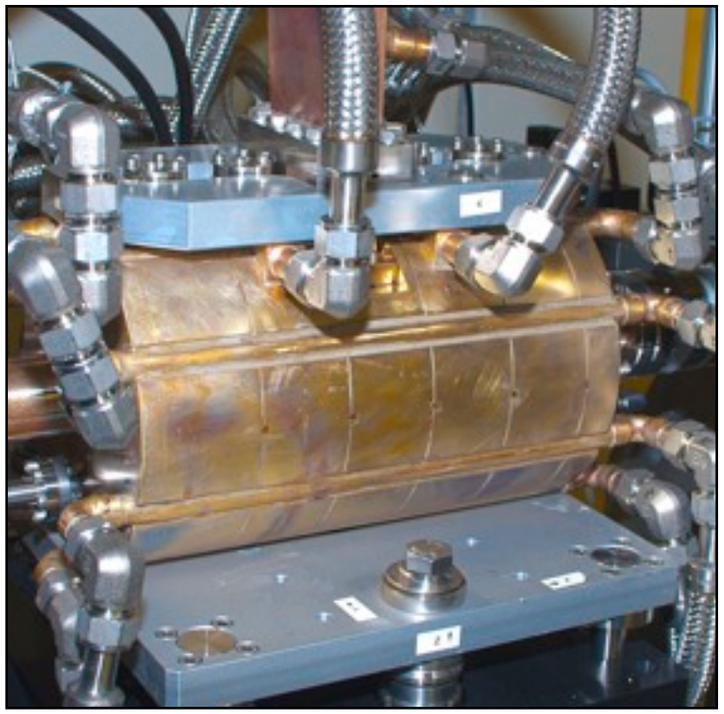
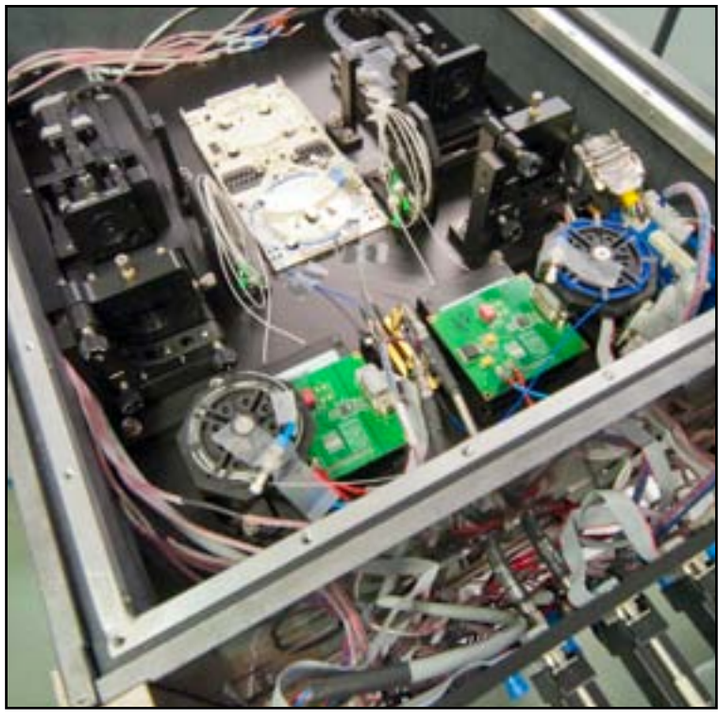
PAUL SCHERRER INSTITUT

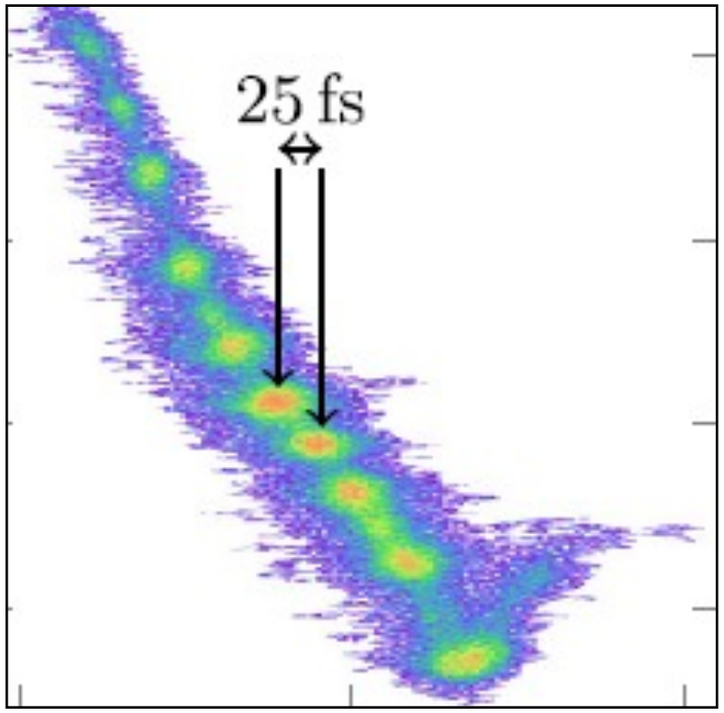




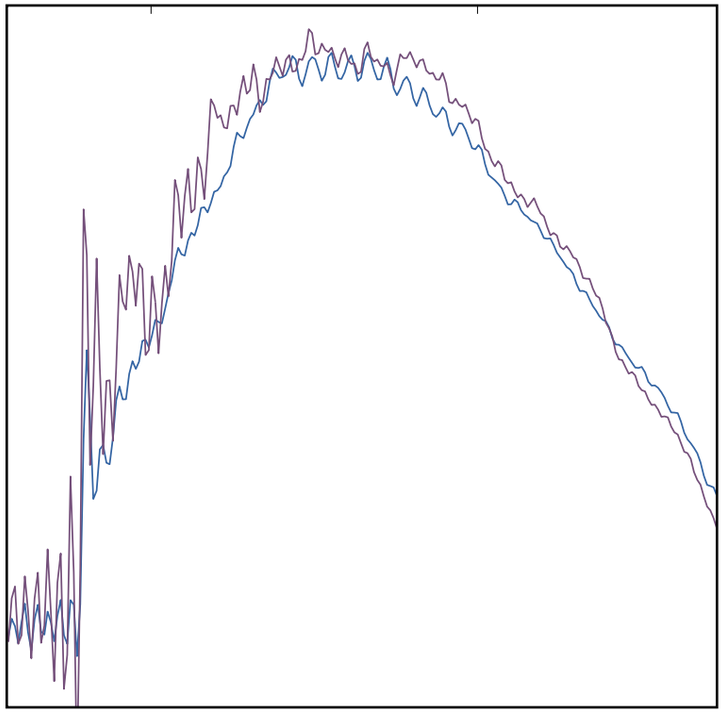
Longitudinal Diagnostics for FELs

Rasmus Ischebeck, Paul Scherrer Institut

Longitudinal Diagnostics for Free Electron Lasers



> **Time Domain Methods**
  > Conversion to electrical signals
  > Cross-correlation with external laser in medium
  > Streak Cameras



> **Spectral Methods**
  > Spectrometers with 1,4…N channels
  > Autocorrelation of the radiation (Fourier transform spectroscopy)

> **More Methods**
  > Optical Replica Synthesizer
  > Measurement of multiple ionization ratio
  > Correlation in the spectral content of incoherent radiation
  > FROG of visible radiation

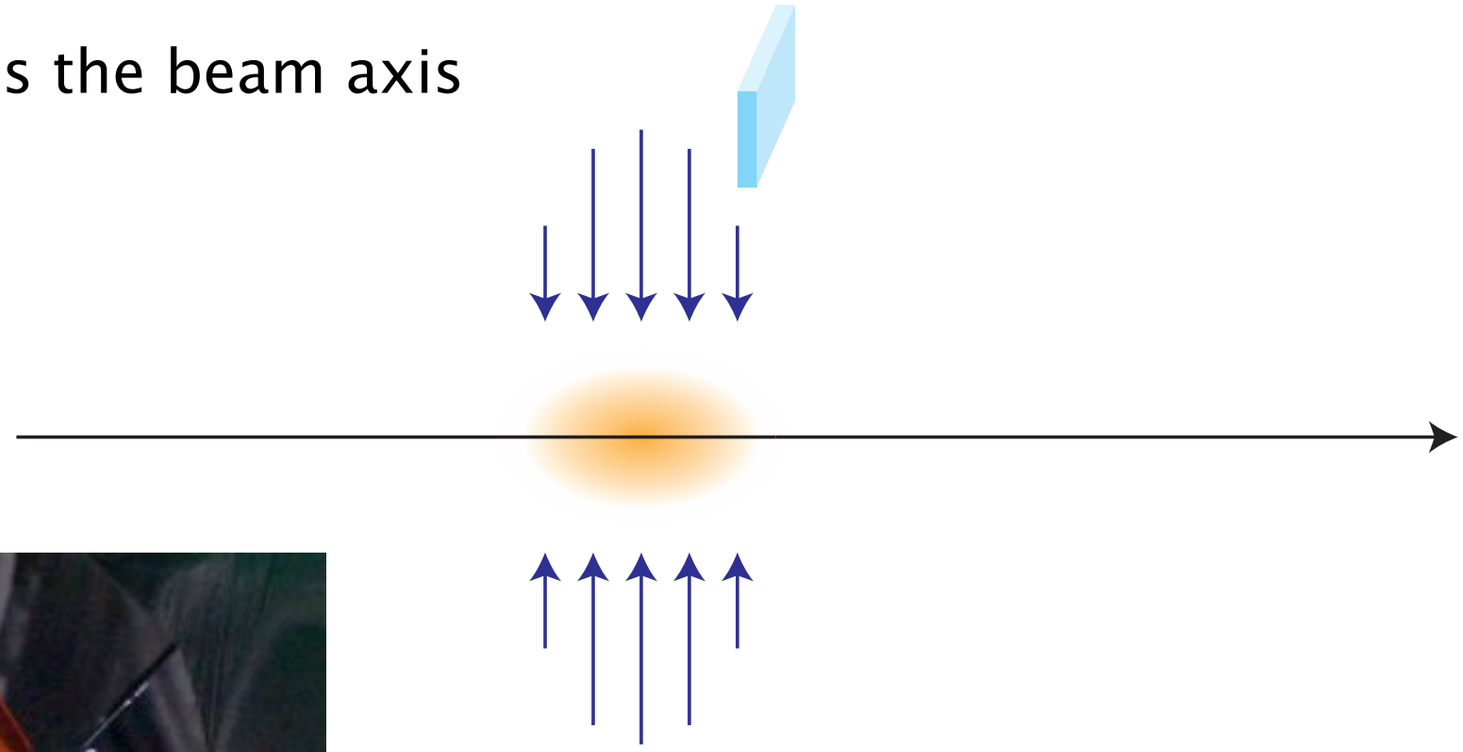
Use the Coulomb Field of the Bunches

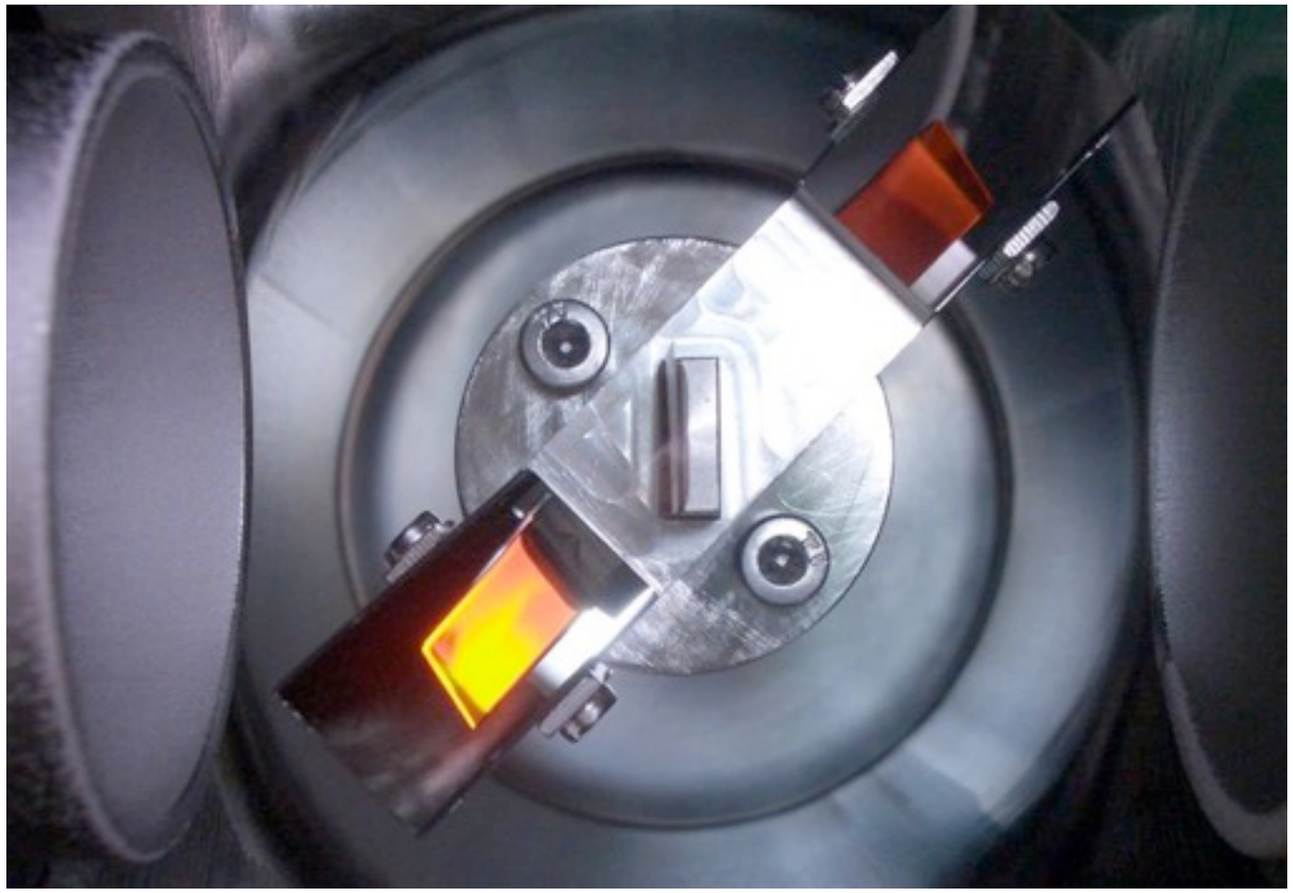
> Ultra-relativistic bunches have a field that is purely transverse to the direction of motion

> The field can be probed besides the beam axis

  > Electrical pickup

  > Direct pickup

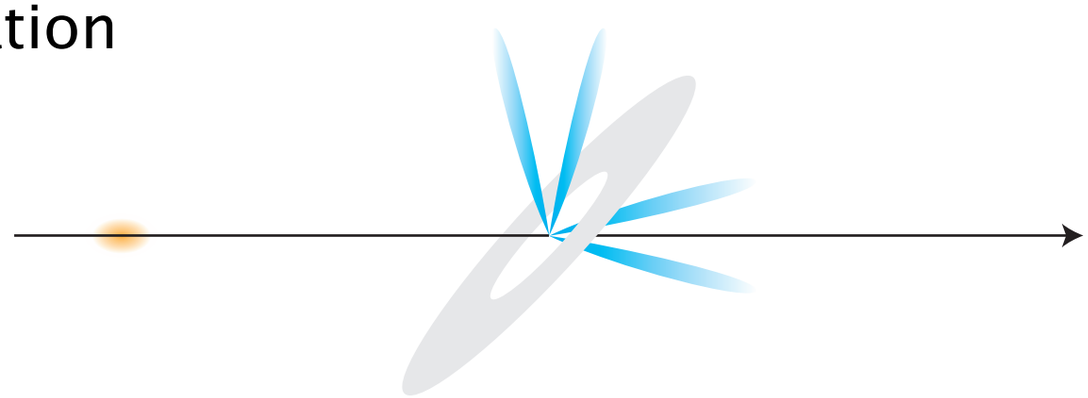




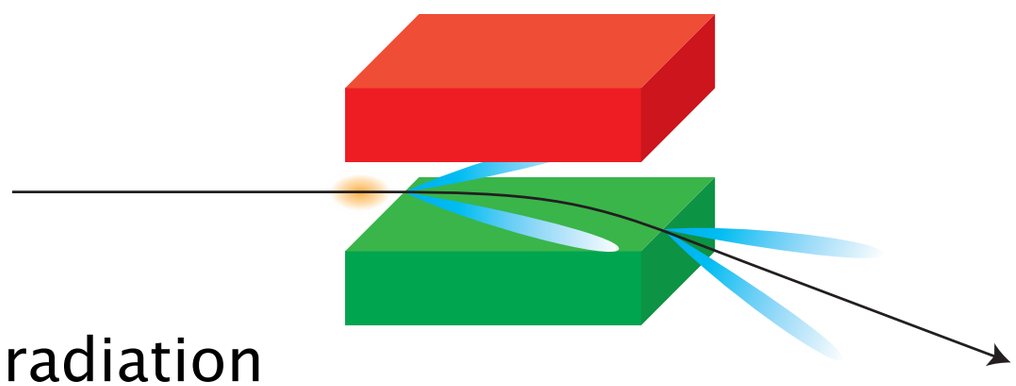
Generate Radiation from the Bunches

> Transition radiation

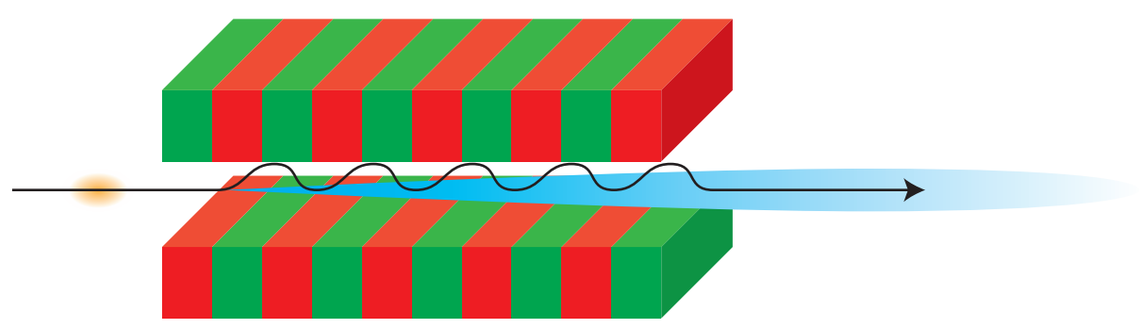
> Diffraction radiation



> Synchrotron / edge radiation

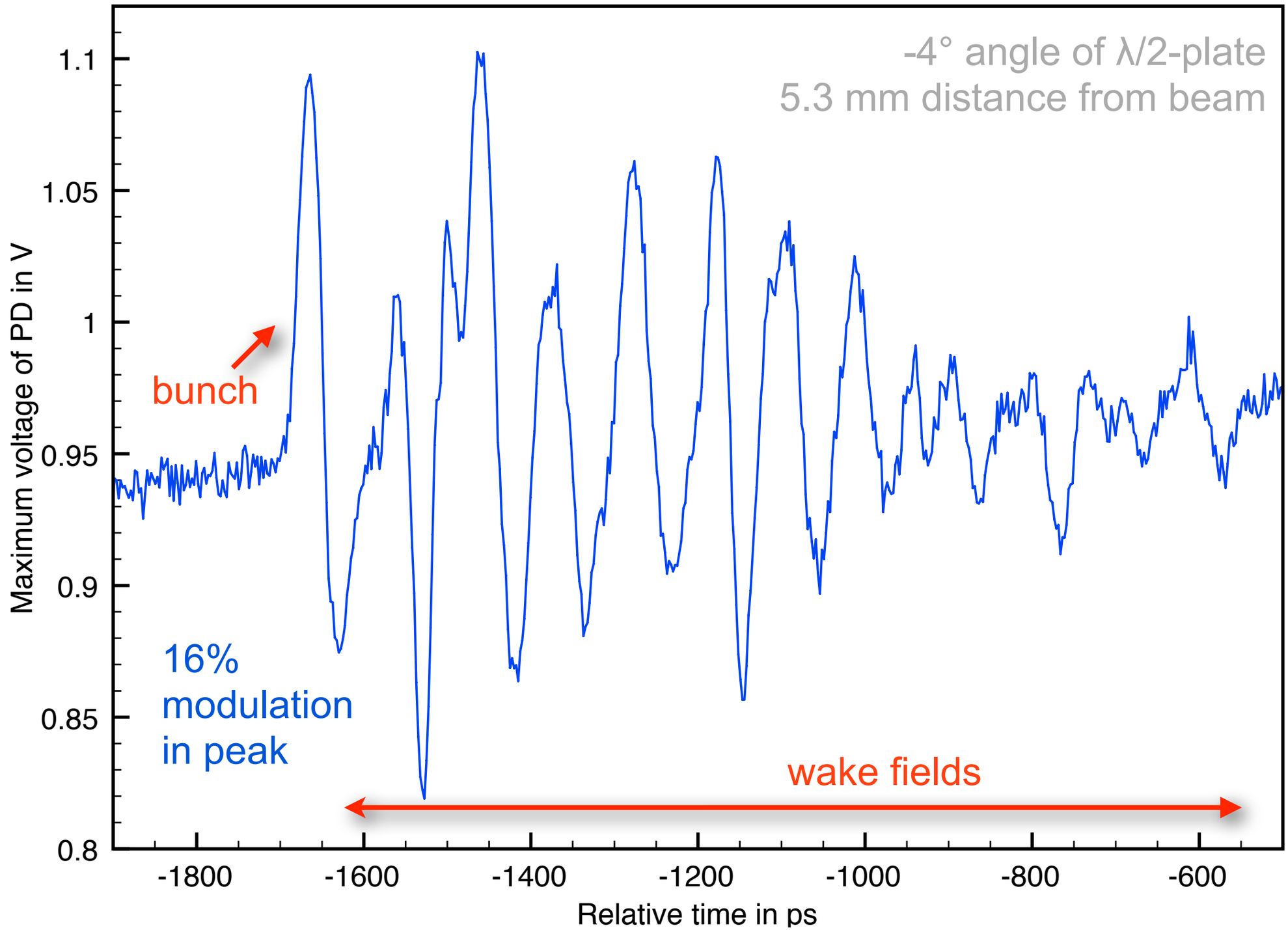


> Undulator / FEL radiation



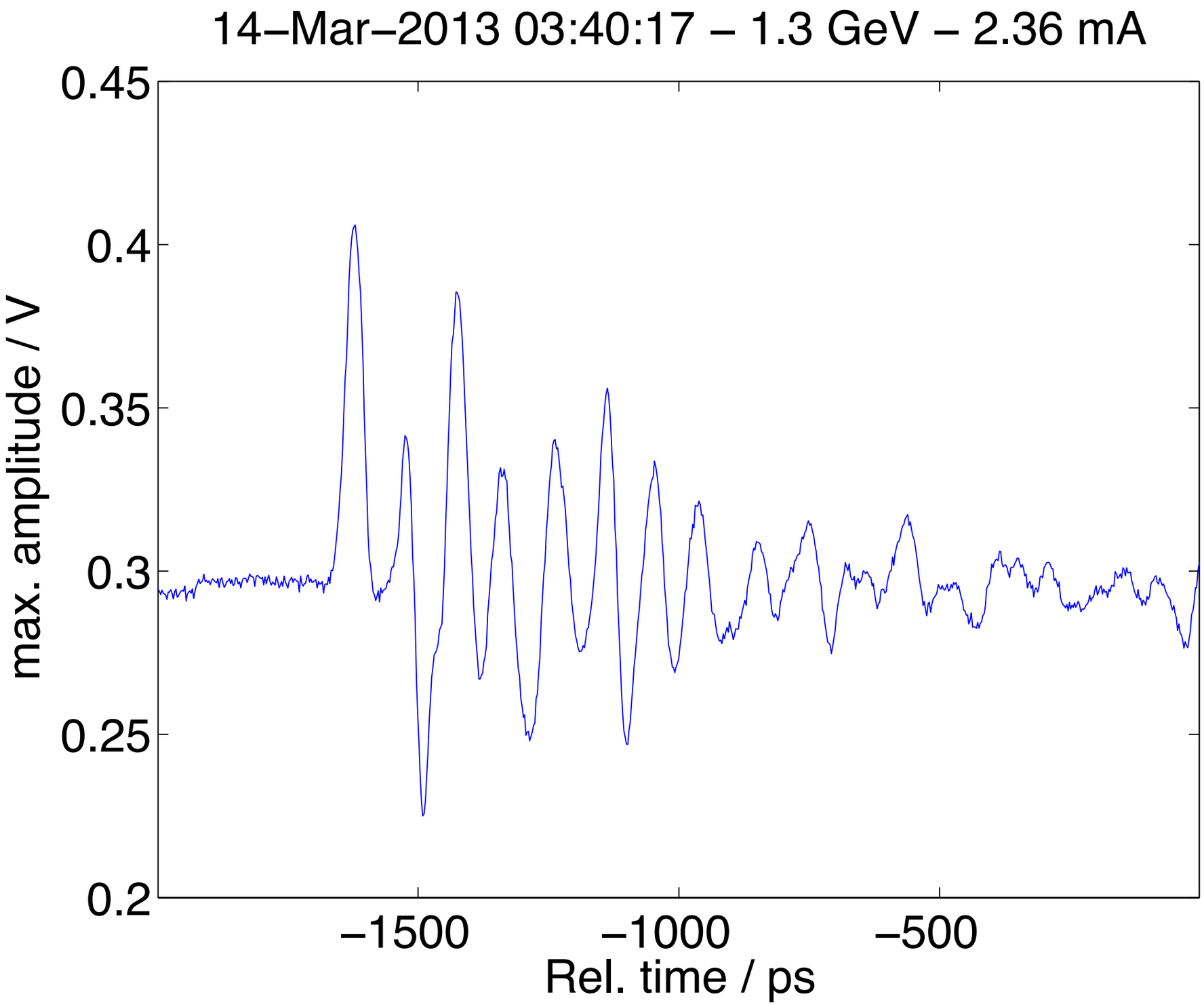
Wakefields

> Signal picked up near a beam in a storage ring



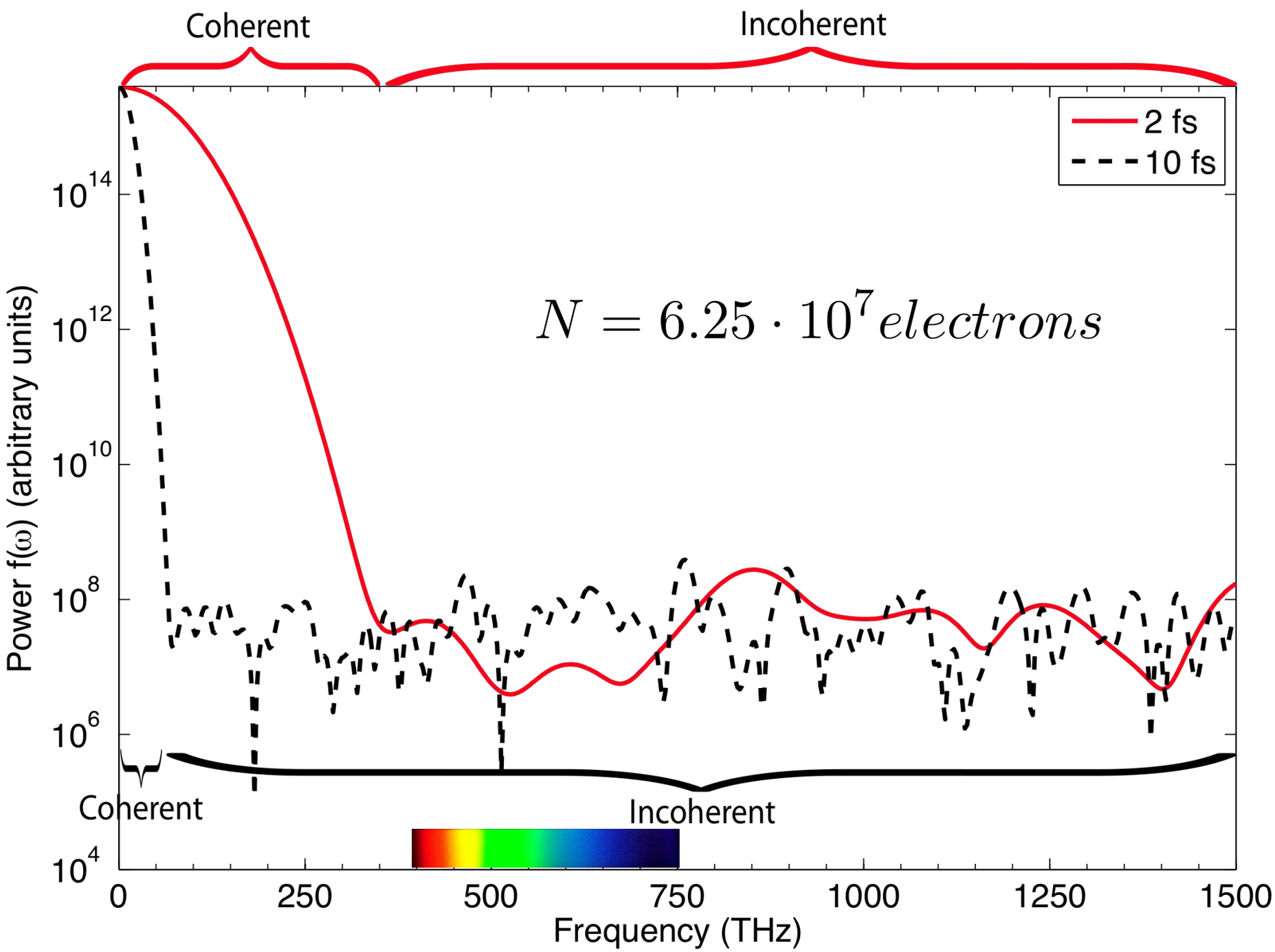
Wakefields

> Improved setting of waveplates



Radiation Generated by the Bunches

> Coherent <-> incoherent radiation



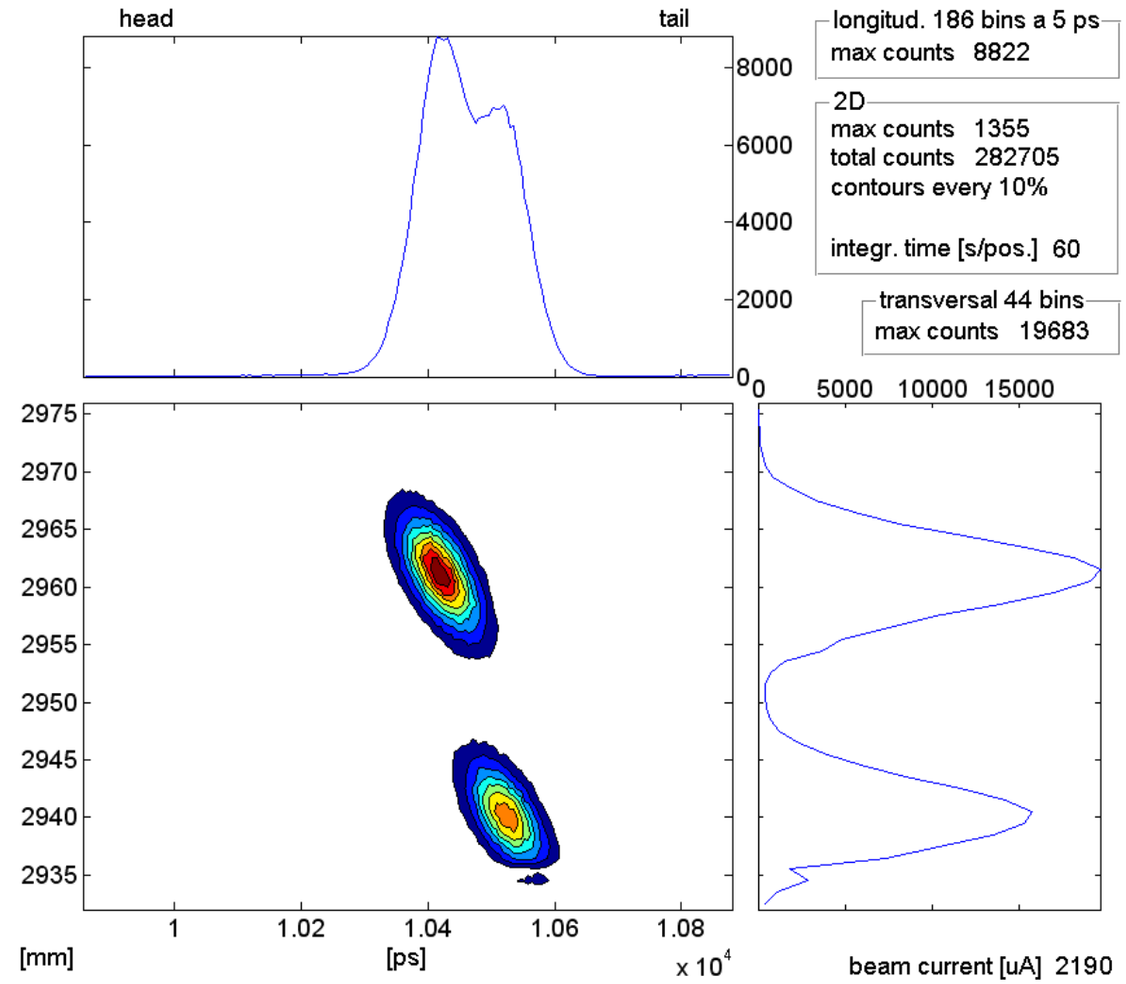
Time Domain Methods

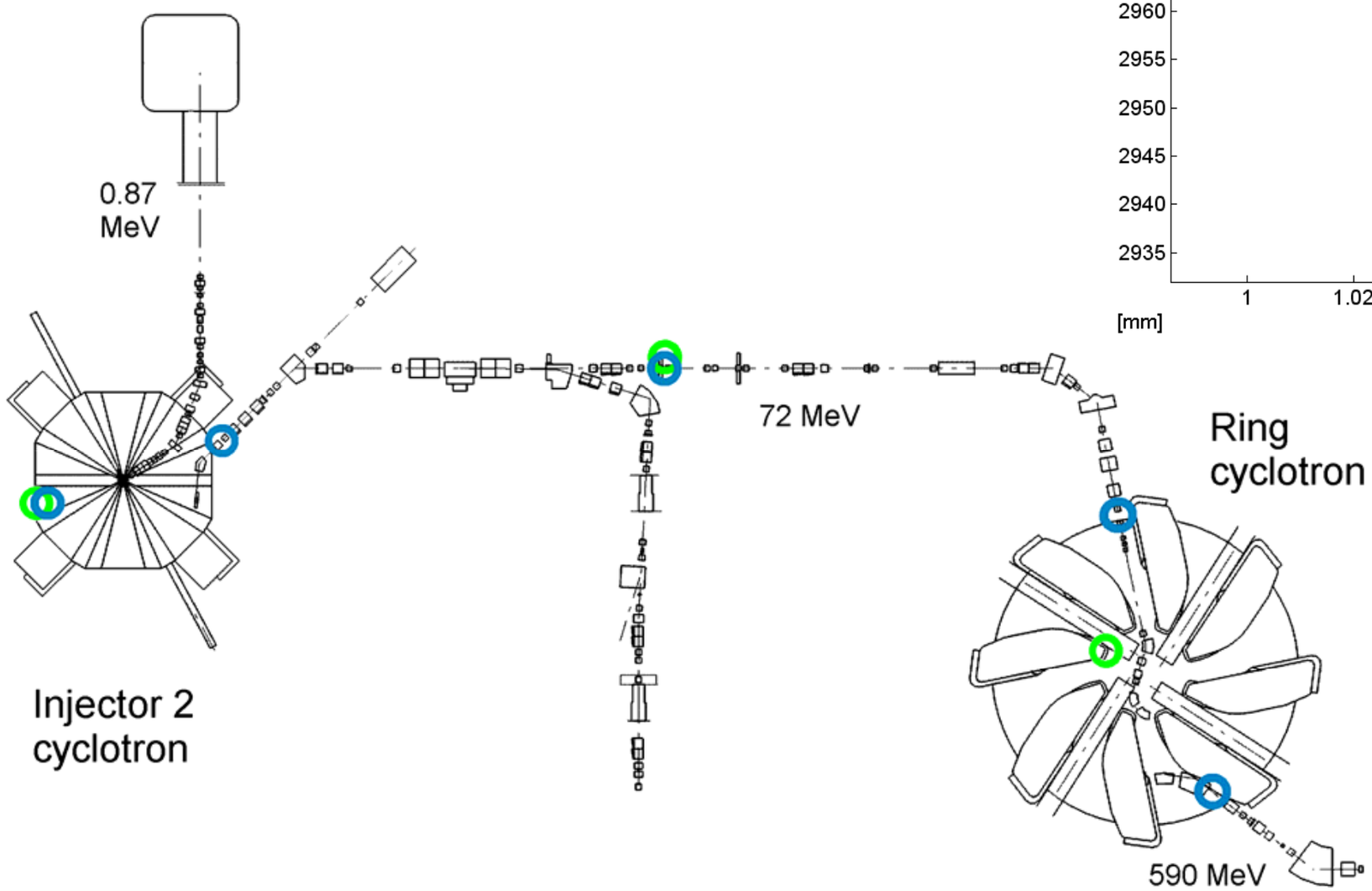
Astronomical Clock in Prague, Wikimedia Commons

Measurement of Electrical Signals

> Measurement at the PSI Proton Cyclotron

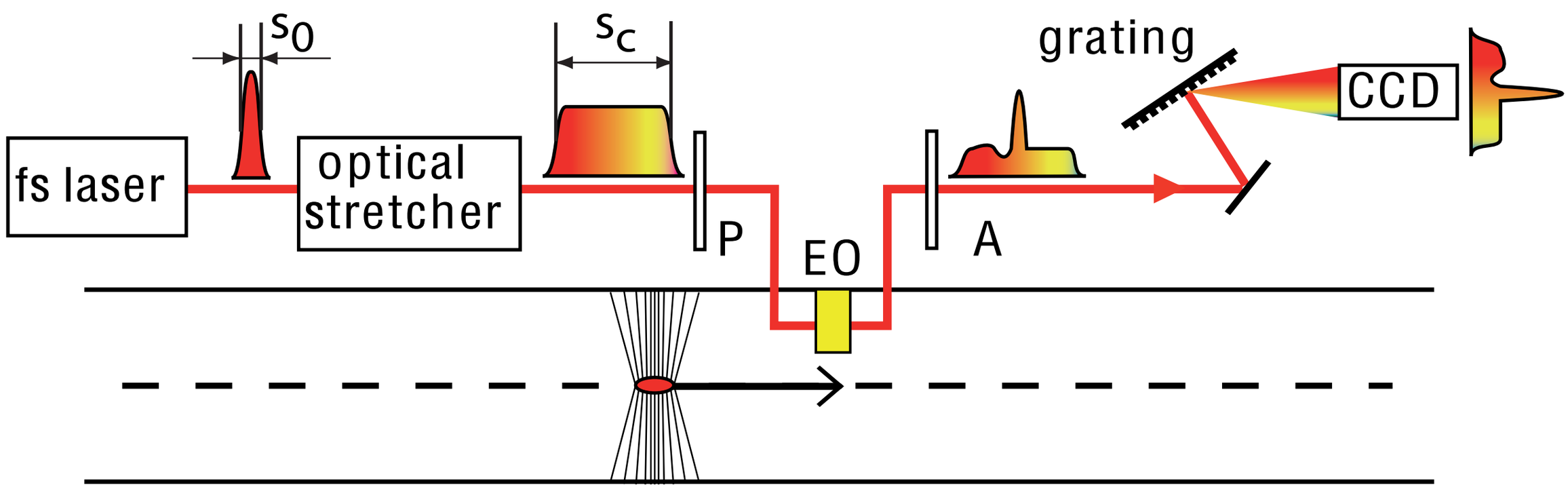
  > Time-to-amplitude converters good for time resolution down to about 30 ps





Cross-Correlation Techniques

> 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



Pockels Effect

> 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

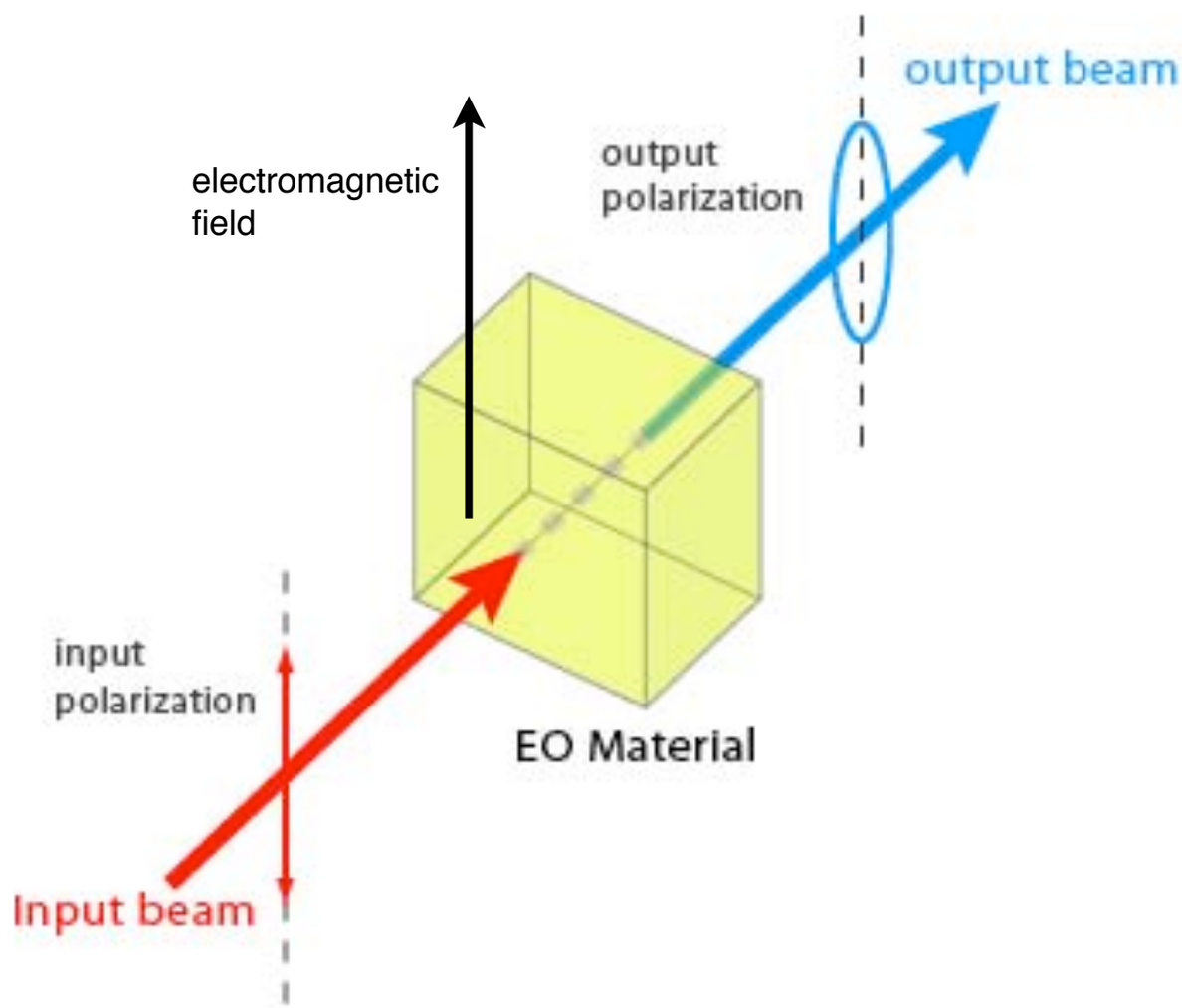
> Effect is totally reversible

> Possible materials

  > ZnTe

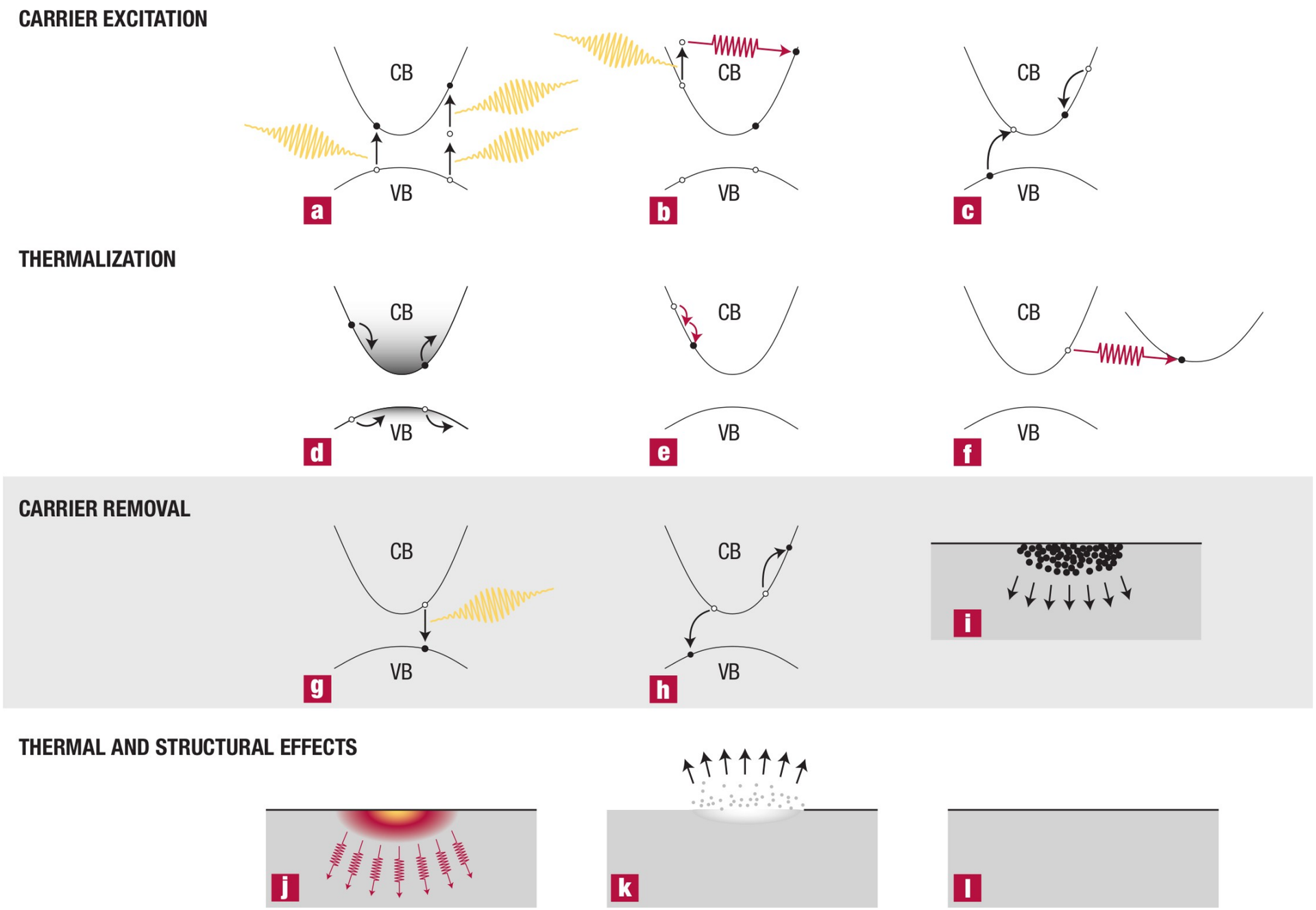
  > LiNb

  > GaP



X-Ray Induced Reflectivity Change

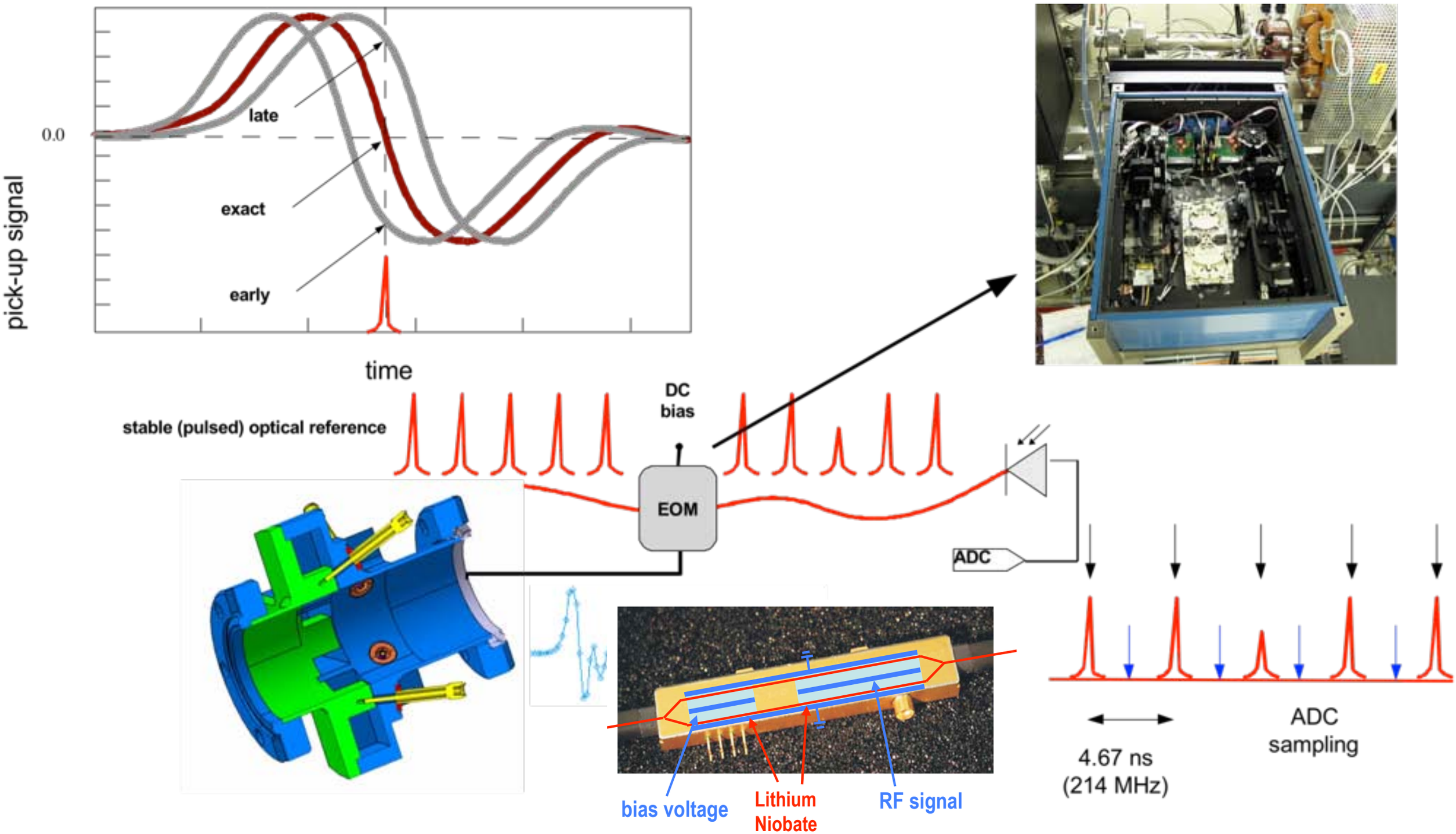
> Index of refraction is changed by X-rays



Sundaram and Mazur Nat. Mat. **1** 217 (2002)

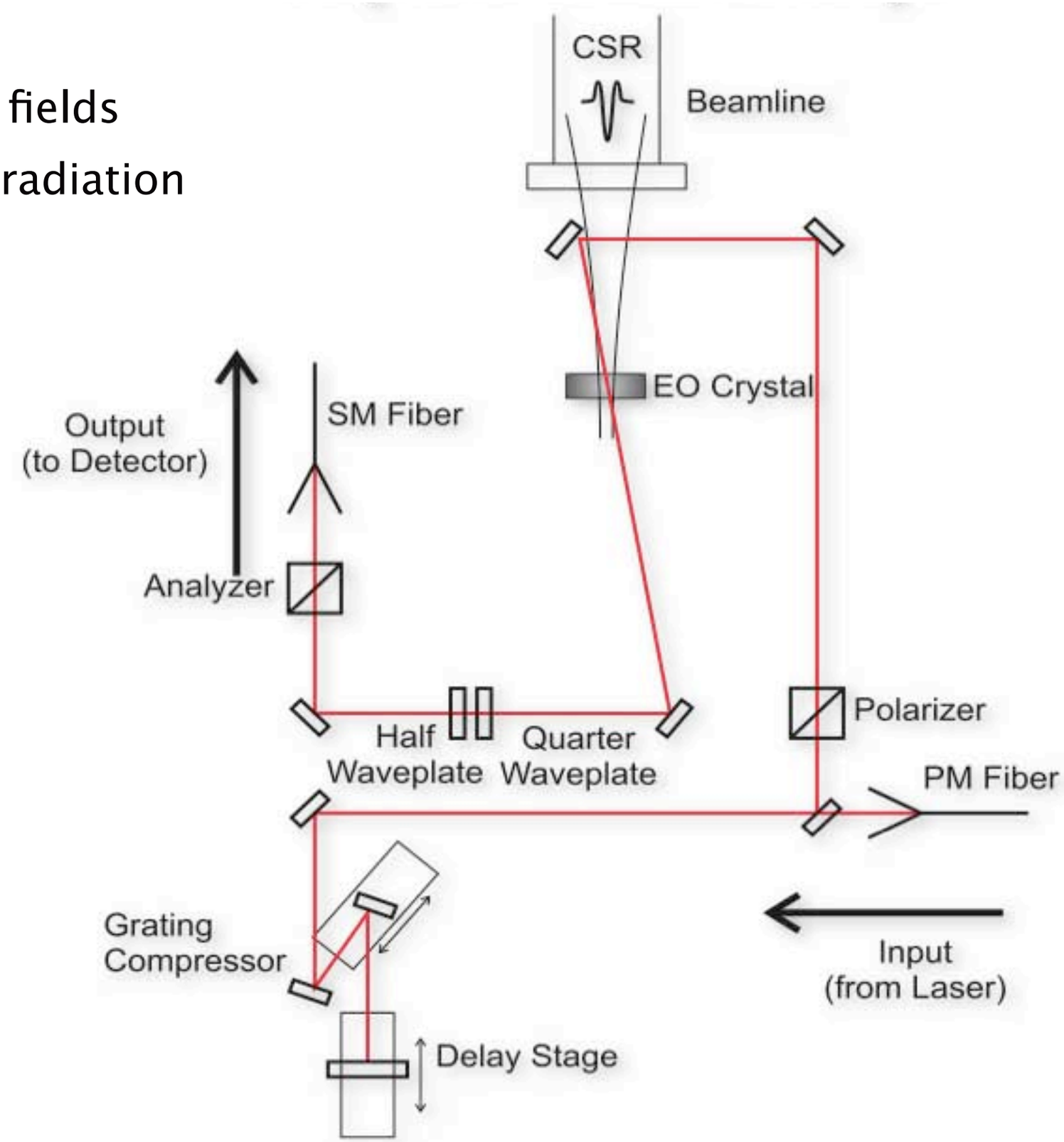
Measurement of Bunch Arrival Time

> Arrival time signal generated at pickup is transferred onto an electro-optical modulator

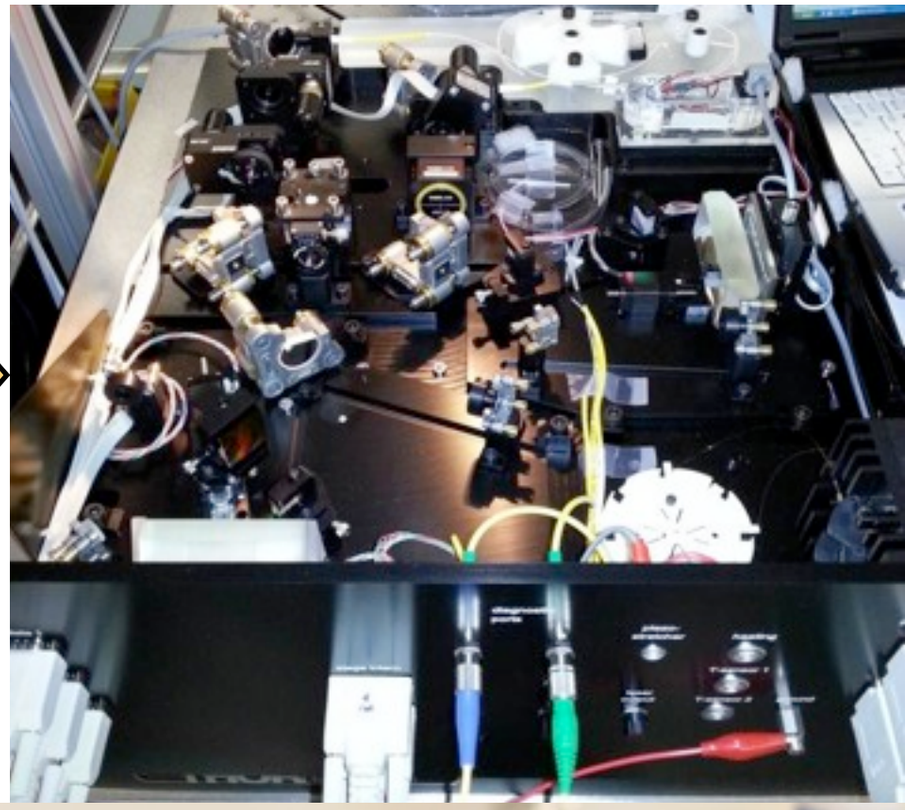


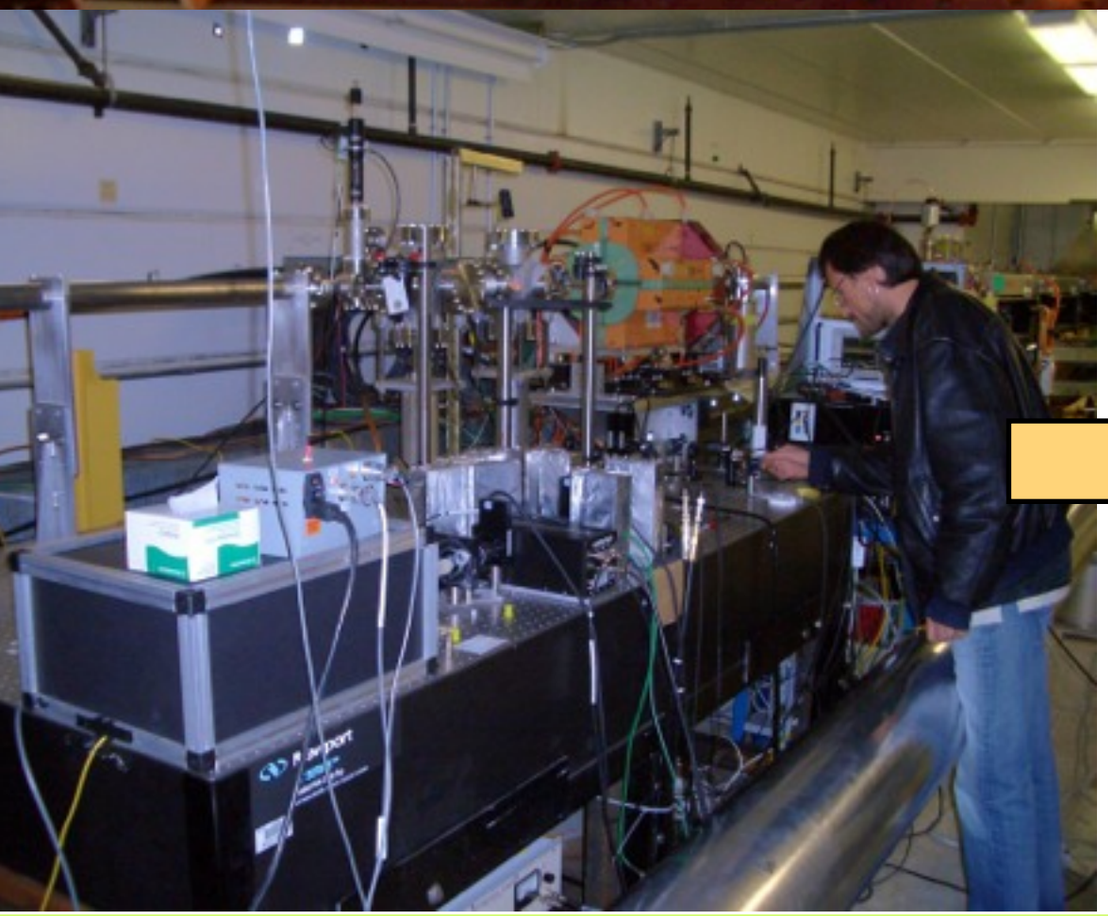
Measurement of Longitudinal Bunch Profile

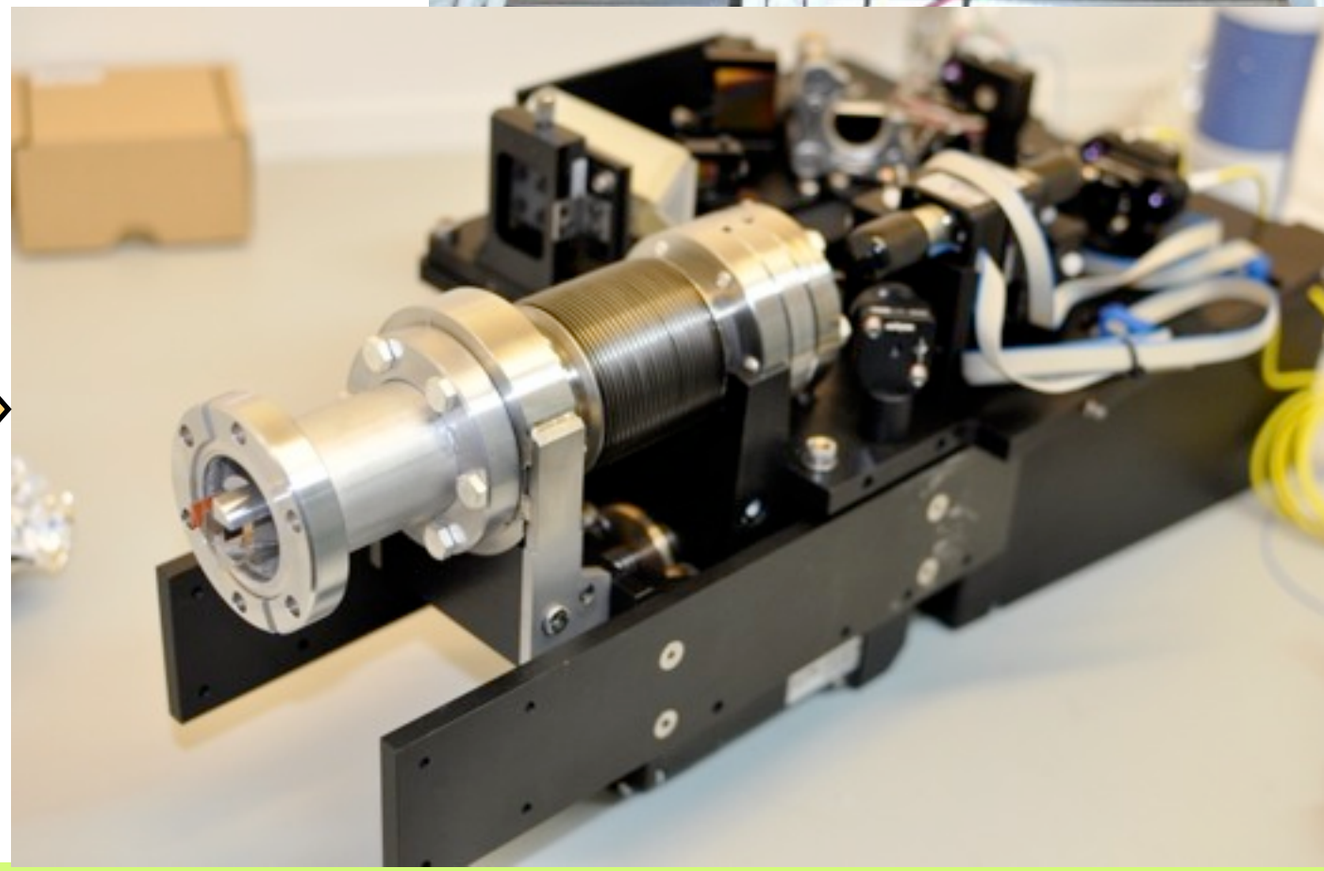
> Need a faster pickup (~THz)
  > Direct sampling of transverse fields
  > Coherent edge / synchrotron radiation (CSR)



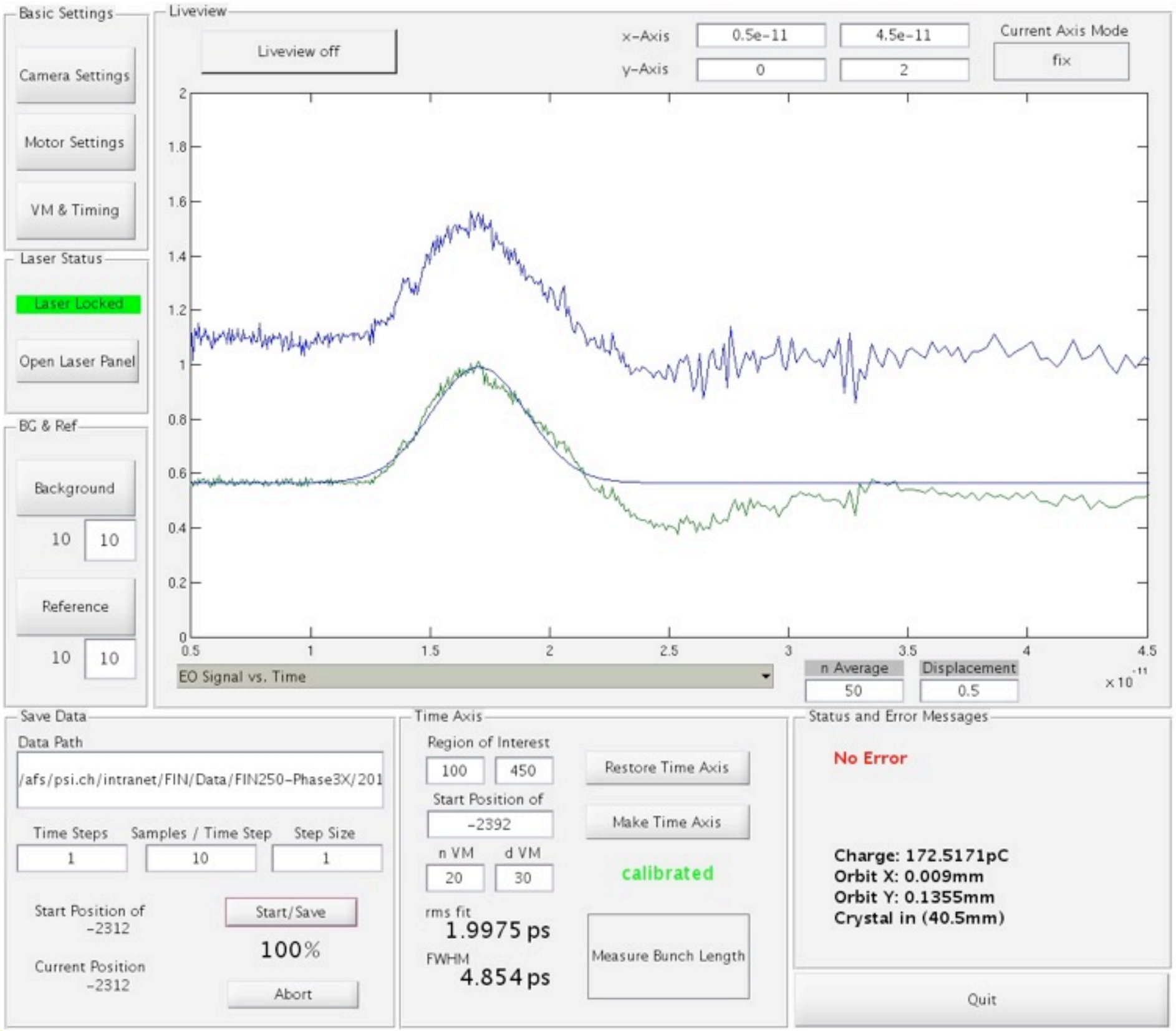
Measurement of Longitudinal Bunch Profile



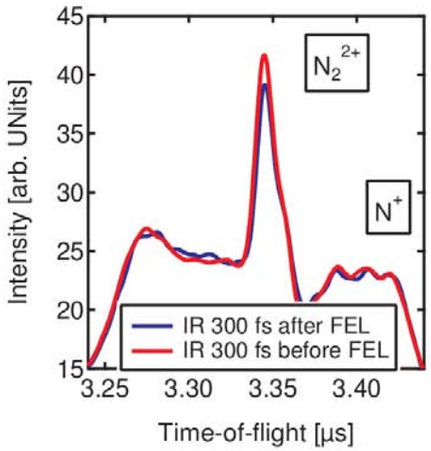


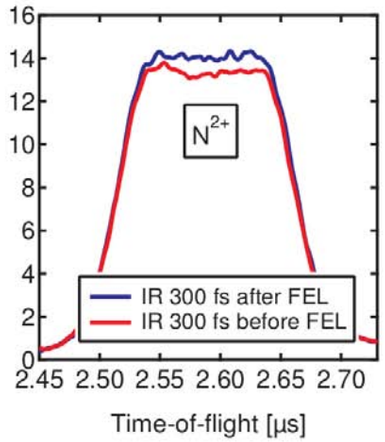


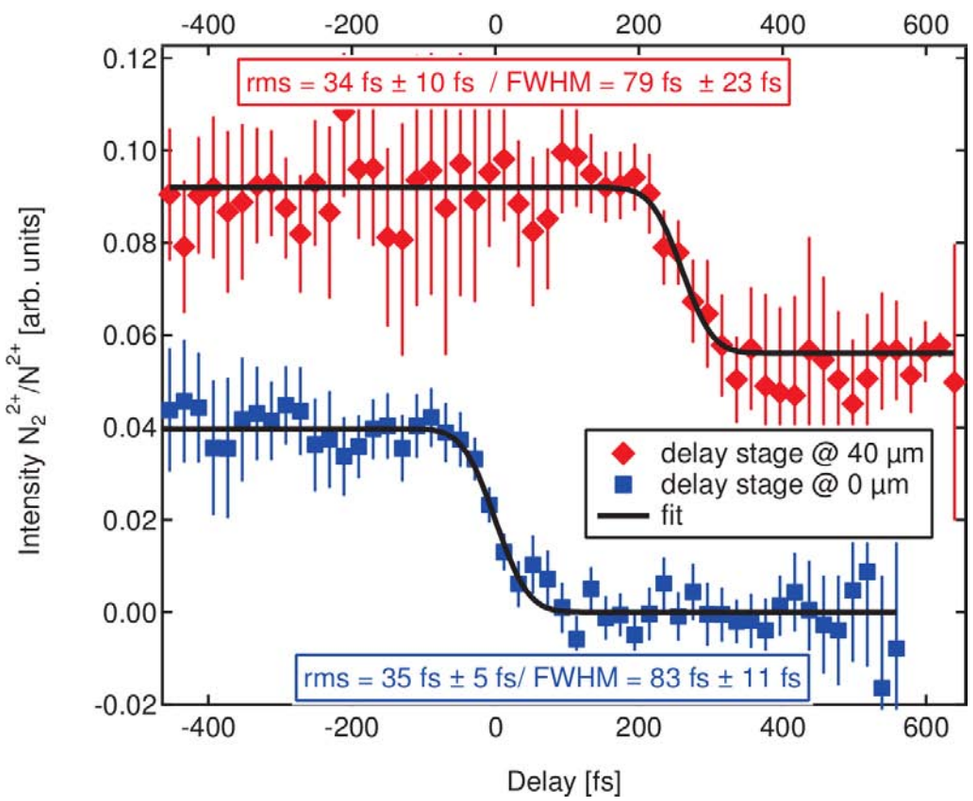
Measurement of Longitudinal Bunch Profile

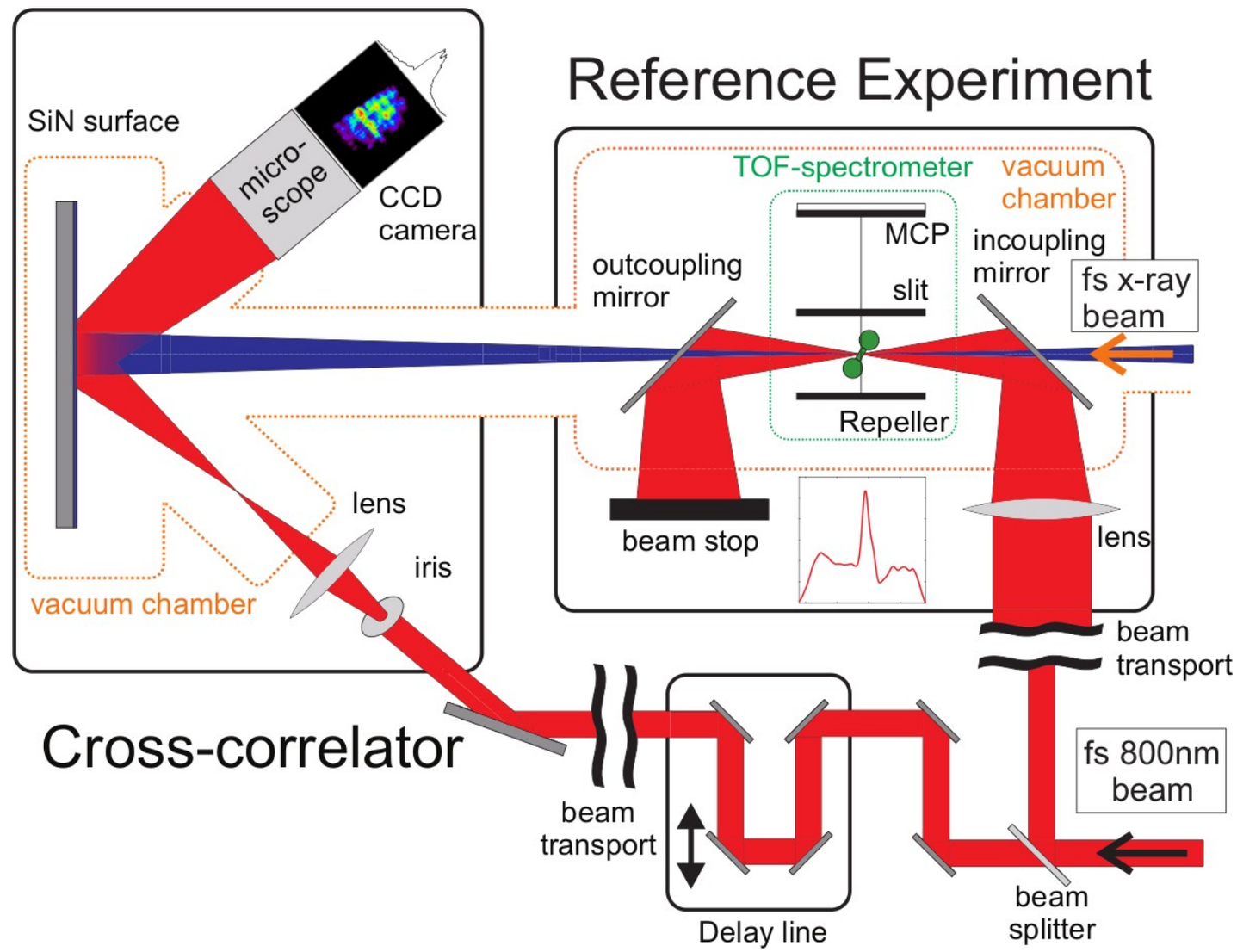


Measurement of Arrival Time









Schorb *et al.*, App. Phys. Lett. *in production*

Encoding Techniques

> Spatial encoding

+ Easy to set up

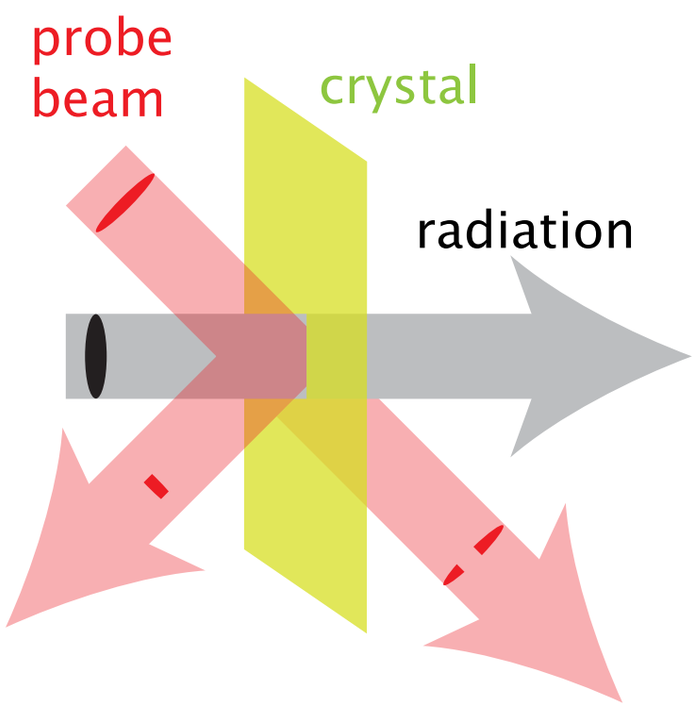
– Need imaging setup

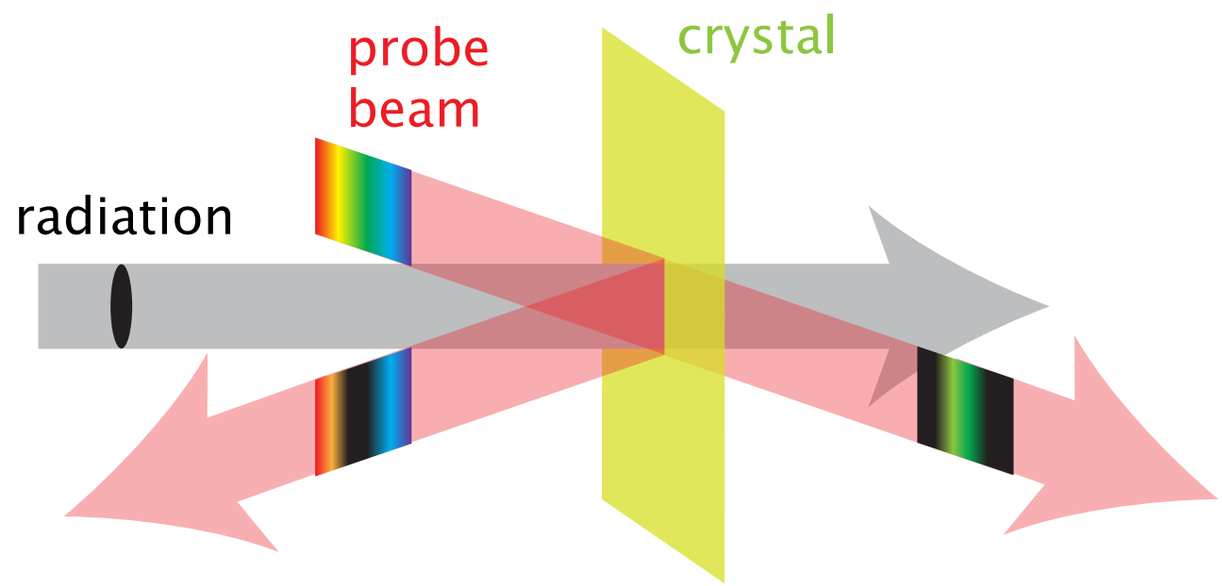
> Spectral encoding

+ Easy to set up

+ Insensitive to transverse inhomogeneities and jitter

– Resolution limited by Fourier limit





> Temporal encoding

+ Very high resolution possible

– Complex setup

– Need high laser power

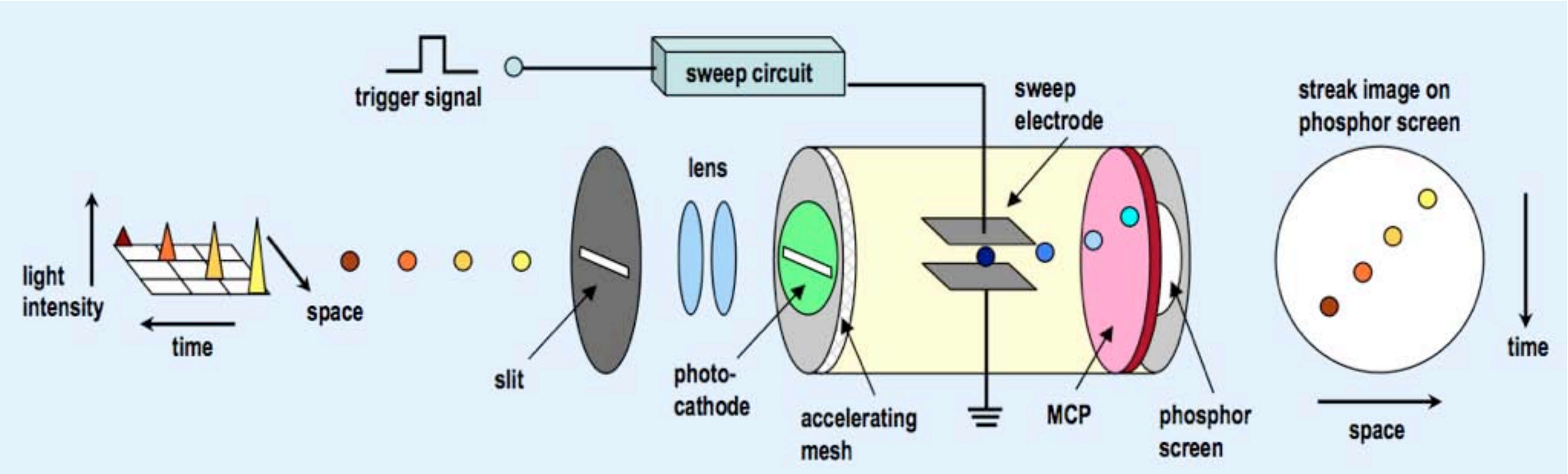
Streak Camera

> Radiation generates photoelectrons from a photocathode

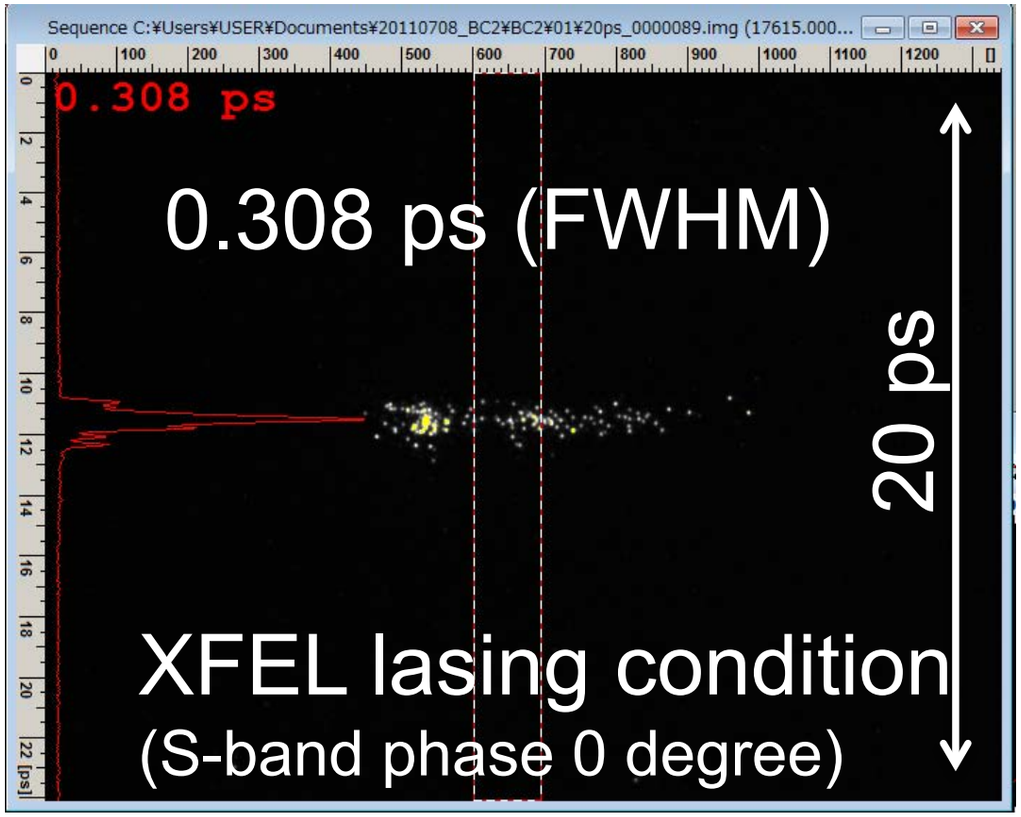
> Accelerated electrons are swept transversely by sweep electrodes

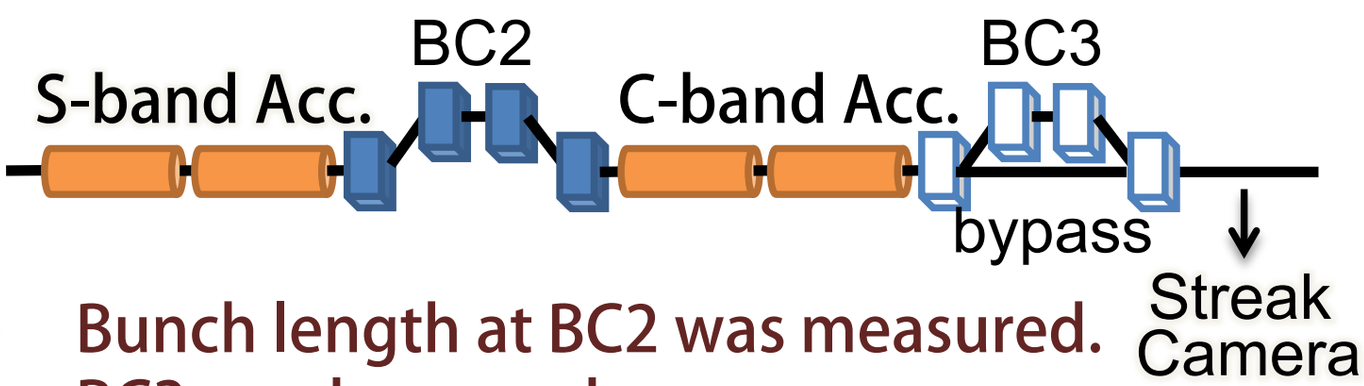
> Detection of photoelectrons with a 2-dimensional sensor

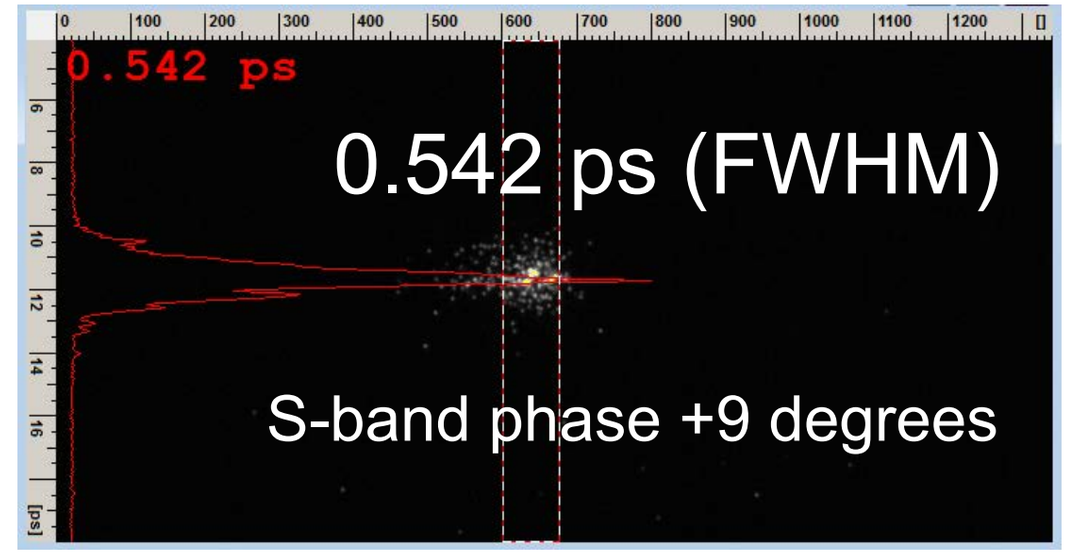
> Achievable resolution: ~300 fs FWHM

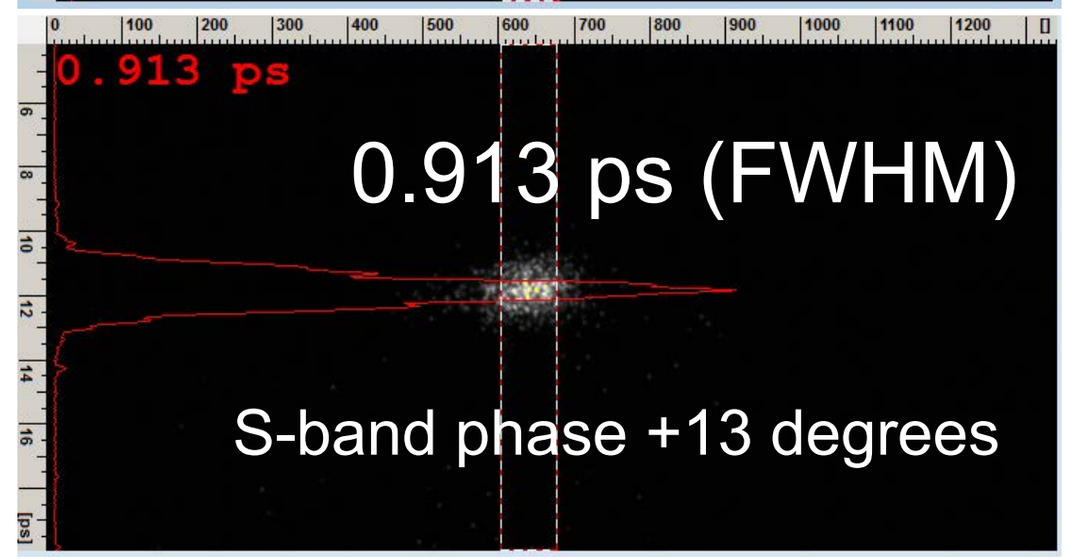


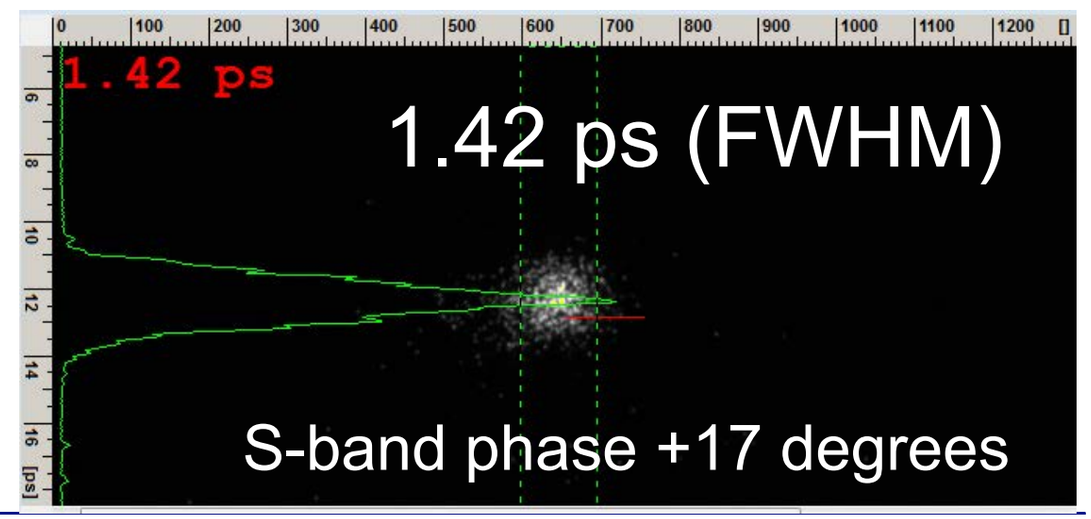
Streak Camera







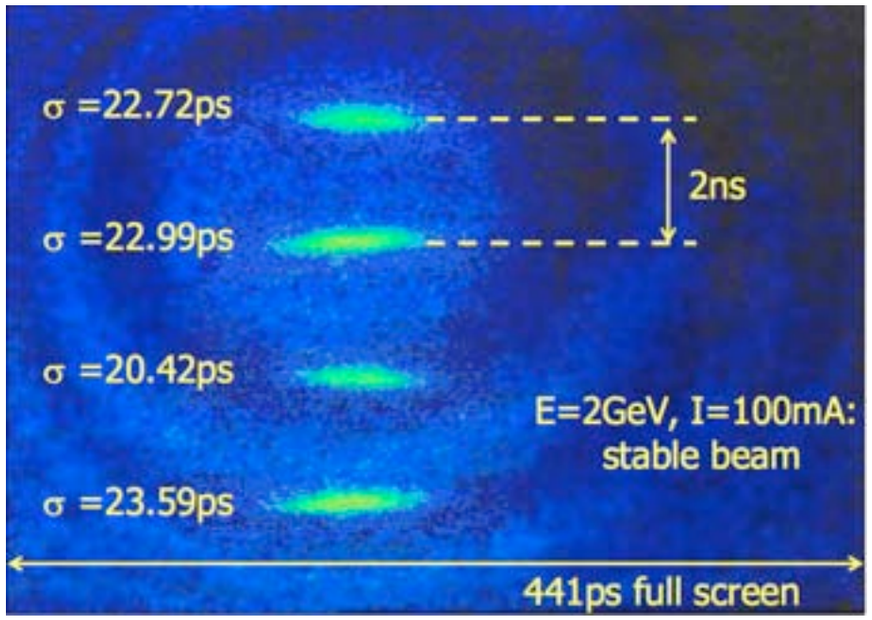




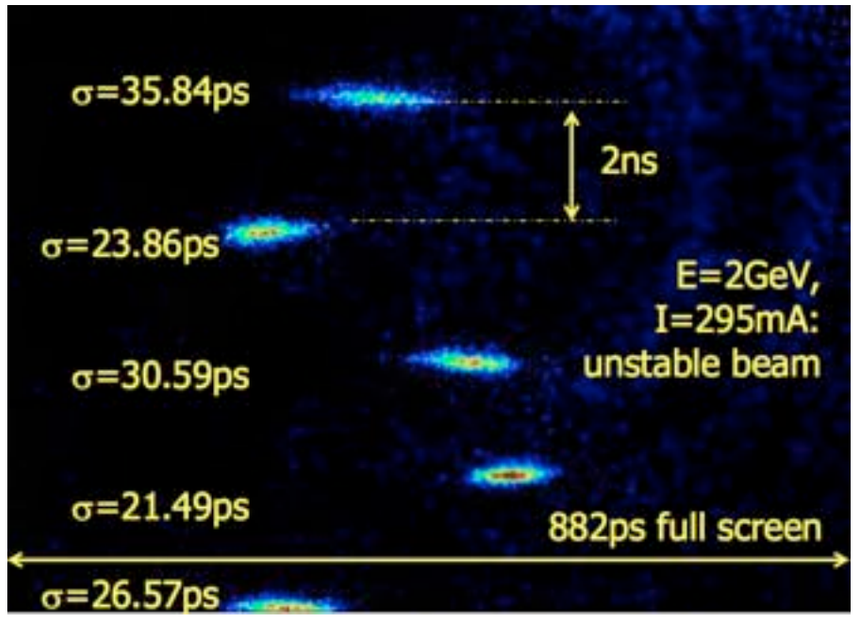
- Bunch length at BC2 was measured.
- BC3 was bypassed.
- S-band phase was shifted to change the bunch length.
- Each figure shows 50-shot integrated image.
- Bunch length of < 1 ps (FWHM) was obtained.

Examples of Synchroscan Streak Camera Measurements (by M. Ferianis, ELETTRA)

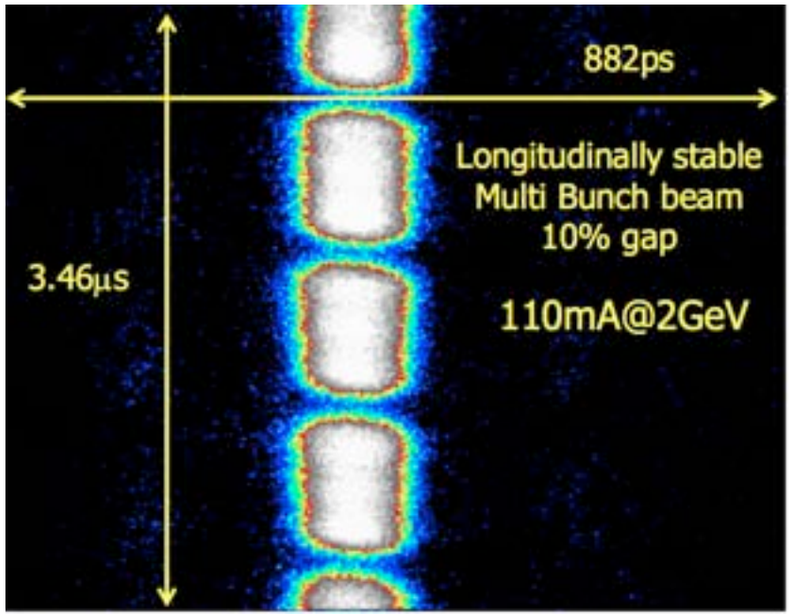
Four Bunch Mode – Stable Beam



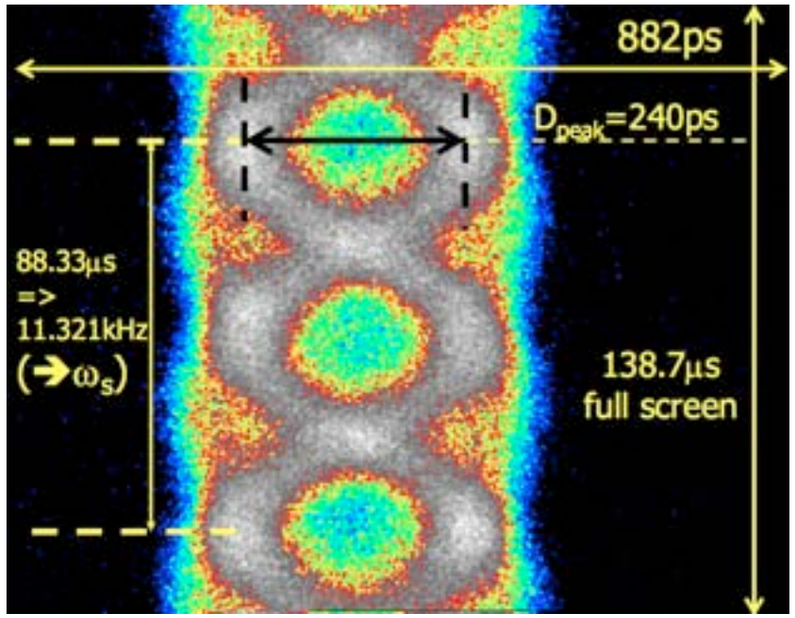
Four Bunch Mode – Unstable Beam



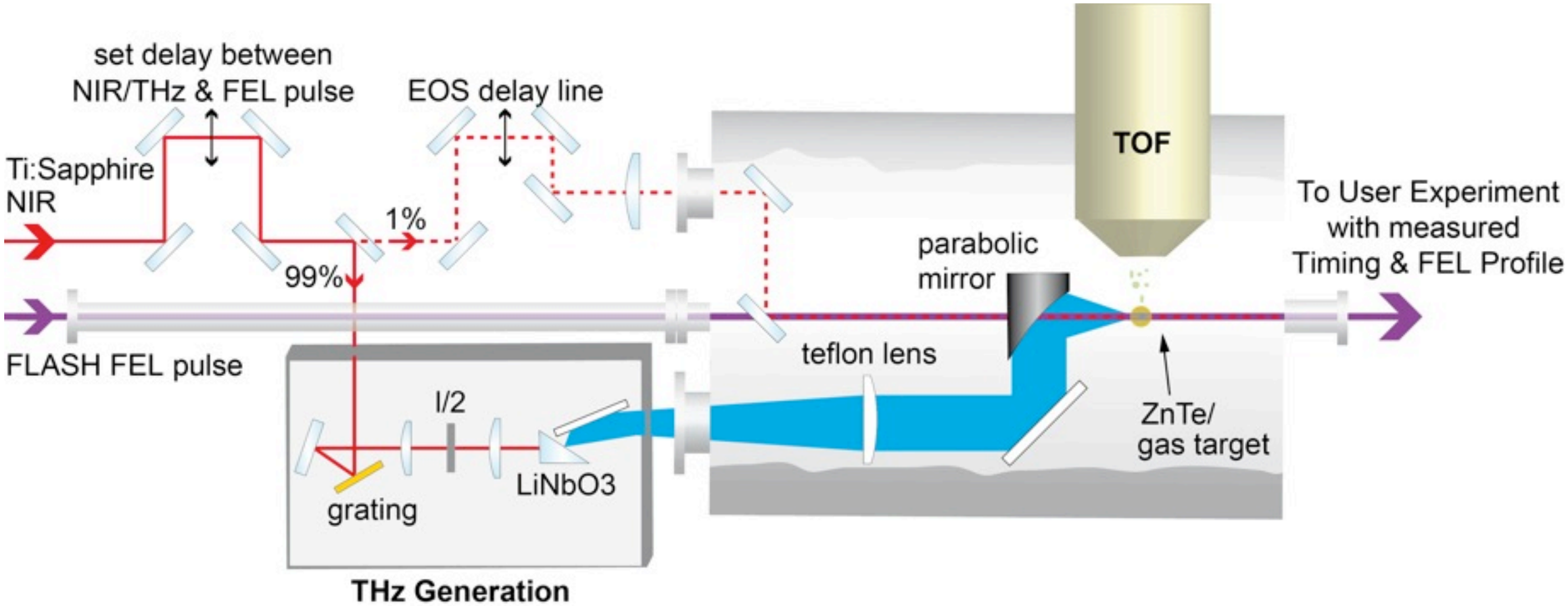
Multi-Bunch Mode – Stable Beam



Multi-Bunch Mode – Unstable Beam

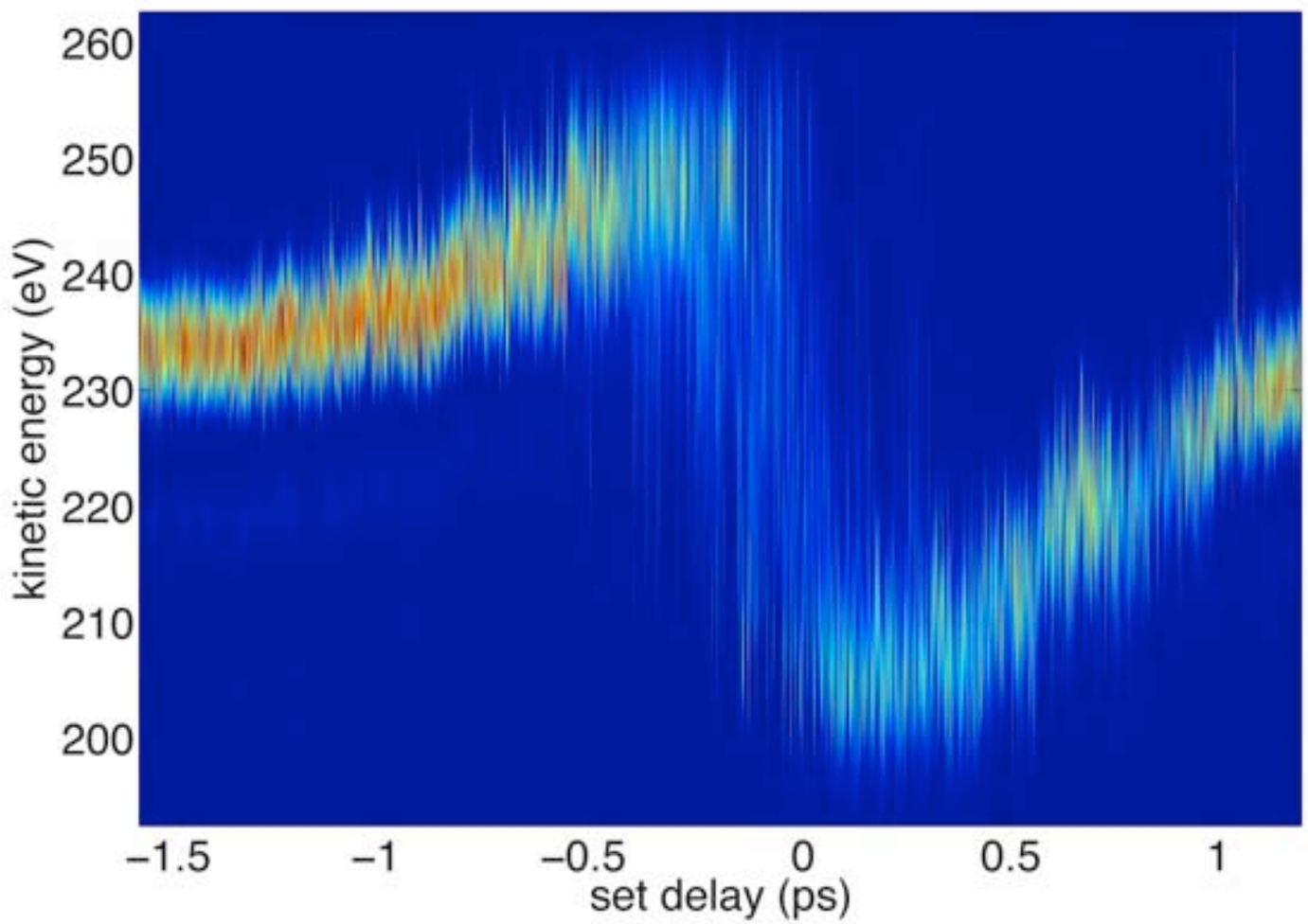


Terahertz Streak Camera



- THz pulse generated in LiNO3 by tilted wavefront method
- THz pulse characterized on-target using EOS
- EOS also establishes spatial and temporal overlap of THz pulse with NIR probe
- Use NIR probe to find coarse temporal overlap with XUV
- Block probe and use THz pulse to streak XUV induced photoemission

Terahertz Streak Camera



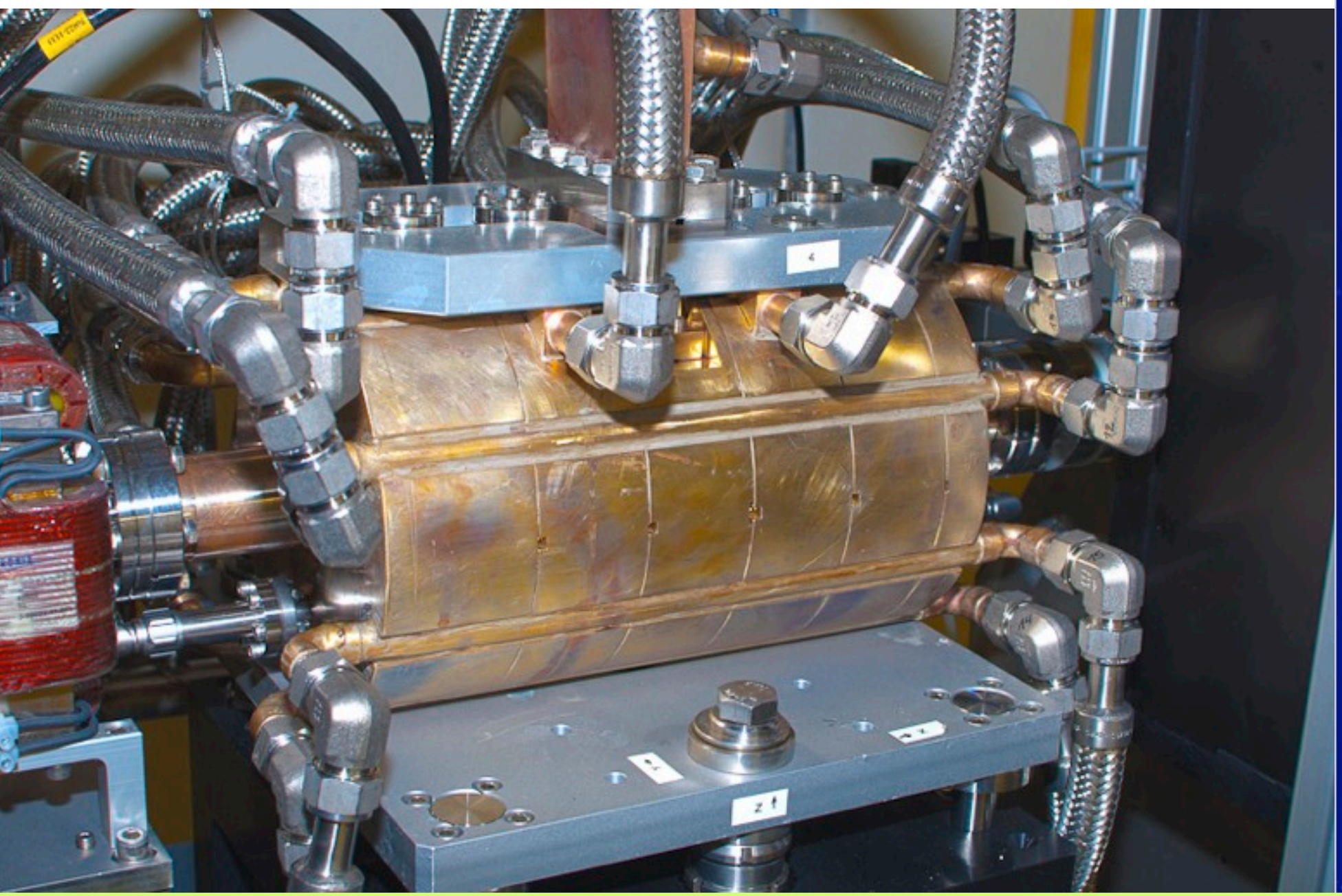
- All single-shots displayed for timescan #56
- Interaction in Helium (isolated line)
- 0.3nC bunches; ~260eV; ~10μJ/pulse

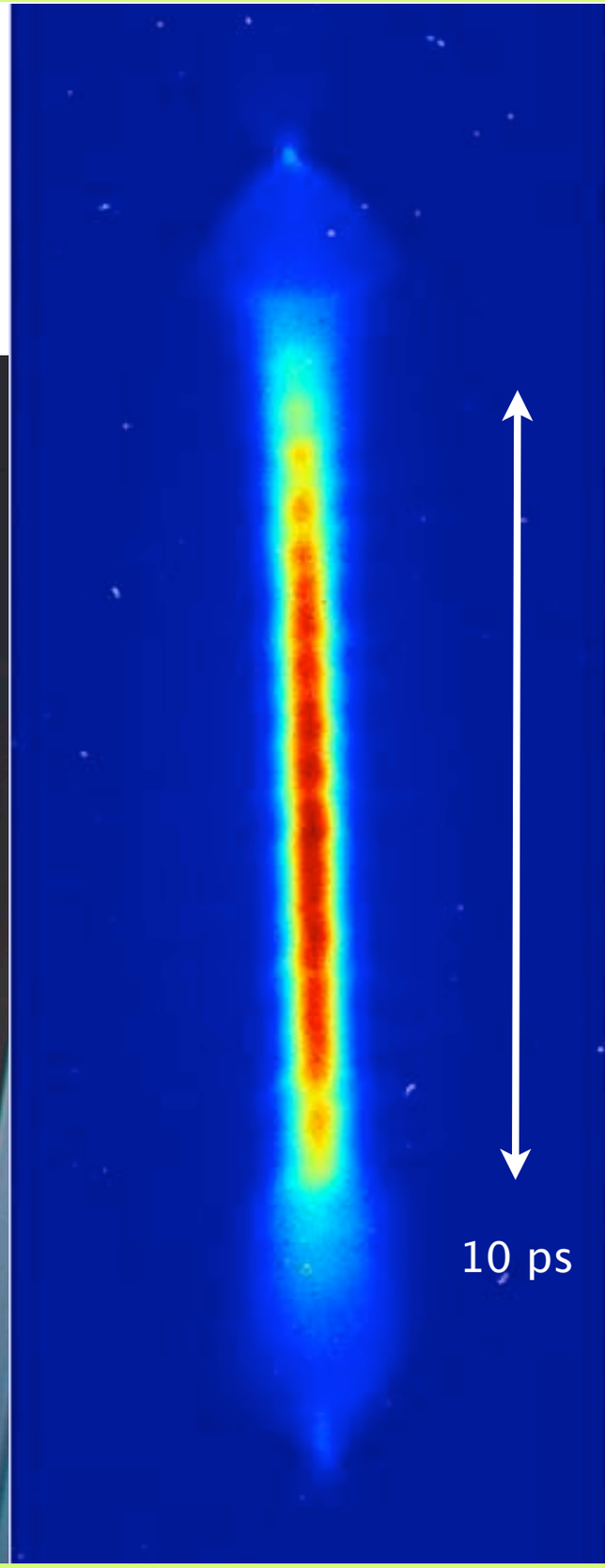
Direct Streaking of the Electron Beam

> Requires integrated transverse field of several MV

> Use transverse deflecting RF structure, powered by klystron

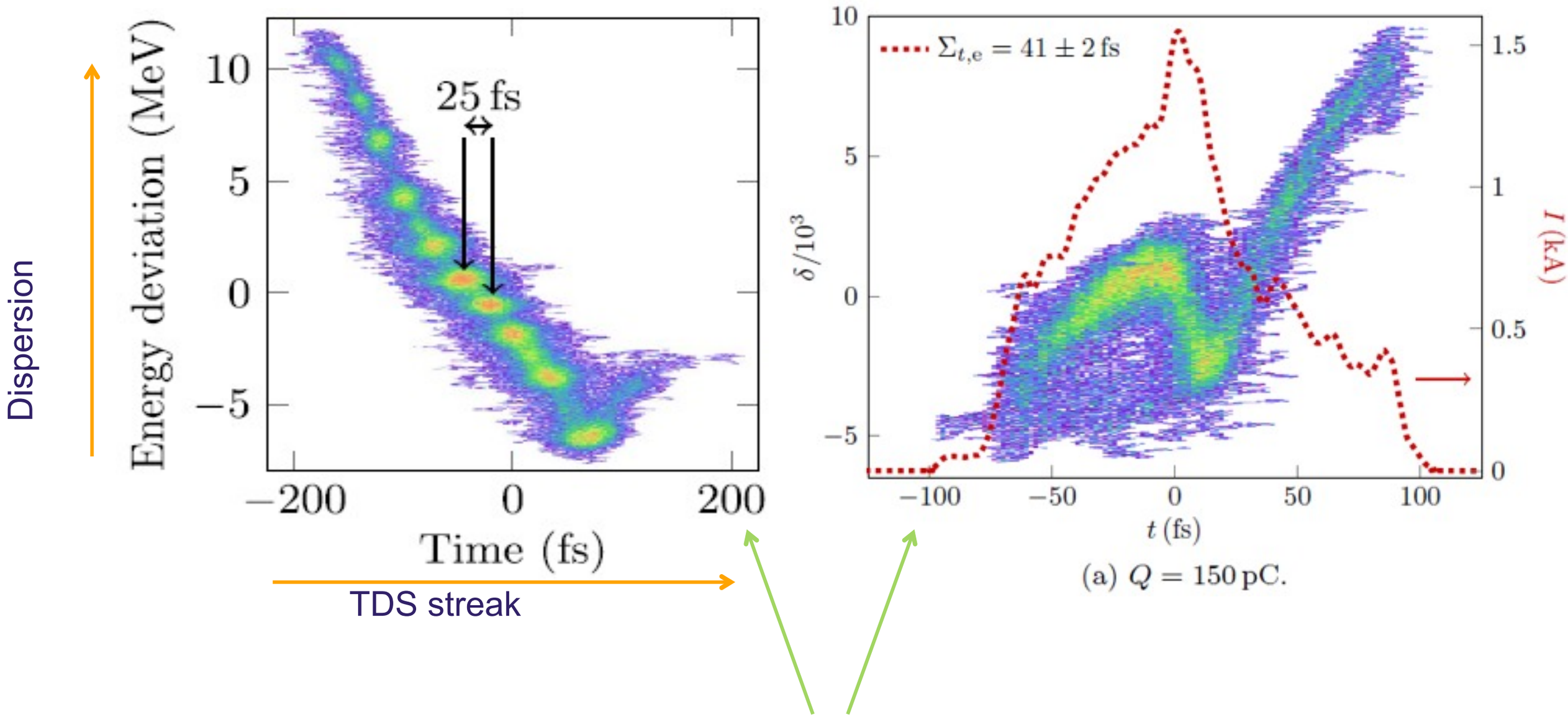
> Two-dimensional measurements possible





2-Dimensional Measurements

> More examples of 2-dimensional measurements



(a) $Q = 150$ pC.

Behrens et al., Phys. Rev. ST Accel. Beams 15, 062801 & 030707 (2012)

Comparison of Time Domain Methods

Method		Bunch length	Arrival time	Limitation	Invasiveness	Additional Advantages	Ref
Electrical Signals		≳ 30 ps	≳ 30 ps	Pickups, cables	:–)	2-d mea-surements	[1]
Cross-Correlation	THz / Pockels effect	≳ 30 fs	≳ 5 fs	Absorption in crystal	:–)		[2]
	X-rays / reflectivity	—	≳ 10 fs	Thermal processes	:–)		[3]
Streak Cameras	GHz streaking (cathode)	≳ 300 fs	≳ 1 ps	Streak frequency	:–)		[4]
	THz streaking (gas)	≳ 35 fs	≳ 5 fs	Gas target	:–|		[5]
	Direct streaking	≳ 8 fs	≳ 100 fs	Streak field, Profile monitor resolution, Optics	:–(	2-d mea-surements	[6]

[1] Dölling, Proceedings of HB2010, Morschach, Switzerland, [2] Müller et al., Proceedings of FEL2010, Malmo, Sweden, [3] Bionta et al., Opt. Exp. 19 21855 (2011) : Bionta et al., SPIE Proc. 8504 8504M (2012) : Harmand et al. Nat. Photonics 7 215 (2013), [4] Maesaka, IBIC 2012, Japan, [5] Adrian Cavalieri, private communication (2013), [6] Behrens et al., Phys. Rev. ST Accel. Beams 15, 030707 (2012)

Spectral Methods

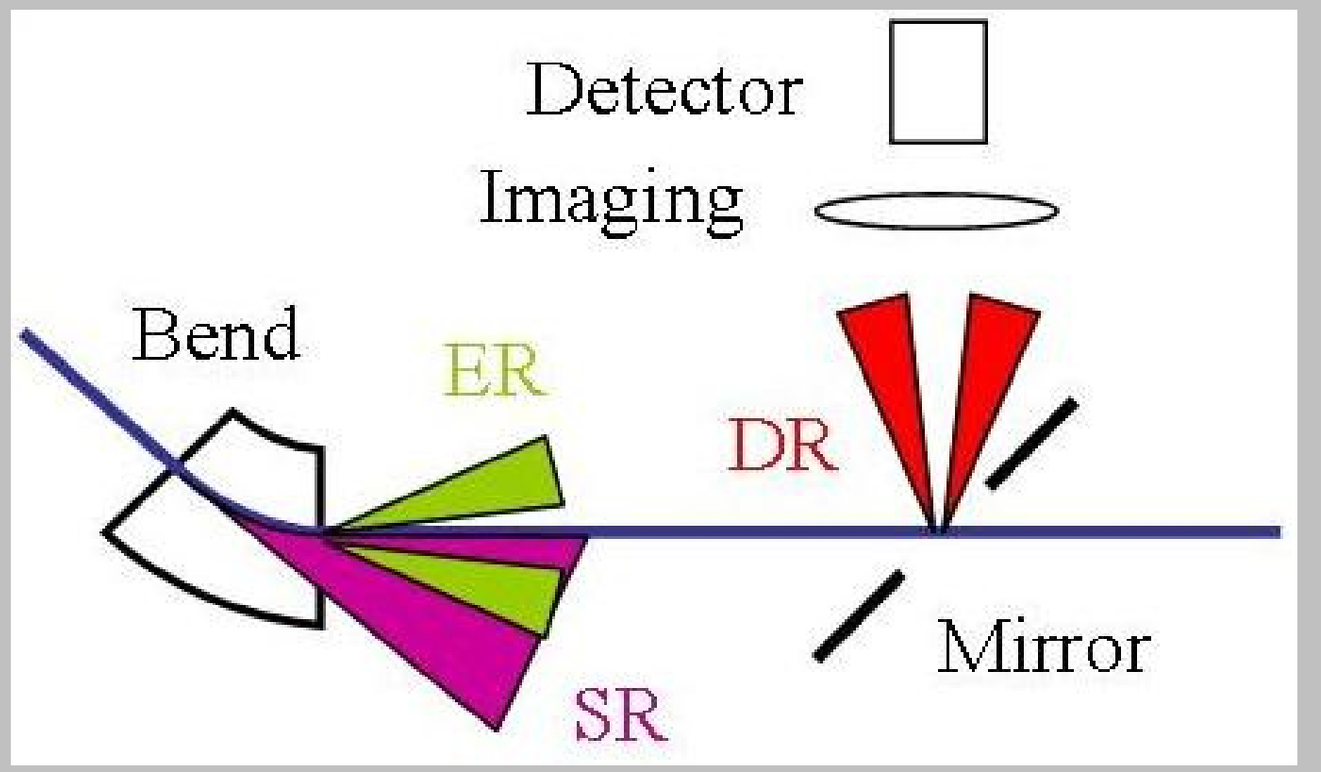
Spanish Pipe Organ, Prague, Wikimedia Commons

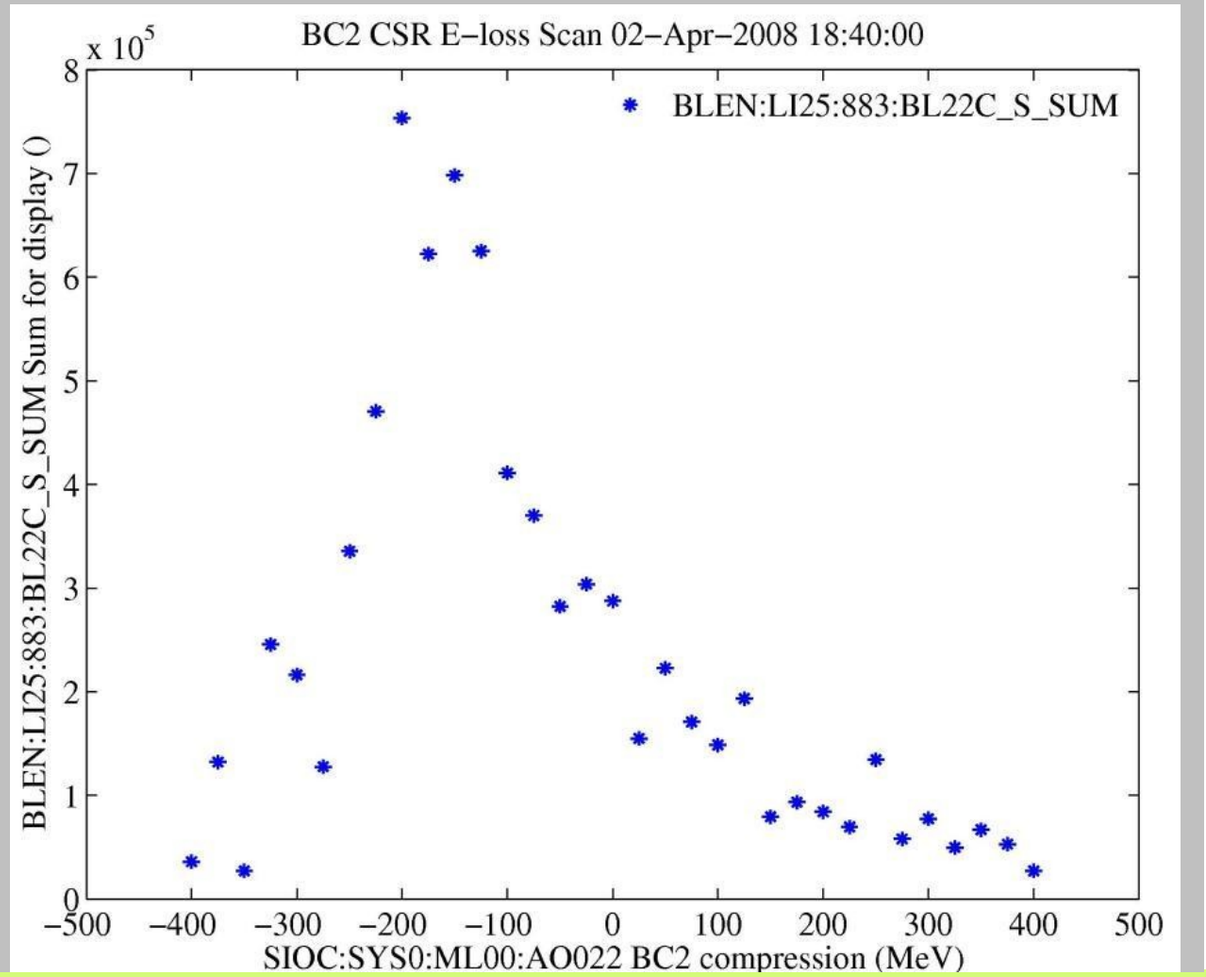
Spectral Methods

> Spectrum is the Fourier transform of the longitudinal form factor
  > Measurement of the spectrum can be used to infer bunch length
> But: typically, phase information is lost
  > Reconstruction possible if the complete spectrum is measured
  > Use as relative monitor
> Varying complexity:
  > Single channel
  > 3 channels
  > 5 channels
  > 120 channels

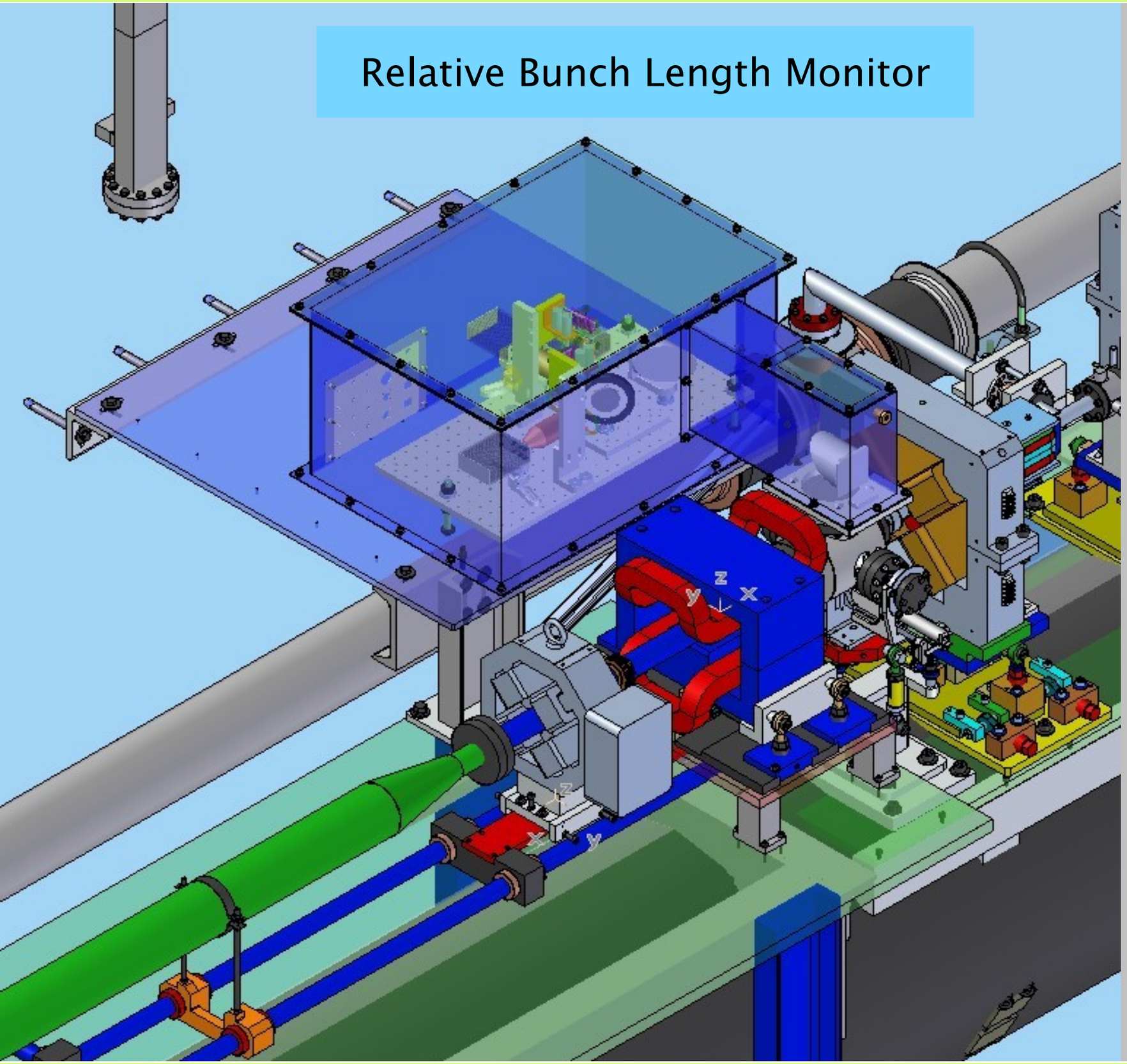
1-Channel "Spectrometer"

- Need shot to shot non-invasive bunch length monitor.
- Diffraction aperture and broadband (pyroelectric) detector.





1-Channel “Spectrometer”



Pyroelectric detector good from 100GHz to light (response is not flat)

Si window transmits from mm-wave to ~1 micron.

Can also use mm-wave diodes for BC1 (< 1 THz)

17

1-Channel "Spectrometer"

Setup of bunch length Calibration at BC2

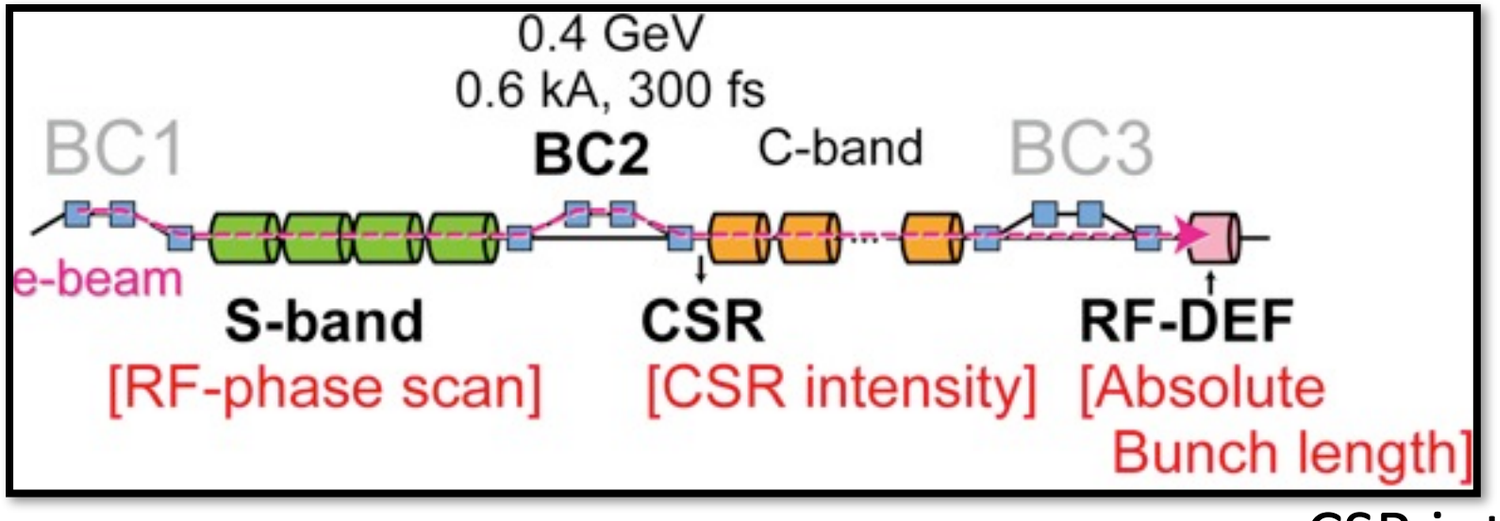
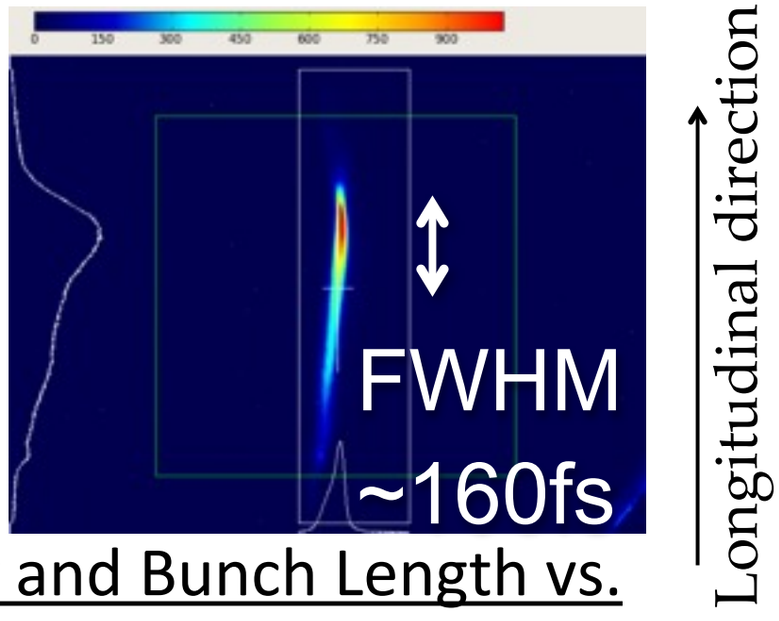
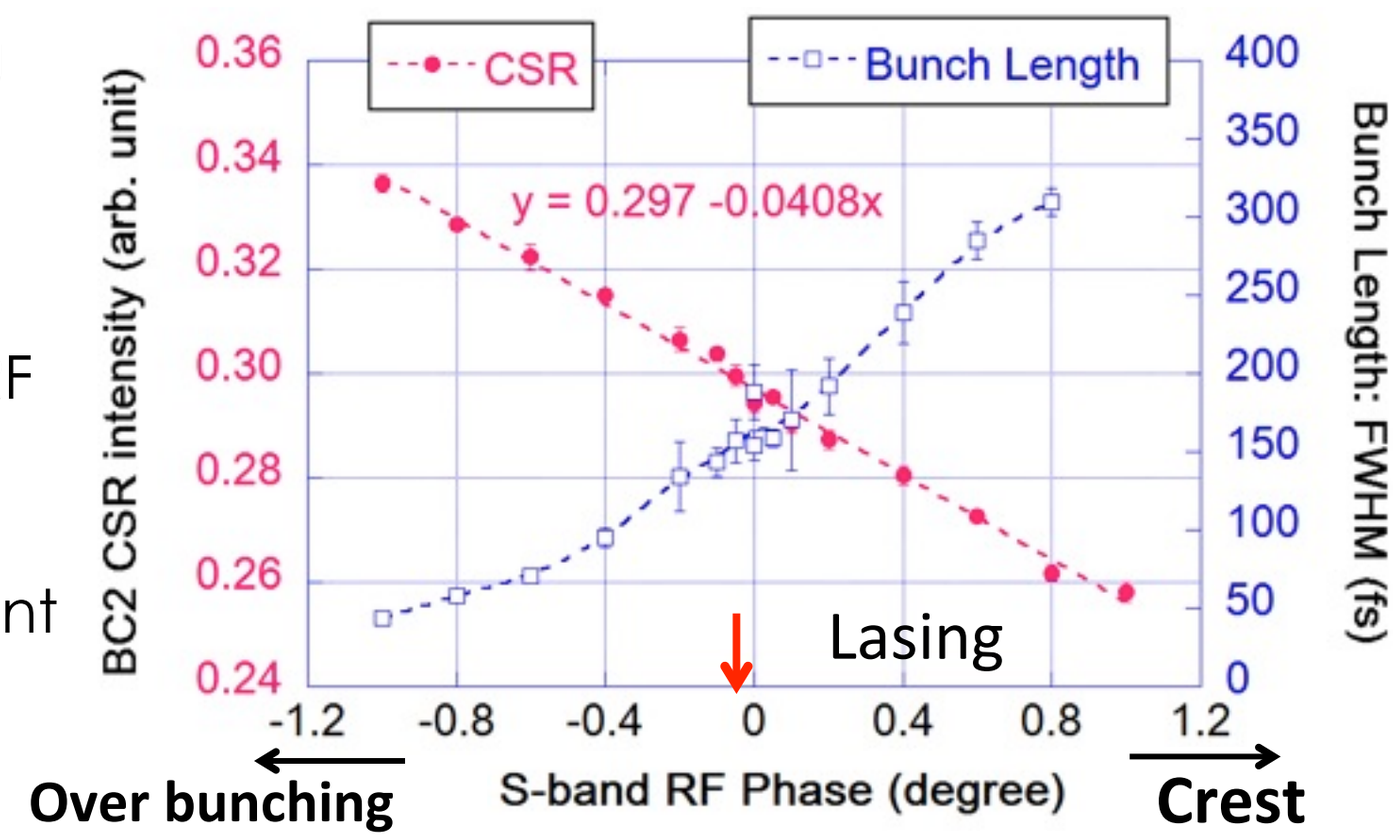


Image of Beam kicked by RF-def.



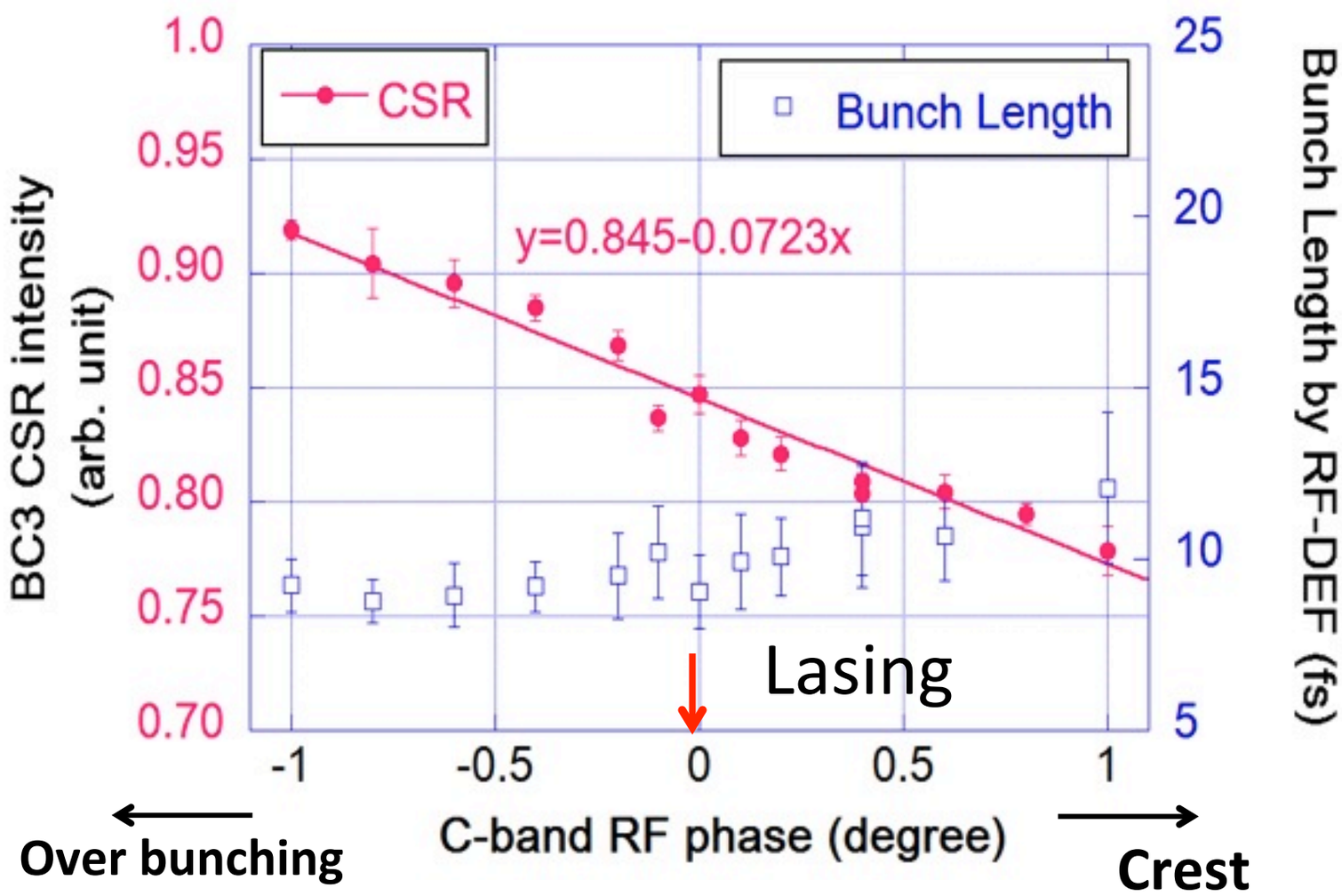
- The bunch length observed with the CSR monitor was calibrated by using the RF-deflector's data.
  - Electron beam was bypassed through BC3.
- Bunch length was changed by the RF phase of the S-band accelerating structures.
- Estimated bunch length measurement sensitivity is about 6% at a bunch length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

CSR intensity and Bunch Length vs. RF Phase of S-band Accelerating Structures



1-Channel "Spectrometer"

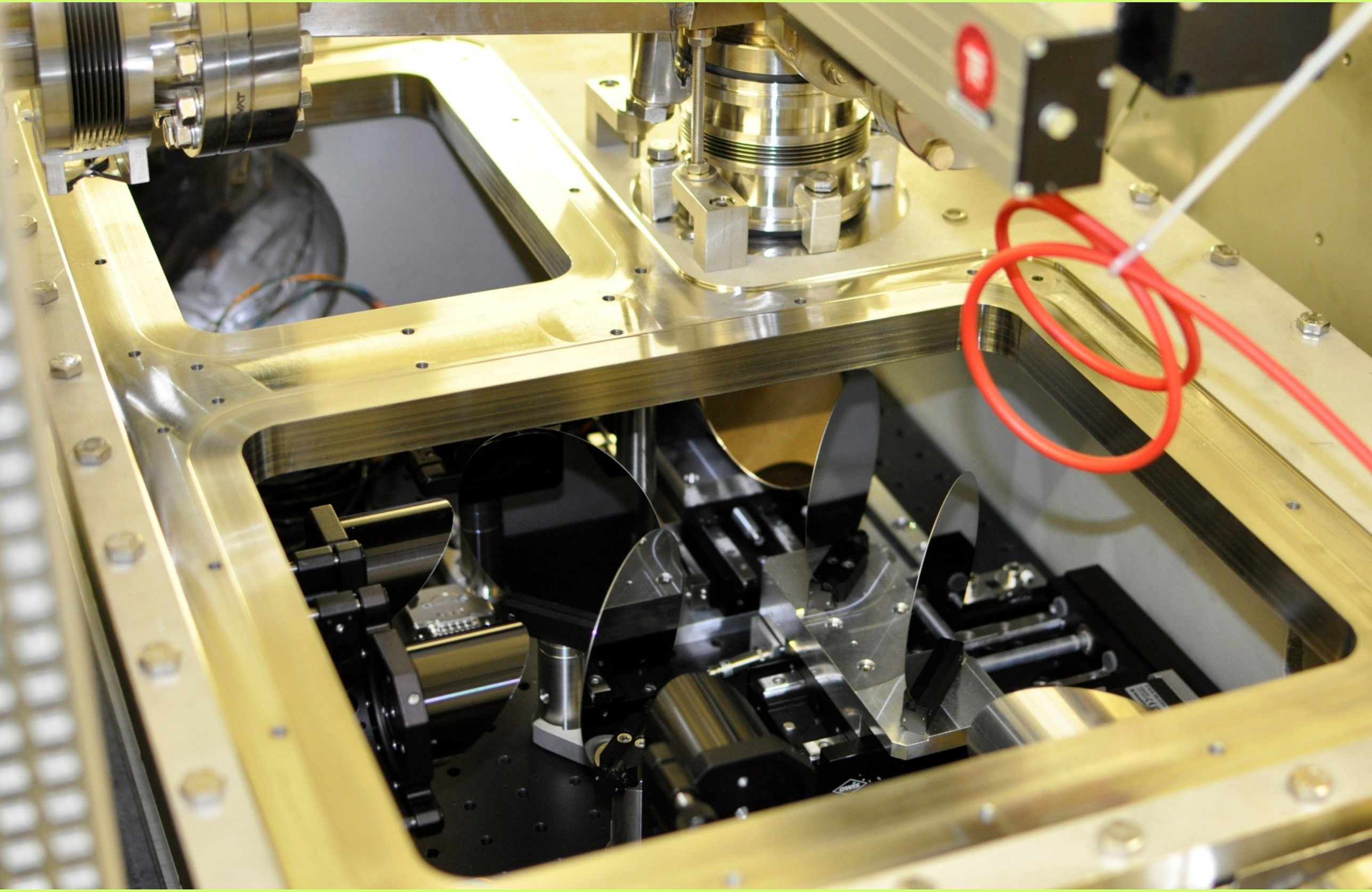
CSR intensity as a function of the RF Phase of the C-band accelerating structures before BC3



CSR intensity was linearly changed by the RF phase of the C-band (5712 MHz) accelerating structure before BC3.

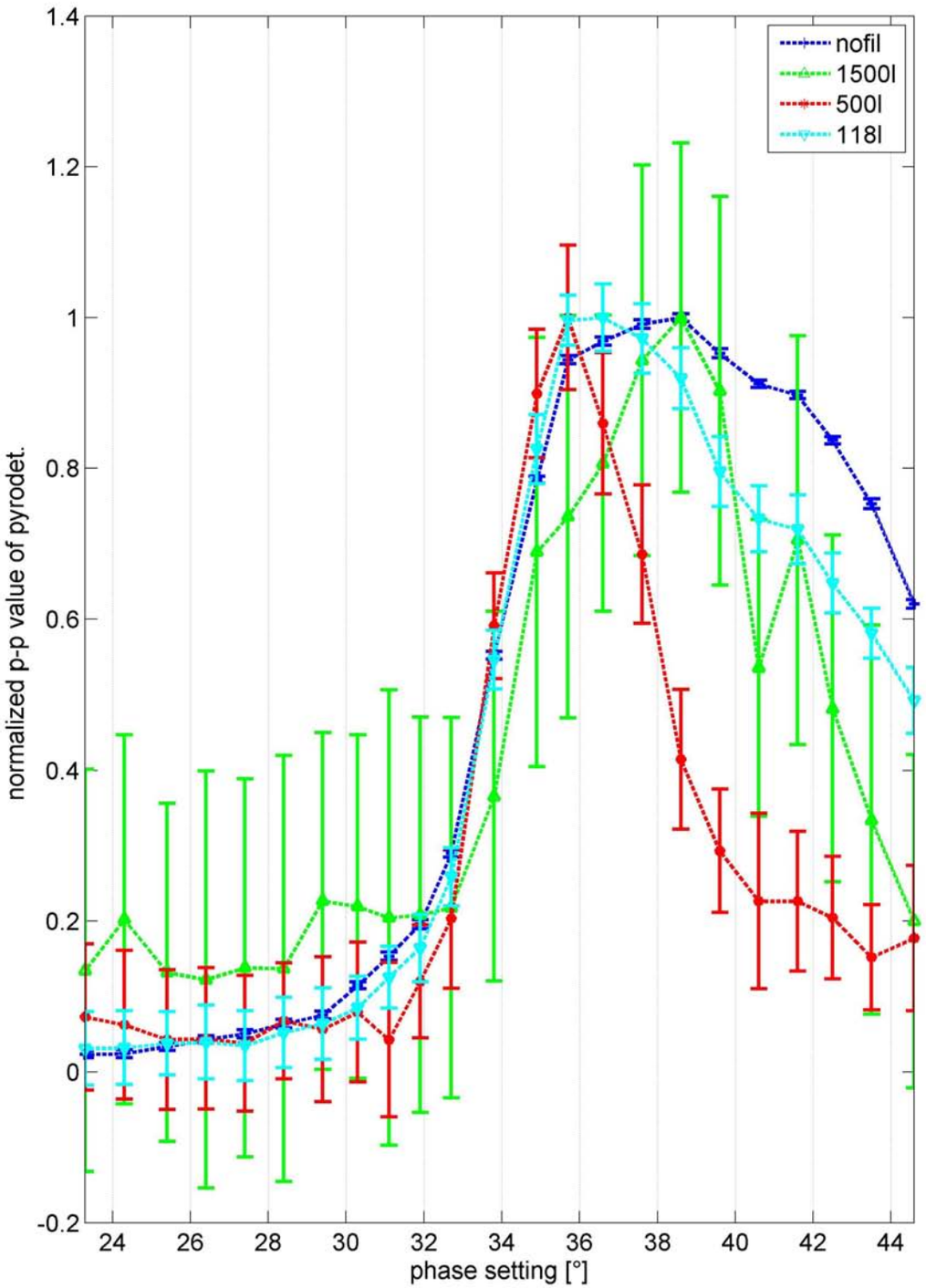
Estimated bunch length measurement sensitivity is less than 0.1 deg., which is better than that of the RF deflector.

4-Channel ‘Spectrometer’

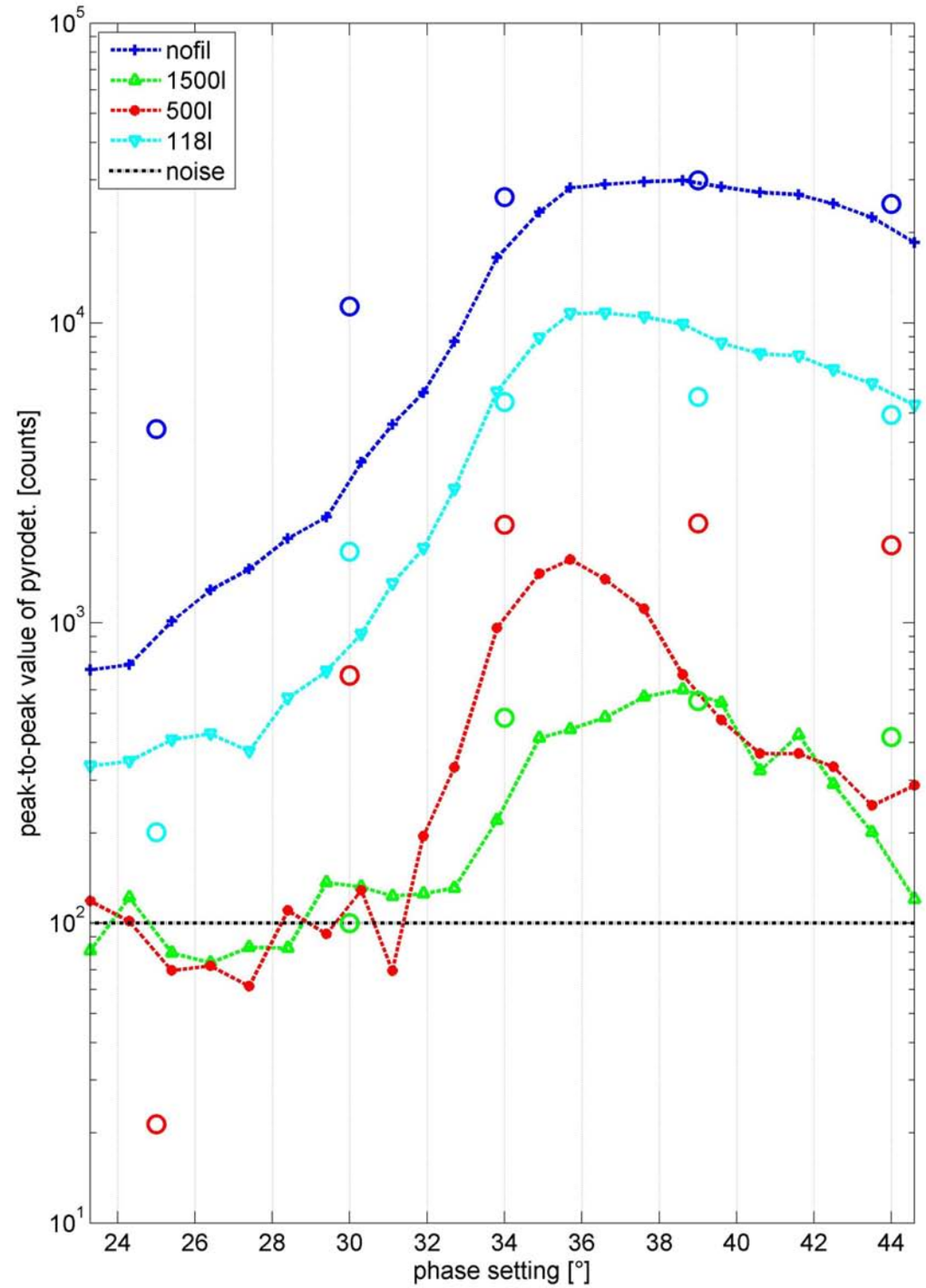


4-Channel 'Spectrometer'

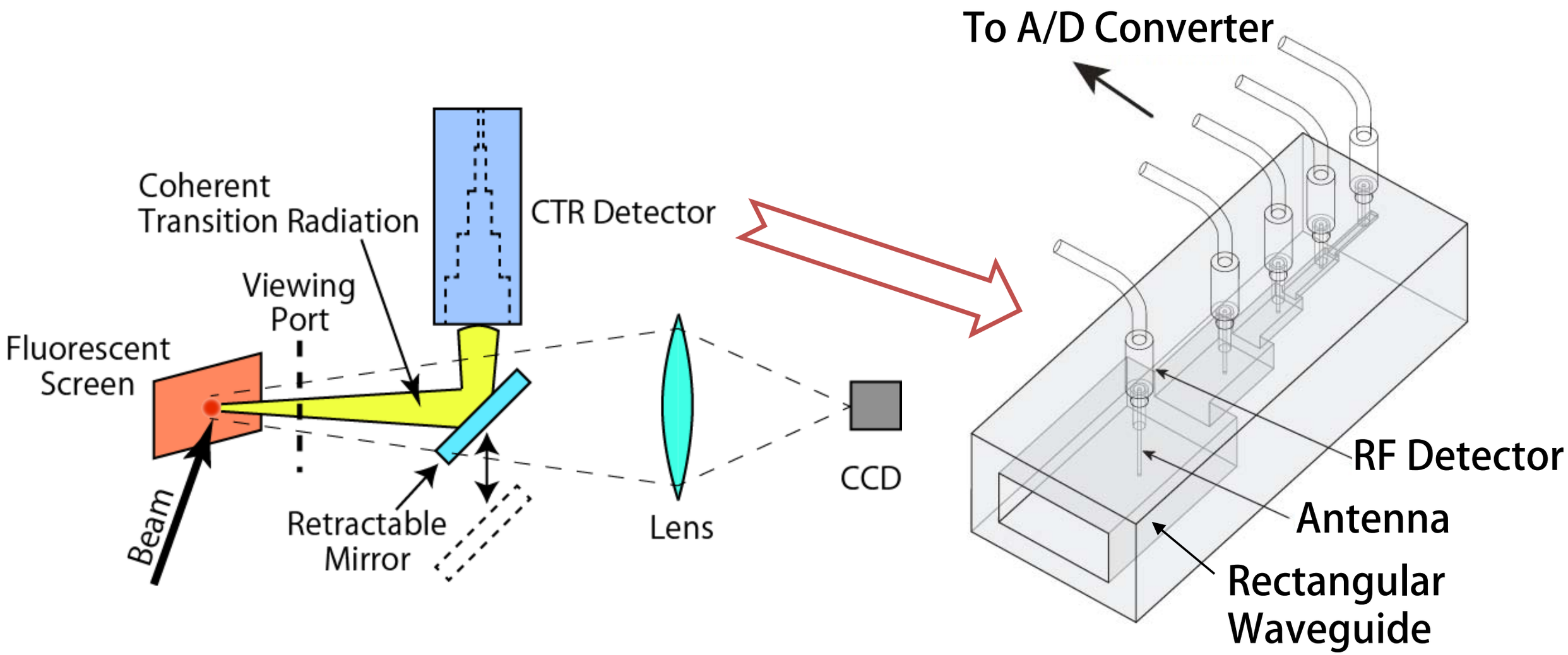
Normalized signals from pyros with different filters



Pyro signals compared to expected response

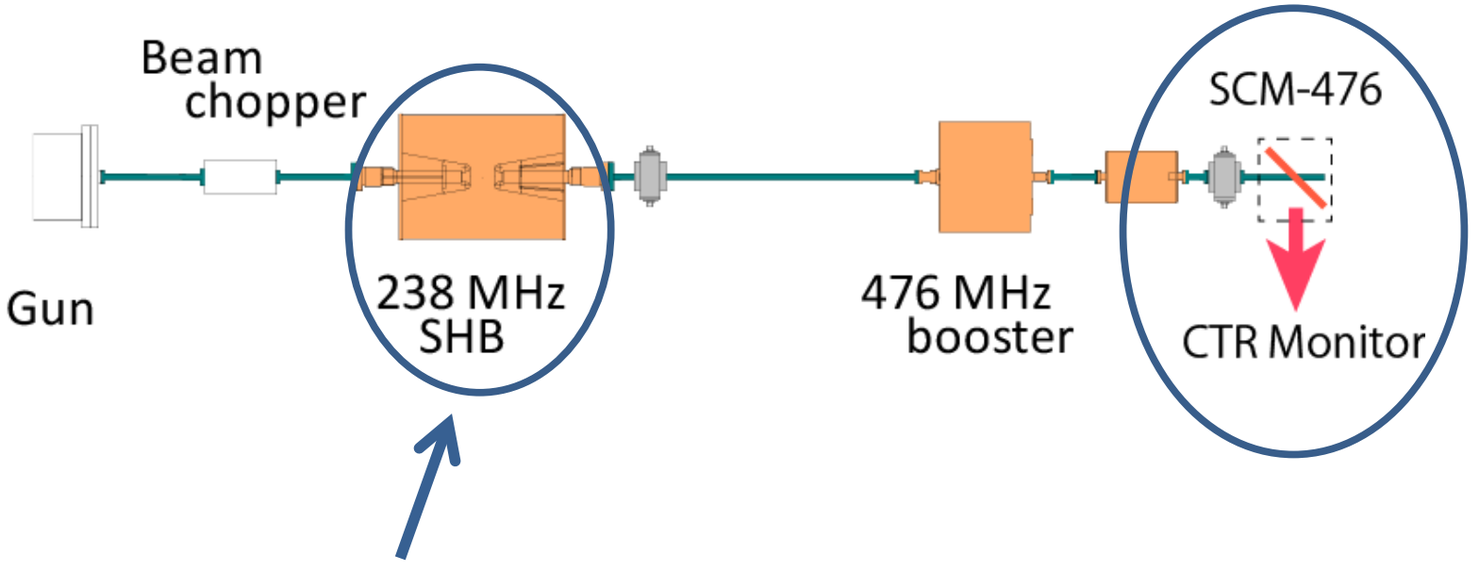


5-Channel Spectrometer

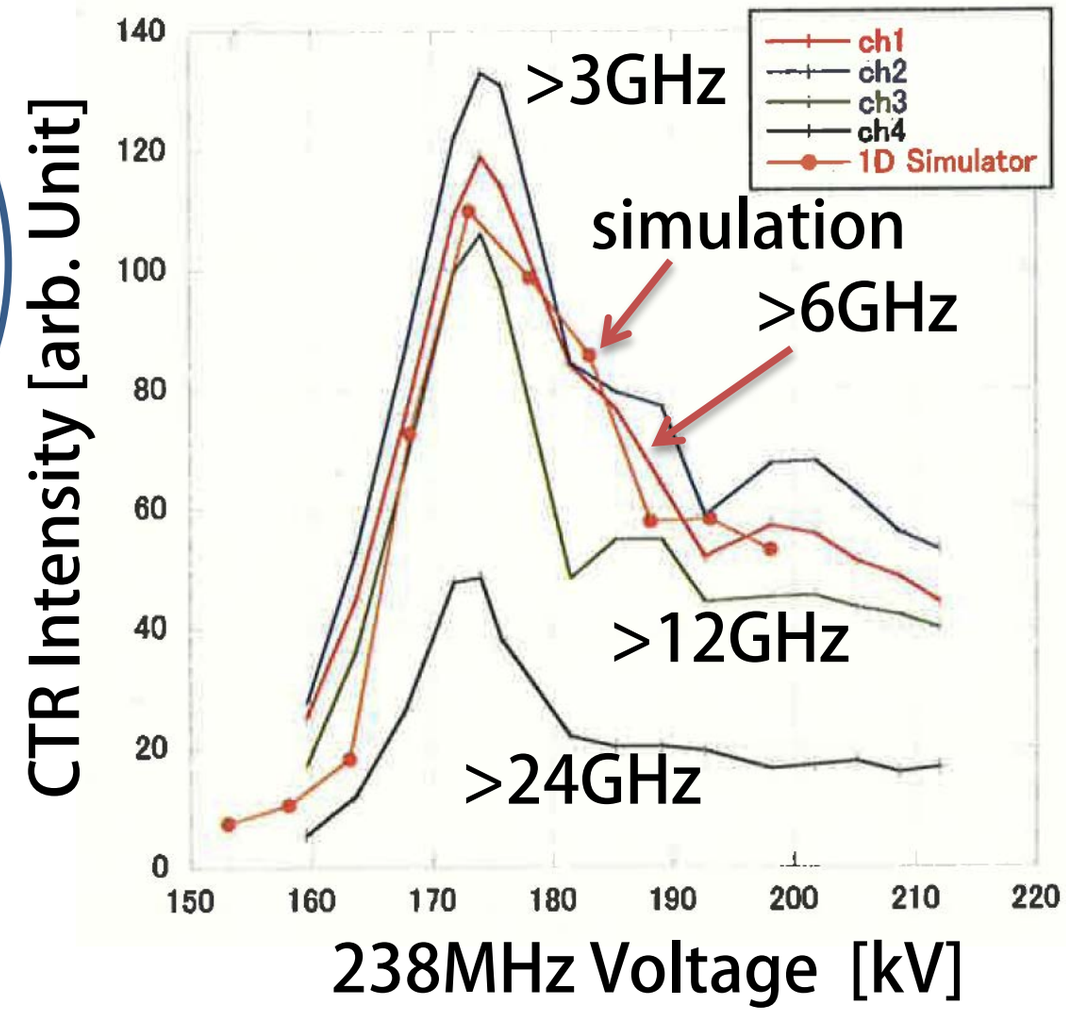


- Coherent transition radiation from a fluorescent screen is detected.
- By using a cut off of a rectangular waveguide, this works as a single-shot spectrometer.
- In the injector part, about 10 GHz rf signal is obtained.
  - Bunch length ~ 100 ps

5-Channel Spectrometer

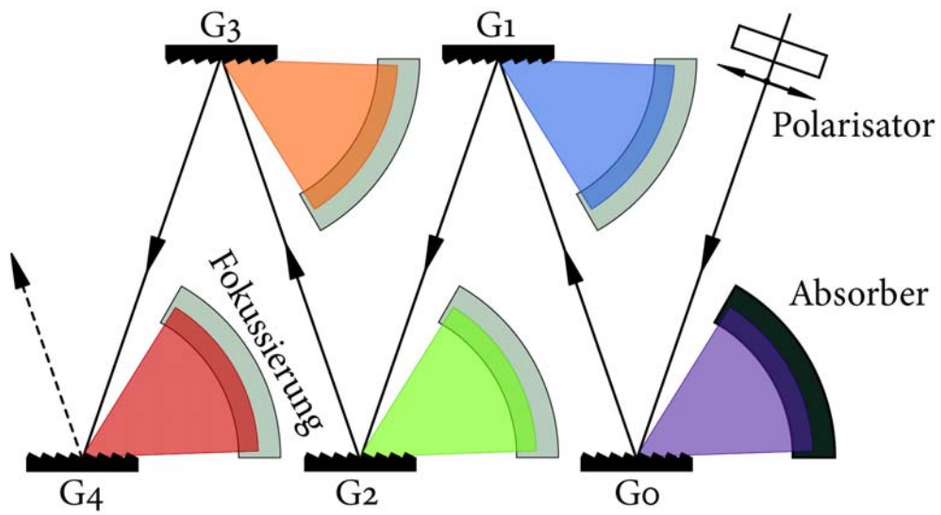


Accelerating voltages of 238MHz sub-harmonic buncher cavity was scanned.
(476 MHz booster was turned off.)



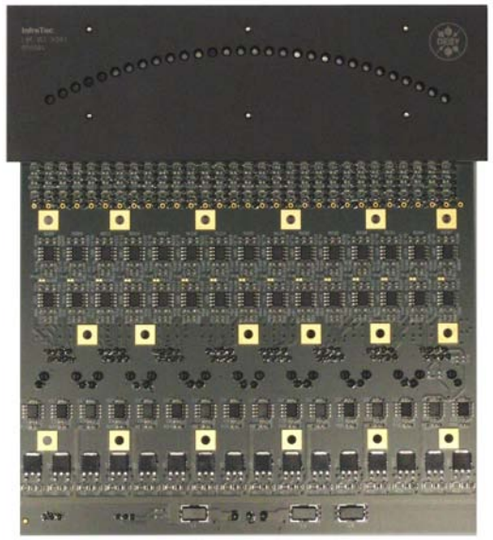
- The signal strength has a correlation with the bunch length.
  - Consistent with 1D simulation
  - Amplitude and phase of the sub-harmonic cavities can be determined

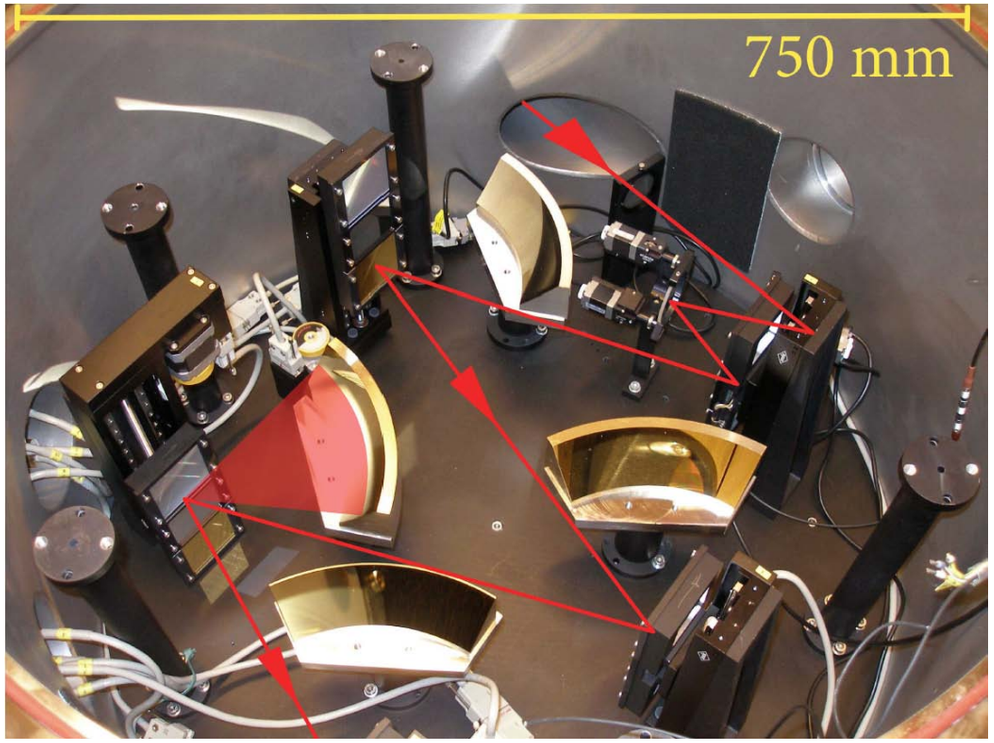
120-Channel Spectrometer



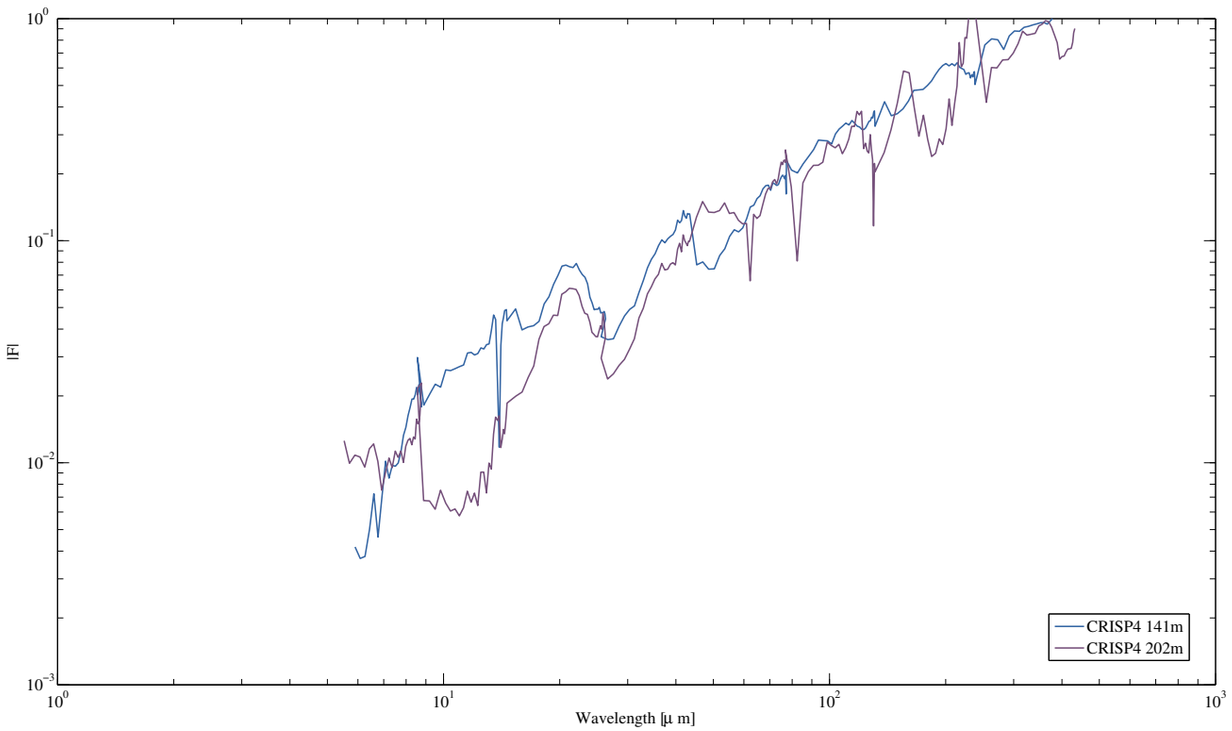
Courtesy of S.Wesch

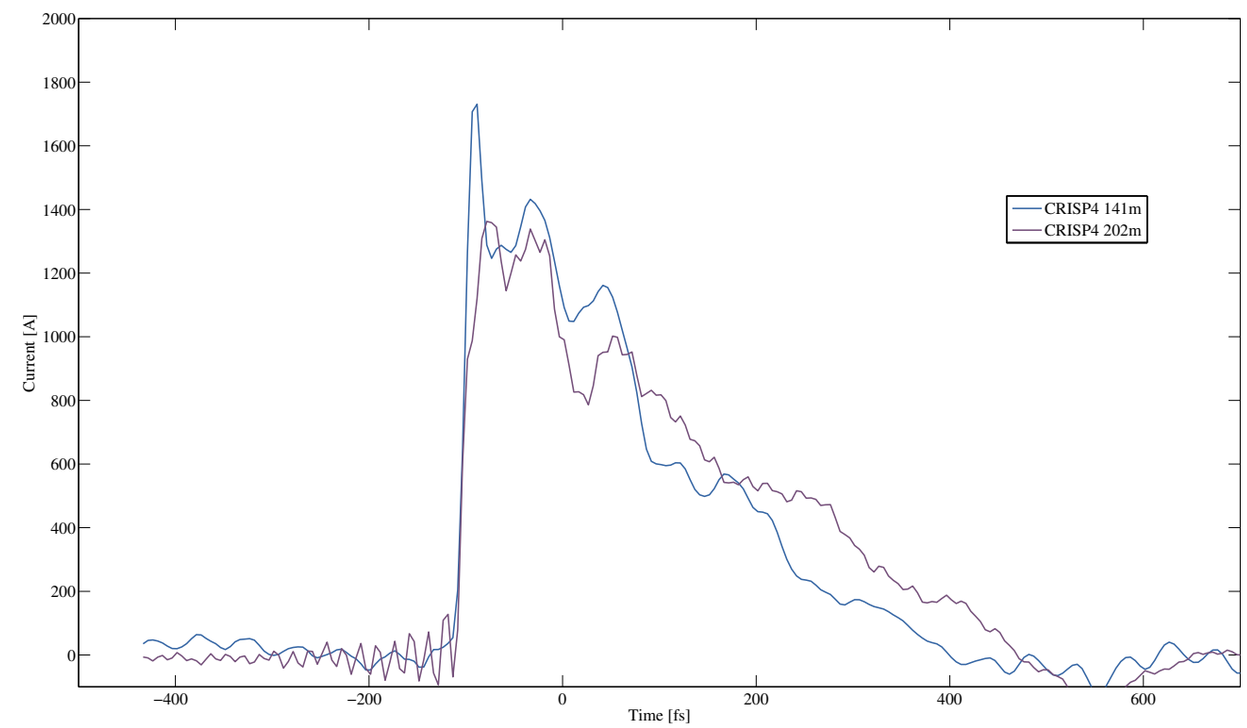
- Five consecutive gratings as prefilter and dispersive devices
- Wavelength coverage from 5.5 to $440\mu m$ with two sets of gratings
  - Set one: 5.5 to $44\mu m$
  - Set two: 44 to $440\mu m$
- One order of magnitude in λ for four gratings
- Parallel readout of 120 channels for one set of gratings

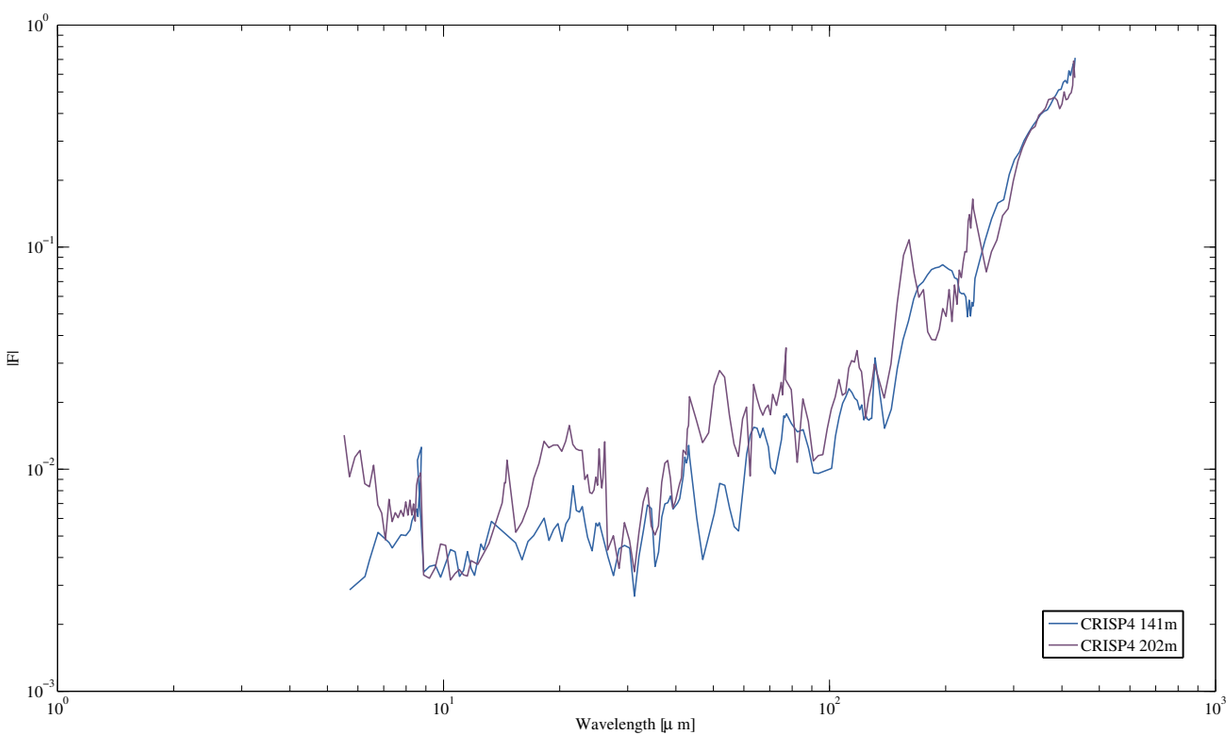


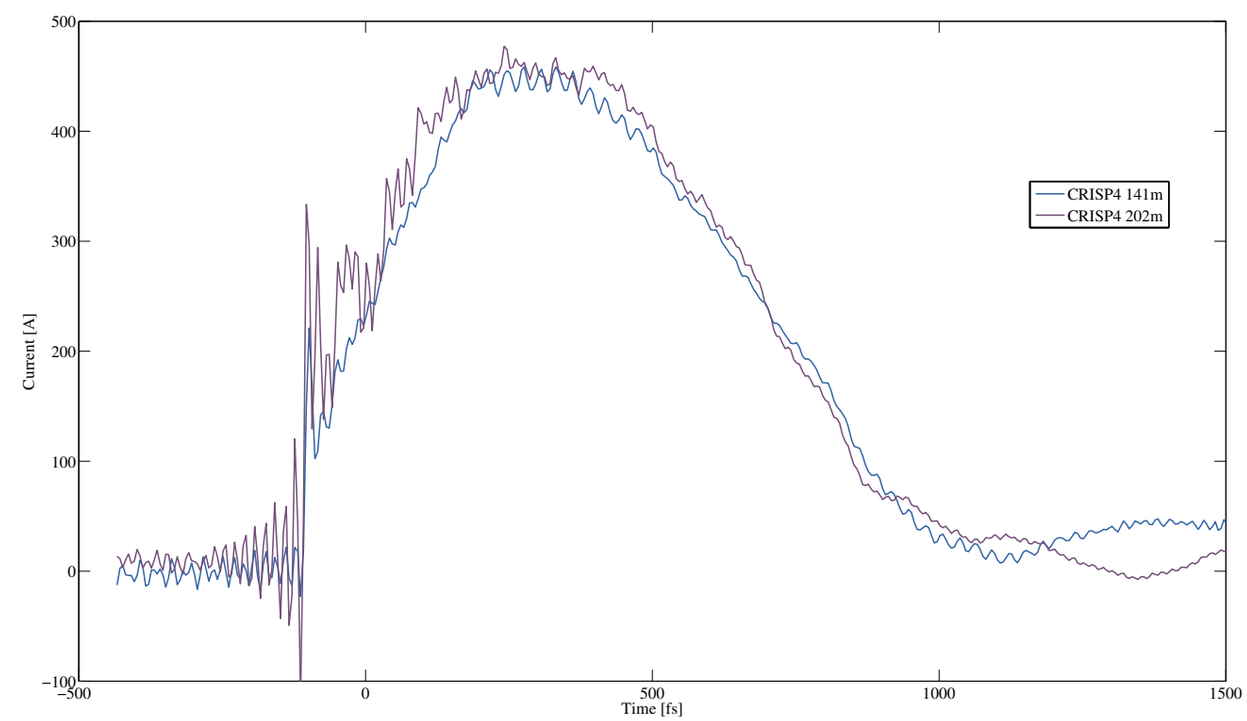


120-Channel Spectrometer



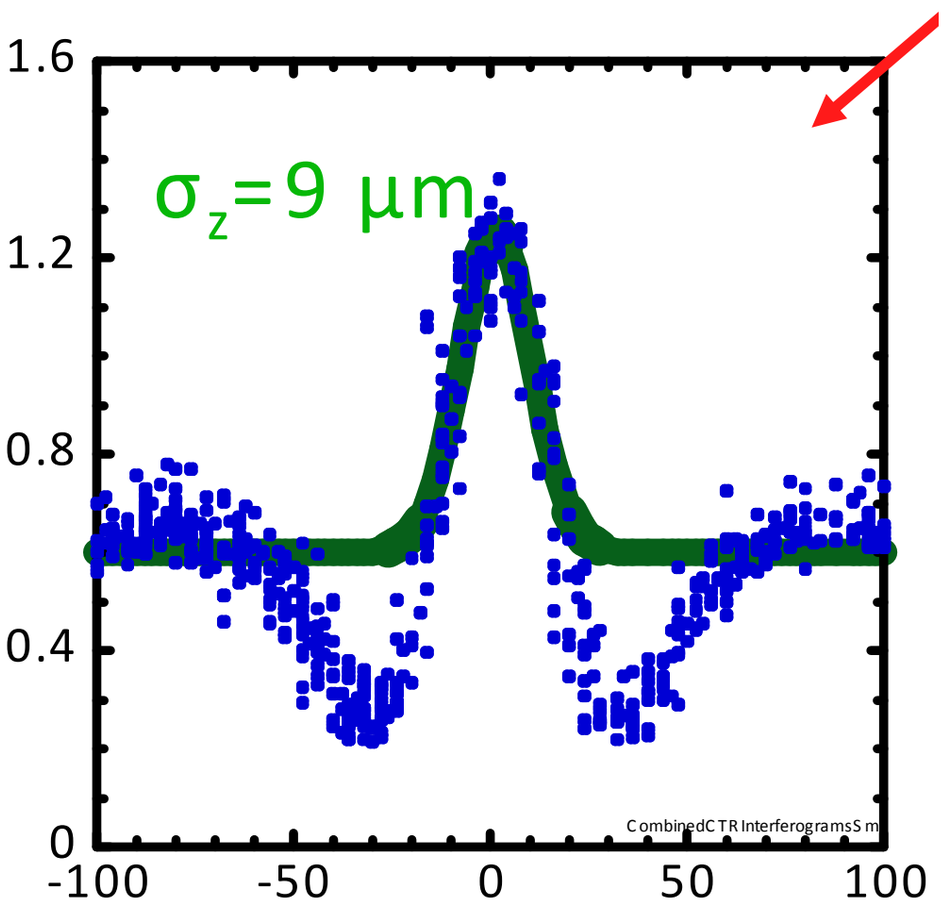


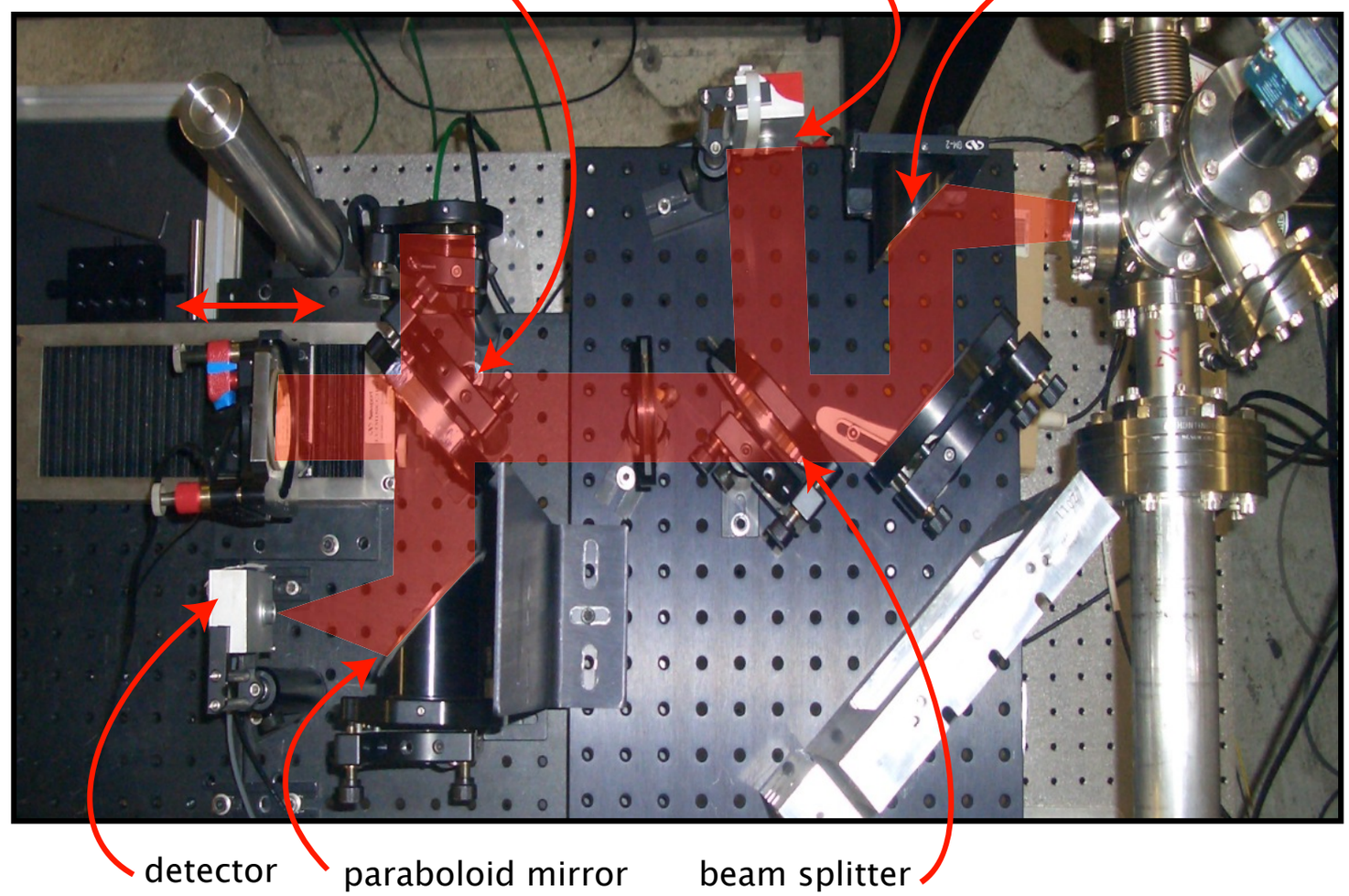




Autocorrelation of the Radiation

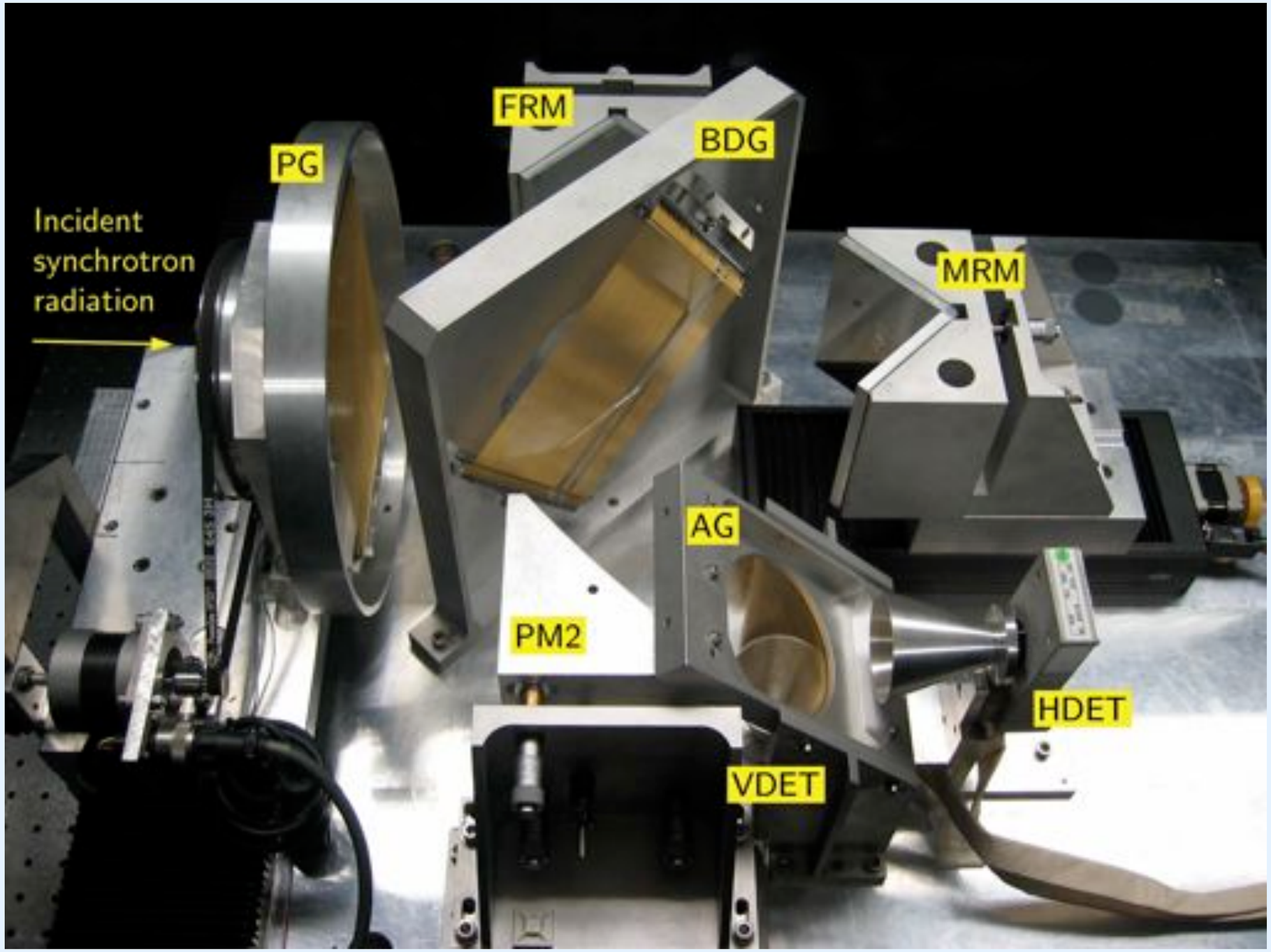
> Autocorrelation is the Fourier transform of the form factor





Autocorrelation of the Radiation

Example of Martin-Puplett Interferometer (installed behind FLASH Synchrotron Radiation Beamline)



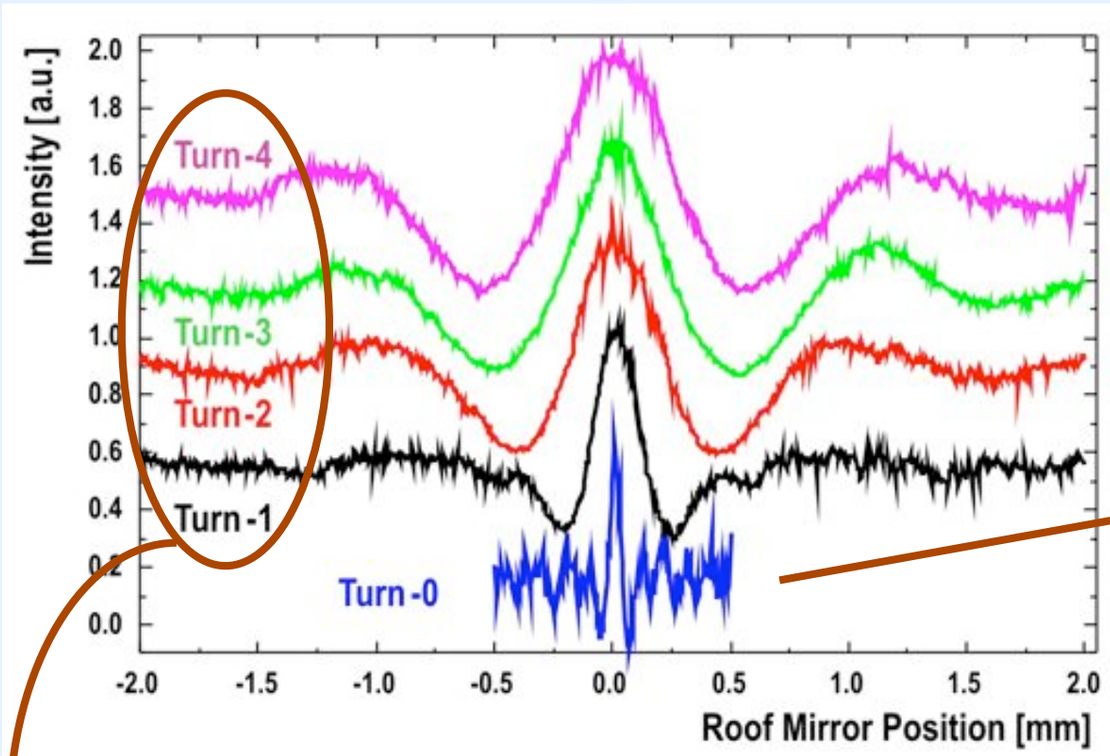
courtesy of Lars Fröhlich, DESY

- **PG** - polarizing grid
- **BDG** - beam splitter grid
- **FRM** - fixed roof mirror
- **MRM** - movable roof mirror
- **PM2** - parabolic mirror
- **AG** - analyzing grid
- **VDET** - pyro-detector for vertical polarization
- **HDET** - pyro-detector for horiz. polarization

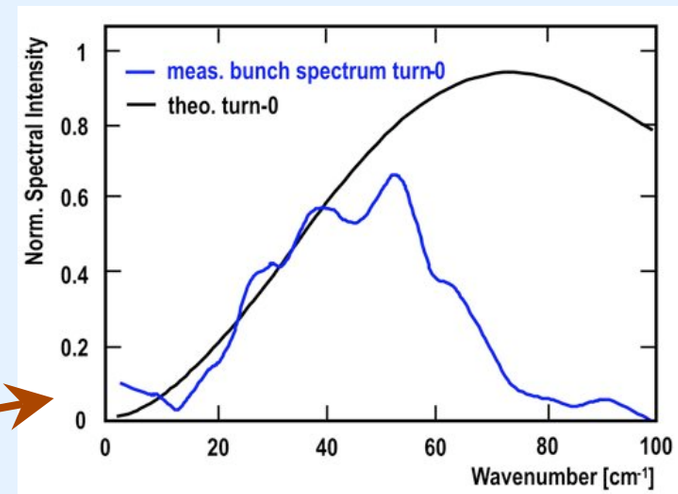
SLS FEMTO Bunch Slicing - Turn-by-Turn Bunch Length Evolution III

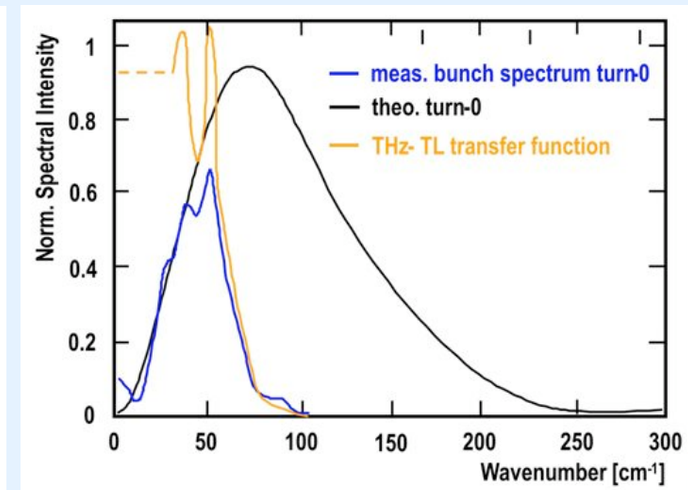
prelim. data from: D. Abramsohn, Diploma thesis in preparation

Interferogramms from 5 consecutive turns after slicing

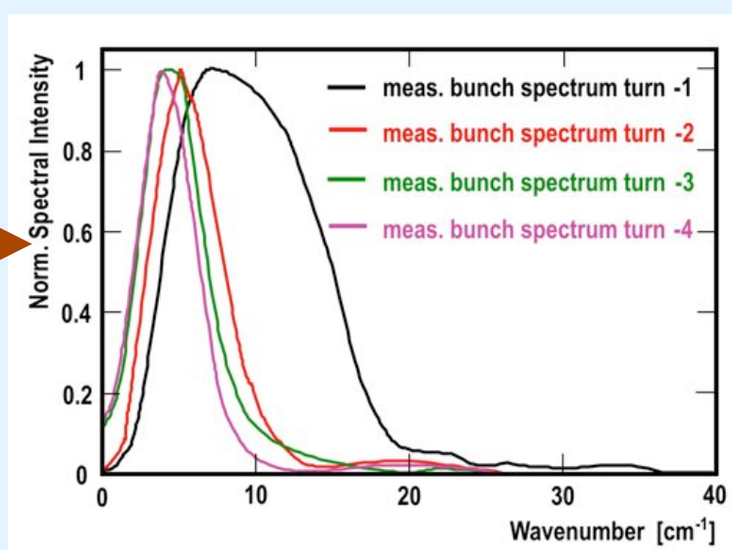


Spectral Intensity of Turn 0 (Theory and Experimental Data)

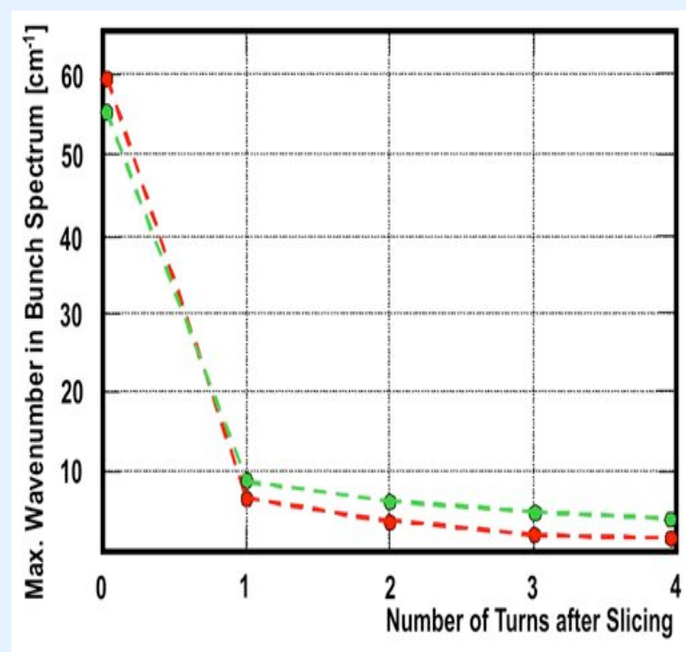


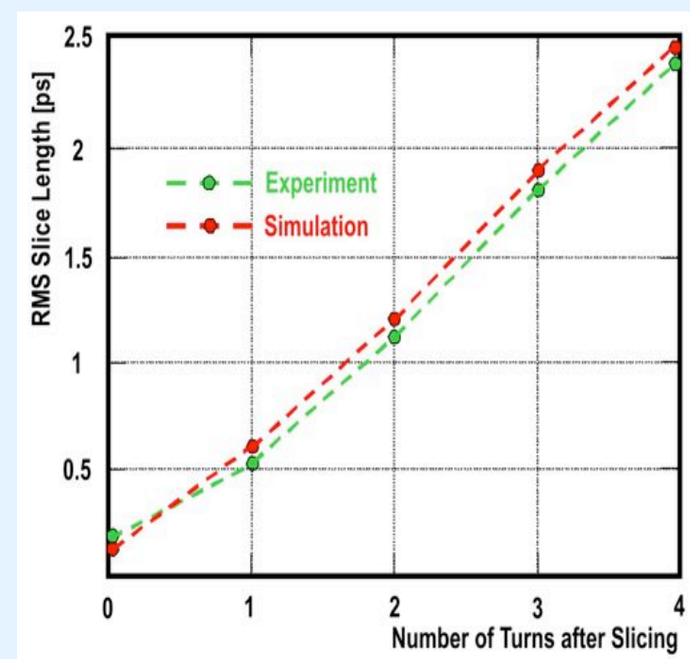


Spectral Intensities of Turns 1 to 4 after Slicing



Bunch Lengths Evolution after Slicing in SLS Storage Ring





Temporal vs Spectral Methods

:-) Temporal Methods	:-) Spectral Methods
Absolute determination of bunch length and shape	Easy to set up
2-d measurements possible	Very sensitive to bunch length changes
Allow to measure arrival time	Robust setup allows for feedbacks
	Methods become easier for shorter bunches
:-∫ Temporal Methods	:-∫ Spectral Methods
Require an external reference	Phase reconstruction methods require graduate students

Longitudinal Diagnostics for Free Electron Lasers

Rasmus Ischebeck, Paul Scherrer Institut

> Thank you for slides, graphics, photos and plots provided by:

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- Peter Peier
- Eduard Prat
- Volker Schlott
- Bennie Smit

> Slides available at: http://people.web.psi.ch/ischebeck

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