Beam Diagnostics at the VUV-FEL Facility

Josef Feldhaus, DESY

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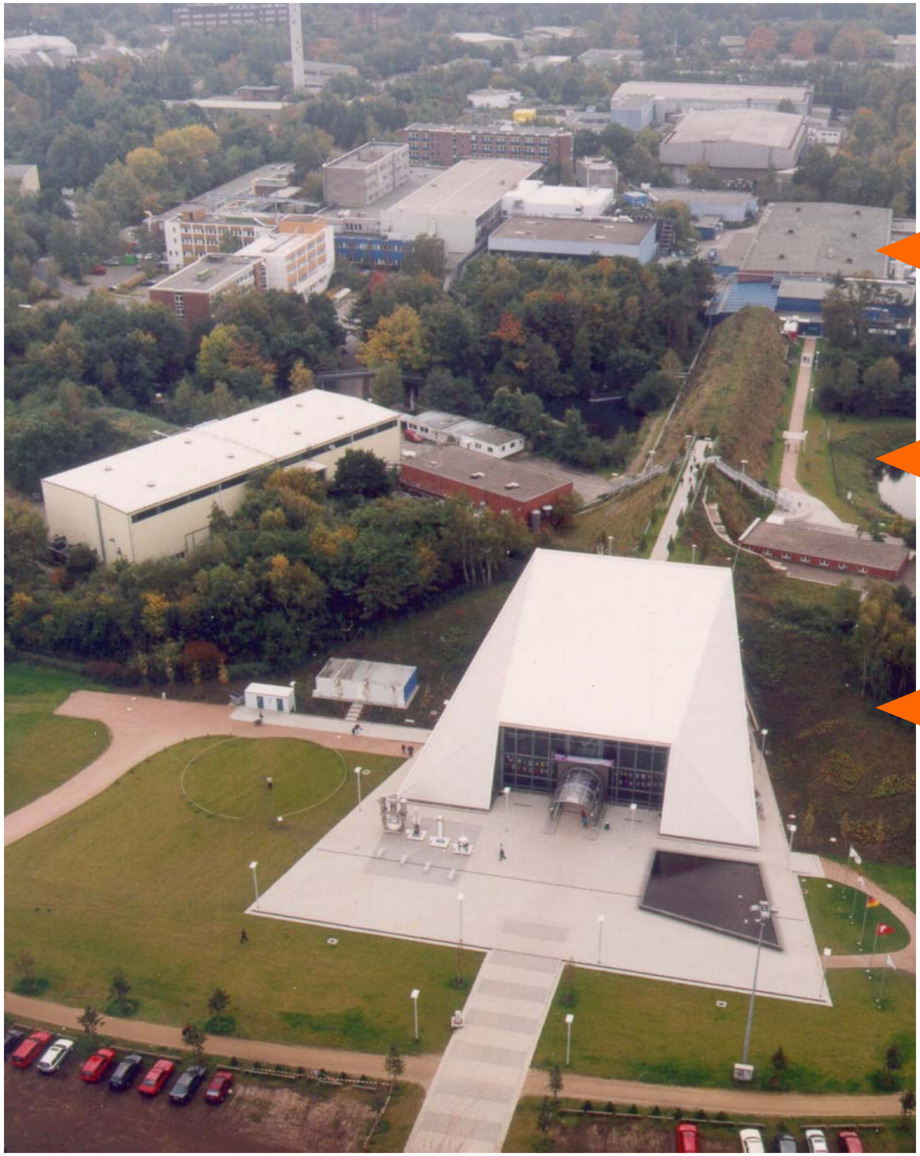
TESLA Collaboration

- Introduction
- Diagnostics for operating the linac
- Long. diagnostics for controlling the FEL process
- Photon diagnostics

VUV-FEL User Facility at DESY



TESLA Test Facility (TTF 1, 1995-2002)

- 300 MeV
- 80-120 nm
- 30-100 µJ
- 1 GW_{peak}
- 30-100 fs

TTF 2

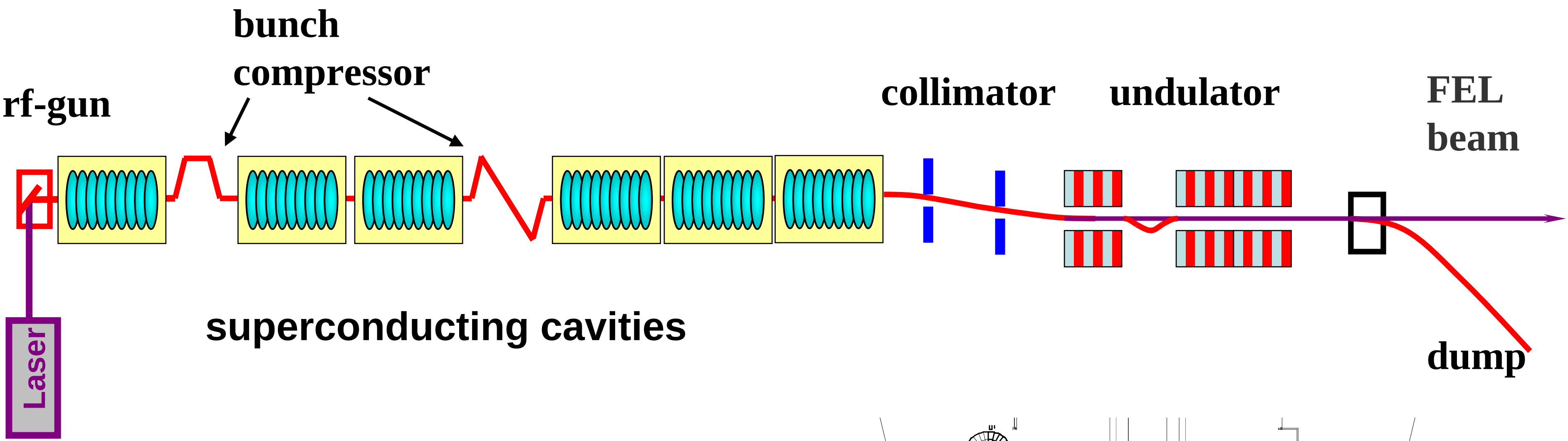
experimental hall

- 1 GeV: 6 - 60 nm
- 0.1 – 1 mJ
- 30 - 300 fs

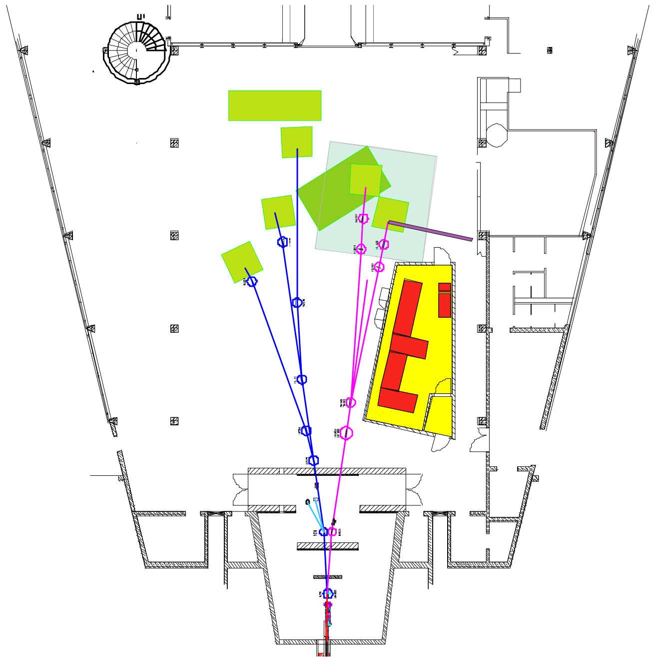
Commissioning in 2004

User operation in 2005

Layout of the VUV-FEL at DESY



- 1 GeV superconducting LINAC
- Nominal bunch charge 1 nC
- Normalized emittance < 2 π mm mrac
- Up to 7200 bunches in 800 µs at 10 H
- ~30 m fixed-gap undulators
- Spectral range ~6-60 nm
- Five experimental stations



Photon/electron diagnostics

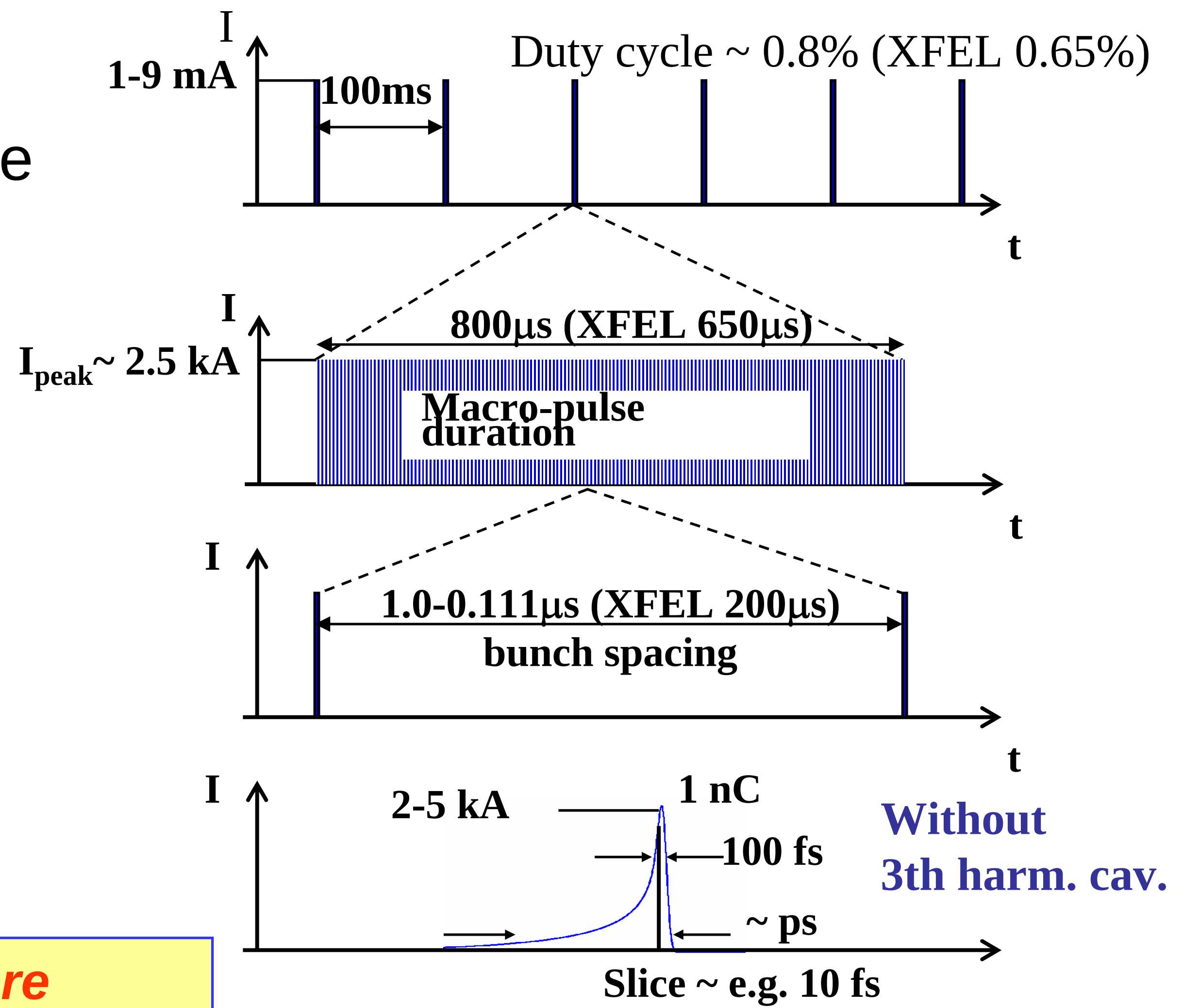
- **Photon/electron diagnostics measure FEL/electron beam parameters**
  - pulse energy and statistical properties / bunch charge
  - angular distribution, spatial coherence / emittance
  - wavelength and spectral distribution / energy and energy spread
  - arrival time, pulse duration, temporal structure

- **Photon/electron diagnostics is needed for**
  - tuning and operating the FEL and the LINAC
  - characterizing and understanding the FEL
  - supplying user experiments with basic beam parameters (*only photons*)

- **Challenges**
  - new source with unusual properties
  - ultra-short pulses / bunches
  - single pulses with very high intensity / fast protection system
  - development of pulse-resolved online techniques

VUV-FEL Time Structure

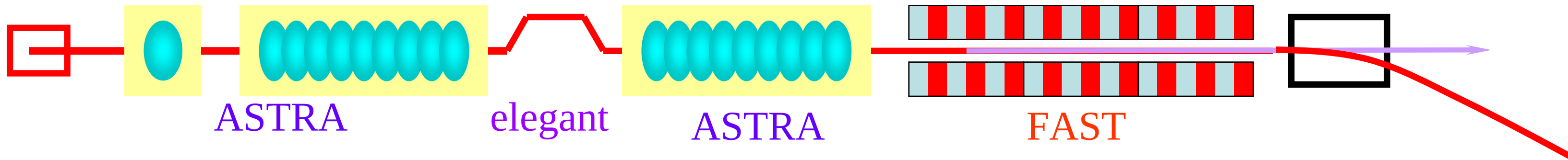
- Repetition rate
- Macro-pulse
- Bunch
- Slice

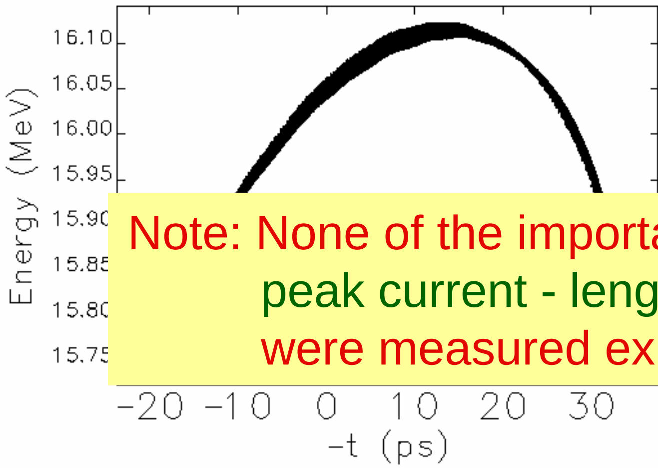


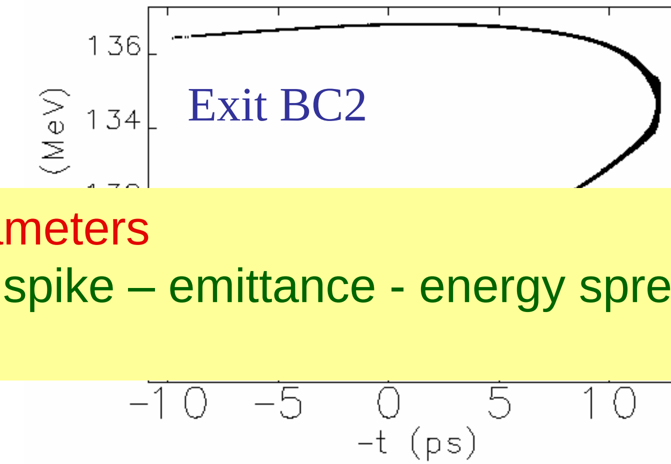
The slice properties are relevant for the FEL process!

TTF1 results: „Full physics“ start-to-end simulations

M. Dohlus, K. Floettmann, O.S. Kozlov, T. Limberg, Ph. Piot, E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov

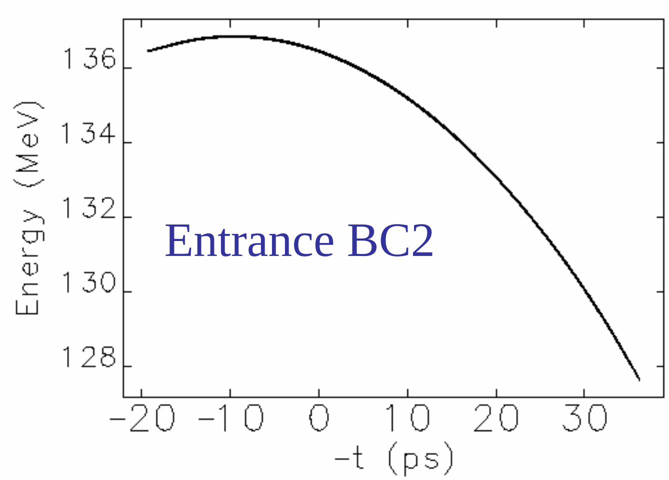


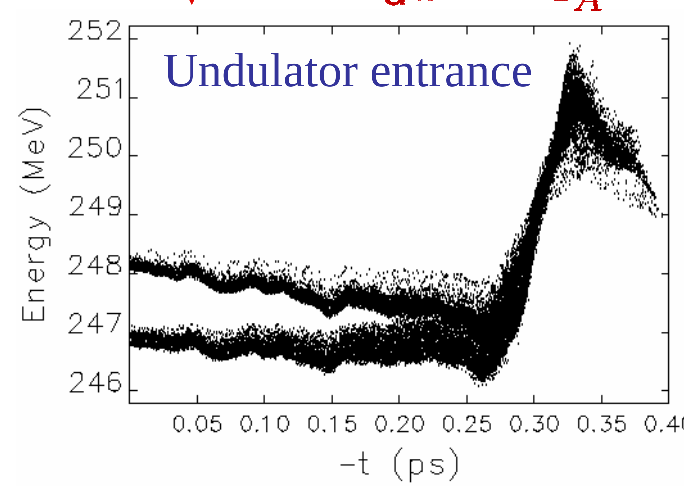




Note: None of the important slice parameters
peak current - length of leading spike – emittance - energy spread
were measured experimentally.

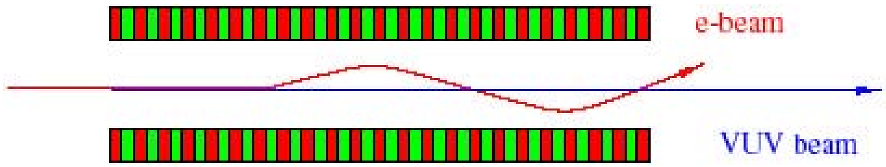
$$\frac{d(\Delta\gamma)}{dz} \simeq \frac{I}{I_A} \frac{\ln(\gamma\sigma_z/\sigma_r)}{\gamma^2\sigma_z}$$

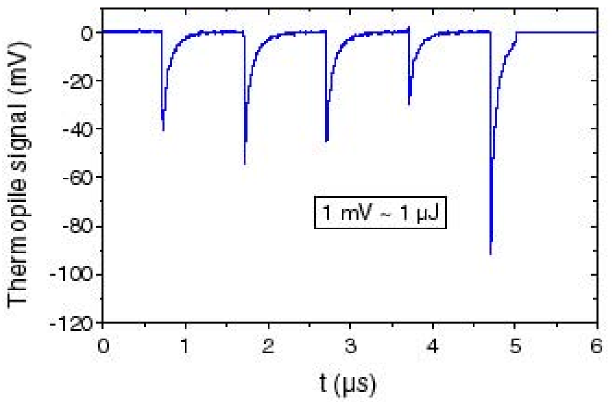


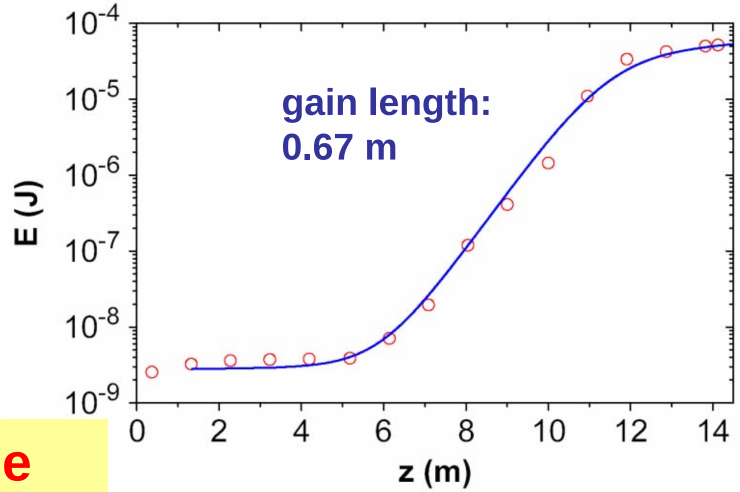


FEL pulse energy

TTF1 results

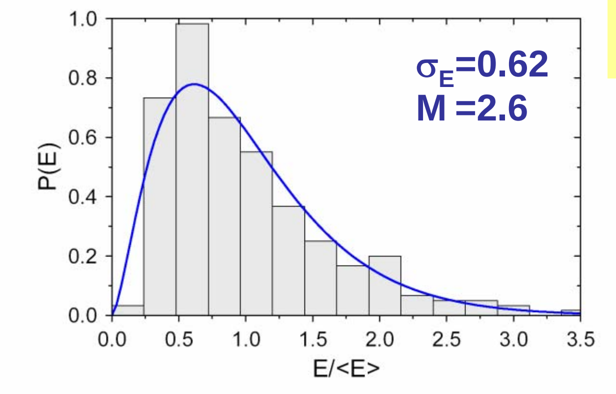




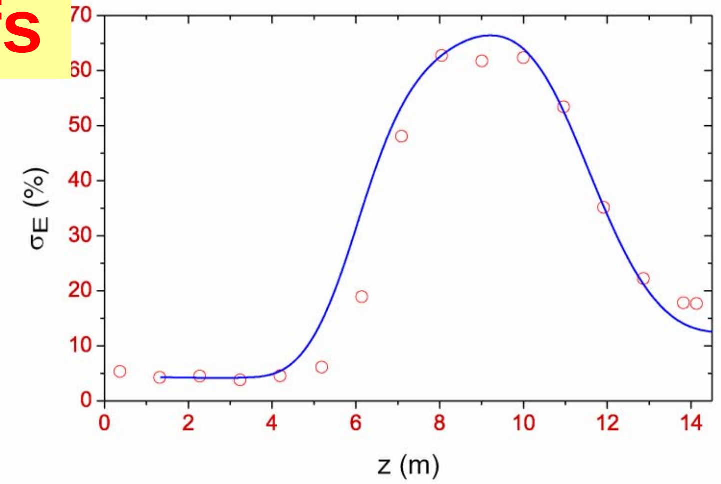


FEL saturation at 95 nm

pulse duration ~ 50 fs



Intensity distribution at z = 9 m

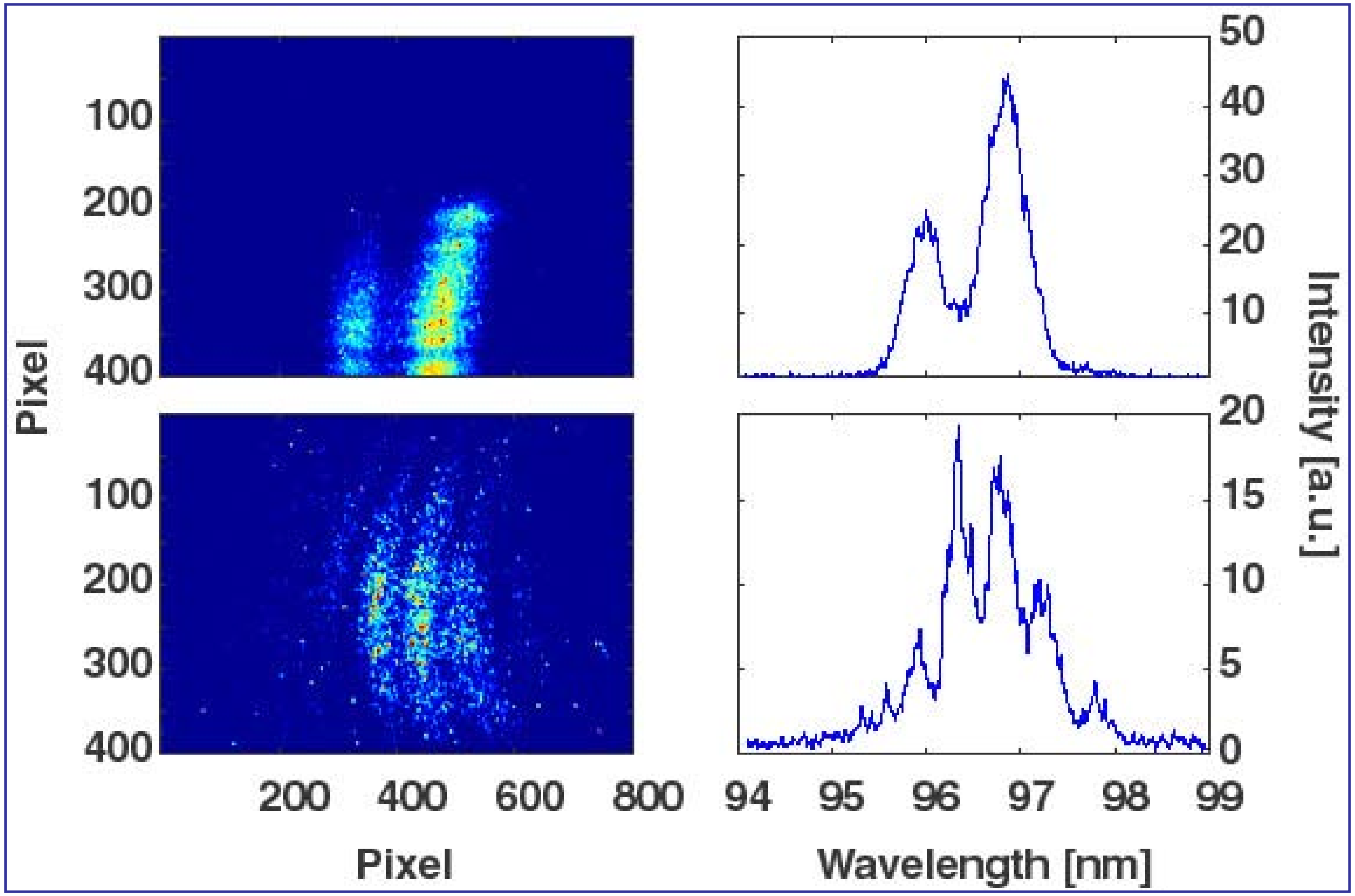


TTF1 results

Spectra of single FEL pulses

Short pulse (~50 fs)

Long pulse (~200 fs)

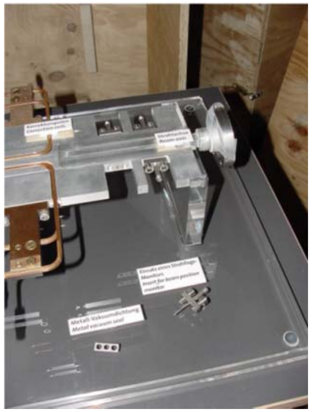


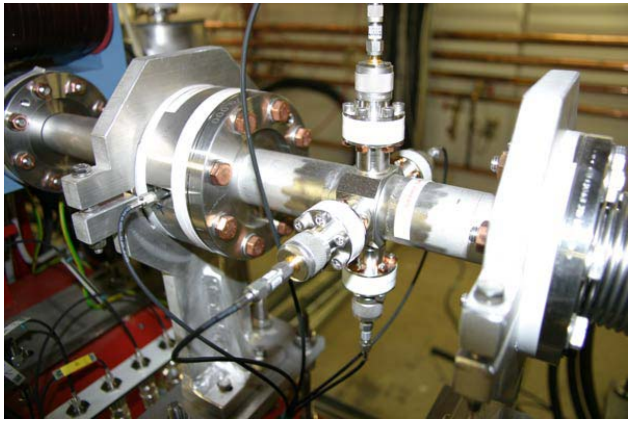
each pulse is different → **need online spectrometer with single shot resolution**

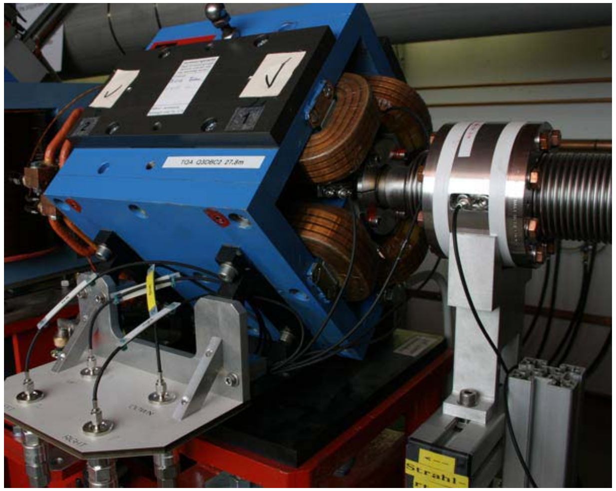
Standard Electron Beam Diagnostics

- **beam position**
- **beam shape/emittance**
- **charge**
- **energy and energy spread**
- **protection systems** based on
  - toroids (charge transmission)
  - photomultipliers
  - optical fibers

Beam Position Monitors



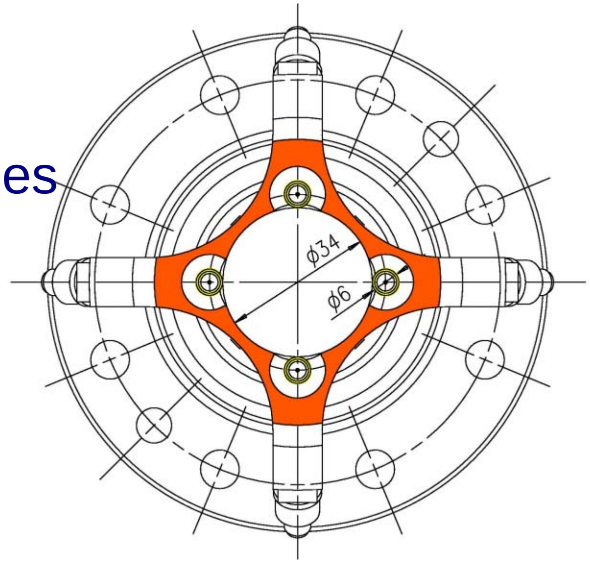




~60 BPMs installed at TTF2

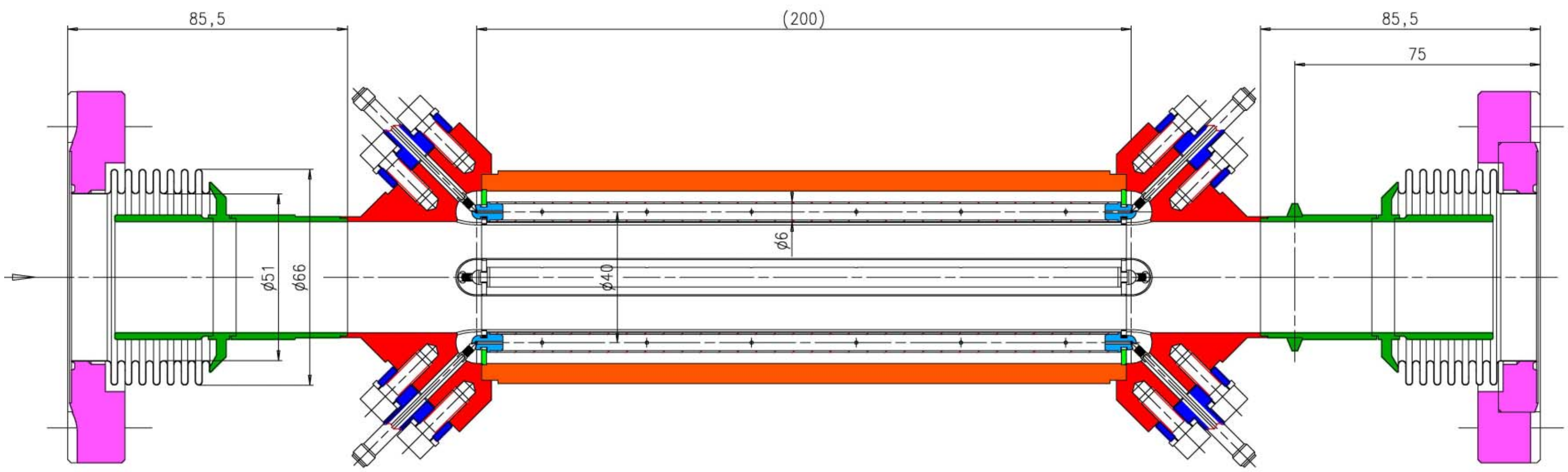
- Striplines < 30 µm (single bunch)
  installed inside and aligned to the quads
- Pickups
  injector and bunch compressor
- Undulator pickups < 10 µm (single bunch)
  19 stations in and between the 6 undulator segments

Stripline BPM

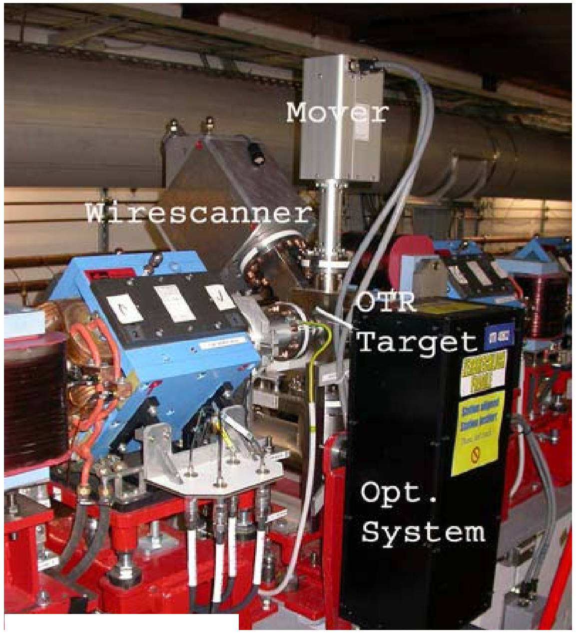


- Based on S-Band and FFTB (SLAC) designs.
- 200mm long longitudinal slotted semi-coaxial striplines
- Two appertures:
  - Type A (34 mm diameter, 16 stations)
  - Type B (44 mm diameter, 9 stations)
- Stripline pickup fits inside the quadrupole!

Longitudinal- and cross-section of a stripline pickup



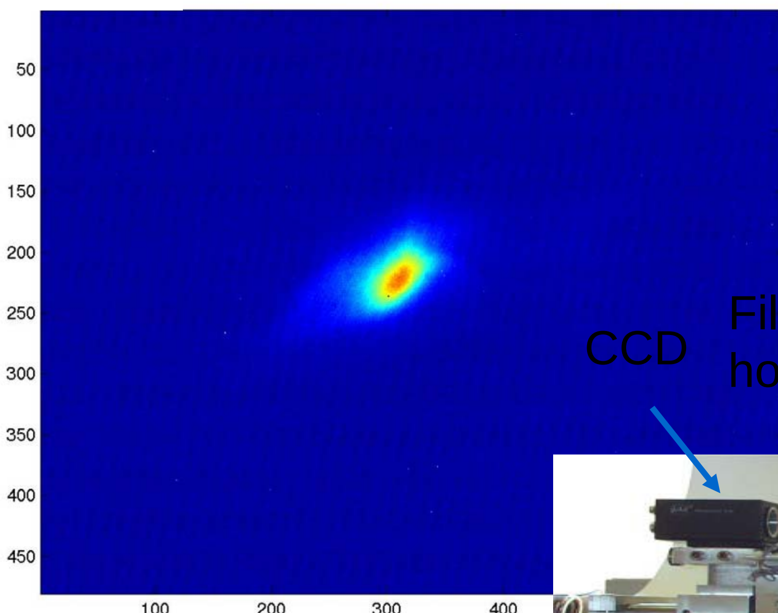
Emittance Measurements
Screens and Wirescanners

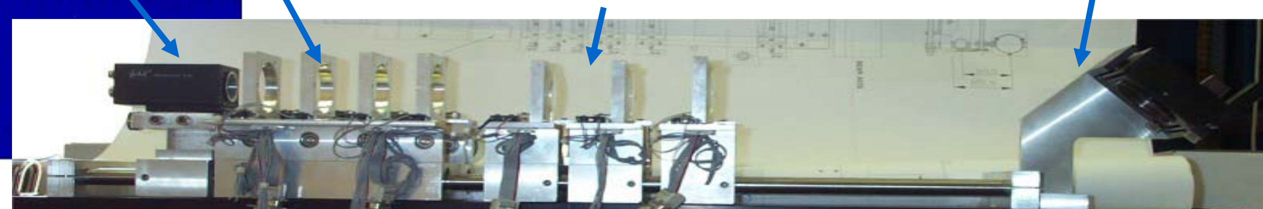


10DBC2

Bunch Shape and Emittance

- 30 OTR-Screens and 15 WS
- 4 Cell FoDo Section with 4 Stations (OTR/WS)
- OTR: Digital Camera System
  - Resolution of 10 µm
  - Network of Triggered and Gated Kameras
  - Kollaboration of DESY/INFN Frascati





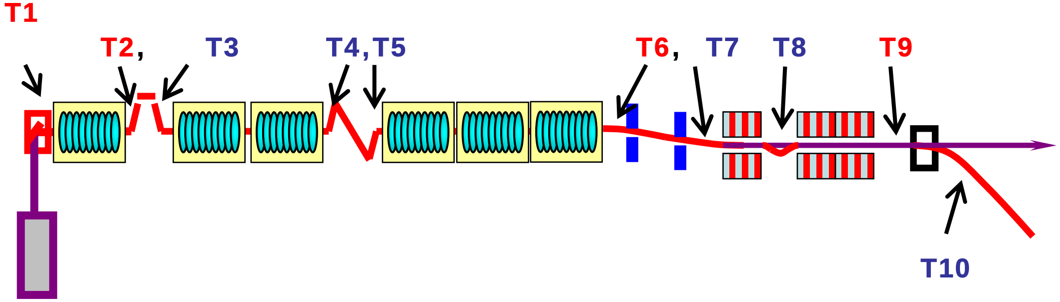
Protection Systems

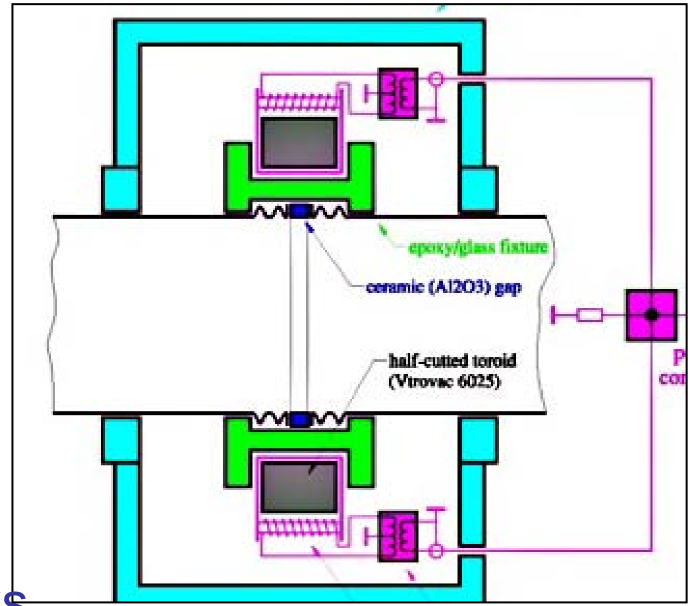
- **TTF2 LINAC delivers up to 72 kW beam power, requiring**
  - active and passive systems
  - fast interlocks to avoid mechanical damage
  - continuous monitoring to minimize radiation damage

- **Transmission and loss based systems**
  - thresholds determined by most sensitive component (undulator)
  - fast and slow systems
  - reaction time by „worst case events“ (and signal travel)

Loss detection down to 10^{-7} !

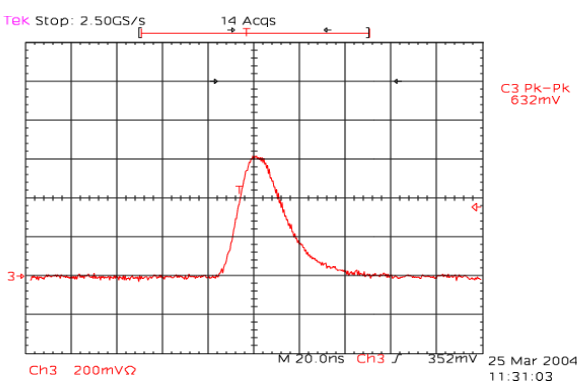
Charge Measurement: Toroids



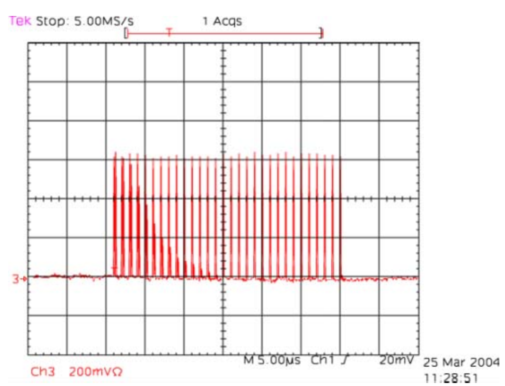


Diagnostics and Interlock

- single bunch resolution ~ 5pC
- bunch charges up to 5nC (0.5V/nC)
- charge variation across macro pulse
- suited for 9MHz operation
- pairs used for fast transmission interlocks (in collaboration with CEA, Saclay)

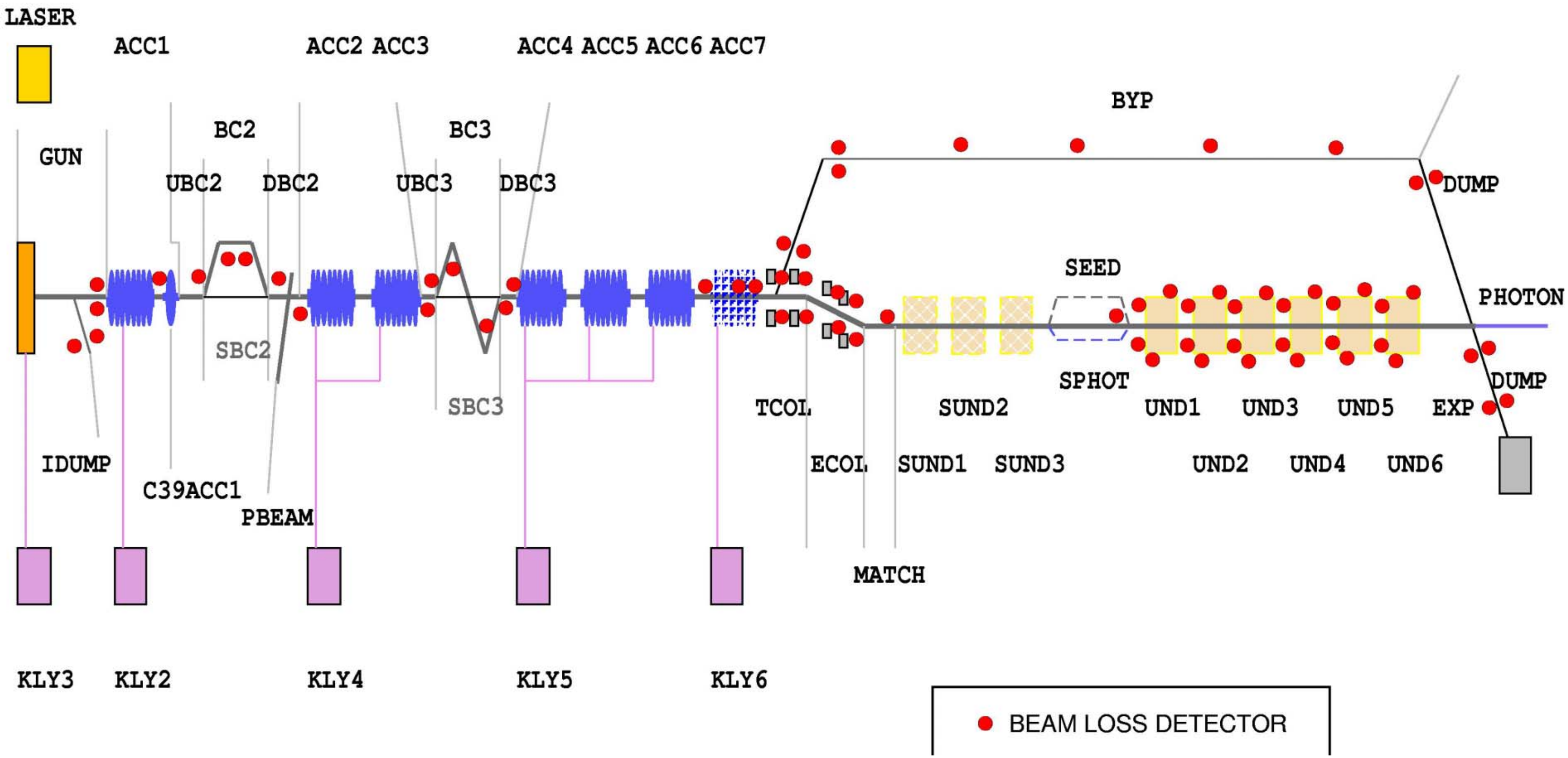


Single bunch 1.2 nC



Train of 30 bunches

Loss Monitor System



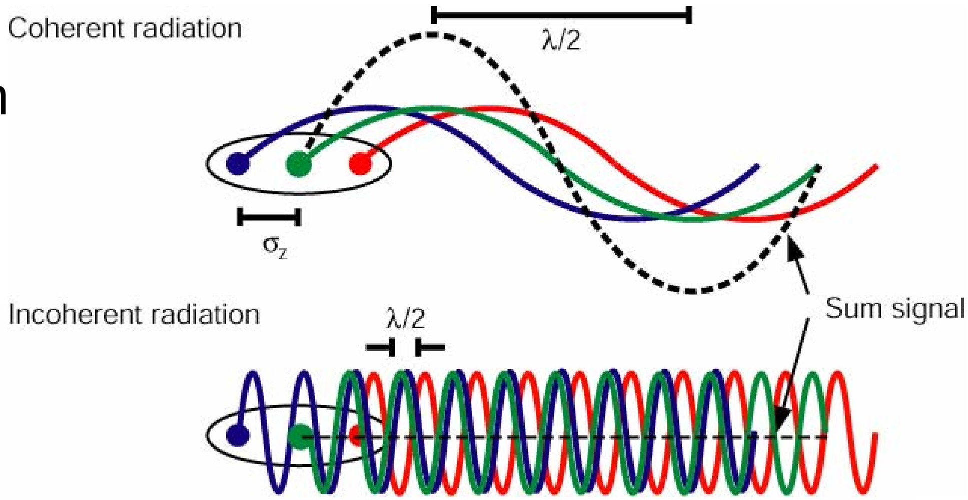
≈ 50 fast loss monitors (photomultipliers) at critical machine parts

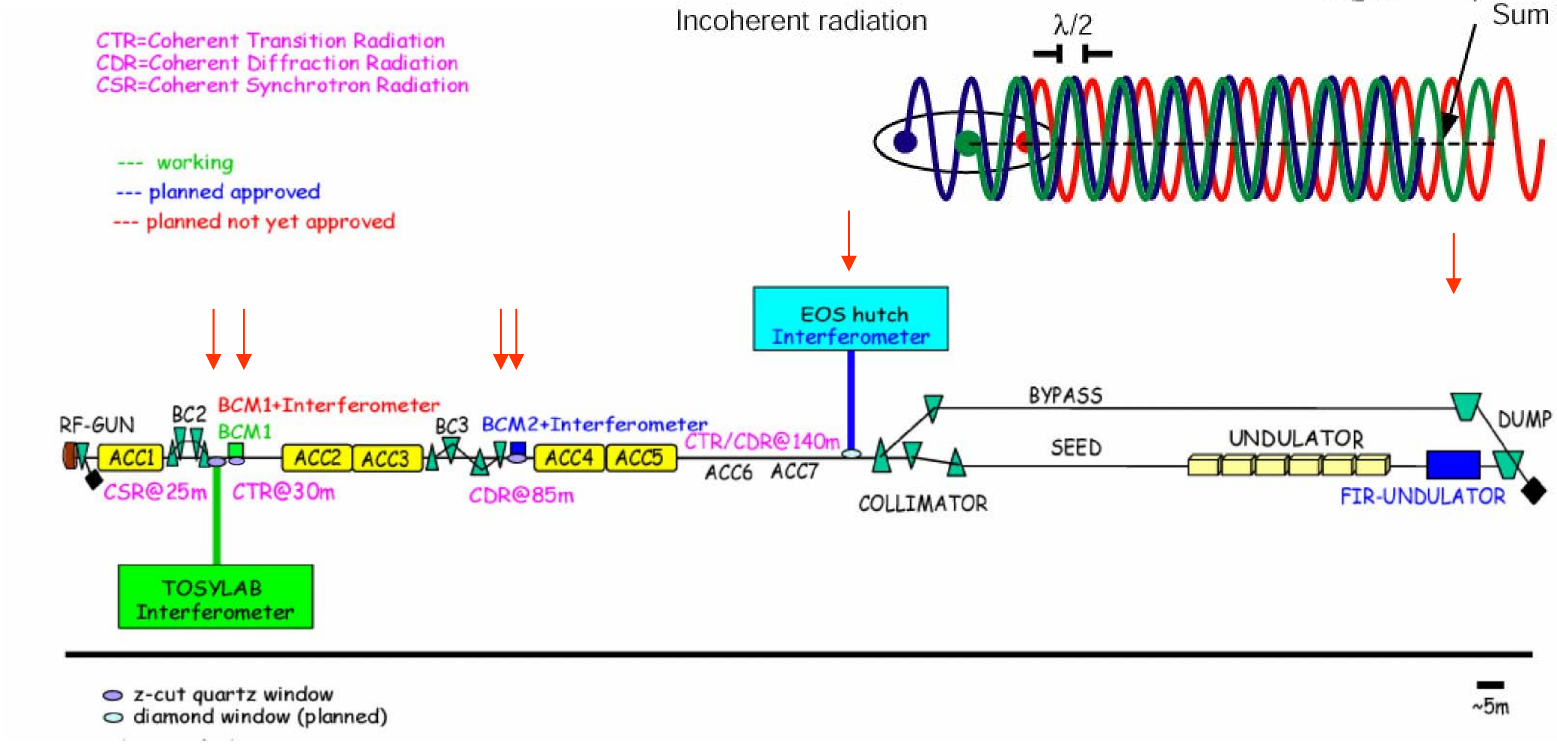
Special Electron Beam Diagnostics

- **bunch length / compression**
- **longitudinal structure / slice parameters**
  - Coherent FIR radiation
  - Electro-Optical-Sampling
  - Transverse Mode Cavity (integrated Streak Camera)
- **timing / time jitter**

Coherent radiation monitors

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





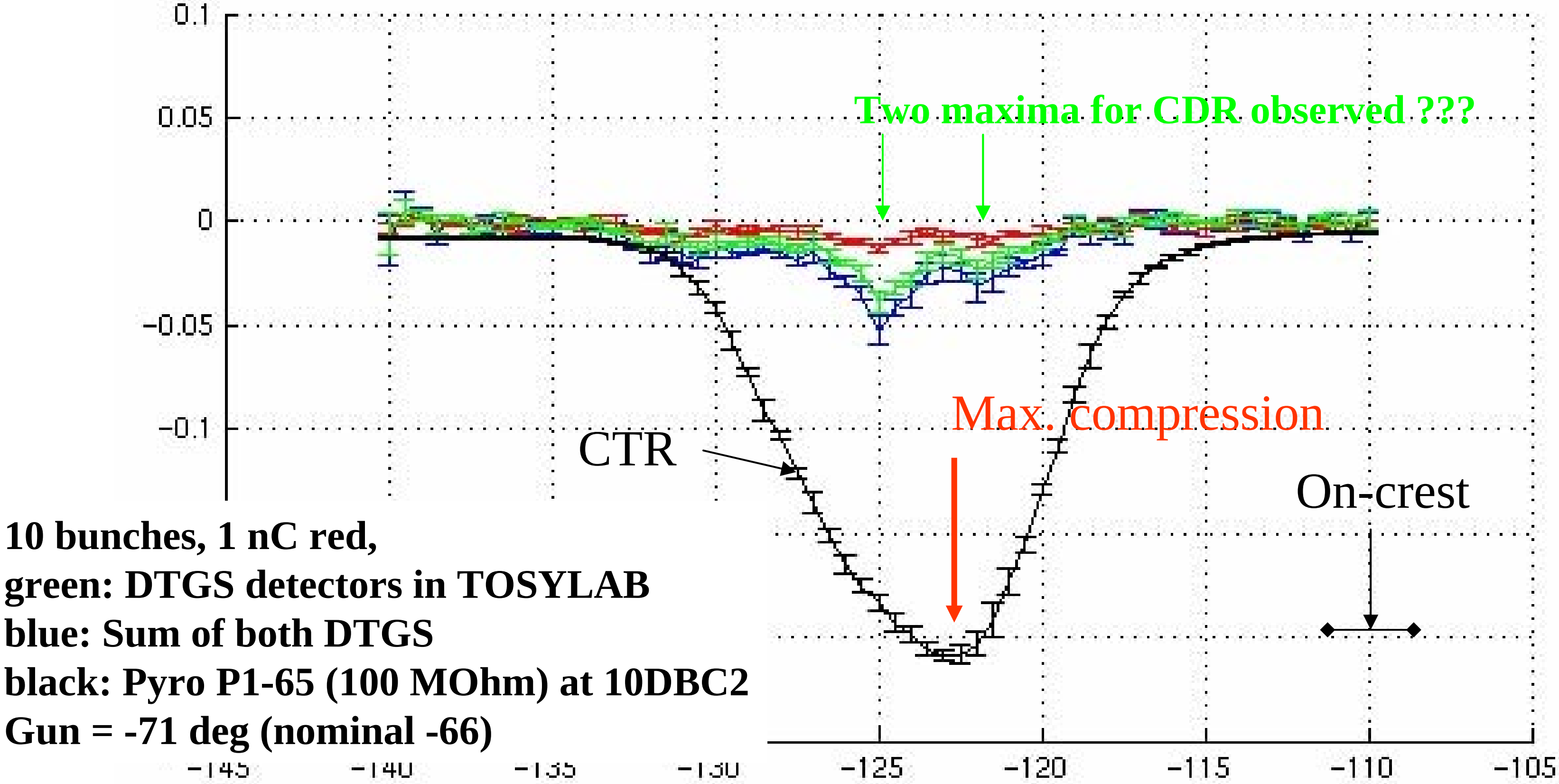
Compression monitor

Pyroelectric detector for coherent radiation

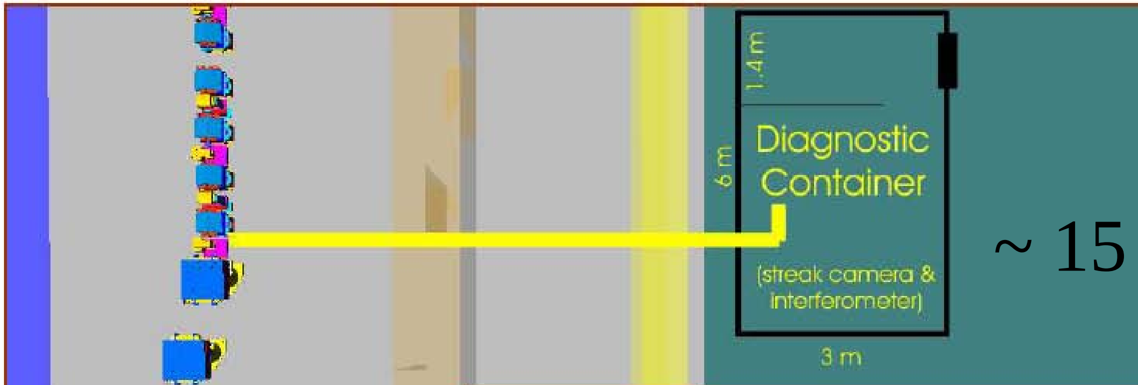
coherent power ~ $1/\sigma_z$

$\Rightarrow$ ideal suited to detect bunch length change

Feedback on pyro-detector established at SPPS

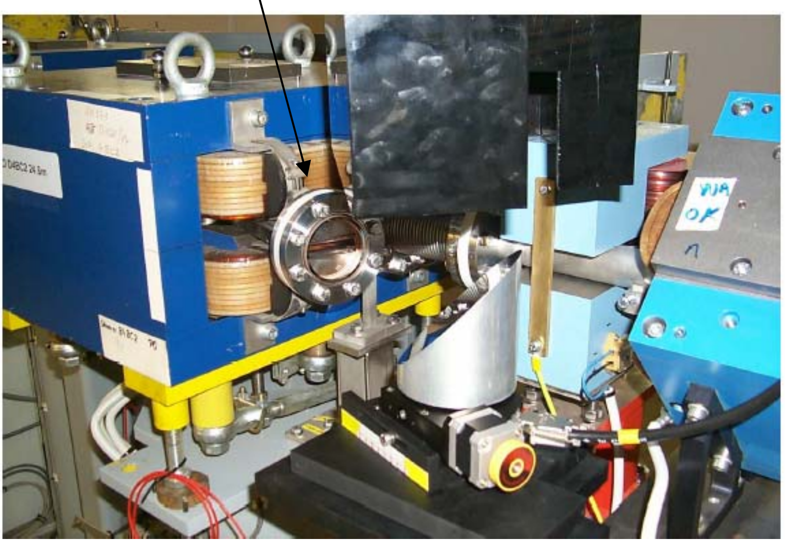


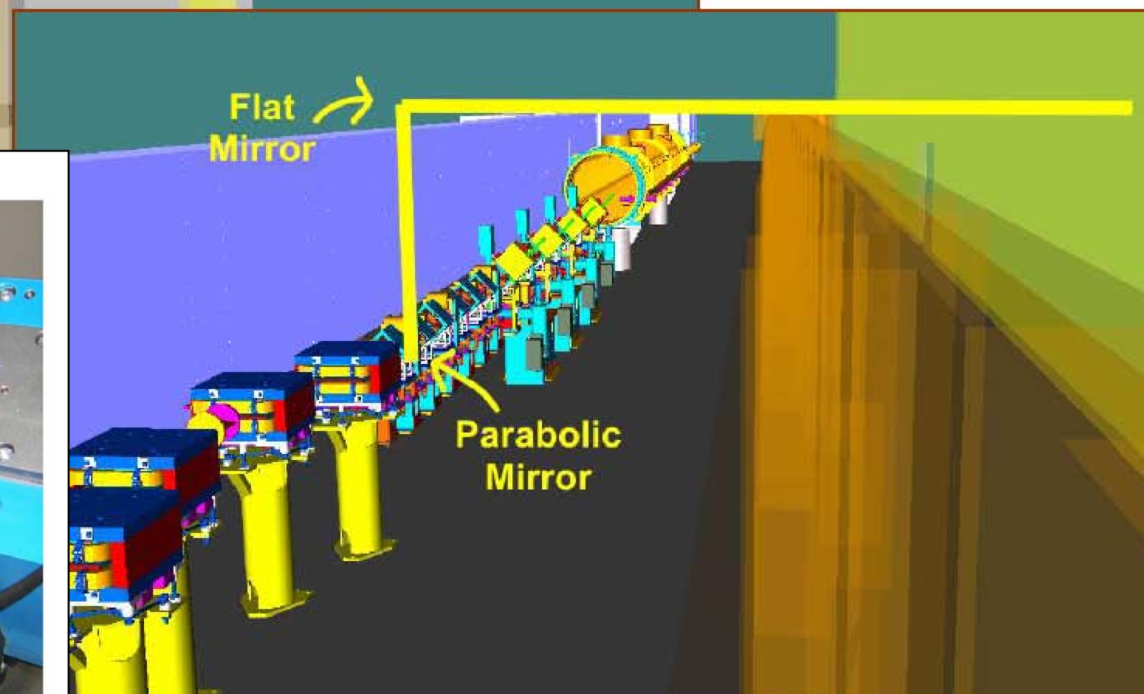
Coherent radiation monitors



~ 15 m transfer line

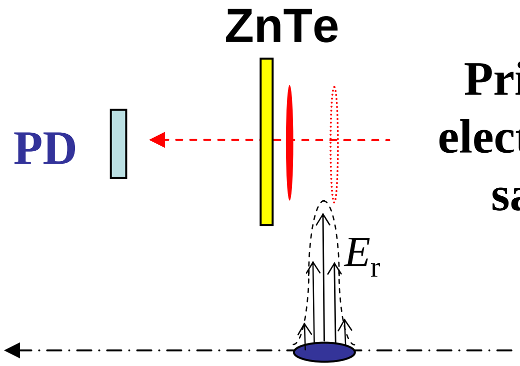
Z-cut Quartz window





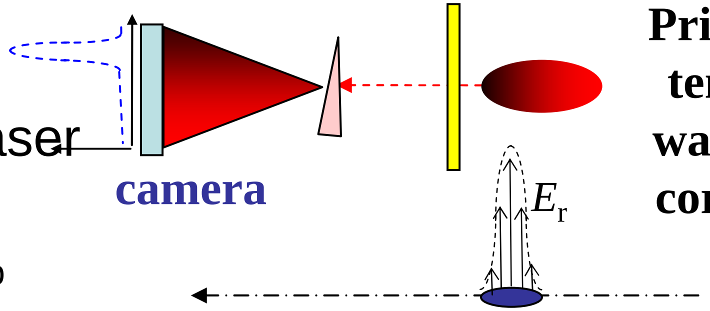
Electro-optical methods

Sampling:
- arbitrary time window possible
- simple analysis
- balanced detector allows high sensitivity
- good synchronization required
- multi-shot method



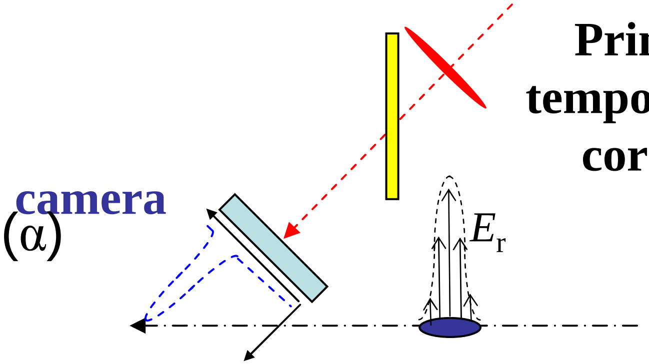
Principal of electro-optical sampling

Chirped laser method:
- single shot method
- some more effort for laser and laser diagnostics required
- resolution due to laser ~ $\sqrt{t_0 \cdot t_{chirp}}$
- time window ~ 1-20ps



Principal of temporal-wavelength correlation

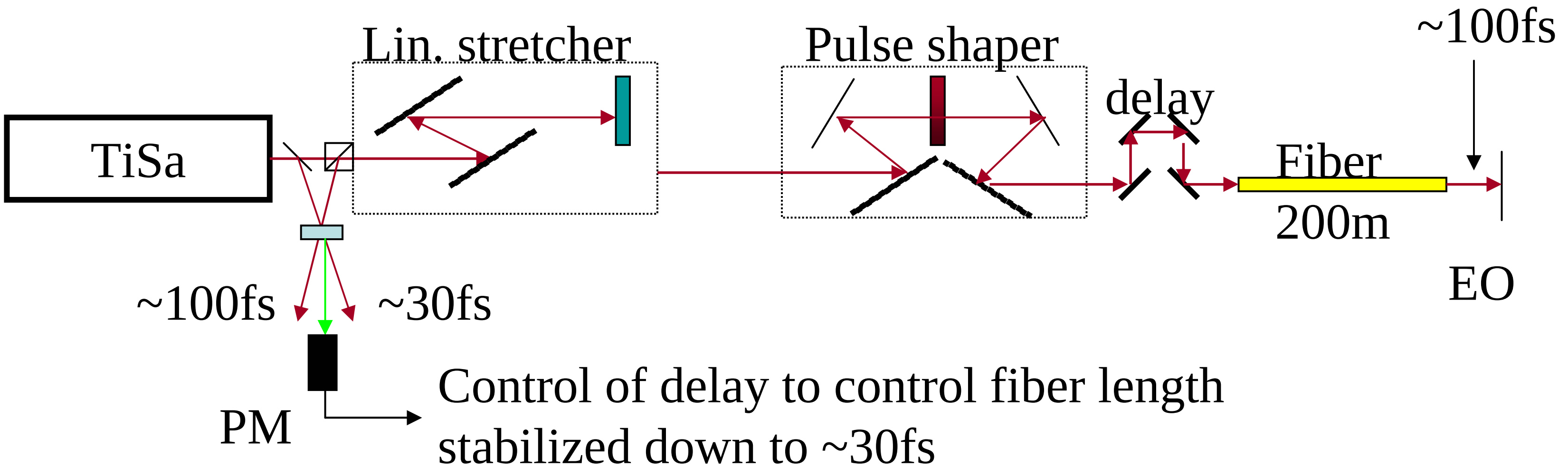
Spatial method:
- single shot method
- imaging optics is critical
- resolution due to geometry > $t_0/\cos(\alpha)$
- time window ~ 1-20ps



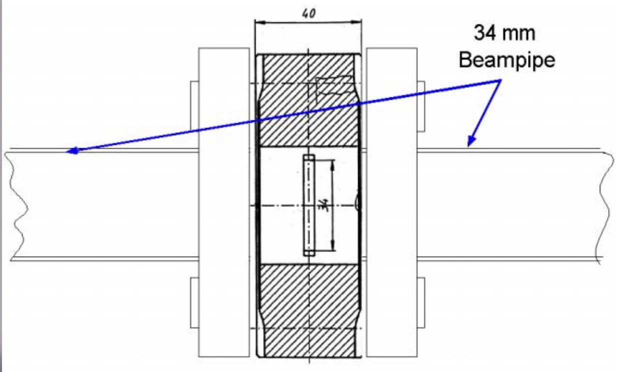
Principal of temporal-spatial correlation

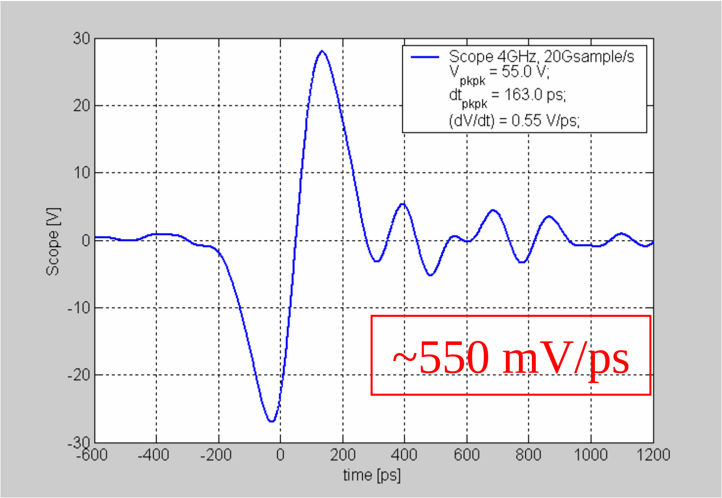
Timing EO (TEO)

- Idea has been developed by Univ. of Michigan (D. Ries et. al.)
- Successfully tested SPPS (res. <200 fs FWHM, 30fs timing jitter)
- Improved version installed at TTF2, uses pump-probe laser

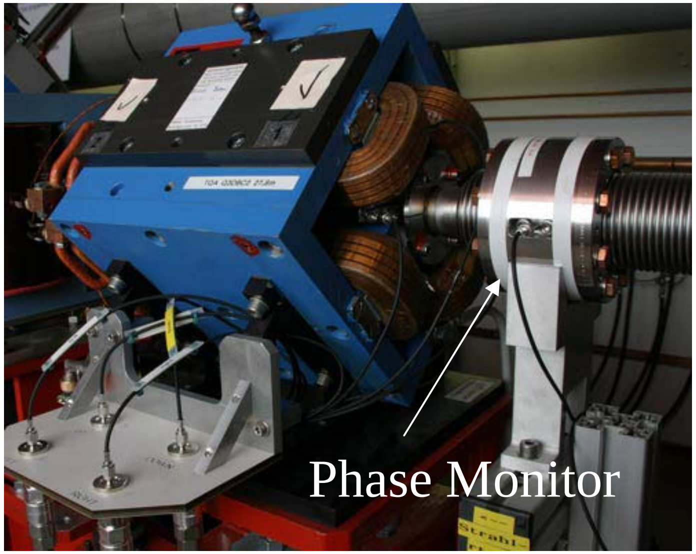


Phase Monitor





- **Isolated impedance-matched ring electrode mounted in a „thick flange“**
- **Broadband, position independent signal, sub-ps resolution**
- **Installed after the gun, each magnetic chicane (both BCs, the collimator + before undulator)**



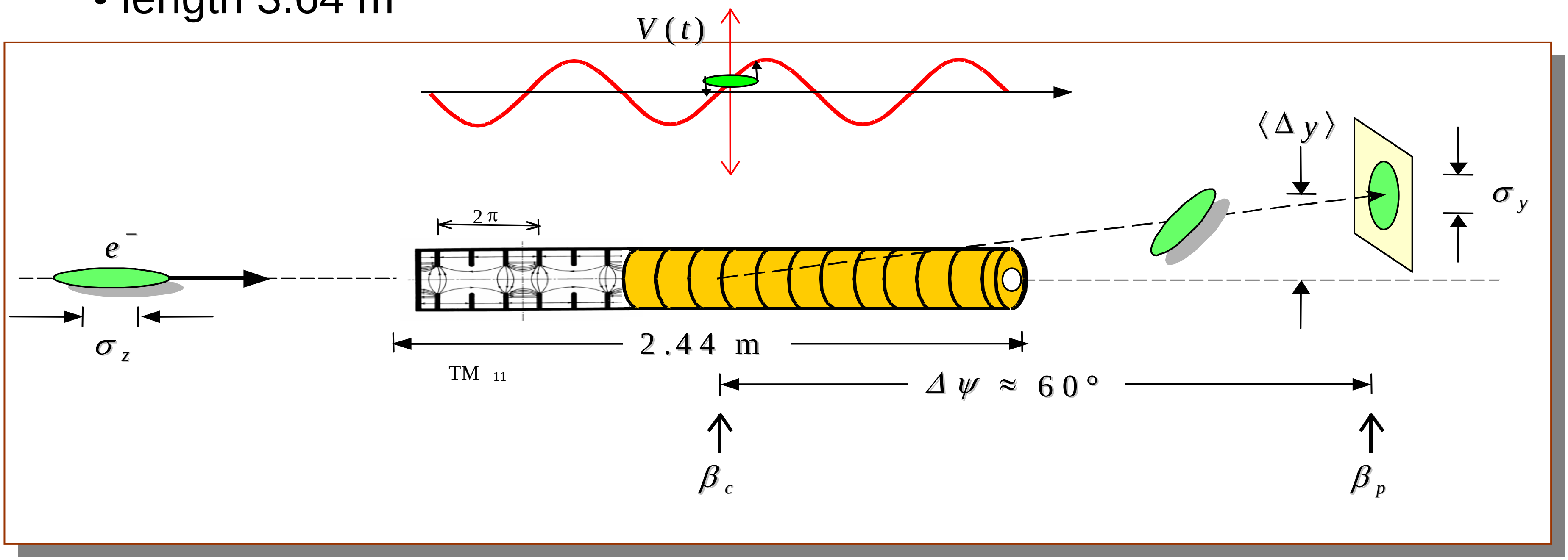
Transverse deflecting cavities

First test at SLAC (Krejcik et. al.):

- "LOLA" S-band cavity installed at end of linac
- 25 MW klystron power to "streak" the 28.5 GeV linac beam
- Measurement with beam profile monitor

Second structure installed at TTF2 (M.Ross et. al./M.Nagel et al.)

- length 3.64 m

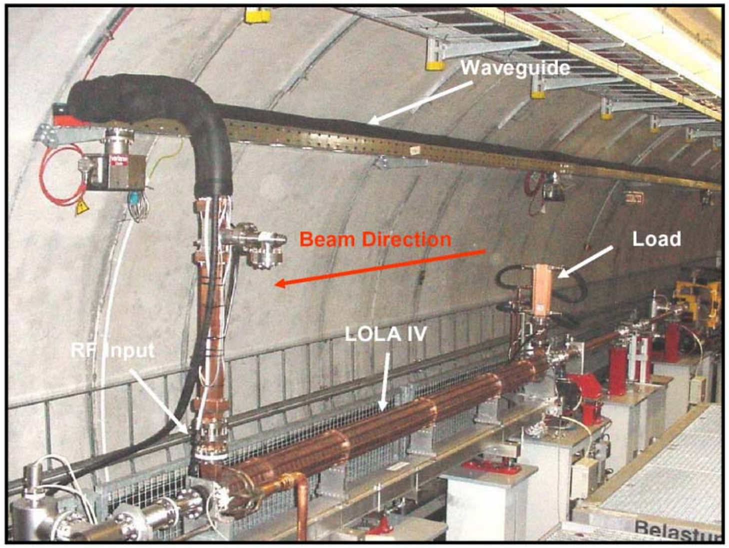


Transverse deflecting cavities

Parameters of LOLA IV

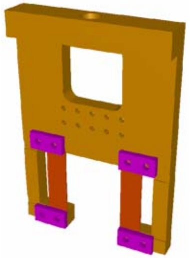
Type of structure	Constant impedance structure
Mode type	TM 11 (Hybrid Mode)
Phase shift / cell	120° (2 Pi / 3)
Cell length	35 mm
Design wavelength	105 mm
Nominal operating frequency	2856 MHz
Nominal operating temperature	45 °C
Quality factor	12100
Relative group velocity	**-** 0.0189 **!!**
Filling time	0.645 μs
Attenuation	0.477 N = 4.14 dB
Transverse shunt impedance	16 MOhm / m
Deflecting voltage	$V_o = 1.6$ MV·L/m·$(P_o/MW)^{1/2}$
Nominal deflecting voltage	26 MV at 20 MW
Maximum operating power	25 MW
Length of structure	3640 mm (about 12 feet)
Disk thickness	5.84 mm
Iris aperture	44.88 mm
Cavity inner diameter	116.34 mm
Cavity outer diameter	137.59 mm

LOLA IV in the TTF2-Tunnel



Recently added:

- horizontal kicker before LOLA
- off-axis screen

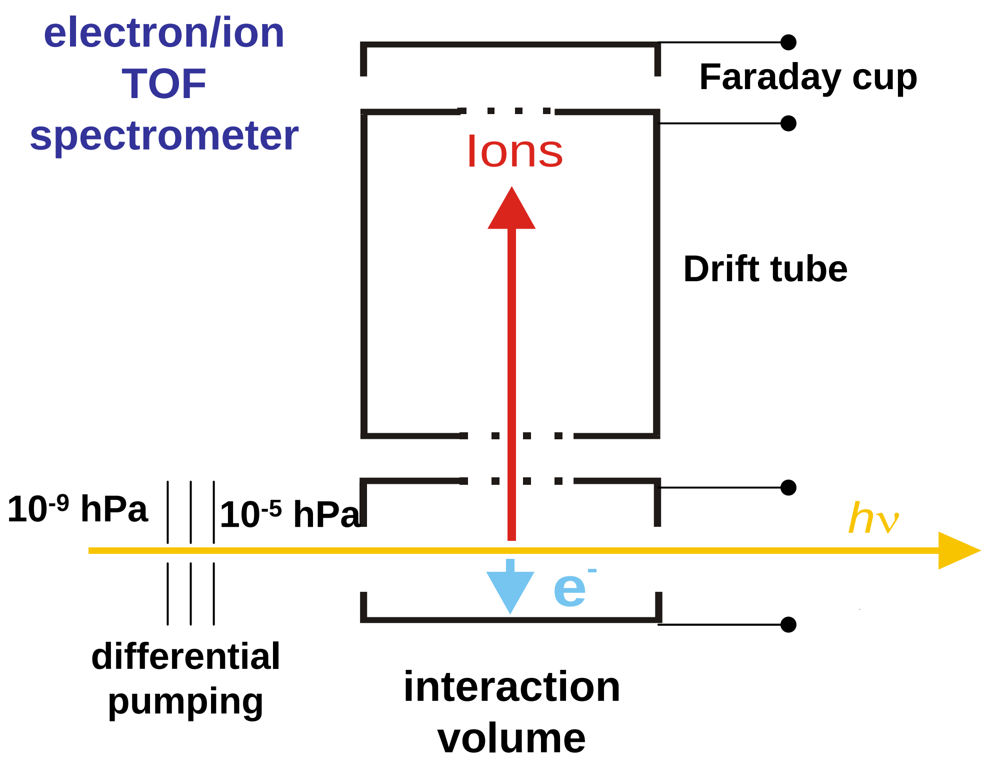


Photon Diagnostics

- pulse energy and beam position
- spectral distribution online
- correlation techniques, synchronisation

Online monitor of FEL pulse energy

Gas ionisation detector



- + transparent
- + wide dynamic range (spont. to sat.)
- + independent of beam position
- + can **measure beam position**
- + no saturation effects
- + λ < 93 nm
- + absolute calibration (~10%)

successfully tested at TTF1

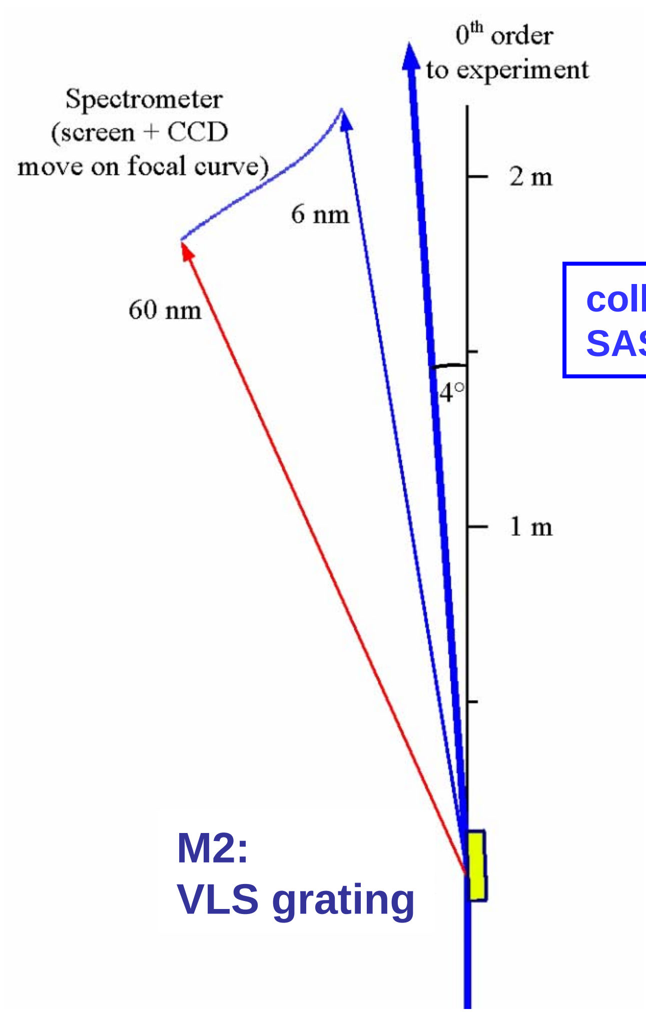
Single photoionisation:

$$N = N_{ph} \times n \times s \times l$$

N = number of electrons or ions
N_{ph} = number of photons
n = target density
s = photoionisation cross section
l = length of interaction volume

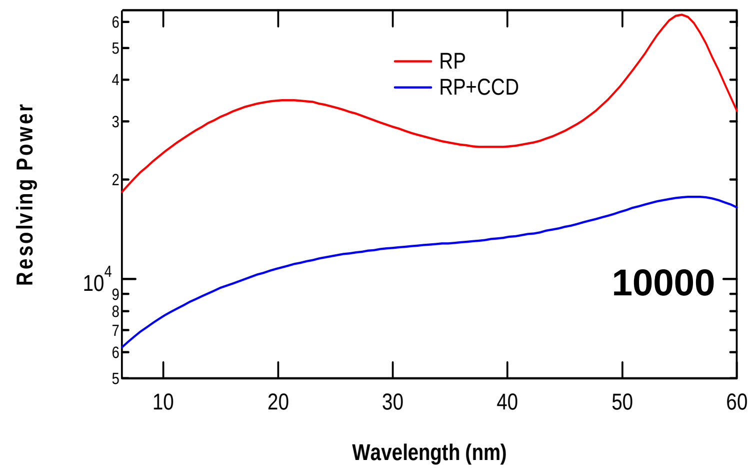
Collaboration with PTB, Berlin, and Ioffe Institute, St. Petersburg

Online spectrometer for single pulses

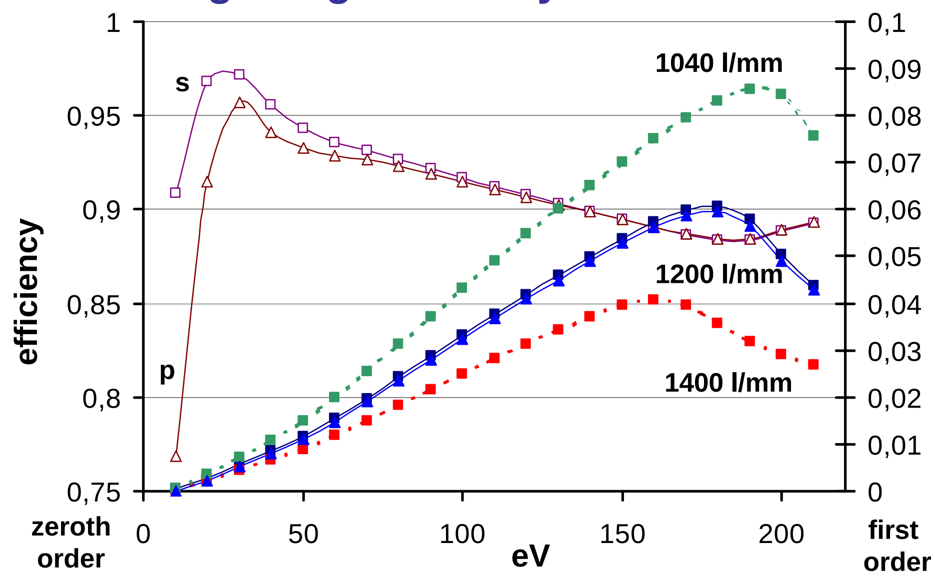


collaboration with SAS and CLRC

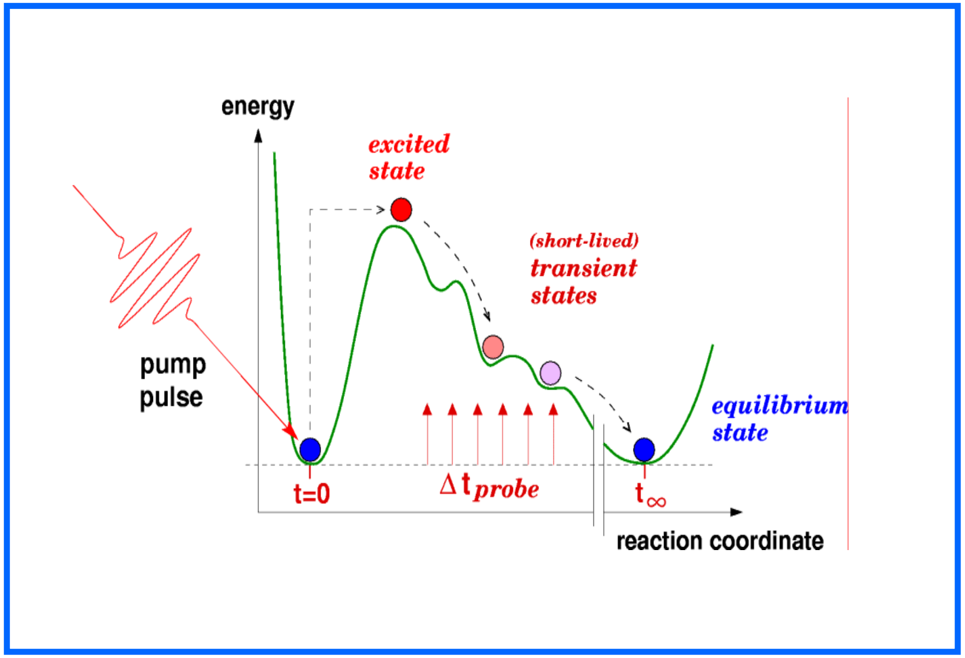
resolving power 1200 lines/mm



grating efficiency



Time-resolved experiments



Schematic presentation of transition states in a chemical reaction

- **pump-probe experiments need fs laser systems synchronised with the FEL**
- **need accurate time delay between laser and FEL**
- **need information on pulse duration**

The synchronisation challenge

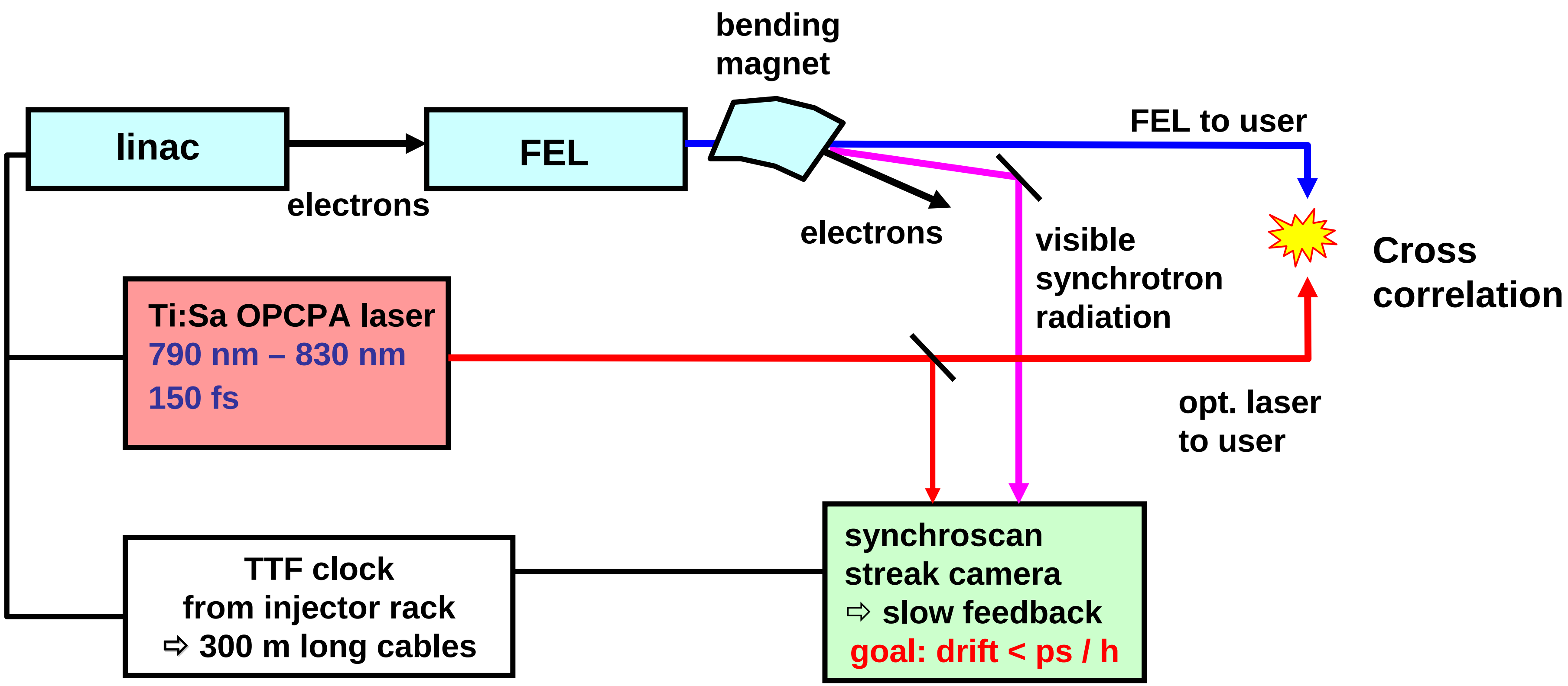
- **Two independent lasers can be synchronised with <fs precision *, but:**
- **Photocathode laser, pump-probe laser and accelerator RF independently synchronised with master oscillator and far apart**
- **Thermal drifts**
- **Accuracy of the electronic synchronisation? Initially a few 100 fs.**
- **Phase jitter of the accelerator RF pulses causes ~0.1% energy jitter of the electron bunches → several 100 fs time jitter**

Measurement of exact timing – Feedback

- Streak camera (vis. SR, FEL – opt. laser, slow)
- Cross correlation (single shot)
  - Visible synchrotron radiation – optical laser
  - Electron bunch – optical laser (EOS)
  - FEL – optical laser

* R. Shelton et al., Opt. Lett. 27, 312 (2002)

Synchronisation optical laser - FEL



Current developments

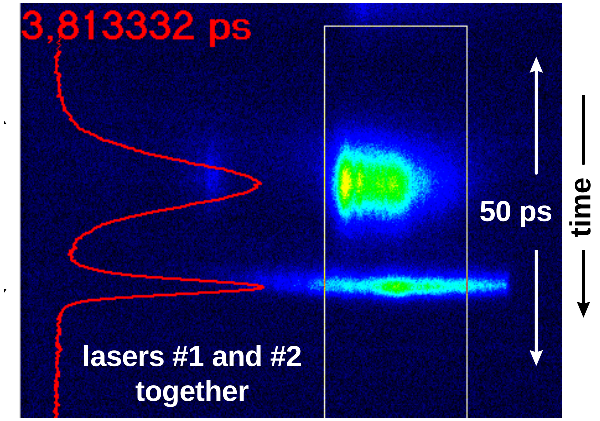
(funded by FP6 and HGF)

Cross correlation techniques, electro-optical sampling

⇨ Fast feedback

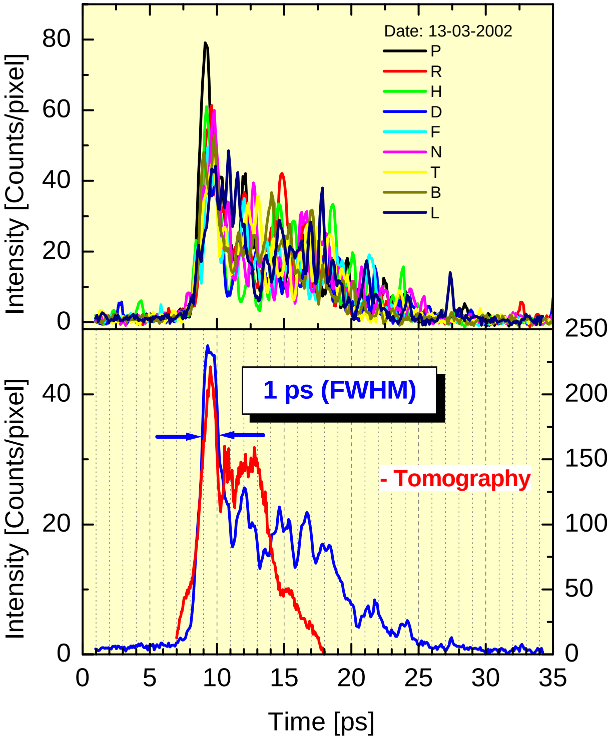
Phase detection, test experiments

Streak camera



two independent laser beams (MBI)

TTF1 result

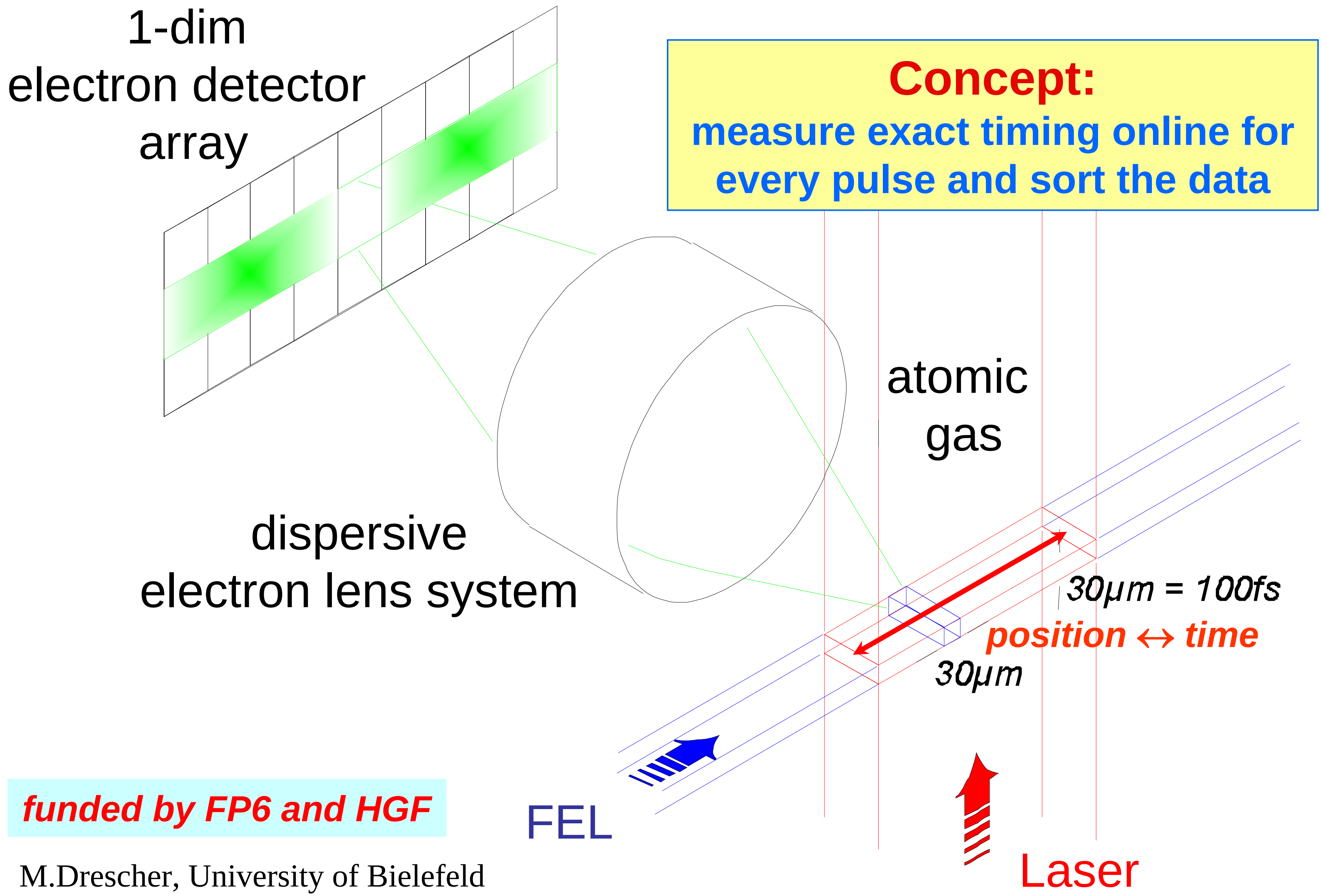


FESCA 200 at TTF1 green dipole radiation

Single-shot cross correlator

for the VUV FEL

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



funded by FP6 and HGF

M.Drescher, University of Bielefeld

Conclusions

- **Electron and photon beam diagnostics are crucial for FEL operation**
- **Photon techniques are particularly suitable for online diagnostics**
- **Much will be learned during the next few years from current R&D and user operation of the VUV-FEL**
  - **FEL performance at nm wavelengths, understand beam dynamics and FEL physics**
  - **pulse-resolved online diagnostics**
  - **synchronisation of all subsystems, measurement of exact timing and temporal structure**
  - **FEL beam transport: pointing stability,** (radiation damage, mirror quality and coherence preservation)
  - **hardware and software integration of all systems**
  - **user experiments: ~30 projects are waiting for beam at the VUV-FEL**
- ***Collaboration of all teams (electrons + photons) has been very stimulating and fruitful, will be exciting and successful in the future***