Bunch Length Diagnostics: Current Status & Future Directions
Part 1

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Electron bunch profile diagnostics approaching femtosecond resolution

Part 1

- Why do we need femtosecond bunch profile measurements?
- Direct Particle Techniques
- Revision of Ultrashort Pulses
- Aside: Free Electron Lasers

Part 2

- “Radiative” Techniques
- Electro Optic Techniques & Variants
- Other Methods
- Summary & References

Qualification

In these talks I interpret “sub-ps bunch length monitor” to mean an accelerator diagnostic that attempts to provide a “true” temporal profile of an ultrafast electron bunch, rather than one which only aims to inform on the first moments of the bunch profile, or on the presence of structure on a particular time scale of interest.

The need for femtosecond longitudinal diagnostics

1. Advanced Light Sources: 4^{th} & 5^{th} generation

Free-Electron Lasers (explained later) kA peak currents required for collective gain

older devices: τ *= 200fs FWHM, q ~ 200pC* *(< 2010, standard)*
newer devices: τ *= 10fs FWHM, q ~ 10pC* *(increasing interest)*

Low-emittance Storage Rings

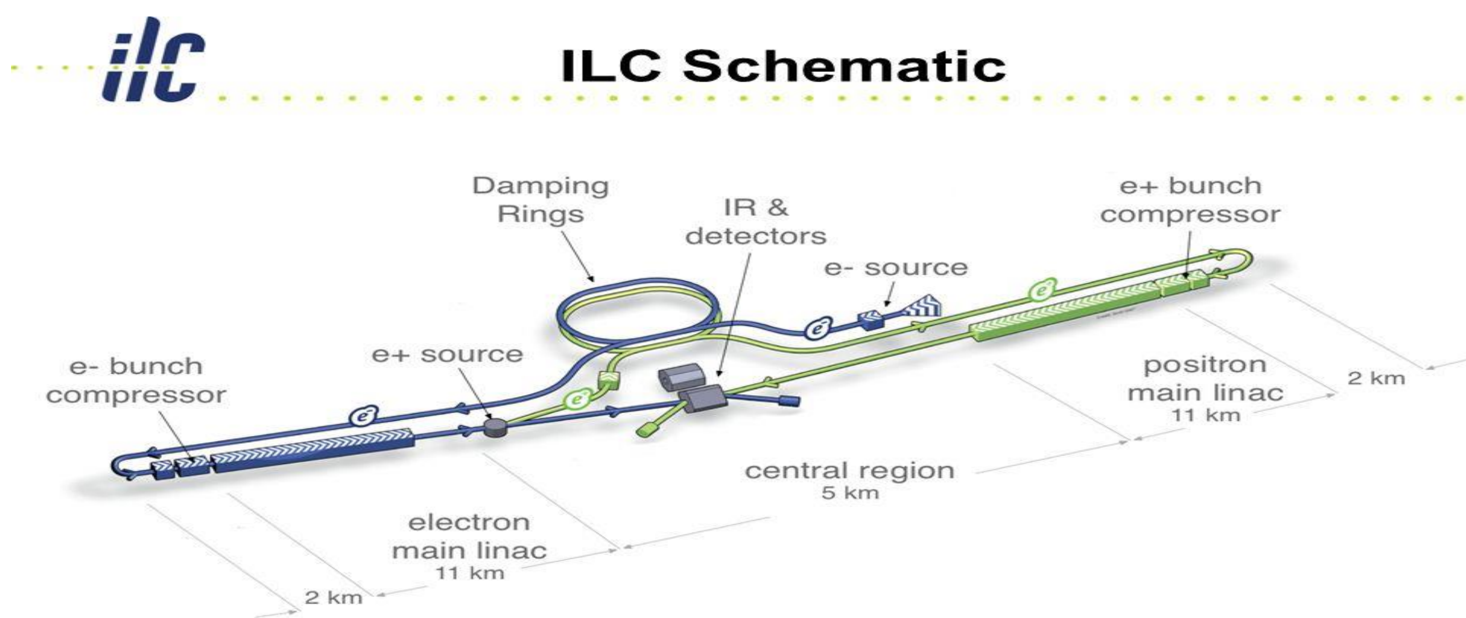
τ *= 10-200 ps rms,* ε_H *= 150-300 pm.rad (e.g. MAX-IV, ESRF II)*

2. Particle Physics:

Linear Colliders (CLIC, ILC) e^+-e^- and others

short bunches, high charge, high quality - *for high luminosity*

- *~150fs rms, ~1nC stable, known (smooth?) longitudinal profiles*



3. Laser Plasma Wakefield Accelerators [LPWA] & variants:

Laser-plasma accelerators operate via ultra-short electron bunches!

- *1-5 fs FWHM (and even shorter in principle), ~20pC + future FELs*

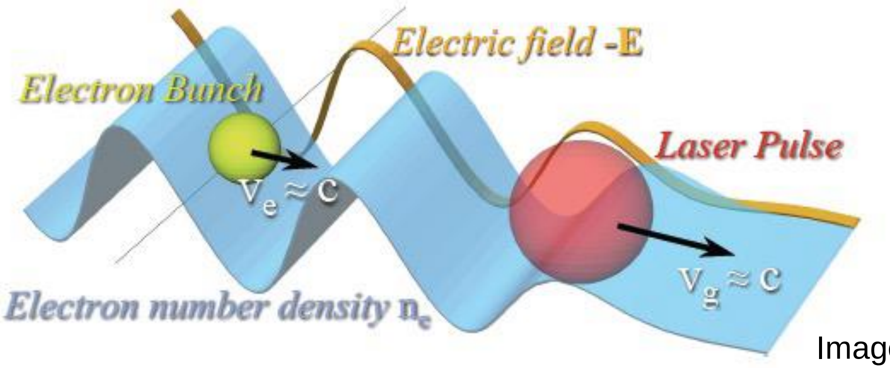


Image courtesy of A.G.R. Thomas

In general, can have significant influence on bunch profile from …

wake fields

space charge

CSR

collective instabilities

machine stability & drift

⇒ ***must therefore develop single-shot diagnostics***

Two distinct classes of diagnostics

Grouped by similar physics and capabilities / limitations

Direct Particle Techniques

$\rho(t) \rightarrow \rho(x)$

longitudinal $\rightarrow$ transverse imaging

RF zero-phasing

$\rho(t) \rightarrow \rho(\gamma) \rightarrow \rho(x)$

Transverse Deflecting Cavities

$\rho(t) \rightarrow \rho(x') \rightarrow \rho(x)$

"Radiative" Techniques

$\rho(t) \rightarrow E(t)$

propagating & non-propagating

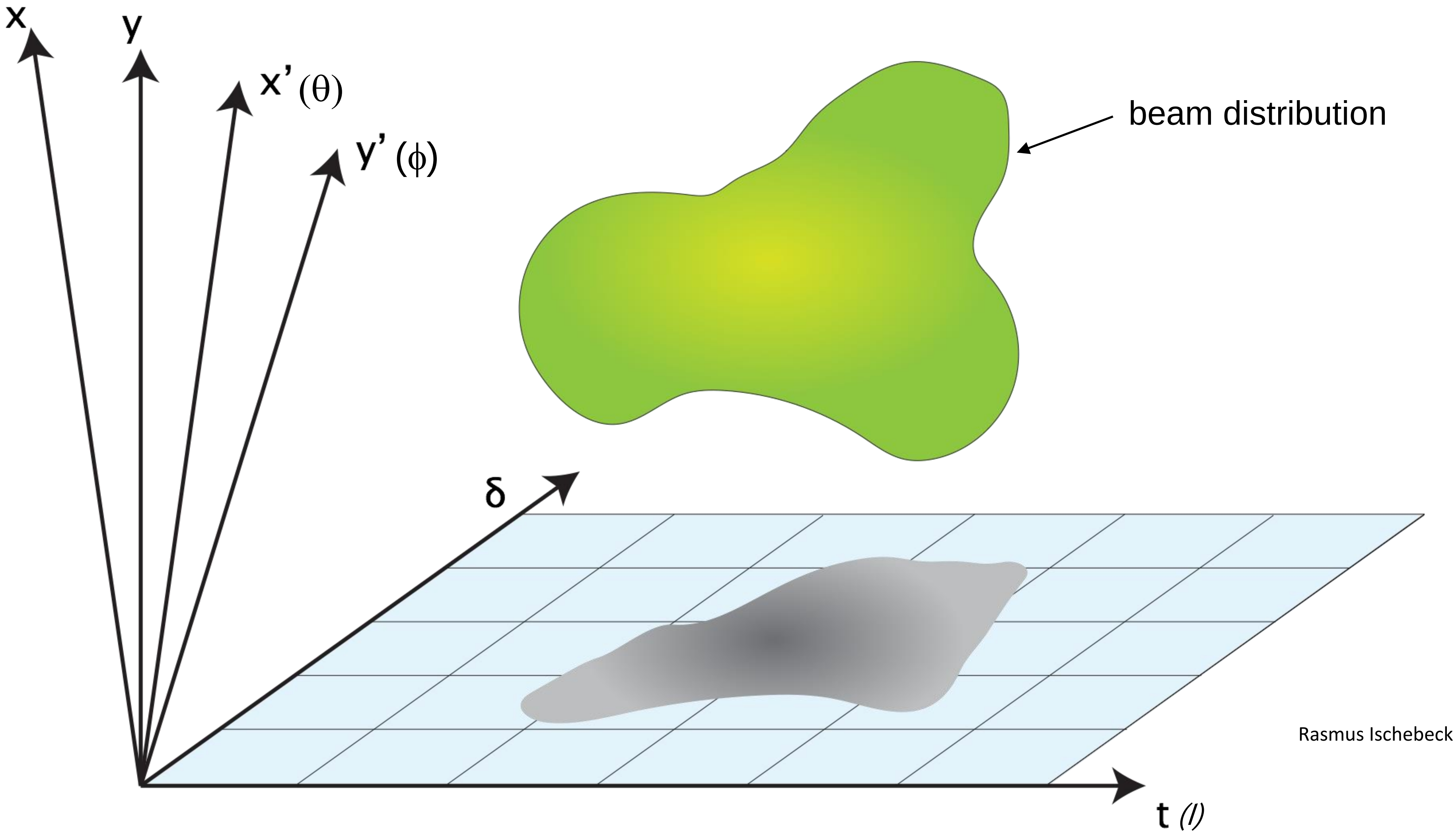
Spectral domain:

- CTR, CDR, CSR (spectral characterisation)
- Smith-Purcell
- Electro-Optic

Time domain:

- CTR, CDR (autocorrelation)
- Optical Replica
- Electro-Optic + Transposition
- Other techniques

6-dimensional beam phase space



The *longitudinal phase space* is the projection on these last two dimensions, and in particular the time, which is very difficult to measure with femtosecond accuracy. No diagnostics exist for the entire distribution.

Phase Space Transformations

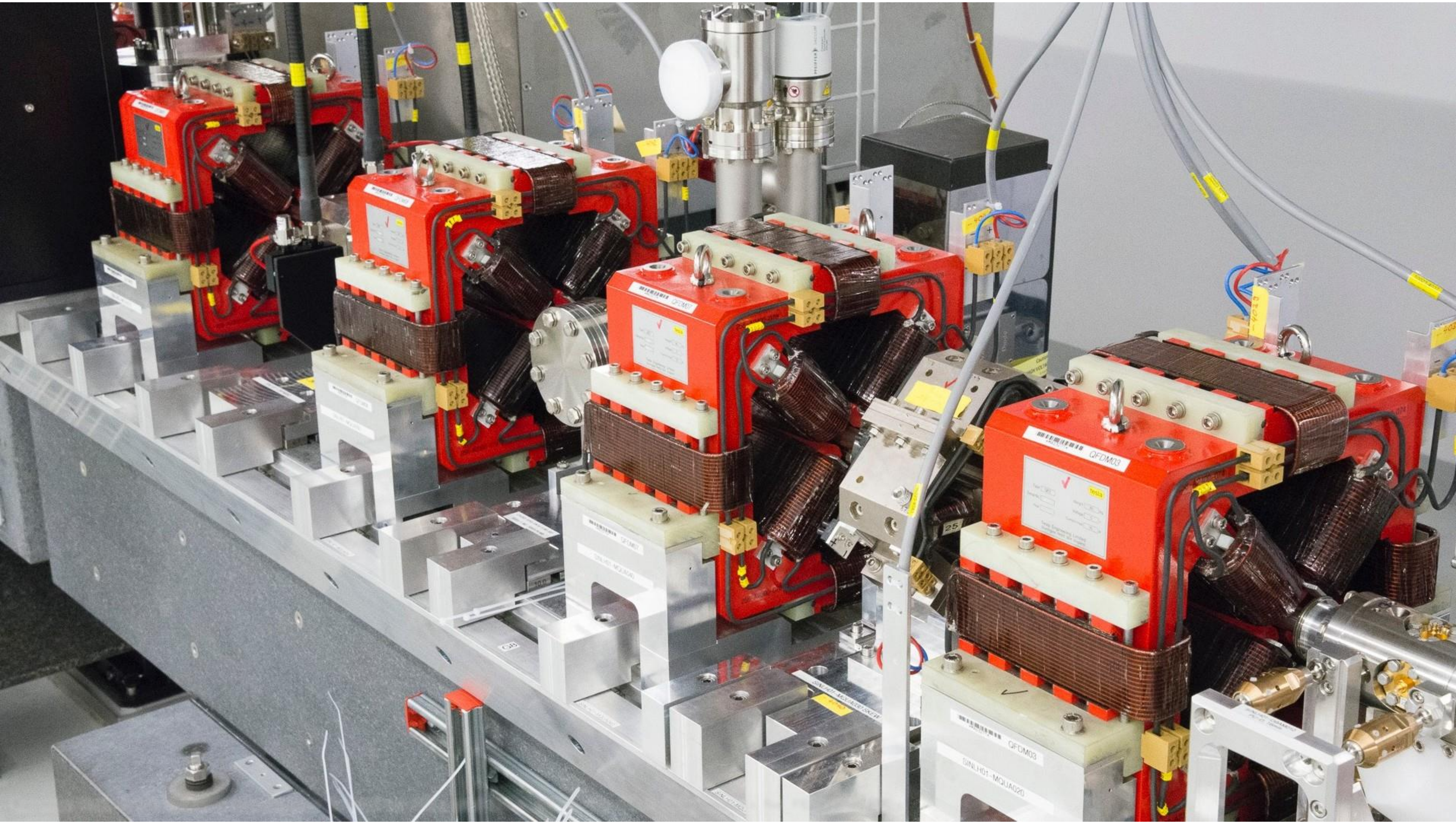
Most charged-particle beam diagnostics are carried out by performing phase space transformations of the charged particles themselves or their products (usually photons).

Charged-particle phase space transformations can be performed by:

- quadrupole magnets (x-x', y-y')
- dipole magnets (δ-x')
- RF deflectors (t-x')

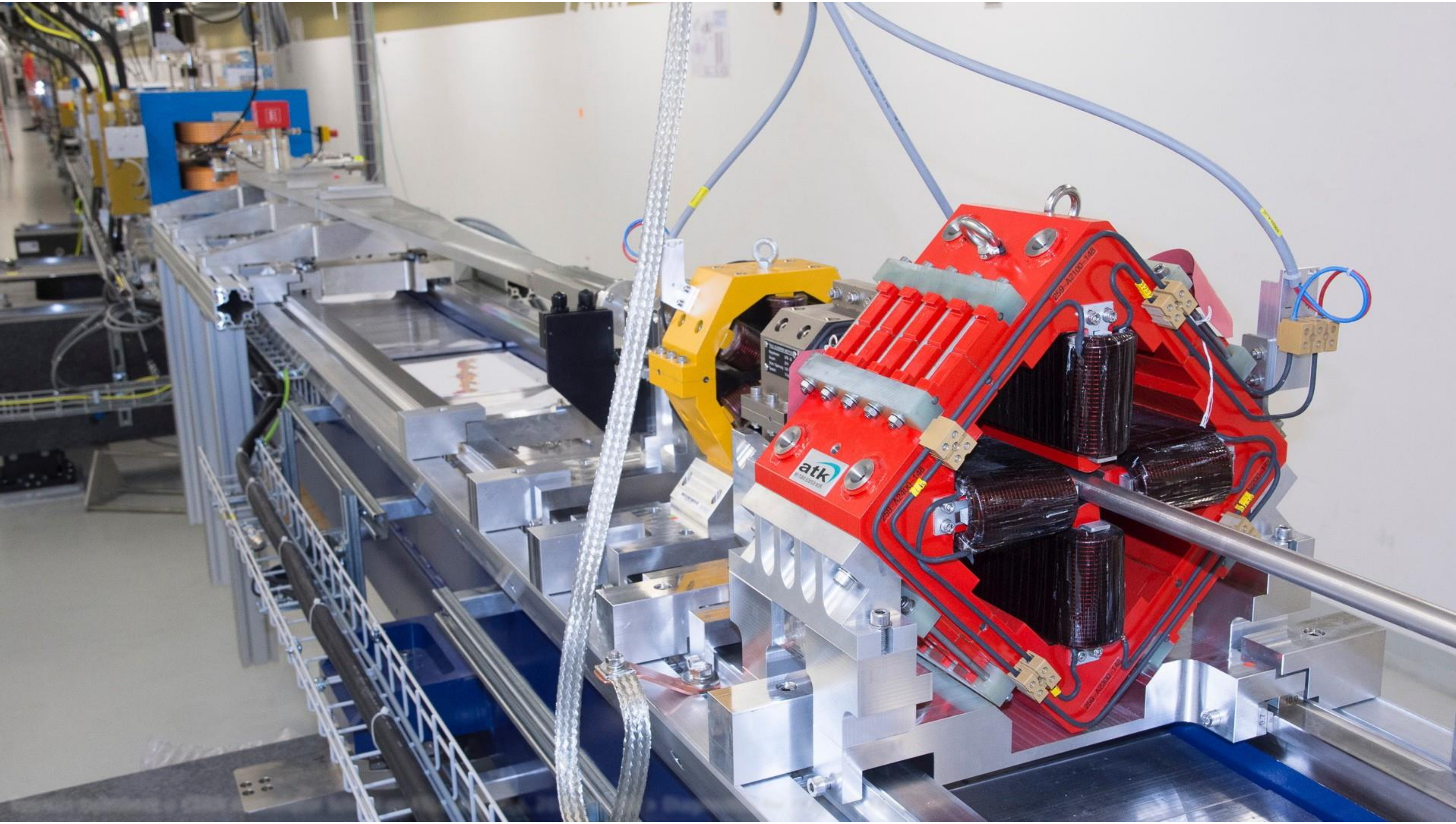
Specialist transformations can be carried out by (e.g.):

- off-crest RF acceleration
- dispersive systems
- magnetic bunch compressors
- energy compressor systems



Rasmus Ischebeck

Passage through quadrupole magnets results in a phase space transformation between x and x'(θ), and between y and y'(ϕ).



Rasmus Ischebeck

Skew (or rotated) quadrupoles couple the horizontal coordinates x—y’ and y —x’.
Skew quadrupoles in dispersive sections (pictured here in a bunch compressor) couple energy-momentum and transverse coordinates.

Class 1. Direct Particle Techniques

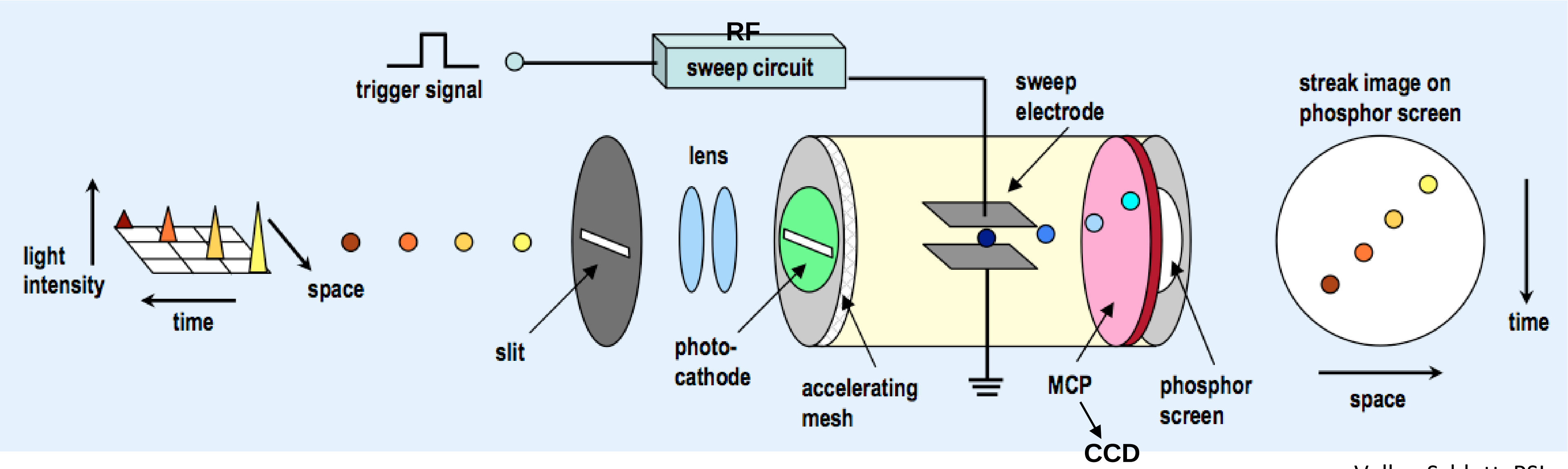
Here we act *directly* on the electron beam
to deflect or disperse the beam particles

We shall see that in all cases we have to be
very sure about the electron beam optics
throughout the diagnostic

1.1 RF Streak Camera

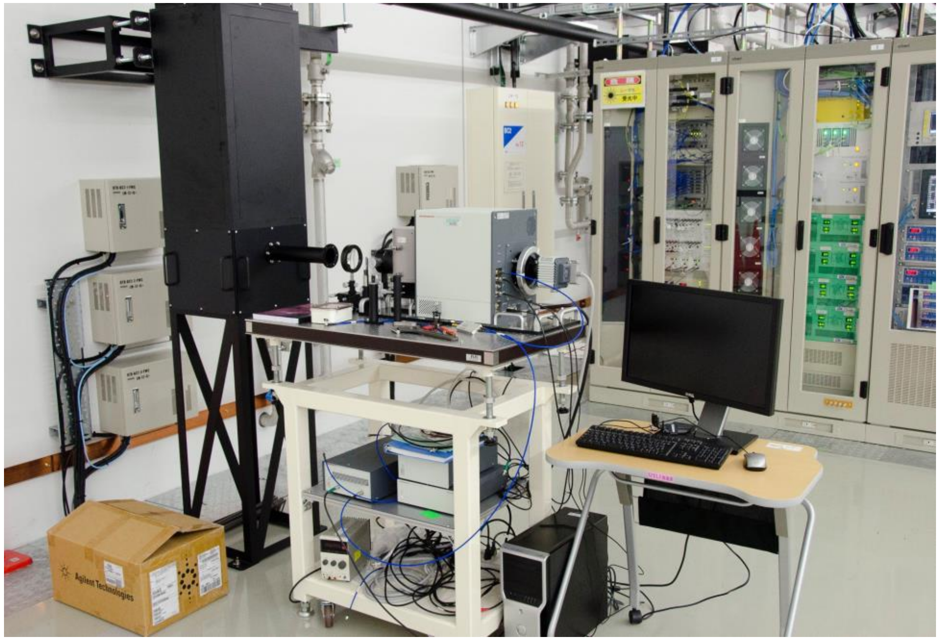
- *Radiation photons* liberate *photoelectrons* from a photocathode
- Accelerated electrons are swept transversely by sweep electrodes
- Detection of photoelectrons with a 2-dimensional sensor
- Achievable time resolution ~300fs FWHM

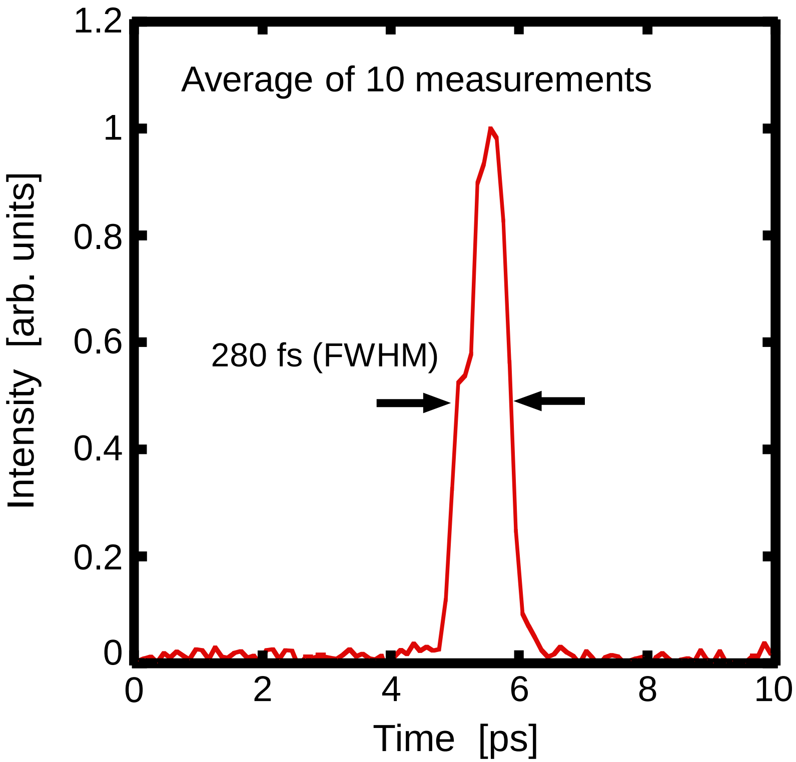
Hamamatsu



Volker Schlott, PSI

Traditional method to determine photon pulse length. The time variation of the incoming photon pulse intensity - a replica of the longitudinal bunch profile - is converted into a spatial intensity variation.

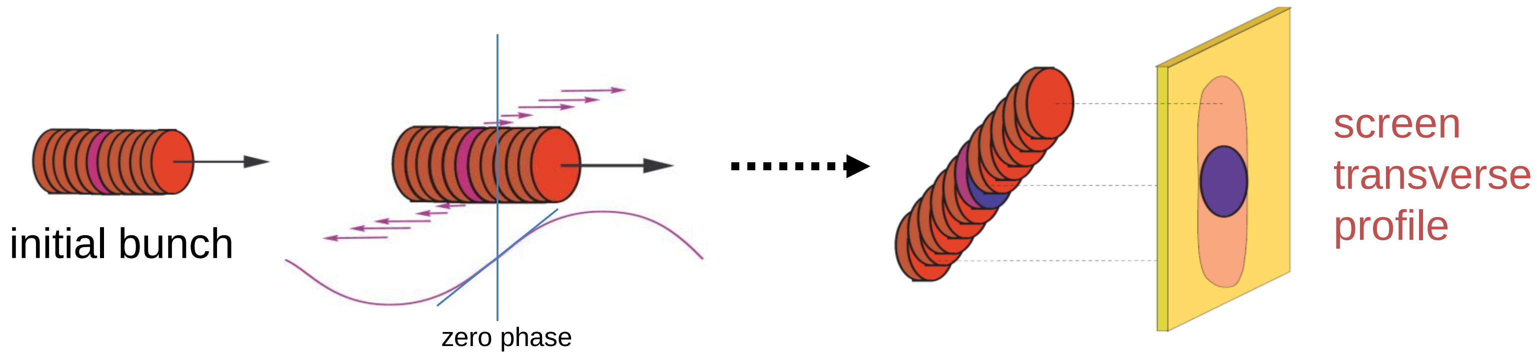




Streak cameras (and synchroscan streak cameras) can achieve sub-picosecond time resolution. Shown here: a measurement at SACLA, Japan

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

1.2 RF zero-phasing



RF cavity:
z-dependent accel/deceleration

beam optics:
energy dispersion

- Introduce energy chirp to beam via “linear” near-zero crossover of RF
- Measure energy spread with downstream spectrometer ⇒ infer initial bunch profile

time resolution dependent on:

- gradient of energy gain
- dispersion of spectrometer (needs to be high!)
- initial energy spread (needs to be low!)

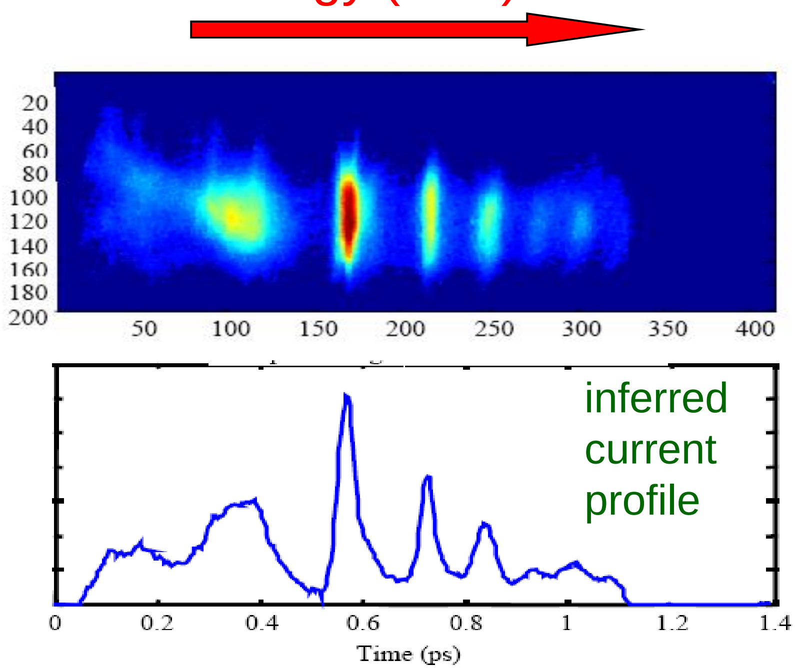
problems if initial γ–z correlation present?

Primary Disadvantage - destructive to electron beam

RF zero-phasing examples

DUV-FEL: at 75 MeV

energy (time)

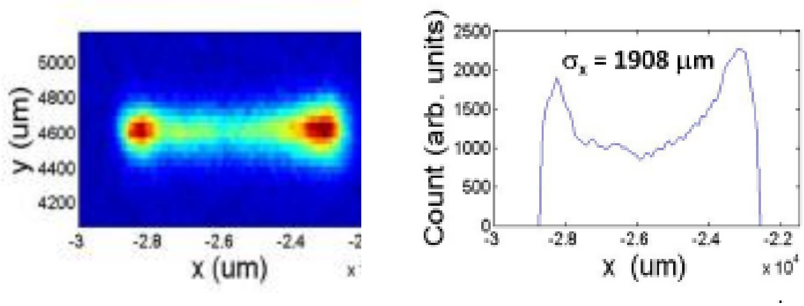


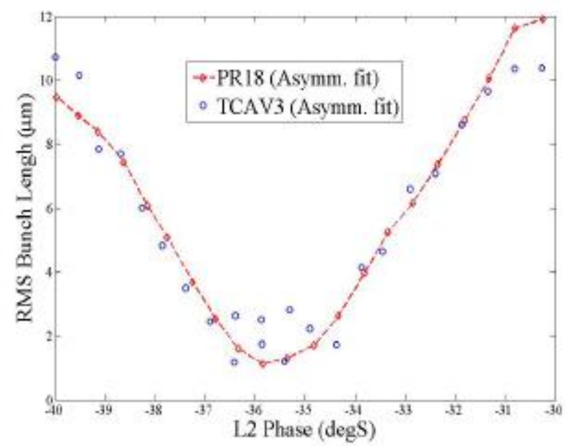
time resolution of ~50 fs

W. Graves et al., PAC 2001, Chicago, 2224

SLAC LCLS: at 4.7 GeV

- 550m of linac at RF zero crossing!
- <u>6m dispersion</u> on A-line spectrometer!

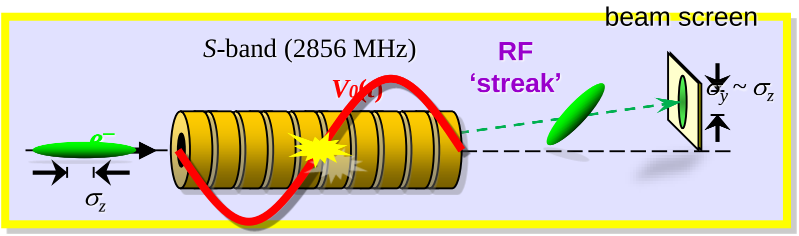




TCAV3
~ 1 fs rms bunch length at 4.7 GeV

Z. Huang et al. PAC 2011, FEL2013

1.3 Transverse Deflecting Structures

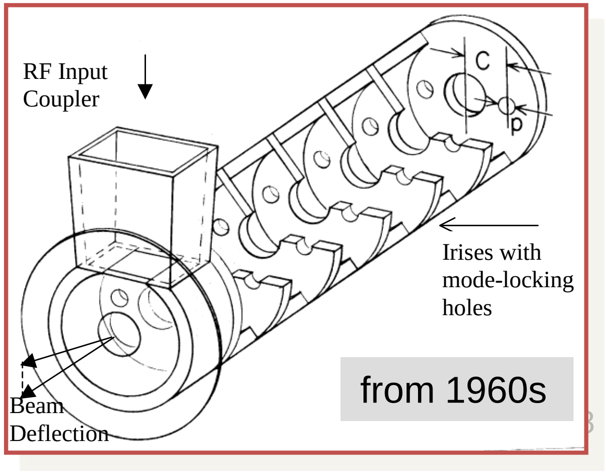


- **Well-established technique at SLAC to measure bunch length**
- **Uses a time-varying transverse electric field to "streak" the beam across a monitor screen**
- **can be looked at as a sort-of intra-beam streak camera**
- **3 m-long S-band 2856 MHz ('LOLA') structures built in the 1960s**
- **Installed in the LCLS linac, but are invasive to operation for photon users**

Diagnostic capabilities linked to beam optics

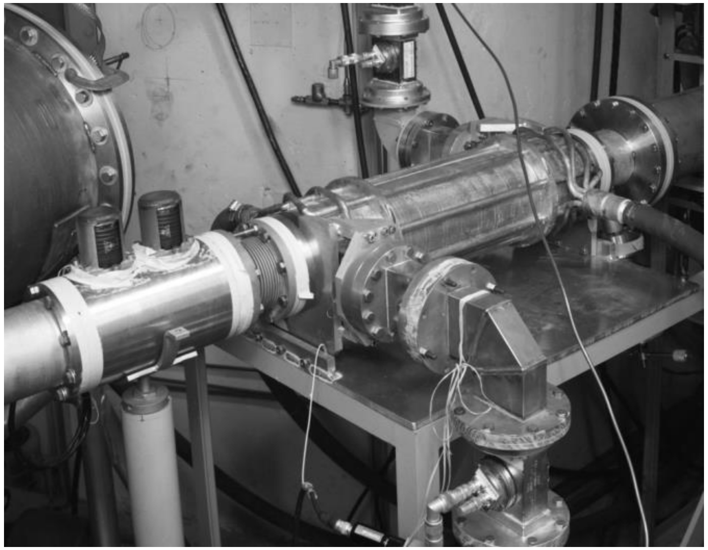
Primary Disadvantage - destructive to electron beam

- iris loaded "LOLA-type" RF waveguide structure
- designed to provide hybrid deflecting modes ($HEM_{1,1}$)
- → linear combination of $TM_{1,1}$ and $TE_{1,1}$ dipole modes, resulting in transverse force that acts on synchronously moving relativistic particle beam
- used for beam separators and RF deflectors

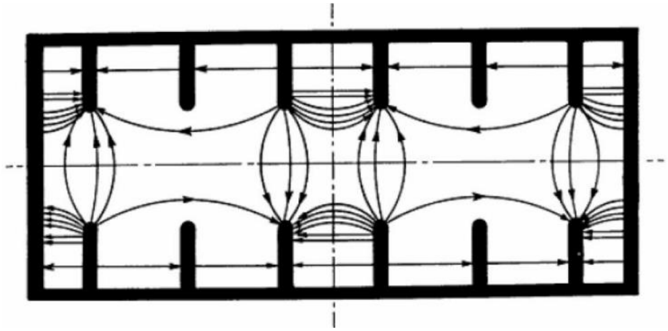


"LOLA": G.A. Loew, R.R. Larsen, O.A. Altenmueller

G. A. Loew et al., SLAC Technical Report SLAC-PUB-135 (1965)

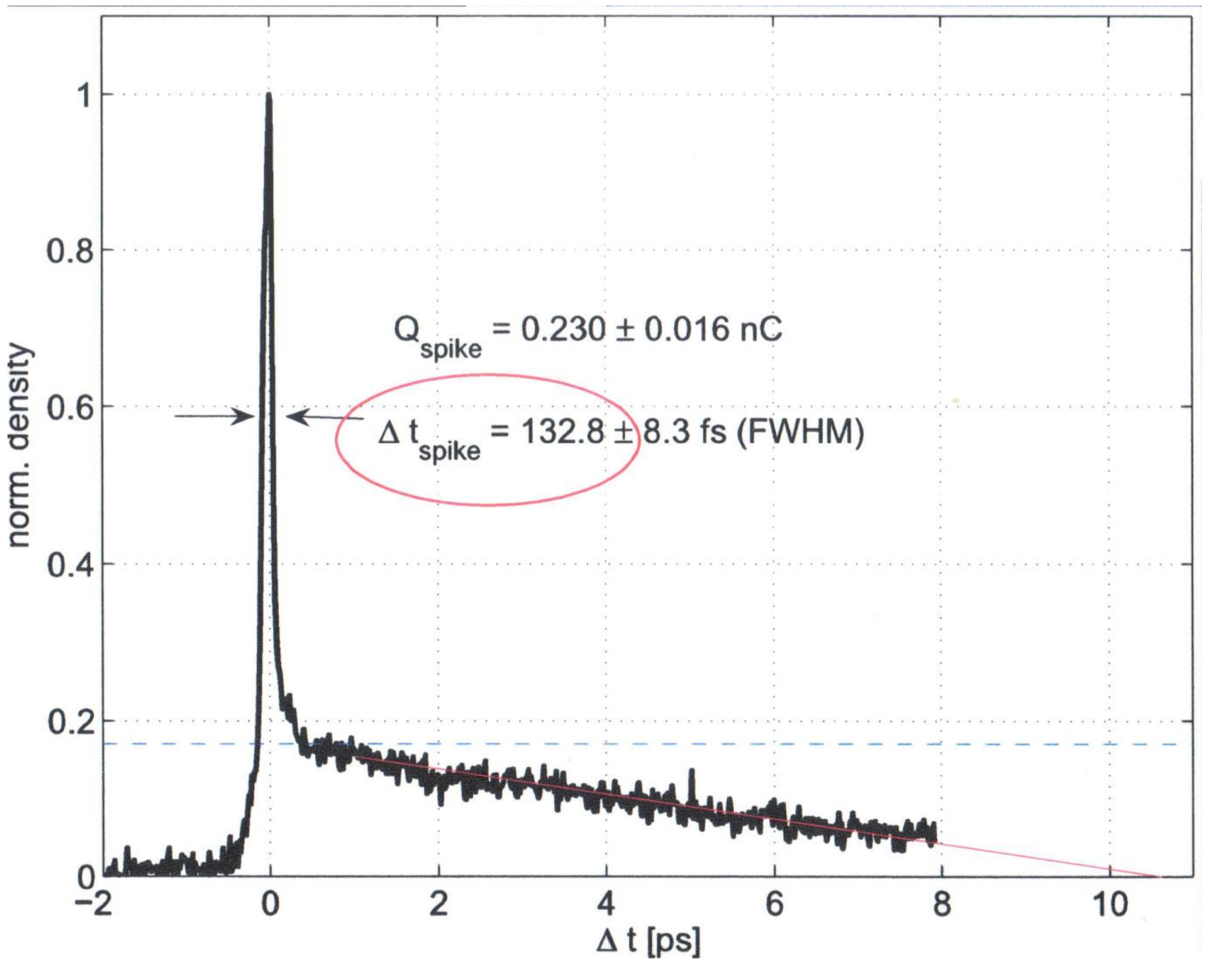


2π/3 phase shift per cell



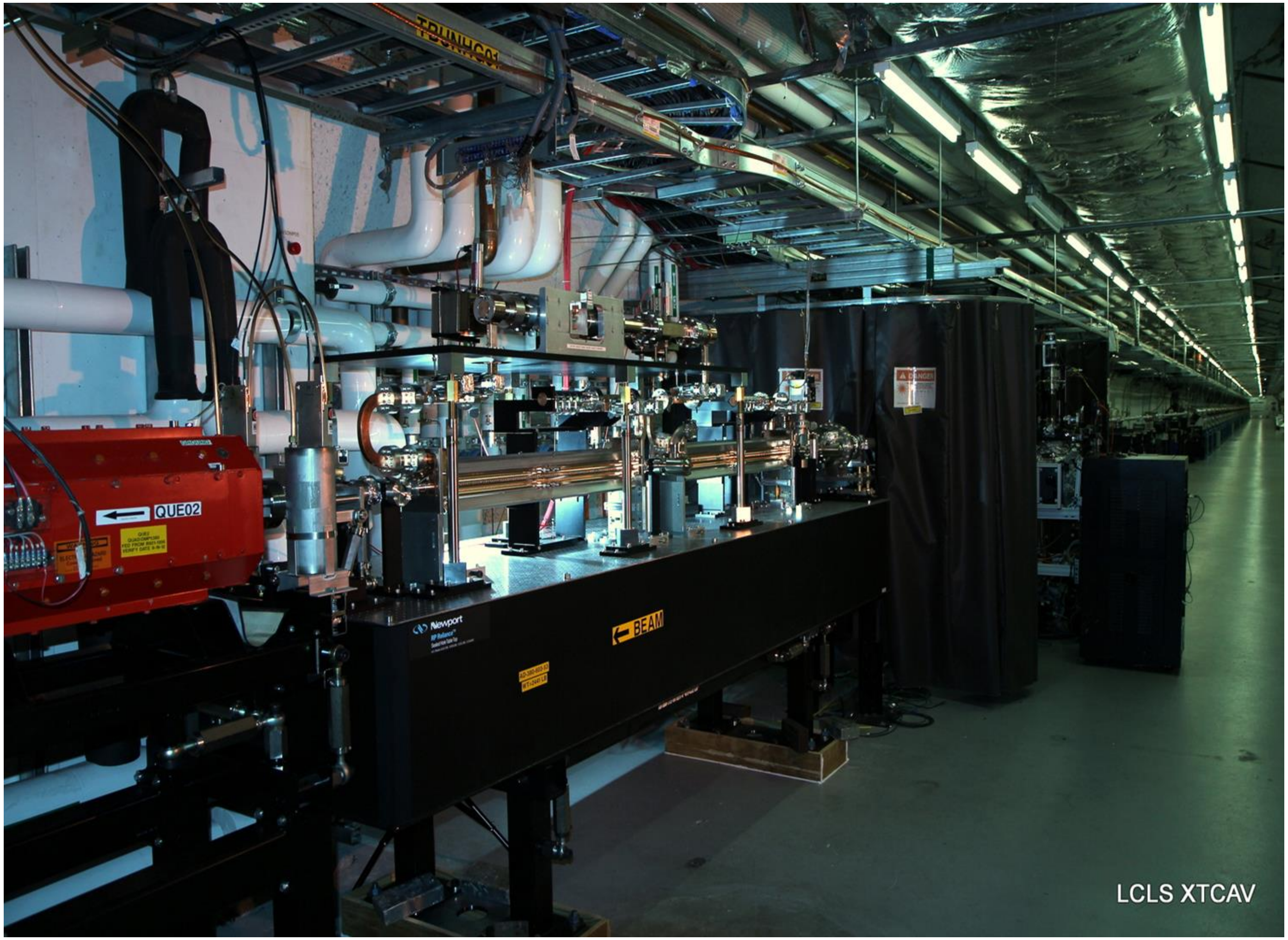
TCAV installation at FLASH

Typical resolution. 20-50 fs



B. Schmidt, FEL 2006, Berlin

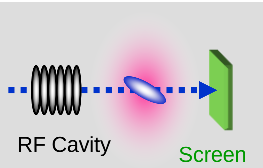
Recent example: SLAC LCLS X-band Transverse Deflecting Cavity (XTCAV)

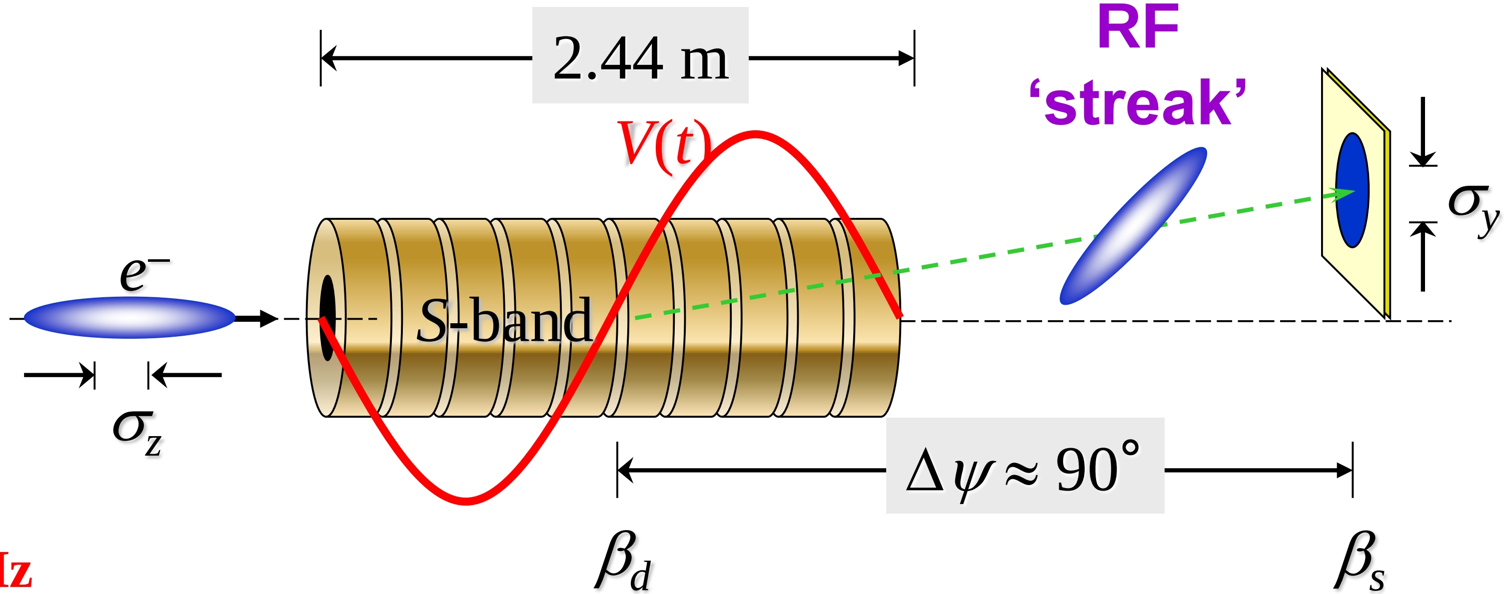


SLAC NATIONAL ACCELERATOR LABORATORY

Slides courtesy of Pat Krejcik, SLAC

Transverse Deflector Cavity (TDC)

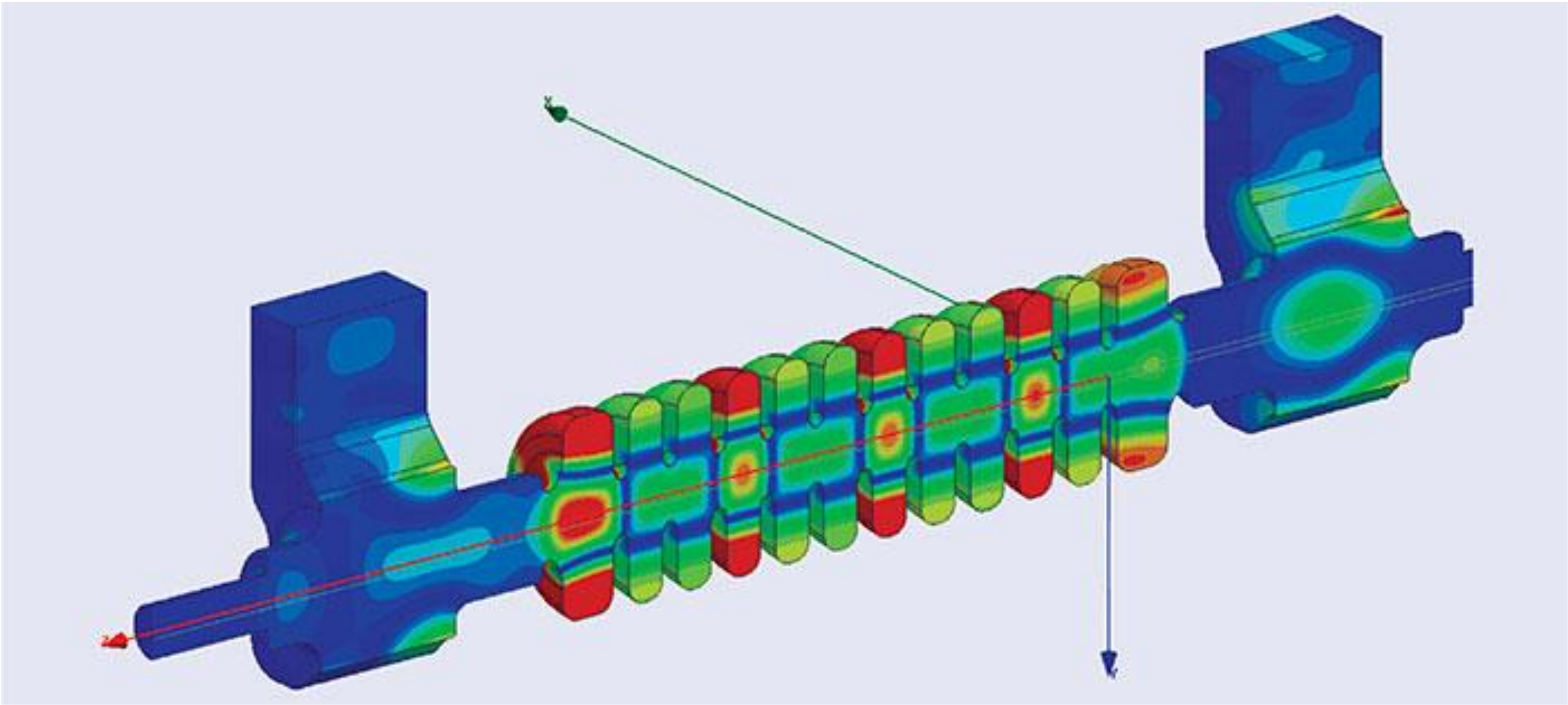




$V_0 > 20$ MV
$f_{RF} = 2856$ MHz
$E_S = 13.6$ GeV

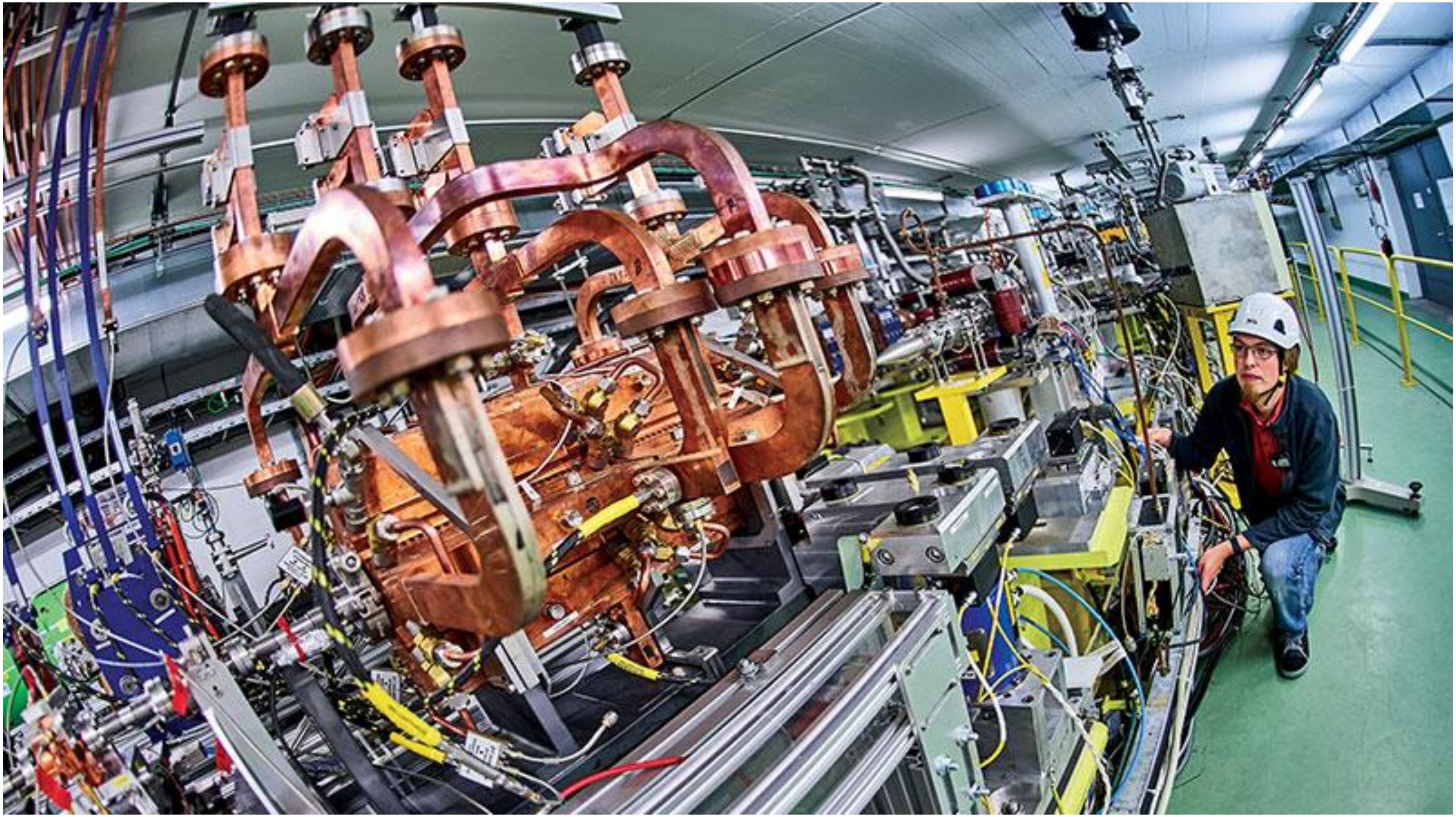
$$\sigma_y^2 = \sigma_{y0}^2 + \beta_d \beta_s \sigma_z^2 \left(\frac{k_{RF} e V_0}{E_s} \sin \Delta\psi \cos\phi \right)^2$$

- Map time axis on to transverse coordinate
- Simple calibration by scan of cavity phase

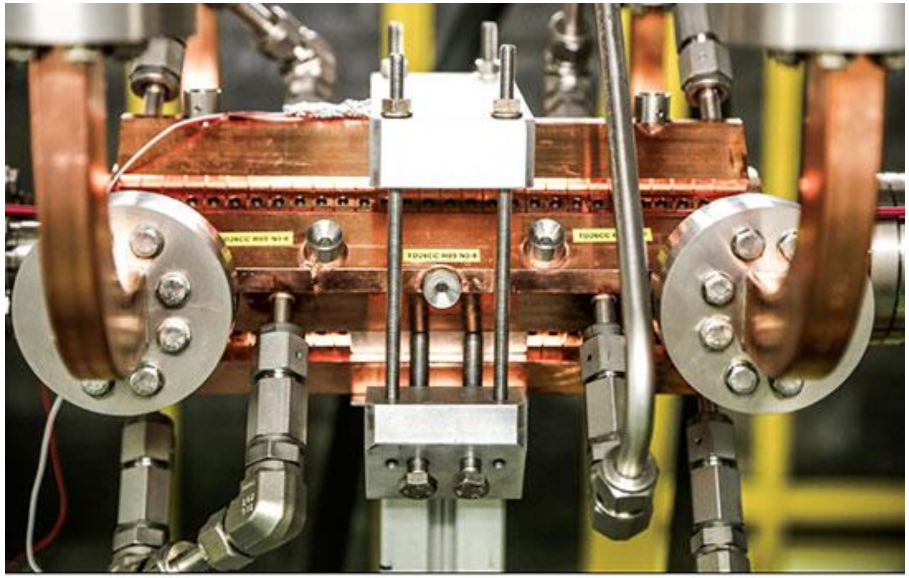


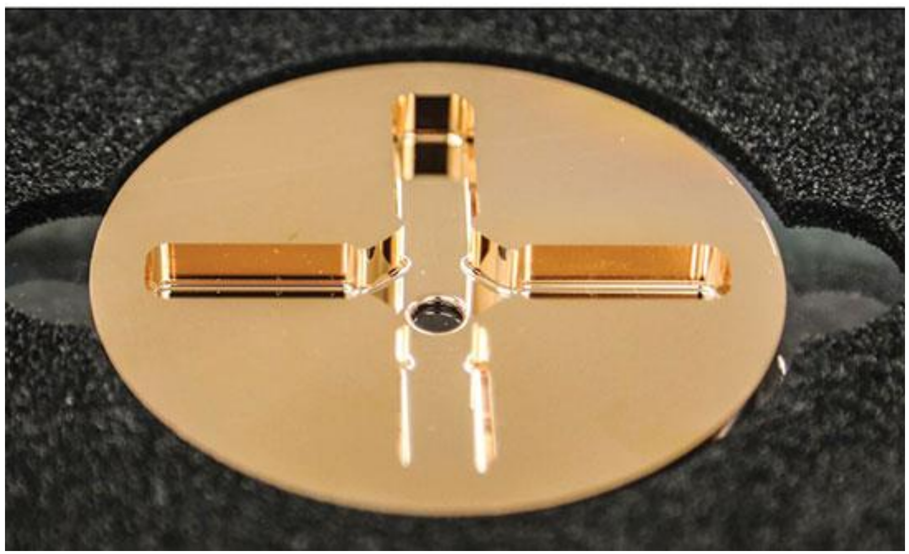
Simulation of the field inside an RF deflector (red and blue correspond to high and low fields, respectively) used to measure the bunch characteristics at XFELs, which is an application well suited to high-gradient X-band technology.

Image credit: A Grudiev



X-band technology at the CLEAR test facility at CERN. Image credit: J Ordan/CERN



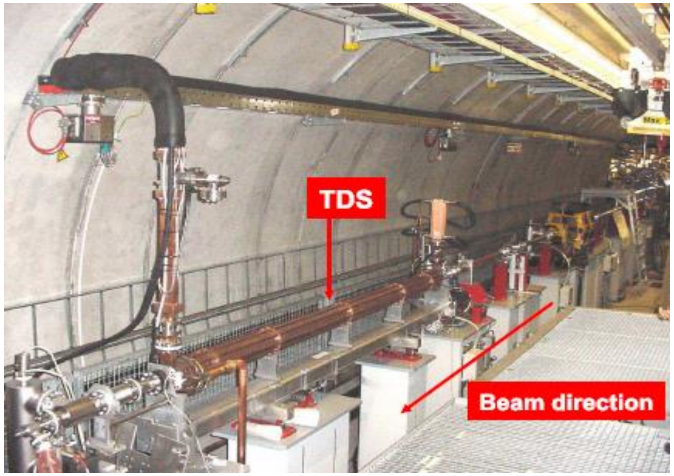


A high-gradient structure for CLIC measuring 25 cm across, showing the waveguides that feed power in and out. The structures are made up of disks (bottom) bonded together to form a series of resonating cells that accelerate the beam. The cells are made to micron-level precision and have a highly optimised geometry to ensure maximum accelerating gradient. Image credit: M Volpi

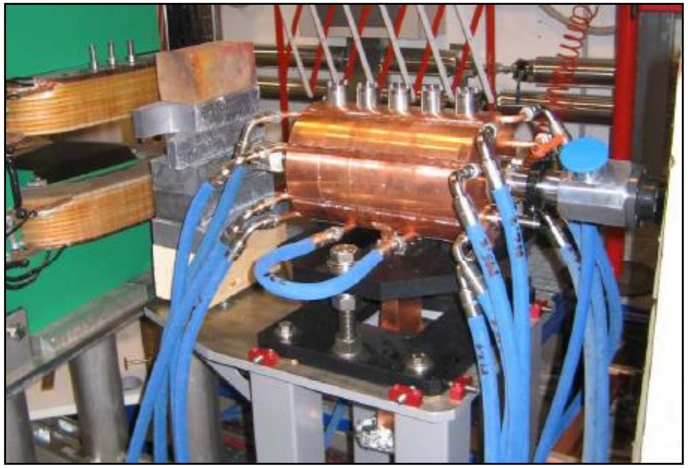
TDCs @ LCLS, FLASH & SPARC

low-energy TW RF deflector @ LCLS

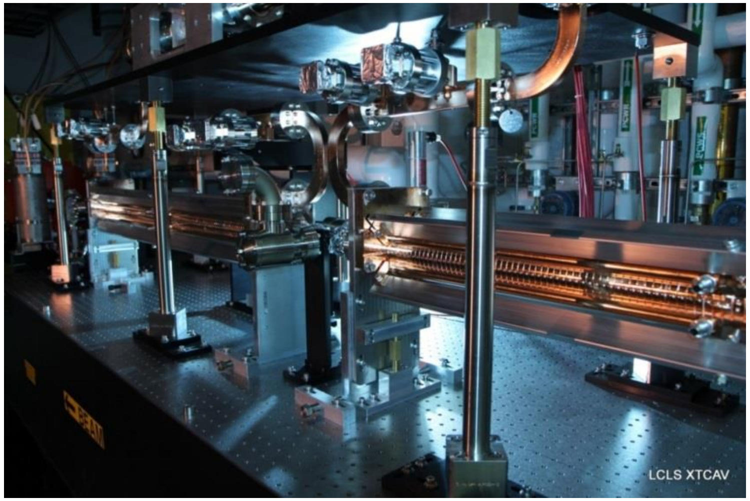
TW RF deflector @ FLASH



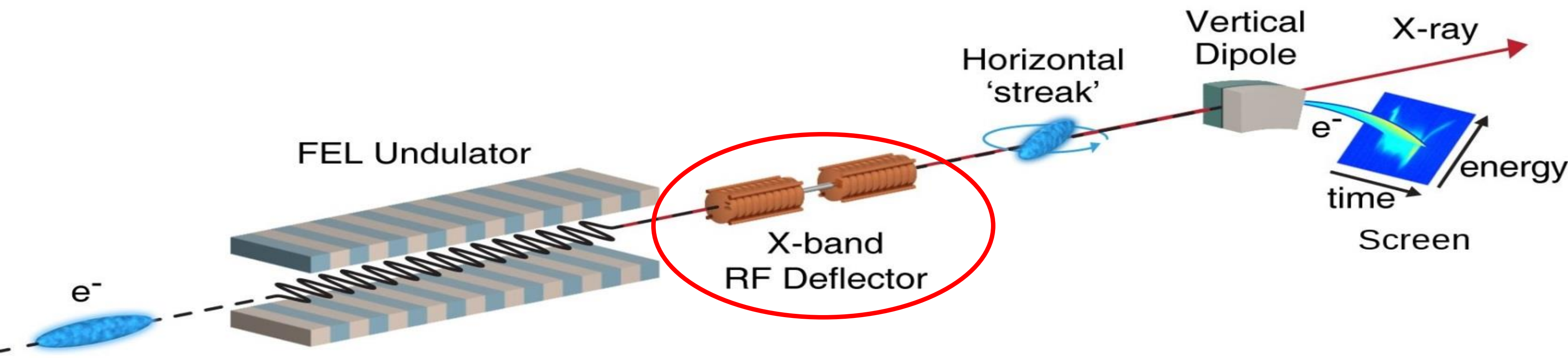
SW RF deflector @ SPARC



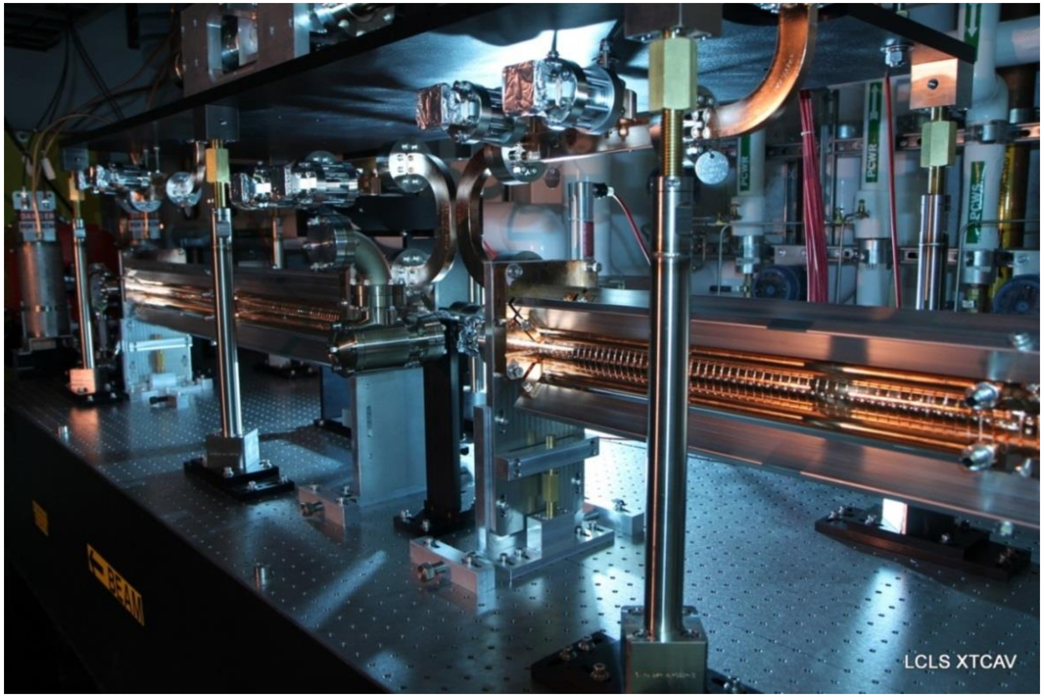
X-band TDC @ LCLS



LCLS implementation: Horizontal XTCAV plus Vertical Spectrometer

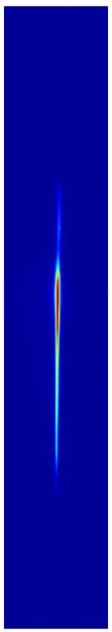


Imaging the temporal profile of the electron beam by horizontally streaking with an RF deflecting cavity and measuring the time-dependent energy via a vertical spectrometer.

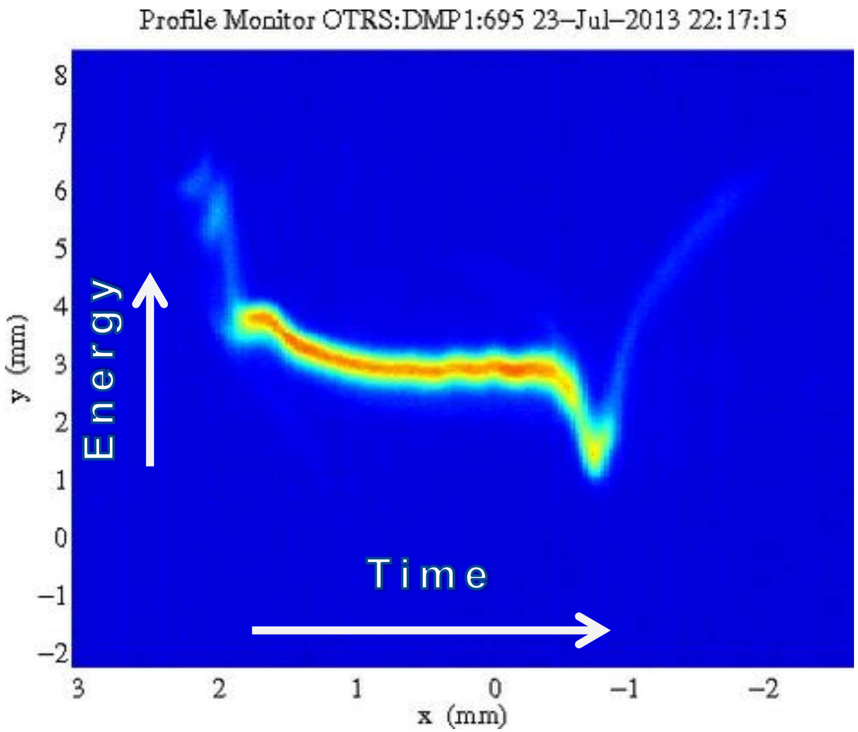


FEL energy spectrum at 4.7GeV, 150pC

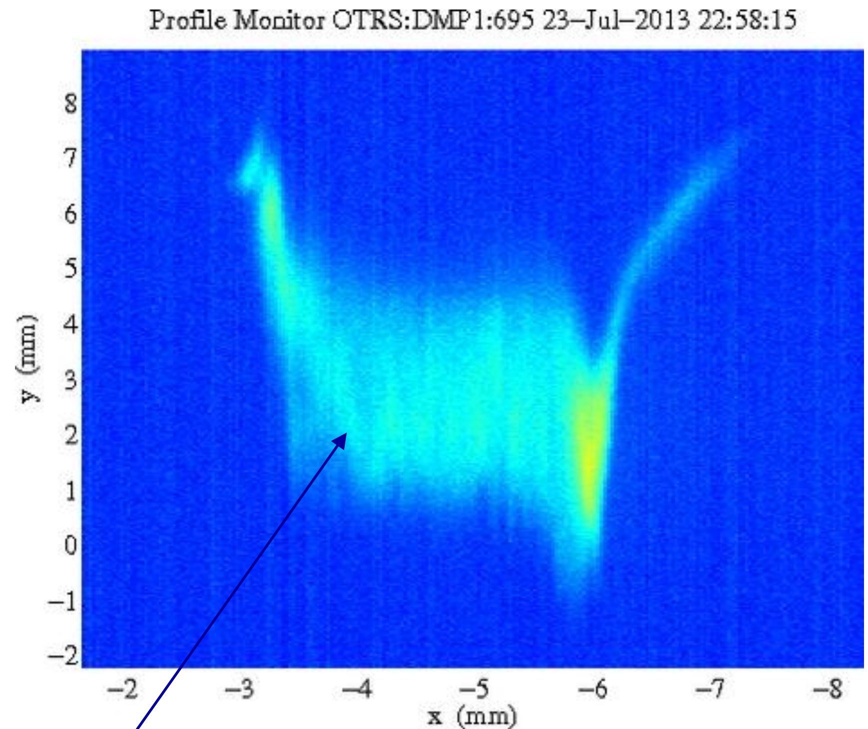
Three images at the electron dump spectrometer screen



XTCAV Off



XTCAV On
FEL Suppressed
(baseline)



XTCAV On
FEL On
~1mJ FEL pulse energy

Transfer of energy to photons causes electron energy loss and spread

3 new important features:

- **Operates at 11.424 GHz**

  ⇒ 8 times better temporal resolution

  – **4 from shorter λ and 2 from V gradient**

  – **allows measurement of slice emittance**

- **Located downstream of the undulator**

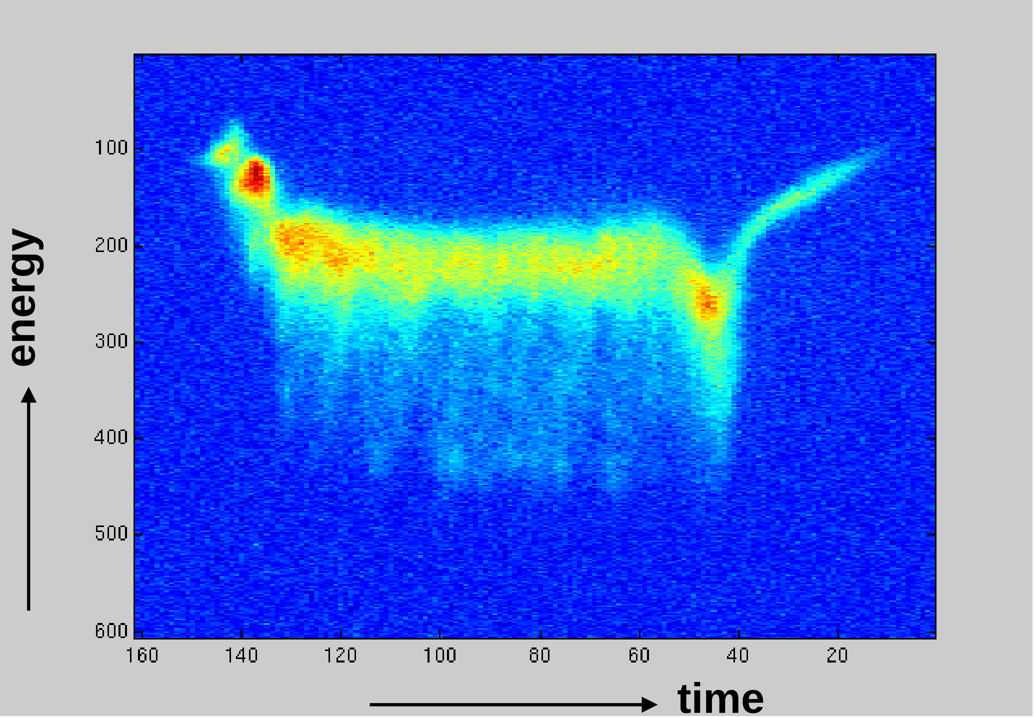
  ⇒ cannot interfere with photon operation

  – **Continuous non-invasive operation**

  – **Every shot analyzed at 120 Hz**

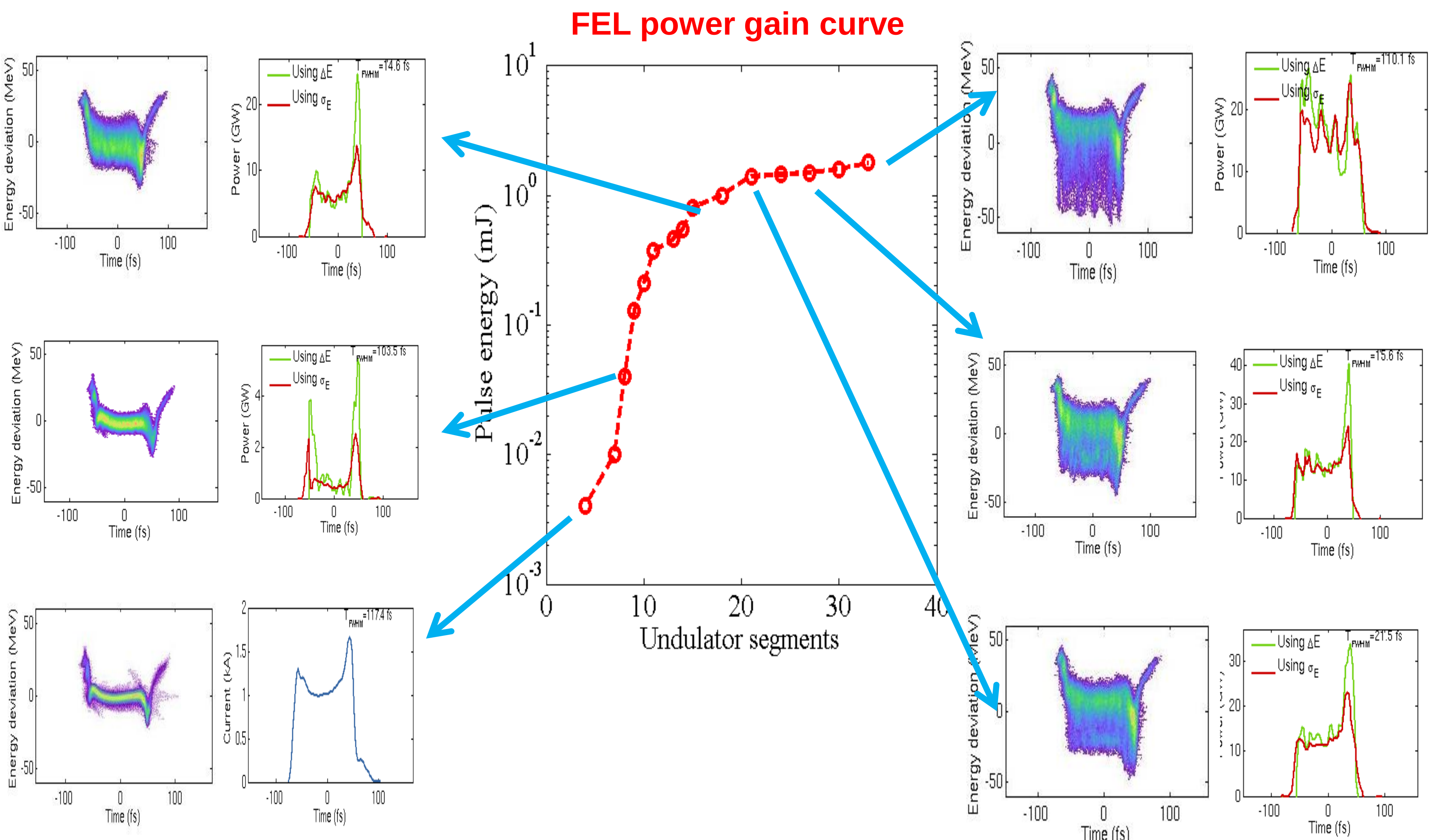
- **Reconstructs temporal profile of x-ray beam from e-loss profile of electrons**

20 consecutive shots (1keV, 150pC)

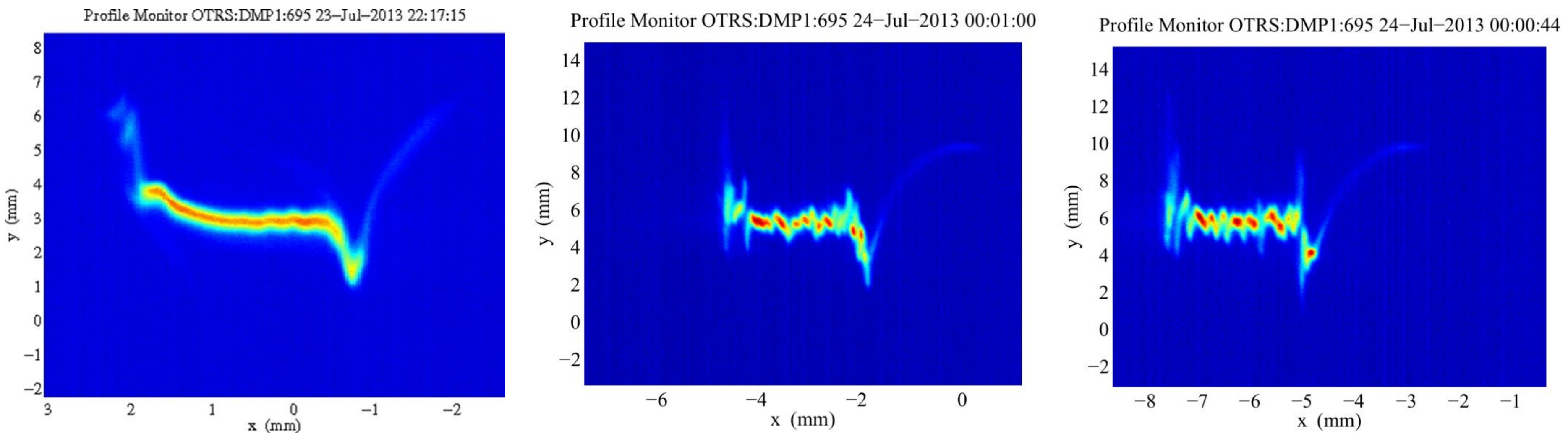


Demonstrated resolution of 0.8 ± 0.2 fs

Evolution of SASE along the FEL Power Gain Curve at 4.7GeV, 150pC (1keV)

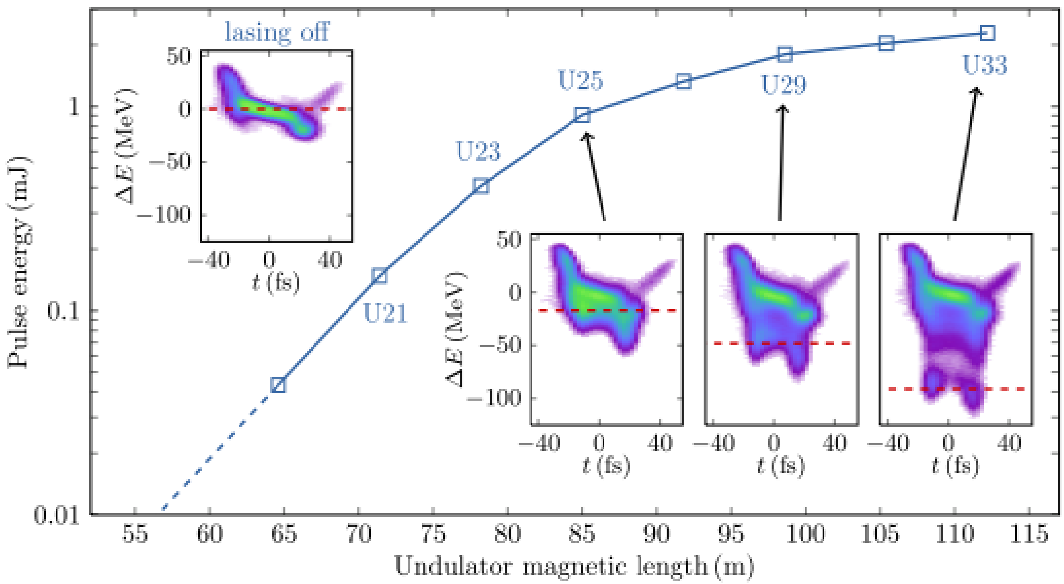


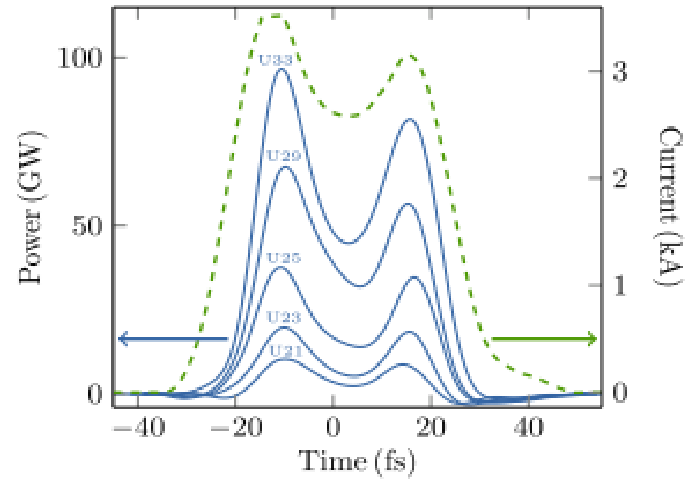
Direct Observation of Microbunching Instability with XTCAV

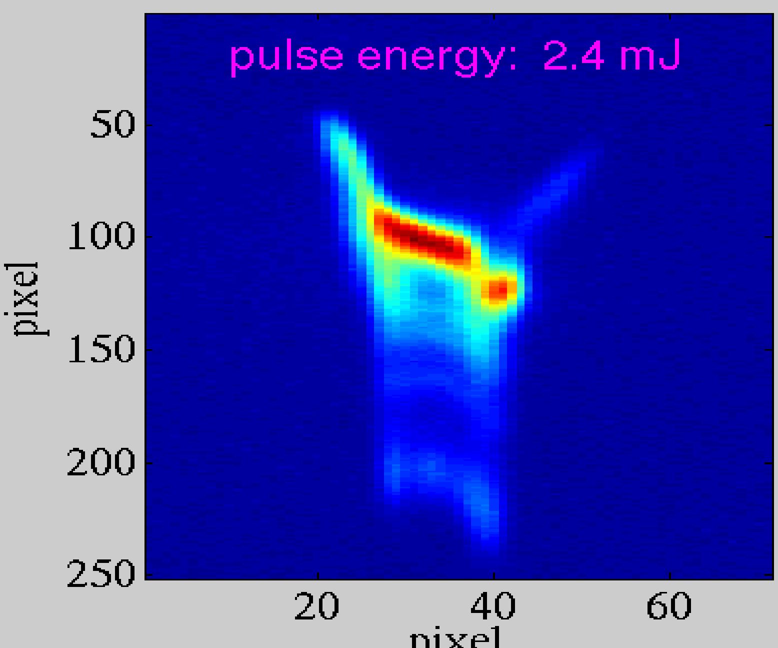


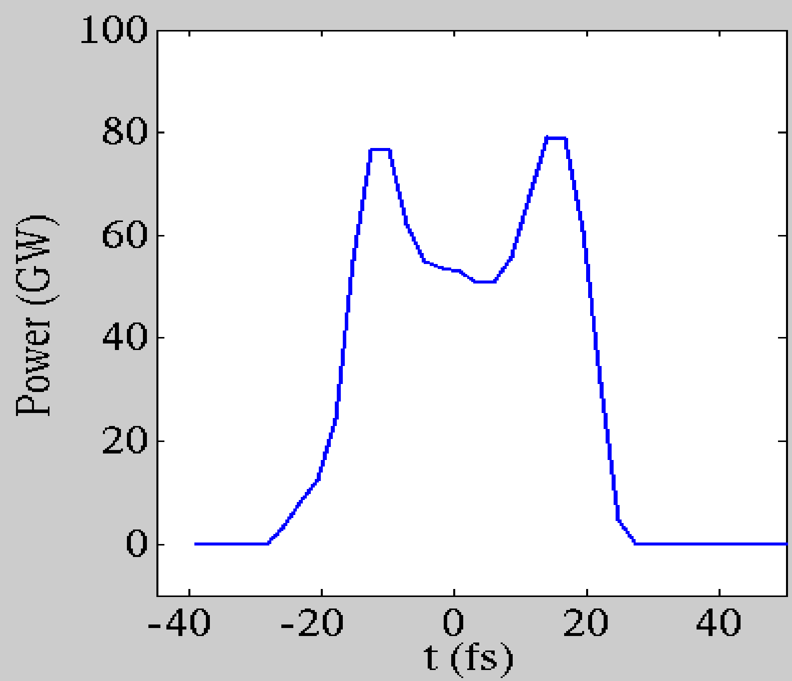
Decreasing gain on the Laser Heater

Taper optimization and resonant trapping at 15.2GeV, 150pC, 10.2keV

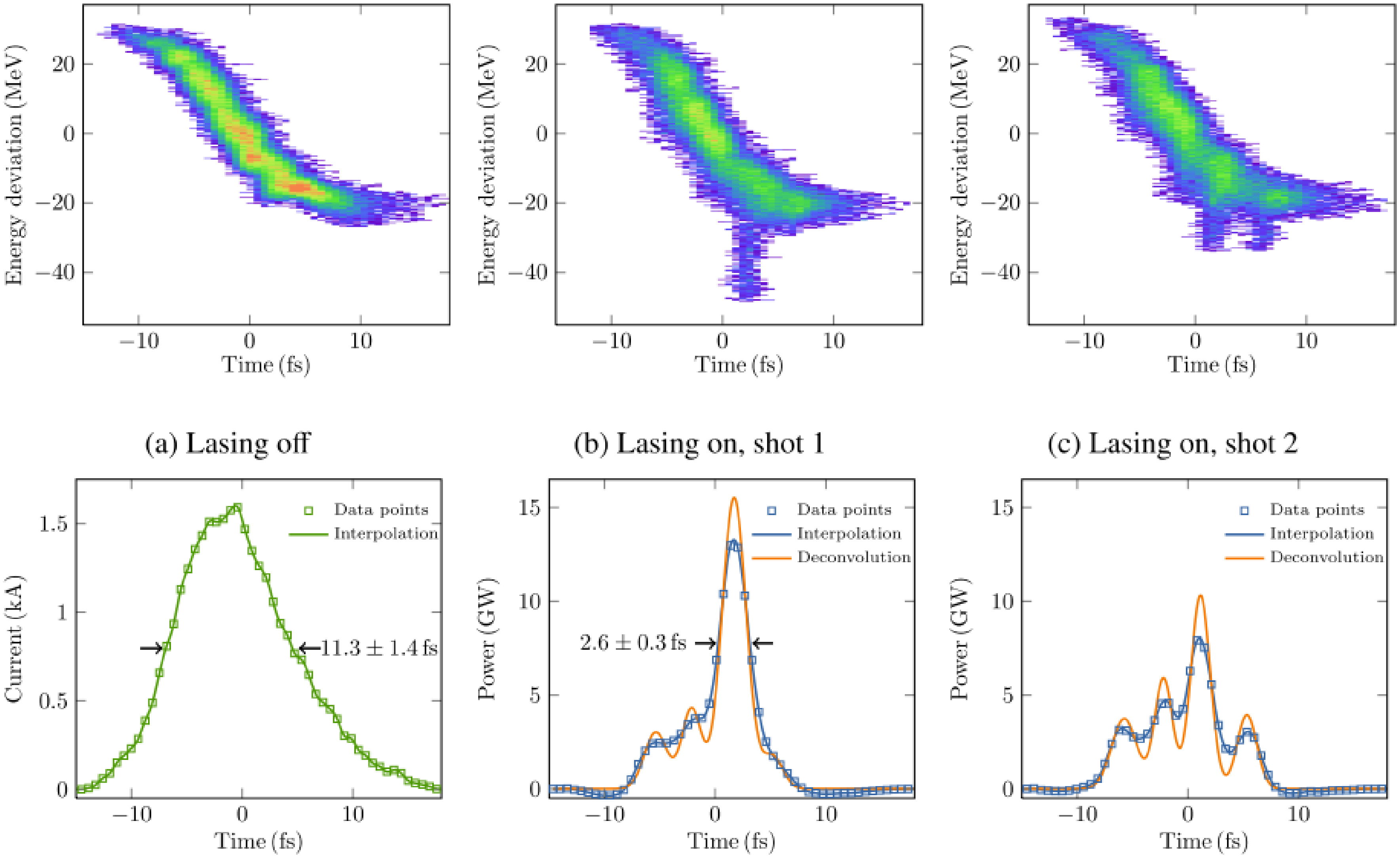








Short pulse -- 20pC, 1keV examples

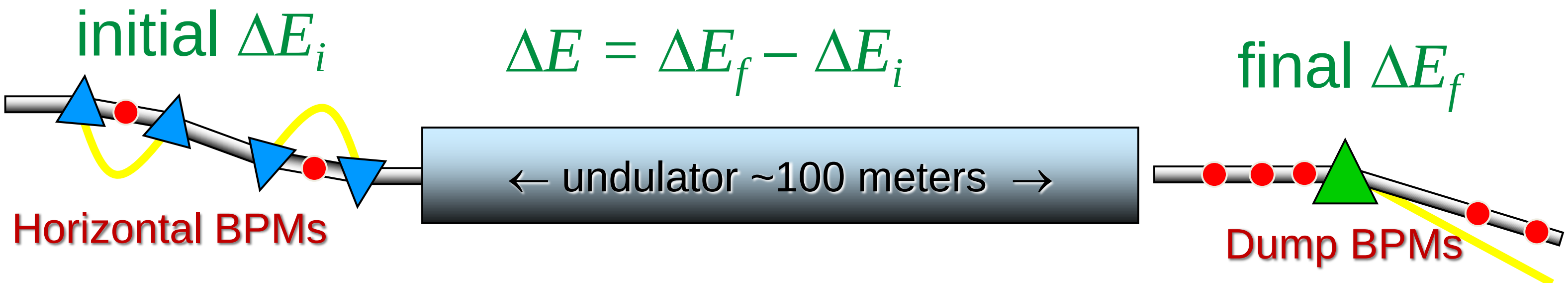


(a) Lasing off (b) Lasing on, shot 1 (c) Lasing on, shot 2

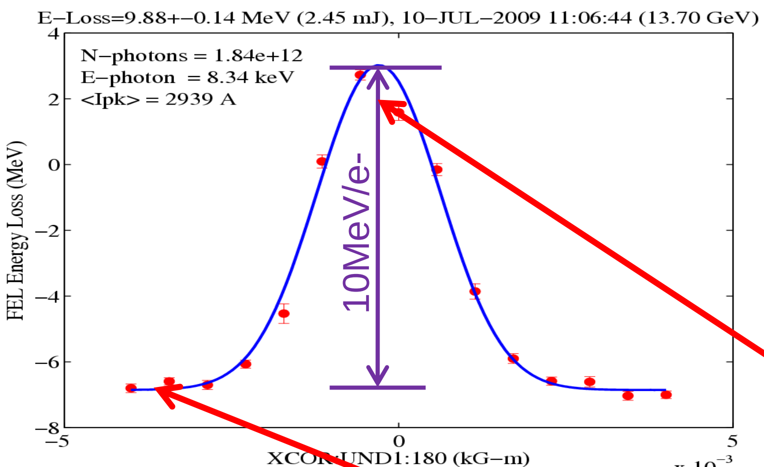
(d) Electron current (e) X-ray power, shot 1 (f) X-ray power, shot 2

How to retrieve the x-ray temporal profile?

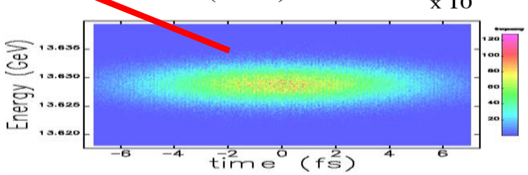
- The E-loss scan for measuring x-ray pulse energy:

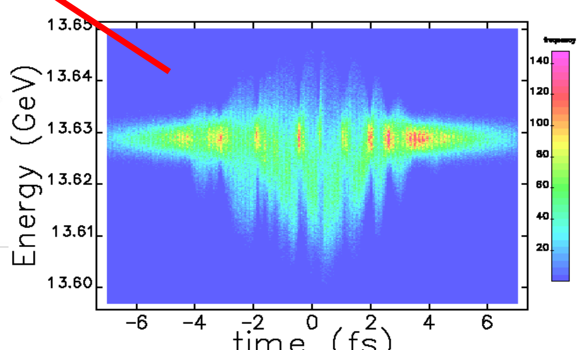


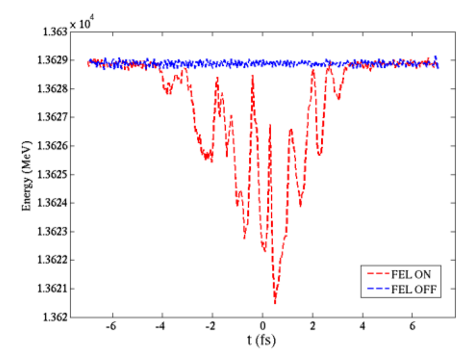
vary FEL power with oscillations & record e^- energy loss



→ to measure the ***time-resolved*** lasing effect ("footprint") left on the electron bunch. (**Ding et al., PRSTAB2011**)







XTCAV System Improvements

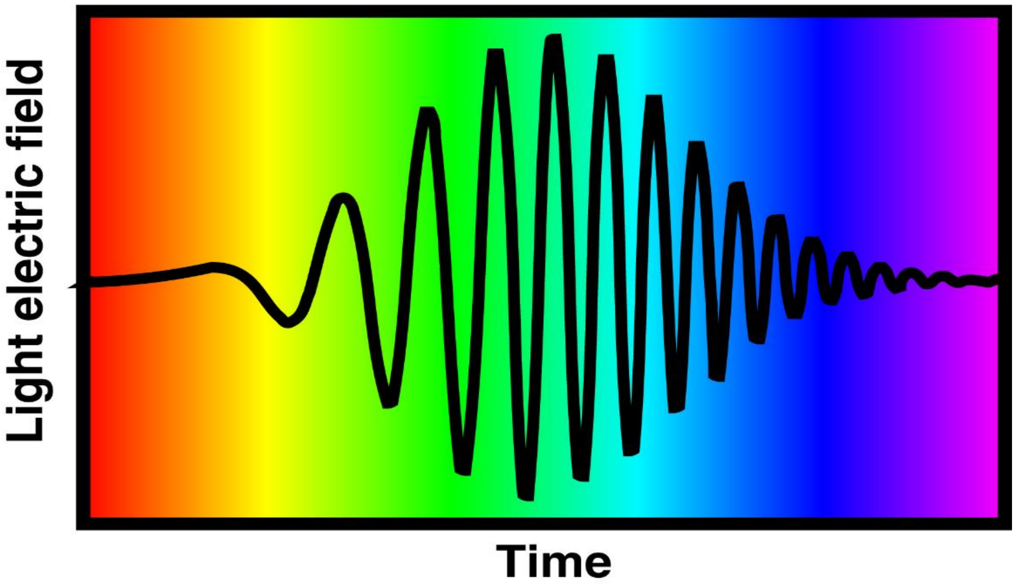
- **120 Hz camera** installed so that images can be captured at full beam rate
  - Raw images are written to photon experiment DAQ in real-time
  - Real time processing of x-ray slice profiles (TREX) is underway

- **Doubling the temporal resolution** by raising the RF power by a factor 4 is being proposed

Remember:

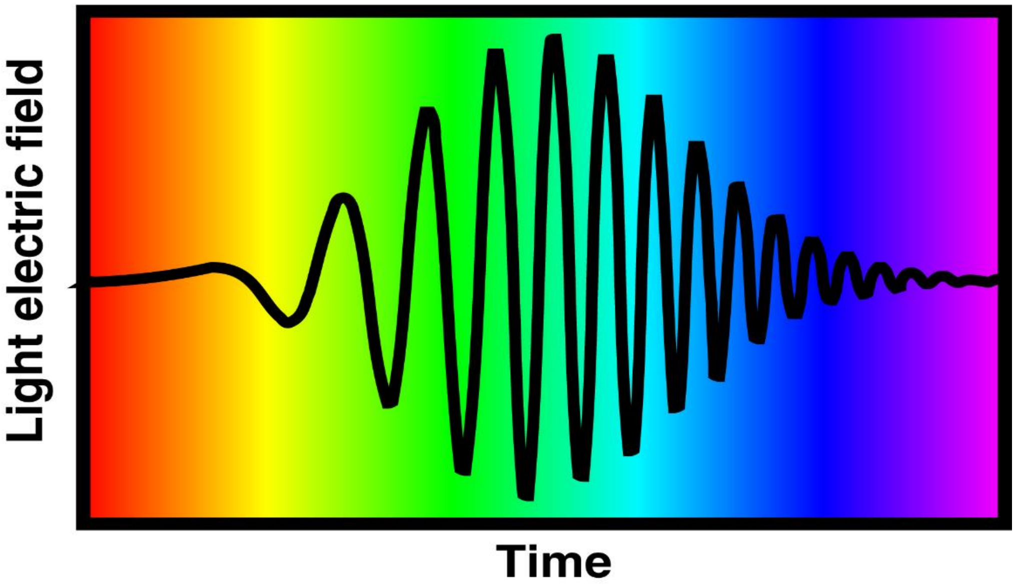
- proper behaviour depends on optimised beam transport optics between TDC and view screen
- the setup that gives optimum performance and resolution may not be the same as the one required for normal accelerator / FEL operation
- TDC can give access to slice parameters of electron beam (Important for optimising performance of an FEL)
- provides non-invasive, single-shot X-ray temporal profiles during FEL user experiments
- Single-bunch capable, not multi-bunch capable
- "semi-parasitic" (sacrifices 1 bunch)
- Slow read out (imaging)
- requirement for absolutely non-intercepting operation within an accelerator may make a TDC impossible

Revision of Ultrashort Pulses



Slides from Rick Trebino, Georgia Tech.

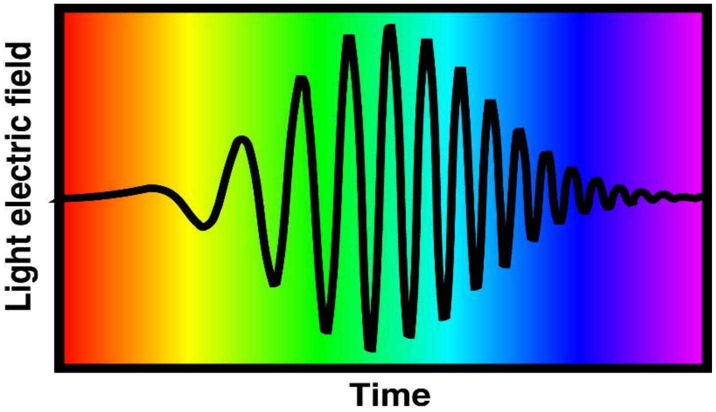
An optical (laser) pulse can have a frequency that varies in time.



This pulse frequency increases linearly in time (from red to blue).

In analogy to bird sounds, this pulse is called a "chirped" pulse.

A linearly chirped Gaussian pulse



We can write a linearly chirped Gaussian pulse as:

$$E(t) = E_0 \exp\left[-(t/\tau_G)^2\right] \exp\left[i\left(\omega_0 t + \beta t^2\right)\right]$$

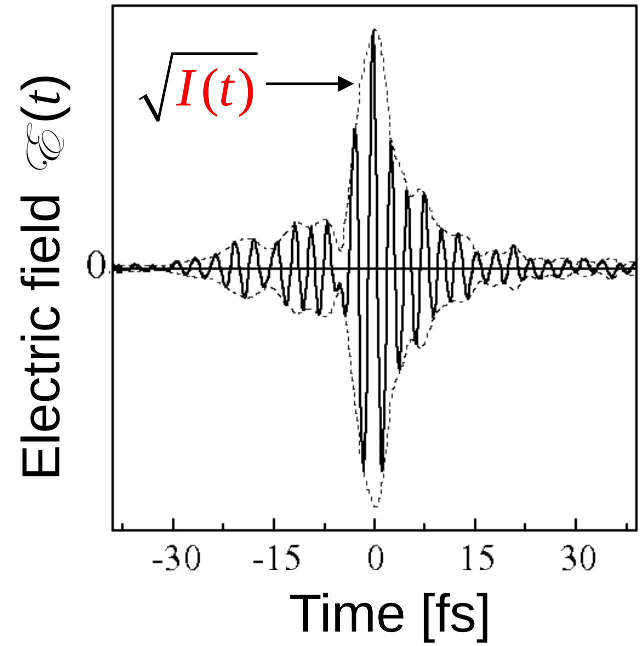
Gaussian amplitude

Carrier wave

Chirp

Note that for $\beta > 0$, when $t < 0$, the two terms partially cancel, so the phase changes slowly with time (so the frequency is lower). And when $t > 0$, the terms add, and the phase changes more rapidly (so the frequency is larger).

An ultrashort laser pulse has an intensity and phase vs. time.



Neglecting the spatial dependence for now, the pulse electric field is given by:

$$\mathcal{E}(t) = \tfrac{1}{2}\sqrt{I(t)}\,\exp\{i[\omega_0 t - \phi(t)]\} + c.c.$$

Intensity A(t)

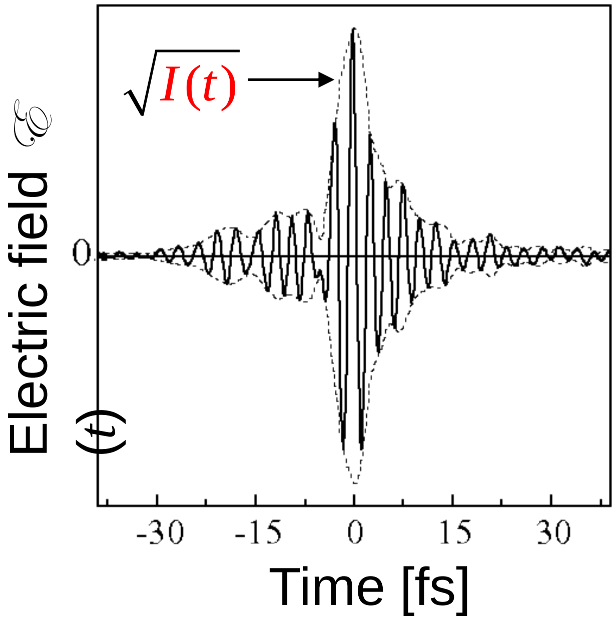
Carrier frequency

Phase

A sharply peaked function for the intensity yields an ultrashort pulse. The phase tells us the colour evolution of the pulse in time.

The real and complex pulse amplitudes

Removing the 1/2, the c.c., and the exponential factor with the carrier frequency yields the ***complex amplitude, E(t),*** of the pulse:



$$E(t) = \sqrt{I(t)}\,\exp\{-i\phi(t)\}$$

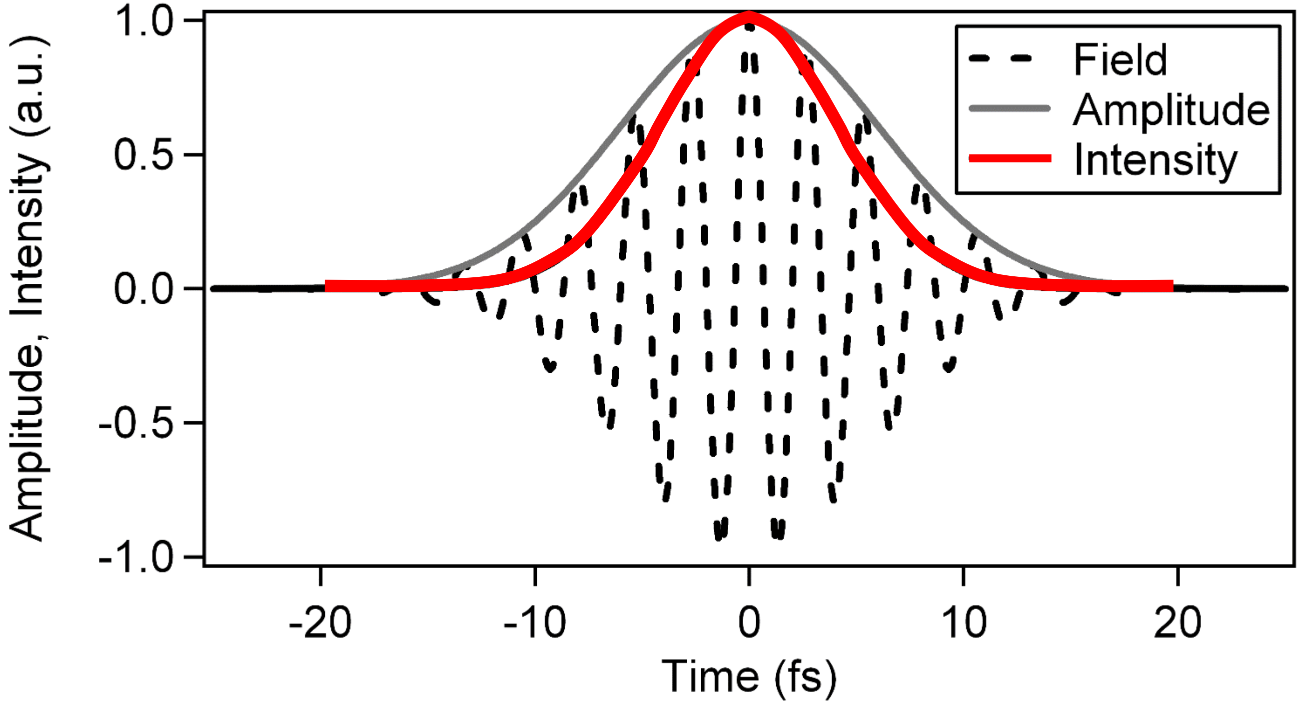
This removes the rapidly varying part of the pulse electric field and yields a complex quantity, which is actually easier to calculate with.

$\sqrt{I(t)}$ is often called the ***real amplitude, A(t) ,*** of the pulse.

For almost all calculations, a good first approximation for any ultrashort pulse is the ***Gaussian pulse*** (with zero phase).

$$E\,(t) = E_0 \exp\left[\, -1.38\,(t / \tau_{FWHM})^2 \,\right]$$

Intensity vs. amplitude



The phase of this pulse is constant, $\phi(t)$ = 0, and is not plotted.

The intensity of a Gaussian pulse is √2 shorter than its real amplitude. This factor varies from pulse shape to pulse shape.

Intensity and phase of a Gaussian

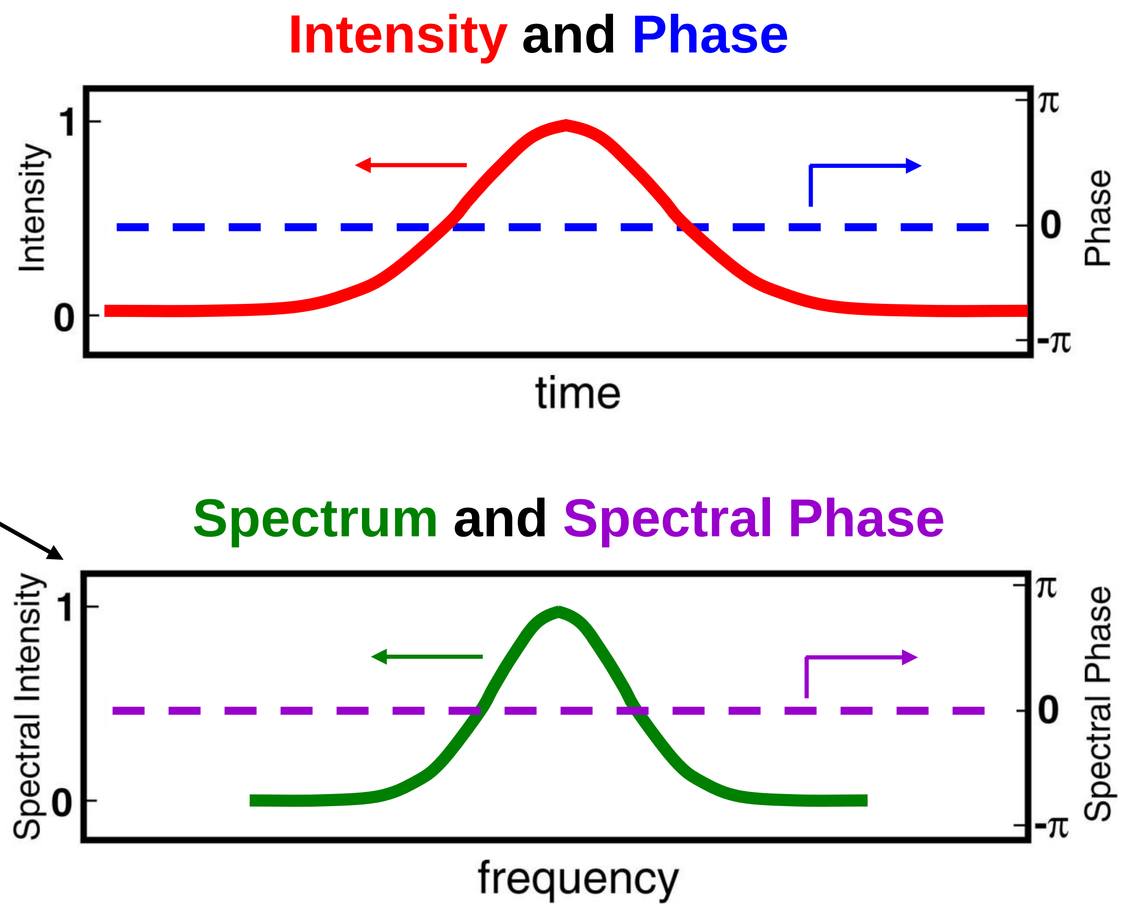
- The Gaussian is real, so its phase is zero.

Time domain:

A Gaussian transforms to a Gaussian

Frequency domain:

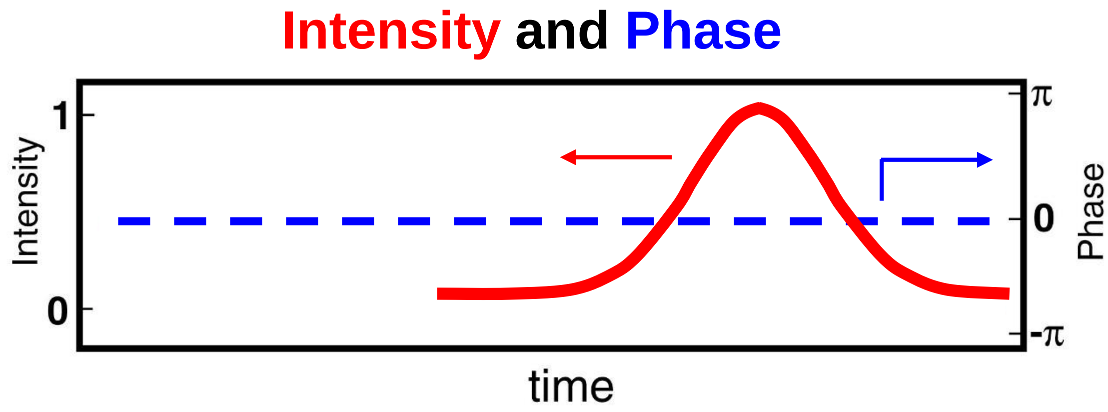
So the spectral phase is zero, too.



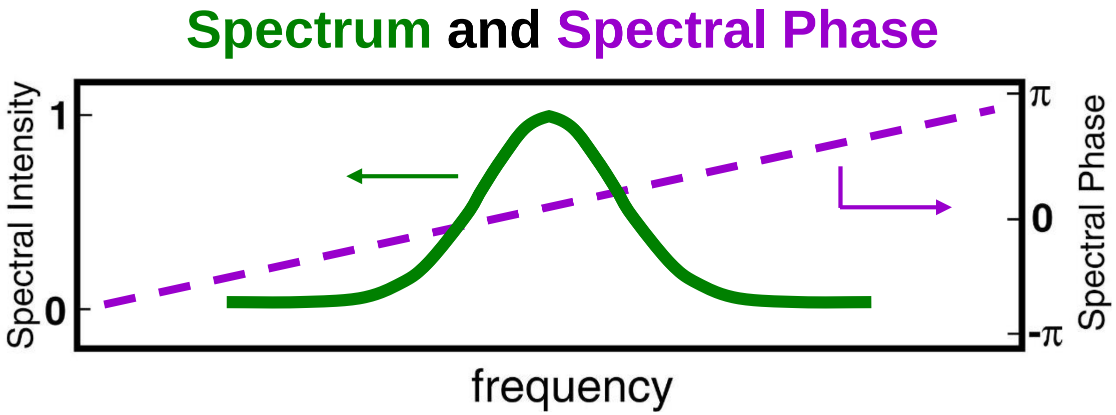
The spectral phase of a time-shifted pulse

Recall the Shift Theorem: $\mathscr{F}\{f(t-a)\} = \exp(-i\omega a)F(\omega)$

Time-shifted Gaussian pulse (with a flat phase):

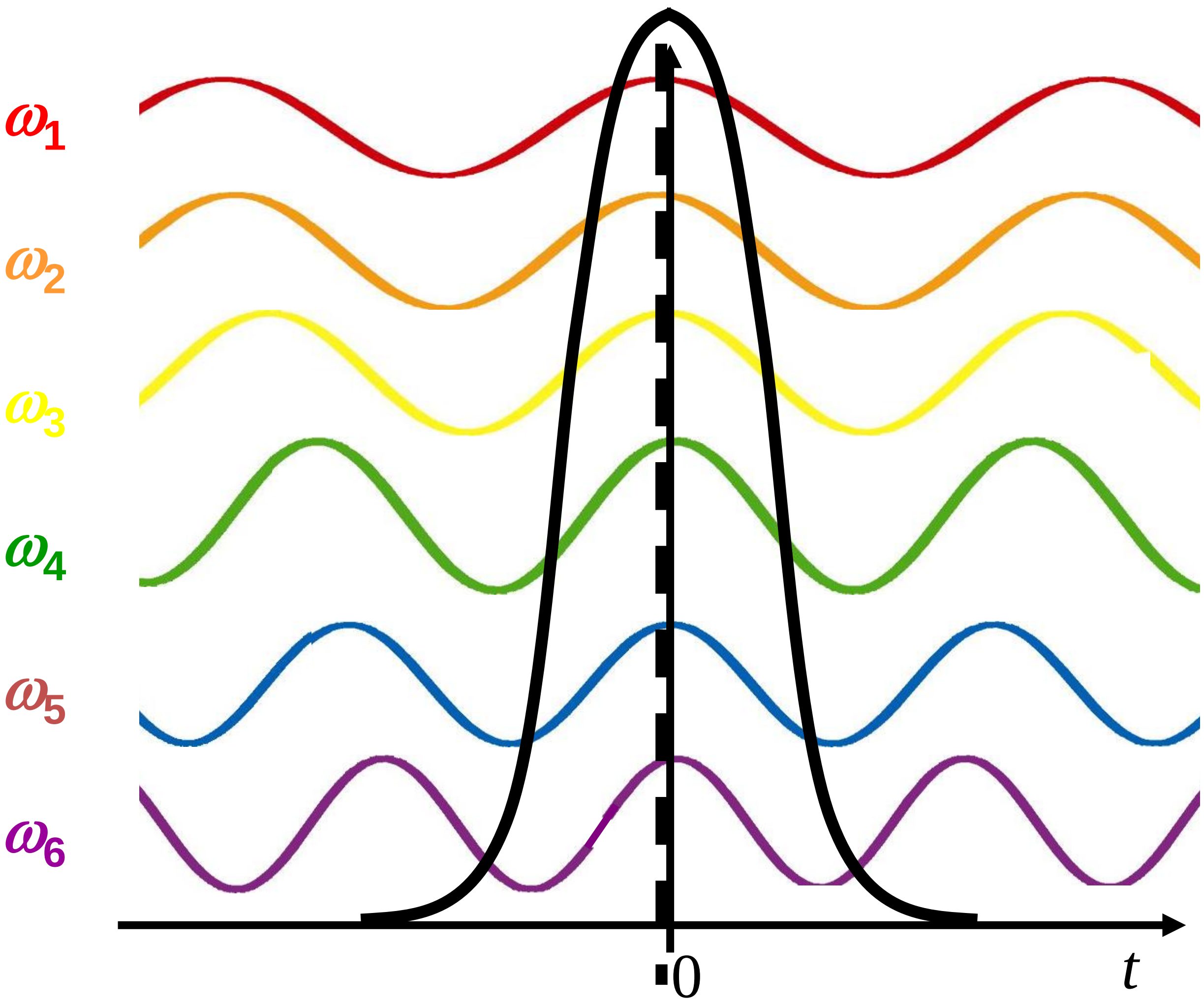


So a time-shift simply adds some linear spectral phase to the pulse!



Effect of the Spectral Phase

The spectral phase is the phase of each frequency in the wave-form.



All of these frequencies have zero phase. So this pulse has:

$\varphi(\omega) = 0$

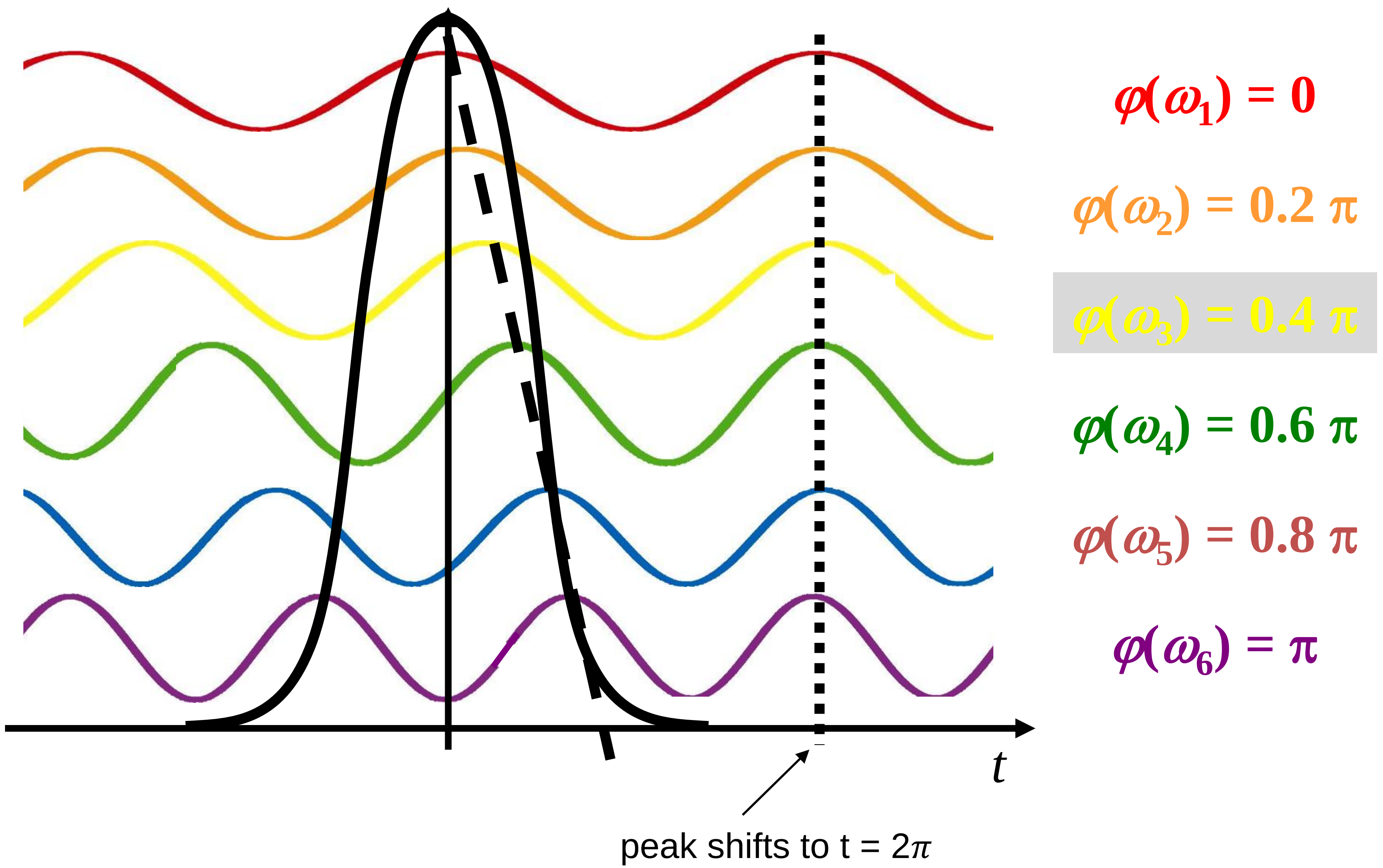
Note that this has constructive interference at $t = 0$.

..and it has cancellation everywhere else.

"*Transform limited pulse*" – cannot get any shorter for the given spectral content

Effect of the Spectral Phase

Now set a phase that varies linearly with frequency : $\varphi(\omega) = a\omega$



Basic Description of an Ultra-short Pulse

Assuming linear polarisation we can construct a simple pulse:

$$E(t) = \underbrace{A(t)}_{\text{envelope}} \underbrace{\cos(\varphi(t))}_{\text{carrier}}$$

where

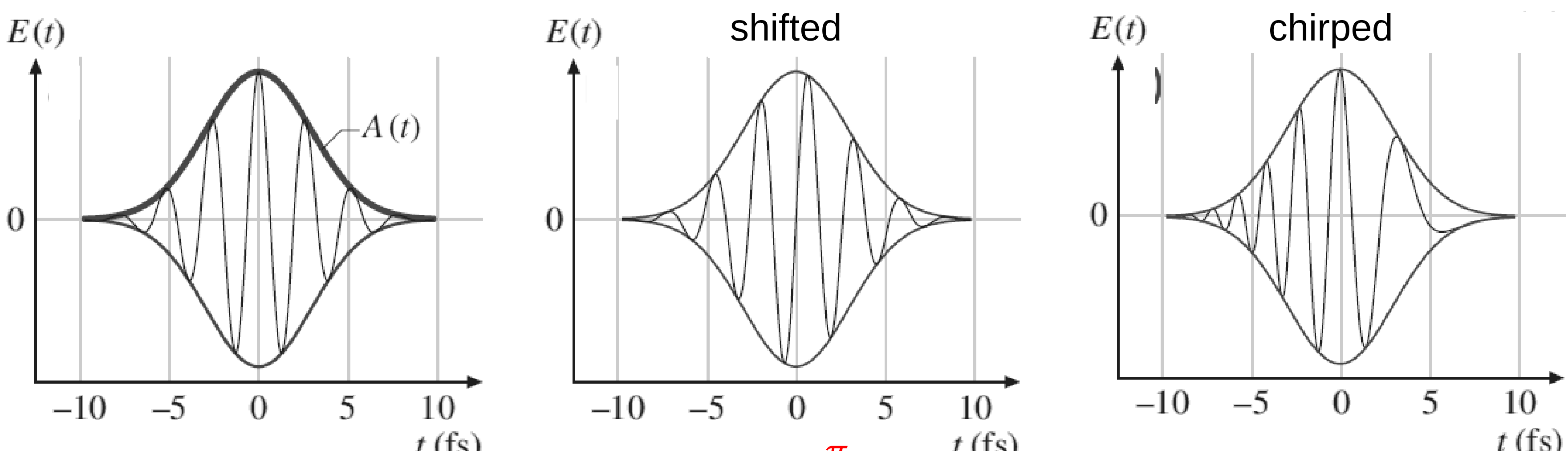
$$\varphi(t) = \varphi_0 + \frac{d\varphi}{dt}t + \frac{1}{2}\frac{d^2\varphi}{dt^2}t^2 + \cdots$$

$$\varphi_0 + \omega_o t + \frac{1}{2}\beta t^2 + \cdots$$

t, time. φ_0, absolute phase. ω_0, 'carrier' frequency.

Can define an instantaneous frequency $\quad \dfrac{d\varphi(t)}{dt} = \omega_{\ inst} = \omega_o + \beta t + \cdots$

Assuming a 800nm carrier wave with Gaussian envelope $A(t)$:



$\varphi_0 = 0 \qquad \varphi_0 = \frac{\pi}{2} \qquad \beta \neq 0$

Fourier Relationship

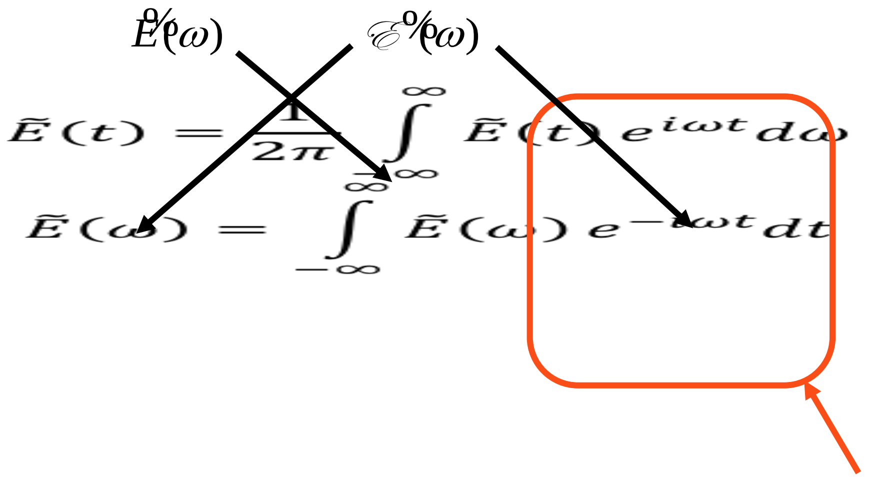
Regularly swap between frequency and time descriptions via the Fourier Transform:

- Generally, the time domain is what we require knowledge of. Also, nonlinear processes easier to calculate.
  - *Convolution Theorem*: multiplication in the time domain equivalent to a convolution in the frequency domain. FFT and multiplication can be more computationally efficient.
- Dispersion and propagation more easily analysed in frequency domain.

The spectrum with and without the carrier frequency

$$\tilde{E}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{E}(t)\, e^{i\omega t} d\omega$$

$$\tilde{E}(\omega) = \int_{-\infty}^{\infty} \tilde{E}(\omega)\, e^{-i\omega t} dt$$



Frequency Domain

Complex spectral amplitude, $\tilde{E}(\omega)$:

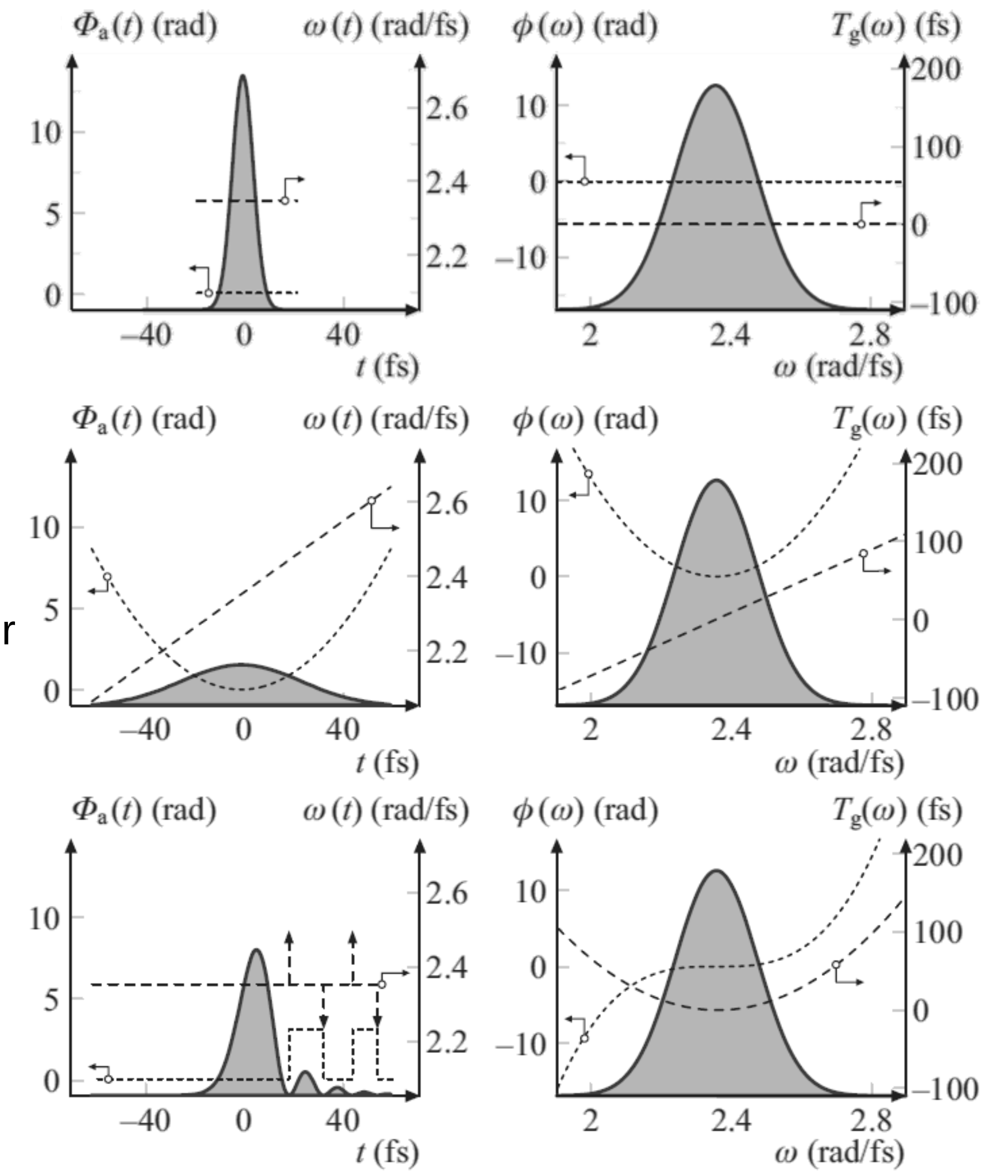
$$\tilde{E}(\omega) = S(\omega)e^{i\varphi(\omega)}$$

Similarly to the phase in time, It is helpful to consider the phase as a Taylor series:

$$\varphi(\omega) = \underbrace{\varphi(\omega_0)}_{\text{“absolute”}} + \underbrace{\frac{d\varphi(\omega_0)}{d\omega}(\omega-\omega_0)}_{\text{“linear”}} + \underbrace{\frac{1}{2}\frac{d^2\varphi(\omega_0)}{d\omega^2}(\omega-\omega_0)^2}_{\text{“quadratic”}} + \underbrace{\frac{1}{6}\frac{d^2\varphi(\omega_0)}{d\omega^2}(\omega-\omega_0)^3}_{\text{“cubic”}} + \cdots$$

<u>It is important to consider the effect of the spectral phase on the temporal profile</u>

Effect of the Spectral Phase



Constant Phase

Quadratic Phase

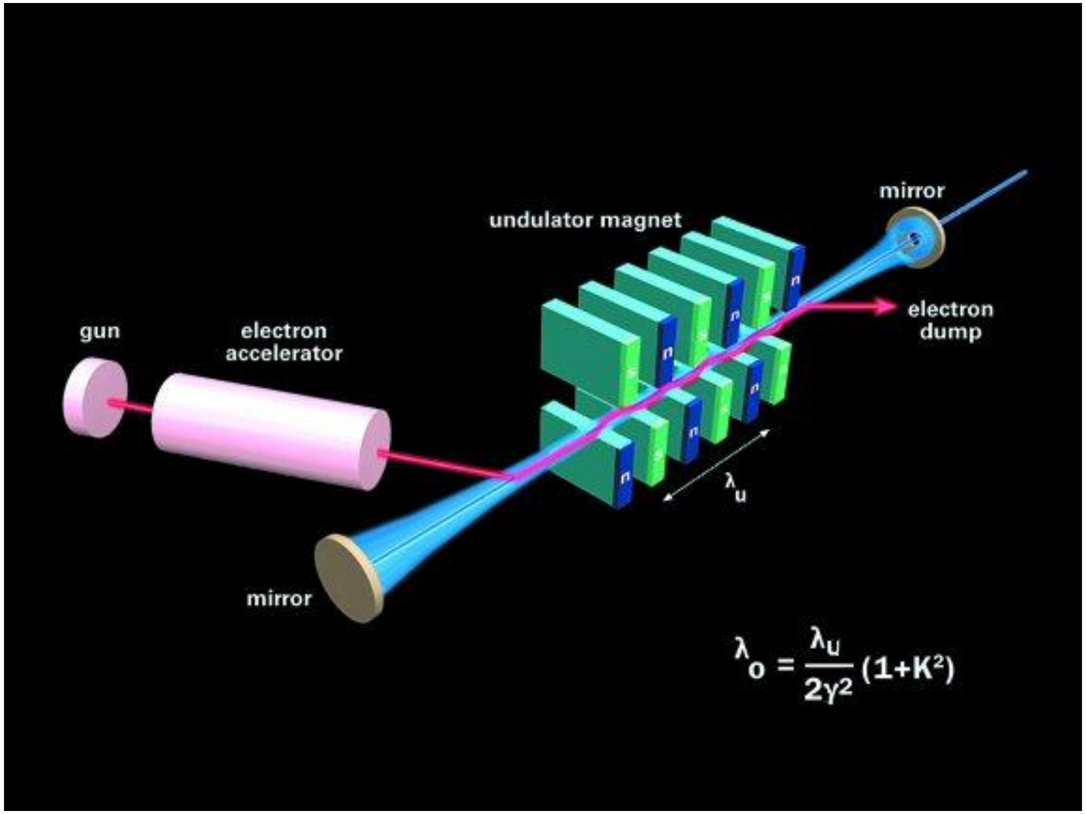
Creates a linear chirp, as seen earlier

"Group delay" $\frac{d\varphi(\omega)}{d\omega} = \tau_g$

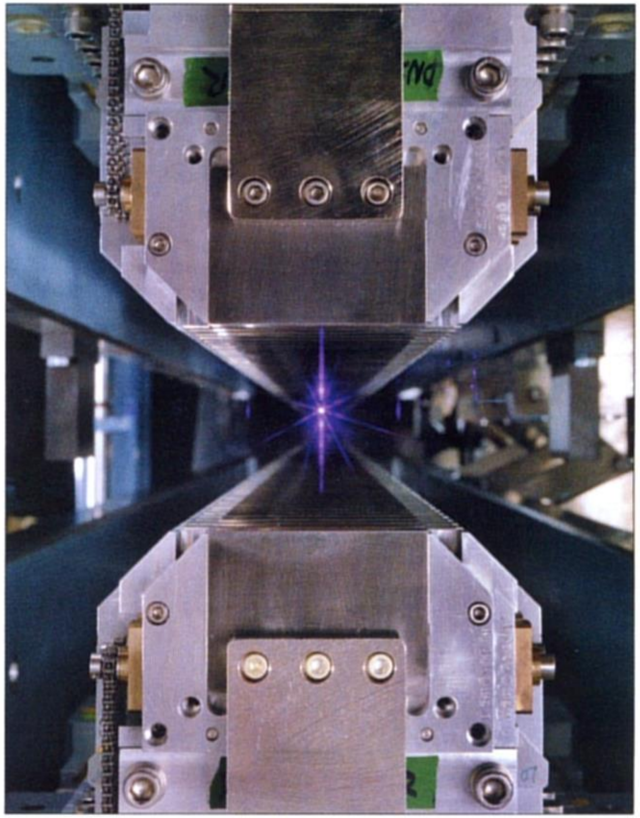
Cubic Phase

Aside: Free-Electron Lasers

FEL can be oscillator or single-pass amplifier, depending on application



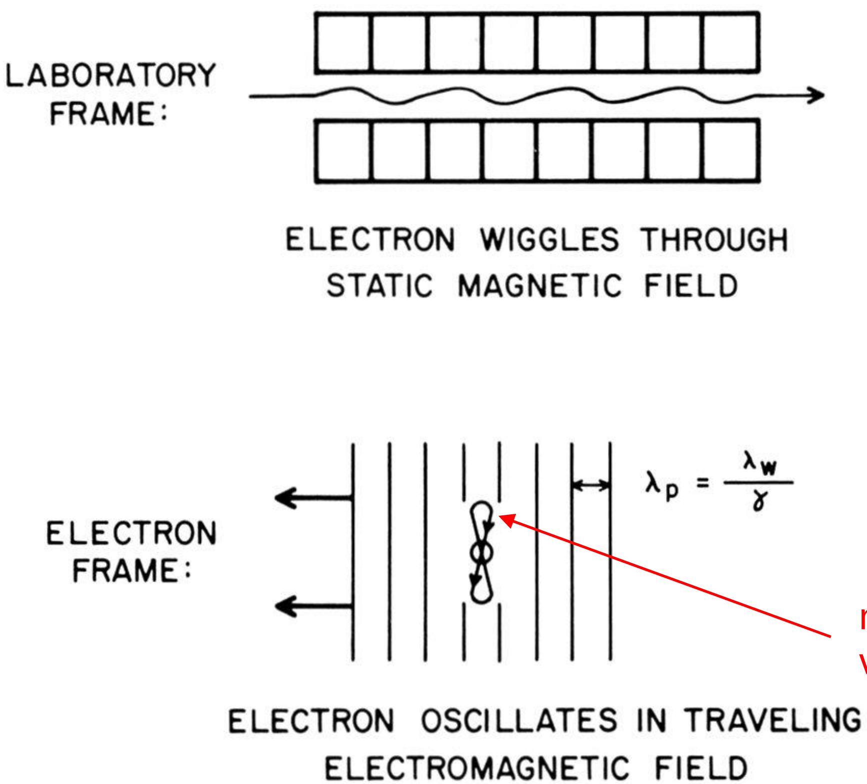
Principle of FEL oscillator



Typical end-on view of undulator
(here at ALS Argonne)

FEL operates by (relativity)^2

1. Relativistic electrons "see" Lorentz-contracted undulator (by a factor γ).
   Emit radiation due to large transverse oscillations
2. Radiation emitted in *rest frame* of electrons. Transforming back to LAB frame *upshifts* frequency by *another factor* γ



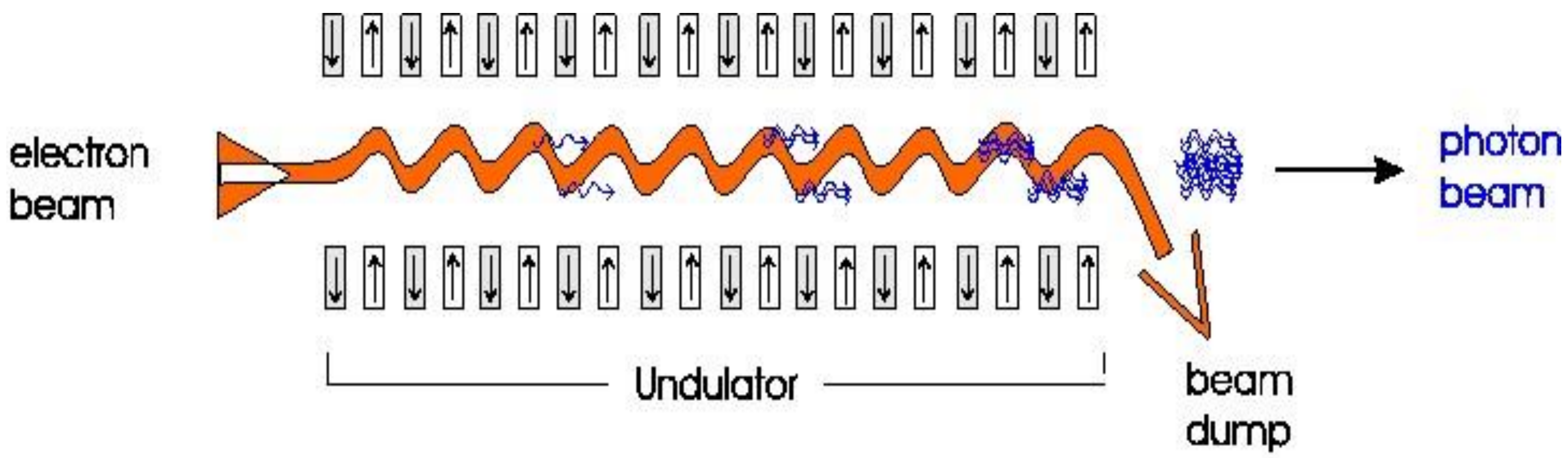
So emitted wavelength is:

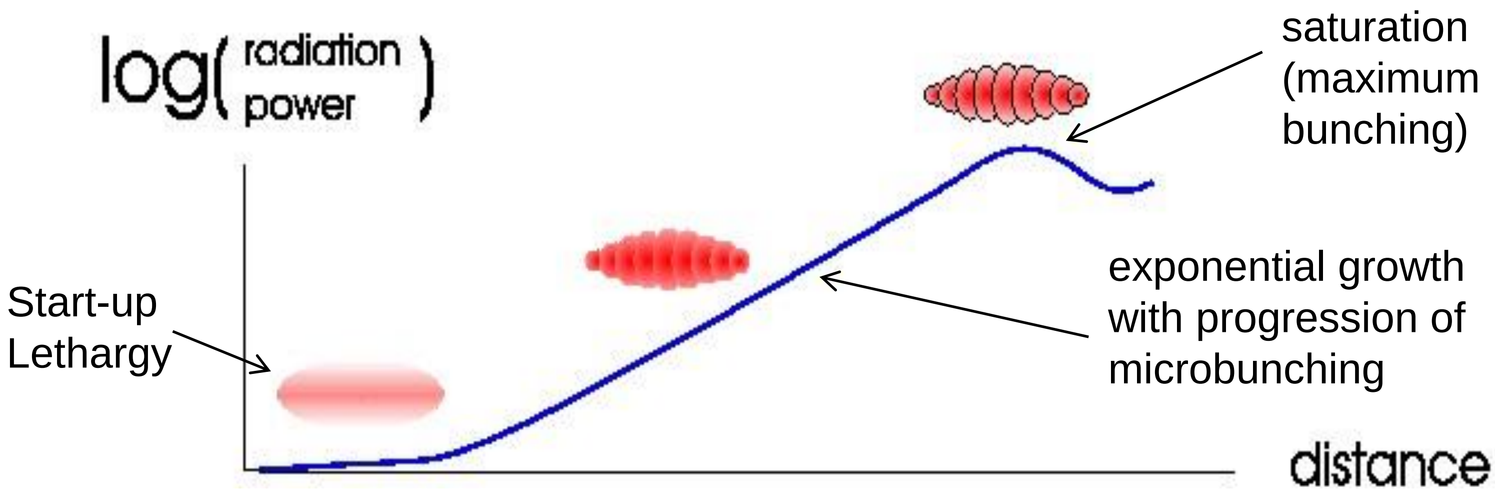
$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1 + \tfrac{1}{2}K^2\right)$$

magnetic field gives both transverse and longitudinal velocity additions – hence "figure-of-eight"

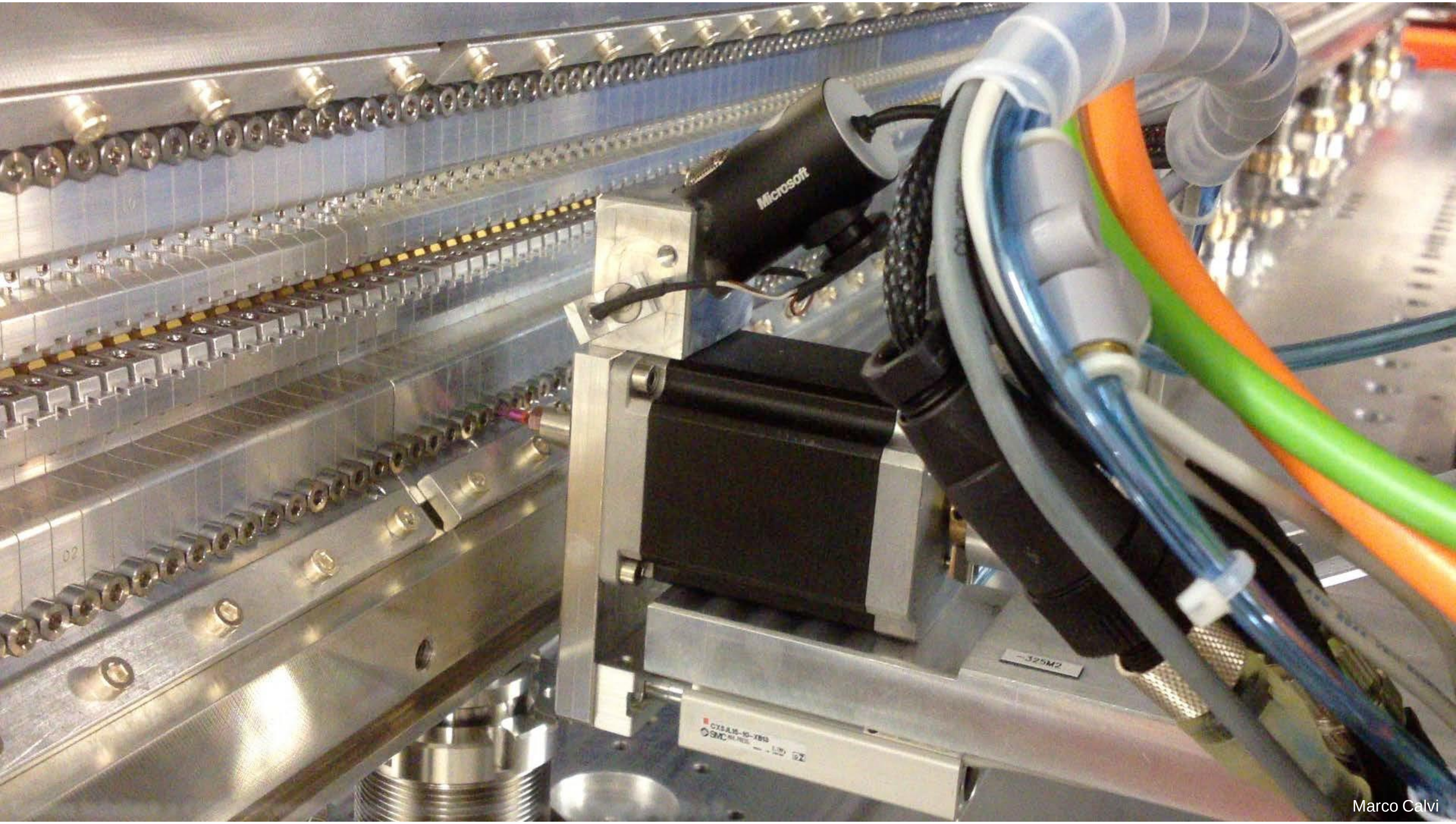
High K $\Rightarrow$ copious harmonics!

Single-pass high-gain amplifier (long undulator) operates by self-amplified spontaneous emission (SASE)





Long undulator at SPring-8 SACLA facility



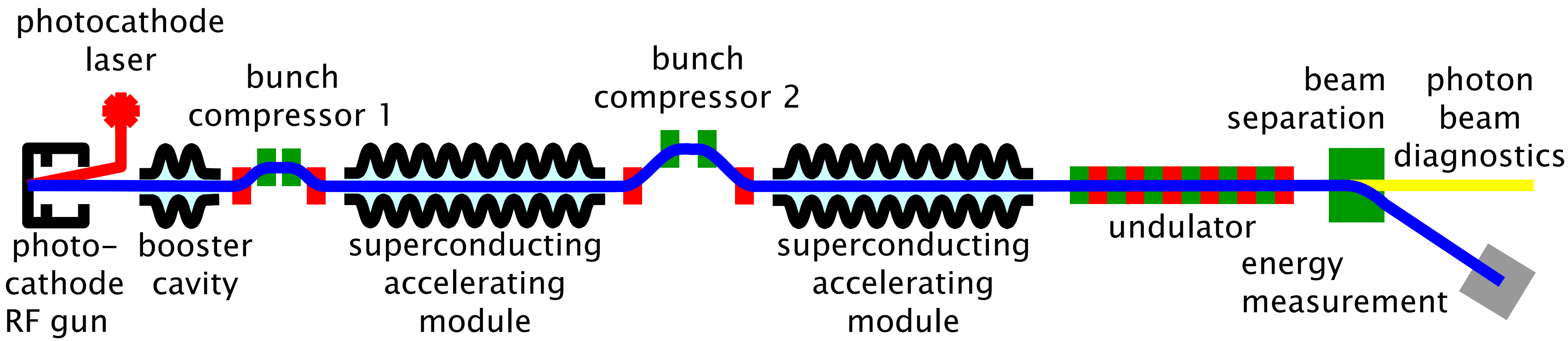
undulator permanent magnet elements

Example: LCLS and LCLS-II @ SLAC National Accelerator Laboratory, Calif., USA.

SACLA X-ray free-electron laser, Hyogo Prefecture, Japan: E = 8.5 GeV, $\tau \sim 30\ fs$

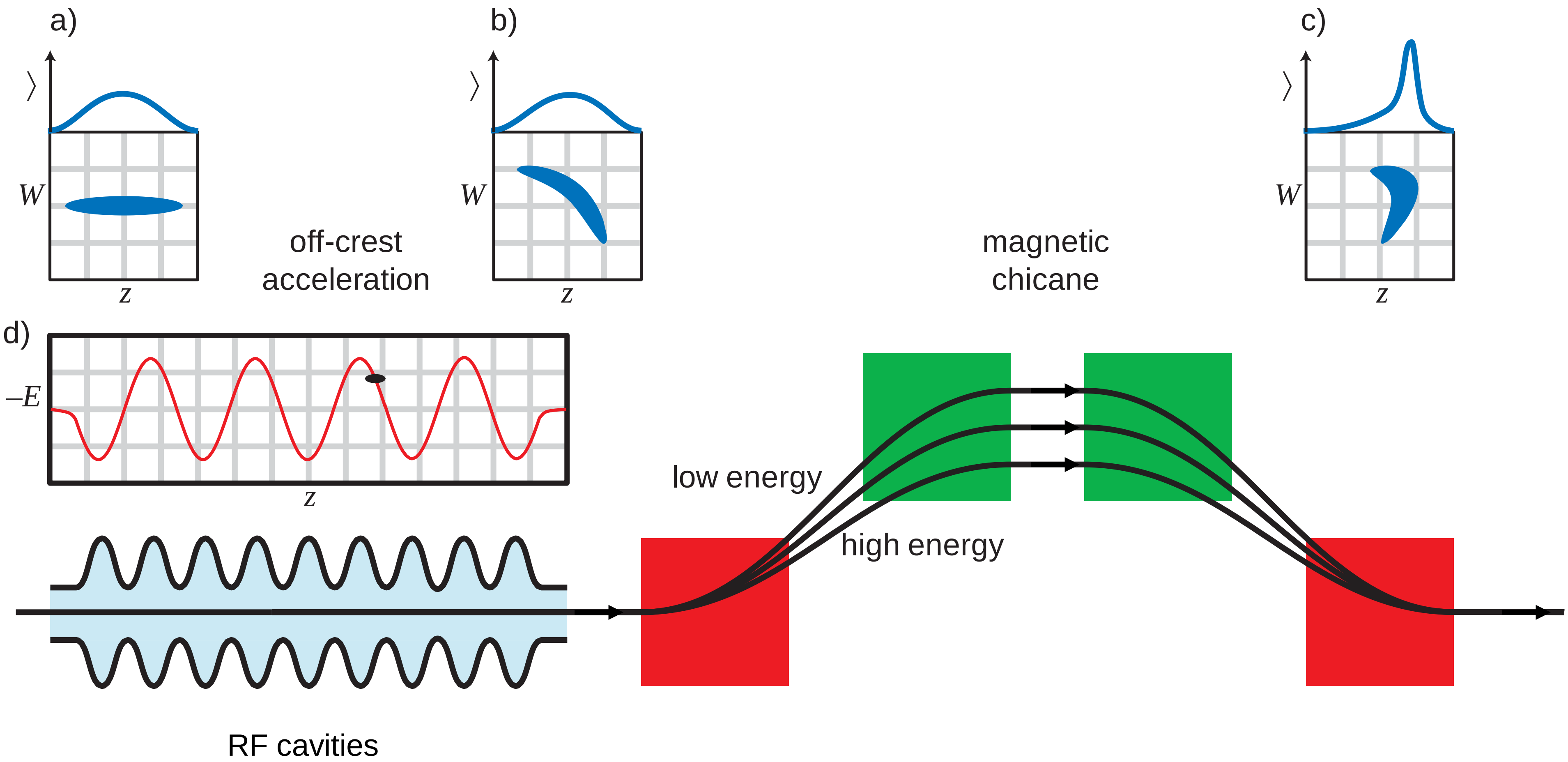
SwissFEL X-ray laser at PSI, Villigen: E = 5.8 GeV, $\tau = 5 - 25\ fs$

Typical modern SC FEL layout



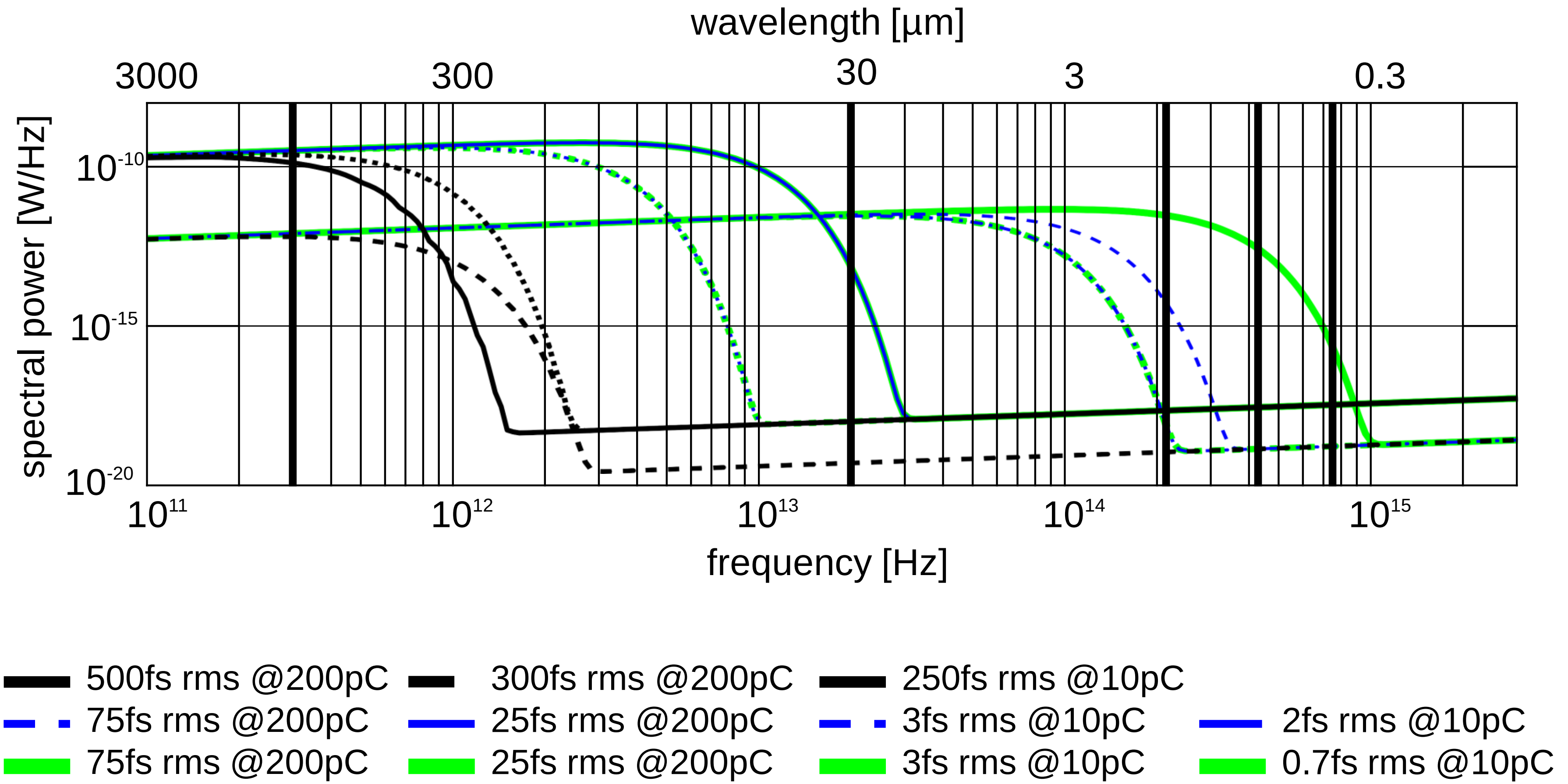
rasmus ischebeck

Principle of magnetic bunch compression



Problems:

- coherent synchrotron radiation
- CTR due to “microbunching” for narrow bunch profiles



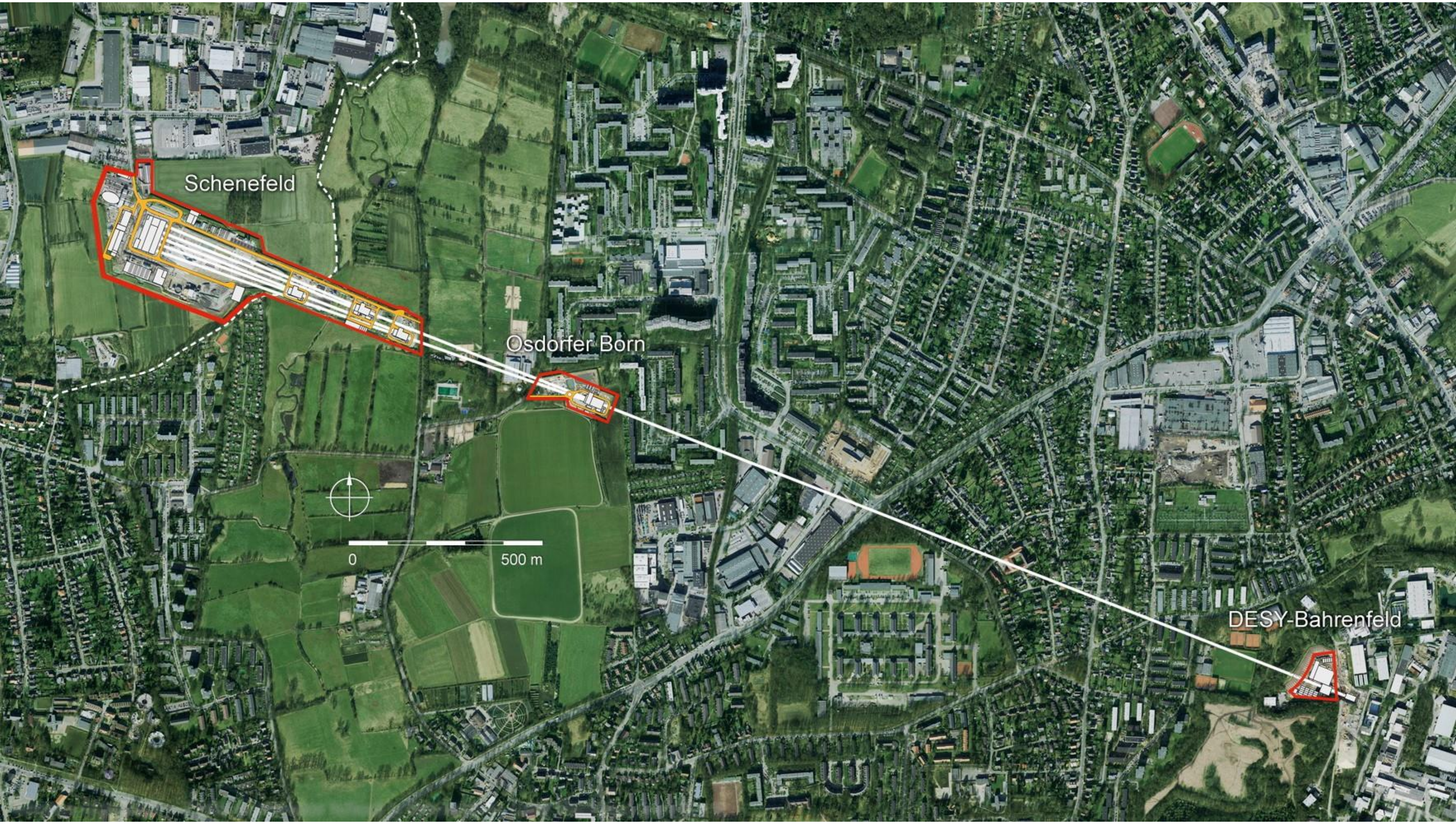
Franziska Frei, Proceedings of FEL2014

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

Elettra Sincrotrone Trieste

FERMI seeded free-electron laser in Trieste: E = 1.2 GeV, $\tau \sim 200\ fs$

FLASH and FLASH2 FELs at DESY, Hamburg: E = 1.25 GeV, $\tau = 30 - 300\ fs$



European superconducting E-XFEL at DESY, Hamburg: 3.4 km long, E = 17.5 GeV, τ = 5-85 fs

POS TECH free-electron laser in Pohang, Korea: E = 2.5 GeV, $\tau \sim 100\ fs$

HGHG SASE free-electron laser in Shanghai, PRC: E = 1.5 GeV, $\tau < 1\ ps$

The SwissFEL C-band linac at the Paul Scherrer Institute (left) and the injection linac for the SINAP XFEL test facility at the Shanghai Institute of Applied Physics (right). Both projects work closely with CLIC to advance high-gradient RF technology.

Image credits: PSI (left) and SINAP (right).

Thanks for your attention ….