5th Topical Workshop on Beam Diagnostics
23 - 24 March, 2015
Son Caliu Hotel, Palma

RF techniques for ultra-short bunches

Enrica Chiadroni (INFN-LNF)

March 24th, 2015

Outline

- **Motivation**
- **Principle of RF-based longitudinal beam diagnostics**
- **Time resolved measurements**
  - Absolute bunch length, current profile, slice emittance
    - Resolution limits, impact of jitters
  - Longitudinal Phase Space Distribution
- **Examples of RF deflecting cavities**
  - Standing and Traveling Wave
  - S/X band
- **Special applications**
  - Time-resolved X-ray diagnostics
- **Conclusion**

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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

$$\varepsilon_n \approx 1\ mm\ mrad$$

- low energy spread

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

- high peak current
  - **ultra-short electron bunches**

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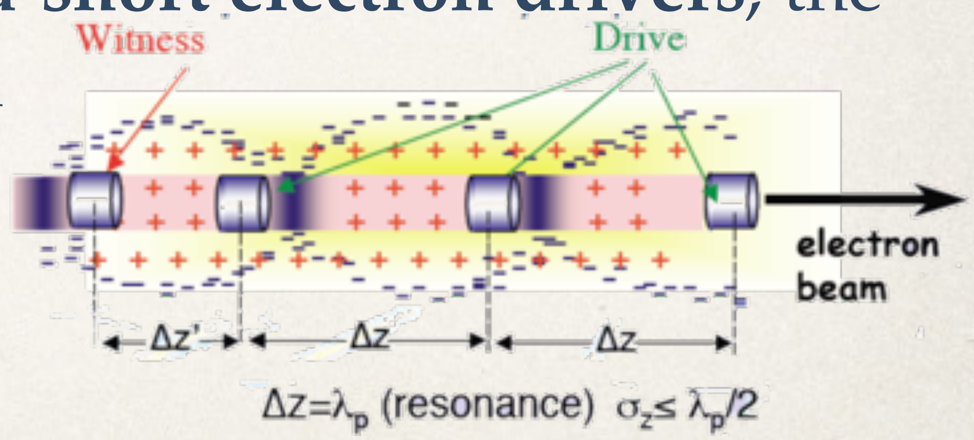
Motivation

- 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
- In particular, **for PWFA driven by trains of ultra-short electron drivers**, the measurement and control of bunches length and time inter-distance will allow to inject the witness bunch at the phase of accelerating field



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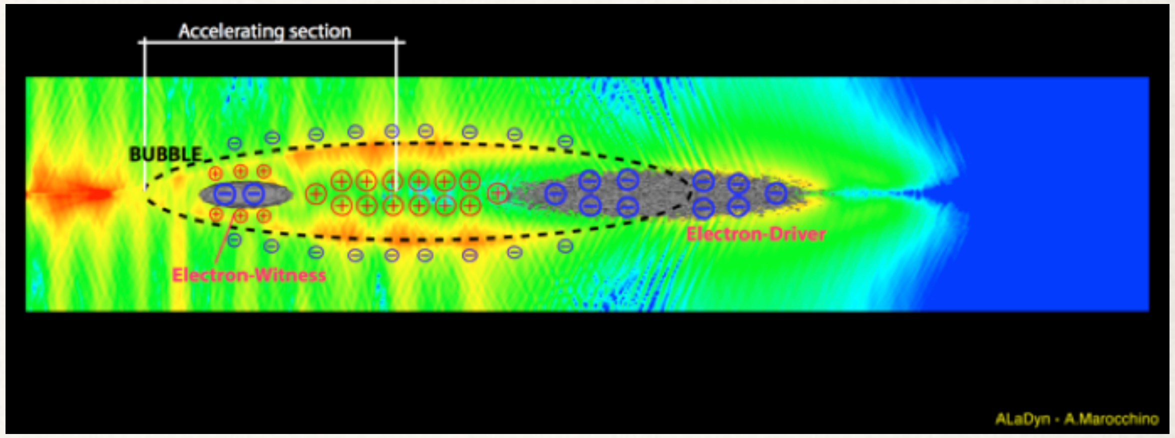
What does "ultra-short" bunch mean?

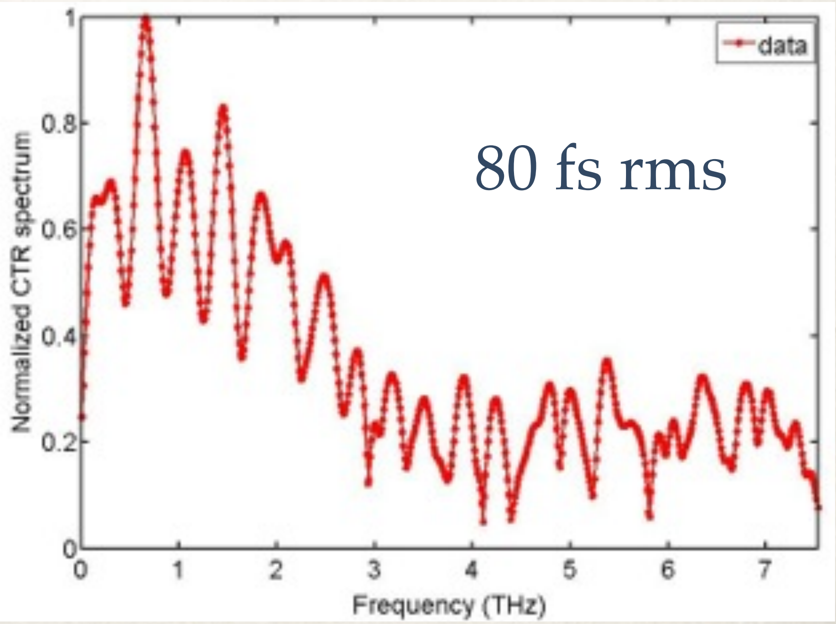
- **Plasma-based accelerators**
  - The characteristic scale length of the accelerating field, i.e. the plasma wake, is the plasma wavelength

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



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

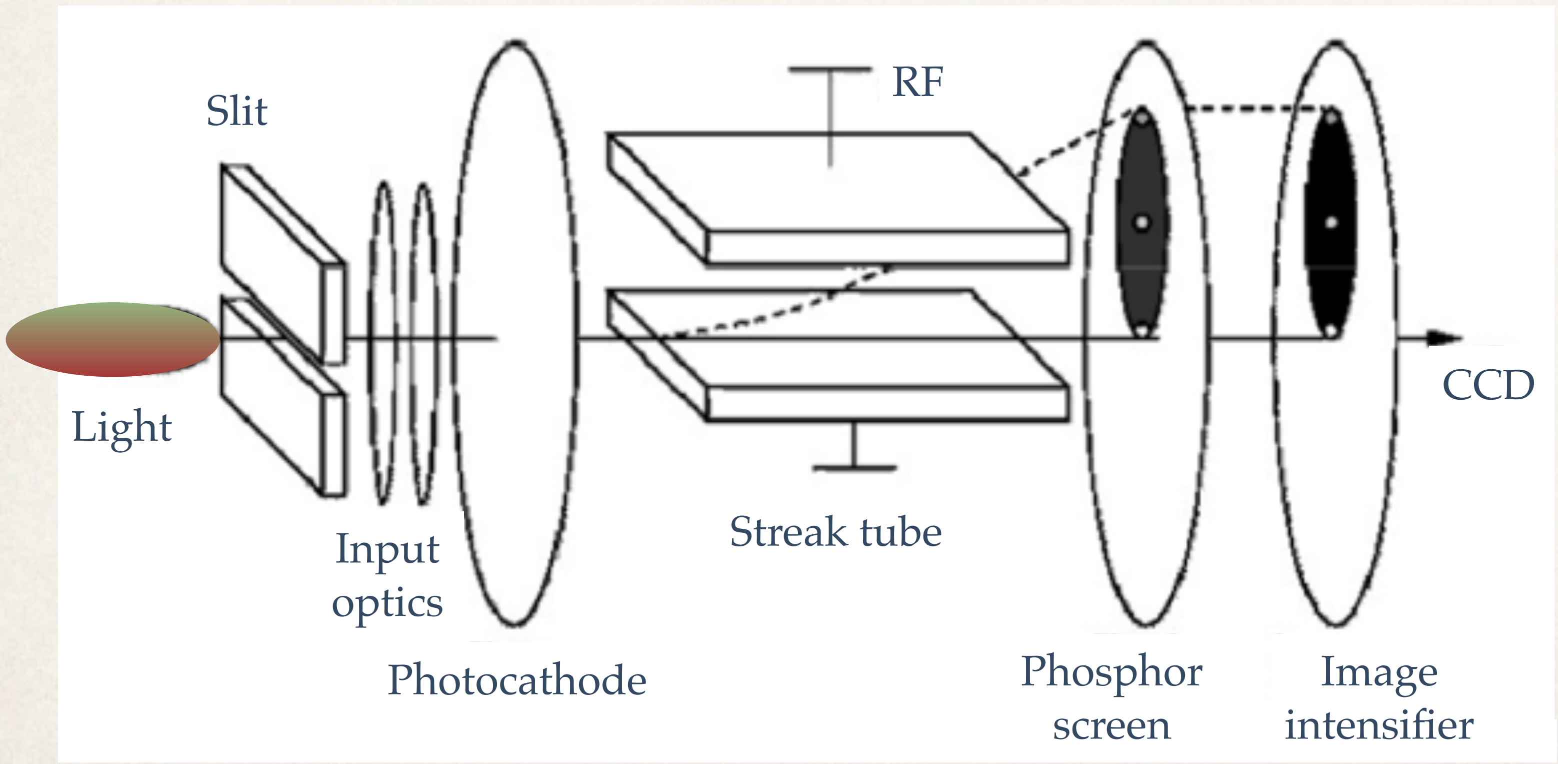
- **Linear colliders**
  - Minimize hourglass effect: transverse beam sizes vary with beta function
    - not all particles collide at minimum of transverse beam size
      - luminosity degradation
    - $\beta_y \geq \sigma_z$ ~ **sub-ps scale**



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

Streak camera

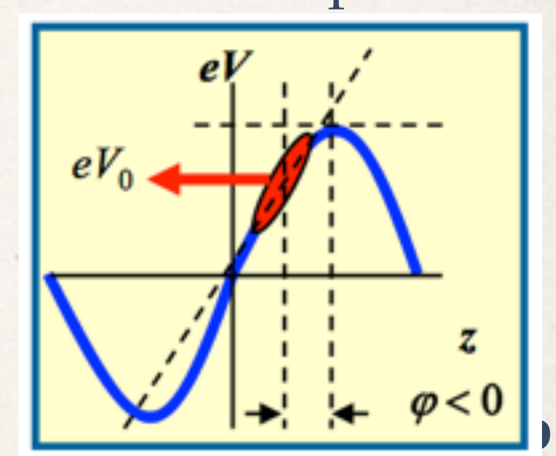
- Sub-ps down to fs scale is well beyond the range of applicability of conventional streak cameras
  - a photocathode converts radiation into electrons by photoemission,
  - electrons are accelerated in a cathode ray tube and then "streaked" transversely by a DC electric field.
  - The deflected electrons then impinge upon a phosphorescent surface or detector.



- **Resolution limited** to **200-300 fs** FWHM

Radio-Frequency based Diagnostics

- **An RF deflecting field can directly 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 (*SLAC-PUB-135, Aug. 1965*)
- 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 opposite sign, thereby producing a **strong correlation longitudinal position and energy**



  - **RF structures that operate in an electromagnetic mode similar the TM110 mode of a cylindrical pillbox**, and delivers a transverse momentum kick to the electron beam
    - **strong correlation between longitudinal position and transverse angle**

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Principle of an RFD cavity

- Let's consider an instantaneous **sinusoidal transverse voltage** imparted to the beam **followed by a drift** of length L

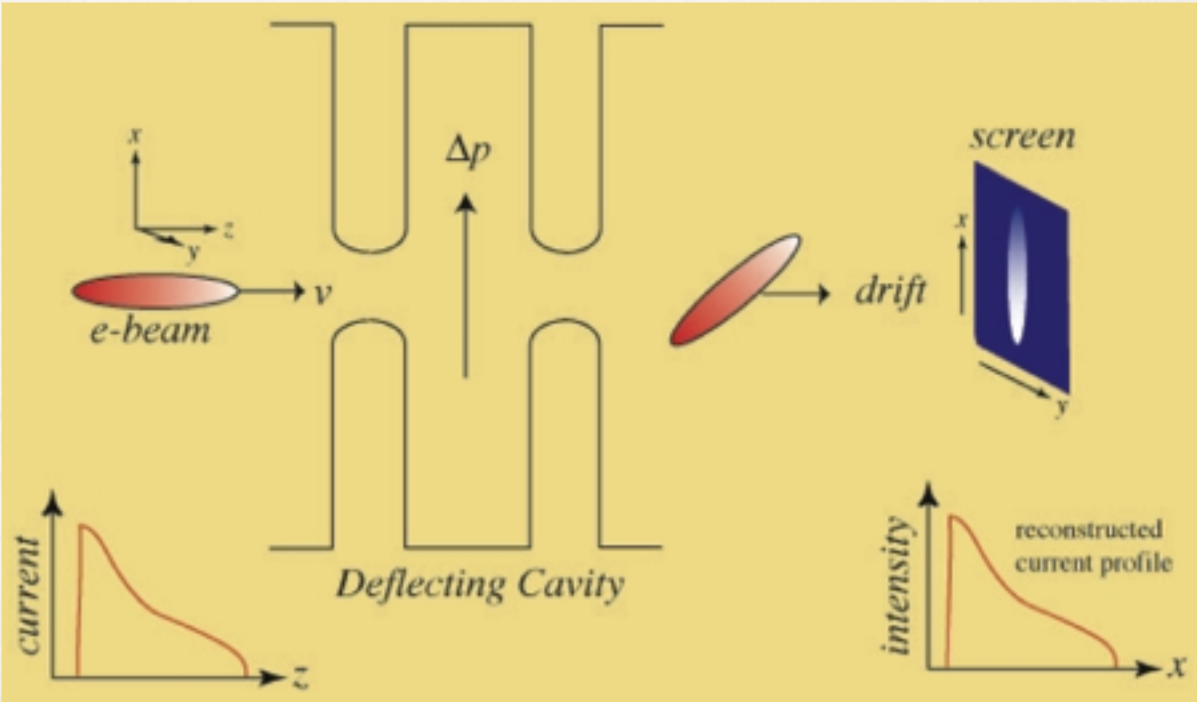
$$V(\psi) = V_0 \sin(\psi)$$

V_0 is the amplitude of the deflection

- The **y-z correlation** given by the deflection and the drift can be written in matrix formalism

$$\begin{pmatrix} y \\ z \end{pmatrix} = \begin{pmatrix} \hat{Q} \\ 0 \end{pmatrix} + \begin{pmatrix} 1 & \hat{M} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ z_0 \end{pmatrix}$$

y_0 and z_0 are the particle coordinates at the screen when $V_0 = 0$;

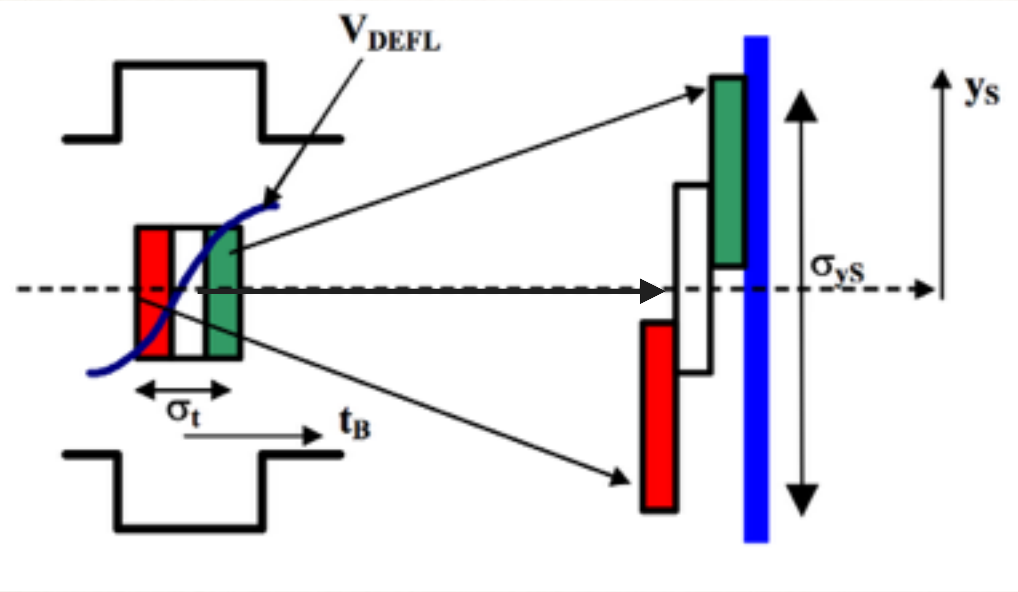


R. J. England, PhD Thesis "Longitudinal Shaping of Relativistic Bunches of Electrons Generated by an RF Photoinjector"

Principle of an RFD cavity

$$\hat{Q} = \frac{eV_0}{p_0 c}\sqrt{\beta_d \beta_s}\sin(\psi_0)\sin(\Delta)$$

vertical deflection of the **beam centroid**, which **is not deflected if the beam is injected at the zero-crossing phase**, *i.e.* $\psi_0 = 0$



β_d , β_s beta functions at the deflector and screen

Δ betatron phase advance from the deflector to the screen

λ RF wavelength

$$\hat{M} = \frac{eV_0}{p_0 c}\sqrt{\beta_d \beta_s}\frac{2\pi}{\lambda}\cos(\psi_0)\sin(\Delta)$$

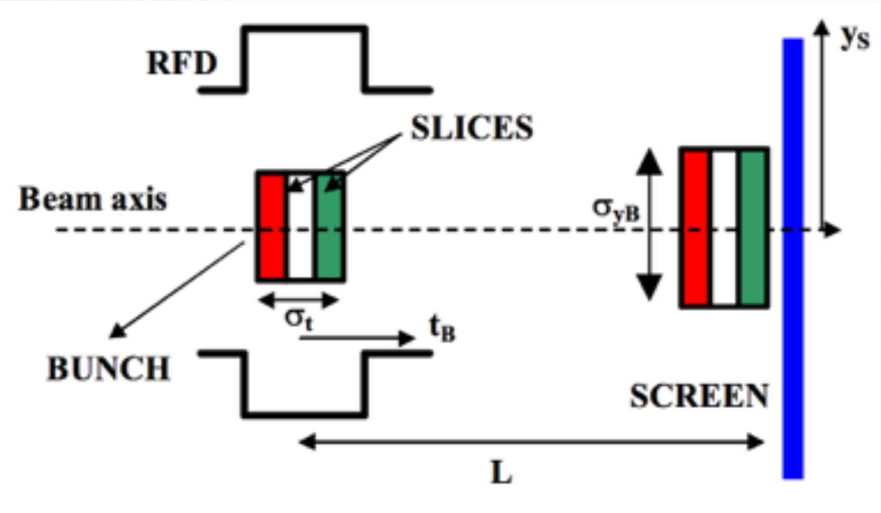
vertical expansion coefficient of the beam following the drift

Principle of an RFD cavity

If the beam were a wire, i.e. zero vertical size, the contribution to the vertical beam size due to the deflection would be given by

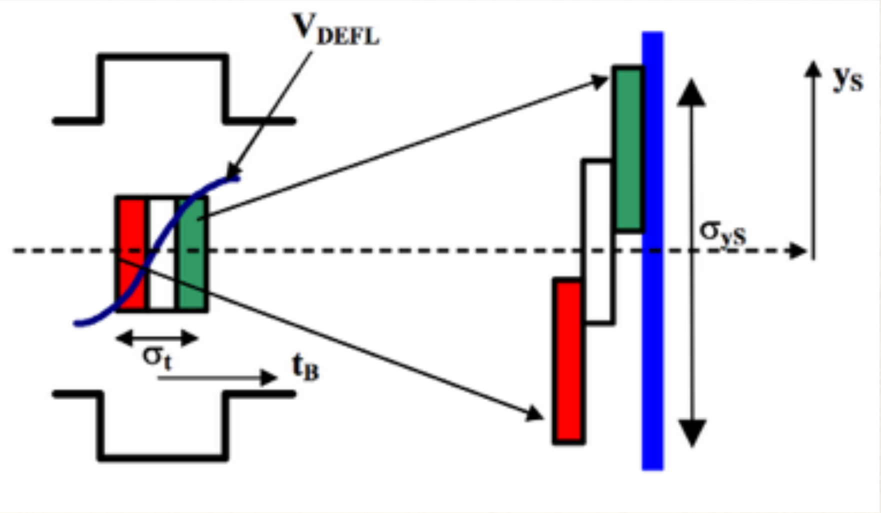
$$\sigma_{def} = \hat{M}\sigma_z = \frac{eV_0}{E}\sqrt{\beta_d\beta_s}\sin(\Delta)\frac{2\pi}{\lambda}\sigma_z = \frac{eV_0}{E}L\frac{2\pi}{\lambda}\sigma_z$$

However, $\sigma_{yB} \neq 0$ and the total beam size depends on the non-deflected vertical beam size



$$\sigma_{ys} = \sqrt{\sigma_{yB}^2 + \sigma_{def}^2}$$

$$\sigma_{ys} = \sqrt{2}\sigma_{yB}$$



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

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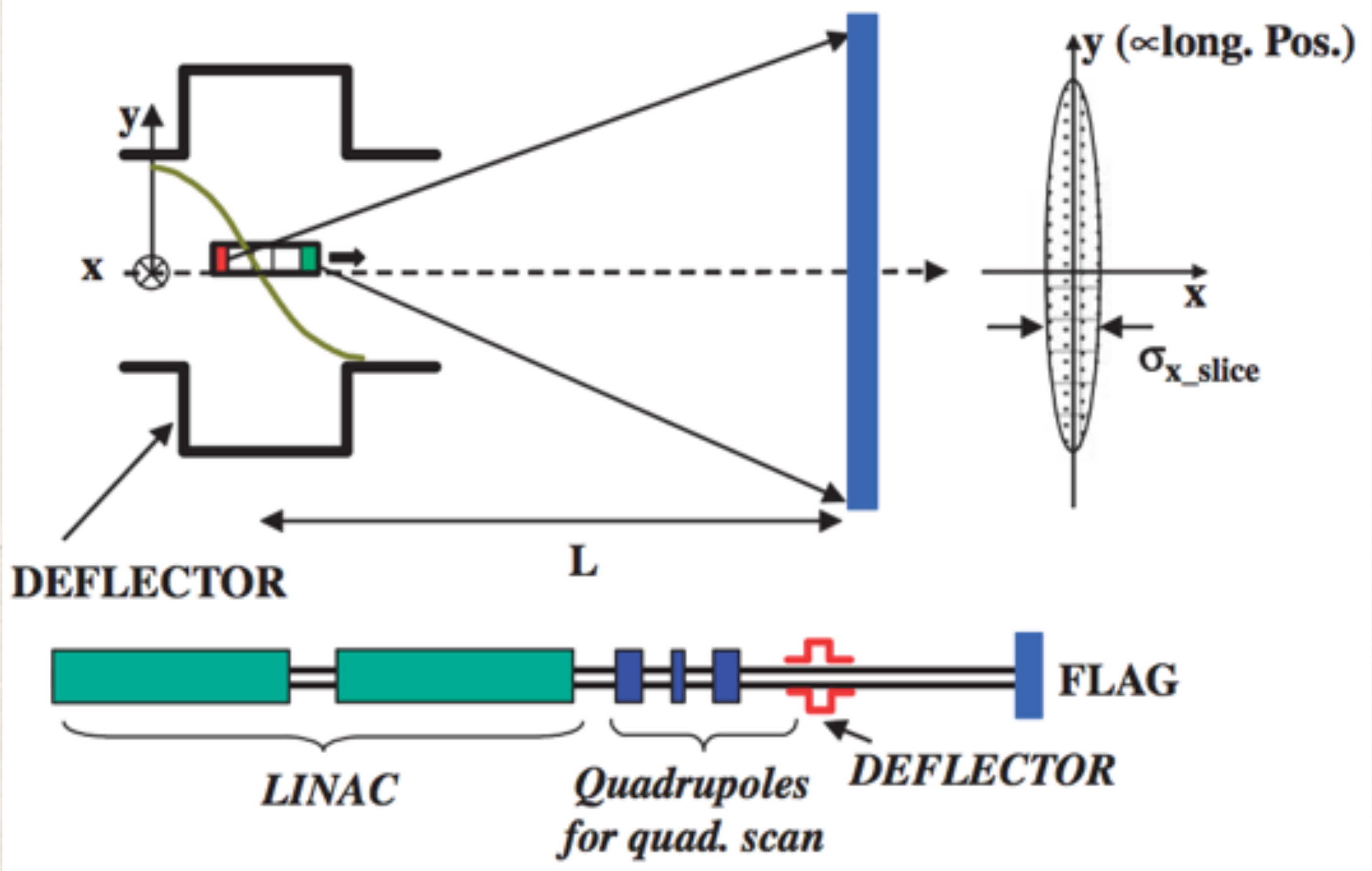
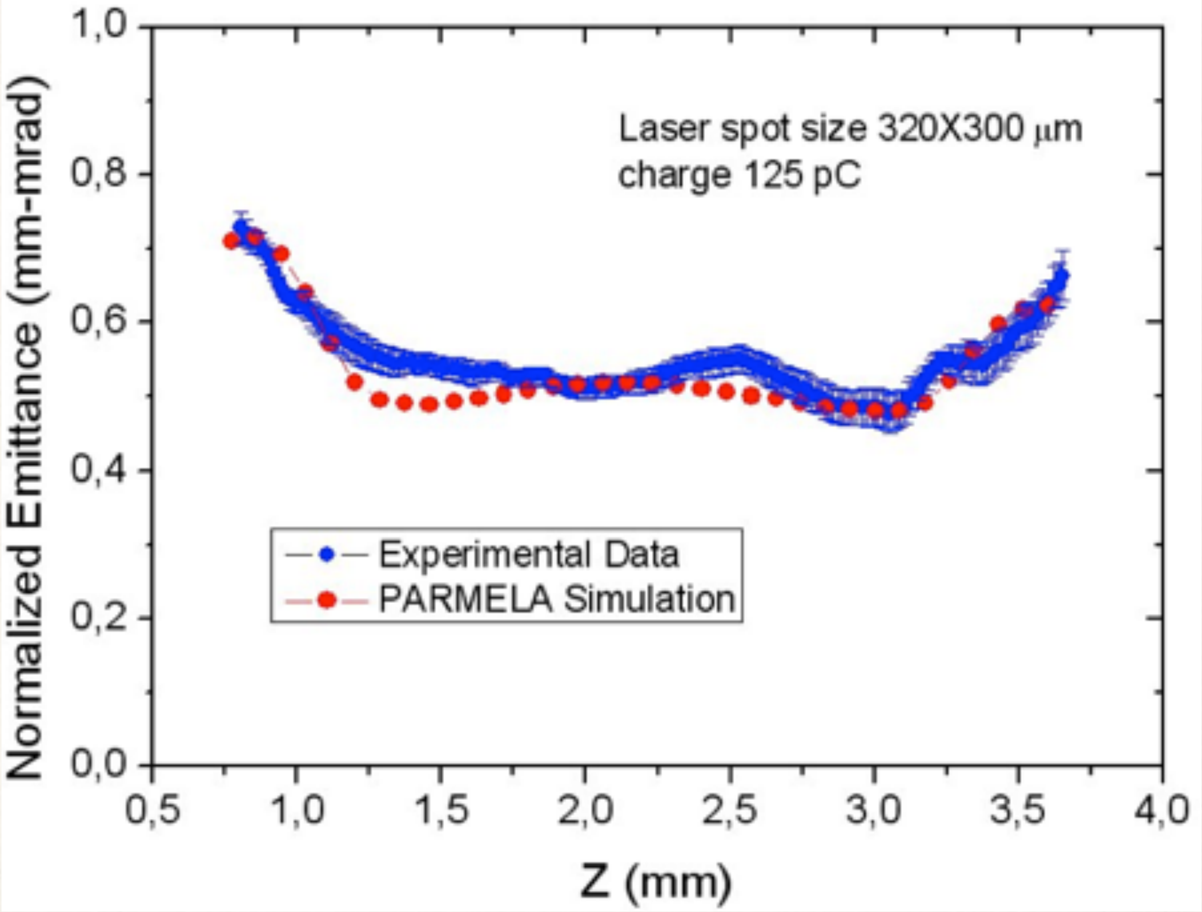
Time-resolved Measurements: Slice Emittance

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





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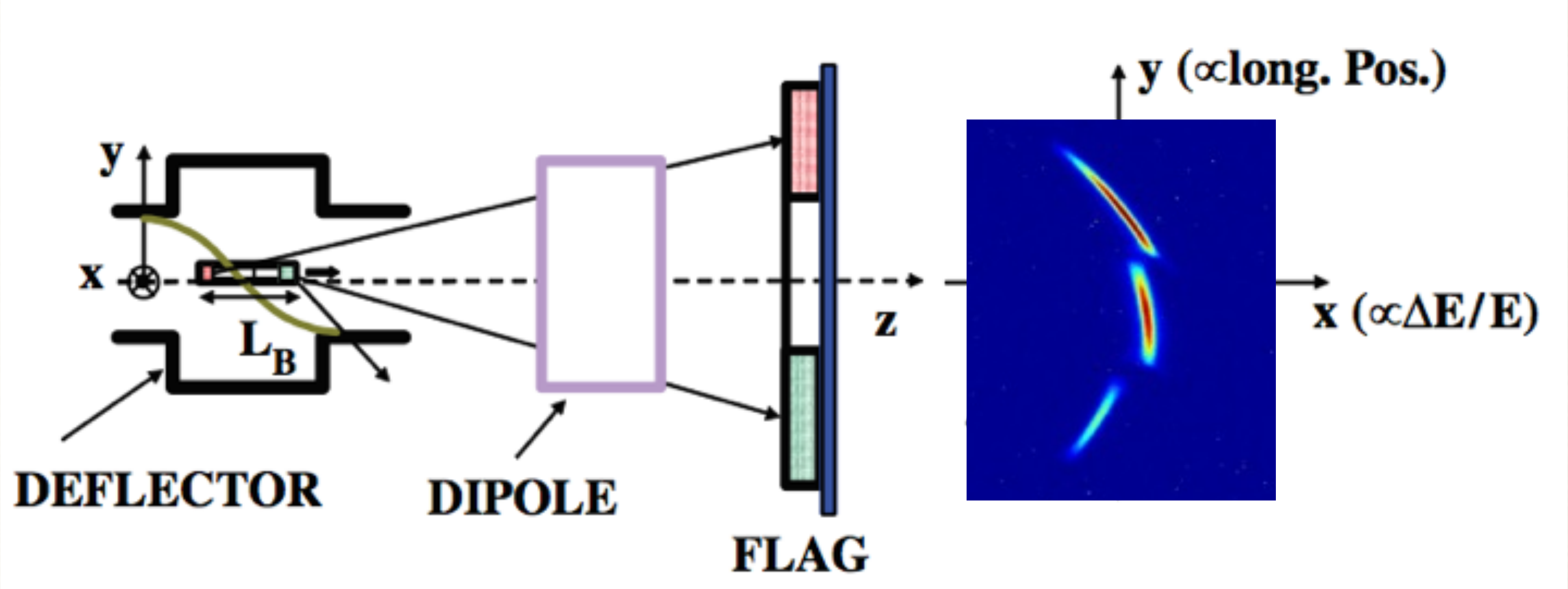
Longitudinal Phase Space Distribution

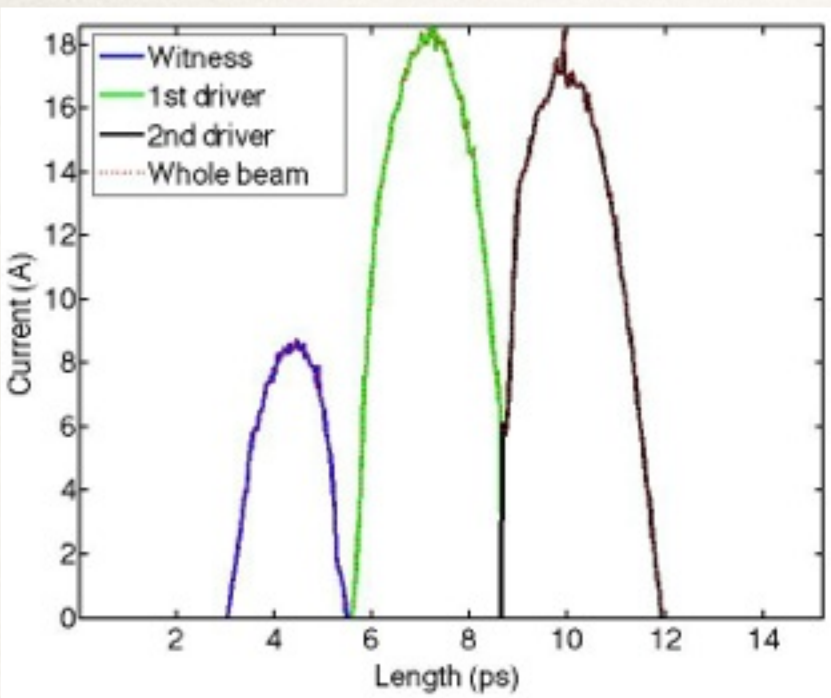
Together with a dispersive system, an RFD cavity allows the measurement of the longitudinal beam phase space distribution



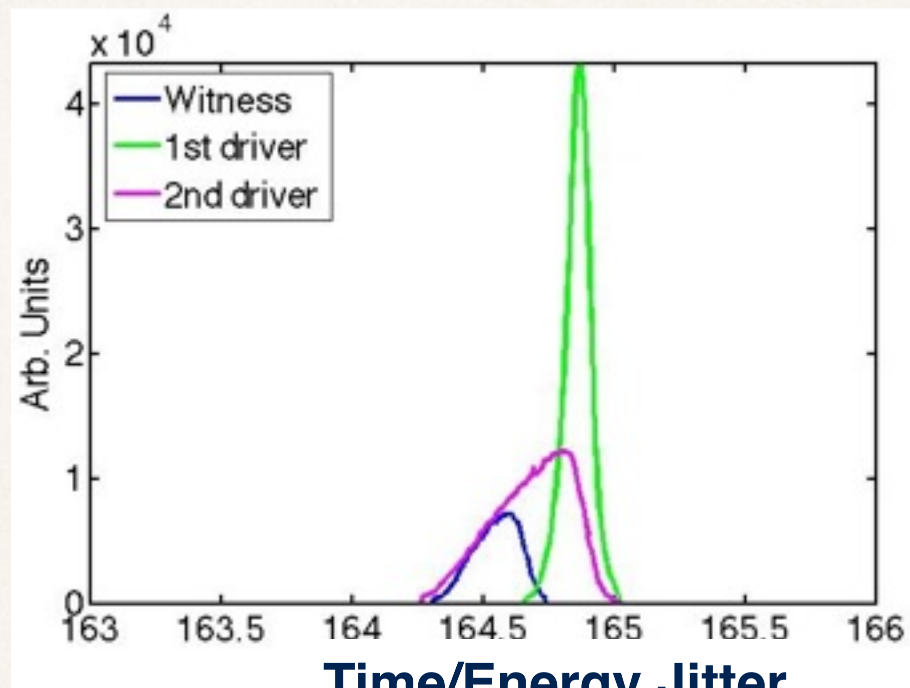
The slice energy spread can be extrapolated by slicing the beam vertically and measuring the beam thickness in energy as function of time

Longitudinal Phase Space Distribution

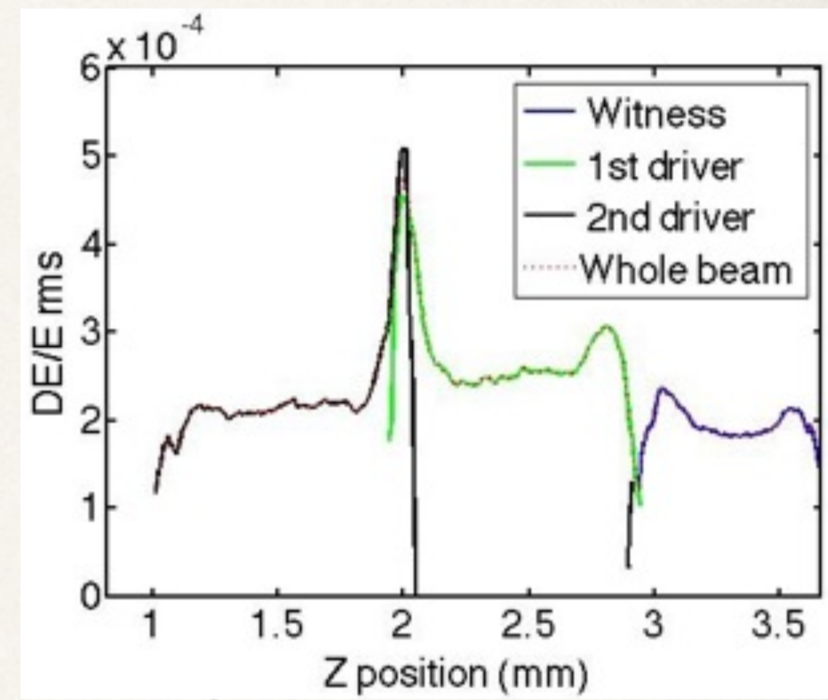
Current Profile



Energy Profile



Slice energy spread

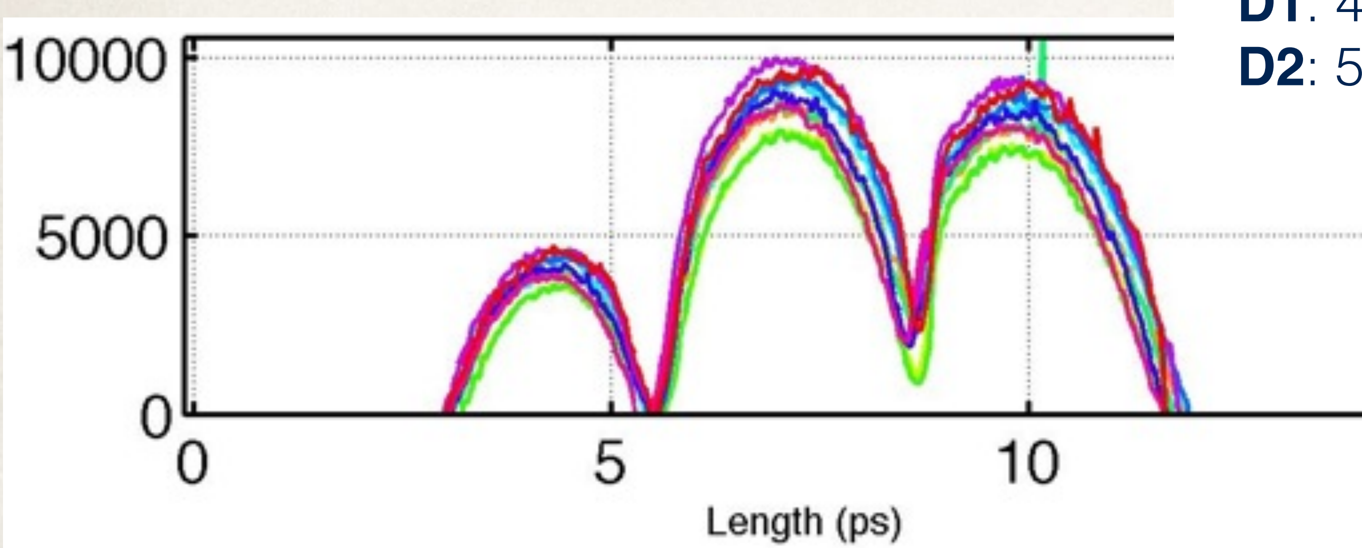


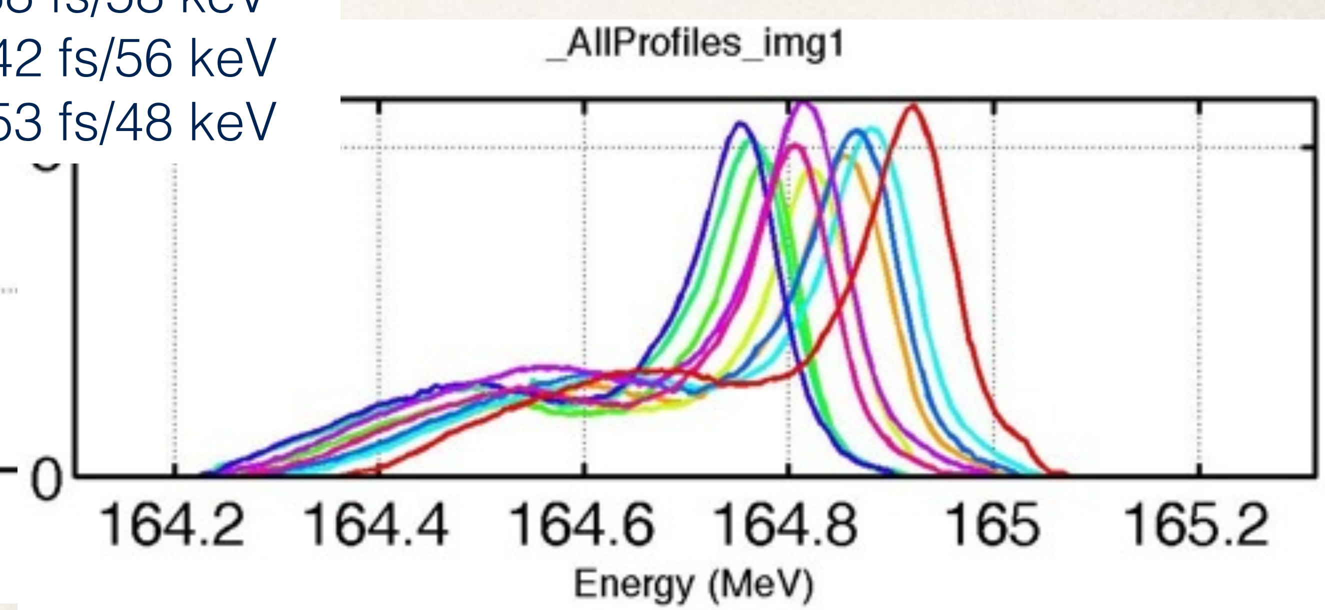
Time/Energy Jitter

W: 38 fs/58 keV

D1: 42 fs/56 keV

D2: 53 fs/48 keV





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

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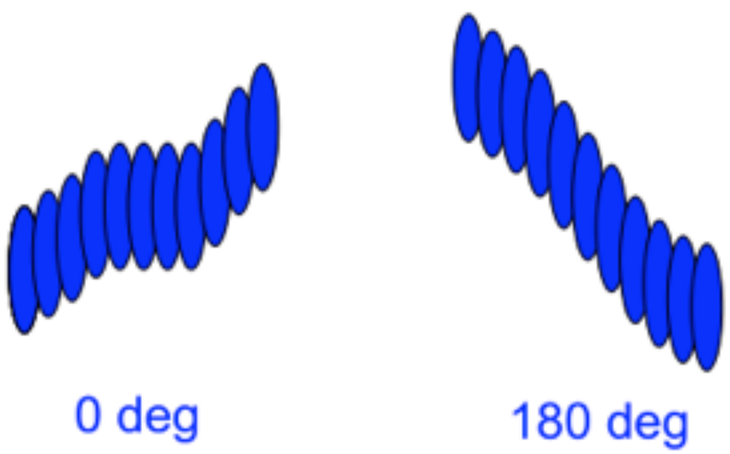
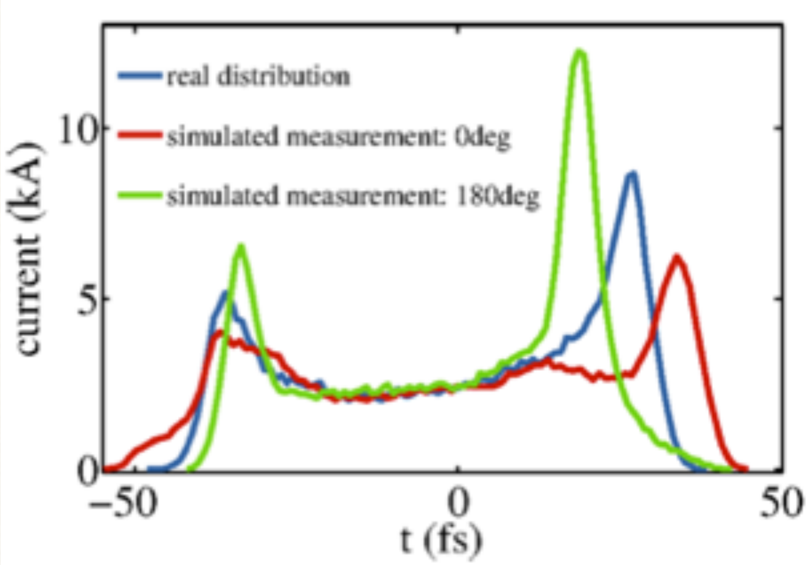
Systematic Errors

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)

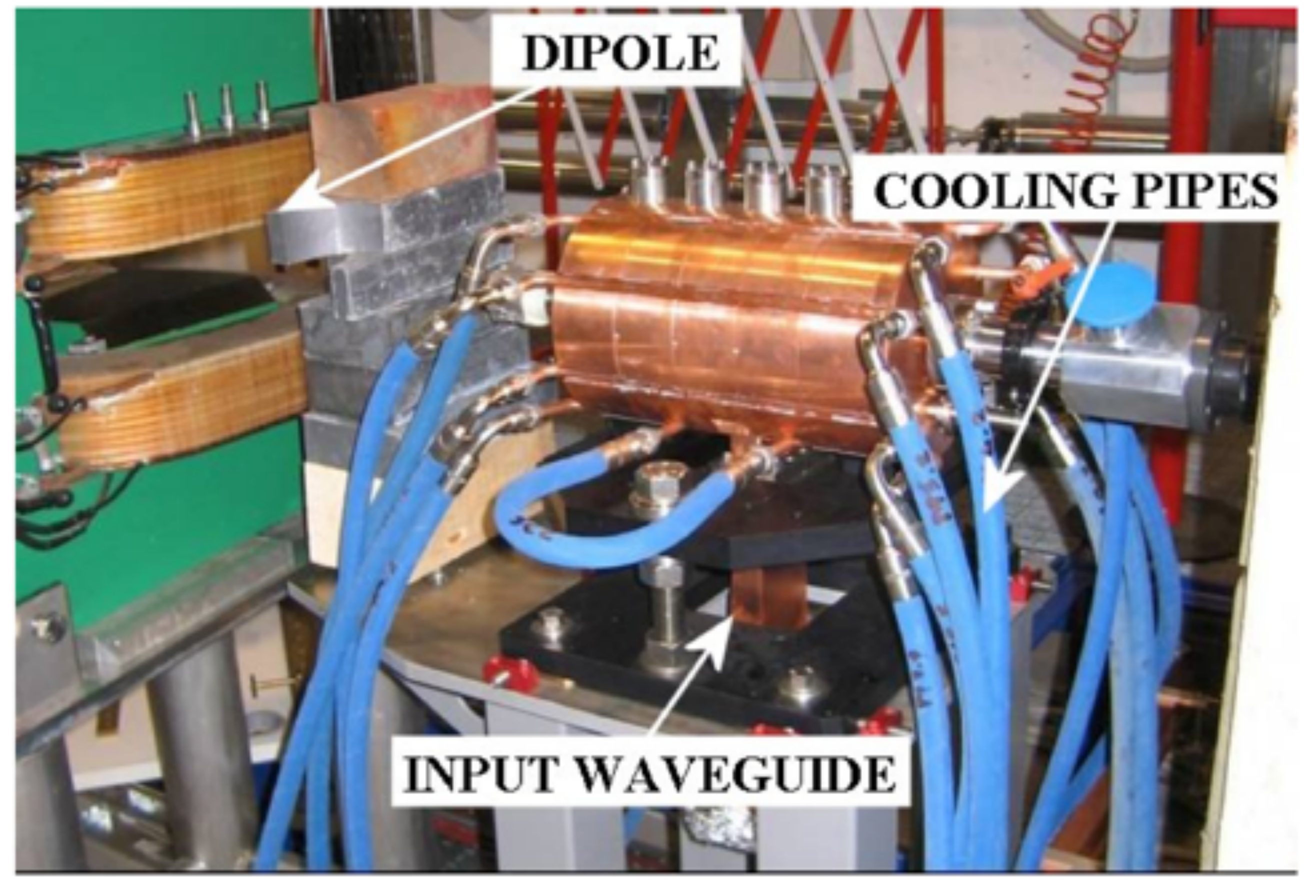


- Strong effects in head and tail

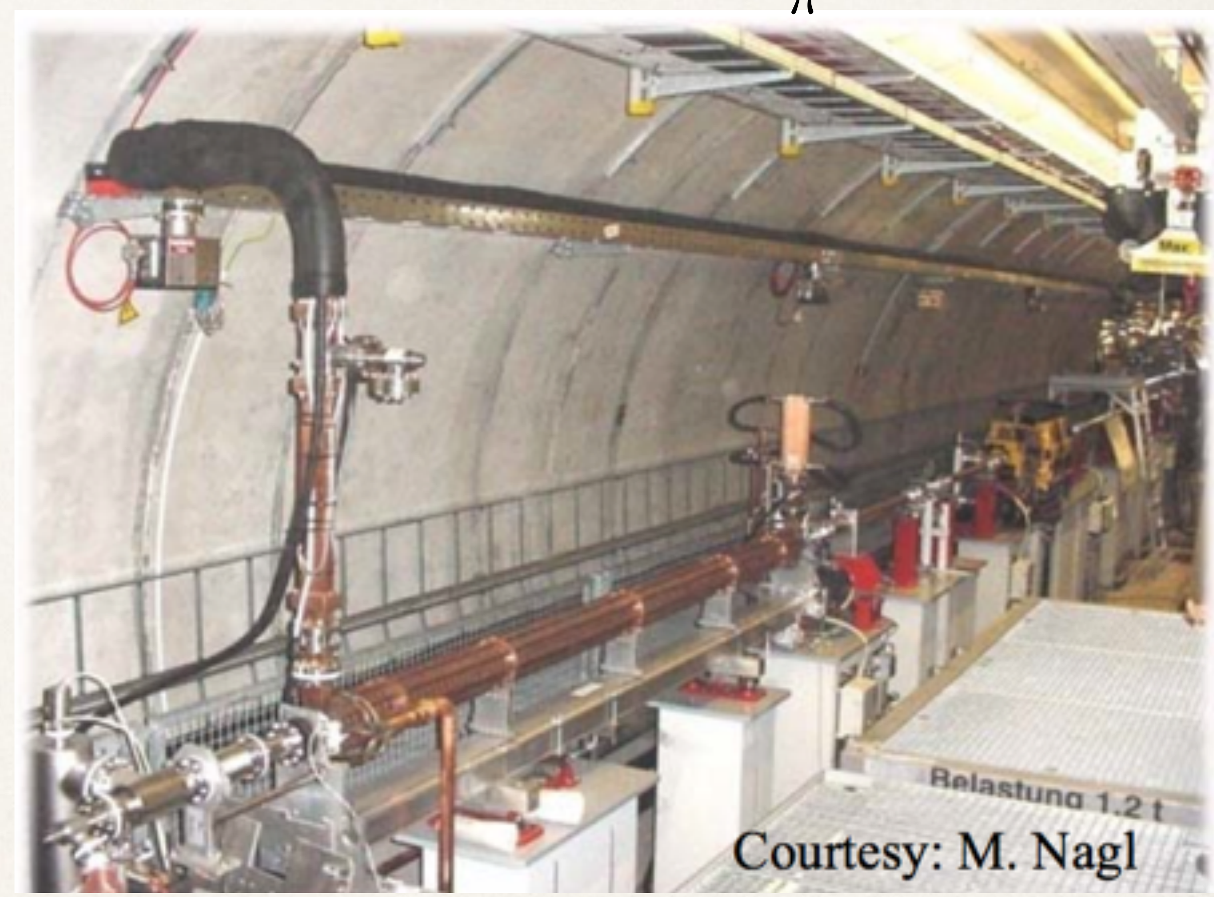
C. Behrens, FEL 2011, Shanghai

Examples of RF Deflectors

SPARC_LAB, 5-cell Standing Wave operating on the π mode at 2.856 GHz



LOLA@FLASH, Traveling Wave 2π/3, TM_{11} at 2.856 GHz



- **Traveling wave** deflecting cavities are **less sensitive to temperature**, can have more cells per cavity and fill faster
  - They require **more RF power**
- **Standing wave** have higher efficiency per unit length, but limited number of cells because of mode overlapping
  - **Higher filling times**

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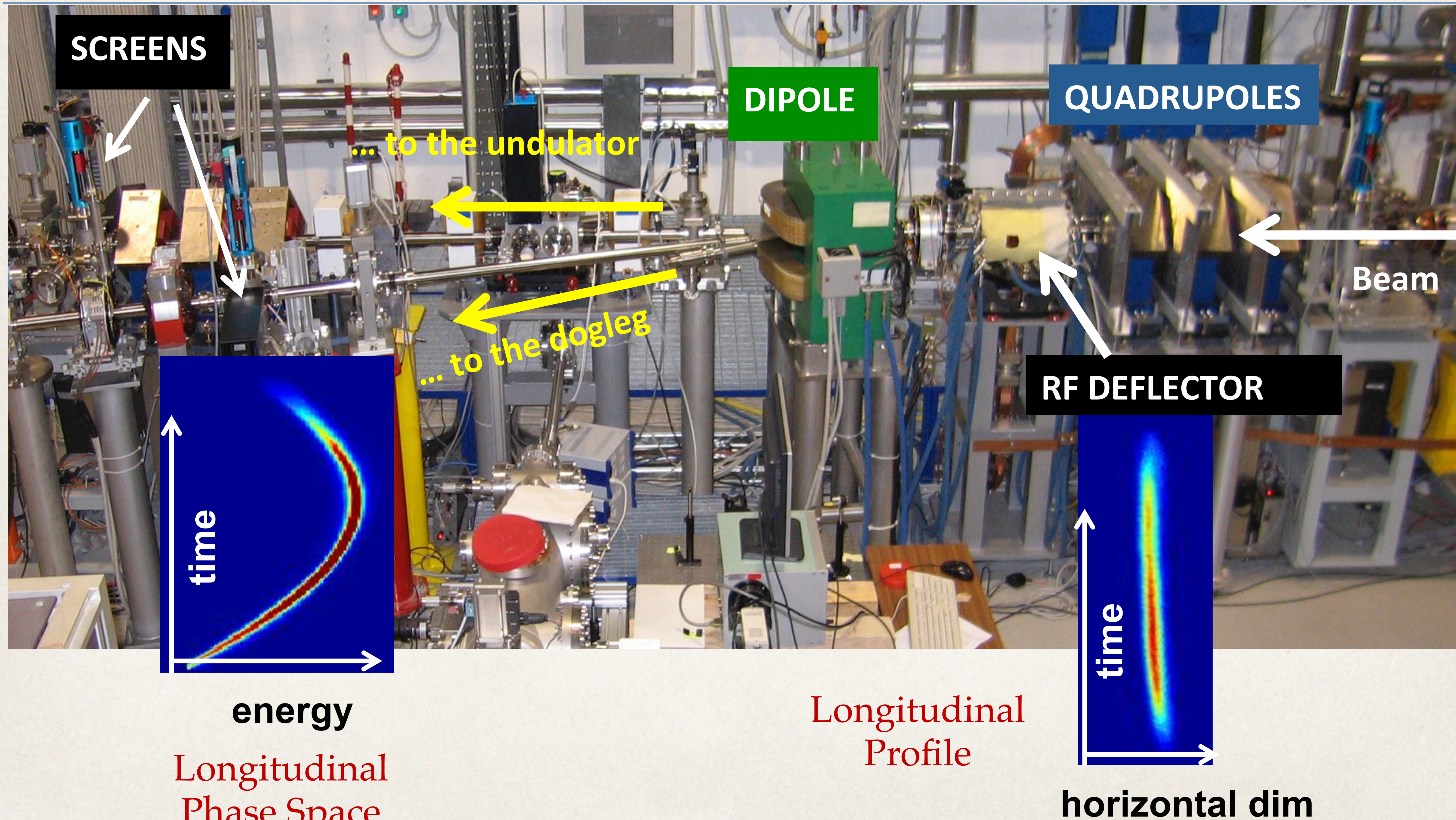
The SPARC_LAB RF Deflector

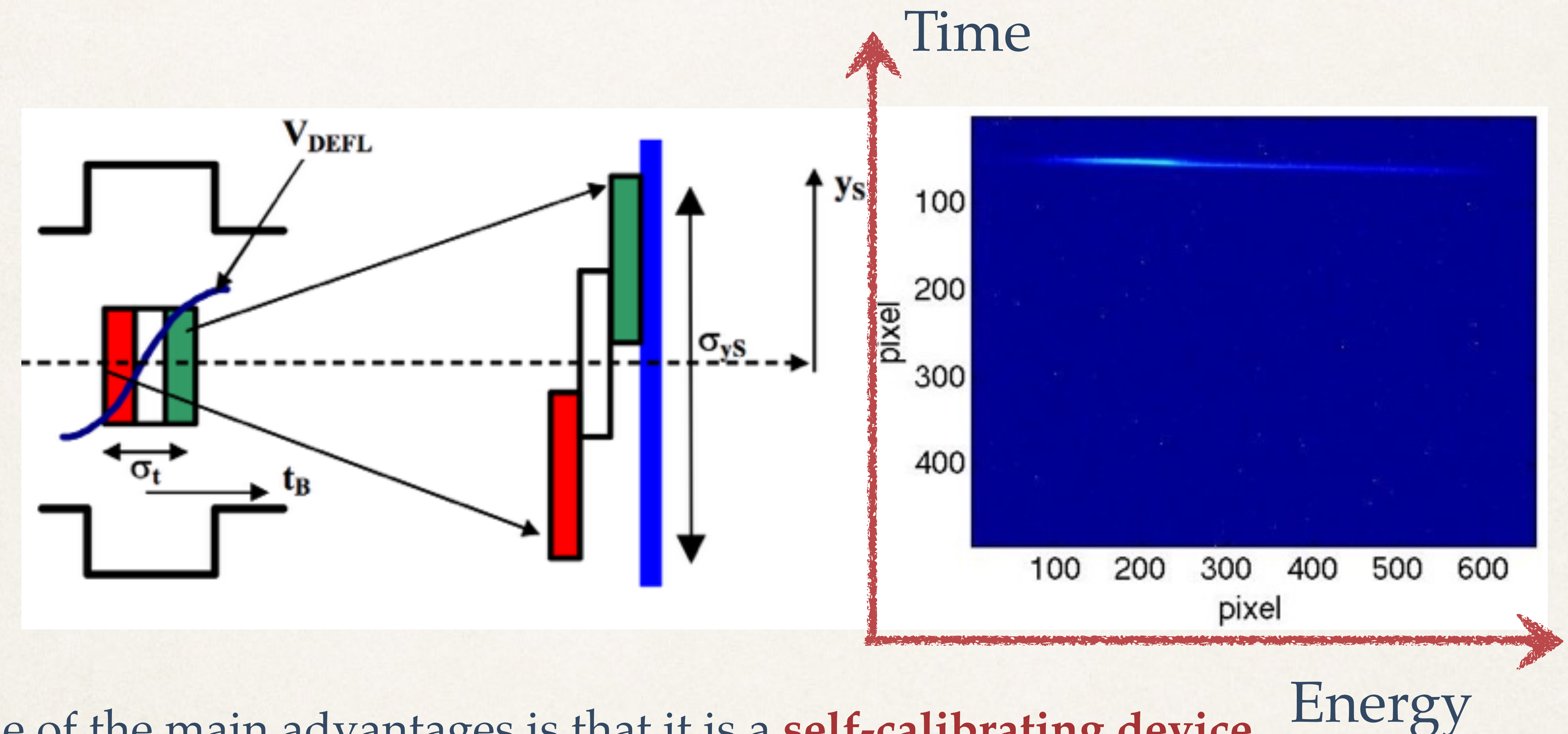
D. Alesini et al., NIM A **568** (2006) 488–502



Longitudinal Phase Space

Longitudinal Profile

Examples of Operation

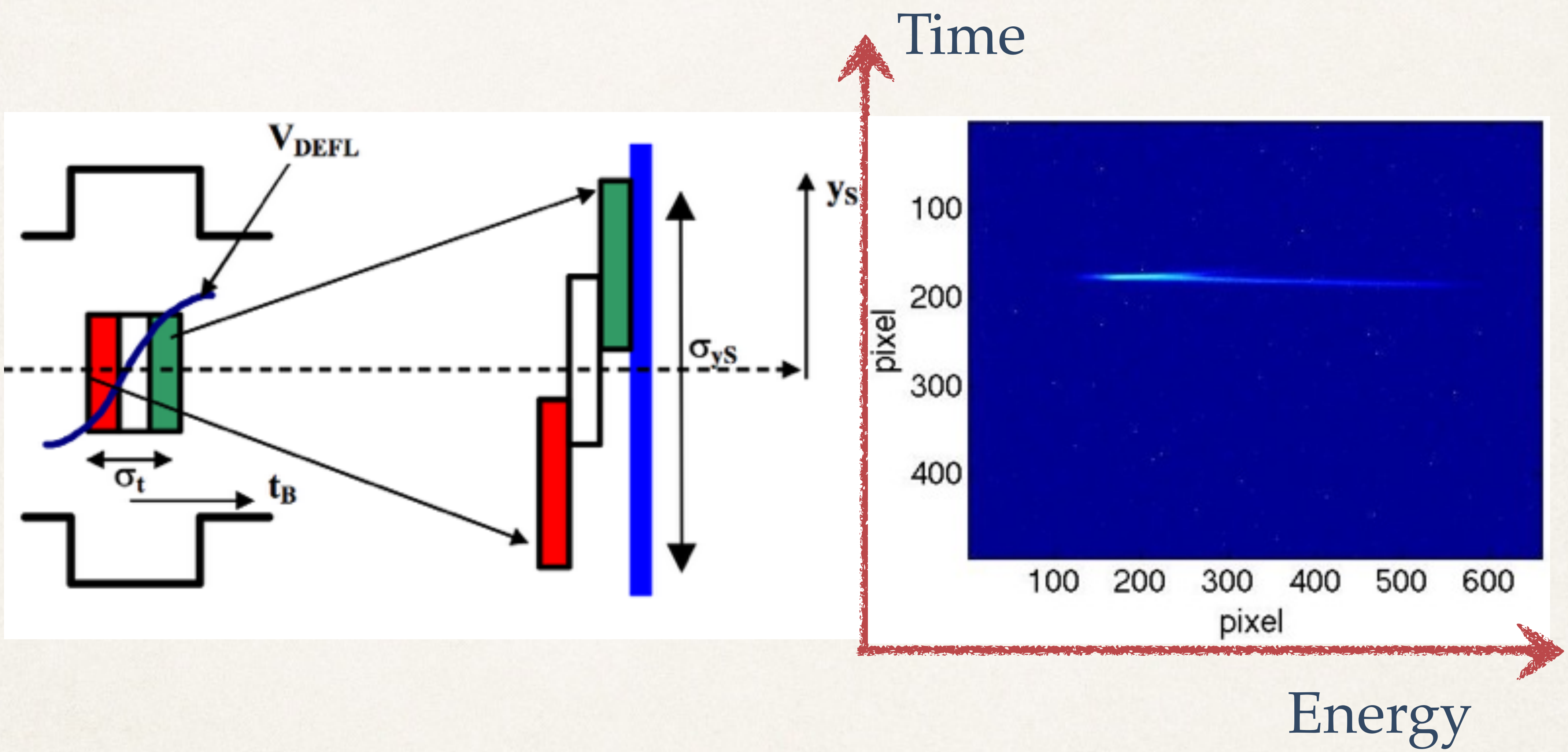


- One of the main advantages is that it is a **self-calibrating device**
- The coefficient K_{cal}

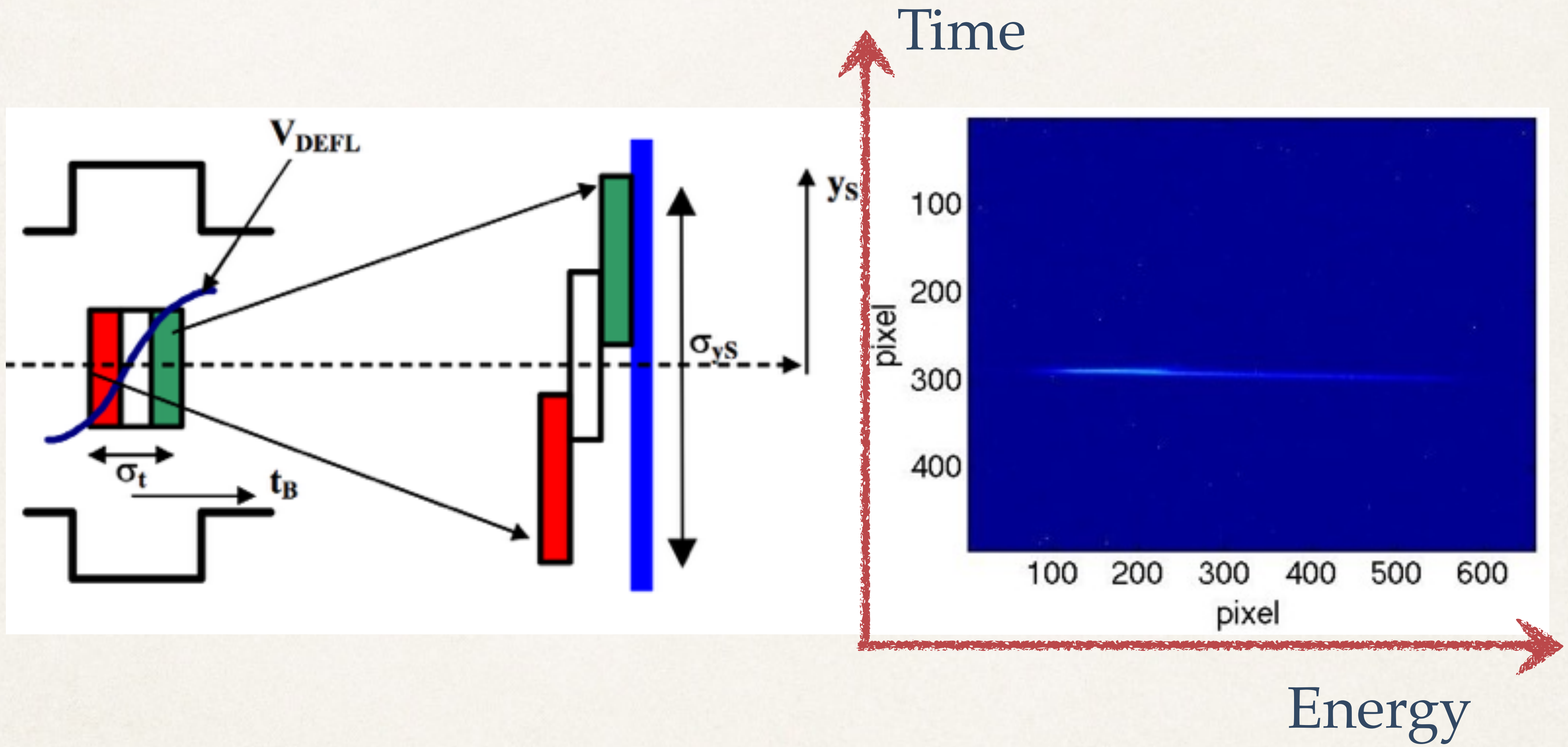
$$K_{cal} = \frac{eV_0}{E} L \frac{2\pi}{\lambda}$$

can be directly retrieved by measuring the bunch centroid position on the screen for different values of the RFD phase

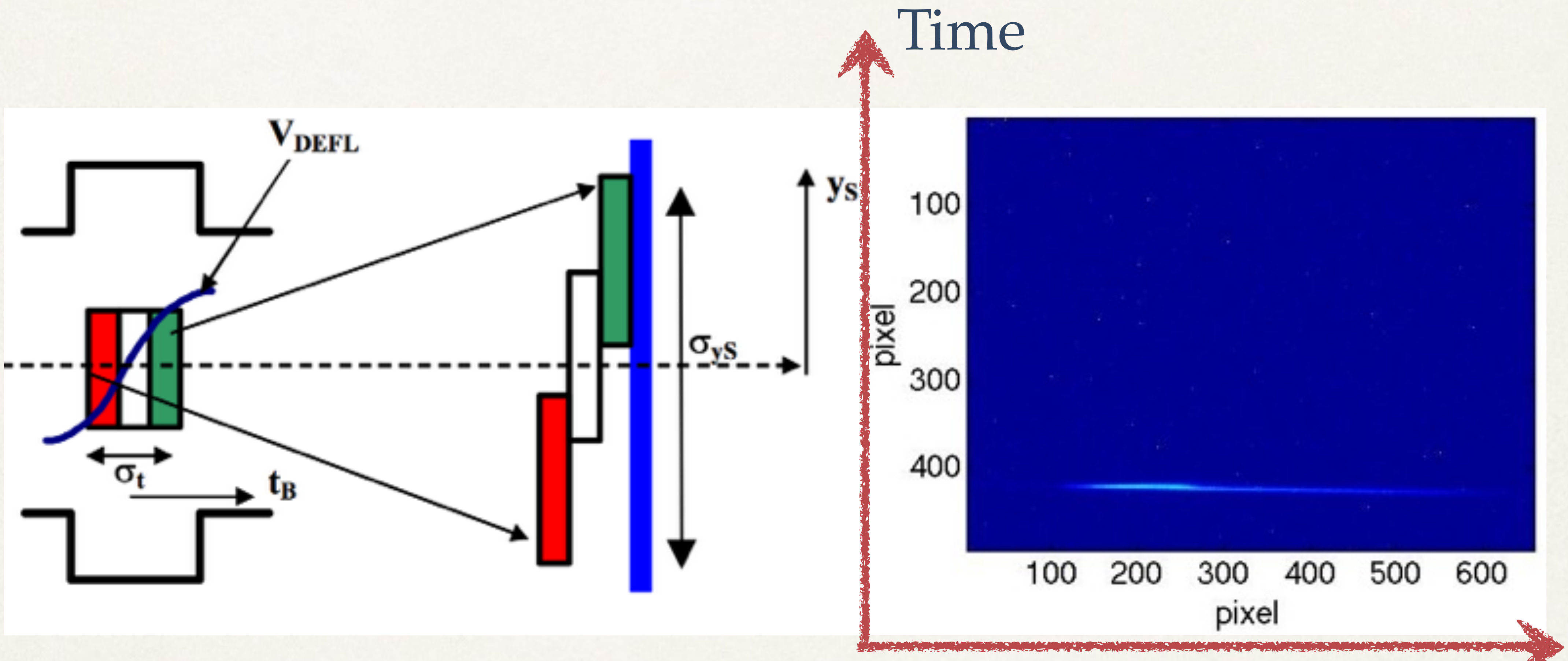
Examples of Operation



Examples of Operation

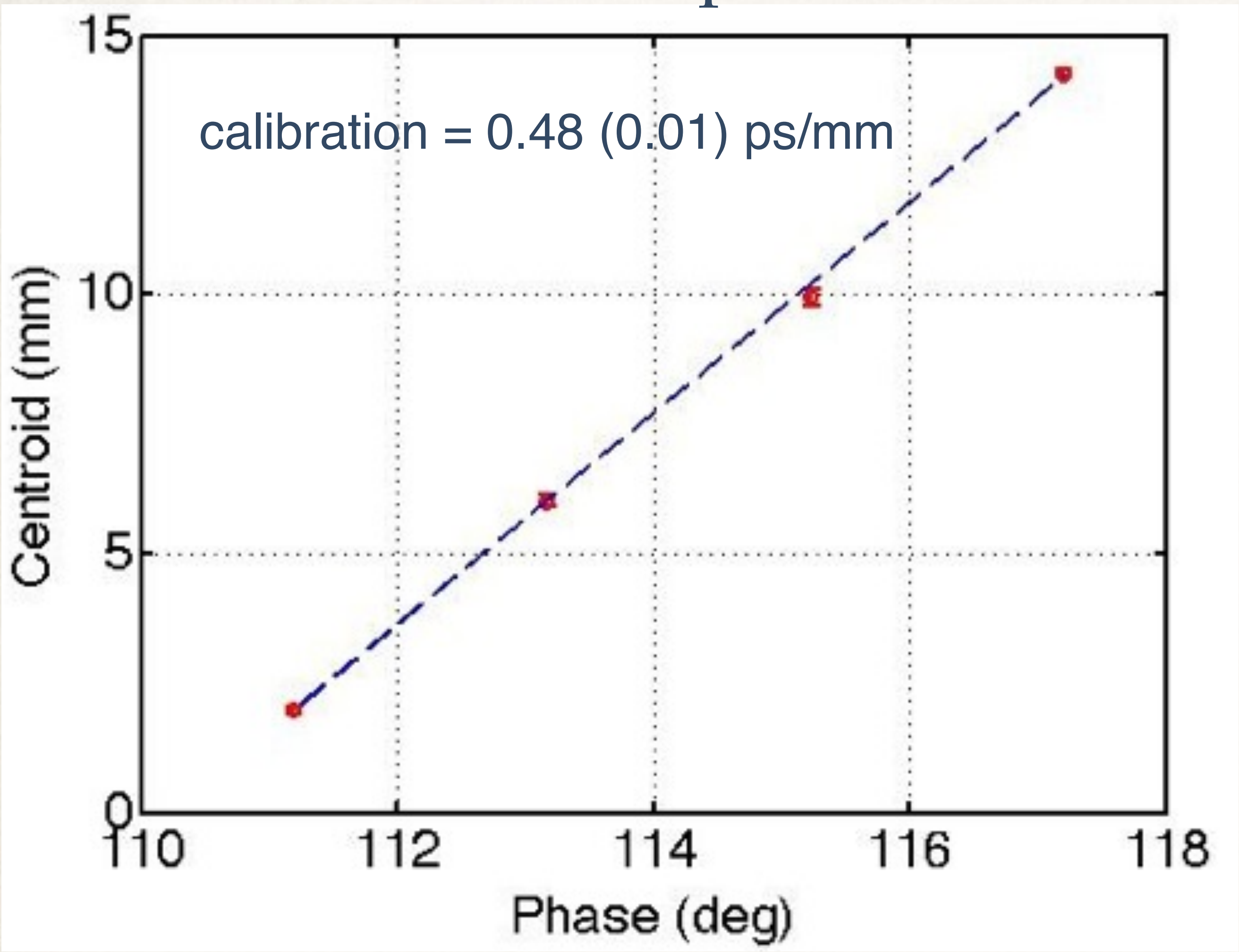


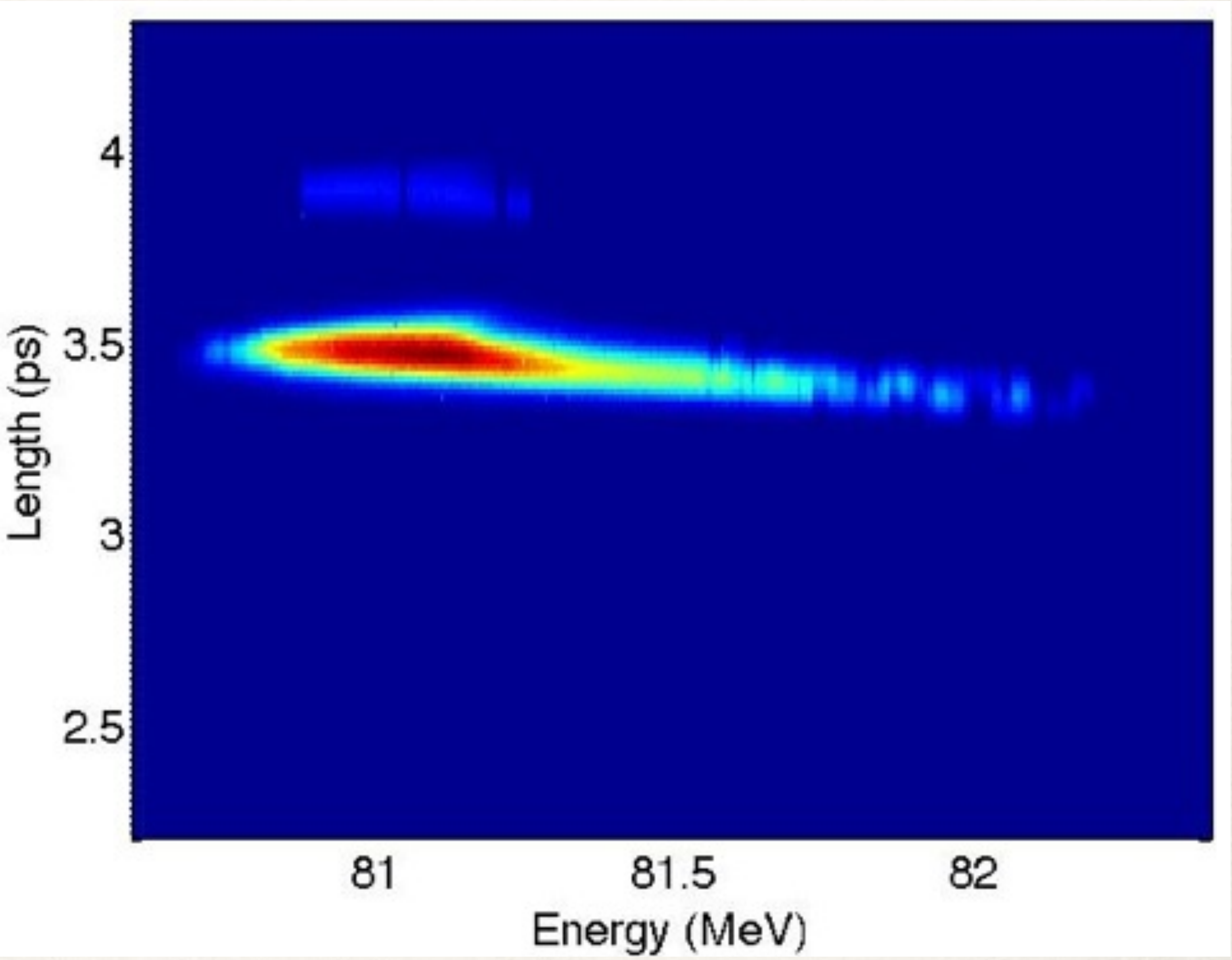
Examples of Operation



Time Calibration

Multi-shot procedure





$\sigma_{ys} = 70\ fs$

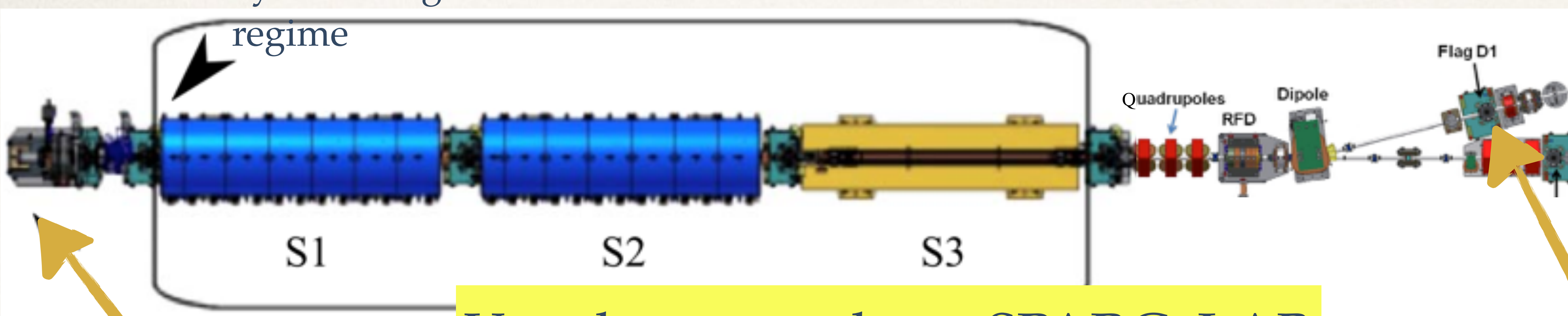
$\sigma_{yB} \cdot \text{calibration} = 45\ fs$

$\Rightarrow$

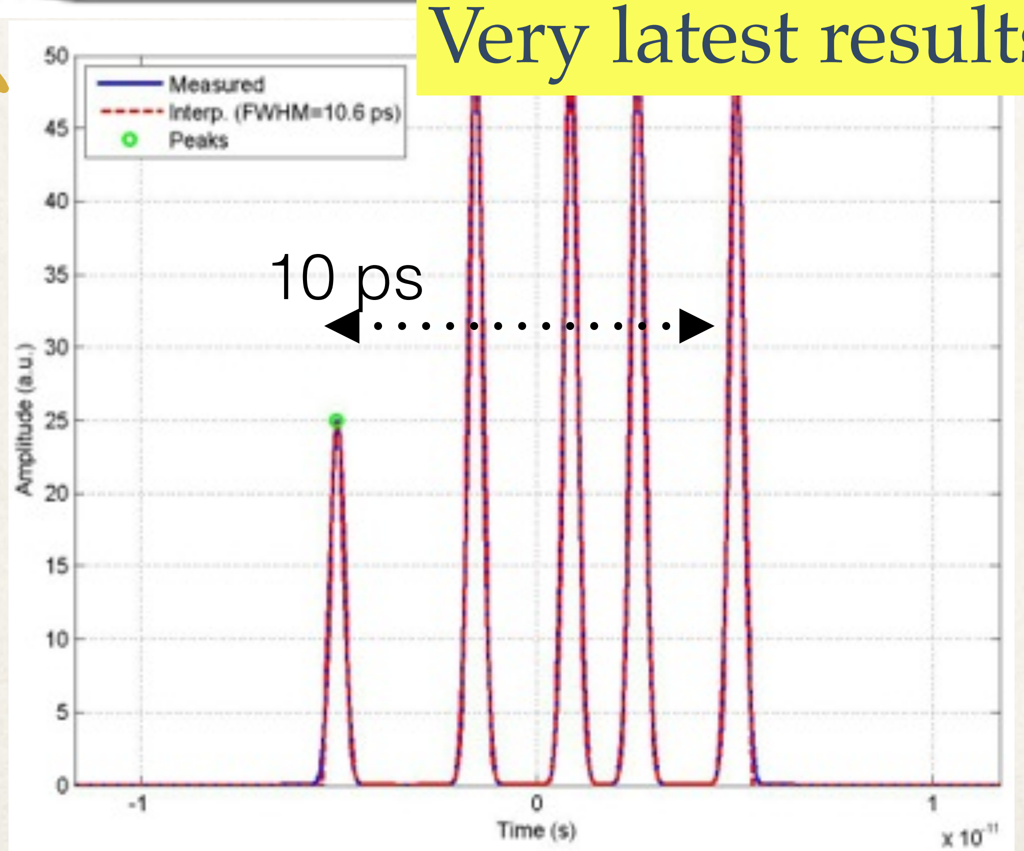
$\sigma_t = 50\ fs$

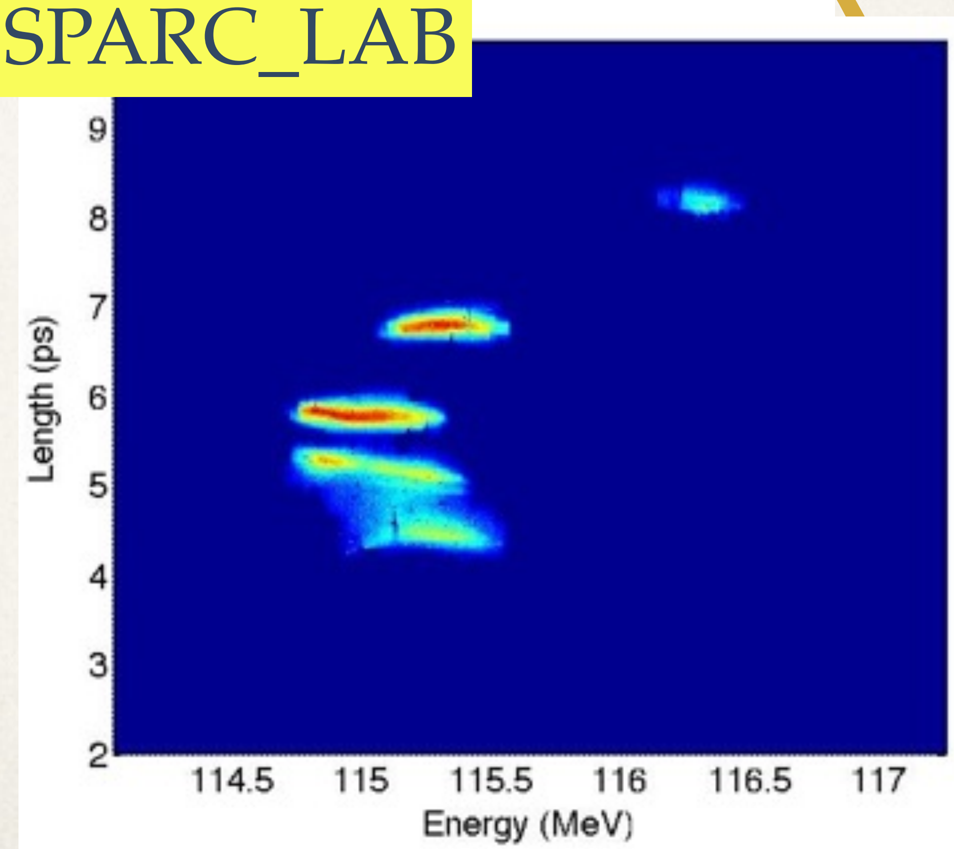
Example of Multi-bunches Operation

Velocity bunching regime



Very latest results at SPARC_LAB





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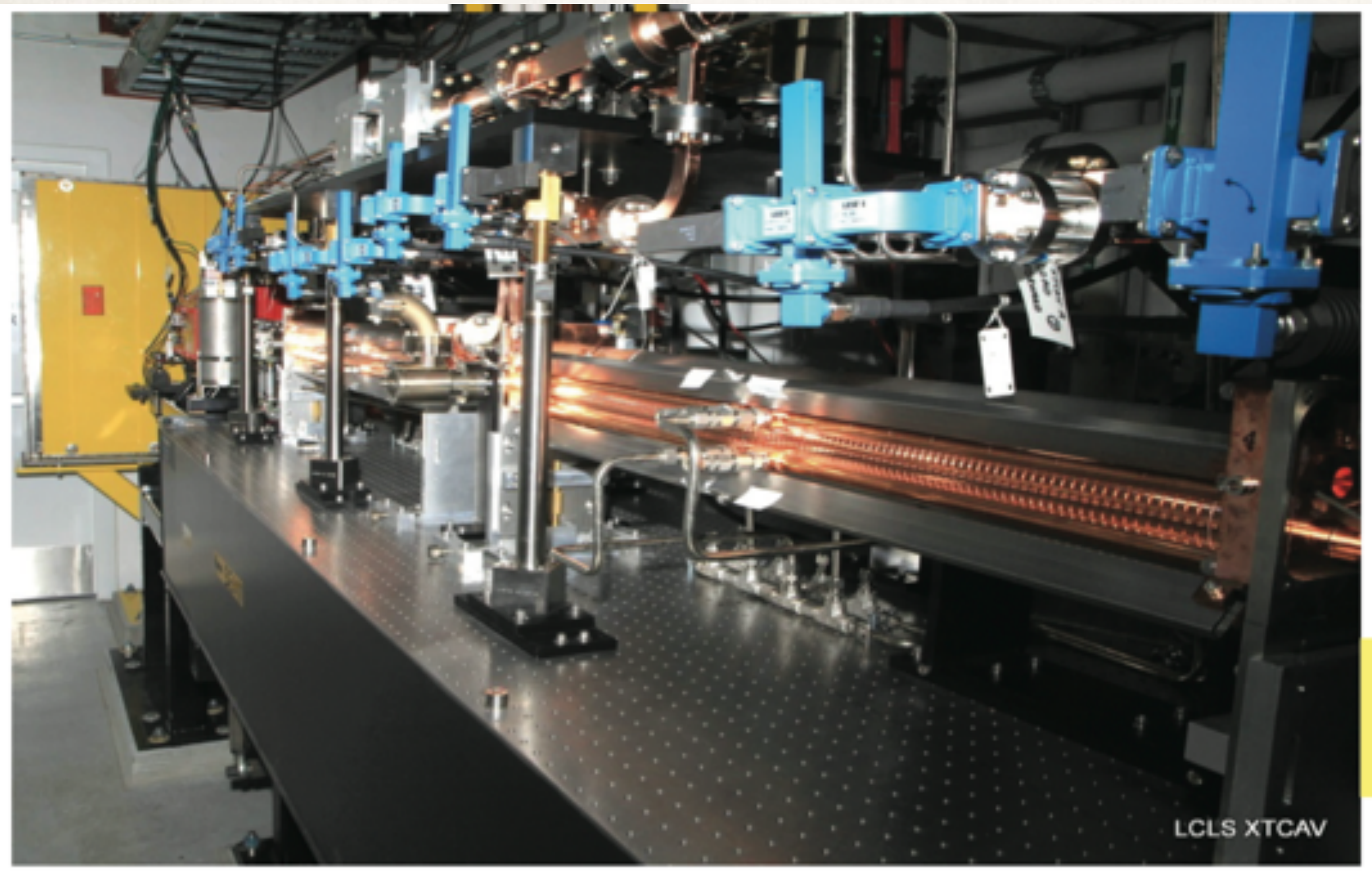
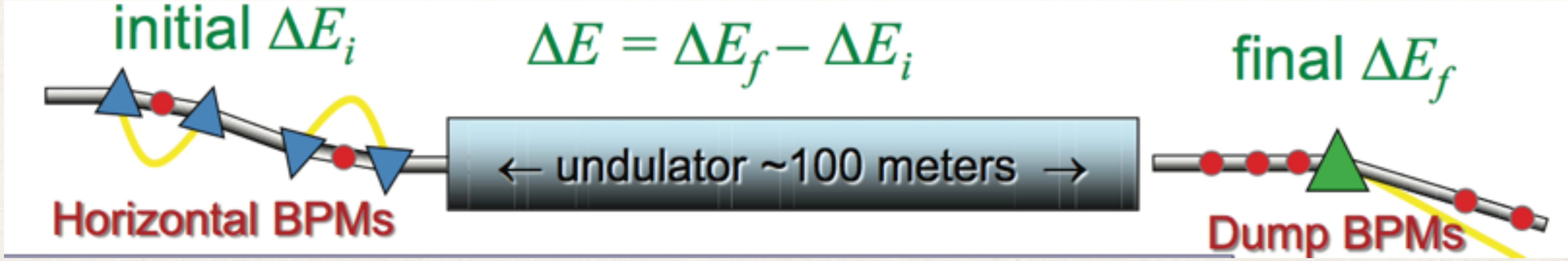
Time-resolved X-ray diagnostics



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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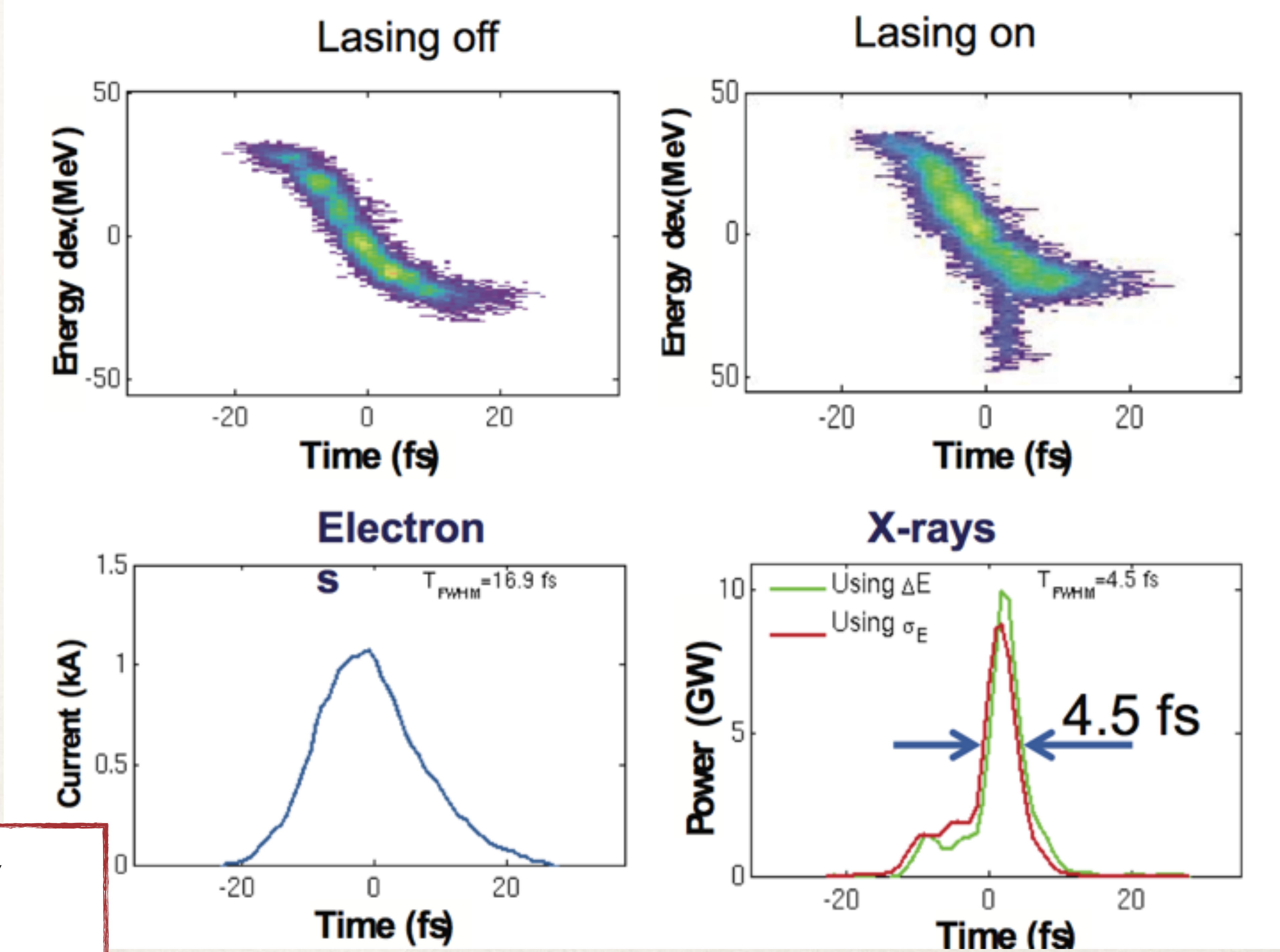
Time-resolved X-ray diagnostics

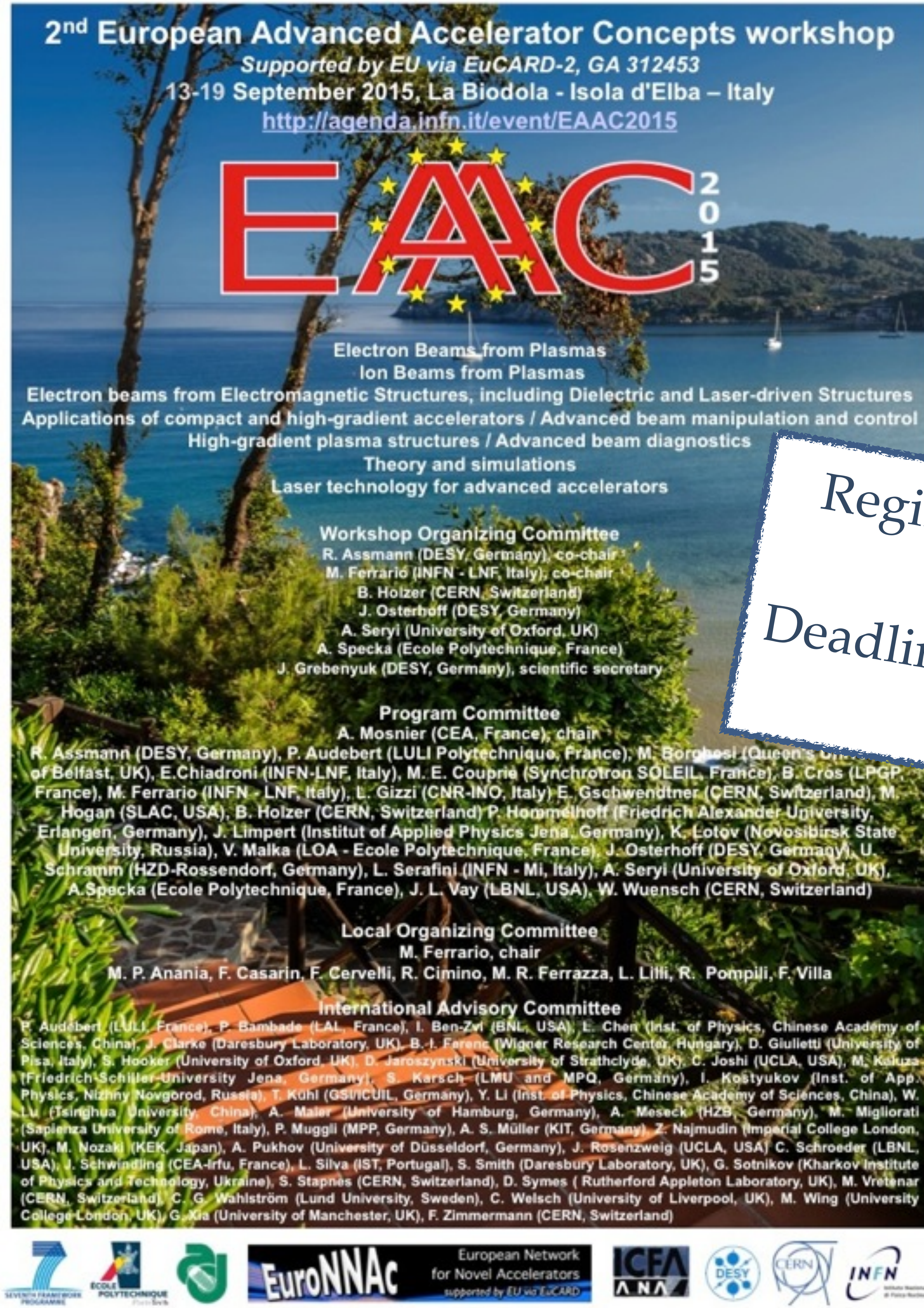


V. A. Dolgashev et al., PRST-AB **17**, 102801 (2014)

Y. Ding, FEL 2013

Conclusions

- The **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



Registration is now open!
Deadline on May 31st, 2015