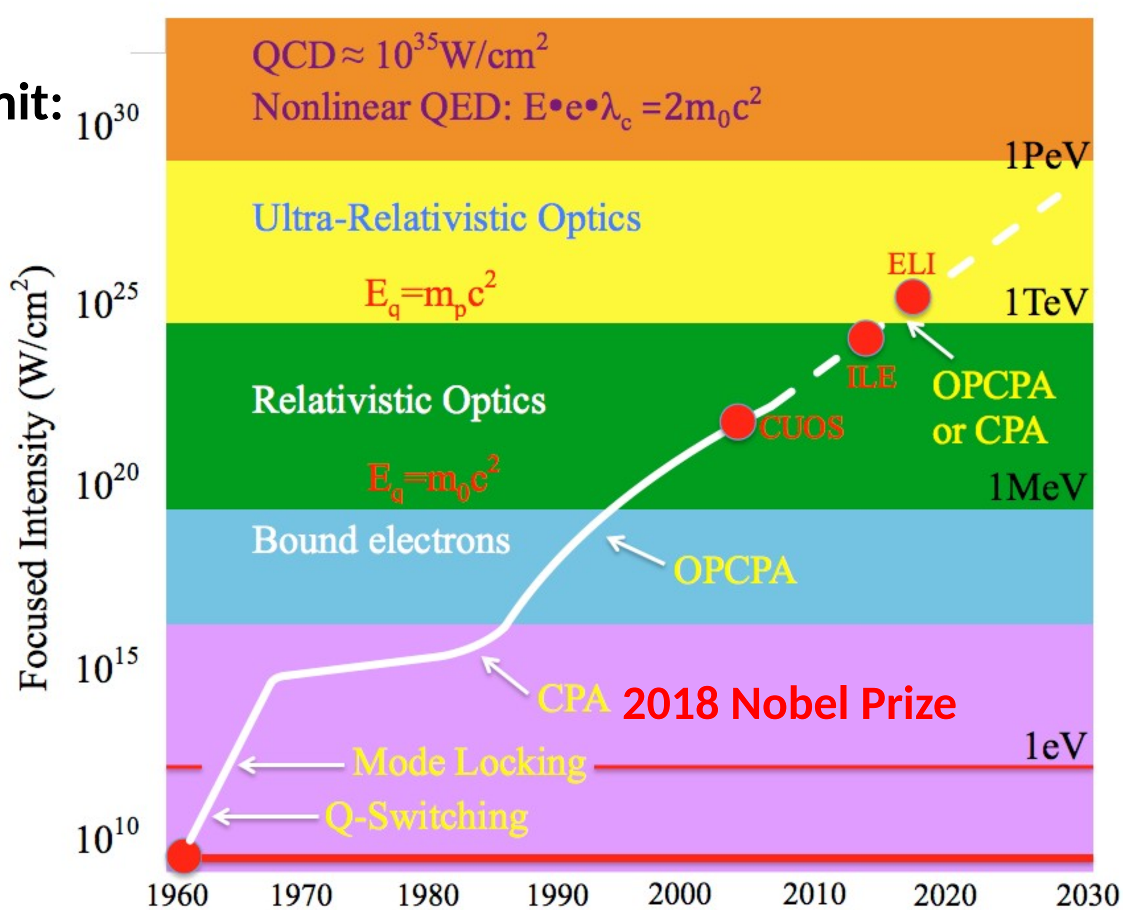
Laser diagnostics

Rajendra Prasad
LUXE, DESY

- **Progress in laser intensity over years**

Schwinger limit:
10^{29} W/cm^2

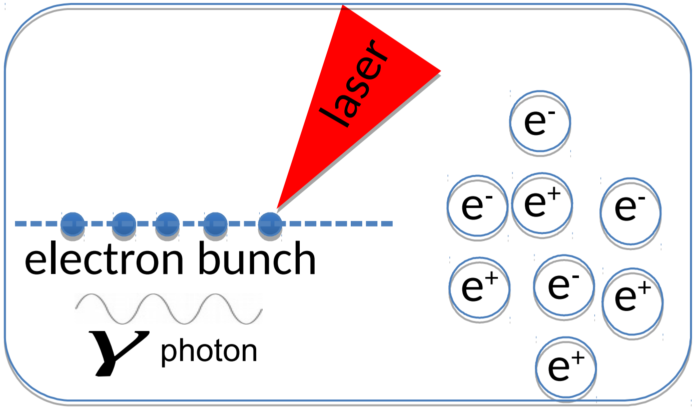


Year

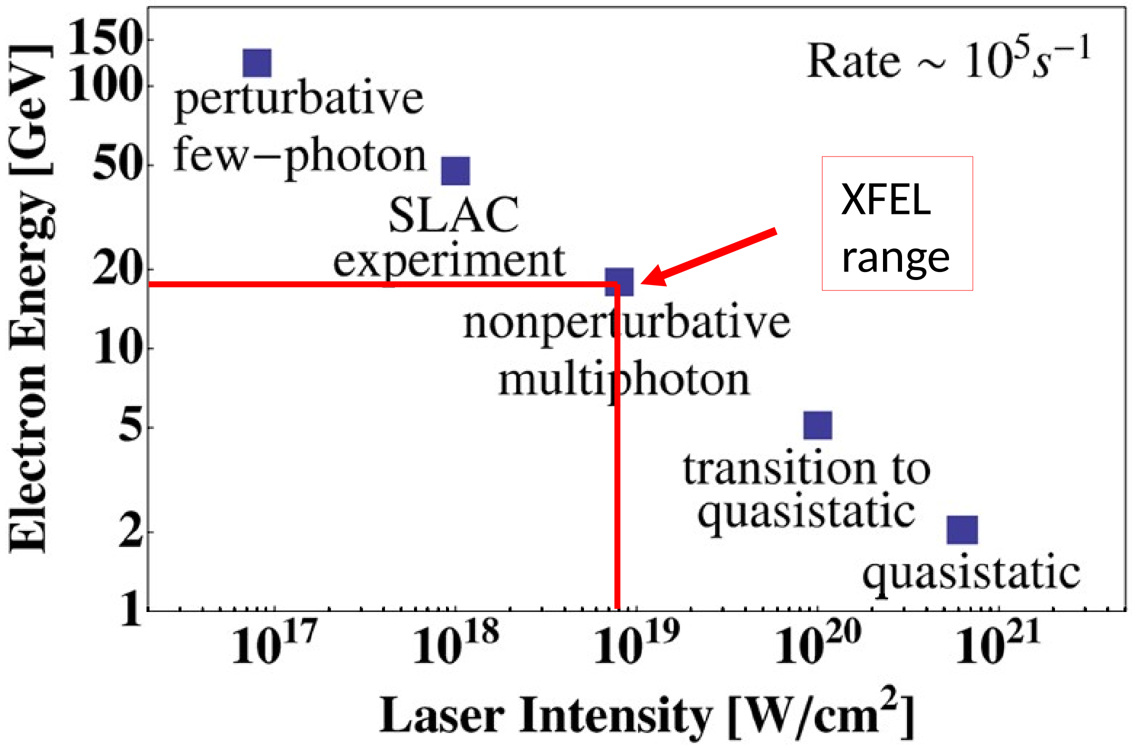
Electron energy

Tajima and Mourou (Rev. Mod. Phys. 2002)revised

LUXE Project- aiming to make some ground breaking discoveries



$a_0=1 \sim 10^{18}W/cm^2$



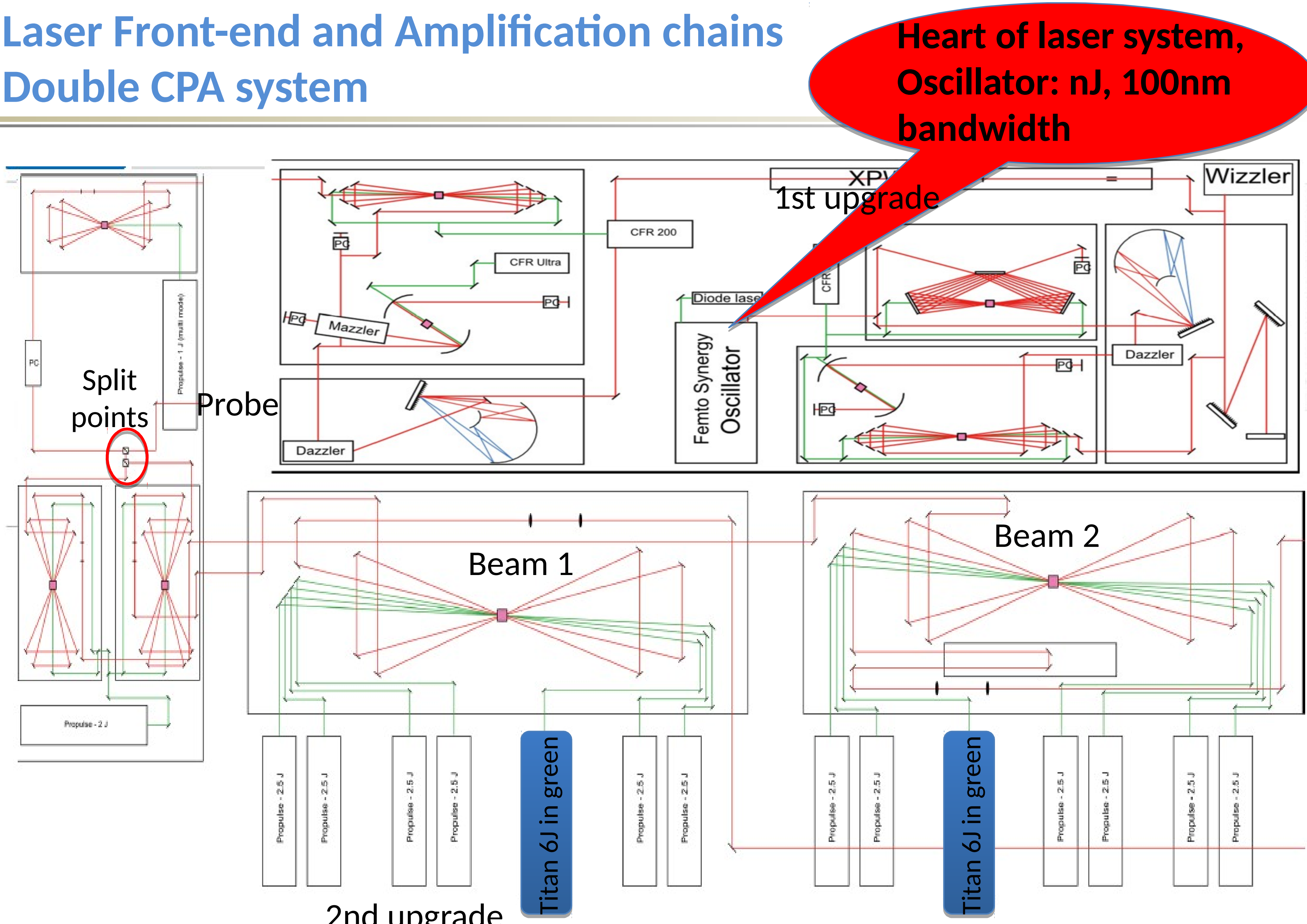
a_0<<1 , perturbative regime

a_0>1 , nonperturbative regime

- **Very few experiments to test the theory in non-perturbative regime**

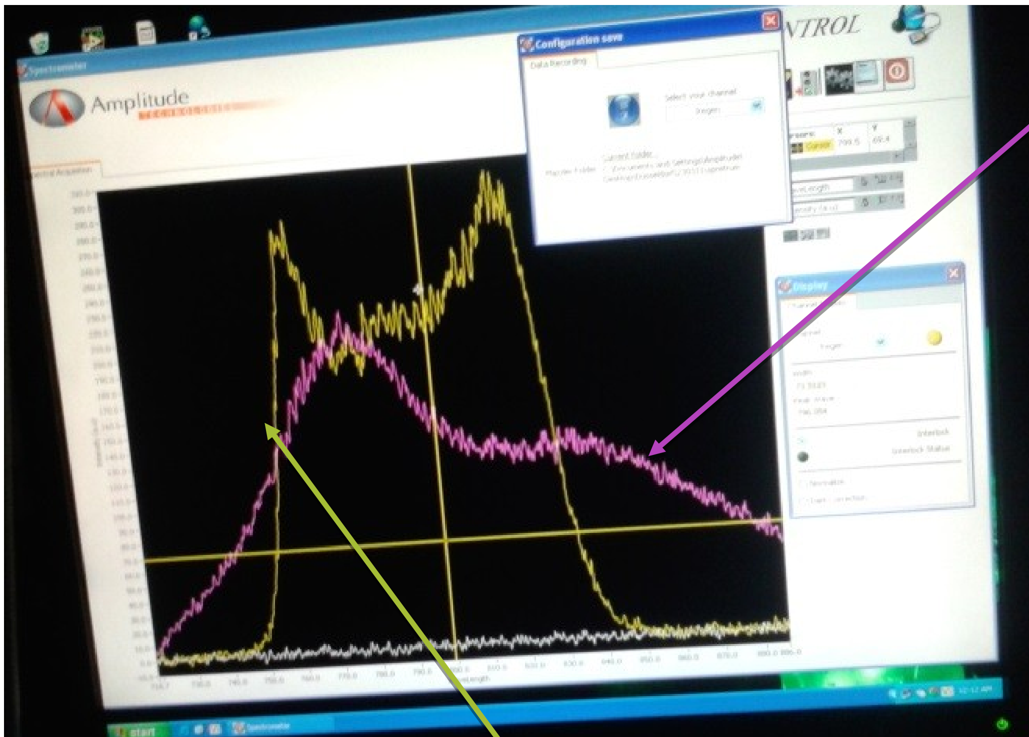
Huayu Hu, Carsten Müller and Christoph H Keitel, PRL 105, 080401 (2010)

Laser Front-end and Amplification chains
Double CPA system



After final amplification stage- 7J in each beam

Typical oscillator and amplified spectra



- Oscillator spectrum, >100nm bandwidth

$$\Delta\tau \propto \frac{1}{\Delta\lambda}$$

- This implies that larger the bandwidth, shorter is the pulse length!

- Spectrum after amplification-70nm,
- This is the spectrum going in the compressor

En route to amplification

- **Amplification, a simplest way to gain high energy, i.e, high intenisty: nJ energy level to J level: 10^9 gain in energy**
- **Laser beam passes through many crystals (gain medium), lenses, which have certain damage threshold.**

- **B integral, often used to estimate the total change in phase accumulated during passes through the medium**

$$B = \frac{2\pi}{\lambda} \int n_2 I(z) dz$$

n_2 **is the non linear refractive index**

$I(z)$ **Laser intensity**

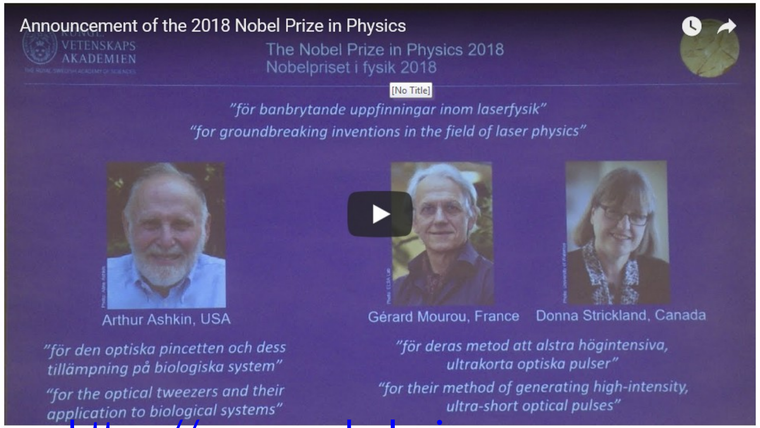
- **B< 1 is safe.**

- **However, already 100s of GW/cm^2 intensity could be at damaging level**

- **As the intensity increases, B increases and can start self focusing the beam in the medium!!**

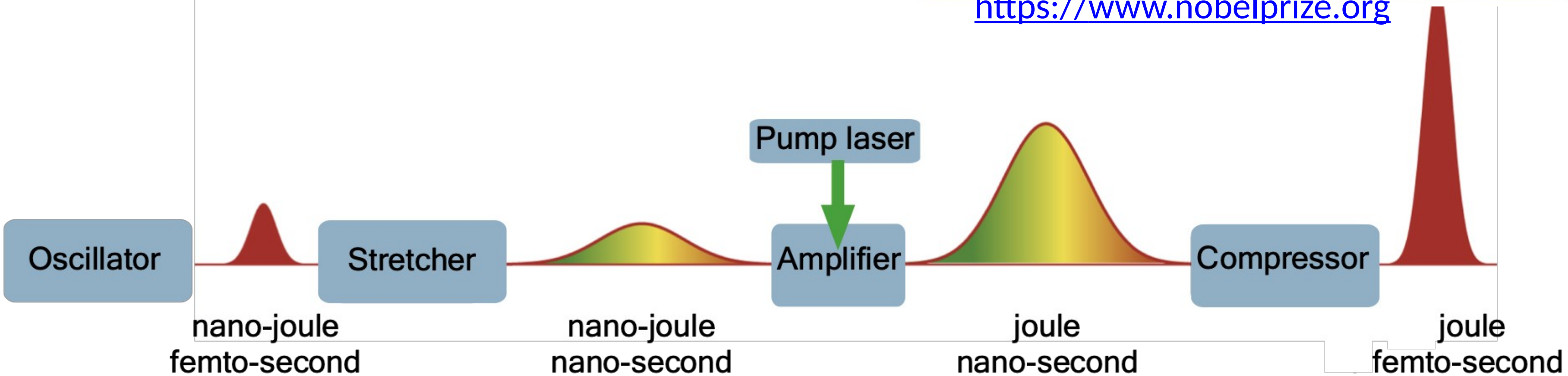
Chirped pulse amplification (CPA) technique

- **That’s why better to stretch the pulse before the amplification. That’s where the CPA played vital role.**
- **Invented in 1985 by G Mourou et al.**
- **2018 Nobel prize in physics**



https://www.nobelprize.org

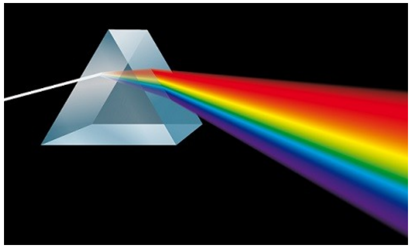
Standard CPA laser - commerci

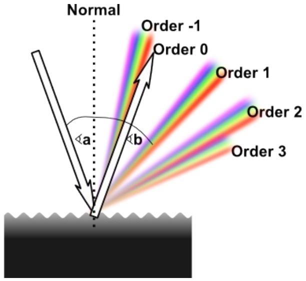


- **The pulse is compressed at the very end. Need to know what is the final compressed pulse length**

Stretcher and compressor

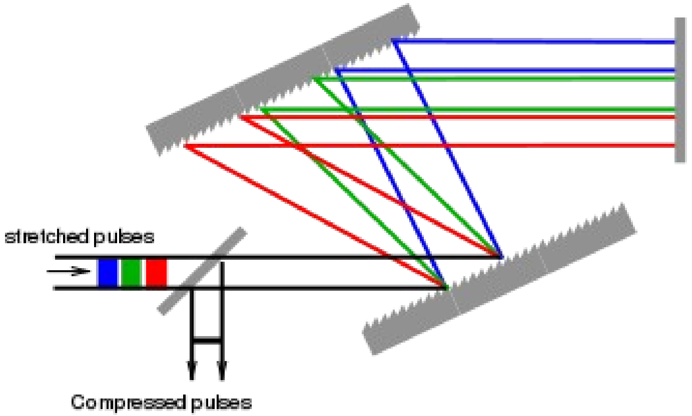
- Typical set up involves dispersive elements like prism or grating





- In the Stretcher, basic idea is to delay the frequency components (eg red and blue) with respect to each other. This is done by adjusting their optical path using geometry of the grating/prism

- Compressor is the reverse of the stretcher



https://en.wikipedia.org/wiki/Chirped_pulse_amplification#/media/File:CPA_compressor.svg

Different type of diagnostics used in different laser system

For spectrum, wavefront, beam profile, energy, beam pointing, pulse duration, focus spot

$$\xi = a_0 = 0.85\left(\frac{I\lambda_{\mu m}^2}{10^{18}Wcm^{-2}}\right)^{1/2}$$

Laser intensity $$I = \frac{E}{\tau A}$$

E is energy, tau- pulse duration, A as focus spot size

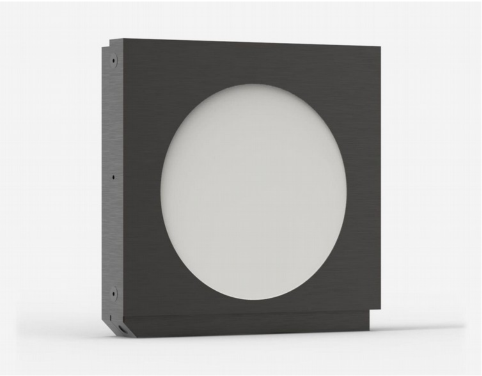
- **The quantum parameter** $\chi \propto \gamma . \sqrt{I}$

  - we concentrate on intensity

Energy measurement

$$I = \frac{E}{\tau A}$$

- **Energy detector from Gentec company**
- **Calibrated using NIST traceable sources and proven calibration techniques**
- **With calibration uncertainties of ±3%, and repeatability better than ±2%**
- **Can work in single shot, online mode**



- **Another method is to image the attenuated beam in high dynamic range CCD camera.**
- **This as well can work in single shot, online mode and more accurately**

https://www.gentec-eo.com/products/qe95lp-s-mb-qed-d0

Pulse duration measurement

$$I = \frac{E}{\tau A}$$

- **Need to measure ultra short pulses- 10^{-15}- 10^{-12} s**
- **Probably no electronic device is fast on such scale!**

There is a way

- **Classical technique- Auto-correlator, measuring the intensity over time (not the phase!)**

$$A(\tau) = \int_{-\infty}^{\infty} I(t)\, I(t-\tau)\, dt$$

- **A time dependent component of the electric pulse can be given as:**

$$E(t) = \mathrm{Re}\{\sqrt{I(t)}\ \exp(i\omega_0 t - i\varphi(t))\},$$

I(t) is the time dependent intensity and Φ(t) is the phase

- **Phase info is needed to correct any higher order dispersion from dispersive elements, eg, grating in the compressor**

What to do to get the phase and intensity both?

- **One can get the phase information from the spectrum**

- **Spectrally resolved autocorrelator signal gives a spectrogram:**

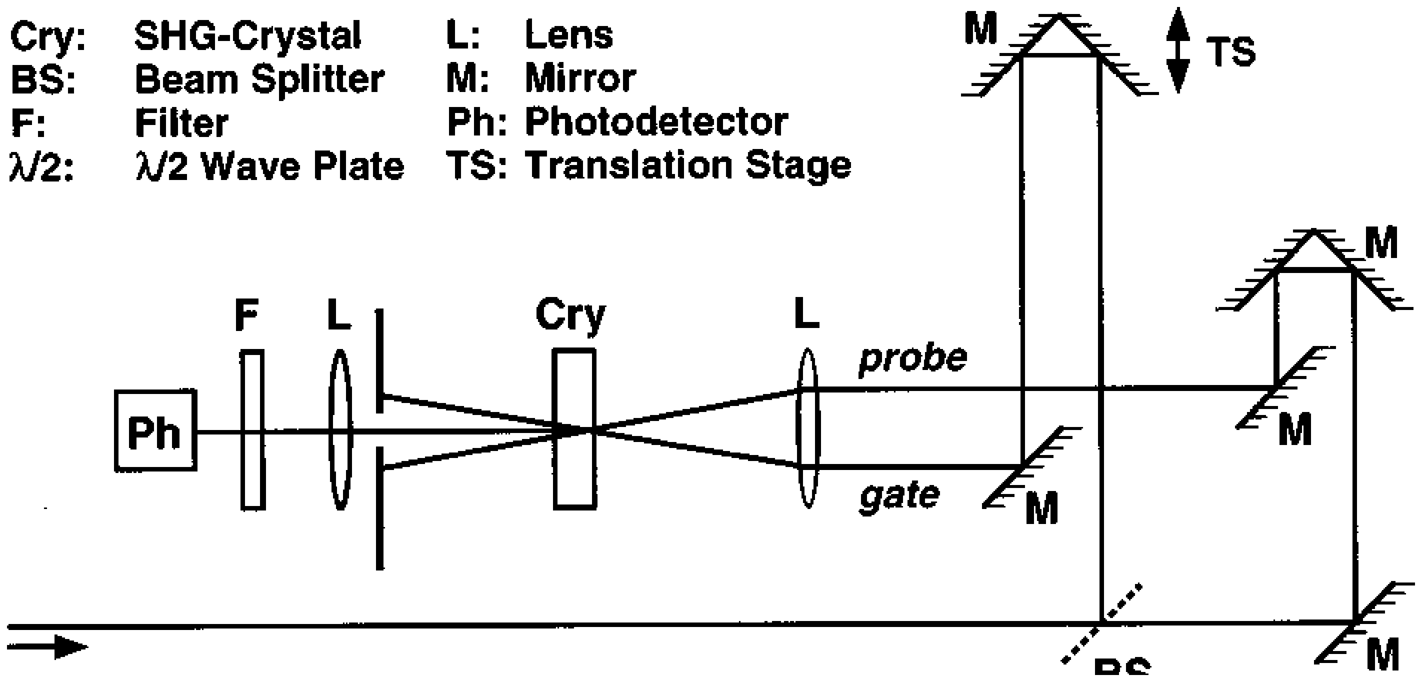
$$I^{SHG}(\omega,\tau)=\left|\int_{-\infty}^{\infty} E(t)E(t-\tau)\exp(-i\omega t)\,dt\right|^2$$

Here tau is the relative delay between two pulses

- **Gate the pulse by itself which is the shortest event. This avoids any artificial/residual signal in the main pulse**

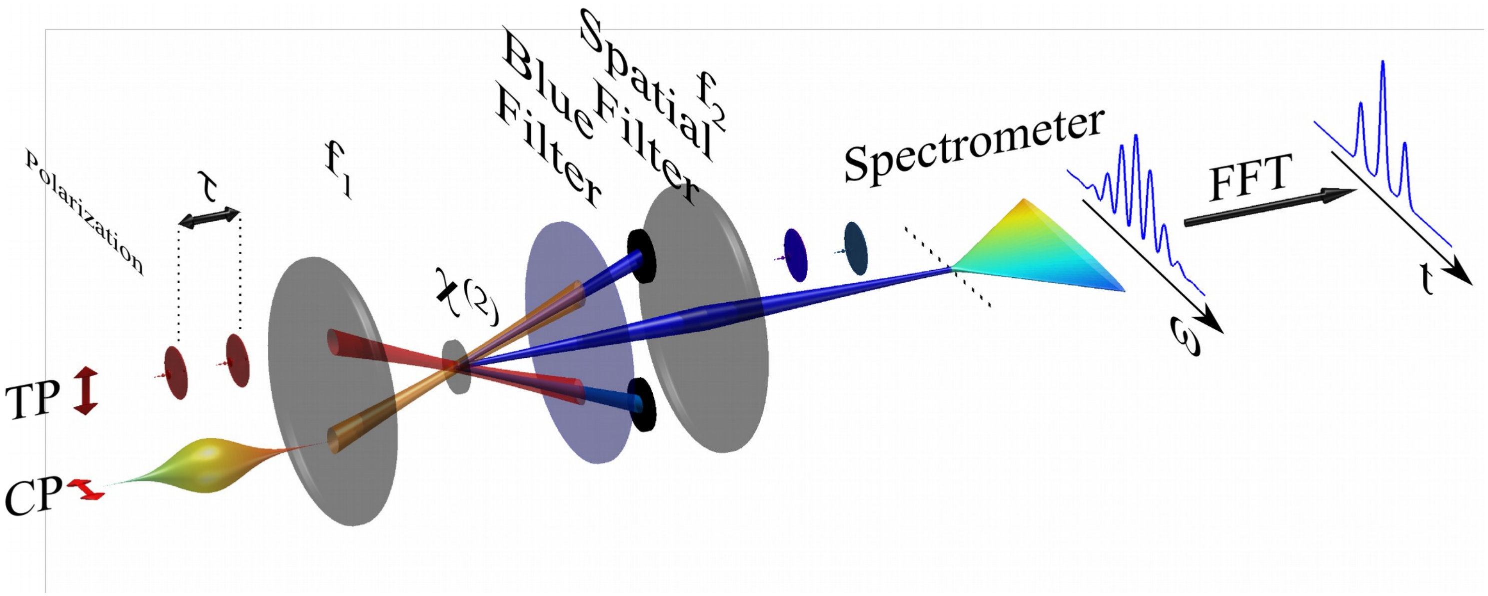
- **A nonlinear crystal such as CaF_2 can be used to help the gating work**

Frequency resolved optical gating (FROG)



- Can work in single, multi shot mode
- Easy to use
- 1-2% accuracy

Spectral phase interferometry for direct electric-field reconstruction- SPIDER

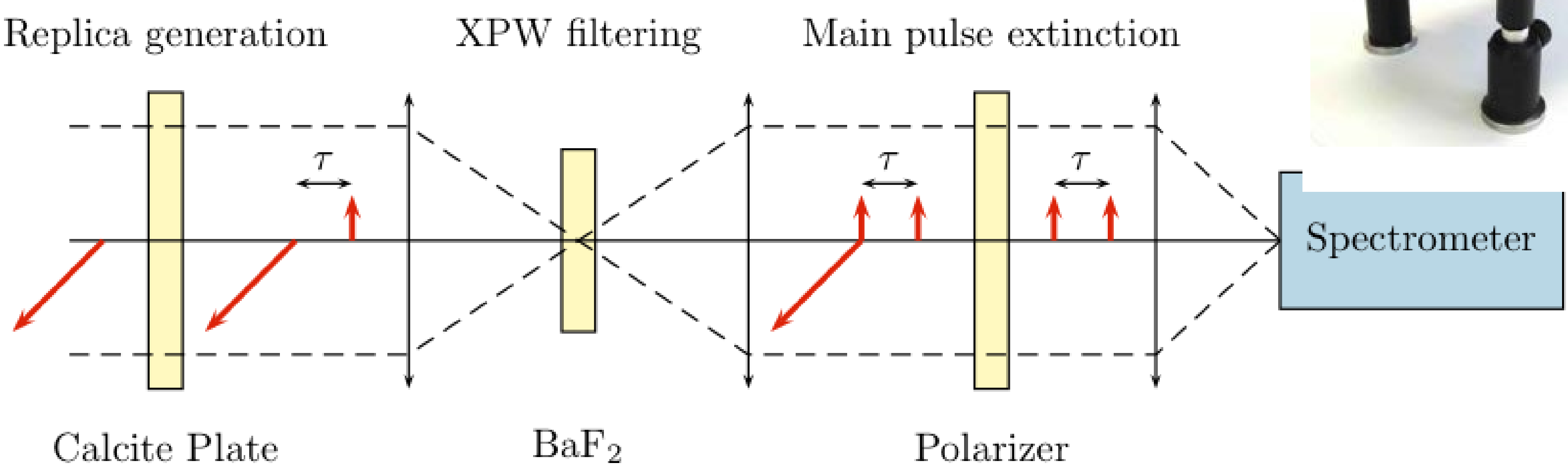


- Works on the gating principle, however, does not need time delay stage
- 1-2% accuracy
- More accurate compare to FROG as does not need iterative algorithm

https://en.wikipedia.org/wiki/Spectral_phase_interferometry_for_direct_electric-field_reconstruction#/media/File:Conventional_SPIDER_concept.png

Wizzler- Fastlite

Self-Referenced Spectral Interferometry



Bierfringence effect

3rd order nonlinearity

- **In this case even split beam is not needed.**

https://fastlite.com/produits/wizzler/

WIZZLER

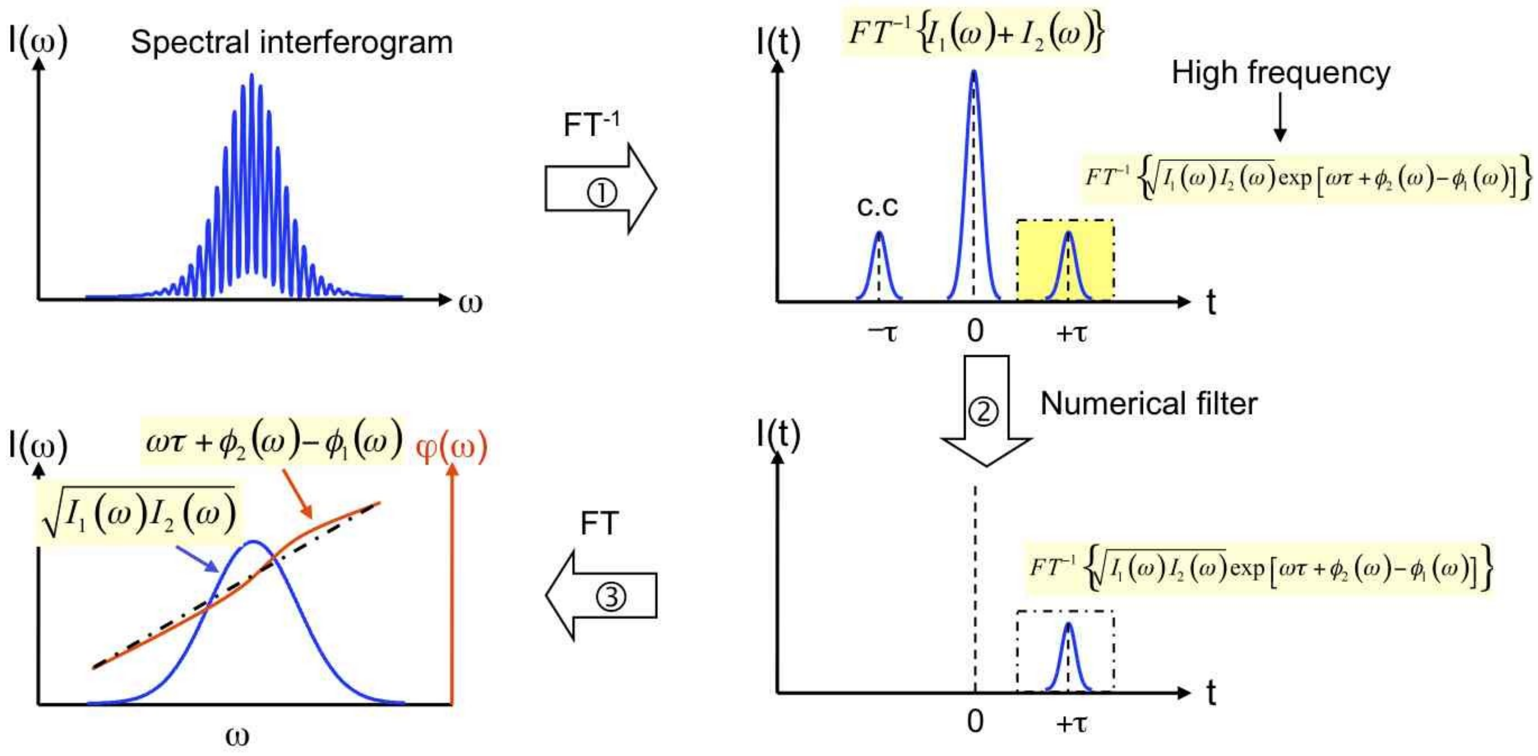
Femtosecond pulse measurement device

Standard Models

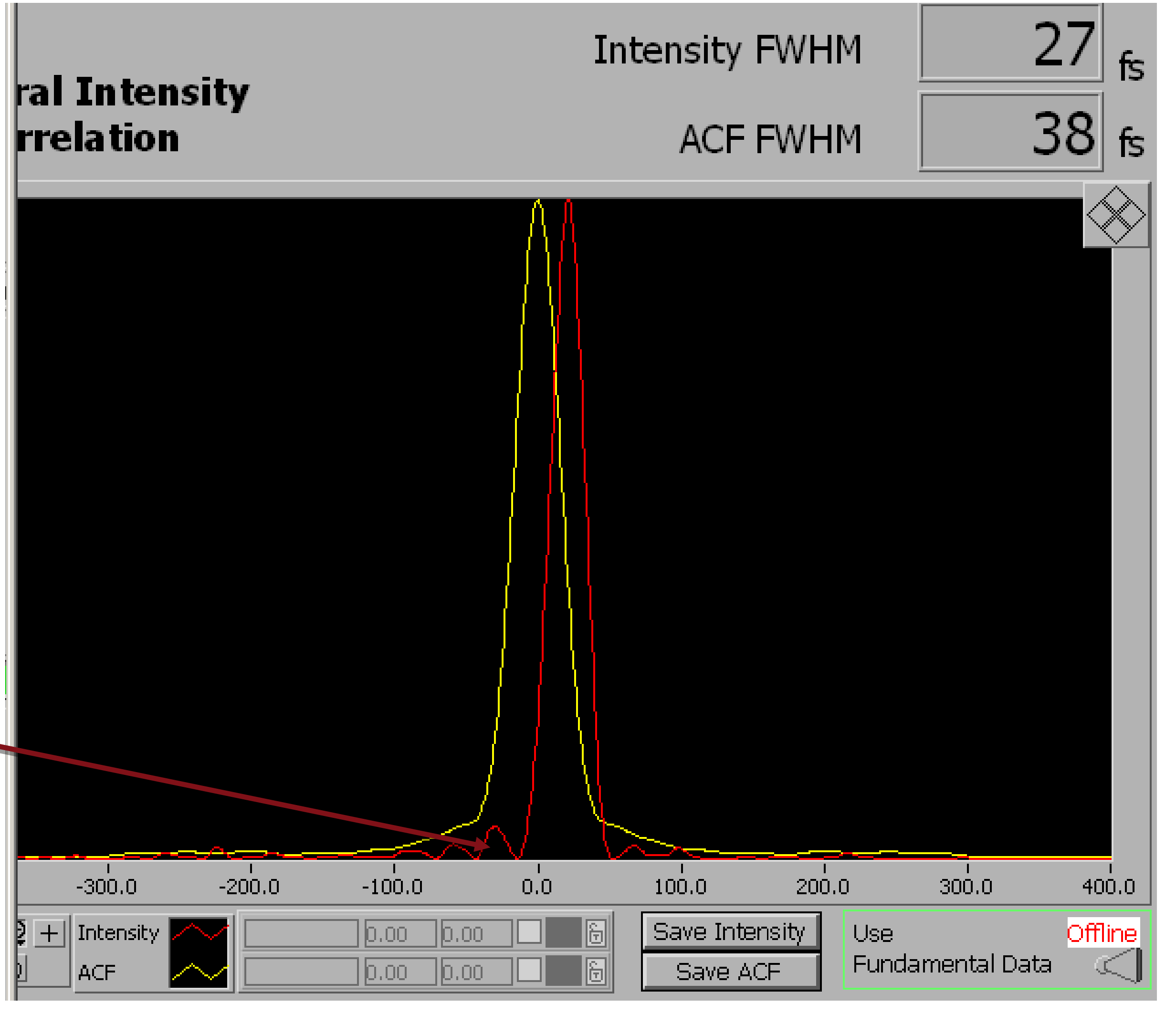
- Highest dynamic range
- Single shot, single beam
- Extreme ease of use
- Calibration-free
- Direct retrieval algorithm
- Data logging
- Vacuum-compatible option
- Pulse compression optimization for Dazzler users

https://fastlite.com/wp-content/uploads/spec-wizzler-2018.pdf

Fourier- transformed spectral interferometry



Spider trace example



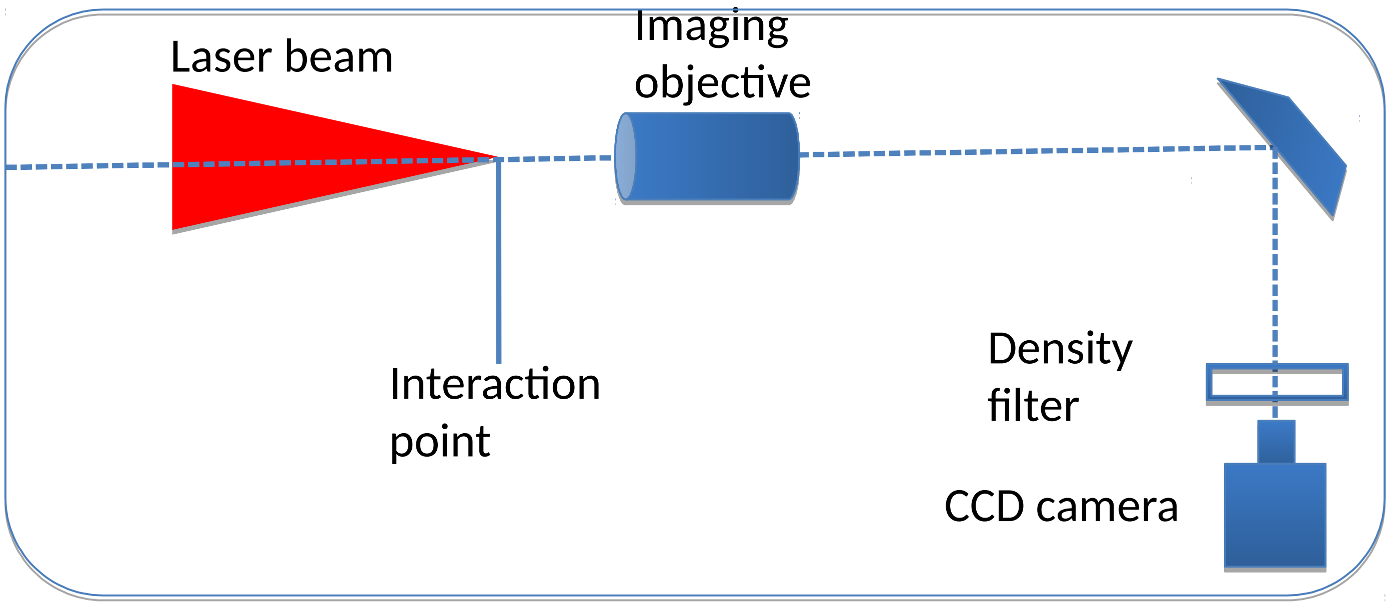
higher order dispersion

One can compensate using other device so called DAZZLER

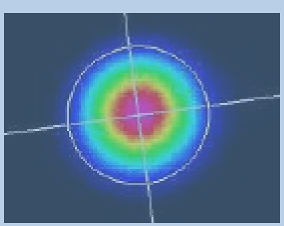
Focus diagnostics

$$I = \frac{E}{\tau A}$$

Typical setup

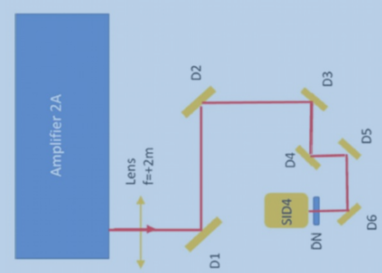


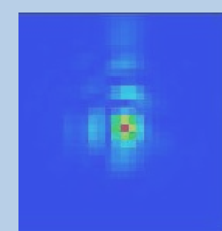
Low energy method



By reducing the energy in the pulse, eg, switching of pump laser

High energy method





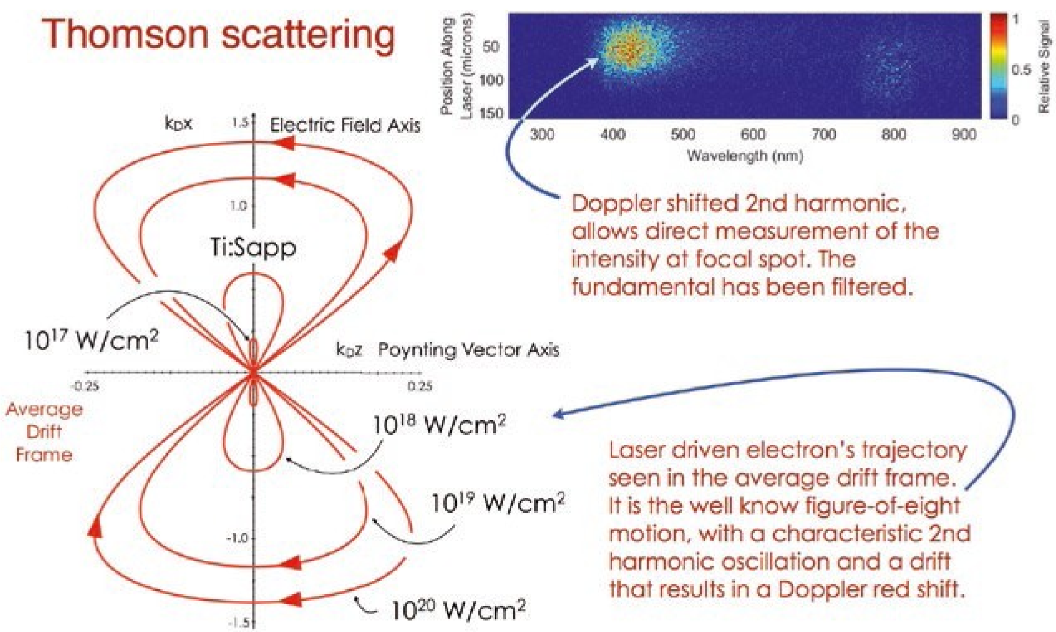
Can one simply measure the intensity?

$$I = \frac{E}{\tau A}$$

- Intensity as a function of the observed nth harmonic wavelength

$$I(\lambda^{(n)}, \theta; n) = \frac{2\pi m_e c^3}{r_0 \lambda_0^2 (1 - \cos\theta)} \left(\frac{n\lambda^{(n)}}{\lambda_0} - 1 \right), \qquad (1)$$

where λ_0, θ, m_e, r_0 and c are the laser wavelength, the polar angle relative to $\vec{k}$, the electron mass, the classical electron radius and the vacuum light speed respectively.



Electron dynamics in electromagnetic field: famous Figure of eight

https://www.laserlab-europe.eu/news-and-press/newsletter-archive/issue-28

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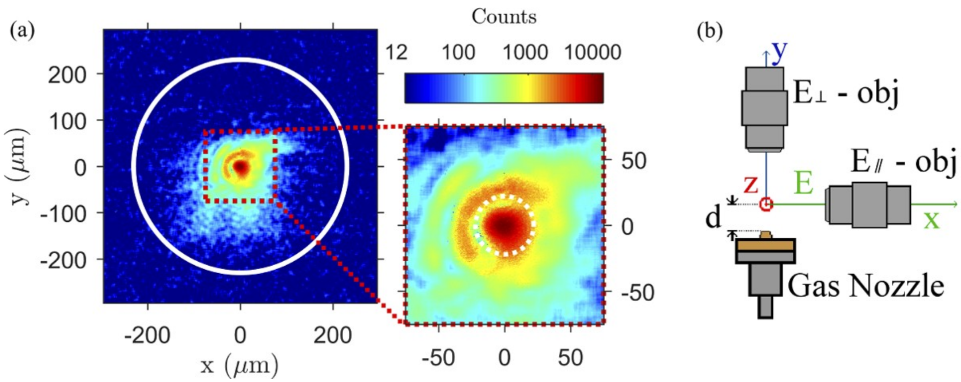
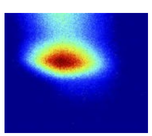
Experimental set up at Salamanca Pulsed Lasers Center- Spain

Low intensity measurement- via focus

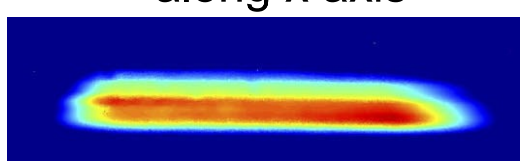


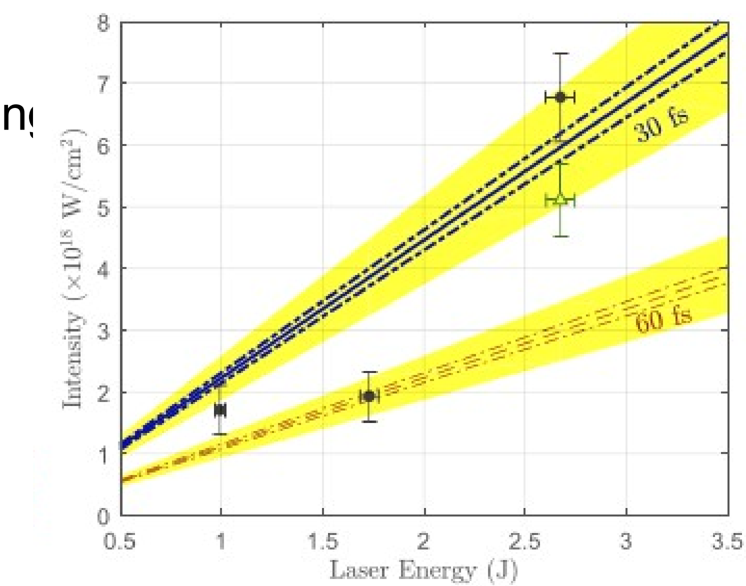
High intensity measurement via Thomson scatterin

along y axis



along x axis





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Other indirect methods for intensity measurement

- **Characterizing extreme laser intensities by ponderomotive acceleration of protons from rarified gas- “proposed”**
  - Density limit $<10^{16}/cm^3$
  - Experimental challenges- detection sensitivity etc

- **Precise in-situ measurement of laser pulse intensity using strong field ionization**
  - Suitable for low energy (low intensity range)

- **Compton edge shift -scattered photon energy scaling** $1/\sqrt{1+\xi^2}$

Summary

- **There are various possible way to diagnose the laser parameters.**
- **Different direct and indirect methods for intensity measurement need to be tested**

Thanks for your kind attention