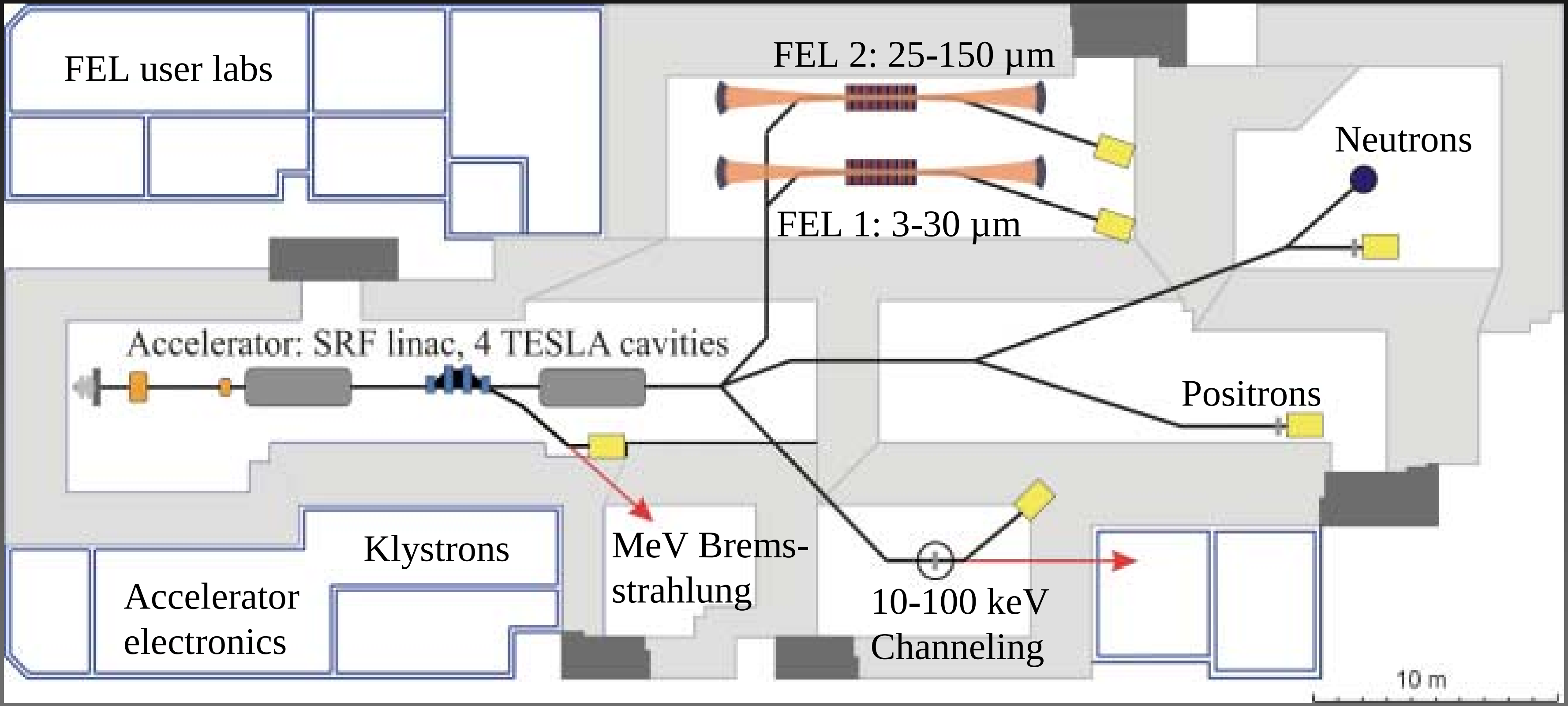
Instrumentation, beam characterization and commissioning of the ELBE FEL

Outline

- Radiation source ELBE
- Electron beam quality requirements
- Transverse emittance
- Bunch length measurements
- FEL commissioning

The radiation source ELBE



- nuclear physics experiments are running since January 2002
- channeling radiation since September 2003
- FEL 1 commissioned May 7-th 2004

  FEL2 in the design phase

Electron beam quality requirements (from FEL)

The main criteria - the electron parameters change may modify the radiation wavelength for less than the natural bandwidth of the spontaneous radiation.

$$\lambda = \frac{\lambda_u}{2 \cdot \gamma^2}(1 + K^2 + \gamma^2\theta^2) \quad \Rightarrow \quad \frac{\Delta\lambda}{\lambda} = \frac{-2\Delta\gamma}{\gamma} + \frac{K \cdot \Delta K}{1+K^2} + \frac{\gamma^2 \cdot (\Delta\theta)^2}{1+K^2}$$

- Transverse emittance $\varepsilon < \lambda / 2\pi$
- Energy spread ($\Delta E < 0.4\%$ with 64 periods)
- Peak current (bunch charge/bunch length)
- Overlap of the electron beam and the optical mode of the resonator
- The electron beam stability

Transverse emittance

One of the ways to define the transverse emittance is the statistical approach

$$\varepsilon_{RMS} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x \cdot x' \rangle^2}$$

Emittance is the second order momentum of the distribution function of the electrons

Two different techniques were used to measure the transverse emittance.

- The multislit mask in the injector at 250 keV
- Quadrupole scan for accelerated beam

Beam envelope analysis

σ - RMS beam size, ε - geometrical emittance
I - the beam peak current, I_A – Alfen current

$$\sigma'' + k^2\sigma + \frac{\gamma'}{\beta^2\gamma^2}\sigma' - \frac{2I}{I_A\beta^3\gamma^3}\frac{1}{\sigma} - \frac{\varepsilon^2}{\sigma^3} = 0$$

external field (focusing)

synchrotron radiation

space charge force

influence of emittance

It is reduced in a drift space to:

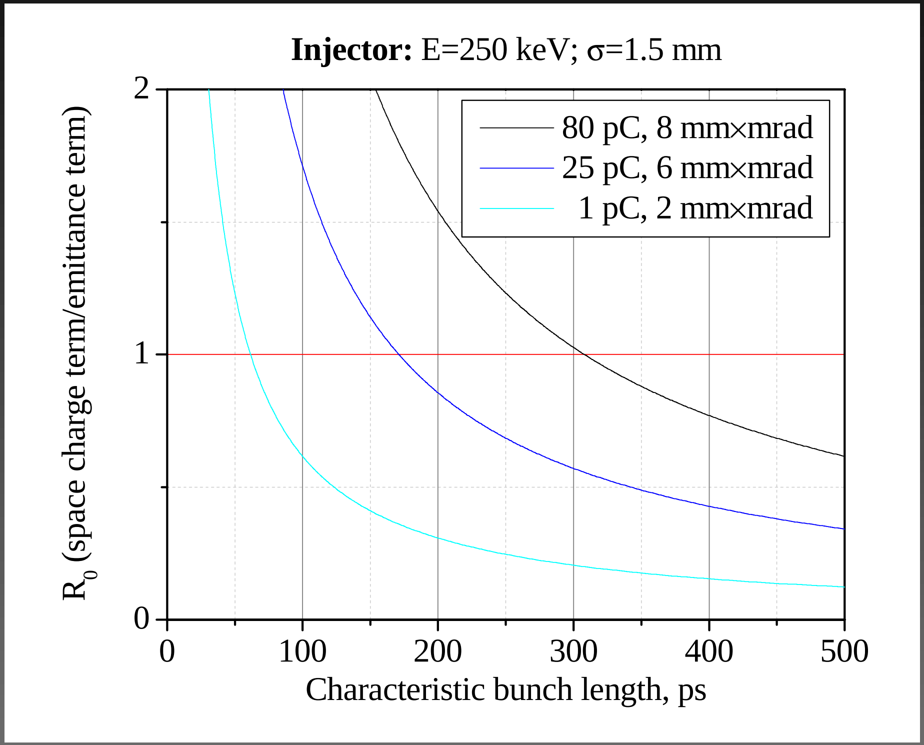
$$\sigma'' = \frac{2I}{I_A\beta^3\gamma^3}\frac{1}{\sigma} + \frac{\varepsilon^2}{\sigma^3}$$

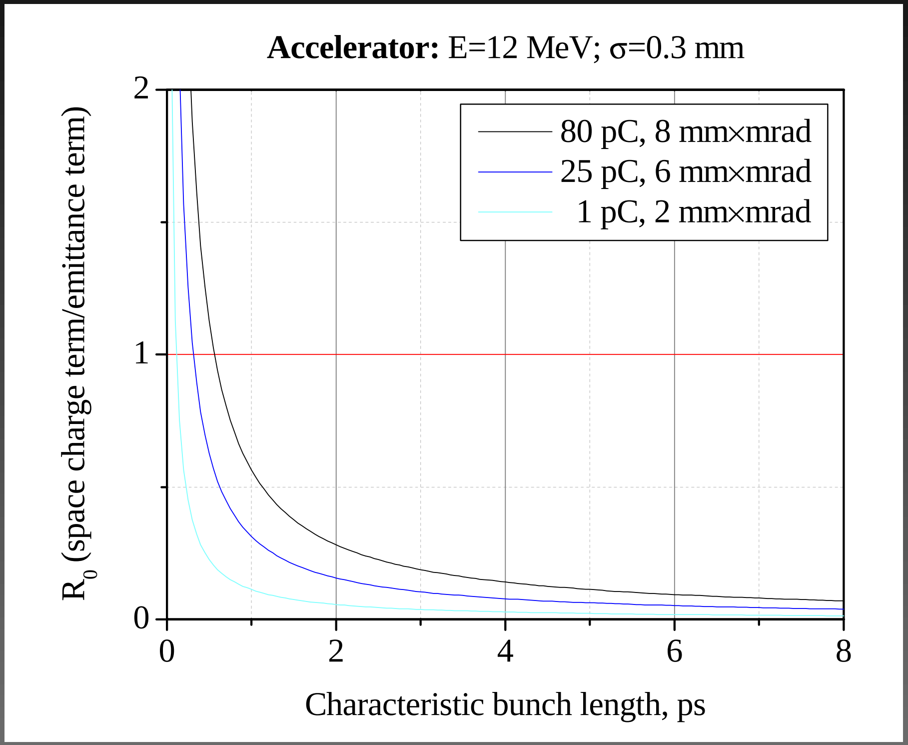
The following ratio tells either the beam is
emittance dominated $R_0<1$ or space charge dominated $R_0>1$.

$$R_0 = \frac{2I\sigma^2}{I_A\gamma\beta\varepsilon_n^{\ 2}}$$

Space charge / emittance (R_0)

$$R_0 = \frac{2I\sigma^2}{I_A \gamma \beta \varepsilon_n^2}$$





Even for a bunch coming out of the gun the s.c. is not negligible.

For the bunch compressed in injector ***R_0>>1***.

Quadrupole scan dose not work properly.

Accelerated beam is emittance dominated ***R_0<1***.

Linear matrix formalism works properly.

Quadrupole scan method can be used.

The multislit mask design

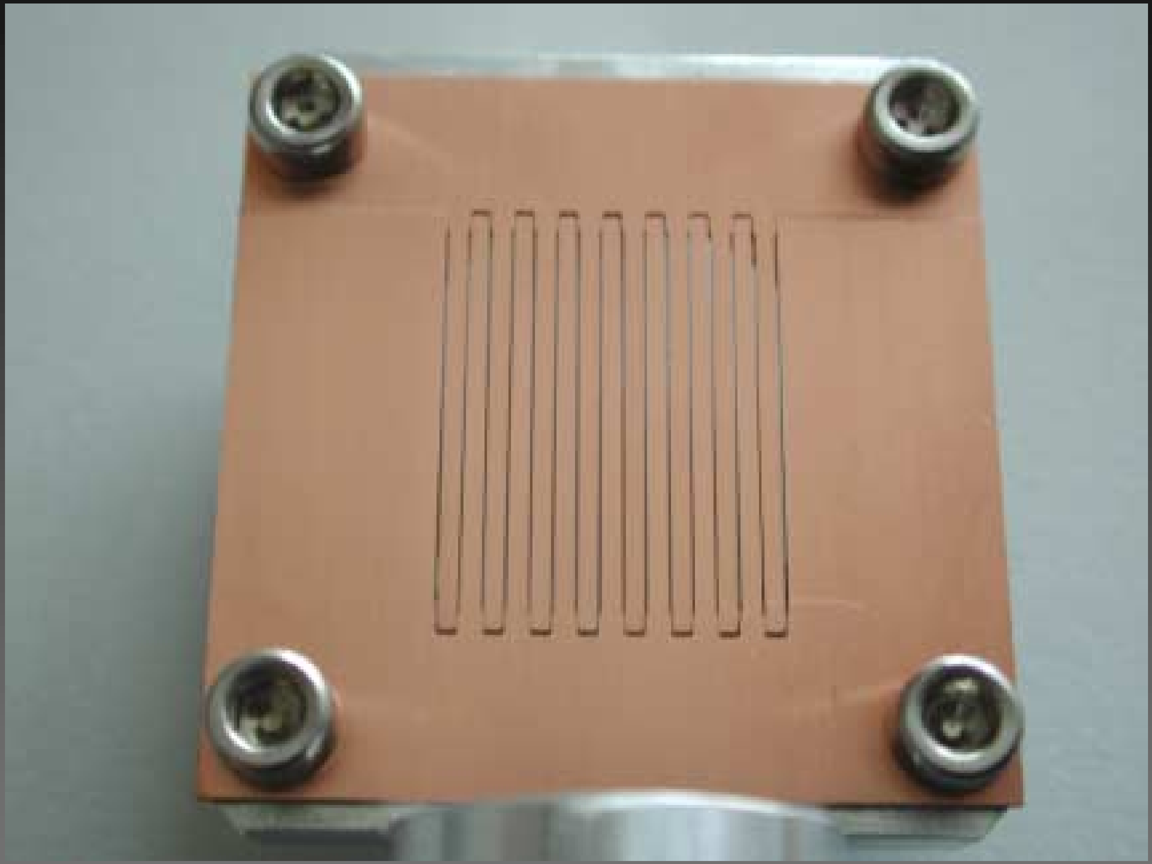
- Angular acceptance of the slit must be significantly bigger then the beam divergence.

- At the end of the drift space the distance from any beamlet to a neighboring has to be bigger than the beamlet width

- The drift space has to be long enough to let the beamlet expand so that at the end of the drift space its RMS size is much bigger than the slit width

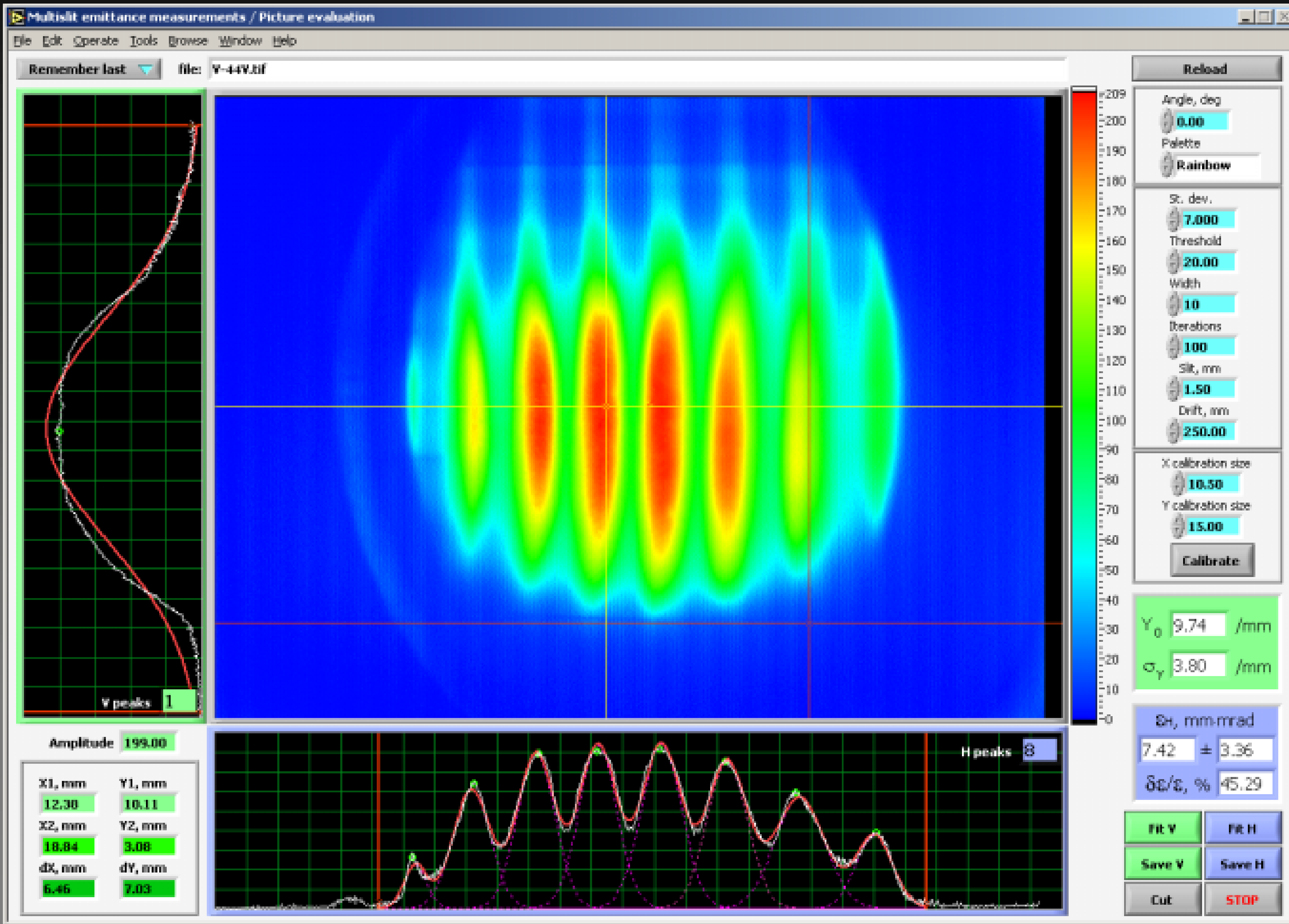
- Residual space charge force between the beamlets has to be negligible, i.e., the beam behind the mask is emittance dominated

The multislit mask



- the mask is made of 1mm thick cupper
- it consists of two parts; 1.6 mm period; 100 μm slit width
- made on a wire-cut machine
  (the machine has resolution of 5 μm)

Multislit data evaluation



Quadrupole scan emittance measurements basics

The method is based on the linear matrix formalism
and works properly for emittance dominated beams.

- the beam matrix defines the phase space ellipse

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \varepsilon \begin{pmatrix} \beta_T & -\alpha_T \\ -\alpha_T & \gamma_T \end{pmatrix}$$

- the R matrix describes evolution of the beam matrix

$$\sigma^1 = R\sigma^0 R^T$$

- beam profile can be measured

$$r_{rms}{}^2 = \langle x^2 \rangle = \varepsilon\beta_T = \sigma_{11}$$

- for a beam line consisting sequentially of a quadrupole, a drift space and a view screen

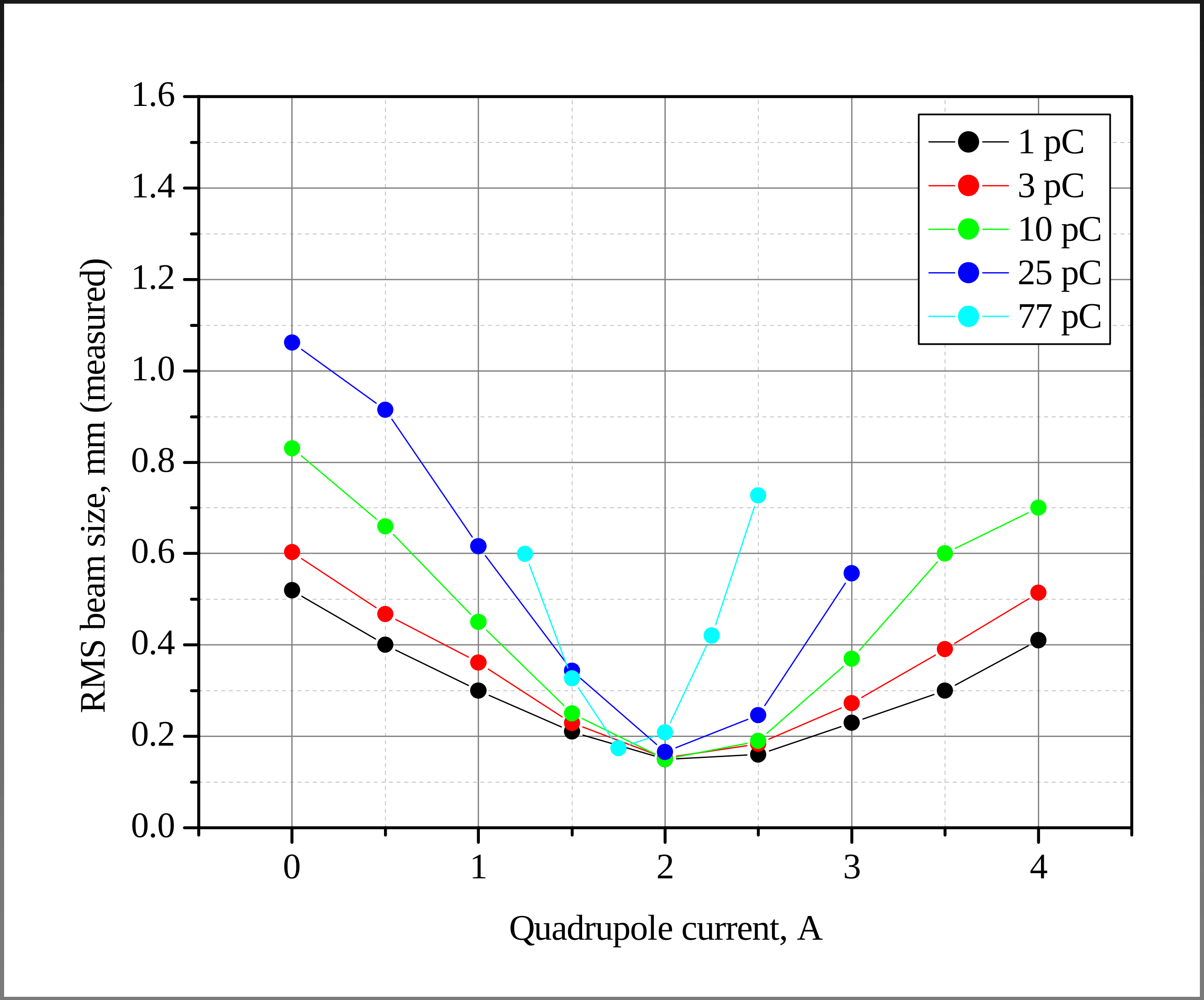
is measured

are known

$$\sigma_{11}^1 = R_{11}^2\sigma_{11}^0 + 2R_{12}R_{11}\sigma_{12}^0 + R_{12}^2\sigma_{22}^0$$

are found as a solution of a system of linear equations

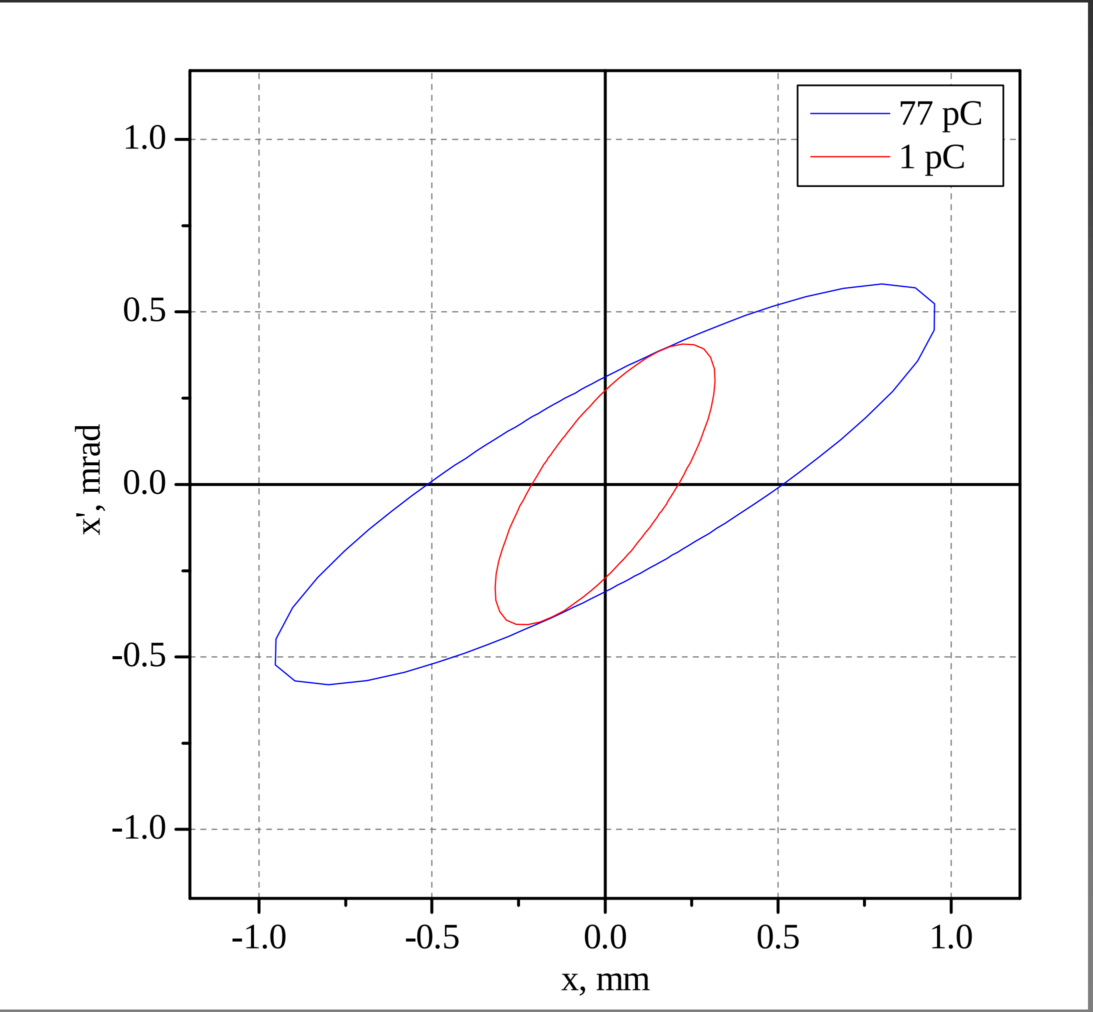
Experimental data



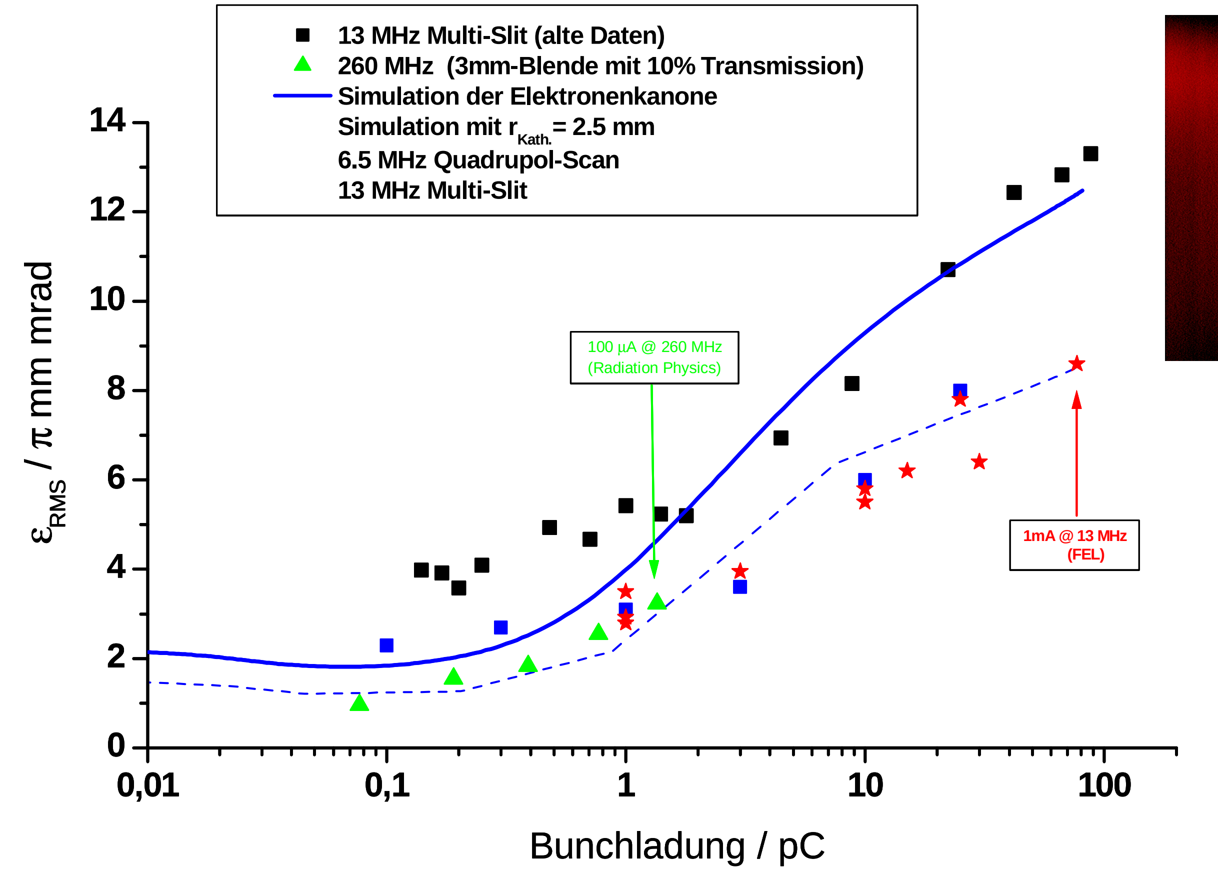
At 12 MeV we use OTR view screens (5 µm thick aluminum foil) and again the vidicon video cameras.

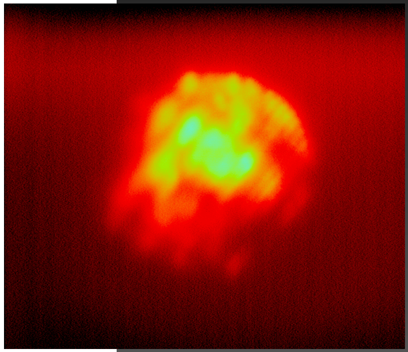
Apertures to get smaller emittance

Since the NLSF results in all elements of the beam matrix σ
We can plot the phase space ellipse.

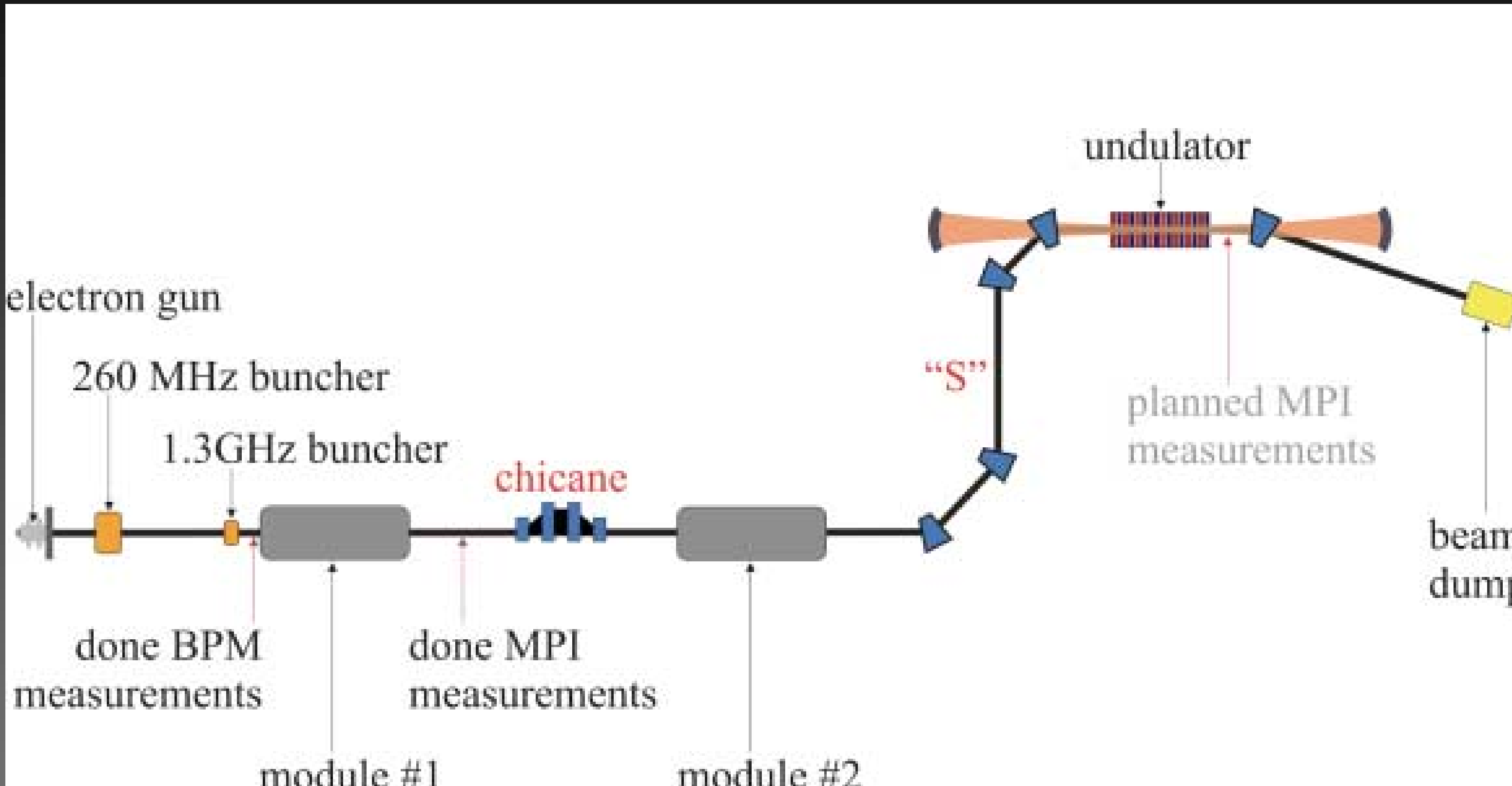


The transverse emittance vs. bunch charge





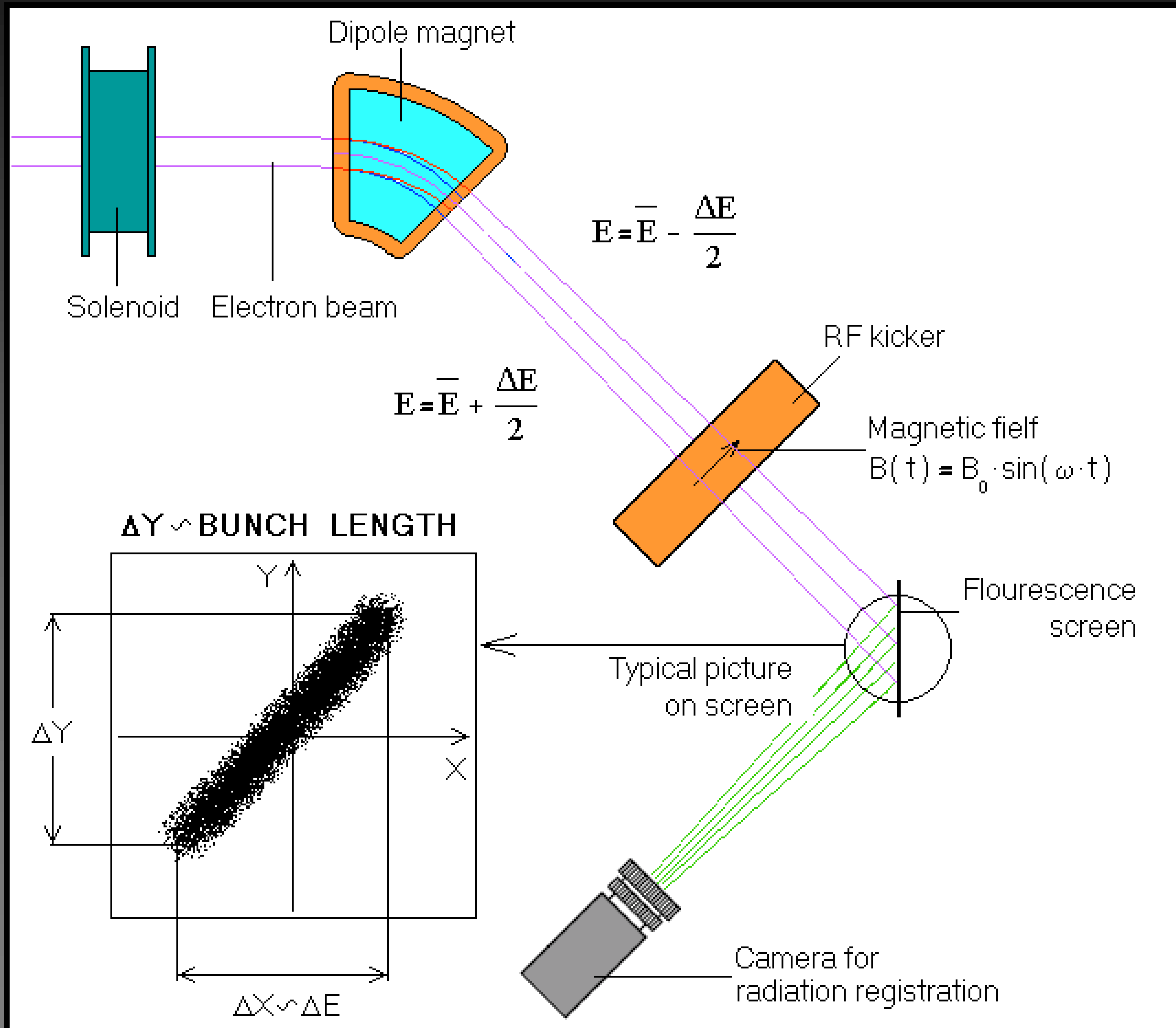
Bunch length evolution (general idea)



- the gun produces 450 ps long bunch
- compressed down to 10 ps in the injector
- at the module #1 exit is about of 1ps
- chicane with adjustable R_{56}
- "S" with constant R_{56}

- Goal – to minimize the bunch length at the undulator entrance

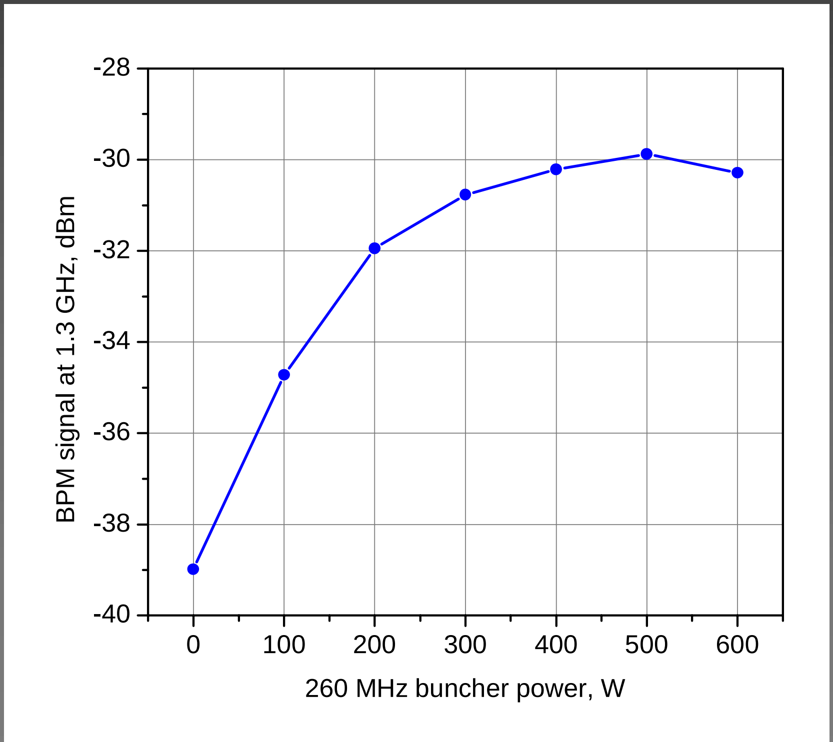
A kicker cavity to measure the bunch length

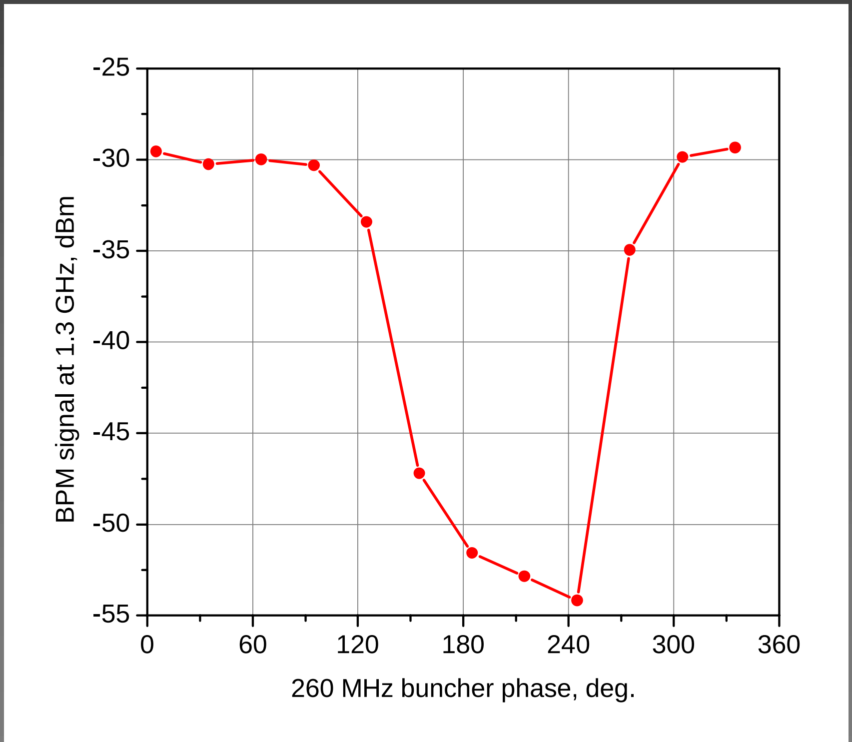


Bunch length minimization in the injector

450 ps long bunch coming out of the gun is compressed in the injector down to about of 10 ps by two bunches.

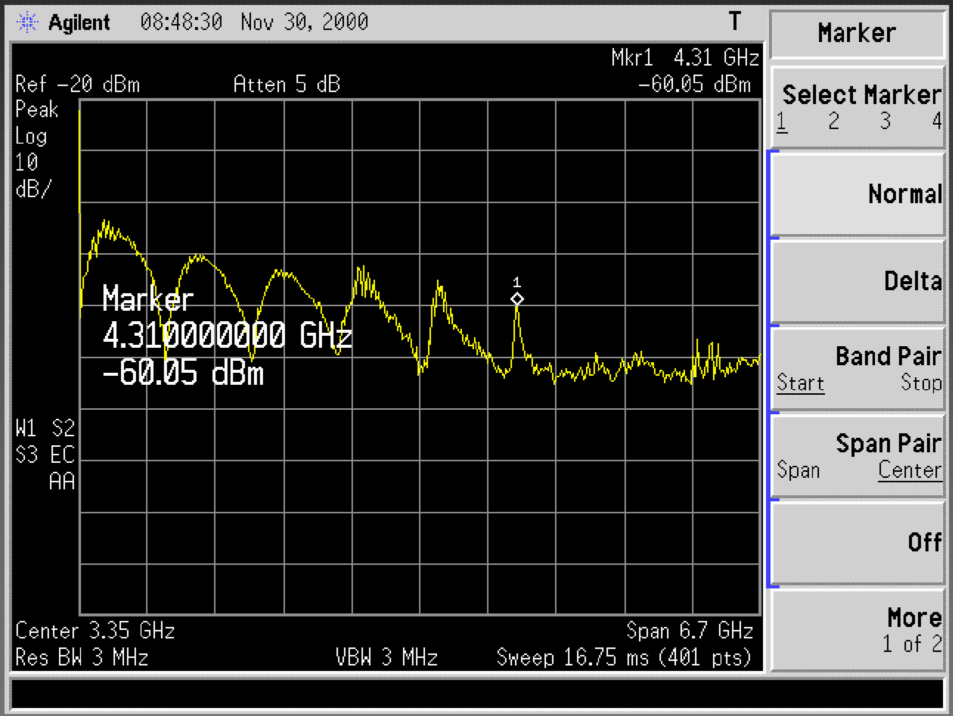
The 260 MHz buncher has the main impact on the compression.
The bunch length at the module #1 entrance has to be minimized.

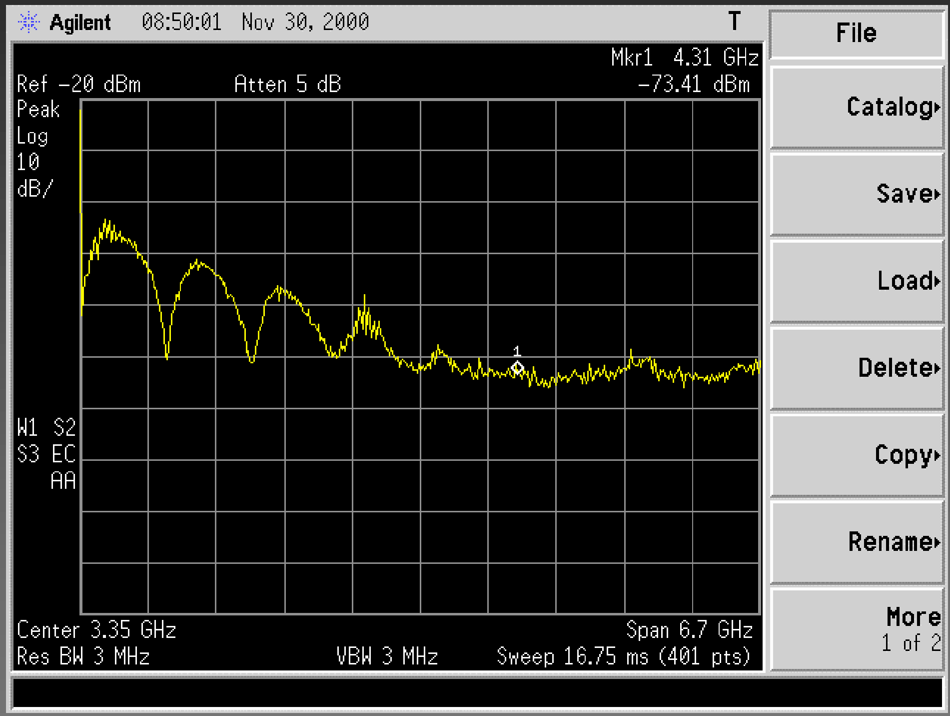




<u>the larger BPM signal at fixed frequency – minimum bunch length</u>

Bunch length minimization in the injector





the 260 MHz buncher is optimized

the 260 MHz buncher is off

ps bunch length measurements using CTR

1. Transition radiation is produced when the electron bunch passes a boundary of two media.

2. Respond time is zero. Shape of the radiation pulse is a “copy” of the electron bunch shape.

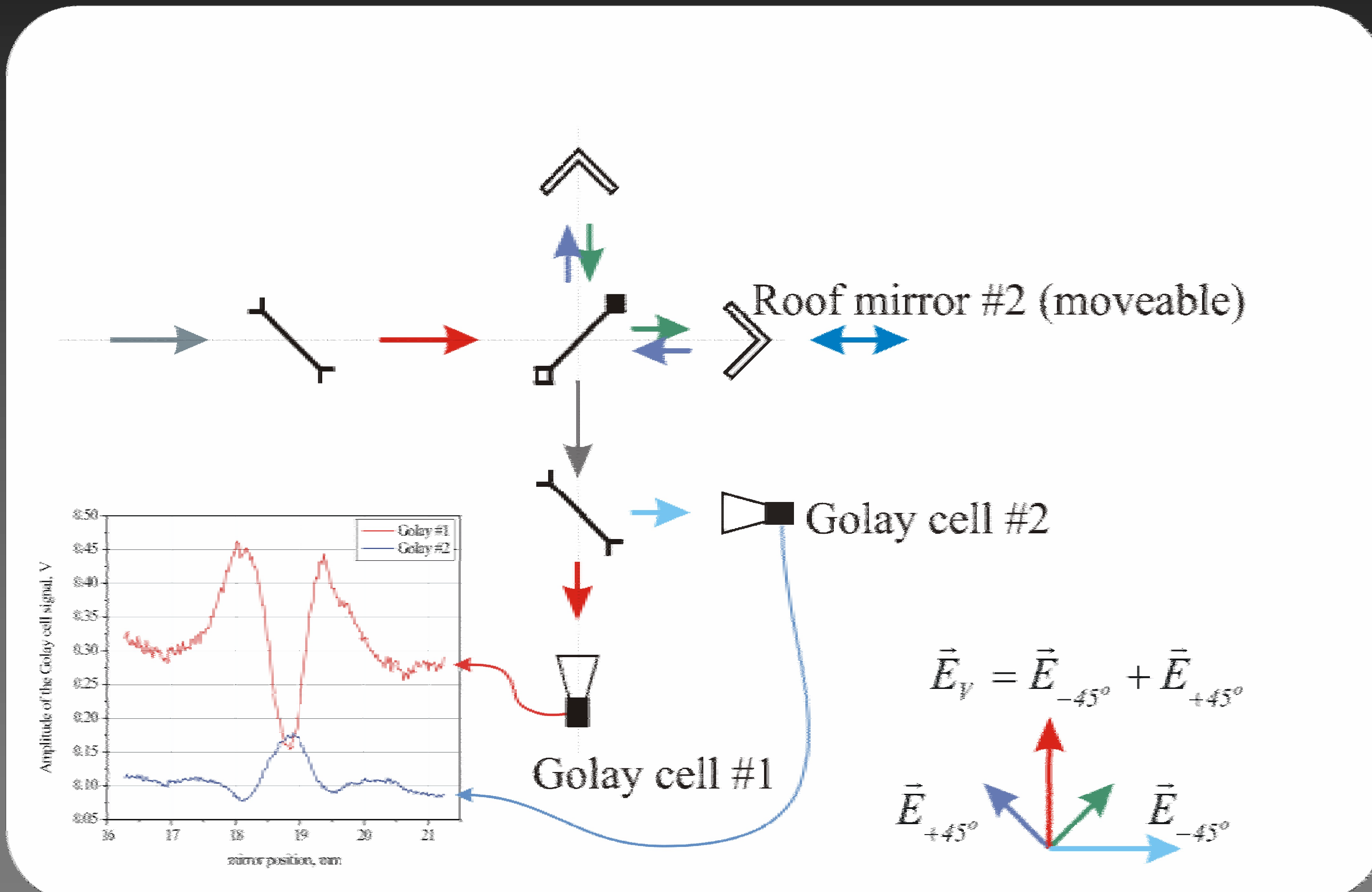
3. When the wave length of the radiation becomes more than the bunch length the radiation becomes COHERENT. ($\lambda >> L$)

4. Power is proportional to:
   incoherent radiation ~ N
   coherent radiation ~ N^2
   at 77pC N~ 5×10^8

5. Measurements of the radiation spectrum give information about the bunch length.

the Martin-Puplett interferometer is used to measure the spectrum

The Martin-Puplett interferometer operation



The Martin-Puplett interferometer

- longitudinal field profile at the MPI entrance

$$E_{in}(t) = E_0\, g(t)$$

- longitudinal field profile at the MPI exit

$$E_{out}(t) = \sqrt{T_\perp R_{||}/2}\, E_0 \left(g(t) + g(t-t)\right)$$

- detectors measure intensity $I \propto E^2$

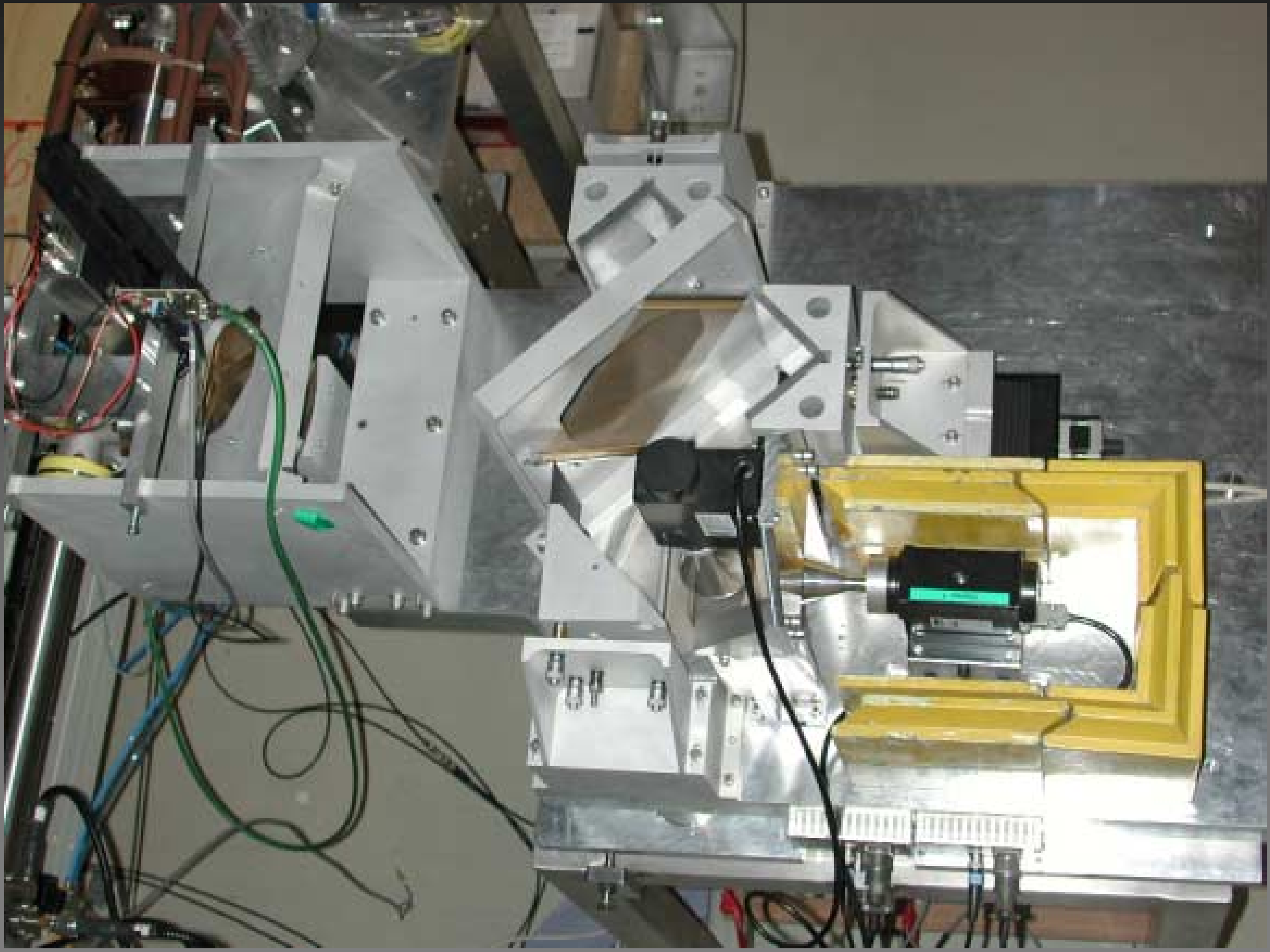
$$U(\tau) \propto E_o^{\,2} T_\perp R_{||} \int_{-\infty}^{+\infty} \left((g(t))^2 + g(t)\, g(t-\tau) \right) dt$$

the autocorrelation function is measured with the help of the MPI

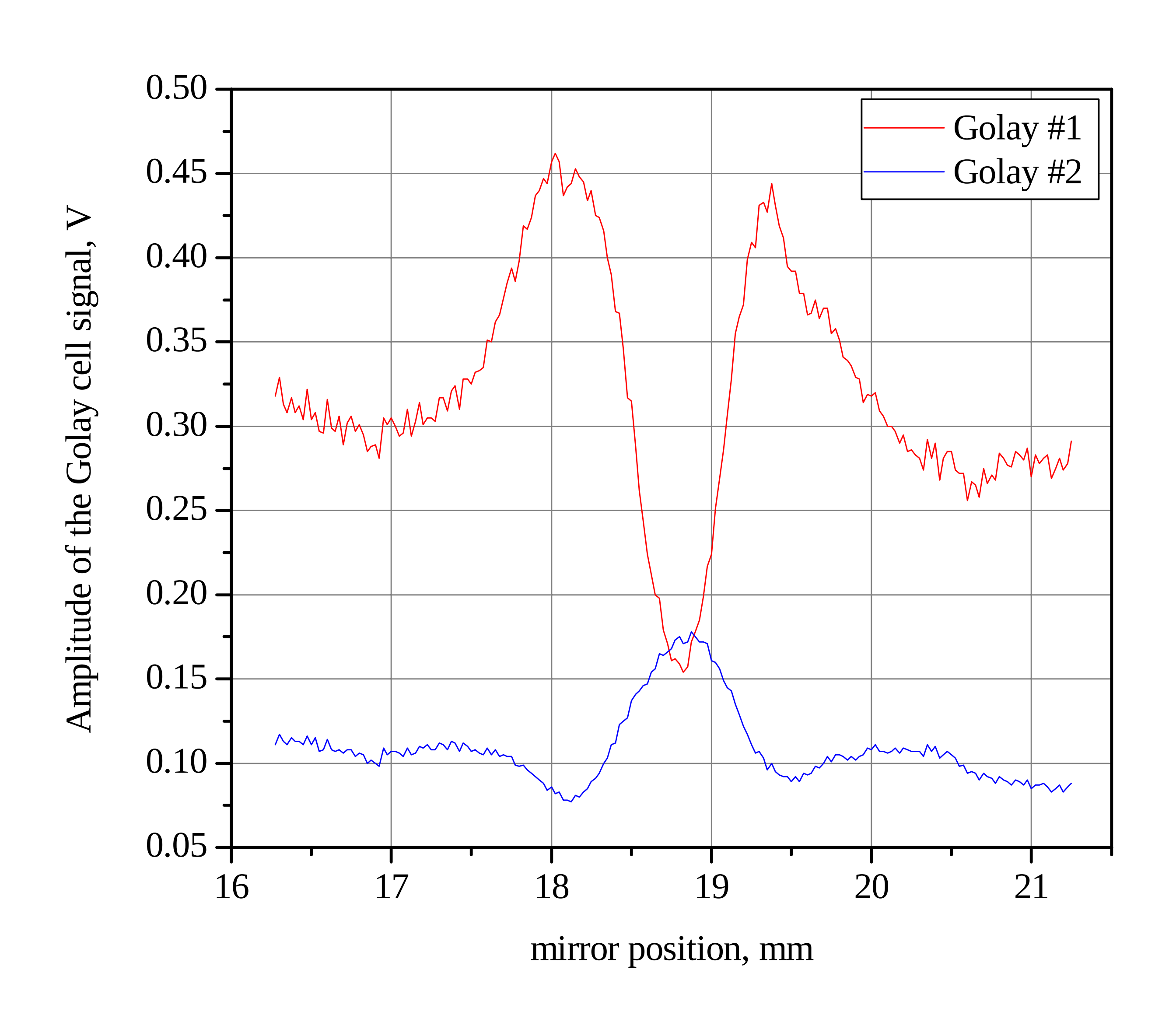
- The Wiener-Khintchine theorem says:
“the Fourier transform of the autocorrelation function is the power spectrum”.

The Martin-Puplett interferometer

(polorizing Michelson inter feromeer)

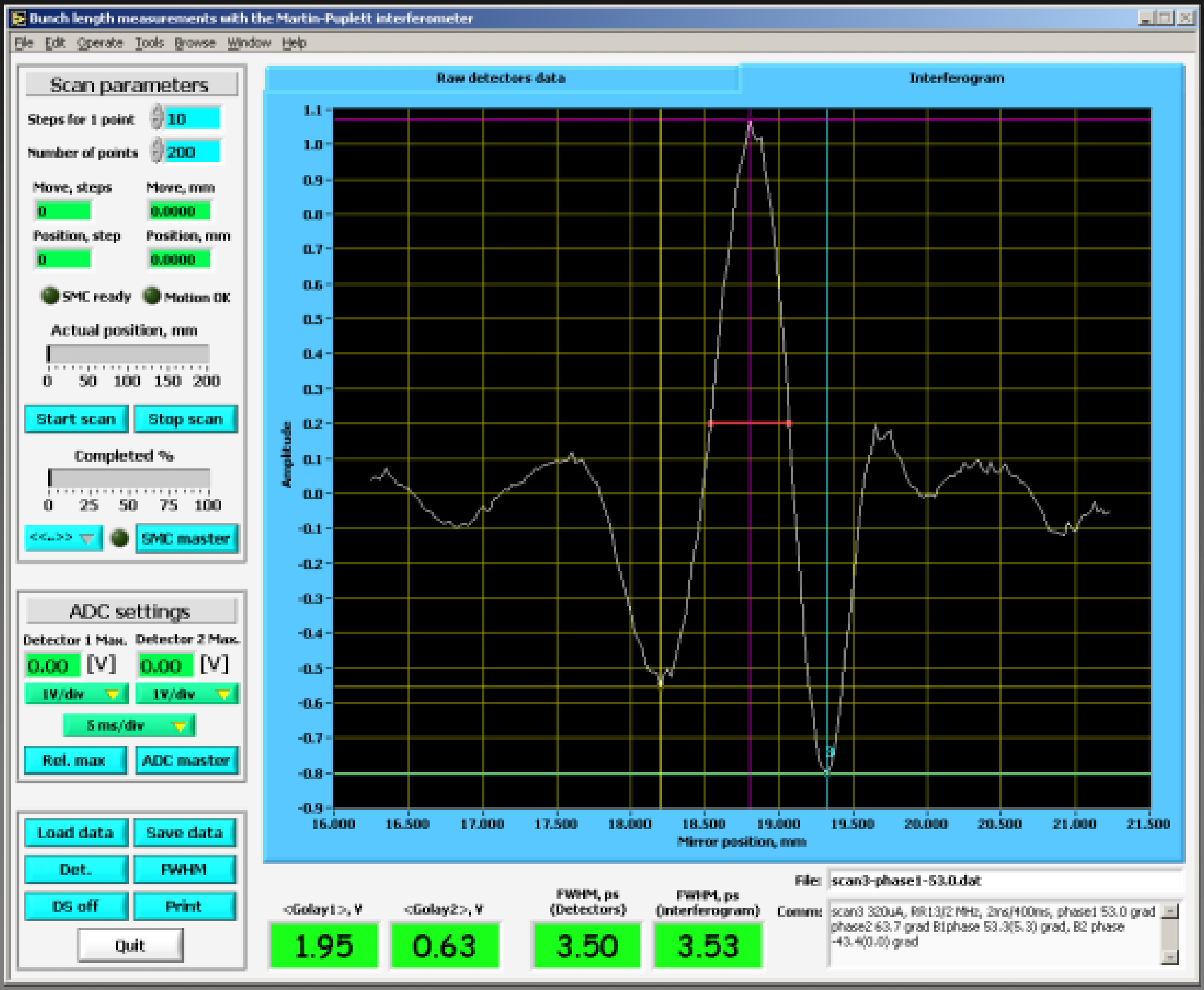


The MPI scan

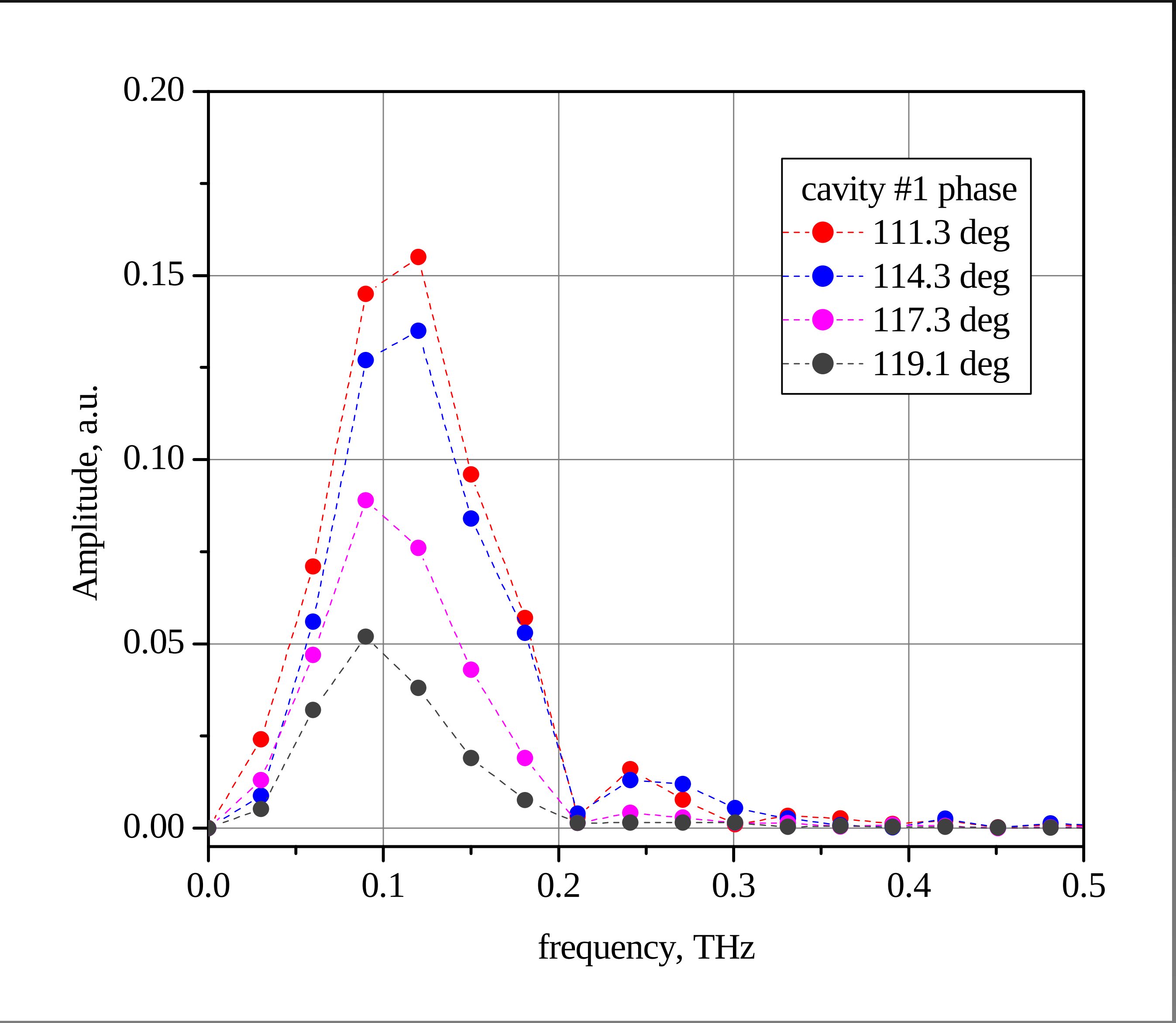


Amplitude of the Golay cell signal, V
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
16
17
18
19
20
21
mirror position, mm
Golay #1
Golay #2

The use of two detectors: raw data vs. interferogram

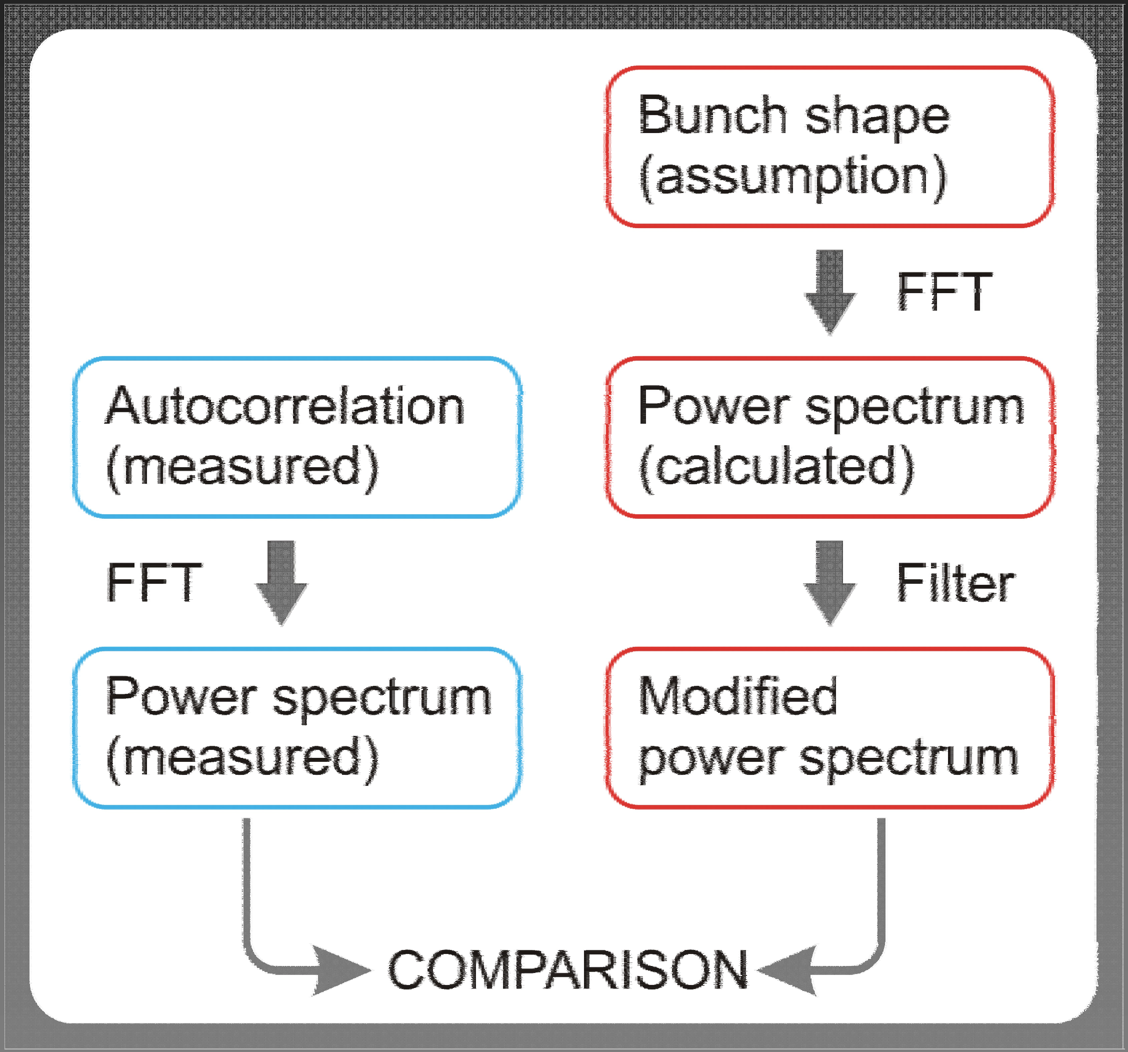


The power spectrum



Only real part of the spectrum is used

The MPI data evaluation



The MPI data evaluation (2)

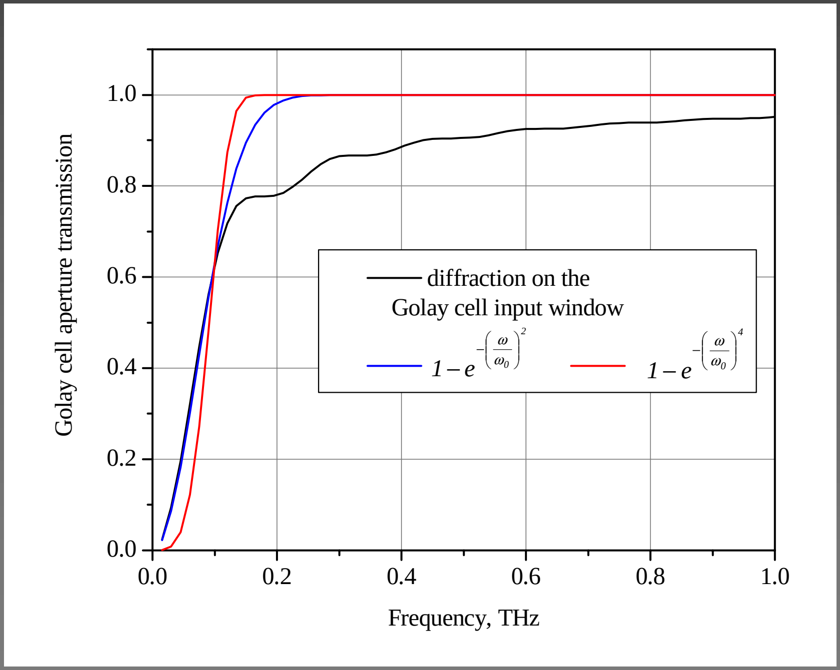
- the Gaussian shape of the bunch is assumed

$$n(t) = \frac{Q}{c\sigma_t\sqrt{2\pi}} e^{-\left(\frac{t}{\sigma_t\sqrt{2}}\right)^2}$$

- its power spectrum is also Gaussian

$$\tilde{P}(\omega) = C\, e^{-(\omega\sigma_t)^2}$$

- low frequency cut-off diffraction on the Golay cell input window



two filter functions were considered:

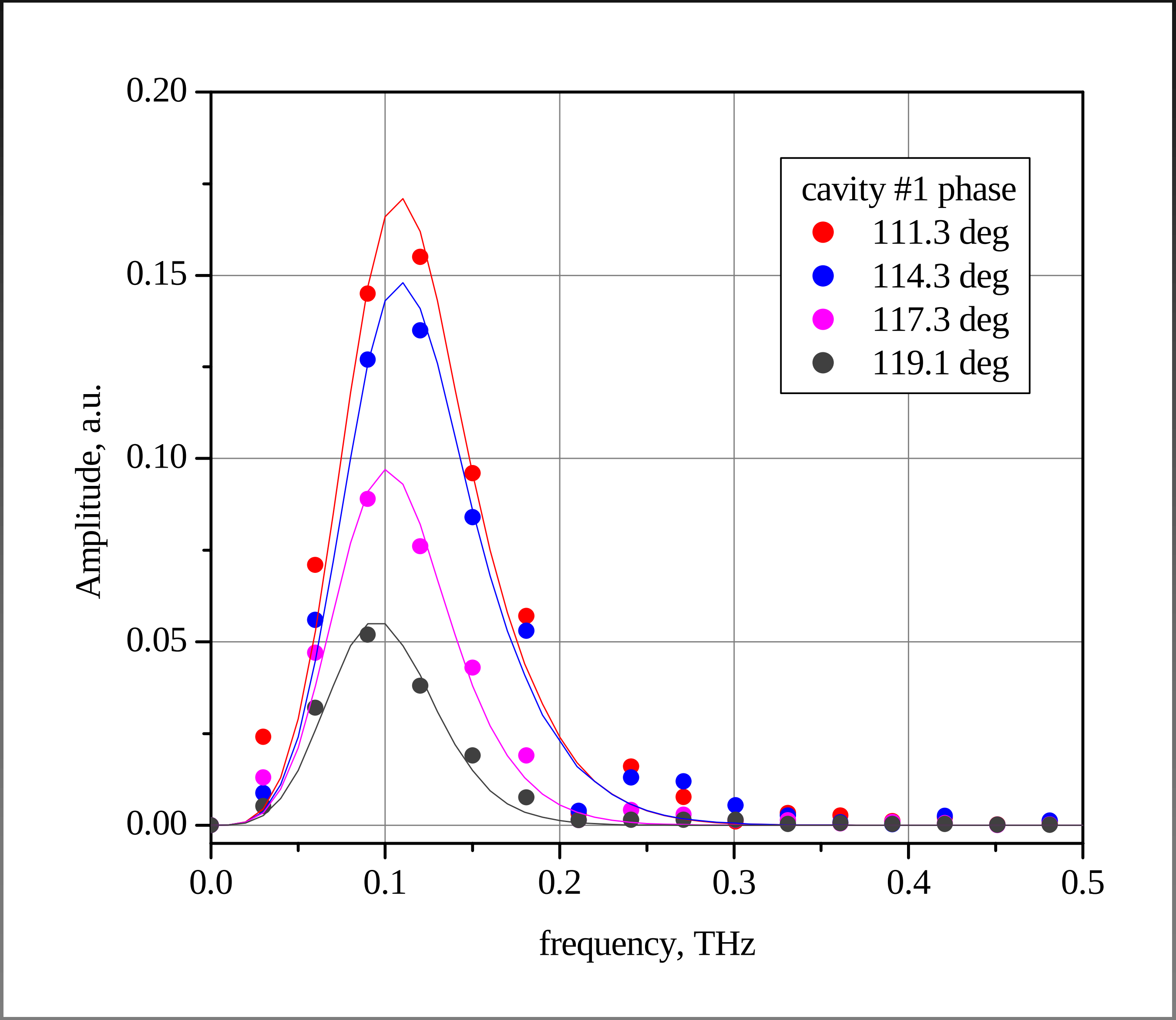
$$F1_{filter}(\omega) = 1 - e^{-(\omega/\omega_0)^2}$$

$$F2_{filter}(\omega) = 1 - e^{-(\omega/\omega_0)^4}$$

- The fit function is used

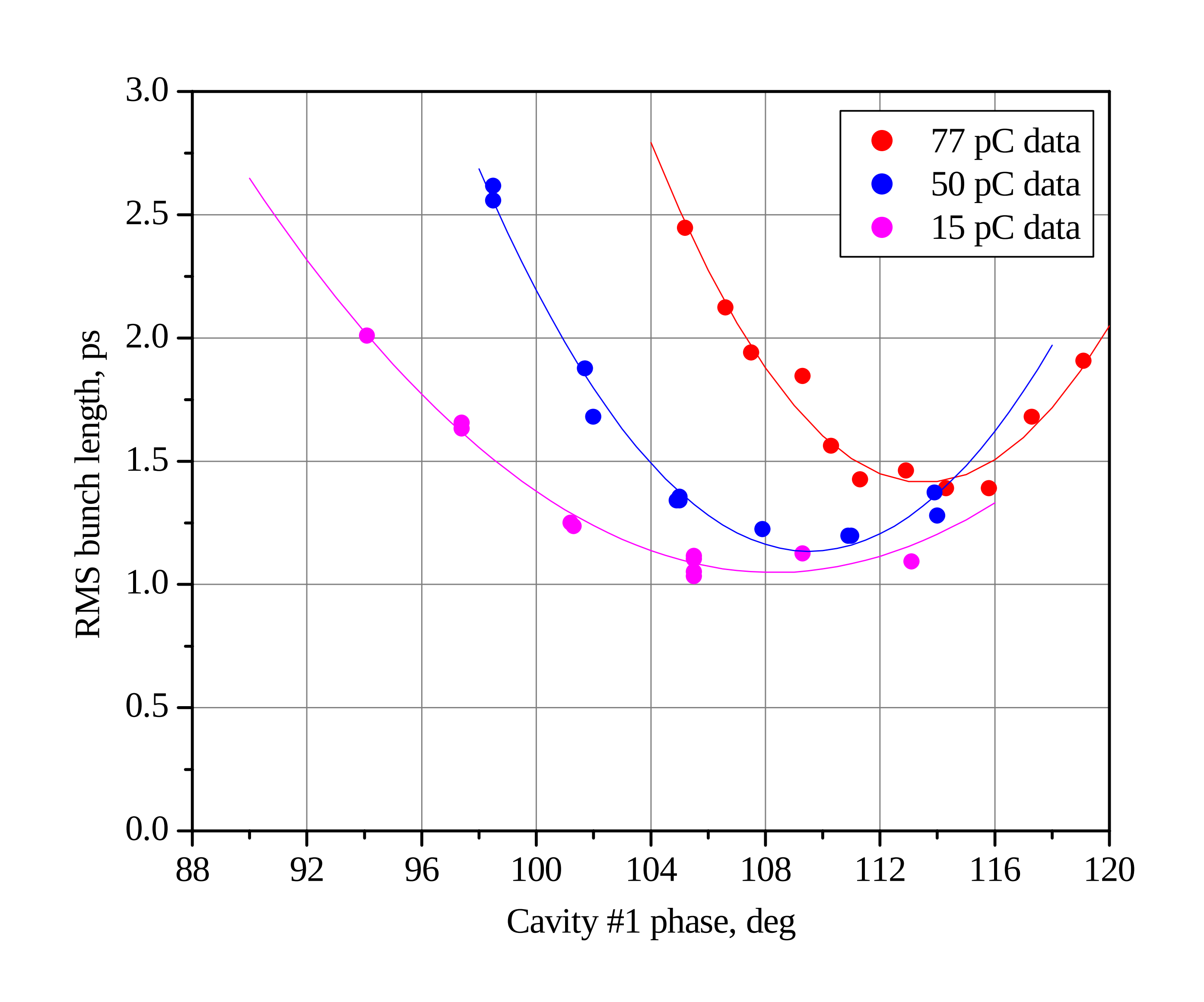
$$f_{fit}(\omega) = \left(1 - e^{-(\omega/\omega_0)^4}\right) C\, e^{-(\omega\sigma_t)^2}$$

The power spectrum and the fit funtions



Main paremeters are the cavity #1 phase and the bunch charge

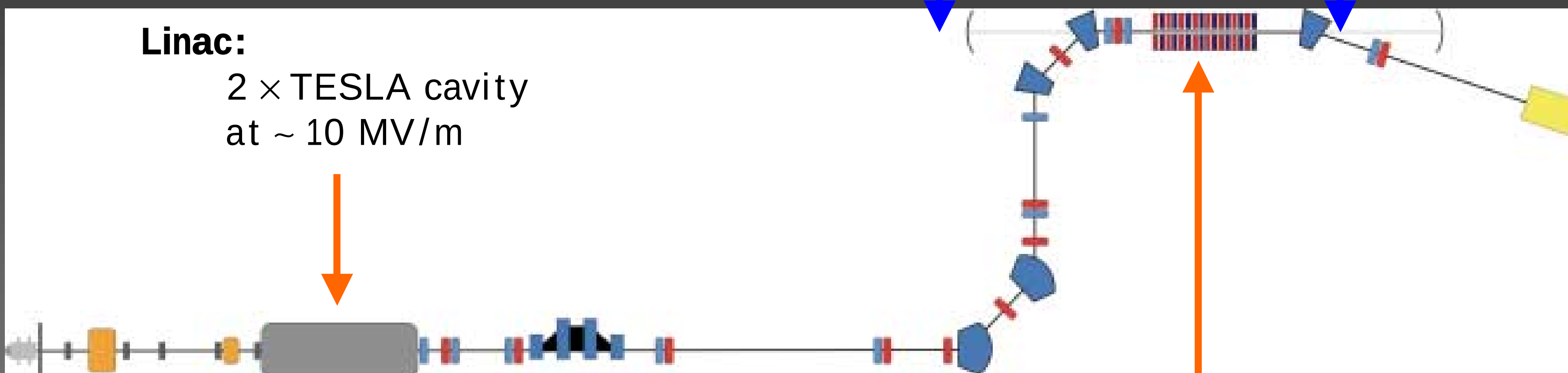
RMS bunch charge vs. cavity #1 phase



ELBE FEL layout

MTC to see the spontaneous radiation

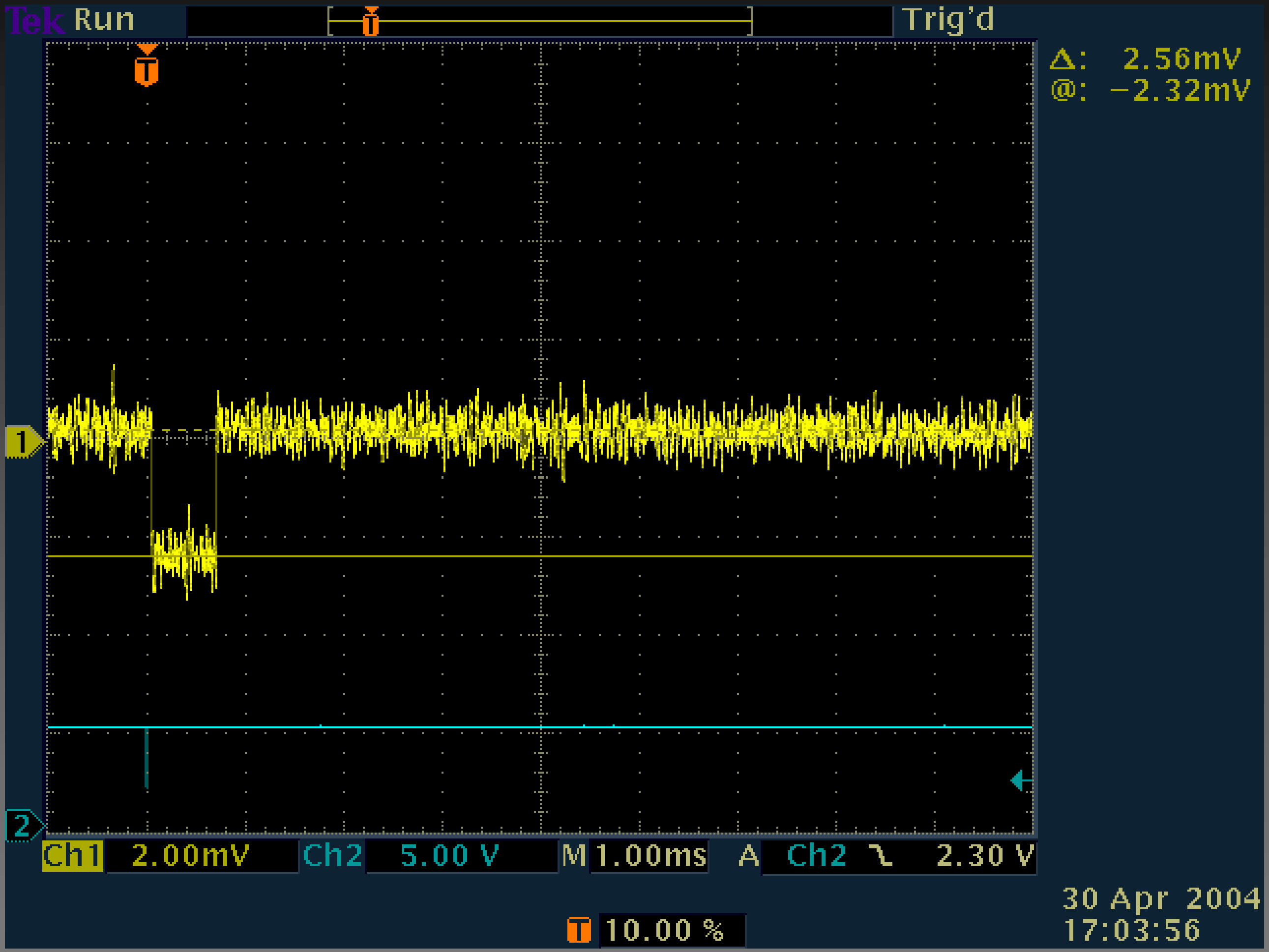
Linac:
2 × TESLA cavity
at ~ 10 MV/m



Injector:
250 keV
13 MHz CW
up to 77 pC
8 mm×mrad @ 77 pC
450 ps compressed to 10 ps

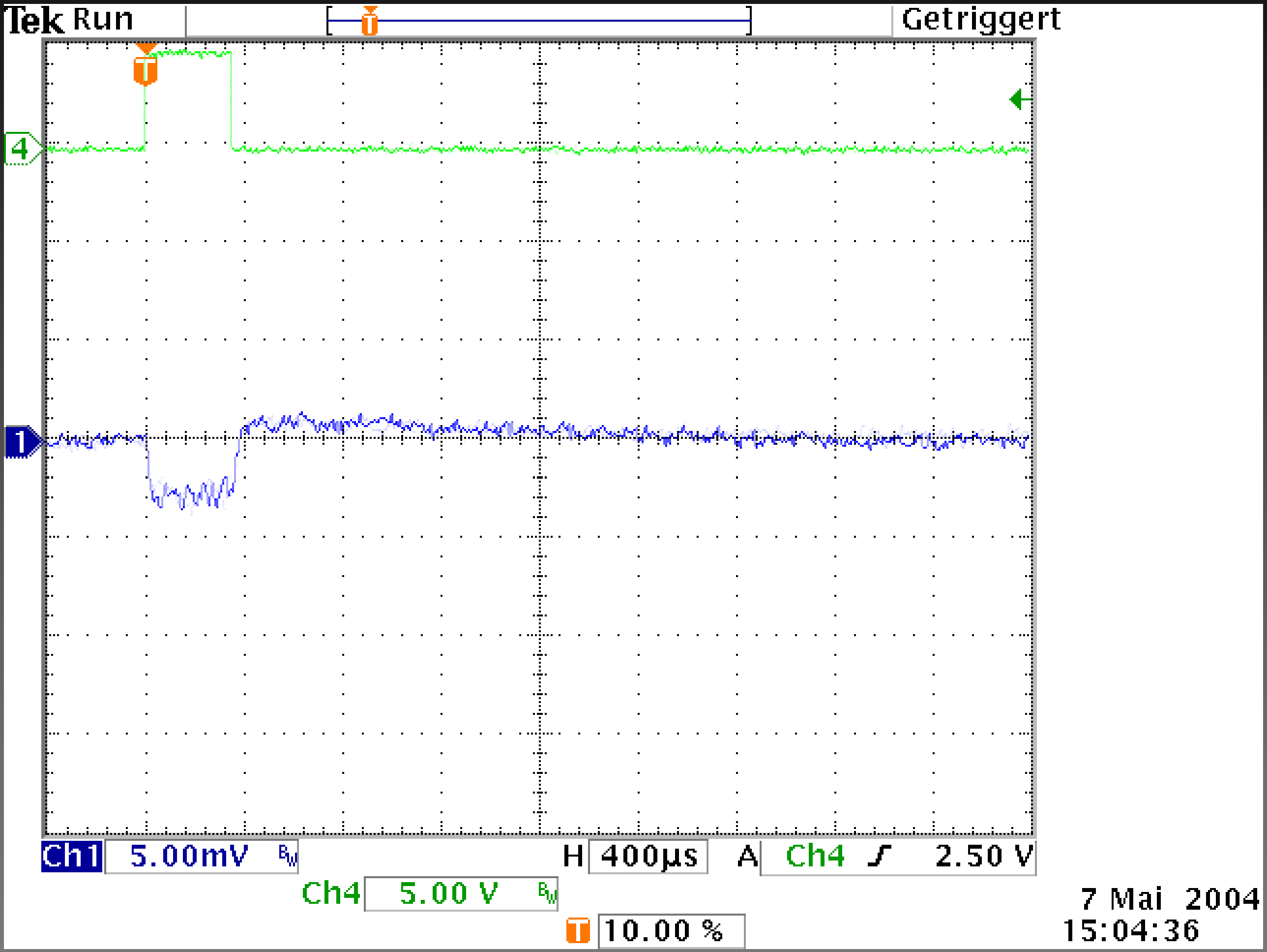
Undulator:
27.3 mm period
2 × 34 periods
K_{rms}=0.8 @ 12 mm gap

First lasing timeline



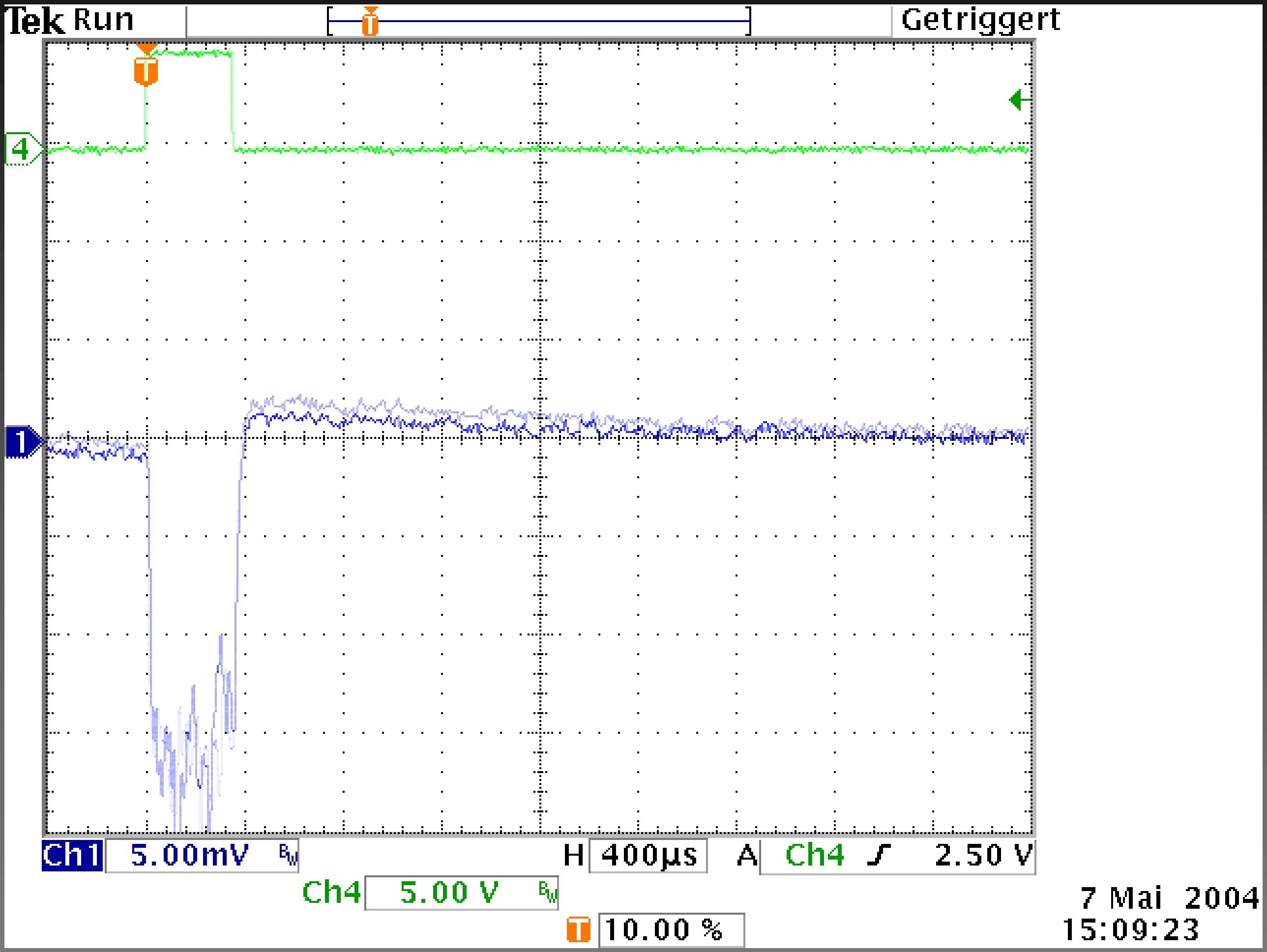
First spontaneous radiation downstream of the undulator

First lasing timeline



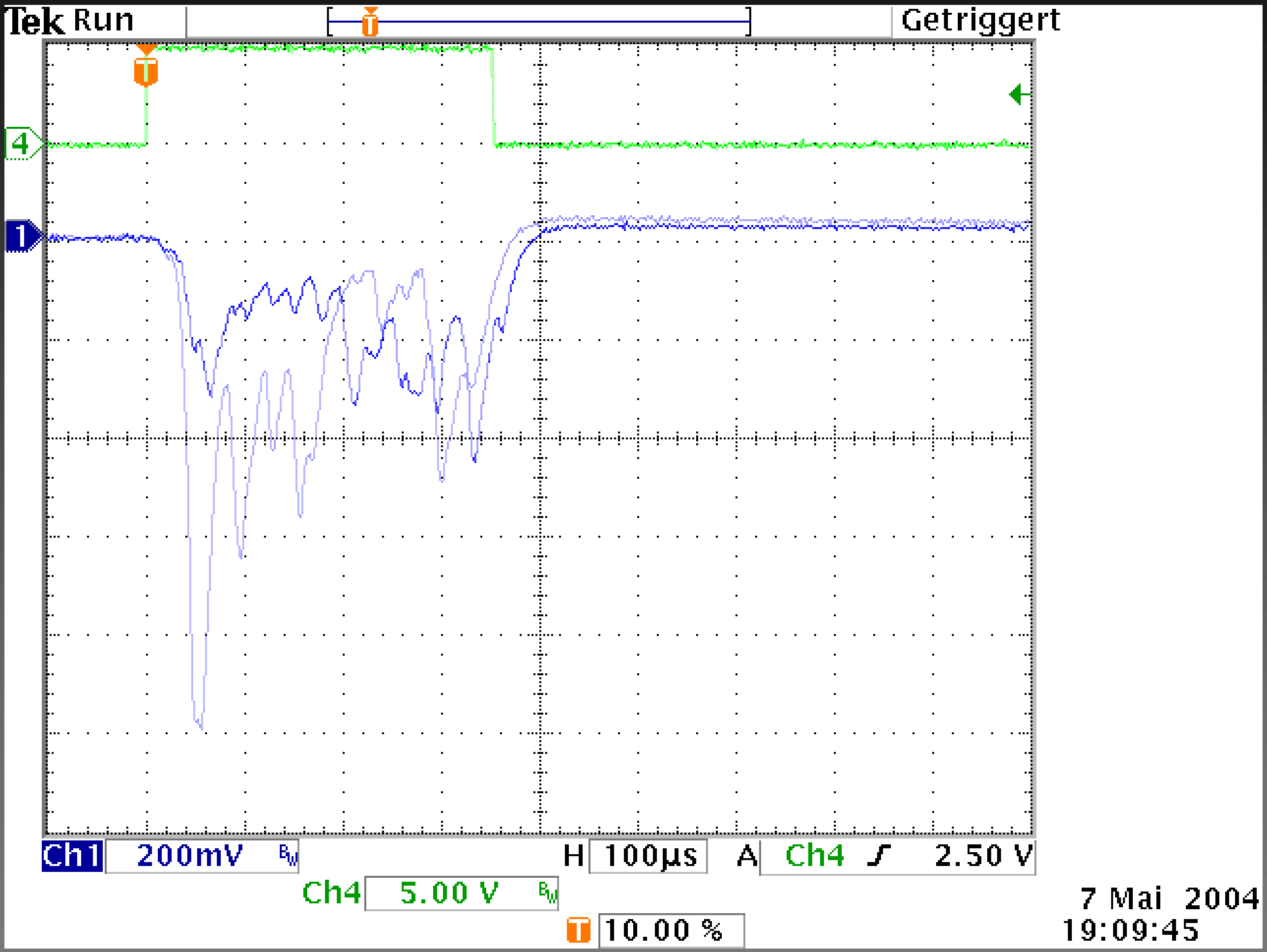
First spontaneous radiation coupled out of the optical resonator

First lasing timeline



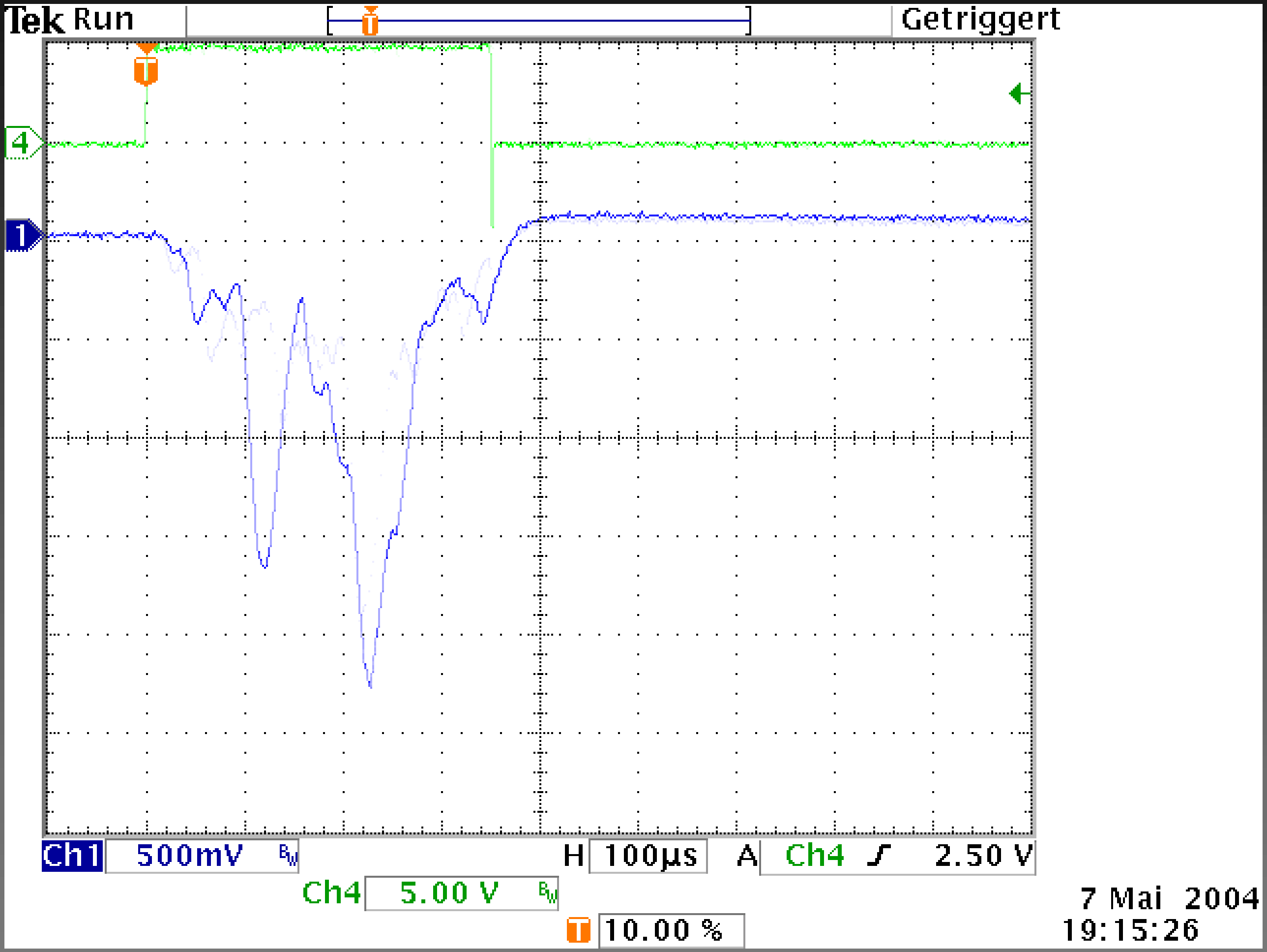
from 3 mV to 15 mV in 5 min.

First lasing timeline



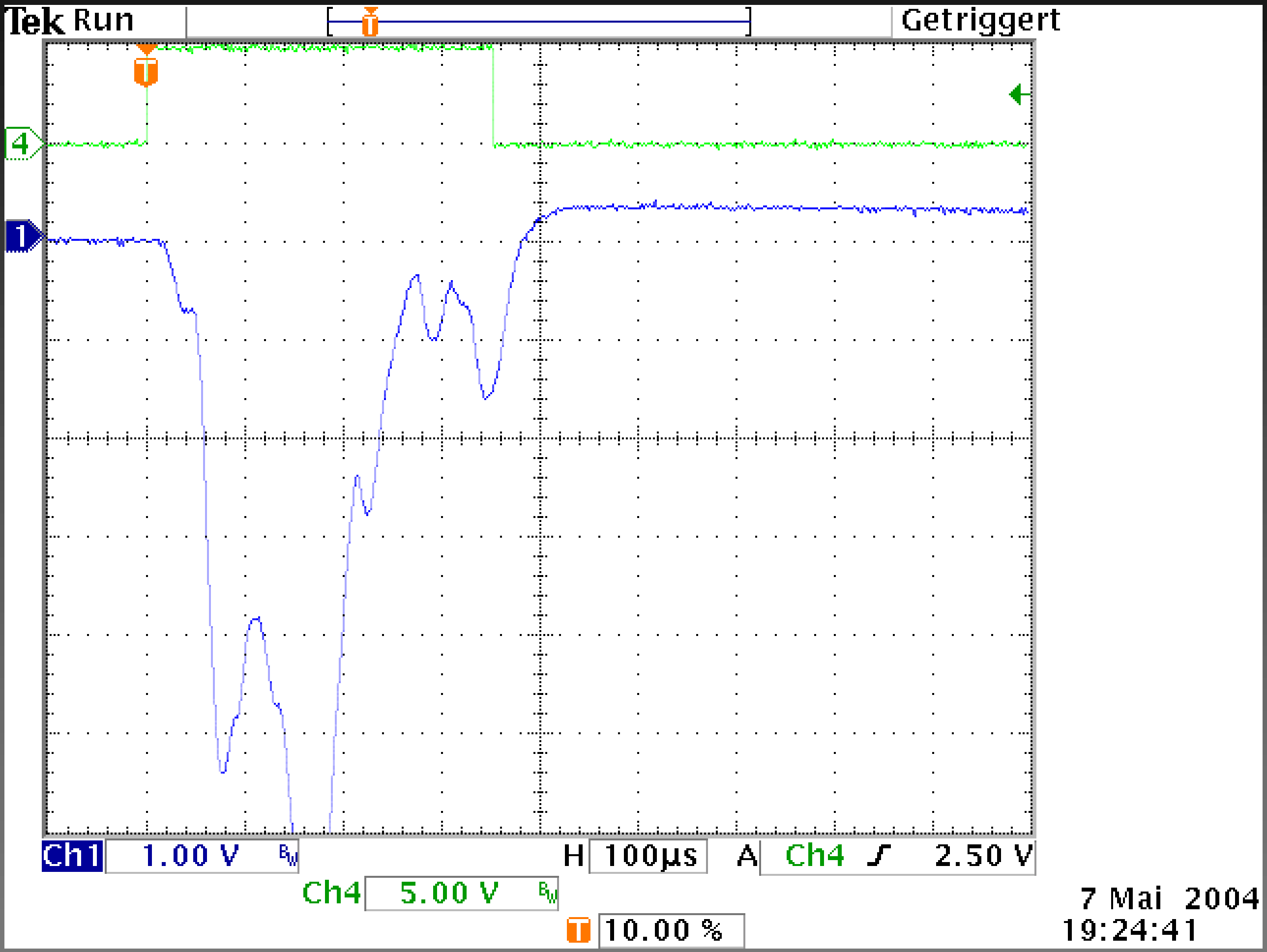
from 15 mV to 200 mV in 4 hours

First lasing timeline



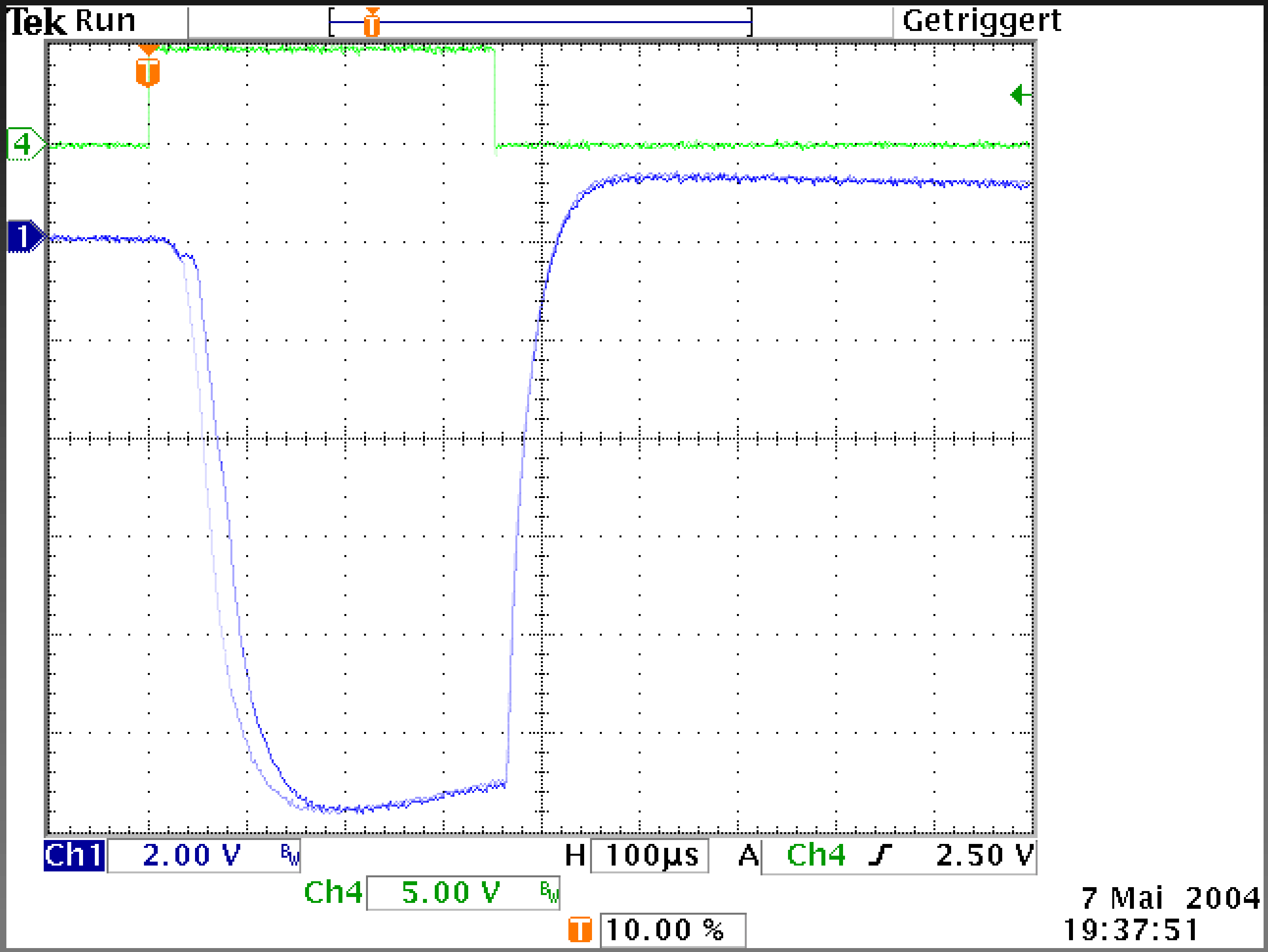
from 200 mV/div to 500 mV/div another 5 min.

First lasing timeline



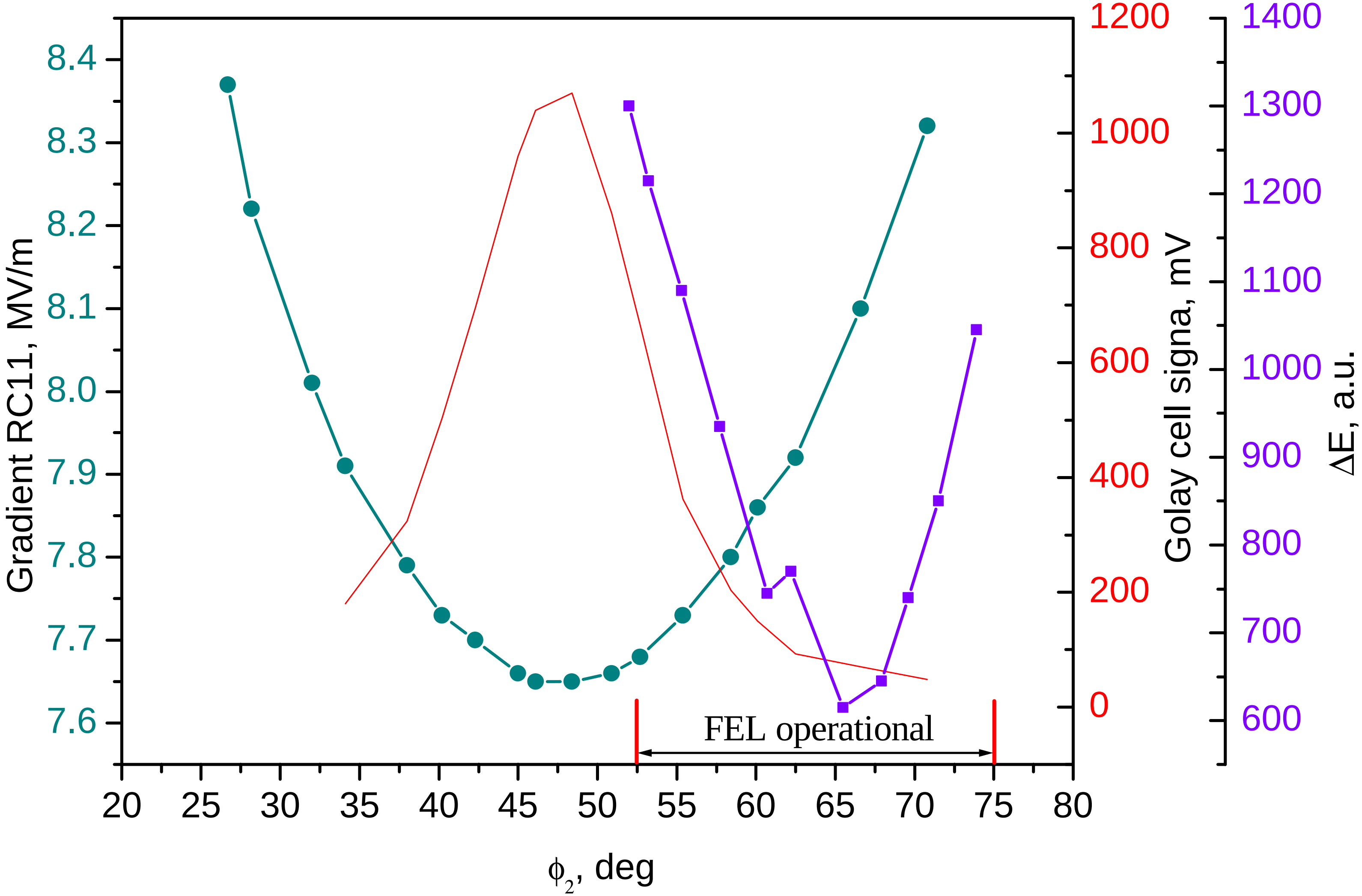
uuuuuuuuuuuuuu......

First lasing

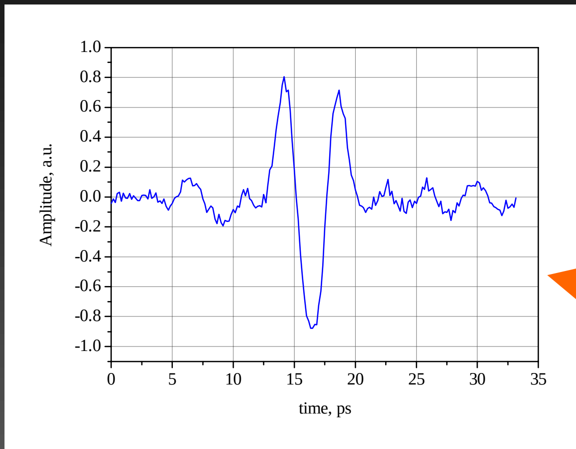


HOORAY !!!

ΔE and σ_z vs. cavity #2 phase

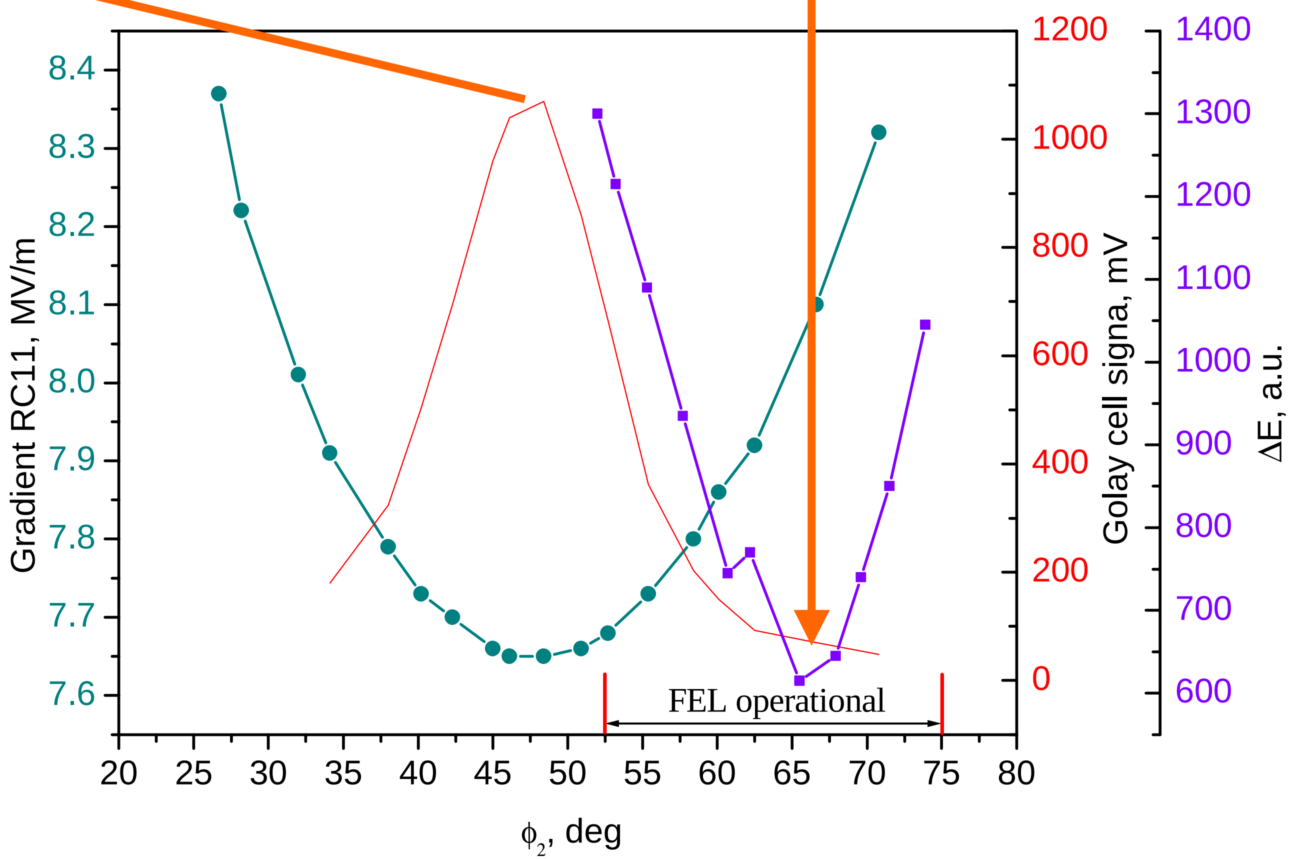


ΔE and σ_z vs. cavity #2 phase

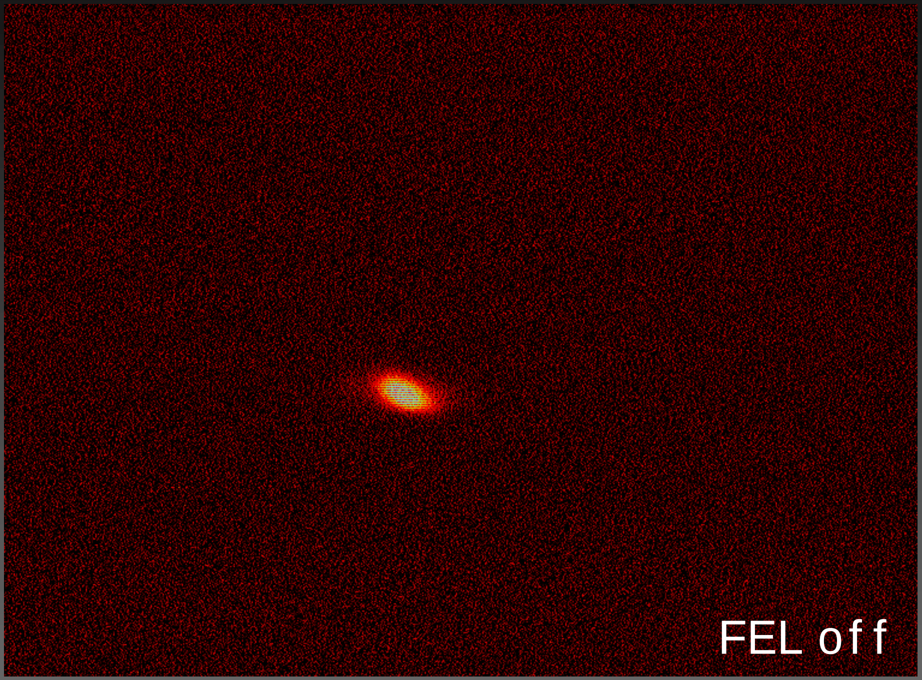


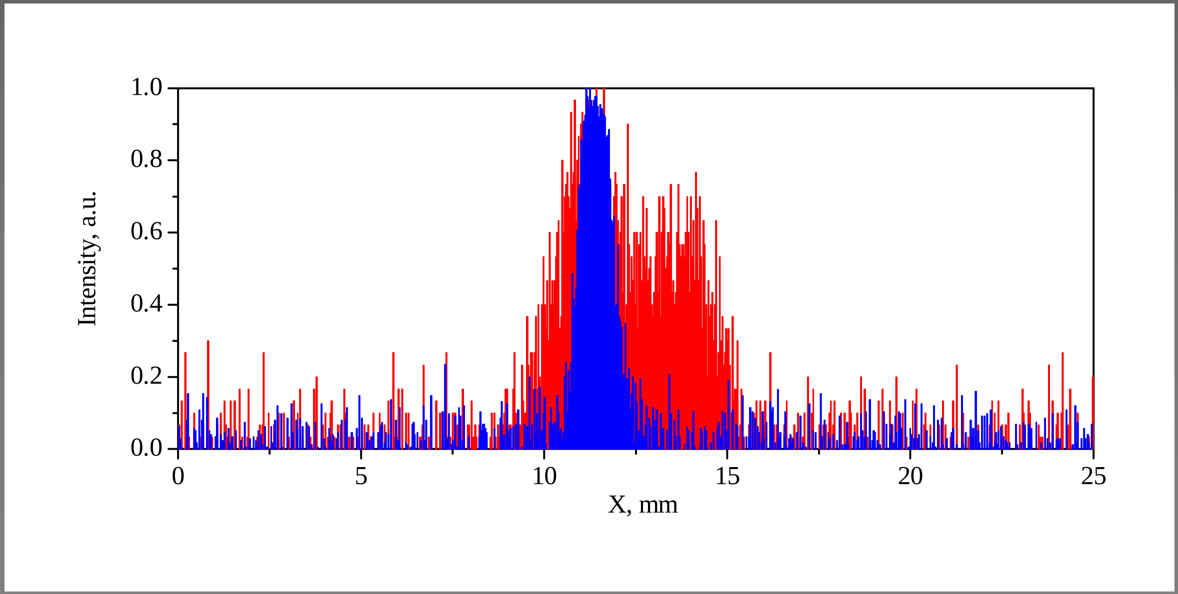
~ 2.5 ps FWHM

too long to measure with the Martin-Puplett interferometer

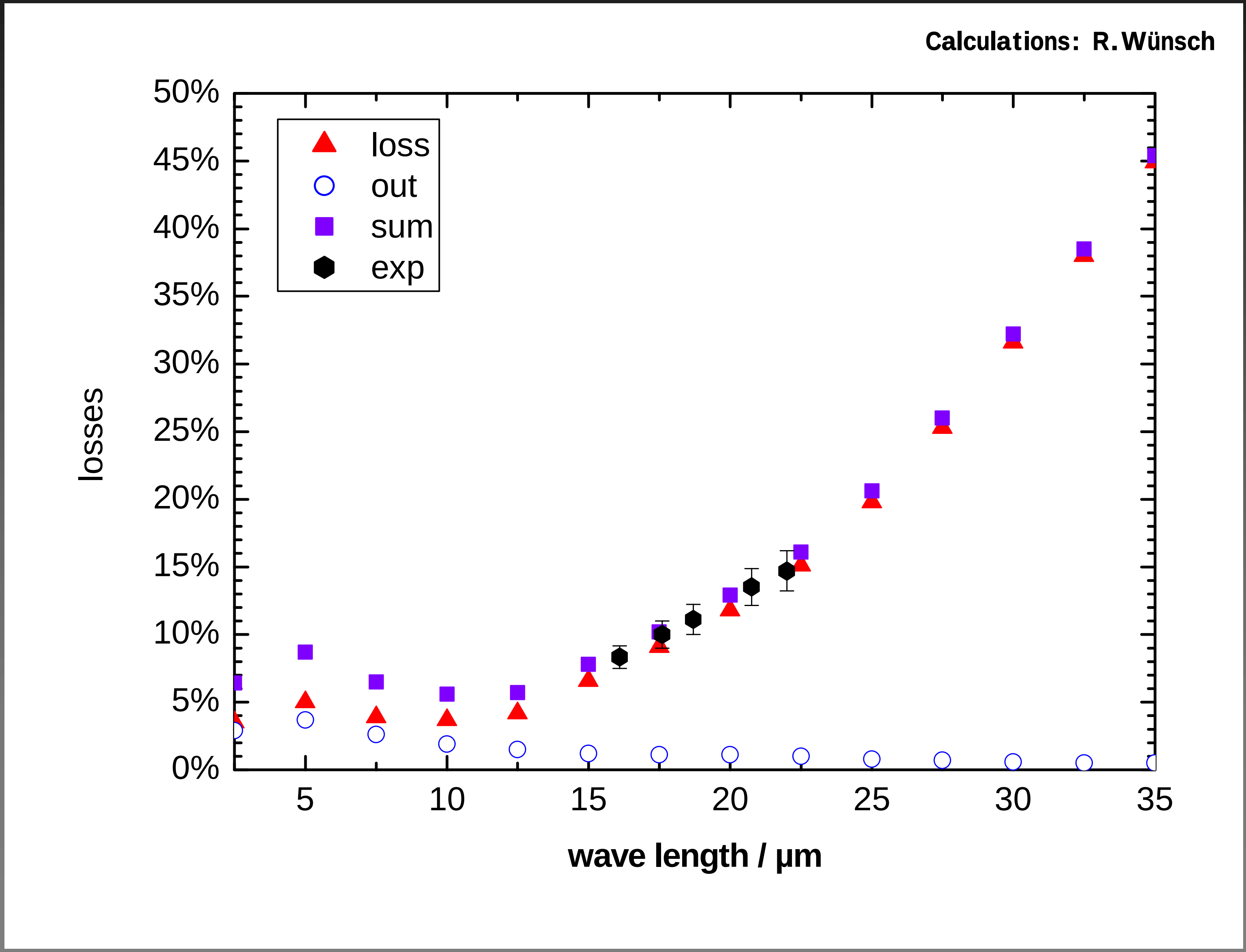


Electron beam energy spectrum





The optical cavity losses



The optical cavity detuning