RF Control for the DESY UV-FEL

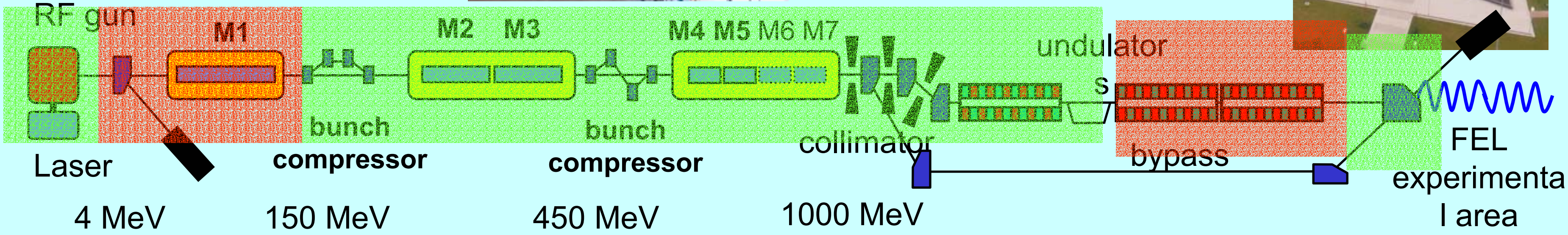
Stefan Simrock

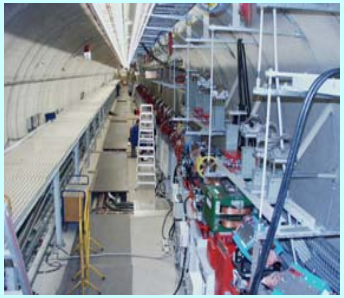
DESY

- DESY UV-FEL
- Configuration of the RF Systems
- Requirements for RF Control
- Design of the LLRF
- Issues for the European X-FEL
- Outlook

Status of beamline installations



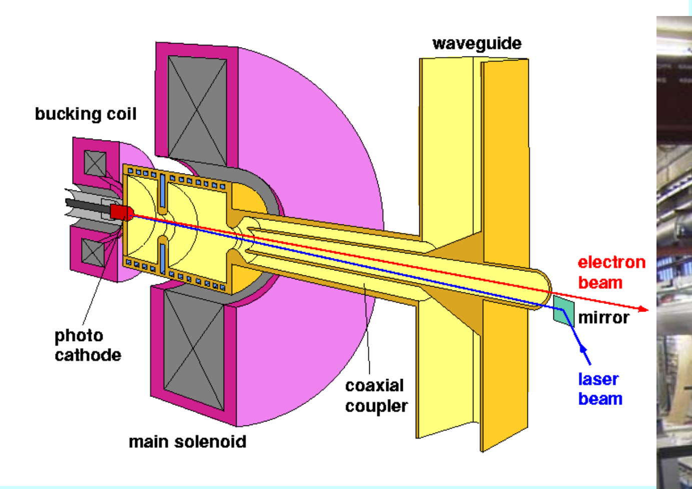



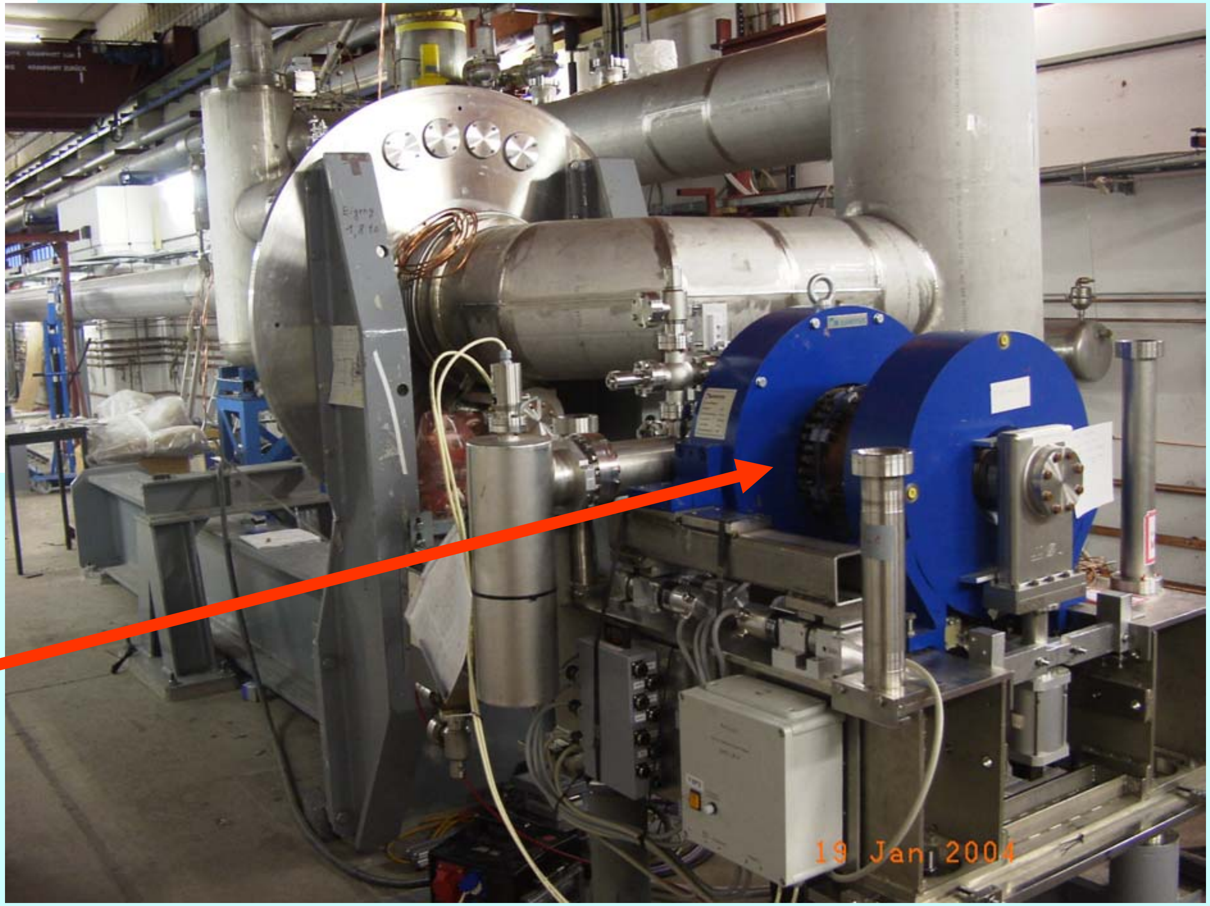
250 m

General LLRF Requirements

- Set and maintain accelerating fields during TTF II operation as
  - UV FEL user facility
  - Tesla Test Facility
- Cavities to be controlled:
  - RF Gun (nc)
  - 3rd harmonic cavity (3.9 GHz)
  - Vector-sum of cryomodule 1
  - Vector-sum of cryomodules 2+3
  - Vector-sum of cryomodules 4,5,6,(7)
  - S-Band cavity (nc) at 2.856 GHz
  - Provide stable phase reference for Laser, and diagnostics

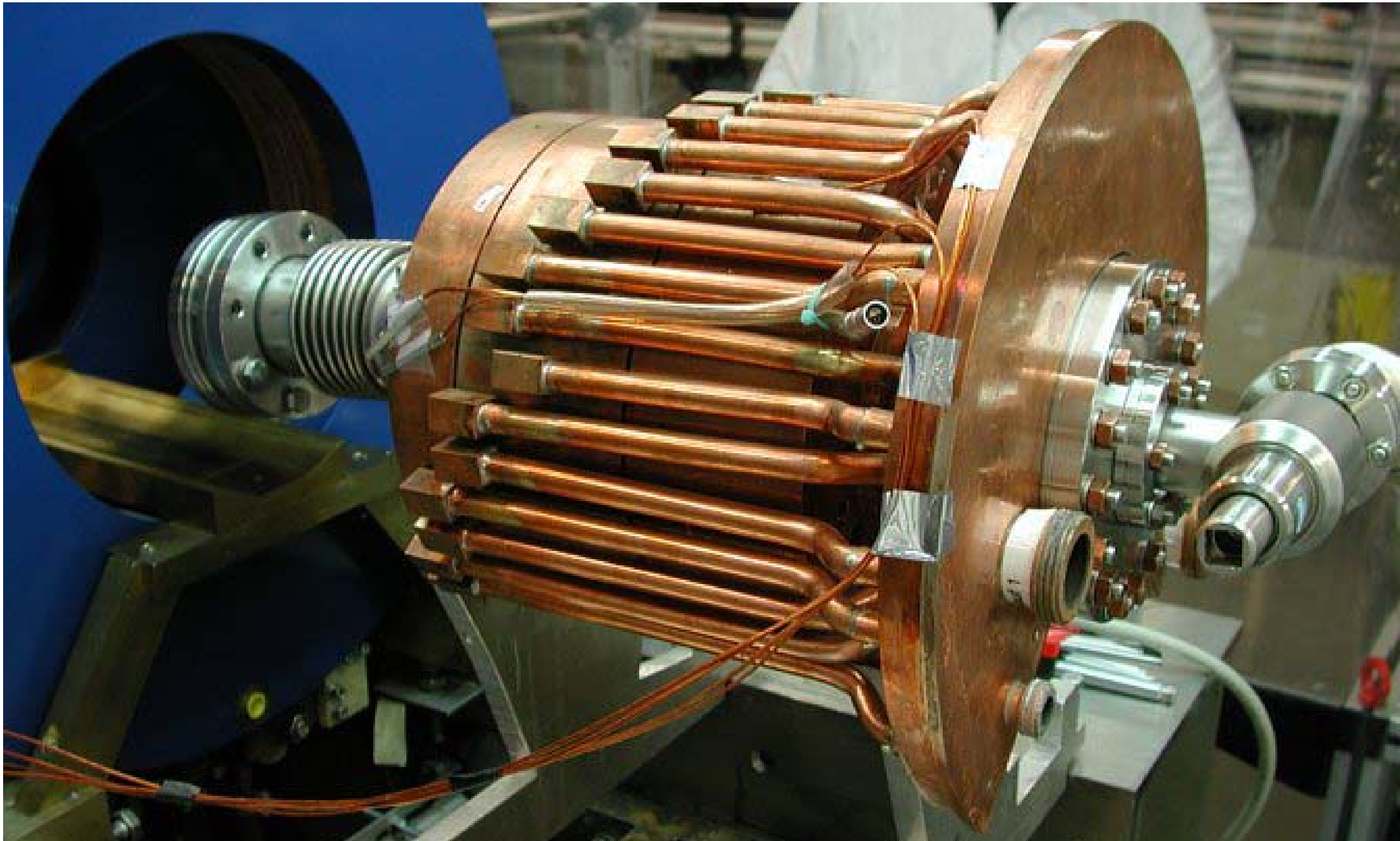
Electron gun for minimum emittance: PITZ





PITZ gun installed into TTF Jan 2004

TTF2 RF GUNAT PITZ

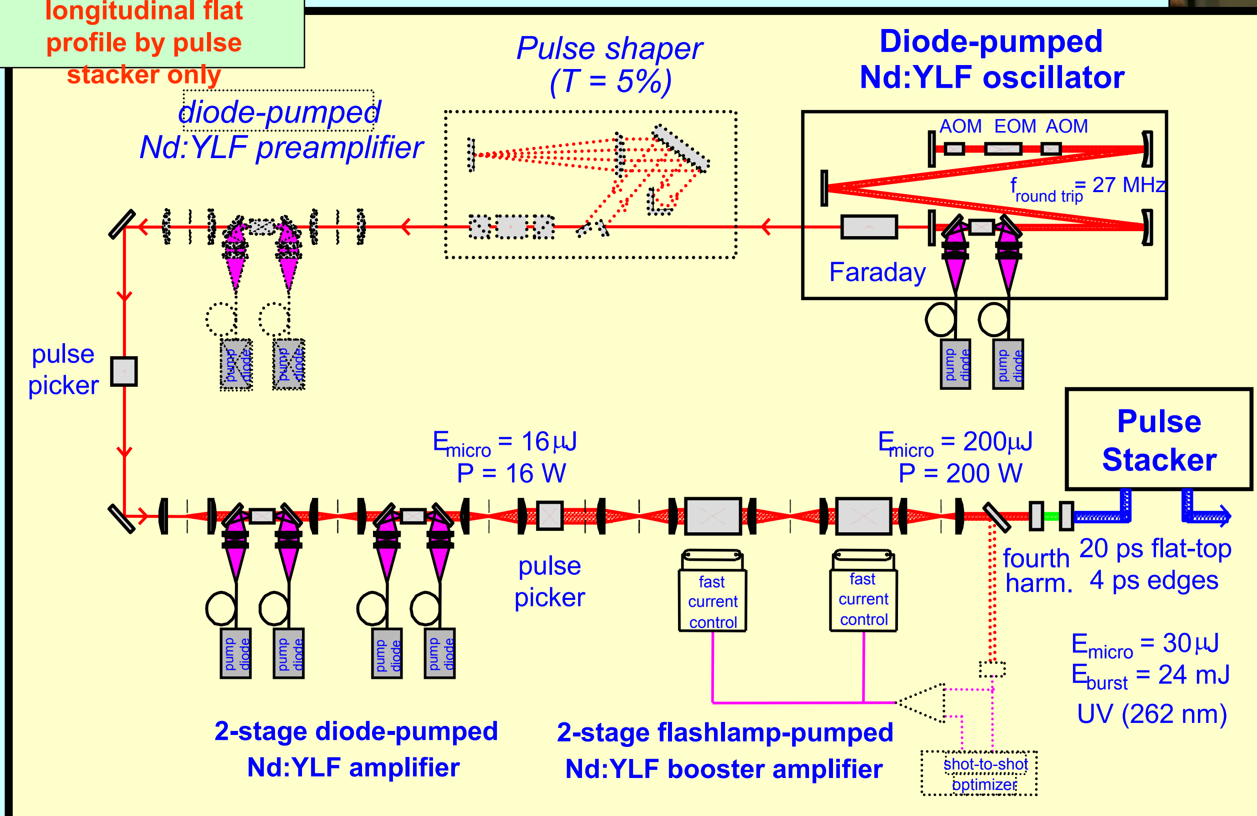


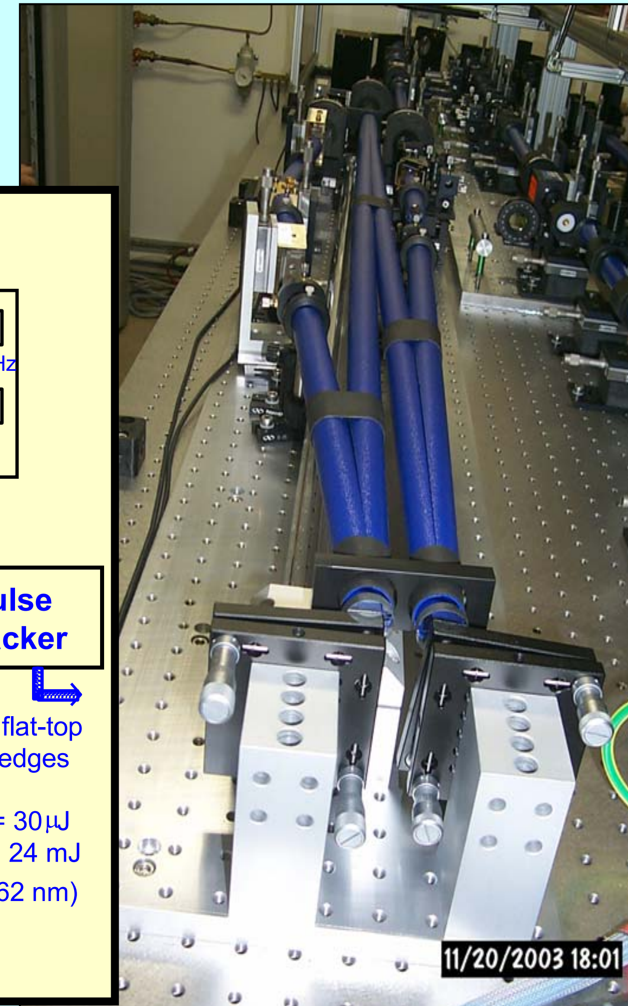
TTF 2 Laser Upgrade

- Together with Max-Born-Institute, Berlin (I. Will et al.)
- Upgrade has been tested at PITZ

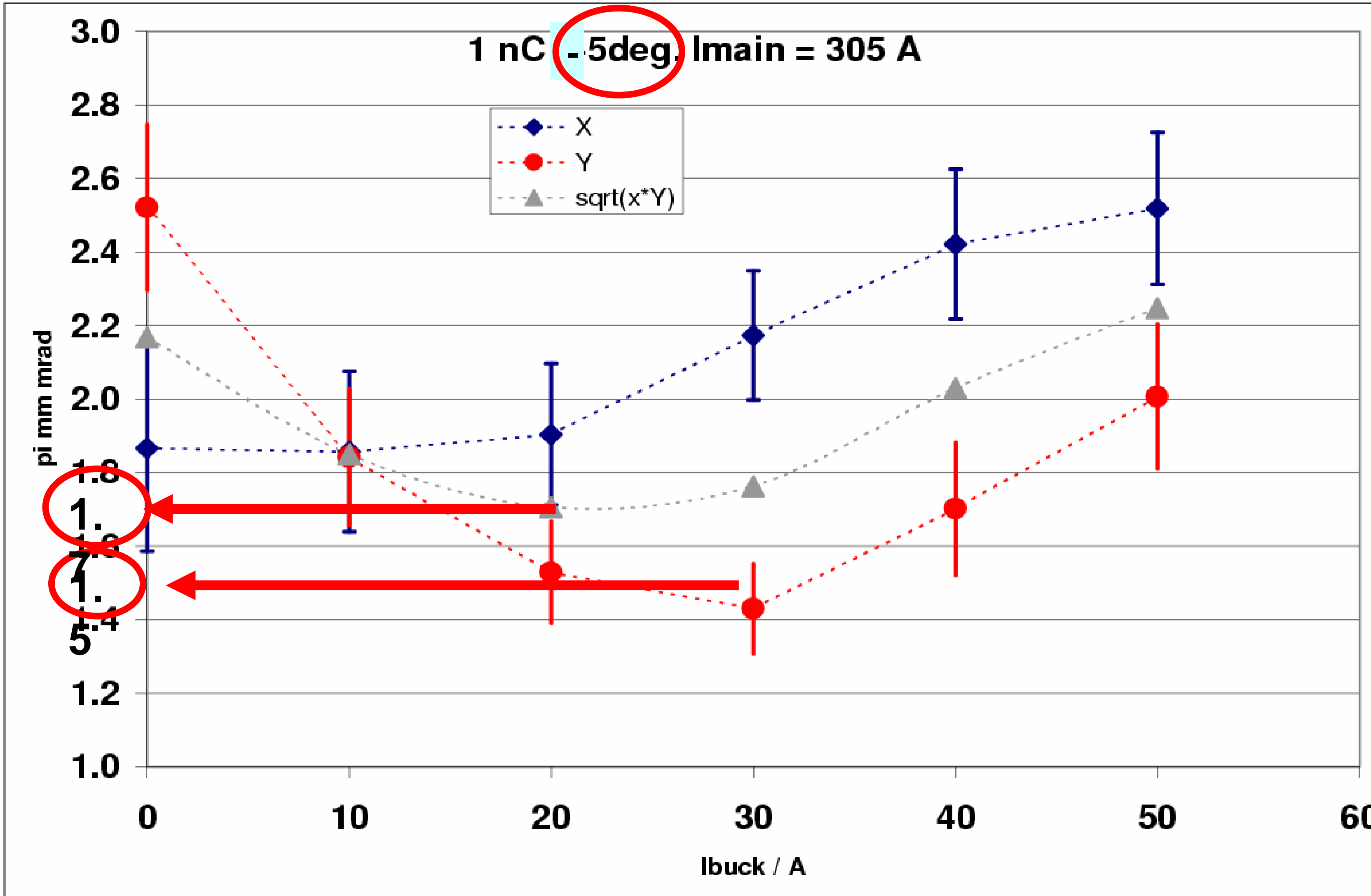
Note:

longitudinal flat profile by pulse stacker only



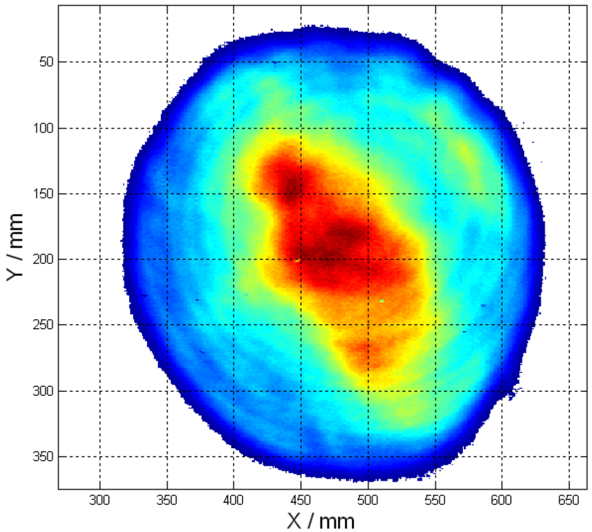


Transverse Emittance Measurement @ PITZ



Fine Tuning of Laser Parameters

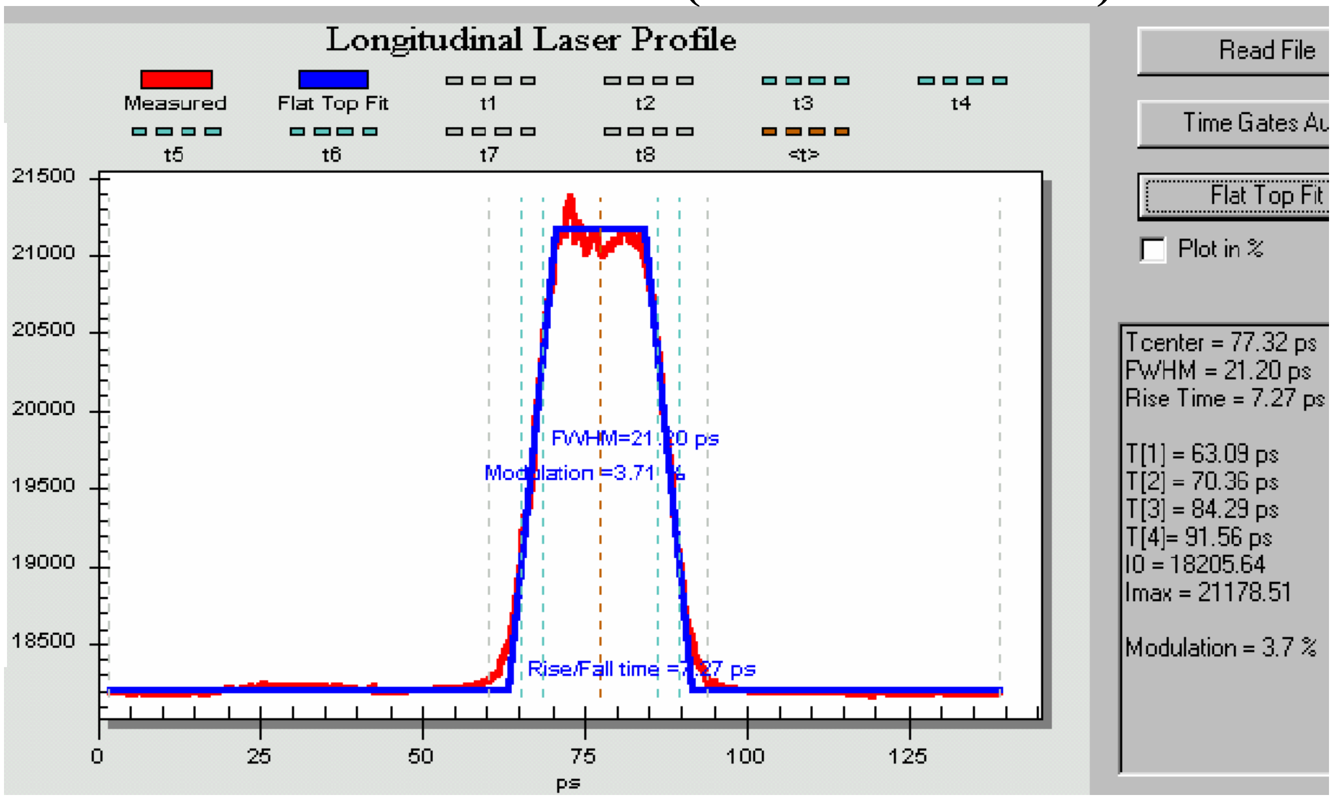
transverse profile
(D=1.2 mm)



$\sigma_x = 0.55 \pm 0.02$ mm

$\sigma_y = 0.61 \pm 0.02$ mm

(measured in UV)



FWHM ≈ 21 ps; rise/fall time ≈ 7 ps

General LLRF Requirements (Cont'd)

- The LLRF System for the FEL user facility must be
  - Reliable
  - Operable
  - Reproducible
  - Maintainable
  - Well Understood
  - Meet (technical) performance goals
- The LLRF System for the TESLA Test facility must
  - demonstrate high gradient operation at 35 MV/m
    - requires piezo tuners for Lorentz force compensation
    - requires operation close to klystron saturation
    - exception handling
  - Demonstrate of operation with electronics installed in tun-nel

LLRF Requirements:

- Field Calibration
- Beam phase measurement
- Beam loading compensation
- Finite State Machine
- Exception handling
- Cavity frequency tuning
  - motor tuner
  - piezo tuner
- Adaptive feedforward
- Waveguide tuner control

Support by:

ELHEP Group

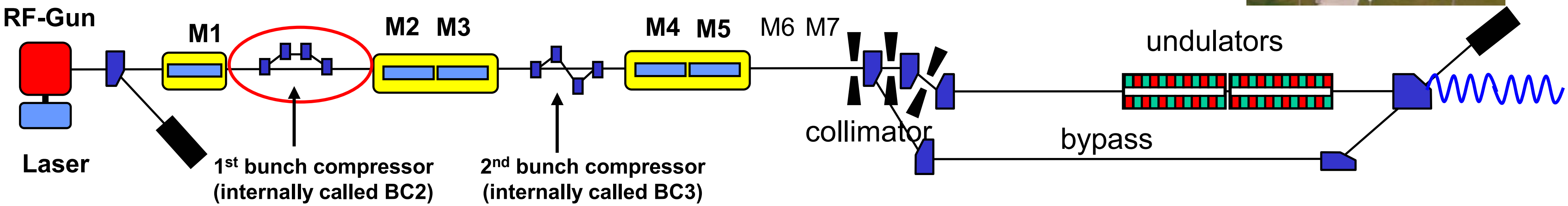
Warsaw University of Technology
Institute Electronic System

Team:
About 20 people scientists, engineers and students (Ph.D. and M.Sc.)
working at:
Warsaw, CERN, DESY

Amplitude and Phase Stability

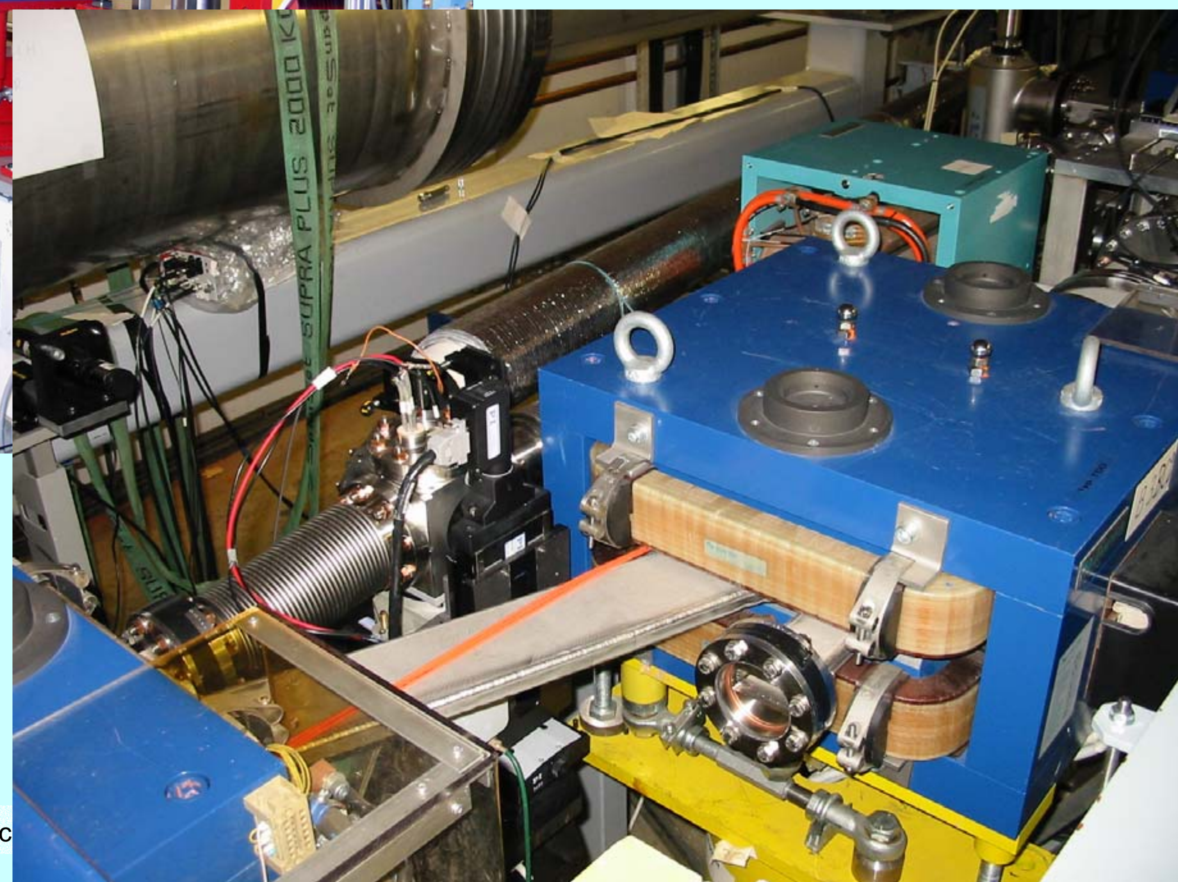
- Typically requirements are
  - $\sigma_A/A < 10^{-3}$ amplitude
  - $\sigma_\phi < 0.3$ deg. for phase (fast fluctuations)
    - Must distinguish correlated and uncorrelated errors, intra-pulse, inter-pulse, and long-term (thermal > minutes). Long term stability of better than 1 deg. is difficult to achieve.
- Other requirements
  - ACC1: cav. 1-4 at 12.5 MV/m, cav. 5-8 at 20 MV/m phase of accelerating field -10.8 deg.
  - ACC39 at 14 MV/m at 183 deg.
  - S-Band cavity at 2856 MHz phase stability < 1 deg.
  - RF Gun operation without field probe. Rep. rate, pulse length and power must be variable.

TTF2 linac



← 250 m →

Magnetic chicane for longitudinal compression



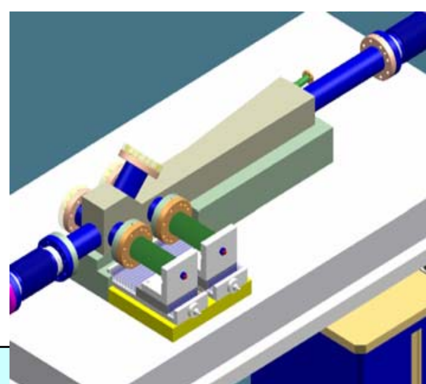
Temporary beamline for seeding

Beam dump

Longitudinal bunch shape measurements at TTF2

- Streak camera
  - FESCA 200 (Hamamatsu)
- Transverse deflecting cavity
  - S-band travelling wave cavity from SLAC

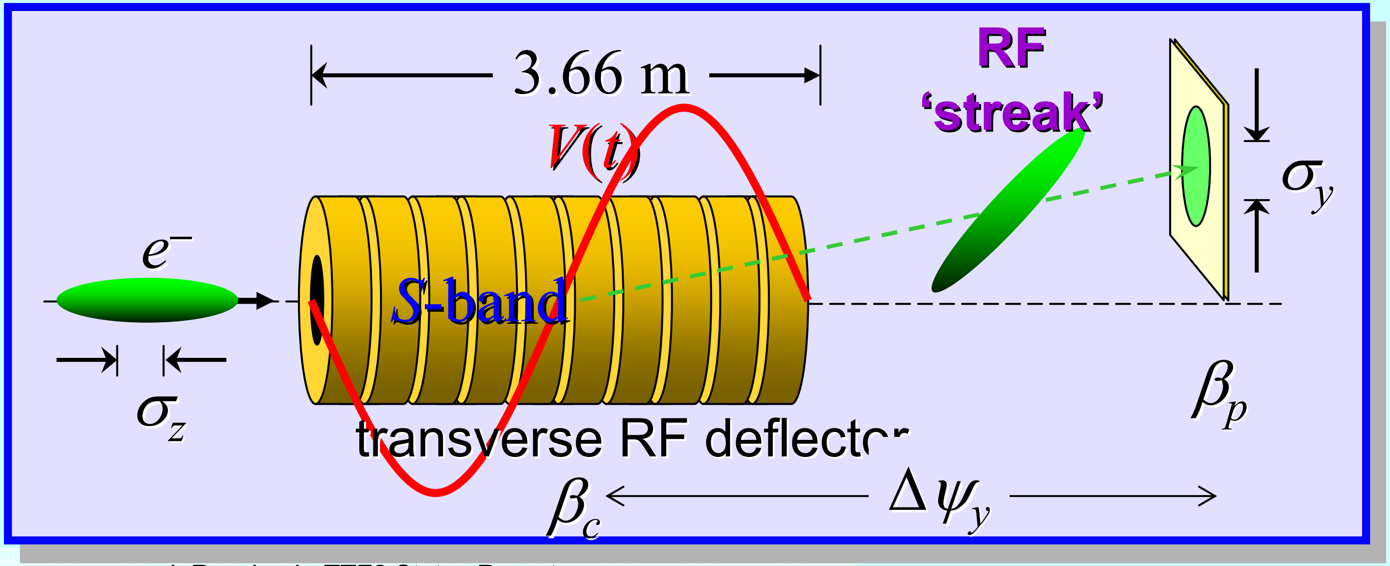
- Coherent radiation
  - Interferometer from RWTH Aachen
- Electro-optical sampling



LOLA Shipment from SLAC to DESY

- Vertically deflecting cavity for bunch length measurements at TTF2
- Built in the late 60ies by G. Loew et al.
- SLAC contribution to TTF2

"Intra-Beam Streak Camera"

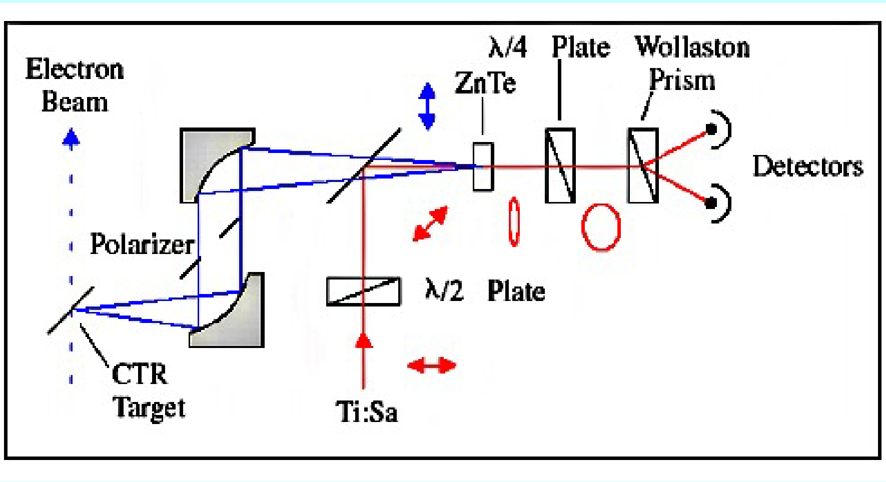


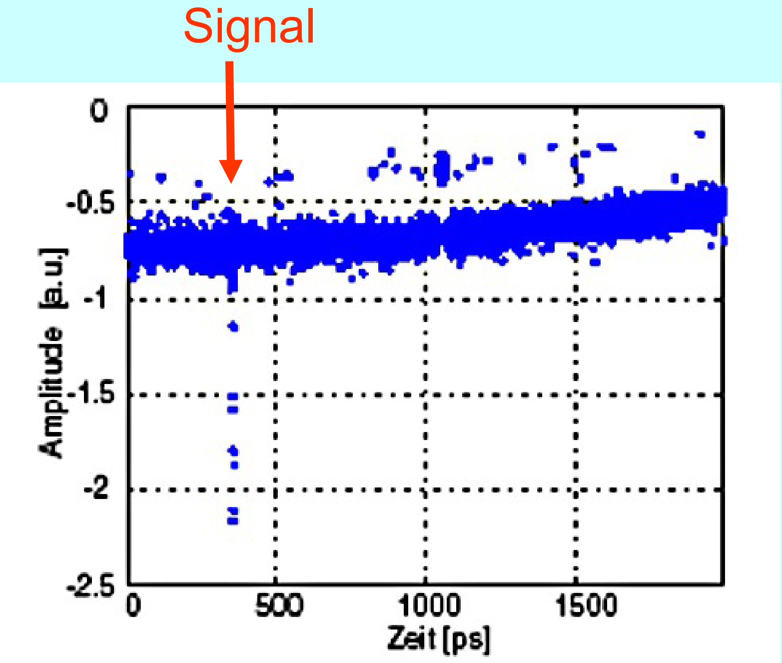
LOLA shipment

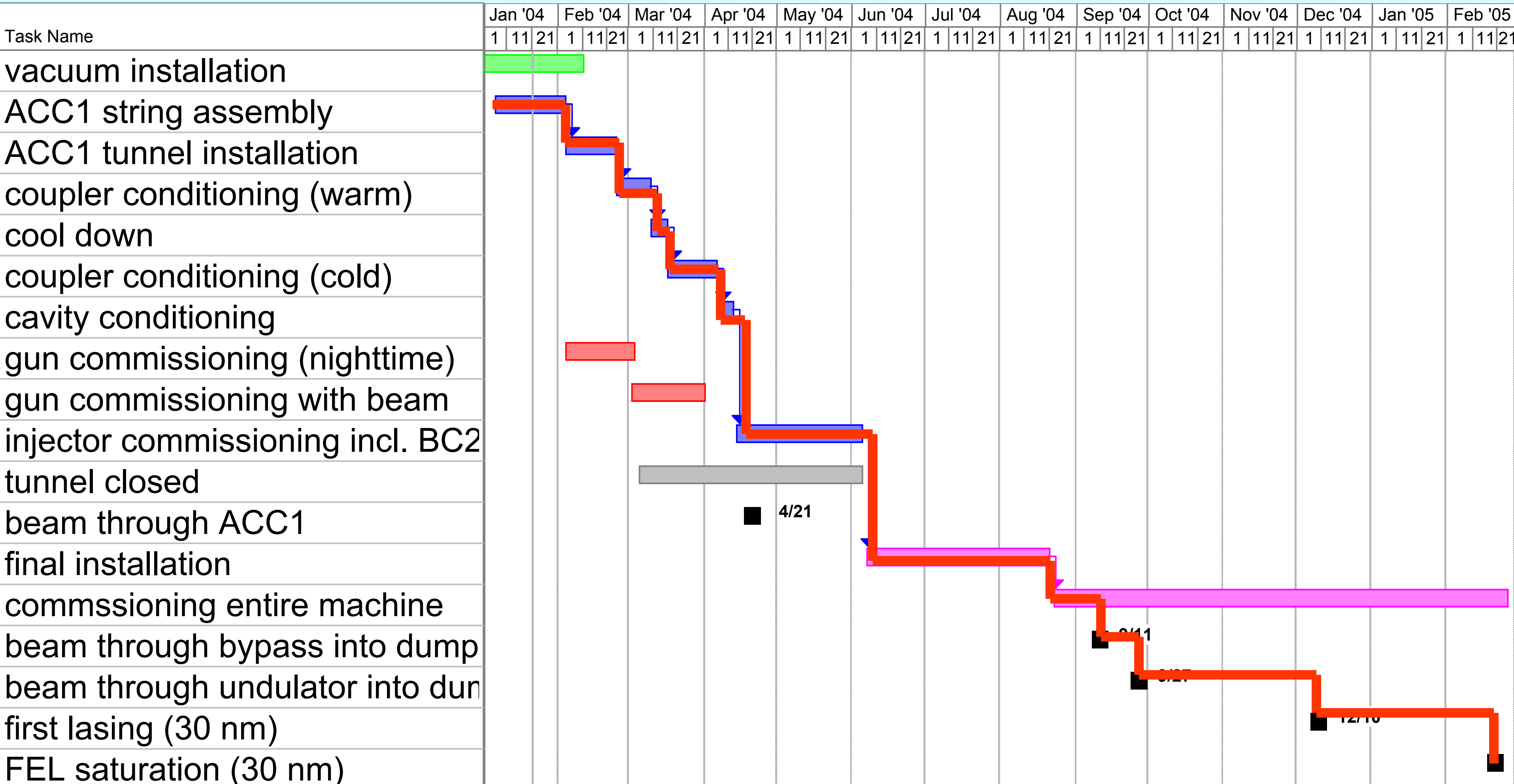
LOLA installed

Electro-optical sampling at TTF1

- Ti:Saphire laser (15 fs) and ZnTe crystal
- Electron bunch can be scanned by varying the delay of the laser
- Polarization of the laser changes depending on the amplitude of the "beam fields"



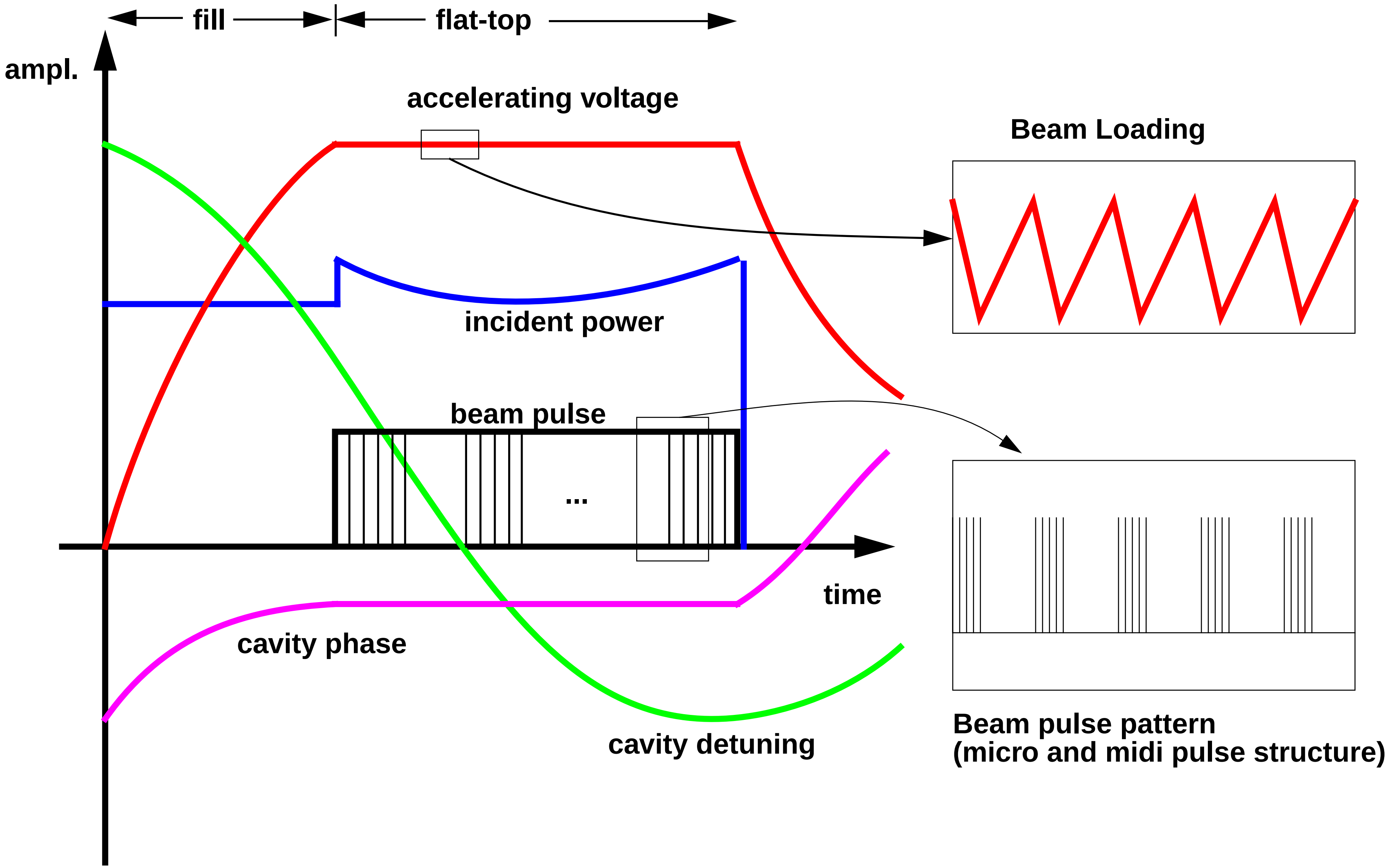




Major schedule for TTF2 installation and commissioning

More detailed schedule (400 items) to be presented in WG3 by M. Körfer

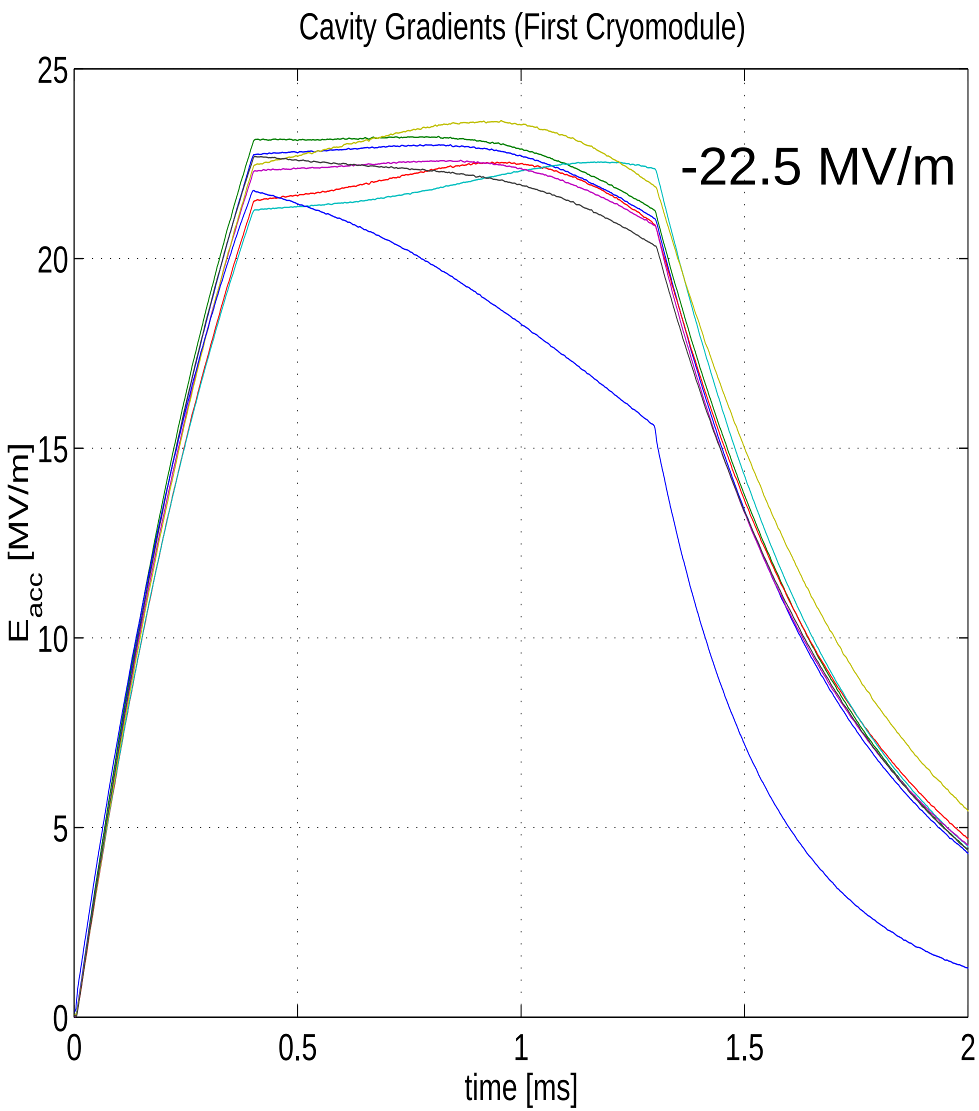
Typical Parameters in a Pulsed Linac



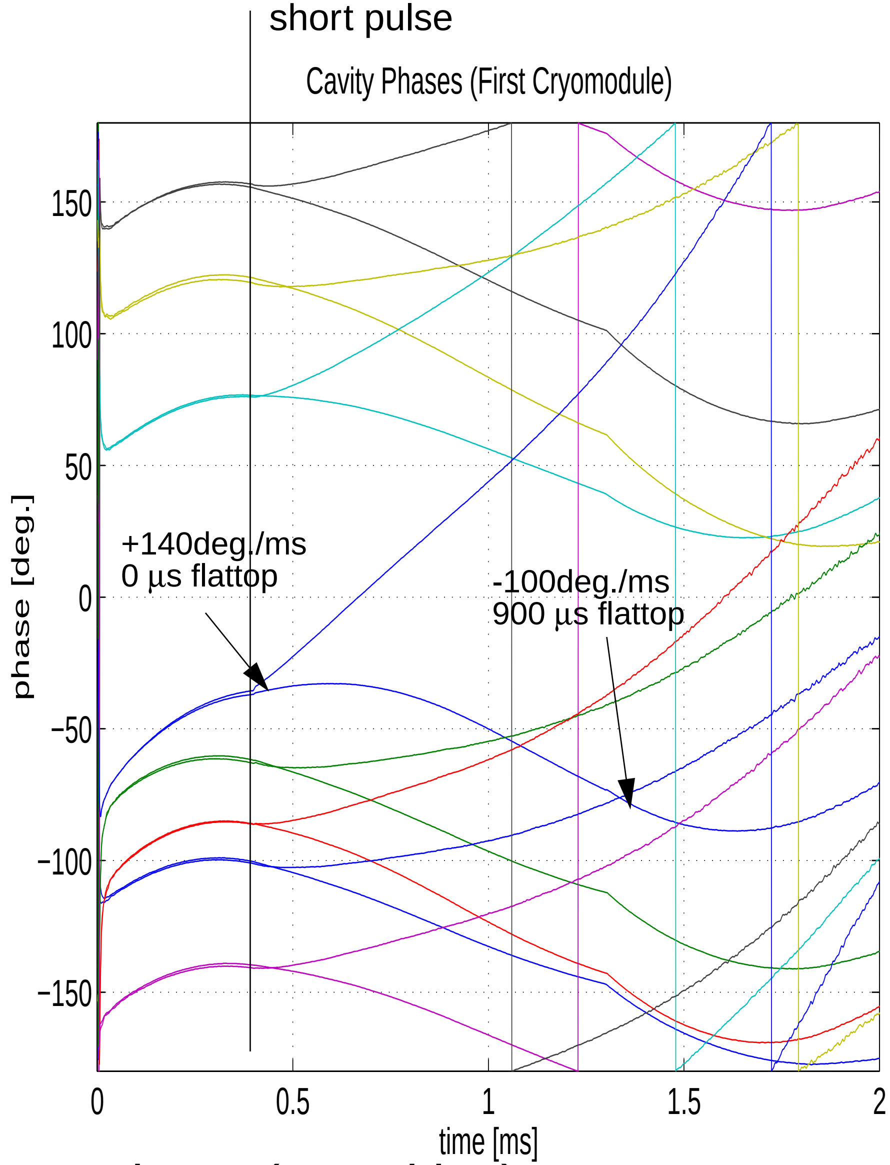
Sources of Perturbations

o Beam loading - Beam current fluctuations - Pulsed beam transients - Multipacting and field emission - Excitation of HOMs - Excitation of other passband modes - Wake fields o Cavity drive signal - HV- Pulse flatness - HV PS ripple - Phase noise from master oscillator - Timing signal jitter - Mismatch in power distribution	o Cavity dynamics - cavity filling - settling time of field o Cavity resonance frequency change - thermal effects (power dependent) - Microphonics - Lorentz force detuning o Other - Response of feedback system - Interlock trips - Thermal drifts (electronics, power amplifiers, cables, power transmission system)

Pulsed Operation at High Gradients

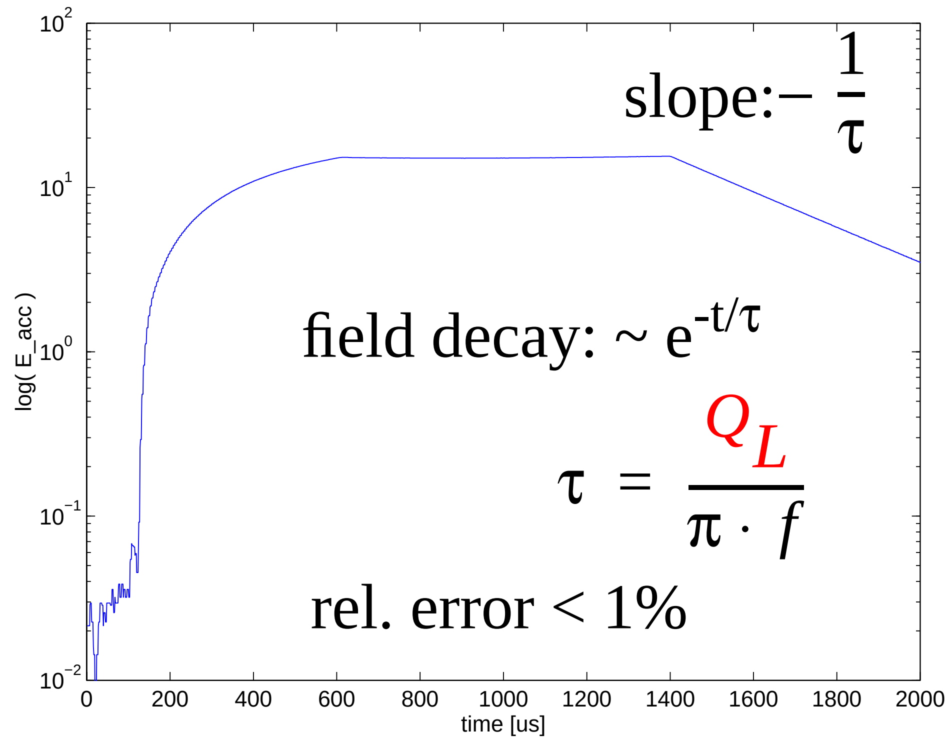


Gradient (8 cavities)

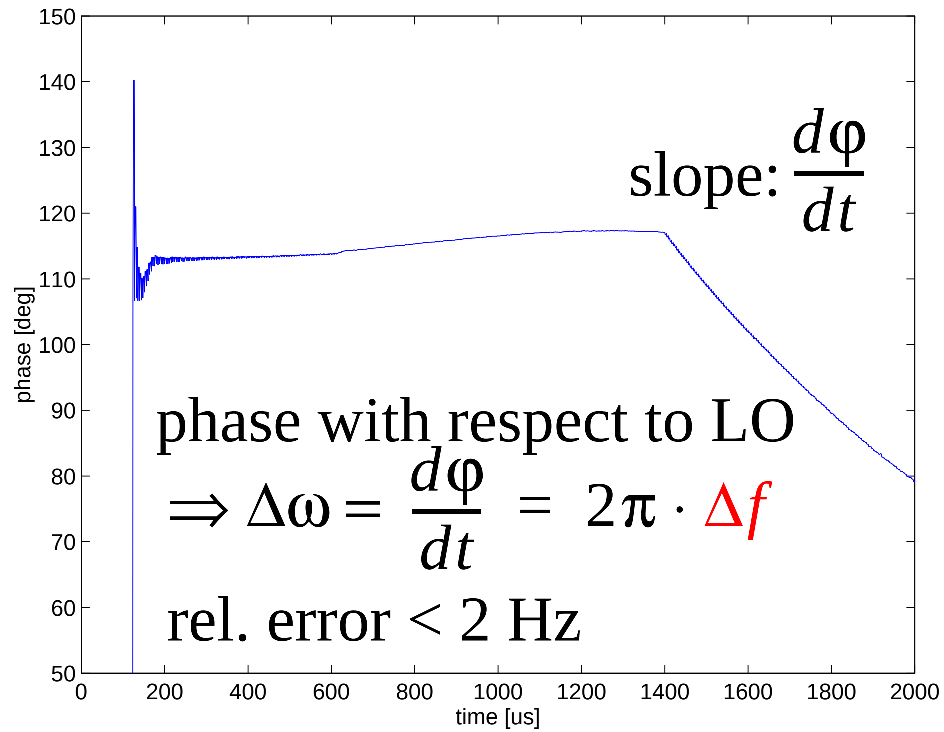


Phase (8 cavities)

Measurement of Cavity Q_L and Detuning

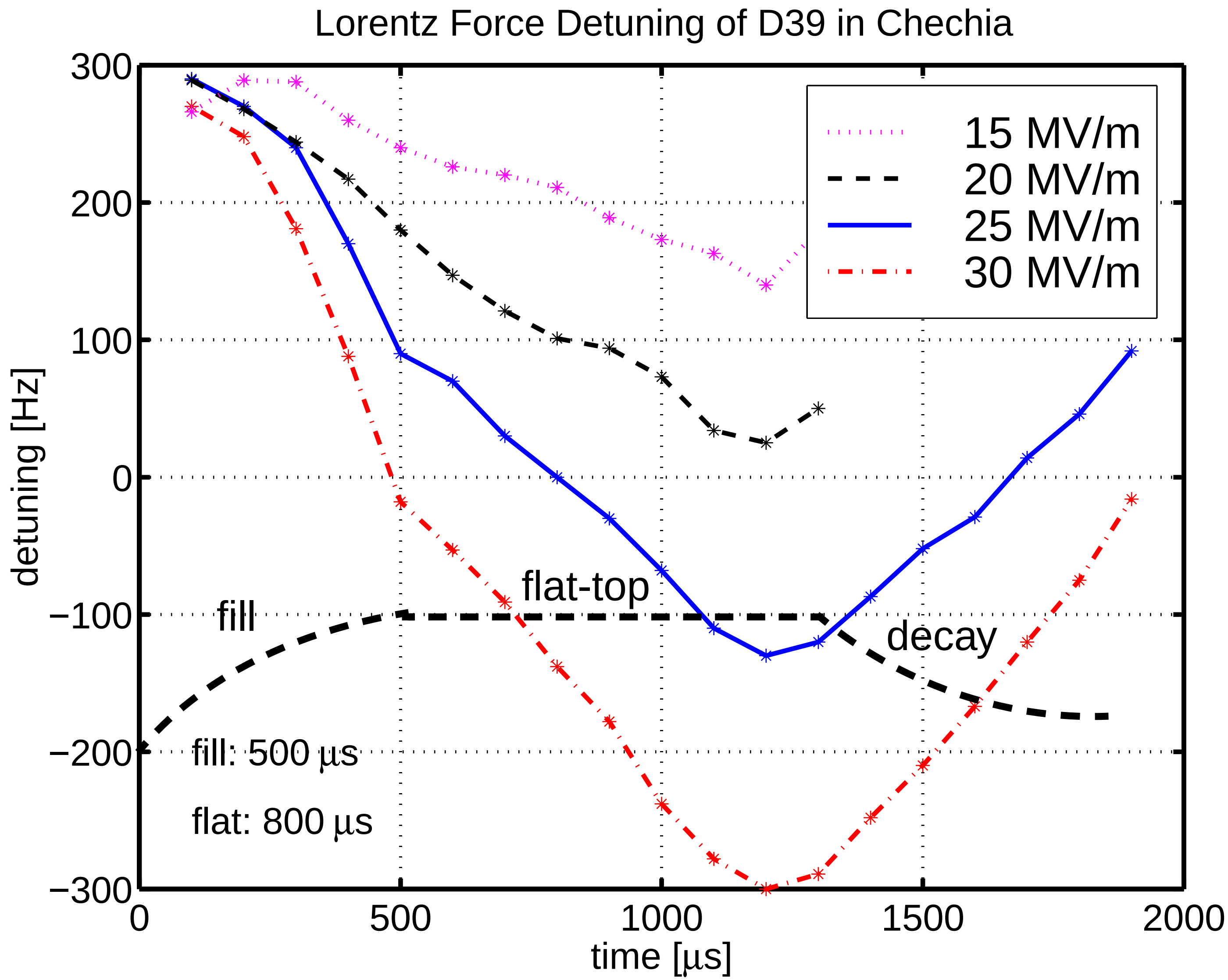


Loaded Q

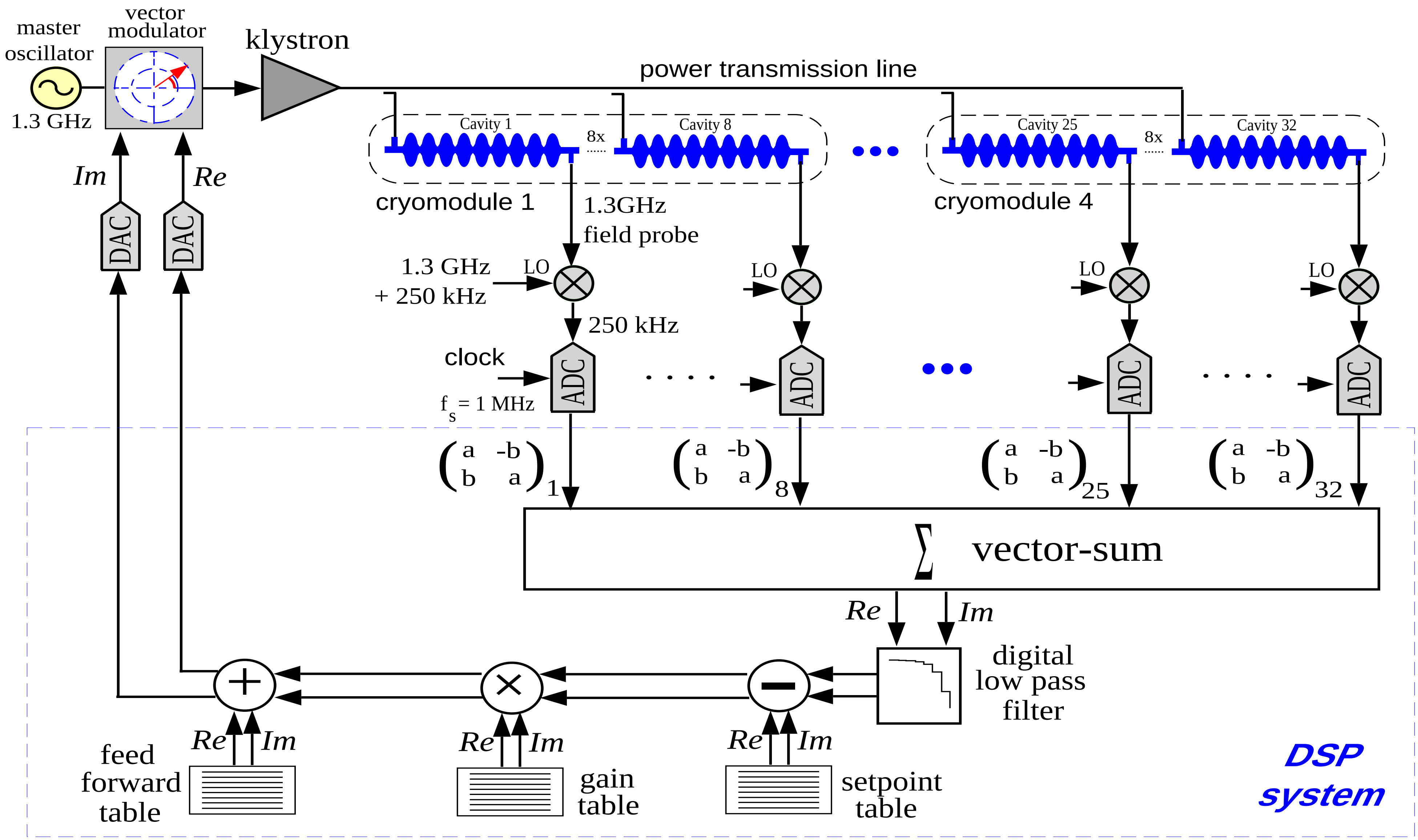


Detuning

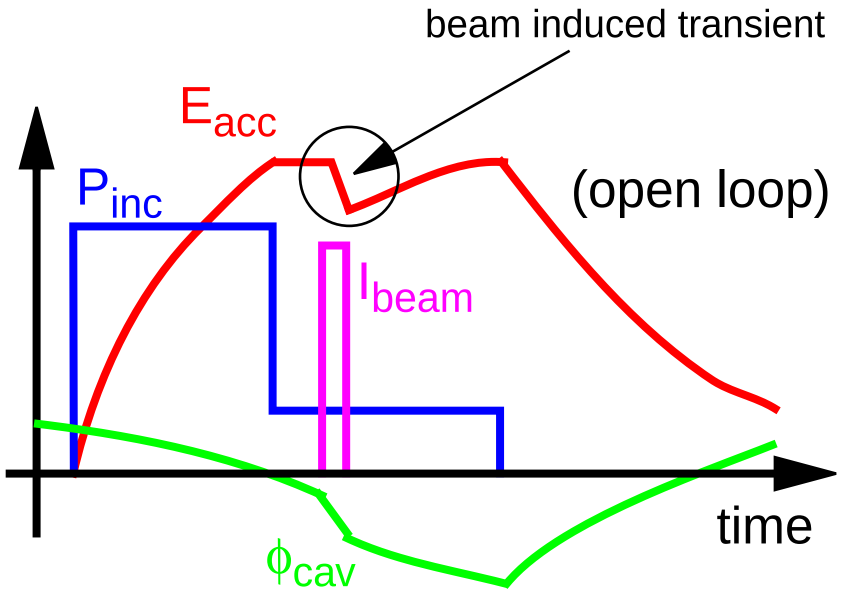
Lorentz Force Detuning

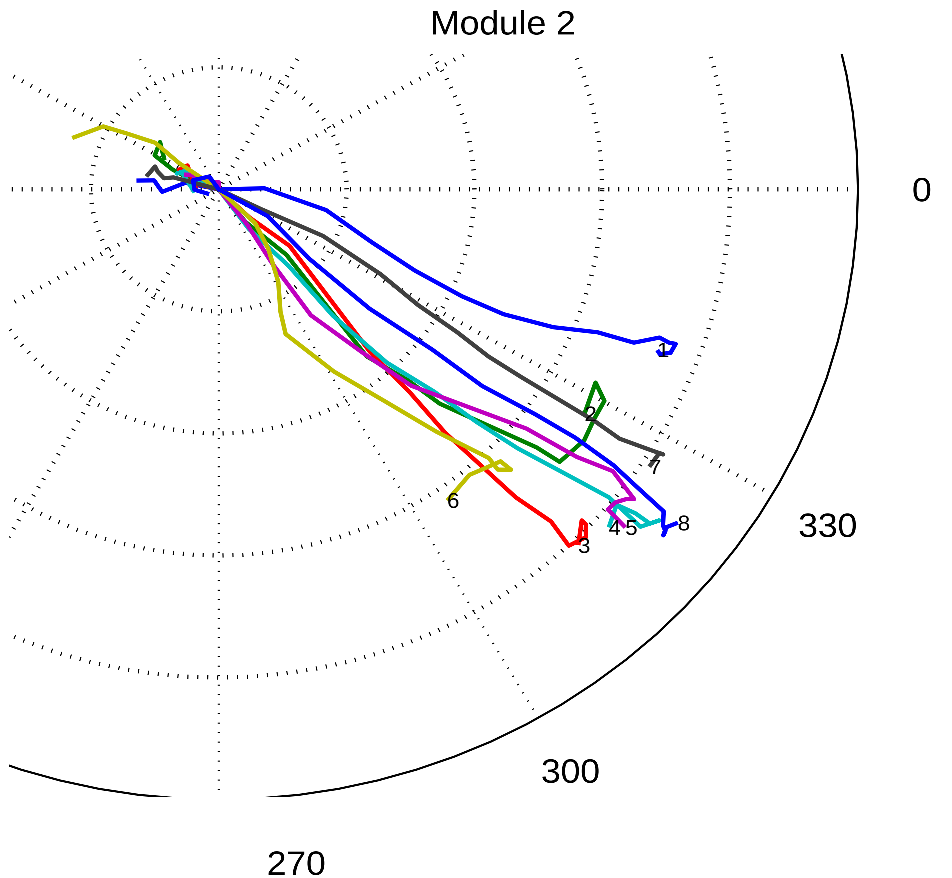


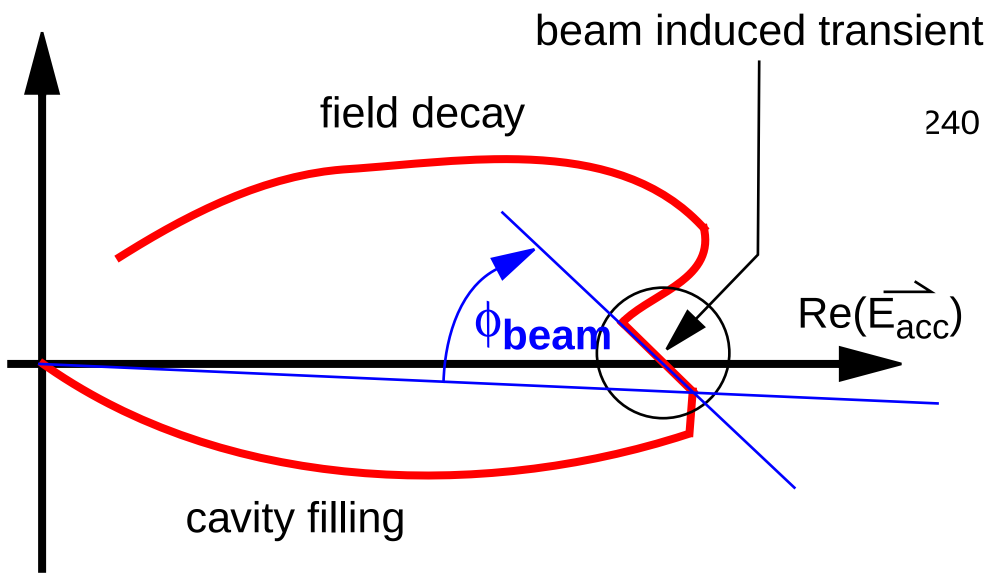
Digital Control at the TTF



Beam Transient based Phase and Gradient Calibration



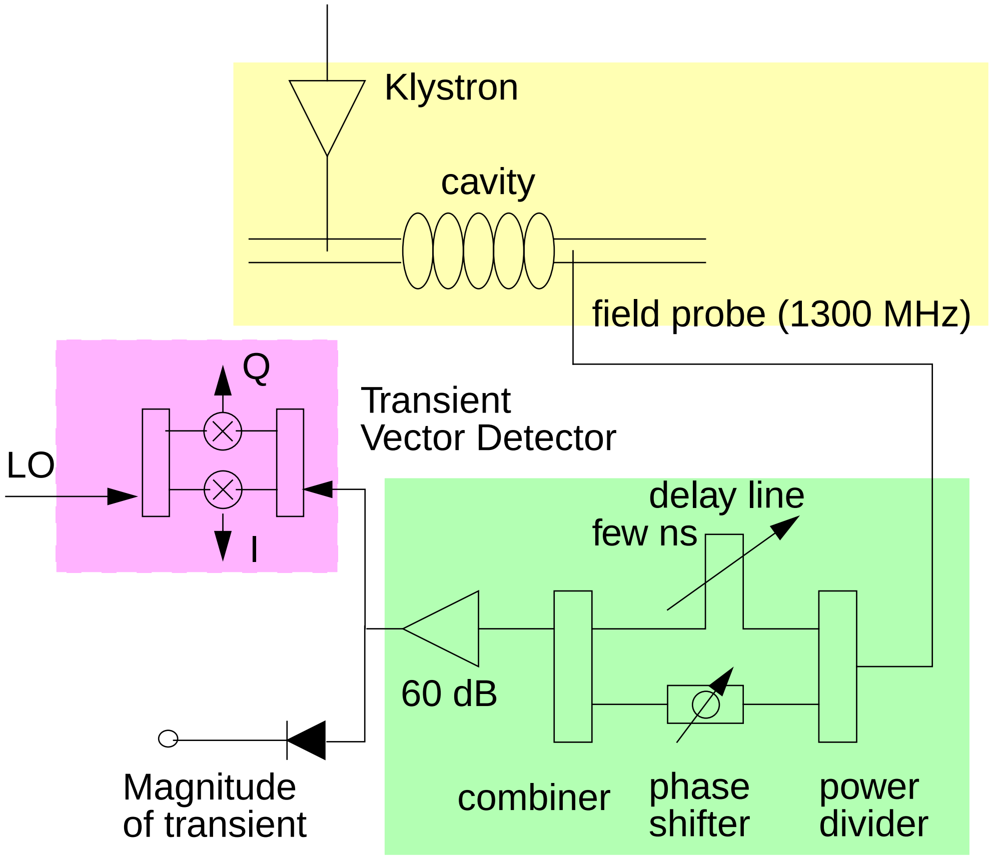




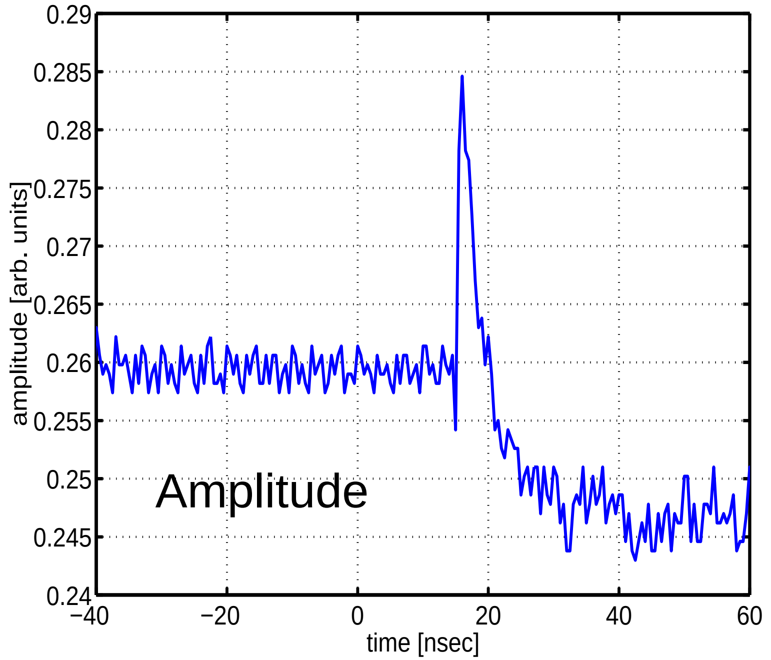
for $\Delta t << \tau_{cav}$:

$$\Delta V_{ind} = I \cdot \Delta t \cdot \left(\frac{r}{Q}\right) \cdot \pi \cdot f$$

Single Bunch transient Detection

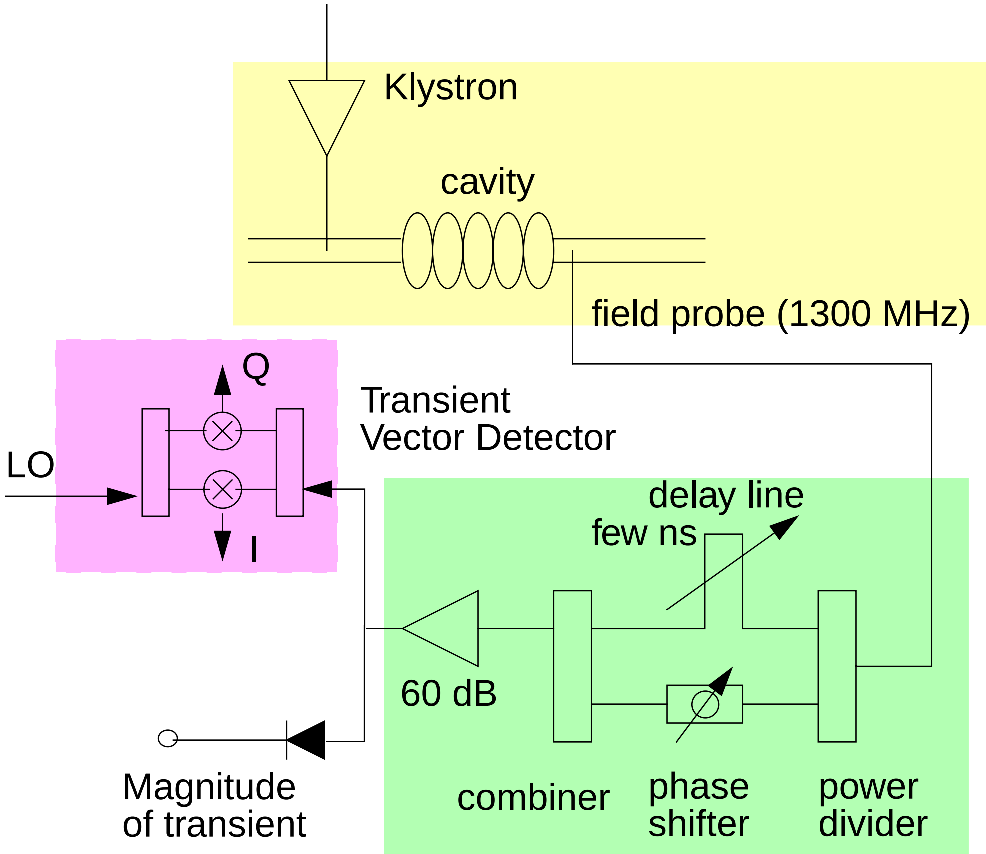


Principle of high resolution transient detector

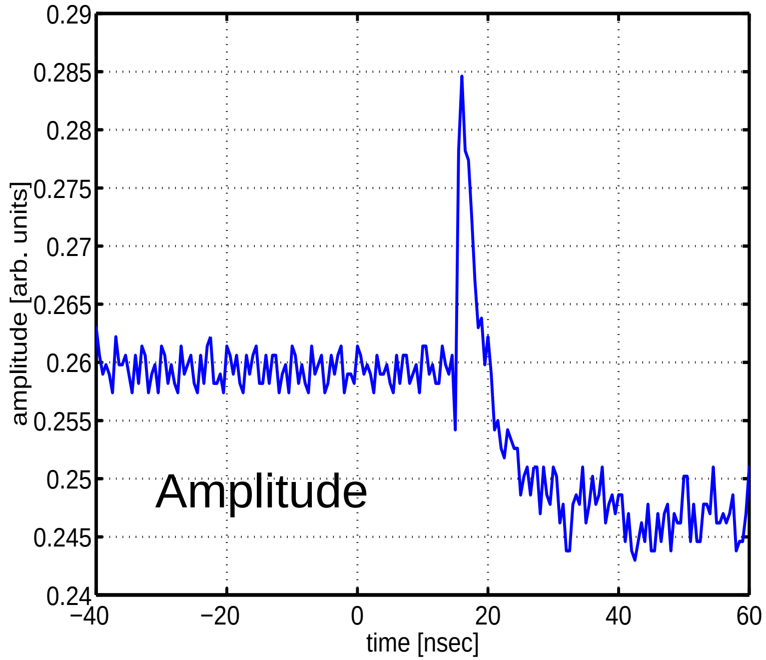


Single Bunch Transient (ΔA/A=0.1%)

Single Bunch transient Detection



Principle of high resolution transient detector

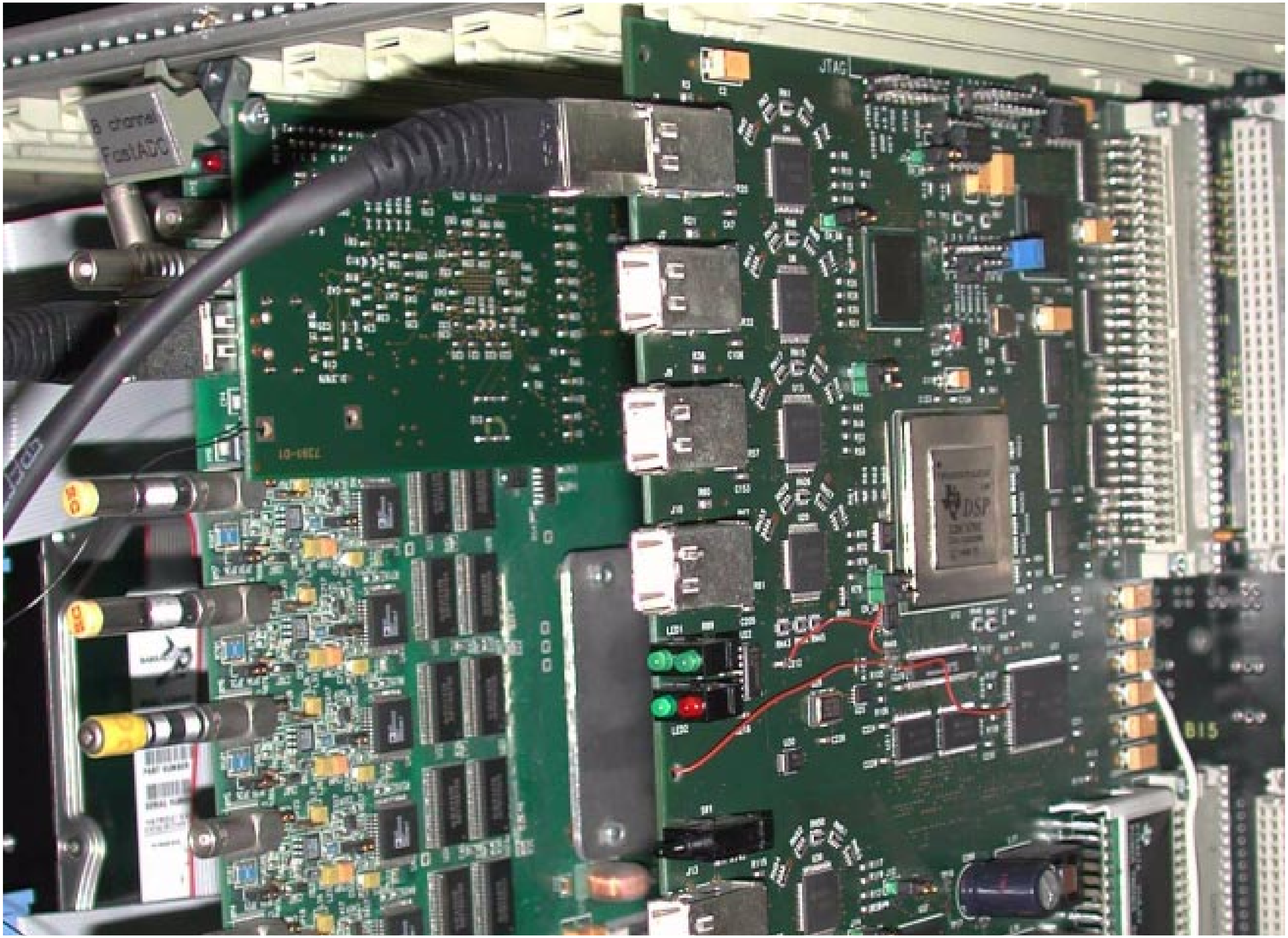


Single Bunch Transient (ΔA/A=0.1%)

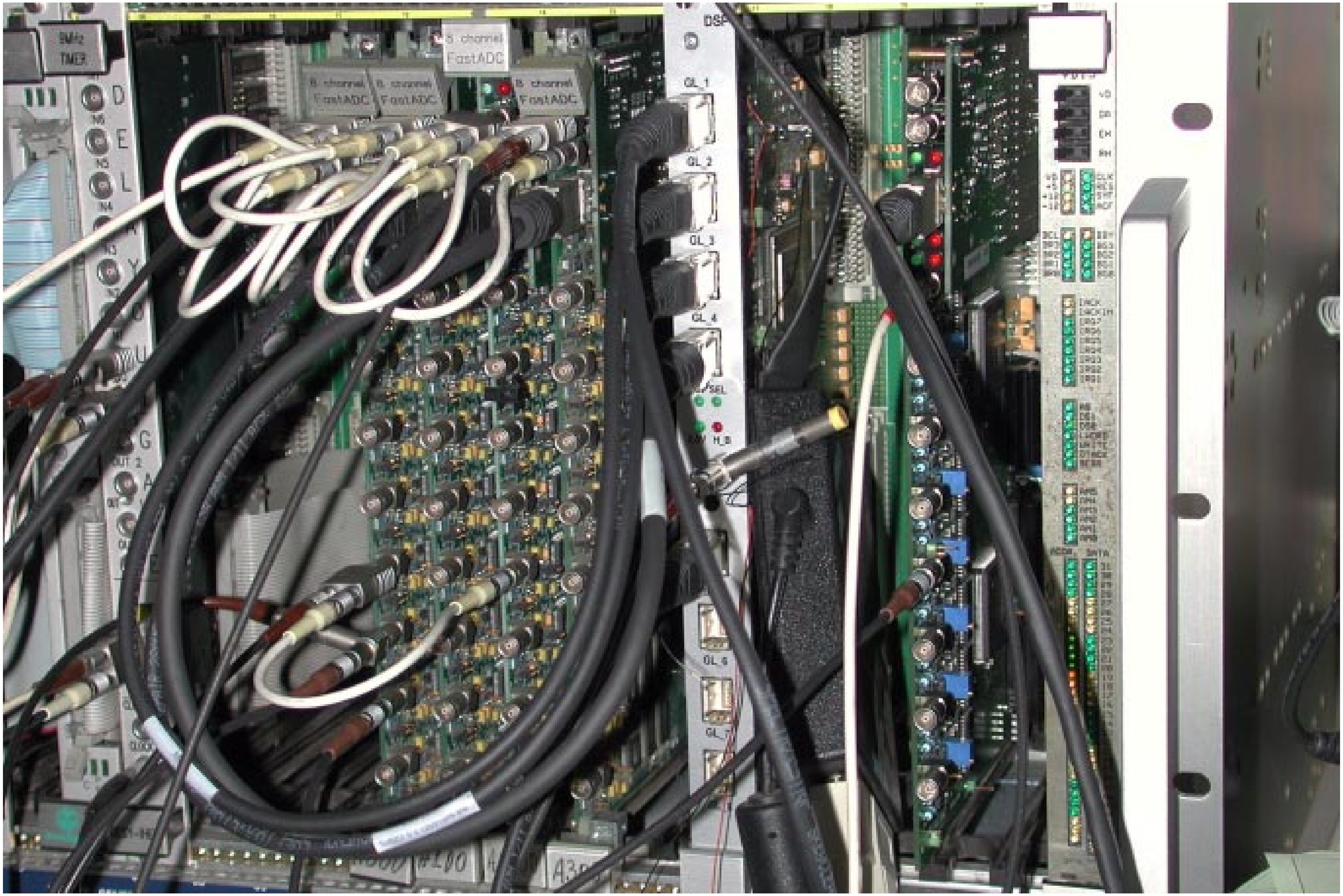
LLRF for TTF II

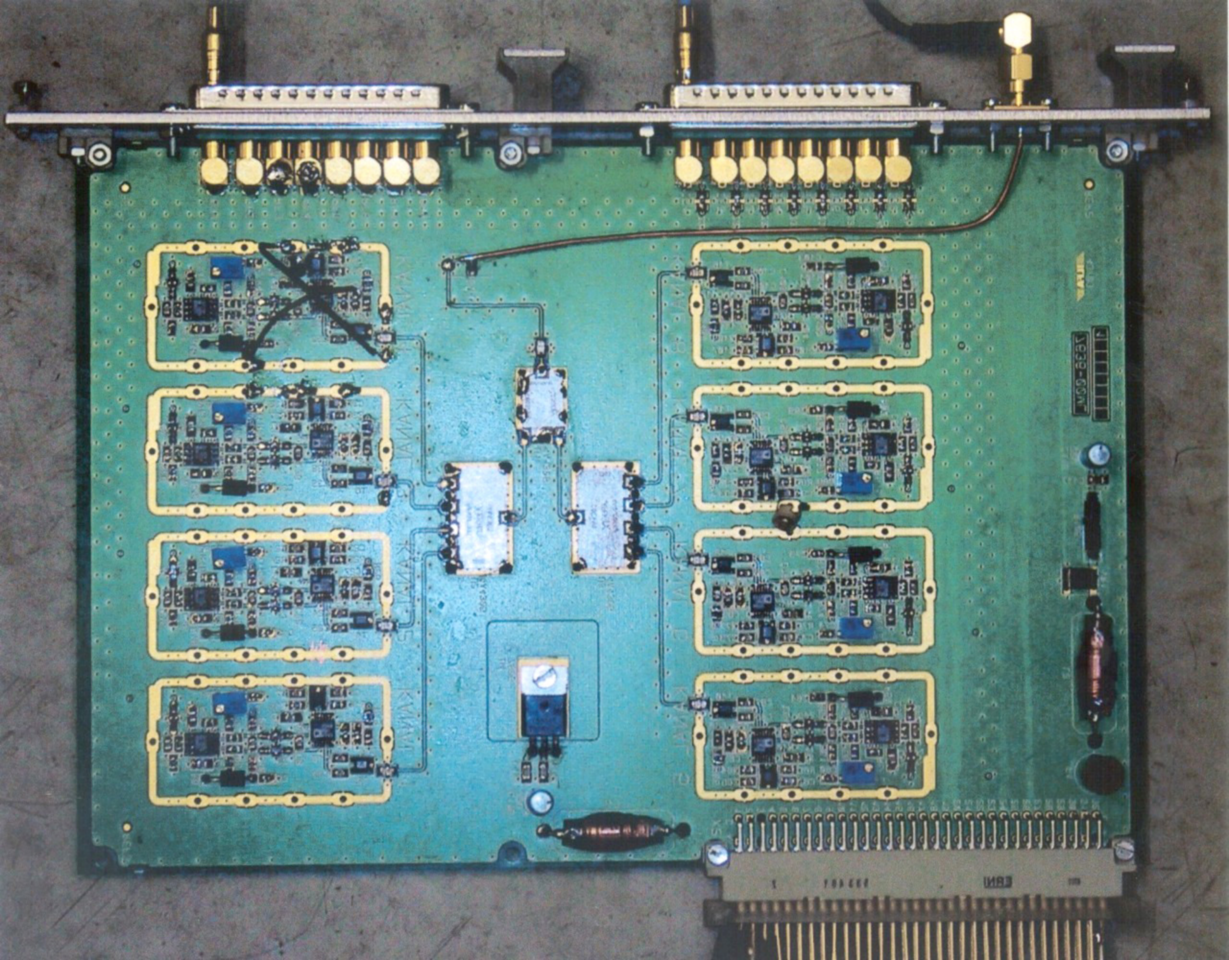
- Digital Feedback
  - C67 based DSP board
  - 8 channel ADC boards
  - 8 channel DAC board
  - Gigalink interface between boards
- Downconverter based on AD 8343
- Master Oscillator and Frequency Distribution
  - New Frequencies 13.5 MHz and 2856 MHz

C67 DSP board

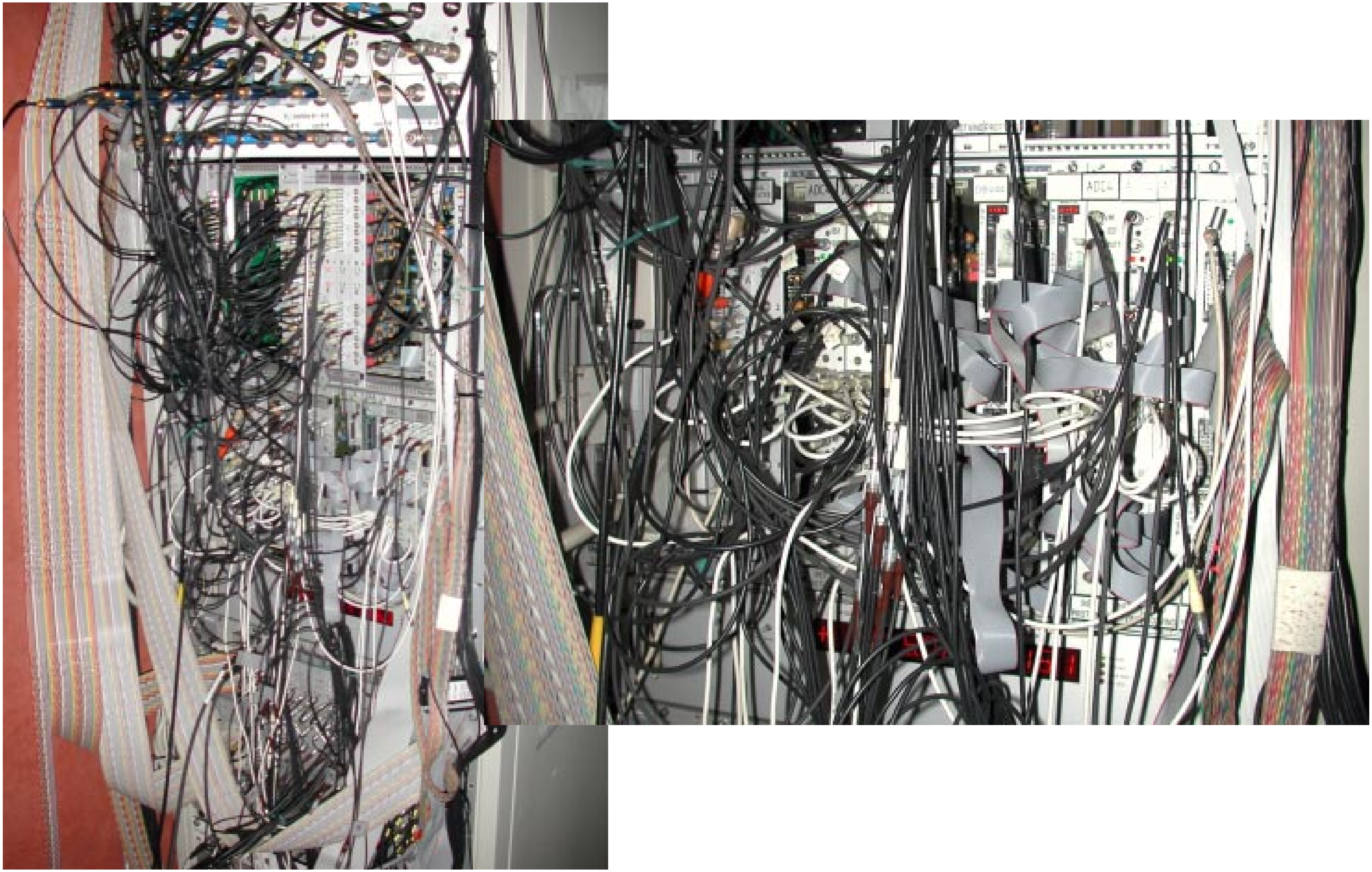


C67 DSP board

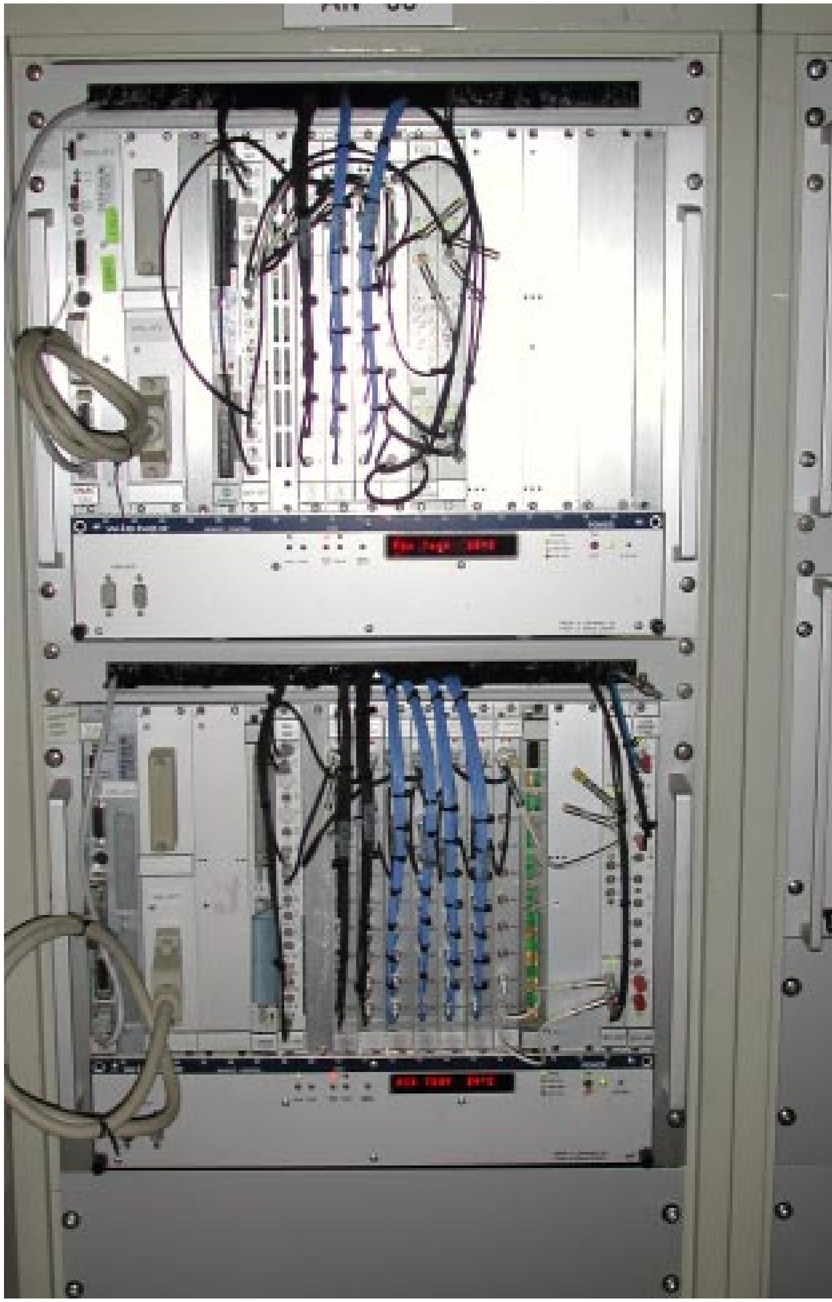




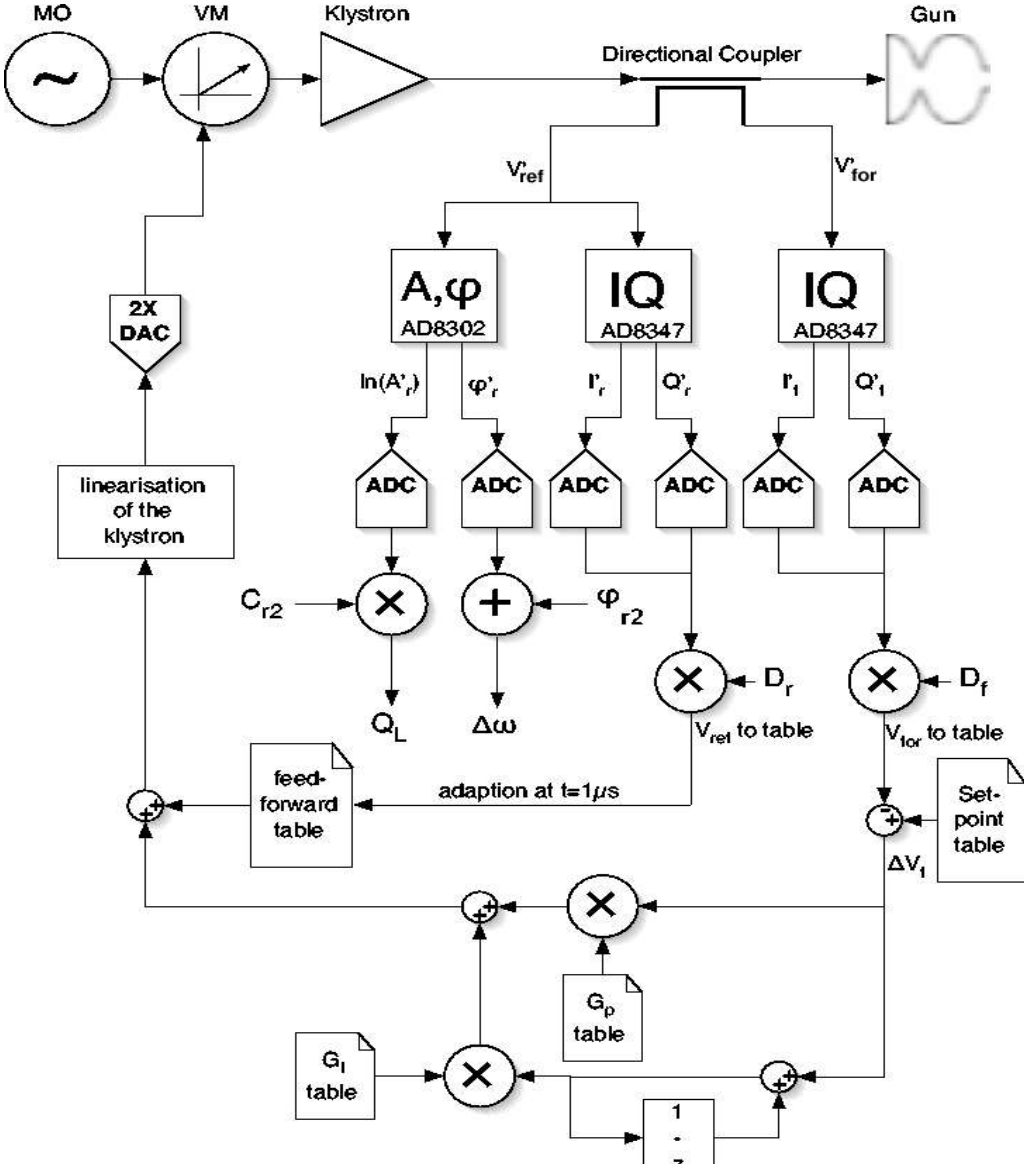
Rack Layout and Cabling for TTF I



Installation Status of LLRF for ACC 2-6



FB and FF Scheme

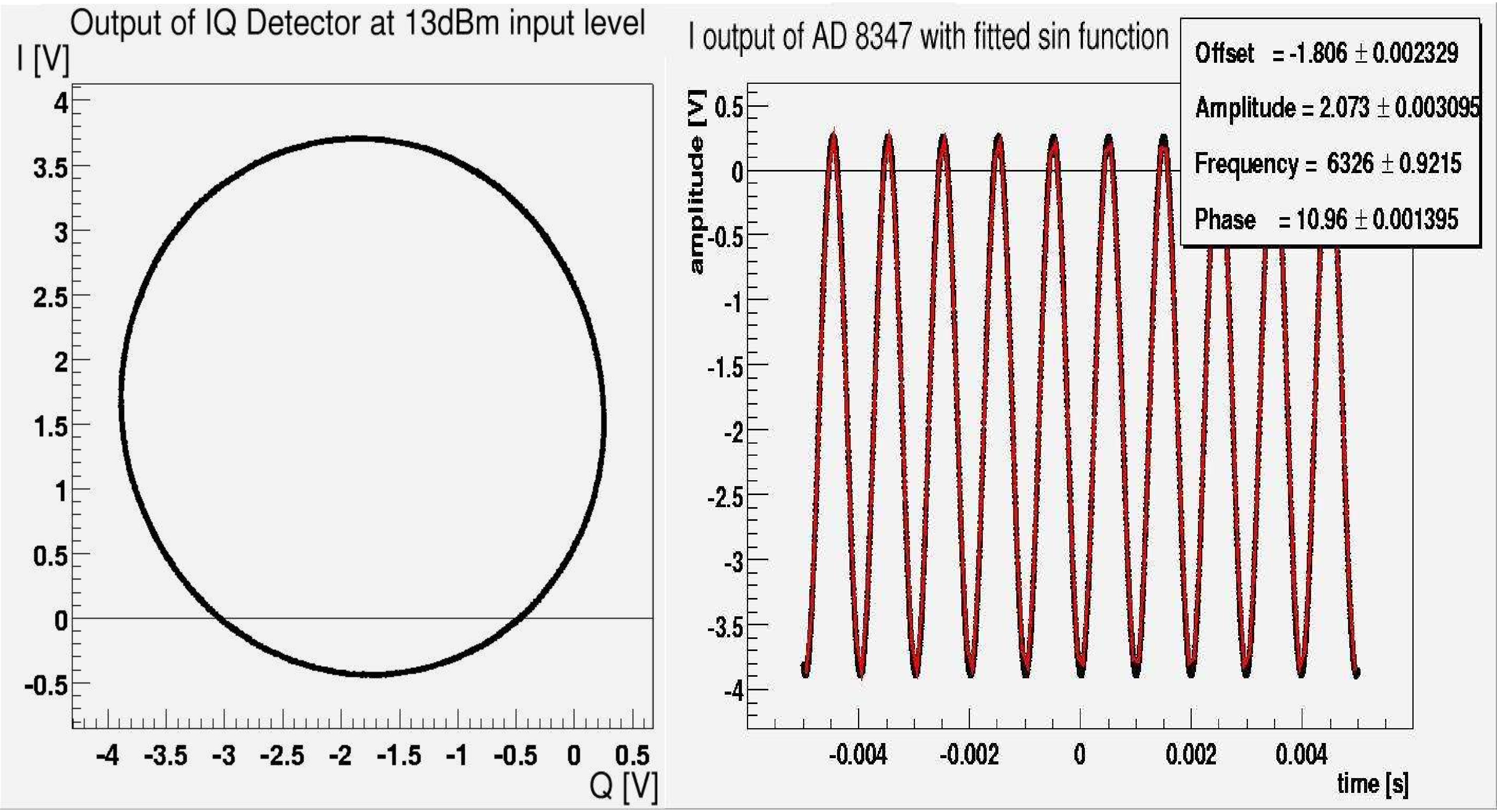


- No probe in the cavity
  - $V_{acc}=V_{for}+V_{ref}$
- Feedback on V_{for} (later with V_{acc} ?) with variable G_p and G_I
- Feedforward on V_{for}
- adaption of FF with V_{ref}

Detectors for Gun Control

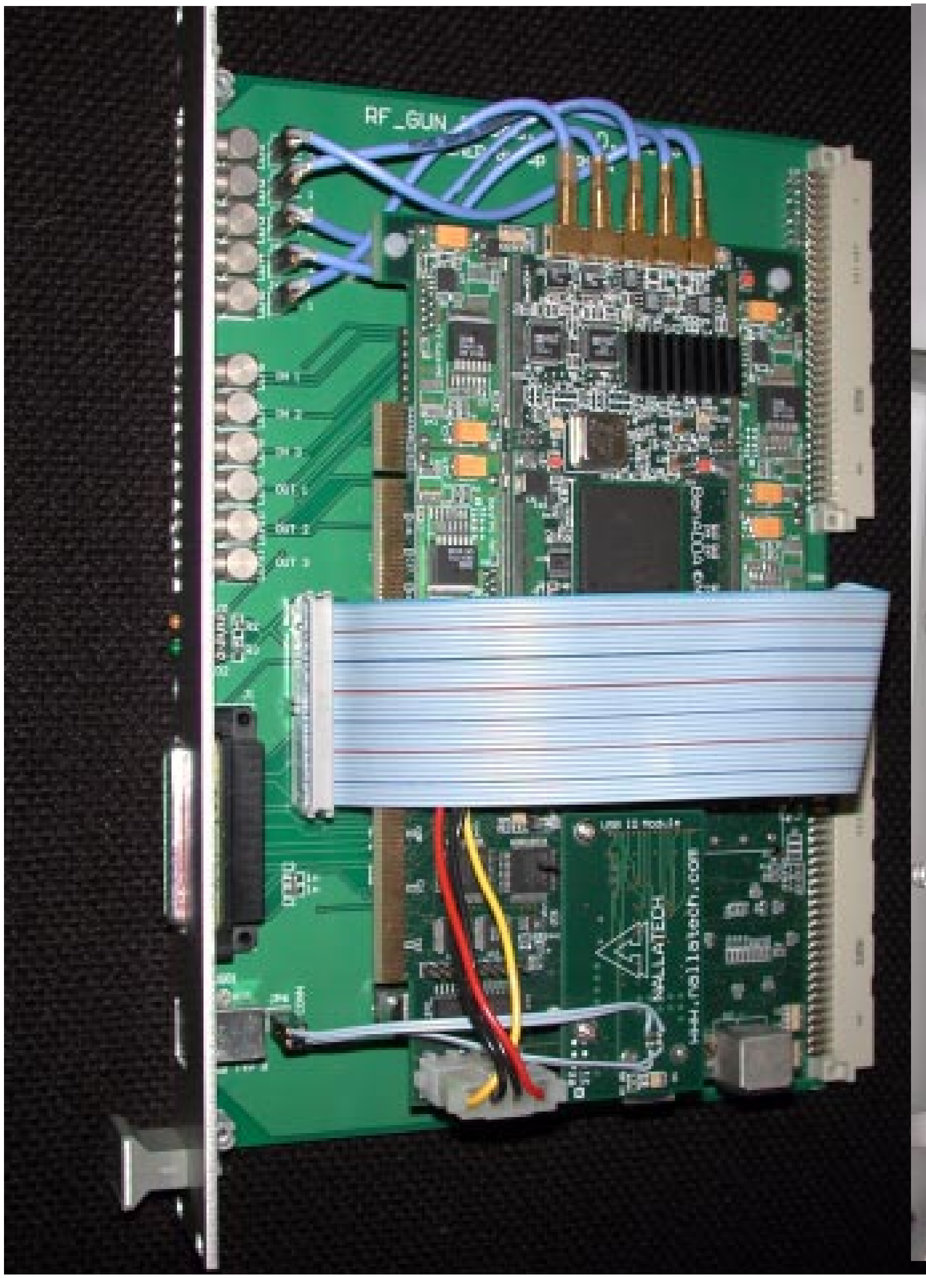
- The same detectors for forward and reflected power
- Field control with IQ detectors (AD 8347)
- Measurement of Loaded Q and detuning with logarithmic amplitude and phase detector (AD 8302)
- Modern phase detector (HMC 439) for phase monitoring
- Detector diode for amplitude monitoring

Performance of the IQ Detector

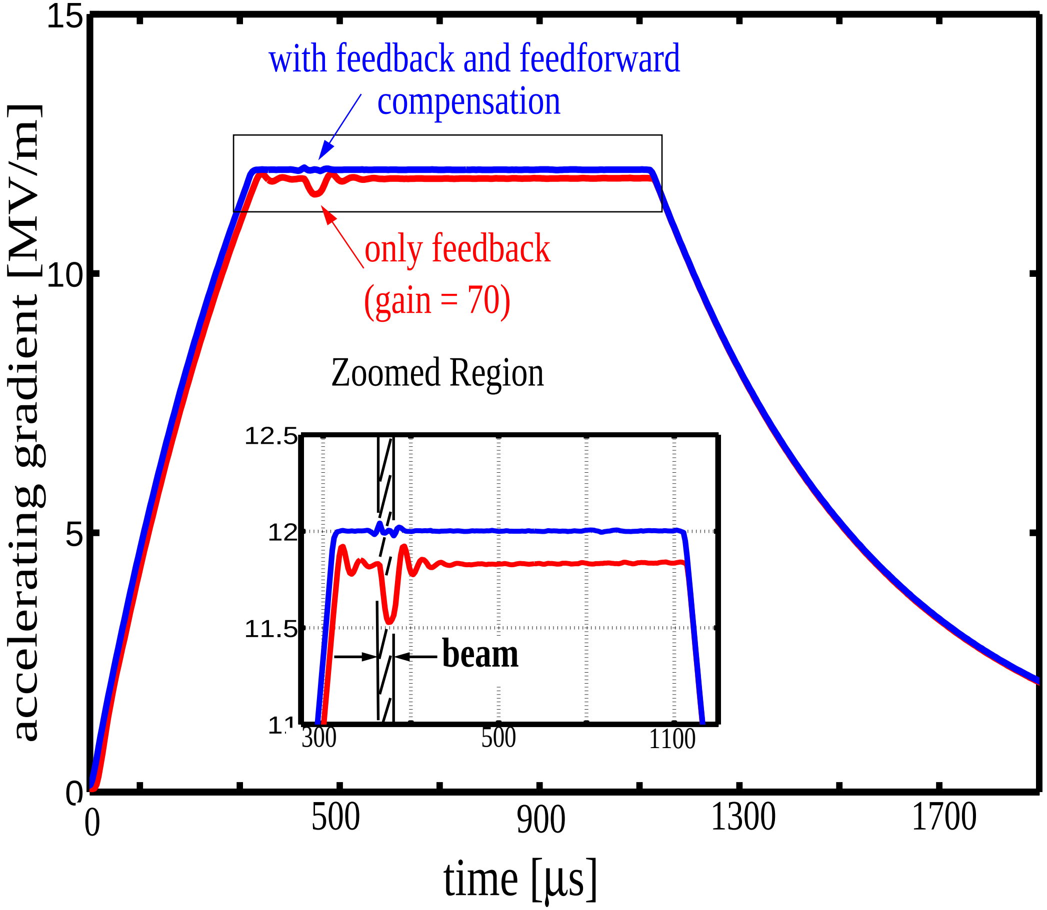


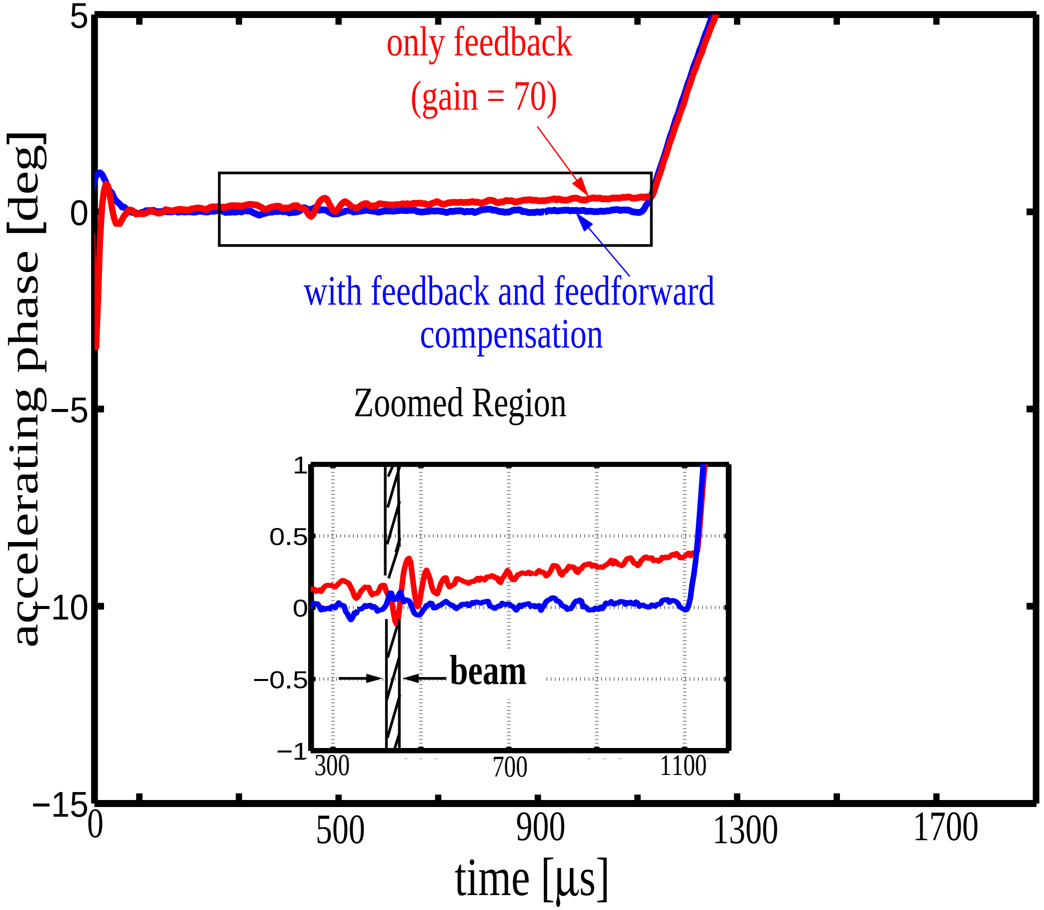

FORWARD
PHASE+
I+
Q+
AMP+
PHASE+
AMP
LO
REFLECTED
AMP
AMP+
PHASE+
I+
Q+
AD8302
ROHDE&SCHWARZ
SIGNAL GENERATOR · 9 kHz
SML 03
POWER
QUICK SELECT
MENU / VARIATION

FPGA based RF Gun ControllerFPGA



Performance at TTF (1)

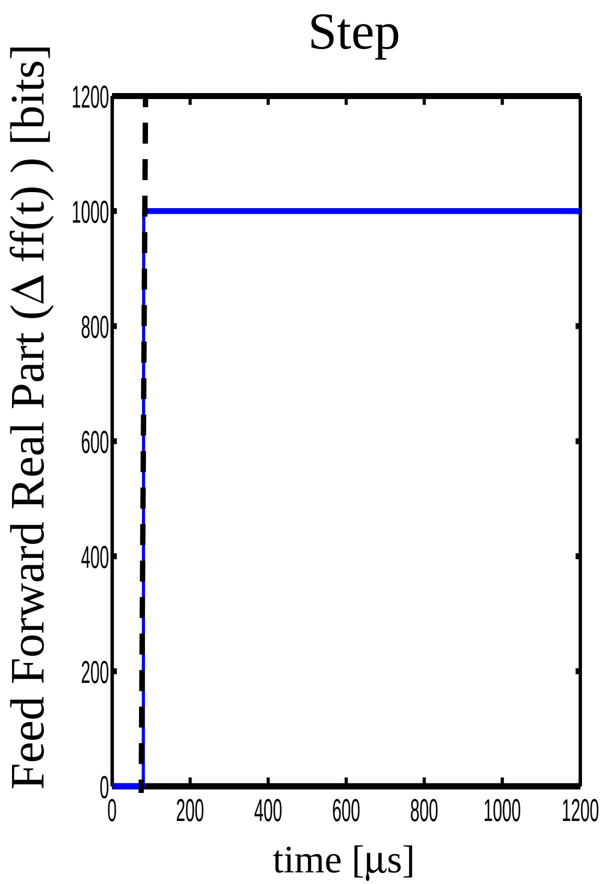


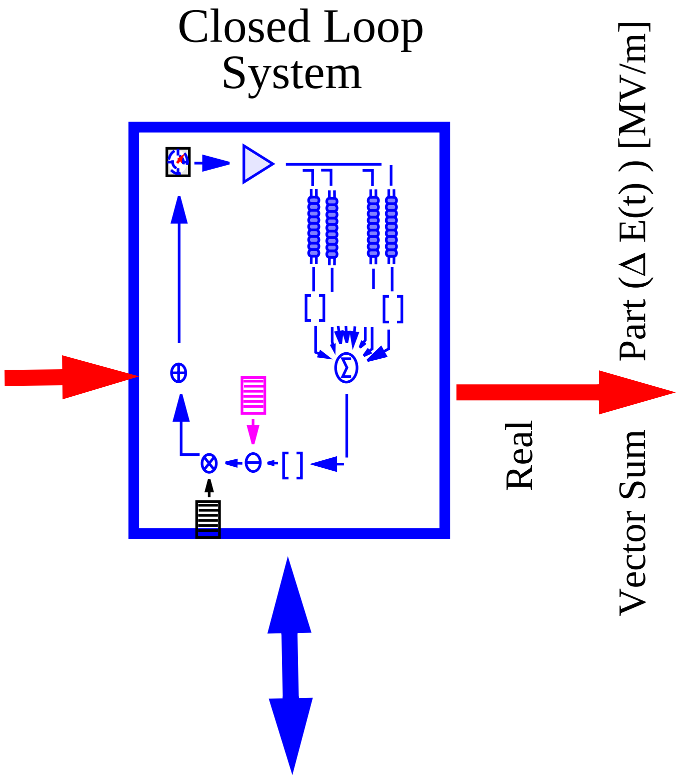


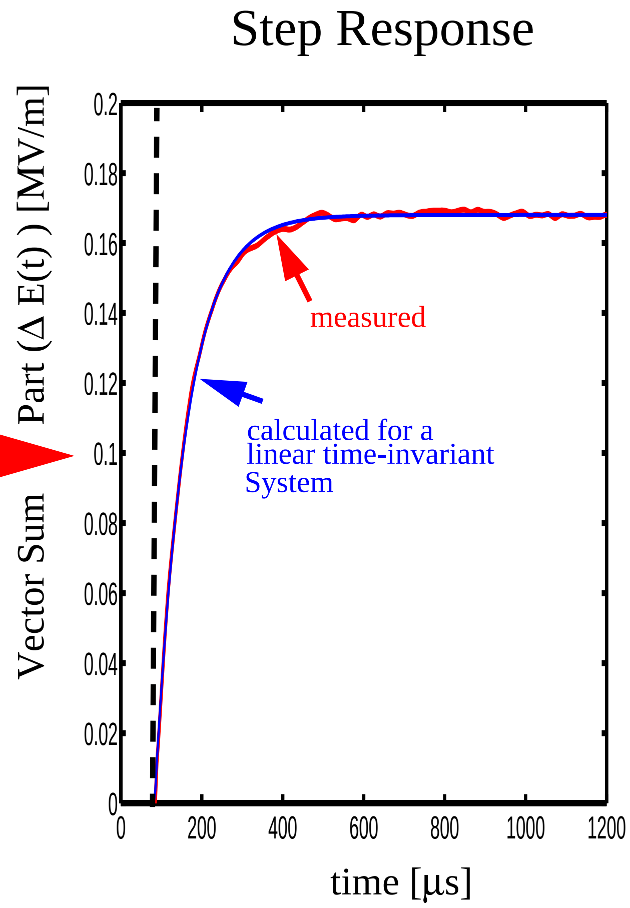
Amplitude

Phase

Adaptive Feedforward



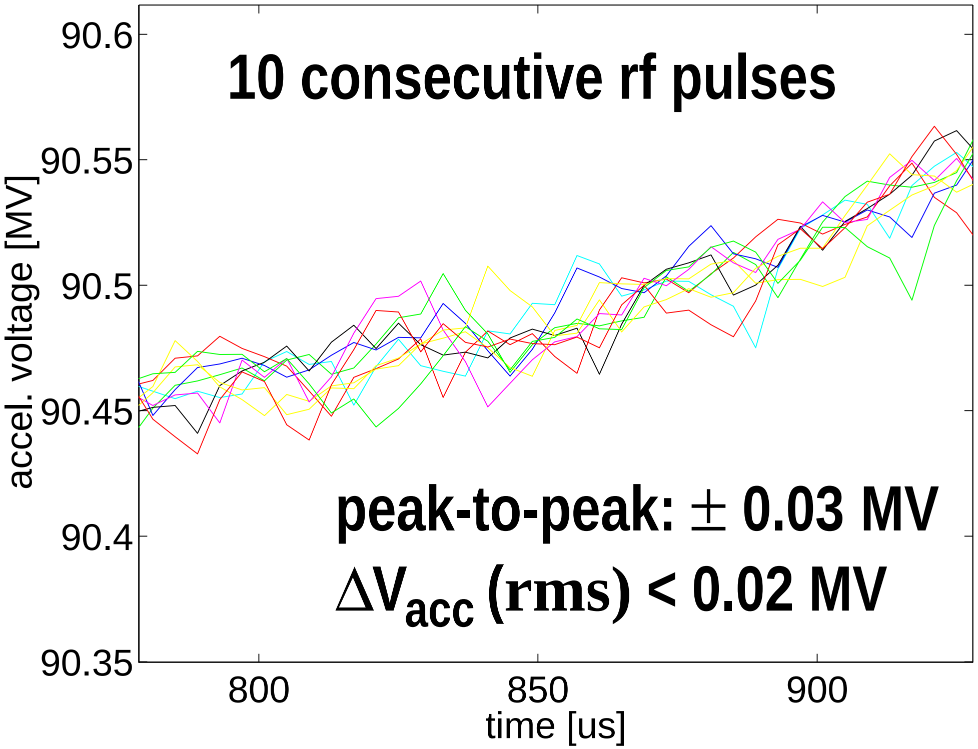


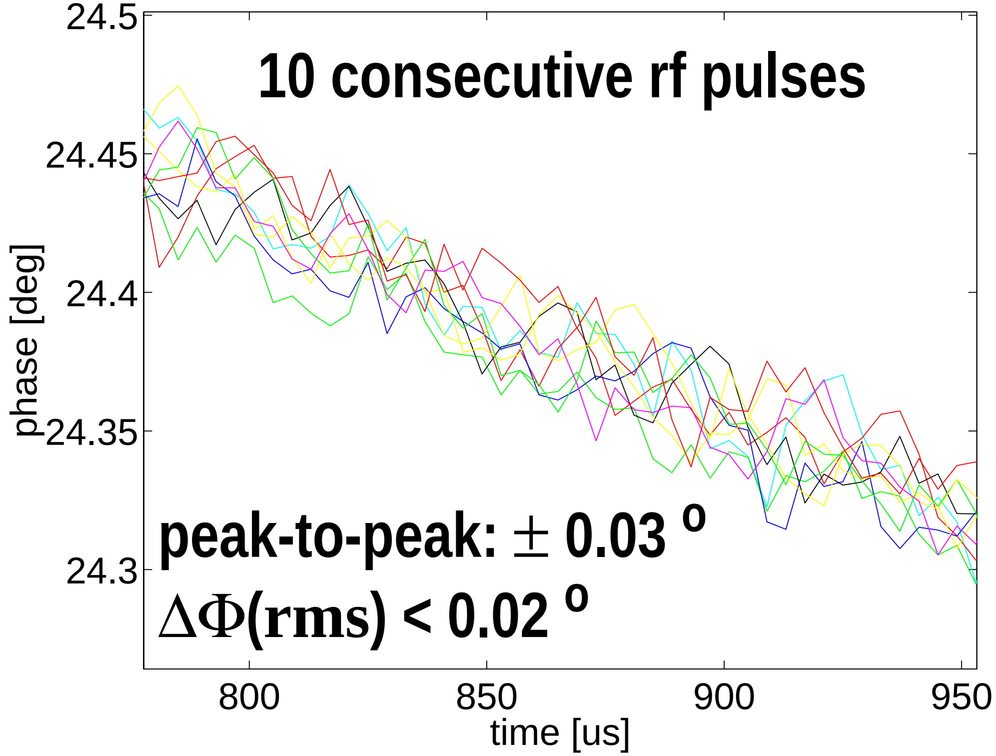


$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \dots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1n} \\ T_{21} & T_{22} & \dots & T_{2n} \\ \dots & \dots & \dots & \dots \\ T_{n1} & T_{n2} & \dots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta ff_n \\ \dots \\ \Delta ff_n \end{bmatrix}$$

$$\Delta ff(t) = \sum_j \Delta ff_j \Theta(t - t_j).$$

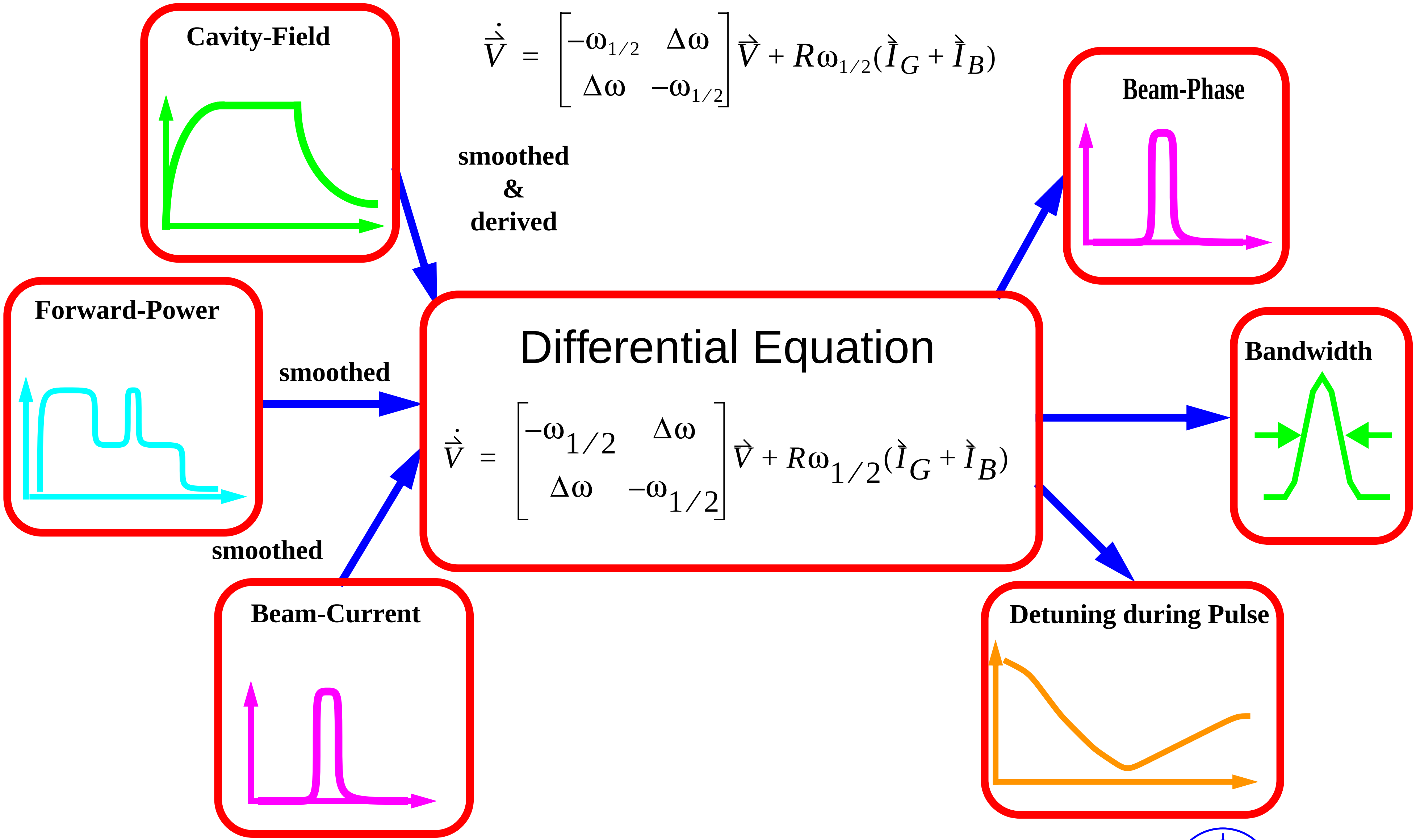
Reproducibility of Subsequent Pulses of Vector-Sum



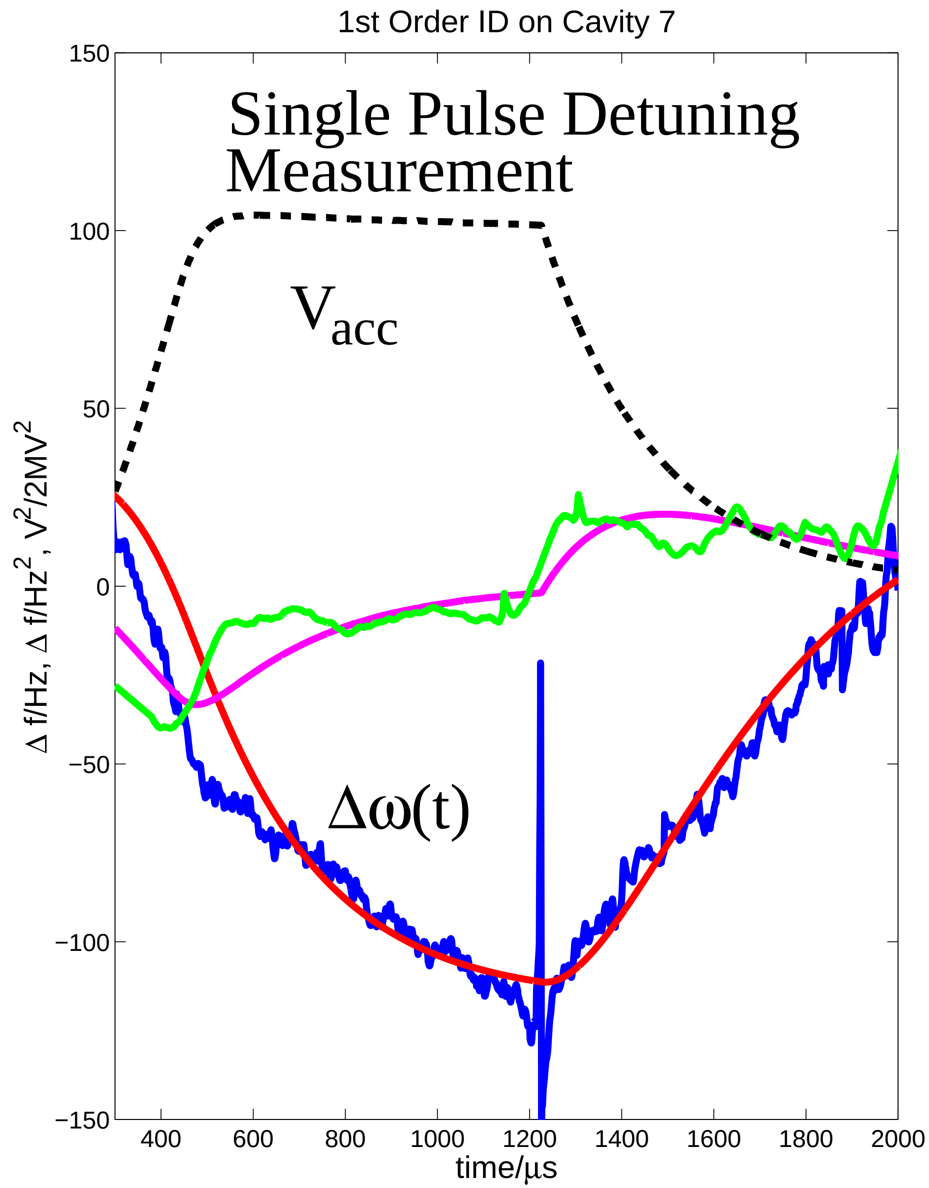


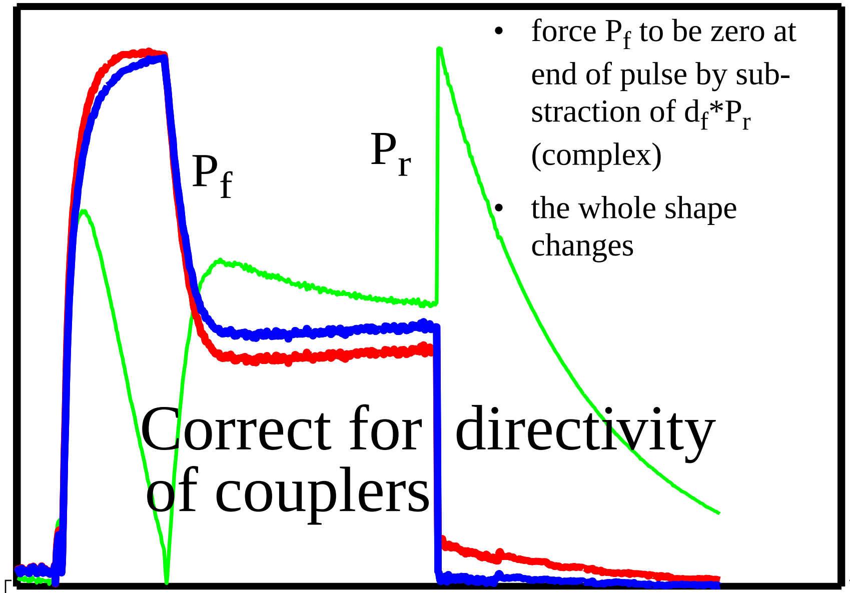
Gradient **Phase**

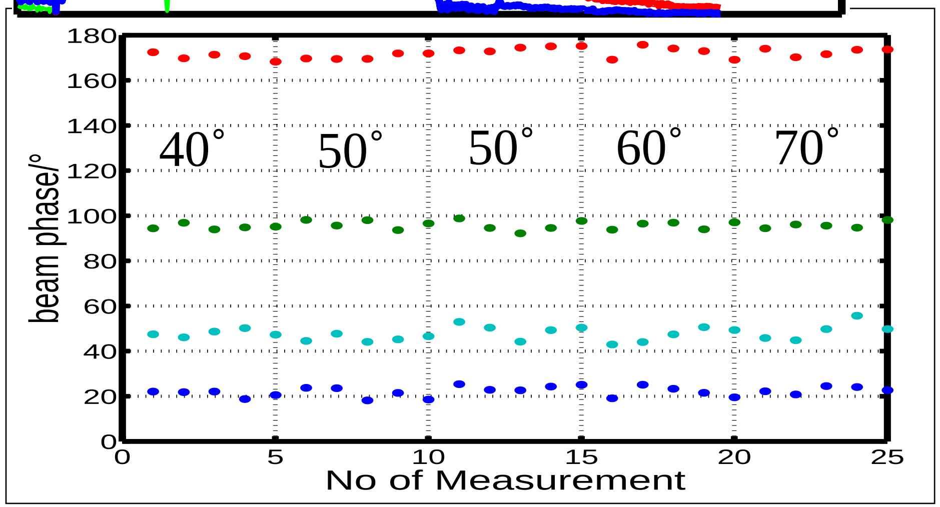
System Identification (1)



System Identification (2)

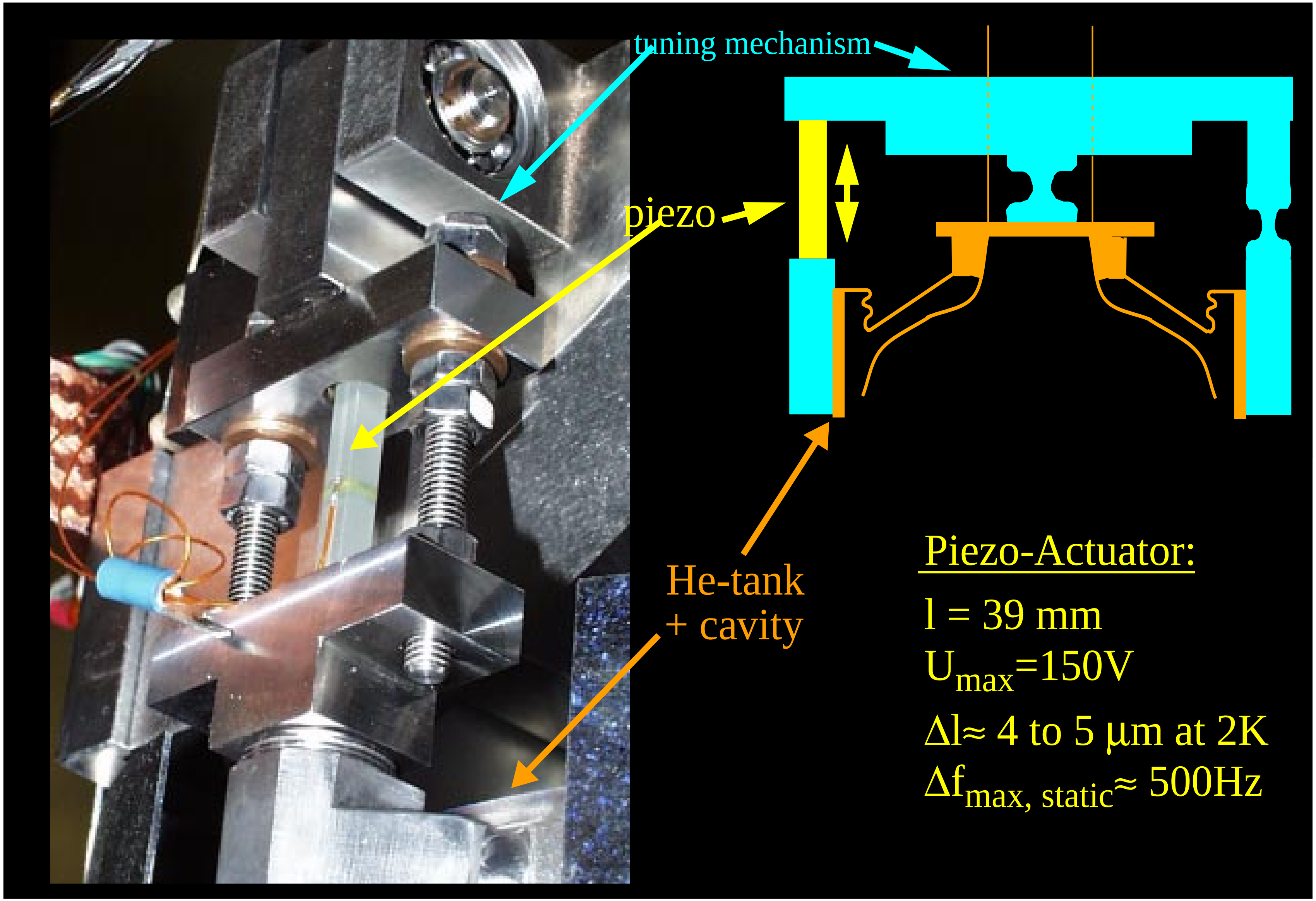




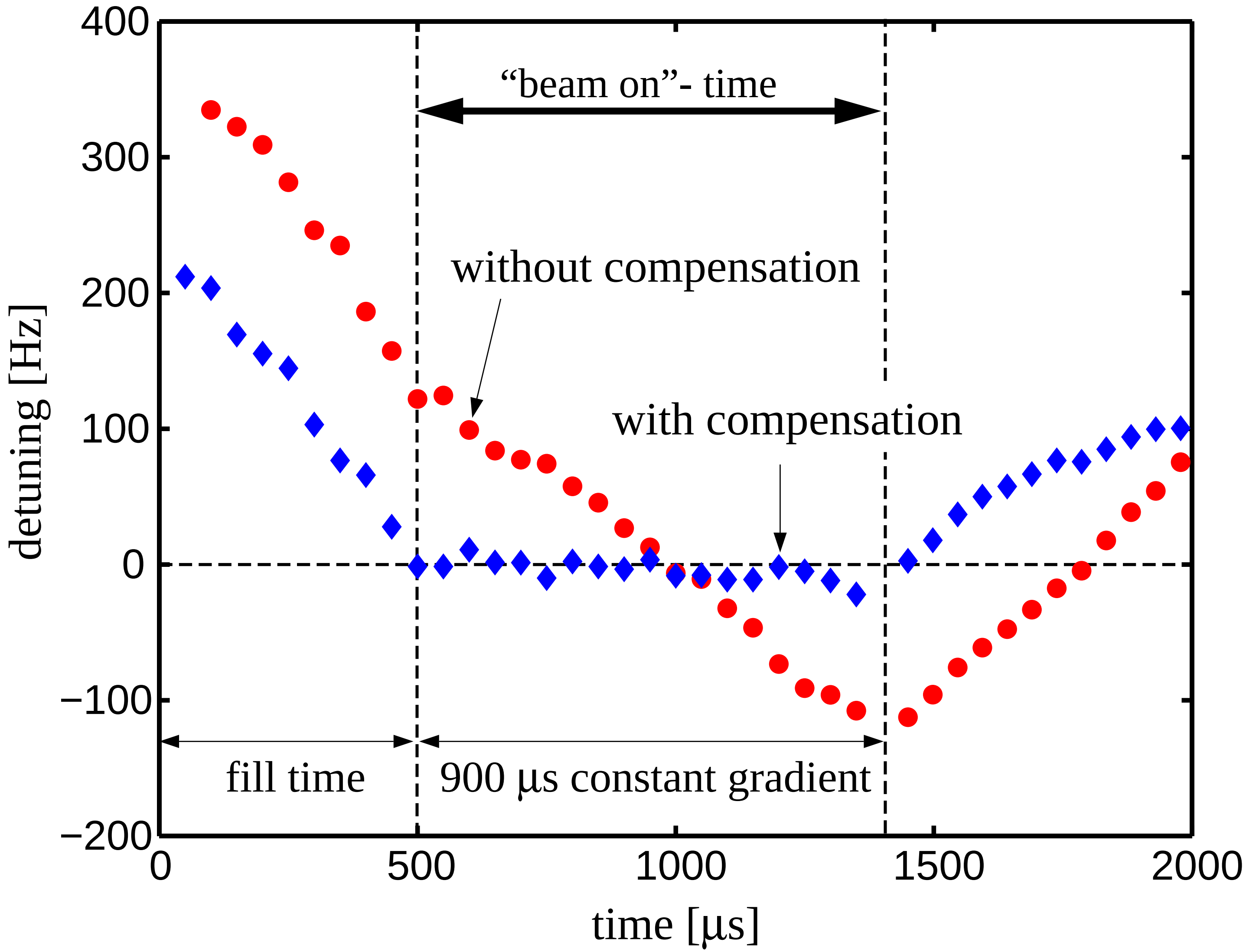


Beam phase of 4 cavities for different phase of V_{acc}

Active Compensation of Lorentz Force Detuning (1)



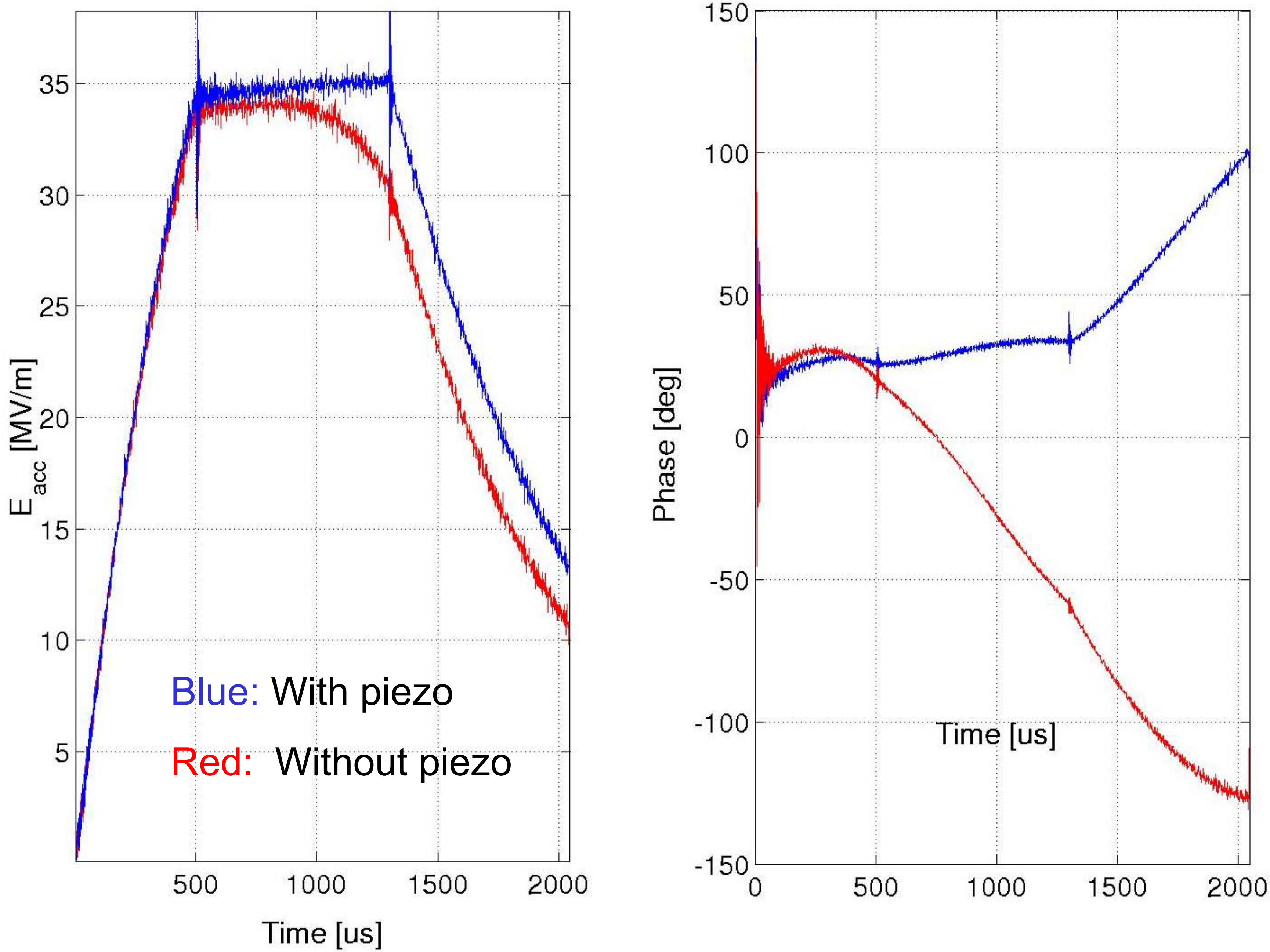
Active Compensation of Lorentz Force Detuning (2)



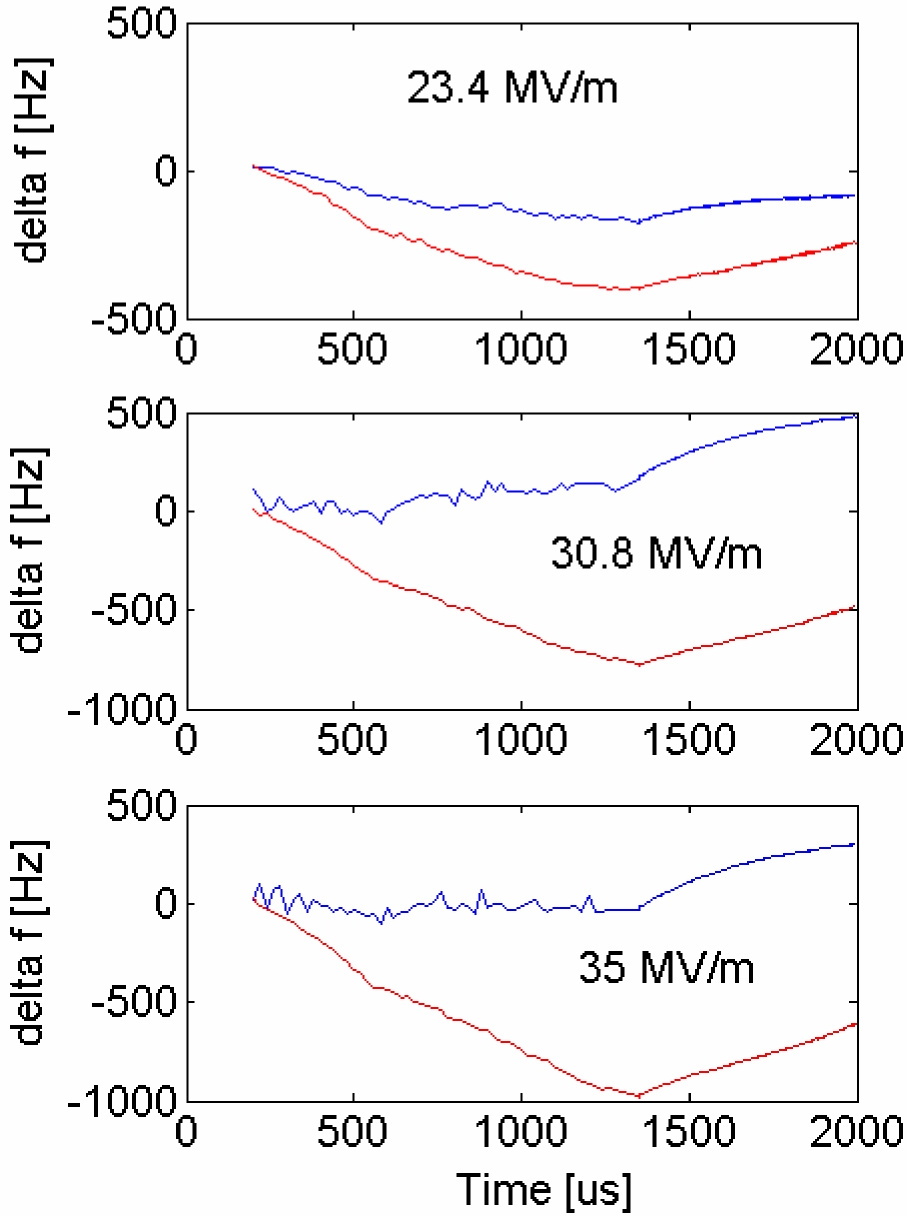
9-cell cavity operated at 23.5 MV/m

Lorentz force compensated with fast piezoelectric tuner

RF signals at 35 MV/m



NEW: Frequency stabilization at 35 MV/m



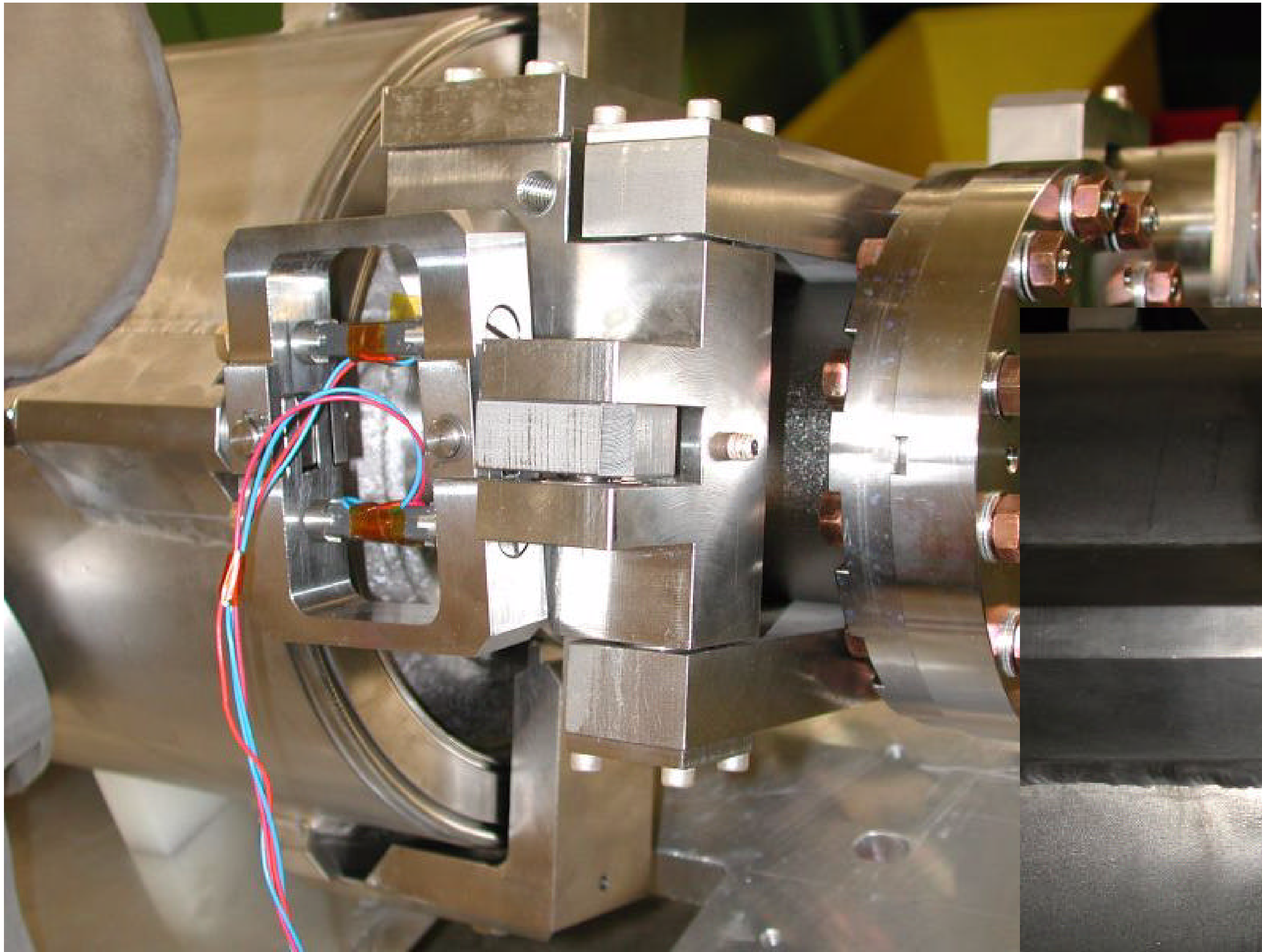
Blue: With piezo

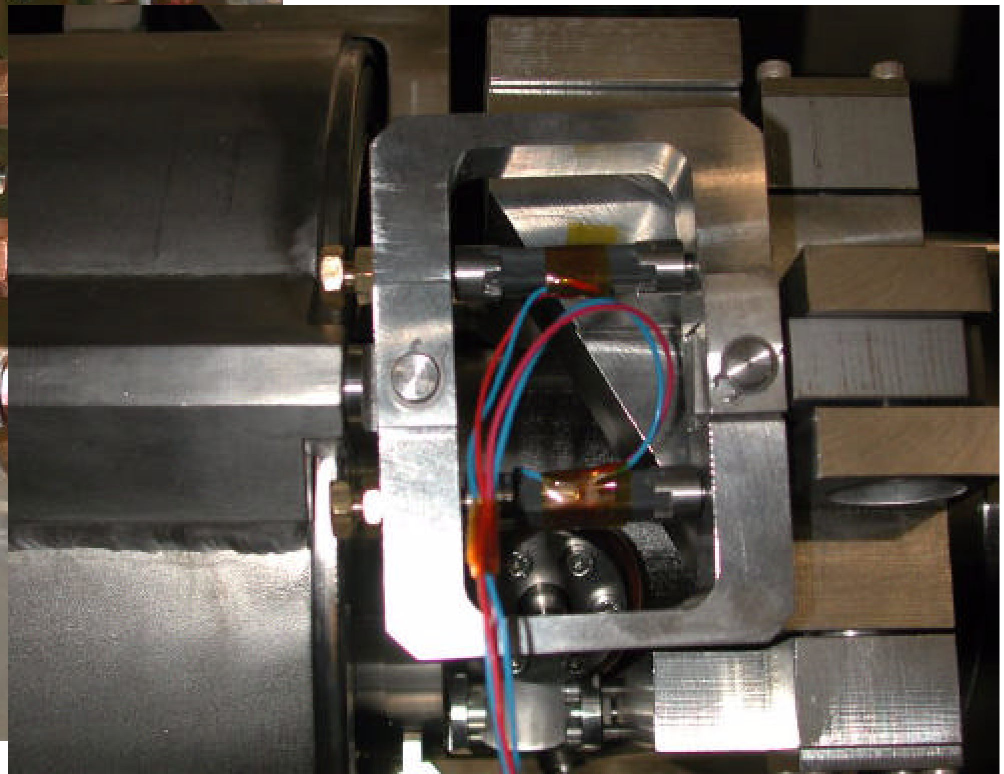
Red: Without piezo

Frequency detuning of ~1000 Hz compensated with resonant excitation of a mechanical cavity resonance at 230 Hz.

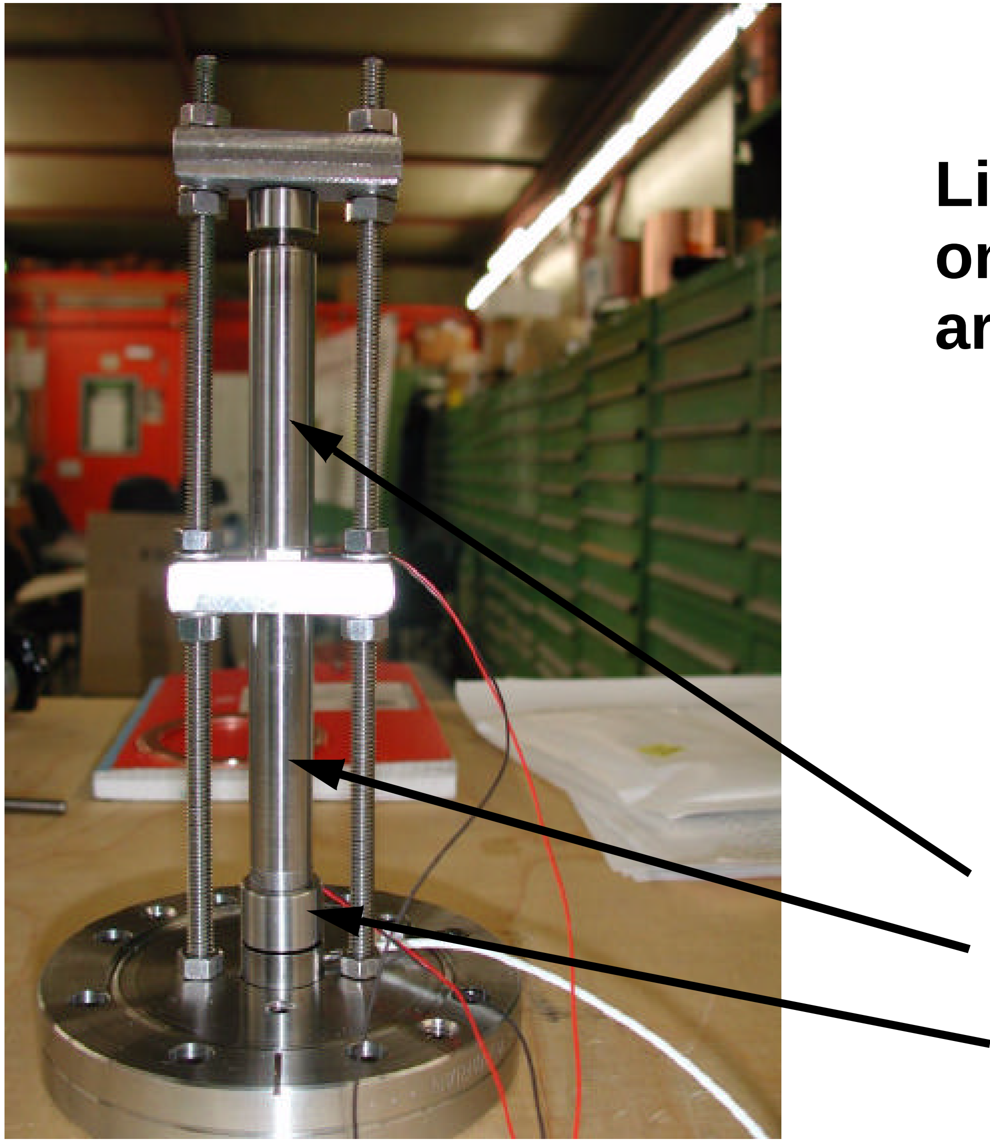
NOTE: This is rather an demonstration of the capability of active tuning. Application in a real machine is probably difficult/impossible.

Integration of Piezo Tuner for TTF

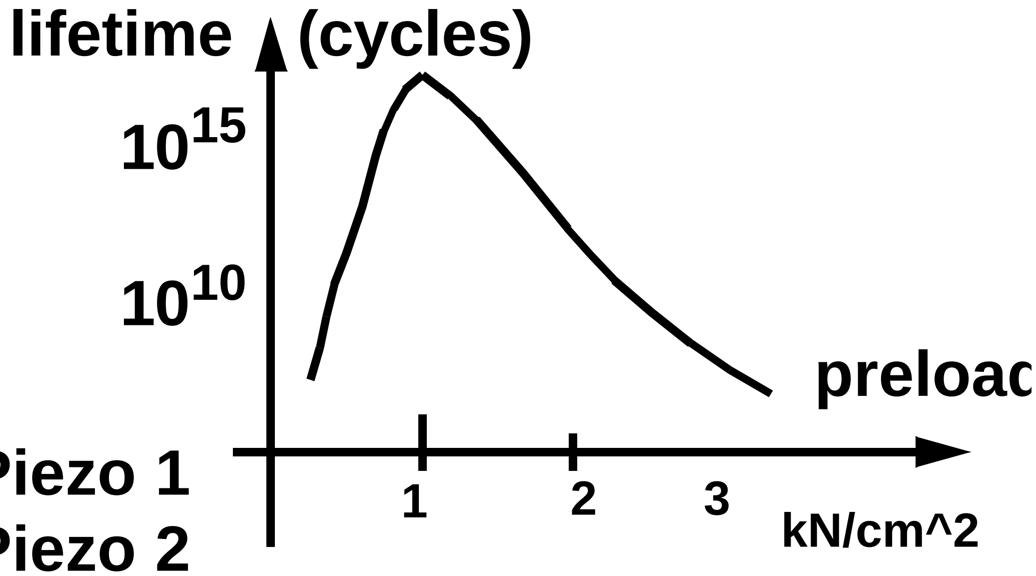




Measurement of Mechanical Preload

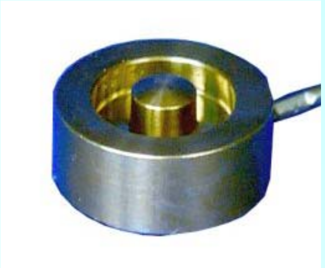


Lifetime of piezo depends strongly on mechanical preload. Optimum around 1 kN/ cm^2.

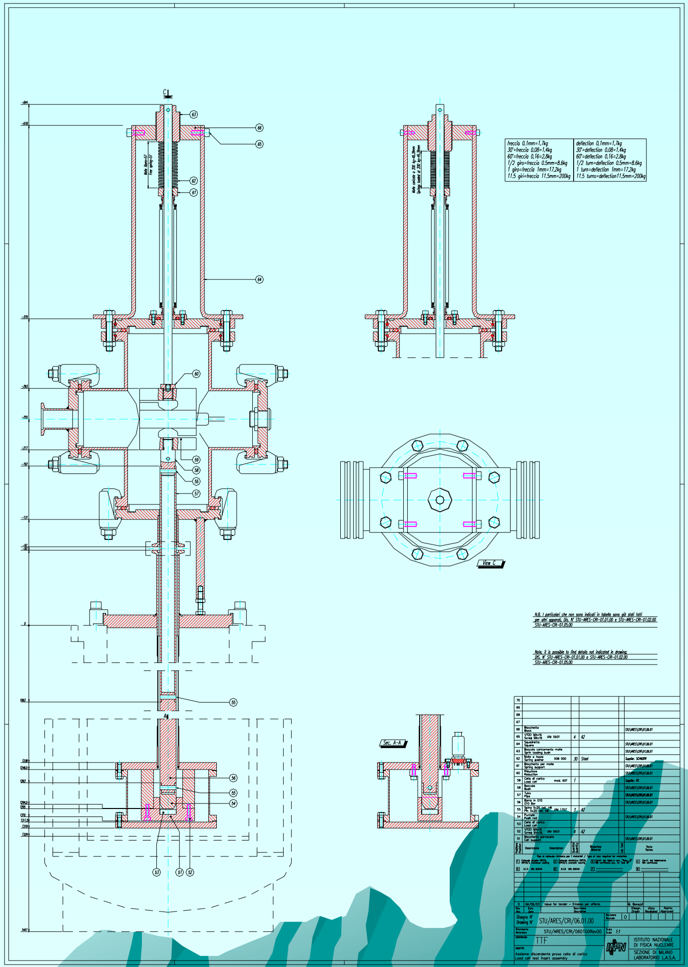


Characterization of the load cell

A new insert was designed to host different load cells and the load generating device. Our goal is the characterization of the sensor at 4 K up to 2kN.



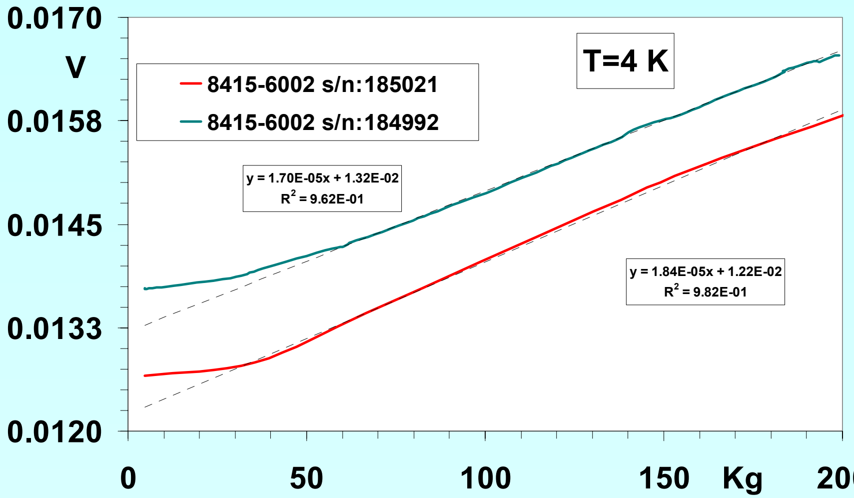
A load cell under test – from Burster

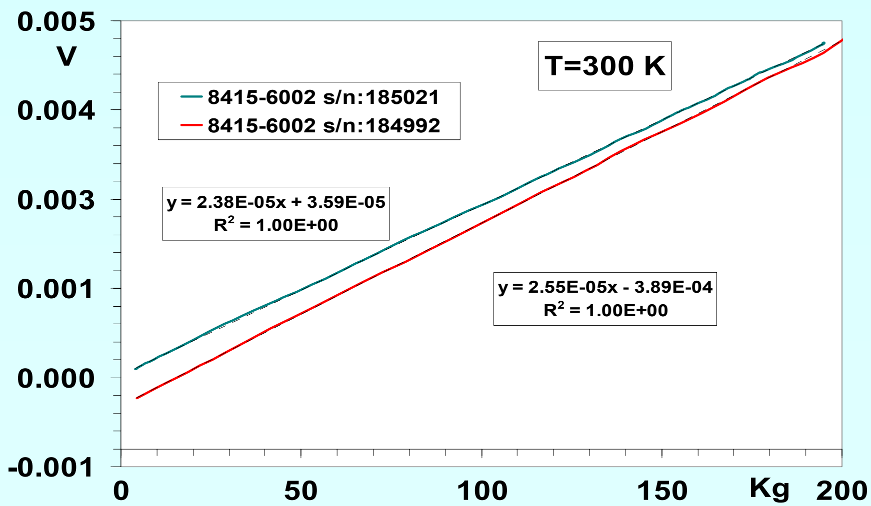


- The button on the cell is **pushed** by stainless steel rod, 20 mm diameter.
- The loading force is **generated** by a screwing device provided with washer springs at the top of the insert.
- The loading force is **measured** by a calibrated load cell placed in the cross junction, working at room temperature.

Some results

Up to now some 2kN load cells from Burster have been tested at 4K.



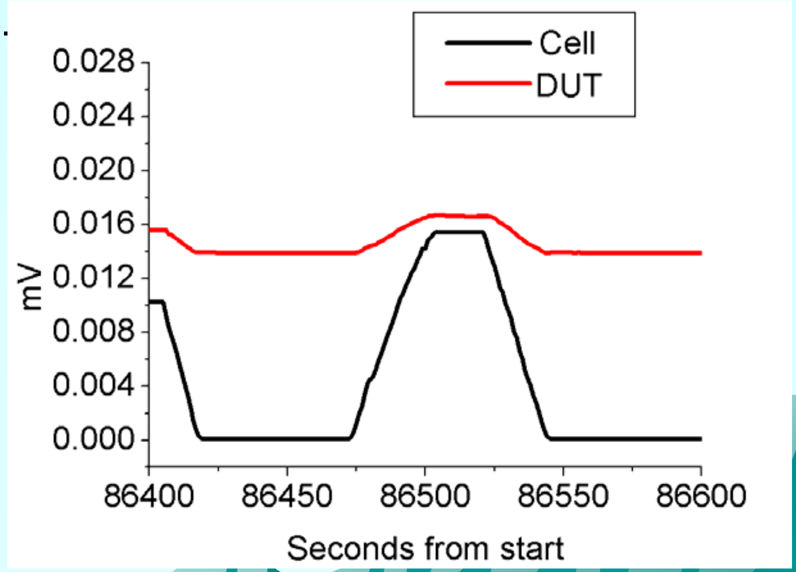


The measured TF of two 8415 model and their beaviour vs time

Now some points are clear:

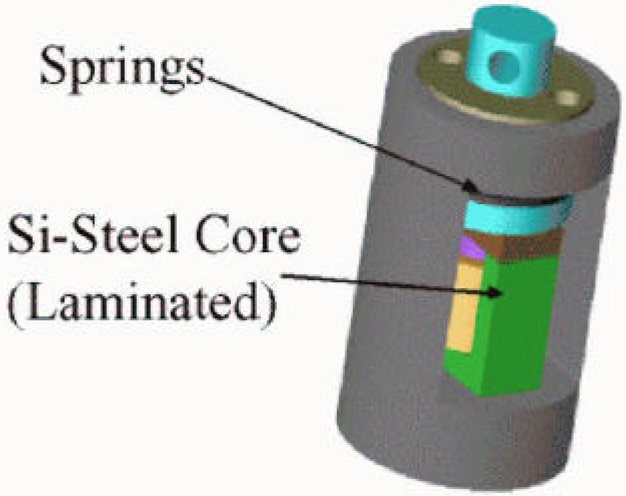
•High *offset* and low *reproducibility* are the main critical problems

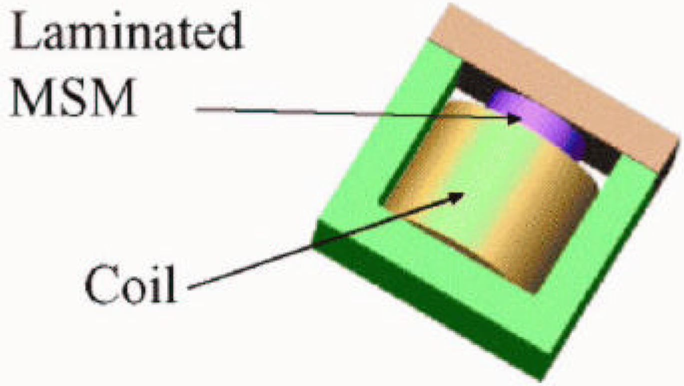
•Linear range reduces and reproducibility fails at cold => we'll test cells with *specific cryogenic* features and *higher RT range* (10-

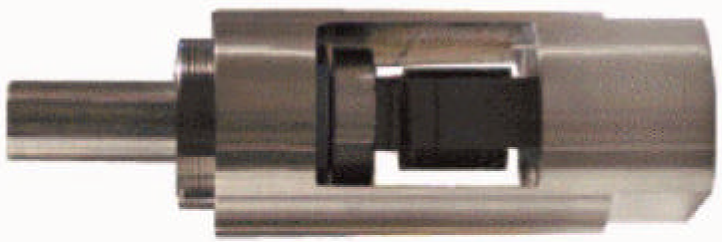


ENERGEN, INC.

The Fast Tuner

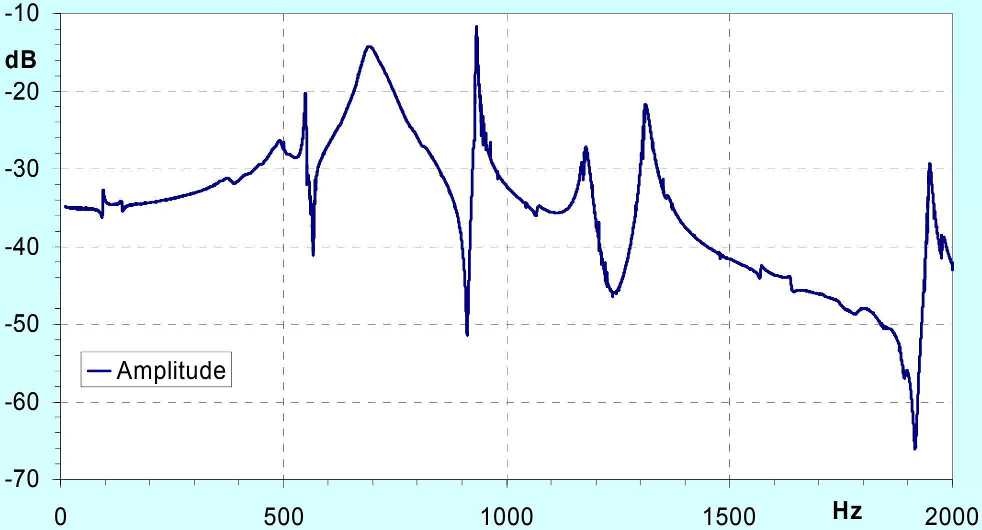


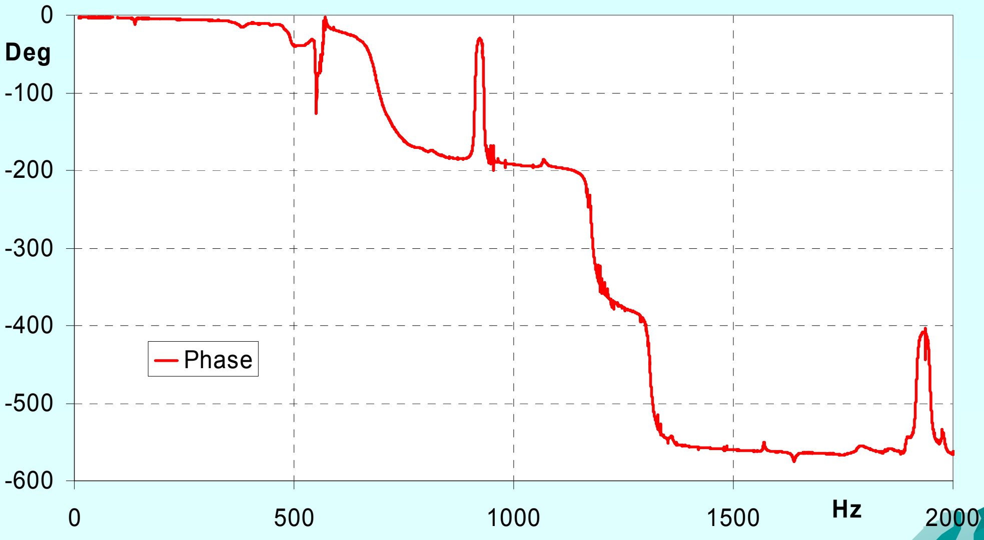




3

New facility transfer functions

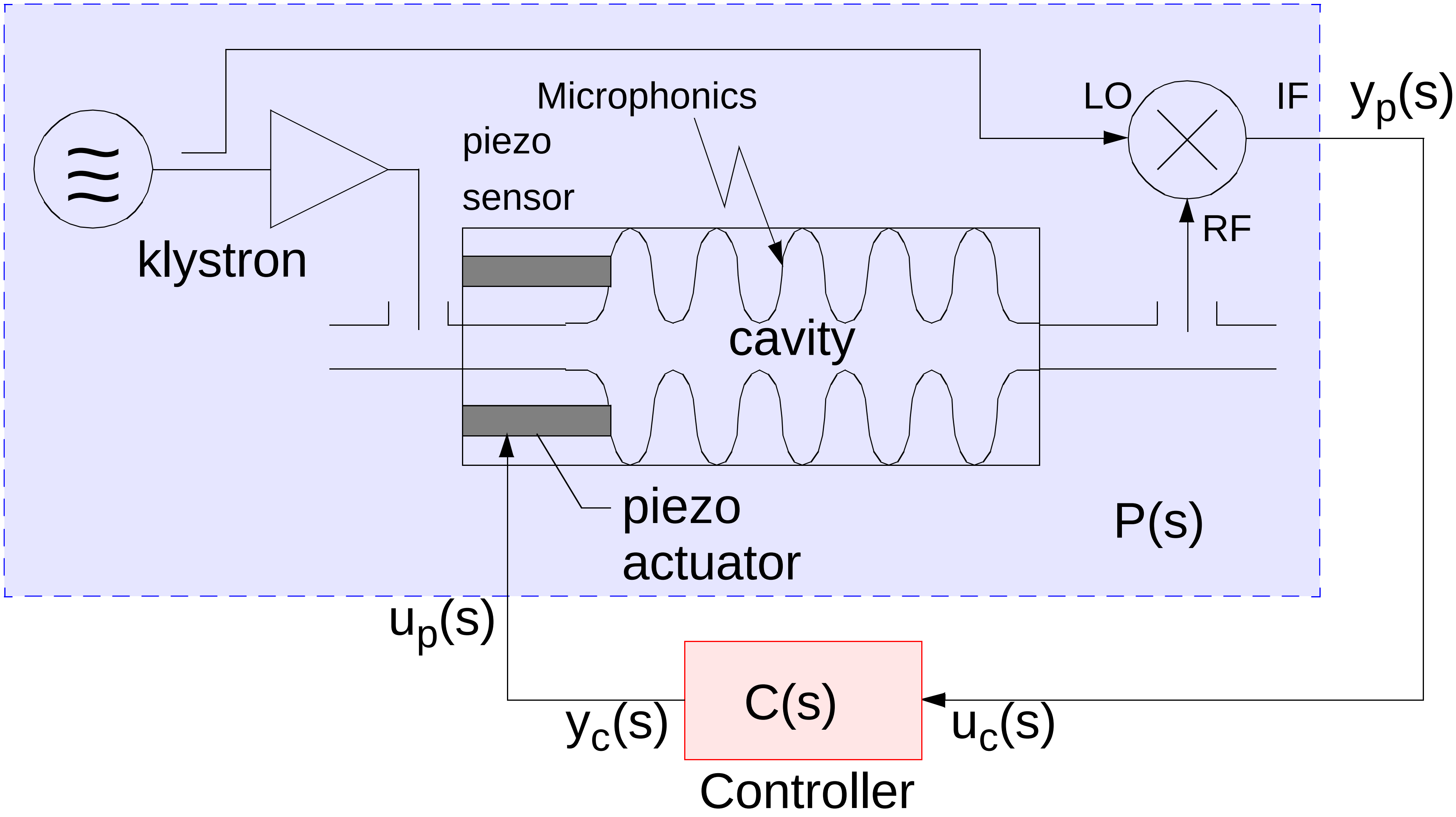




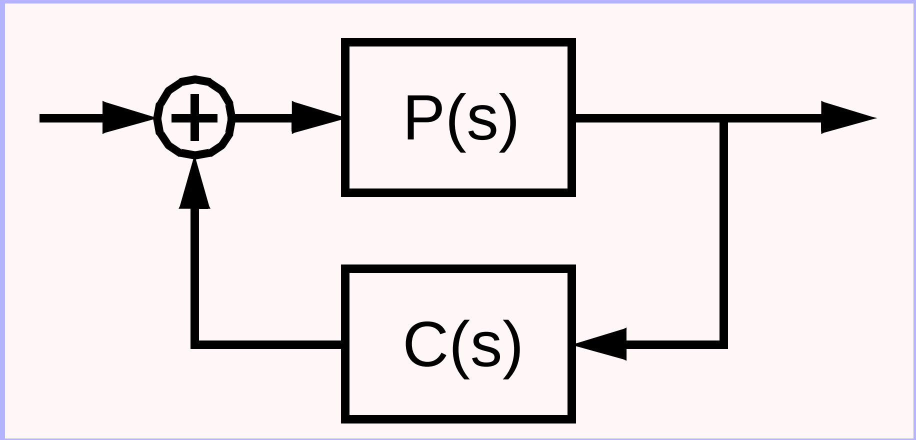
The single copper cell system has been caractherized measuring the transfer function between the piezoelectric *actuator voltage* and the *phase detuning* of the cavity.

Closed loop tests seem possible up to 2 kHz.

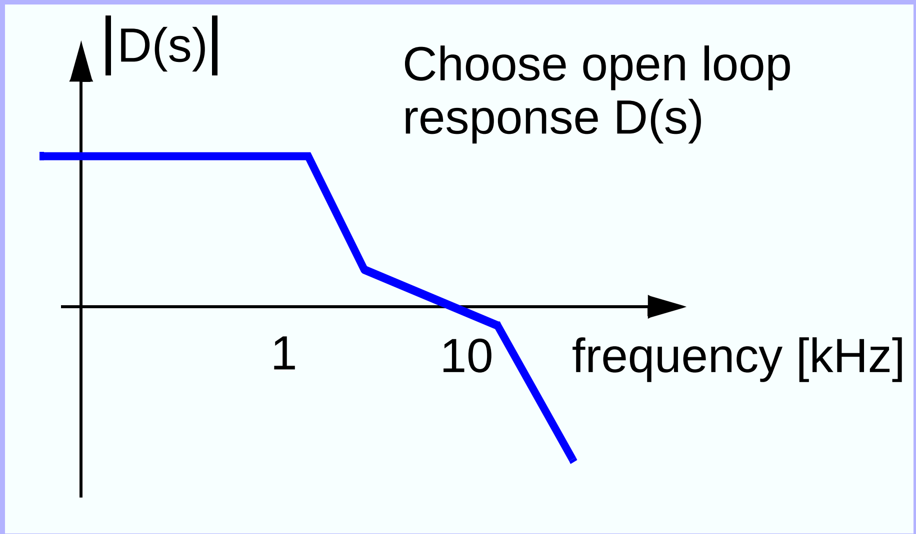
Microphonics Control



Controller Design



$$\Rightarrow \quad C(s) = \frac{D(s)}{P(s)}$$



D(s) : stability criteria fulfilled
high gain at low freq.
fast roll-off at high freq.

Feedback Successfully Applied to QWR

- C6701 processor from TI on PCI board (M67) with 4 ADCs and DACs (200kHz sampling rate)
- Programmed state space equation for 20th order system:

$$\vec{x}_{k+1} = A\vec{x}_k + B\vec{u}_k$$
$$\vec{y}_{k+1} = C\vec{x}_{k+1} + D\vec{u}_{k+1}$$

- Latency only 20 µs for 20x20 matrix multiplication (C++)
- Applied only notchfilter (672 Hz) and low pass (1kHz) to control microphonics in QWR

Requirements for the M.O. for TTF2

- Required frequencies: 50Hz, 50Hz(TTL), 1MHz, 9MHz, 13.5MHz, 27MHz, 81MHz, 108MHz, 1.3GHz, 1.517GHz, 2.856GHz
- Required stability:

    within macropulse (1ms): 0.1ps

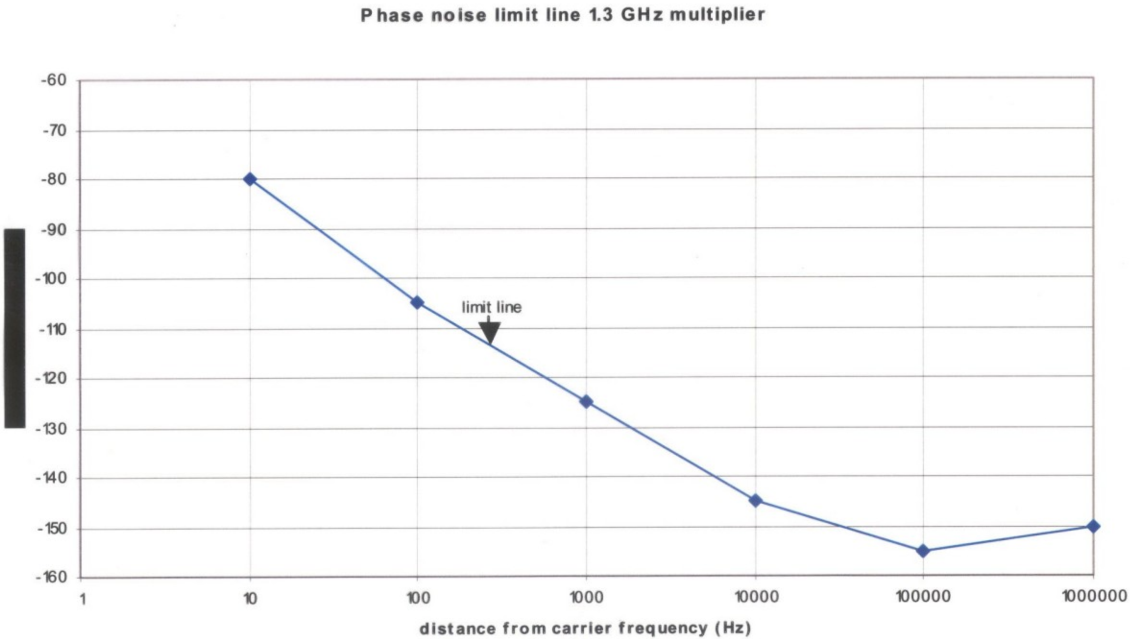
    integrated timing jitter (Δf=1MHz): 1ps
    long term: 1ps (minutes)

    2ps (hours)

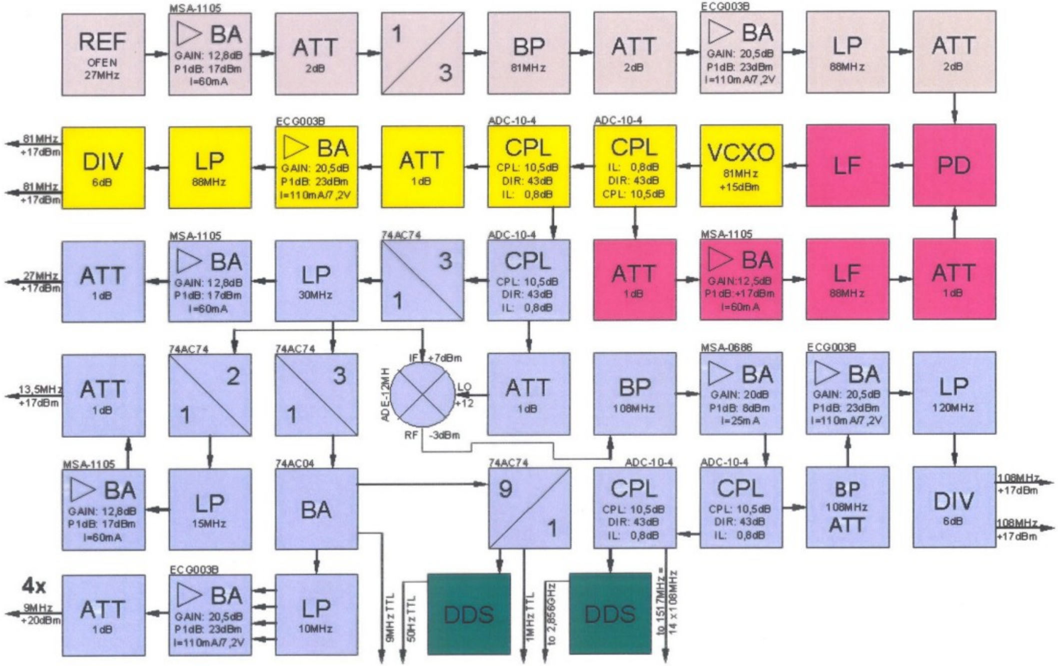
    10ps

K.Czuba, B.Lorbeer, S.Simrock, H.Weddig

Required Phase Noise Spectrum:

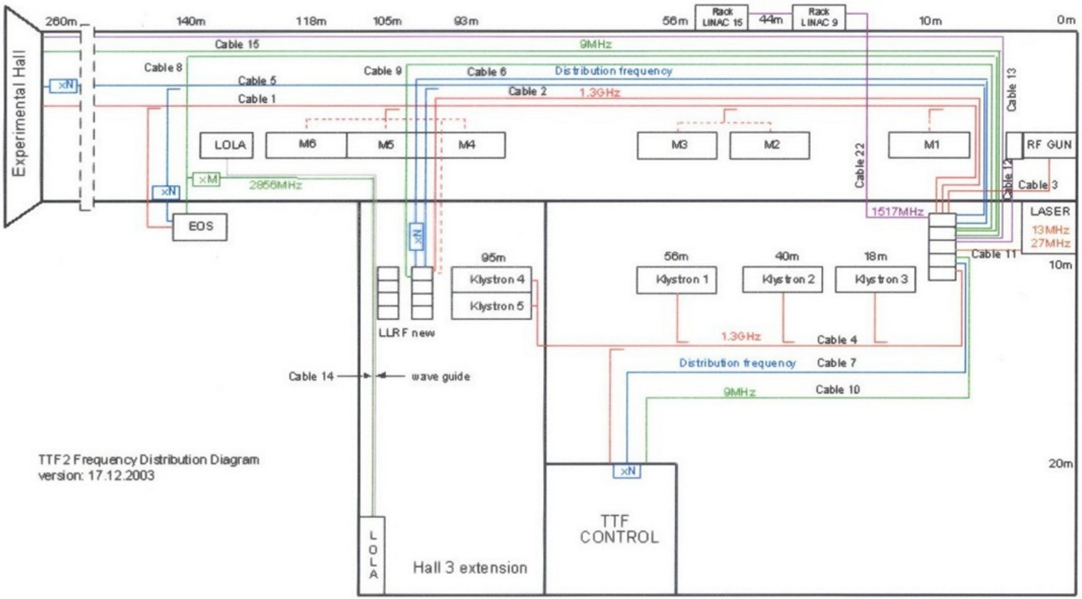


Blockdiagram of M.O.:

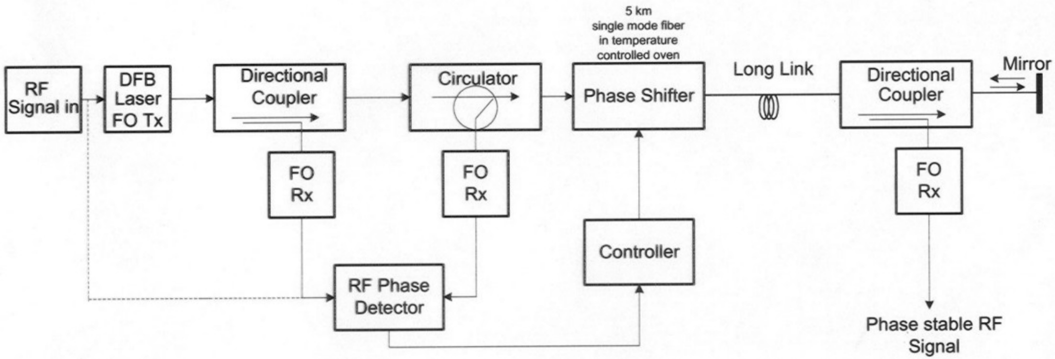


The new Master Oscillator for TTF2

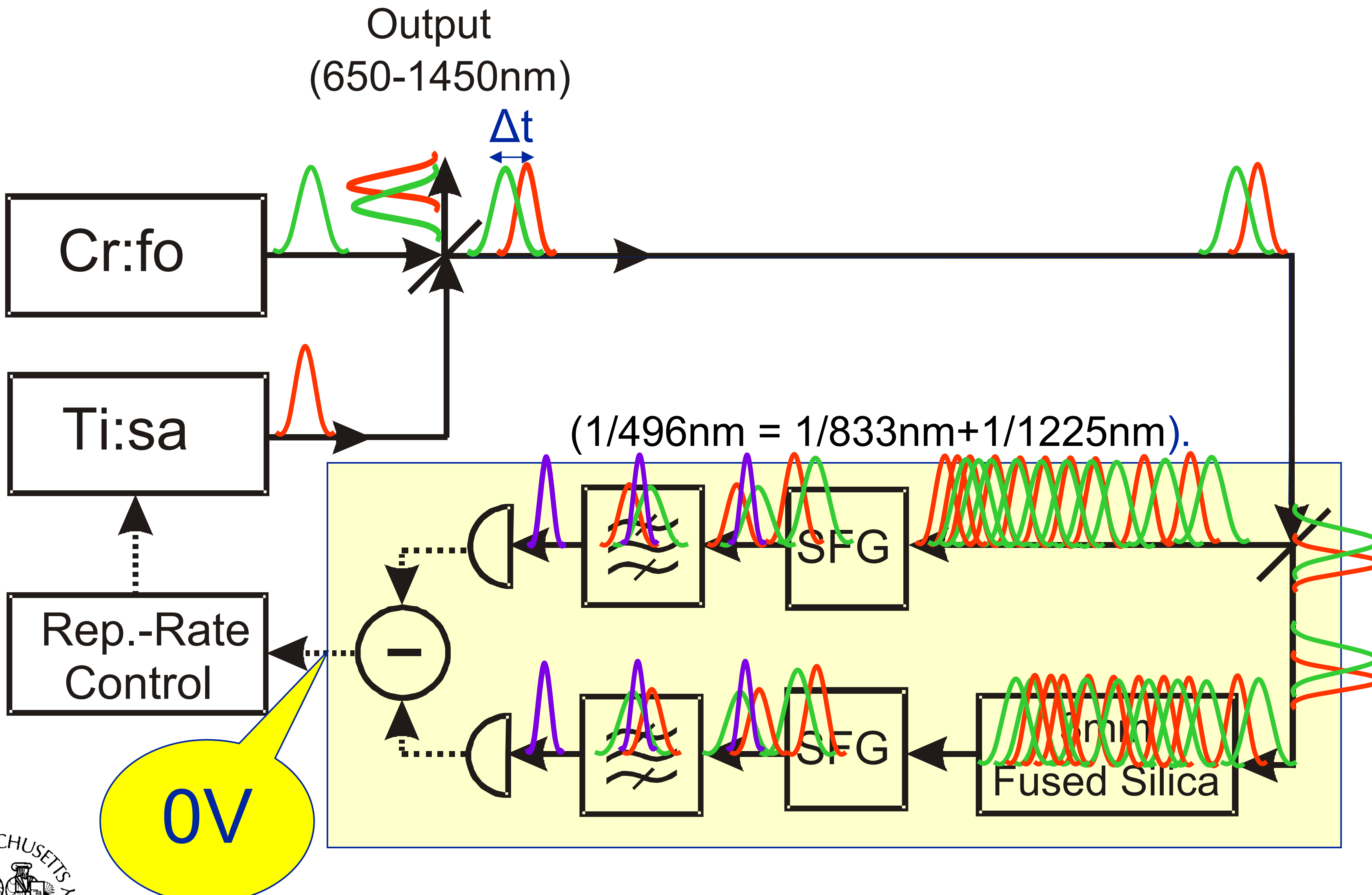
TTF2 cable distribution layout:



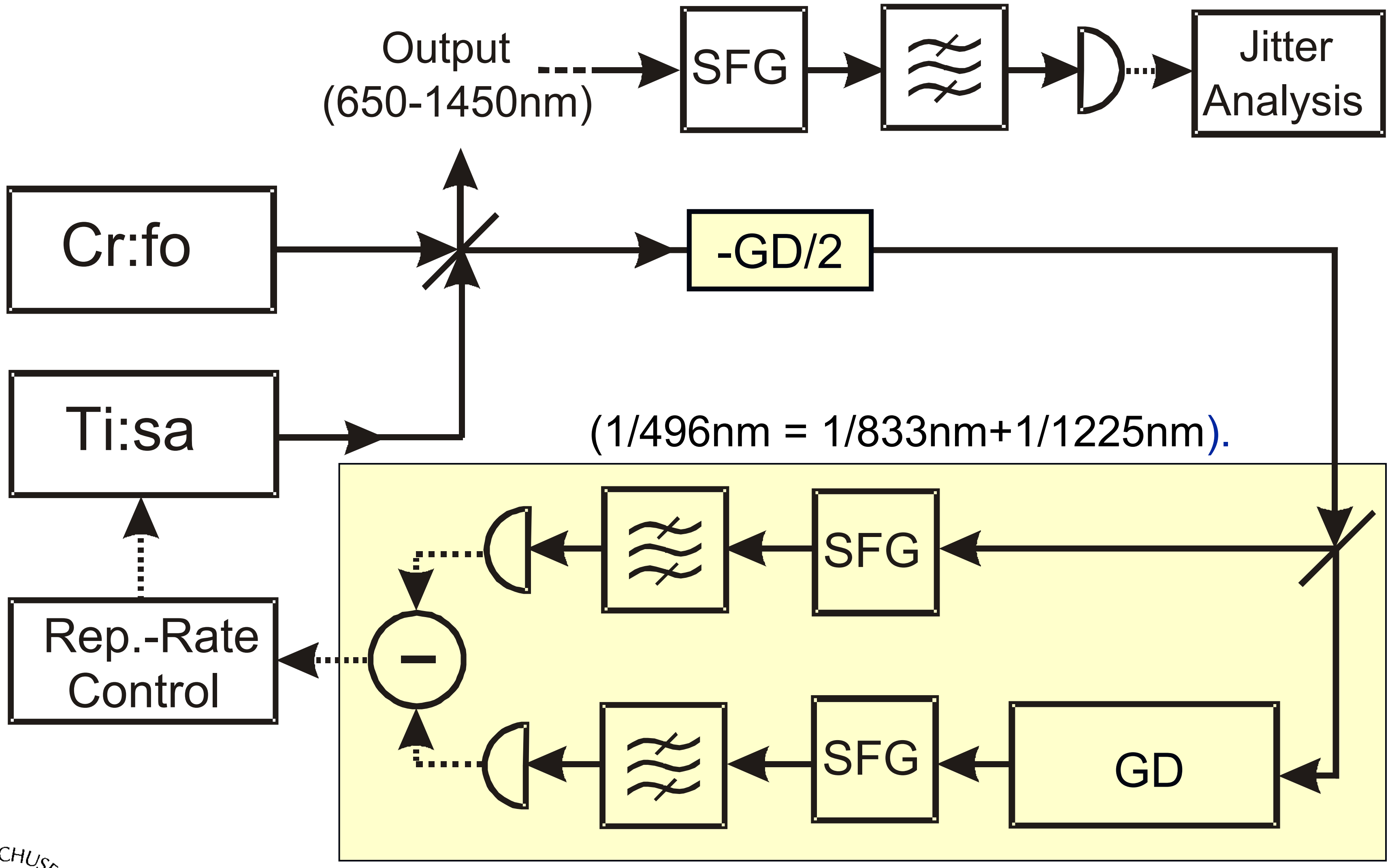
Fiber-optic Distribution System



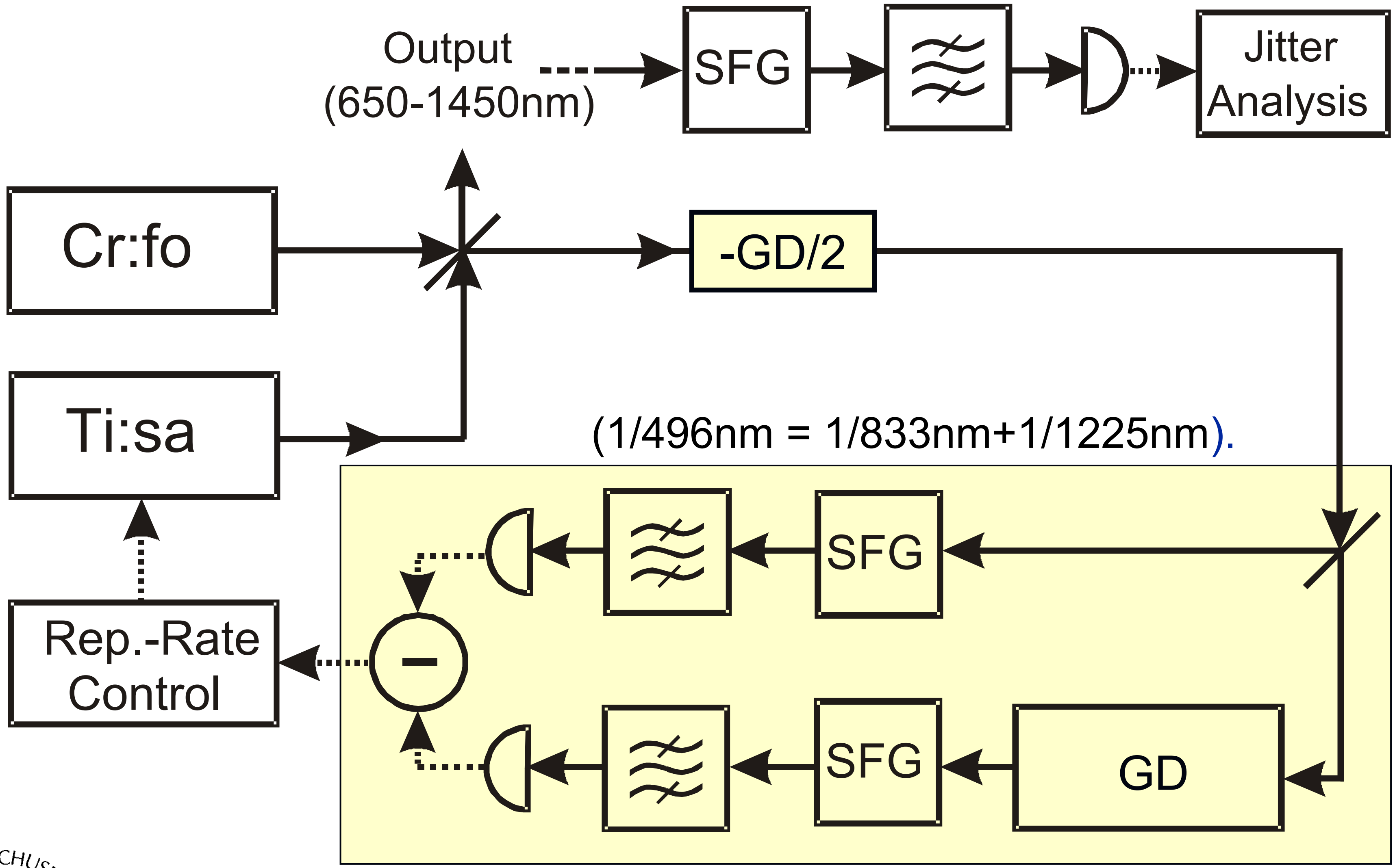
Balanced Cross-Correlator



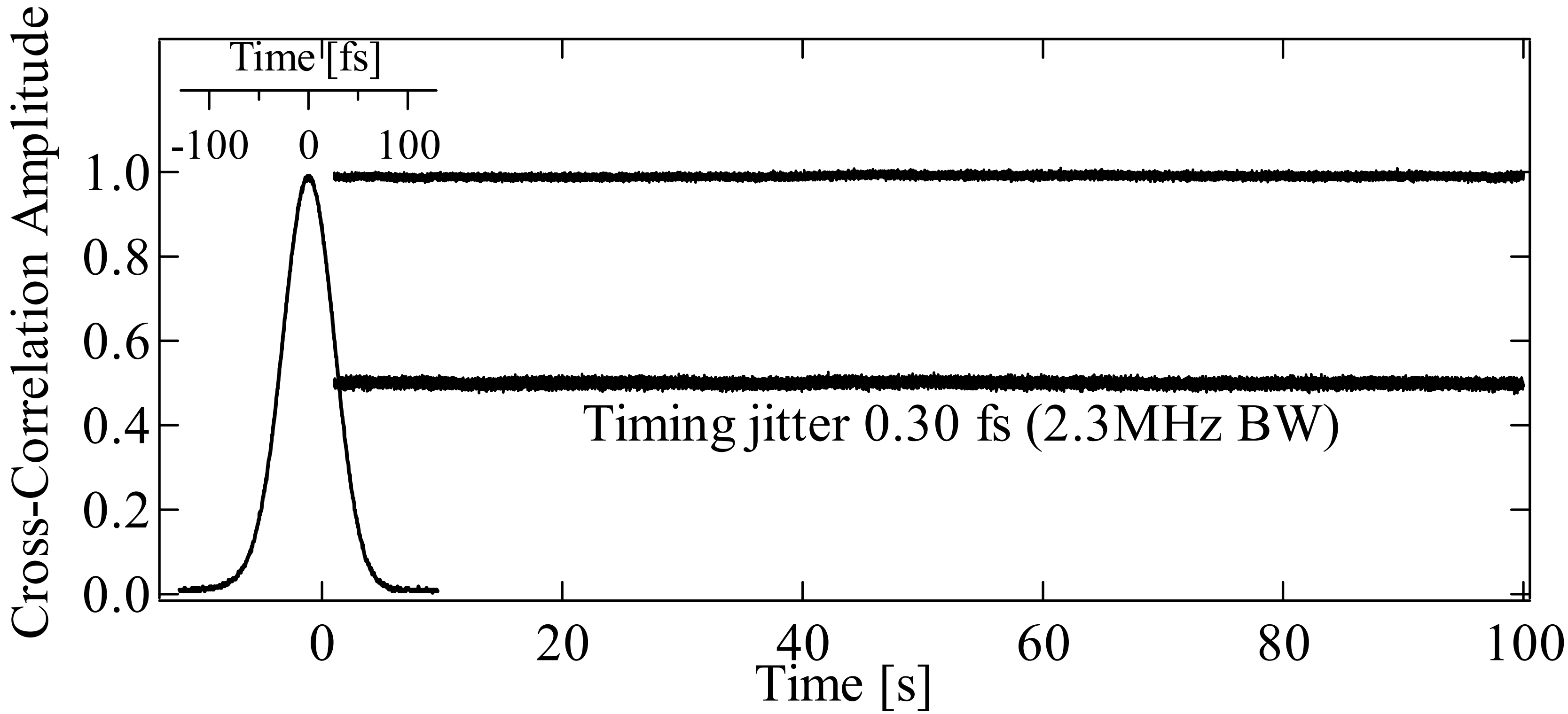
Measuring the residual timing jitter



Measuring the residual timing jitter



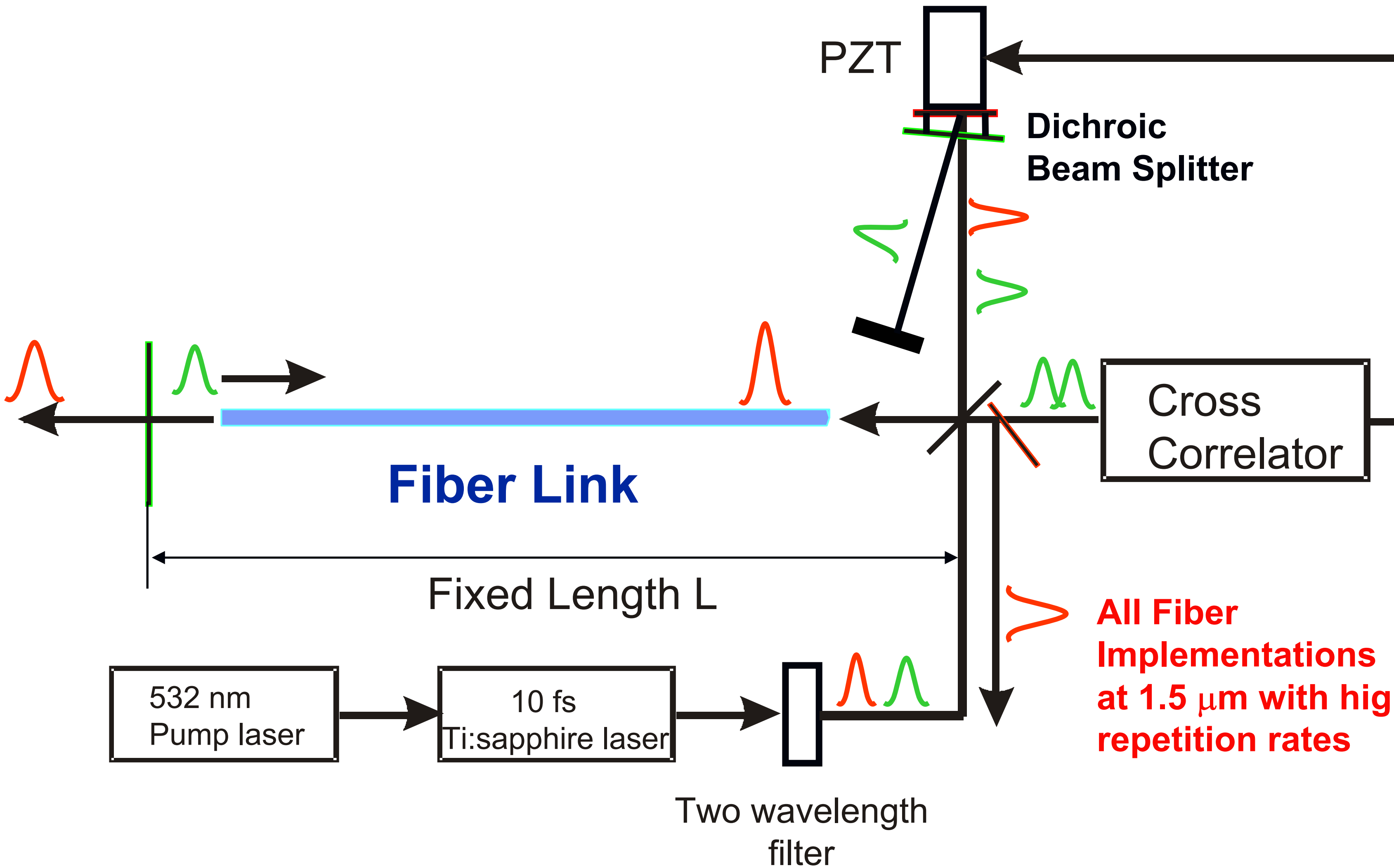
Experimental result: Residual timing-jitter



The residual out-of-loop timing-jitter measured from 10mHz to 2.3 MHz is 0.3 fs (a tenth of an optical cycle)

Long Term Drift Free

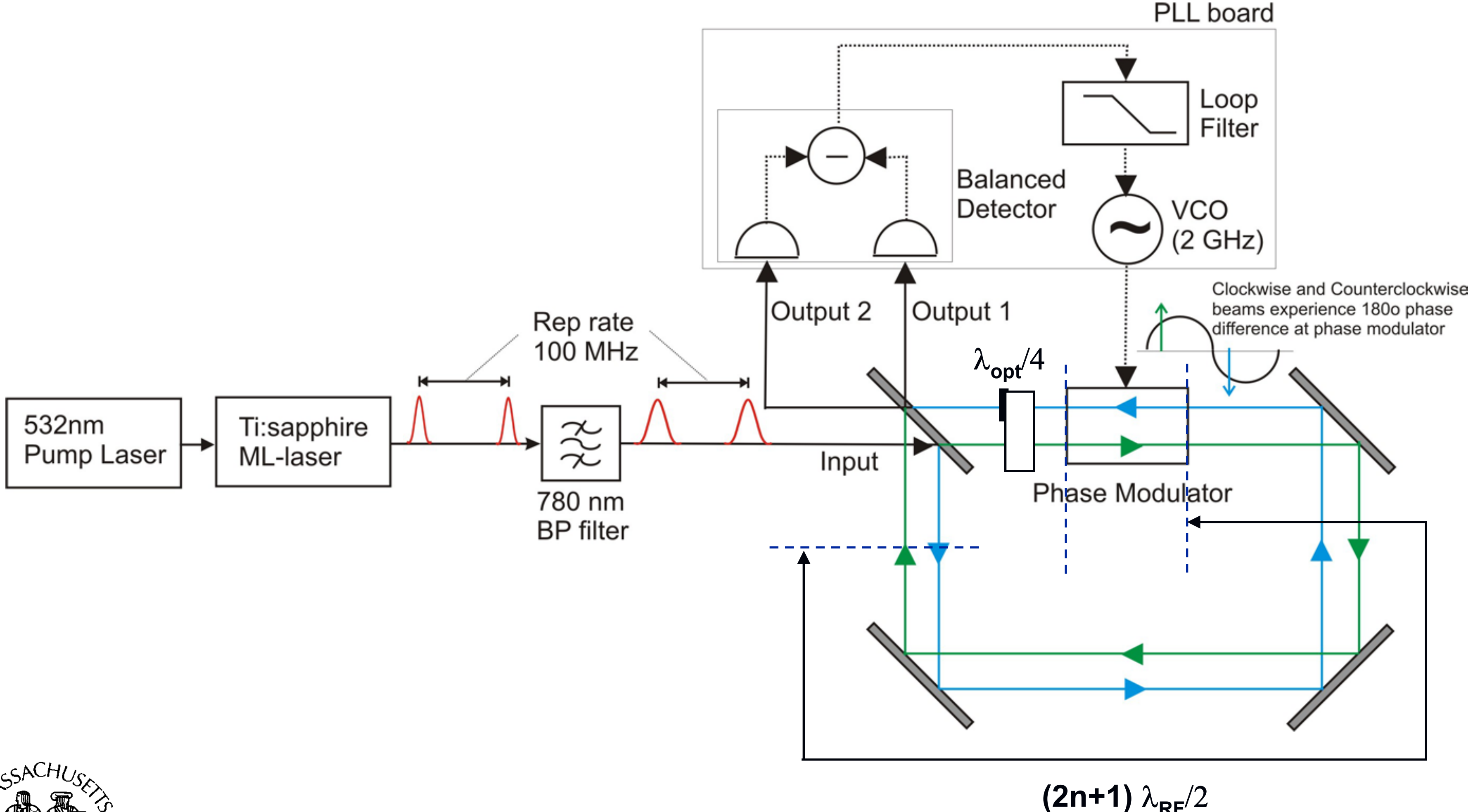
Timing Stabilized Fiber Links (<1km)



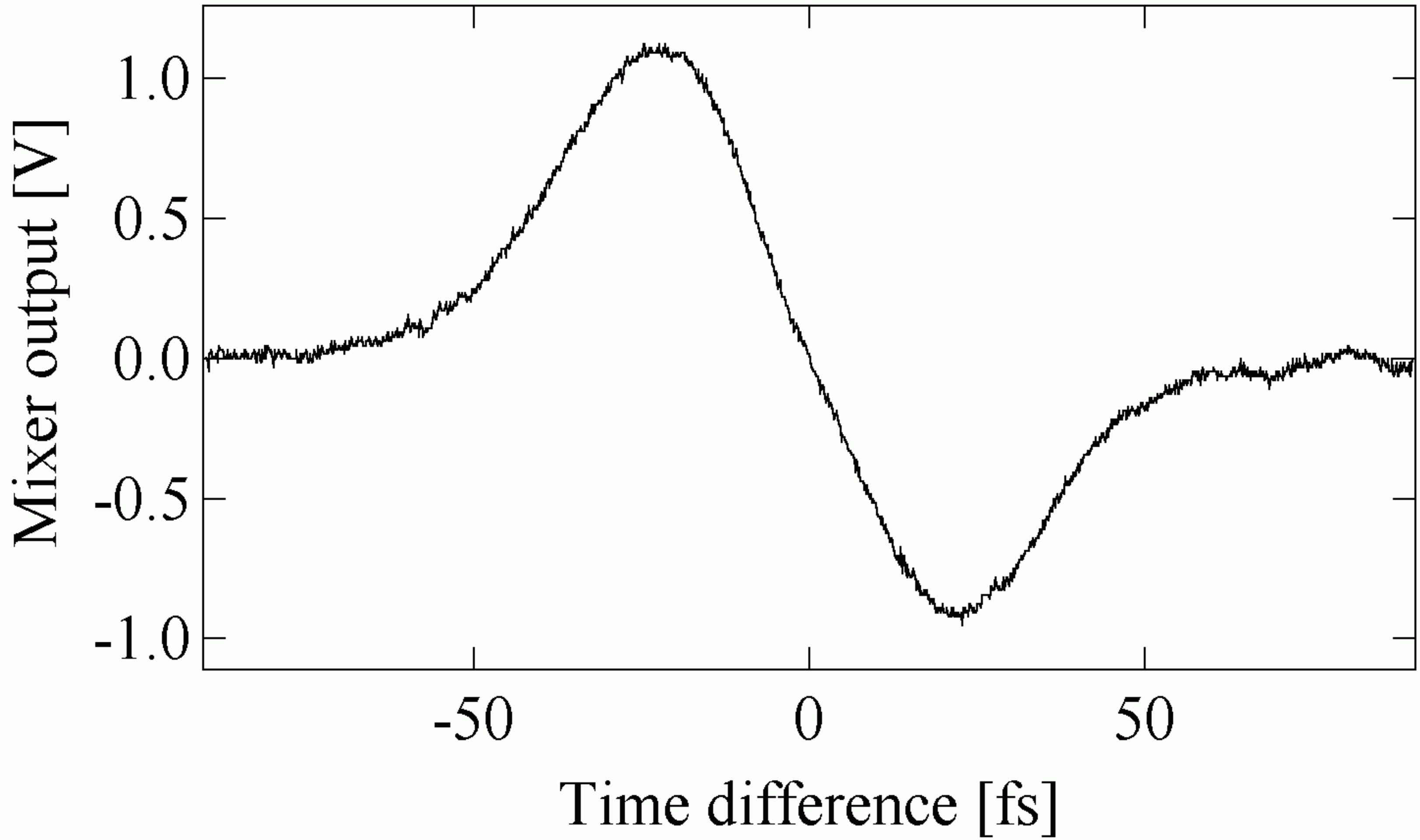
All Fiber Implementations at 1.5 μm with high repetition rates

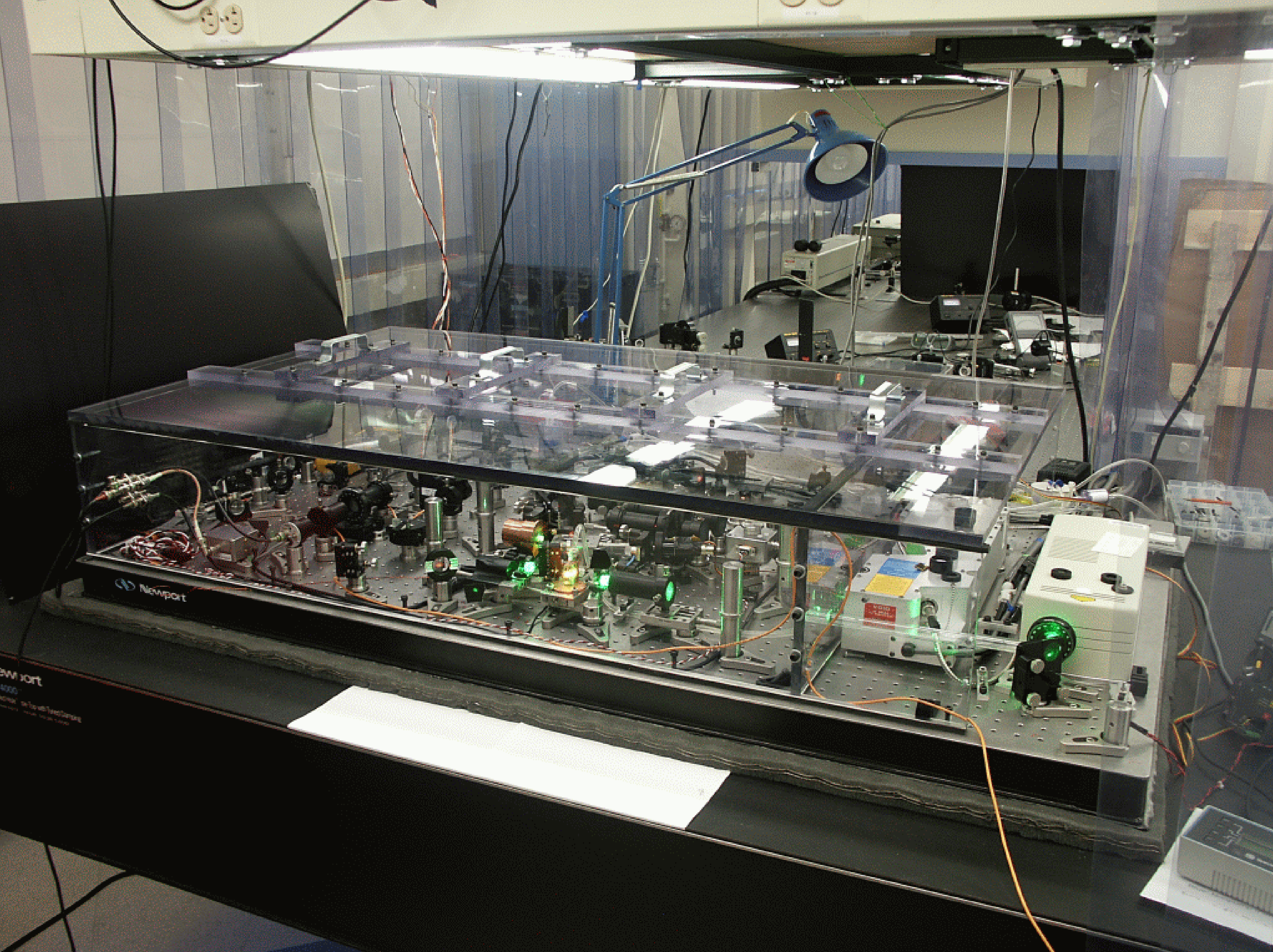
Assuming no fiber length fluctuations faster than 2L/c.

Self-balanced sub-10 fs RF-Synchronization



Balanced Cross-Correlator




Newport

LLRF Subsystems/Components

o RF phase reference **- from main driveline** **- LO for downconverter** **o Timing System** **o Vector modulator** **o Downconverter** **o Digital Control (Fdbck + FF)** **- ADC, DSP, DAC** **- includes exception handling** **o Redundant simple feedforward** **o Redundant monitoring system** **o Transient detection** **o Interfaces to other subsystems** **- includes interlocks**	**o Waveguide tuner and controls** **o Cavity resonance control** **- slow (motor) tuner** **- fast (piezo) tuner** **o CPU in VME crate** **o Network to local controls** **o Cabels and connectors** **o Power supply for electronics** **o Airconditioning in racks** **o Software** **- DSP (FPGA) code** **- server programs** **- client programs** **- LLRF Parameters** **- Finite State Machine**

LLRF Team

Name	Field of Expertise
Ayvazyan, Valeri	Software, FSM, DOOCS, Controls, Applications, Linac Operation
Bienkowski, Andrej	RF Hardware, analog and digital hardware
Brandt, Alexander	Finite state machine
Bruns, Thomas	Computer (Unix) administration
Cichalewski, Wojciech Koseda, Boguslaw	FSM and applications
Czarski, Tomasz	RF Modelling, FPGA development, optimal control
Czuba, Krzysztof	M.O. and Distribution, Fiber optic link
Eints, Frank	Hiwi
Felber, Matthias	Hiwi
Froelich, Thomas	Installation, Documentation, Maintenance
Hensler, Olaf	DOOCS control system (deputy of K. Rehlich)
Grecki, Mariusz	TUL-DMCS group leader
Ignachin, Nikolai Sytov, Sergei	Analog, digital, and rf electronics
Jezynski, Tomasz	FPGA control for RF Gun/XFEL
Kierzkowski,	FPGA hardware and programming
Kotthaus, Daniel	RF Gun Control
Lilje, Lutz	Piezo tuner, high gradient cavities
Lorbeer, Bastian	Master Oscillator and Distribution
Makoswki, Dariusz	Radiation issues for electronics
Matsumoto, Toshiyushi	RF System Modelling, LLRF Development
Moeller, Guenter	RF Hardware, Downconverter, vector-mod, rf-gate
Pawlik, Pawel	Single bunch transient
Petrosyan, Gevorg	DSP programming, DSP code and server
Petrosyan, Lyudvig	Timing expert, ADC server
Posniak, Krzysztof	FPGA hardware and software
Pucyk, Piotr	DOOCS control of FPGA
Rehlich, Kay	DOOCS control system (group leader)
Romaniuk, Ryzard	WUT-ISE group leader
Rutkowksy, Peter	DOOCS control of FPGA
Rybka, Dominik	Radiation damage to electronics
Schrader, Matthias	RF Control
Sekalski, Przemyslaw	Piezotuner and control
Simrock, Stefan	LLRF (group leader)
Vetrov, Piotr	DSP hardware (DSP board, Gigalink, ADC, DAC)
Wagner, Richard	Hera Protonen HF, NT Administration
Weddig, Henning	RF Hardware, M.O. and Distribution, Analog and digital electronics, RF Measurements
Zabolotny, Wojciech	FPGA hardware and programming

Summary

- Commissioning of LLRF for TTF II is well underway
  - Feedforward for ACC 4,5,6 (old IQ drivers) available
  - New C67 based DSP System for RF Gun and ACC1 under commissioning. In operation with cavity simulator
  - New "field" detectors for RF Gun
  - Prototype of FPGA based controller and cavity simulator
- Master oscillator and frequency distribution are presently being installed
  - New frequencies (2856 MHz, 13.5 MHz)
  - Temperature stabilized coaxial distribution
  - Highly stable fiber optic monitoring system
- Automation of LLRF operation under development