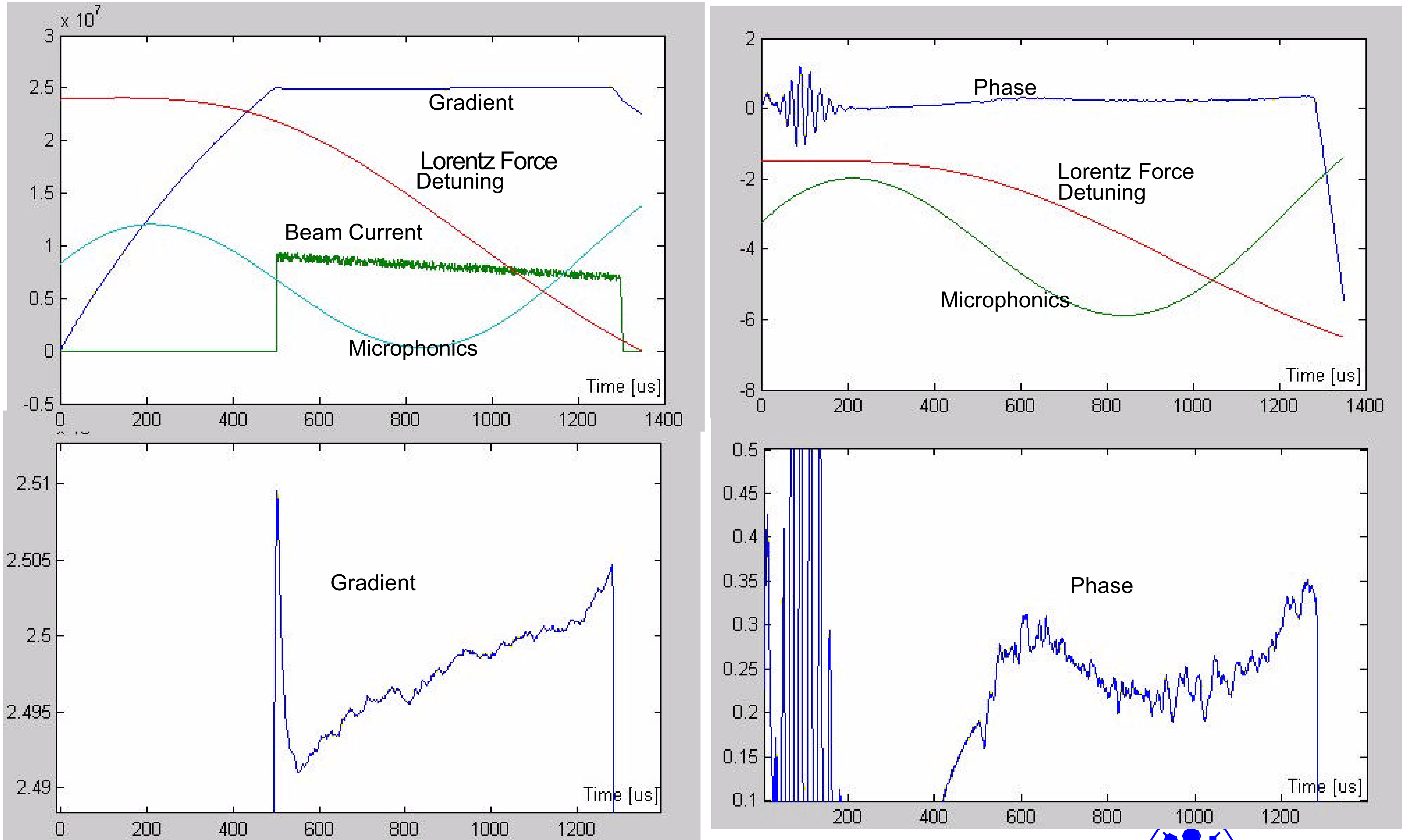
Achieving 0.01 deg. Phase Stability

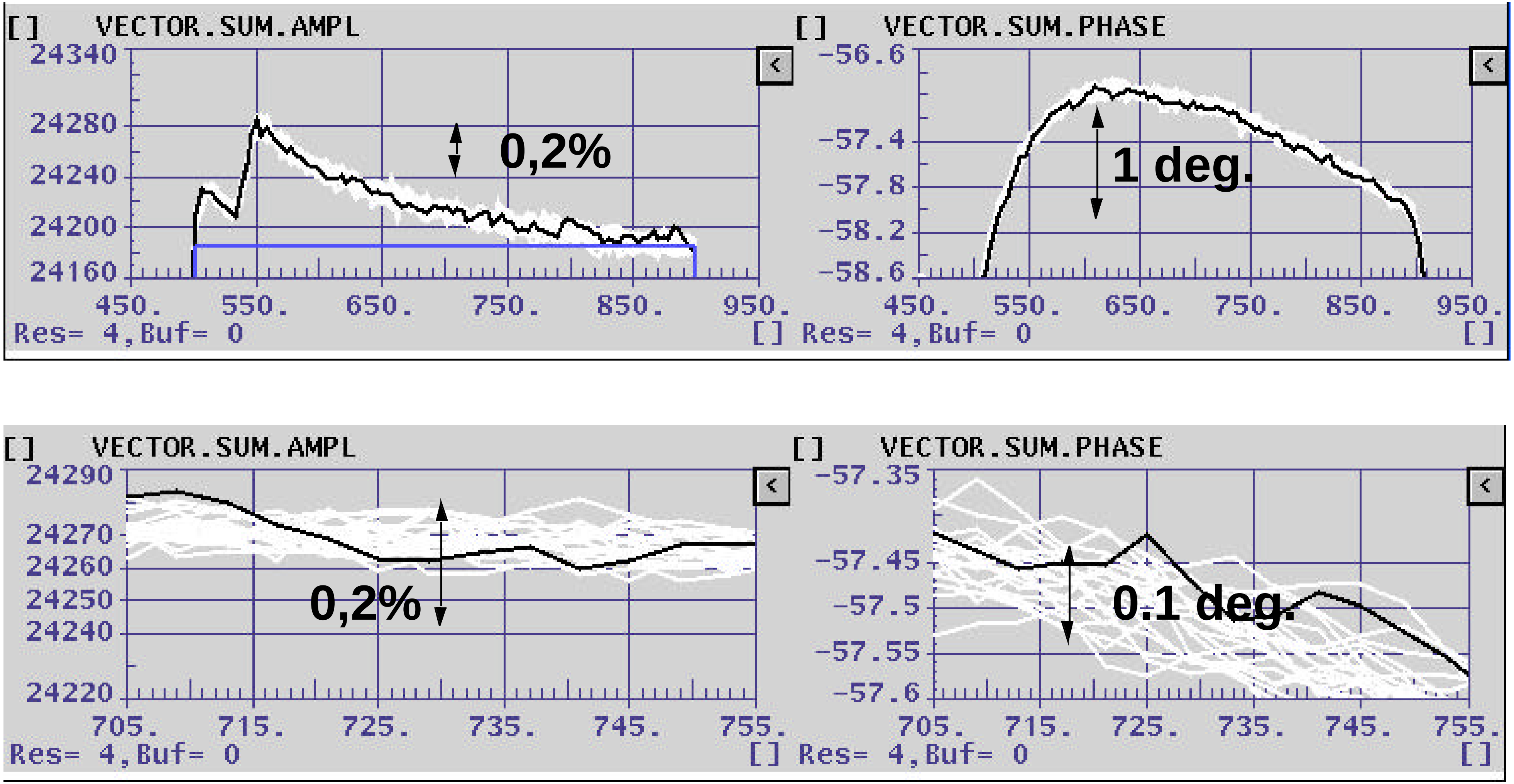
- Short term (within in 1 ms pulse)
- medium term (pulse to pulse, several seconds)
- long term (thermal time scale, minutes to hours)

- Sources of cavity field perturbations
  - Lorentz force detuning
  - Microphonics
  - Beam loading
  - other (electronic noise in field detectors, phase noise and drifts of phase reference, ripple of klystron power supply, etc.)

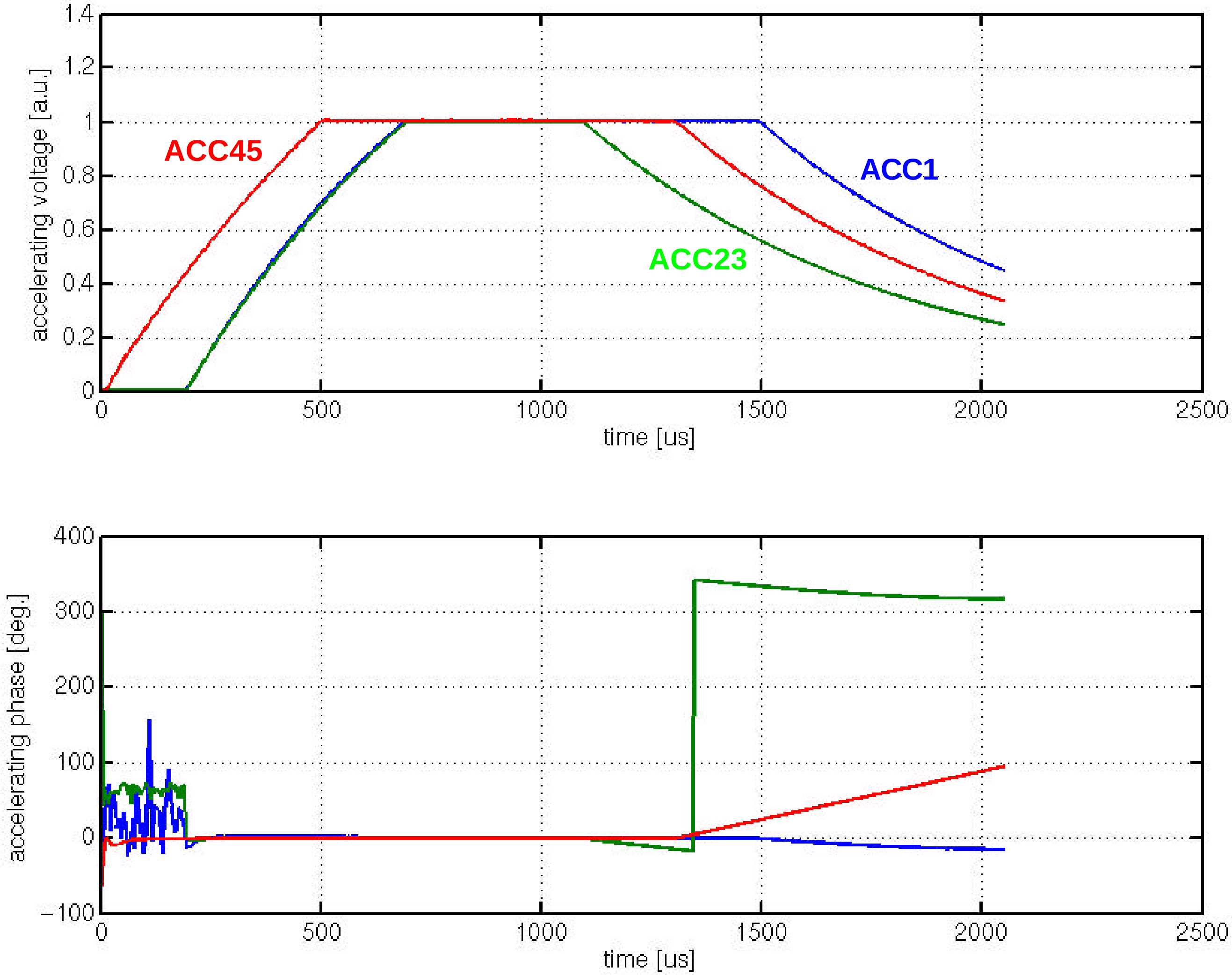
RF Regulation TESLA Cavity (Simulation)



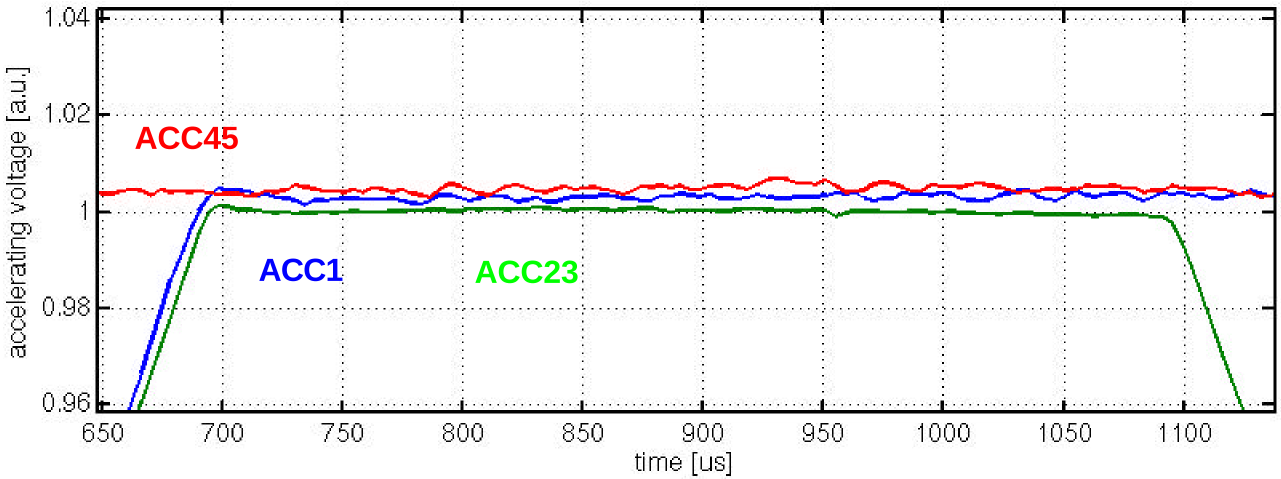
Measured Stability in ACC 2+3

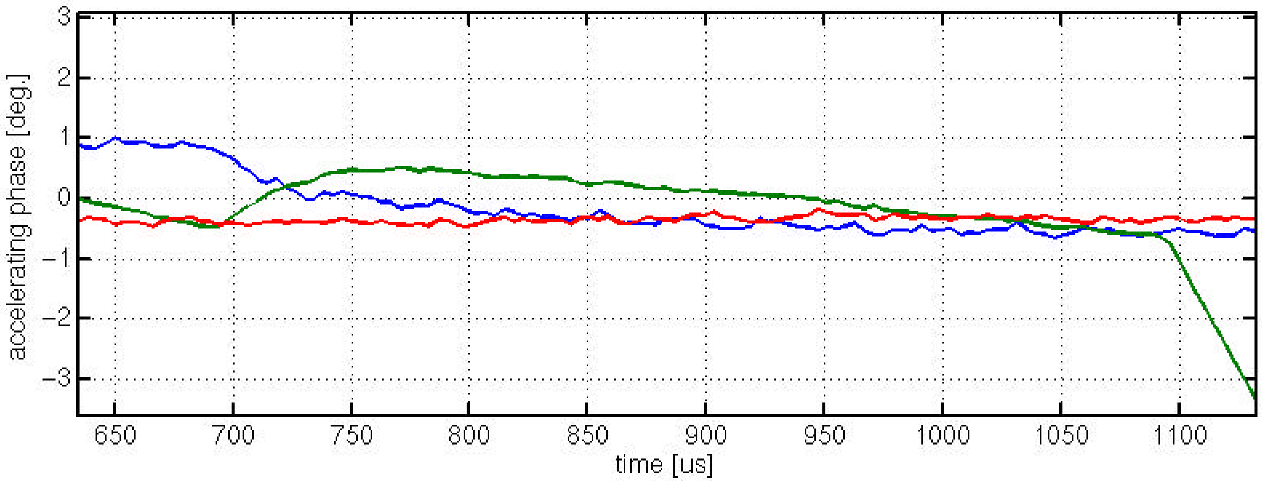


Field Regulation at VUV-FEL

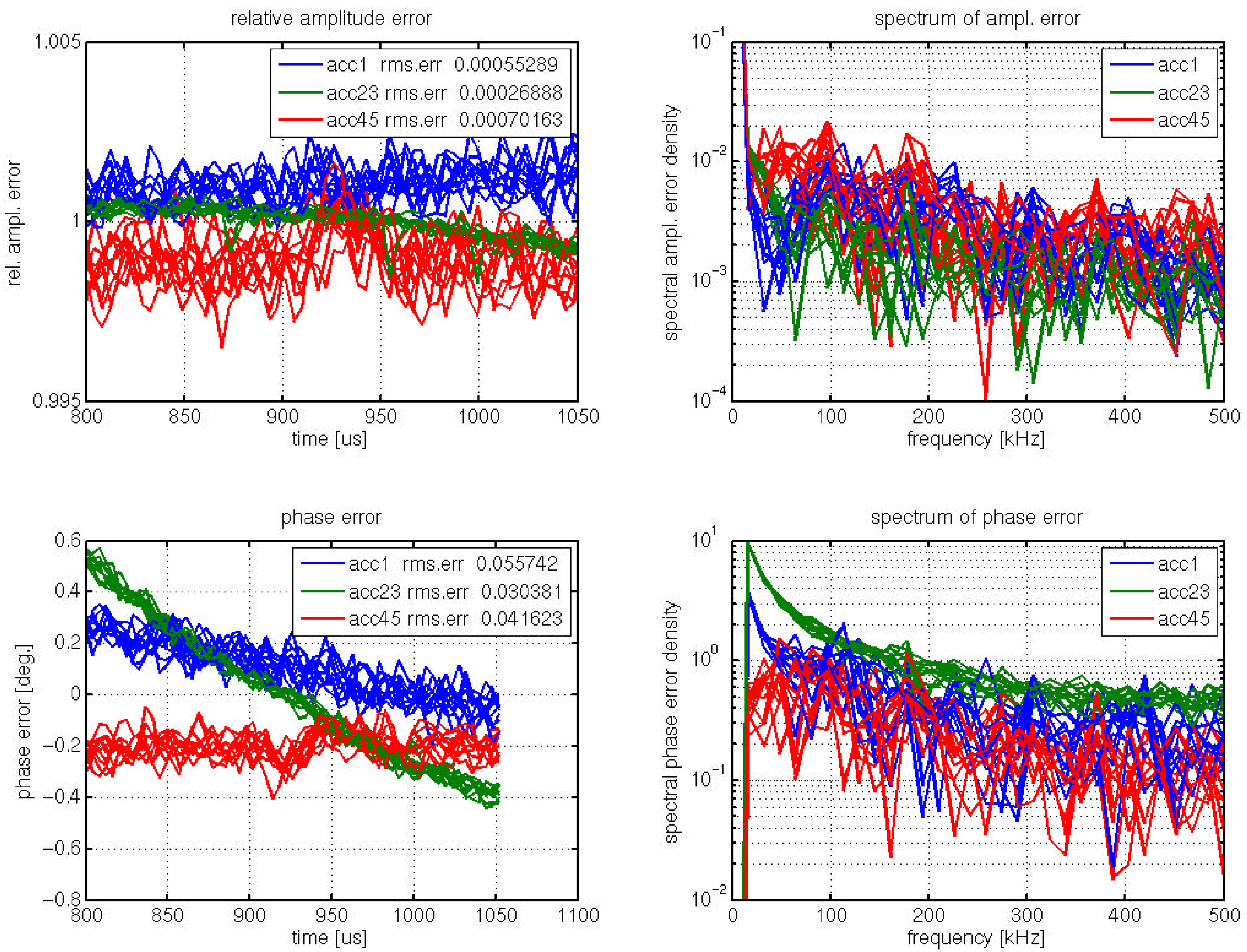


Field Regulation at the VUV-FEL

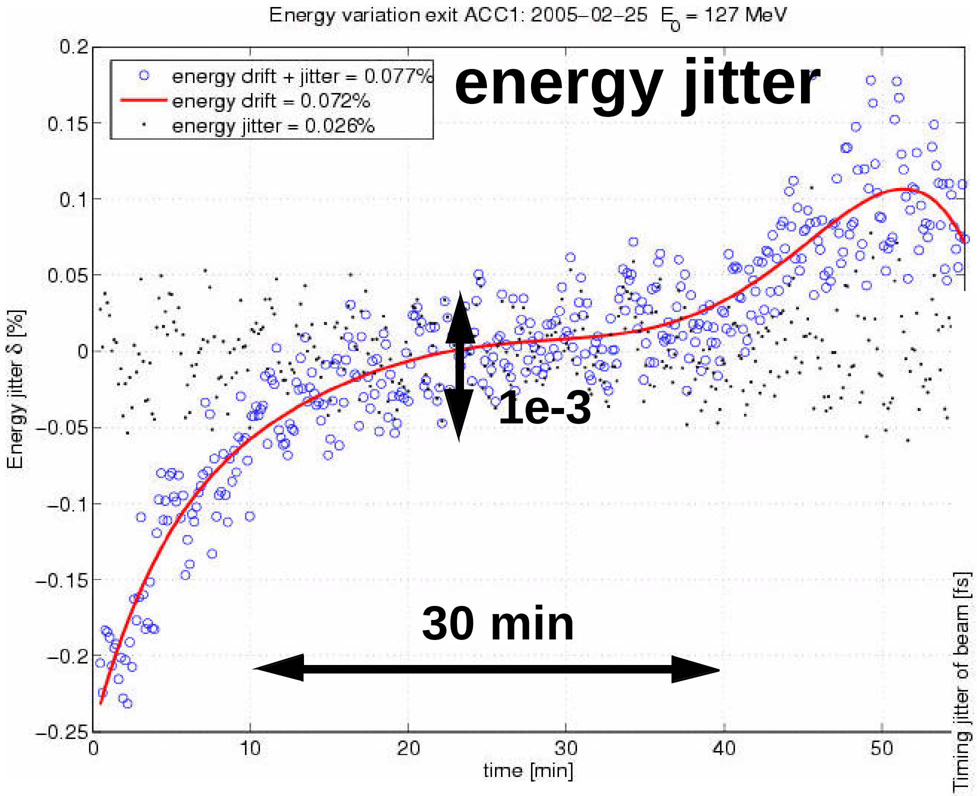


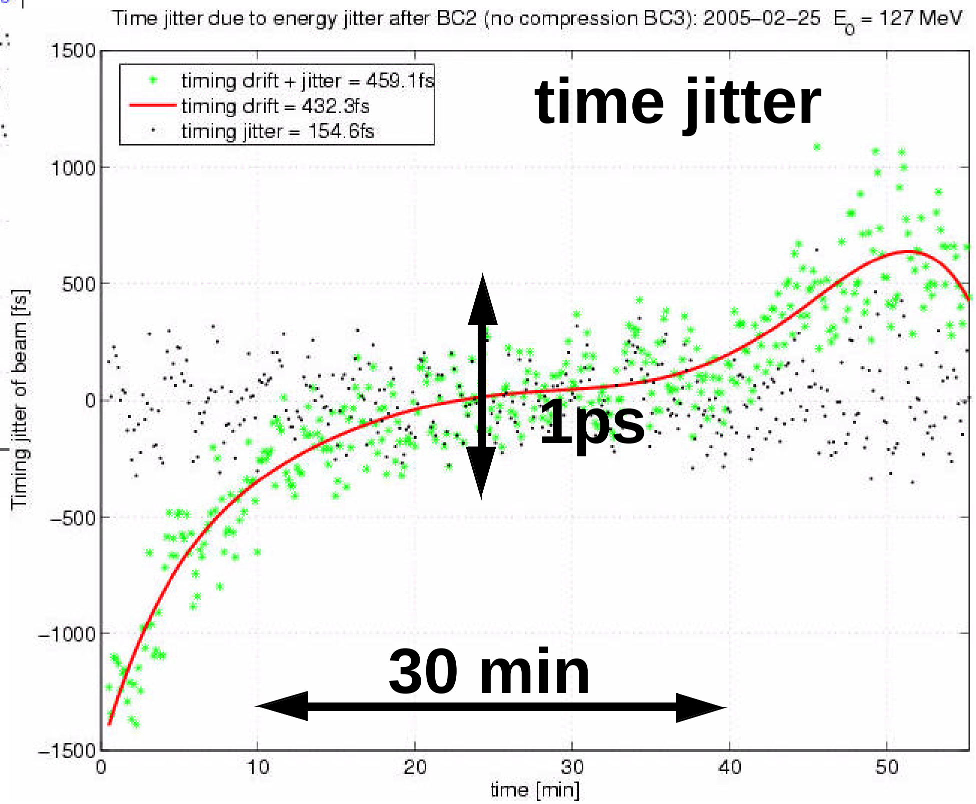


Field Regulation at VUV-FEL

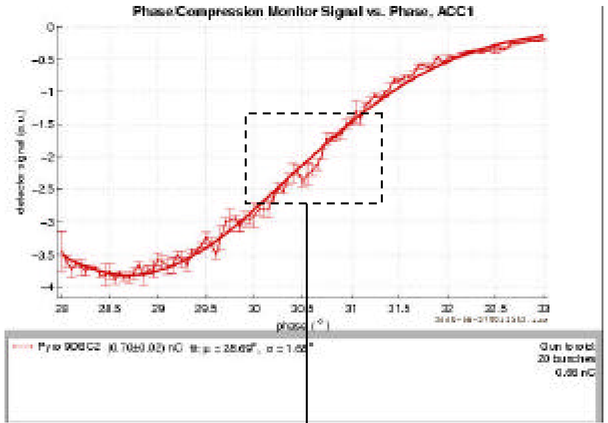


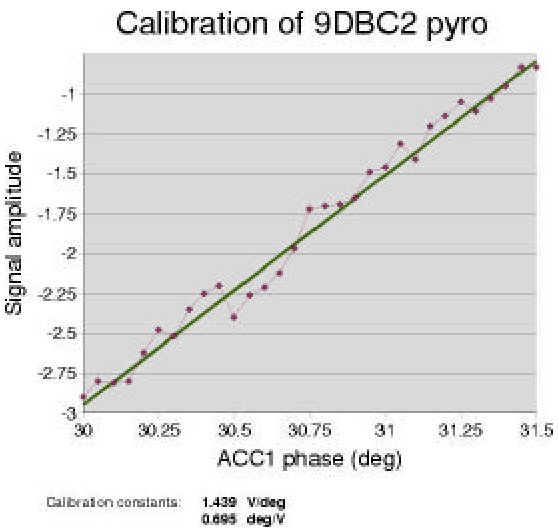
Drift ACC1 (cryomodule before BC) at TTF

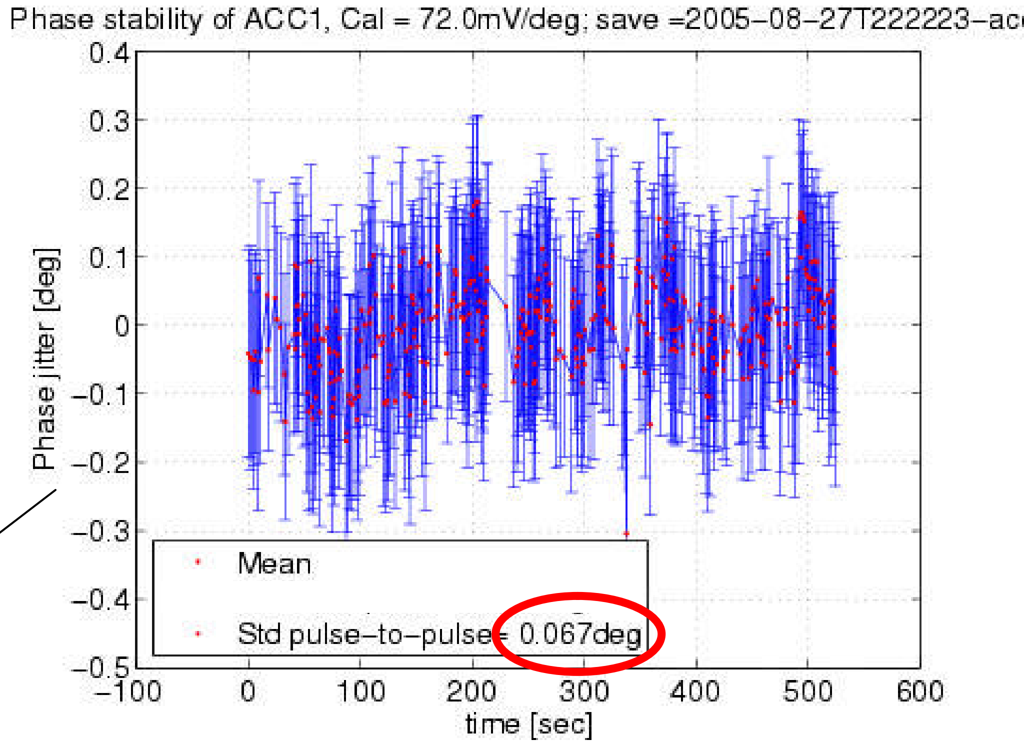




Phase stability with pyro-detector



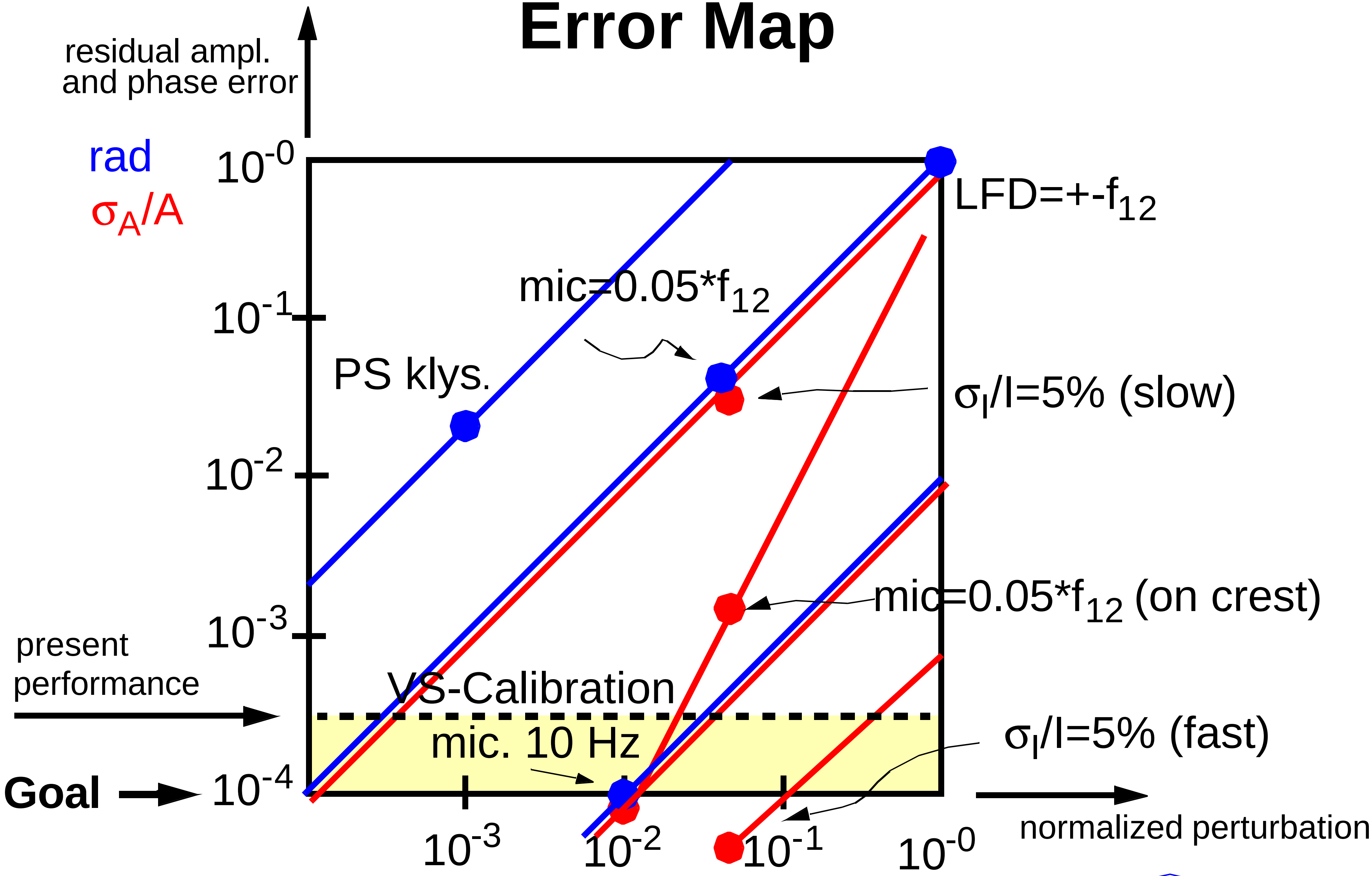




But! This is the phase stability between the beam arrival into the acceleration module relative to the RF phase!!!

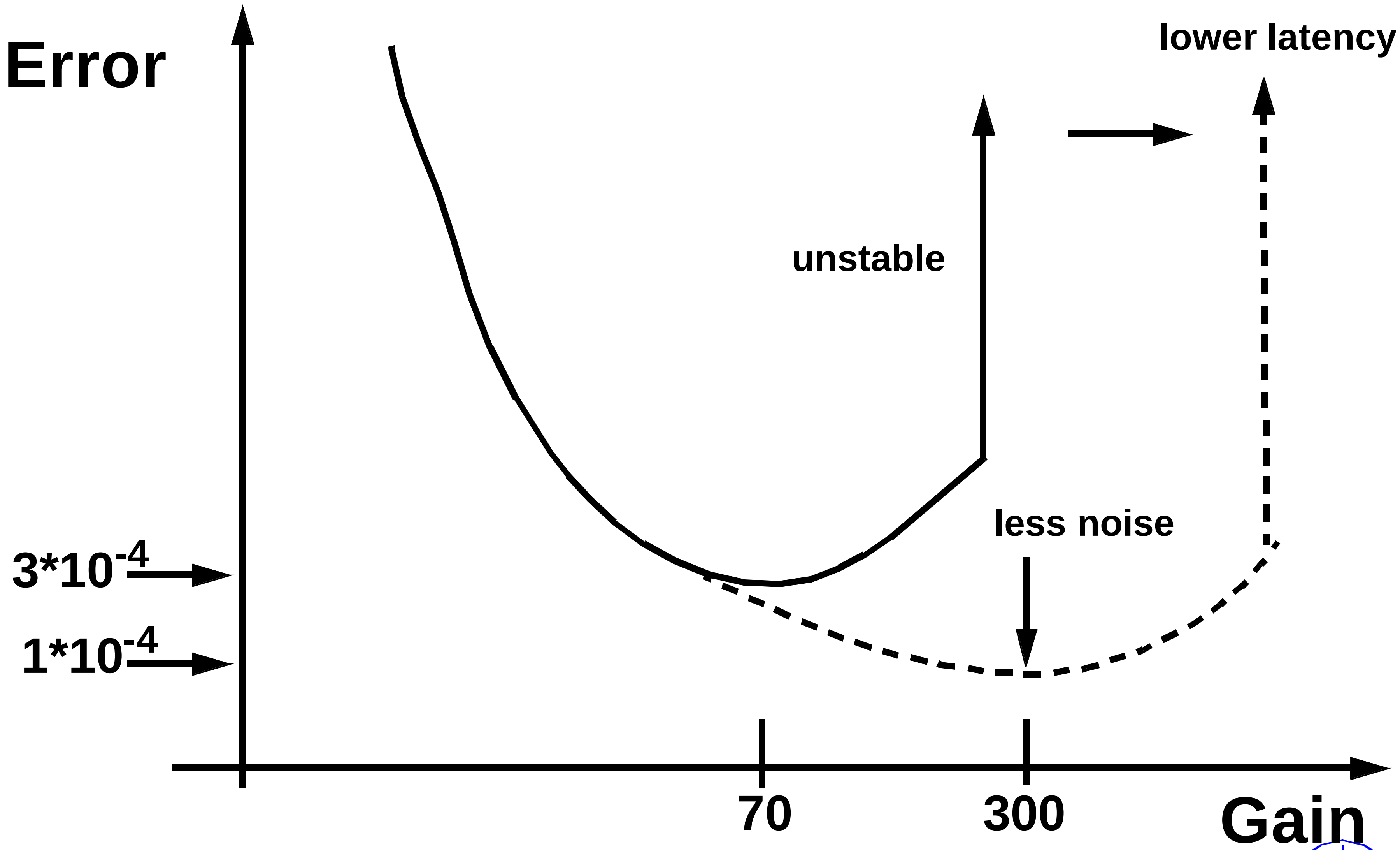
=> Major contribution is likely from laser

Error Map



residual ampl.
and phase error
rad
σA/A
10-0
10-1
10-2
10-3
10-4
LFD=+-f12
mic=0.05*f12
PS klys.
σI/I=5% (slow)
mic=0.05*f12 (on crest)
present
performance
VS-Calibration
mic. 10 Hz
σI/I=5% (fast)
Goal
10-3
10-2
10-1
10-0
normalized perturbation

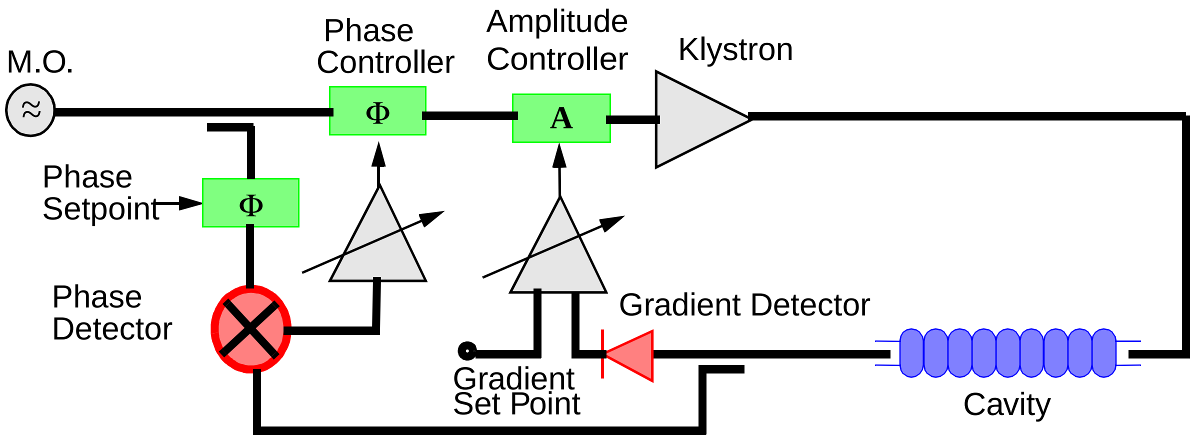
Improving Cavity Field Regulation



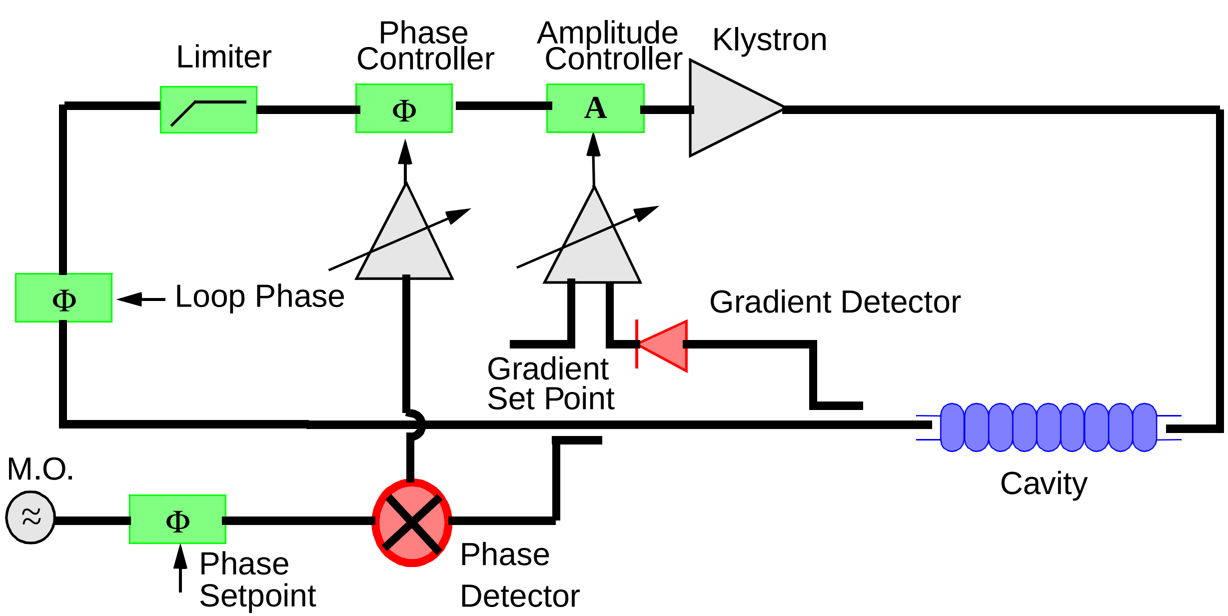
Control Choices (1)

- 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

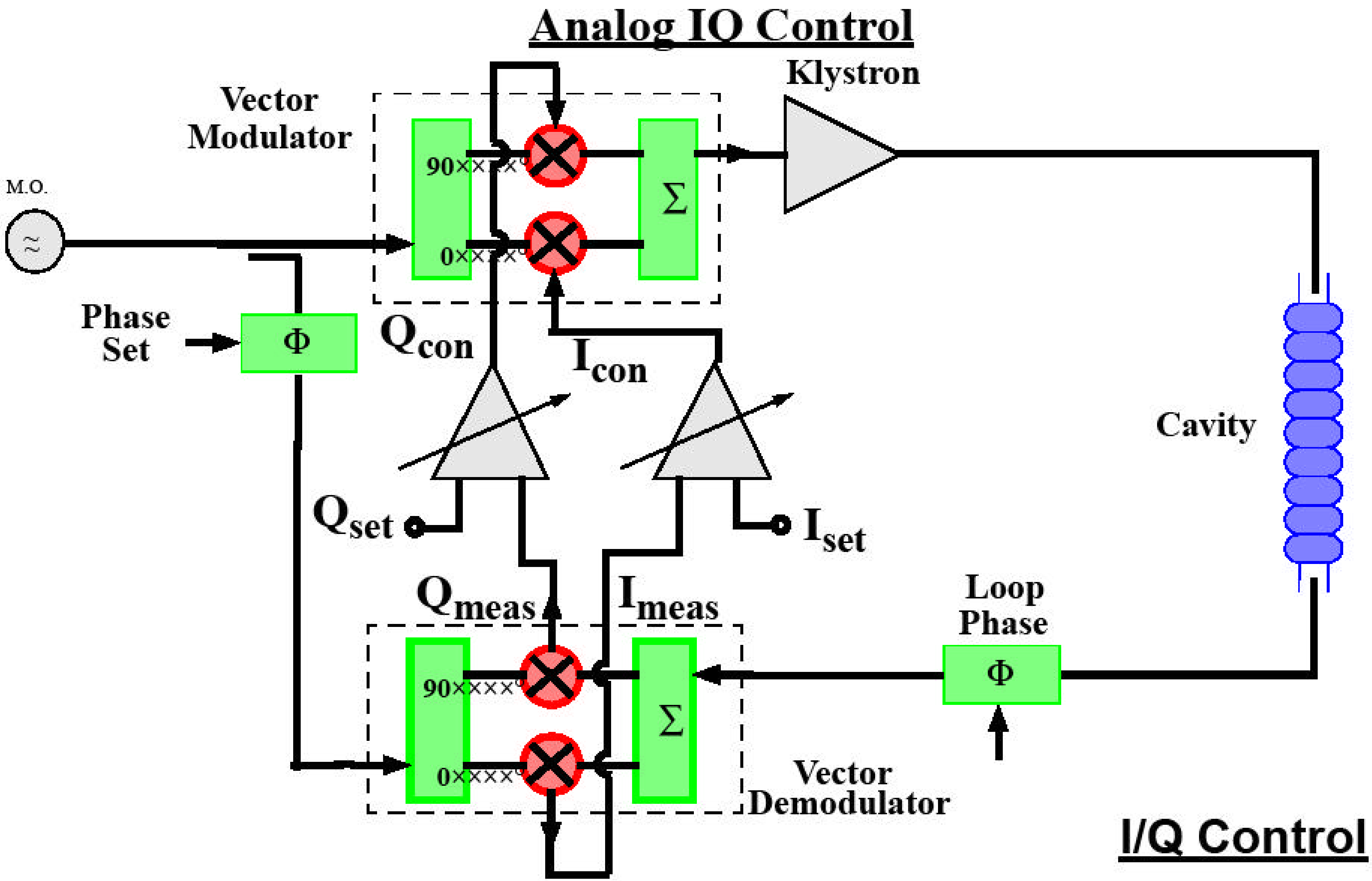
Control Choices (2)



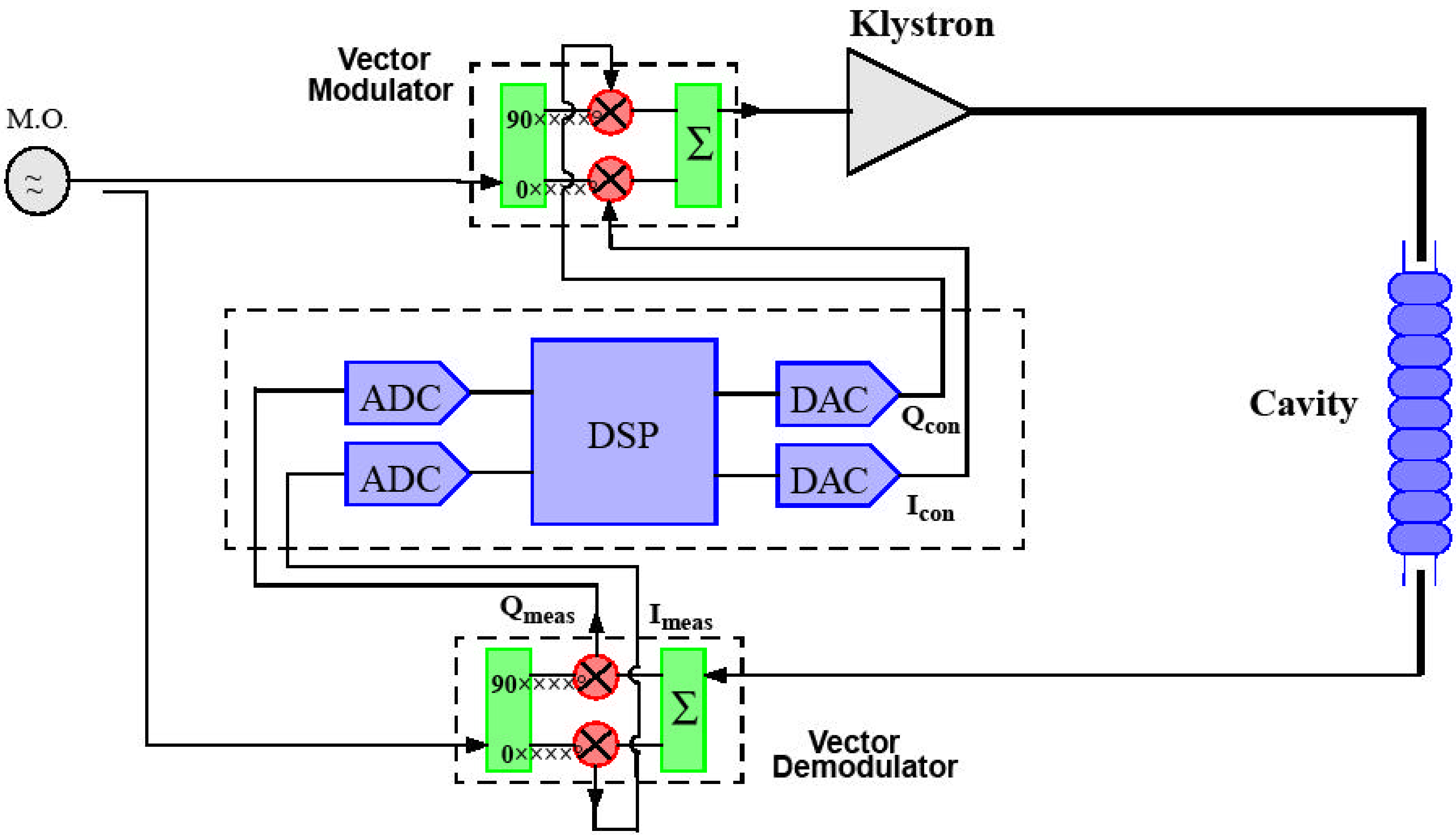
Generator Driven Resonator



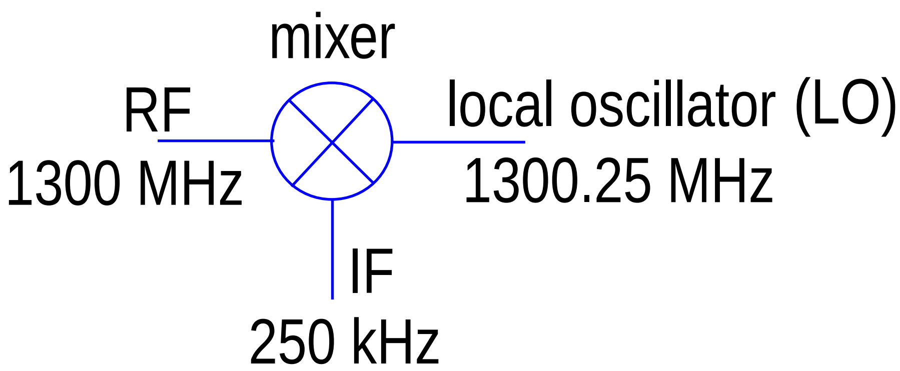
Self Excited Loop


Analog IQ Control
Klystron
Vector
Modulator
M.O.
90××××°
0××××°
Σ
Phase
Set
Φ
Qcon
Icon
Cavity
Qset
Iset
Qmeas
Imeas
Loop
Phase
Φ
90××××°
0××××°
Σ
Vector
Demodulator
I/Q Control

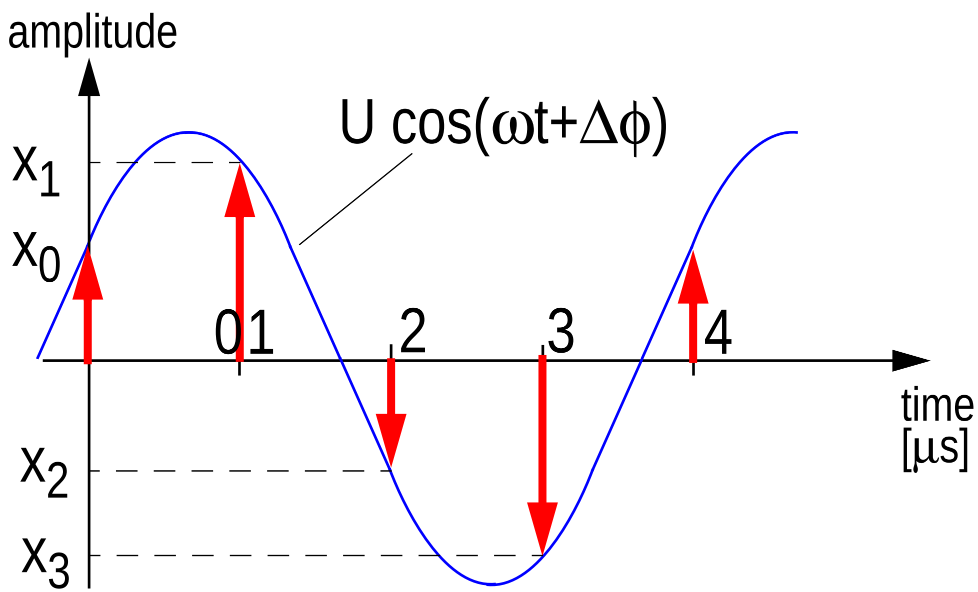
Digital IO Control



Digital I/Q Detection

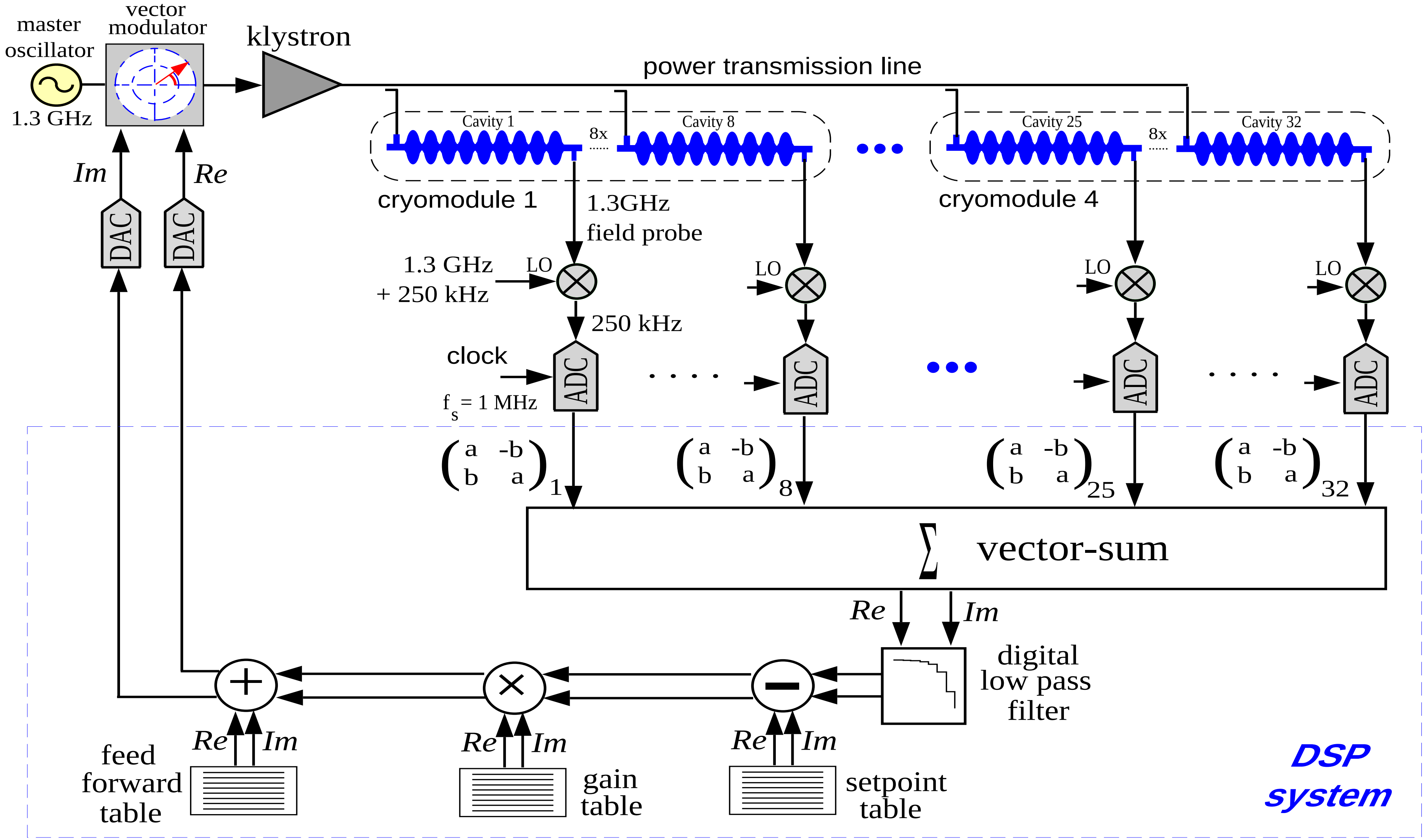


- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.



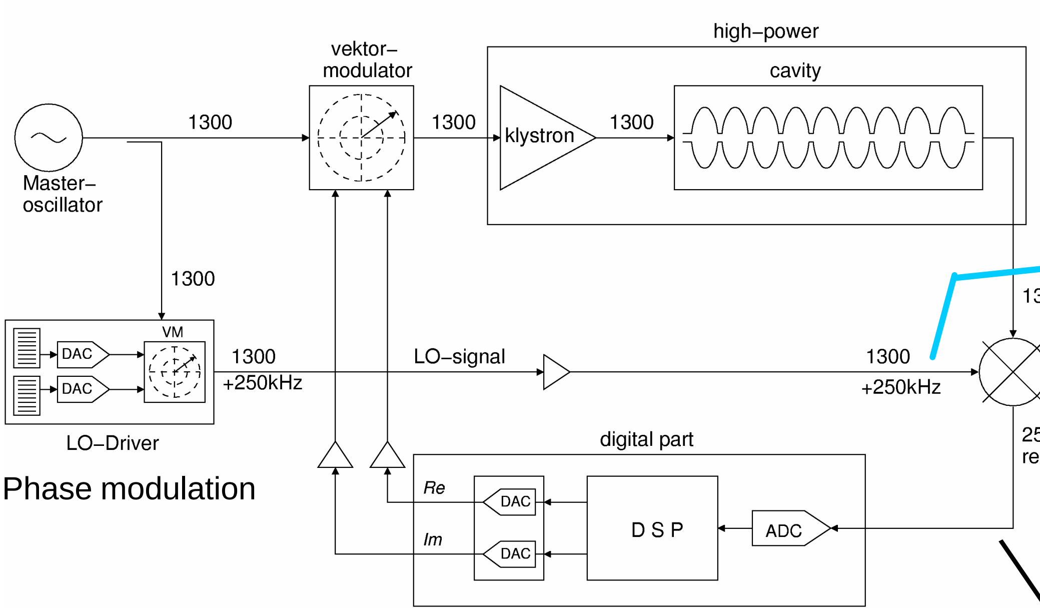
- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

Digital Control at the TTF



Noise characterization of the LLRF System (TTF2)

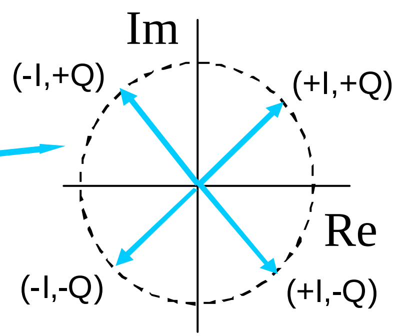
- **RF digital feedback system (TTF2) :**



Phase modulation

- **+I,-I,+Q,-Q detection scheme :**

Rotation of the LO-signal in four 90° steps

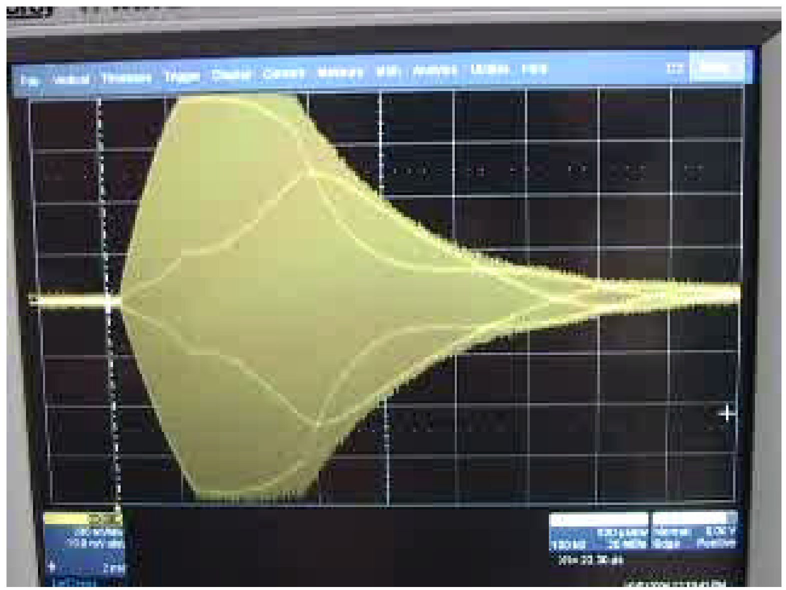


Bandwidth for transforming 250kHz squared pulses :

$$Df \approx 10 MHz$$

Required regulation bandwidth only :

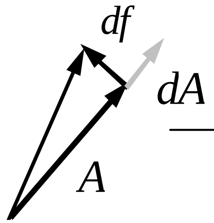
$$Df \approx 1MHz$$



- **Stability requirements on phase and amplitude of the cavity field vector :**

Amplitude stability : and linearity $\frac{dA}{A} < 10^{-4}$

Phase stability : $df < 0.01°$



$dU_{XFEL} < 100\,\mu V$ (normalized to A=1V)

- **Noise measurement at input of an ADC :**

$dU_{TTF2} \approx 1.0mV = 10 \times dU_{XFEL}$

rms-voltage noise :

$$dU = \sqrt{\int_{Df} S_U(f)df} \approx \sqrt{S_U}\sqrt{Df}$$

+ *Reduce the measuring bandwidth*
+ *Low-noise design*
+ *Averaging, switched low-pass!*
- *Correlation methods*

Superposition of all noise contributions :

$$\sqrt{dU_{DWC}^2 + dU_{IQ}^2 + dU_{MO}^2 + dU_{extern}^2 + \ldots} < 100\mu V$$

Requirement for CEBAF (JLAB)

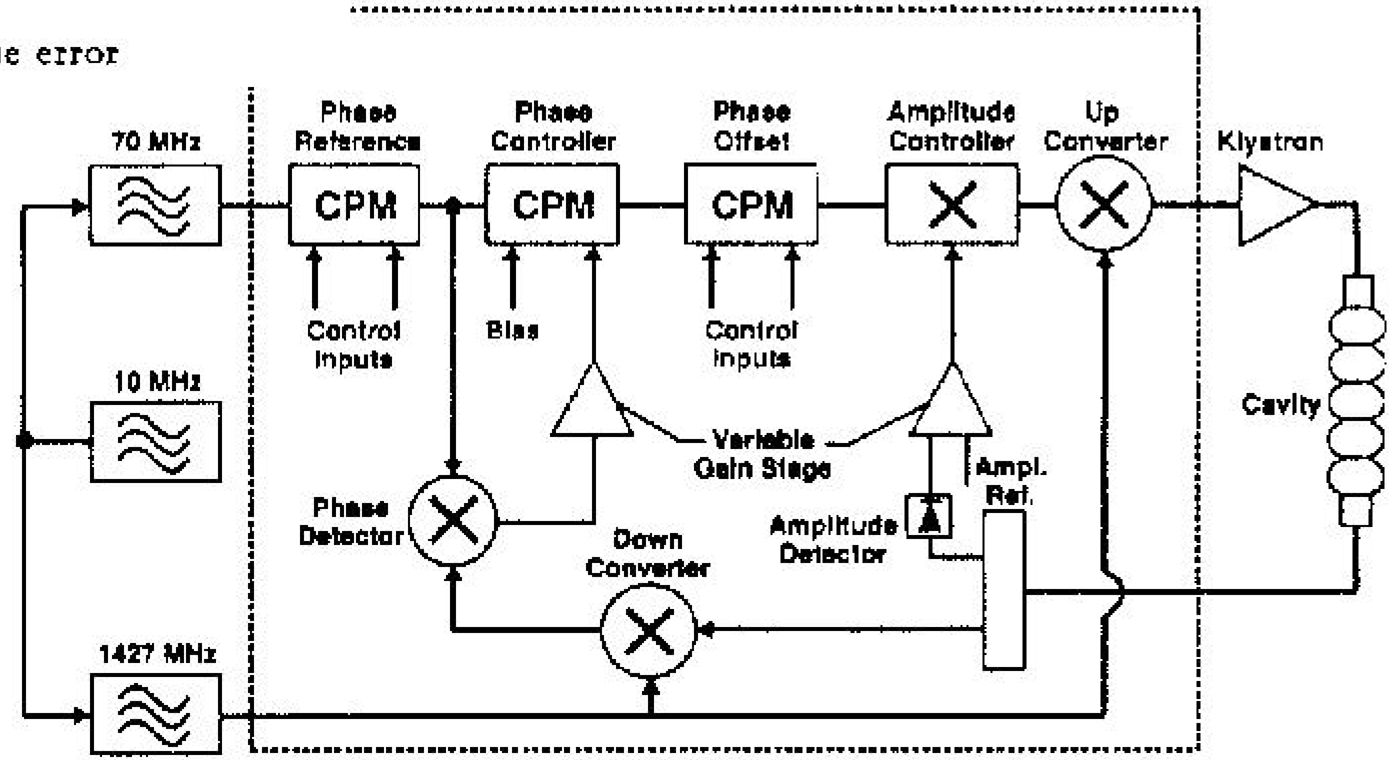
RF control requirements with vernier

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

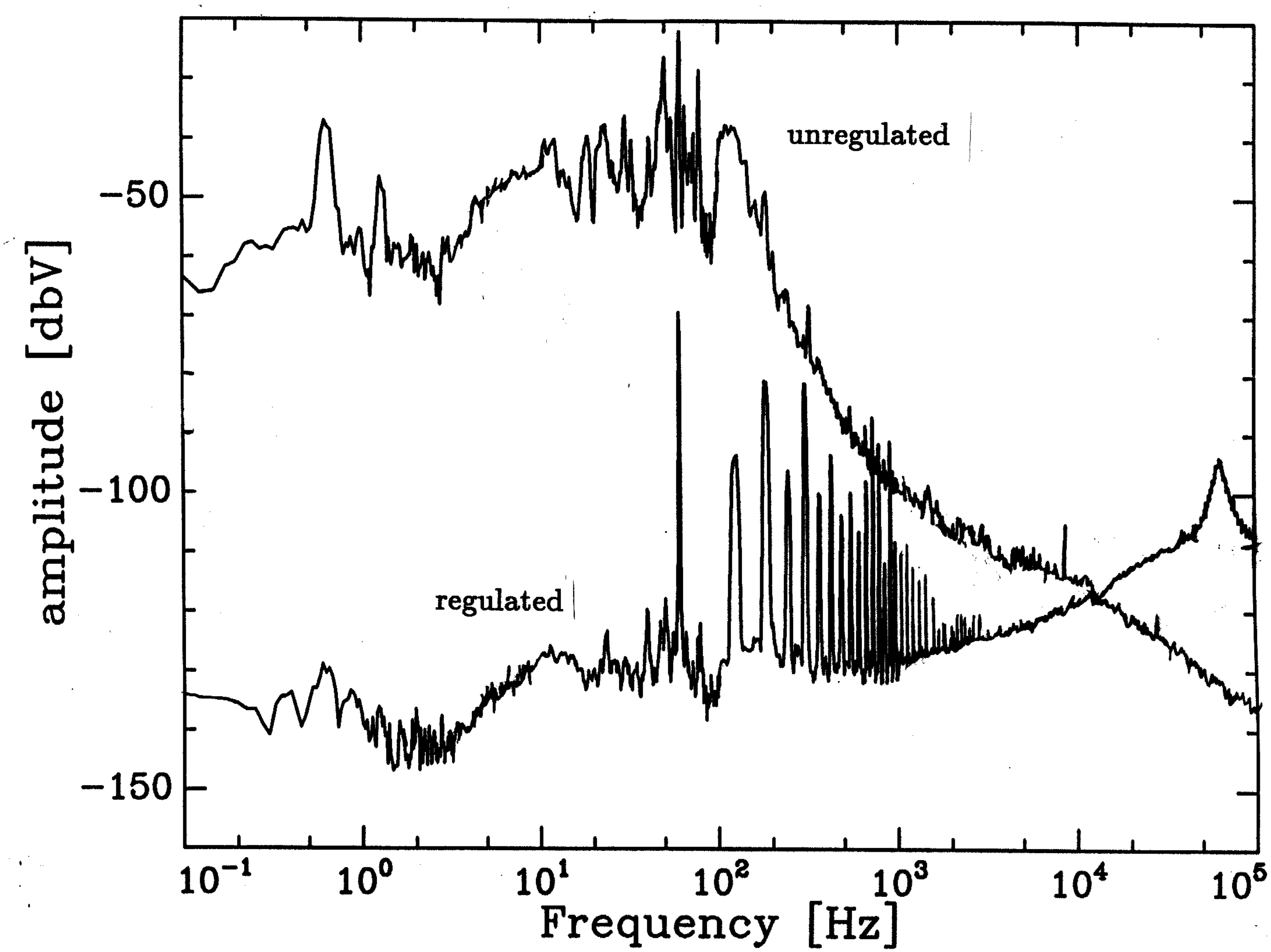
σ_A : relative RMS amplitude error

σ_f : fast RMS phase error

σ_s : slow RMS (along linac) phase error



Performance Measured at JLAB



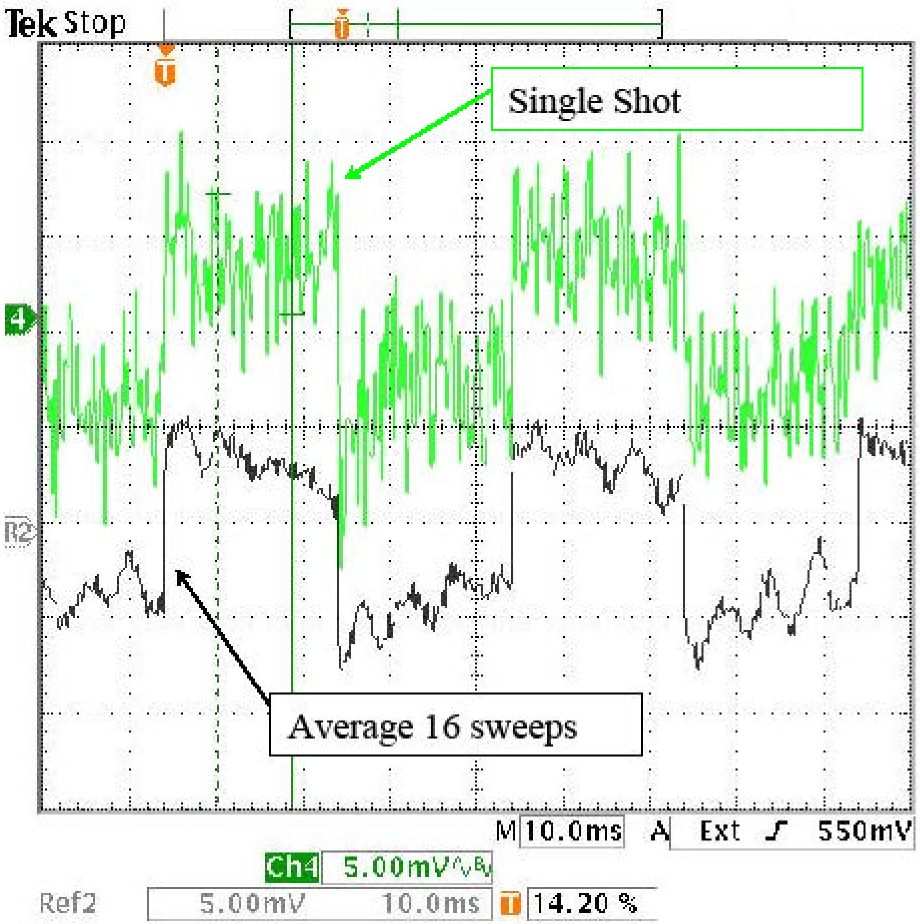
Performance Measure at JLAB

Measured RMS errors

Frequency Range [Hz]	Relative Amplitude Error	Phase Error [°]
0 - 10^0	5.5×10^{-6}	1.1×10^{-3}
0 - 10^1	1.1×10^{-5}	1.2×10^{-3}
0 - 10^2	3.5×10^{-5}	3.0×10^{-3}
0 - 10^3	4.1×10^{-5}	4.6×10^{-3}
0 - 10^4	5.5×10^{-5}	7.0×10^{-3}
0 - 10^5	7.0×10^{-5}	1.6×10^{-2}
0 - 10^6	7.5×10^{-5}	

Performance at Rossendorf

CW SRF at Rossendorf - 8 June 2004



Courtesy of F. Gabriel

- Q_{ext} = 1E7
- 7.64 MV/m
- 50% Duty Cycle
- 0.464 mA Peak

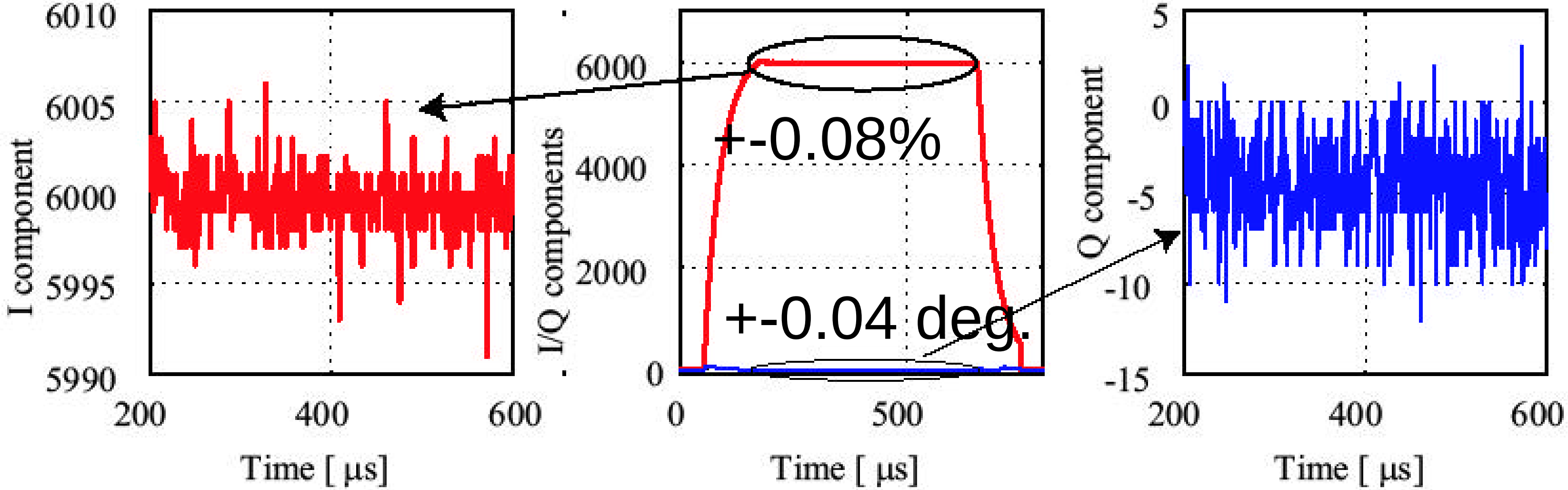
0.03° rms Phase Stability!

Underlying 300 Hz structure at 0.015°

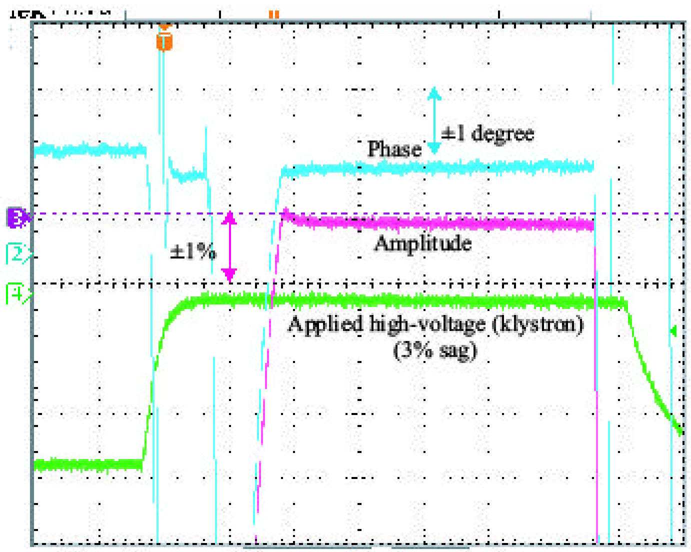
AC Line pickup or Real Phase drift?

Feed Forward Required?

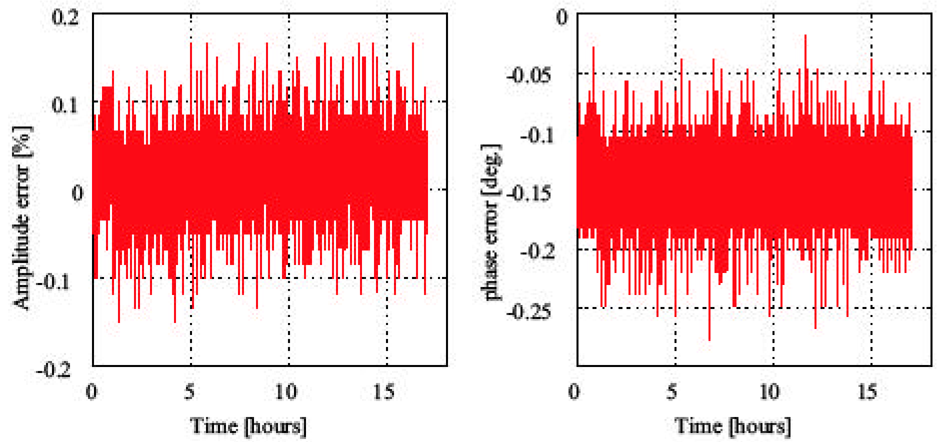
Stability Measured for J-PARC



Measured I/Q components during rf operation. Fullscale I/Q:center, expansion I: left, expansion Q: right. No feedforward was used. The proportional and integral gains for the feedback are 10 and 15/1000 at a 48-MHz clock, respectively.

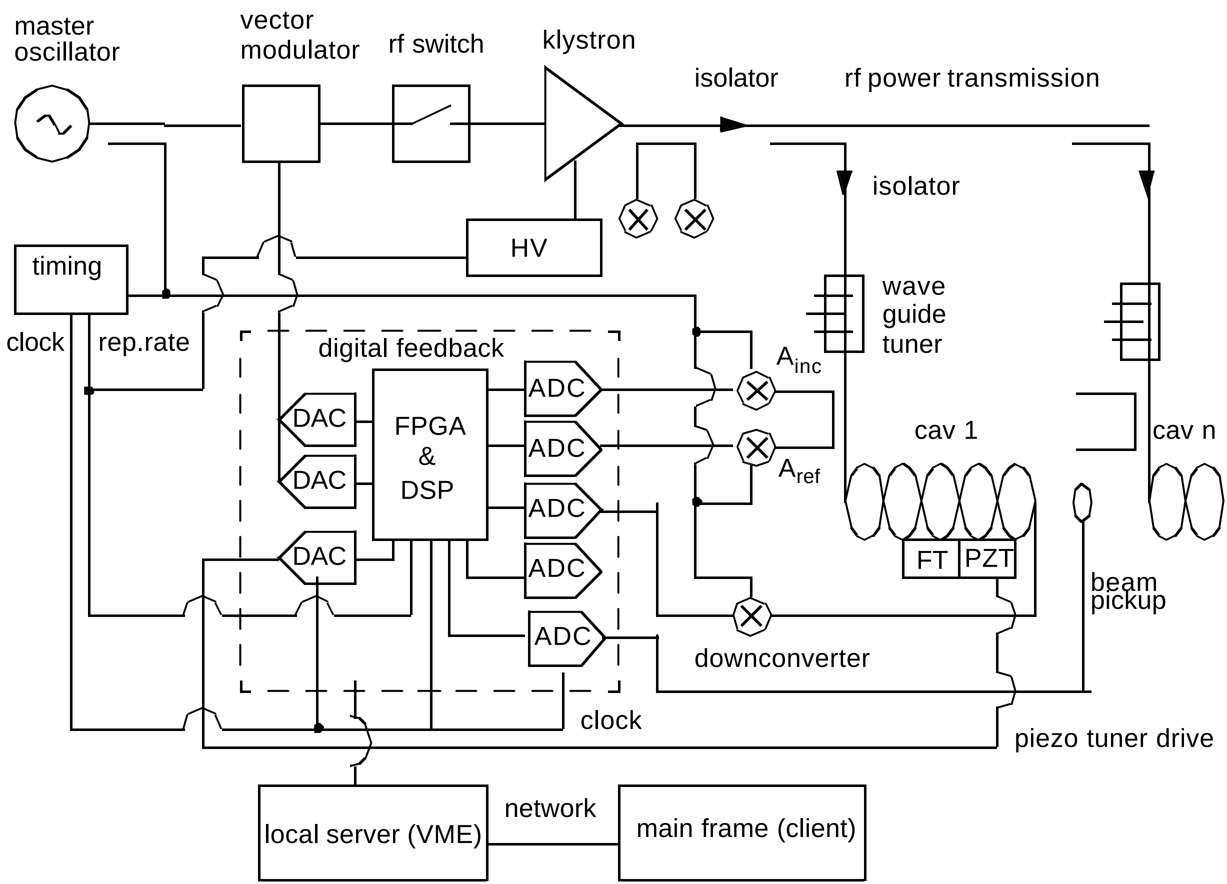


Waveforms of the amplitude and phase obtained by external monitors.



Trend-graphs of the amplitude and phase stabilities.

S. Michizono


master
oscillator
vector
modulator
rf switch
klystron
isolator
rf power transmission
isolator
HV
timing
clock
rep.rate
digital feedback
wave
guide
tuner
A_{inc}
DAC
DAC
FPGA
&
DSP
ADC
ADC
ADC
ADC
ADC
A_{ref}
cav 1
cav n
FT
PZT
DAC
beam
pickup
downconverter
clock
piezo tuner drive
local server (VME)
network
main frame (client)