Beam Dynamics meets Diagnostics

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Convitto della Calza, Florence, Italy

Longitudinal Electron Beam Diagnostics

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Outline

- **Motivation**
- **Longitudinal beam diagnostics**
  - More than only bunch length
    - Energy and energy spread, beam arrival time, time and energy jitter
- **Time resolved measurements: Streak camera, RF-based techniques, Electro-Optics Sampling**
  - Convert time information into spatial one
  - Absolute bunch length, current profile, slice emittance
    - Resolution limits, impact of jitters
- **Frequency domain techniques: Coherent radiation spectrum**
  - Shorter bunch <=> broader bunch frequency spectrum
    - phase retrieval …
- **Towards fs and sub-fs bunch length measurement**
- **Summary**

Motivation

- Plasma-based accelerators, Linear colliders, Novel radiation sources require **High Brightness Electron Beams**

$$B_{6D} = \frac{2I_p}{\frac{\Delta\gamma}{\gamma}\varepsilon_n^2}$$

- small transverse emittance

$$\boxed{\varepsilon_n \approx 1\ mm\ mrad}$$

- low energy spread

$$\boxed{\frac{\Delta\gamma}{\gamma} \approx 10^{-3}}$$

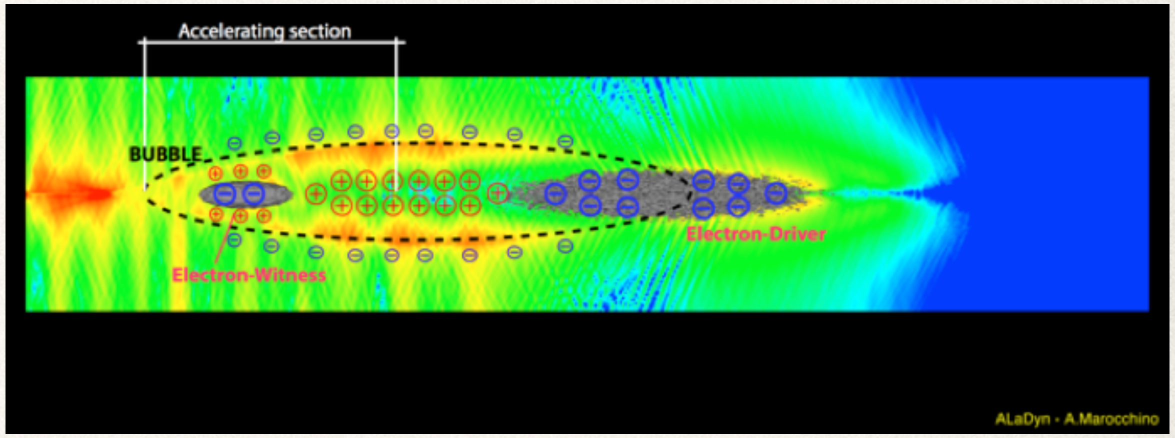
- high peak current
  - **ultra-short electron bunches**
- **The characterization of both longitudinal and transverse phase spaces of the beam is a crucial point in order to verify and tune photo-injector parameters**
  - charge, emittance, bunch length, energy and energy spread
  - injection, accelerating and compression phases, accelerating gradients, focusing strength

What does "ultra-short" bunch mean?

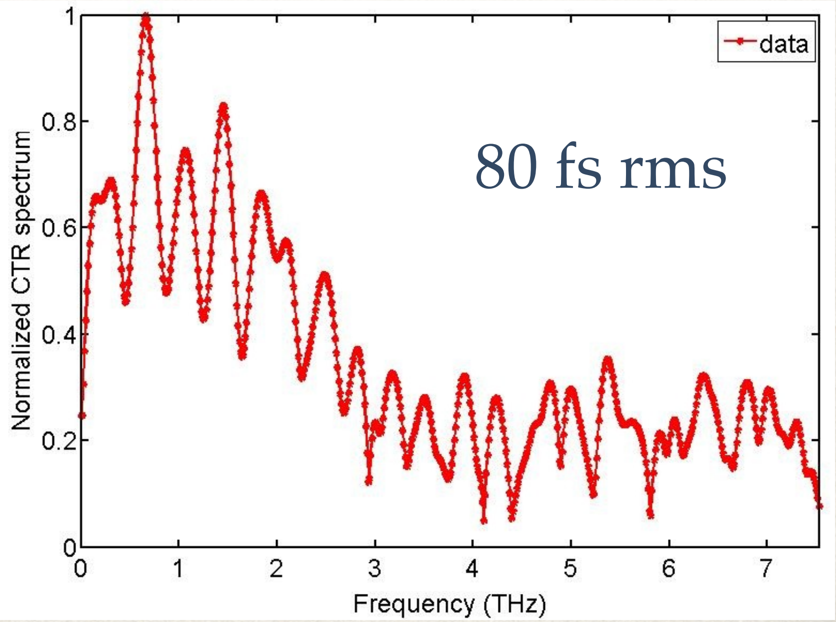
- **Plasma-based accelerators**
  - The characteristic scale length of the accelerating field, i.e. the plasma wake, is the plasma wavelength

$$\boxed{\lambda_p(\mu m) \approx 3.3 \cdot 10^4\ n_e^{-1/2}(cm^{-3})}$$

  - Bunch length of tens of fs down to **fs scale**



- **Linear colliders**
  - Minimize hourglass effect: transverse beam sizes vary with beta function
    - not all particles collide at minimum of transverse beam size
      - luminosity degradation
    - $\boxed{\beta_y \geq \sigma_z}$ ~ **sub-ps scale**



- **Novel coherent radiation sources**, e.g. THz sources
  - **sub-ps down to fs scale** to extend the frequency spectrum

Methods for Longitudinal Diagnostics

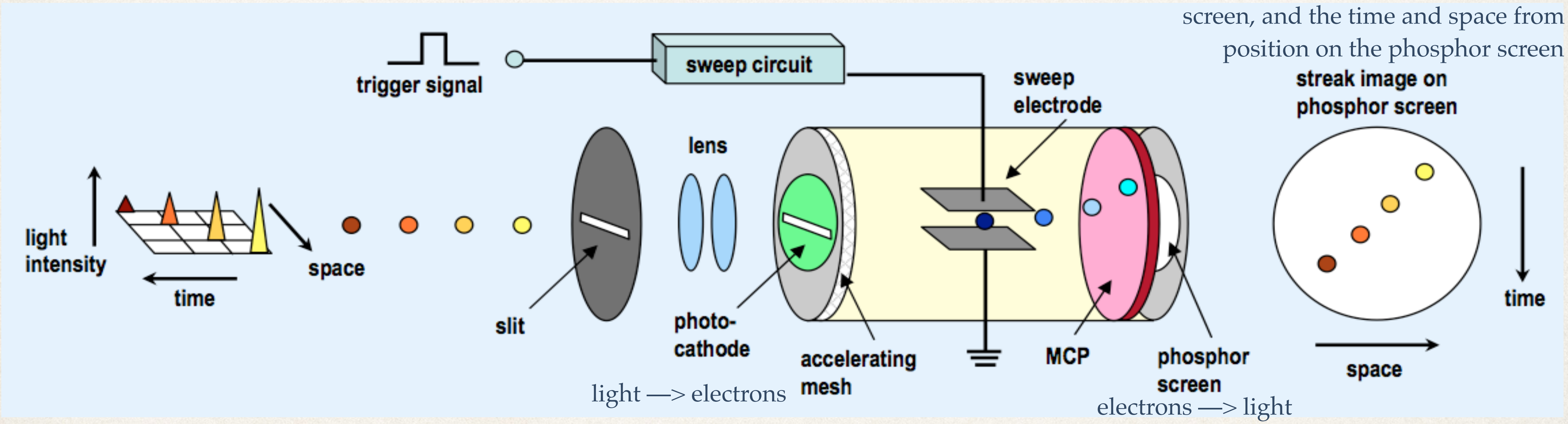
- A **direct** time resolved **measurement** requires ultrafast detectors
  - Often the longitudinal phase space is transformed into the transverse phase space allowing the use of standard methods like screens viewed with standard cameras
- Several techniques can be used to measure electron beam longitudinal parameters
  - **Time domain**
    - Streak camera (~ ps down to sub-ps)
    - RF deflecting cavity (~ ps down to fs scale)
    - Electro-optic sampling which uses the wakefield induced by the beam in a crystal to modulate the field of a laser (down to tens of fs)
  - **Frequency domain**
    - Autocorrelation of coherent radiation emitted by a relativistic electron bunch (~ ps down to fs scale)
    - Spectrometers with N channels
- **Goal**
  - Precise information about the beam
  - **Single shot** measurements
    - to avoid jitter
  - **Non-intercepting** diagnostics
    - on line monitoring to help beam dynamics

Time domain techniques

Streak camera

- Streak cameras use a **time dependent deflecting electric field to convert time information in spatial information** on a CCD
- The method is based on the **prompt emission** of light in the optical wavelength range, e.g. OTR, Cherenkov radiation
- The **light pulse is a "replica" of the longitudinal shape of the electron pulse**
    - a photocathode converts radiation into electrons by photoemission
    - electrons are accelerated in a cathode ray tube and then "streaked" transversely by a DC electric field
    - The deflected electrons then impinge upon a phosphorescent surface or detector

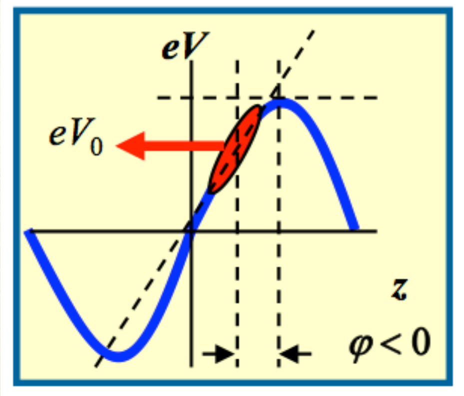
The intensity of the incident light can be read from the brightness of the phosphor screen, and the time and space from the position on the phosphor screen



- The **time resolution** mainly is **limited by space charge effects** of the electron beam emitted by the cathode, **dispersion effects** in the optics and by the **quality and speed of the streak tube**
    - A resolution of **200-300 fs** FWHM is attained by a state-of-the-art camera

Radio-Frequency based Diagnostics

- **An RF deflecting field can <u>directly</u> streak the electron beam**
  - Deflecting mode cavities were originally invented in the **early 1960s** as a way to separate different species of particles in an accelerator (*<u>SLAC-PUB-135, Aug. 1965</u>*)
- Two types of RF cavities can be used
  - **accelerating structures operated at the zero-crossing of the RF** (i.e. at the RF phase where the beam centroid experiences no acceleration)
    - The head and tail of the beam experience accelerating forces of opposite sign, thereby producing a **strong correlation between longitudinal position and energy**
  - **RF structures that operate in an electromagnetic mode similar to the TM_{110} mode of a cylindrical pillbox**, and delivers a transverse momentum kick to the electron beam
    - **strong correlation between longitudinal position and transverse angle**
    - the bunch is set to the zero crossing of the field, where the **time dependence of the RF field is linear and has the steepest slope**
      - The **deflection** is proportional to the field, and thus, due to the time dependence of the field, is **proportional to the arrival time of the electrons**, or in other words, to the longitudinal position z of the electron in the bunch



Principle of an RFD cavity

The deflecting force imparts a transverse momentum on the bunch which varies in time over the passage of the bunch. The kick angle $\Delta y'$ as a function of longitudinal position along the bunch, *z*, is given by

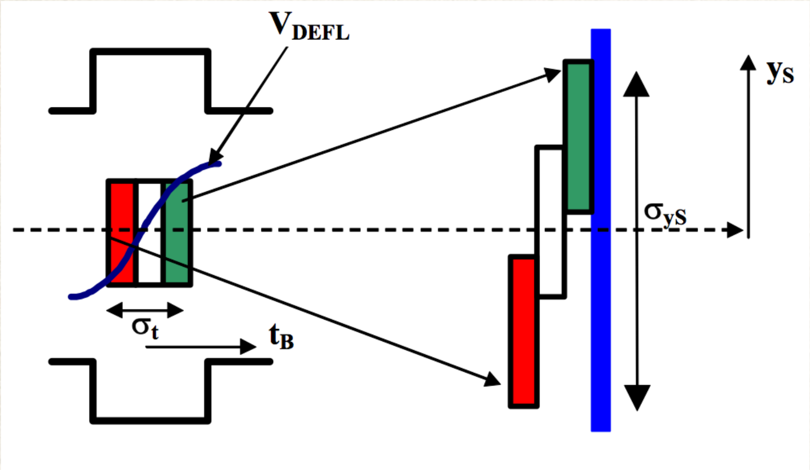
$$|z| \ll \frac{\lambda}{2\pi}$$

$$\Delta y'(z) = \frac{eV_0}{p_z c}\sin(kz + \psi) \approx \frac{eV_0}{p_z c}\left(\frac{2\pi}{\lambda}z\cos\psi + \sin\psi\right)$$

λ RF wavelength
V_0 peak deflecting voltage
ψ RF phase, = 0 at the zero-crossing
p_z beam's longitudinal momentum in the structure

A spatial deflection can be measured at a screen placed downstream of the deflector, where the beam has been transported through a transfer matrix with angular-to-spatial element $R_{12} = \sqrt{\beta_d \beta_s}\sin\Delta$, where β_d, β_s beta functions at the deflector and screen, and Δ betatron phase advance from the deflector to the screen

The transverse position of each ultra-relativistic electron on the screen is then given by



$$\Delta y(z) = \frac{eV_0}{pc}\sqrt{\beta_d \beta_s}\sin\Delta\left(\frac{2\pi}{\lambda}z\cos\psi\sin\psi\right)$$

(*LCLS-TN-00-12, Aug. 2000*)

Principle of an RFD cavity

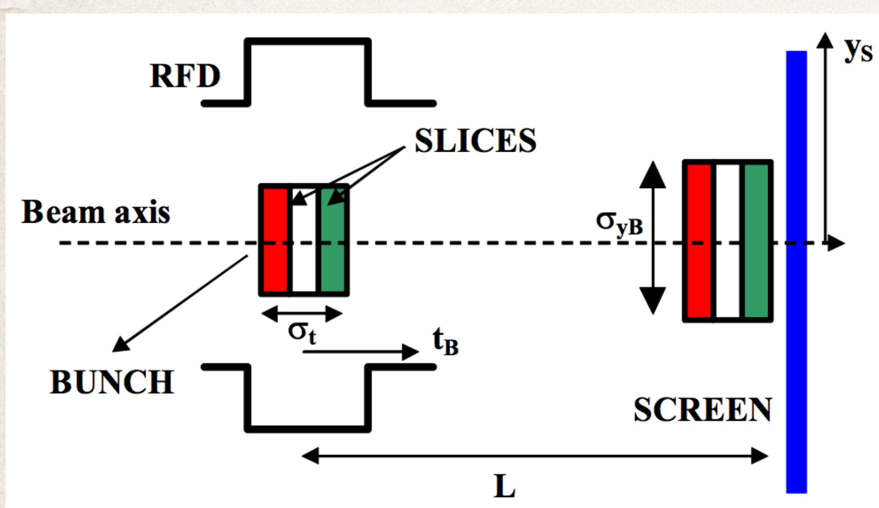
For the ensemble of particles, the transverse centroid offset at the screen is given by

$$\langle \Delta y(z) \rangle = \frac{eV_0}{pc}\sqrt{\beta_d \beta_s}\, \sin\Delta\, \cancel{\sin\psi} \qquad \psi = 0$$

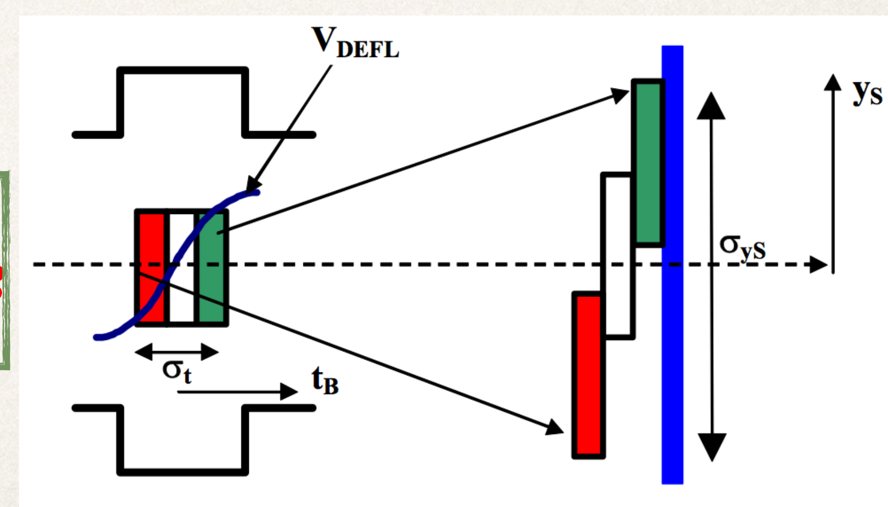
If the beam is injected at the zero-crossing phase, the **beam centroid** is **not deflected**

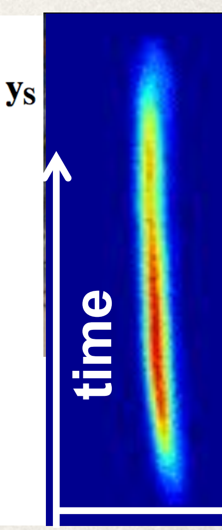
Since the beam has a finite transverse emittance, the distribution of the deflected bunch at the screen position is the superposition between the deflected beam profile and the transverse size of each bunch slice.

$$\left\langle \left(y - \langle y \rangle\right)^2 \right\rangle = \sigma_y = \sqrt{\sigma_{y_0}^2 + \sigma_z^2 \beta_d \beta_s \left(\frac{2\pi e V_0}{\lambda pc} \sin\Delta \cos\psi\right)^2} \boxed{= \sqrt{\sigma_{yB}^2 + \sigma_{def}^2}}$$

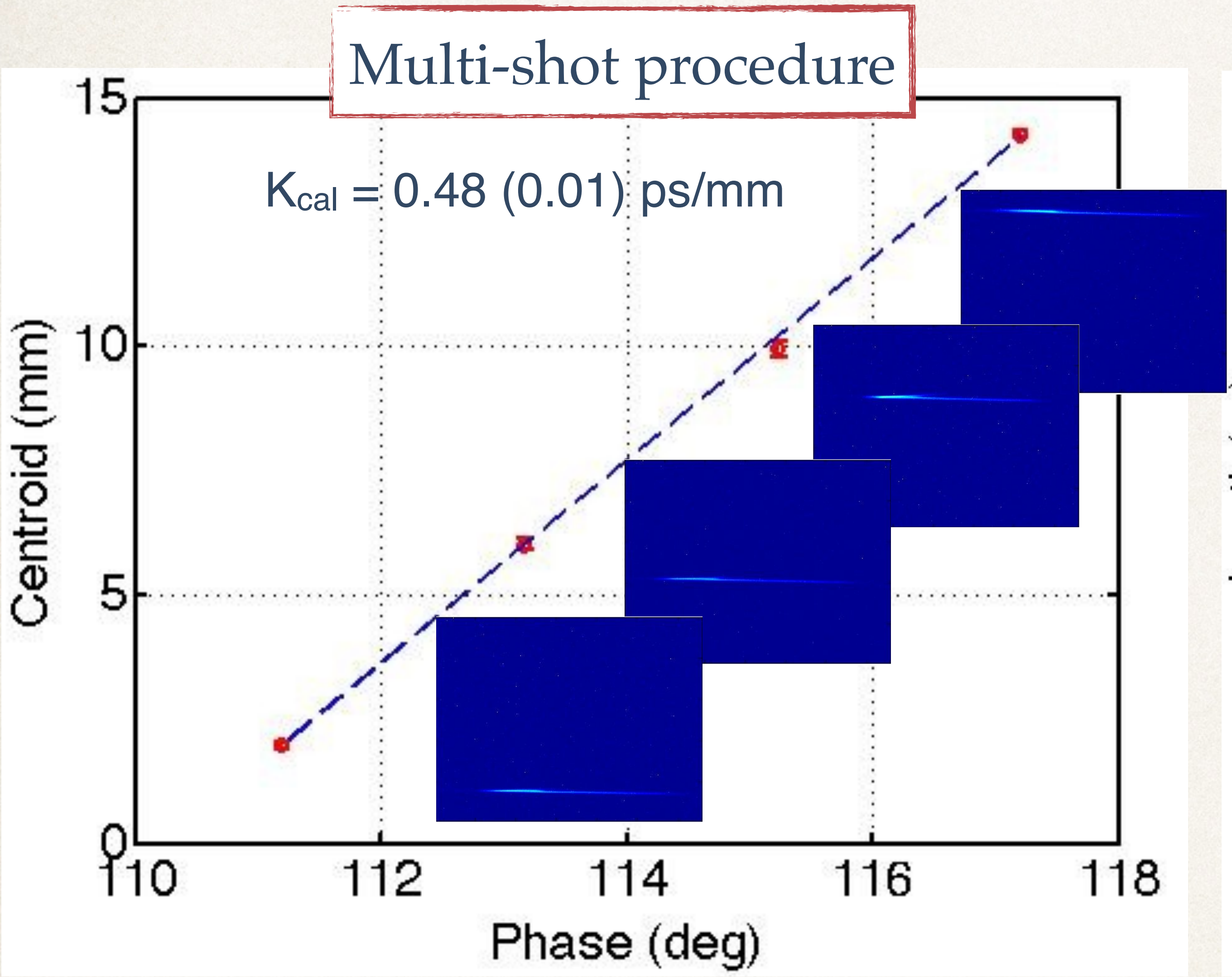


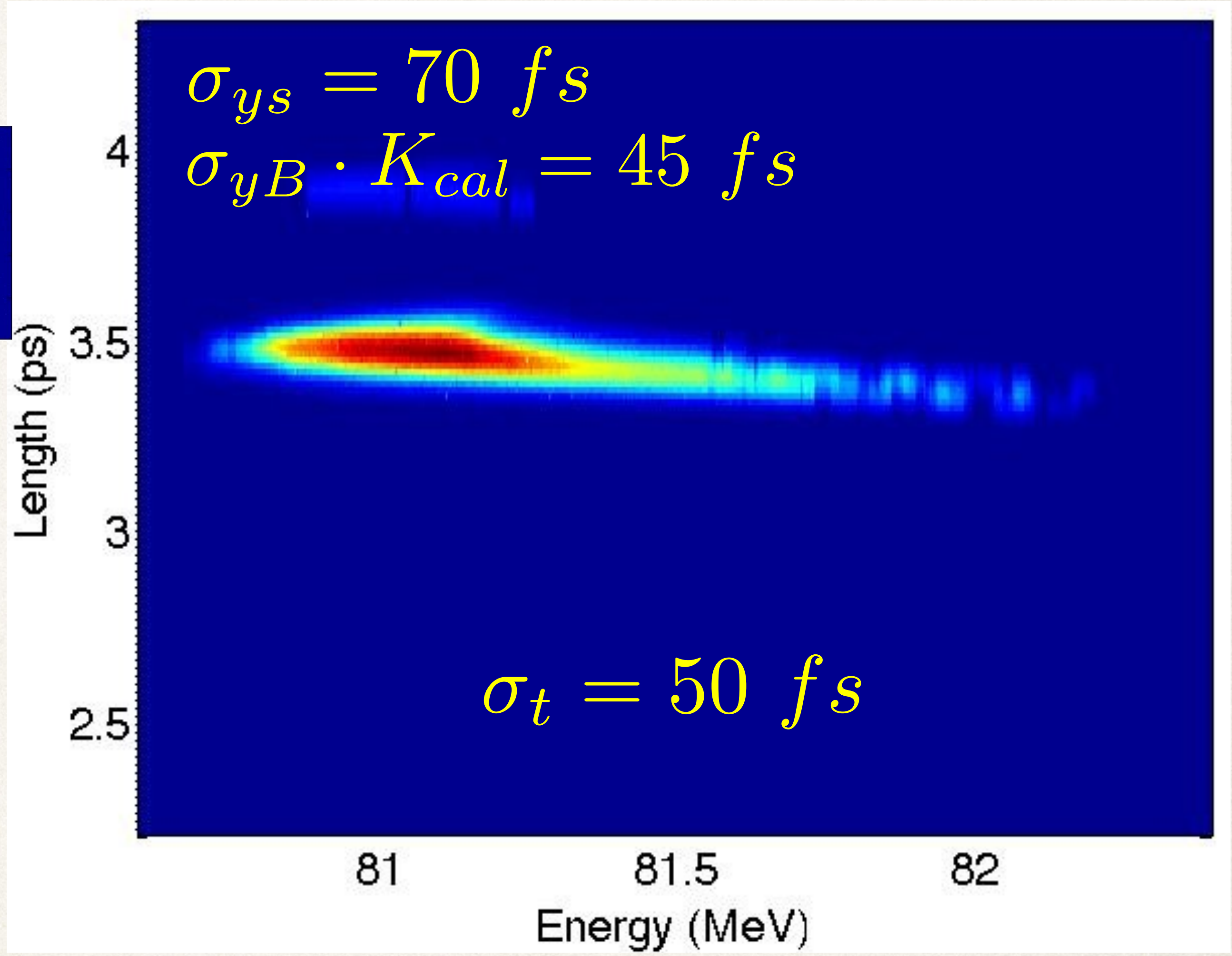
$$\boxed{\sigma_z^{res} = \frac{E}{eV_0 L} \frac{\lambda}{2\pi} \sigma_{yB}}$$





Self-calibrating device





The coefficient $K_{cal} = \frac{eV_0}{E} L \frac{2\pi}{\lambda}$ can be directly retrieved by measuring the bunch centroid position on the screen for different values of the RFD phase

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Intrinsic Effects

- The **TM_{11}-like deflecting modes has 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

$$\tilde{V}_y = i\frac{c}{\omega}\int \nabla_y \tilde{E}_z e^{i\frac{\omega}{c}z} dz$$

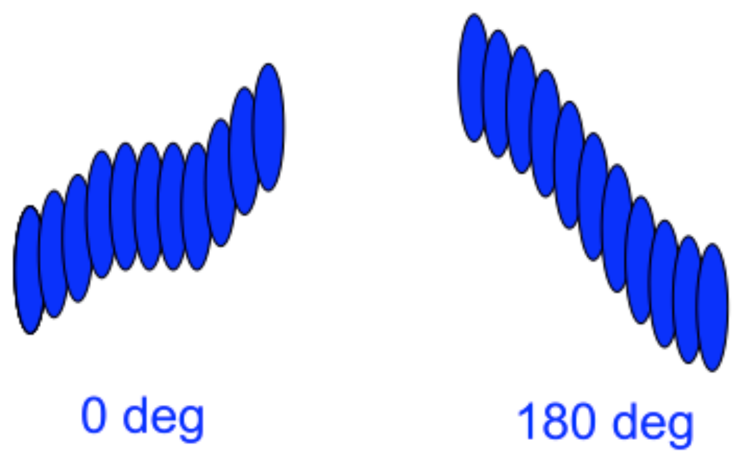
- Since this gradient is 90 deg out-of phase with respect to the deflecting voltage, it introduces an energy spread in the bunch
    - it depends linearly on the vertical slice size inside the RFD

$$\sigma_{E-RFD} \approx \frac{2\pi}{\lambda} V_0 \sigma_{yB-RFD}$$

D. Alesini et al., TUOA01 Proceedings of DIPAC09, Basel, Switzerland

Systematic Errors

Initial correlations in (y′,t) may give different results when changing zero-crossing

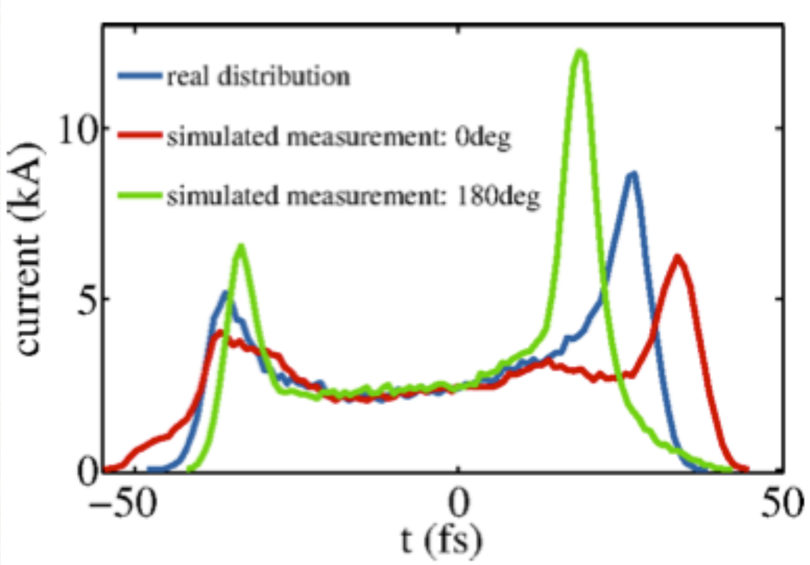


- $\sigma_x = \sqrt{\sigma_{x_0}^2 + (C \pm S)^2 \cdot \sigma_t^2}$

★ If C is a constant: simple calculation using values at $\pm S$ (0 and 180 deg)

★ If C varies along the bunch (i.e. $C(t)$): reconstruction from both projections is possible (idea and Ref. by H. Loos (SLAC))

Simulated measurements with both zero-crossings (0 and 180 deg)



- Strong effects in head and tail

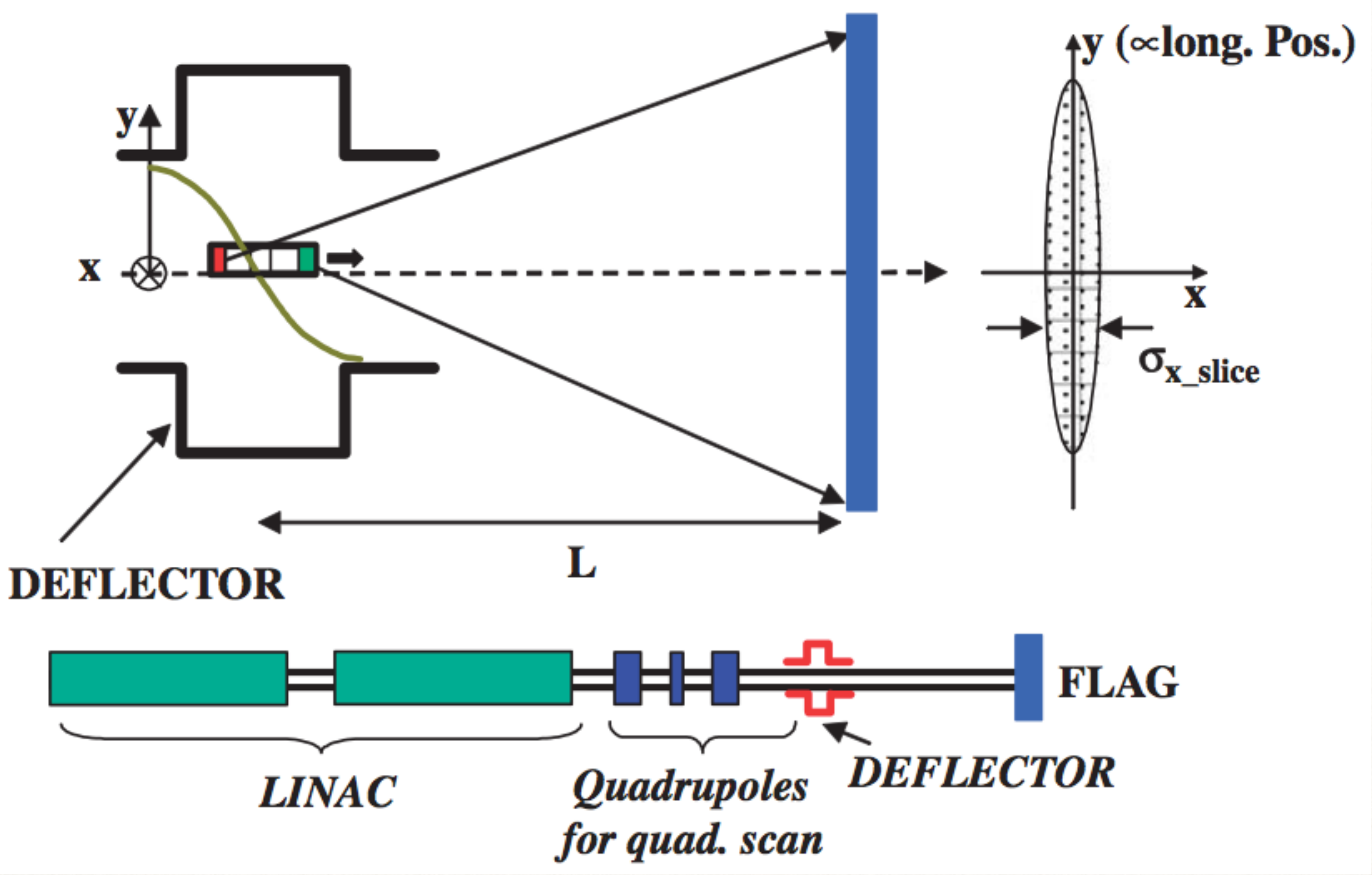
C. Behrens, FEL 2011, Shanghai

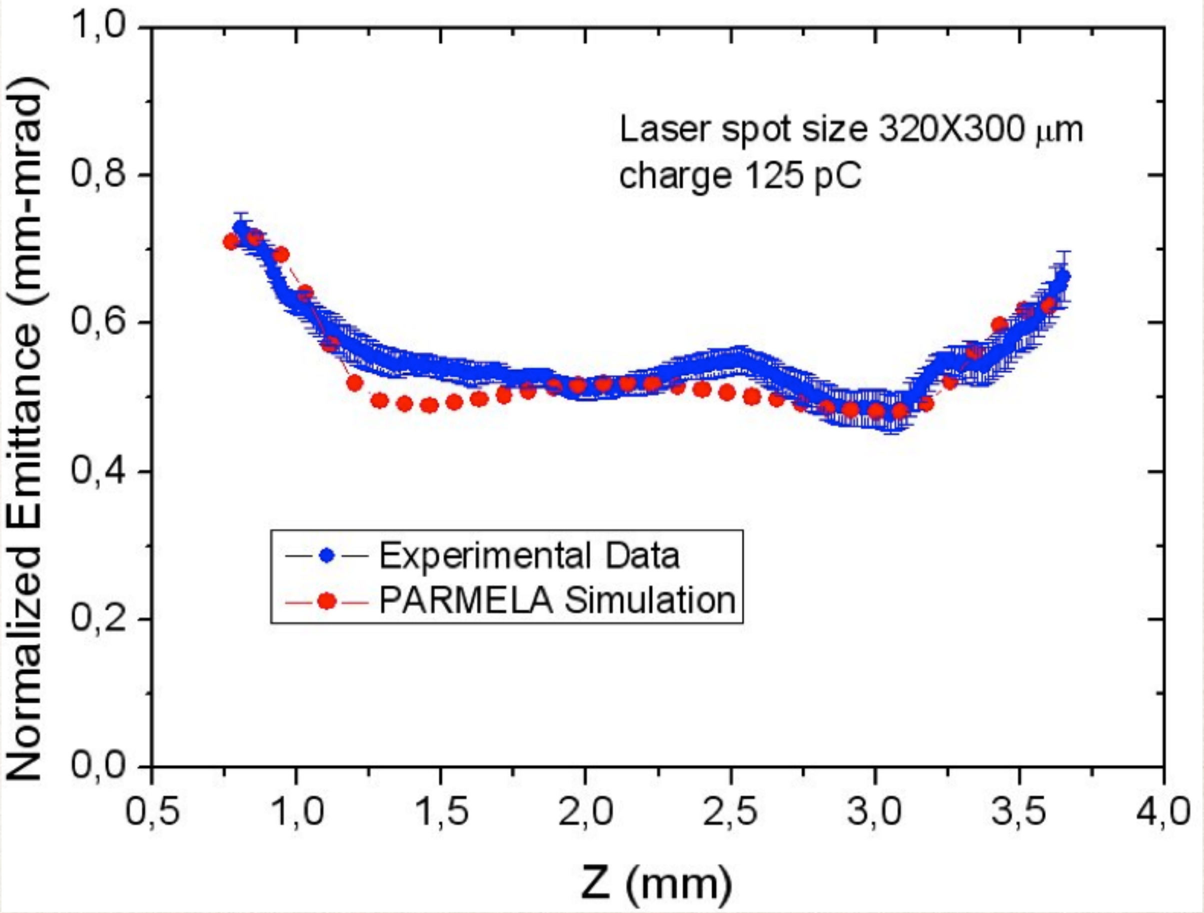
Time-resolved Measurements: Slice Beam Parameters

The slice emittance is one of the fundamental parameter that defines the FEL process.

Photons travel faster than electrons in the undulator field, therefore the photon slippage with respect to the electron bunch in one gain length defines the longitudinal coherence length of a SASE FEL.

Radiated photons only interact and feel a small fraction of the electron beam => **slice** beam parameters

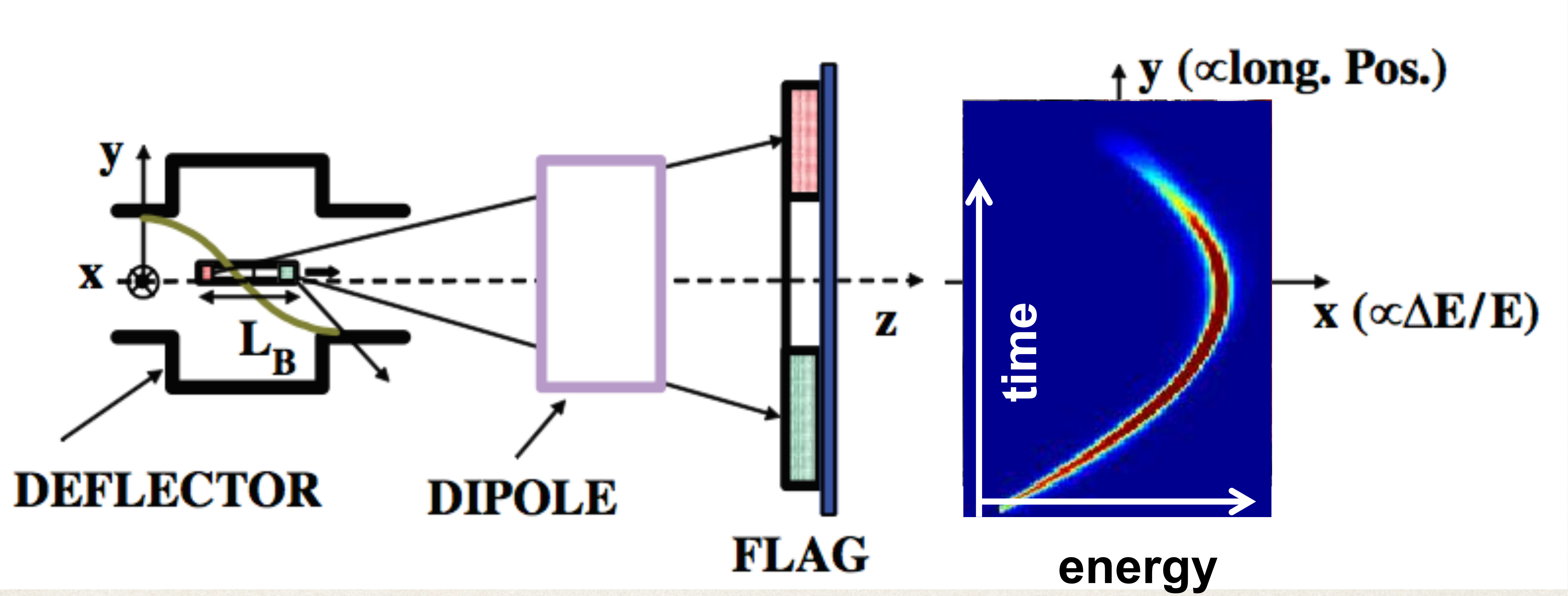




Time-resolved Measurements: Slice Beam Parameters

Together with a dispersive system, an RFD cavity allows the measurement of the longitudinal beam phase space distribution.

The slice energy spread can be extrapolated by slicing the beam vertically and measuring the beam thickness in energy as function of time



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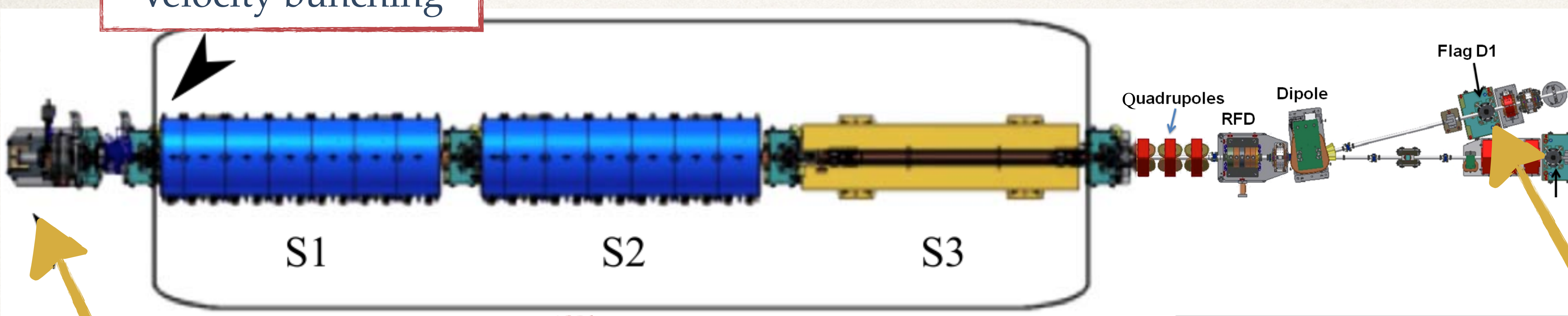
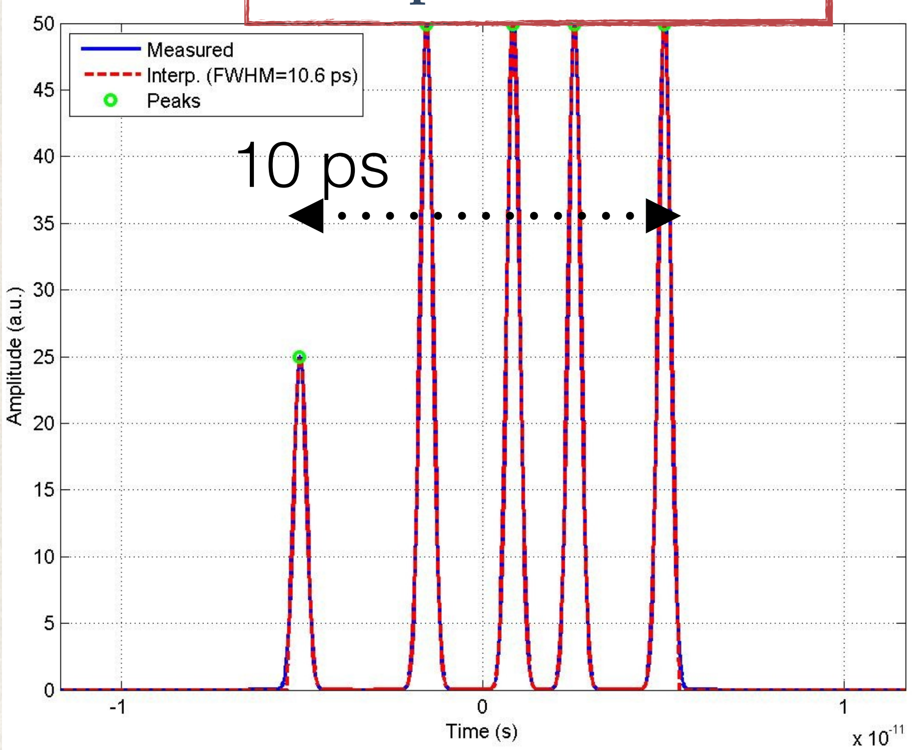
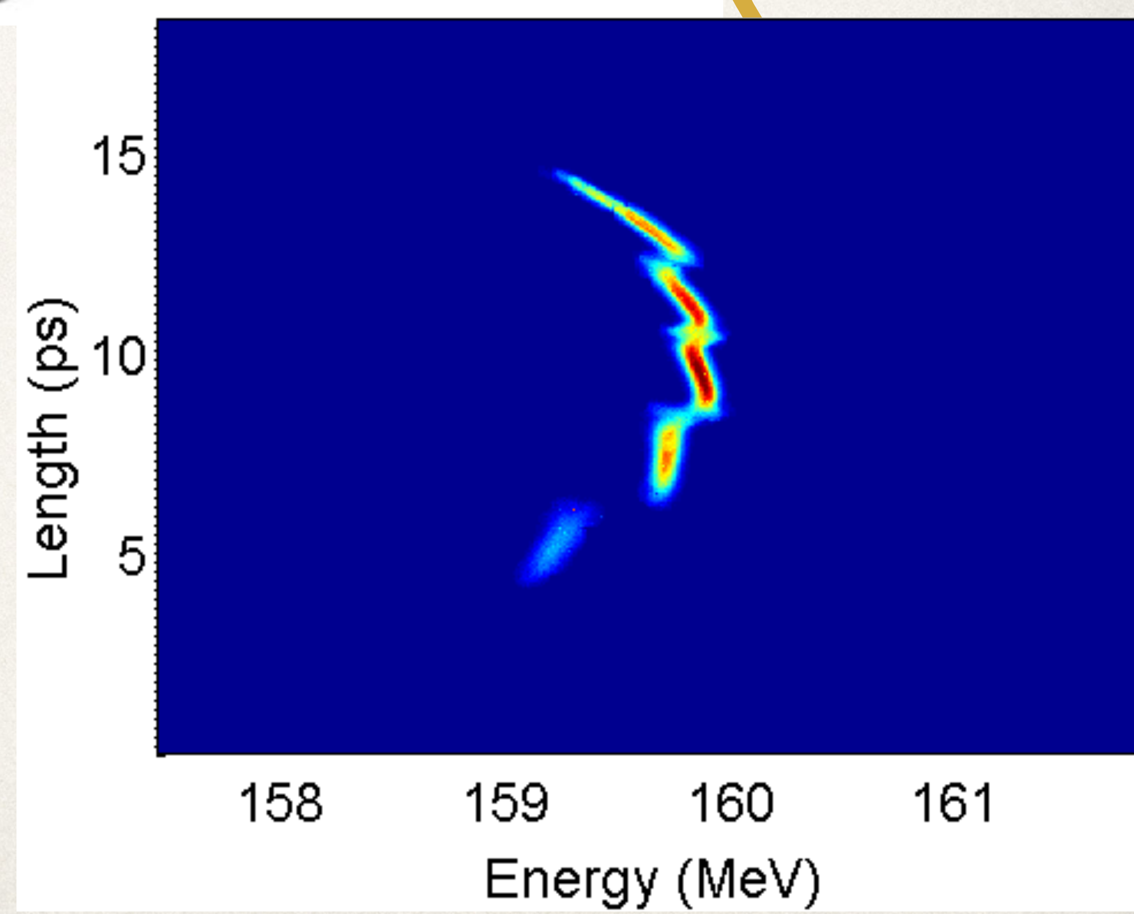
Beam Dynamics meets Diagnostics

RF longitudinal compression:
Velocity bunching



Laser pulse shape at the photo-cathode





Beam Dynamics meets Diagnostics

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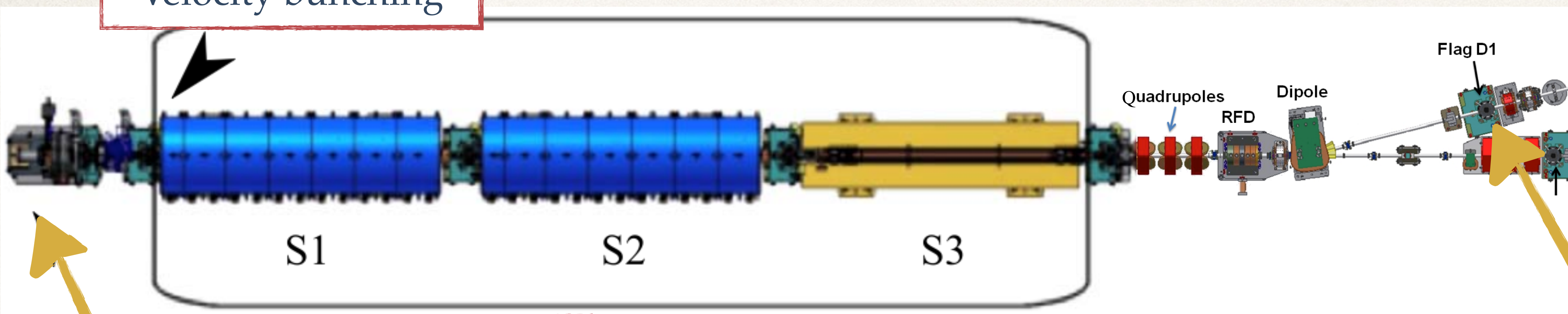

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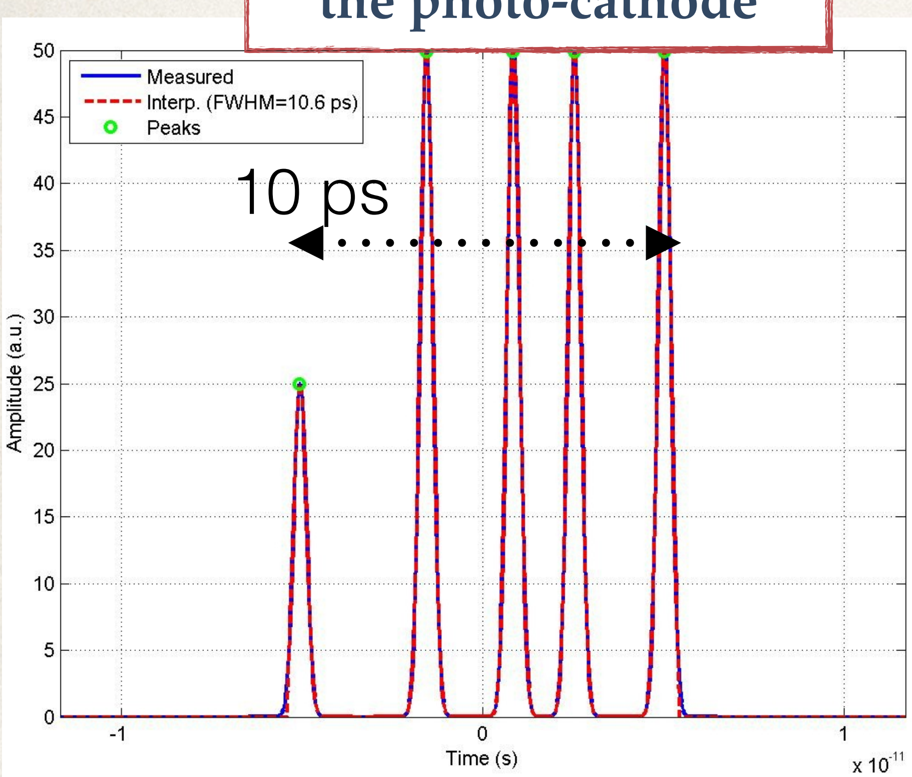
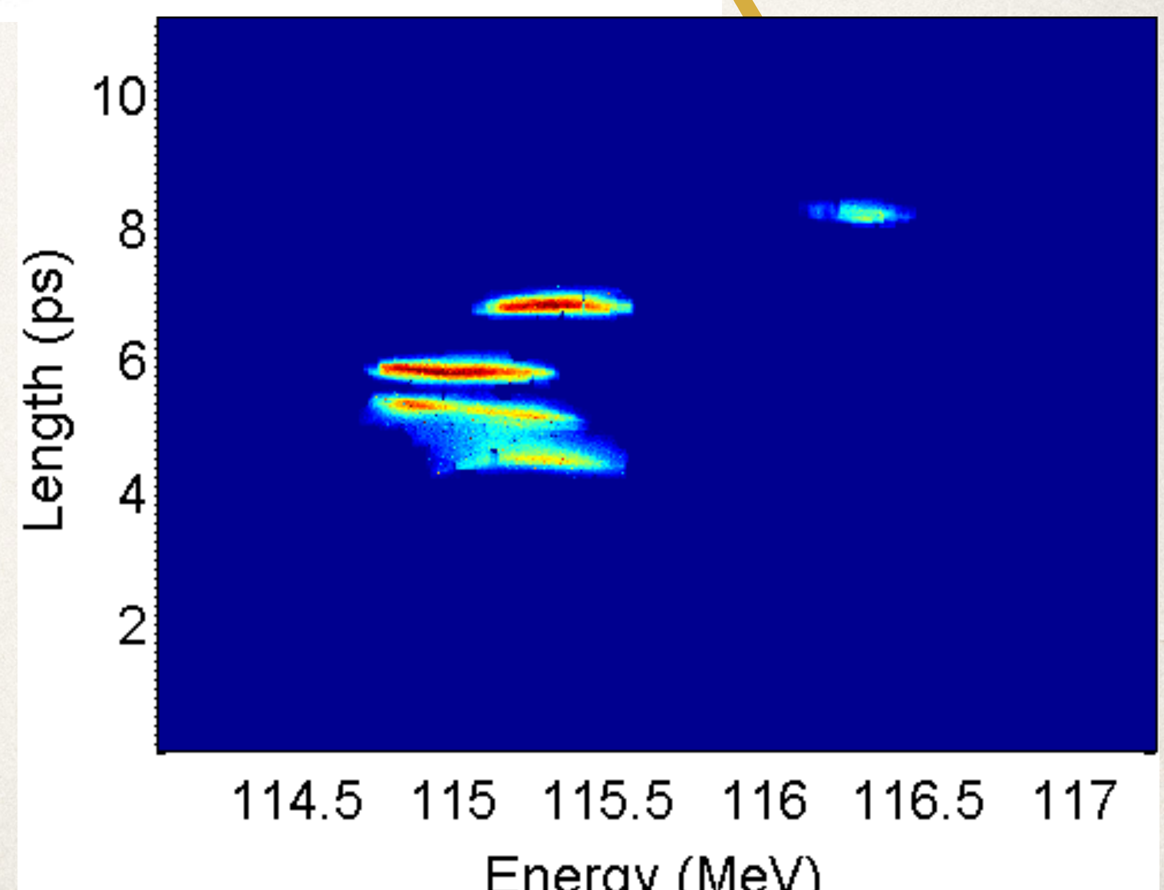




Electro-Optic Methods

- The **electric field of a relativistic electron bunch**, E_r component of Lorentz contracted Coulomb field, **induces birefringence** in an Electro-Optic crystal like ZnTe, GaP, …, which becomes anisotropic

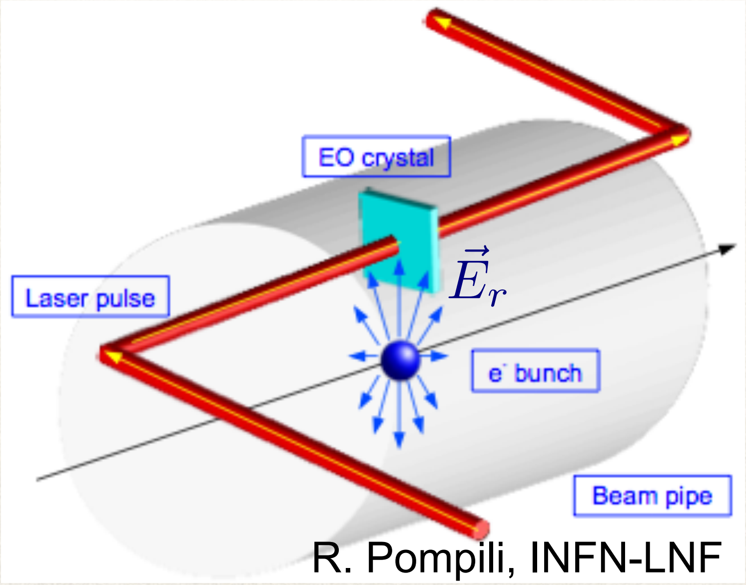
$$P = \varepsilon_0(\chi_e^{(0)} E + \chi_e^{(1)} E^2 + \ldots)$$

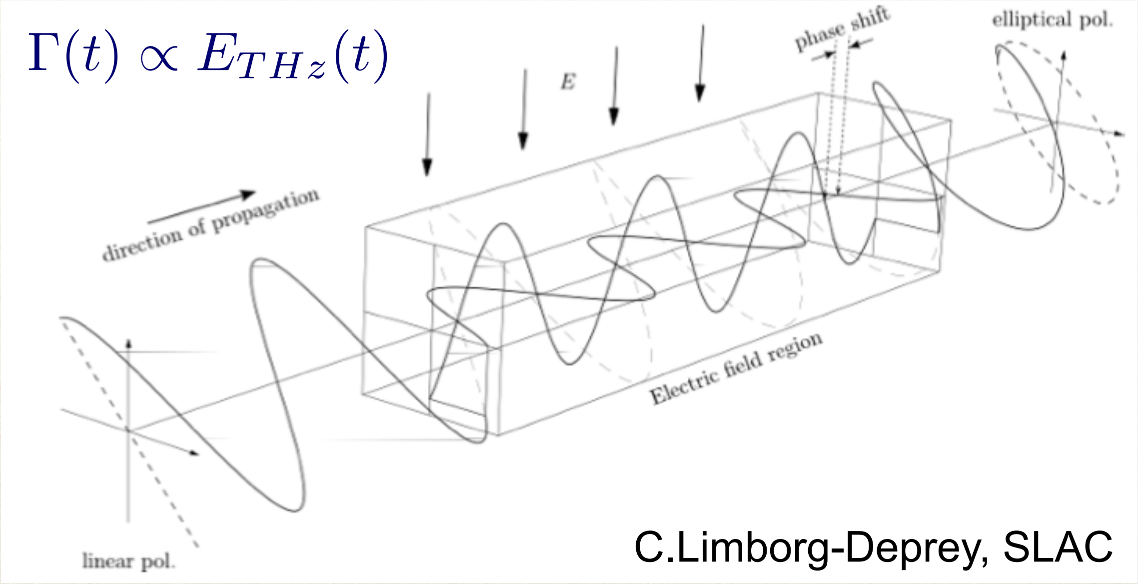
Pockels **Kerr**

- The electric field of a polarized laser passing in the crystal would be decomposed along the two optical axes with characteristic refractive indices $n_i = n_{1,2}$
- The **relative phase delay** of the two components, traveling at different velocities $v_i = c/n_i$, at the end of the crystal is

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

- **The bunch temporal profile has been encoded in** $\Gamma(t)$
  - **temporal resolution** depends on the **crystal** and its **thickness**, the width of the optical **laser pulse** and the **decoding technique**

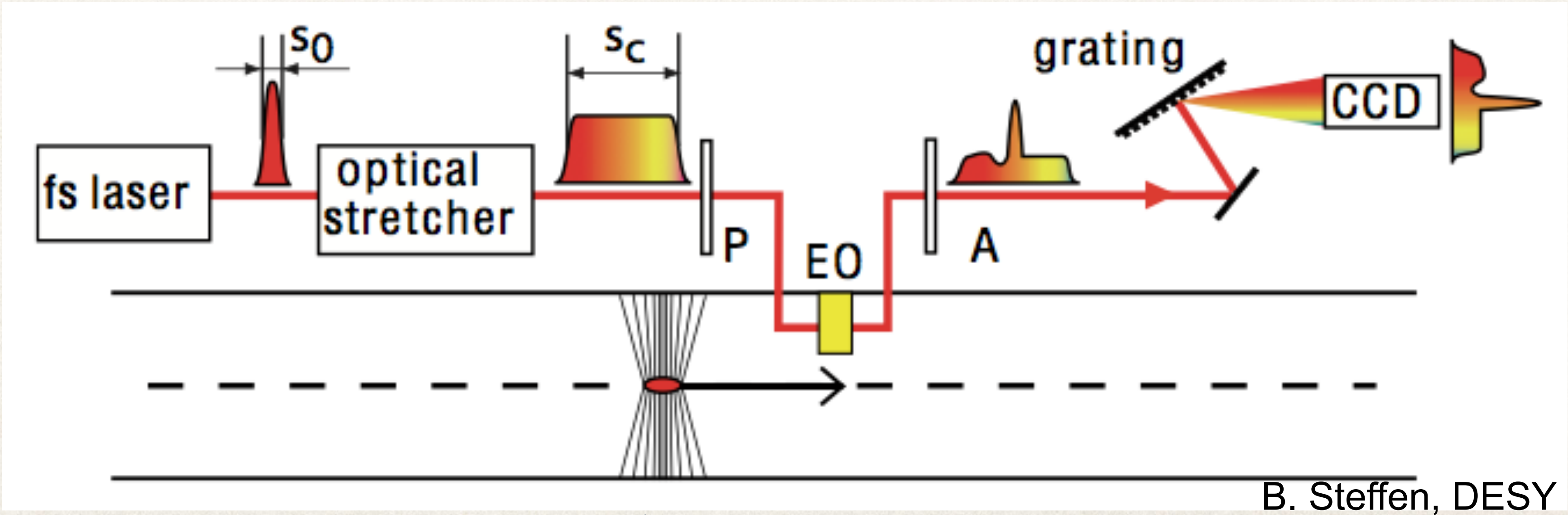




Encoding Techniques

Spectral encoding

- The **laser pulse** is passed through a dispersive material and **stretched** (chirped) to a length of several ps, longer than the electron bunch
  - long chirped laser with linear λ-t correlation
  - In the chirped pulse the long wavelengths are at the head of the pulse and the short ones at the tail
- In the crystal the temporal structure of the electron bunch is imprinted onto the spectral components of the laser pulse
  - With a diffraction grating and a gated CCD camera the time information can be recovered

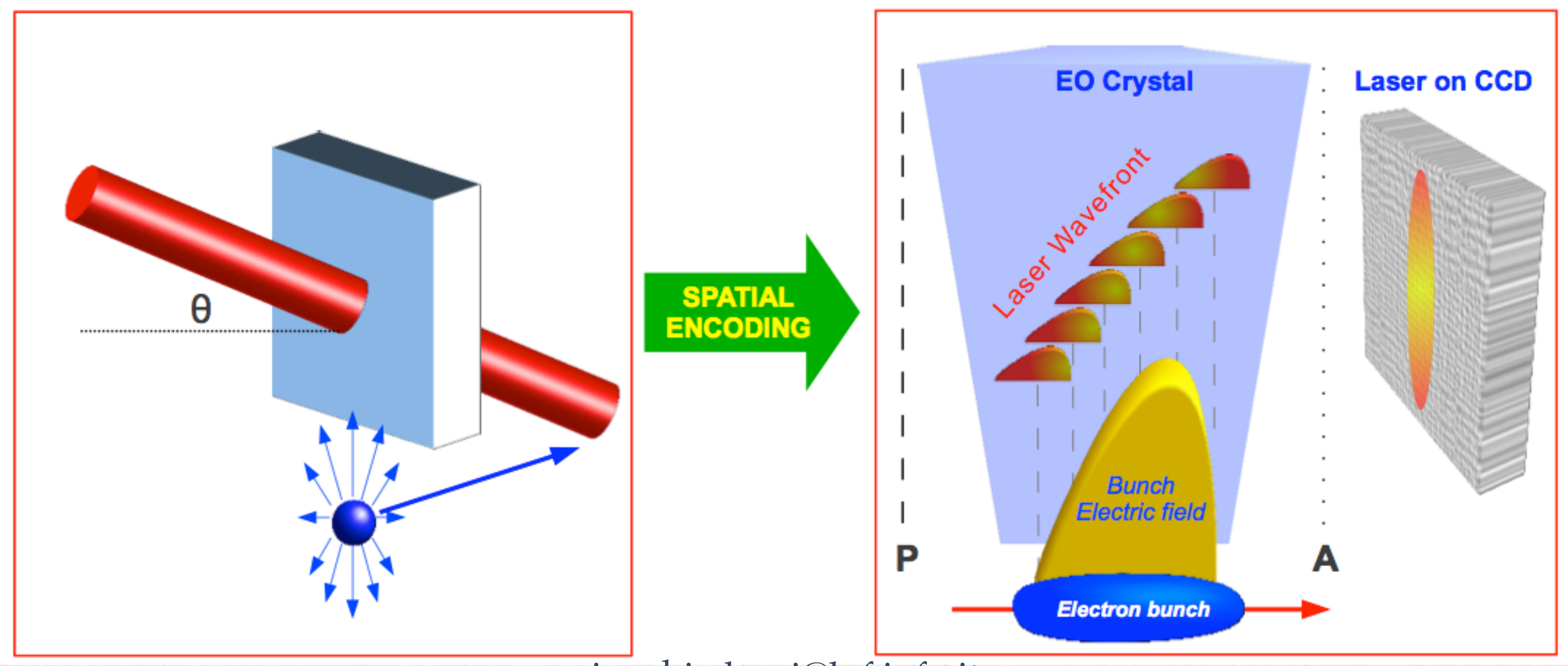


B. Steffen, DESY

Encoding Techniques

Spatial encoding

- The laser crosses the crystal with an incident angle
- Because the laser hits the EO crystal with an angle, different spatial components of the laser pass through the crystal at different times and acquire a different polarization.
- The analyzer A turns the spatial modulation of the polarization into a spatial intensity modulation which is detected by the CCD camera
  - Measured intensity is equal to $I_{det} = I_{laser} \sin^2 \Gamma \propto E_{THz}^2$



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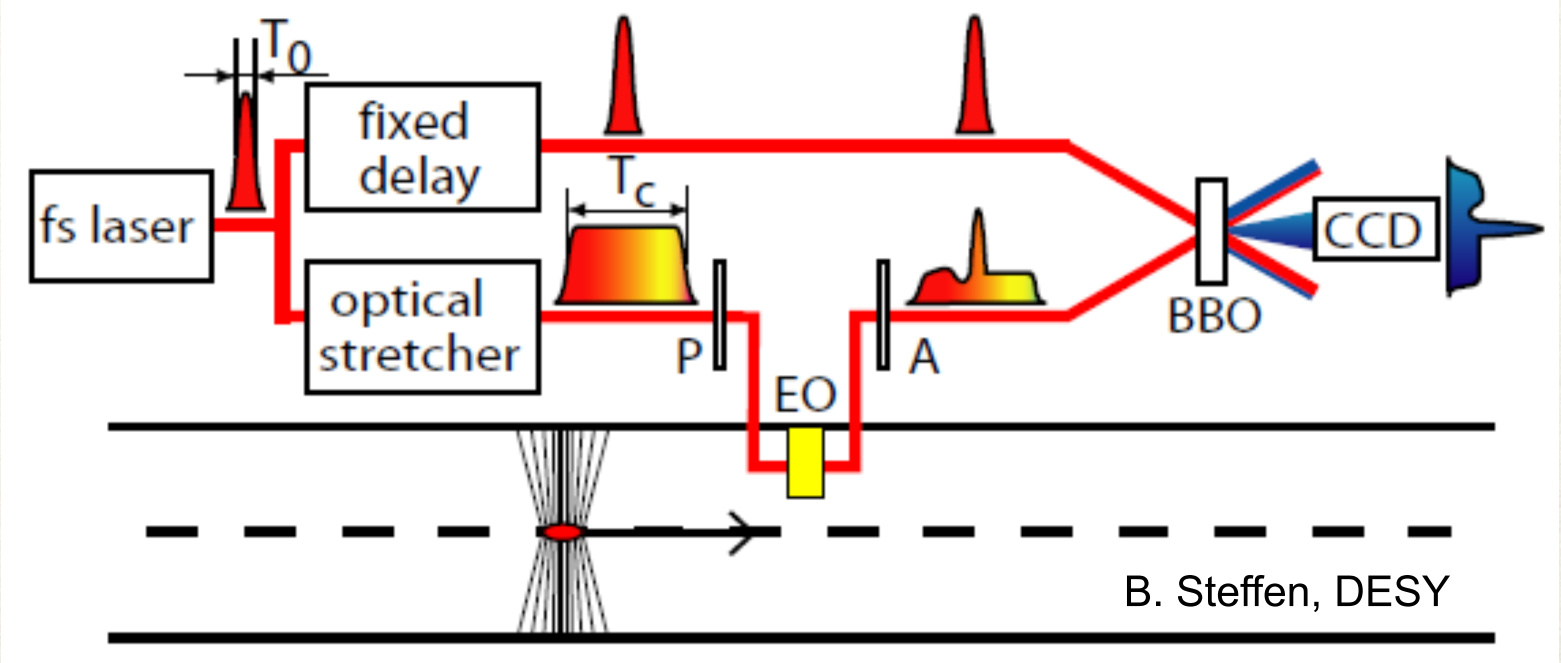
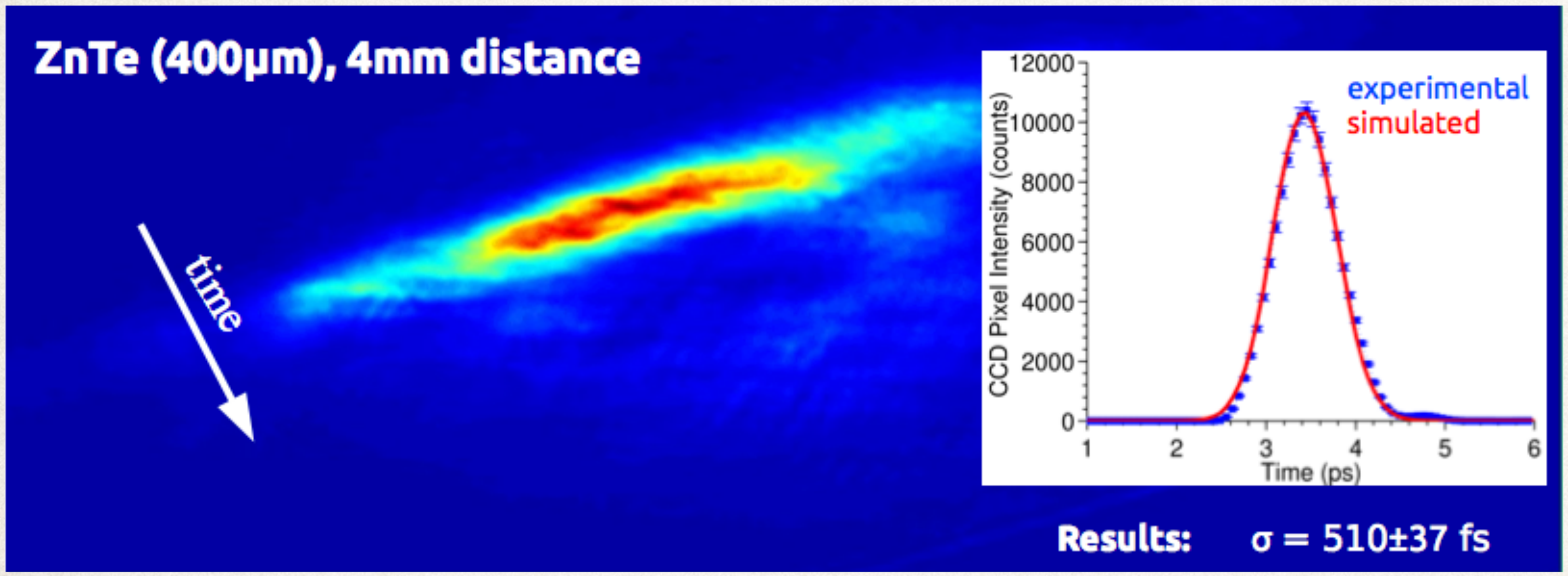
Encoding Techniques

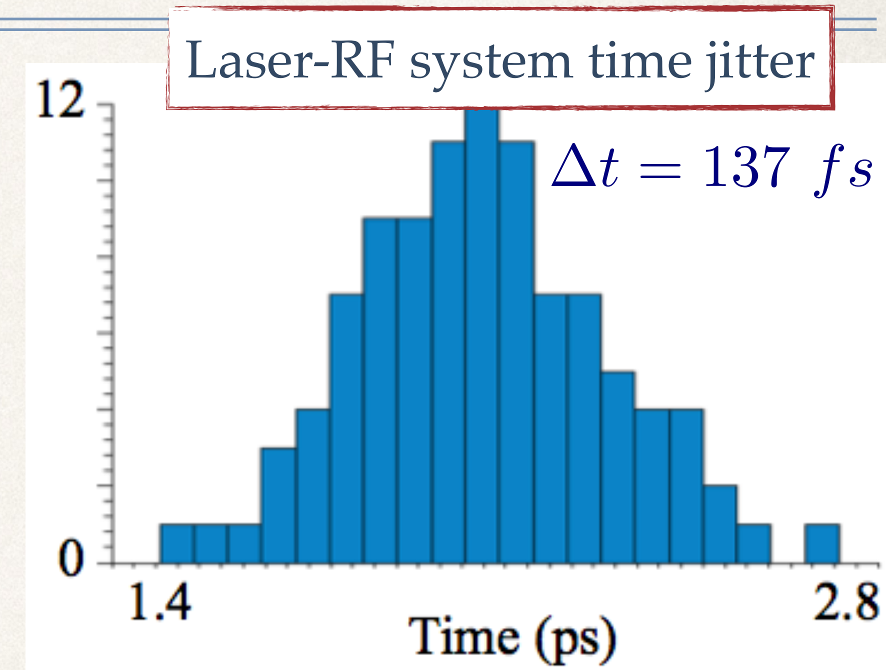
Temporal encoding

- A short laser pulse is split into two part: one part is stretched to several ps and sent through the polarizer P and the EO crystal in parallel with the Coulomb field of the electron bunch, the second part remains un-stretched
- In the EO crystal the stretched laser pulse acquires an elliptic polarization with an ellipticity which is proportional to the electric field of the electron bunch and has the same temporal structure
- The analyzer A turns the elliptical polarization into an intensity modulation, which is then sampled by the short pulse in a single-shot cross-correlator
- The two pulses overlap spatially, but since they are not collinear in the BBO crystal, there is a position dependent time delay between them
    - the temporal modulation of the EO pulse is transferred to spatial distribution of the SHG light
- Resolution: duration of the gate beam, thickness of the SHG crystal
    - 100 fs or slightly better
- low efficiency SHG process, approx. 1mJ laser pulse energy necessary



Example of Measurements





- EOS limited temporal resolution prevents its use for fs-scale electron beams, but not for timing measurement
- The position of signal, where laser crosses with crystal indicates the time of arrival of the electron beam
- The width of signal is related to its longitudinal profile

Courtesy of R. Pompili (SPARC_LAB)

Frequency domain techniques

Frequency-domain Techniques

- Frequency domain measurements use **Coherent Radiation** emitted by ultra-relativistic, ultra-short electron bunches (transition, diffraction, or synchrotron radiation).
  - A bunch emits coherently at wavelengths longer than the bunch length
- Coherent Radiation from short (sub-ps) relativistic electron bunches is a powerful diagnostic of electron bunches that drive FELs, plasma-based accelerators, advanced radiation sources
  - Non-intercepting radiation phenomena
  - Single-shot diagnostics
- The technique gives some hints on the bunch length and with some assumption one can retrieve the charge density using the dispersion relation to reconstruct the (lost) information on the complex part of the radiated field.
  - The method can also serve as a **bunch length monitor** (relative measurement)

Radiation from an Electron Bunch

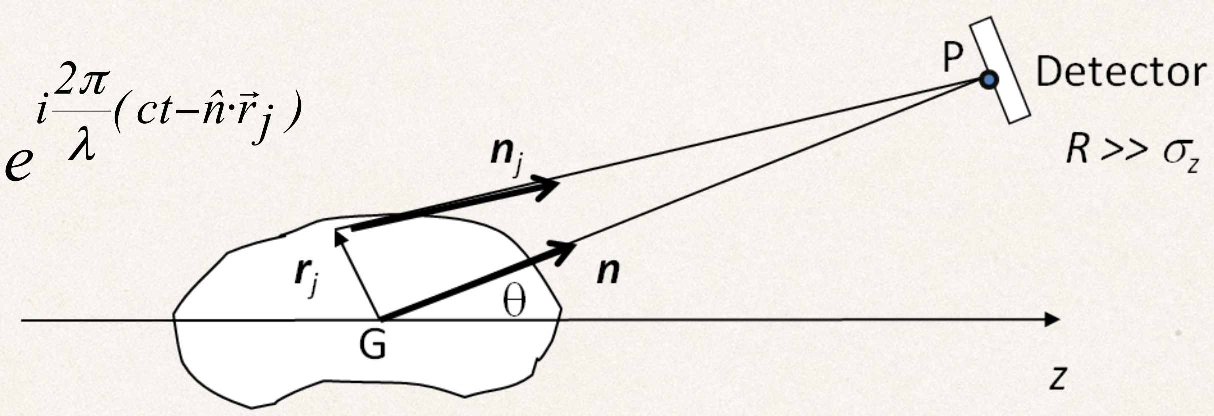
For an electron bunch of arbitrary shape, the time delay between electron j and the reference electron in G is

$$\Delta t_j = \frac{R_j - R}{c}$$

The basic assumption that all electrons contribute to the same electric field pulse in time-domain except for a time delay defines a far-field condition: $\boldsymbol{n}_j$ and $\boldsymbol{n}$ are nearly parallel.

The **time delay** leads to a **phase shift** between the em waves emitted from electron *i* and the reference electron in *G*.

$$E_j = e^{i\frac{2\pi}{\lambda}(ct - \hat{n}\cdot\vec{r}_j)}$$



$$I(\omega) = I_{sp}(\omega)\sum_{j,k=1}^{N} E_j E_k^* = I_{sp}(\omega)\left(N + \sum_{j\neq k}^{N} e^{i\frac{\omega}{c}\hat{n}\cdot(\vec{r}_j - \vec{r}_k)}\right)$$

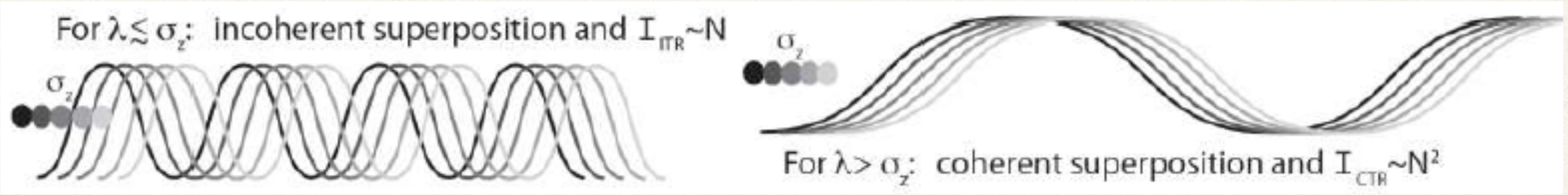
Coherent Radiation Theory

The total radiation intensity emitted by a bunch of N electrons is given by

$$\frac{d^2 I}{d\omega\Omega} = \frac{d^2 I_{sp}}{d\omega\Omega}\left(N + N(N-1)F(\omega)\right)$$

in which $d^2I_{sp}(\omega)/d\omega d\Omega$ is the radiation intensity emitted by a single particle and $F(\omega)$ the bunch form factor.

The phase difference depends on particle inter-distance and the emitting angle.

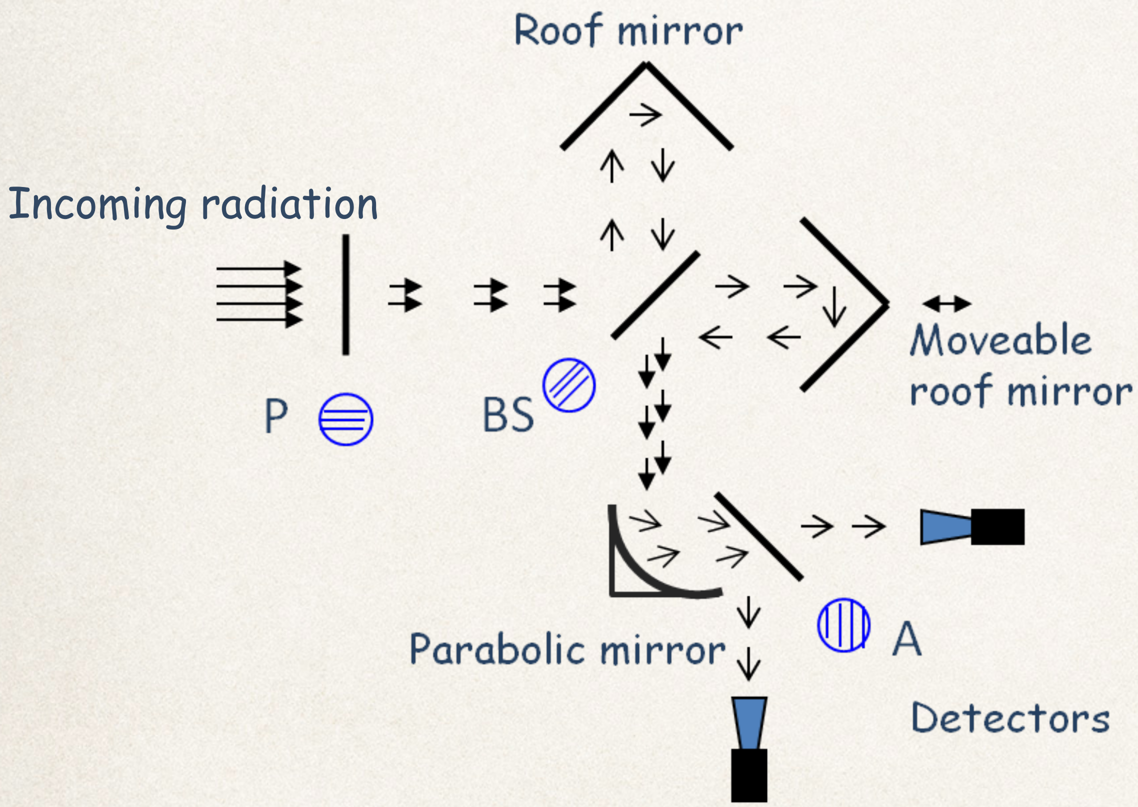


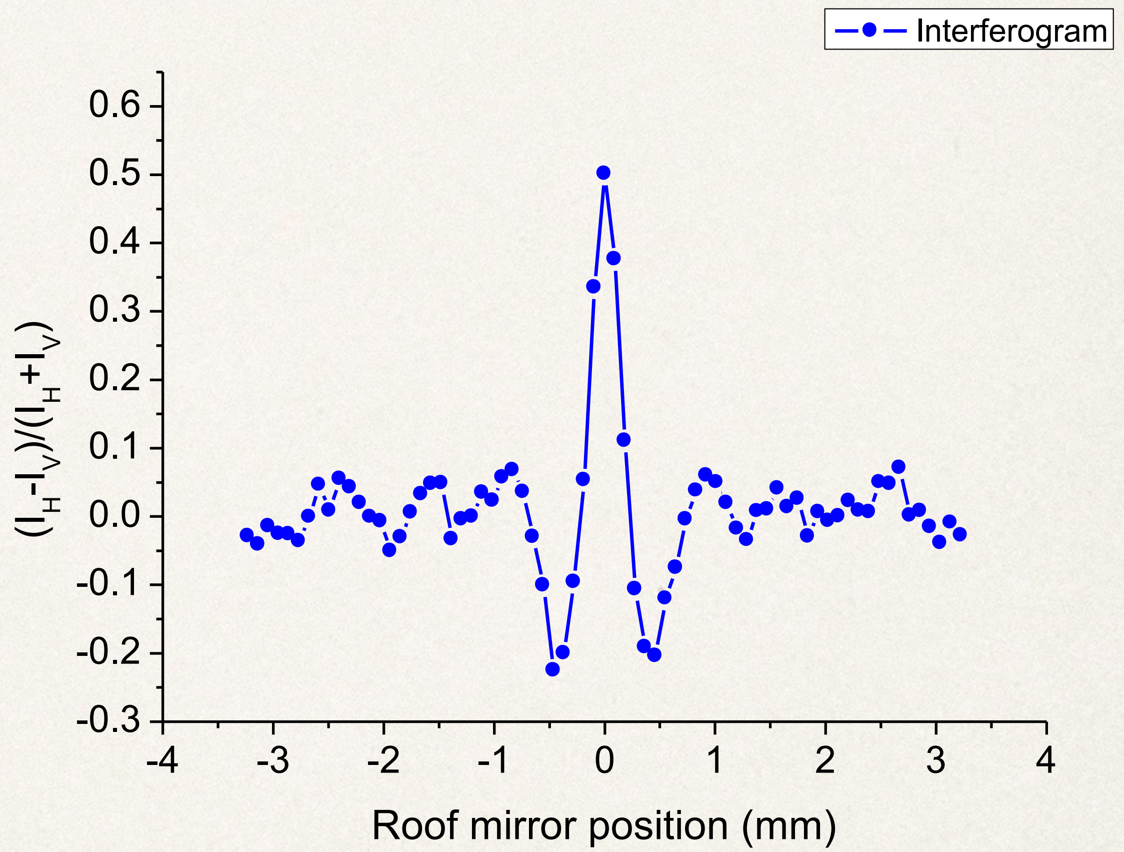
Coherent emission dominates on incoherent one at wavelengths equal or longer than the bunch length. Measuring the coherent spectrum it is possible to reconstruct the bunch length and even its longitudinal structure

$$F(\omega) = \left|\int_{-\infty}^{\infty} S(z) e^{i\omega z/c} dz\right|^2$$

Autocorrelation Measurement

Michelson, Rayleigh: The interference pattern of a two-beam interferometer, obtained by altering the path difference between the two beams, is the Fourier transform of the radiation passing through the interferometer





$$\delta(\tau) = \frac{\int_0^\infty I(\omega)\cos(\omega\tau)d\omega}{\int_0^\infty I(\omega)d\omega}$$

Bunch Length Retrieval

$$\left(\frac{dI}{d\omega}\right)_{measured} \Rightarrow \frac{dI}{d\omega} \Rightarrow \left|F(\omega)\right| \Rightarrow F(\omega) \Rightarrow S(z)$$

Beam line transmission, instrument response

Single-electron spectrum, bunch charge

Phase reconstruction

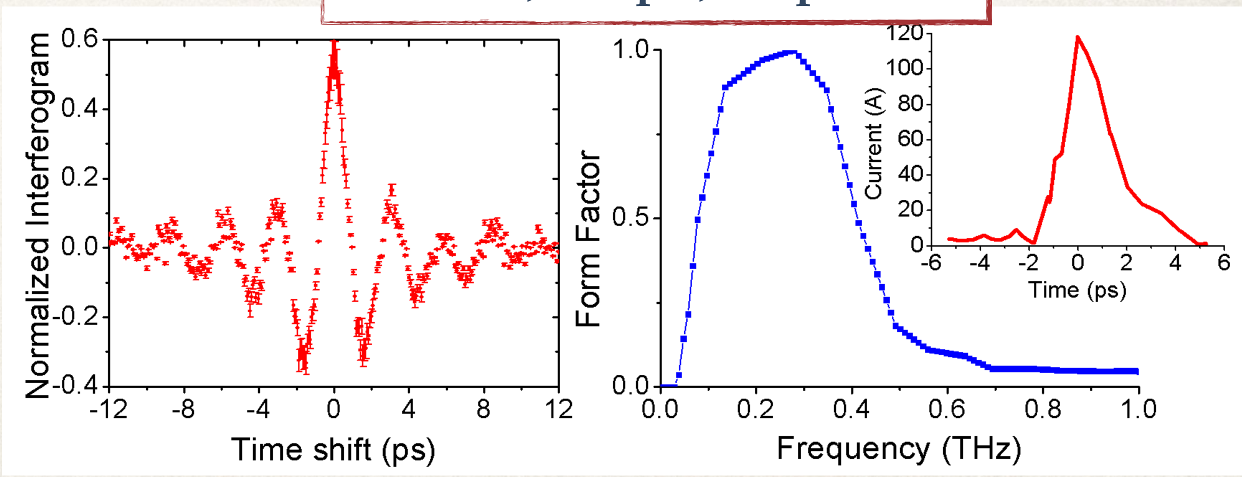
Inverse Fourier transform

- No direct reconstruction of the longitudinal profile from an inverse Fourier transform of the coherent radiation (CR) spectrum
  - a CR measurement only yields the amplitude and not the phase
  - in practice, the CR spectrum can only be measured over a limited range of frequencies
- No information on bunch asymmetry

$$S(z) = \frac{1}{\pi c}\int_0^\infty \sqrt{F(\omega)}\cos\left(\frac{\omega z}{c}\right)$$

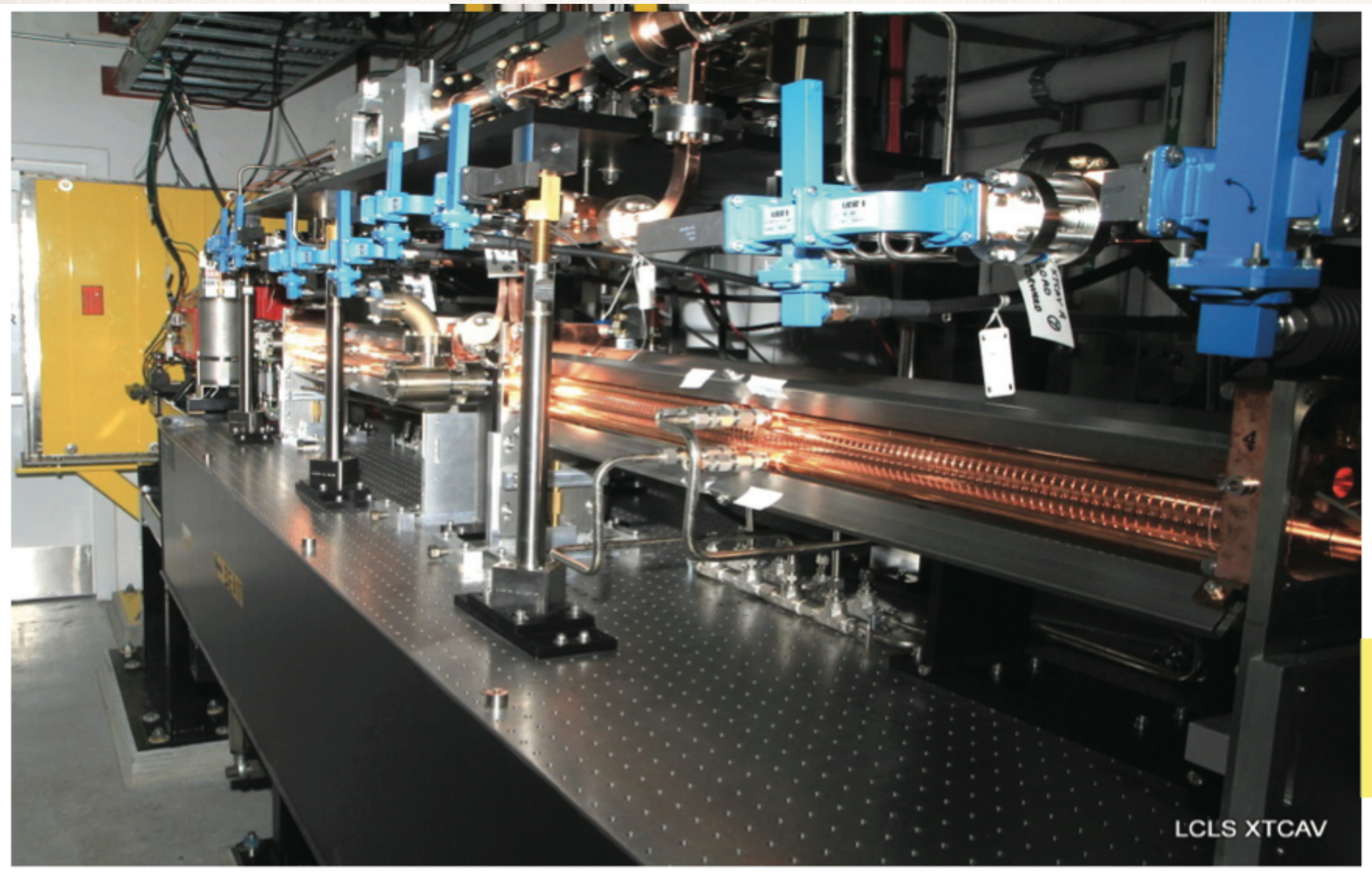
- Even with symmetric bunches, no unique bunch profile
  - the phase information is missing
  - infinite distributions give the same autocorrelation function

120 MeV, 300 pC, 1.4 ps (rms)



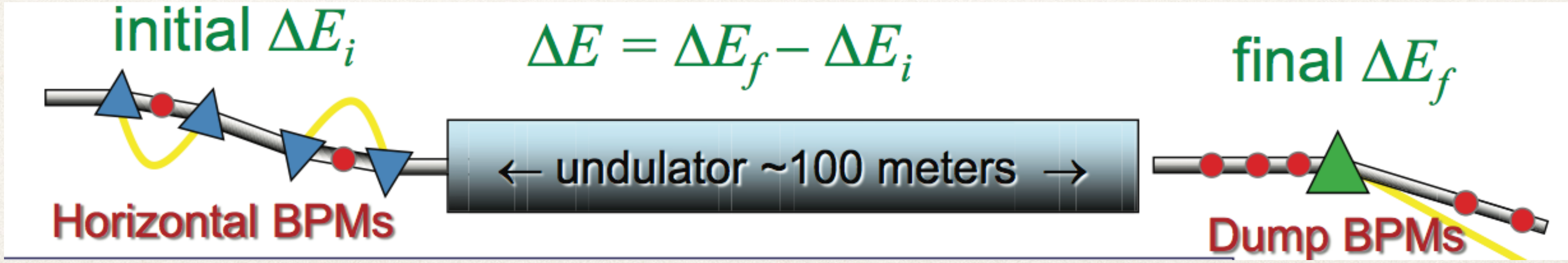
Down to fs and sub-fs bunch length

Time-resolved X-ray diagnostics



X-band TCAV	
Frequency	11.424 GHz
Max kick	48 MV @ 40 MW

	14 GeV	4.3 GeV
Calib factor	42	136
Temporal resolution	3 fs	1 fs



V. A. Dolgashev et al., PRST-AB **17**, 102801 (2014)
Y. Ding, FEL 2013

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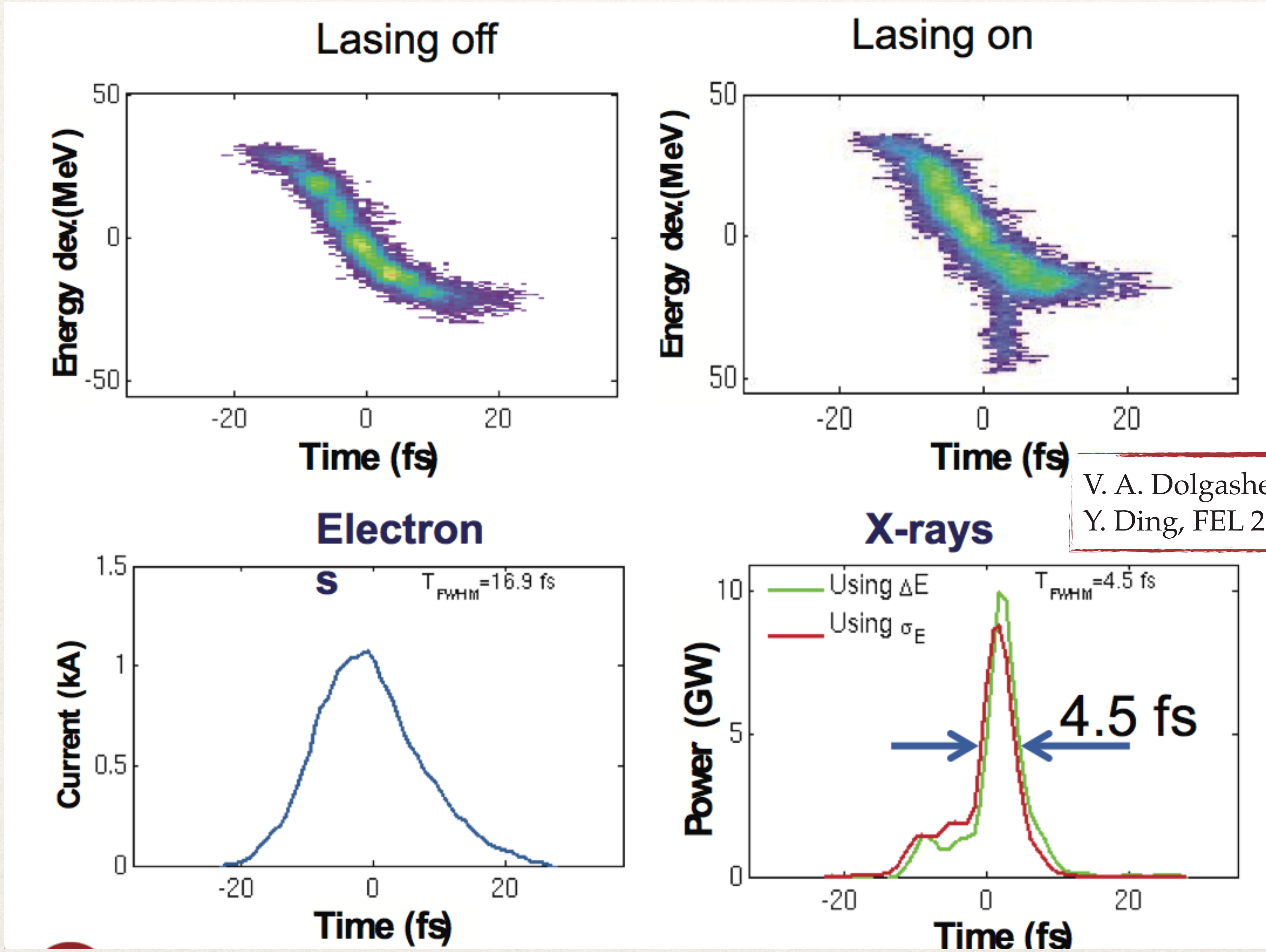
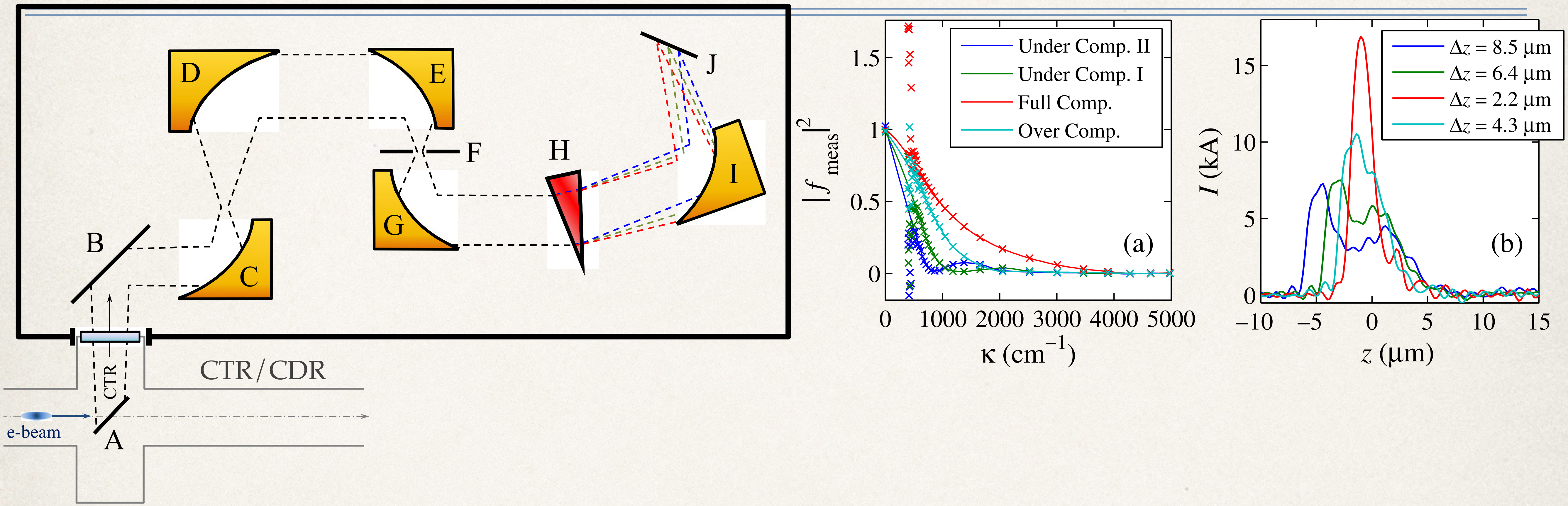


V. A. Dolgashev et al., PRST-AB **17**, 102801 (2014)
Y. Ding, FEL 2013

Single-shot THz Spectrometer



- **KRS-5** (Thallium Bromo-Iodide crystal): flat transmission and strong dispersion in the 0.6 μm - 50 μm range
- Linear pyroelectric array consisting of 128-elements: Pixels are 60 μm wide and 500 μm tall with a 100 μm pitch
  - Calibration is an issue

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T. J. Maxwell et al., PRL 111, 184801 (2013)

Plasma-based Deflector

Plasma-driven ultrashort bunch diagnostic

Irene Dornmair

Laser drives linear wakefields => injecting the electron beam off-axis in y, it experiences a streaking field

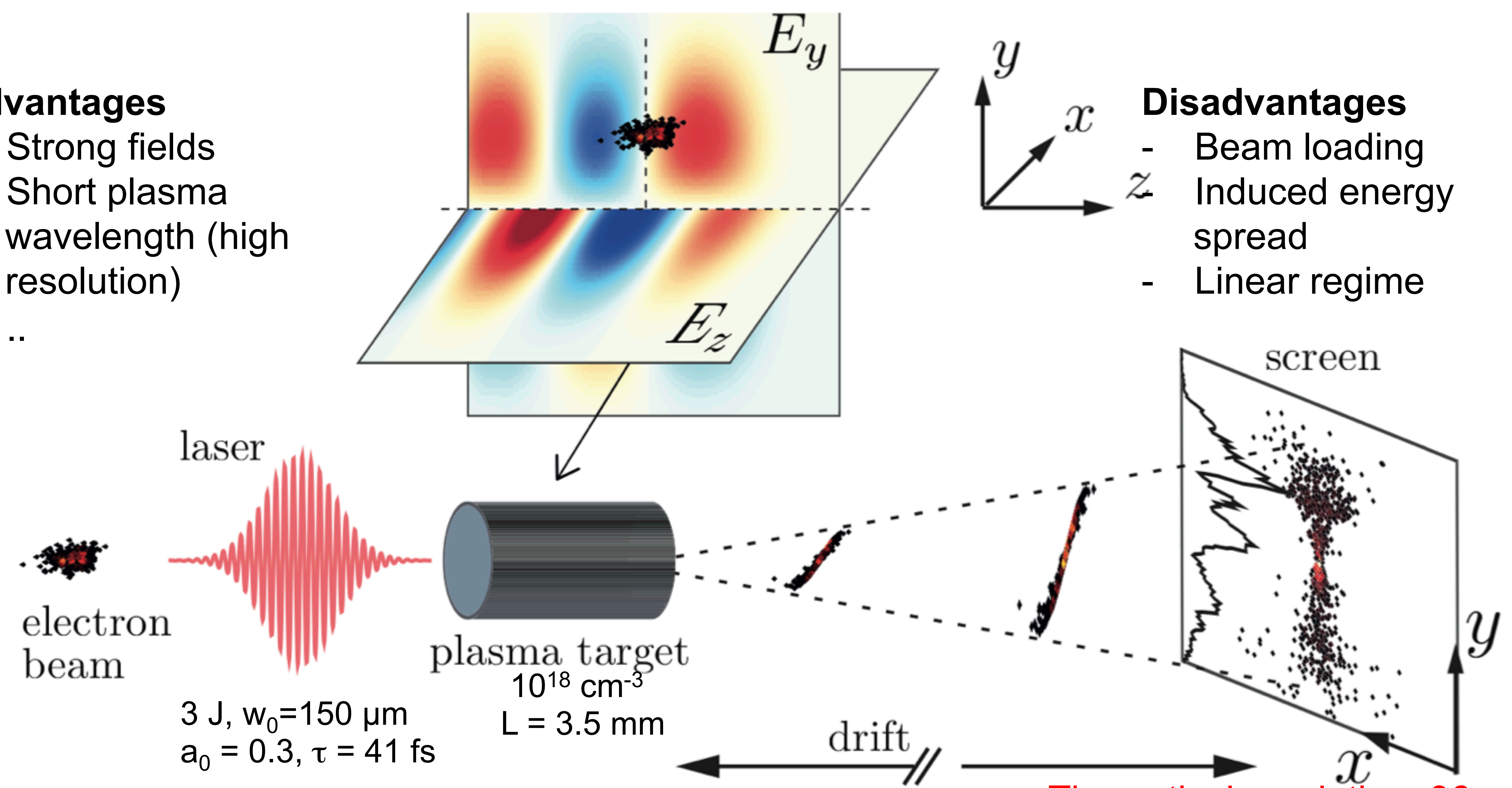
PIC simulations

Advantages

- Strong fields
- Short plasma wavelength (high resolution)
- ..

Disadvantages

- Beam loading
- Induced energy spread
- Linear regime

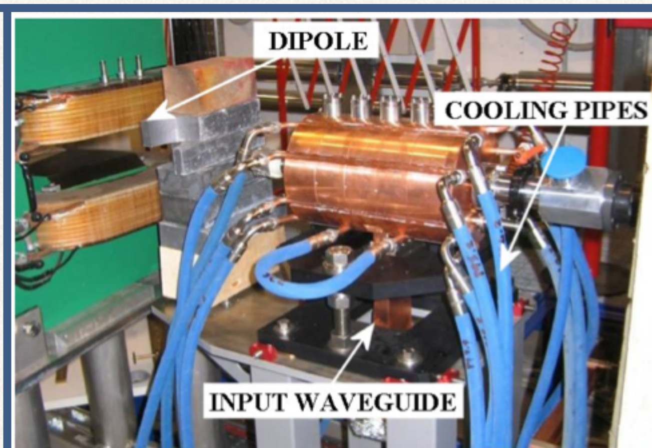


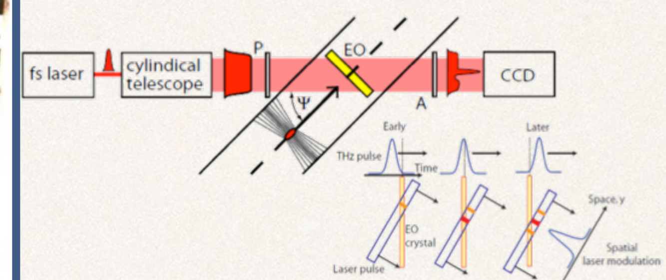
Theoretical resolution: 96 as

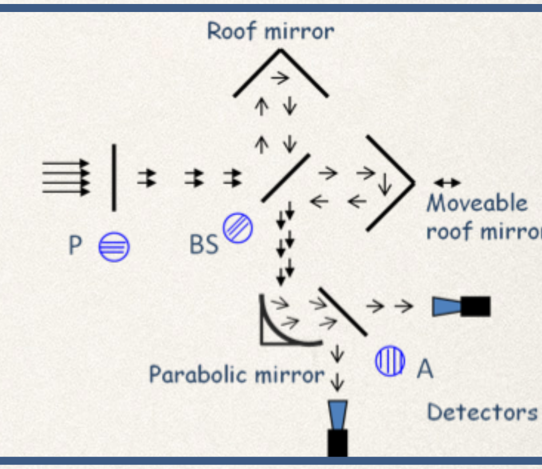
Summary

- **RF deflecting cavity** is a very **well known and established diagnostic** device
  - **fs-scale** resolution is achievable operating at **higher frequencies** (e.g. X band)
  - High deflecting voltage, but also **good emittance**
- An **RFD**, together **with a dispersive system**, allows to measure all the needed beam parameters, i.e. **bunch length, slice emittance, energy and slice energy spread**
  - It is a **self-calibrating** system
  - It is an **intercepting** device
- The **EO techniques** are inferior to the RF deflecting cavities in terms of time resolution but have the considerable advantage of being "**non-destructive**"
- **EO techniques** allows the measurement of **timing jitter**
- **Coherent Radiation** based diagnostics allows for **fs scale resolution**, are **not-invasive**, but suffers frequency domain problems, i.e. knowledge of frequency spectrum, and phase reconstruction methods

Summary







Time domain techniques	Absolute single shot determination of bunch length and shape, because directly sensitive to the longitudinal charge distribution, allow to measure arrival time and jitter intercepting	
Frequency domain techniques		Easy to set up, multi-shot, sensitive to bunch length change, therefore more powerful as online bunch compression monitor, non-intercepting, to phase retrieval methods