Ultrafast Instrumentation for Accelerators I

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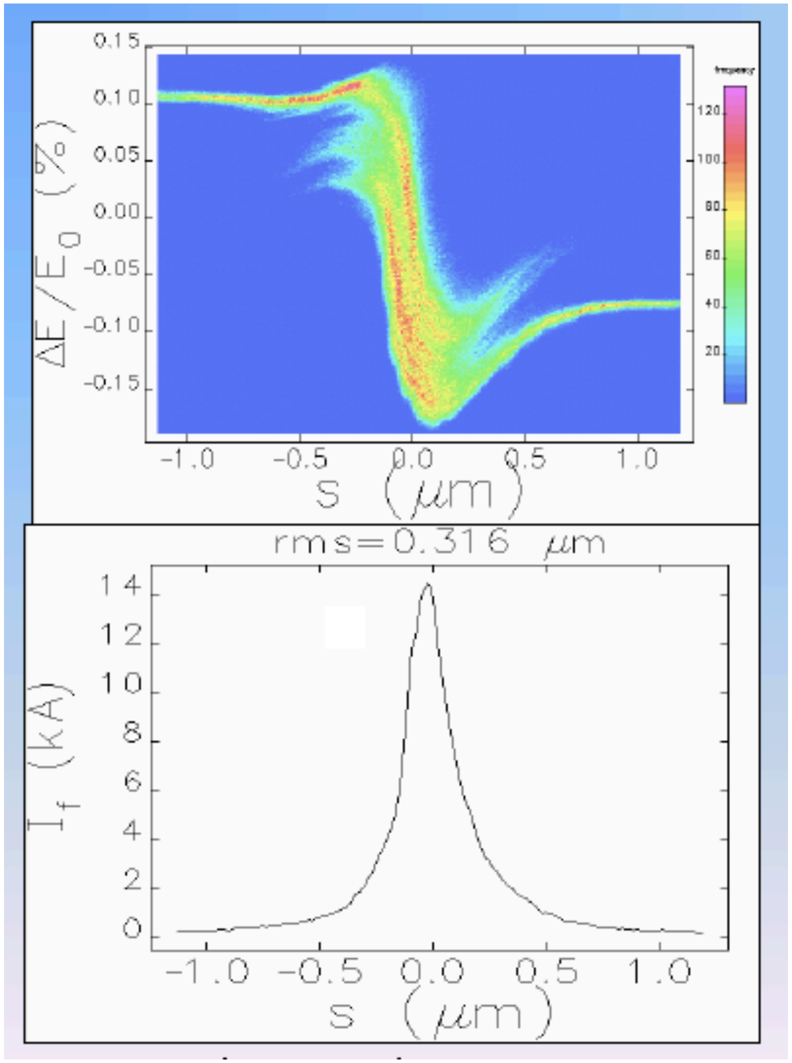
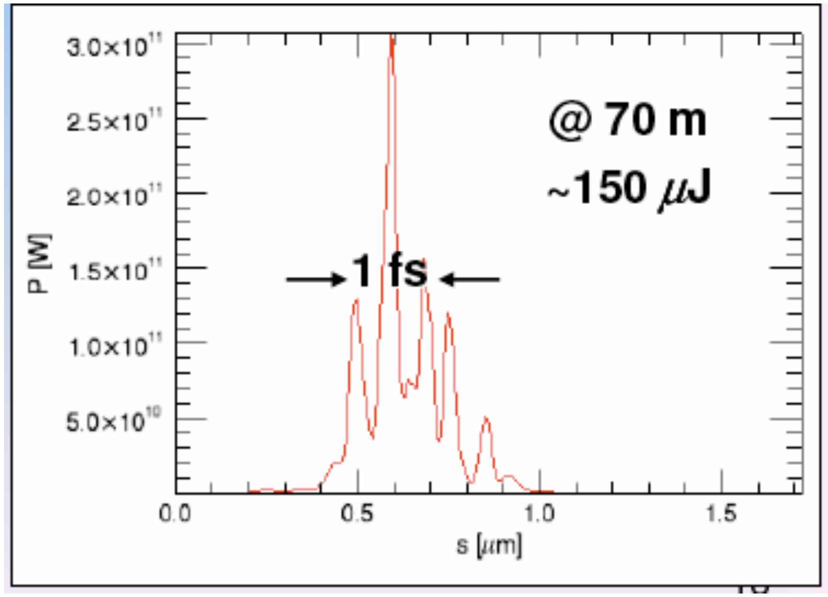
Lecture Overview

- Provide an overview of techniques for characterizing short pulses of electrons and photons (1 psec-1 fsec) in accelerators
  - Pulse length
  - Arrival time
  - Energy spread (electrons) and spectral content (photons)
  - Femtosecond timing and synchronization

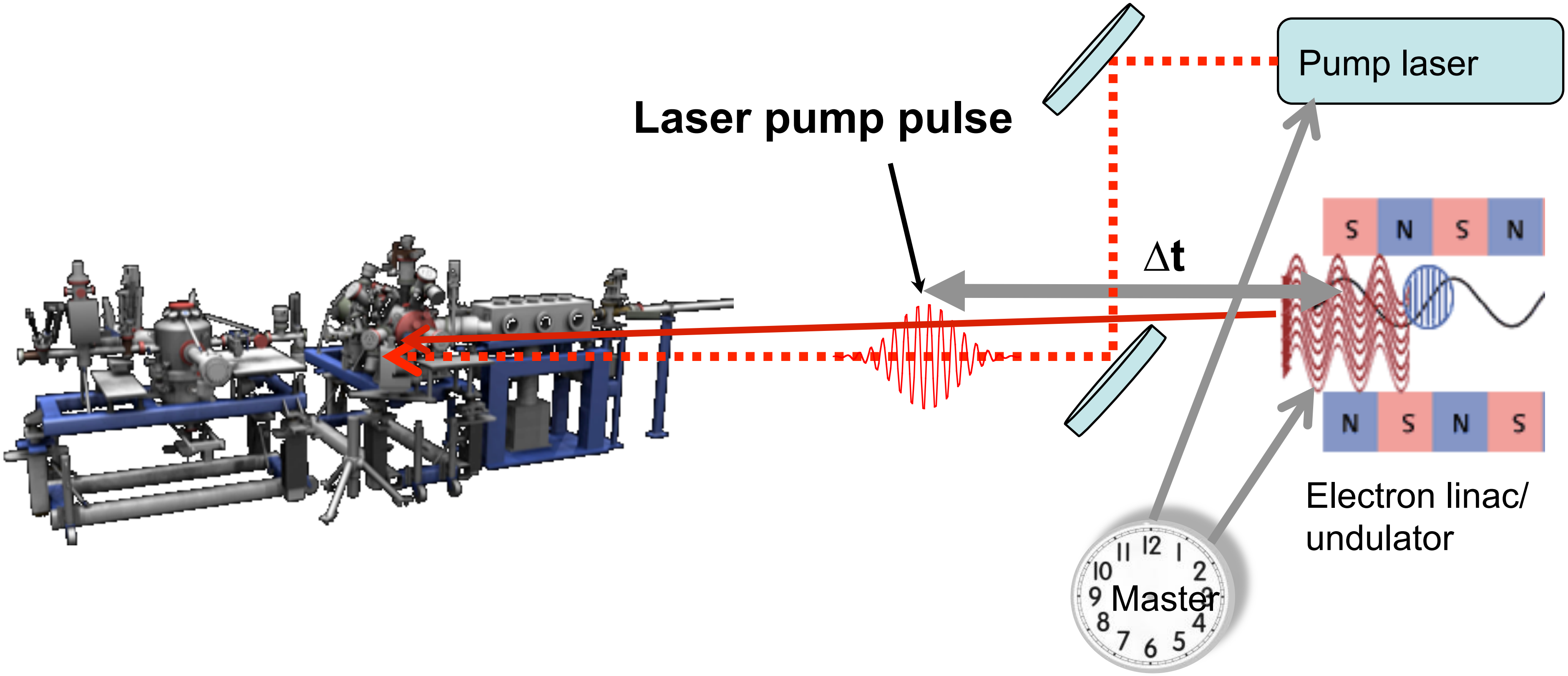
Ultrafast x-rays are here!



- LCLS E=13.6 GeV (Y. Ding, PRL 2009)
- Q=20 pC
- Single or few-spike SASE already gives powerful fs pulses!!!

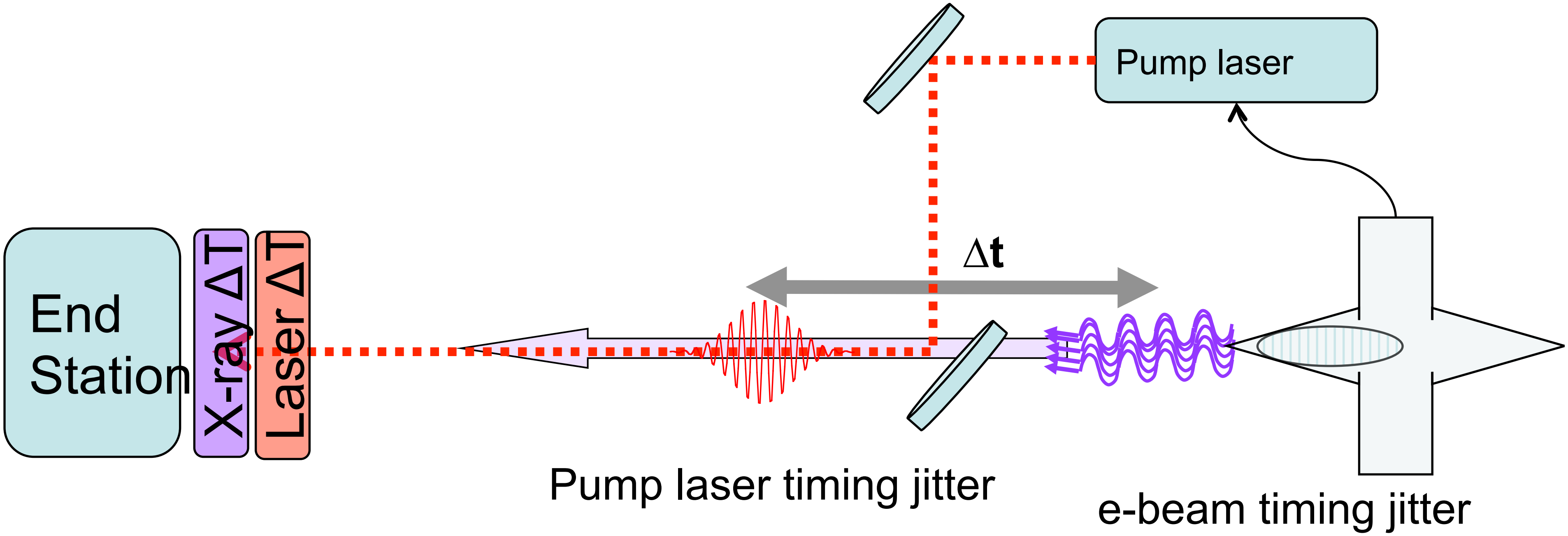


X-ray/optical Pump-probe



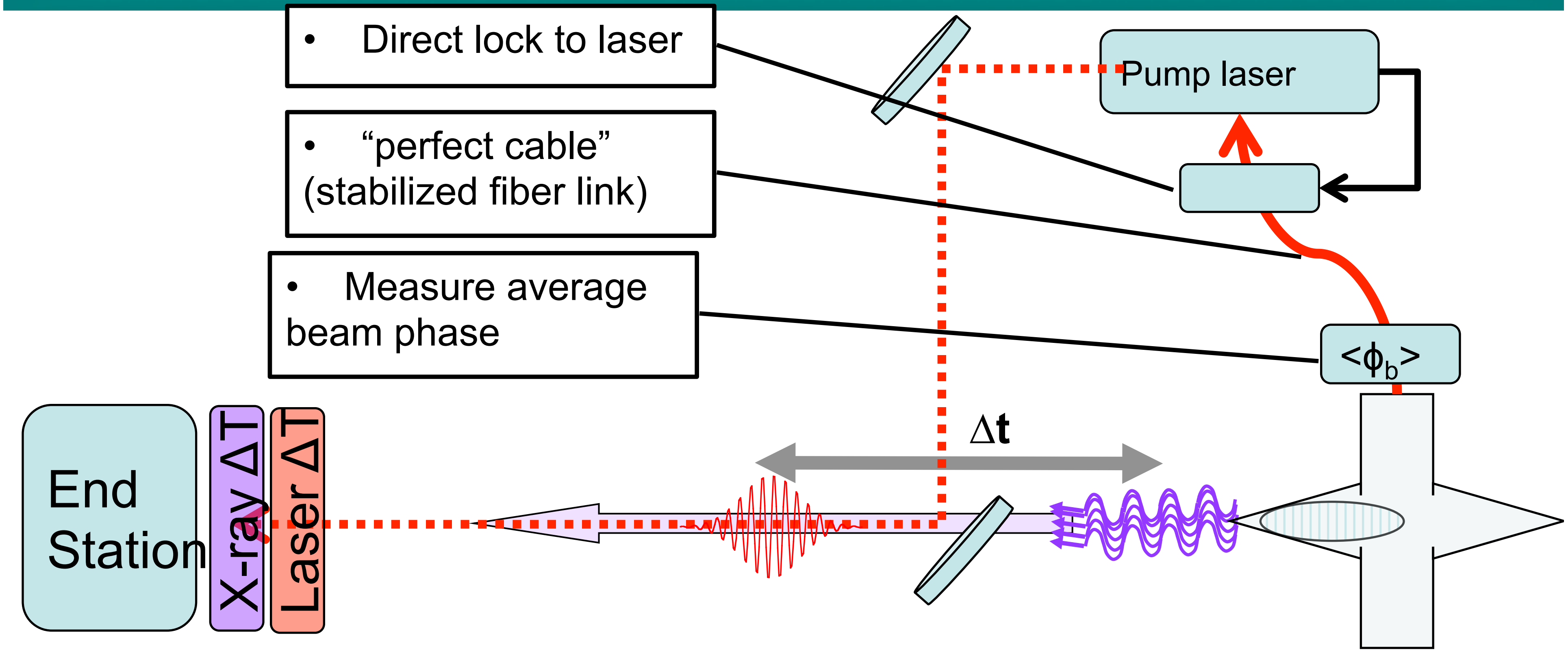
- Ultrafast laser pulse "pumps" a process in the sample
- Ultrafast x-ray pulse "probes" the sample after time Δt
- By varying the time Δt, one can make a "movie" of the dynamics in a sample.
- Synchronism is achieved by locking the x-rays and laser to a common clock.

FEL Timing is not perfect



- Ideal Solution: Measure the relative x-ray and pump arrival times and use it to bin the experimental data.
- Present LCLS Solution: Measure the electron arrival time and lock the pump laser to the average electron arrival time.

Synchronize Pump and Probe


- Direct lock to laser
- “perfect cable” (stabilized fiber link)
- Measure average beam phase

- Ability to lock laser to beam driven by
  - Precision measurement of beam phase
  - Transmission of beam phase to laser hutch over 100s of meters
  - Ability of laser to follow beam phase

Three Challenges

- Provide long-term stable clock over entire accelerator complex: injector, linac, diagnostics, and lasers
    - Use stabilized links to maintain stable relative phase

- Lock remote clients to stable clock
    - Advanced digital controllers (RF and mode-locked laser oscillators)
    - Direct seeding of remote lasers

- Measure resulting electron and photon timing stability
    - Femtosecond electron arrival time and bunch length and energy spread monitors
    - Femtosecond x-ray arrival time, pulse length, spectrometer

I will try to give a sense of all three activities with a focus on **electron beam measurements**

Small things

1 femtosecond

= $1\text{x}10^{-15}$ sec

= 0.3 microns

= 0.008 mrad@1.3 GHz

= 0.00045 deg@1.3 GHz

= 0.018 mrad@2856 MHz

= 0.001 deg@2856 MHz

= $(1000\ \text{TeraHertz})^{-1}$

= (1.5 micron)/5

Measurement techniques

- RF, microwave, Terahertz and optical beam signals
  - Beam pickups
  - Coherent THz radiation
  - Coherent optical signals
  - Incoherent fluctuations
- Beam manipulation
  - Transverse deflecting structure
  - Zero-phase
  - Streak cameras

Measurement techniques

- Laser-based techniques
  - Electro-optic techniques
  - Optical replica
  - Timing and synchronization

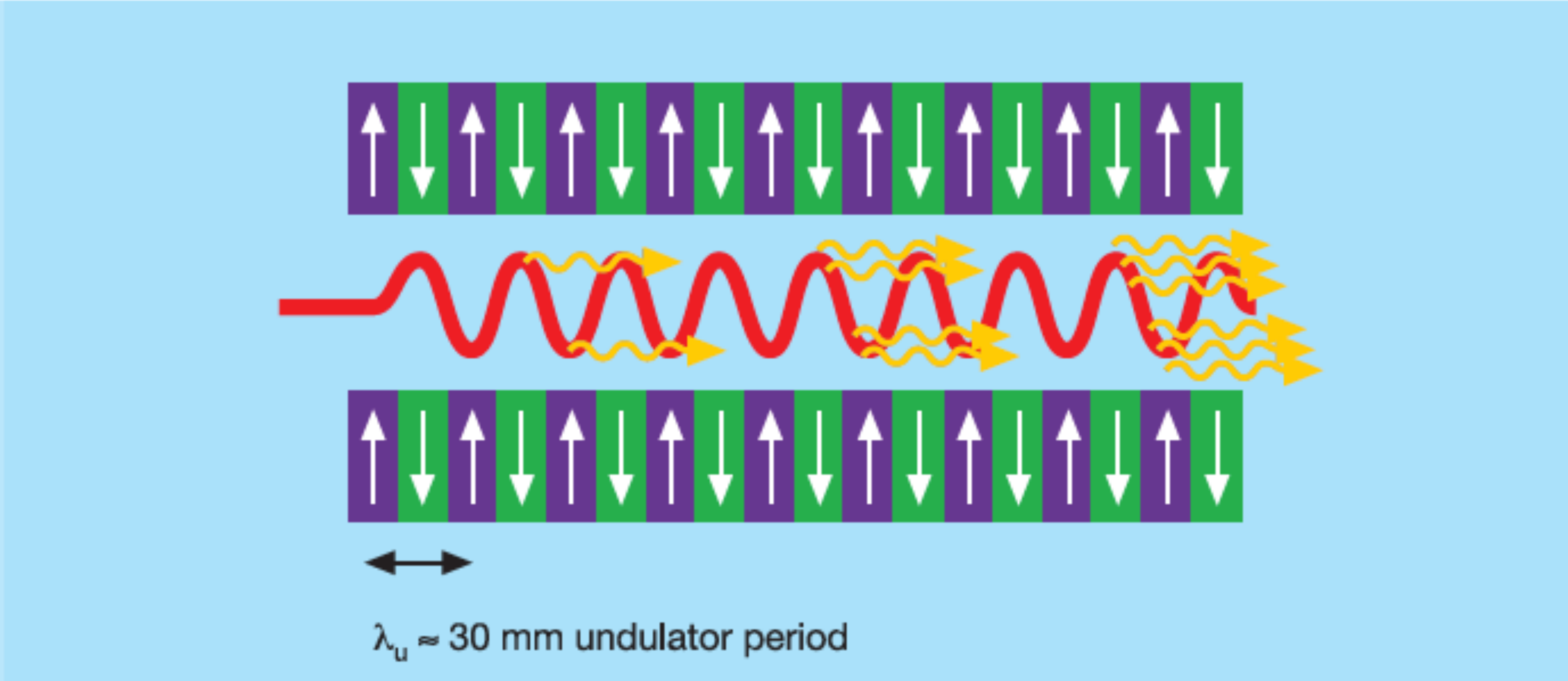
Lectures

- **Lecture 1**
  - **Introduction**
  - **Coherent THz Radiation**
    - **Detectors**
    - **Interferometers/Spectrometers**
  - **Femtosecond timing and synchronization**
  - **Transverse Deflecting Structures**
- Lecture 2
  - Basics of nonlinear optics
  - Basics of mode-locked lasers
  - Nonlinear optic techniques for short pulses
    - Electro-optic sampling
    - Auto and cross correlation
  - X-ray Streak cameras
  - New directions…

Why do we need short bunches?

- Ultrafast science needs
  - Study dynamics of atomics/molecular reactions on a femtosecond time scale
    - Sub-100 fsec x-ray/electron pulses synchronized with fsec optical laser pulses
  - Single-shot ultrafast x-ray diffraction
    - High peak flux to allow measurement before destoying the sample

Ultrafast x-rays via FELs



$$\lambda_\ell = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$K = \frac{eB_0\lambda_u}{2\pi\, m_0 c} \approx 1$$

FEL Gain depends on peak current

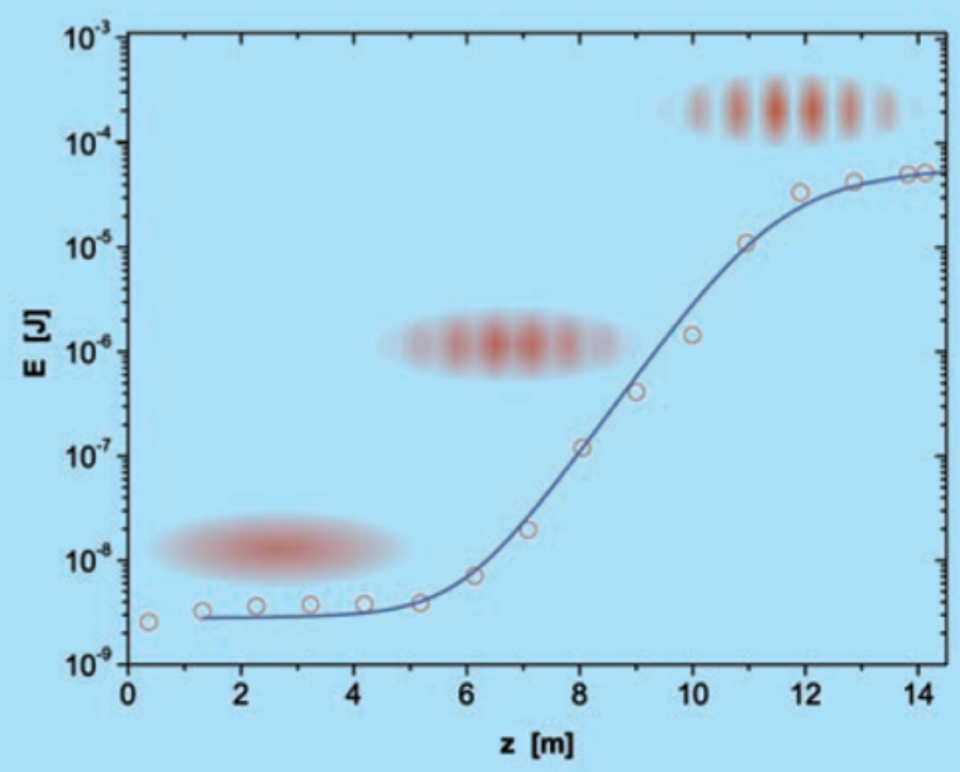
- The FEL gain length is inversely proportional to the peak current.

$$L_g = C\left(\frac{\gamma\varepsilon\beta}{I_{peak}}\right)^{1/3} \quad with \quad C = \frac{1}{\sqrt{3}}\left(\frac{2m_0 c\lambda_u}{\mu_0 e K^2}\right)^{1/3}$$

- The total FEL power grows exponentially up to saturation

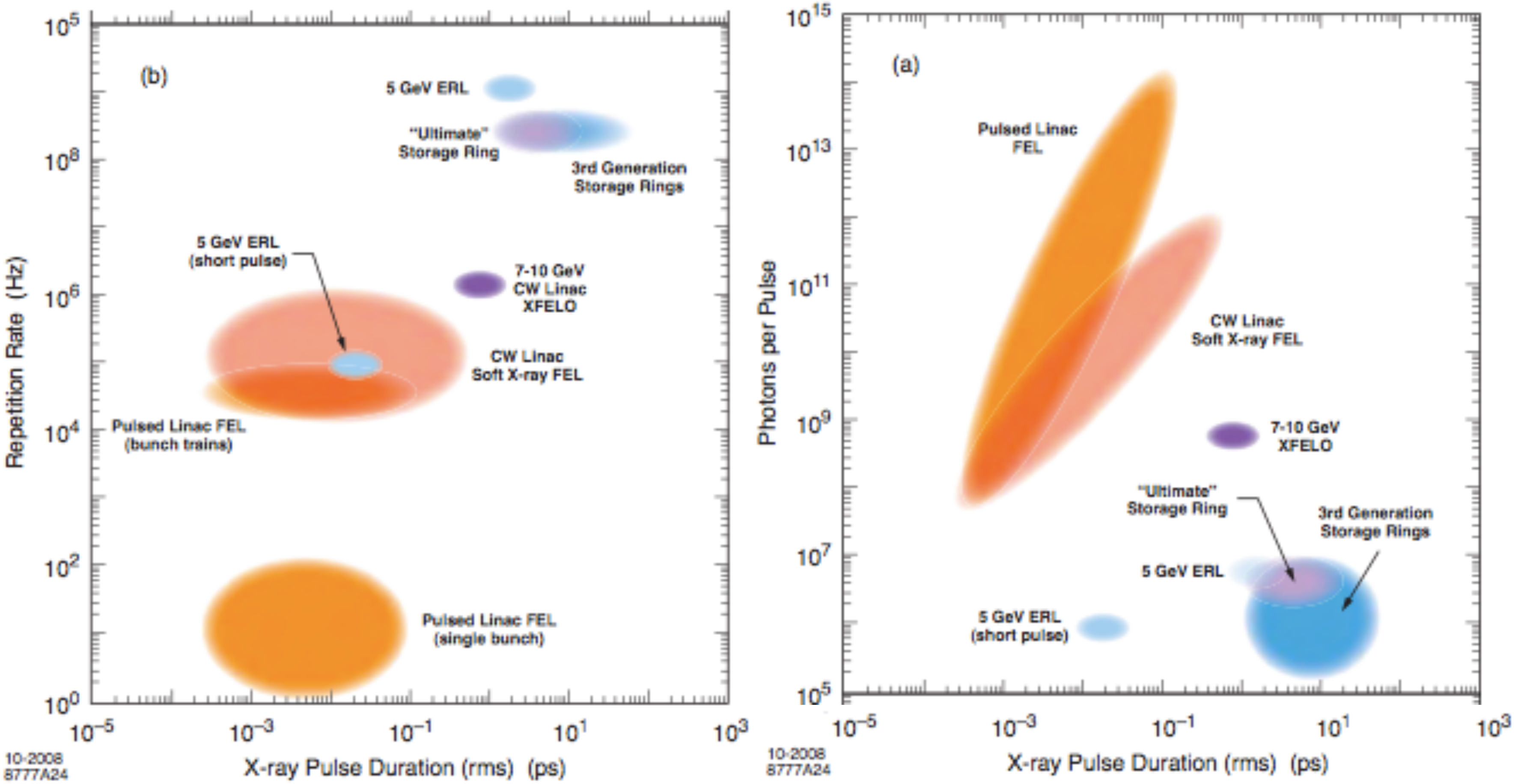
$$P(z) = \frac{P_0}{9}\exp(z/L_g) \quad for \quad z \geq 2L_g$$

- Shorter bunches/higher peak currents helps make shorter FELs



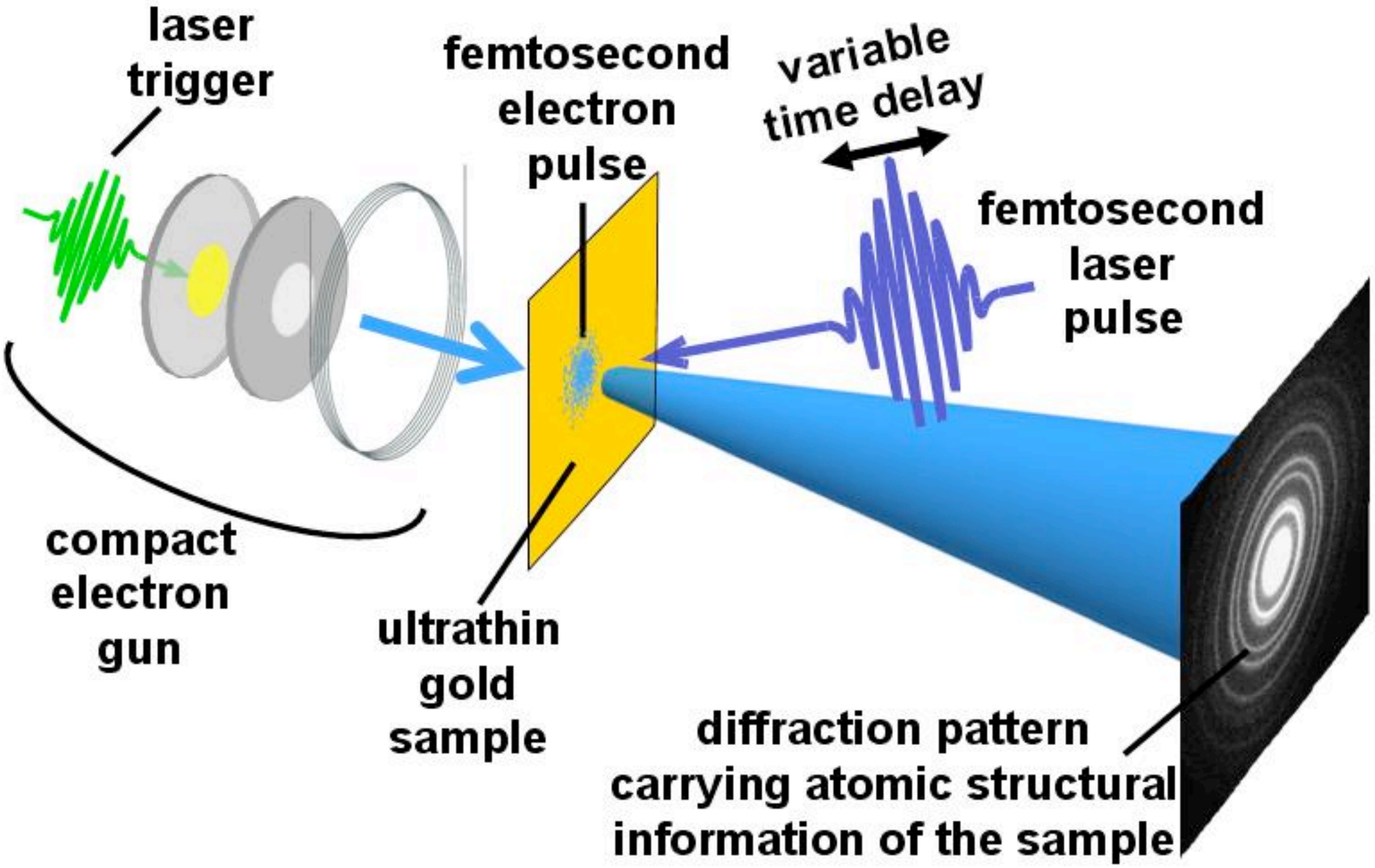
Pulse widths and rates

- Future light sources are pushing to enable sub-picosecond time scales in experiments.



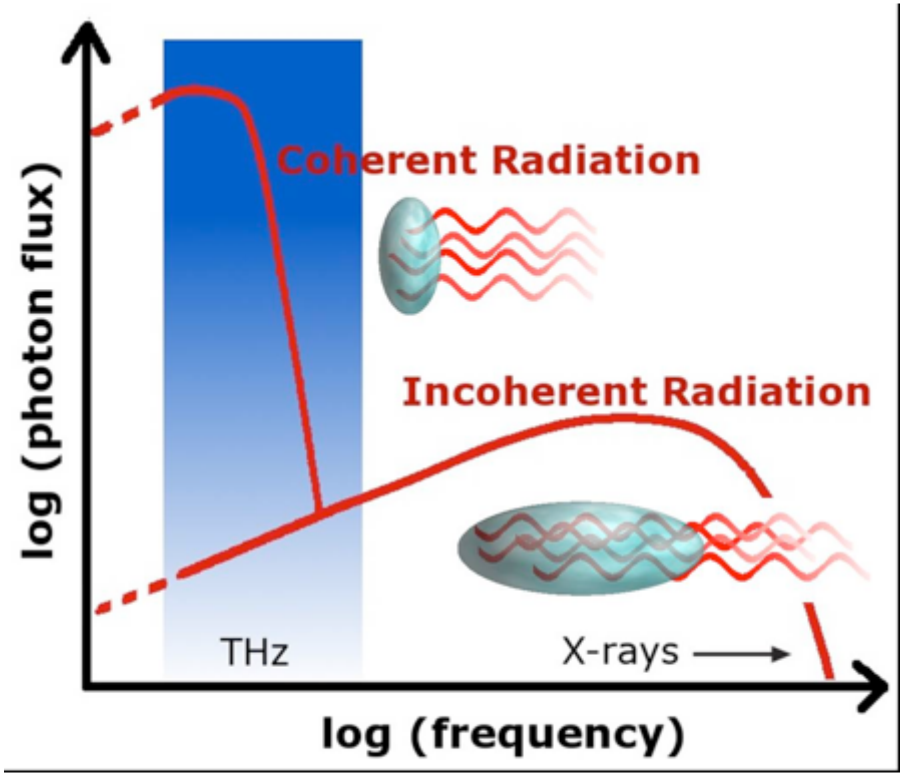
Ultrafast Electron Diffraction

- Use scattering of low energy femtosecond electron bunches to probe ultrafast dynamics.

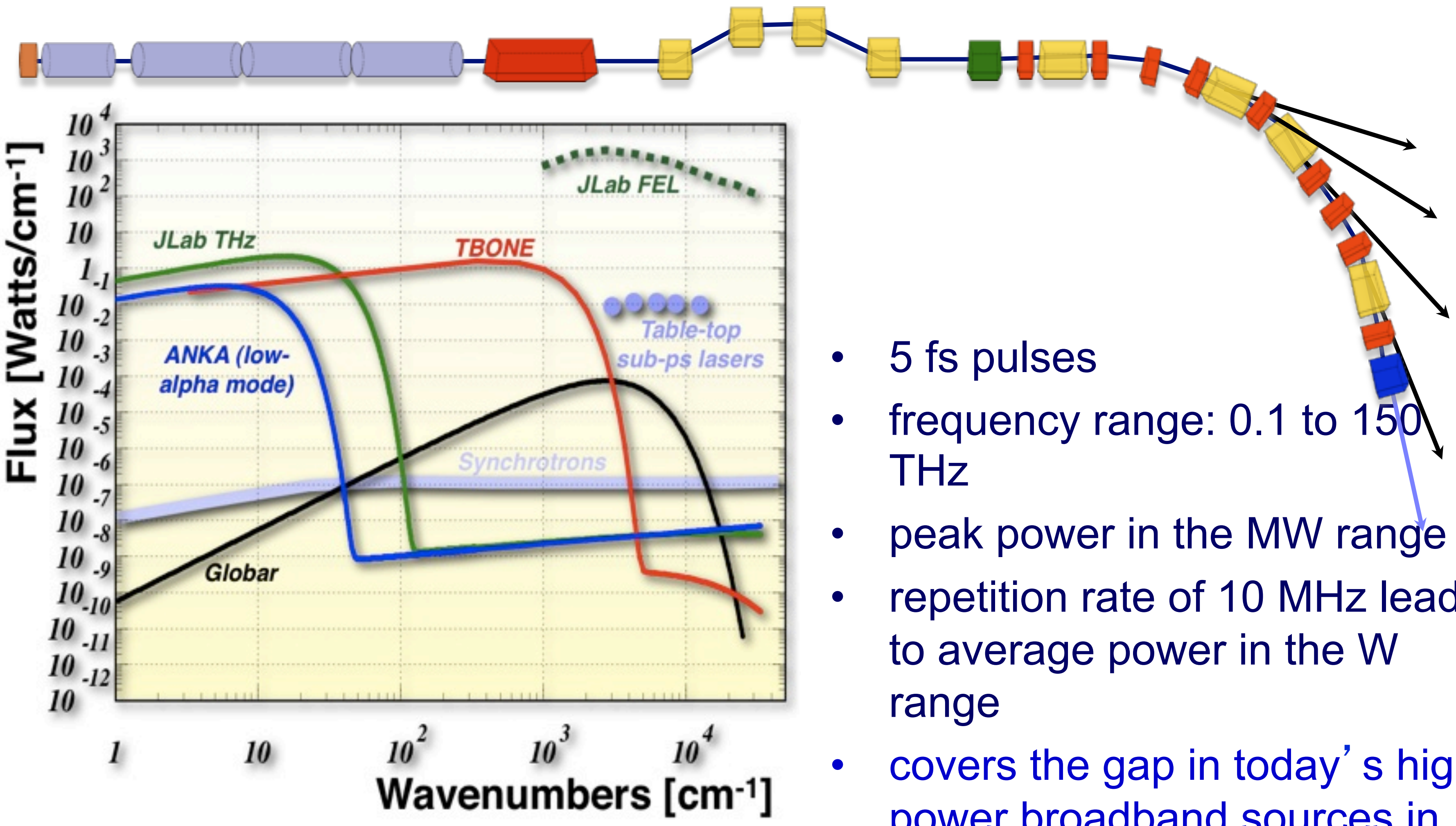


High power T-ray Sources

- Generate coherent THz pulses in storage ring and linacs.
- Time-resolved x-ray spectroscopy in storage ring light sources.



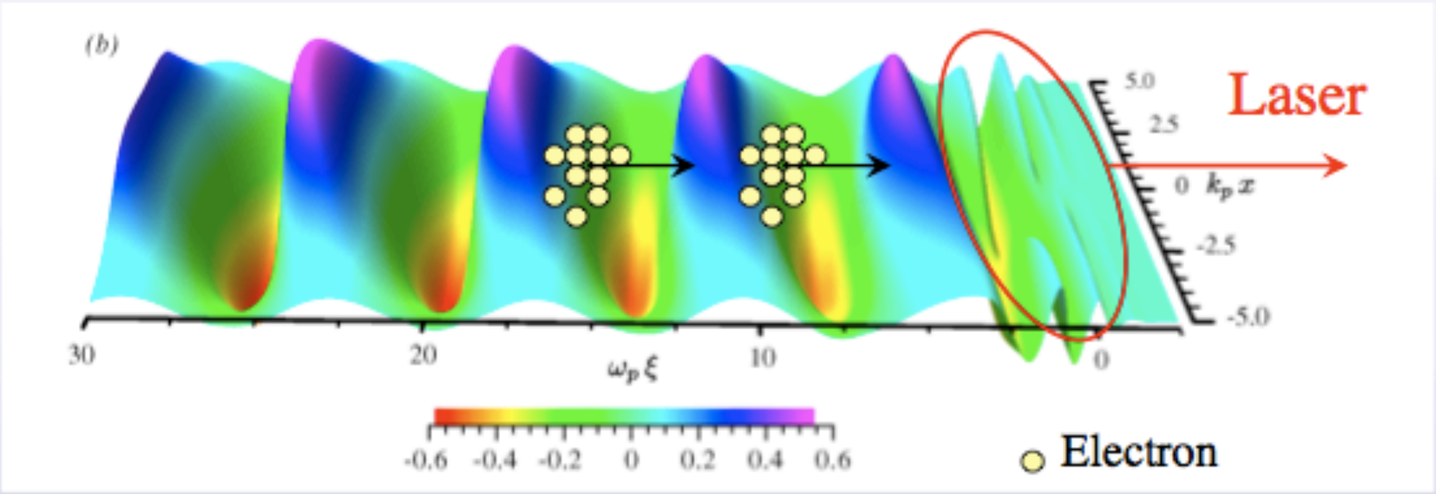
TBONE - A THz/Mid-IR Installation A Future User Facility at ANKA



- 5 fs pulses
- frequency range: 0.1 to 150 THz
- peak power in the MW range
- repetition rate of 10 MHz leads to average power in the W range
- covers the gap in today's high power broadband sources in the THz / mid-IR

Laser/Plasma Accelerators

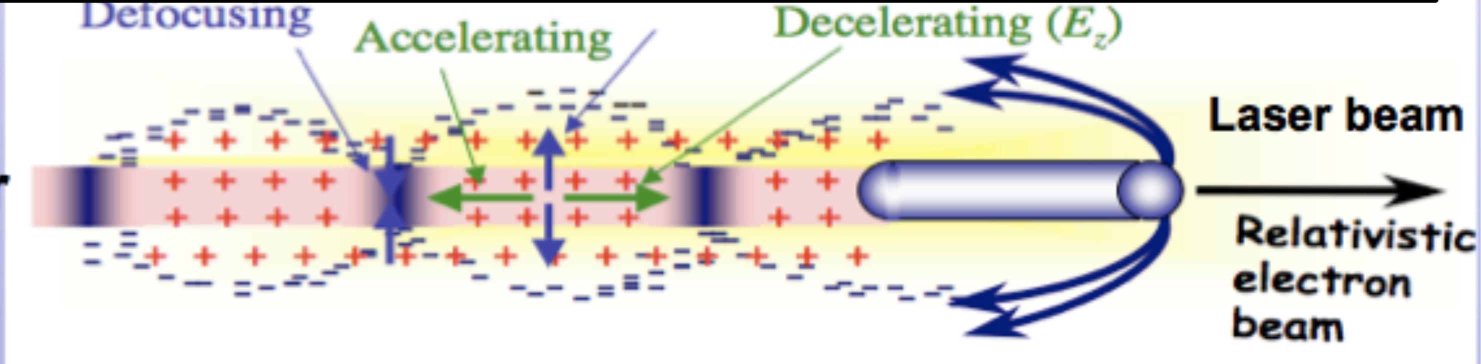
Linear



- Laser driver--Tajima&Dawson, PRL'79
- Beam driver--P. Chen et al., PRL'85
- E-fields: 10 – 100 GV/m
- Phase velocity wake=Group velocity driver

Produces inherent sub-10 fsec bunches!

Non-Linear



Measuring short bunches

- Sense coherent radiated Coulomb field and reconstruct bunch shape
  - Coherent synchrotron/diffraction/transition/edge radiation
    - Measure radiation spectrum
    - Time domain sampling of field
  - RF and microwave beam PUs
- Manipulate incoherent electron or radiated beam
  - Deflecting cavity
  - Streak camera
  - fluctuations

Short bunches has it all…

X-ray detectors

Lasers

Ultrastable clocks

Beam dynamics

Electronics

Short Bunches

Fiber optics

Plasma physics

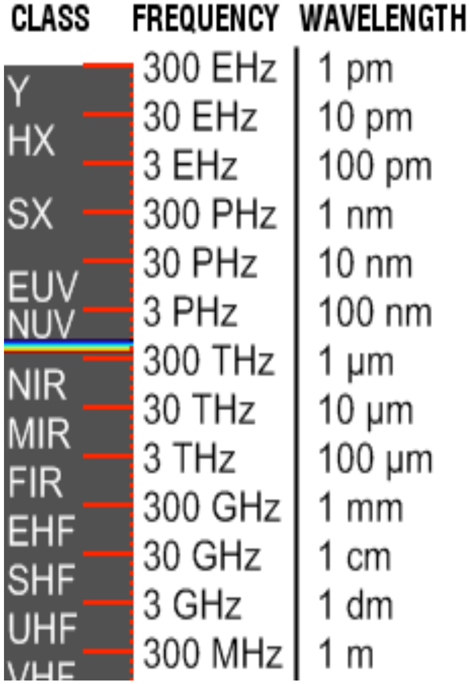
Nonlinear optics

RF and microwaves

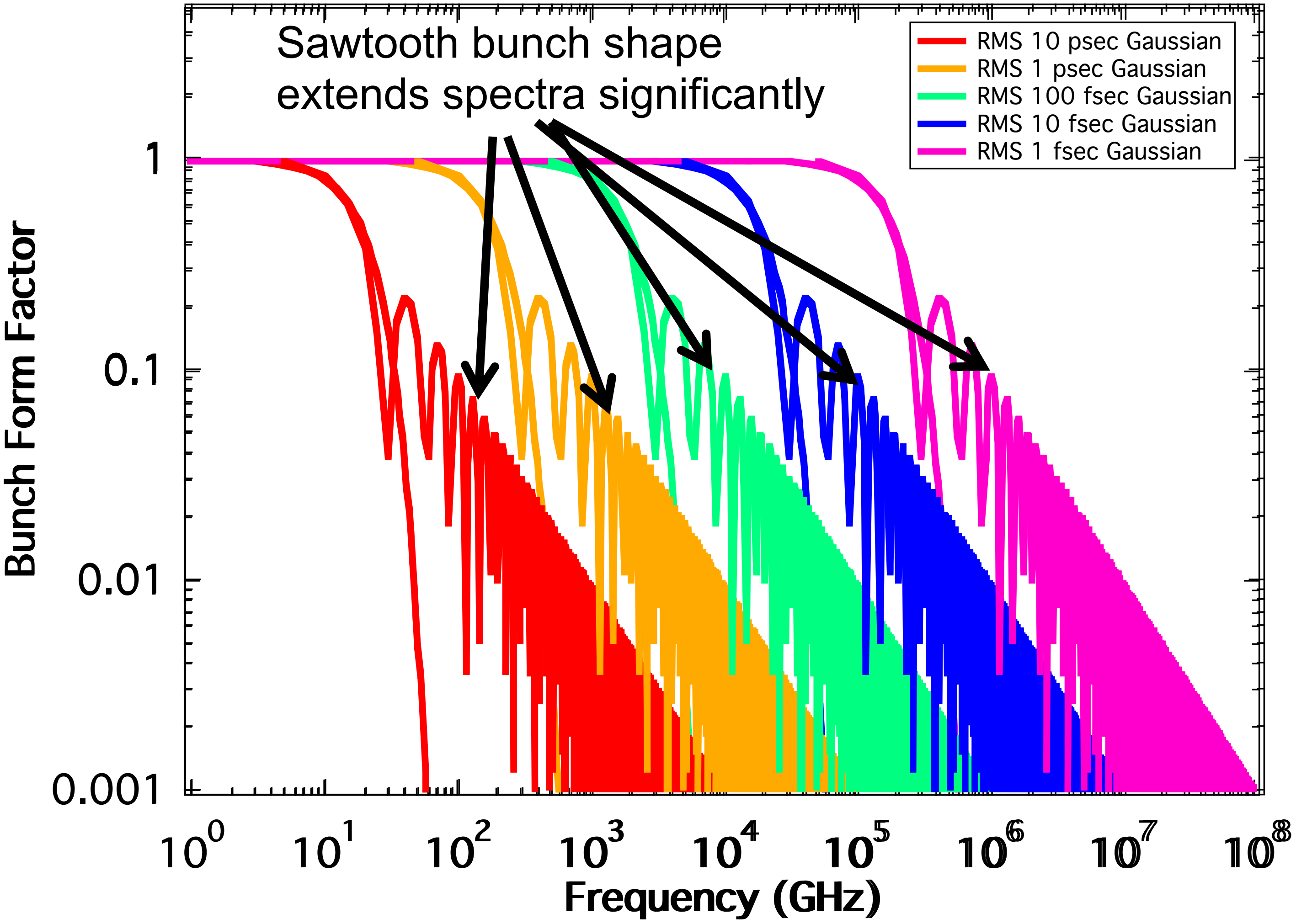
TeraHertz

Challenging problems inspire innovative solutions and attract very good people

Bunch Spectra: From DC to Daylight

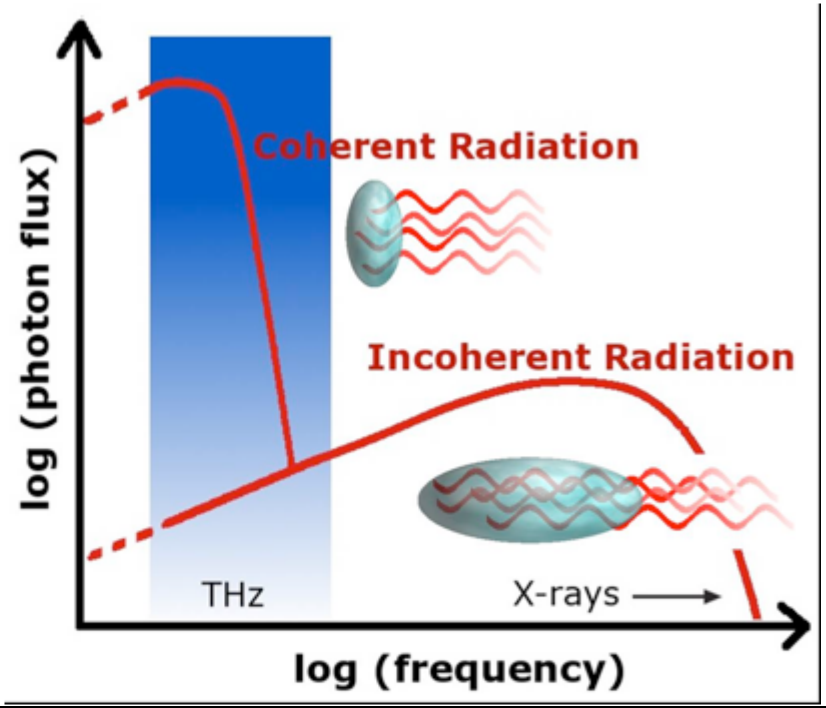


CLASS	FREQUENCY	WAVELENGTH
	300 EHz	1 pm
Y	30 EHz	10 pm
HX	3 EHz	100 pm
SX	300 PHz	1 nm
EUV	30 PHz	10 nm
NUV	3 PHz	100 nm
NIR	300 THz	1 µm
MIR	30 THz	10 µm
FIR	3 THz	100 µm
EHF	300 GHz	1 mm
SHF	30 GHz	1 cm
UHF	3 GHz	1 dm
VHF	300 MHz	1 m


Sawtooth bunch shape extends spectra significantly

Coherent Terahertz Radiation

- Picosecond bunches radiate at THz frequencies
- Approach 1: measure radiation spectrum and derive bunch shape from Kramers-Kronig
  - Auto-correlation
  - Gratiing spectrometer
- Approach 2: measure relative radiation power on edge of spectrum to derive relative bunch length
- Approach 3: Measure time domain radiation field (covered in next lecture)

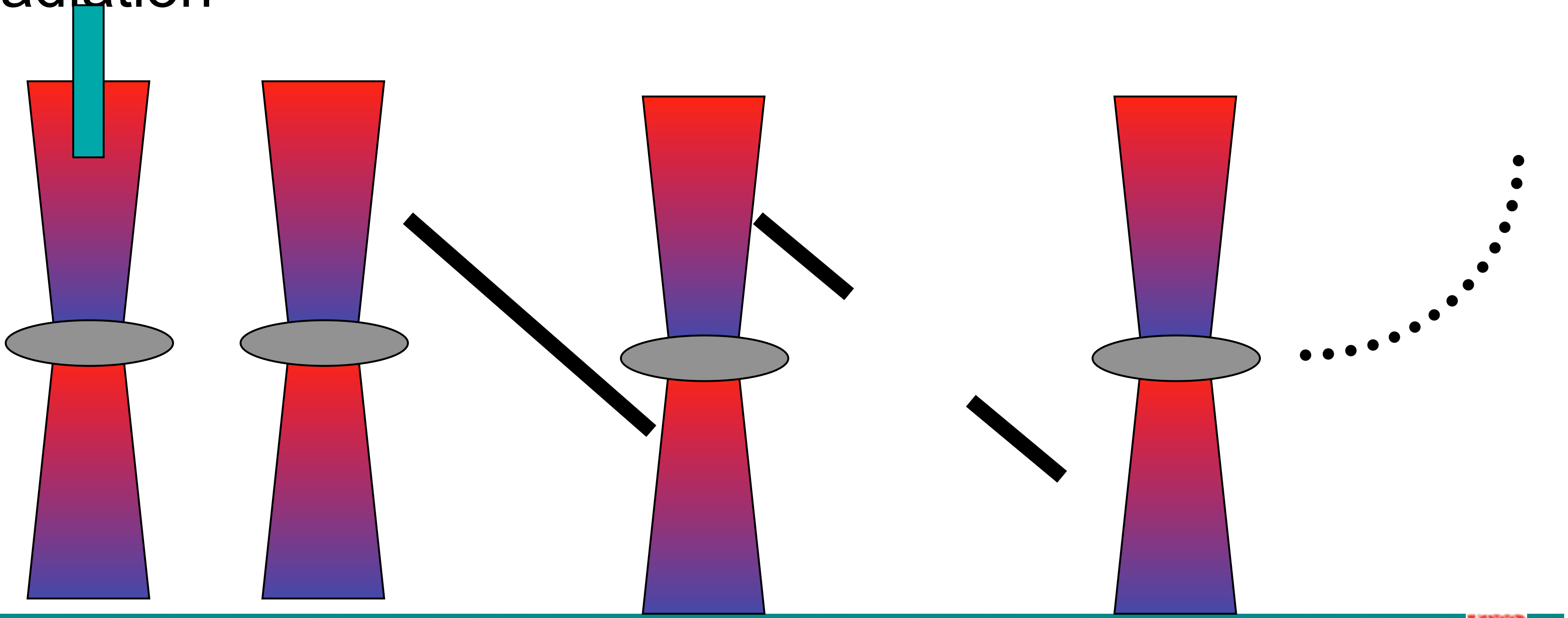


Challenges

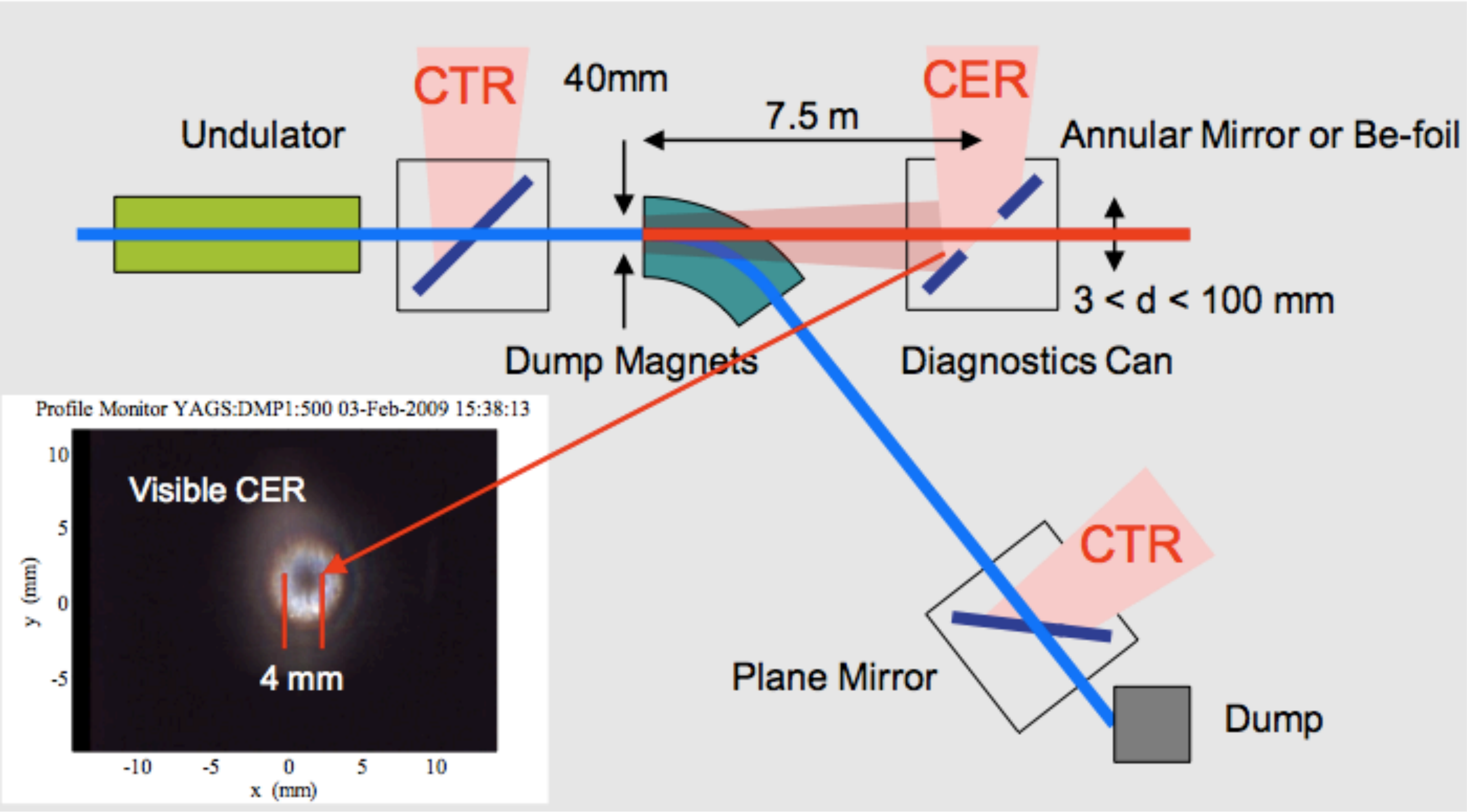
- Extracting radiation from vacuum chamber
  - Multiple source points
  - Multiple reflections
  - Single vs. multishot techniques

Sampling beam fields

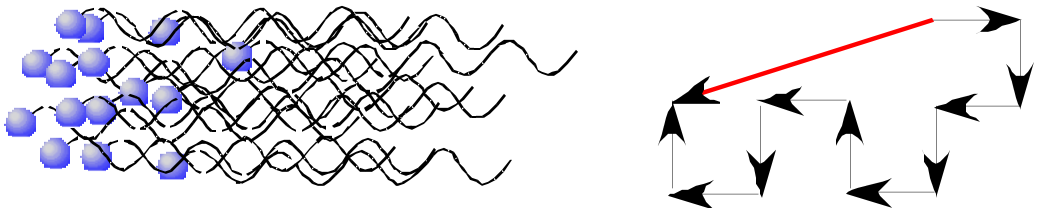
- The bunch electric field can be extracted via
  - Direct probe in the vacuum chamber
  - Extracted via transition radiation
  - Extracted via diffraction radiation
  - Separated from the beam via synchrotron or edge radiation



Extracting Coherent radiation for fsec bunches

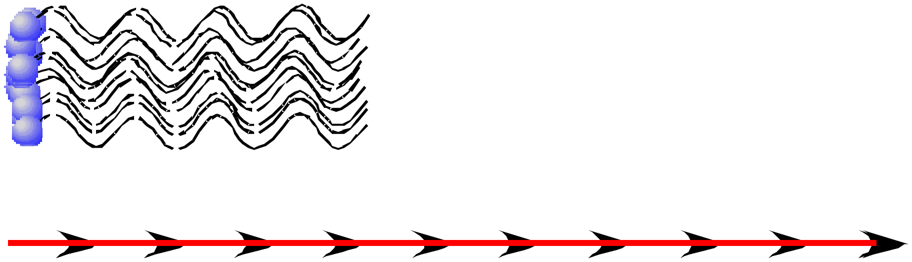


Coherence of Radiation



Incoherent Emission

If the electrons are independently radiating light then the phase of the their electric fields are random with respect to one another and the electric field scale as the square root of the number of electrons



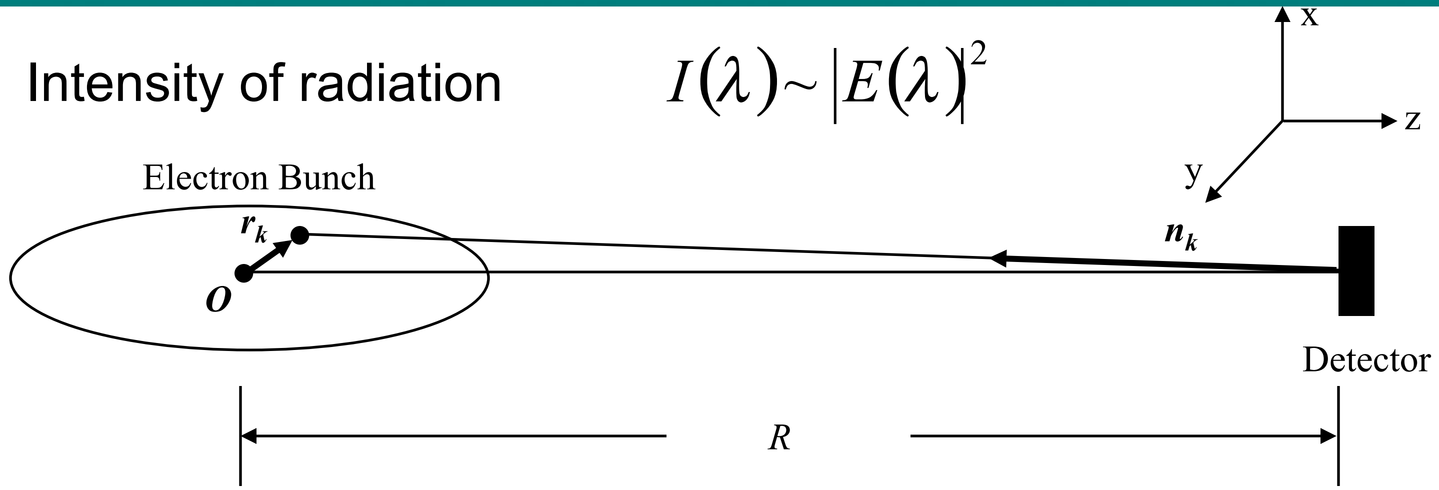
Coherent Emission

If the electrons are in lock synch are radiate coherently then the electric field grows linear with the number of electrons

The power goes as the square of the field and if N is very large one can get an enormous gain in power emitted.

Coherent Radiation

- Intensity of radiation $I(\lambda) \sim |E(\lambda)|^2$



- The component of the electric field from an electron seen by the detector at wavelength / is $E_k(\lambda) = E_1(\lambda) e^{2\pi\, n_k \cdot r_k / \lambda}$
- The total field of all electrons is $E_{tot}(\lambda) = E_1(\lambda) \sum_{k=1} e^{2\pi i n_k \cdot r_k / \lambda}$
- And the total intensity is

$$I_{tot}(\lambda) = I_1(\lambda) \left| \sum_{k=1}^{N} e^{2\pi i n_k \cdot r_k / \lambda} \right|^2 = I_1(\lambda) N + I_1(\lambda) \sum_{j \neq k}^{N} e^{2\pi i (n_k \cdot r_k - n_j \cdot r_j) / \lambda}$$

- The 1st is the incoherent term and the 2nd is the coherent

Nodvick and Saxon, Phys. Rev. **96** (1954) 180.

THz Detectors

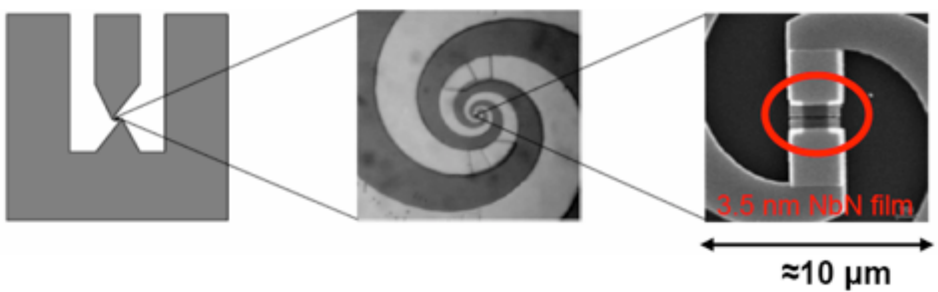
Pyroelectric


Virginia Diodes, Inc., Char

Diode

FIR Bolometer

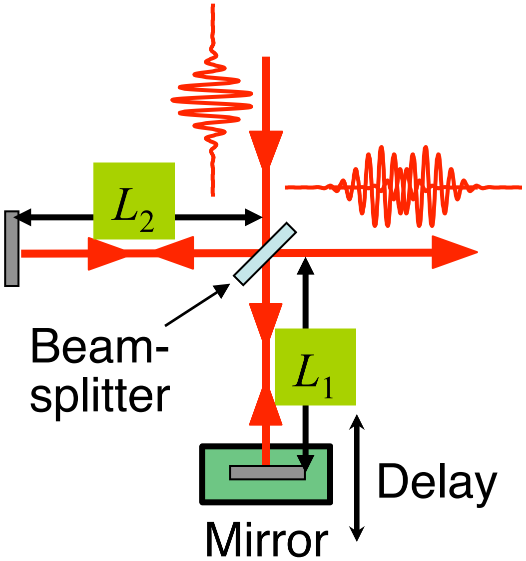
Log-spiral antenna receiver



Hot electron MicroBolometer

Golay Cell

The Michelson Interferometer is a Fourier Transform Spectrometer



Suppose the input beam is **not monochromatic** (but is perfectly spatially coherent):

Þ $I_{out} = 2I + c\,e\,\mathrm{Re}\{E(t+2L_1/c)\,E^*(t+2L_2/c)\}$

Now, I_{out} will vary rapidly in time, and most detectors will simply integrate over a relatively long time, T :

$$U \propto \int_{-T/2}^{T/2} I_{out}(t)\,dt \quad \Rightarrow \quad U \propto 2IT + c\varepsilon\,\mathrm{Re}\int_{-T/2}^{T/2} E(t+2L_1/c)E^*(t+2L_2/c)\,dt$$

Changing variables: $t' = t + 2L_1/c$ and letting t$= 2(L_2 - L_1)/c$ and T ®¥

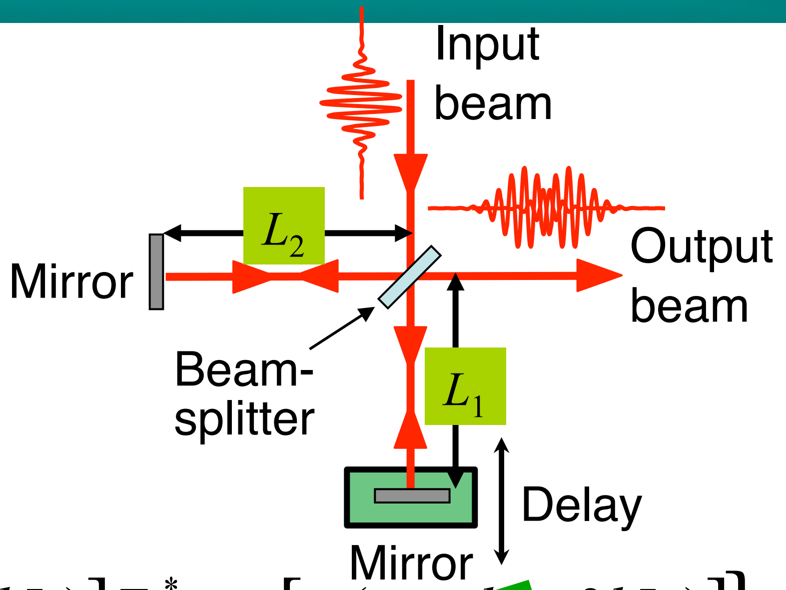
$$U \propto 2IT + c\varepsilon\,\mathrm{Re}\int_{-\infty}^{\infty} E(t')E^*(t'-\tau)\,dt'$$ **The Field Autocorrelation!**

The Fourier Transform of the Field Autocorrelation is the **spectrum**!!

The Michelson Interferometer

The Michelson Interferometer splits a beam into two and then recombines them at the same beam splitter.

Suppose the input beam is a plane wave:



$$I_{out} = I_1 + I_2 + c\varepsilon\,\mathrm{Re}\left\{E_0 \exp\left[i(\cancel{\omega t - kz} - 2kL_1)\right] E_0^* \exp\left[-i(\cancel{\omega t - kz} - 2kL_2)\right]\right\}$$

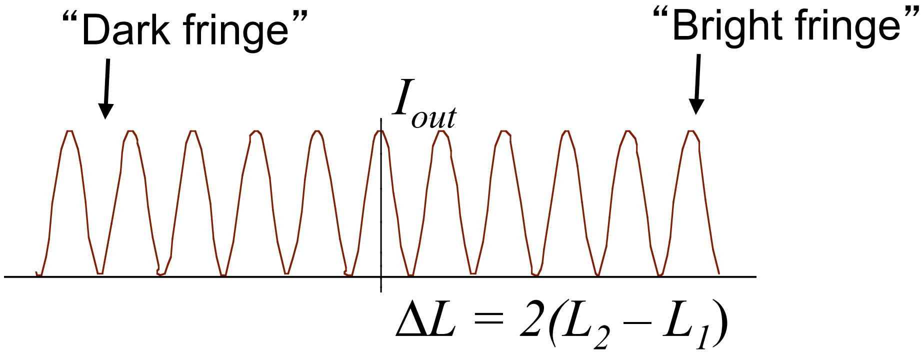
$$= I + I + 2I\,\mathrm{Re}\left\{\exp\left[2ik(L_2 - L_1)\right]\right\}$$

since $I \equiv I_1 = I_2 = (c\varepsilon_0/2)\left|E_0\right|^2$

$$= 2I\left\{1 + \cos(k\Delta L)\right\}$$

where: $\Delta L = 2(L_2 - L_1)$

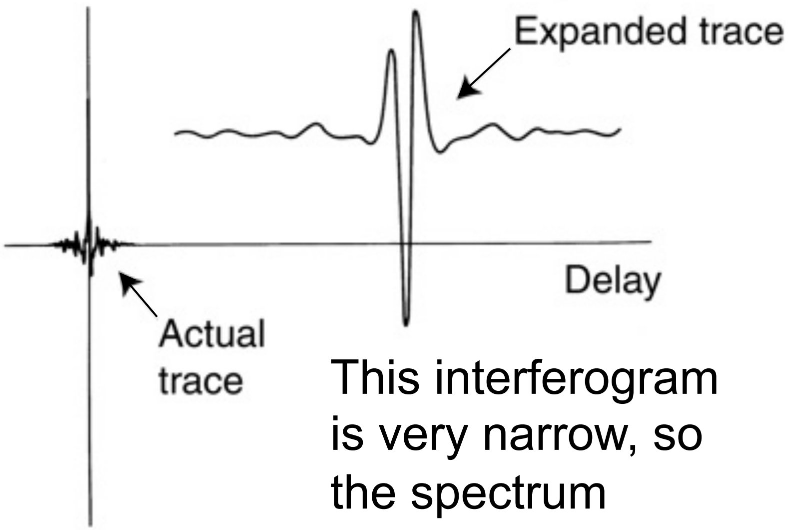
Fringes (in delay):



Fourier Transform Spectrometer Data

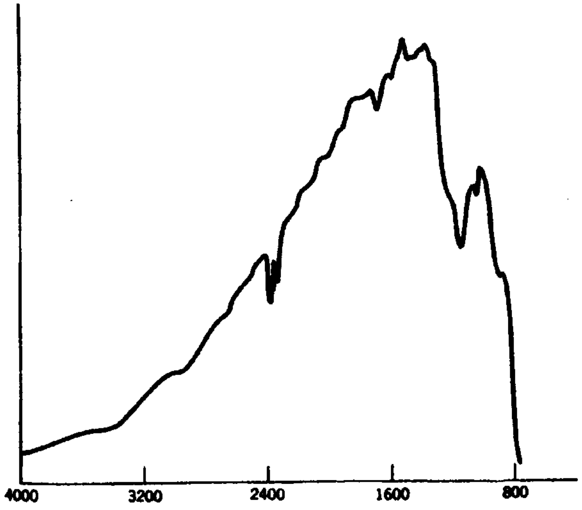
Actual interferogram from a Fourier Transform Spectrometer

Interferogram



This interferogram is very narrow, so the spectrum is very broad.

Spectrum



Wavenumber

Fourier Transform Spectrometers are most commonly used in the infrared where the fringes in delay are most easily generated. As a result, they are often called FTIR's.

Fourier Transform Spectrometers

Maximum path difference: 1 m

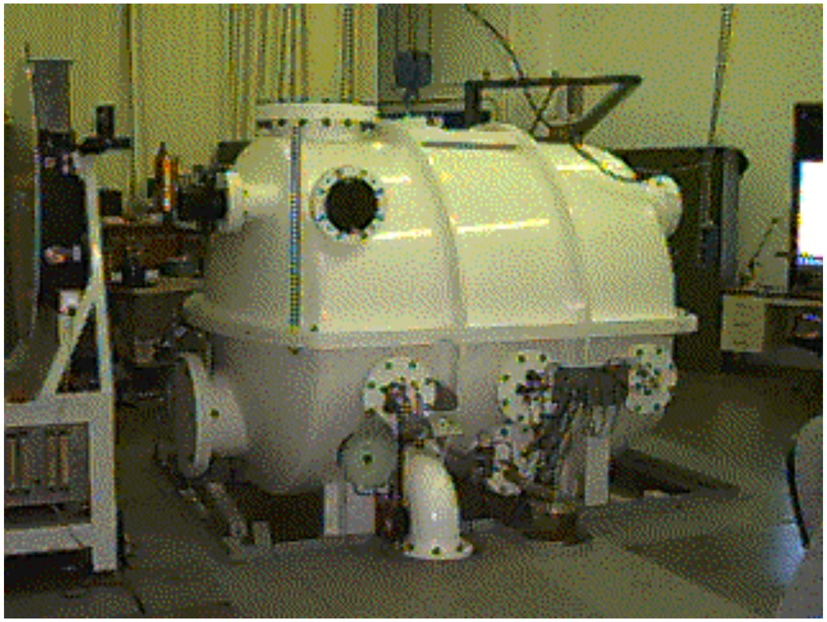
Minimum resolution: 0.005 /cm

Spectral range: 2.2 to 18 mm

Accuracy: 10^{-3} /cm to 10^{-4} /cm

Dynamic range: 19 bits (5 x 10^{5})

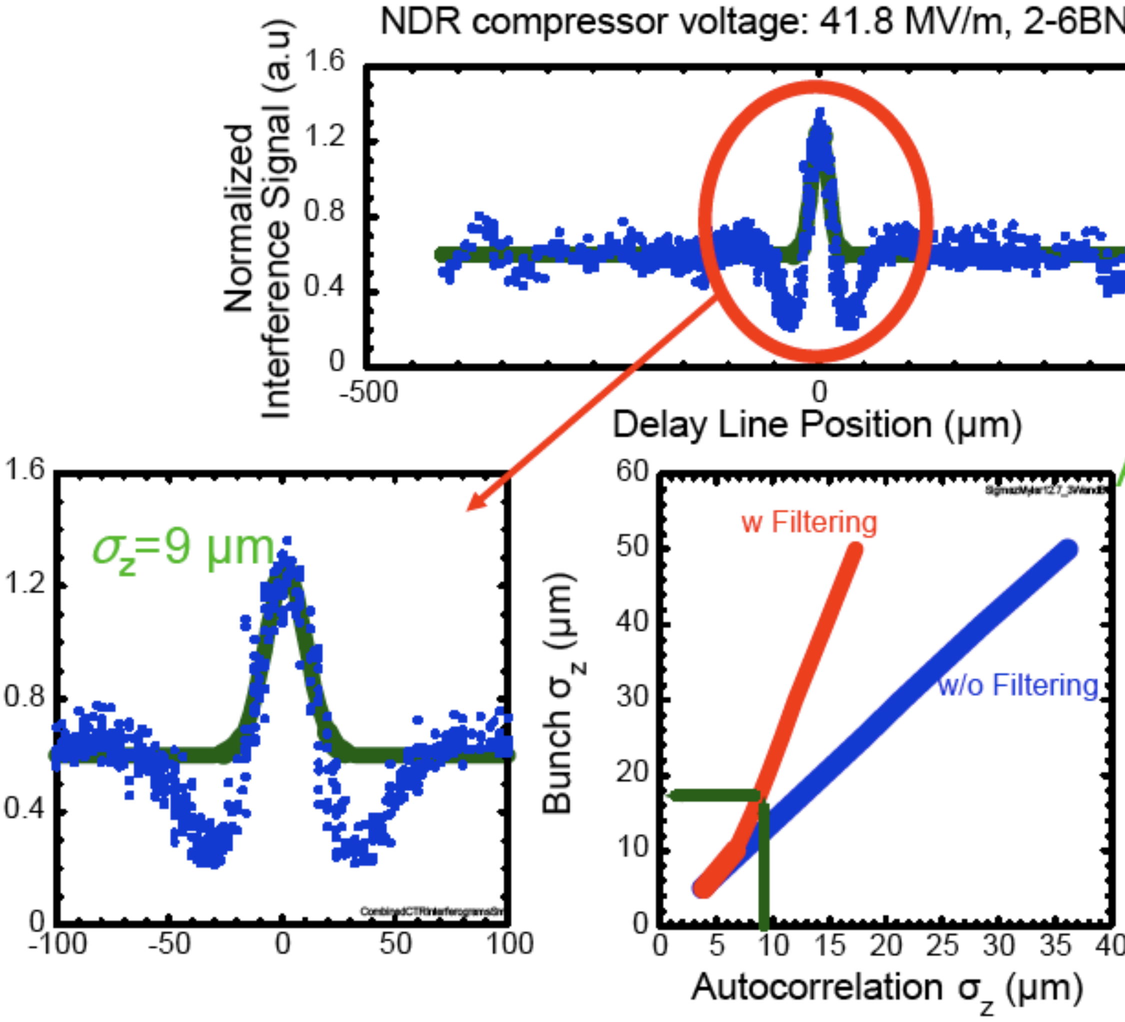
National Solar Observatory



A compact commercial FT spectrometer from Nicolet

Fourier-transform spectrometers are now available for wave-lengths even in the UV! Strangely, they're still called FTIR's.

Autocorrelator Results



Autocorrelation:

σ_z=9 µm

Gaussian Bunch

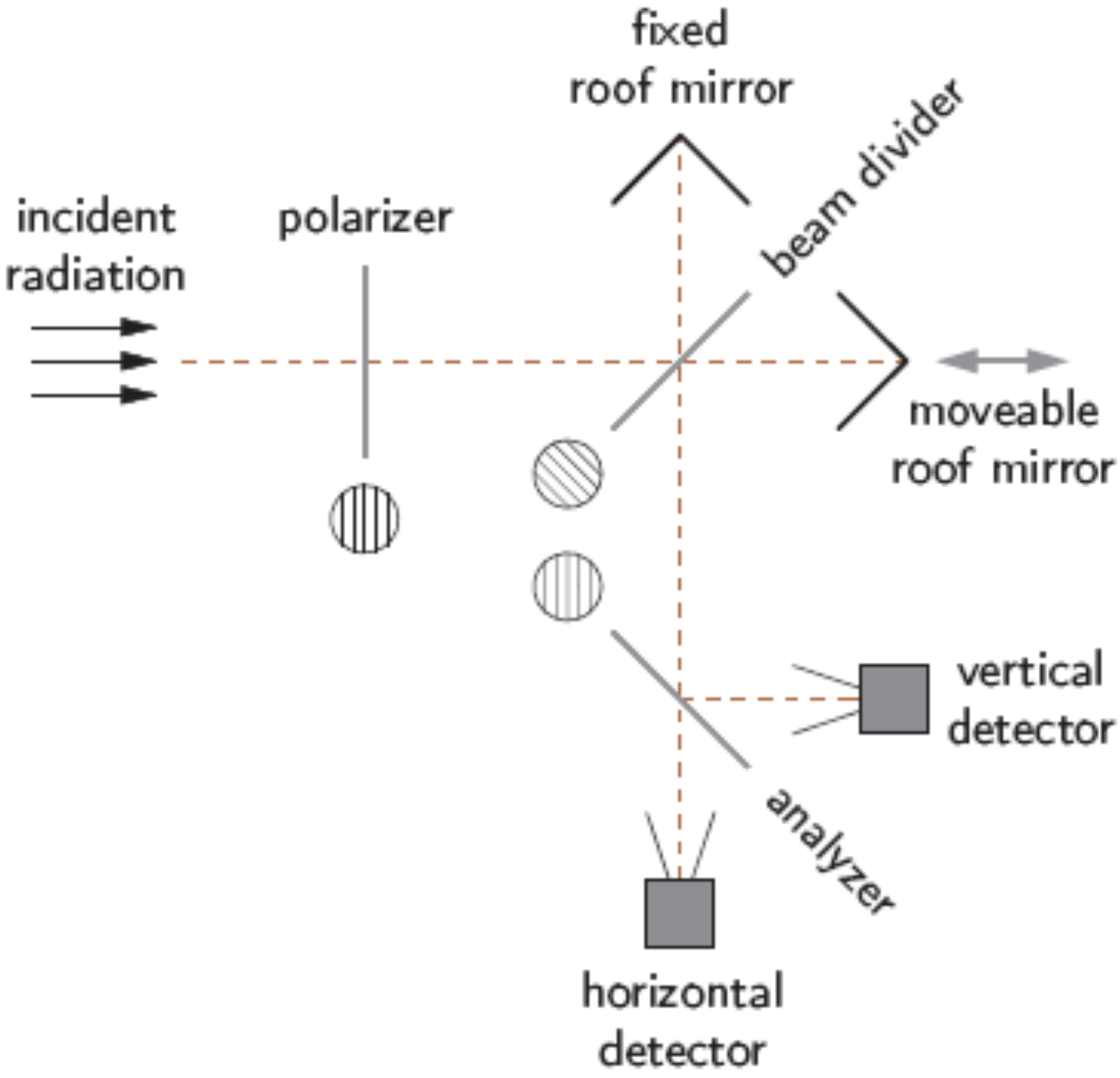
σ_z=18 µm

or

τ=60 fs

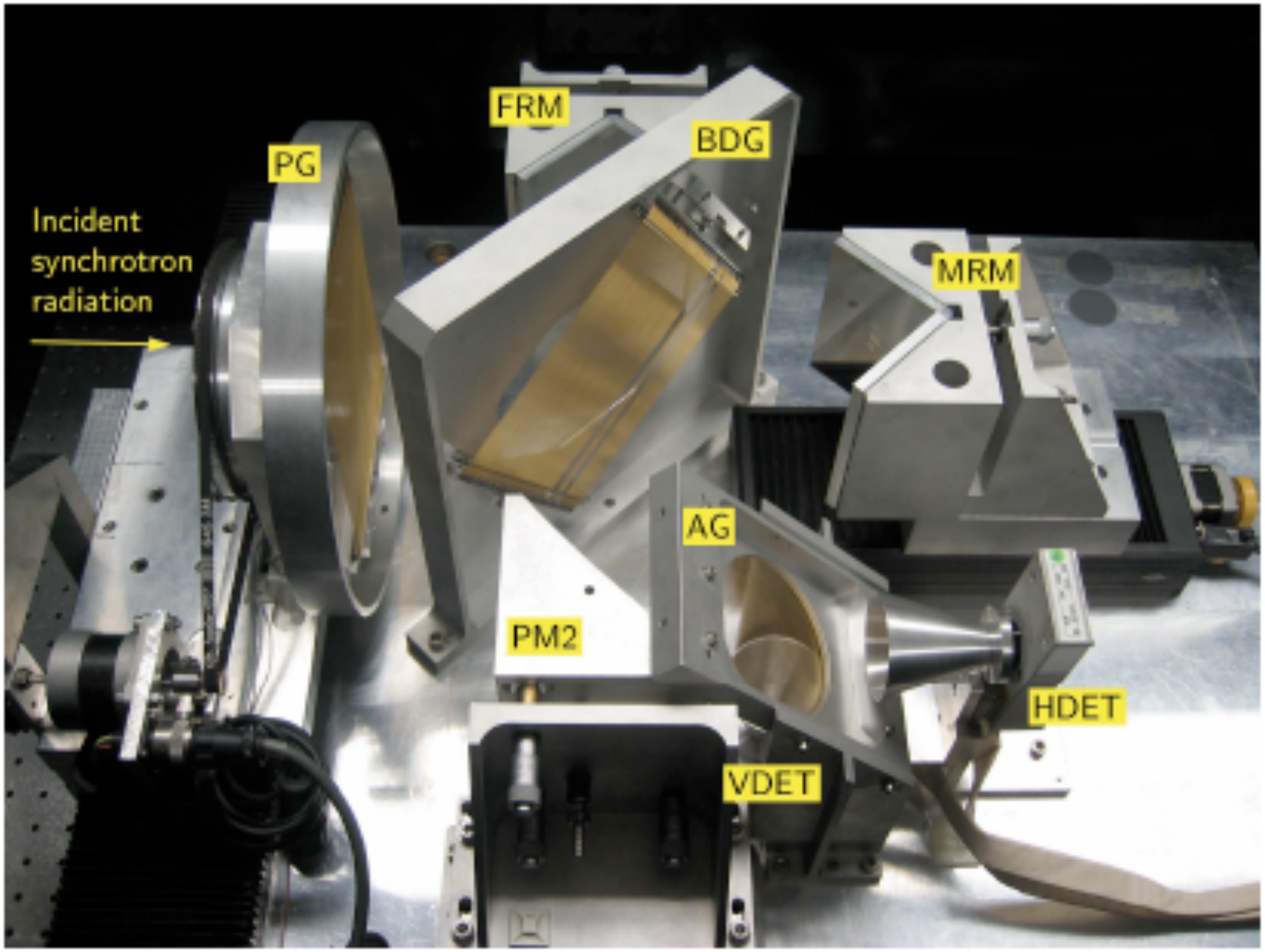
Figure 4: measured autocorrelation trace

Martin Puplett Configuration

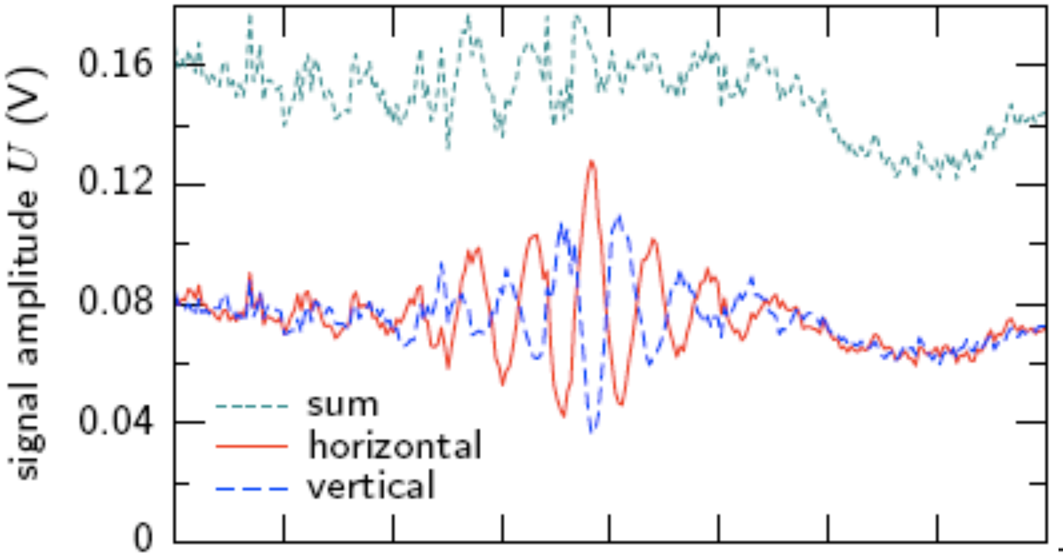


- Operates much like the M-I
- Horizontally polarized input light is split into two orthogonal 45 deg polarizations.
- Polarization is mirrored by roof mirrors, allowing transmission/reflection through splitter.
- Analyzer recombines horz and vert polarizations and detects each signal.

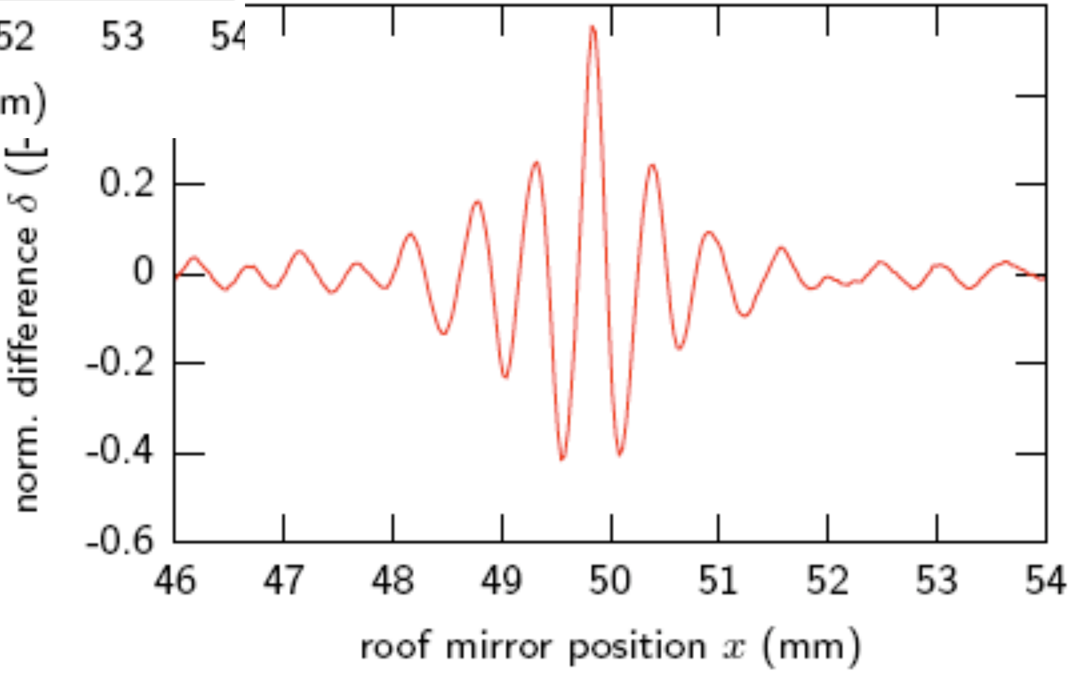
FLASH Configuration



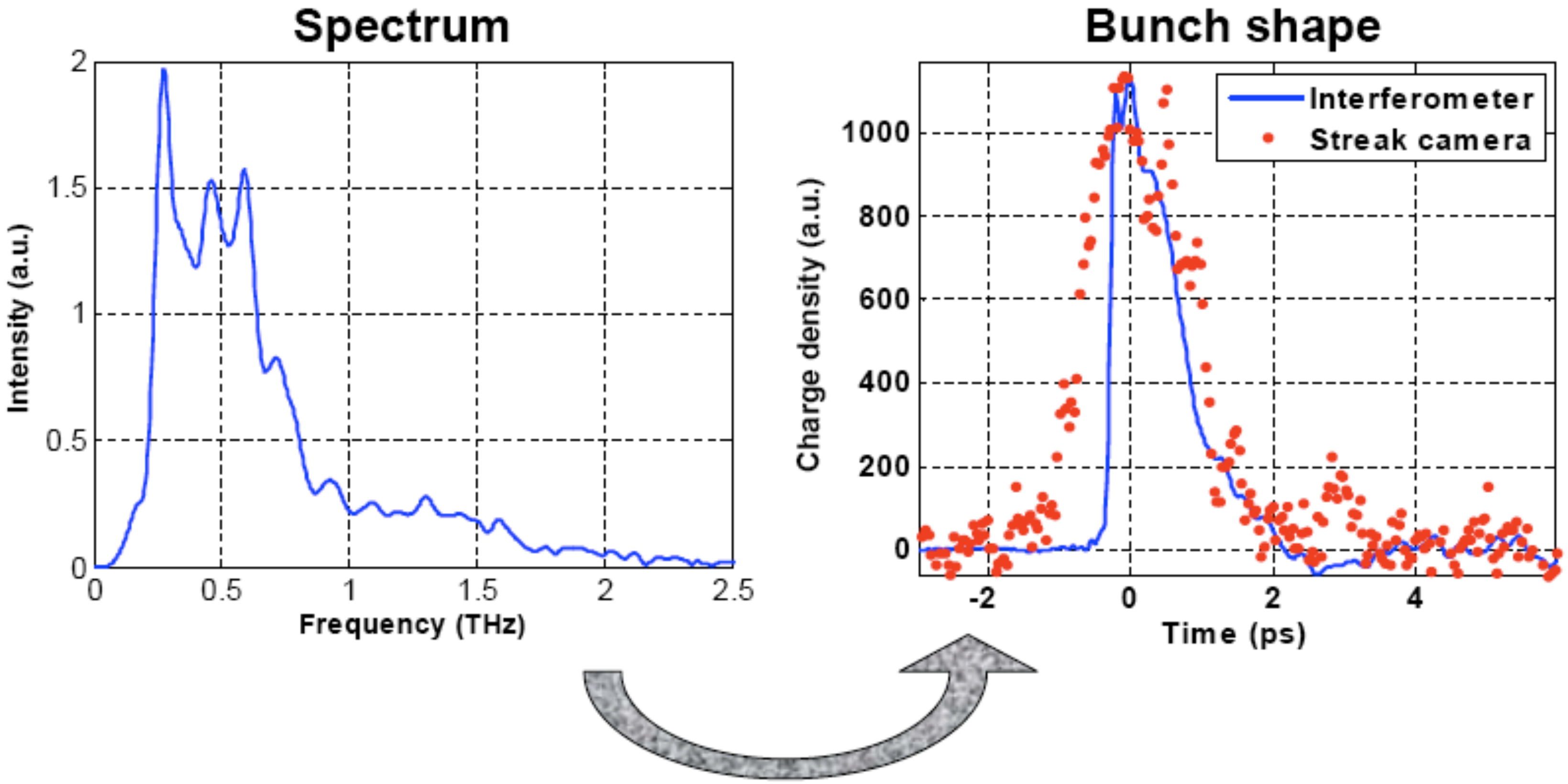
Example measurement



$$\delta(x) = \frac{U_\mathrm{h}(x) - U_\mathrm{v}(x)}{U_\mathrm{h}(x) + U_\mathrm{v}(x)}$$



Bunch Reconstruction



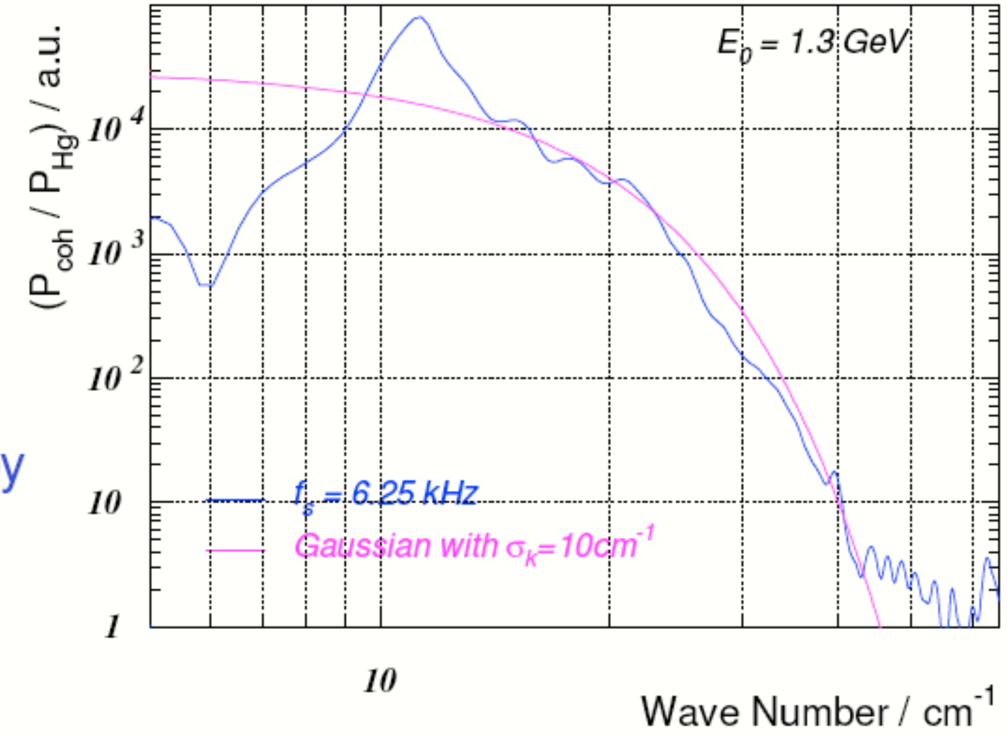
Spectrum

Bunch shape

through inversion of $$\frac{\mathrm{d}U}{\mathrm{d}\upsilon} = \left(\frac{\mathrm{d}U}{\mathrm{d}\upsilon}\right)_1 \left(N + N(N-1)\left|F(\upsilon)\right|^2\right) \quad F(\upsilon) = \int S(t) e^{2\pi i \upsilon t} \mathrm{d}t$$

Bunch length from Spectrum

- Determination of σ from normalised spectrum
- Ideally normalisation by incoherent spectrum
  - ➜ Problem: low intensity
  - ➜ Alternative: Normalise by spectrum of Hg lamp



- The bunch length is related to the spectral bandwidth σ_k by (G. Wüstefeld, SBSR05):

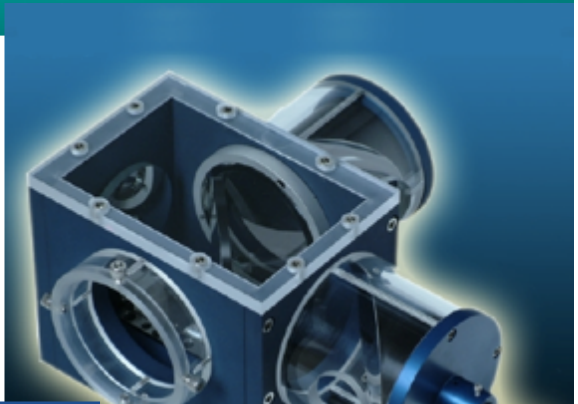
$$\sigma_s = \frac{1}{2\pi\sqrt{2}\,\sigma_k}$$

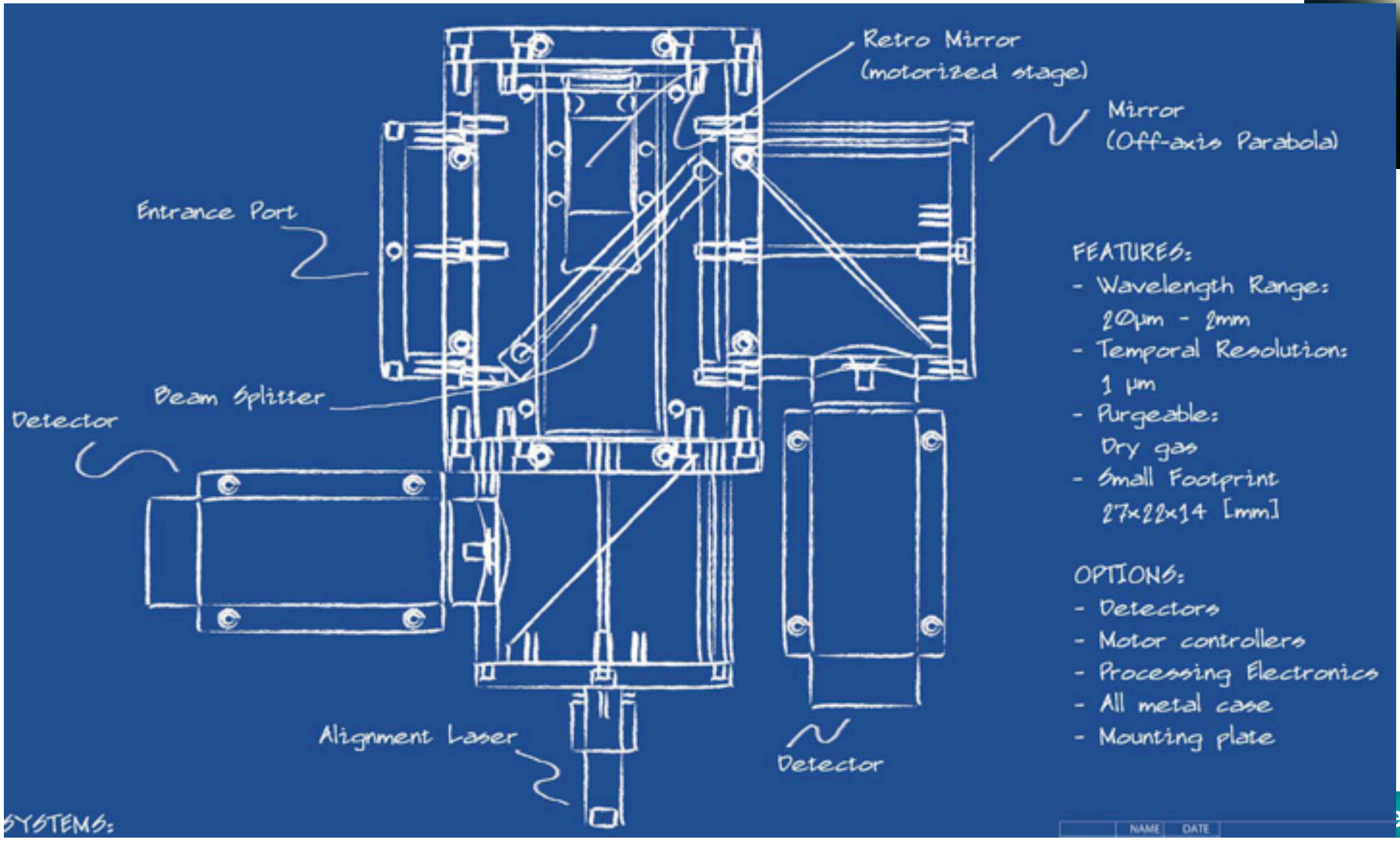
Anke Susanna Mueller, KIT

- The bunch length determined thus is 0.375 ps.

Commercial bunch length monitors

Radiabeam

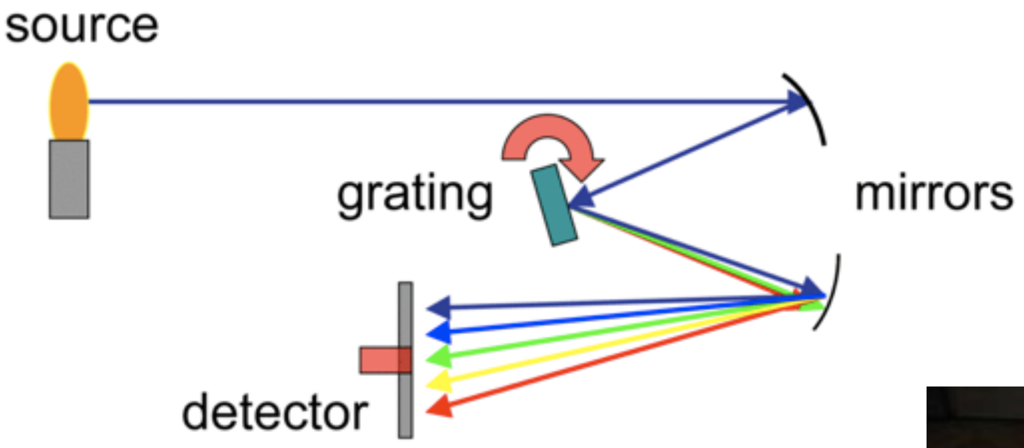




FEATURES:
- Wavelength Range:
  20μm - 2mm
- Temporal Resolution:
  1 μm
- Purgeable:
  Dry gas
- Small Footprint
  27x22x14 [mm]

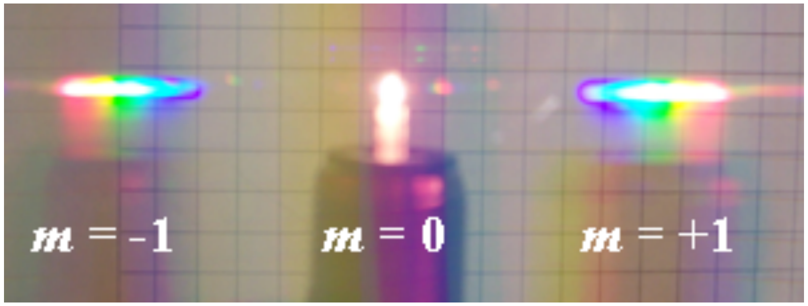
OPTIONS:
- Detectors
- Motor controllers
- Processing Electronics
- All metal case
- Mounting plate

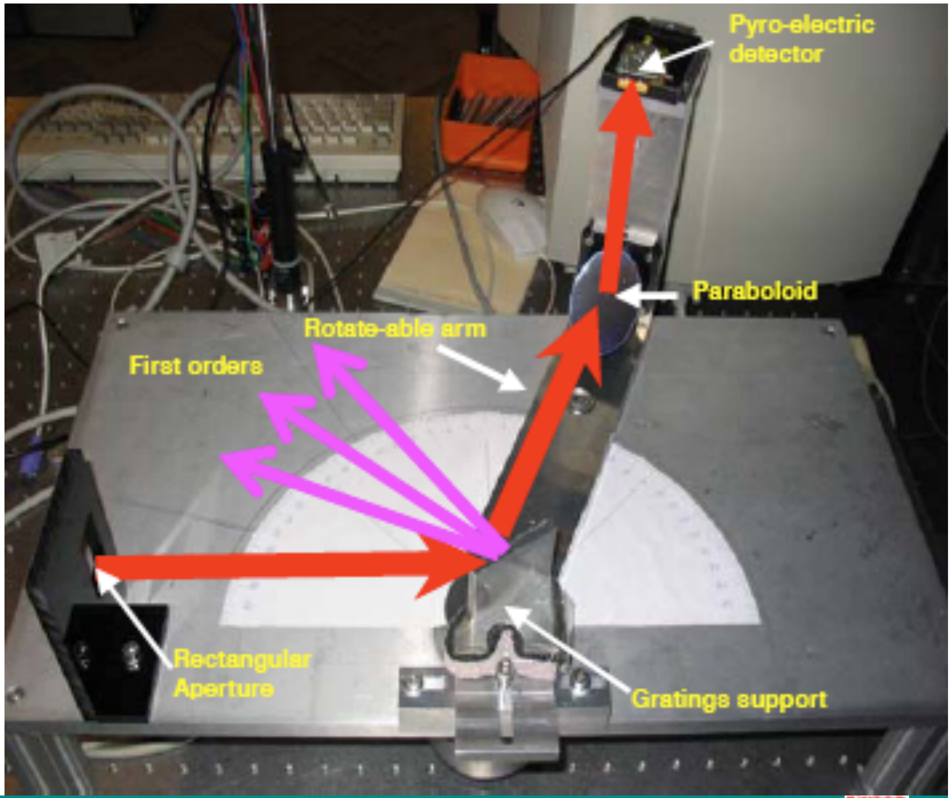
Grating spectrometers



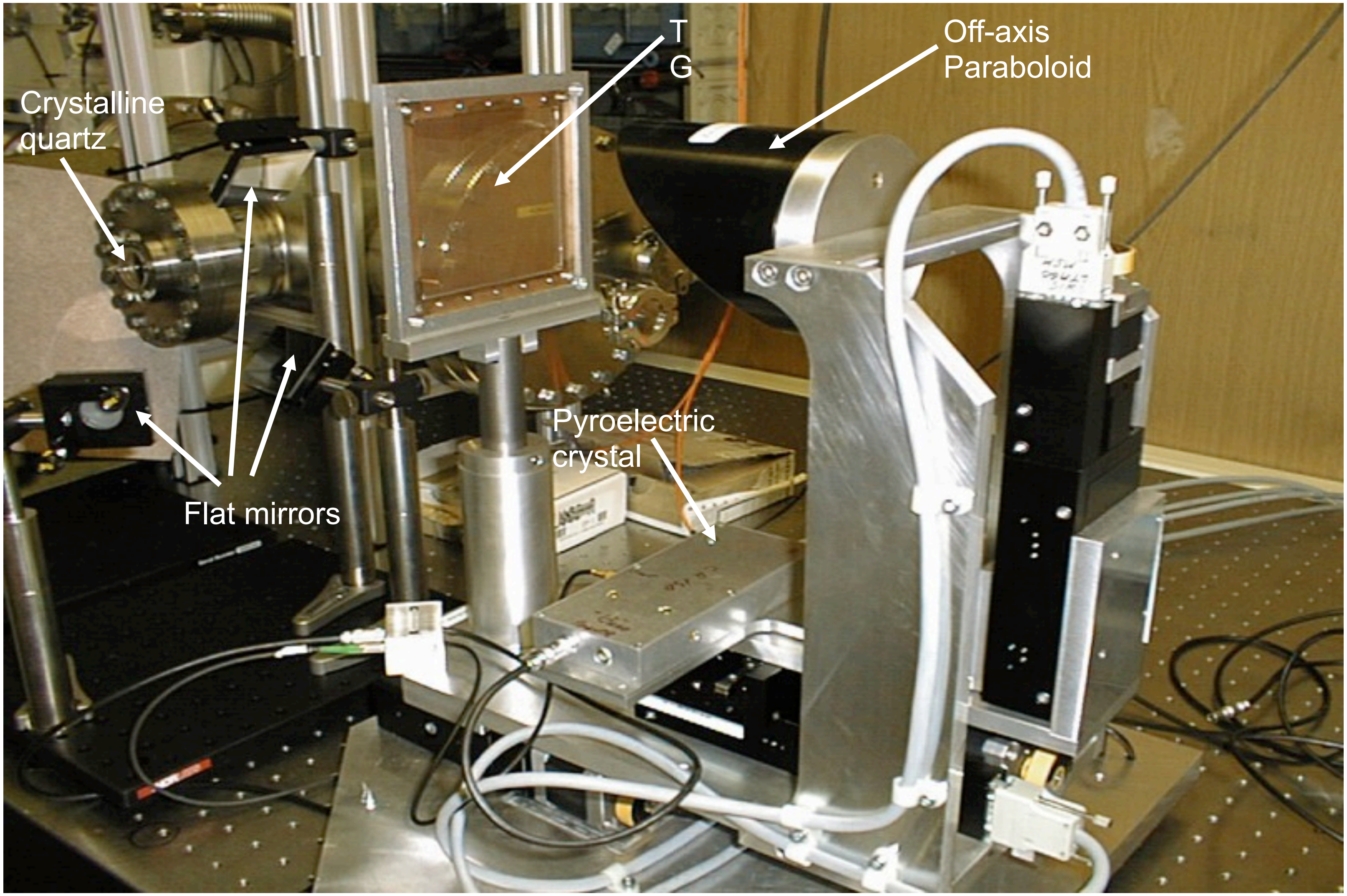
Use dispersion to separate wavelength components

$$d\left(\sin\theta_m(\lambda)+\sin\theta_i\right)=m\lambda$$

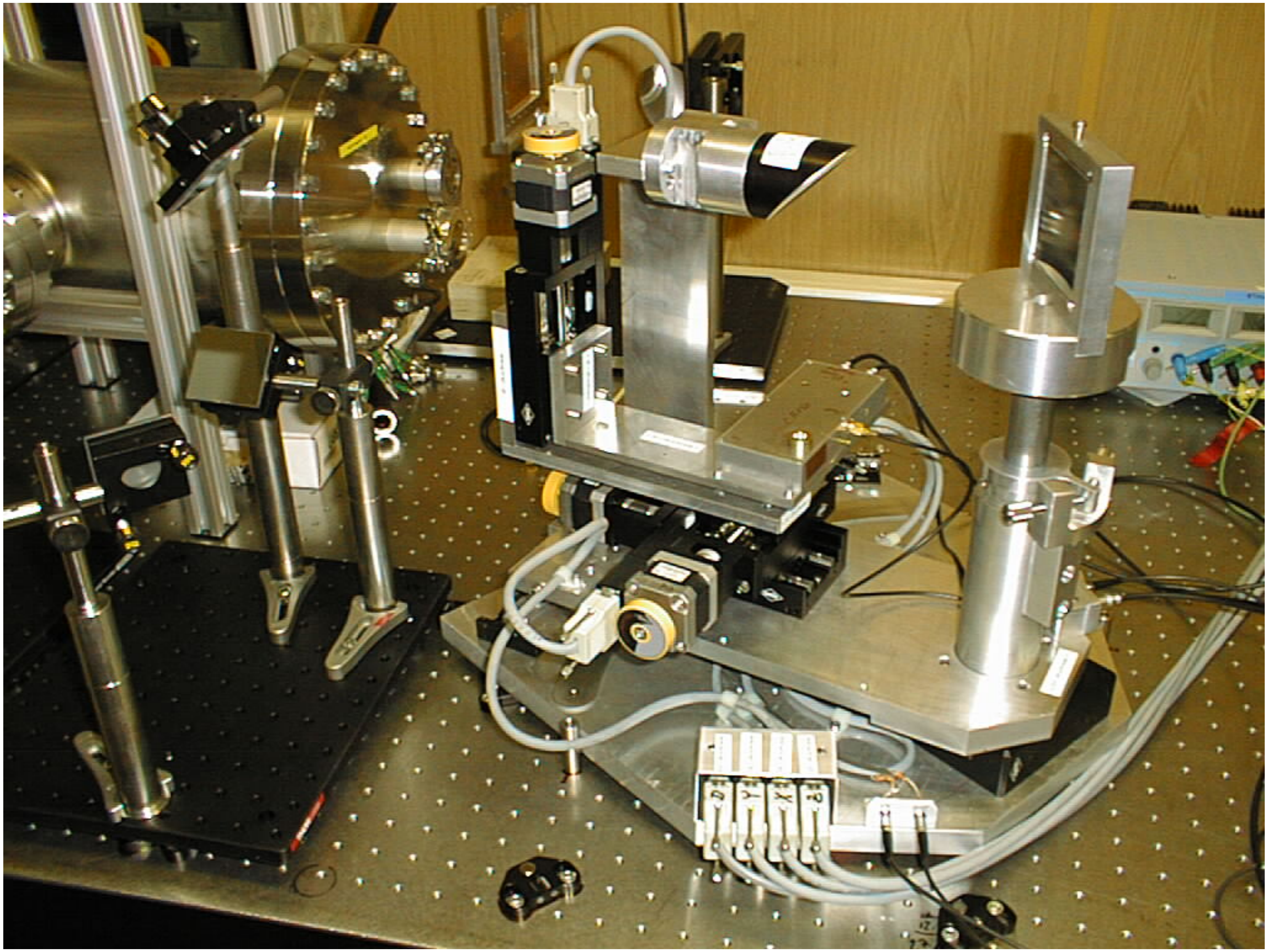




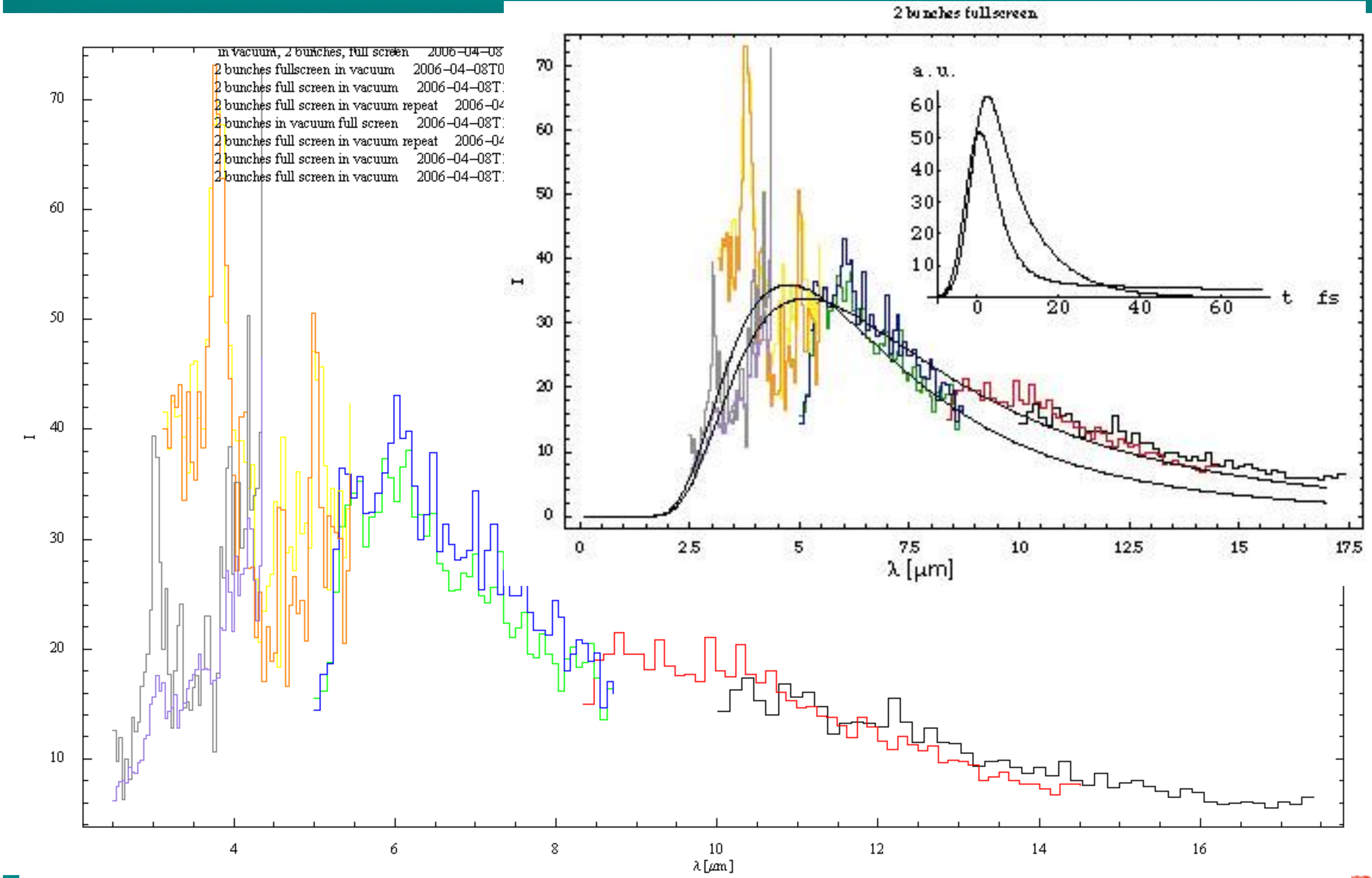
Rotating grating spectrometer



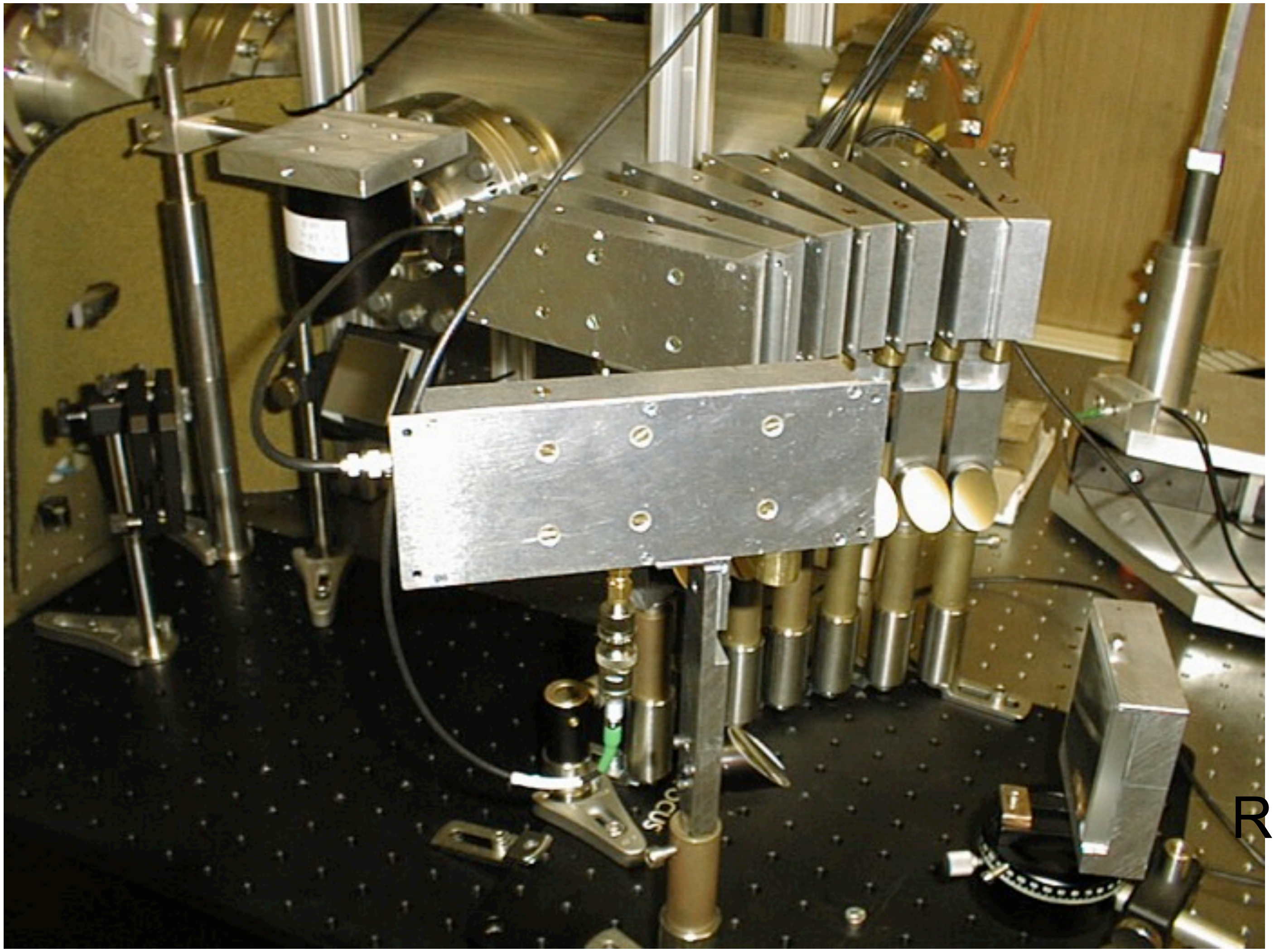
Rotation reflection grating



Some results (short wavelengths in vacuum)



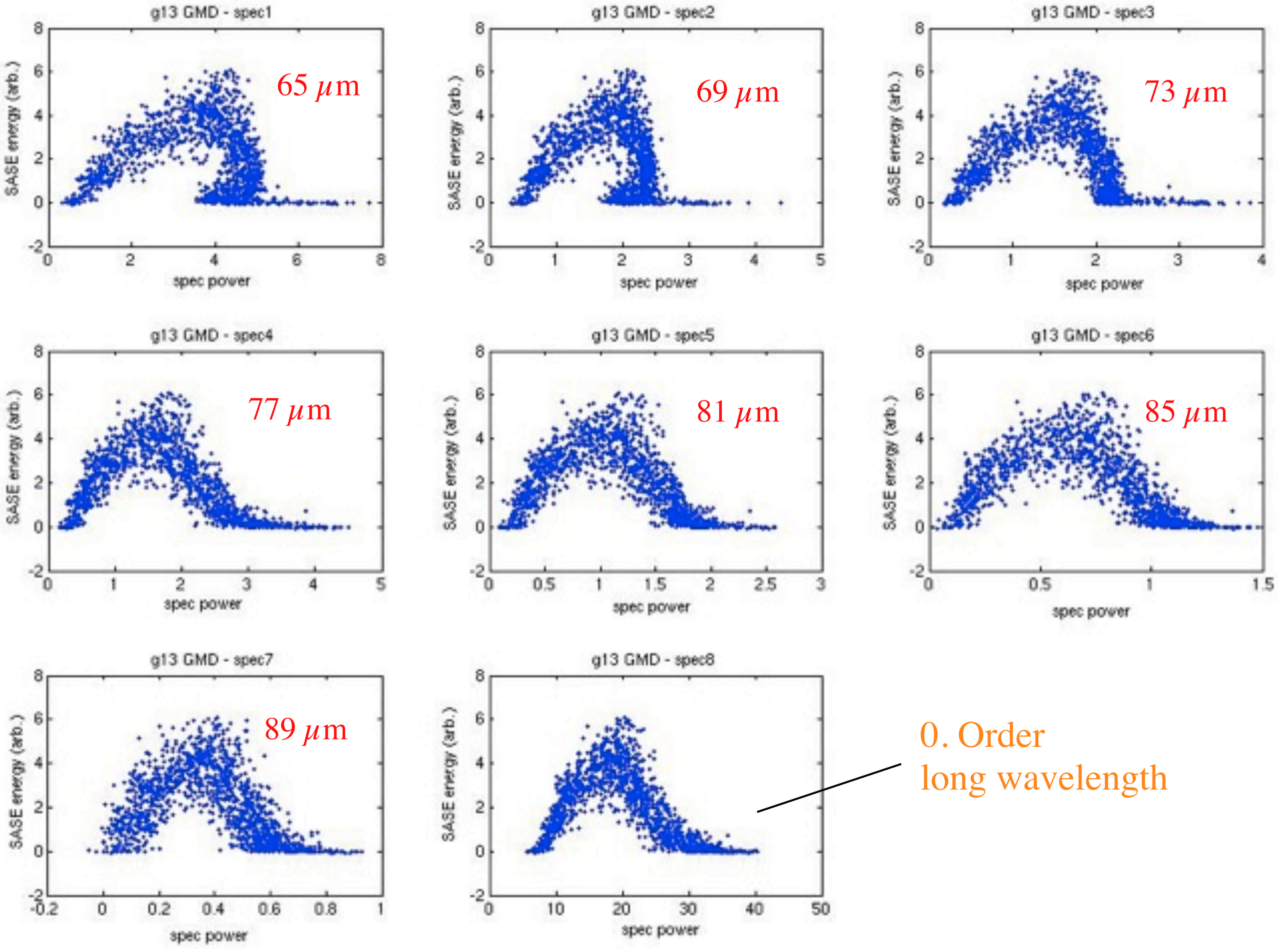
Single shot spectrograph



PD array

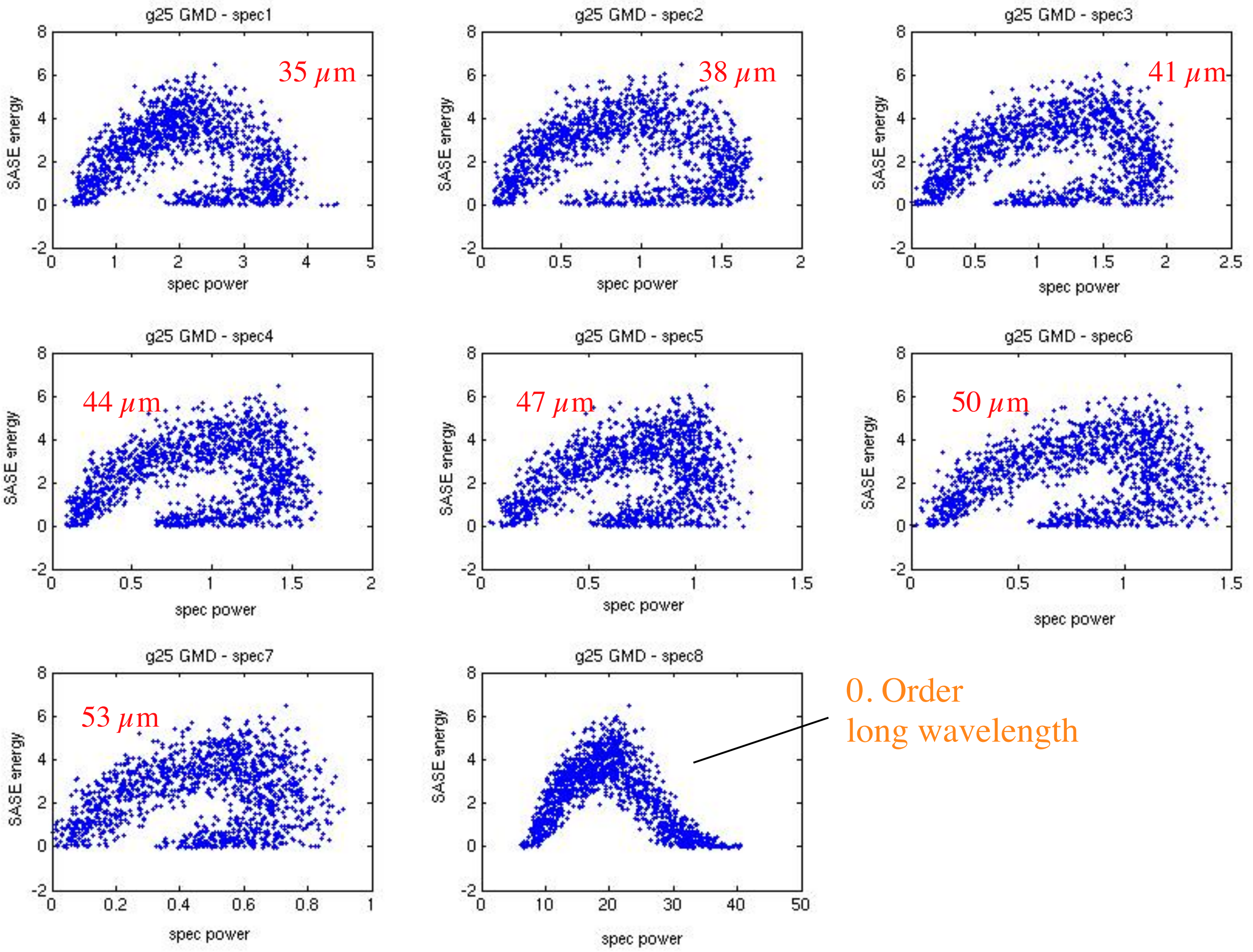
Reflection grating

Correlations SASE - short wavelengths - I



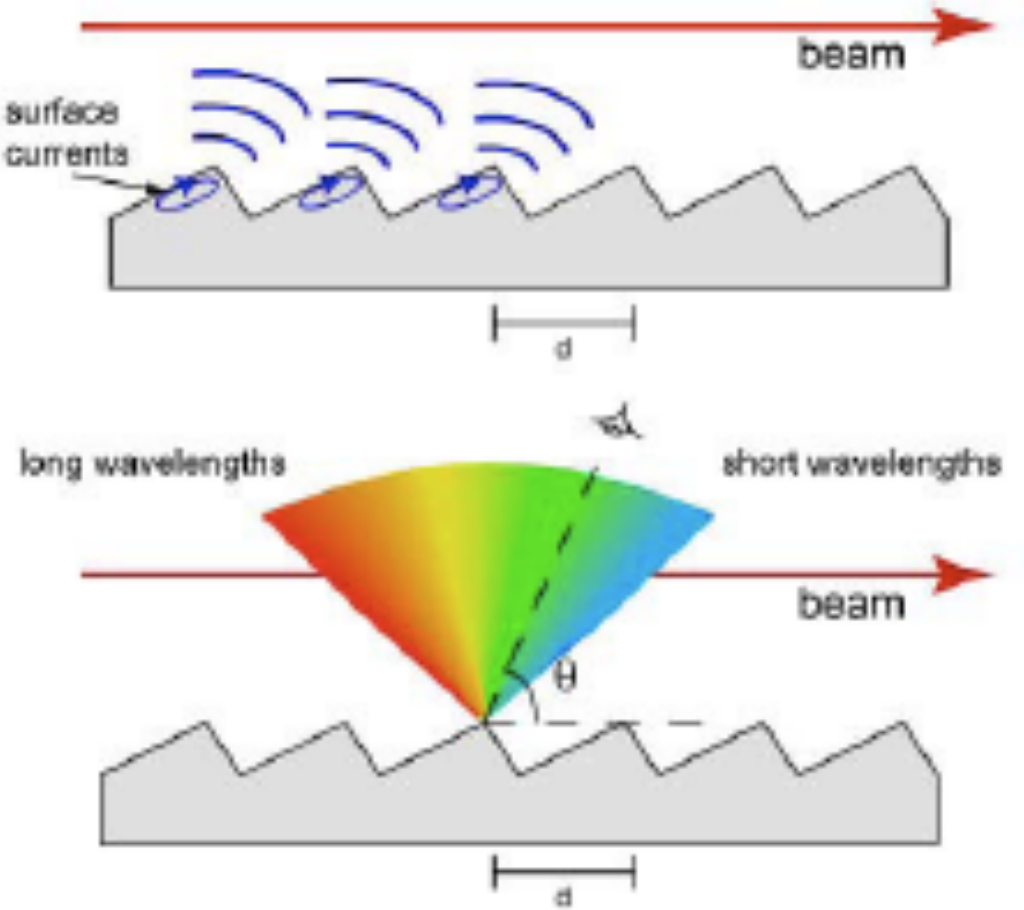
0. Order
long wavelength

Correlations SASE - short wavelengths - II



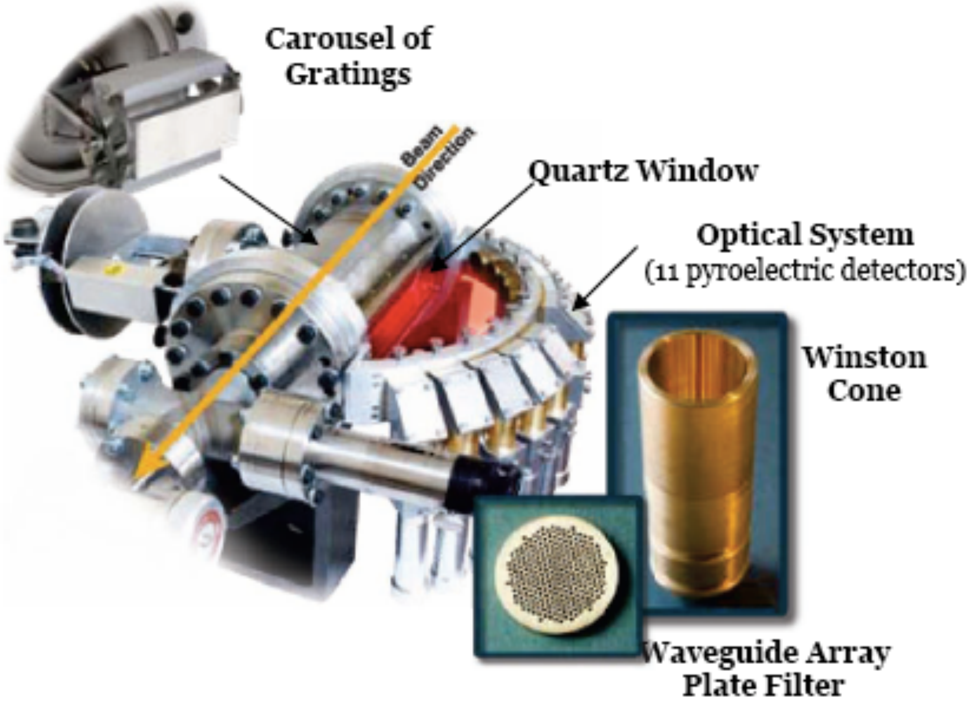
0. Order
long wavelength

Direct grating spectrometer; Smith-Purcell radiation

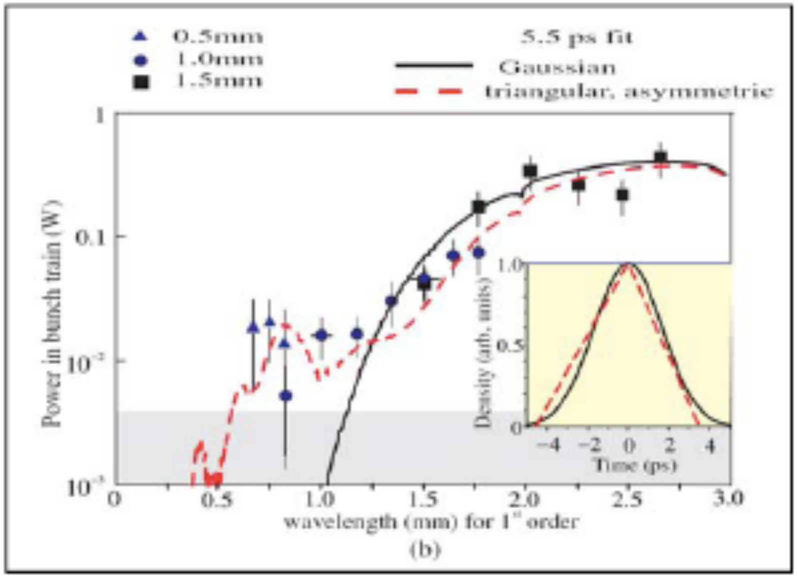


Smith-Purcell radiation is interference of multiple diffraction radiators

Smith-Purcell spectrometer



Measurement at 45 MeV, FELIX

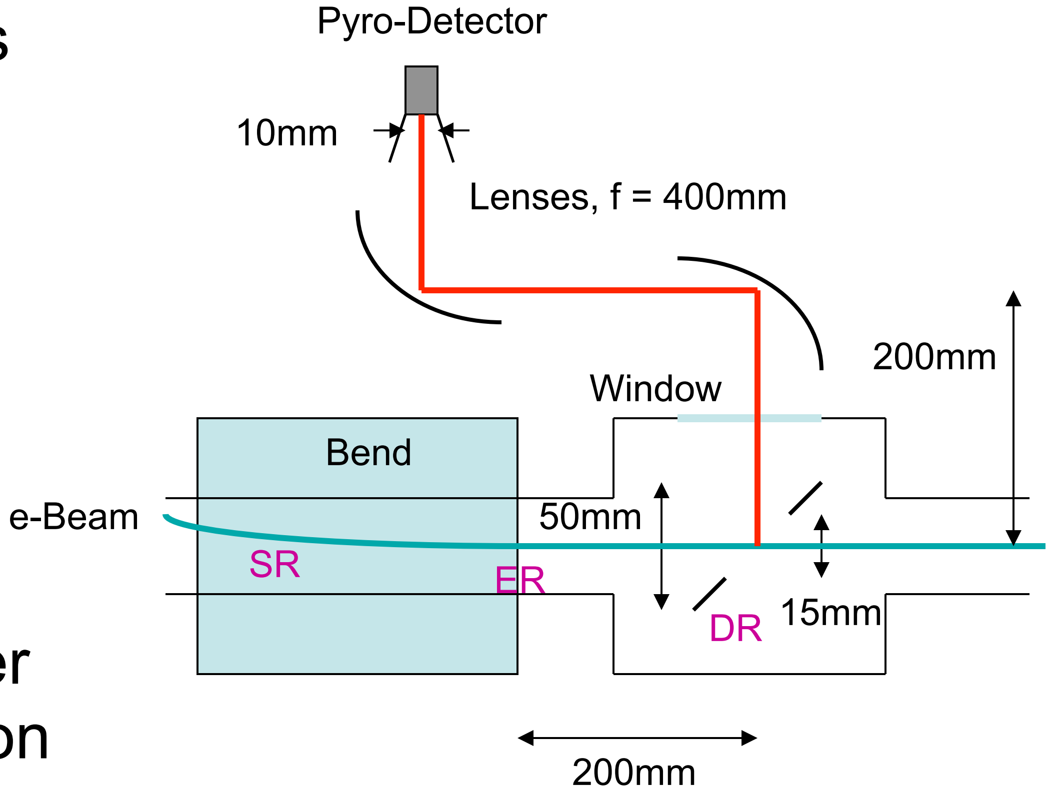


see PRST 9,092801 (2006)

Results of a run at 28.5 GeV from SLAC are currently being analyzed.

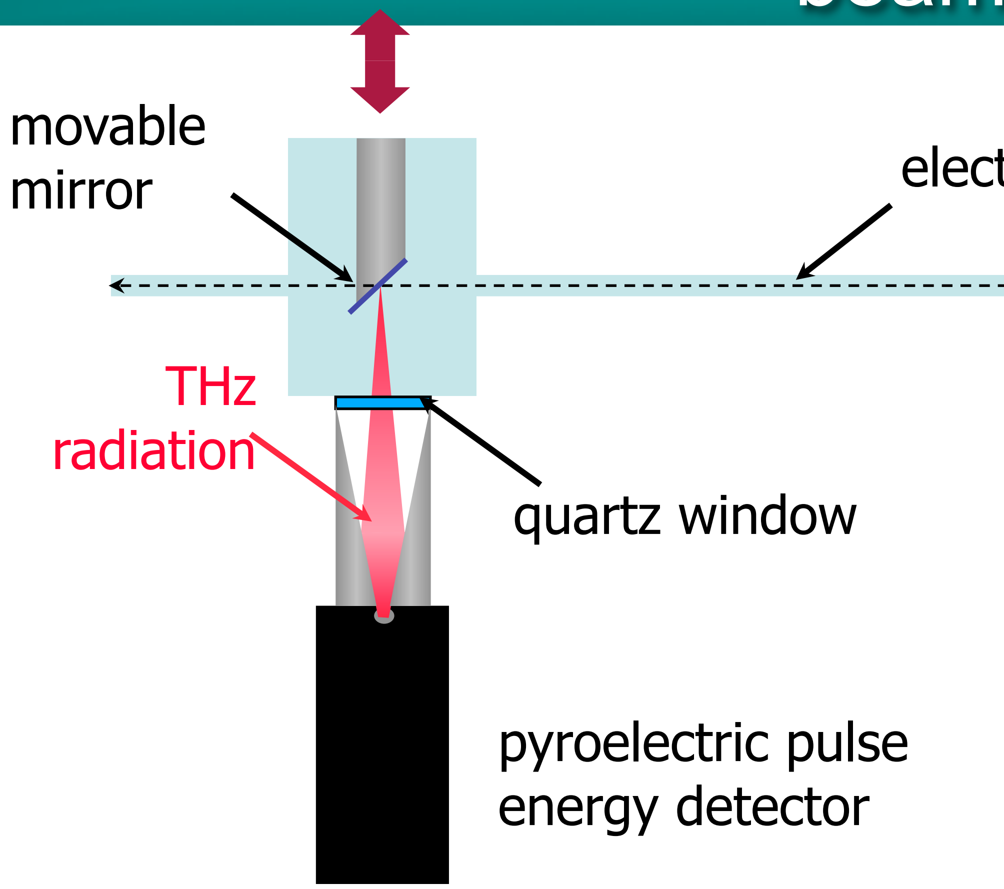
Relative Bunch Length Measurements

- Absolute bunch length is not always needed.
- A relative bunch length monitor is sufficient for feedback accelerator control.



- Edge rad. dominates over synchrotron and diffraction
- Near field calculation necessary for radiation spectrum at detector

Coherent Transition Radiation from a LINAC beam



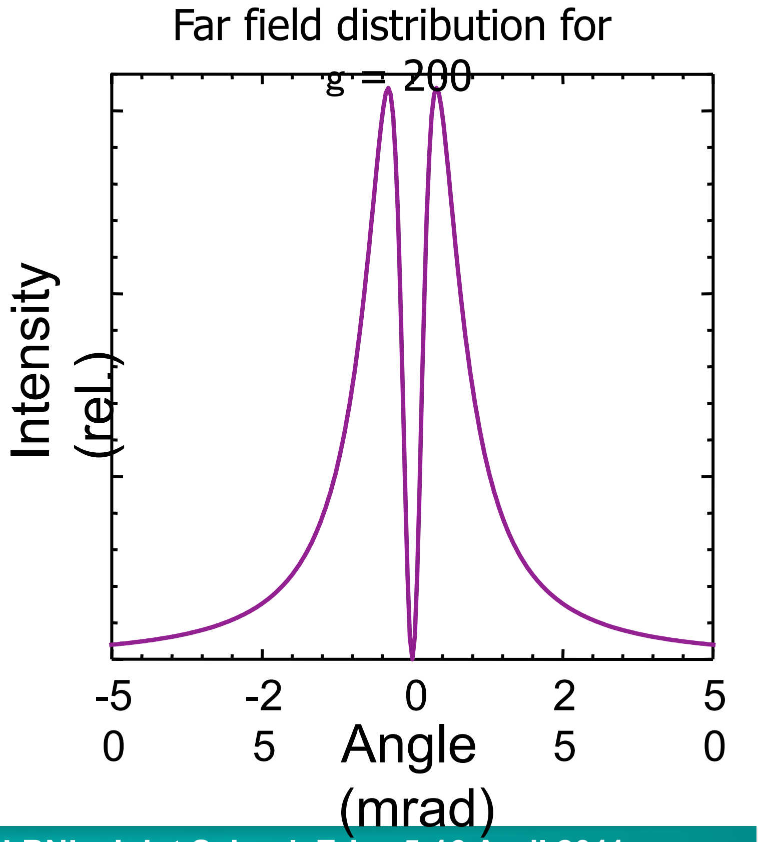
movable mirror

electron beam

THz radiation

quartz window

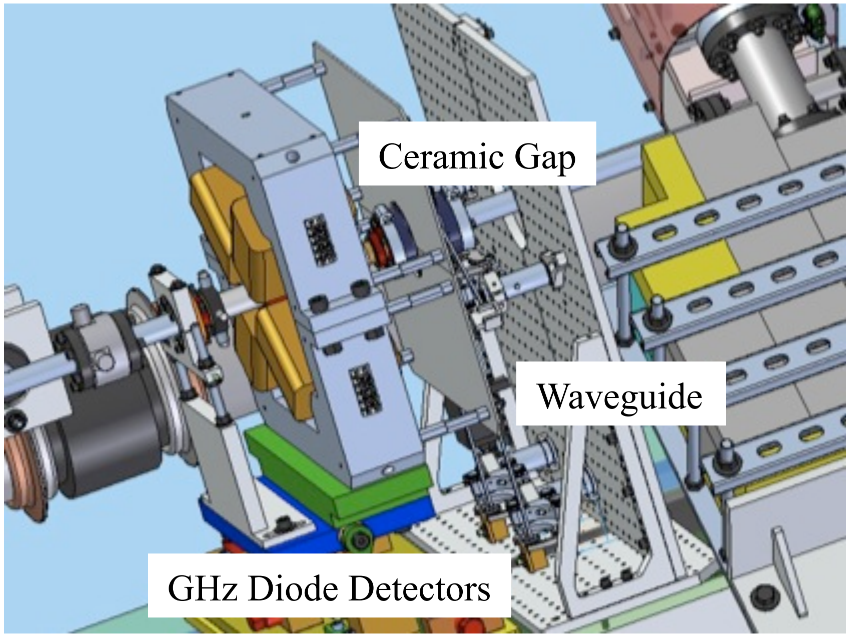
pyroelectric pulse energy detector



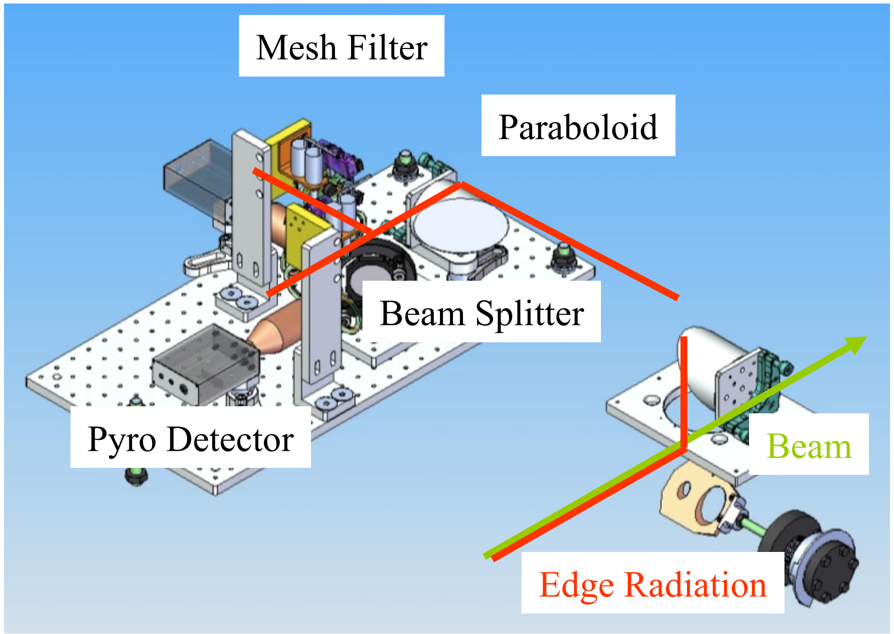
Far field distribution for g = 200

LCLS Relative bunch length monitors

BL12 – Ceramic Gap



BL11 – Coherent Edge Radiation

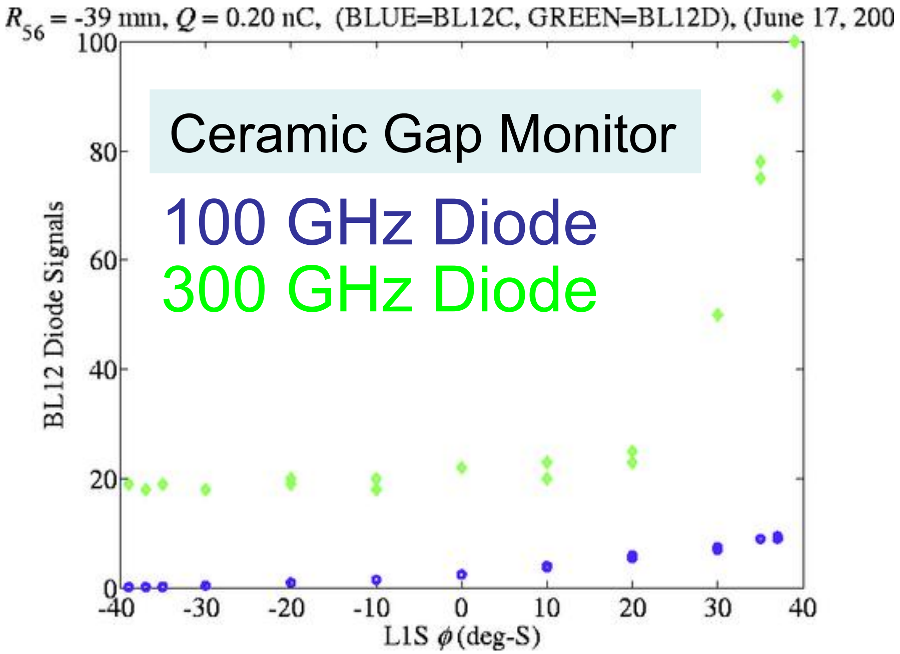


- Wide range of bunch lengths from 25um to 300um
- Diode detectors work well below 300GHz
- Pyroelectric detectors work well above 300GHz
- Long bunches- Couple radiation from ceramic gap in beam pipe into waveguides with different diode detectors
- Short bunches-Extract coherent radiation from bend magnet with hole mirror and send to a pyroelectric detector

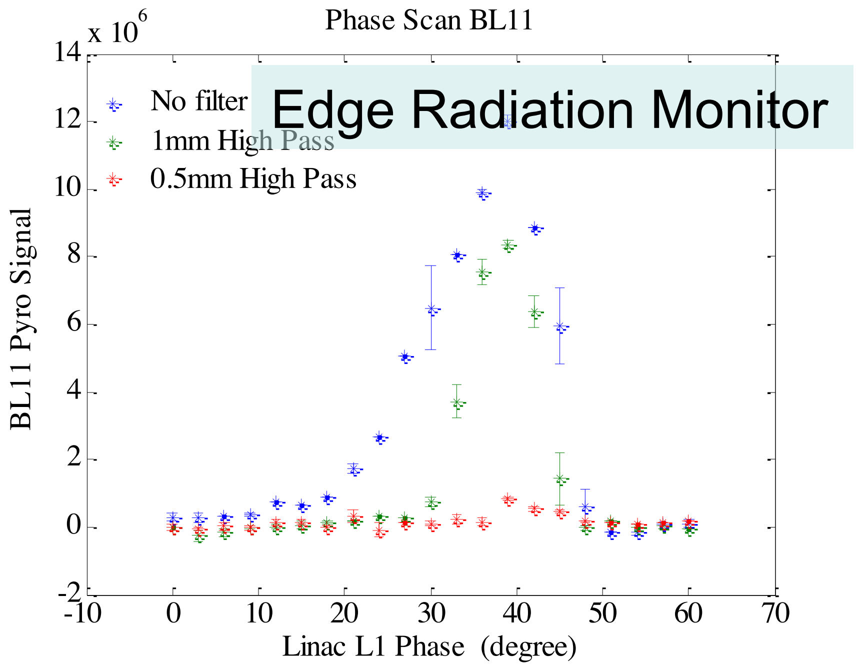
Bunch Length Monitors

- Both bunch length monitors installed
- Signal from wave guide diodes and pyroelectric detectors available

- All signals show strong correlation with accelerator phase and bunch compression
- Absolute calibration with TCAV in S29 to be done



Ceramic Gap Monitor



Edge Radiation Monitor

Femtosecond Timing and Synchronization

- A revolution is going on in optical metrology due to several coincident factors:
  - development of femtosecond comb lasers
  - breakthroughs in nonlinear optics
  - wide availability of optical components

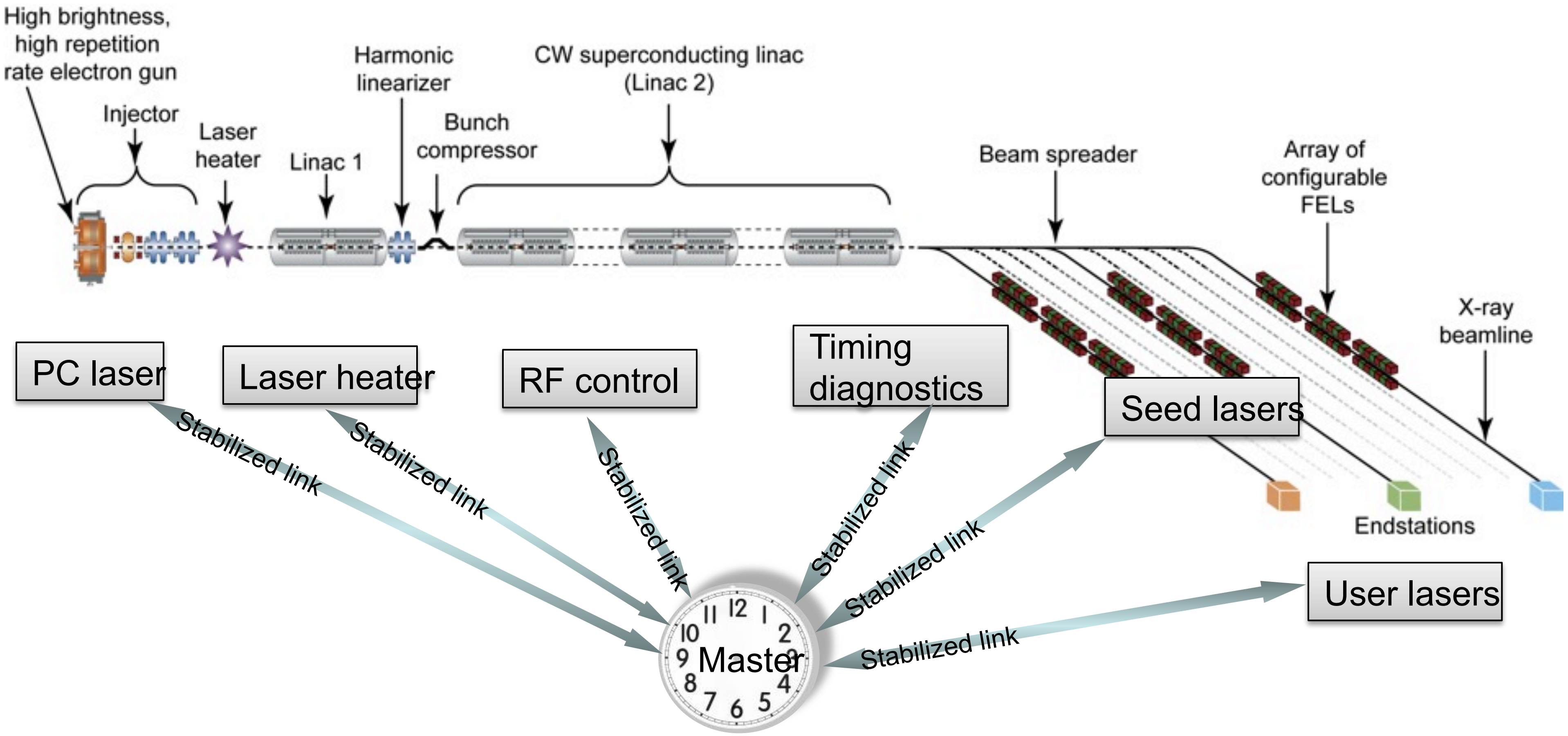
2005 Nobel Prize in Physics awarded to John L. Hall and Theodor W. Hänsch "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

> “The resulting new capabilities are unbelievably rich in terms of the tools and capabilities that have been created, and these in turn are reinforcing progress in these related contributing fields…Generation II comb applications now include: **low-jitter time synchronization between ultra-fast laser sources... Attractive topics of research for Generation III applications include precise remote synchronization of accelerator cavity fields**”
>
> Nobel Lecture, December 8, 2005
> by John L. Hall

This technology is ready for applications in precision synchronization in accelerators

The Big Picture

- The eventual goal is to provide *remote* synchronization between all FEL driver systems: x-rays, lasers, and RF accelerators. Our current focus is to synch user laser systems with timing diagnostics.

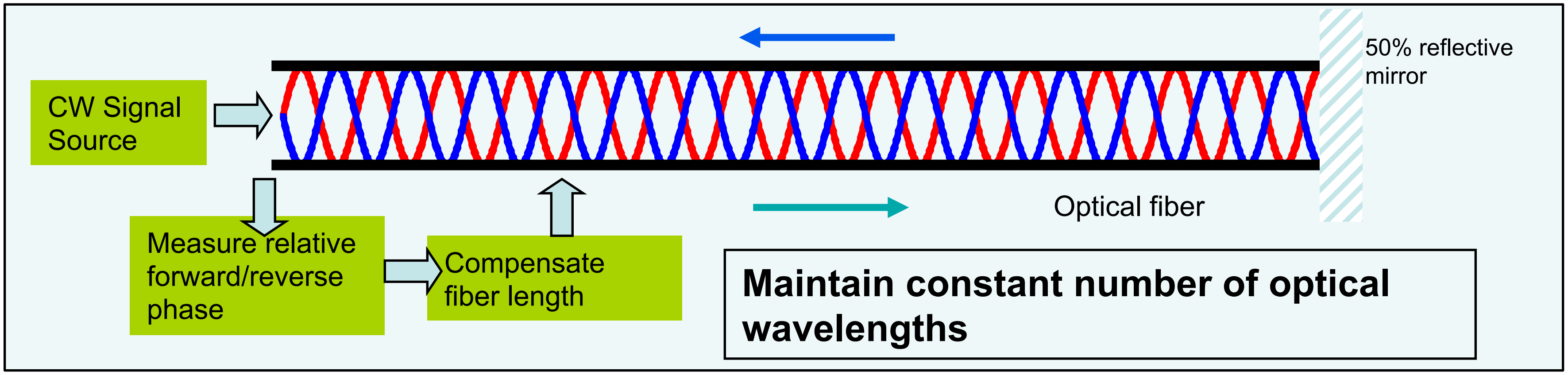


Why optical fiber links?

- Problem: coaxial cables and optical fiber have a temperature dependence of propagation delay of about 50 psec/km/deg-C.
  - Completely unacceptable for next-gen light sources both for RF systems and lasers.
  - Temp. stabilized cables impractical for large installations.
- Solution: use optical interferometry over fiber links to measure length change and actively feedback to stabilize signal propagation delay.
  - Fiber provides THz bandwidth, low attenuation, electrical isolation. Acoustically sensitive.
  - Optical signal transmission allows very sensitive interferometry (time or frequency domain).
  - Commodity grade fiber technology relatively cheap.

Time and Frequency Domain Stabilized Links

- Fiber links can be stabilized based on the revolution in metrology time and wavelength standards over the past decade.



CW Signal Source

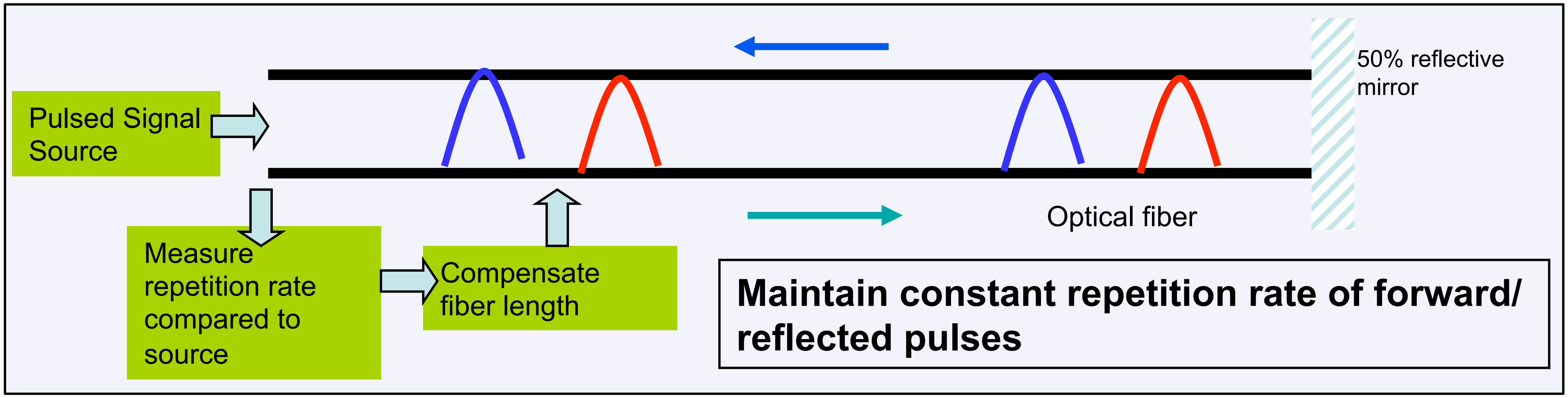
Measure relative forward/reverse phase

Compensate fiber length

Optical fiber

50% reflective mirror

Maintain constant number of optical wavelengths



Pulsed Signal Source

Measure repetition rate compared to source

Compensate fiber length

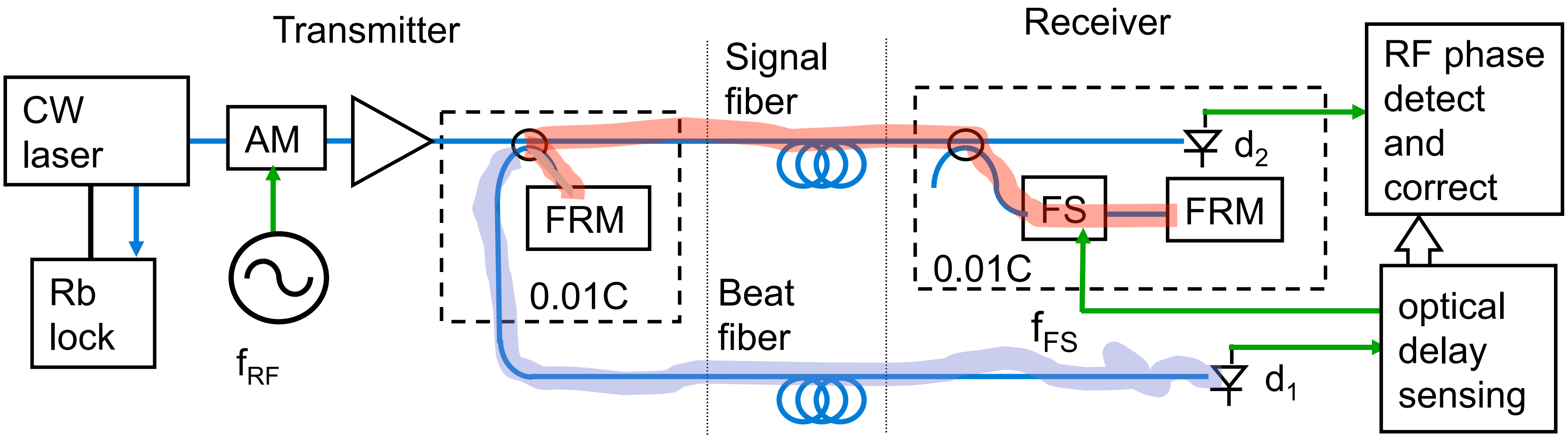
Optical fiber

50% reflective mirror

Maintain constant repetition rate of forward/ reflected pulses

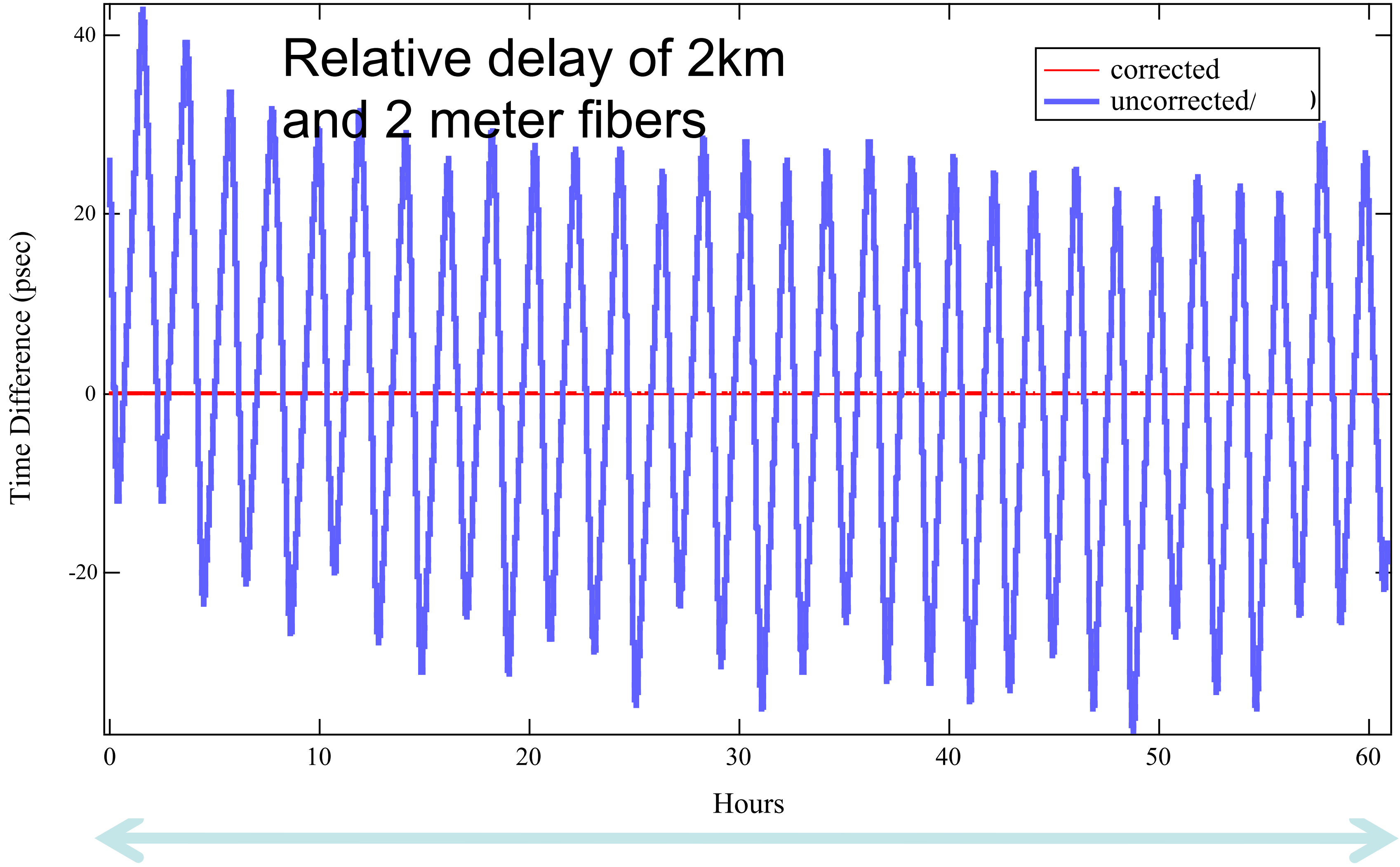
Correction BW limited to R/T travel time on fiber (e.g. 1 km fiber gives 100 kHz)

Single Channel Link



- FRM is Faraday rotator mirror (ends of the Michelson interferometer)
- FS is optical frequency shifter
- CW laser is absolutely stabilized
- Transmitted RF frequency is 2856 MHz
- Detection of fringes is at receiver
- Signal paths not actively stabilized are temperature controlled

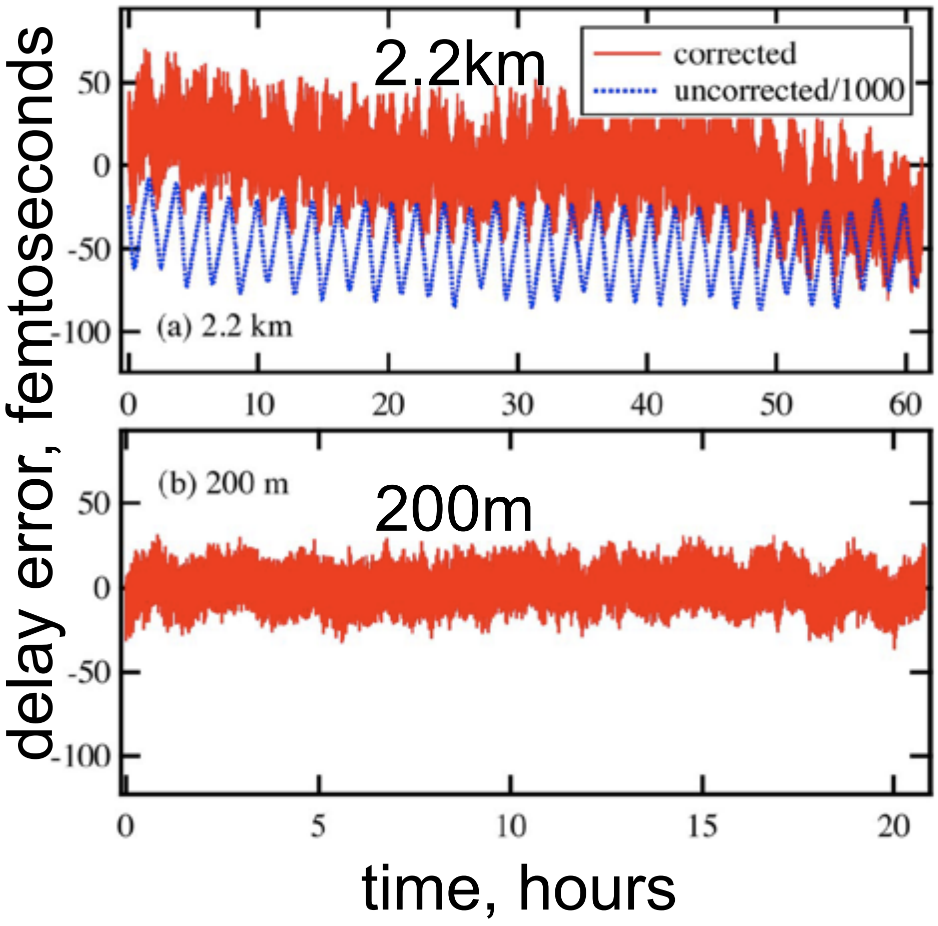
RF Transmission results



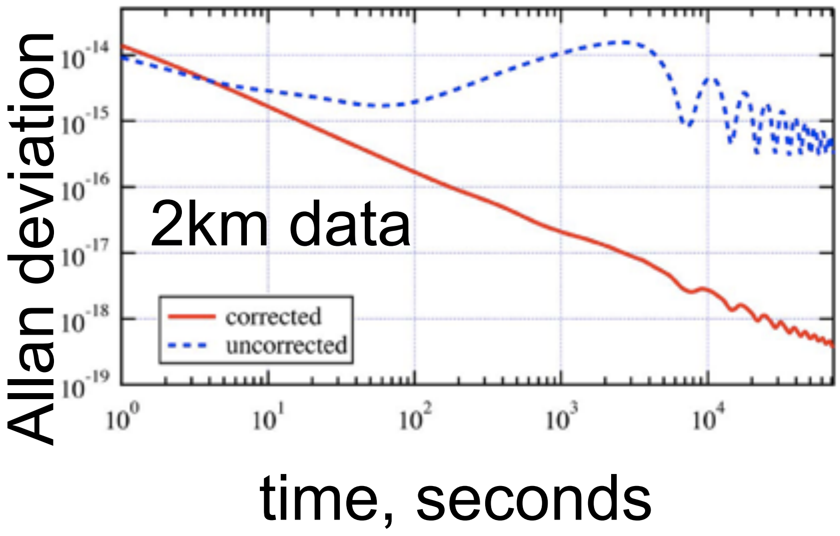
Relative delay of 2km and 2 meter fibers

61 hours

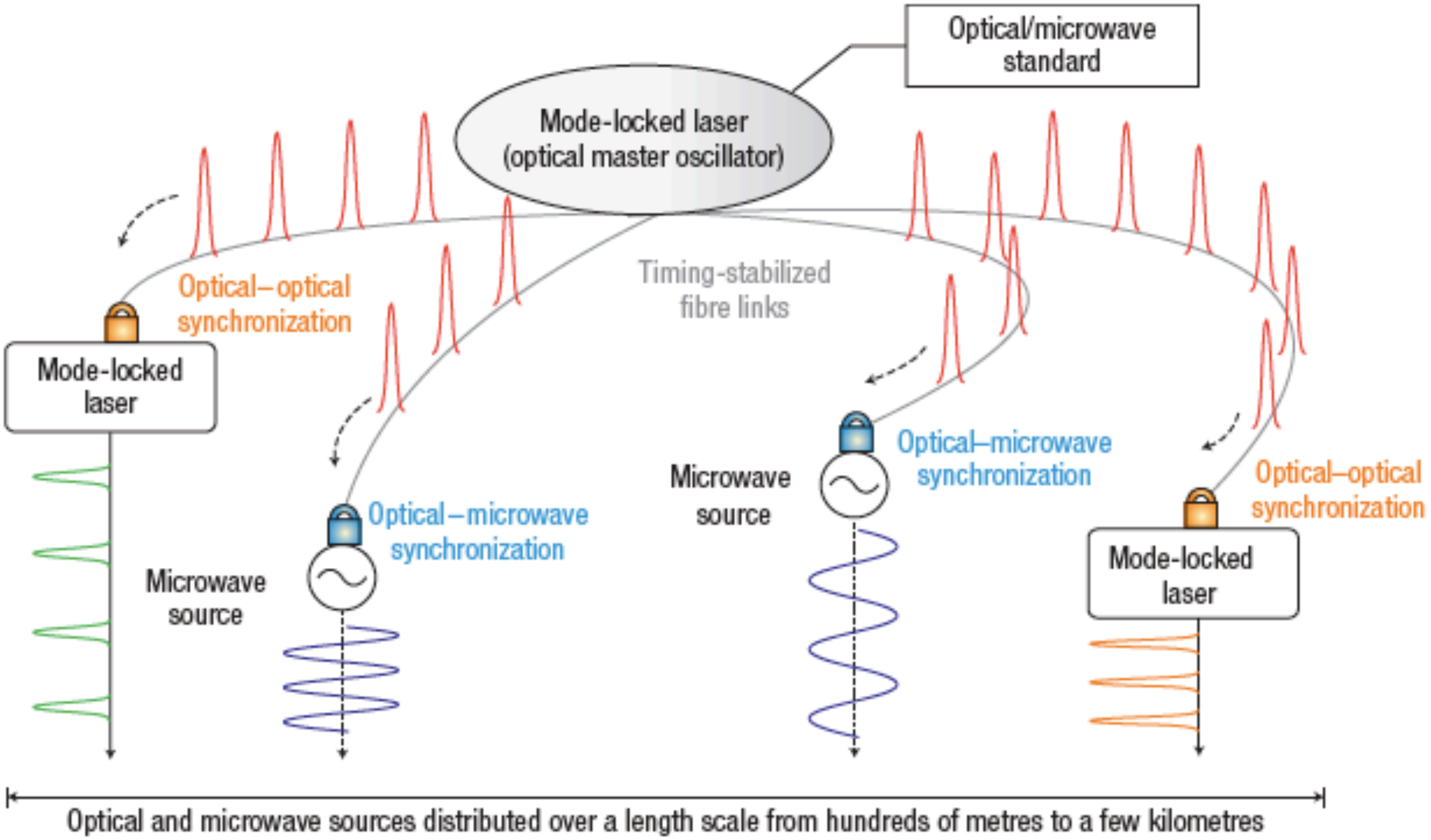
Detailed results



- 1 kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours
- 2-hour variation is room temperature



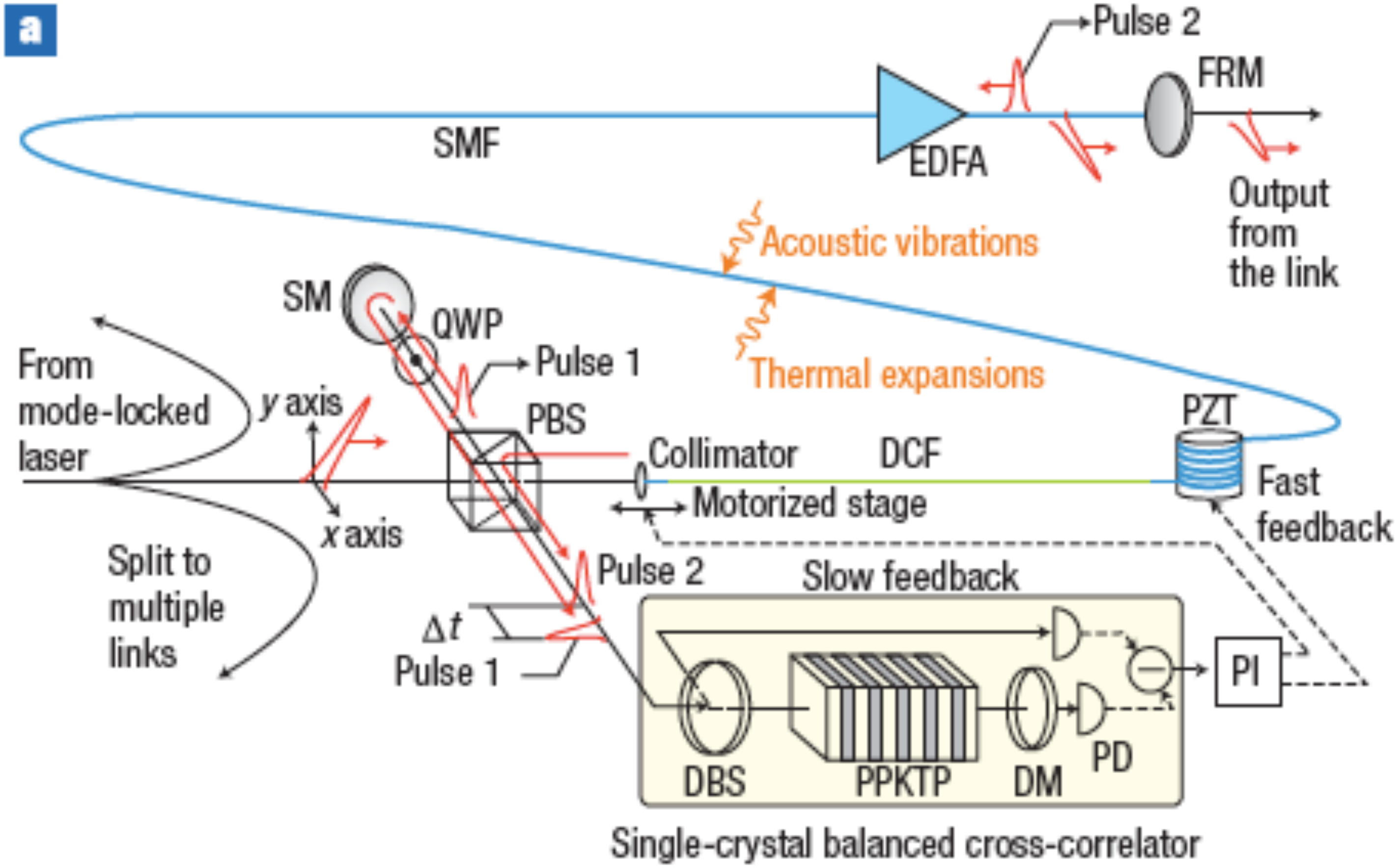
Pulsed Approach



- The timing signal, a low-noise optical pulse train, is generated from the mode-locked laser (optical master oscillator). The pulse train is distributed to the optical and microwave subsystems by means of timing-stabilized fibre links.
- Remotely located lasers and microwave oscillators are synchronized with the delivered pulse trains.

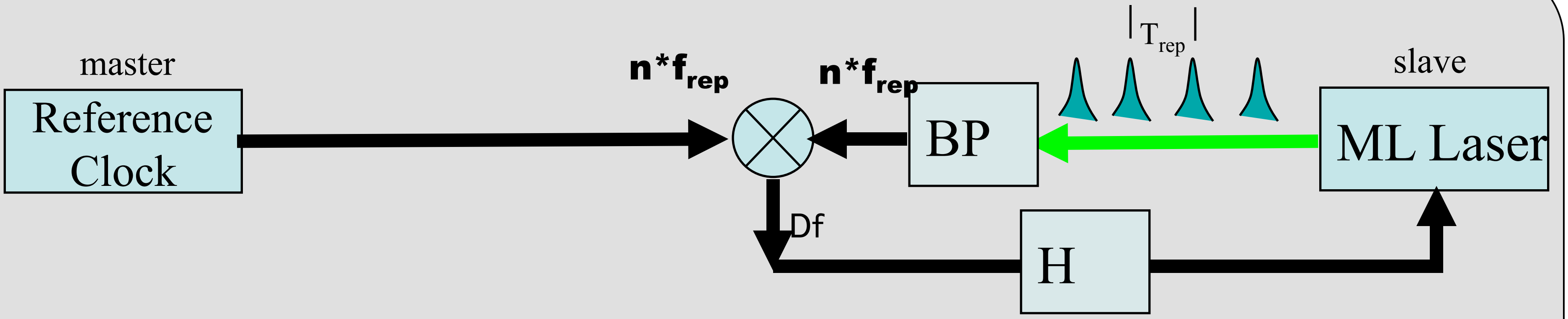
J. Kim, et al. Nature Photonics, 2008

Pulsed stabilized links

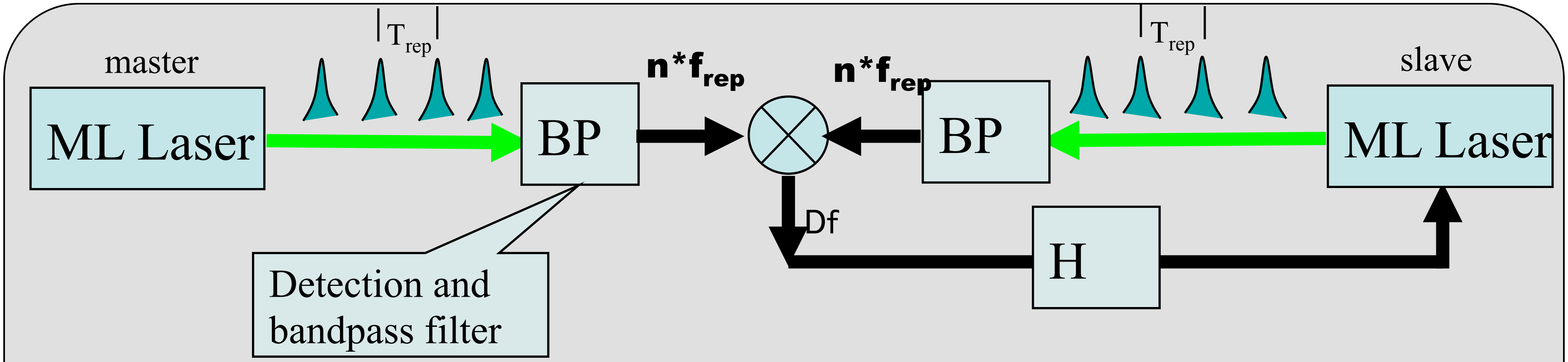


- Schematic of the timing-stabilized fibre link (SM, silver mirror; QWP, quarter-wave plate; PBS, polarizing beamsplitter; DBS, dichroic beamsplitter; DM, dichroic mirror; PPKTP, periodically poled KTiOPO4; PD, photodiode; DCF, dispersion-compensating fibre; PZT, piezoelectric transducer; PI, proportional-integral controller; SMF, single-mode fibre (SMF-28); EDFA, erbiumdoped fibre amplifier; FRM, Faraday rotating mirror).

Synching mode-locked lasers



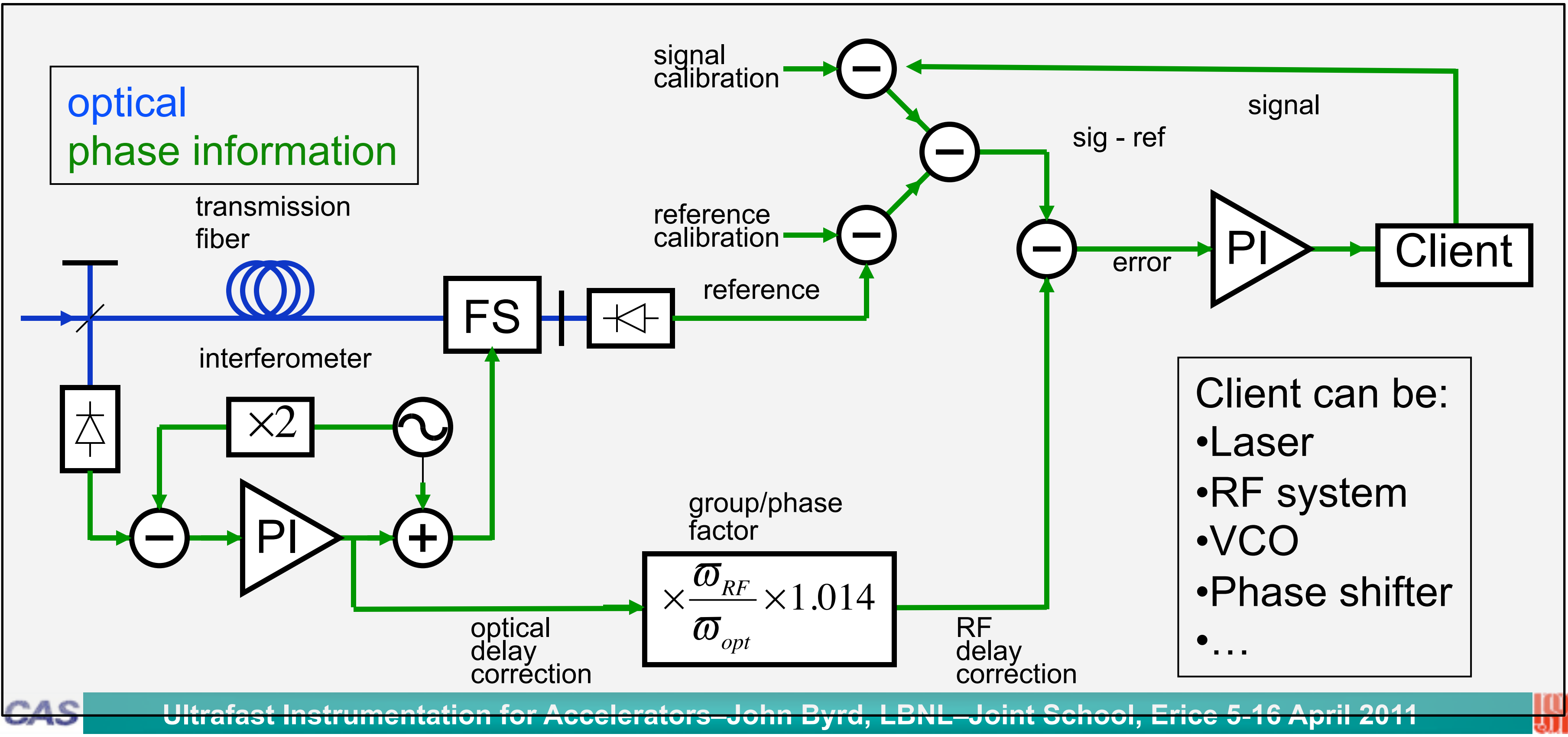
Lock laser to a reference clock



Locking slave laser to master laser

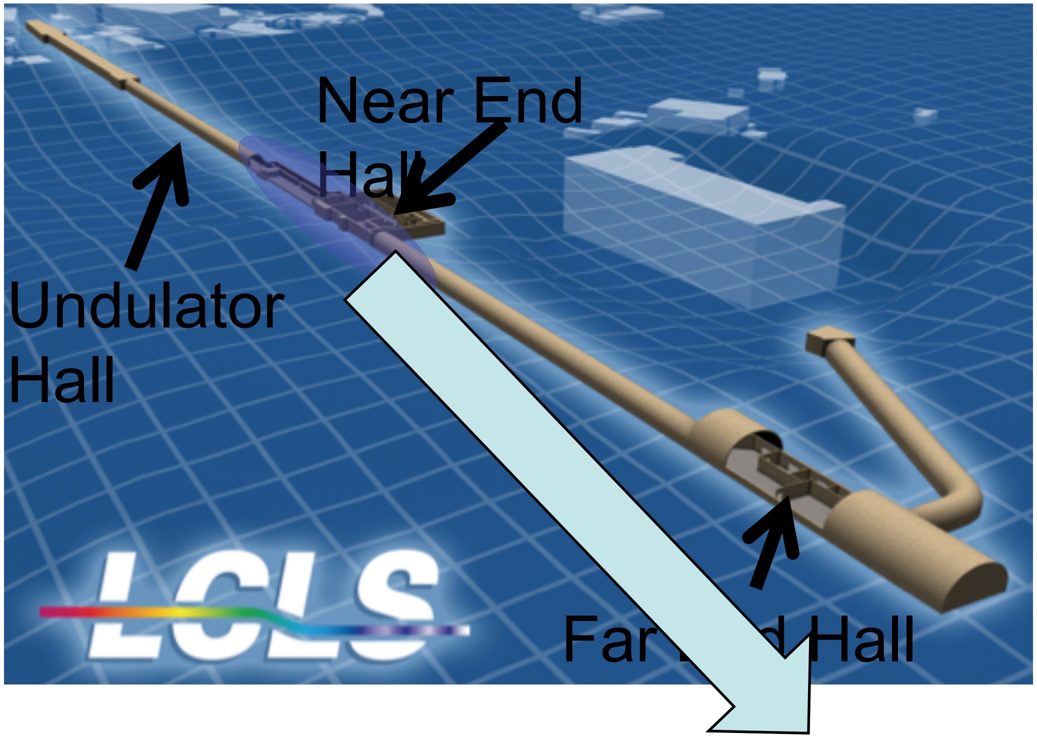
Locking laser to stabilized fiber timing signal

- All possible drift sources from the master to the client must be either actively compensated or thermally stabilized.
  - Thermal effects of cables and RF components are actively compensated via calibration signals
  - Group delay is compensated via feed-forward



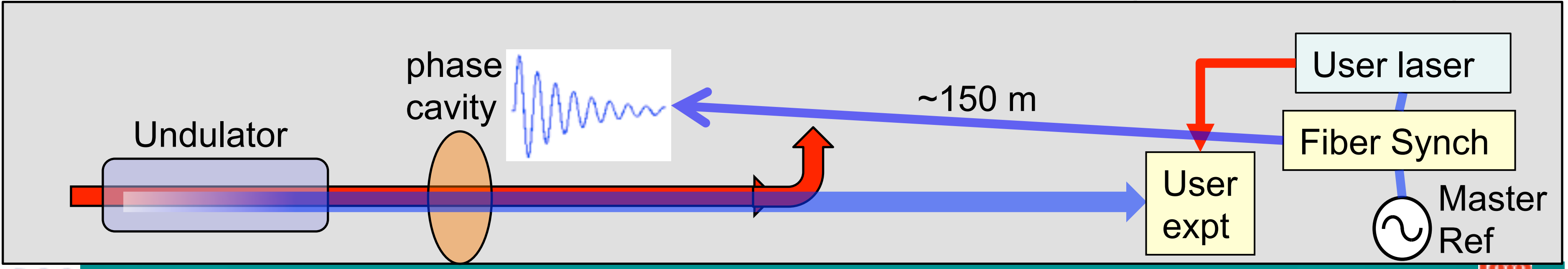
Client can be:
- Laser
- RF system
- VCO
- Phase shifter
- …

LCLS: Initial Configuration

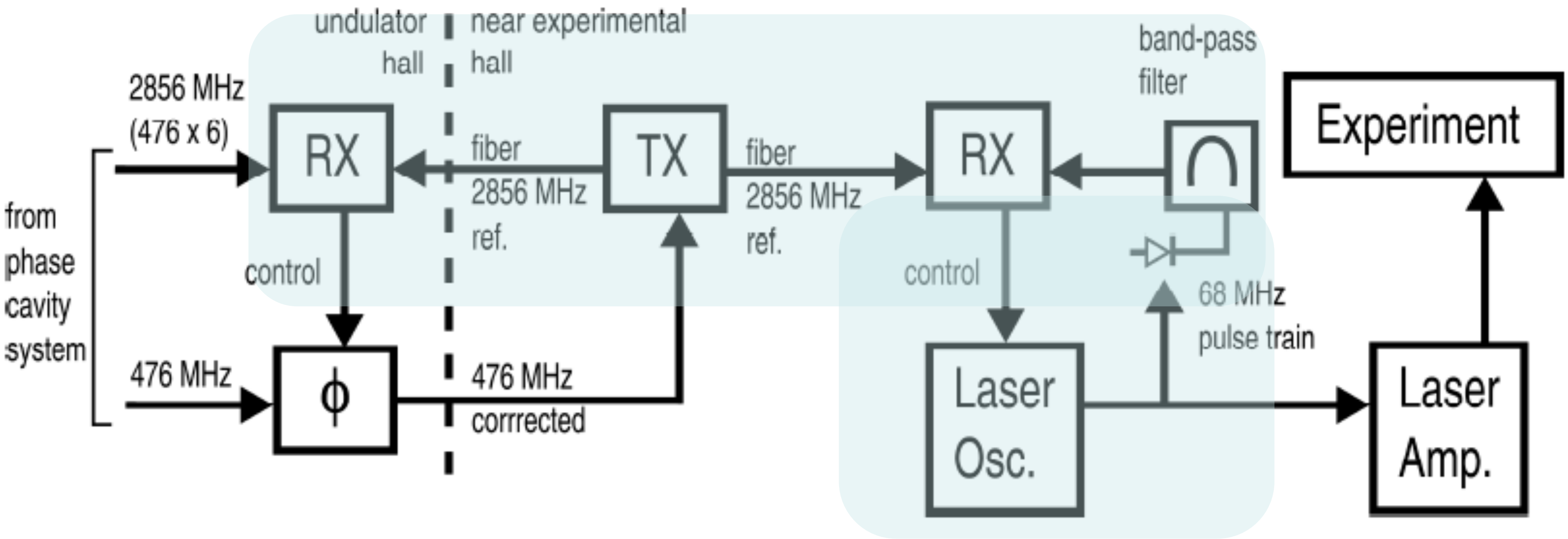


Goal: Synchronize NEH and FEH lasers to a bunch arrival time diagnostic to allow time-stamping of each beam pulse.

Initial configuration synchronizes phase cavity and one NEH laser (Ti:Sapph osc)



Detailed LCLS Configuration



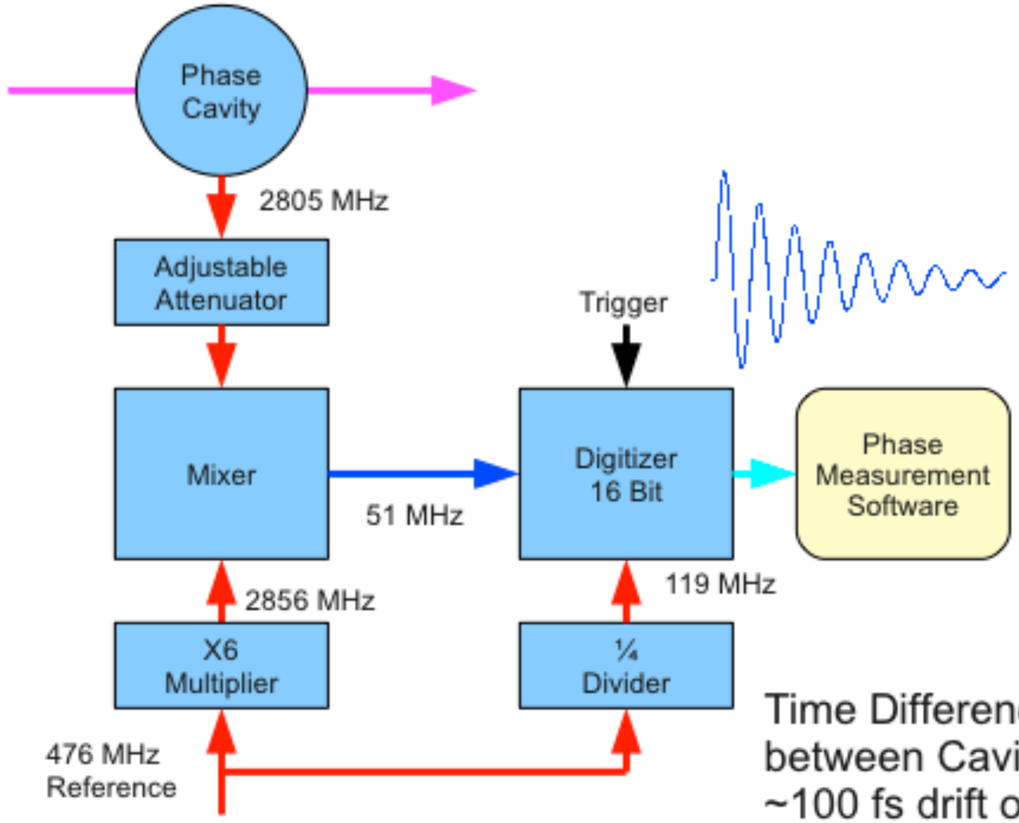
- Controlled transmission from e-beam phase cavity to NEH laser oscillator.

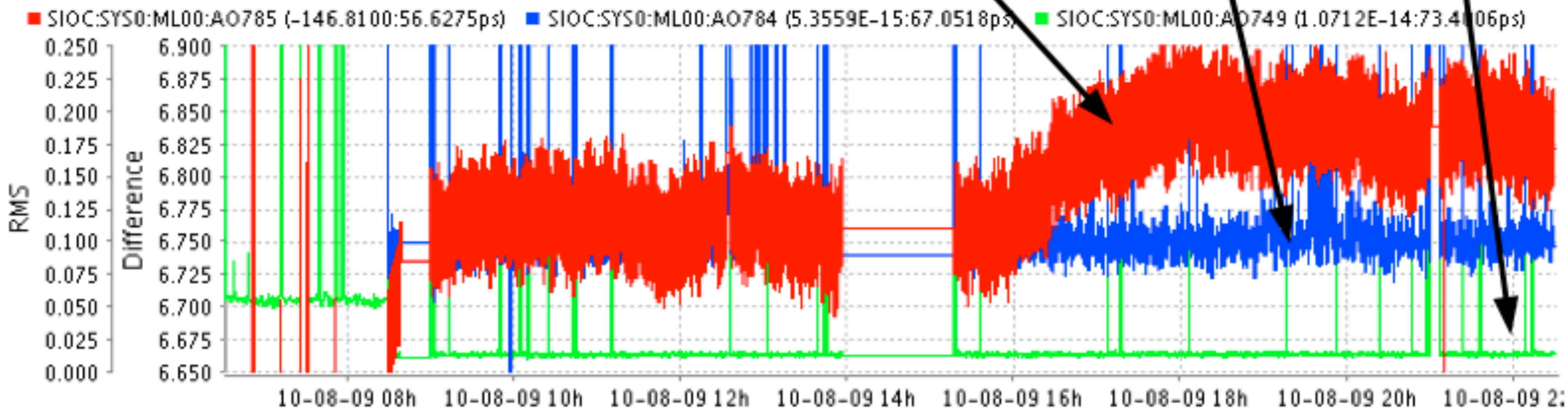
LCLS System

- TX occupies half of standard rack.
- Each RX has a Synch-head and stabilizer chassis. S/H sits as close as possible to client.
- Fiber links are run in SMF28 in 12 fiber cables.

Phase Cavity System

Joe Frisch, SLAC



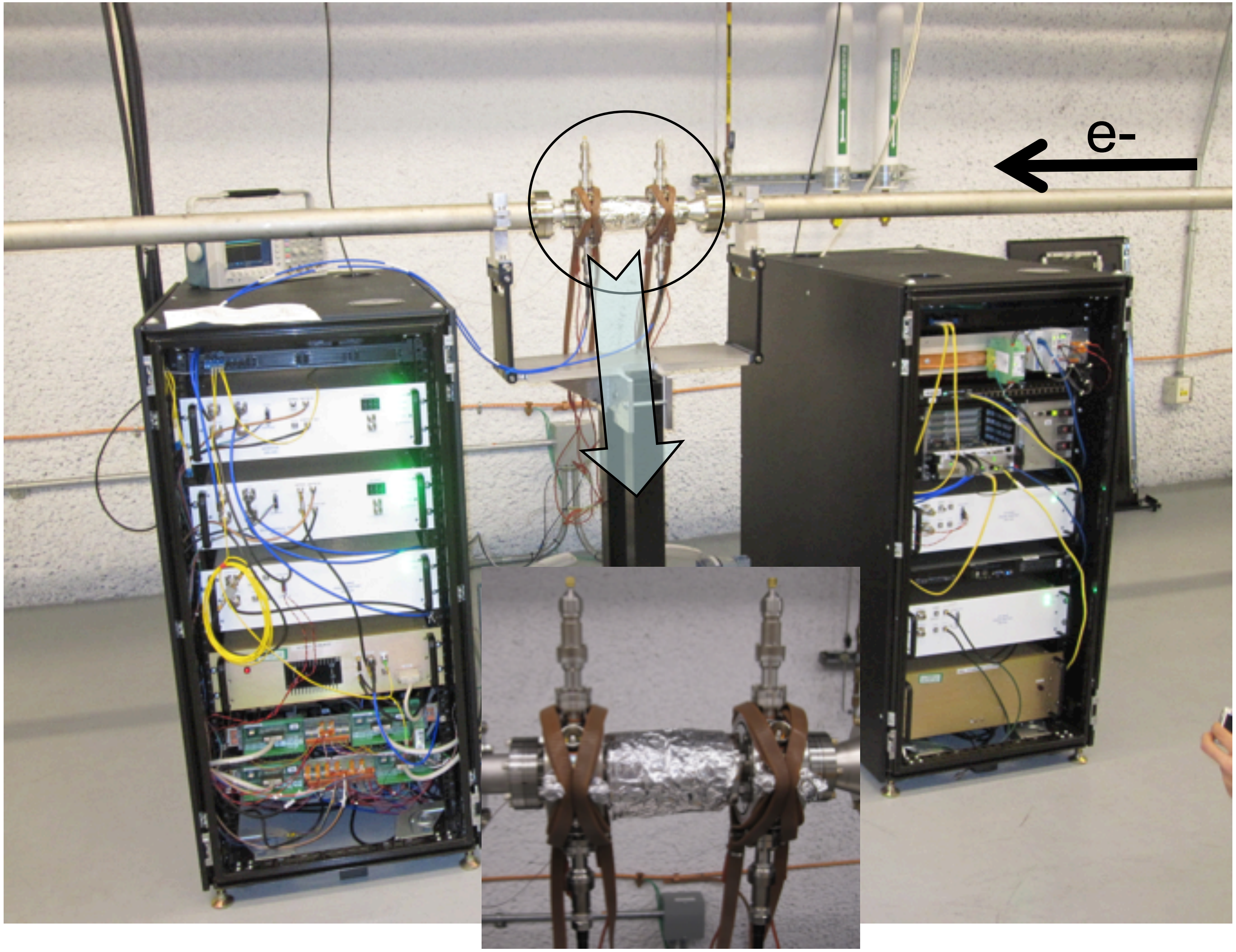


Standard deviation of difference between cavities ~15 fs RMS

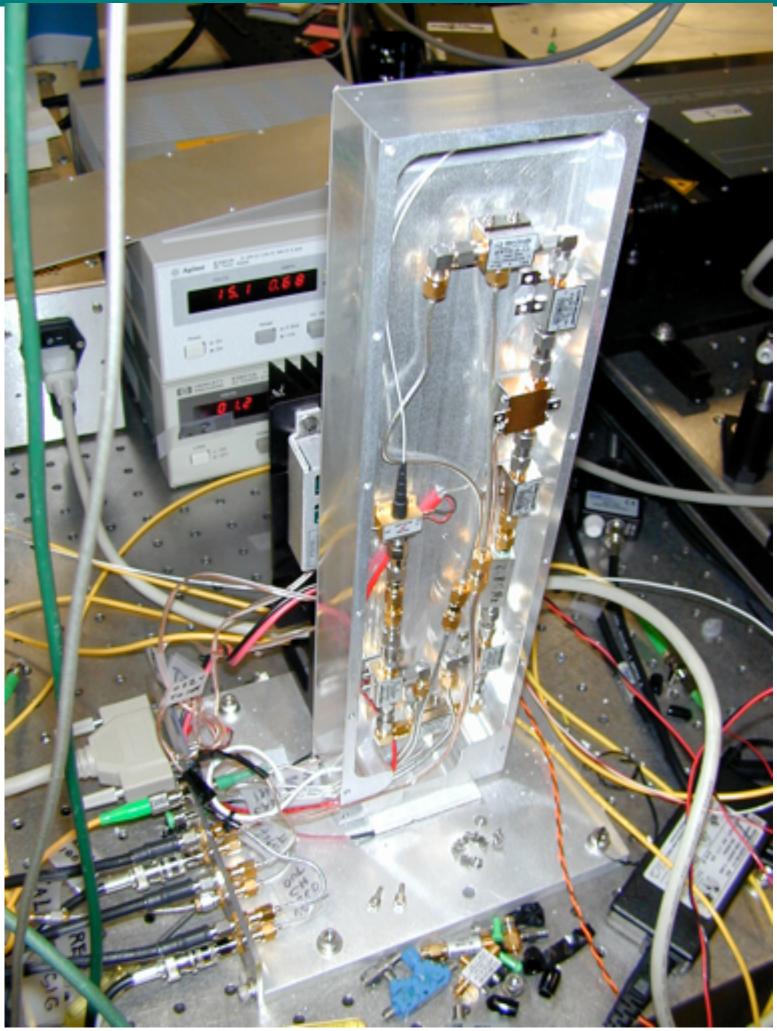
Time Difference between Cavities ~100 fs drift over 1 day

Standard Deviation of single cavity ~100fs RMS

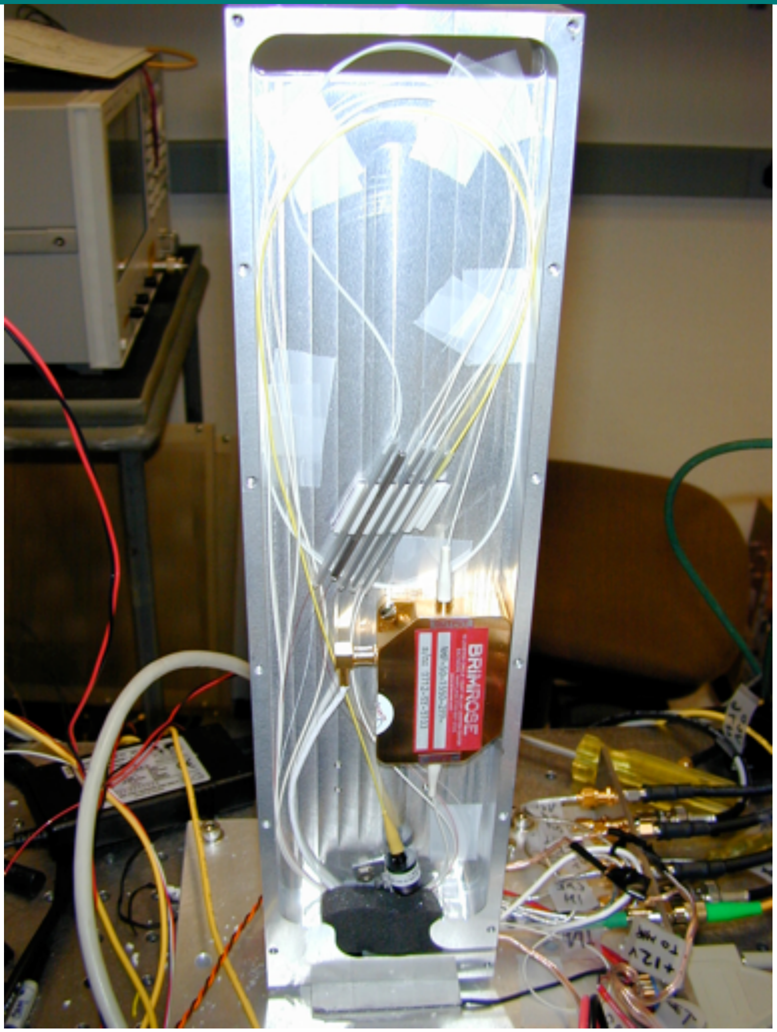
LCLS Phase Cavities



Synch/Head

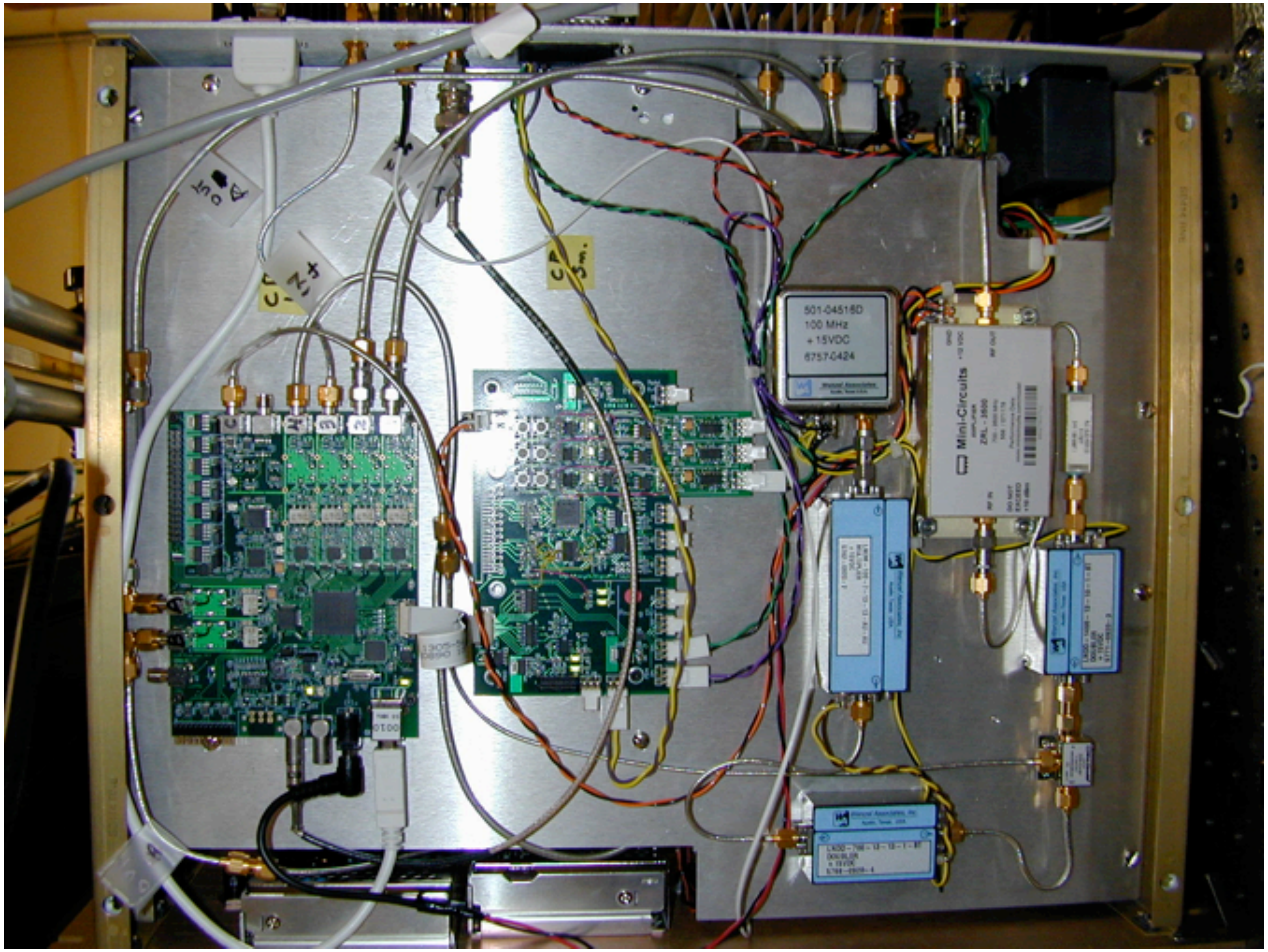


Electronic side



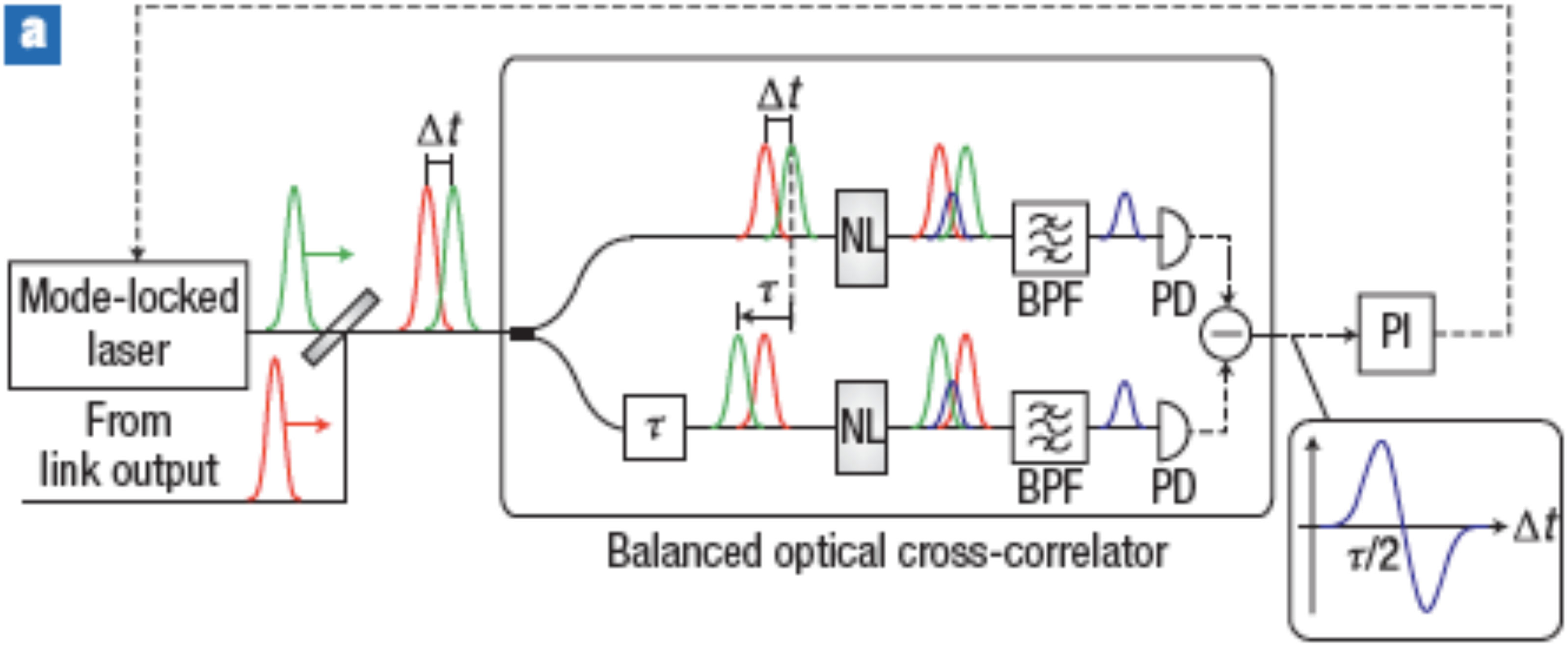
Optical side

Receiver



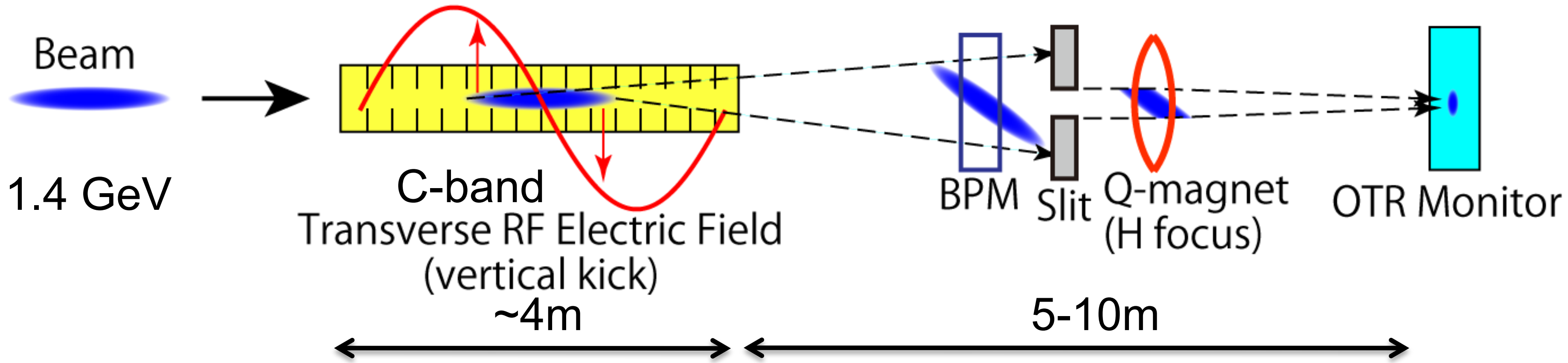
FPGA side (RF receiver on other side)

Optical-optical synchronization using pulsed link



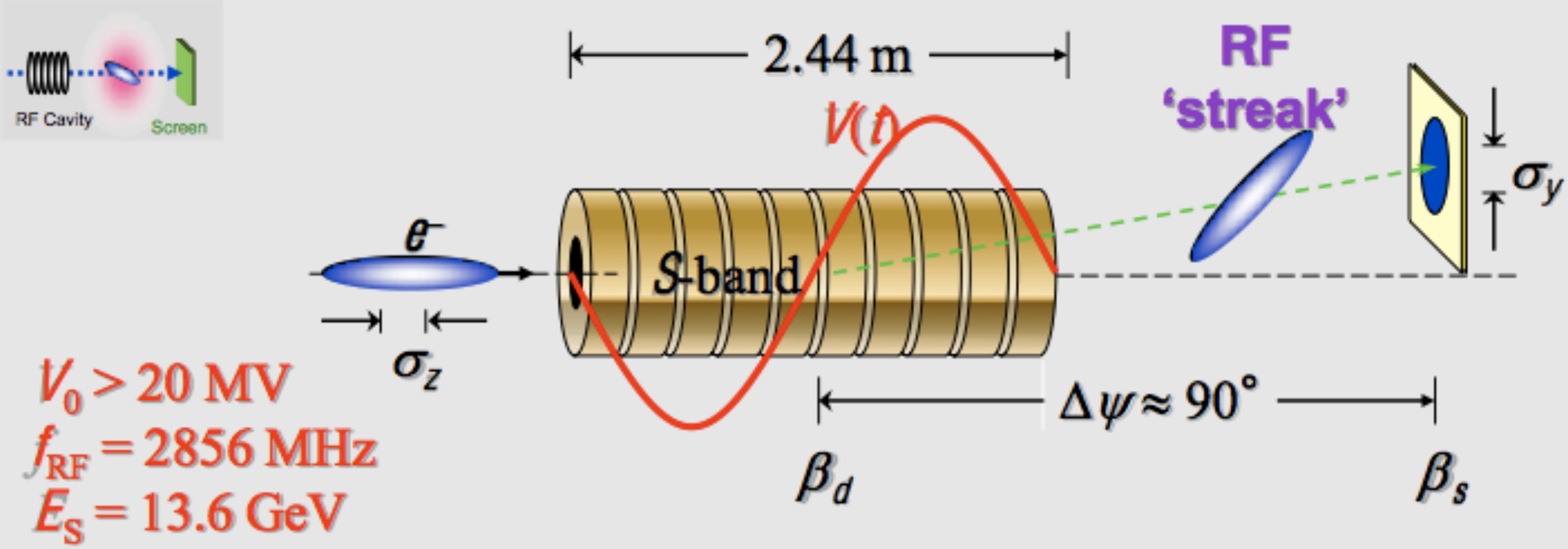
- Schematic of the optical–optical synchronization using a balanced optical cross-correlator (NL, nonlinear crystal; BPF, bandpass optical filter; PD, photodiode; PI, proportional-integral controller; τ, time delay element for shifting the timing offset between the two pulses).

Transverse Deflecting Structure

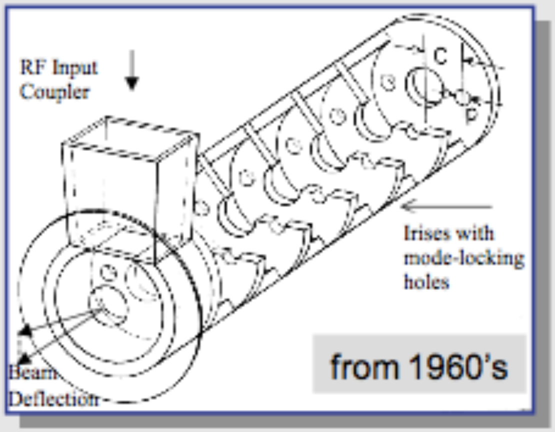


- The electron bunch is vertically pitched by transverse RF voltage and the temporal structure is converted to a spatial distribution.
- Beam image is taken by an OTR monitor.

Deflecting cavities



$V_0 > 20$ MV
$f_{RF} = 2856$ MHz
$E_S = 13.6$ GeV



from 1960's

$$\sigma_y^2 = \sigma_{y0}^2 + \beta_d\beta_s\sigma_z^2\left(\frac{k_{RF}eV_0}{E_s}\sin\Delta\psi\cos\phi\right)^2$$

- Map time axis onto transverse coordinate
- Simple calibration by scan of cavity phase
- Typical calibration factor ~10 from z → y

Resolution and bunch parameters

Longitudinal Resolution σ_ζ

- $\boxed{\sigma_\zeta = \frac{\sigma_{y_\beta}(s)}{S(s)}} = \sqrt{\epsilon_y} \cdot pc \cdot \frac{1}{\sqrt{\beta(s_0)} \cdot \sin(\Delta\Phi_y)} \cdot \frac{1}{eV_0 k} \quad \Leftarrow$ important for lattice design
- Example: $\sigma_{y_\beta} = 100\,\mu\text{m}$ and $S = 10$: $\Rightarrow \sigma_\zeta = 10\,\mu\text{m}\ (30\,\text{fs})$.

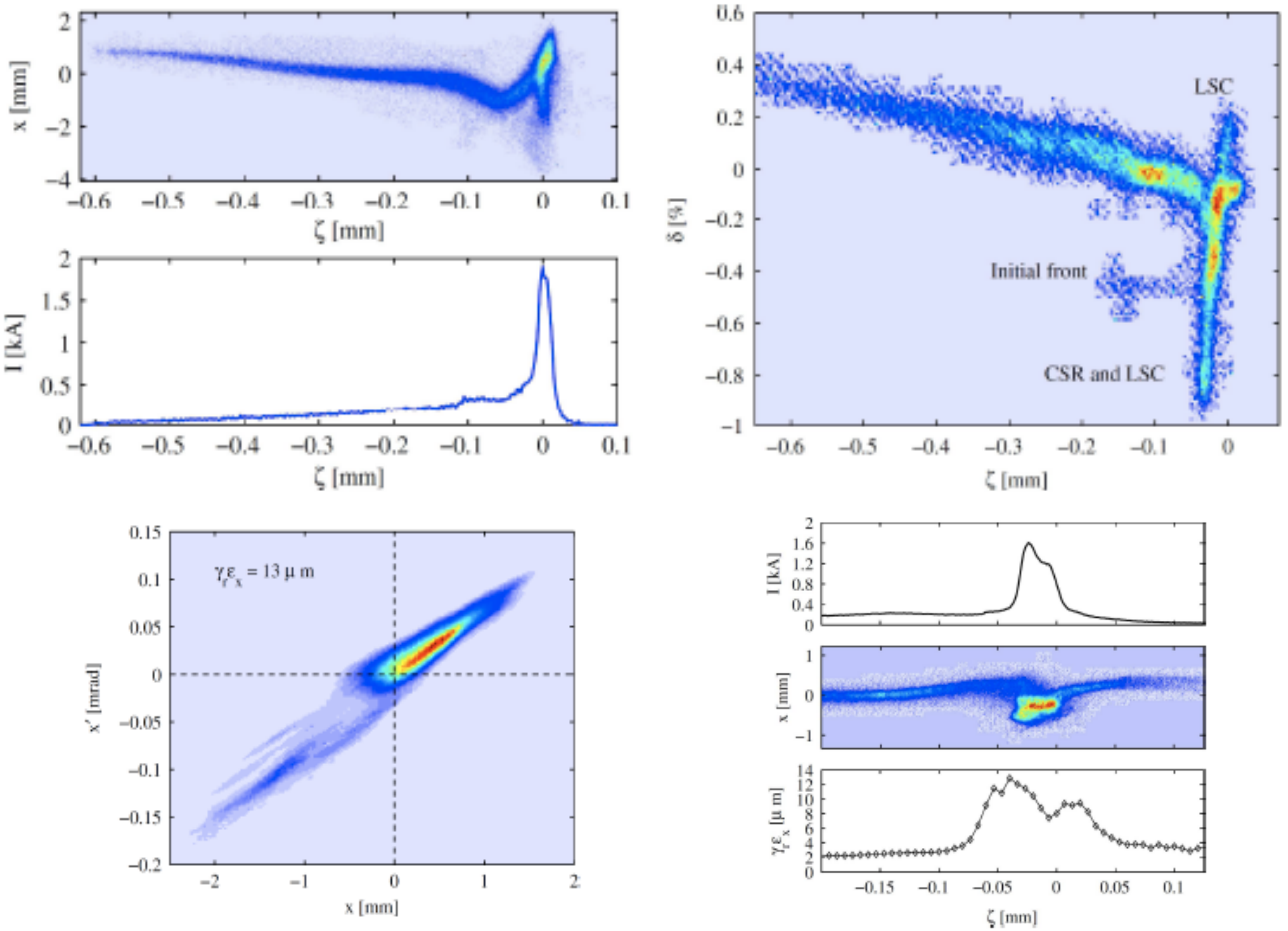
Relative Energy Resolution σ_δ

- $\boxed{\sigma_\delta = \frac{\sigma_{x_\beta}(s)}{D_x(s)}} = \sqrt{\epsilon_x} \cdot \frac{\sqrt{\beta_x(s)}}{D_x(s)} \quad \Leftarrow$ important for lattice design
- Example: $\sigma_{x_\beta} = 100\,\mu\text{m}$ and $D_x = 1000\,\text{mm}$: $\Rightarrow \sigma_\delta = 1 \cdot 10^{-4}$.

Obtainable Bunch Parameters

- Bunch current and length.
- Energy spread (slice and projected).
- Transverse emittance (slice and projected).
- Transverse phase space by tomographic methods.

Example FLASH Results



Rohrs, et al., PRST-AB 12, 050704 (2009)

Resolution limits

Longitudinal Resolution

- Beam optics and RF power.

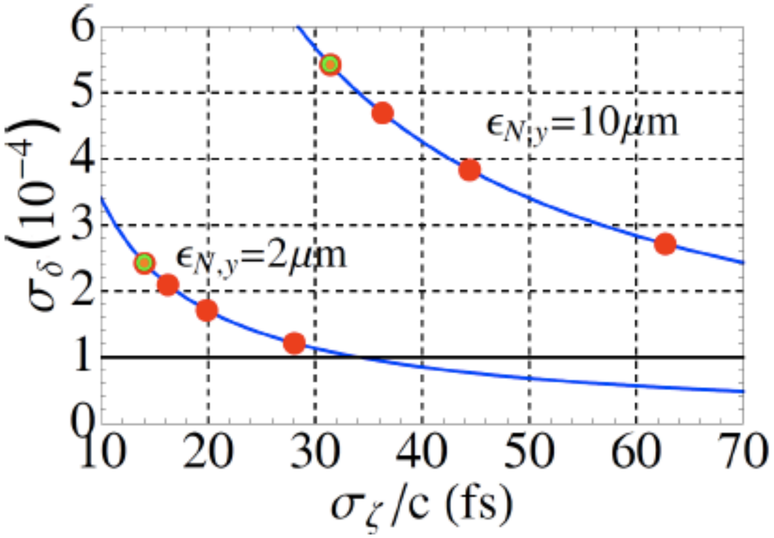
Energy Resolution

- CSR effects in the spectrometer ⇒ minor impact.
- The TDS itself ⇒ can be a large effect.

The TDS induces energy spread due to longitudinal electric fields. (Panofsky-Wenzel Theorem)

Relations

- Induced energy spread: $\sigma_\delta = \frac{eV_0 k}{pc} \cdot \sigma_y$
- Induced energy spread is inversely proportional to the longitudinal resolution.
- Analytical results: checked by simulations using `elegant`.



Coming up next….

- Lecture 1
  - Introduction
  - Coherent THz Radiation
    - Detectors
    - Interferometers/Spectrometers
  - Femtosecond timing and synchronization
  - Transverse Deflecting Structures
- **Lecture 2**
  - **Basics of nonlinear optics**
  - **Basics of mode-locked lasers**
  - **Nonlinear optic techniques for short pulses**
    - **Electro-optic sampling**
    - **Auto and cross correlation**
  - **X-ray Streak cameras**
  - **New directions…**