Diagnostics for (SASE) FEL

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Outline

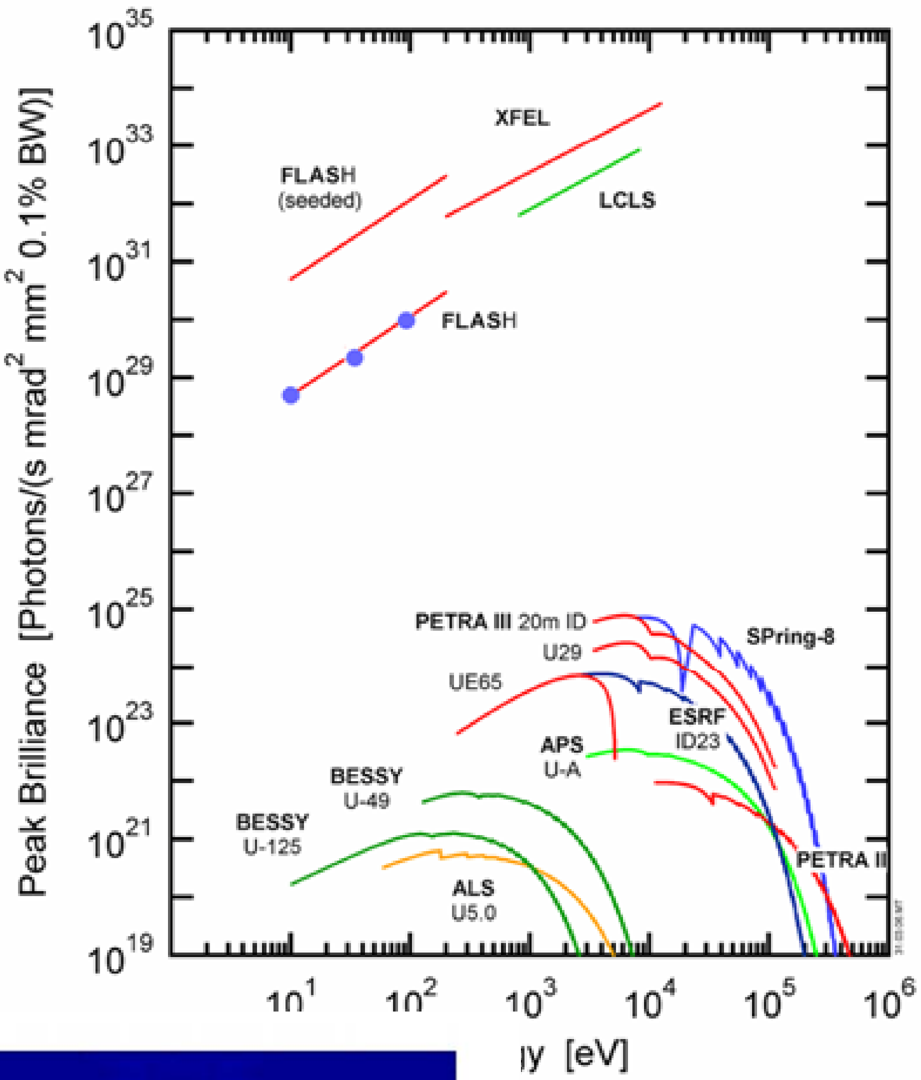
- What is a Free-Electron-Laser Facility?
  - Why?
  - How?
- What are the demands to the diagnostics?
- What is special for (SASE) machines?
  - Single bunch
  - High duty Cycle
- Small Selection of System
- Some Remarks on Feedback
- Conclusion

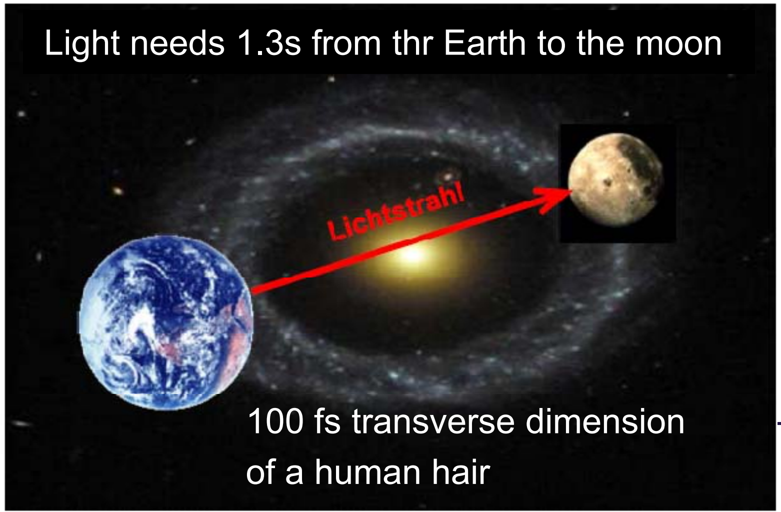
European XFEL

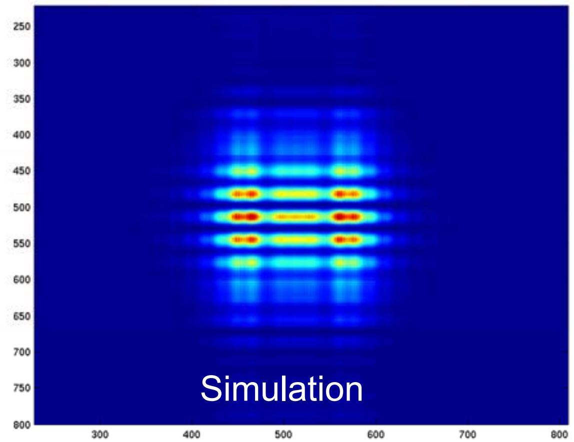
What and Why: Why?

What makes FEL Facilities different from conventional Light Sources

- X-ray FEL radiation (0.2 - 14.4 keV)
  - ultrashort pulse duration <100 fs (rms)
  - extreme pulse intensities 10^{12}-10^{14} ph
  - coherent radiation x10^{9}
  - average brilliance x10^{4}
- Spontaneous radiation (20-100 keV)
  - ultrashort pulse duration <100 fs (rms)
  - high brilliance







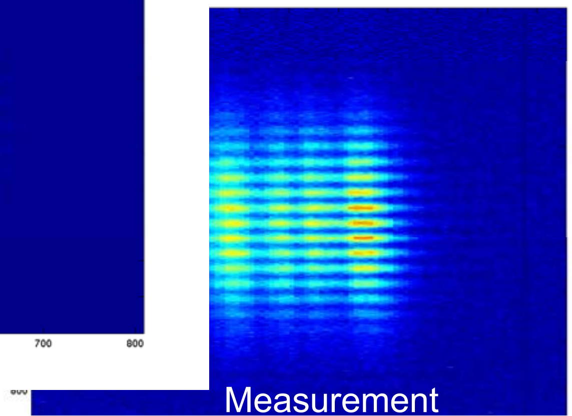
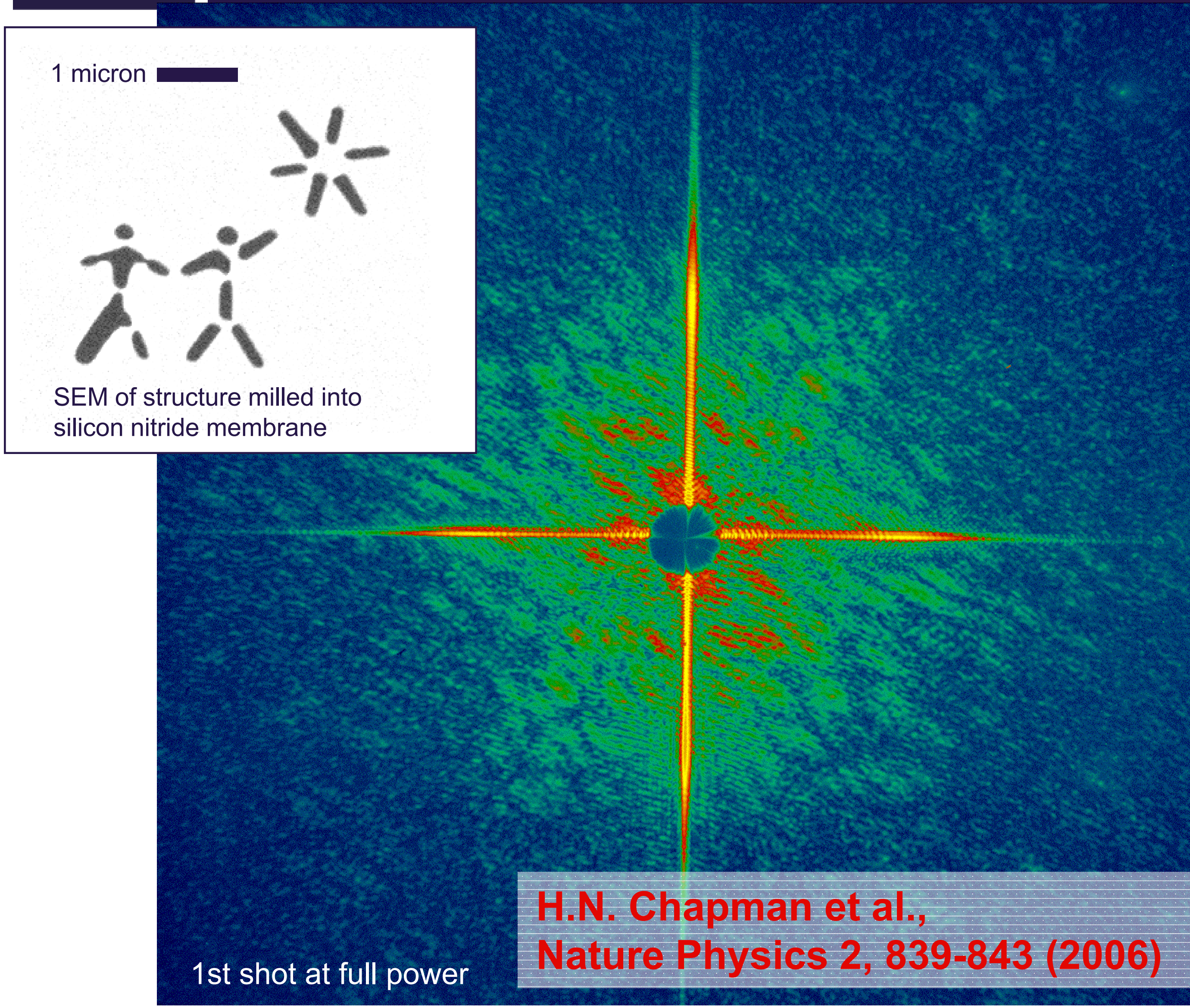
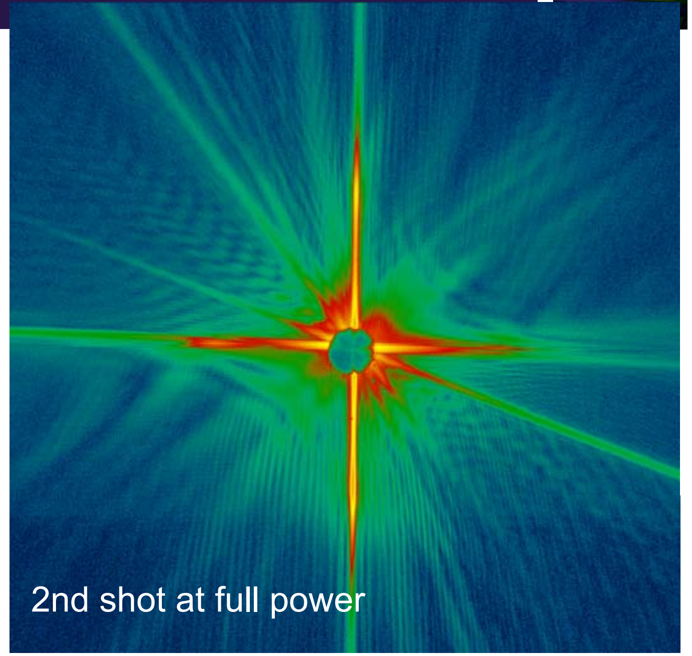
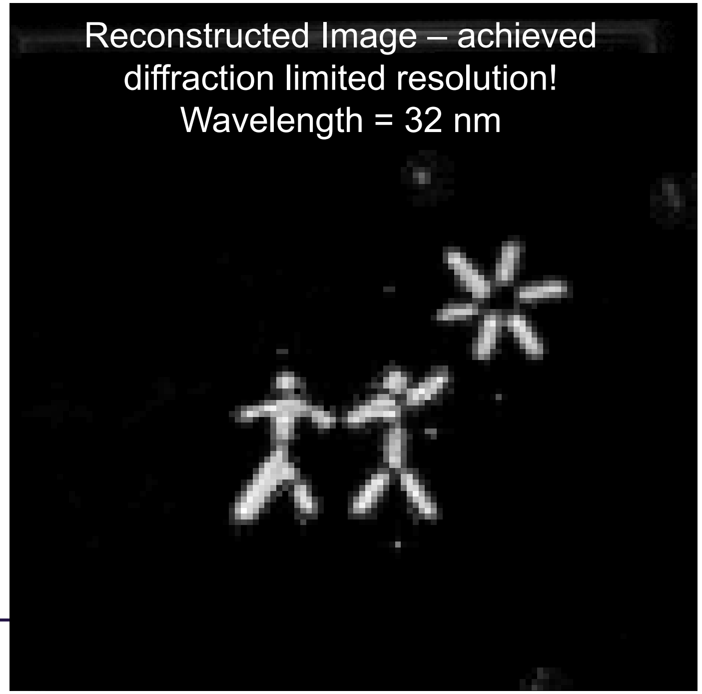


Image Reconstruction from ultra fast Diffraction Pattern
Two Cowboys under the Sun @ FLASH





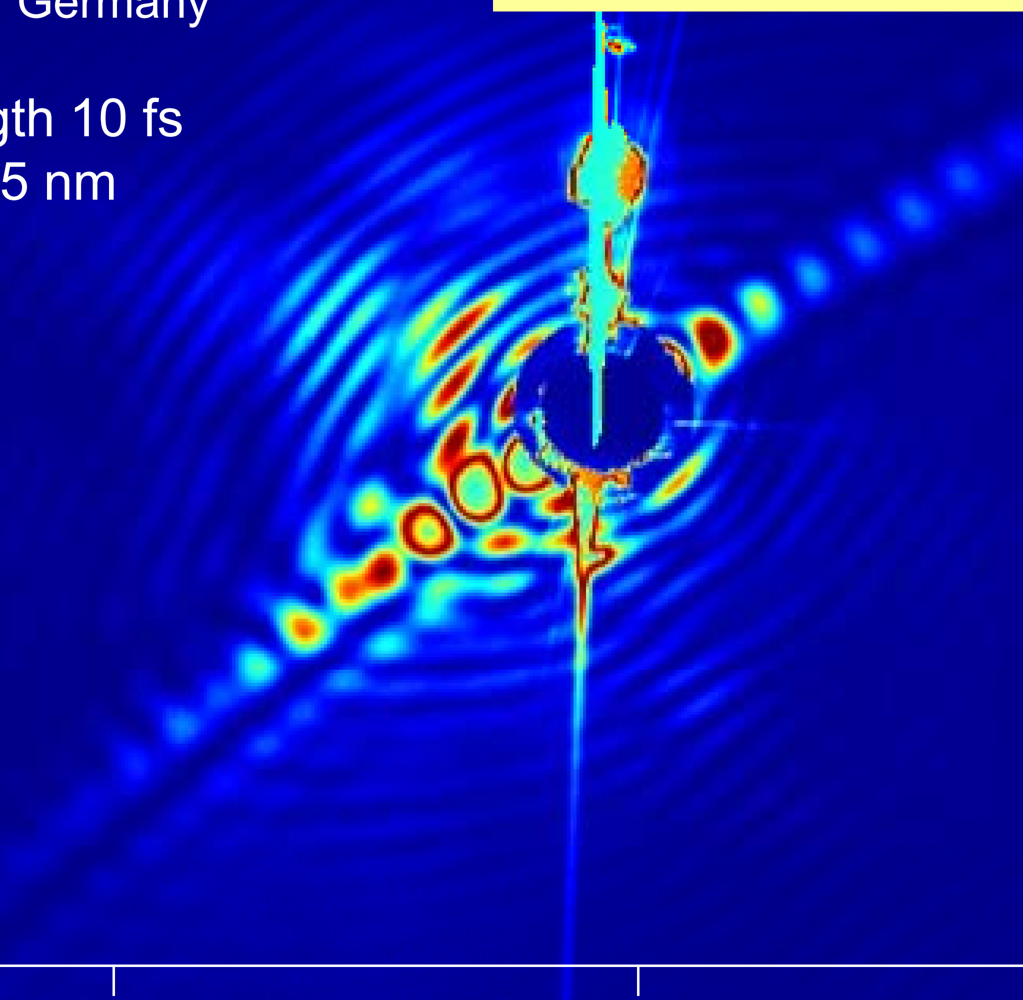


First "FLASH" Diffraction Image of a living Pikoplankon

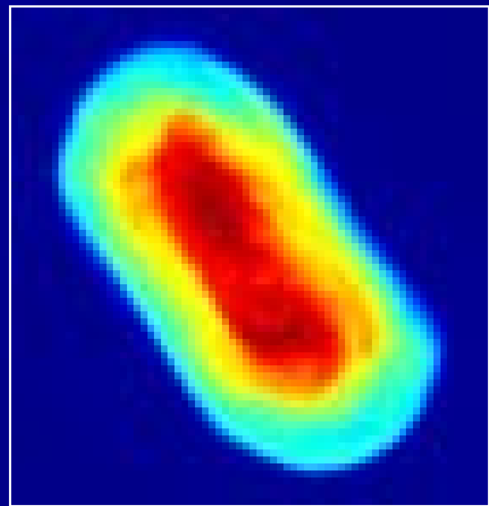
The smallest inhabitants of the Oceans , that do Photosynthesis are named PIKOPLANKTON. In Some places 80% of the biomass consists of such Species. (Discovery 1988)

March 2007
FLASH, Hamburg, Germany

FLASH-Pulslength 10 fs
Wavelength: 13.5 nm



RECONSTRUCTED STRUCTURE OF THE CELL



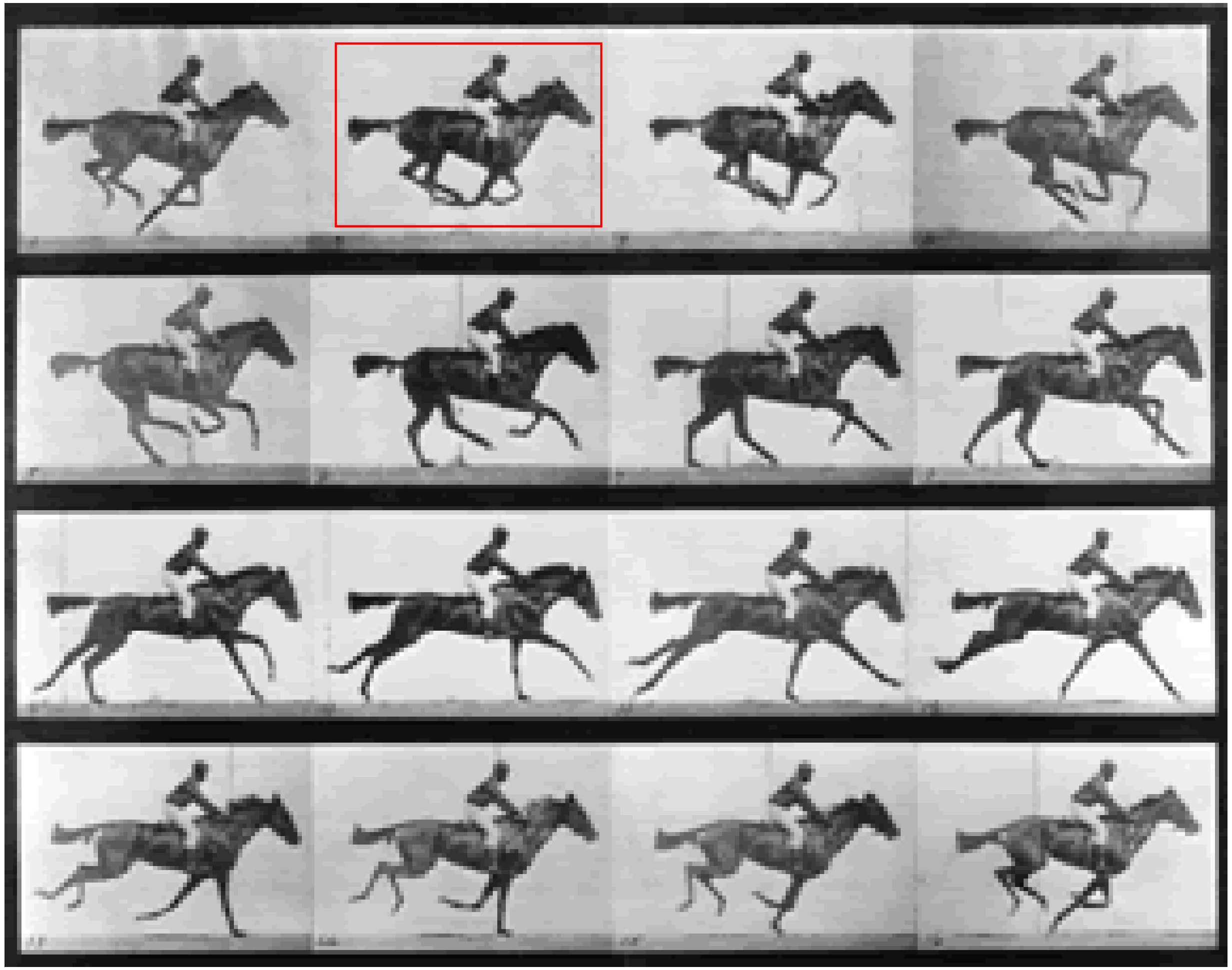
Filipe Maia, Uppsala

H.Chapman, J.Hajdu et al.

What means fast:

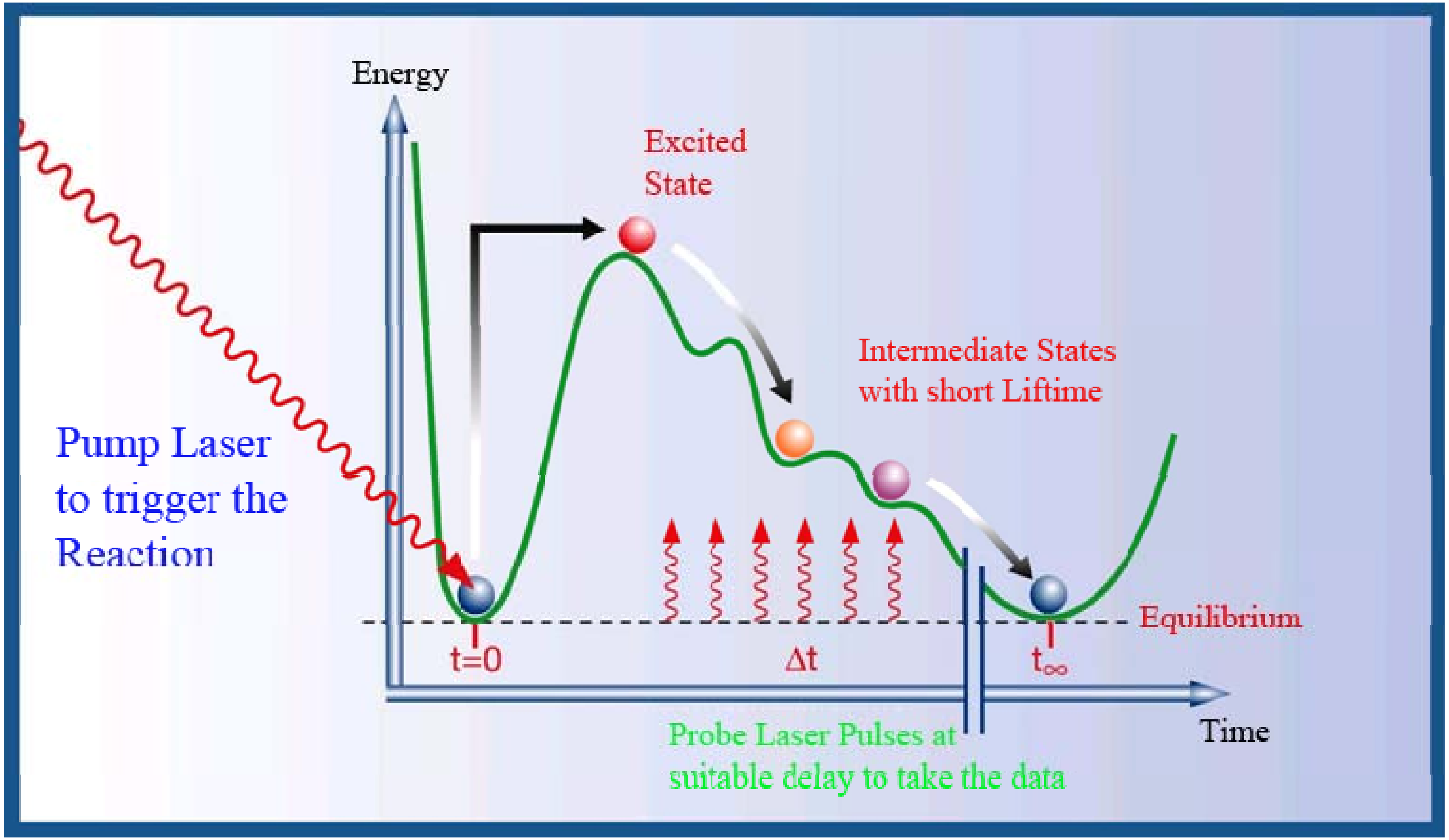
Once upon a time: The galloping horse, are all 4 feet in the air at some point of the movement.?

1878 Edward Muybridge



Today: Time resolveded spectroscopic Experiments

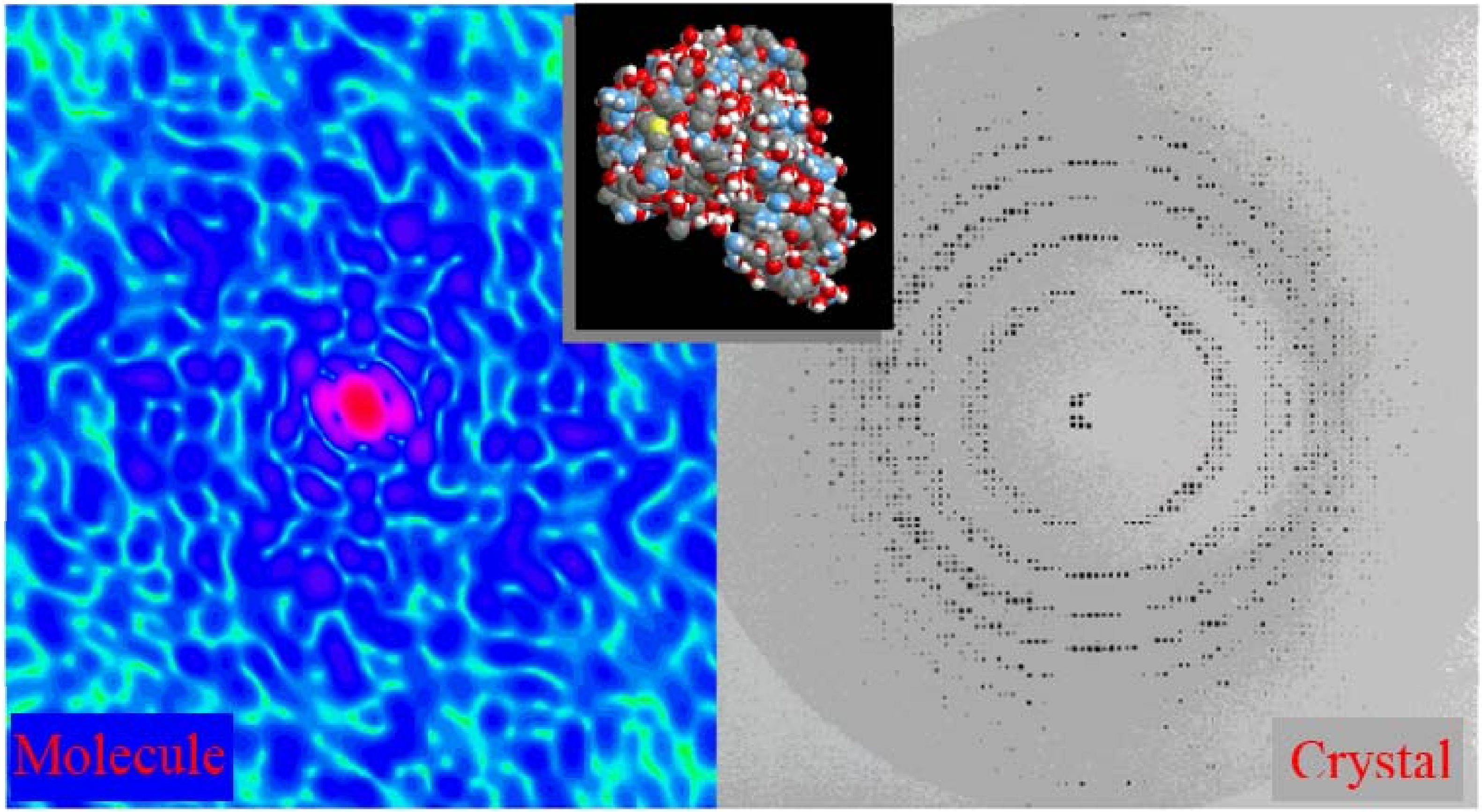
Investigate the dynamics of chemical reactions. How the hell does this enzyme manage to….?



Snapshots at different times after the impact
➔ „Movie“ of the Reaction

Coutesy: T. Treusch

Biology: Is it possible to investigate the structure of single proteins in natural environment?



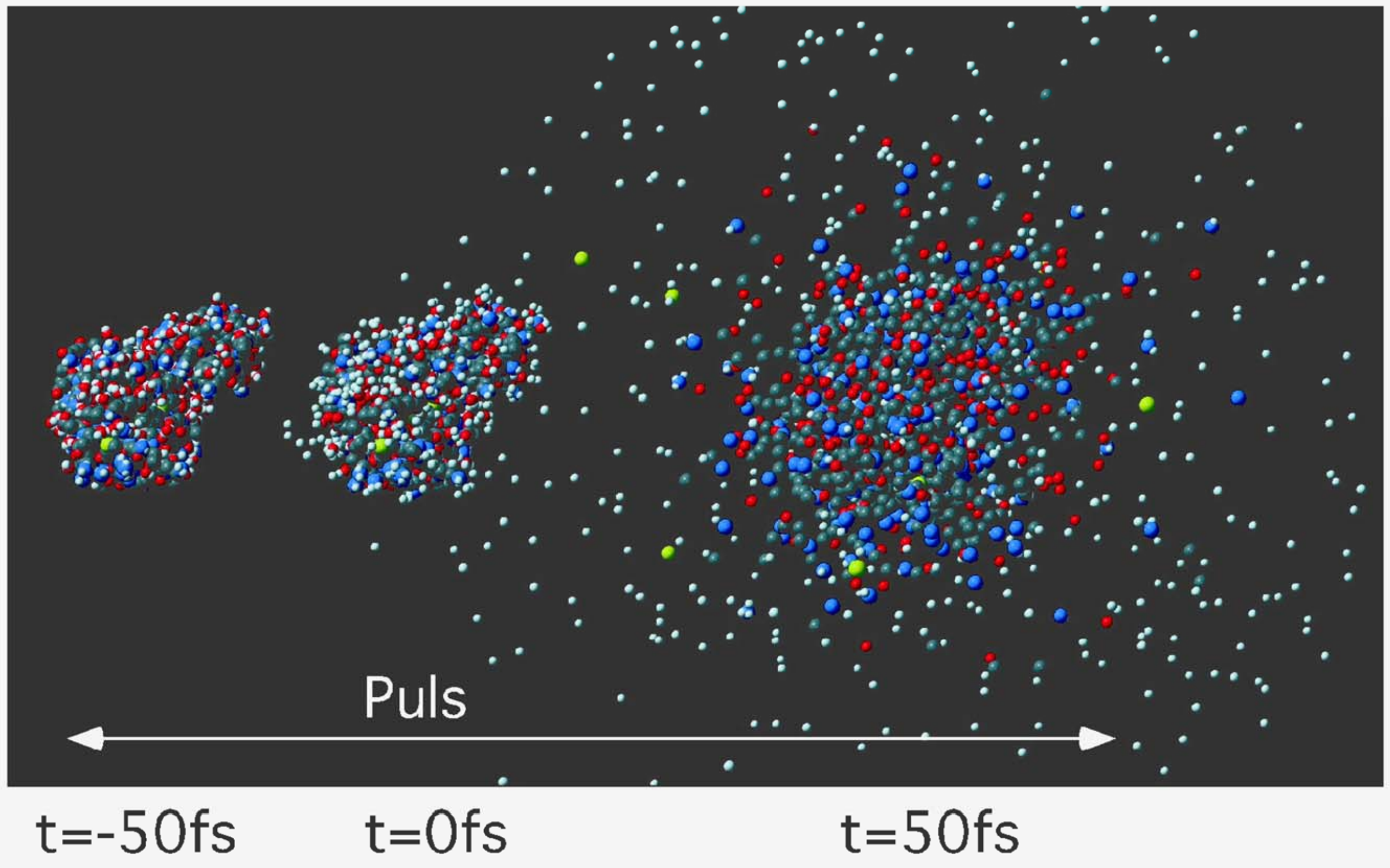
Calculated diffraction image of a single lysozym molecule

Measured diffraction image of lysozym crystal by means of synchrotron radiation

J.Hajdu et al.

It´s only a question of the number of photons !

Challenge: The Coulomb-Explosion



Example Lysozym:

White: Hydrogen,
Grey: Carbon,
Blue: Nitrigen,
Red: Oxigen,
Yellow: Sulfur

R. Neutze et al.
Nature 406, 752 (2000)

Callenge: Take Data before the sample is destroyed
Extremly short pulses and good amplitude control.

Coutesy: T. Treusch

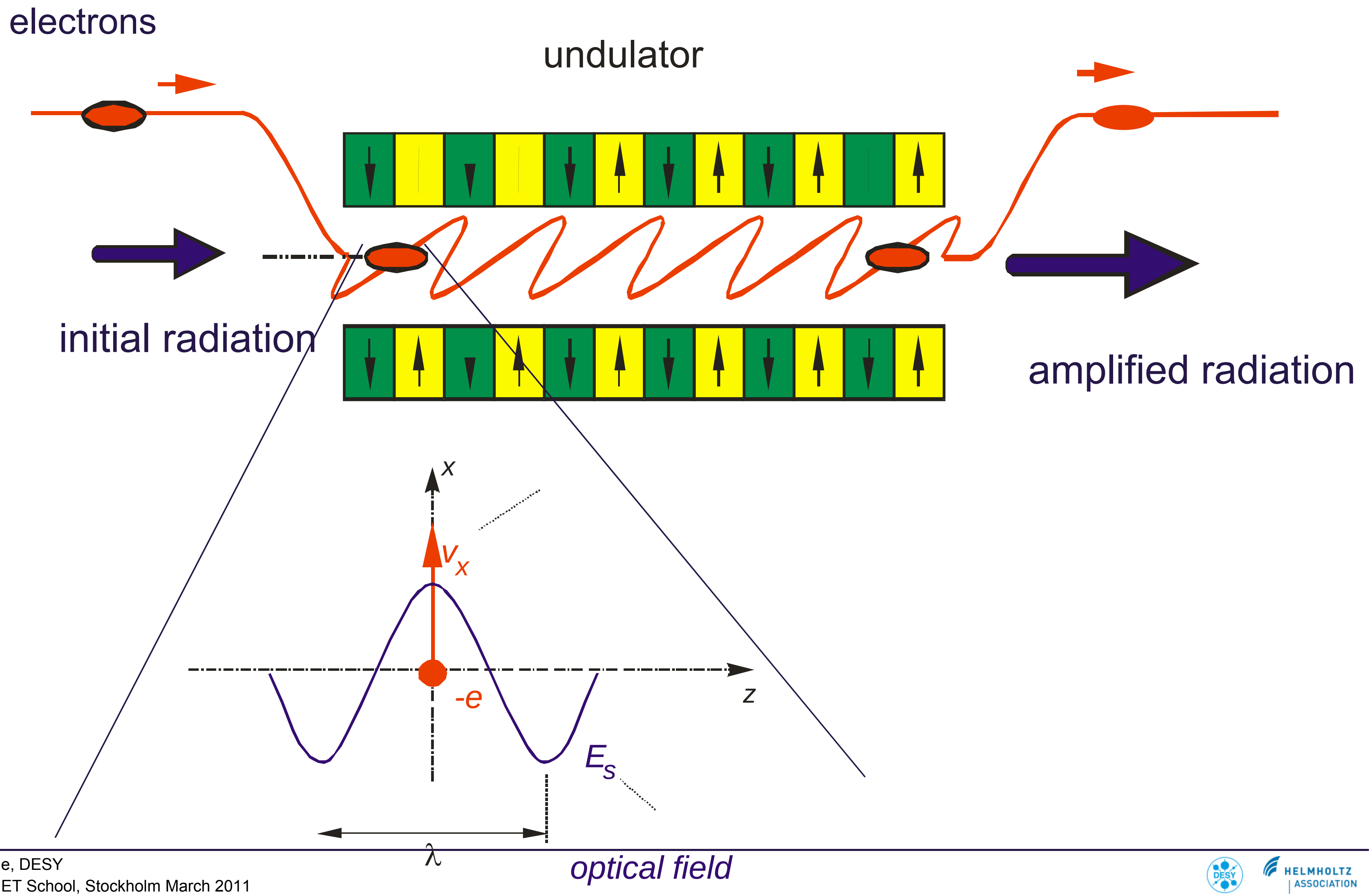
How? FEL Principle (I)

Energy Exchange :

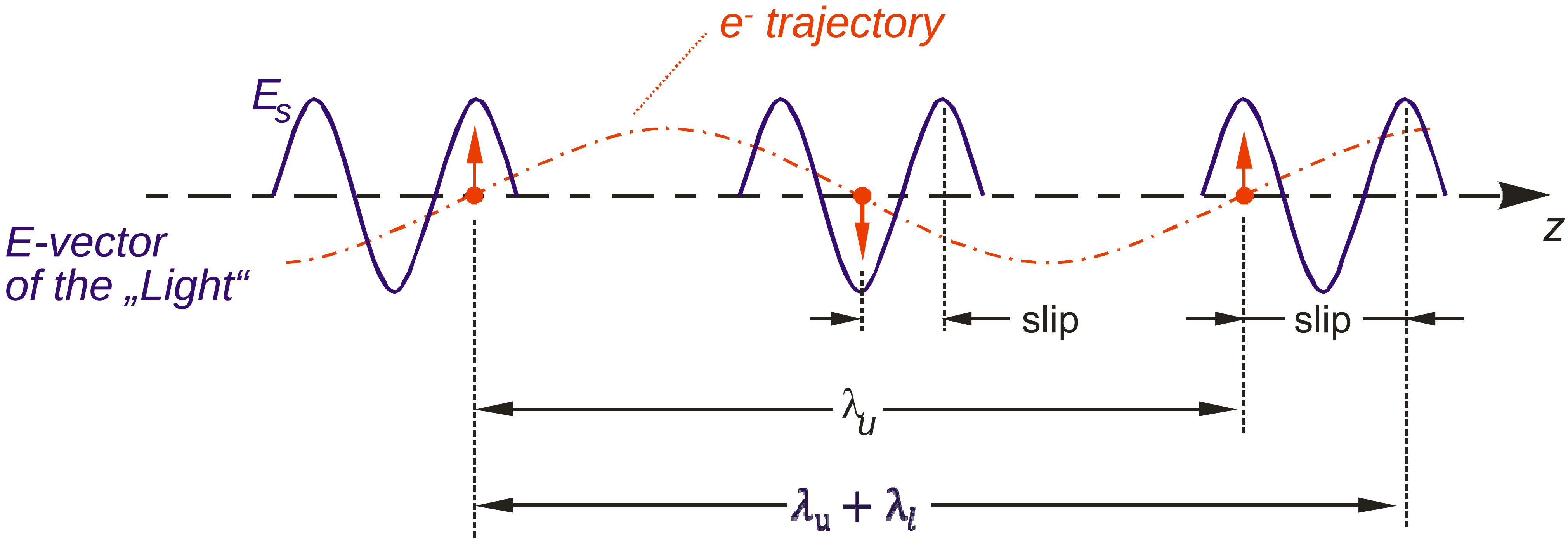
$$mc^2 \frac{d\gamma}{dt} = -e \cdot \vec{v} \cdot \vec{E}$$

- Goal: Get energy from the electrons to laser field.
- Problem: Field vector of the elm wave is perpendicular to the velocity of the electrons.
- Idea: use periodic magnetic fields to produce transverse electron velocity component, and thus coupling

How? FEL Principle (II)



How? FEL Principle (III)



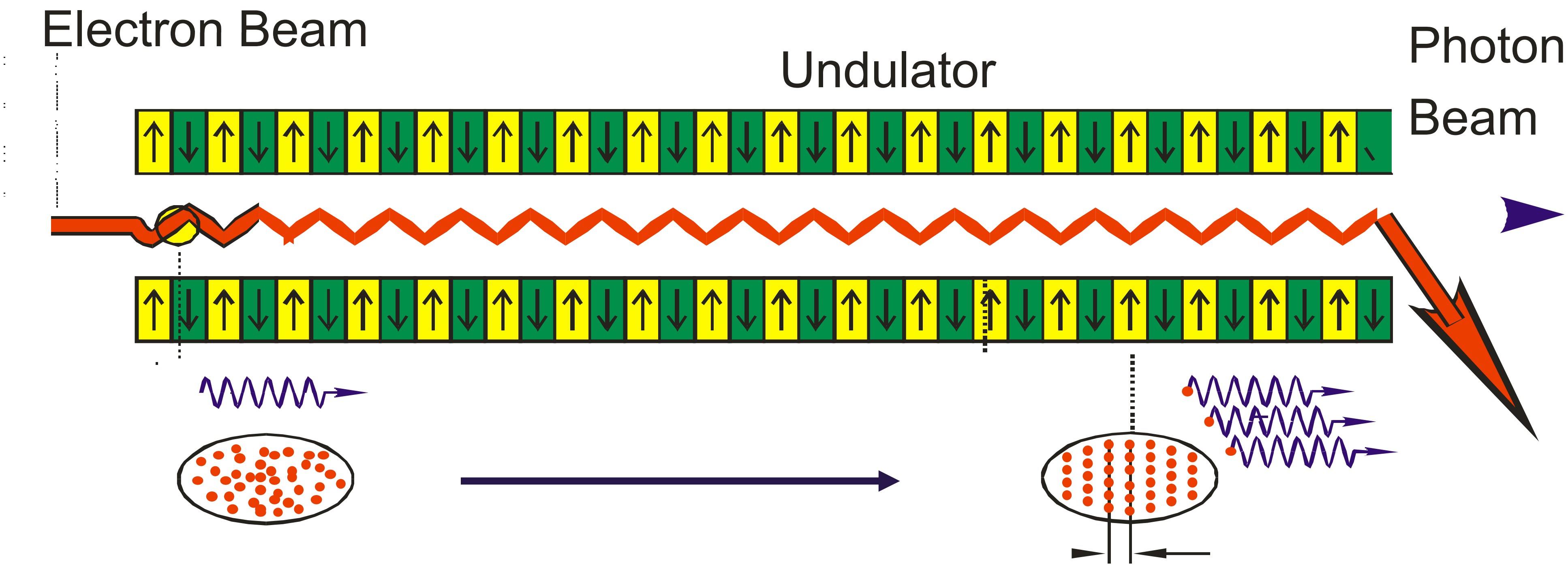
But: ϕ_0 is a random phase

$\Rightarrow$ there is only an energy modulation in the beam t!

Resonance Condition: $$\frac{\lambda_u + \lambda_l}{c} = \frac{\lambda_u}{v_z} \Longleftrightarrow \lambda_l = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Energy Exchange: $$mc^2 \frac{d\gamma}{dt} \approx -e \cdot \frac{B_0 \cdot E_0}{\gamma} \sin(\phi_0)$$

How? FEL Principle (IV)



Energy modulation

Dispersion in the Magnetic Field
Energy modulation gets „velocity“ modulation

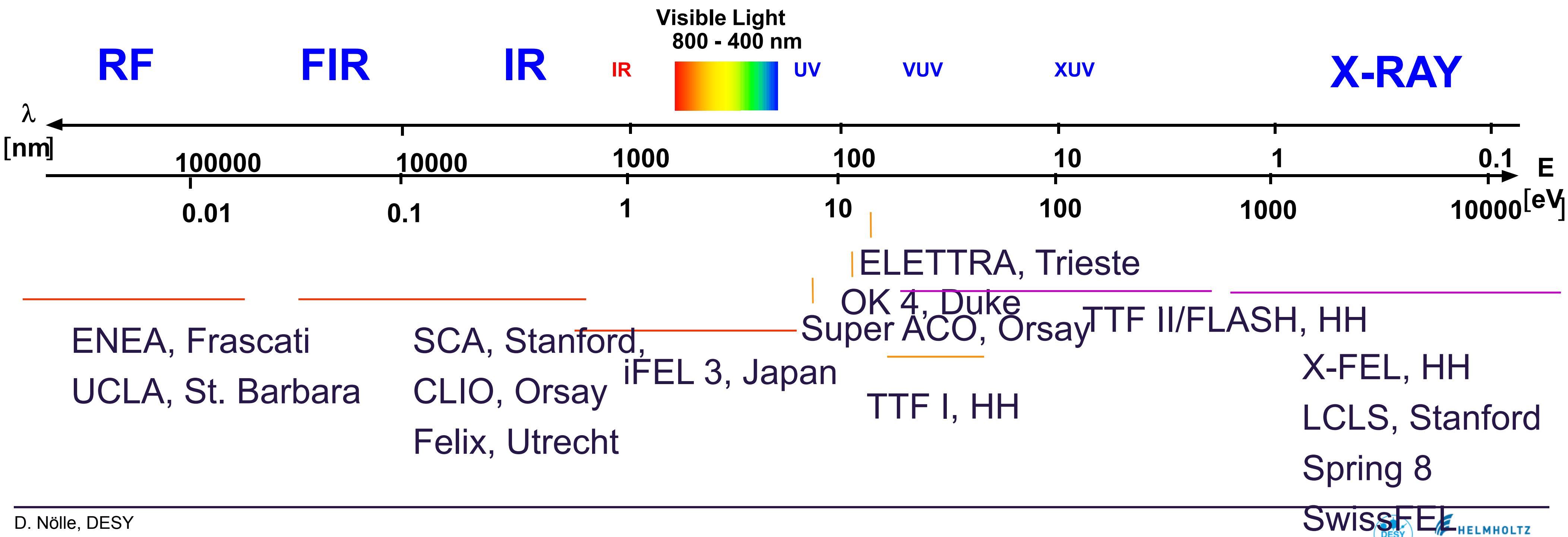
Bunching develops, resulting in
- Phase modulation
- Energy exchange
- FEL Amplification

How? FEL Principle (V)

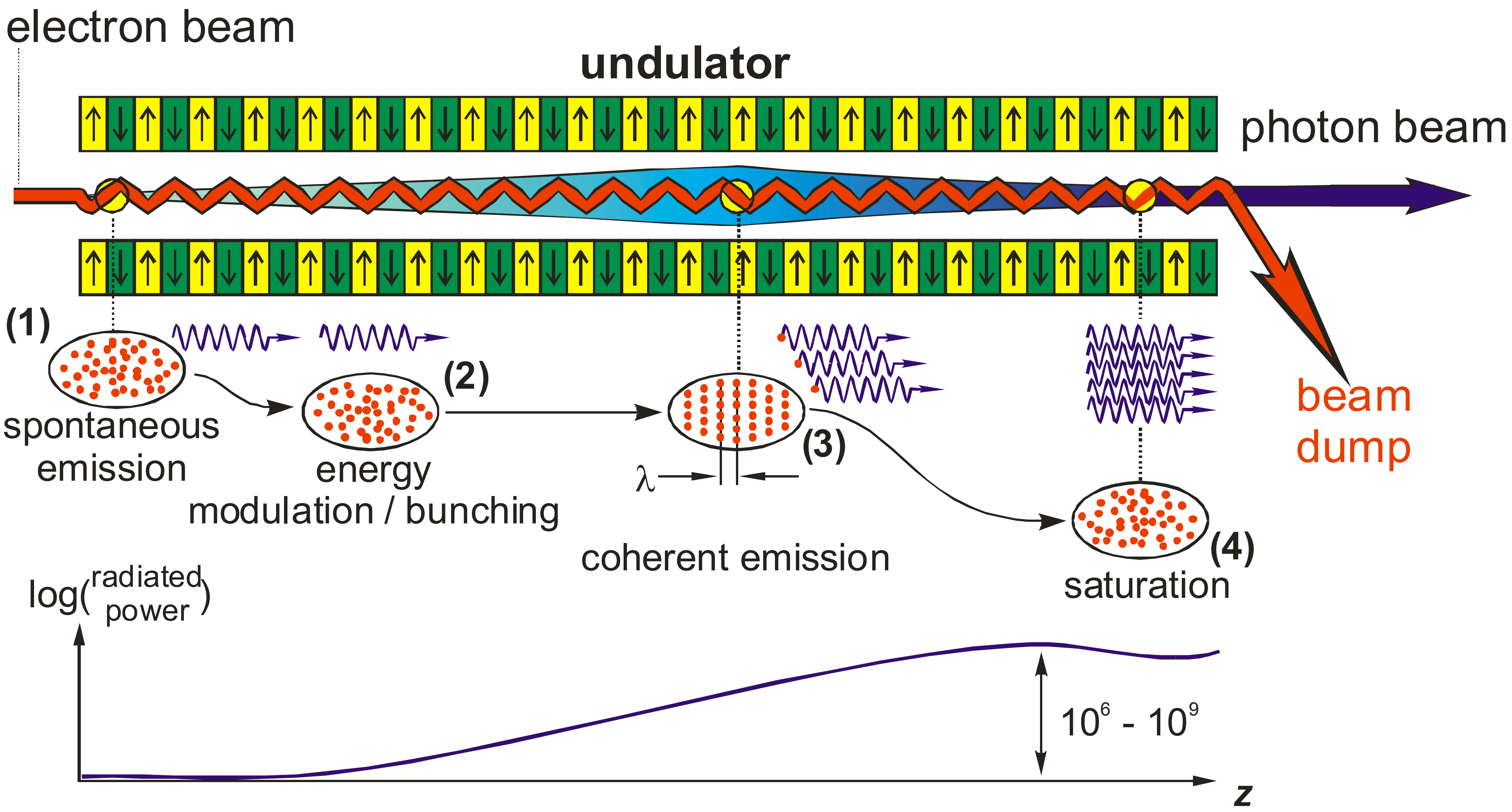
- Remark
  - FEL physics is pure Maxwell´s Equation
  - All depends on Fields and Energy

→ There are no Wavelength Restrictions by Principle

→ We are facing technological Limits only!

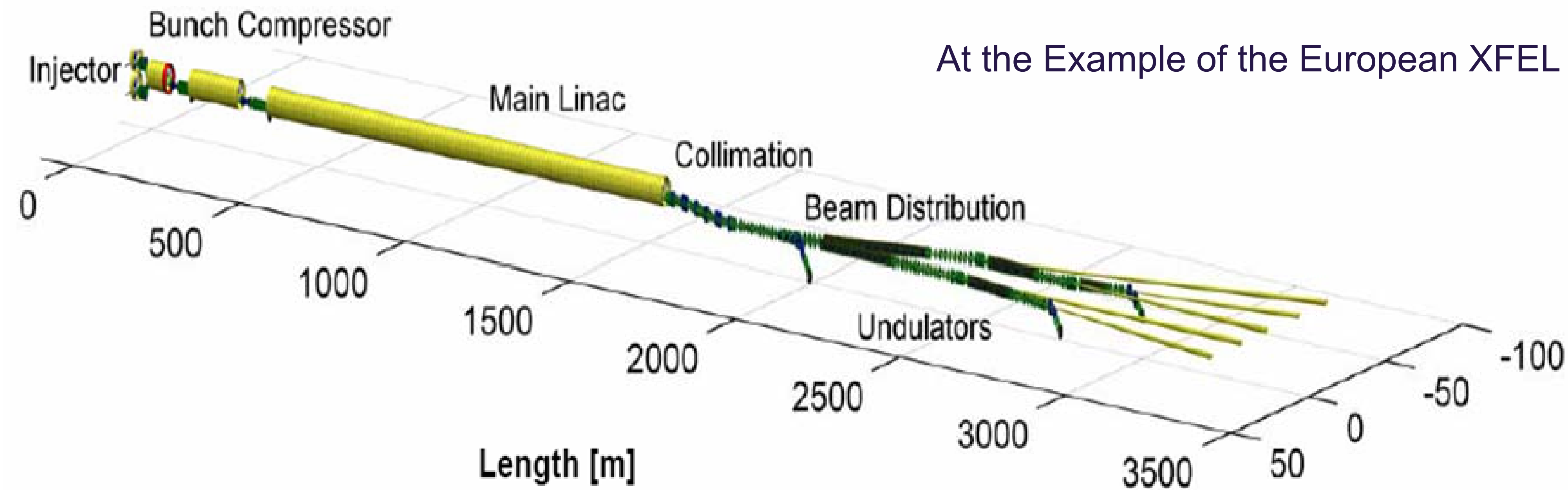


How ? FEL Principle (VI)
Self Amplified Spontanous Emission



How: Layout of an XFEL Facilty

At the Example of the European XFEL



- Electron Gun: usuallly a Photoinjector RF Gun
- Injector LINAC
- 2 stage Bunch Compression
- Main LINAC
- Collimation and Beam Distribution
- Undulator Sections
- Photon Beamlines

SASE FEL Diagnostics: What is special?

Typical Beam Properties (I)

- Single or Few Bunches typically with large separation
  - → Need to do Single Bunch Measurements
- Charge per bunch few pC up to about 1 nC
  - → Standard design was 1 nC for many years, now short pulse operation requires lower and lower charge
  - → Run into signal to noise problems at low charge, even if we a talking kA peak currents.
- Short Pulses 10 – 100 fs
  - → Complicates longitudinal diagnostics
  - → new methods required to verify pulse length of electron bunch and laser pulse

SASE FEL Diagnostics: What is special?

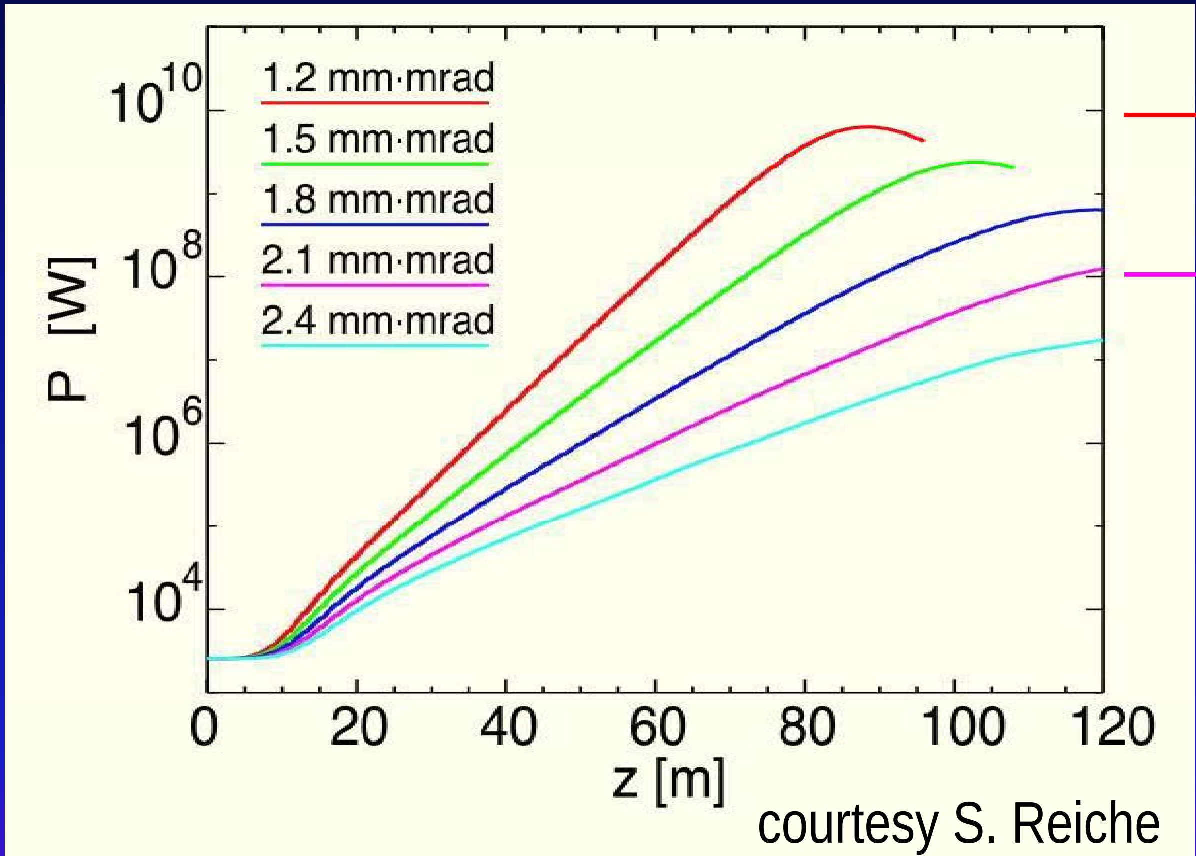
Typical Beam Properties (II)

- Extremely Small Emittance
  - ➔ Beam gets extremely small, often weird shape
  - ➔ Emittance is no equilibrium property, many effects like to waste it
  - ➔ Open Loop: Optics errors propagate through the entire machine
  - ➔ Coherent effects due to short pulses
- µm Orbit Straightness over hundreds of meters in the undulator
  - ➔ Need to guarantee overlap, “stable” power level, pointing stability
- Synchronization of fs SASE pules to external lasers:
  - ➔ Pump Probe requires arrival time with fs stability
- High demand on loss control due to sensitive undulators
  - ➔ 10 mm gaps over hundreds of m with many million $ undulators
  - ➔ 10^{-7} Losses in the undulator; this would be a no lifetime storage ring
  - ➔ Machine Protection is essential

LINAC – Storage Ring

- Open Loop
  - LINACs are open loop systems, optics mismatch is not easy to detect and propagates in the machine.
  - No Damping mechanisms for emittance
  - Emittance and optics matching are a function of section, but it can get only worse.
- Low Current
  - 33 µA (XFEL) compared to 100 mA (PETRA III)
  - No heating due to wakefields possible
  - High Impedance monitors for sensitive measurements
- Single Pass, large bunch distance
  - Need data sets of each bunch from all monitors time stamped
- Beam Loss
  - 10^{-7} Losses in the undulator; this would be a no lifetime storage ring

Please Remember:
Comment (from J. Hastings LCLS)



$\varepsilon_N = 1.2\ \mu m \rightarrow P = P_0$

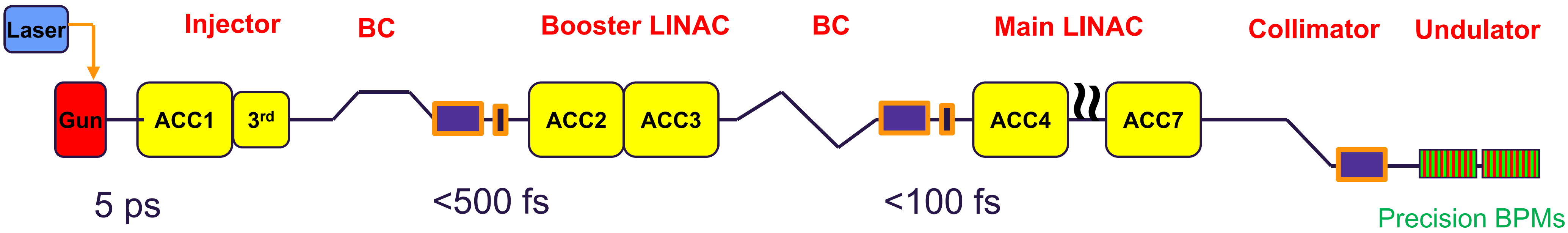
$\varepsilon_N = 2.0\ \mu m \rightarrow P = P_0/100$

Similar of course for XFEL, VUV-FEL, …

SASE FEL is not forgiving — instead of mild brightness loss, power nearly switches OFF

electron beam *must* meet brightness requirements

Where does the Music play?



- Need to prepare kA low emittance beams
- Preserve excellent emittance of the gun to the undulator
- Beam manipulation compression takes place in the BC
- Diagnostic sections with emittance measurements
- Longitudinal and slice diagnostics
- Precision BPM for straight orbit and optimum overlap

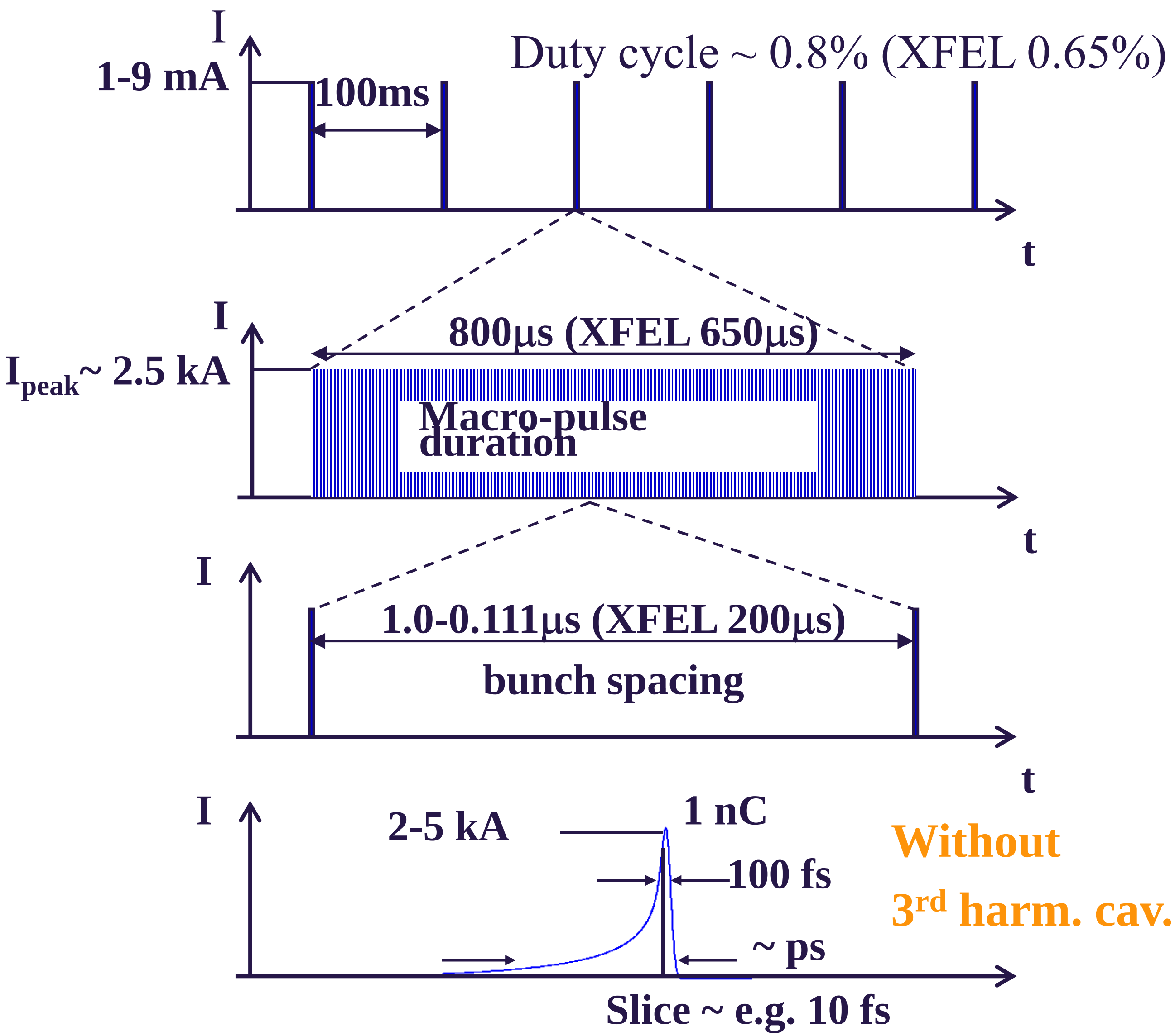
Just to Remember: Superconducting Linacs (FLASH, XFEL): Time Structure

Repetition rate

Macro-pulse

Bunch

Slice



Some of the Systems

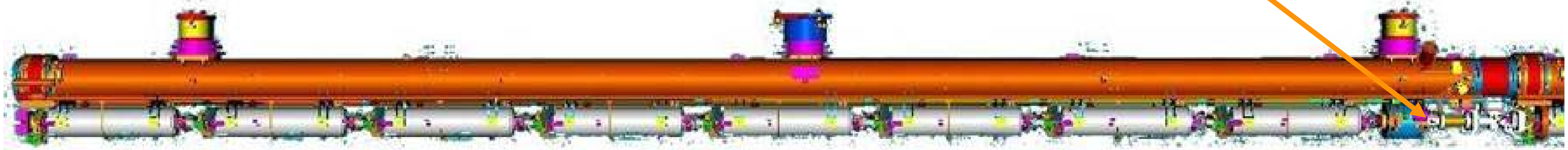
- BPM
- Charge monitoring
- Screens (no comment on wirescanners)
- Machine protection and loss Monitors
- Pyro detectors
- LOLA and other transverse mode structures
- Synchronisation and BAM

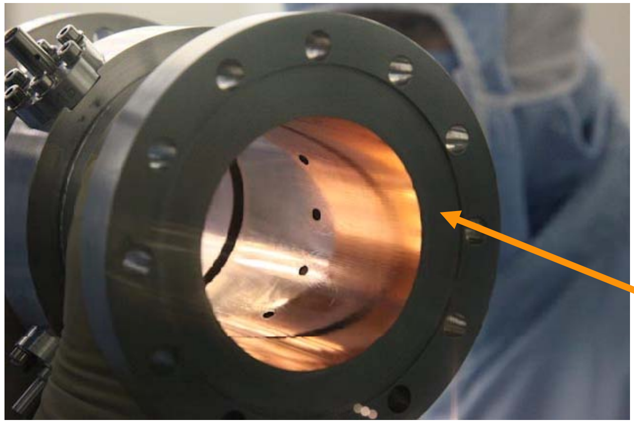
Butter&Bread: BPMs
Example: Short Version X-XFEL BPM Spec

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

Butter&Bread: BPMs

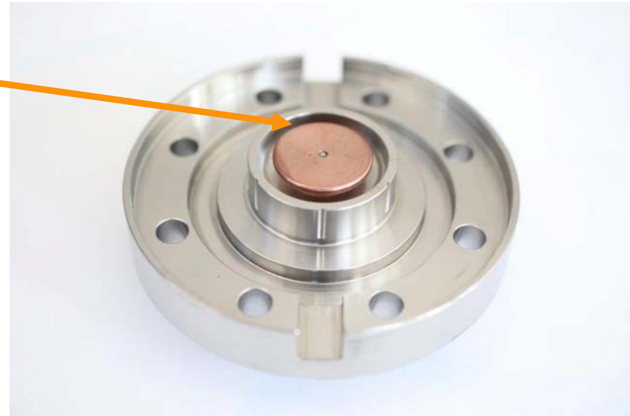
Cold BPMs in the E-XEL Cryo Module





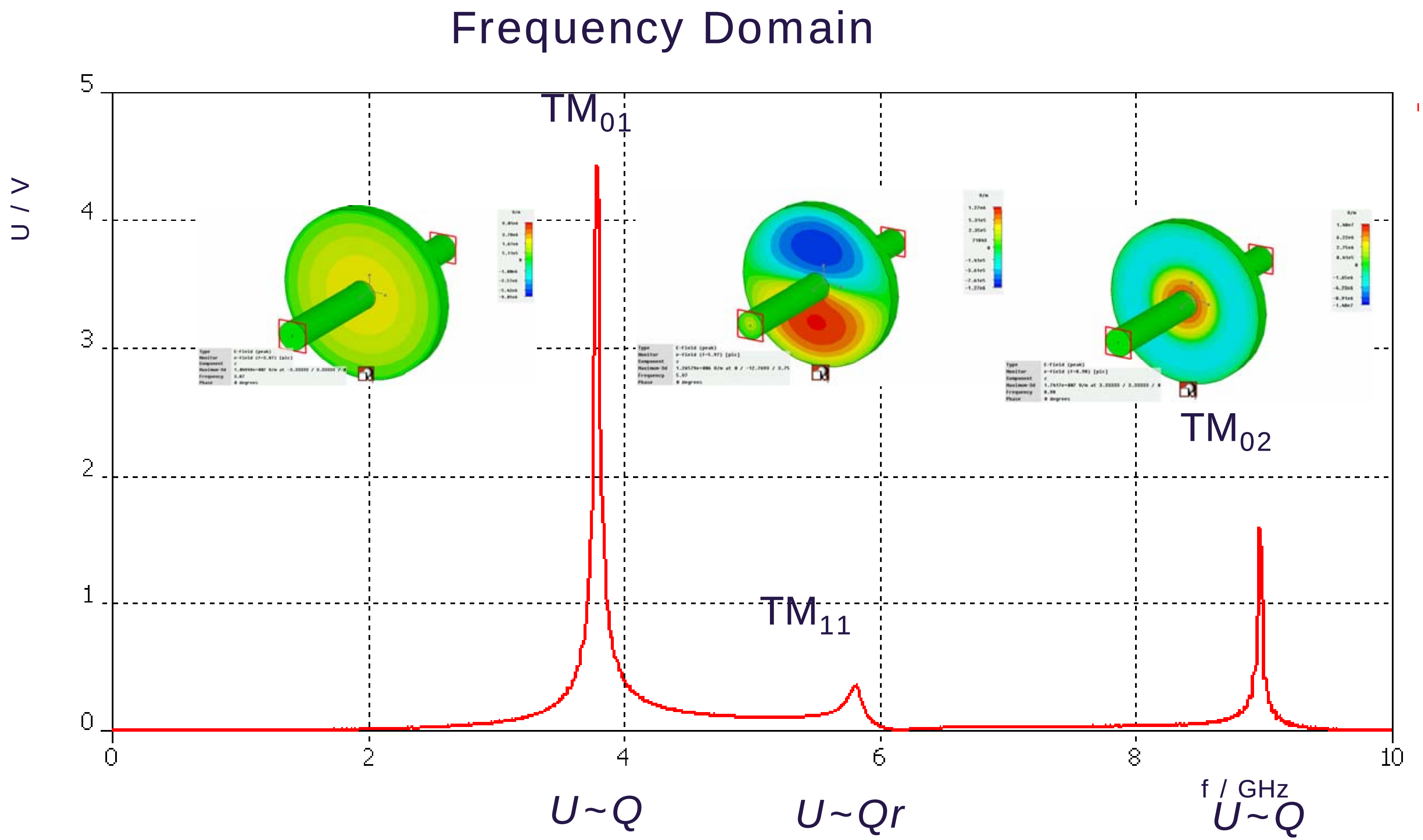
Reentrant Cavity BPM
During Preparation in
The Cleanroom

Button



- Safe Design: One BPM at each quad (max. flexibility for optics)
- In LINAC relaxed requirements concerning resolution, except
  - Compression Chicanes
  - Undulator Entrance
  - Working Horses: (cheap) Button or (better) Stripline BPM
- Precision BPM: Cavity Types (Undulator, Around Chicanes)

… Cream: High Precision BPMs

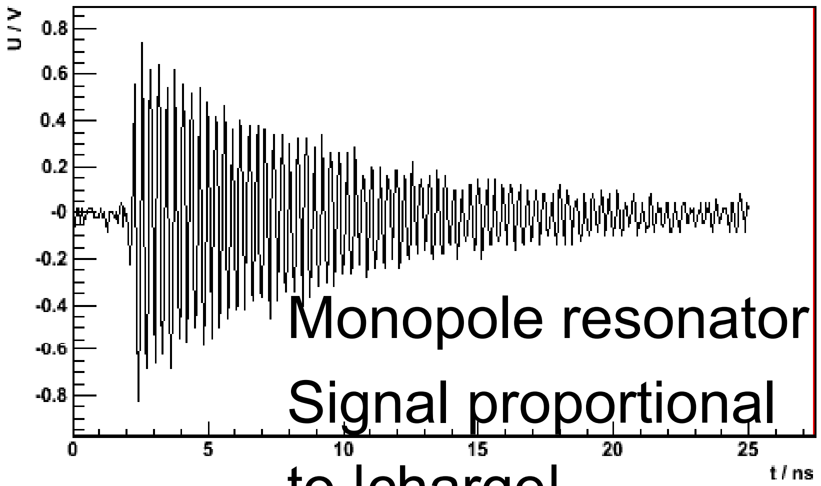


Cavity BPM are High Impedance BPMs with excellent Performance

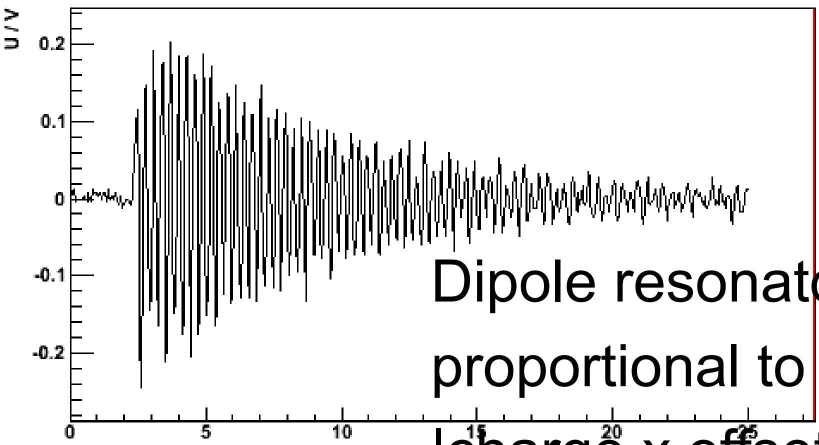
Potential to go to sub µm Resolution

Coutesy: D. Lipka

… Cream: Cavity BPM Signals

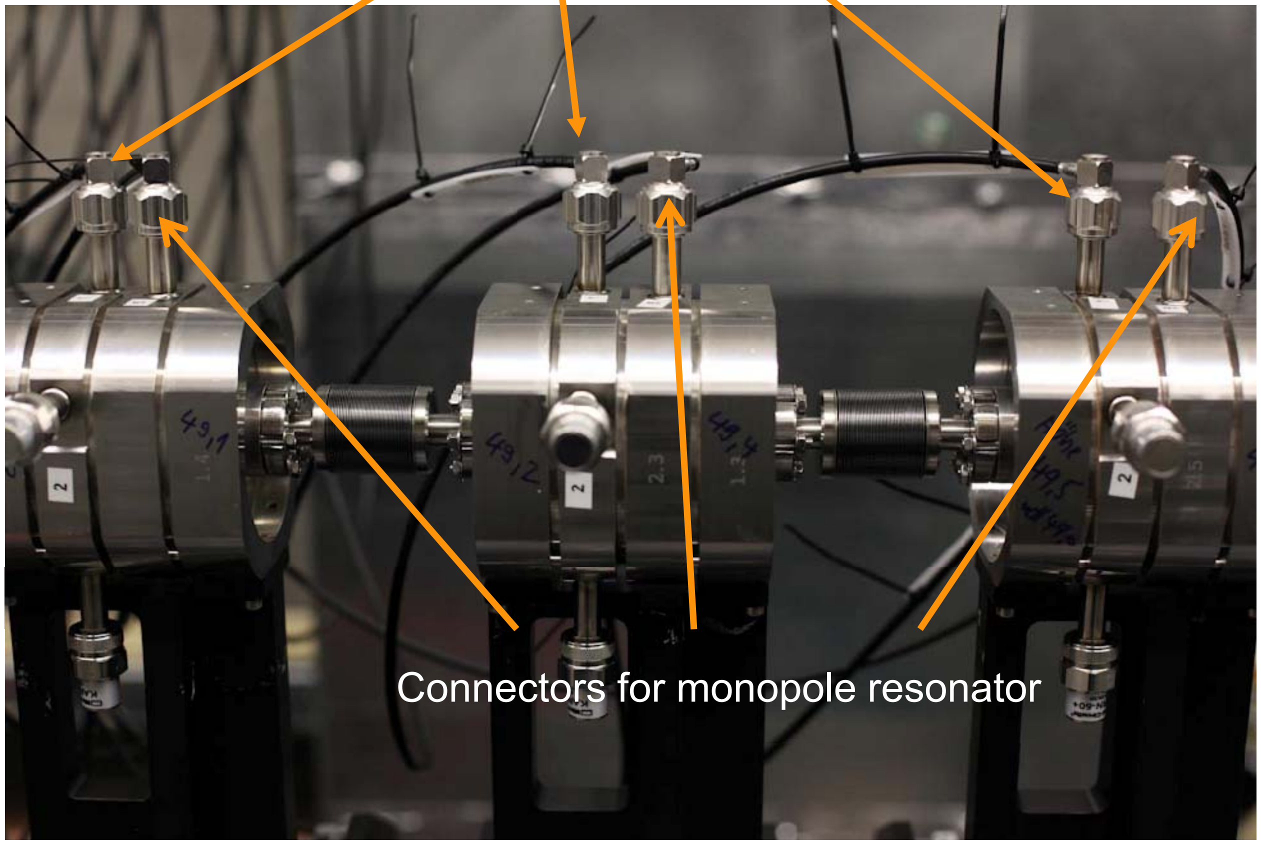


Monopole resonator Signal proportional to |charge|



Dipole resonator signal proportional to |charge x offset|

Connectors for dipole resonator



Connectors for monopole resonator

Photo: D. Nölle

Phase Relation of Monopole and Dipole Signal determines Sign

Coutesy: D. Lipka

… Cream:
Cavity BPM; Cut Through an E-XFEL Type

Holes for coupling Antennas

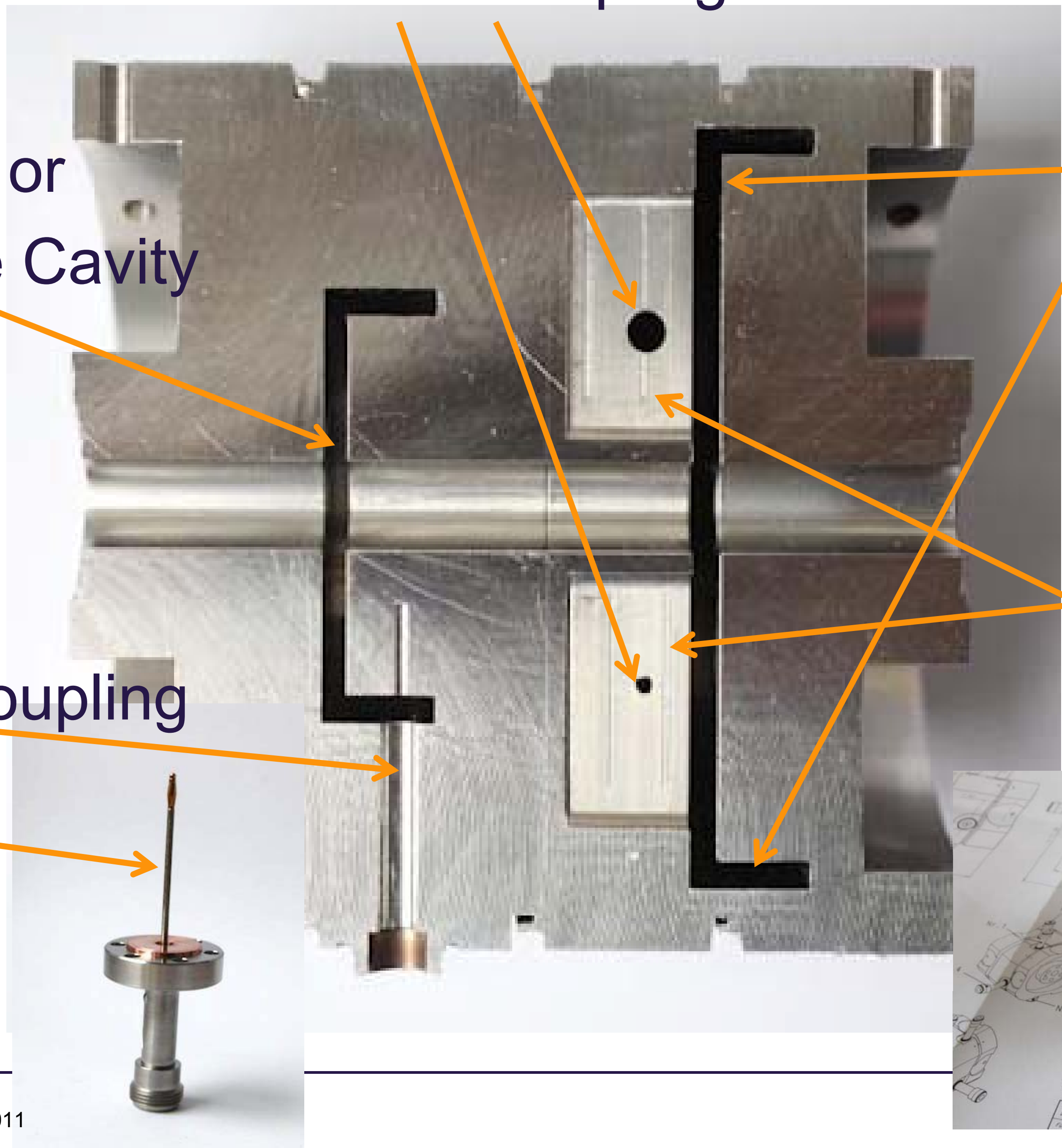
Monopole or Reference Cavity

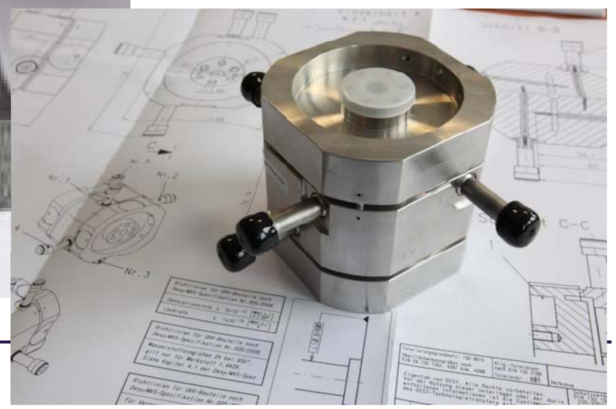
Dipole Cavity

Coupling Slots To TM11 Mode

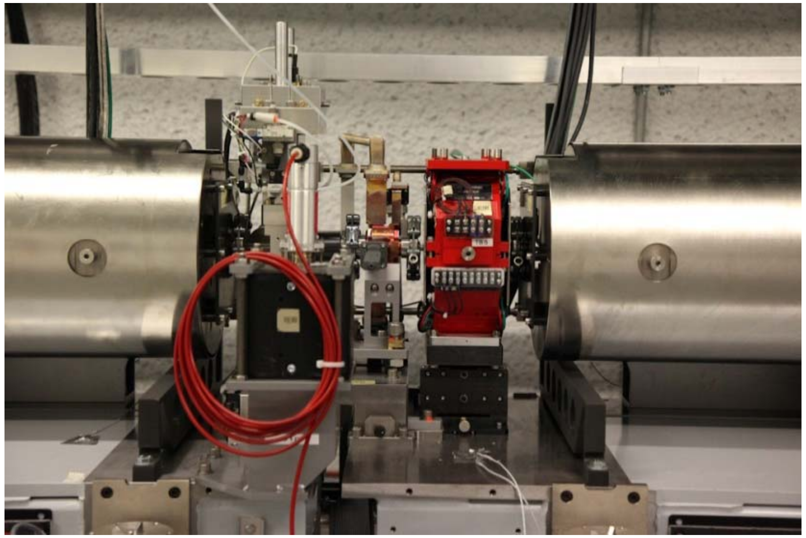
Hole for Coupling Antenna

Capacitive Coupling

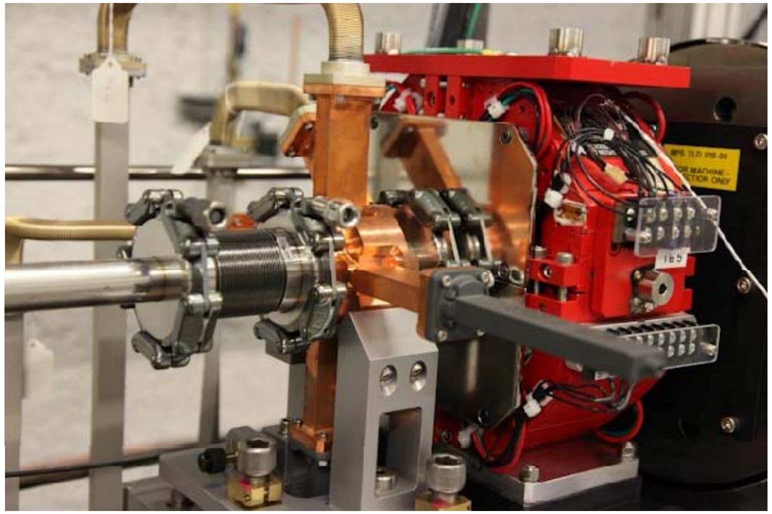




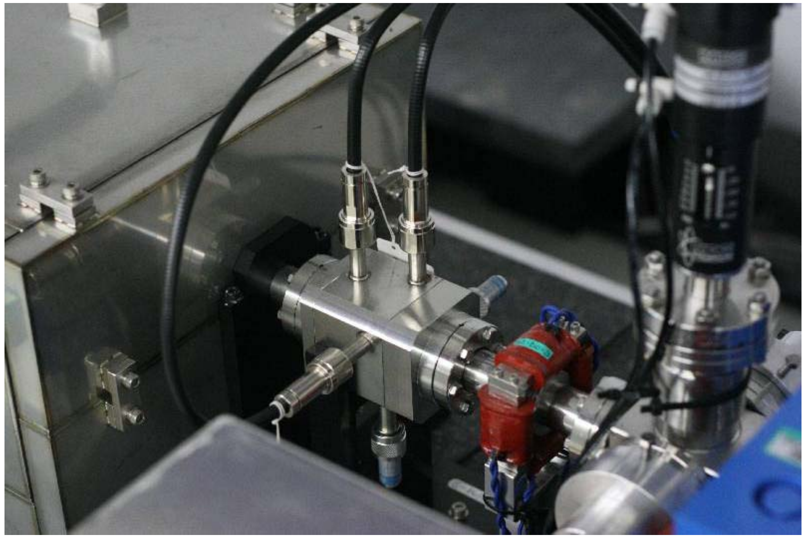
… Cream: Cavity BPMs for SASE Machines



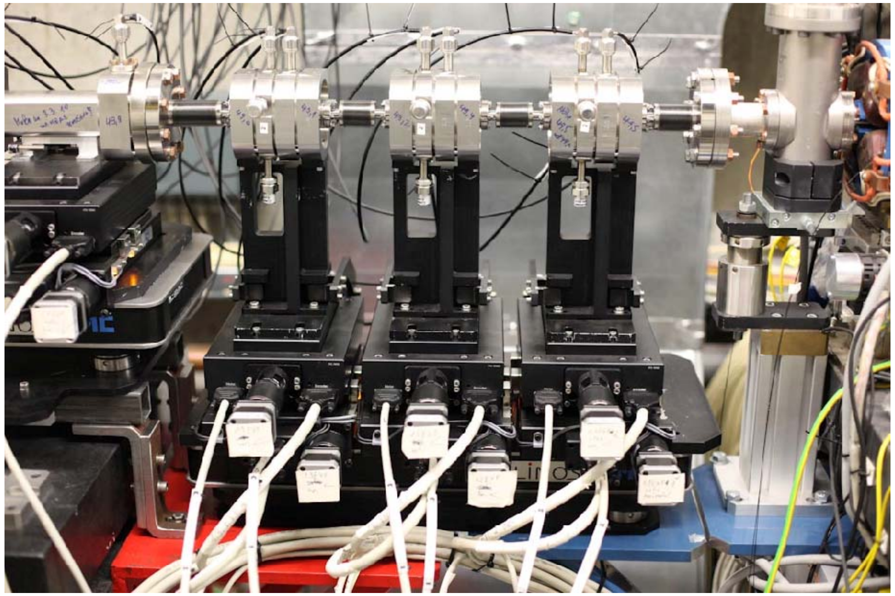
Undulator intersection @ LCLS



Cavity BPM @ LCLS



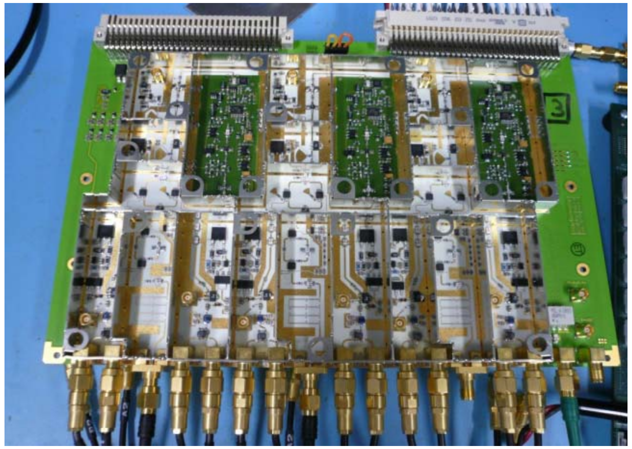
Low Q Cavity BPM @ SCSS



E-XFEL Cavity BPM Test @ FLASH

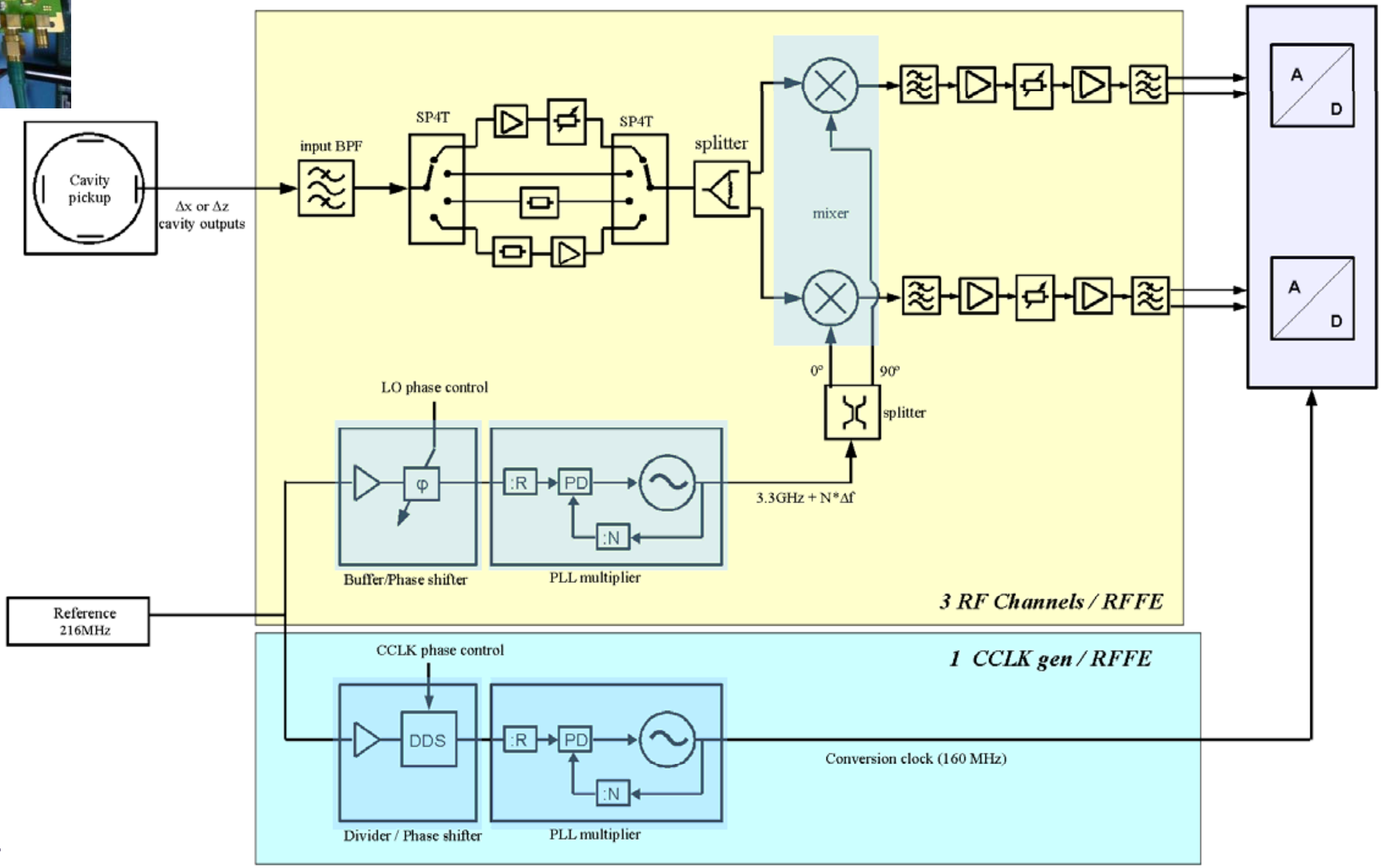
European XFEL

Cream: Cavity BPM Electronics; Front End Part



Schematic of a single Channel incl. Reference Clock

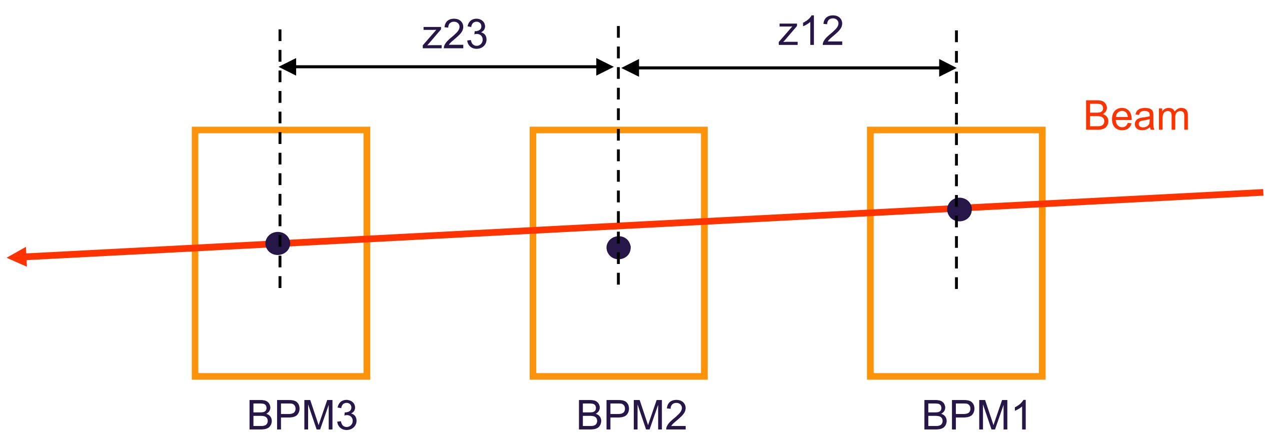
- Signal conditioning and amplification
- Range Adjustment
- IQ Detection



Ref: M. Stadler, PSI

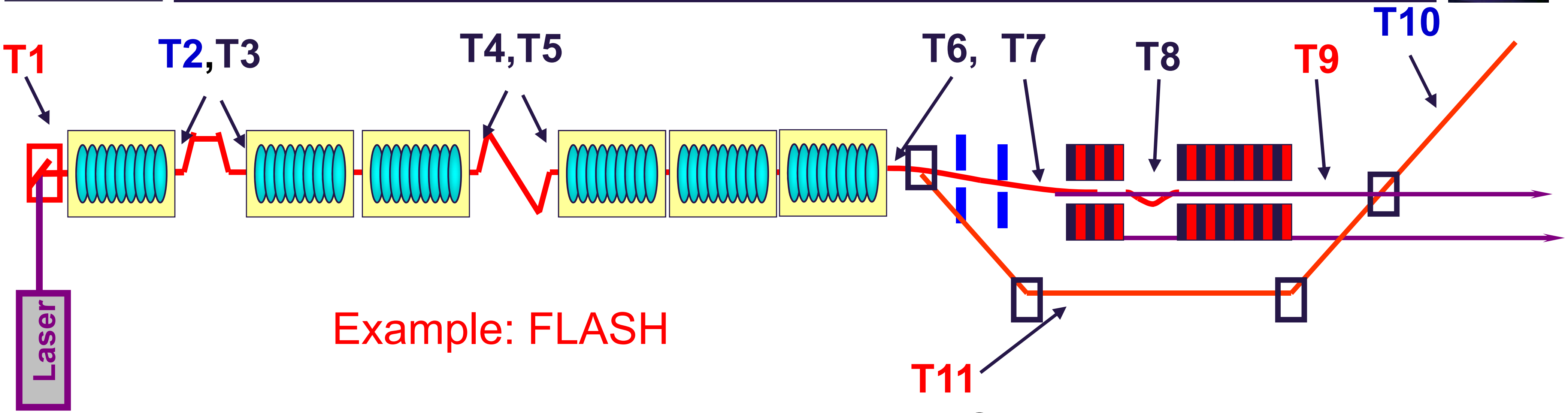
Remark: BPM Resolution Measurement

- 3 BPMs in a drift space without any Magnet in between
  - Beam has to travel on a straight line
- Both outer BPMs predict beam position at BPM2, difference result in residual



Coutesy: D. Lipka

Charge and Transmission Monitors



- Poor transmission is easy to produce in LINACs and will be awarded with high activation levels.

-> Measure Single Bunch Charge along the Machine

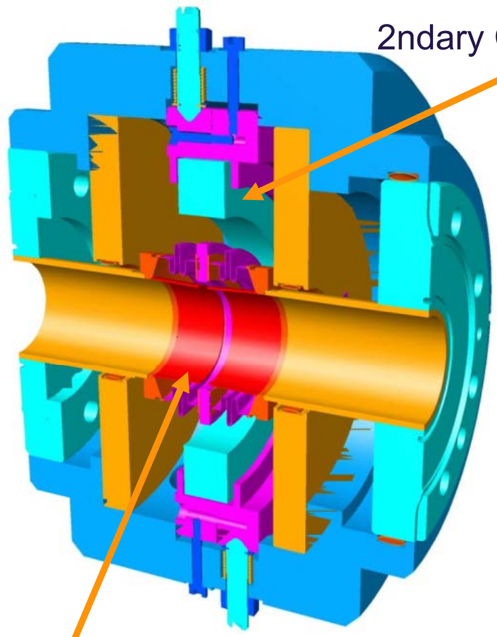
- Typical position Start and End of a functional section of the machine, e.g.:
  - Start and End of a Bunch Compressor
  - Start and end of a Collimation section
  - Before and after the Undulator
  - After the Gun and Before the Dump
- Comparison of Toroids allows tracking the Transmission

Charge and Transmission Monitors

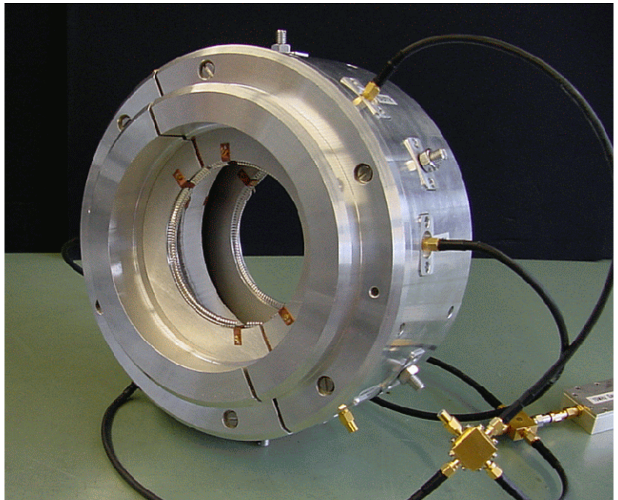
- XFEL: DESY Style Toroid:
  - about 40 devices required
  - charge range 0.02 …1 nC
  - min. bunch spacing 222 ns
  - arbitrary bunch pattern

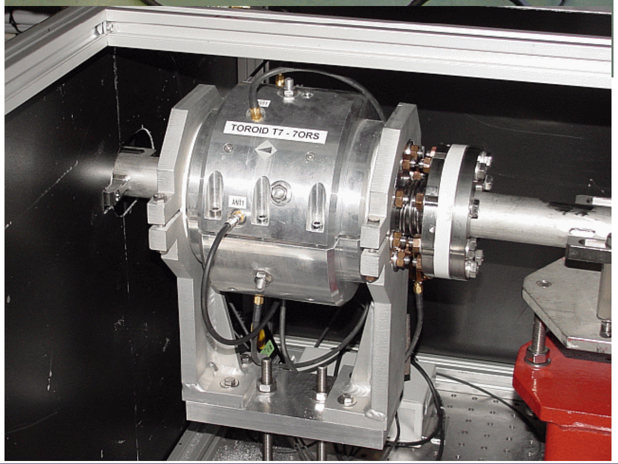
Ceramic Gap

Ferite core (Transformer)
2ndary Coils not visible



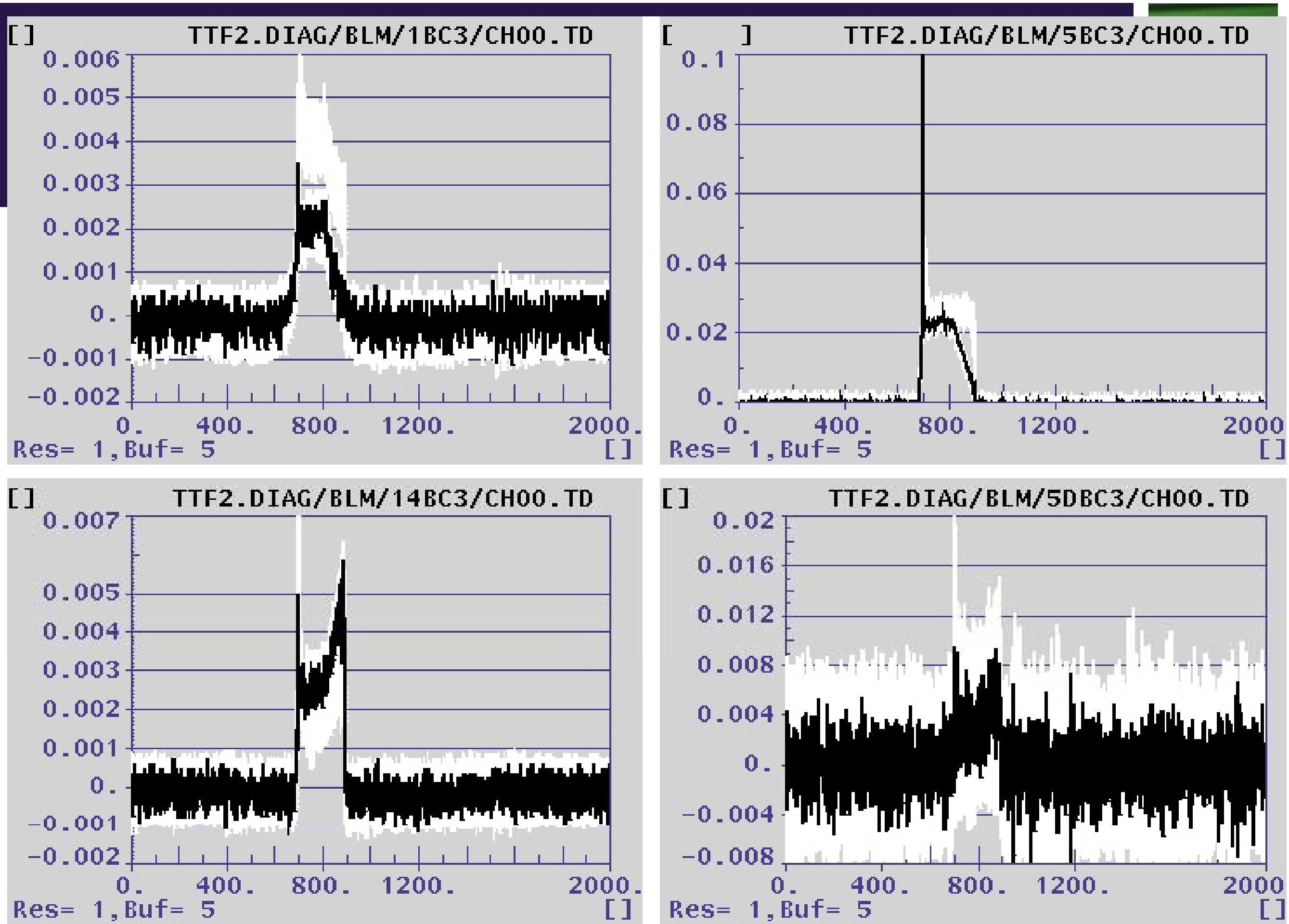
Beampipe with shielded Gap





Dark Current

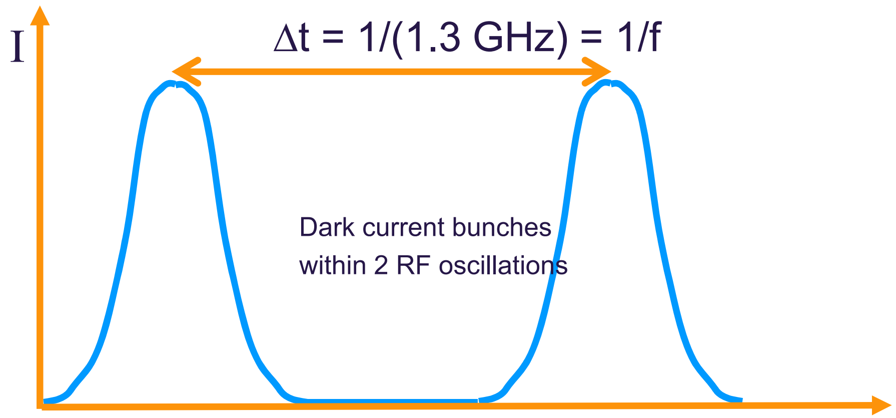
Dark Current is present in each RF bucket
Example 1.3 GHz, 1 µs Bunch Spacing
-> 1300 RF bucket/bunch



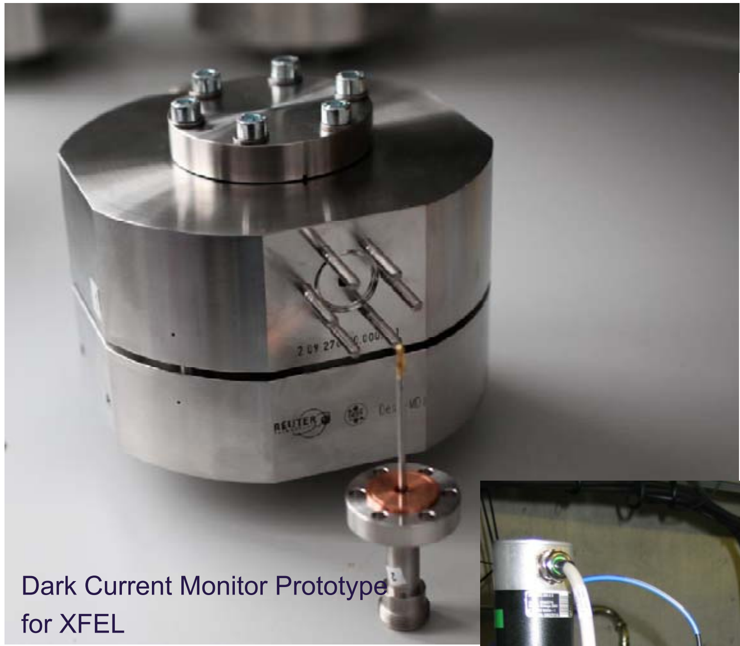
Beam Loss monitor signals from FLASH: The beam is the spike, the envelope is dark current

- Hot topic for super-conducting machines (long RF pulses)
- Source: Field emission in high gradient RF structures
- Dark Current from the gun might be transported through the entire machine
- Dark Current from accelerating structures is normally dumped in the vicinity of the source (X-rays and activation).

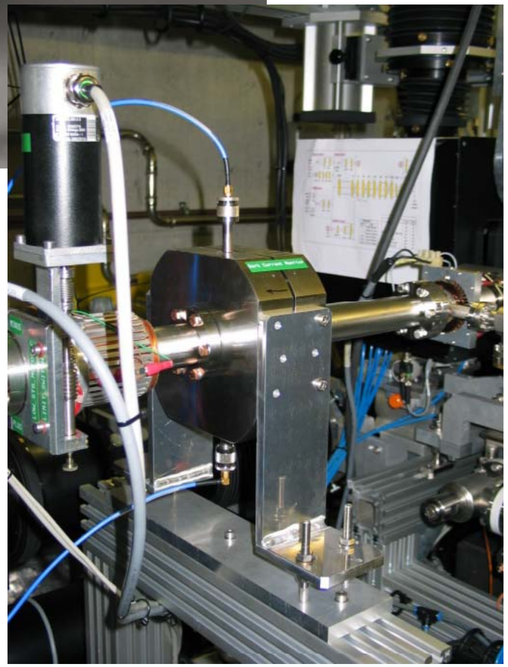
Dark Current Monitor



Dark current frequency is equal to RF frequency

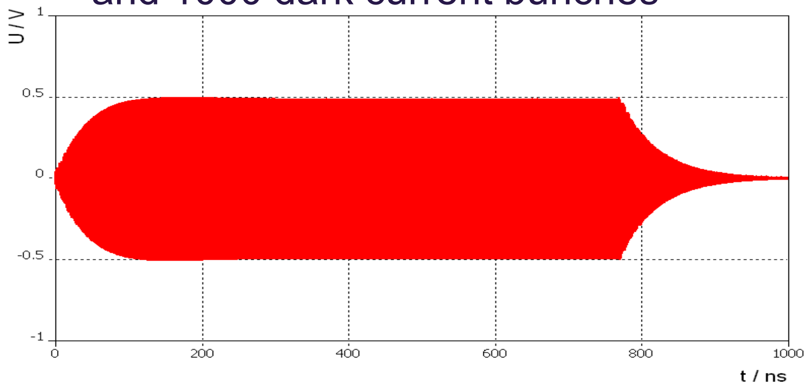


Dark Current Monitor Prototype for XFEL



Measurement with first Prototype at PITZ, DESY Zeuthen

Expected voltage at DCM for I=1 mA and 1000 dark current bunches

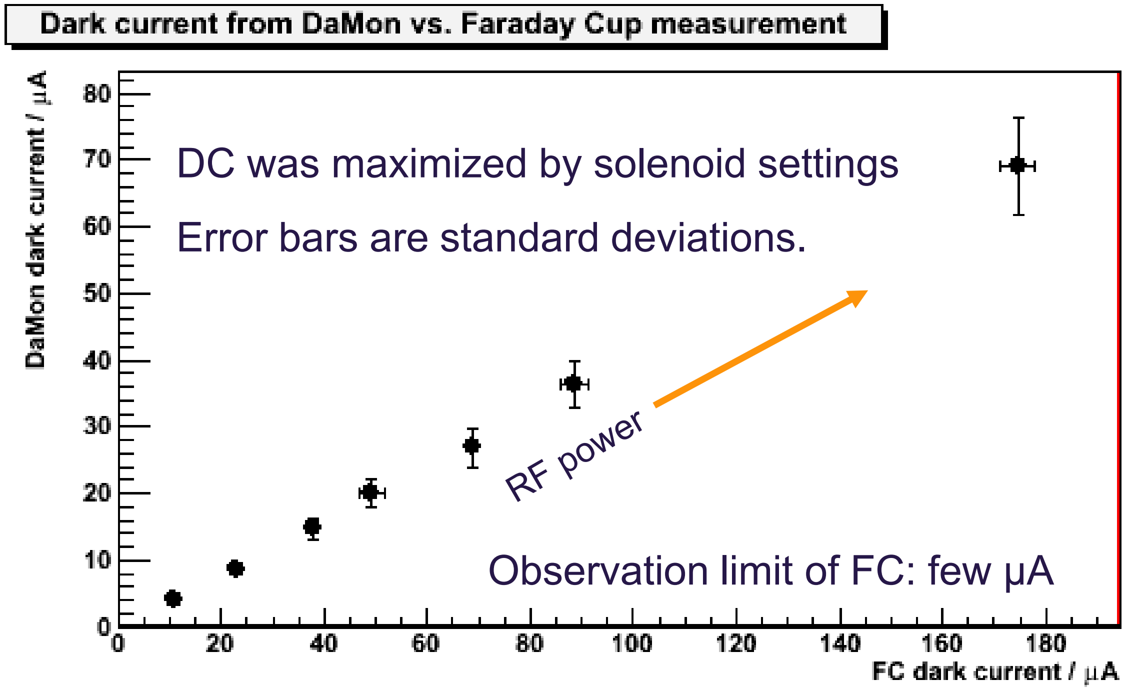


Use resonant pile up in cavity for reasonable signals

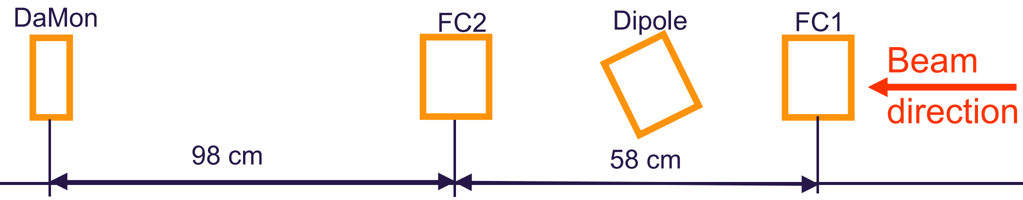
Transient oscillation finished after 150 ns

Coutesy: D. Lipka

Dark current vs. Faraday Cup



- Clear corelation between FC and DC
- Loss of DC particles in the line comparable with simulation
- Observation limit of DaMon system about 40 nA (measured at FLASH)



Coutesy: D. Lipka

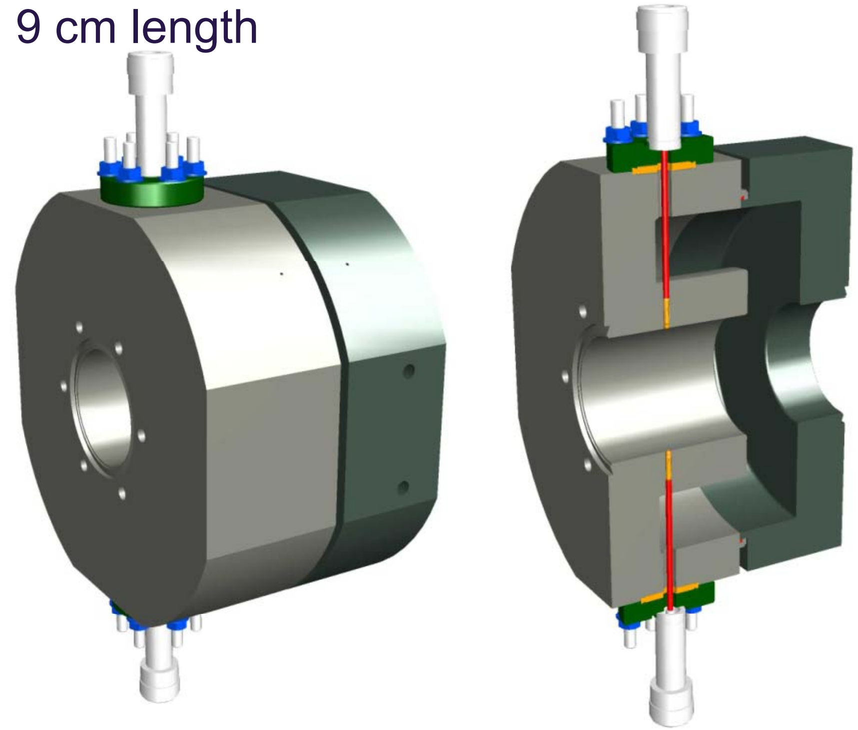
E-XFEL Design

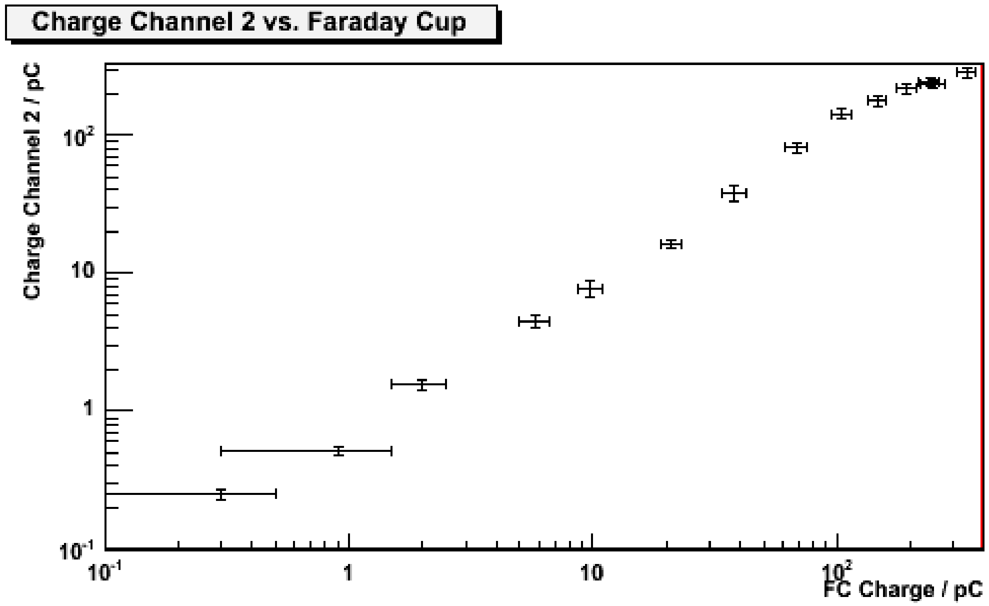
E-XFEL design

40.5 mm diameter tube

9 cm length

by the way …..





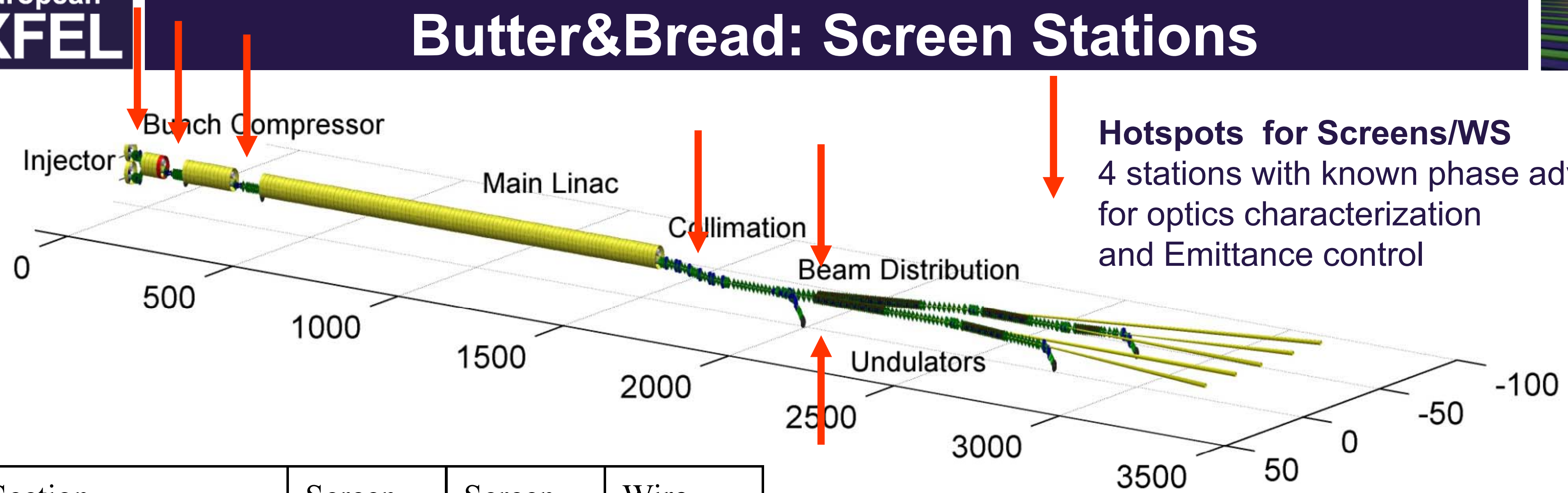
Design:

Wiebke Kleen

… this monitor can also measure the normal charge
and this with sub-ps resolution
might be the future standard charge monitor for few ps FEL operation

Coutesy: D. Lipka

Butter&Bread: Screen Stations

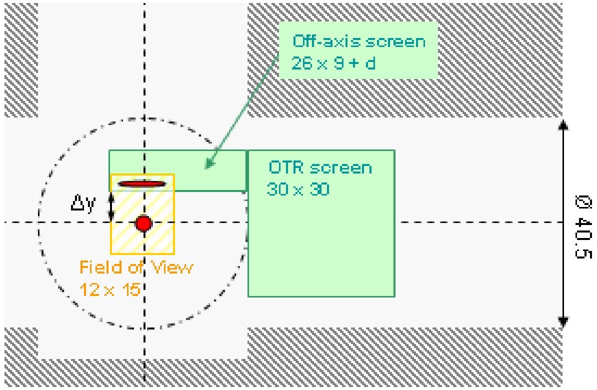


Hotspots for Screens/WS
4 stations with known phase advance for optics characterization and Emittance control

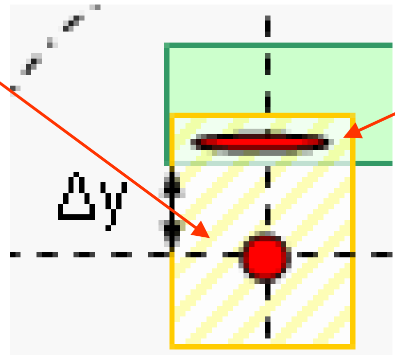
Section	Screen	Screen Off Axis	Wire-scanners (WS)
Injector	3	4	0
BC1	5	4	0
BC2	5	4	0
Collimator	4		4
Beam Distribution	3		
Undulator Lines			8
Total	**21**	**12**	**12**

XFEL uses screens and fast wire scanners
- to check and detect beam at critical places
- to match the optics and to measure emittance at
  - Injector (Screen)
  - Bunch Compressor B1 and B2 (Screen)
  - in the Collimator (Screen/WS)
  - before the Undulator (WS)
- Off Axis Screens for slice parameters with a transverse mode structure in
  - Injector
  - Bunch Compressors B1 and B2

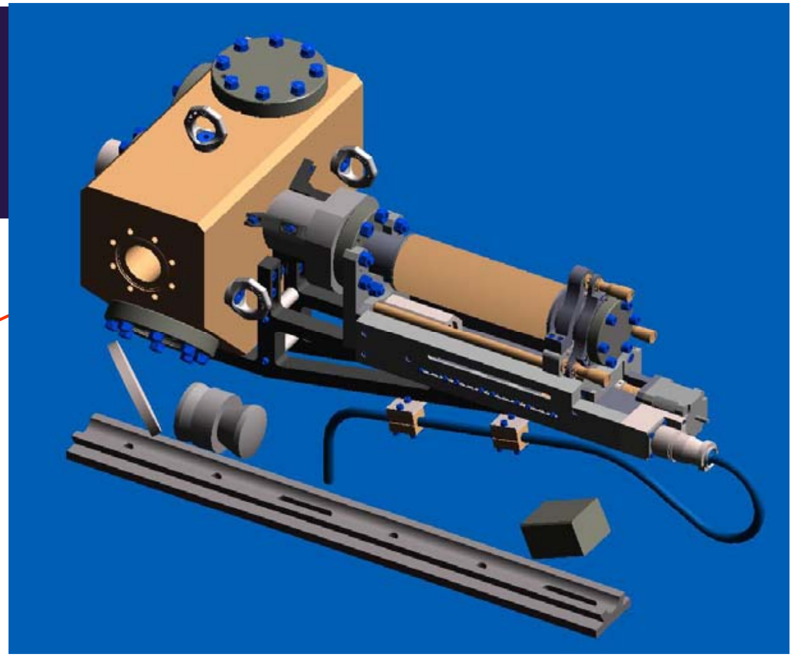
Requirement: Record On-Axis and Off-Axis (kicked/streaked) Profiles



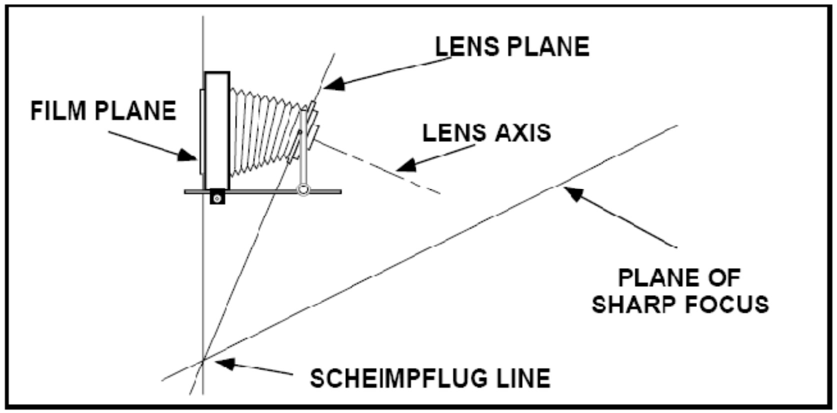
C. Gerth



Resolution 10 μm


Light Out under 45°

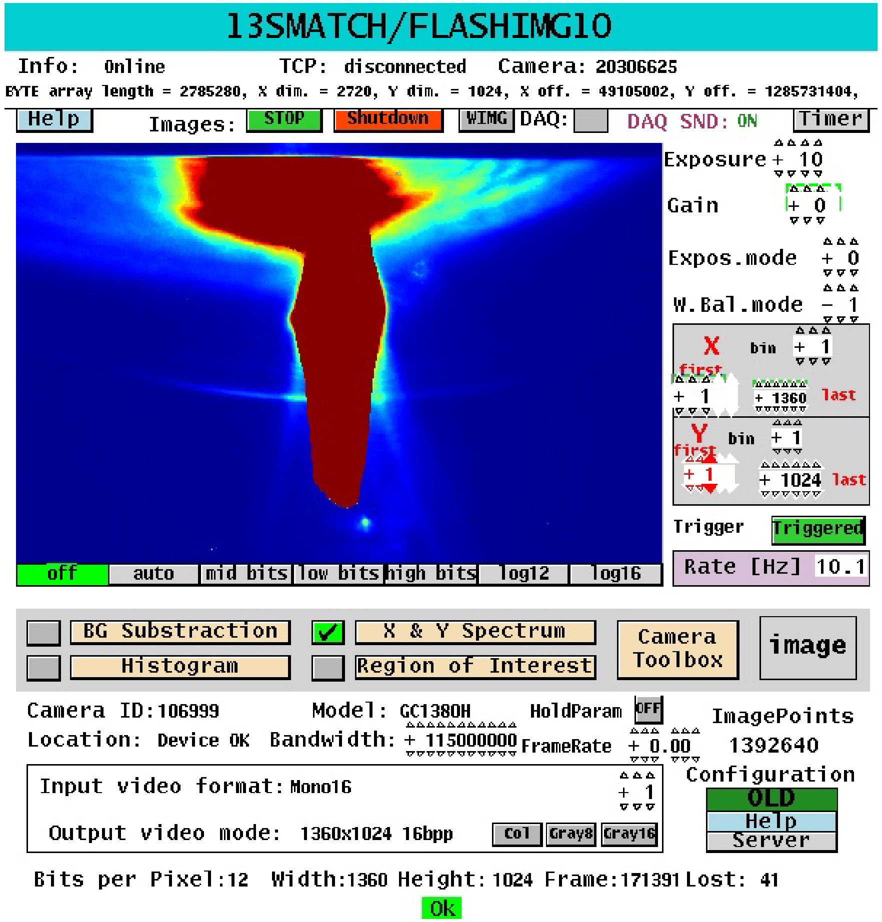
Idea: Use “Scheimpflugs” Principle
from large format photography




picture by Linhof

Get a sharp image of an entire plane,
if focus, image, and object plane cut in a single line

Problems: Coherent Transition Radiation



COTR on a Screen before FLASH Undulator

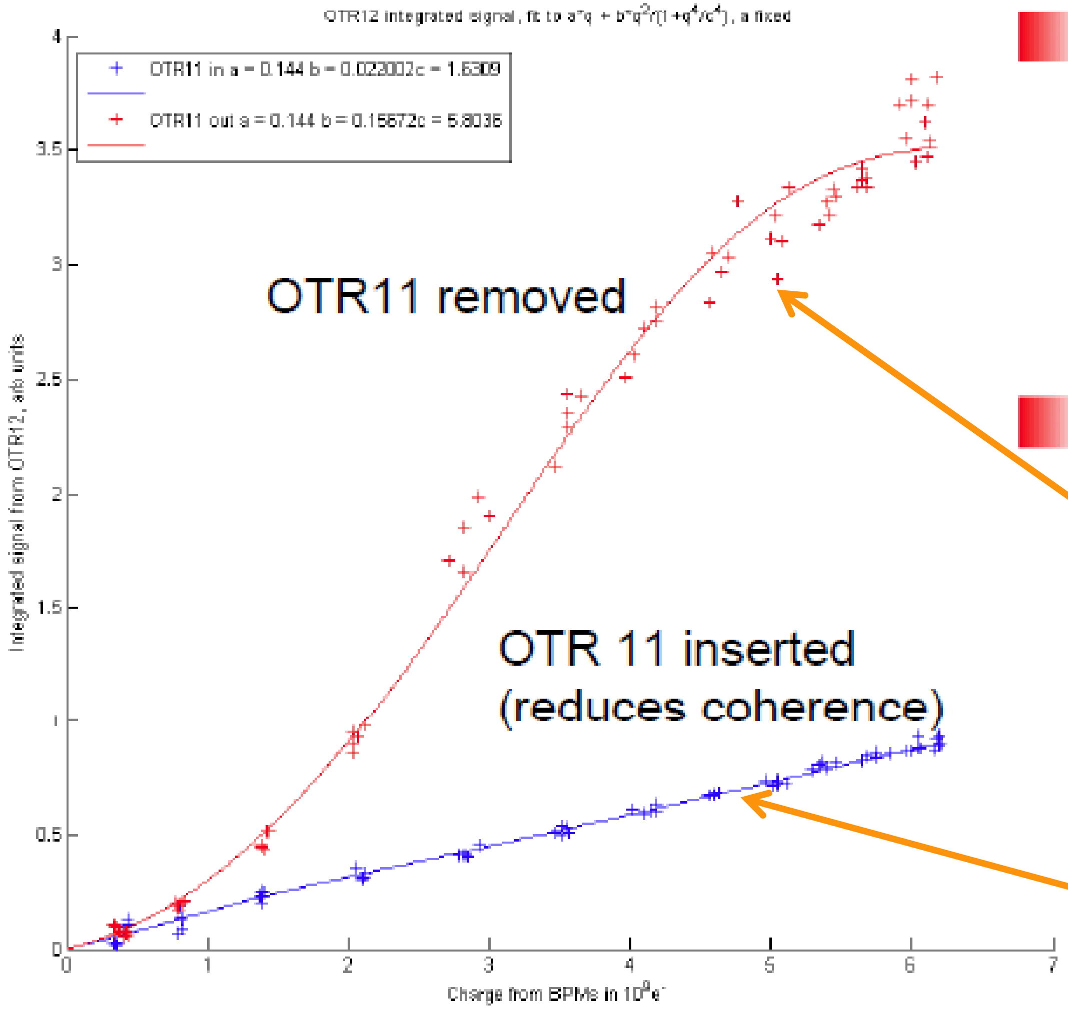
- Up to a year or so:

  OTR was The solution for screen stations!

- But Machines like LCLS and FLASH with strong, linearized bunch compression bring the coherent spectrum of the beam close to the visible spectrum.

- If the spectrum leaks into the visible OTR images get useless. ($I_{Hotspots} \sim N^2$)

Integrated Optical signal at OTR12 vs Charge



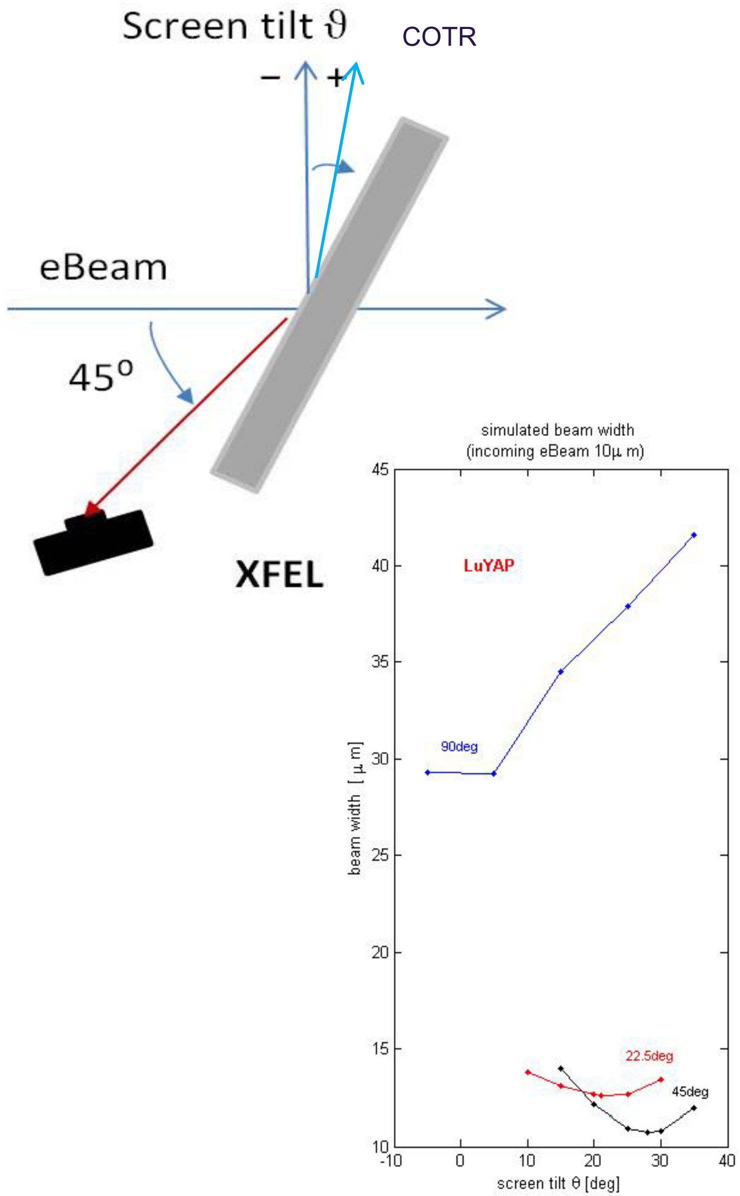
- Optical signal vs charge
  - Linear term
  - Q^2 term, attenuated above some frequency
- $P = aq+bq^2/(1+q^4/c^4)$
  - Empirical

Coherent

Spontaneous

Josef Frisch
frisch@slac.stanford.edu

Way out: Go back to Szinitlating Screens



- Simulations show:
  - 45° Geometry superior to standard 90°
  - Strange tilt of the crystal
    - → Mirrors away COTR
    - → Provides better resolution
    - → Nevertheless broadening due to volume effects cannot be avoided
  - Material candidates: LaYAP, BGO
  - Scheimpflug scheme mandatory
- Other COTR workaround:
  - Szintilator + gated camera
- Beam tests at FLASH and MAMI this spring

Courtesy: Minjie Yan, G. Kube

Machine Protection Systems & Loss Monitors

Superconducting LINACs vs. Ring Based $e^{-/+}$ Machines

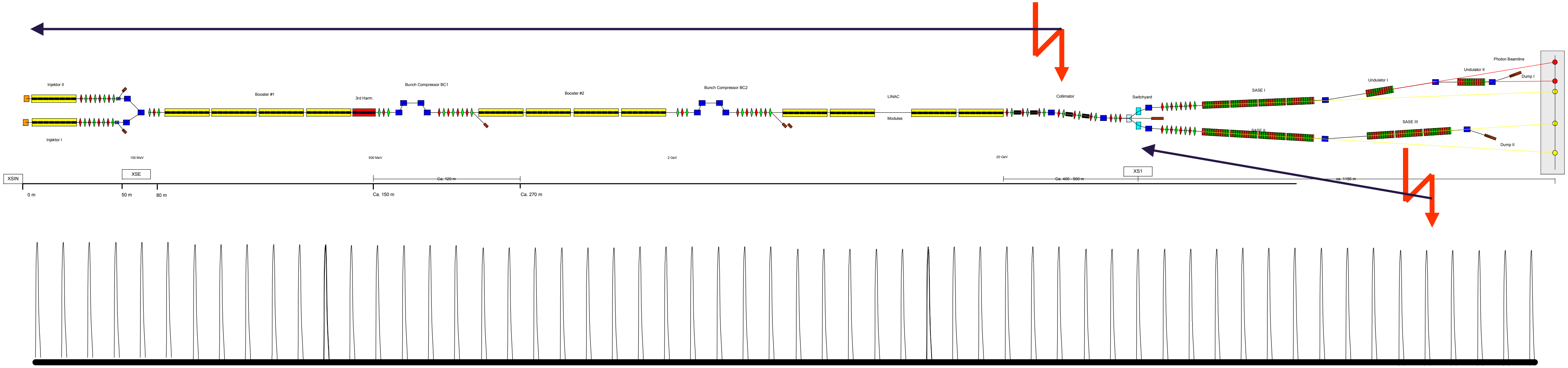
	Lightsource	HERA	FLASH/TTF2	XFEL
Energy	2 GeV	27 GeV	1.0 GeV	20 GeV
Length/ Circumference	200 m	6300 m	250 m	3300 m
<I>	200 mA	50 mA	0.00072 mA	0.00033 mA
Charge/Fill/Bunch Train	0.130 μC	1 μC	7,2 μC	3.3 μC
Beam Power $P = \langle I \rangle E$	0.4 GW	1,3 GW	7.2 10^{-5} GW	6.6 10^{-4} GW
Dumped Energy /Fill /Bunch Train	260 J	27 kJ	7.2 kJ @ 10 Hz	66 kJ @ 10 Hz

Superconducting-LINAC have zero current but transport energy!

Losses for sensitive components need to be small:

->Detection of beam loss down to 10^{-6} level! ?

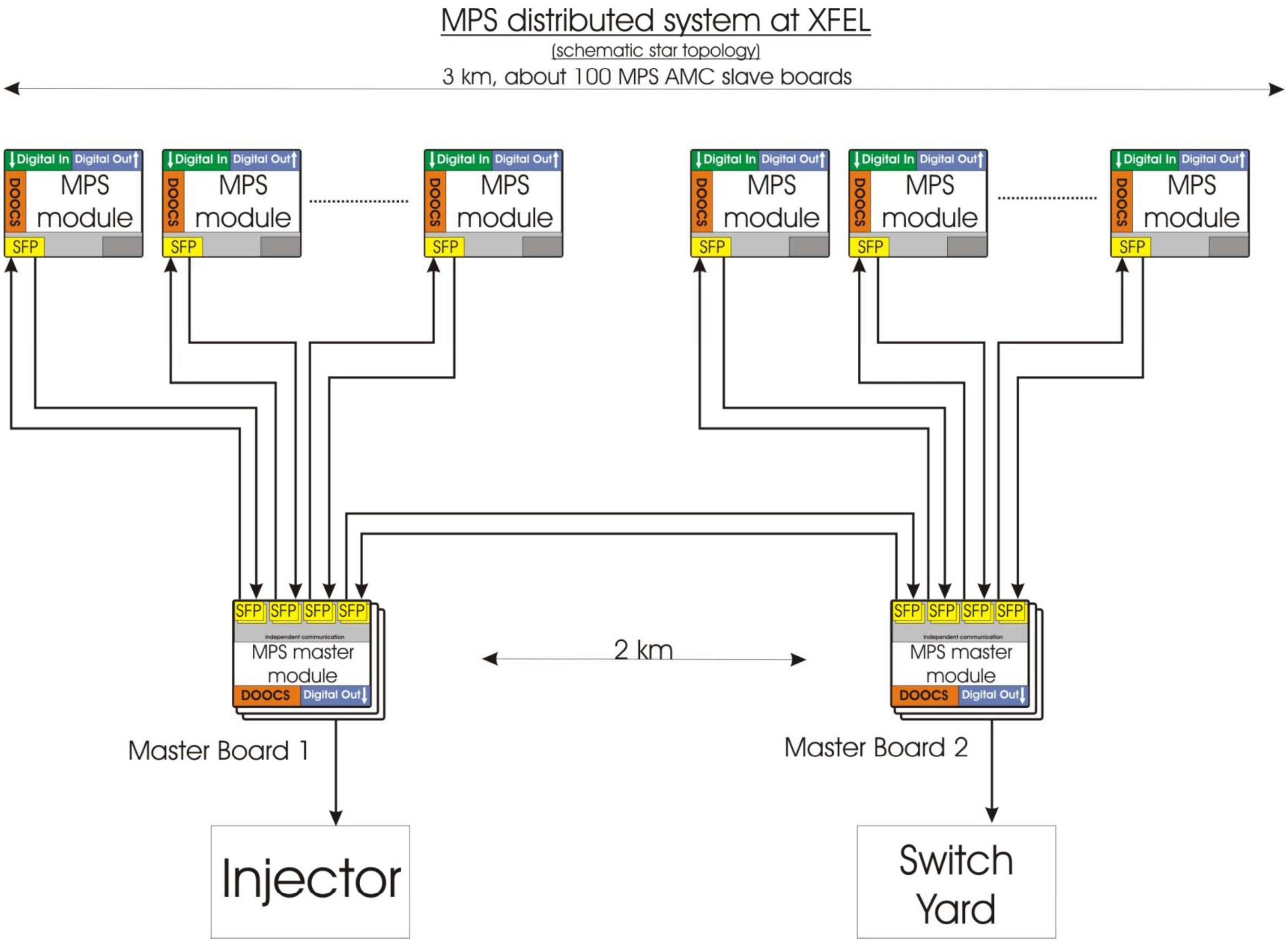
Active Systems



- Example E-XFEL -> Longitudinal scale 3 km
- Loss of Single Bunches -> No Means
- Losses within the Bunch Train -> Reaction dominated by Signal Travel
  - About 55 bunches are in the machine
  - Interlock signals have to travel to the gun to stop the beam
  - ➔ By stopping the laser
  - About 80 more bunches leave the gun during this time
  - -> Components (hopefully collimators) are hit by up to 130 bunches (2.75 kJ/135μs)
  - -> Or: Need tools to stop beam not only at the gun
    - -> Emergency Dump in the Switchyard (600 m to Dump + 1μs for Kicker) (up to 30 Bunches, < 1 kJ/10μs)

Need passive systems (collimators) in addition!

MPS: Electronics Backbone
A Distributed Intelligent „Or“ Gate

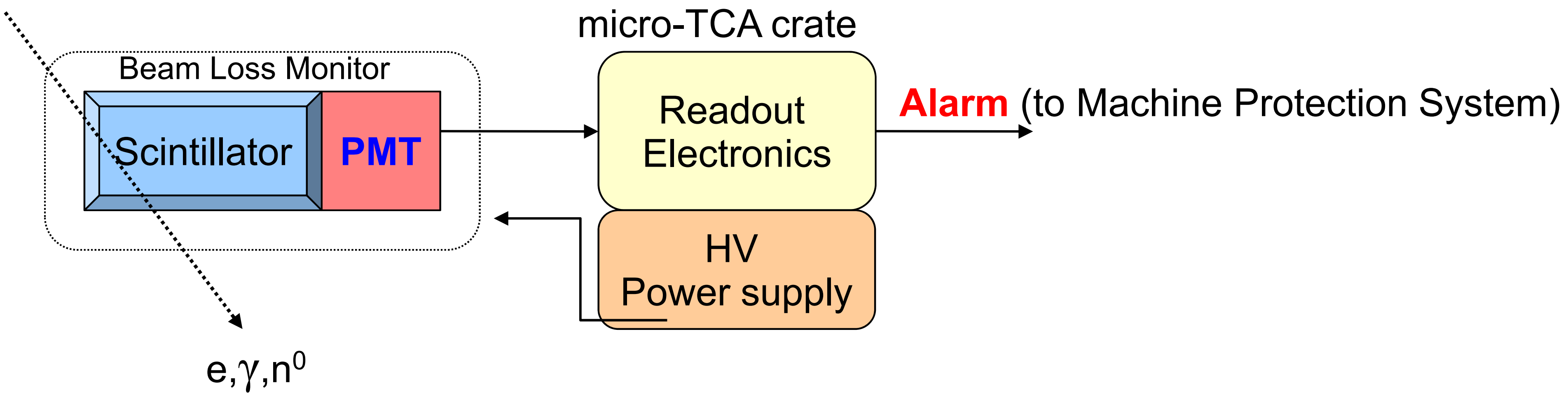


Coutesy: S. Karstensen

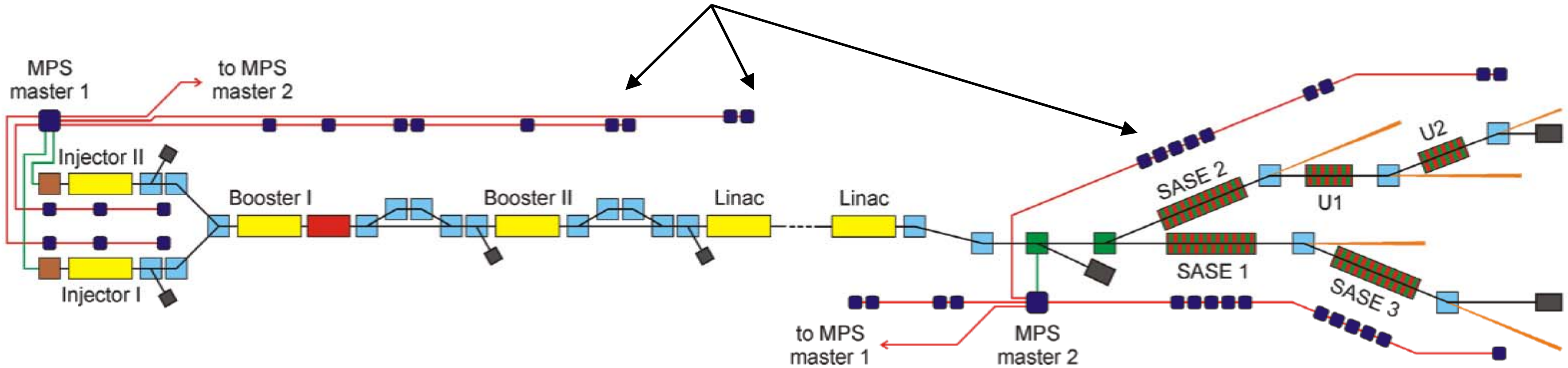
MPS: Sensors and Actors

- XFEL System based on the FLASH Experience
- Sensors connecting to the MPS
  - Beam Loss Monitors
  - Transmission Monitors
  - RF signals, like coupler interlocks, Spark Detectors …
  - Status Signals
    - → Valves, Screens, RF Stations, Wire Scanners, Magnets
  - Mode Information
    - → Magnets, Valves
- Actors connected to the MPS
  - Photo-Injector Laser
  - Gun
  - RF Stations
  - Distribution and Abort Kickers

Sensors: Beam Loss Monitors



~300 Beam Loss Monitors (More than half – in undulator area)



Coutesy: A. Kaukher

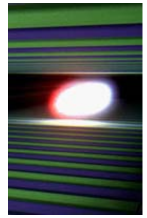
Longitudinal Methods
Bunchlength and Compression

Requirement: Resolve Structures of 100 fs and less

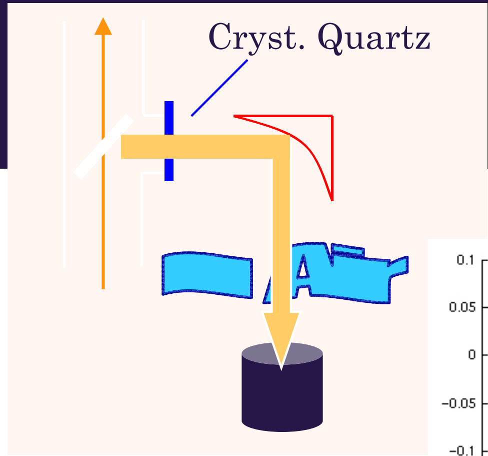
- Qualitative: Optimization of the Compression
  - Emission $\approx n^2$ for $\sigma_s \leq \lambda$
    - Phase Tuning by maximizing coherent FIR Emission
    - Use of simple Pyro-Detectors in the FIR
    - Useful for Tuning / Feedback (on RF-Phase)

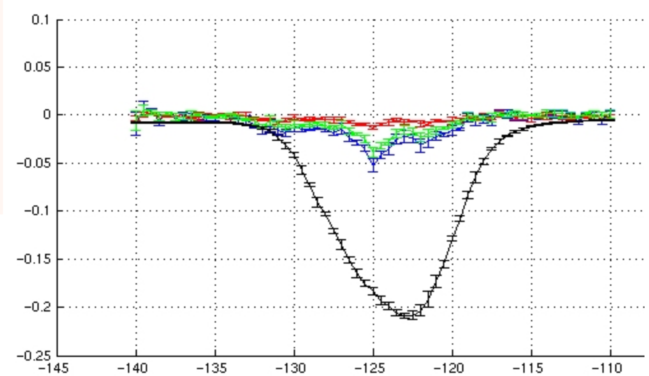
- Quantitative: Measurement of Bunch Length
  - Use coherent FIR Radiation and Autocorrelation Methods.
  - Transverse Mode Cavity (integrated Streak Camera)
  - Electro-Optical-Sampling
  - Optical Replica
  - All are more complicated -> no online Tools (currently)

Compression Monitors

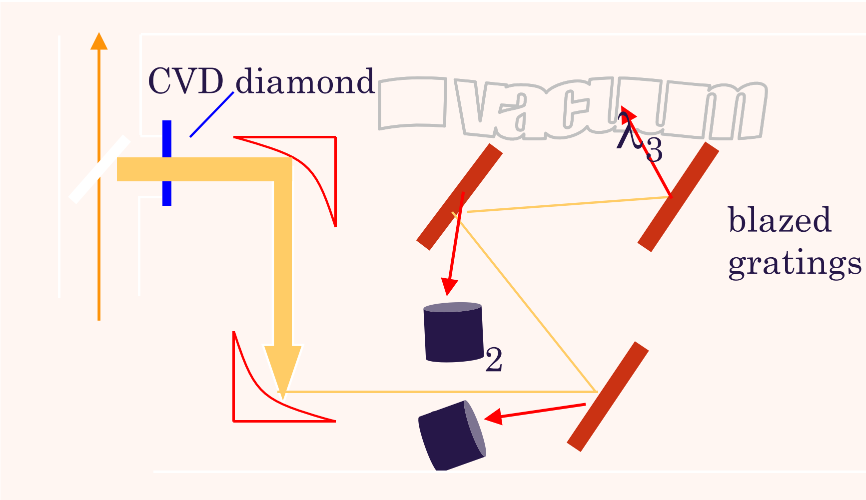


- The 'classical' compression monitor
  - integral intensity, > 100 µm
  - overall compression strength
  - robust, simple, workhorse
  - all bunches
  - used to feedback
- The 'advanced' compression monitor (EPAC, H.Delsim-Hashemi)

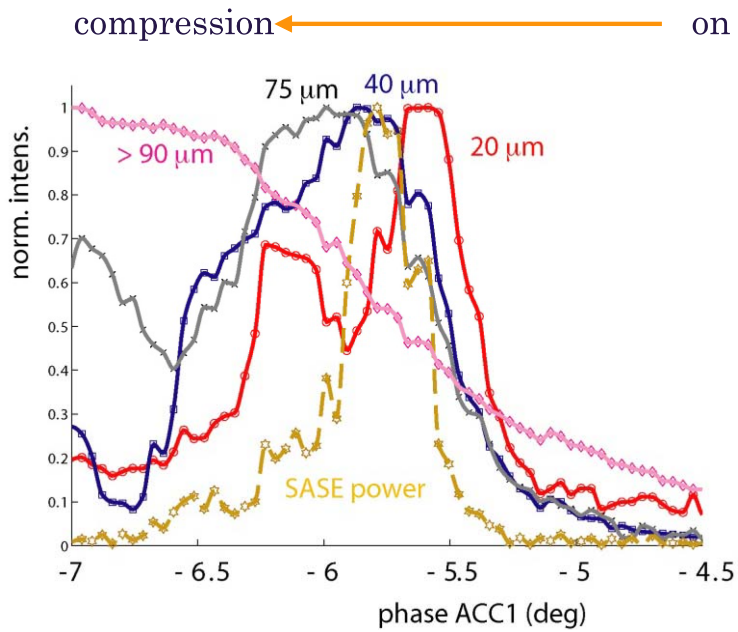




A BCM phase scan (FLASH), CTR single bunch kicked from train

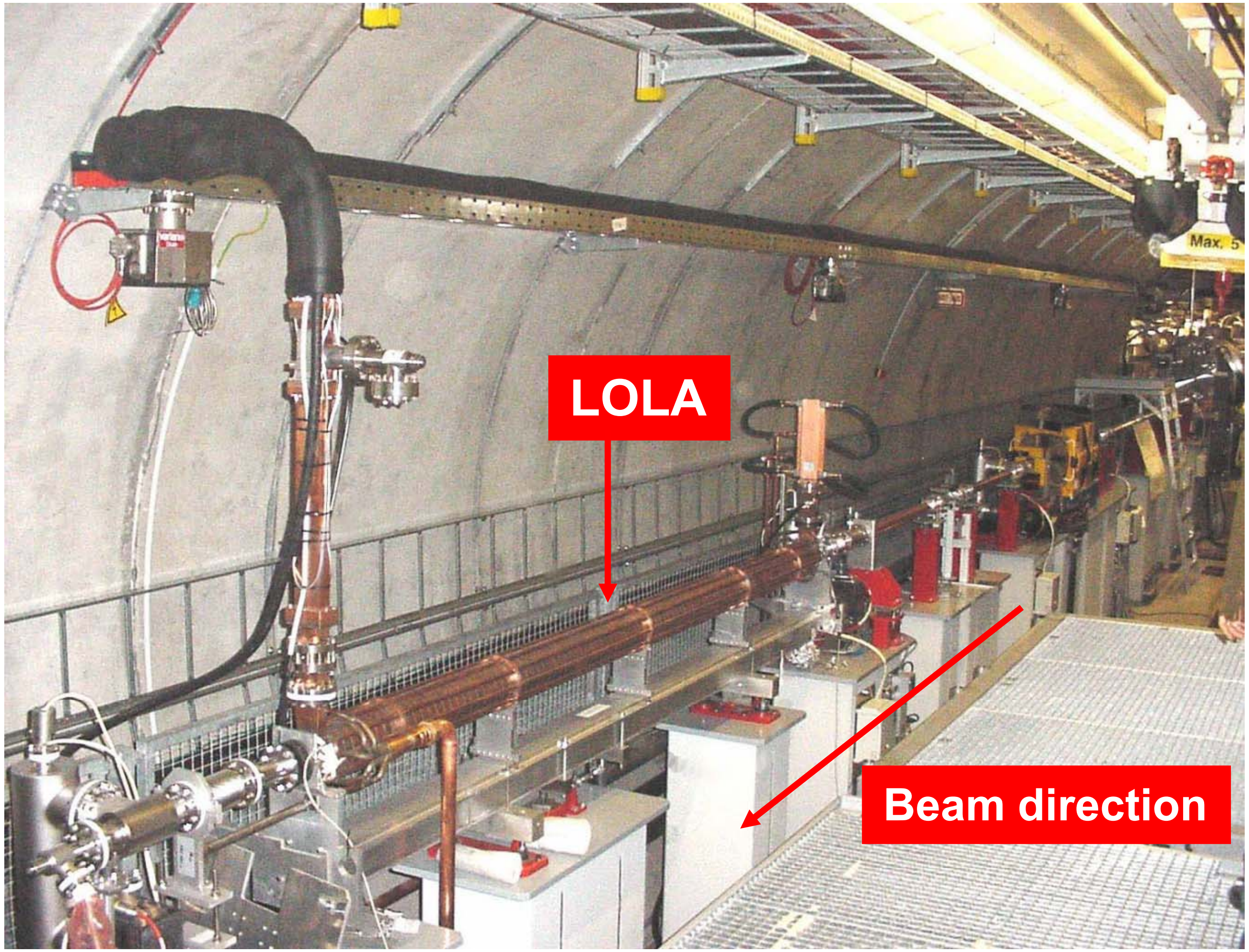


- wavelength specific intensity (bands)
- reveals 'long. features' of the bunch
- complex, still experimental



Coutesy: B. Schmidt

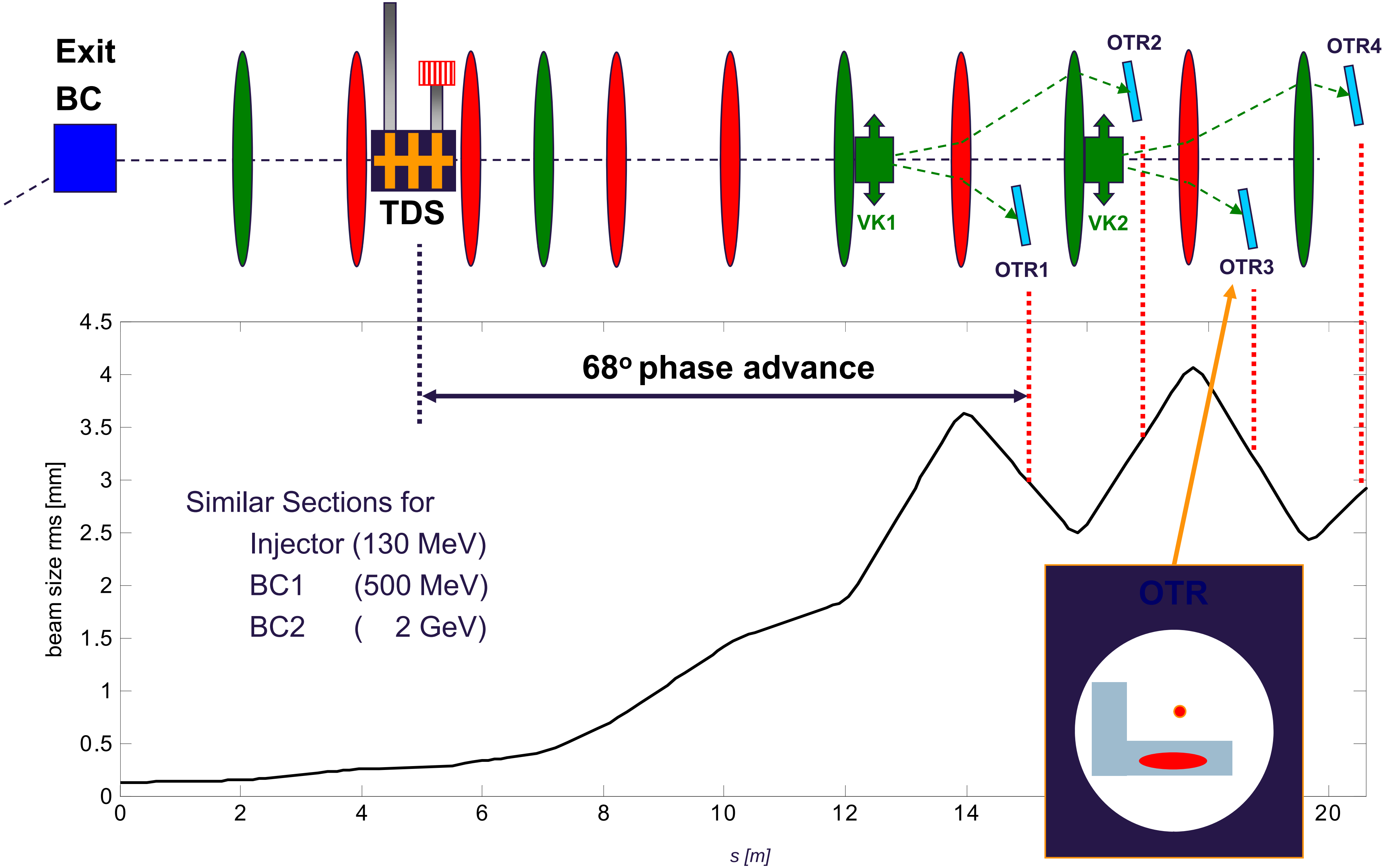
Transverse Mode Structures: LOLA



- Almost 50 year old idea
- Installed in 2003, Collaboration DESY-SLAC
- Travelling-wave, constant impedance, Frequency: 2.86 GHz
- Length: 3.6 m
- Maximum deflecting voltage ~ 25 MV @ 20 MW input power
- Similar systems work at LCLS

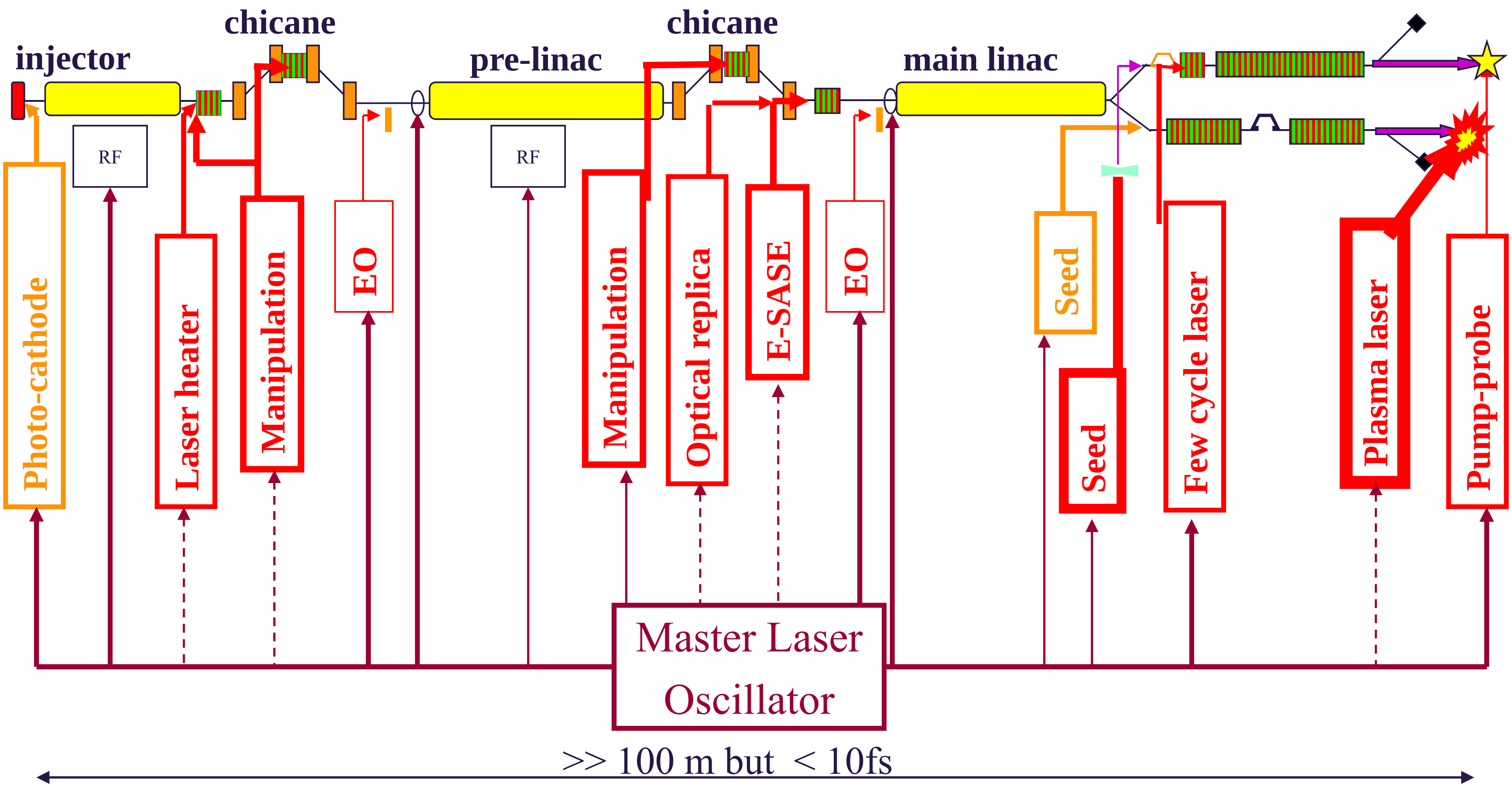
Coutesy: C. Gerth

Extension to the 4 Screen Principle



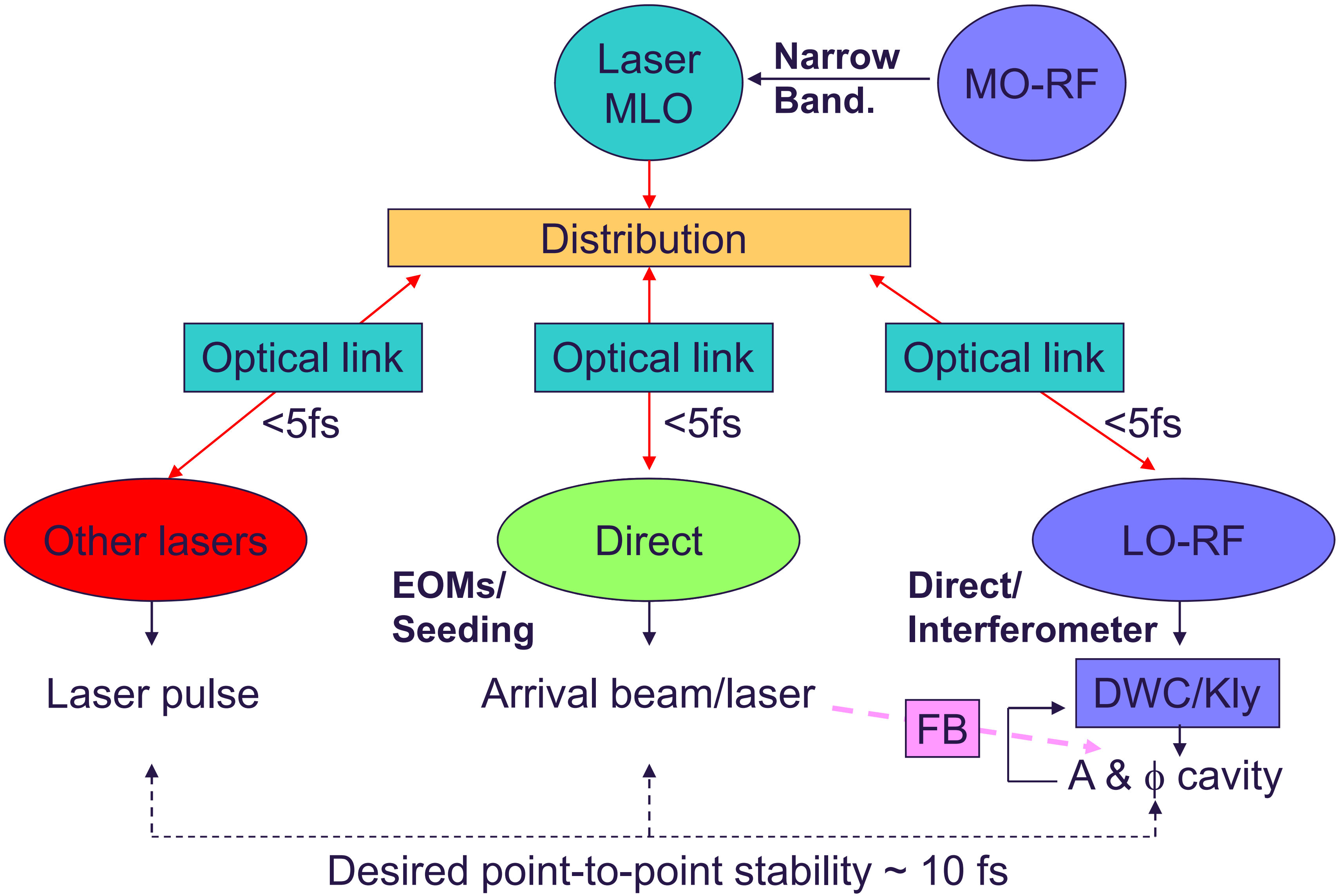
Coutesy: C. Gerth

… very special: Laser based Stuff, eg. Synchronisation and Arrival Time



Coutesy: H. Schlarb

Optical synchronization system



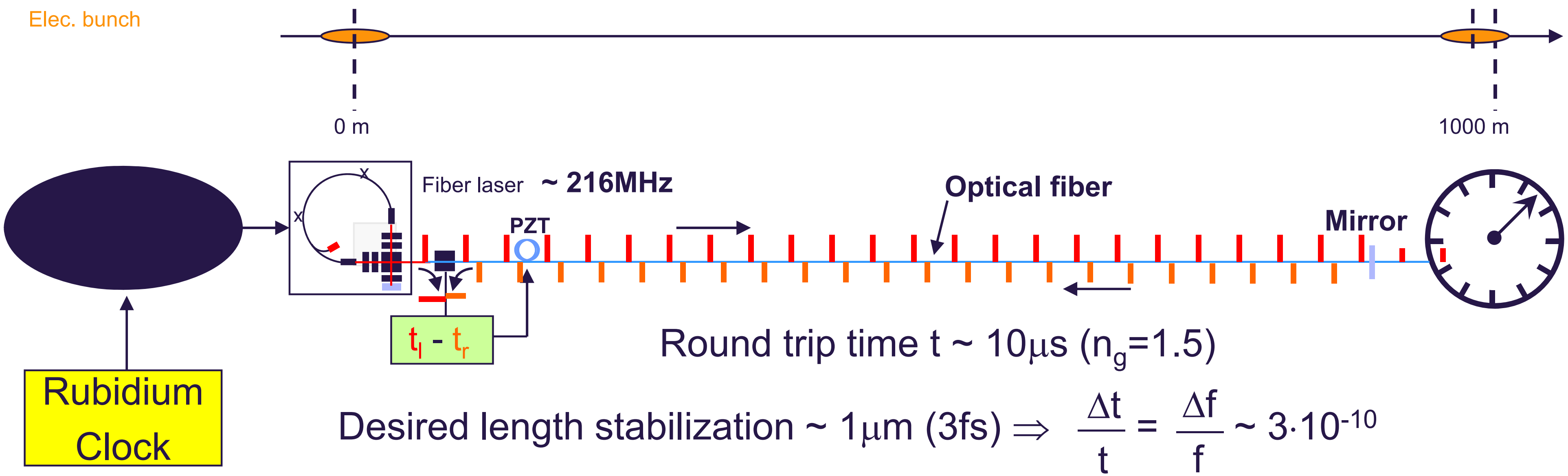
Main issue: robustness, stability and maintainability ⇒ Prototype at FLASH

Coutesy: H. Schlarb

Synchronization using a pulsed Laser

Synchronization: Desired accuracy ~ 10 fs!

2) Synchronization using fiber lasers



Round trip time t ~ 10μs (n_g=1.5)

Desired length stabilization ~ 1μm (3fs) $\Rightarrow \frac{\Delta t}{t} = \frac{\Delta f}{f} \sim 3 \cdot 10^{-10}$

Fiber laser provides excellent stability on short time scales

But drifts due to environmental changes over long time scales

Requires locking of the fiber laser to cheap atomic clock

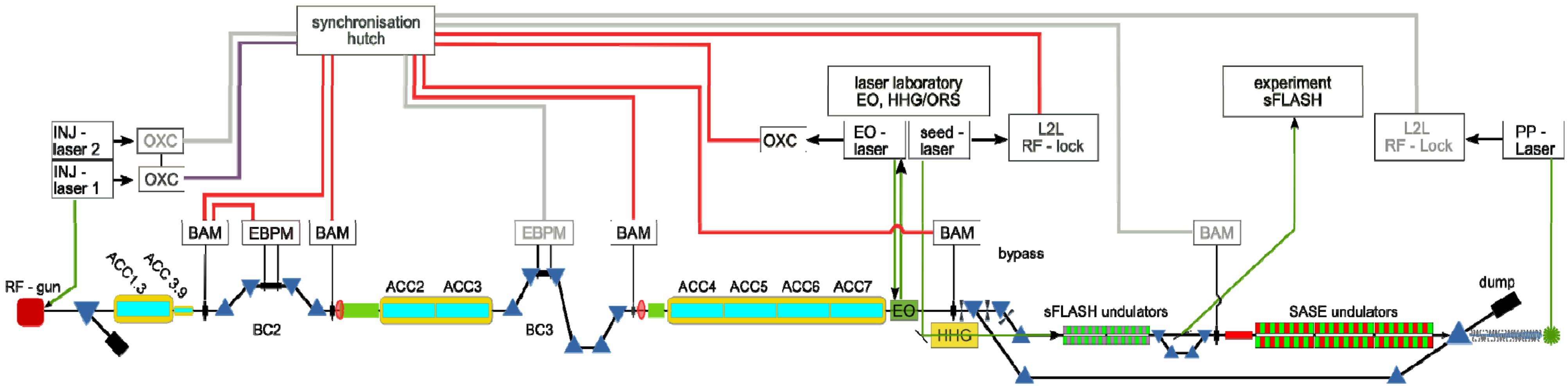
Timing drifts with respect to external clock may occur

BUT all synchronized sub-systems drift together => phase stability

Coutesy: H. Schlarb

European XFEL

Overview for FLASH



- 2 master Laser Oscillator (RF locked to MO)
- Free space distribution system to 16 ports
- Optical Links: 6 stabilized using OXC & 1 passive
- Front-ends
    - 4 Bunch arrival time monitors (BAM)
    - OXC for INJ / TiSA lasers
    - RF locked for TiSA (HHG)

Courtesy: M. Bock

European XFEL

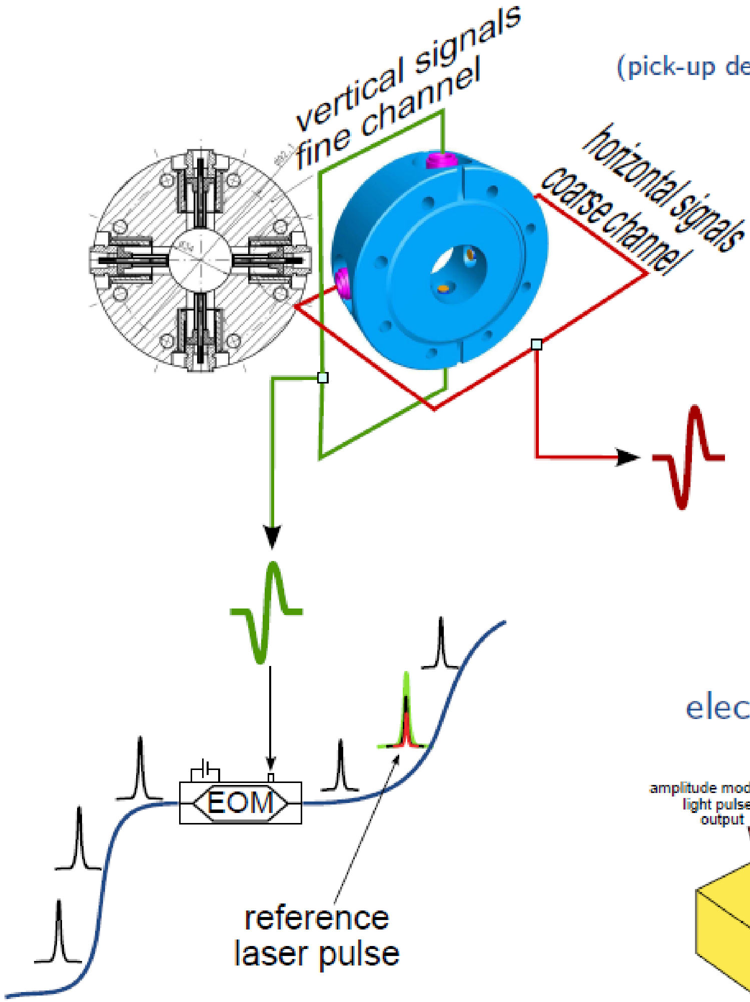
Beam Arrival Monitor

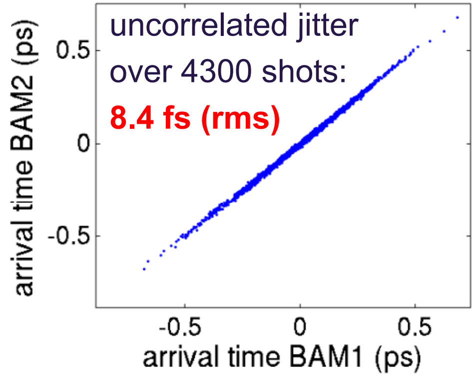
(pick-up design drawing, courtesy: K. Hacker)

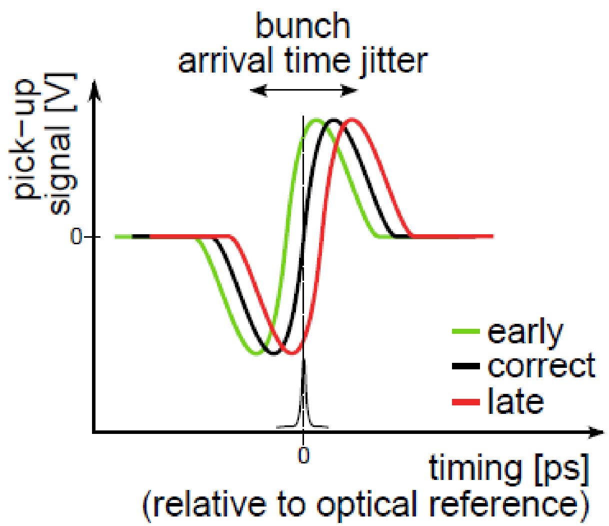
reduced dependency on beam orbit

reduced dependency on bunch charge

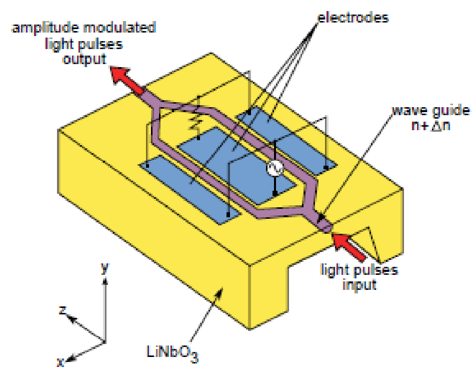
sensitivity in terms of
% modulation per fs timing change







electro-optical modulator

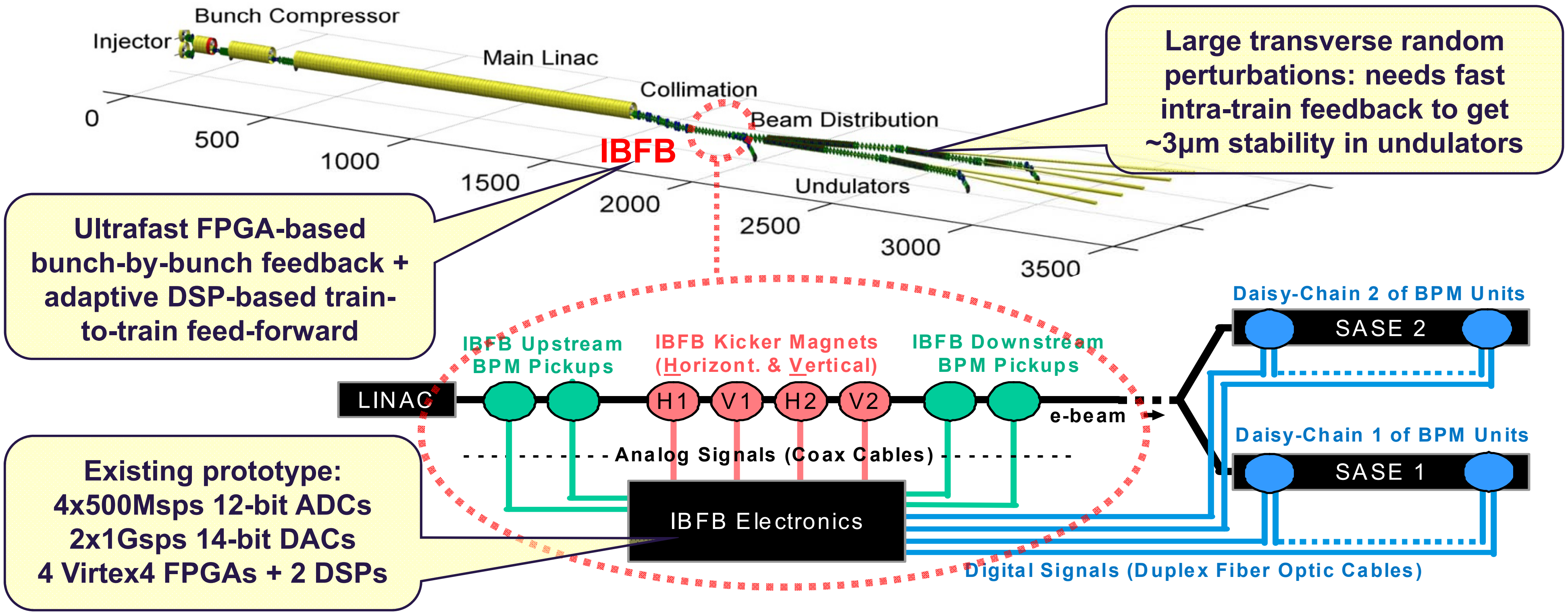


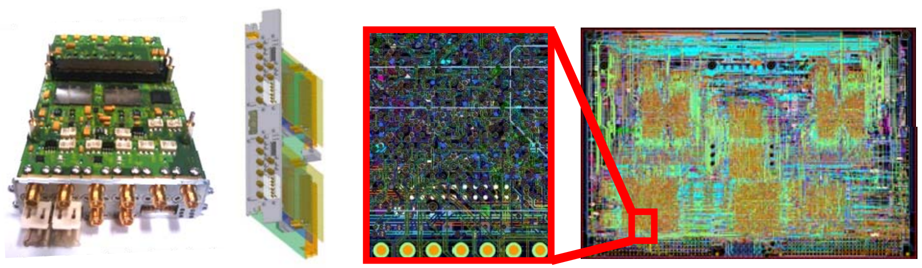
Coutesy: H. Schlarb

Some Words on Feedbacks

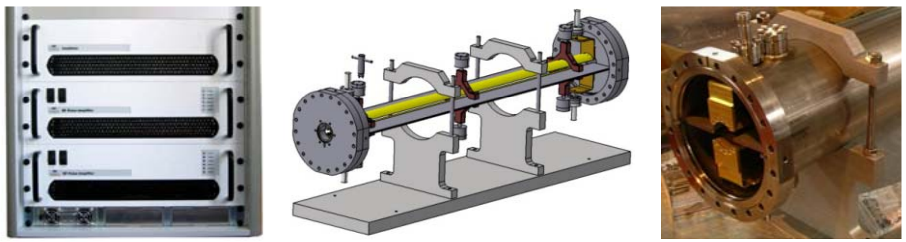
- Today Diagnostics goes digital
- Fast digital links are standard technology
- Therefore, almost all diagnostics devices can be used as input for fast feedbacks (if a fast link is foreseen)
- Examples from XFEL/FLASH
  - Fast Intra Train Feedbacks
    - → Orbit Straightness over the pulse
  - Beam Based Feedbacks on
    - → Energy
    - → Arrival Time

Intra-Bunchtrain Feedback (PSI Contribution)





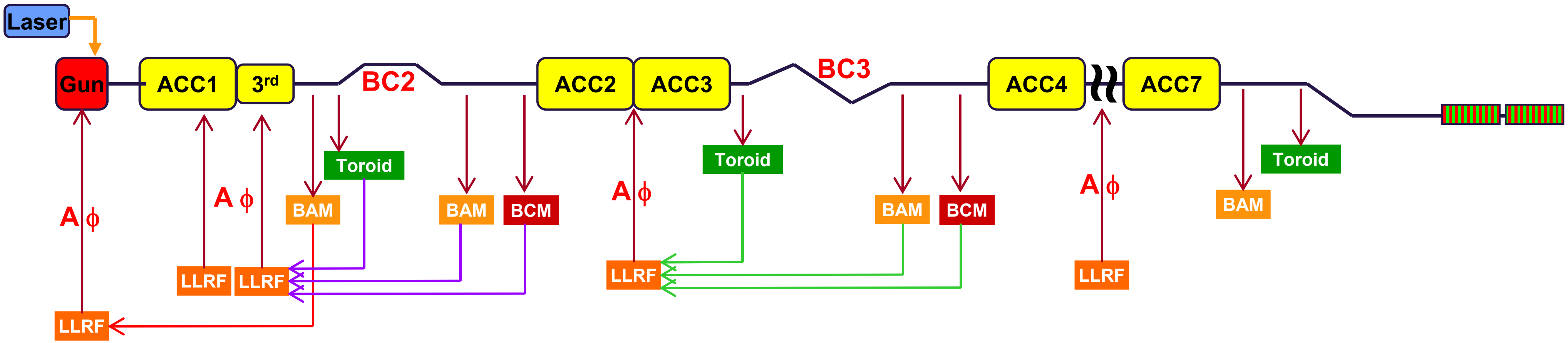
Low-Latency BPM & Signal Processing Electronics



High-BW Stripline Kicker Magnets & Power Amps

Coutesy: B. Keil

Beam based feedback: Energy/Phase/Arrival time feedback



Beam Based Feedbacks:

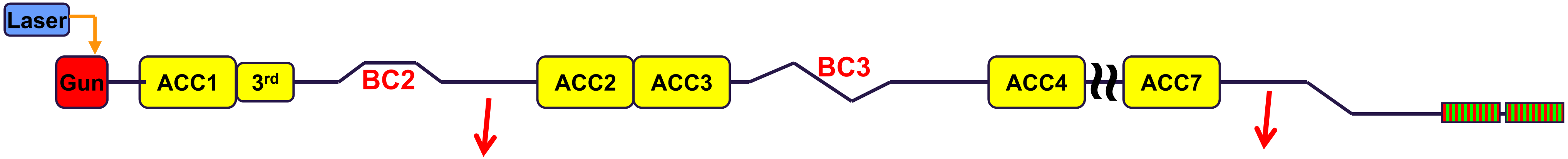
- BAM before BC2 corrects phase in RF-Gun
- BAM and BCM after BC2 simultaneously correct amplitude and phase in ACC1 and 3rd harmonic
- BAM and BCM after BC3 correct amplitude and phase in ACC23

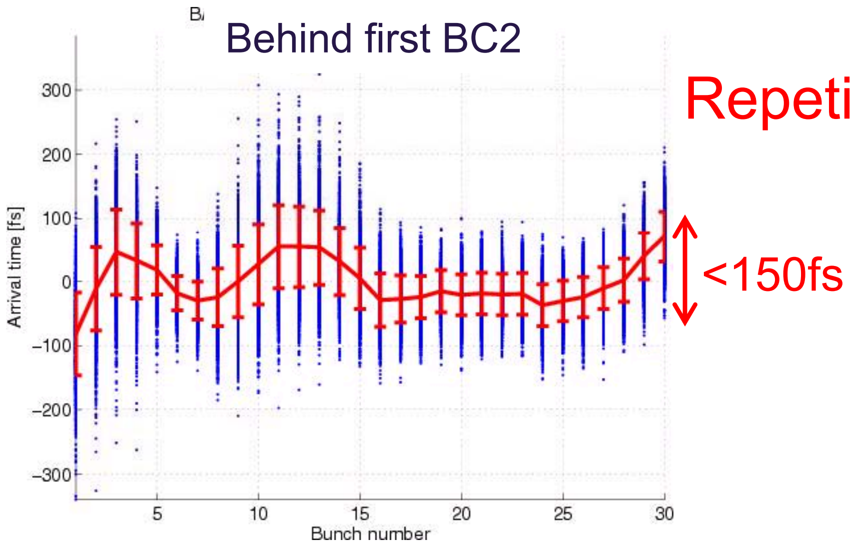
Results from BBF running at BC2

Coutesy: H. Schlarb

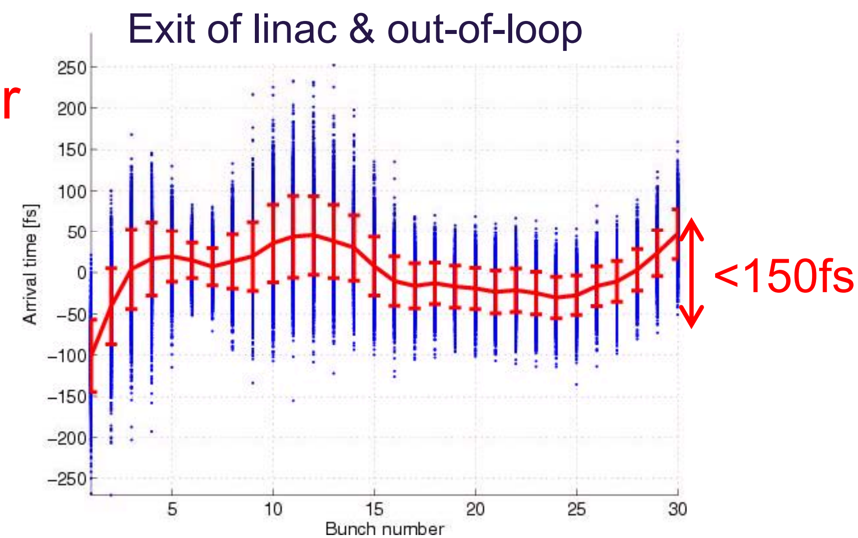
European XFEL

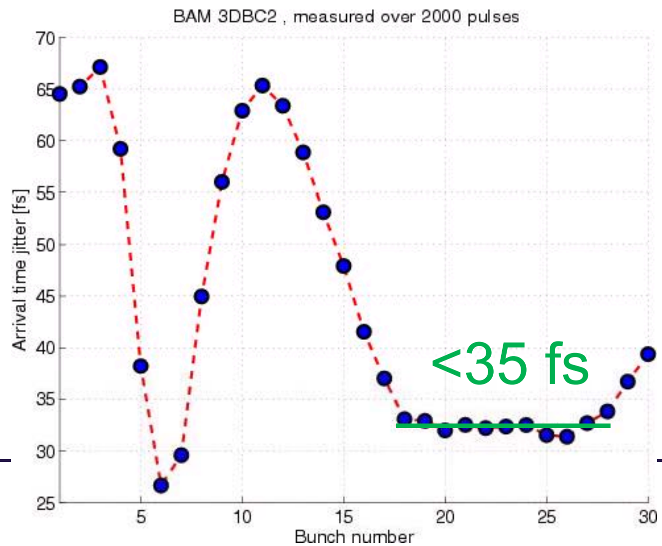
Beam based feedback: most recent results





Repetitive error

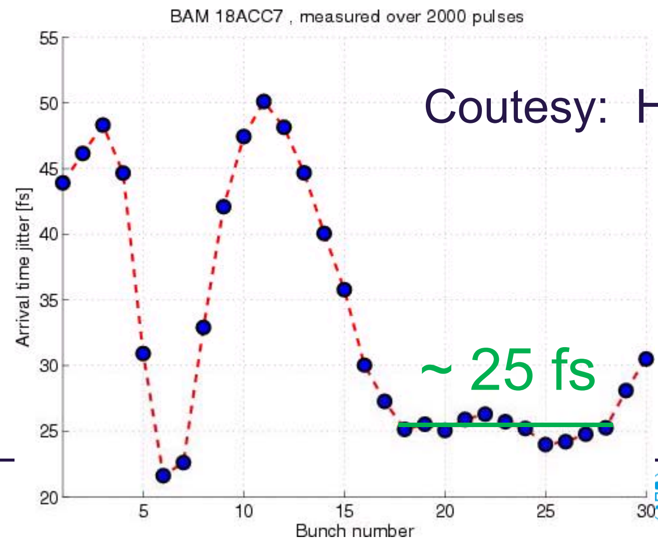




Bunch jitter

2000 shots

(3.5 min)



Coutesy: H. Schlarb

Conclusions

We had

- What is a Free-Electron-Laser Facility?
- What are the demands to the diagnostics?
- What is special for (SASE) machines?
  - ➔ Single bunch
  - ➔ High duty Cycle
- Small Selection of Systems
- A little bit of Feedback

Thank you very much for your attention ….

… and I would like to thank all the colleagues for providing material and their help for the preparation of the talk, specially (arbitrary order):

- W. Decking
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- H. Tiessen
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- P. Vetrov
- P. Göttlicher
- V. Krivan
- K. Rehlich
- A. Brenger
- R. Neumann
- N. Wentowski
- D. Lipka
- M. Staack
- S. Wesch
- B. Faatz
- R. Bakker
- V. Gharybian
- H.C. Schröder
- G. Kube
- S. Karstensen
- K. Wittenburg
- C. Behrens
- M. Bock
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- J. Frisch
- B. Schmitt
- R. Treusch