Longitudinal Beam Diagnostics for the DESY VUV-FEL

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- **Introduction long. dynamics**
- **TCAV**
- **Electro-optic sampling**
- **Coherent radiation diagnostics**
- **Summary**

Why to produce high peak currents …

$$P_{rad} = P_0 \exp\left(z / L_g\right)$$

Radiation power:

$$L_G = \frac{1}{\sqrt{3}}\left(\frac{I_A \gamma^3 \sigma_r^2 \lambda_u}{4\pi \hat{I} K^2}\right)^{1/3}$$

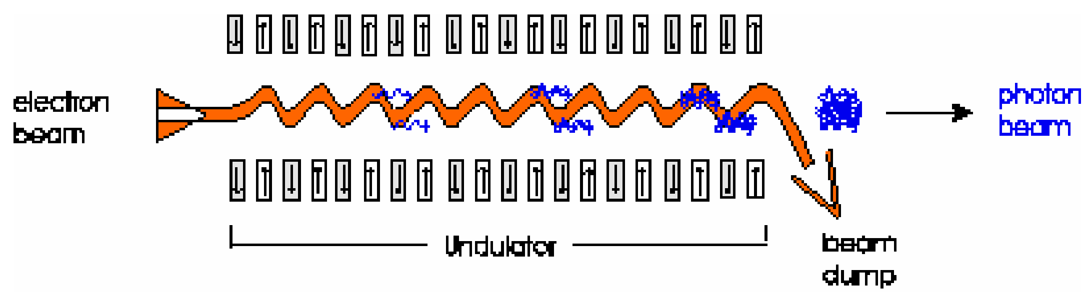
I = Peak current ~ 2.5 kA

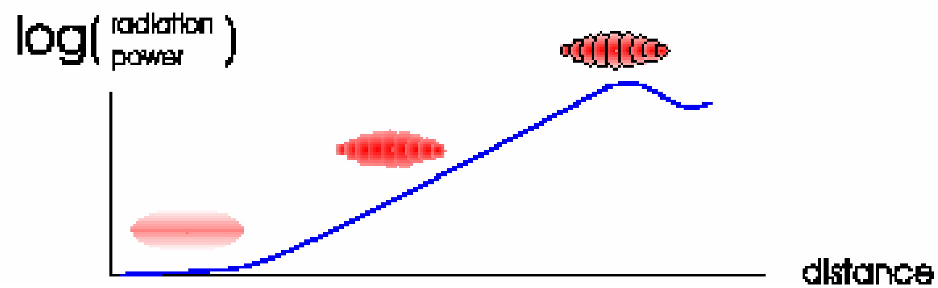
σ_r = Beam radius

γ = E/m_0 ~ beam energy

λ_u = Undulator period

K = Undulator parameter



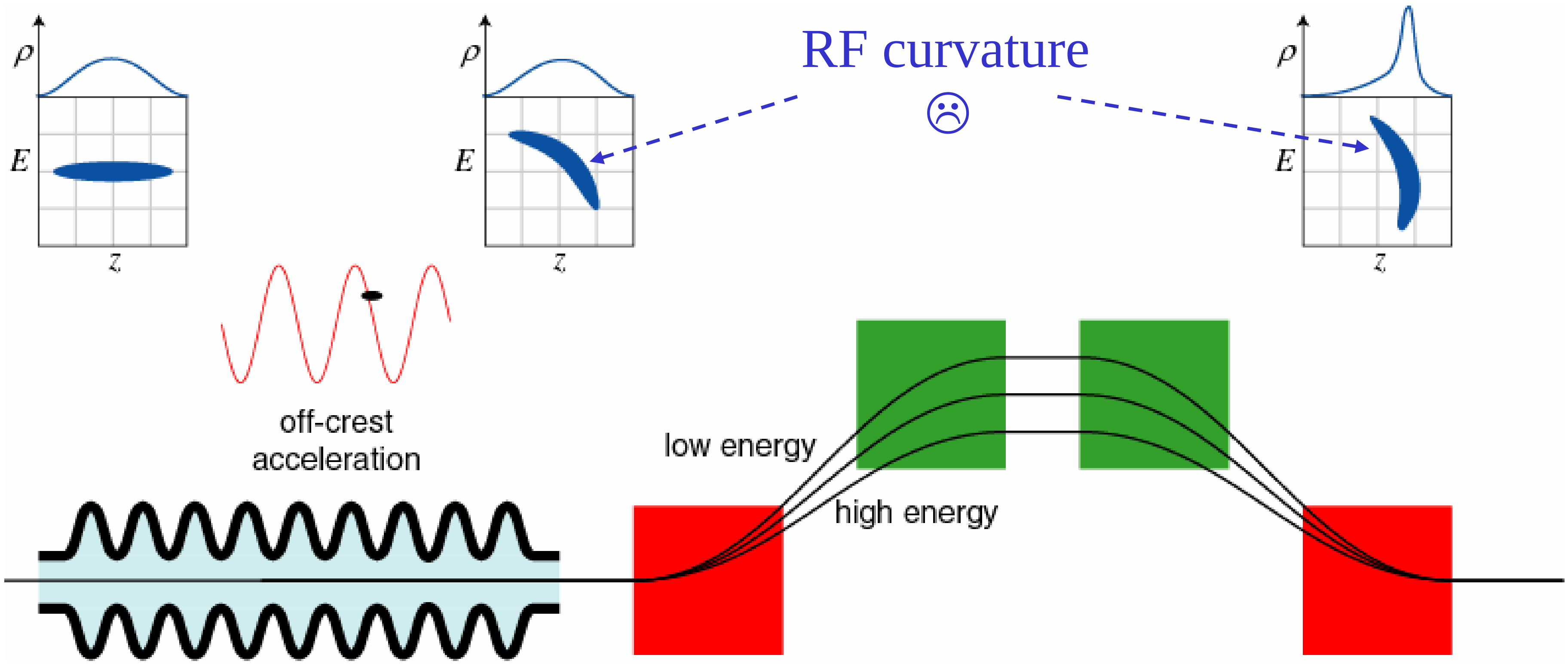


How to produce high peak currents …

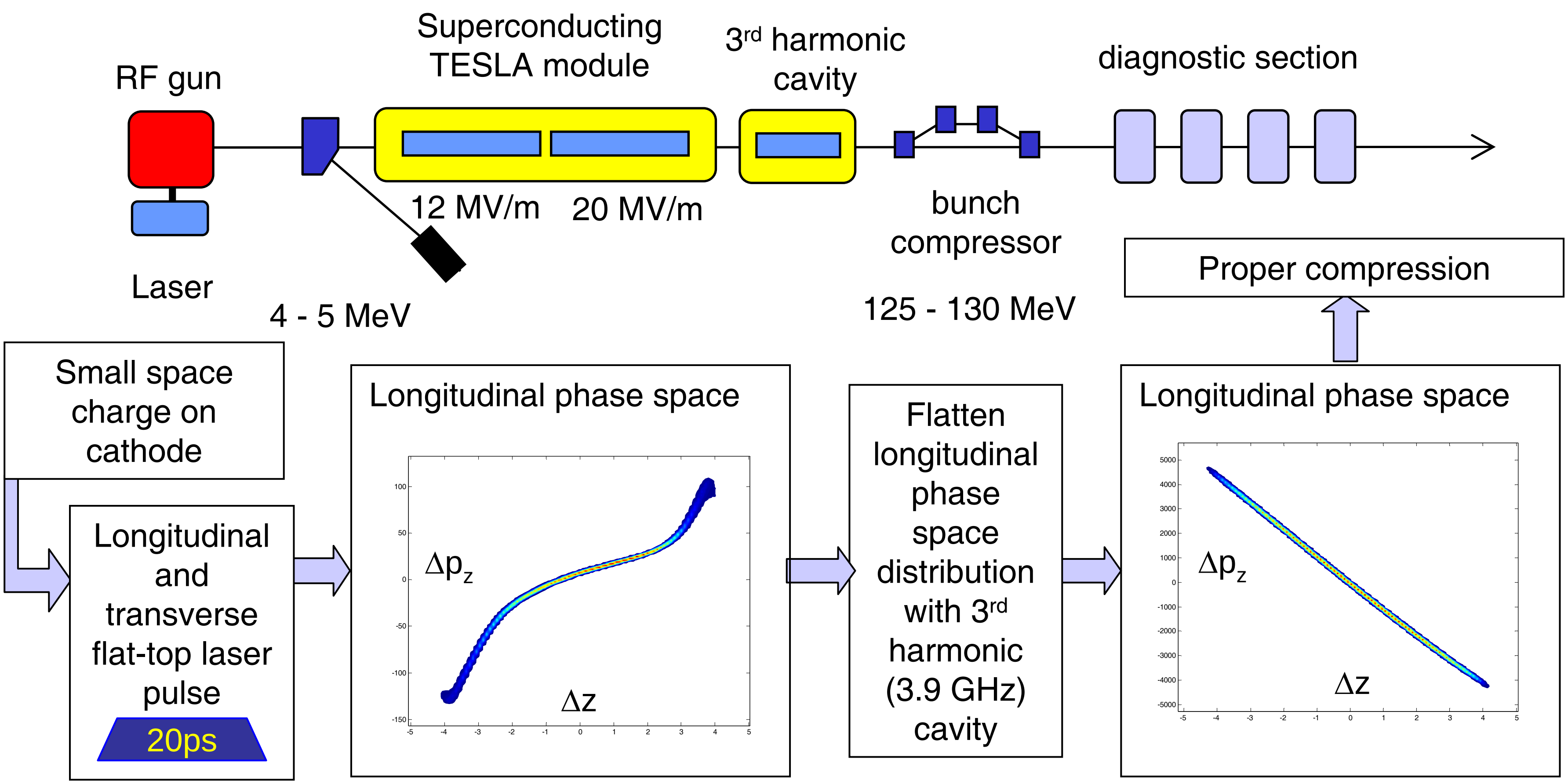
- at high energy (140 MeV) electrons have 99.9993% c_0

⇒ Introduce energy chirp to e- beam

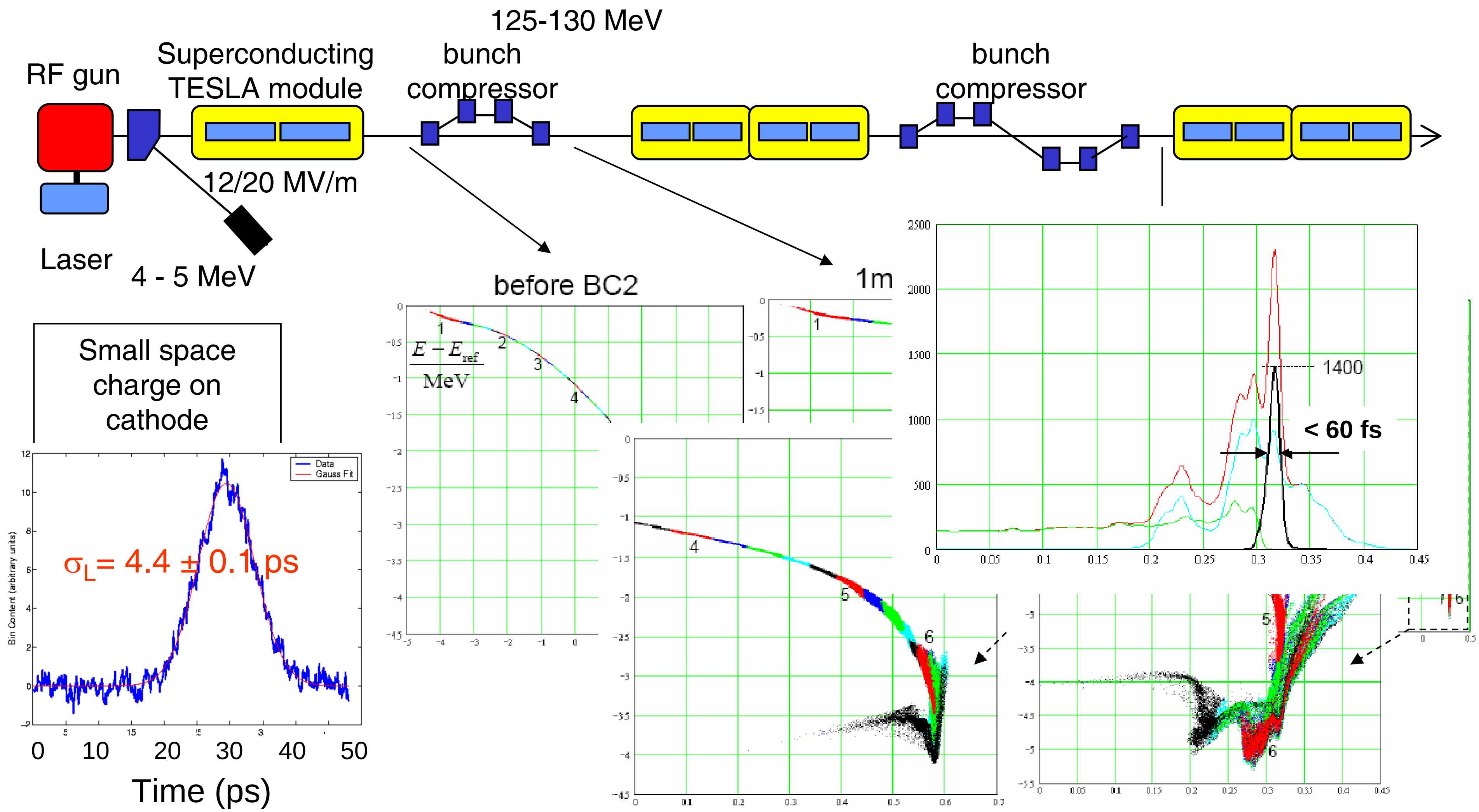
⇒ section with energy dependent path length using magnetic bunch compressors



Longitudinal phase space injector
- final design -

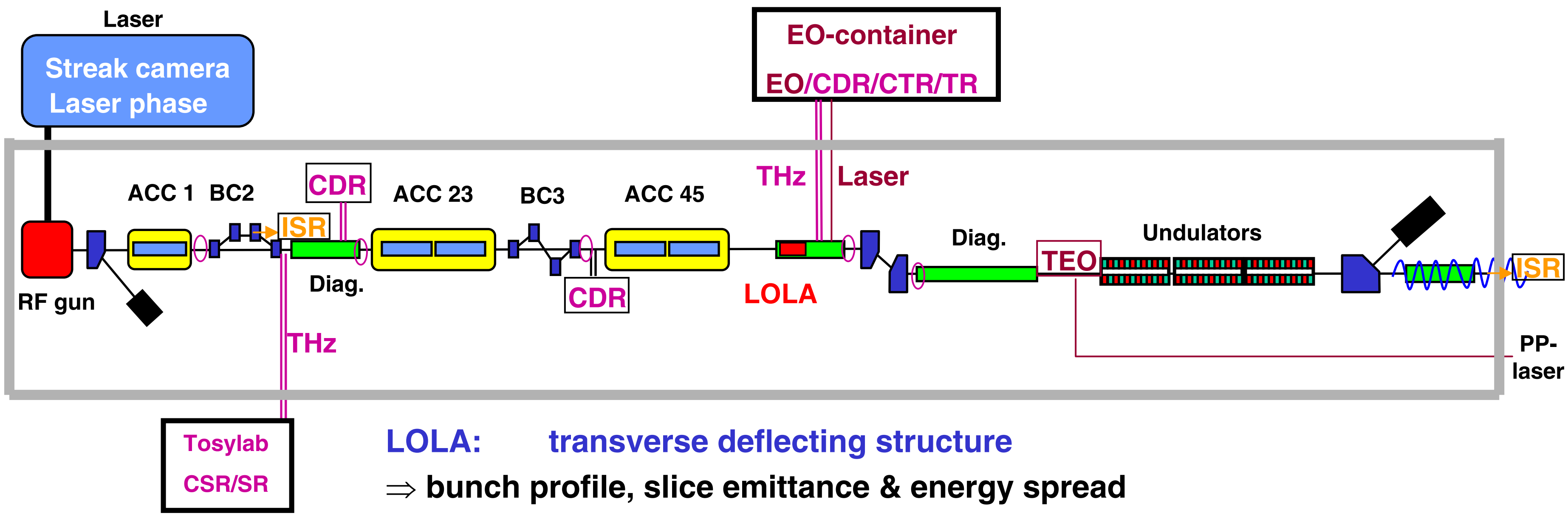


Longitudinal phase space injector
- present design -



Courtesy: M. Dohlus

Diagnostics for long. phase space



LOLA: transverse deflecting structure

⇒ bunch profile, slice emittance & energy spread

EO: electro-optic

⇒ bunch profile, timing (TEO)

ISR: incoherent synchrotron radiation

⇒ energy spread & beam energy

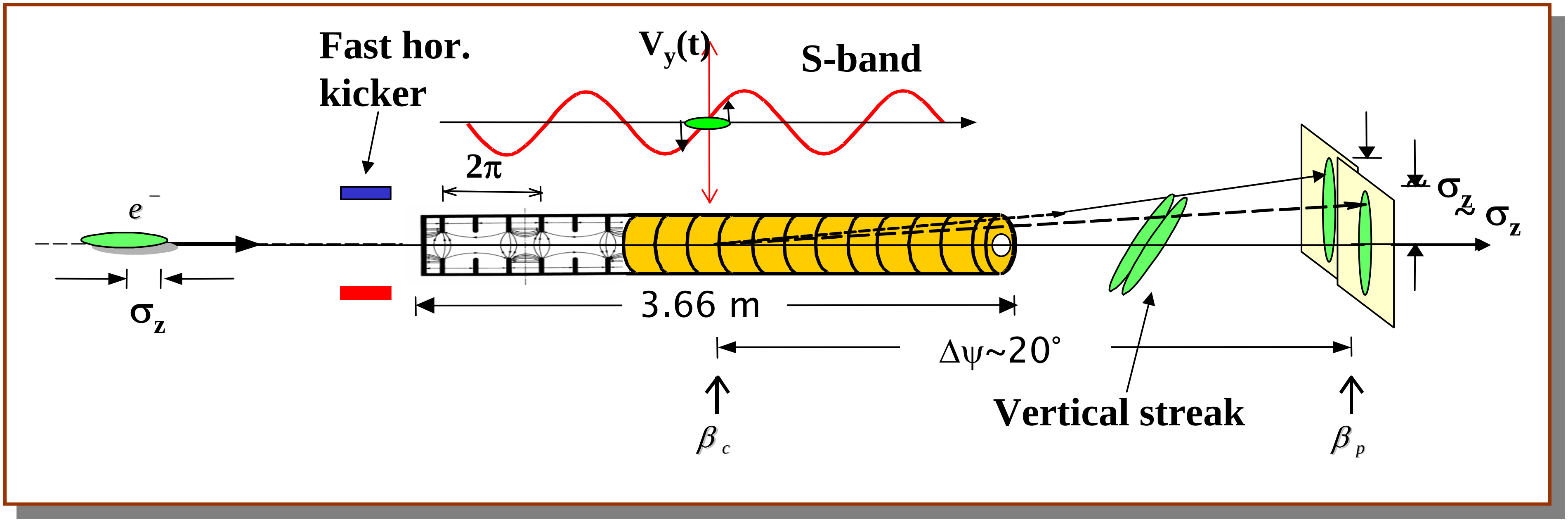
CRD: coherent radiation diagnostics

⇒ longitudinal spectrum of e-beam (THz radiation, 10GHz-30THz)

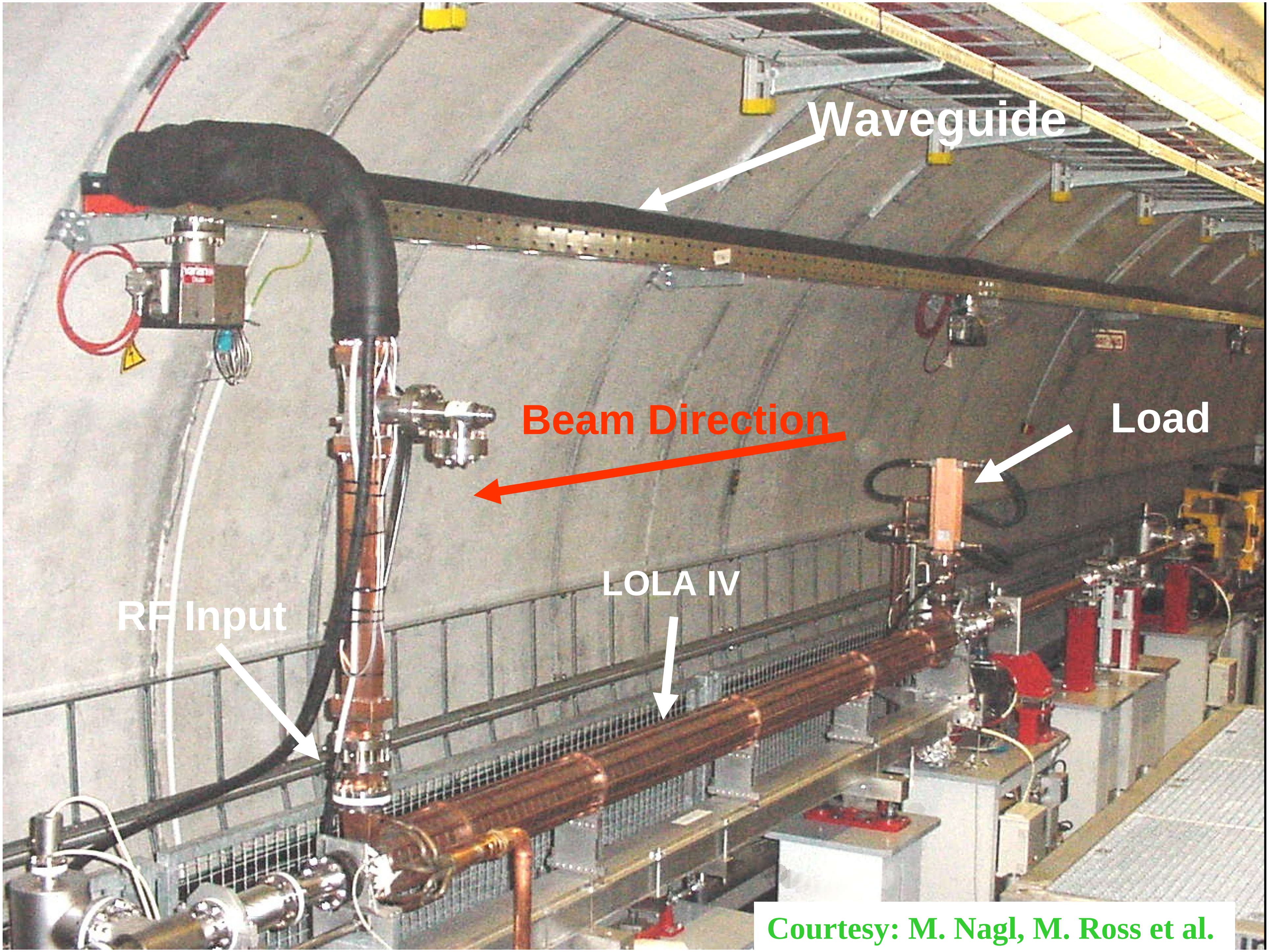
- CTR : coherent transition radiation
- CSR: coherent synchrotron radiation
- CDR: coherent diffraction radiation

Transverse deflecting structure

- collaboration between DESY and SLAC
- vertical deflecting RF structure (2.856 GHz) operated at zero crossing
- vertical size of beam at imaging screen ⇒ depends on bunch length
- 40 MW klystron power to "streak" the 0.5 GeV at TTF2 (26MV@20MW)
- 'Parasitical' measurement using hor. kicker and off-axis screens
- Resolution: TTF2 ~ 10-50 fs (depending on vertical beam size)



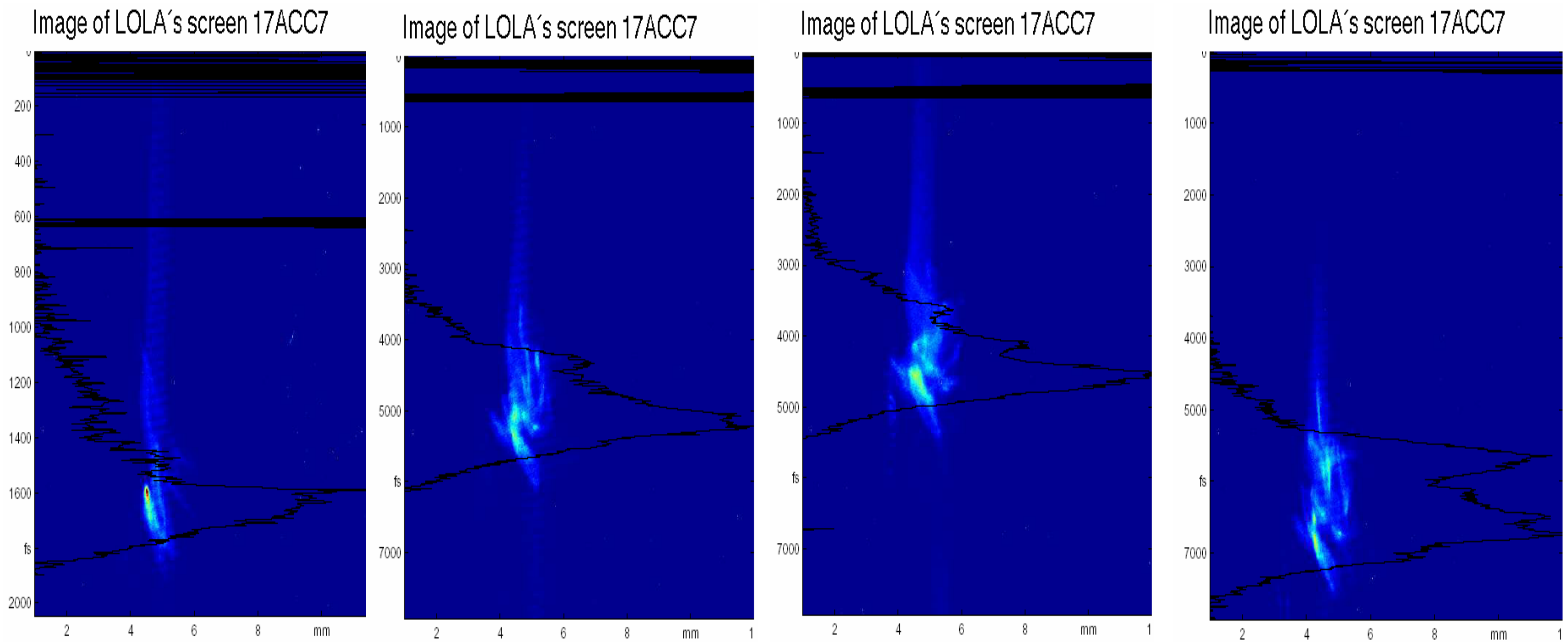
TTF2: M. Ross et.al. + MIN DESY


Waveguide
Beam Direction
Load
LOLA IV
RF Input
Courtesy: M. Nagl, M. Ross et al.

Beam profile for different compressions

Phase from maximum pyro-electrical signal …

+3° +2° +1° +0° (max.)



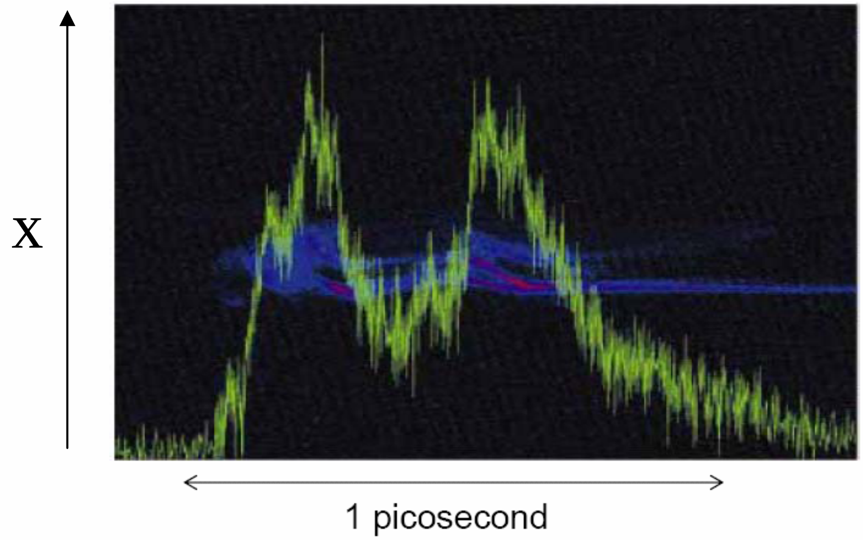
Fragmentation of beam in longitudinal and x direction (csr+space charge)

$\Rightarrow$ Ideal suited for slice emittance measurements

Courtesy: A. Bolzmann (DESY)

First attempts to compare TCAV & simulations

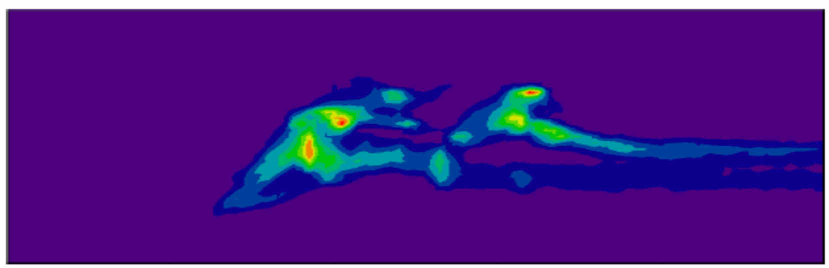
Image with LOLA

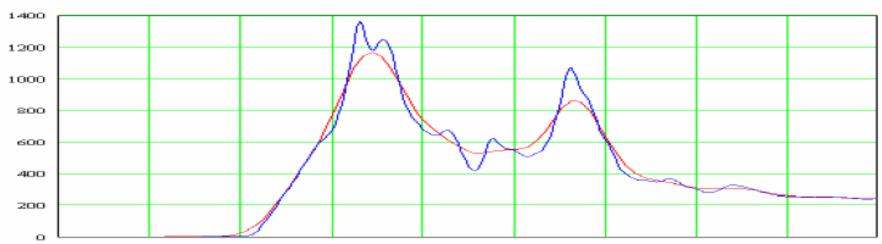


Simulation with CSR

optics = option 1

$\varphi_{rf} = 12$ deg

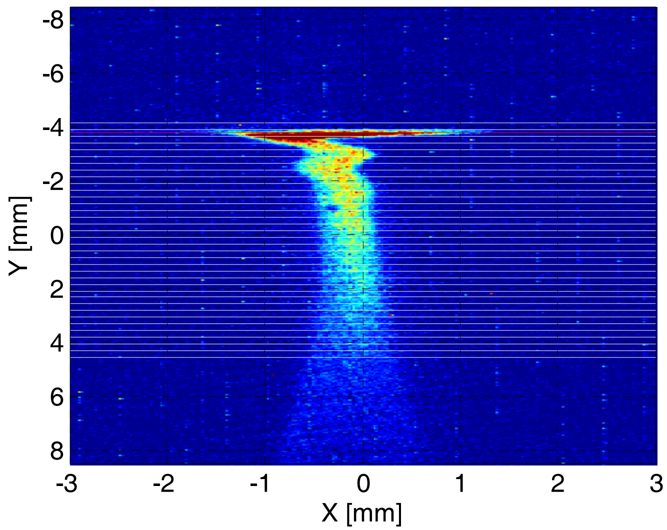


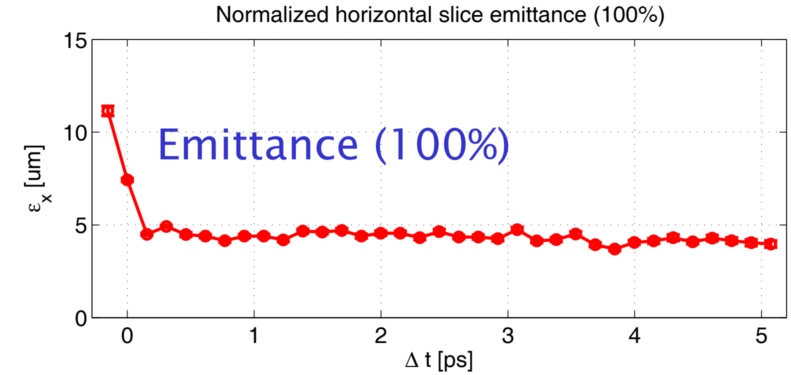


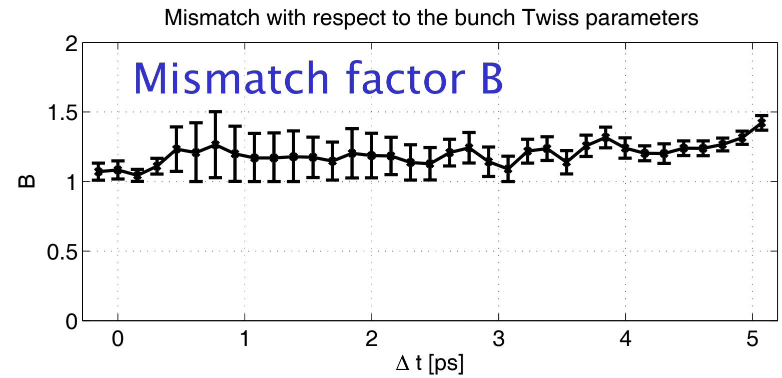
Courtesy: M. Dohlus (DESY)

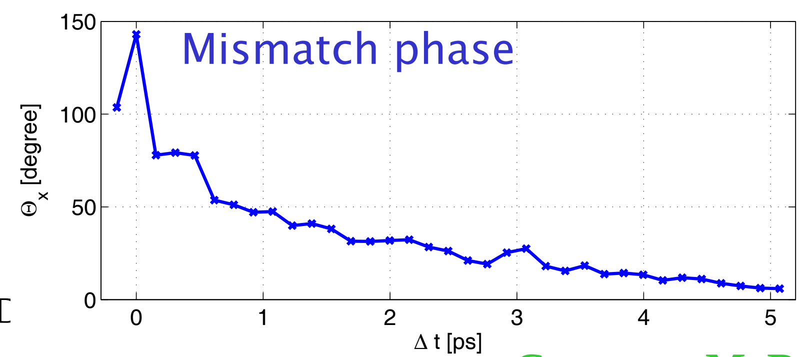
Measurement results for projected and slice emittance

Slicing used for meas.









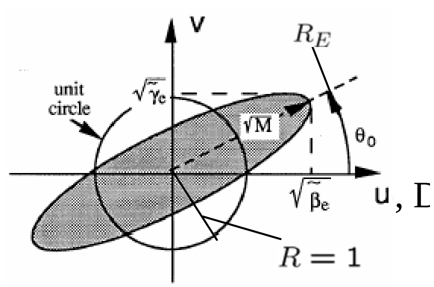
- Longitudinal Slices of 250um or 154fs
- ε(100%) ~ 7.5um head … 4 um tail
- ε(90%) ~ 6.3 um head … 1.5 um tail
- Mismatch phases indicate gradual rotation of the slice rms –ellipses in hor. phase space along the bunch. Most likely caused by chromaticity.

Normal coordinates:

$$B = \frac{1}{2}(\beta\gamma' - 2\alpha\alpha' + \beta'\gamma)$$

$$B = \frac{1}{2}(M + \frac{1}{M})$$

$$M = (R_{ellipse}/R_{circle})^2$$



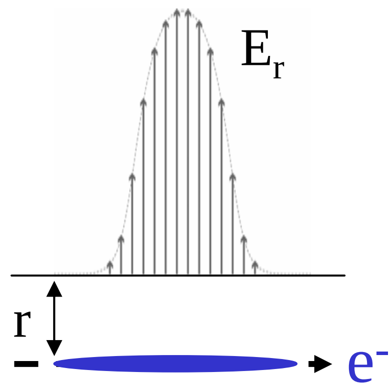
Courtesy: M. Röhrs

Electro-optic technique

Scheme of electro optic (EO) sampling experiment
for bunch length measurement & arrival timing!

Ultra-relativistic electrons:

- Co-propagating E_r electric field $\propto$ longitudinal charge profile
- Valid if $r/\gamma << \sigma_z$
- Large fields (1-400MV/m)
- f_{THz} up to10 THz

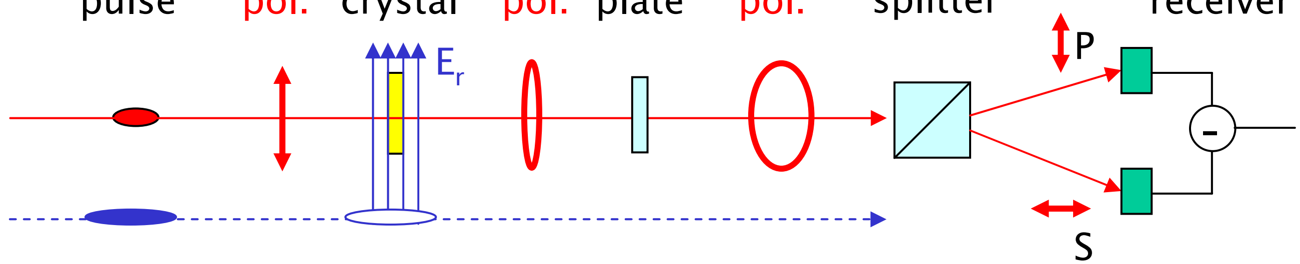


Charge (1nC)

$$E_r = \frac{Z_0 c_0 Q}{2\pi\, r}\,\lambda(z)$$

radial distance   long. profile

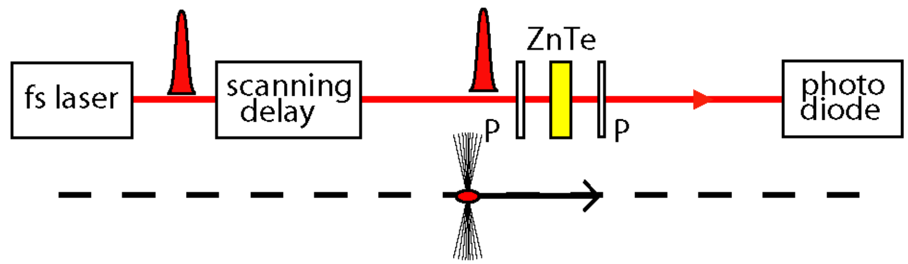
Principle scheme:



Overview on EO-techniques

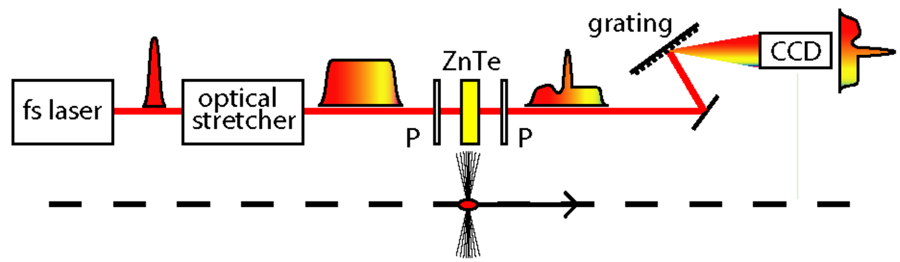
Electro-optic Sampling :

+ simple (laser) system
+ arbitrary time window
+ high resolution
- no single bunch



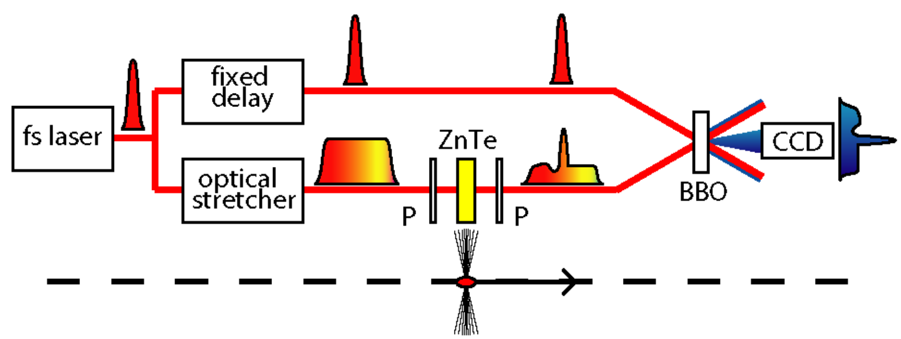
Spectral Decoding:

+ simple (laser) system
+ high repetition rate
- limited resolution (**500fs**)
- distorted signal for e-bunches < 200fs



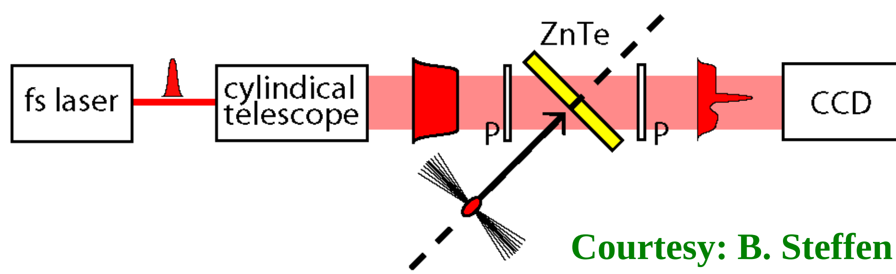
Temporal Decoding:

+ large time window
+ high resolution (**120fs, GaP**)
- mJ laser pulse energy
- low repetition rate



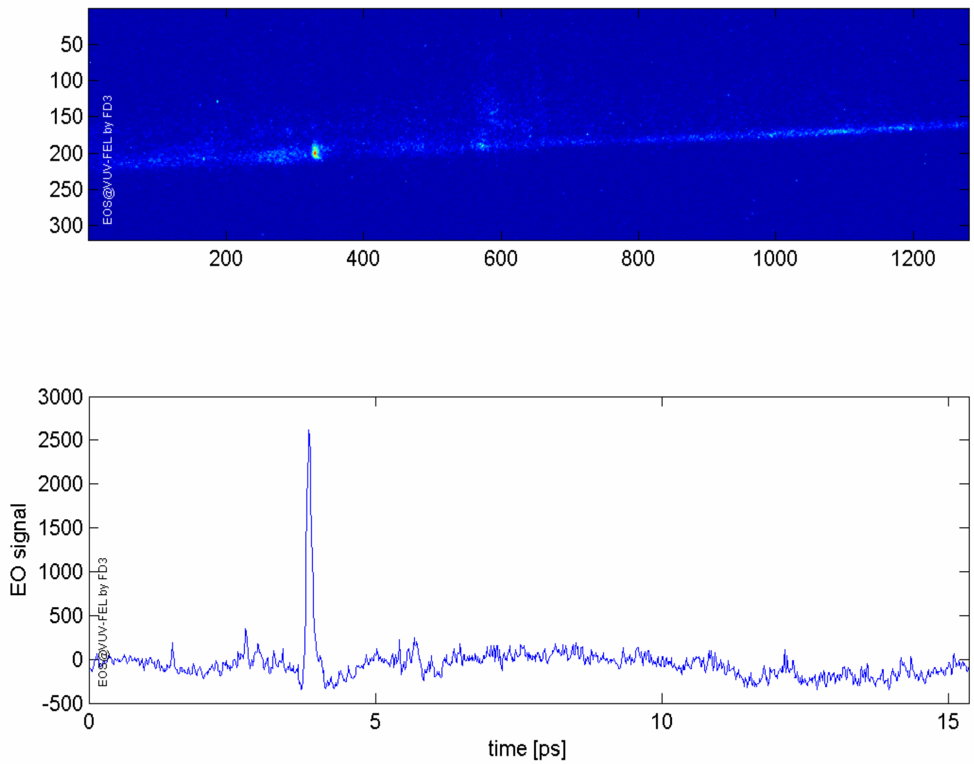
Spatial Decoding:

+ simple laser system
+ high repetition rate
+ high resolution (**170fs, ZnTe**)
- more complex imaging optics

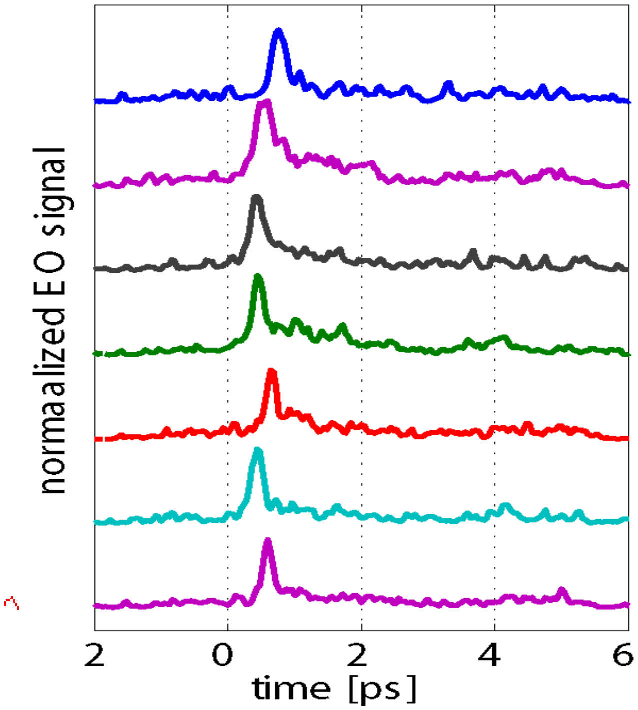


Courtesy: B. Steffen et al

Results on temporal decoding
- cross-check of theory -



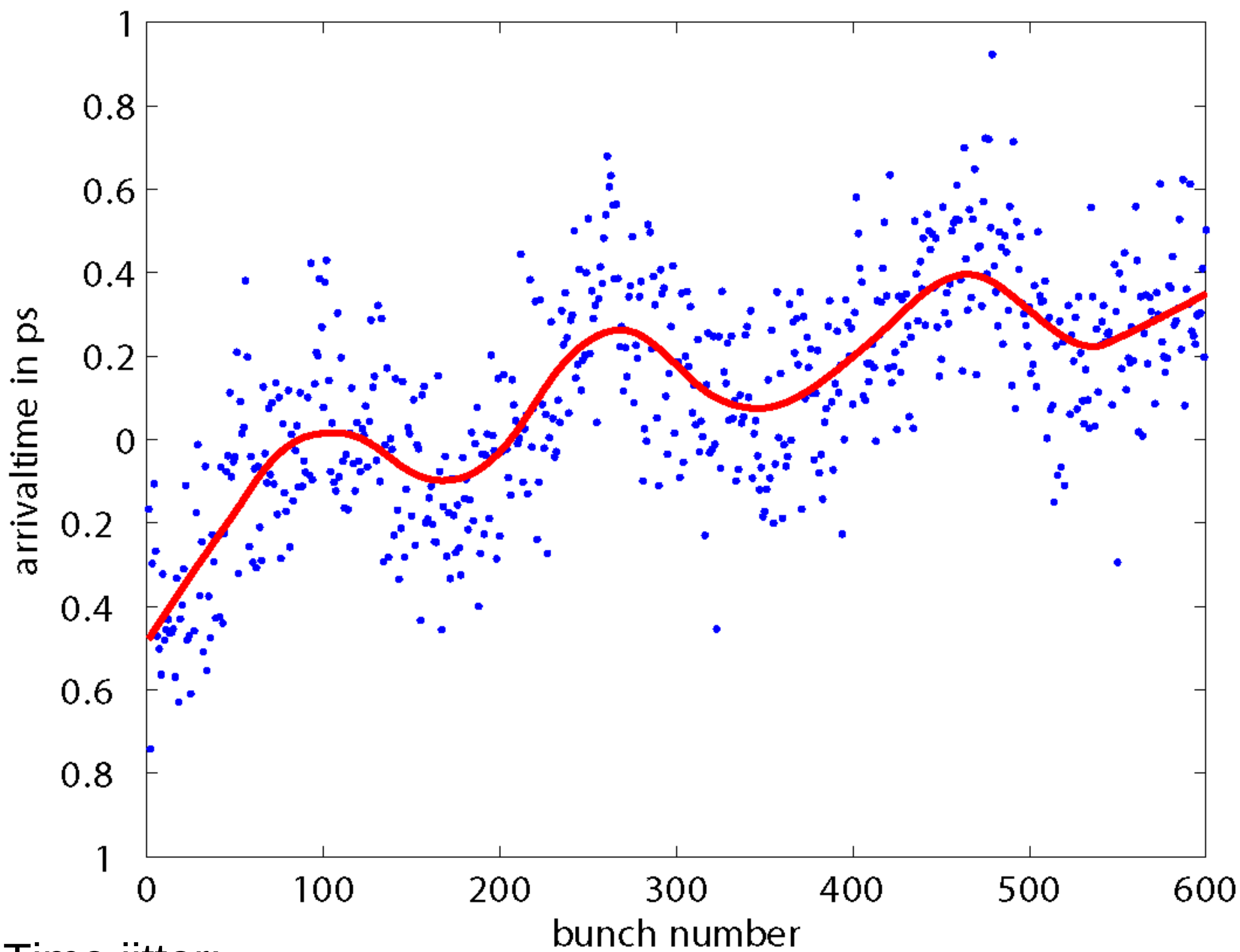
Typical measurement at medium compression



EO signals seen: typical 150 fs-200 fs (FWHM) with GaP, corresponds to 220-290 fs for e-bunch due to crossed polarizer setup.

Courtesy: B. Steffen et al (DESY)
G. Berden (FELIX)
S. Jamison et al (Dundee)

Time jitter measured by EO-SD



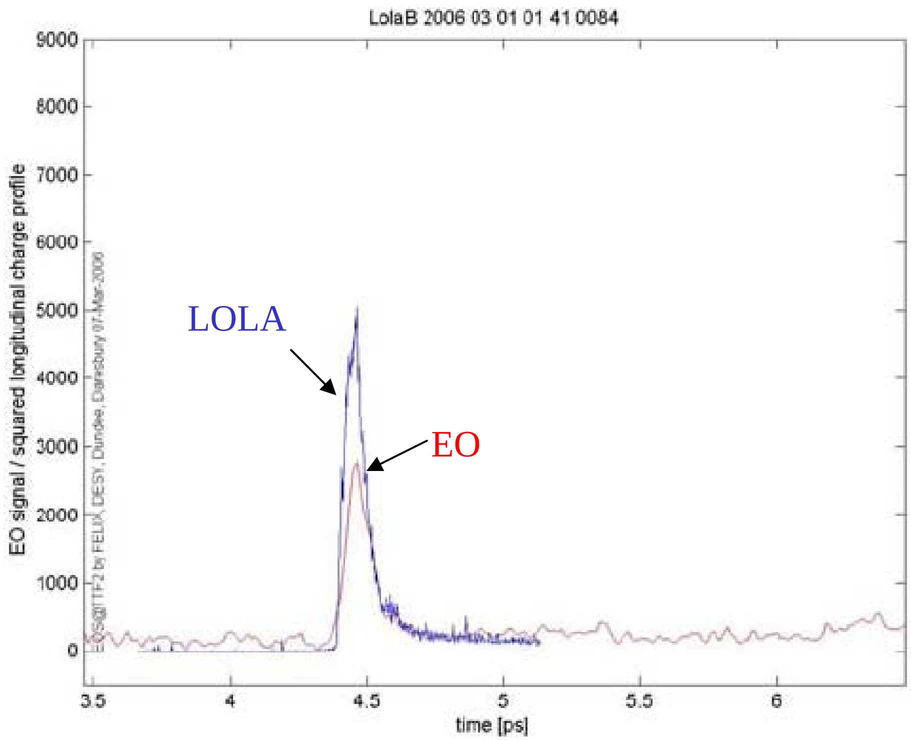
Time jitter:

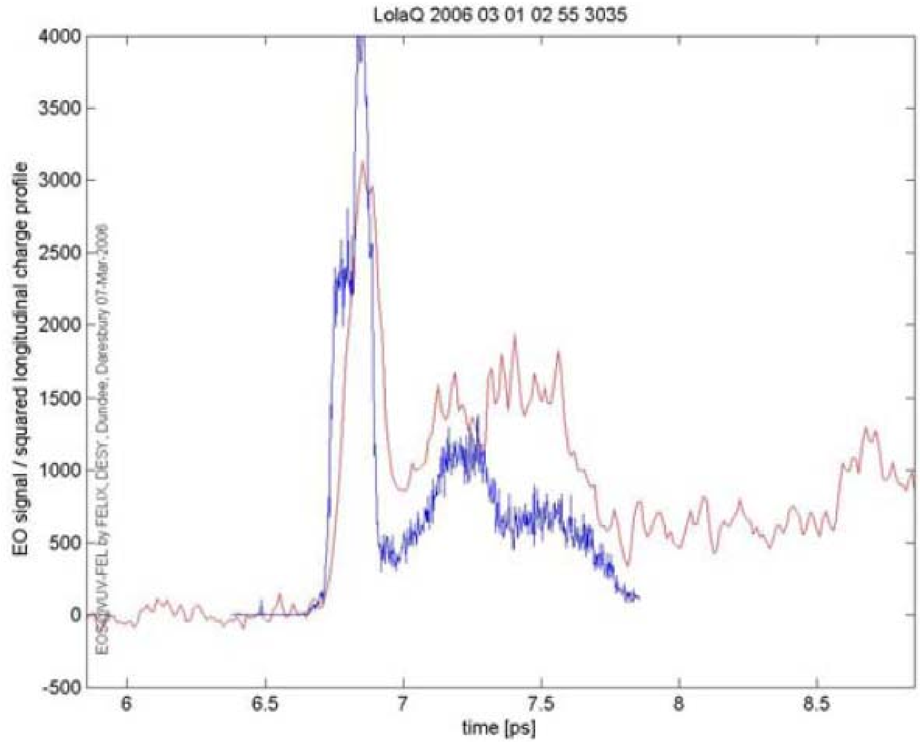
- here 270 fs (rms) over 5 min incl. slow drifts
- without slow drifts typically <200 fs (rms)

Courtesy: B. Steffen et al (DESY)

EO measurement and LOLA

Longitudinal profile for two different compression scenario





red: temporal decoding

blue: squared signal from a transverse deflecting cavity

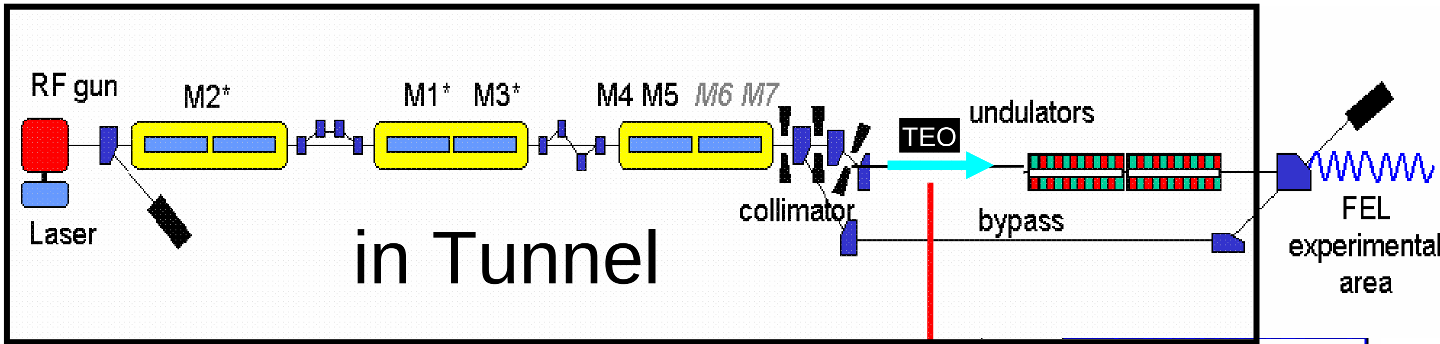
Reasonable good agreement, cross-check for resolution!

needs further analysis …

Courtesy: B. Steffen et al (DESY)
G. Berden (FELIX)
S. Jamison et al (Dundee)

Timing between pump-probe laser & FEL

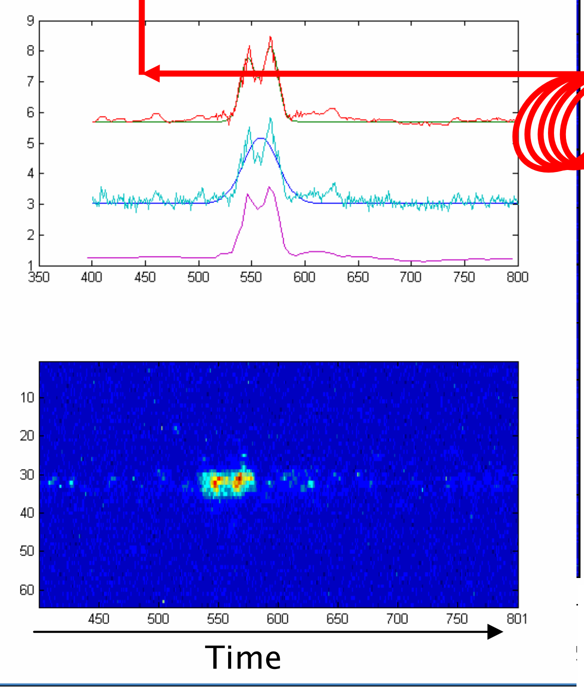
- Transport of laser pulse critical

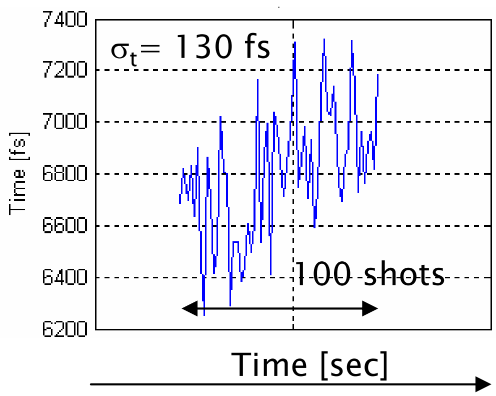


150m

Pulse in fiber will be broadened (50 fs to 0,4 ns)

and distorted due to high order dispersion (~100 pulses seen)

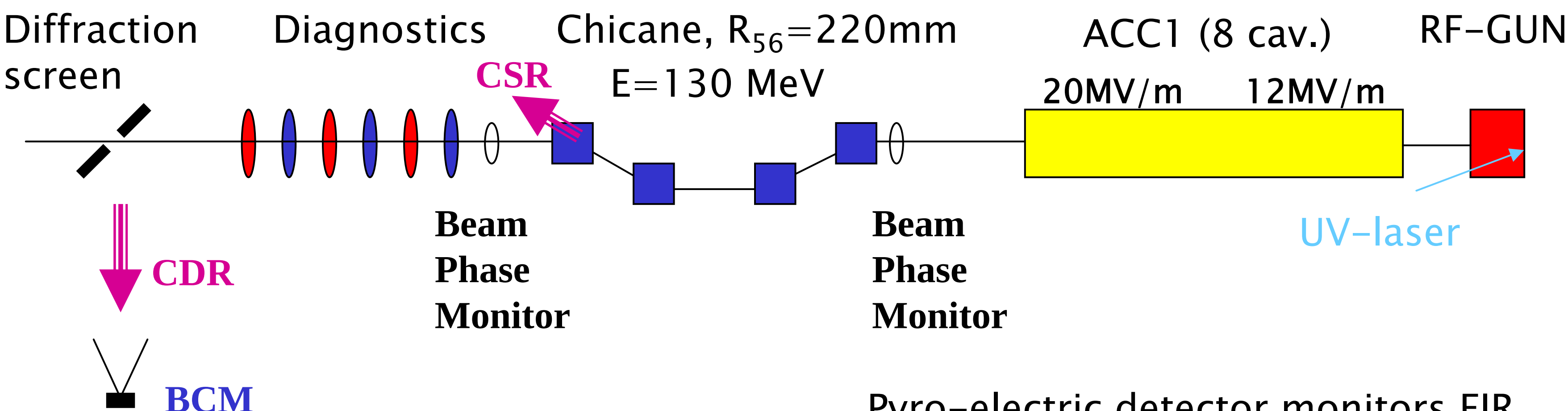




Courtesy: Armin Azima DESY
D. Fritz/A. Cavalieri
Michigan

4/6/2006

Beam compression monitor (BCM) for RF ACC1 feedback



$$P = P_0(\lambda)\, T(\lambda)\, \rho^2(\lambda)\, N_e^{\,2}$$

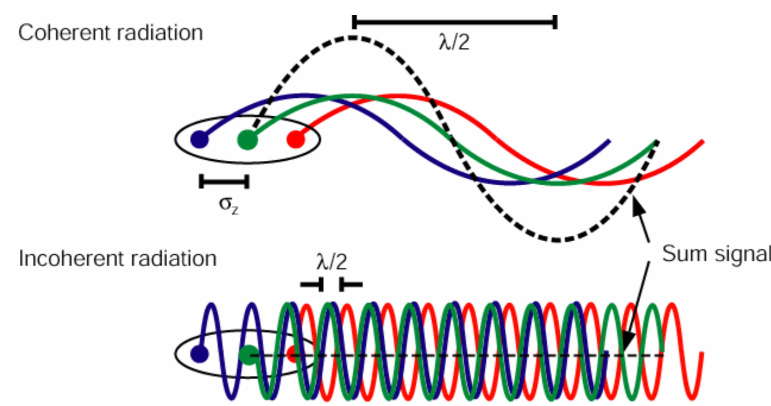
Form factor of bunch

Transfer function + detect response

Power emitted by single electron

Energy detected from bunch ~ $1/\sigma_z$

Pyro-electric detector monitors FIR power emitted by diffraction radiator

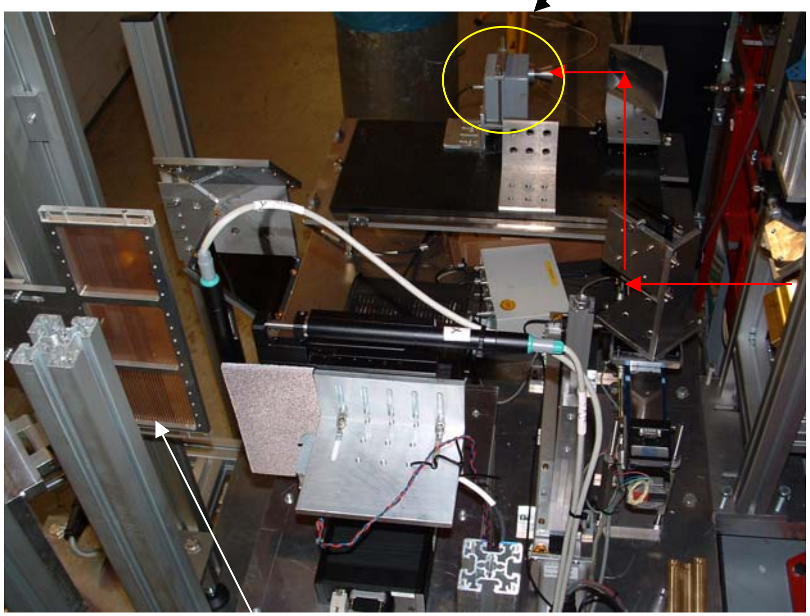


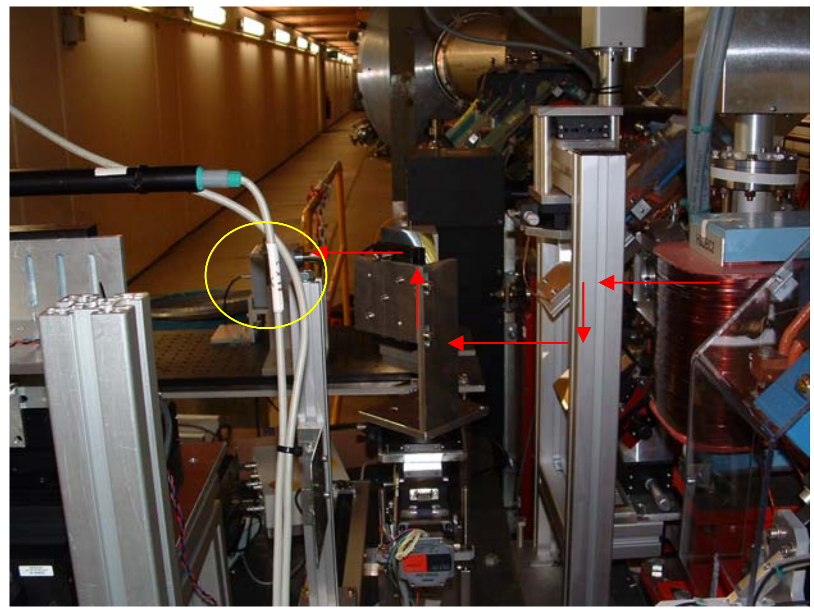
Beam compression monitor (BCM) for RF ACC1 feedback

Top view

Detector unit

Front view

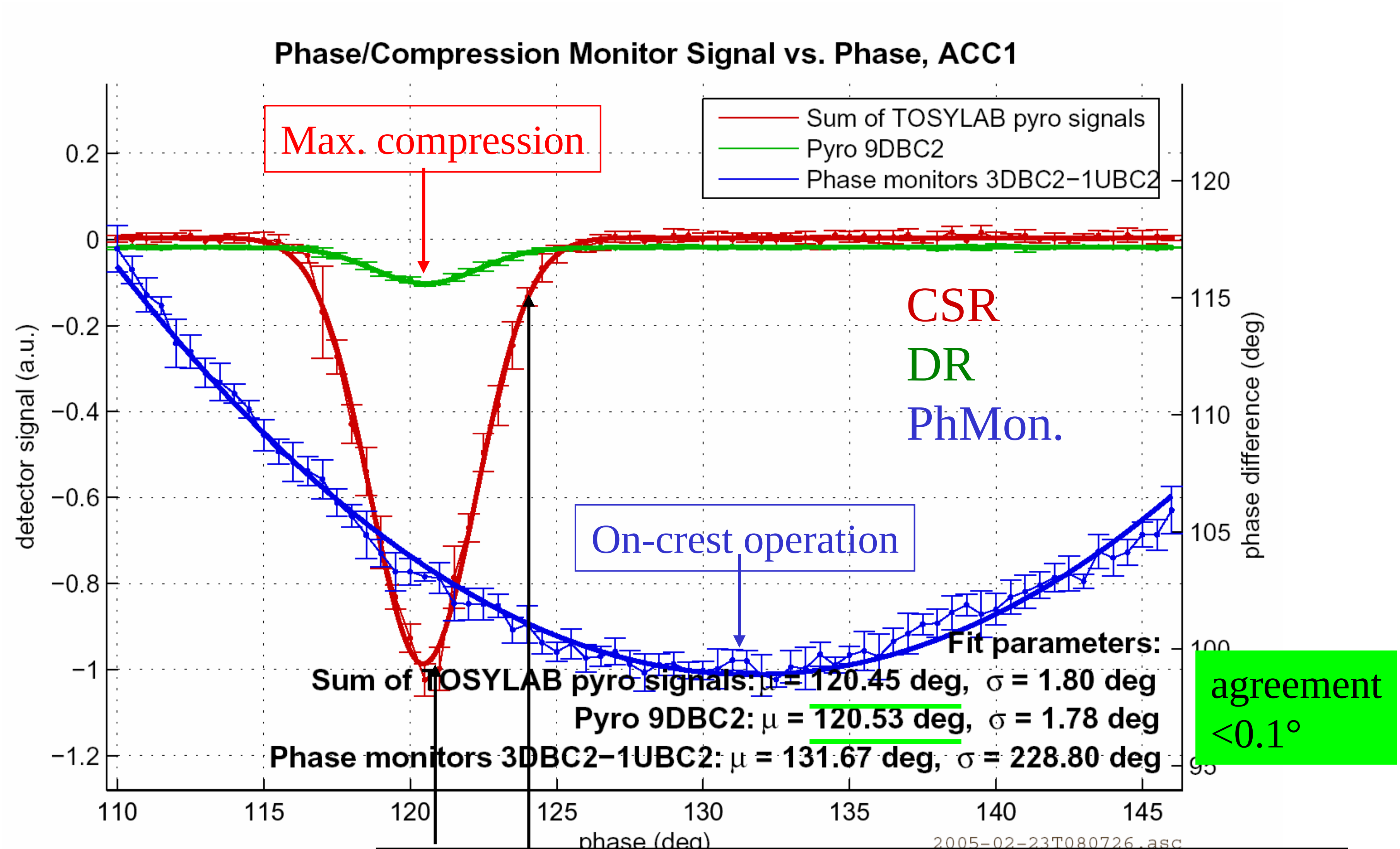




Single shot FIR spectrometer (still R&D)

Courtesies: B. Schmidt, H. Delzim, O. Grimm (see FEL2005)

Beam compression monitor (BCM) for RF ACC1 feedback



Typical operation for SASE FEL, to lock ACC1 with FB

Summary

No longitudinal measurement technique fulfill all requirements

- high resolution to ~ 10 fs level
- non-invasive, suited for macro-pulse operation ~ 3000 bunches
- single shot and bunch to bunch readout
- fast processing time ~ 200 ns for fast longitudinal feedback system (mapping to line array)

⇨combination of methods required

Transverse deflecting structure:

allows for precision measurement (longitudinal prof., slice emittance/energy)
cross-calibration of other techniques

Electro-Optical & Coherent radiation monitors:

for tracking bunches in macro-pulse and
operation of longitudinal feedback systems

Outlook: 2007 installation of optical replica synthesizer (< 5fs resolution)
in cooperation with Uppsala & Uni. Stockholm

Summary II:

remains a challenging area

but very exciting too!