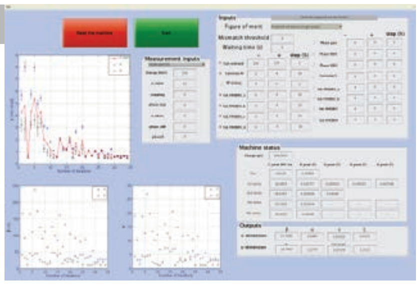
Rasmus Ischebeck

Diagnostics for FELs and ERLs

CERN Accelerator School: Free Electron Lasers and Energy Recovery Linacs

2016-06-08

Usage of Diagnostics: Measurement and Optimization of Beam Parameters

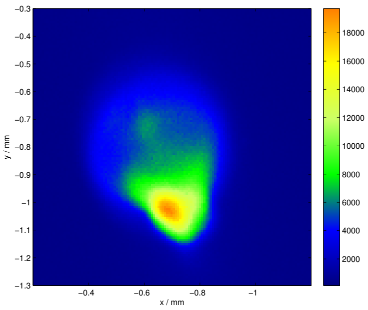


- Optimization of the emittance from a photocathode gun
- Figure of merit: emittance measured on screen
- Optimization of magnetic fields in the gun, and of RF parameters

Simona Bettoni, PSI

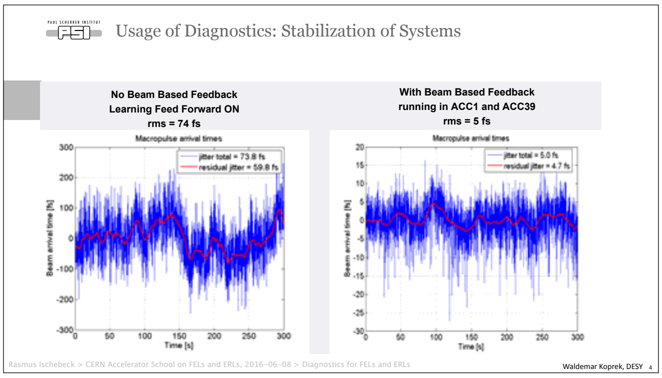
Measure and optimize beam parameters
> Optimization of one or several parameters, summarized in a figure of merit
> Manual or automatic optimization possible

Usage of Diagnostics: Find Errors

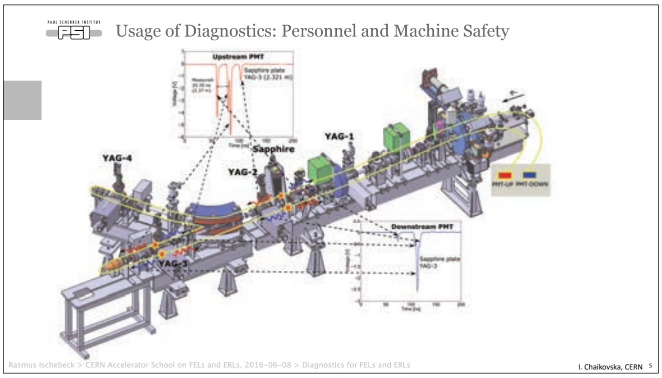


- Asymmetry in the beam caused by mis-alignment

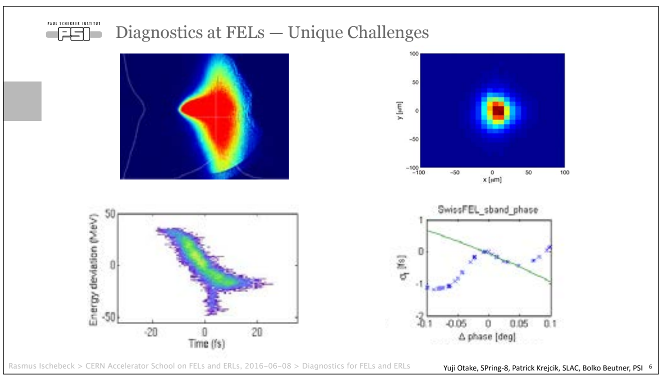
Find errors
> Errors in beam setup (alignment, phase, …)
> Mistakes in hardware setup



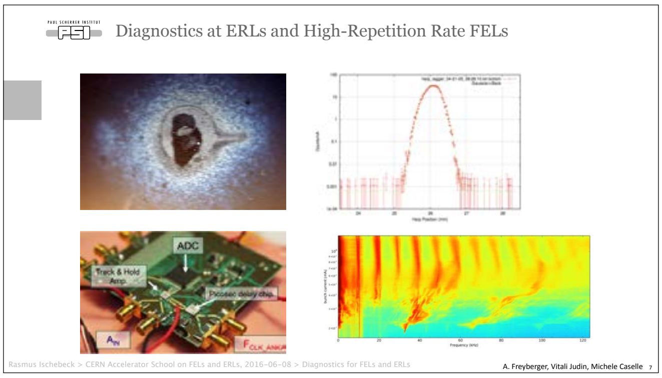
Stabilization of systems
> measure parameter and automatically adjust accelerator parameters
> feed-backs
> here: beam-based feedback of arrival time, acting on RF parameters
Note the different scale on the plots!



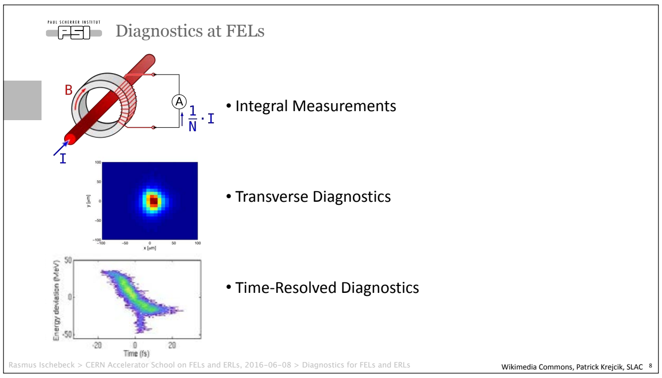
Personnel and machine safety
> Beam loss detection by Cherenkov radiation in optical fiber
> Mapping of arrival time to position through propagation speed in the fiber



> Top left: High brightness: coherent optical transition radiation spoils the usage of OTR as beam profile monitors
> Top right: Small beam diameters: beam of 14 μm rms size measured in the SwissFEL Injector Test Facility
> Bottom left: Short pulses shown in this measurement of electron phase space after the undulator at LCLS
> High accuracy requirements: Simulated dependency of the pulse length on S band phase in the SwissFEL injector

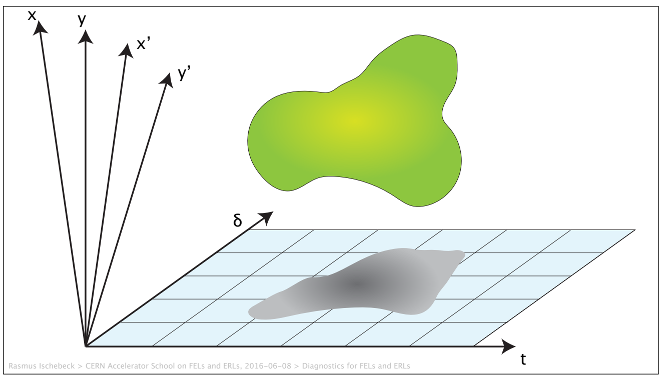


Special challenges:
> High repetition rate may destroy anything inserted into the beam
> Halo measurements require large dynamic range
> Large data sets require special processing

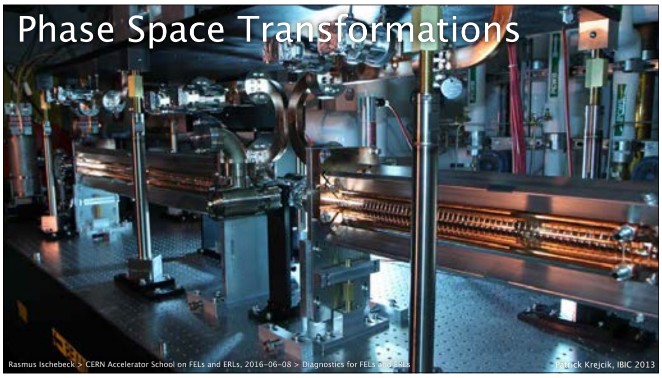


When designing an accelerator, we can carefully choose an instrumentation suite that lets us
> set up the accelerator
> measure beam properties
> control the stability of the machine via feedbacks

Thus, let us distinguish longitudinal and transverse diagnostics. It is not a clear distinction, as we can transform the phase space dimensions, but it's a start.

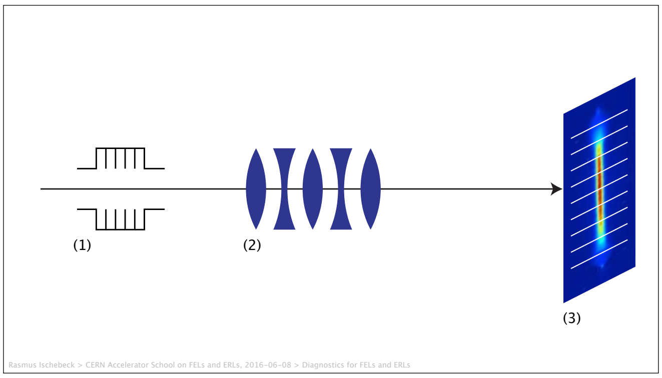


Let's first have a look at the object of study, the beam.
This beam can be represented by the particle distribution in the six-dimensional phase space, extended by transverse coordinates x and y, transverse angles x' and y', time t and energy delta.
When we speak about the longitudinal phase space, we mean the projection on these last two dimensions, and in particular the time, which is very difficult to measure with femtosecond accuracy.
No diagnostics exists for the entire distribution.

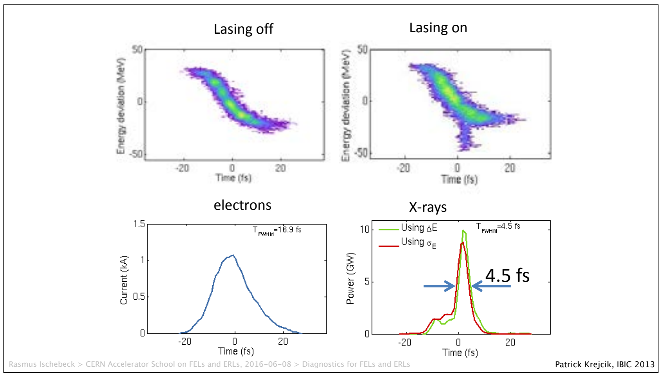


Phase space transformation with RF deflecting cavity
Reference for all longitudinal diagnostics
Shown here: installation in LCLS

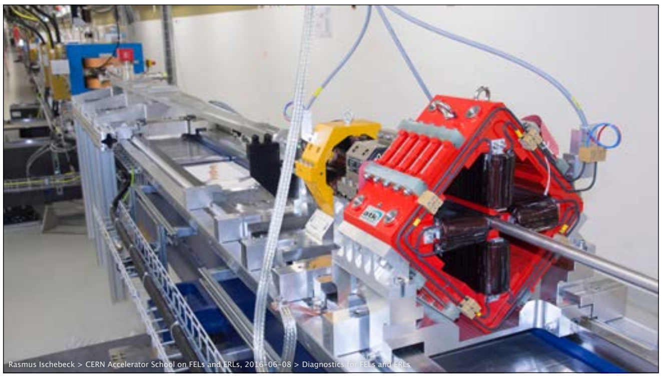
Quadrupole magnets result in a phase space transformation between x and x’, and between y and y’



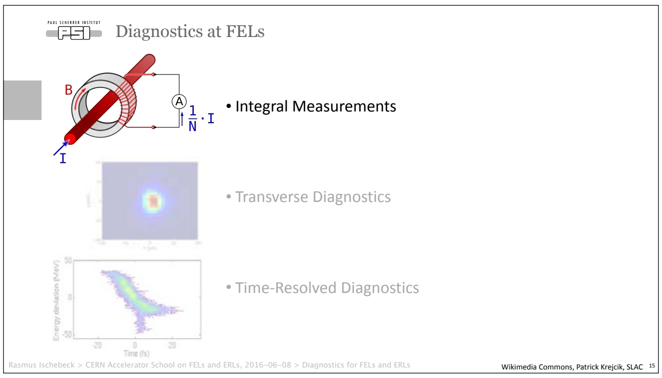
Beam transport
Phase advance with quadrupoles
Detection on screen



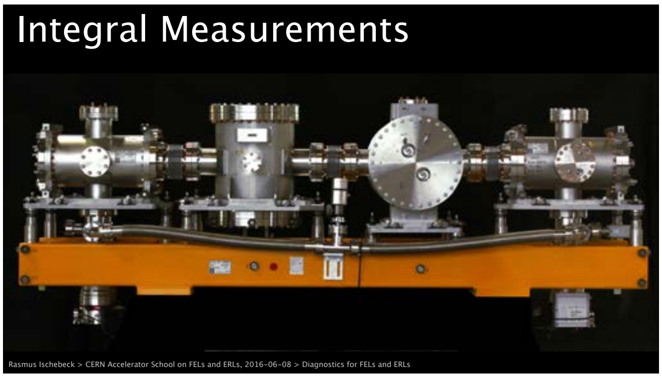
Measurements of full phase space possible!
Femtosecond resolution, depending on:
— emittance
— streak strength



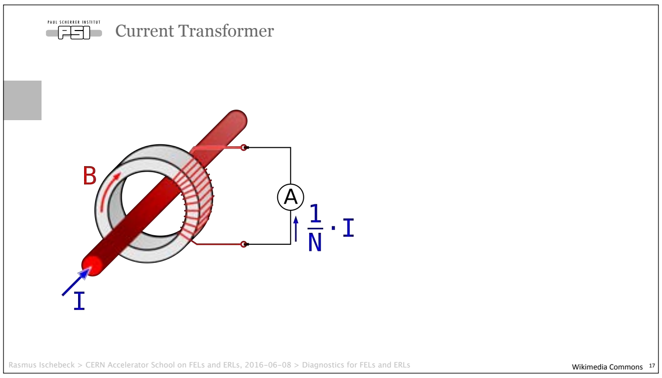
Skew quadrupoles couple the horizontal coordinates x—y’ and y—x’
Skew quadrupoles in dispersive sections (pictured here: bunch compressor) couple energy and transverse coordinates



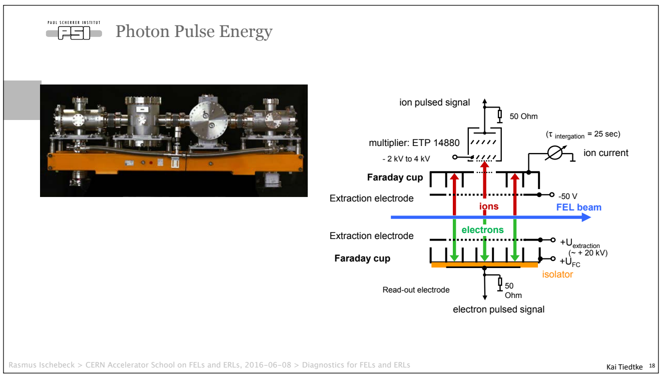
Integral Measurements
> Bunch charge
> Photon pulse energy



Integral measurements
> Let’s first look at diagnostics for integral properties of the beam, i.e. number of electrons / photons
> Of course, many diagnostics in the next two chapters also measure integral properties
> What is important here: absolute calibration



Integrating current transformer (ICT)
> acts like a transformer, but the primary coil is the beam
> response on secondary coil depends on the number of windings

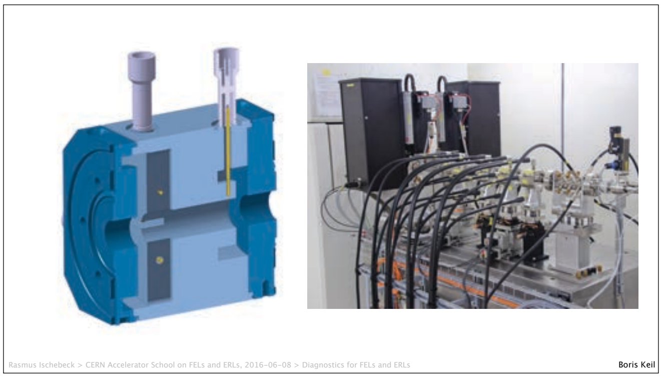


X-ray pulse energy measurements
> Photodiode (for low intensities)
> Back-scattering from thin membrane
> Transparent measurement of X-ray pulse energy by ionization of a gas

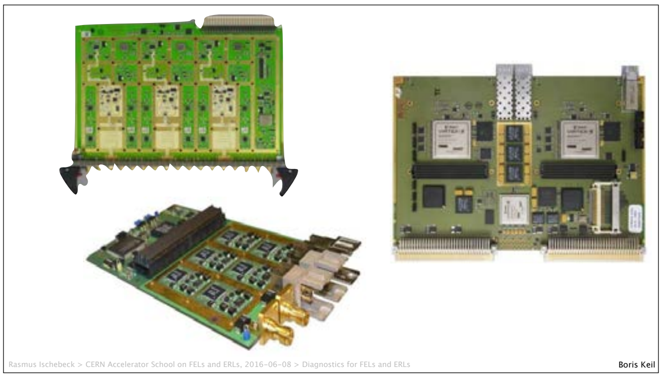
Absolute measurement of losses: leakage current in field effect transistor (FET)

Transverse Diagnostics

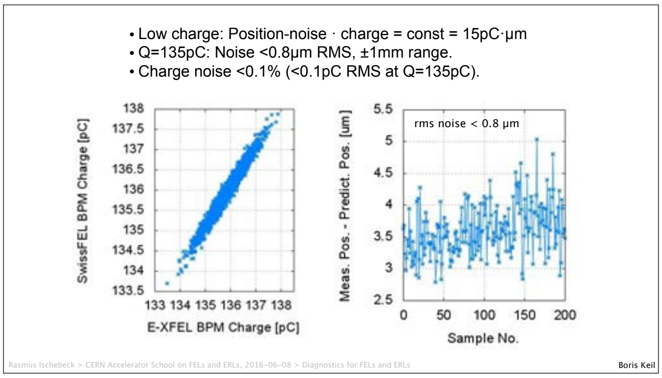
> Beam position monitors
> Profile monitors:
  > Scintillator
  > Synchrotron radiation
  > Optical transition radiation



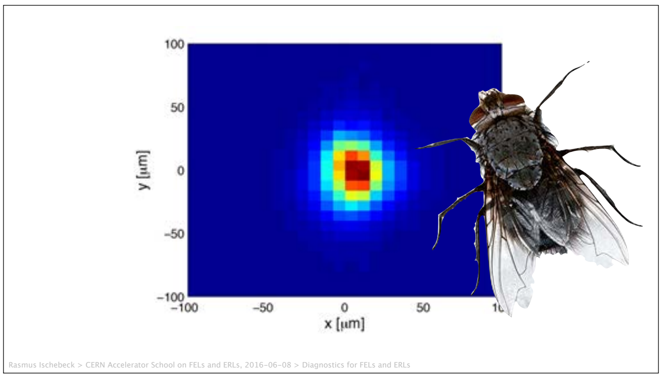
Beam position monitors: cavity pickups



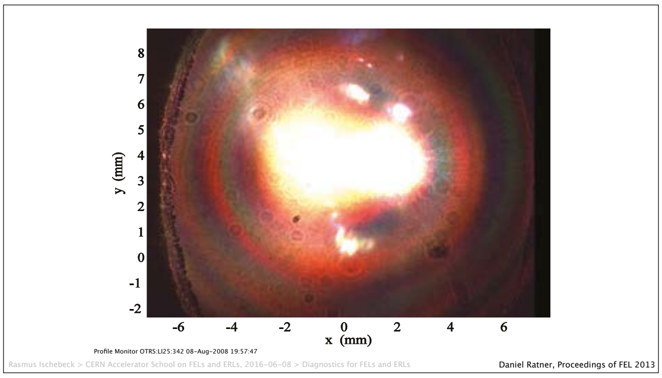
Signal processing, digitization and digital data processing



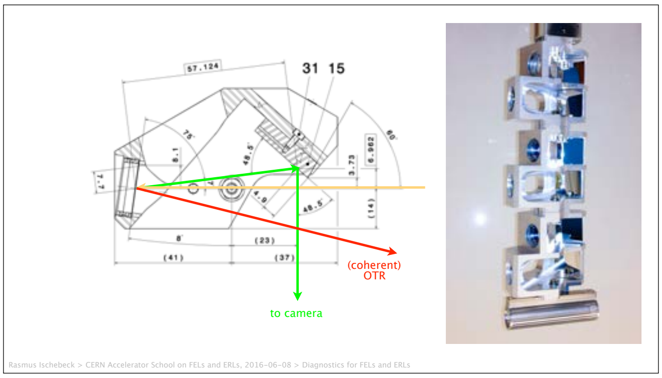
Very low noise readout of cavity BPMs results in sub-micrometer accuracy



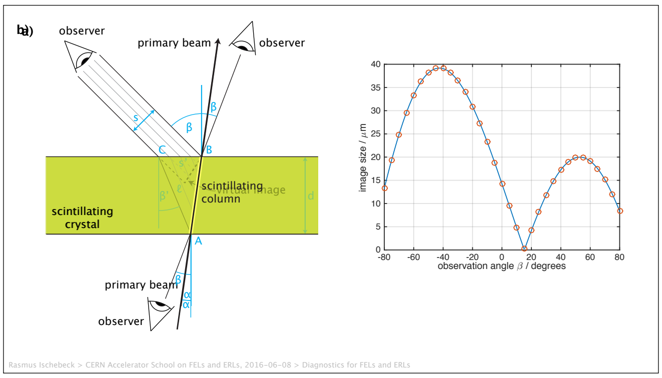
Beams in modern accelerators are small!



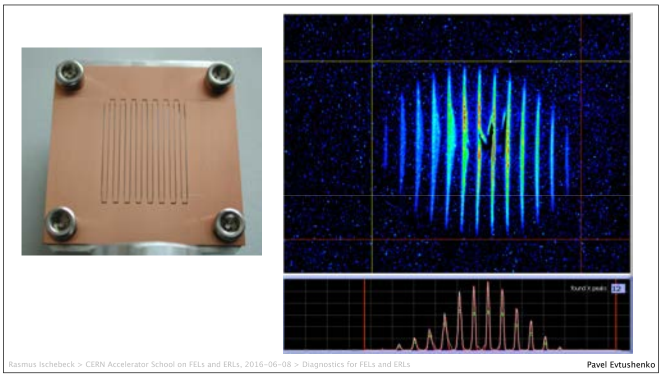
…but now: COTR!
Intense light, has made all the high-energy OTR monitors at LCLS useless



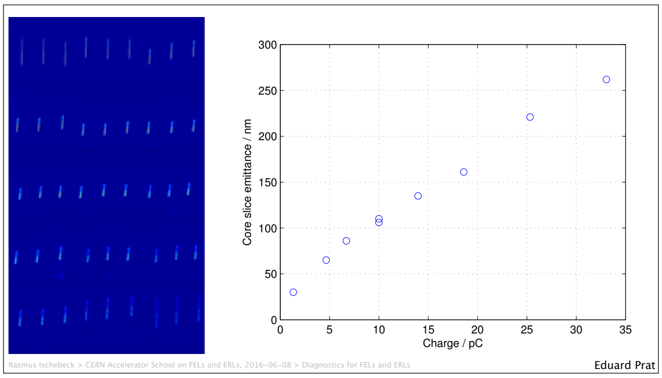
Direct COTR away from the imaging system!
At the same time, observe
> Snell's law of refraction
> Scheimpflug imaging condition



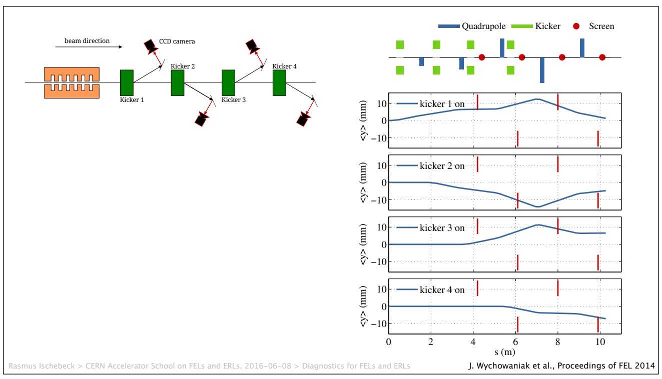
Snell's law of refraction results in an angle-dependent broadening of the virtual image



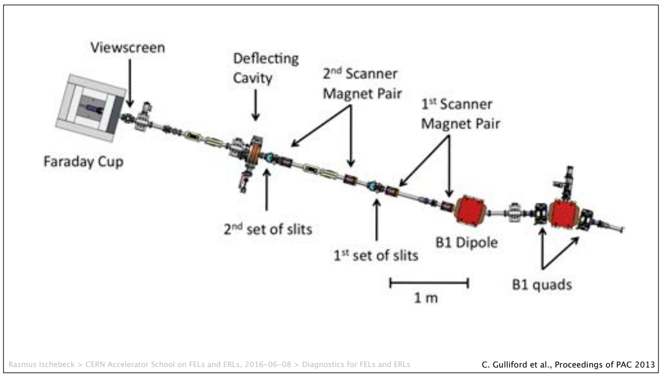
Measurement of emittance by slits



Measurement of small emittances by quadrupole scan
RF deflector allows measurement of time-resolved beam properties
> slice emittance
> beam optics (matching)



At high repetition rates (European XFEL):
Kicking the beam sideways to the screen



Measurement at ERL: making use of high repetition rate beam to measure emittance by scanning beam across slits

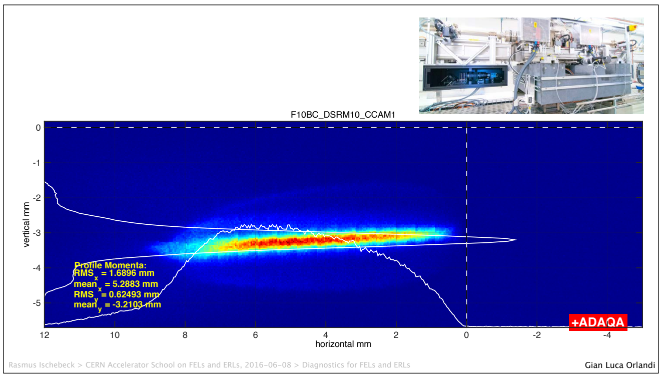
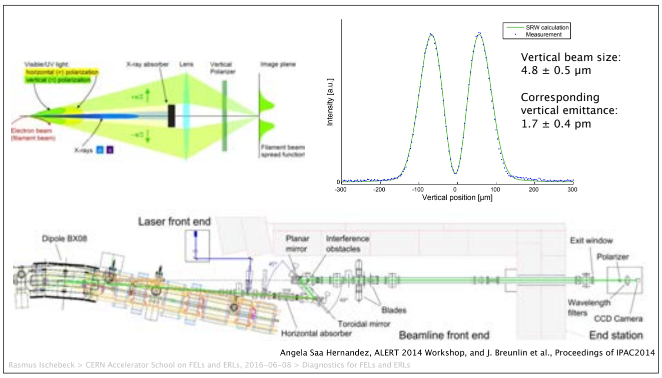


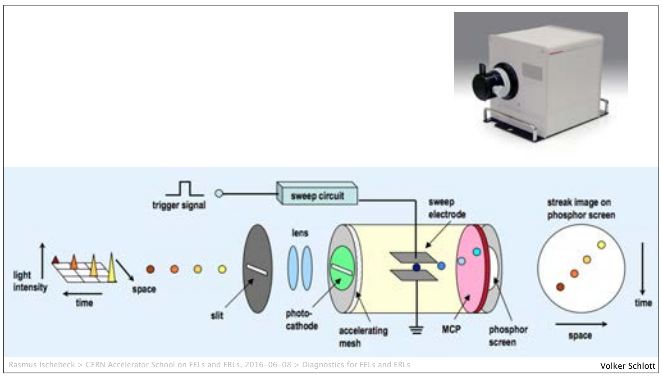
Image from synchrotron radiation monitor



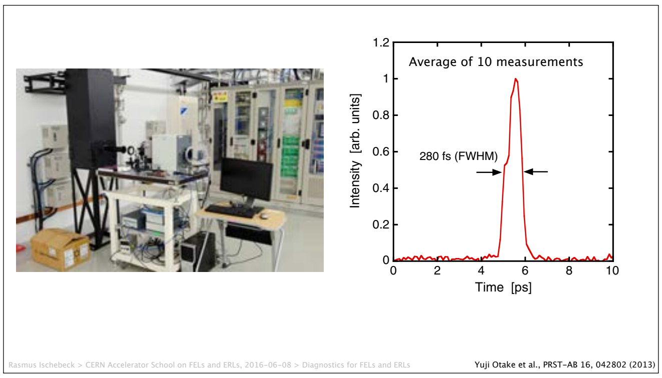
Measurement of synchrotron radiation in storage ring
> Measurement principle: interference of vertically polarized synchrotron light
> Measurement of very small beams possible, even at a large distance
> Requirement: very good knowledge of the beam shape (here: Gaussian)

Time-resolved instrumentation is especially challenging at FELs, due to the very short bunches

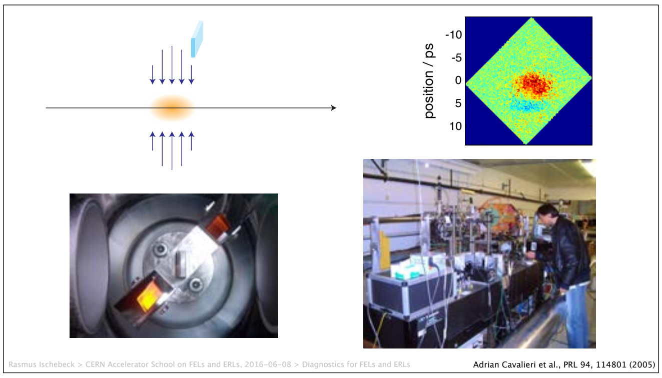
Let's first look at direct time domain methods!



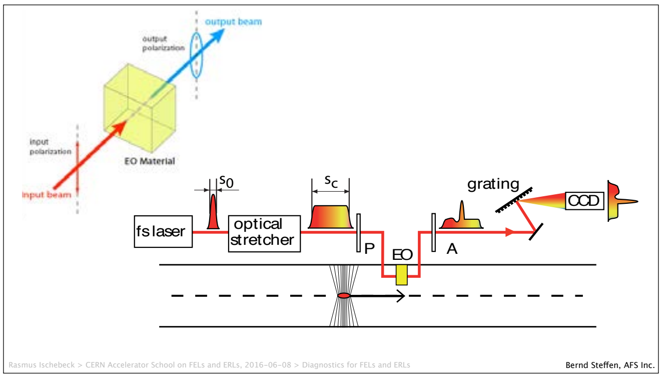
Streak Camera
Traditional method to determine pulse length
Resolution down to ~1 ps possible
Commercially available devices



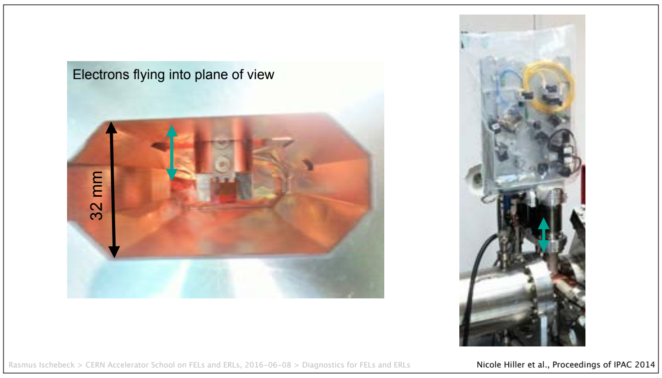
A sub-picosecond time resolution can be achieved with the latest generation streak camera.
Shown here: a measurement at SACLA



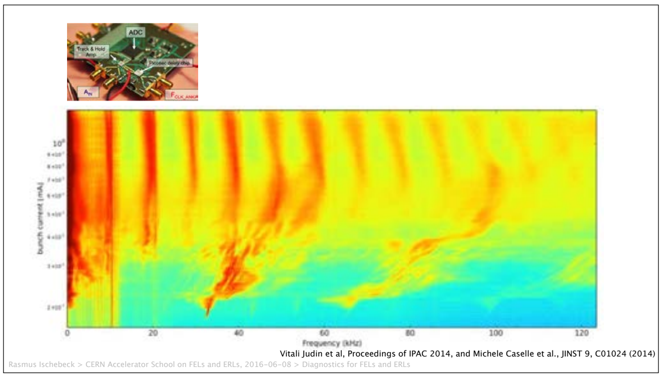
Another method to achieve sub-picosecond resolution is to probe directly the transverse electromagnetic field of the electron bunches.
An electro-optical crystal, i.e. one that exhibits the Pockels effect, is introduced into the vacuum chamber, and the change in birefringence is probed by a short laser pulse.



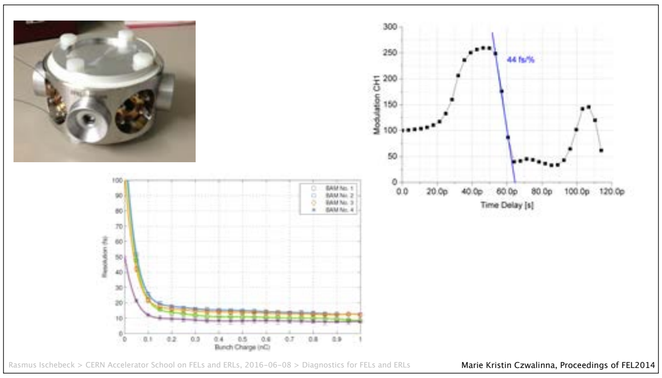
Cross-correlation with an external laser pulse
Pockels effect allows to cross-correlate coherent THz fields with laser
Reflectivity change allows to cross-correlate X-rays with laser
Measure: Bunch arrival time & Bunch length
Also known as “Electro-optical effect”
Electric field induces birefringence in crystal
Birefringence can be probed with a polarized laser
Pockels Effect can probe down to time scales of 10…100 fs
Effect is totally reversible



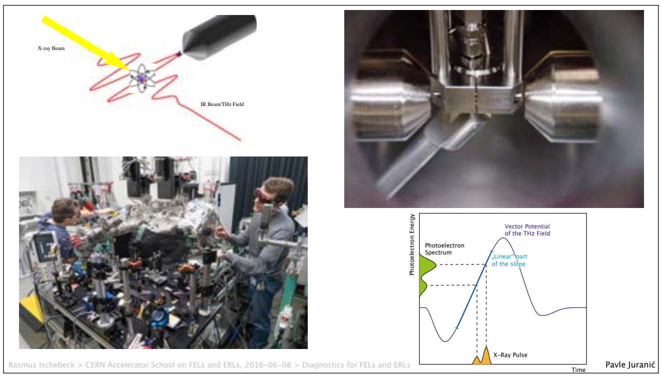
The setup has been transformed from an experiment to a reliable diagnostics.
Shown here: electro-optical monitor at the ANKA storage ring, designed in a KIT-DESY-PSI collaboration.



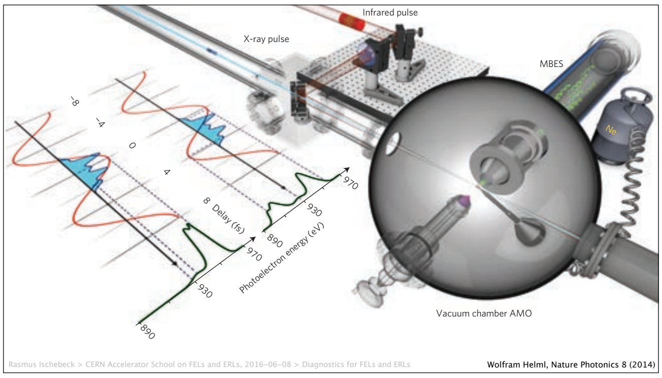
Interesting detail: fast readout of the detector.
Measurement of instabilities as a function of beam current in a storage ring



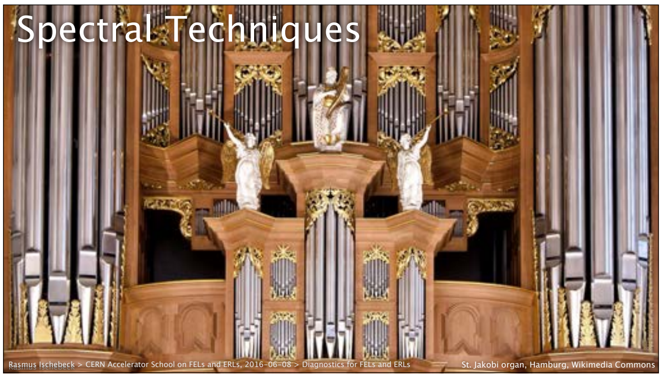
Another possibility: put the electro-optical crystal in a box outside the accelerator vacuum, and transmit the EM field through cables.
—> Possibility to measure arrival time



THz Streak Camera installed at SACLA
Measurement principle: X-ray photons ionize a gas
Photoelectron spectrum is equal to photon spectrum minus binding energy
Additional electromagnetic field (THz) streaks the photoelectrons

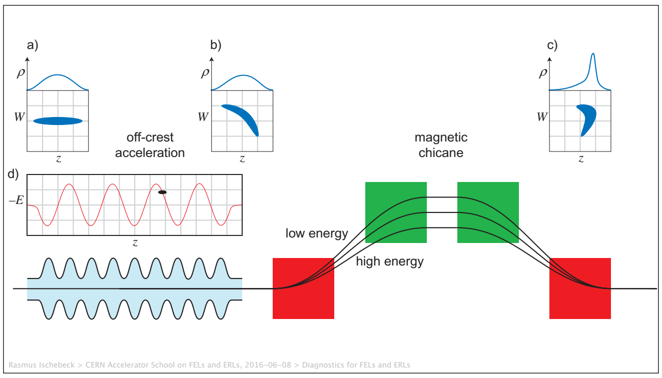


Measurements at LCLS confirm sub-cycle pulse length

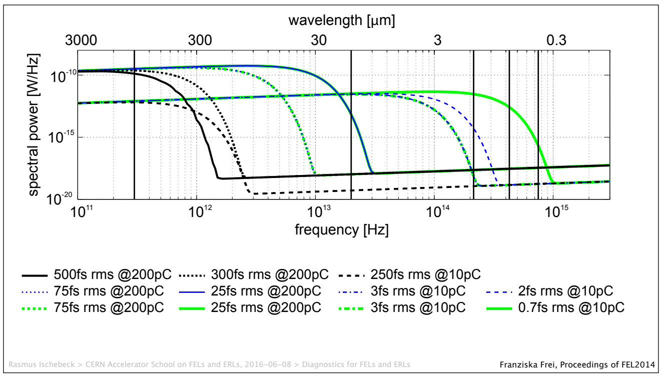


Another possibility: ignore the phase of the spectrum of the bunch, and measure only spectral amplitude

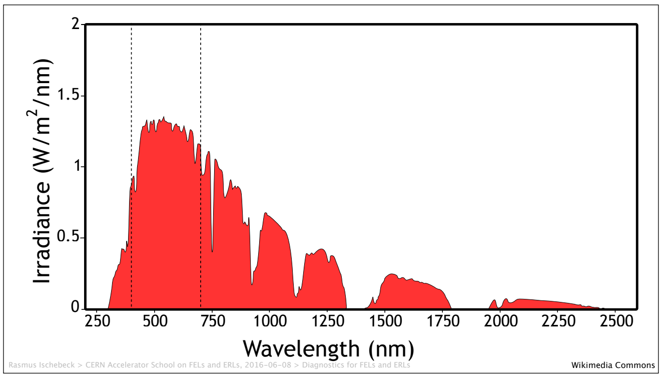
—> Stabilization for feedbacks



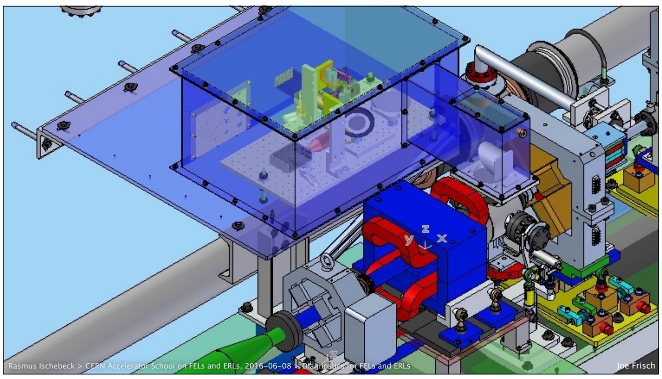
Reminder: bunch compression



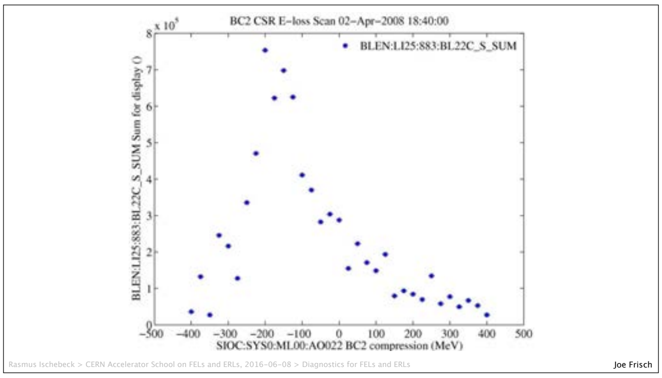
Calculated spectrum, assuming Gaussian bunches, for different compression stages, and for different operation modes of SwissFEL.
Note logarithmic scales on both axes!



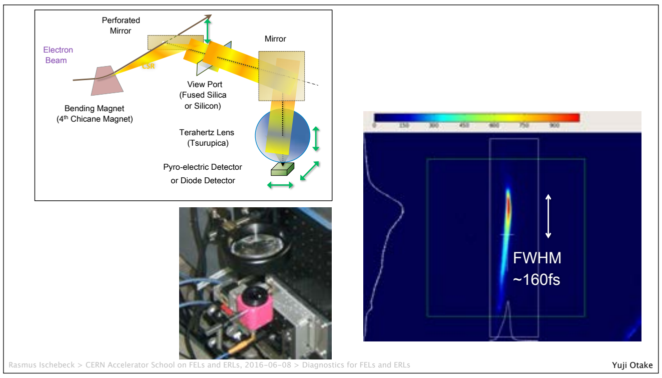
Careful! Ignoring the phase of the radiation means that generally, you cannot reconstruct the bunch length from the spectrum.



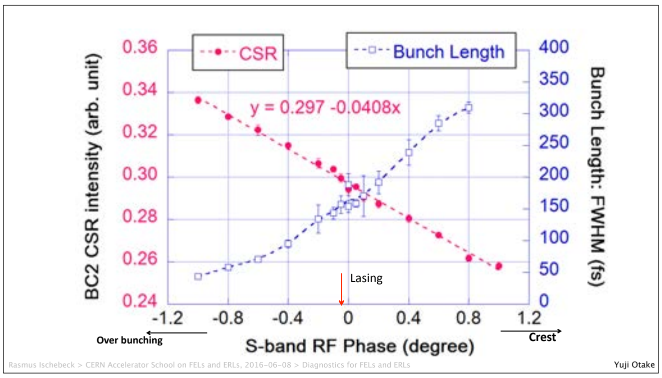
Setup at LCLS
Detection of coherent edge radiation from the bunch compressor



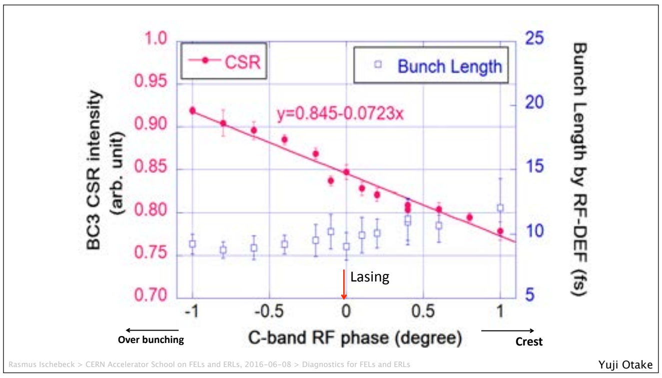
Signal peaks at maximum compression



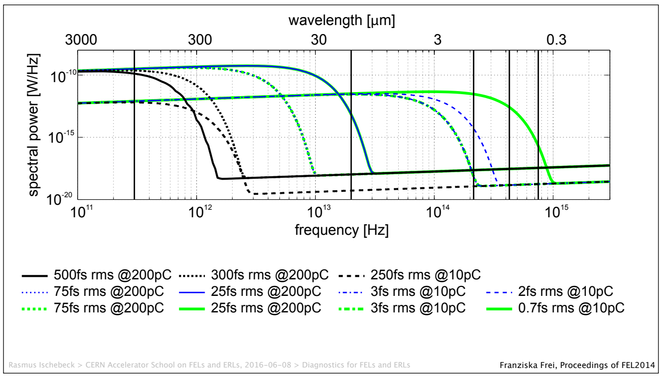
Similar setup at SACLA (free electron laser at SPring8 in Japan)
I will now show a comparison of CSR measurement with bunch length measurements using transverse deflecting cavity



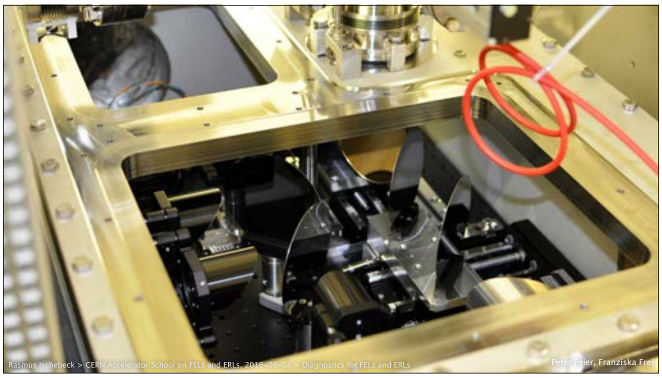
The bunch length observed with the CSR monitor was calibrated by using the RF-deflector's data.
Electron beam was bypassed through BC3.
Bunch length was changed by the RF phase of the S-band accelerating structures.
Estimated bunch length measurement sensitivity is about 6% at a bunch length of 170fs.



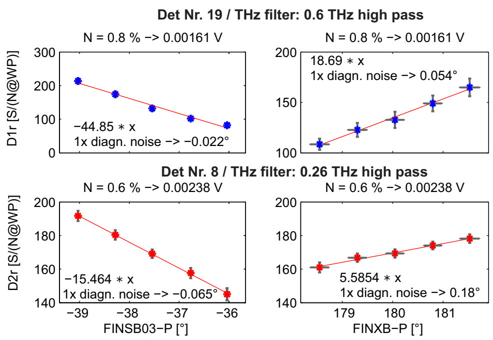
CSR intensity as a function of the RF Phase of the C-band accelerating structures before BC3
CSR intensity was linearly changed by the RF phase of the C-band (5712 MHz) accelerating structure before BC3.
Estimated bunch length measurement sensitivity is less than 0.1 deg., which is better than that of the RF deflector.



Coming back to the power distribution of CSR, we see that we could improve resolution if we detect selectively near an edge

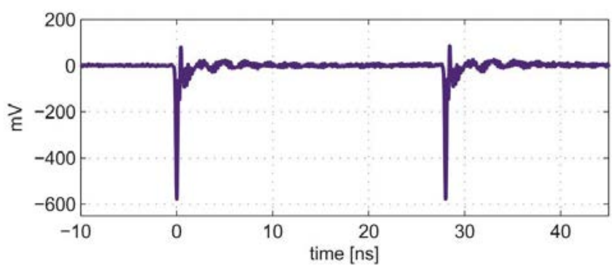


Setup installed at the SwissFEL Injector Test Facility
Beam splitters, then using grids as edge pass filters



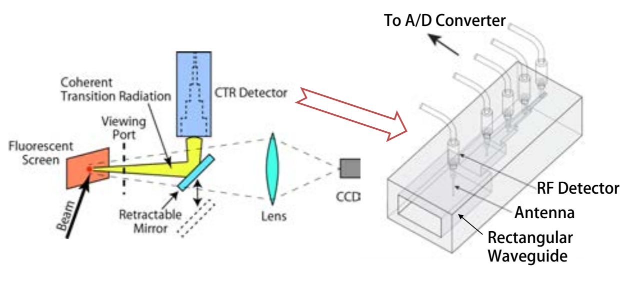
Franziska Frei, Proceedings of FEL2014

Indeed, sensitivity to X-band phase changes (i.e. compression changes) increased when using only high-frequency radiation



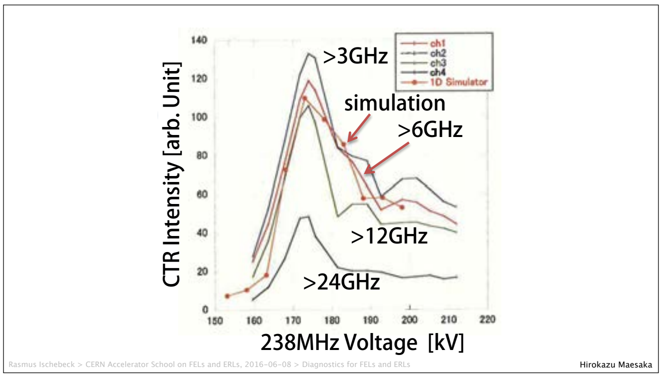
Franziska Frei

This detector is very fast: detection of two bunches separated by 28 ns easily possible

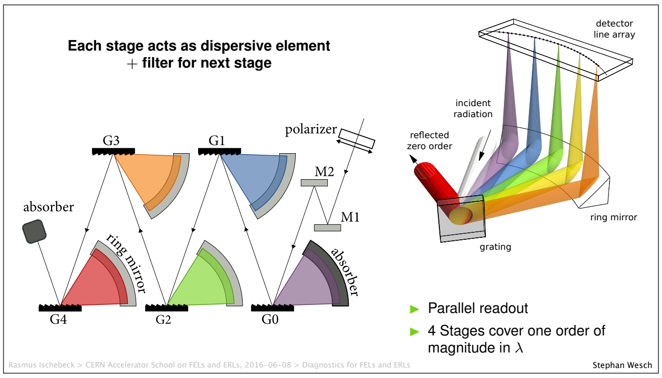


Hirokazu Maesaka

Similar idea: detect different frequency components. Here: five channels separated by waveguides, for GHz frequencies
(SACLA after first compression)



Dependency of different frequency signals on compression



THz spectrometer with 120 channels implemented at DESY, for FLASH

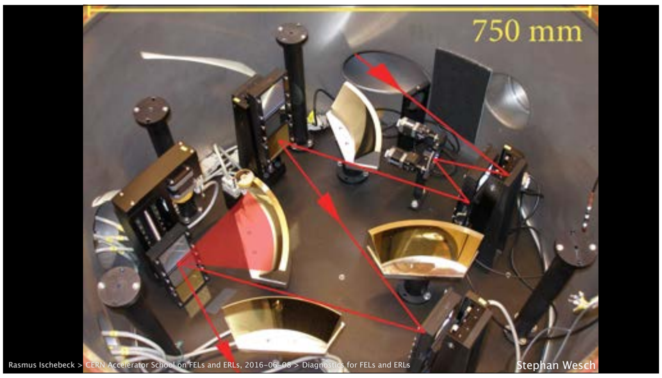
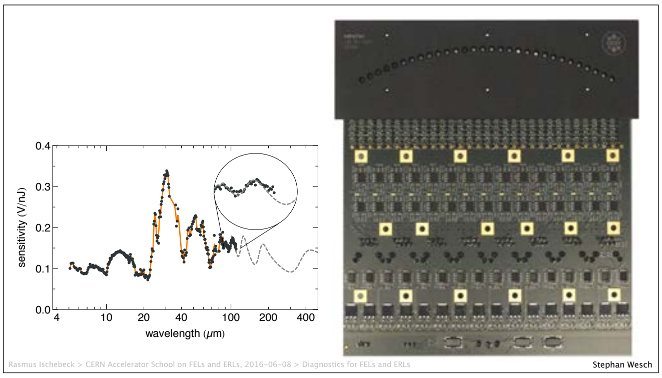
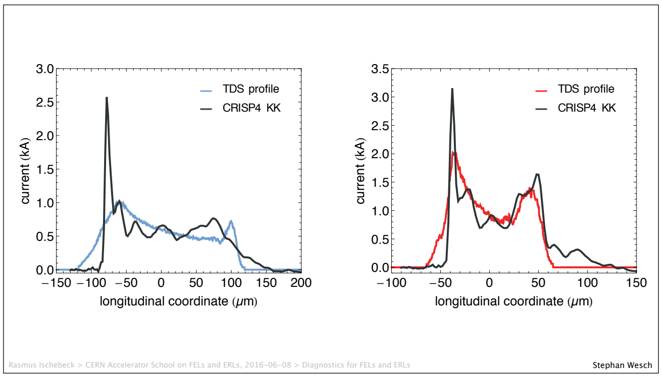


Photo of the setup



Parallel readout of a total of 120 channels in pyro detector arrays



Reconstruction with Kramers-Kronig relation.
Keep in mind: this is the shortest pulse compatible with the spectrum.
The spectrum in itself is also compatible with a bunch length of 4.6 billion years!

Rasmus Ischebeck > Diagnostics for FELs and ERLs

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