Design of an Electro-Optic Bunch Length Monitor for the CERN-CTF3 probe beam

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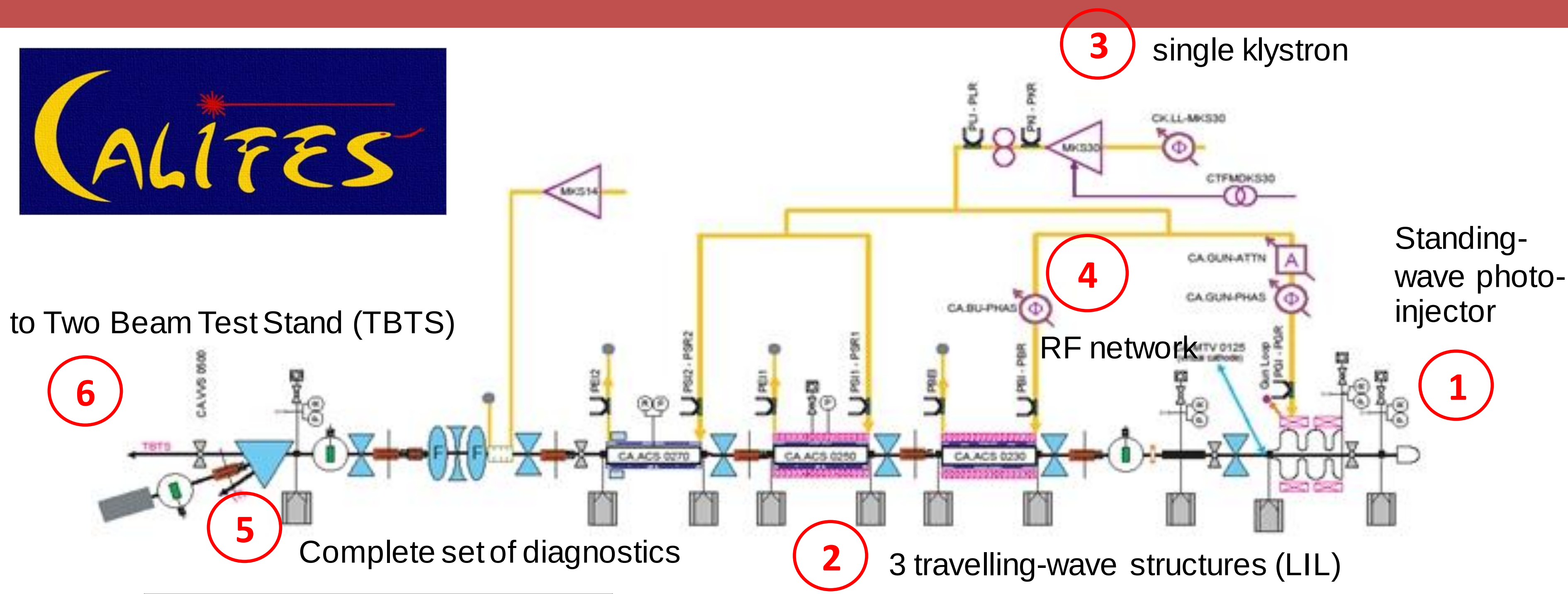
Outline

- Introduction for Califes
- EOSD and Simulation
- Schemes and comparison
- Resolution
- Summary and Outlook

Introduction ---- CALIFES in a nutshell



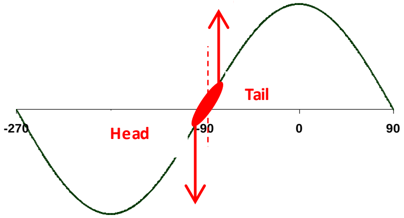
Energy	**200 MeV**
Energy spread	1% (FWHM)
Pulse length	0.6–150 ns
Bunch frequency	1.5 GHz
Bunch length	1.4 ps
Bunch charge	0.085–0.6 nC
Intensity	
- short pulse	1 A
- long pulse	0.13 A
Repetition rate	0.833 – 5 Hz

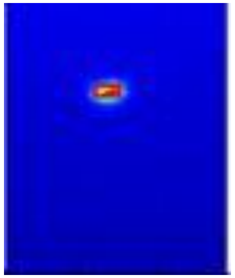
Existing bunch profile monitor:

1. Deflecting cavity
2. Bunch length measurement with the 12 GHz high gradient acceleration structure

Existing bunch profile monitors

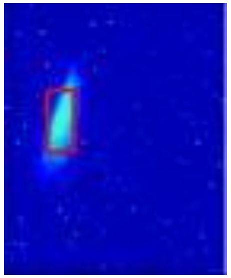
Deflecting cavity





Cavity OFF

$\sigma_y = 0.24$ mm



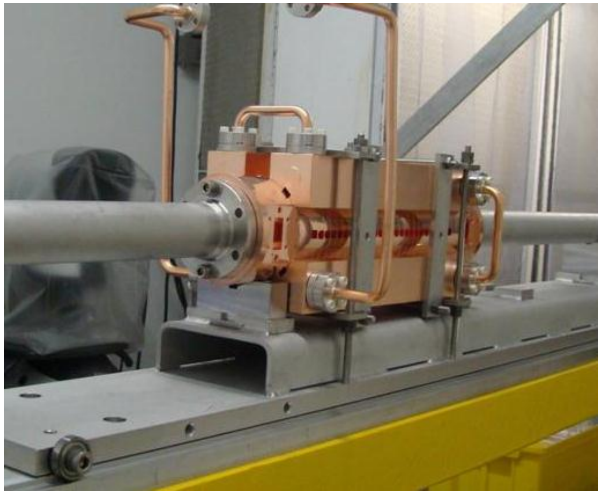
Cavity ON

$\sigma_y = 1.47$ mm

Operating principle:

- bunch pass at zero crossing in a deflecting cavity
- bunch head experiences a transverse kick downward, bunch tail upward
- bunch transverse size is then measured downstream on a beam profile monitor

12 GHz high gradient acceleration structure

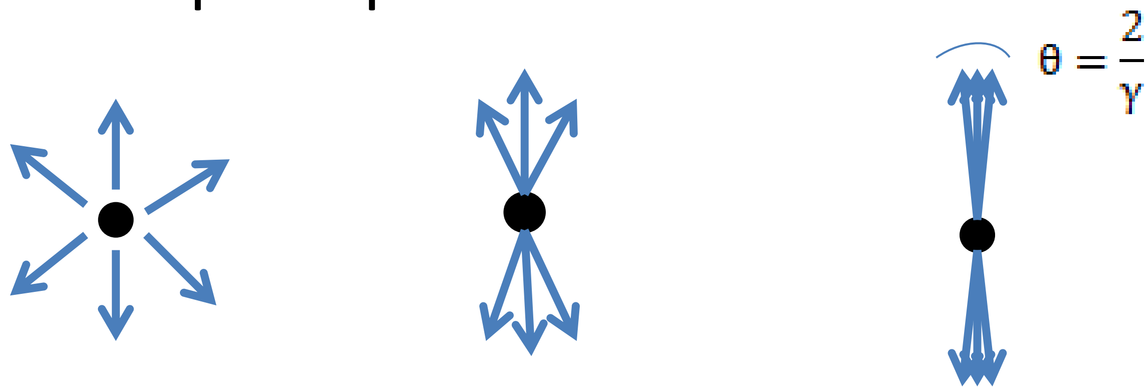


Operating principle:

- bunch pass at zero crossing in the accelerating structure (12 GHz – 100 MV/m)
- bunch head is decelerated, bunch tail accelerated
- Energy spread is measured downstream in the spectrometer line
- Increase of energy spread is related to bunch length

Simulation: Coulomb field of e-bunch

Coulomb field temporal profile



β=0 β=0.9 β=0.9999

$$E_{e0}(r_0, t) = \frac{e_0\gamma}{4\pi\varepsilon_0} \cdot \frac{r_0}{(r_0^2 + \gamma^2 v_e^2 (t - t_0)^2)^{3/2}}$$

Coulomb field of one electron

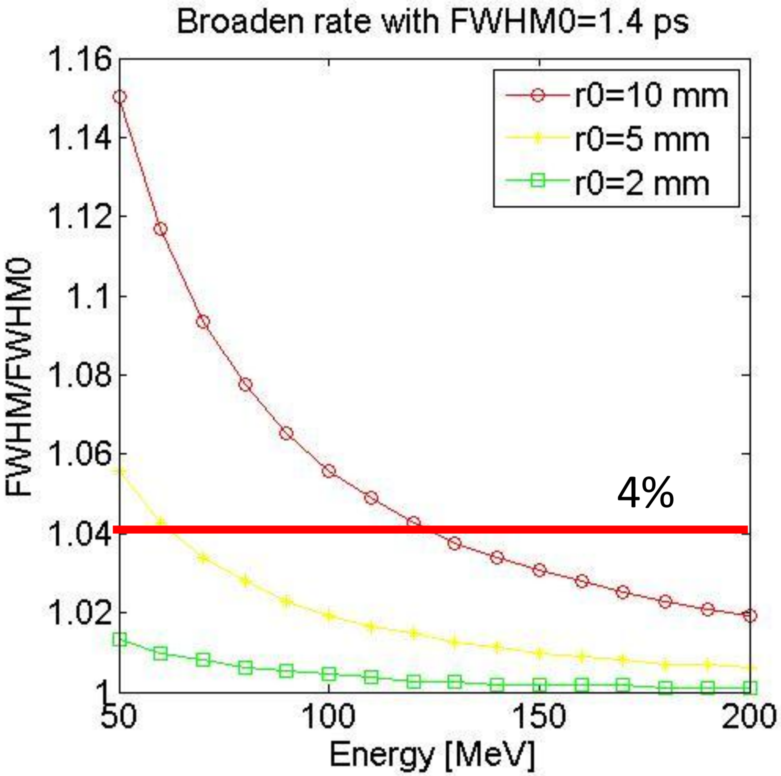
- High energy , Coulomb field temporal profile is approximately the bunch temporal profile
- Broadening of profile: $\Delta t \sim \frac{2r}{\gamma}$

Simulation: Coulomb field of e-bunch

Coulomb field temporal profile and broadening

$$E_{Colm} = E_{e0} * \rho$$

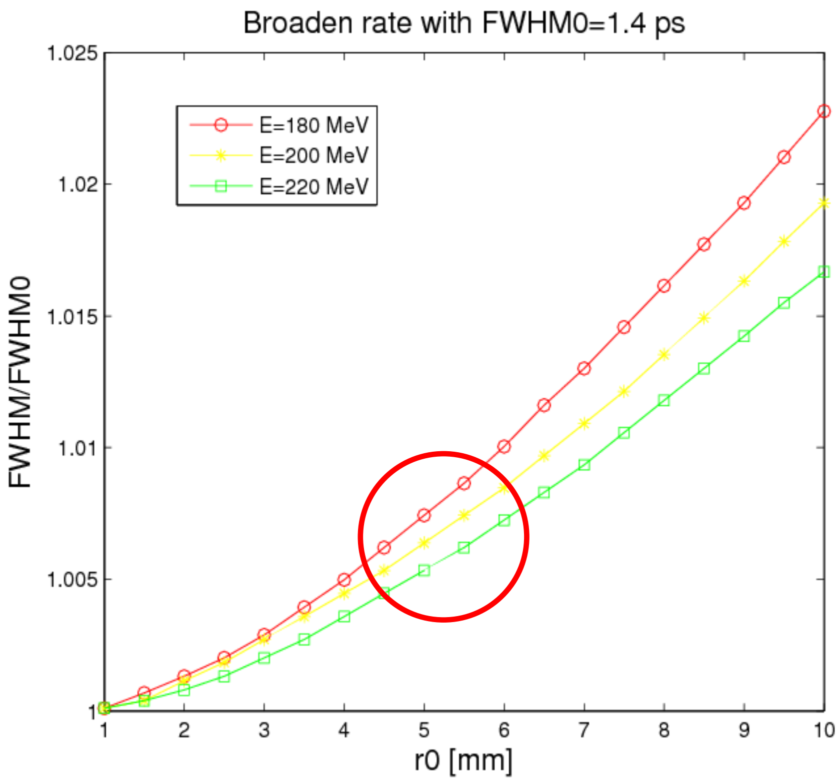
- Radial offset from single electron E_{e0}
- Electrons' density distribution within one bunch ρ
- Convolution

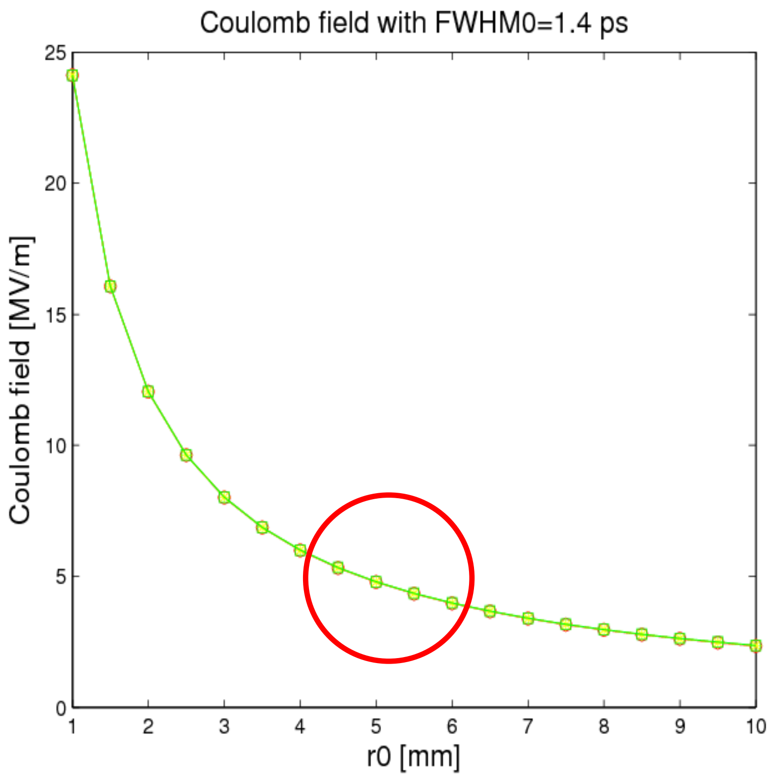


For high energy beam (>150 MeV):

Broadening rate < 4%
@ 10 mm

Simulation: Coulomb field of e-bunch





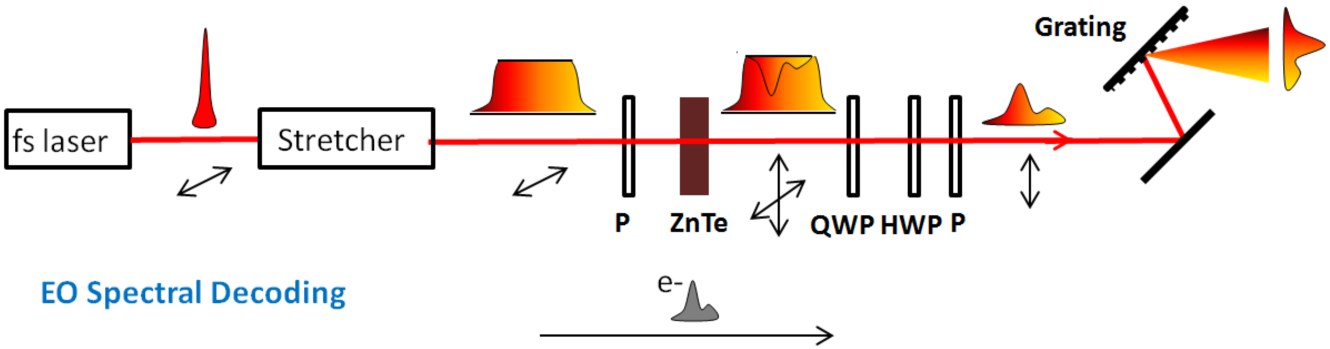
r0: the distance far away from e-bunch

Damage to crystal ⟷ Crystal survives, low Coulomb field

Closer Further

Simulation: EOSD

Electro-Optical Spectral Decoding:



- Linear chirped optical pulse
- Polarization variation caused by Coulomb field—laser nonlinear effect
- Polarization → Intensity, by two crossed polarizers
- I(λ) ←→ I(t)

$$E_{out} = (0 \quad 1) R(\varphi) M_{hw} R(-\varphi)\, R(\alpha) M_{qw} R(-\alpha)\, R(\theta) M_{EO} R(-\theta) \begin{pmatrix} E_{opt}^{chirp}(f) \\ 0 \end{pmatrix}$$

$R(\theta)$ ---- rotation matrix

M_{qw} ----Jones matrix for quarter waveplate

M_{hw} ----Jones matrix for half waveplate

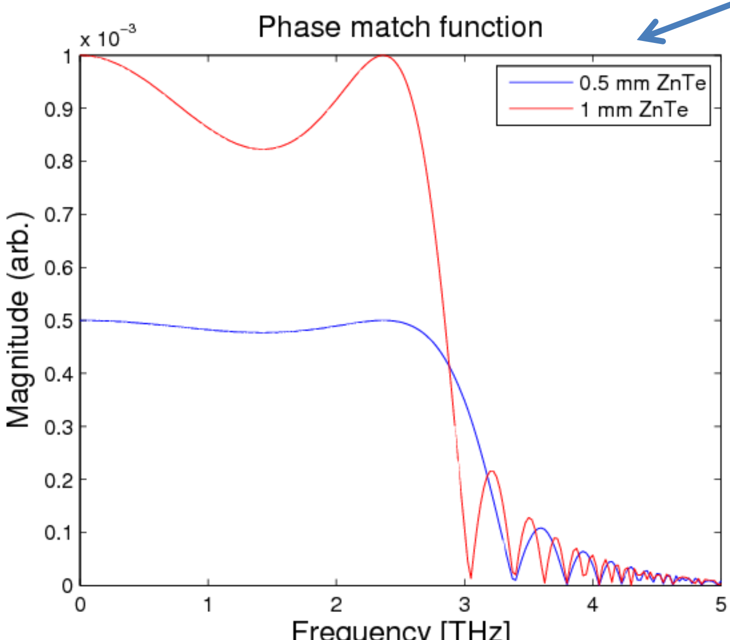
Simulation: EOSD

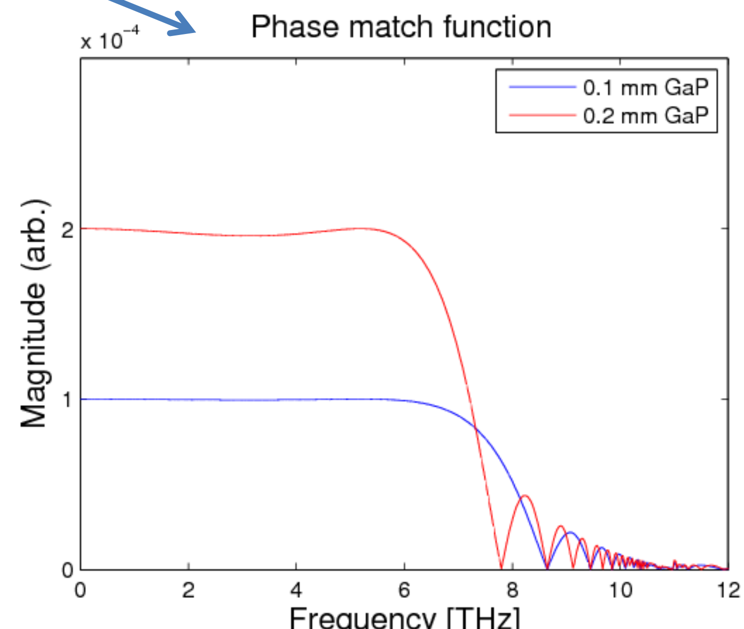
EO effect: **Frequency mixing** —induce→ **Polarization variation**

$$\tilde{E}_{sum}(z,\omega) = \frac{i\omega^2}{2c^2 k_{opt}^R(\omega)} \exp\left[ik_{opt}(\omega)z\right] \times \int_{-\infty}^{+\infty} d\Omega \left\{ \chi_{eff}^{(2)}(\omega,\Omega) \left[\frac{\exp(i\Delta k(\omega,\Omega)z)-1}{i\Delta k(\omega,\Omega)}\right] \times \tilde{E}_{THz}(0,\Omega)\tilde{E}_{opt}(0,\omega-\Omega) \right\}$$

Coulomb field

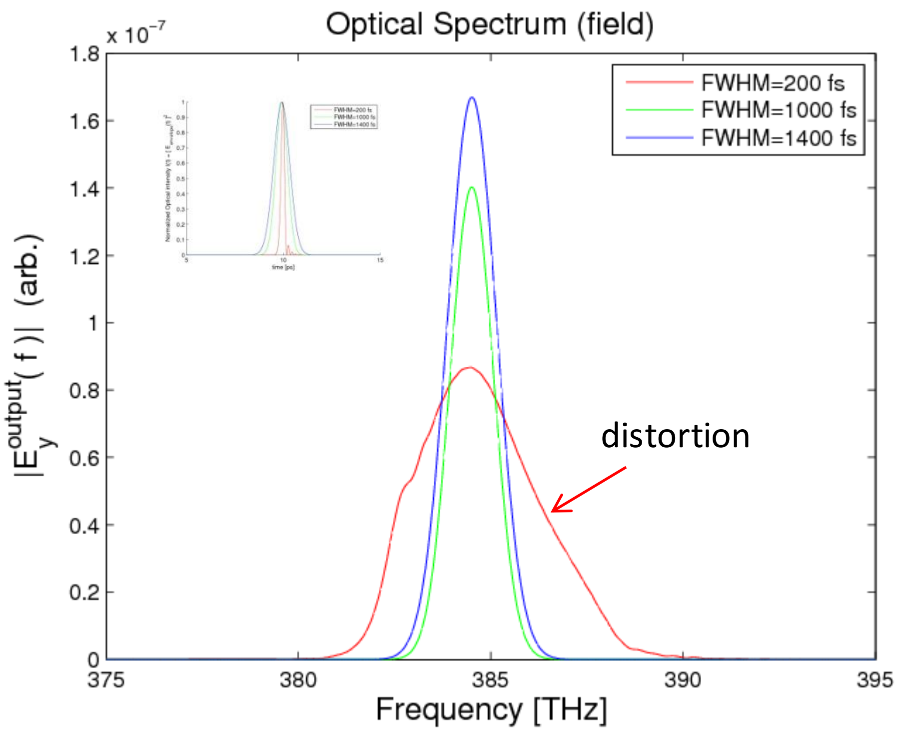
Laser

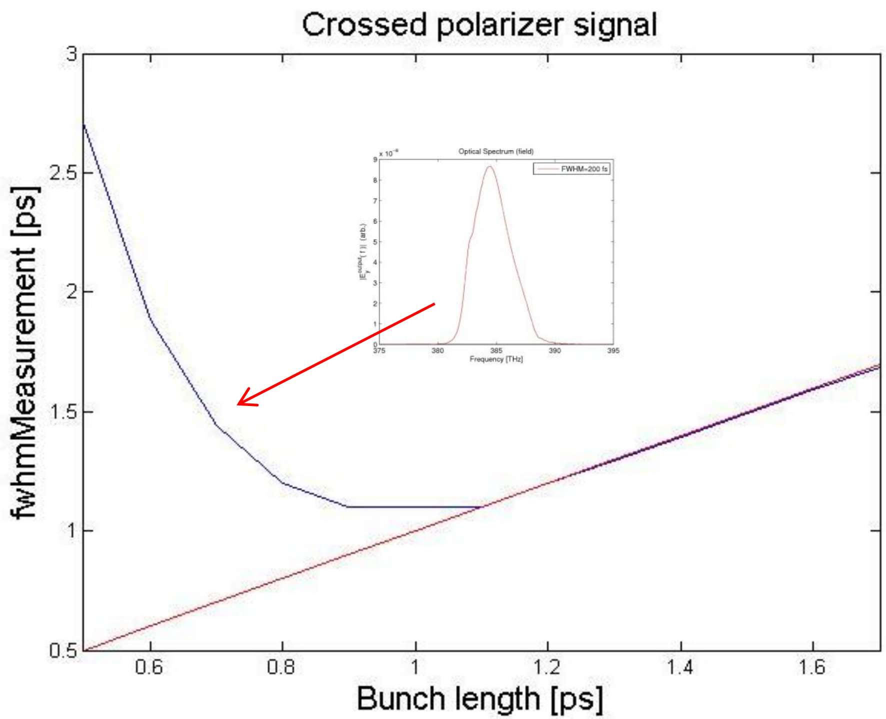




Wider bandwidth, better resolution !

Simulation: EOSD results





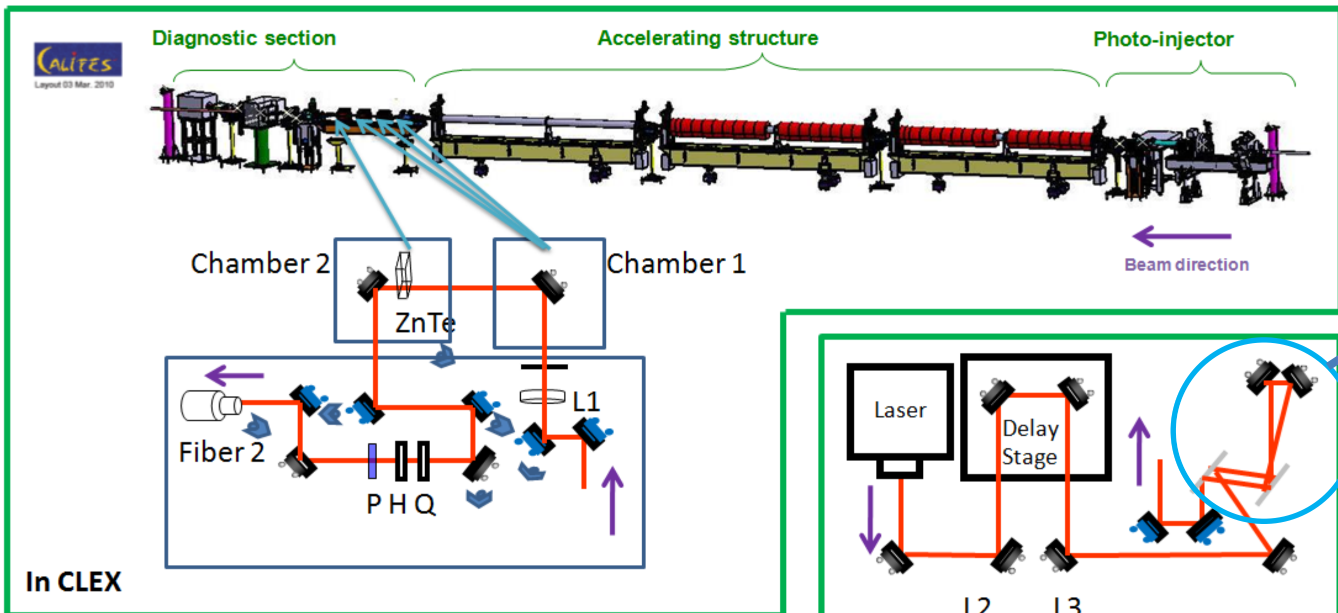
Distortion: bunch length < 1 ps

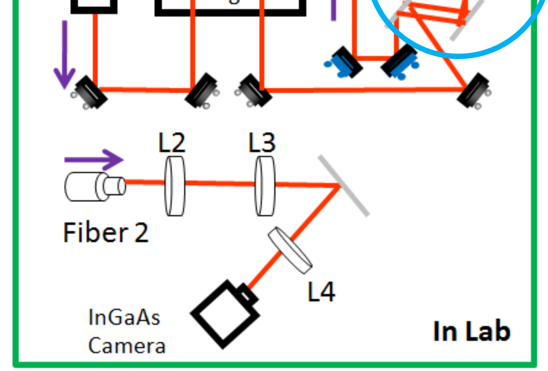
Other parameters:
Laser wavelength: 780nm
Laser pulse energy: 1.5nJ
Pulse duration: 150fs

Crystal thickness: 500µm
Distance: 5mm

Short bunch----fast temporal modulation---- spectral content ---- t~λ mapping

EO monitor Design for Califes





In CLEX		In Lab	
10 Motors	7 plane mirrors	1 Laser	10 plane mirrors
3 Rotate motors	2 polarizers	1 InGaAs Camera	3 gratings
6 Pinhole cameras	3 wave plates	1 motor stage	3 lens
	1 lens	4 Motors	1 fiber head
	1 fiber head		
	2 photodiodes		

Scheme

Stretcher:

- SF11 glass
- 100fs----3.24ps

Simulation: EOSD results

Laser performance comparison

Laser	Wavelength (nm)	Pulse energy (nJ)	Crystal	Thickness (μm)	EO coefficient (pm/V)	Non-linear energy (pJ)
1	1030	10	GaP	200	0.97	0.118
2	780	1.8	ZnTe	1000	3.9	0.9
3	780	1.2	ZnTe	1000	3.9	0.6
4	780	2.7	ZnTe	1000	3.9	1.37

Laser 1: Standard ytterbium fiber laser
Laser 2: Standard erbium fiber laser
Laser 3: Custom Er fiber laser with fiber transport
Normal fiber: higher energy, not stable
PM fiber: lower energy, stable
Laser 4: Custom Er fiber laser with pulse picker
pulse energy can be changed

Assume :

Bunch charge = 0.2 nC,
r_0 = 5 mm

EO monitor Design for Califes

Laser room safety

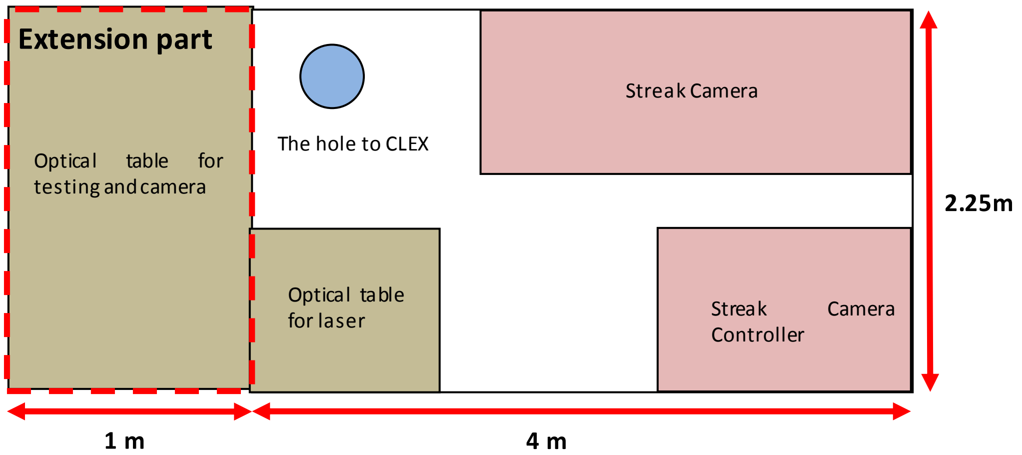
• An interlock shutter is needed for the laser room. When the door of the lab is opened, laser will be blocked automatically by the interlock shutter.

• When the laser is running, people in the lab should wear laser protection glasses.

• Signs (usually these are lights) should be both inside and outside of the lab to warn people that the laser is running.

• Follow the safety rules of laser room at CERN.

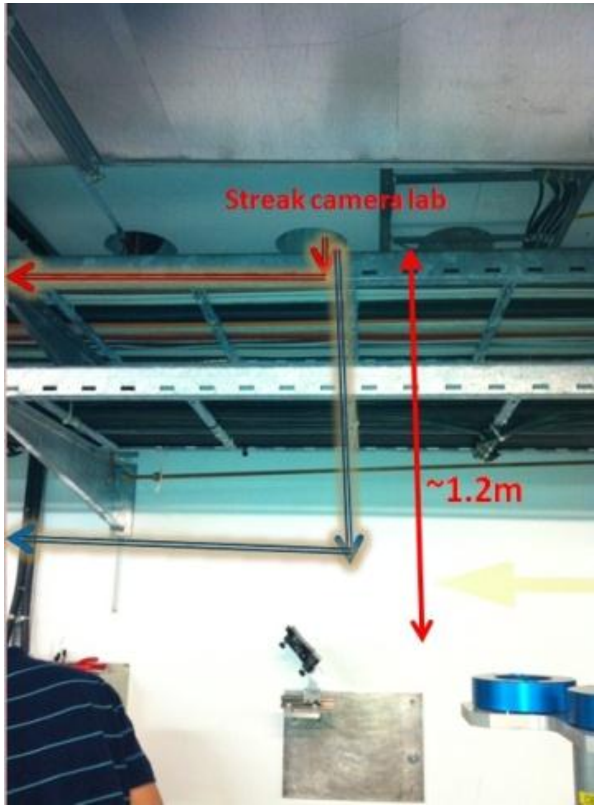
Laser room extension



Height: 2.62 m

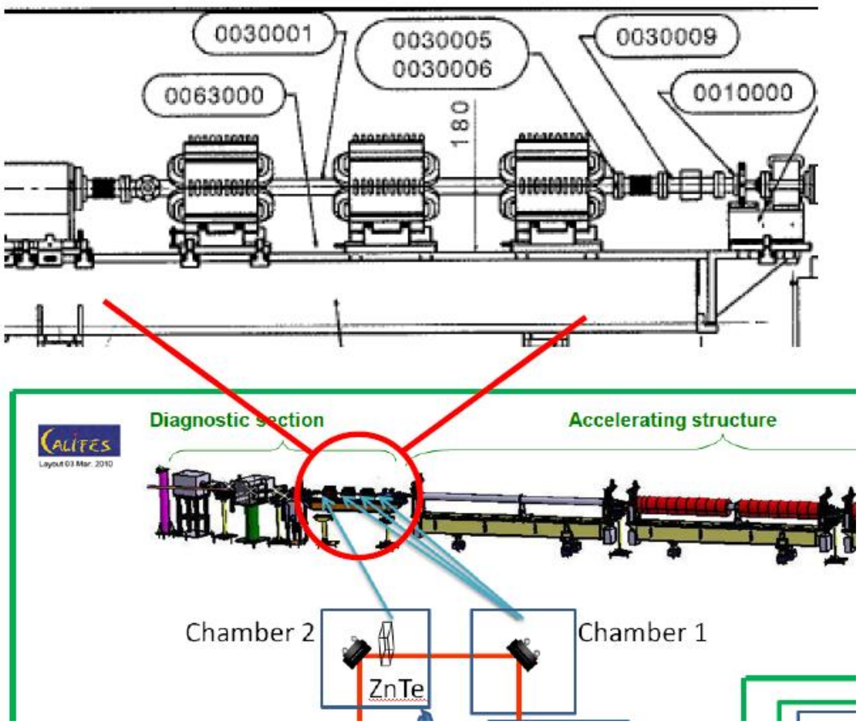
EO monitor Design for Califes

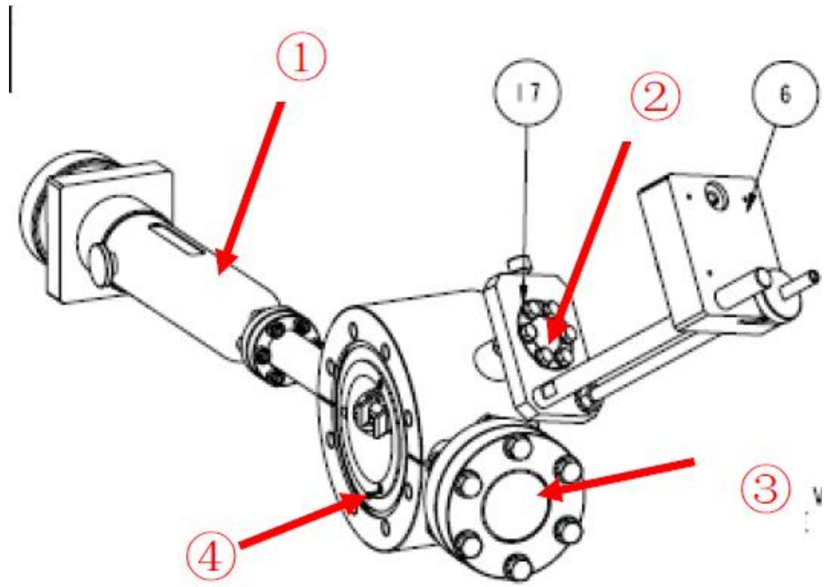
Laser Transport Line



EO monitor Design for Califes

Chamber design





① Adjustable arm

② Observation port

③ Laser input/output viewport

④ Central chamber

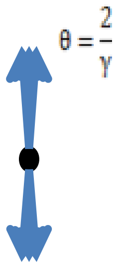
Operation and Commissioning

Laser	Motors and Observers	Chambers	ICCD gated camera
● Synchroniz-ation ● Timing : phase shifter and delay stage	● Controlled from the laser lab	● Controlled in CTF3 control room	● Controlled in laser lab ● Trigger signal: beam loss monitor around chamber

Expected Resolution

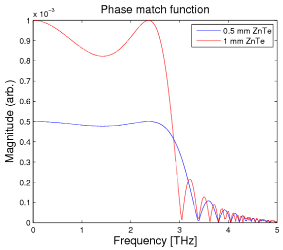
1. Distance between crystal and e-beam

$$\Delta t \sim \frac{2r}{\gamma}$$ ~10 fs at r=5 mm



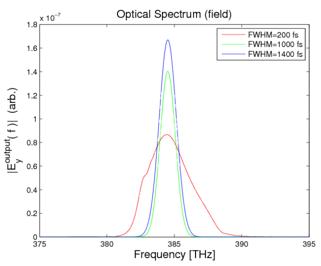
2. The frequency response of crystal (material and thickness)

for 1 mm ZnTe: ~333 fs ~1/(3THz)

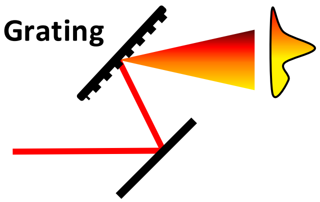


3. EOSD limitation (Laser pulse duration and chirped duration)

$$\tau_{\lim} = \sqrt{\tau_0^{FWHM} \tau_c^{FWHM}}$$ ~550 fs (100 fs→3 ps)



4. Resolution of spectrometer and CCD ~40 fs (512 pixels)



Summary & Outlook

Summary:

- EO system scheme and Laser room are prepared. All the optical items are ordered.
- Based on numerical simulation, the resolution of this system is expected to be sub-picosecond.
- A EO bunch length measurement system will be installed at CTF3 in the summer of 2012.

Outlook:

- Build up the optical system and continue to do experiments based on frequency up-conversion method and other new methods for resolution improvement.

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Thank You !

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