Karlsruhe Institute of Technology

Bunch Length Measurements at ANKA

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Joint Quasar & THz Group Workshop - 2009

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Universität Karlsruhe (TH)
Research University • founded 1825

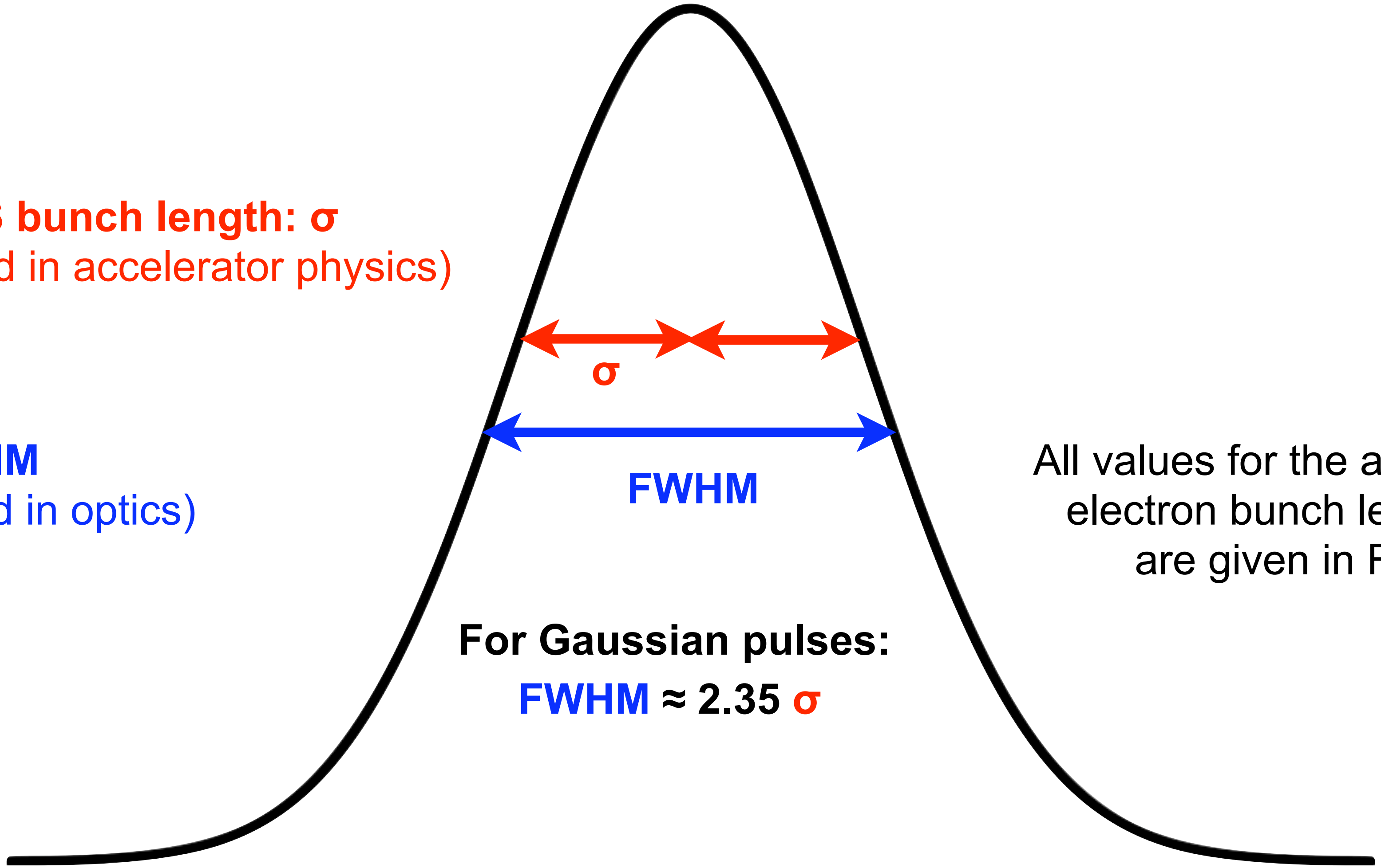
Outline

- Definition of the bunch length
- Introduction to the ANKA facility
- Methods used at ANKA to measure the bunch length
- Summary & Outlook

Bunch length / pulse length

RMS bunch length: σ
(used in accelerator physics)

FWHM
(used in optics)



For Gaussian pulses:
FWHM ≈ 2.35 σ

All values for the actual electron bunch length are given in RMS.

ANKA synchrotron radiation source at the KIT

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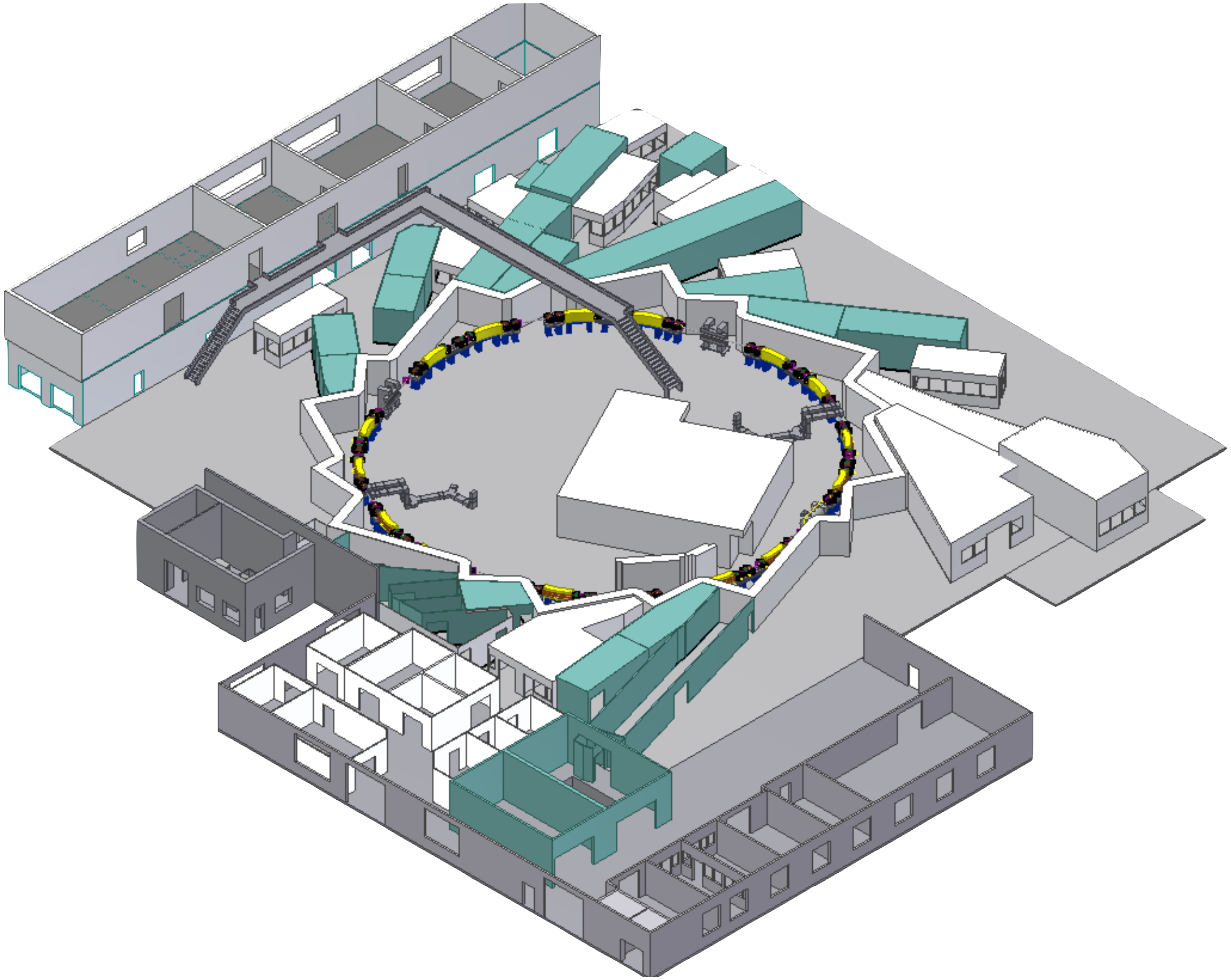
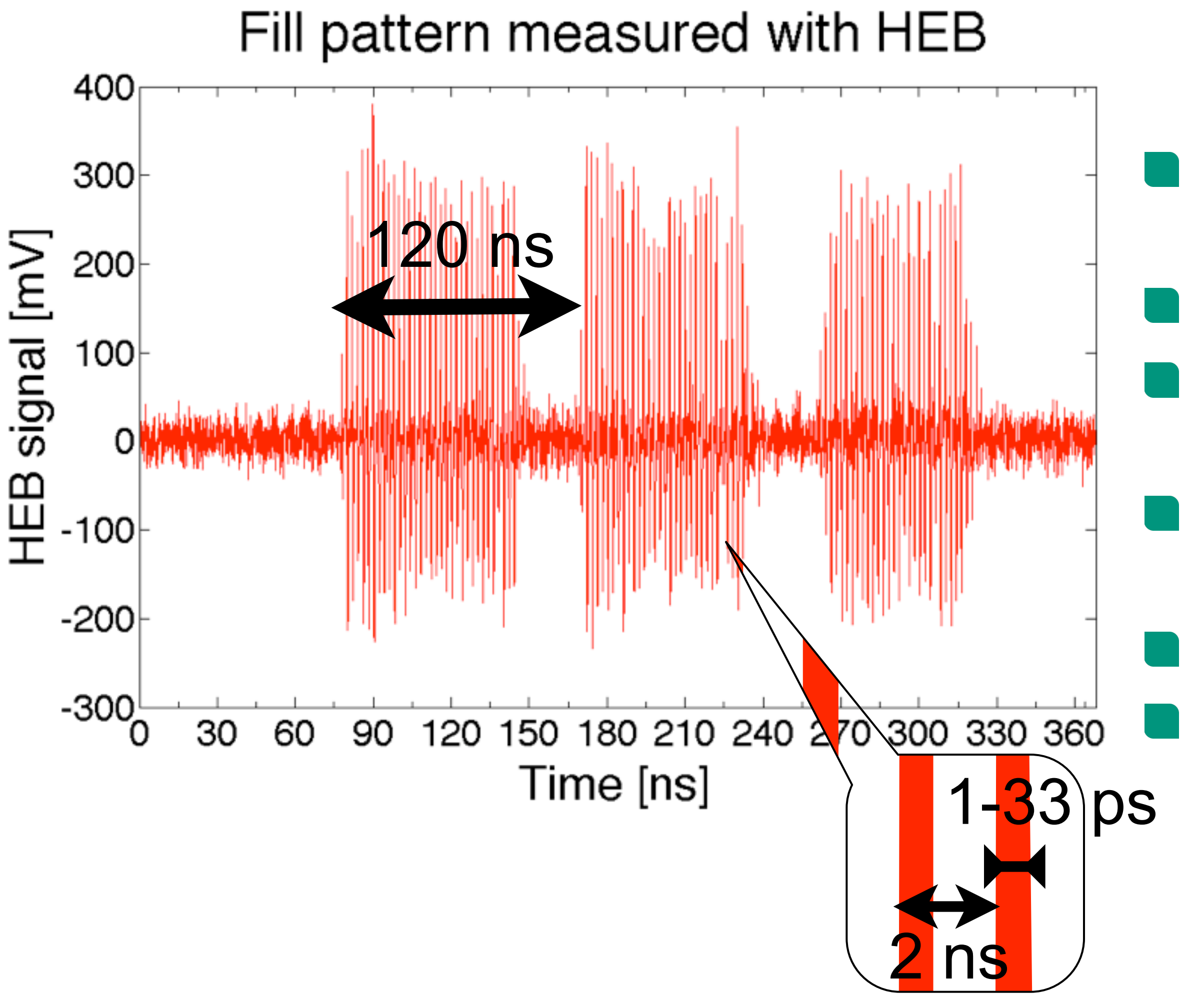


- **normal operation:**
  - energy 2.5 GeV
  - current 200 mA
  - **bunch length σ ≈ 33 ps (RMS)**
- **low Alpha mode:**
  - energy 1.3 GeV
  - current ≈ 70mA
  - **bunch length σ ≈ 1 - 15 ps (RMS)**
  - coherent THz radiation

Filling pattern at ANKA



- filling pattern of the electrons is imprinted into the emitted synchrotron radiation
- circumference 110 m = 368 ns
- 184 RF buckets
- 2 ns between bunches
- 1-3 trains with around 30 bunches each
- 120 ns between trains
- now single bunch operation is possible as well

Idea & Motivation

- bunch length at ANKA between 1 and 33 ps (RMS) (0.3 - 10 mm)
  - can be measured at ANKA by:
    - synchrotron tune (electrons)
    - streak camera (visible light)
    - interferometry (THz-range, results shorter than expected from tune)

→ intensity autocorrelation for comparison in the near IR range

Using f_s to calculate the bunch length

- **Measurement gives the actual electron bunch length**
- **Synchrotron tune is proportional to the bunch length**

energy
spread

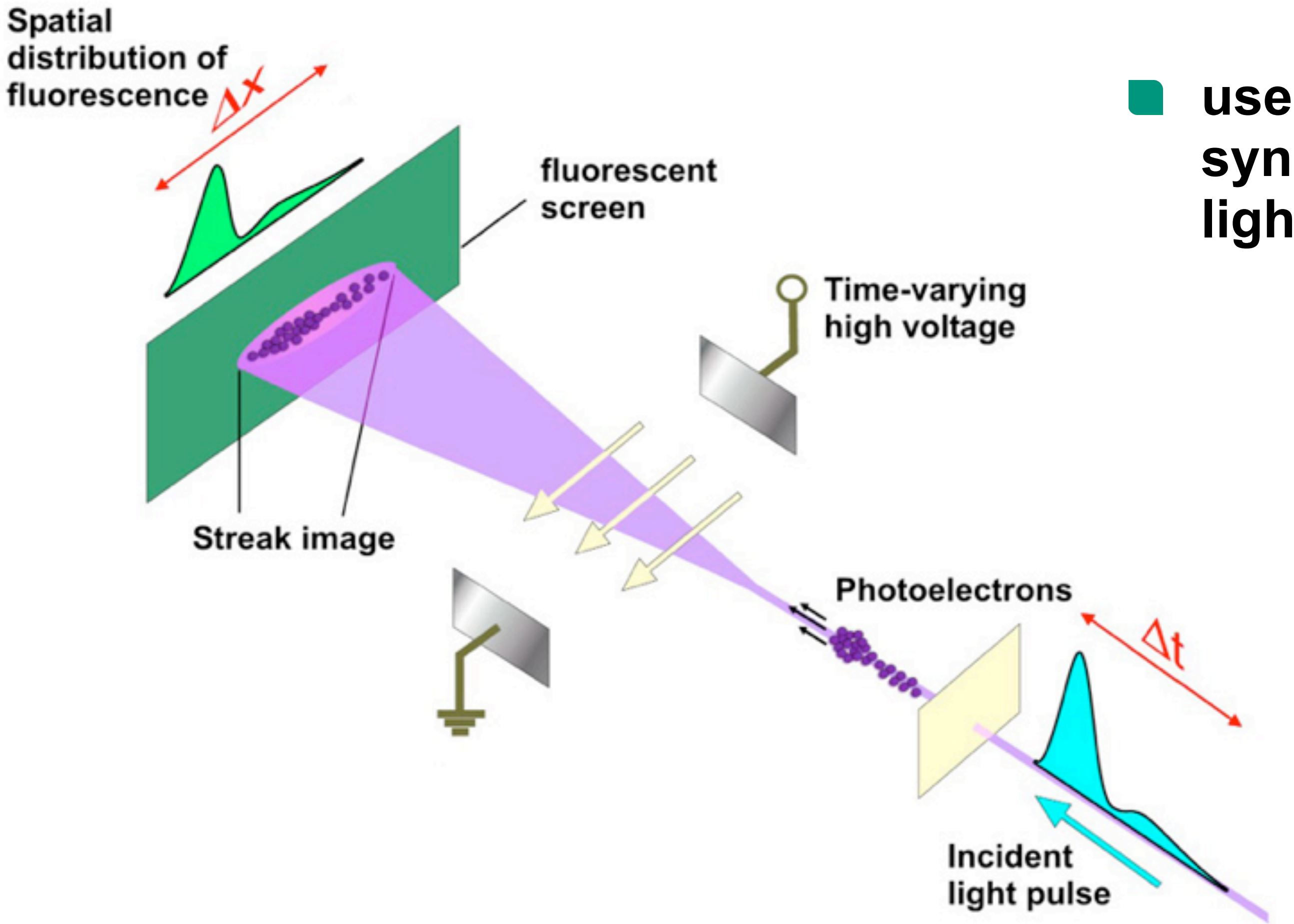
$$\sigma_z = f_s \cdot \frac{cE\delta_E}{f_{rev} f_{RF} \sqrt{g(eV_{RF})^2 - U_0^2 + k}}$$

higher
order
losses

RF voltage
calibration
factor

losses in
the dipoles

Streak camera - principle of function

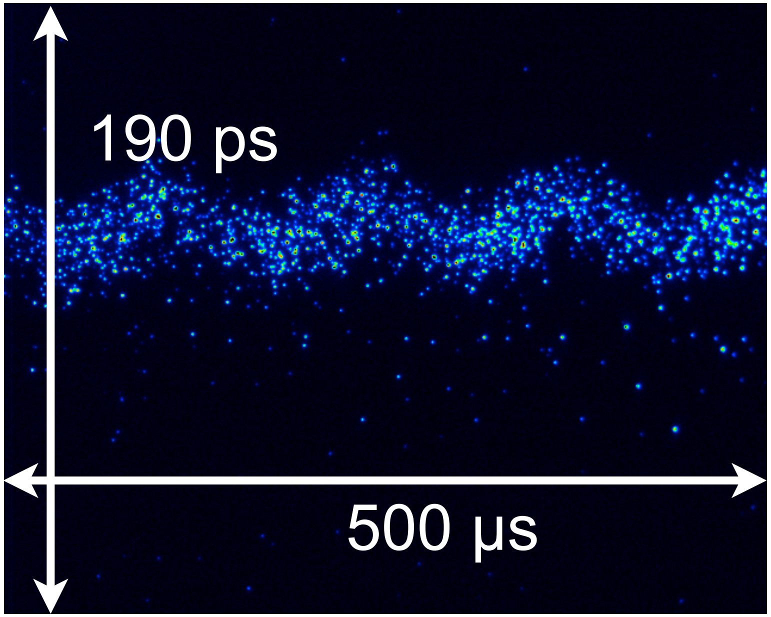


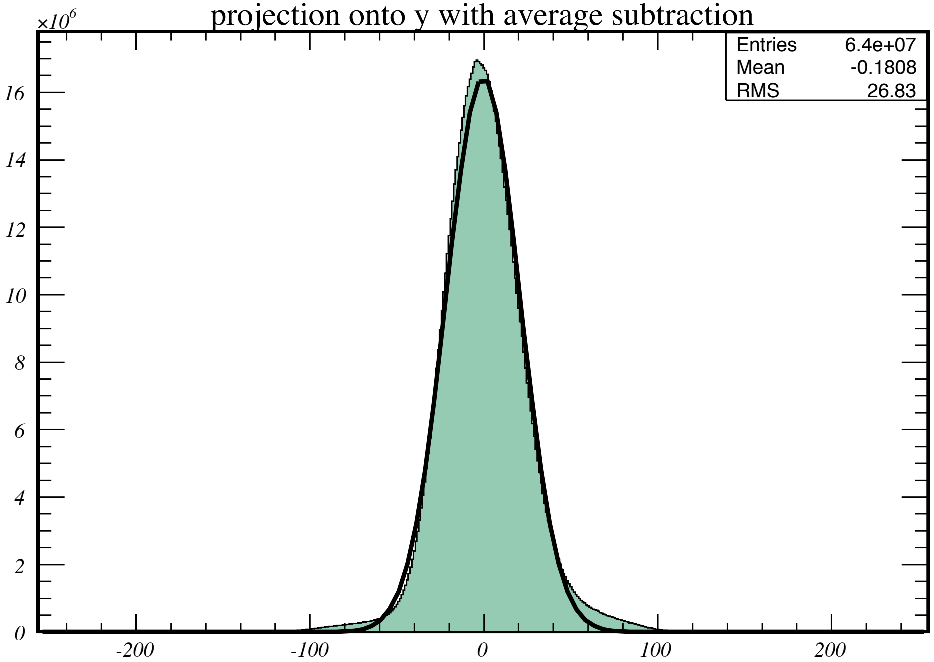
- uses the visible synchrotron light

Source: http://www.mpg.de/bilderBerichteDokumente/multimedial/bilderWissenschaft/2004/02/Krausze2/pressebild.html

Streak Camera - Evaluation

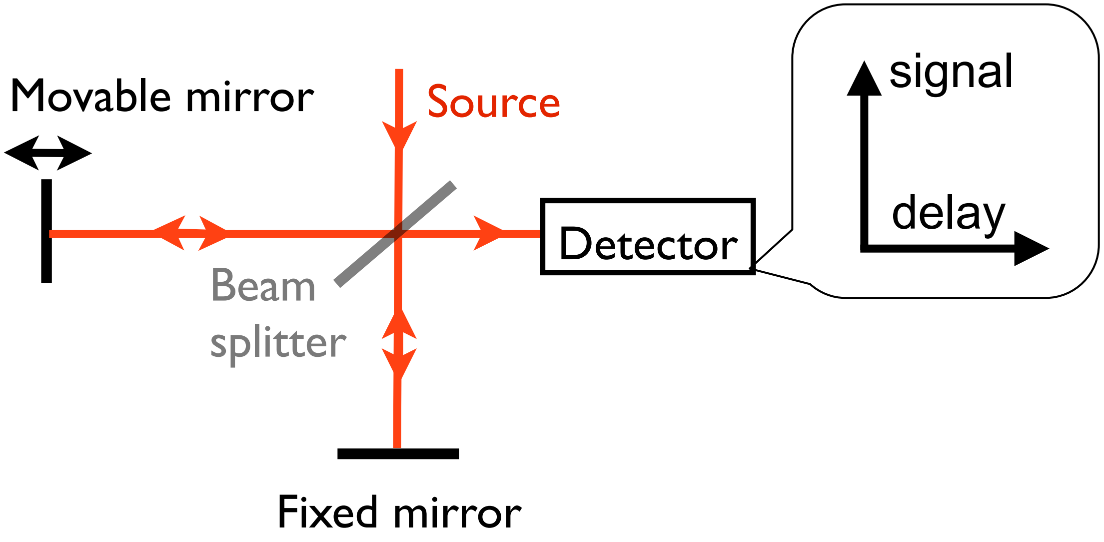
- projection on y-axis gives bunch shape and length
- not bright enough for evaluation of single picture
- integration causes widening because of synchrotron oscillation & jitter on the trigger signal





Single Bunch E = 1.3 GeV, f_s = 7.2 kHz, 21 ps FWHM (expectation from f_s = 10±1 ps)

Optical Autocorrelation



Measured with the synchrotron radiation.

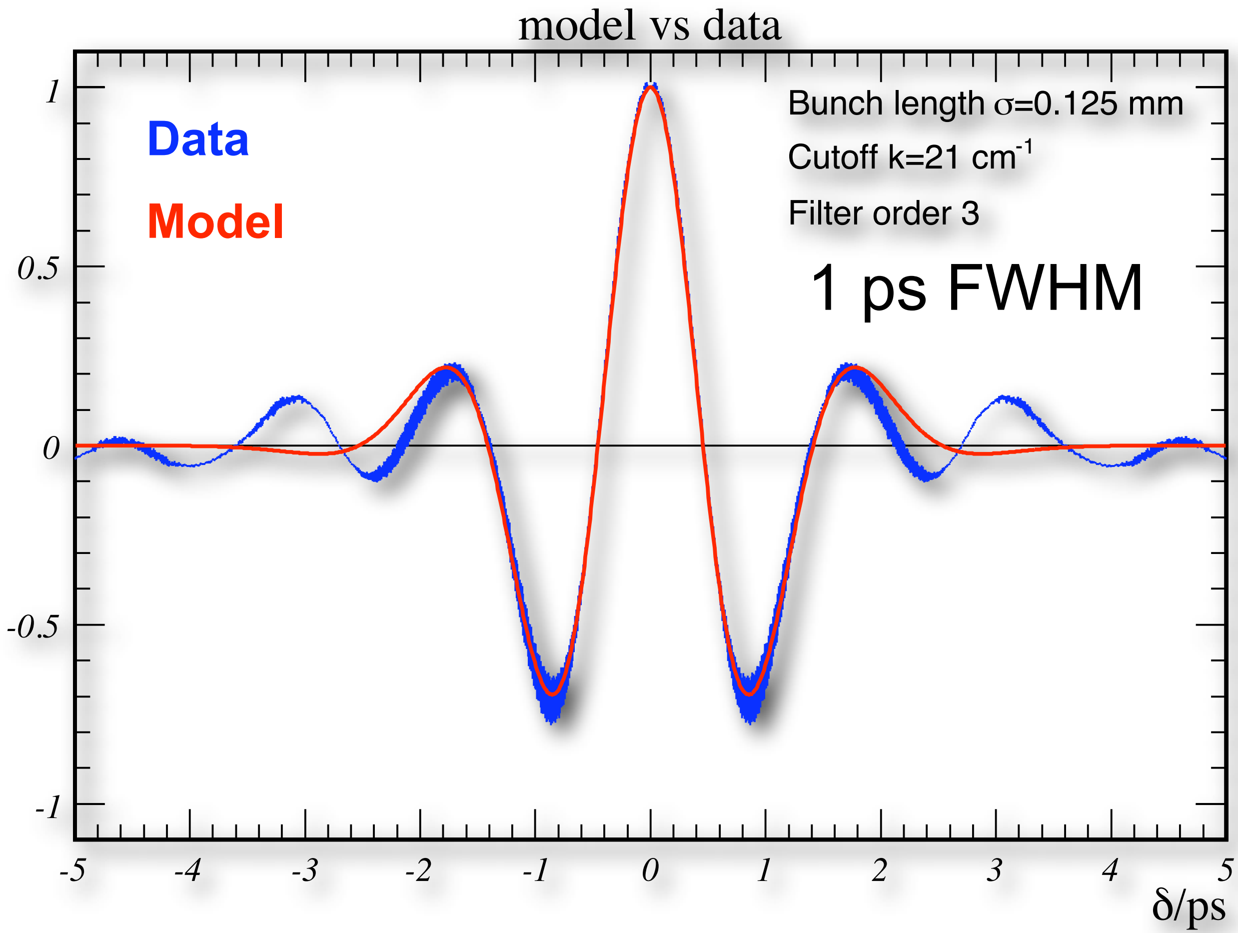
Comparison of signal with itself at a delayed time.

$$I(t) = |E(t)|^2$$

- **field autocorrelation → 1st order** $A^{(1)}(\tau) = \int_{-\infty}^{\infty} E(t)E^*(t+\tau)dt \quad \propto I$
  - **fourier transform gives spectrum**
- **intensity autocorrelation → 2nd order** $A^{(2)}(\tau) = \int_{-\infty}^{\infty} I(t)I(t-\tau)dt \quad \propto I^2$
  - **pulse length (for known pulse shape)**
- **interferometric autocorrelation → intensity autocorrelation with interference**

Field autocorrelation in the THz-range

- spectrum can be obtained through FT
- effective pulse length can be extracted (could be shorter than electron bunch length)



Interferogram of a coherent THz-pulse measured at ANKA with a Michelson interferometer.

Intensity Autocorrelation

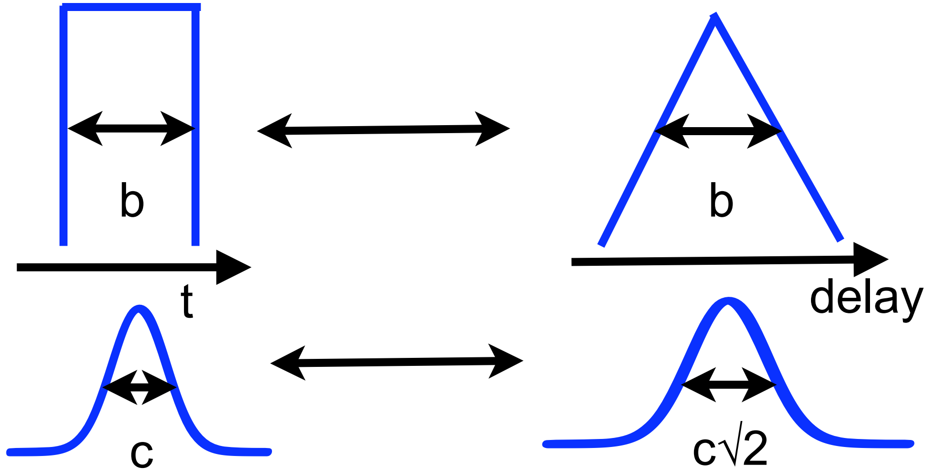
$$A^{(2)}(\tau) = \int_{-\infty}^{\infty} I(t)I(t-\tau)dt \quad \propto I^2$$

- Commonly used detectors:
  - Non-linear crystals (e.g.. BBO) with photodetectors
    → second harmonic generation (SHG)
  - semi-conductors
    → two-photon absorption (TPA)

- Detector must have:
  - Quadratic intensity response
  - Slow rise time (sees a constant signal for a pulsed beam unless delay is changed)

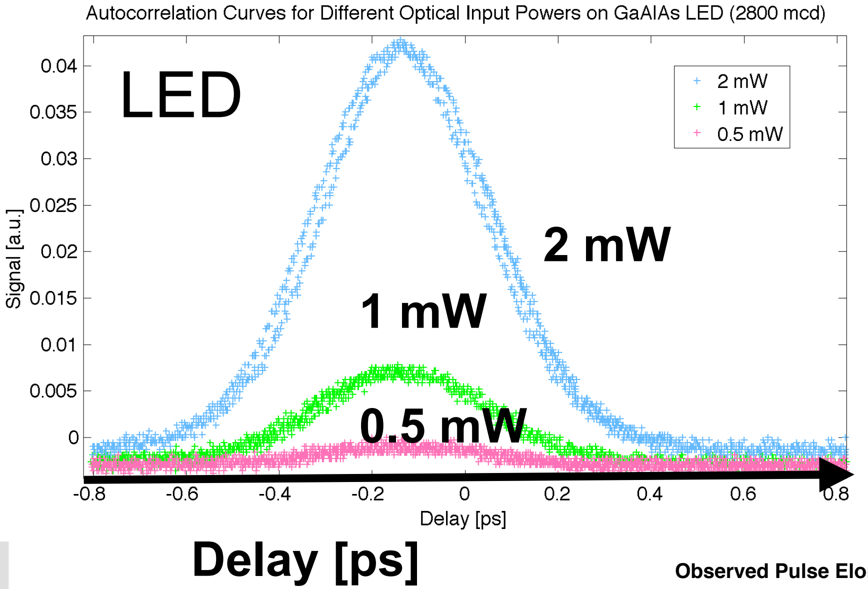
$$\text{Signal} \sim P_{peak} \cdot P_{average}$$

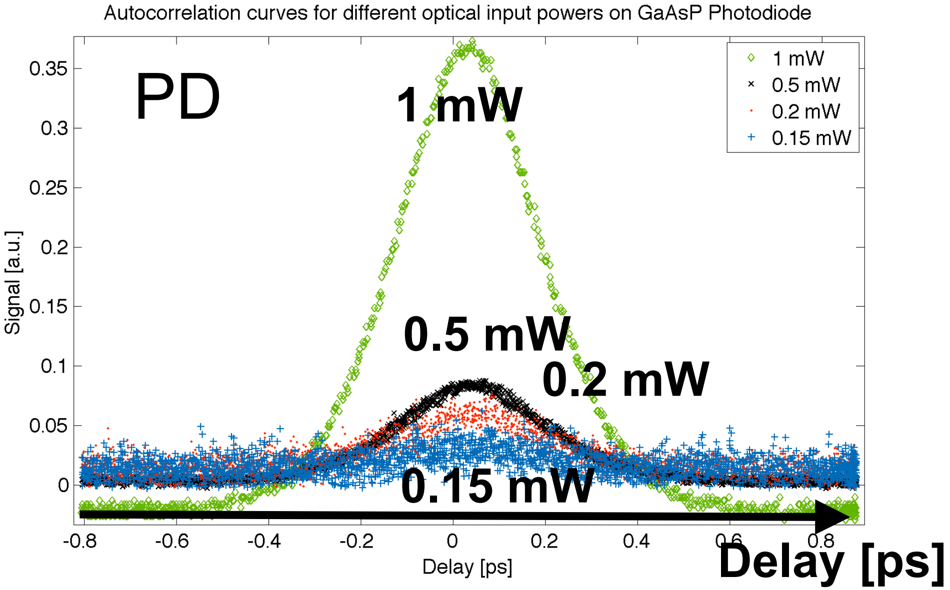
initial pulse **autocorrelation signal**

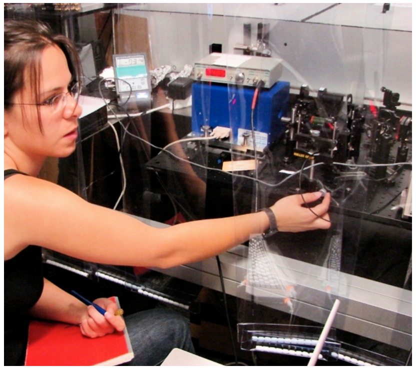


autocorrelation loses phase information → initial pulse shape has to be known / assumed to allow evaluation

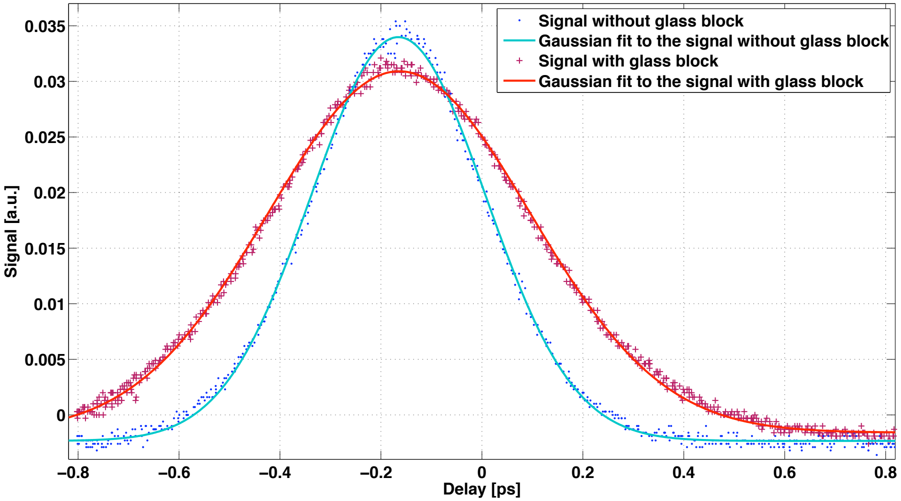
Test Measurements with a fs-Laser





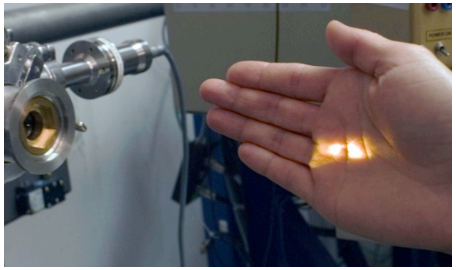


Observed Pulse Elongation due to Dispersion in Glass



- Signal of PD 8x larger than of LED
- Signal to background ratio for PD more than twice as large as for LED

Challenges



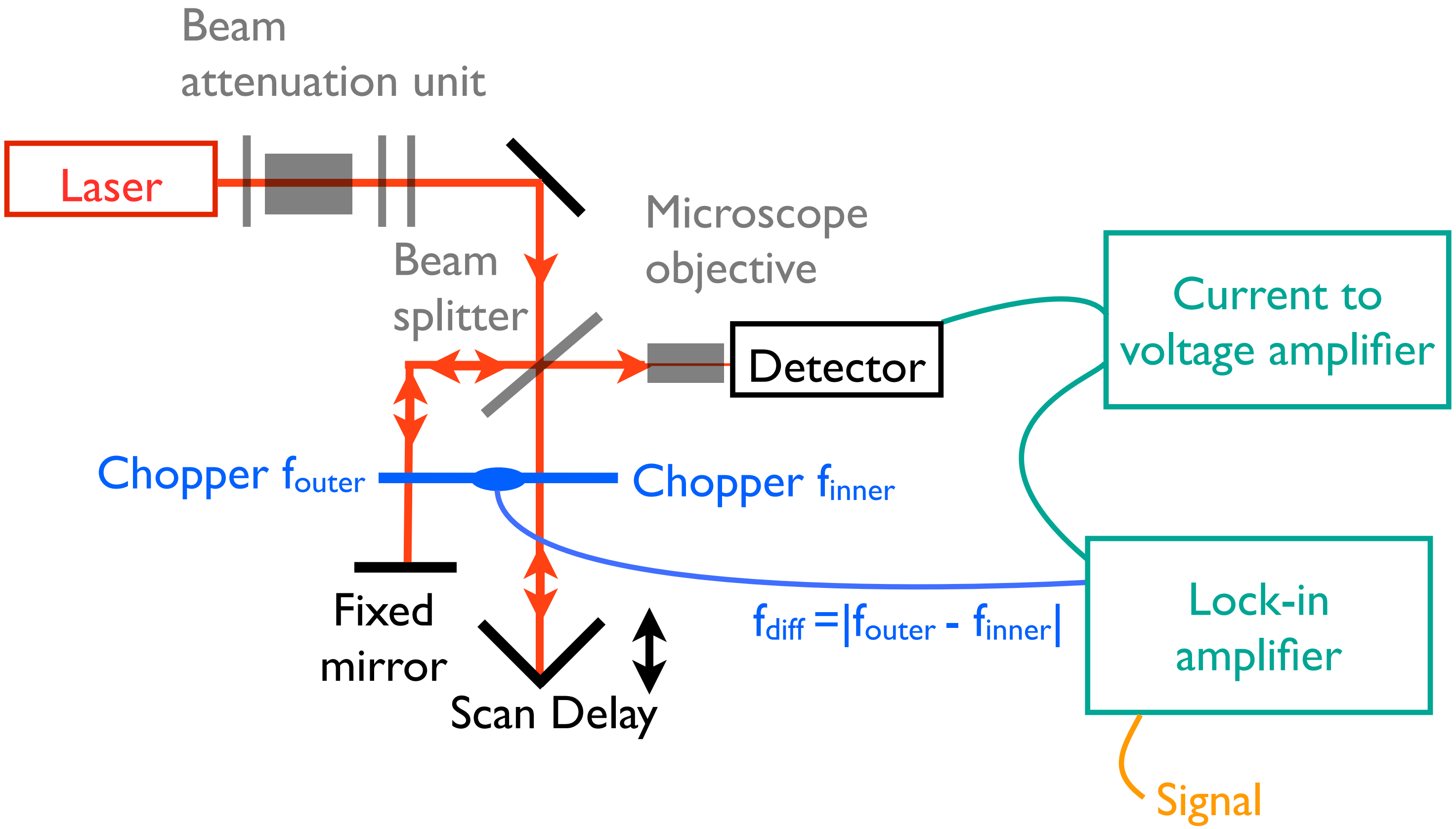
- Set up needs very good alignment.
- Intensity of synchrotron light is just too weak for an autocorrelation to work with the presented set up.
- A more sensitive detector (e.g. PMT) could be used.

Summary & Outlook

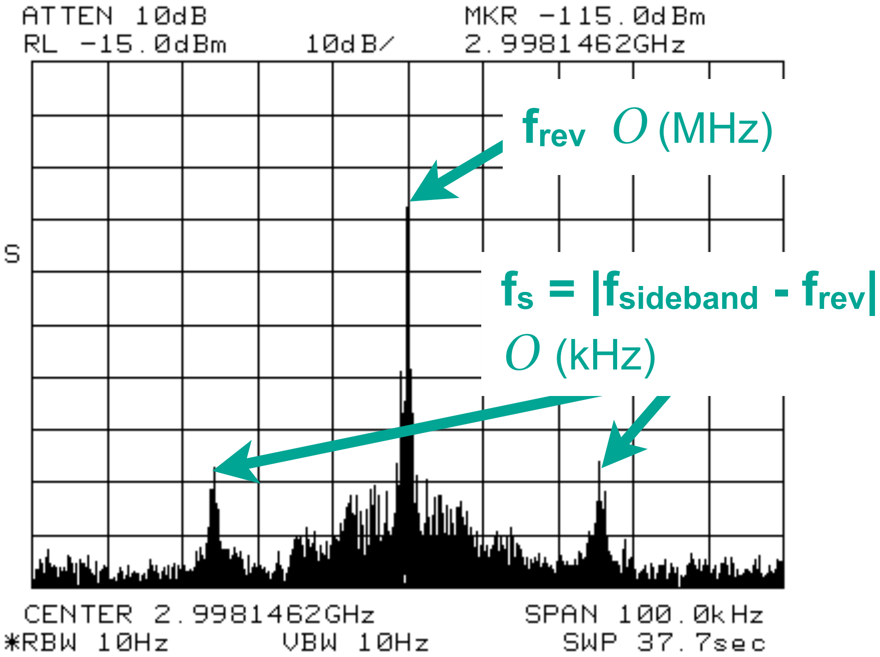
- Every method has its downside:
  - Streak camera: Jitter on the trigger, averaging required.
  - Synchrotron tune: Model required.
  - THz-Interferometry: Gives only effective bunch-length for coherent THz pulses.
  - Autocorrelation: Does not work with low intensity.
- Next steps:
  - optimizing the streak camera and the autocorrelation
  - improving the model for the tune

Thank you for your time.

Laser set up - detailed



Measurement of the Synchrotron Tune



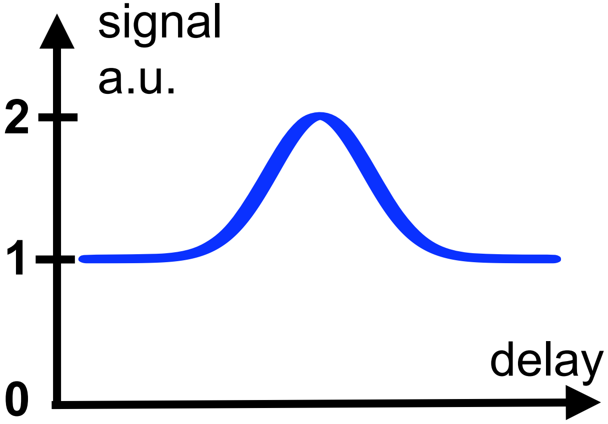
f_{rev} $\mathcal{O}$ (MHz)

$f_s = |f_{sideband} - f_{rev}|$ $\mathcal{O}$ (kHz)

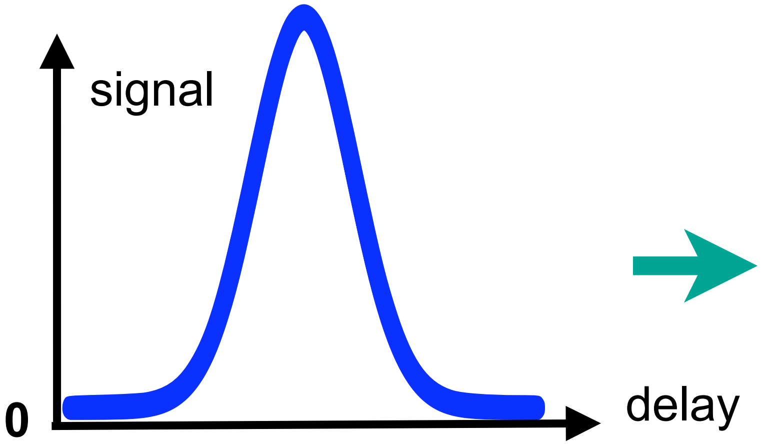
- **measured with spectrum analyzer (FFT) - direct signal from the electrons passing by**
- **Very quick and easy measurement, but a good model of the accelerator is required.**

Background Reduction - Chopper + Lock-In Amplifier

Without background reduction



With background reduction



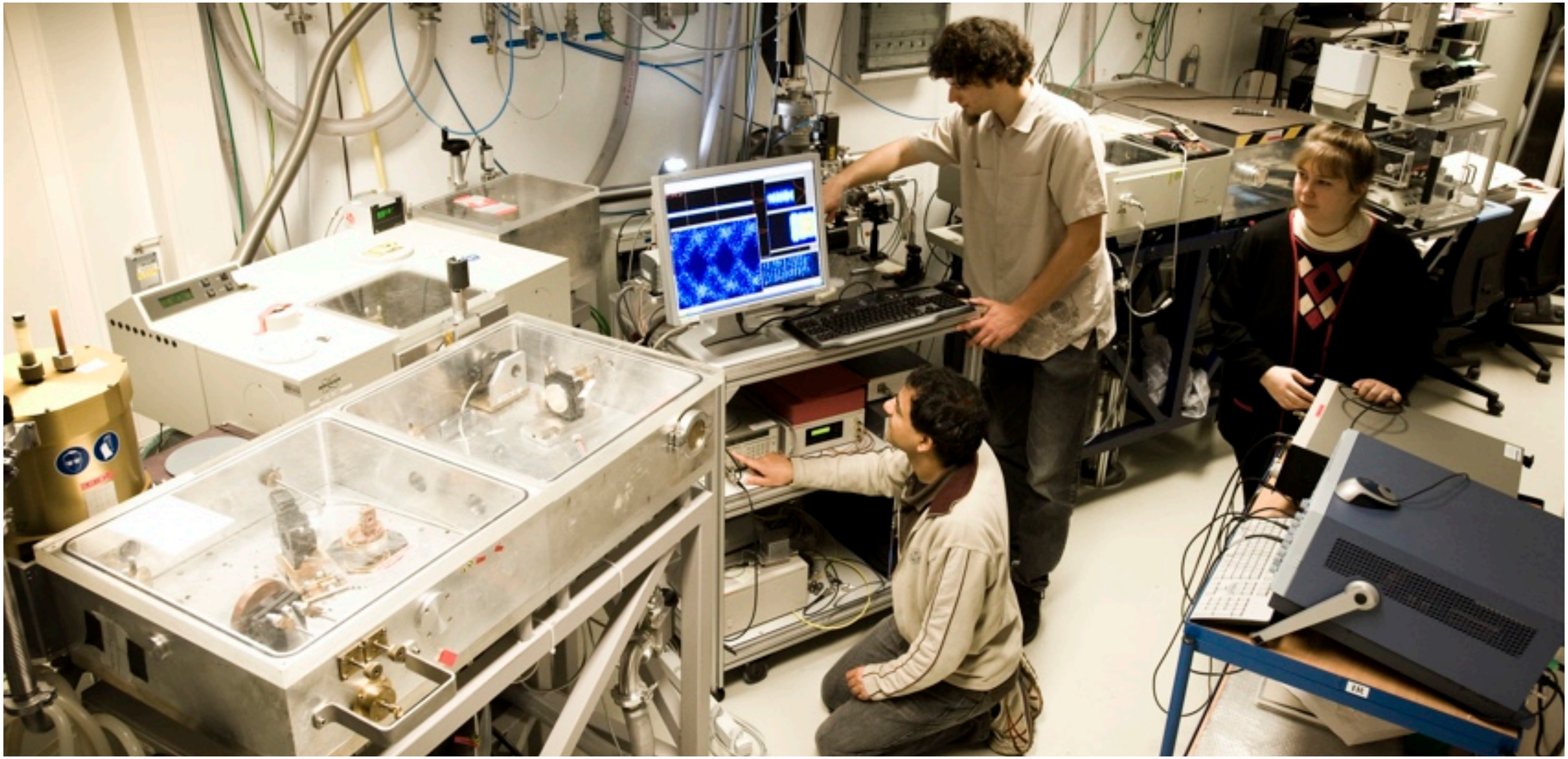
Background: TPAs from photons within beam A or within beam B
Signal: TPAs between one photon from A and one from B

- **Both split beams are chopped at different frequencies**
- **Lock-In searches for signal at f_{dif} and subtracts the background**
  - Signal: Beam A and beam B hit the detector
  - Background: Either beam A or beam B hits the detector

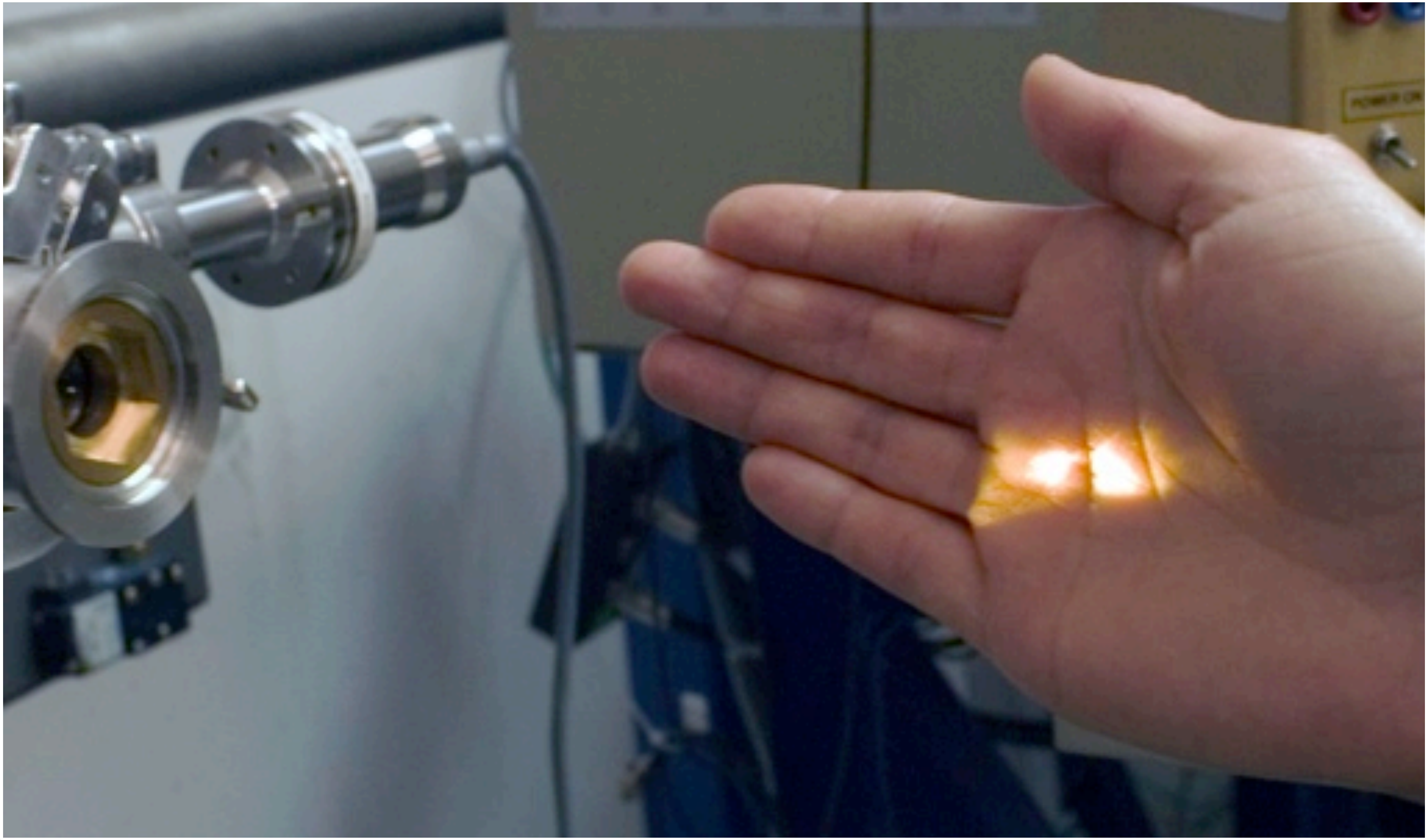
→ **Greatly enhances the signal to background ratio (reached values of around 17 experimentally)**

Infrared beamline (IR1)

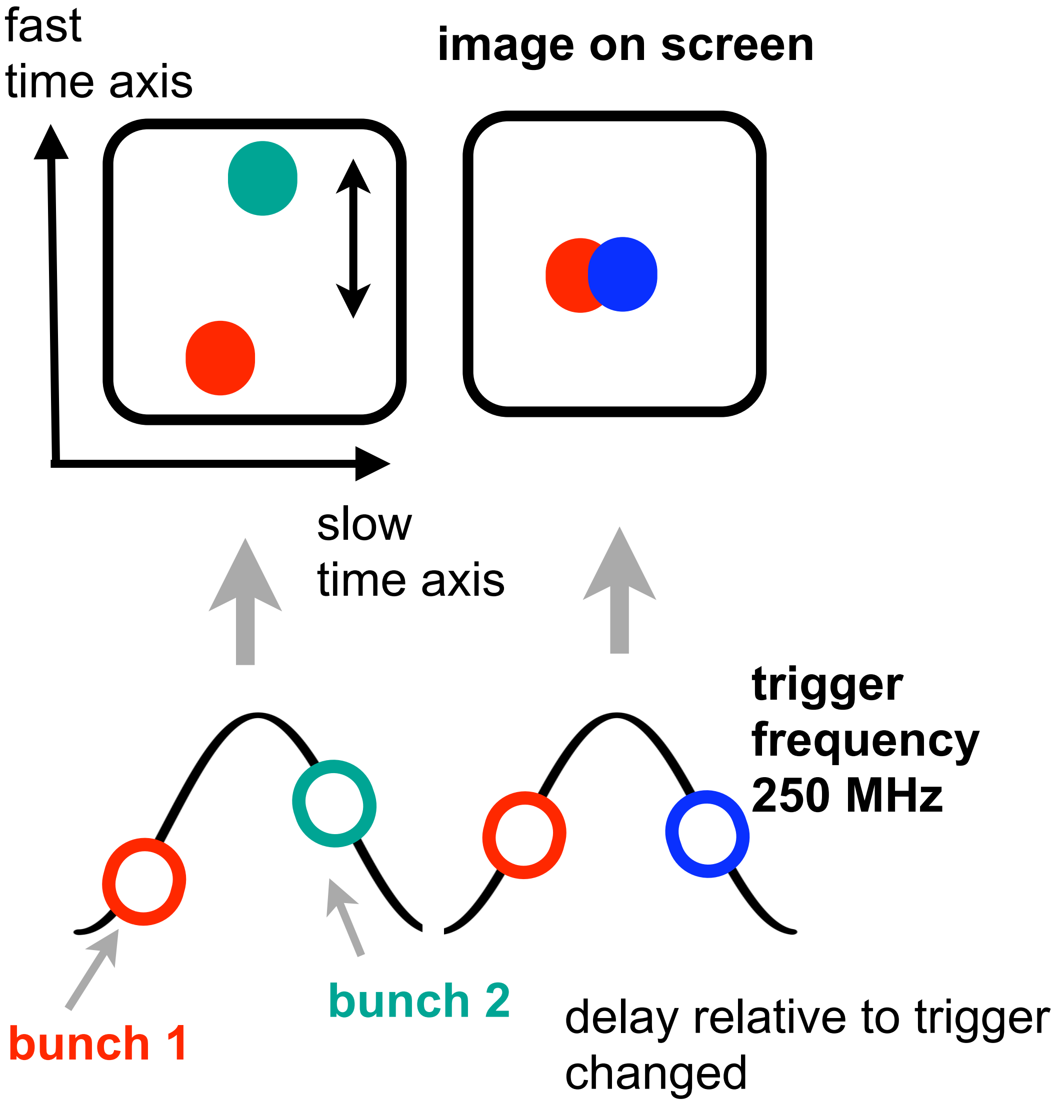
- ellipsometry, infrared spectroscopy, interferometry
  optical port (visible light → THz-range)



Optical port at the IR1



Streak camera - triggering



fast
time axis

image on screen

slow
time axis

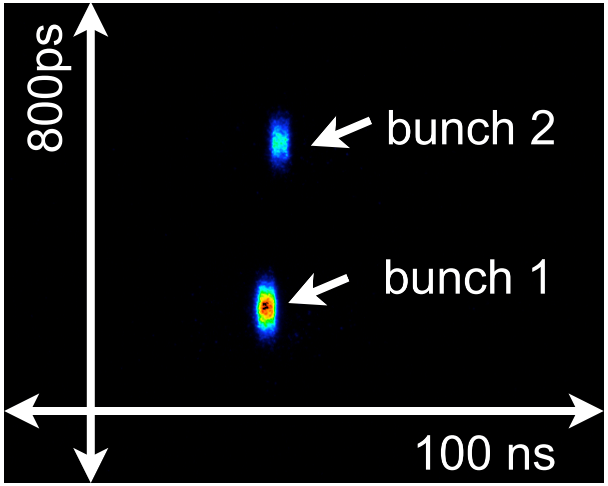
**trigger
frequency
250 MHz**

bunch 1

bunch 2

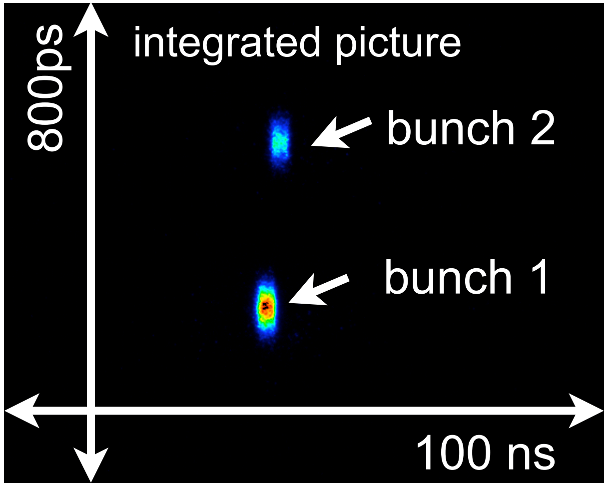
delay relative to trigger
changed

- **relative delay to trigger frequency can be adjusted**
- **jitter on the trigger affects measurement**

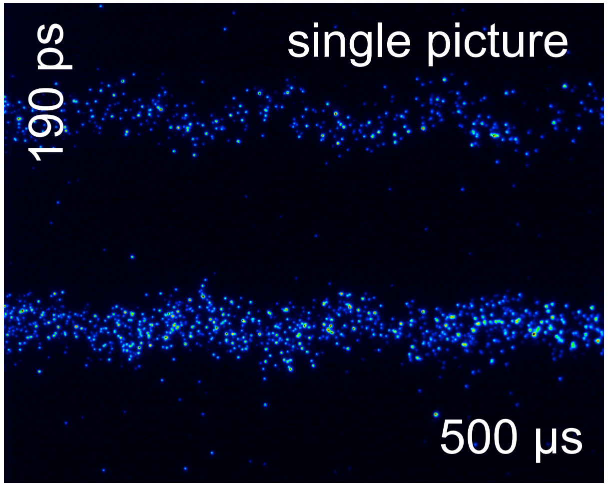


1.3 GeV (f_s = 29 kHz)

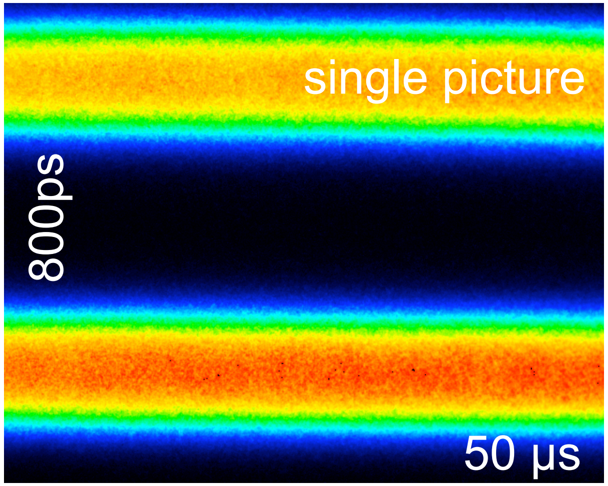
Streak camera



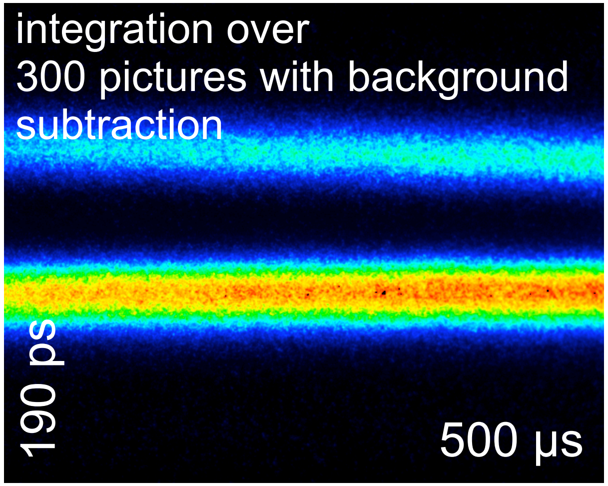
1.3 GeV (f_s = 29 kHz)



1.3 GeV (f_s = 8 kHz)



2.5 GeV (f_s = 30 kHz)



1.3 GeV (f_s = 8 kHz)

- **projection on y-axis gives bunch shape and length**
- **not bright enough for evaluation of single picture**
- **integration causes widening because of synchrotron oscillation & jitter on the trigger signal**

Autocorrelation - theory

- **cross-correlation of two identical functions = autocorrelation**

$$A_f(\tau) = \int_{-\infty}^{\infty} f^*(t) f(t+\tau) dt$$

  - symmetrical
  - maximum for $\tau = 0$
  - periodicity is conserved

- **optical autocorrelation**

$$I(t) = |E(t)|^2$$

  - **field autocorrelation** → 1st order
    - **fourier transform gives spectrum**

$$A^{(1)}(\tau) = \int_{-\infty}^{\infty} E(t) E^*(t+\tau) dt$$

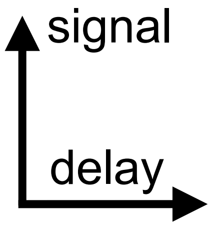
  - **intensity autocorrelation** → 2nd order
    - **pulse length (for known pulse shape)**

$$A^{(2)}(\tau) = \int_{-\infty}^{\infty} I(t) I(t-\tau) dt$$

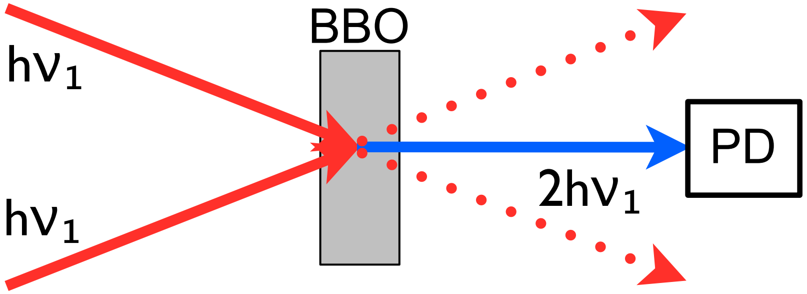
  - **interferometric autocorrelation → intensity autocorrelation with interference pattern**

Intensity autocorrelation - detector

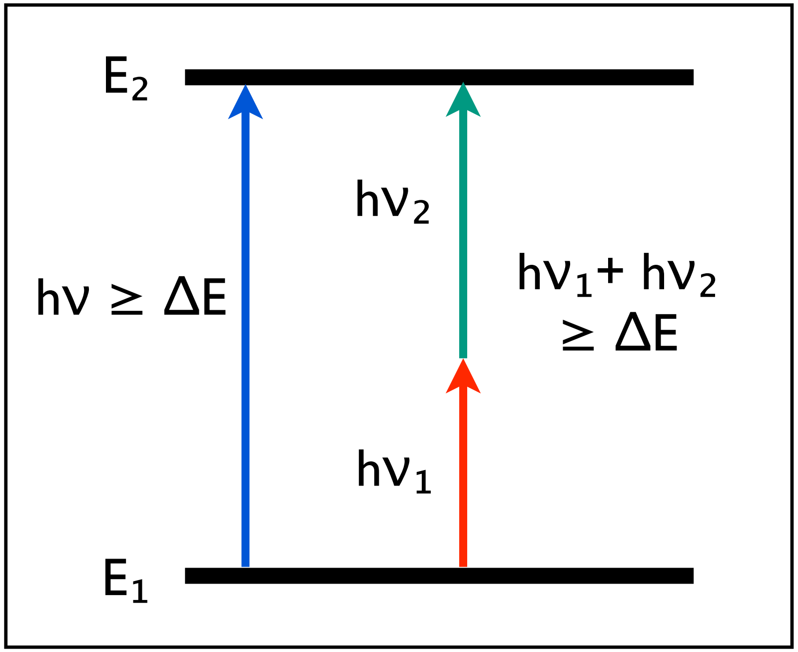
- **requirements:**
  - **slow rise time compared to pulse duration → detector must see a constant signal from a pulsed beam unless delay is changed**
  - **quadratic intensity dependance → sensitive to changes in intensity distribution**



- **commonly used detectors:**
  - **non-linear crystals (e.g.. BBO) with photodetectors**
    → second harmonic generation (SHG)
  - **semi-conductors**
    → two-photon absorption (TPA)



Two-photon absorption semi-conductors



- **using free carrier generation by two-photon absorption (TPA) processes in a semi-conductor**
- **to suppress direct absorption: photon energy < band gap**
- **desired signal ~ N^2/τ (N = # of photons, τ = pulse length) however: linear contribution due to doping impurities & stray light**
- **free carrier generation is fast → but rise time slow enough → detector sees a constant beam → signal only varies when delay is changed**

Detector

LED → “LAD” (“light absorbing diode”)

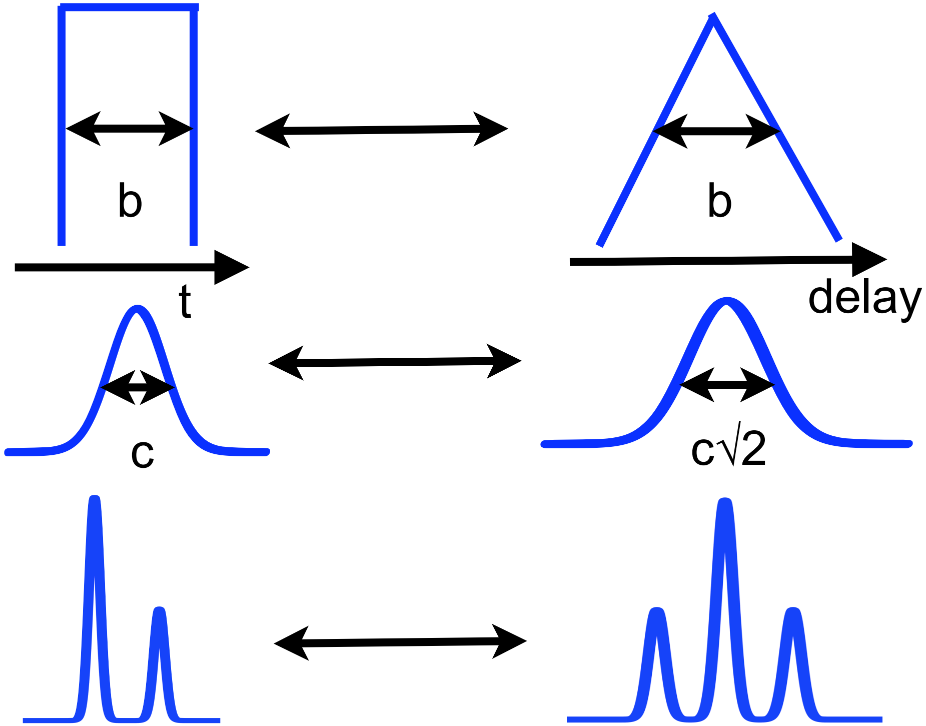
Source: Grapetonix

- standard 5 mm GaAlAs LED (red) $\Delta E = 660$ nm
- tip cut off
- glued into aluminum ring
- surface polished

How to extract the initial pulse length from the intensity autocorrelation?

$$A^{(2)}(\tau) = \int_{-\infty}^{\infty} I(t)I(t-\tau)dt \qquad I(t) = |E(t)|^2$$

initial pulse **autocorrelation signal**



$A^{(2)}(\tau)$:	Autocorrelation signal on detector
$I(t)$:	Intensity of initial pulse
t :	Time
τ :	Delay
$E(t)$:	Electric field of initial pulse

autocorrelation loses phase information → initial pulse shape has to be known / assumed to allow evaluation