The European X-FEL: RF Control Challenges

S. Simrock, DESY

Outline

- Part I: TESLA and X-FEL
- Part II: RF Control

500 *(→ 800)* GeV e+e- Linear Collider

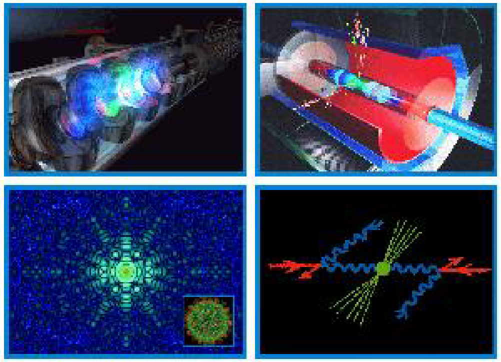
Based on superconducting linac technology

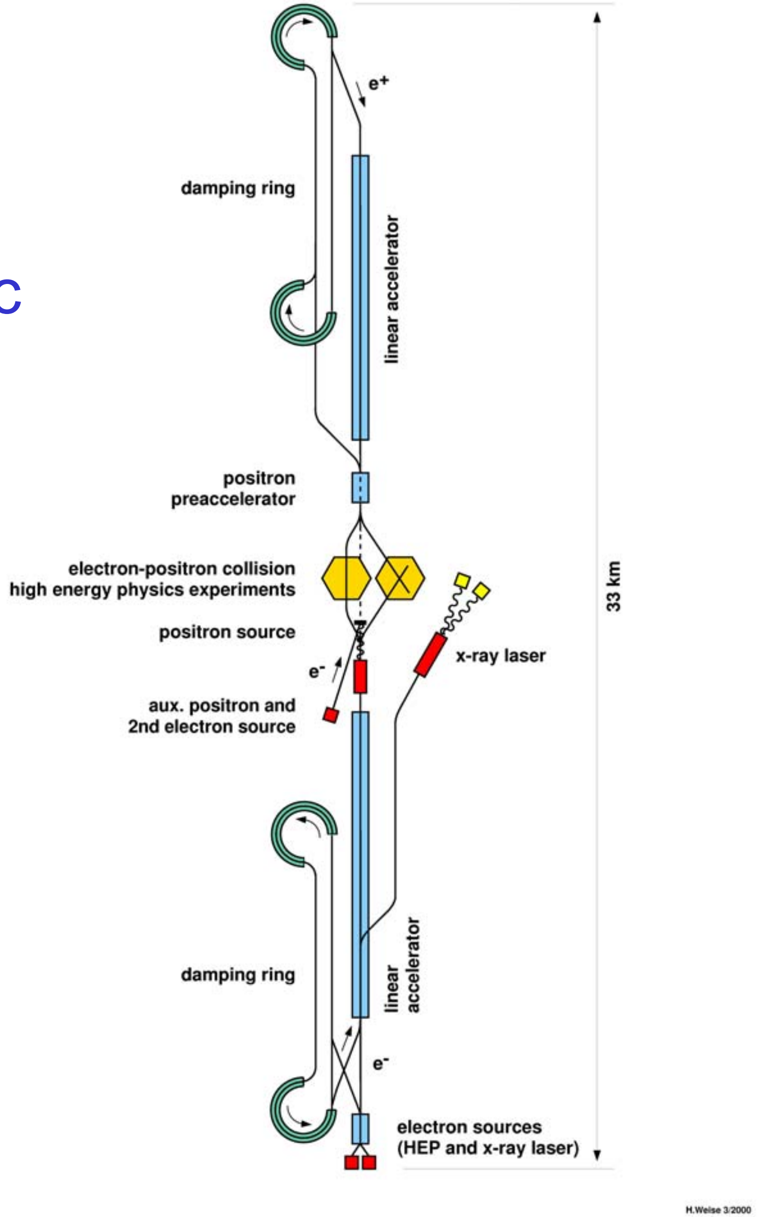
TESLA

The Superconducting Electron-Positron Linear Collider

with an Integrated X-Ray Laser Laboratory

Technical Design Report





TESLA

The TESLA Collaboration:

54 Institutes from 12 countries

Members of the TESLA Collaboration

CANDLE, Yerevan

Yerevan Physics Institute, Yerevan

Institute for High Energy Physics (IHEP), Academia Sinica, Beijing

Tsinghua University, Beijing

Peking University

Institute of Physics, Helsinki

CEA/DSM DAPNIA, CE-Saclay, Gif-sur-Yvette

Laboratoire de l'Accélérateur Linéaire (LAL), IN2P3, Orsay

Institut de Physique Nucléaire (IPN), Orsay

Rheinisch-Westfälische Technische Hochschule, Aachen

Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, BESSY, Berlin

Hahn-Meitner Institut Berlin

Max-Born-Institut, Berlin

Technische Universität Berlin

Technische Universität Darmstadt

Technische Universität Dresden

Universität Frankfurt

GKSS-Forschungszentrum Geesthacht

Deutsches Elektronen-Synchrotron DESY in der Helmholtz-Gemeinschaft, Hamburg und Zeuthen

Universität Hamburg

Forschungszentrum Karlsruhe

Universität Rostock

Bergische Universität-GH Wuppertal

CCLRC-Daresbury and Rutherford Appleton Laboratory, Cheshire

Royal Holloway, University of London (RHUL)

Queen Mary, University of London (QMUL)

University College London (UCL)

University of Oxford

Laboratori Nazionali di Frascati, INFN, Frascati

Istituto Nazionale di Fisica Nucleare (INFN), Legnaro

Istituto Nazionale di Fisica Nucleare (INFN), Milan

Istituto Nazionale di Fisica Nucleare (INFN), Rome II

Sincrotrone Trieste

Institute of Nuclear Physics, Cracow

University of Mining and Metallurgy, Cracow

Soltan Institute for Nuclear Studies, Otwock-Swierk

High Pressure Research Center, Polish Academy of Science, Warsaw

Institute of Physics, Polish Academy of Science, Warsaw

Polish Atomic Energy Agency, Warsaw

Faculty of Physics, University of Warsaw

Moscow Engineering and Physics Institute, Moscow

Institute for Theoretical and Experimental Physics (ITEP), Moscow

Budker Institute for Nuclear Physics (BINP), Novosibirsk

Budker Institute for Nuclear Physics (BINP), Protvino

Institute for High Energy Physics (IHEP), Protvino

Institute for Nuclear Research (INR) Russian Academy of Sciences, Troitsk

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid

Paul-Scherrer-Institut (PSI), Villigen

Argonne National Laboratory (ANL), Argonne IL

Fermi National Accelerator Laboratory (FNAL), Batavia IL

Cornell University, Ithaca NJ

University of California, Los Angeles CA

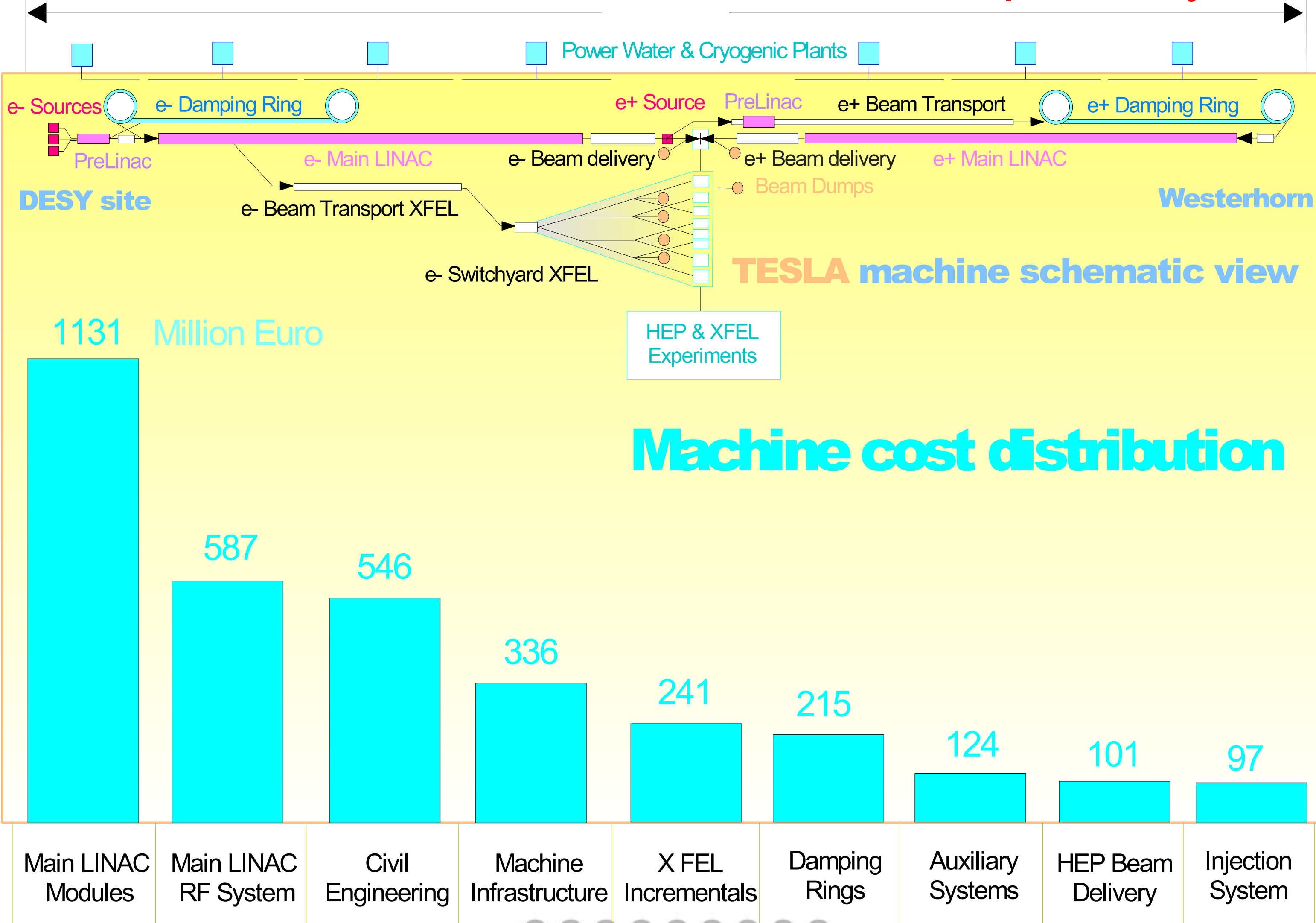
Jefferson Lab, Newport News VA ← MIT (Jan 2004)

Joint Institute for Nuclear Research (JINR), Dubna

September 2003

Cost estimate 500GeV LC, one e+e- IP:

3,136 M€ (no contingency, year 2000) + ~7000 person years



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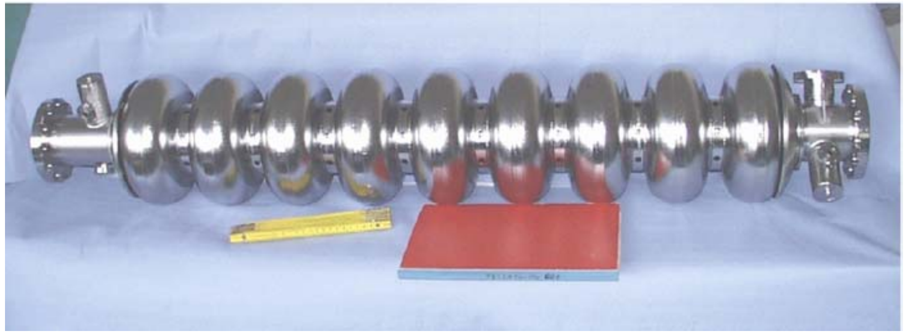
Why…



…technology?

Low RF losses in resonators ($Q_0 = 10^{10}$,pure Nb at T=2K)

→ High AC-to-beam efficiency

→ Long pulses/many bunches with low RF peak power

→ Fast intra-train orbit&energy feedback & luminosity stabilisation

Low frequency (f=1.3 GHz), small wakefields $\propto f^3$

→ Relaxed alignment tolerances, good beam stability

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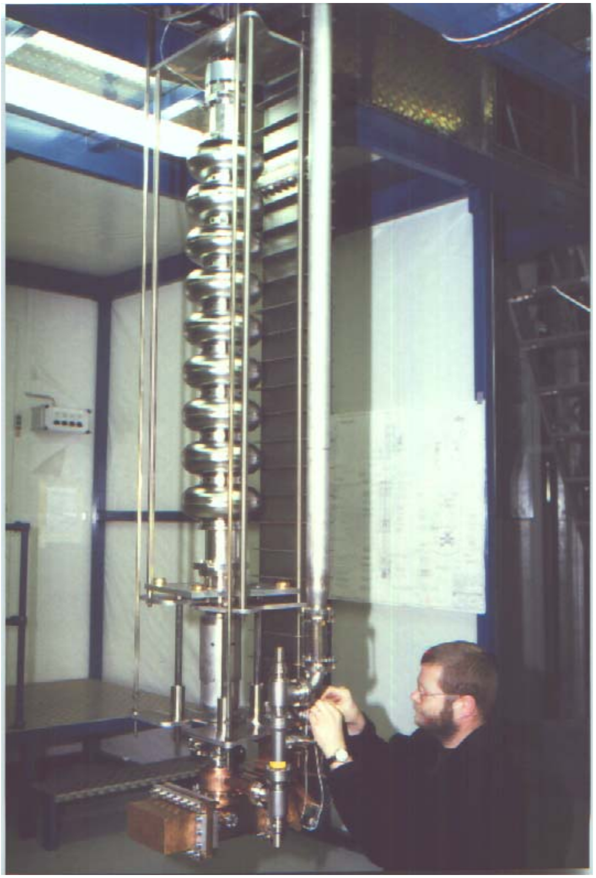
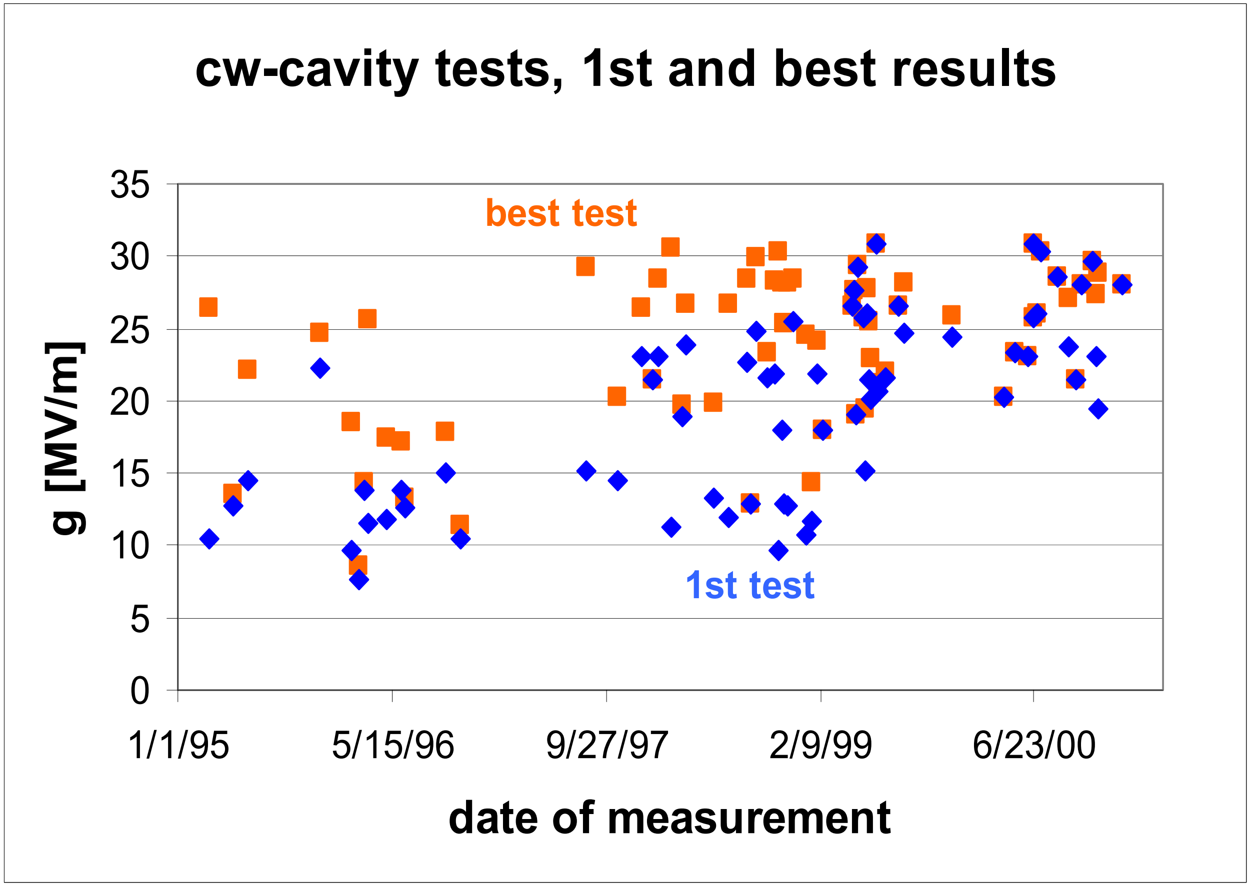
Accelerating gradient on test stand reached 25 MV/m ***on average*** for 1999/2000 cavity production





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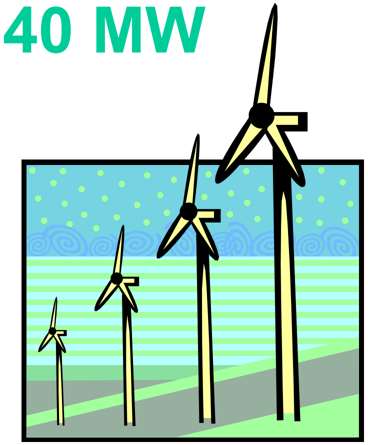
Site power: **140 MW**



Linac: 97MW

Sub-systems: 43MW

RF: 76MW

78%

Cryogenics: 21MW

Injectors

Damping rings

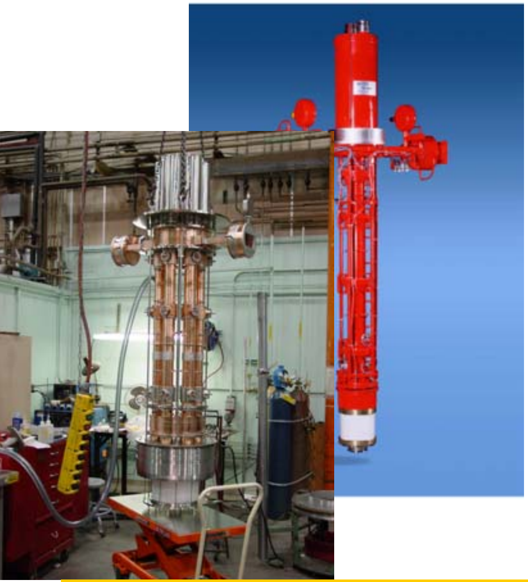
Water, ventilation, …

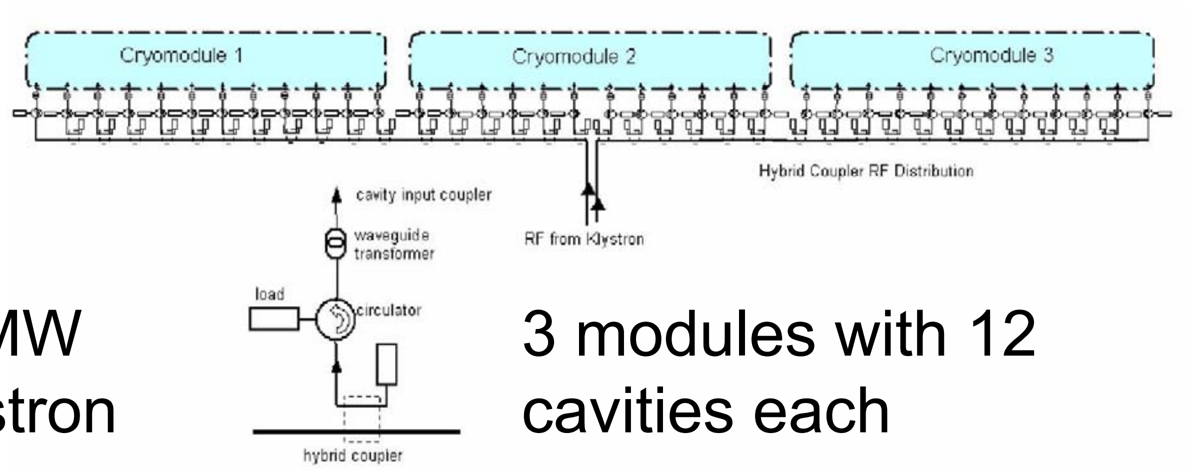
65%

Beam: 22.6MW

60%

Main Linac basic unit:





10MW klystron

3 modules with 12 cavities each

3 prototypes delivered from European industry operated at design spec

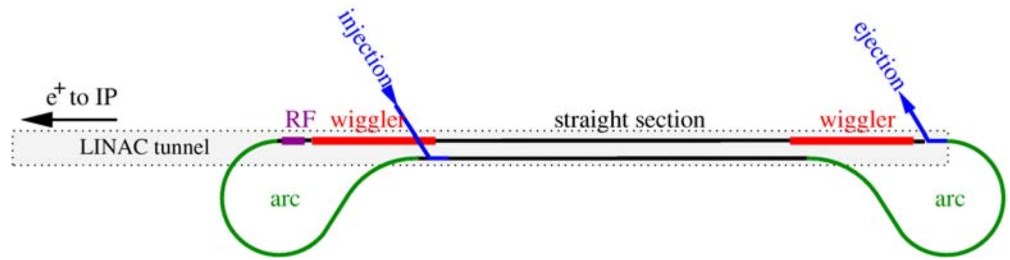
Ongoing: prototypes from two more vendors

Per main linac:

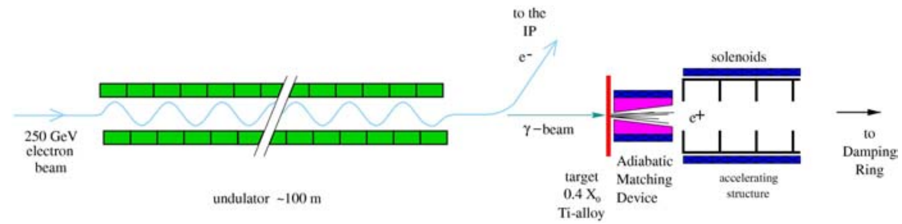
286 units, incl. 2% reserve for failure handling

The sub-systems…

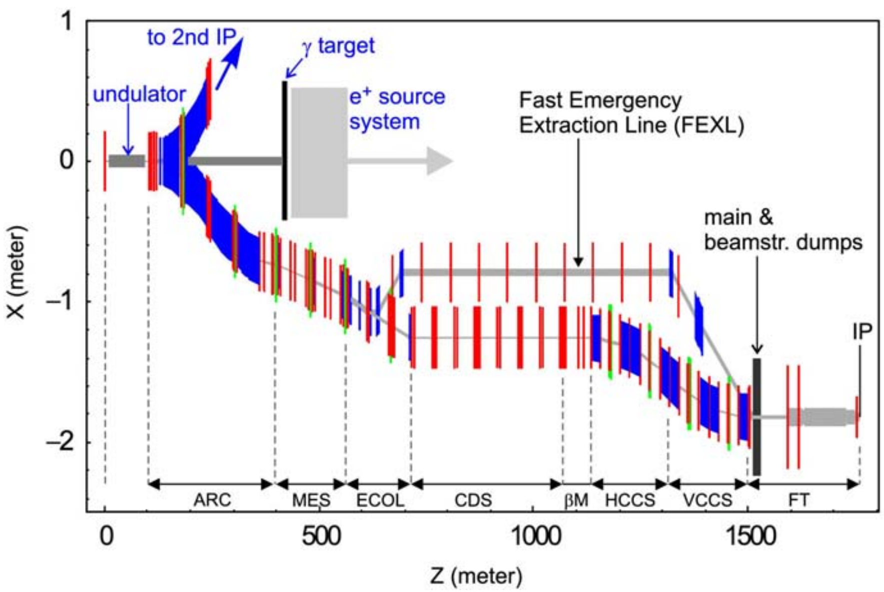
- Considerable complexity
- technical and beam dynamics challenges



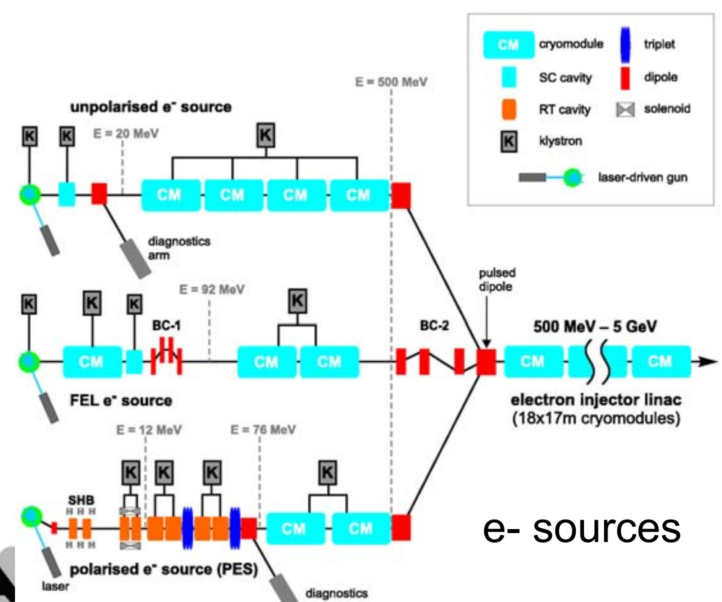
Damping ring



e+ source



Beam delivery



e- sources

Preparation of Cavities

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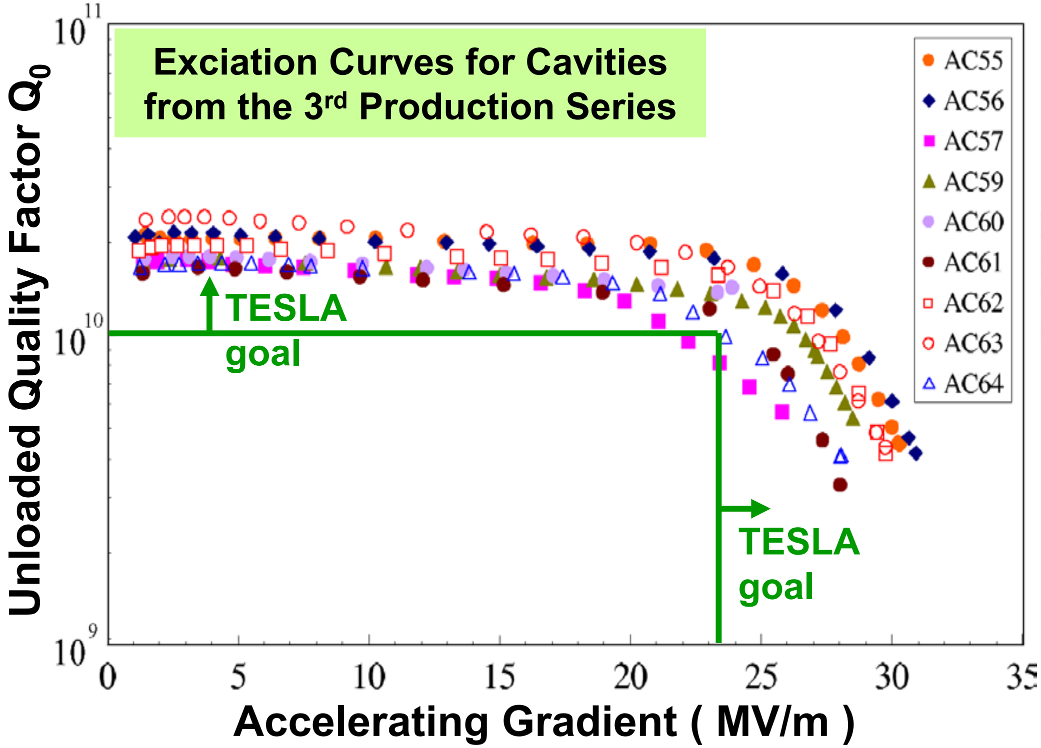
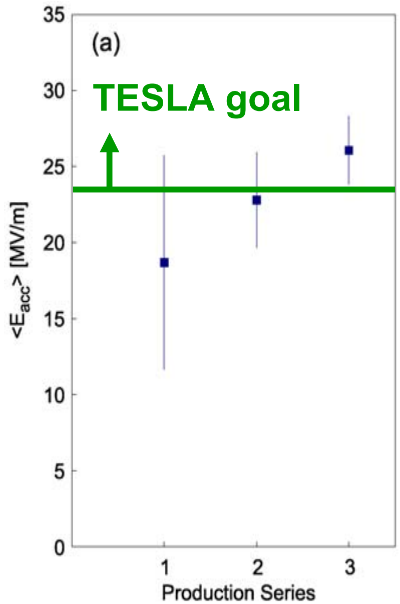
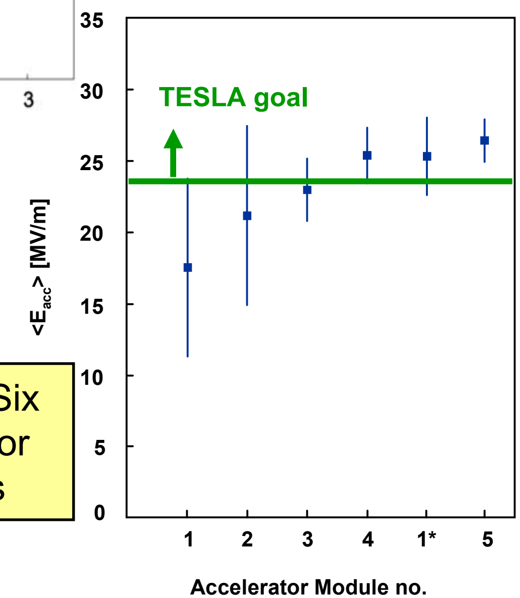
High Gradient Performance





The First Three Production Series

(without electro-polished cavities)

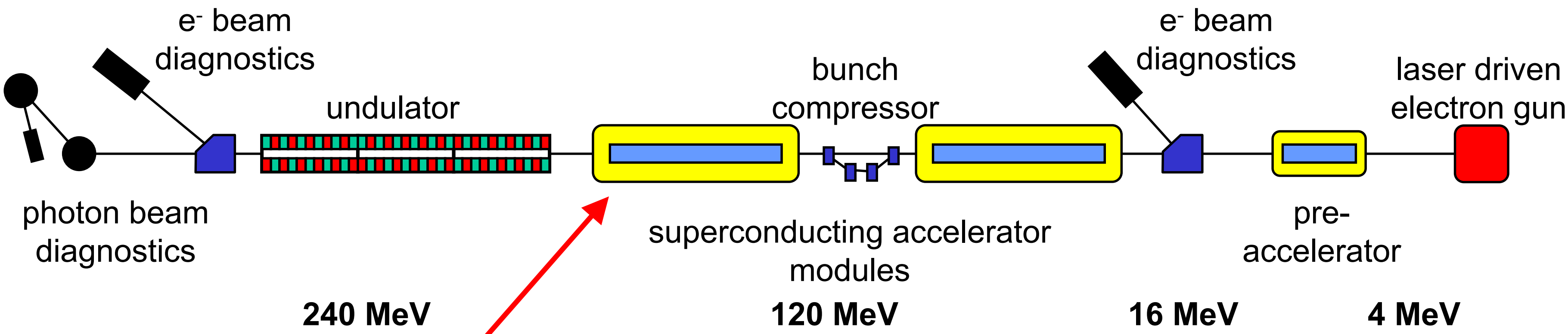


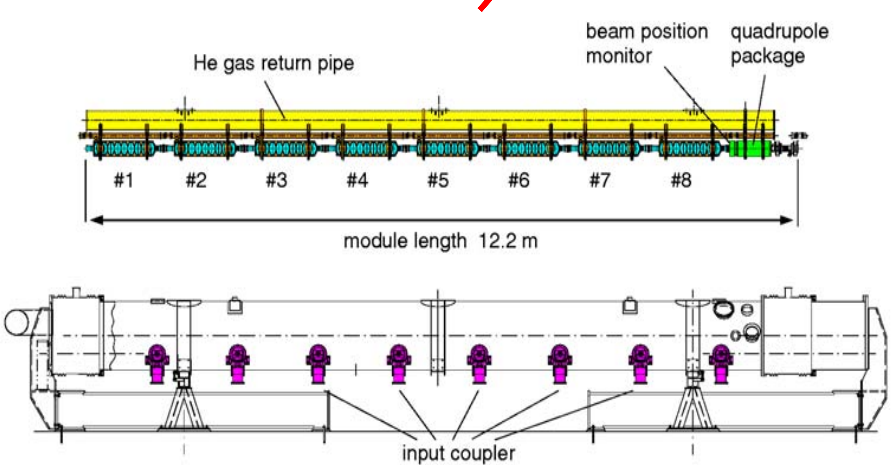
The First Six Accelerator Modules

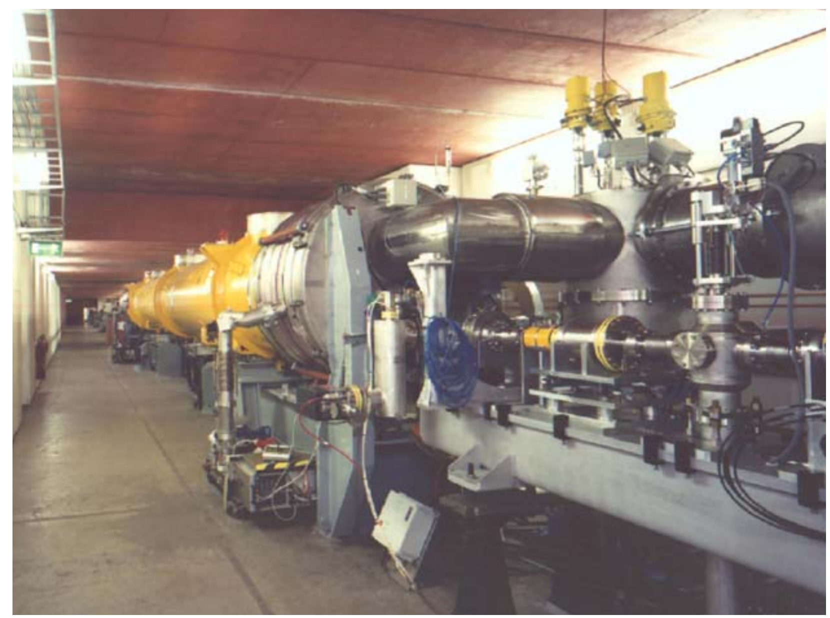
Approx. 70 cavities were produced in three production series. **Gradient and gradient spread improved a lot.**

Six accelerator modules with 8 cavities each were assembled. Three of them were used in the TTF Linac. **Modules 4 and 5 tests started in autumn 2003.**

TESLA Test Facility Linac (Phase-I until 2003)







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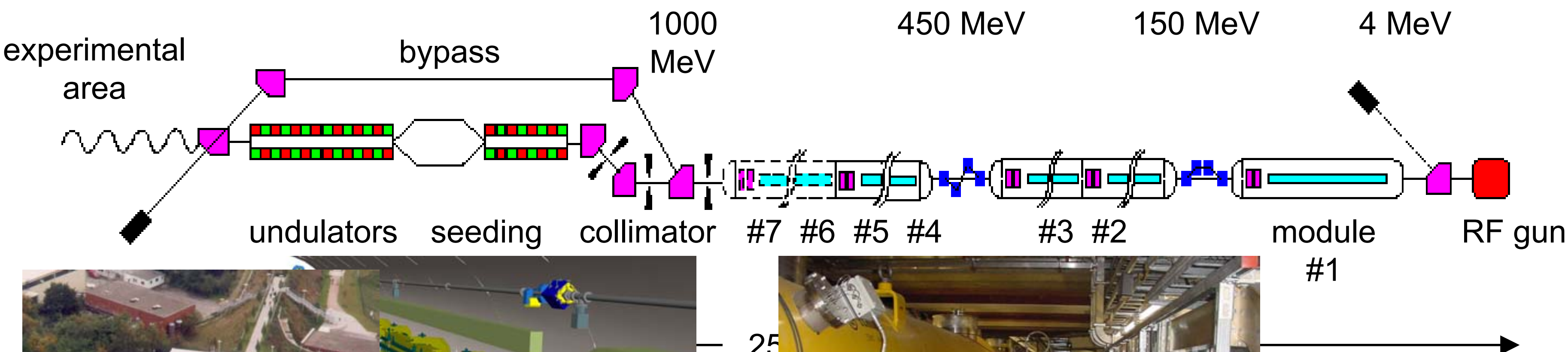
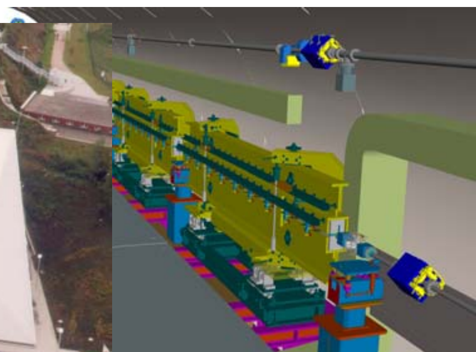
TTF Phase-II (from 2004)





acilit ... gth

l experience with 5 a

- Beam test of module with high-performance EP cavities (M6)

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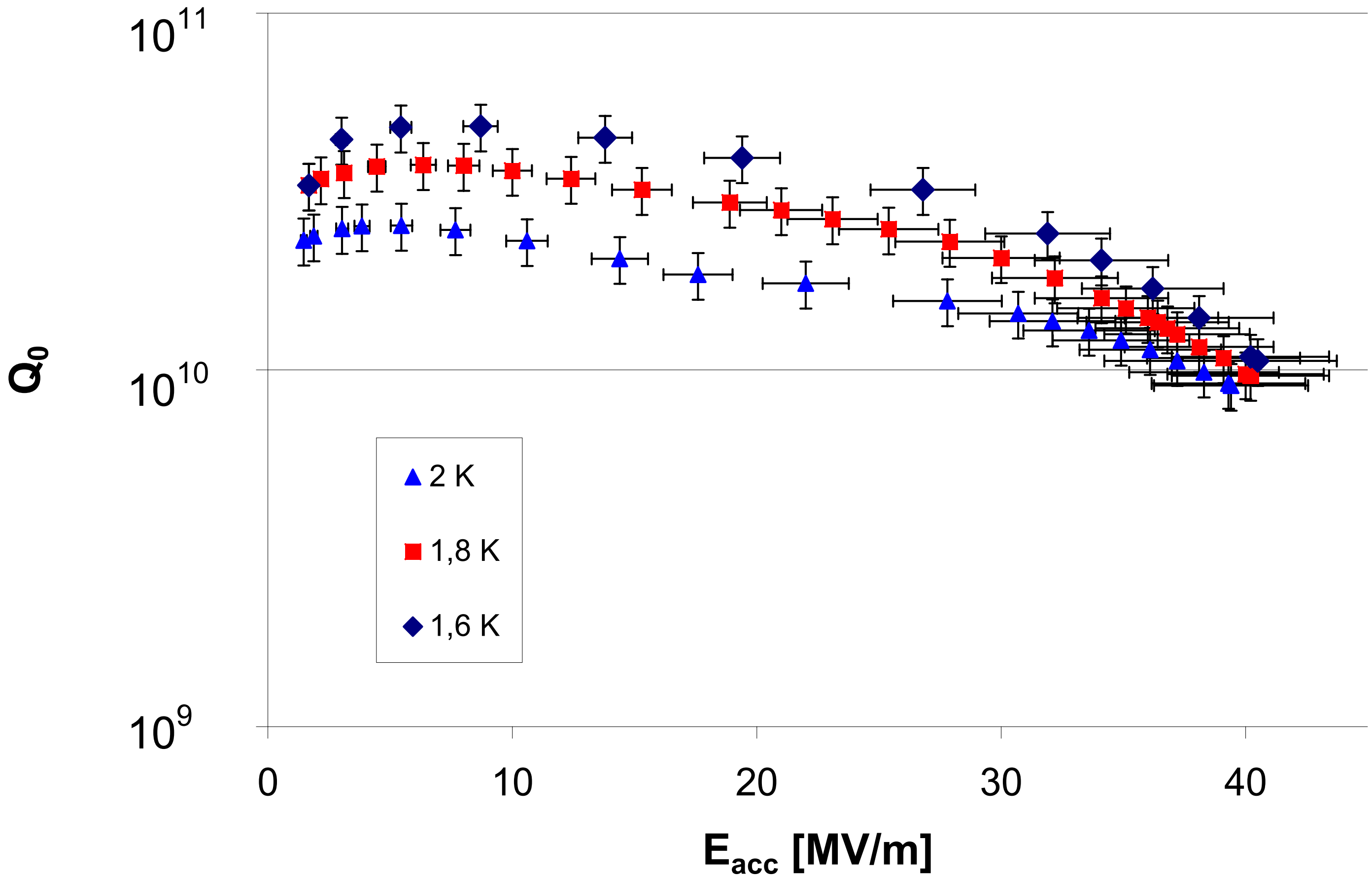
CW test of best 9-cell EP-treated (at DESY) cavity
note: no 1400 C titanisation treatment!



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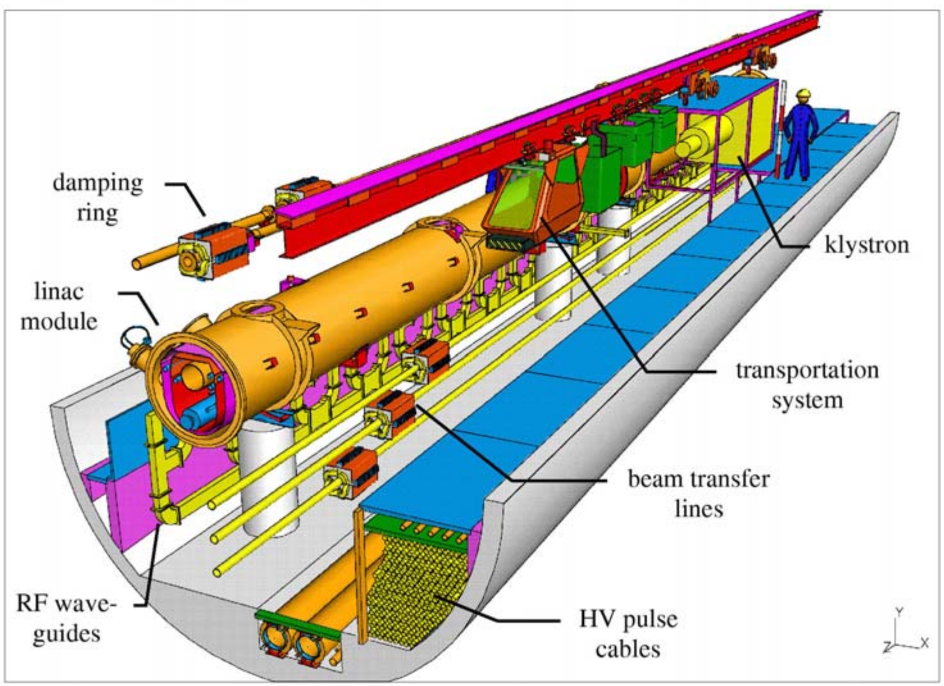
Tunnel layout being reviewed:

Optimise usage of the cross section



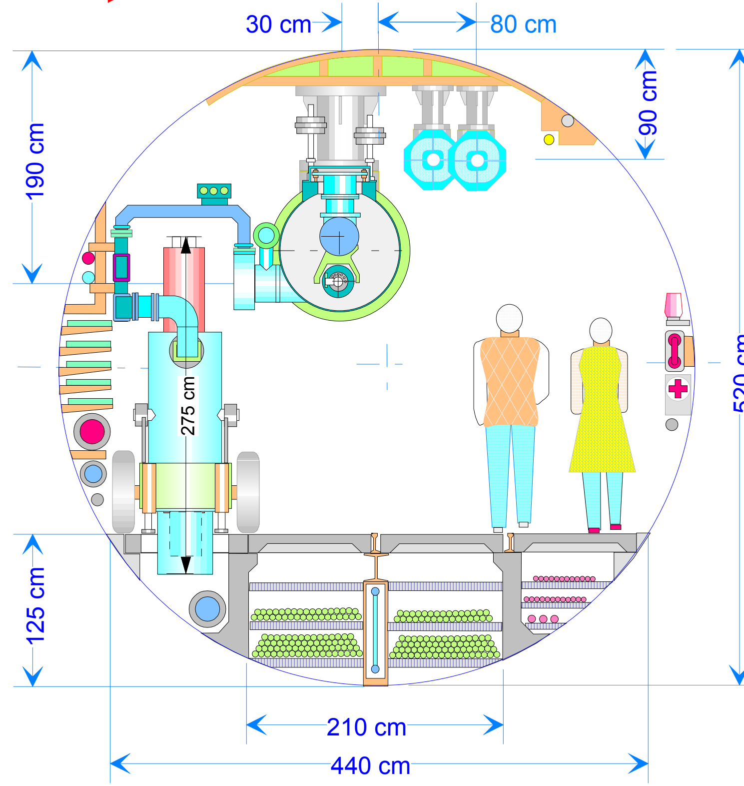


Figure 3. Main LINAC, Damping Ring & Klystron Station

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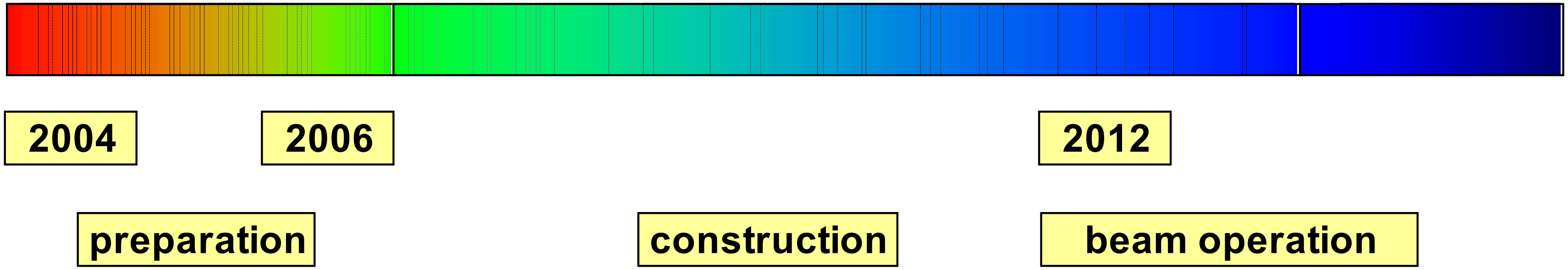
XFEL Project - brief overview

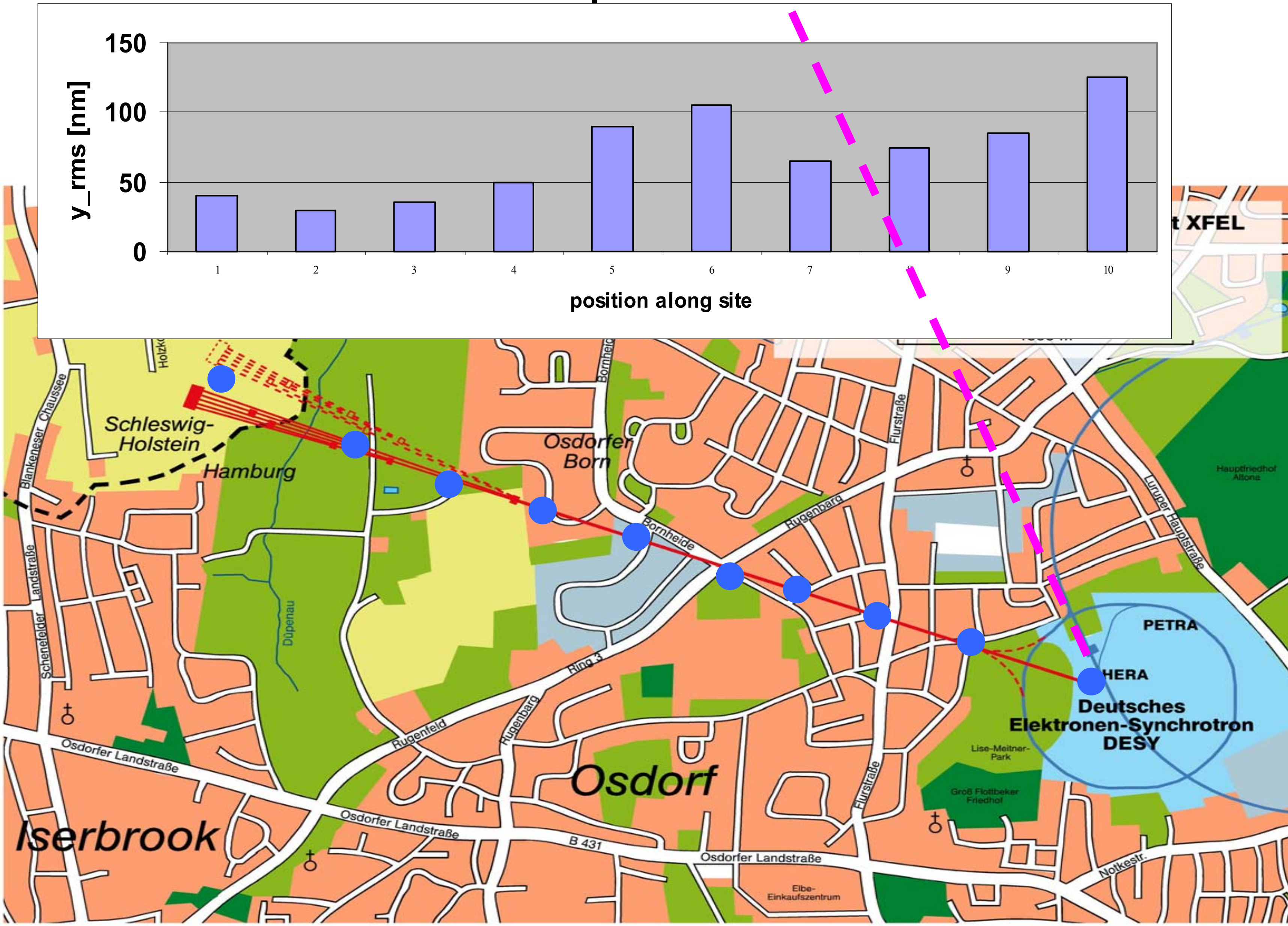
- 4th generation SR user facility with SASE-FEL concept in the 1 – 100 Angstroem (→ 0.5Å) wavelength (1st harmonic) and 100fs (→ < 1fs) pulse length regime
- In 1st stage 3 SASE & 2 spontaneous undulator beam lines, 10 experimental stations
- Driver: 1.5km linac in TESLA technology, 20GeV beam energy @ 23MV/m gradient

Overview cont'd

- German government Feb. 2003: go-ahead for XFEL as European project, incl. funding 50% of total 684 M€ (year 2000) project cost, + contribution from Länder HH & Schleswig-Holstein, ~ 40% European Partners
- Project organisation at Europ. Level (scientific/technical & administrative/financial) ongoing, completed in 2005



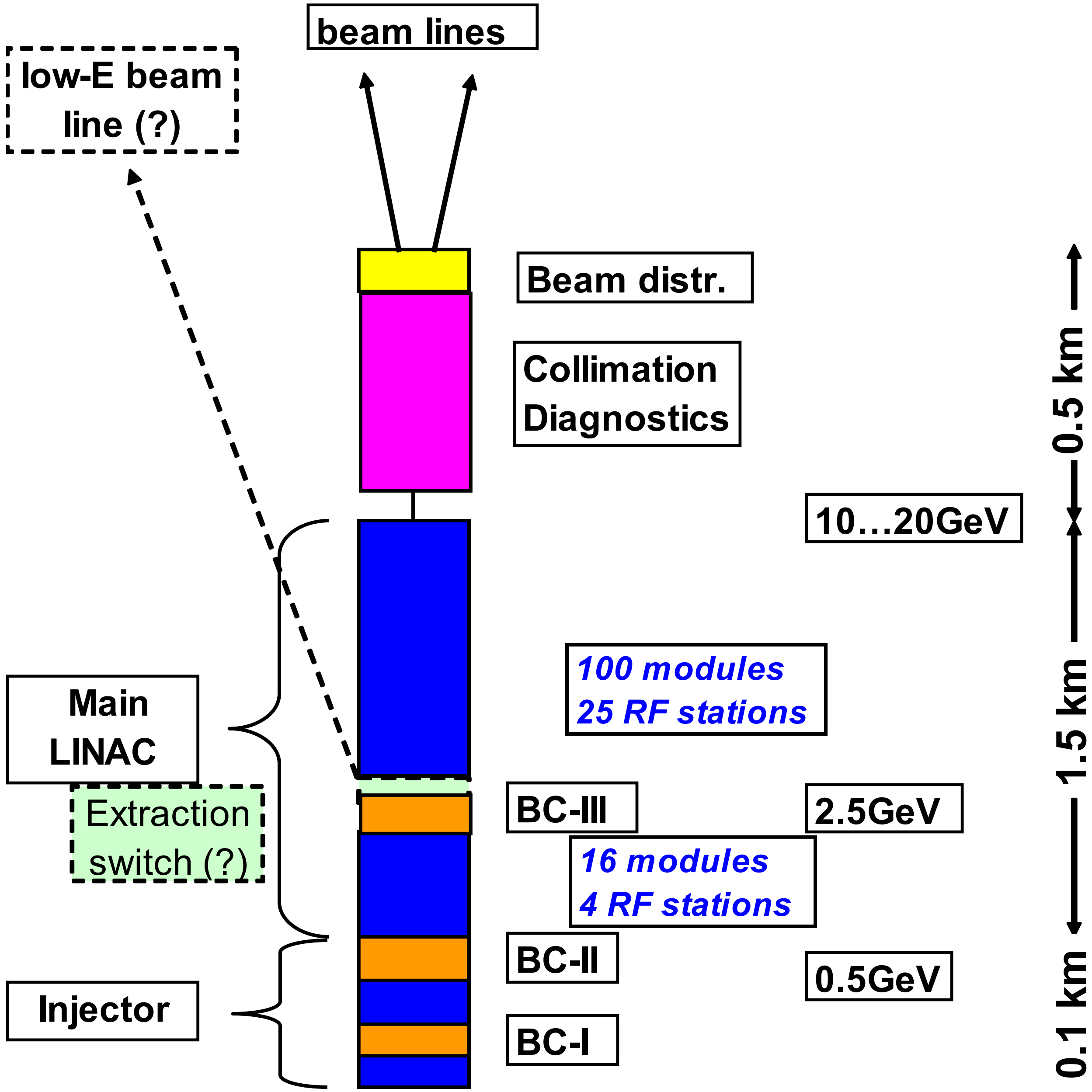
New XFEL site: independent from LC site



Accelerator reference parameters

Main linac	
Energy gain	0.5 → 20 GeV
# installed modules	116
# active modules	104
acc gradient	22.9 MV/m
# installed klystrons	29
Bunch spacing	200 ns
beam current	5 mA
power→beam p. klystron	3.8 MW
incl. 10% + 15% overhead	4.8 MW
matched Q_{ext}	$4.6 \cdot 10^6$
RF pulse	1.37 ms
Beam pulse	0.65 ms
Rep. rate	10 Hz
Av. Beam power *	650 kW
Total AC power	≈ 9 MW

* Power limitation to ~300kW per beamline → solid beam dump possible


beam lines
low-E beam line (?)
Beam distr.
Collimation
Diagnostics
10…20GeV
0.5 km
100 modules
25 RF stations
1.5 km
Main LINAC
Extraction switch (?)
BC-III
2.5GeV
16 modules
4 RF stations
BC-II
0.5GeV
Injector
BC-I
0.1 km

Layout with ***single*** linac tunnel

E.g.:

Electronics in tunnel/radiation environment (→ test in DESY-LINAC-II)

Handling of RF and cavity, power supply failures

Stray fields?

Supports and alignment

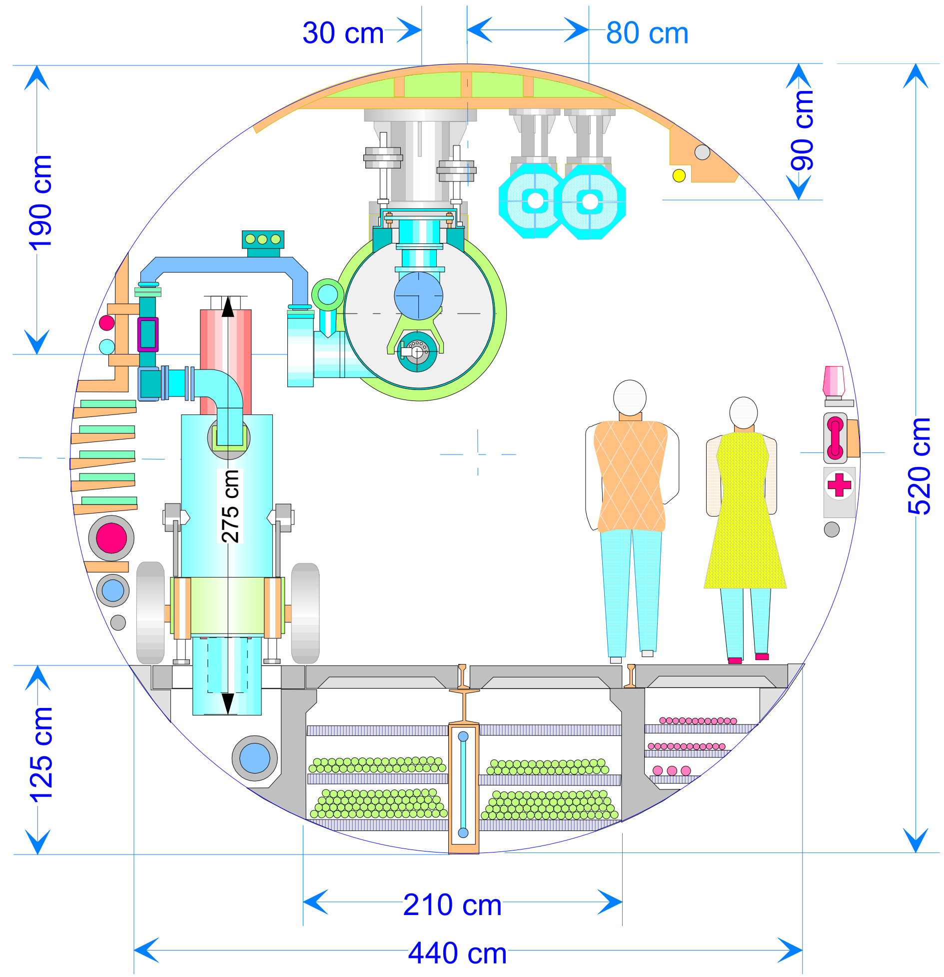


Figure 3. Main LINAC, Damping Ring & Klystron Station

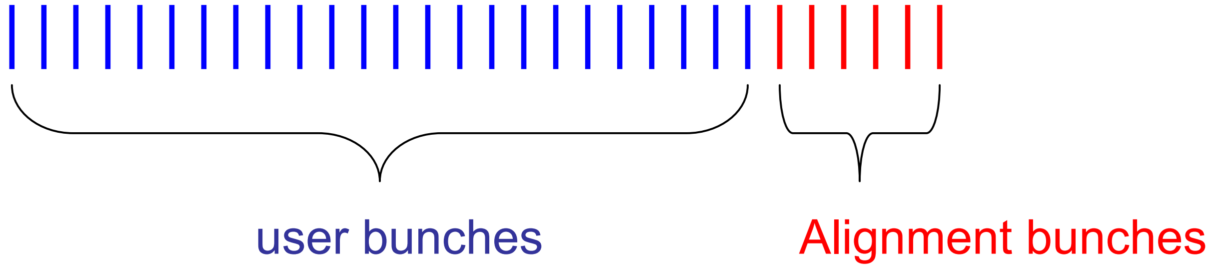
Beam dynamics

(assuming same alignment tolerances; comparison not exhaustive; rough scaling ±factor 2 for some of the XFEL parms)

Issue	parameter	TESLA LC	XFEL	comment
m.b. transverse wake	peak orbit ampl.	1σ	0.2σ - 0.4σ	intra-train feed-forward!
BC / Φ_{RF} error	ΔE, time, σ_z	O(0.1°)	O(0.01°)	
Synchronisation	Δt	<0.5ps	<0.05ps	
1μm Orbit stab. BDS / undulator	$\Delta\varepsilon/\varepsilon$ / Δy'	few %	0.1σ'	intra-train feedback!
Energy jitter	ΔE/E	O(10^{-4})	(O10^{-4})	

Intra-train beam stabilisation

- From ground vibration: jitter ~ 0.1σ at end of linac
  - Can be enhanced during “single events” e.g. heavy traffic, and by quad support eigenmodes
  - Other effects: stray fields, HOMs, …
- → feedback system between linac and distribution to undulators

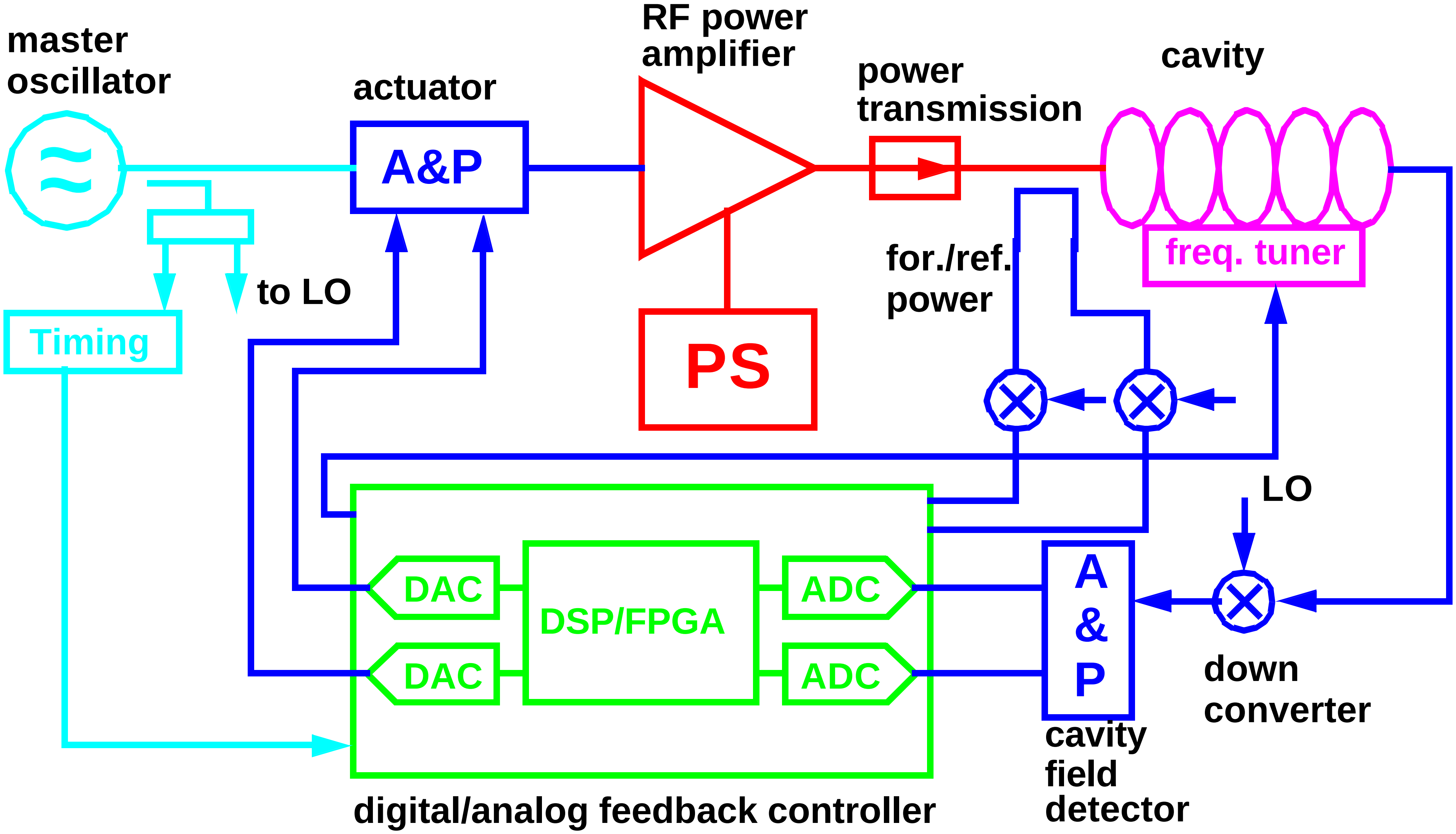


Also active stabilisation of energy and possibly other beam parameters

RF Control

- RF System Architecture
- Requirements for RF Control
- Sources of Perturbations
- RF Control Design Considerations
- Measured and Predicted Performance
- Conclusion

RF System Architecture



RF Control Requirements

- Maintain Phase and Amplitude of the accelerating field within given tolerances to accelerate a charged particle beam

- Minimimize Power needed for control

- RF system must be reproducible, reliable, operable, and well understood.

- Other performance goals
  - build-in diagnostics for calibration of gradient and phase, cavity detuning, etc.
  - provide exception handling capabilities
  - meet performance goals over wide range of operating parameters

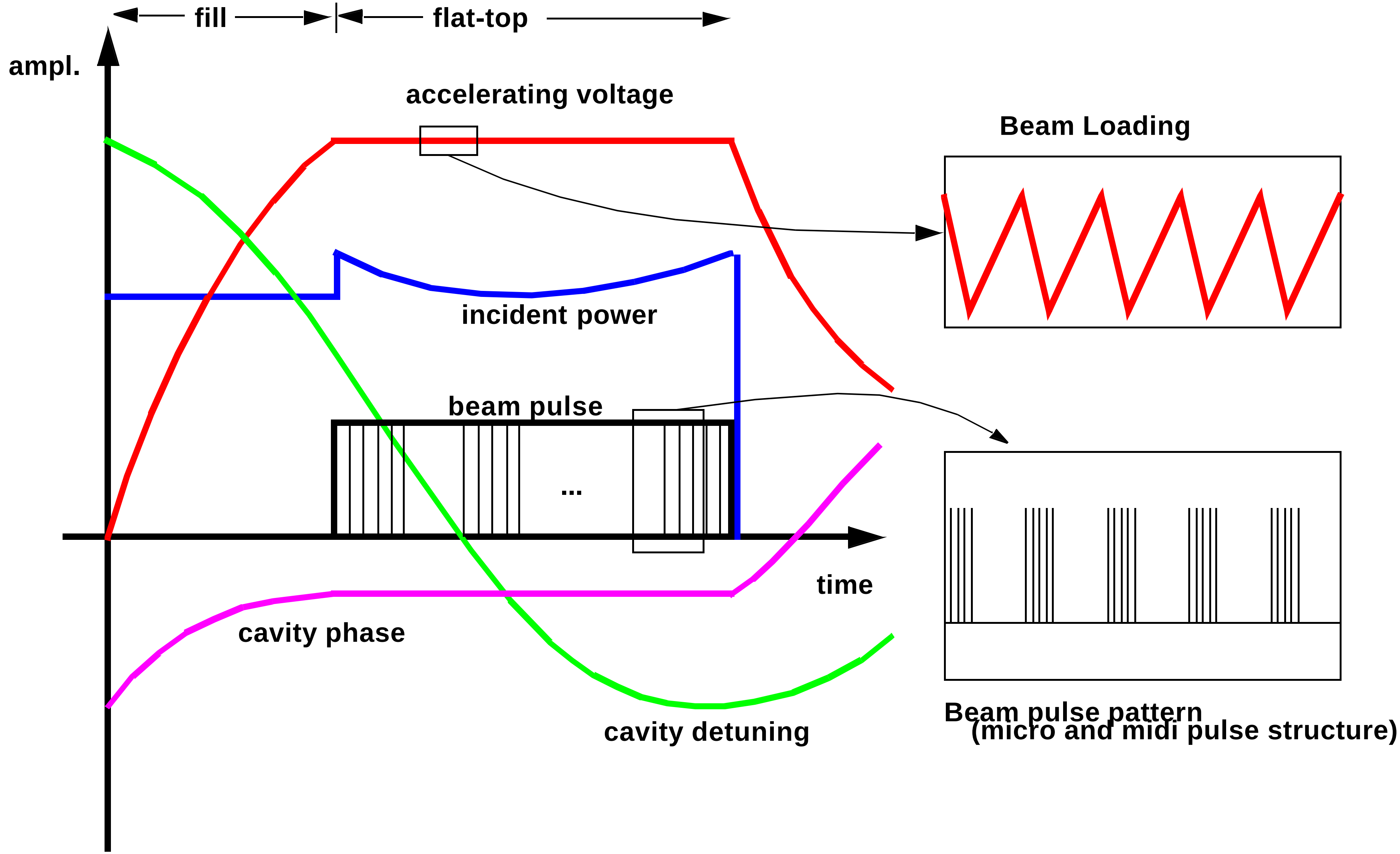
Requirements RF Control

- Derived from beam properties
  - energy spread
  - emittance
  - bunch length (bunch compressor)
  - arrival time

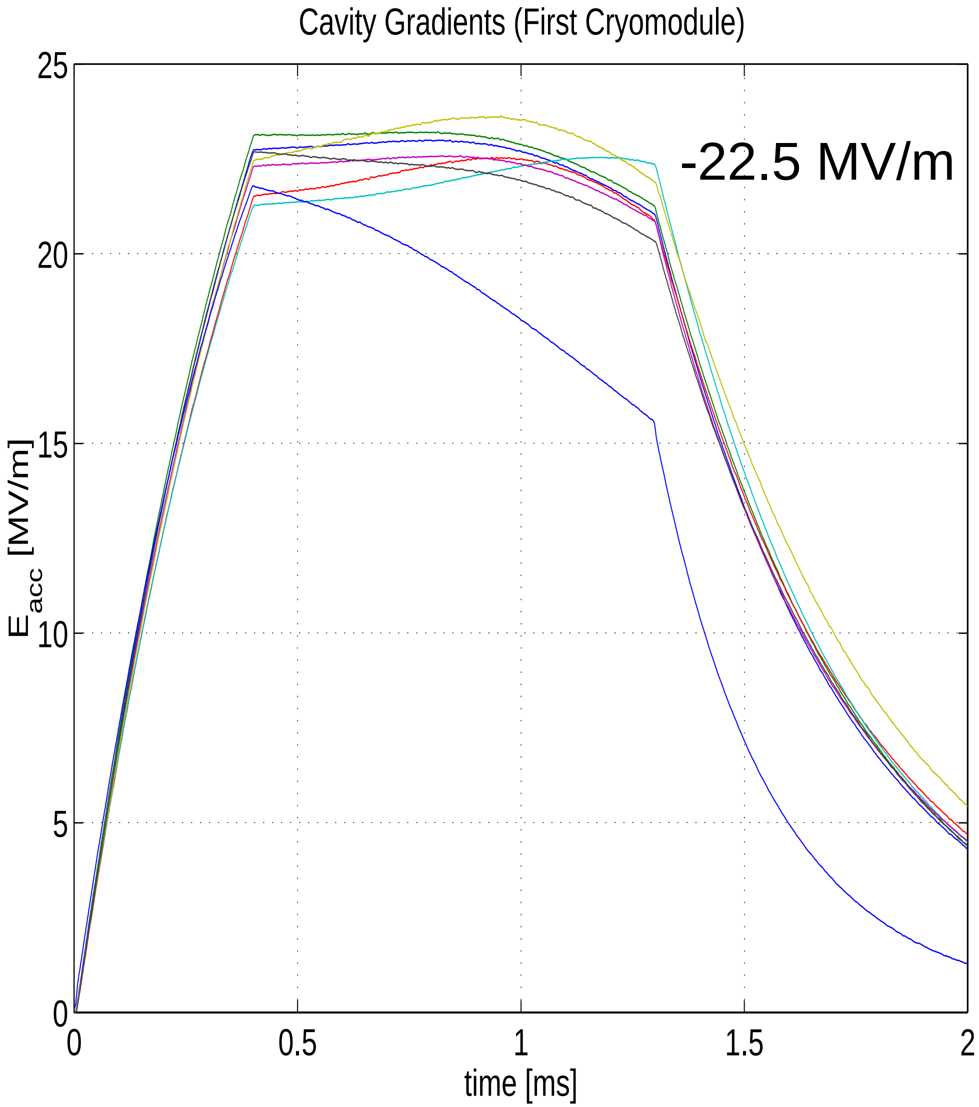
- Different accelerators have different requirements on field stability (approximate RMS requirements
  - 1% for amplitude and 1 deg. for phase (example: SNS)
  - 0.1% for amplitude and 0.1deg.for phase (linear collider)
  - up to 0.01% for amplitude and 0.01 deg. for phase (XFEL)

Note: Distinguish between correlated and uncorrelated error

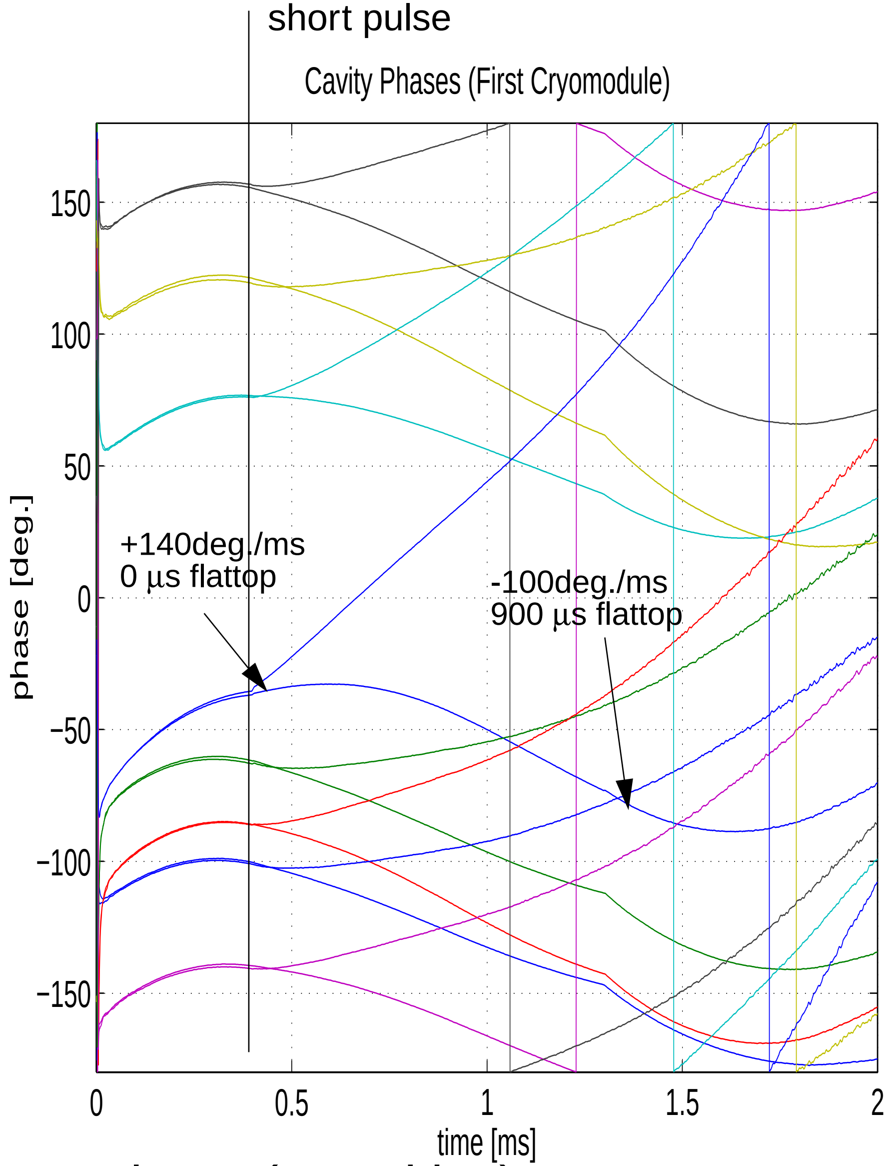
Typical Parameters in a Pulsed RF System



Pulsed Operation at High Gradients



Gradient (8 cavities)

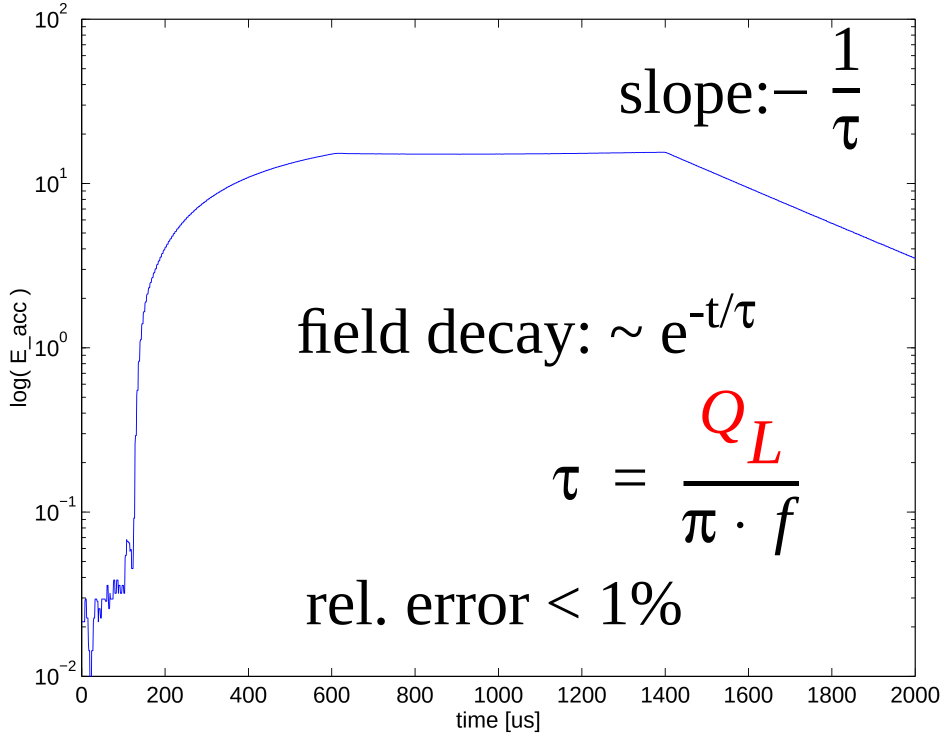


Phase (8 cavities)

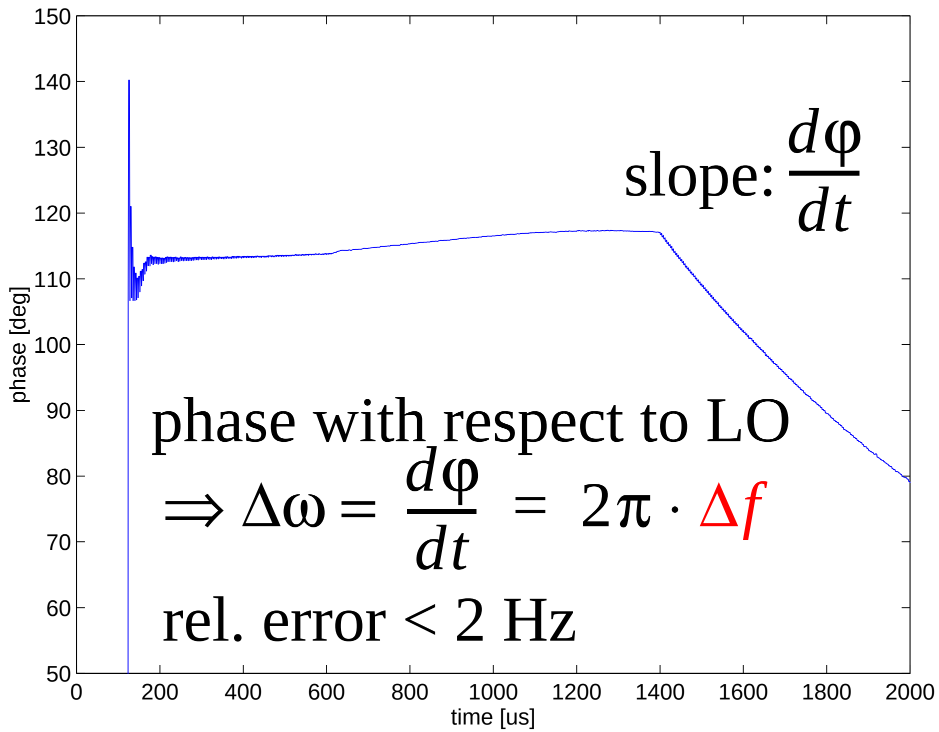
Sources of Perturbations

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

Measurement of Cavity Q_L and Detuning

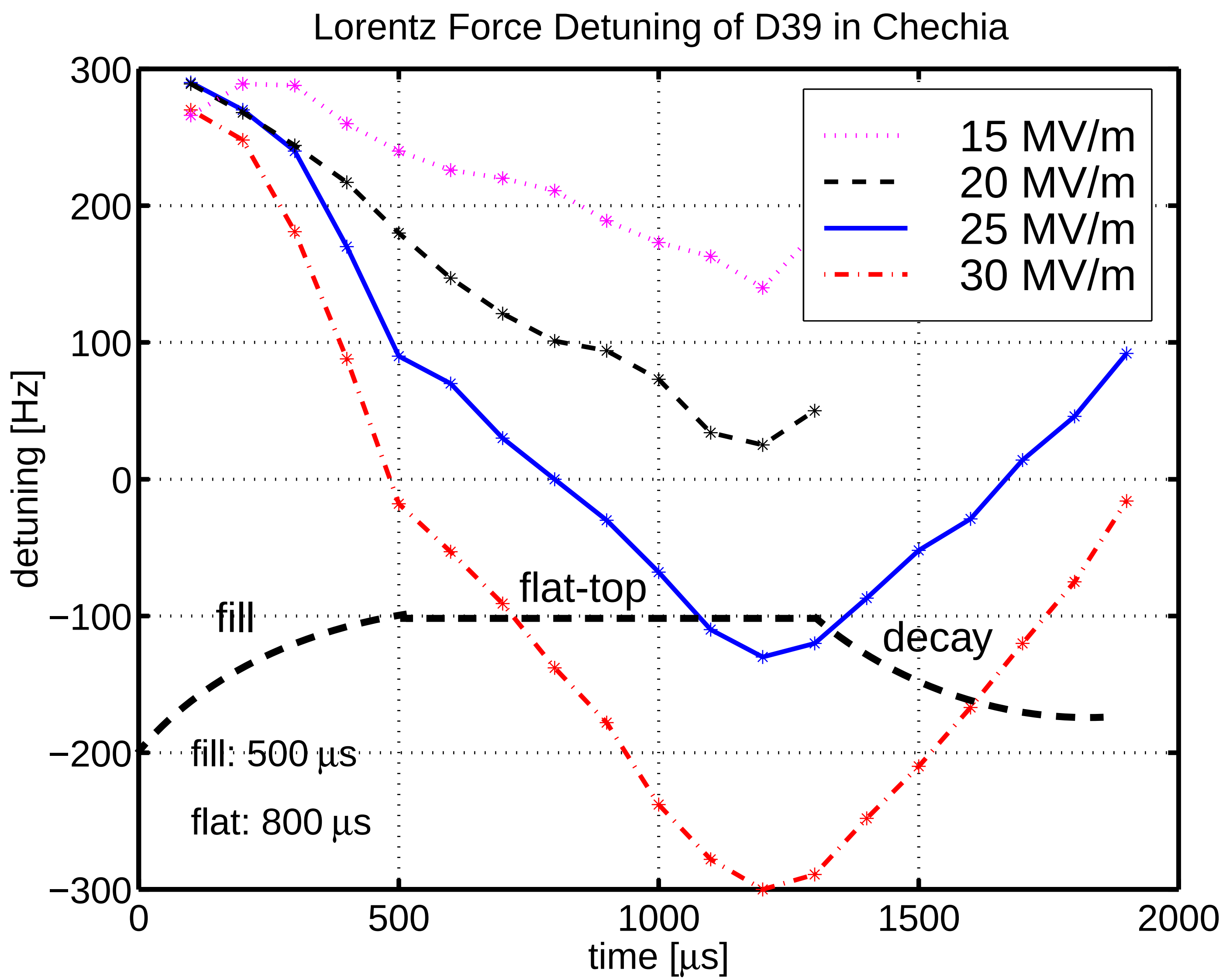


Loaded Q

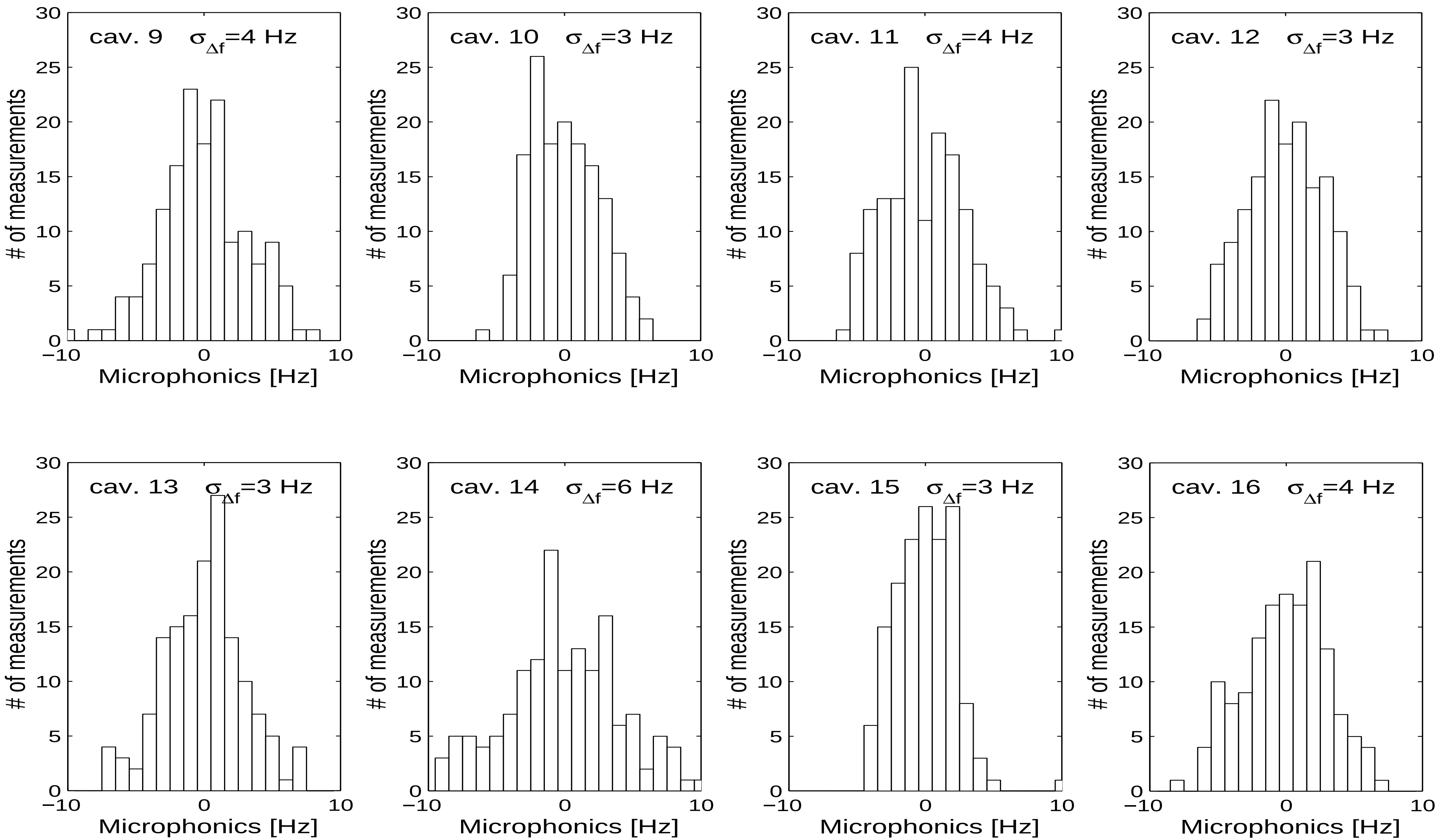


Detuning

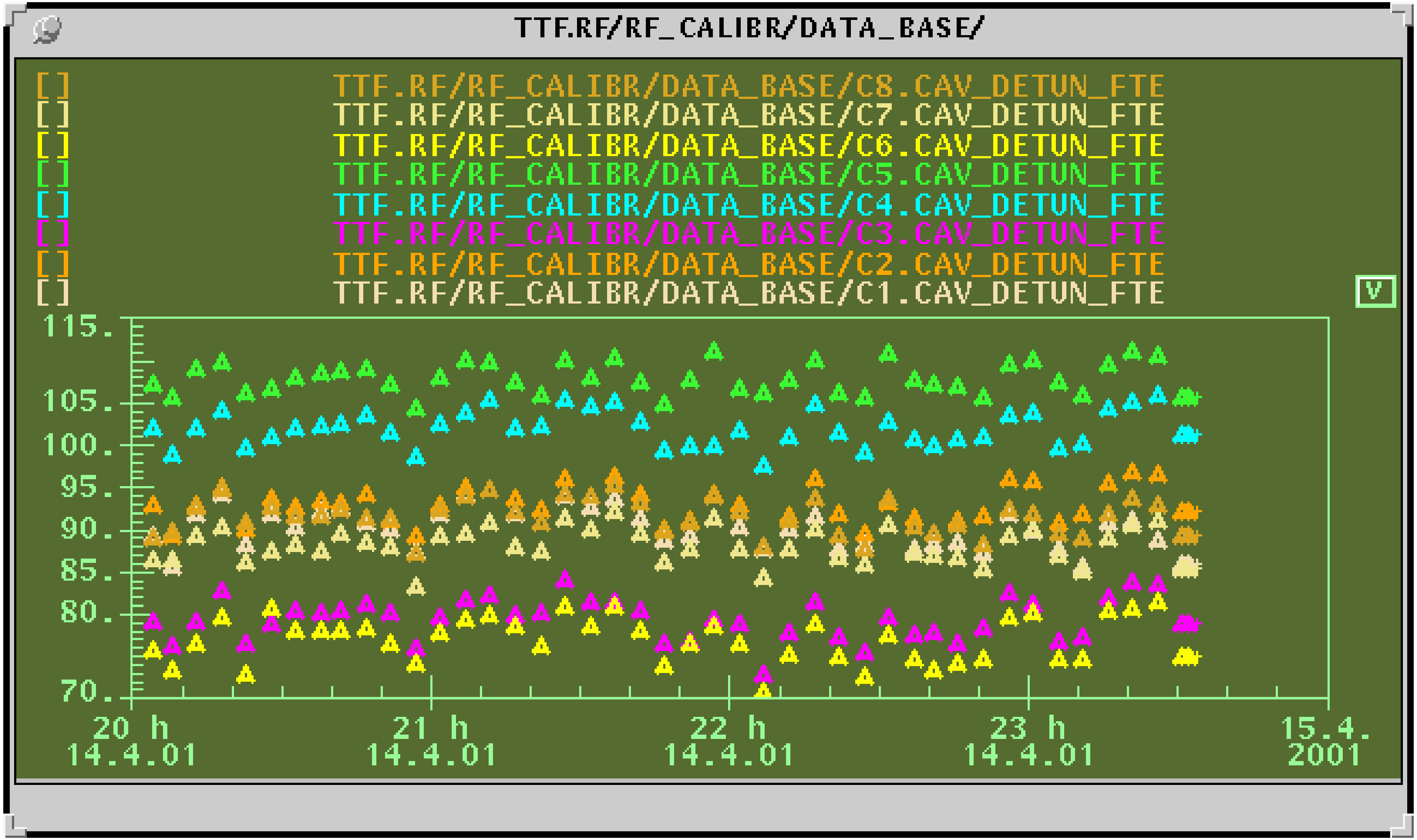
Lorentz Force Detuning



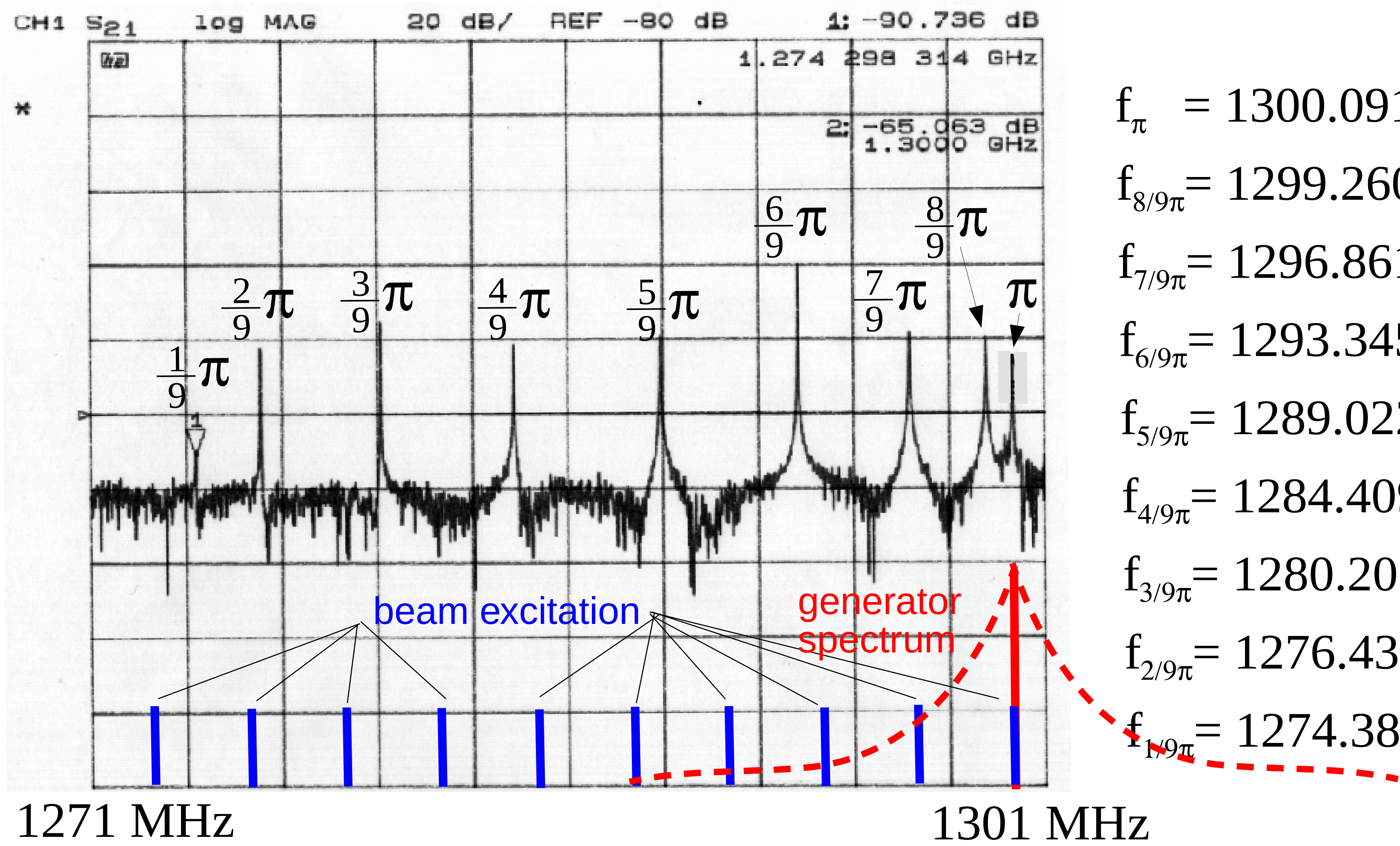
Microphonics at TTF



Long Term Drift of Resonance Frequency



Excitation of other Passband Modes



f_{π} = 1300.091 MHz

$f_{8/9\pi}$ = 1299.260 MHz

$f_{7/9\pi}$ = 1296.861 MHz

$f_{6/9\pi}$ = 1293.345 MHz

$f_{5/9\pi}$ = 1289.022 MHz

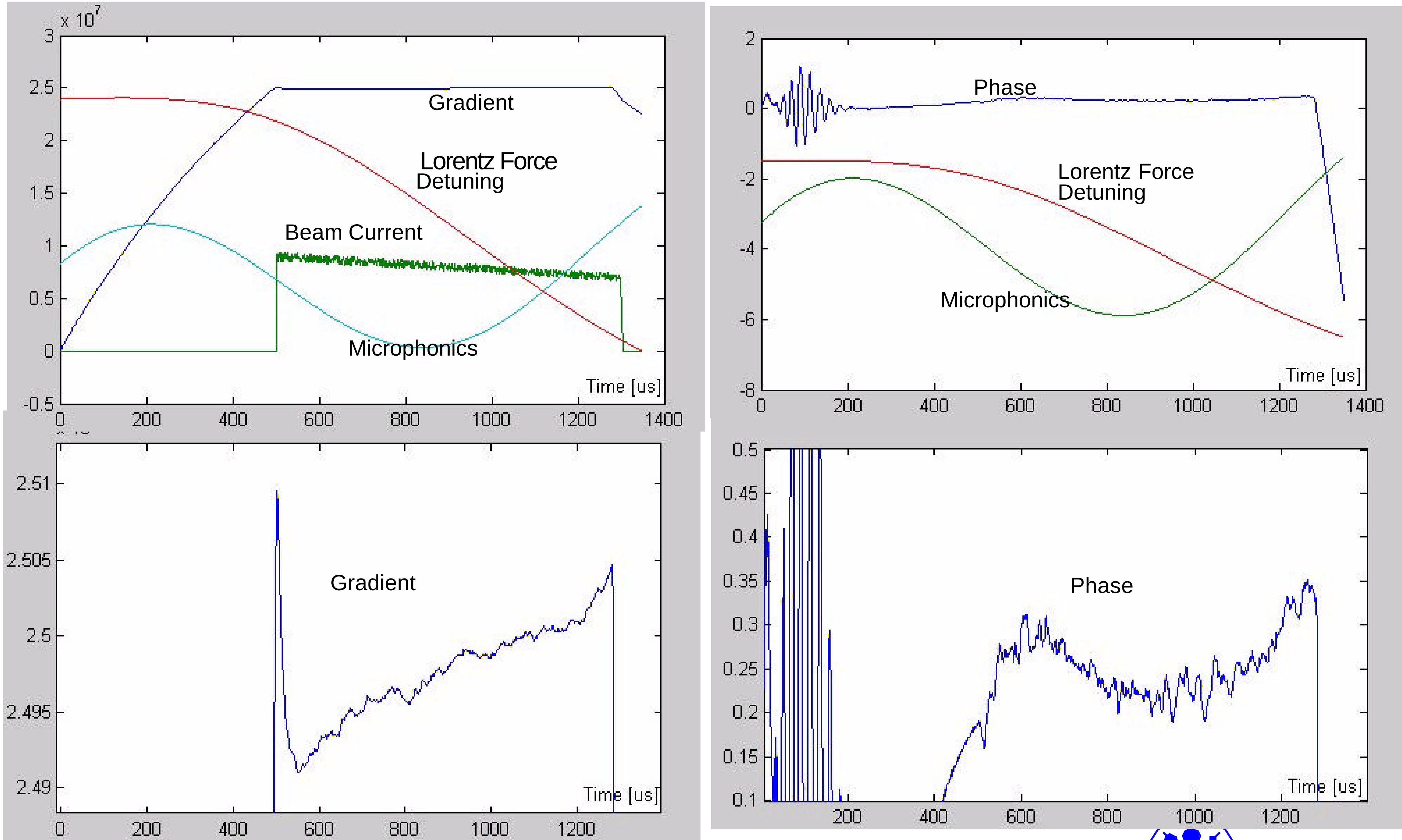
$f_{4/9\pi}$ = 1284.409 MHz

$f_{3/9\pi}$ = 1280.206 MHz

$f_{2/9\pi}$ = 1276.435 MHz

$f_{1/9\pi}$ = 1274.387 MHz

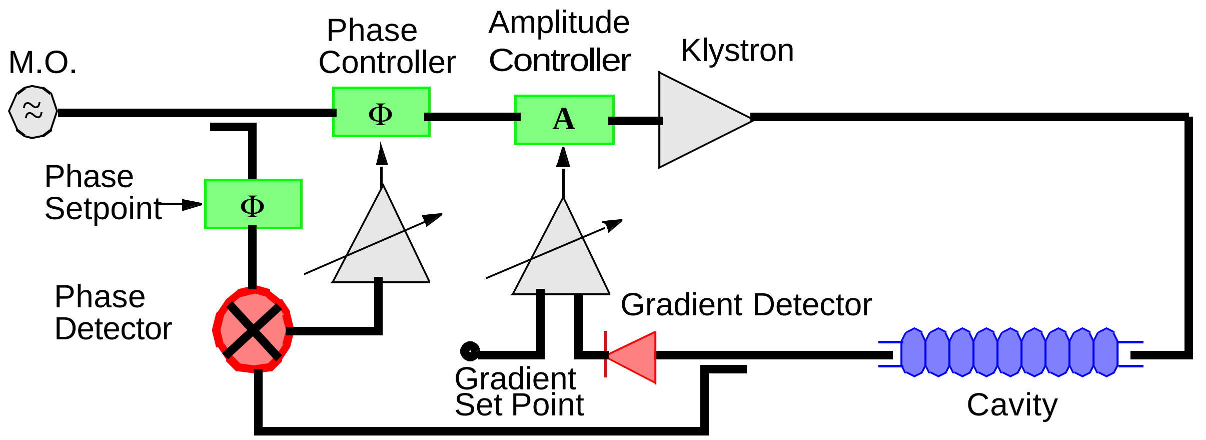
RF Regulation TESLA Cavity (Simulation)



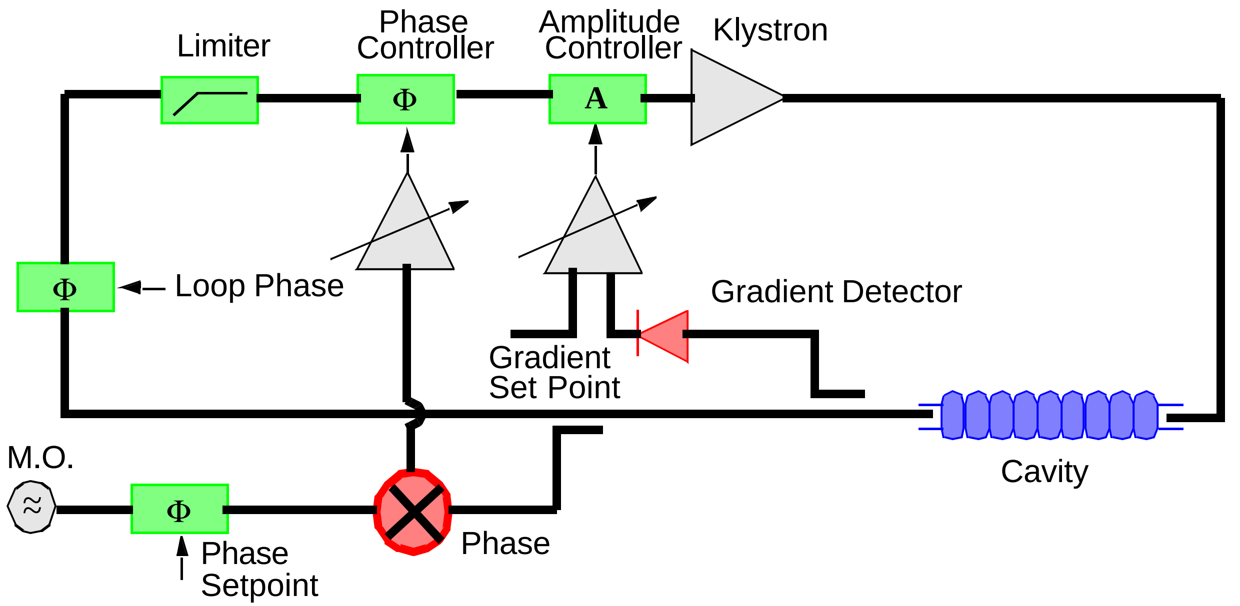
Control Choices (1)

- Self-excited Loop (SEL) vs
  Generator Driven System (GDR)
- Vector-sum (VS) vs individual cavity control
- Analog vs Digital Control Design
- Amplitude and Phase (A&P) vs
  In-phase and Quadrature (I/Q) detector and controller

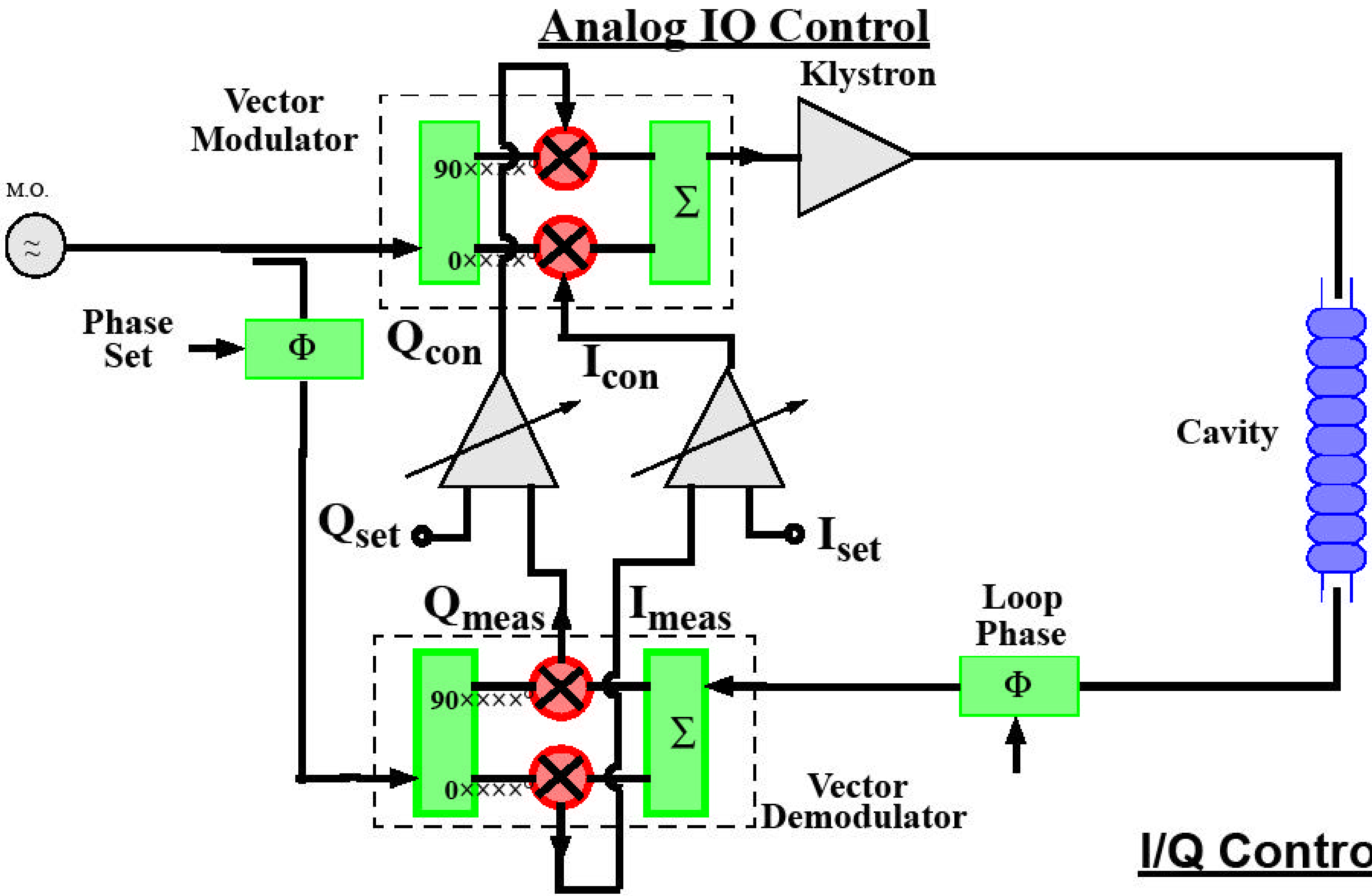
Control Choices (2)



Generator Driven Resonator

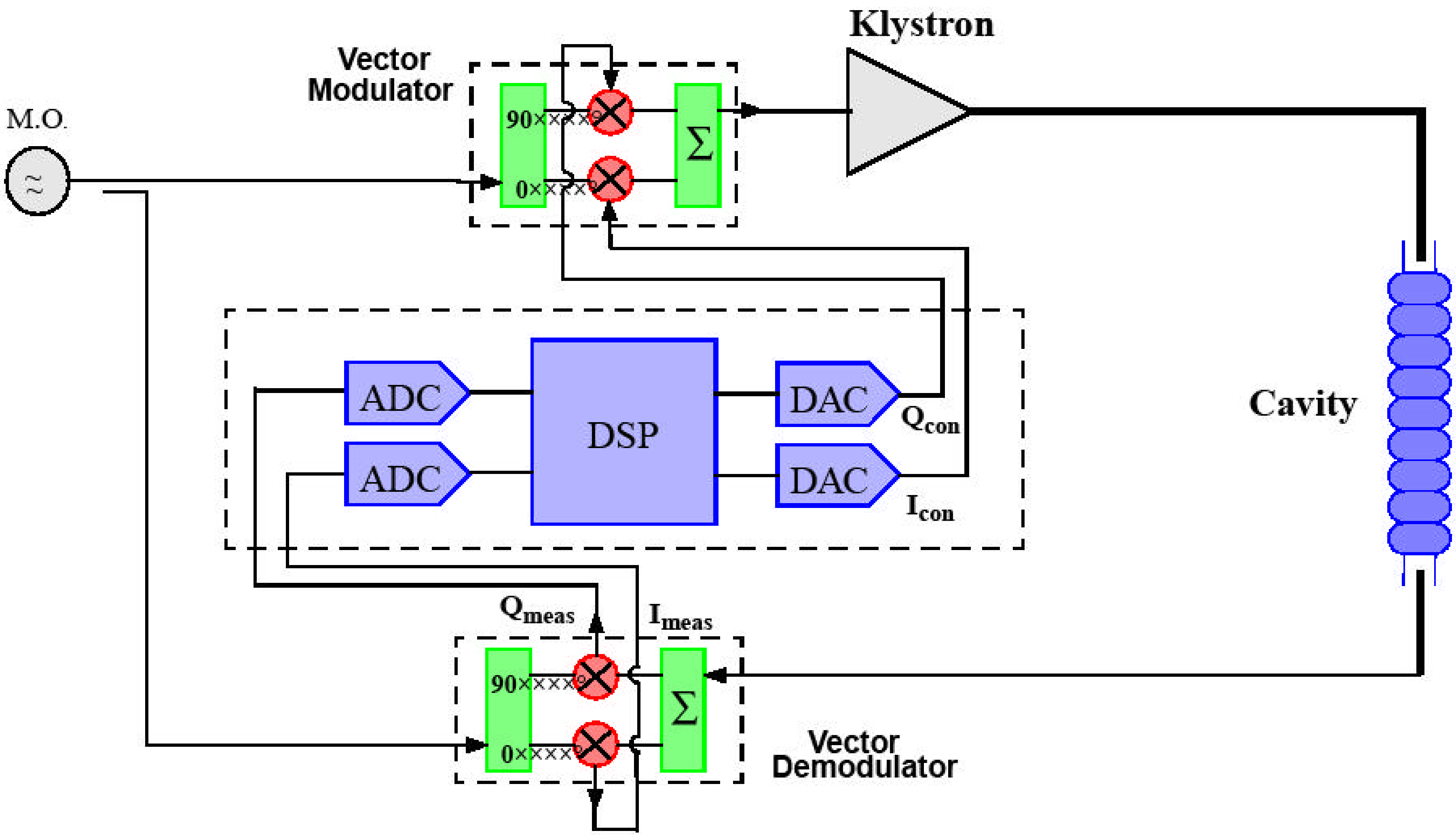


Self Excited Loop

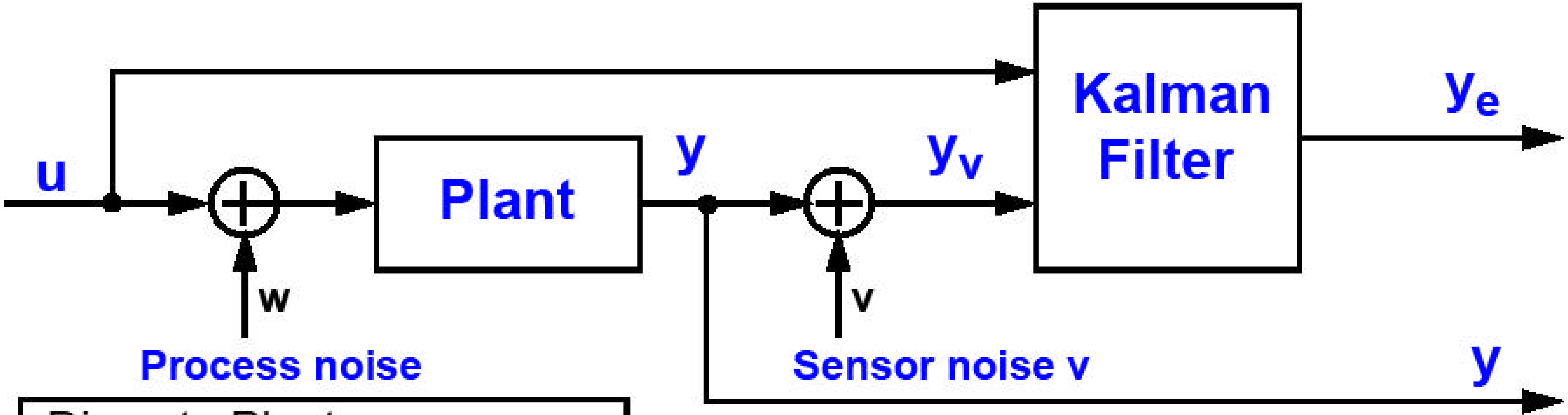

Analog IQ Control
Klystron
Vector
Modulator
M.O.
≈
90××××°
0××××°
Σ
Phase
Set
Φ
Q_{con}
I_{con}
Cavity
Q_{set}
I_{set}
Q_{meas}
I_{meas}
Loop
Phase
Φ
90××××°
0××××°
Σ
Vector
Demodulator

I/Q Control

Digital IQ Control



Principle Kalman Filter (steady state)



Discrete Plant:

$x[n+1]=Ax[n]+B(u[n]+w[n])$

$y[n]=Cx[n]$

Noisy output measurement: $y_v[n]=Cx[n]+v[n]$

Measurement update:

$$\hat{x}[n|n]=\hat{x}[n|n-1]+M(y_v[n]-C\hat{x}[n|n-1])$$

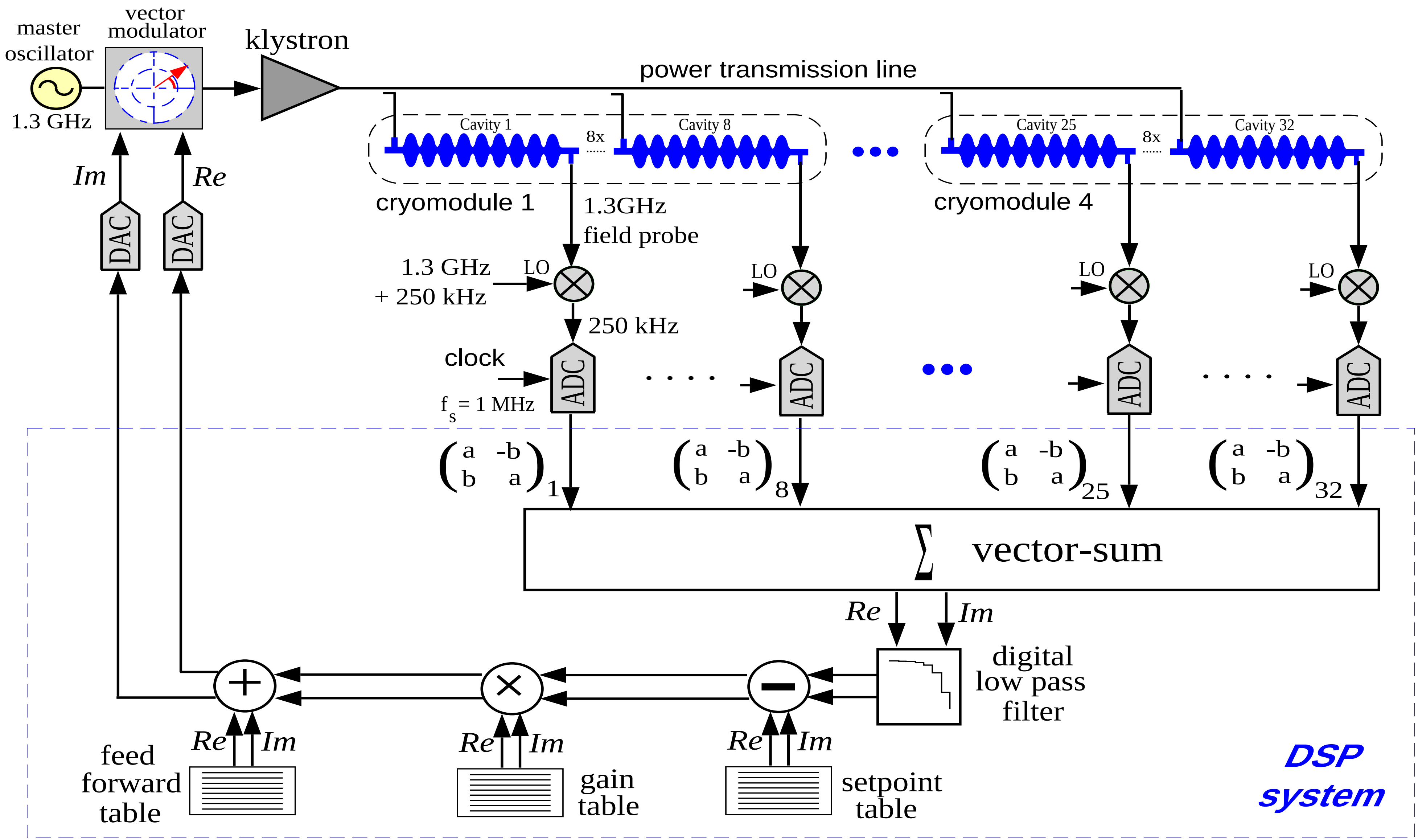
Time update: $\hat{x}[n+1|n]=A\hat{x}[n|n]+Bu[n]$

The correction term is a function of the innovation, i.e. the discrepancy

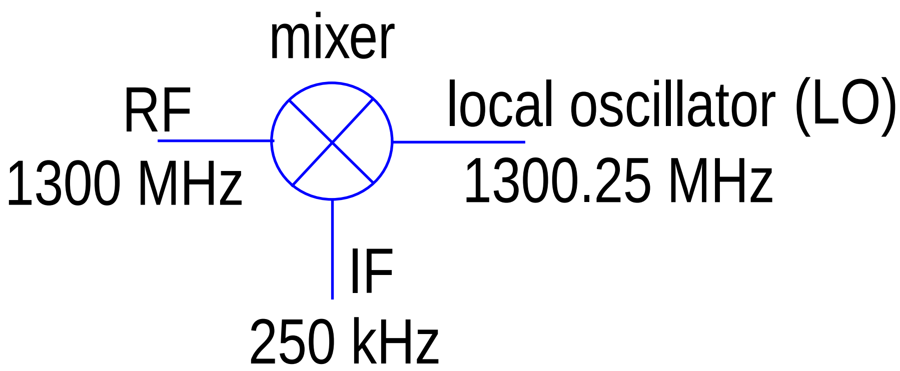
$$y_v[n+1]-C\hat{x}[n+1|n]=C(x[n+1]-\hat{x}[n+1|n])$$

The innovation gain matrix M is chosen to minimize steady-state covariance of the estimation error given the noise covariances $E(w[n]w[n]^T)=Q$ and $E(v[n]v[n]^T)=R$

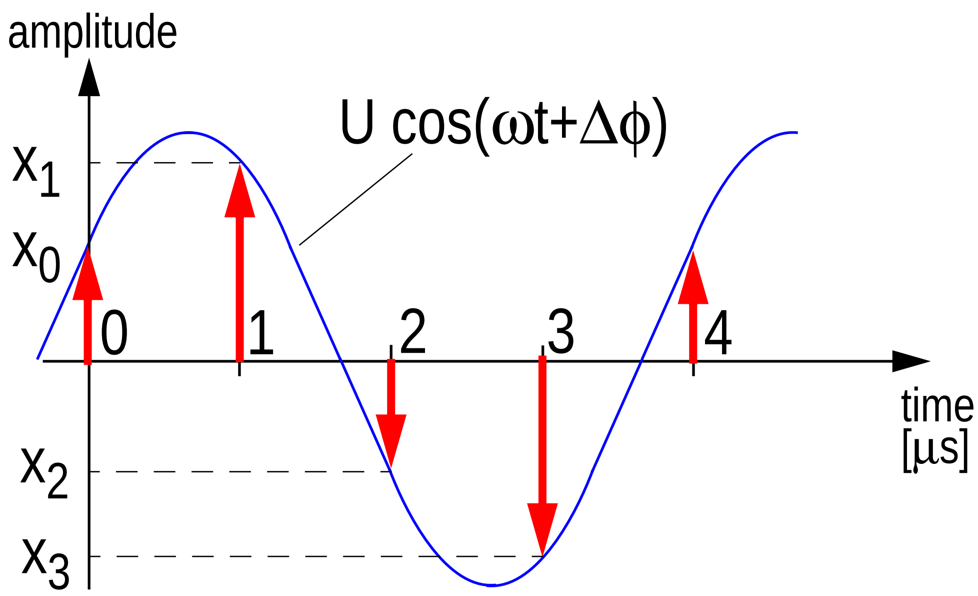
Digital Control at the TTF



Digital I/Q Detection

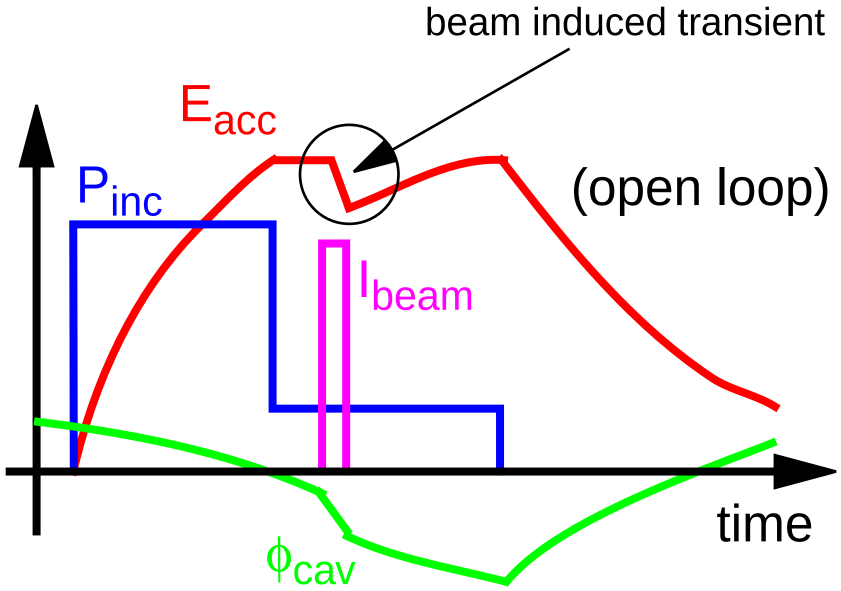


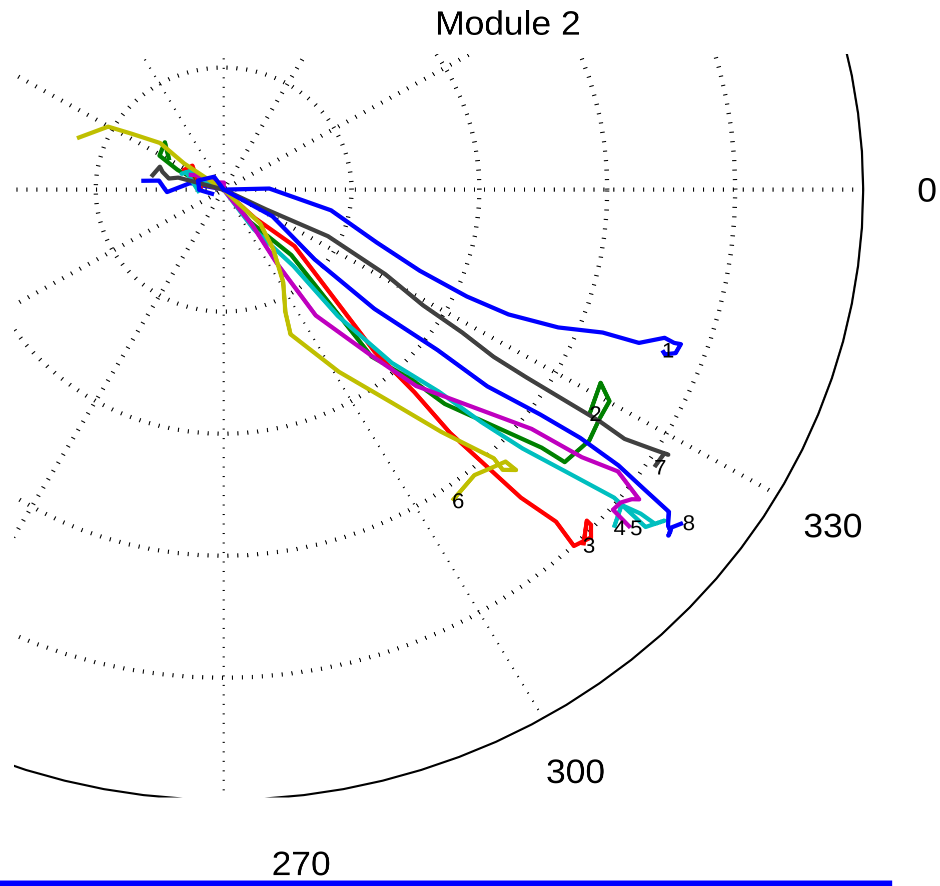
- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.

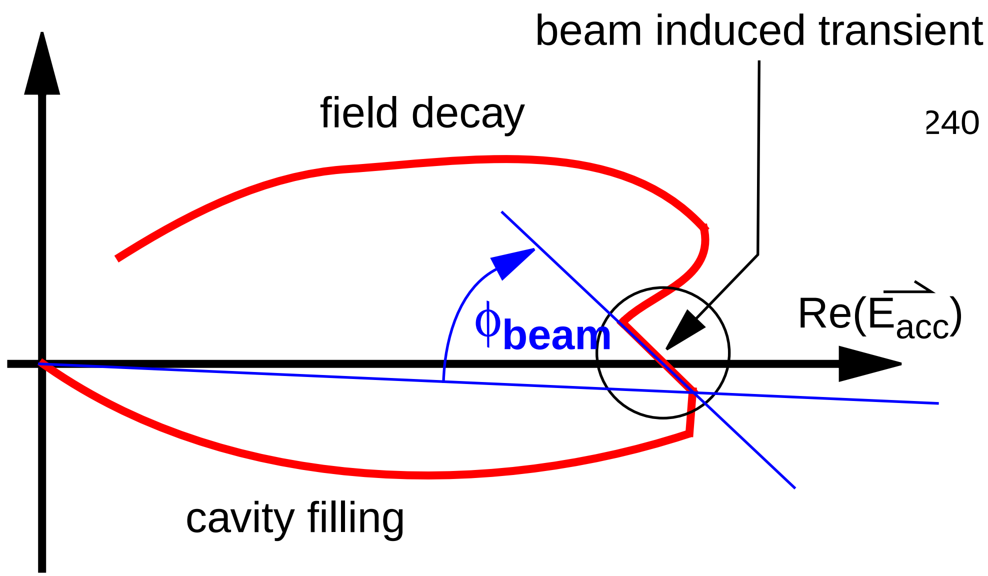


- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

Beam Transient based Phase and Gradient Calibration



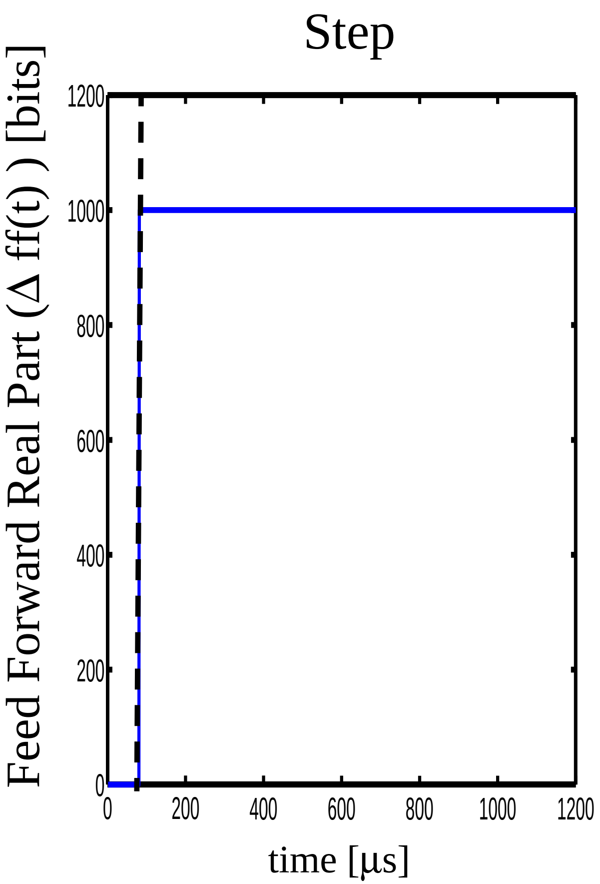


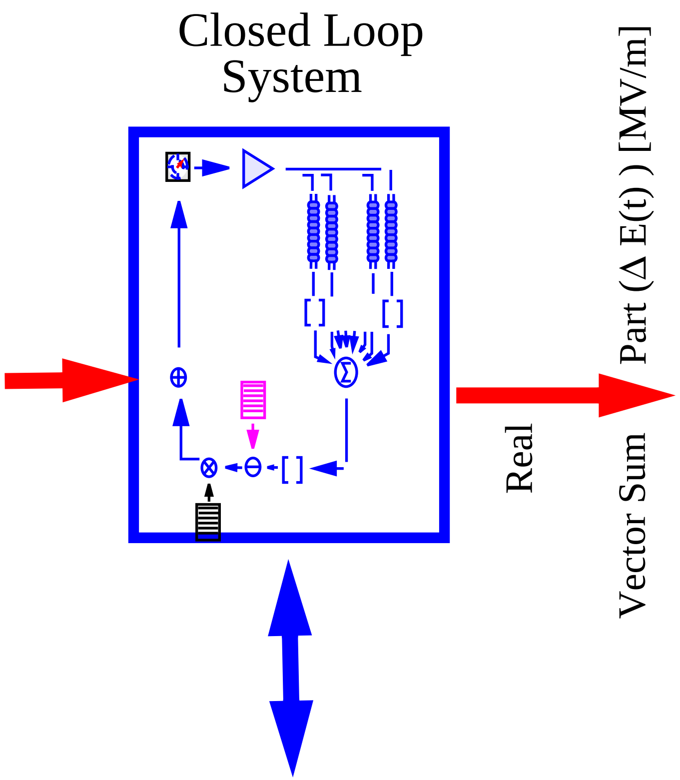


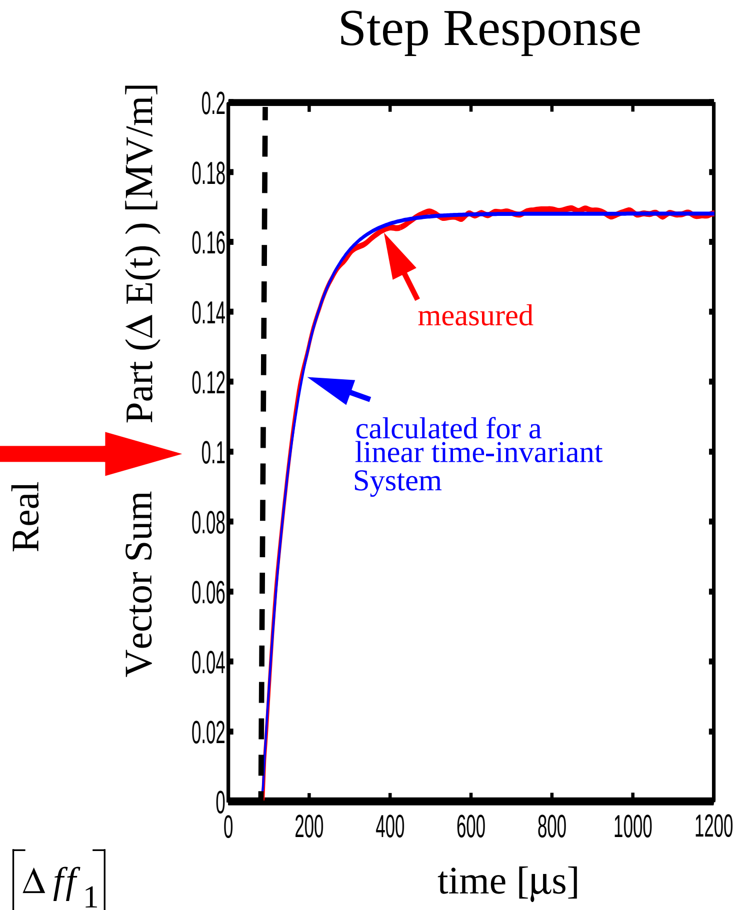
for $\Delta t \ll \tau_{cav}$:

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

Adaptive Feedforward

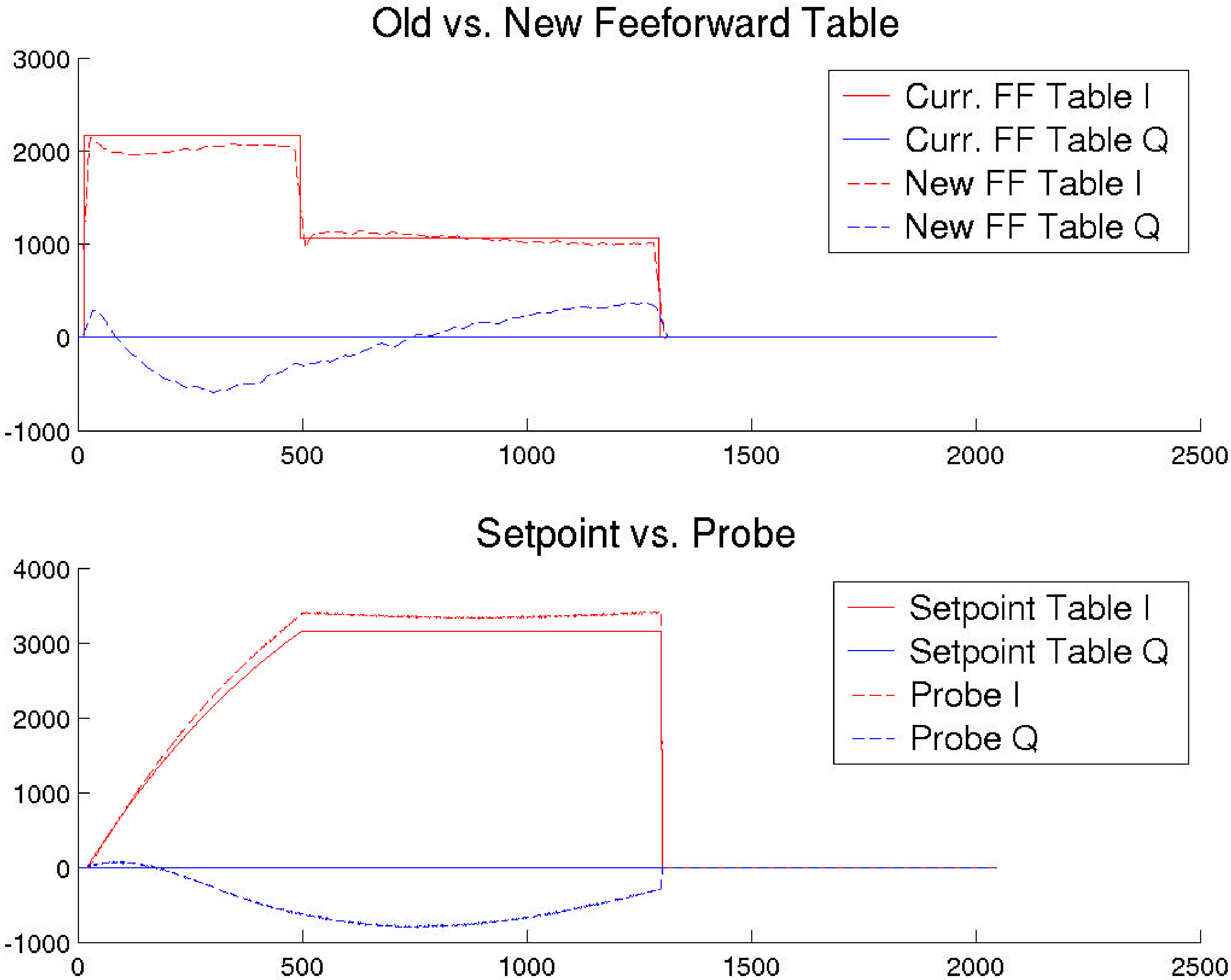




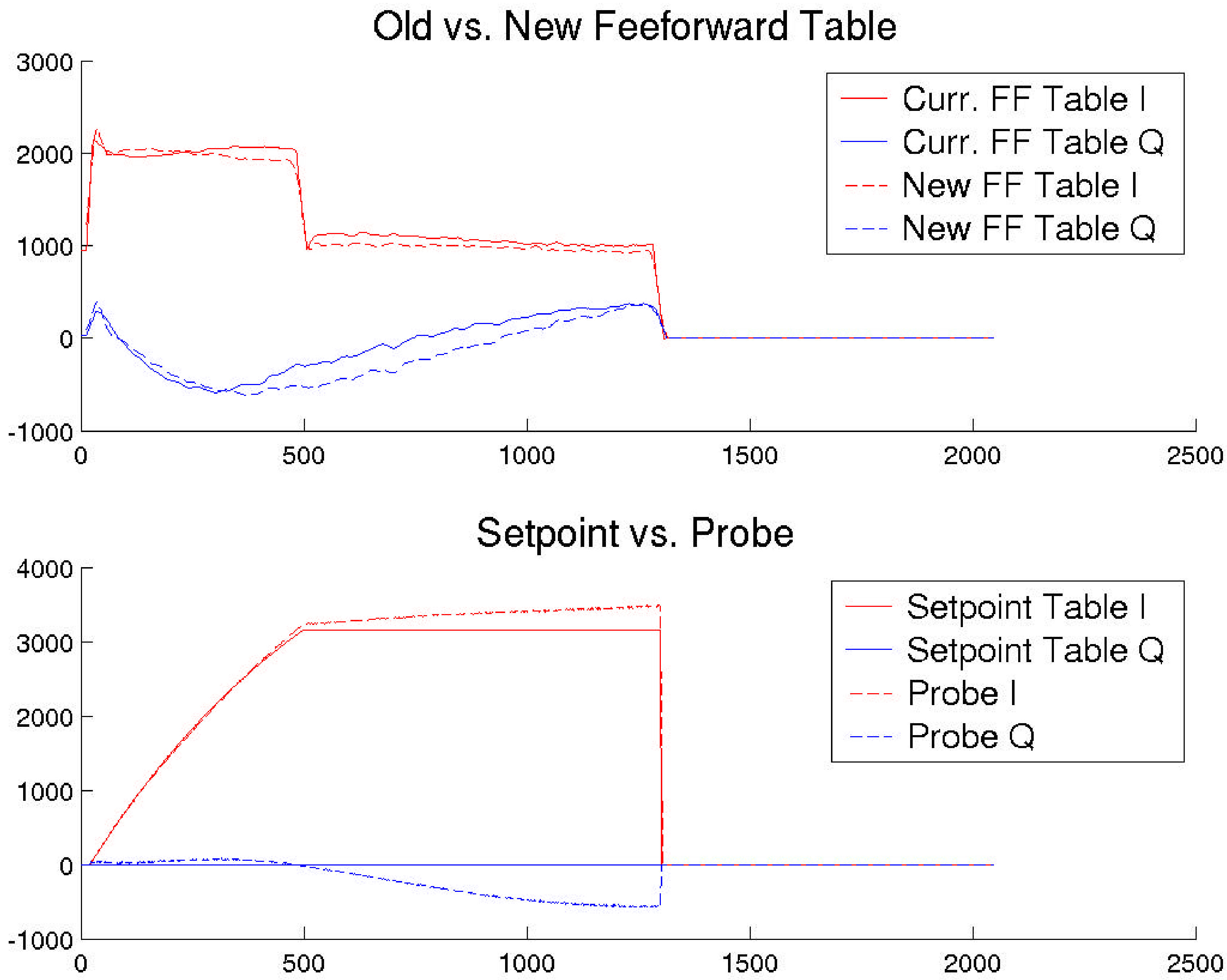


$$\begin{bmatrix} \Delta E(\tau_1) \\ \Delta E(\tau_2) \\ \dots \\ \Delta E(\tau_n) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1n} \\ T_{21} & T_{22} & \dots & T_{2n} \\ \dots & \dots & \dots & \dots \\ T_{n1} & T_{n2} & \dots & T_{nn} \end{bmatrix} \begin{bmatrix} \Delta ff_1 \\ \Delta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

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



Old vs. New Feeforward Table
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500
Setpoint vs. Probe
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q
4000
3000
2000
1000
0
-1000
0
500
1000
1500
2000
2500



Old vs. New Feeforward Table
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2000
1000
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-1000
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500
1000
1500
2000
2500
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
Setpoint vs. Probe
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-1000
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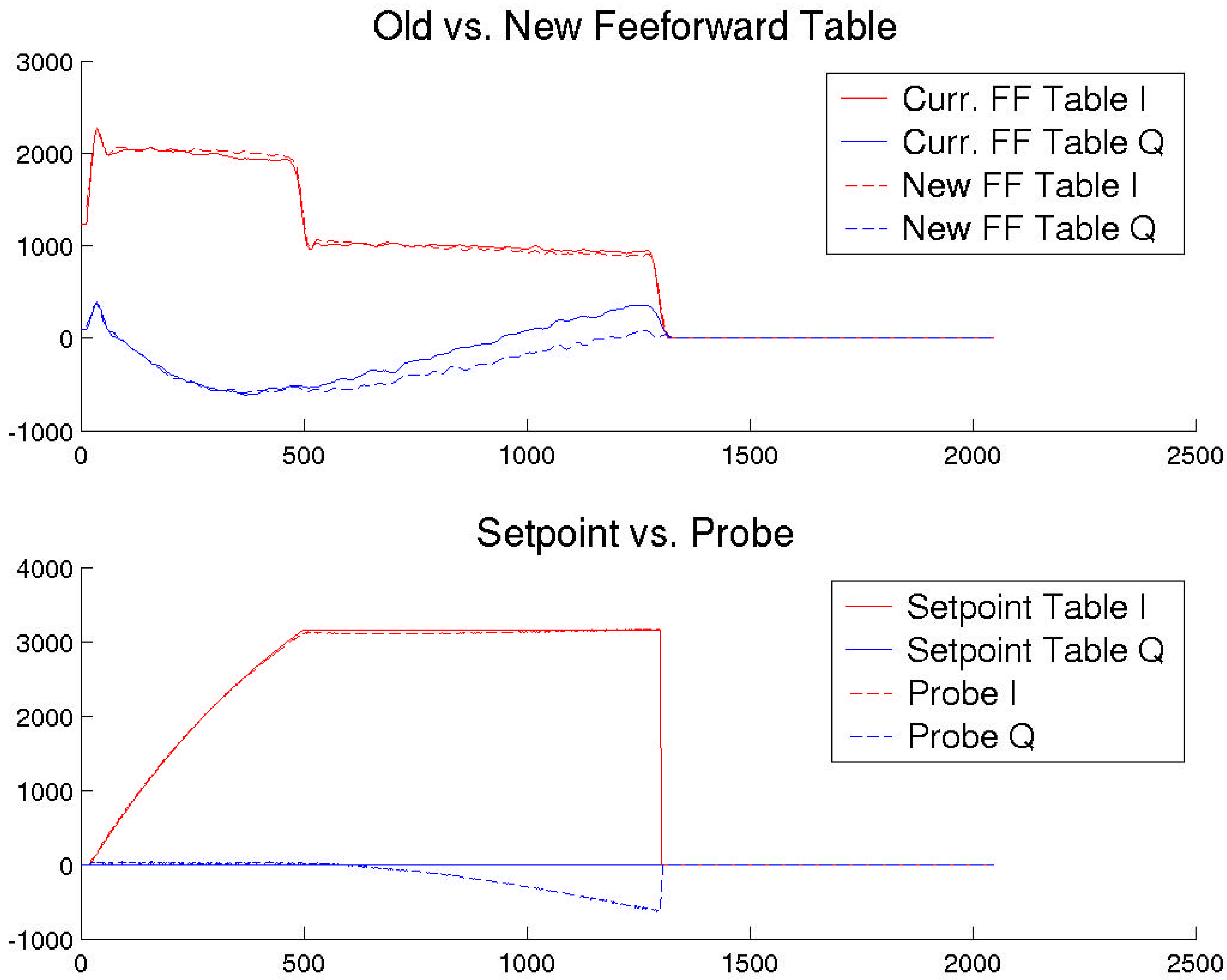
2000
2500
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q



Old vs. New Feeforward Table
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Curr. FF Table I
Curr. FF Table Q
New FF Table I
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Setpoint vs. Probe
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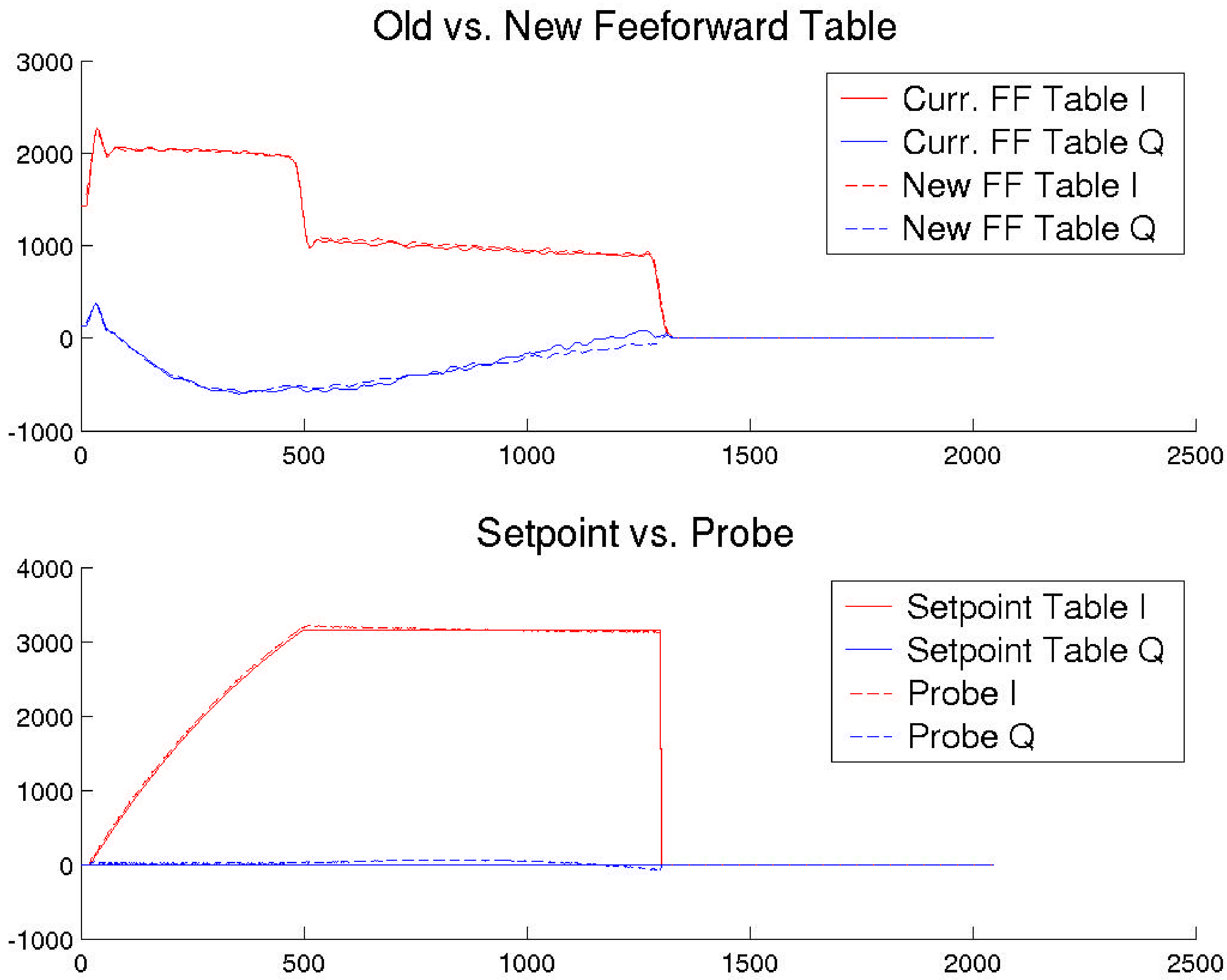
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q


Old vs. New Feeforward Table
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Curr. FF Table I
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New FF Table I
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Setpoint vs. Probe
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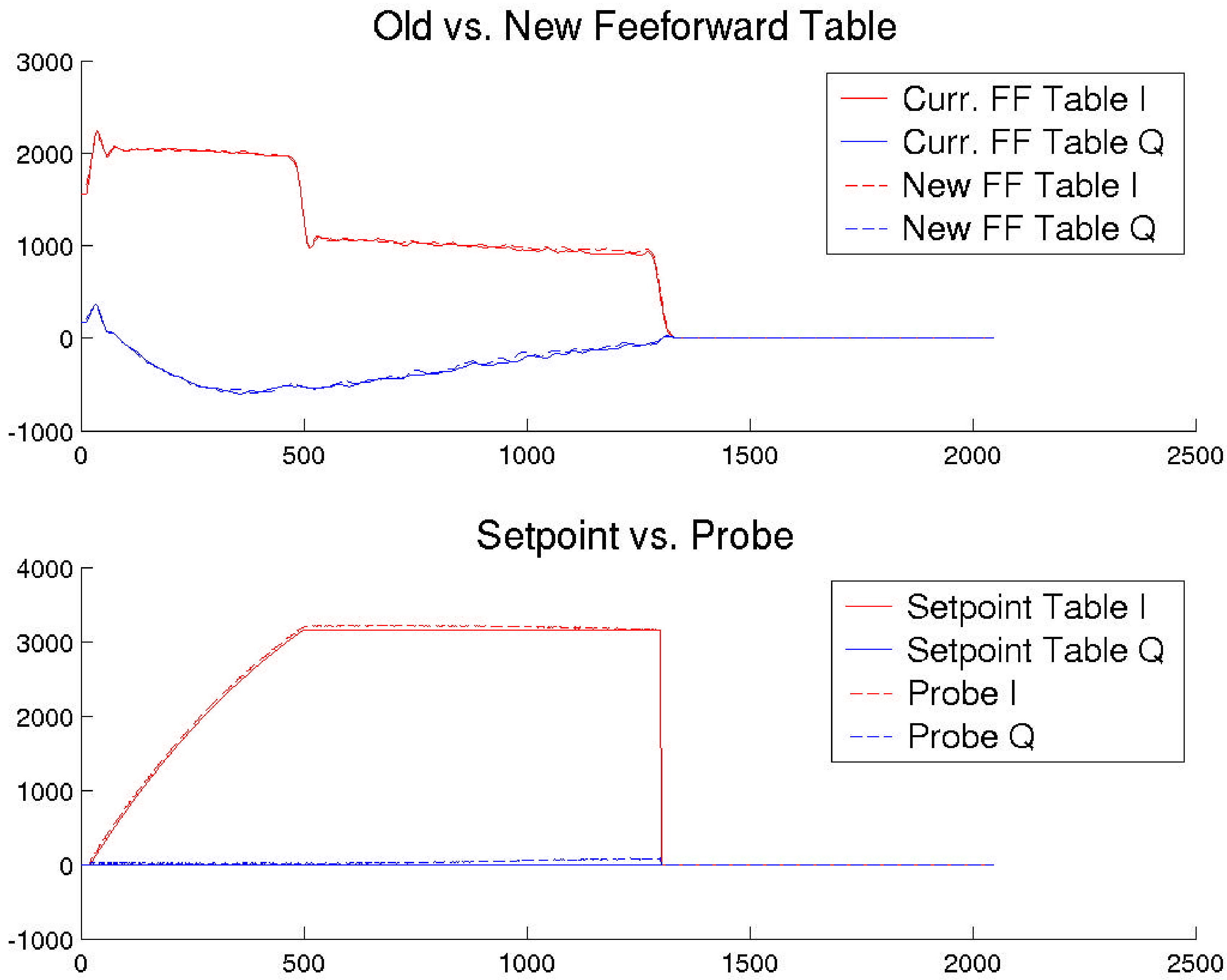
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q


Old vs. New Feeforward Table
Curr. FF Table I
Curr. FF Table Q
New FF Table I
New FF Table Q
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Setpoint vs. Probe
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Probe I
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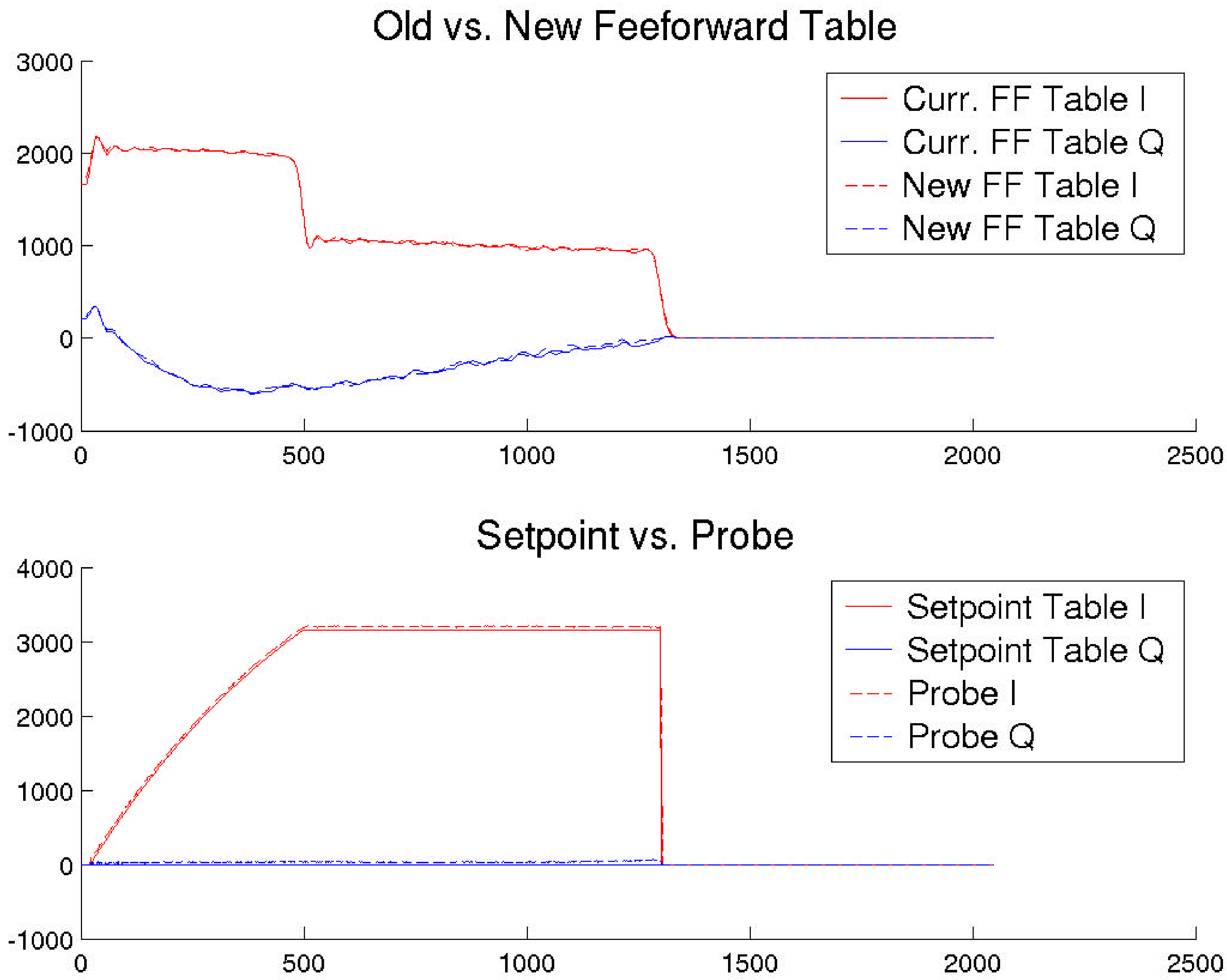

Old vs. New Feeforward Table
Curr. FF Table I
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New FF Table I
New FF Table Q
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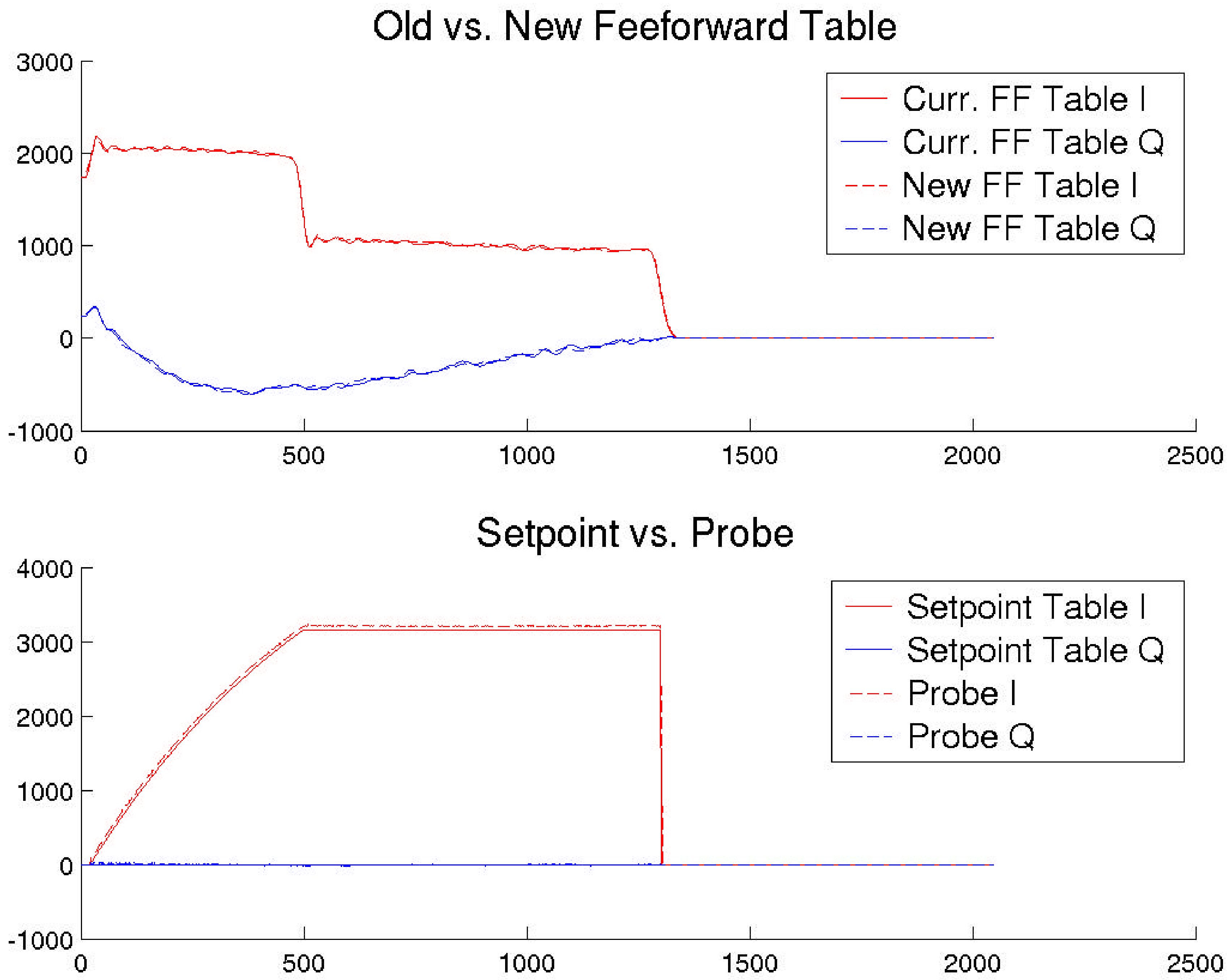
Old vs. New Feeforward Table
Curr. FF Table I
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Setpoint vs. Probe
Setpoint Table I
Setpoint Table Q
Probe I
Probe Q
4000
3000
2000
1000
0
-1000
0
500
1000
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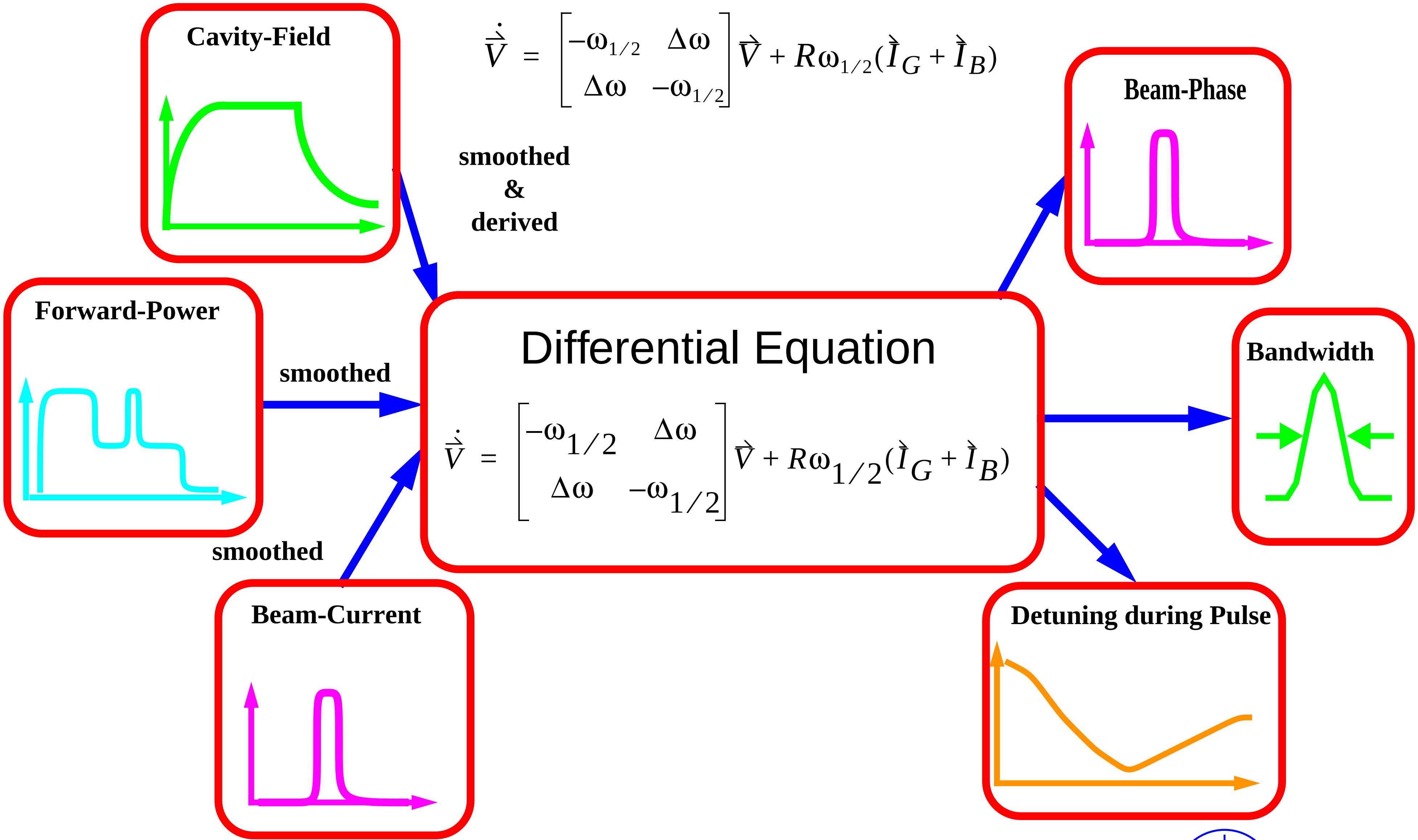
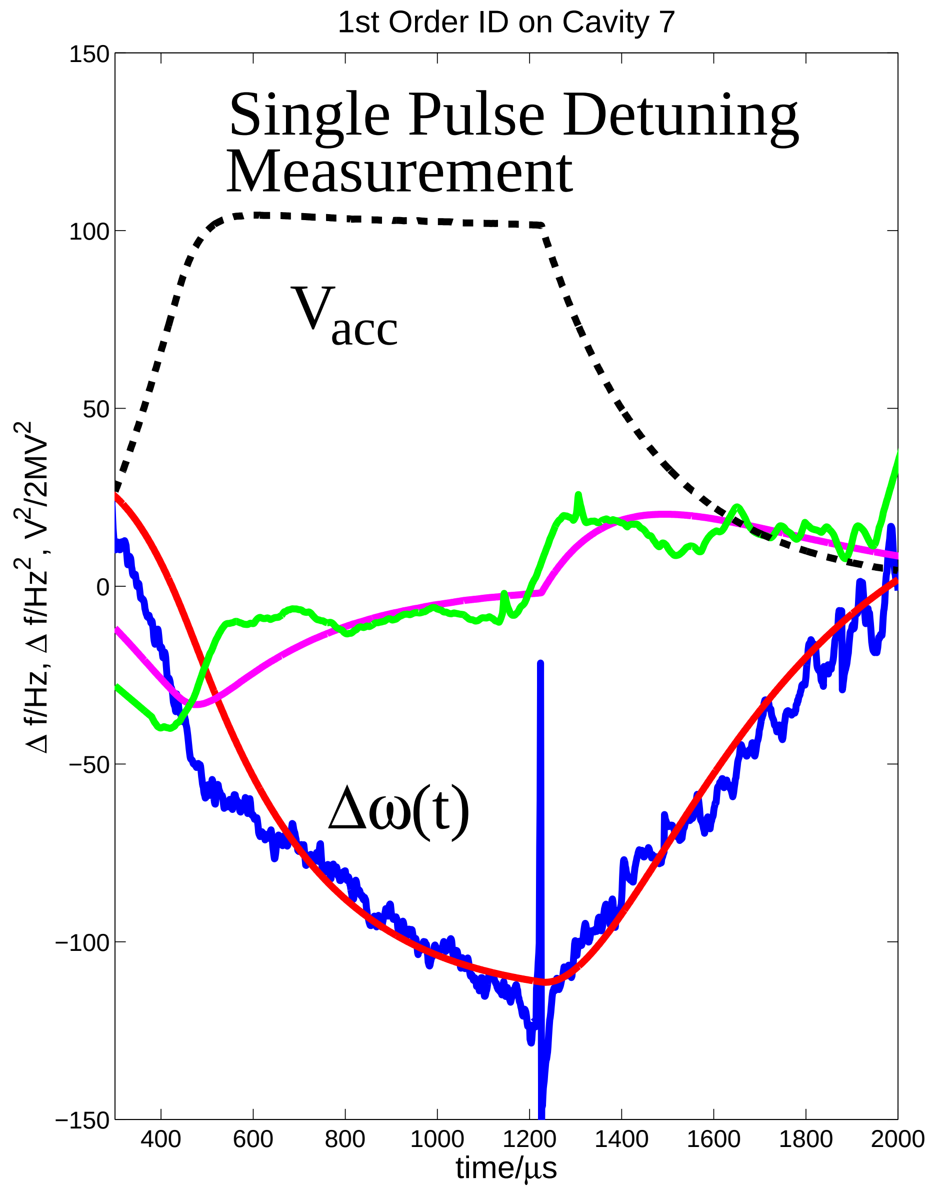
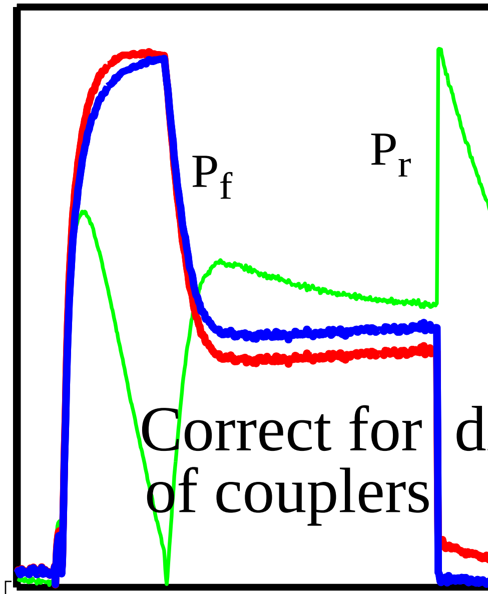
2000
2500

System Identification (1)

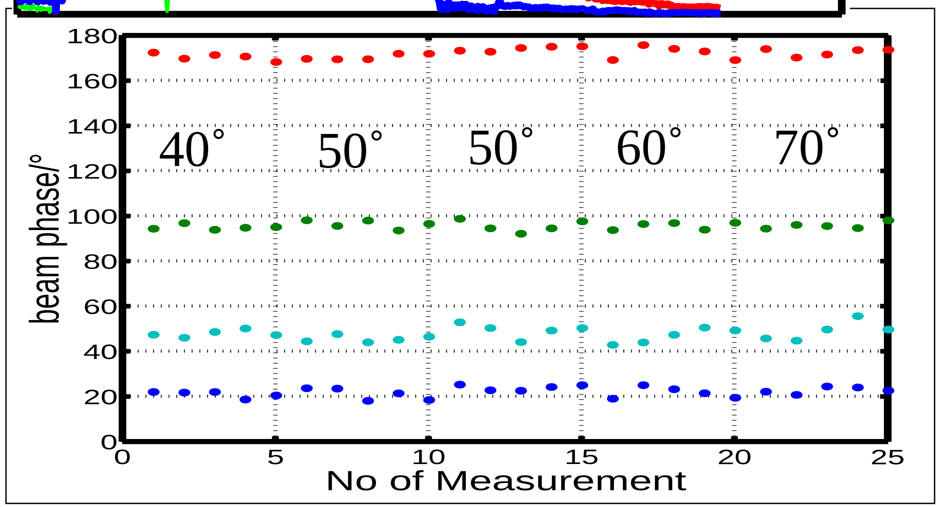


System Identification (2)



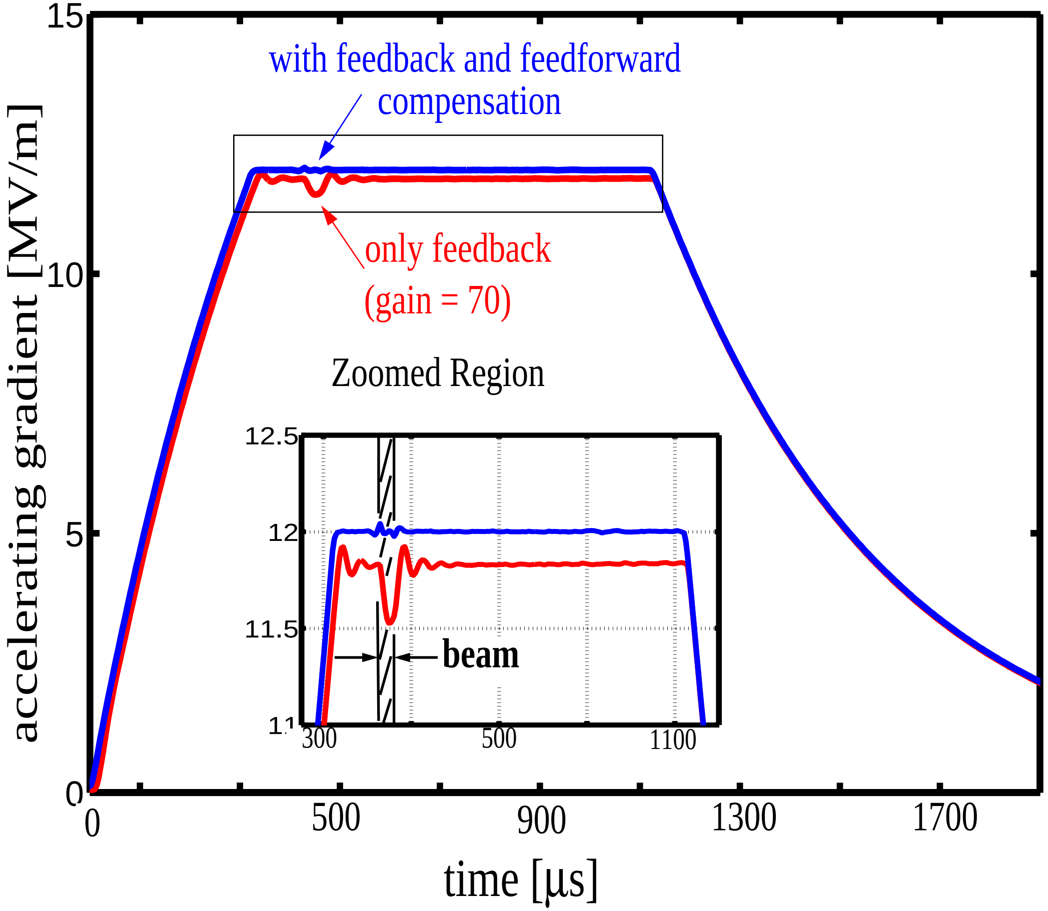


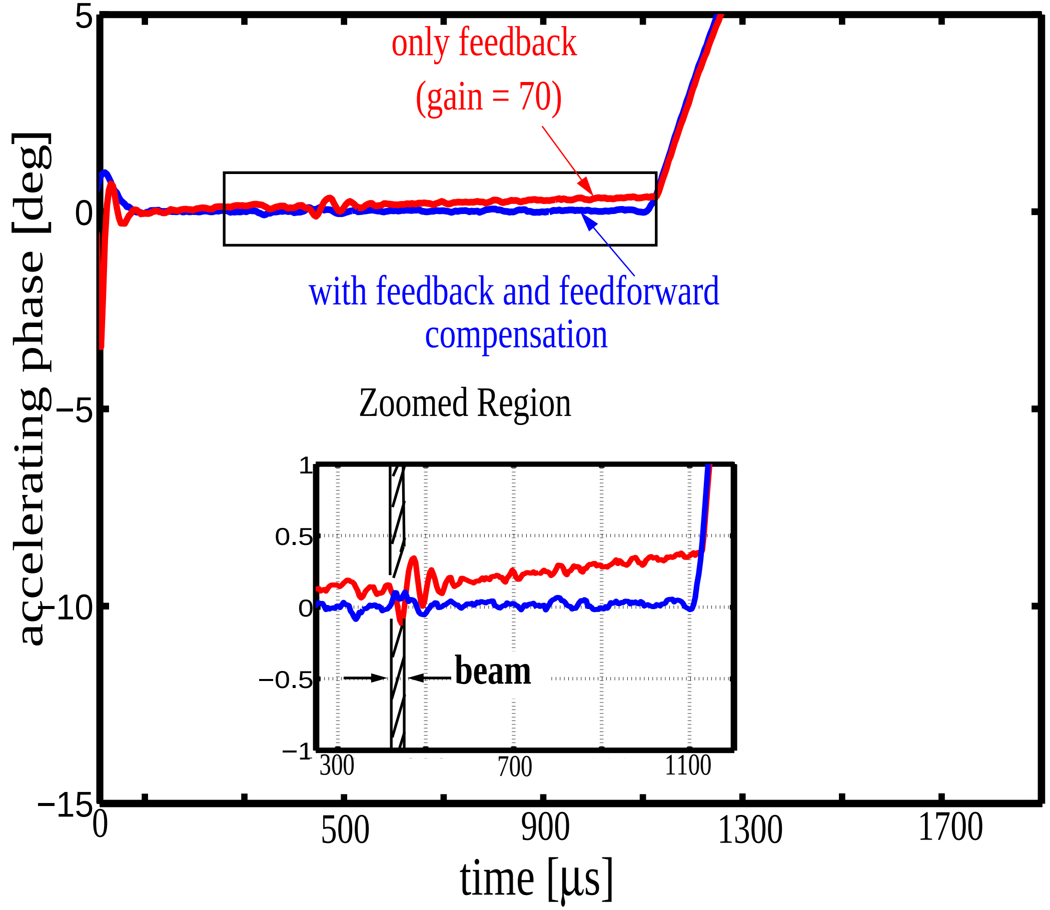
- force P_f to be zero at end of pulse by sub-straction of d_f*P_r (complex)
- the whole shape changes



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

Performance at TTF (1)

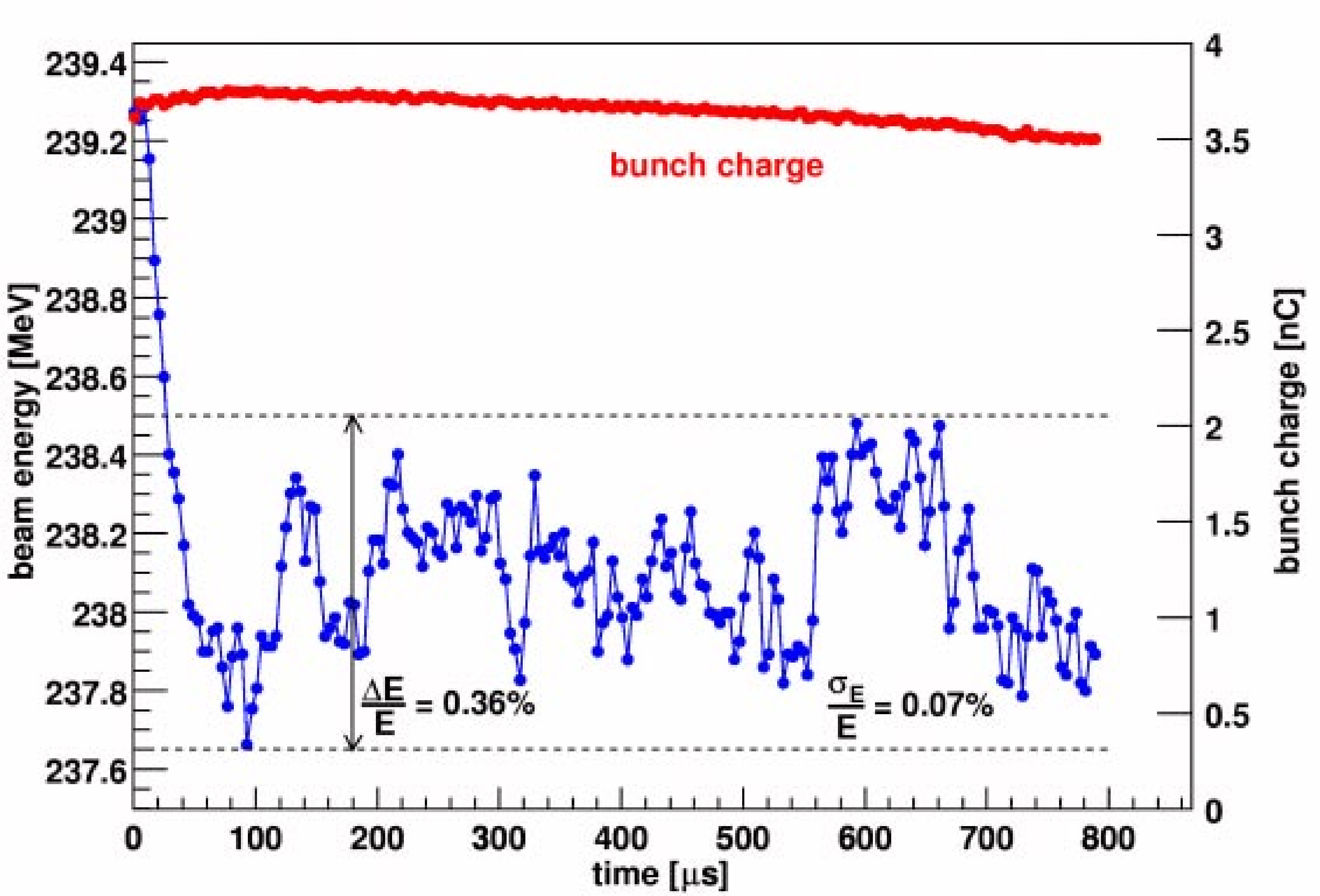




Amplitude

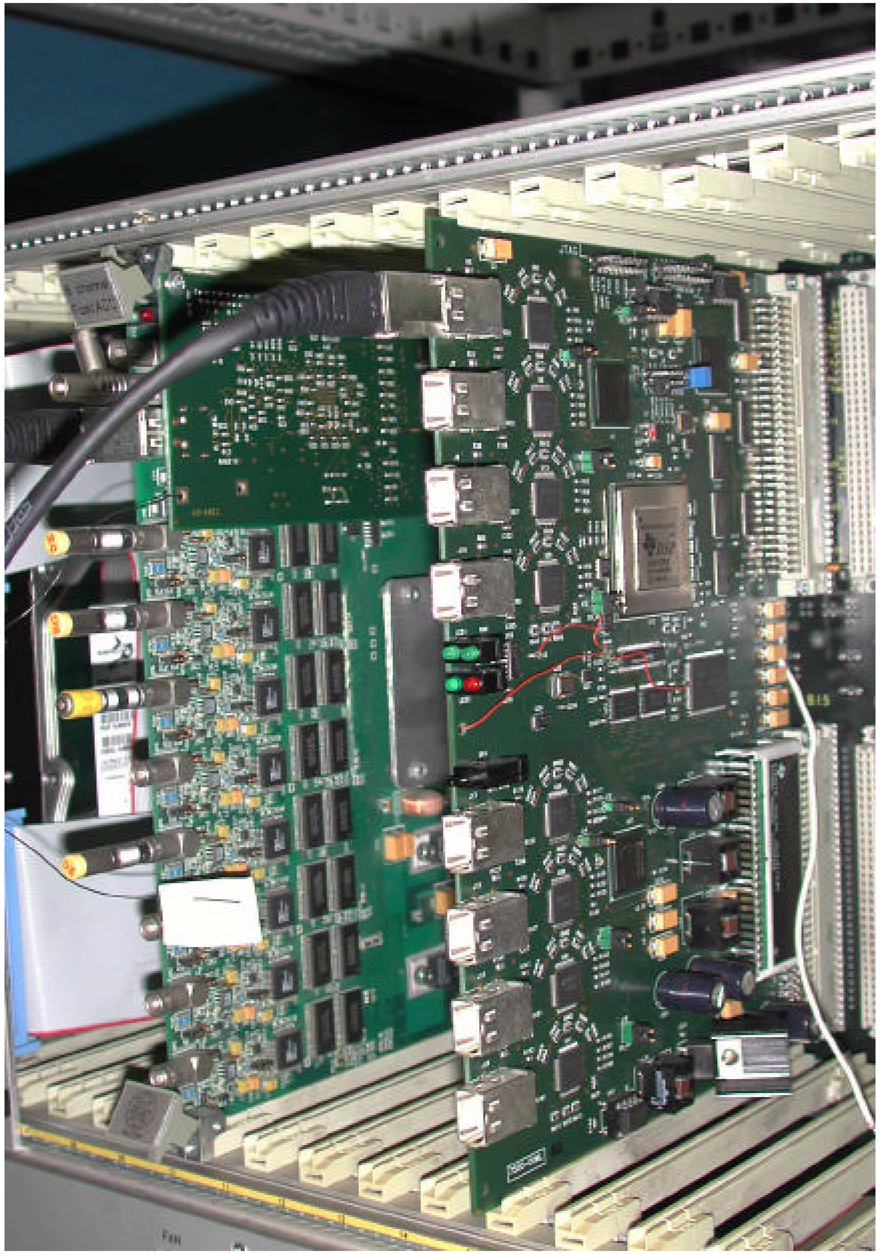
Phase

Performance at TTF (2)

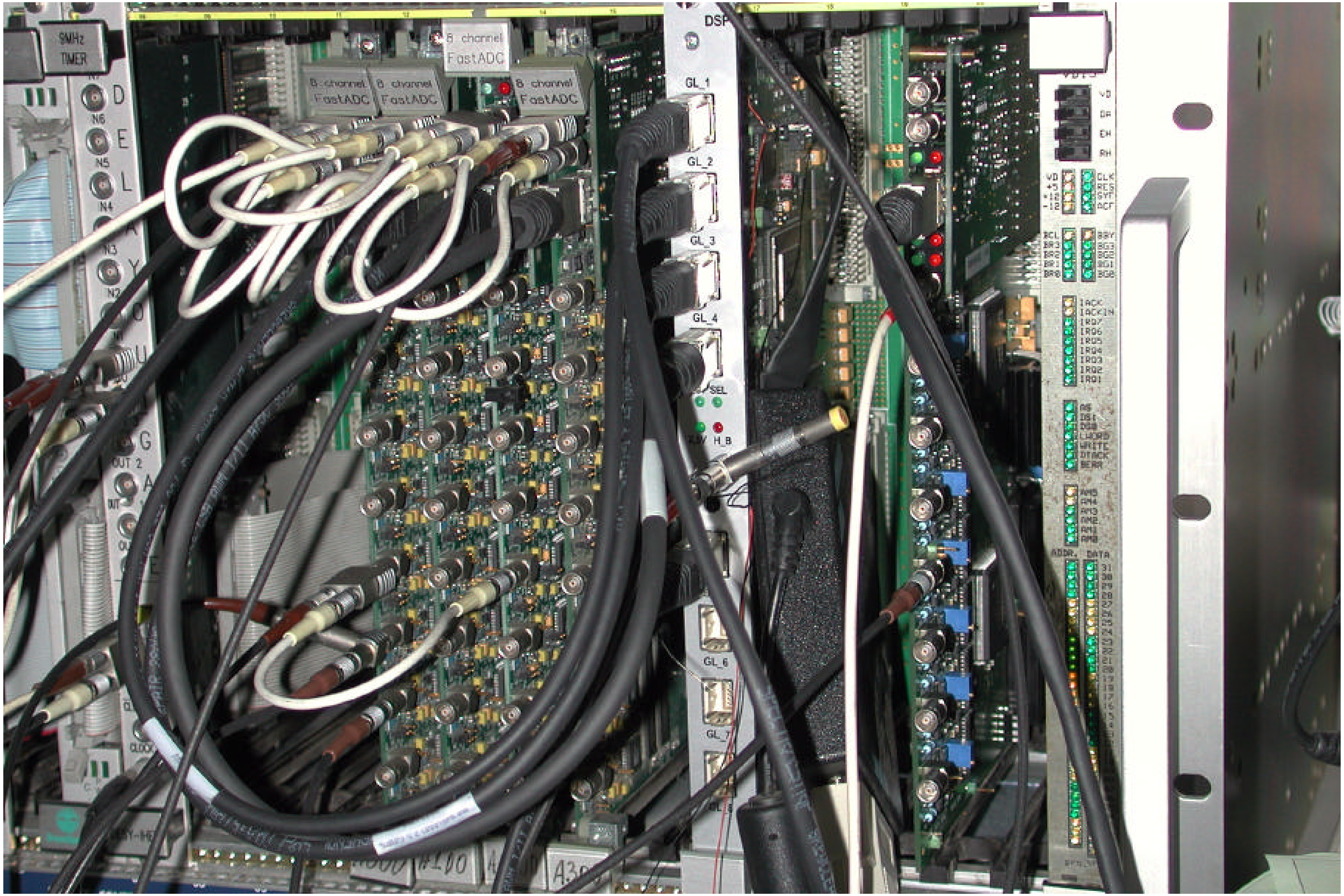


Operation with long beam pulses

C67 DSP board

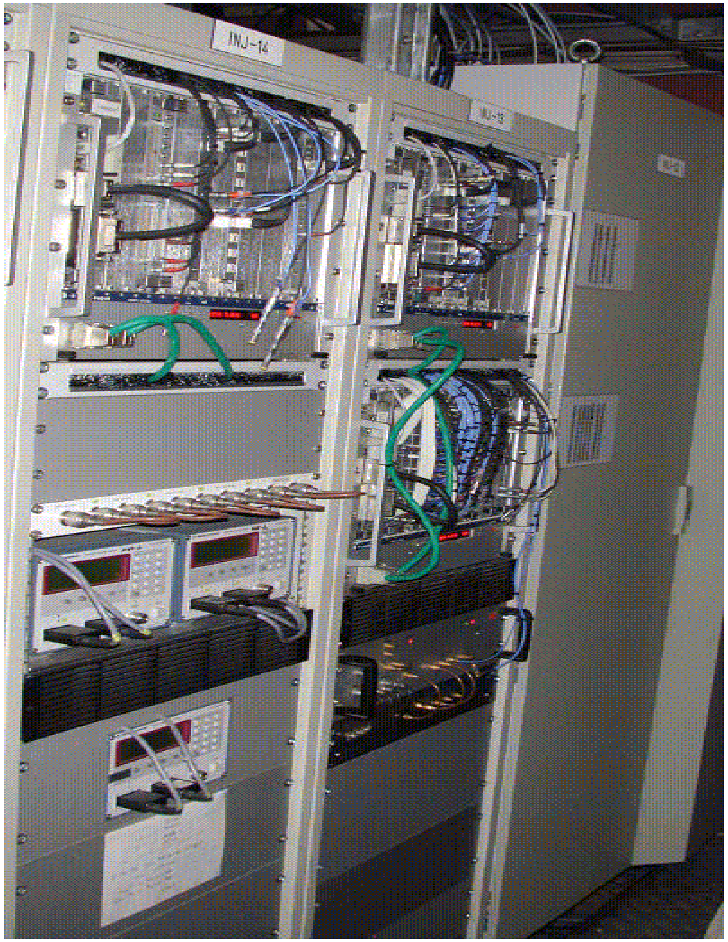


C67 DSP board

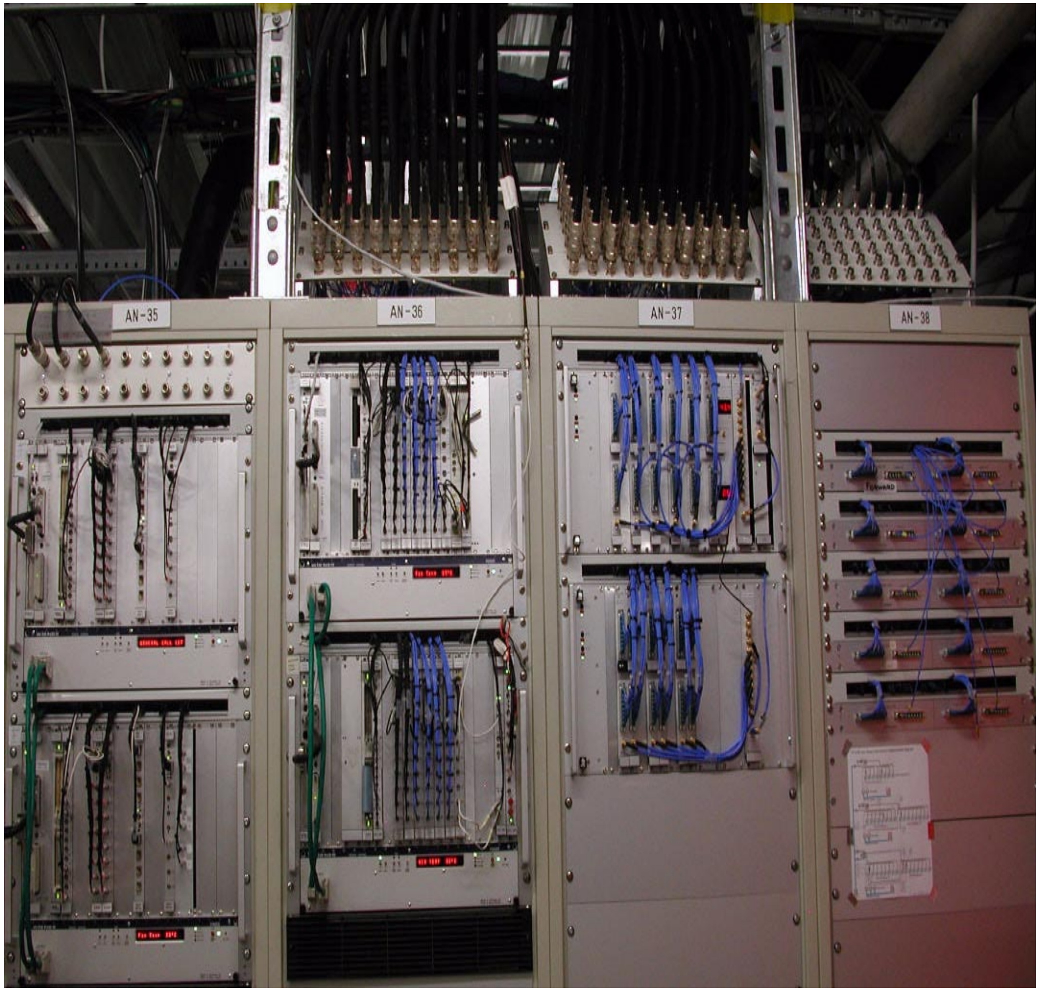


Digital Feedback Hardware

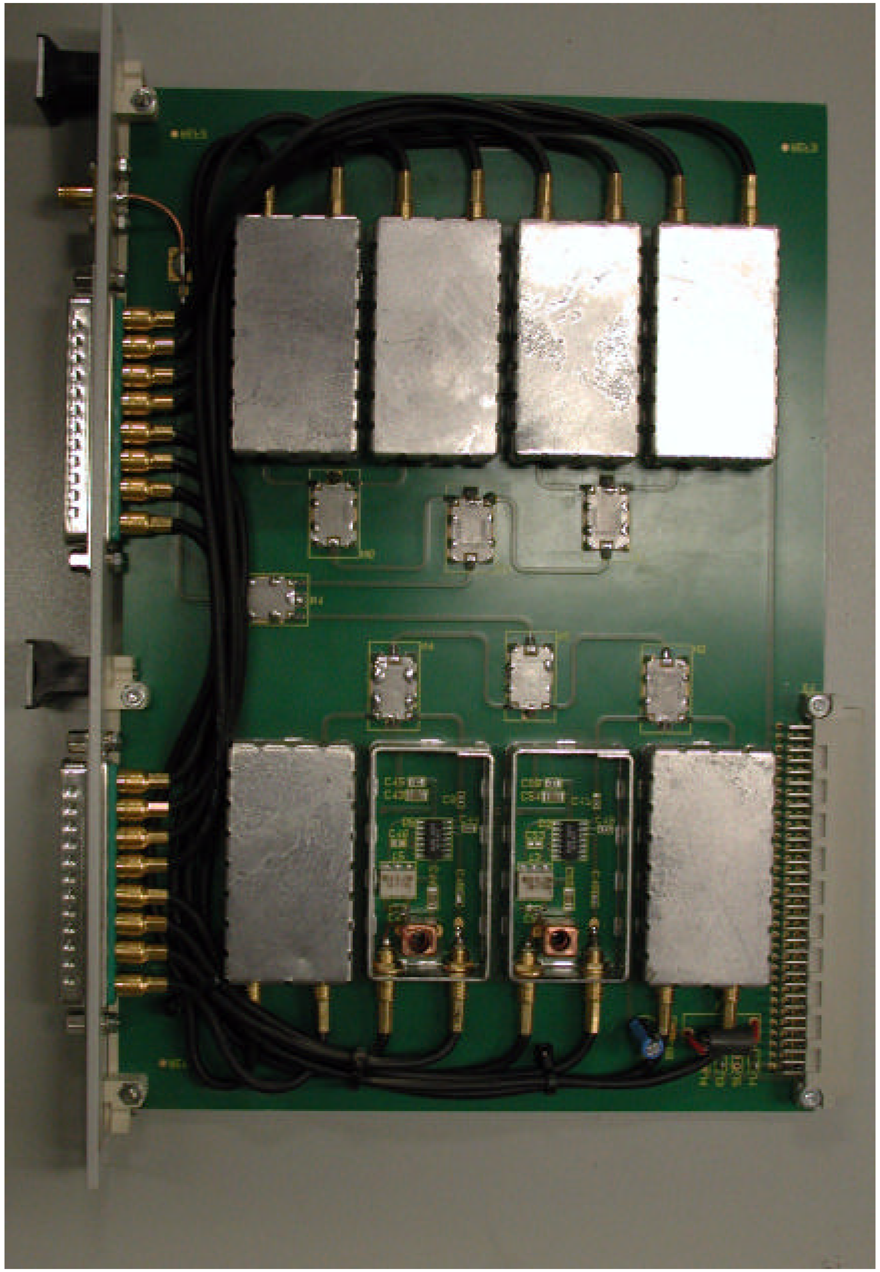
Gun and ACC1

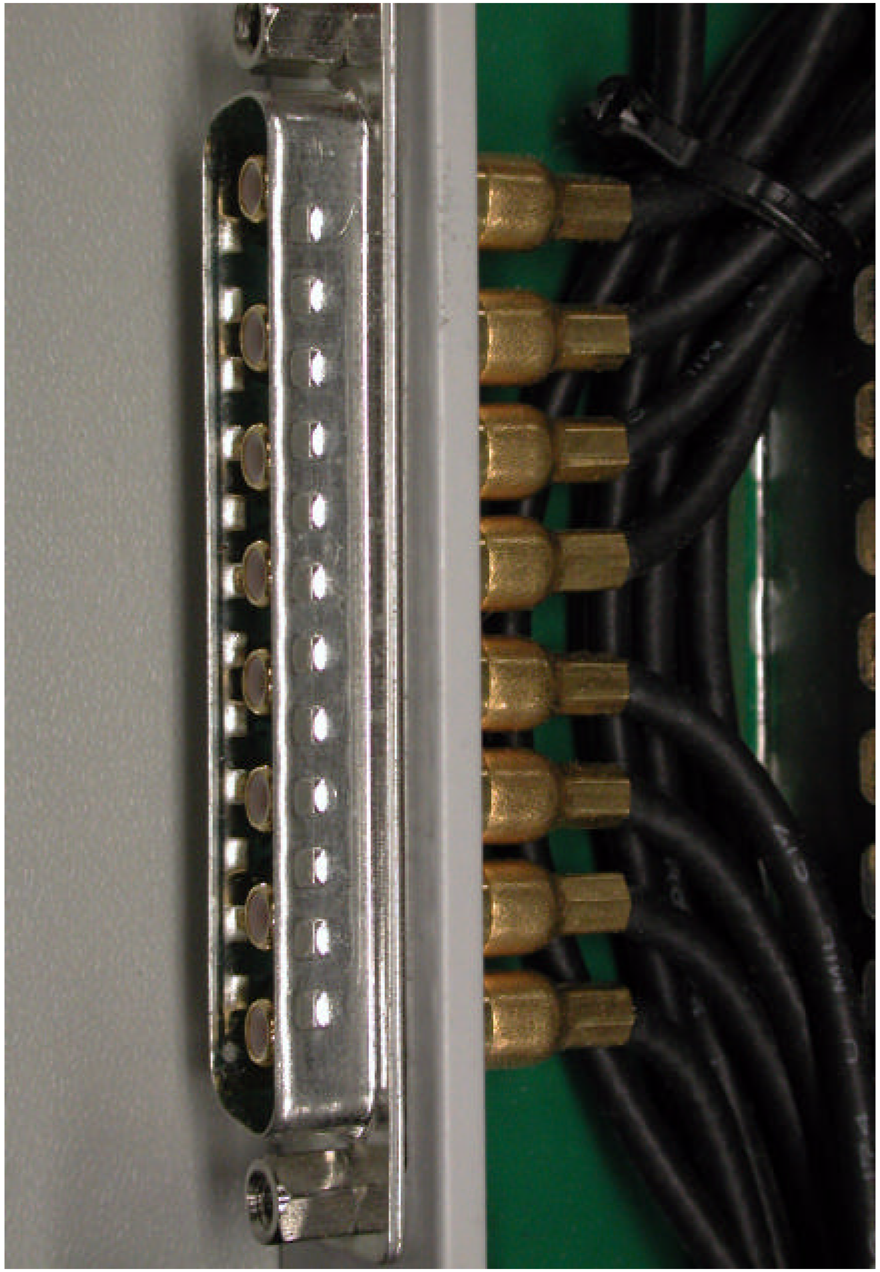


ACC2, ACC3, ACC4 & ACC5

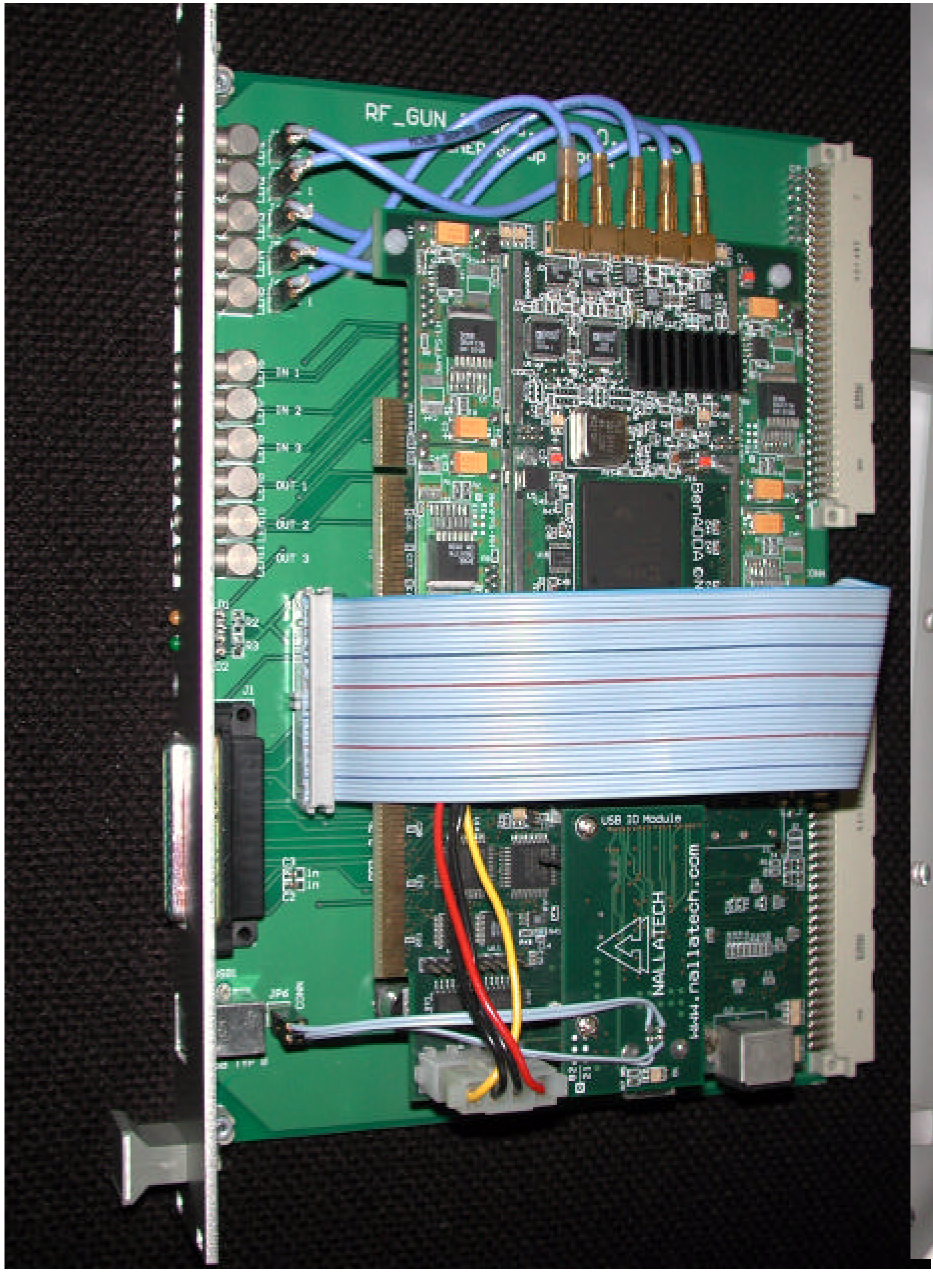


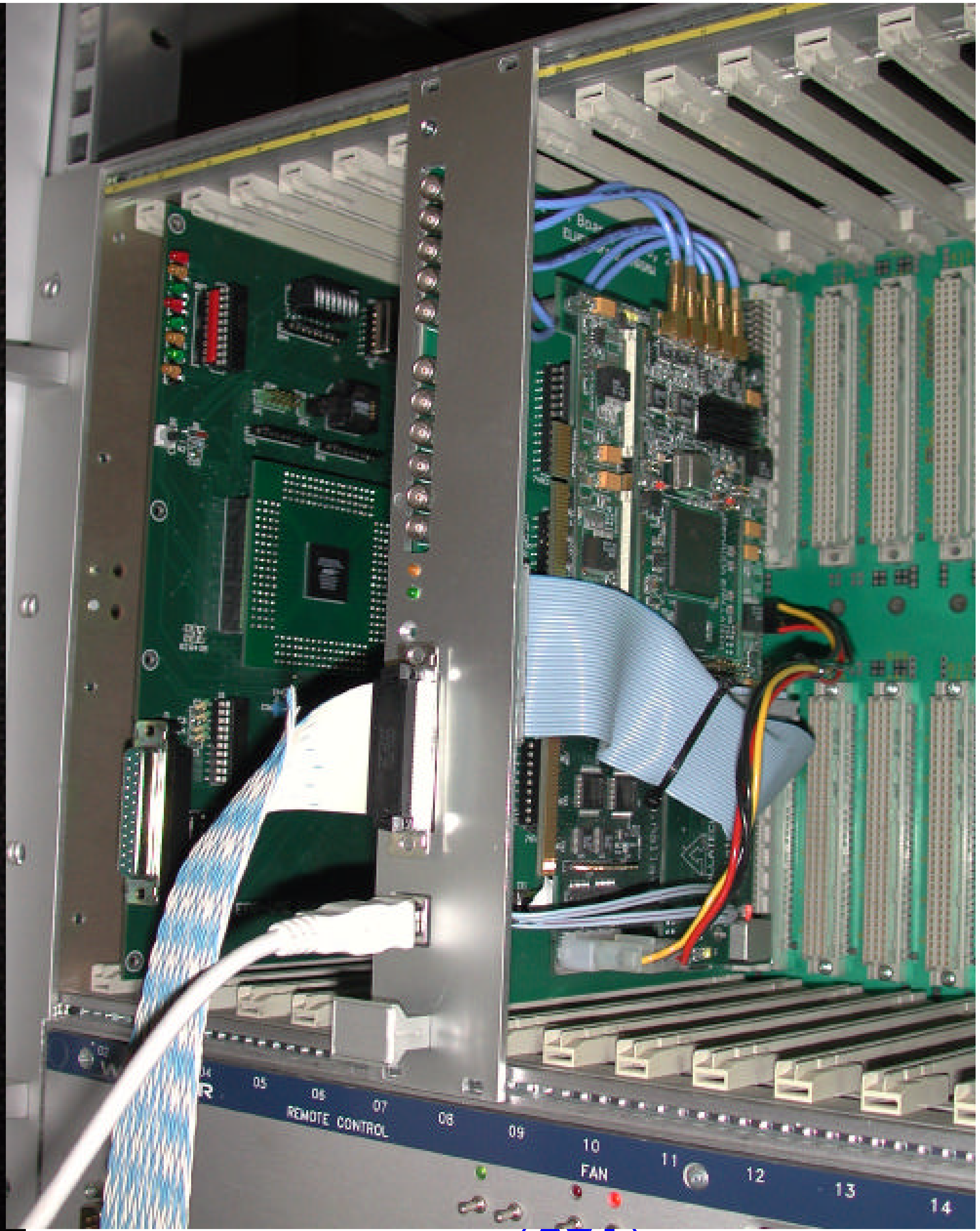
Downconverter



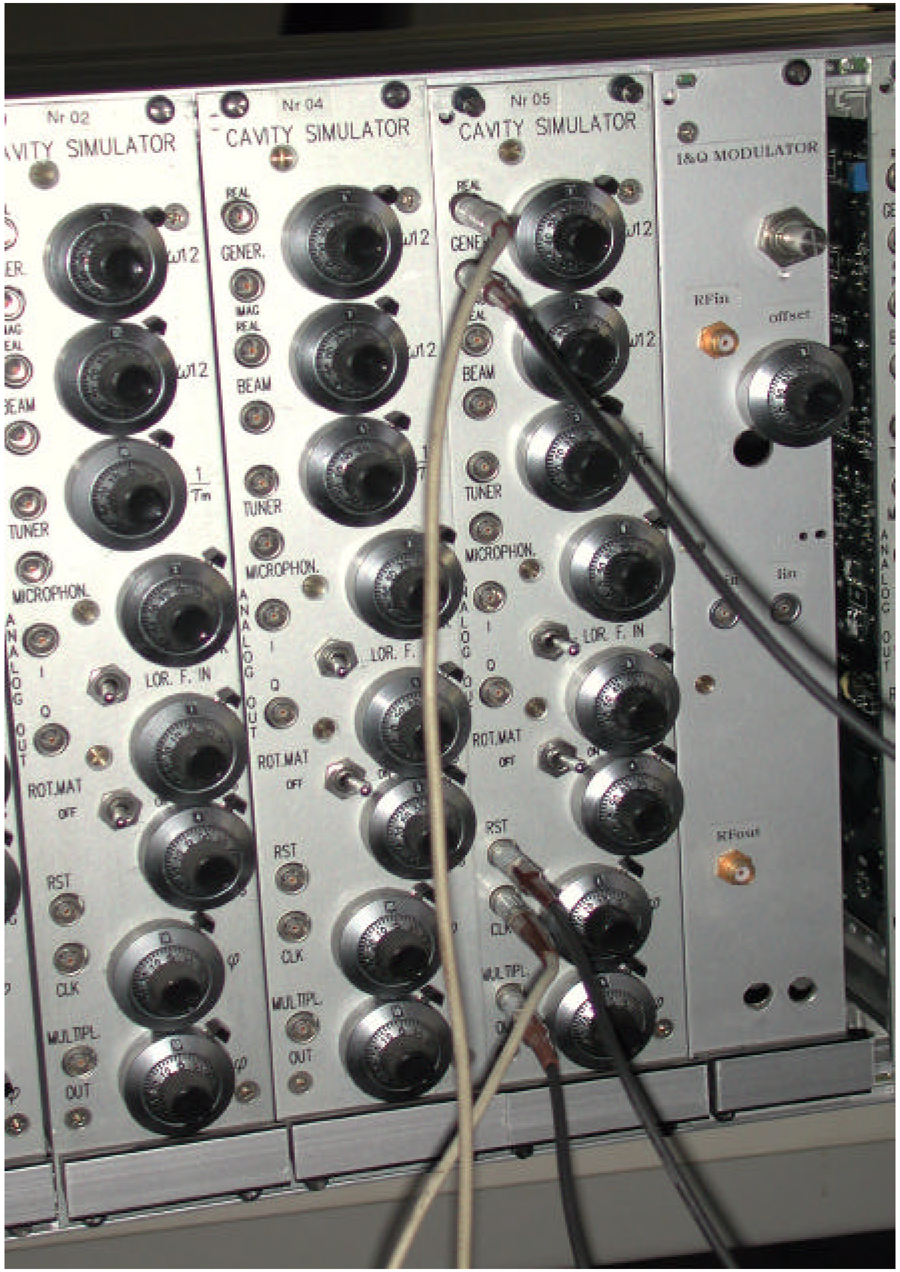


FPGA based RF Gun Controller



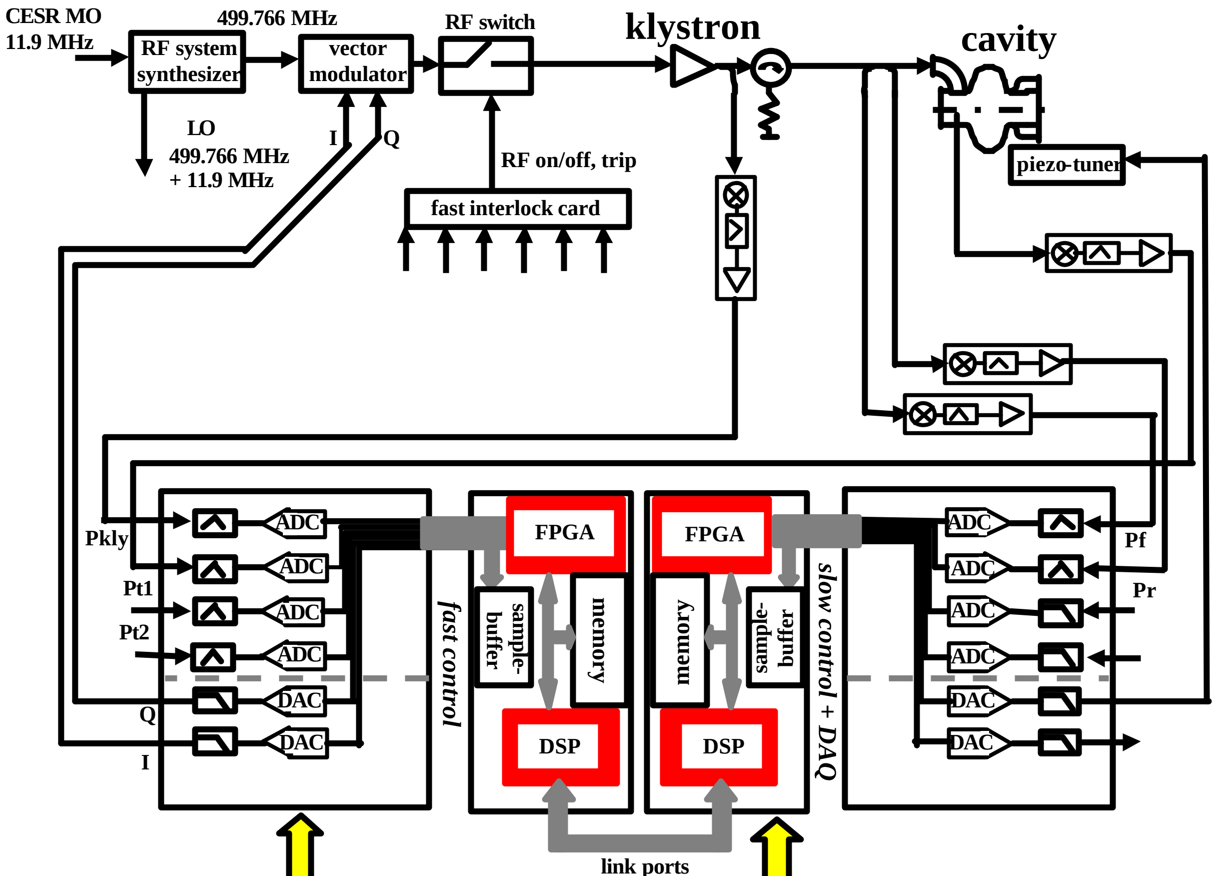


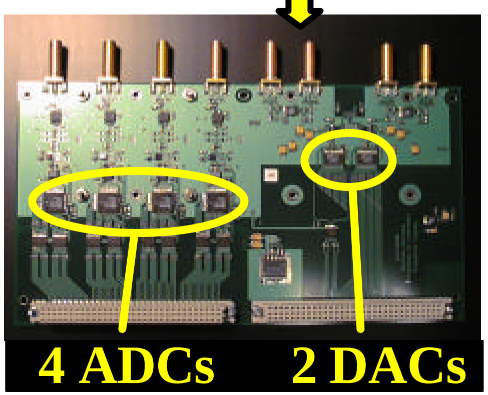
Cavity Simulator

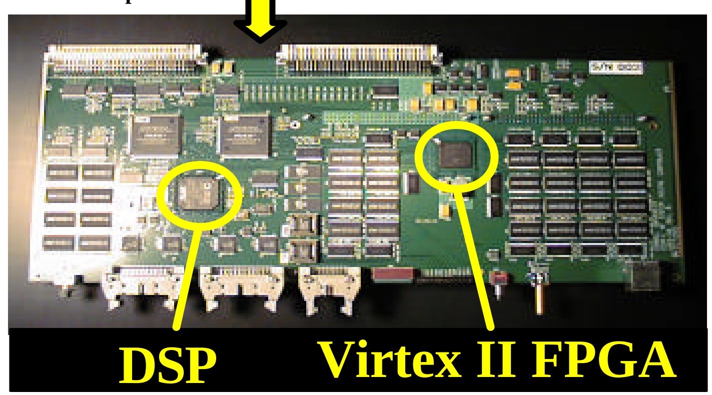


Matthias Liepe
CORNELL UNIVERSITY

Ultra-Fast Digital RF Field Control System for CESR and ERLs







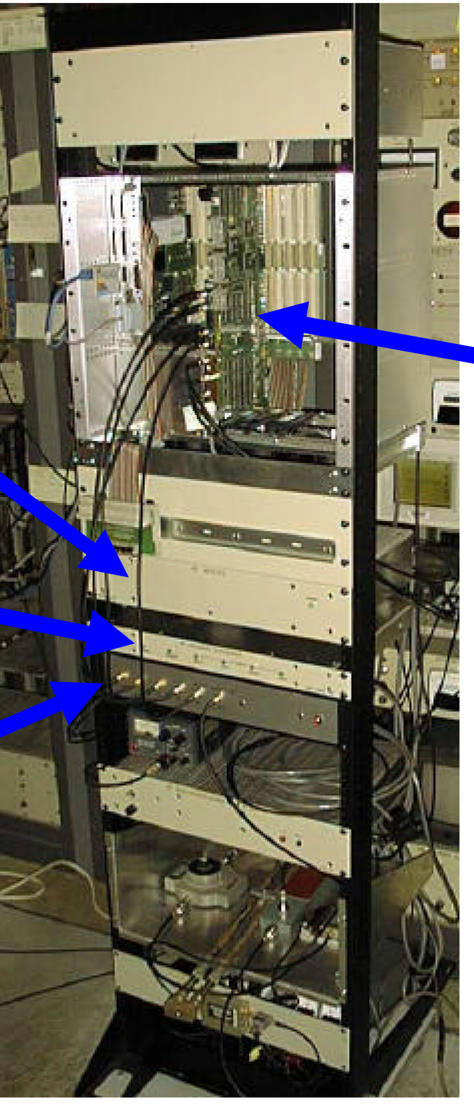
- *very low delay in the control loop (» 1 ms)*
- *Field Programmable Gate Array (FPGA) design combines the speed of an analog system and the flexibility of a digital system*
- *high computation power allows advanced control algorithms*
- *all boards have been designed in house*
- *generic design: digital boards can be used for a variety of control and data processing applications*

Cornell's Digital RF Control System:

RF Down-Converters

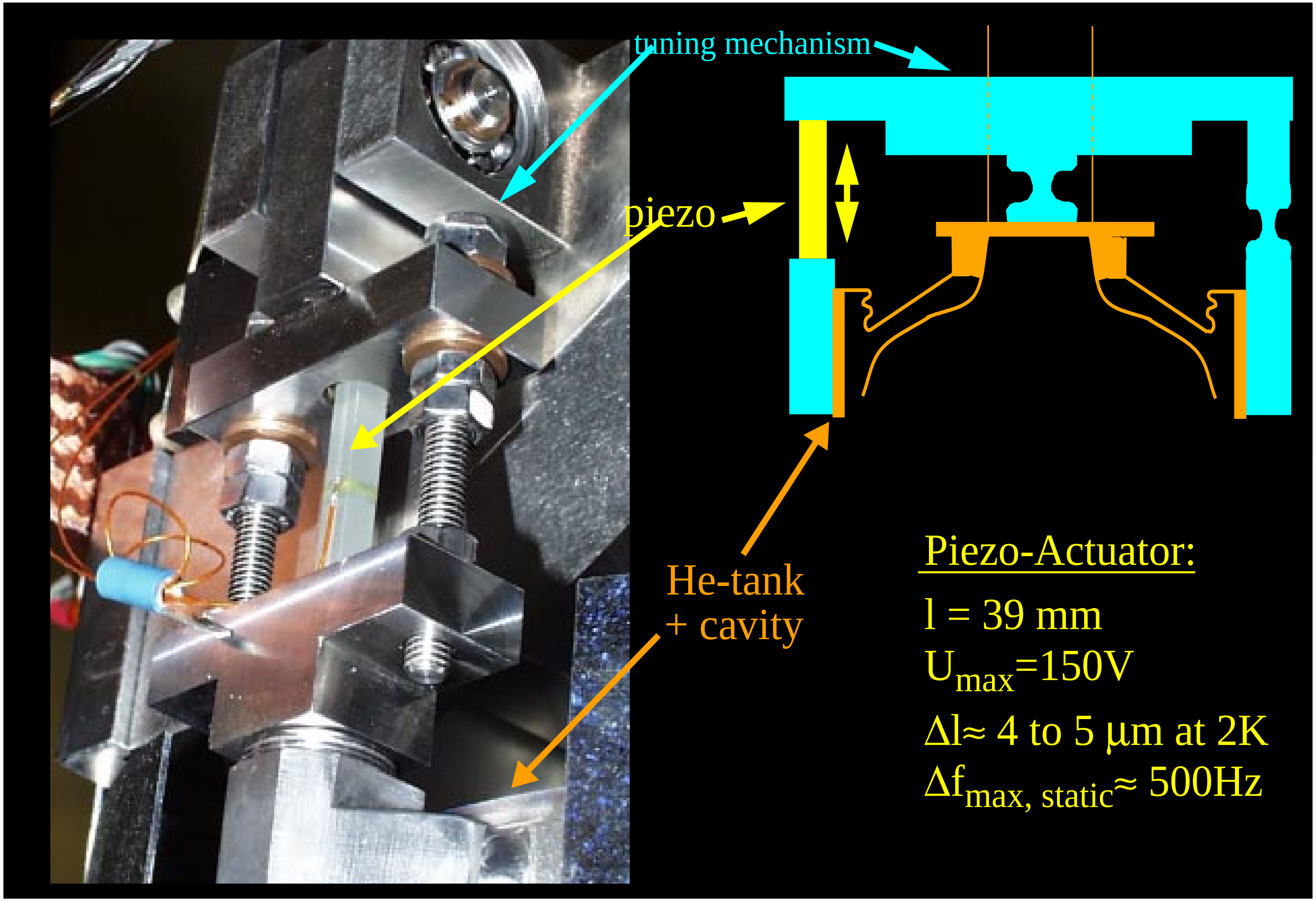
500 MHz frequency synthesizer

vector modulator



Digital Boards:

Active Compensation of Lorentz Force Detuning (1)



Piezo-Actuator:

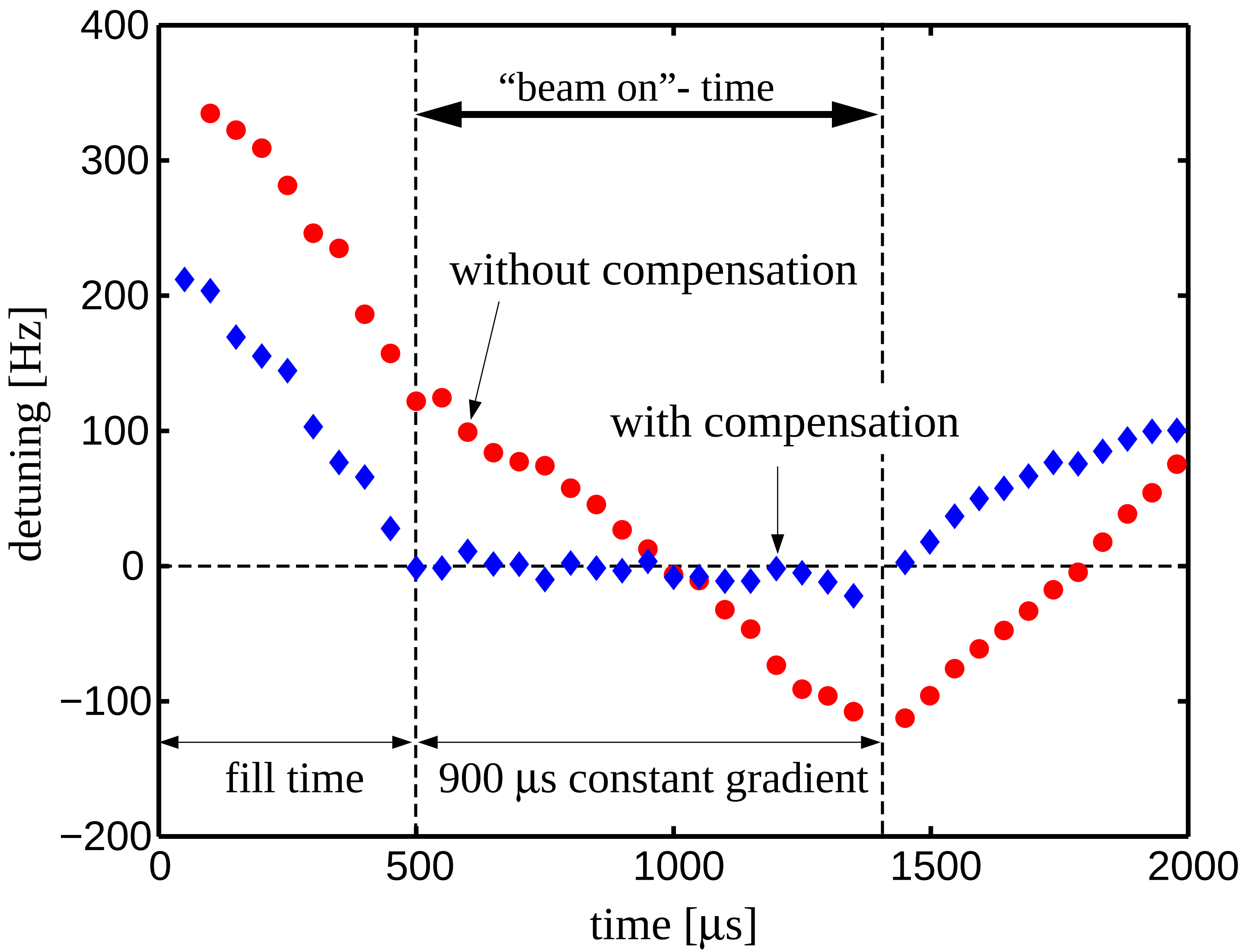
$l = 39$ mm

U_{max}=150V

$\Delta l \approx$ 4 to 5 µm at 2K

$\Delta f_{max,\ static} \approx$ 500Hz

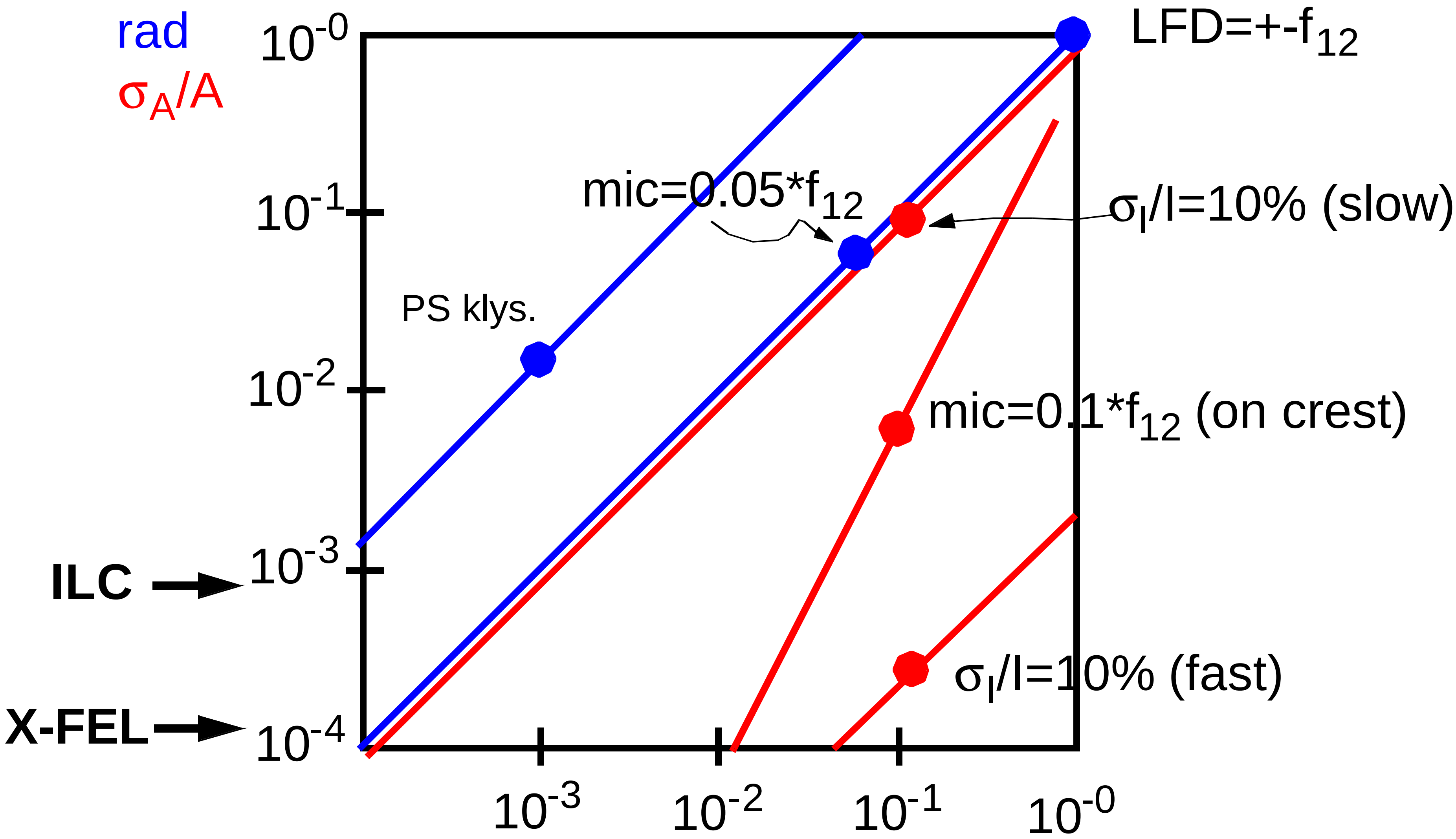
Active Compensation of Lorentz Force Detuning (2)



9-cell cavity operated at 23.5 MV/m

Lorentz force compensated with fast piezoelectric tuner

Open Loop Errors



Conclusion

- Field regulation ranging from 1% to 10^{-4} amplitude and 1 deg. to 0.01 deg. for phase (in critical sections) will be required for future superconducting and normalconducting accelerators

- Noise sources for superconducting cavities are understood
  - Microphonics (typ. 10 Hz)
  - Lorenz force detuning (1-3 Hz/(MV/m)^2)
  - Beam loading (few %)

- Rapid development in digital technology (DSP, FPGA, ADC, DAC) favors digital design for feedback/feedforward control.

- Fast Control with incident wave
  - feedforward for repetitive errors (beam,LFD, klystr.)
  - feedback (stochastic errors)

- Limitation of feedback: Latency in Loop (limits loop gain) and Noise
- Limitation of feedforward: Measurement and Estimation of Perturbations
- Resonance control with fast mechanical tuner promising
  - Lorentz force compensation successfully demonstrated
  - For microphonics control first result promising results
- Present achievements
  - 10^{-4} in amplitude and 0.03 deg. have been achieved at QL=1e7
- Outlook: Phase stability of 0.01 deg. appears feasible

Additional Requirements for X-FEL & ILC

- Installation in Tunnel
  - Packaging (airconditioned racks)
  - Availability (Redundancy)
  - Maintenance
  - Upgradability (20 years operation)
- Radiation environment
  - Total ionizing dose
  - Single Event Upset (SEU)
- Large Scale Installation
  - Operability (Automated operation with FSM)
  - Exception handling
- X-FEL specific: Field stability and higher rep. rate
- ILC specific: High gradient (35MV/m)