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LLRF Challenges for ILC, Project X, HTS, NML, Achievements, Plans

Brian Chase

Outline

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- FNAL LLRF Program
- Progress/accomplishments
  - Scope
  - Progress
- Plans forward
  - Relevance of infrastructure or development to the needs of Project X and ILC.
- The plan for ARRA funds
- Technical Milestones
- Conclusion

LLRF Program

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- **FNAL has been heavily involved with the ILC design effort for 4 years - America's region leader**
- **ILC LLRF efforts $\Rightarrow$ Project X LLRF and NML**
- **LLRF is manpower, not M&S intensive**
  - **At FNAL - 12 people are engaged in development**
  - **The LLRF is coordinated by the LLRF group in AD - important contributions from CD and TD.**
- **Outside collaborators include LBNL(MOU), ANL, DESY, KEK, SNS and INFN**
- **FNAL Engineering Team**
  - Julien Branlard, Gustavo Cancelo, Ruban Carcagno, Ed Cullerton, Paul Joireman, Yuriy Picshainikov, Warren Schappent, Ken Triptow, Vitali Tupokov, Philip Varghese, Ted Zmuda

LLRF Scope

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- **RF Unit Test Facility at NML**
  - RF gun
  - Capture Cavity 1 (CC1) – Presently at A0
  - Capture Cavity 2 (CC2) – Installation in progress
    - 1300 MHz Ferrite Vector Modulator control
  - Cryomodule #1 (2&3 to follow)
    - 32 Channel Multi-Channel Field Controller (MFC)
    - Resonance Control – Fast Piezo control
  - 3.9 GHz cavities
- **HINS 325 MHz**
  - Short term – RFQ and 6 cavity beam test
    - Ferrite Vector Modulator based field control
  - Field and Resonance control of Spoke Resonators

LLRF Scope

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- **ILC design efforts**
  - **System specification and integration**
    - **Controllers, Microwave systems, Software**
    - **Cost Reduction**
  - **Resonance Control**
    - **Piezo controllers - LFD and microphonics**
    - **Piezo drive amplifiers**
  - **Full ILC Beam Current Test (9mA tests at FLASH)**
    - **Operation near klystron saturation (Power budget)**
    - **Operation with cavities at different gradients**
    - **Evaluation of control system (FB, FF)**
- **Synergy with other FNAL LLRF projects**
  - **Low Energy Linac LLRF Upgrade (MFC)**
  - **Main Injector Comb Filter (MFC)**

Technical Progress

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- System and Hardware Status
  - Operational 1.3 GHz systems at A0, HTS, CC2
  - 325 MHz system for HINS
  - 3.9 GHz system for HTS and A0
  - NML installation in progress for CC2 and cryo-module #1
  - (10)ESECON and (35)MFC 32 ADC Controllers produced
  - 1300 &325 MHz Up/Down-converters in production
- ILC and Project X/HINS RD&D
  - Promising intermediate results from FLASH 9 mA test
    - Analysis of power headroom requirements
    - Vector Sum Calibration
  - Advances on controller algorithms for multi-cavities/klystron
    - Ferrite Vector Modulators
  - Resonance control
    - Lorentz Force Detuning - sinusoidal excitation
    - Microphonic studies

Regulation of CC1 at A0

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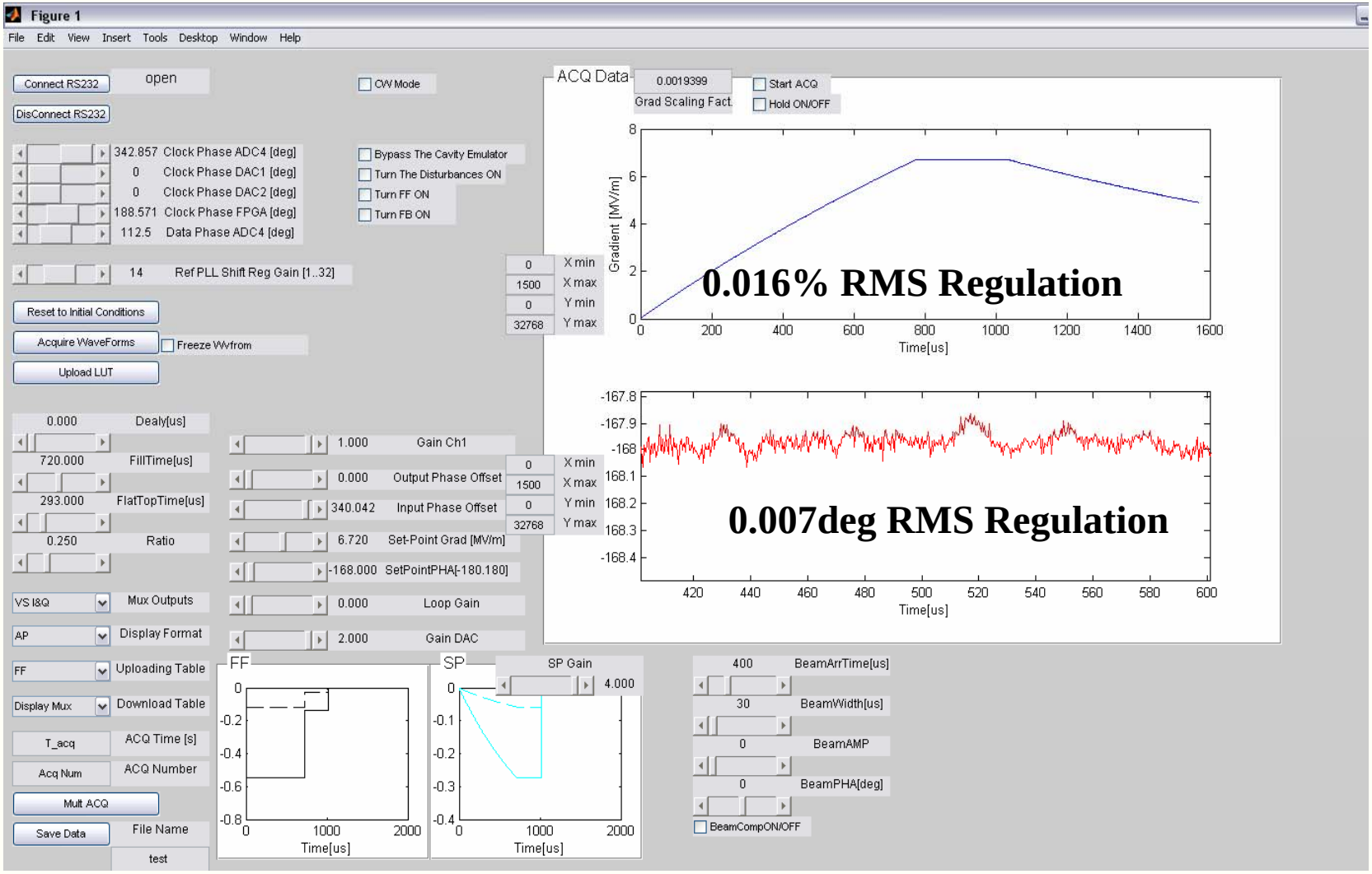
loop gain up to 1200



Response to Disturbance

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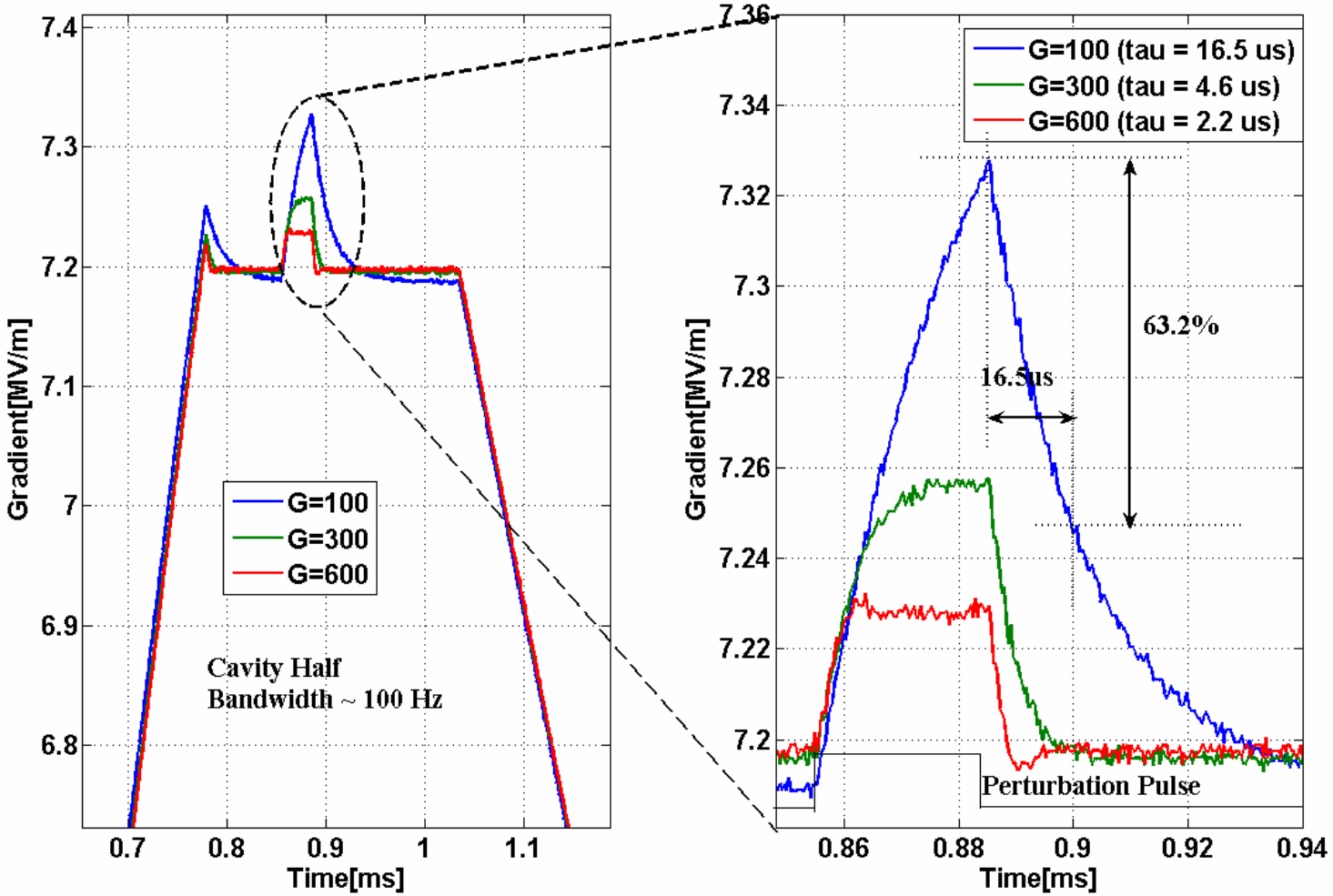

Real Time RF Simulator (RTS) and control

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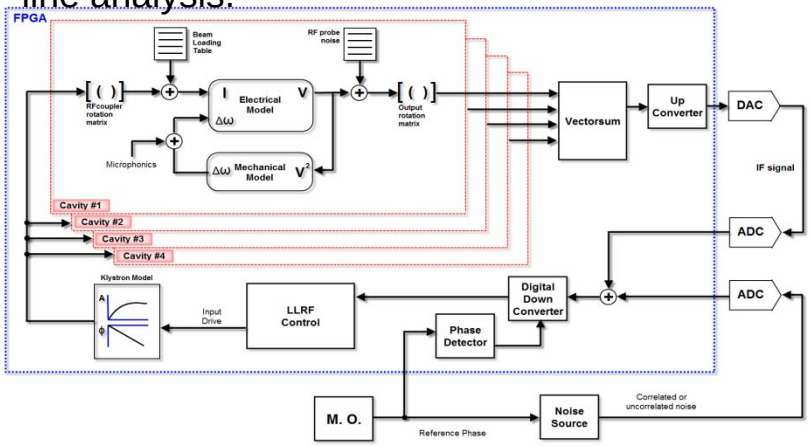
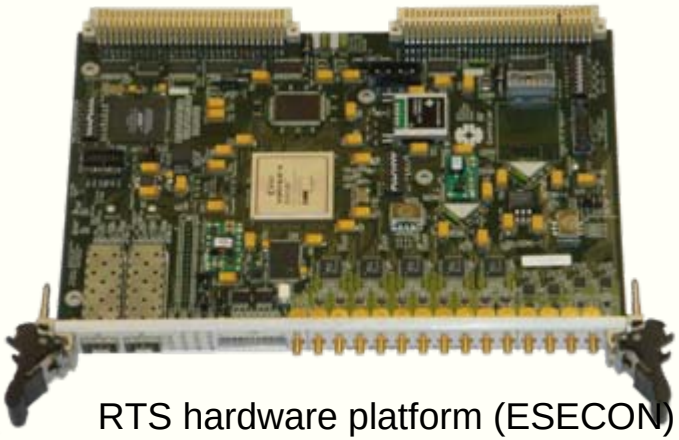
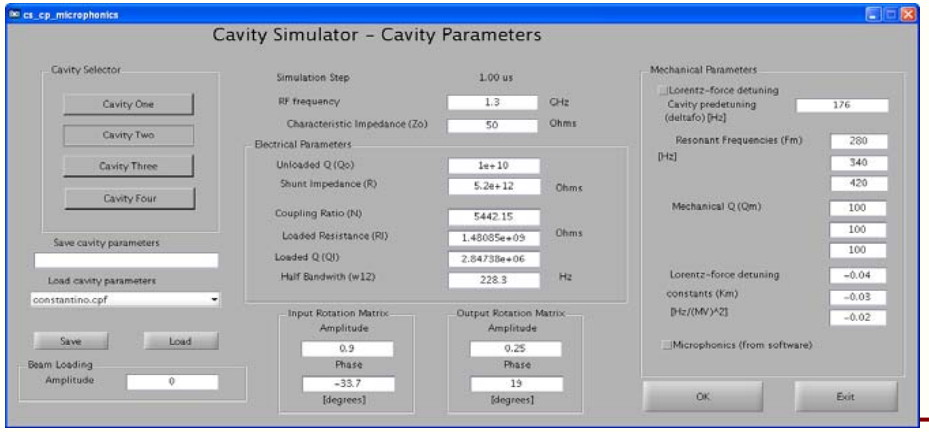
The RTS simulates the amplitude and phase dynamics of multiple RF cavities. The RTS implements the TTF electrical and mechanical dynamic models. It also includes several noise and disturbance sources. Al simulation parameters can be uploaded or saved to a file, or entered through the RTS control panel. The simulator outputs can be displayed on an oscilloscope and they are also logged on file through the DAQ for off line analysis.



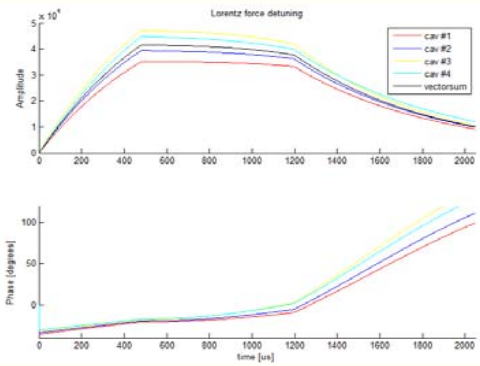
RTS block diagram



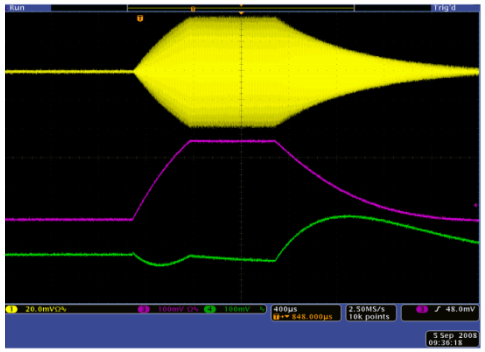
RTS hardware platform (ESECON)



RTS control panel



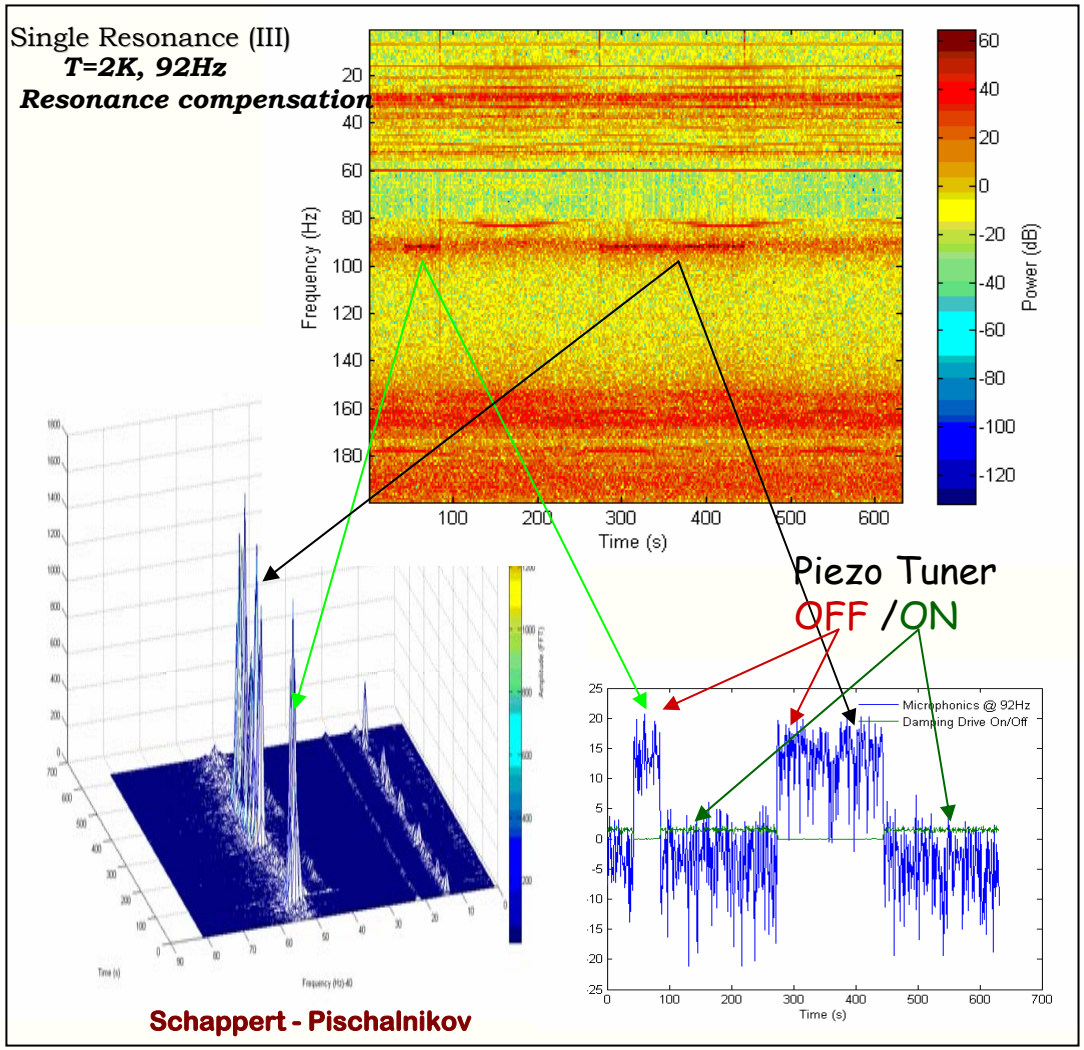
RTS cavity outputs into DAQ log file

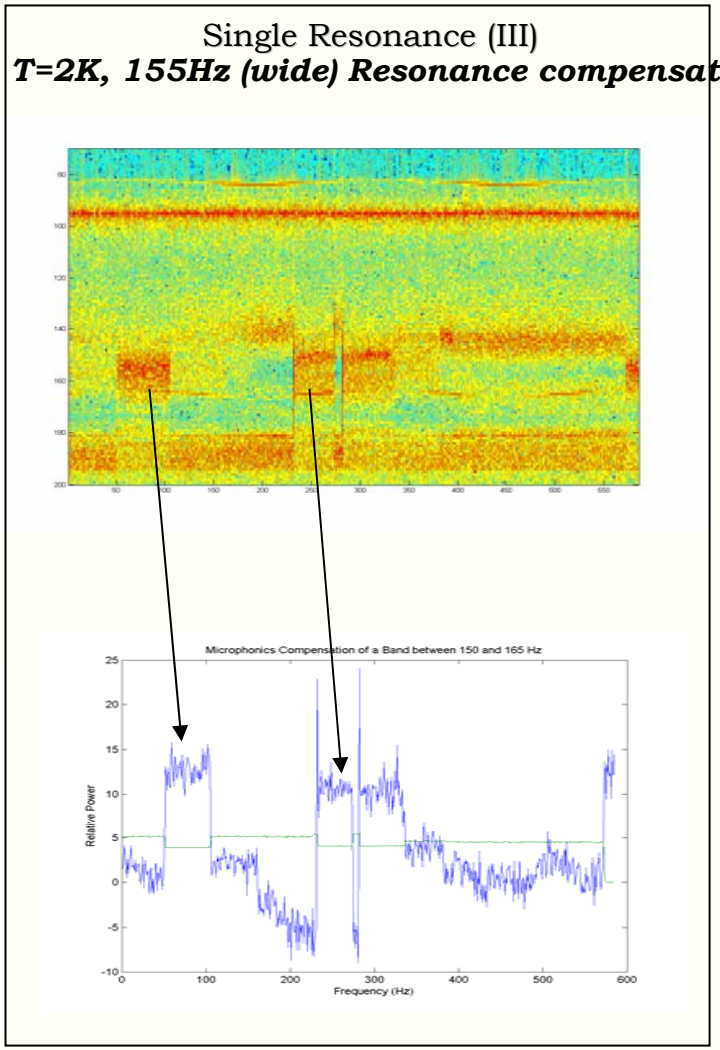


RTS outputs on the oscilloscope

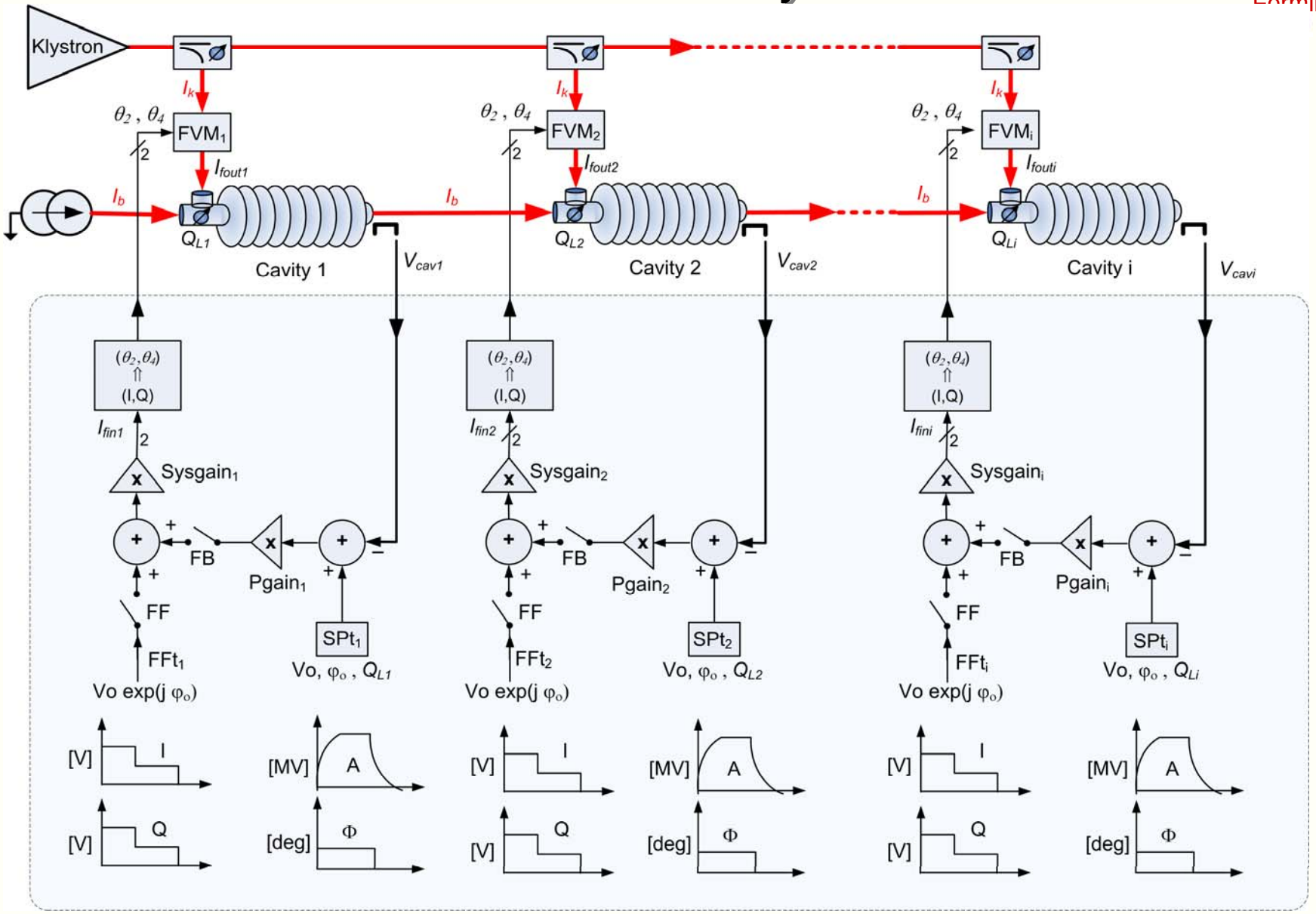
Active Compensation of Microphonics in CCII (cont.)

- Run CCII in CW mode (low power). Forward Power and Probe signals feed to AD8302EB (RF/IF Gain and Phase Detector board from Analog Devices). Analog Phase detector signal used as input signal for "**Narrow Band Filter**".
- Illustrated damping vibration of CCII (at 52Hz, 92Hz, 155Hz, etc.) up to 15db.





HINS with FVM: individual Cavity Feedback Control



Using the klystron FF to compensate for beam loading

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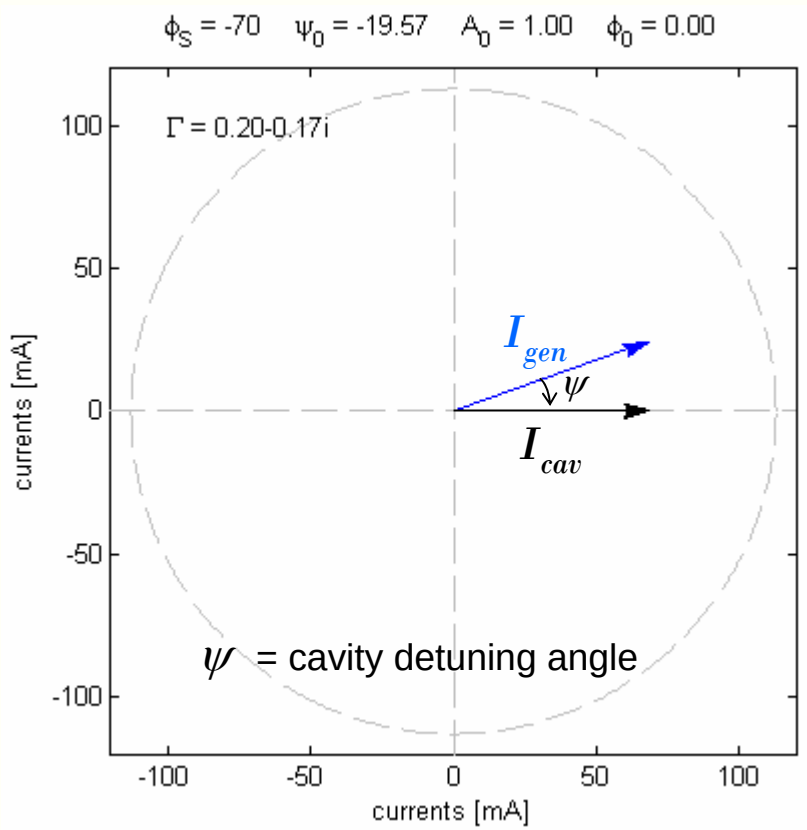
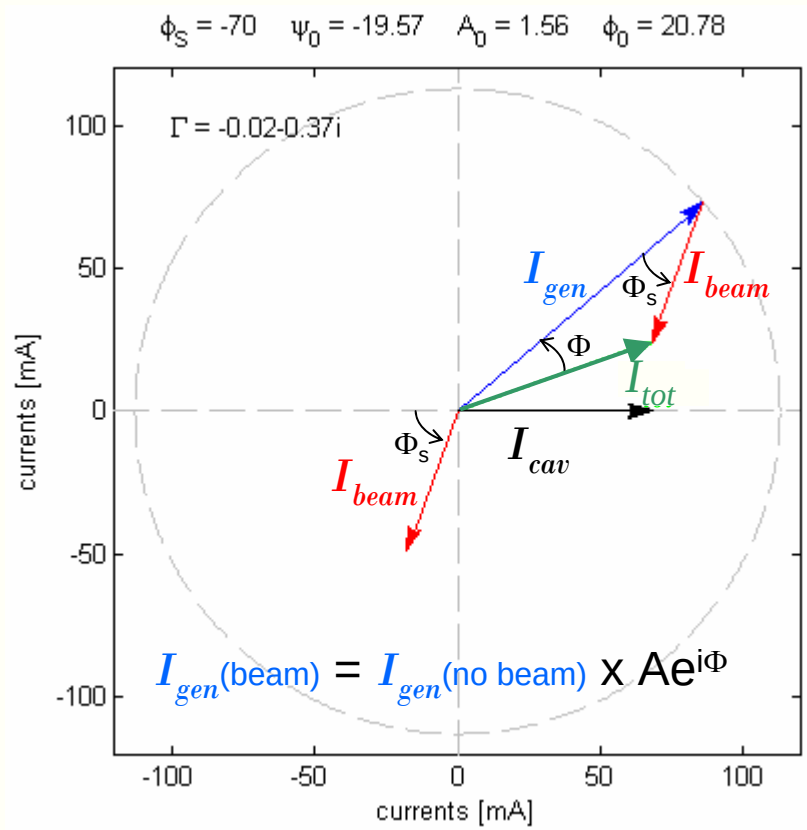
➔ No dynamic use of FVM



Beam OFF



Beam ON

Assuming nominal beam loading, there is no need to modulate the klystron forward power using the ferrite vector modulator if I_{tot}(beam OFF) = I_{tot}(beam ON)

Plans for 2009-11

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- **NML Test String**
  - Capture Cavity 2 with FVM
  - Cryomodule #1 (8)channel vector sum
  - RF Gun
  - Master Oscillator, Phase Reference line
  - Piezo Resonance Control of 8 cavities
- **HINS Short String Beam Test**
  - Control RFQ and six copper cavities with FVM
- **9mA tests at FLASH**
  - Deliver 24 down-converter channels
  - Provide controller option
  - Participate in studies and analysis

Plans for 2009-11

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- Continue with ILC collaborations
  - Hardware and software development to validate performance requirements
- Both Project X and the ILC have challenging regulation requirements and low RF power headroom
  - Power headroom requirements must be well understood
  - Ferrite Vector modulators must be proven with beam loading
- What components will be built?
  - Field controllers
  - Down-converters
  - Reference line
  - Software and firmware modules
- How do ARRA funds help?
  - Invest in fiber optics infrastructure for long haul phase reference lines
  - Invest in RF test equipment for lab and NML use
  - Local reference line evaluation
- Industrialization ?
  - No options at this time in the America's

Technical Milestones

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- **NML**
  - **July 09 - CC2 in closed loop operation**
  - **Aug. 09 - CC2 feedforward control of FVM**
  - **Fall 09 - Cryomodule #1 closed loop operation**
    - **8 cavity vector sum regulation and fast resonance control**
  - **2011 - RF Gun in in closed loop operation**
  - **2011 - Meet ILC cavity regulation requirements for cryomodules and Photoinjector gun**
- **HINS**
  - **summer 2010 - Validation of Ferrite Vector Modulator Control with beam through six cavities driven with one klystron**
  - **2011 - Controlling multiple SRF spoke resonators using FVMs**

Conclusions

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- **Advances in LLRF Control Systems promise:**
  - **Better machine performance**
    - **Tight regulation**
    - **Improved exception handling**
  - **Reduced machine cost**
    - **Multi-cavities per klystron**
    - **Low power headroom**
    - **Ferrite Vector Modulators**
- **FNAL has made good progress with the current RD&D program. The test facilities and plans will allow us to meet ILC and Project X LLRF requirements**

Supporting Slides

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3.9GHz Regulation - ESECON

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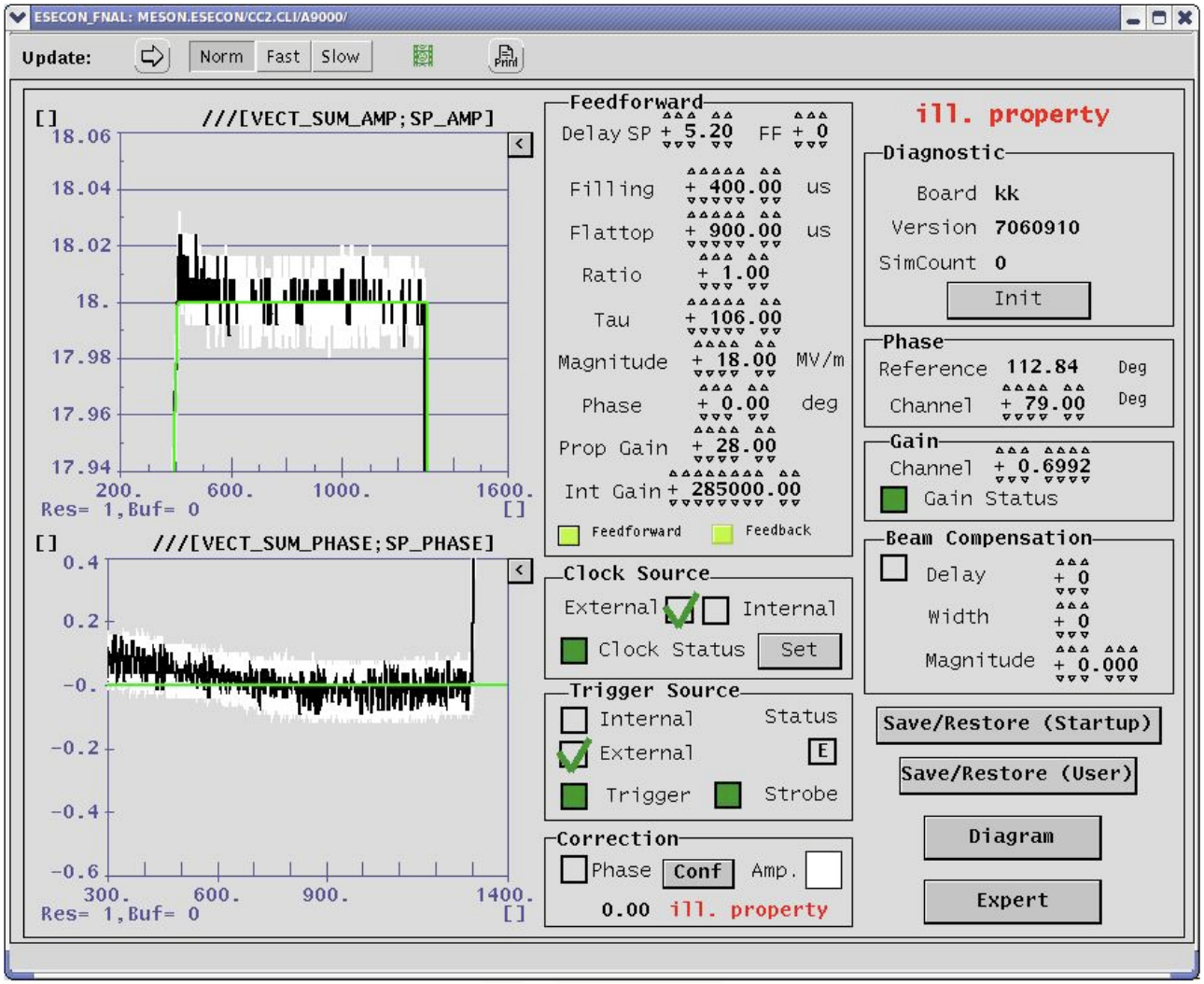

HTS cavity 3
QL = 1.2e6
w12 = 9.42
Krad/s Pgain = 28
Igain 285000.

Closed Loop Response of Cavity Model and Controller

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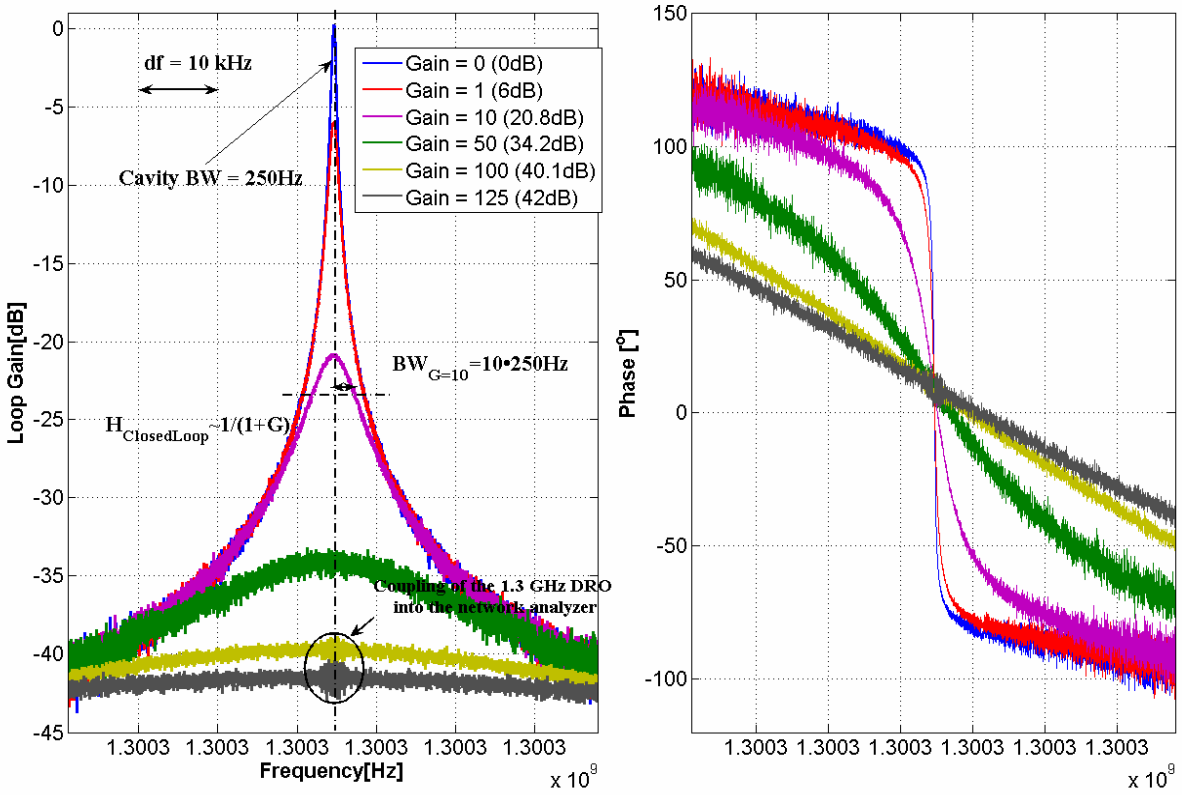

CC1- Error as a Function of Gain

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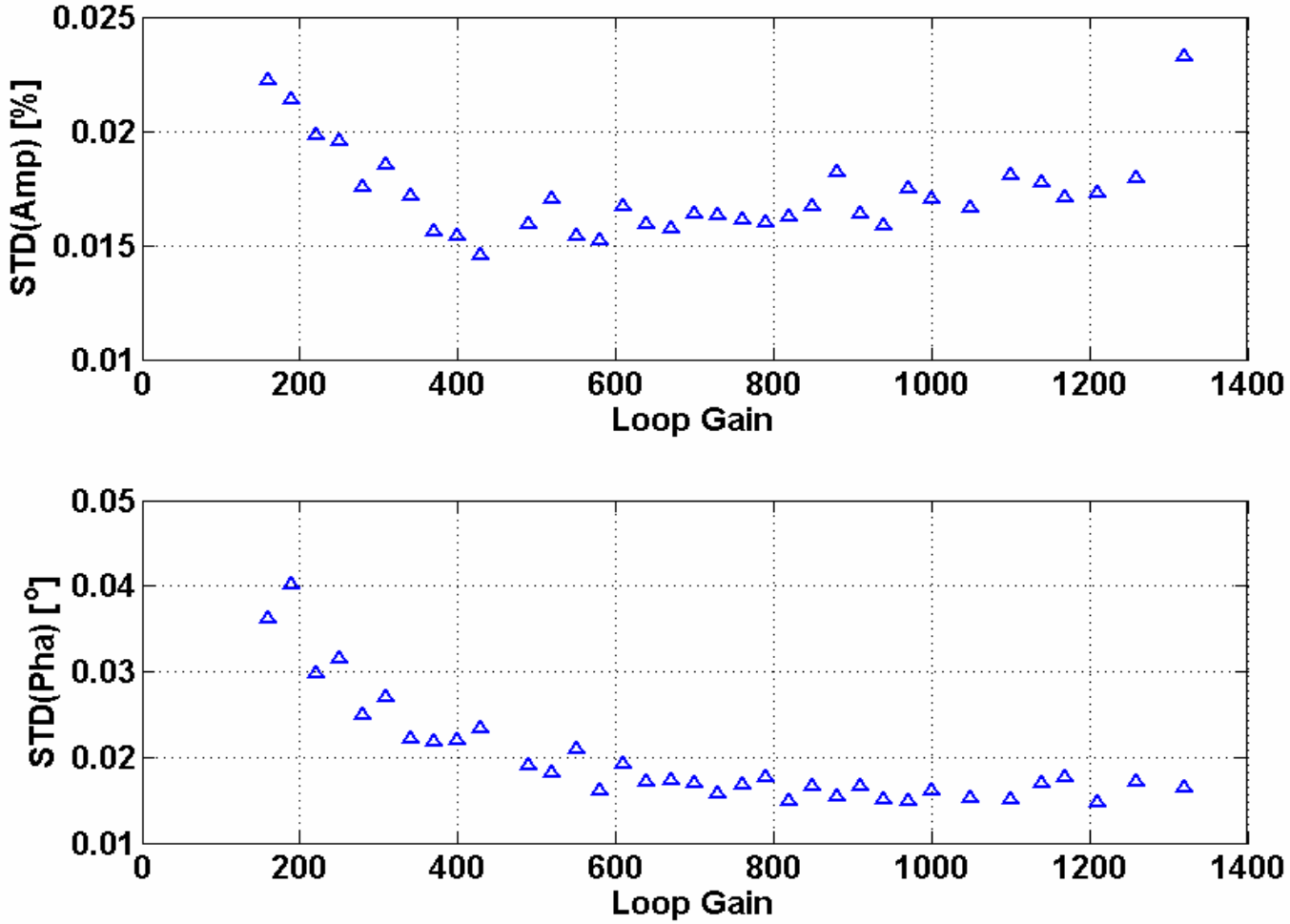

Beam Jitter Measurements

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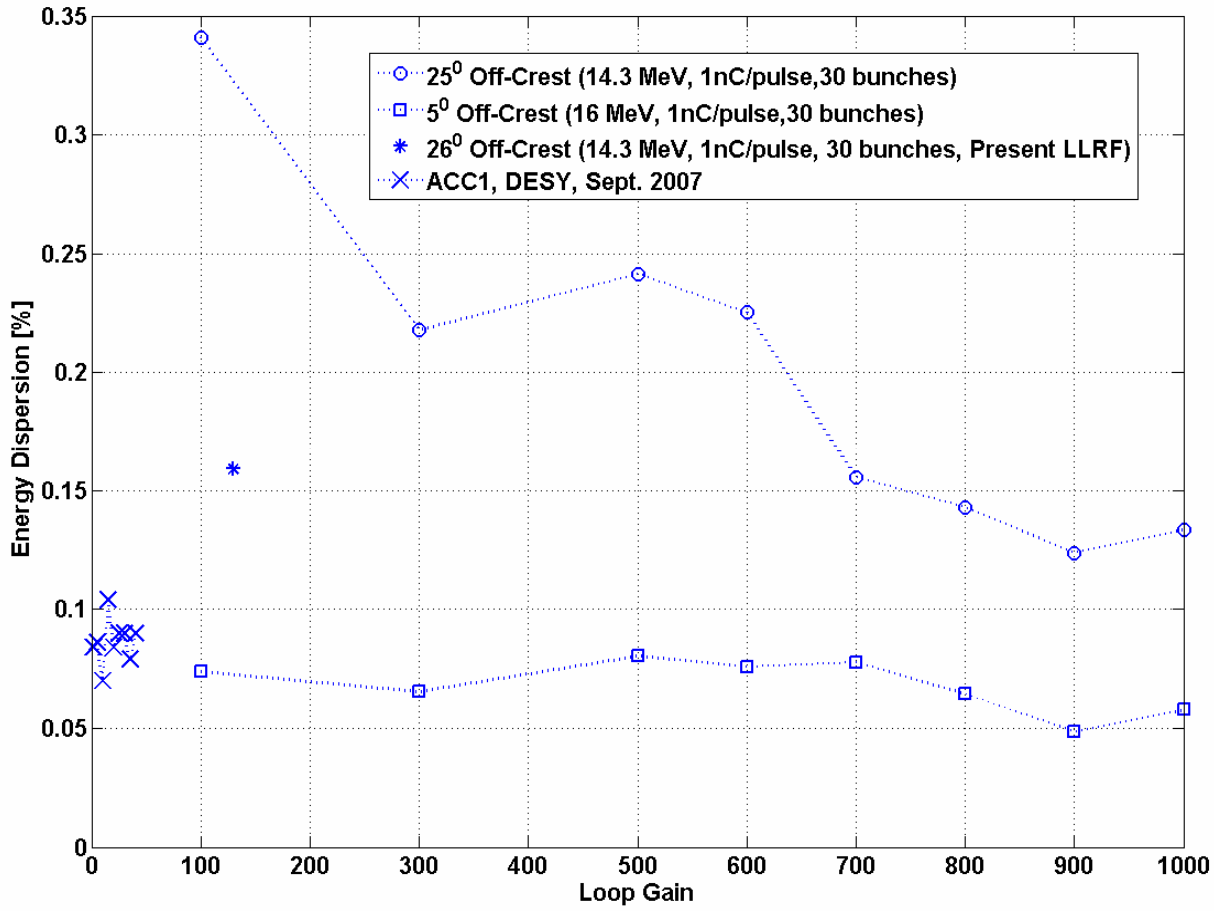
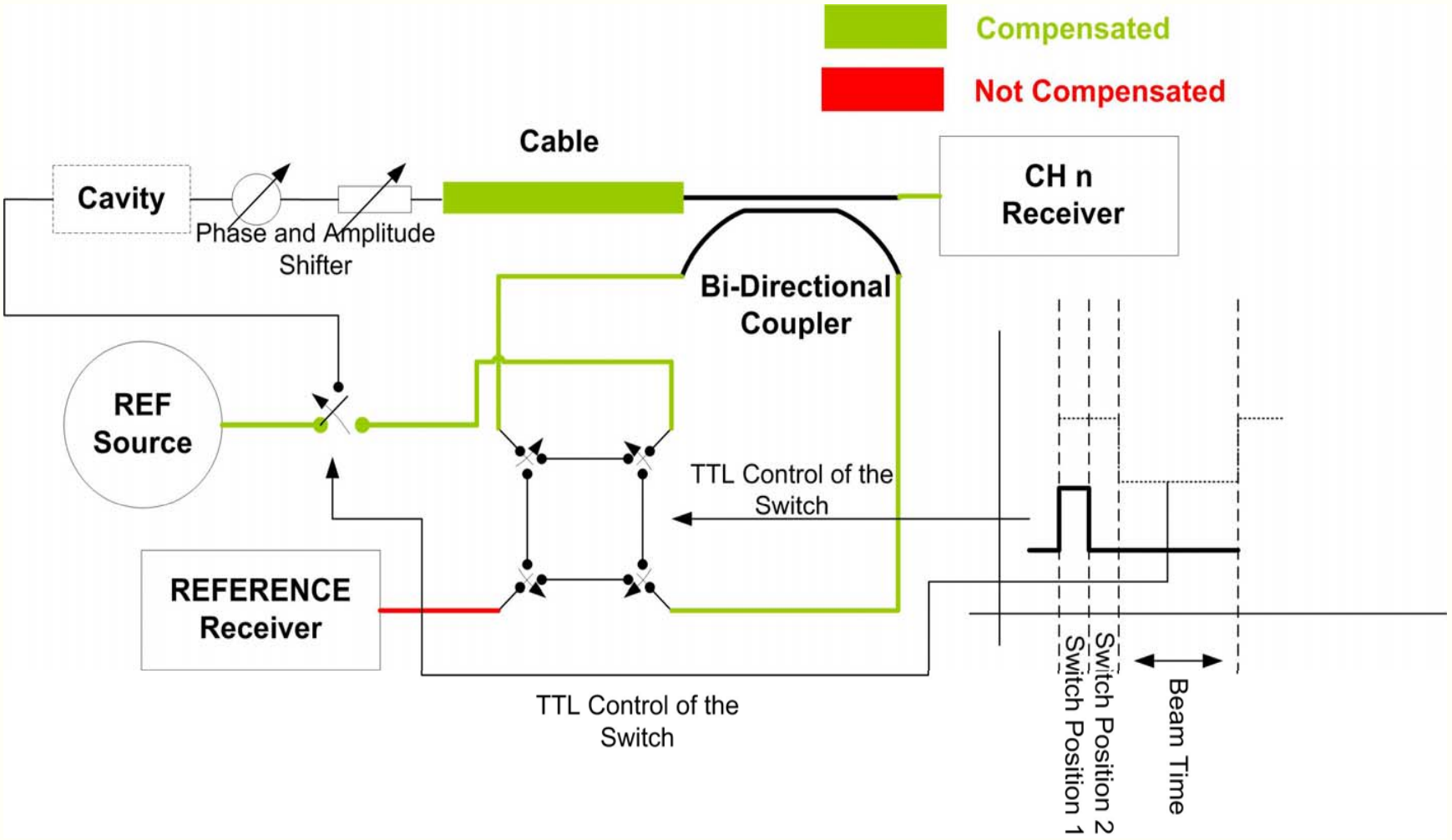


Drift Calibration



325 MHz LLRF System With MO and LO Generation

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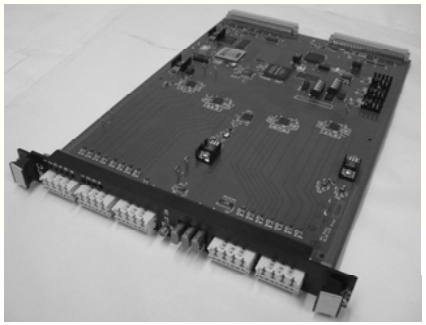
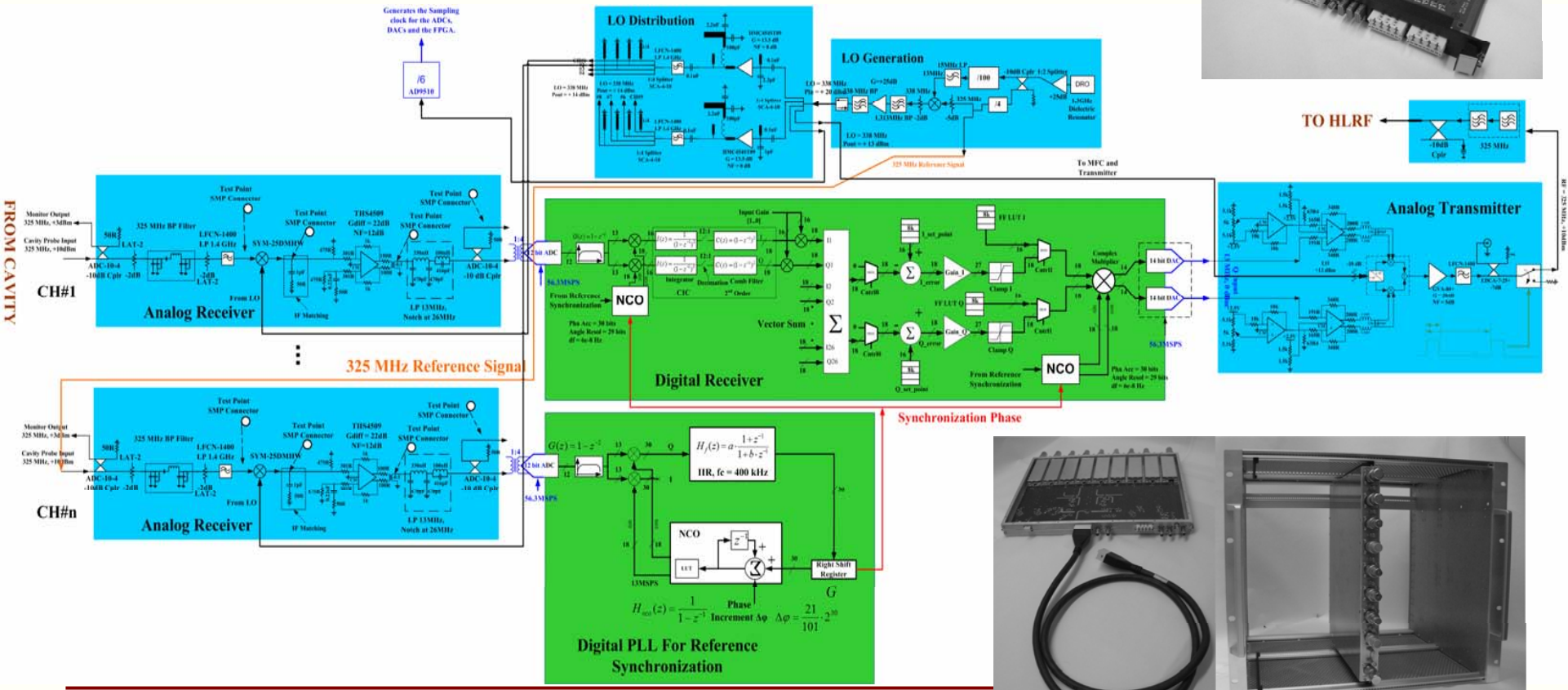
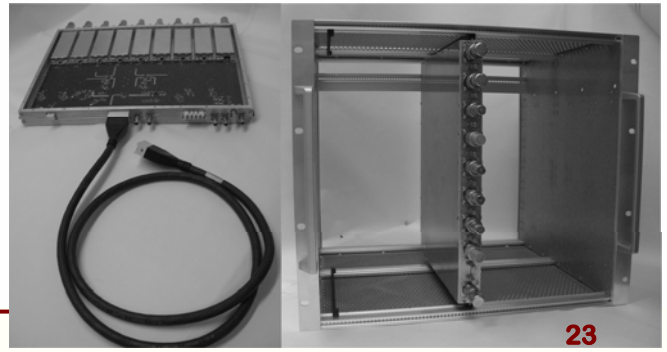






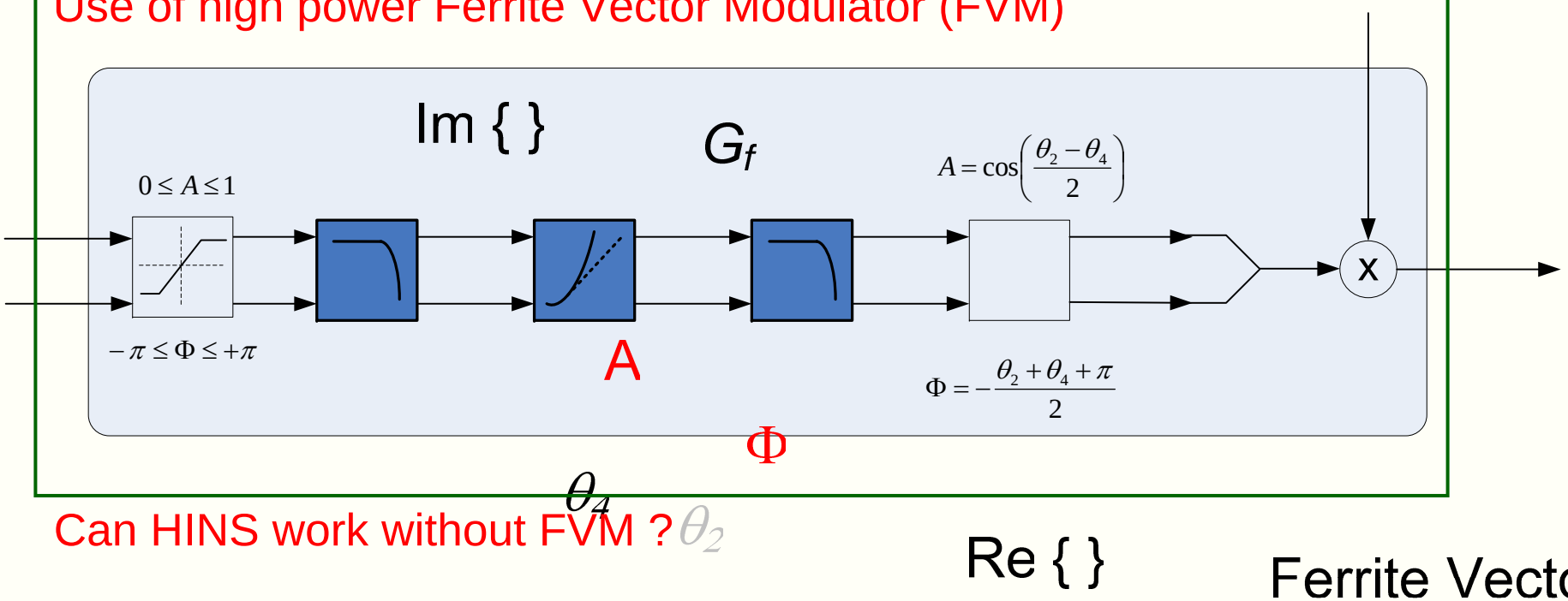
Cavities operating at different synchronous phase angles

HINS/PROJECT X

What's unique

- **normal and super conducting cavities with 1 klystron ?**
- **each cavity has its own: Q_0, V_0, Φ_s, ψ, Q_L**

Use of high power Ferrite Vector Modulator (FVM)

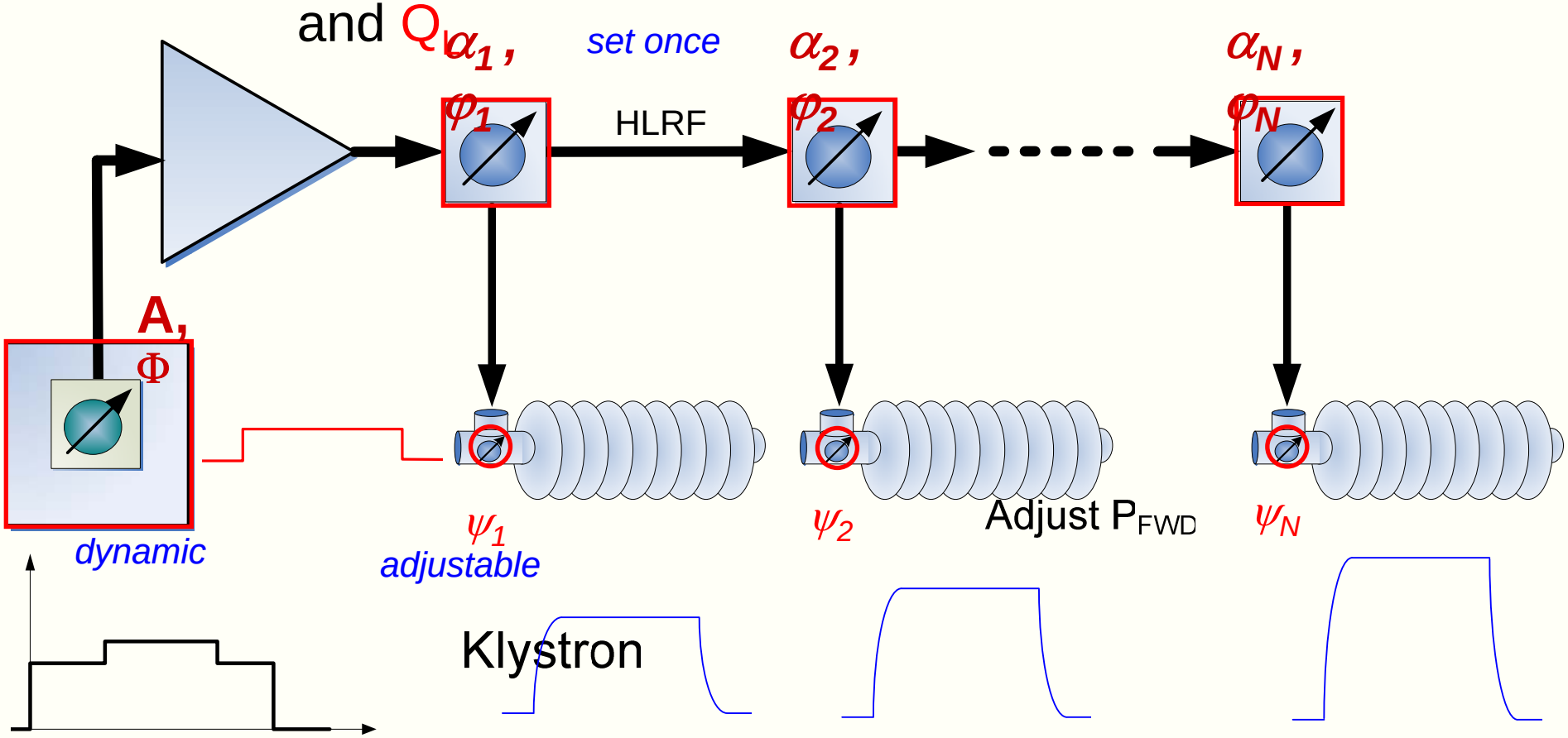


Can HINS work without FVM ?

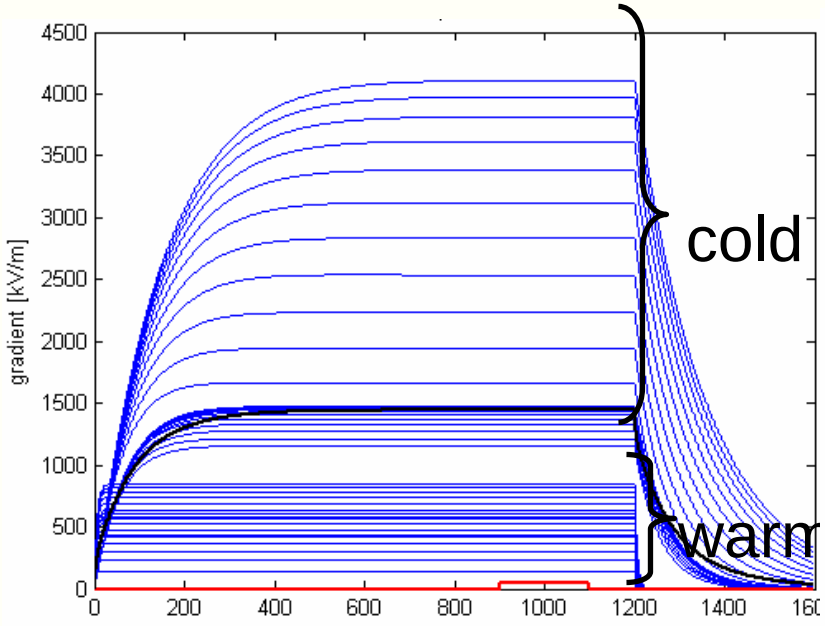
Beam loading compensation: Approach B

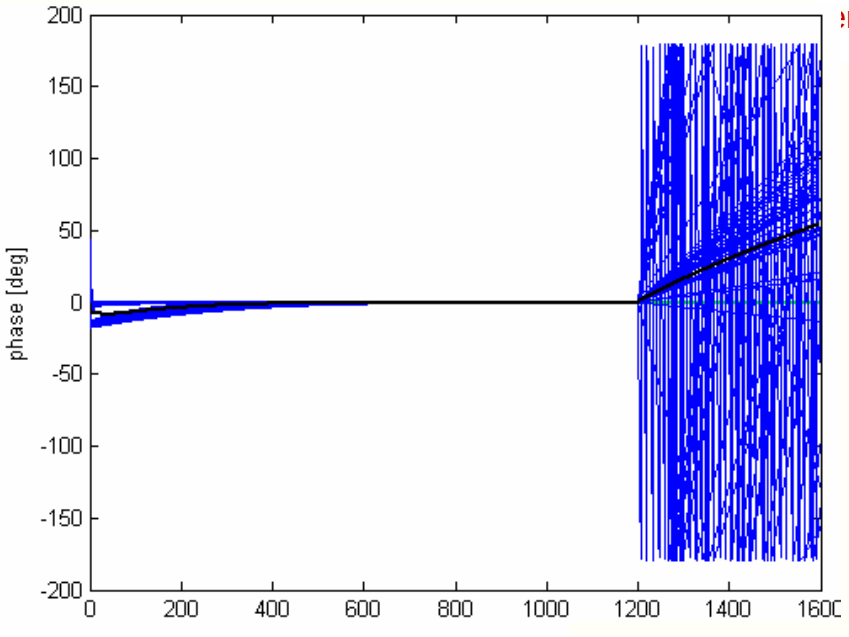
Using FF klystron amplitude and phase modulation

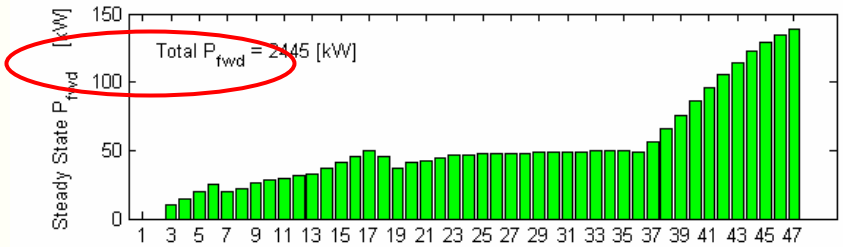
→ Find each cavity's unique α, φ, ψ and Q_L

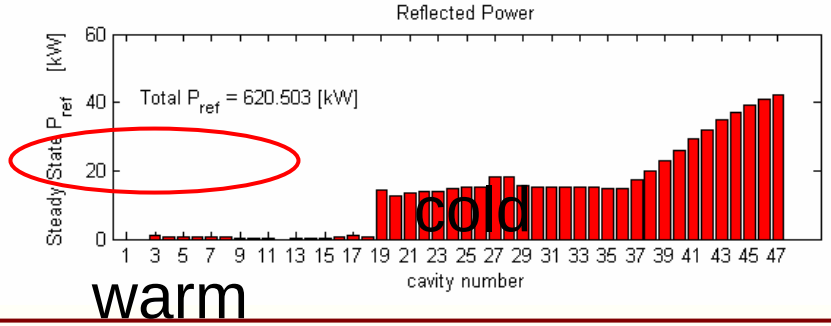


Hins Mult-cavity Simulations









beam ON (900 usec)

Fill time ~ **600-700 usec**

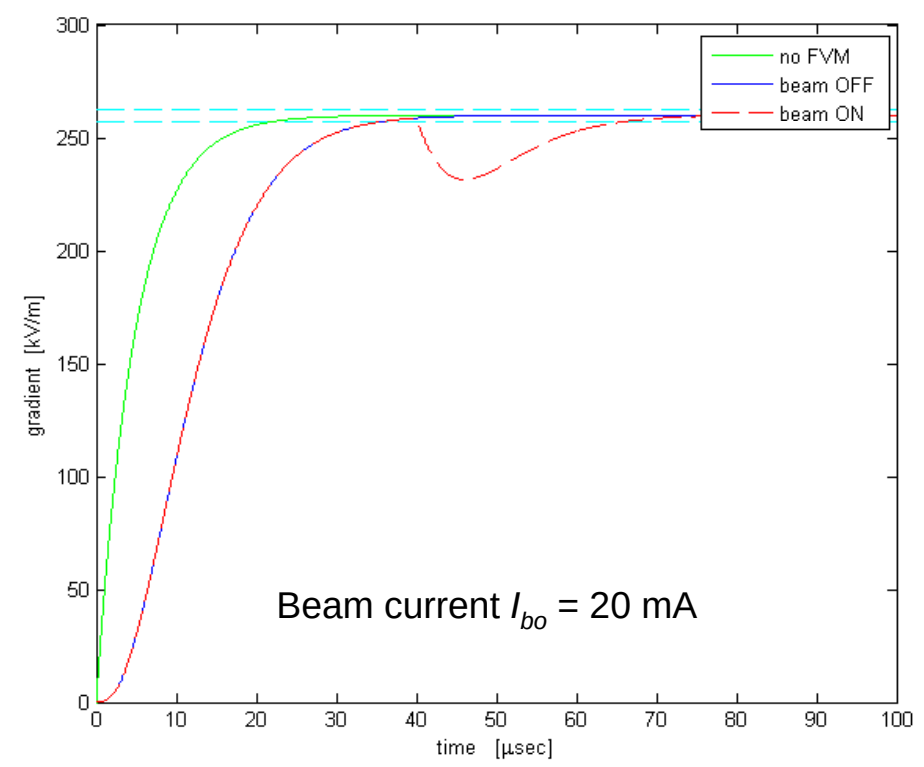
Total **P_{fwd} = 2.5 MW**

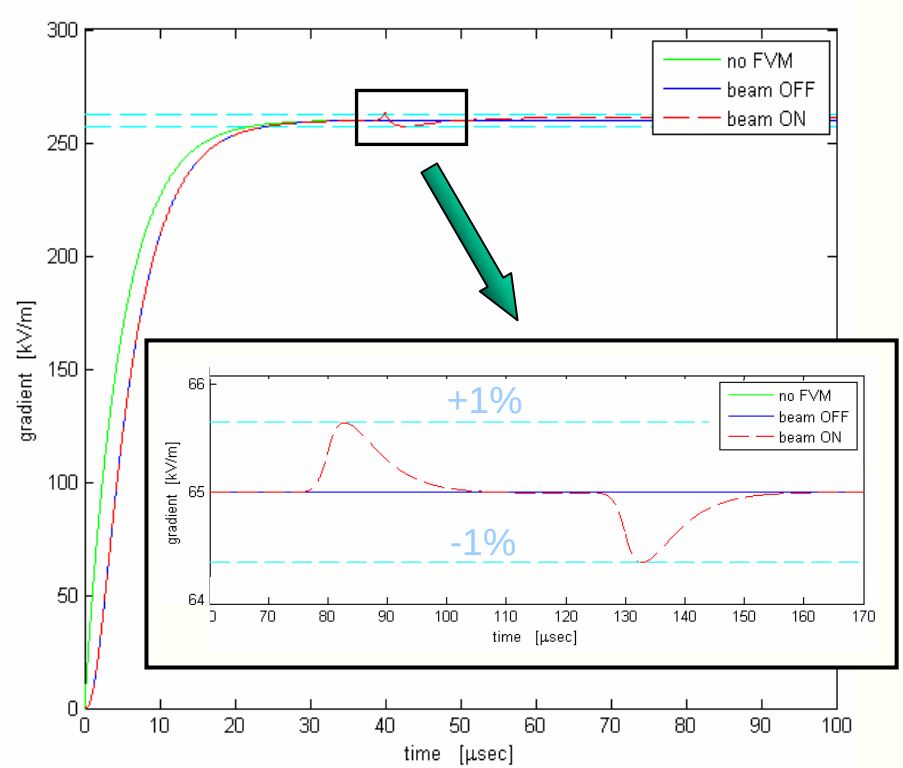
Total **Pref = 620 kW**

P_{ref} matched for cavity #12

Julien Branlard

HINS with FVM: simulation results





- "warm" cavity Q_L ~ 5000
- rise time τ ~ 30 usec
- beam arrival during steady state
- slow FVM response time

- ramping beam over 50 sec
- anticipate FVM response
- introduce pole cancellation
- ability to regulate beam loading ±1% amplitude

325 MHz Ferrite Vector Modulator

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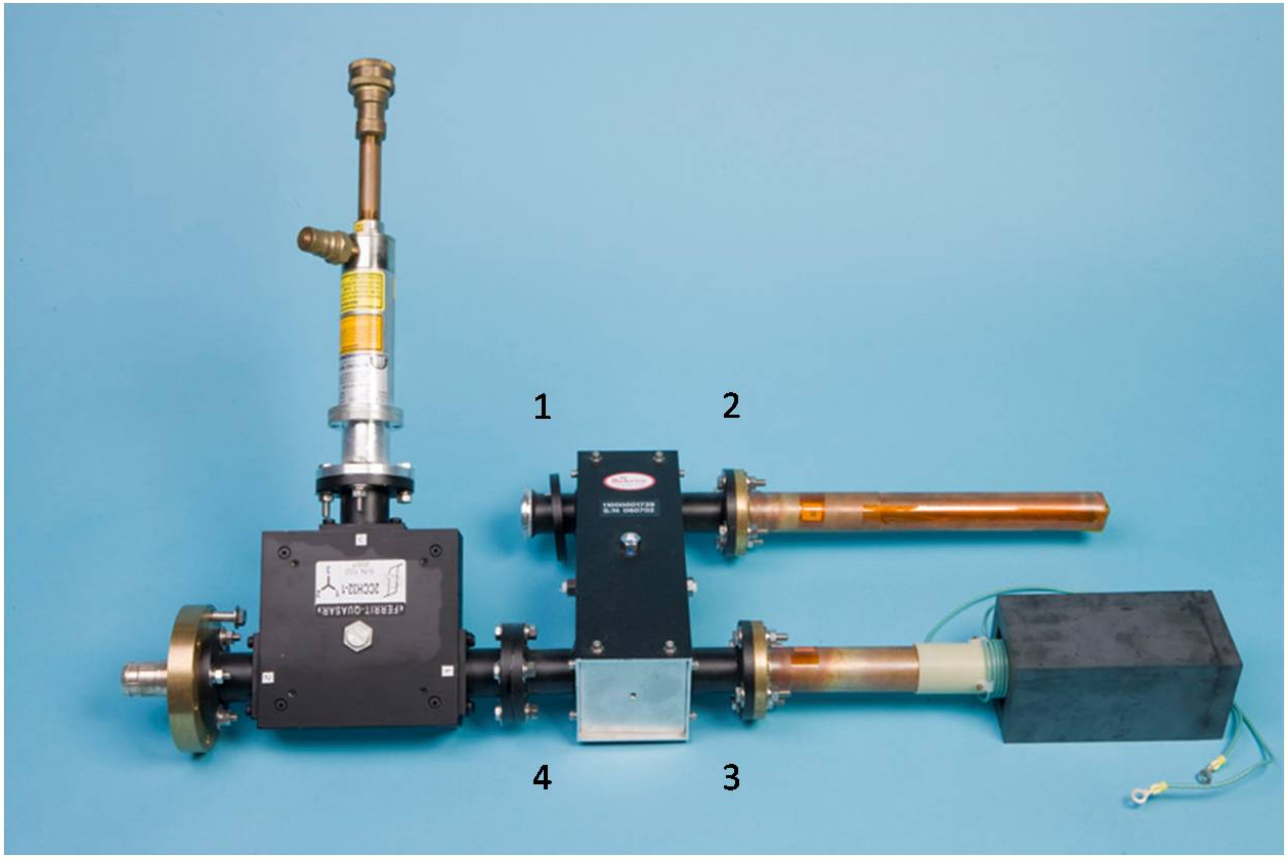
75 kW peak power



Active Compensation of Microphonics in CCII

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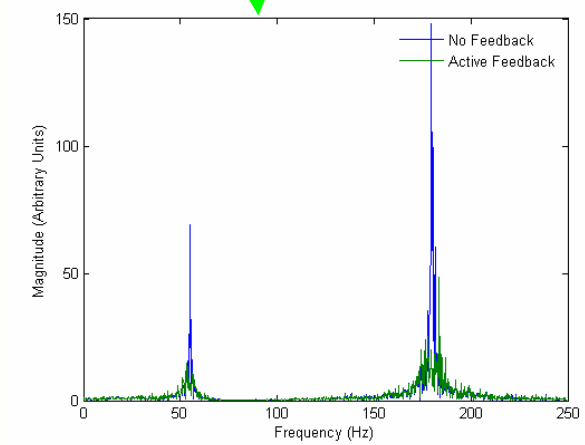
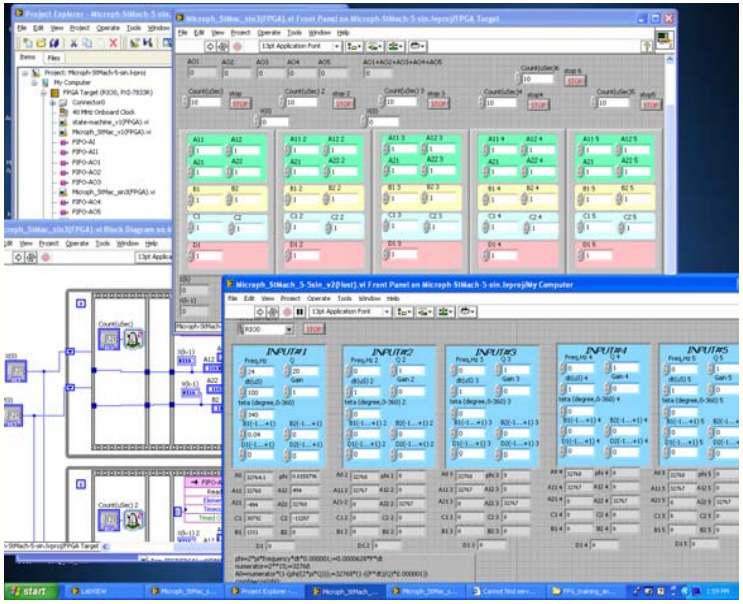
- Reviewed 3 different algorithms used with SCRF cavities to actively dump random vibrations.
  - *High Order Transfer Function (DESY)*
  - *LMS Adaptive Filter (FNAL)*
  - *Narrow Band Filter Bank (Michigan State)*

- Developed code and implemented on NI FPGA PXI-7833R " Narrow Band Filter Bank " algorithm (with up to 5 resonances/poles).
- Matlab simulation of NBFB in CW cavity. Two mode system (55 Hz and 180 Hz) driven by white noise. Predicts 15 dB of suppression possible.

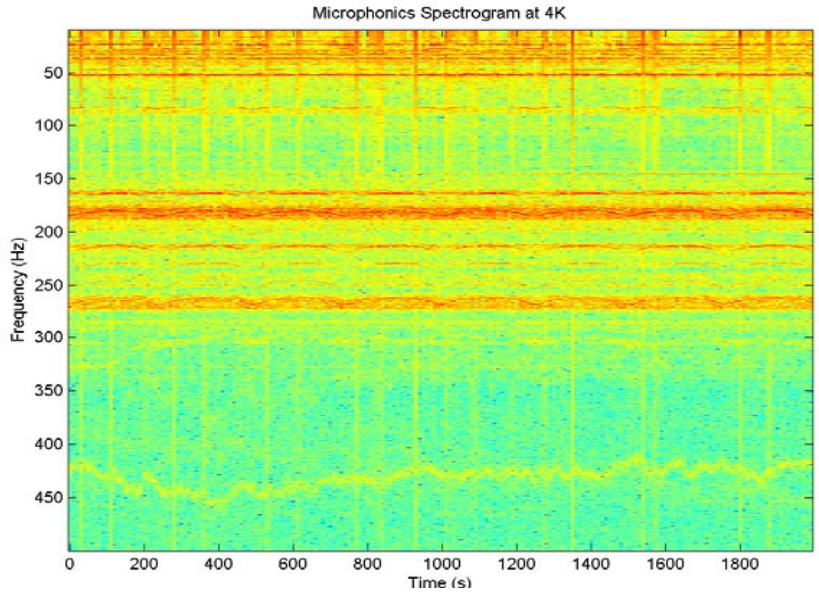


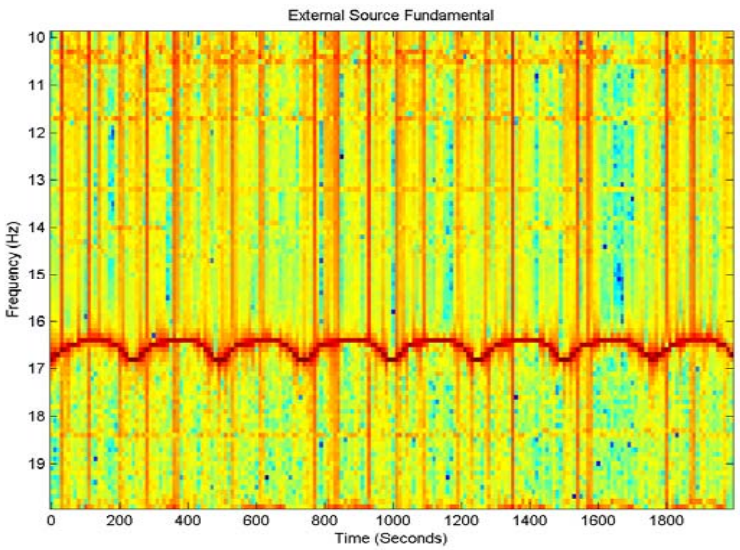
Matlab simulation of NBFB in CW cavity

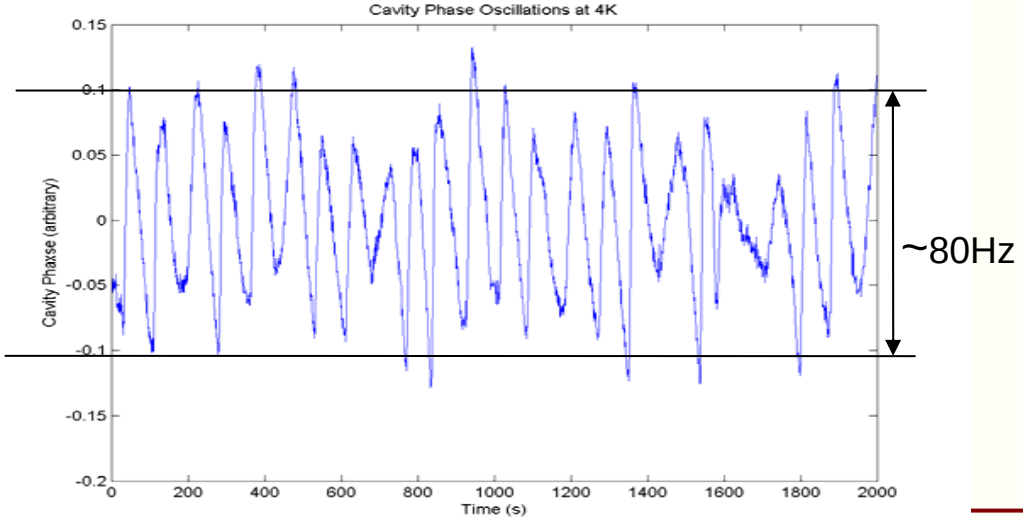


Active Compensation of Microphonics in CCII (cont.)

- Measured CCII vibration at 4K, 2K during many hours of operation (long term stability of microphonics vibrations).







Experimental results with LFDC system proposed for NML/CM1/CC2

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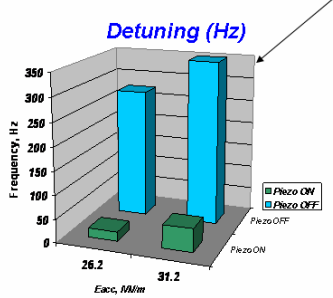
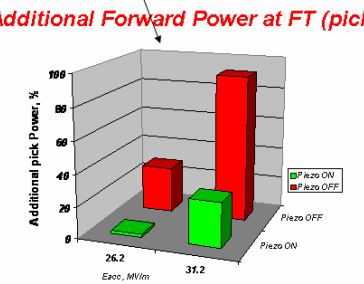
FNAL's Resonance Control Group used this system for LFD compensation at ***CC2***.

	Detuning (Hz)		Additional Forward Power at FT (pick)		Piezo Voltage, [V] (max=120V)
	Piezo OFF	Piezo ON	Piezo OFF	Piezo ON	
26.2 MV/m	275	20	29%	2%	20V
31.2 MV/m	350	50	92%	28%	40V

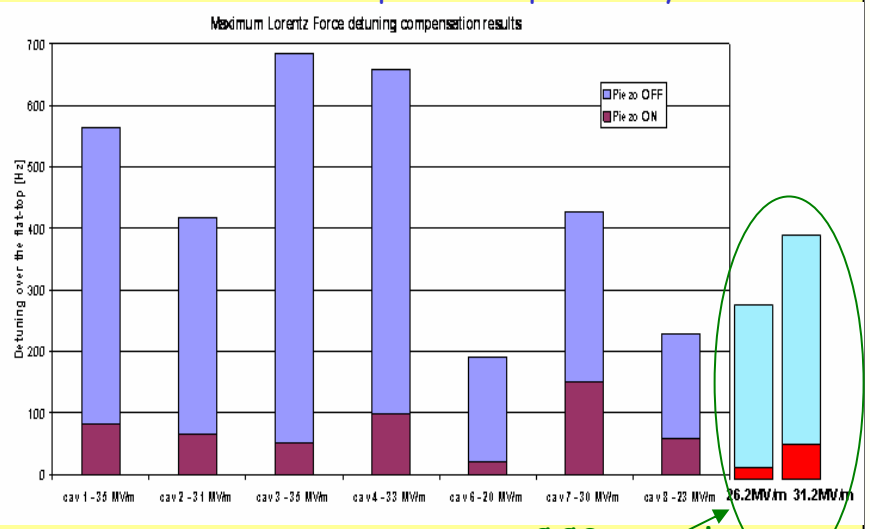




DESY

Experimental results from **FLASH**, Module#6 (L. Lilje)

Maximum Compensation per Cavity



CC2 results

FLASH Accelerator Layout

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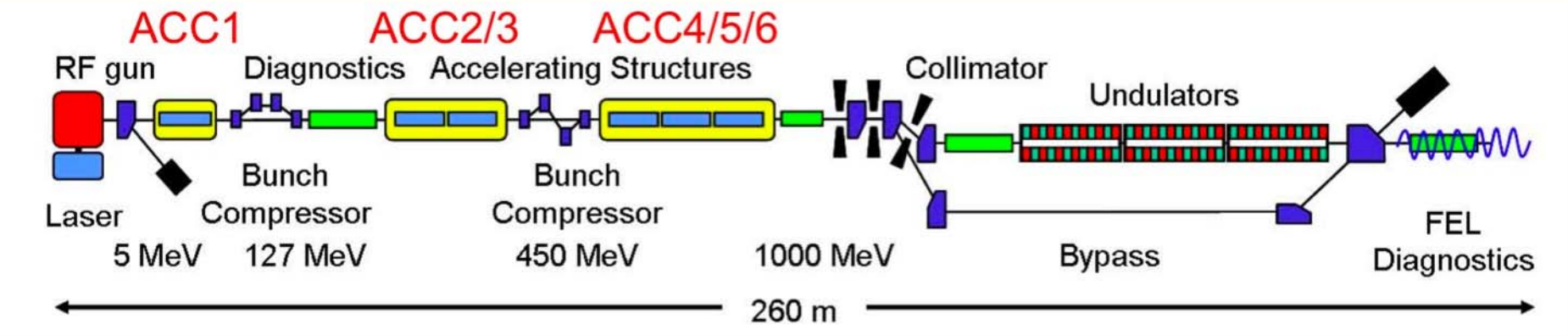

Comparison of machine parameters

		XFEL	ILC	FLASH design	9mA studies	STF-II	NML	Proj-X (1MW)	HINS
Bunch charge	nC	1	3.2	1	**3**		3.2		
# bunches		3250	2625	7200	**2400**		2850		
Pulse length	μs	650	970	800	**800**		950	1250	
Average current	mA	5	9	9	**9**		9	20	
Cavity Loaded-Q		3e6	3e6	3e6	**3e6**		3e6	1.25e6	
Cavity Frequency	MHz	1300	1300	1300	**1300**	1300	1300	1300	325
Gradient	MV/m	25	31.5		**20-32**		25	25	
Cavities / klystron		32	26	8-24	**8-24**		24	16	

The 9mA experiment in context:

Addressing R&D issues of several projects

- **ILC: GDE stated milestone for Technical Design Phase**
  - **Primary motivation and driver for the experiment**
- **XFEL: Close collaboration with world-wide LLRF groups**
  - **Focus (potentially accelerate) development and planning**
  - **Critical design/dev't input from "operation at limits" experience**
- **FLASH: Addresses many operational issues**
  - **Focus / accelerate upgrades and enhancements**
  - **Better characterization of machine**
  - **Towards routine high-power long-pulse operation for users**
- **NML, Project-X, HINS, STF-II**
  - **LLRF for heavily beam-loaded cavities is a stated critical R&D topic**
  - **Important design/dev't input from "operation at limits" experience**
  - **Opportunity to develop and test hardware, software, and algorithms**

US contributions to the 9mA program (FY08-)

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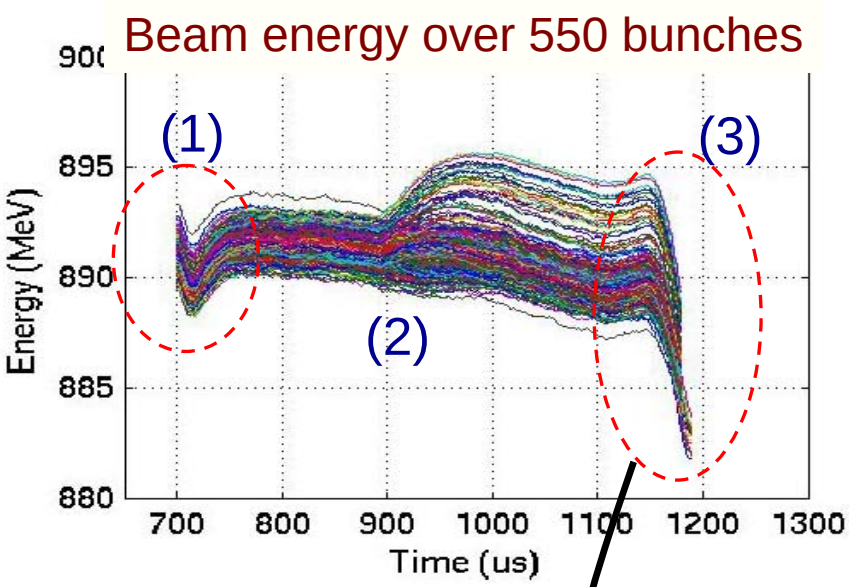
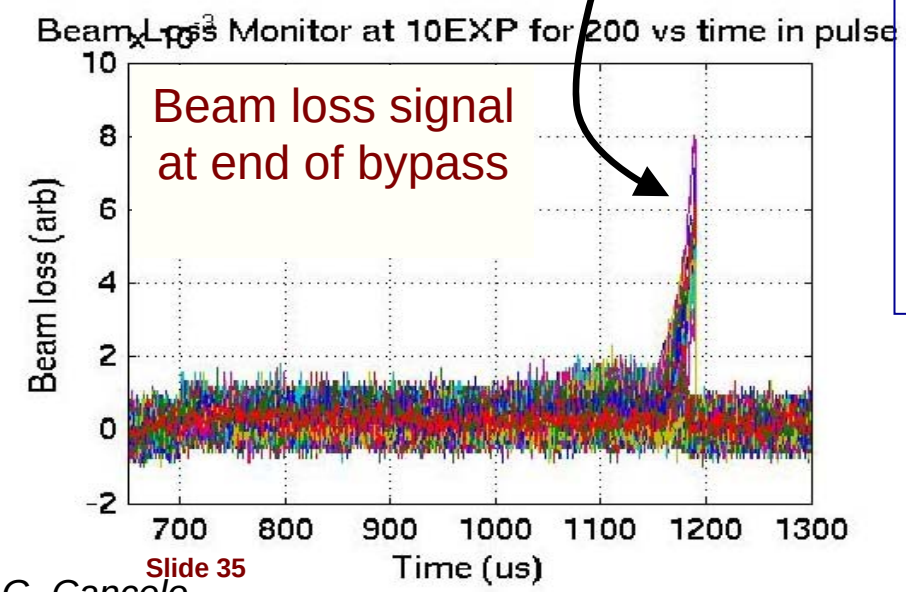
- Over the past year we have been climbing the learning curve on the FLASH LLRF systems and accelerator ops
- On-shift participation in three periods of 9mA studies
  - Initially observers, now active participants
- Gained operations experience tuning and running the FLASH LLRF and accelerator with long bunch trains at 3mA
- 'Beta' test new DAQ archiving tools
- Lead role in RF overhead studies
- Analyze key operational data: LLRF performance, RF overhead data, machine tuning data

Energy profile over long bunch trains (Sept 08 studies)





Systematic effects

1. Beam turn-on transient (regulator)
2. Slope over flat top (bunch charge?)
3. Droop at end of the flat top (imprecise beam loading compensation)

Improve LLRF regulation through…

- Increase feedback gain!
- Upgrade to latest generation LLRF
- Better beam loading compensation
- Better feed-forward tables

G. Cancelo

WBS and Schedule

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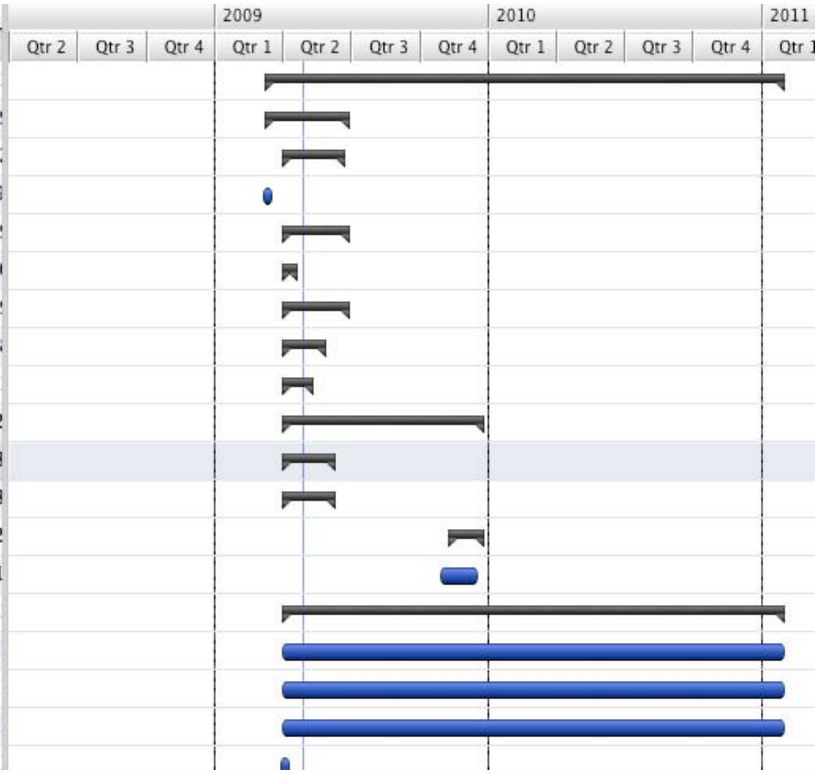
Gant chart snippet

#	Name	Duration	Start	Fir
1	SRF LLRF Tasks	496.0 d	3/9/09	1/3
2	HINS	81.0 d	3/9/09	6/2
3	Resonance Control	60.0 d	3/31/09	6/2
10	Order 325 MHz amplifiers for HINS	1.0 d	3/9/09	3/9
11	Field Control	65.0 d	3/31/09	6/2
12	Update controller Software/Firmware	15.0 d	3/31/09	4/2
16	Ferrite Vector Modulator Control	65.0 d	3/31/09	6/2
37	Master Oscillator	43.0 d	3/31/09	5/2
45	Reference line	30.0 d	3/31/09	5/1
48	Up and Downconverters	194.0 d	3/31/09	12/2
49	325 MHz	50.0 d	3/31/09	6/8
54	1300 MHz	50.0 d	3/31/09	6/8
60	Build 10 boards	35.0 d	11/9/09	12/2
64	3.9 GHz	35.0 d	10/30/09	12/1
65	LLRF Controller	480.0 d	3/31/09	1/3
66	Software	24.0 mo	3/31/09	1/3
67	Firmware	24.0 mo	3/31/09	1/3
68	Algorthms	24.0 mo	3/31/09	1/3
69	MO and LO	1.0 d	3/31/09	3/3