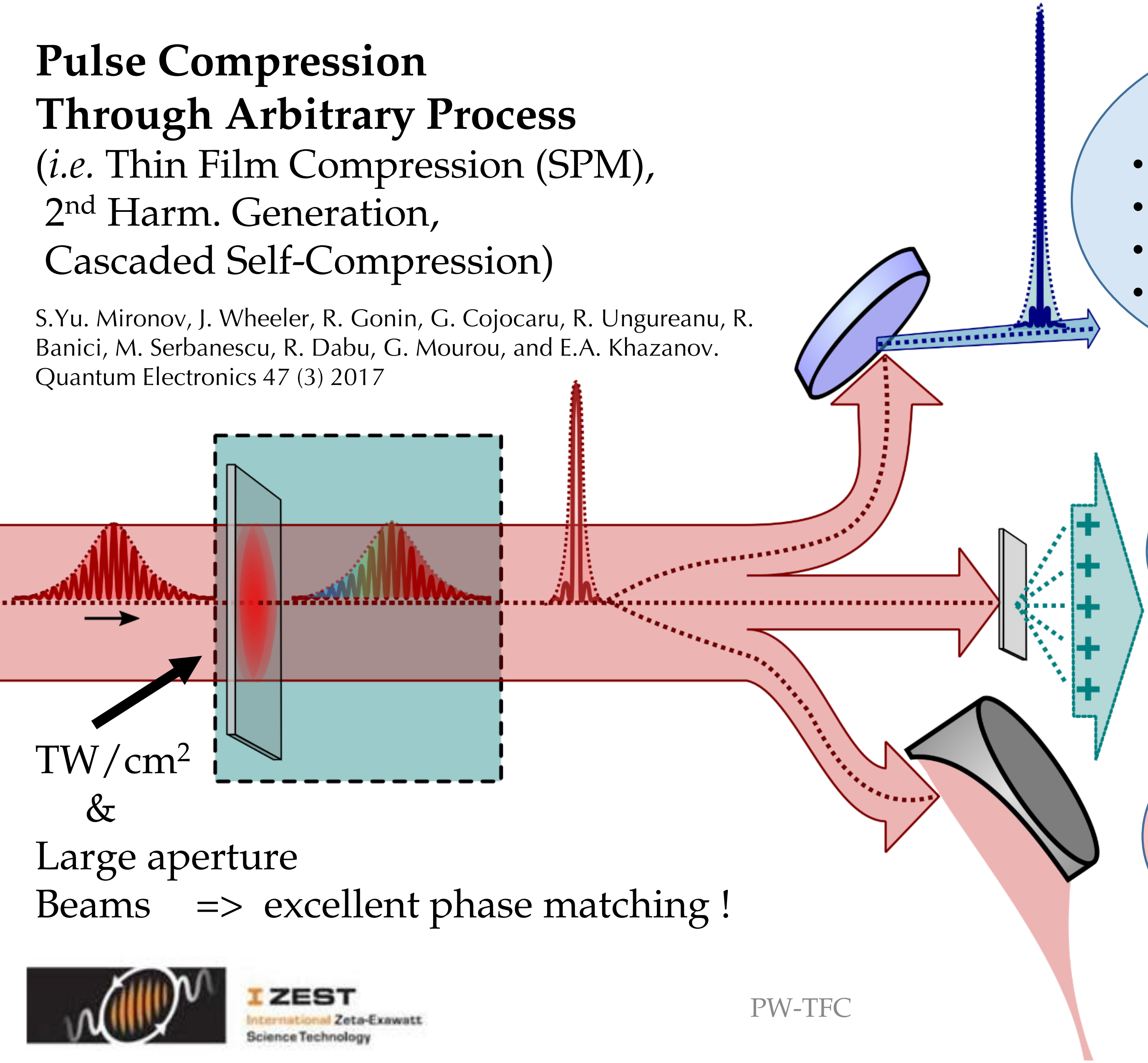
Short Pulse (*i.e.* 15 fs to 50 fs) --> Toward Single Cycle



Pulse Compression Benefitting Several Directions

Pulse Compression
Through Arbitrary Process
(*i.e.* Thin Film Compression (SPM),
2^{nd} Harm. Generation,
Cascaded Self-Compression)

S.Yu. Mironov, J. Wheeler, R. Gonin, G. Cojocaru, R. Ungureanu, R. Banici, M. Serbanescu, R. Dabu, G. Mourou, and E.A. Khazanov. Quantum Electronics 47 (3) 2017



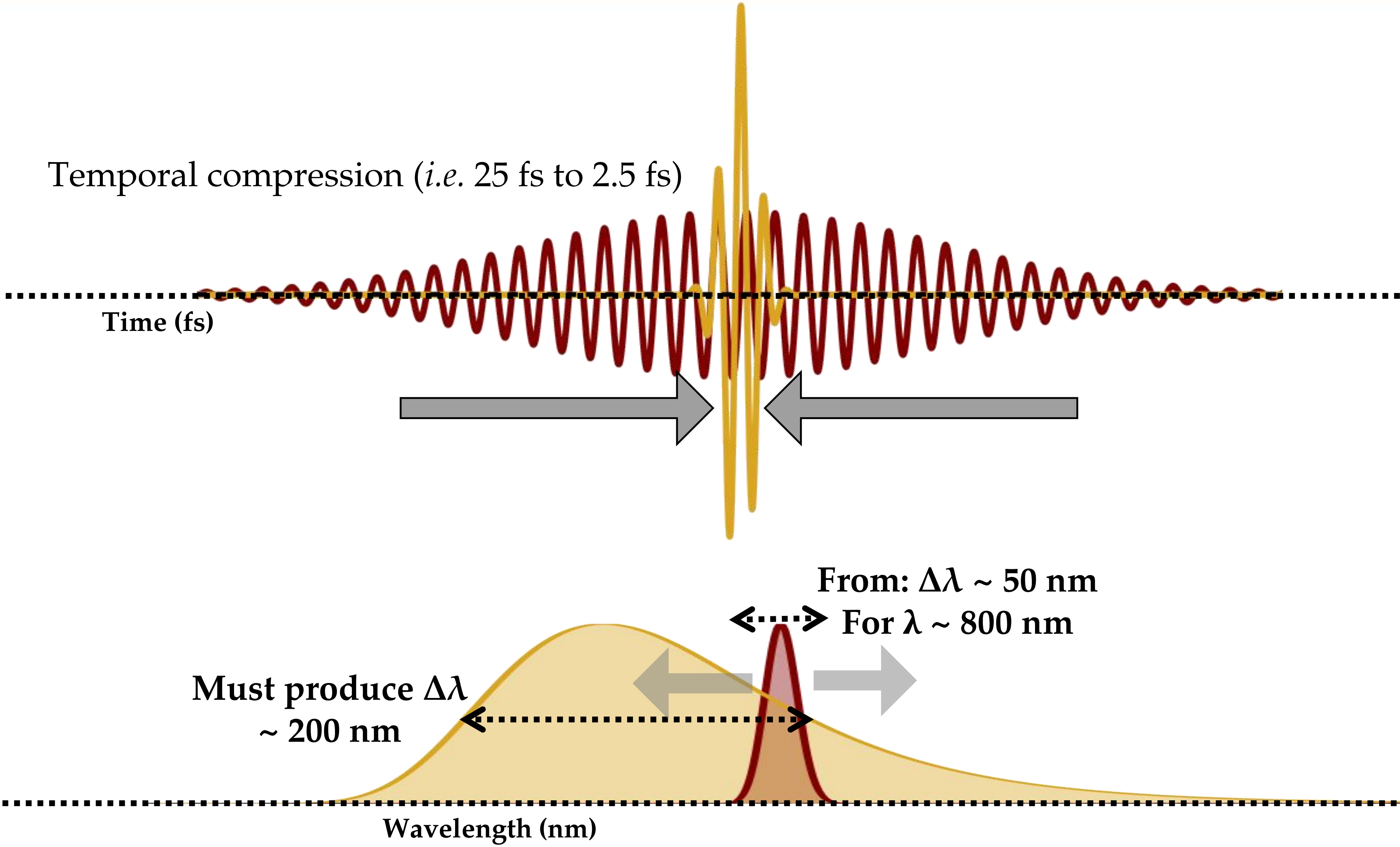
TW/cm^2
&
Large aperture
Beams => excellent phase matching !

X-ray Production:
- Exawatt, Attosec. γ-Pulses
- TW/cm LWF Acceleration
- QED Vacuum Physics
- Table Top Cosmos

Proton Acceleration:
- Energy Enhancement (GeV
- Radio-isotope Production

Direct Use:
- Peak Power Enhancement
- Beam Transport Studies
- Pulse Diagnostics

Compressing toward Single-Cycle Requires Bandwidth



Temporal compression (*i.e.* 25 fs to 2.5 fs)

Time (fs)

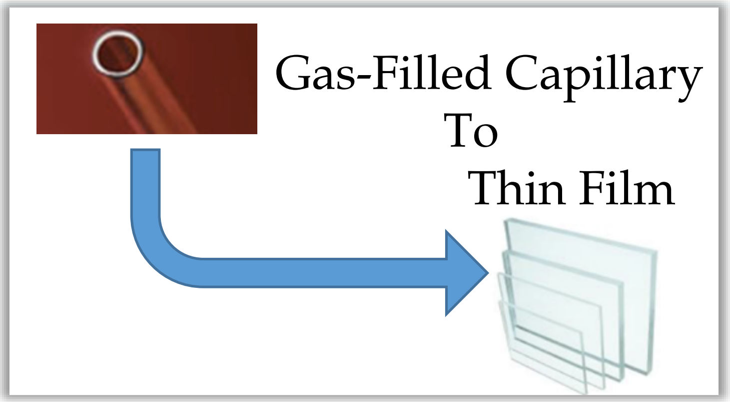
From: Δλ ~ 50 nm
For λ ~ 800 nm

Must produce Δλ
~ 200 nm

Wavelength (nm)

Broaden Spectra through Self-Phase Modulation (SPM)

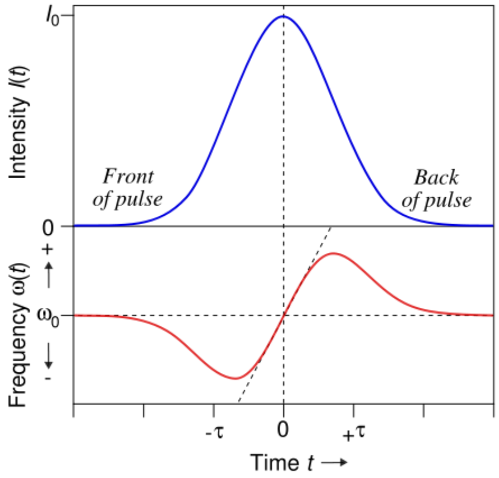
$$n \sim n_o + \underbrace{n_2\, I(x,t)}_{\text{Intensity variation in :}}$$

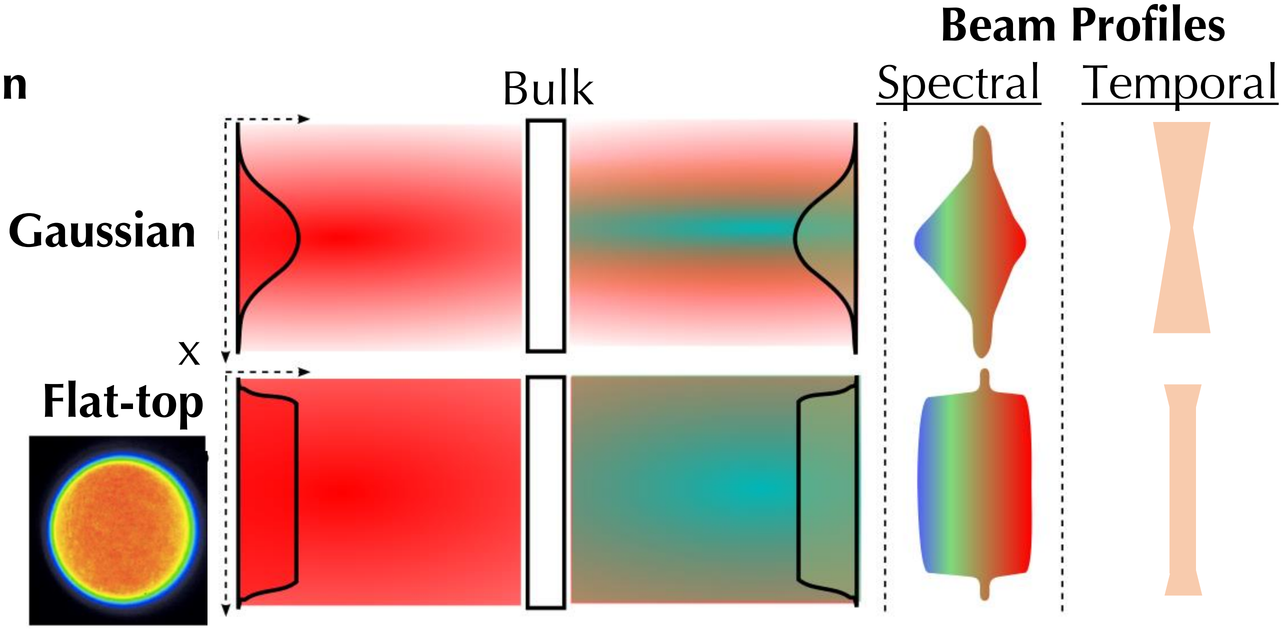


Gas-Filled Capillary
To
Thin Film

Time → Spectral Broadening **Space** → Non-uniformity & Instability

Self – Phase Modulation





Beam Profiles

Spectral Temporal

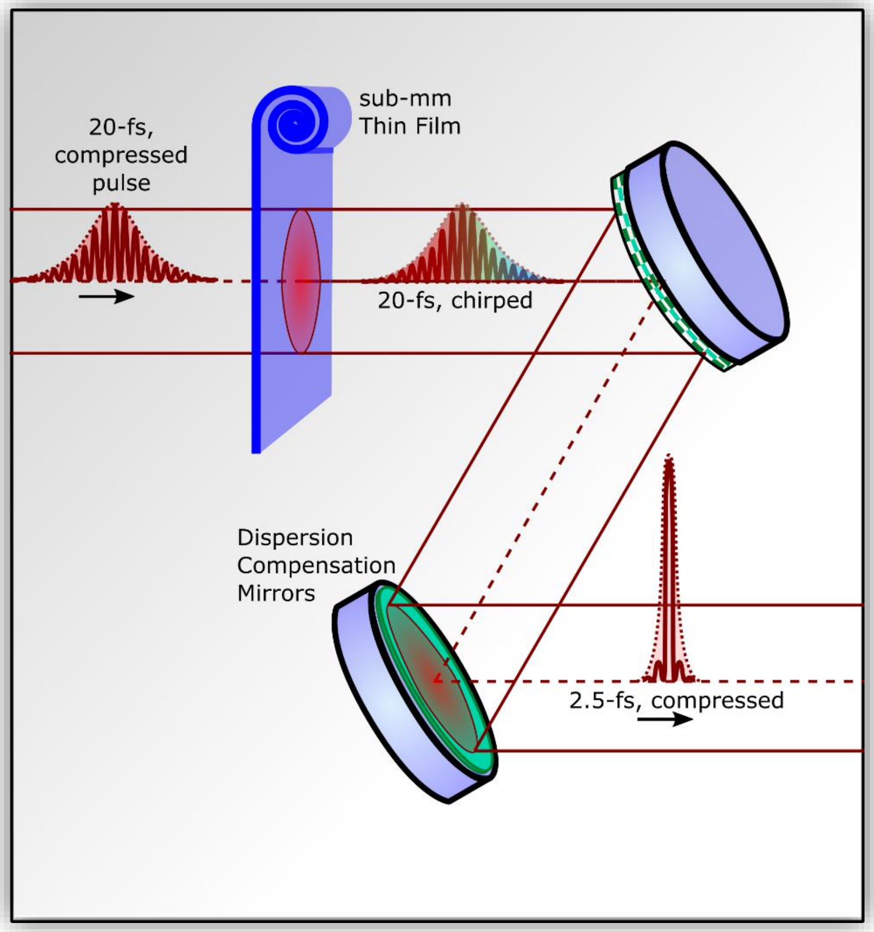
Bulk

Gaussian

x

Flat-top

Thin Film Compression Scheme



G. Mourou, G. Cheriaux, C. Radier Patent 2009
A.A. Voronin, A.M. Zheltikov, T. Ditmire, B. Rus and G. Korn Optics. Com. 2013

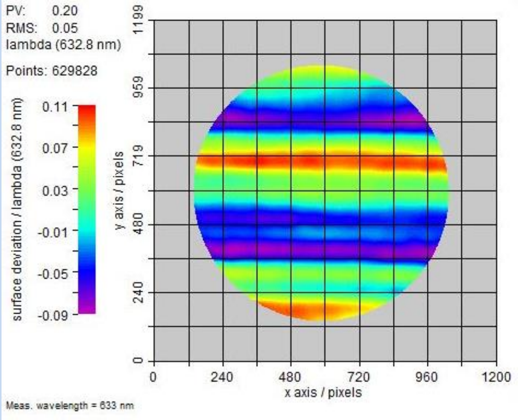
Thin Film Material Requirements

- 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)

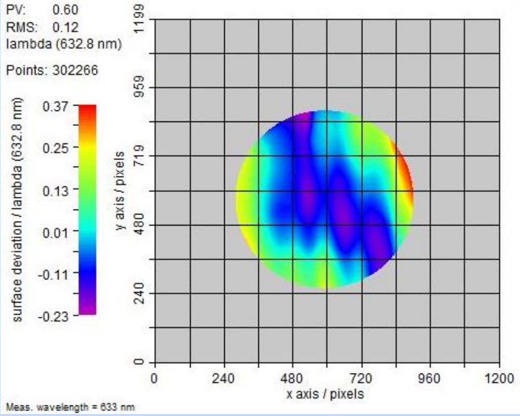
Thin Film Characterization at LULI

R. Gonin, S. Savalle

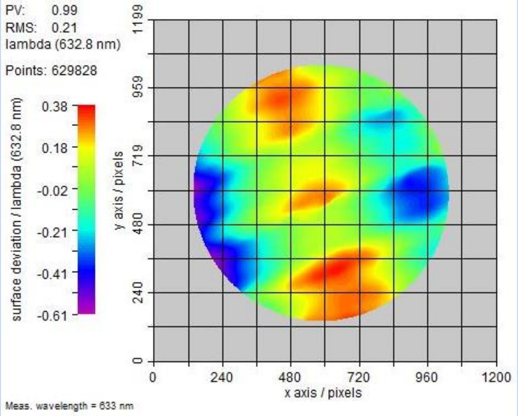
Thin Glass (Schott AF32: 0.10 mm)



Cyclo Olefin Copolymer (APEL: 0.10 mm)

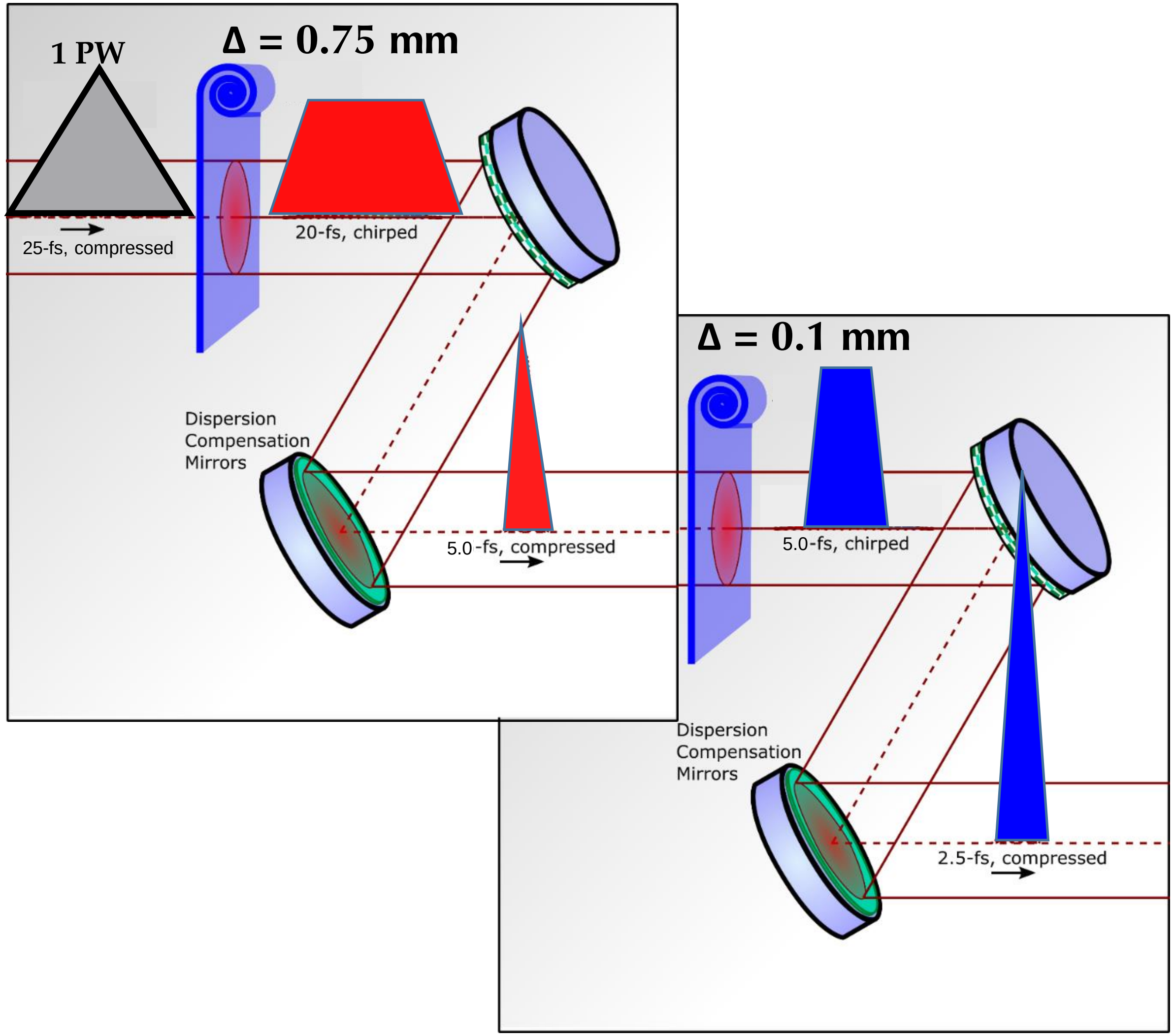


PMMA (acrylic glass: 0.50 mm)

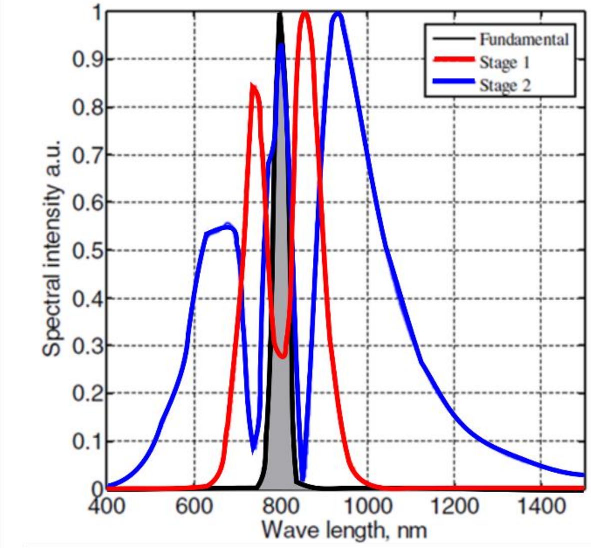


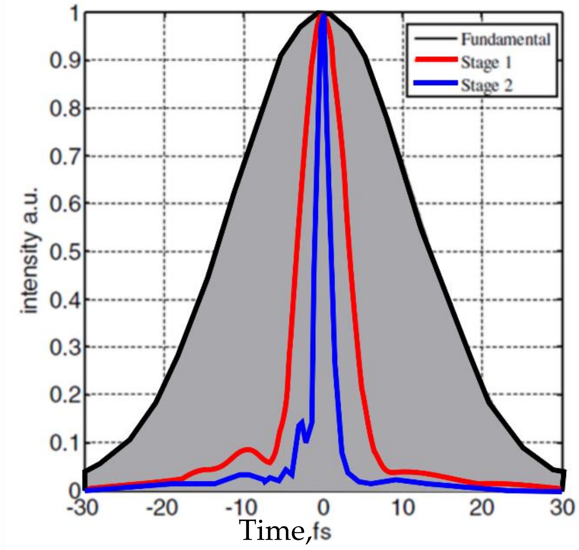
Material	Thickness (mm)	Peak to Valley (633nm)
Cyclo Olefin Copolymer (APEL)	0.10	0.56 ± 0.03 λ
Cyclo Olefin Copolymer (Zeonor - ZF16)	0.10	TBD
-	-	-
Thin Glass (Schott D263)	0.90	0.39 λ
Thin Glass (Schott D263)	0.21	0.32 +/- 0.07 λ
Thin Glass (Schott AF32)	0.50	1.12 ± 0.08 λ
Thin Glass (Schott AF32)	0.10	0.05 λ
-	-	-
Multilayer film (Phone Protector)		0.44 λ
PMMA (acrylic glass)	0.50	0.99 λ
Di-acetate (low quality)	0.50	2.3 ± 0.3 λ
PET (low quality)	0.125	1.78 λ

Thin Film Compression Modeling



S. Mironov, E. Khazanov

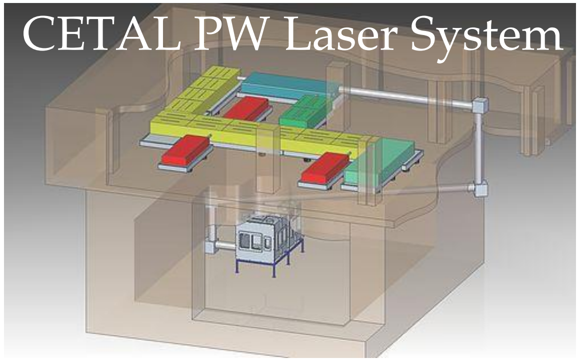




Design based on the CETAL 1-PW laser system.
Mourou G. et al. *Eur. Phys. J. Spec. Top.* **223** 1181–8 (2014)

Thin Film Compression at CETAL 1PW

G. Cojocaru, R. Ungureanu, R. Banici, M. Serbanescu


CETAL PW Laser System

PW output specification

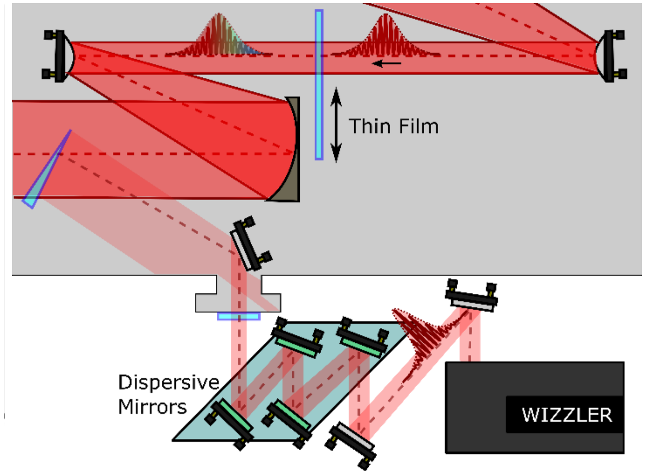
- Peak power ≥ 1 PW
- Pulse duration < 25 fs
- Repetition rate 0,1Hz
- ps pre-pulse contrast 10^{11} @ 100ps

TW output specification

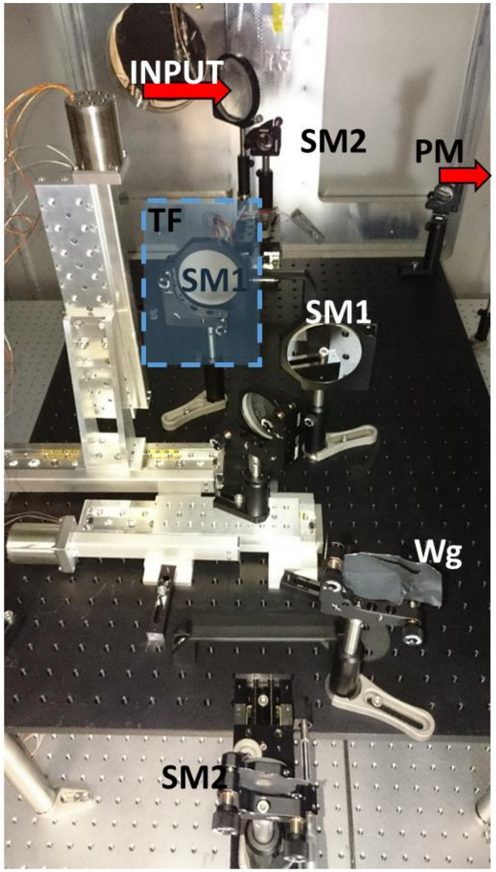
- Peak power ≥ 45 TW
- Pulse duration < 25 fs
- Repetition rate 10Hz
- Ps pre-pulse contrast 10^{11} @ 100ps

by Thales Optronique S.A

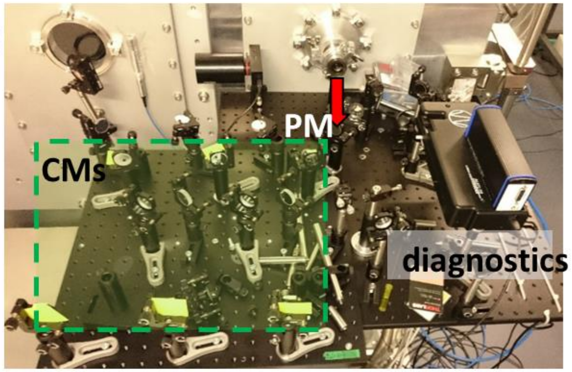
200mJ; 50fs; beam area: 1 cm^2
Intensities at interaction: 1.0 – 3.0 TW/cm^2



b)



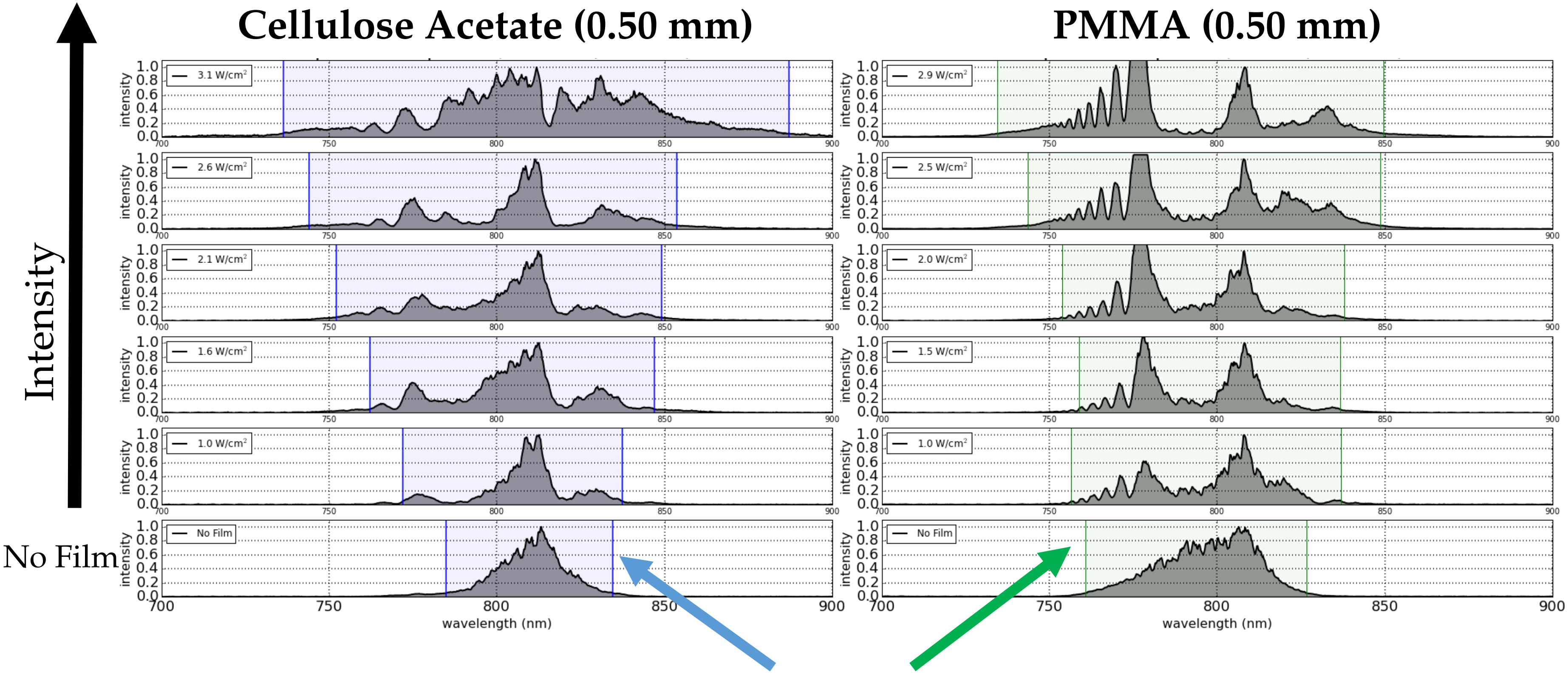
c)



The Measured Spectral Broadening

200mJ; 50fs

Intensities at interaction: 1.0 – 3.0 TW/cm^2



Cellulose Acetate (0.50 mm)

PMMA (0.50 mm)

Shaded regions represents spectrum at 5% of maximum

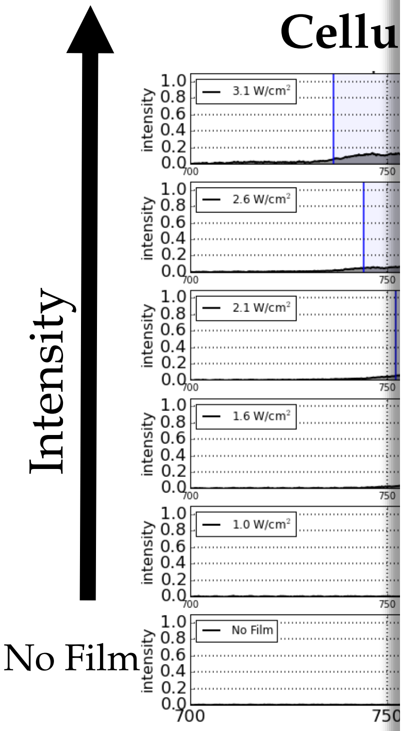
The Measured Spectral Broadening

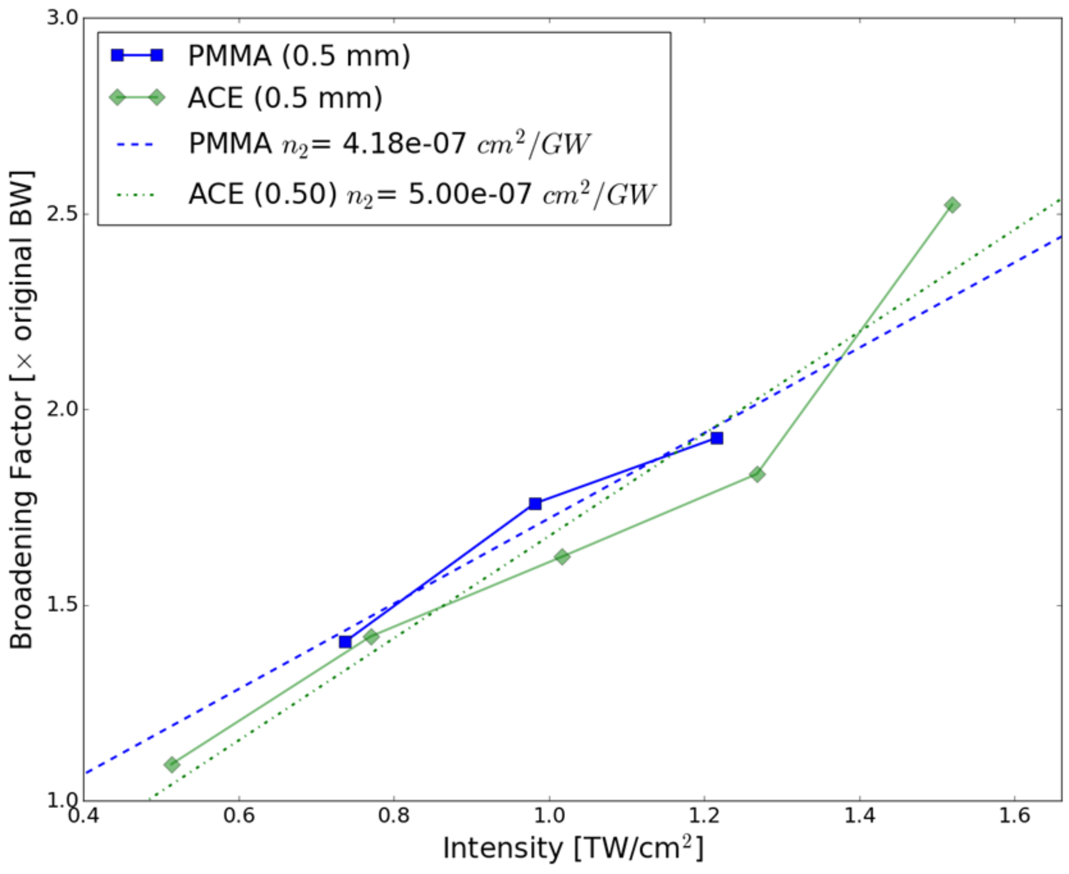
200mJ; 50fs

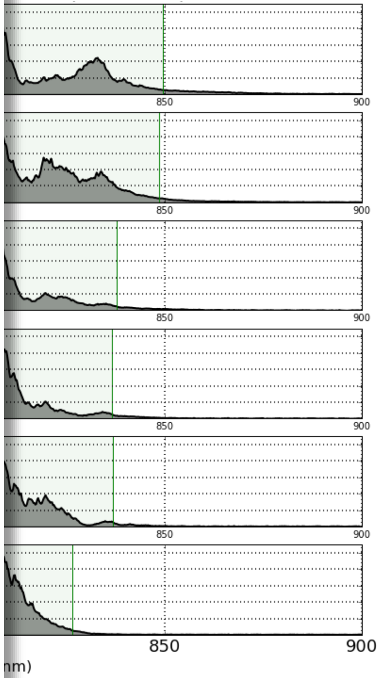
Intensities at interaction: 1.0 – 3.0 TW/cm²

Cellu

50 mm)

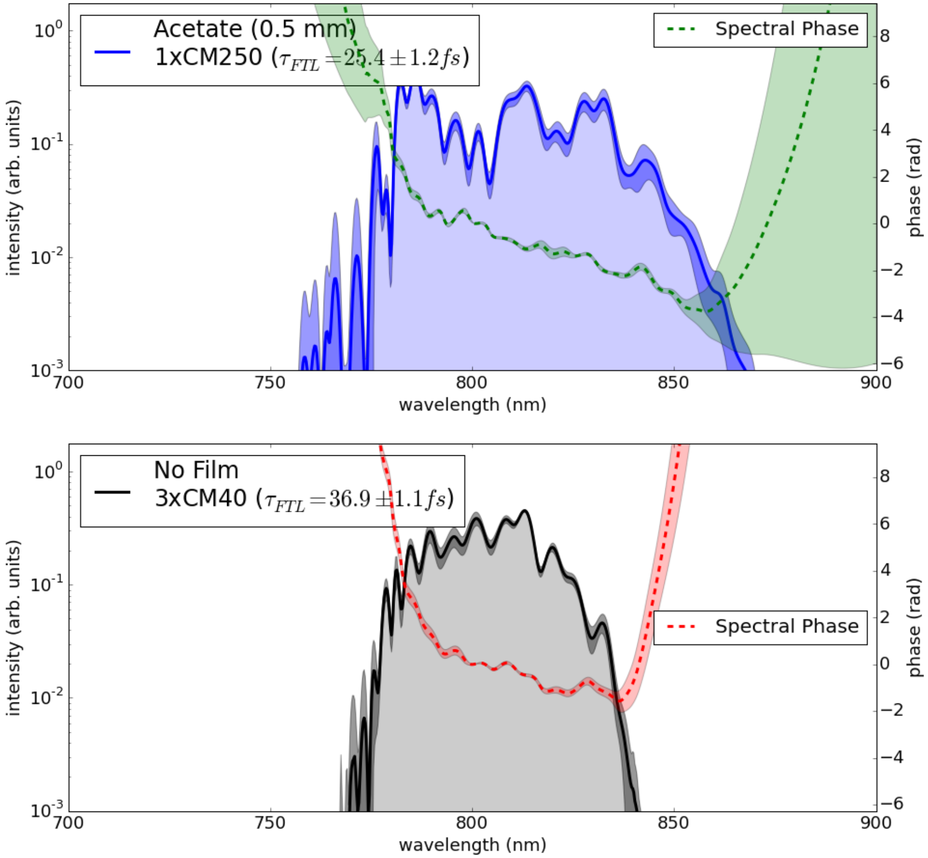


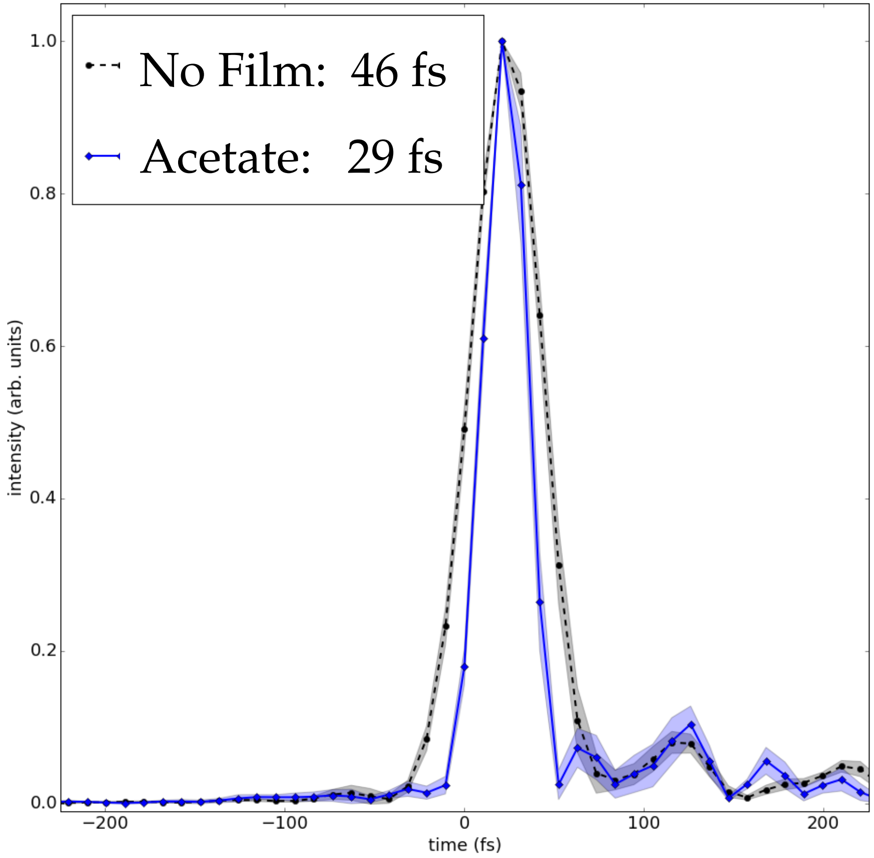




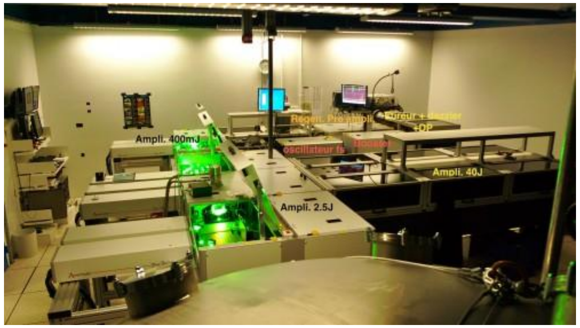
Shaded regions represents spectrum at 5% of maximum

Recompression Achieved with a pair of chirped mirrors





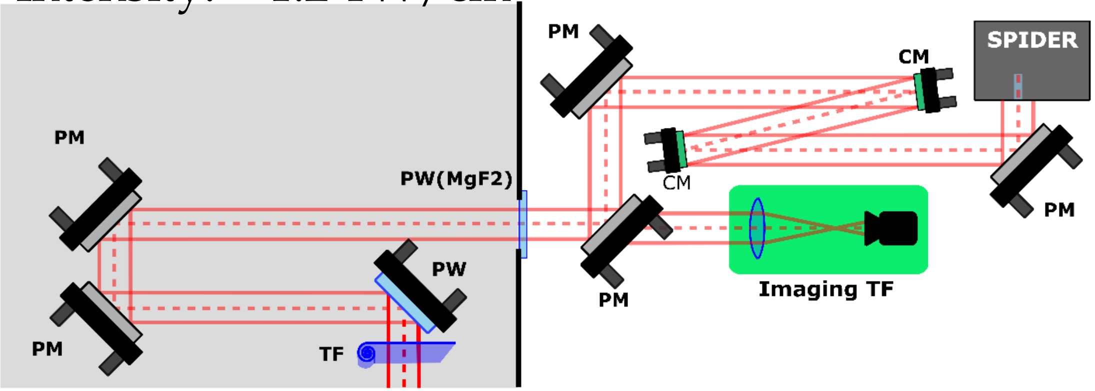
Thin Film Compression at Laserix



R. Gonin, J. Demailly, E. Baynard, M. Pittman, D. Ros

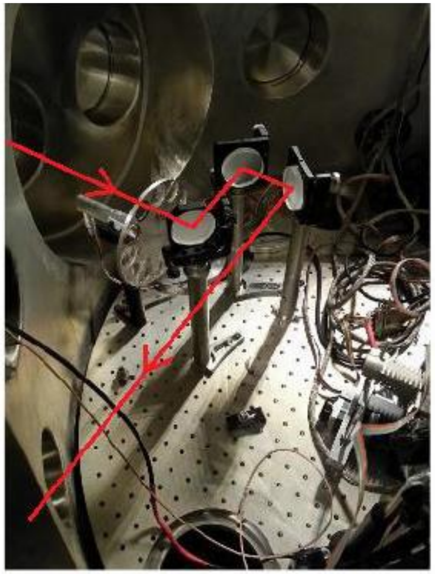
250mJ; 50fs; beam area: 2.25 cm^2

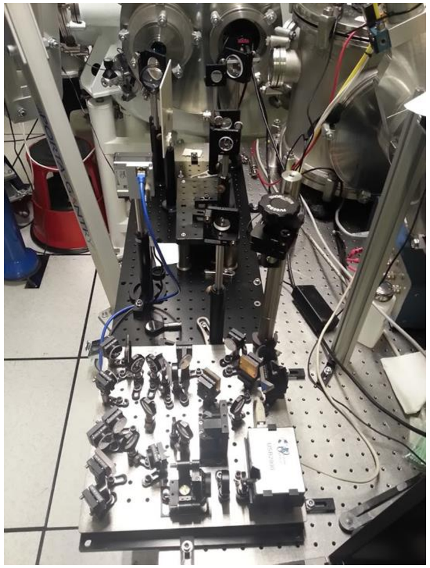
Intensity: ~ 1.2 TW/cm^2



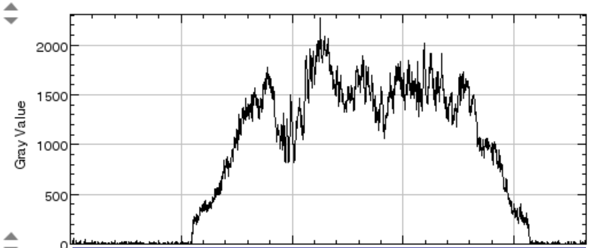
Output specifications :

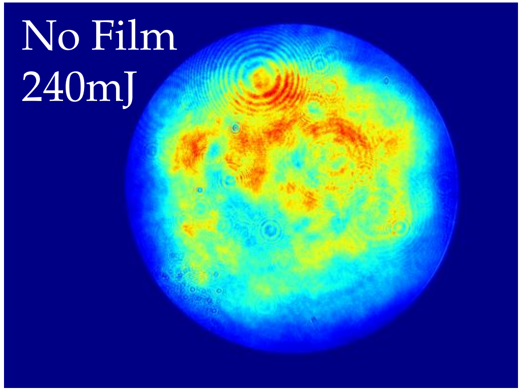
- Peak power ≥ 50 TW
- Pulse energy = 2.5 J
- Pulse duration < 40 fs
- Repetition rate 10 Hz
- Temporal contrast 10^8

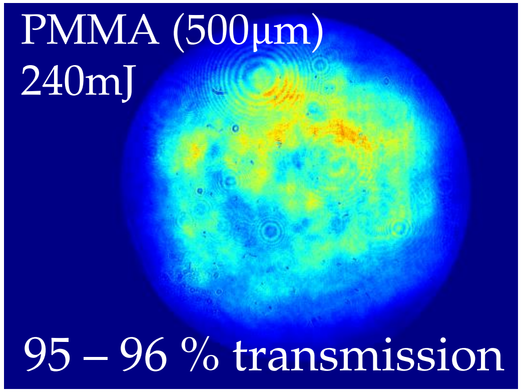


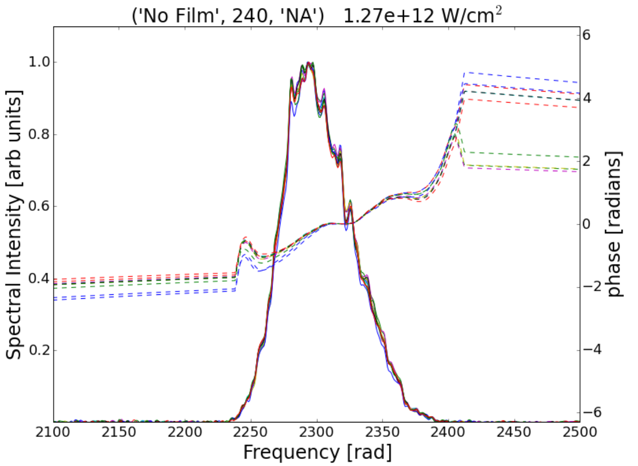


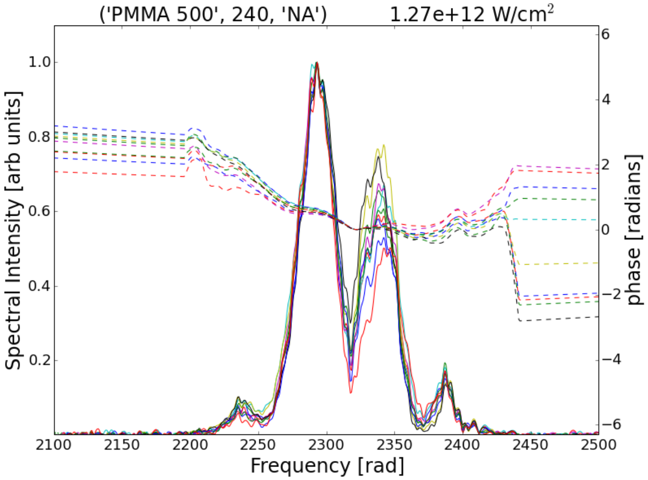
Thin Film Compression at Laserix

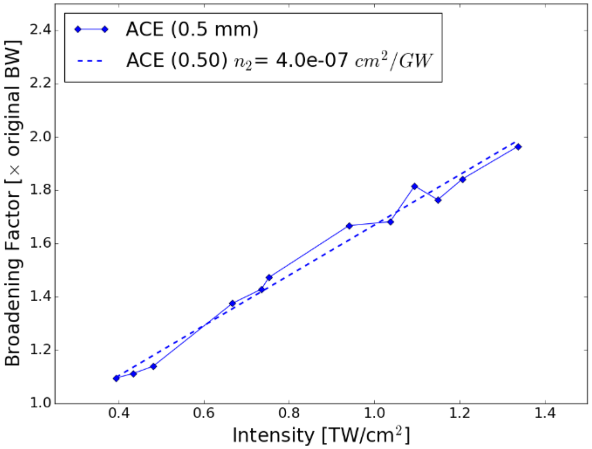






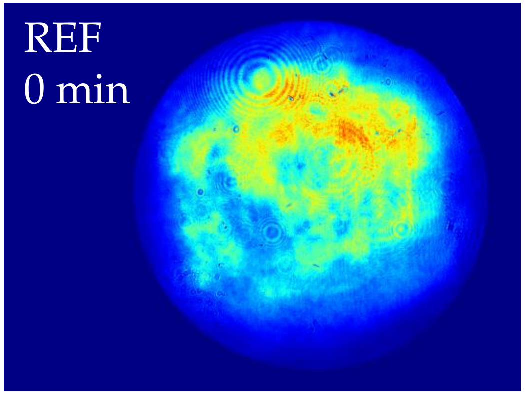


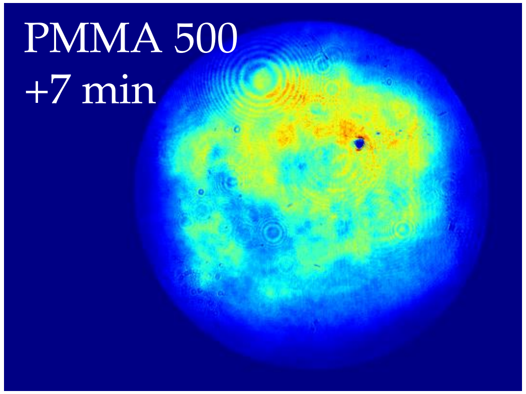


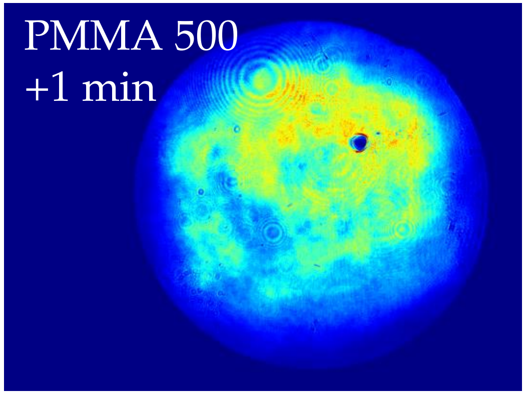


- Input Pulse duration:
  - **approx. 80 fs**
- ⇧ ~ 2x Bandwidth
- Estimate $n_2 \alpha$ slope :
  - **2.4x10^{-7} cm^2/GW**
- B-integral of ~ 1.3

Thin Film Compression at Laserix





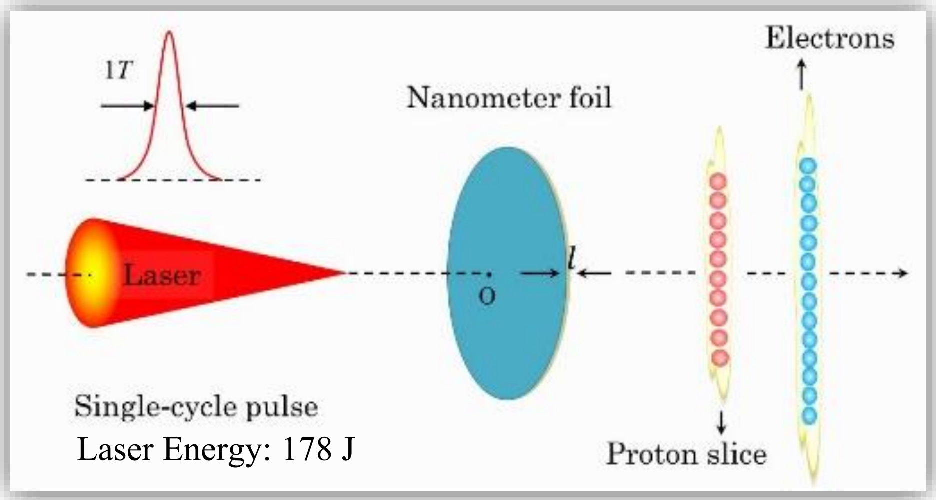


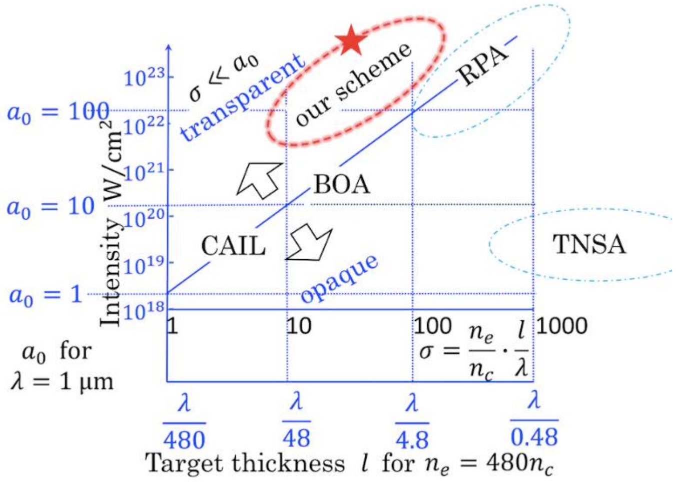
PMMA film (500 μm) damage after 7 minutes at 10 Hz (~ 4000 shots)

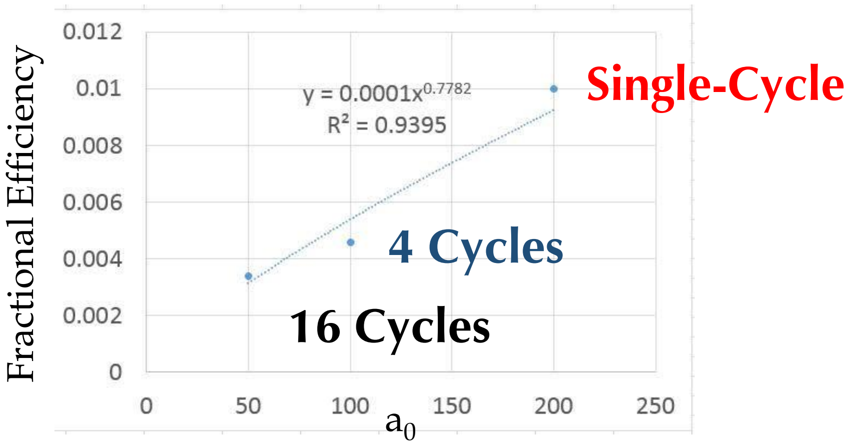
Average Intensity: 1.6 TW/cm^2 → upper end of desired range

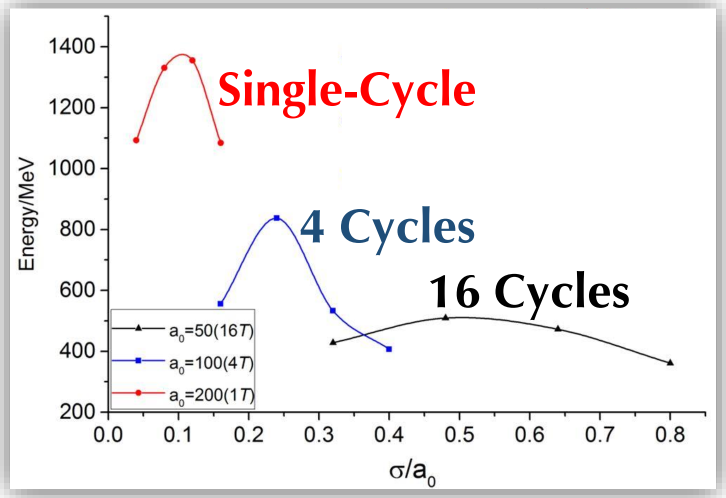
BUT Intensity near damage is nearly 2x at over 3.5 TW/cm^2

Stable Proton Acceleration



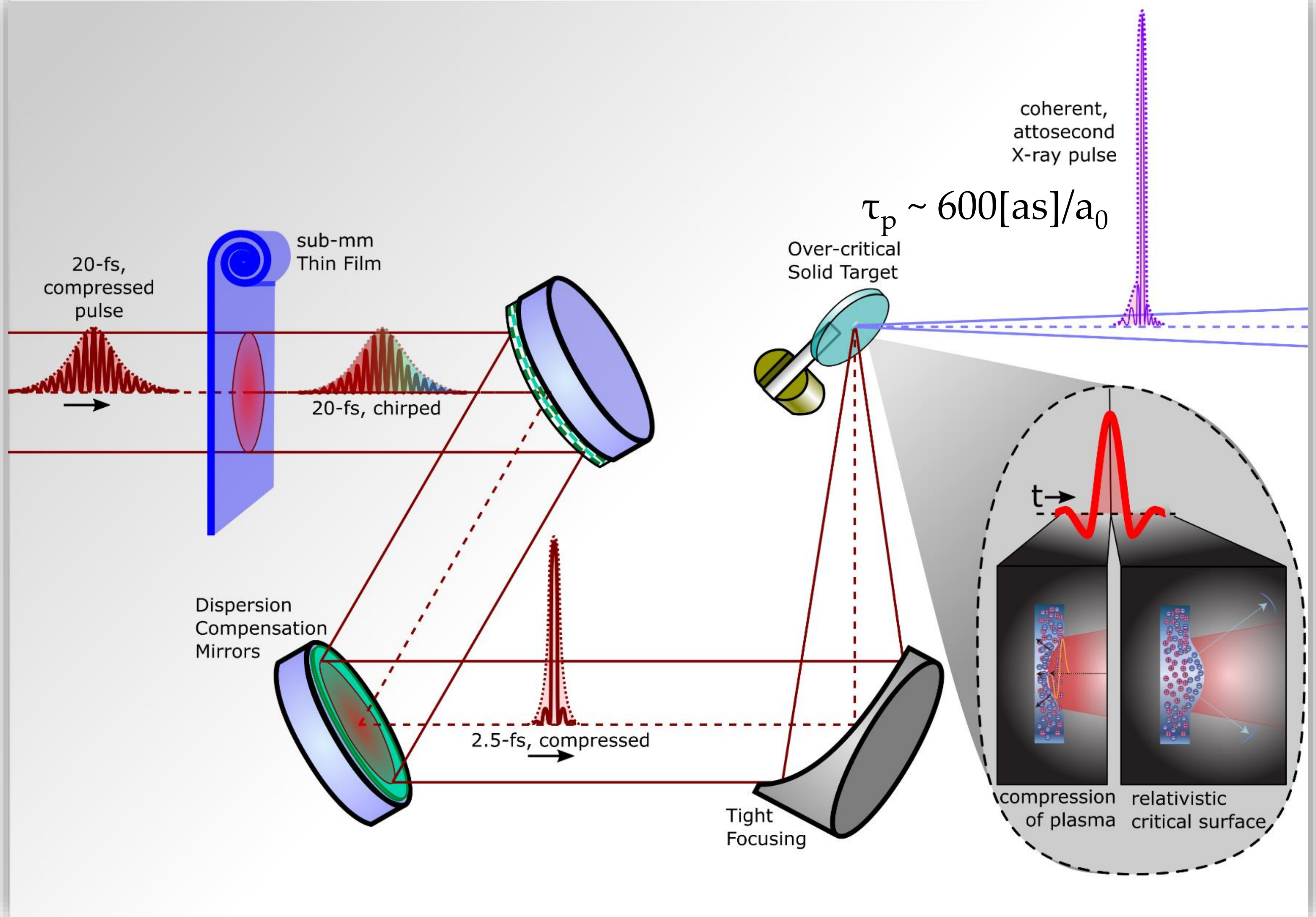






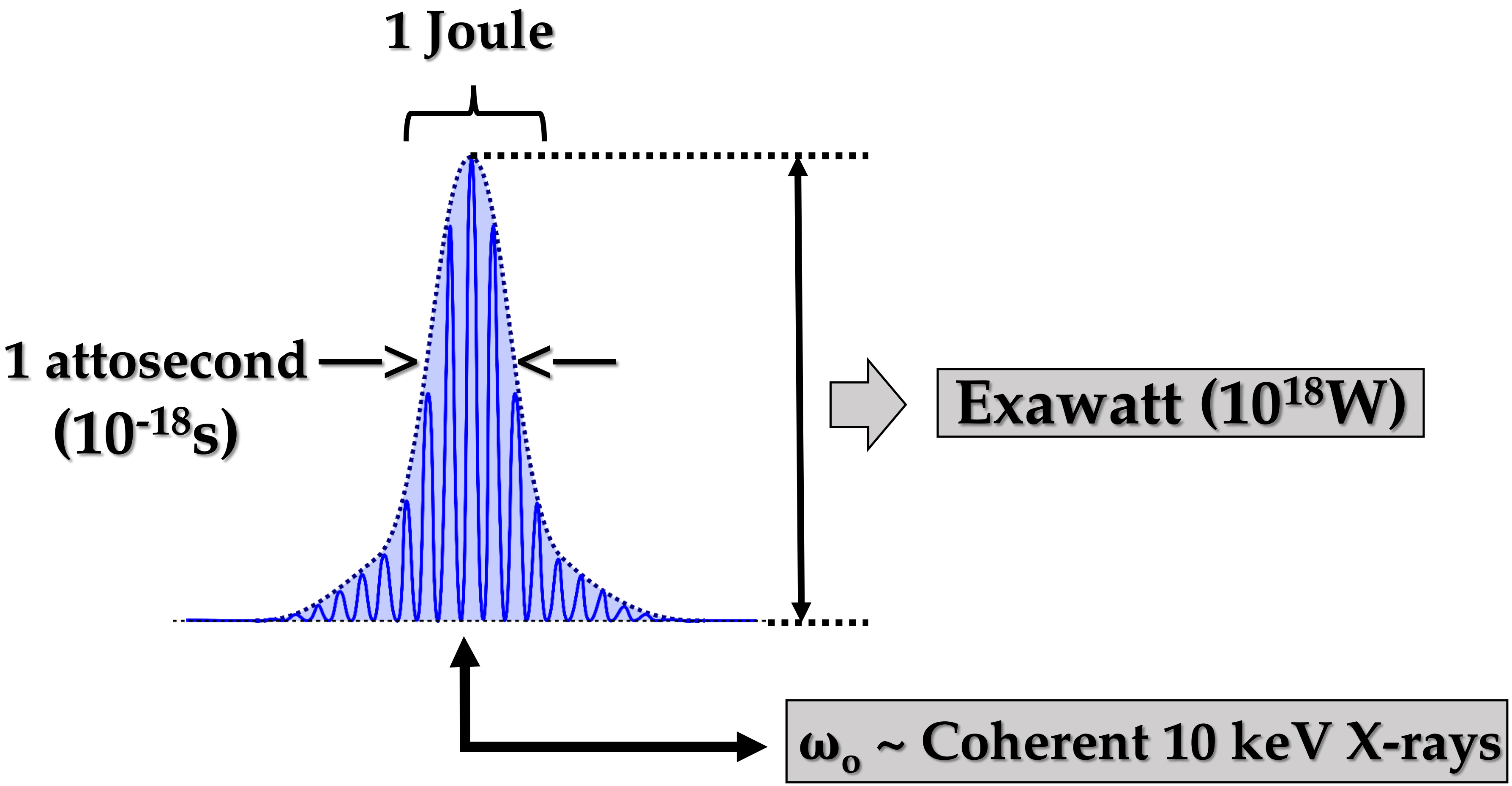
M. L. Zhou *et al. Phys. Plasmas*, **23** (4), p. 43112 (2016)
“Proton acceleration by single-cycle laser pulses offers a novel monoenergetic and stable operating regime,”

Extreme Compression to X-rays



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

Shorter makes Exawatt achievable



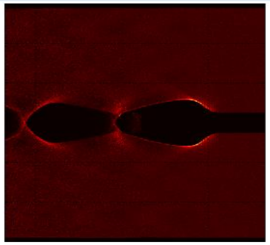
1 Joule

1 attosecond —> <—
(10^{-18}s)

Exawatt (10^{18}W)

ω_o ~ Coherent 10 keV X-rays

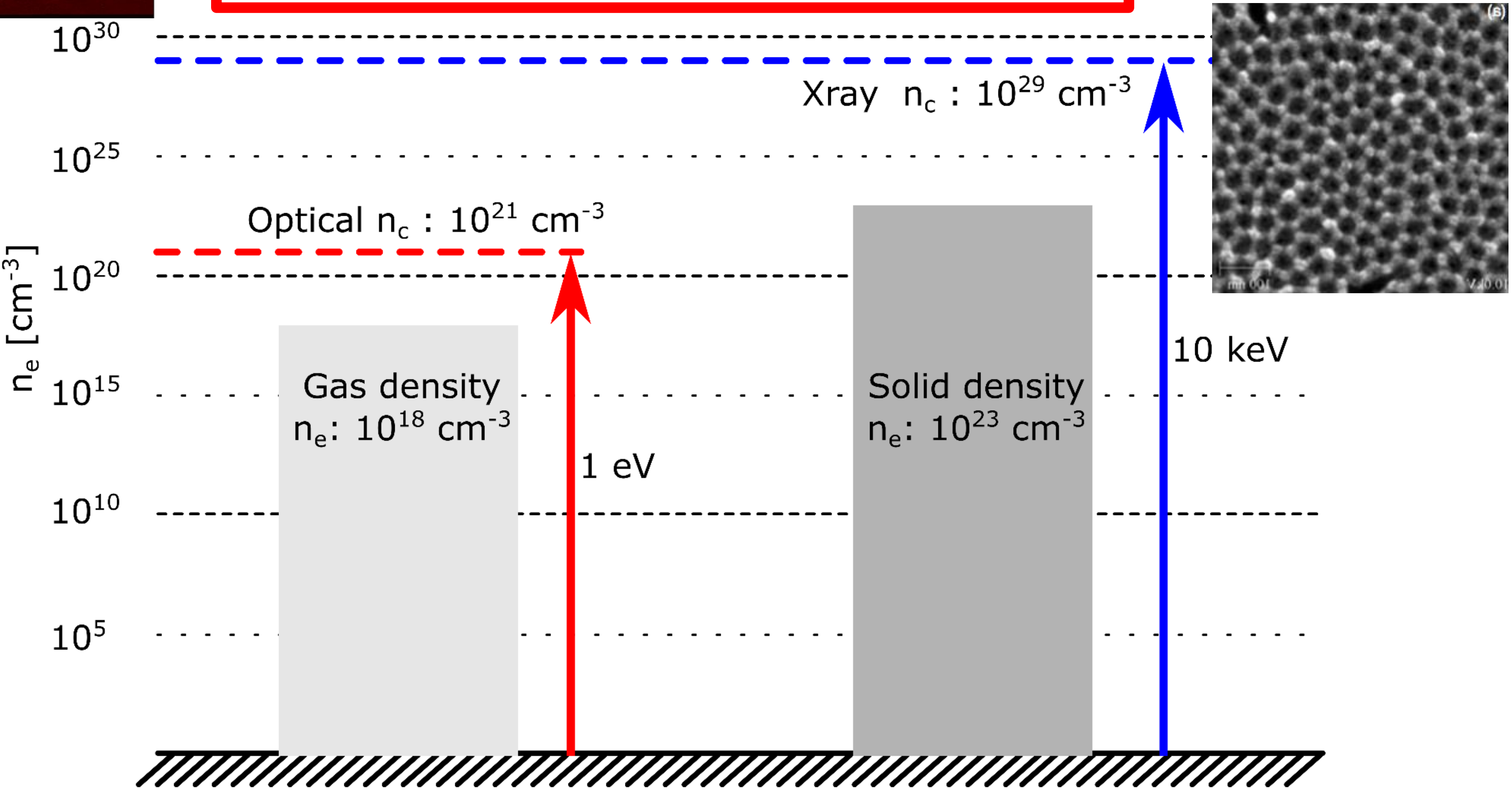
Laser Wakefield Acceleration: Gas/Optical vs Solid/ X-Ray



Energy Gain: $E=a_0^2 m_o c^2 (n_c/n_e)$

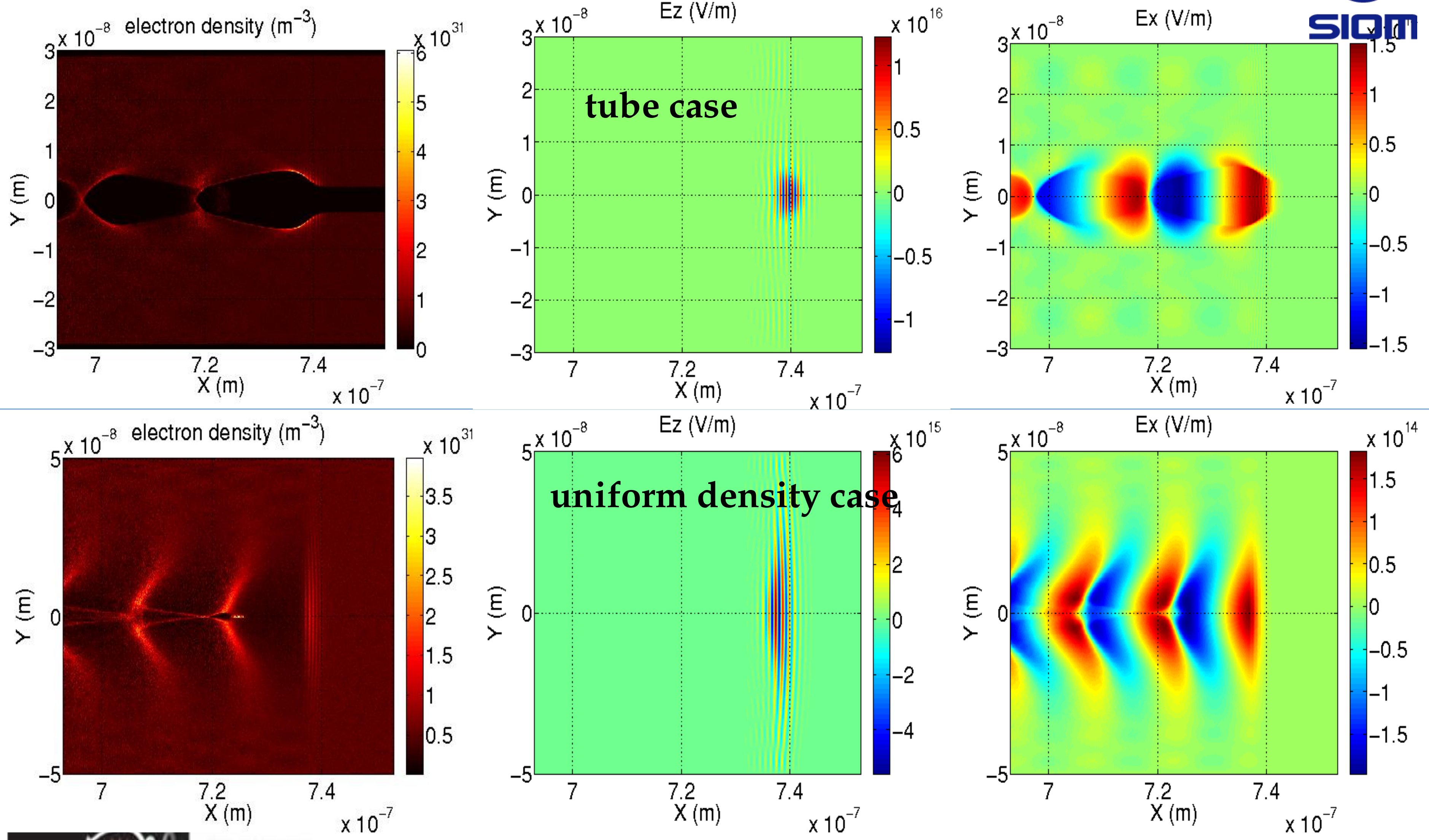
Gas: $(n_c / n_e) \sim 10^3$

Solid: $(n_c / n_e) \sim 10^6$



Wakefield comparison: nanotube vs. uniform density

X. Zhang *et al.*, Phys. Rev. Accel. Beams 19, 101004 (2016).



X. M. Zhang

Collaborators & Acknowledgements

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- Vladislav Ginzburg
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- Elsa Baynard

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