Longitudinal beam dynamics & diagnostics

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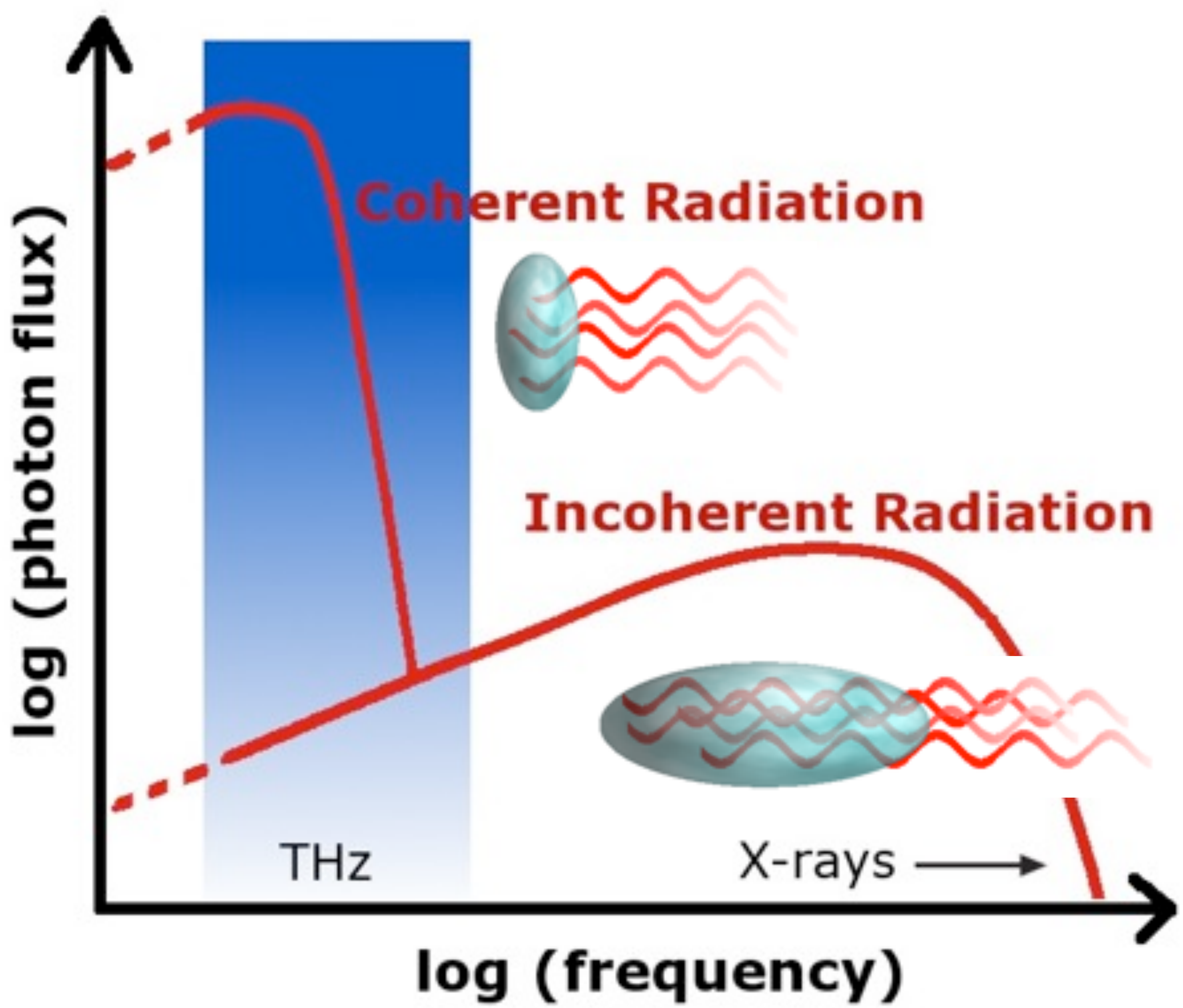
Overview

- Introduction
  - Coherent synchrotron radiation (CSR)
  - The low alpha mode
  - Time structures at ANKA
- Wake fields and impedances
  - Self fields
- Potential well distortion
  - Bunch shape
  - Bunch length → Nicole's talk
- Bursting stable threshold
  - Microbunching
  - Bursting behavior → Vitali's talk
- Power spectra of coherent radiation

Coherent synchrotron radiation (CSR)

- Short bunches emit usable coherent synchrotron radiation
- Enormous increase in power in comparison to incoherent emission
- Dedicated optics with negative dispersion in the long and short straight sections for flexible bunch length tuning
  - Low-α_c optics



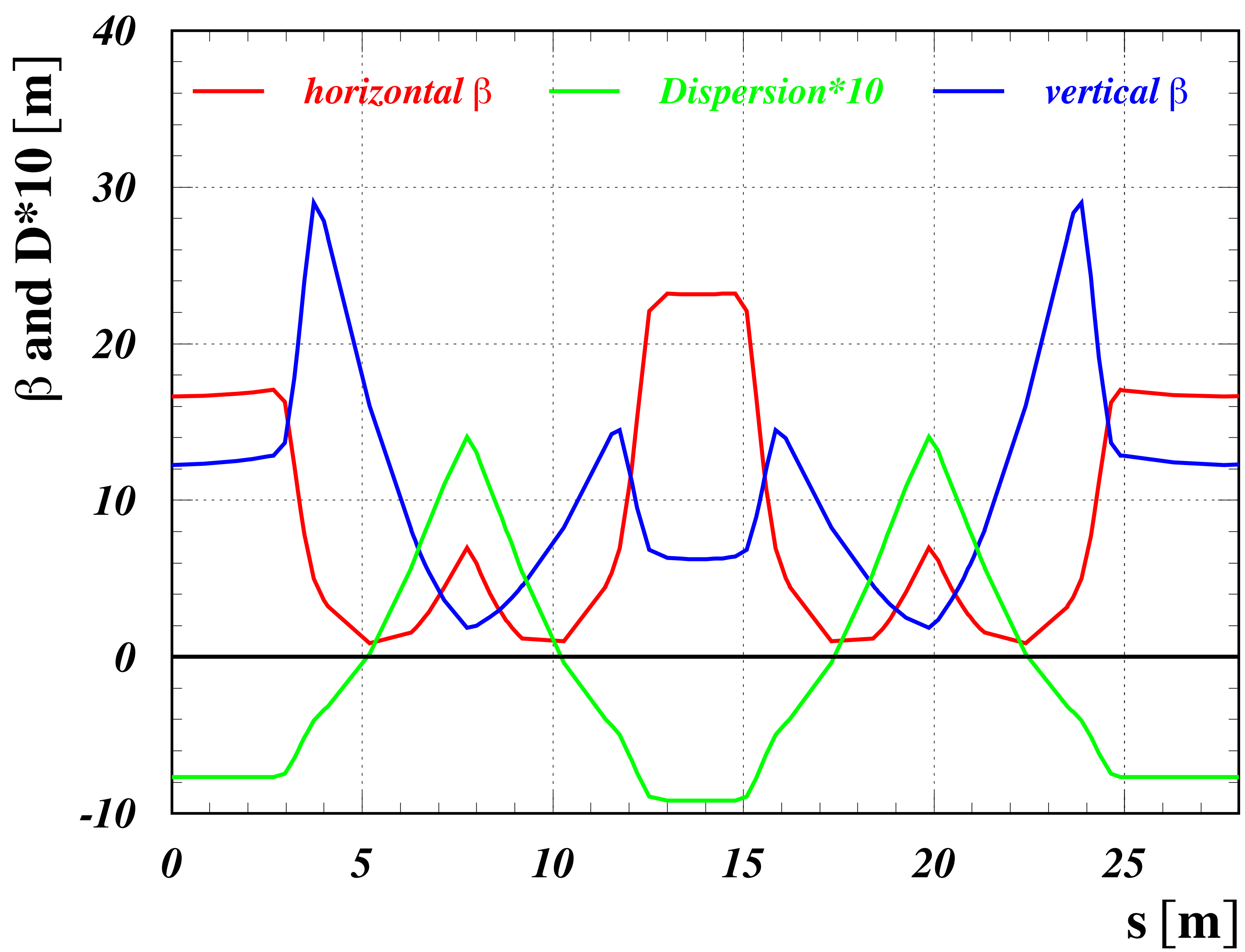
- Coherent radiation is produced in two regimes:
  - low power stable emission
  - high power radiation bursts

The low-alpha mode

- Low-alpha user operation: 12 days/year

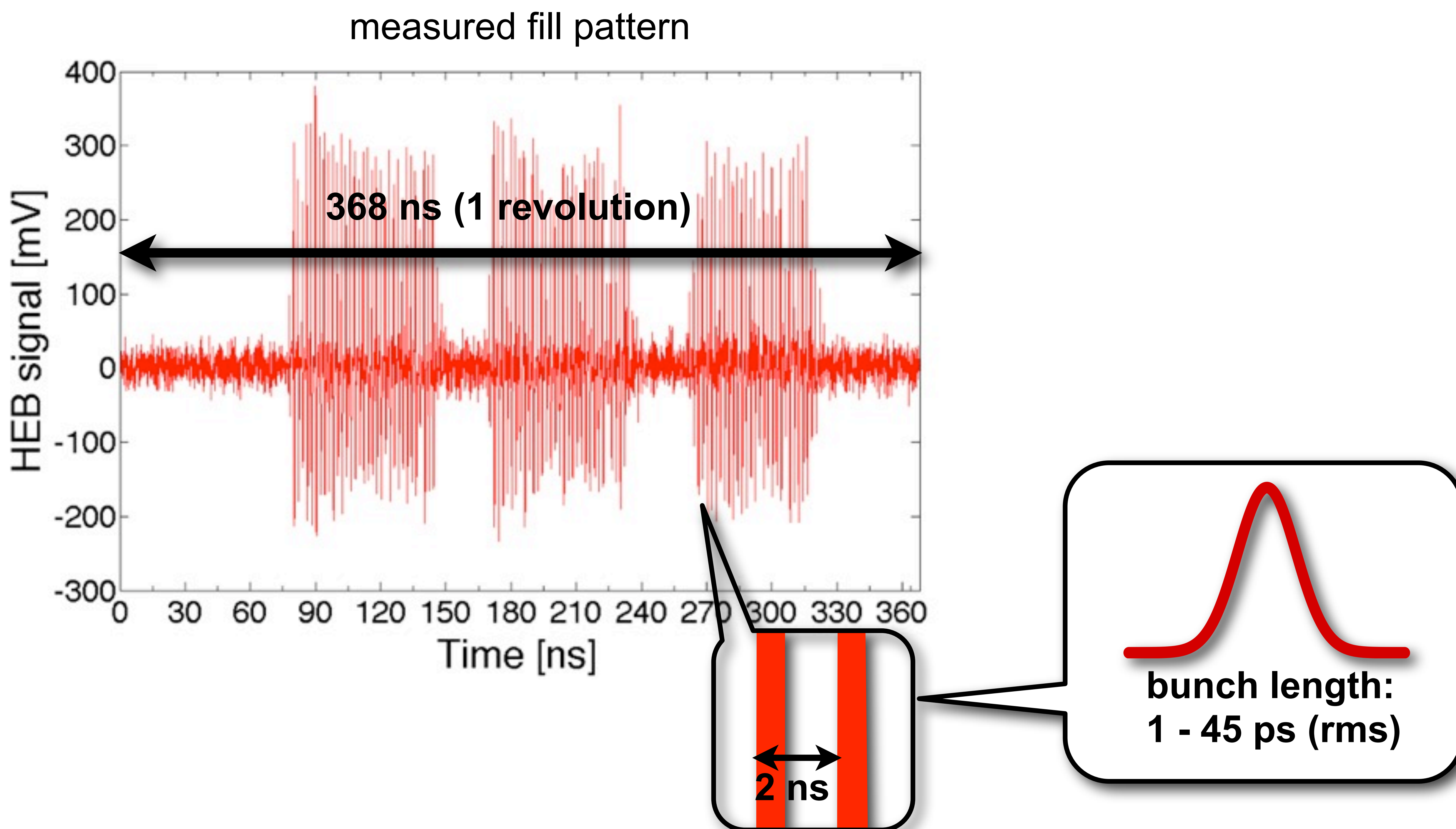
Operation procedure:

- Fill at 0.5 GeV
- Ramp energy (regular optics) to 1.3 GeV
- Low-α_c "squeeze"
  - change quadrupoles & sextupoles
  - orbit correction between steps



- Observed α_c range as derived from Q_s measurements:
  - from 7.2 10^{-3} to 1.4 10^{-4}

Time scales at ANKA

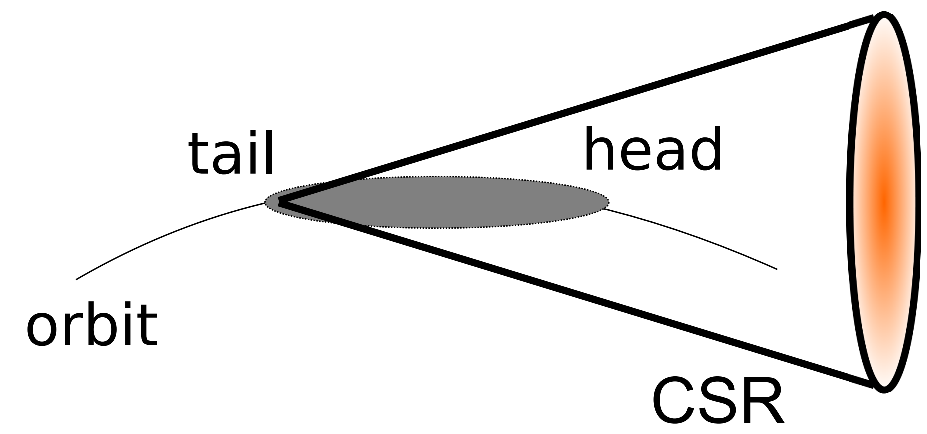


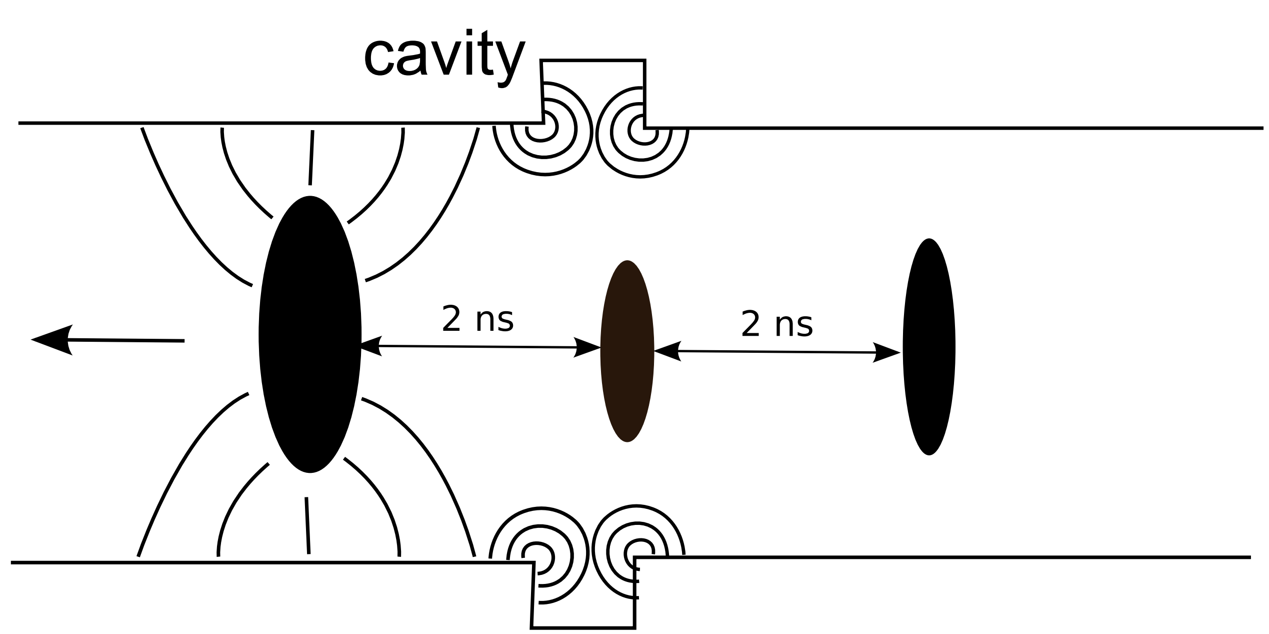
Wake fields and impedances

Karlsruhe Institute of Technology

- Wake fields are el.-mag. fields which are left behind by a particle
- They influence the motion of following particles
- The impedance is the fourier transform of the wake field
- Wake fields / impedances interact with the environment

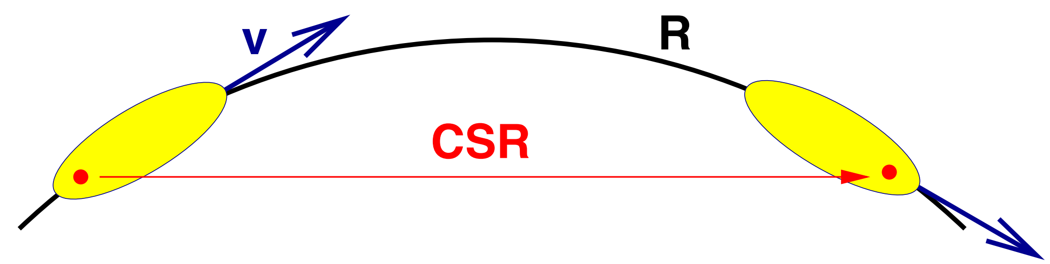
- Superposition of different impedances:
  - Broad band impedance (inductive + reactive + resistive part)
  - Synchrotron radiation impedance
  - CSR impedance
  - ...

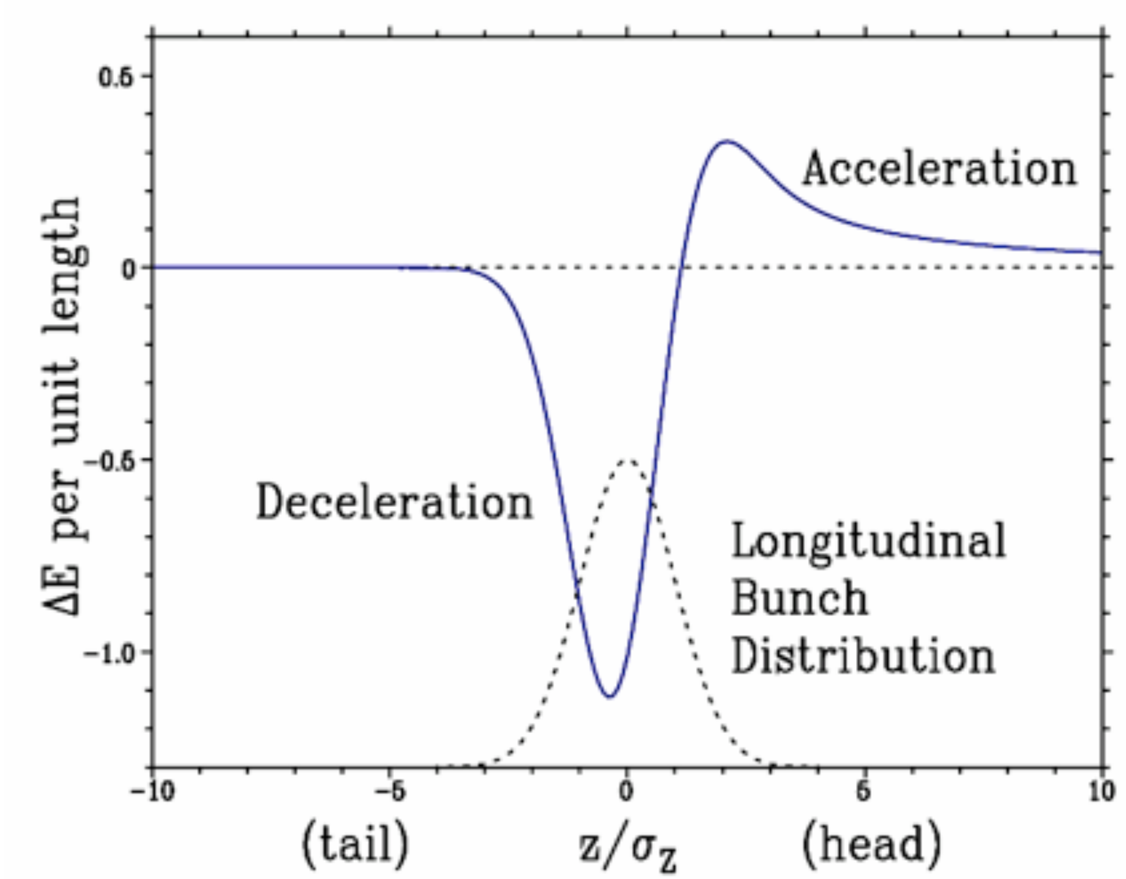




Self fields

- **The CSR wake field can act back on the same bunch**
- **Different ways to model the CSR wake / impedance:**
  - **free space, no shielding**
  - **shielding by ideal conducting parallel plates**
  - **shielding by rectangular beam pipe**
  - **...**
- **Electrons in the head of the bunch are accelerated, electrons in the tail of the bunch are decelerated.**

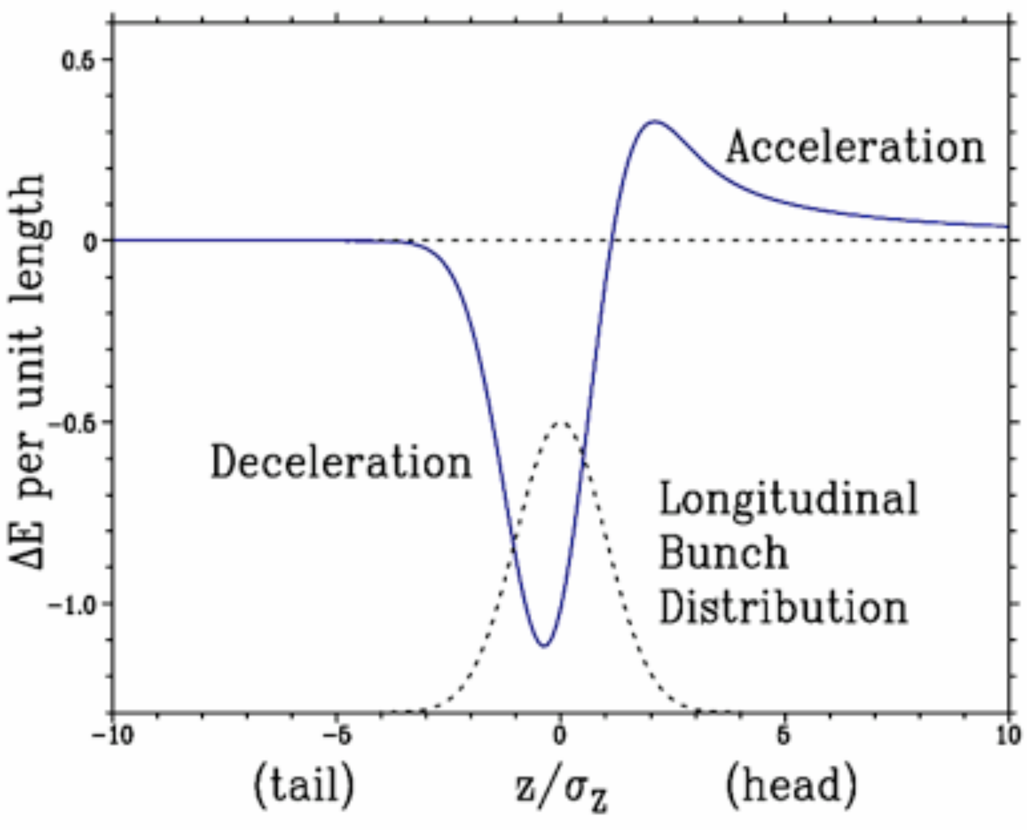


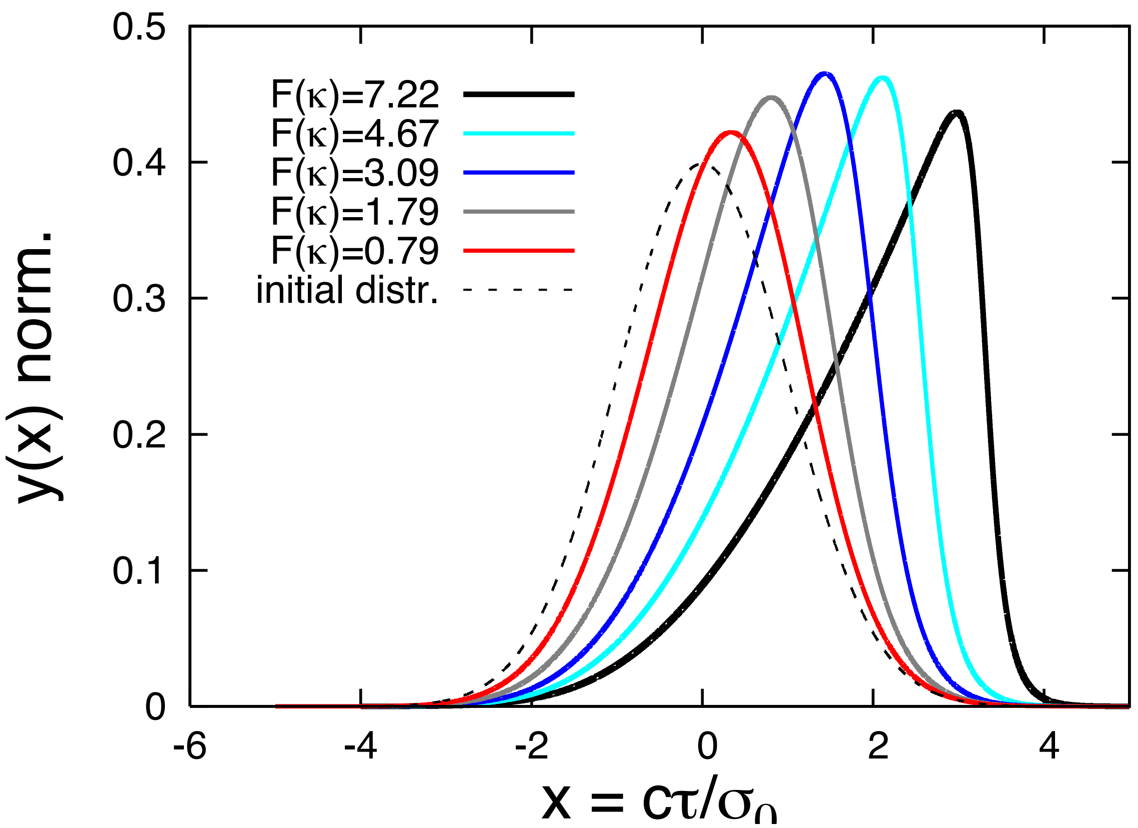


T. Agoh, „Dynamics of Coherent Synchrotron Radiation by Paraxial Approximation“, Doctoral Thesis

Potential well distortion

- The CSR wake can distort the longitudinal potential well
- The equilibrium bunch distribution of the distorted bunch can be calculated iteratively
- The integral over the bunch distribution F(κ) connects the bunch shapes with accelerator parameters

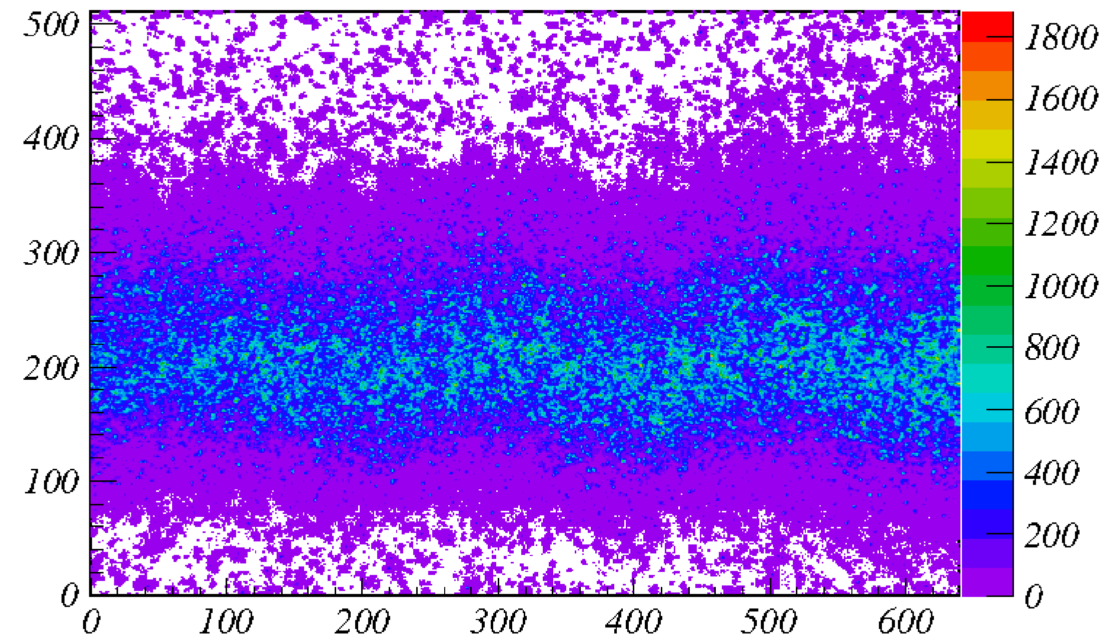


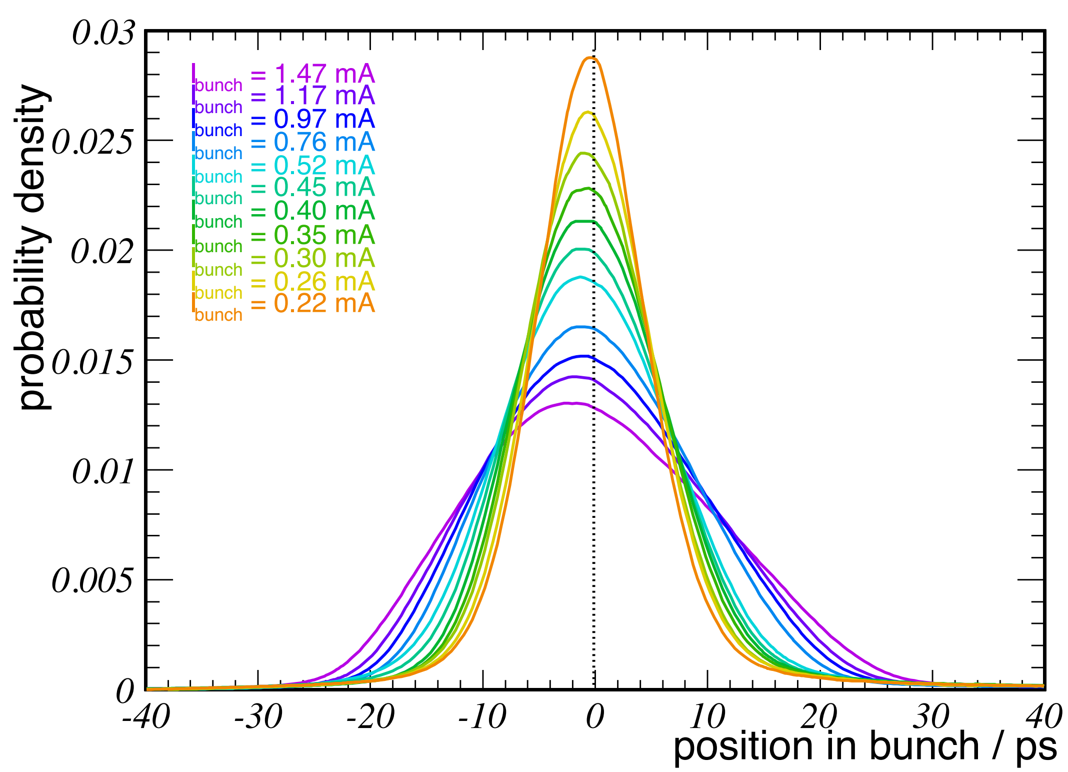


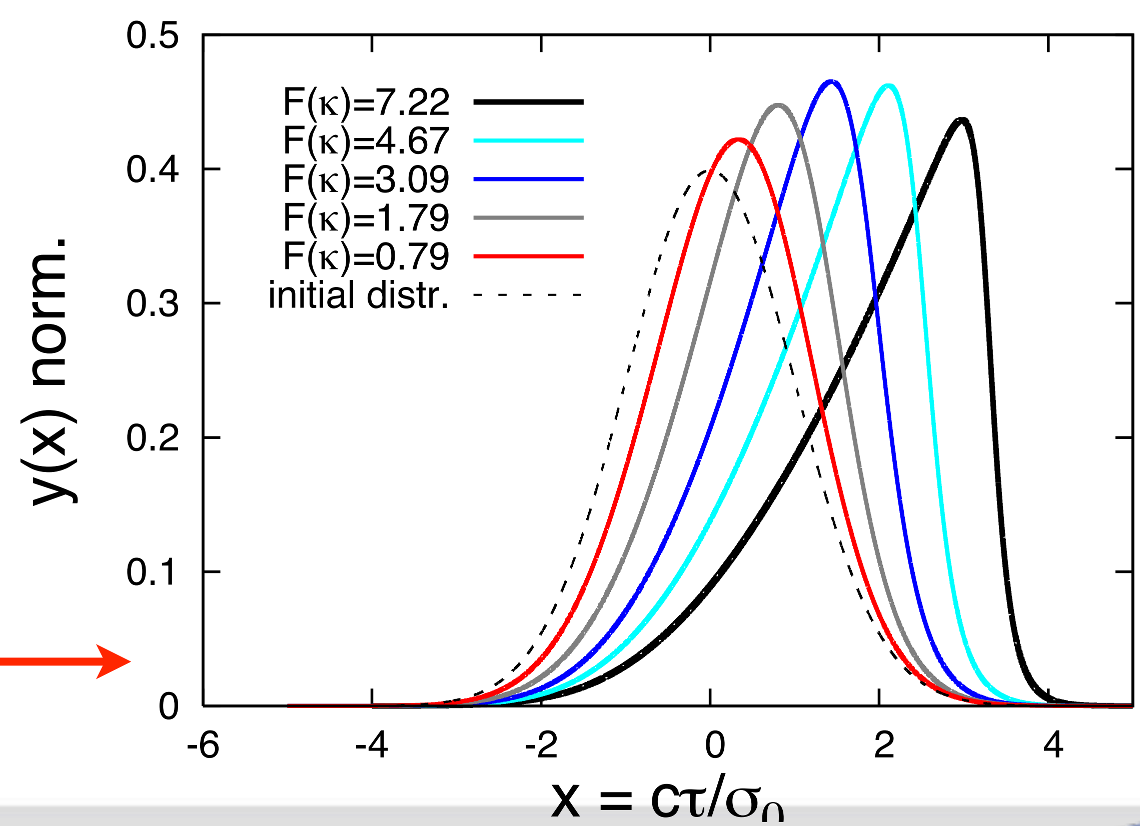
Bunch shape

- **Measurements with a streak camera**
- **Subtraction of oscillations**
- **Comparison with calculations**

▷ **Nicole's talk**

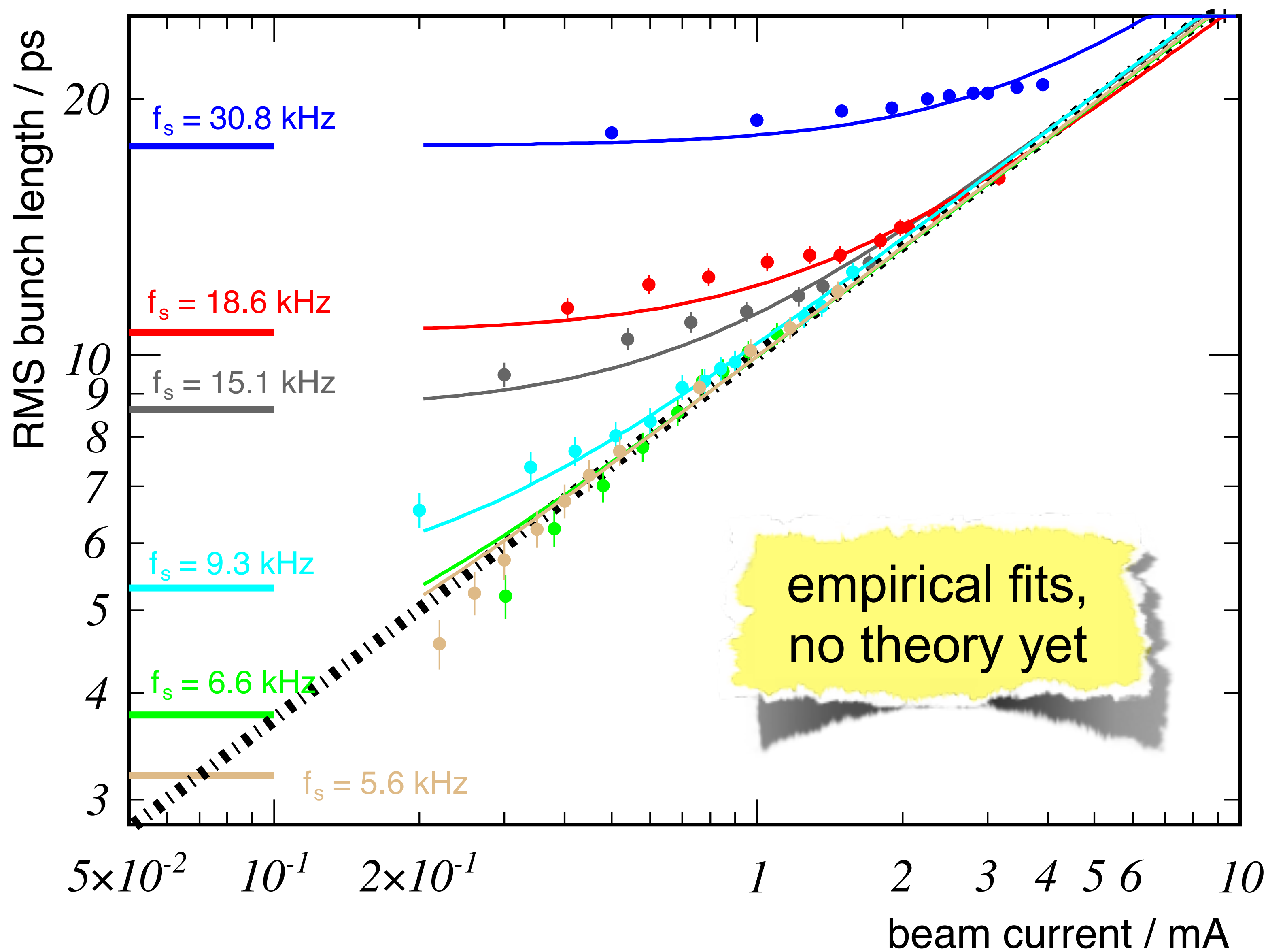






Bunch length

- **Low currents: Converging to the zero current bunch length**
- **Above bursting stable threshold: Turbulent bunch lengthening**

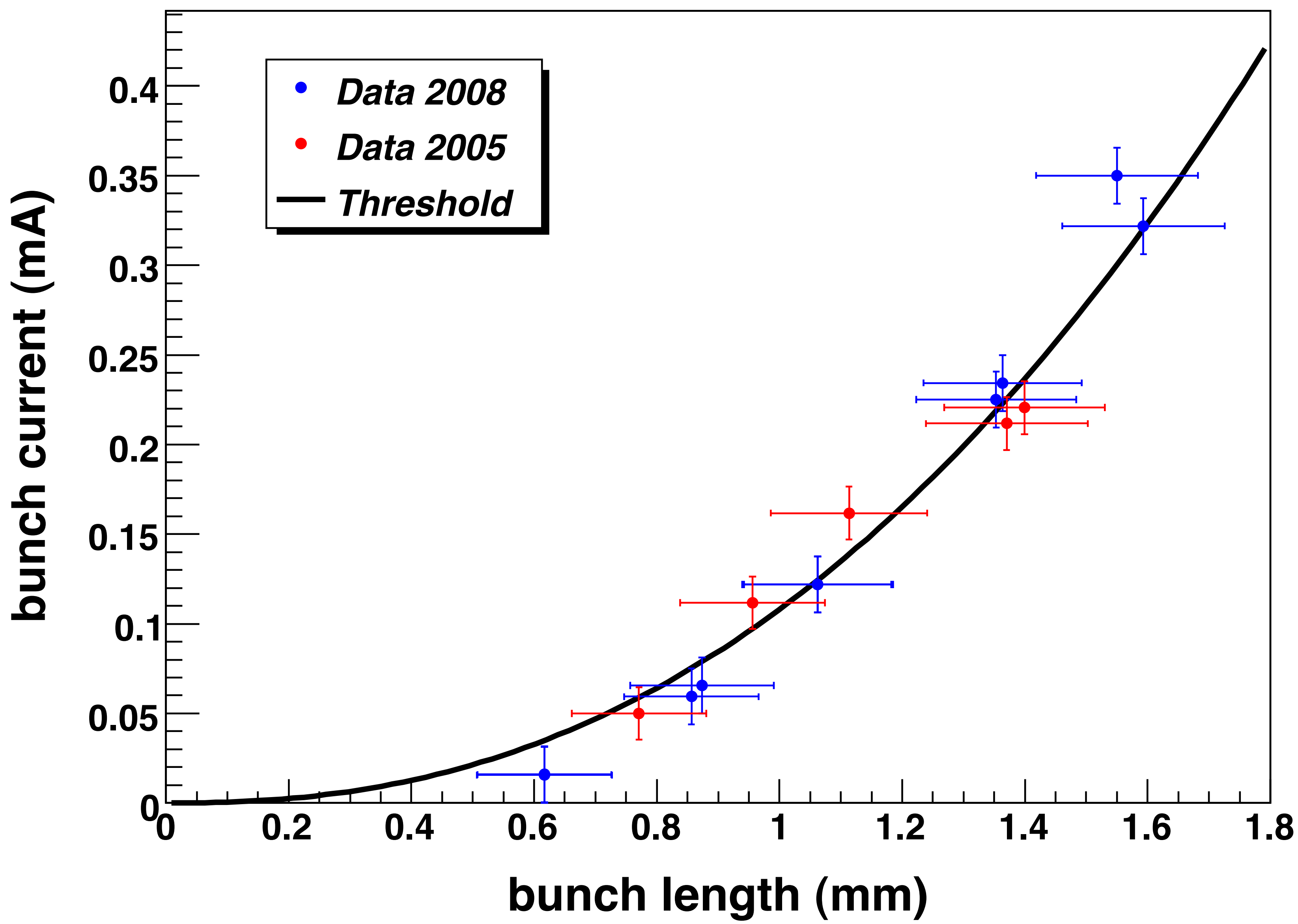


$$\sigma_z \propto I^{7/3}$$

▷ **Nicole's talk**

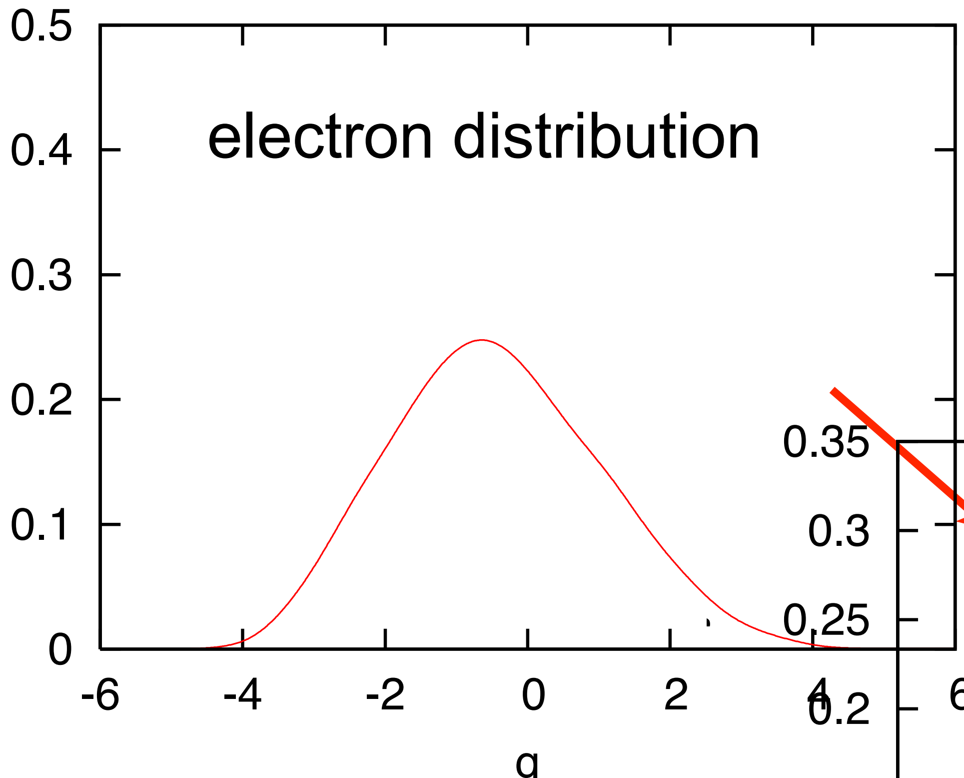
The bursting stable threshold

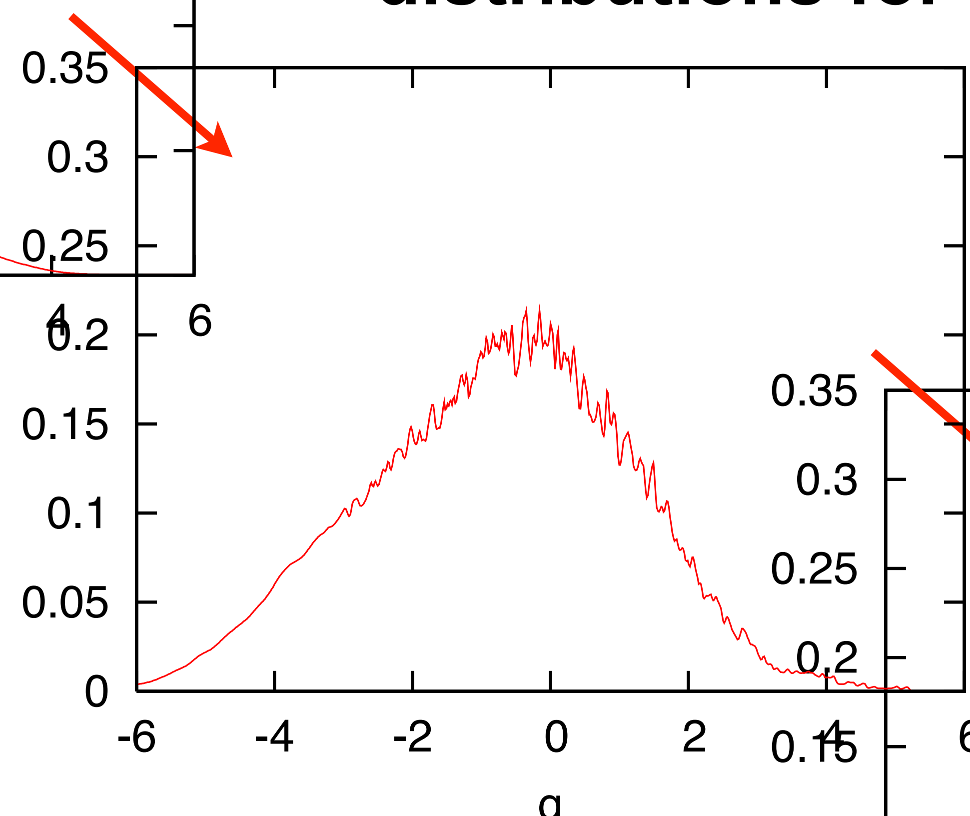
- **Measured bursting stable threshold with Si bolometer**
- **Good agreement with theoretical prediction:**

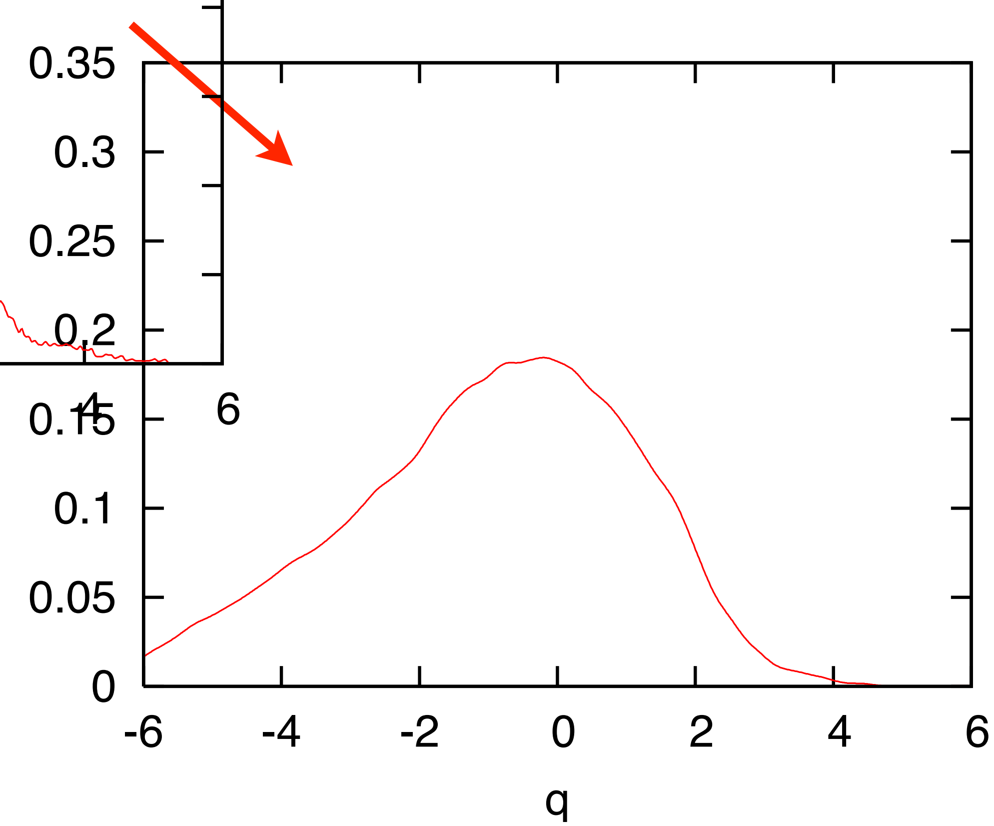


$$I_{thresh} \propto \sigma_s^{7/3}$$

Microbunching

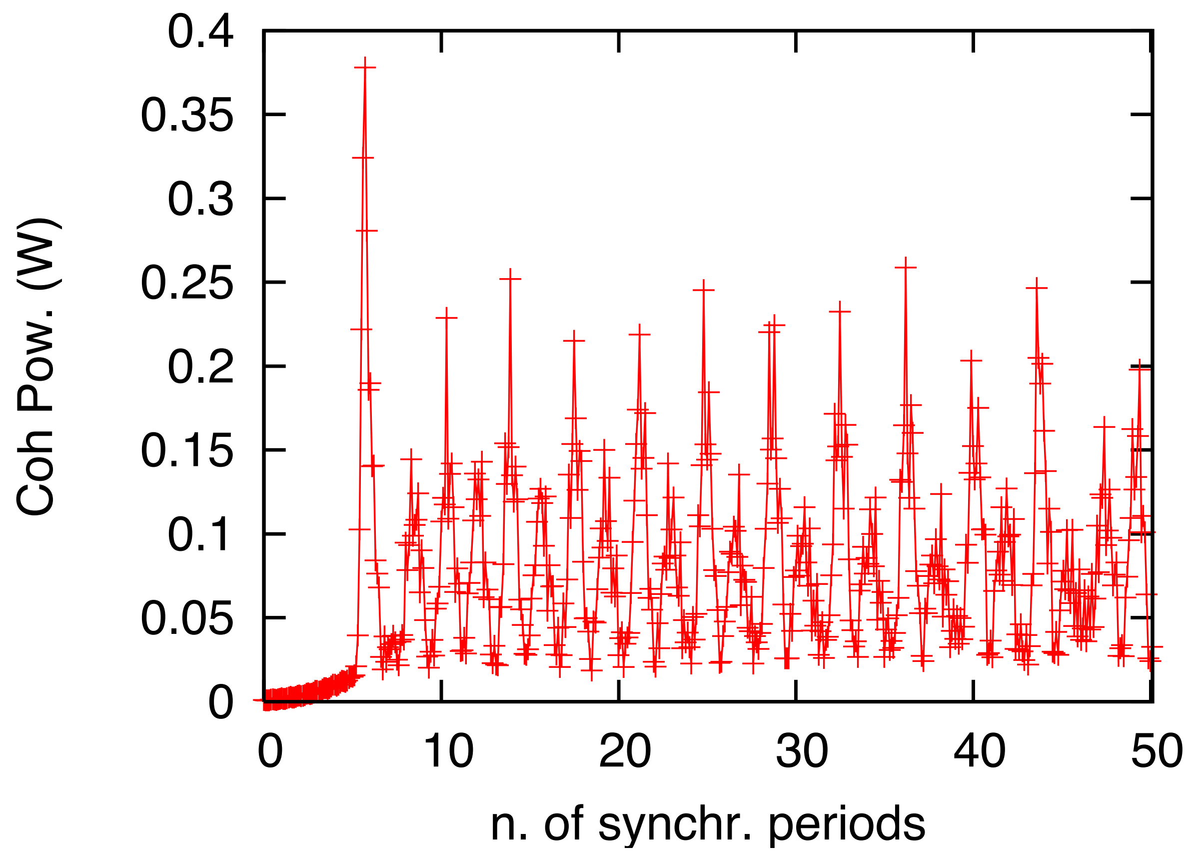




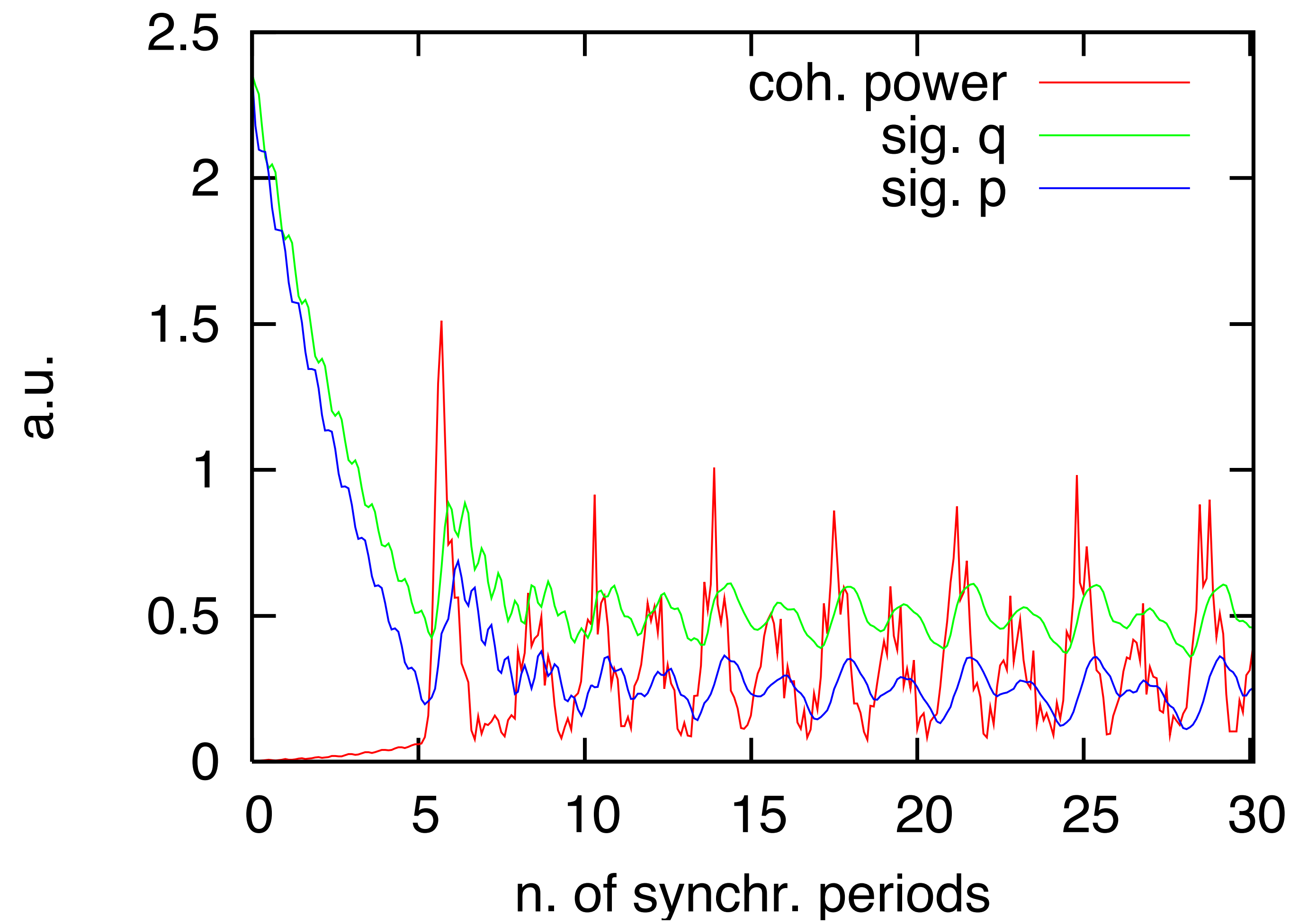


- **Longitudinal dynamics described by the Vlasov-Focker-Planck equation**
- **A Vlasov solver calculates electron distributions for advancing time**
- **In the beginning small fluctuations grow under the influence of self fields**
  - **Microbunching**

Bursting behavior



- **Microbunching is accompanied by coherent radiation bursts**
- **Bursts can have periodic or chaotic behavior**

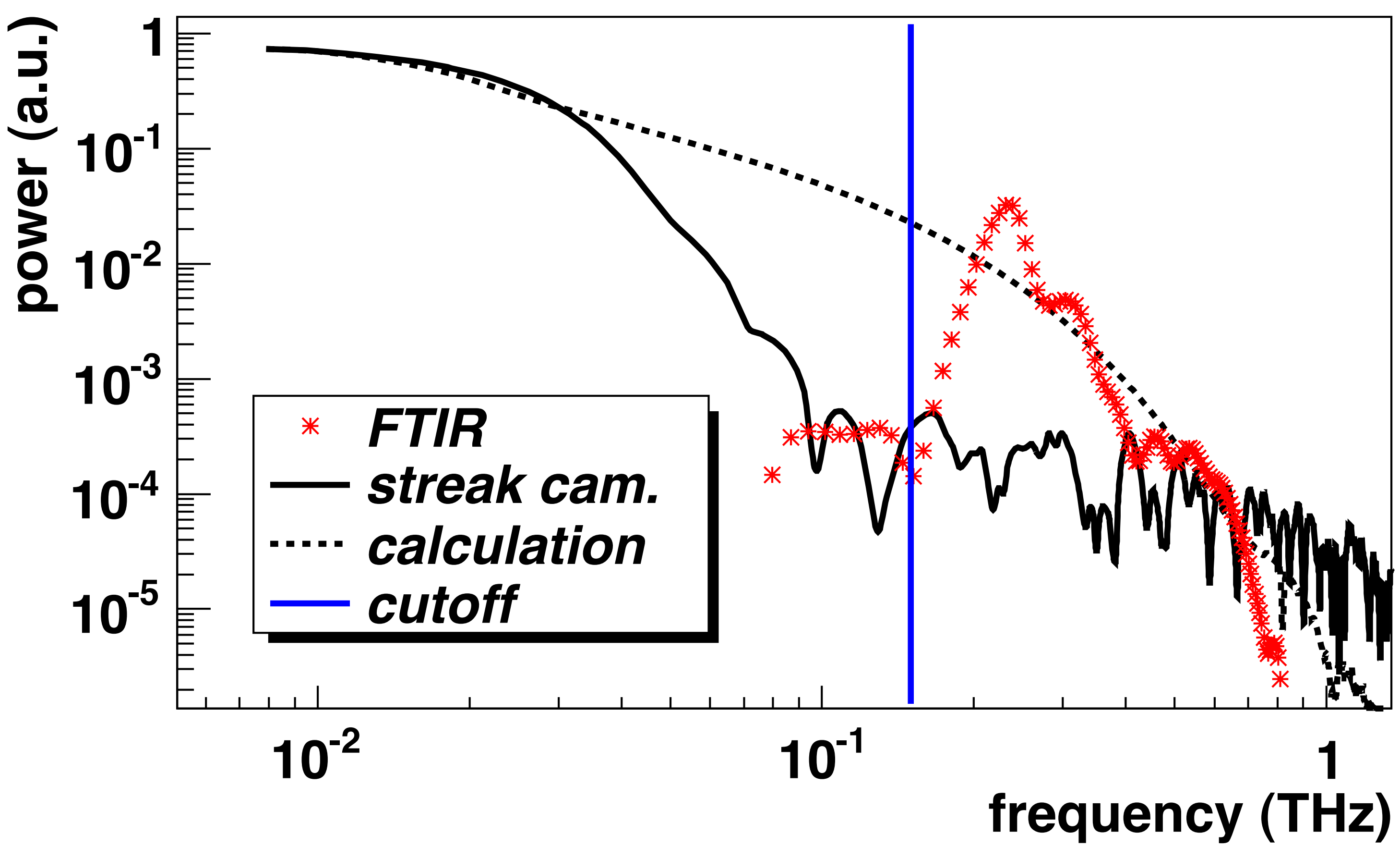


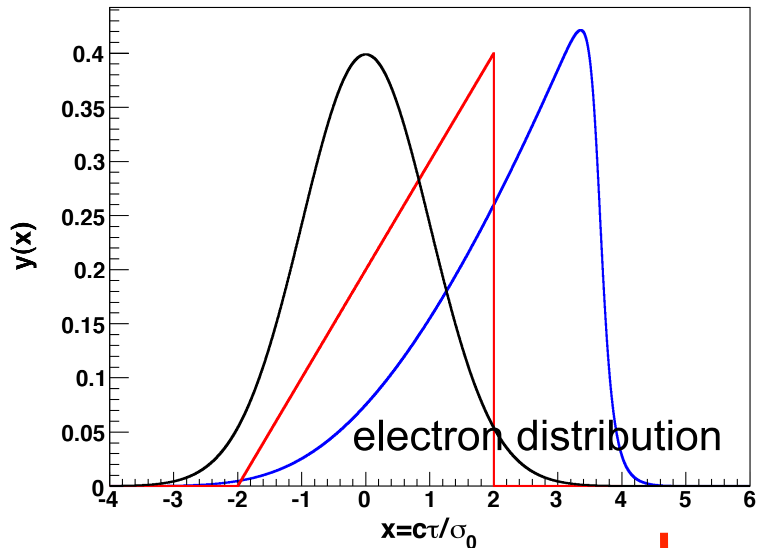
- **Phase space distribution (q,p) and bunch length varies during bursting cycle**

▷ **Vitali's talk**

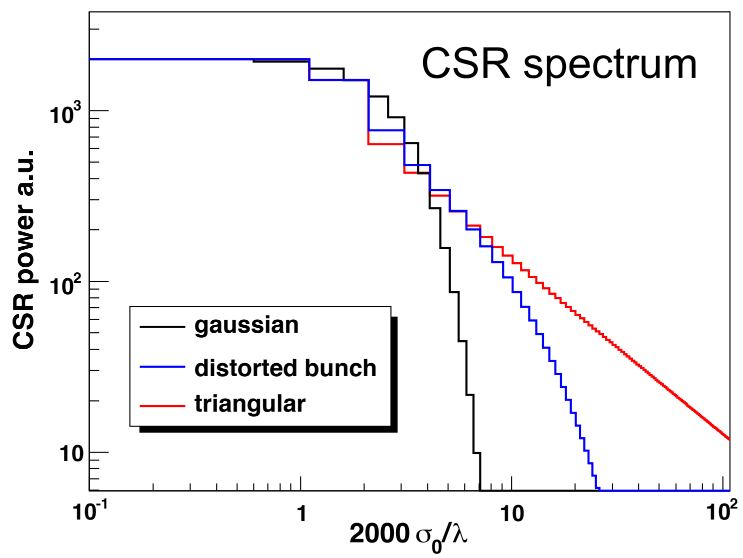
Measured and Expected Spectra

- The CSR spectrum is the Fourier transform of the electron distribution
- Present Michelson interferometer: No information about low frequencies
  - Martin Puplett Interferometer
- Expectation from streak cam. measurement below cutoff
- Explanation: substructure or stronger deformation
  - Single shot measurement needed: Nicole's talk





FFT

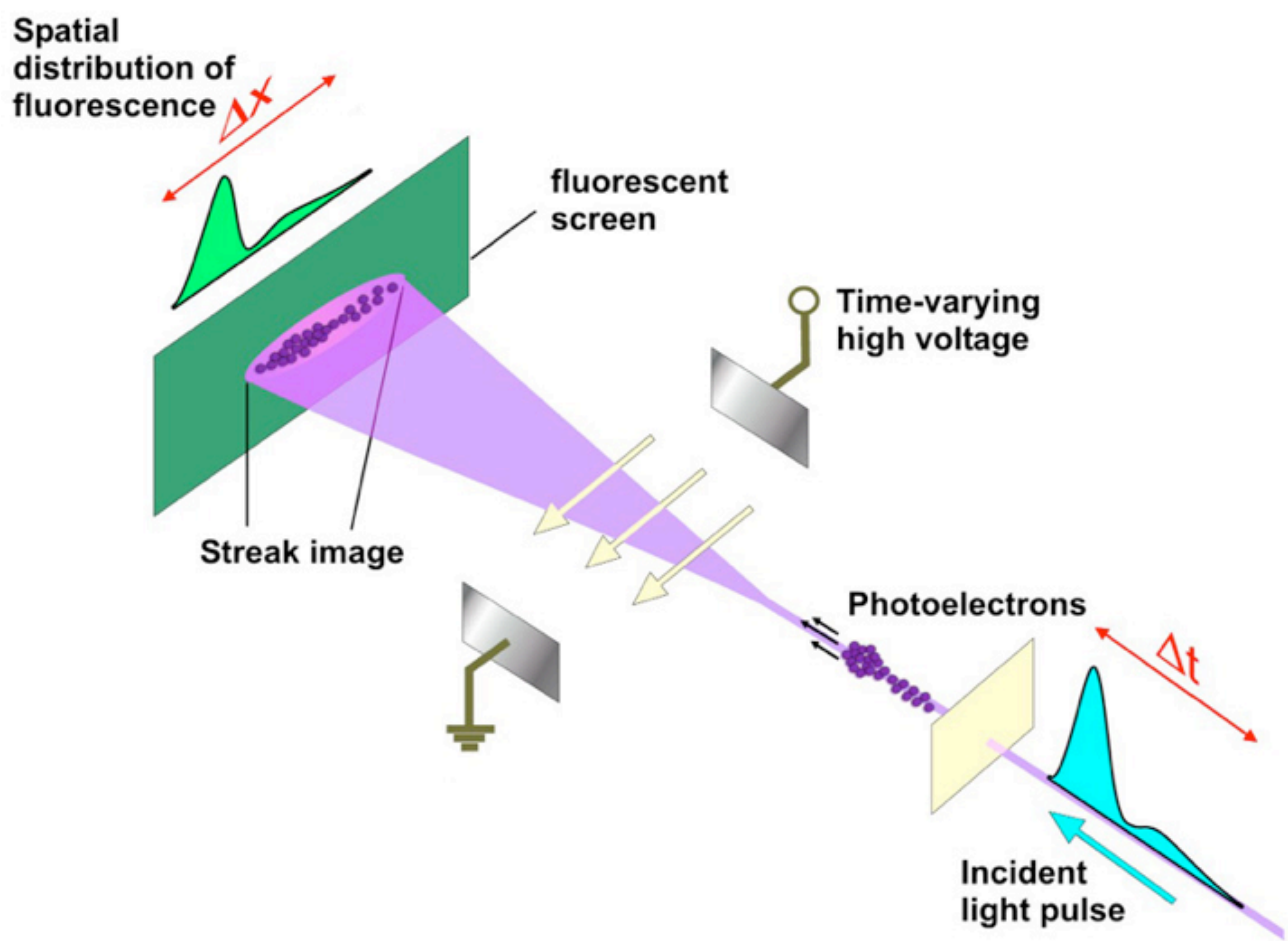


Overview - Time domain bunch length & shape measurements

- Introduction
- Methods
  - Streak camera (currently in use)
  - Electro-optic techniques (will be implemented)
- Conclusion & outlook

Streak camera - working principle

- **Allows measurement of intensity distribution of visible synchrotron light pulses**

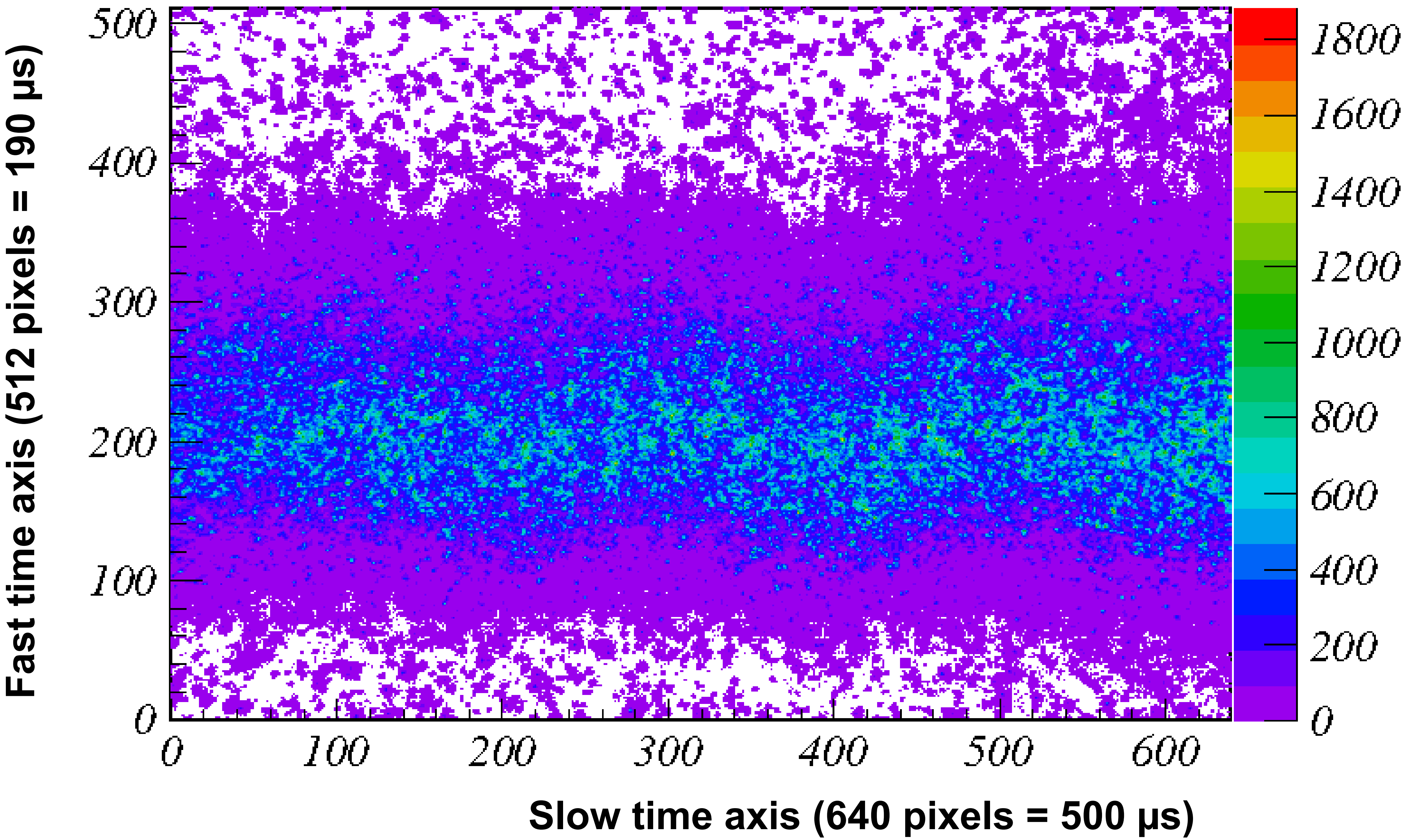


electrons ➜ photons ➜ electrons ➜ photons ➜ averaging needed

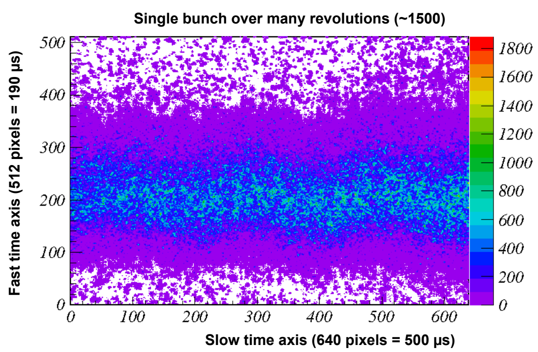
picture source: http://www.mpg.de/

Obtaining bunch profiles from SC images

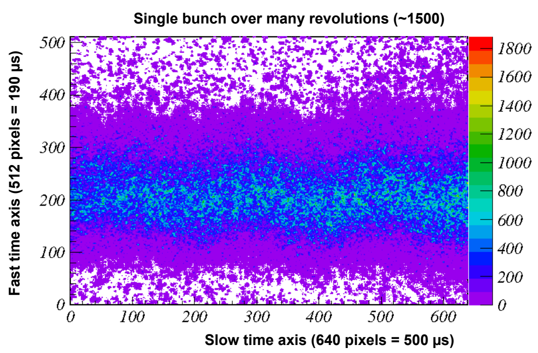
Single bunch over many revolutions (~1500)



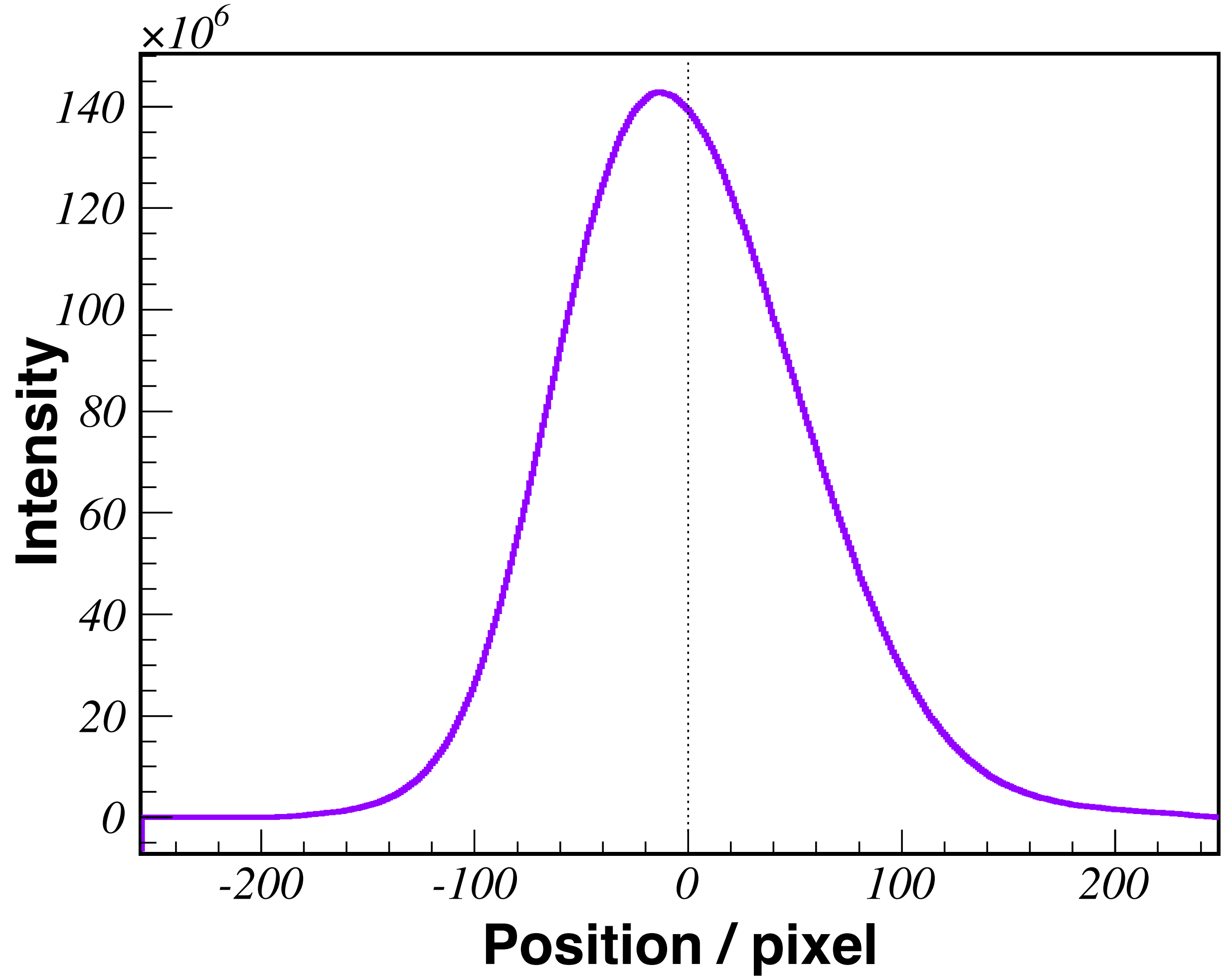
Obtaining bunch profiles from SC images



Obtaining bunch profiles from SC images

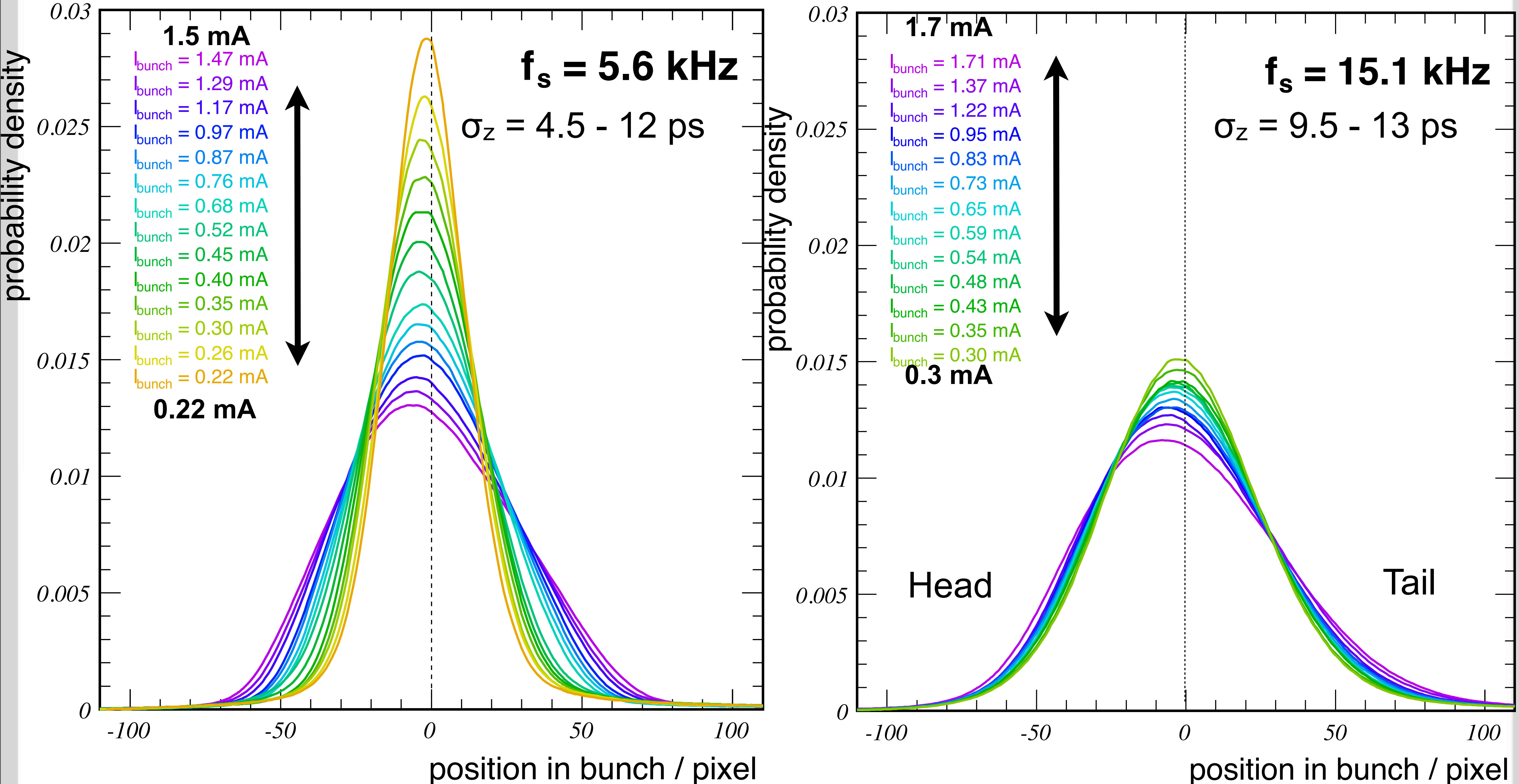


500 images



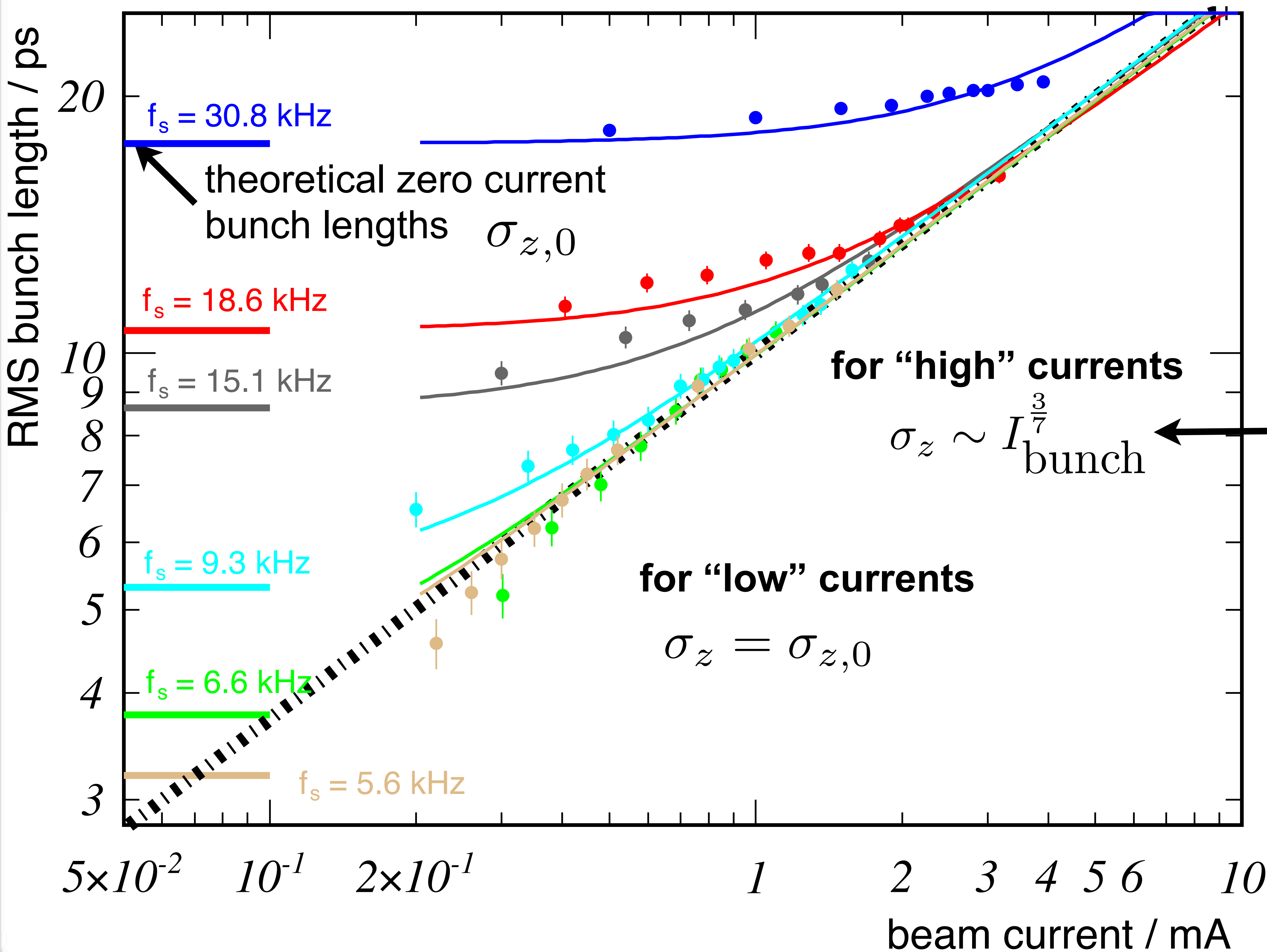
Correct oscillation and project onto fast time axis
➜ smooth bunch profile

Normalised bunch profiles for various bunch currents



Problem: broadening due to SC resolution and jitter

Current dependent bunch lengthening



empirical fits

theoretical prediction (Stupakov)

"high" and "low" depends on threshold current

Streak camera - limitations

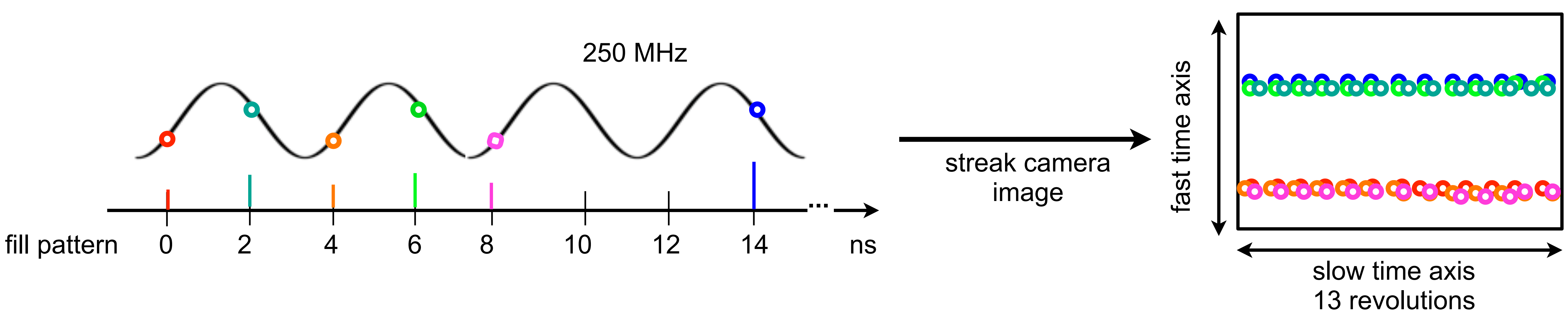
- **resolution:** 1 pixel ≙ 0.4 ps further limited by:
  - slit opening
  - jitter on trigger signal

    ➜ laser calibration measurements show:

    measured pulse length will not go below **1.7 ps (rms)**

    ➜ **value is quadratically subtracted from bunch length**

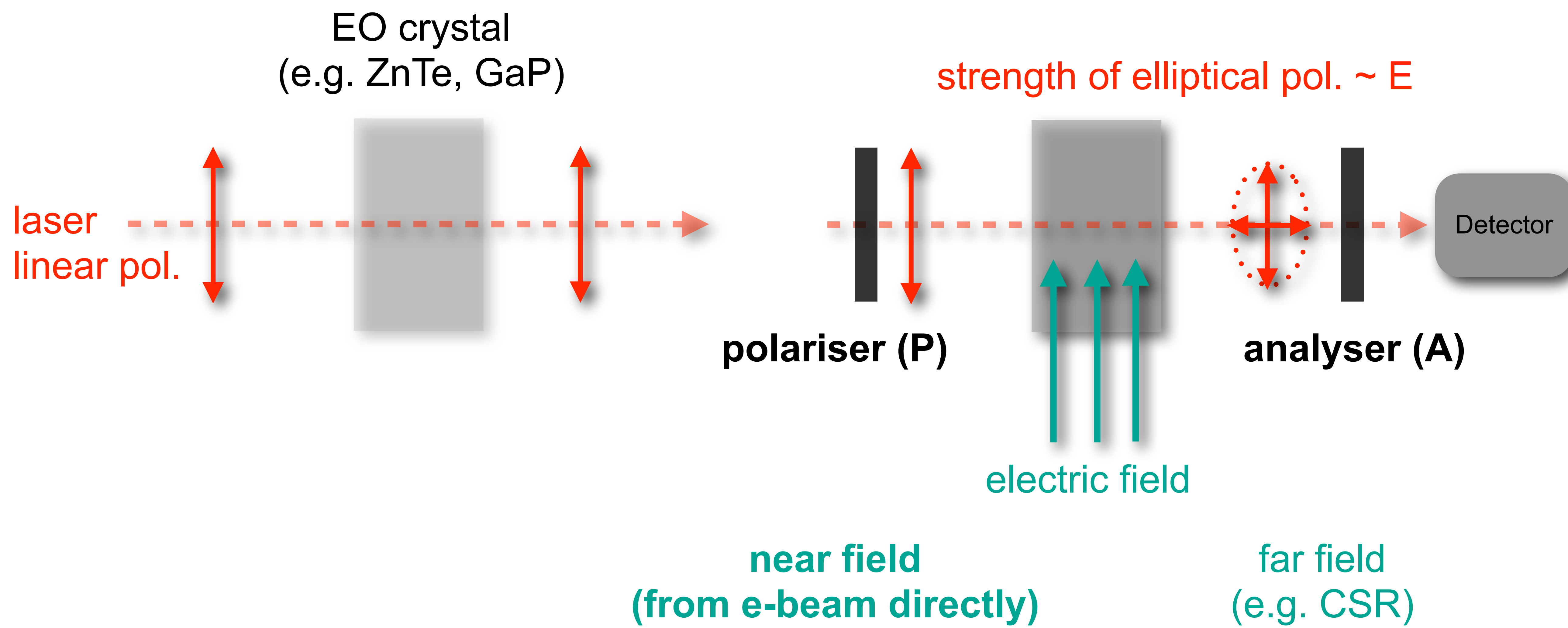
- can only separate bunches in odd and even RF buckets (for slow axis > 100 ns, 100-500 µs needed for good signal) because fast sweep is controlled by a consecutive sinusoidal signal at f_{RF} / 2 = 250 MHz



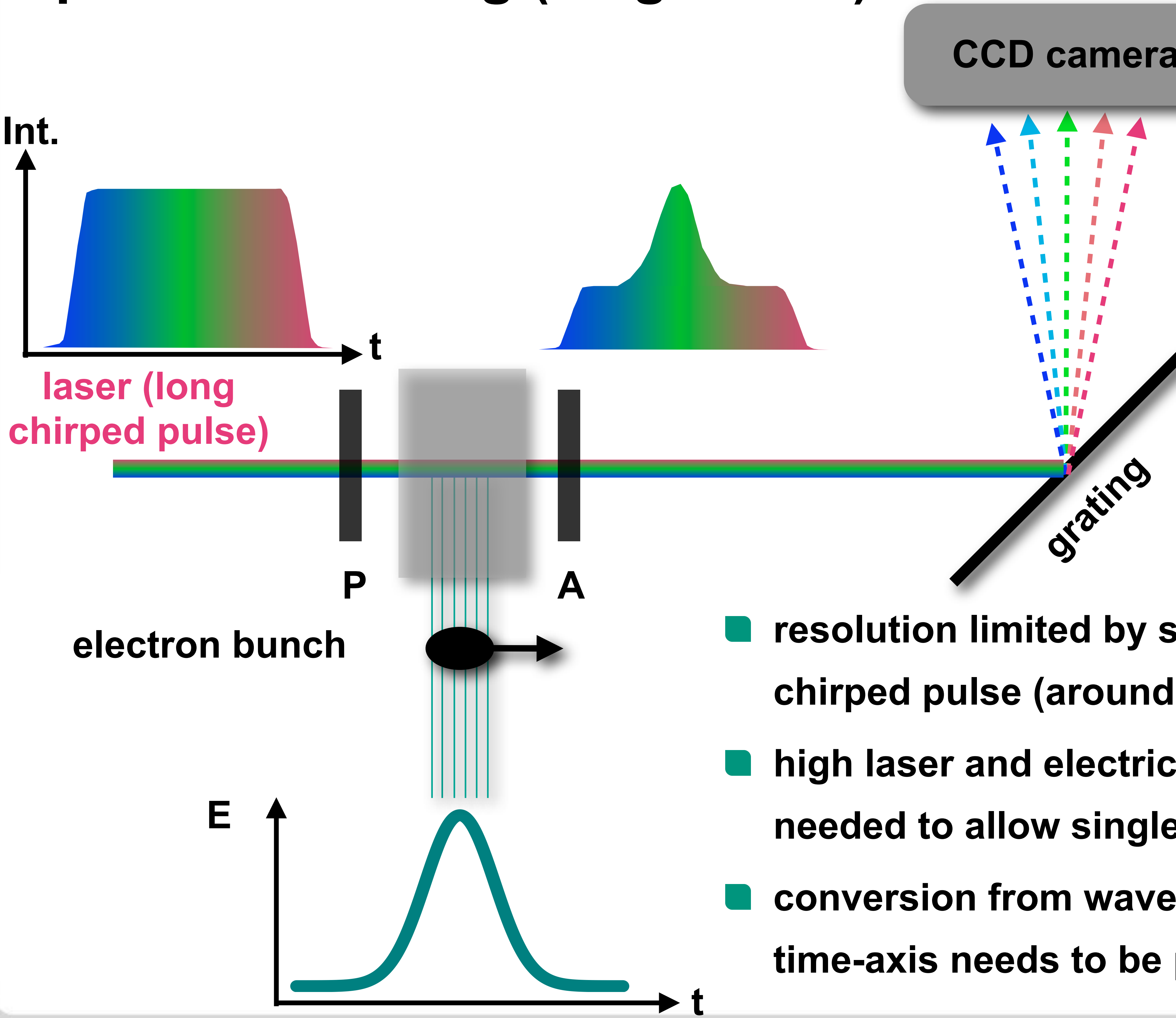
Electro-optic techniques - working principle

Intensity distribution of electron bunch is modulated on laser pulse which is then analysed

Modulation in electro-optic crystal:

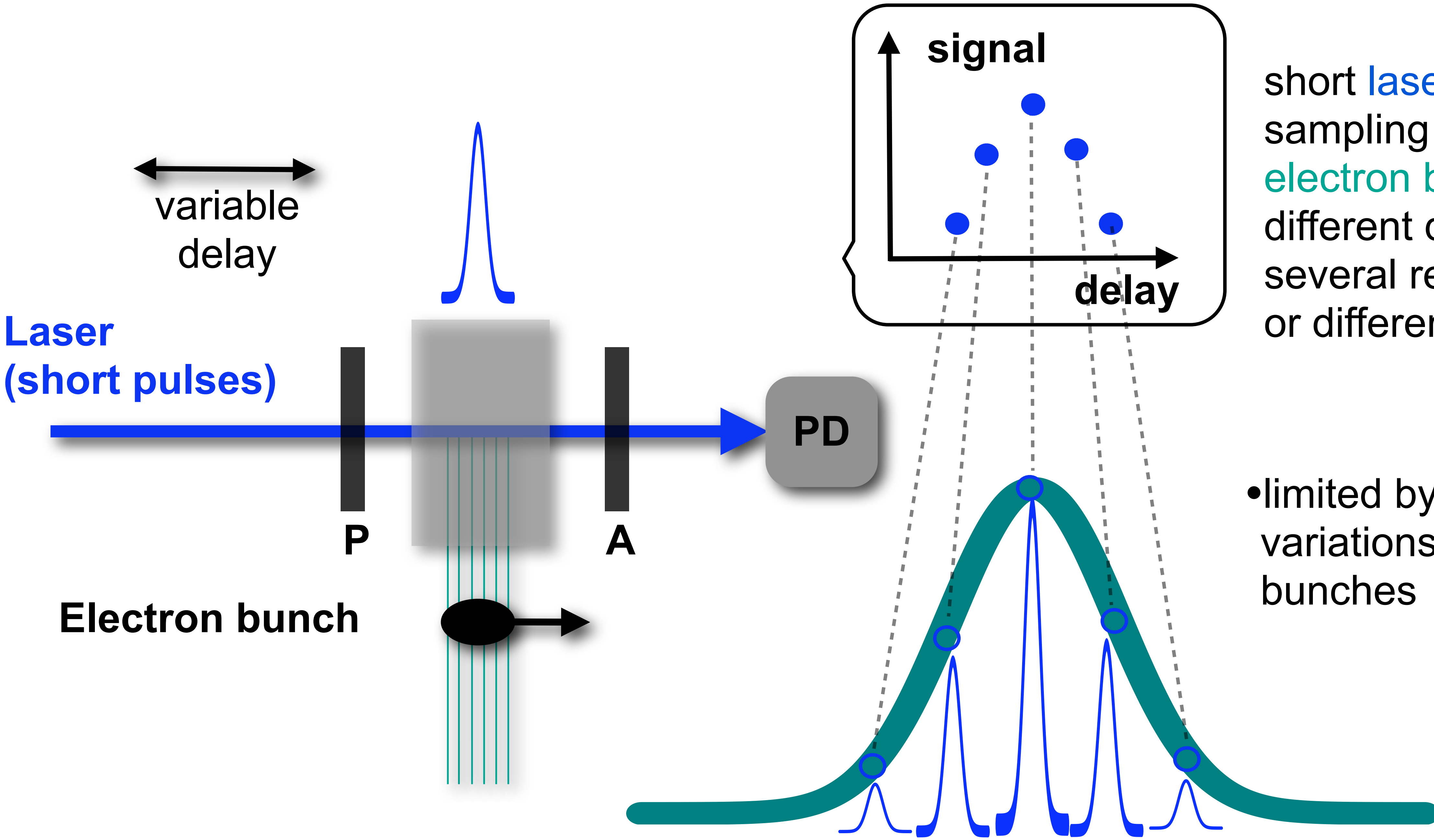


Spectral decoding (single shot)



- resolution limited by spectral width of chirped pulse (around 60 - 100 nm)
- high laser and electric field intensities needed to allow single shot evaluation
- conversion from wavelength- to time-axis needs to be precise

Electro-optical sampling (multi shot)



short laser pulses sampling the electron bunch at different delays over several revolutions / or different shots

- limited by ToA-variations of electron bunches

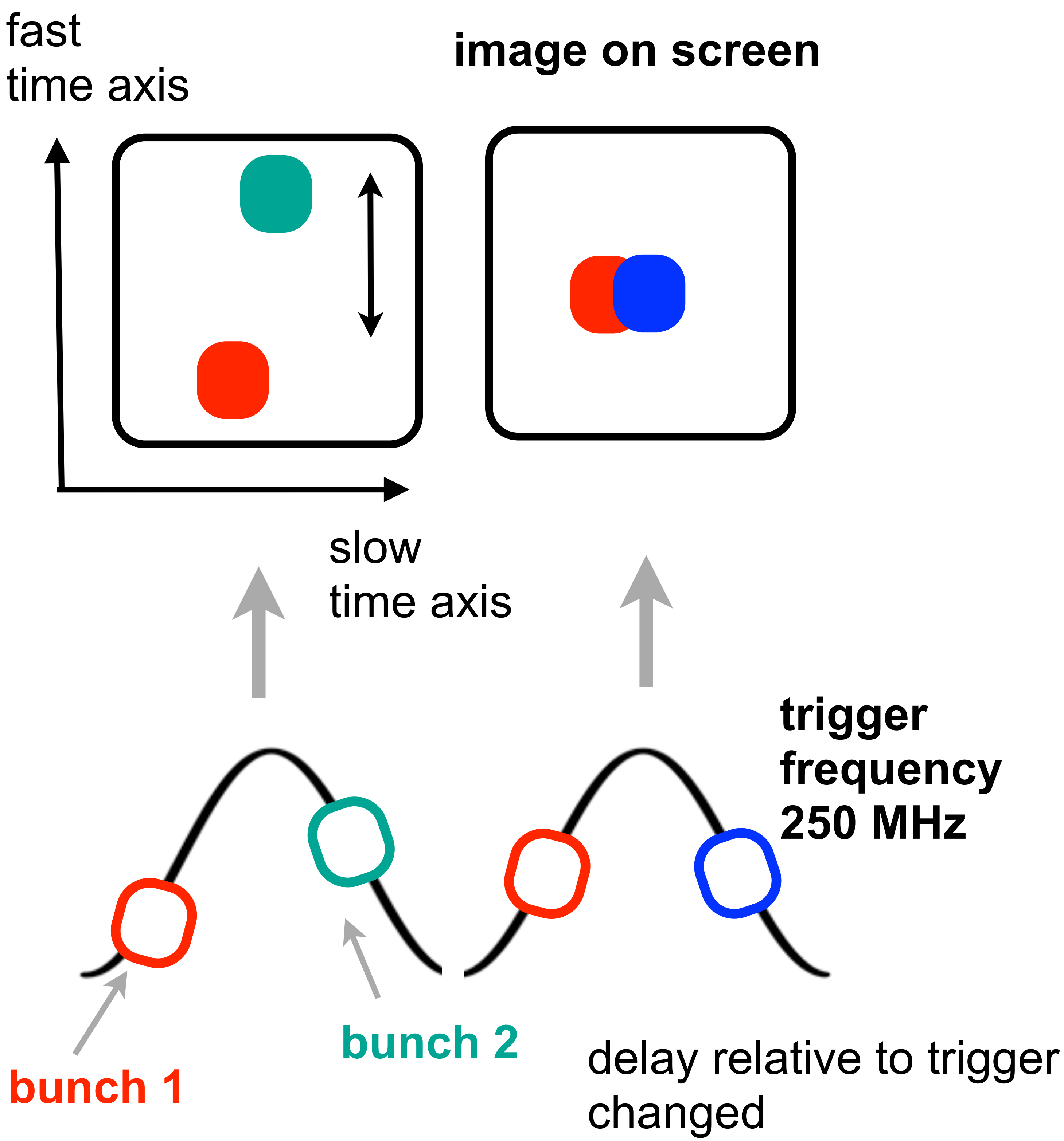
also possible to use “asynchronous sampling” for which the laser is slightly detuned from revolution frequency

Conclusion & outlook

- **Streak camera**
  - results for bunch length in good agreement with theoretical predictions ➜ better characterisation of the low alpha mode
  - deconvolution of bunch shape not yet fully understood (work in progress)
  - not properly usable for multi-bunch
- **EO set up will allow single shot measurements and a better temporal resolution**

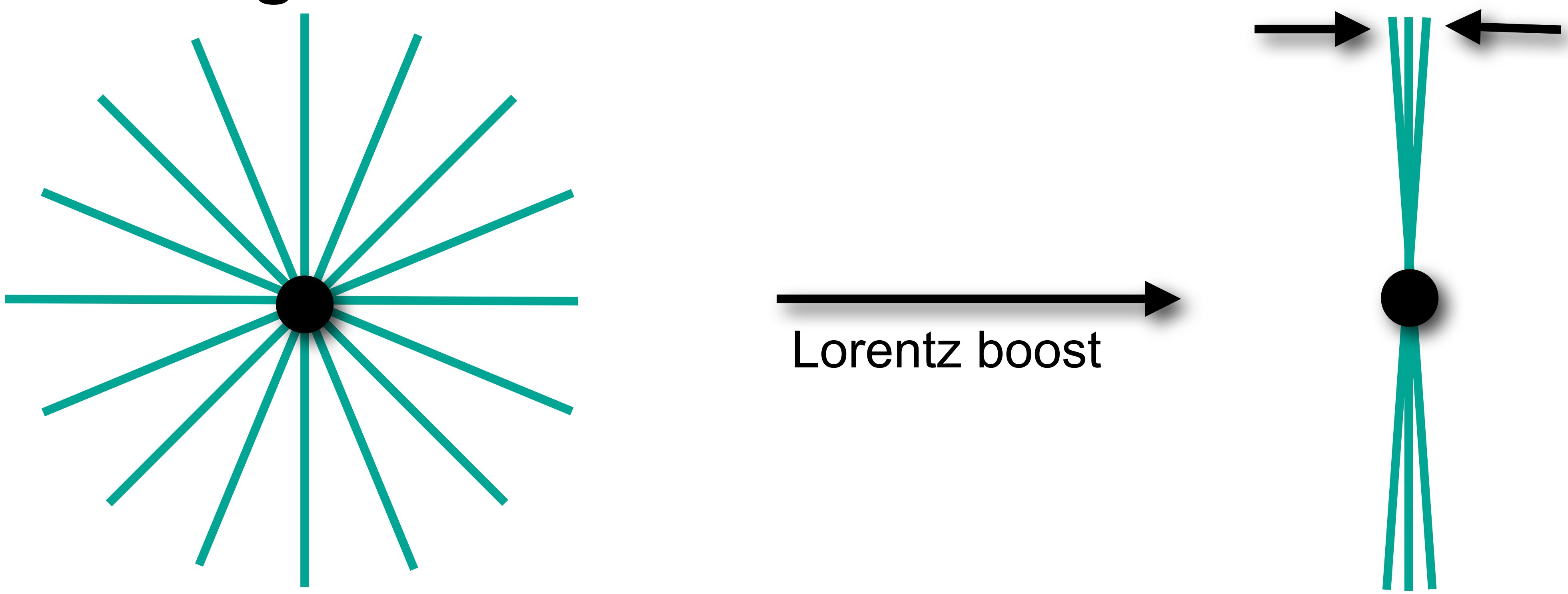
Thank you for your attention!

Streak camera triggering



Coulomb field

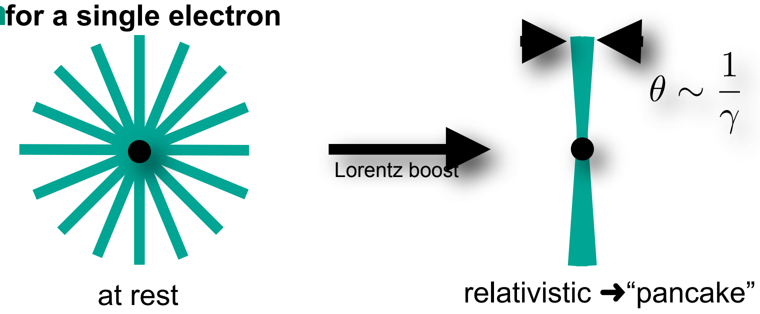
- **for a single electron**



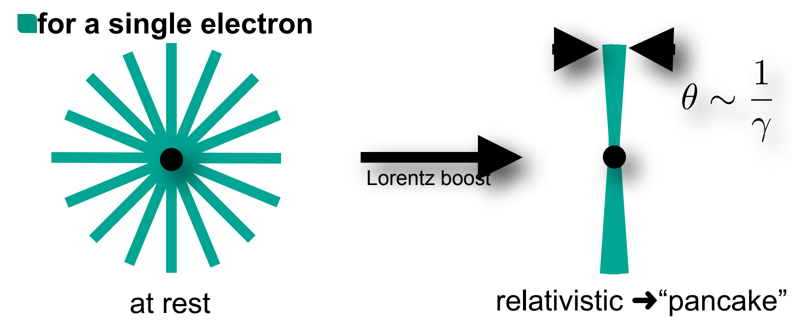
$$\theta \sim \frac{1}{\gamma}$$

Coulomb field

- for a single electron



Coulomb field



- **for a highly relativistic "long" (>1ps) electron bunch**

➜ $E_{r,Q}(t) \sim Q(t)$ (every electron has their own really thin pancake; pancakes don't overlap)

➜ Frequency components are given by Fourier transform