Injector beam control studies winter 2006/07

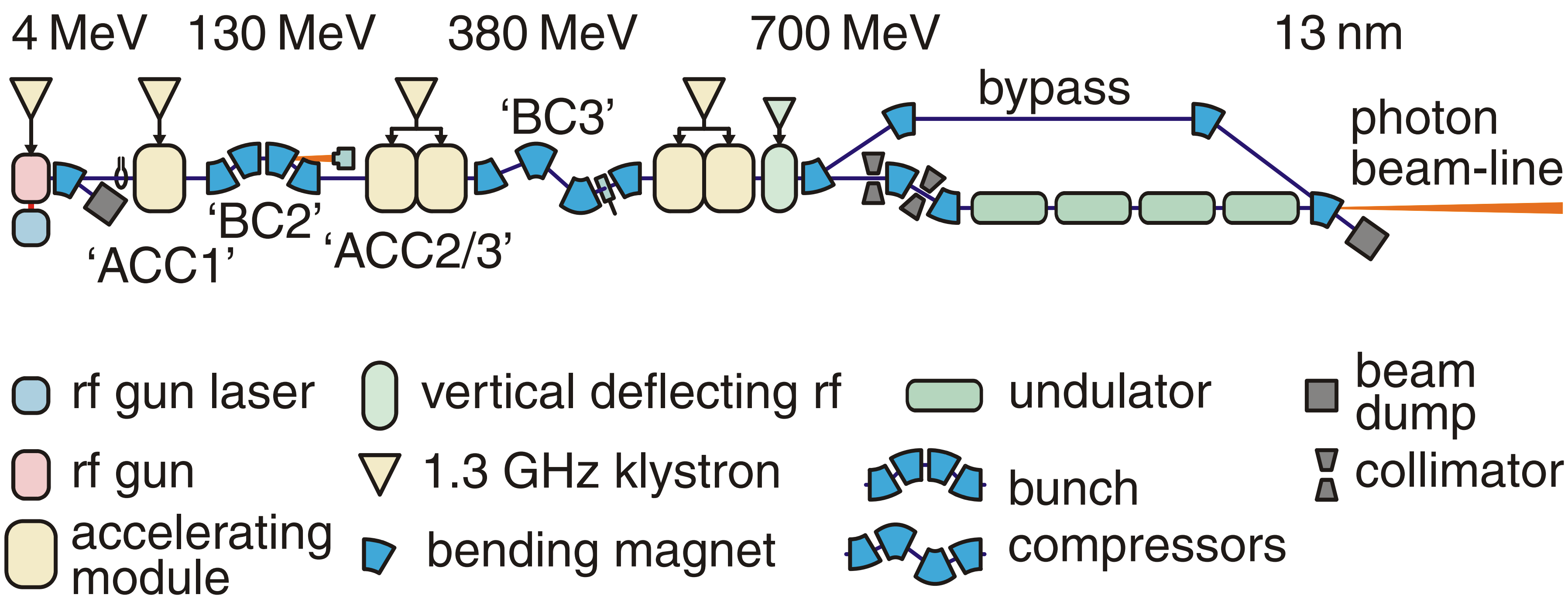
talk from E. Vogel

on work performed by

W. Cichalewski, C. Gerth, W. Jalmuzna,W. Koprek, F. Löhl, D. Noelle, P. Pucyk, H. Schlarb, T. Traber, E. Vogel, …

FLASH Seminar at June 19th 2007

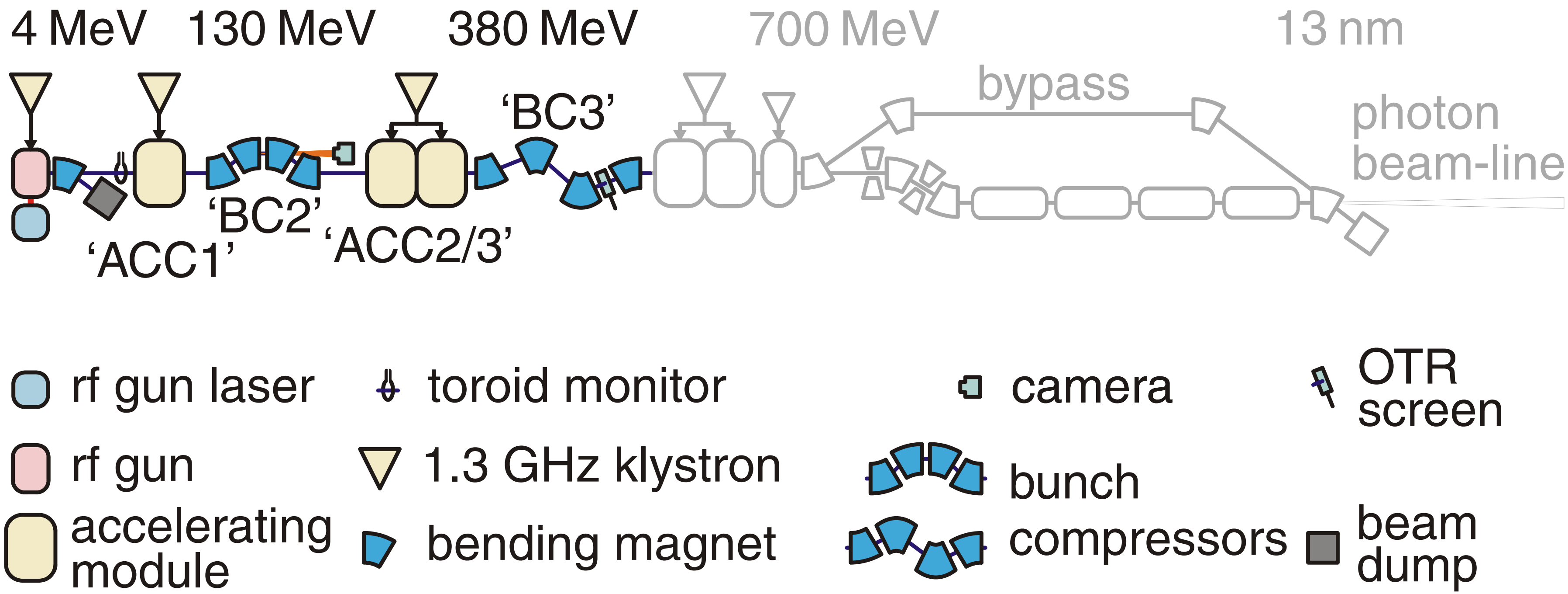
The FLASH objective: SASE between 60 and 13 nm



Major prerequisites for SASE

- 100 fs short bunches obtained by bunch compression for 2 kA peak current
- small beam energy variations

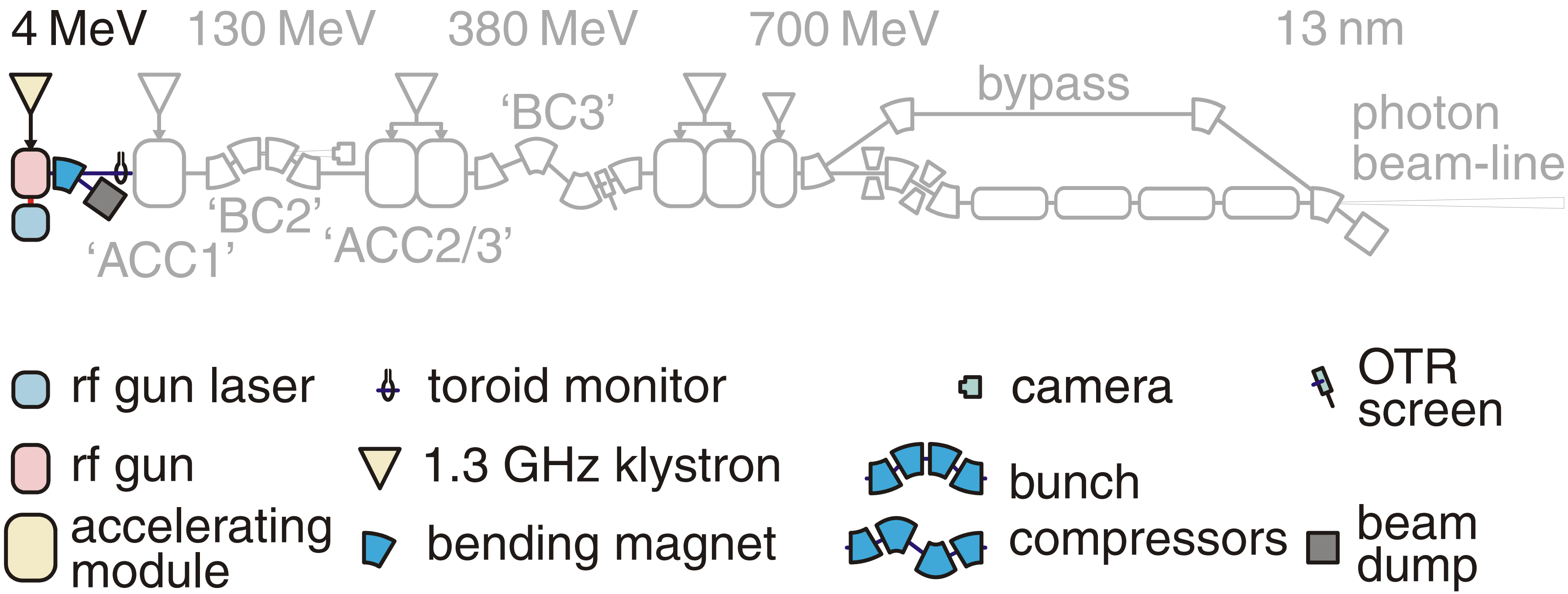
Short bunches are created by the 'FLASH injector'



Bunch compression is **sensitive to** **beam energy variations caused by**

- rf gun laser pulse arrival time variations
- gun rf phase variations
- ACC1 rf amplitude and phase variations
- ACC2/3 rf amplitude variations

The 'source' of the bunches: rf gun laser and rf gun

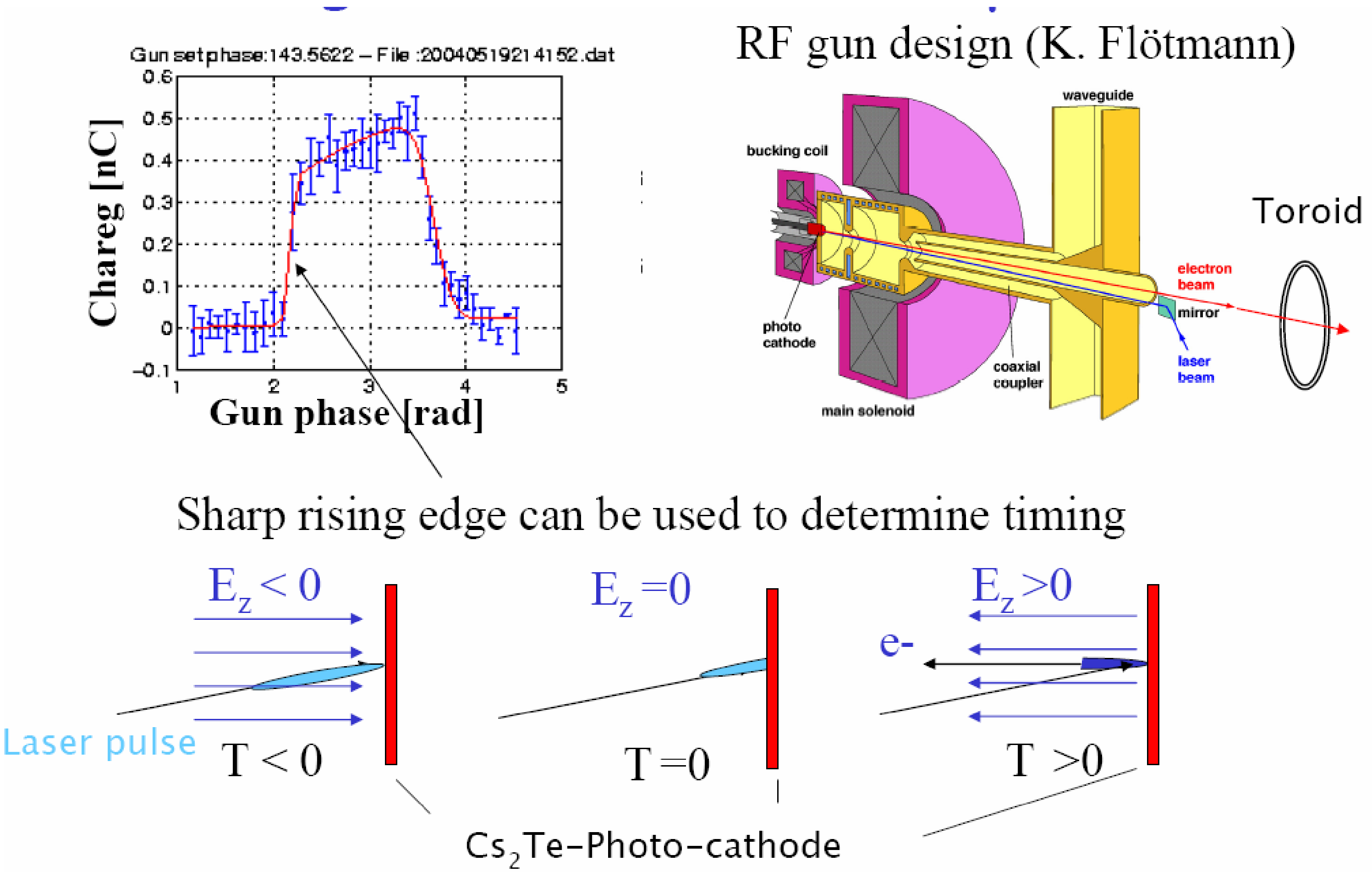


- laser pulses shoot onto the cathode determine the bunch (timing) structure
- a stable gun rf phase is required for minimal arrival time jitter at ACC1
- emission phase measurement with off crest accelerated beam

Emission phase stability measured with beam

Emission phase = phasing between rf gun laser pulses and gun rf

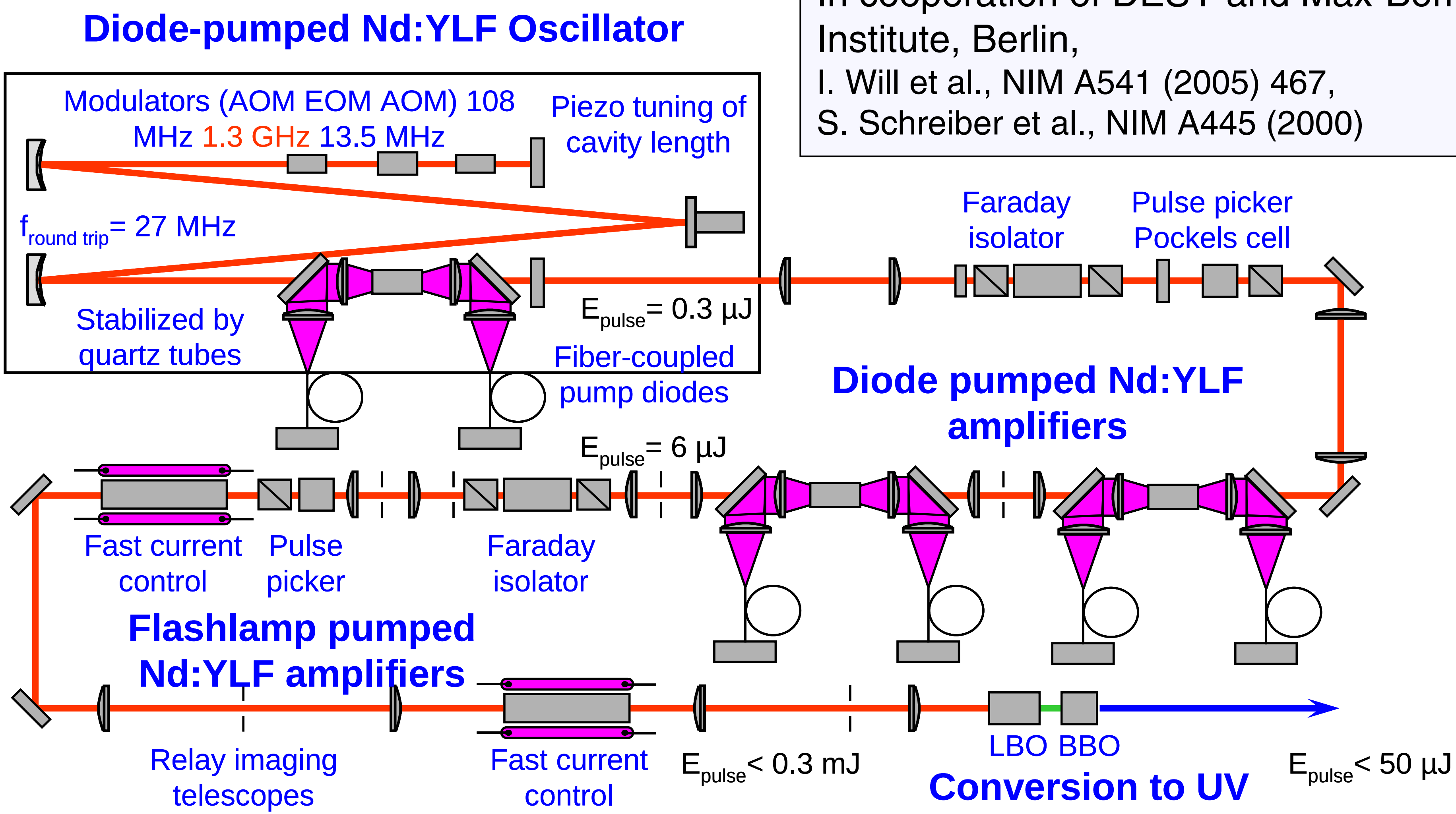
- indirect rf phase measurement
- bunch charge depends on rf phase at 'edge'
- present resolution about ± 0.01° (20 fs)



The laser pulse arrival time AND the gun rf phase affect the emission phase!

Creating the laser pulses

In cooperation of DESY and Max-Born-Institute, Berlin,
I. Will et al., NIM A541 (2005) 467,
S. Schreiber et al., NIM A445 (2000)

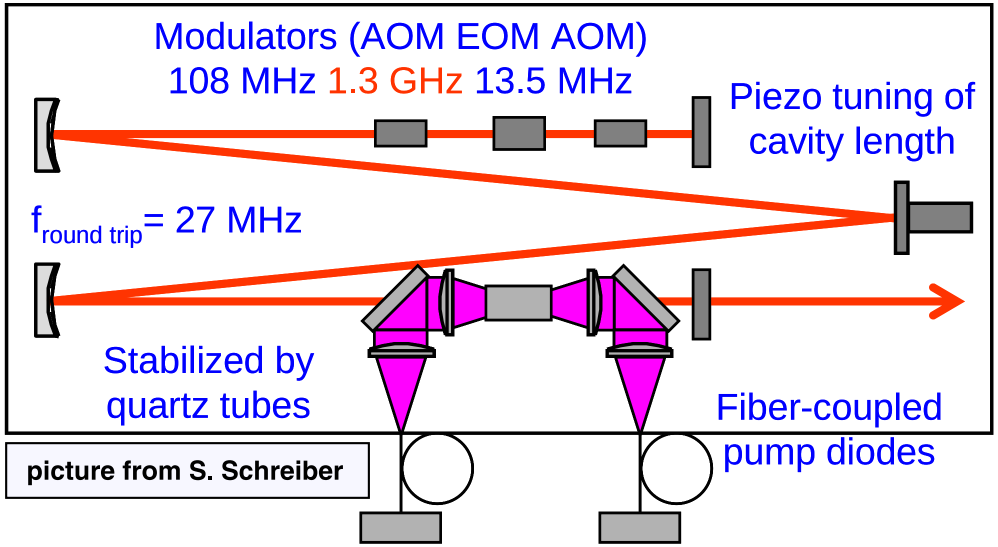


picture from S. Schreiber

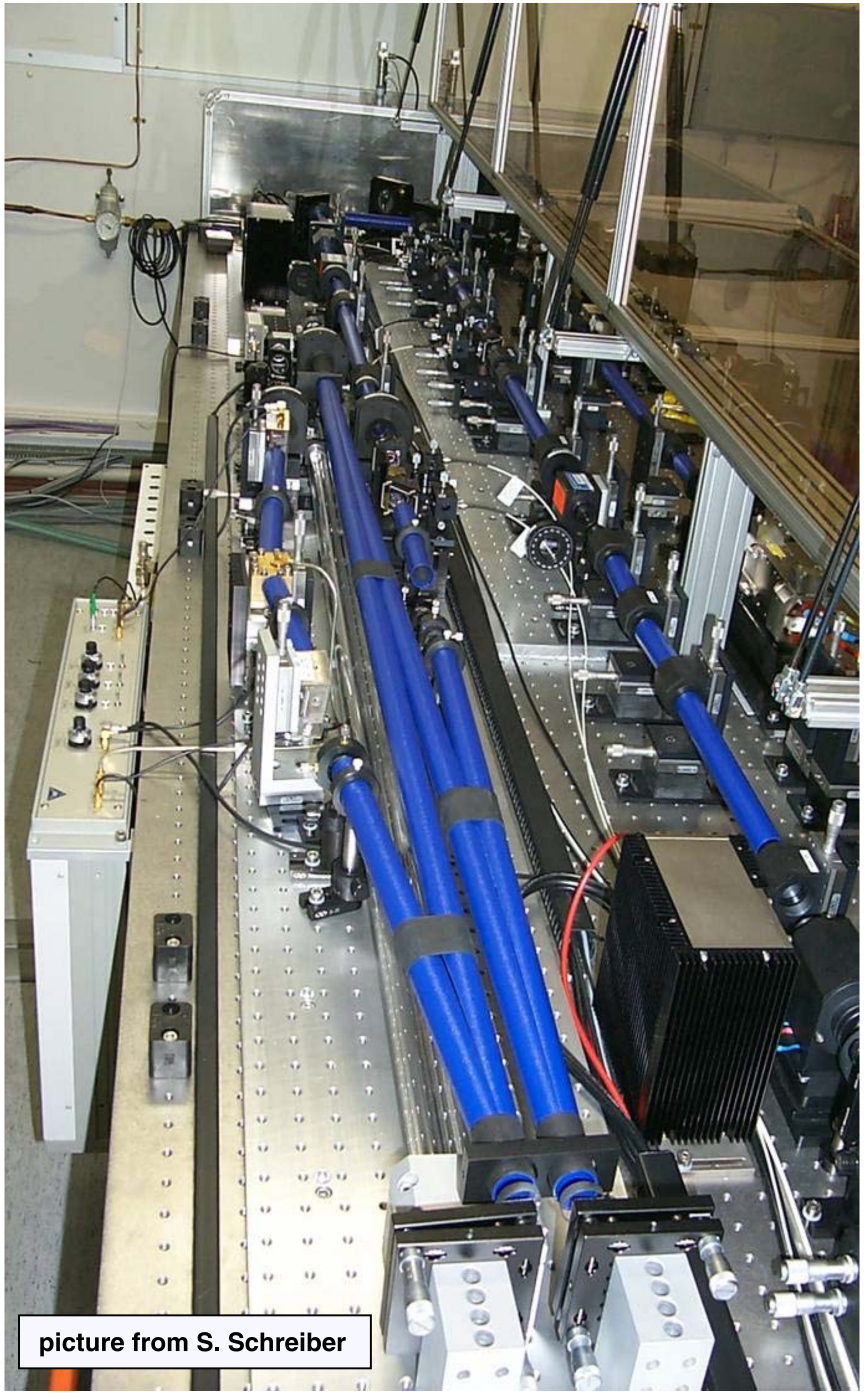
Pulse Train Oscillator (PTO)

The electro optic modulator (EOM)

- composed of 1.3 GHz amplifier and cavity
- potential candidate creating laser pulse arrival time variations (slope)
- well-aimed phase variations of 1.3 GHz master oscillator (MO) signal can correct the arrival time



picture from S. Schreiber

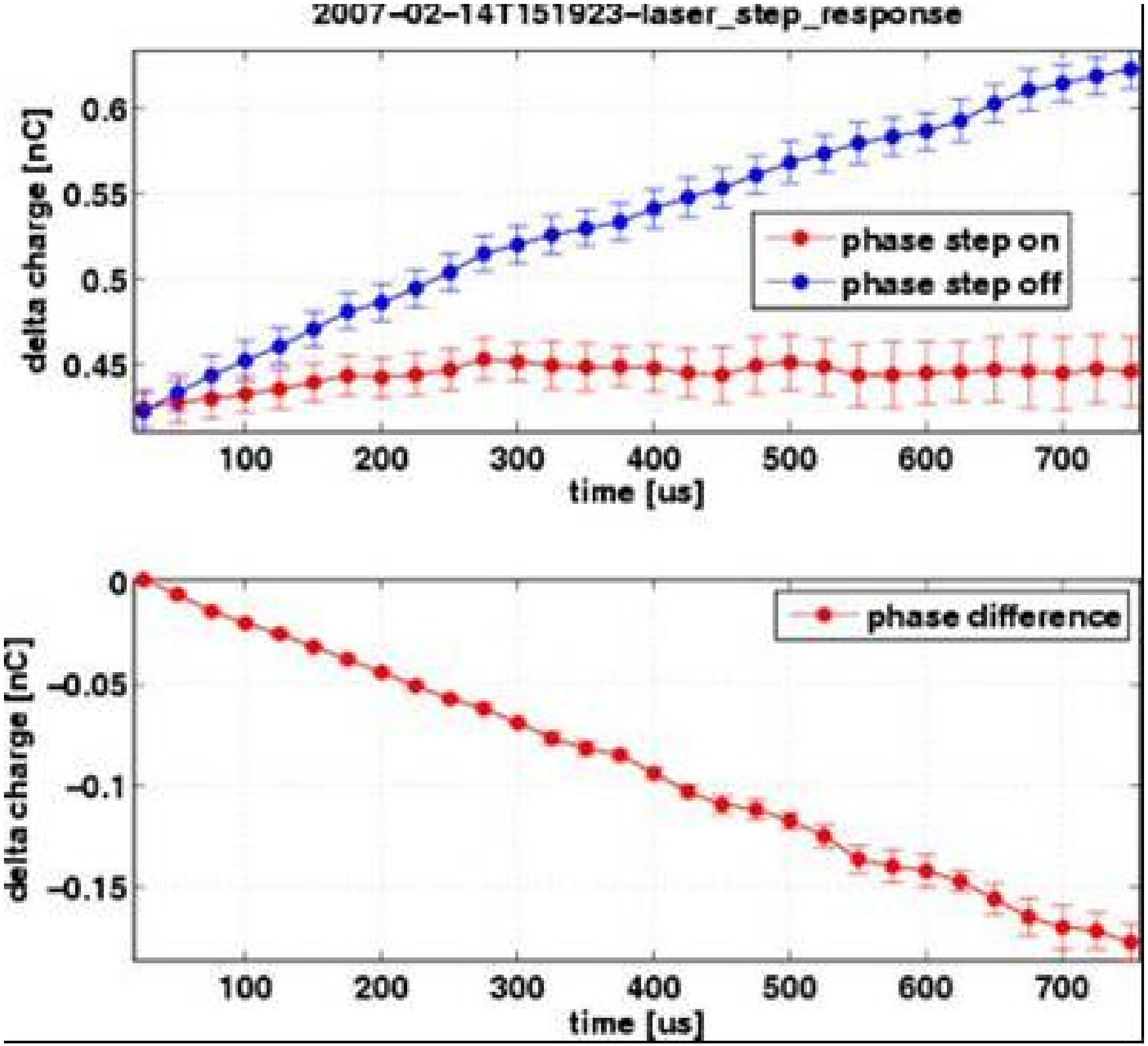


picture from S. Schreiber

Emission phase variation by EOM MO signal manipulation

- we assume no influence of laser amplifier on slope
- we measured the step response of the laser on 1.3 GHz phase changes
- and adapted phase slope onto 1.3GHz of laser: see adjacent picture (not knowing better!)

➢ **What's about the gun rf?**

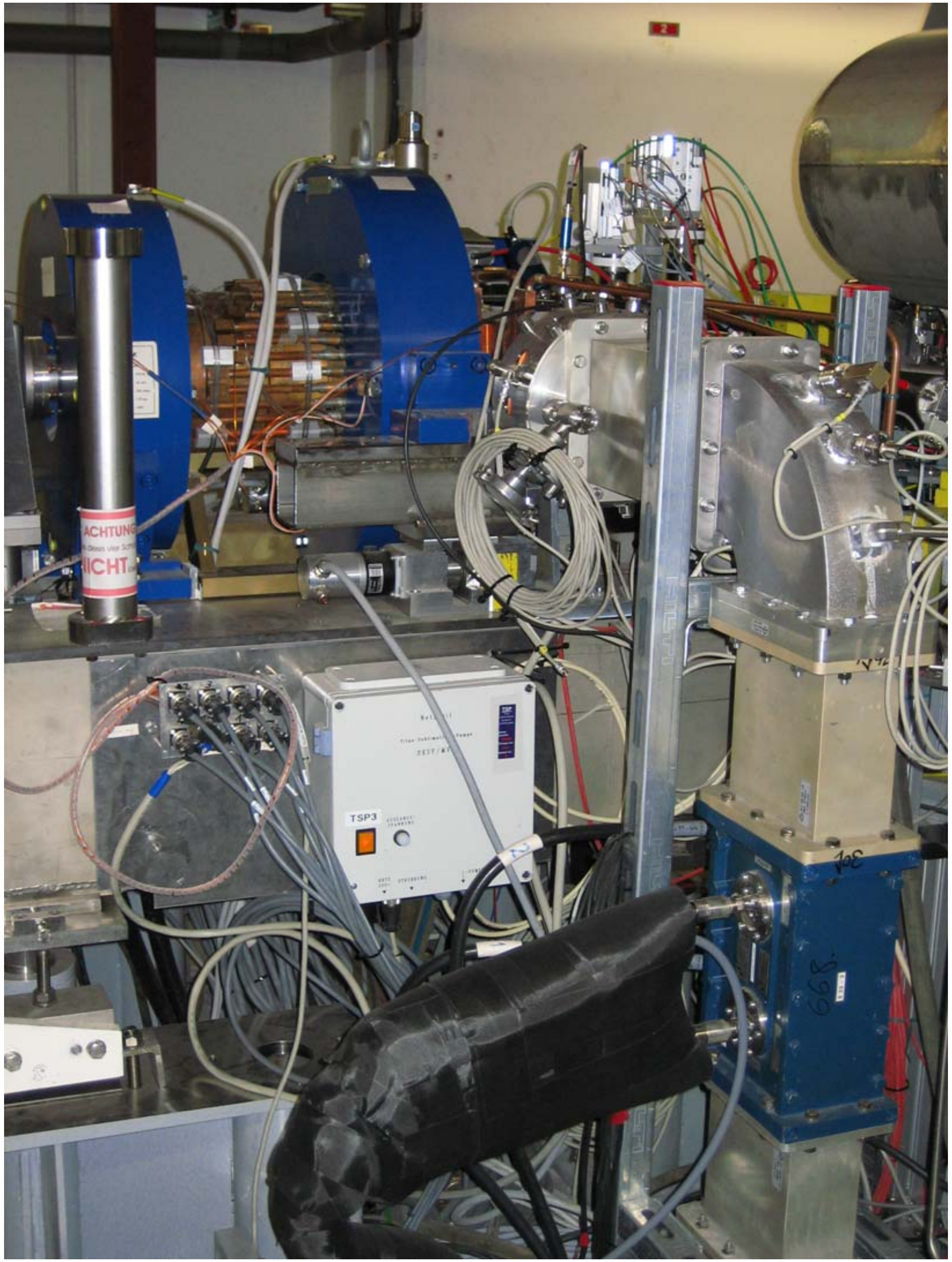


FLASH rf gun

- filling time: typical 55 µs
- flat top time: up to 800 µs
- pulse repetition: up to 5 Hz
- high RF field: 40 MV/m

Perfect rf field symmetry, no sparks and easier cooling by

- no rf probe
- no mechanical tuner
- via the temperature the frequency is controlled (0.1 deg Celsius corresponds to 2.1 deg in RF phase)



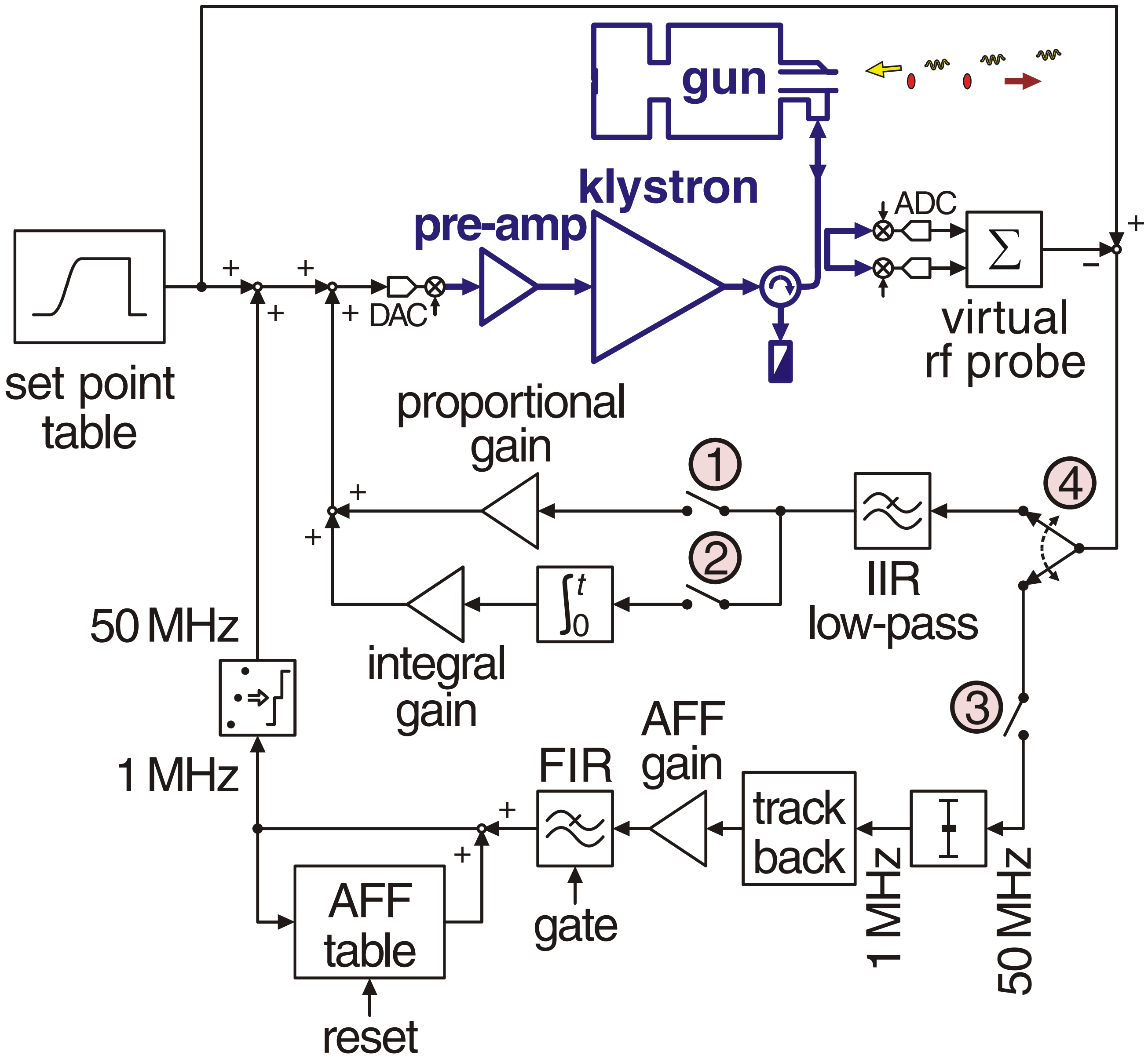
Rf control by SimCon 3.1 and sophisticated algorithms

Implications of missing probe:

- calculation of probe form forward and reflected rf
- calibration and linearization is an issue

Algorithms:

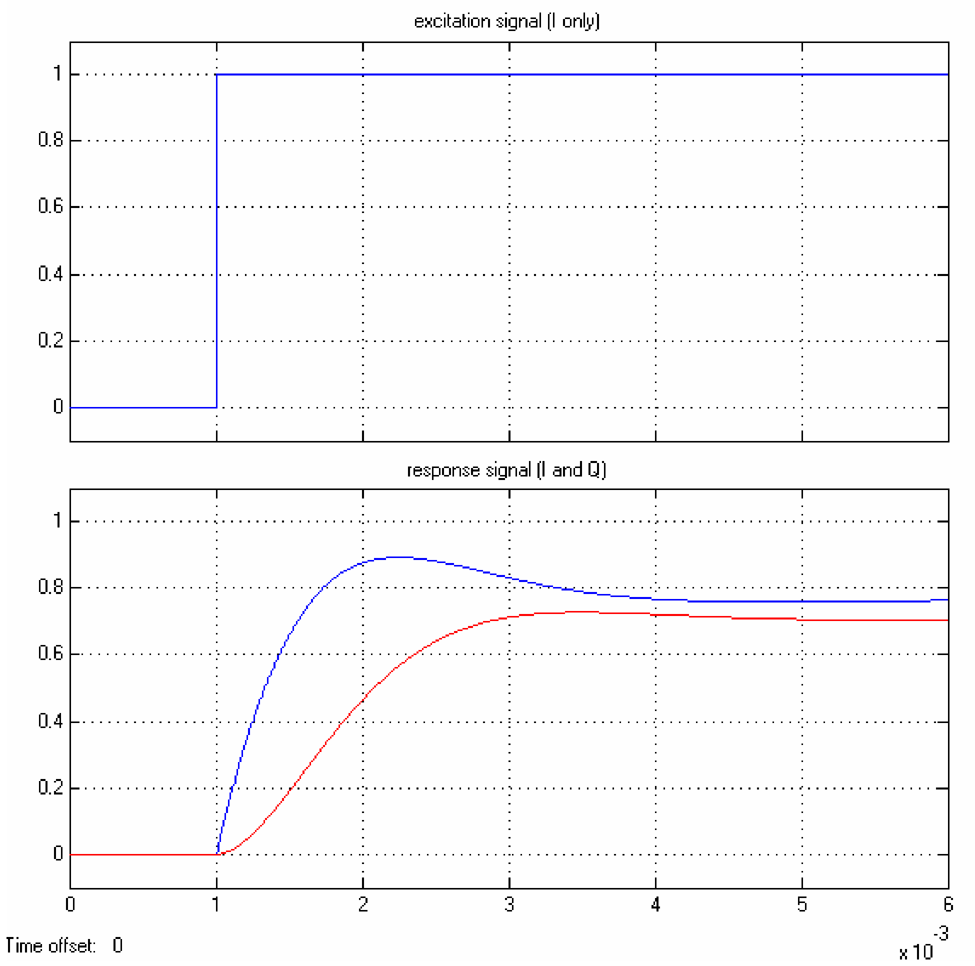
- P(I) control with recursive 20 kHz low-pass (IIR) for stability at 'high' gain (>5)
- Adaptive feed forward (AFF) from rf pulse to rf pulse



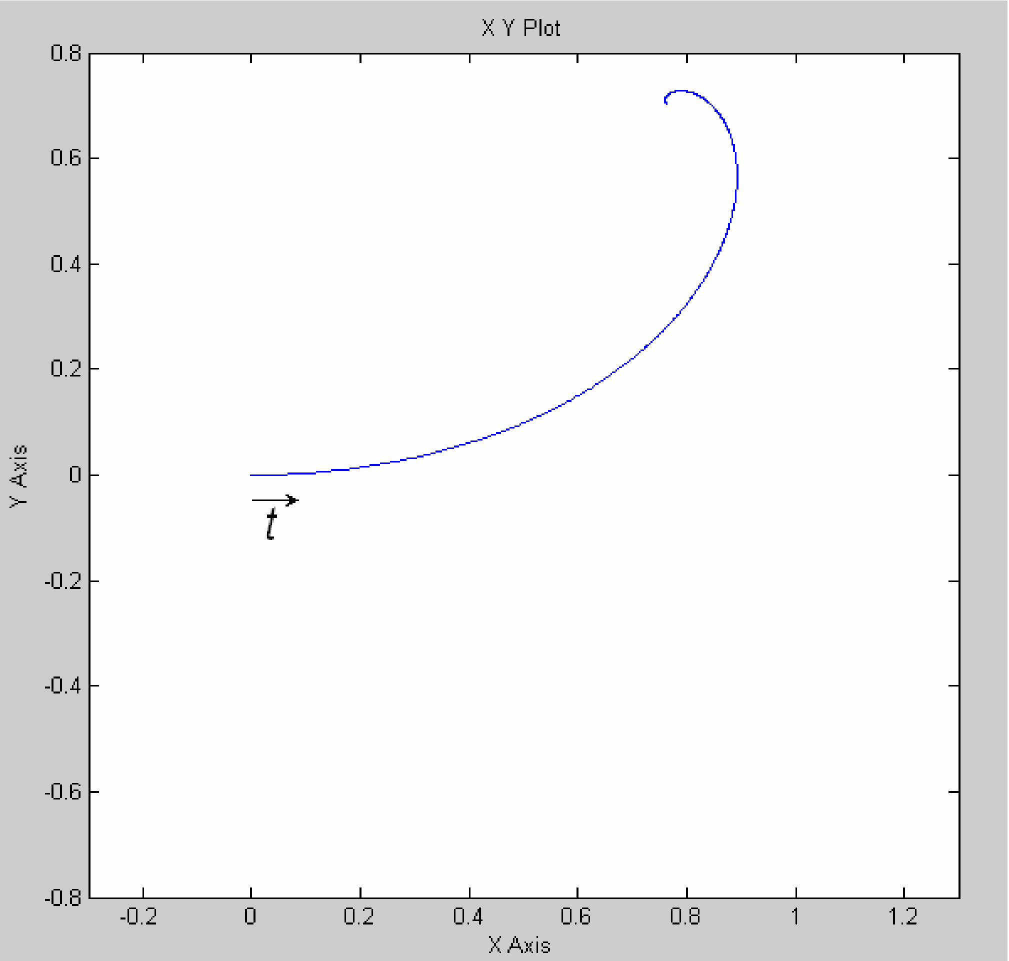
Calibration of virtual probe signal & phase determination

- non zero (loop) phase leads to an unwanted mixture of I and Q
- applying a step function (I only) and recording the response (example for $\Delta f = 200\,\mathrm{Hz}$)

excitation & response in time domain



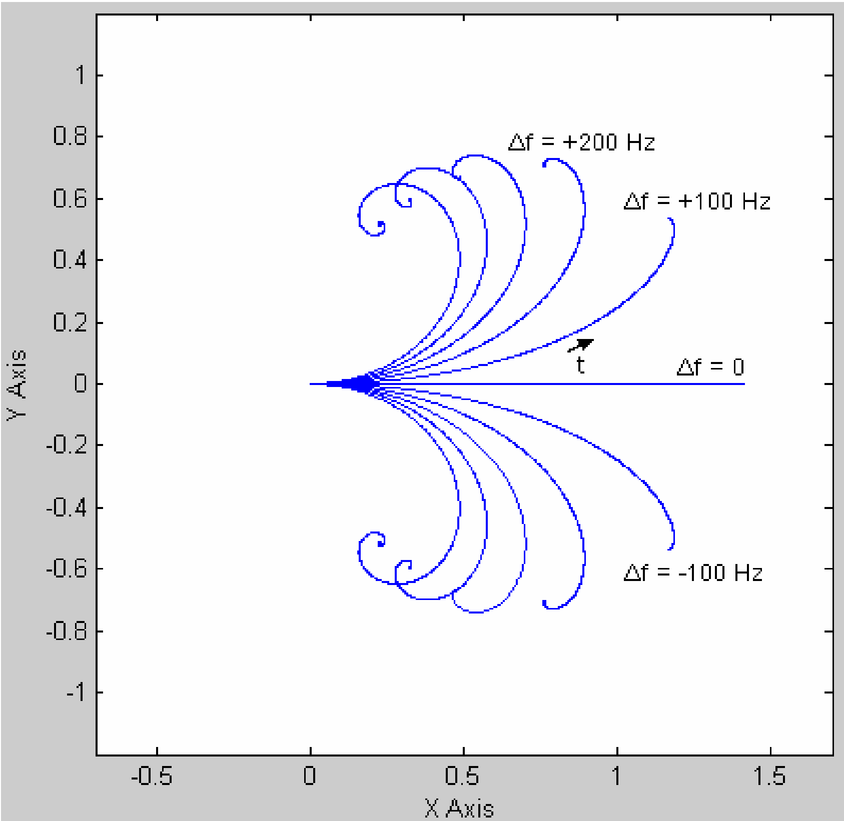
response plotted in IQ plane



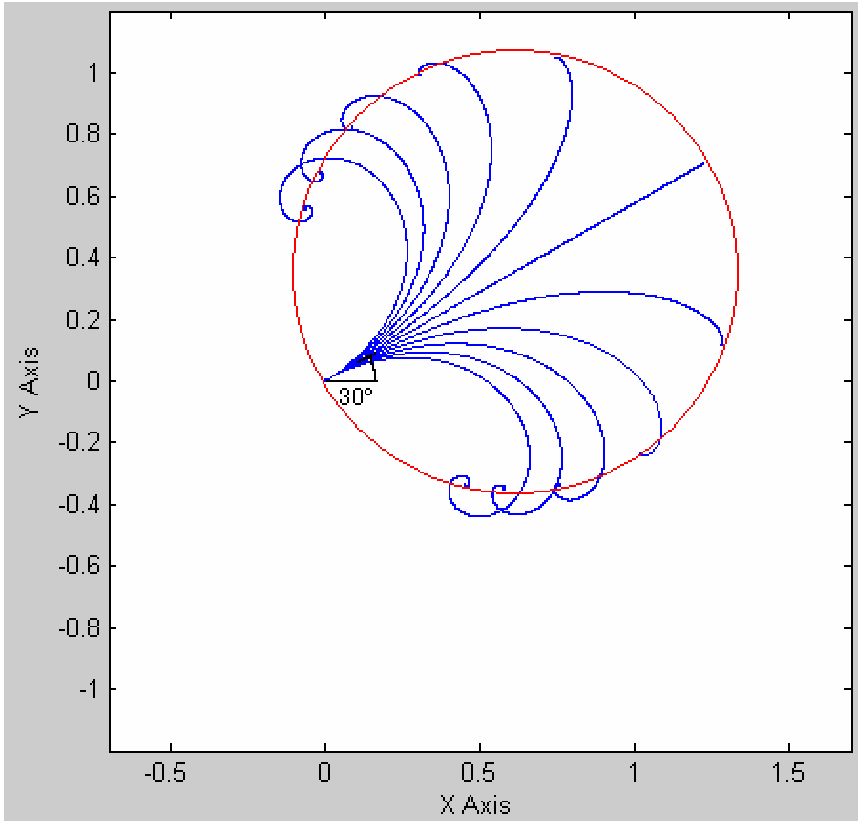
Spiral like cavity response

- the initial angle gives the loop phase
- final IQ values for different tuning describe a circle
- Alexander Brandts loop phase calibration method is based on 'circle fitting'

cavity response for loop phase zero



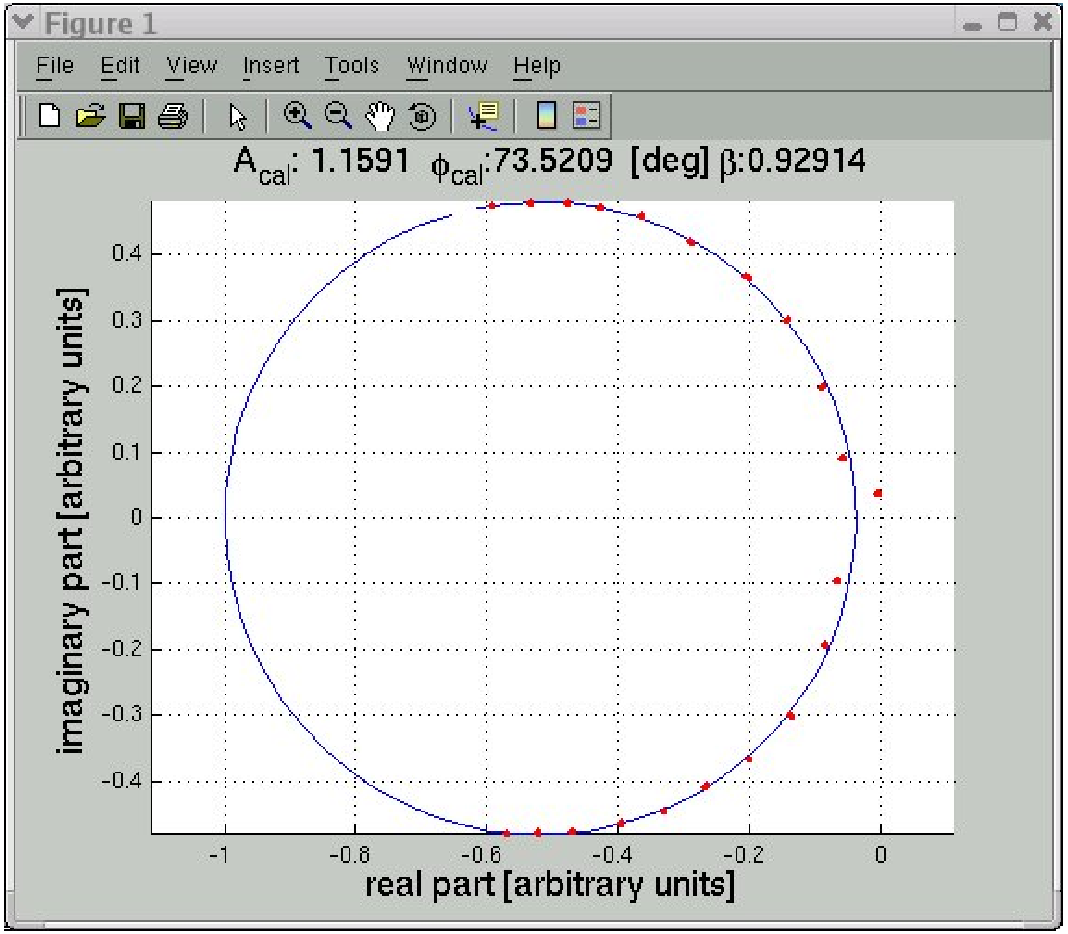
cavity response for (loop) phase 30°



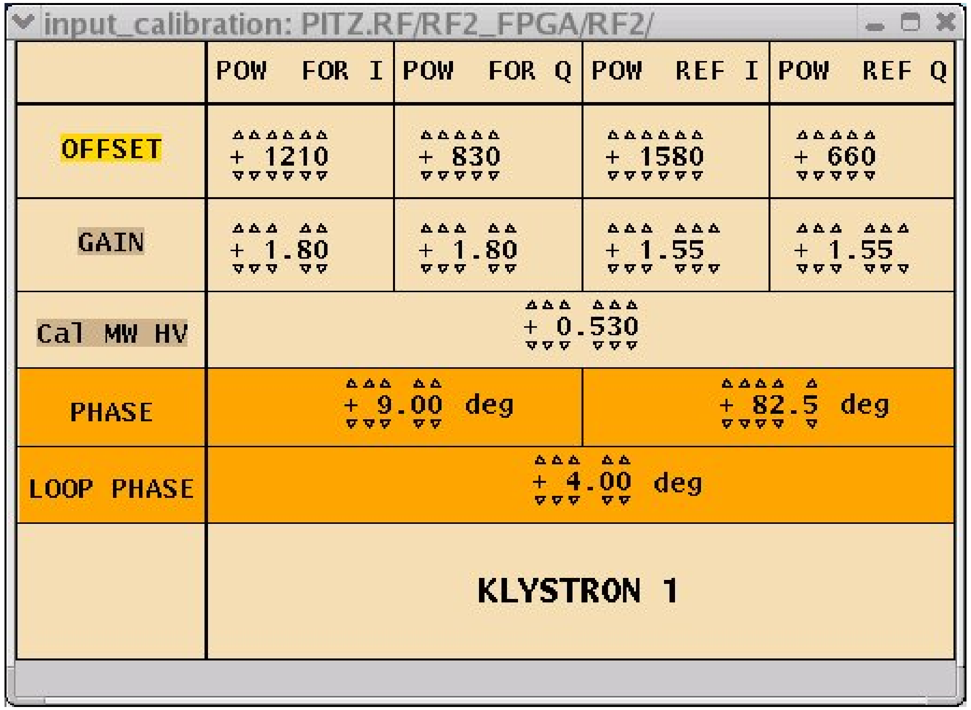
Plots for the sc 1.3 GHz TESLA cavities, the RF gun behaves similar!

Virtual probe signal calibration (method established at FLASH by A. Brandt)

circle fitting after frequency variation



DOOCS panel for calibration parameters



Plots taken at PITZ – the plots and panels look similar at FLASH!

Nonlinearity compensation of virtual probe signal

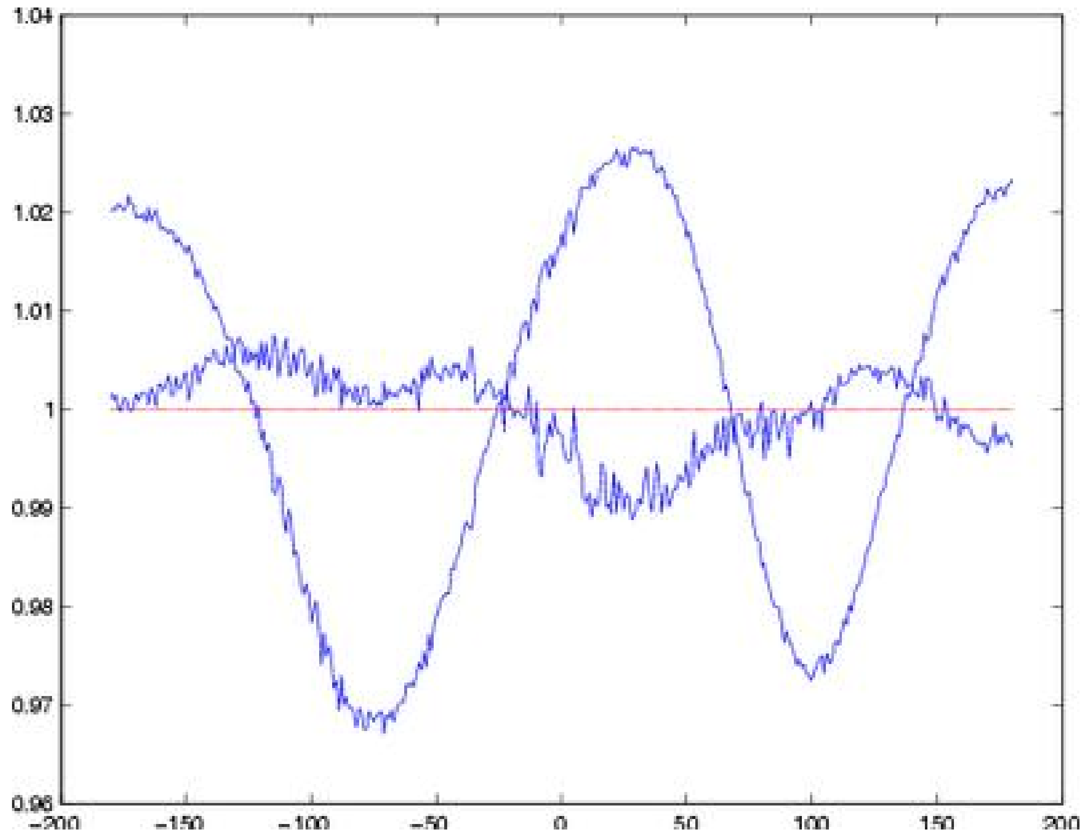
Problem:

- IQ detectors are not perfect
- rf phase changes lead to amplitude changes
- amplitude changes lead to heat load changes within gun and as a consequence within the circulator
- this causes reflected power interlocks at the klystron
- time consuming restart for getting gun temperature equilibrium

Countermeasure:

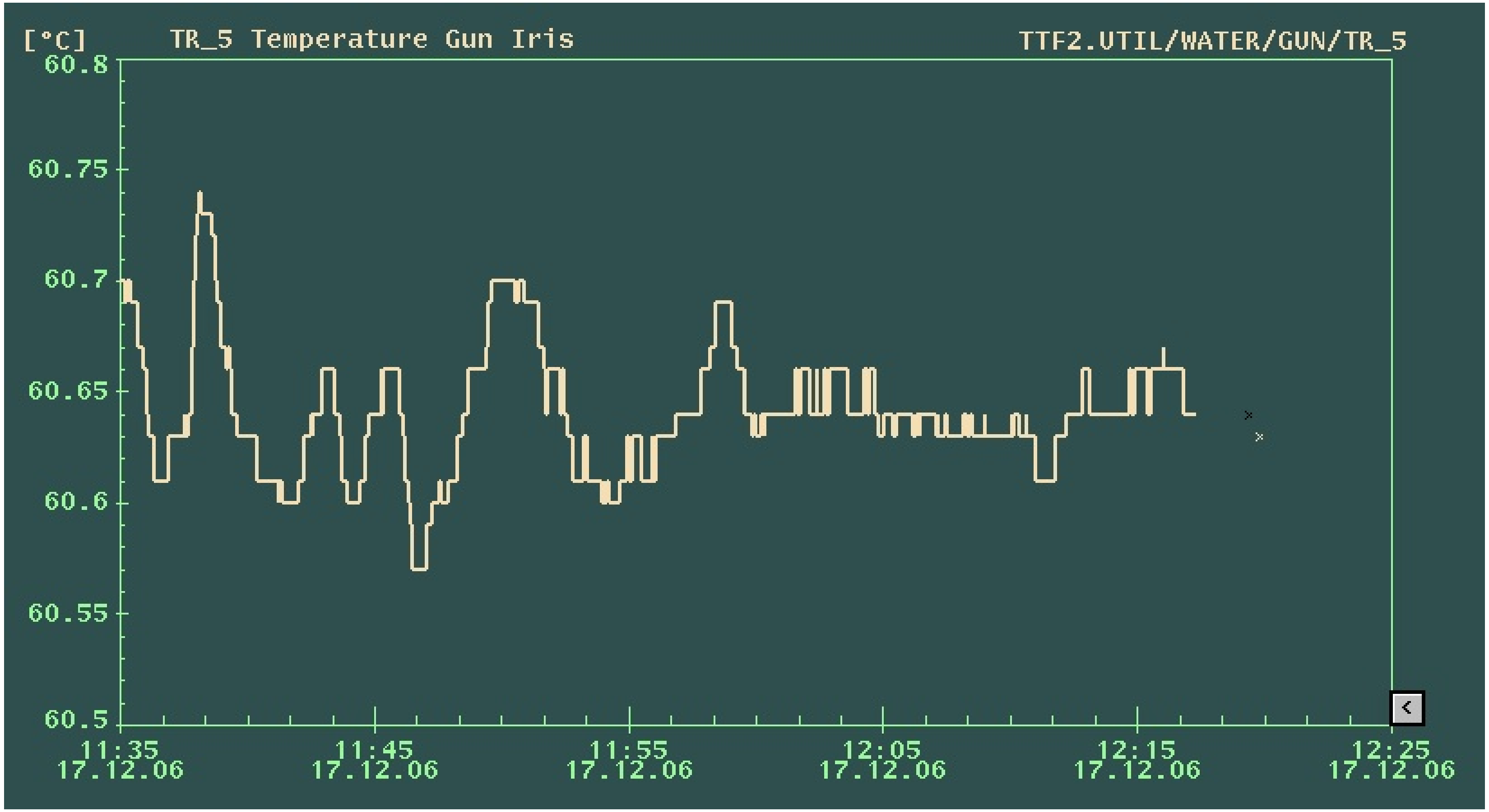
- linearization of virtual probe signal by an algorithm

RF phase scan amplitude response before and after the linearization :



No longer heat load changes caused by rf phase changes

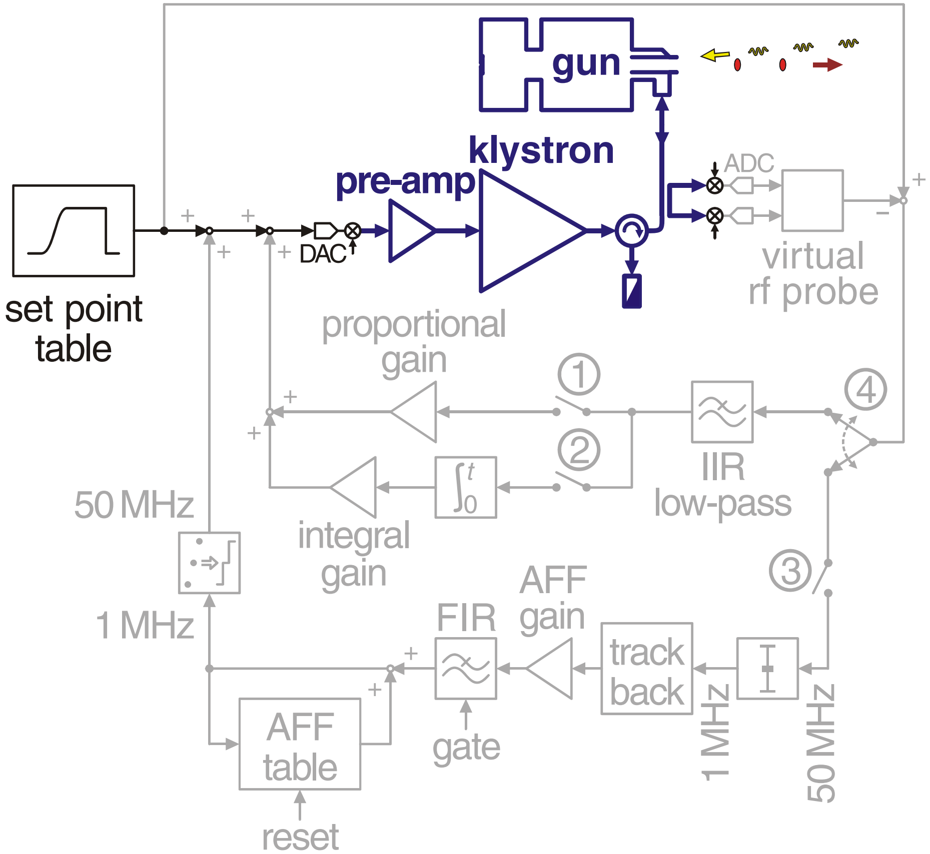
RF gun temperature changes while scanning the rf phase:



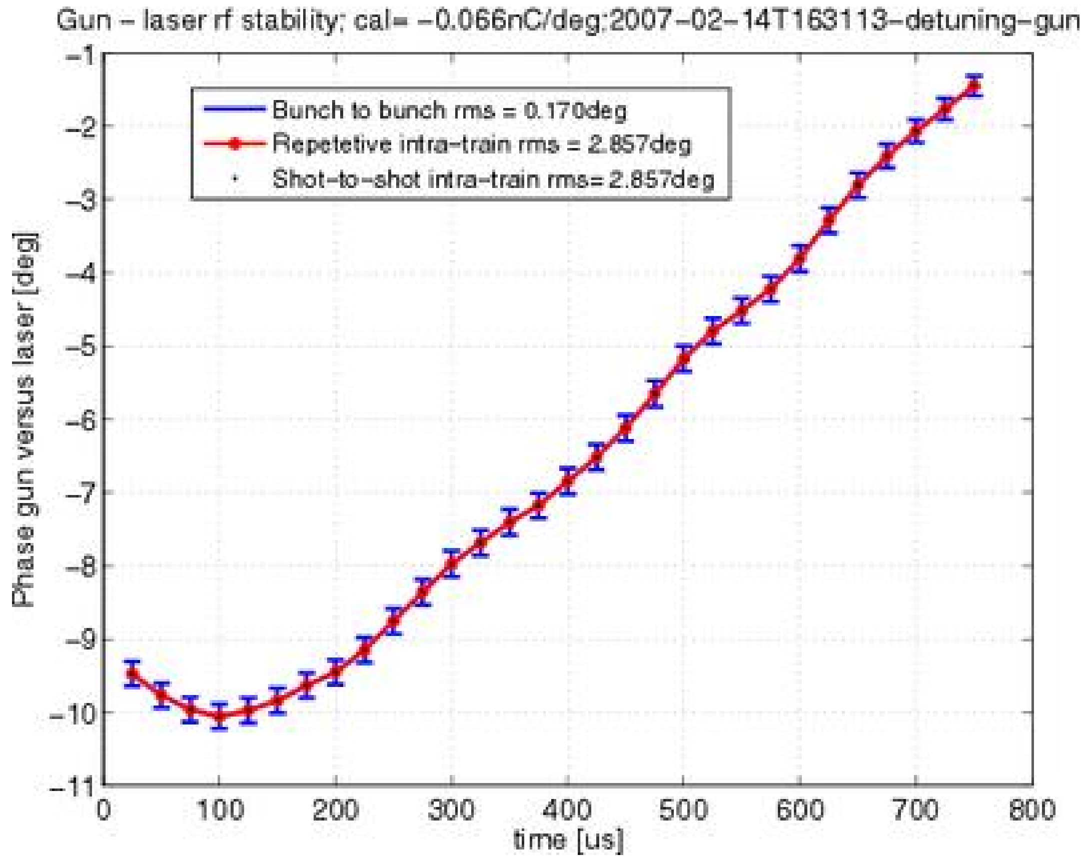
before the compensation

after some iterations to obtain the compensation parameters

Action of control loops - the case without control



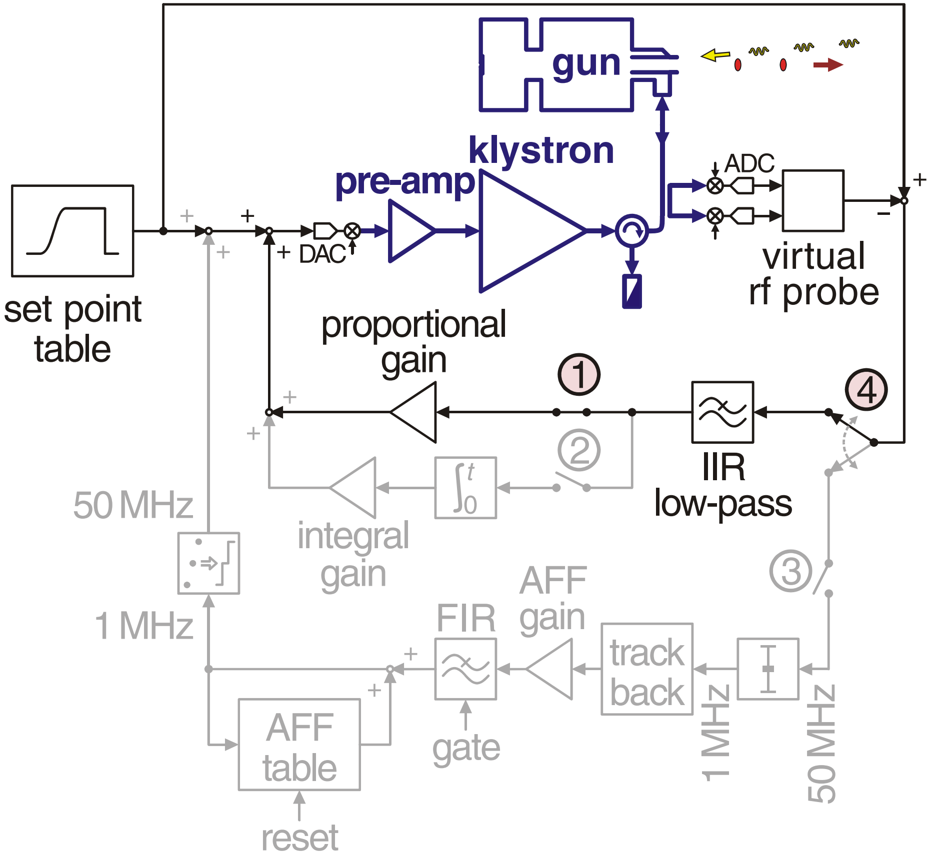
Beam based emission phase measurement:



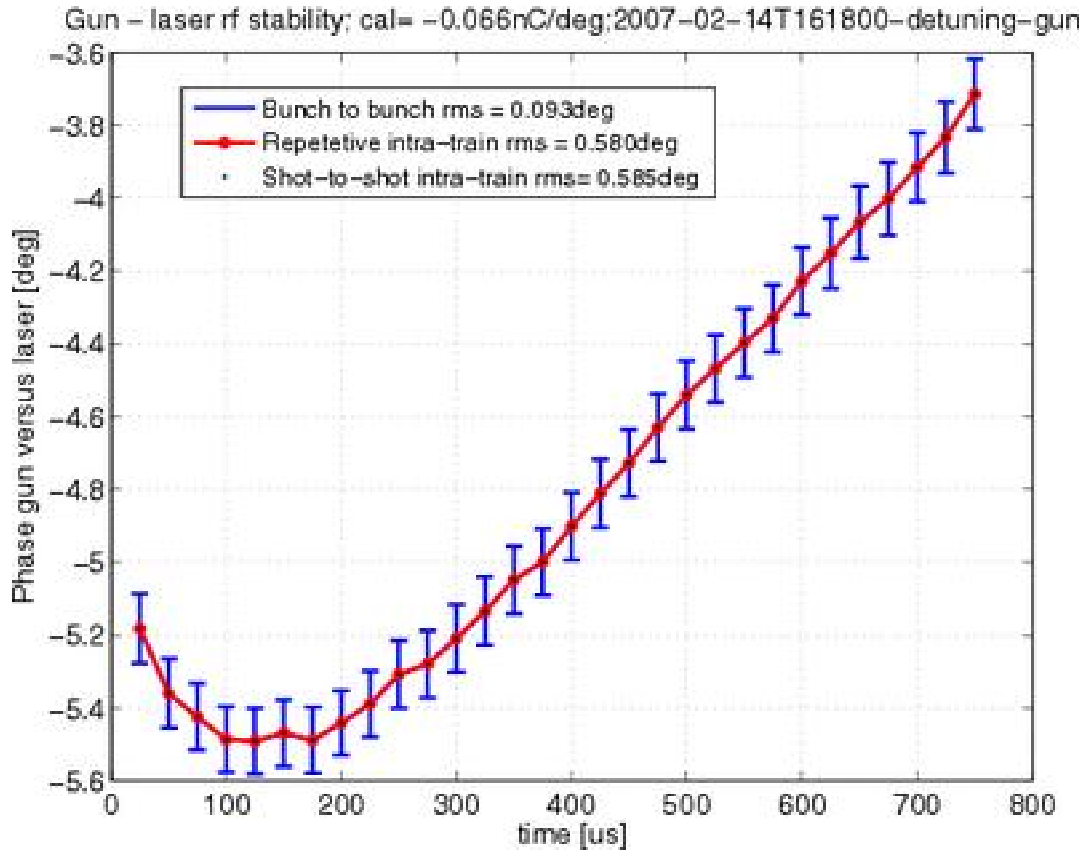
- gun heats up within rf pulse
- gun resonance frequency changes

➢ **the emission phase changes by 8.5°**

The case with P control only



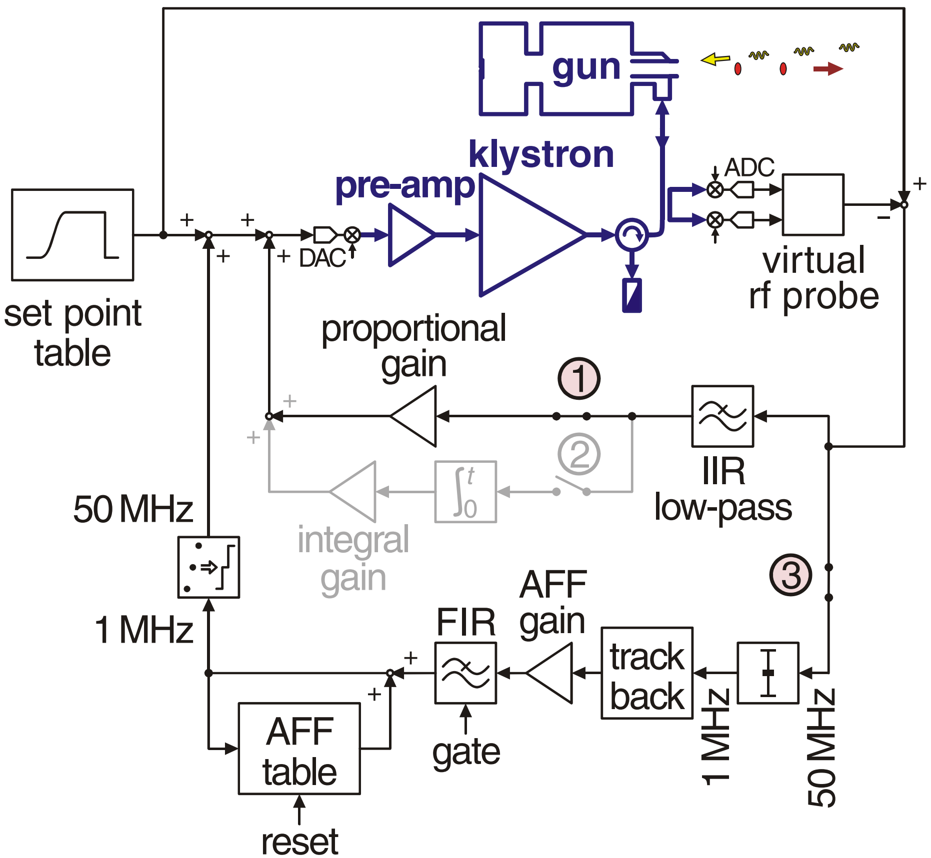
Beam based emission phase measurement:



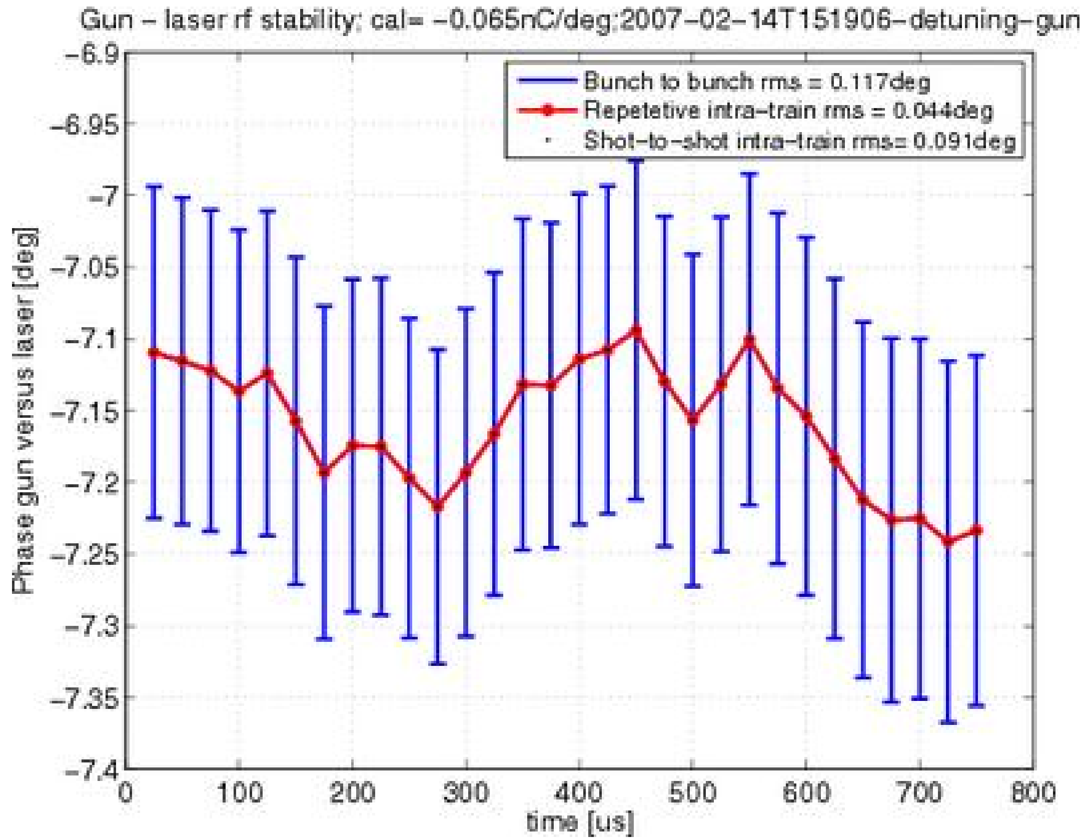
- proportional control with gain 4
- emission phase change suppressed

➢ **the emission phase changes by 1.7°**

Case with P control and adaptive feed forward (AFF)



Beam based emission phase measurement:

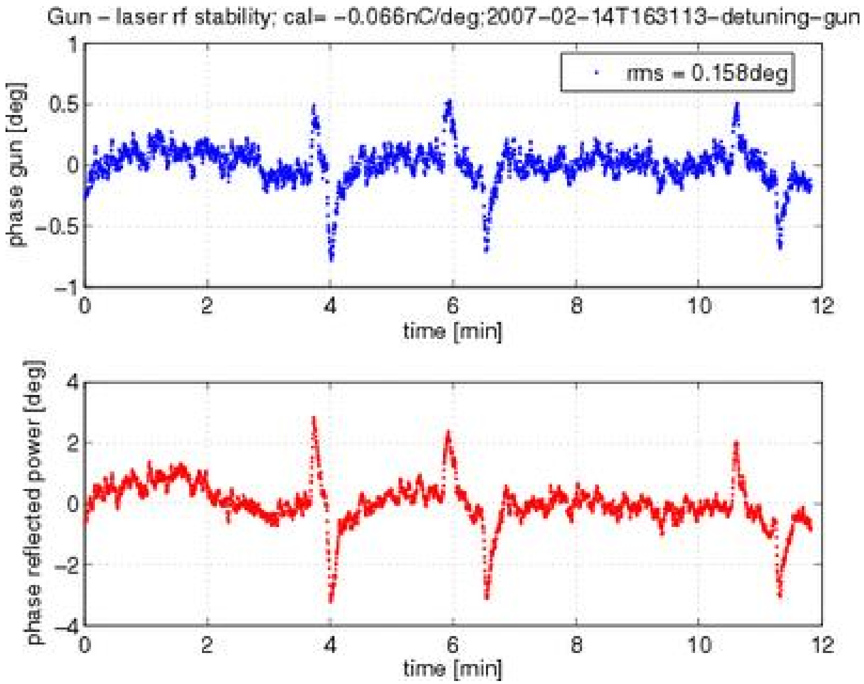


- AFF corrects systematic errors
- AFF gain of 0.4

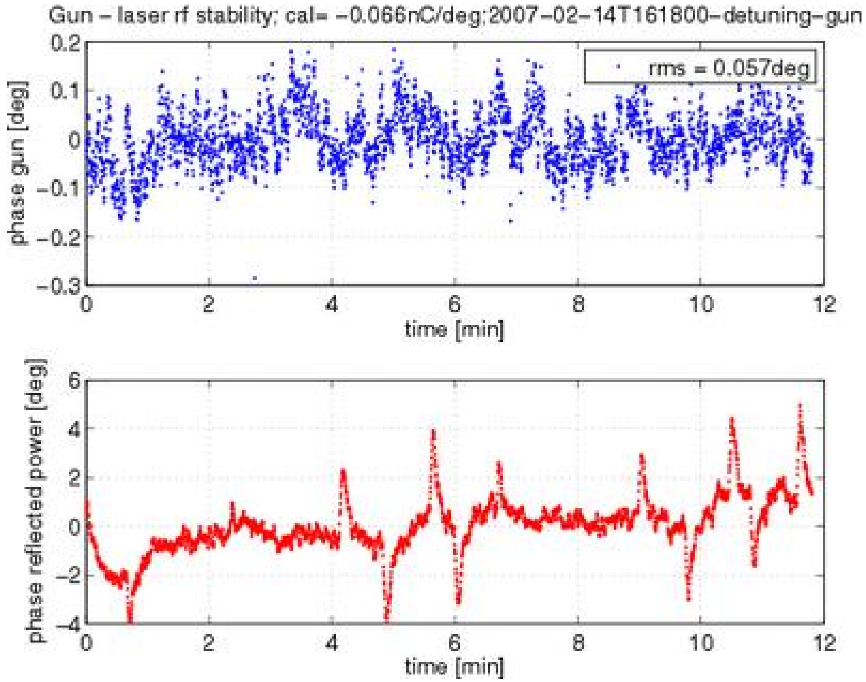
➢ the emission phase changes by 0.14°

Long term stability

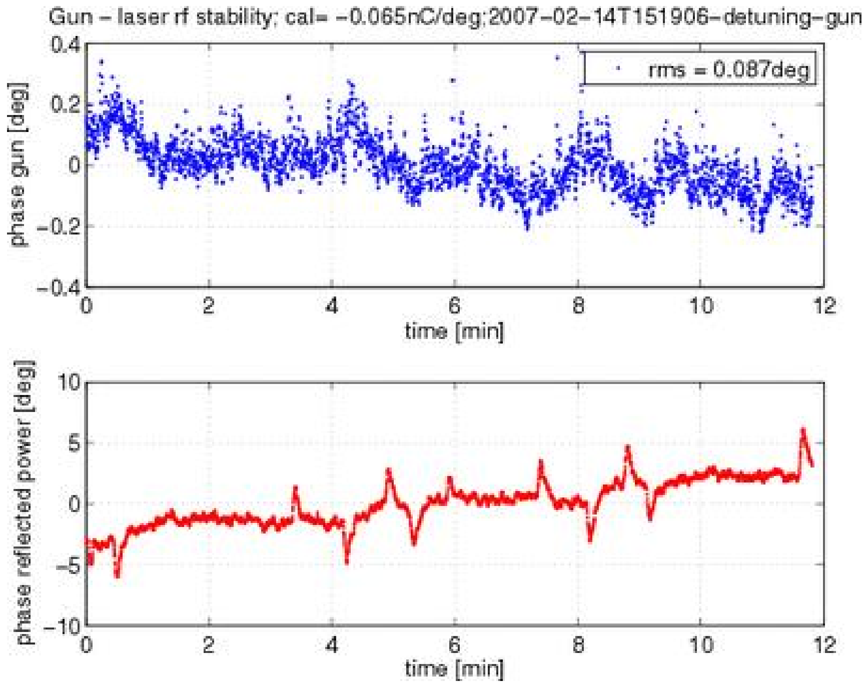
(1)



(2)



(3)



Observed emission phase stability:

(1) RF drive only: peak-to-peak 1.3°

(2) P control only: peak-to-peak 0.4°

(3) P and AFF control: peak-to-peak 0.4°

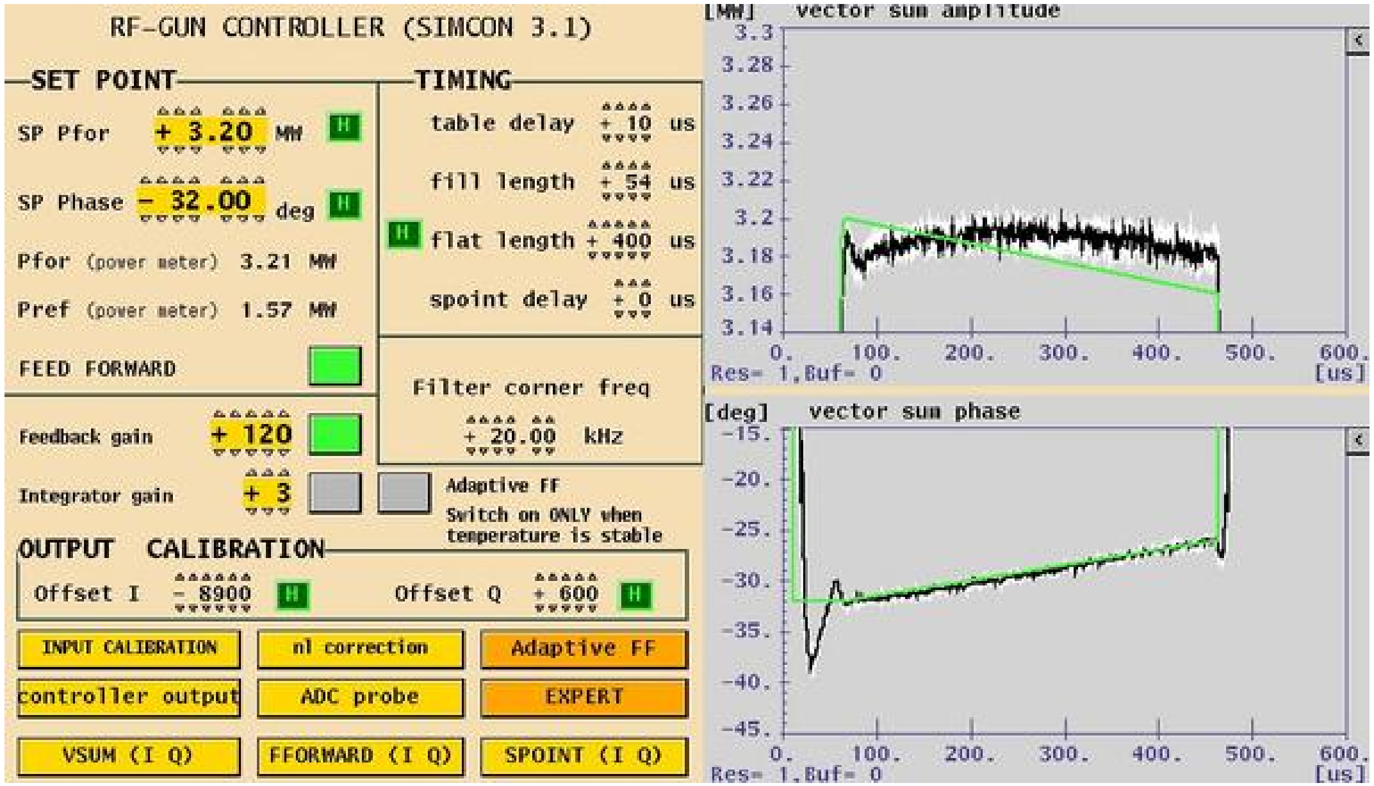
The gun rf phase slope feature

Potential sources of emission phase slopes:

- uncertainties in probe calibration
- gun laser pulse arrival time changes
- drifts due to wave guide heating (distance between directional coupler and gun)
- and so on…

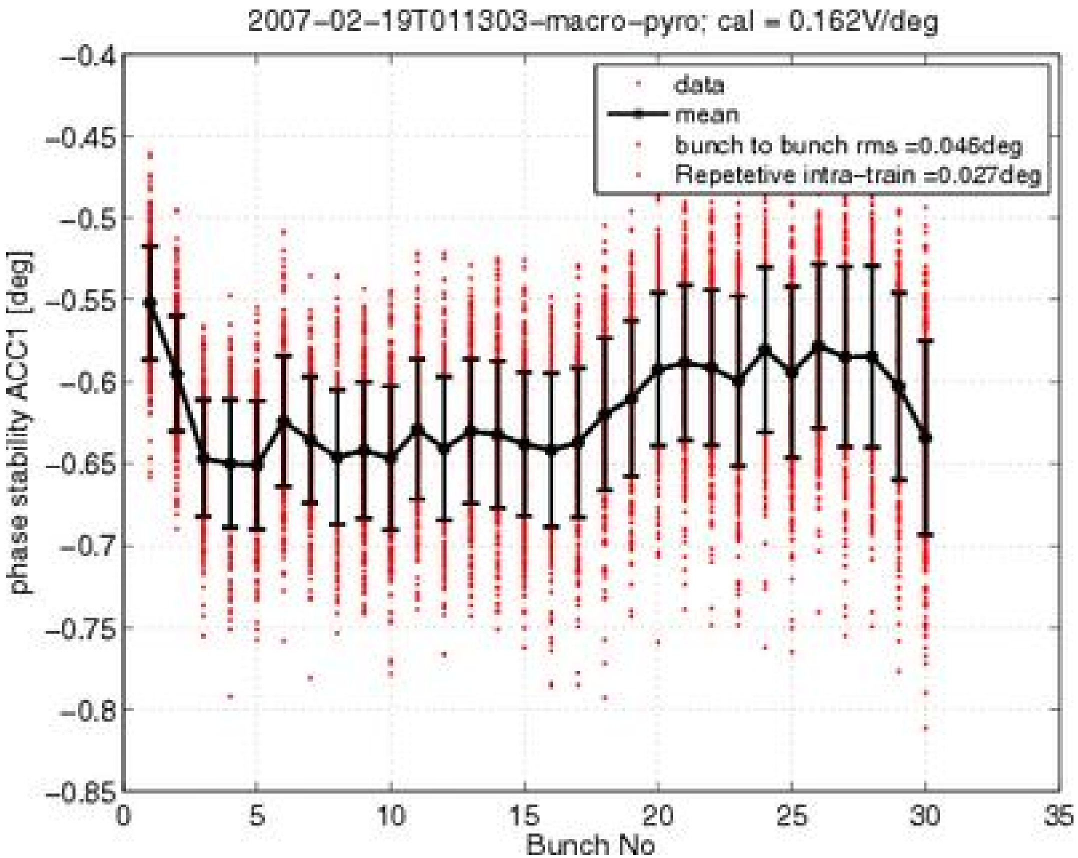
Countermeasures:

- slope at gun laser arrival time changing 1.3 GHz MO EOM phase
- phase slope at gun rf:



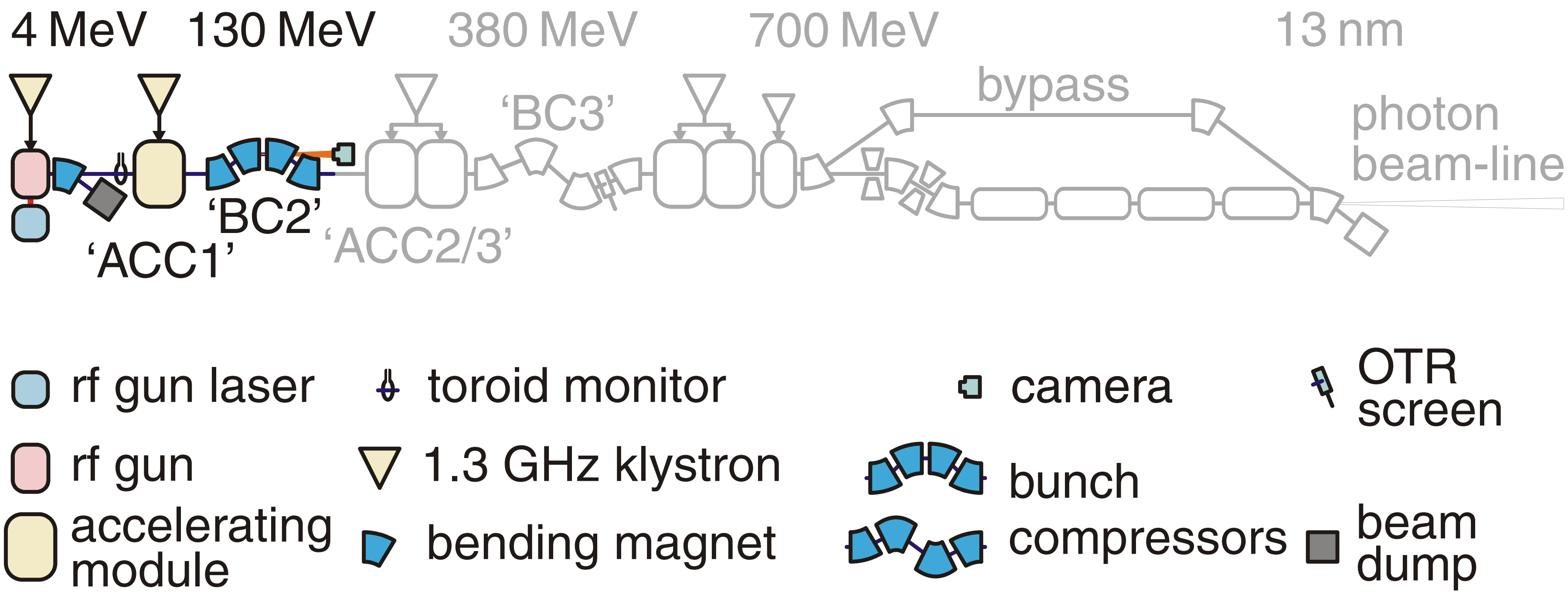
Which 'slope' to use at the gun?

According to measurements at BC2, applying a combination of both slopes (gun laser arrival time and gun rf phase) results in the most stable beam!



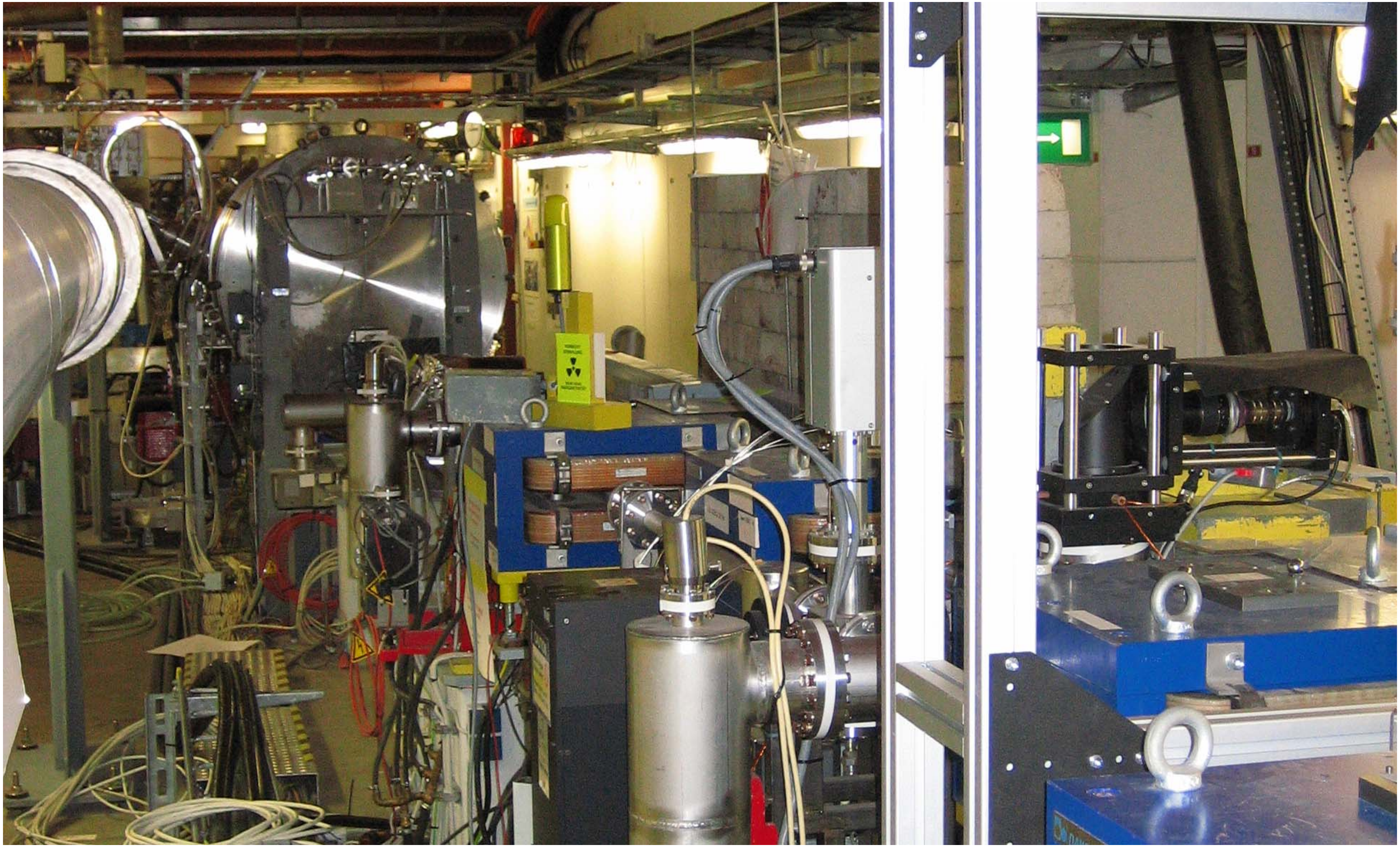
➢ **Let's go to ACC1 and beam stability measurements at BC2…**

Accelerating the bunches up to 130 MeV



- beam stability measurement via synchrotron light monitor in BC2
- beam energy in BC2 dominated by ACC1 energy gain (only 3% from gun)
- beam energy stability measured in BC2 yields upper limit for ACC1 rf stability

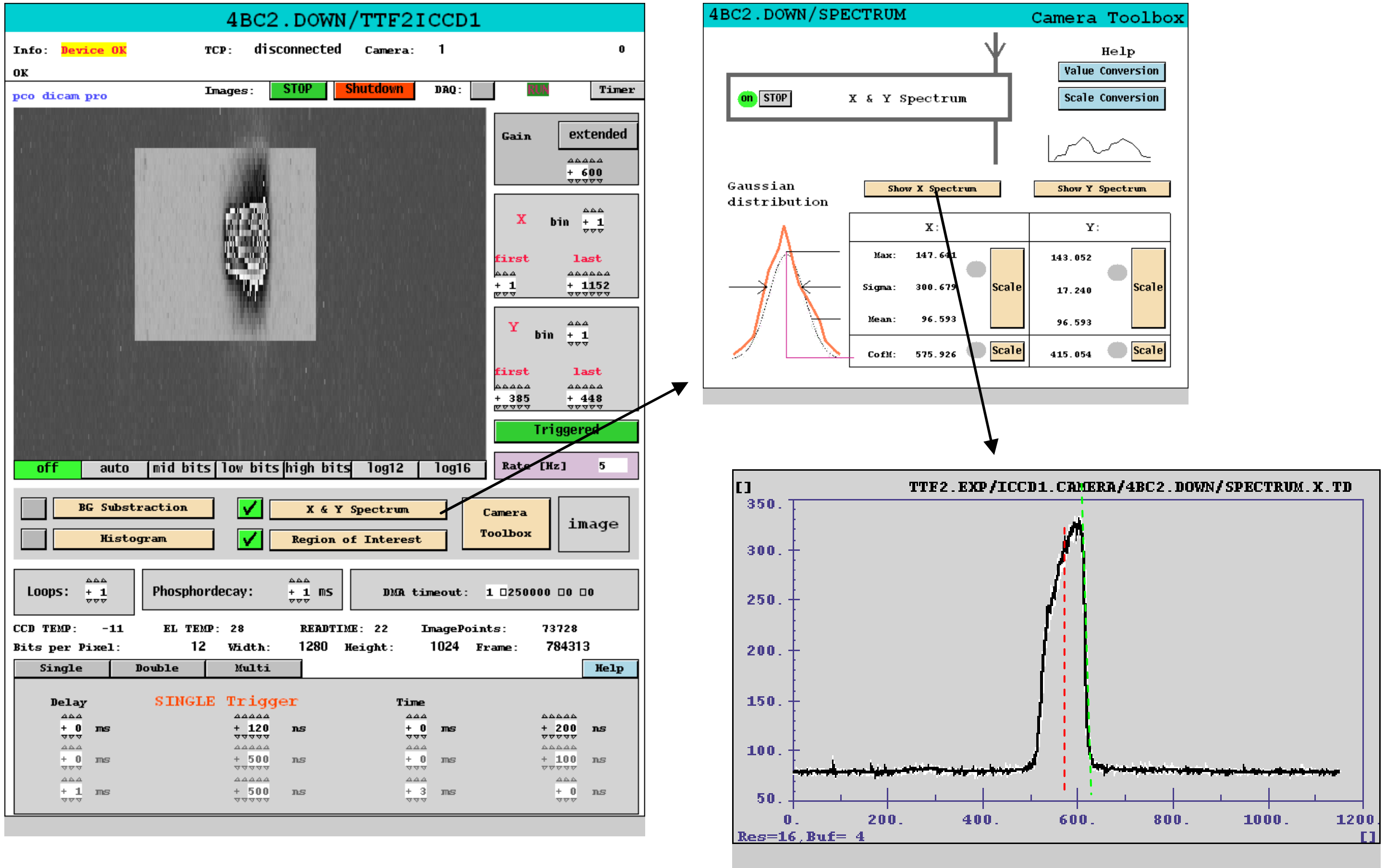
To make the material less monotonous: picture of ACC1 and BC2



Beam energy determined by synchrotron light spot at BC2

Fitting methods:

- Fit 1: slope at head
  → gives information on rf amplitude
- Fit 2: Gaussian fit to profile
  → information on rf amplitude and rf phase



Resolution:

- $\Delta E/E = 10^{-4}$

ACC1 rf control:
P control with beam based beam loading compensation

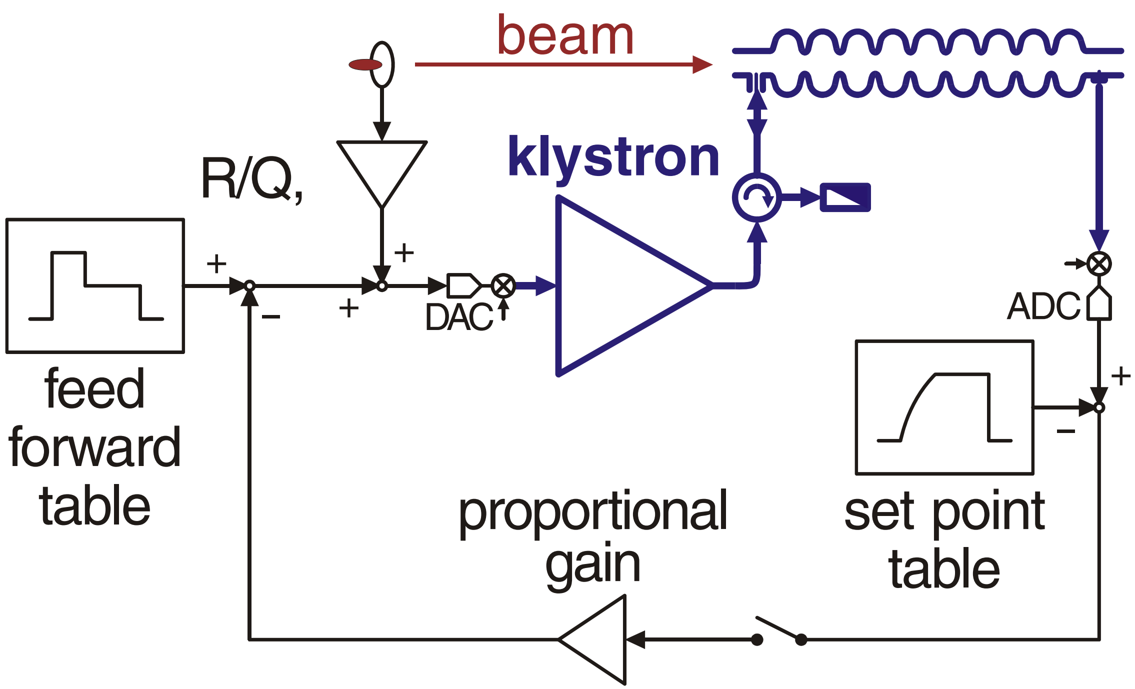
Problem:

- cavity with fast proportional (P) RF control corrects after 20 µs
- first 20 bunches suffer
- correction within 2 bunches required

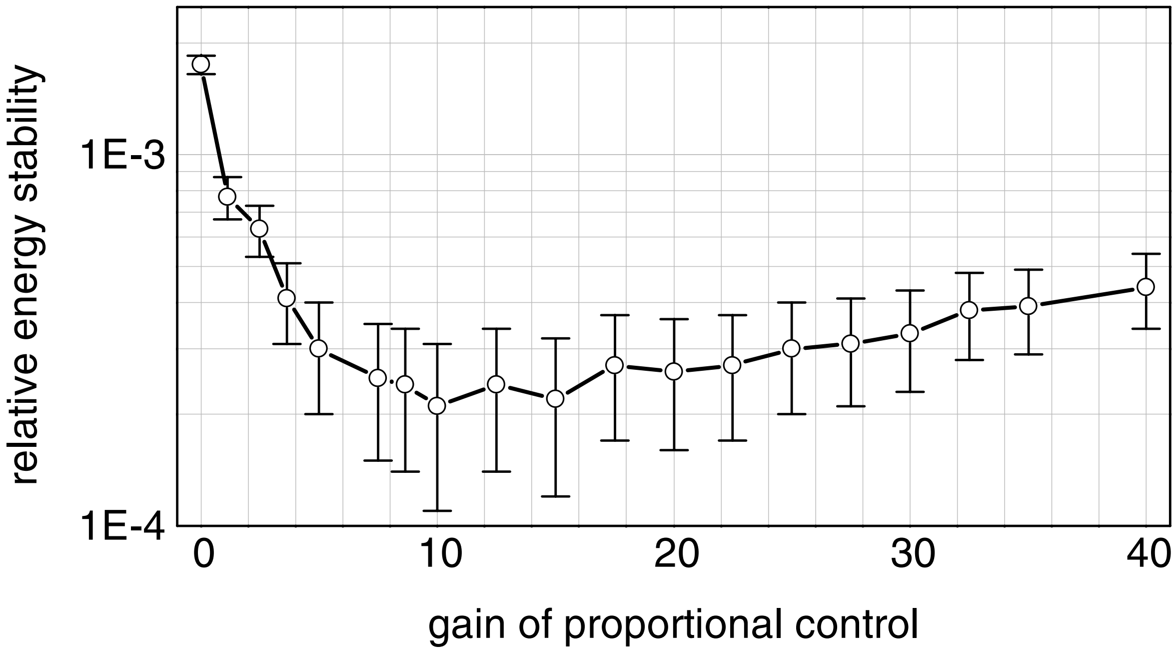
Countermeasures:

- prediction of beam current and derivation of compensation
- measurement of beam current in real time and applying appropriate compensation

Scheme implemented for ACC1 at FLASH:



'Ideal' gain for proportional rf control at ACC1



Gain resulting in most stable beam:

- error suppression for small gain values
- noise amplification for large gain values
- 'ideal' gain between both cases
- best single bunch stability: **$\Delta E/E = 2x10^{-4}$**

Gain limitations:

- noise at pick up signal: G = 15
- theory w/o paying attention to the 8/9 π mode: G = 40
- theory with paying attention to the 8/9 π mode: G > 100

Plus points:

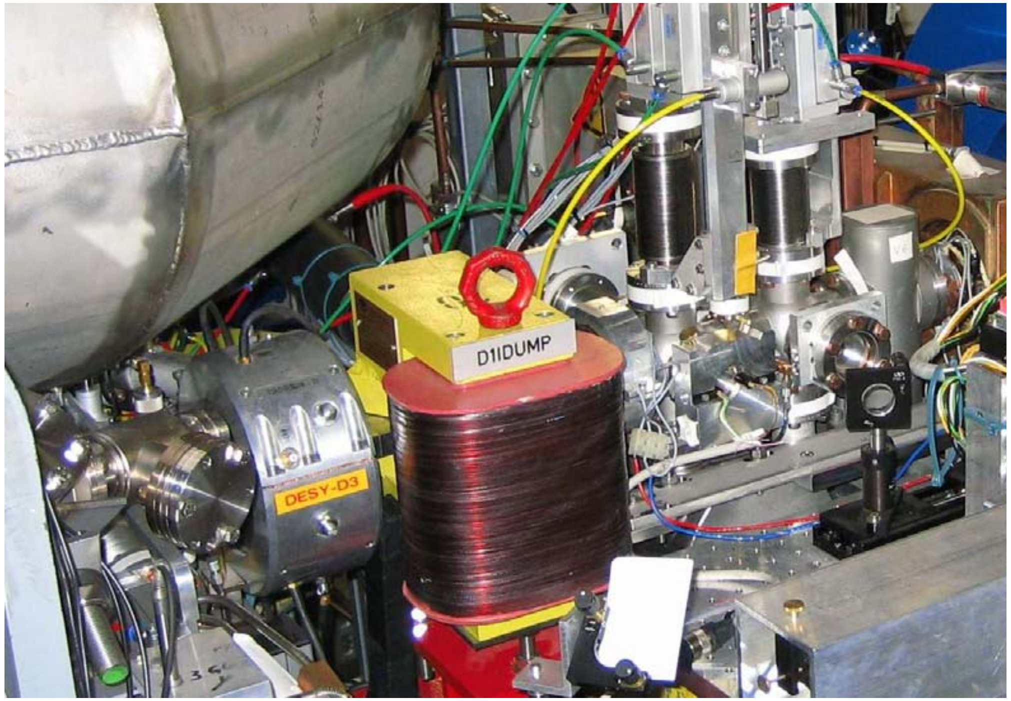
- XFEL requirement: **$\Delta E/E = 10^{-4}$**
- we controlled only 7 cavities (one pick up makes trouble)
- XFEL injector has four instead of only one module

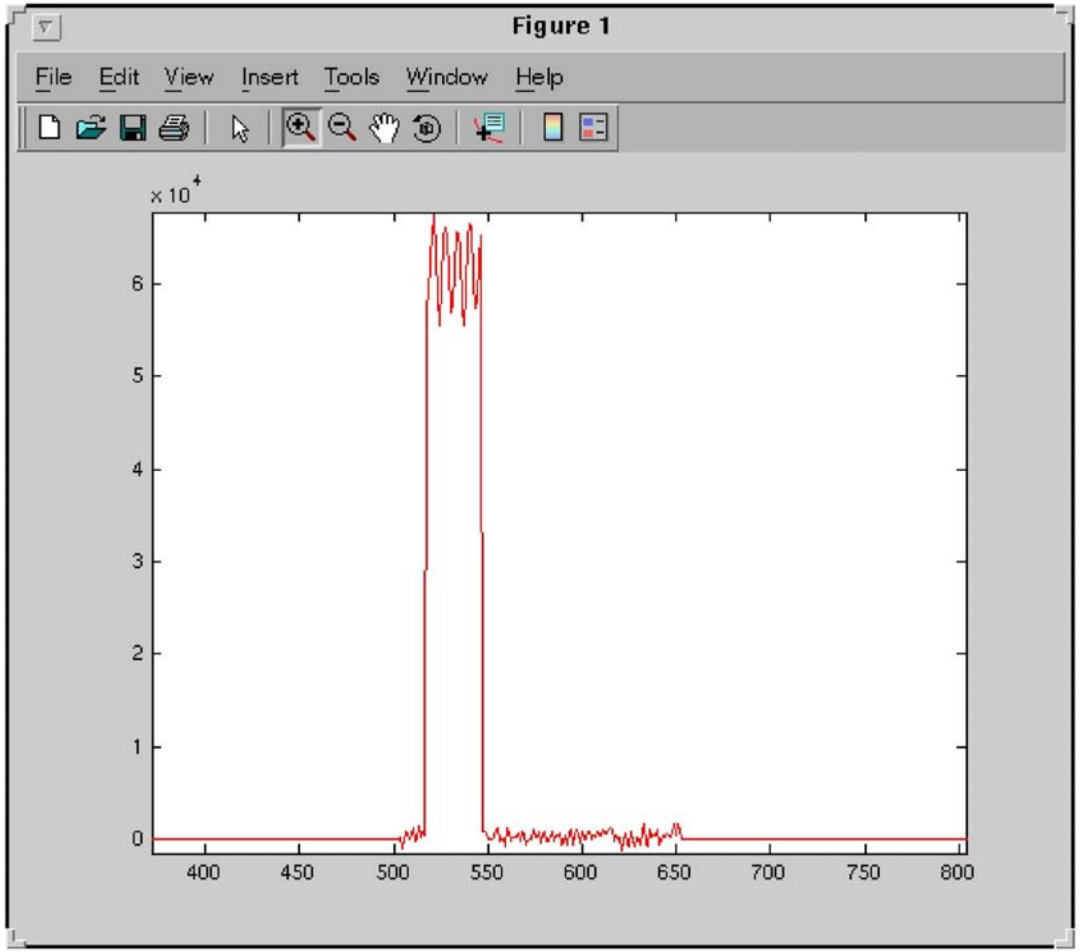
If we accelerate multiple instead of one bunch…

- all bunches shall show similar relative energy stability $\Delta E/E$
  $\rightarrow$ ok with the proportional control
- all bunches shall show similar absolute energies E
  $\rightarrow$ beam loading compensation required

Charge proportional signal from toroid monitor

- taking several samples (5) per bunch from analogue monitor signal
- sum of samples
- offset correction using samples at times without beam





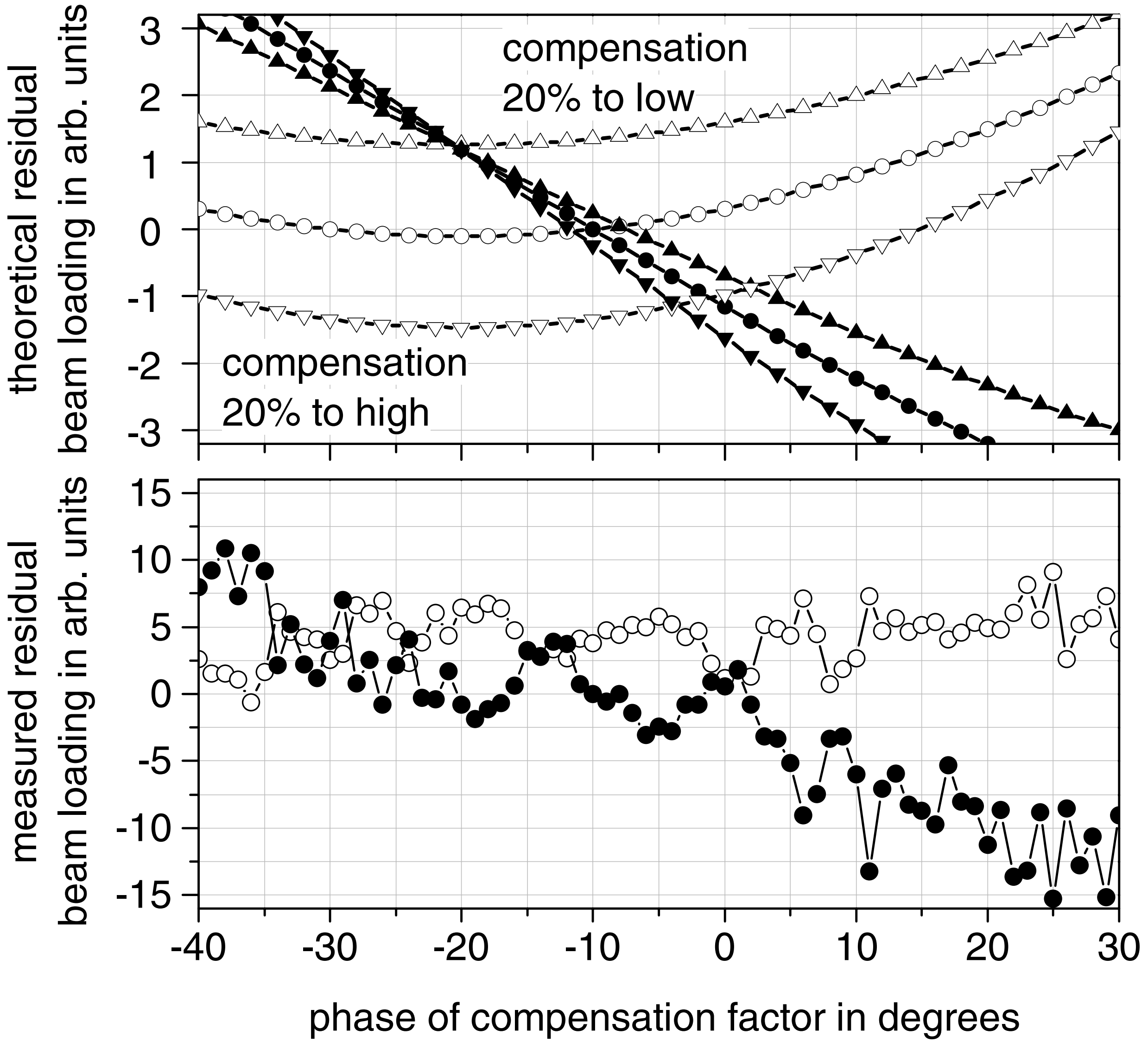
Calibration of compensation signal with phase scan

Method:

- rf feedback off
- identical signal without beam and with beam and compensation
- for correct amplitude I and Q cross zero at same phase value (-10°)

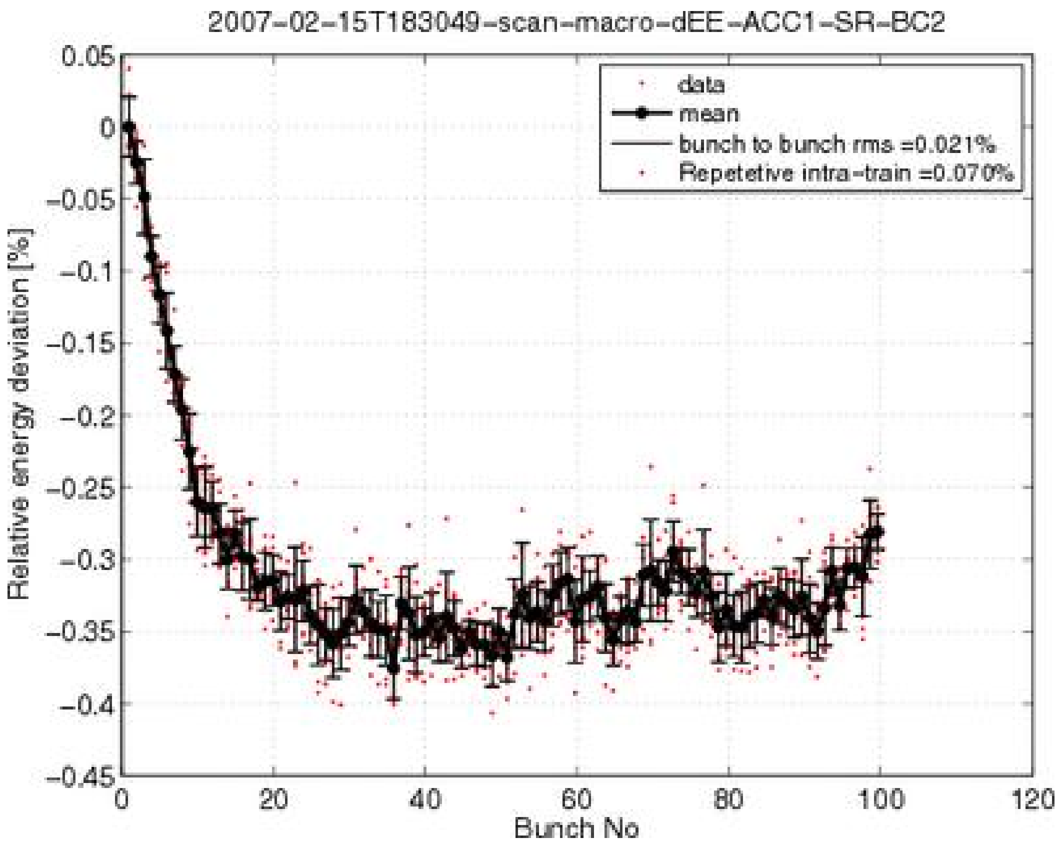
Calibration problem:

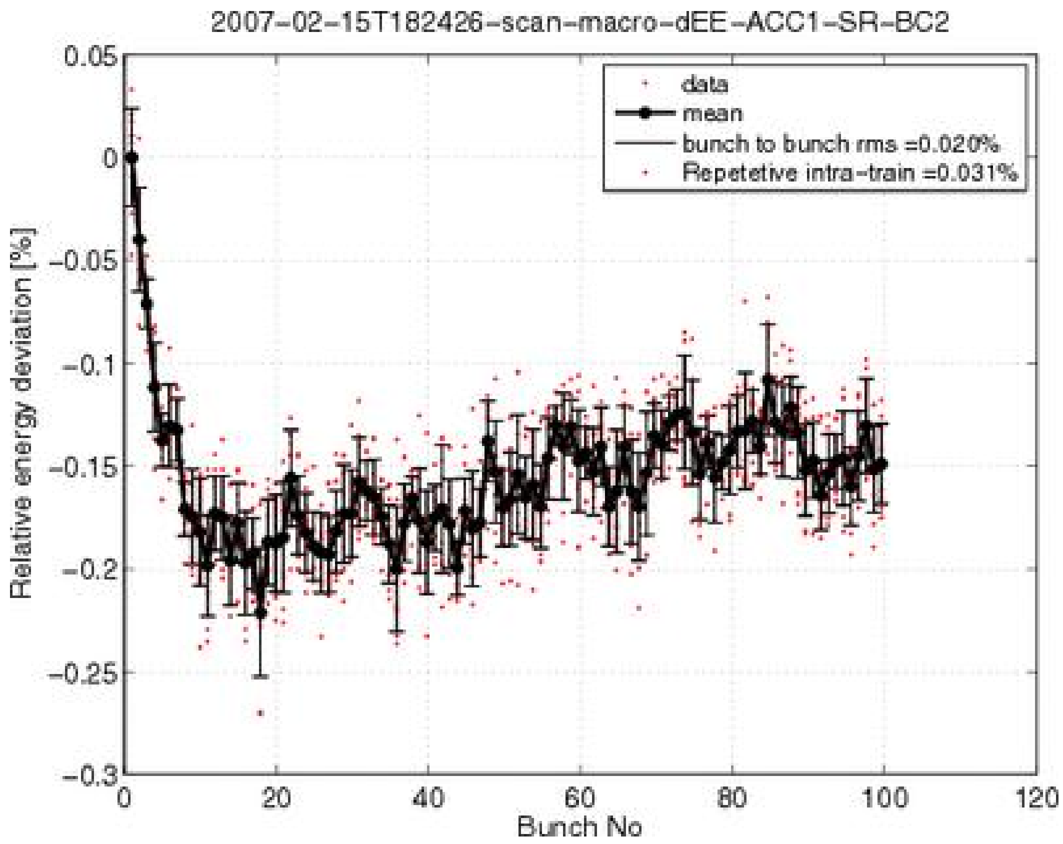
- rf power from klystron output fluctuates from rf pulse to pulse



Actual status of the beam loading compensation

Operation with P control only (G = 15) **Beam loading compensation switched on**

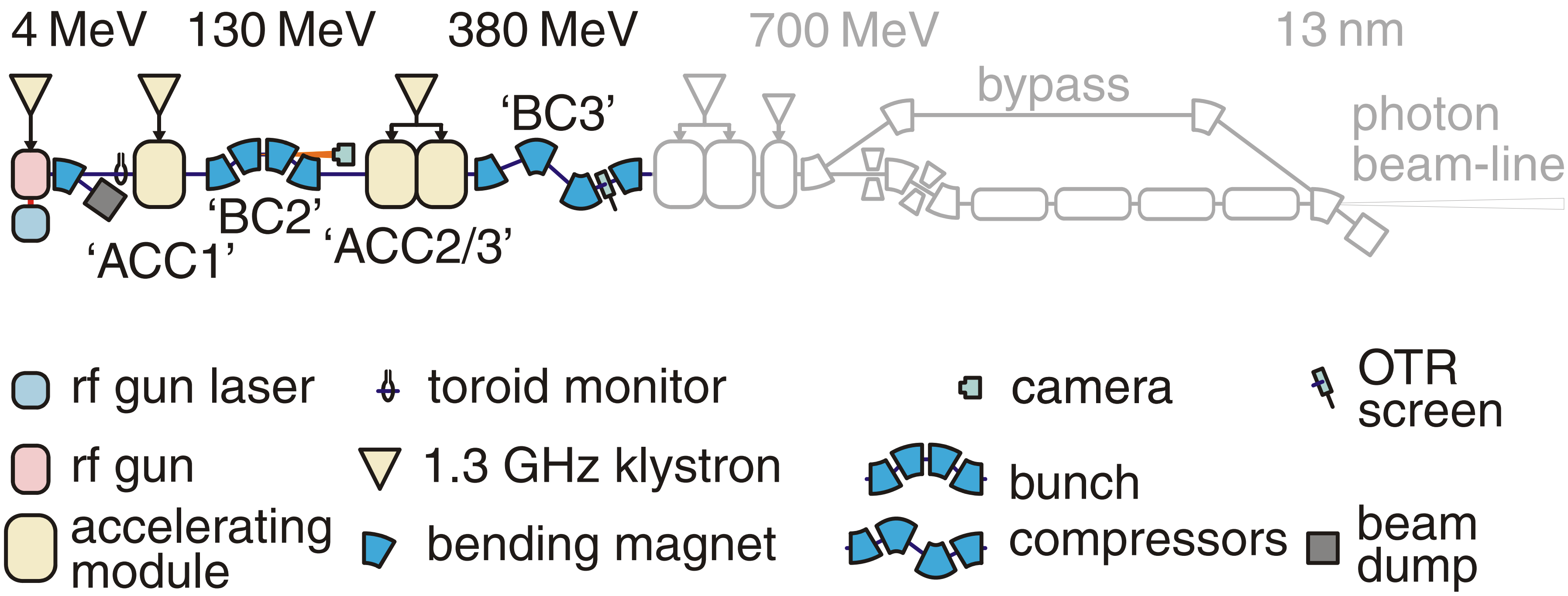




Next steps:

Improvement of the calibration and further qualification of method by measuring energy stability of beam in BC2.

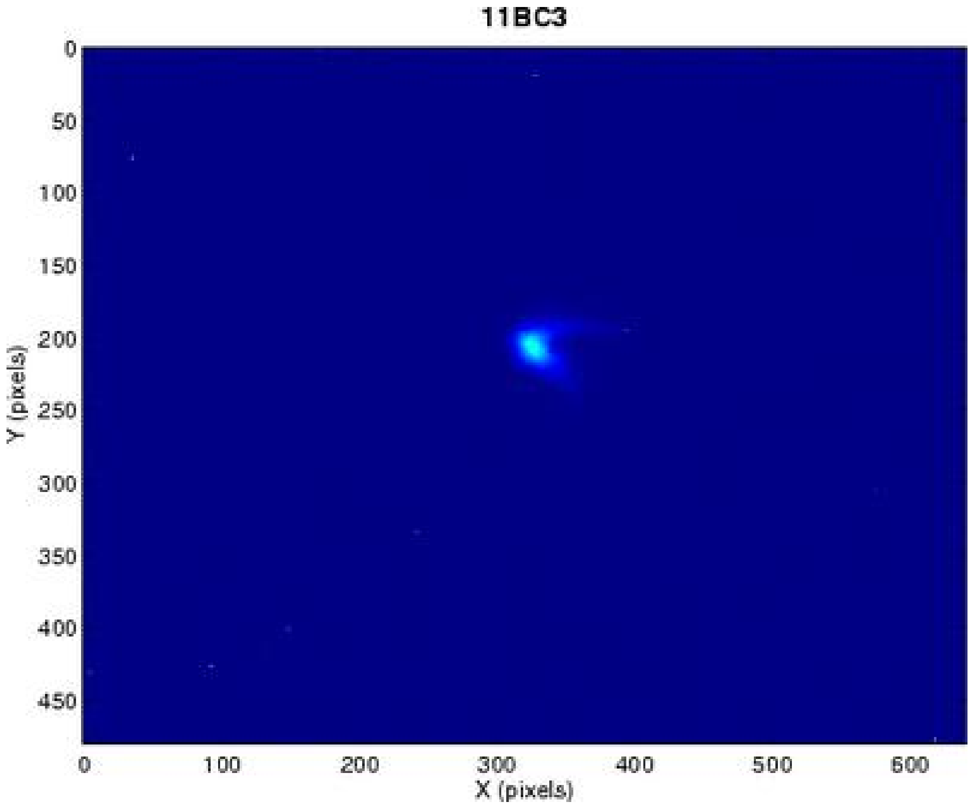
Accelerating the bunches up to 380 MeV



- beam stability measurement via OTR screen in BC3
- beam energy in BC3 is a results from the ACC1 and ACC2/3 rf stability
- nevertheless, the beam energy stability measured in BC3 yields an upper limit for the ACC2/3 rf stability

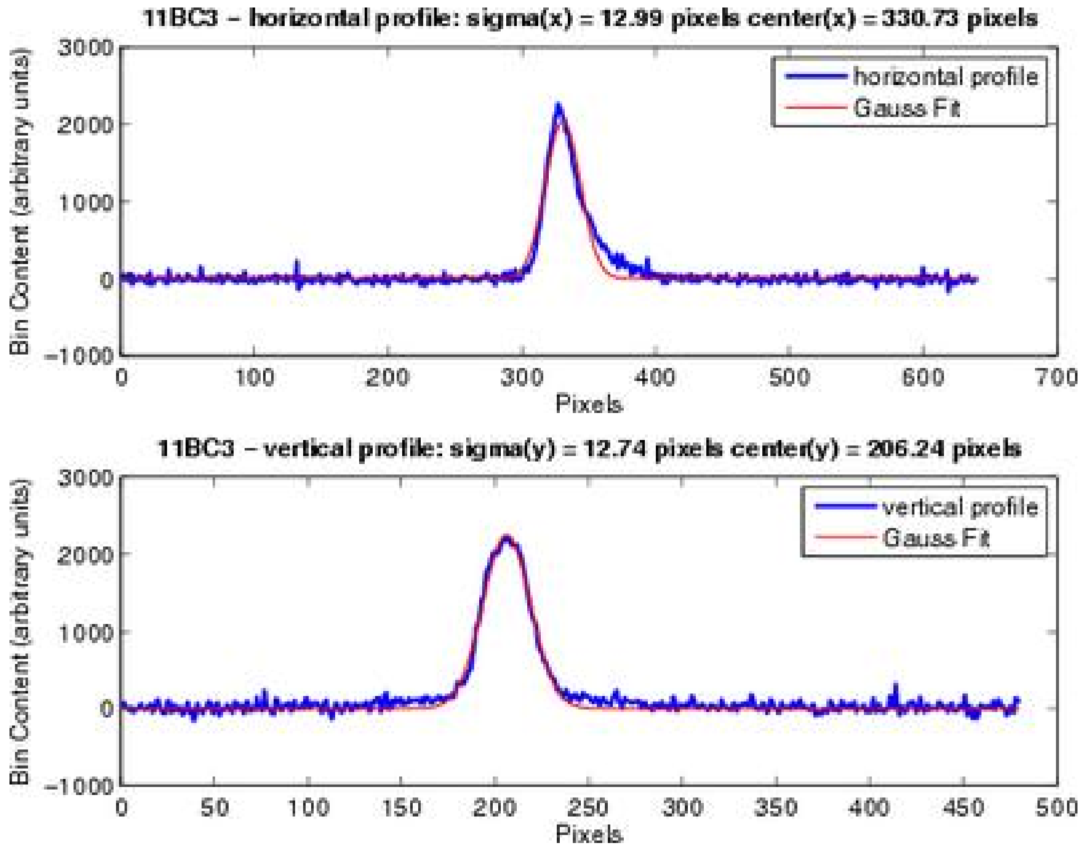
Beam energy determined by OTR screen in BC3

The beam position measured with an OTR screen in a dispersive section



yields beam energy information.

Gaussian fit to profile for beam position:



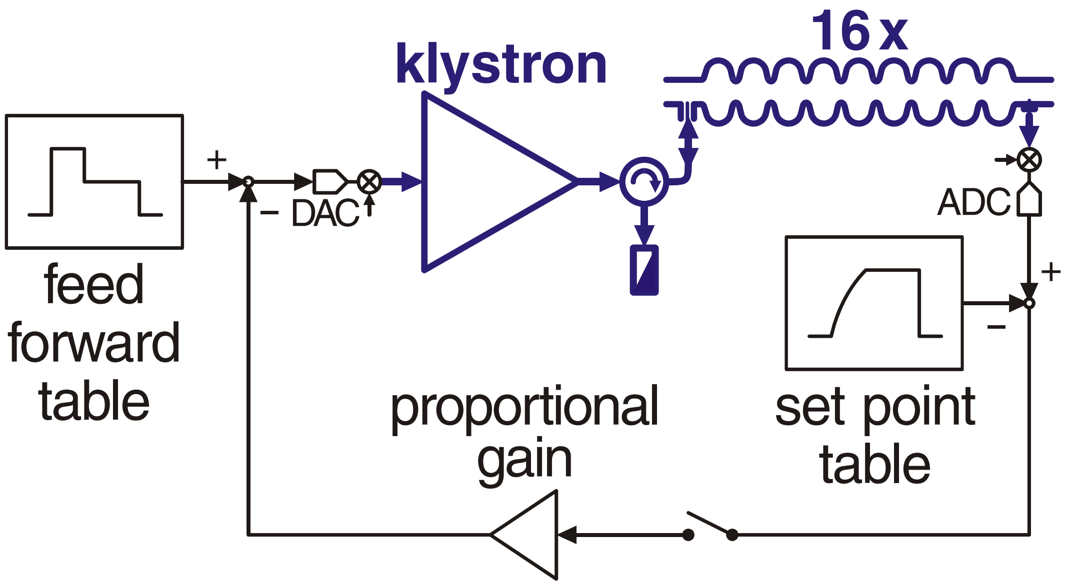
Resolution: $\Delta E/E = 3\times10^{-5}$

ACC2/3 rf control: proportional control for 16 cavities

Key features for this control:

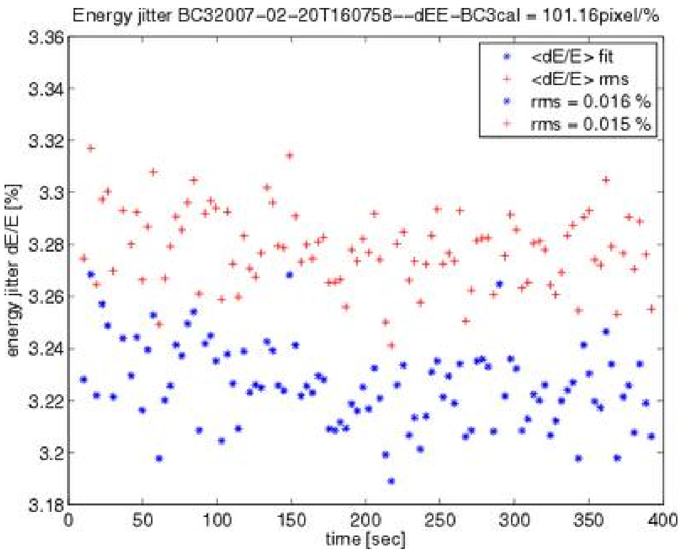
- connection of two SimCon 3.1 boards as master and slave to control the vector sum of 13 cavities (3 cavities have been excluded form the control)
- klystron linearization was switched on
- no beam loading compensation applied as only two bunches has been accelerated within this studies

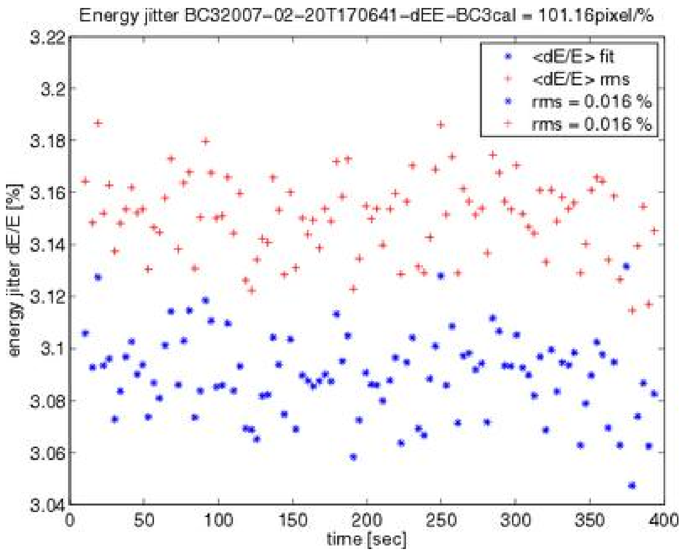
Control scheme used at ACC2/3:

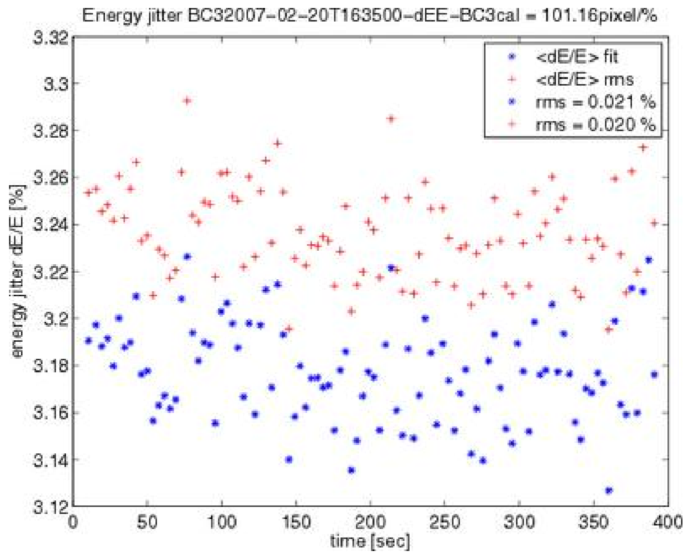


Beam energy stability observed at BC3

P control with gain = 0	P control with gain = 10	P control with gain = 40







$\Delta E/E = 1.6\times10^{-4}$	$\Delta E/E = 1.6\times10^{-4}$	$\Delta E/E = 2\times10^{-4}$

No beam energy stability improvement due to rf control?

- sensor noise (down converters)
- the **klystron it selves** seems to be **well stabilized** due to the **gain = 0 result!**

Summary and outlook

RF gun:

- emission phase can be manipulated via the gun laser and the rf control
- which one to manipulate for optimal FLASH performance?
- systematic way for virtual probe calibration
- nonlinearities compensated: no longer problems with reflected power interlocks
- rf control with P control and adaptive feed forward well established
- beam based emission phase measurement established
- measured with beam: reasonable and sufficient performance of gun rf control

First accelerating module ACC1:

- energy and rf amplitude stability measurement established at BC2
- ideal P control gain determined
- single bunch energy stability **$\Delta E/E = 2 \times 10^{-4}$** (XFEL specs $\Delta E/E = 10^{-4}$)
- beam based beam loading compensation works
- calibration of beam based beam loading compensation remains to be improved

Summary and outlook (continued)

Second and third accelerating modules ACC2/3:

- beam stability measurement available at BC3 using an OTR screen
- two SimCon 3.1 are able to control vector sum of 16 cavities
- no improvement by proportional rf control observed
- rf sensor noise (from down converters?) remains to be reduced drastically
- rf drive from klystron at ACC2/3 well stabilized:
  compare $\Delta E/E = 1.6\times10^{-4}$ @ ACC2/3 to $\Delta E/E = 1.7\times10^{-3}$ @ ACC1 for gain = 0
- multi bunch beam stability remains to be measured

Within the accelerator studies in winter 2006/2007, we carried out quite some amount of work!