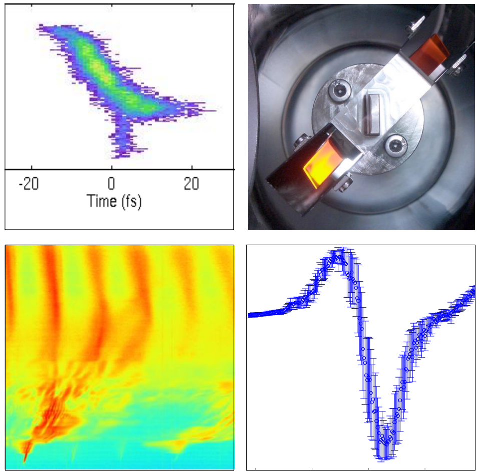
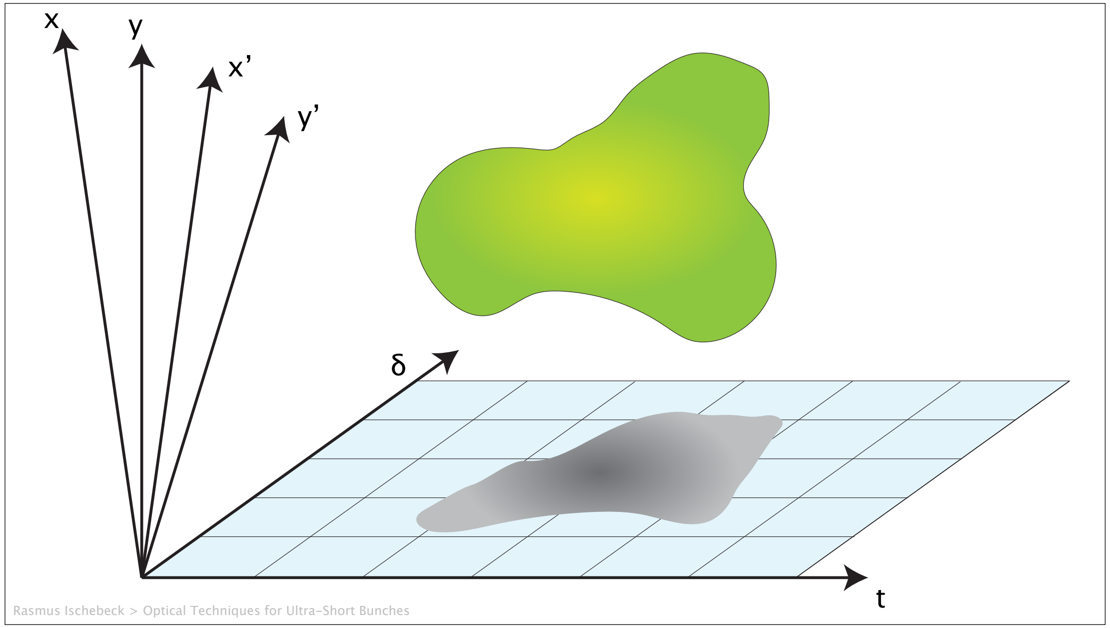


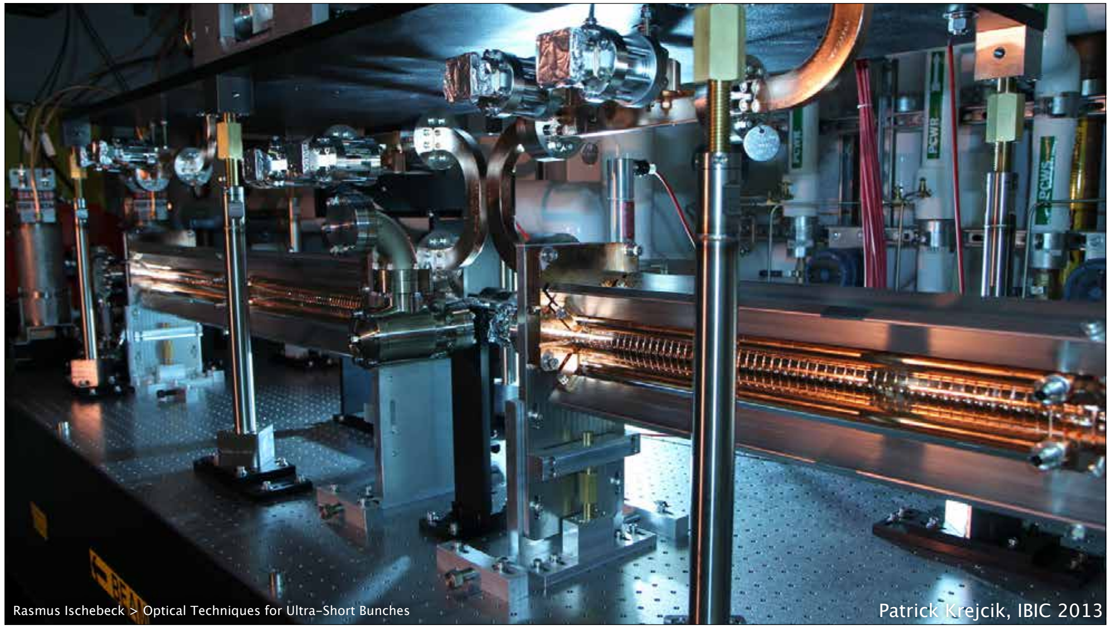
Optical Techniques for Ultra-Short Bunches

Rasmus Ischebeck

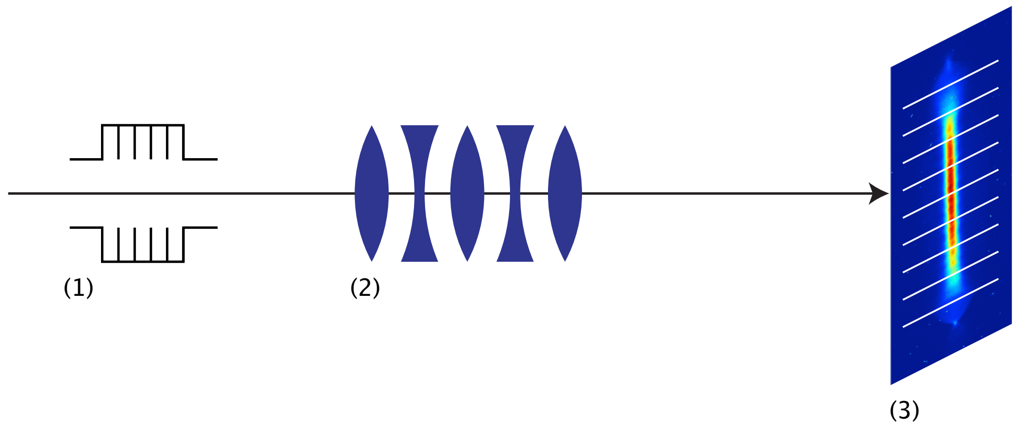


Let's first have a look at the object of study, the beam.
This beam can be represented by the particle distribution in the six-dimensional phase space, extended by transverse coordinates x and y, transverse angles x' and y', time t and energy delta.
When we speak about the longitudinal phase space, we mean the projection on these last two dimensions, and in particular the time, which is very difficult to measure with femtosecond accuracy.

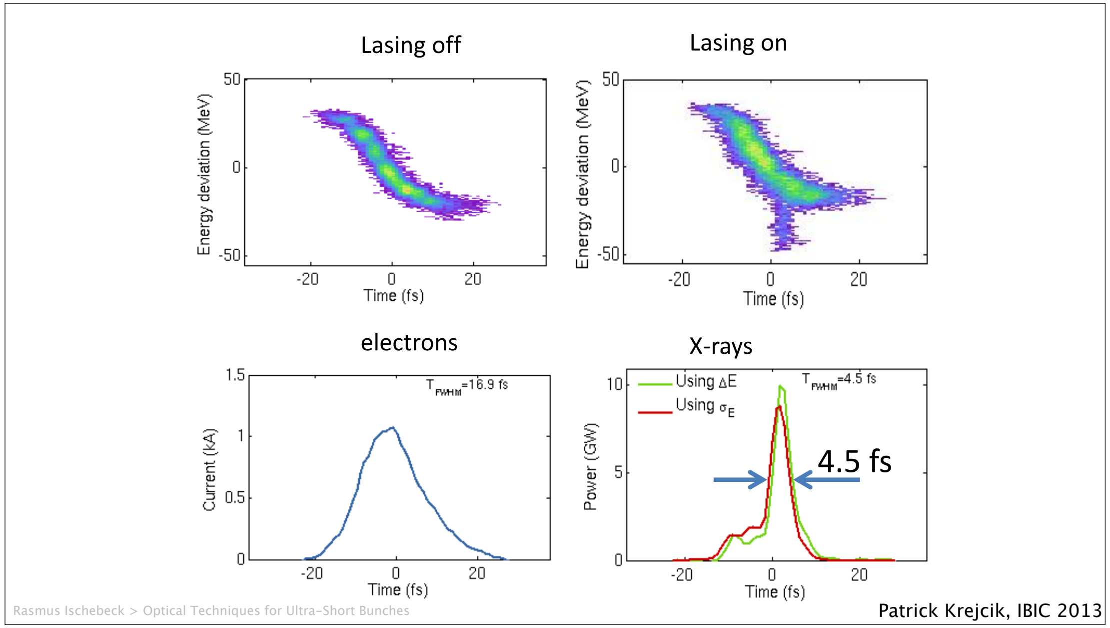
There are ways to transform the beam in phase space.
No diagnostics exists for the entire distribution.
We can only measure projections into one or two of these dimensions.
Additional beam line elements, such as quadrupole magnets and transverse deflecting RF cavities can then be used to do phase space transformations, which allow us to see dimensions that are not easily accessible, and we can use mathematical reconstruction algorithms to infer 3d information.



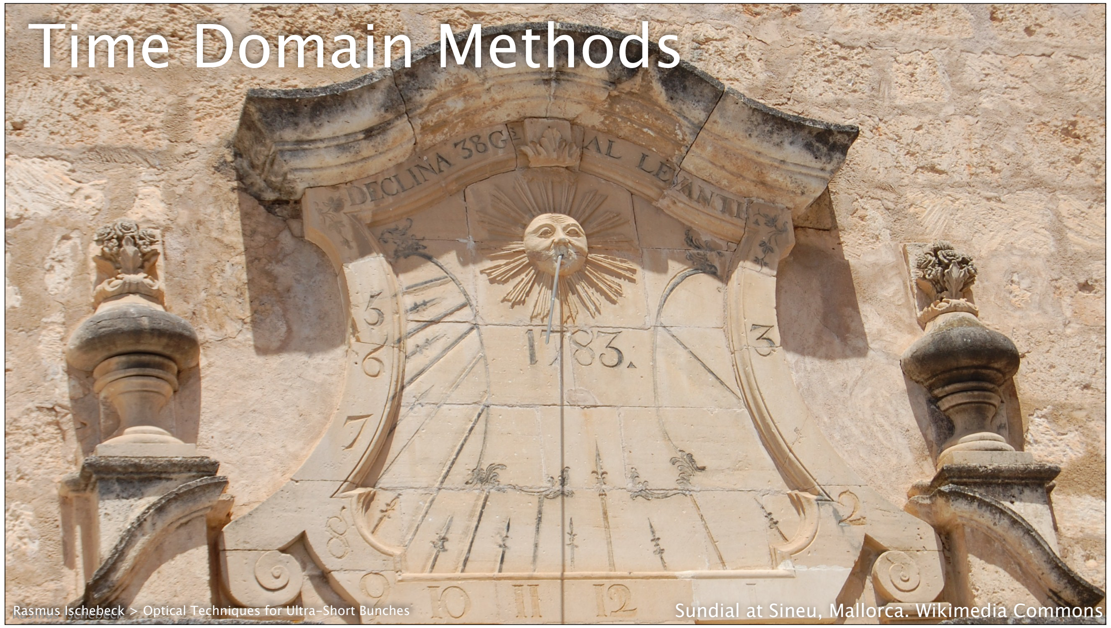
Phase space transformation with RF deflecting cavity
Reference for all longitudinal diagnostics
Shown here: installation in LCLS



Beam transport
Phase advance with quadrupoles
Detection on screen



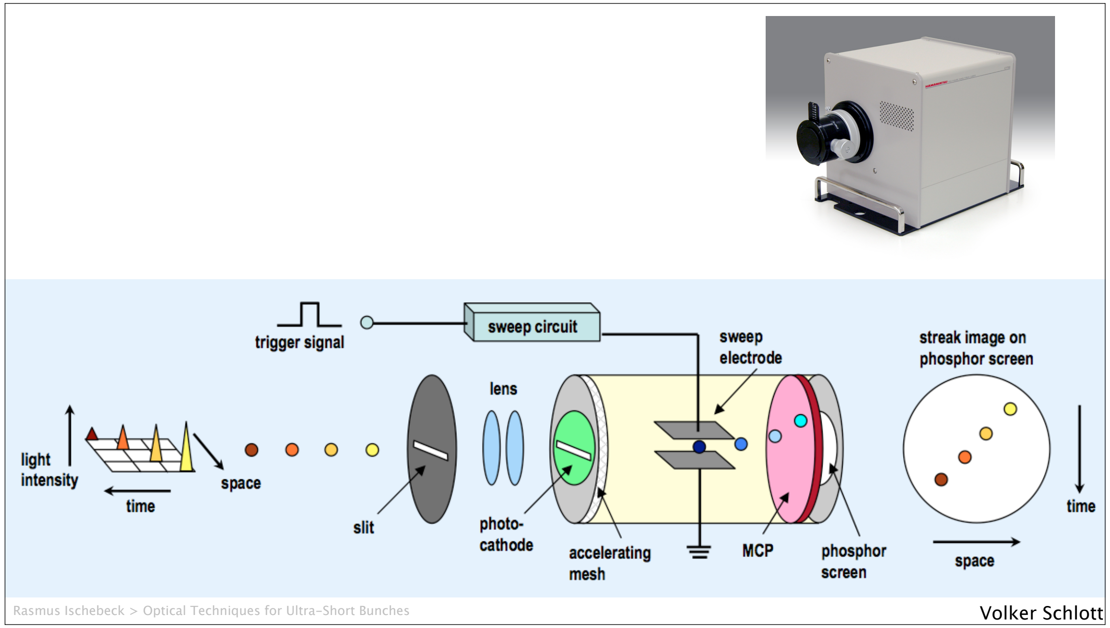
Measurements of full phase space possible!
Femtosecond resolution, depending on:
— emittance
— streak strength



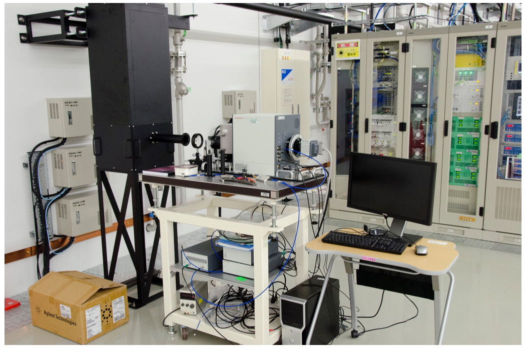
When designing an accelerator, we can carefully choose an instrumentation suite that lets us
> set up the accelerator
> measure beam properties
> control the stability of the machine via feedbacks

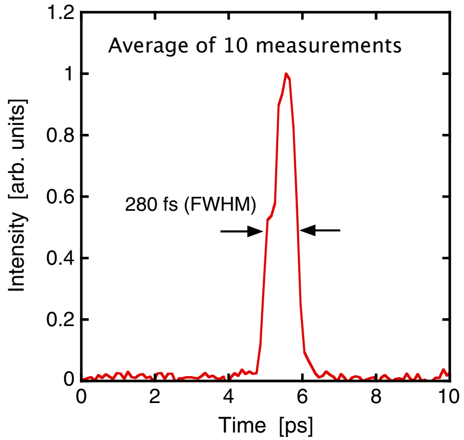
Thus, let us distinguish longitudinal and transverse diagnostics. It is not a clear distinction, as we can transform the phase space dimensions, but it's a start.

Let’s start with direct time domain methods.



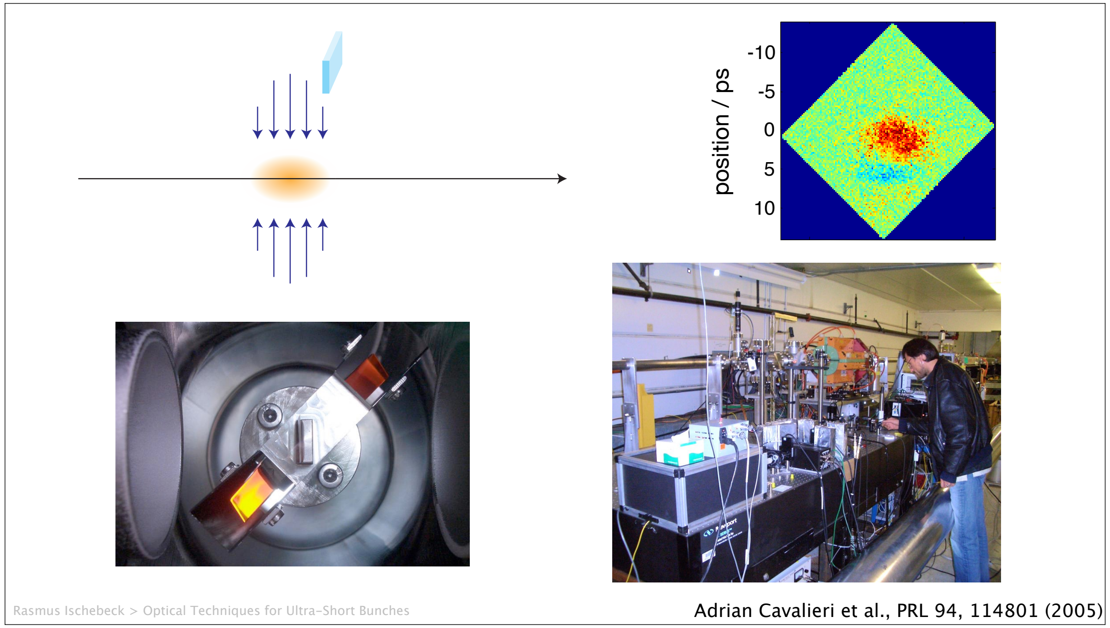
Streak camera



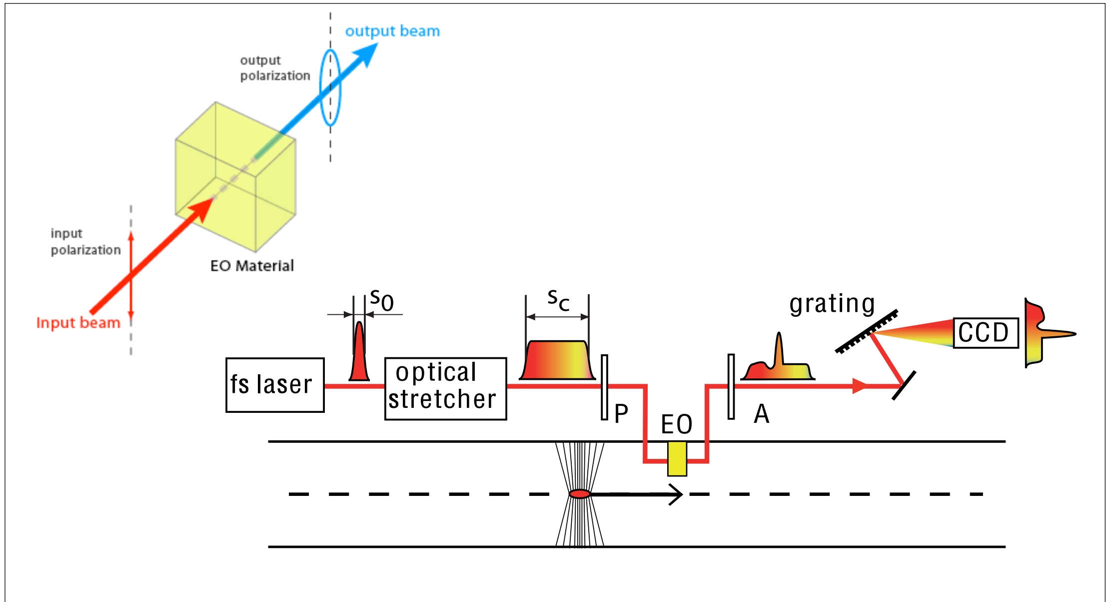


Yuji Otake et al., PRST-AB 16, 042802 (2013)

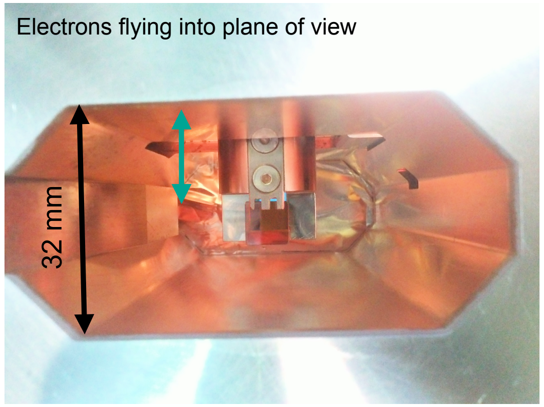
A sub-picosecond time resolution can be achieved with a streak camera.
Shown here: a measurement at SACLA



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.

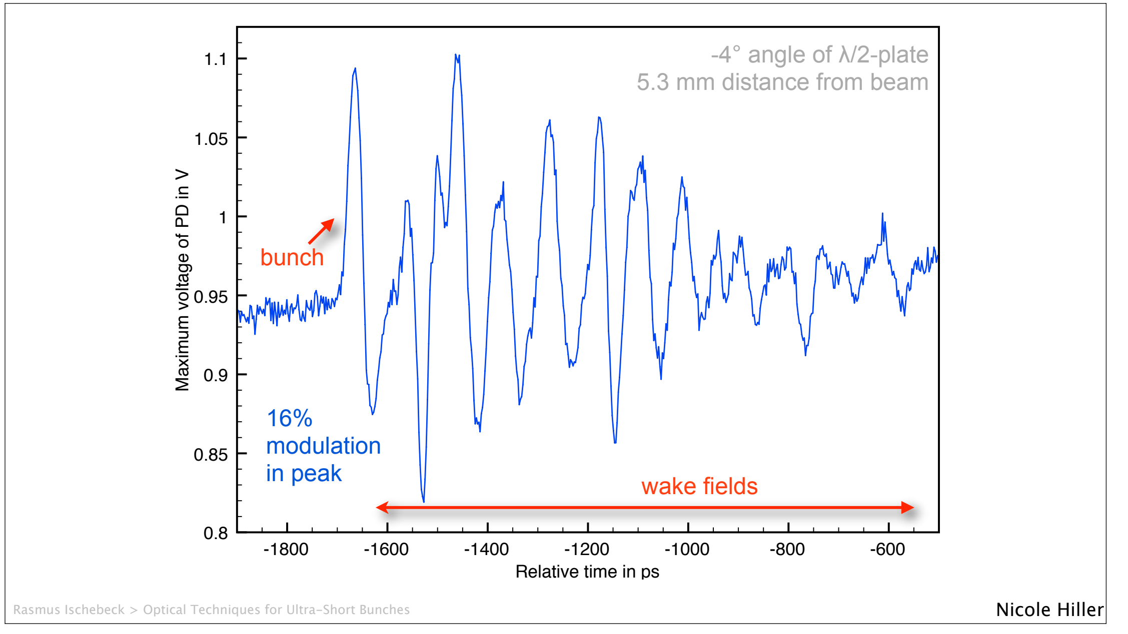


Cross-correlation with an external laser pulse
Pockels effect allows to cross-correlate coherent THz fields with laser
Reflectivity change allows to cross-correlate X-rays with laser
Measure:
Bunch arrival time
Bunch length
Also known as “Electro-optical effect”
Electric field induces birefringence in 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
Possible materials
ZnTe
LiNb
GaP

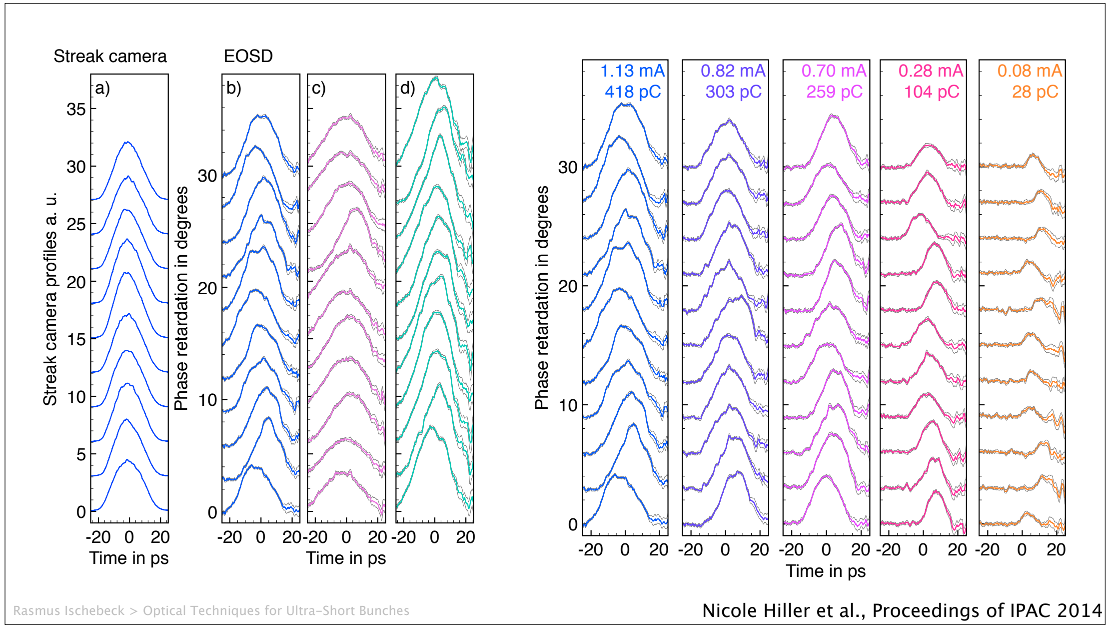


Nicole Hiller et al., Proceedings of IPAC 2014

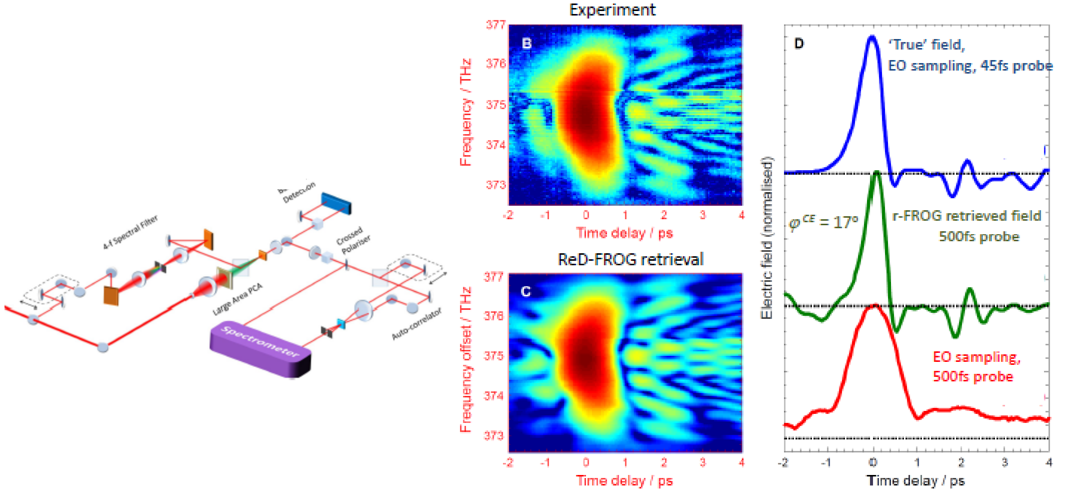
The setup has been transformed from an experiment to a reliable diagnostics.
Shown here: electro-optical monitor at the ANKA storage ring, designed in a KIT-DESY-PSI collaboration.



Beware of wake fields!

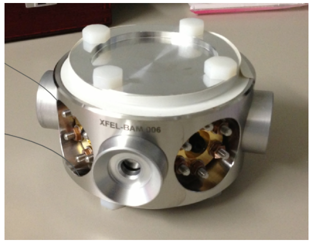


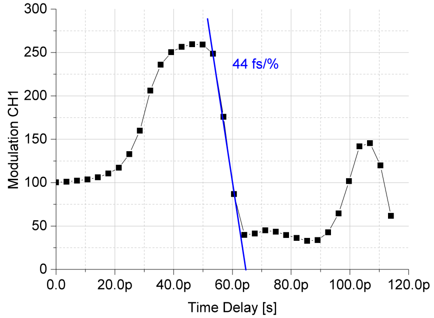
Measurements with this monitor for different compression (middle), and for different bunch charges (right). To the left, a comparison with a streak camera measurement

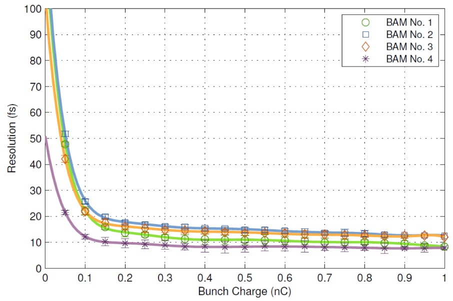


Steve Jamison, 4th Workshop on Longitudinal Instrumentation for Future Accelerators (2015)

Limitations: resonances in crystal, and available laser pulse length.
Two-pulse Cross-FROG:
Electro-optic sampling with sub-pulse width time-resolution
> Sampling with 500fs FWHM transform limited probe
> ReD-FROG with sum- & difference frequency sidebands
=> Retrieve electric field profile as obtained with 45fs FWHM probe

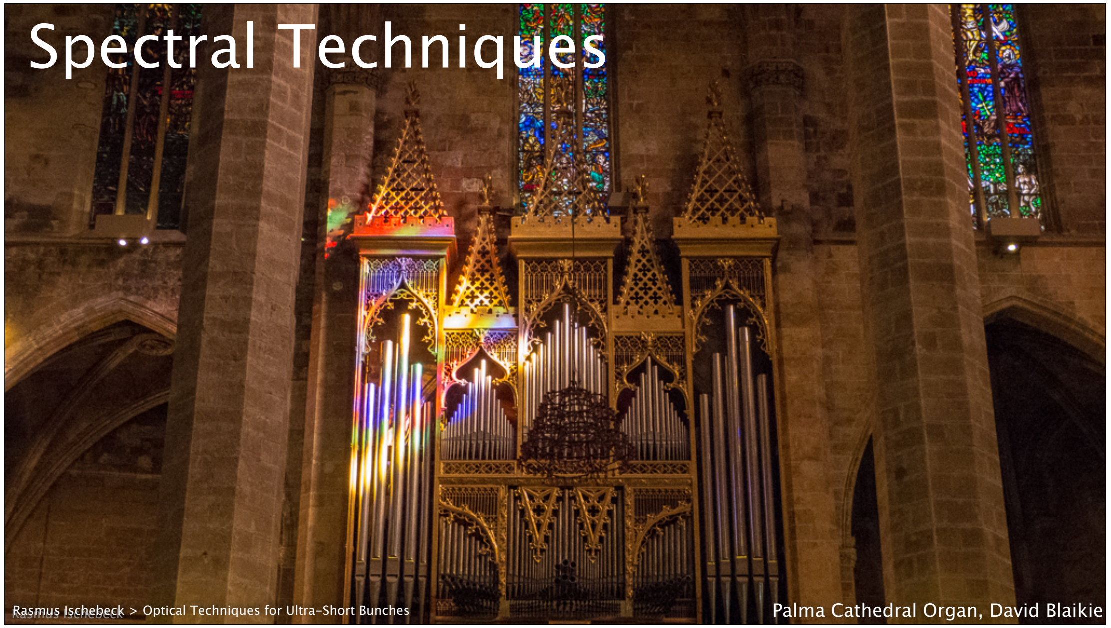




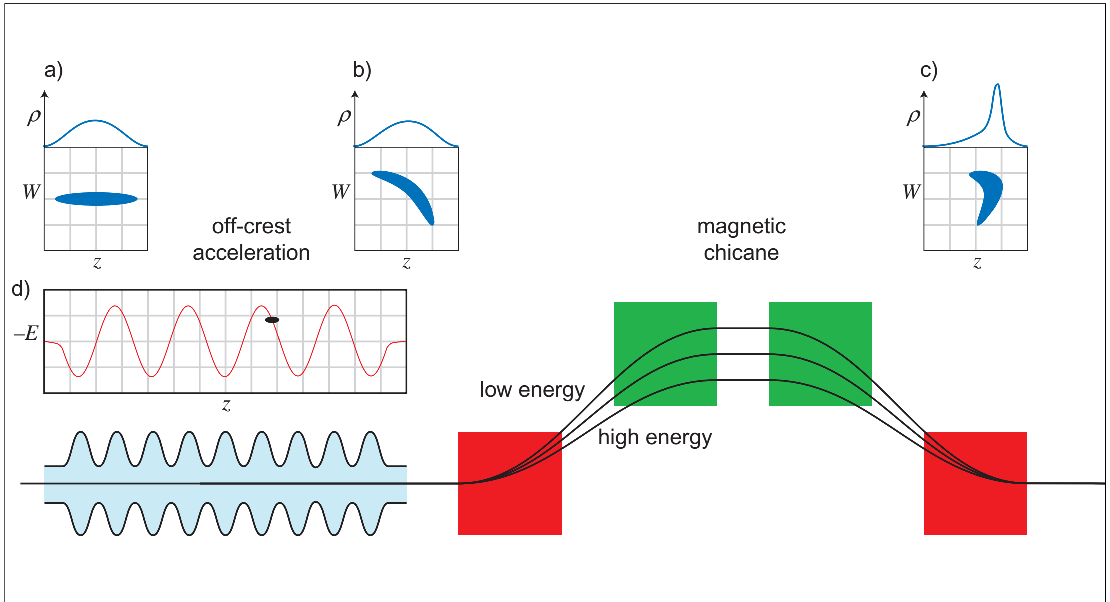


Marie Kristin Czwalinna, Proceedings of FEL2014

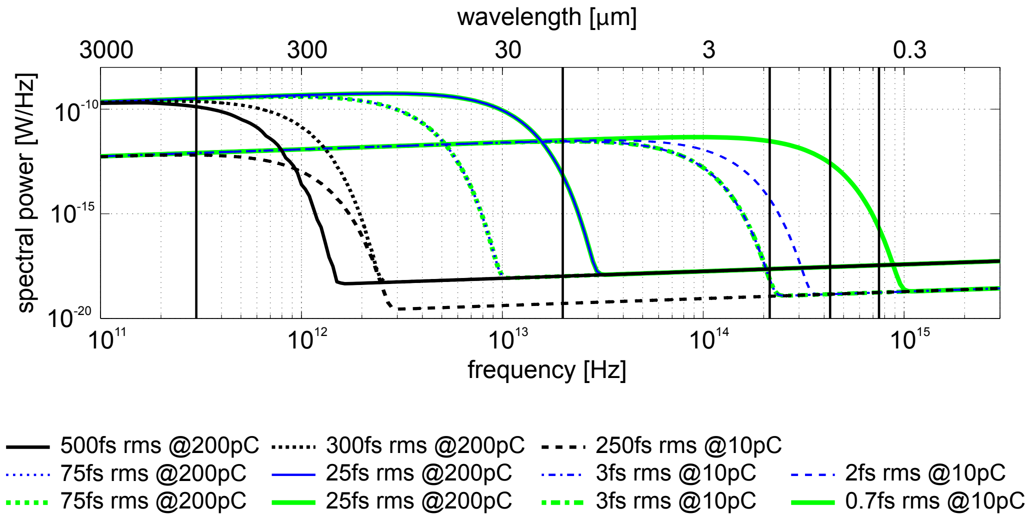
Another possibility: put the electro-optical crystal in a box outside the accelerator vacuum, and transmit the EM field through cables.
—> Possibility to measure arrival time



Another possibility: ignore the phase of the spectrum of the bunch, and measure only spectral amplitude
—> Stabilization for feedbacks

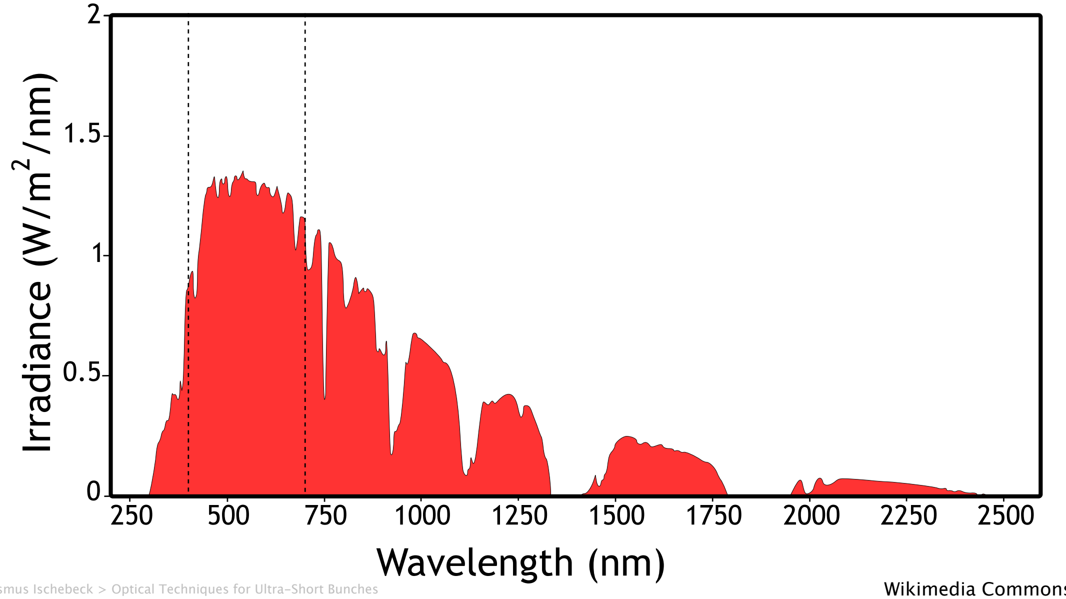


Reminder: bunch compression



Franziska Frei, Proceedings of FEL2014

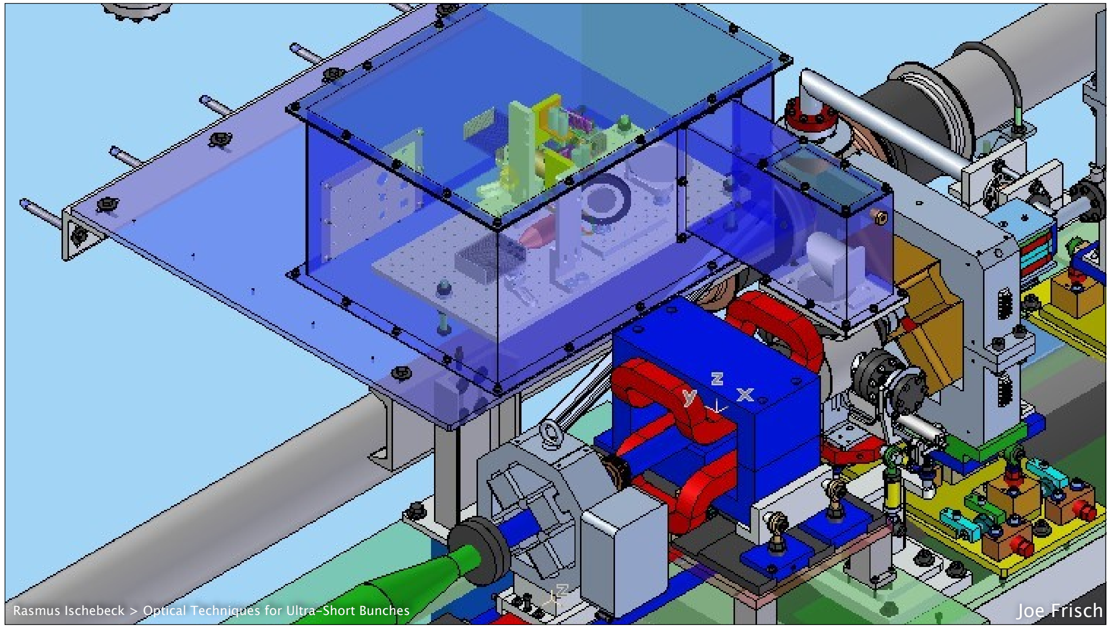
Calculated spectrum, assuming Gaussian bunches, for different compression stages, and for different operation modes of SwissFEL.
Note logarithmic scales on both axes!



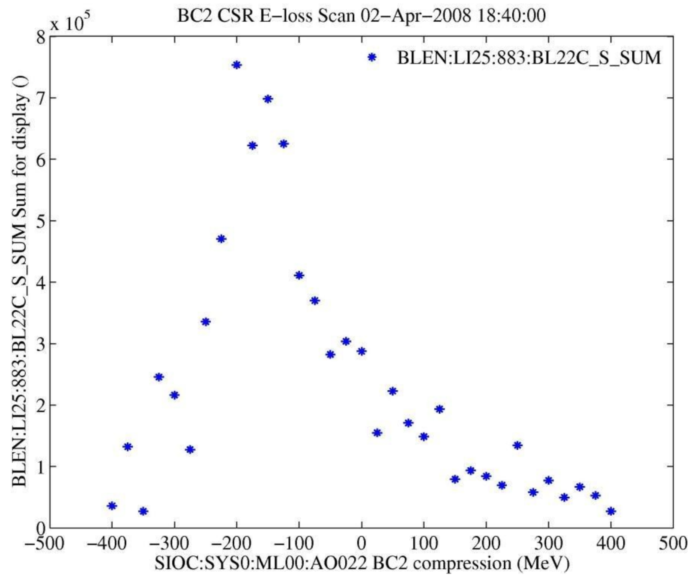
Wikimedia Commons

Careful! Ignoring the phase of the radiation means that generally, you cannot reconstruct the bunch length from the spectrum.
Take a look at this spectrum: it peaks at 550 nm, so you may be lead to believe that the pulse is 1.8 fs long.

In fact, this is the spectrum of the sun.
Pulse length = age of the sun: 4.6 billion years! — almost 32 orders of magnitude off…

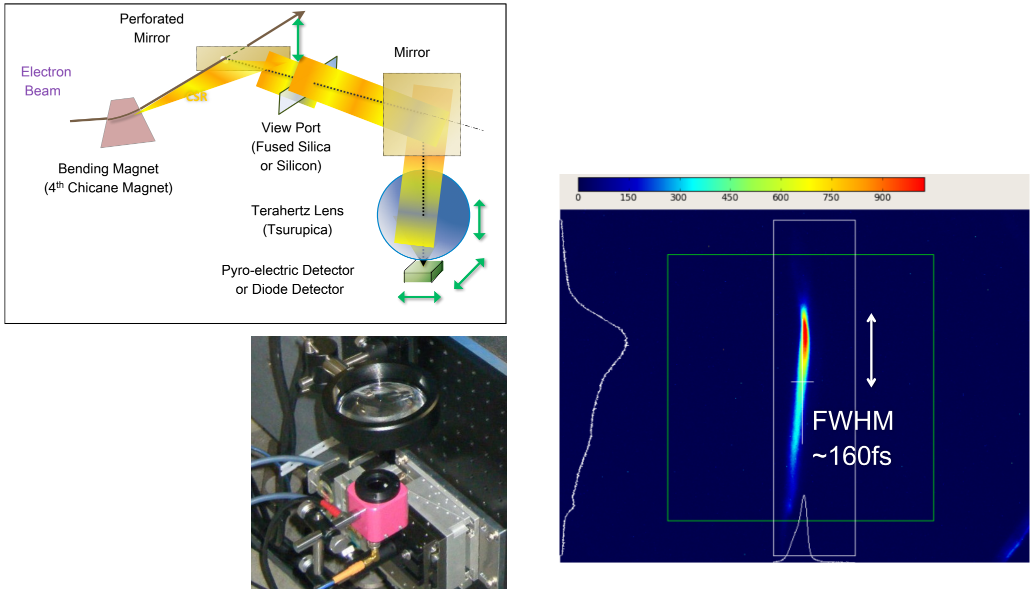


Setup at LCLS
Detection of coherent edge radiation from the bunch compressor



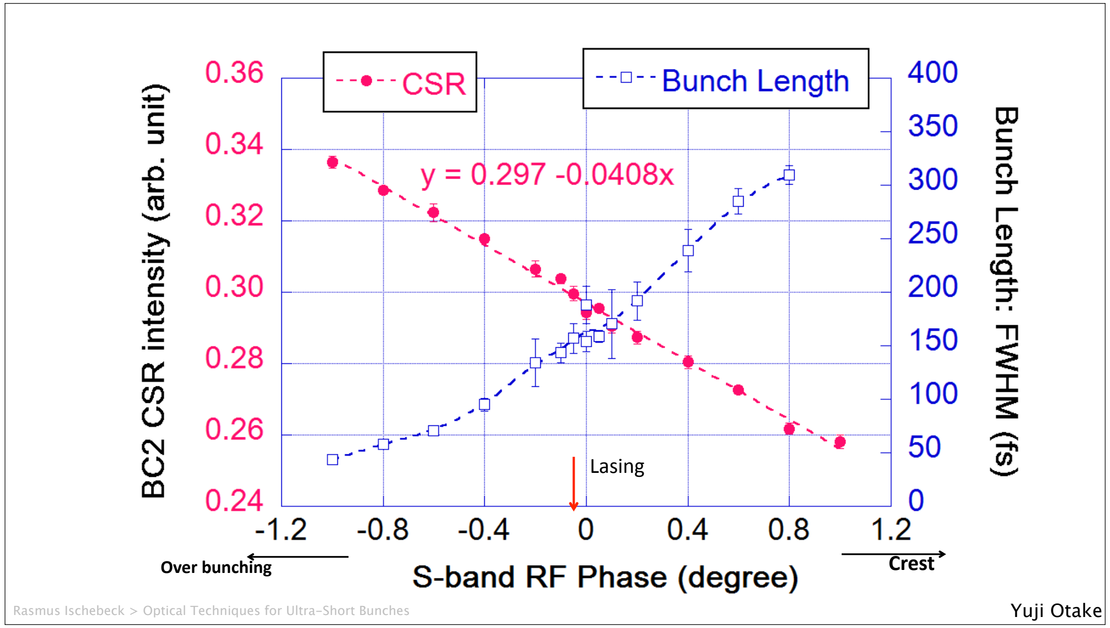
Joe Frisch

Signal peaks at maximum compression

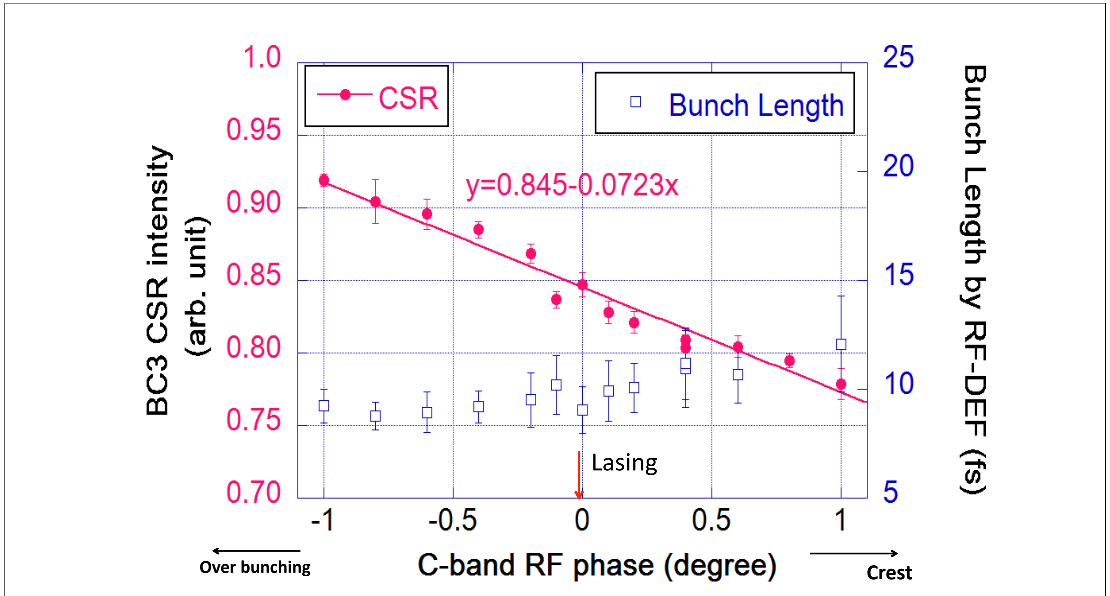


Yuji Otake

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

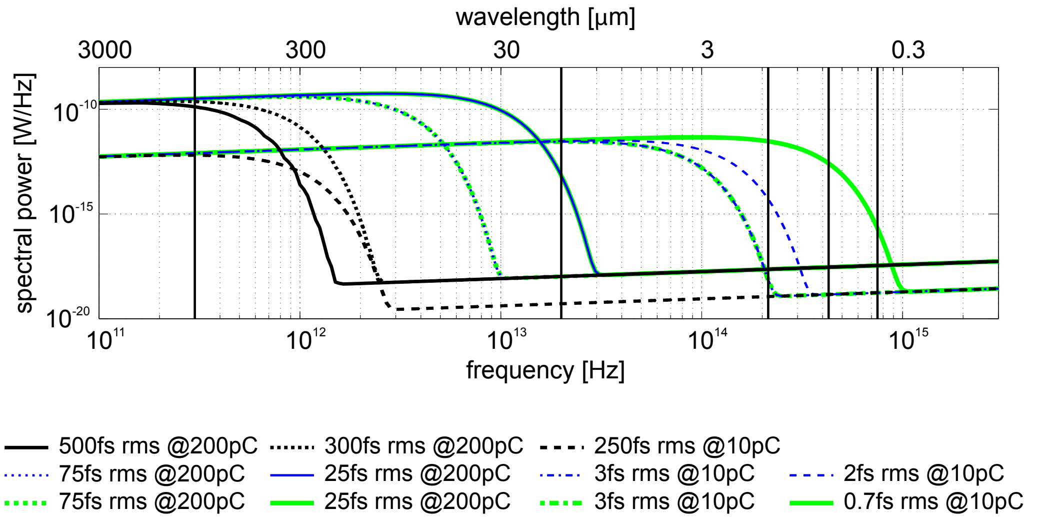


The bunch length observed with the CSR monitor was calibrated by using the RF-deflector's data.
Electron beam was bypassed through BC3.
Bunch length was changed by the RF phase of the S-band accelerating structures.
Estimated bunch length measurement sensitivity is about 6% at a bunch length of 170fs.



Yuji Otake

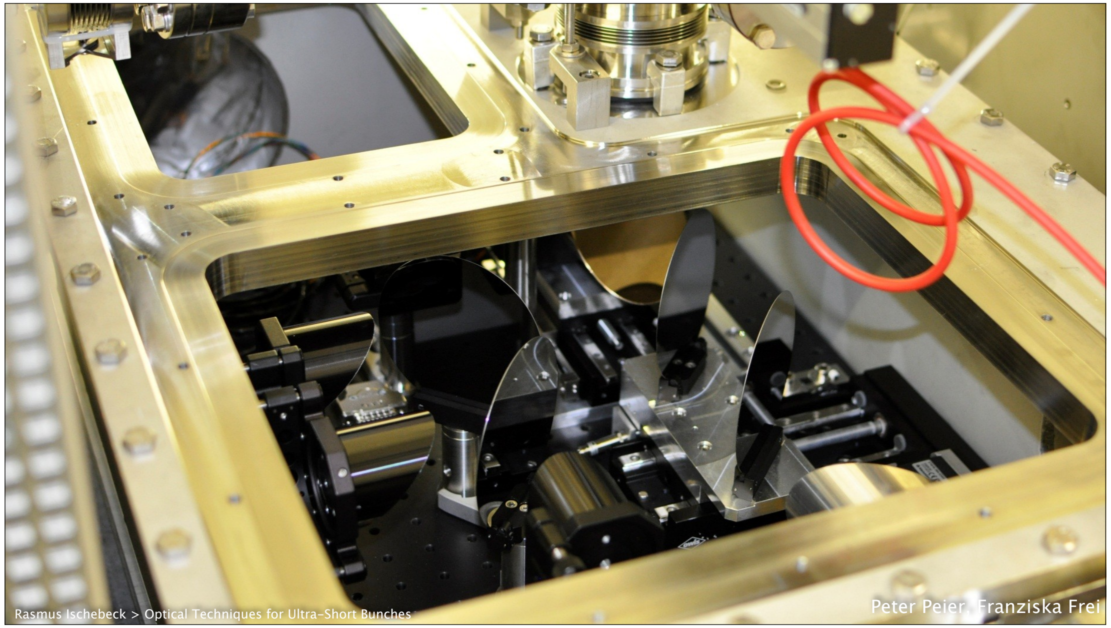
CSR intensity as a function of the RF Phase of the C-band accelerating structures before BC3
CSR intensity was linearly changed by the RF phase of the C-band (5712 MHz) accelerating structure before BC3.
Estimated bunch length measurement sensitivity is less than 0.1 deg., which is better than that of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



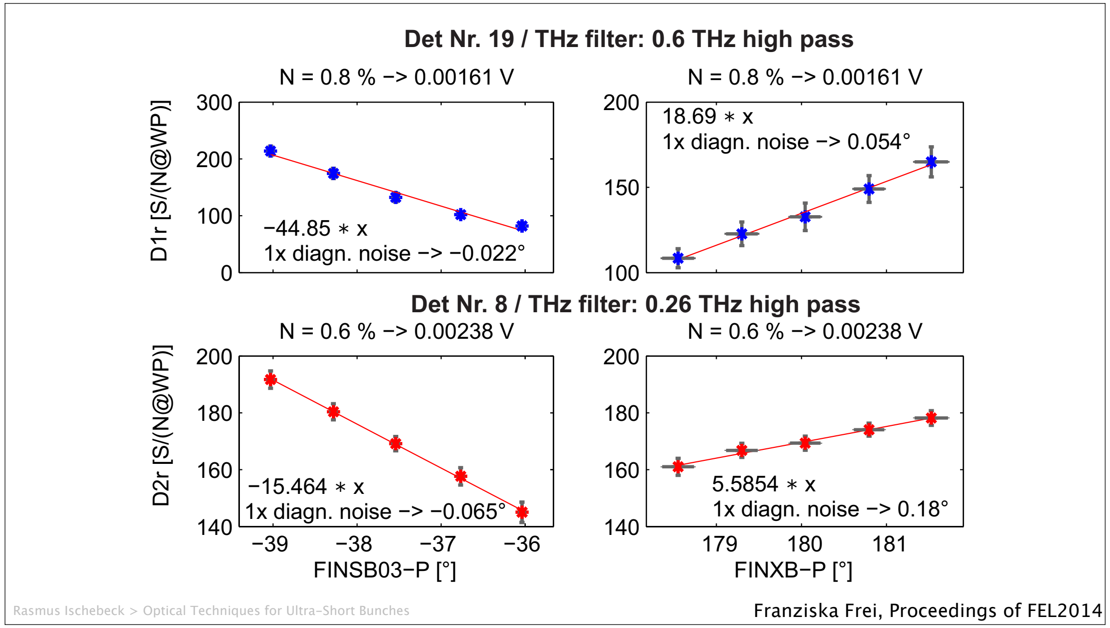
Rasmus Ischebeck > Optical Techniques for Ultra-Short Bunches

Franziska Frei, Proceedings of FEL2014

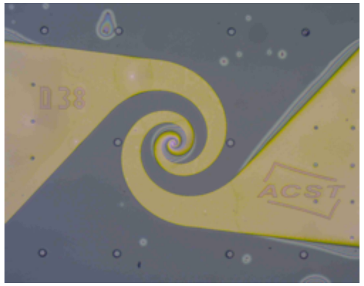
Coming back to the power distribution of CSR, we see that we could improve resolution if we detect selectively near an edge

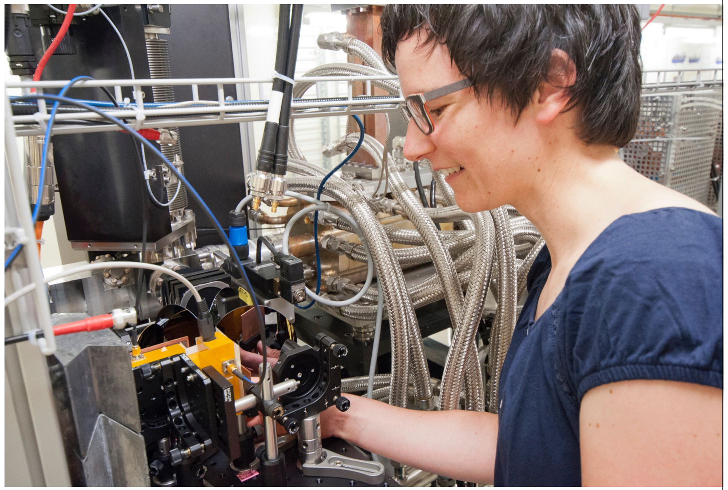


Setup installed at the SwissFEL Injector Test Facility
Beam splitters, then using grids as edge pass filters



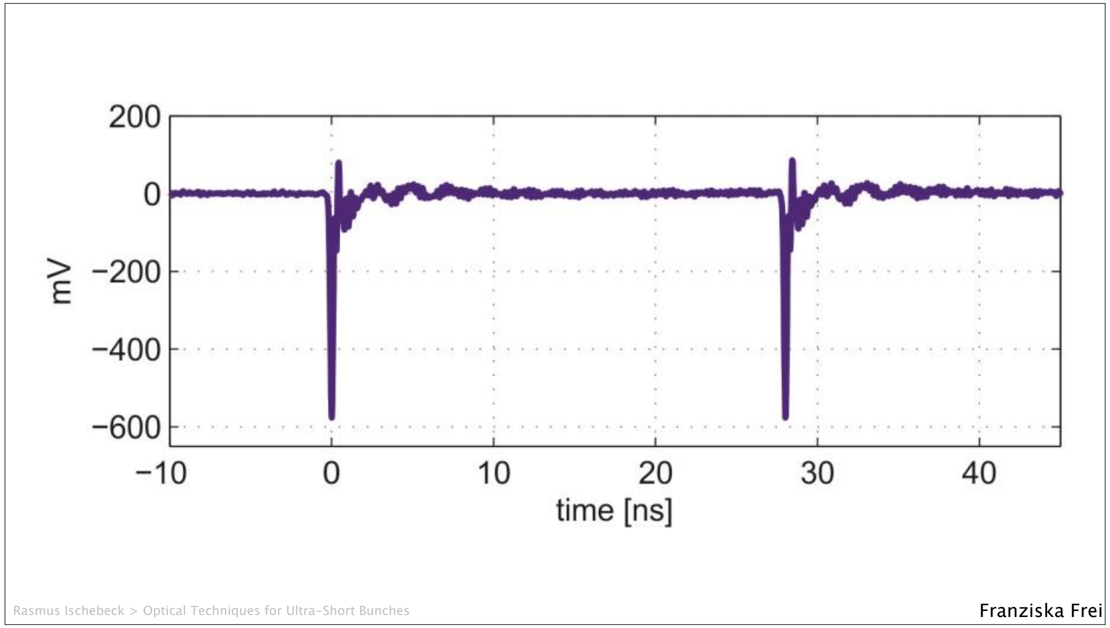
Indeed, sensitivity to X-band phase changes (i.e. compression changes) increased when using only high-frequency radiation



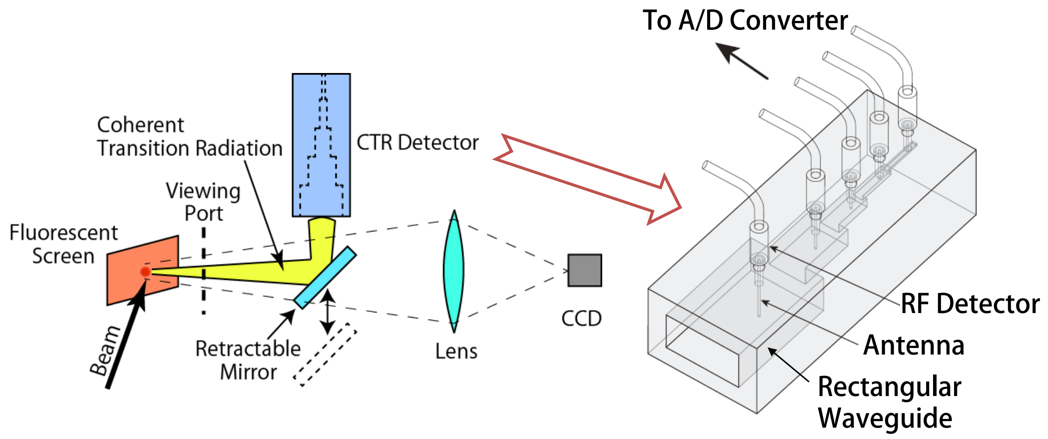


Franziska Frei; ACST GmbH

SwissFEL has very low charge operation modes, thus we are looking especially into sensitive THz detectors.
Here: Schottky diode with spiral antenna for broadband sensitivity

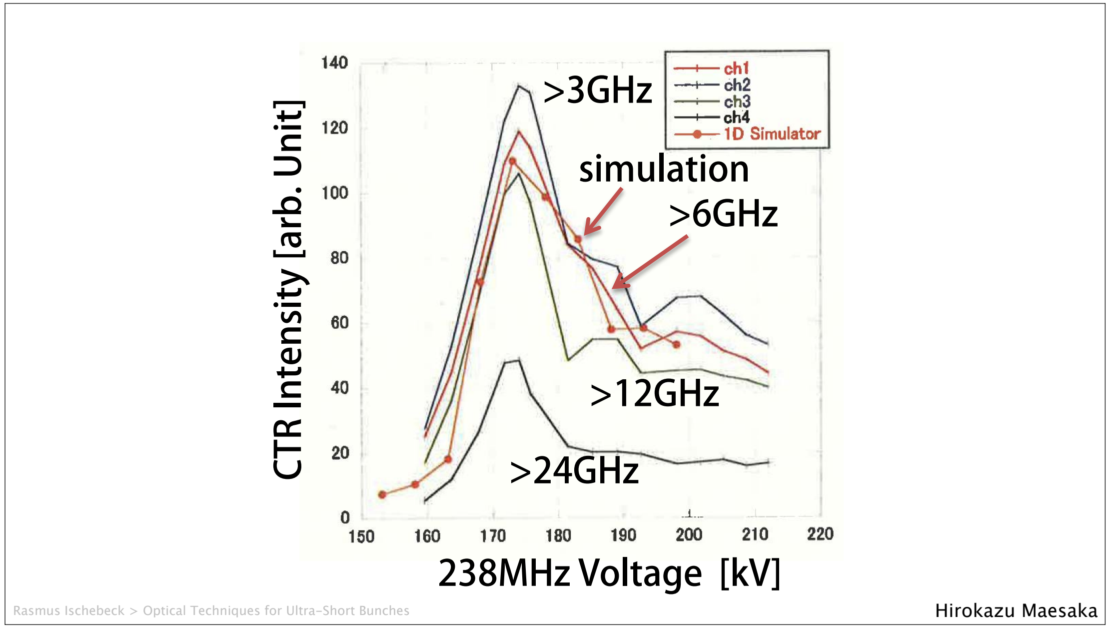


This detector is very fast: detection of two bunches separated by 28 ns easily possible

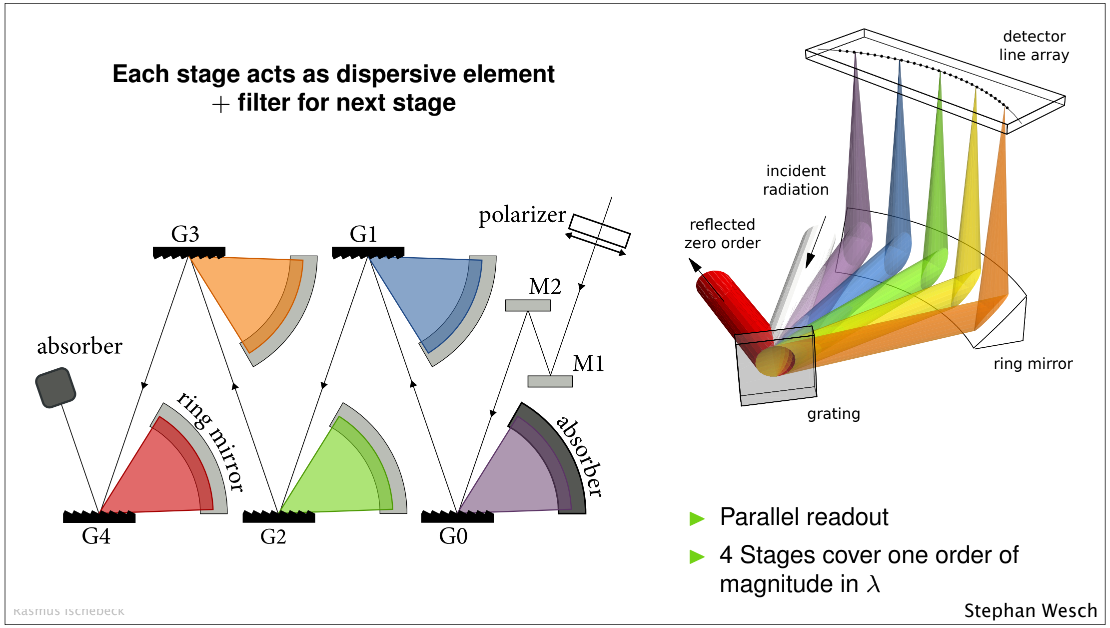


Hirokazu Maesaka

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

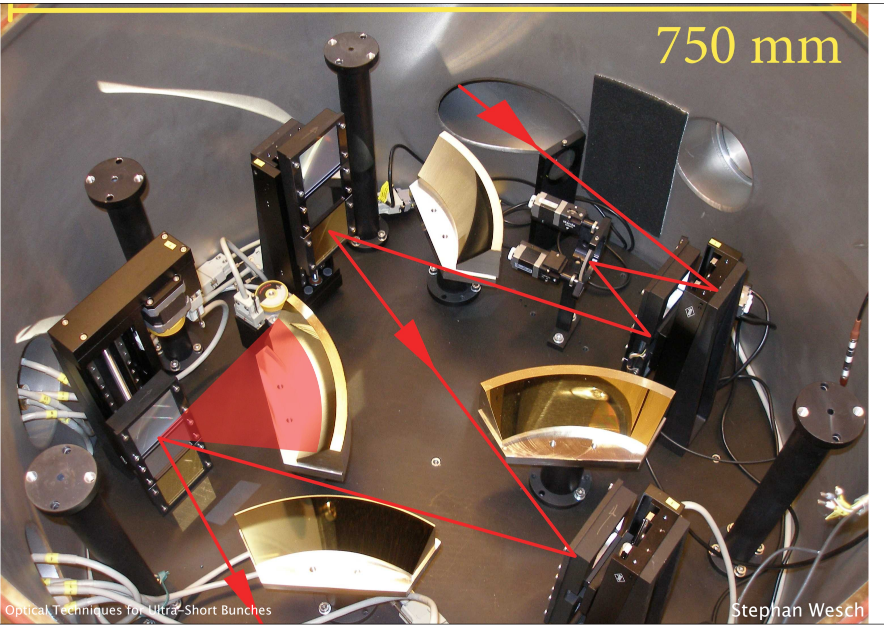
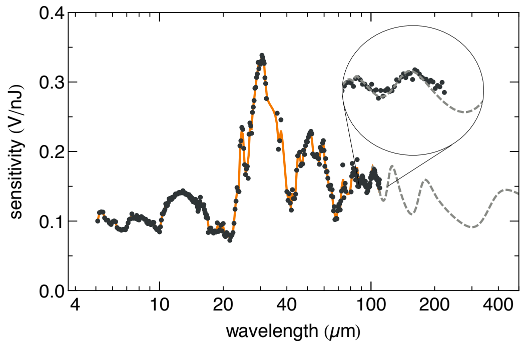
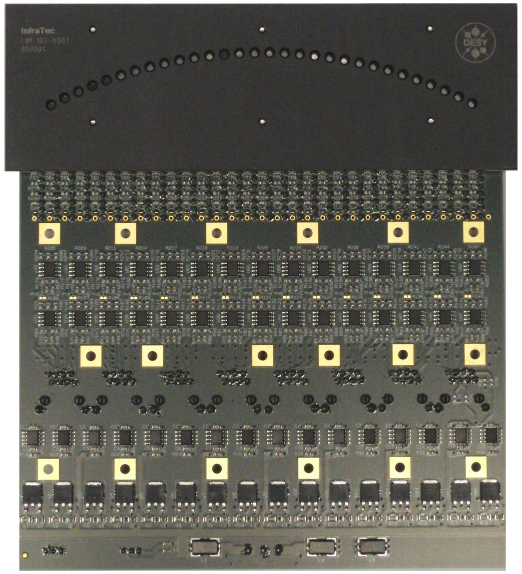


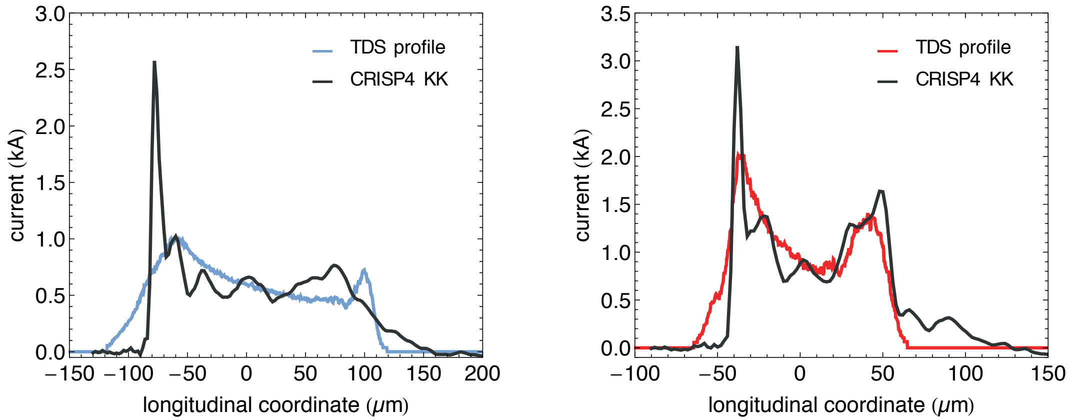
Photo of the setup





Stephan Wesch

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



Stephan Wesch

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!

Optical Techniques for Ultra-Short Bunches

Rasmus Ischebeck

> Thank you for slides, graphics, photos, movies and plots provided by:
- > Franziska Frei
- > Joe Frisch
- > Nicole Hiller
- > Patrick Krejcik
- > Hirokazu Maesaka
- > Yuji Otake
- > Volker Schlott
- > Stephan Wesch
- > ACST GmbH
- > AFS Inc.
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☞ Slides available at: http://www.ischebeck.net

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