# Introduction: Measurement and diagnostics of short bunches in accelerators

John Byrd

# Course Overview

- Provide an overview of issues for short bunches (10 psec-1 fsec) in accelerators
  - Making short bunches: How? Why? Limits?
    - Linac bunch compressors
    - Storage rings
    - Laser/plasma accelerators
    - Photocathode guns
  - Measurement techniques
    - Beam signals: RF to x-rays
    - Beam manipulations

# Syllabus-Measurement techniques

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

# Syllabus-Measurement techniques

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

# Syllabus- Applications

- Free electron lasers (FELs)
  - high peak currents required to achieve gain
- Ultrafast electron diffraction
- High field magnetic switching
- Drivers for LWFA
- Linear colliders
- Time resolved experiments at storage ring light sources

# Syllabus-Beam dynamics

- Beam-radiation interaction
  - – Single pass microbunching instability
    - CSR
    - Longitudinal Space Charge
  - – Storage ring effects
    - Potential well distortion
    - Microbunching instability

# Lectures

- Course Introduction
- Short bunches in storage rings
- Short bunch instabilities
- Bunch compressors
- Radiation mechanisms
- Nonlinear optic techniques for short pulses
  - Electro-optic sampling
  - Auto and cross correlation
- RF and Microwave signal techniques
- Streak cameras
- Femtosecond timing and synchronization
- THz Techniques
  - Detectors
  - Spectrometers

# Course grade

- Course grade will be based on
  - 80% Class project
    - Collaboration encouraged but all students should submit their own work
  - 20% class participation
- We encourage all students to take the class for credit.

# Schedule

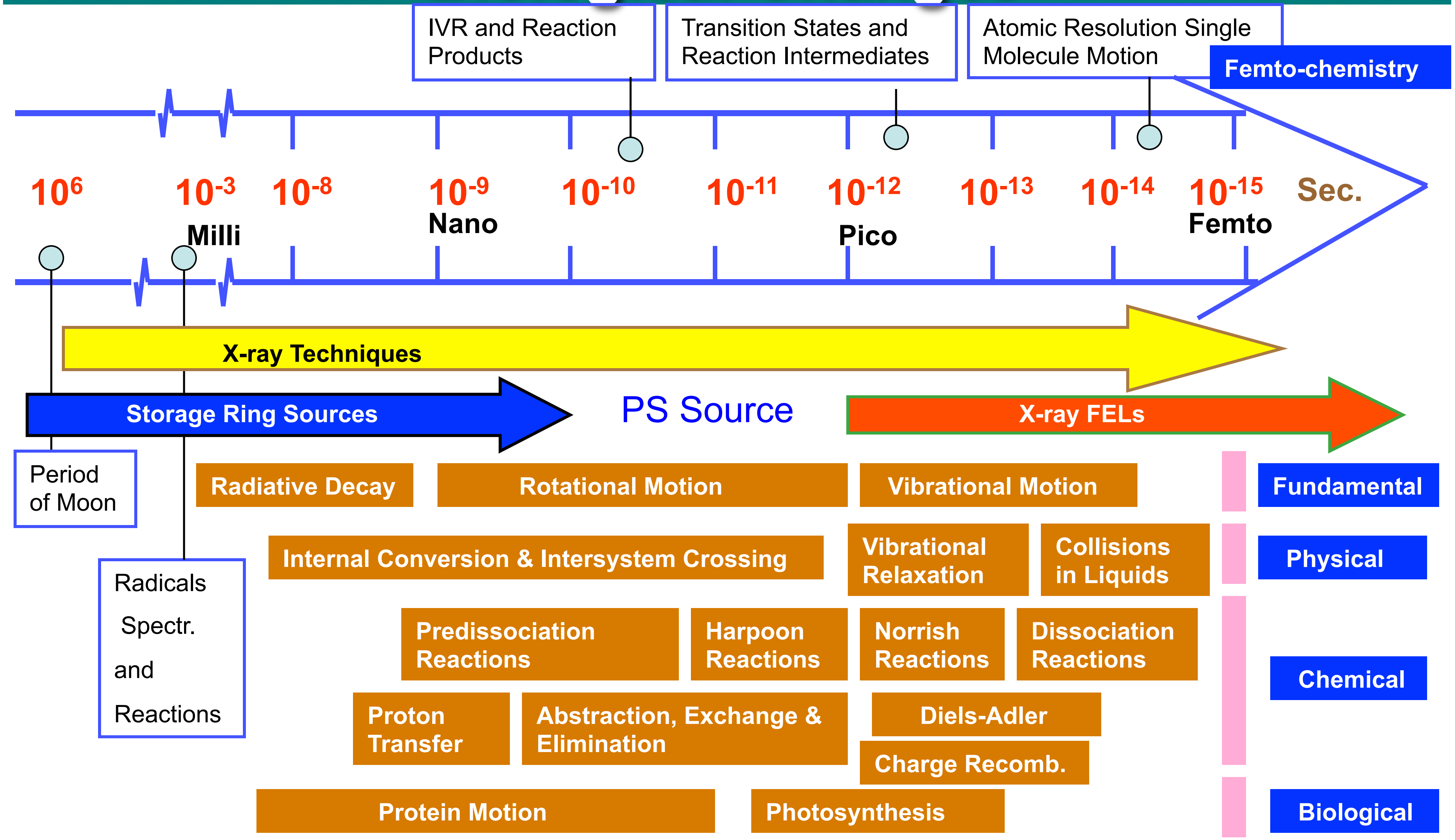
| | Monday | Tuesday | Wednesday | Thursday | Friday |
|---|---|---|---|---|---|
| 9:00-10:30 | Lecture: Introduction | Lecture:<br>THz Detectors<br>Lecture: THz Spectrometers | Lecture:<br>Bunch compressors<br>Lecture: Short Bunch Instabilities | Lecture: Streak Cameras<br>Lecture: New techniques | Class project#1<br>Class project#2 |
| 10:45 - 12:15 | Lecture:<br>Review of Radiation mechanisms | Lecture: Nonlinear Optics<br>Lecture: Electro-optic Sampling | Lecture: Short bunches in Storage Rings | Lecture: Femtosecond timing | Class project#3<br>Class project#4 |
| 2:30-4:30 | Lecture: RF and Microwave<br>Discussion | Discussion | Discussion | Presentation Dry Runs | |

- Schedule will be flexible.
- Afternoon sessions can be used for discussion, homework solutions, Lecture overruns, and background lectures if needed.

# 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

# Time Scales: Physical, Chemical, and Biological Changes



IVR and Reaction Products

Transition States and Reaction Intermediates

Atomic Resolution Single Molecule Motion

**Femto-chemistry**

$10^{6}$ $10^{-3}$ $10^{-8}$ $10^{-9}$ $10^{-10}$ $10^{-11}$ $10^{-12}$ $10^{-13}$ $10^{-14}$ $10^{-15}$ Sec.

**Milli** **Nano** **Pico** **Femto**

**X-ray Techniques**

**Storage Ring Sources**

PS Source

**X-ray FELs**

Period of Moon

Radicals Spectr. and Reactions

**Radiative Decay**

**Rotational Motion**

**Vibrational Motion**

**Fundamental**

**Internal Conversion & Intersystem Crossing**

**Vibrational Relaxation**

**Collisions in Liquids**

**Physical**

**Predissociation Reactions**

**Harpoon Reactions**

**Norrish Reactions**

**Dissociation Reactions**

**Chemical**

**Proton Transfer**

**Abstraction, Exchange & Elimination**

**Diels-Adler**

**Charge Recomb.**

**Protein Motion**

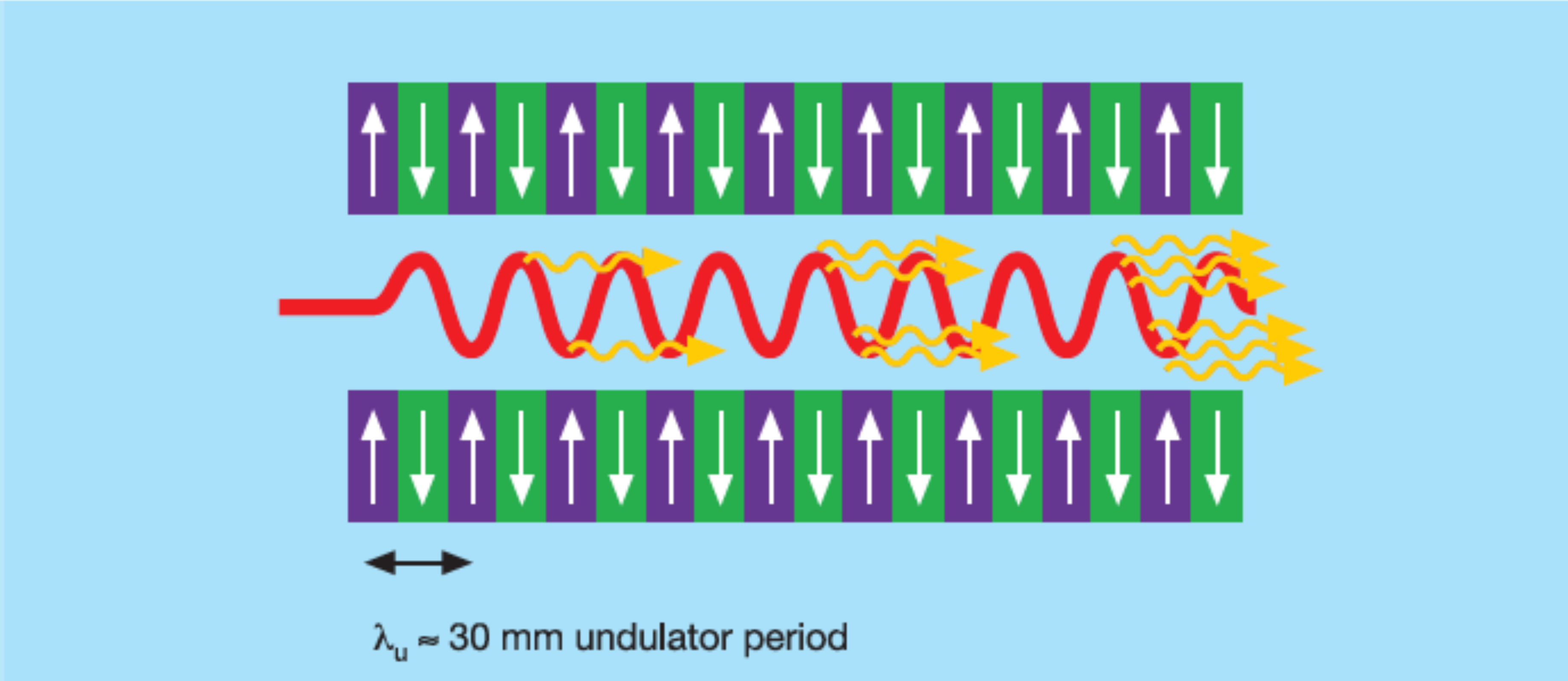
**Photosynthesis**

**Biological**

# Existing and Future Sources

- Table-top Plasma Sources
  - Short pulse 300 fs - 10 ps
  - Divergent radiation - low flux
  - Low rep-rate (10 Hz -1kHz)
  - Not tunable (target dependent)
- Storage Rings
  - ~100-ps duration pulse
  - Spontaneous x-ray radiation
  - High average brightness at high repetition rate
- Laser Slicing (ALS, SLS, BESSY)
  - Short pulse 100-300 fs
  - Rep-rate kHz
  - Low flux 105 ph/s @ 0.1% BW
  - Not effective at high-energy sources
- Linacs (LCLS/XFEL)
  - Short pulse 100 fs
  - Fully coherent
  - Extremely high brilliance
  - Low rep-rate (100 Hz)
  - Limited tunability

# Ultrafast x-rays via FELs



$$\lambda_\ell = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad K = \frac{eB_0\lambda_u}{2\pi\, m_0 c} \approx 1$$

# FEL Gain depends on peak current

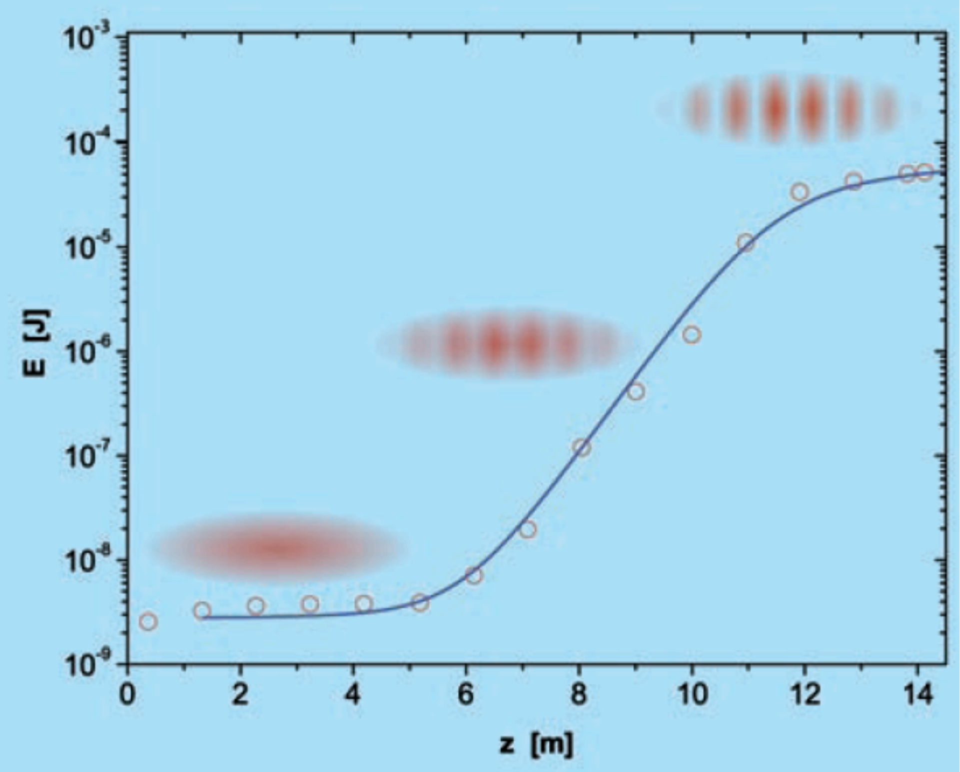
- The FEL gain length is inversely proportional to the peak current.

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

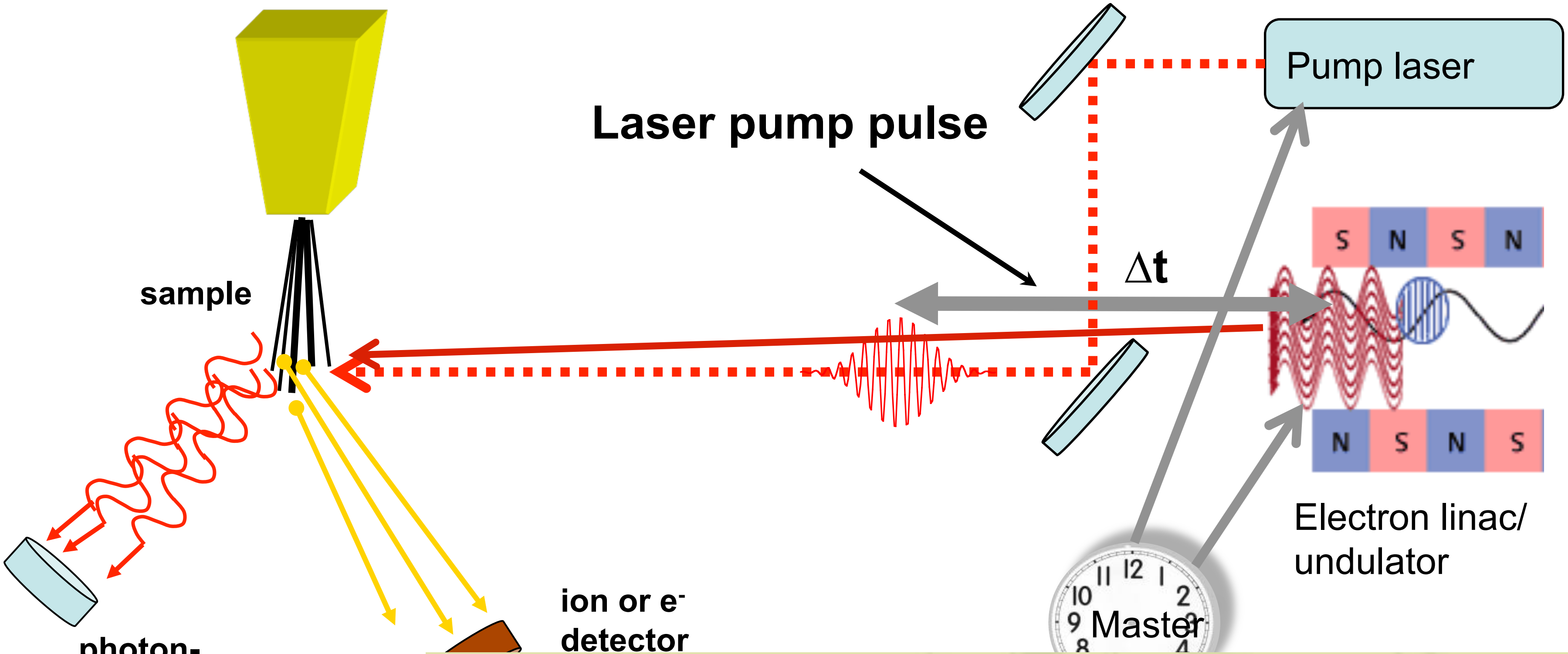
- The total FEL power grows exponentially up to saturation

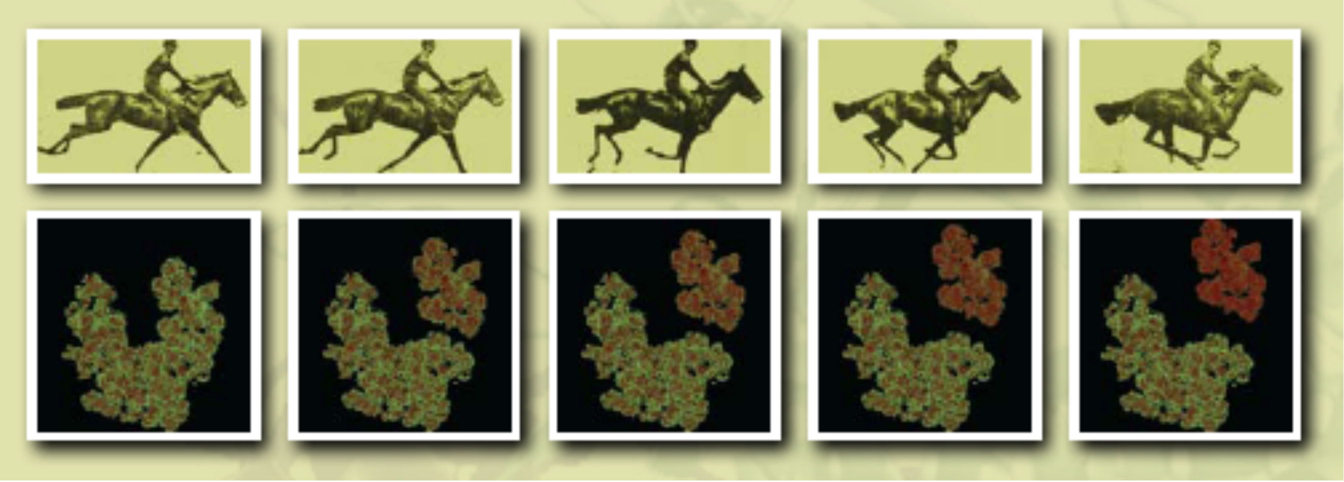
$$P(z) = \frac{P_0}{9}\exp(z/L_g) \;\; for \;\; z \geq 2L_g$$

- Shorter bunches/higher peak currents helps make shorter FELs



# X-ray/optical Pump-probe

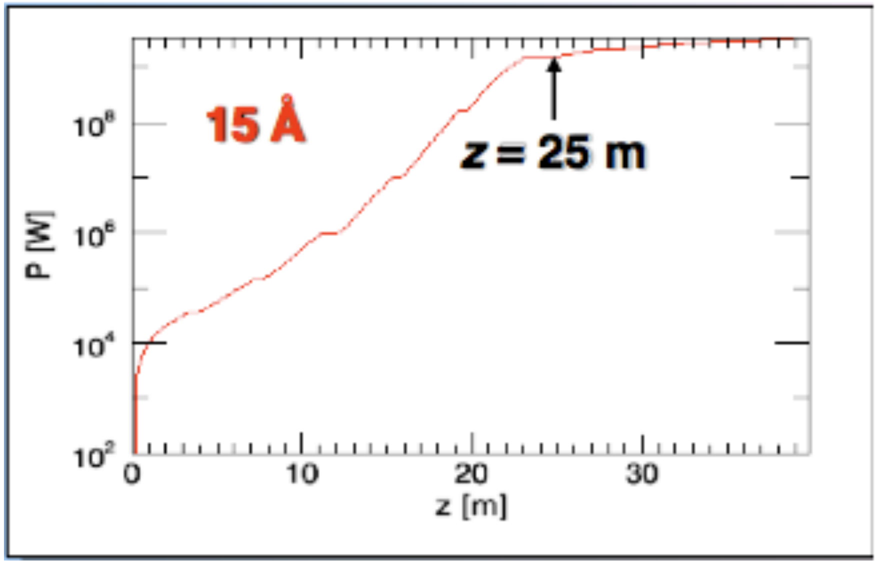




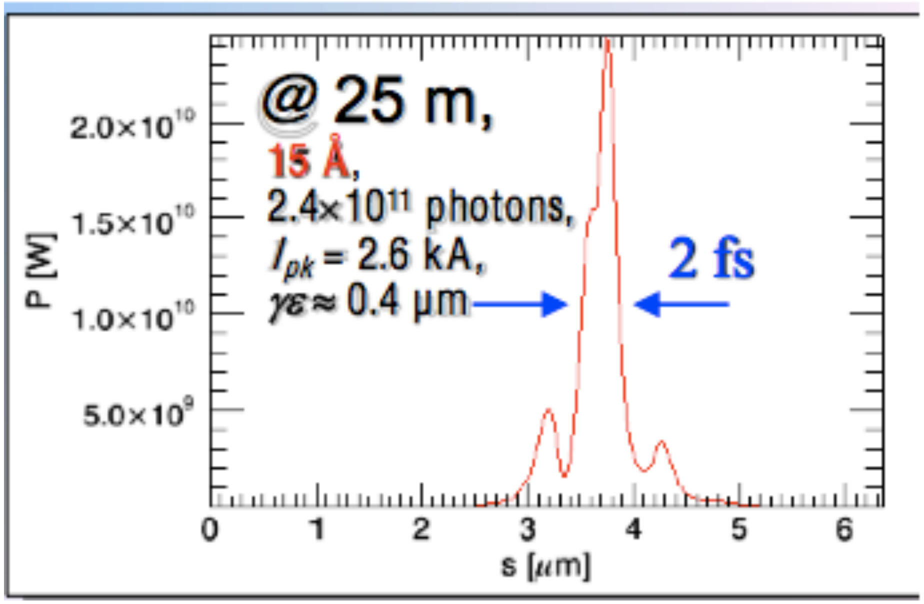
- Ultrafast laser pulse
- Ultrafast x-ray pulse
- By varying the time
  sample.
- Synchronism is achi
  clock.

# Single spike SASE FEL

- SASE (Self Amplified Spontaneous Emission) FELs amplify fluctuations in the bunch radiation emission.
- X-ray SASE has many random spikes, each spike ~1 fs.
- Less charge, shorter bunch, same peak current gives shorter x-ray pulses.

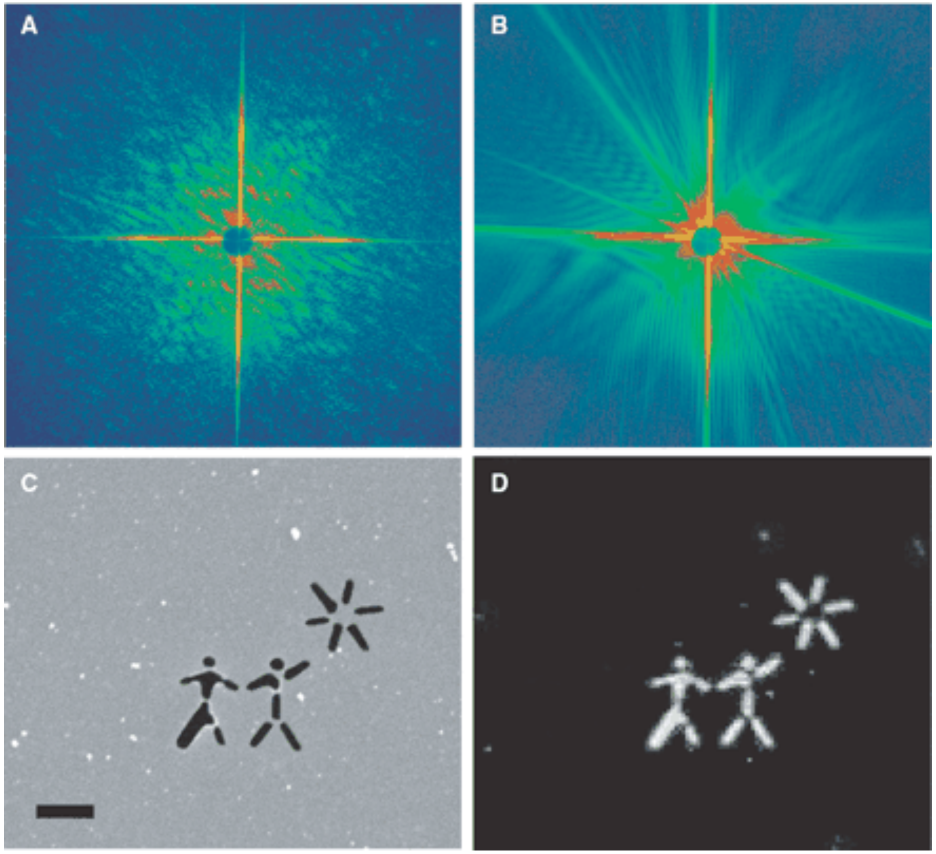


LCLS FEL **simulation** at based on measured injector beam and *Elegant* tracking, with CSR and LSC, at 20 pC.



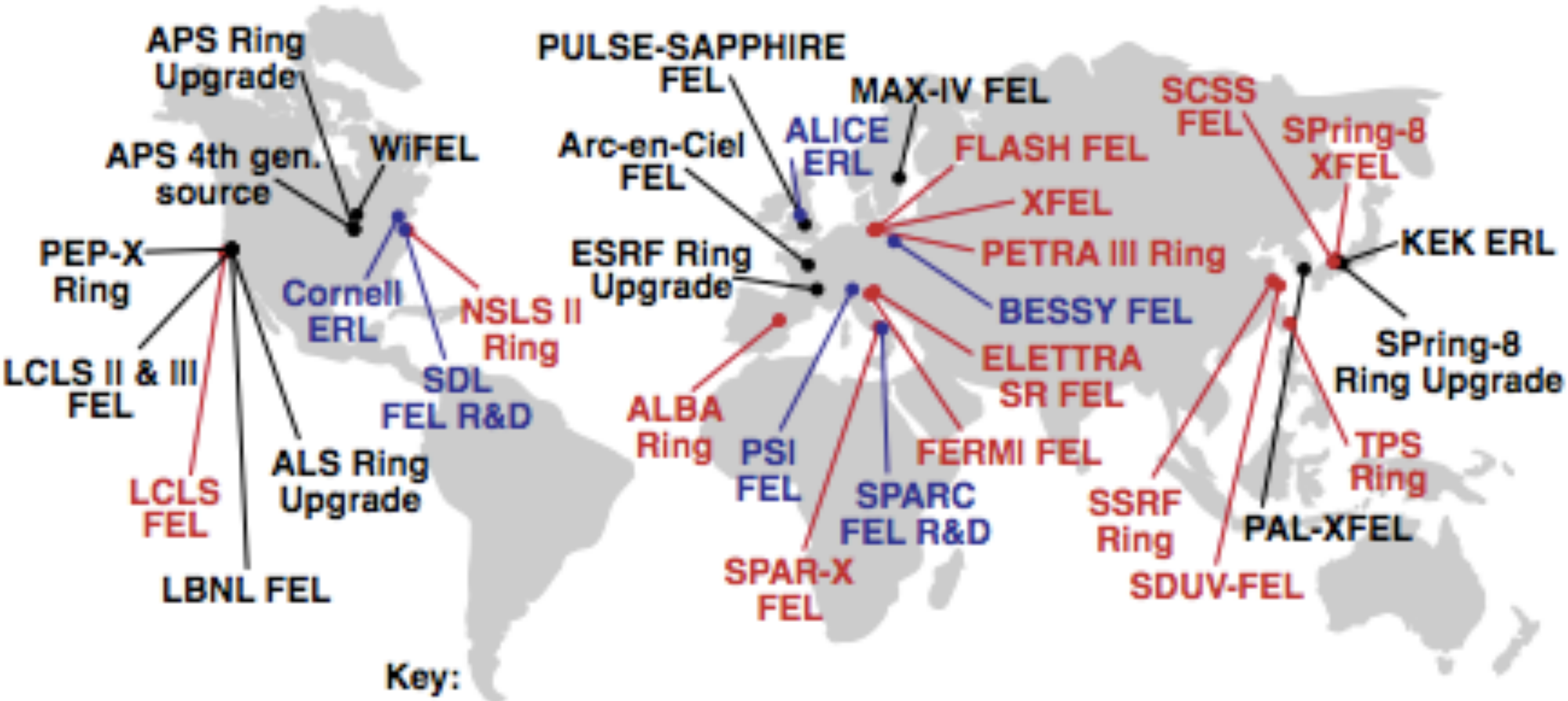
# Single shot x-ray diffraction

- (**A**) Diffraction pattern recorded with a single FEL pulse from a test object placed in the 20-μm focus of the beam (*8*). (**B**) The diffraction pattern recorded with a second FEL pulse selected with a fast shutter, showing diffraction from the hole in the sample created by the first pulse. (**C**) Scanning electron microscope image of the test object, which was fabricated by ion-beam milling a 20-nm-thick silicon nitride membrane. The scale bar denotes 1 μm. (**D**) The image reconstructed from the single-shot diffraction pattern shown in (A).



H. N. Chapman et al., Nat. Phys. 2, 839 (2006).

# Worldwide Future Light Sources



Key:

Red - funded (operational or under construction)

Blue - funded R&D program

Black - concepts and proposals

10-2008
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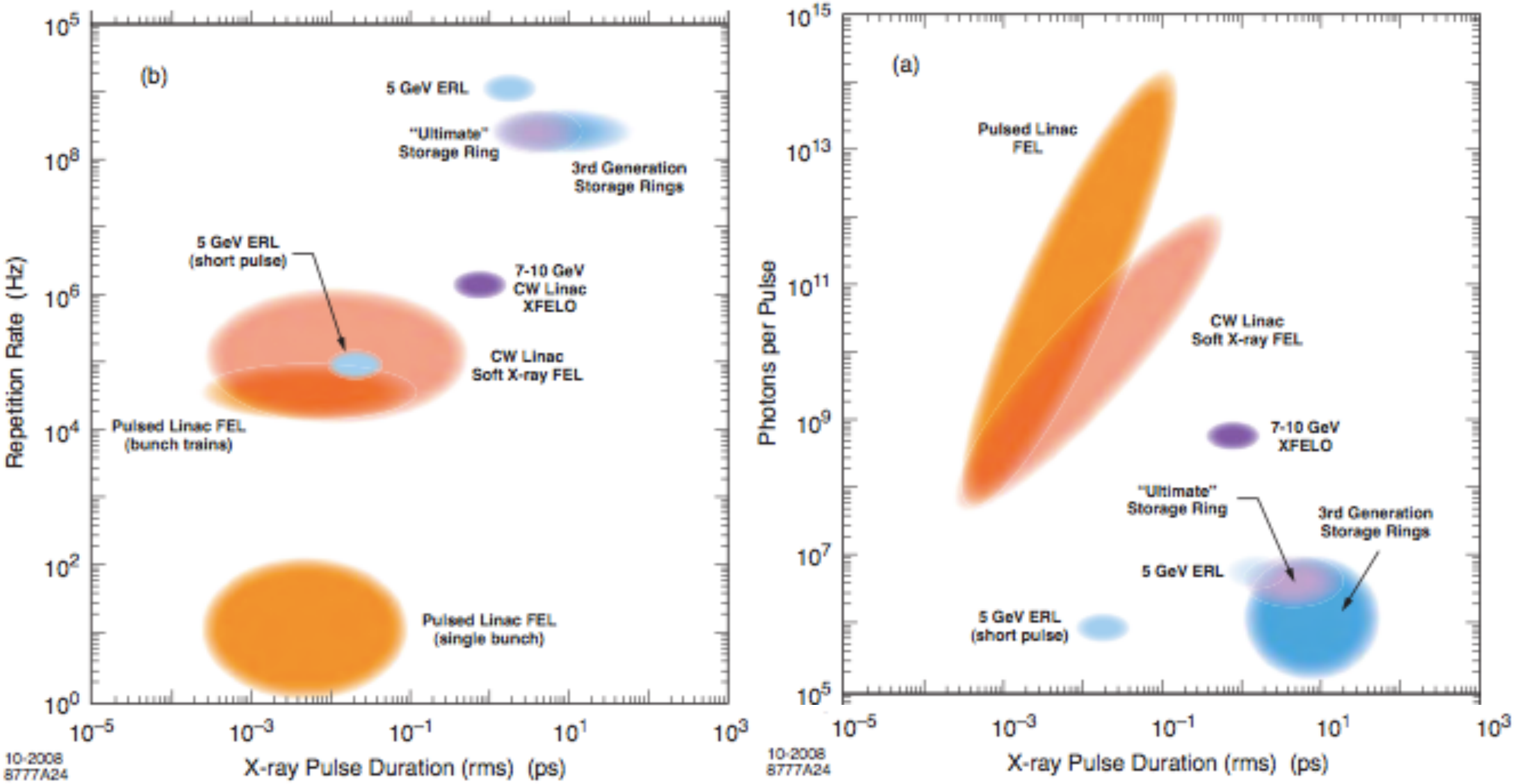
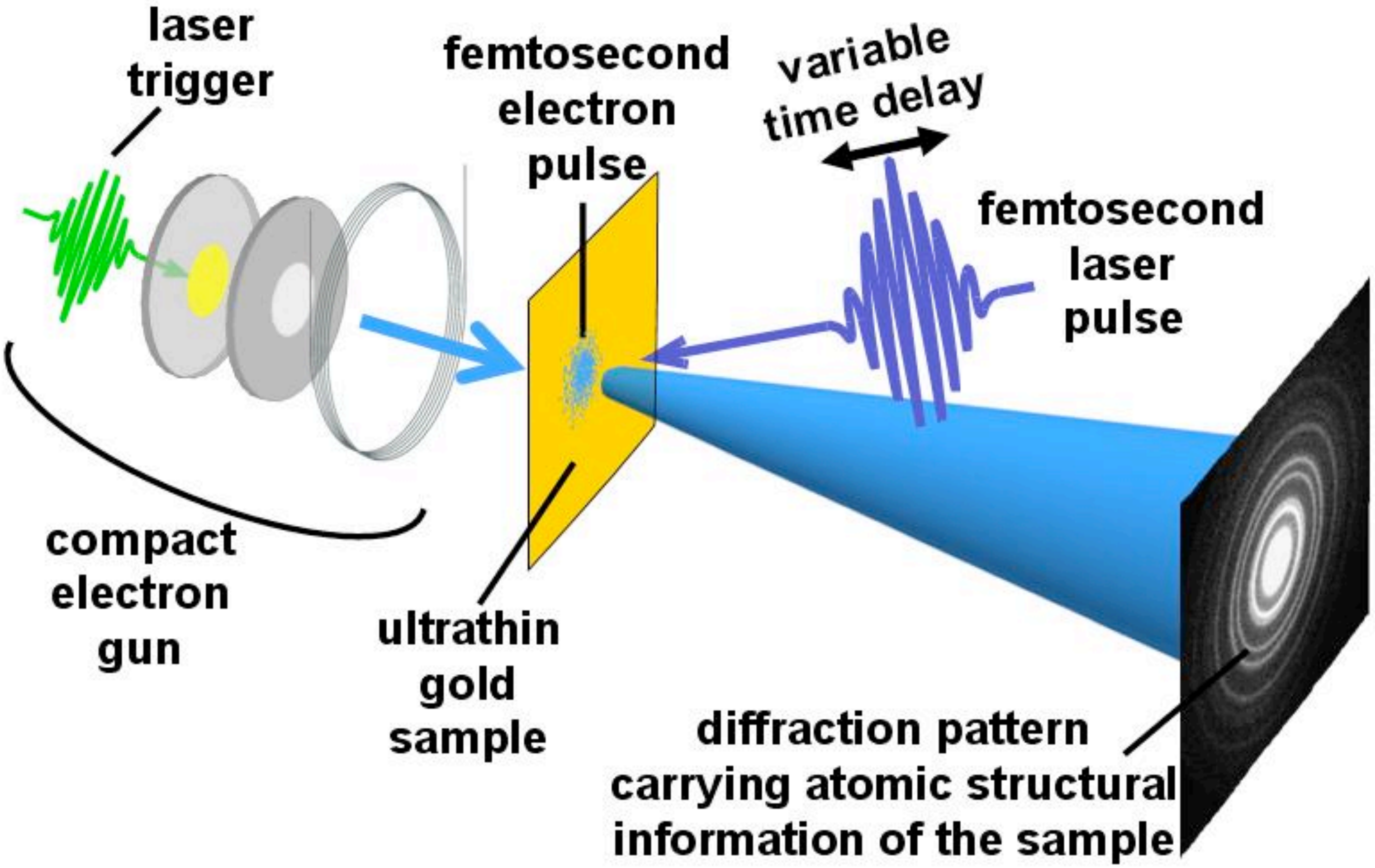
# Pulse widths and rates

- 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.



# Luminosity of a high energy collider

Collider luminosity ($cm^{-2}\,s^{-1}$) is approximately given by

$$L = \frac{n_b N^2 f_{rep}}{A} H_D$$

where:

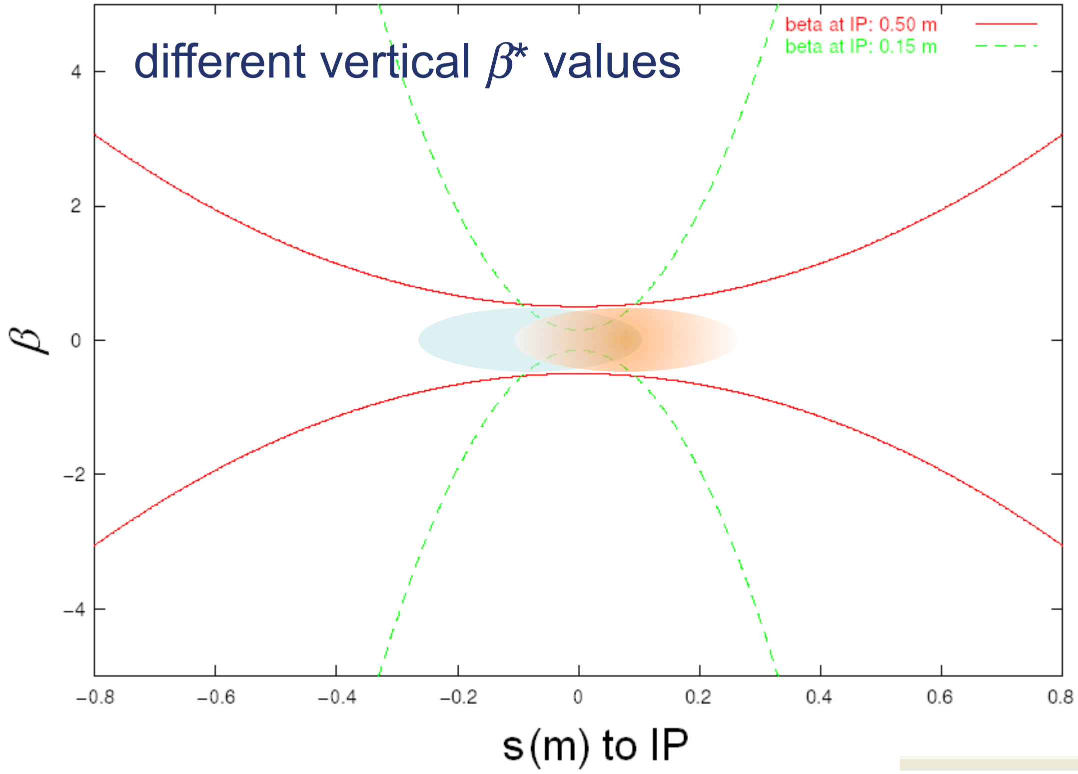
$N_b$ = bunches / train
$N$ = particles per bunch
$f_{rep}$ = repetition frequency
$A$ = beam cross-section at IP
$H_D$ = beam-beam enhancement factor

For *Gaussian* beam distribution:

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

***No need for short bunches?***

# Colliding beams: the Hourglass effect


different vertical $\beta^*$ values

Transverse beam sizes cannot be considered constant but vary with *b* near IP. Beta has quadratic dependence with distance s

$$\beta(s) = \beta^*\left(1 + \left(\frac{s}{\beta^*}\right)^2\right)$$

Beam sizes $\sigma_y(s) = \sqrt{\beta_y(s) \cdot \varepsilon_y}$ vary linearly with s at IP

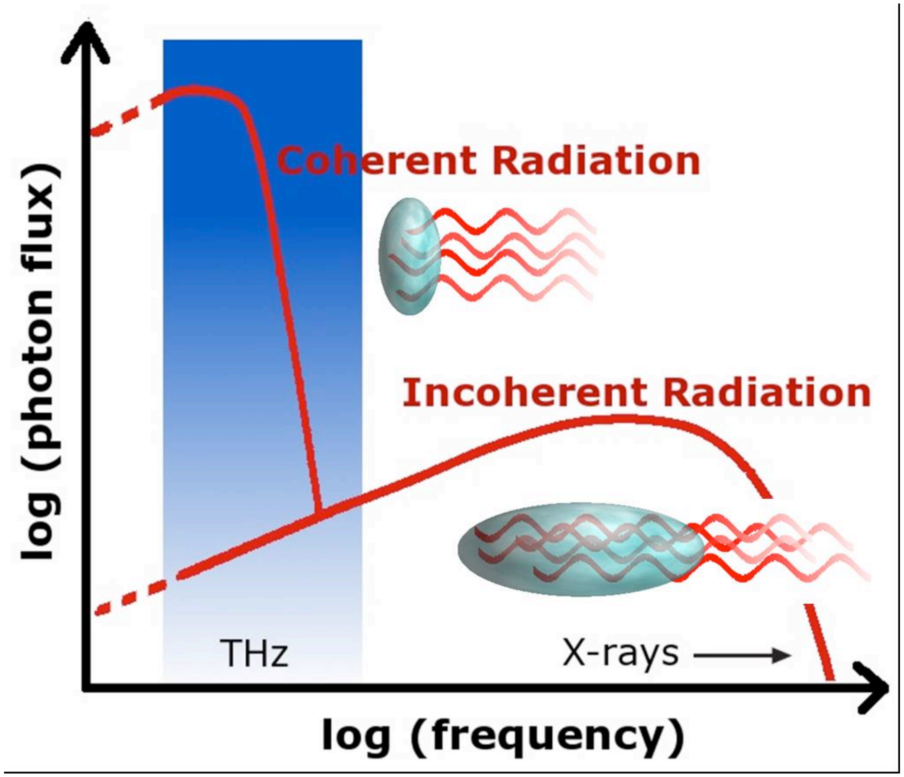
- important when $\beta_y < \sigma_z$ since not all particles collide at minimum of transverse beam size → reducing luminosity.

Rule: $\sigma_z \leq \beta_y$

- “hour-glass” effect from shape of $\beta$

# High power T-ray Sources

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



# MLS at Bessy

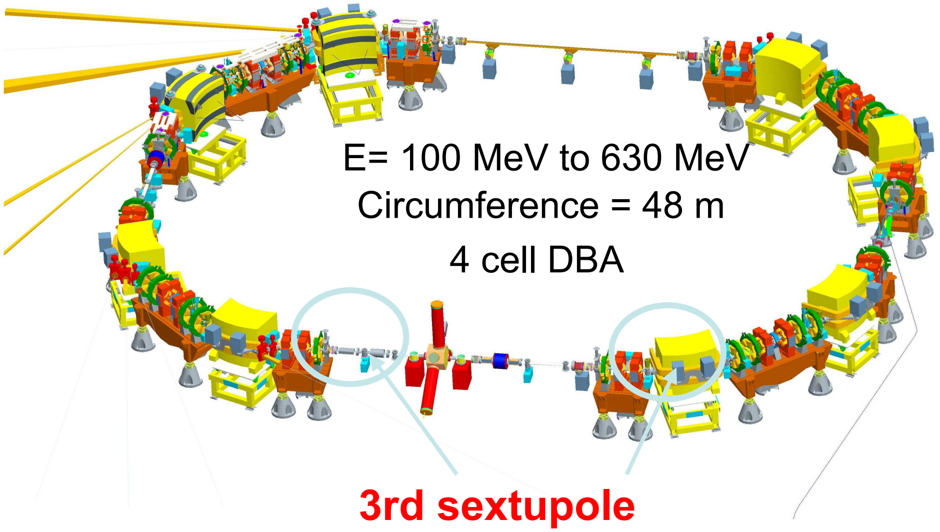
- The Metrology Light Source at Bessy is a small ring with flexible optics to reach psec bunches

tuning range of low alpha optics

$4.4 < f_s < 145$ kHz

$0.0001 < \alpha < 0.12$

low alpha tuning → 3rd sextupole & 1 octupole families

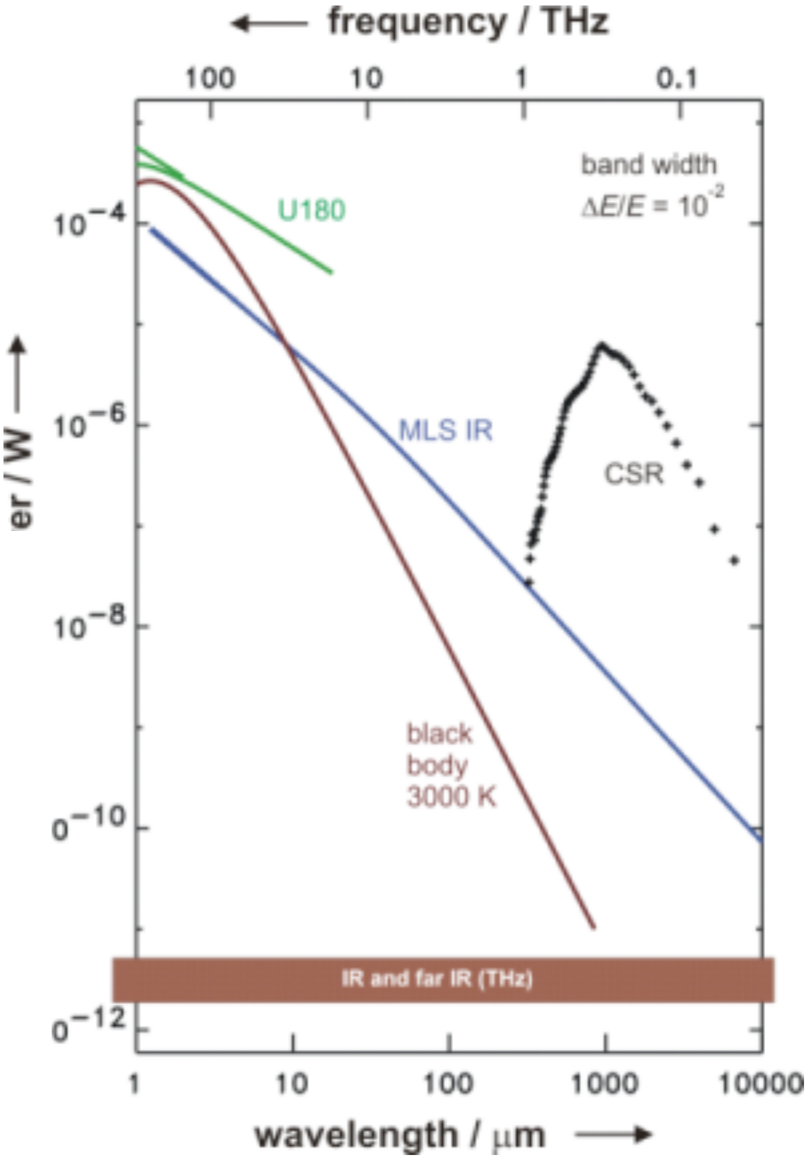


E= 100 MeV to 630 MeV

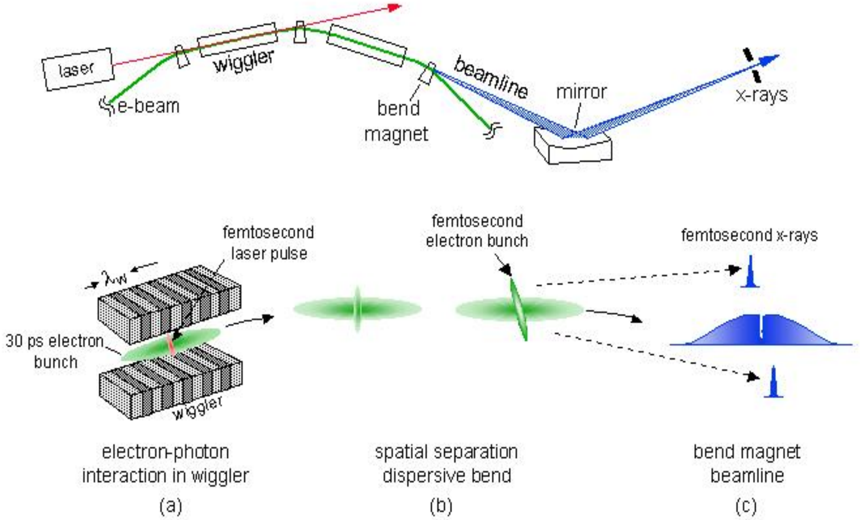
Circumference = 48 m

4 cell DBA

**3rd sextupole family**



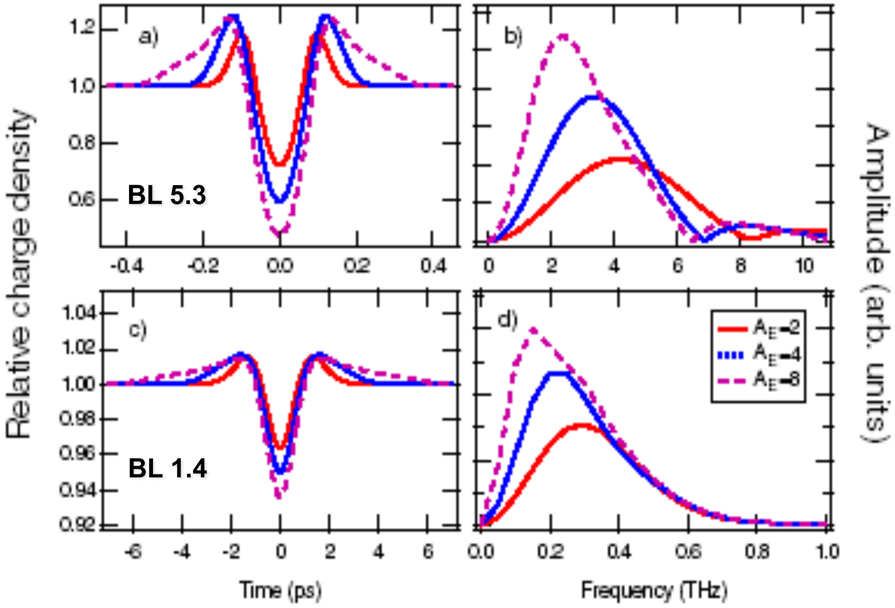
# Laser Tailoring of Beams



Laser slicing is a technique for generating ~100-200 fsec xray pulses in a storage ring. In operation at ALS since 1999, Bessy-II since 2004 and recently commissioned on SLS.

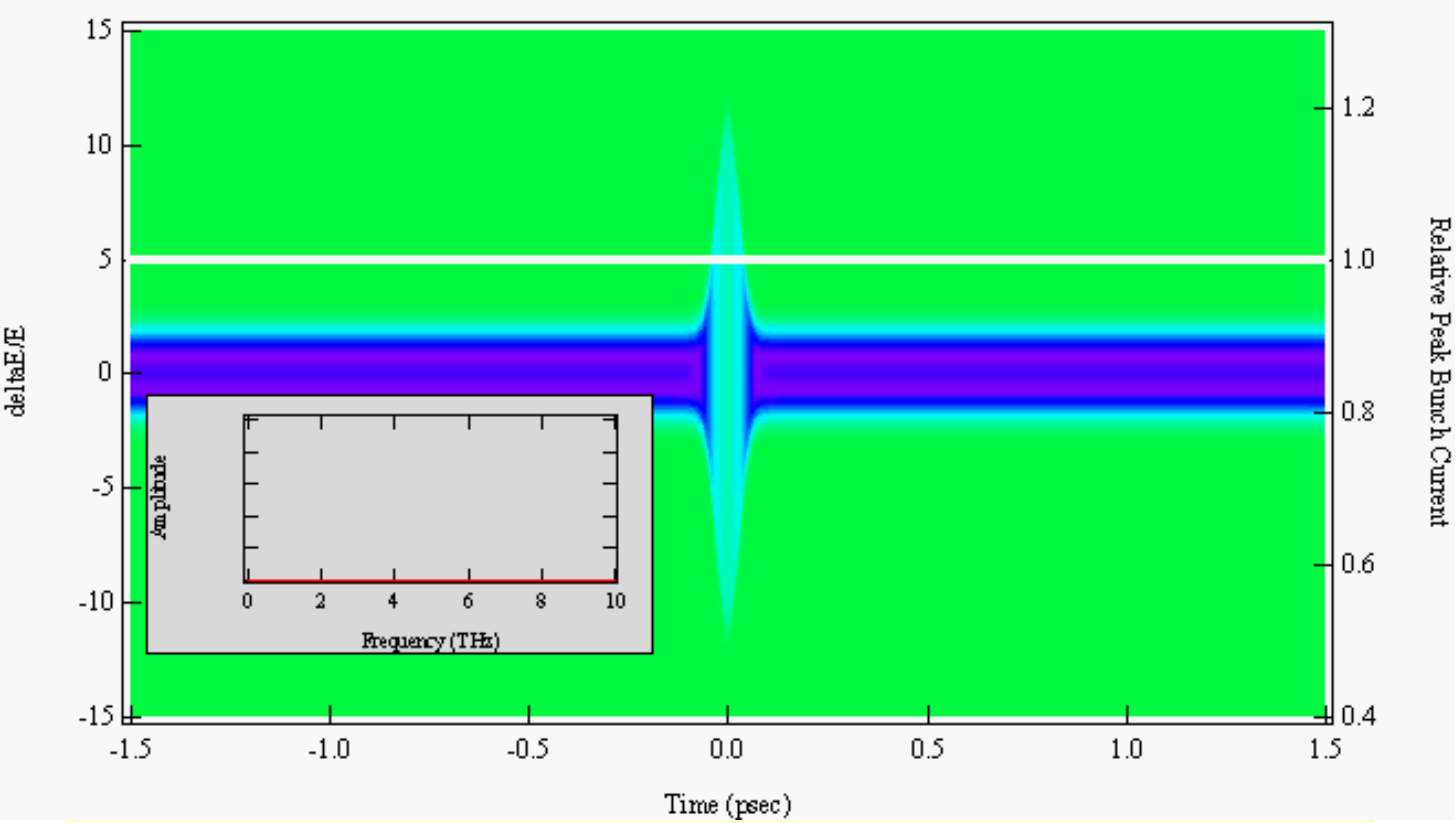
- A. A. Zholents, M. S. Zolotorev, PRL 76, 912, (1996)
- R.W. Schoenlein, et al., Science, Mar 24, (2000) 2237.
- R. W. Schoenlein, *et al*., Appl. Phys. B 71, 1-10, 2000.

- After the energy modulation, the ring longitudinal dispersion generates a perturbation, or “hole” on the bunch distribution.
- The resulting hole in the bunch radiates coherently the same a bunch of the same length.



Calculated hole and spectrum at BLs 5.3 and 1.4.

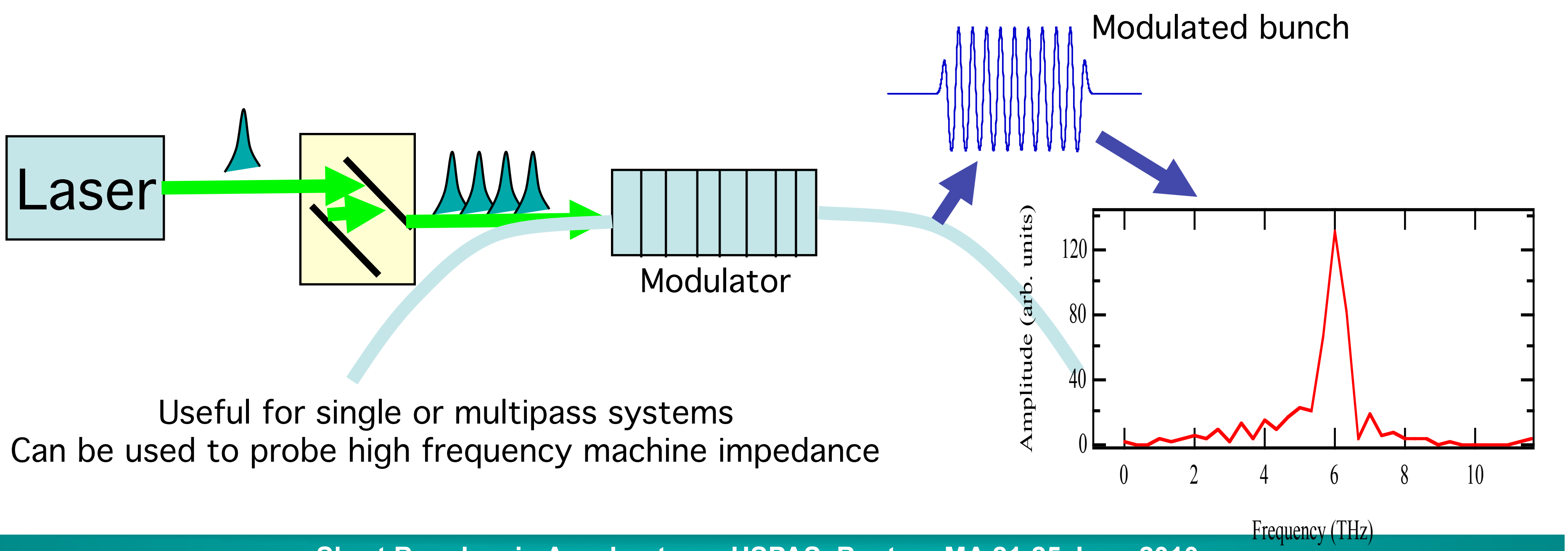
# Slice evolution



The 'hole' fills at a rate proportional to the momentum compaction and the energy modulation.

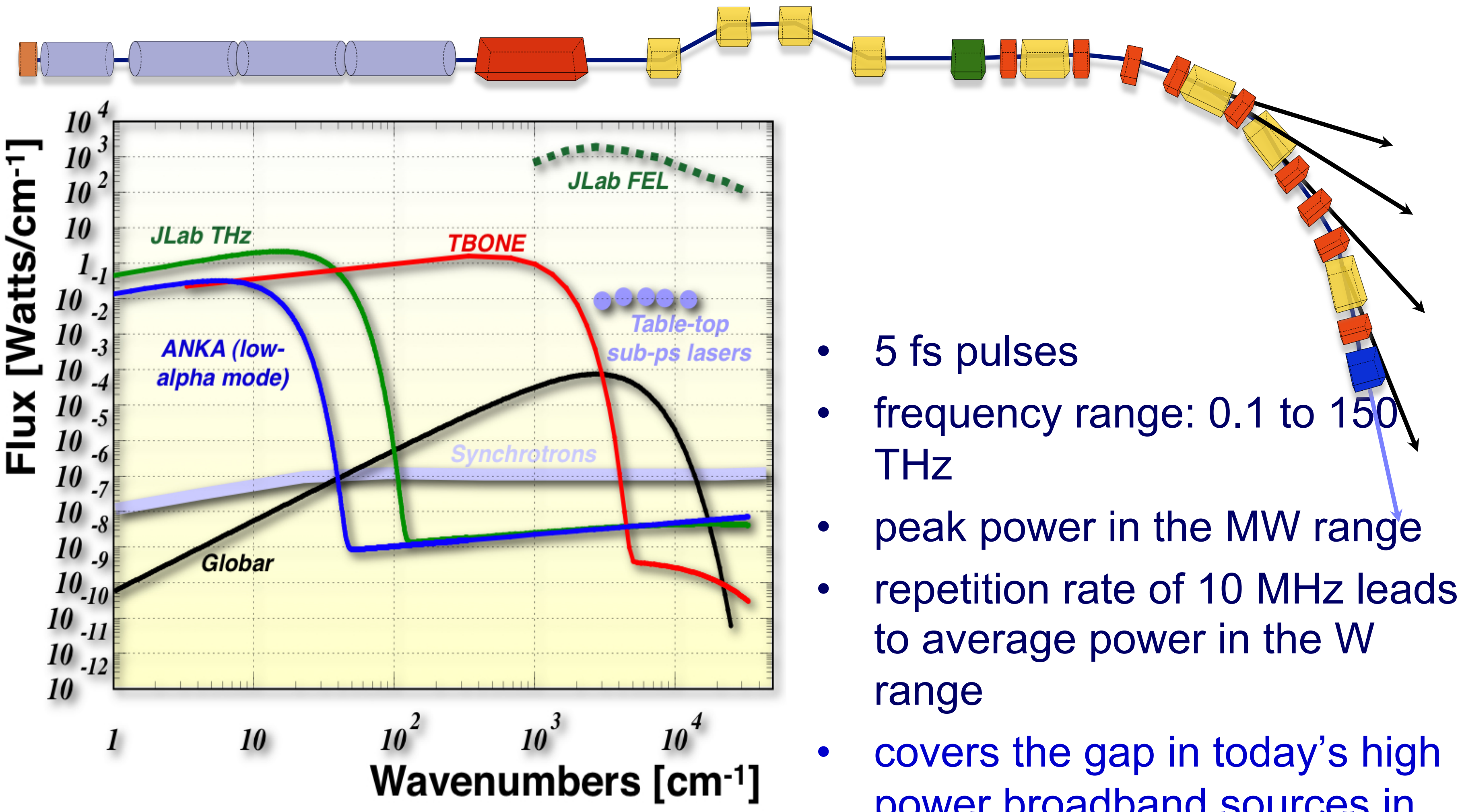
# Tailored THz Pulses

- The original slicing concept uses high power Gaussian laser modulation to optimize energy modulation
- Smaller, temporally shaped laser pulses can be used to modulate arbitrary patterns on the bunch
  - Smaller modulations disperse more slowly
  - Bandwidth limited by modulator and beam dispersion
- Simple example: etalon



Useful for single or multipass systems
Can be used to probe high frequency machine impedance

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

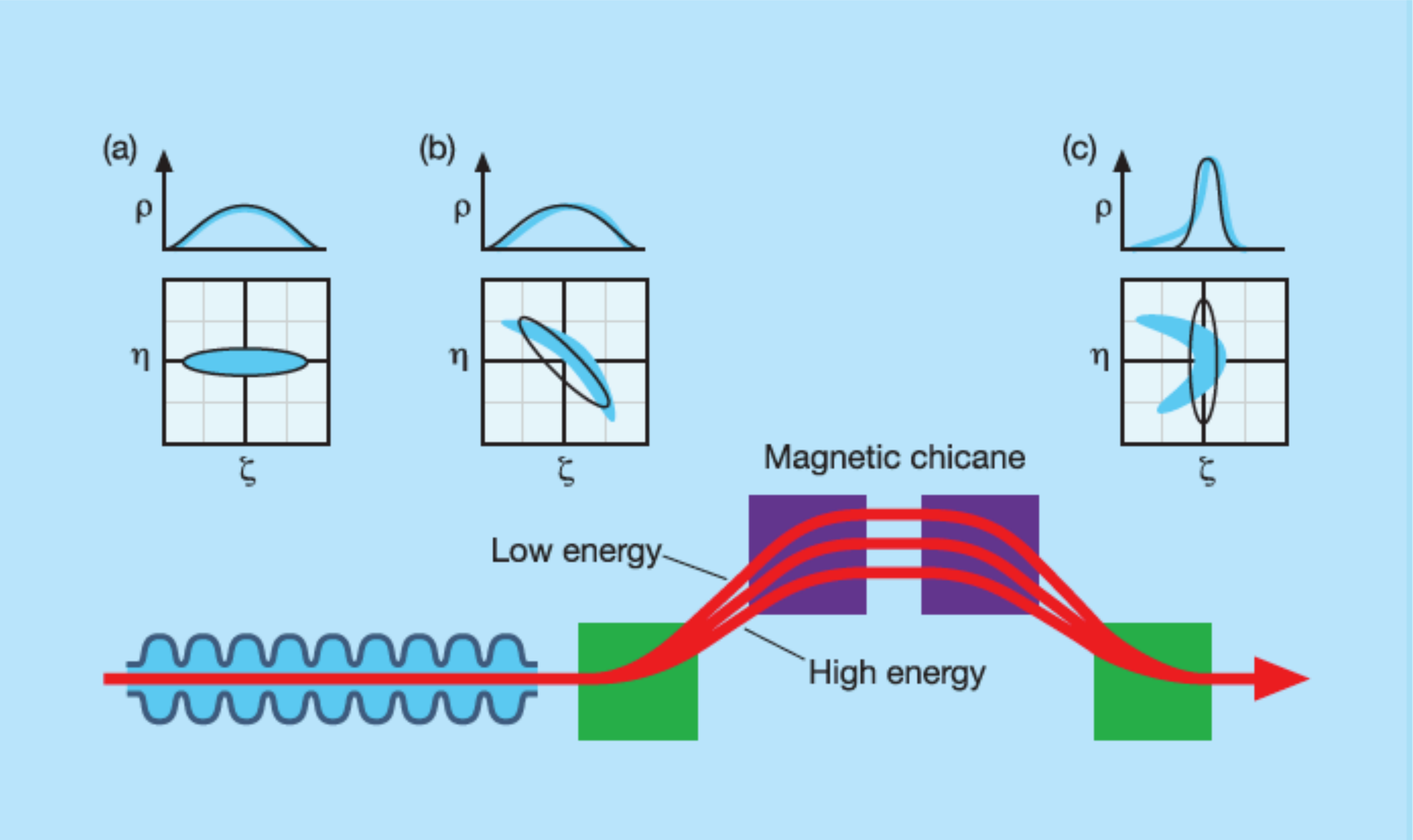


- 5 fs pulses
- frequency range: 0.1 to 150 THz
- peak power in the MW range
- repetition rate of 10 MHz leads to average power in the W range
- covers the gap in today's high power broadband sources in the THz / mid-IR

# Generating short bunches

- Linac beams
  - Longitudinal phase space manipulation
- Storage rings
  - Optimize weak longitudinal focussing
  - Strong focussing
- Photoemission
- Plasma wakefield accelerators

# Magnetic Bunch Compression



# Short bunches from storage rings

- Shorten bunch by decreasing momentum compaction factor (i.e. low alpha)

$$\sigma_\tau \propto \left(\frac{\alpha_C E^3}{V_{RF} f_{RF}}\right)^{\frac{1}{2}}$$

$\alpha_C \equiv momentum\ compaction$

$V_{RF} \equiv peak\ RF\ \ voltage$

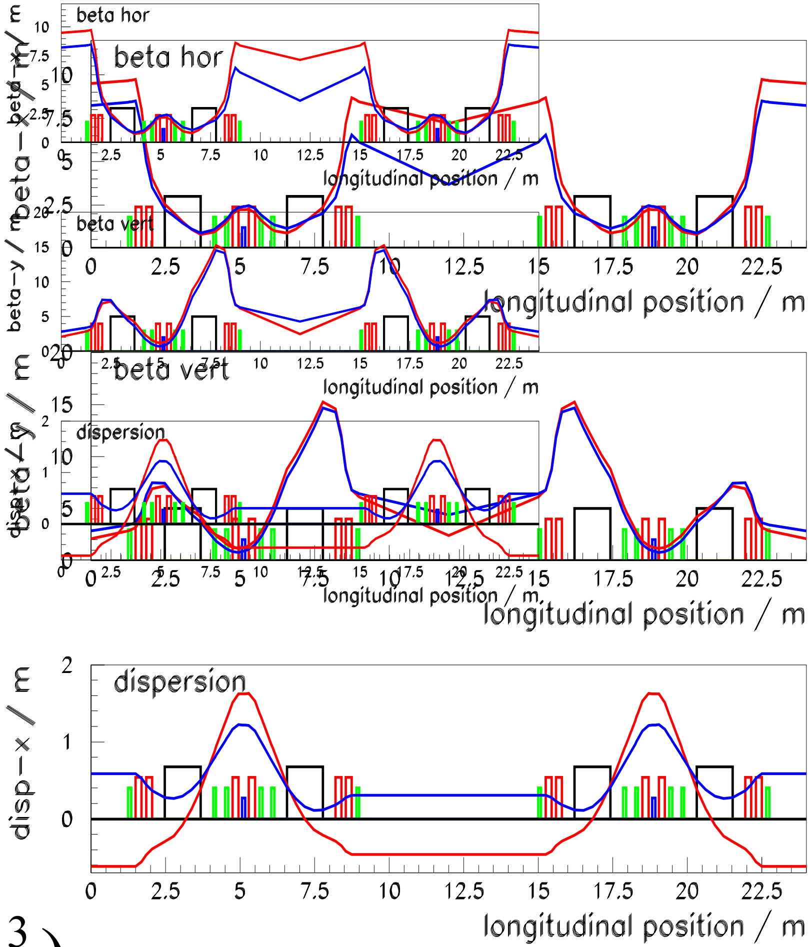
$f_{RF} \equiv RF\ \ frequency$

$E \equiv beam\ energy$

$$\alpha = \frac{1}{L}\oint\frac{\eta}{\rho}\mathrm{d}s$$

Lower alpha via negative dispersion in a bend

$$\alpha(\delta)=\alpha_1+\alpha_2\delta+\alpha_3\delta^2+O(\delta^3)$$



# Nonlinear Longitudinal Phase Space

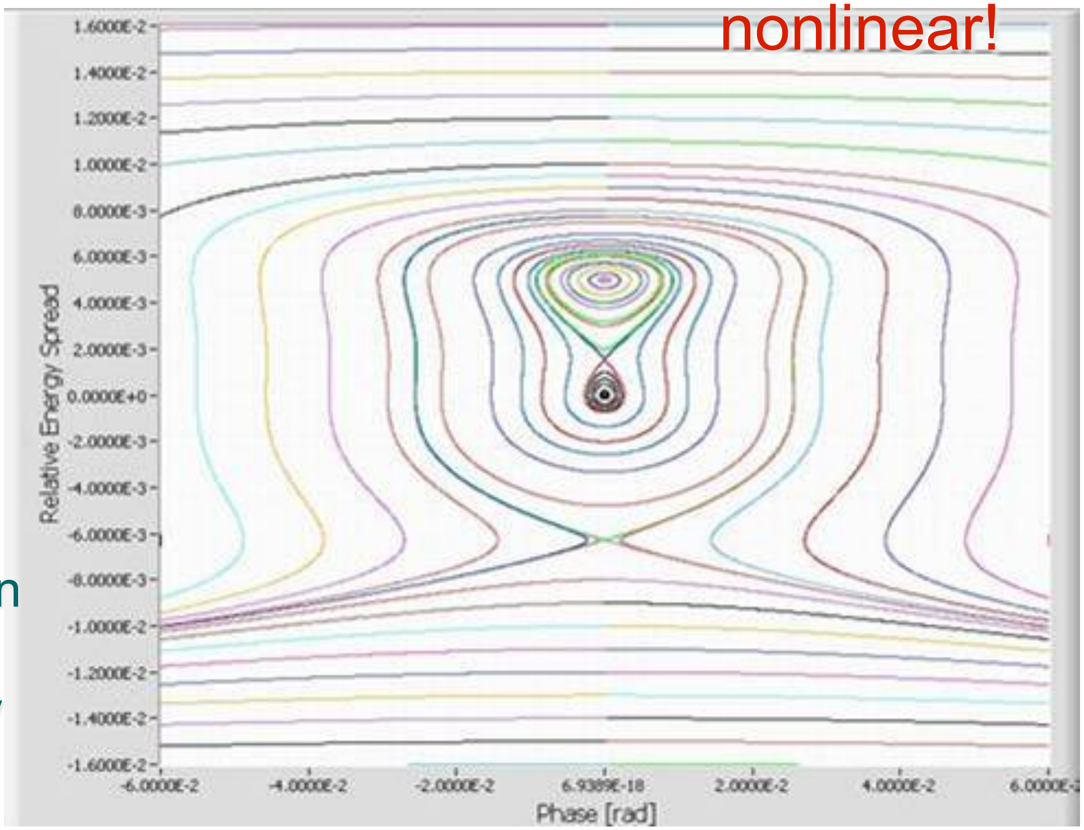
$$E_0 = 1.7\ GeV,\ f_{RF} = 500\ MHz,\ V_{RF} = 1.3\ MV,\ L = 240\ m$$

$$\boxed{\alpha_1 = 3\times10^{-6},\ \ \alpha_2 = -1\times10^{-3},\ \ \alpha_3 = -5\times10^{-3},\ \ \alpha_4 = 1.5\times10^{1}}$$

The simulation is performed without damping, and the figure shows the longitudinal phase space trajectories

Two stable "buckets" with different energy are clearly visible.

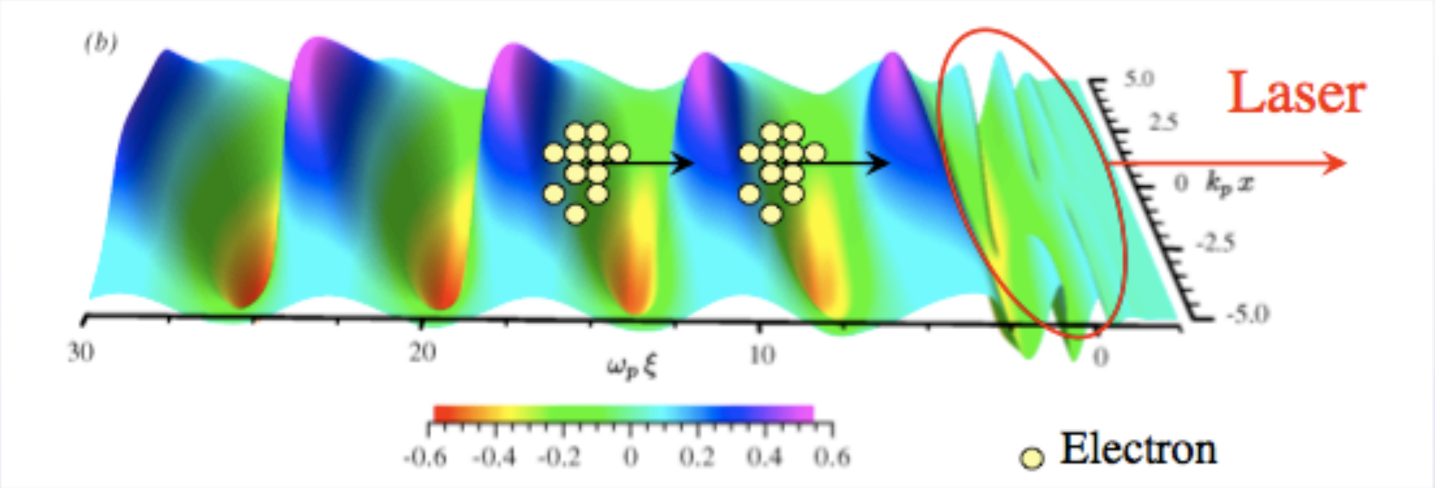
The bunch distribution is given by the projection of the phase space on the phase axis.
The figure shows perfect symmetry respect to the zero phase and so symmetric bunch distributions...



Strongly nonlinear!

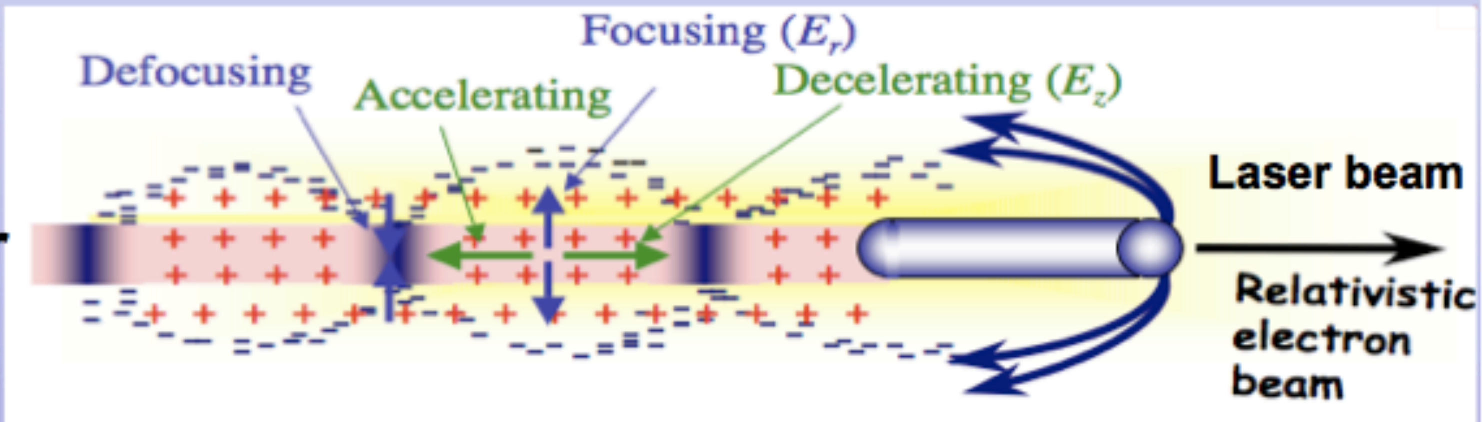
# Laser/Plasma Accelerators

**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

**Non-Linear**



# Measuring short bunches

- Sense coherent radiated Coulomb field and reconstruct bunch shape
  - Coherent synchrotron/diffraction/transition/edge radiation
  - Electro-optic sampling
  - 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

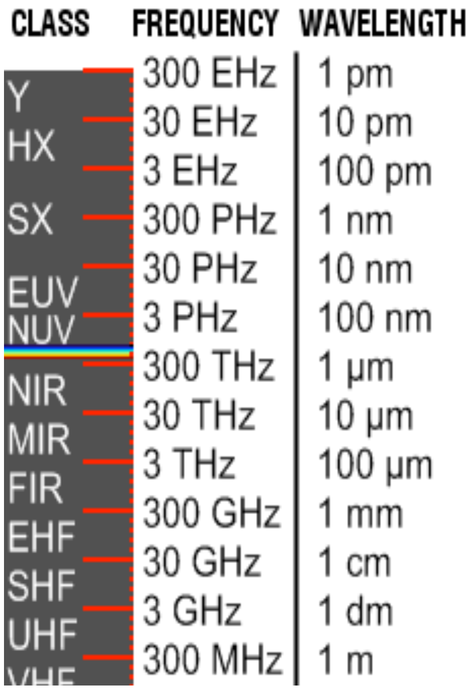
Nonlinear optics

RF and microwaves

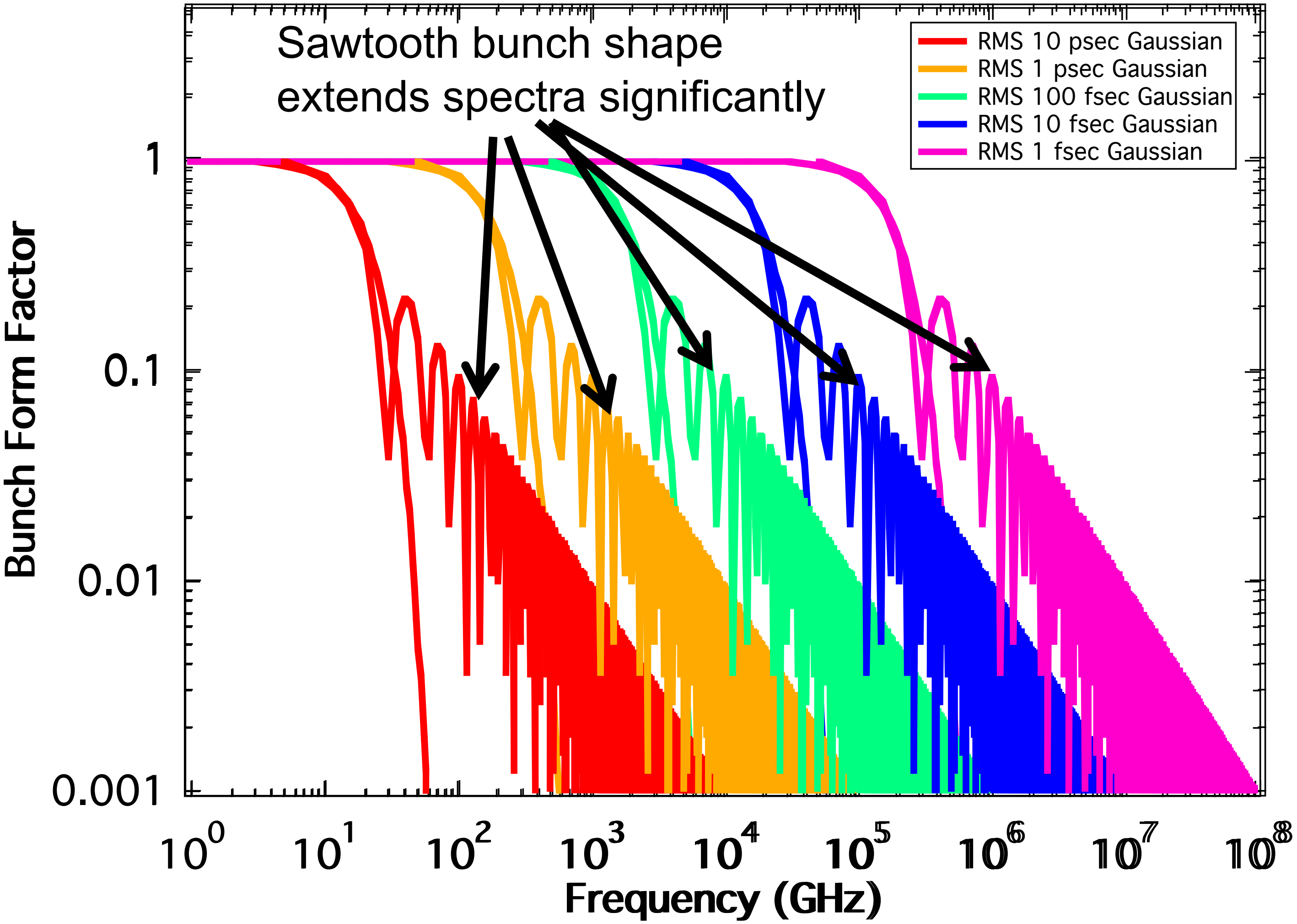
TeraHertz

Challenging problems inspire innovative solutions and attract very good people

# Bunch Spectra: From DC to Daylight

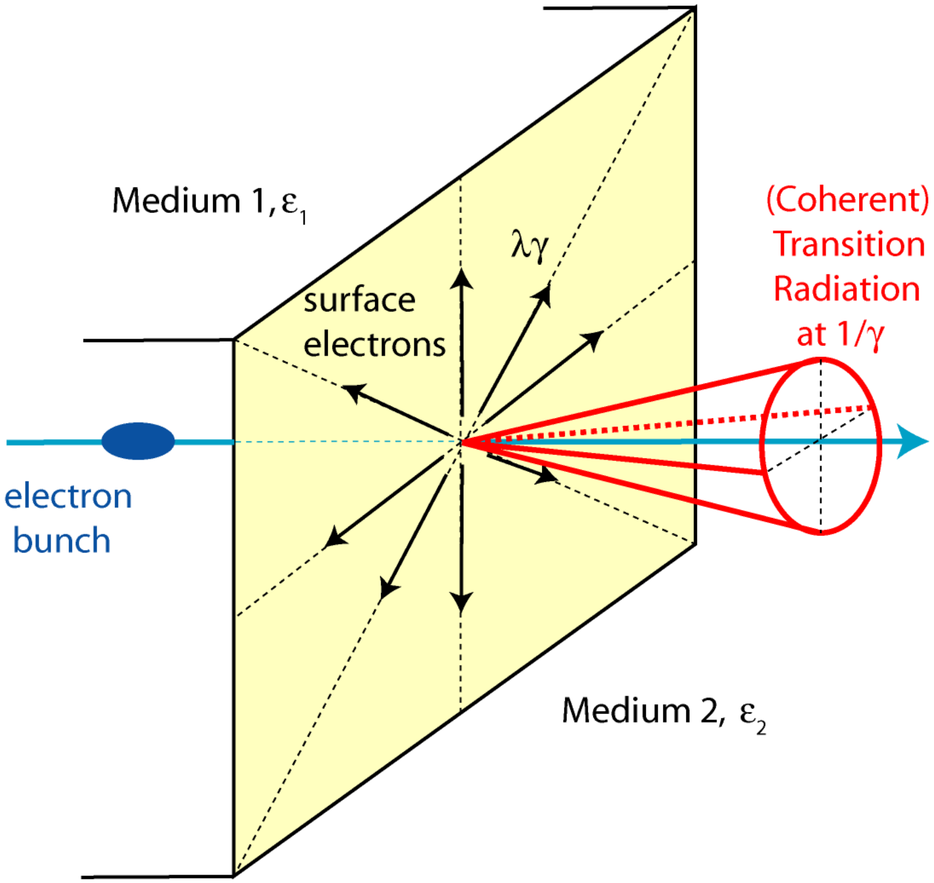


| FREQUENCY | WAVELENGTH |
|---|---|
| 300 EHz | 1 pm |
| 30 EHz | 10 pm |
| 3 EHz | 100 pm |
| 300 PHz | 1 nm |
| 30 PHz | 10 nm |
| 3 PHz | 100 nm |
| 300 THz | 1 µm |
| 30 THz | 10 µm |
| 3 THz | 100 µm |
| 300 GHz | 1 mm |
| 30 GHz | 1 cm |
| 3 GHz | 1 dm |
| 300 MHz | 1 m |

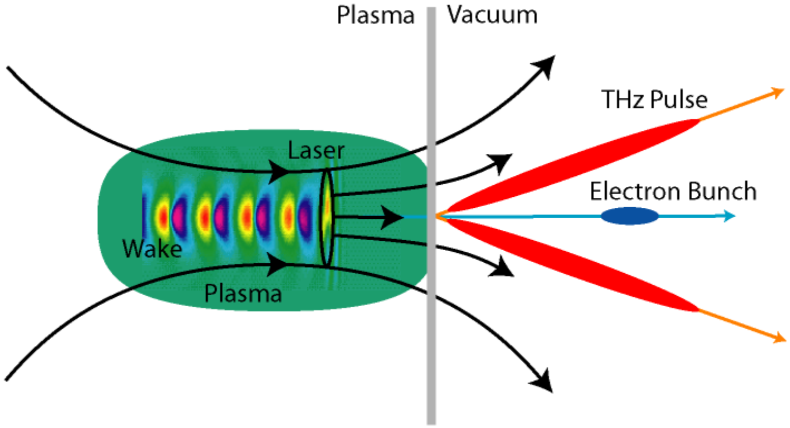


# Coherent Transition Radiation from the plasma-vacuum boundary

## Schematic for Transition Radiation



## Laser-Wakefield Accelerator



- First experimental observation in 2003, (Leemans *et al.,* Phys. Rev. Lett.)
- Theoretical analysis by Schroeder *et al.,* Phys. Rev. E (2004)

Leemans *et al*. Phys. Plasmas 11, 2899 (04)
van Tilborg *et al*. Laser Part. Beams (04)
Lepore *et al*. Phys. Rev. D (76)
van Tilborg *et al*. Phys. Plasmas, submitted

# CTR (THz) in spectral and temporal domain

Diffraction function

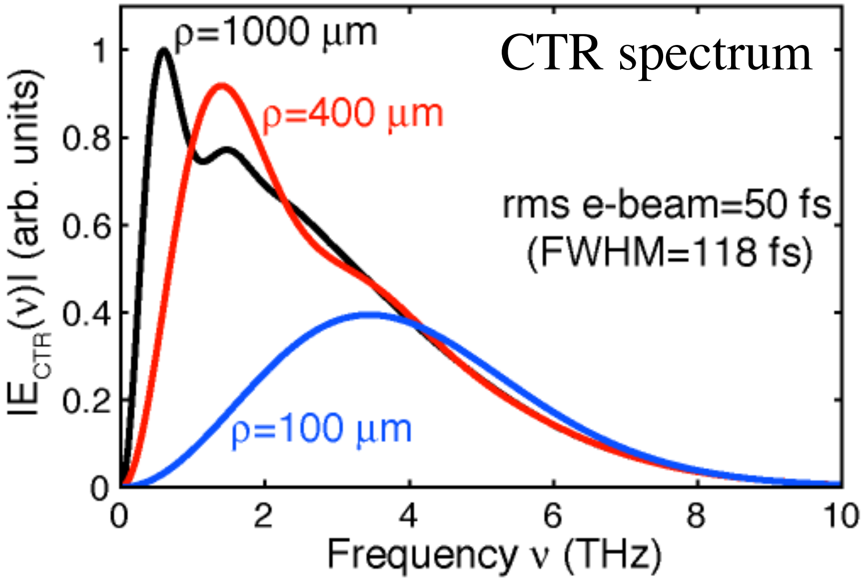
$$E_{\mathrm{CTR}}(\omega) \propto N\mathcal{E}(u)D(\omega,u,\rho)F(\omega)$$

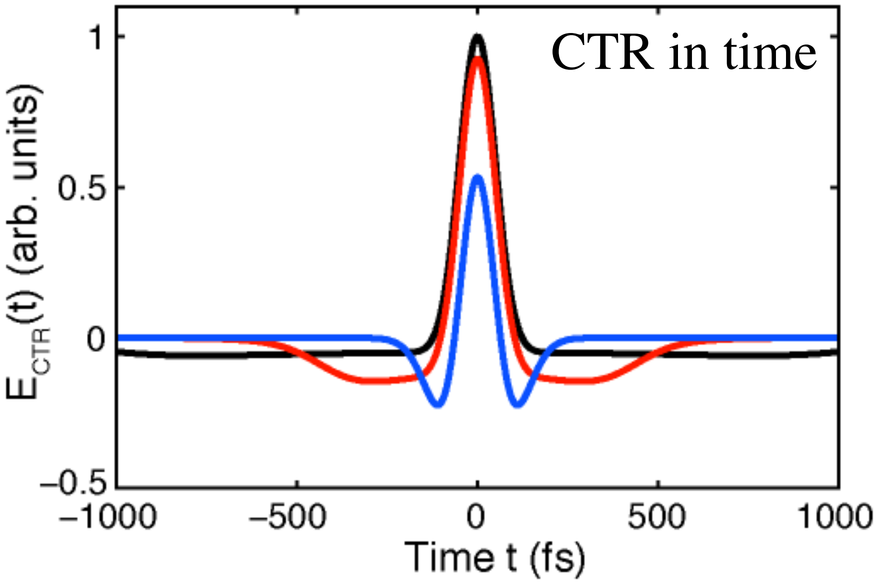
Single electron TR

Form factor

**Intense THz source**

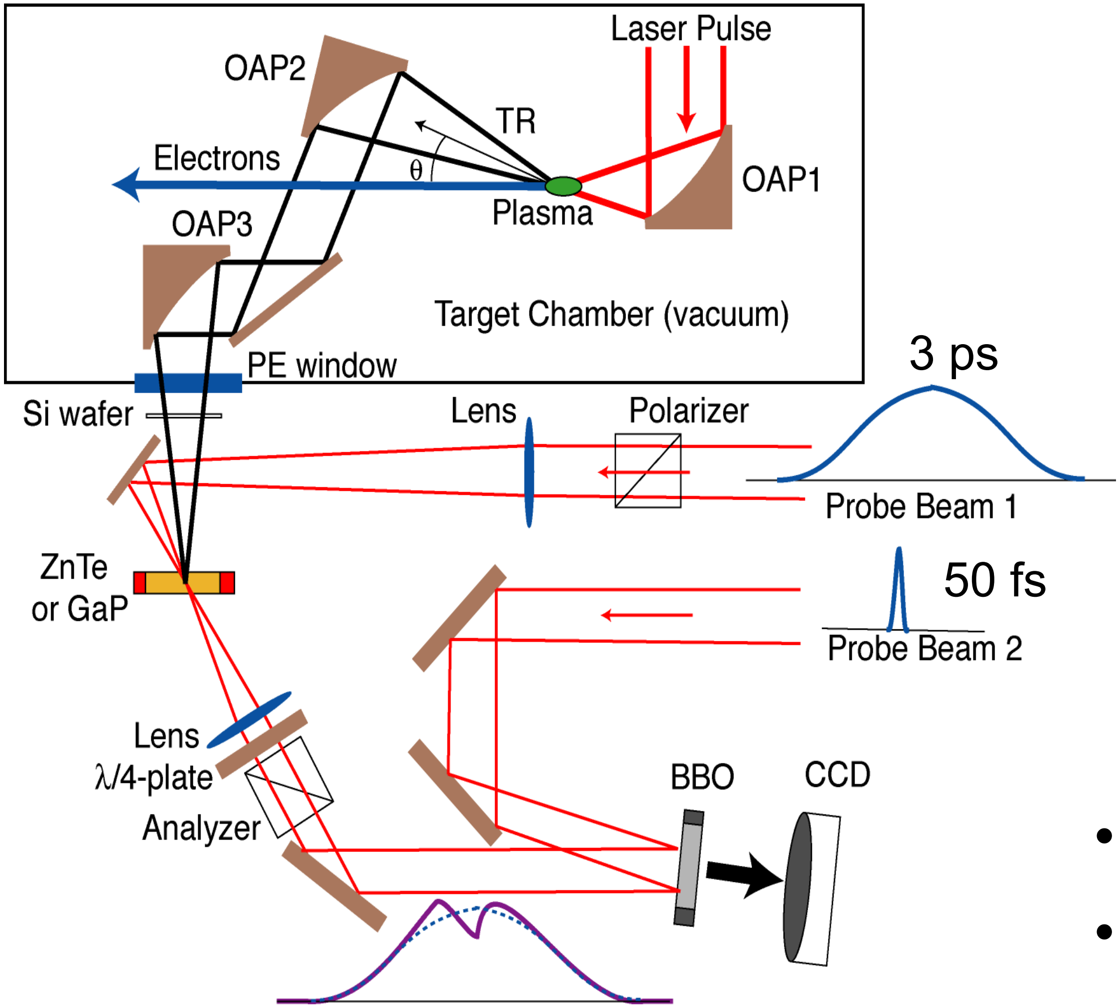
- **0.01-10 MV/cm** at focus (up to **10's of microJ** in THz pulse)
- 'traditional' laser-based sources deliver <100 kV/cm



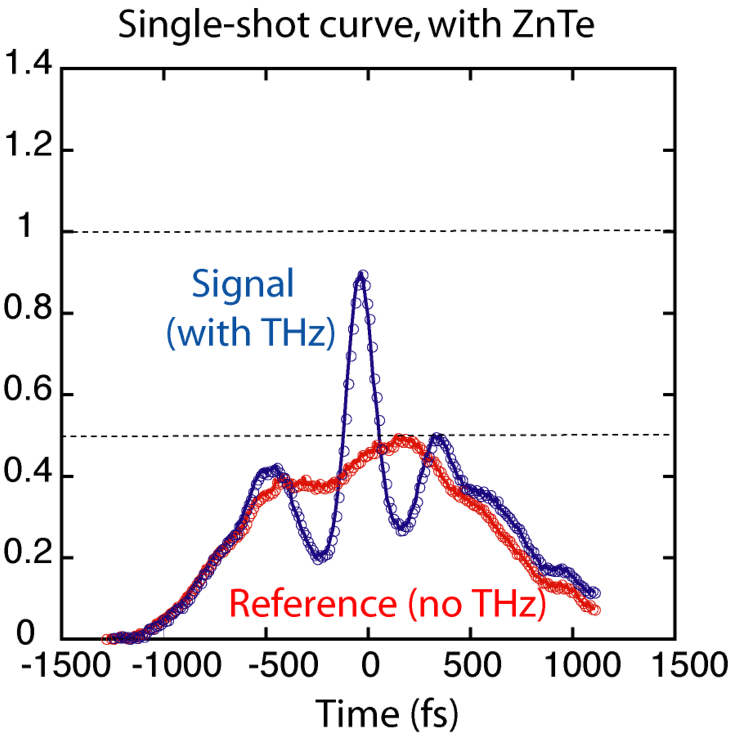


Schroeder *et al*., Phys. Rev. E (04)
van Tilborg *et al*., Laser Part. Beams (04)
van Tilborg *et al*., Phys. Plasmas, submitted

# EO detection of THz pulses:



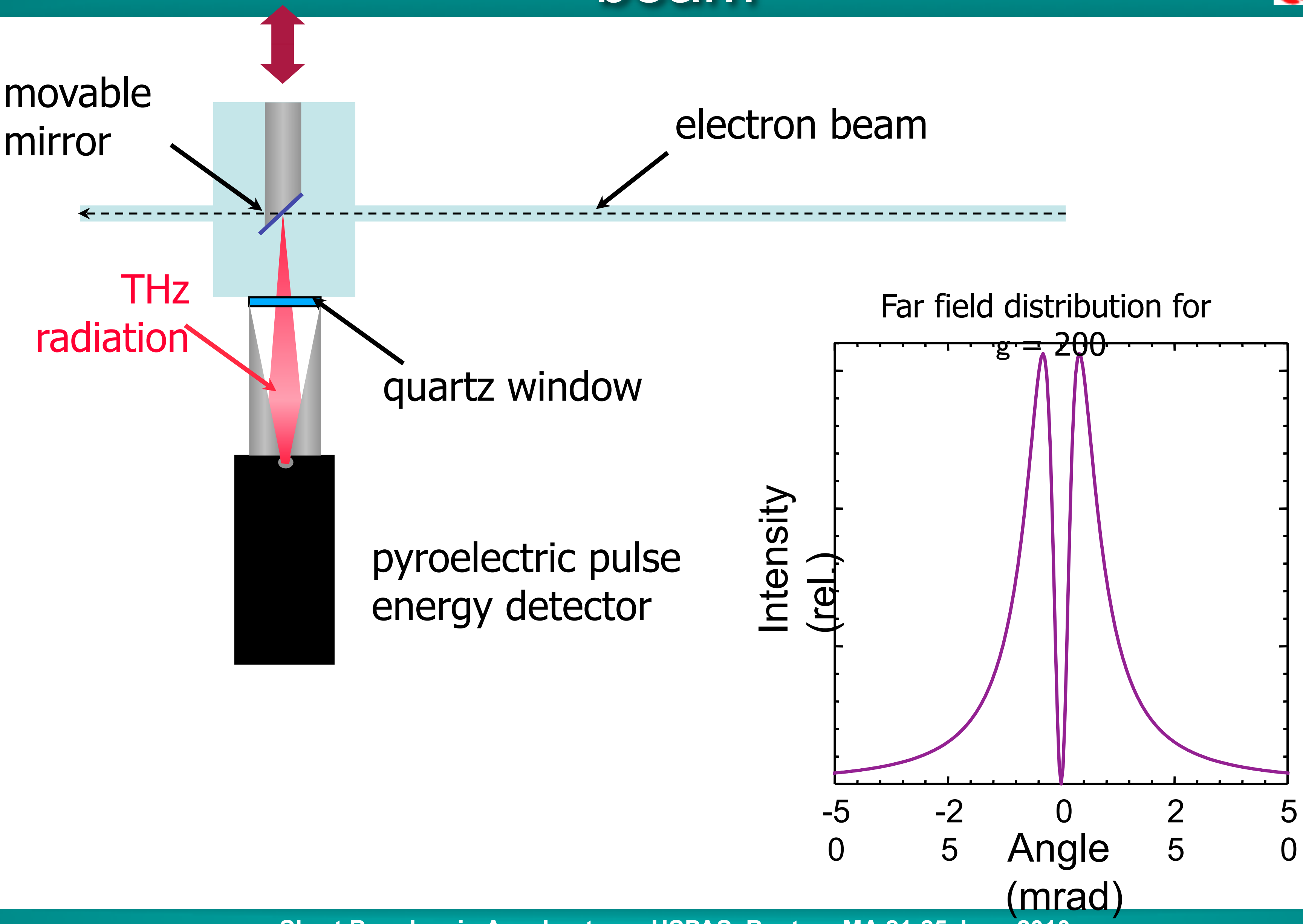
G. Berden et al., Phys. Rev. Lett. 93, 114802 (2004)



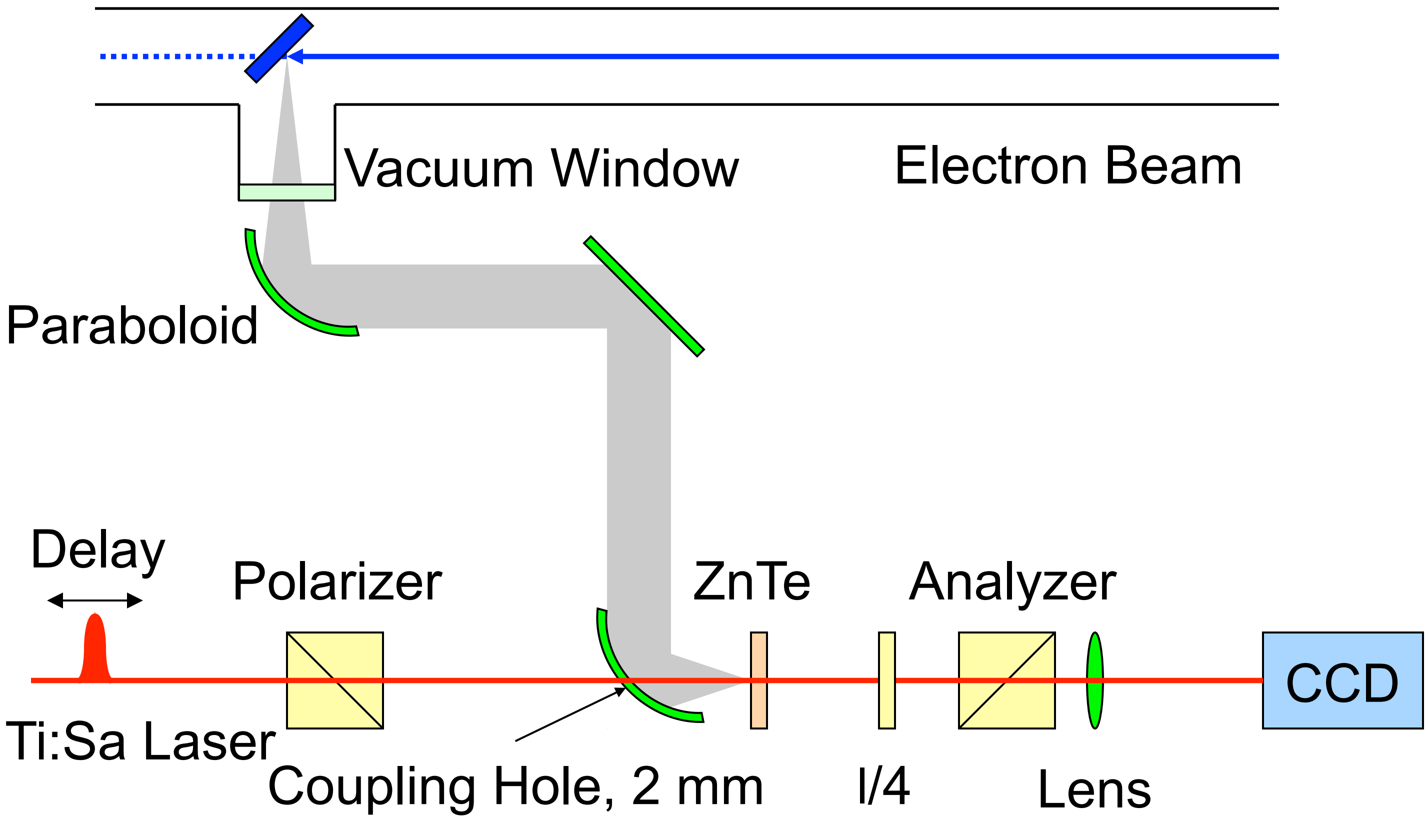
- < 50 fs bunches
- peak E-field of $E_{CTR} \approx 150$ kV/cm

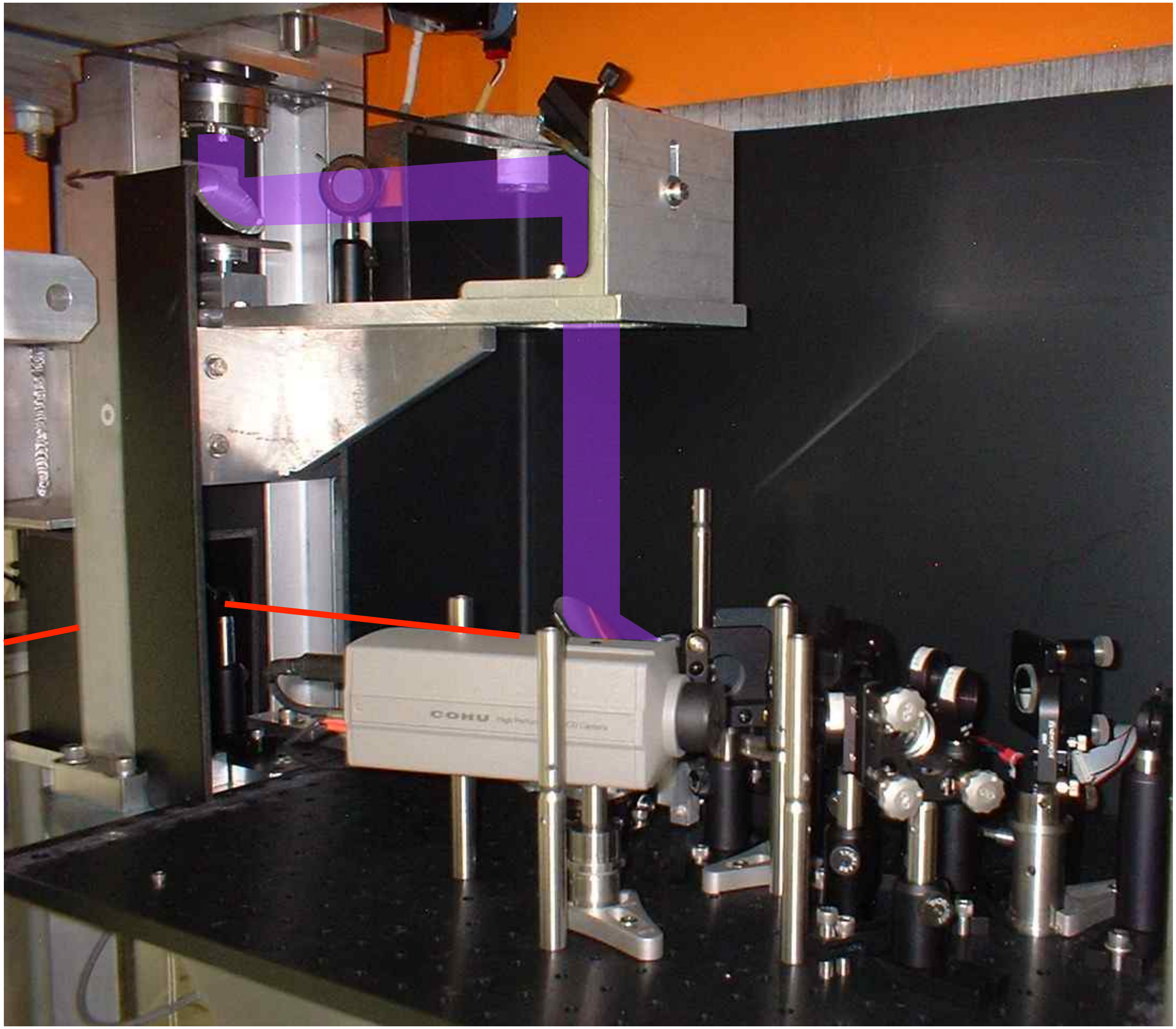
J. van Tilborg et al., submitted to PRL

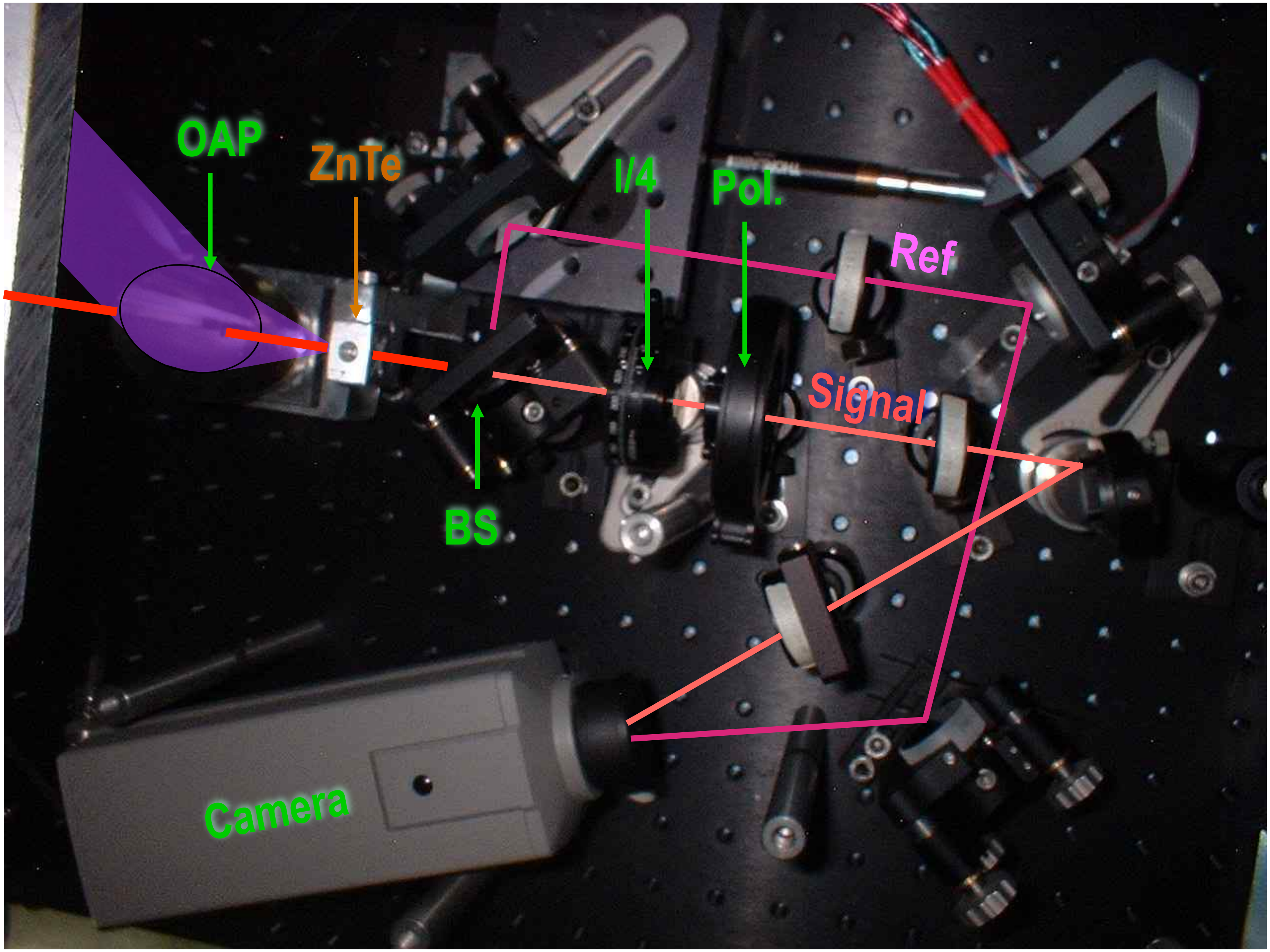
# Coherent Transition Radiation from a LINAC beam



# Electro-Optic THz Radiation Setup

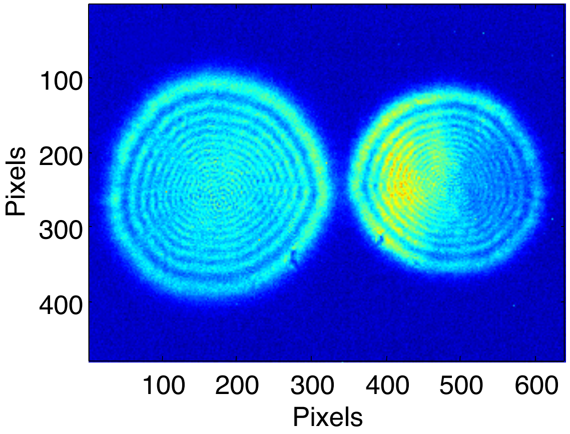



COHU

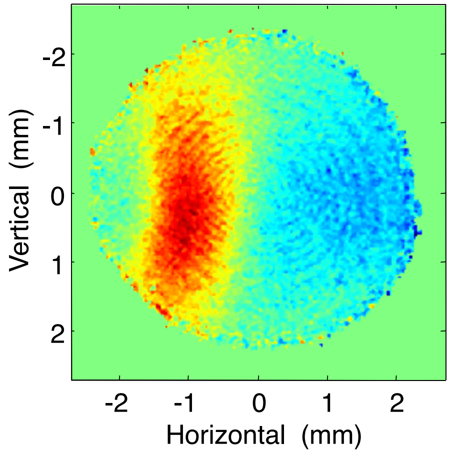

OAP
ZnTe
l/4
Pol.
Ref
Signal
BS
Camera

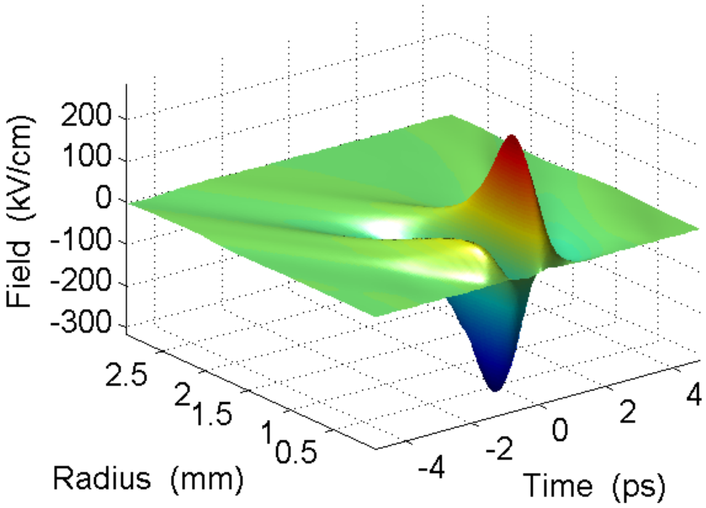
# Image Processing for Field Measurement

- Use compensator waveplate to detect sign of polarization change.
- Reference $I_R$ (left) and Signal $I_S$ (right) obtained simultaneous.
- Rescale and normalize both.
- Calculate asymmetry $A$ of Signal.
- Subtract asymmetry pattern w/o THz.



$$\xrightarrow{A = 2I_S/I_R - 1}$$





# AutoCorrelation of Coherent Diffraction Radiation

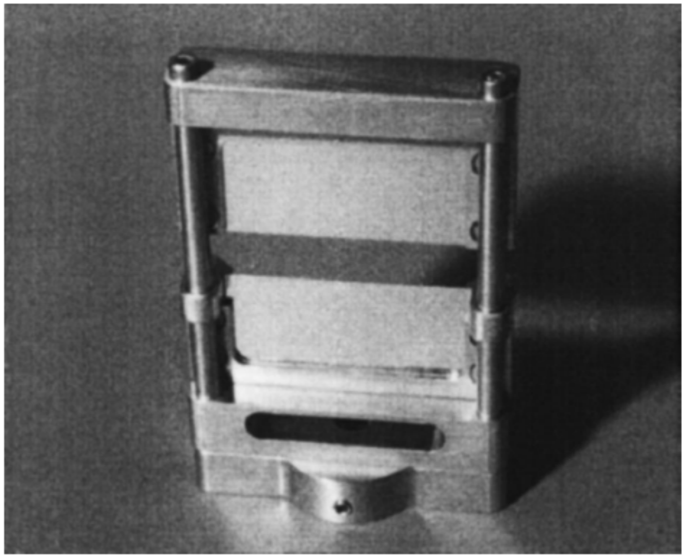


FIG. 1. Diffraction radiator in the open position.

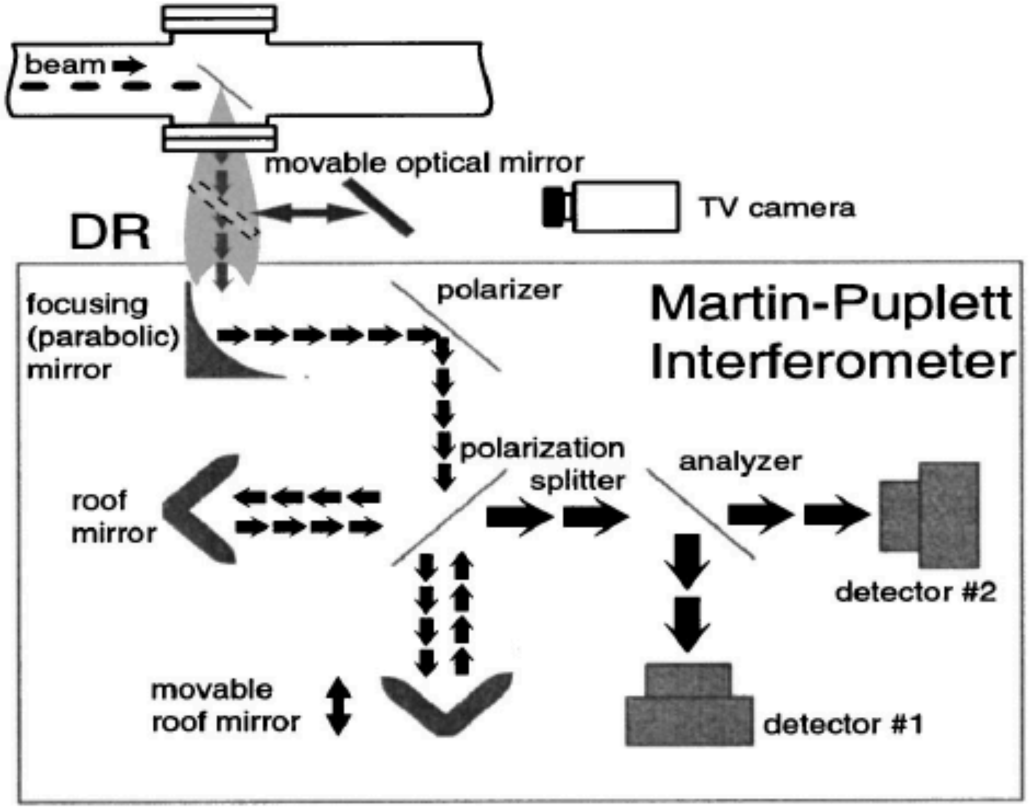


FIG. 2. In the Martin-Puplett interferometer the orthogonal polarization components from a polarizating beam splitter go along the two different arms, are rotated by roof mirrors, and recombine before reaching the detectors.

# AutoCorrelation of Coherent Diffraction Radiation

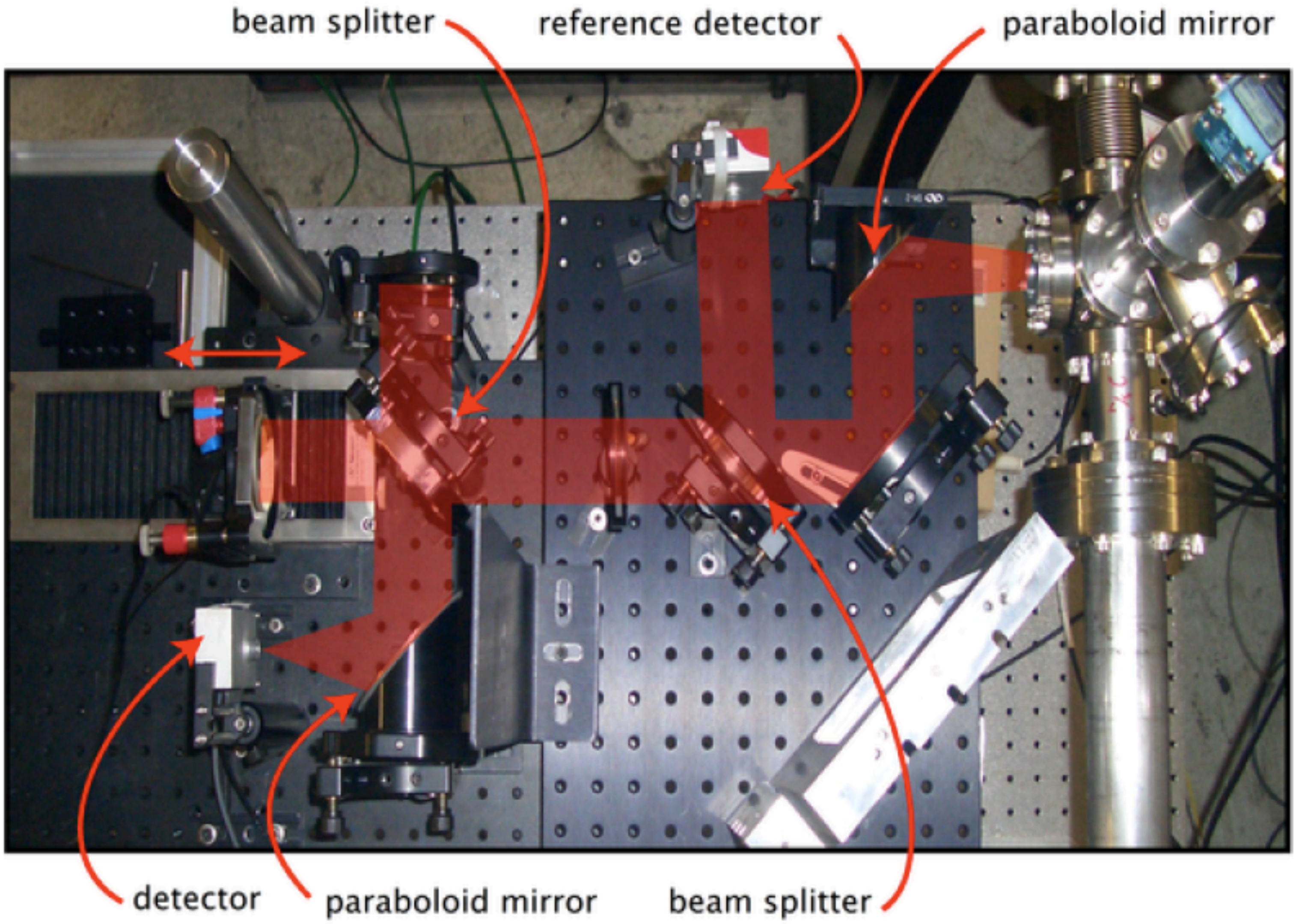
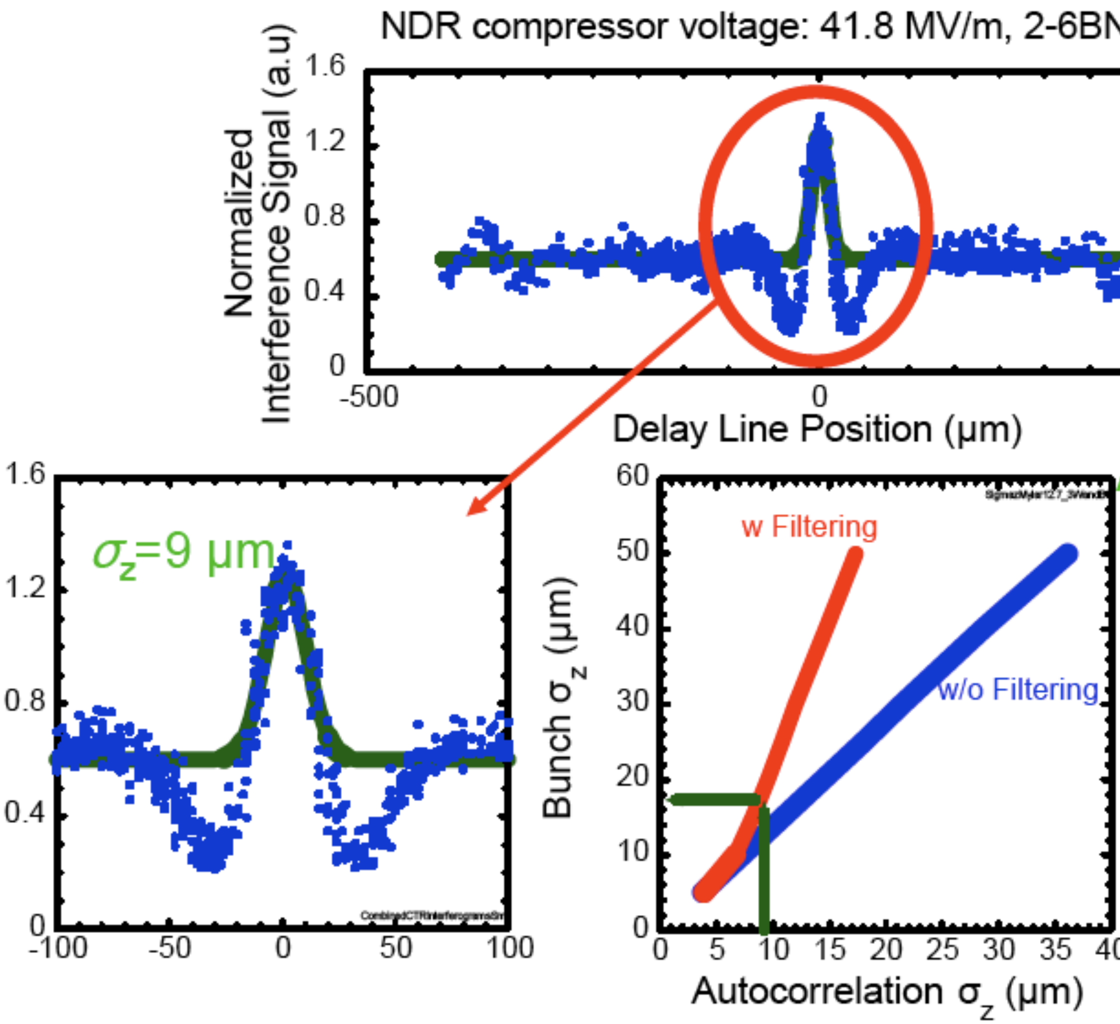


Figure 3: existing autocorrelator at SLAC

# Autocorrelator Results



Autocorrelation:

$\sigma_z$=9 μm

Gaussian Bunch

$\sigma_z$=18 μm

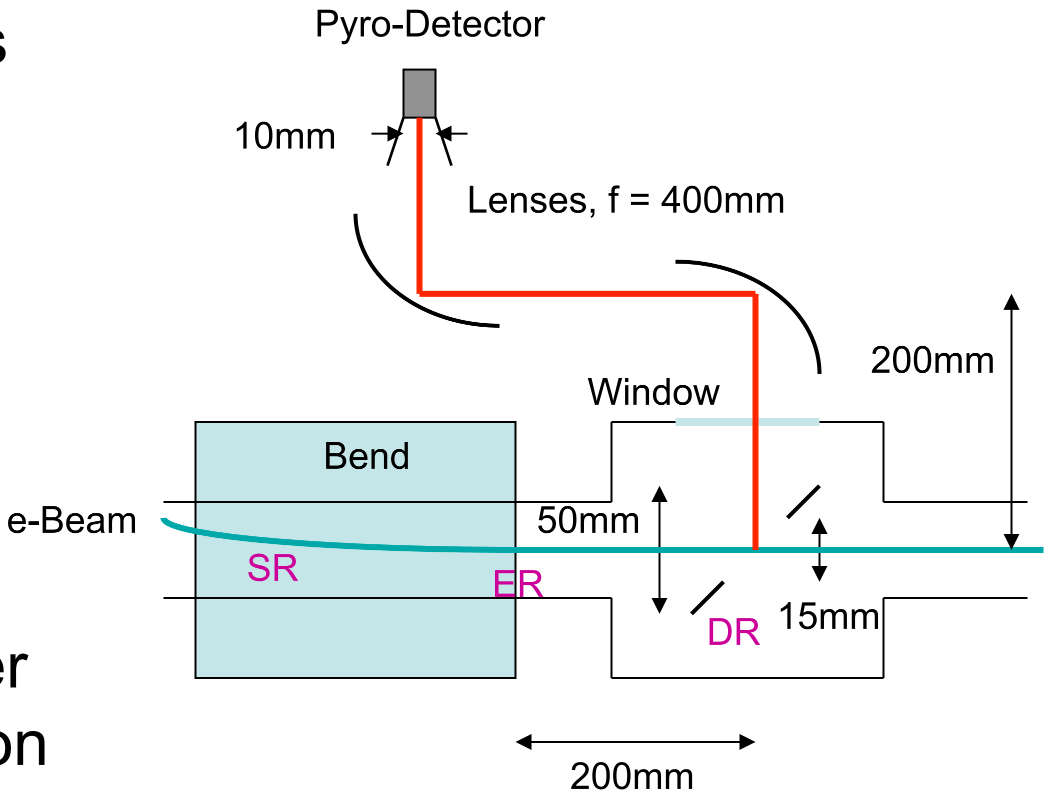
or

$\tau$=60 fs

Figure 4: measured autocorrelation trace

# Relative Bunch Length Measurements

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

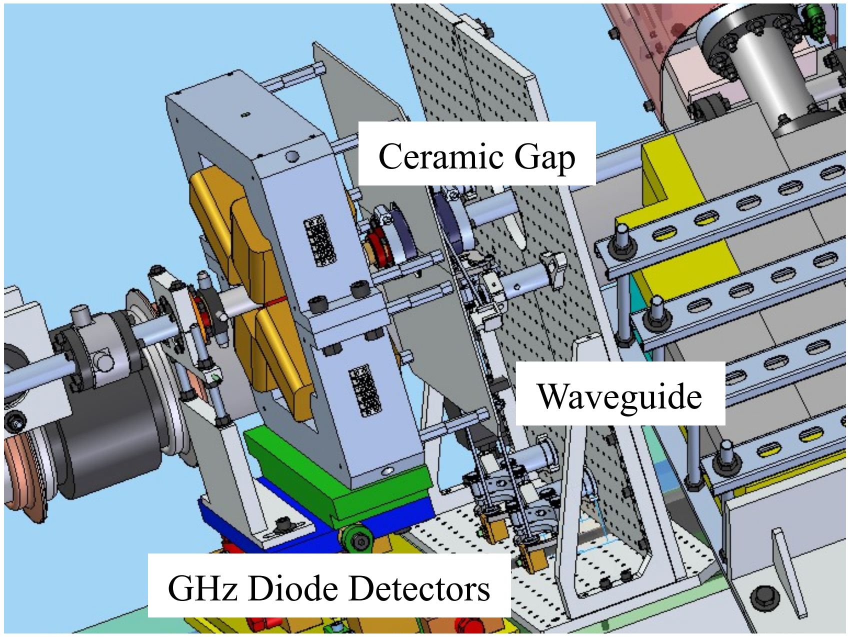


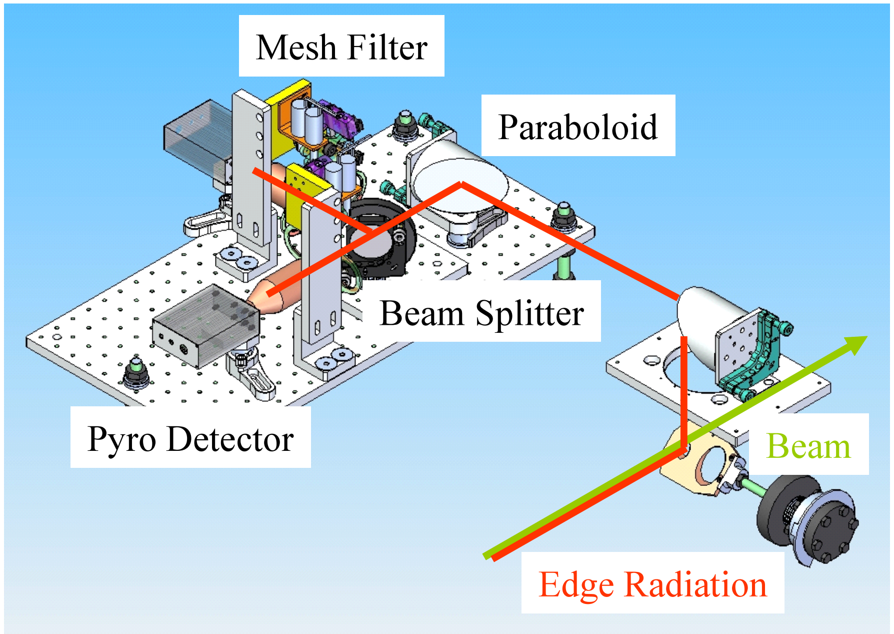
- Edge rad. dominates over synchrotron and diffraction
- Near field calculation necessary for radiation spectrum at detector

# LCLS Relative bunch length monitors

## BL12 – Ceramic Gap

## BL11 – Coherent Edge Radiation



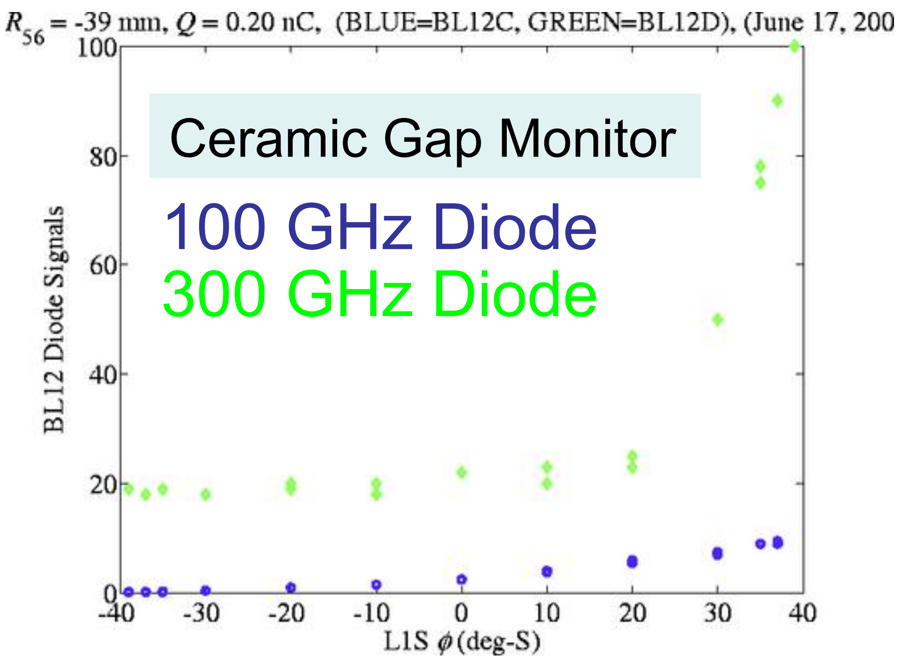


- Wide range of bunch lengths from 25um to 300um
- Diode detectors work well below 300GHz
- Pyroelectric detectors work well above 300GHz
- Long bunches- Couple radiation from ceramic gap in beam pipe into waveguides with different diode detectors
- Short bunches-Extract coherent radiation from bend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

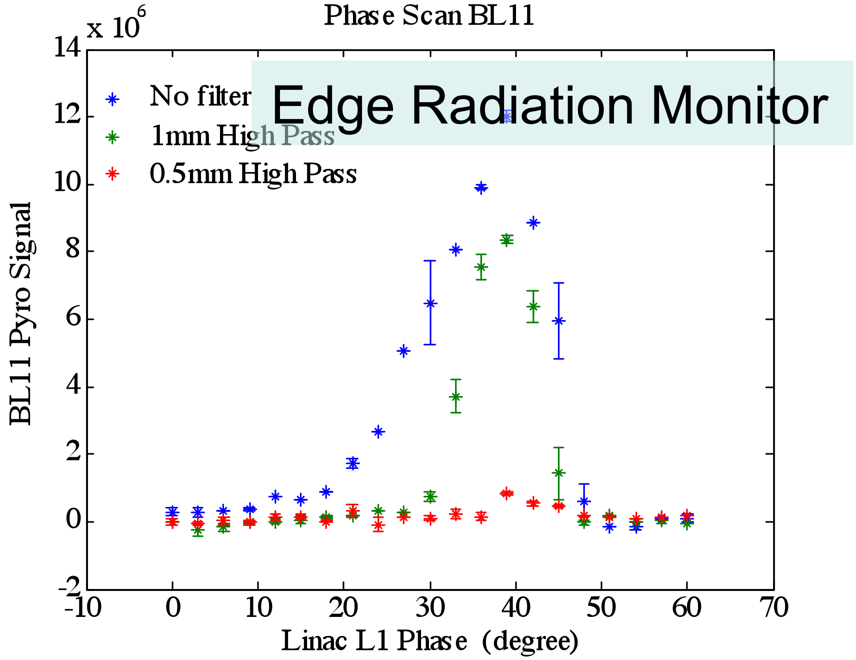
- All signals show strong correlation with accelerator phase and bunch compression
- Absolute calibration with TCAV in S29 to be done



Ceramic Gap Monitor

100 GHz Diode

300 GHz Diode



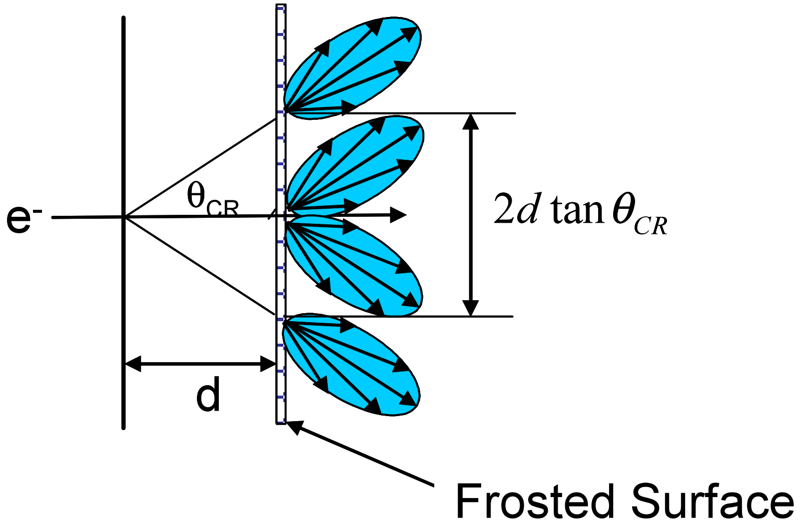
Edge Radiation Monitor

# Cherenkov Radiators: LCLS gun

- Located in gun region for temporal diagnostics of 6 MeV beam from gun
- Convert electron beam time structure into light pulse for streak camera measurement
- Cherenkov light suitable at low beam energies
- Design requirements
  - Match time resolution of radiator to streak camera (Hamamatsu FESCA-200, < 300fs)
  - Generate and transport a sufficient # of photons for 200pC beam to streak camera in laser room (10m away)

# Cherenkov Radiator Design

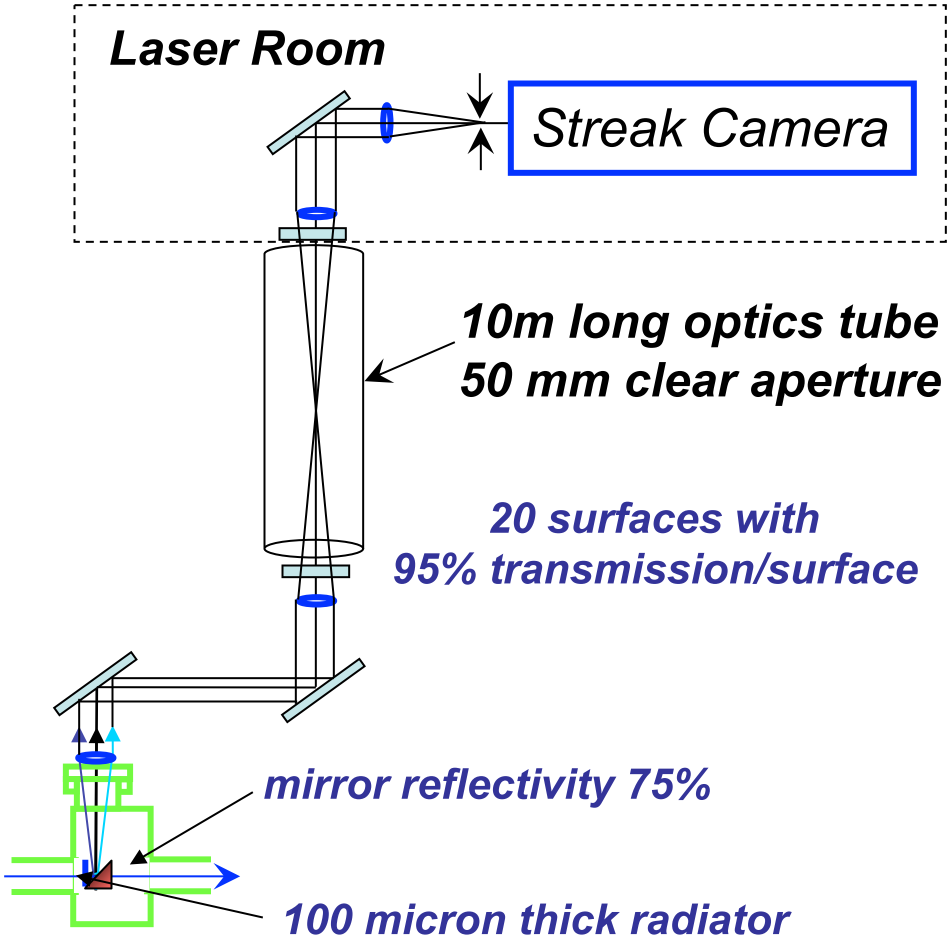
- Fused silica
  - n = 1.458, $\theta_{CR}$ = 46.7°
  - Total internal reflection
  - Frosting of back surface
  - $N_\Phi$ = 7.5/e/mm/50nm @400nm
- Temporal and spatial resolution
  - Thickness of 100μm
  - $\Delta t$ = 375fs
  - $\Delta x$ = 190μm



Courtesy D. Dowell

# Optical Transport Layout

- 1:1 relay imaging from radiator to streak camera
- Assume 1% efficiency from frosting to scatter into 100mrad
- 6% acceptance through tube for source of 5mm x 100mrad
- $1.5 \cdot 10^5$ photons on slit of streak camera for 200 pC

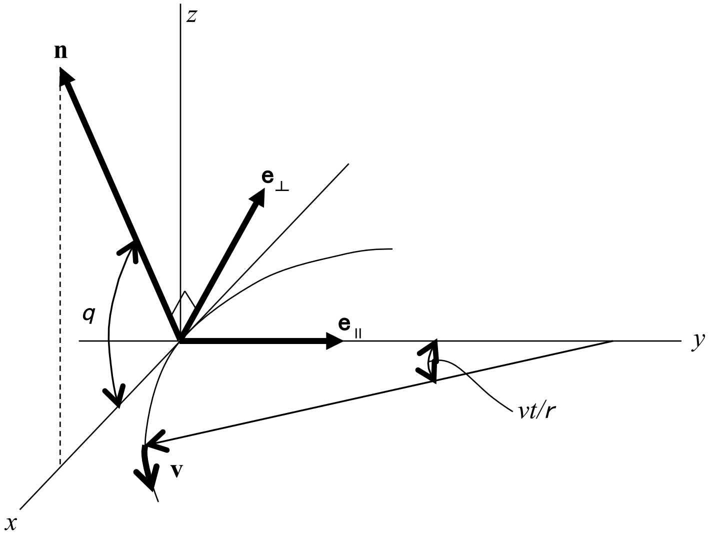


Courtesy D. Dowell

# Synchrotron Radiation

- The energy distribution of a relativistic electron in an instantaneous circular motion (Jackson V.2 14.83)

$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2}{3\pi^2 c}\left(\frac{\omega\rho}{c}\right)^2\left(\frac{1}{\gamma^2}+\theta^2\right)^2\left[K_{2/3}^2(\xi)+\frac{\theta^2}{(1/\gamma^2)+\theta^2}K_{1/3}^2(\xi)\right]$$



Where: $I$ : energy emitted by electron

$w$: frequency

W : solid angle

$e$ : charge of electron

$c$ : speed of light

$r$ : radius of curvature

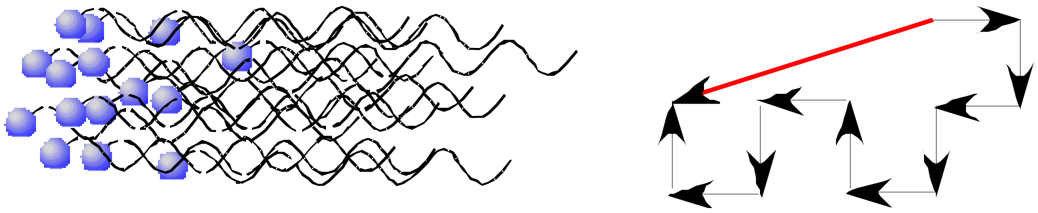
$g$ : relativistic normalized energy of electron

$K$ : modified Bessel function

$$\xi = \frac{\omega\rho}{3c}\left(\frac{1}{\gamma^2}+\theta^2\right)^{3/2}$$

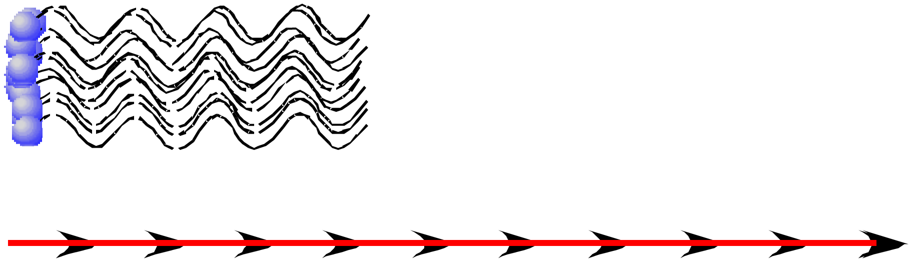
Note: The first term in the square bracket is for the polarization in the plane of acceleration and the second term is for the polarization perpendicular to the acceleration plane.

# 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



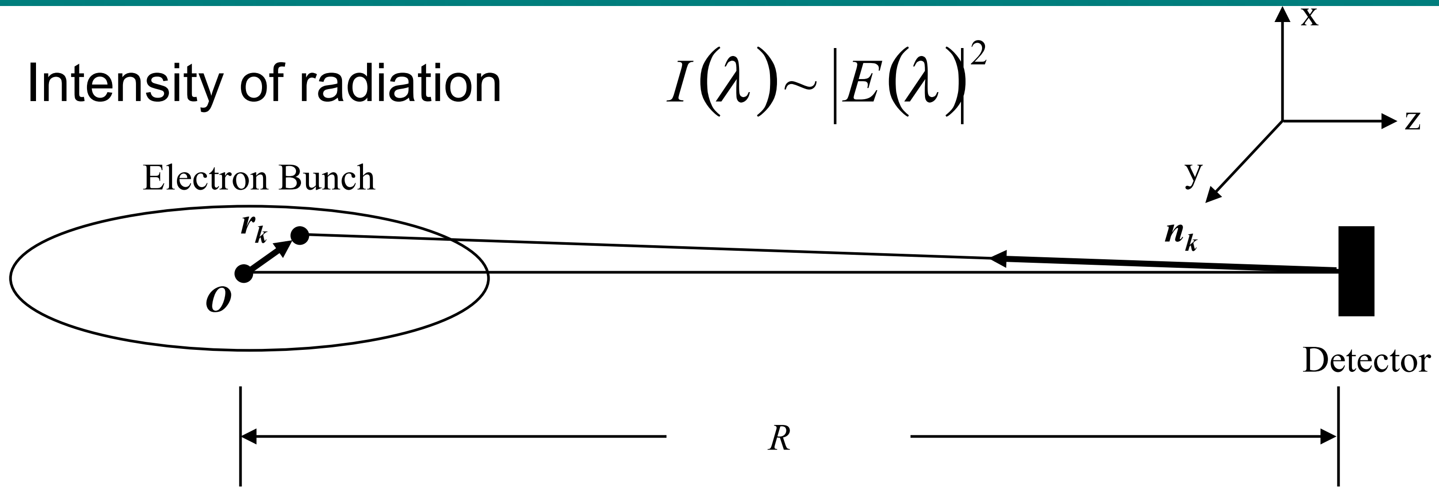
Coherent Emission

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.

# Coherent Radiation

- Replace the sum with an integral and assume a normalized distribution symmetric about *r* = 0

$$I_{tot}(\lambda) = I_1(\lambda)\left[N + N(N-1)f(\lambda)\right]$$

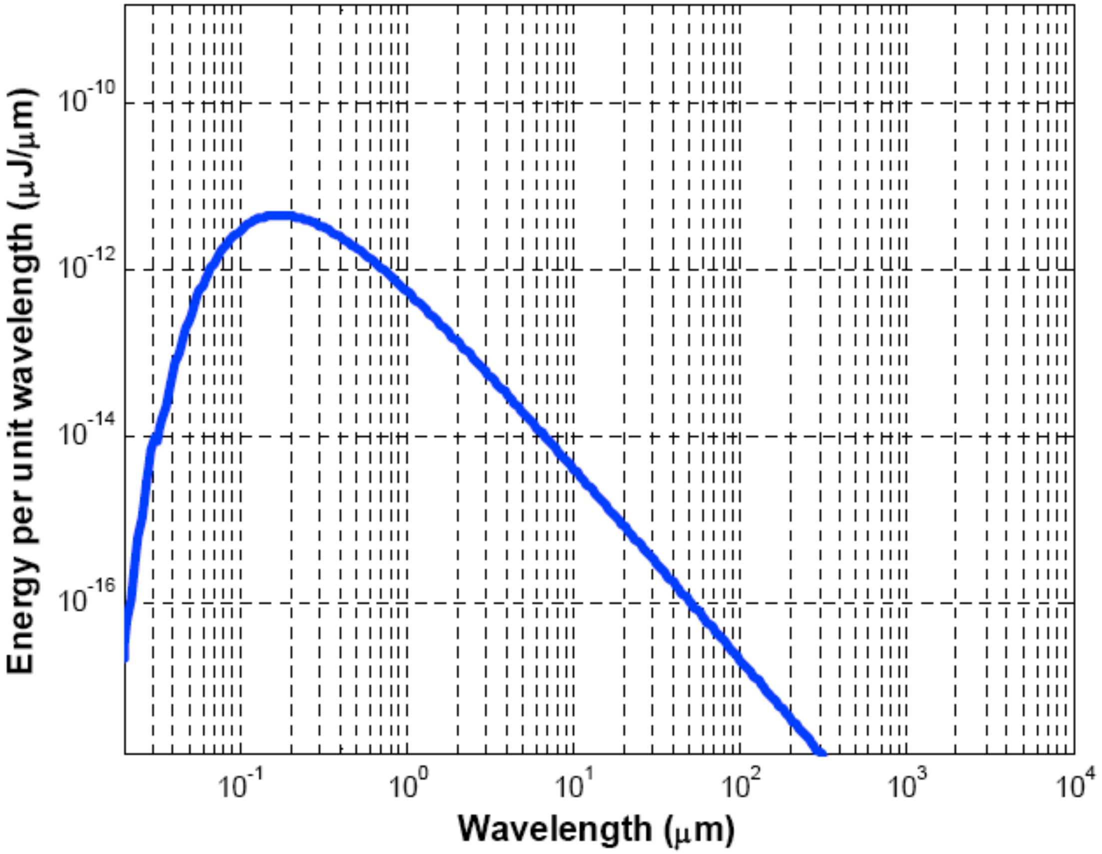
$$I_{tot}(\lambda) = I_{inc}(\lambda)\left[1 + (N-1)f(\lambda)\right]$$

Where $I_{inc}(\lambda) = N\, I_1(\lambda)$ is the total incoherent intensity emitted by the bunch of N particles

and $f(\lambda) = \left|\int dz\, e^{2\pi i z/\lambda} S(r)\right|^2$ is the form factor for the normalized bunch distribution $S(r)$. Here we have assumed that the detector is located at a distance much larger than the length of the electron bunch.

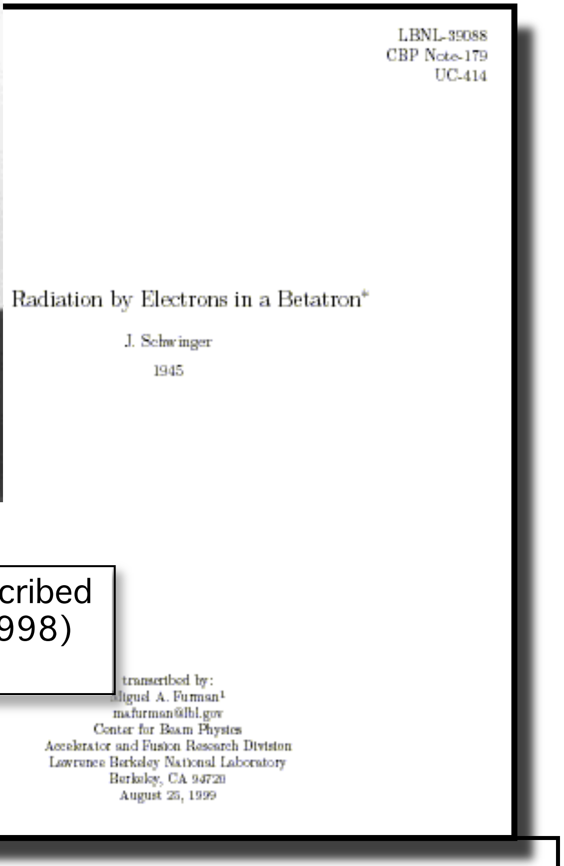
# Coherent SR and bunch shape

Example: Single electron synchrotron radiation spectrum
Circular motion, 130 MeV, R=1.6 m



# Schwinger saves synchrotrons

- First comprehensive report on radiation effects in synchrotron/betatron's is by Schwinger - 1945 unpublished manuscript.
- Questions addressed:
  - Does a single-particle calculation apply to betatrons where the electron current is distributed along the orbit circumference?
  - Will coherent radiation from bunched beams in synchrotrons cause unacceptable power loss? (Recall: scaling is ~$N^2$)



LBNL-39088
CBP Note-179
UC-414

Radiation by Electrons in a Betatron*

J. Schwinger

1945

transcribed by:
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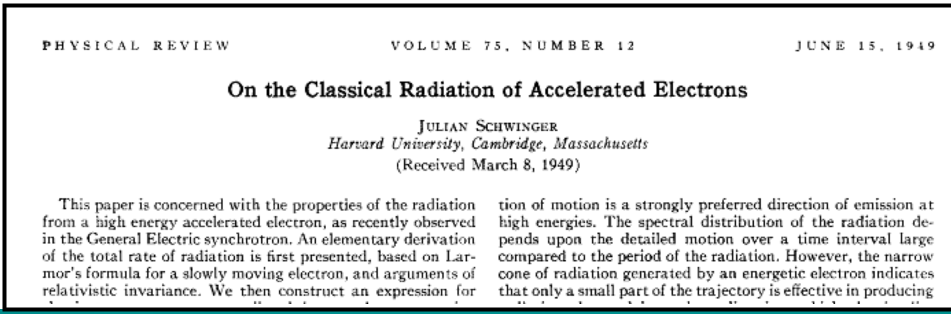
Center for Beam Physics
Accelerator and Fusion Research Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
August 25, 1999

Manuscript transcribed by M. Furman (1998) LBNL-39088



PHYSICAL REVIEW VOLUME 75, NUMBER 12 JUNE 15, 1949

On the Classical Radiation of Accelerated Electrons

Julian Schwinger
*Harvard University, Cambridge, Massachusetts*
(Received March 8, 1949)

This paper is concerned with the properties of the radiation from a high energy accelerated electron, as recently observed in the General Electric synchrotron. An elementary derivation of the total rate of radiation is first presented, based on Larmor's formula for a slowly moving electron, and arguments of relativistic invariance. We then construct an expression for

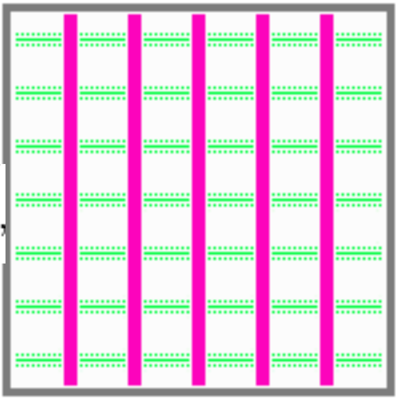
tion of motion is a strongly preferred direction of emission at high energies. The spectral distribution of the radiation depends upon the detailed motion over a time interval large compared to the period of the radiation. However, the narrow cone of radiation generated by an energetic electron indicates that only a small part of the trajectory is effective in producing

*In 1949 Schwinger published a paper on radiation in accelerators but left out any reference to coherent effects*

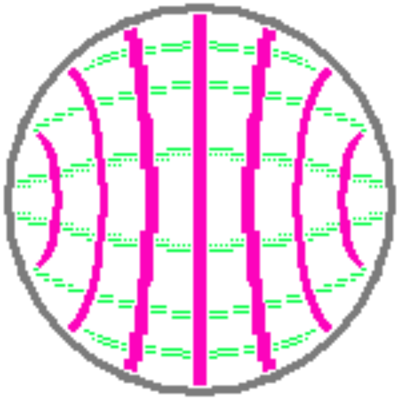
# Shielding of synchrotron radiation

The typical SR spectrum for high energy beams indicates emission from x-rays to DC. However, at long wavelengths, the vacuum chamber can inhibit SR emission from a waveguide cutoff. Consider a rectangular and circular waveguide:

$$\omega_c = c\sqrt{\left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2},$$



$TE_{1,0}$ mode

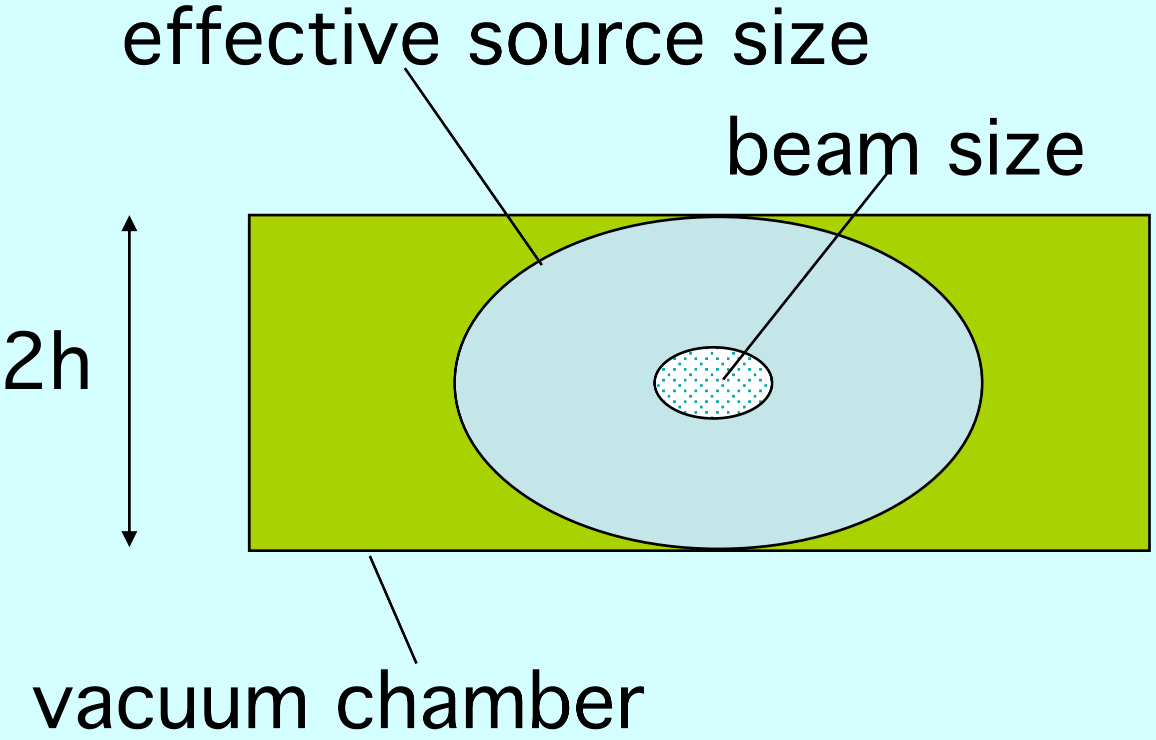


$TE_{1,1}$ mode

$$\omega_c = c\frac{\chi_{01}}{r} = c\frac{2.4048}{r},$$

This condition holds for plane waves. However, SR is not a plane wave. This effect significantly reduces the cutoff wavelength of SR emission.

# Effect of vacuum chamber

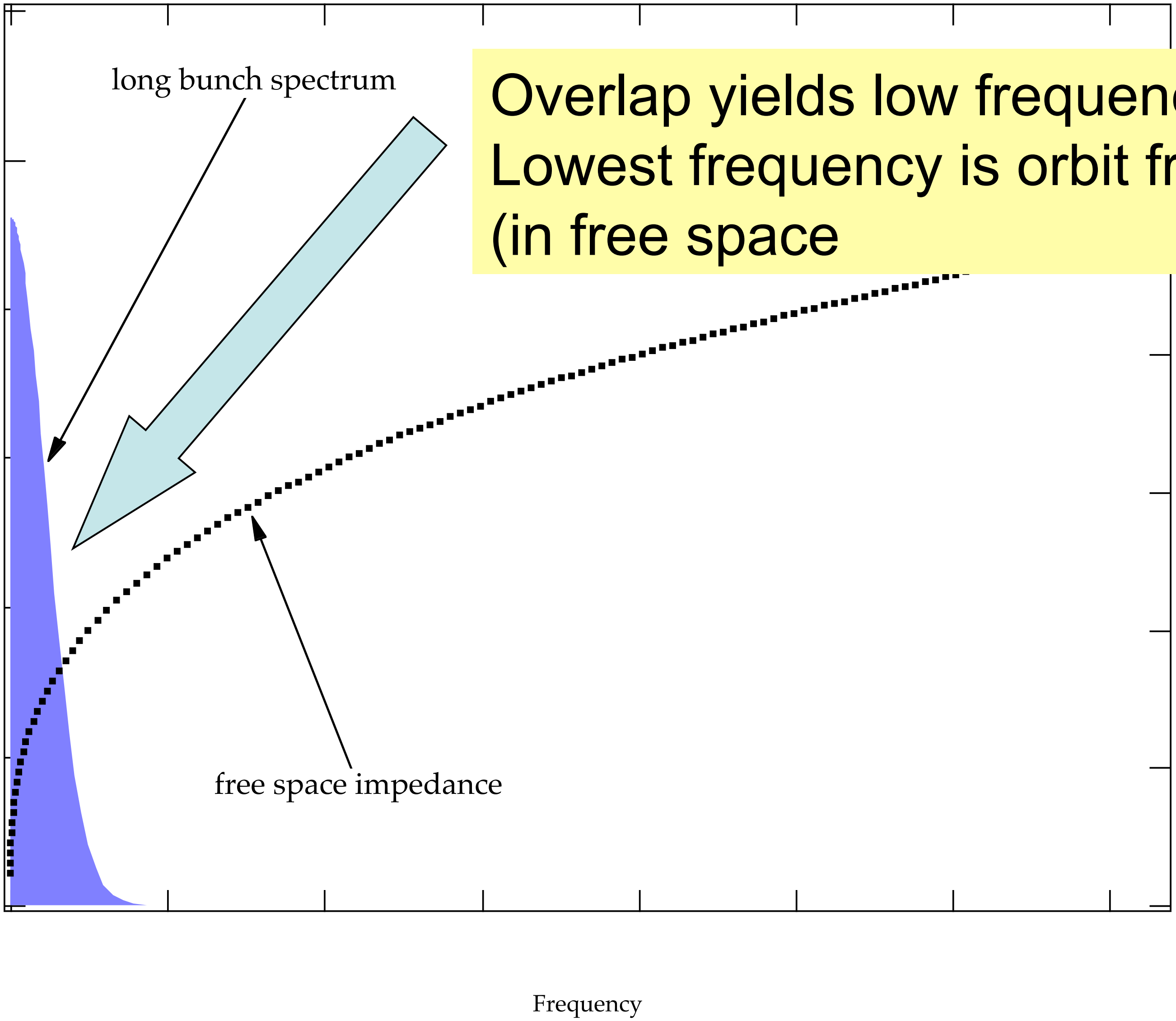


$$\varepsilon_{rad} = \frac{\lambda}{4\pi}$$

$$\varepsilon_{rad} = \sigma\theta$$

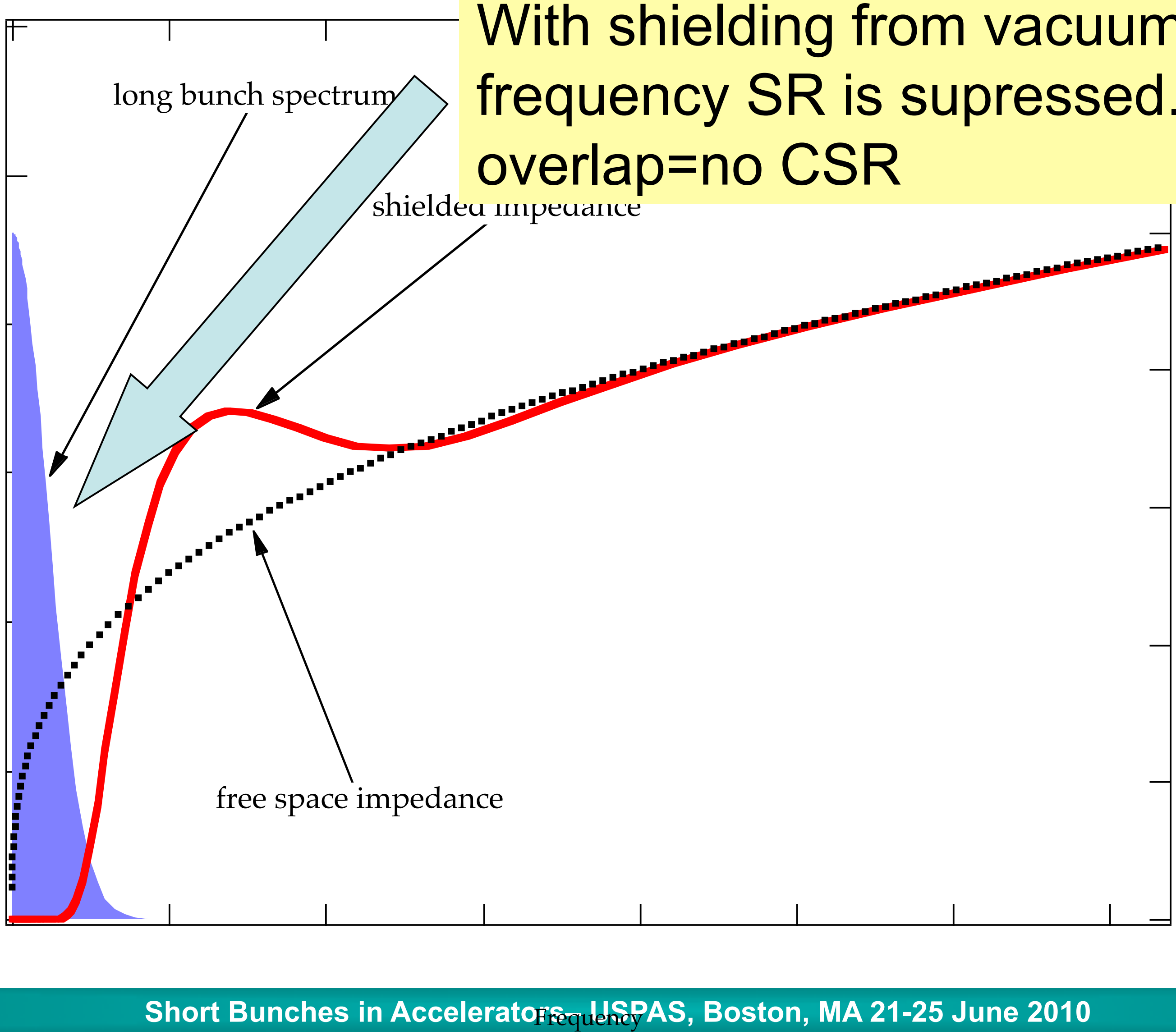
When the effective size of the SR source is equal to the height of the vacuum chamber, SR is suppressed.

# Shielding and bunch length



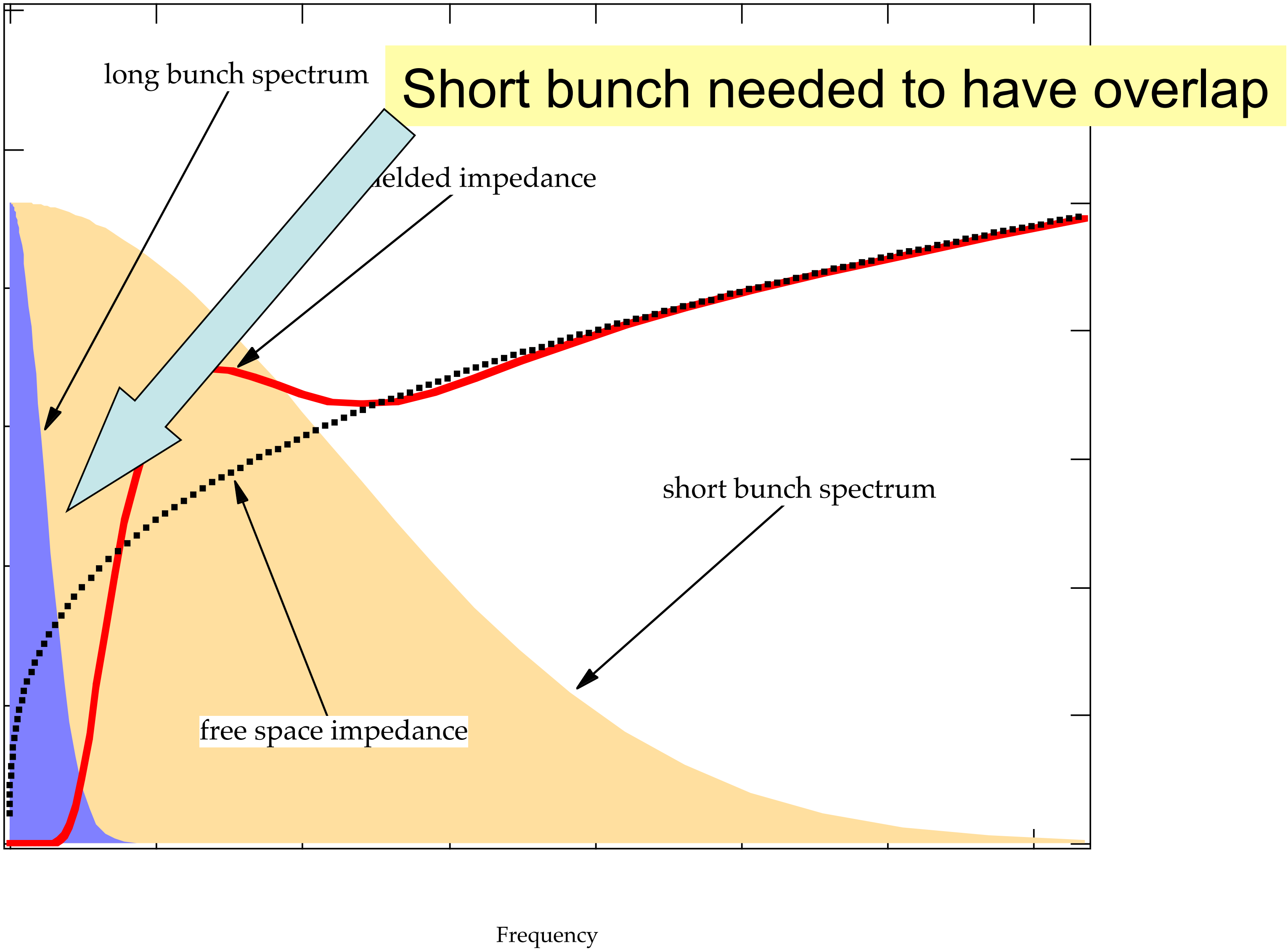
Overlap yields low frequency CR;
Lowest frequency is orbit frequency
(in free space

# Shielding and bunch length



With shielding from vacuum, low frequency SR is supressed. No overlap=no CSR

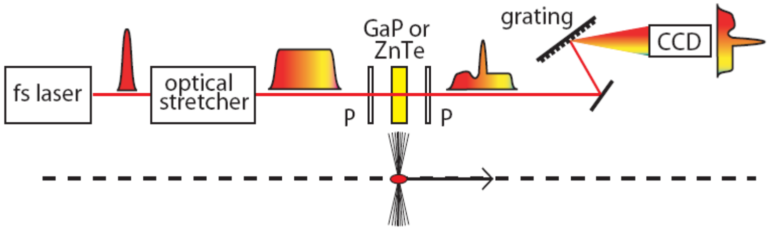
# Shielding and bunch length



Short bunch needed to have overlap

# Electro-Optic Detection of Direct Beam Fields

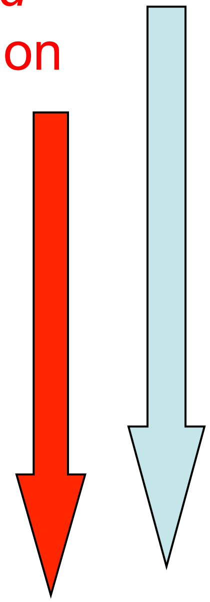
## Spectral Decoding



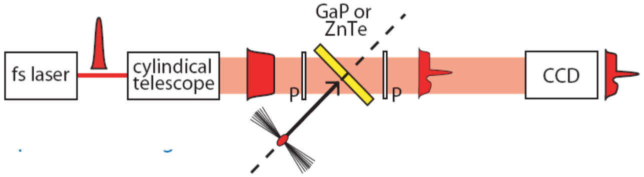
**FELIX**
**DESY**
**LBNL**
**...**

complexity

*demonstrated*
time resolution

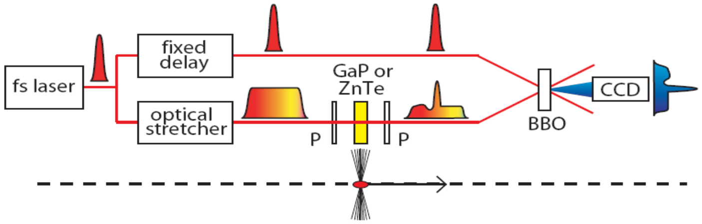


## Spatial Encoding



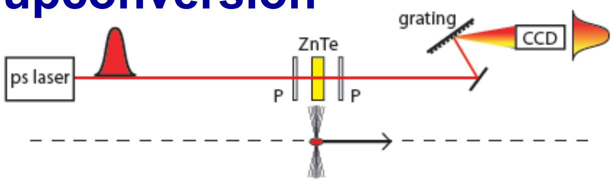
**SLAC**
**DESY**
**LBNL, ...**

## Temporal Decoding

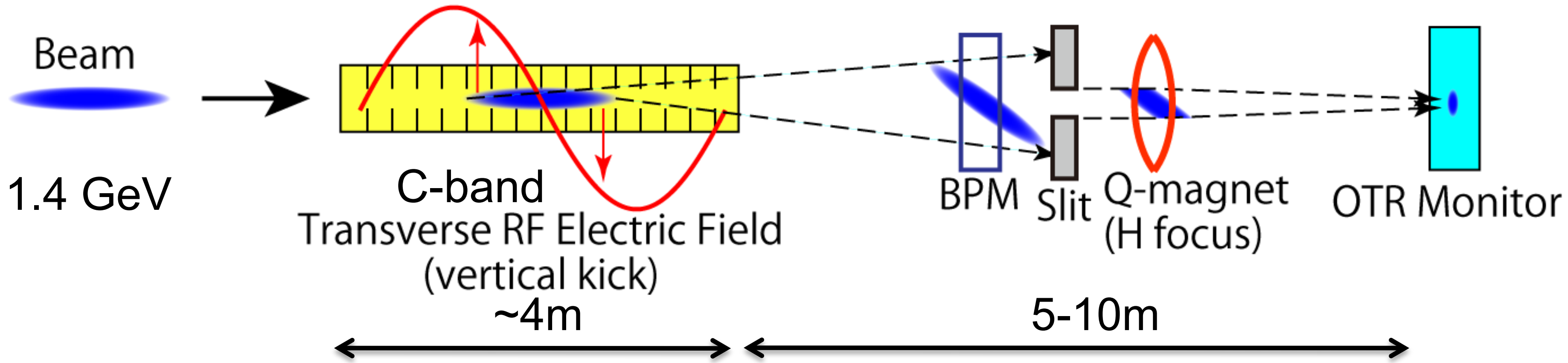


**FELIX**
**DESY**
**RAL(CLF)**
**MPQ**
**Jena, ...**

## spectral upconversion

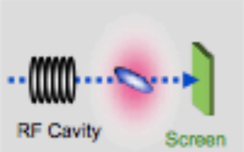


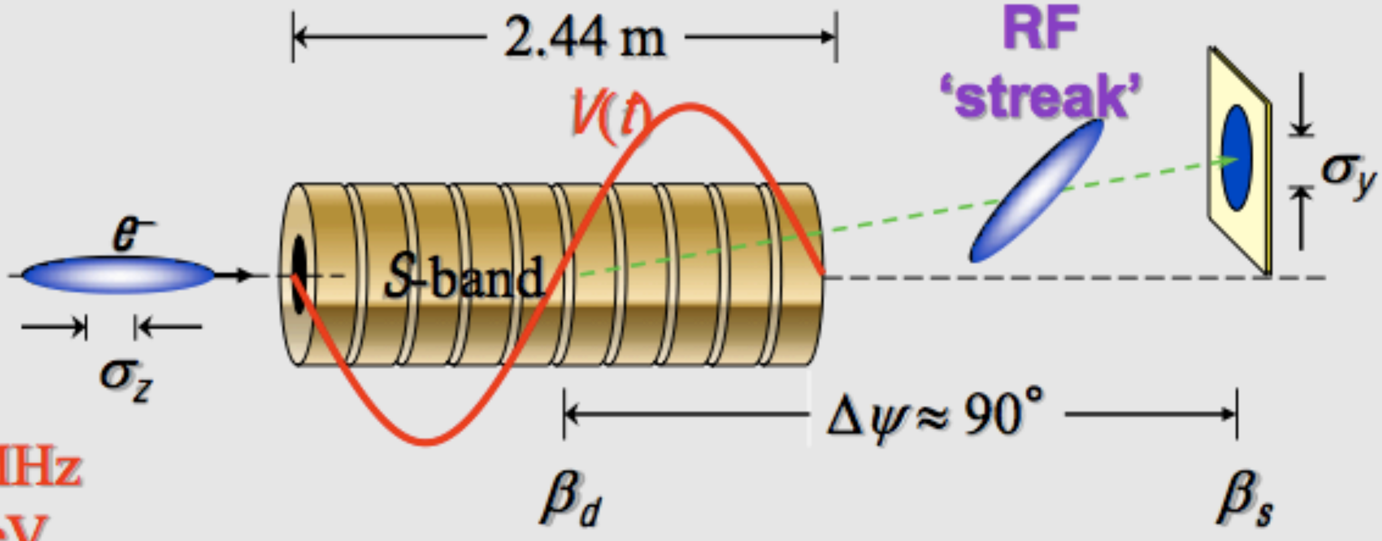
# Transverse Deflecting Structure



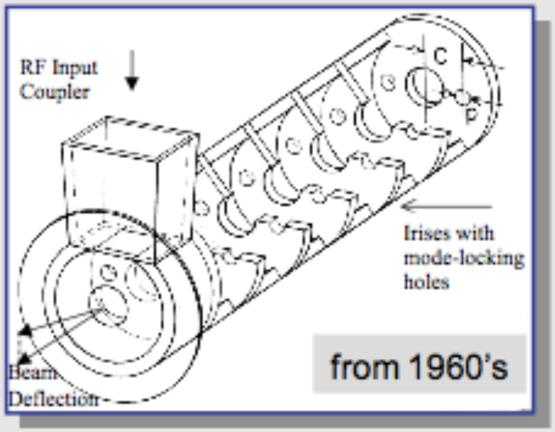
- The electron bunch is vertically pitched by transverse RF voltage and the temporal structure is converted to a spatial distribution.
- Beam image is taken by an OTR monitor.

# Deflecting cavities





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

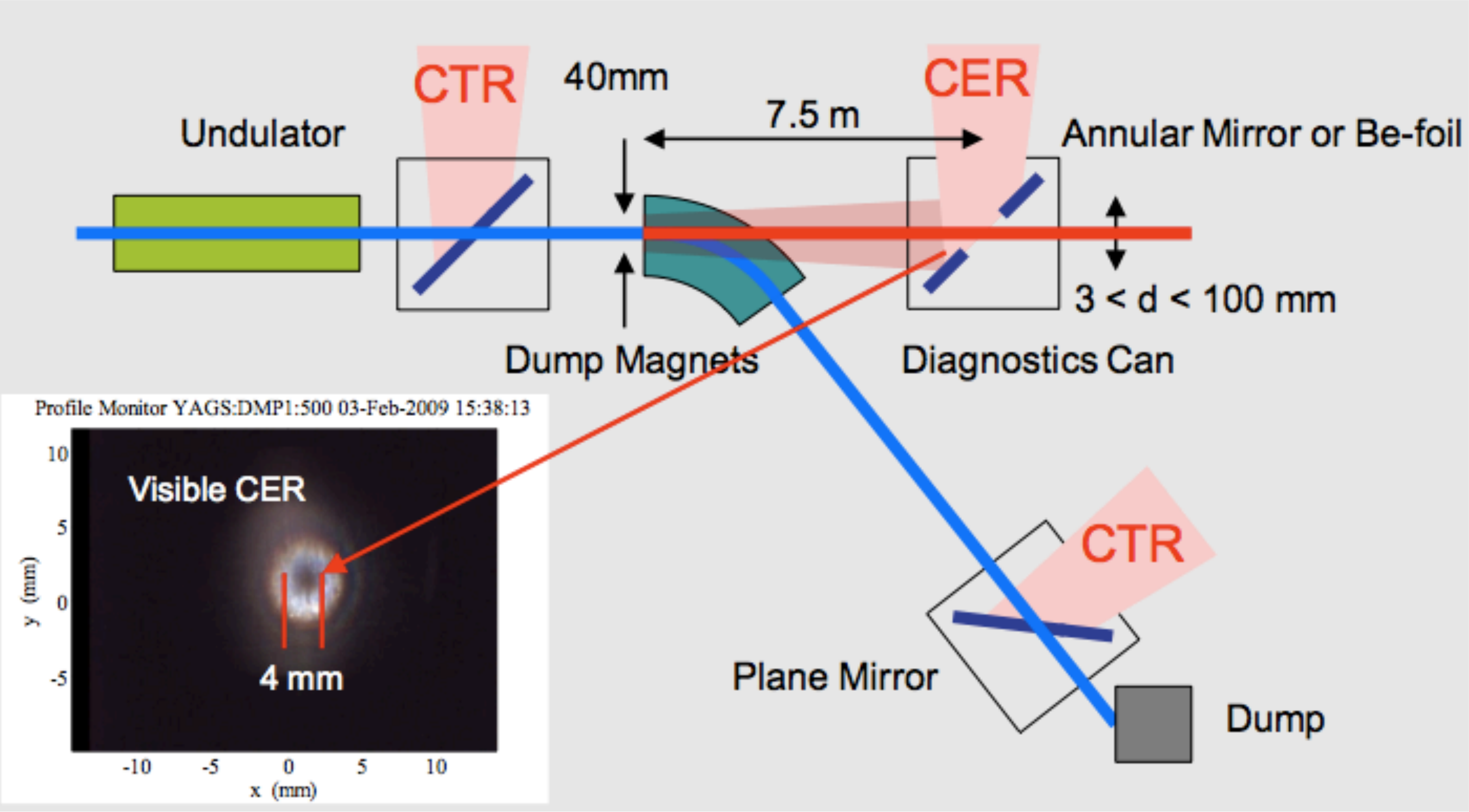


from 1960's

$$\sigma_y^2 = \sigma_{y0}^2 + \beta_d \beta_s \sigma_z^2 \left( \frac{k_{RF} e V_0}{E_s} \sin\Delta\psi \cos\phi \right)^2$$

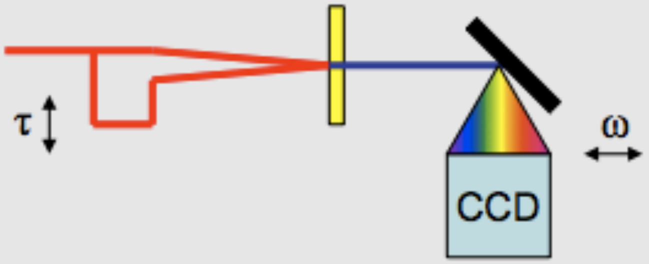
- Map time axis onto transverse coordinate
- Simple calibration by scan of cavity phase
- Typical calibration factor ~10 from z → y

# Extracting Coherent radiation for fsec bunches



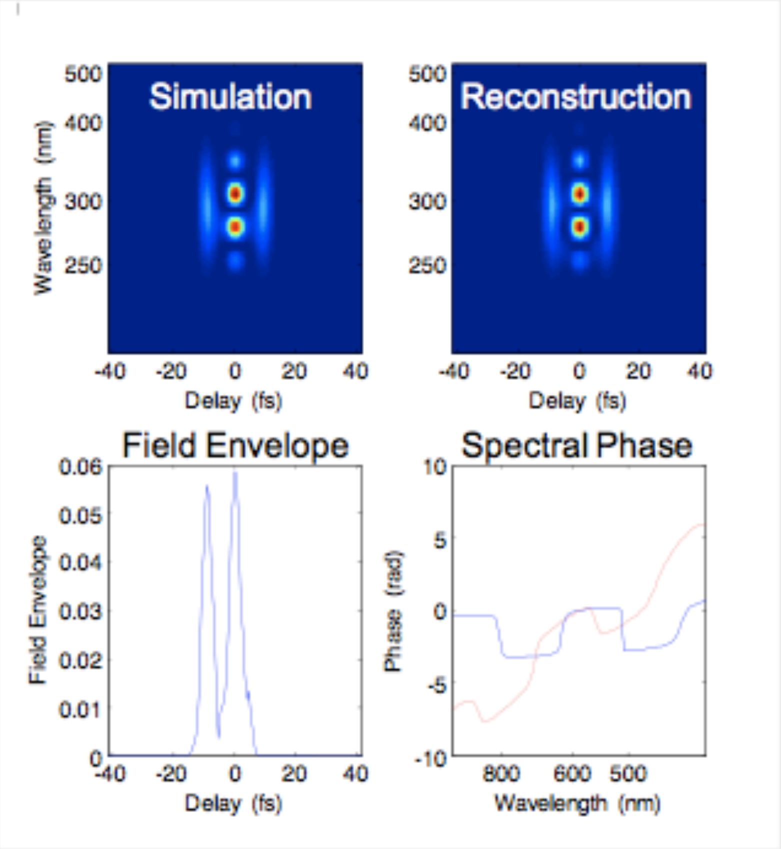
# Optical techniques: FROG

- Measure spectrum of SHG in BBO vs. delay

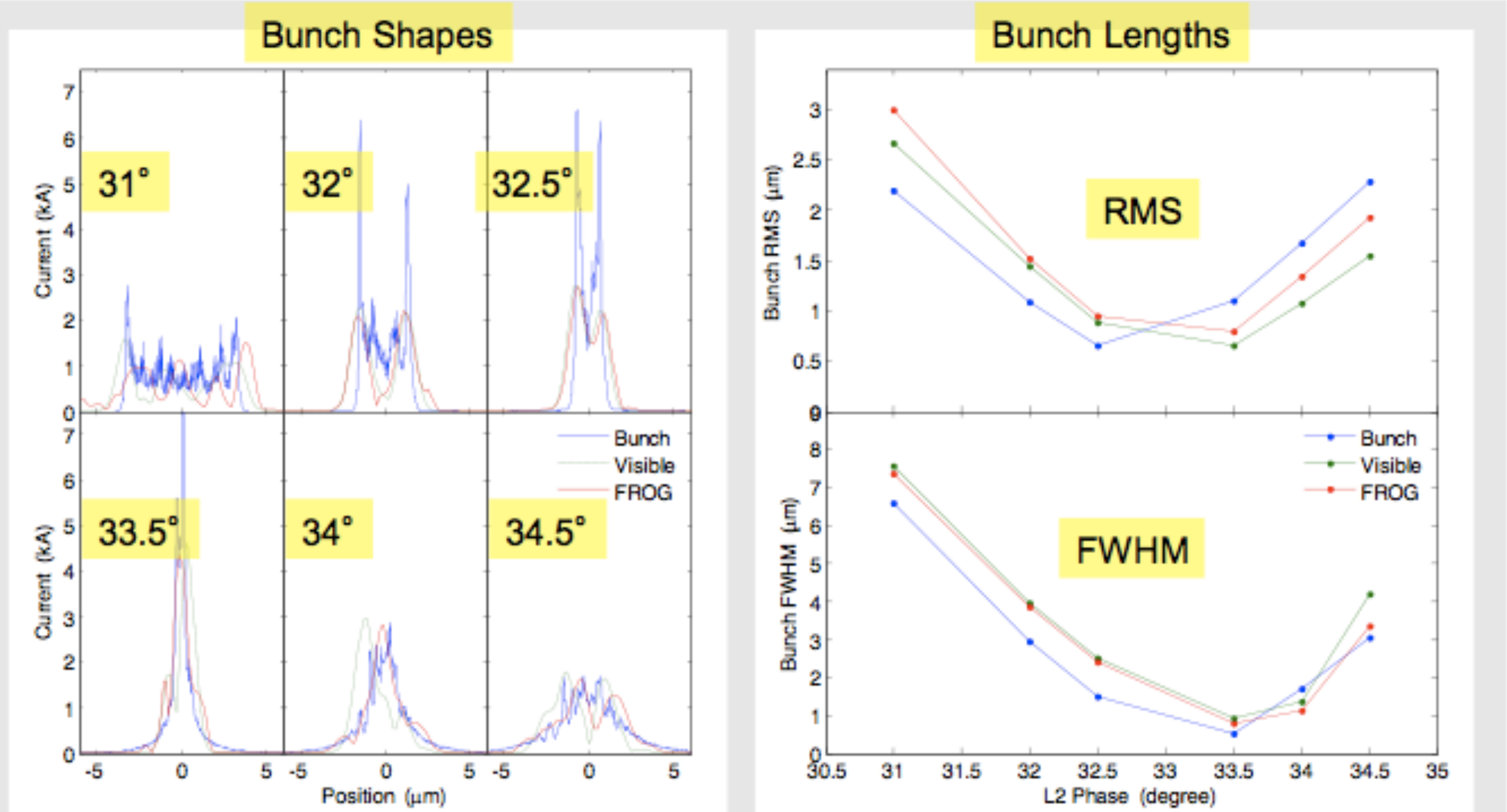


$$I(\omega,\tau) \propto \left| \int E(t)E(t-\tau)e^{-i\omega t}\,dt \right|^2$$

- Remove carrier frequency from reconstructed field
- Envelope is $|E(t)|^2$
- Required pulse energy is few 100 nJ
- COTR energy between 0.1 – 1 μJ
- Phase matching over 300 nm BW requires few μm crystal

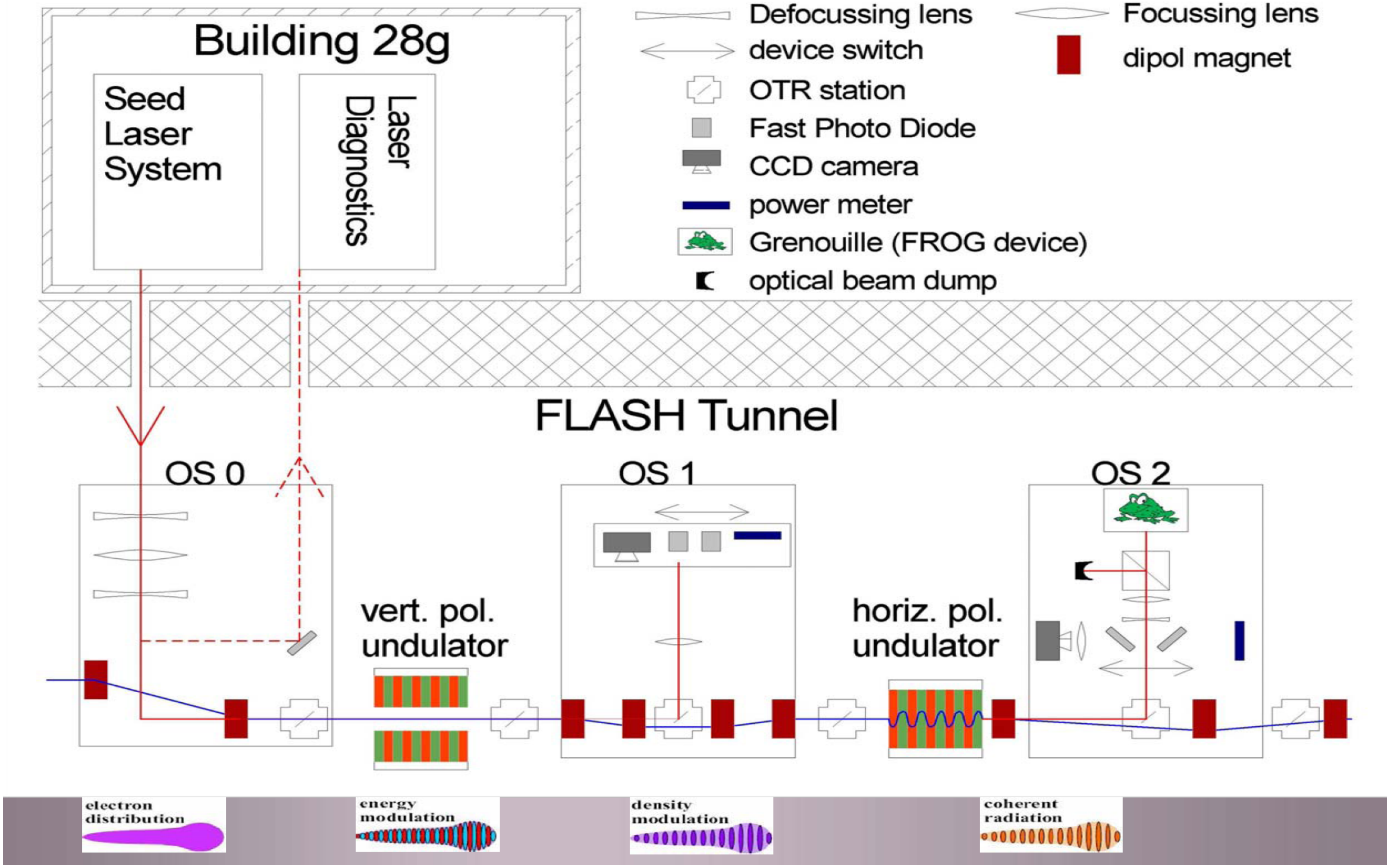


# Simulated FROG results for LCLS



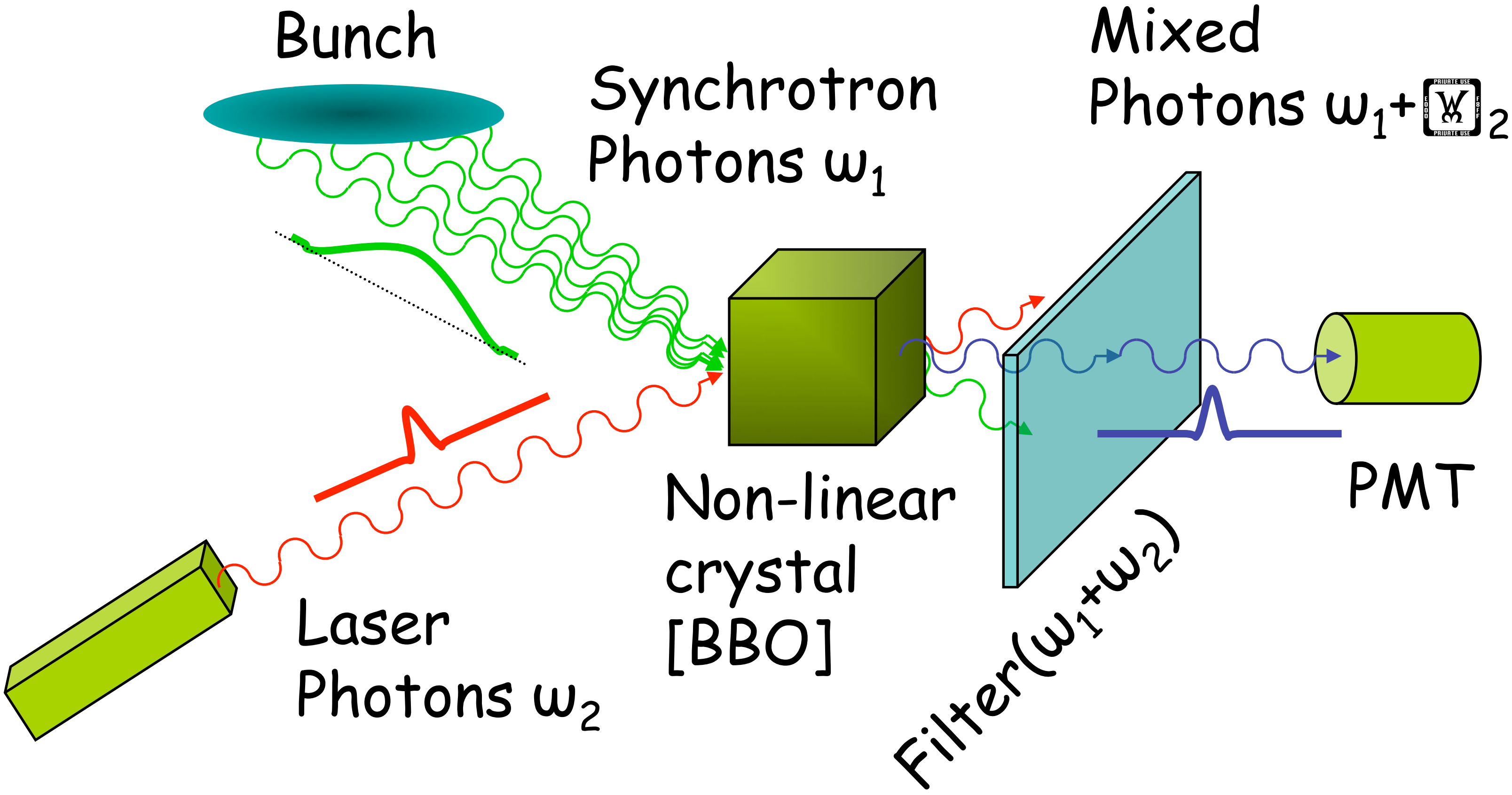
- Reconstruction longer for undercompressed and shorter for overcompressed bunches

# ORS: Optical Replica Synthesizer



# Cross-correlator with SR

$\omega_1+\omega_2$ = visible wavelength



Bunch

Synchrotron Photons $\omega_1$

Mixed Photons $\omega_1+\omega_2$

Non-linear crystal [BBO]

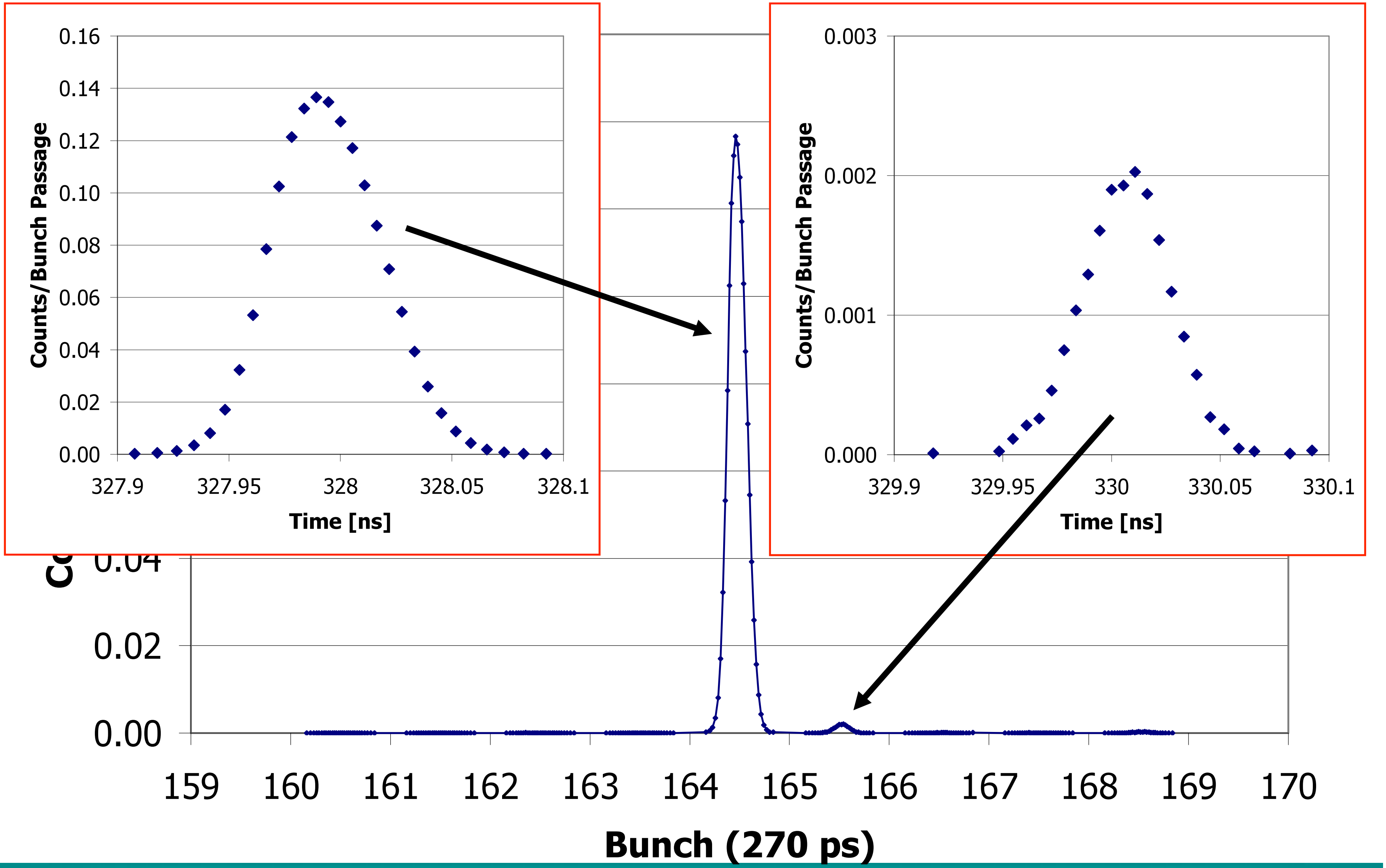
PMT

Laser Photons $\omega_2$

Filter($\omega_1+\omega_2$)

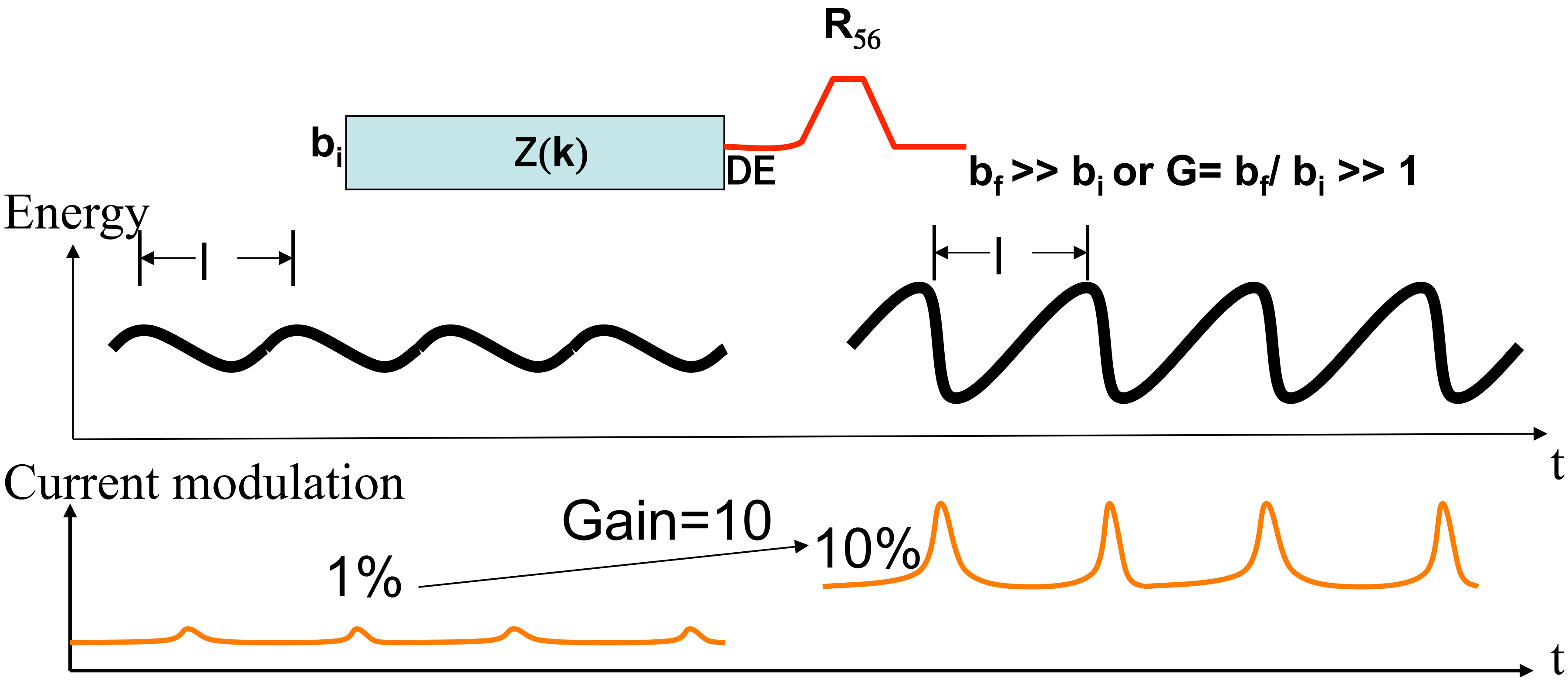
laser pulse length << bunch length

# ALS Cross-correlator measurement



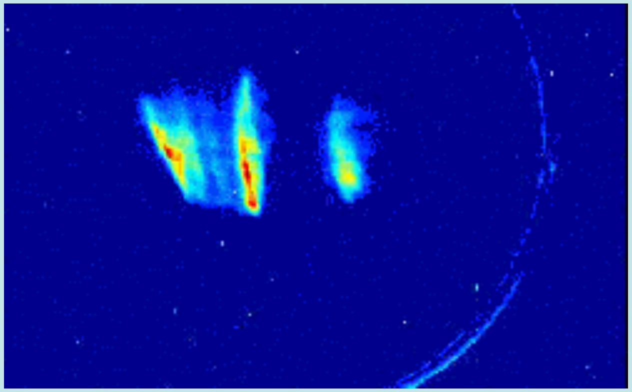
# Microbunching instability

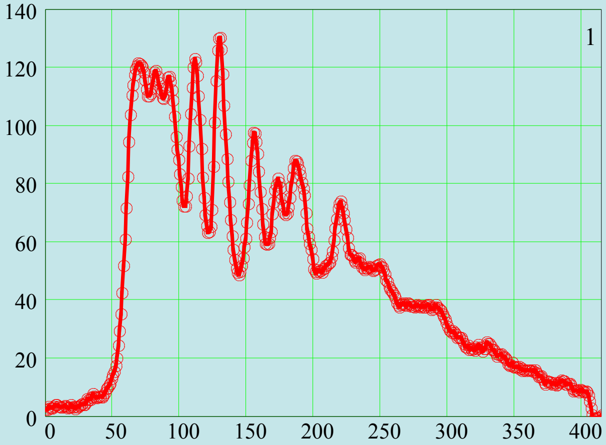
- Initial density modulation induces energy modulation through long. impedance Z(k), converted to more density modulation by a chicane ➔ growth of slice energy spread / emittance!



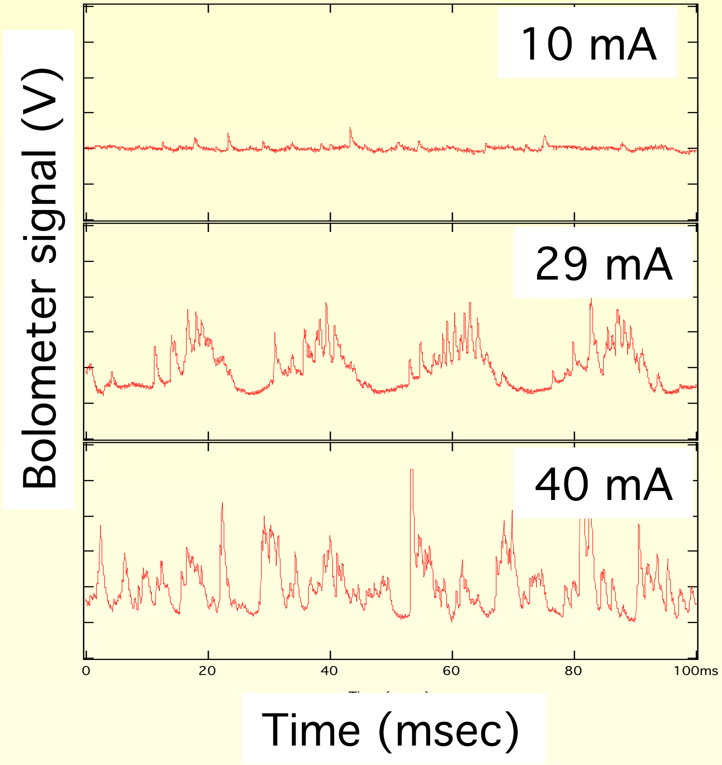
# Microbunching observations

## BNL SDL Linac





## ALS Storage Ring



Bursts of far-IR CSR observed on a bolometer. Threshold depends on beam energy, bunch length, energy spread, and wavelength.

# THz Detectors

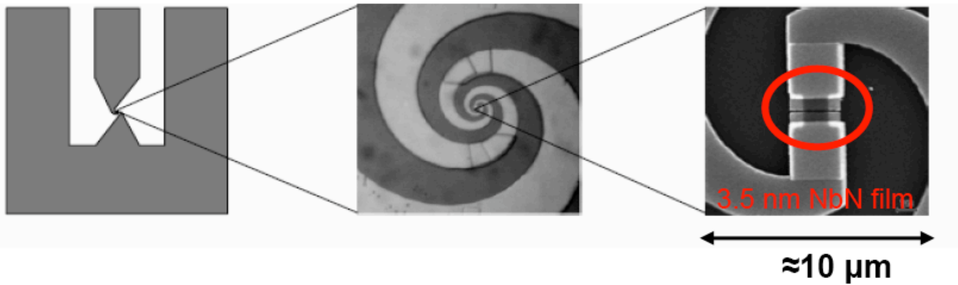
Pyroelectric


Virginia Diodes, Inc., Char

Diode


FIR Bolometer

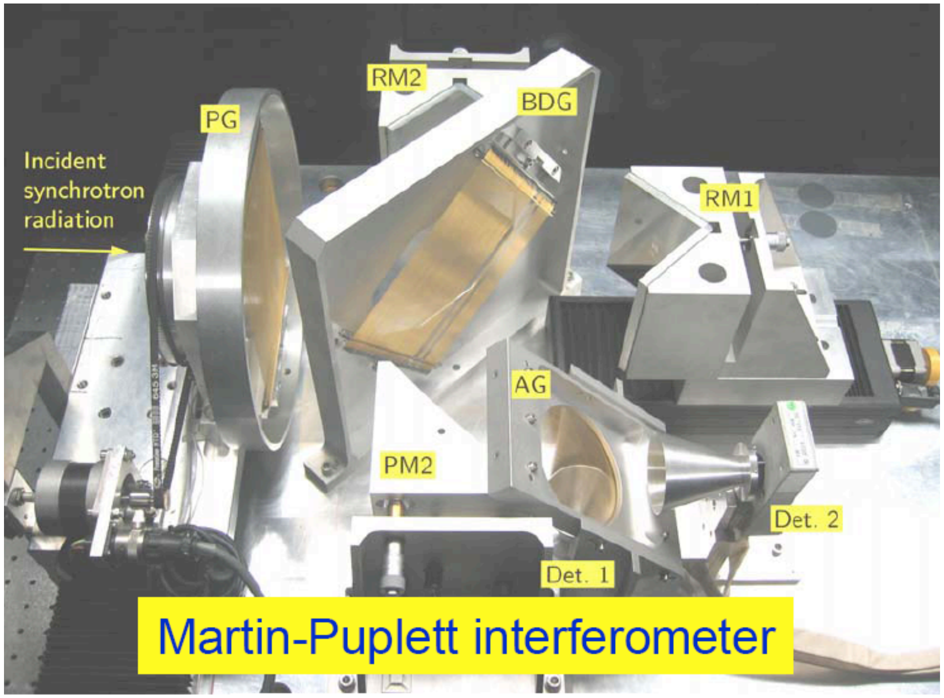
Log-spiral antenna receiver



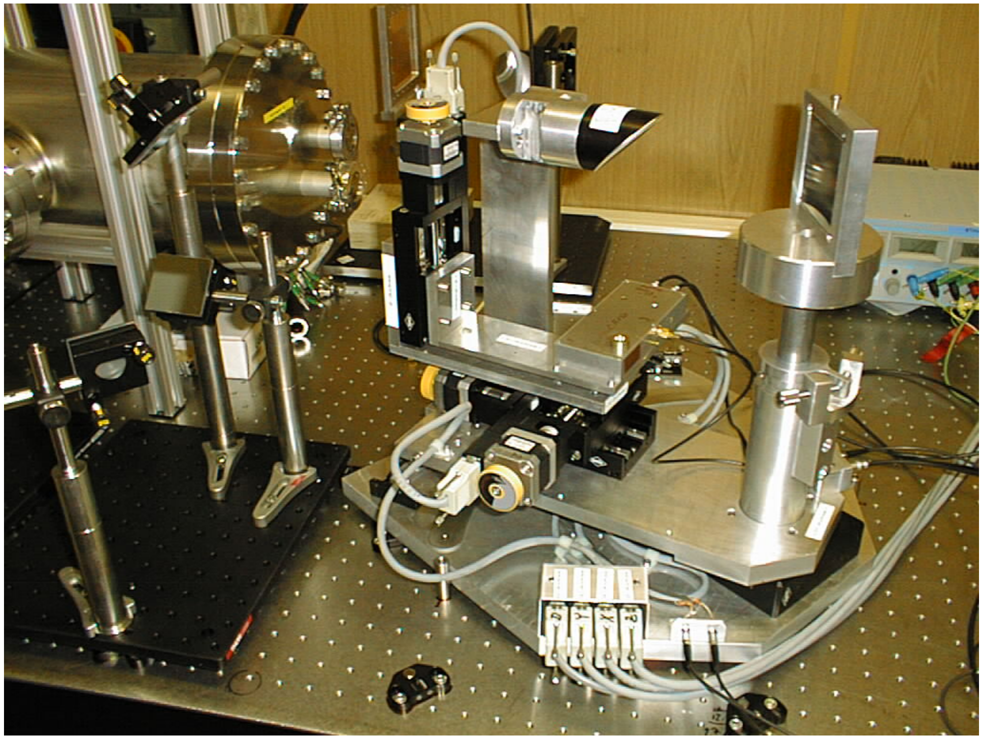
Hot electron MicroBolometer

Golay Cell

# THz spectrometers



Grating spectrometer



# Class Projects

- Four topics: choose one
  - Applications of deflecting cavities
  - Bunch length measurement from fluctuation of radiation
  - Ultrafast Electron Diffraction
  - Microbunch trains
- Your group will make a 1-hour presentation on this topic on Friday with a dry-run on Thursday afternoon.
- I will provide a collection of background materials. Feel free to look for more.

# Presentations guidelines

- Presentation time should be split equally within the group
- Focus on explaining the basic concept of the technique and highlight any bunch measurement techniques used.
- Cite references wherever needed.