Laser Applications at Accelerators Conference 2015

25-27 March 2015
Son Caliu Hotel

Beam Diagnostics at Free Electron Lasers

Gero Kube
DESY / MDI
gero.kube@desy.de

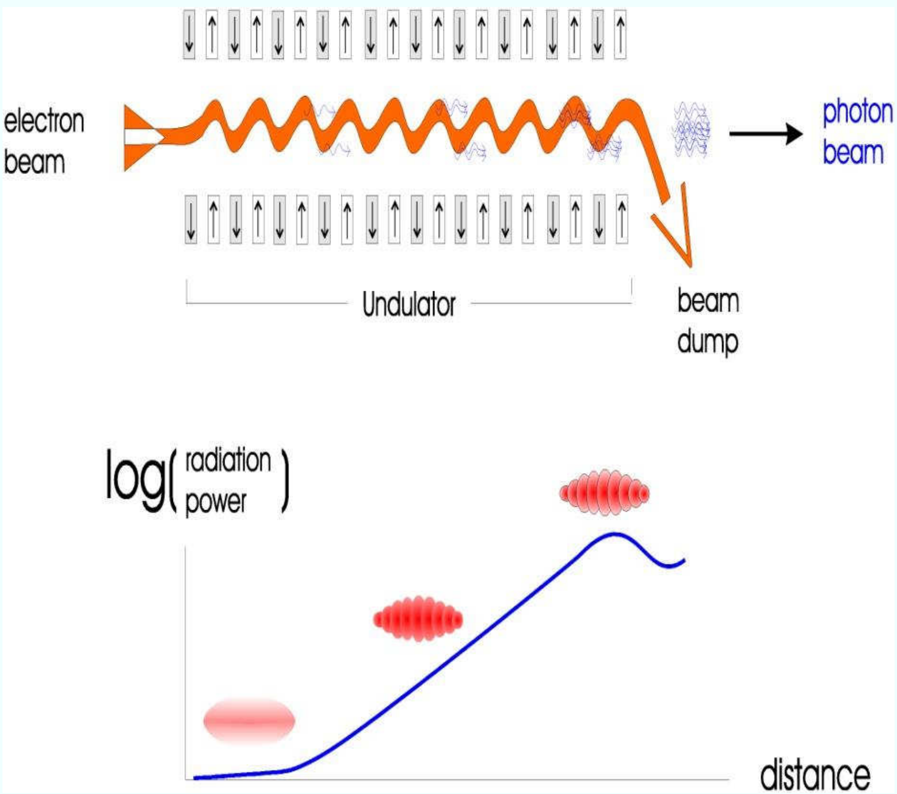
- Introduction
- Beam Position (Intensity)
- Transverse Profile Diagnostics
- Longitudinal Profile Diagnostics
- Timing and Synchronization

Free Electron Lasers (FELs)

- linac (single pass) based 4th generation light sources

Linac based Self Amplification of Spontaneous Emission (SASE) FELs

(→ no matter for diagnostics which FEL type)



electron bunch modulated with its own synchrotron radiation field

- micro-bunching
- more and more electrons radiate in phase until saturation is reached

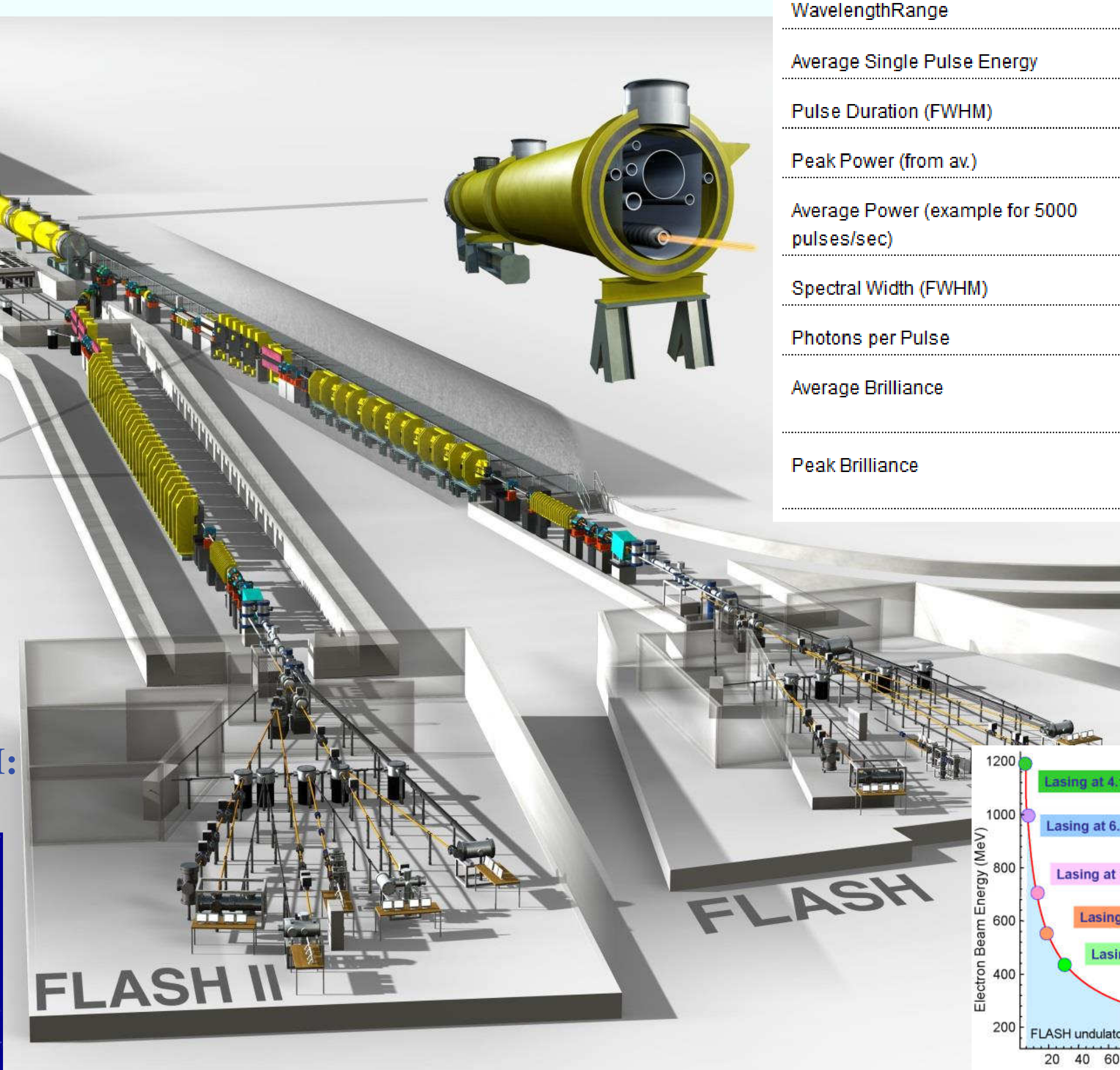
- SASE FEL projects
  - European X-FEL @ DESY
  - LCLS @ SLAC
  - SACLA @ SPring8
  - Swiss FEL @ PSI
  - FLASH @ DESY
  - SPARC @ INFN-Frascati
  - …

FLASH @ DESY

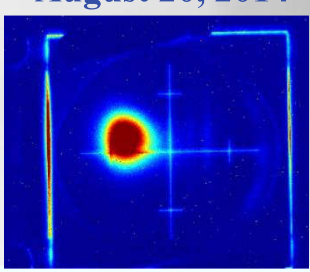
- FLASH accelerator, FLASH I/II SASE FELs

Parameter	Value
WavelengthRange	4.2 - 45 nm
Average Single Pulse Energy	10 - 500 µJ
Pulse Duration (FWHM)	<50 - 200 fs
Peak Power (from av.)	1 - 3 GW
Average Power (example for 5000 pulses/sec)	up to 600 mW
Spectral Width (FWHM)	0.7 - 2 %
Photons per Pulse	10^{11} - 10^{13}
Average Brilliance	10^{17} - 10^{21} photons/s/mrad^2 /mm^2/0.1%bw
Peak Brilliance	10^{29} - 10^{31} photons/s/mrad^2 /mm^2/0.1%bw

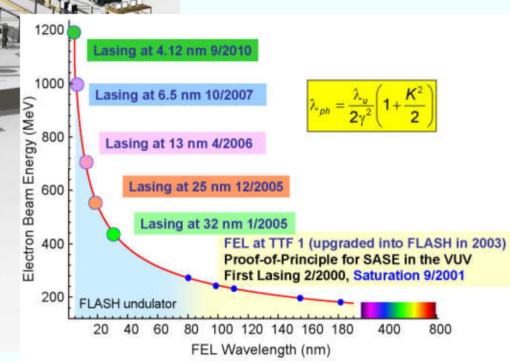
FEL radiation parameters 2012



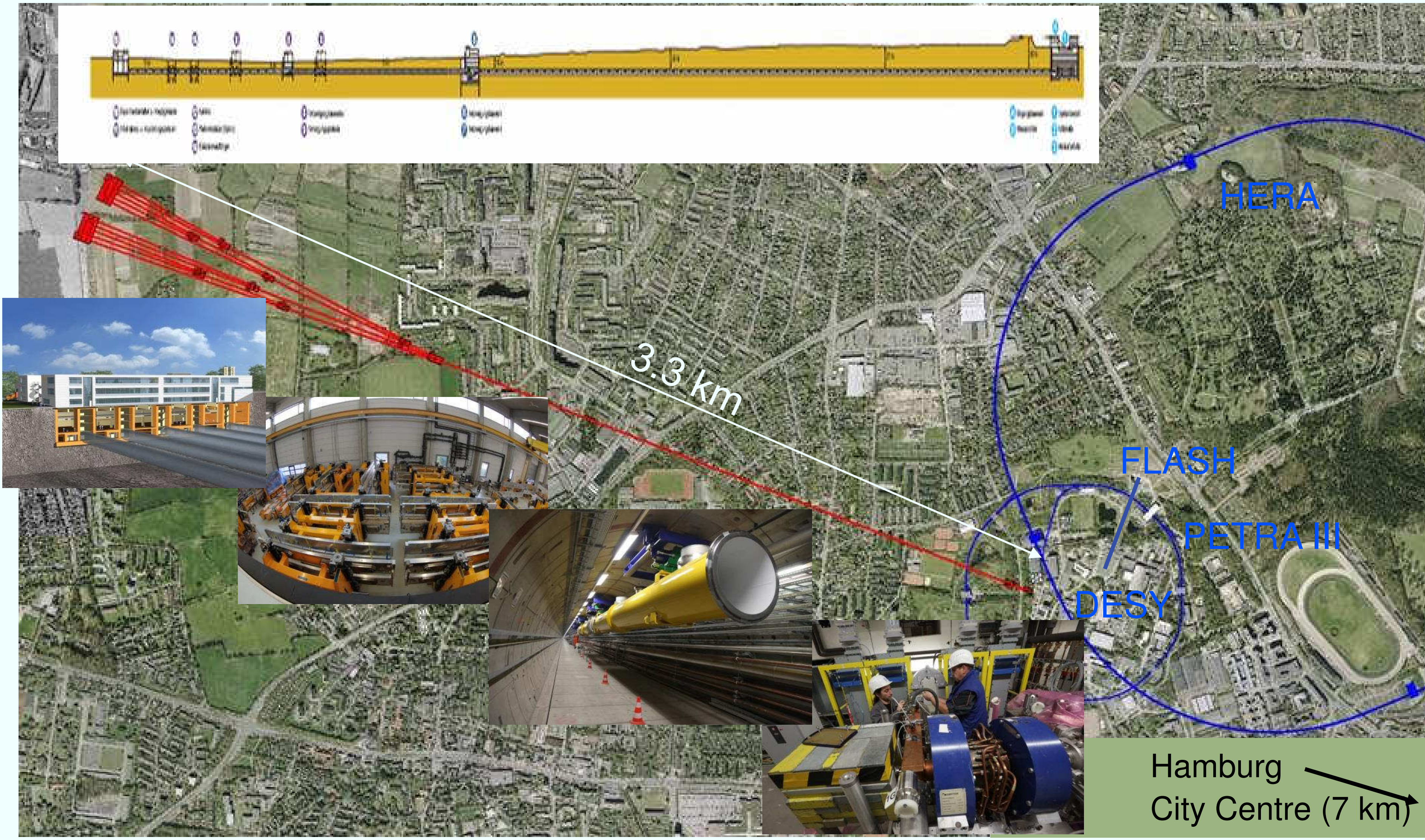
- **first lasing FLASH II:**
  → **August 20, 2014**



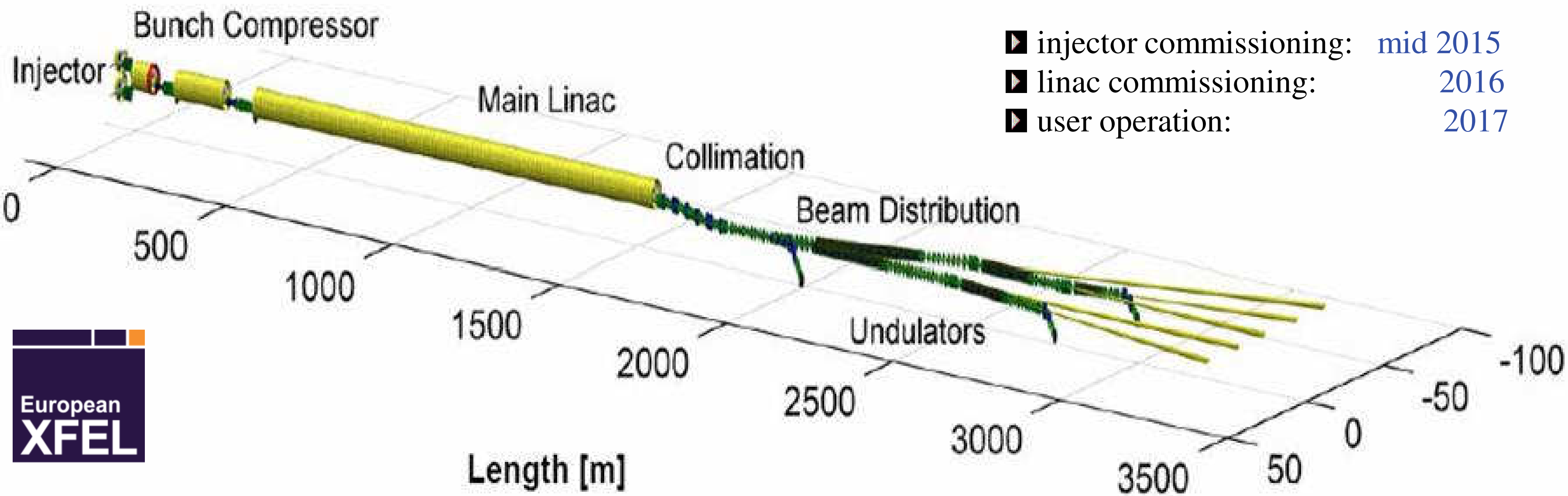
- **lasing @ FLASH:**



The European XFEL @ DESY



E-XFEL @ DESY



- injector commissioning: mid 2015
- linac commissioning: 2016
- user operation: 2017

- photo-injector RF electron gun
- injector linac
- two-stage bunch compression
- collimation and beam distribution
- undulator sections
- photon beamlines

maximun energy:	17.5 GeV
normalized emittance:	1-2 mm mrad
typical rms beam sizes:	20-200 µm
bunch charge :	0.1-1 nCb
min. bunch spacing:	222 nsec
max. macro pulse length:	600 µsec
bunches within macro pulse:	1-2700
bunch pattern:	arbitrary
RF repetition rate:	< 30 Hz
λ_{min}	0.1 nm (12.4 keV)

Beam Properties (1)

- single or few bunches, typically with large separation

⇒ requires single bunch measurements

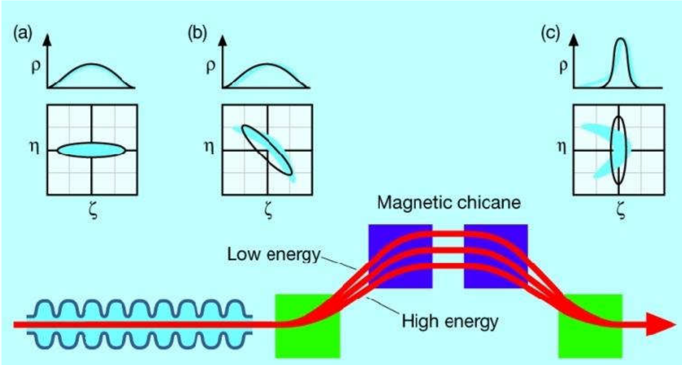
- high current density
  - sufficient energy transfer from electron beam to radiation field
  - natural scale: number of electrons per wavelength

$$N_{e,\lambda} = \frac{I\lambda}{ec}$$

$$N_{e,\lambda} = 1 \;\Rightarrow\; I = \begin{cases} 0.5\,\mu\text{A} & (\lambda = 100\,\mu\text{m}) \\ 0.5\,\text{A} & (\lambda = 0.1\,\text{nm}) \end{cases}$$

⇒ [redacted]uires additional bunch compression in order to increase current density

⇒ extremely short bunch lengths O(10-100 fsec)



- charge per bunch: pCb up to about nCb
  - new trend: short pulse operation, requires lower and lower charges…
  - signal to noise problems at low charge, even for kA peak currents

Beam Properties (2)

- high electron beam quality
  - energy spread $$\frac{\sigma_e}{E} \approx 10^{-4}$$
  - transverse emittance $$\varepsilon \leq \frac{\lambda}{4\pi}, \quad \varepsilon = \varepsilon_n / \beta\gamma$$ (→ high energy helps)

  for resonant energy exchange and good overlap with radiation field

→ high demands on 6-dimensional phase space

longitudinal phase space

- short bunches require complicate longitudinal diagnostics
- new methods required to verify pulse lengths of electron and laser bunch

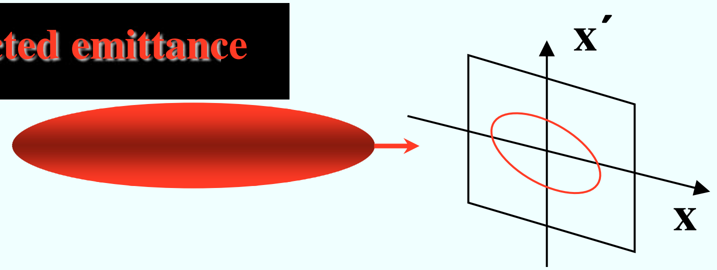
transverse phase space

- beam gets extremely small, often weird shape
- emittance is no equilibrium property, many effects can spoil it
- optics errors propagate through entire machine (linac is open loop system)
- coherent effects due to short pulses and instabilities

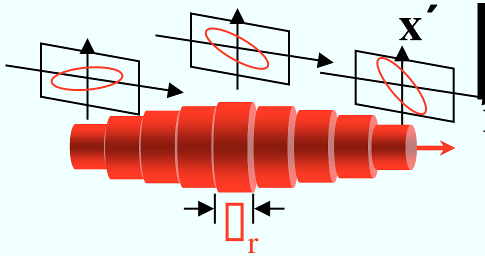
Beam Properties (3)

- comment: transverse emittance
  - electrons slip back in phase with respect to photons by λ_r each undulator period
  - FEL integrates over slippage length → slice emittance f importance

projected emittance



slice emittance



- stability
  - energy stability → wavelength stability $\frac{\Delta\lambda}{\lambda} = -2\frac{\Delta E}{E}$
  - arrival time stability → pump probe experiments
  - position stability
    → overlap between beam and radiation in undulators

LLRF feedback

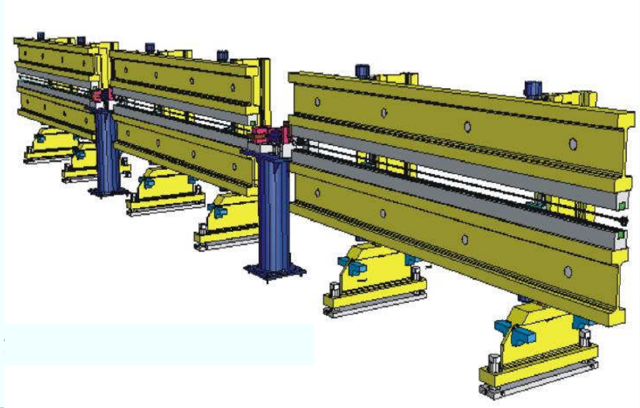
high level synchronisation

high resolution BPMs, orbit feedback

example: XFEL @ DESY

- length of undulator section: 100-150 m
- BPM position resolution:

1 µm (single bunch), **100 nm** (average over bunch train)



Standard FEL Diagnostics @ FLASH

		FLASH1	FLASH2
Charge	Toroids	12	5
	Dark Current Monitor	1	
	Faraday Cups	3	
	BPMs	6	33
Transverse Size	OTR-Screens	~30	
	Scintillating-Screens	1	7
	Wire scanners (MDI)	10	
	Wire scanners (Zeuthen)	9	
Transverse Position	Button-BPMs	26	12
	Stripline-BPMs	33	4
	Cold Cavity BPMs	6	
	Cavity BPMs		17
	HOM-based monitors	39	
Beam Loss	BLMs	>70	~55
	Cherenkov Fibers	2	1
	Beam Halo Monitors	1x4	1x4
	Ionization Chambers	4	4

about ~ 400 monitors

and a lot of additional special diagnostics…

Standard FEL Diagnostics @ E-XFEL

Monitor (Standard Diagnostics Only)	Number
BPMs (cold)	120
BPMs (Striplines, Pickups)	250
Undulator BPMs (Cavity, 1µm Resolution)	140
Charge Monitors (Toroids, Faraday Cups)	40
Beam Size: OTR, Wirescanners	77
Dark Current	10
Loss Monitors (PM Systems, Fibers)	320
Phase	15
Other	about 50
Total	**about 1000**

and a lot of additional special diagnostics…

Beam Position Monitors

- short version of E-XFEL BPM specification

specified charge range: 0.1 – 1nC	Number	Beam Pipe	Length	Type	Single Bunch Resolution (RMS)	Train Averaged Resolution (RMS)	Optimum Resolution Range	Relaxed Resolution Range	x/y Crosstalk	Bunch to Bunch Crosstalk	Trans. Alignment Tolerance (RMS)
		mm	mm				mm	mm	%	µm	**µm**
Standard BPM	219	40.5	200/ 100	Button			± 3.0	± 10	1	10	**200**
Cold BPM	102	78	170	Button/ Re-entrant			± 3.0	± 10	1	10	**300**
	12	40.5	255	Cavity			± 1.0	± 2	1	1	**200**
	117	10	100	Cavity			± 0.5	± 2	1	0.1	**50**
IBFB	**4**	**40.5**	**255**	**Cavity**	**1**	**0.1**	**± 1.0**	**± 2**	**1**	**0.1**	**200**

➡ different BPM types to meet different requirements

courtesy: D.Nölle (DESY)

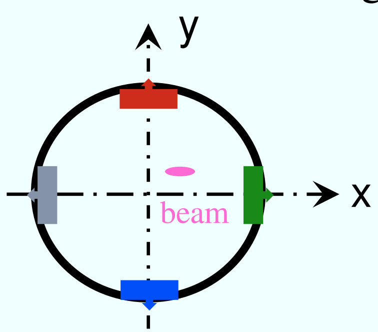
Beam Position Monitors

- **operation principle of (capacitive) button pickup**

LHC button pickup

courtesy: R.Jones (CERN)

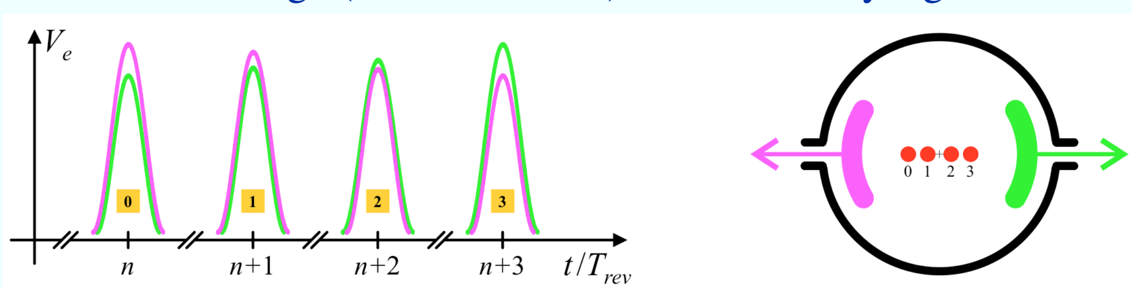
  - electric field induces image charge on pick-up
    - → pick-up mounted isolated inside vacuum chamber
    - → amount of induces charge depends on distance between beam and pick-up



  - processing example: **Δ/Σ method**

$$x = K_x \frac{P_1 - P_3}{P_1 + P_3} \qquad y = K_y \frac{P_2 - P_4}{P_2 + P_4}$$

- **beam position information**
  - amplitude modulated on large (common mode) beam intensity signal

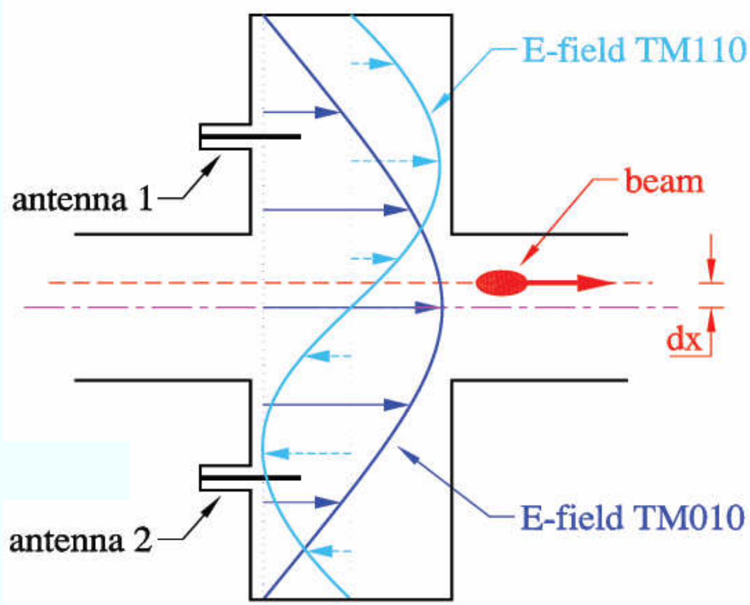


Courtesy: *M. Gasior (CERN)*

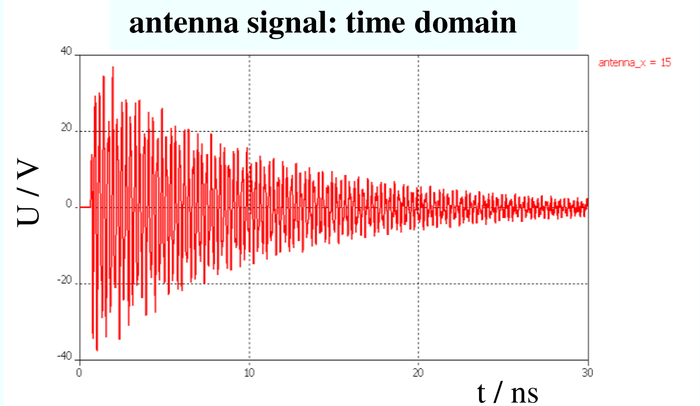
  - signal subtraction to obtain position information
    - → difficult to do electronically without some of the intensity information leaking through

Cavity BPM

- collect directly position information
  - bunch excites several resonating modes while passing a pillbox-like cavity
    - → short bunches deliver wide spectrum of frequencies
  - monopole mode $TM_{01(0)}$: beam intensity
    - → maximum at center
    - → strong excitation
  - dipole mode $TM_{11(0)}$: beam position
    - → minimum at center
    - → excitation by beam offset
    - → slightly shifted in frequency wrt. monopole mode

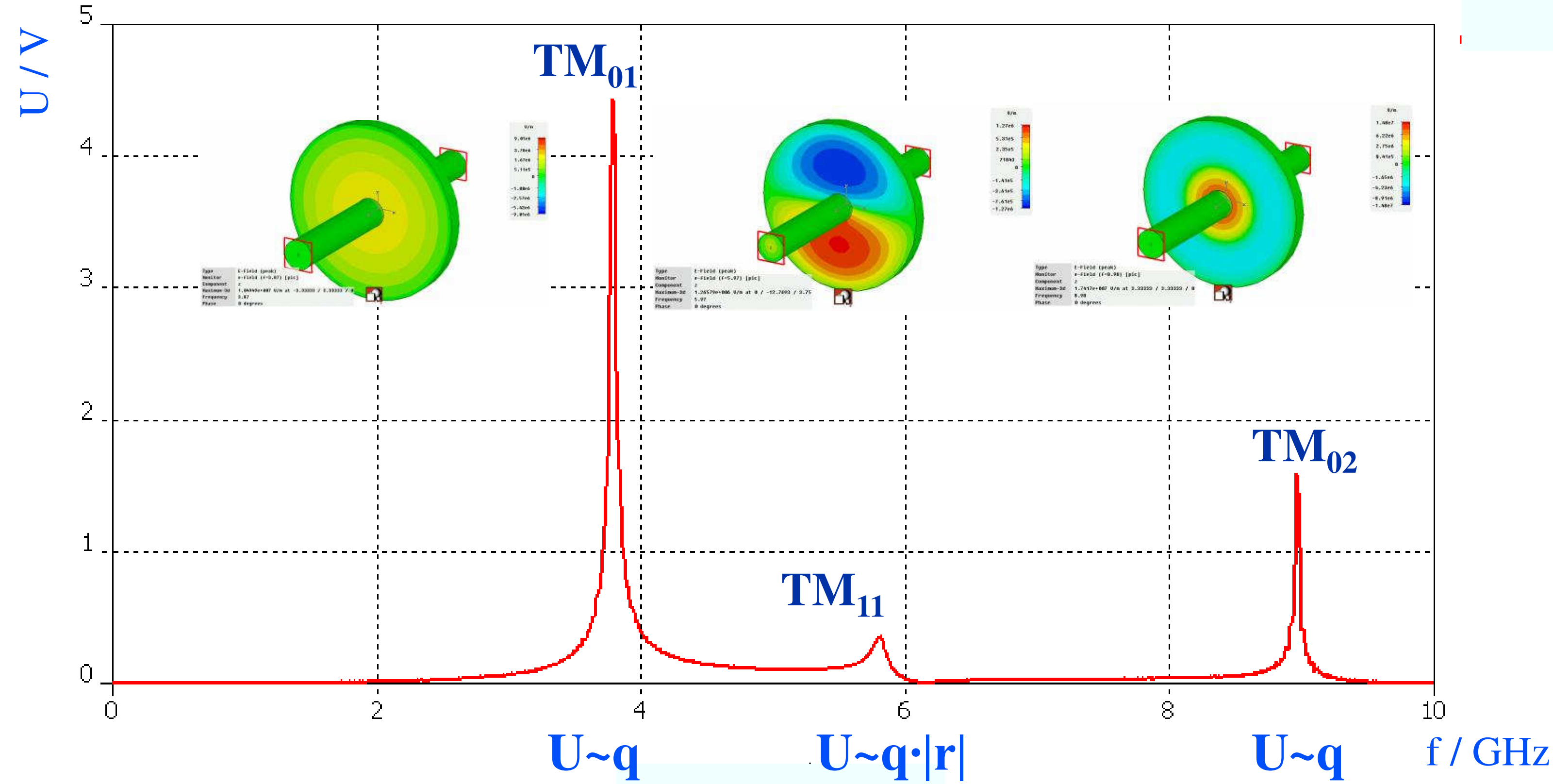


- antenna for outcoupling of dipole mode
  - **amplitude**: position information
    - → only absolute value !
  - **phase** (wrt. monopole mode): sign information
    - → simultaneous measurement required !



Cavity BPM

- cavity frequency spectrum



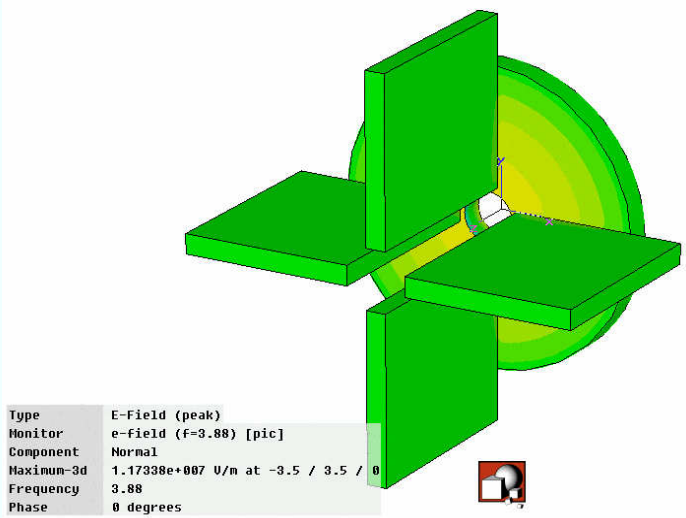
- **q:** beam charge, **r:** beam offset
- **problem**: monopole mode (TM_{01}) leakage into dipole mode (TM_{11})
  → suppression of monopole mode required

courtesy: D.Lipka (DESY)

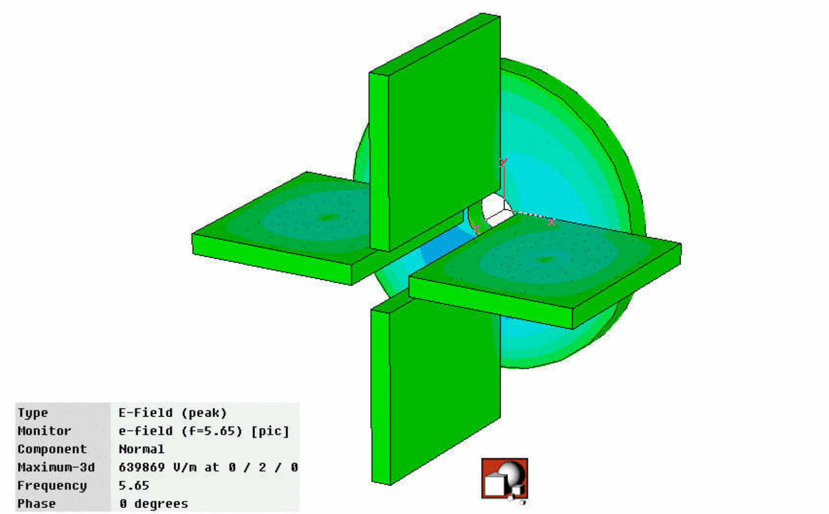
Cavity BPM

- suppresion of monopole mode
  - dipole mode (TM_{11}) signal coupled out via **waveguide**
    → choose outcoupling at position of large TM_{11} electric field amplitude
  - design waveguide with cutoff frequency above f_{01} (monopole mode) resonance
- influence of outcoupling waveguide

Monopole Mode



Dipole Mode

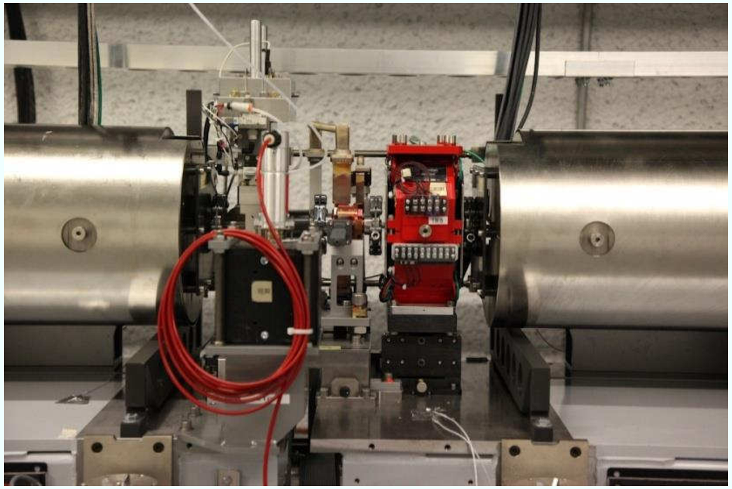


courtesy: D.Lipka (DESY)

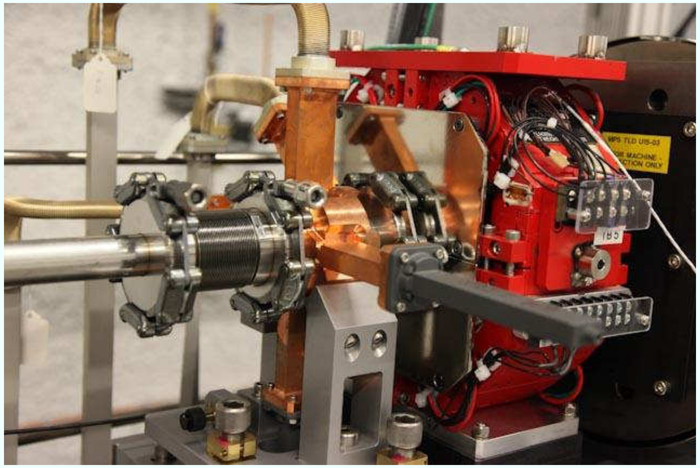
- narrow-band electronics for signal processing

  → B.Keil, Proc. DIPAC'09, Basel (Switzerland) 2009, TUOC01, p.275
  → D.Lipka, Proc. DIPAC'09, Basel (Switzerland) 2009, TUOC02, p.260

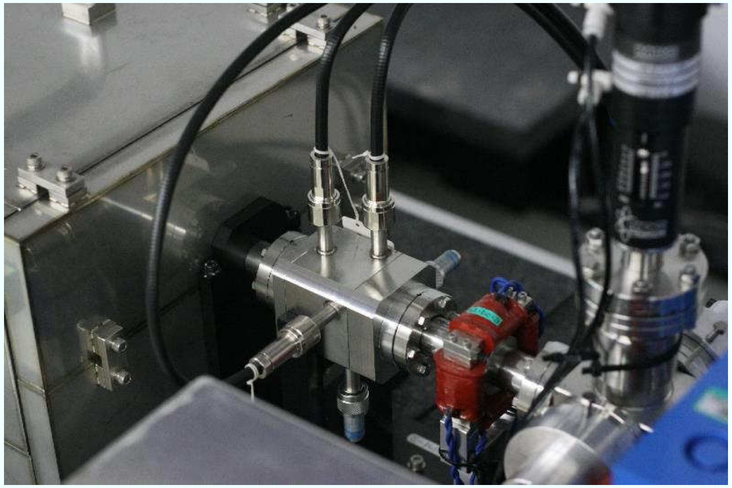
Cavity BPMs for SASE Machines



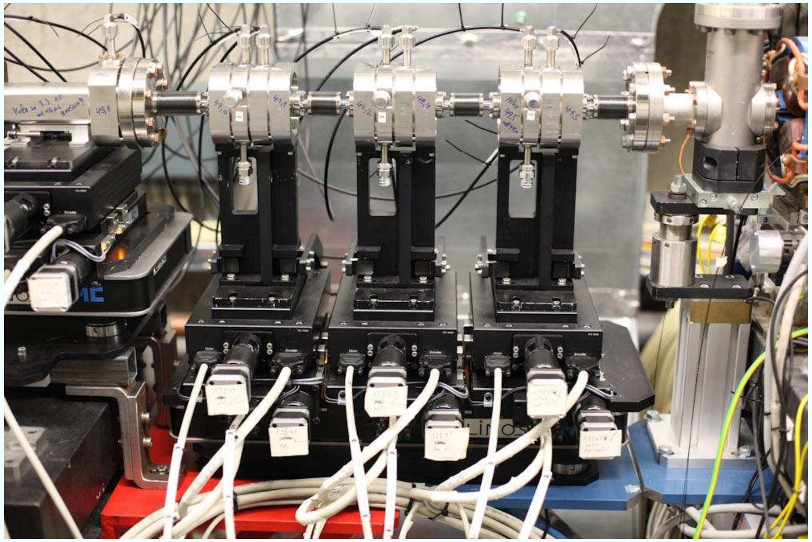
Undulator intersection @ LCLS



Cavity BPM @ LCLS



Low Q Cavity BPM @ SCSS

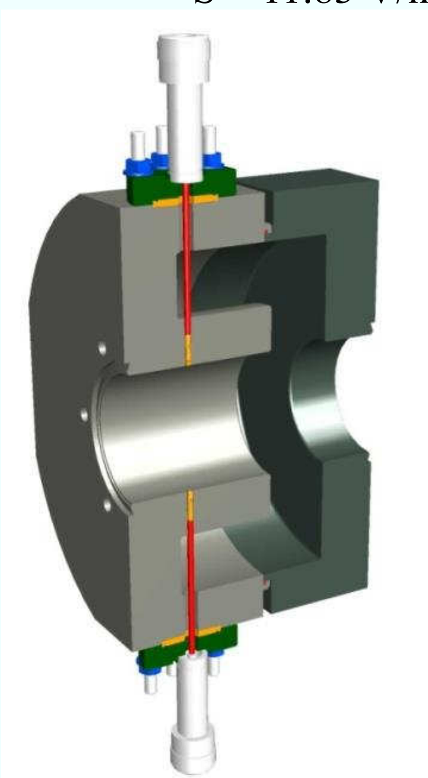


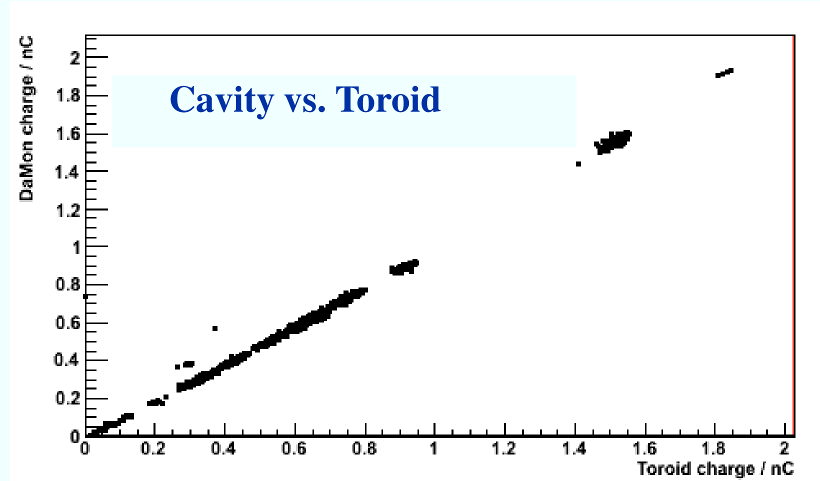
E-XFEL Cavity BPM Test @ FLASH

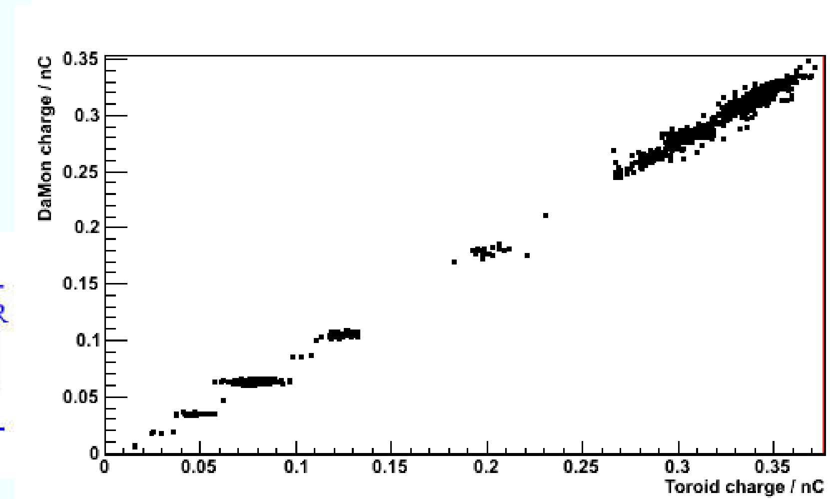
courtesy: D.Nölle (DESY)

Cavity Monitor for Bunch Current

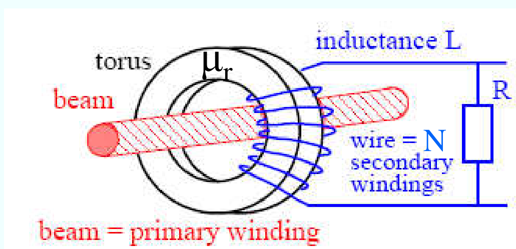
- **E-XFEL design**
  - parameters:
    - → f_{res} = 1.3 GHz, Q_L = 198.4
    - → 40.5 mm diameter tube, 9 cm length
  - achieved sensitivity:
    - → S = 11.83 V/nCb







- **Toroid principle**

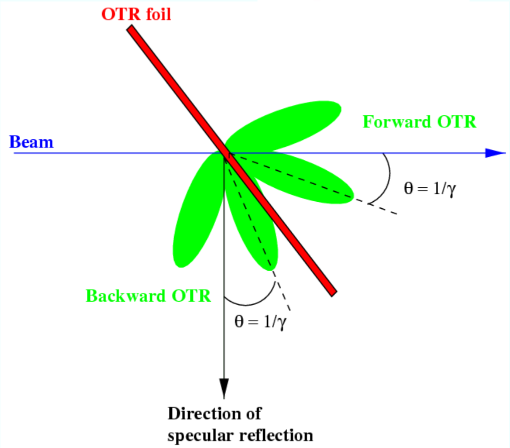


P. Forck, "Lecture Notes on Beam Instrumentation and Diagnostics", JUAS 2011

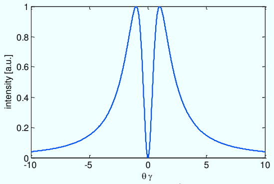
D.Lipka et al., Proc. DIPAC 2011, Hamburg (Germany) 2011, WEOC03

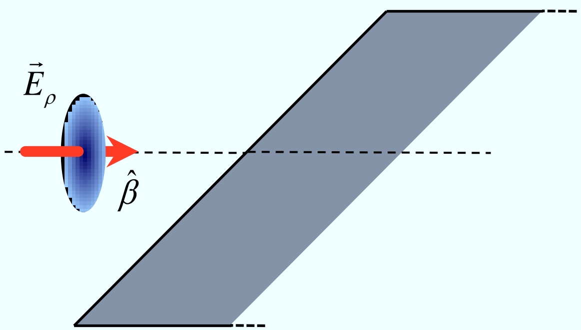
Transverse Profile / Emittance

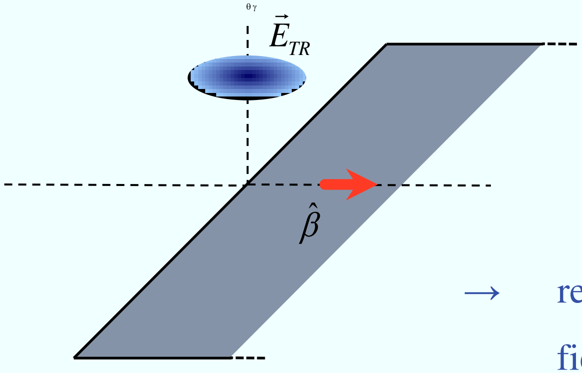
- working horse: **Transition Radiation**
  electromagnetic radiation emitted when a charged particle crosses boundary between two media with different optical properties



- visible part: **Optical Transition Radiation (OTR)**
- beam diagnostics: backward OTR
  typical setup: image beam profile with optical system
- radiation generation
  → virtual photon reflection at boundary
  (perfect conductivity)







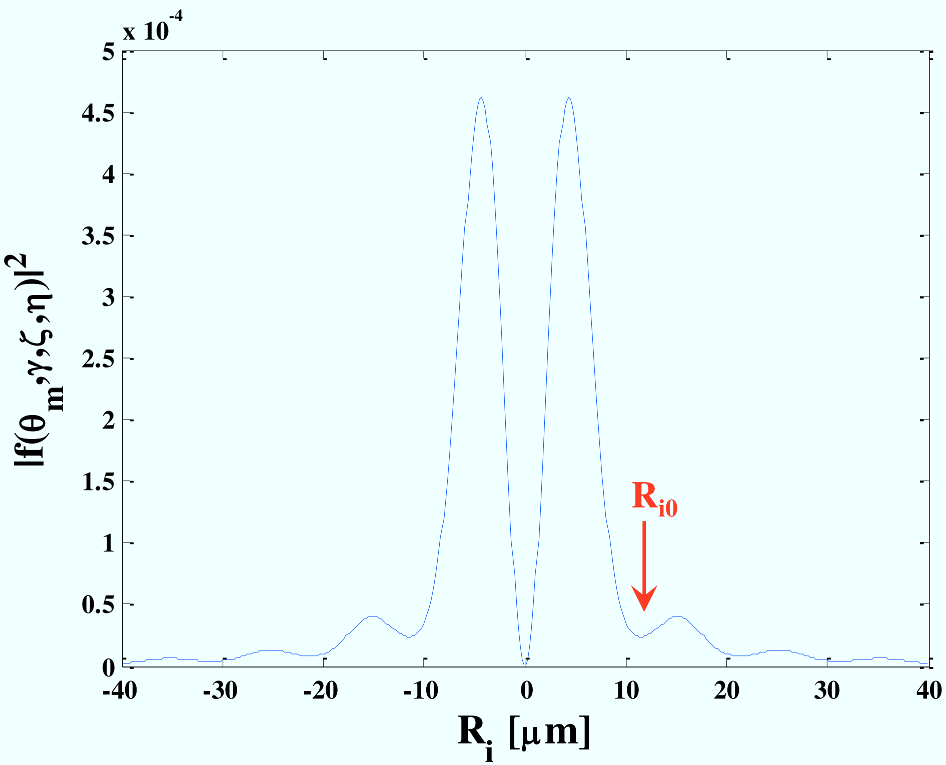
→ reflected and incident field are the same

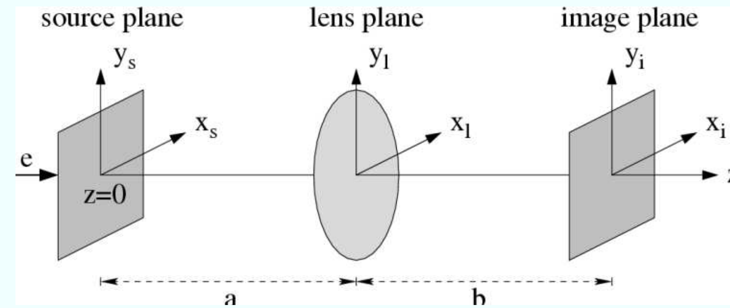
- advantage: fast single shot measurement
  linear response (neglect coherence !)
- disadvantage: high charge densities may destroy radiator → limitation on bunch number

OTR Monitor Resolution

- calculation of point spread function in image plane

G. Kube, TESLA-FEL Report 2008-01





- parameters of calculation

E = 1 GeV
λ = 500 nm
f = 250 mm
a = b = 500 mm (1:1 imaging)
lens-Ø = 50.8 mm

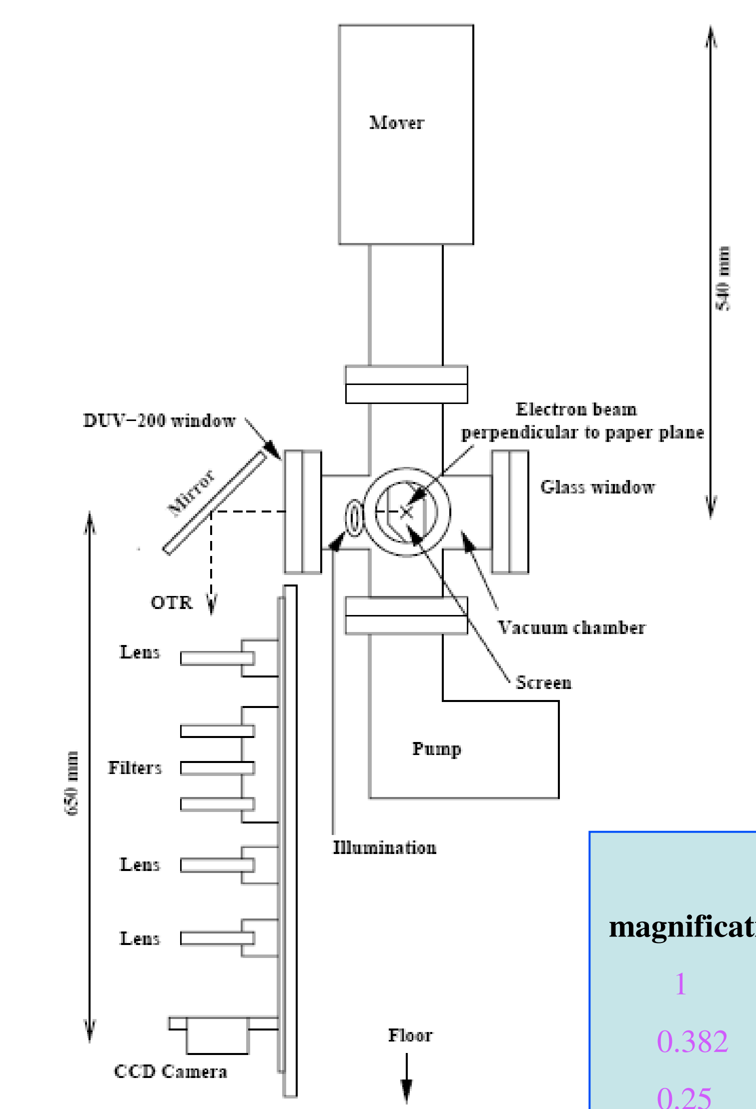
- OTR resolution
  - resolution definition according to classical optics:

⟹ first minimum of PSF (→ diameter of Airy disk)

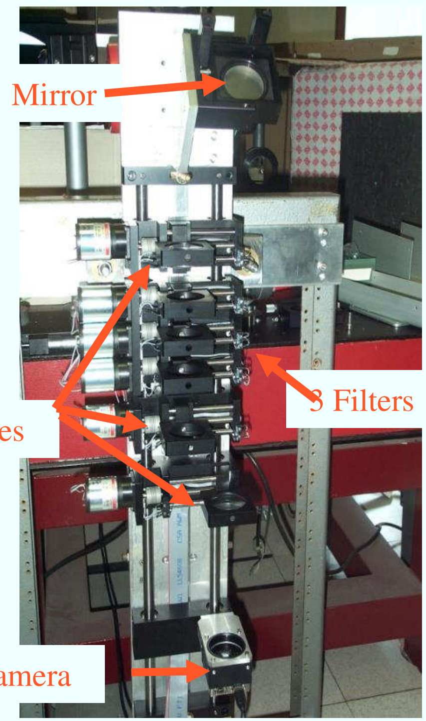
M: magnification

θ_m: lens acceptance angle

OTR Monitors at FLASH



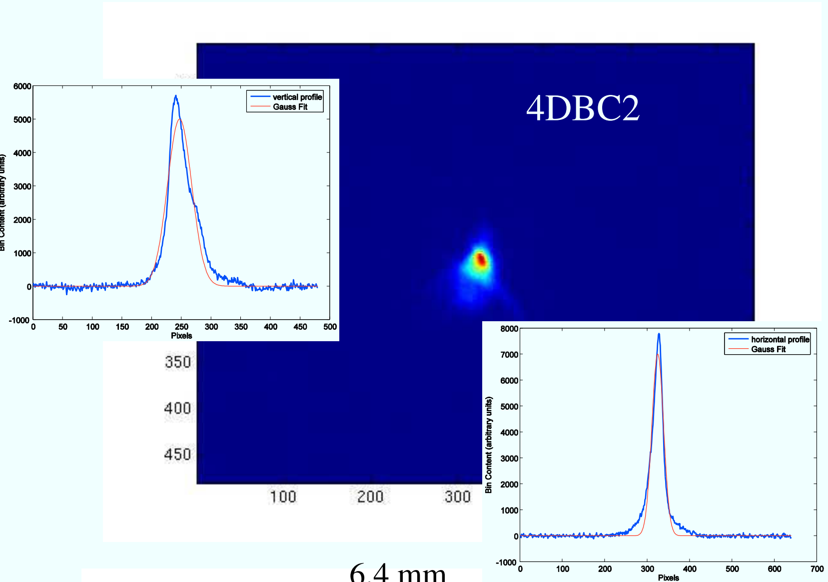
K. Honkavaara et al., Proc. PAC 2003, p.2476

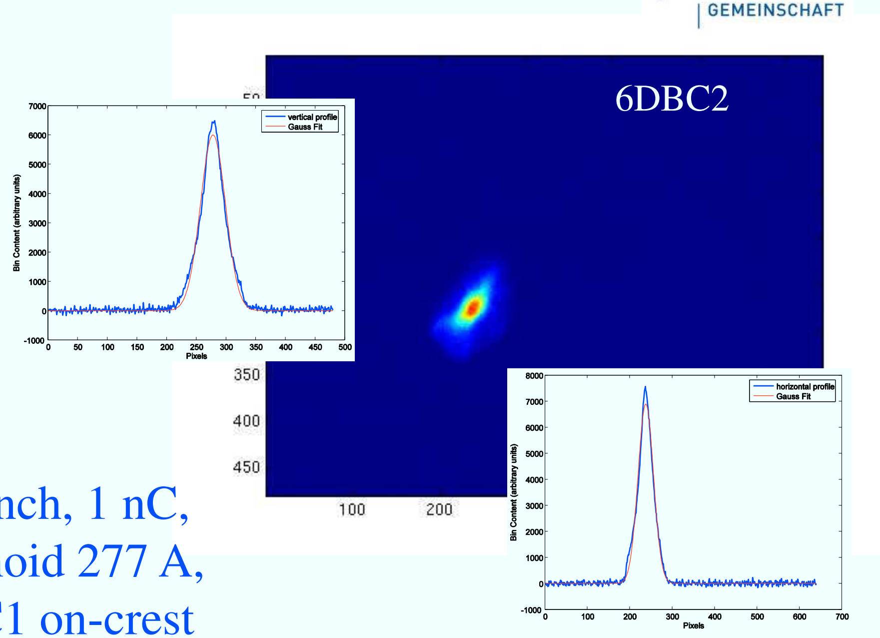


optical system

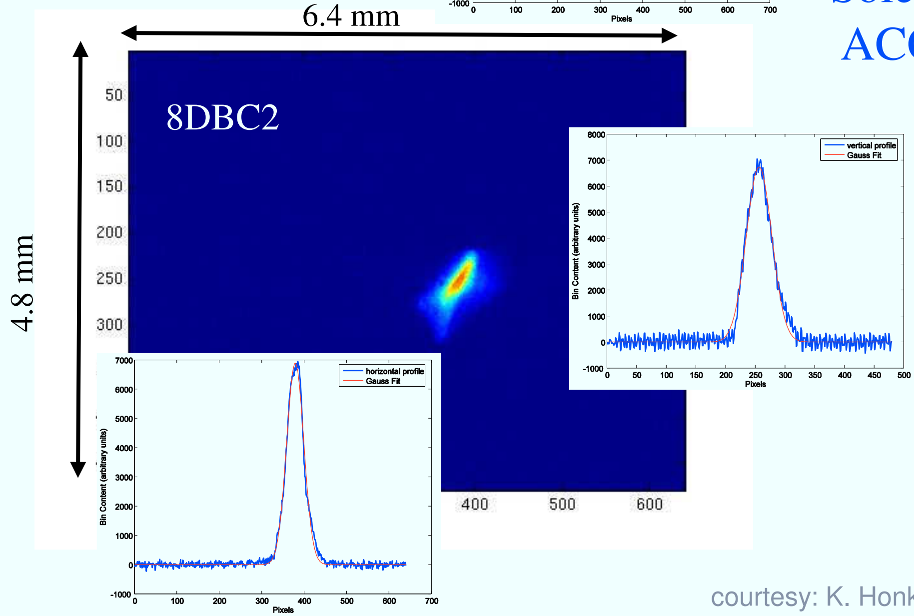
magnification	f / mm	a / mm	b / mm
1	250	500	500
0.382	200	724	276
0.25	160	800	200

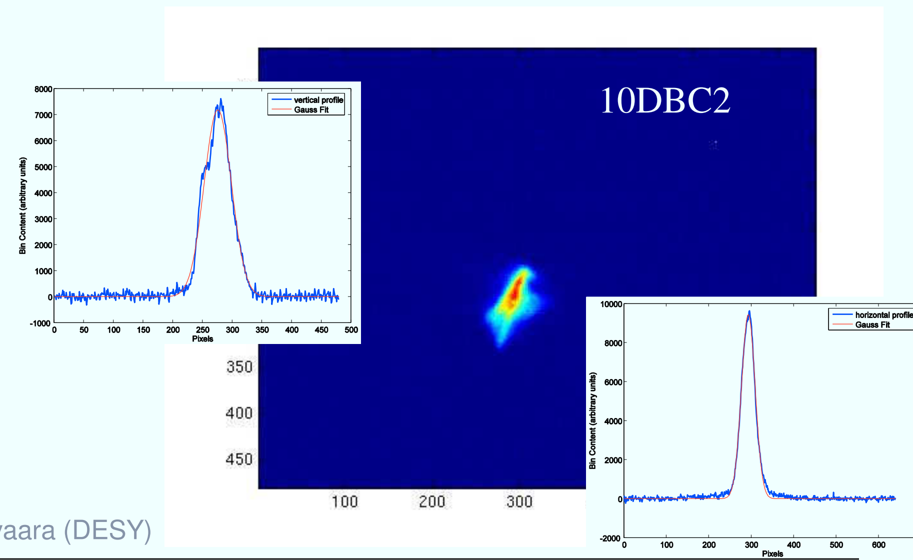
Example of Beam Images (matched)





1 bunch, 1 nC,
Solenoid 277 A,
ACC1 on-crest





courtesy: K. Honkavaara (DESY)

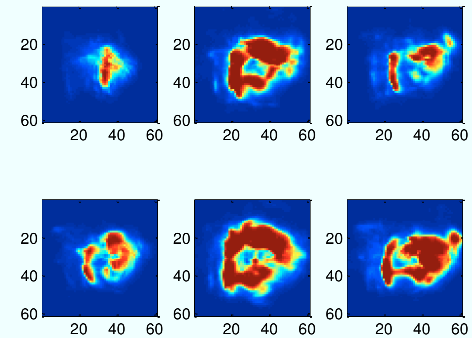
COTR and possible Mitigation

- unexpected Coherent OTR observation during LCLS commissioning

R. Akre et al., Phys. Rev. ST Accel. Beams **11** (2008) 030703 H. Loos et al., Proc. FEL 2008, Gyeongju, Korea, p.485.

- strong shot-to-shot fluctuations
- doughnut structure
- change of spectral contents

→ measured spot is no beam image!



courtesy:

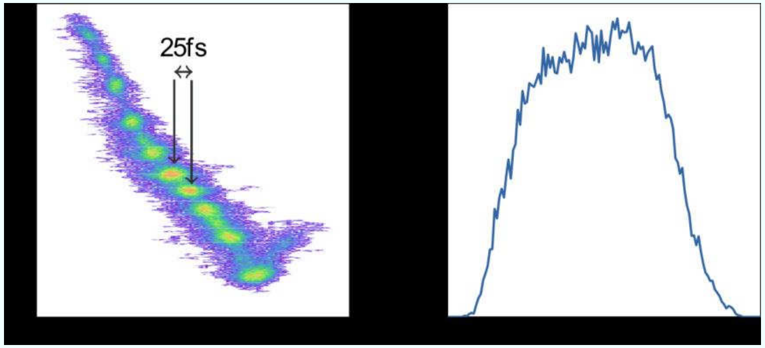
H. Loos (SLAC)

- interpretation of coherent formation in terms of "Microbunching Instability"

E.L. Saldin et al., NIM **A483** (2002) 516

Z. Huang and K. Kim, Phys. Rev. ST Accel. Beams **5** (2002) 074401

G. Stupakov, Proc. IPAC 2014, Dresden, Germany (2014), p.2789.



- alternative schemes for transverse profile diagnostics
  - long term perspective: TR imaging at smaller λ

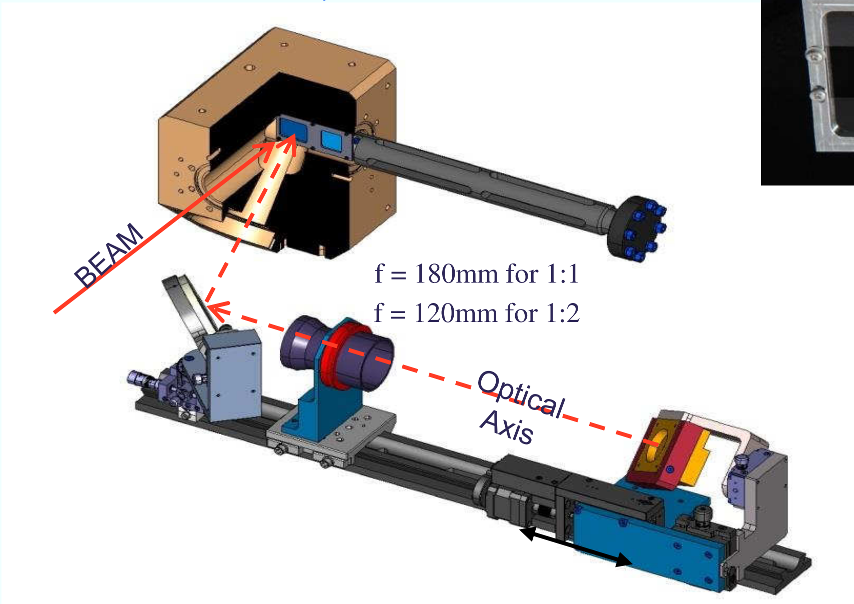
⟹

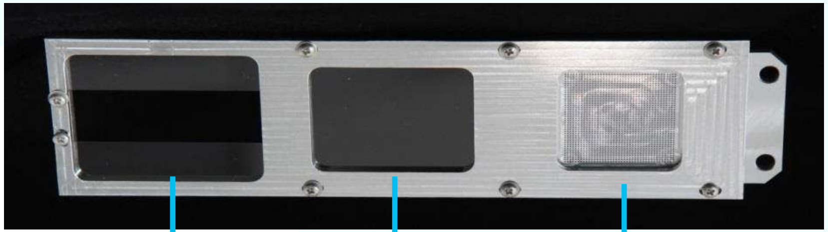
proof of principle experiment @ λ = 19.6 nm: L.G. Sukhikh, G. Kube, S. Bajt et al., Phys. Rev. ST Accel. Beams **17** (2014) 112805

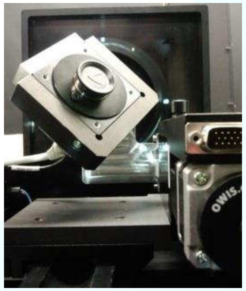
  - short term perspective: scintillating screen monitors

Screen Station for E-XFEL

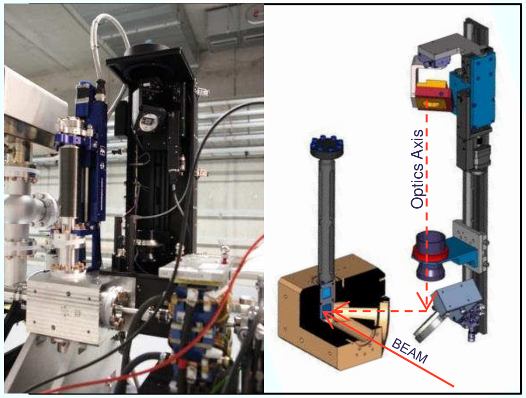
- monitor setup



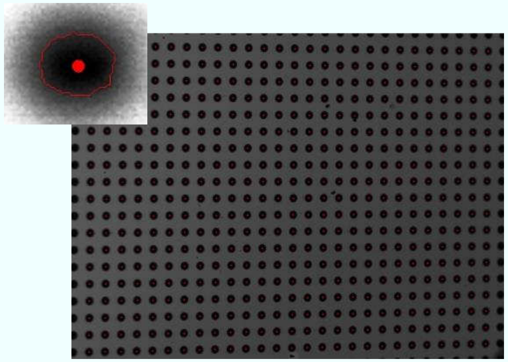


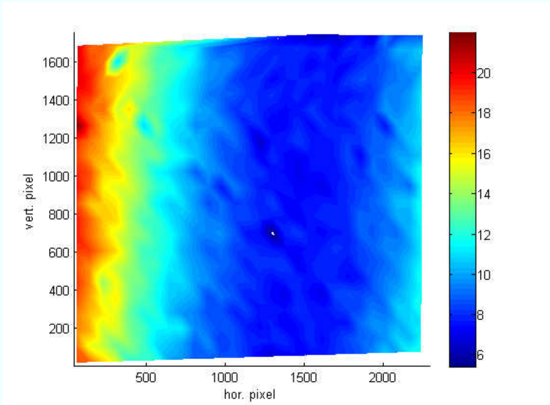


FLASH II installation



- optical resolution





- Scheimpflug observation geometry
- **10.5 µm** average resolution

  (dot → optical „step“ function)

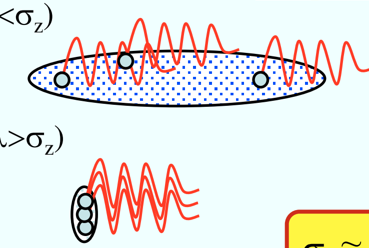
Longitudinal Profile Diagnostics

- **Coherent Radiation Diagnostics (CRD)**
  - standard method for radiation based bunch length diagnostics

    O. Grimm, Proc. PAC 2007, Albuquerque, USA, p.2653

long bunch ($\lambda<\sigma_z$)

short bunch ($\lambda>\sigma_z$)



$\sigma_t \approx 100$ fsec

- **electro-optical (EO) techniques**

principle idea:

- statement about bunch profile via longitudinal extension of particle bunch Coulomb field

  → good approximation for ultra-relativistic beam energies (1/γ opening angle)

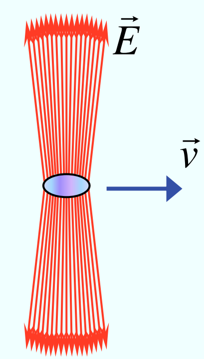
task:

- detection of transient Coulomb field → electro-optical detection in THz region

  - imprint influence of Coulomb field onto electro-optical crystal
  - convert action in crystal into detectable signal

    opt. intensity variation → laser + polarizer + analyzer

following 2 talks by Andrii Borysenko and Mateusz Tyrk



$\sigma_t \approx 30$ fsec

- **Transverse Deflecting Structure (TDS)**
  - intra-beam streak camera

    → potential for sub-fsec resolution → access to slice parameters

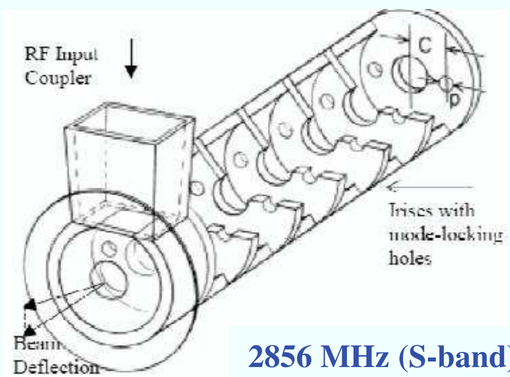
RF Cavity Manipulation

Transverse Deflecting Structures (TDS)

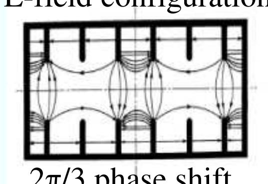
- iris loaded RF waveguide structure
- designed to provide hybrid deflecting modes ($HEM_{1,1}$)

  → linear combination of $TM_{1,1}$ and $TE_{1,1}$ dipole modes, resulting in transverse force that act on synchronously moving relativistic particle beam
- used for beam separators and RF deflectors

traveling wave RF deflector ”LOLA-type”
→ SLAC design



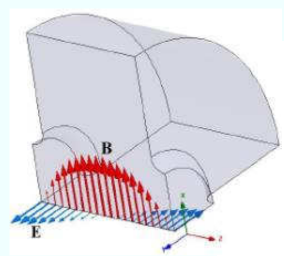
E-field configuration

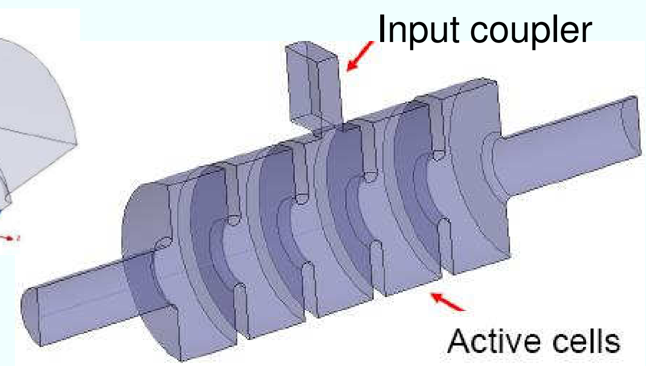


2π/3 phase shift per cell

2856 MHz (S-band)

standing wave RF deflector
→ SPARC-INFN design





courtesy D. Alesini (INFN-LNF)

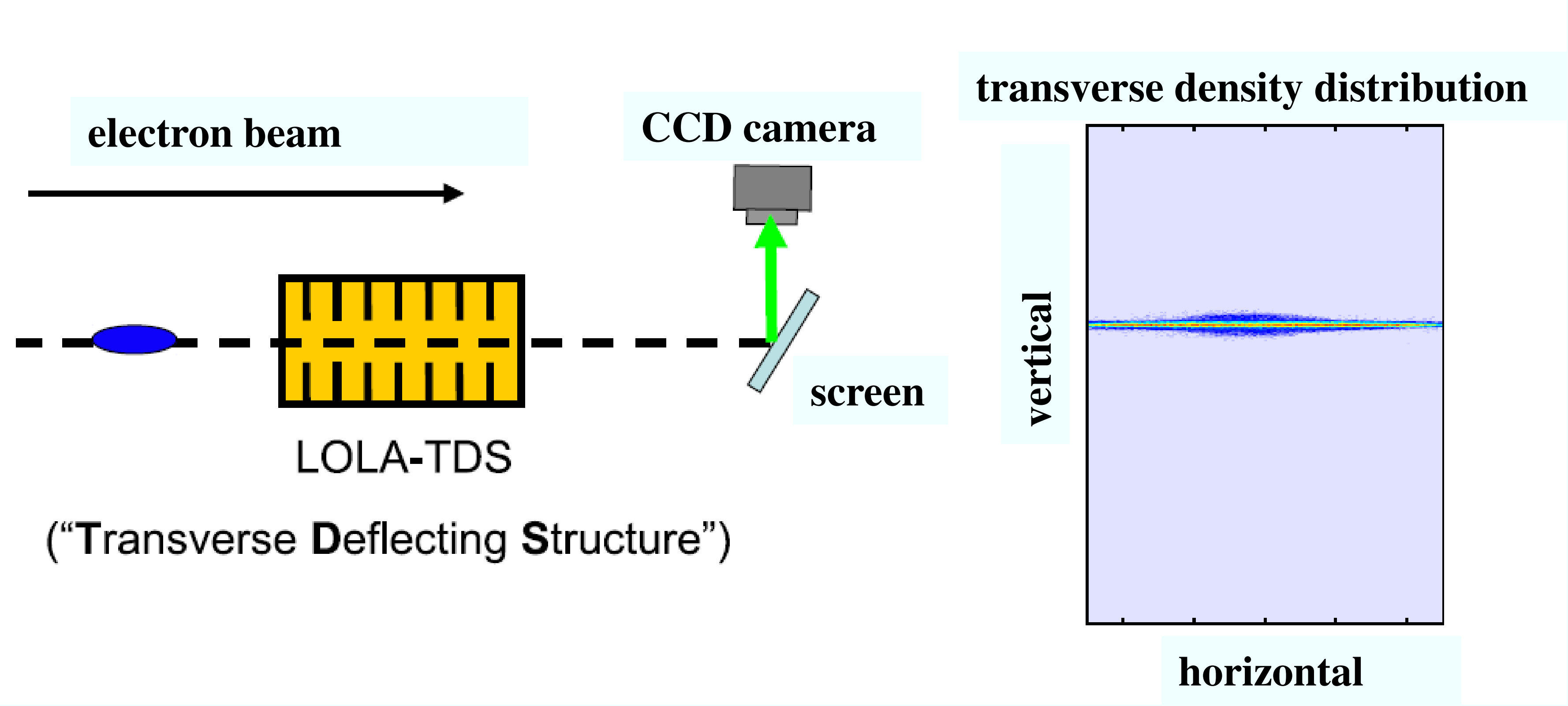
“LOLA”: G.A. <u>Lo</u>ew, R.R. <u>L</u>arsen, O.A. <u>A</u>ltenmueller

G. A. Loew et al., SLAC Technical Report SLAC-PUB-135 (1965)

D . Alesini et al., NIM **A568** (2006) 488
L. Ficcadenti, Proc. PAC‘07, Albuquerque, (2007), p.3994

TDS Working Principle

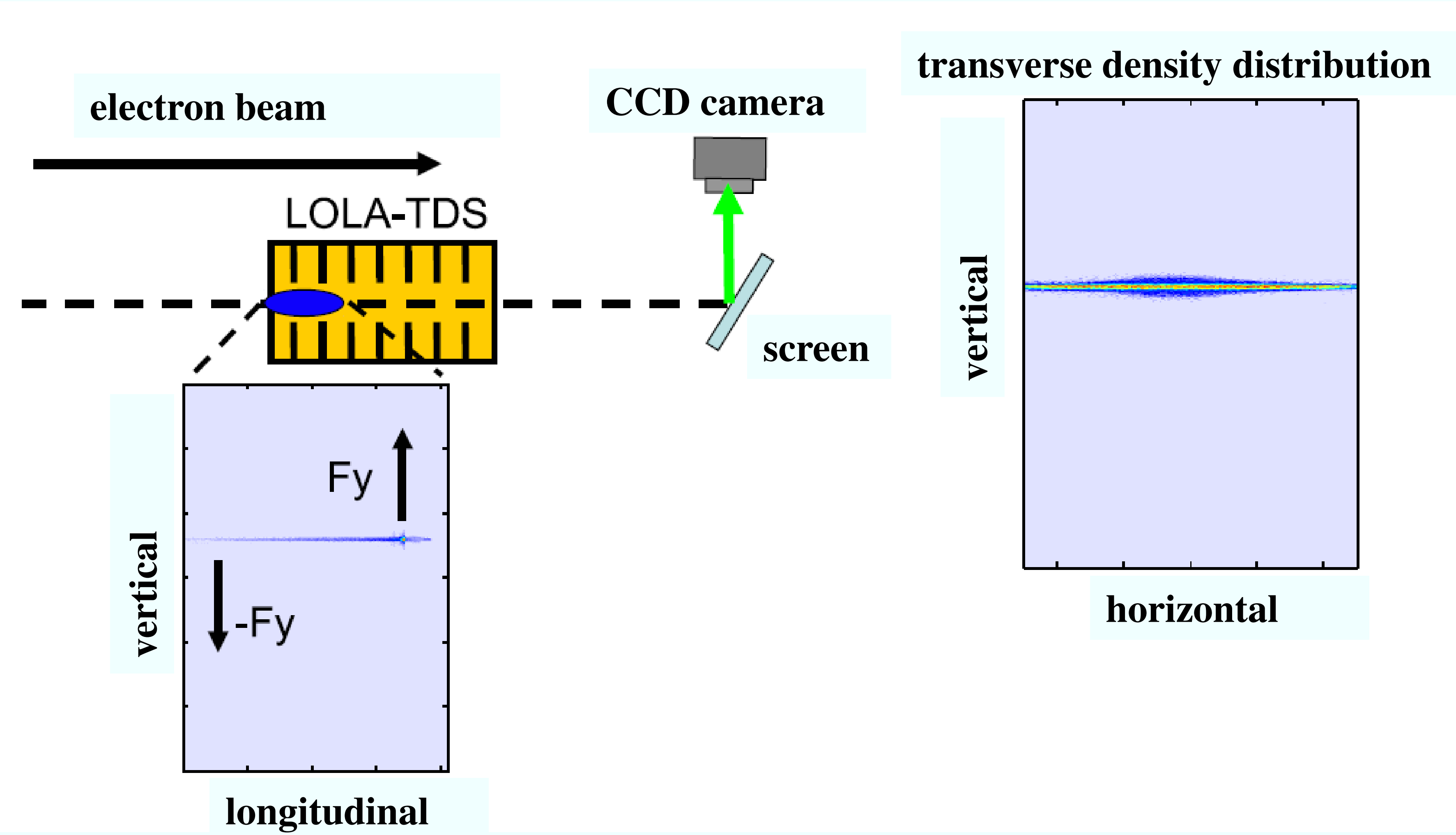
- TDS as intra-beam streak camera



courtesy C. Behrens (DESY)

TDS Working Principle

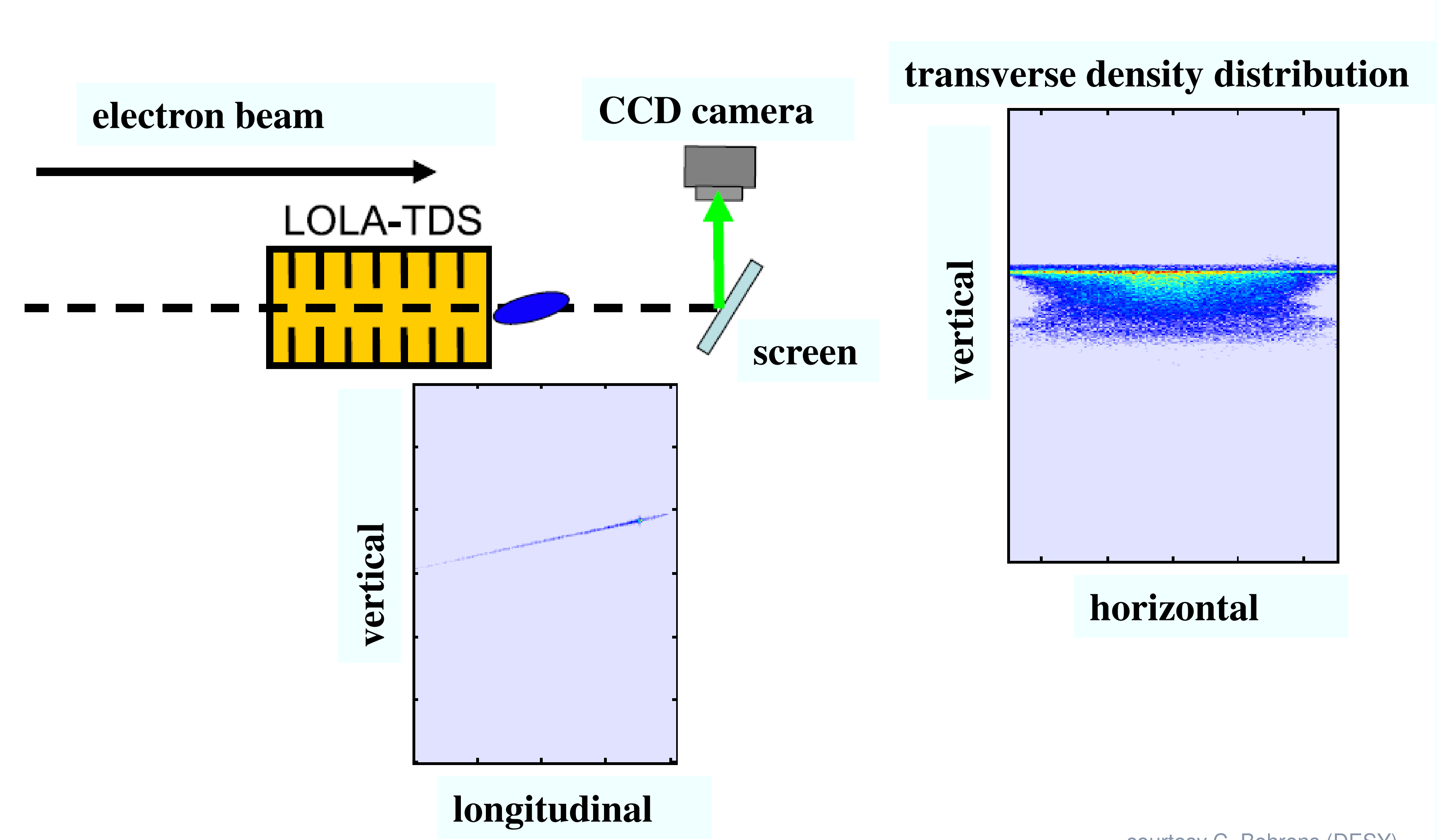
- TDS as intra-beam streak camera



courtesy C. Behrens (DESY)

TDS Working Principle

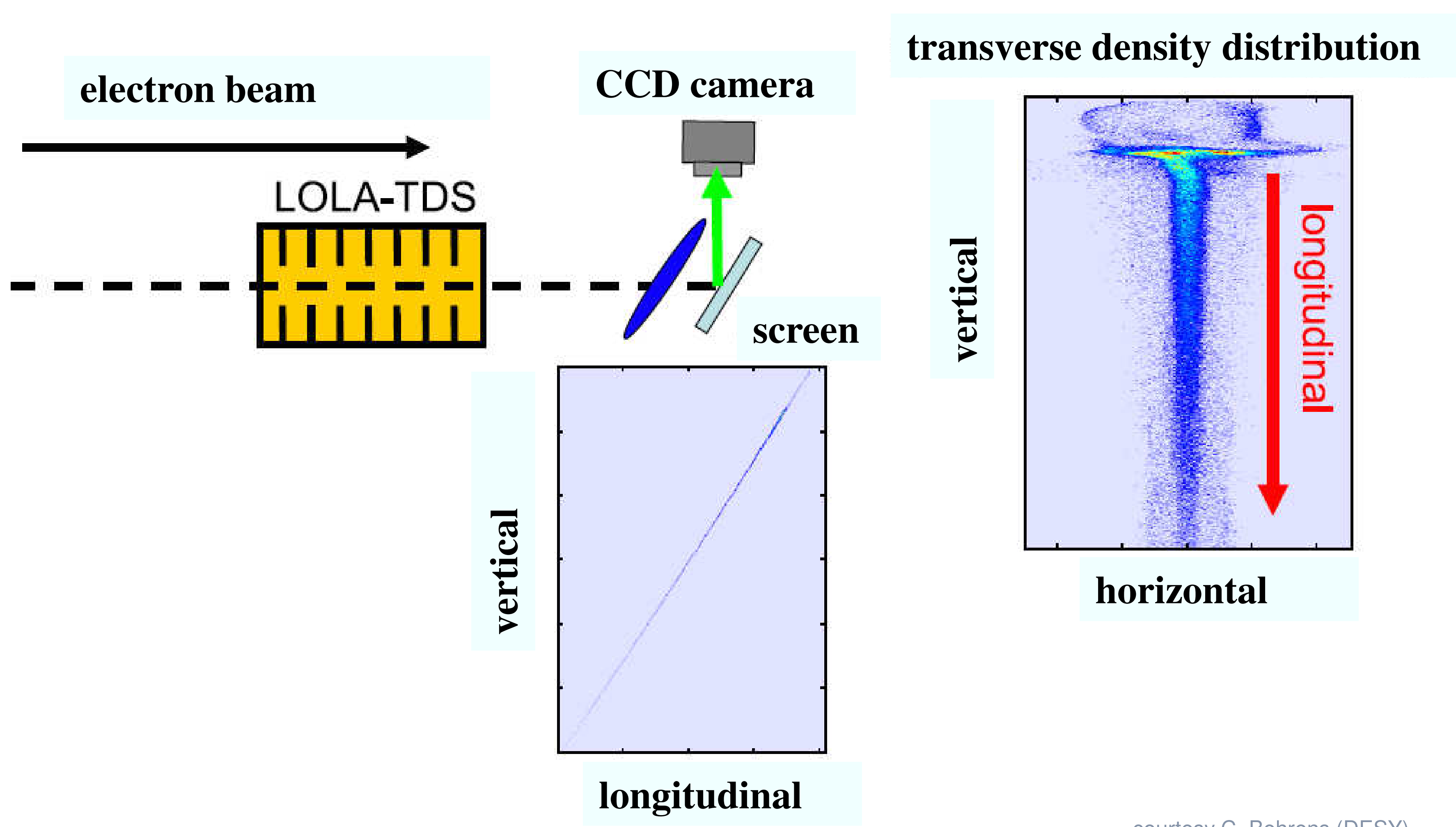
- TDS as intra-beam streak camera



courtesy C. Behrens (DESY)

TDS Working Principle

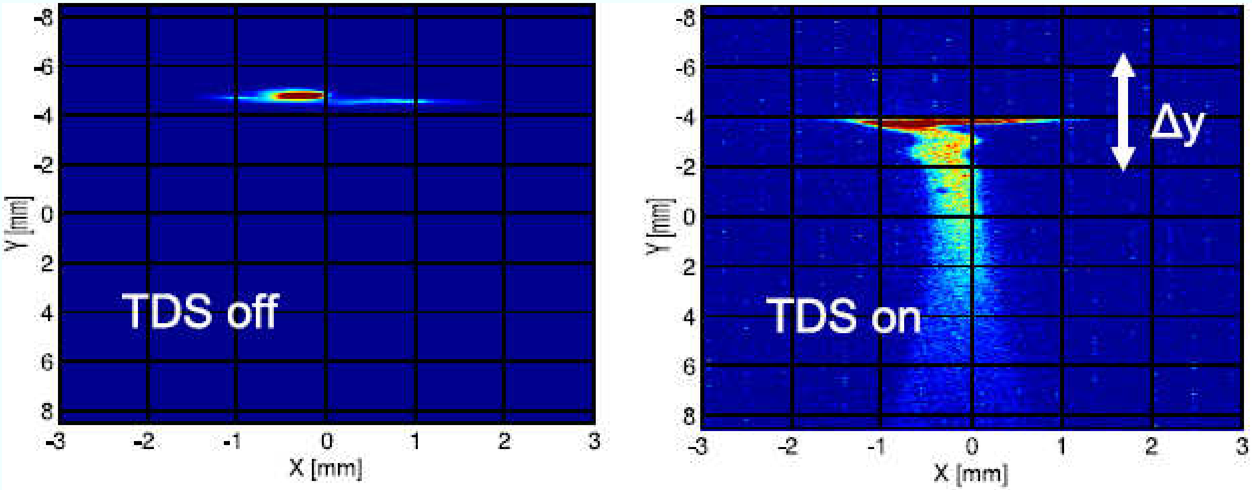
- TDS as intra-beam streak camera



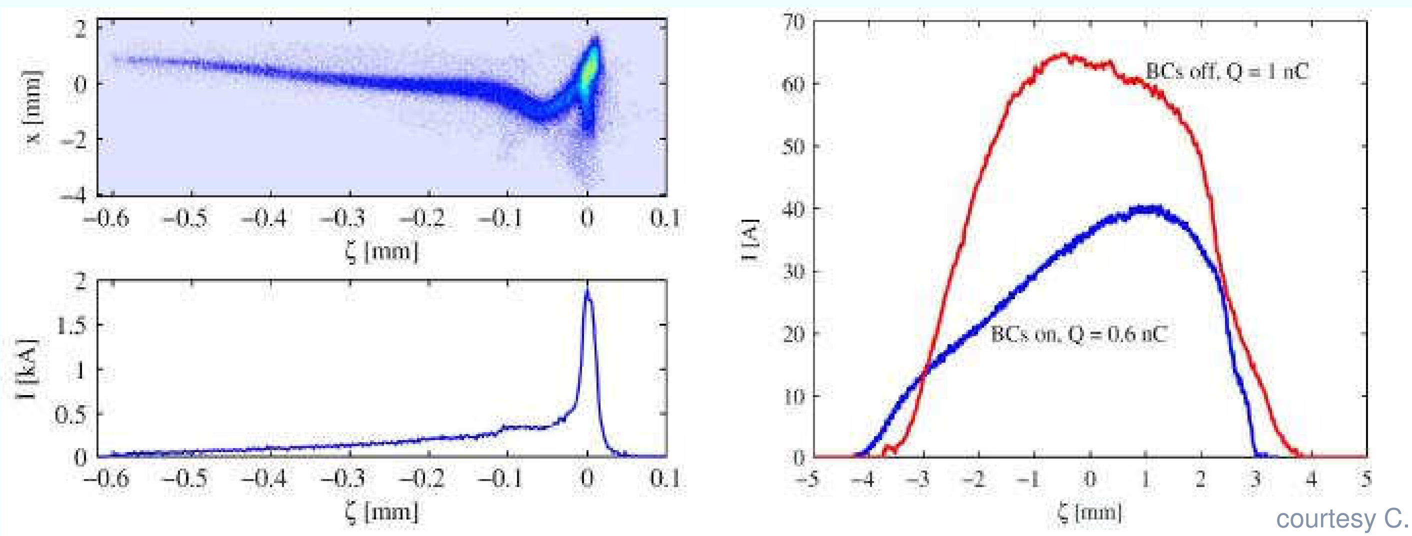
courtesy C. Behrens (DESY)

TDS Measurements

- effect of TDS on observation screen



- current profiles with (left) and without (right) magnetic compression



courtesy C. Behrens (DESY)

TDS Properties

resolution limit

- deflected spot size σ_{defl} equals un-deflected beam size σ_{beam} : $\sigma_\zeta \rightarrow \sigma_{\zeta,res} = c \cdot \sigma_{t,res}$

$\Rightarrow$

- good resolution:
  - $\rightarrow$ $\Psi = 0$ zero-crossing for bunch centroid
  - $\rightarrow$ β_{tds} as large as possible for most effective kick
  - $\rightarrow$ $\Delta\Phi$ 90/270° ideal for phase advance
  - $\rightarrow$ V_0 high deflecting voltage (high RF power)
  - $\rightarrow$ f_{RF} high RF frequency

X-band TDS @ LCLS: $f_{RF} = 11.424$ GHz $\rightarrow$ $\sigma_{t,res} = 1 - 4$ fsec (rms)

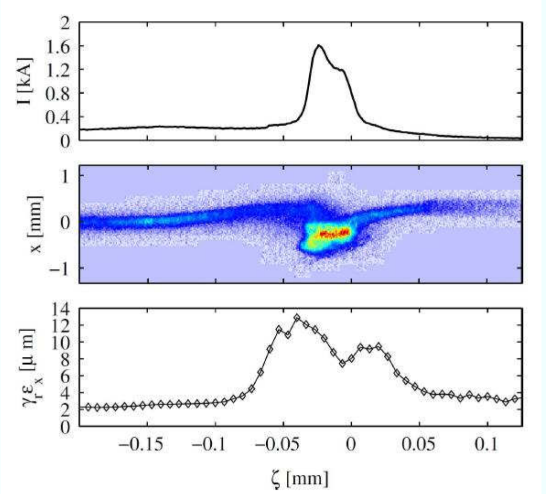
C. Behrens et al., Nature Communications 5:3762 (2014), DOI:10.1038/ncomms4762

example:

$\boldsymbol{\sigma_{t,res} = 10.5 \text{ fsec} / \sin\Delta\Phi}$

TDS for slice profile (emittance) diagnostics

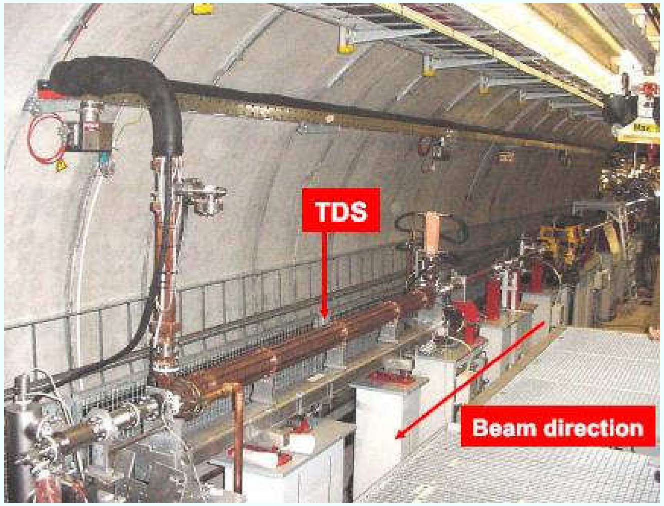
- camera at view screen (OTR) delivers 2D information
  - $\rightarrow$ vertical beam size: bunch length information
  - $\rightarrow$ horizontal beam size: transverse profile information
- streaked image
  - $\rightarrow$ transv. profile as function of long. position (slice) ζ
  - $\rightarrow$ access to slice emittance



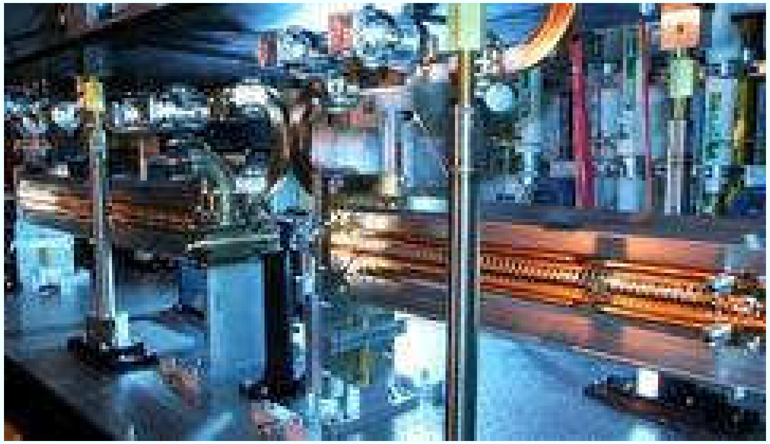
TDS @ LCLS, FLASH, SPARC, ...

- low energy TW RF deflector @ LCLS

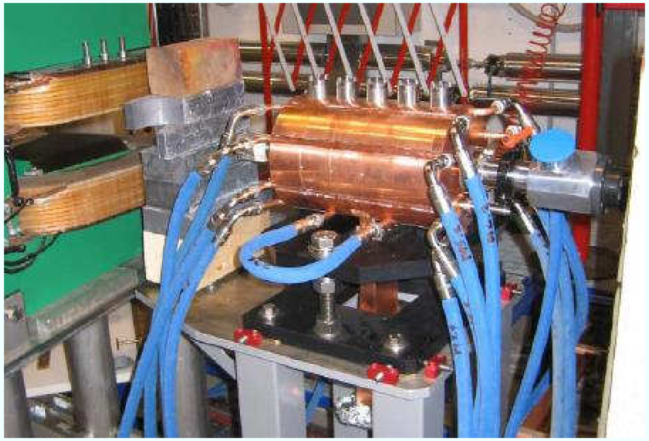
- TW RF deflector @ FLASH



- X-band TDS @ LCLS



- SW RF deflector @ SPARC



Beam Synchronous Timing (BST)

BST tasks

T. Korhonen , Proc. ICALEPCS'99 , Trieste, Italy (1999) p.167

- generate and remotely distribute phase reference
- trigger fast sub-systems
- trigger slow systems
- interface to the control system

two levels of timing

- fast timing → level of individual bunches
- slow timing → level of revolution clock (circ. accelerator) or bunch (train) repetition rate (linac)

synchronization

- local task → implemented at different clients of timing system

BST building blocks (expected timing jitter)

- reference oscillator → phase reference for all sub-systems (≈ ps to fs)
- master time-base (event system) → trigger, bunch clock, injection/extraction, experiment triggers (≈ ns to ps)
- distribution system (coaxial vs. fiber optics) → phase reference (down to fs), trigger (100ps to <10ps)
- interface to the control system

courtesy M. Ferianis (Sincrotrone Trieste)

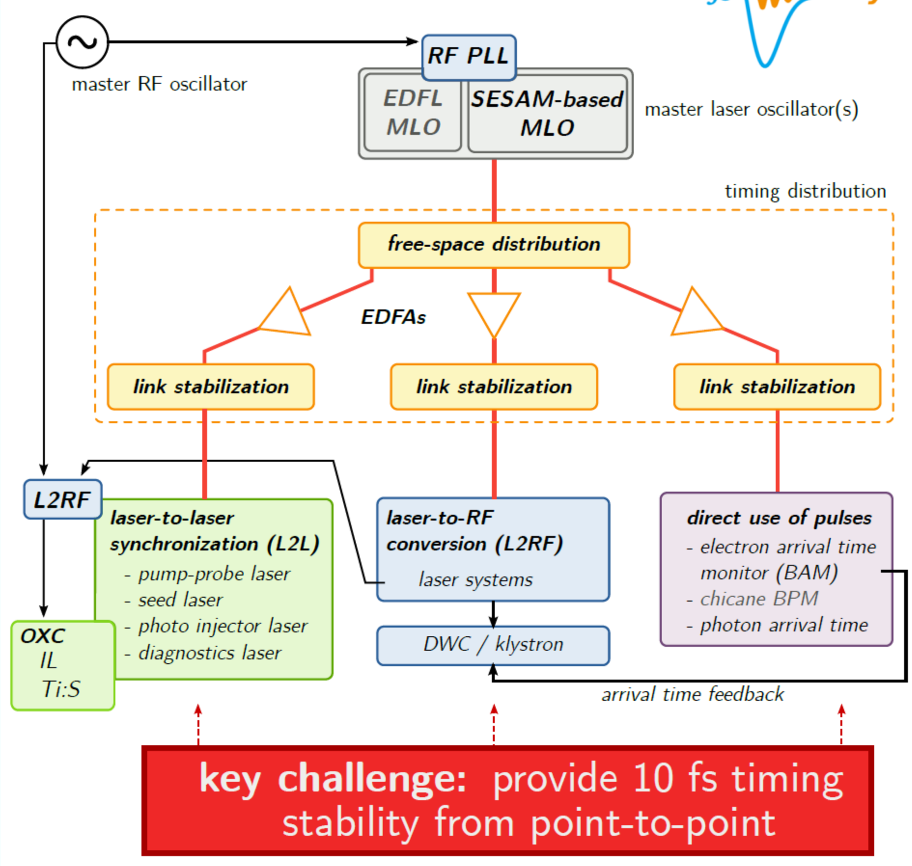
fs-Synchronization System @ FLASH

- distribution of synchronization reference
  - star topology
- optical reference pulse train
  - mode-locked **E**rbium **D**oped **F**iber **L**aser
  - repetition rate 216.7 MHz

    → 6th subharmonic of accelerator RF
- point-to-point stability over several km:
  - short term: < **1 fsec**
  - long term: < **3.5 fsec**

    → rms values, measured out-of-loop with independent detector

courtesy M. Felber (DESY)



→ user driven (pump-probe)

- applications:
  - Bunch Arrival Time Monitor (BAM)

    → beam based arrival time feedback
  - laser synchronisation

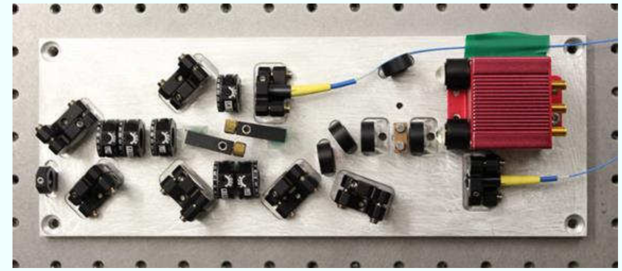
    → e.g. pump-probe, seed, injector,…
  - RF reference stabilization or generation

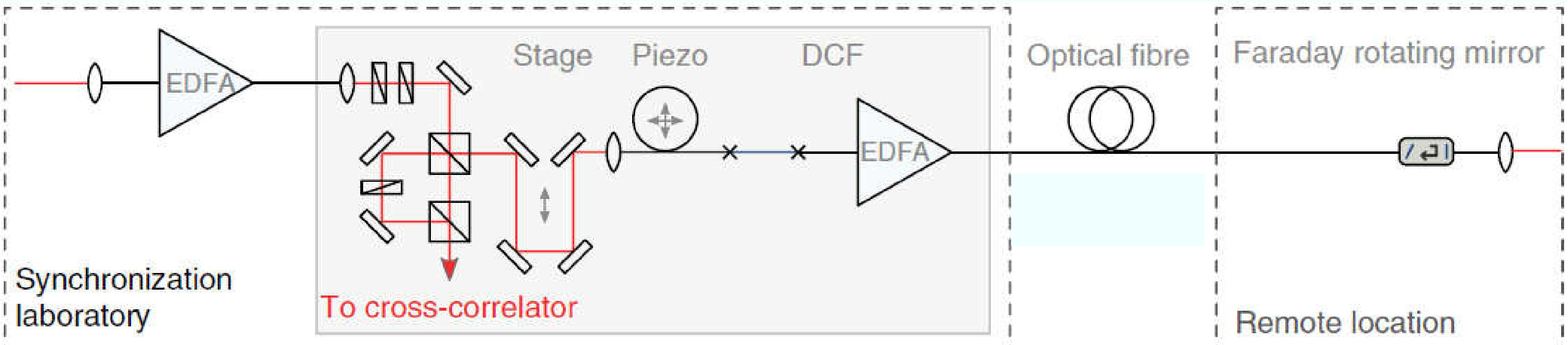
    → LLRF stability

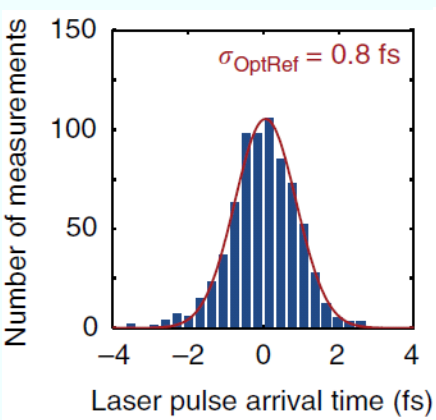
Fiber Link Stabilization

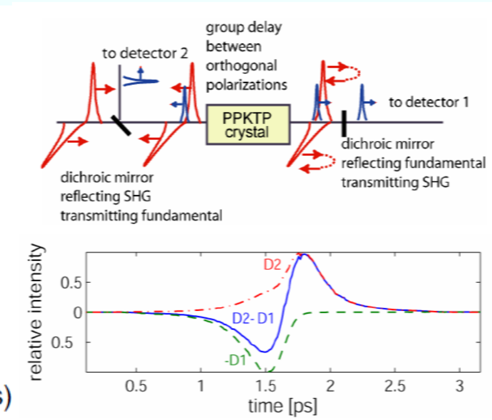
- interferometric method
  - based on balanced optical cross-correlation
    - → fast actuator: piezo stretcher
    - → coarse actuator: motorized delay

courtesy M. Felber (DESY)

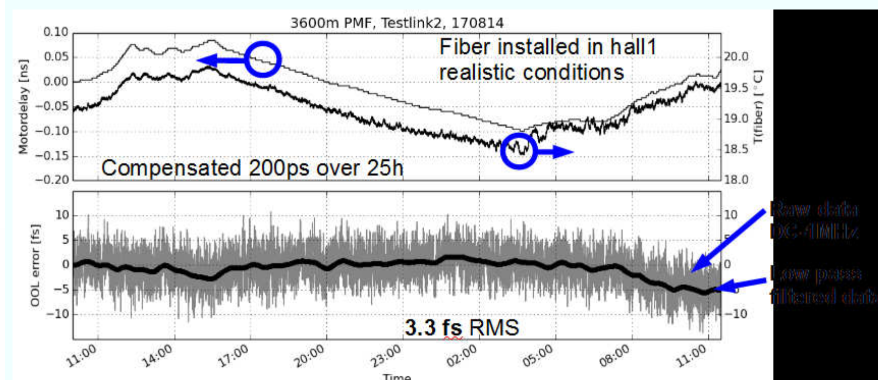






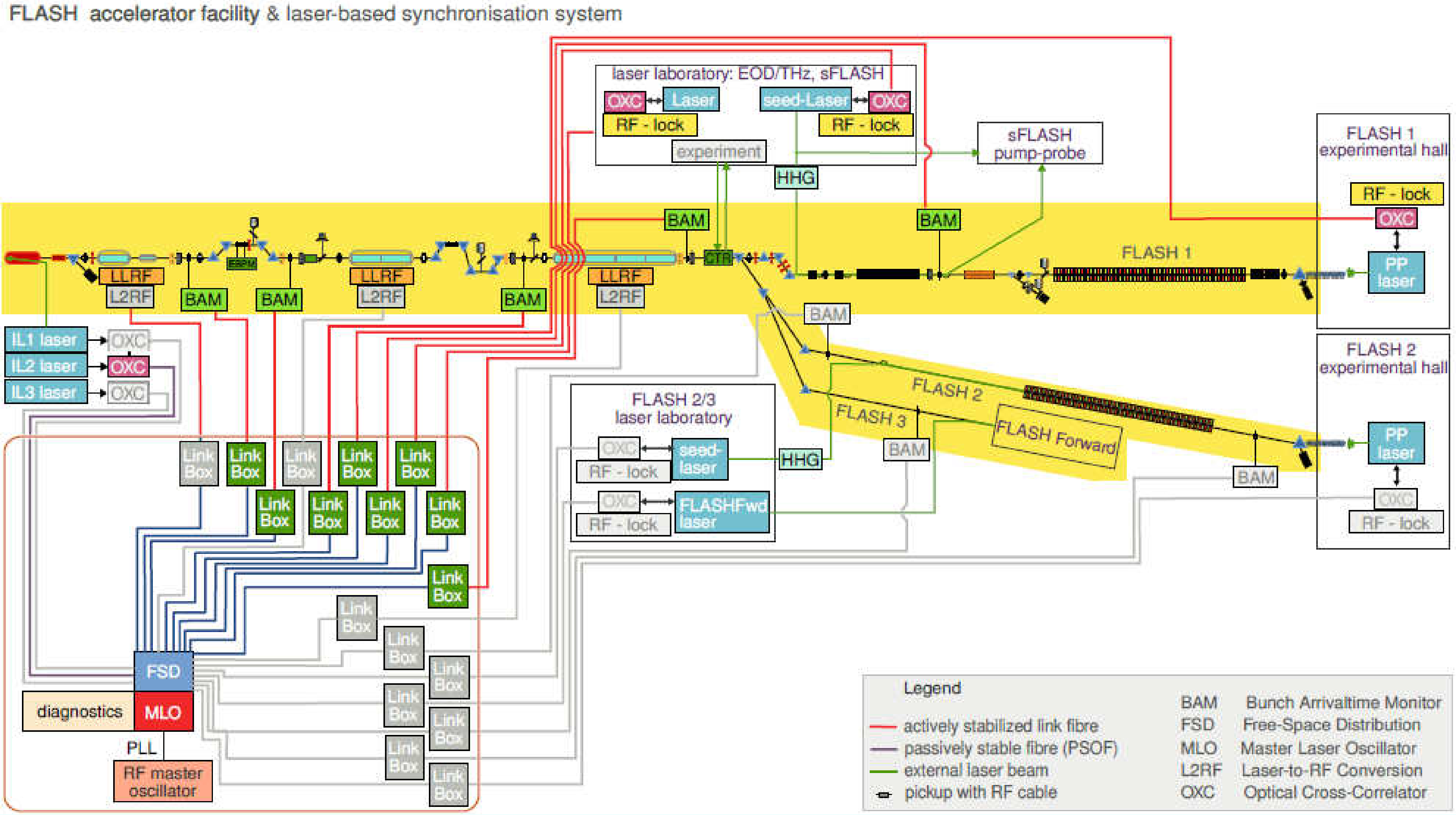


Schulz, S. et al., Nat. Commun. 6:5938 doi: 10.1038/ncomms6938 (2015).



C. Sydlo et. al. Femtosecond timing distribution for the European XFEL, FEL 2014, August 25-29, 2014

Synchronization System @ FLASH

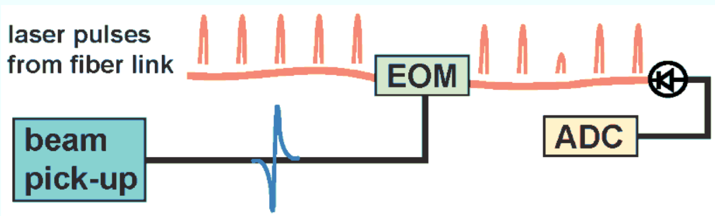


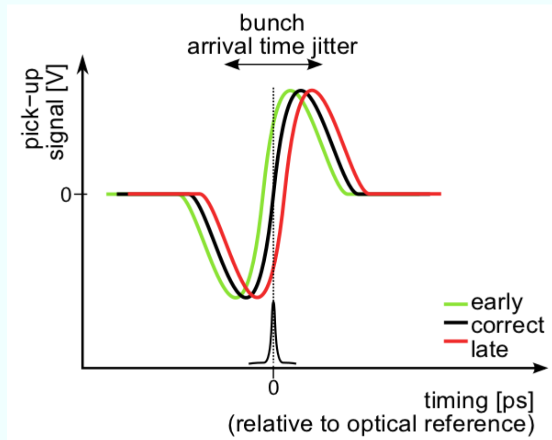
S. Schulz et al., "Femtosecond all-optical synchronization of an X-ray free-electron laser"
Nat. Commun. 6:5938 doi: 10.1038/ncomms6938 (2015).

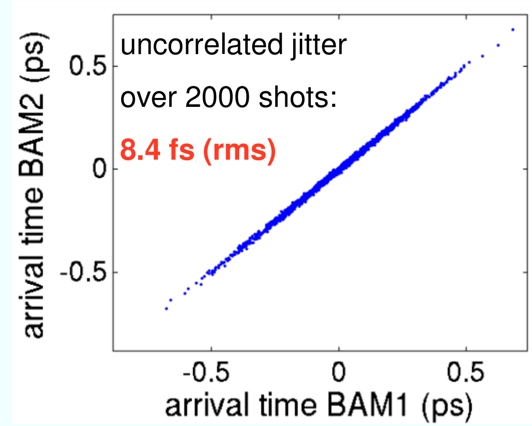
Beam-based Arriv. Time Stabilization

Bunch Arrival Time Monitor (BAM)

F. Loehl et al., Phys. Rev. Lett. 104, 144801 (2010)



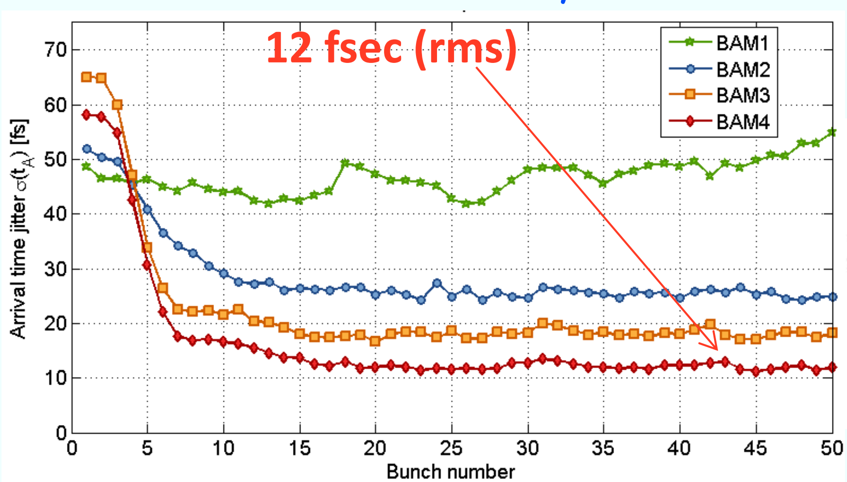


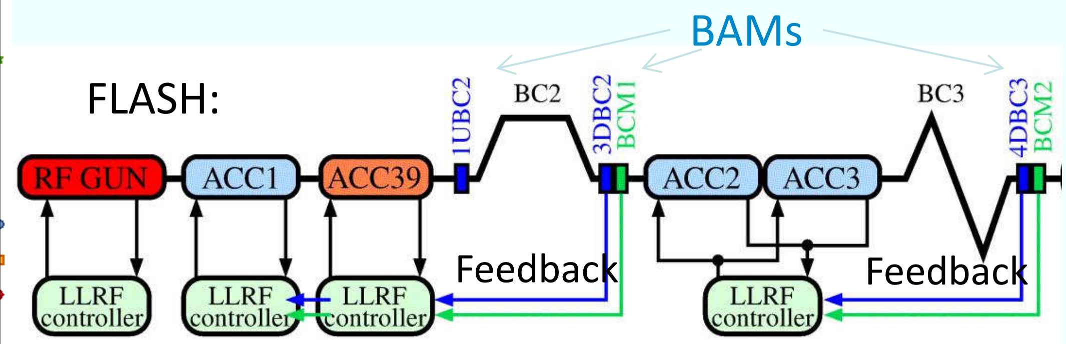


- electro-optical arrival time measurement:

  → **< 10 fsec** precision (> 300 pCb)

arrival time stability:





- fast feedback to LLRF station before bunch compressor (2 μsec latency, settling within 7 μsec)

  → arrival time stabilization to **< 20 fsec** precision

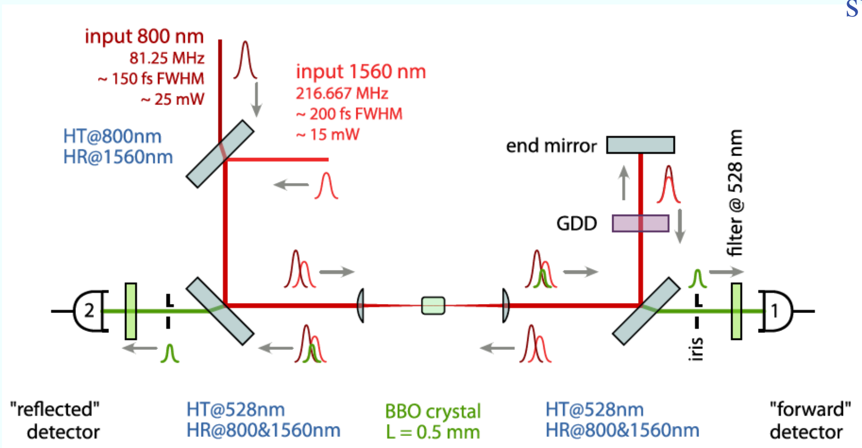
courtesy M.K. Czwalinna, S. Pfeiffer (DESY)

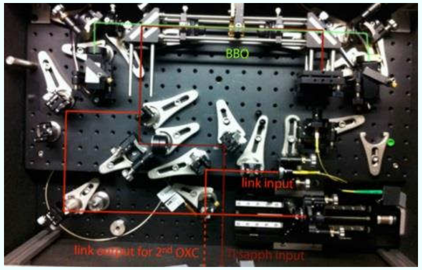
Laser Synchronization

- e.g. Ti:Sa pump-probe laser
- balanced optical cross correlation
  - twofold sum frequency generation in BBO
  - pure timing sensitive response

courtesy S. Schulz (DESY)

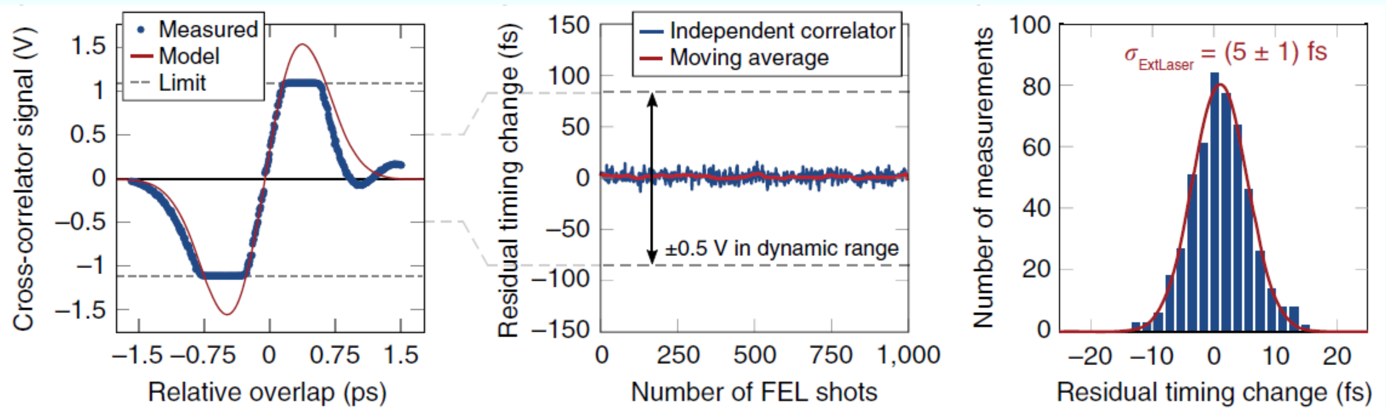
- balanced detection scheme
- elimination of amplitude changes by subtraction of both detector signals

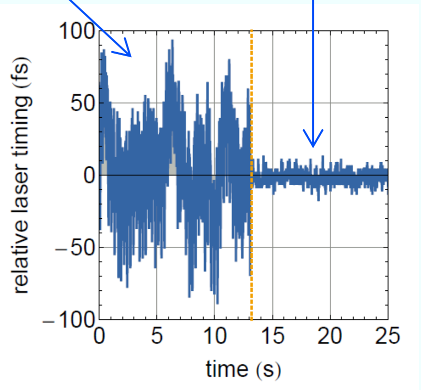




conventional RF lock: 35 fs rms

optical lock: **6 fs rms**

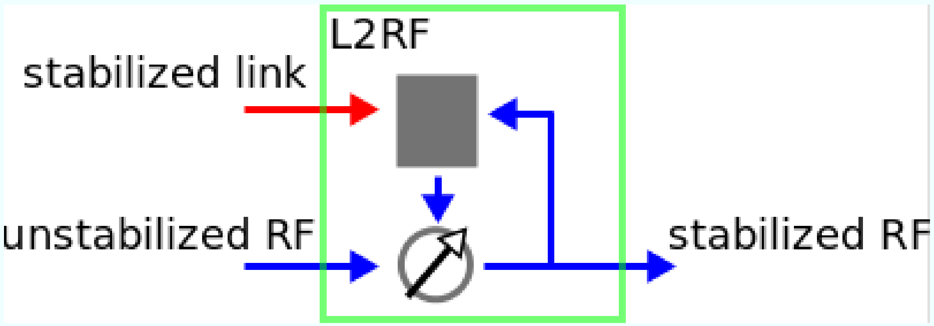


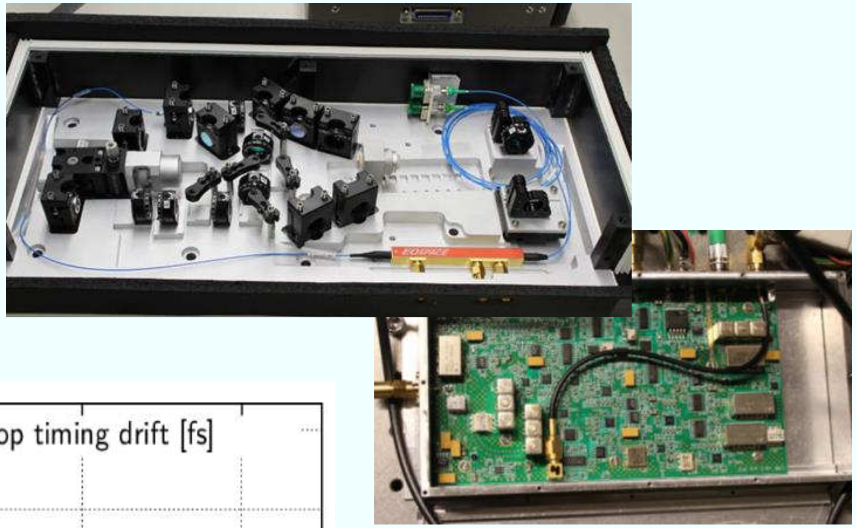


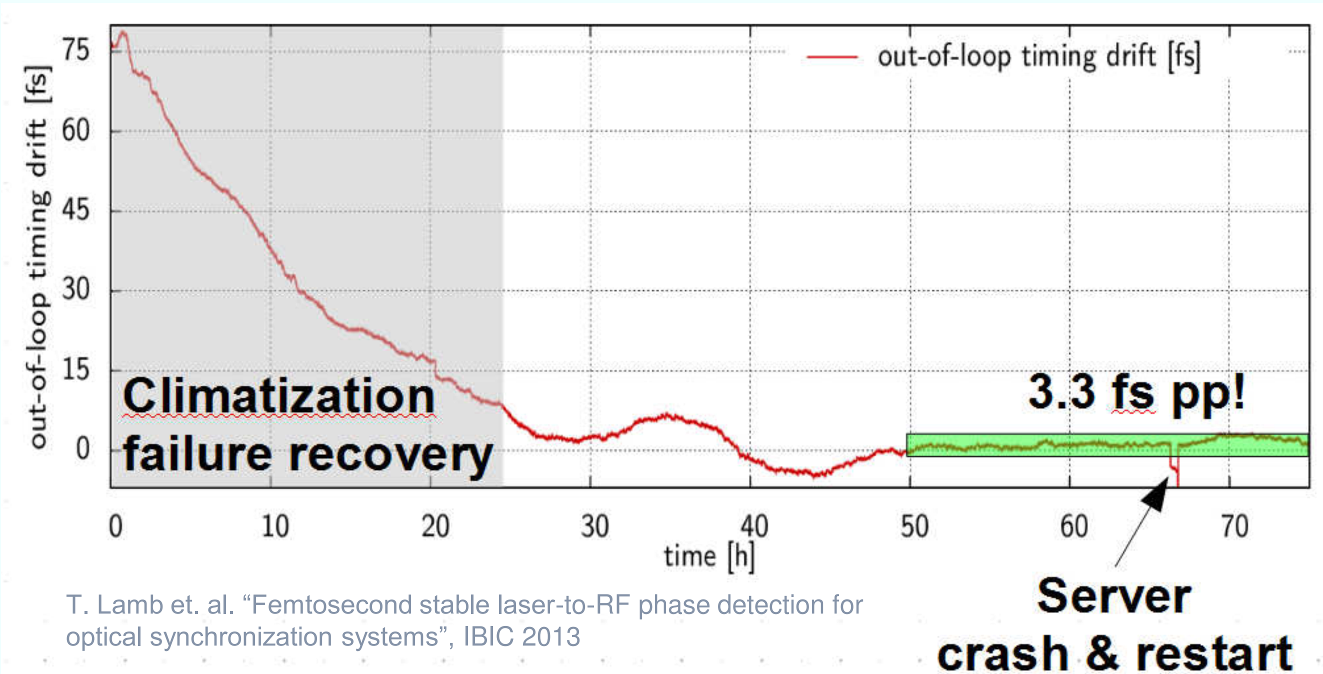
Laser RF Phase Detector

- for RF synchronization or laser-to-RF lock

courtesy E. Janas (DESY)







T. Lamb et. al. “Femtosecond stable laser-to-RF phase detection for optical synchronization systems”, IBIC 2013

- **2.44 fsec** integrated jitter measured out of loop (10 Hz to 1 MHz)
- **3.3 fsec** peak-peak drift over 24 hours

Summary

- overview of diagnostic systems at modern 4th generation light sources
- machine parameters and the requirements are challenging
  - fancy monitor concepts
- monitor design offers the combination of various fields
  - physics → radiation physics, interaction with matter, el.magn. theory, laser technology,…
  - electrical engineering → analog/digital signals, communication technology, control theory,…
  - mechanical engineering → material science,…
  - optical engineering → classical optics, lens design, wave optics, electro-optics,…
  - IT technology → computer science,…
- lasers in beam diagnostics play important role
  - laser wire scanners, EO techniques, timing and synchronization issues,…

- many thanks ….
  - for your attention
  - to my DESY colleagues M. Felber, D. Lipka, D.Nölle, K.Wittenburg for their help in the preparation and many stimulating discussions
  - special thanks to C. Welsch, R. Ashworth for organizing the LA^{3}NET conference and their invitation