MDI
Maschine, Diagnose und Instrumentierung

Detector Needs for Machine Physics

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Contents

- Accelerators from users point of view
- Requirements on machine diagnostics
- Beam monitors
- Machine operation
- Summary
  - Will talk mostly about FLASH

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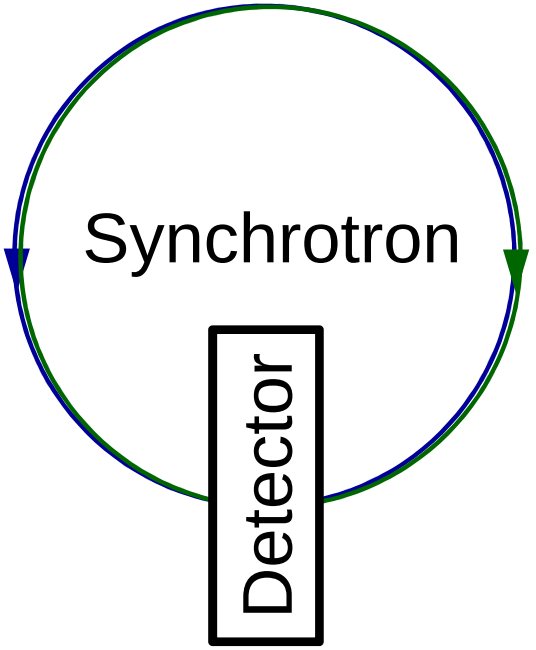
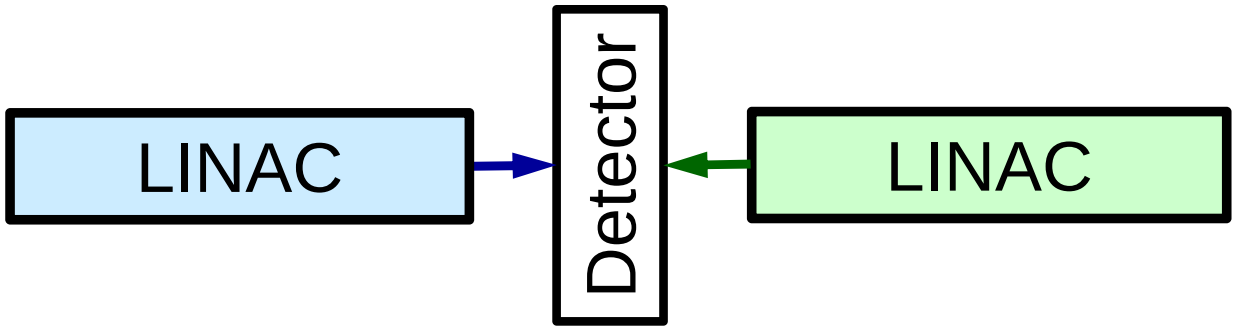
User Needs: Particle Physicists

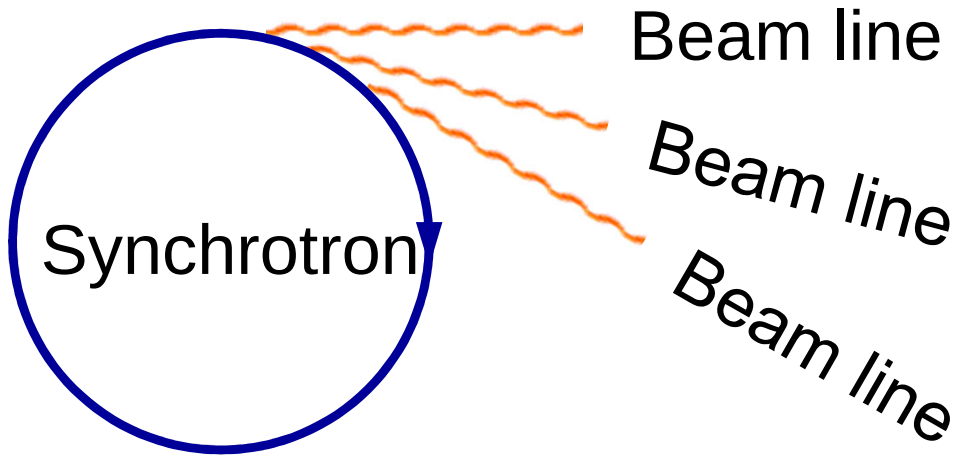
- Want to study physics for certain
  - particle types
  - energy
  - beam current and structure
  - cross-section
  - polarization etc.
- From here result the needs
  - for the detectors [your job]
  - for the accelerator
    - including the needs for machine diagnostics



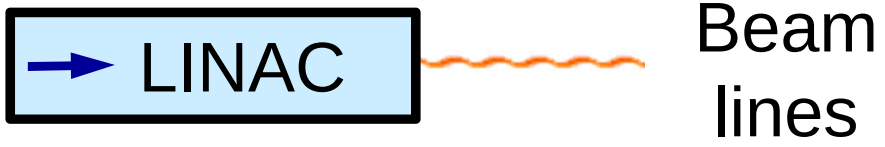


User Needs: Photon Scientists

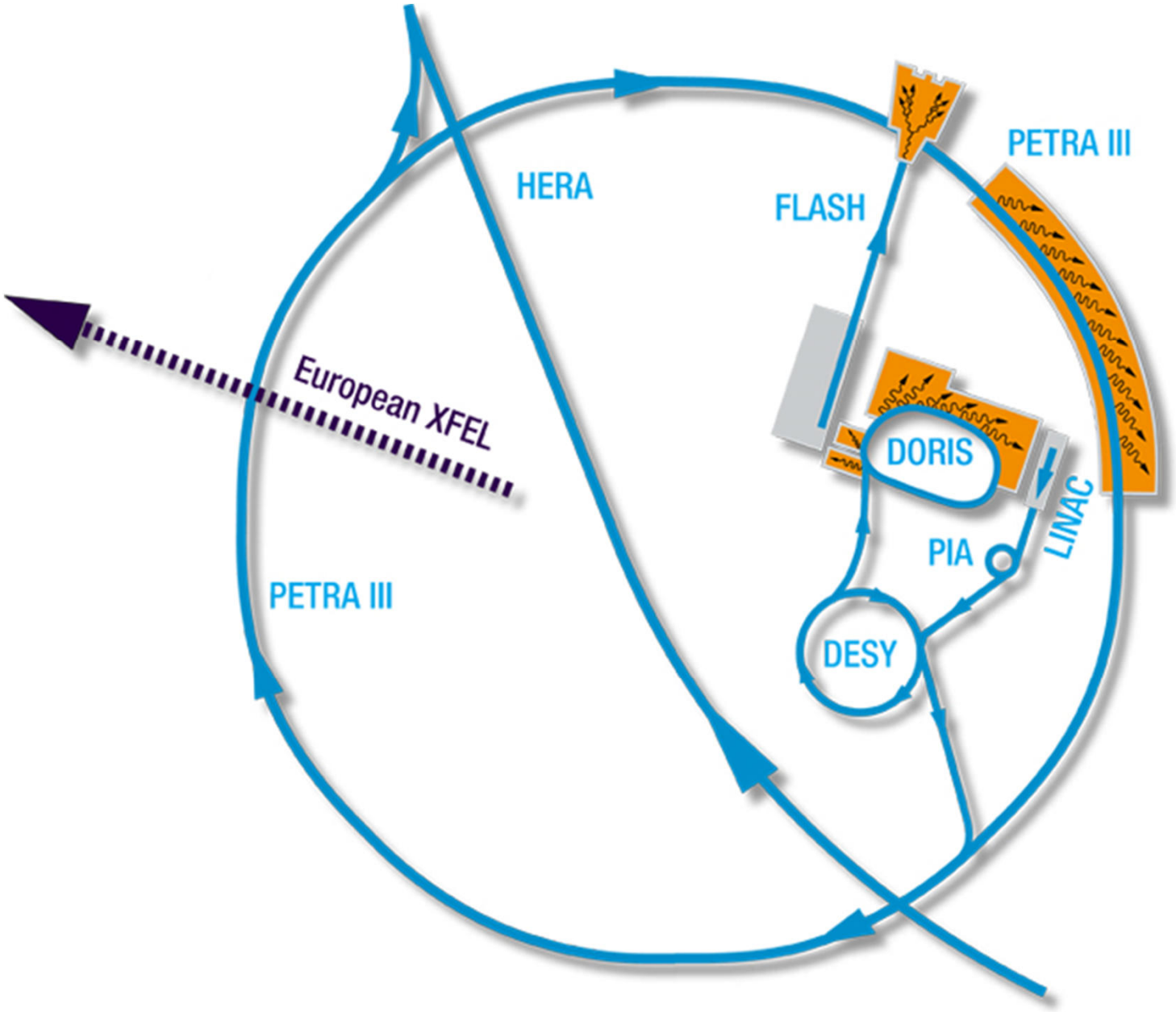
- Want radiation with certain
  - wavelength (range) / energy
  - brilliance
  - size
  - possibility to study dynamic processes
  - etc.



- From here result the needs
  - for the detectors [your job]
  - for the accelerator
    - including the needs for the machine diagnostics



Accelerators at DESY



Also groups involved in the LHC and the ILC

Requirements on Machine from Users

Particle Physics	Photon Science	Machine
Particle type, energy	Depend on source: SR, wiggler, undulator, FEL	
CM energy	Wavelength	Beam energy *E*
Beam current	Photon beam energy	Beam current *I* / bunch charge *q*
Transverse size, emittance	Source size	Beam size σ_x, σ_y, emittance ε_x, ε_y
Transverse beam position	Source location	Transverse beam position *x, y*
Bunch length	Photon beam length	Bunch length σ_z
Low background		Keep track of beam losses
Etc.	Etc.	

- In the following: **beam = charged particle beam**

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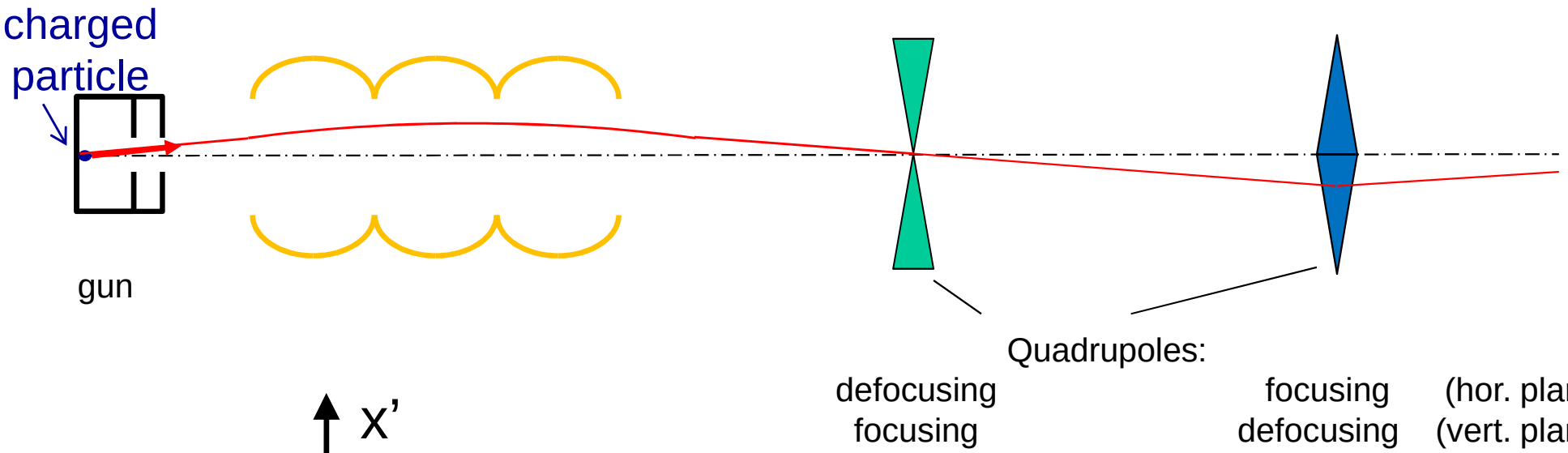
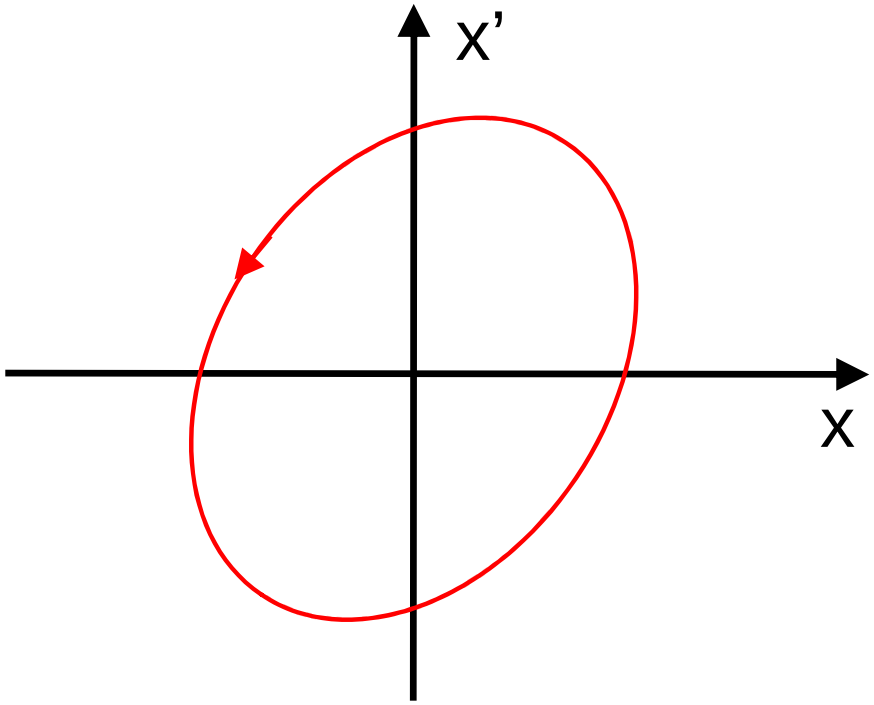
Requirements on the Machine Diagnostics

- Requirements from Users
- Additional requirements
  - Machine protection
    - Keep track of losses
    - Dump the beam safely
  - Keep machine stable
    - Feedbacks
    - Be able to tell what happened / changed
- You (detector designers)
  - take care of the diagnostics from the interaction point or photon source onwards
- We (machine diagnostics people)
  - take care of the diagnostics in the rest of the accelerator, including the pre-accelerators

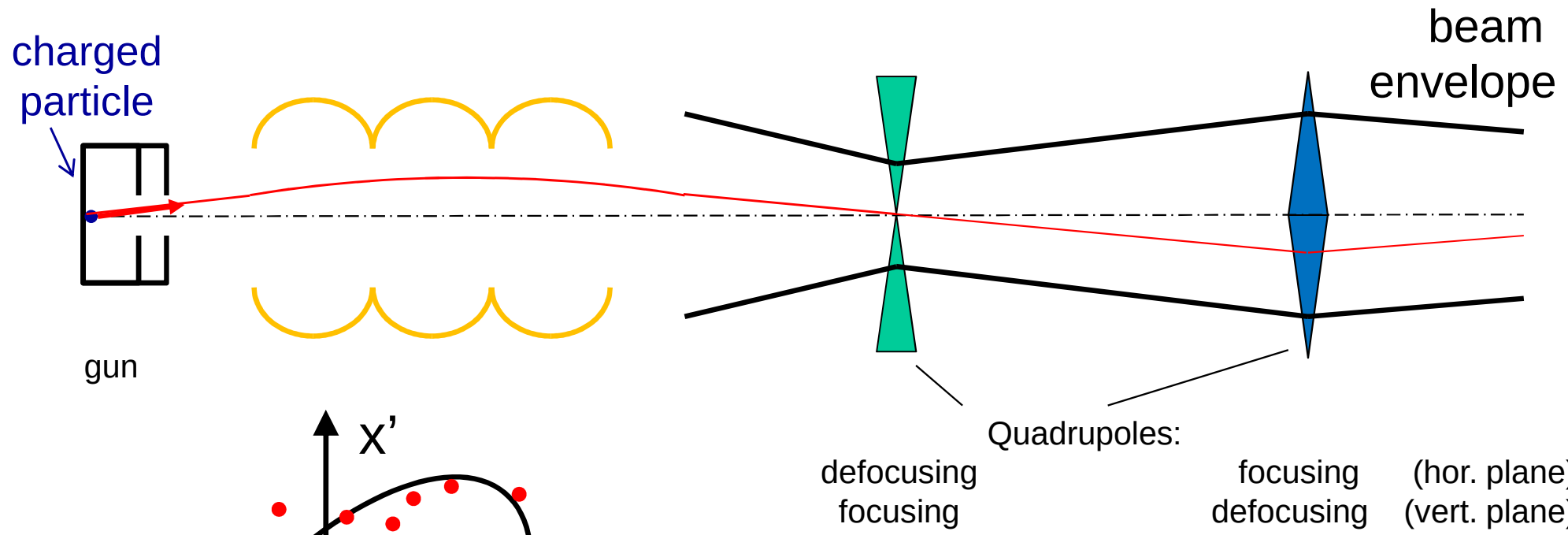
Betatron Oscillations

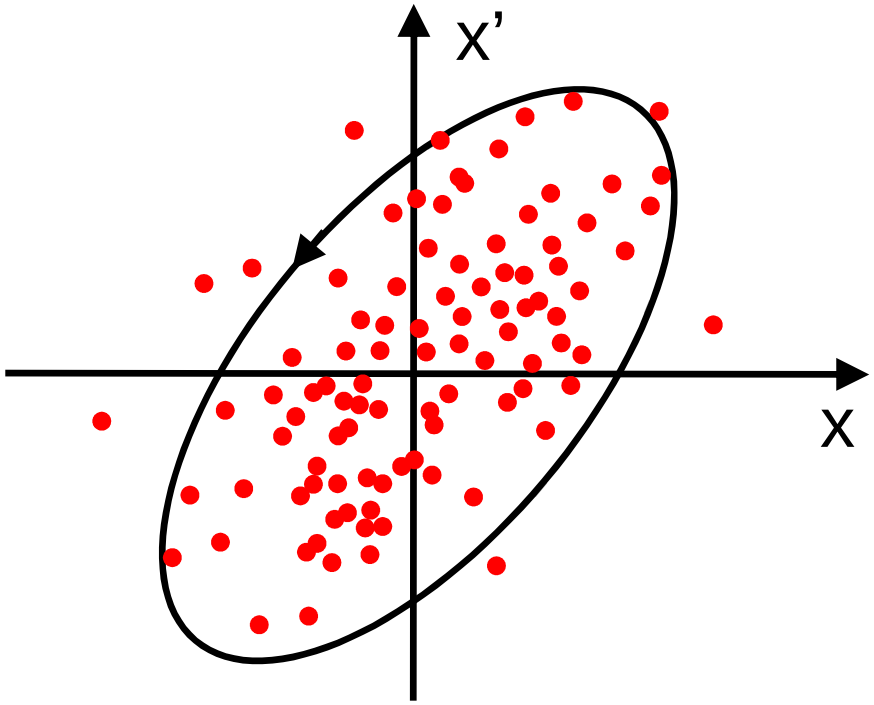




- Particle oscillates around golden orbit
  → betatron oscillations
- Trajectory is an ellipse in phase space (x, x')

Beam Emittance

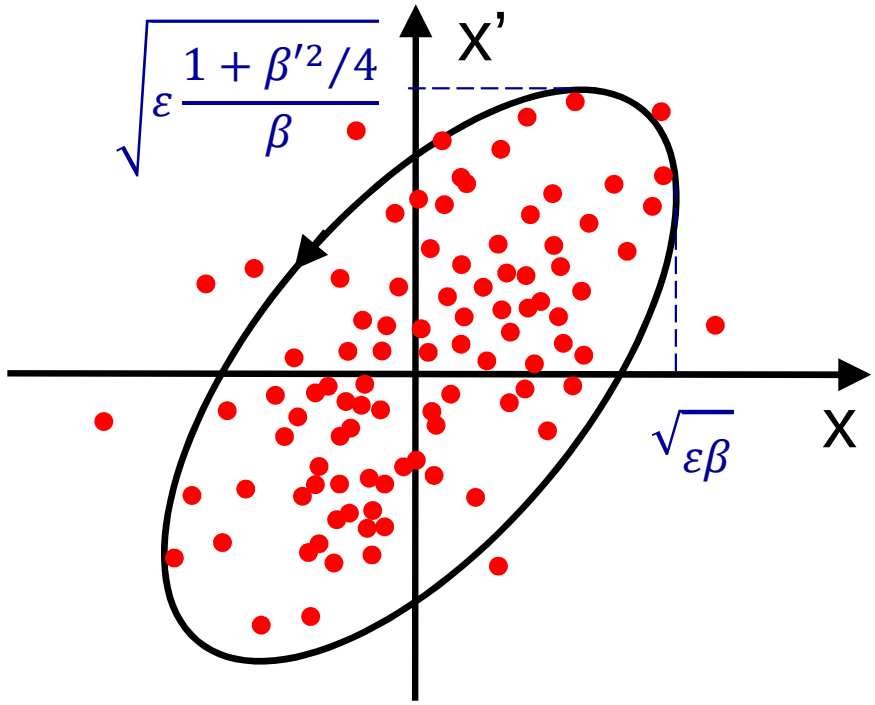




- For a bunch of particles
  - Emittance $\varepsilon_{90} \rightarrow$ ellipse containing 90% of particles
  - Various definitions of ε

Beam Emittance (cont.)

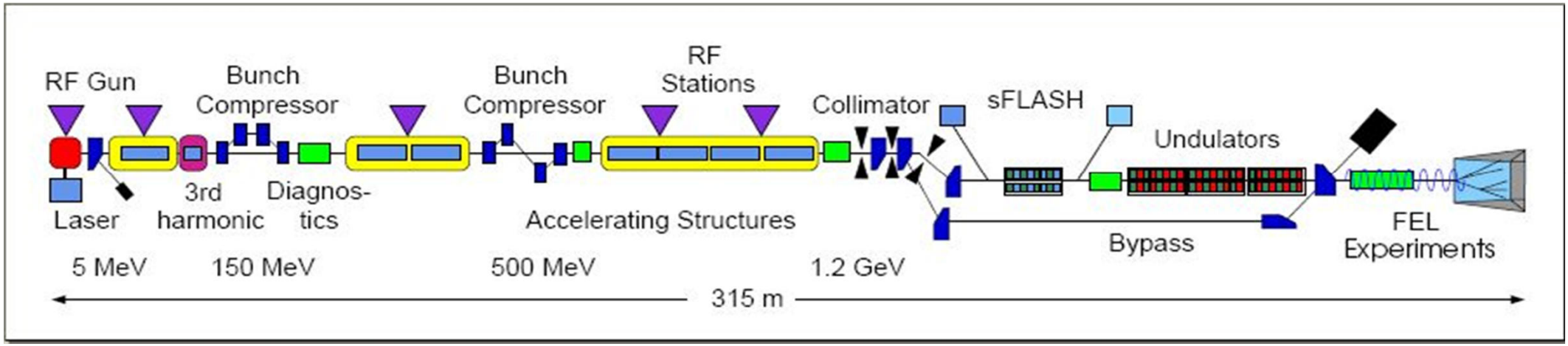
- The emittance ellipse
  - Is rotating (and deforming) in the phase space
  - Its area (emittance ε) is constant along accelerator if only conservative forces
  - During acceleration ε shrinks
    - the normalized emittance $\varepsilon_n = \beta\gamma\varepsilon$ is constant
- In practice
  - In linacs emittance grows
    - $\rightarrow$ need to measure it at several locations along the accelerator
  - in synchrotrons, ε shrinks due to SR till equilibrium
- Beta function β
  - Important machine parameter

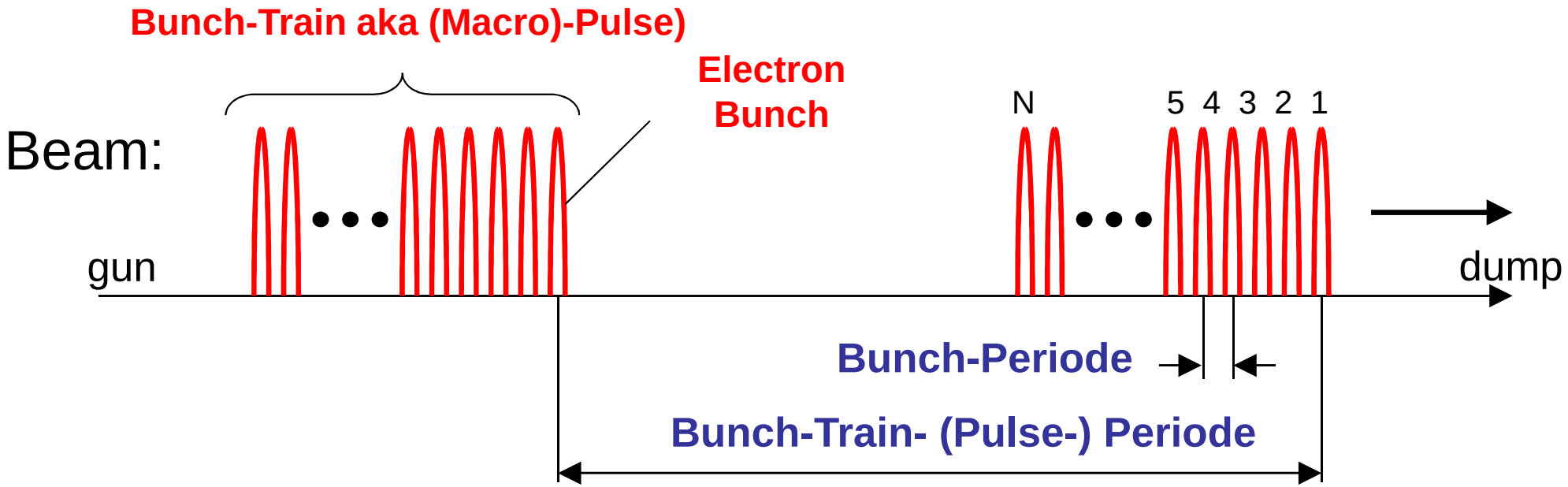


Linacs versus Synchrotrons

Linacs	Synchrotrons
Always new beam from gun, which may differ significantly from previous	Same beam in the machine for many turns
Measure every single bunch	Average over several turns (few single bunch measurements needed)
Measure q, ε at several locations	Measure I, ε at one location only needed
Beam can get lost anywhere, all the time	The same beam can get lost only once
Talk about bunches	Talk about beam

Example of an Accelerator: FLASH





Typical FLASH Beam Parameters

Charge	0.2 – 1 nC
Energy	450 – 1200 MeV
Photon wavelength	4.1 – 40 nm
Bunch frequency	0.1 – 1 MHz
Macro-pulse frequency	10 Hz
Macro-pulse length	≤ 800 μs
RF frequency	1.3 GHz
Bunch length	> 10-50 fs
Peak current	~2.5 kA
Average current	< 8 μA

Requirements on Diagnostics at FLASH

- From beam size, beta function, stability
  - ⇒ requirements on diagnostics components
    - Careful design to achieve required resolution
    - Mechanical construction
      - Material, tolerances, cleanness etc.
      - Component movement w.r.t. to nearby components
    - Electronics
      - Low noise, dynamic range, drifts, radiation hardness (if in accelerator tunnel) etc.
    - Cables
      - Electrical properties, length, radiation hardness
- Particularly challenging at FLASH
  - Bunch length and the longitudinal bunch profile(~10fs)
  - Ultra-short bunches / low charge: down to 20 pC

How Much Diagnostics Is There in FLASH

- Current monitors: 13
- Bunch Position Monitors: > 60
- Screens: ~25
- Wire Scanners: ~20
- Phase Monitors: 5
- Beam loss monitors: > 80
- Bunch length monitors: ~8
  - Expert diagnostics

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Methods to Monitor Particle Bunches

- Electro-magnetic monitors
  - Monitor image charge: bunch charge, position, phase
- Radiation based monitors
  - look at bunch EM fields directly
  - Synchrotron radiation SR
  - Transition radiation TR
  - Diffraction radiation DR

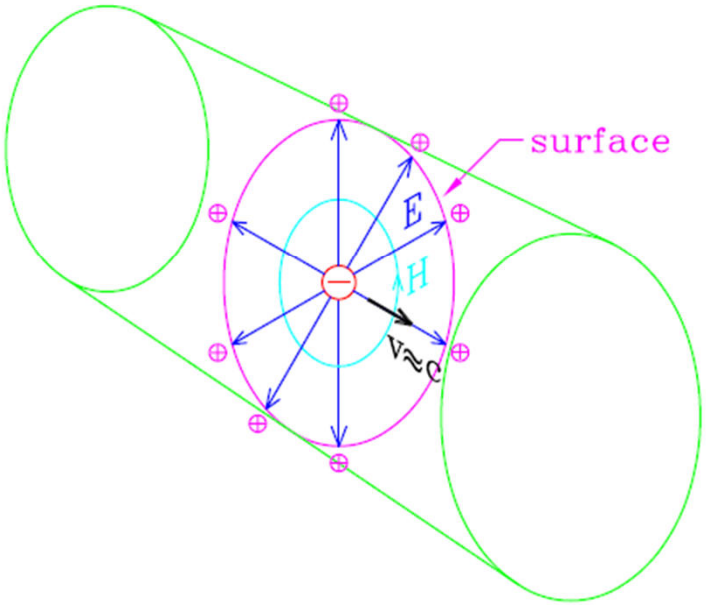
  ] transverse and longitudinal bunch size/profile
  - Electro-optic sampling methods: longitudinal bunch profile
- Interaction of particles with matter
  - Various kinds of interactions

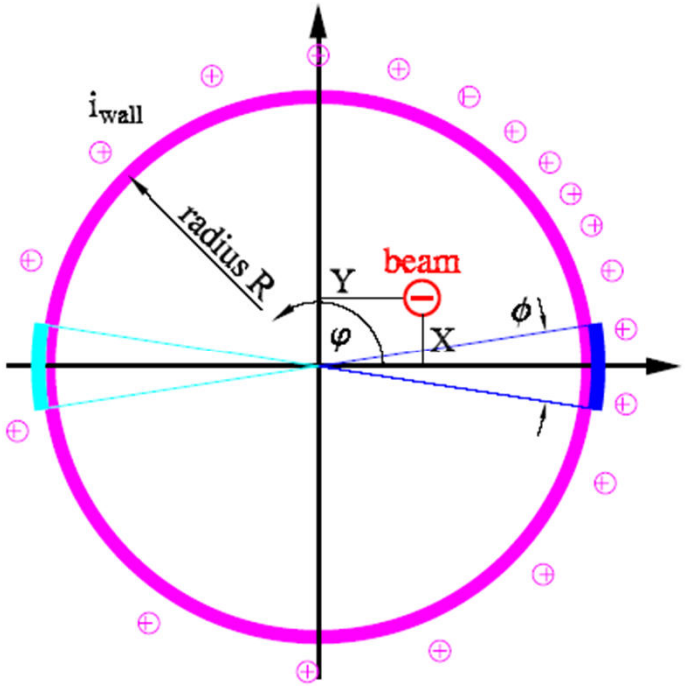
  ] transverse bunch size, length / longitudinal bunch profile, bunch losses etc.

- Since many people work on the diagnostics presented, people who either work on, coordinate the work on that diagnostics or can give you other names are given

Electro-Magnetic Monitors

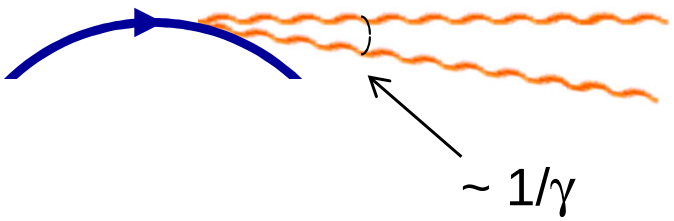
- Image charge
  - Travels parallel to the particle bunches
- Bunch monitors
  - Charge
  - Transverse position
  - Phase





Radiation Based Monitors: SR, TR, DR

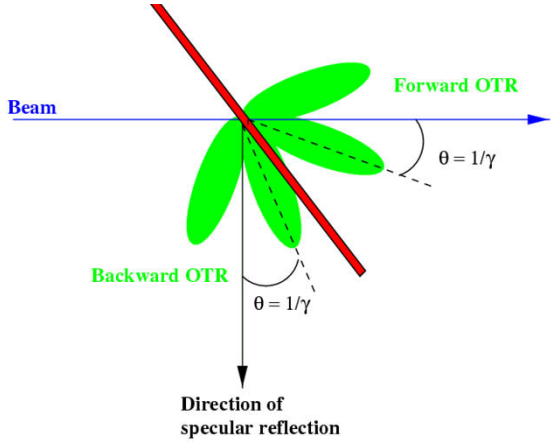
- Synchrotron radiation SR
- Transition radiation TR
- Diffraction radiation DR



- For very short bunches
  - Coherent radiation: CSR, CTR CDR

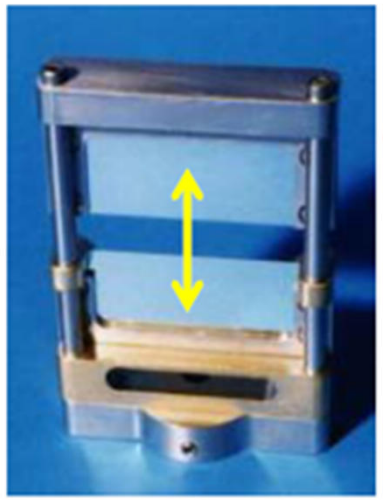
- Beam monitors
  - Transverse bunch profile
  - Longitudinal bunch size or profile

(Optical) transition radiation



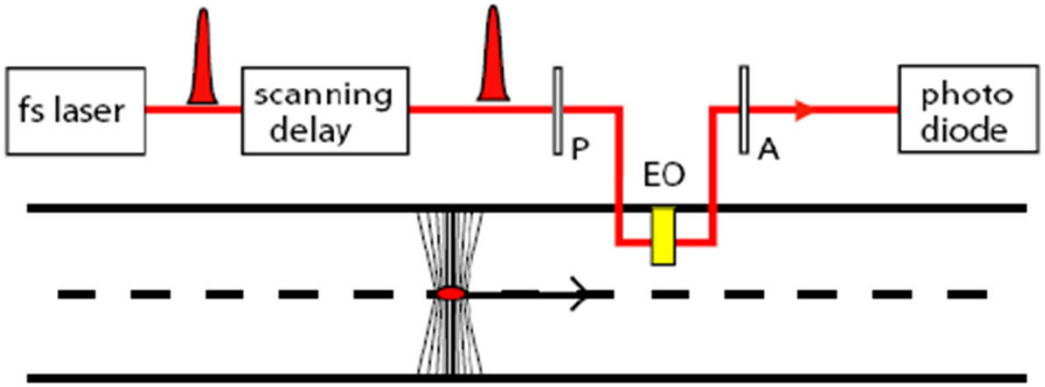
courtesy K. Honkavaara

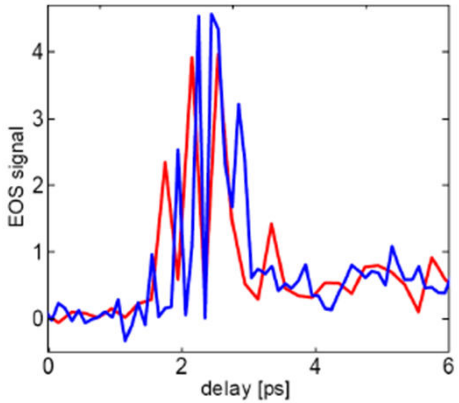
Transition/Diffraction Radiator



Radiation Based Monitors: EOS

- Electro-Optic Sampling (EOS)





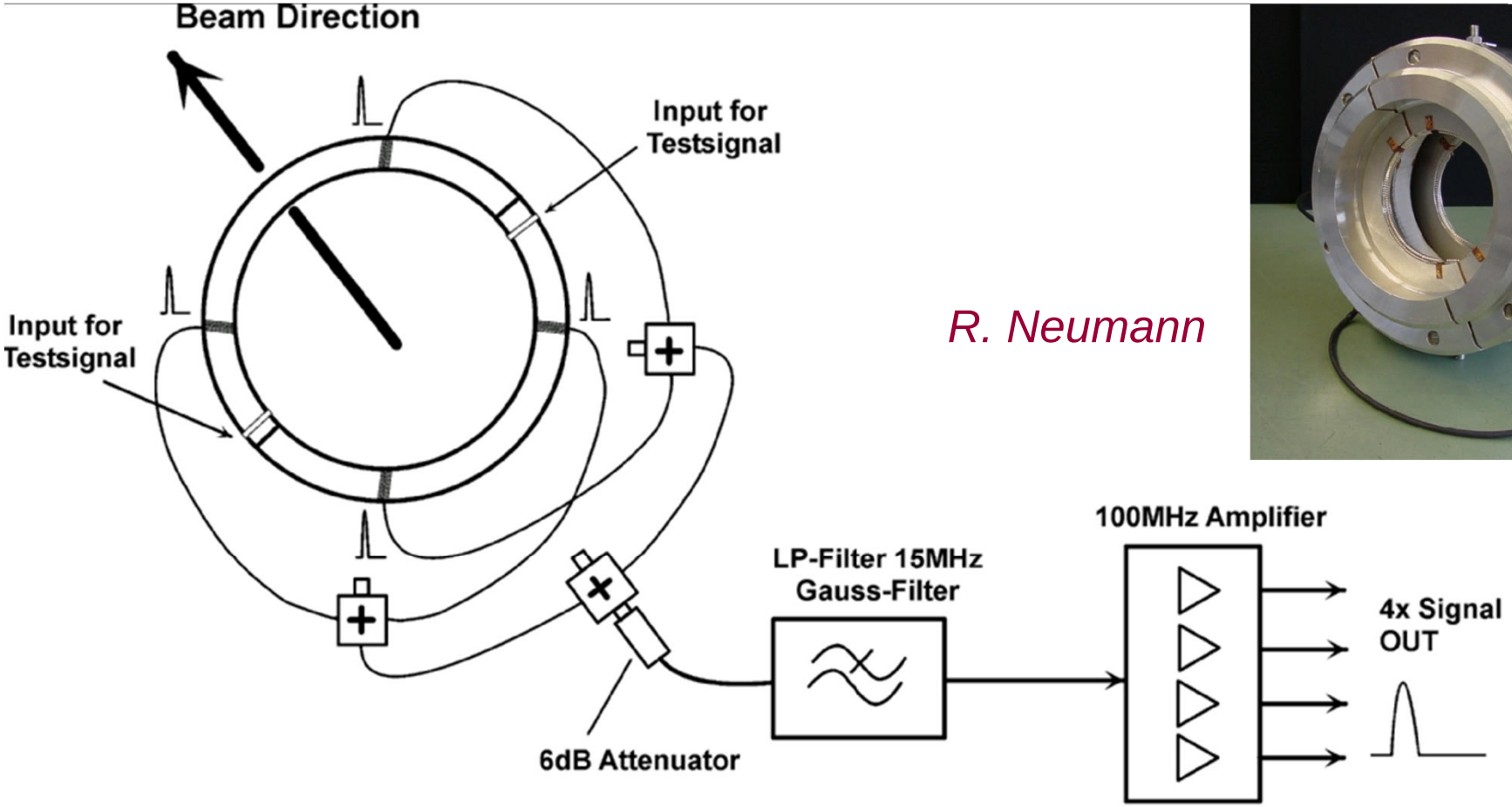
  - Bunch length or longitudinal profile
  - Other methods
    - Electro-Optic Spectral Decoding (EOSD)
    - Electro-Optic Temporal Decoding (EOTD)
    - Spatially Resolved EO (TEO)

B. Steffen, V. Arsov

Interactions of Particles with Matter

- Scintillation
  - YAG screens; loss monitors
- Scattering
  - wire scanners
- Bremsstrahlung
  - wire scanners
- Čerenkov radiation
  - loss monitors
- Secondary electron emission
  - loss monitors
- Ionization
  - loss monitors; profile monitors

Bunch Charge: Toroid



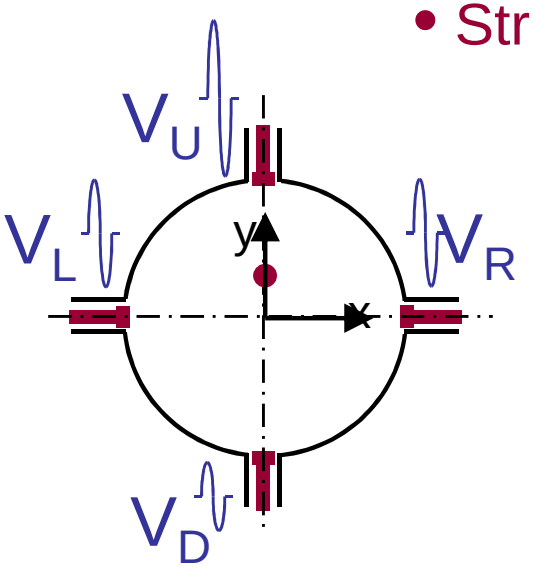
R. Neumann

- Gap in beam pipe
- Toroid signal is sampled by ADC ⇒ one value per bunch
- Single bunch resolution: ~5 pC (0.5 % @ 1 nC)

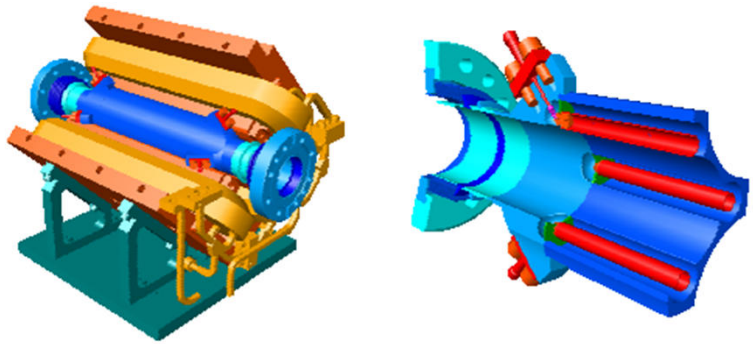
Bunch Position: Button and Stripline Bunch Position Monitors (BPM)

- Signals at 4 pickups depend on beam offset and charge

- Button BPM



- Stripline BPM



S. Vilcins, M. Siemens

- Single bunch resolution at 1nC
  - 30 µm rms for Ø34mm
  - 10 µm rms for Ø9mm
- Limitation
  - Not good below 0.3nC

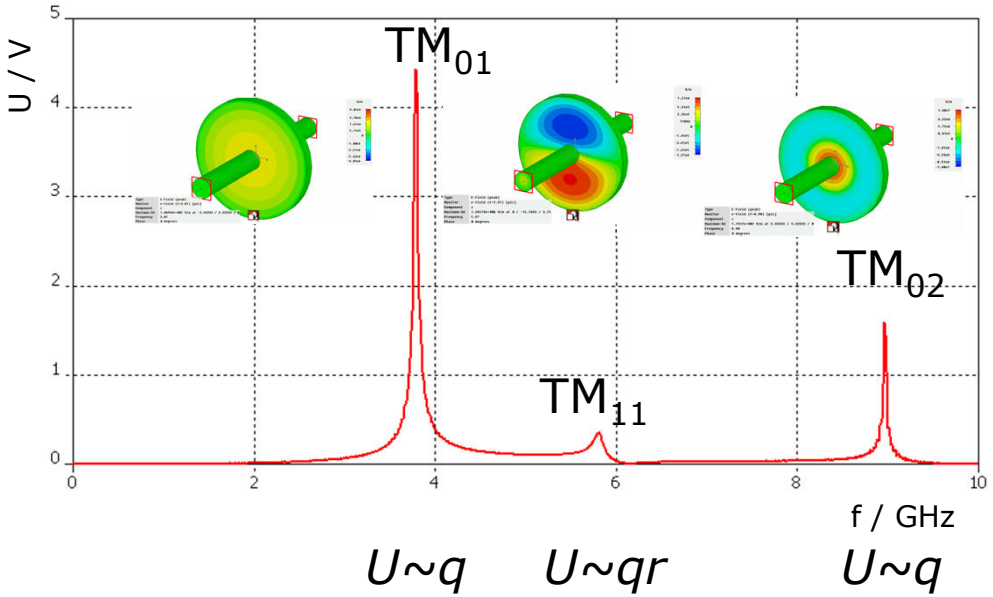
- Single bunch resolution at 1nC
  - 10µm rms for Ø34mm

N. Baboi

Bunch Position: Cavity BPM

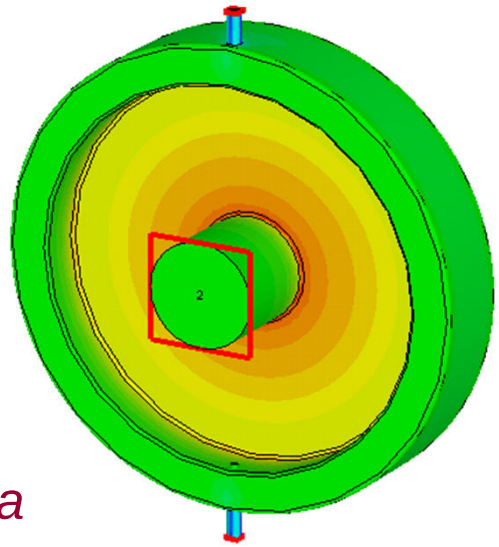
- Resonant modes
  - Excited by beam in cavity
  - Monitor dipole mode (~ qr) and monopole mode (~q)
  - Normalize to monopole mode
- Properties
  - Good resolution
    - Design 1 μm rms for the XFEL (Ø10mm)
  - Well defined zero
    - Zero signal
  - Good also for (relatively) low charges

D. Lipka → XFEL cavity BPMs



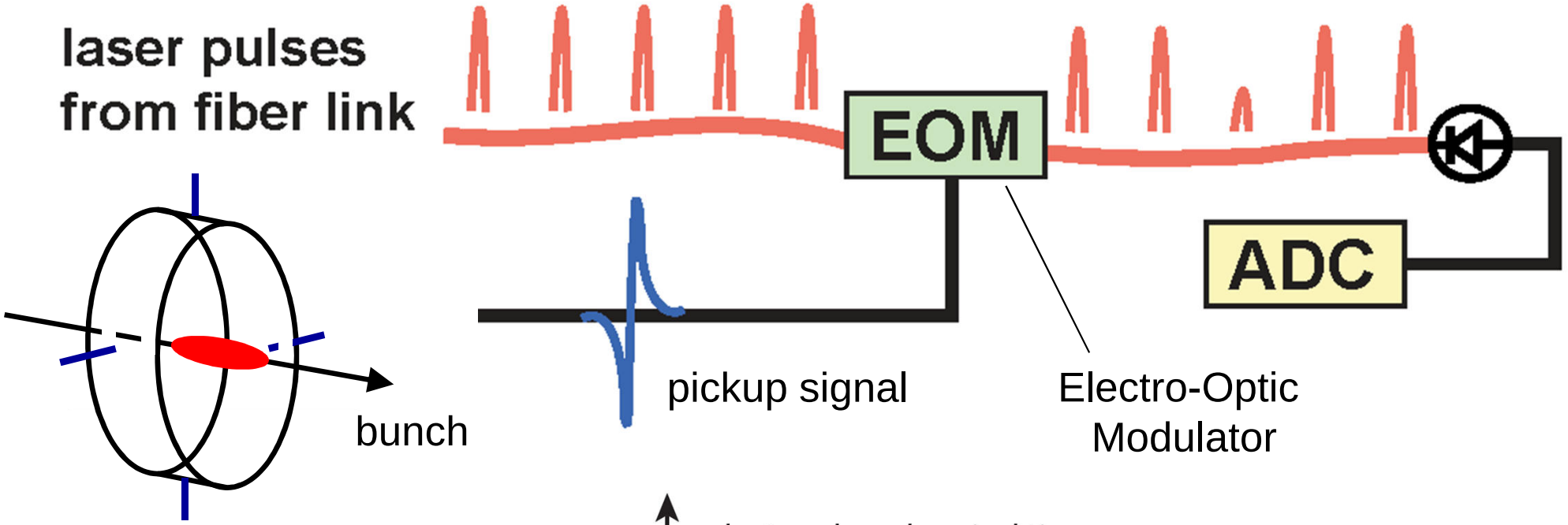
Dark Current Monitor (DaMon)

- Dark current
  - Emitted by RF accelerating cavities (mostly by the gun)
    - Partially collimated
      - if not at same energy and transverse position as bunch
    - Partially kicked away, between bunches
    - Partially transported up to the dump
- DaMon
  - cavity with resonant frequency = RF frequency of accelerating cavities (1.3 GHz)
  - Also good for measuring bunch charge, down to pC level

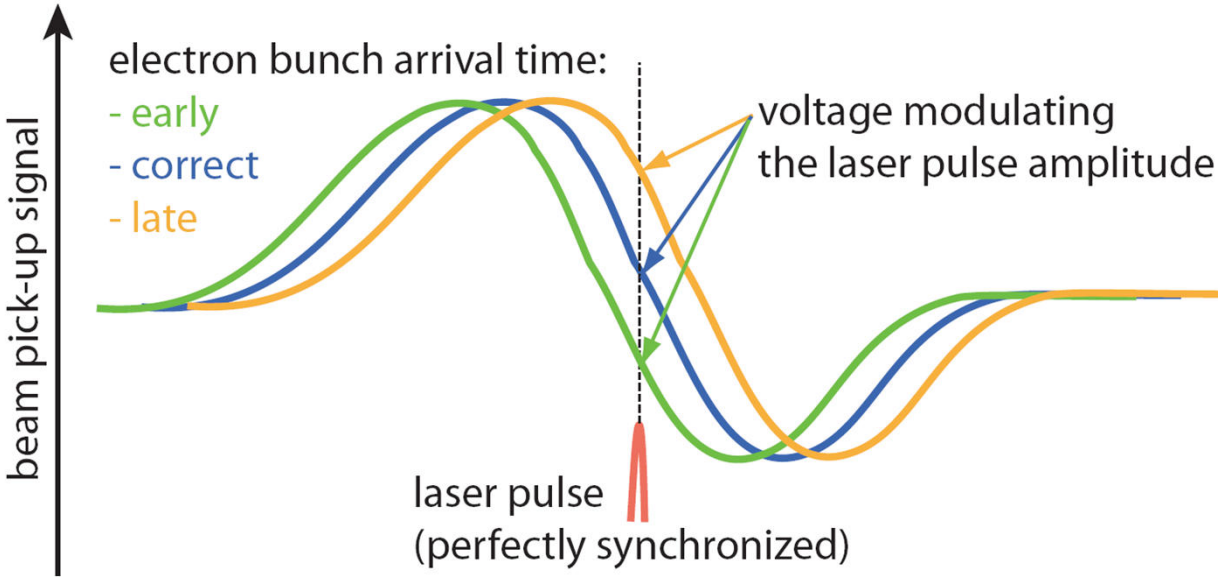


D. Lipka

Bunch Phase Monitor: Beam Arrival Monitor (BAM)



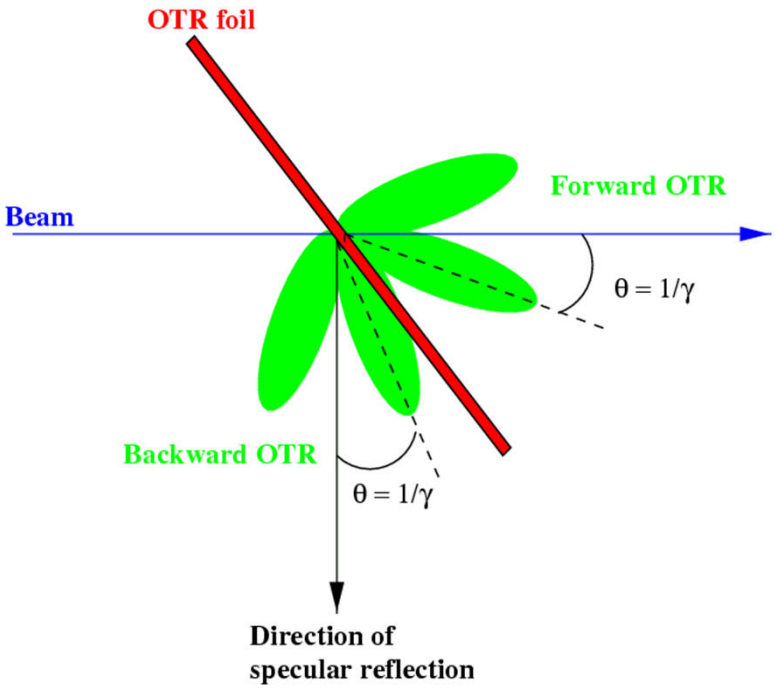
- Resolution achieved
  ~10-20 fs



F. Löhl, H. Schlarb

Transverse Bunch Profile: Screens

- OTR screens
  - Optical Transition Radiation
  - Most screens in FLASH
  - Resolution: 10-25 μm
  - But problems with Coherent TR
    - Observed in LCLS for very short bunches
- Fluorescent screens
  - YAG
  - Less resolution
  - Considered for the XFEL
    - Can avoid problems with CTR

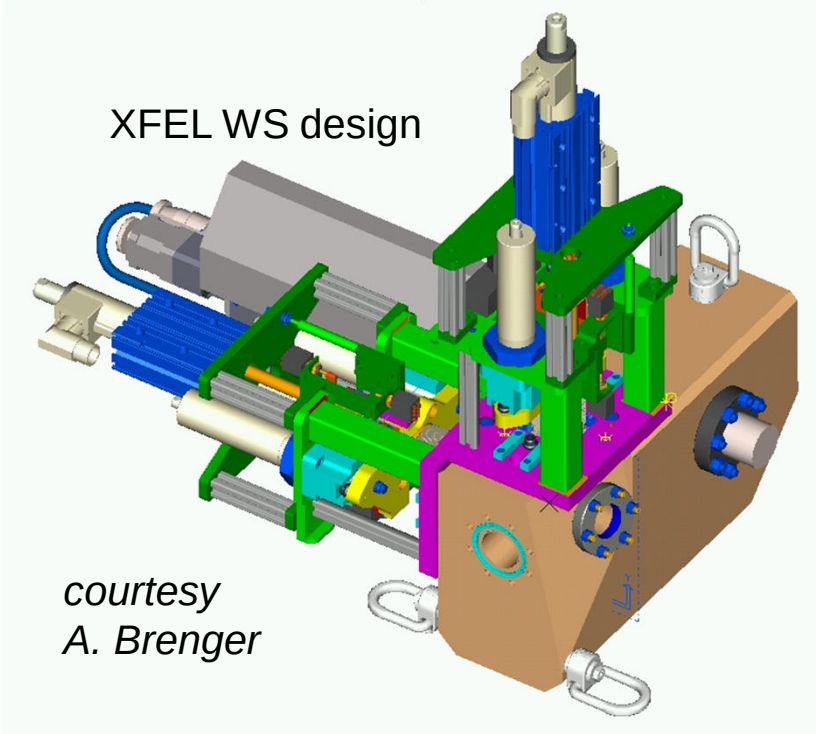


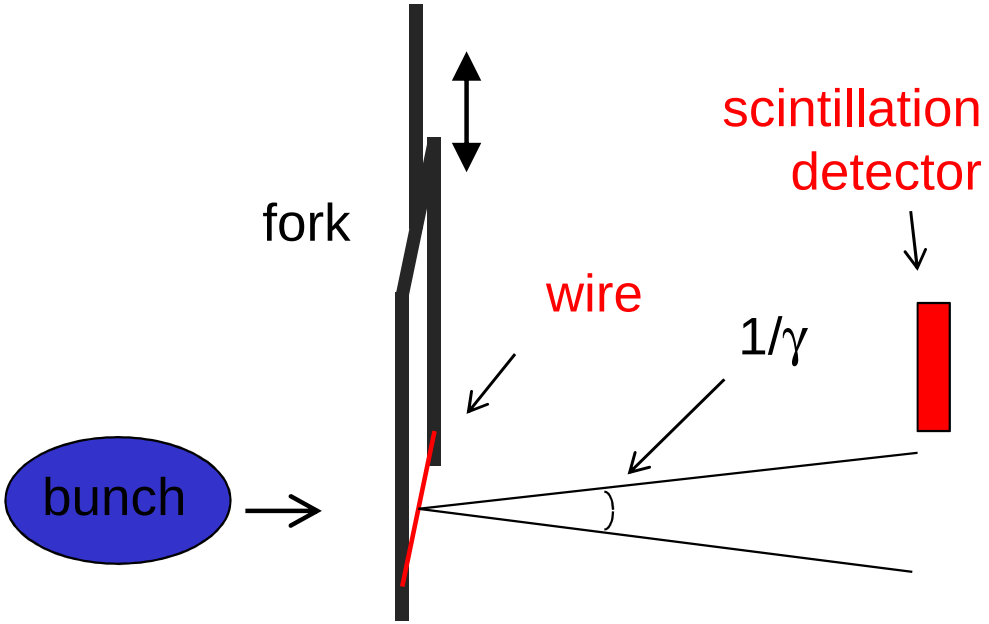
courtesy
K. Honkavaara

H.-C. Schröder, G. Kube, D. Nölle

Transverse Bunch Size: Wire Scanners

- Wire scatters electrons
  - Loss monitor measures the shower produced
  - Slow or fast
  - Typically C or W wire
  - Resolution: ~ 1μm



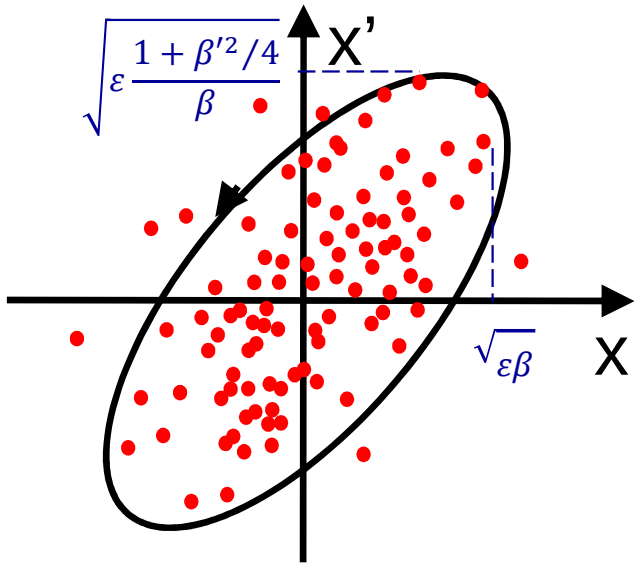


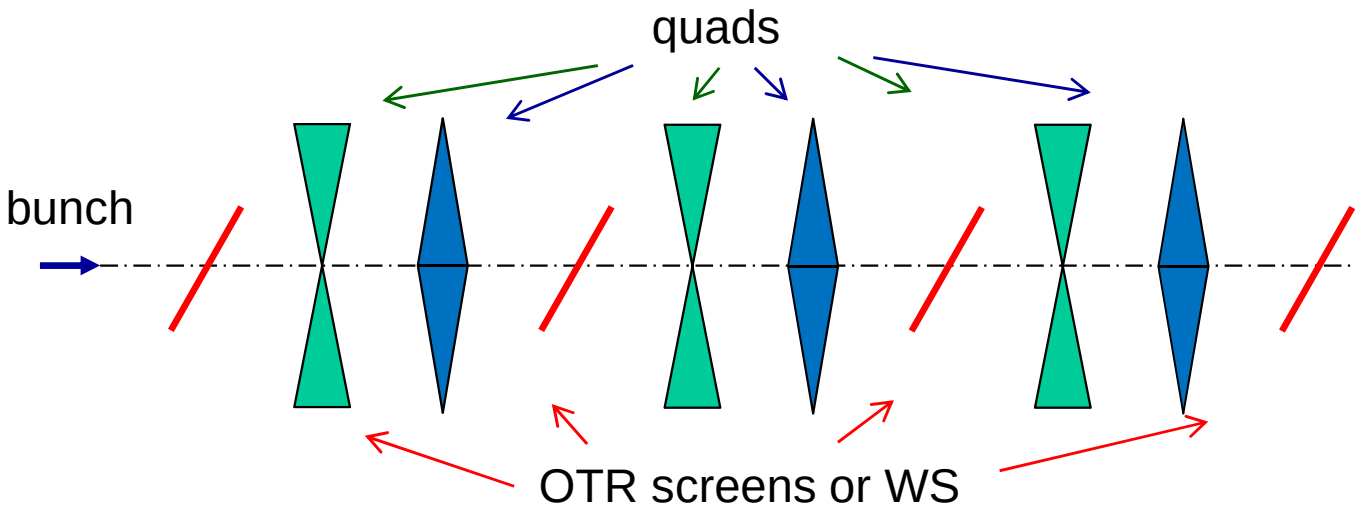
- Comparison to screens
  - Can be used for multi-bunch (in fast mode)

V. Gharibyan

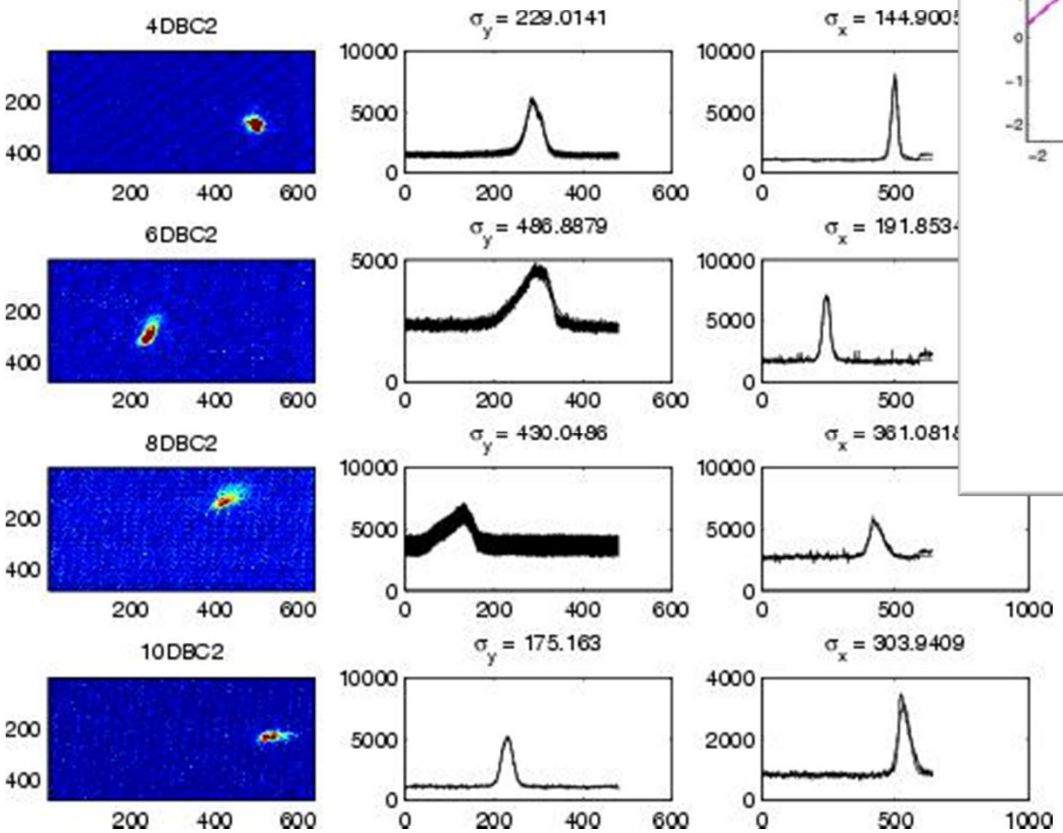
Beam Emittance

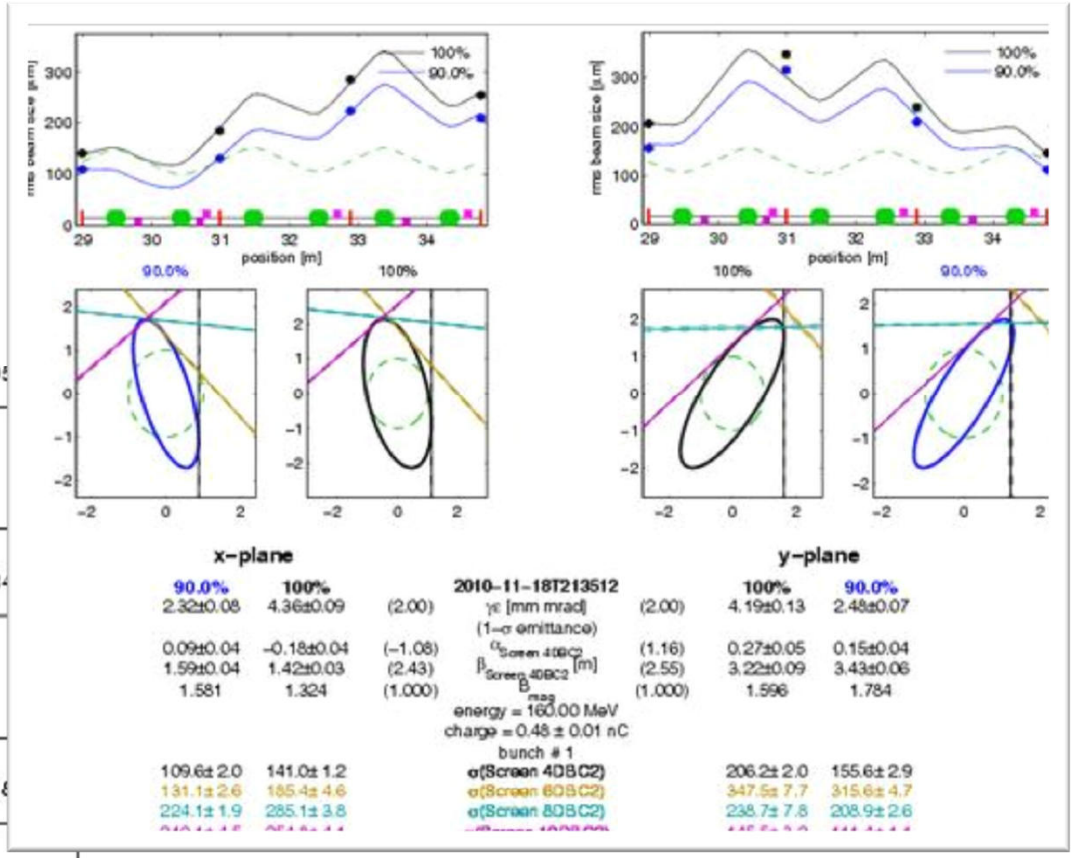
- Multi-screen method
  - 3 unknowns -> measure bunch size at 3 (+1) locations
  - FODO lattice





Beam Emittance (cont.)

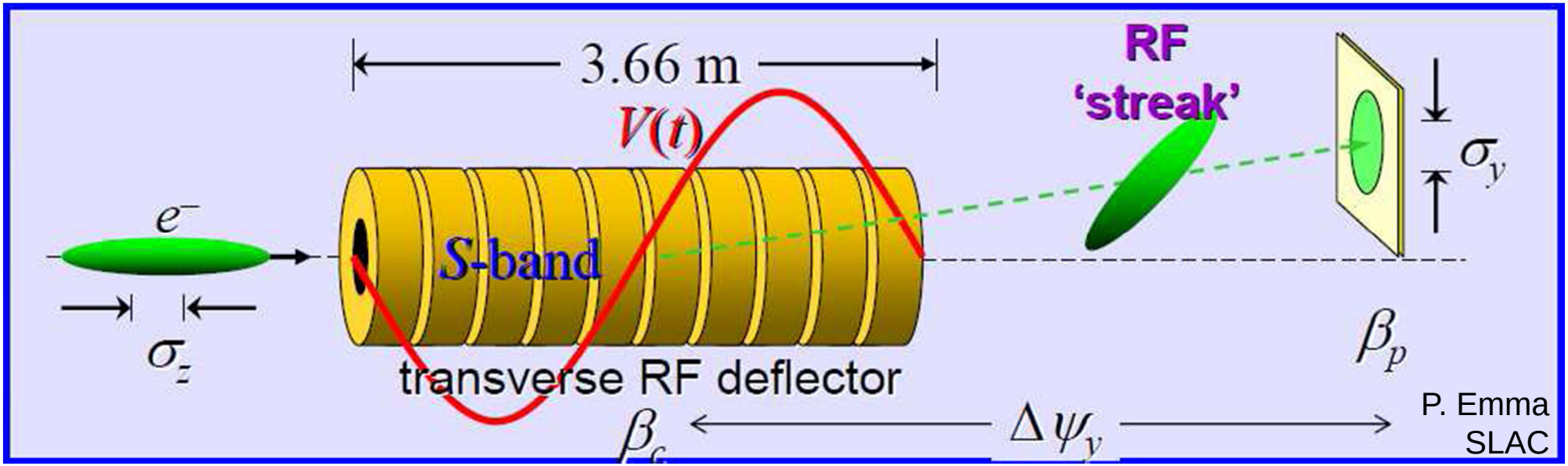




W. Decking, T. Limberg

Longitudinal Bunch Profile: TDS

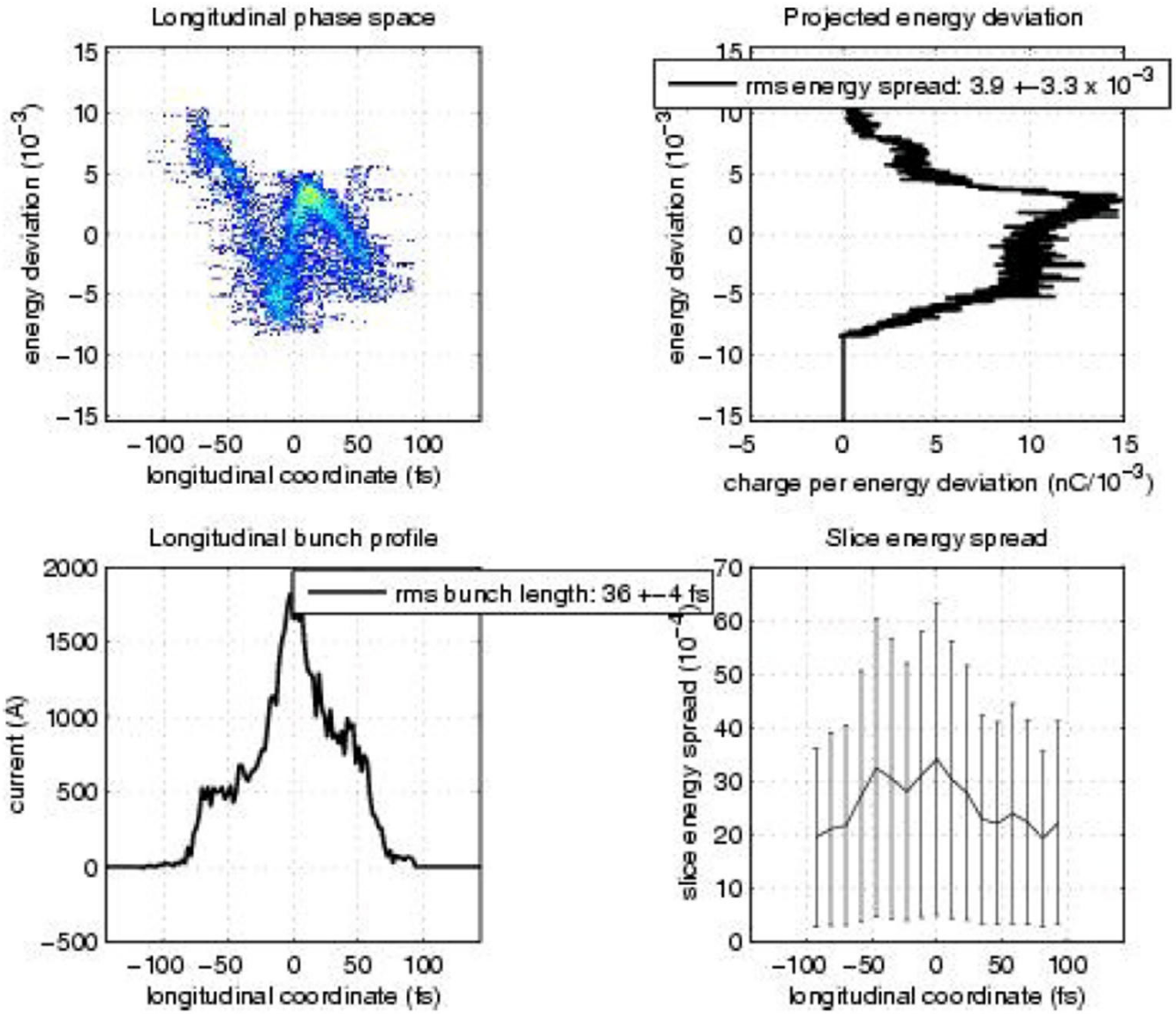
- TDS = Transverse Deflecting Structure TDS
  - aka LOLA



- Streaks bunch
- Parasitical
  - kick one bunch from macro-pulse

Longitudinal Bunch Profile: TDS (cont.)

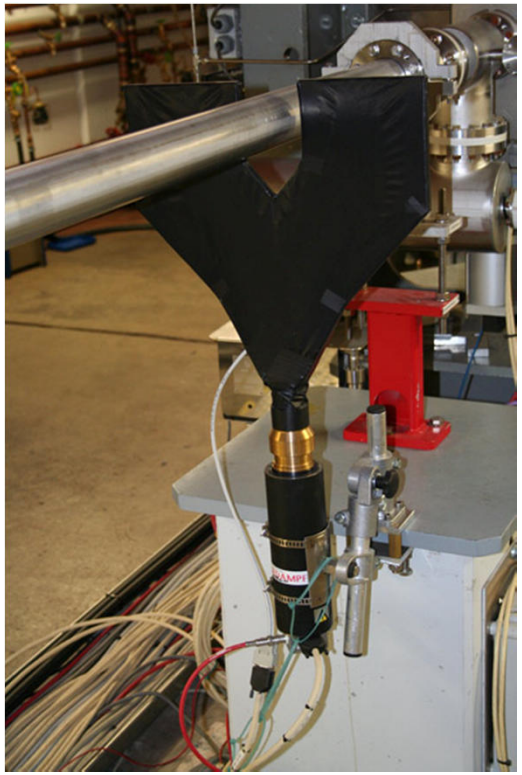
- Measure longitudinal profile of
  - Current
  - Energy
  - Emittance
- Resolution
  - Down to 10 μm (30 fs)



Ch. Behrens

Loss Monitors

- BLM Beam Loss Monitor
  - Scintillator + photomultiplier
  - Included in Machine Protection System (MPS)
- (so-called) Čerenkov detectors
  - Light fibers installed along undulators
- Ionization Chambers IC
  - Air-filled cables
    - Installed along dump line
  - Beam Halo Monitor: solid state IC
    - Installed behind dump vacuum window



A. Kaukher, K. Wittenburg, A. Ignatenko

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Machine Operation

- Manual
  - Operators have to watch the diagnostics and many other things and adjust the machine if necessary
- Feedbacks keep machine stable
  - Pulse-to-pulse and intra-pulse
  - BCM $\rightarrow$ RF phase feedback
  - BPMs $\rightarrow$ position feedbacks
  - BAM and energy monitors $\rightarrow$ timing feedbacks
- Machine Protection System (MPS)
  - BLMs, toroids, screens
  - Gives warnings and switches the beam off if necessary

Machine Operation: Diagnostic Tasks

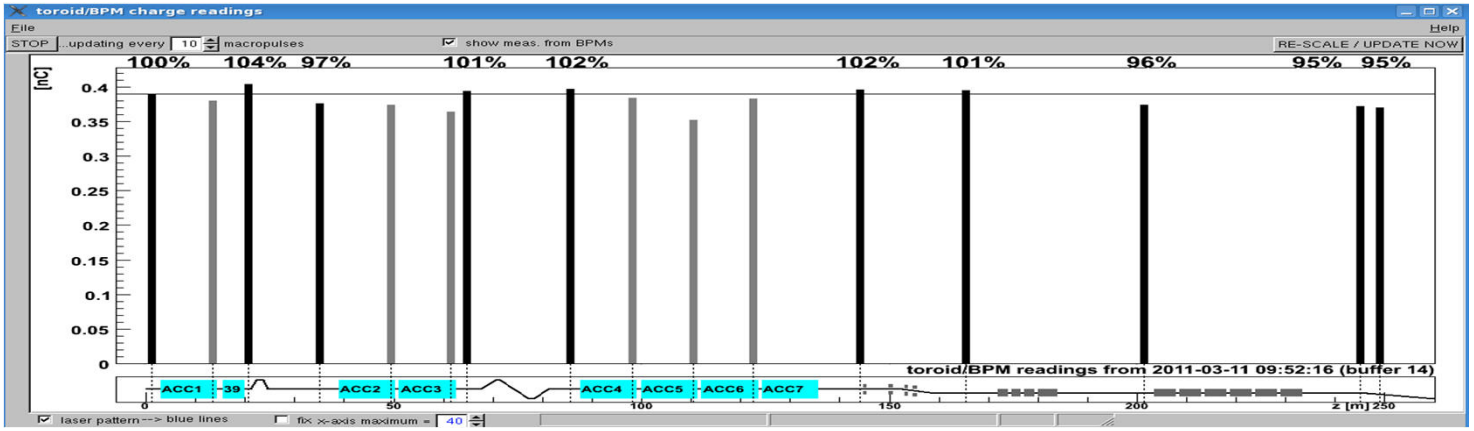
- Commissioning
  - Get the beam bit-by-bit through the machine
    - Look at BPMs, toroids, screens
    - check and adjust how far the beam is along accelerator, if it's (roughly) centered, if it's matched
  - Issue
    - Need beam to commissioning some diagnostics
    - For the XFEL diagnostics has to see the first beam with low resolution, then use beam to commission diagnostics
- Tuning:
  - e.g.
    - increase energy of SASE-FEL photon beam
    - adjust energy for certain wavelength
    - reduce losses

Machine Operation: Diagnostic Tasks (cont.)

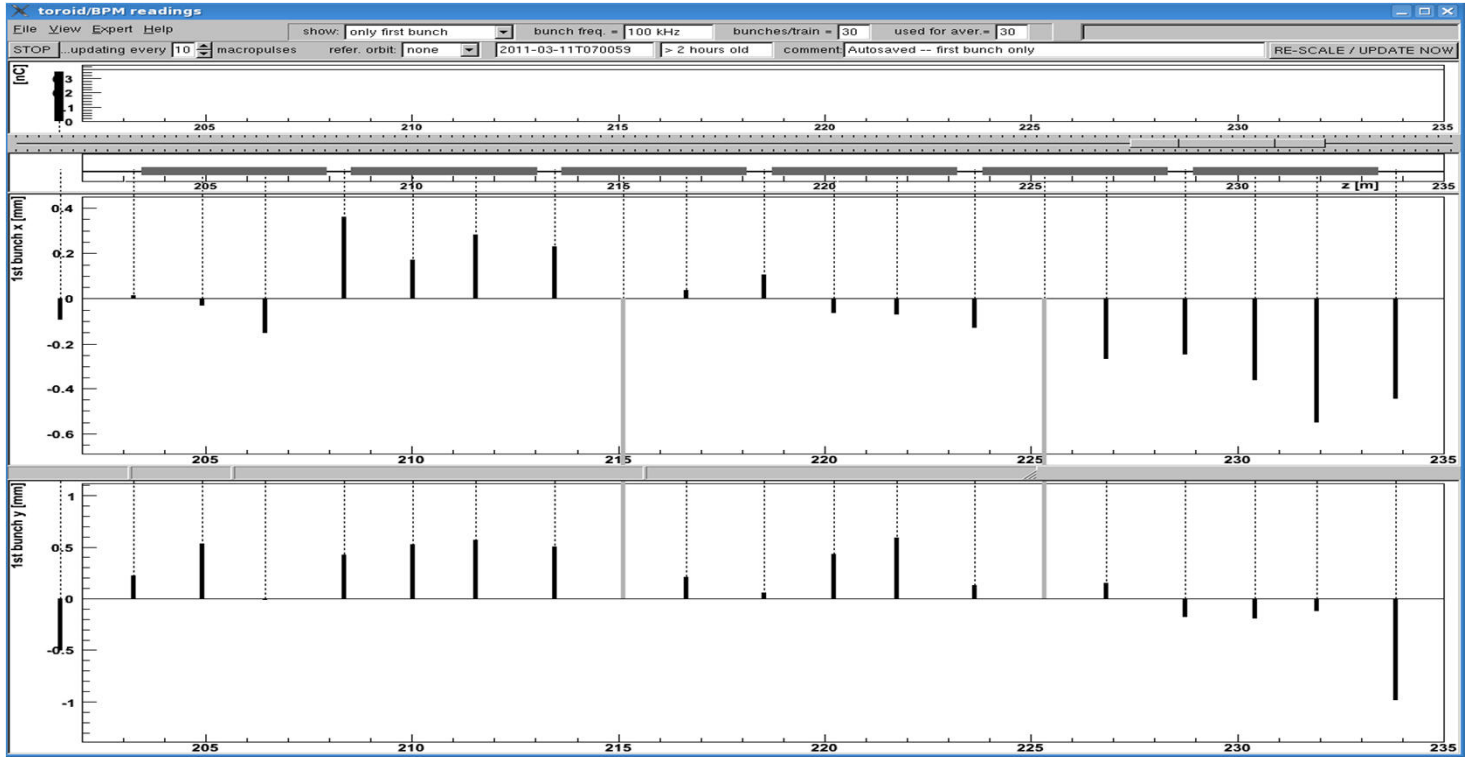
- Restart machine after shutdown
  - Use saved files to bring beam to same state
    - Either recover same magnet or RF settings or same beam positions
  - Then fine tuning
- Find what changed
  - Diagnostics help find what changed in the machine, together with other tools
  - e.g. if SASE-level dropped
    - Orbit, charge, energy changed?
- Machine studies

Beam Transmission and Orbit

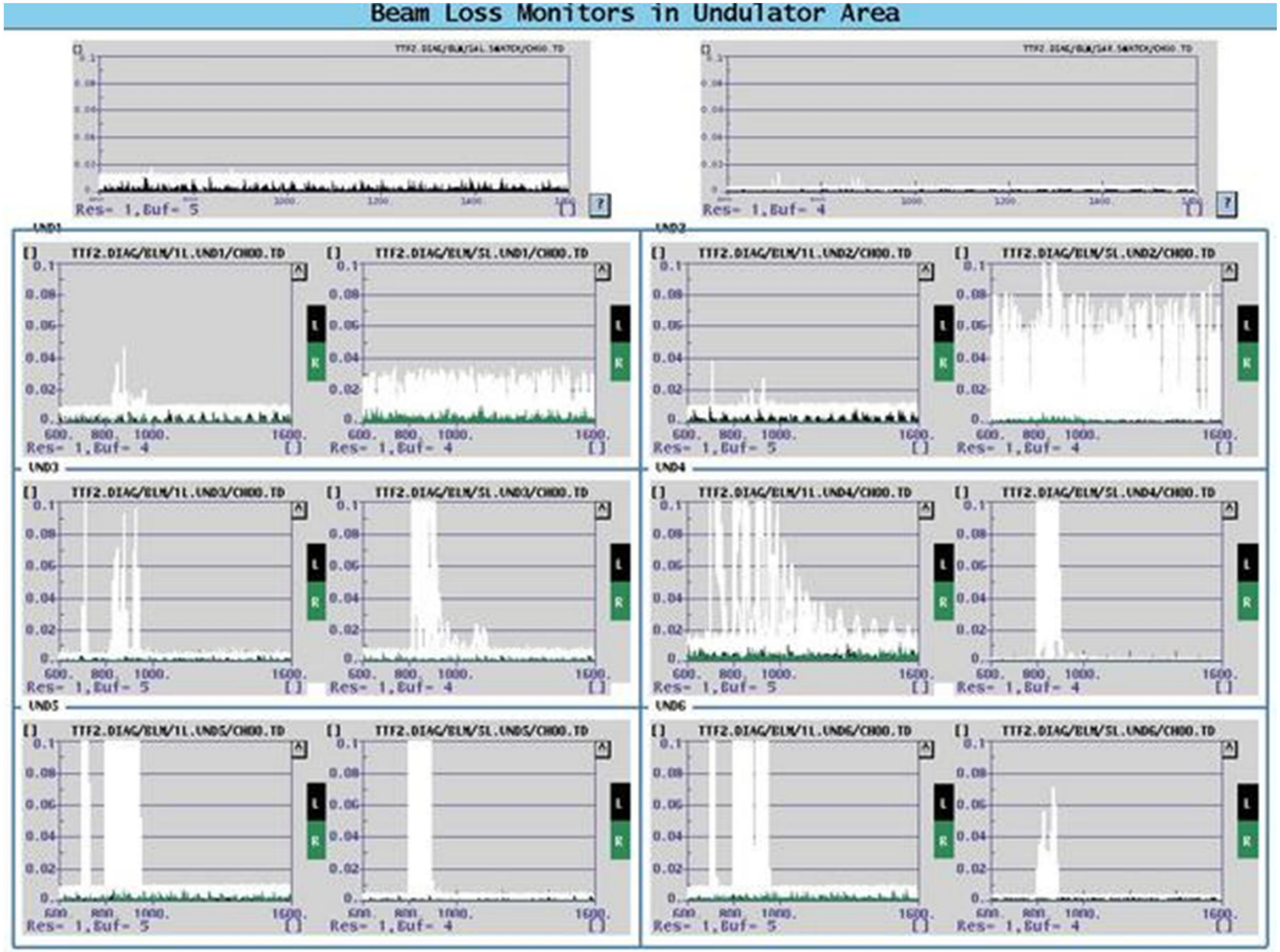
- Transmission



- Orbit
  - betatron oscillations

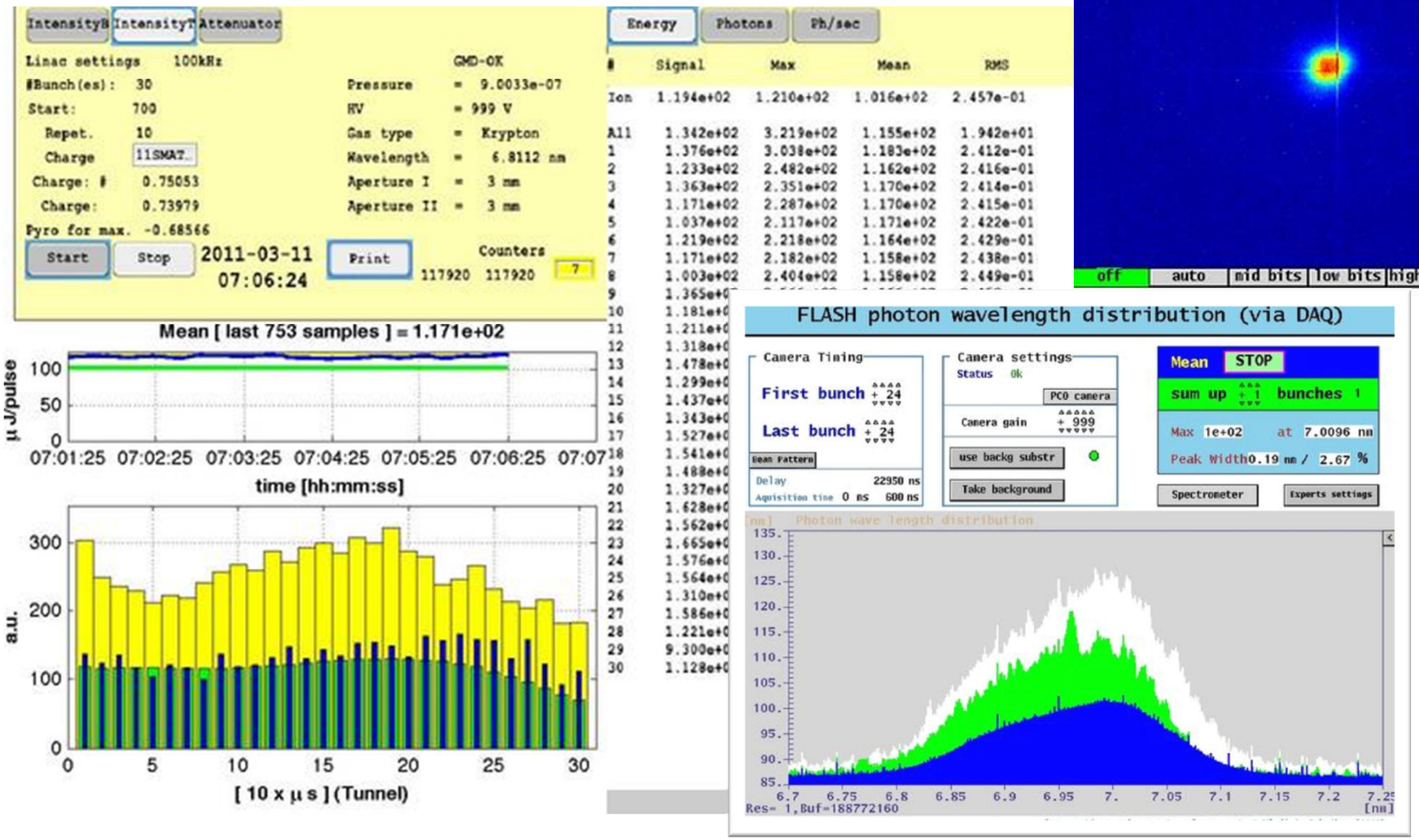


Losses in Undulator Section



Photon Diagnostics

- Used together with particle beam diagnostics
  - Photon beam energy, position, wavelength



Summary

- Machine diagnostics needs and their requirements
  - Come from user and from machine requirements
  - Each accelerator has different needs
- There are many many types of beam monitors
  - Presented a selection
- Diagnostics during machine operation
  - Very important for commissioning, restart, tuning
  - Used in feedbacks or MPS
  - Some have to be watched by operators constantly

Sources Used for This Talk

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Private communications from many colleagues from MDI, FLA, MIN, MPY and Hasylab

XFEL WP17 Design Reports

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