SPARC_LAB PAC Meeting
Frascati, 08/05/13

Results of the Electro-Optic Sampling for COMB

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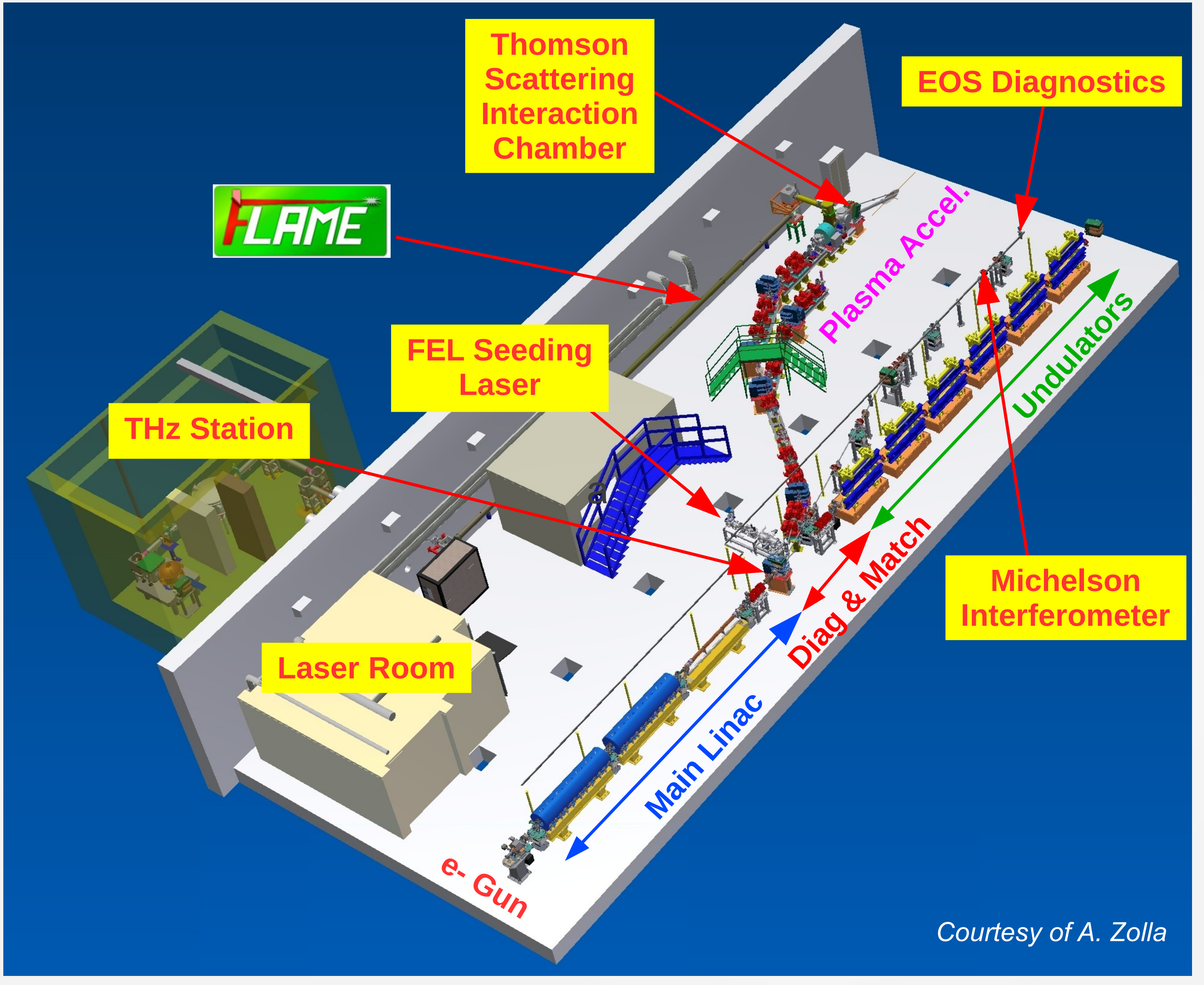
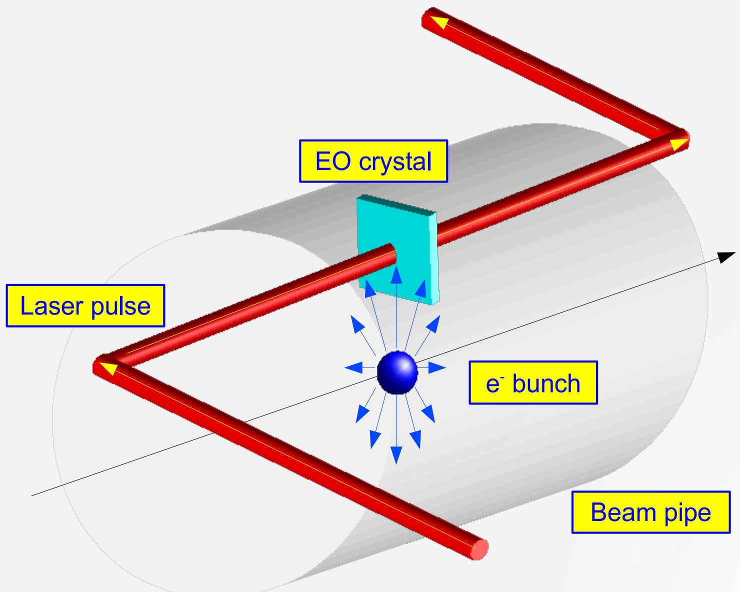
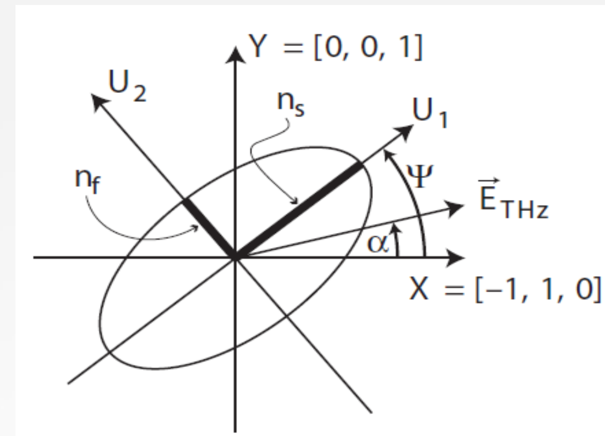
SPARC_LAB Layout



Electro-Optical Sampling

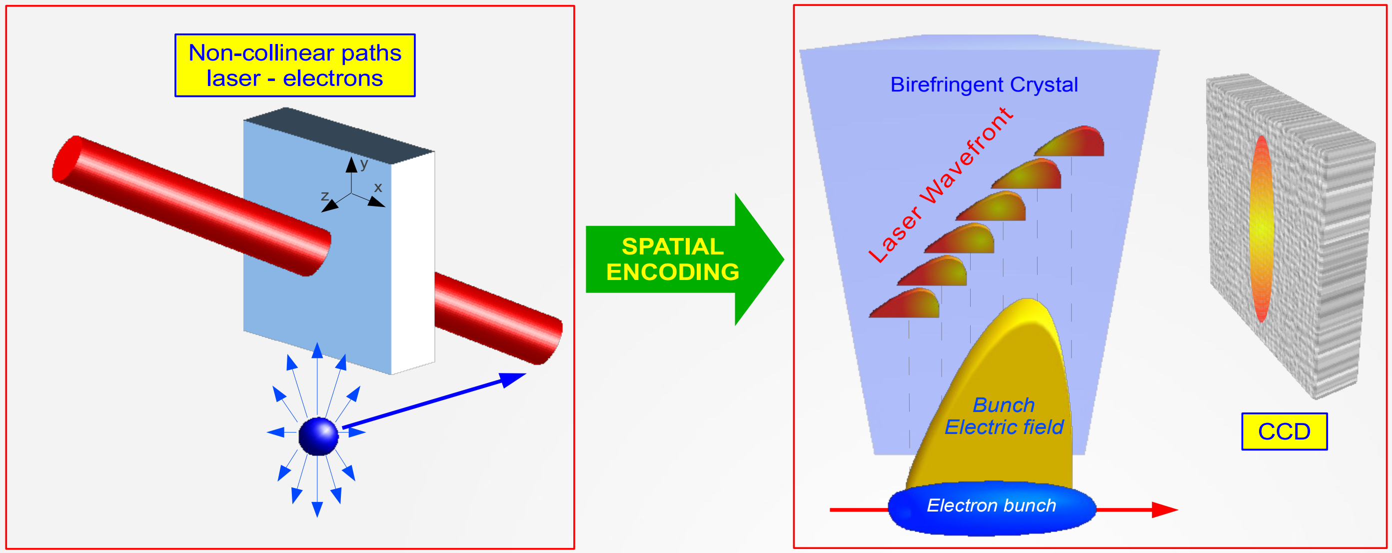




$$\Gamma(\alpha) = \frac{\omega d}{c}(n_1 - n_2) = \frac{\omega d}{2c} n_0^3 r_{41} E_{THz} \sqrt{1+3\cos^2\alpha}$$

- **PWFA**: need to correlate **incoming** and **outgoing** beams from the plasma
  - non-intercepting & single-shot diagnostics for beams to be injected in **plasma**.
- **Electro-Optical Sampling (EOS)** technique is able to measure the longitudinal profile of the electron bunch.
  - The electric field of a relativistic bunch induces birefringence in a non-linear crystal like **ZnTe** or **GaP**, becoming **anisotropic**.
  - If a polarized laser pulse crosses the crystal its polarization will be changed → can be related to an intensity modulation.
- ~50 fs (rms) time resolution.
- Benefits: **single shot, non-intercepting**, time resolution. Disadvantages: small signals (low SNR), complex layout, costs.

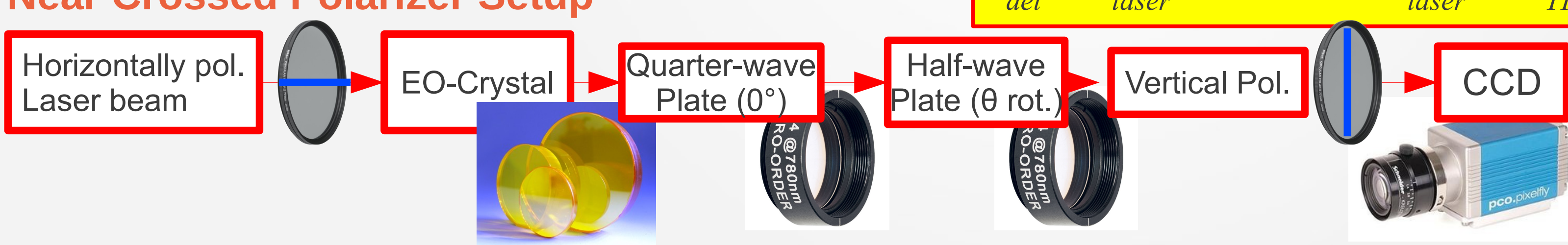
EOS Spatial Encoding Setup



- **Laser crosses the crystal with an incident angle of 30°** → one side of the laser pulse arrives earlier on the EO crystal than the other by a time difference Δt.
- Coulomb field inducing birefringence is encoded in the spatial profile of laser pulse
- Benefits: **simple**, **no high energy laser needed**.
- Drawbacks: **poor surface quality of EO crystals.**

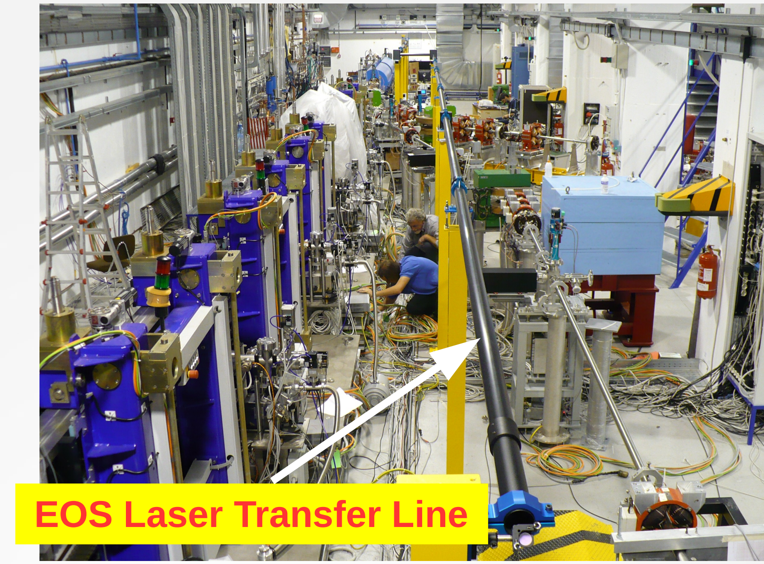
Near Crossed Polarizer Setup

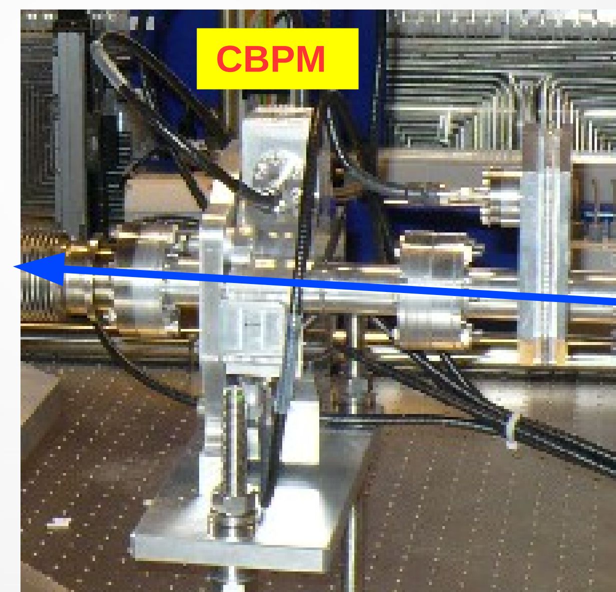
$$I_{det} \sim I_{laser} 2\theta\Gamma + 4\theta^2 I_{laser} \sim E_{THz}$$



Laser-electrons synchronization

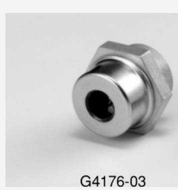
- **EOS uses the SPARC_LAB ptc. laser**
  - 800nm, 60fs (rms, **T.L.**), up to 500μJ pulse energy, 10Hz.
- **Transfer Line of 34m installed**.
- Benefits
  - Simplified EOS layout setup
    - ~~**Independent laser system**~~
  - High energy available
  - **Self-synchronized with e-beam**
    - 1 laser pulse per 1 e- bunch
      - ~~**Intensified CCD**~~





Synchronization laser-electrons

- Laser Time Arrival Monitor: 30ps risetime photodiode.



Item	Symbol	Condition	Value	Unit
Spectral Response Range	λ	$V_b = 7$ V	450 to 870	nm
Peak Response Wavelength	λ_p	$V_b = 7$ V	850	nm
Effective Sensitive Area	A		0.2×0.2	mm^2
Chip Size			1×1	mm^2

- Bunch Time Arrival Monitor: 4GHz Cavity-BPM.

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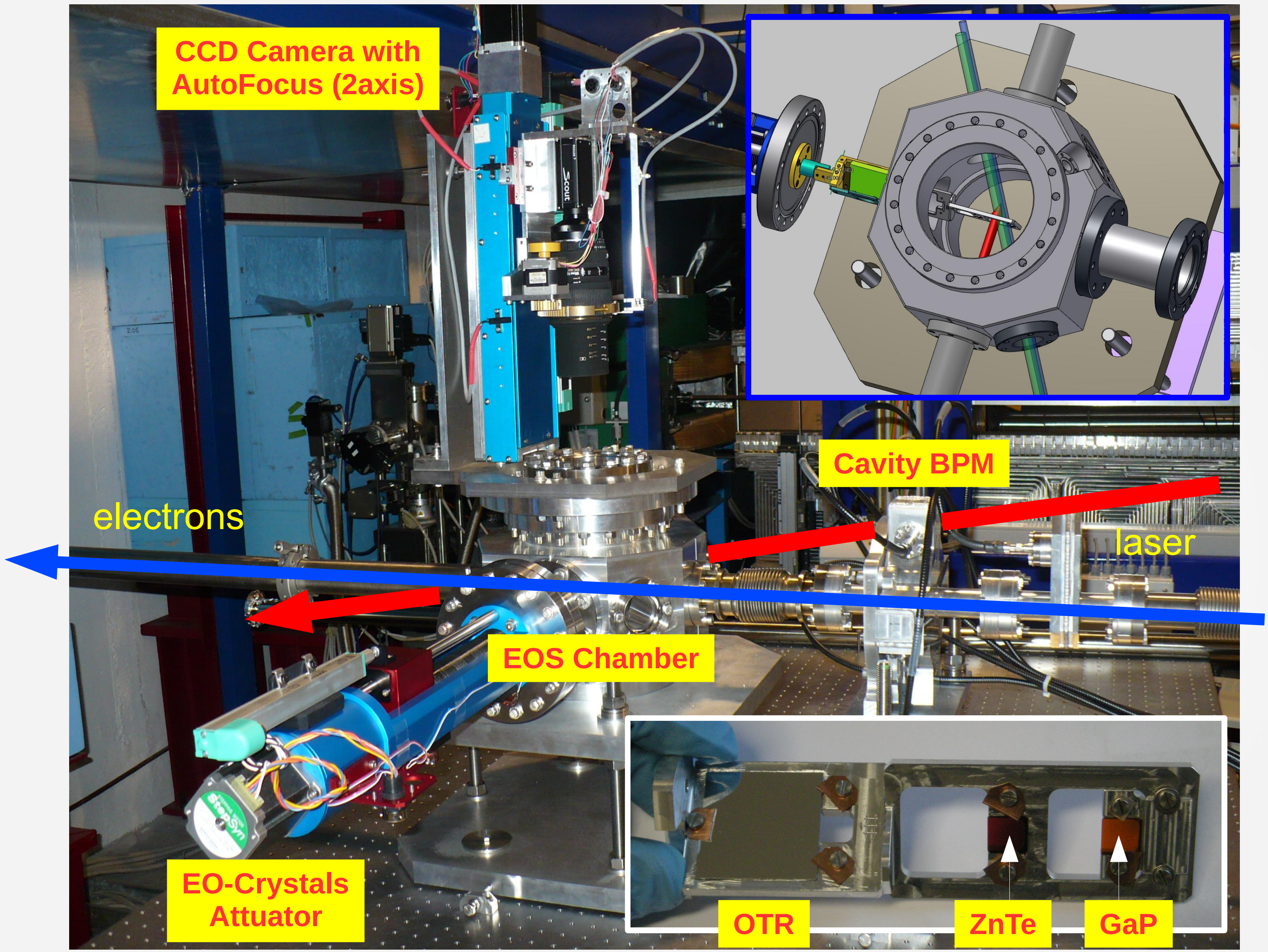
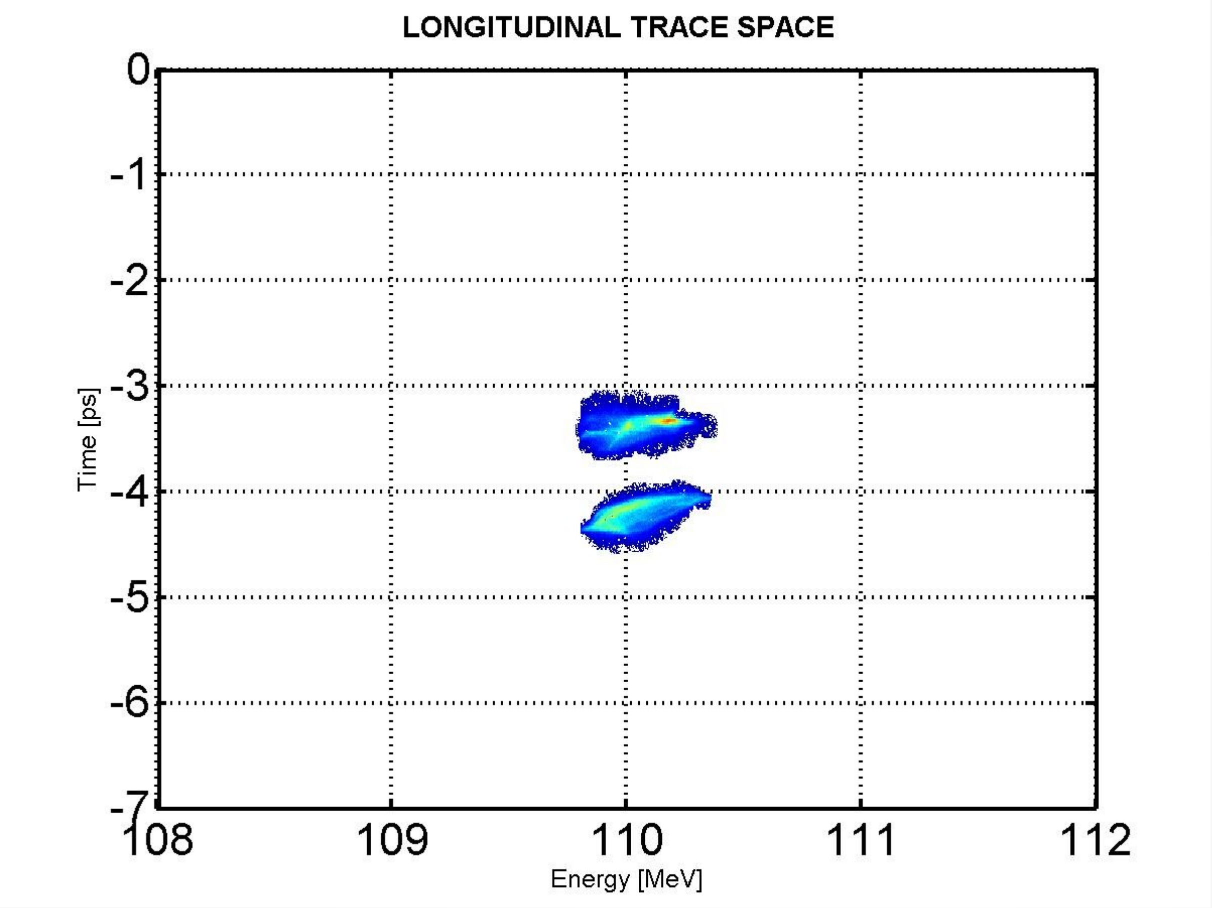
EOS diagnostics chamber

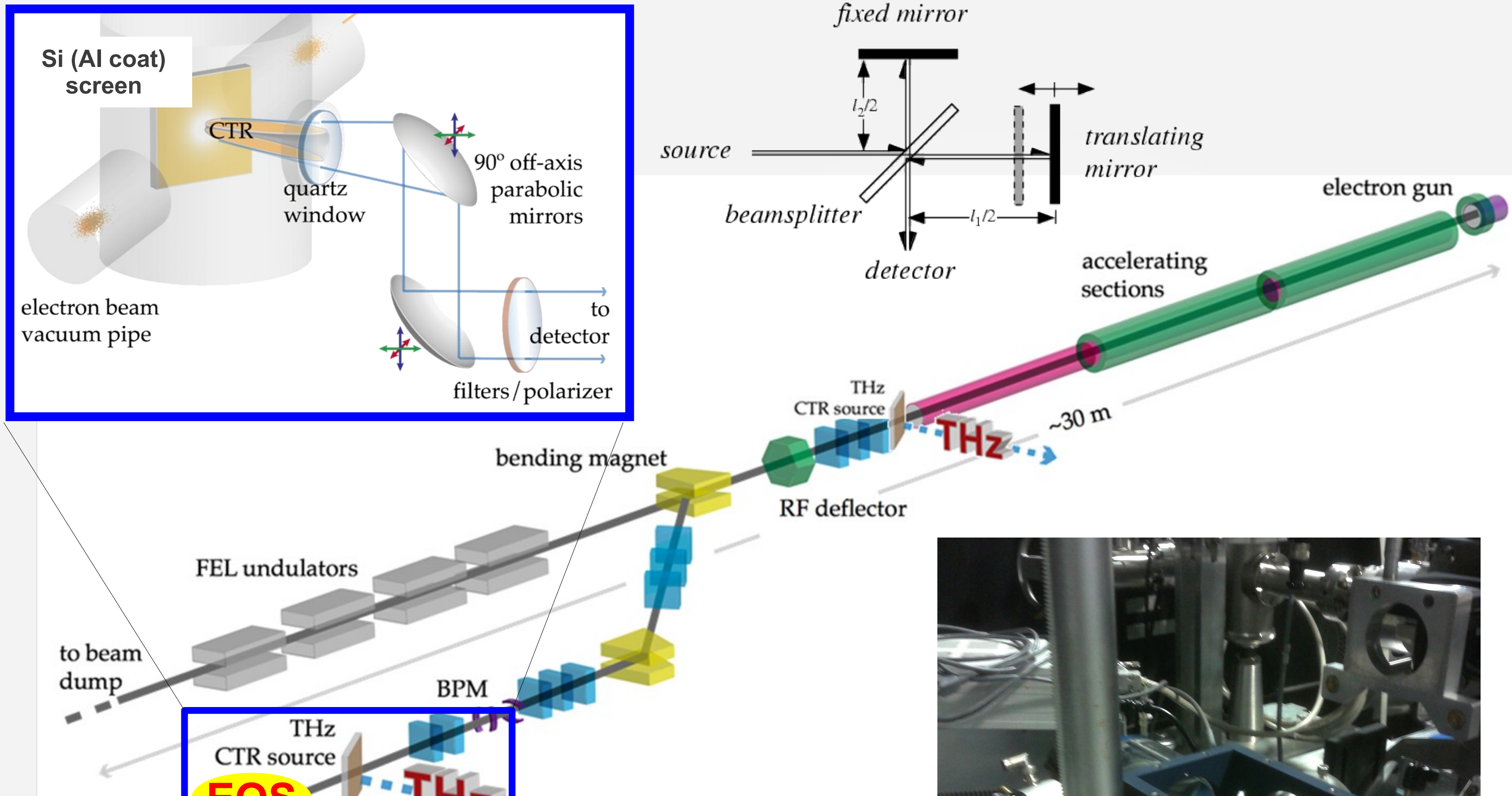


Longitudinal Phase Space

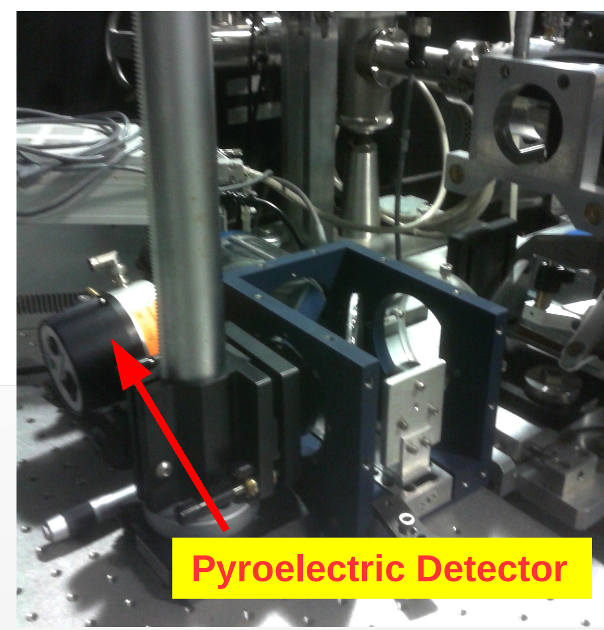


- Charge: 160pC total (80pC + 80pC)
- Energy: 110MeV
- Overall emittance: 2.29mm mrad (Y), 2.56mm mrad (X)
- 2-bunches distance: (830±30) fs (rms)
- Bunch lengths: (64±8) fs, (52±8) fs (rms)

Michelson Interferometer results

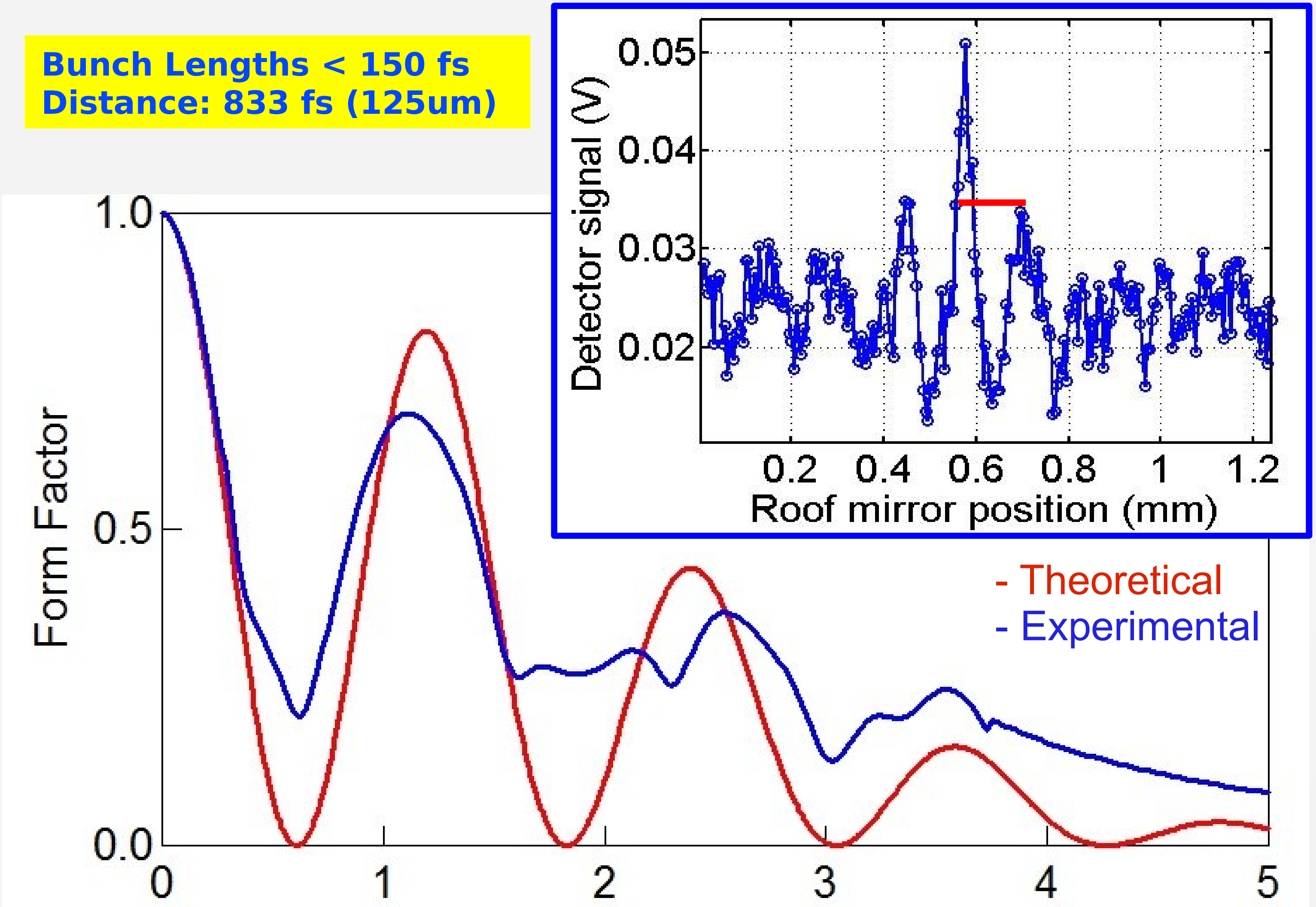


THz Detector: 0.5÷30 THz
Beam Splitter: Mylar 12um
Quartz Window: <3.8 THz



Michelson Interferometer results

Bunch Lengths < 150 fs
Distance: 833 fs (125um)

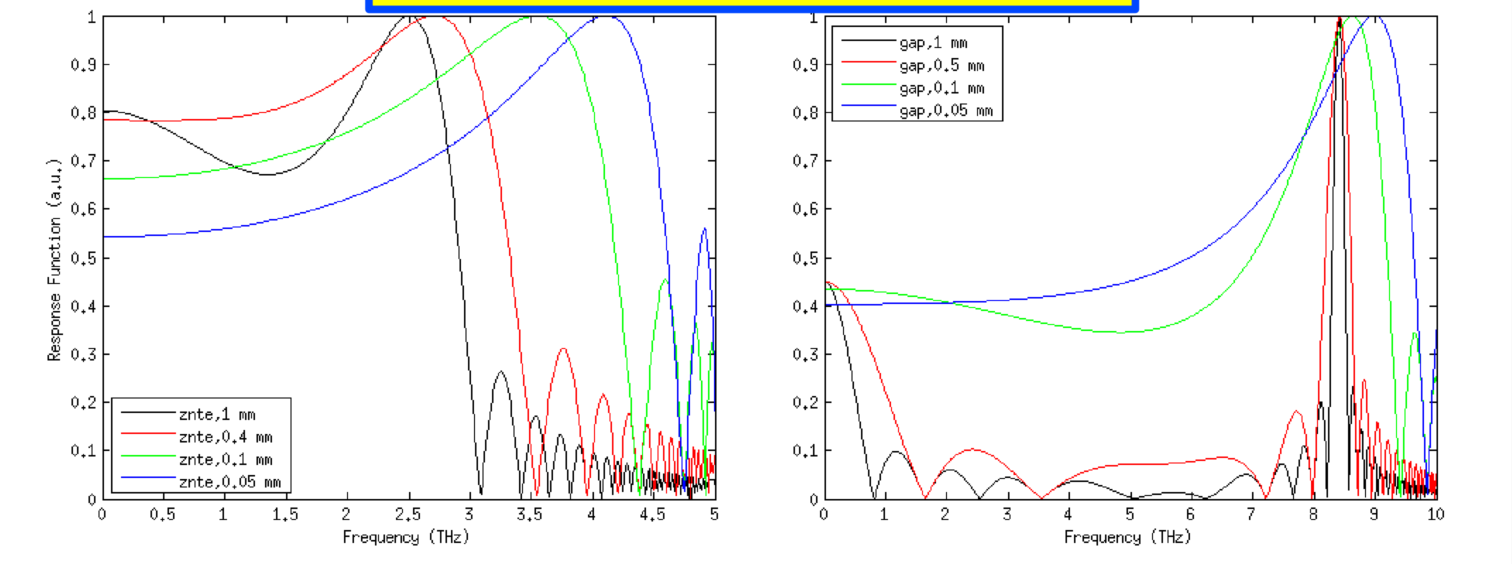


Thanks to F. Giorgianni

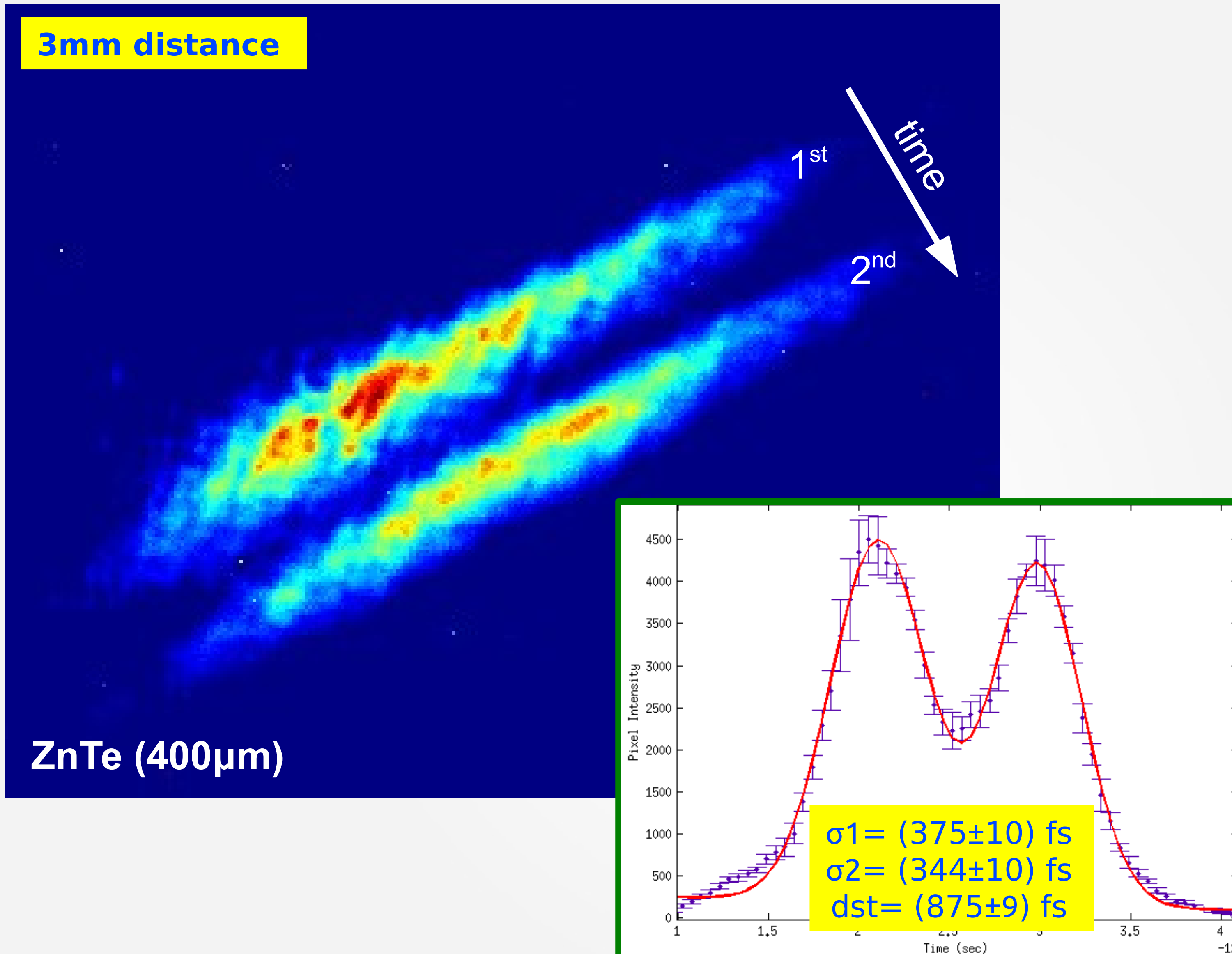
EOS Current Parameters

- Crystals 10x10 mm^2 (provided by IngCrys Ltd.)
  - *ZnTe (400μm), GaP (500μm)*
  - ***140 fs*** *(ZnTe),* ***250 fs*** *(GaP)* ***rms*** *(THz – laser velocity mismatch)*
- Laser
  - *Pulse duration:* ***130 fs (rms)***
  - *Energy:* *200 nJ*
  - *Spot diameter:* *5 mm (**~10 ps time window**)*
- CCD resolution: **1 pixel ≈ 17 fs**
- Better resolution limit σ_{lim} with thinner crystals (but lower signals!)

Bunches with $\sigma_z < \sigma_{lim}$ appear longer!



Very preliminary EOS results



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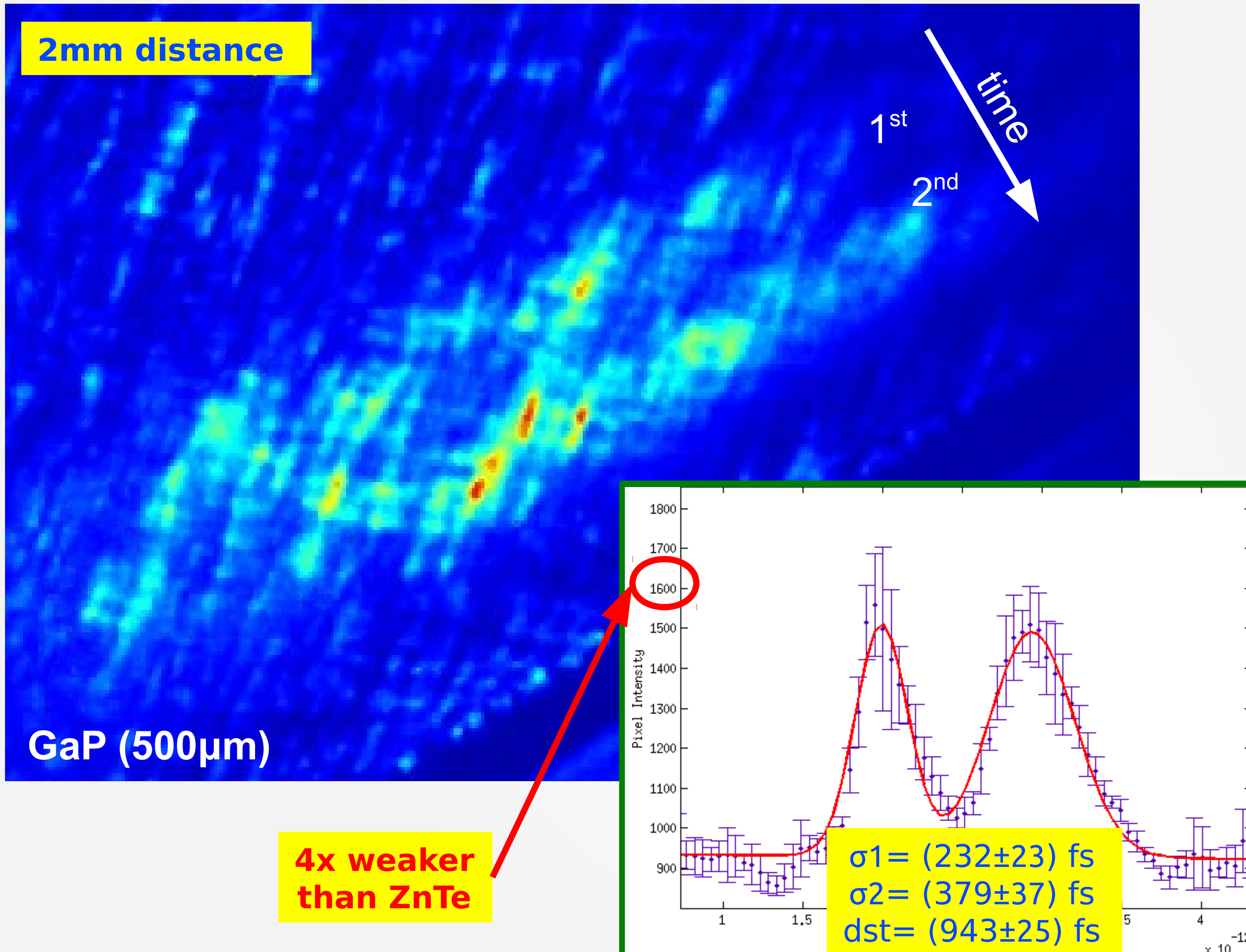
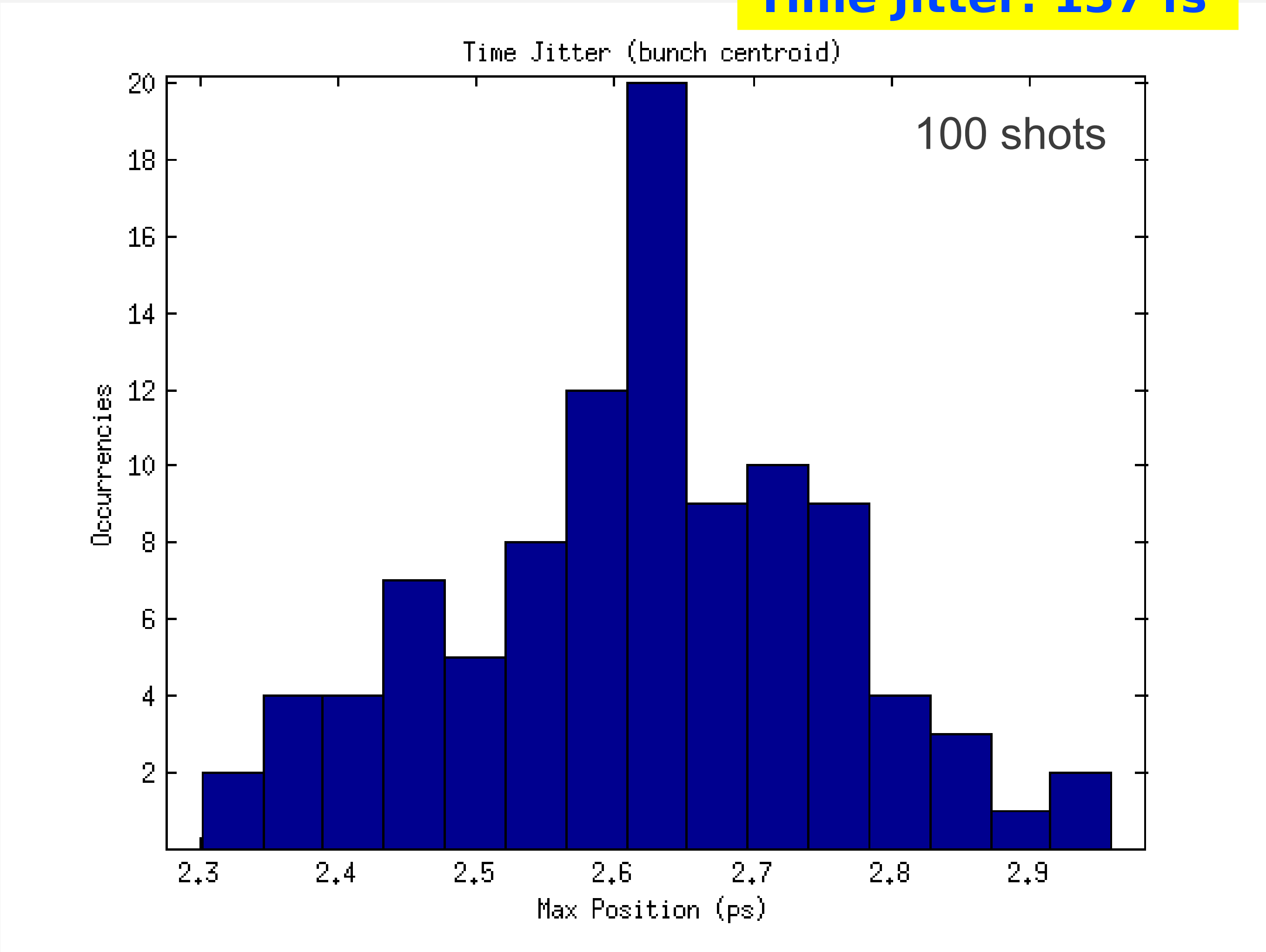
Very preliminary EOS results



Time Jitter evaluation with EOS

Time Jitter: 137 fs

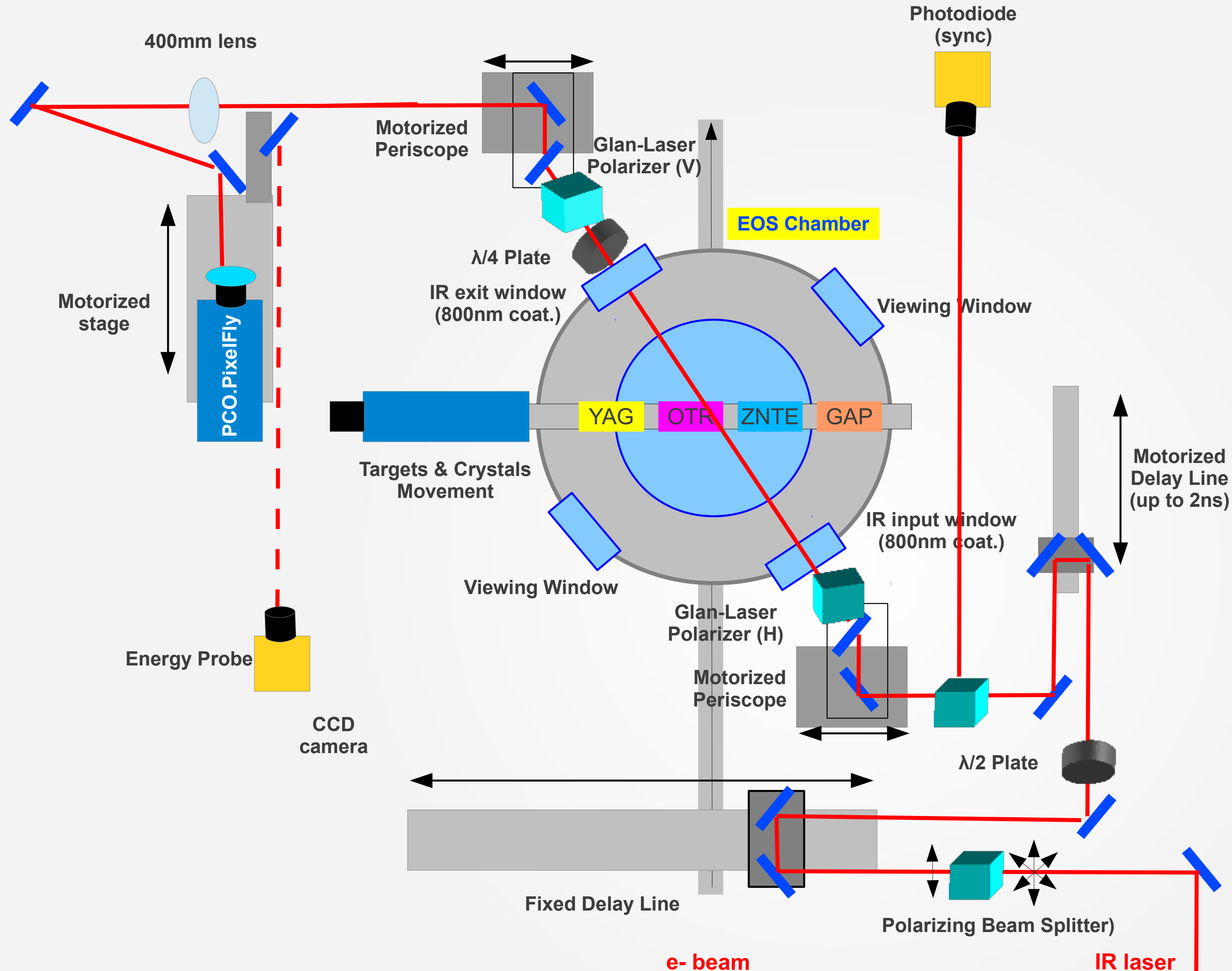


Conclusions & Outlooks

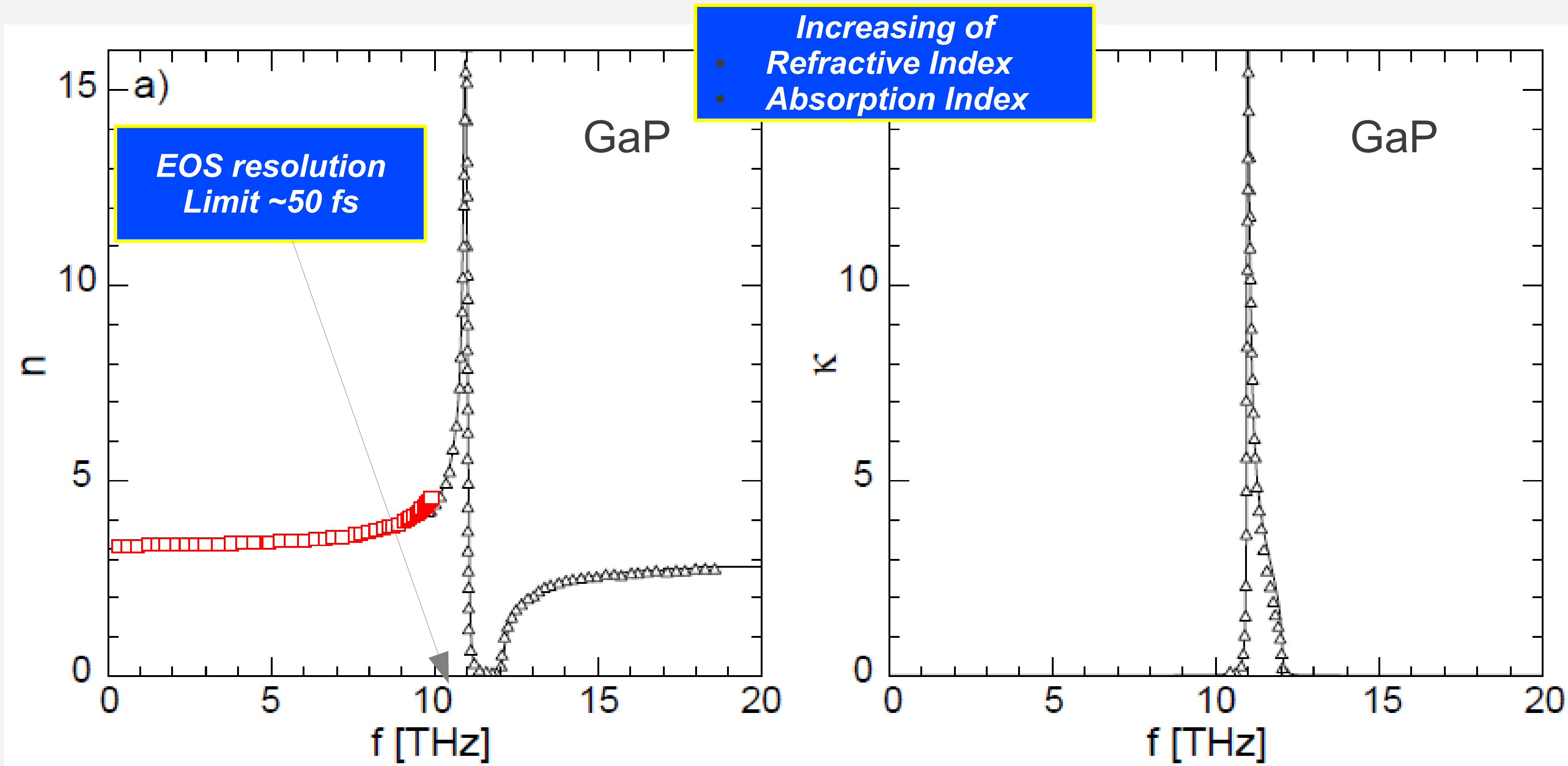
- ✔ EOS Monitor is a useful diagnostics **to measure lengths and spacing** of single and multi-bunch electron beams.
- ✔ It can be used as a **time-stamp** and/or to evaluate the RF **time jitter**.
- ✔ Bunch spacing is well reproduced.
- ✗ As expected the bunch lengths were too short to be correctly measured → improvements needed for sub-100fs bunches:
  - *Shorter laser pulse* → make a pulse compressor to achieve laser TF pulse length of 60 fs (rms).
  - *Use thinner crystals* → with 100um thicknesses we have ~110 fs (ZnTe) and ~50 fs (GaP) rms resolutions.
    - Drawback: very low signals!
  - Use different EO crystals, like **DAST** → 20x higher signals.

Thank you for your attention!

EOS optical setup

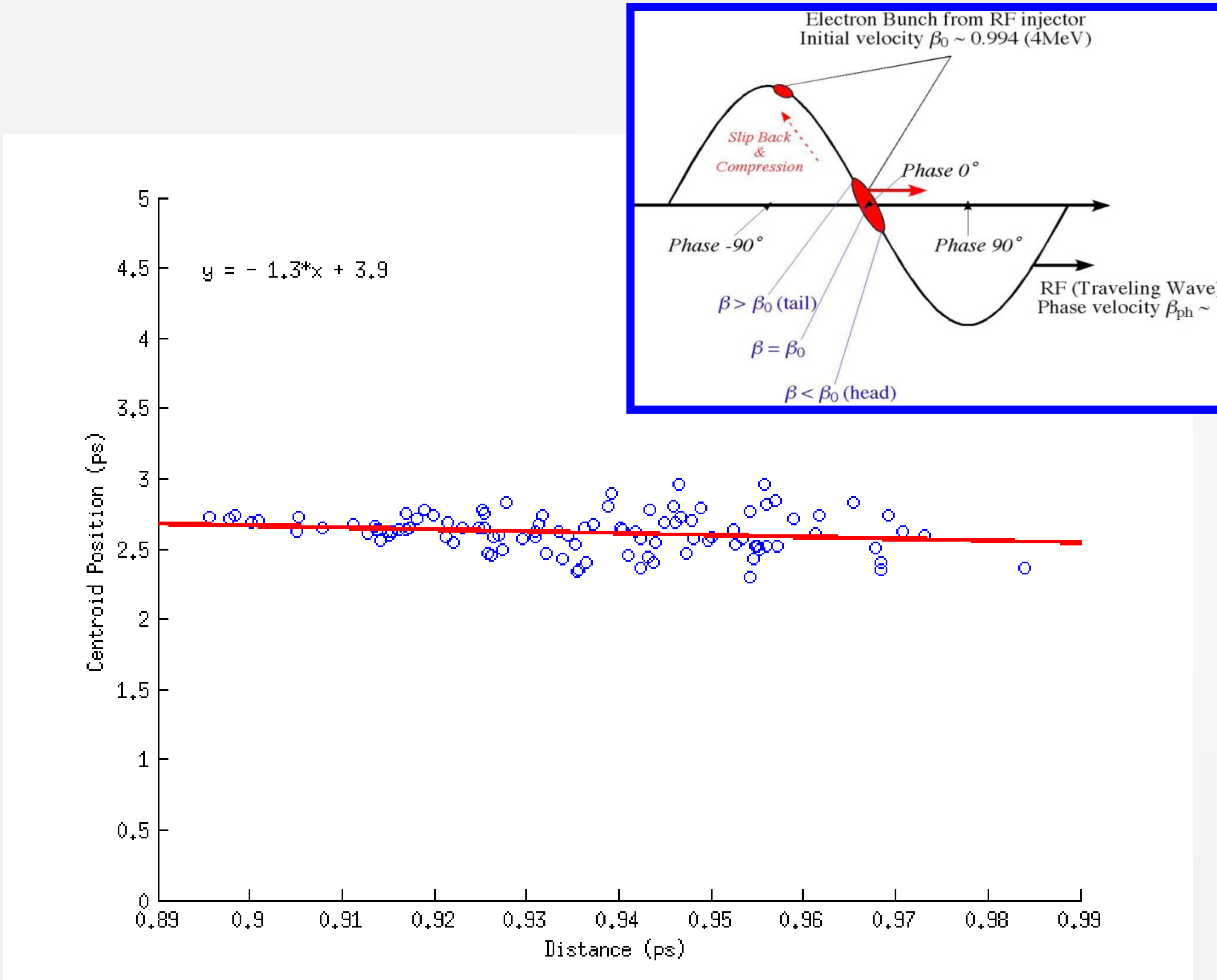


Crystal's resonance

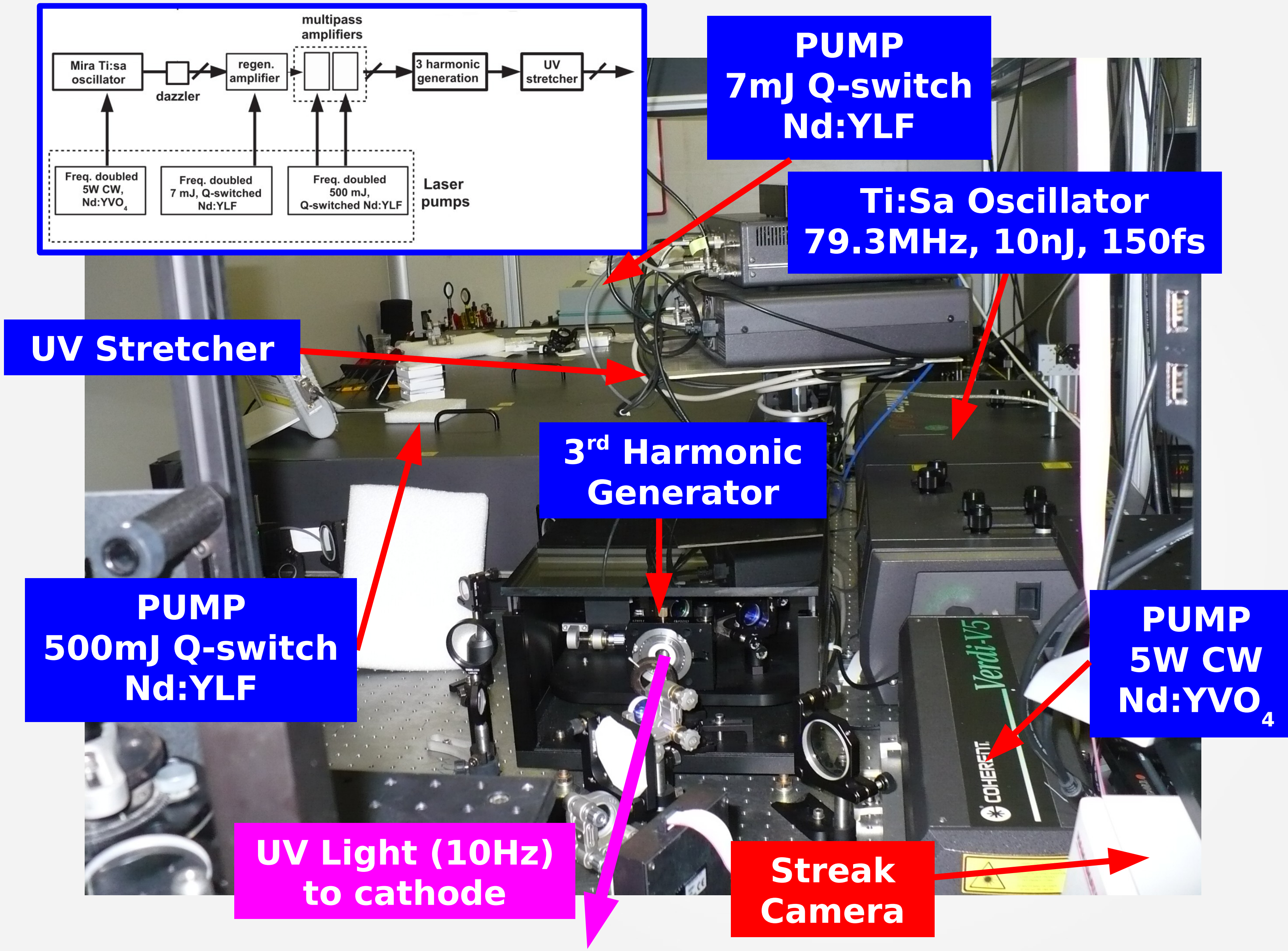


Transverse Optical resonances (TO) @ 11.02 THz
→ increasing gap velocity between laser and THz pulse

Compression jitter



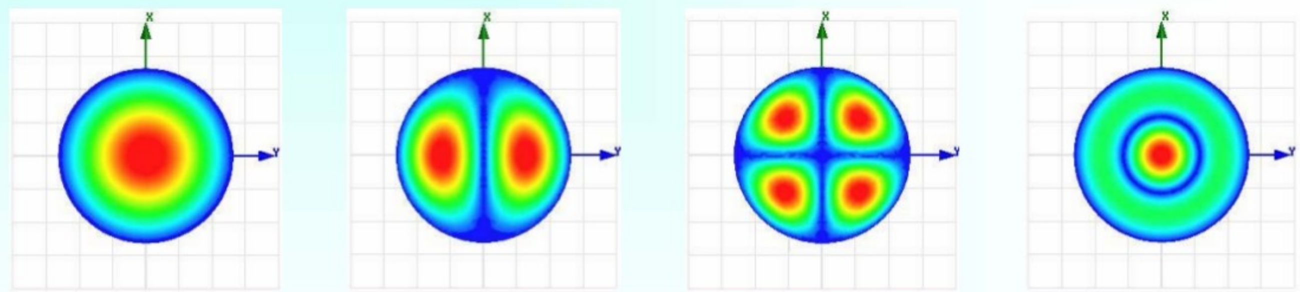
SPARC_LAB: Laser System



Cavity BPM

- The electron beam excites the resonant modes of the cavity
- The first four resonant modes are the following:

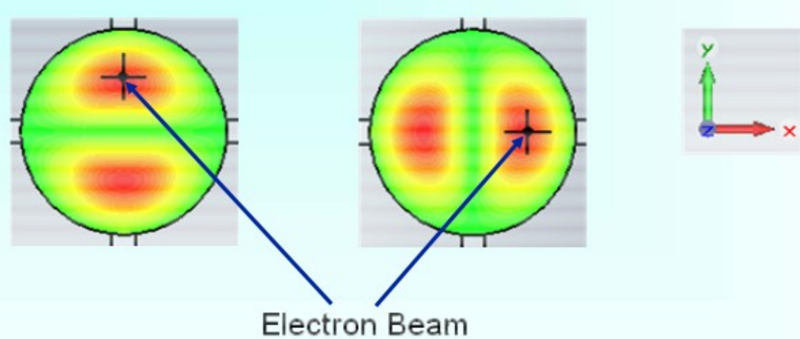
TM_{010}	TM_{110}	TM_{210}	TM_{020}



4.63 GHz	6.5 GHz	9.04 GHz	10.5 GHz

(Frequencies of the FERMI@Elettra BPM)

- It is the position sensing mode
- Its intensity is proportional to the beam offset
- There are two different polarizations: vertical and horizontal



Working Frequency:
~6.5 GHz

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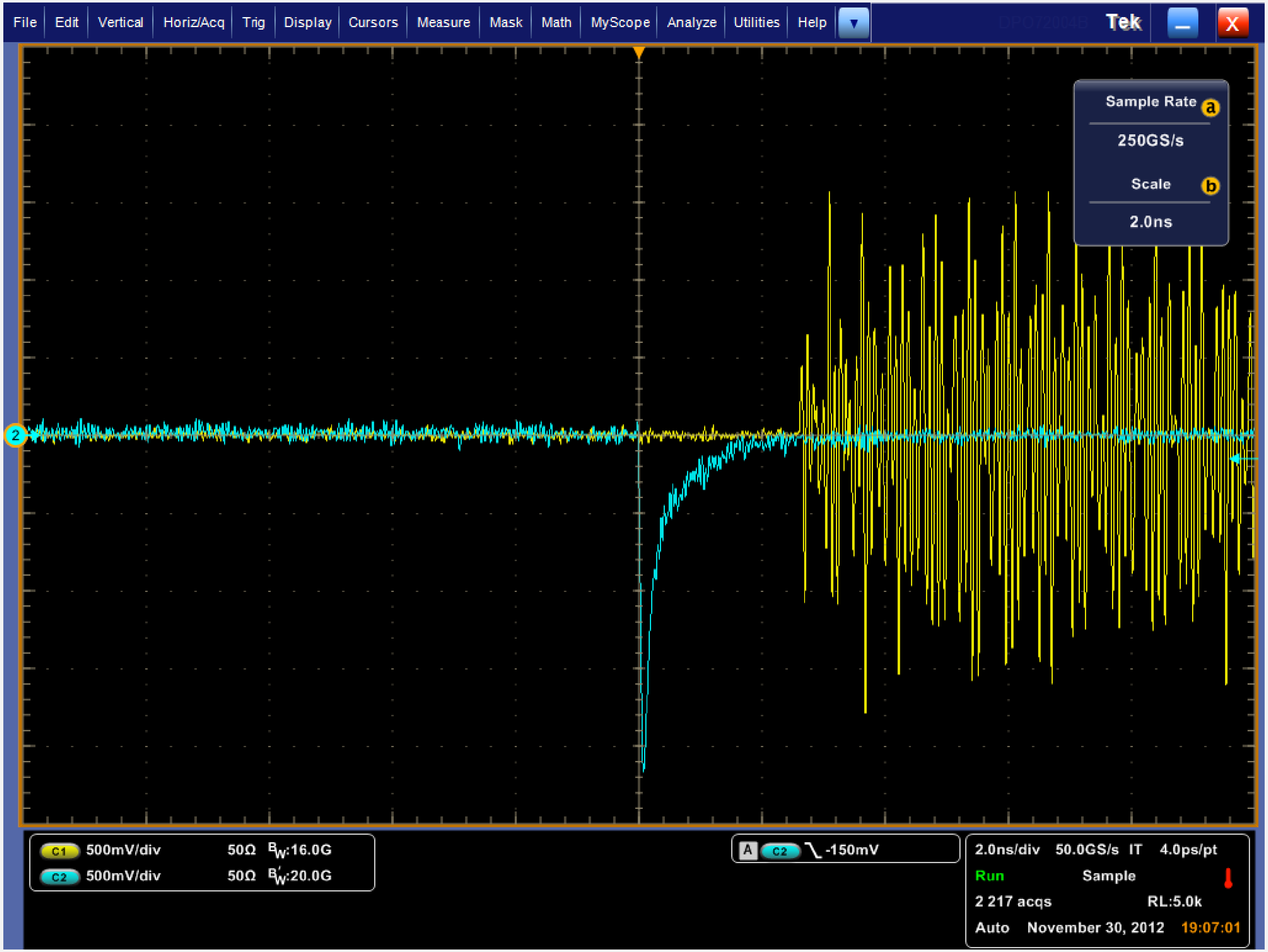
Infrastructure

Experiments

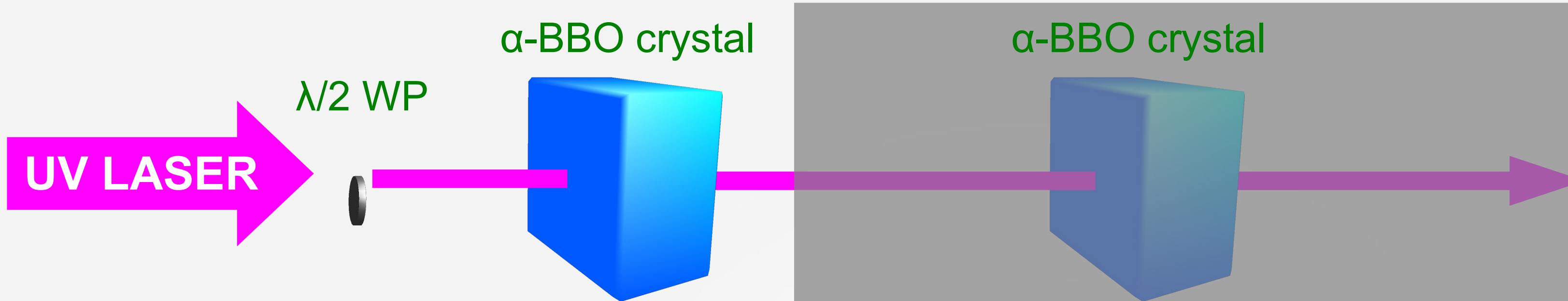
Status & Achievements

Sub-picosecond Diagnostics

Cavity BPM



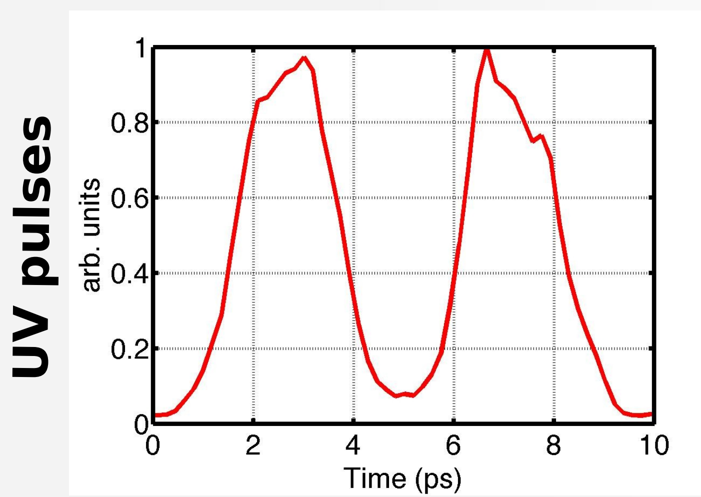
Laser COMB Pulses Generation



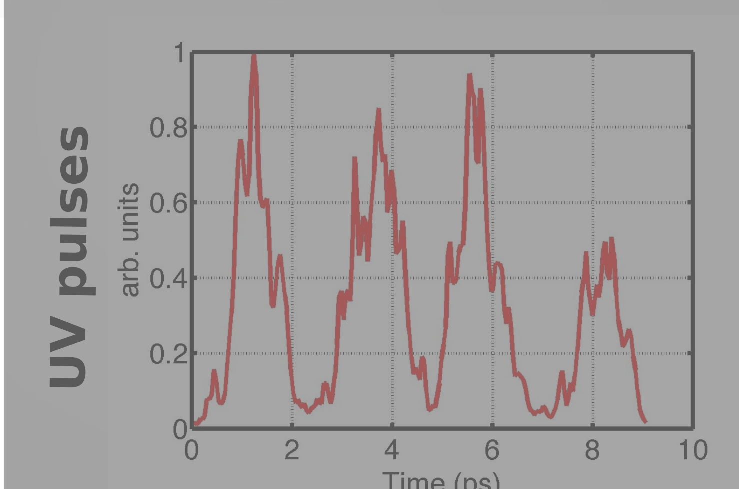
2 pulses ($\Delta\tau$ = 4ps)

2+2 pulses ($\Delta\tau$ = 2ps)

$$\Delta\tau = \left|\frac{1}{v_e^g} - \frac{1}{v_o^g}\right| \cdot L_{crystal}$$



Streak camera



Streak camera

Pockels Effect

- In usual isotropic crystals the polarization vector **P** is parallel to the electric field **E** → simple scalar relation: $P \sim E$
- If instead the medium is **anisotropic**, we have a tensorial relation *(however linear)*

$$\boxed{P_i = \epsilon_0 \chi_{ij} E_j}$$

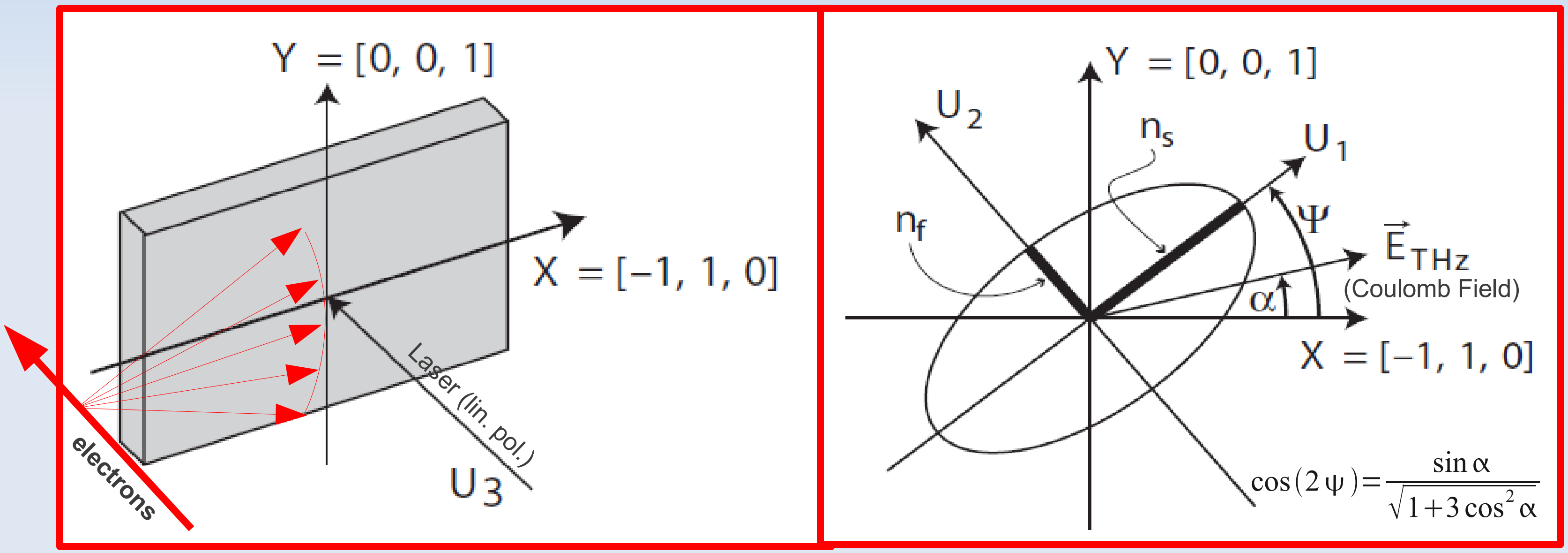
- If an external electric field is applied, it can change the optical proprierties of the crystal;
  - for very high electric field applied (**MV/m**), the relation between **P** and **E** becomes **non-linear** → $P = \epsilon_0 (\chi_e^{(0)} \cdot E + \chi_e^{(1)} \cdot E^2 + \chi_e^{(2)} \cdot E^3 + \ldots)$
- The impermeability tensor is then given by

$$\boxed{\eta = \epsilon^{-1} \rightarrow \eta_{ij} = \eta_{ij}(0) + \underbrace{r_{ijk}}_{\text{Pockels coeff.}} E_k + \cancel{\underbrace{s_{ijkl}}_{\text{Kerr coeff.}} E_k} E_l}$$

for EO crystals
$r_{ijk} \sim 10^{-12} \, m/V$

EO effect in ZnTe and GaP

- If we diagonalize η, knowing $n_i = \sqrt{\epsilon_i}$, we find
  - **optical axes with different refractive indices → different velocities;**
  - **phase delay between the electric field components.**



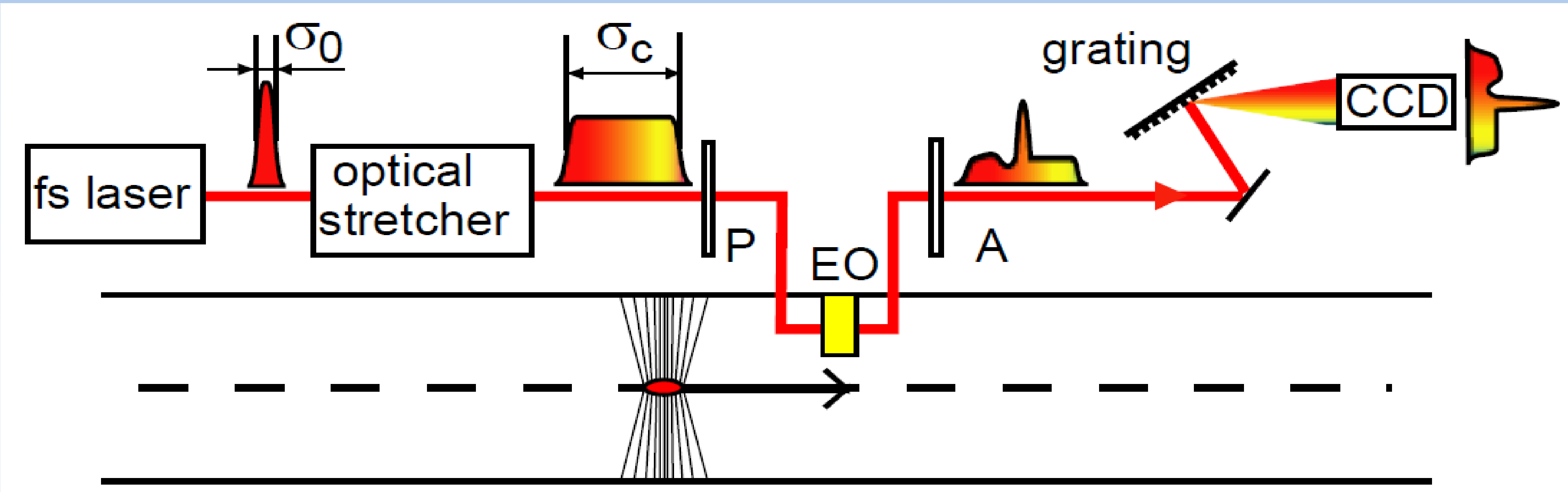
$$v = \frac{c}{n}$$

$$\Gamma(\alpha) = \frac{\omega d}{c}(n_1 - n_2) = \frac{\omega d}{2c} n_0^3 r_{41} E_{THz} \sqrt{1+3\cos^2\alpha}$$

Electro-optic crystals

- **Zinc Telluride (ZnTe)**
  - ✔ High electro-optic coeff — $r_{41} = 4.0 \times 10^{-12}$ m/V
  - ✗ Low TO resonance frequency — f = 5.3 THz
- **Gallium Phosphide (GaP)**
  - ✔ High TO resonance frequency — f = 11.0 THz
  - ✗ Low electro-optic coeff — $r_{41} = 0.9 \times 10^{-12}$ m/V
- **Gallium Selenide (GaSe)** → *under study*
  - ✔ Very high electro-optic coeff — $r_{22} = 22.0 \times 10^{-12}$ m/V
  - ✗ Low TO resonance frequency — f = 6.4 THz
  - ✗ Natural birefringent crystal — signal background!

Spectral Decoding



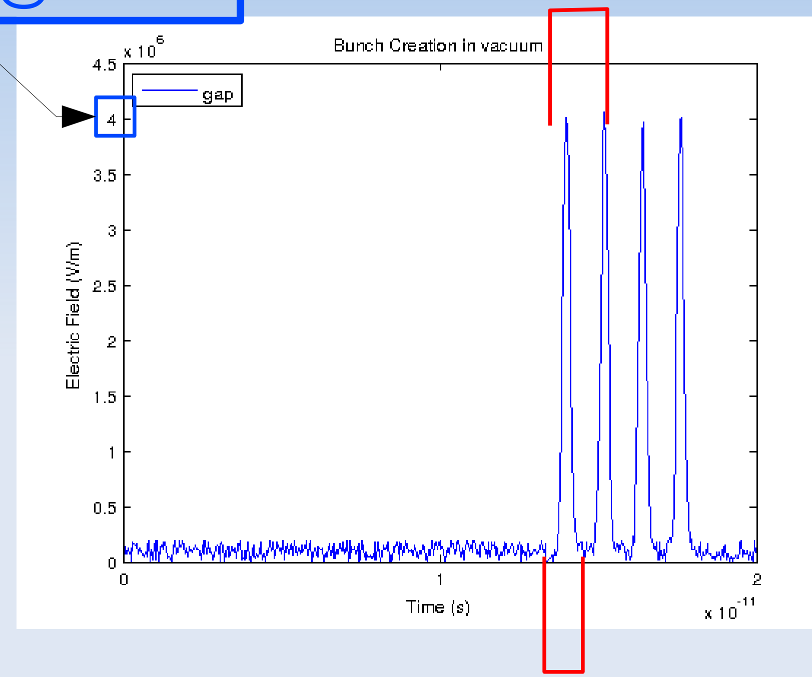
- Linear relationship between wavelength and longitudinal position in laser pulse (“**linear chirp**“).
- Bunch profile is transferred to spectral profile of the laser pulse
  - **Problem**: Frequency mixing with THz pulse creates new frequency components → Distortions at large chirp → $\sigma_{min} \approx 2{,}6\sqrt{\sigma_0 \sigma_c}$

Some simulations

Electron bunch (COMB)

- 4-pulses with 200 pC (total)
- Energy: 120 MeV
- Length 250 fs (FWHM); distance: 1.2 ps
- Distance from observation point: 2.0 mm

Max peak @ 4 MV/m



Laser pulse (from photocatode laser)

- Wavelength: 800nm (Ti:Sa)
- Duration (rms): 100 fs
- Energy pulse: 1 µJ
- Crystal incidence angle: 30° (high induced birefringence and low reflection losses)
- Laser diameter must be related to bunch length → 5 mm to scan pulses of Δt=10 ps

THz pulse propagation in a crystal

- Refractive index and absorption coefficient given by

$$n(f)+ik(f)=\sqrt{\epsilon(f)}$$

- Refractive index approximation in THz range

$$n(f)=\sqrt{\epsilon_{el}\left[1+\frac{f_L^2-f_T^2}{f_T^2-f^2-i\Gamma_0 f}\right]}$$

- Dielectric function approximation in THz range

$$\epsilon(f)=\epsilon_{el}+\frac{S_0 f_0^2}{f_0^2-f^2-i\Gamma_0 f}$$

- f_0 is the Transverse Optical (TO) resonance frequency.
- Different set of values for **GaP**, **ZnTe** and **GaSe**.

Phase delay calculation

- The overlap of the THz and laser pulses in each slice is computed by a **convolution** integral:

Laser pulse

Induced birefringence

$$\Gamma(\tau)=\frac{2\pi}{\lambda_0}\delta\sum_j\left[\int\boxed{\left[n_1(E_{eff})-n_2(E_{eff})\right]}\boxed{\frac{1}{\sqrt{2\pi}\sigma_j}\exp\left(-\frac{(t-\tau)^2}{2\sigma_j^2}\right)}dt\right]$$

$E_{eff} = E_{Coulomb} \times r_{EO}$

- In the previous configuration we have the following values:
  - **GaP**: after 500µm the cumulated Γ is about 0.6°
  - **ZnTe**: after 500µm the cumulated Γ is about 2.2°
  - **GaSe**: after 500µm the cumulated Γ is about 13.1°
- Values with crystals @ 2mm distance from electron bunch, with electric field of ~**4MV/m**!

Simulation results