Review on Progress in RF Control Systems

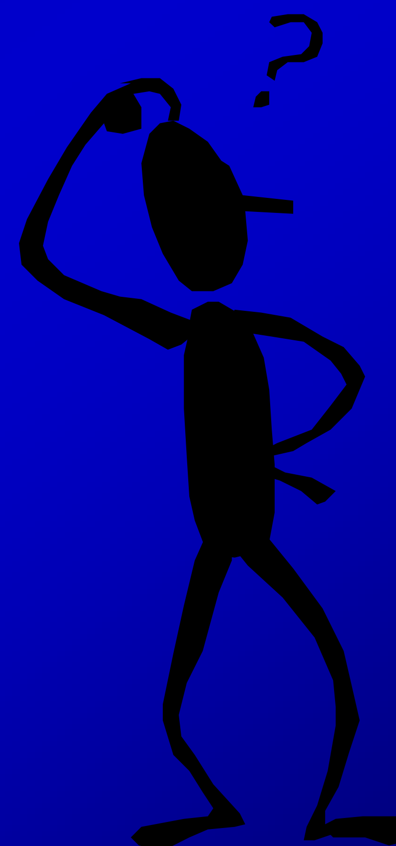
Matthias Liepe

Cornell University

Why this Talk?

As we all know, superconducting cavities have many nice features…

… one of which is very high field stability.



Why?

- High loaded Q factor (long time constant)
- Powerful RF control systems

Goal of this Talk?

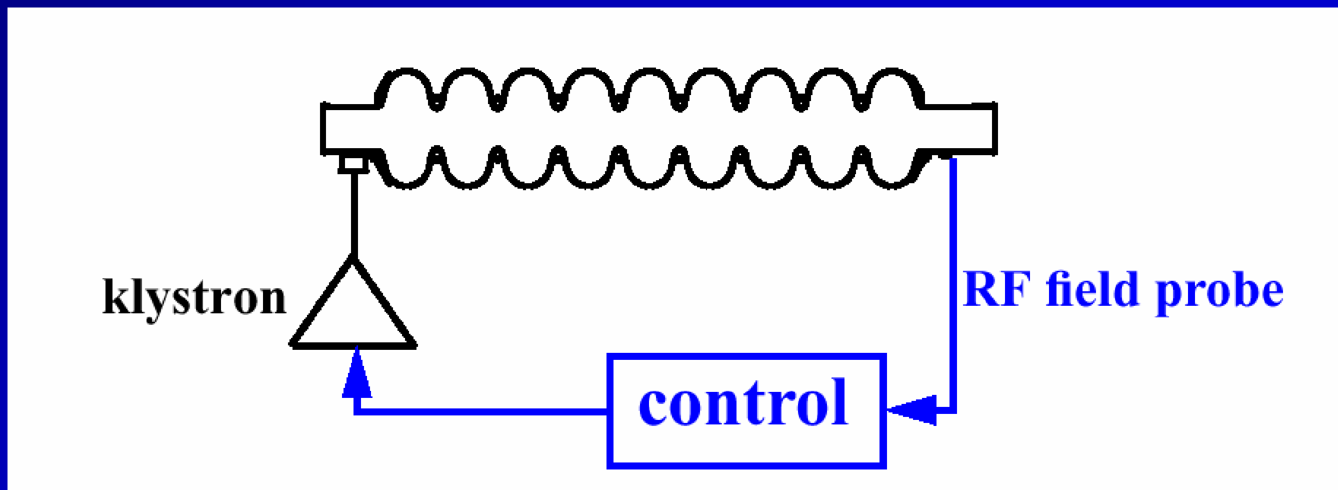
To show you what these two cars have to do with RF Control System…

Outline

- LLRF Systems: An Introduction to a complex system
- Field Perturbations and Requirements: Old Enemies, new Challenges…
- Design Choices: “Recent” Trends
- Design Efforts Worldwide and achieved Performance
- Conclusion

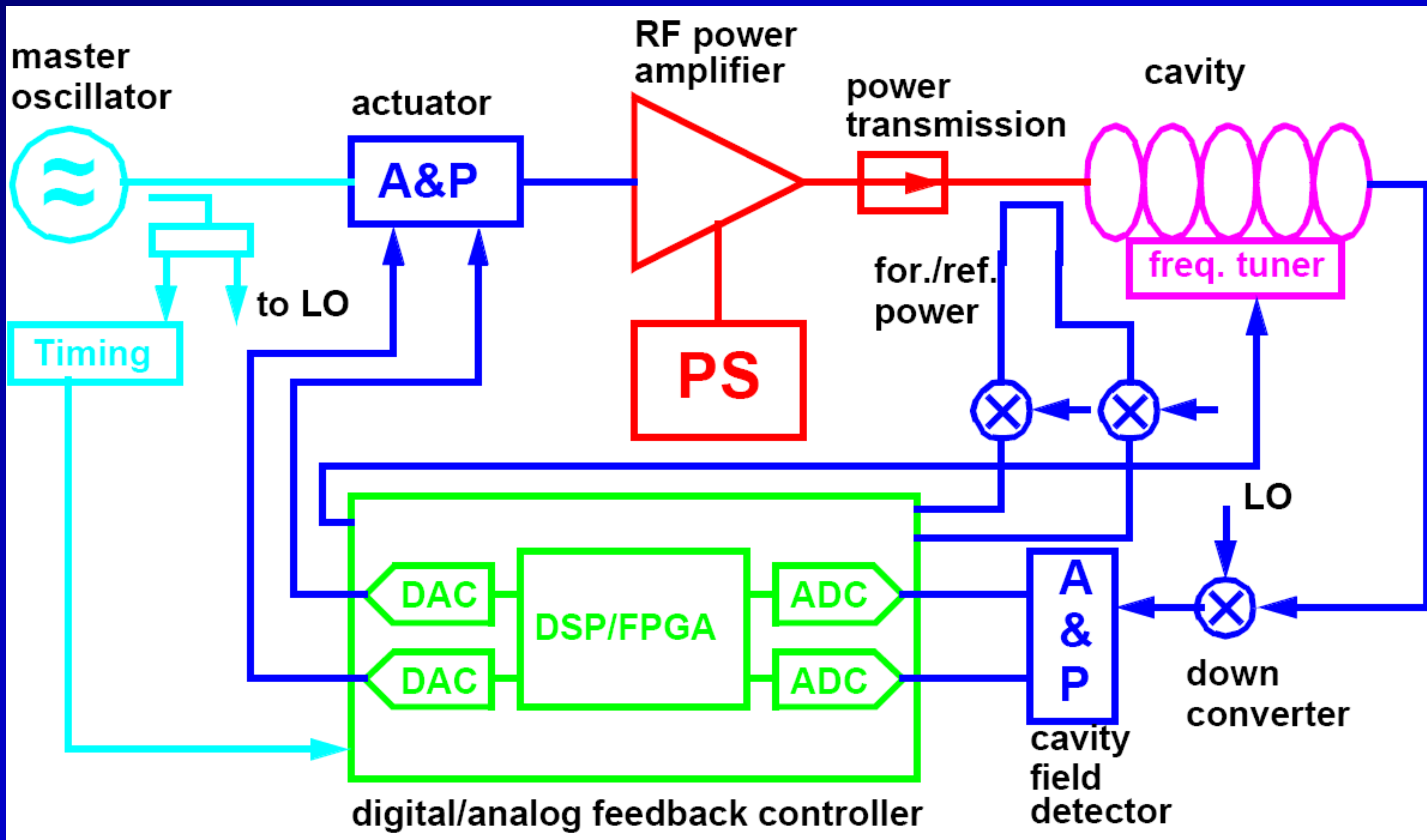
An Introduction

The Simple Picture: LLRF Control



- Measure cavity RF field.
- Derive new klystron drive signal to stabilize the cavity RF field.

The More Complete Picture



Many connected subsystems…

LLRF Control Requirements I

Derived from beam properties:

energy spread, emittance, bunch length, arrival jitter, beam availability…

$\Downarrow$

Primary requirement: *It must work…*

- **Maintain amplitude and phase of the accelerating RF field within given tolerances to accelerate a charged particle beam.**

LLRF Control Requirements II

Secondary requirements:

It must work well…

- RF system must be reliable, reproducible, easy to use, and well understood.
- Provide exception handling and automated fault recovery capabilities.
- Minimize RF power needed for control.
- Provide performance optimization.
- Build-in diagnostics for calibration of gradient and phase, cavity detuning, …
- Meet performance goals over wide range of operating parameters.

Sources of Field Perturbation

high current machines

• ***Beam loading*** - beam current fluctuations - pulsed beam transients - excitation of other passband modes - excitation of HOM's - wake fields • *Cavity drive signal* - HV- pulse flatness - HV PS ripple - phase noise from master oscillator - timing signal jitter - mismatch in power distribution	• *Cavity dynamics* - cavity filling - settling time of field • ***Cavity resonance frequency change*** - microphonics - Lorentz force detuning • *Other* - response of feedback system - interlock trips - thermal drifts (electronics, power amplifiers, cables, power transmission system)

low beam current

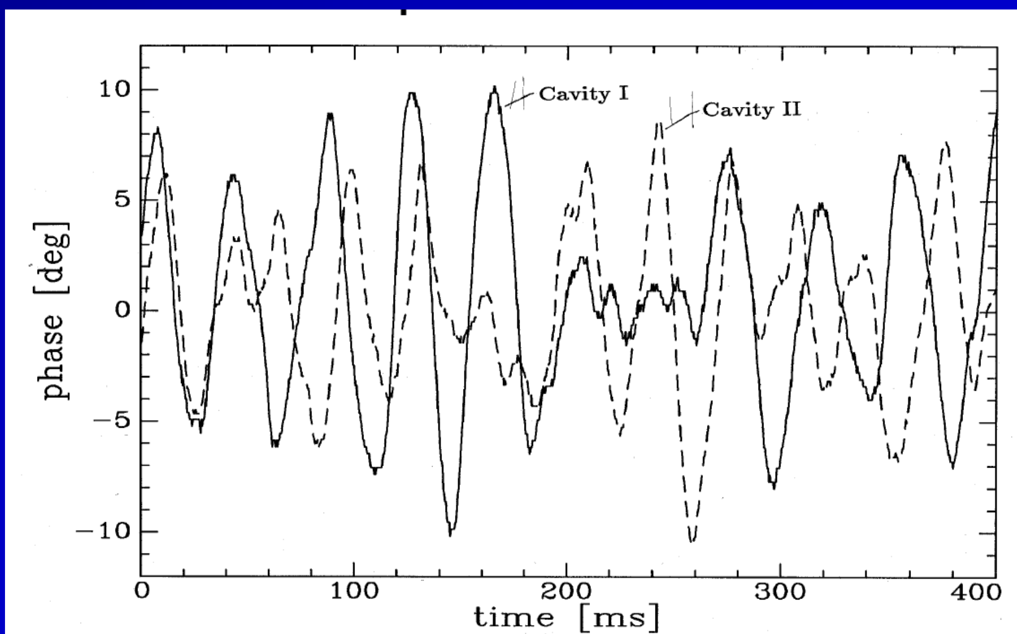
⇒ amplitude and phase fluctuations ⇒ active control required

Field Perturbation: Microphonics

Microphonics: Fluctuation in cavity frequency

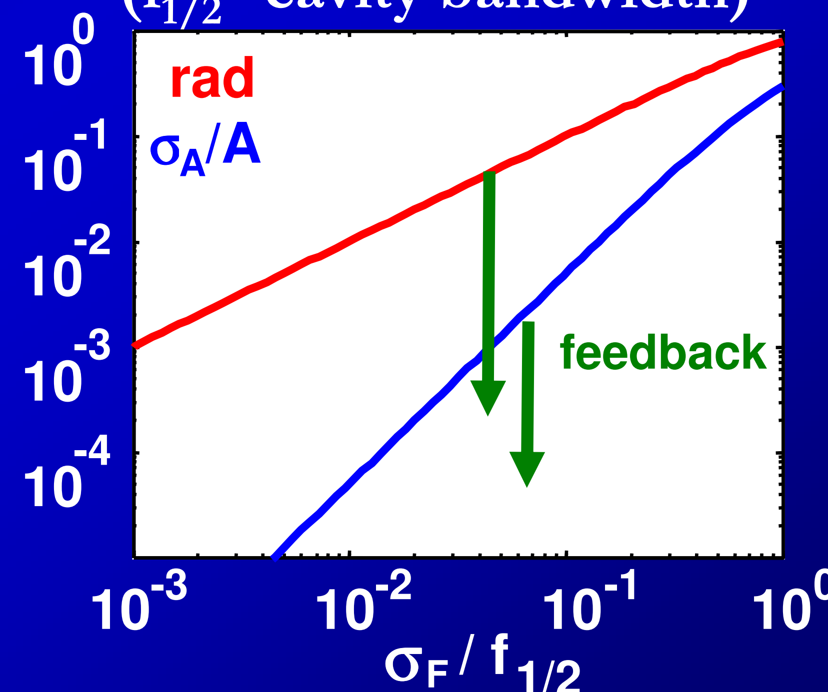
$\Downarrow$

Amplitude and phase field errors

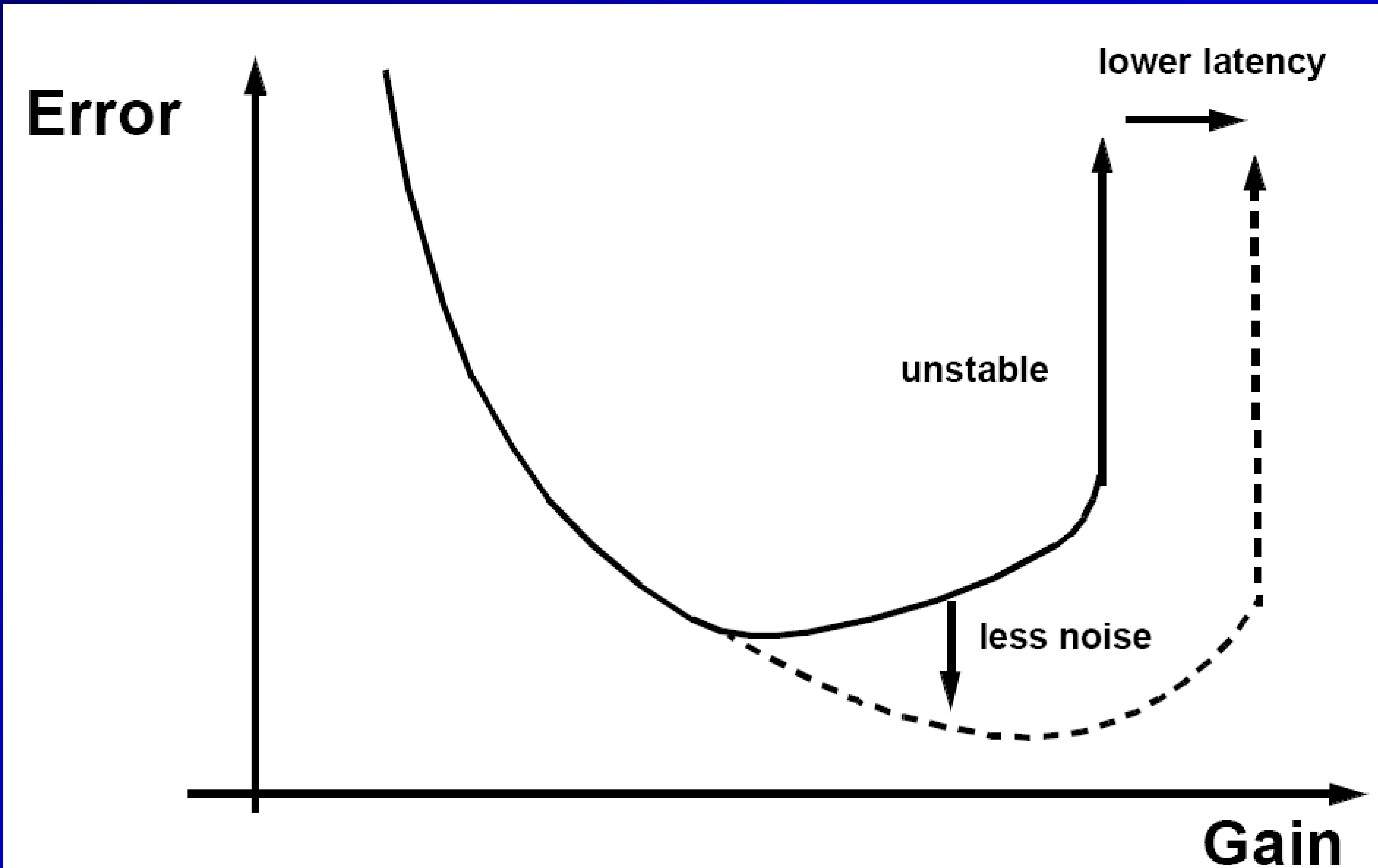


Open loop errors

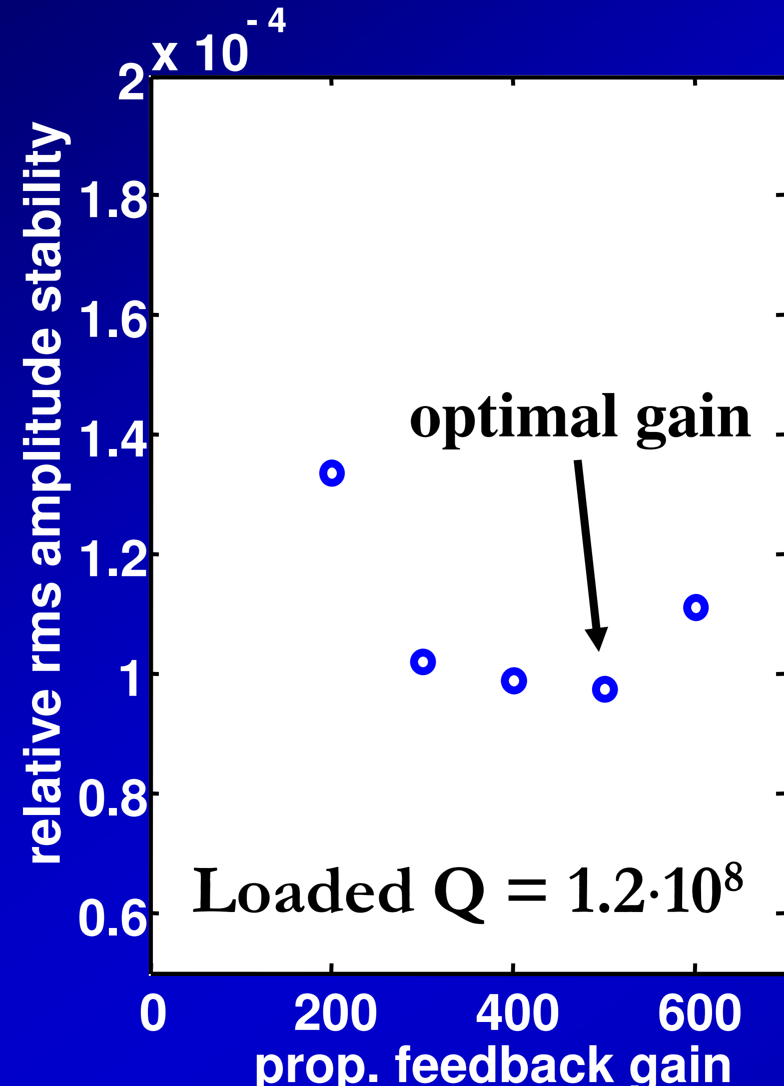
($f_{1/2}$=cavity bandwidth)

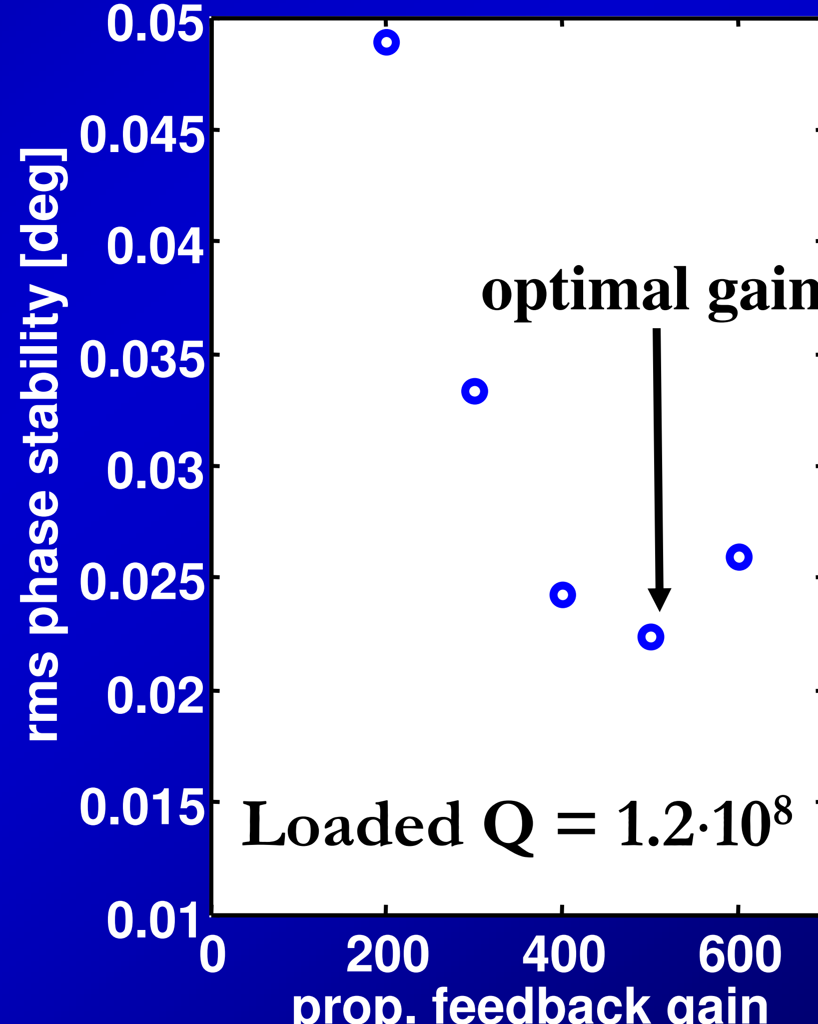


Error as Function of Feedback Gain



Cornell RF Control Test at the TJLab FEL





Perturbation Compensation: Feedback and Feedforward

- ***Active Control of Perturbations***
  - Feedforward: (fixed or adaptive)

Inputs		Outputs
• Vibration signals • Beam current • HV PS ripple	→	• Klystron drive • Frequency tuner drive

  - Feedback:

Inputs		Outputs
• Measured cavity field • Klystron output • Cavity detuning • Beam energy • Bunch length	⇄	• Klystron drive • Frequency tuner drive

Field Perturbations and Requirements: Old Enemies, new Challenges…

Sources of Field Perturbation: Old Enemies...

high current machines

- ***Beam loading***
  - beam current fluctuations
  - pulsed beam transients
  - excitation of other passband modes
  - excitation of HOM's
  - wake fields
- *Cavity drive signal*
  - HV- pulse flatness
  - HV PS ripple
  - phase noise from master oscillator
  - timing signal jitter
  - mismatch in power distribution
- *Cavity dynamics*
  - cavity filling
  - settling time of field
- ***Cavity resonance frequency change***
  - microphonics
  - Lorentz force detuning
- *Other*
  - response of feedback system
  - interlock trips
  - thermal drifts (electronics, power amplifiers, cables, power transmission system)

low beam current

⇒ amplitude and phase fluctuations ⇒ active control required

…New Challenges

- **Very high beam currents (Ampere-scale)**
- **Very high loaded *Q* SRF cavities (few 10 Hz bandwidth): Frequency control, instabilities, …**
- **Large RF systems with many cavities: global control instead of local control**
- **High field stability required : up to 0.01% for amplitude and 0.01 deg for phase (XFELs, ERL light sources)**

⇒ More, complex control loops; connected LLRF systems

Field Stability Requirements

Different accelerators have different requirements for field stability!

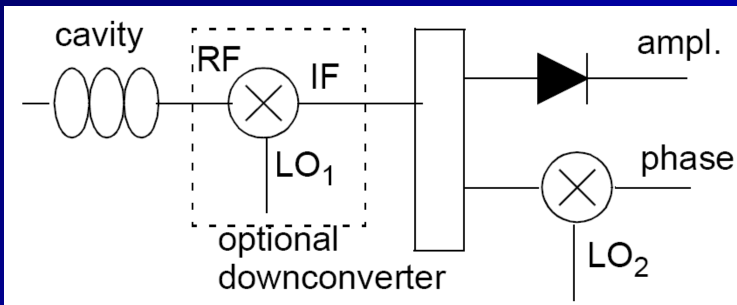
- approximate RMS requirements:
  - 1% for amplitude and 1 deg for phase (storage rings, SNS)
  - 0.1% for amplitude and 0.1 deg for phase (linear collider, …)
  - down to 0.01% for amplitude and 0.01 deg for phase (XFEL, ERL light sources)

Design Choices: “Recent” Trends

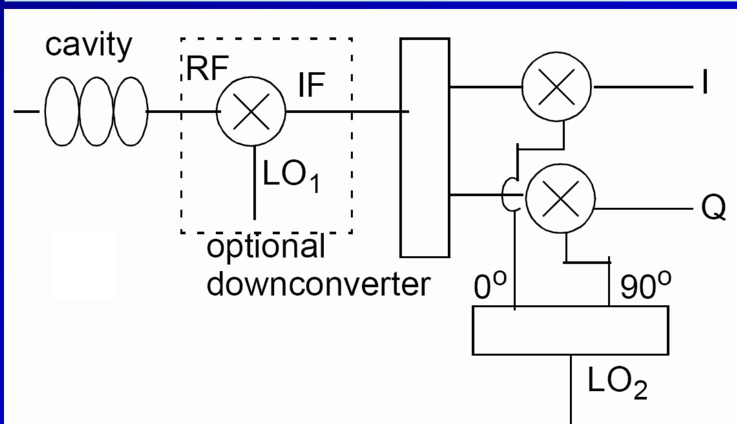
Trend 1:

- (Digital) I-Q field detection
- High IF frequency (> 10 MHz $\Rightarrow$ low noise)

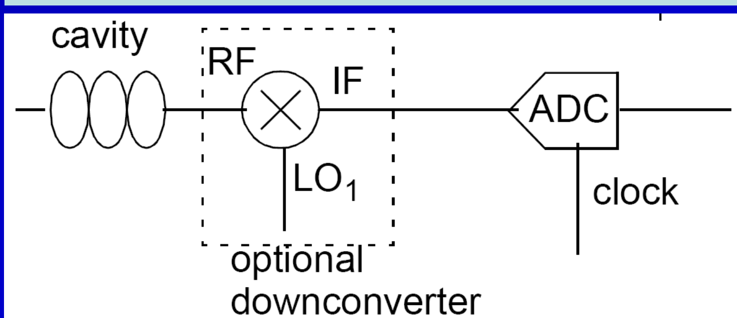
Design Choices: Field Detectors



- Traditional amplitude and phase detection
- Works well for small phase errors



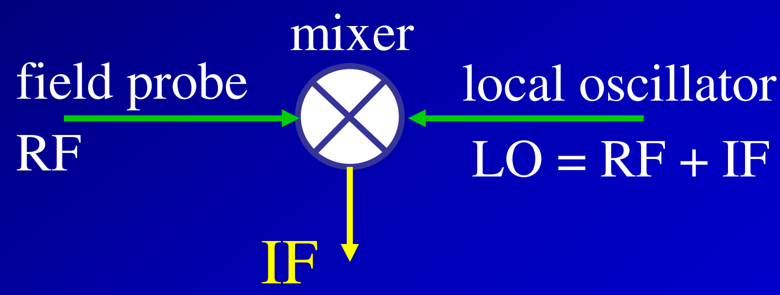
- I /Q detection: real and imaginary part of the complex field vector
- Preferable in presence of large field errors



- Digital I / Q detection
- Alternating sample give I and Q component of the cavity field

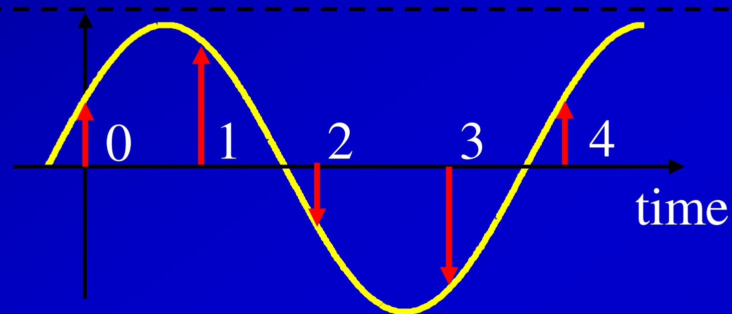
Digital I/Q Detection

1.



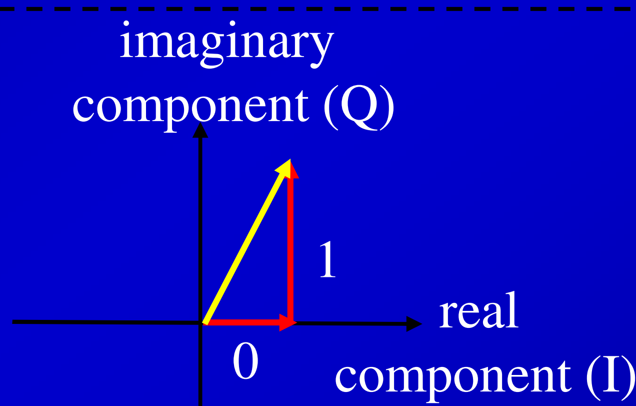
- Down-conversion of cavity field probe signal
- Complete amplitude and phase information is preserved

2.



- IF signal is sampled at 4*IF rate

3.



- Consecutive data points describe real and imaginary part of cavity field (I&Q)

Trend 2:

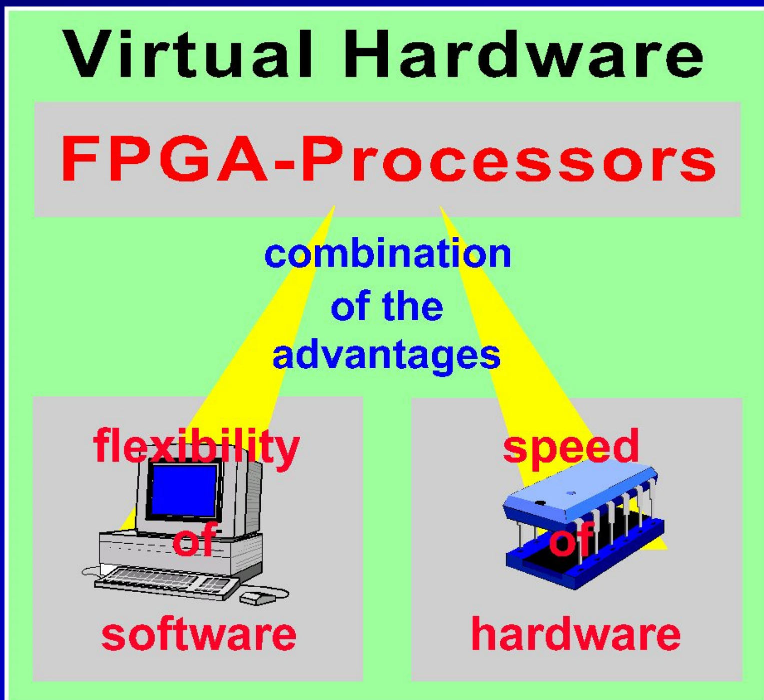
- **Digital controller**
- **High sampling rates (tens of MHz)**
- **Control loop running in a Field-Programmable Gate Array (FPGA)**

Analog vs. Digital Control

- **Analog:**
  - \+ <u>fast</u>; simple; well suited for small numbers of units
  - \- less flexible; digital DAQ needed anyway; digital interface to analog controller needed anyway (state machine, …)

- **Digital:**
  - \+ provides flexibility; easier vector sum control; extensive diagnostic; advanced controllers; advanced exception handling; integrated state machine; …
  - \- somewhat more programming; more latency (but difference becomes smaller from year to year and recently became in many cases insignificant)

FPGAs



- Computing core of an FPGA consists of a matrix of highly complex reprogrammable logic elements.
- Programs do not determine the sequence of execution but the logical structure of the reconfigurable machine.
- Thousands of operations can be performed in parallel on an FPGA computer during every clock cycle.
- Very high data throughput.

The right Choice…

- The right design choice depends on:
  - Performance goals (field stability, …)
  - Expertise
  - Time constrains
  - Manpower constrains
  - …
- There is no single right choice!

  ⇒ Different machines [linacs (pulsed, cw, n.c., s.c., electron, proton, ion,…), storage rings (n.c., s.c.)] have different LLRF control systems!

Trend 3:

- Use of single chip solutions from telecommunication market industry

From the Wireless World…

- Telecommunication market industry offers a wealth of single chip solutions for
  - Amplitude detection
  - Phase detection
  - Up- and down-conversion (analog multipliers)
  - I / Q detection
  - Vector modulation

$\Rightarrow$ Simple field detector design, low noise!

Example: Vector Modulator

Hittite MICROWAVE CORPORATION v00.0504

HMC497LP4

SiGe WIDEBAND DIRECT MODULATOR RFIC, 100 - 4000 MHz

Typical Applications

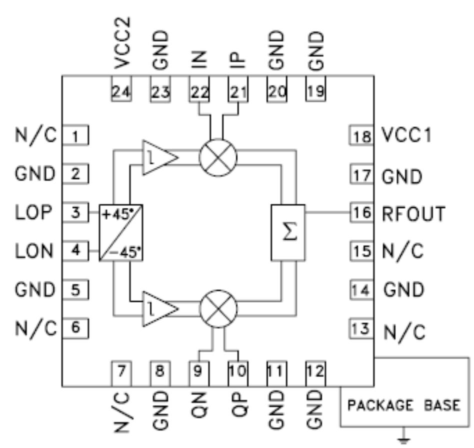
The HMC497LP4 is suitable for various modulation systems:

- UMTS, GSM or CDMA Basestations
- Fixed Wireless or WLL
- ISM Transceivers, 900 & 2400 MHz
- GMSK, QPSK, QAM, SSB Modulators

Features

Very Low Noise Floor, -161 dBm/Hz
Very High Linearity, +22 dBm OIP3
High Output Power, +9 dBm Output P1dB
High Modulation Accuracy
DC – 700 MHz Baseband Input

Functional Diagram



General Description

The HMC497LP4 is a low noise high linearity Direct Quadrature Modulator RFIC which is ideal for digital modulation applications from 100 - 4000 MHz including; Cellular/3G, Broadband Wireless Access & ISM circuits. Housed in a compact 4x4 mm (LP4) SMT QFN package, the RFIC requires minimal external components & provides a low cost alternative to more complicated double up-conversion architectures. The RF output port is single-ended and matched to 50 Ohms with no external components. The LO requires -6 to +6 dBm and can be driven in either differential or single-ended mode while the baseband inputs will support modulation inputs from DC - 700 MHz typical. This device is optimized for a supply voltage of +4.5V to +5.5V and consumes 170 mA @ +5.0V supply.

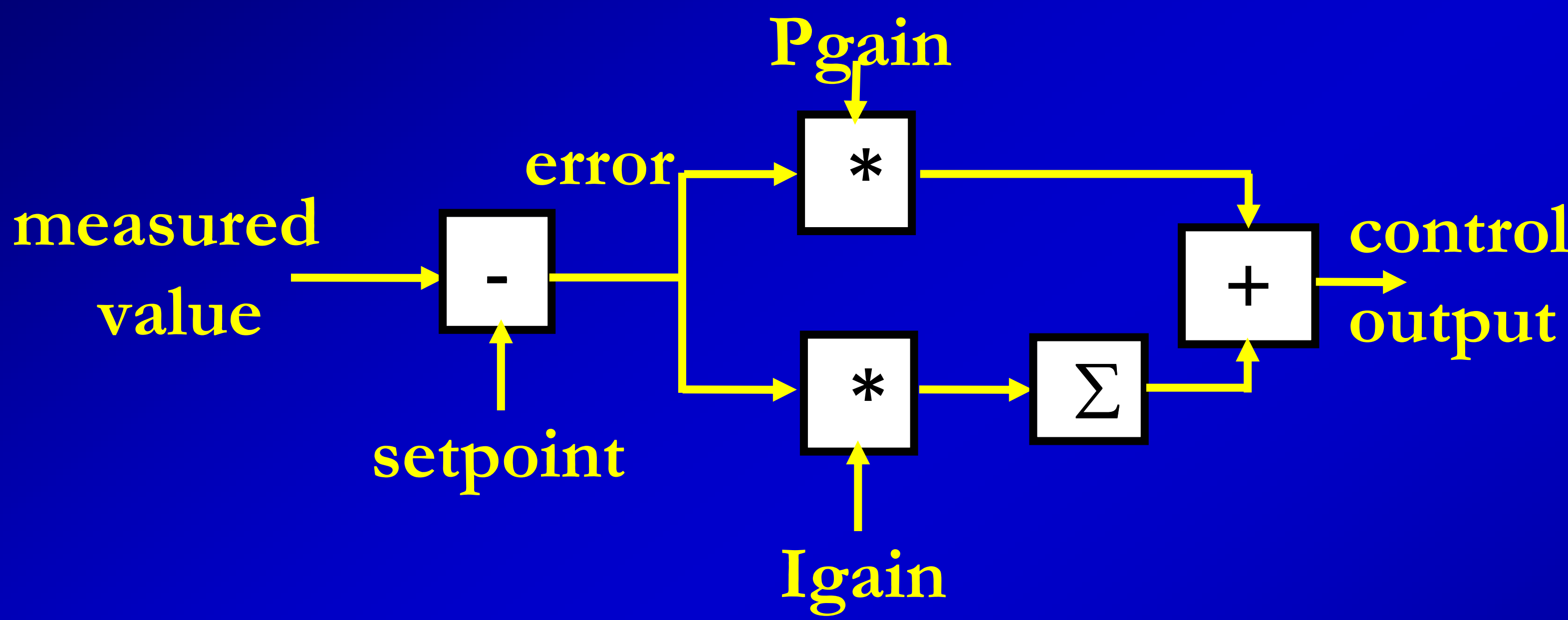
Trend 4:

- **Advanced controllers for**
  - Fast field control
  - Cavity frequency control
  - High level functions

Fast Field Control Algorithms

- Feedback
  - Proportional-Integral-Differential (PID) controller
  - Kalman filter
  - Adaptive filters
  - Smith predictor
  - Optimal controller
  - Beam energy feedback
  - Bunch length feedback, …
- Feedforward
  - Beam loading compensation
  - Klystron high voltage ripple feedforward, …
- Trip and quench detection

Example: Simple PI Loop



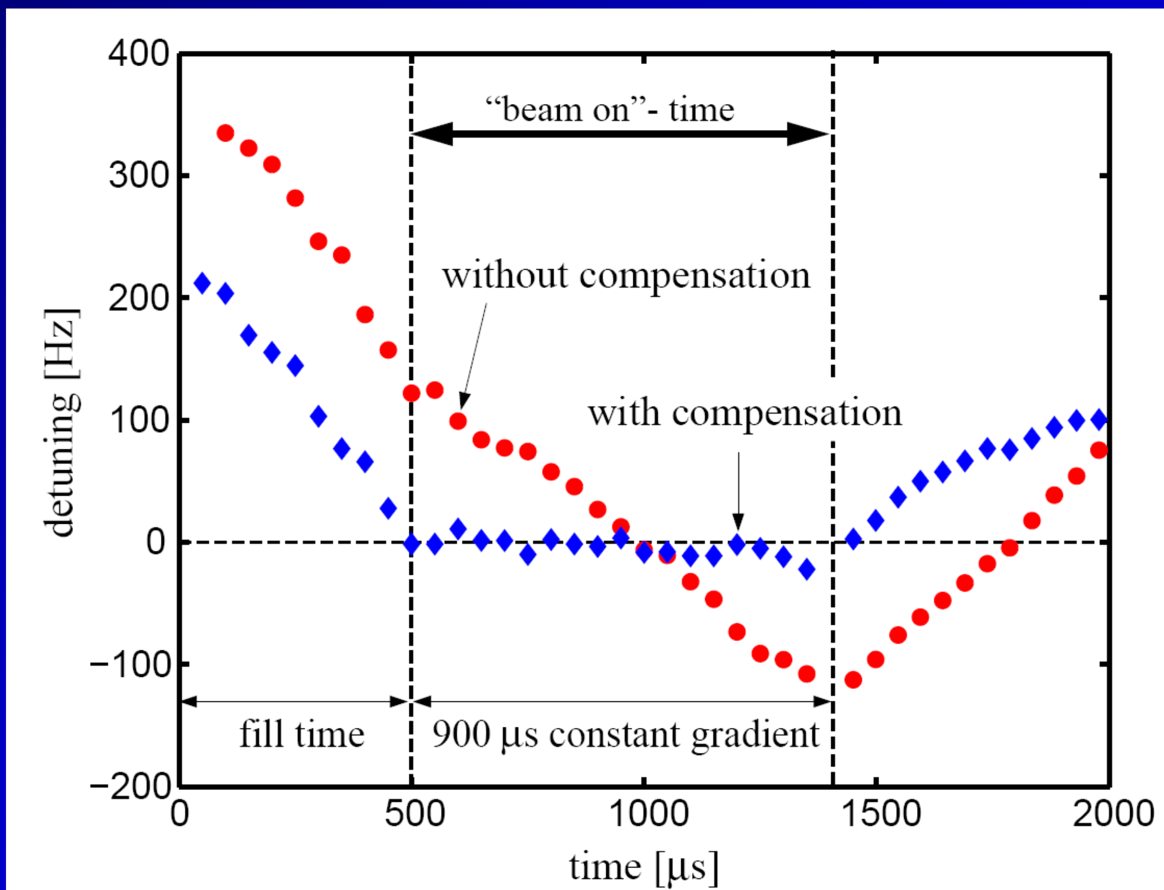
- Very simple, but also robust and fast
- Most LLRF system use this very simple RF field feedback loop.

Cavity Frequency Control

- Slow frequency tuner
  - Feedback loop to maintain average resonance frequency
- Fast frequency tuner
  - Dynamic Lorentz-force compensation (feedforward and/or feedback)
  - Microphonics control (feedforward and/or feedback)

Fast Frequency Control: Pulsed

TTF 9-cell cavity at 23.5 MV/m

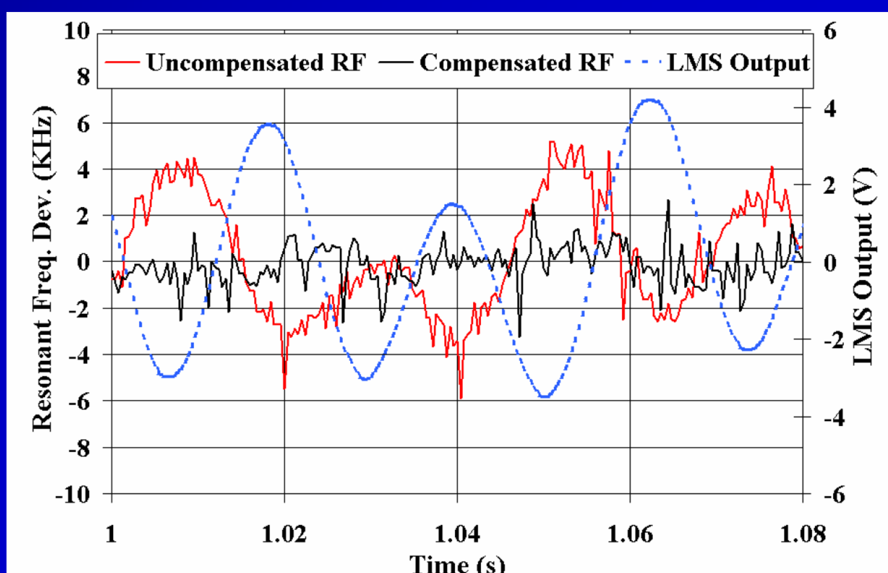


- **Lorentz-force detuning compensated by fast piezoelectric tuner**
- **(Adaptive) feedforward control**

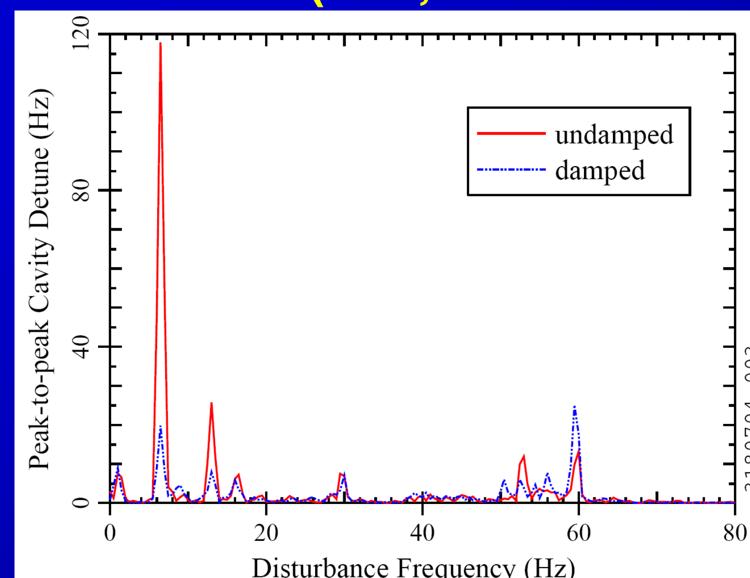
Fast Frequency Control: CW

- Adaptive feedforward suppression of microphonics cavity detuning.
- First baby-steps done; results are encouraging…

Work at Fermilab



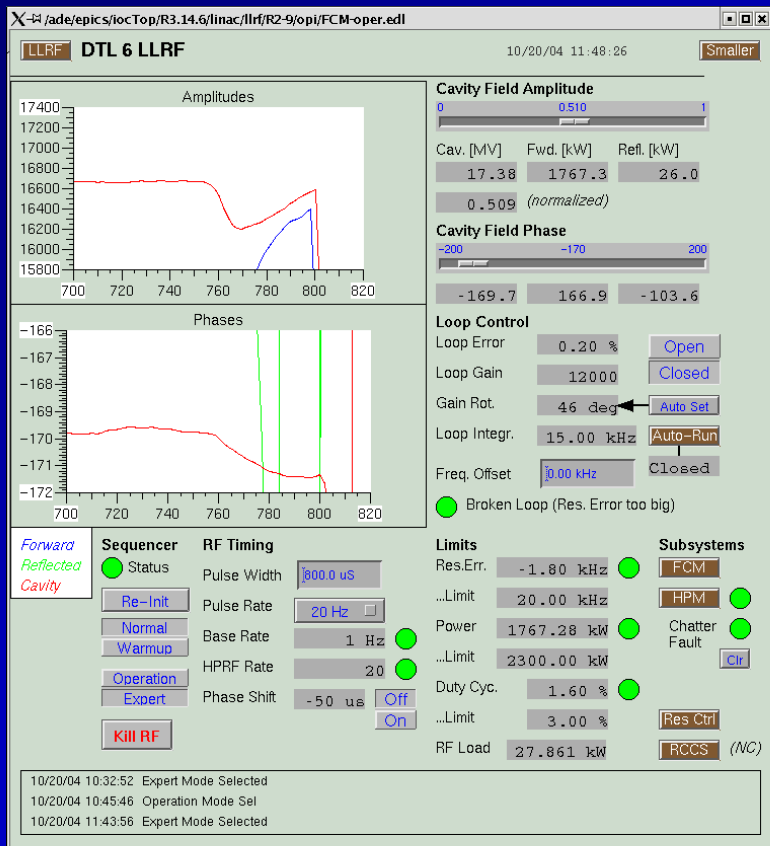
Work at MSU (RIA, T.Grimm et al.)



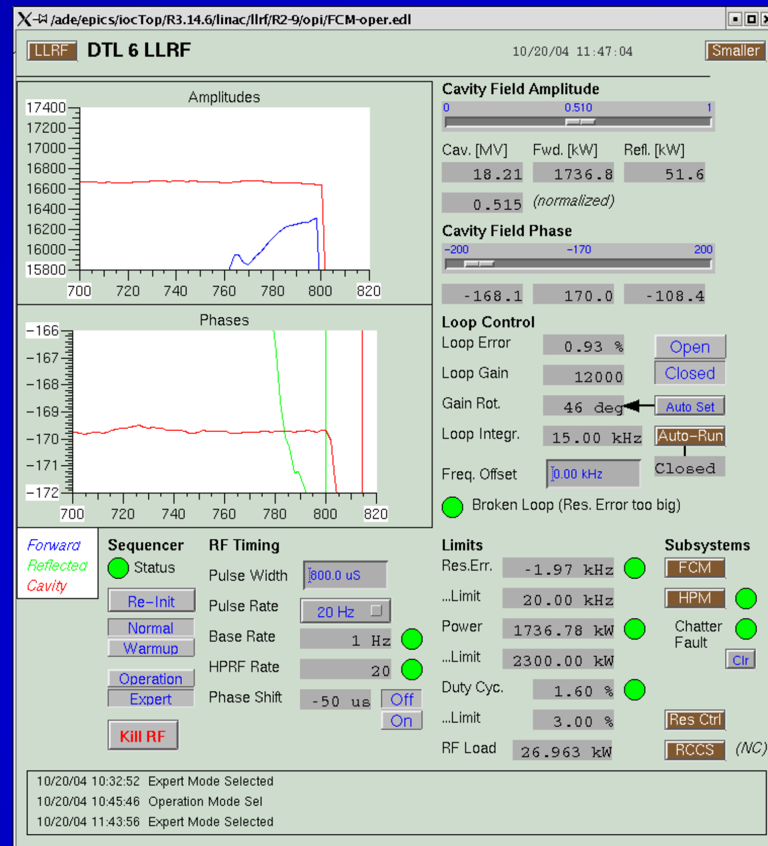
High Level Algorithms

- Adaptive feedforward
- Waveguide tuner control
- Loop phase calibration
- Operation with adjustable klystron high voltage
- Finite state machine, automated start-up and fault recovery
- Cavity / coupler high power processing
- Energy / momentum management system
- System identification and optimization
- Diagnostics
- (Beam based) field calibration (amplitude and phase)
- Forward/reflected power calibration
- Data acquisition; trip capture
- …

Adaptive Feedforward: SNS

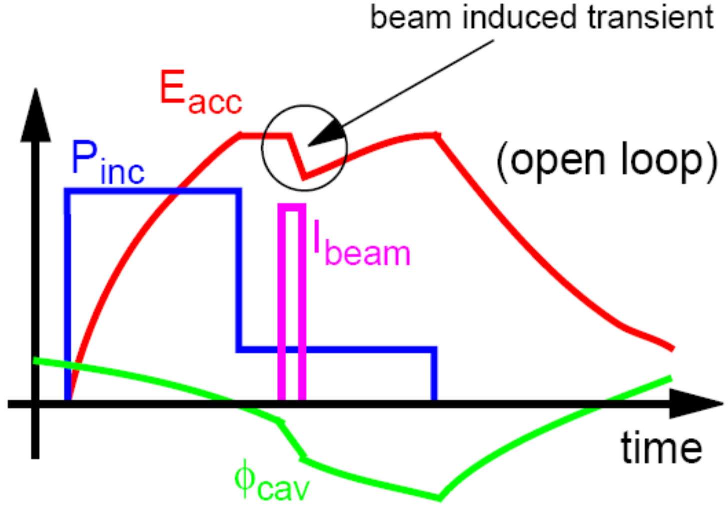


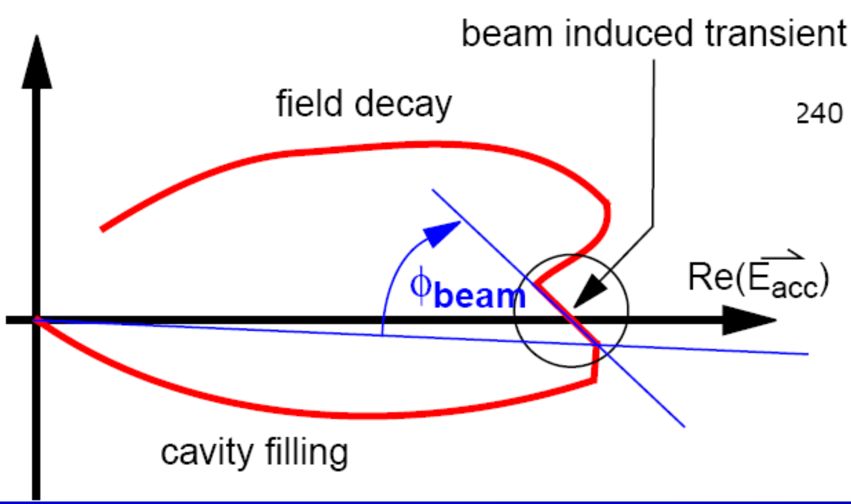
Beam loading in DTL6 with ~40 us, 20 mA beam induced error of 2.7% and 2 deg in amplitude and phase.

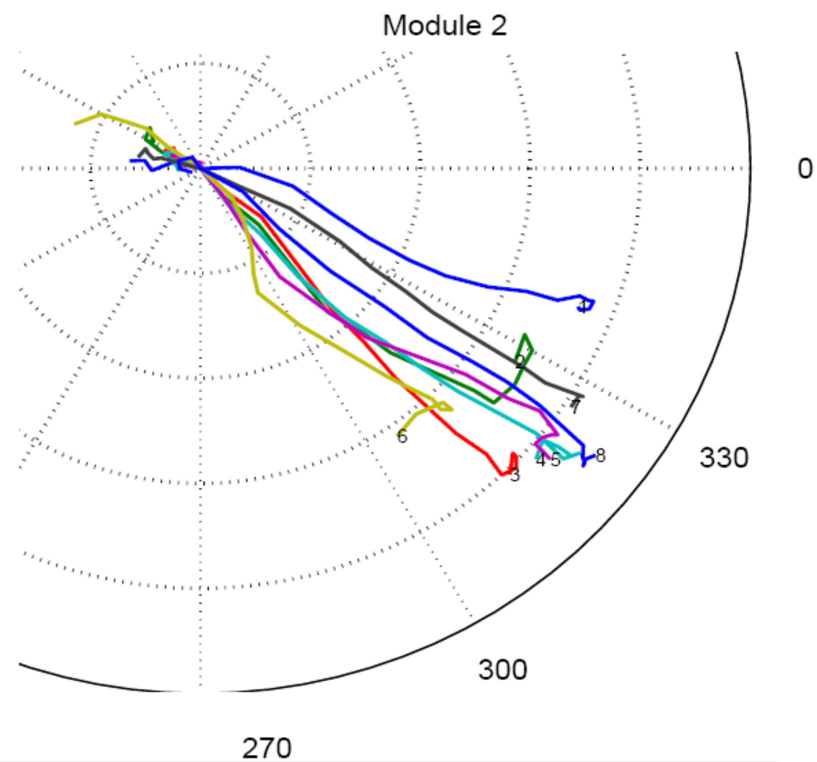


Beam loading eliminated by means of Adaptive Feedforward (M. Champion et al.)

Beam Based Calibration: TTF







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

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

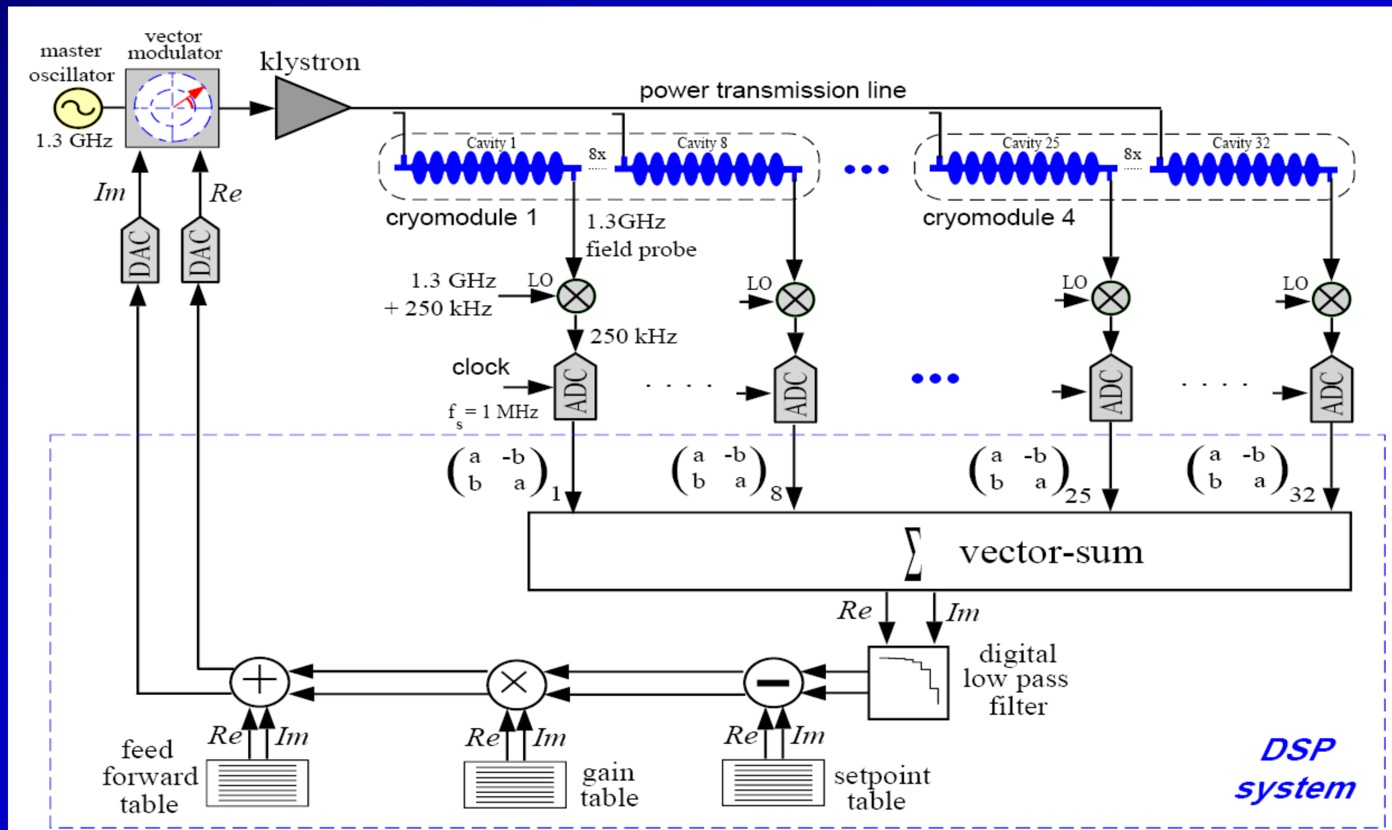
Design Efforts Worldwide and achieved Performance

LLRF Systems for Pulsed Linacs

Examples:

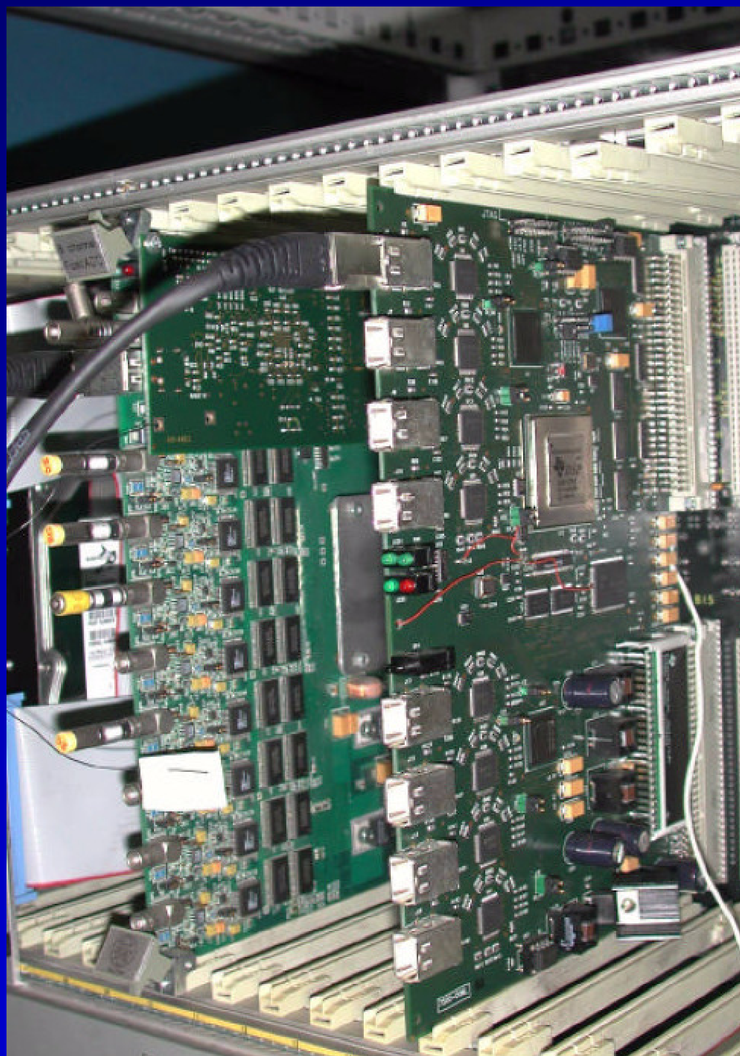
- TTF / UVFEL
- SNS

TTF LLRF System

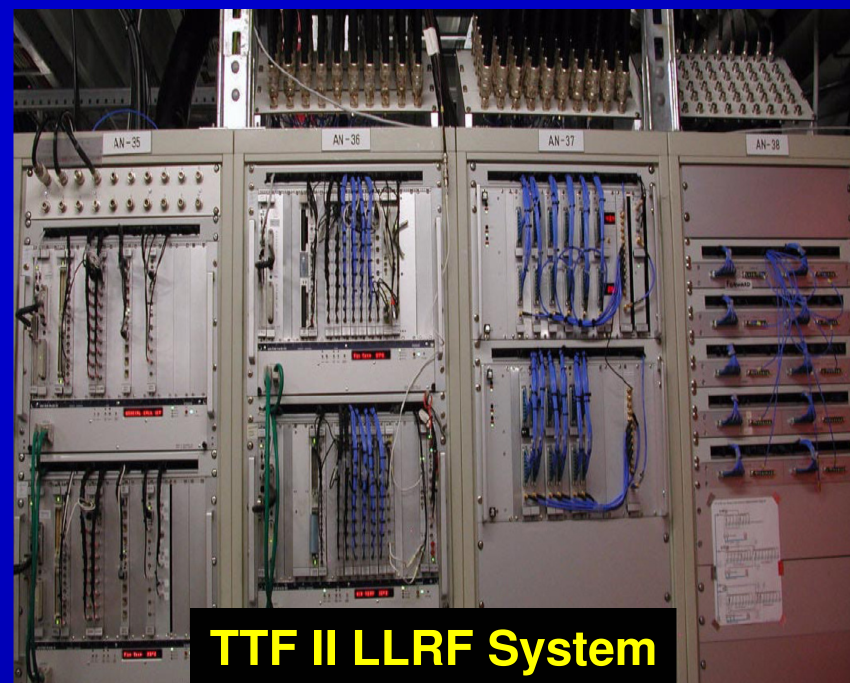


- Pioneering work on digital LLRF control for pulsed machines
- I /Q detection: 250 kHz IF frequency; 1 MHz sample rate

TTF II / UVFEL



- DSP based
- Separate 8 channel ADC boards
- Performance verified by beam measurements (σ_E / E< 10^{-3})

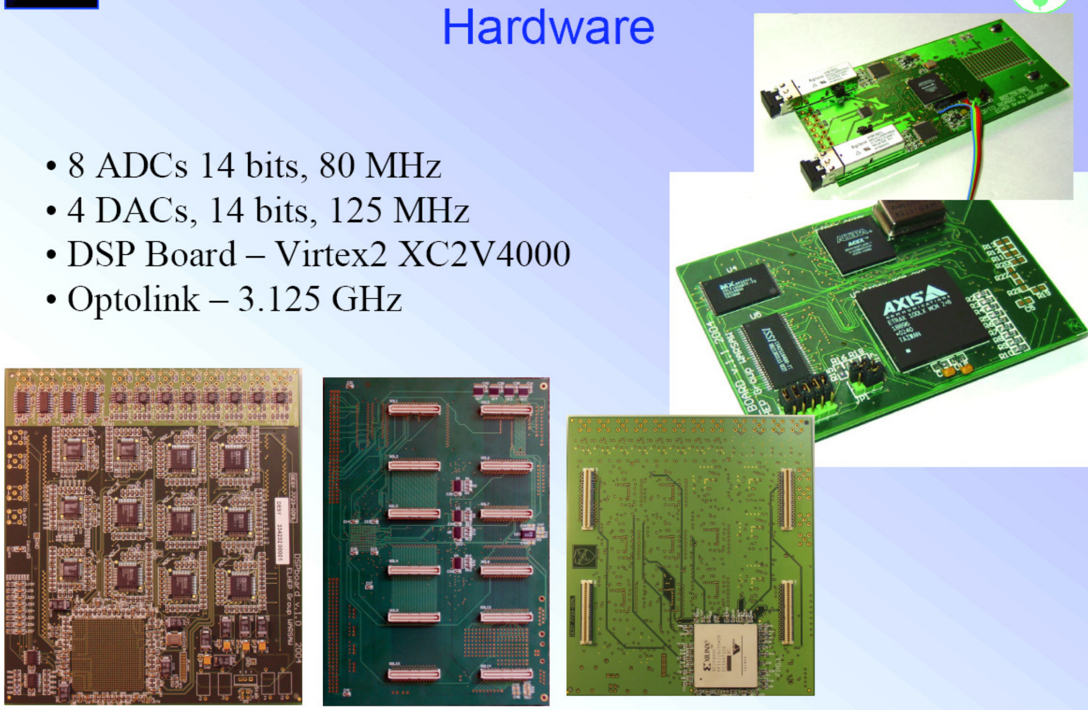


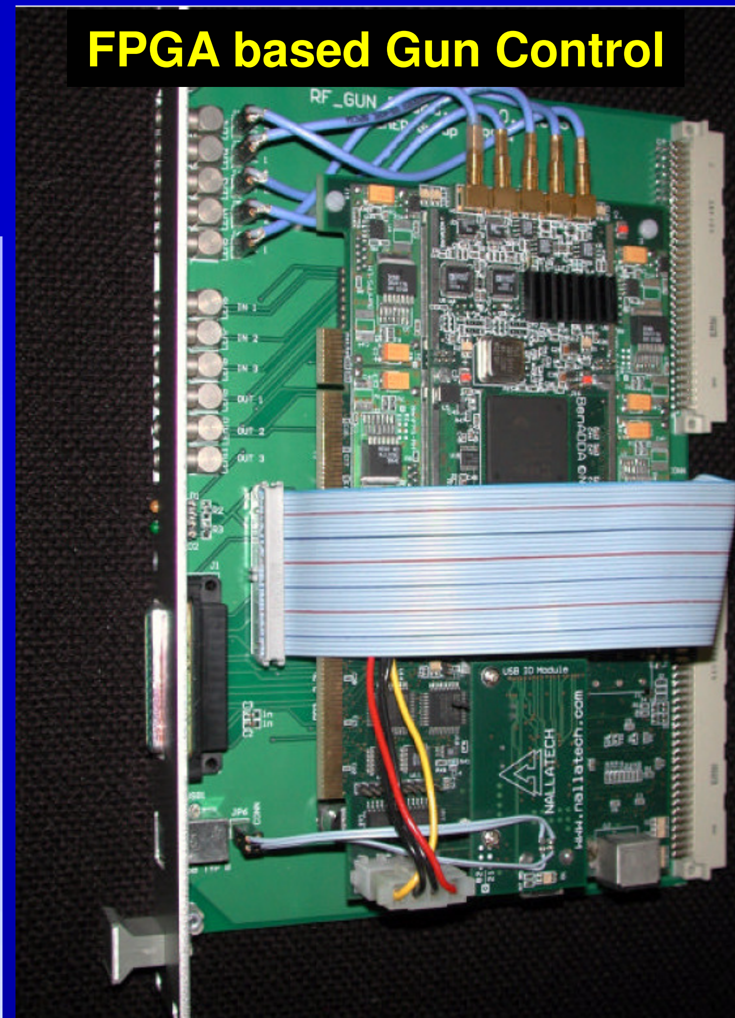
TTF: Next Generation

- **FPGA** based
- High IF frequency > 10 MHz
- Fast links: many ADC for vector sum control (36 cavities!)

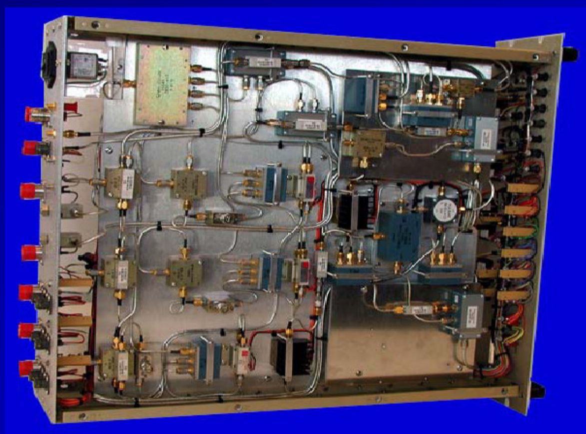
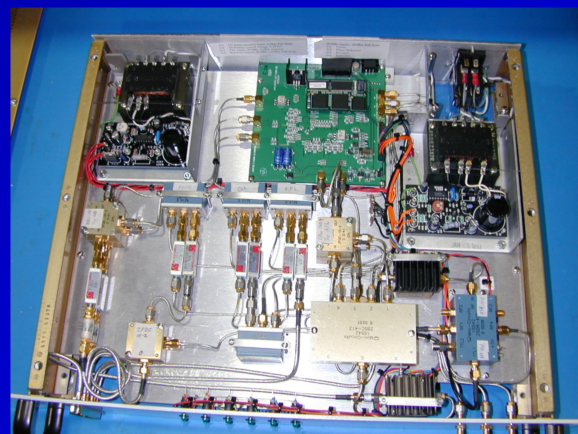
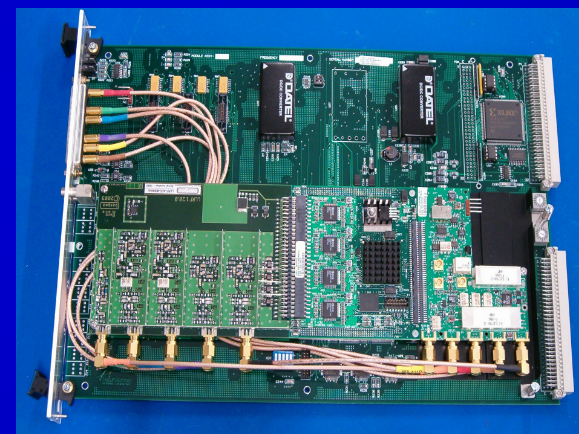
Third Generation RF Control Hardware

- 8 ADCs 14 bits, 80 MHz
- 4 DACs, 14 bits, 125 MHz
- DSP Board – Virtex2 XC2V4000
- Optolink – 3.125 GHz



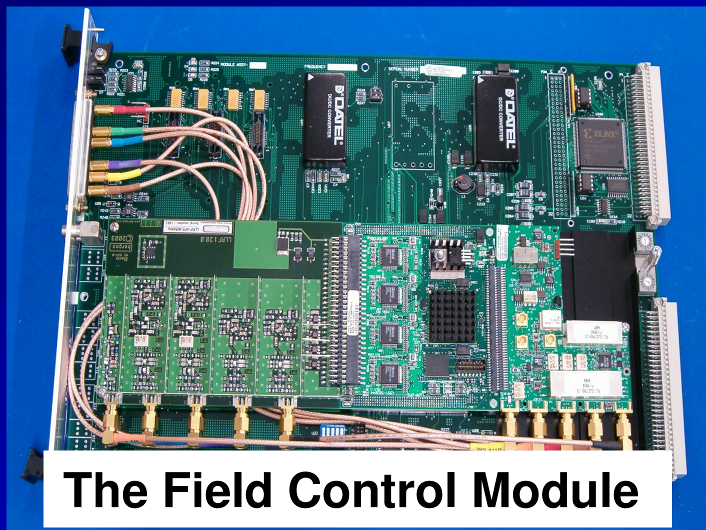


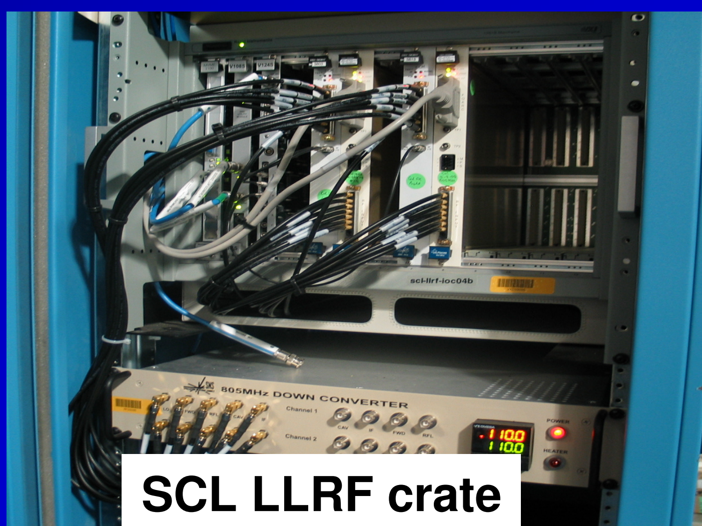
SNS LLRF

1st Generation Control Chassis	2nd Generation Control Chassis	3rd Generation Field Control Module
		
MEBT Rebunchers	RFQ & DTL	CCL, SCL & HEBT
4 installed, 1 spare	7 installed, 3 spares	Retrofit to MEBT, RFQ & DTL
Retrofitted with FCM Nov 04	Retrofitted with FCM Jul 04	98 systems + spares

Evolutionary Development: build on proven concepts, hardware and software

SNS LLRF





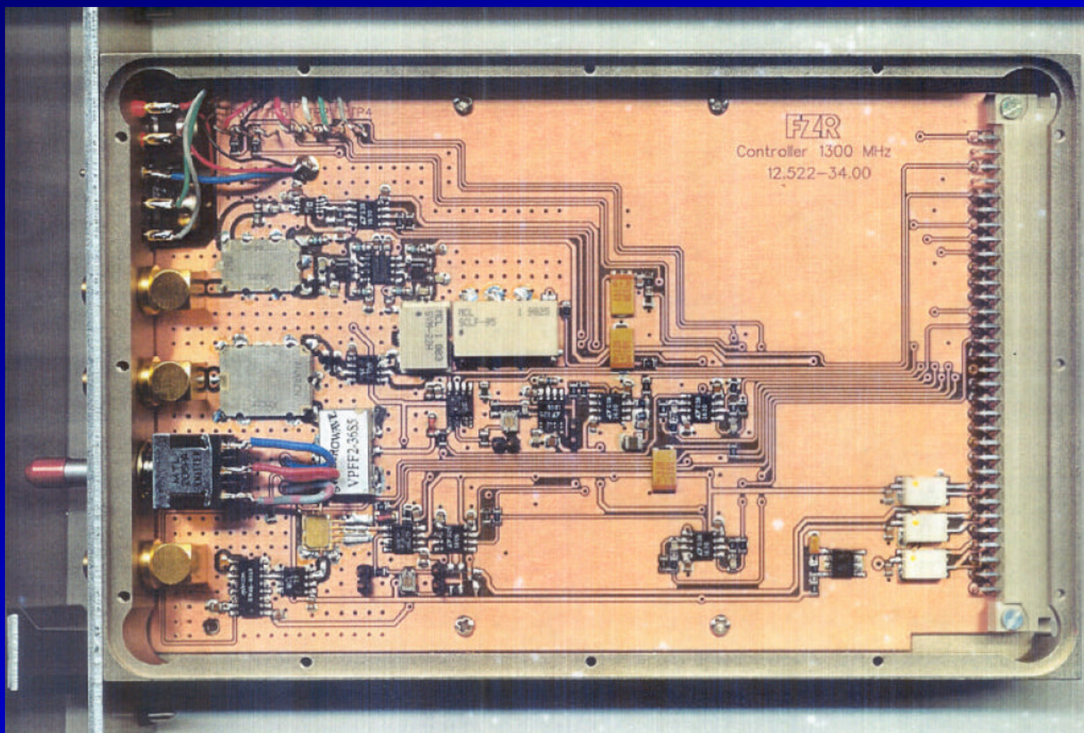
- FPGA based I / Q control
- 40 MHz PI controller with adaptive feedforward
- Installation for all 96 cavities (n.c. and s.c.) is complete
- Requirement of ±1% and ±1deg is readily achieved on normal conducting and superconducting cavities.
- System was successful tested with beam in the n.c. linac section.

LLRF Systems for CW Machines

Examples:

- Rossendorf, Daresbury ERLP
- CEBAF
- BESSY FEL
- Cornell's CESR and ERL

Rossendorf / ERLP (Daresbury)



- Developed for cw operation of 1.3 GHz s.c. cavities at ELBE
- Analog amplitude and phase control
- Achieved very good field stability at $Q_L = 10^7$:
  - 0.02% in amplitude
  - 0.03 deg in phase
- Adopted by Daresbury for the ERL Prototype

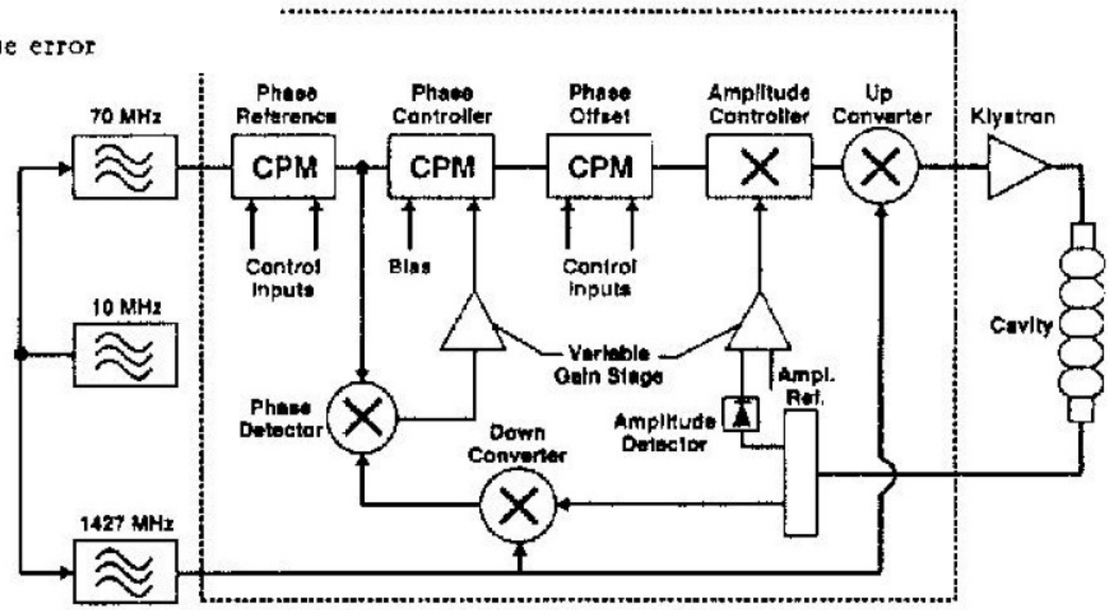
CEBAF LLRF

RF control requirements with vernier

RMS error	uncorrelated	correlated
σ_A	2×10^{-4}	1.1×10^{-5}
σ_f	0.25°	0.13°
σ_s	2.6°	∞

σ_A : relative RMS amplitude error
σ_f : fast RMS phase error
σ_s : slow RMS (along linac) phase error

Loaded Q ≈ $7 \cdot 10^6$
< 12 MV/m
I ≈ 400 μA



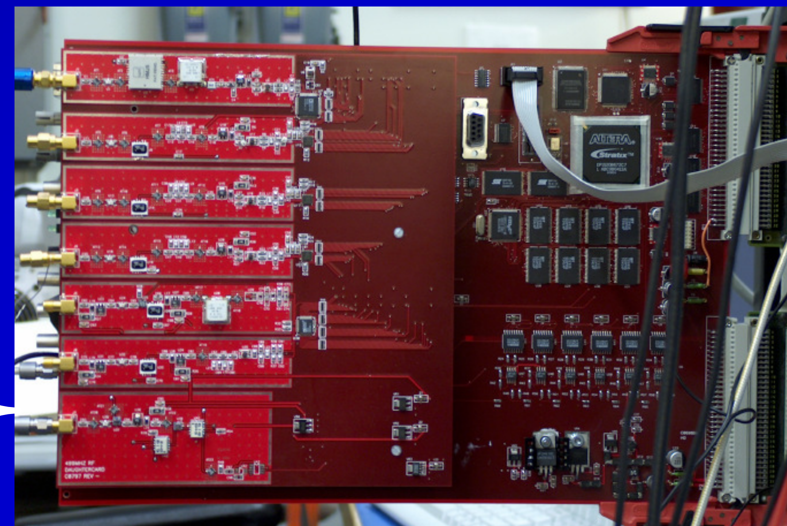
Achieved stability: about 0.007 %, 0.02 deg !

LLRF for CEBAF Upgrade

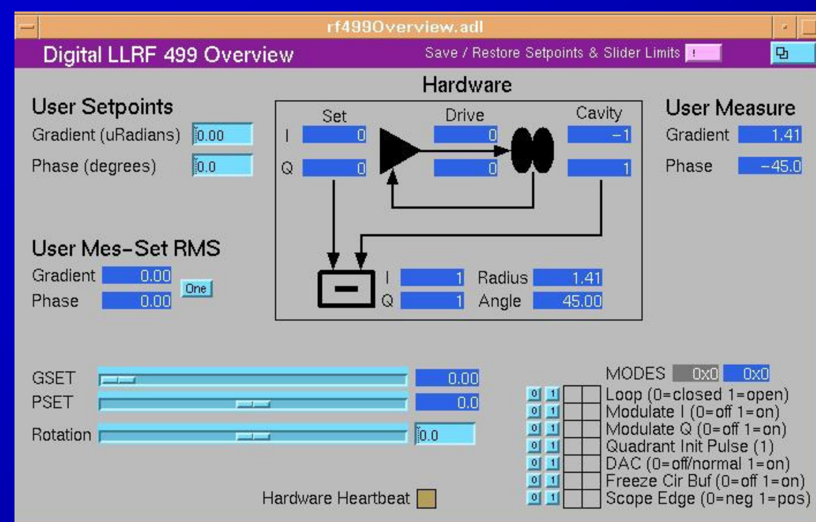
- Upgrade: 20 MV/m , $Q_L = 2 \cdot 10^7$
- Cornell – JLAB Collaboration
  - A very successful collaboration between the two institutions tested the Cornell LLRF system in the JLAB FEL and in CEBAF
- Subsystem Prototyping
  - 1497 MHz Receiver/Transmitter prototype: Daughter card for mother board
  - 499 MHz LLRF System Environmentally Tested (VXI and Boards)
  - Piezo Amplifier/System: tested with Cornell LLRF system
- Model/ Algorithm Development/Firmware
  - Electronic Damping Modeled: PAC 2005 (A. Hofler and J. Delayen)
  - Resonance Control: (Collaborating with Cornell) test in CMTF with Renascence ~August

LLRF for CEBAF Upgrade

- LLRF system designed around a "generic" processor motherboard
  - Motherboard uses large FPGA (Altera) for PID and cavity resonance control.
  - Can support transceivers at different cavity frequencies (499 MHz & 1497 MHz).
  - System has been operated closed loop around copper cavity
- Controlling system through EPICS



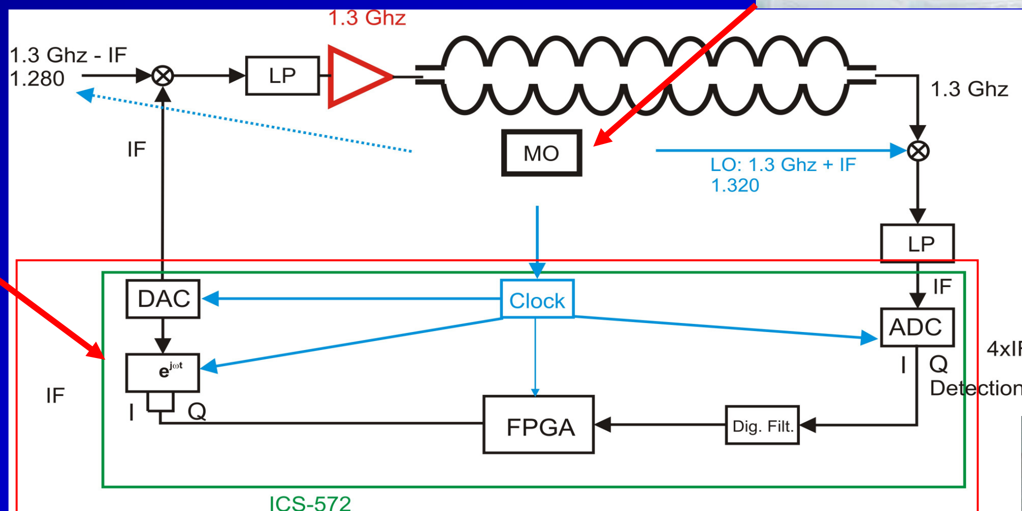
VXI Motherboard & 499 MHz Transceiver



Proto - EPICS Operators Control Screen

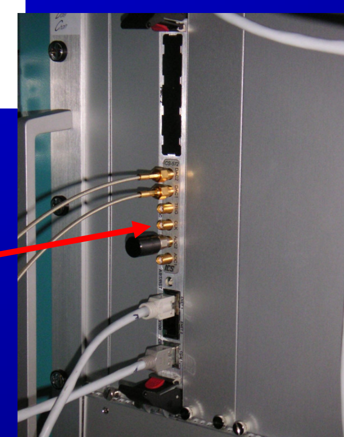
LLRF for the BESSY FEL

- ICS-572 board with Xilinx FPGA and 2 ADC/DAC channels (105/200 MHz)
- Rohde & Schwarz signal generator quartz oscillator

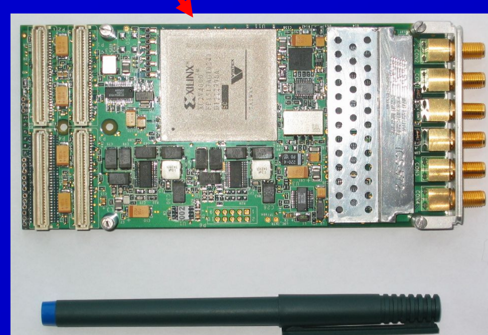


Digital up-conversion

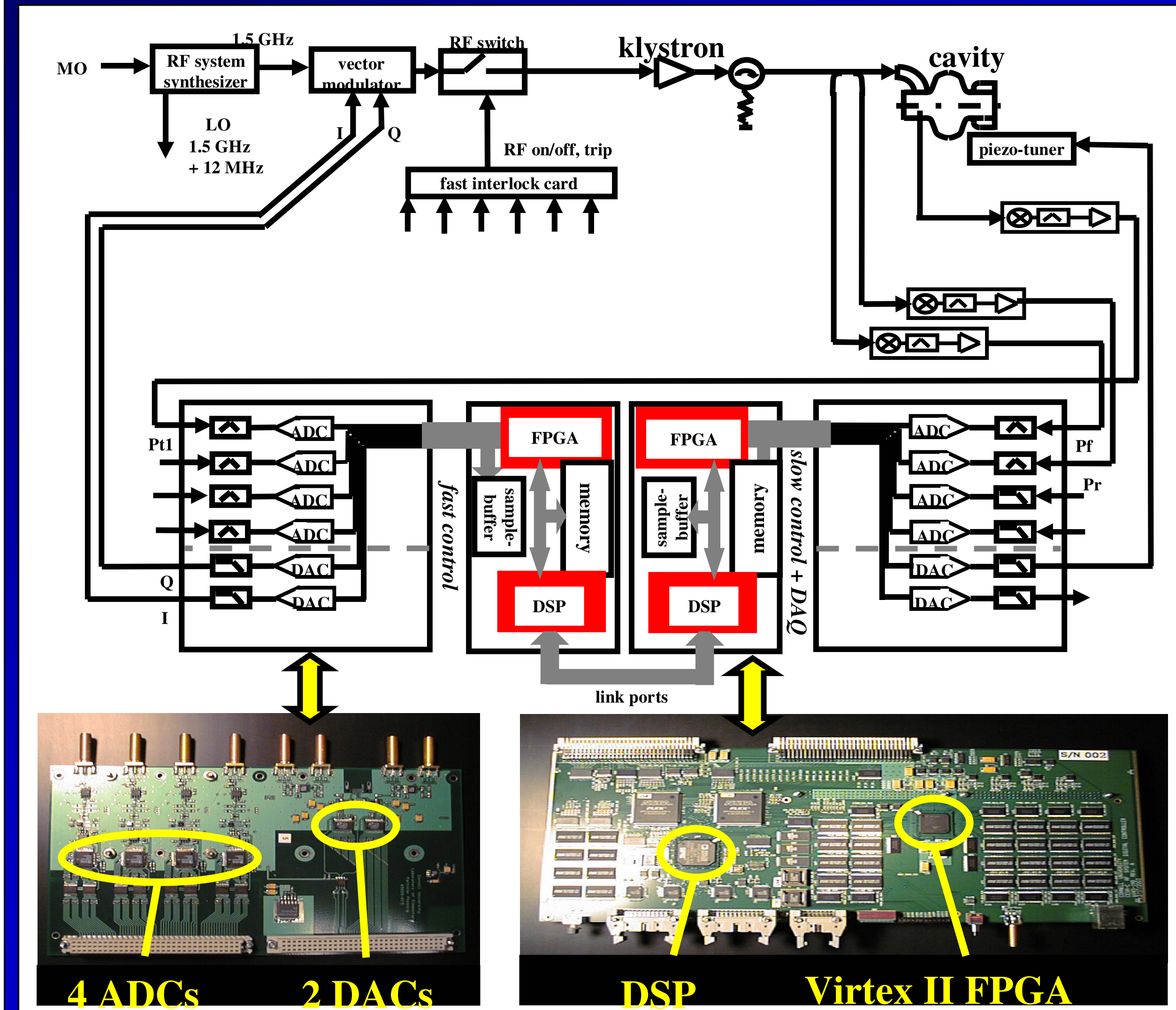
VME Crate
+ Motorola
MVME 5500 Board



IF 20 MHz,
Sampling 80 MHz



Cornell LLRF



- All parts designed in house
- Digital I / Q control
- FPGA/DSP design
  - FPGA: fast feedback loops
  - DSP: trip detection, state machine, tuner control, …

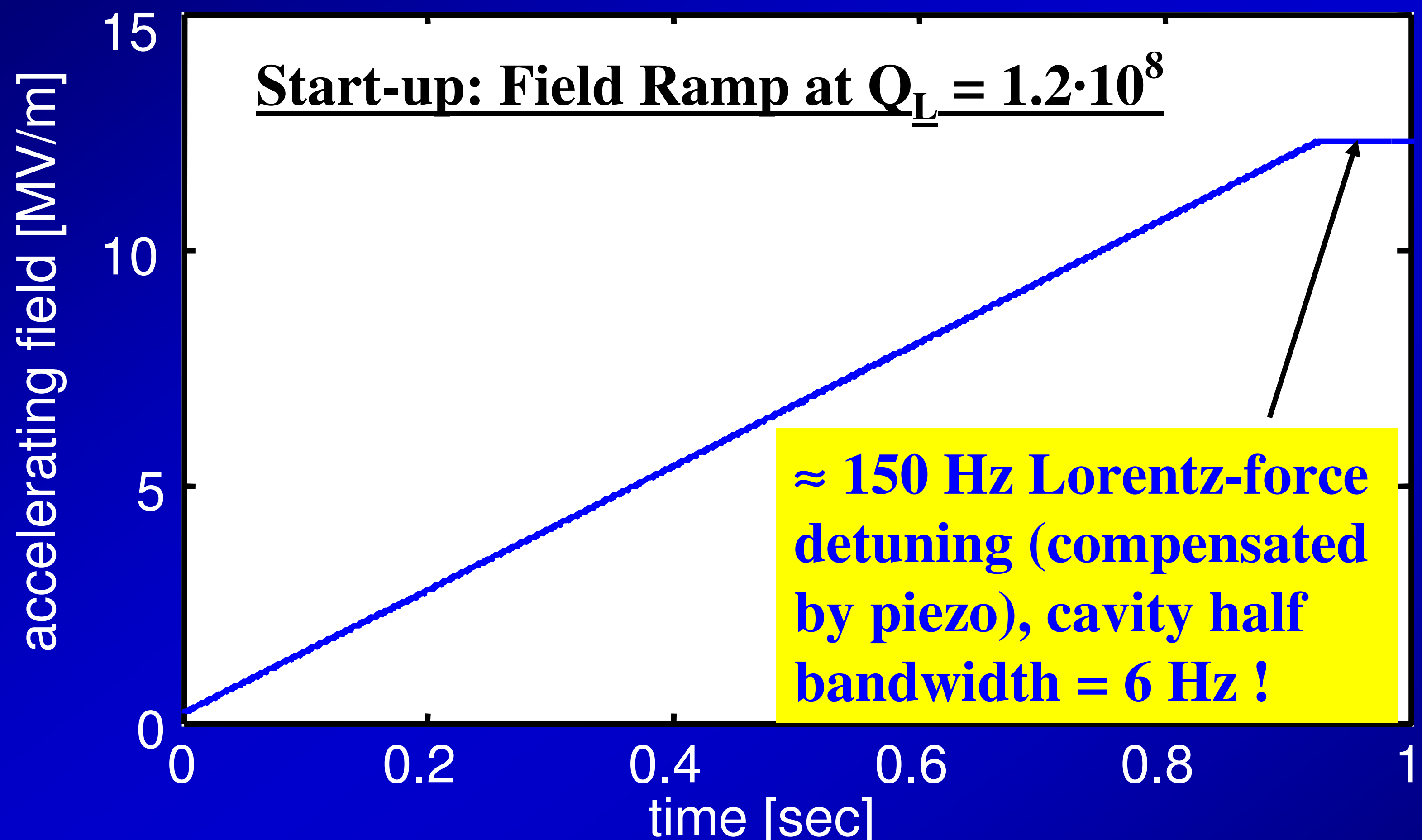
Cornell LLRF: CESR

- Vector sum control of two heavily beam loaded cavities in the CESR storage ring.
- Digital LLRF system is in operation in CESR since Summer 2004.
- No unplanned downtime has been caused by the LLRF system in the last eight months.
- Achieved field stability surpasses requirements.
- Includes: state machine; trip and quench detection; adjustable klystron high-voltage; tuner control (motor and piezo); feedforward compensation of klystron high-voltage ripple; pulsed operation for processing, diagnostics, …

Cornell LLRF: High Q_L Operation

- **ERLs want to operate cavities at highest loaded Q for very efficient cavity operation.**
- **Prove of principle experiment at the JLab ERL:**
  - **Installed Cornell's LLRF system at JLAB FEL to control field in one 7-cell cavity**
  - **Operated cavity at Q_L=1.2·10^8 with 5 mA energy recovered beam.**
  - **Cavity half bandwidth: 6 Hz !**

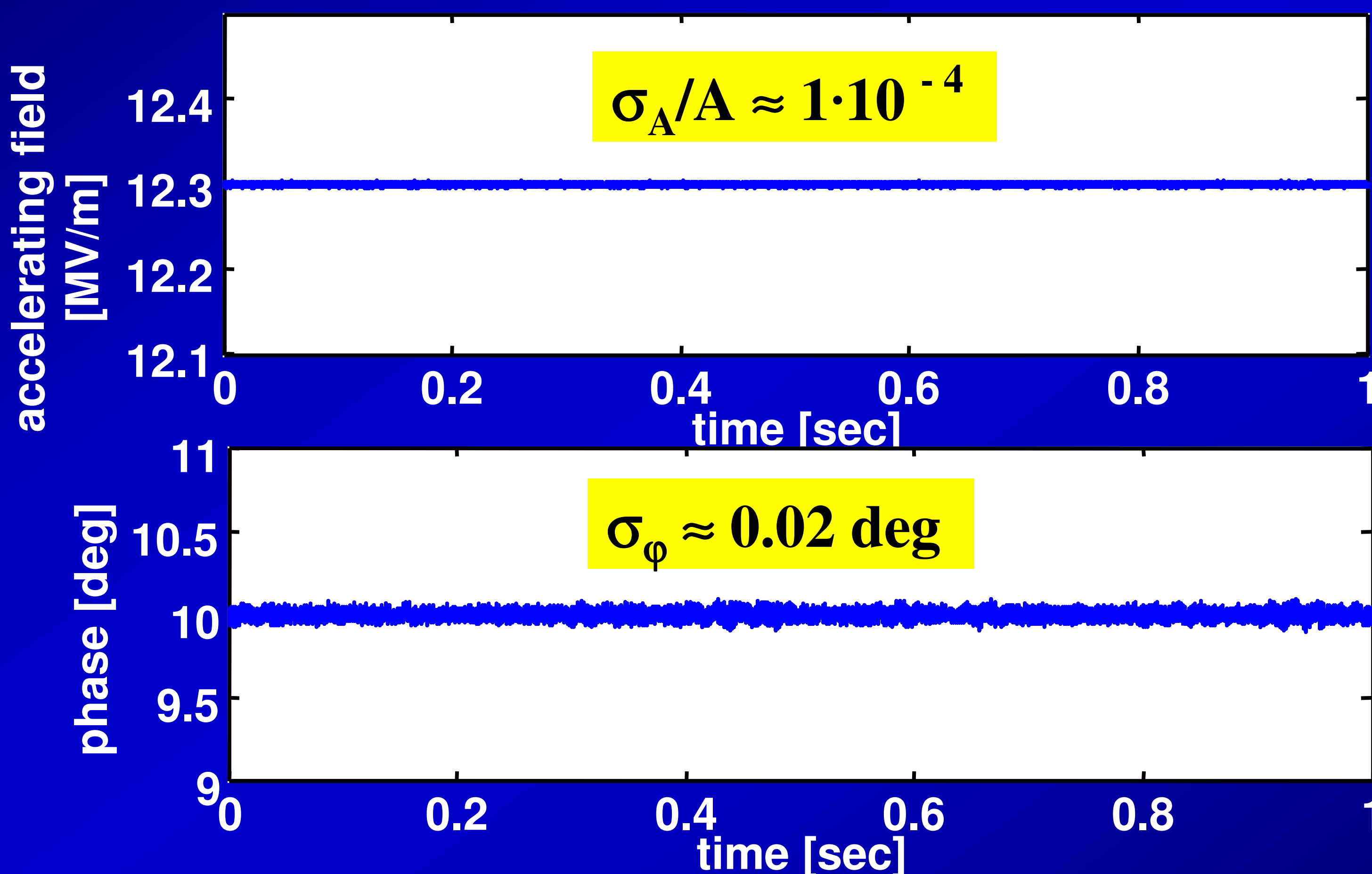
ERL operation at $Q_L = 1.2\cdot10^8$



Fast cavity filling important for fast trip recovery.

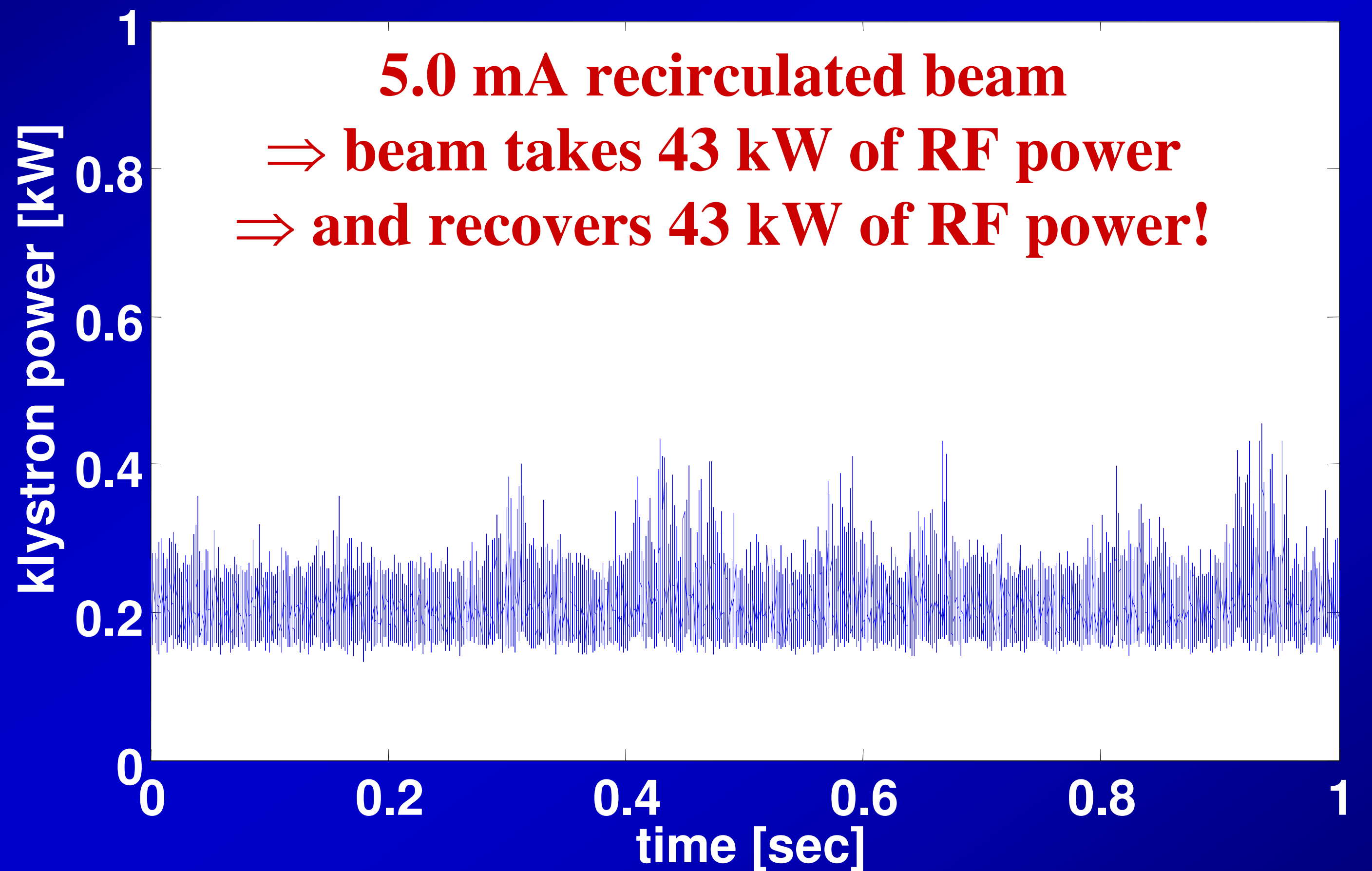
ERL operation at $Q_L = 1.2 \cdot 10^8$

Very good field stability demonstrated with 5 mA beam:



ERL operation at $Q_L = 1.2 \cdot 10^8$

At this high loaded Q, cavity operation at 12.3 MV/m with ERL beam takes only a few 100 W!



Conclusions

Conclusions

- Field stability ranging from 1% to 10^{-4} amplitude and 1 deg to 0.01 deg for phase will be required for future s.c. and n.c. accelerators.
- Sources of field perturbations are well understood.
- LLRF systems are complex systems with multiple feedback and feedforward control loops, state machine, …
- Rapid development in digital technology favors digital design for feedback/feedforward control.
  - But: also analog systems work well and have lowest latency
- Present achievements
  - $<10^{-4}$ in amplitude and $\approx$ 0.02 deg at $Q_L=10^8$
- Resonance control with fast tuner is promising
- Summary: Very active, fast moving field…

Progress in LLRF and Cars…

Analog car / LLRF system

- Reliable
- Relative simple
- Less expensive
- Easy to fix

Digital car / LLRF system

- Many nice features (4-zone climate control, air suspension with adaptive damping system, driver-adaptive 5-speed automatic transmission, electronic stability program, Distronic adaptive cruise control, Parktronic, air bags, …)
- Need experts to fix
- More challenging, but enormous potential…

Workshop on Low Level RF

LLRF05

Sophisticated Low Level RF systems are needed in modern particle accelerators to deal with the characteristics of state-of-the-art RF accelerating structures and their power sources, and to meet unprecedented levels of performance. The goal of the LLRF05 workshop is to share experience between linac and synchrotron projects (SNS, J-PARC, ILC, LHC etc.) and to discuss the best engineering practice.

This four-day workshop will be the 15th in the series of mini-workshops under the auspices of the ICFA Beam Dynamics Panel, and specifically will be the second in a series on low-level RF techniques, initiated at Jefferson Lab, USA, in 2001.

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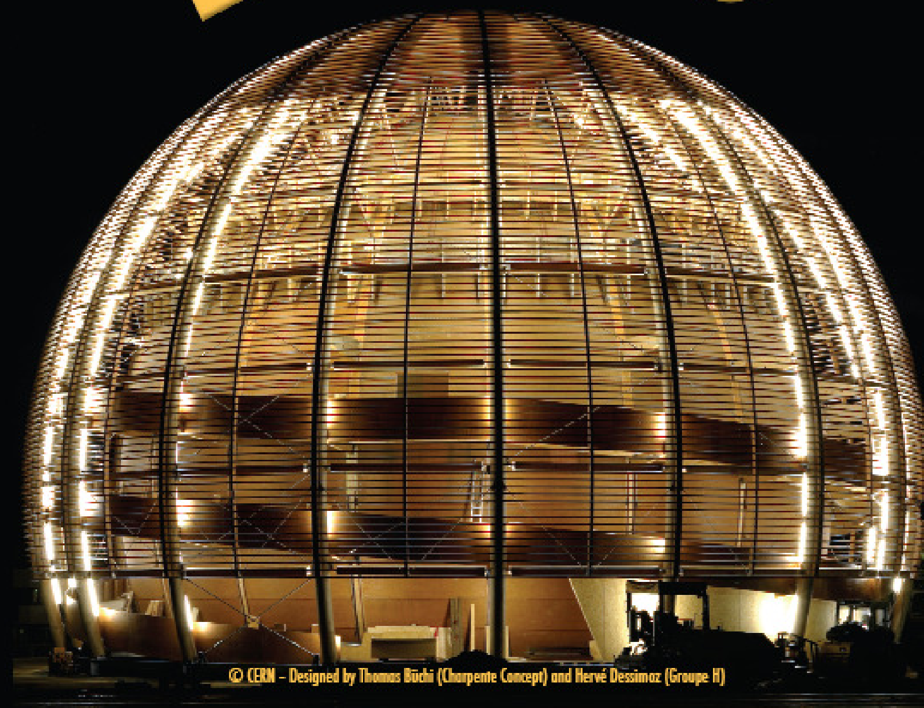

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CERN, Geneva, 10–13 October 2005

http://www.cern.ch/LLRF05