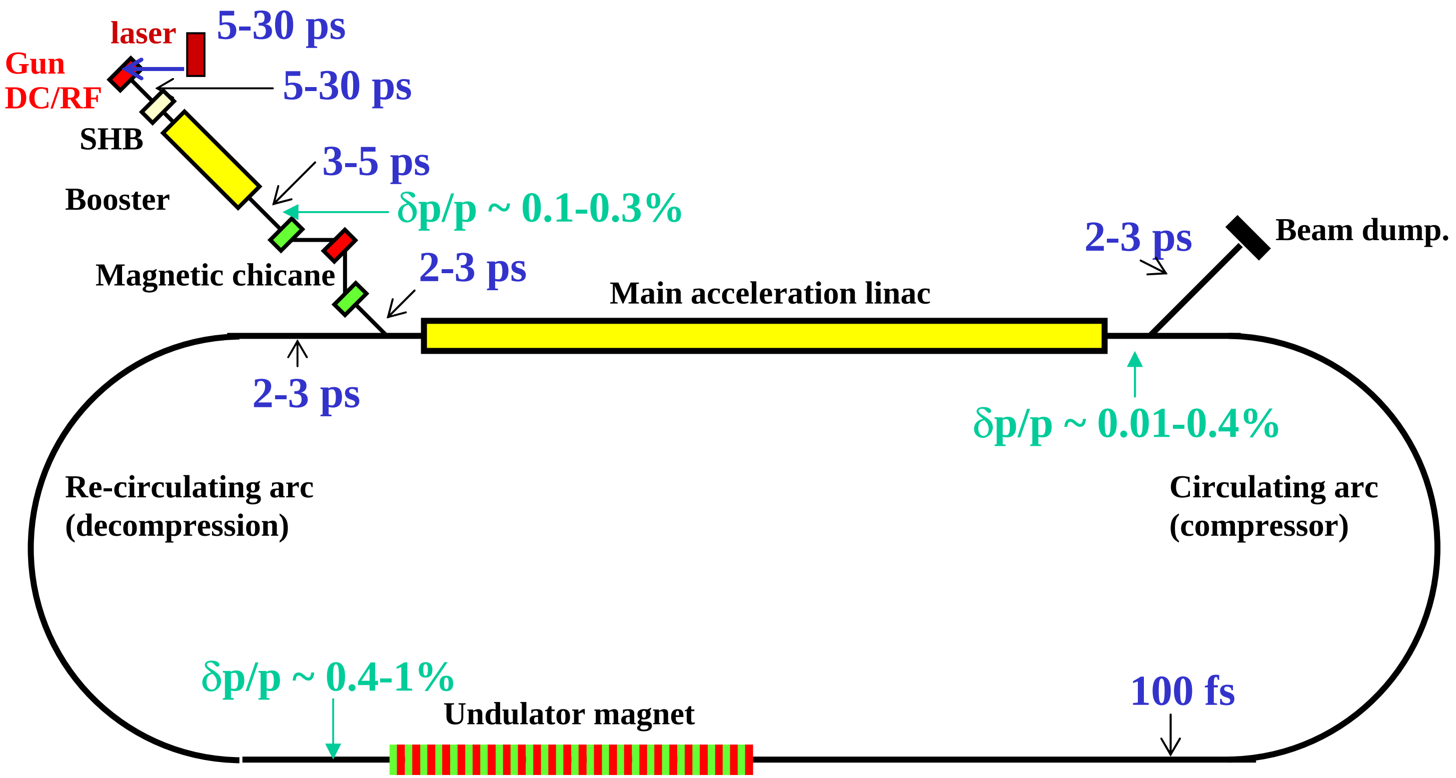
Overview on the longitudinal diagnostics for ERLs

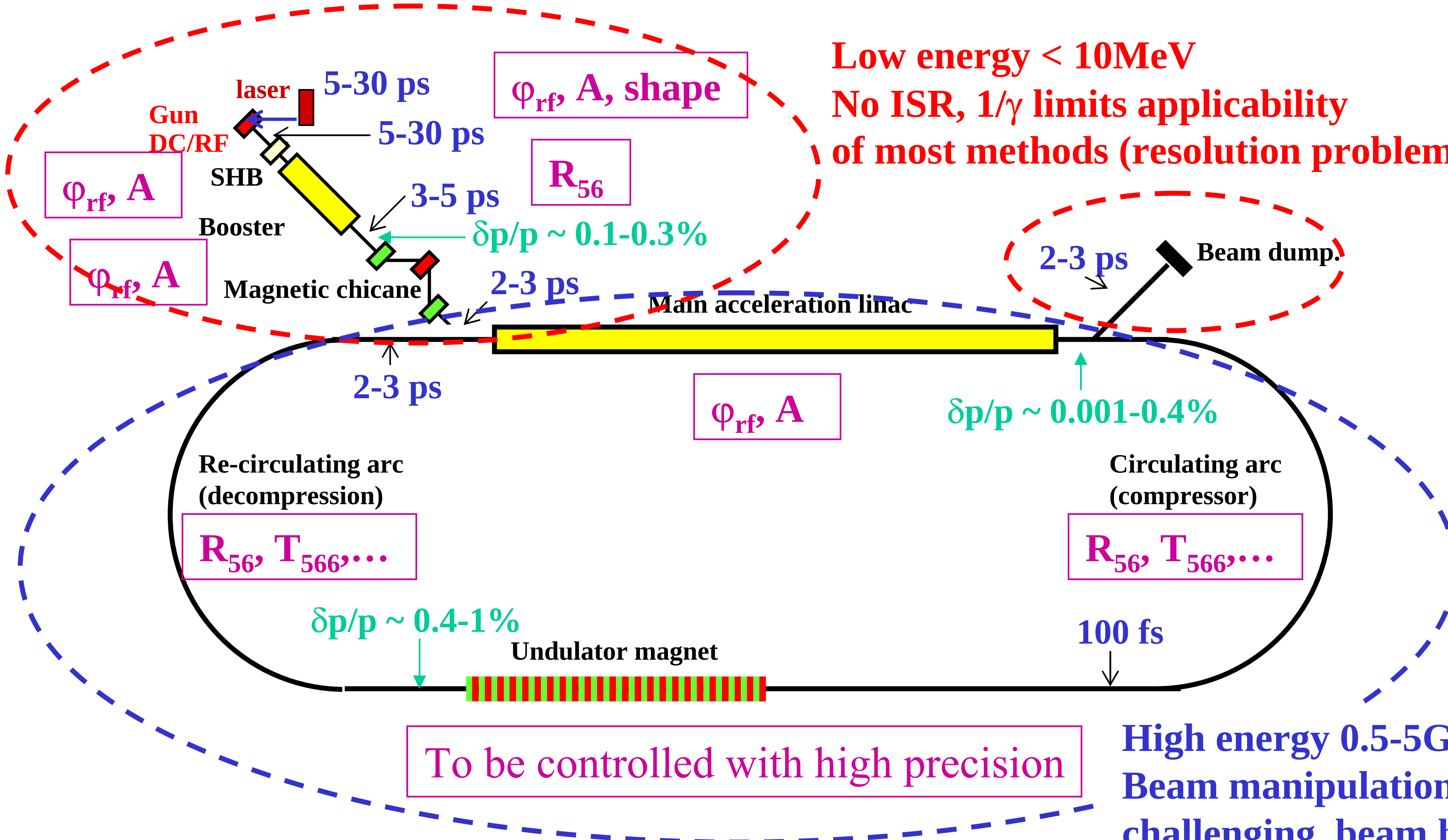
Holger Schlarb
DESY
22607 Hamburg

- introduction
- injector & energy spread
- coherent radiation diagnostics and feedback
- ultra-short pulse diagnostics

Prototype Layout for ERL



Prototype Layout for ERL



Low energy < 10MeV
No ISR, 1/γ limits applicability
of most methods (resolution problems)

High energy 0.5-5GeV
Beam manipulation more challenging, beam highly destructive,
10fs resolution desired!

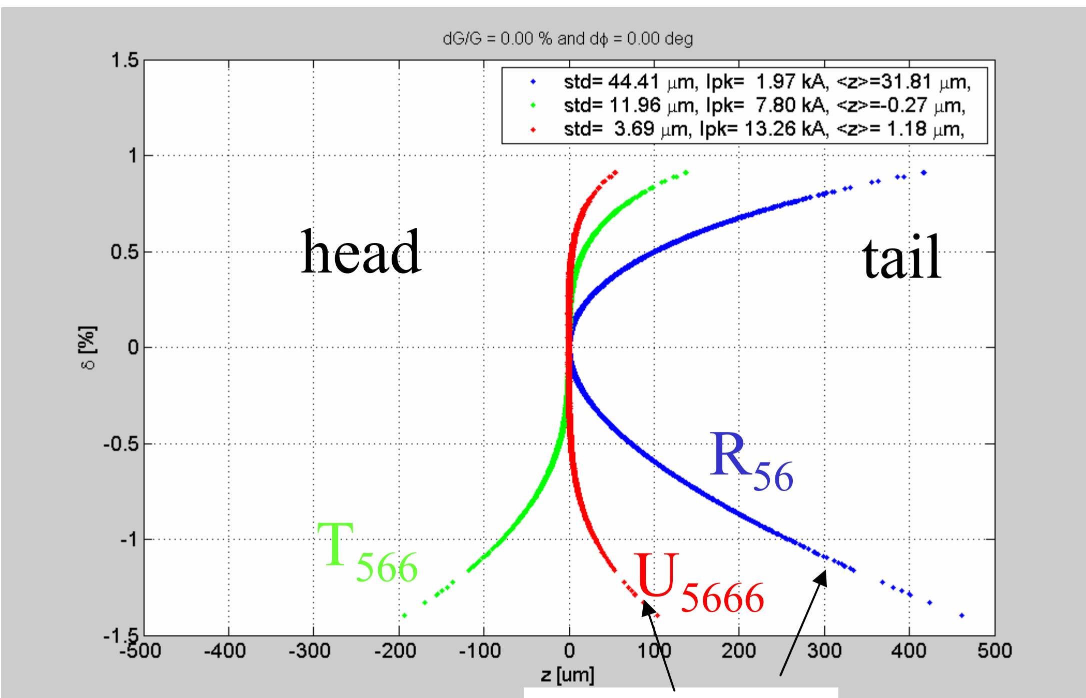
Bunch compression

Low energy spread can cause trouble …

I spike $\rightarrow$Min(σ_z) $\propto$ σ_{E0}/E, CSR: dE/E $\propto$ min(σ_z)$^{-4/3}$/E $\propto$ E$^{1/3}$

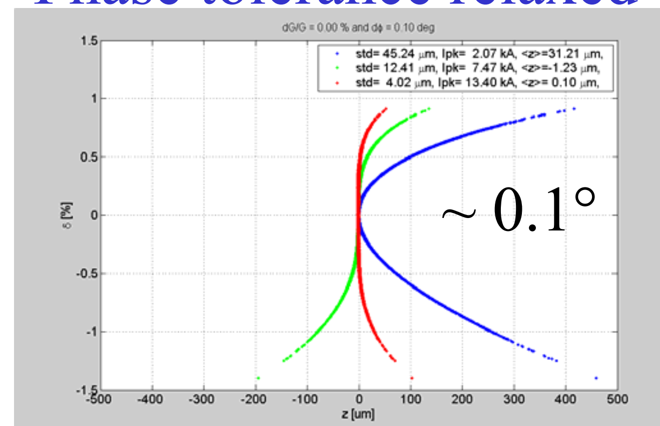
$\Rightarrow$Effect increase with energy

Example: CHESS, E=5.3GeV, σ_{E0}=10keV, 77pC

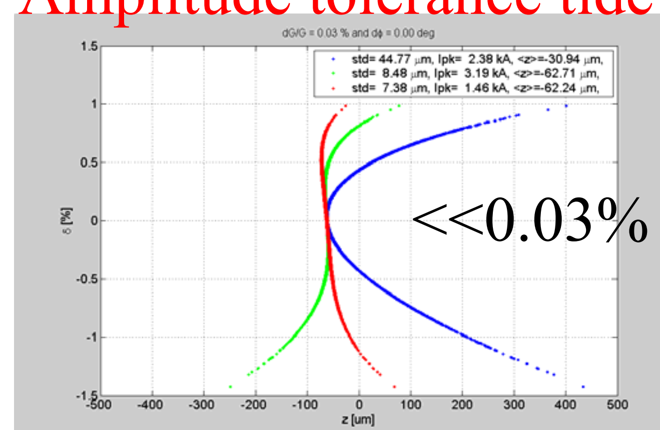


Cross over

Phase tolerance relaxed



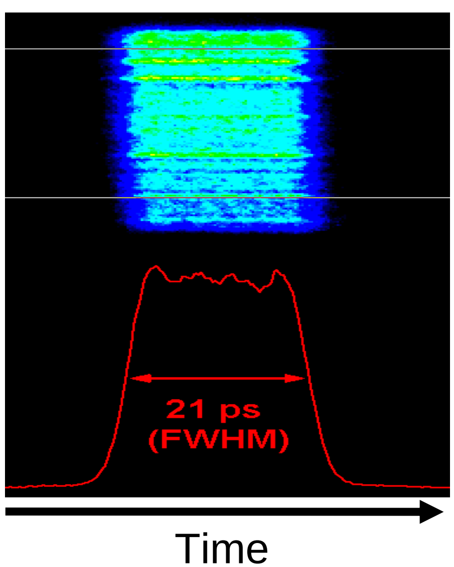
Amplitude tolerance tide

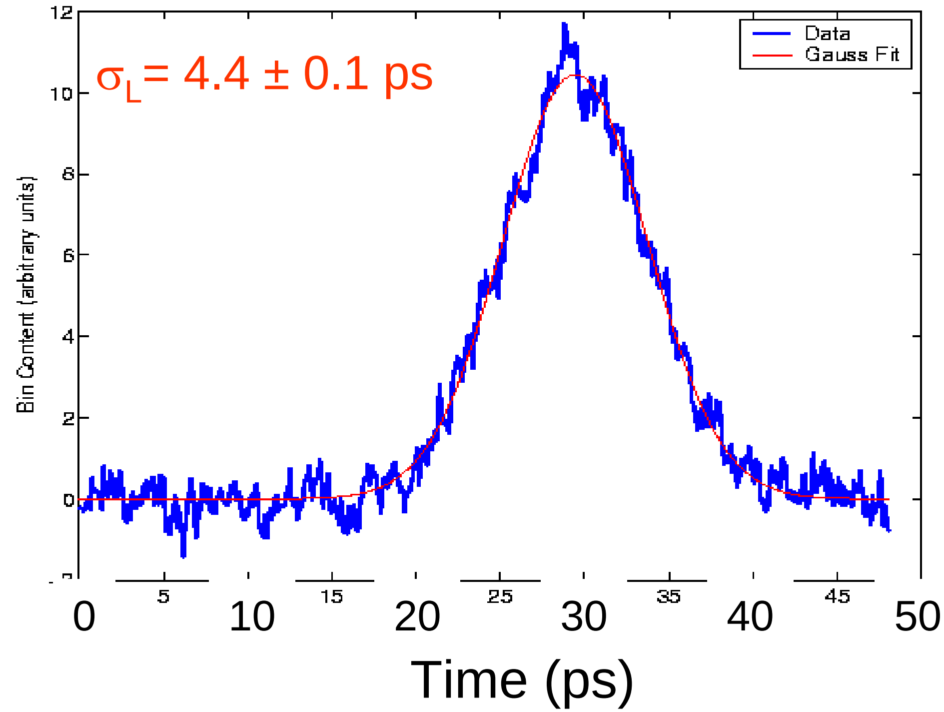


Longitudinal laser profile

Streak camera:

- UV single laser pulse, measured with a streak camera (FESCA 200)
- Average over 50 measurements gives $\sigma_L = 4.4 \pm 0.1$ ps (as expected)
- Longitudinal shape is Gaussian
- Or flat hat profile …





Optical techniques:

- if laser pulses shorter than 1 ps

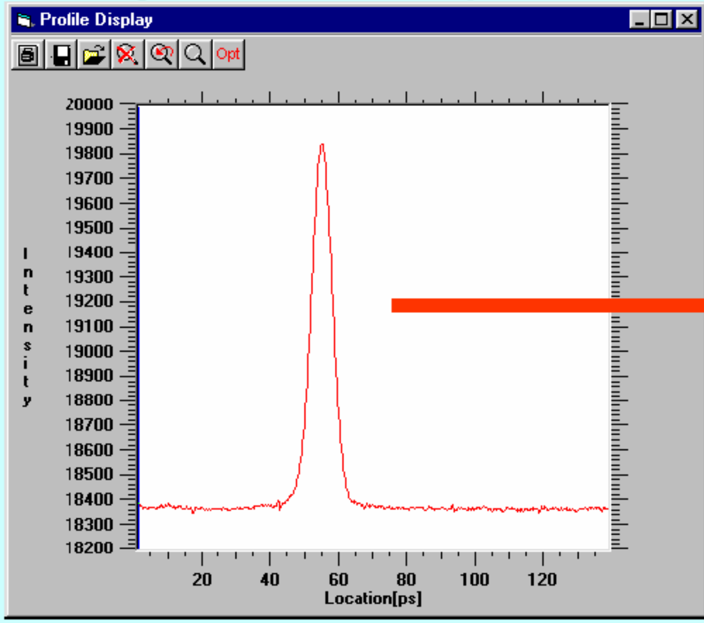
$\Rightarrow$ SHG auto-correlation

$\Rightarrow$ FROG

to achieve higher resolution.

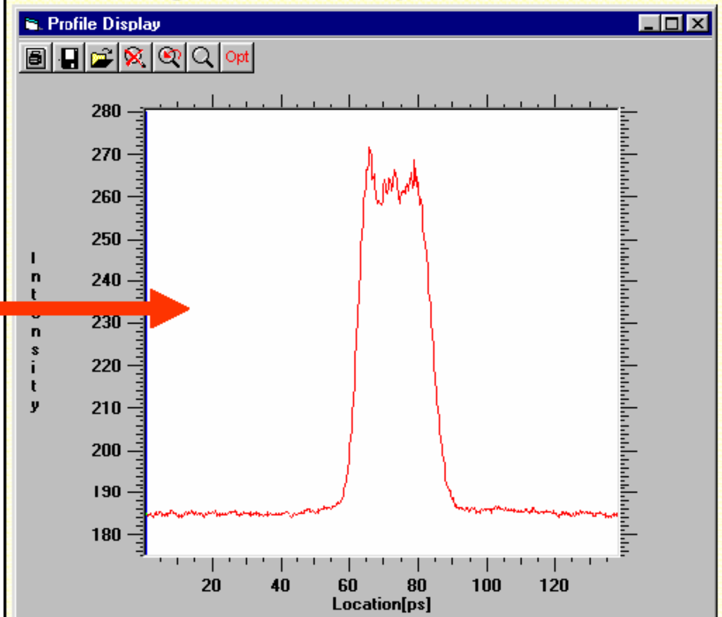
Longitudinal laser profile

Until 23.06.2003 - Gaussian longitudinal laser shape:



FWHM = 7 ± 1ps

On 23.06.2003 longitudinal shape changed to flat top



FWHM ≈ 18-23 ps
rise and fall time about 5-8 ps

Minimum measured emittance

≥ 3 mm mrad

1.6 mm mrad

Phasing of RF gun

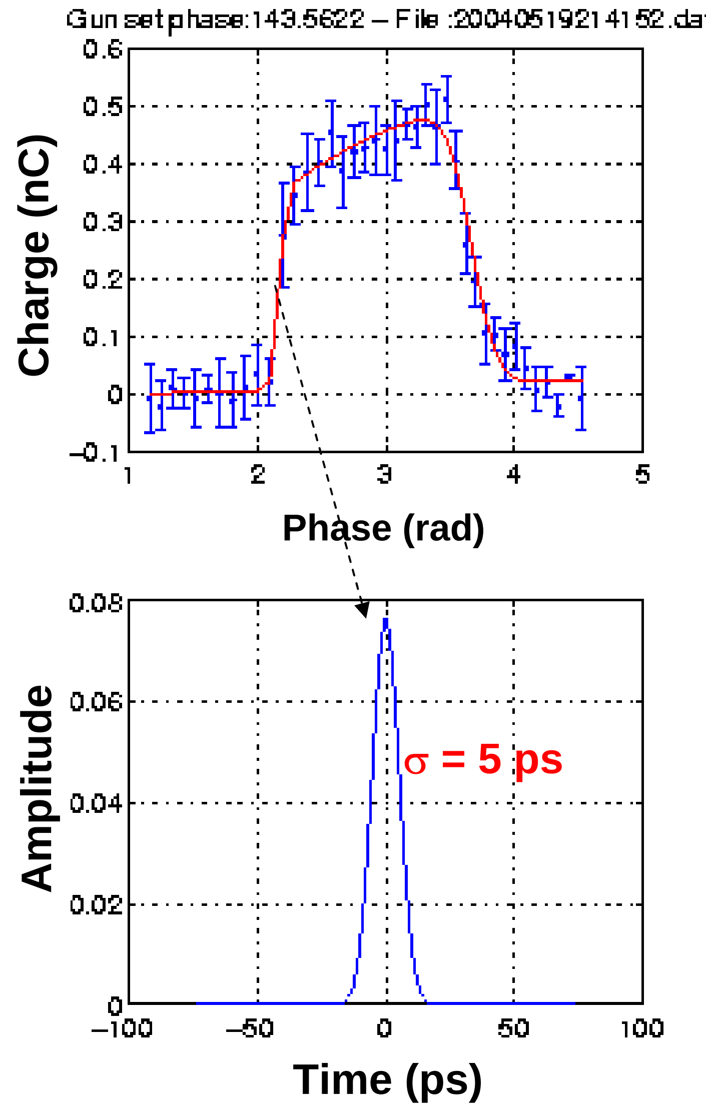
- Measure charge output of the gun as a function of phase laser/gun RF

- Important and fast method to
  - → determine the phase of the laser in respect to the gun RF
  - → to detect longitudinal problems of the laser (satellites, phase jitter etc.)

- We use a fit to the expected shape to chose the right phase:
  - → reproducibility = ± 1.3° (rms)

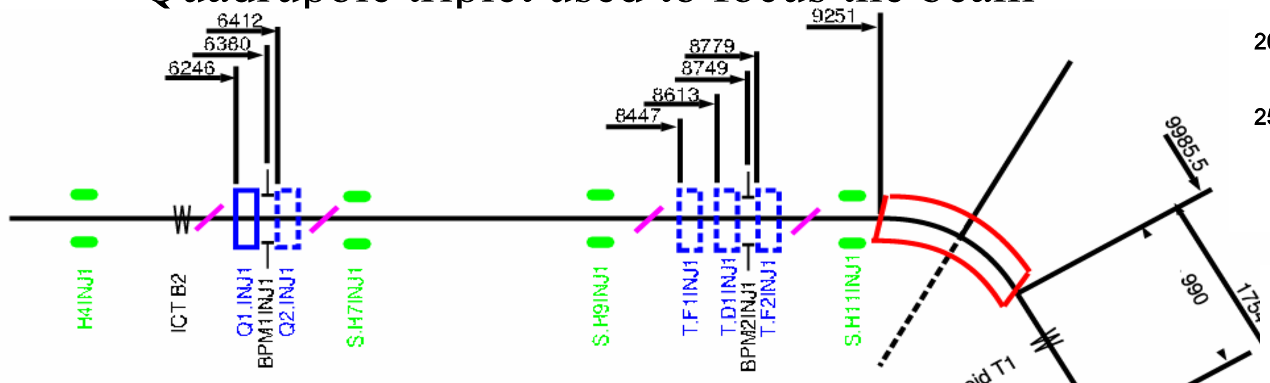
- It gives an estimate of the laser pulse length from the derivative of the rising edge

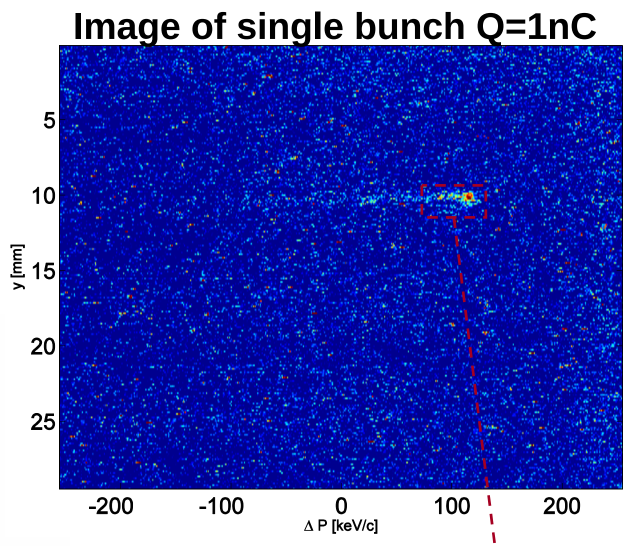
- Invasive ⇒ relevant commissioning

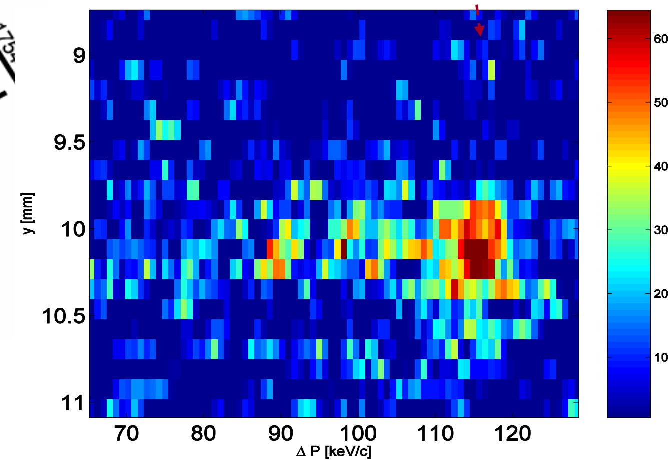


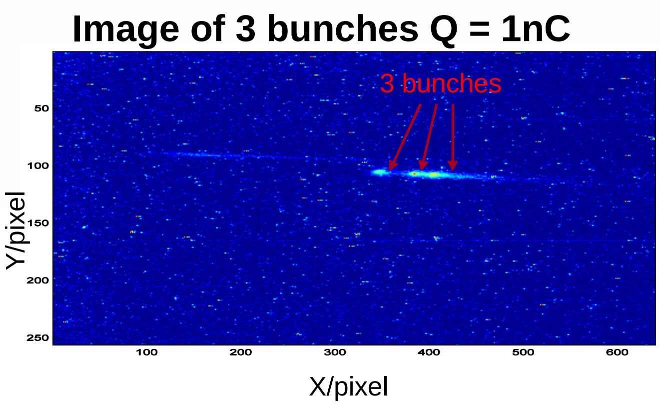
Energy spread measurements

- Screen in dispersive section + tight focusing
- Spectrometer dipole with 60° bend
- Dispersion at OTR screen D = -1.367m
- Diagnostics: BPMs and toroids
- Quadrupole triplet used to focus the beam





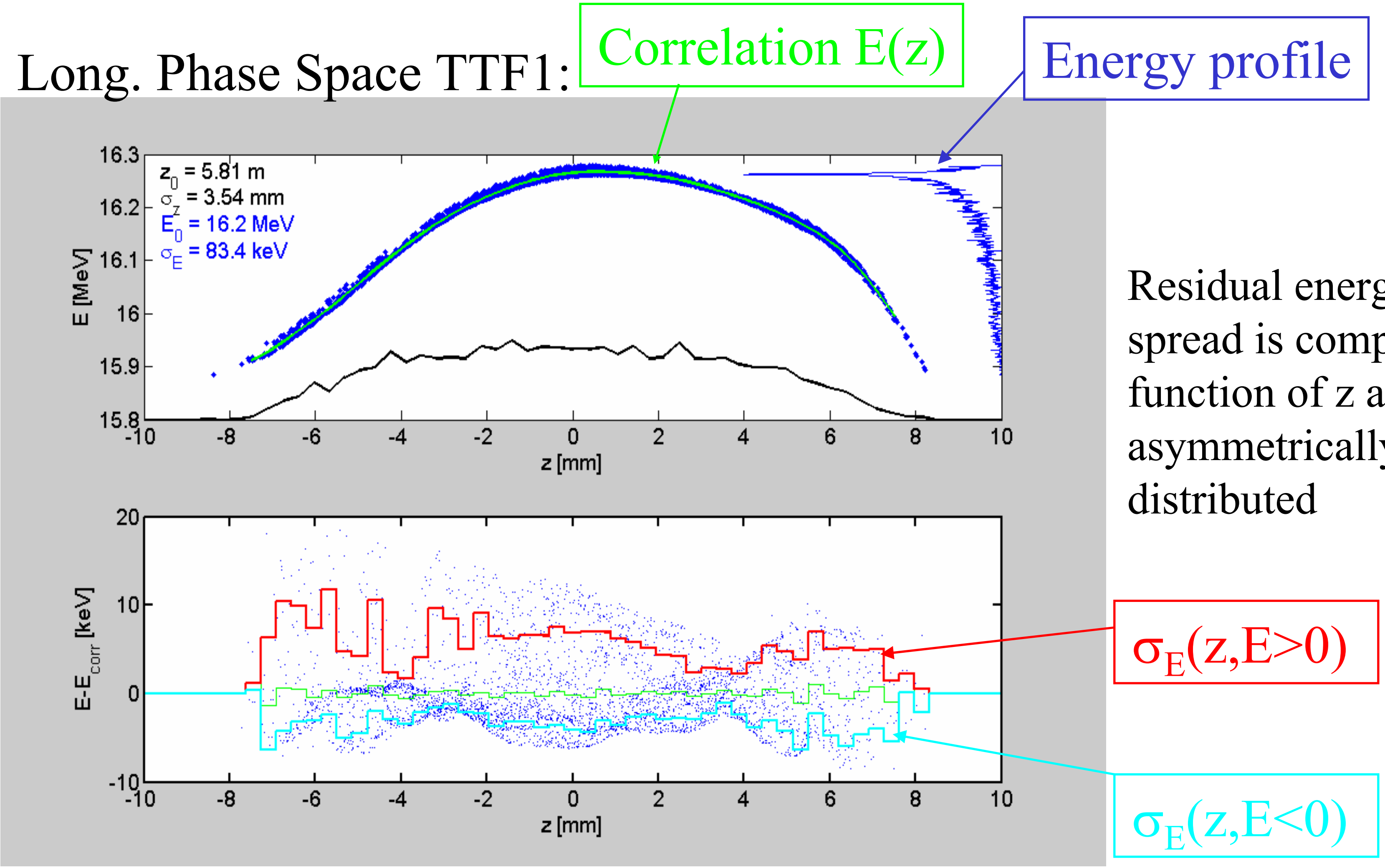




Large low energy tail of about 100 keV but very small residual energy spread 2-4 keV (rms)

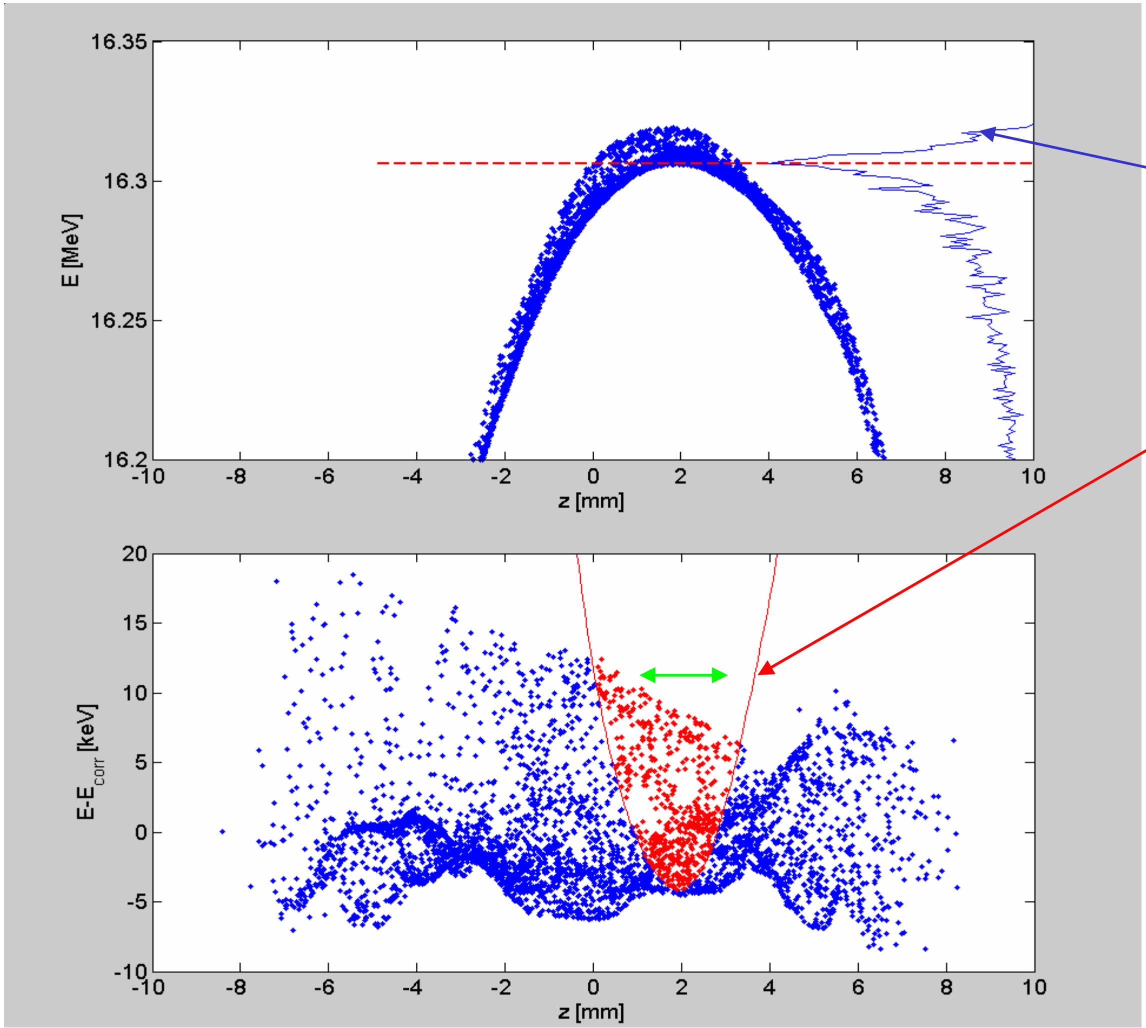
Energy spread measurement - correlated & residual -

Long. Phase Space TTF1:



Residual energy spread is complex function of z and asymmetrically distributed

Energy spread measurement - residual -



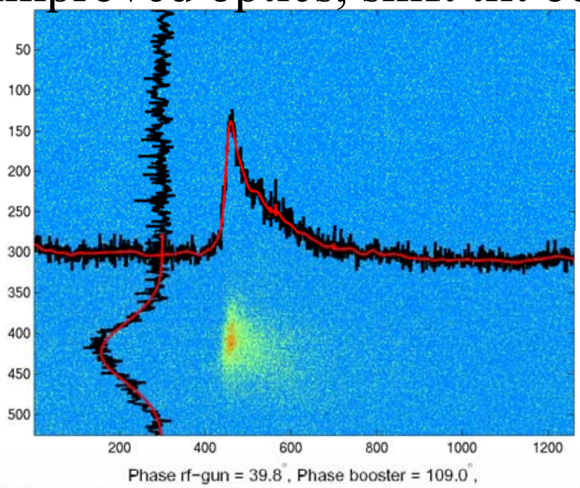
Rising of energy profile is determined by the residual energy spread of particles surround by parabola

Rms width of surround particles amounts to $\sigma_{z,para} = 0.68$ mm

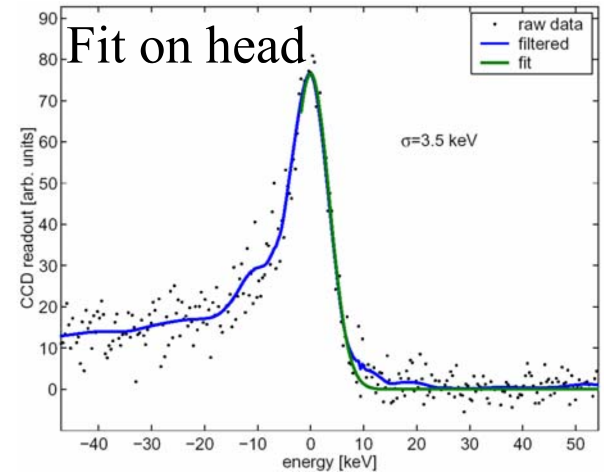
$\Rightarrow$ slice of $0.2^* \sigma_z$

Energy spread measurements - residual -

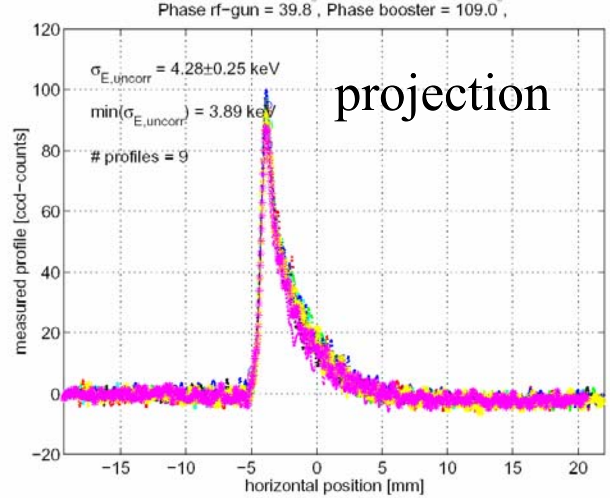
Improved optics, shift tilt obj.



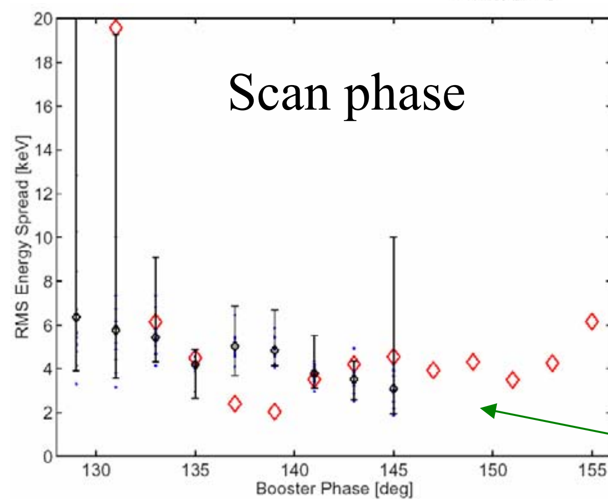
Fit on head



projection



Scan phase



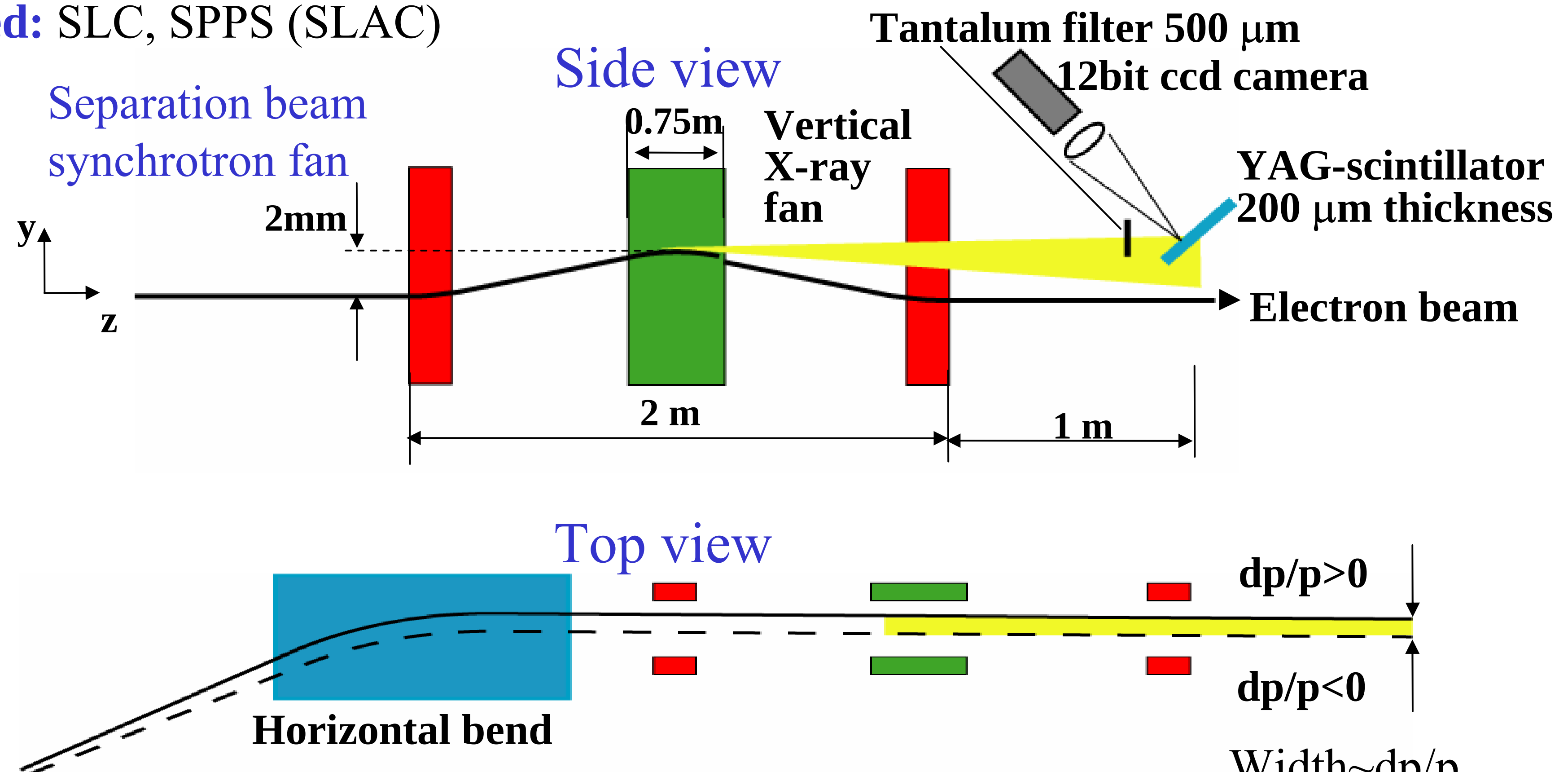
Conditions:
E = 16.3 MeV
Q = 3 nC
20 ps FWHM

2-5 keV

3/24/2005 Holger Schlarb, DESY

Energy spread measurement
-online using vertical chicane -

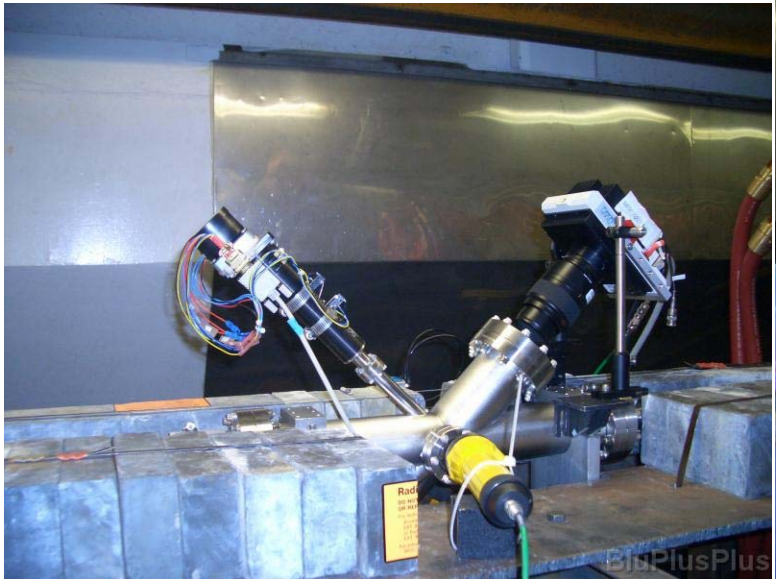
- **Goal:** online, non-interceptive beam energy spread measurement
- **Basic idee**: ISR produced in vertical chicane located in section with large horizontal dispersion
- **Tested:** SLC, SPPS (SLAC)



Experiment prepared by E164 group SLAC, C. Barns

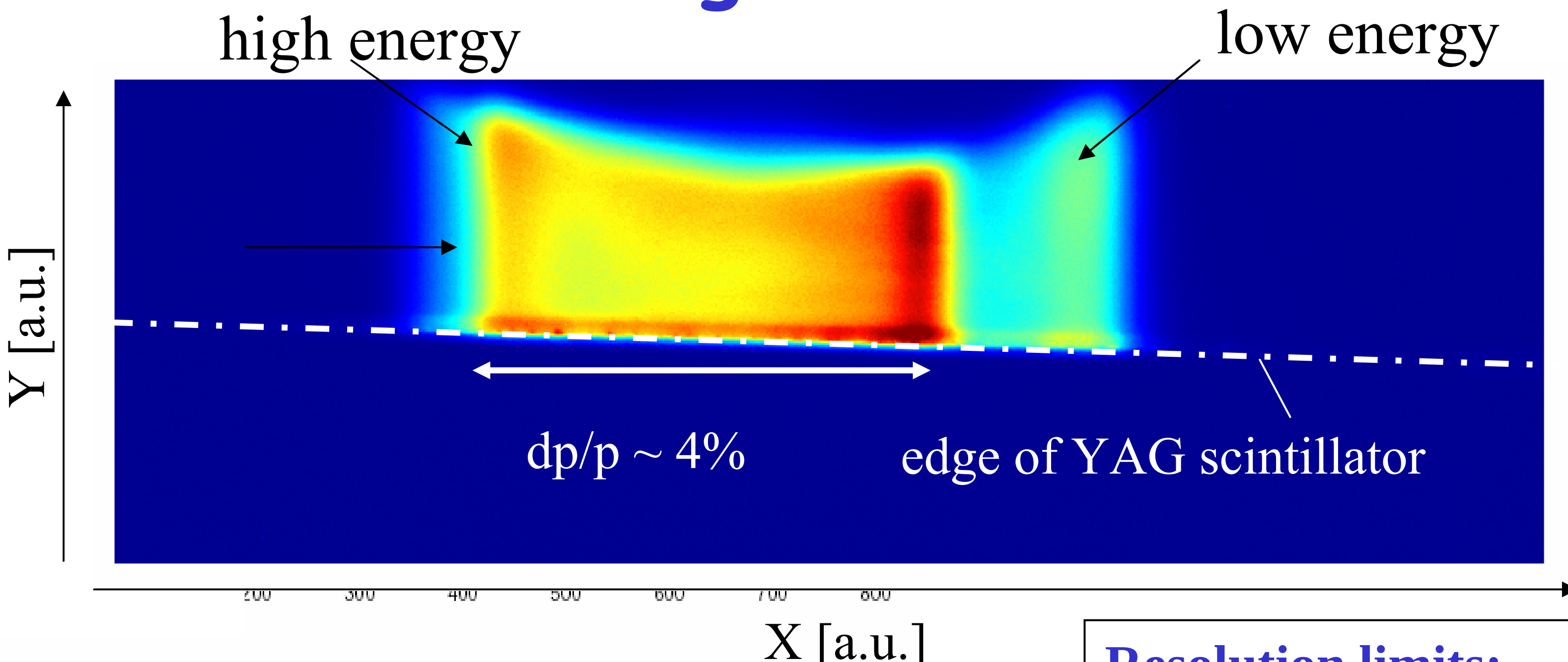
Energy spread measurement
-online using vertical chicane -

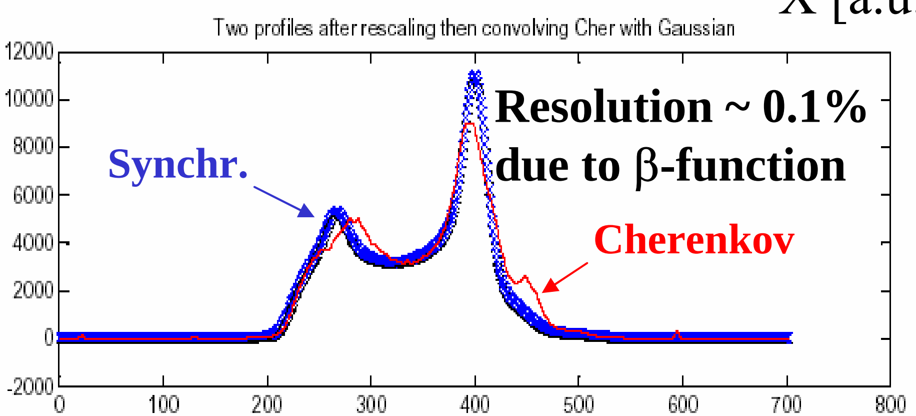
- installation in FFTB tunnel
- old wiggle used
- high resolution camera
- movable scintillator
- E = 28.5 GeV



Experiment prepared by E164 group SLAC, C. Barns

Energy spread measurement
-online using vertical chicane -





Resolution limits:

Beam size: $dp/p \sim \sigma_x/D_x$

Energy: $dp/p \sim \Delta z/\gamma$

(or x-ray imaging)

Blooming in YAG: ~ thickness

$dp/p < 10^{-4}$ possible

$dp/p \sim 10^{-5}$ challenging

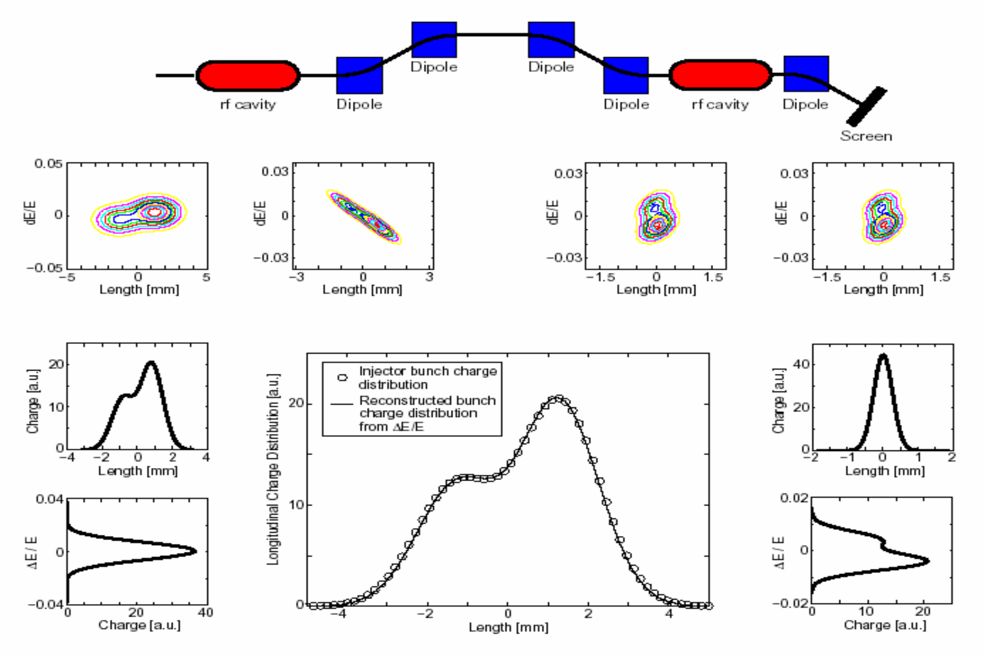
Experiment prepared by E164 group SLAC, C. Barns

Longitudinal tomography

Principle: 'rotation' of z-p phase space + imaging
reconstruction of long. phase space from profiles

Requires: complete picture only possible with $R_{56} \neq 0$

Ideal world:



Real world:

- compress change properties of z-p phase space (CSR, …)
- restricted to one accel. section
- limitation on acceptance of the beam line reduce projection to smaller angle (±60° is much)
- non-linear mapping

Longitudinal tomography

- Radon transformation: standard "Filtered back-projection algorithm"

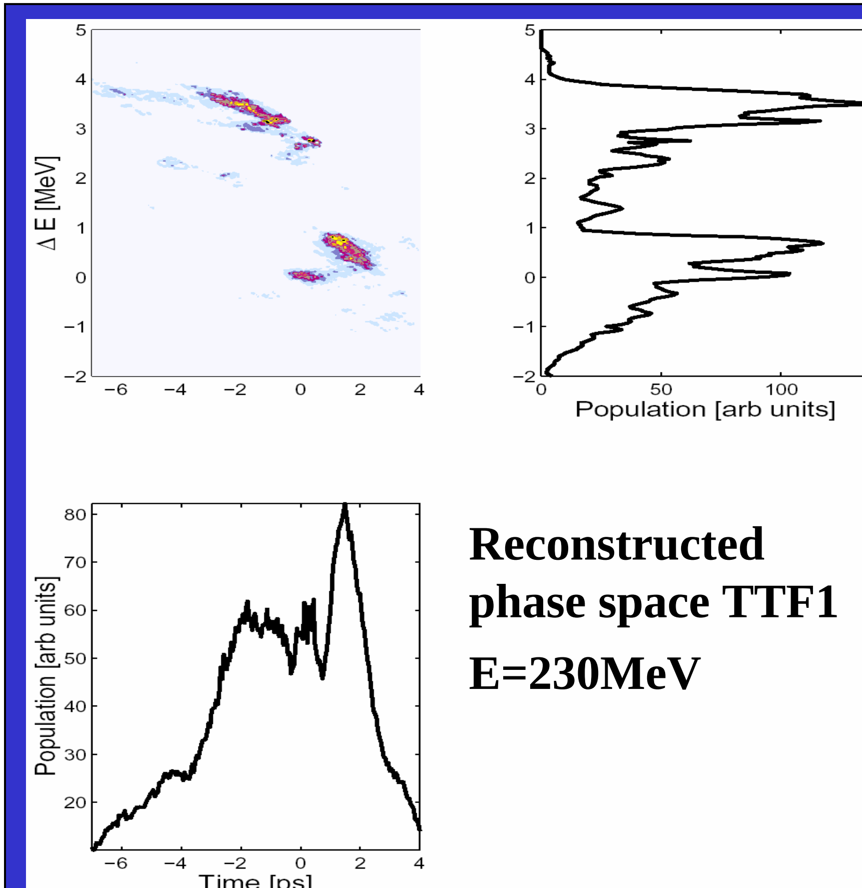
Better suited:

- ART: algebraic reconstruction technique, here
  MENT: Maximum Entropy Algorithm

(See i.e. J. Scheins, TESLA-Report 2004-08)

- Even complex structures can be can be reconstructed

- Disadvantage: multi-shot method, destructive

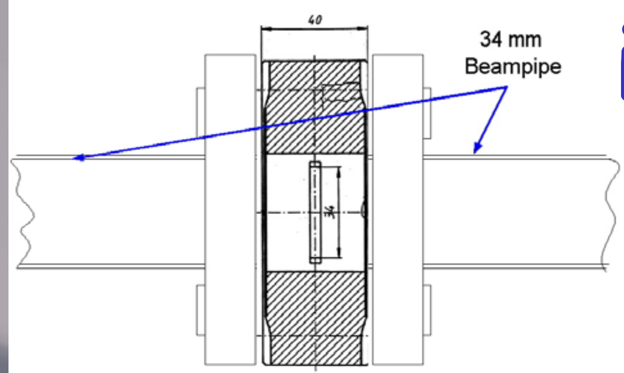


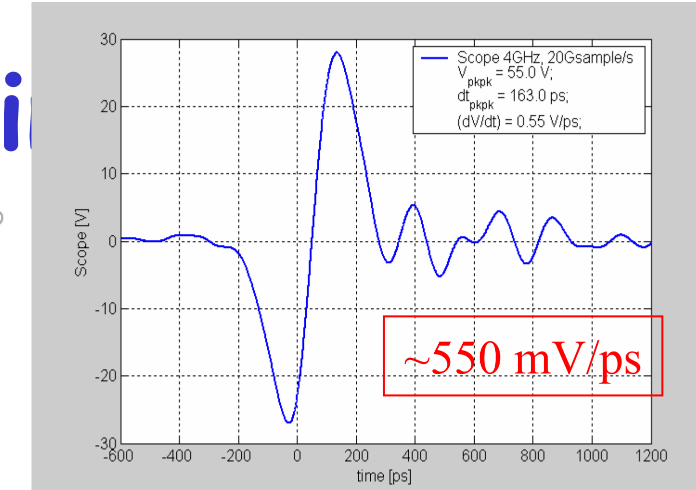
Reconstructed phase space TTF1

E=230MeV

PhD-Thesis, M.Hüning, 2002, Uni. HH

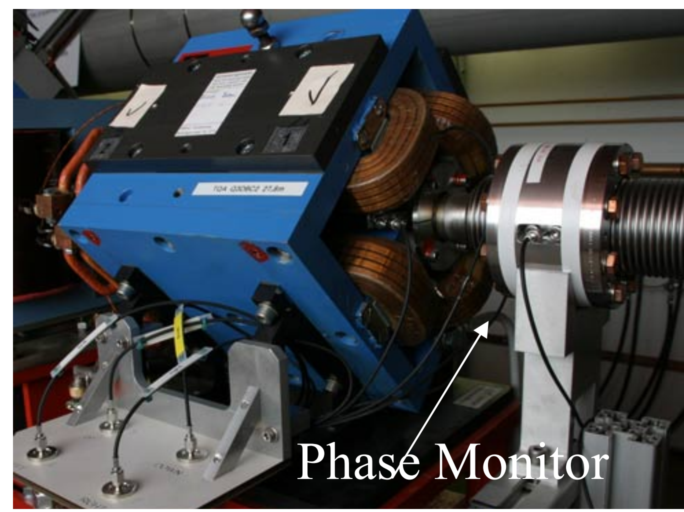
Phase monitor



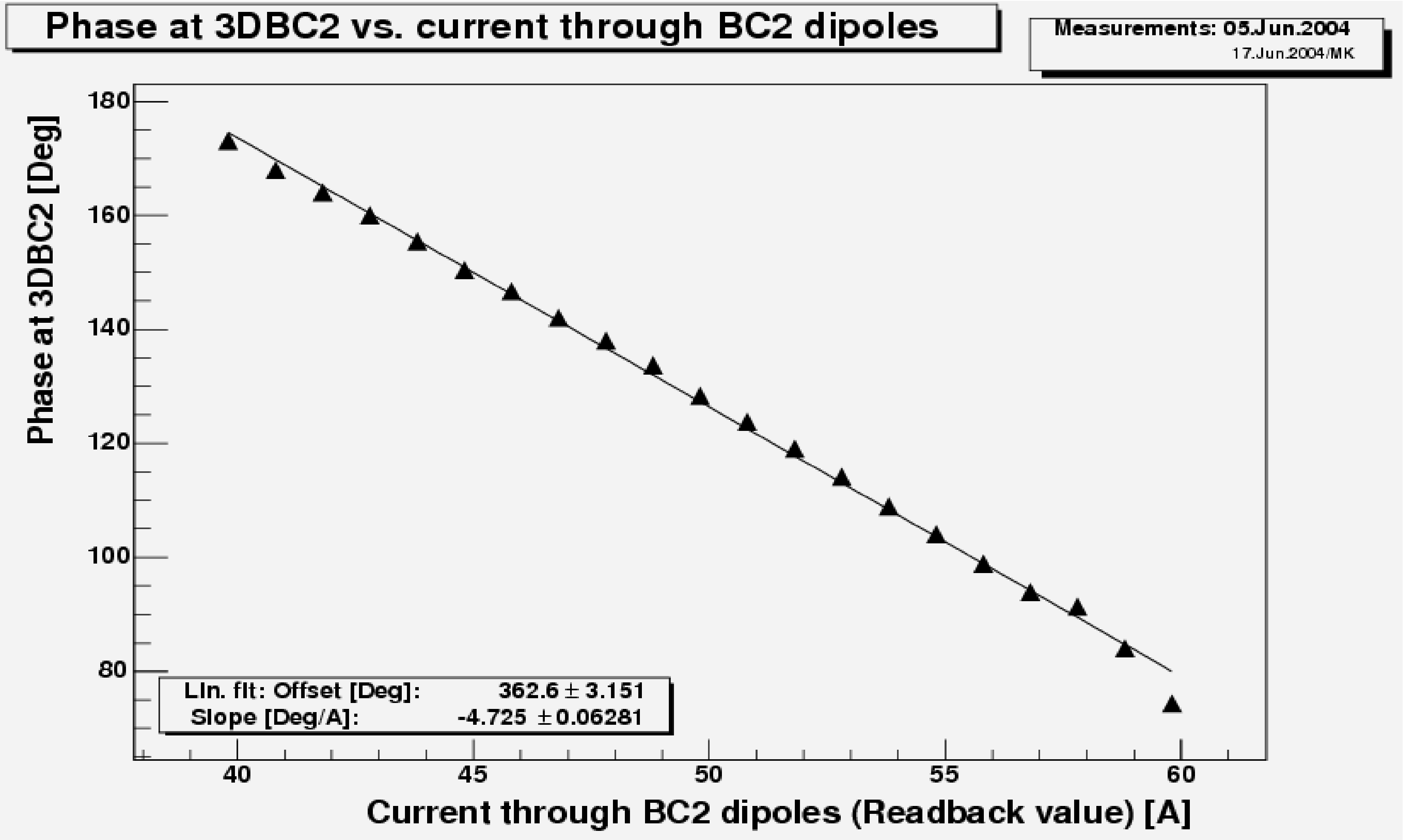


Principle:

- Isolated impedance-matched Ring Electrode installed in a „thick Flange“
- Broadband, Position independent Signal
- One installed after the Gun, each magnetic Chicane (both BCs, the Collimator + before Undulator)
- BC´s: Energy Fluctuations -> Phase Fluctuations TOF Measurement: Resolution ≈ 0.2° or 0.4 ps
- Fast timing signals with sub ps resolution



Phase monitor



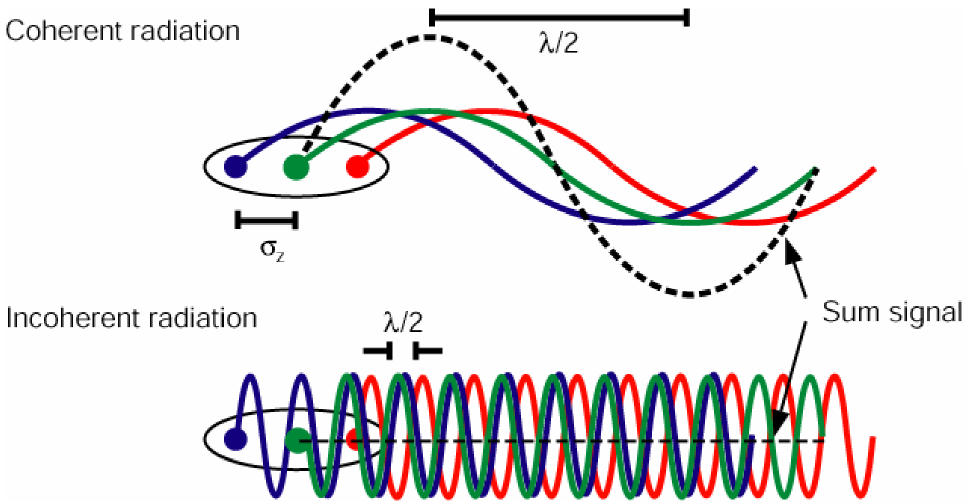
Coherent radiation

Sources:

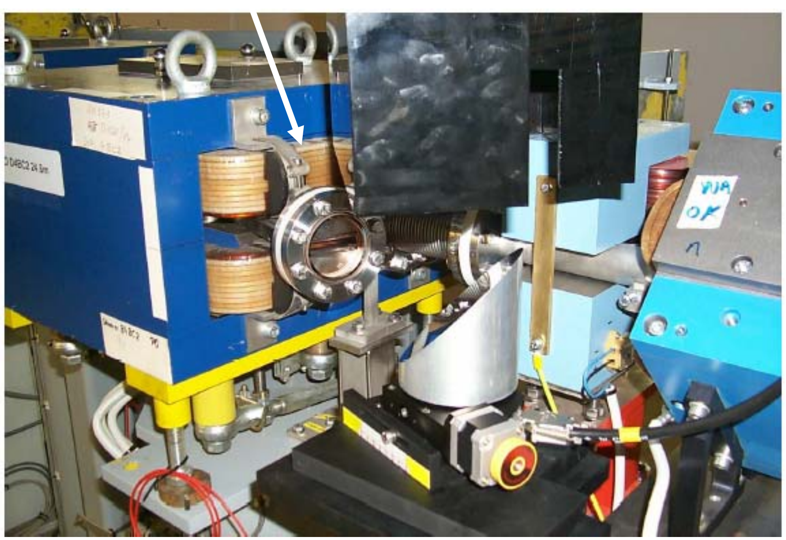
- coh. transition radiation
- coh. diffraction radiation
- coh. synchrotron
- FIR-undulator
- Smith-Purcel rad.
- edge radiation

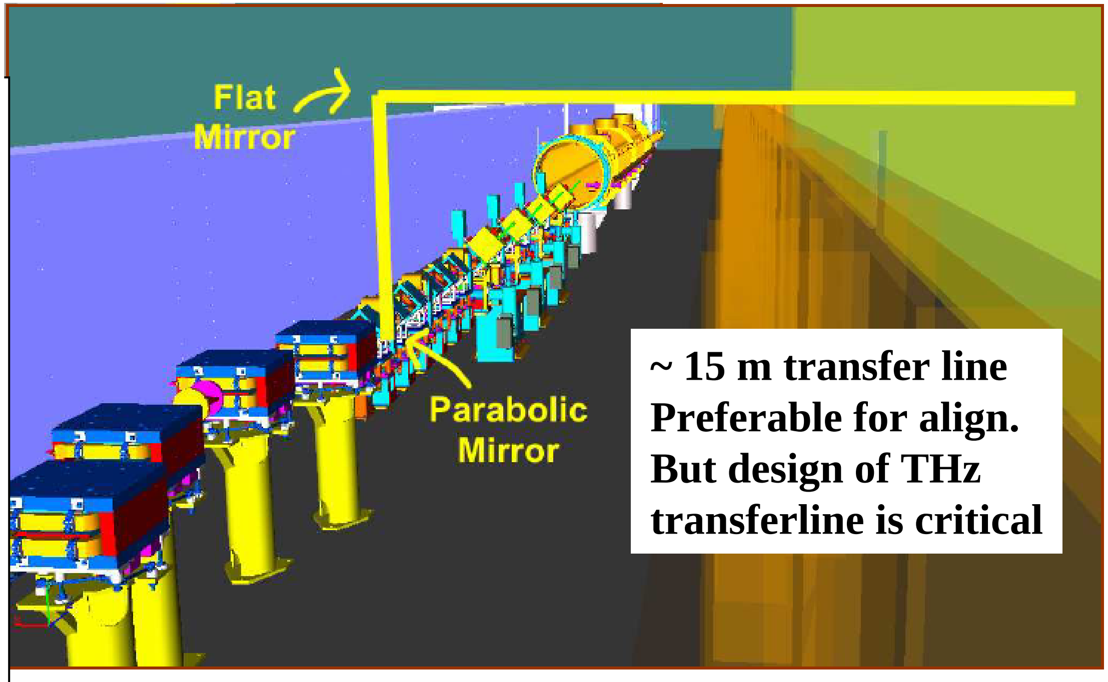
Purpose:

- longitudinal profiling
- compression monitor $P \sim 1/\sigma_z$

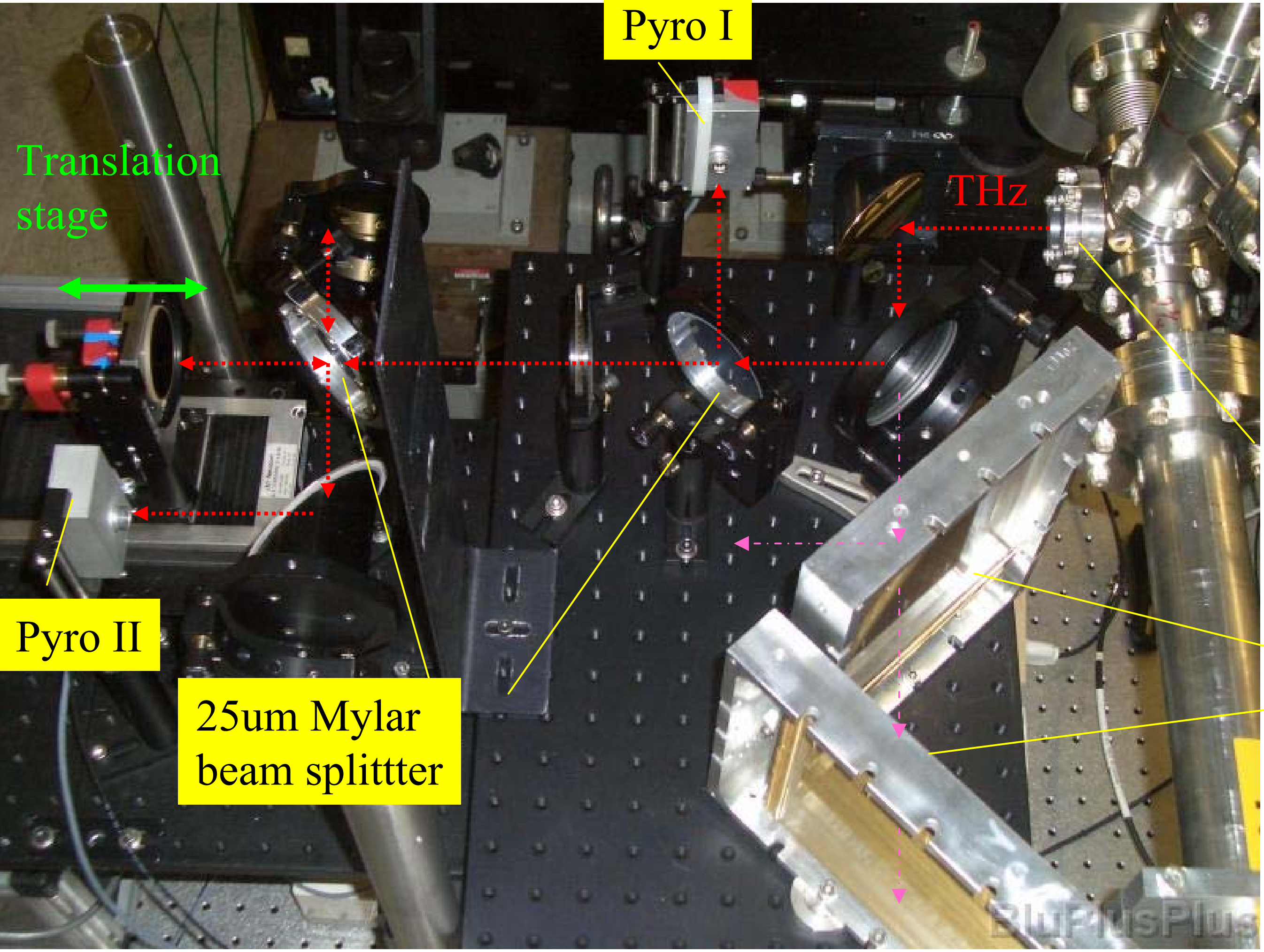


Z-cut quartz window/diamond/mylar



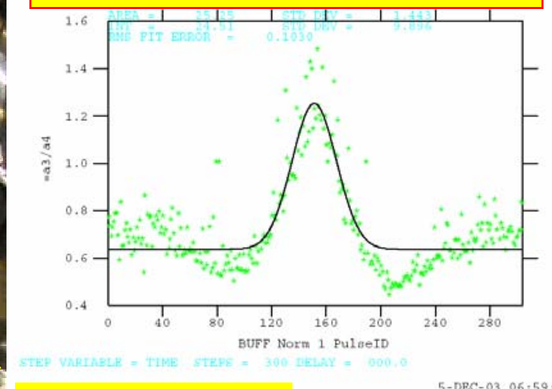


Bunch Length Diagnostics - Michelson Interferemeter-



Rms = 32.7 um

$\Rightarrow$ σ_z ~ 23.1 um

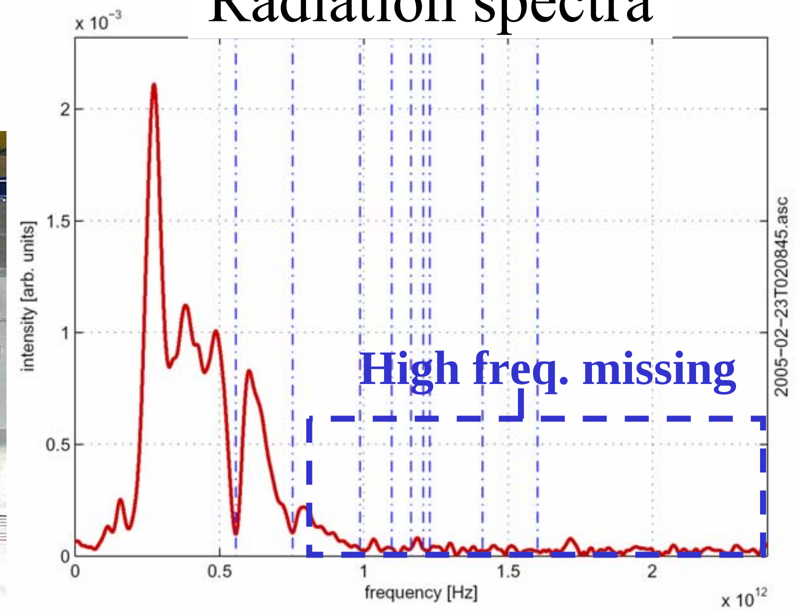


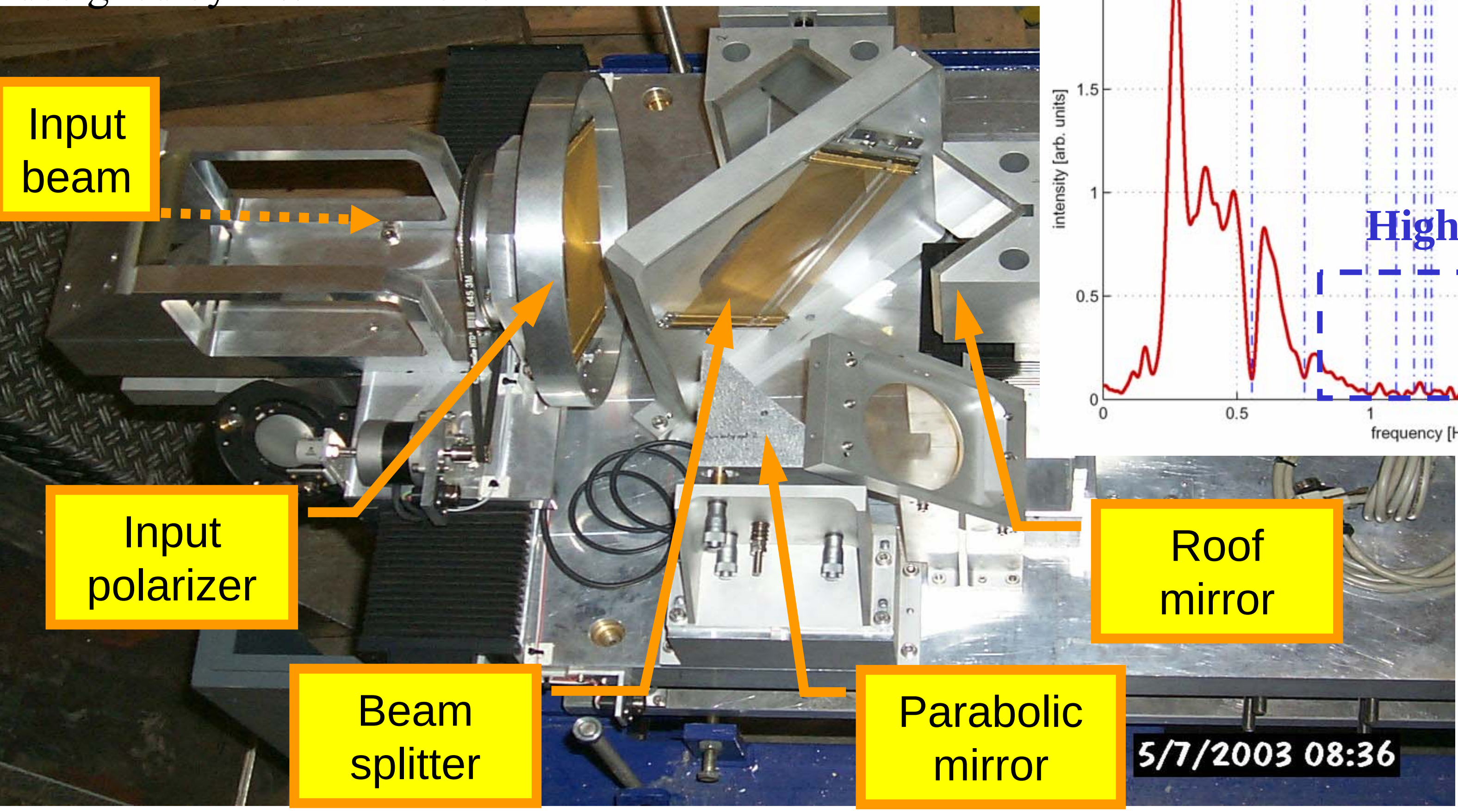
P. Muggli (E164 exp. SLAC)

Bunch Length Diagnostics
- Martin-Puplett Interferometer-

Martin-Puplett Far Infrared Interferometer:
designed by RWTH Aachen

Radiation spectra

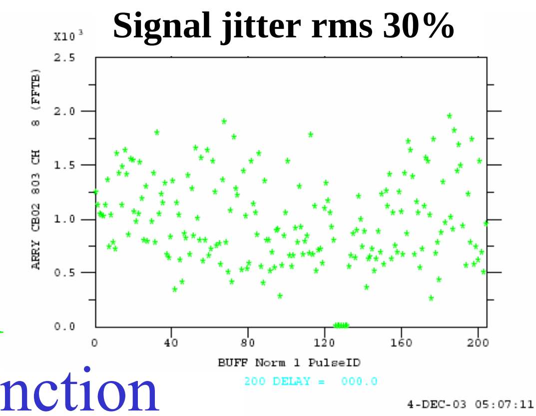




Courtesies
O. Grimm &
L. Fröhlich

Detectors removed, types used DTGS, Pyro, Golay

Interferometers



Challenges related to interferometer setup

- multi-shot measurement
- phase information is missing

⇒ reconstruction via Kramer Kronig disp. relation

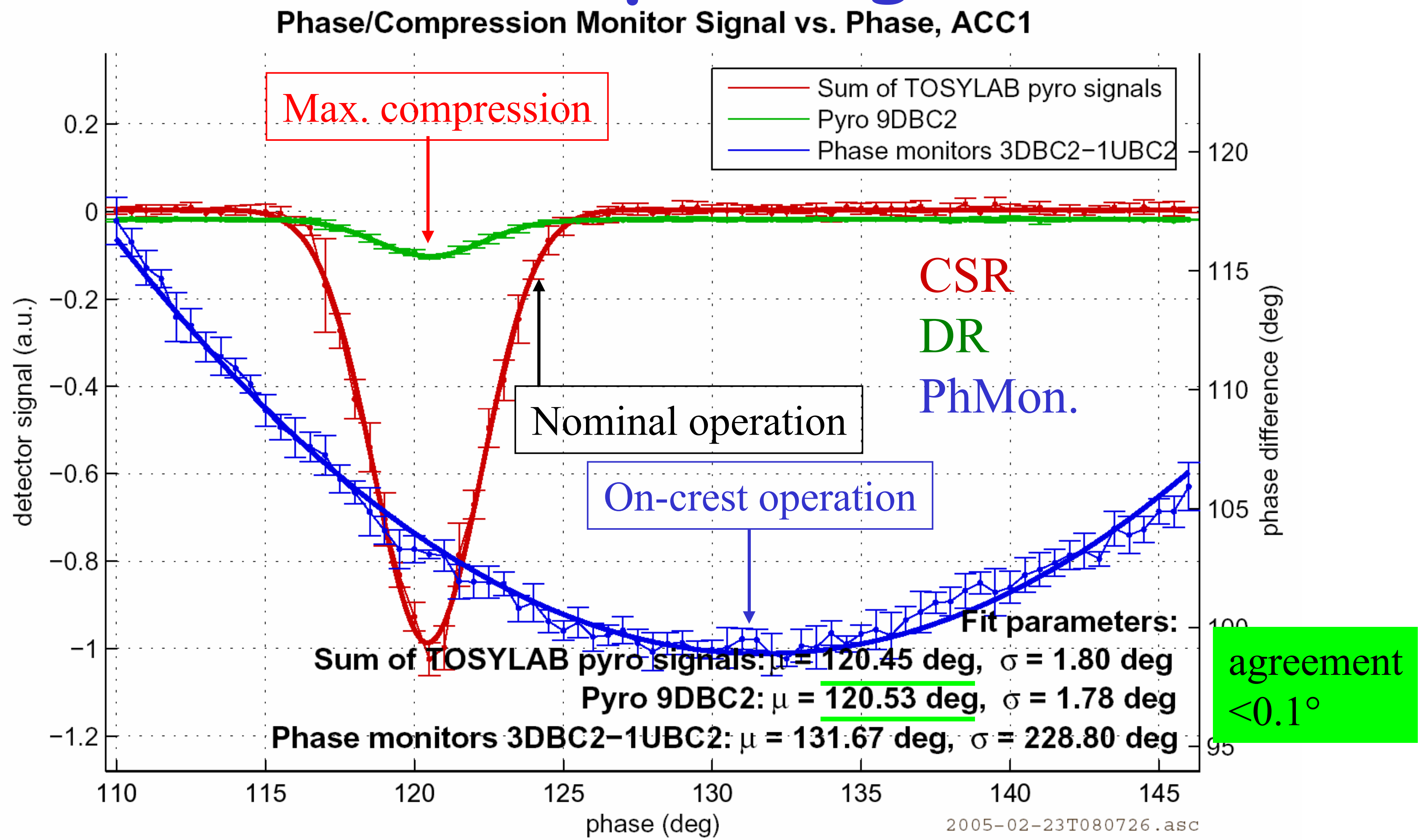
- significant and complicate frequency response function

– effects of finite foil
– diffraction at apertures and diffraction limited transport
– beam splitters and window (lower cutoff)
– near field and far field transitions
– detector response function
– absorption in air

⇒ extraction of "rms" bunch length is feasible, but an accurate measurement of the longitudinal bunch profile is very difficult!

- Future: ideas for single shot FIR bunch length measurements (FIR spectrometer, not yet demonstrated)
- Growing interest: easier for shorter bunches, micro-bunch instability

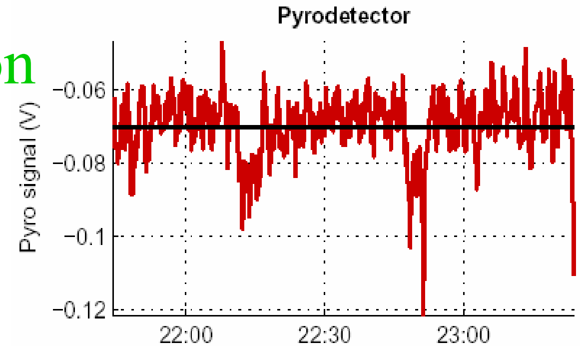
Beam Compression Monitor
- acc. phasing -

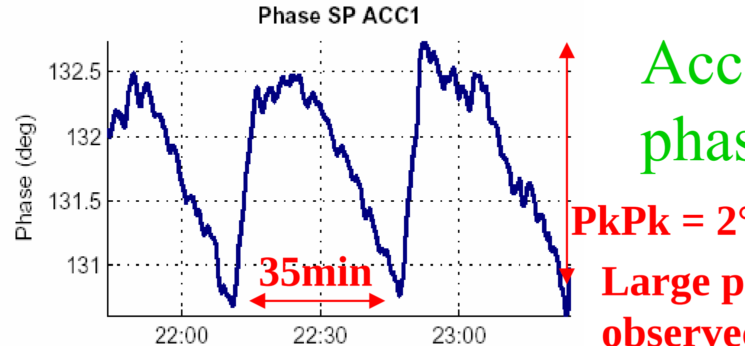


Slow feedback for acc. phase

<u>Monitor signal</u> | <u>Actuator responds</u>

Compression monitor

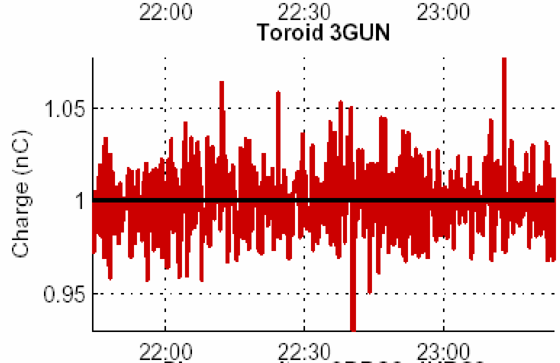


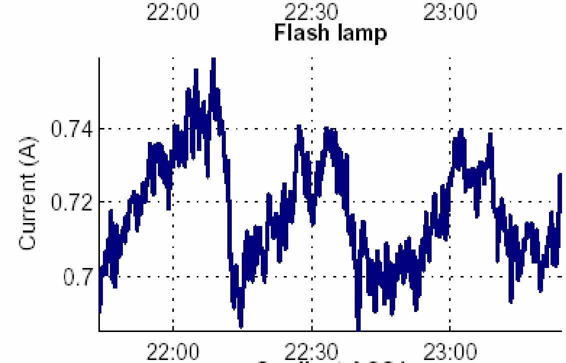


Acceleration phase

Large phase drifts observed!!!

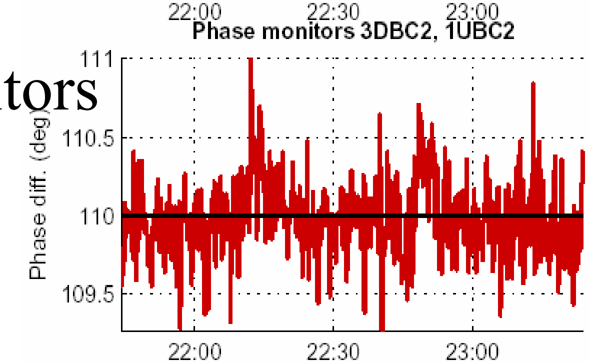
Charge

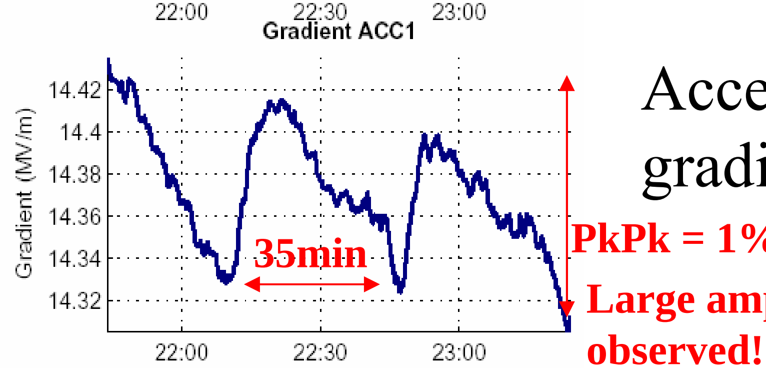




Laser power

Phase monitors (Energy)





Acceleration gradient

Large ampl. drifts observed!!!

Example: TTF2

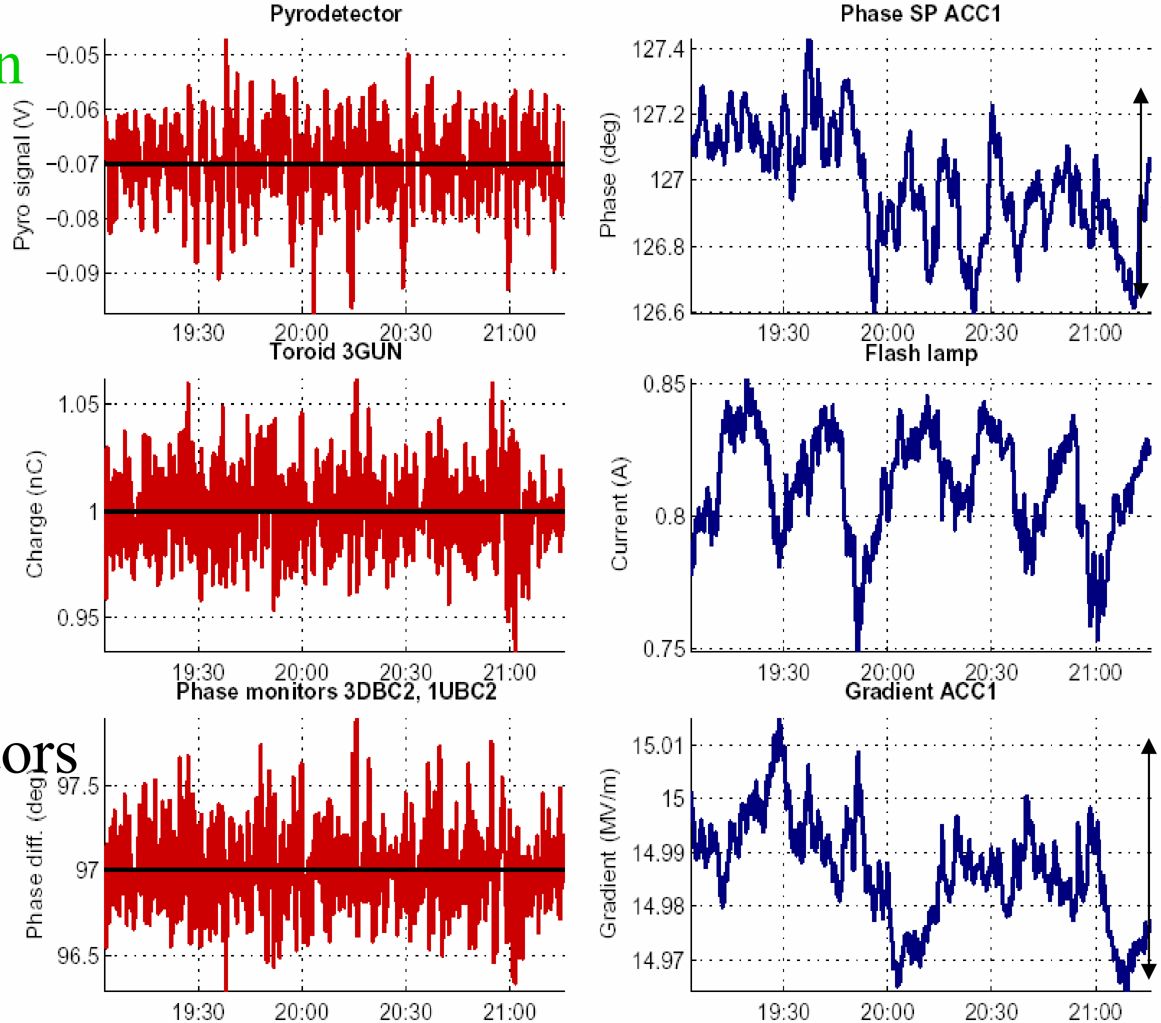
Slow feedback for acc. phase

Monitor signal | Actuator responds

Compression monitor

Charge

Phase monitors (Energy)



Acceleration phase

PkPk = 0.7°

Reasonable phase drift (~0.1° rms)

Laser power

Acceleration gradient

PkPk = 0.4 %

Reasonable ampl. drift (~ 0.1% rms)

Example: TTF2

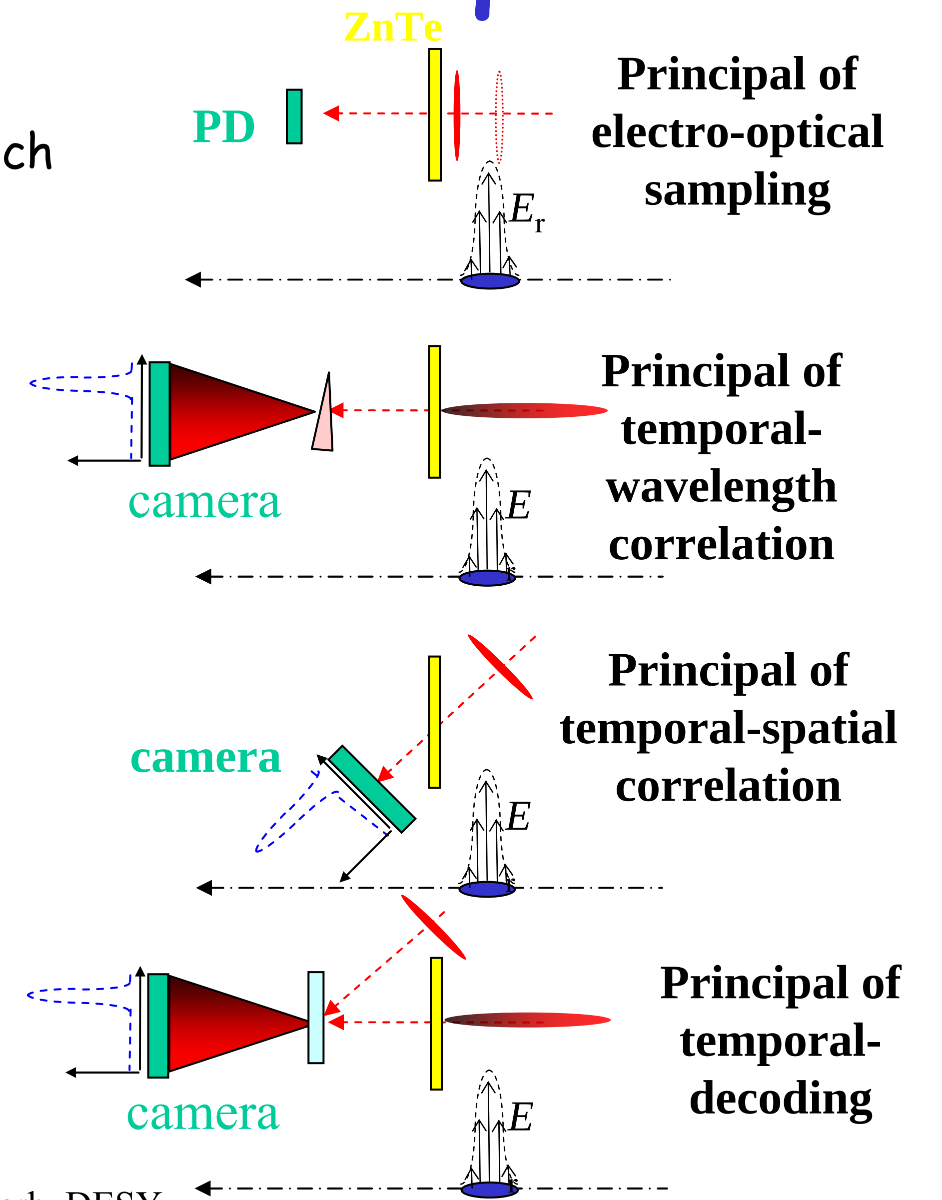
Electro-optical techniques

1. Sampling:
- scan delay to move laser over the bunch
- good synchronization required
- multi-shot method
- arbitrary time window possible

2. Chirp laser method:
- single shot method
- some more effort for laser and laser diagnostics required
- time window ~ 1-20ps
- limit by laser diagnostics ~ 400fs

3. Spatial method:
- single shot method
- imaging optics is critical
- time window ~ 1-20ps

4. Temporal decoding:
- uses single shot auto-correlator
- optical resolution limit 30fs
- requires laser amplifier (~1-10kHz)



Electro-optical techniques

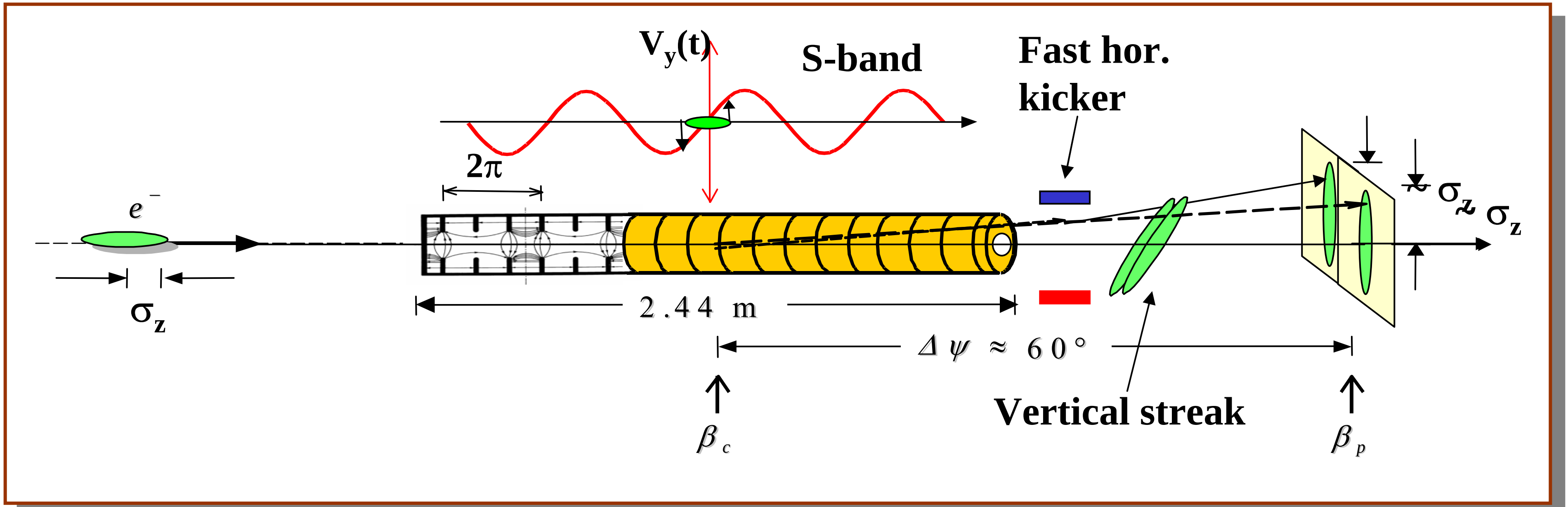
- All techniques have been successfully tested ☺
- Parasitic operation and non-invasive ~ 100mA possible
- High readout rate up to ~ MHz (method 2&3)
- If laser is properly synchronized
  ⇒ high accuracy beam arrival time monitor ~10-30 fs
- Spatial method and temporal decoding overcome
  the optical resolution limits
- but any technique has presently the limitations given
  by the electro-optical process

ZnTe	~	200 fs FWHM
GaP	~	100 fs FWHM
?	<	30 fs FWHM

- limited dynamic range (2 ps, 1 nC ok, but 20 ps, 100pC diff.)
- all together TECHNICAL CHALLENGING

Transverse deflecting structure

- vertical deflecting RF structure (2.856 GHz) operated at zero crossing
- vertical size of beam at imaging screen ⇒ depends on bunch length
- used structures sofar: “LOLA” at exit of SLAC linac, and TTF2 linac
- 25 MW klystron power to “streak” the 28.5 GeV for SPPS, (0.5GeV)
- ‘Parasitical’ measurement using hor. kicker and off-axis screens
- Resolution: SPPS ~ 60 μm, TTF2 ~ 5 μm (expected)



SPPS: P. Krejcik et. al.,TTF2: M. Ross et.al. + MIN DESY

Transverse deflecting structure

Beam size RF off

Bunch Length

Beta fn at cavity & screen

Cavity voltage and beam energy

Phase adv cavity to screen

Beam size on screen

RF phase

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda E_0} \sin\Delta\psi \cos\varphi \right)^2}$$

Net deflection

SLAC cavity shunt impedance

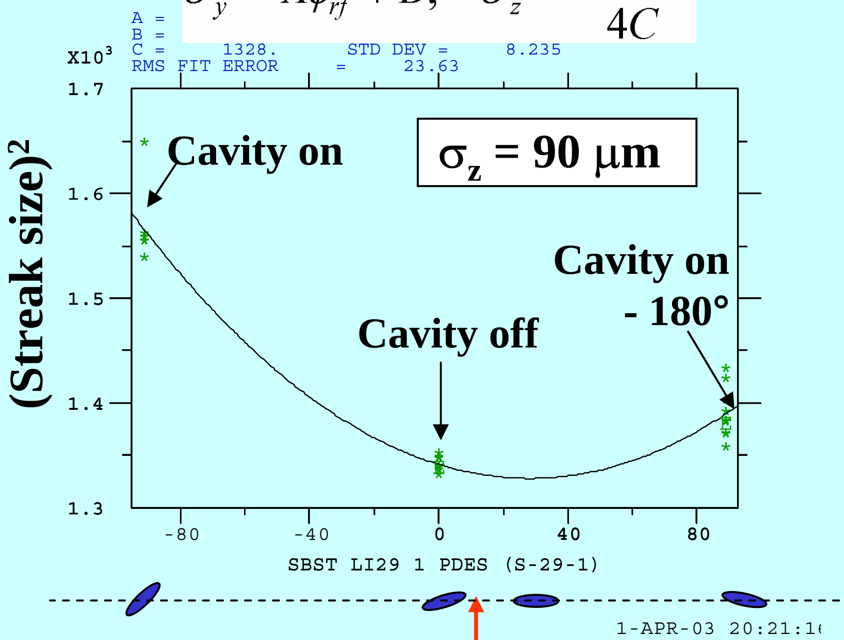
$$\langle \Delta y \rangle = \frac{eV}{E_0} \sqrt{\beta_c \beta_p} \sin\Delta\psi \sin\varphi \,, \qquad V_0 \approx \left(1.6 \text{ MV/m/MW}^{1/2}\right) L \sqrt{P_0}$$

Transverse deflecting structure

Little streak $\sigma_y > \sigma_{y,0}$(SPPS):

rms bunch length reconstruction by measure streak at 3 different phases

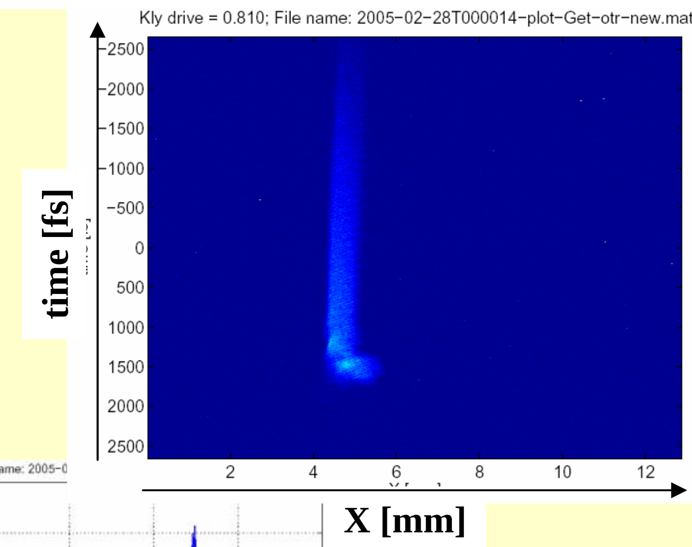
$$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$$

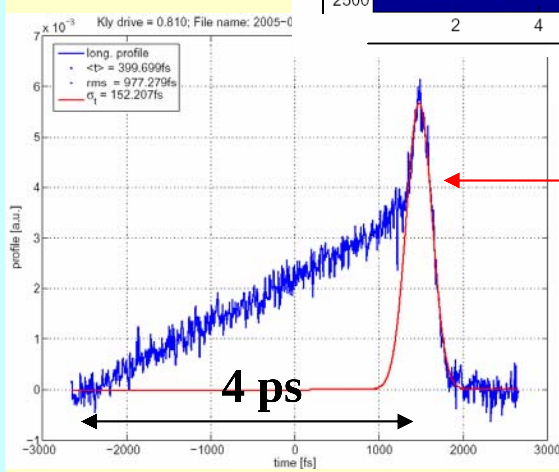


Asymmetric parabola indicates incoming tilt to beam

Strong streak $\sigma_y >> \sigma_{y,0}$(TTF2):

Profile reconstruction





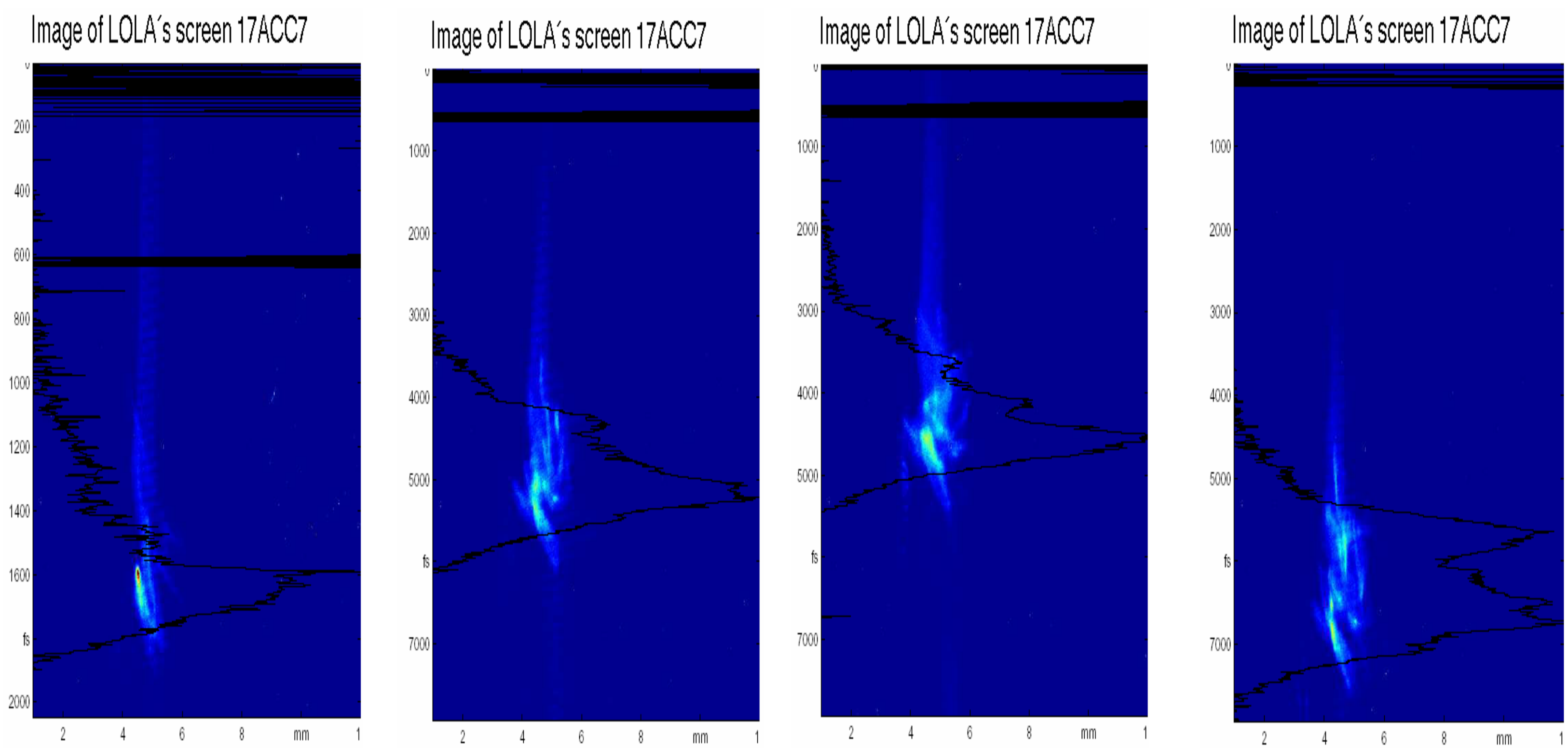
σ_z = 45 μm

Moderate compr.
(+5 from max.)
Not fully streak
Not optimized

Transverse deflecting structure

Phase from maximum pyro-electrical signal …

+3° +2° +1° +0°

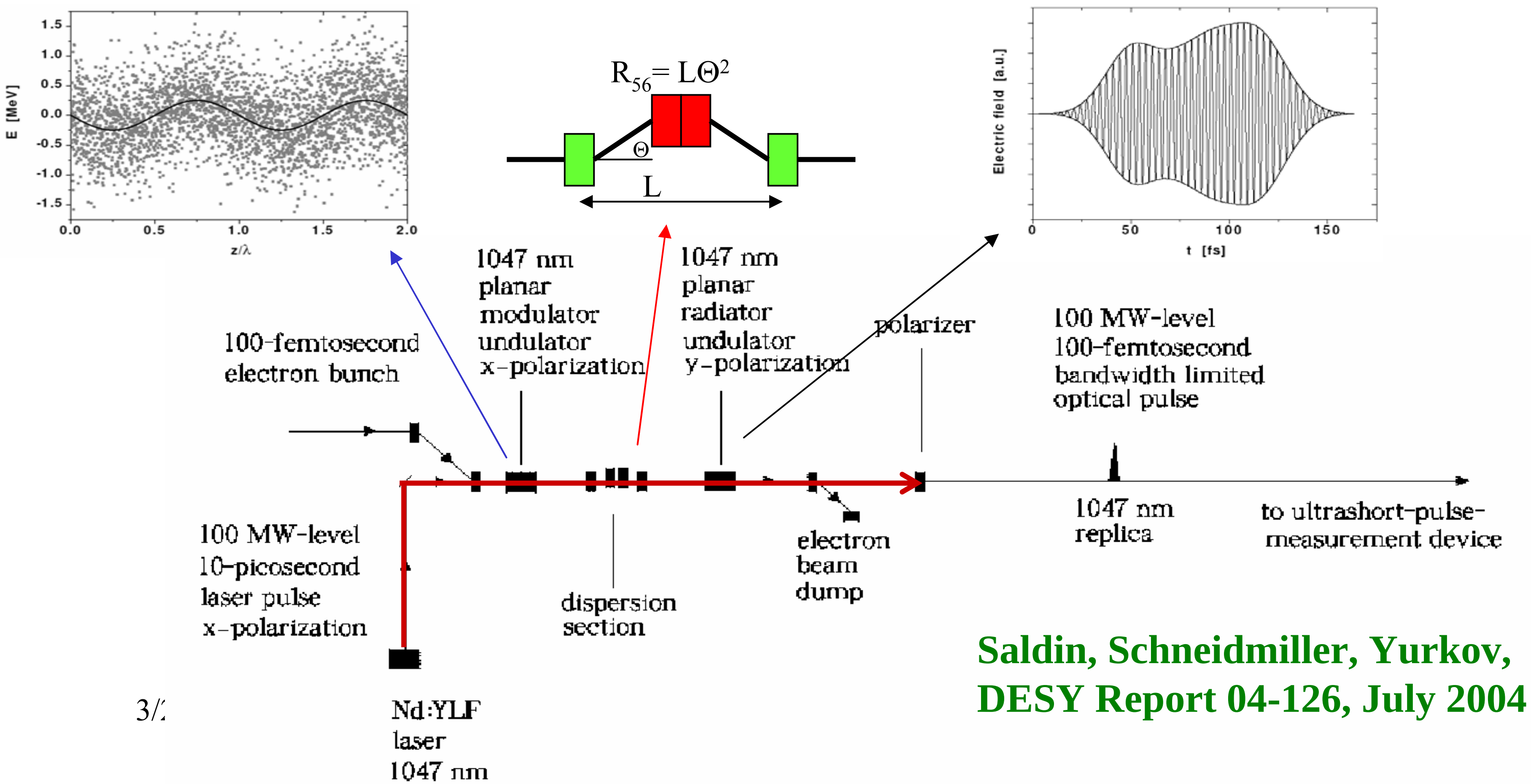


Fragmentation of beam in longitudinal and x direction (csr+space charge)

⇒ Ideal suited for slice emittance measurements

Optical pulse replica

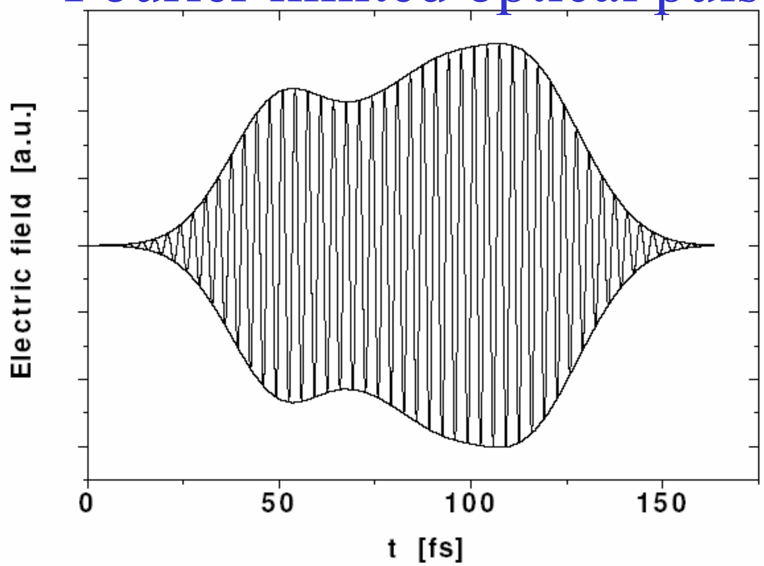
1. energy modulation with external laser in planar undulator
2. conversion to density modulation
3. coherent radiation in output undulator
4. optical pulse measurement (FROG, auto-correlation)



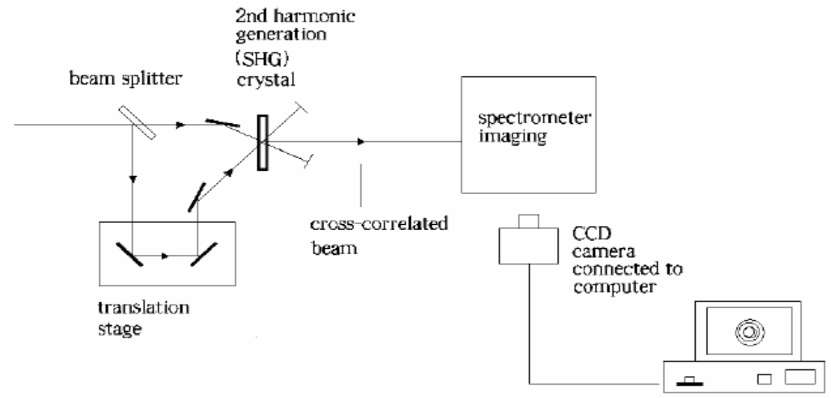
Saldin, Schneidmiller, Yurkov, DESY Report 04-126, July 2004

Optical pulse replica

Fourier limited optical pulse



Scheme of SHG-FROG



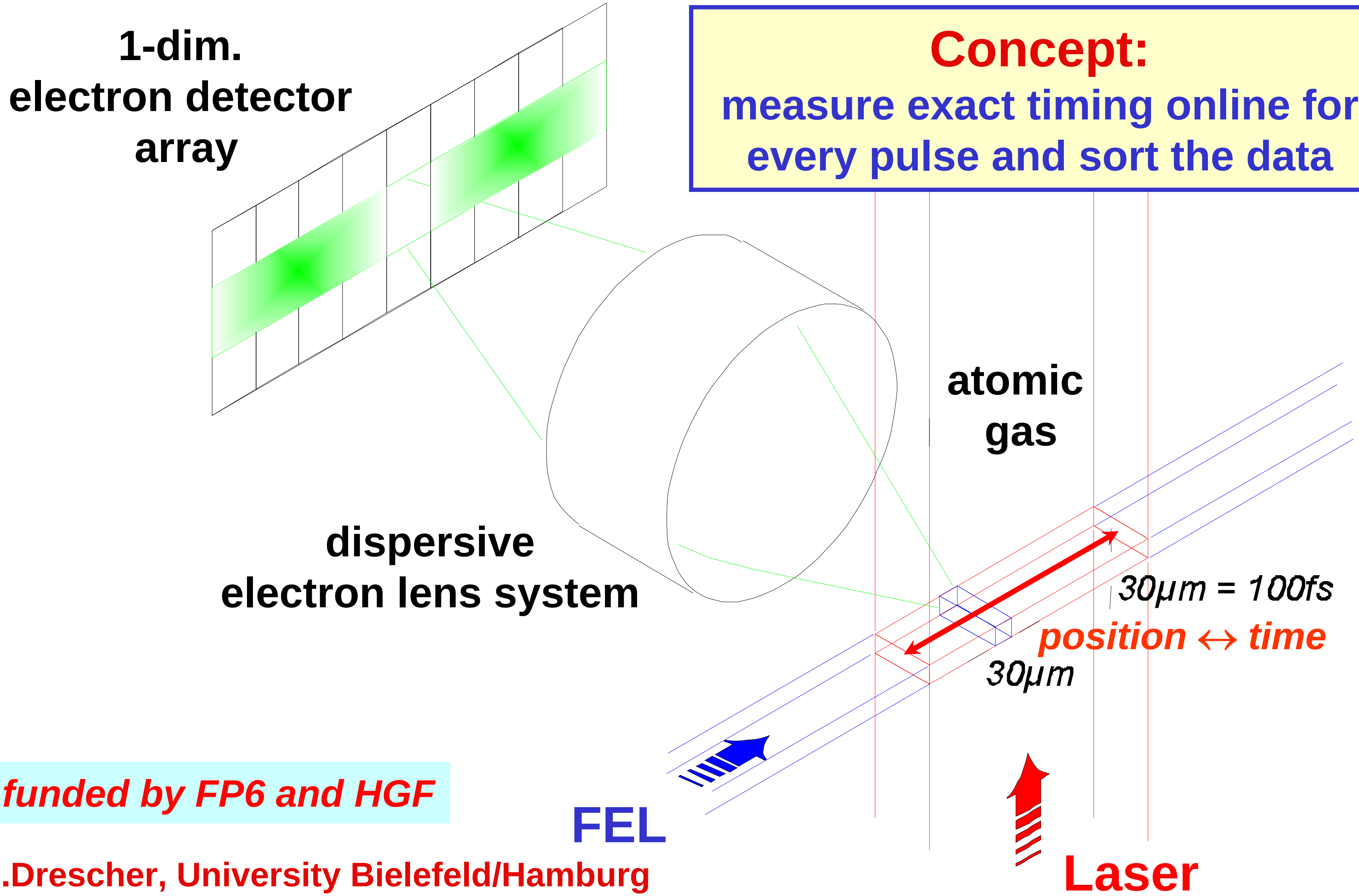
⇒ **Combination of auto-correlation and spectrum provides exact intensity profile**

+ High resolution $\delta z \sim N_w \cdot \lambda \approx 5\mu m$ (limited by slippage only)
+ Allows to extract slice energy spread
+ provides high power synchronized optical pulse (timing)
+ quasi parasitically, online

- low rep. rate (100Hz-1kHz)
- limited dynamic range (pulses <<1ps)
- requires high power seed laser
- challenging if large residual energy spread across the bunch

Single-shot cross correlator

Concept:
measure exact timing online for every pulse and sort the data



funded by FP6 and HGF

M.Drescher, University Bielefeld/Hamburg

Other methods …

- ISR in optical regime in combination with ultra-short pulse lasers (SHG)
- CR in combination with EO (outside tunnel, other EO-materials)
- General for quasi-non destructive methods:
  Ultra fast kickers (<20ns) + …
- Compton back scattering for arrival timing

and hopefully some more new ideas in the near future …