Diagnostics Examples from lepton-linacs and FELs

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and INFN

One minute…

Mainly high brightness electron beams diagnostics

Now plasma based accelerated beams diagnostics

But also…

I’m an experimental physicist

I deposited Nb on Cu for accelerating structures in the past…

I’m actually the scientific responsible for muon tomography of port containers…

Motivations

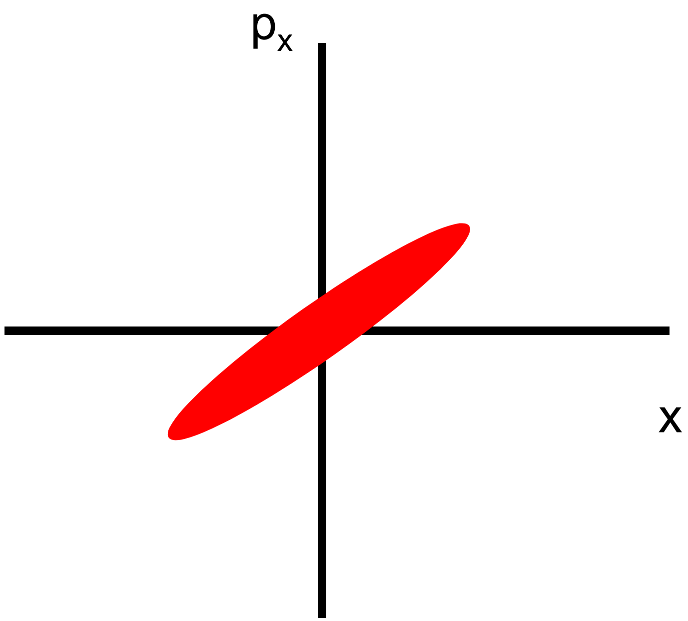
- You have already seen a lot of diagnostics, some of them described with a lot of details
- Also you have already experienced some techniques in the afternoon labs.
- What can I say more??
- I'll add some more information (yes!) looking at some details that make the difference
- The principles ideas are very charming but the real implementation is also a challenge
- I'll also try to clarify which is the relation between measured quantities and real beam parameters

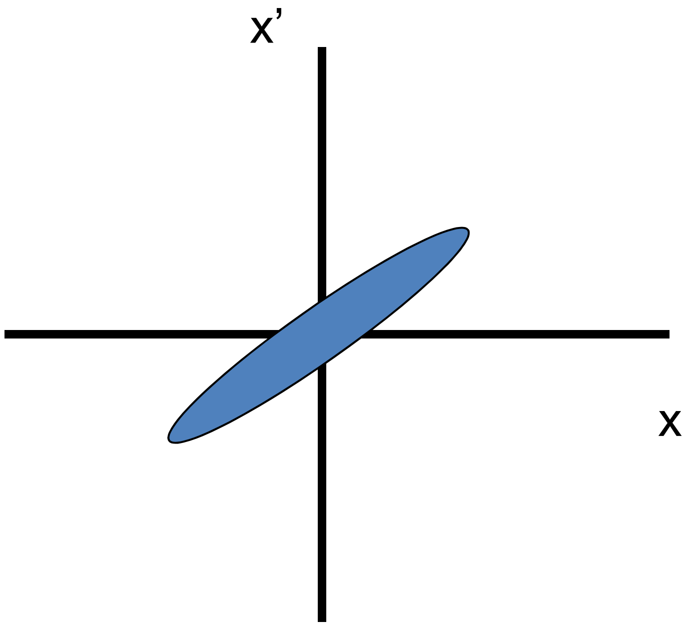
Transverse Emittance

Trace vs Phase space

$$p_x = m_o \, c \, \gamma_{rel} \, \beta_x$$

Trace space

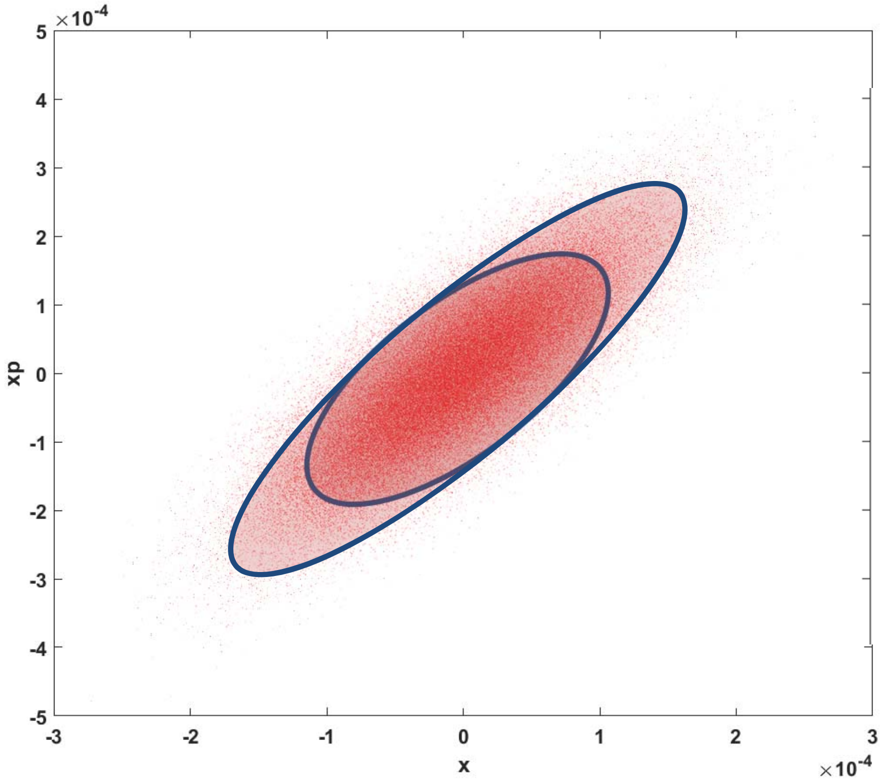




Phase space

$$x' = \frac{dx}{ds} = \frac{dx}{dt} \cdot \frac{dt}{ds} = \frac{\beta_x}{\beta_s}$$

RMS emittance



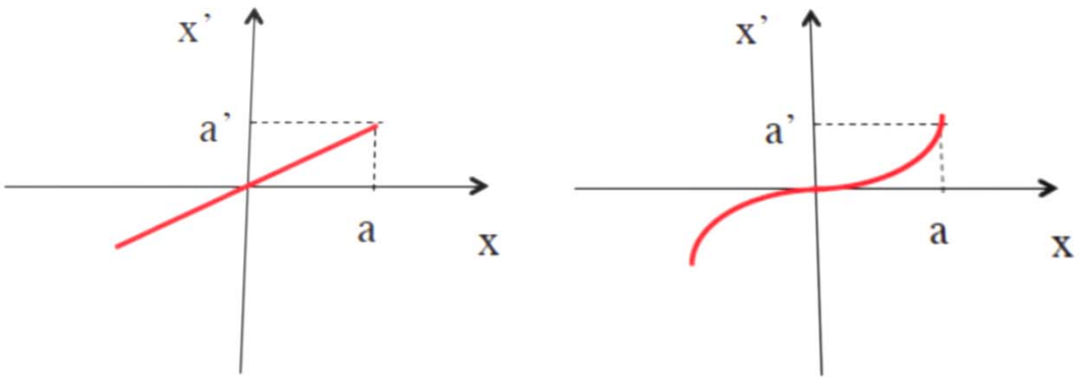
$$\sigma_x^2(z) = \langle x^2 \rangle = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} x^2 f(x,x',z)\,dx\,dx'$$

$$\sigma_{x'}^2(z) = \langle x'^2 \rangle = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} x'^2 f(x,x',z)\,dx\,dx'$$

$$\sigma_{xx'}(z) = \langle xx' \rangle = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} xx' f(x,x',z)\,dx\,dx'$$

$$\varepsilon_{rms} = \sqrt{\sigma_x^2\sigma_{x'}^2 - \sigma_{xx'}^2} = \sqrt{\left(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2\right)}$$

Importance of RMS emittance



$$x' = Cx^n$$

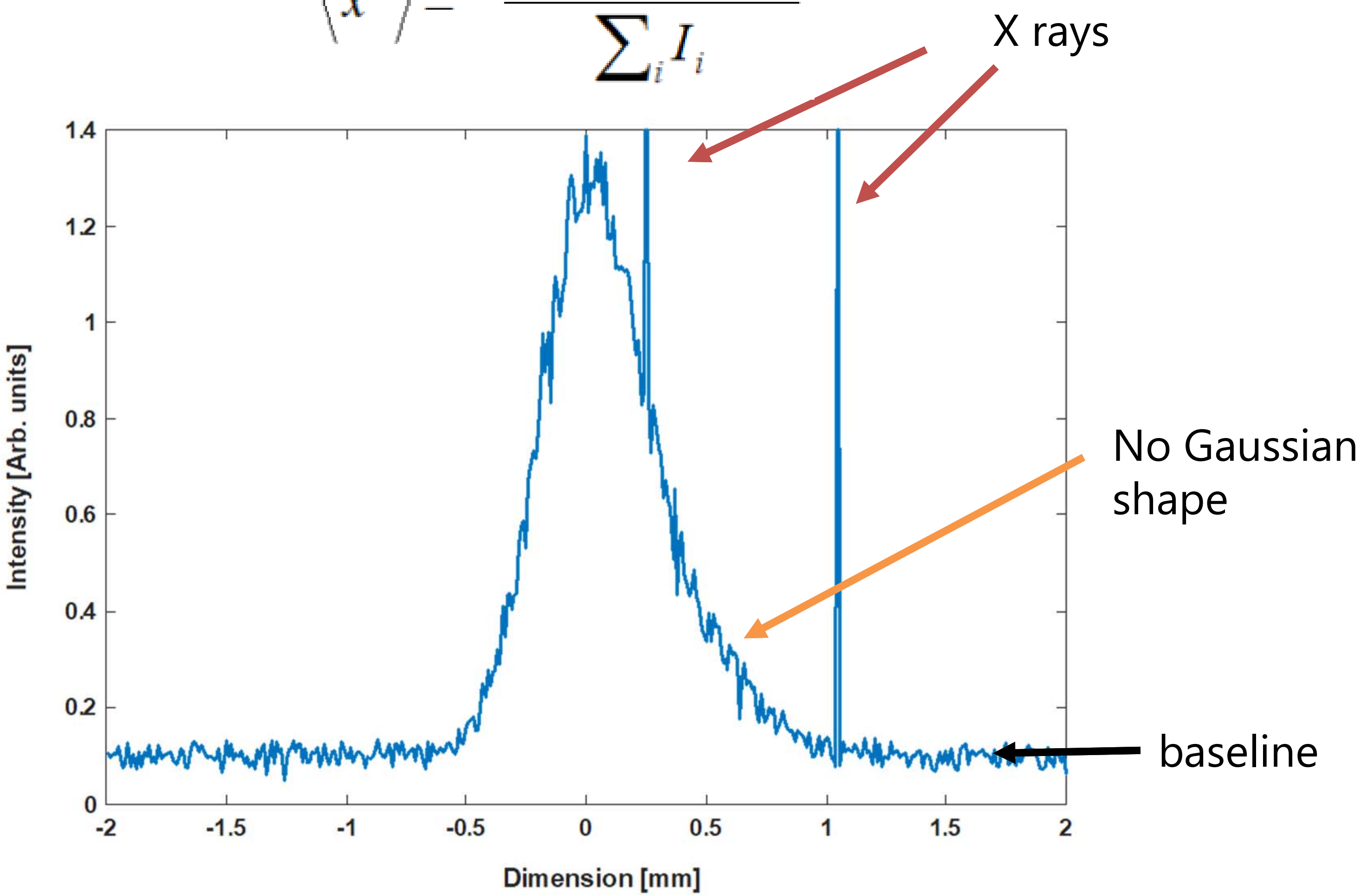
$$\varepsilon_{rms} = C\sqrt{\langle x^2 \rangle \langle x^{2n} \rangle - \langle x^{n+1} \rangle^2}$$

$$\begin{cases} n = 1 \Rightarrow \varepsilon_{rms} = 0 \\ n > 1 \Rightarrow \varepsilon_{rms} \neq 0 \end{cases}$$

Even when the phase-space area is zero, if the distribution lies on a curved line its rms emittance is not zero.
RMS emittance is not an invariant for Hamiltonian with non linear terms.

Root mean square

$$\langle x^2 \rangle = \frac{\sum_i I_i (x_i - \bar{x})^2}{\sum_i I_i}$$



Space charge dominated regime

- The beam must be emittance dominated

$$\sigma_x'' = \frac{\varepsilon_n^2}{\gamma^2 \sigma_x^3} + \frac{I}{\gamma^3 I_0 (\sigma_x + \sigma_y)}$$

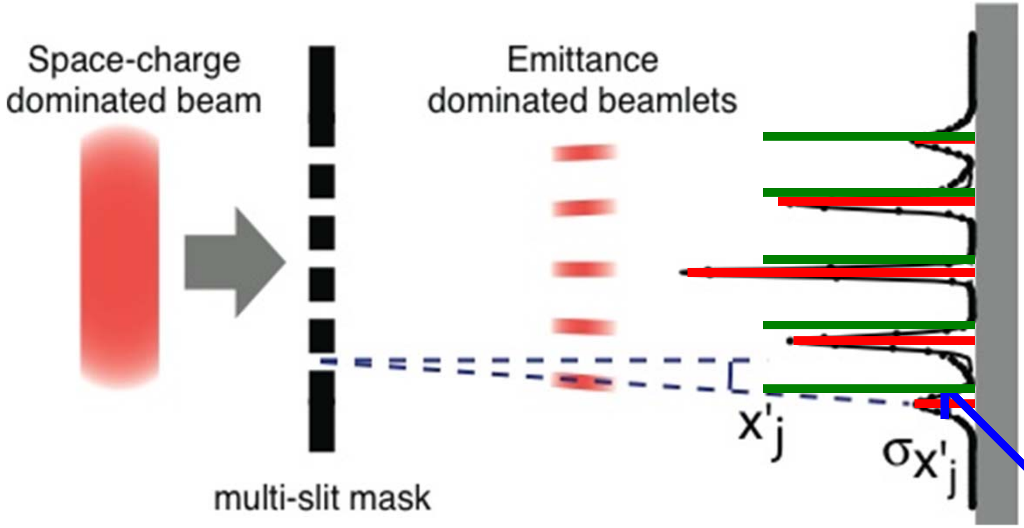
Martin Reiser, Theory and Design of Charged Particle Beams (Wiley, New York, 1994)

- Assuming a round beam

$$R_0 = \frac{I \sigma_0^2}{2 \gamma I_0 \varepsilon_n^2}$$

- The aperture must be chosen so small to obtain $R_0 << 1$, in order to have a beam emittance dominated

Pepper pot



To measure the emittance for a space charge dominated beam the used technique is the well known pepper-pot

The emittance can be reconstructed from the second momentum of the distribution

$$\varepsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

C. Lejeune and J. Aubert, Adv. Electron. Electron Phys. Suppl. A **13**, 159 (1980)
Zhang, Min. *Emittance formula for slits and pepper-pot measurement*. No. FNAL-TM--1988. Fermi National Accelerator Lab., Batavia, IL (United States), 1996.

Design Issues II

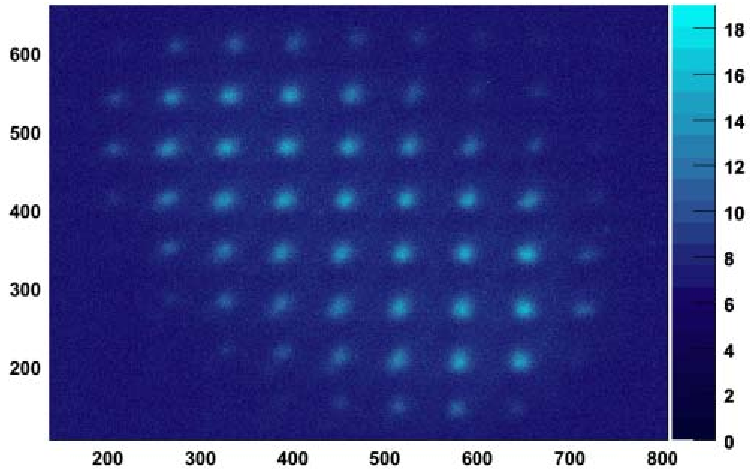
- The contribution of the slit width to the size of the beamlet profile should be negligible
- The material thickness (usually tungsten) must be long enough to stop or heavily scatter beam at large angle
- But the angular acceptance of the slit cannot be smaller of the expected angular divergence of the beam

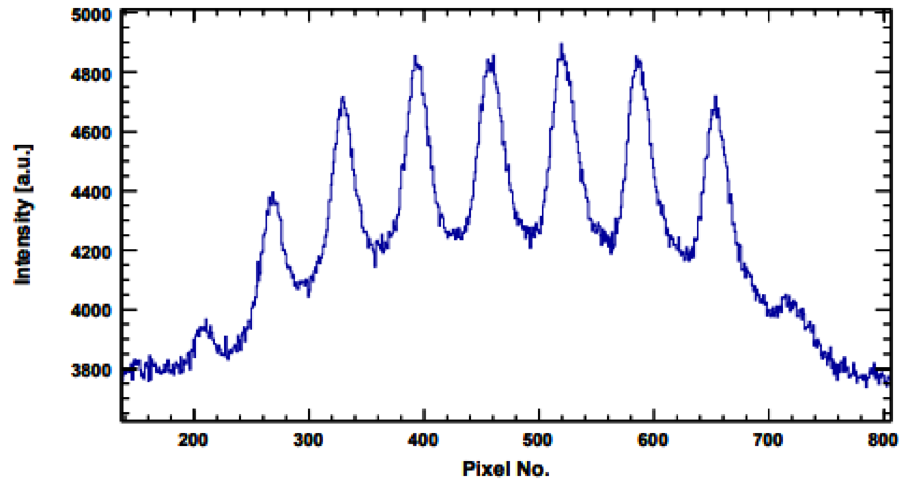
$$\sigma = \sqrt{L \cdot \sigma' + \left(\frac{d^2}{12}\right)}$$

$$L >> \frac{d}{\sigma' \cdot \sqrt{12}}$$

$$l < \frac{d}{2\sigma'}$$

A real pepper pot



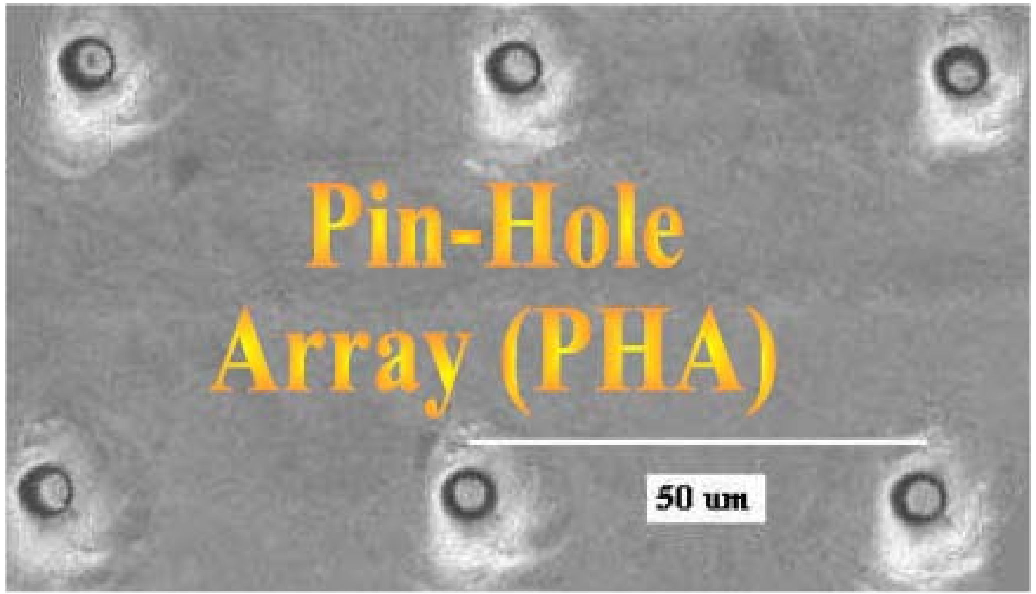


Laserbeam machined tungsten disk of 200 μm thickness. 20 μm diameter holes are separated by 250 μm in both dimensions

Source: Schietinger, T., et al. "Measurements and modeling at the PSI-XFEL 500 kV low-emittance electron source." Proceedings of the 24th Linear Accelerator Conference, Victoria. 2008.

- Single shot measurement in both planes
- Both planes same time
- It works fine without any overlap between X and Y profiles

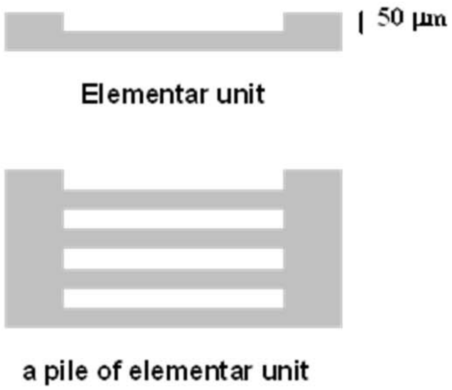
Holes machining

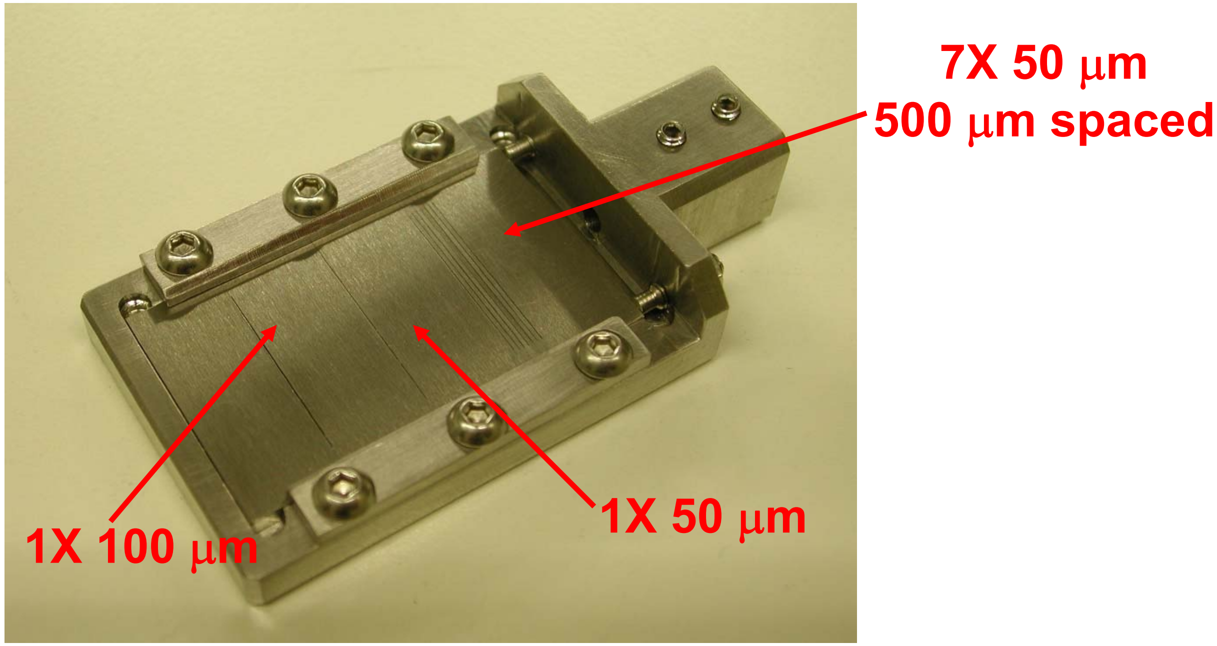


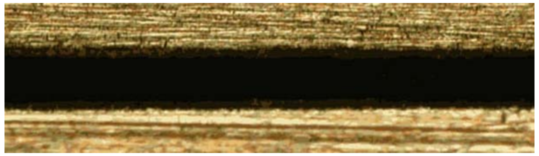
T. Levato and al. "*Fabrication of 3 μm diameter pin hole array (PHA) on thick W substrates*", AIP Conf. Proc. Vol 1209, pp 59-62 (2010)

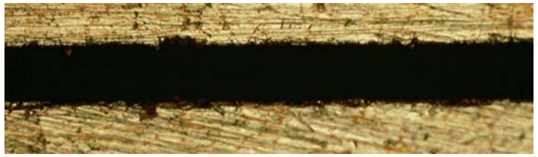
- Holes array have been successfully produced.
- The thickness of the material can be as large as 100 times the hole diameter

Multi slits setup





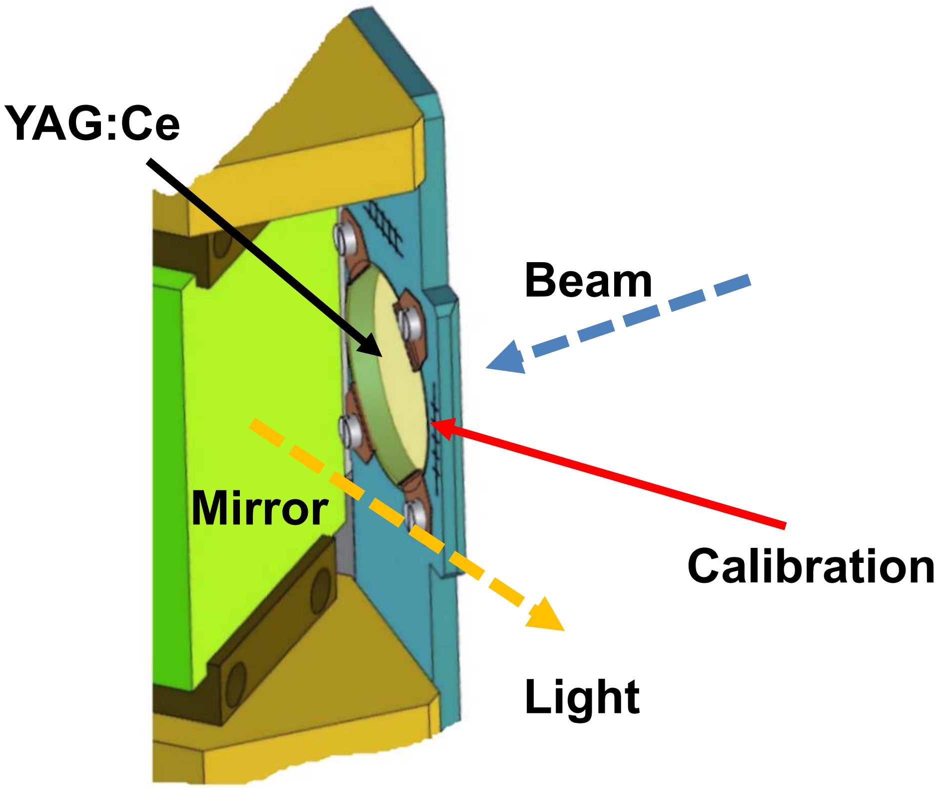




Photochemical machining

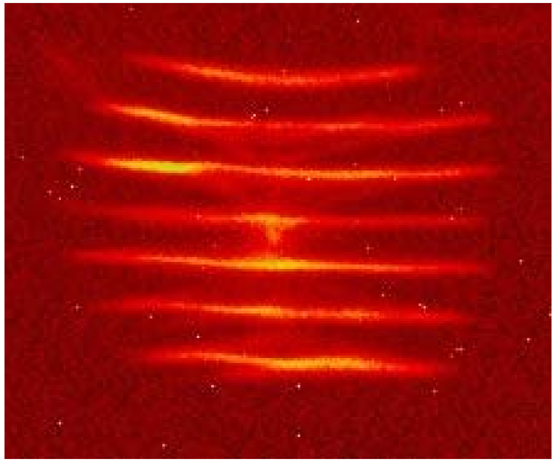
Mechanical machining

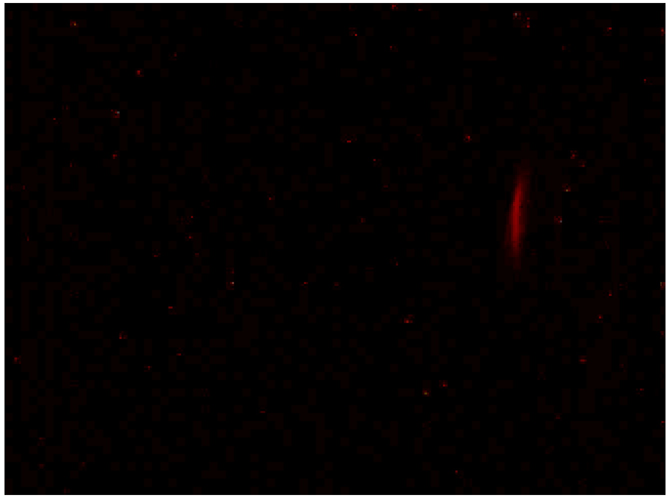
Screen setup



- YAG:Ce mounted at 90 degress to avoid blurring
- Mirror mounted at 45 degrees
- Calibration marks machined on the holder

Slits

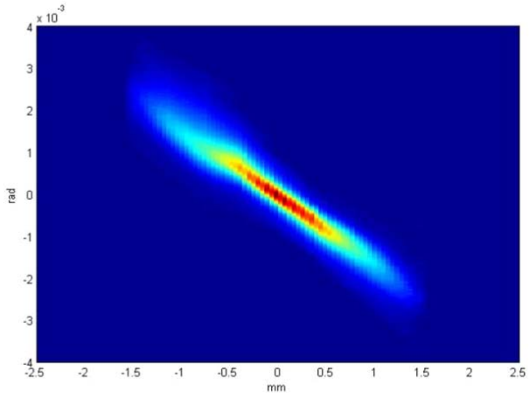


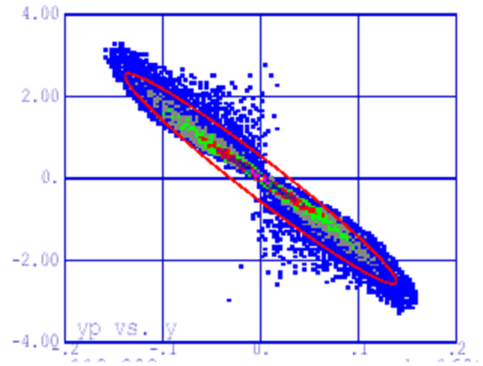


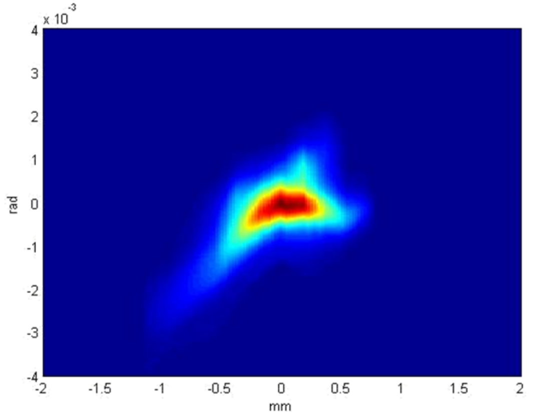
Phase space mapping

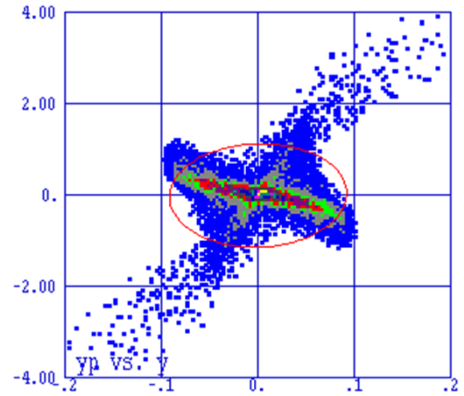
Measurements

Simulations

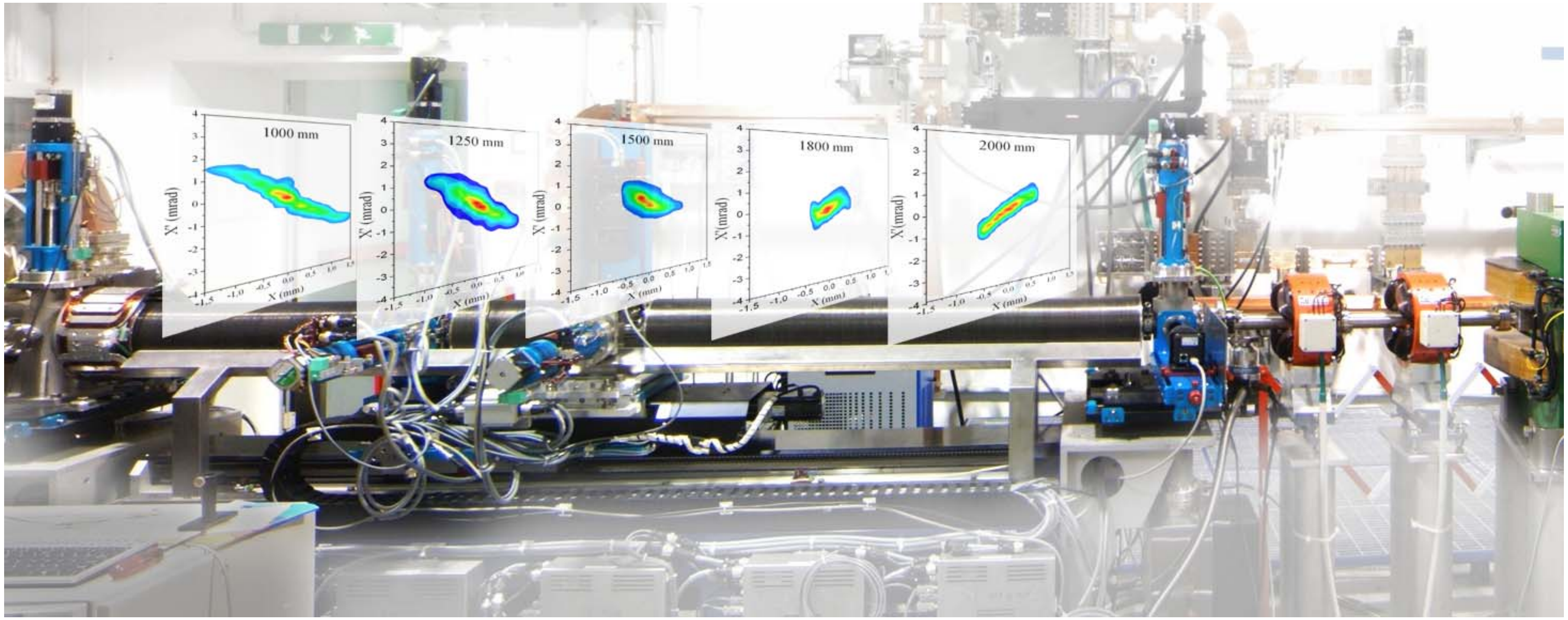






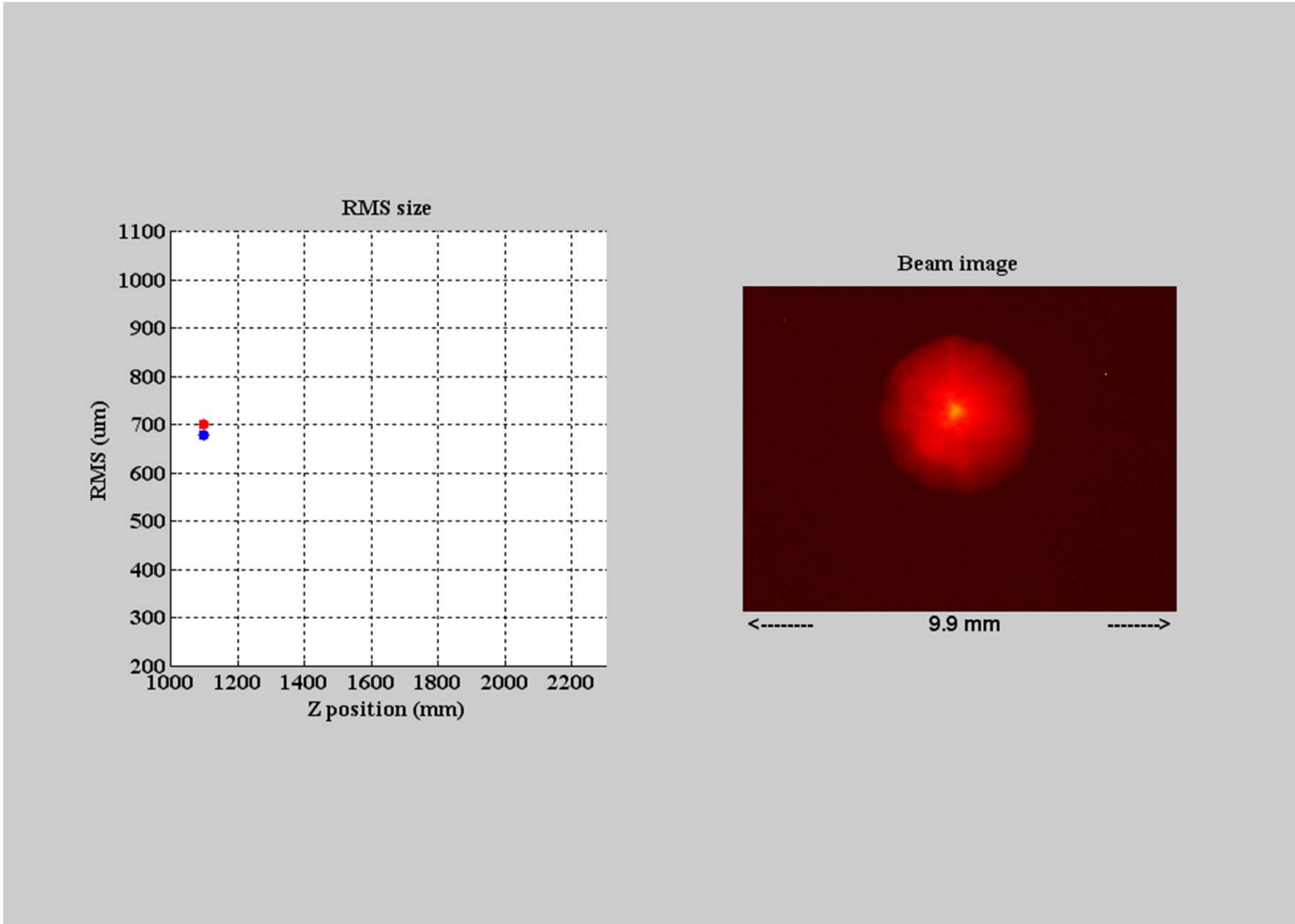


Phase space evolution

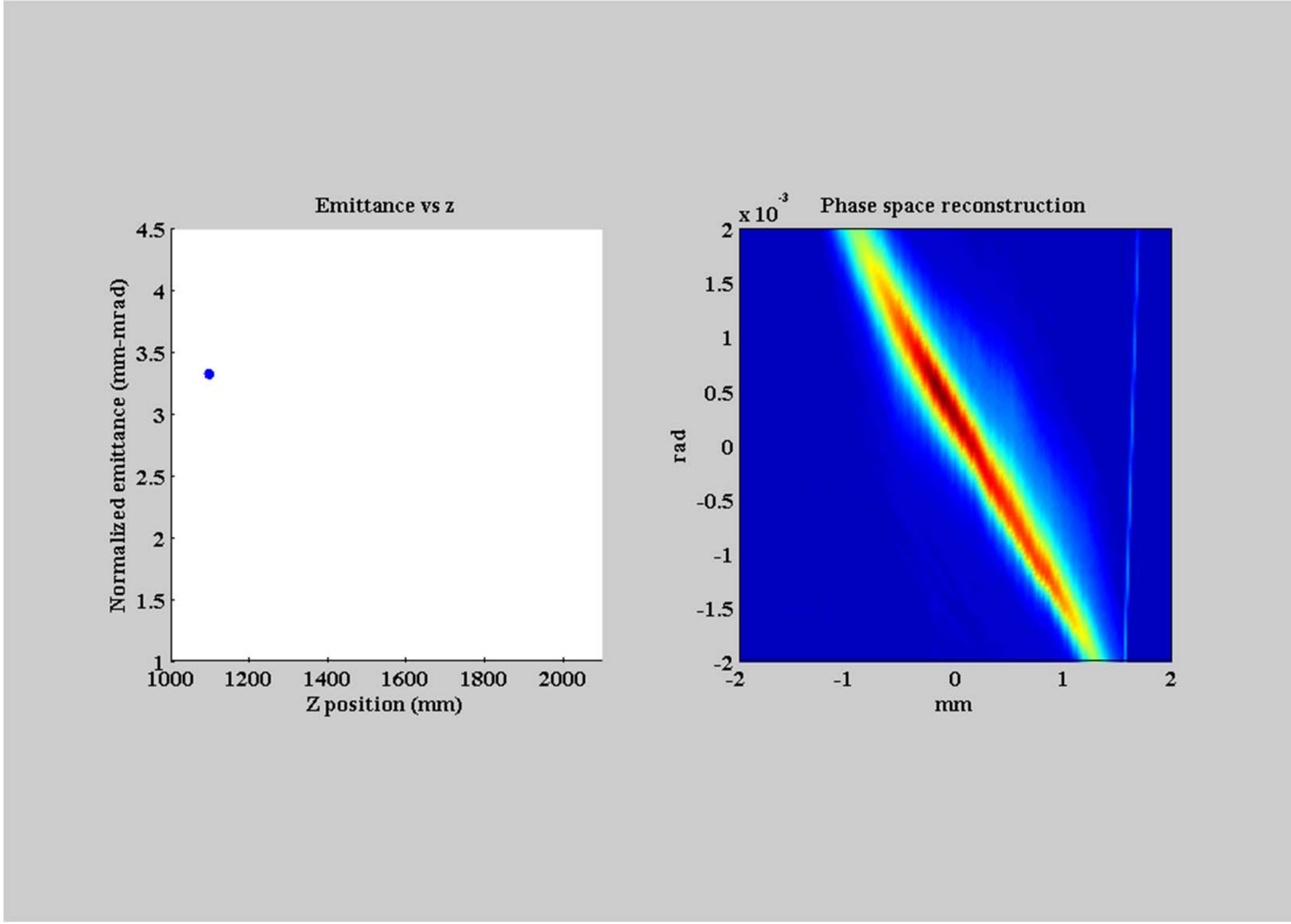


A. Cianchi et al., "High brightness electron beam emittance evolution measurements in an rf photoinjector", Physical Review Special Topics Accelerator and Beams 11, 032801,2008

Automatic envelope



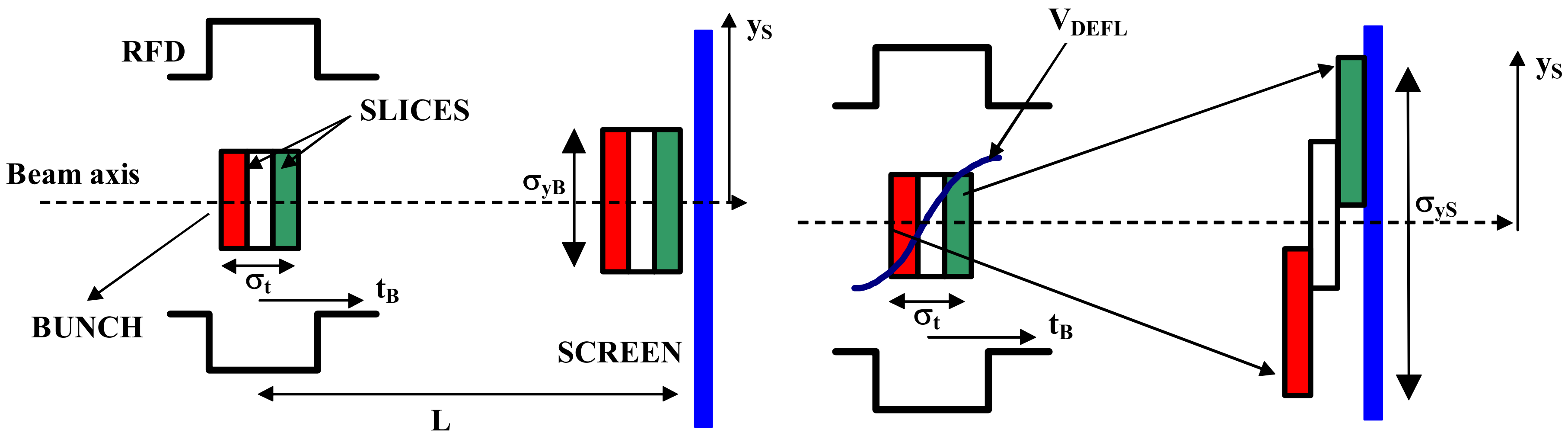
Automatic emittance



Longitudinal Diagnostics

Transverse Deflecting Structure
or
Radio Frequency Deflector

RF deflector



Paul Emma, Josef Frisch, Patrick Krejcik, A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics, LCLS-TN-00-12
Christopher Behrens, Measurement and Control of the Longitudinal Phase Space at High-Gain Free-Electron Lasers , FEL 2011, Shanghai

A bit of equations

$$\ddot{y} = \frac{qE}{m\gamma}$$

$$\dot{y} = \frac{qV}{m\gamma c}$$

$$\Delta y' = \frac{\dot{x}}{\beta_s c} \simeq \frac{qV}{pc}$$

$$V = V_0 \sin(kz + \varphi)$$

$$\sin(kz + \varphi) = \sin(kz)\cos(\varphi) + \cos(kz)\sin(\varphi)$$

$$kz << 1 \Rightarrow \sin(kz + \varphi) \simeq kz\cos(\varphi) + \sin(\varphi)$$

Equation

$$\Delta y' = \frac{qV_0}{pc}\left[kz\cos(\varphi) + \sin(\varphi)\right]$$

Offset

$$R_{12} = \sqrt{\beta\beta_0}\sin\Delta$$

Betatron phase advance

$$y(z) = y_0 + \left(\sqrt{\beta\beta_0}\sin\Delta\right)y_0' \pm \frac{qV_0}{pc}kz\left(\sqrt{\beta\beta_0}\sin\Delta\right)$$

Some mathematics…

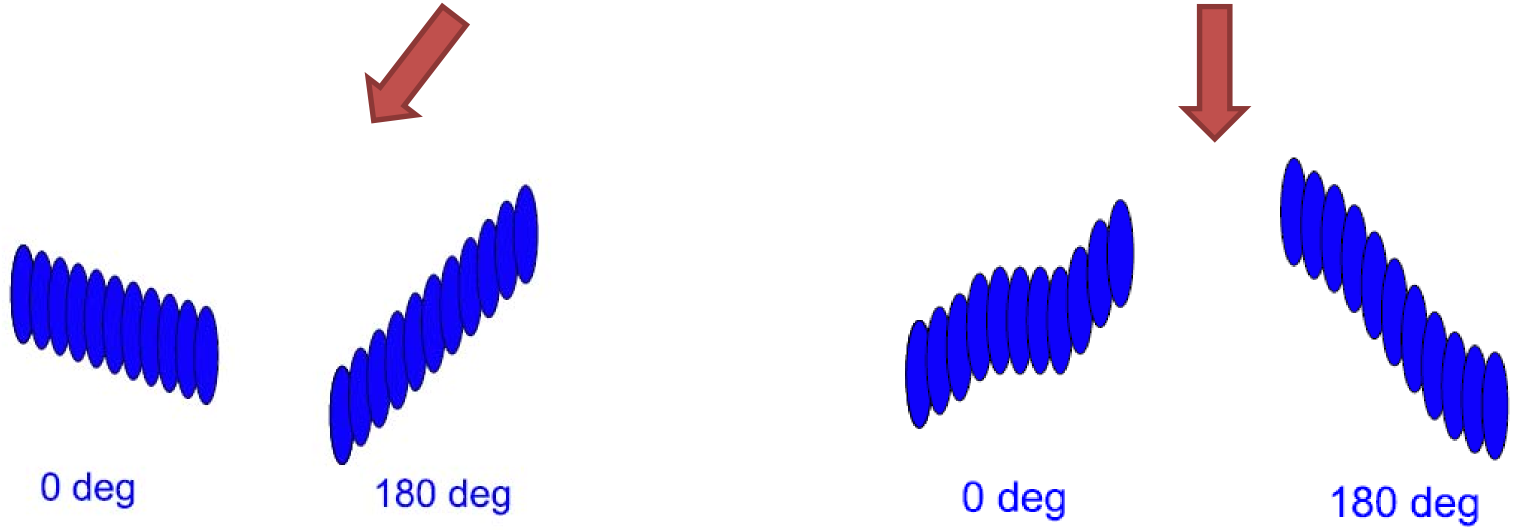
$$\left\langle (y-\langle y\rangle)^2 \right\rangle^{\pm} = \langle y_0^2\rangle + \beta\beta_0 \sin^2\Delta \langle {y_0'}^2\rangle - \langle y_0'\rangle^2 + \beta\beta_0 \sin^2\Delta \left(\frac{qV_0}{pc}k\right)^2 \langle z^2\rangle +$$
$$-\beta\beta_0 \sin^2\Delta \langle y_0'\rangle^2 - \beta\beta_0 \left(\frac{qV_0}{pc}k\right)^2 \sin^2\Delta \langle z\rangle^2 +$$
$$+2\sqrt{\beta\beta_0}\sin\Delta \langle y_0 y_0'\rangle \pm 2\sqrt{\beta\beta_0}\sin\Delta \left(\frac{qV_0}{pc}k\right) \langle y_0 z\rangle - 2\sqrt{\beta\beta_0}\sin\Delta \langle y_0\rangle\langle y_0'\rangle +$$
$$\mp 2\sqrt{\beta\beta_0}\sin\Delta \left(\frac{qV_0}{pc}k\right) \langle y_0\rangle\langle z\rangle \pm 2\beta\beta_0 \sin^2\Delta \left(\frac{qV_0}{pc}k\right) \langle y_0' z\rangle +$$
$$\mp 2\beta\beta_0 \sin^2\Delta \left(\frac{qV_0}{pc}k\right) \langle y_0'\rangle\langle z\rangle$$

$$\sigma_0^2 = \langle y_0^2\rangle + \beta\beta_0 \sin^2\Delta \langle y_0'^2\rangle + 2\sqrt{\beta\beta_0}\sin\Delta \langle y_0 y_0'\rangle$$

Two measurements are needed

$$\left\langle \left(y-\langle y\rangle\right)^2\right\rangle^{\pm} = \langle y_0^2\rangle + \beta\beta_0 \sin^2\Delta \left\langle y_0'^2\right\rangle + \beta\beta_0\sin^2\Delta\left(\frac{qV_0}{pc}k\right)^2\langle z^2\rangle +$$

$$+2\sqrt{\beta\beta_0}\sin\Delta\left\langle y_0 y_0'\right\rangle \pm 2\sqrt{\beta\beta_0}\sin\Delta\left(\frac{qV_0}{pc}k\right)\langle y_0 z\rangle \pm 2\beta\beta_0\sin^2\Delta\left(\frac{qV_0}{pc}k\right)\left\langle y_0' z\right\rangle$$



What we really measure

$$\left\langle \left(y-\langle y\rangle\right)^2 \right\rangle^{\pm} = \left\langle y_0^2 \right\rangle + \beta\beta_0 \sin^2\Delta \left\langle y_0'^2 \right\rangle + 2\sqrt{\beta\beta_0}\sin\Delta\left\langle y_0 y_0' \right\rangle + \beta\beta_0 \sin^2\Delta \left(\frac{qV_0}{pc}k\right)^2 \left\langle z^2 \right\rangle$$

$$\sigma_0^2 = \langle y_0^2 \rangle + \beta\beta_0 \sin^2\Delta\, \langle y_0'^2 \rangle + 2\sqrt{\beta\beta_0}\sin\Delta\, \langle y_0 y_0' \rangle$$

$$\sigma_{defl}^2 = \beta\beta_0 \sin^2\Delta \left(\frac{qV_0}{pc}k\right)^2 \left\langle z^2 \right\rangle$$

$$\sigma = \sqrt{\sigma_0^2 + \sigma_{defl}^2}$$

Resolution

$$\beta\beta_0 \sin^2\Delta\left(\frac{qV_0}{pc}k\right)^2\langle z^2\rangle = L^2\left(\frac{qV_0}{pc}k\right)^2\sigma_z^2 = \sigma_0^2$$

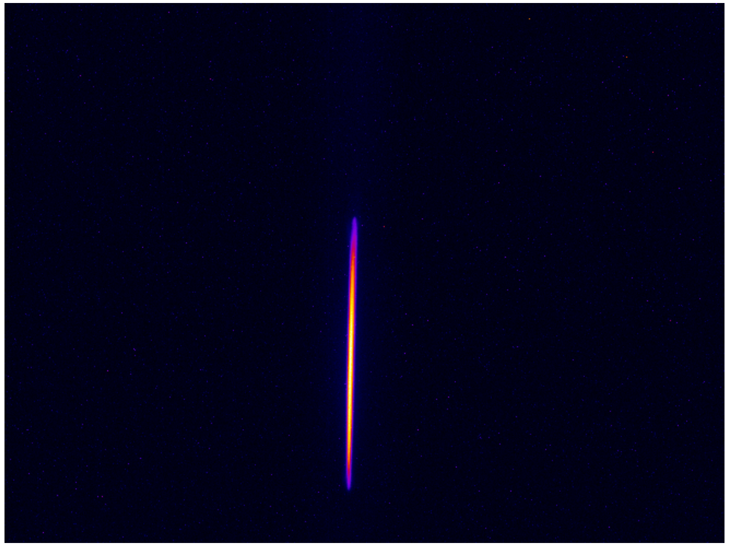
$$\sigma_z^{res} = \frac{E}{q}\frac{\sigma_0}{V_0 L}\frac{\lambda}{2\pi}$$

- Find the resolution limit for a beam with
  - σ_0=10 μm
  - E=100 MeV
  - V_0=1 MV
  - L=2m
  - λ=10 cm

Solution

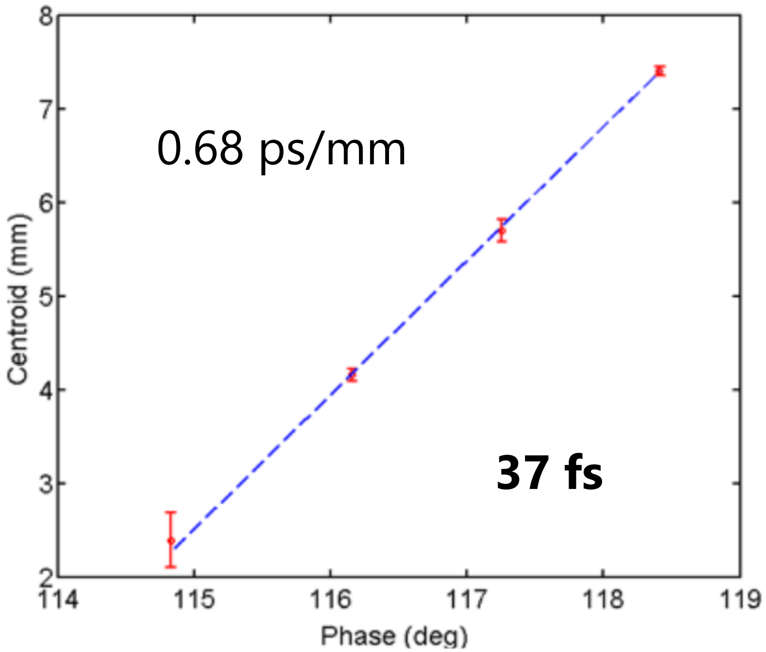
- 8 μm about 27 fs

Calibration



$$\sigma_{defl}^2 = \beta\beta_0 \sin^2\Delta\left(\frac{qV_0}{pc}k\right)^2\langle z^2\rangle$$

First zero

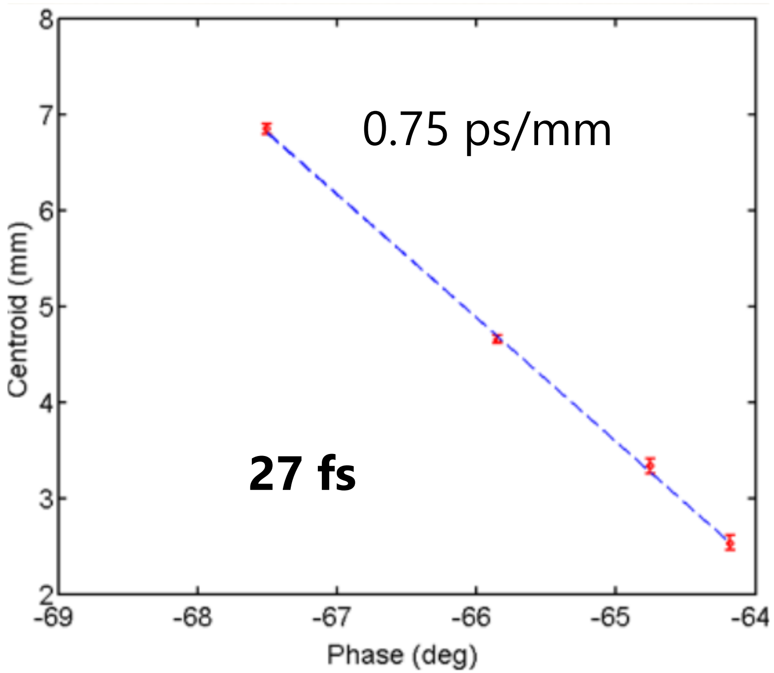


Parameter	Value
Calibration (ps/mm)	6.78E-1
Unc (ps/mm)	1.70E-2
Bunch length (ps)	9.24E-2
Unc Bunch length (ps)	8.43E-3
sigma RFD OFF spot (mm)	1.25E-1
Corrected Bunch Length (ps)	3.70E-2

pixel size = 21.6 μm -> 0.68 ps/mm -> pixel size = 14.7 fs

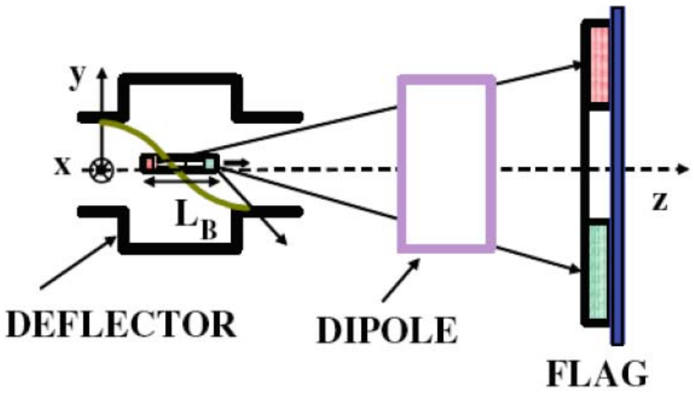
Second zero

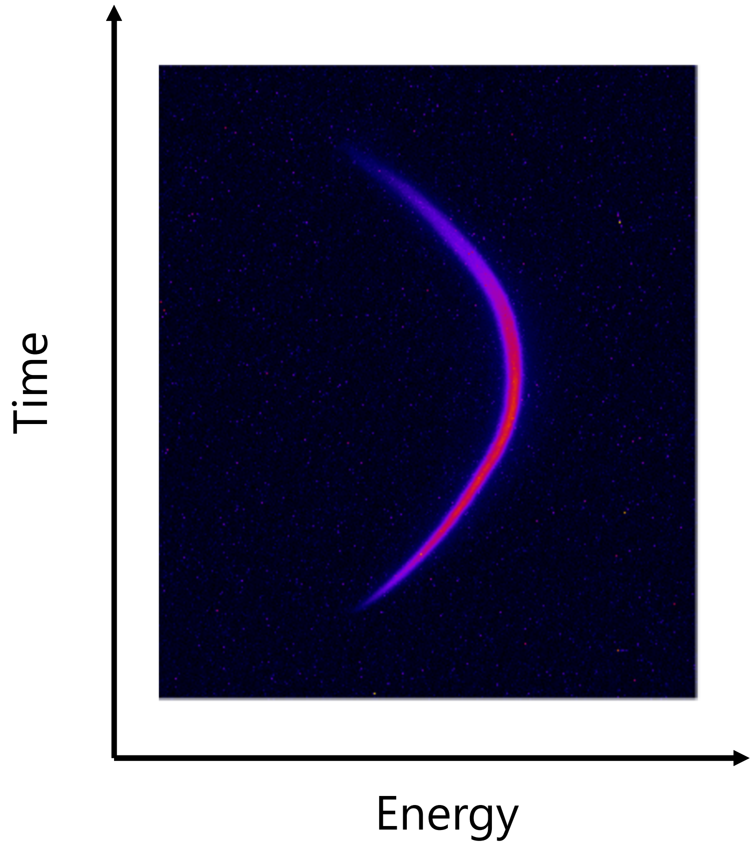
Parameter	Value
Calibration (ps/mm)	7.536E-1
Unc (ps/mm)	1.45E-2
Bunch length (ps)	9.78E-2
Unc Bunch length (ps)	1.94E-3
sigma RFD OFF spot (mm)	1.25E-1
Corrected Bunch Length (ps)	26.7E-2



pixel size = 21.6 μm -> 0.75 ps/mm -> pixel size = 16.2 fs

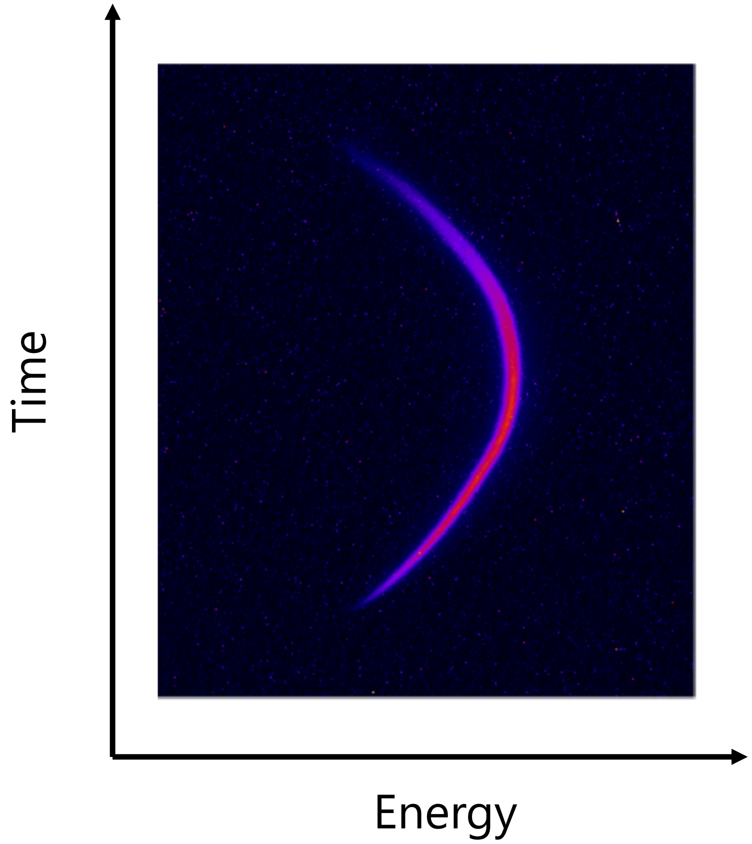
Longitudinal phase space

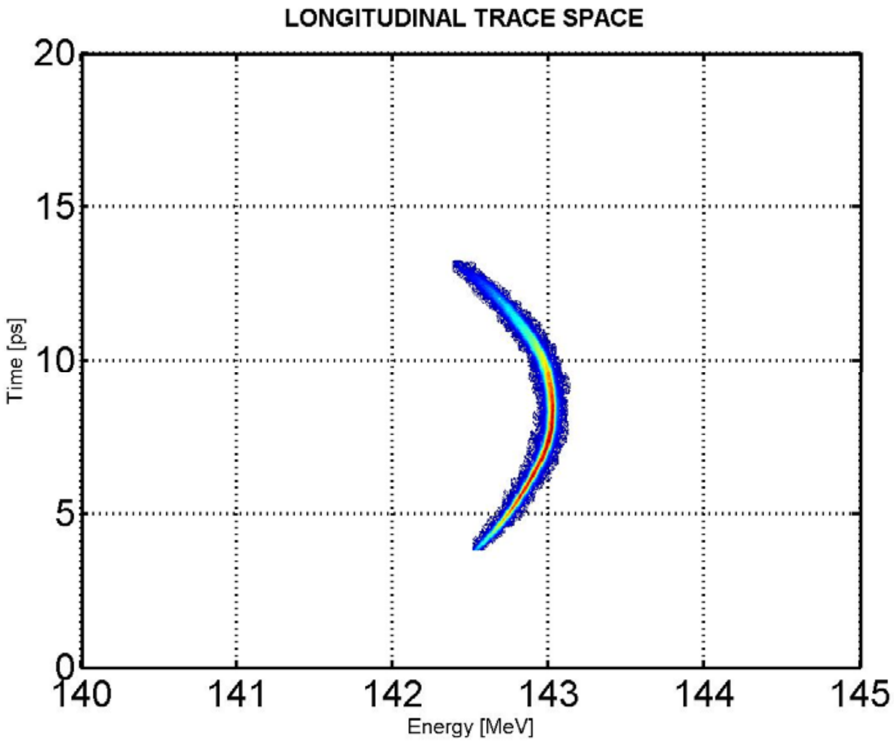




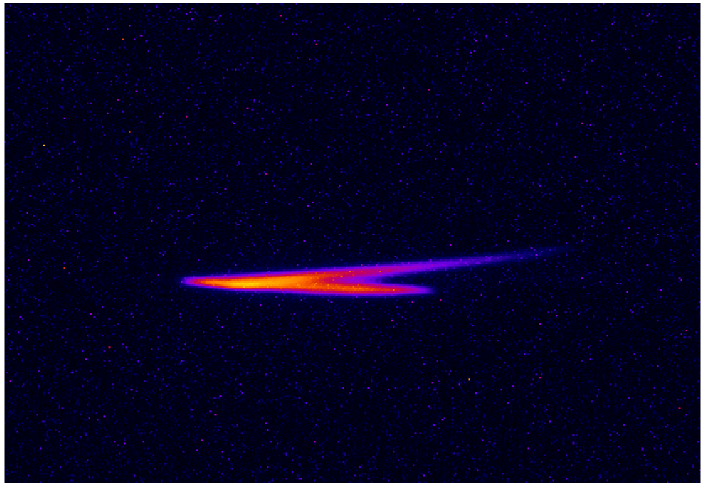
- Using together a RFD with a dispersive element such as a dipole
- Fast single shot measurement

LPS Measurement



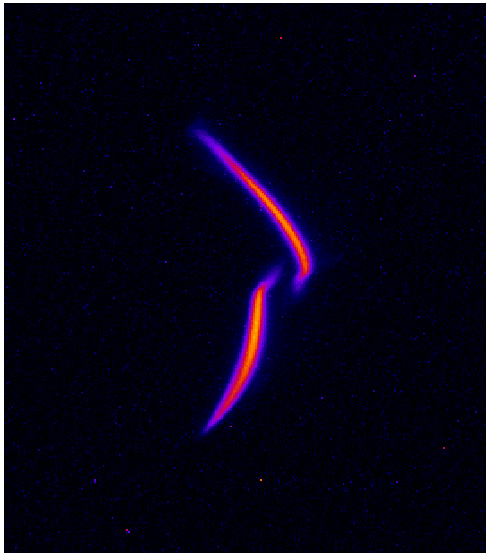


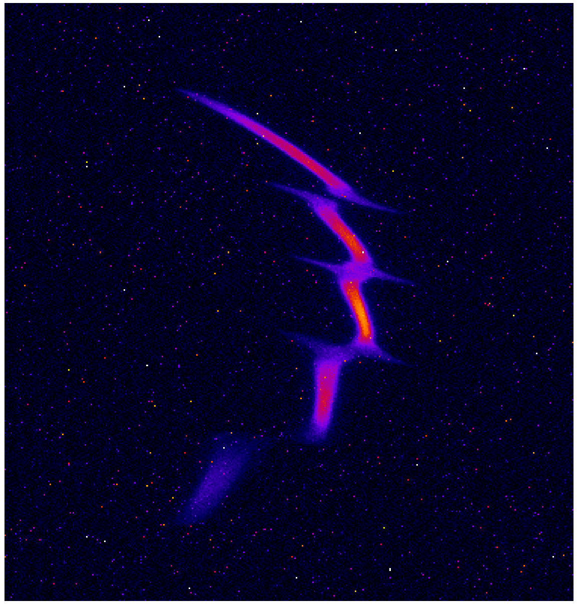
Several scenarios



Compression
about 140 fs

Two bunches





Several
bunches

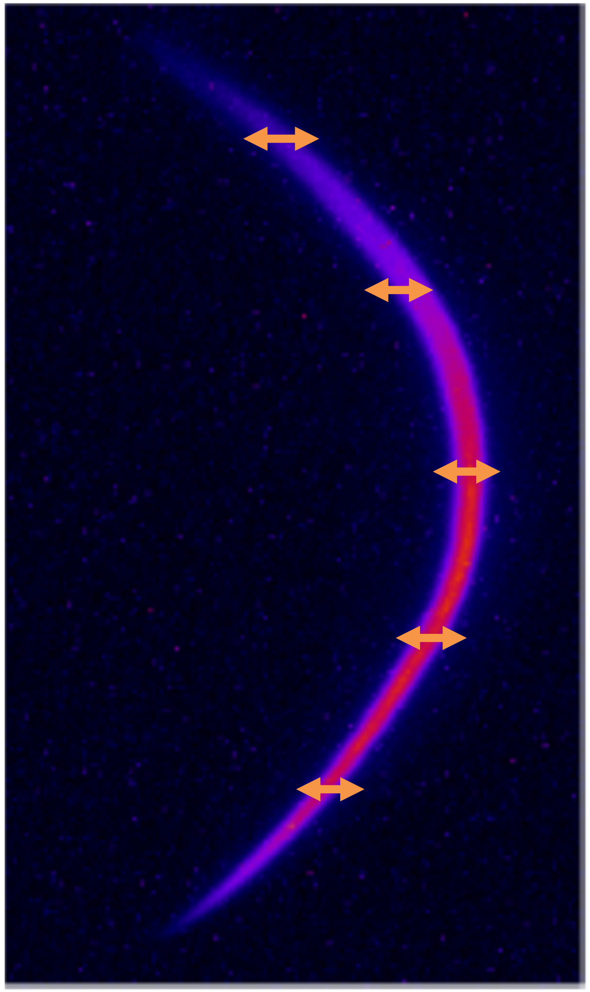
Intrinsic effects

- The TM11-like deflecting modes have a non-zero derivative of the longitudinal electric field on axis
- This is a general property of the deflecting modes because the deflecting voltage is directly related to the longitudinal electric field gradient through the Panofsky-Wenzel theorem by the formula

$$V_y = i\frac{c}{\omega}\int \nabla_y E_z e^{i\frac{\omega}{c}z} dz$$

- The transverse accelerating field in the cavity increases the beam slice energy spread
- The energy spread growth is due to the longitudinal electric field that varies linearly with transverse distance

Increase slice energy spread



$$\sigma_E = \frac{2\pi}{\lambda} V_0 \sigma_{beam}$$

Alesini, D., et al. "Sliced beam parameter measurements." *Proceedings of EPAC*. 2009.

Longitudinal Diagnostics

Electro Optical Sampling

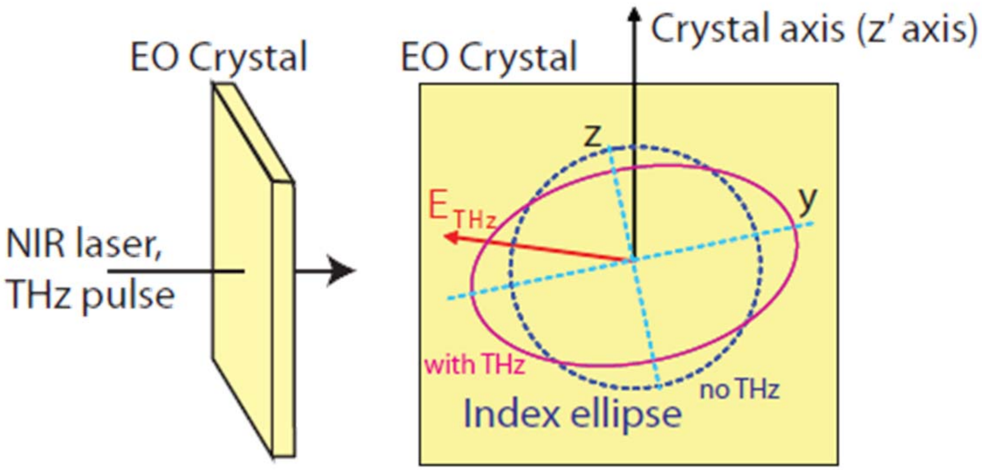
The CERN Accelerator School

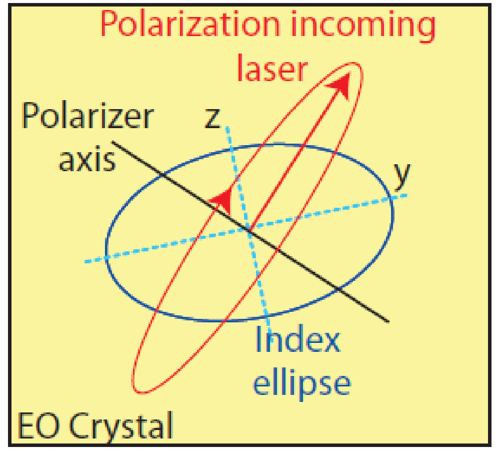
Some references

- I.Wilke et al., PRL, v.88, 12(2002)
- G. Berden et al, PRL v93, 11 (2004)
- A. L. Cavalieri et al., PhysRevLett.94.114801(2005)
- B. Steffen, Phys. Rev. ST Accel. Beams 12, 032802 (2009)
- J.R. Fletcher, Opt. Express 10, 1425 (2002)

- R. Pompili, "Longitudinal diagnostics for comb-like electron beams by means of Electro-Optic Sampling", PhD Thesis, Tor Vergata University (2013)

A bit of theory





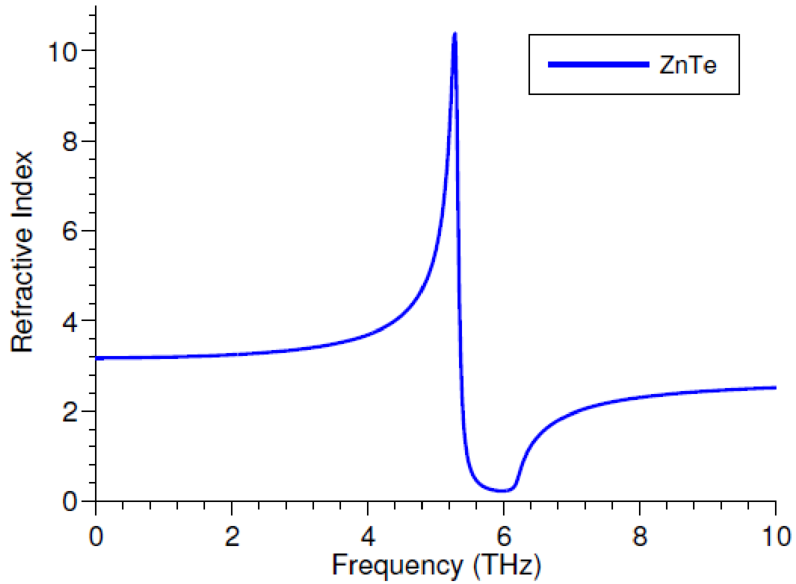
$$E_{M,j}(t) = E_{L,j}(t)e^{\imath\Gamma_j(t)}$$

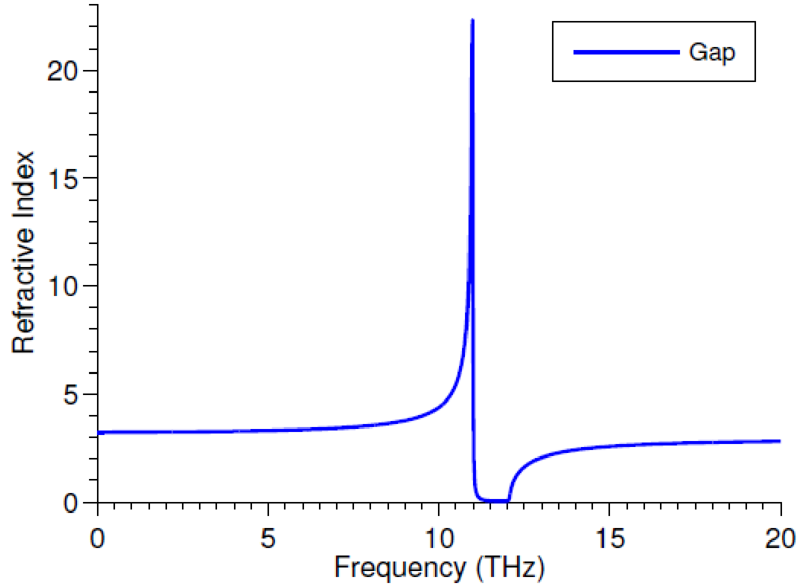
$$\Gamma_j(\omega) = \frac{2\pi}{\lambda_0} L\delta n_j(\omega) T_{\text{crystal}}(\omega),$$

$$\delta n_z = \frac{n_0^3 r_{41} E_{\text{THz}}}{4}\left(cos\phi + \sqrt{1 + 3\sin^2\phi}\right)$$

$$T_{\text{crystal}}(\omega) = \frac{2}{1 + n_{\text{THz}}} \cdot \frac{\exp\left[\imath L(n_{\text{gr}} - n_{\text{THz}})\frac{\omega}{c}\right] - 1}{\imath\frac{\omega}{c}(n_{\text{gr}} - n_{\text{THz}})}$$

Crystal Properties

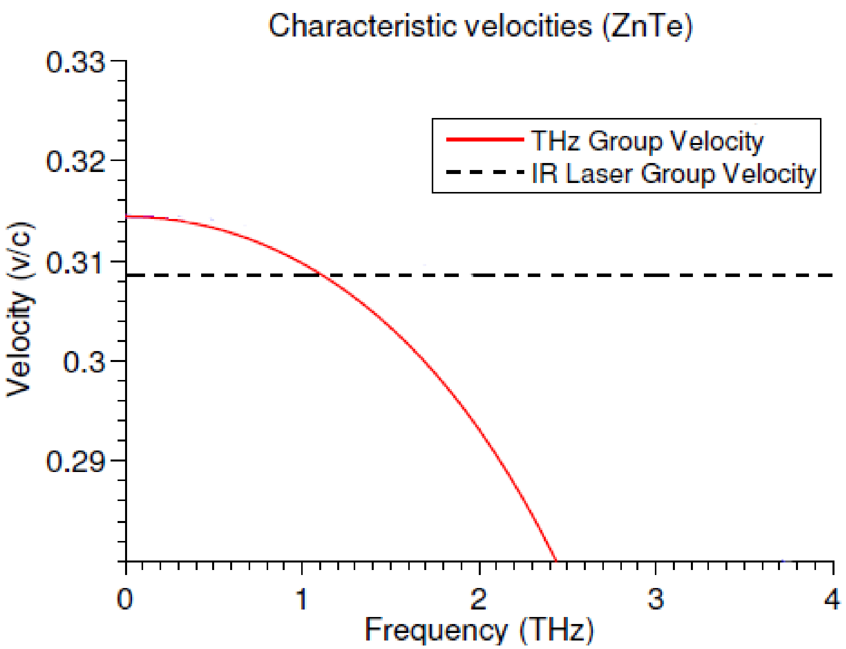


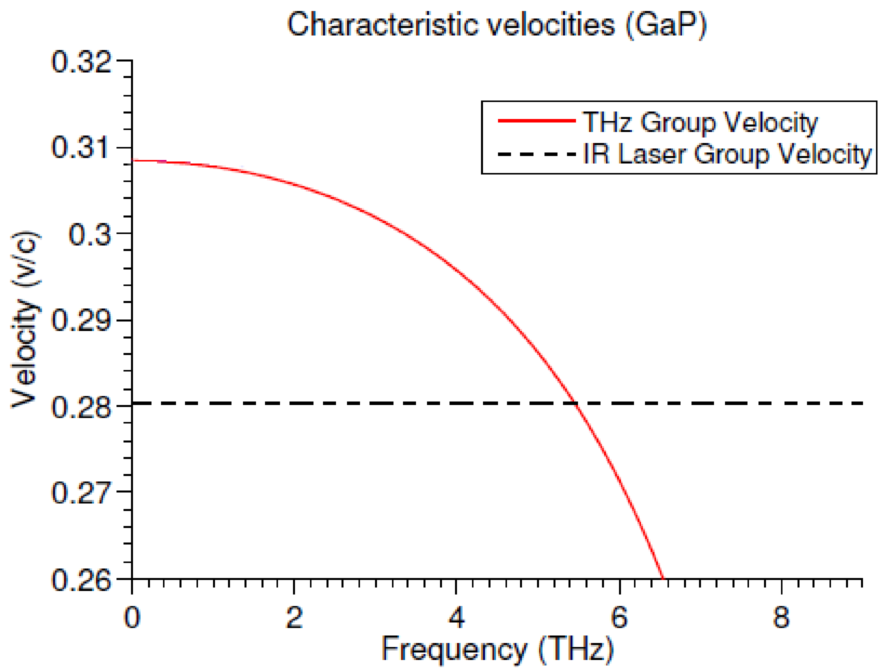


$$r_{41} = 4.25 \times 10^{-12} \text{ m/V}$$

$$r_{41} = 1 \times 10^{-12} \text{ m/V}$$

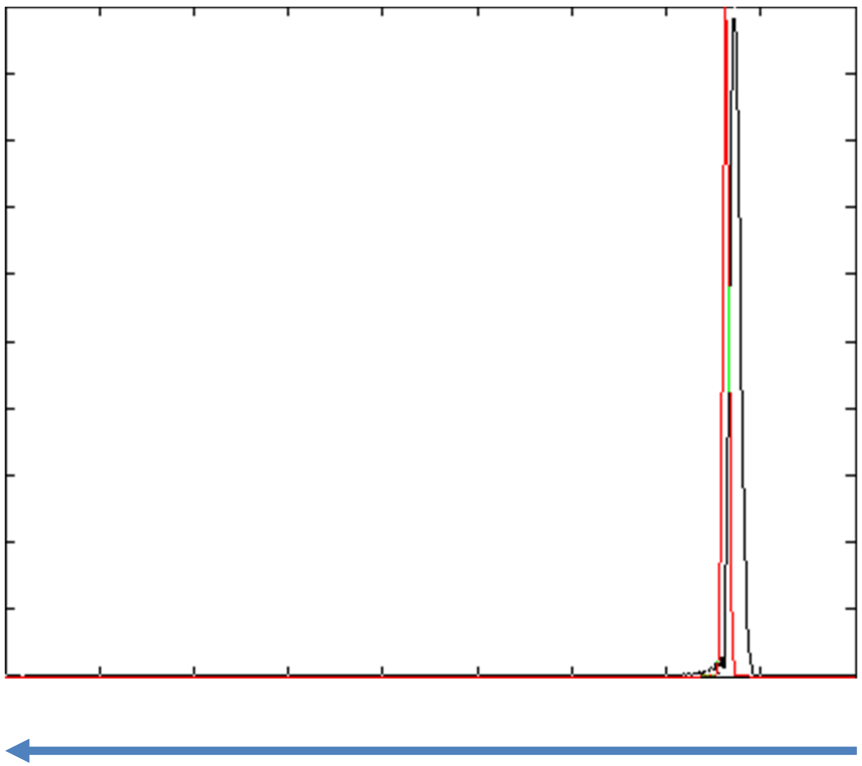
Group velocity





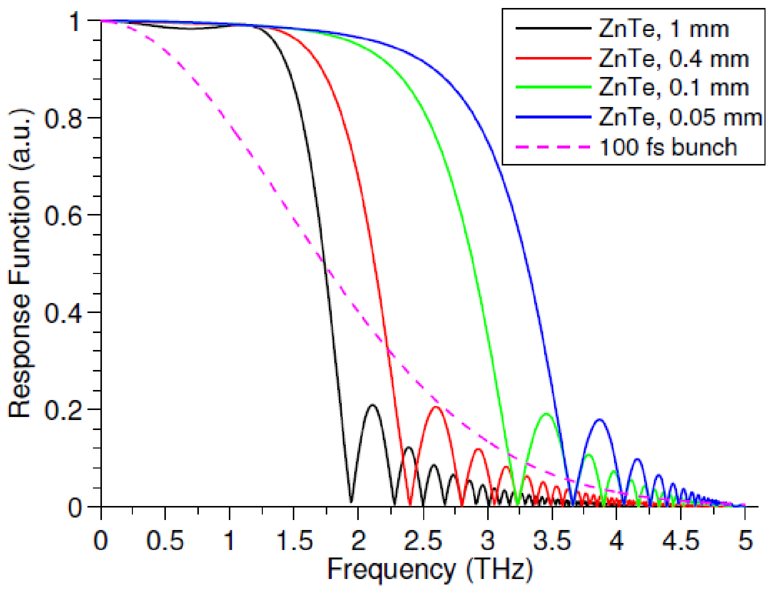
$$\Gamma_j(\omega) = \frac{2\pi}{\lambda_0} L \delta n_j(\omega) T_{\text{crystal}}(\omega),$$

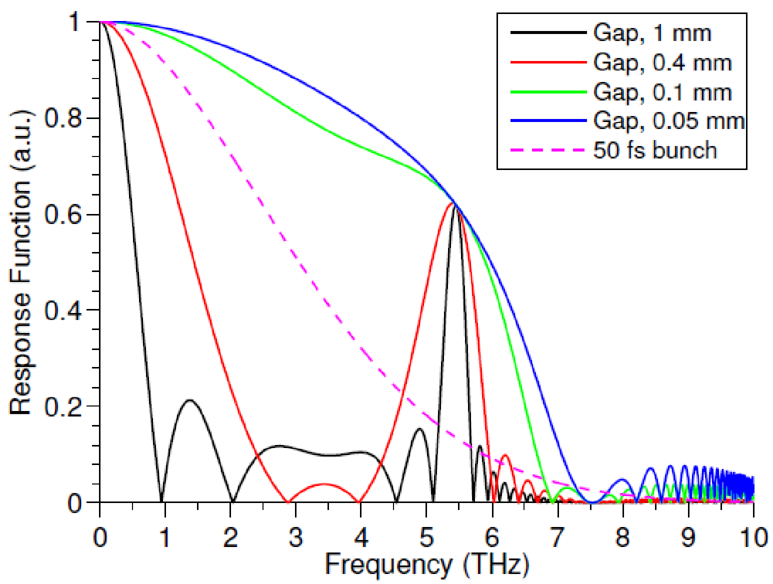
Laser and THz pulse propagation



Crystal thickness

Response function

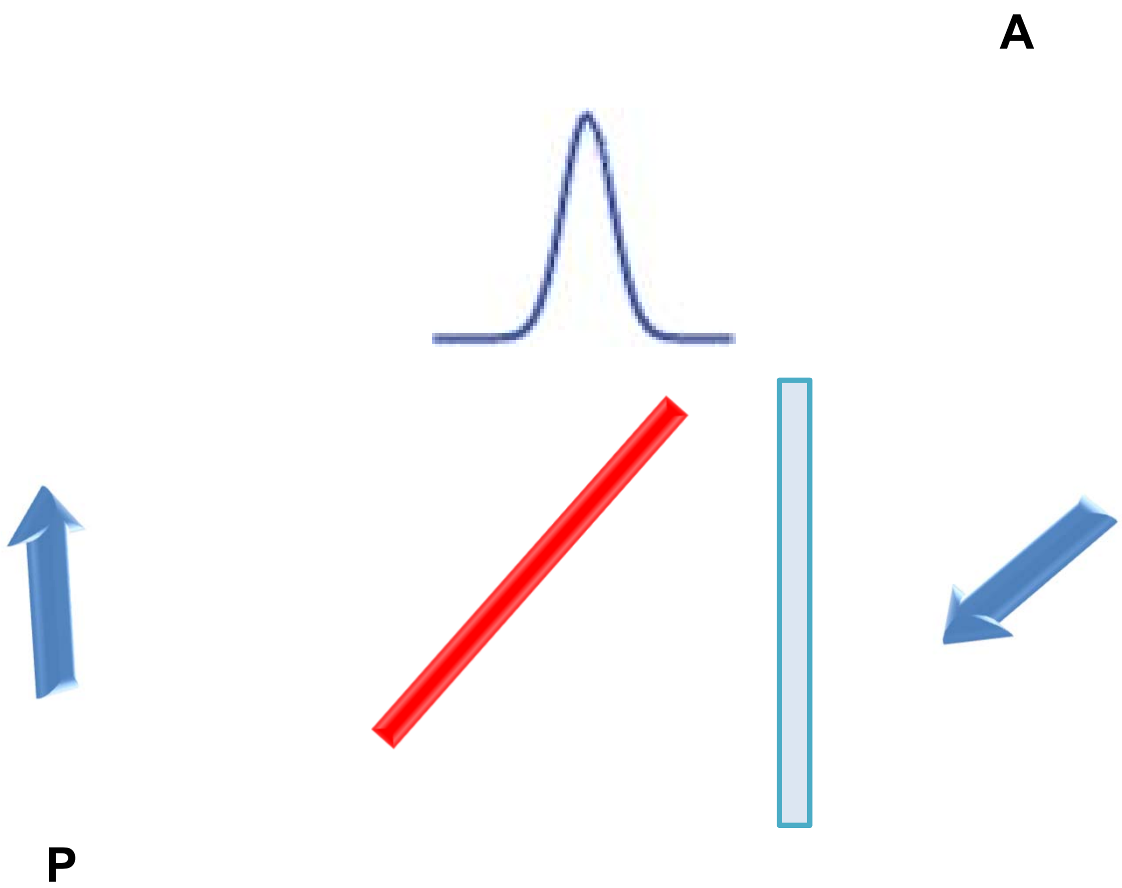


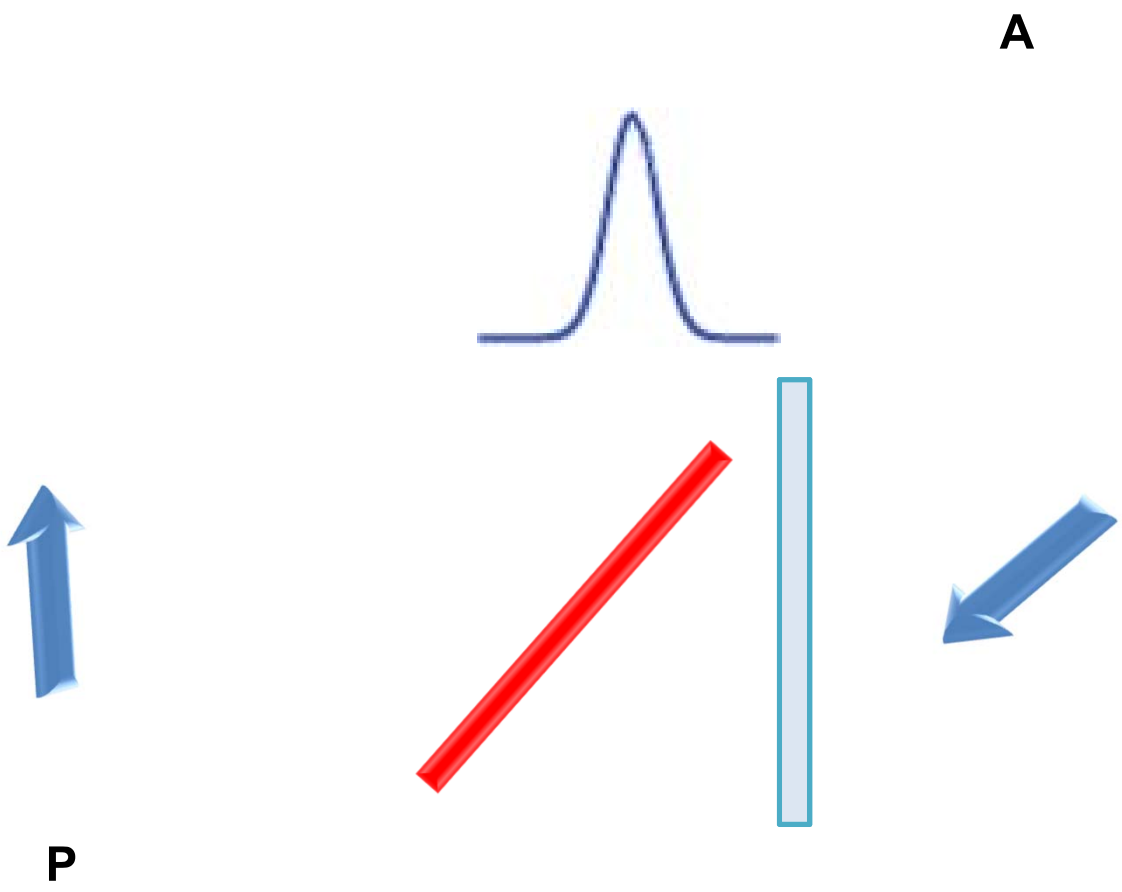


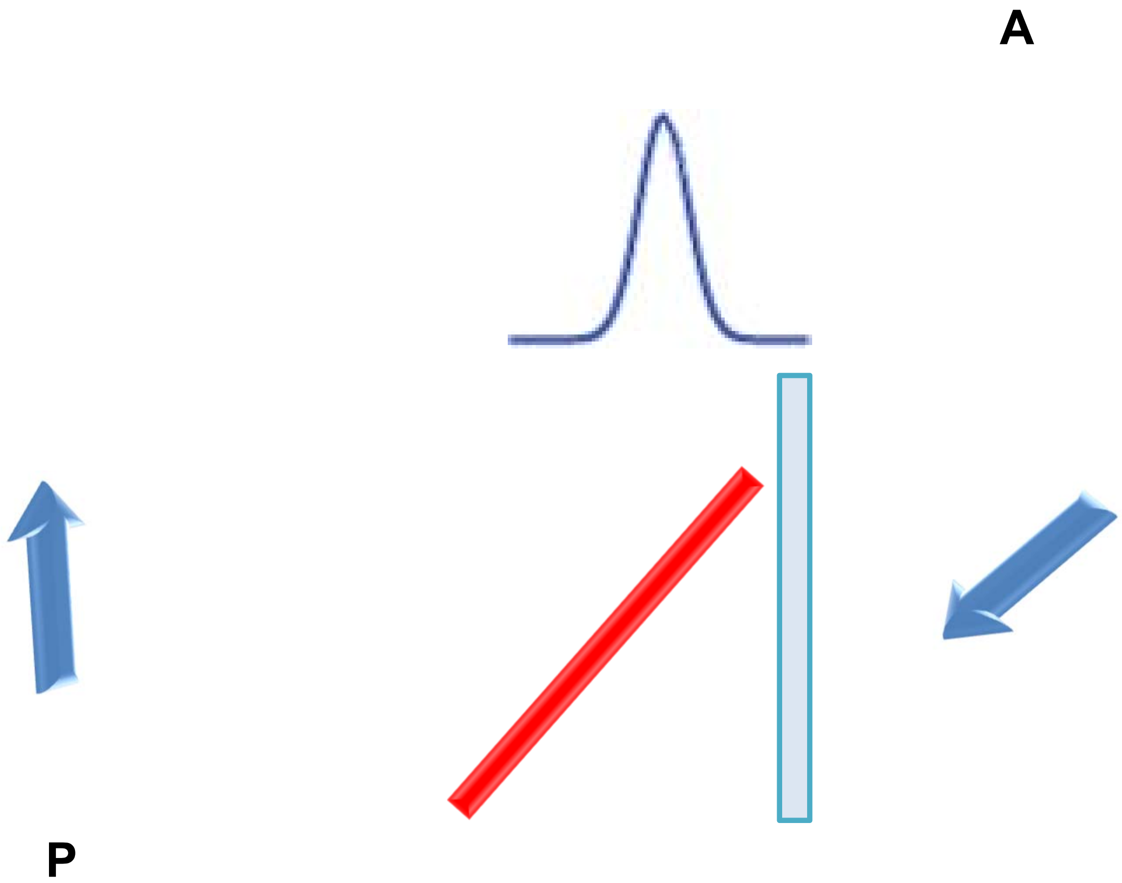
R. Pompili, “Longitudinal diagnostics for comb-like electron beams by means of Electro-Optic Sampling”, PhD Thesis, Tor Vergata University (2013)

Before you start

- Define the range of the bunch length that you want to measure
- Consider the strength of the signal (r_{41})
- Consider the bandwidth of the crystal (thickness and type)
- Define the readout scheme


A
P


A
P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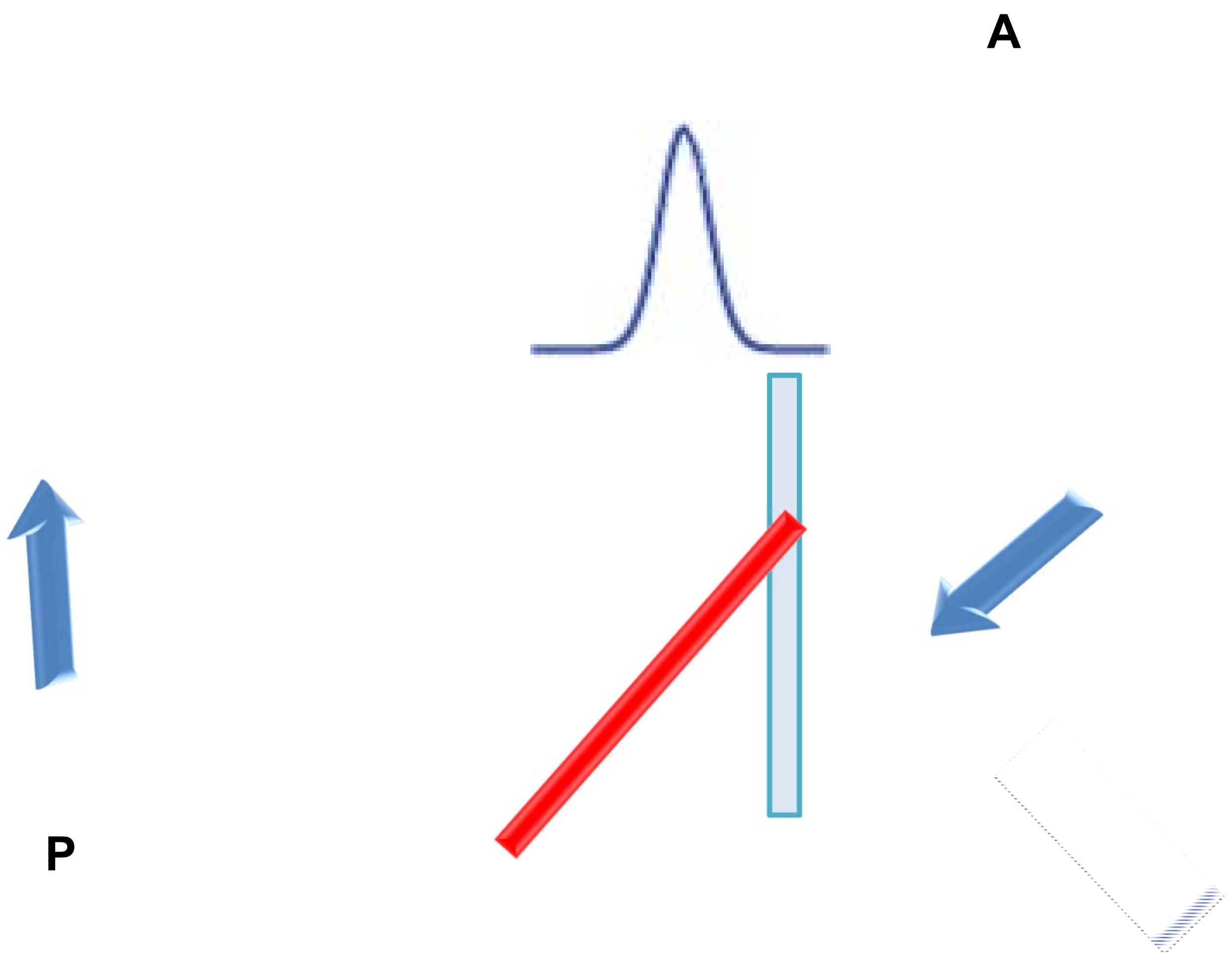
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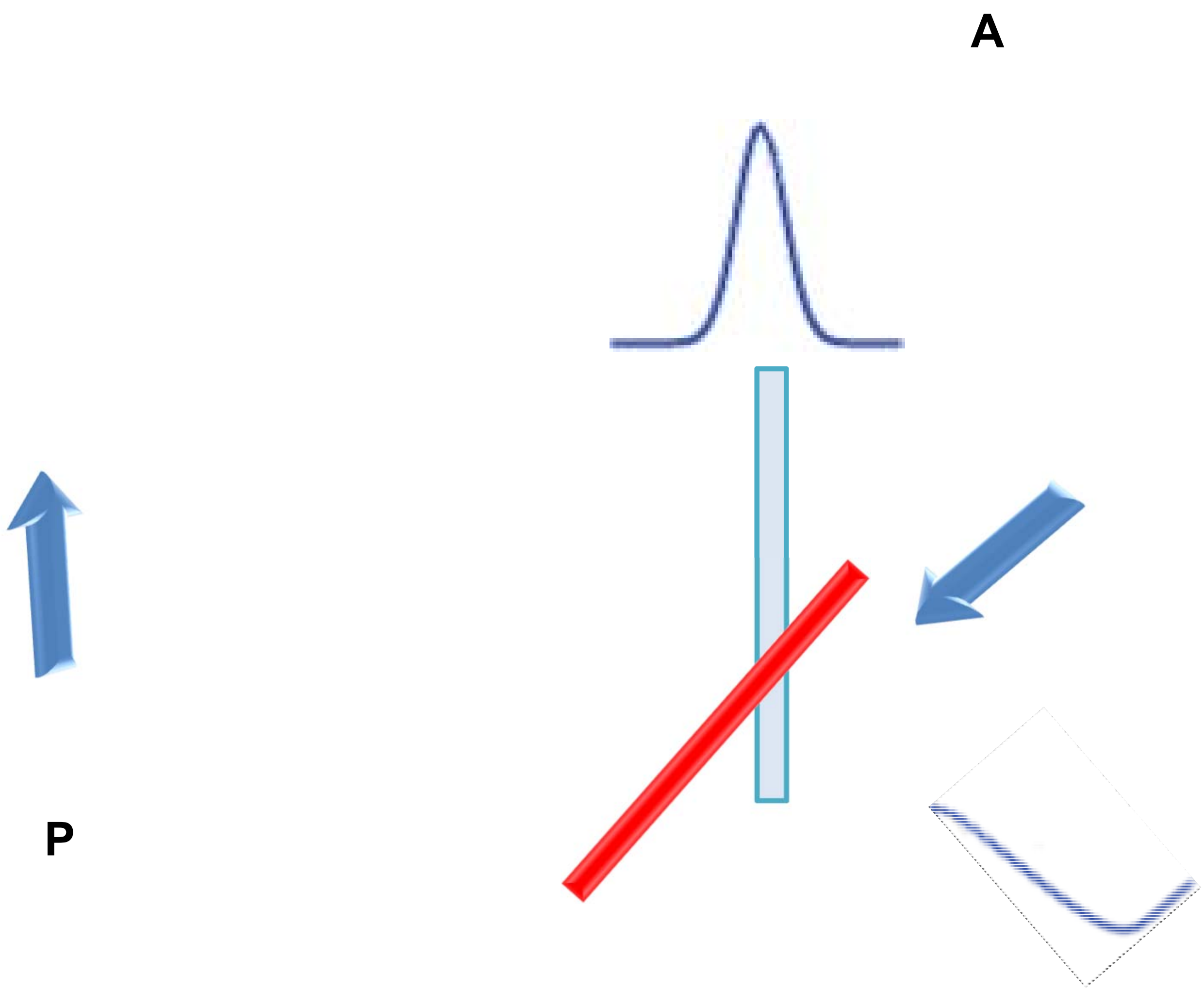
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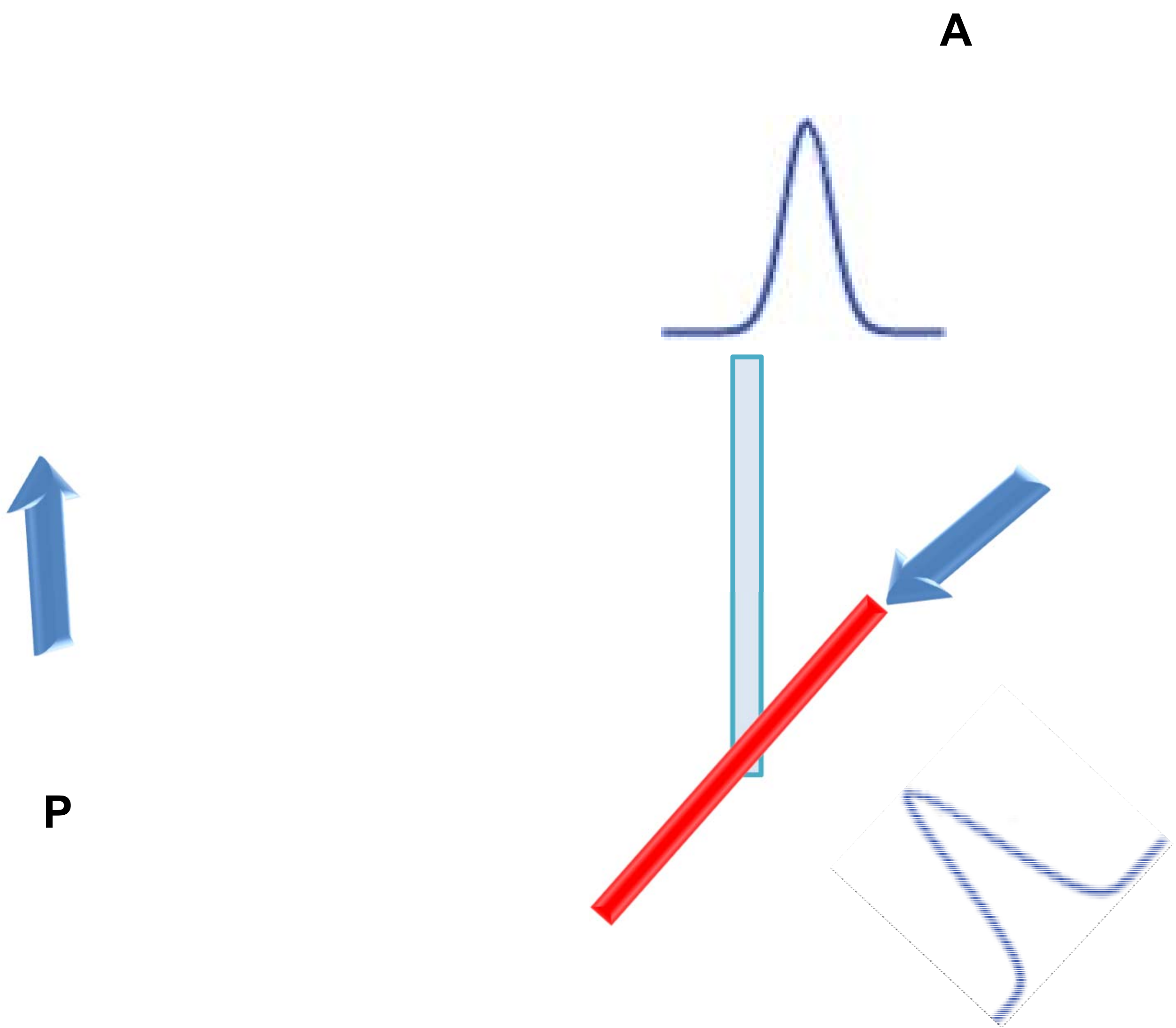
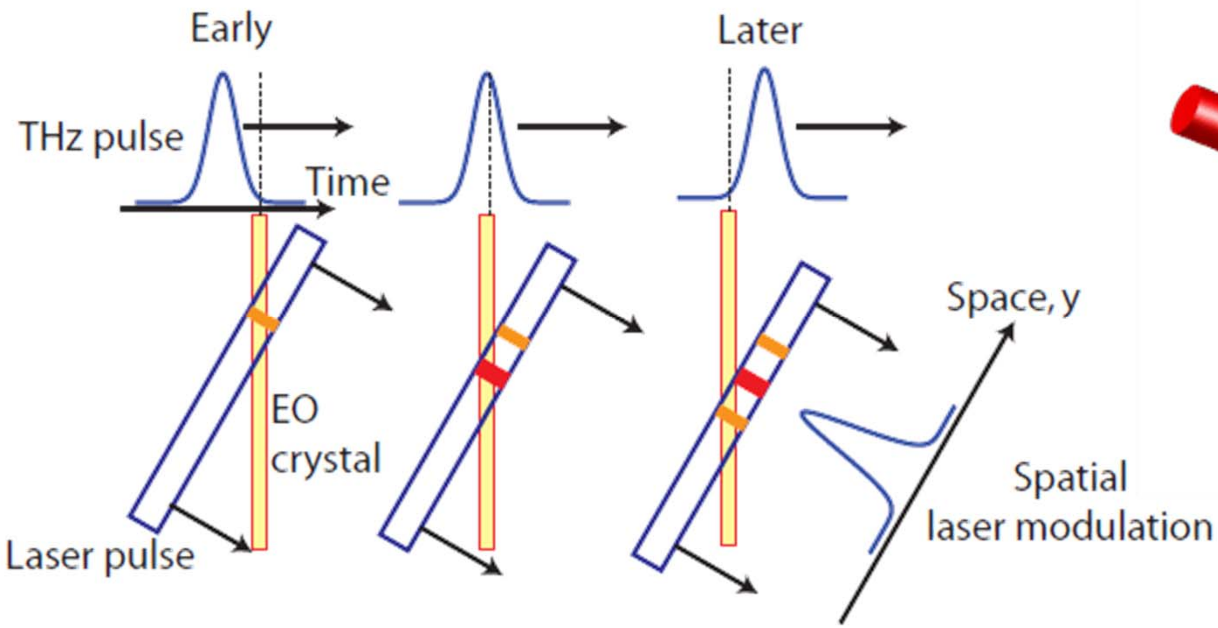
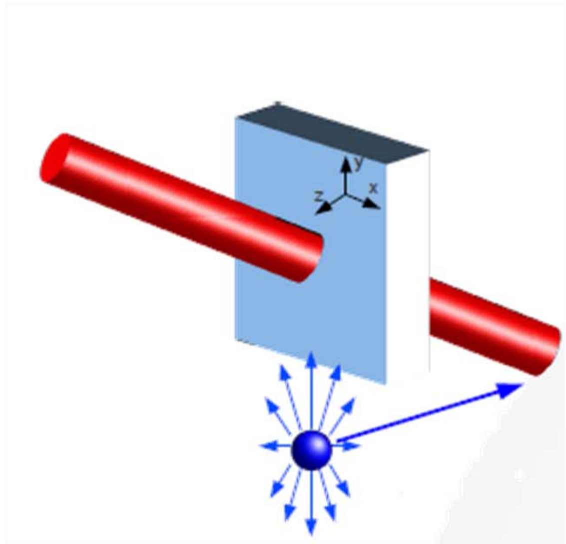

A
P

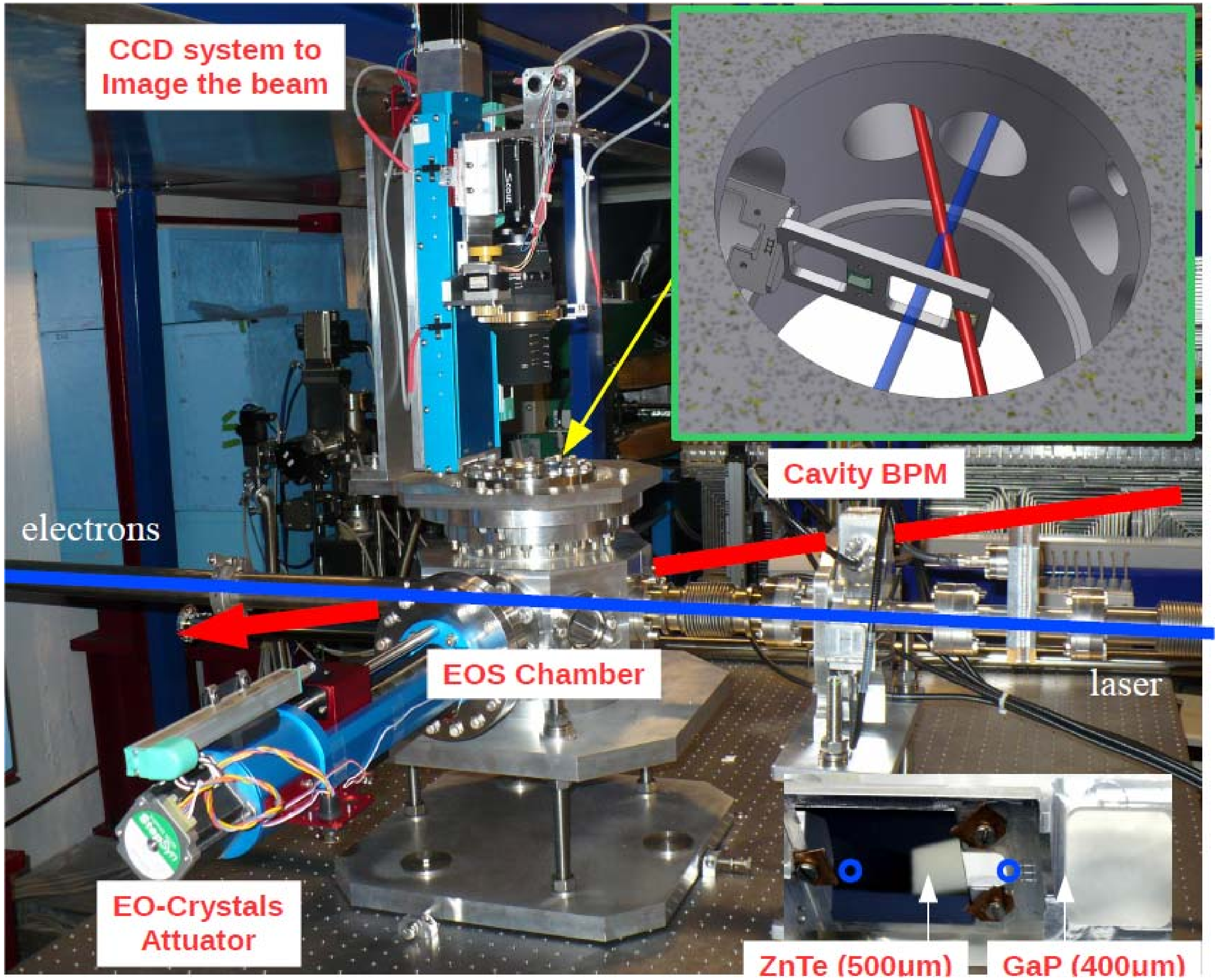
Spatial decoding





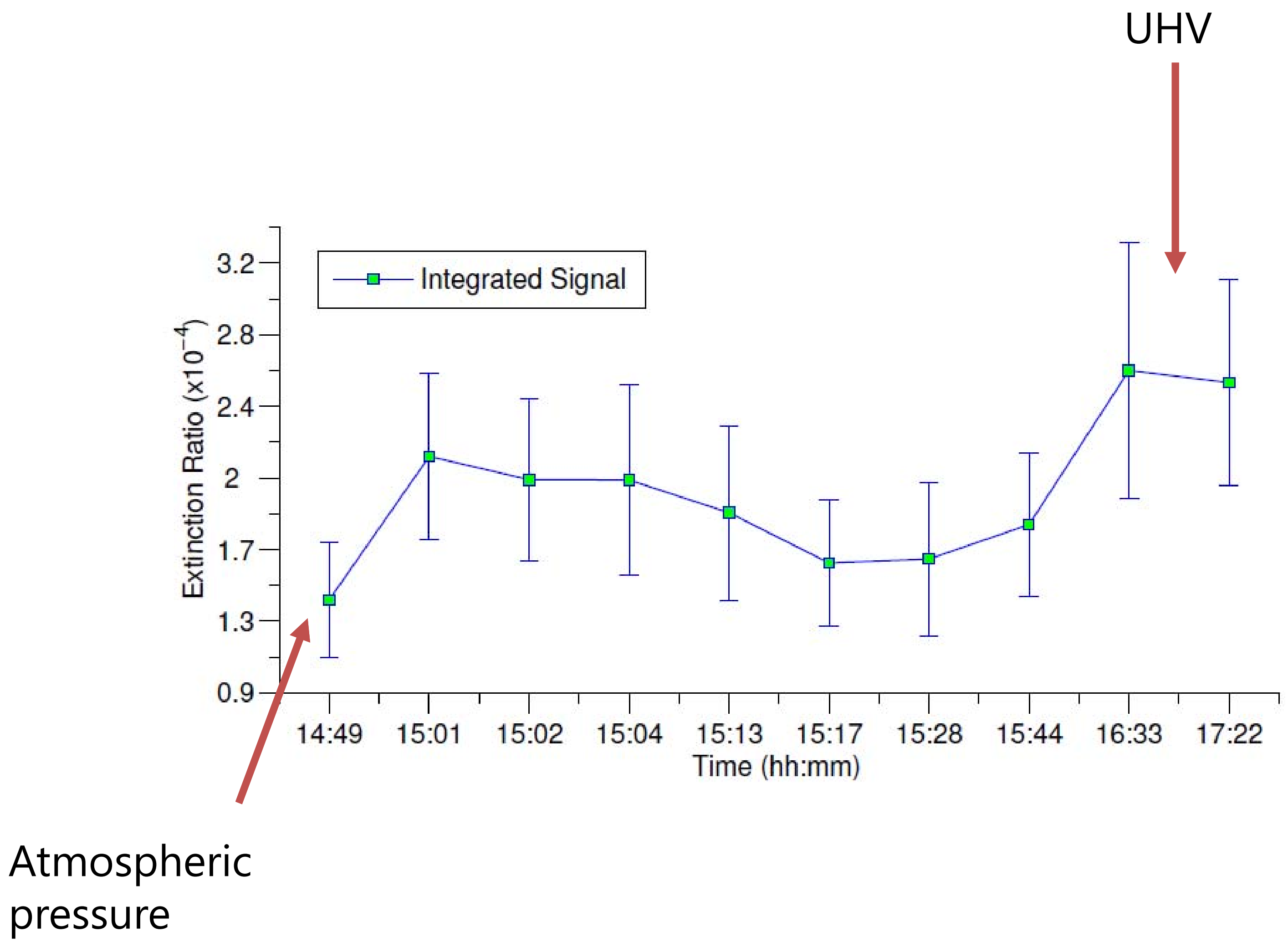
Small angles are required to achieve high temporal resolution by improving both the velocity matching between the laser and the THz pulse inside the crystal, while larger angles increase the temporal window, simplifying the synchronization between the laser and the electron beam

EOS setup

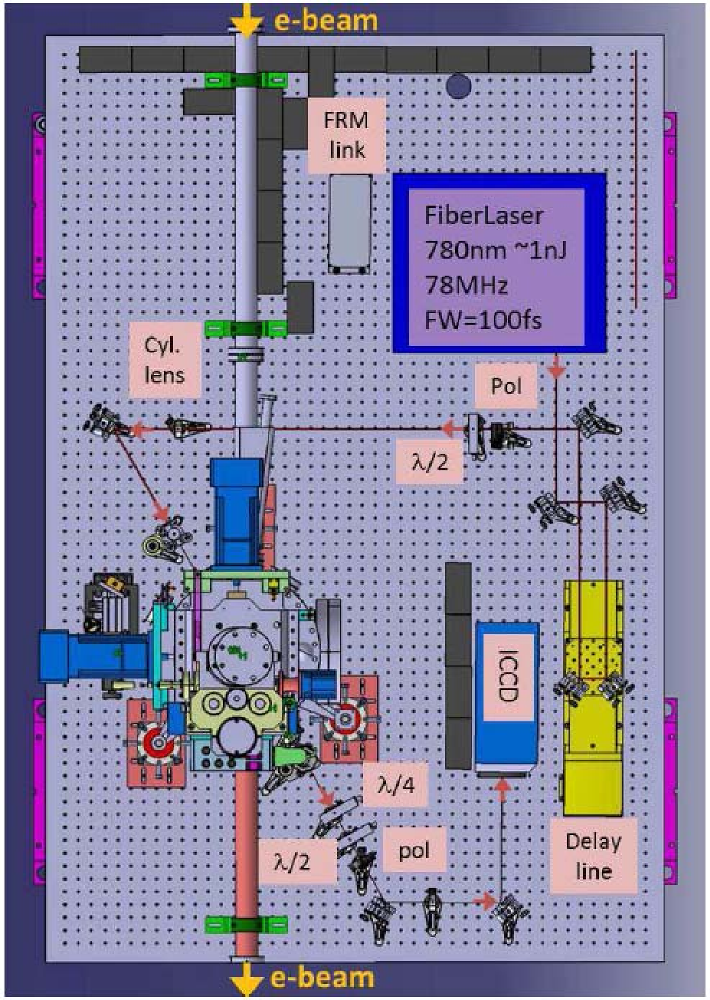


CCD system to
Image the beam
Cavity BPM
electrons
EOS Chamber
laser
EO-Crystals
Attuator
ZnTe (500μm)
GaP (400μm)

Non-zero birefringence



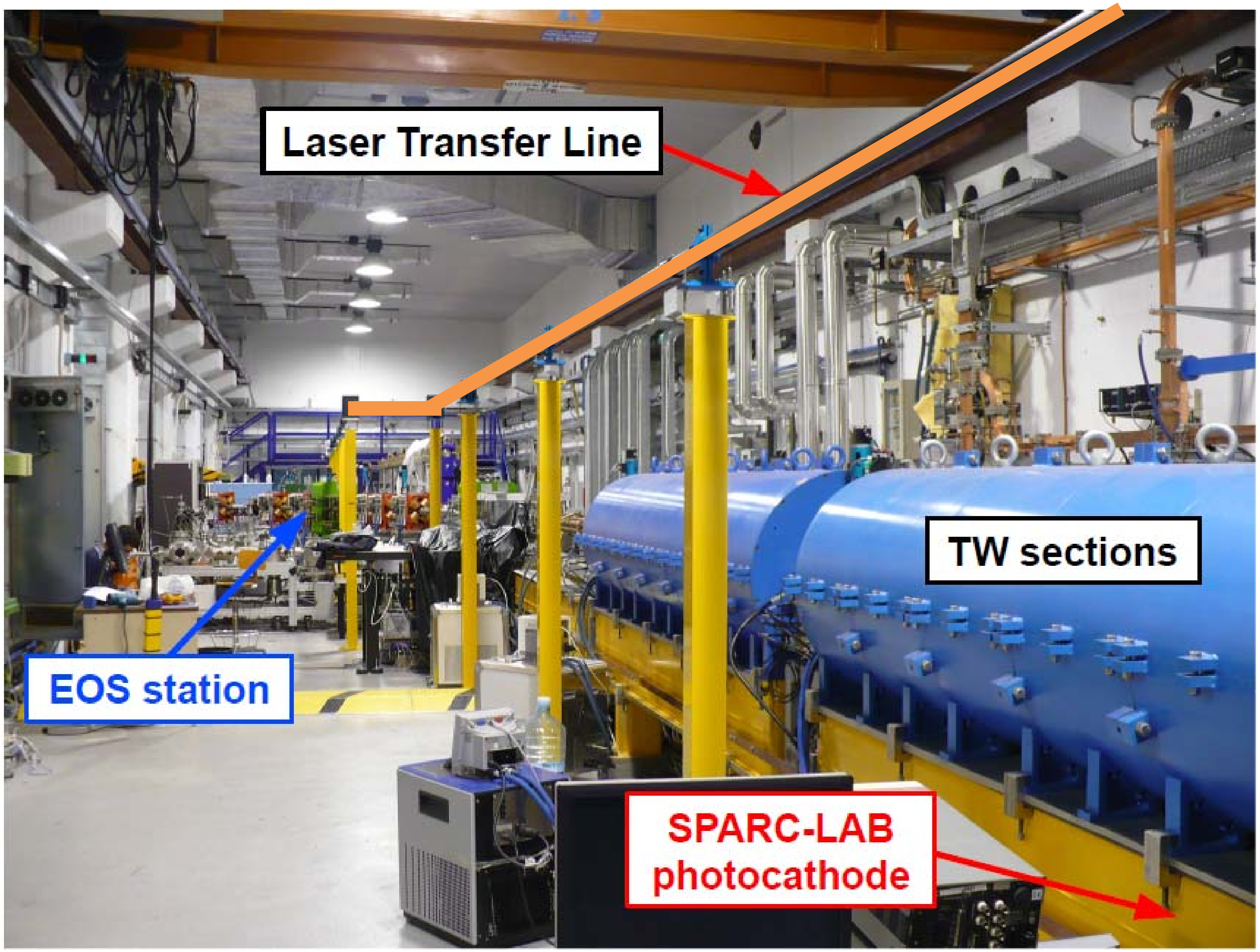
Setup with a ICCD and a fiber laser



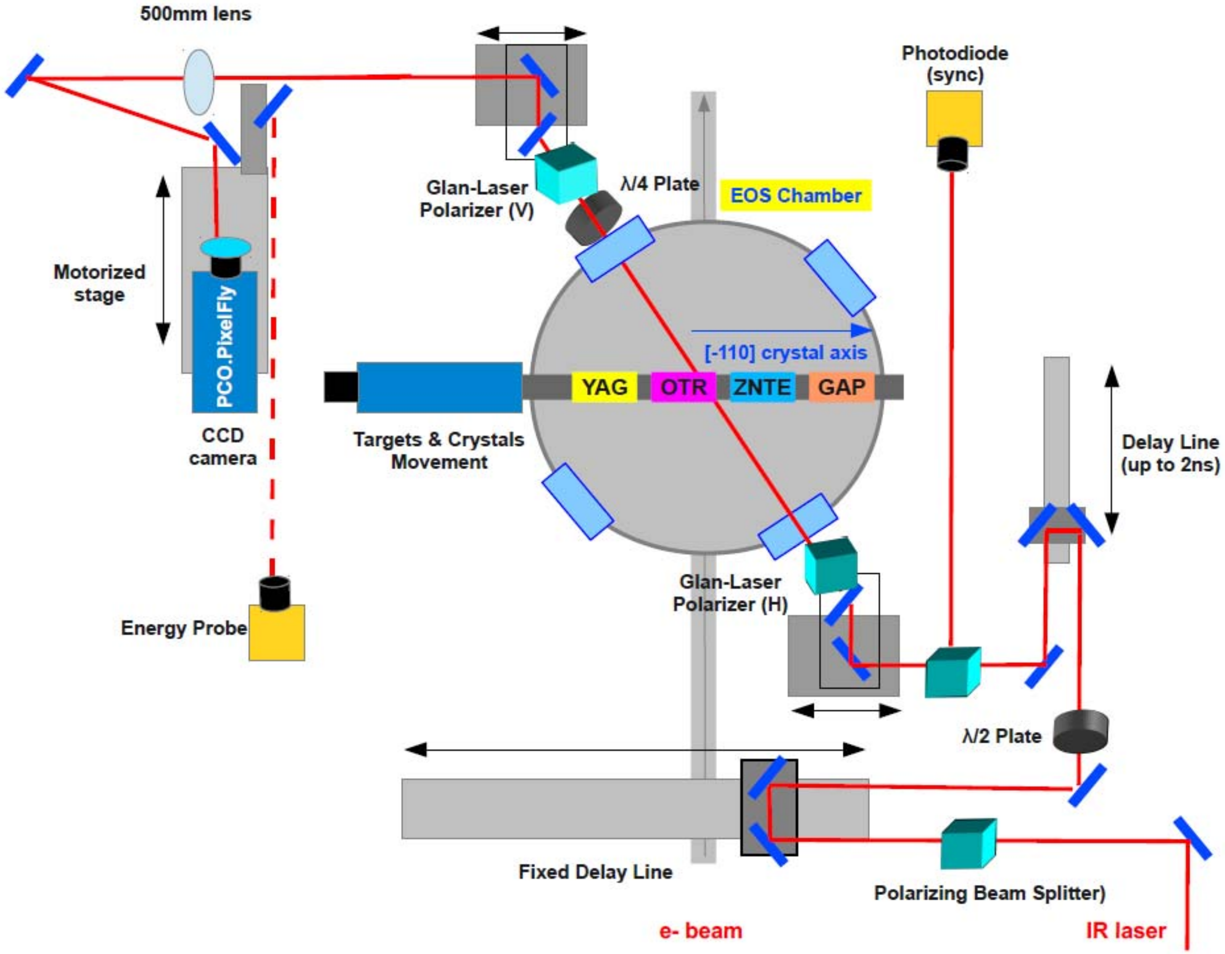
- Veronese, M., et al. "First operation of the electro optical sampling diagnostics of the FERMI@ Elettra FEL." *IBIC* 12 (2012): 449.

- Flexible but expensive setup
- Use of a fiber laser at 78 MHz
- It needs an intensified camera to select one single pulse

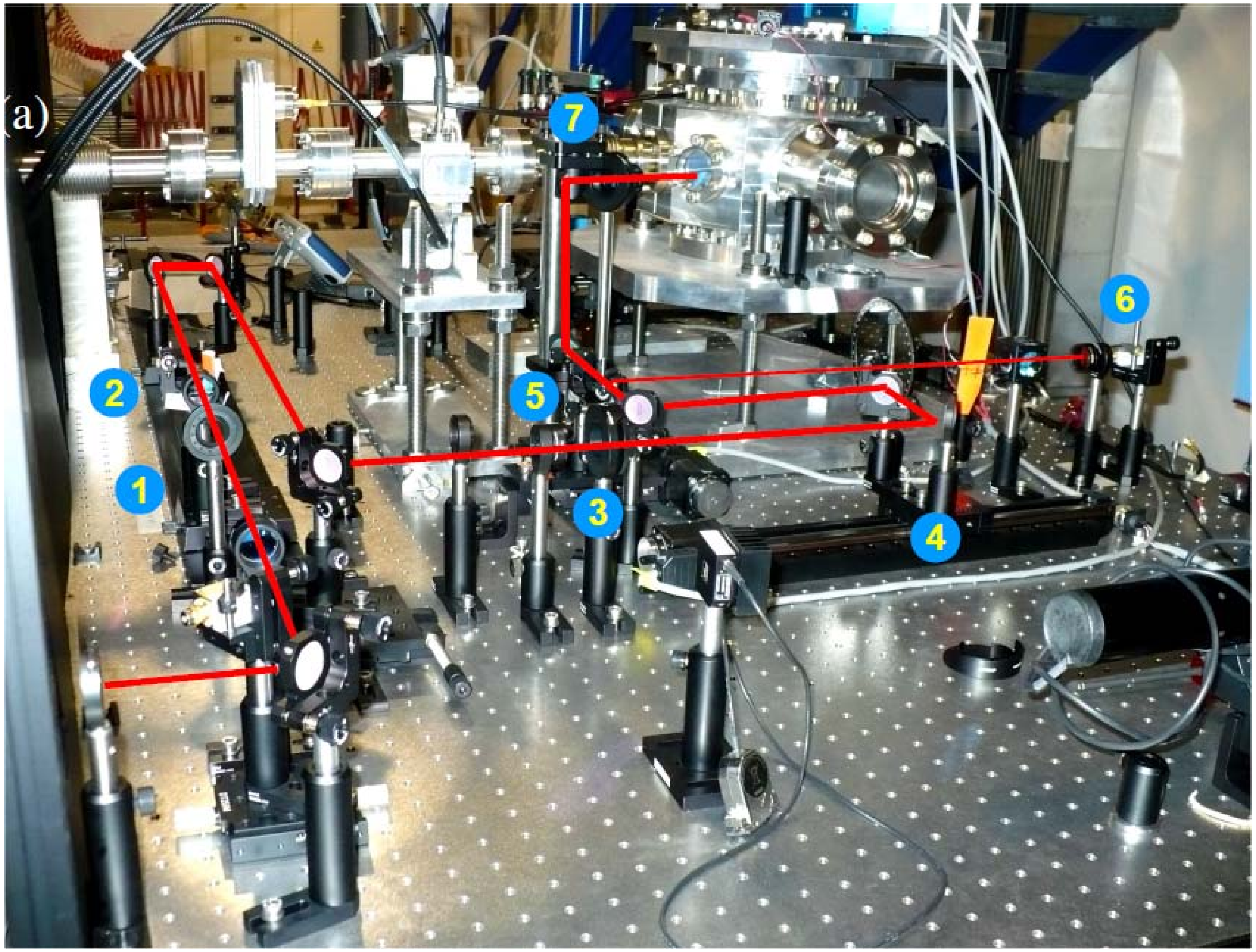
Using 10 Hz photocathode laser



Setup

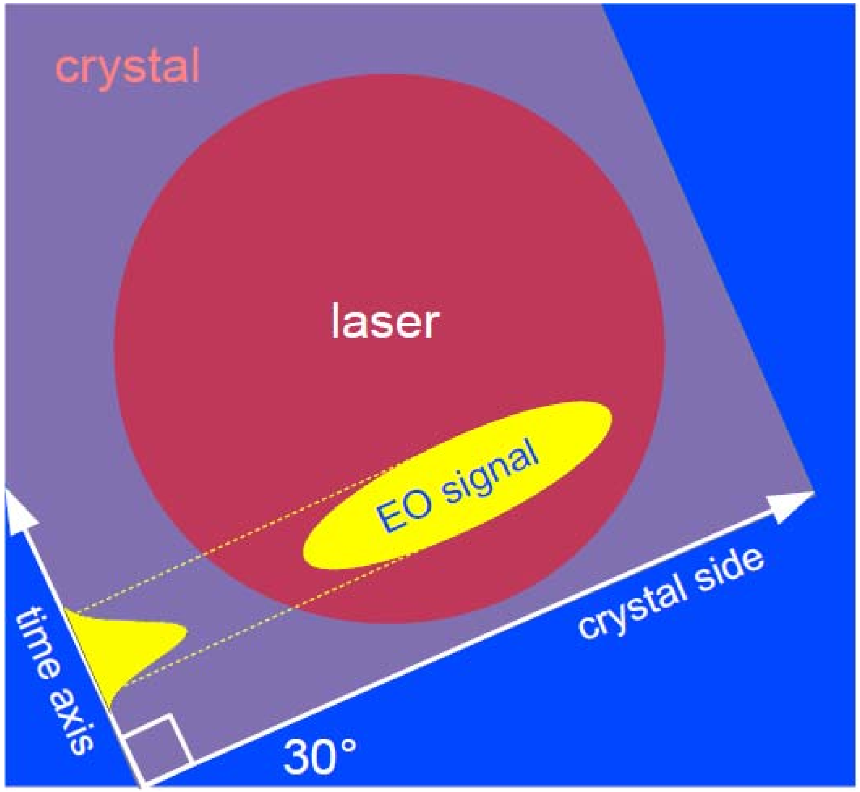

500mm lens
Photodiode
(sync)
Glan-Laser
Polarizer (V)
λ/4 Plate
EOS Chamber
Motorized
stage
PCO.PixelFly
[-110] crystal axis
YAG
OTR
ZNTE
GAP
CCD
camera
Targets & Crystals
Movement
Delay Line
(up to 2ns)
Glan-Laser
Polarizer (H)
Energy Probe
λ/2 Plate
Fixed Delay Line
Polarizing Beam Splitter)
e- beam
IR laser

Experimental setup



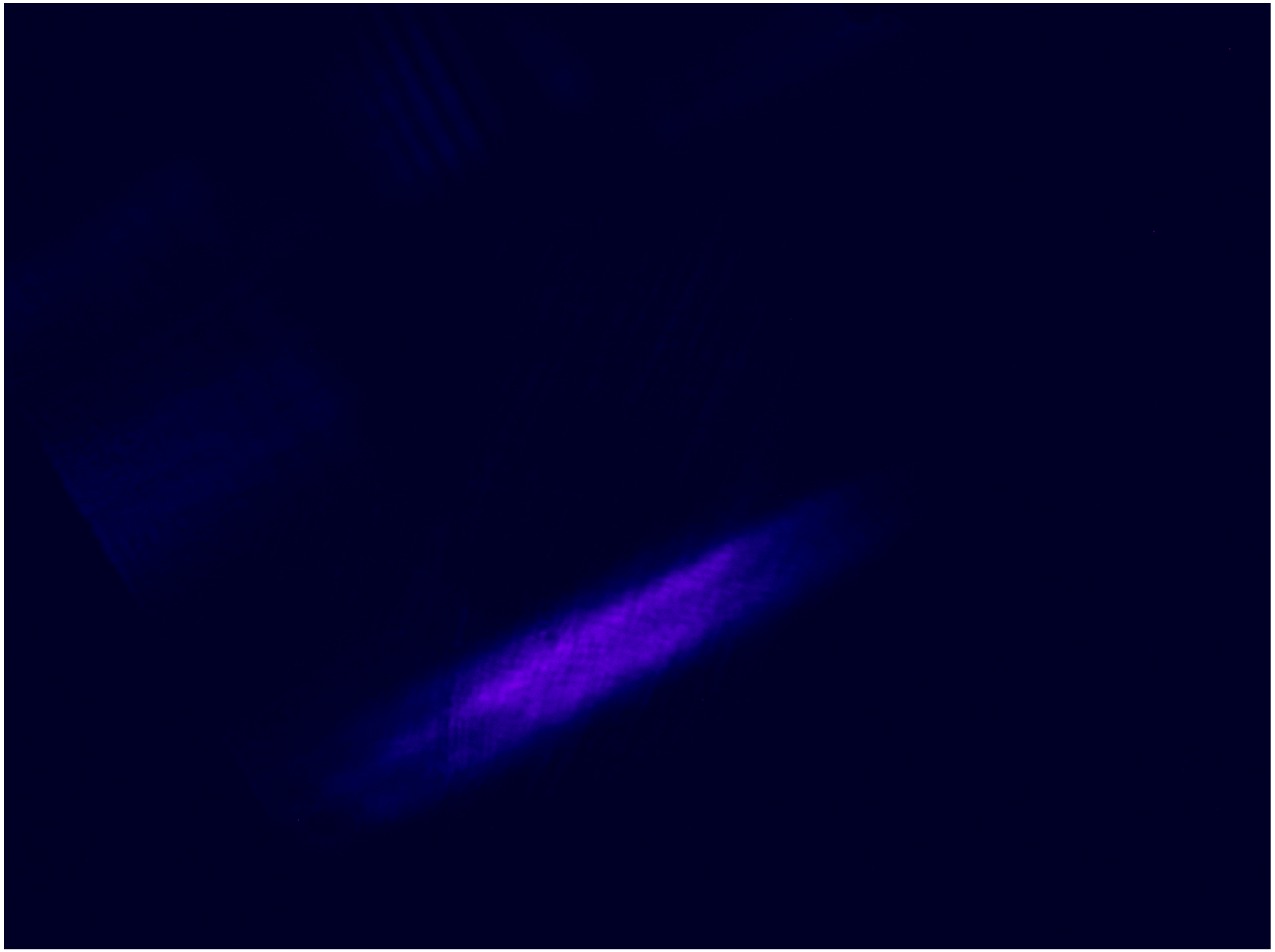
1. a telescopic system
2. polarizing beam splitter
3. half-wave plate
4. an optical delay line
5. a non-polarizing beam splitter
6. synchronization photodiode
7. Glan-laser polarizer

Expected signal and time resolution

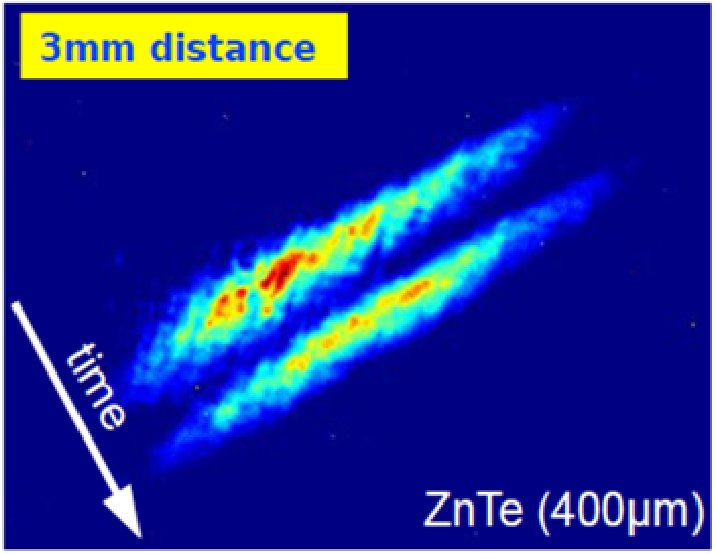


- The laser is shown as a red filled circle while the expected EOS signal shape is plotted as a yellow ellipse.
- The electron bunch is assumed travelling normally to the foil, therefore the time axis is perpendicular to the crystal side facing the bunch.

$$\Delta t_{pixel} = \frac{\Delta x_{pixel}}{Mc} \tan\theta$$



First results



- σ_1=(375±10) fs
- σ_2=(344±10) fs
- dist=(879±9) fs

- R. Pompili et al. “First single-shot and non-intercepting longitudinal bunch diagnostics for comb-like beam by means of Electro-Optic Sampling”, Nuclear Instruments and Methods in Physics Research A740 (2014) 216–221

Conclusions

- There is always a big gap between the diagnostics on the paper and the practical realization
- The mechanical drawings, the implementation, the definition of the detectors, the understanding of what you are really measuring are unavoidable steps in order to build a successful device
- Patience, precision, curiosity are the main qualities that can drive you to the success.

Finally it's over

- Thank you for your attention, if you are still alive…

- See you on Thursday…