Challenges in Project X Longitudinal Beam Control

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Overview

- System Requirements
- 325 MHz Front End
  - Single Klystron - Multiple cavity types
- 1300 MHz ILC "like" section
  - $\beta < 1$ issues
- Present Status of LLRF Development
  - HINS
  - ILC

Linac Parameters

Parameter	Quantity	Unit
Particle Species	H- ion	
Output Beam Energy	8.0	Gev (kinetic)
8-GeV Beam Power	360	kW
Particles per Pulse	5.625	E13
Pulse Repetition Rate	5	Hz
Beam Pulse Length	1	msec
Average Pulse Beam Current	9	ma
Beam Chopping at 2.5 MeV	- 6% at 89 kHz for 700 ns RR/MI abort/extraction gap - 33% at 53 MHz for 'pre-bunching' for transfer to RR	
Particles per Linac bunch	2.73	E8
Nominal Bunch Spacing	3.1	nsec
8-Gev Transverse Emittance	$\varepsilon H = \varepsilon Y = 0.4$	mm-mrad RMS
8-GeV Longitudinal Emittance	2.5E-6	ev-sec/bunch RMS
8-GeV Energy Spread	At Linac output – 2.7 At RR injection – 0.3	MeV RMS
8-GeV Bunch Length	At Linac output – 1.0 At RR injection – 8.6	psec RMS

Table 2.1 Linac Parameters

LLRF Requirements

- Regulation of Phase and Amplitude of the accelerating field within each cavity for beam currents from 0 to 9mA
  - 1% amplitude and 1 degree phase

- RF system must be:
  Reproducible –> digital filtering and processing
  Reliable –> high reliability and high availability technology
  Operable –> minimal, orthogonal control parameters with easy to understand graphical human interface

- Other
  - Build-in diagnostics
  - Automation of calibration of gradient and phase, resonance
  - Exception handling

Sources of Perturbations

o Beam loading	o Cavity dynamics
- Beam current fluctuations	- cavity filling
-Chopped beam transients	- settling time of field
- Excitation of passband modes	
- Multipacting and field emission	o Cavity resonance frequency
Excitation of HOMs	- Microphonics
- Wake fields	- Lorentz force detuning
o Cavity drive errors	
- HV- Pulse flatness	o Other
- HV PS ripple	- Response of feedback system
- Phase noise from master oscillator and local oscillator	- Response of Vector Modulators
- Calibration errors	- Thermal drifts (electronics, power amplifiers, cables, HLRF
- power distribution & cavity Q variations	

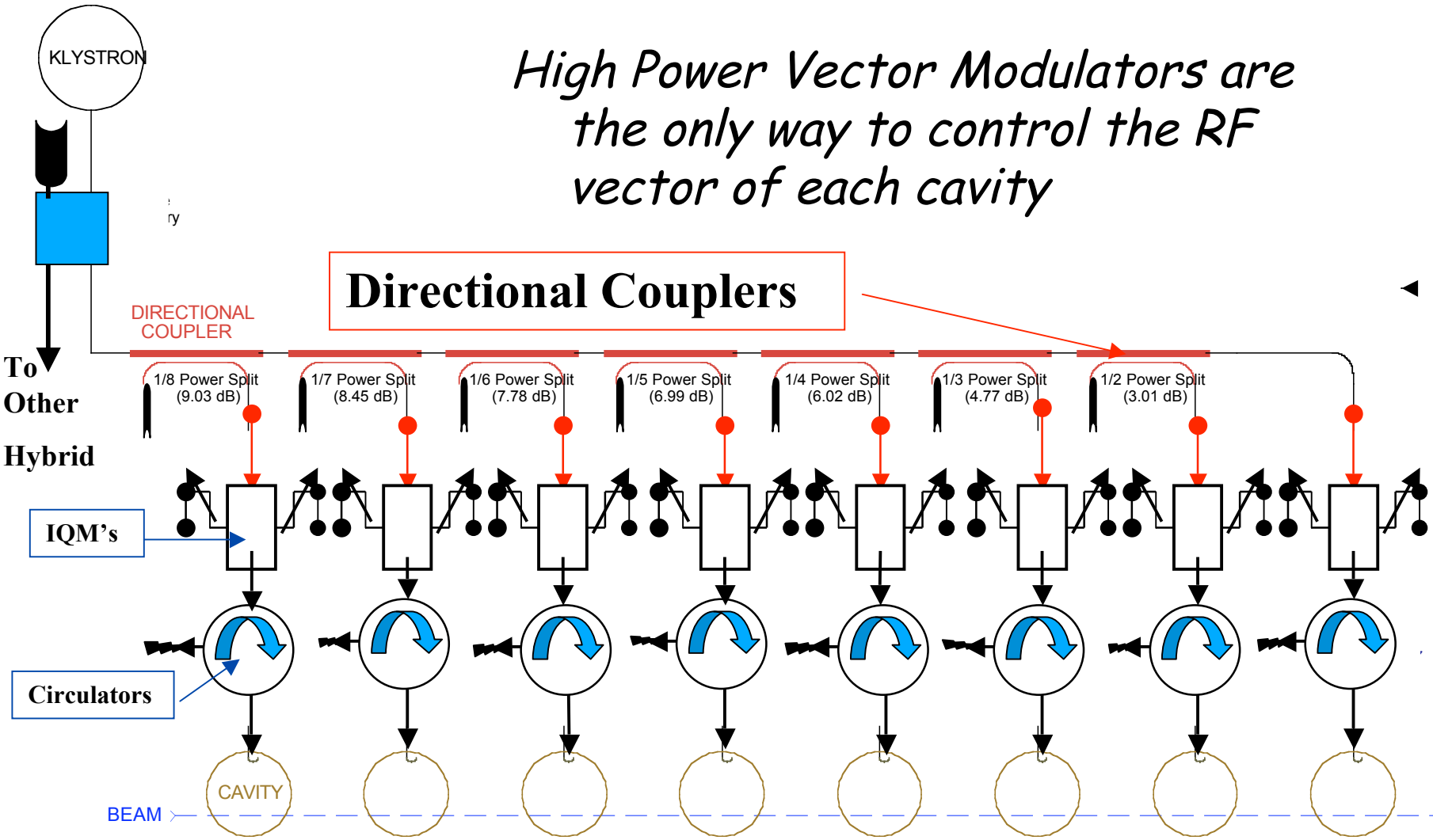
Control Issues are ILC Plus

- Beta = 1 sections have the same issues as the ILC
  - Additional requirements for control on each cavity
- Beta = 0.8 to 0.9 section 8/9 pi mode
  - High coupling to pi mode
- 325 MHz Low Beta section
  - Many different cavity types with unique:
    - *Q values*
    - *Beam loading*
    - *Lorentz Force Detuning*
  - Heavy reliance on High Power Vector Modulators

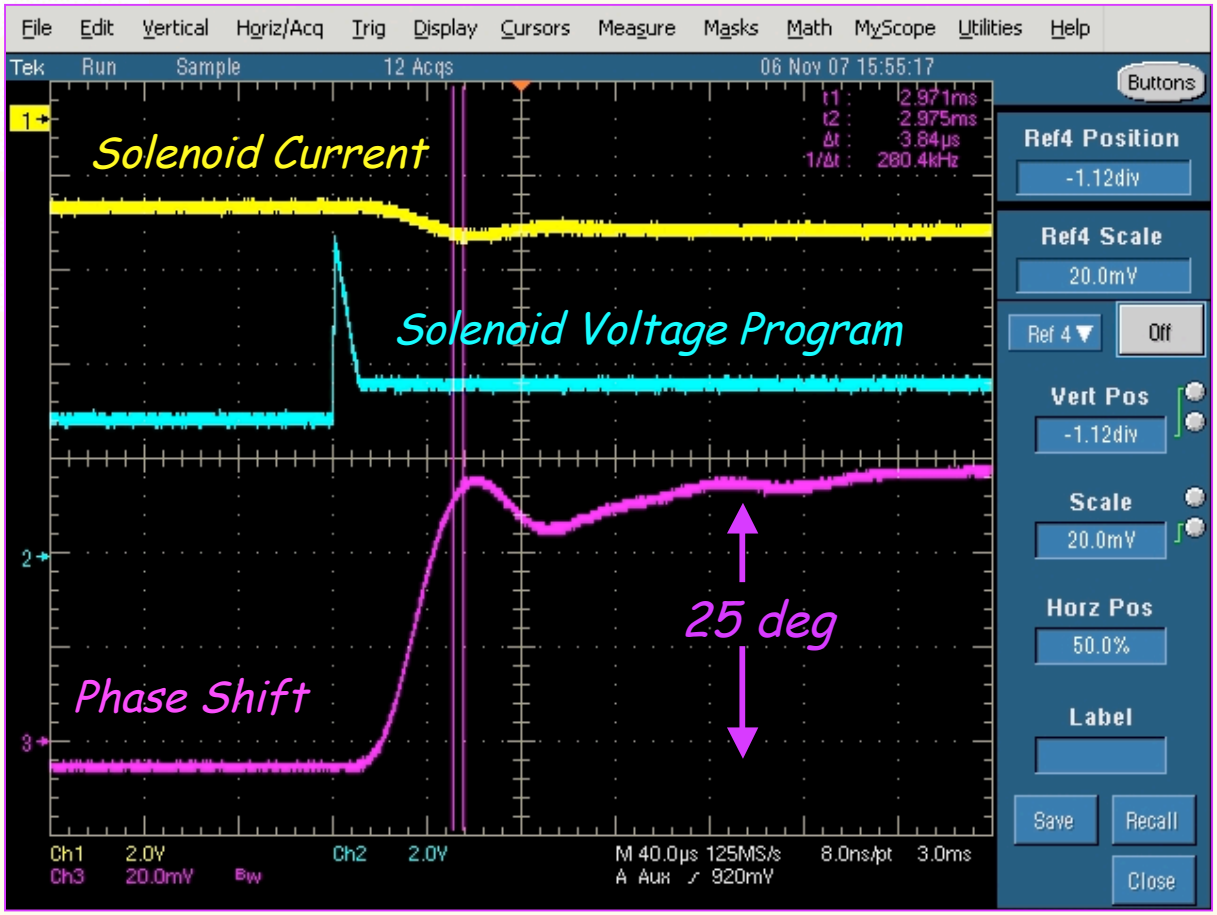
Differences Between Proton and Electron Linacs
(from the Proton Driver Report)

- *1. **Cavity voltage errors cause protons to undergo downstream phase/energy oscillations**, whereas for relativistic electrons only an energy error is produced. For electrons, the energy error is the sum of the voltage errors of all cavities the beam passes through.*
- *2. **The phase oscillations of protons affect the beam loading of the downstream cavities**. This introduces a coupling between upstream voltage errors and downstream beam loading which is not present in electron linacs. This is especially important for SCRF linacs where beam loading is the dominant consumer of RF power.*
- *3. **The transit time factor for protons will vary across a group of identical cavities as the protons accelerate**. This will produce a range of beam loading power in a group of otherwise identical cavities operating at identical gradients.*
- *4. **The synchronous phases for cavities in proton linacs are larger and more varied than in an electron linac.** Normally this phase shift is accomplished by a phase jump of the Klystron associated with each cavity -- however this is impossible when one klystron drives many cavities with different synchronous phases. A more complicated filling strategy is required.*
- *5. **The mixture of warm copper & SCRF cavities present in the front end linac will have very different resonant properties and response times to both beam loading and RF drive.***

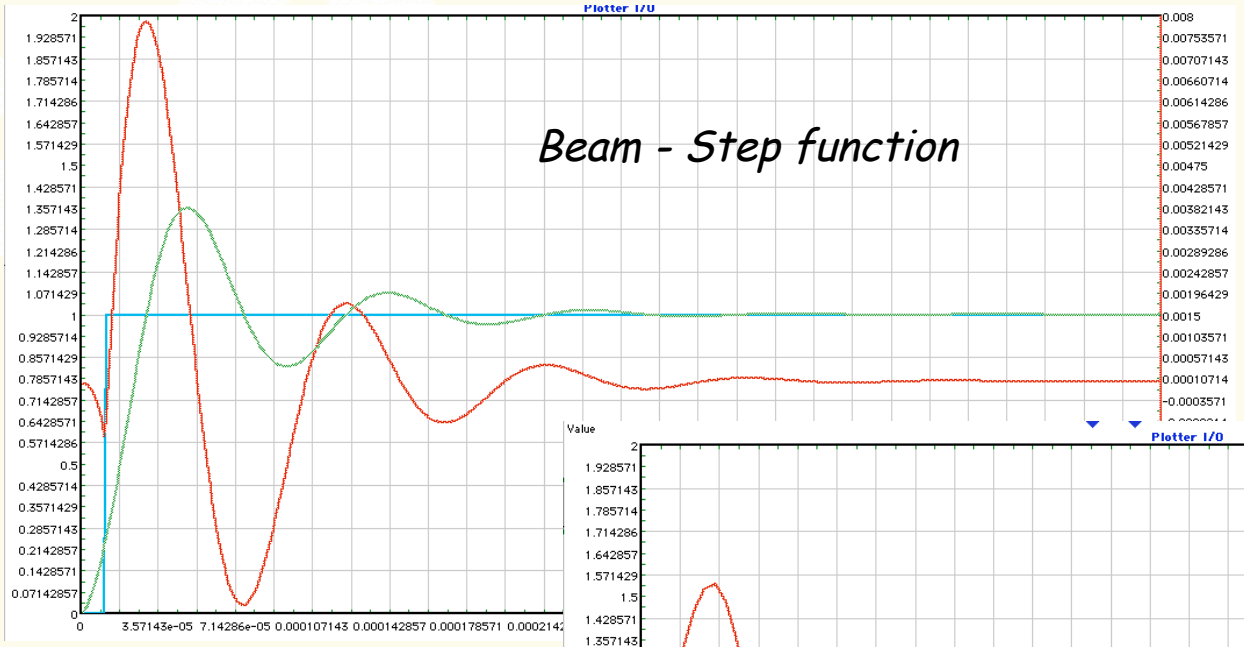
Simplified Layout of the RF Fan-out for 8 GeV HINS Linac



325 MHz High Power Phase Shifter Response



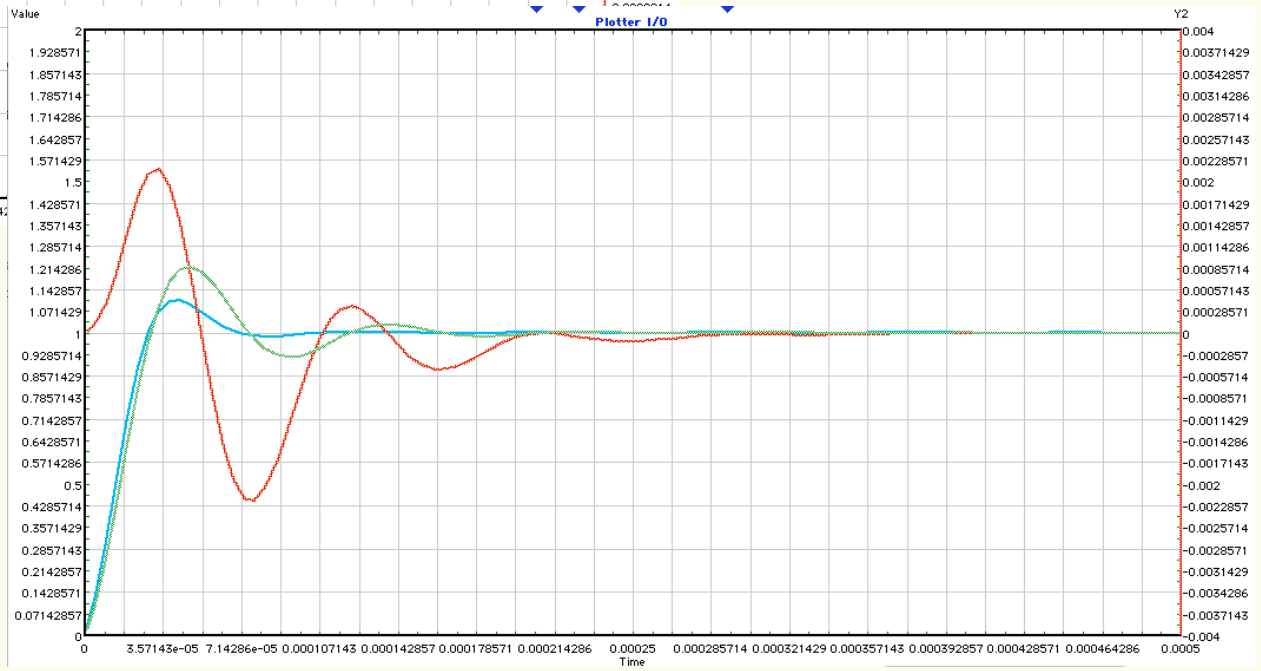
Vector Modulator and Beam Rise-time Interaction



VM phase shift

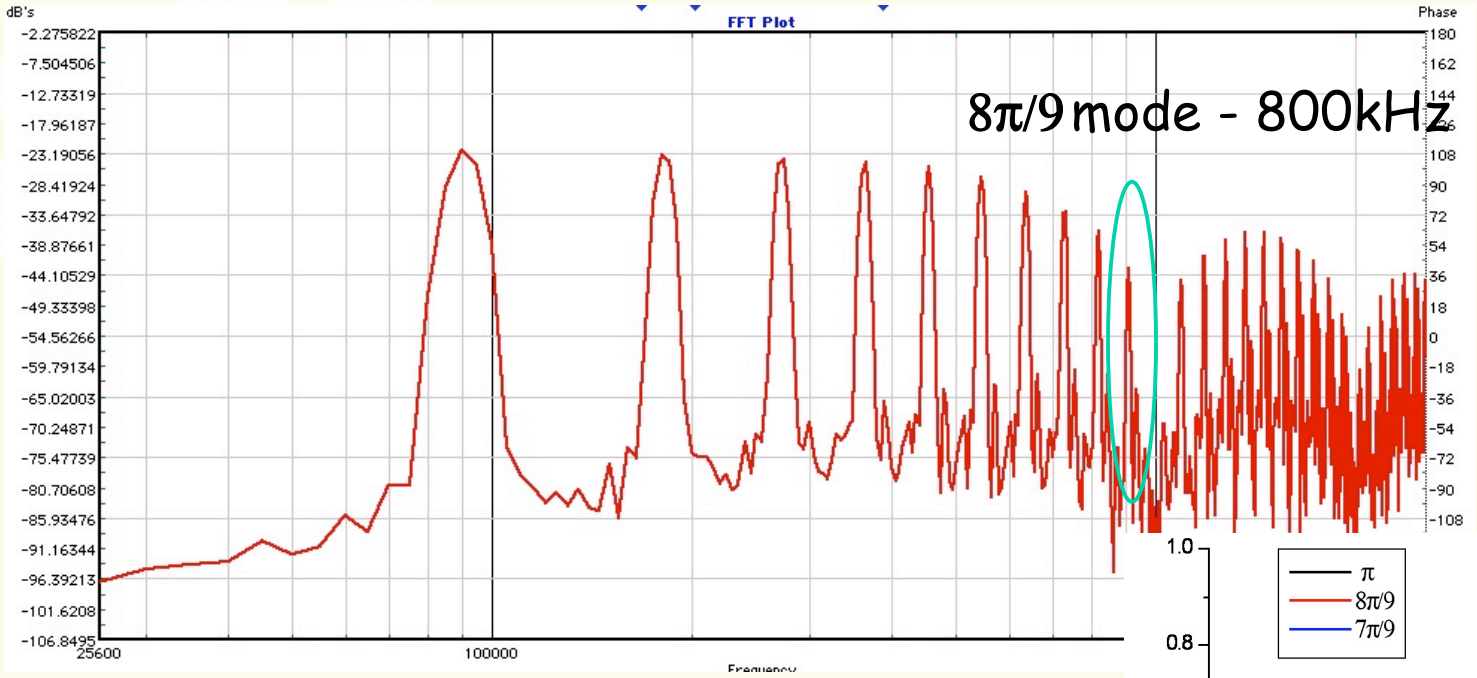
Beam loading

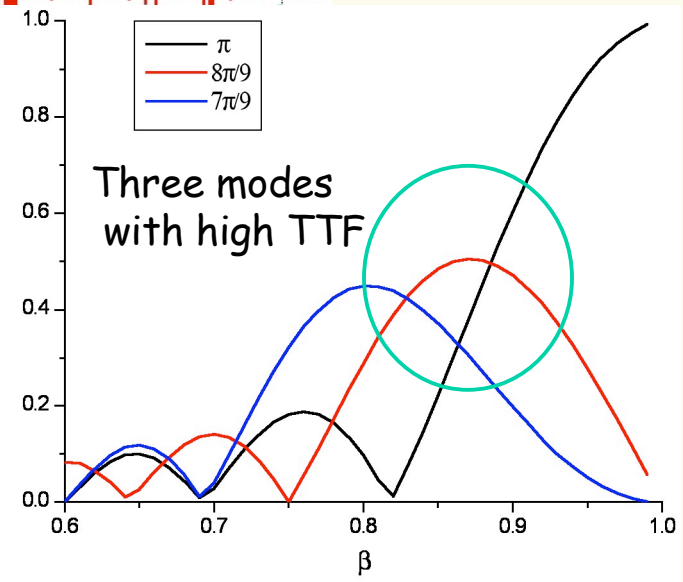
SRF Cavity Response



Solution: match beam current rise-time to the Vector Modulator rise-time

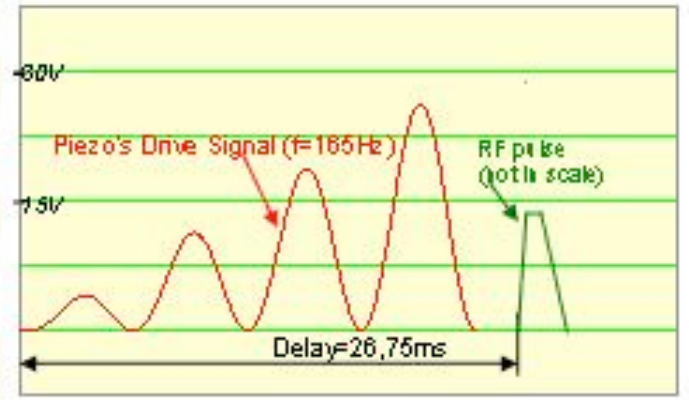
Beam Chopper Harmonics and SRF Cavity Passband Modes

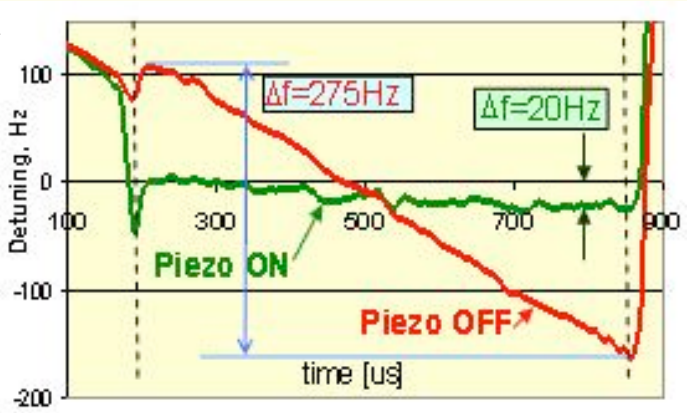


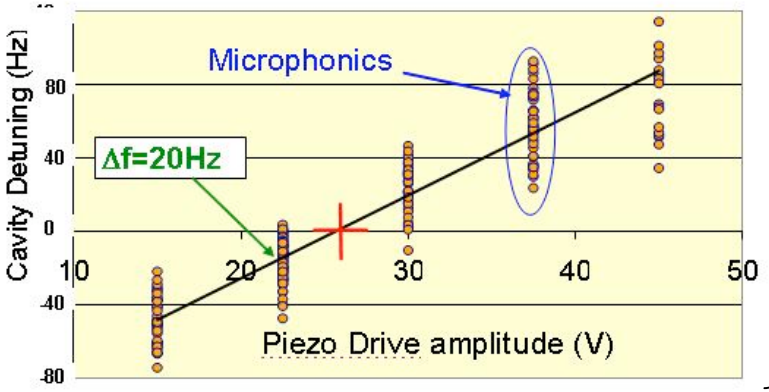


For cavities operating at less than β=1, π or 8π/9 mode, the beam chopper harmonics will excite other pass-band modes. These modes are accelerating and will need to be controlled

Lorentz Force Compensation in CCII







Cavity Vector Calibration

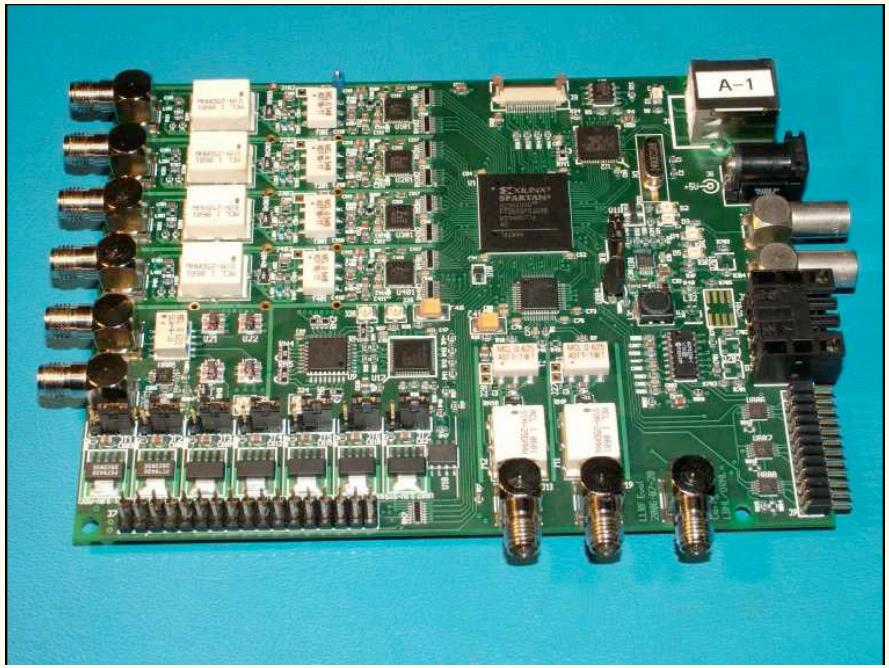
Traditional calibration methods

- *Beam energy measured downstream of the cavity*
  - *Can't drive individual cavities*
- *Beam loading cavity vector measurement*
  - *Needs well understood beam vector*
  - *Works best with high Q cavities*

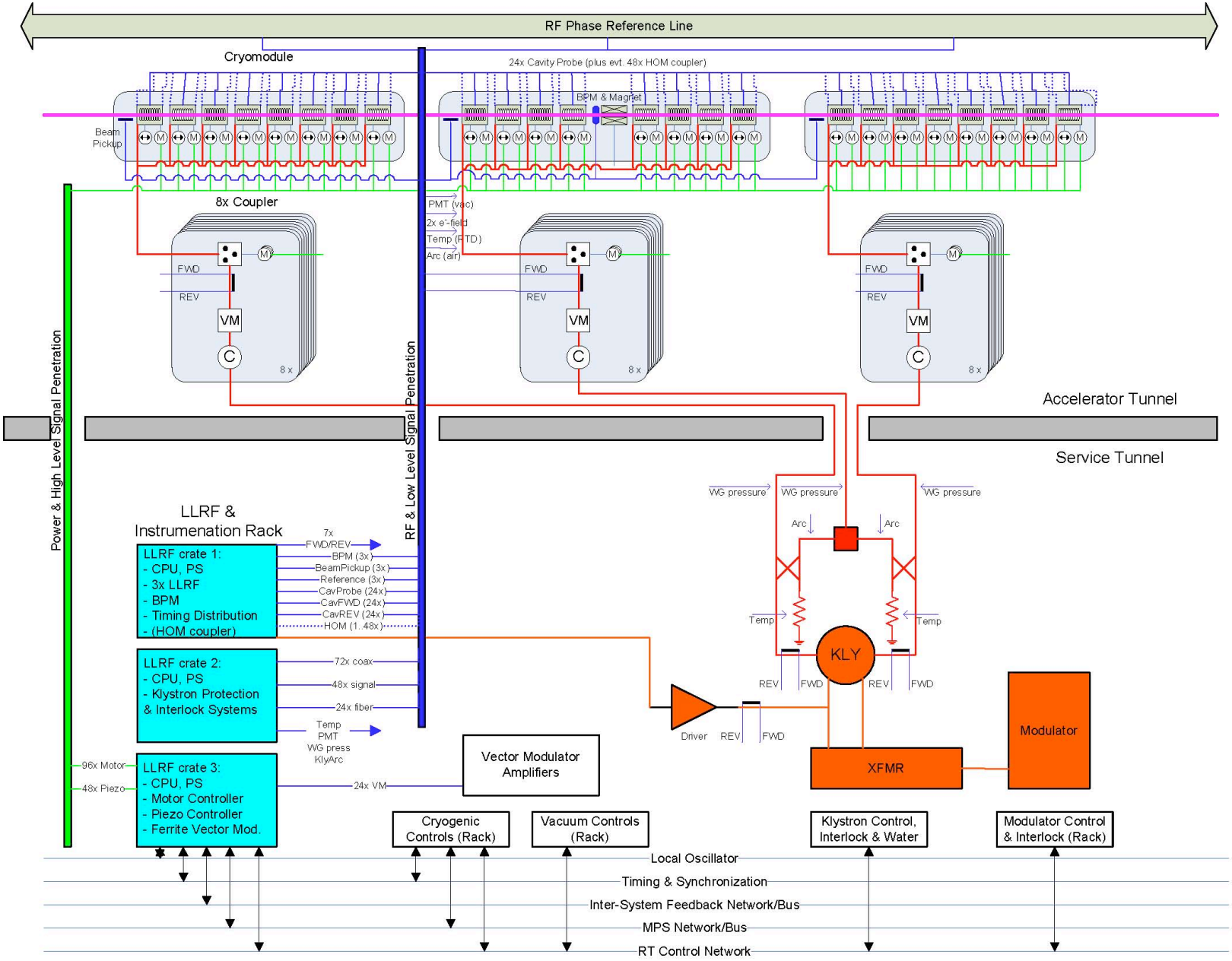
Study program needed

HINS LLRF –near term

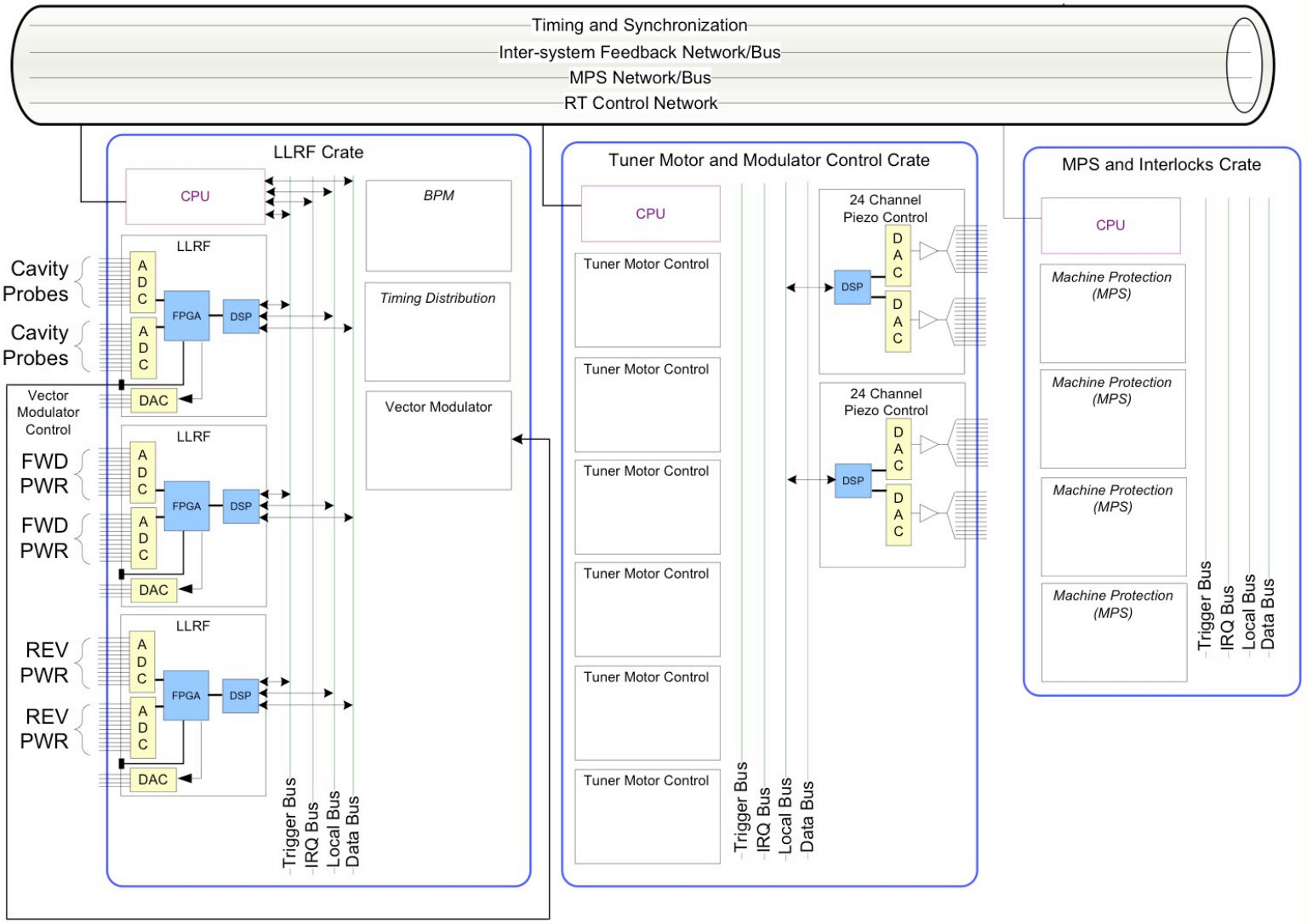
- SNS System modified for 325MHz
  - Complete, operation proven
  - Will not support multi-cavities/klystron
- LBNL - LLRF4
  - Has some field testing and is a proof of principle design
  - Will take further hardware and software development



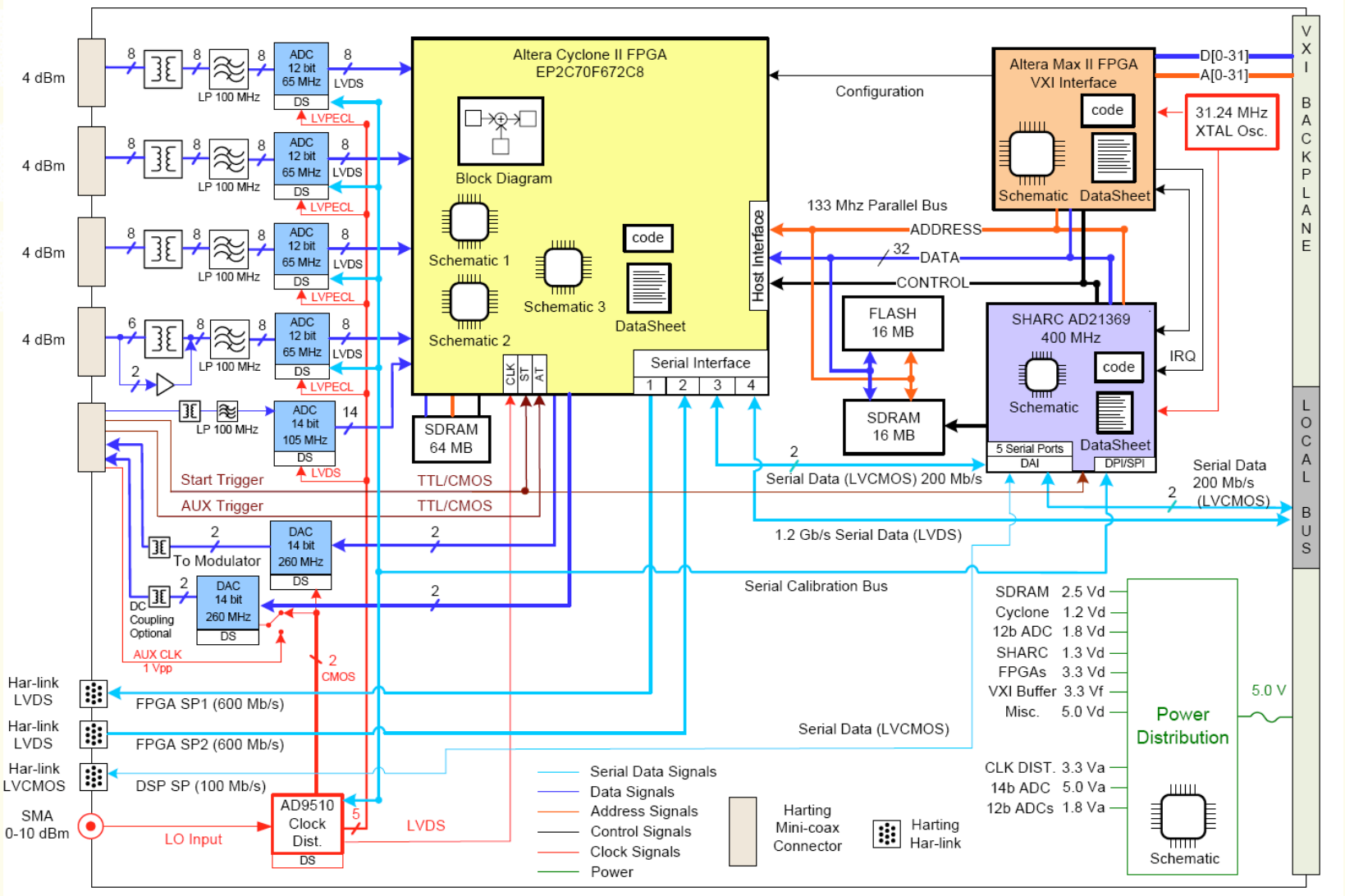
ILC Style Linac Sections



Rack Level Block Diagram

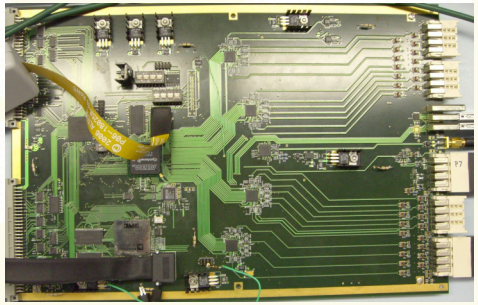


33 Channel Controller (MFC)



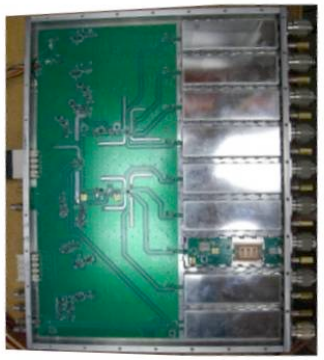
8 Ch Receiver and MFC

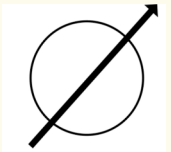
Multi-Channel Field Control Module

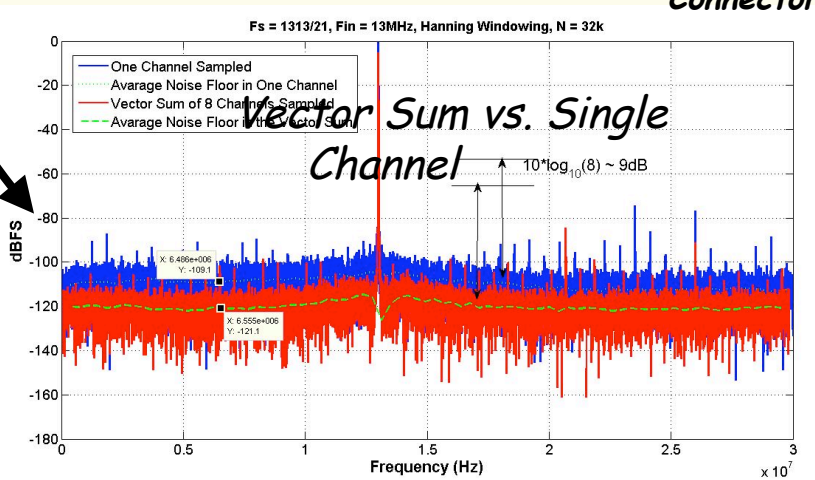


Harting IF Mini-coax Connector

8 Channel Rc







Measured SNR for one channel (12bit ADC):

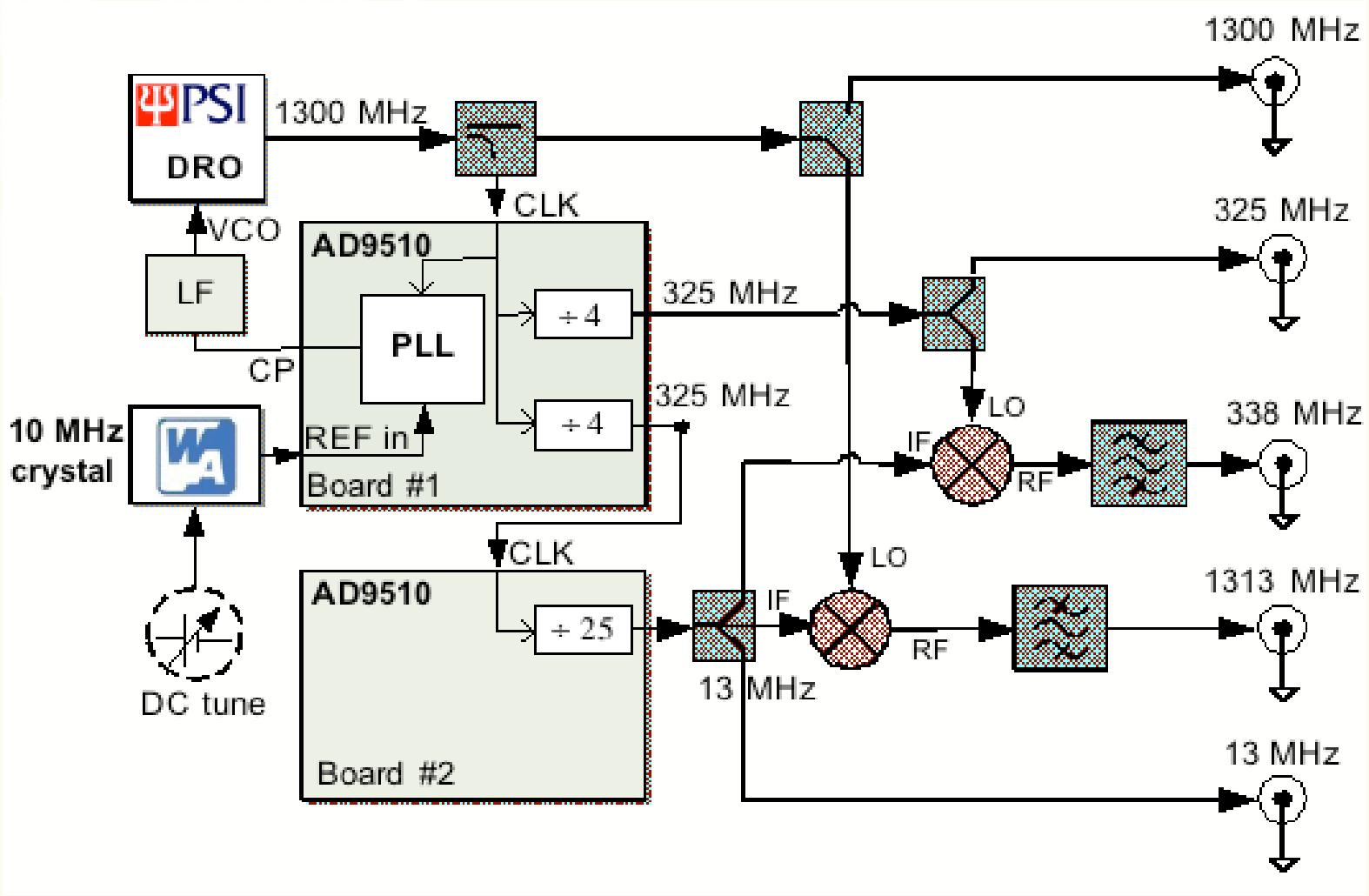
SNR@fs/2 = 112dB - 10log10(32k/2) = 70dB

Measured SNR for vector sum (8x12bit ADC):

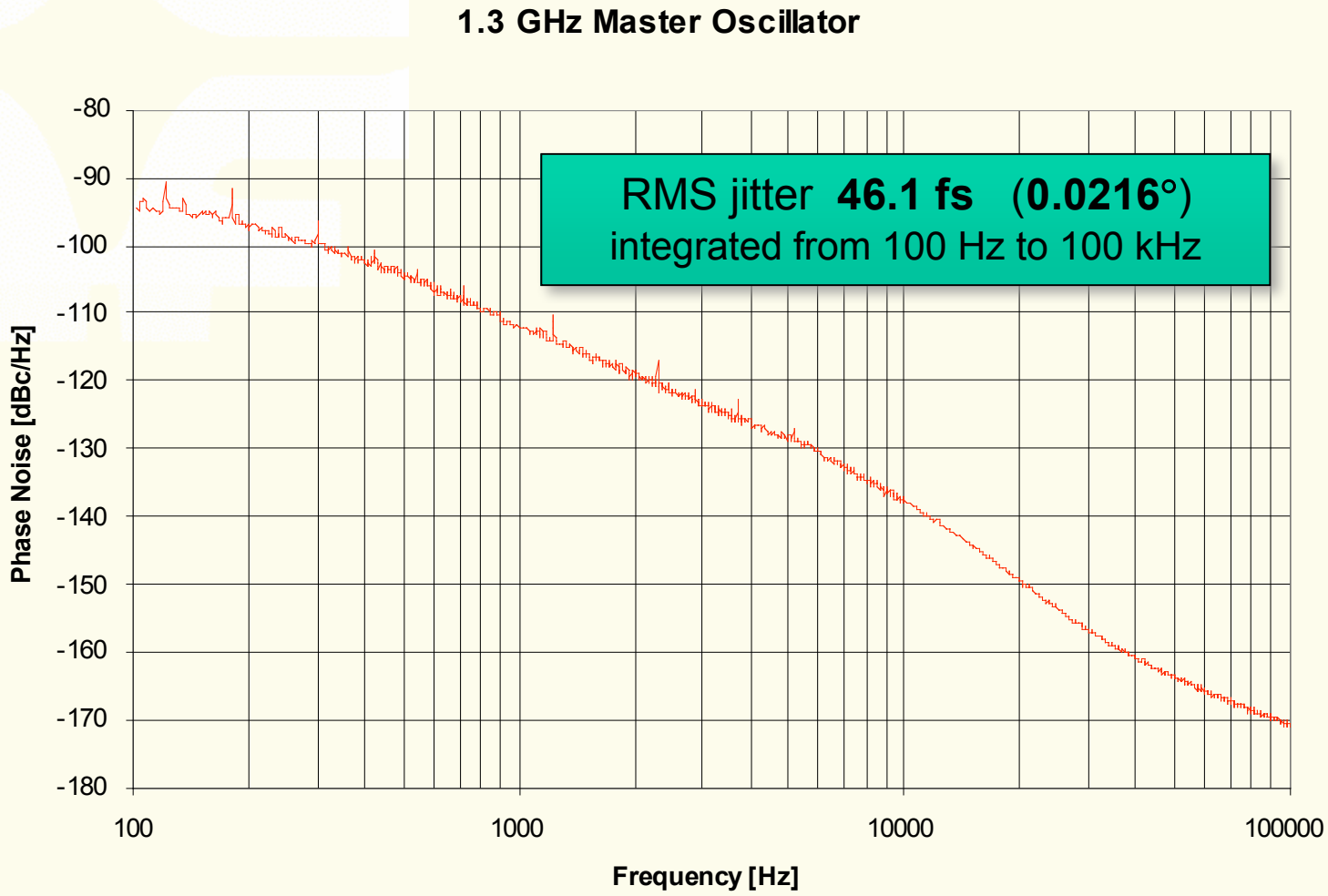
SNR@fs/2 + 10log10(8) = 79dB

The SNR -156dBc/Hz (0.0016% BW:1MHz) is expected.

Low Noise Master Oscillator



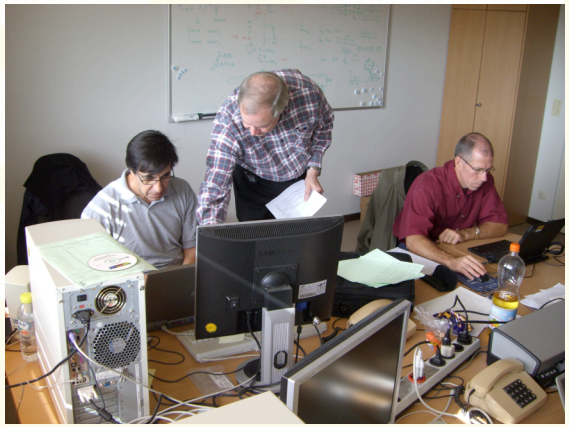
Phase Noise of 1300 MHz Master Oscillator

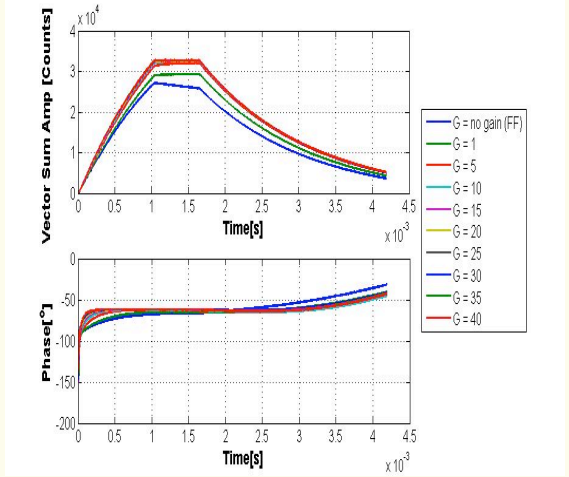


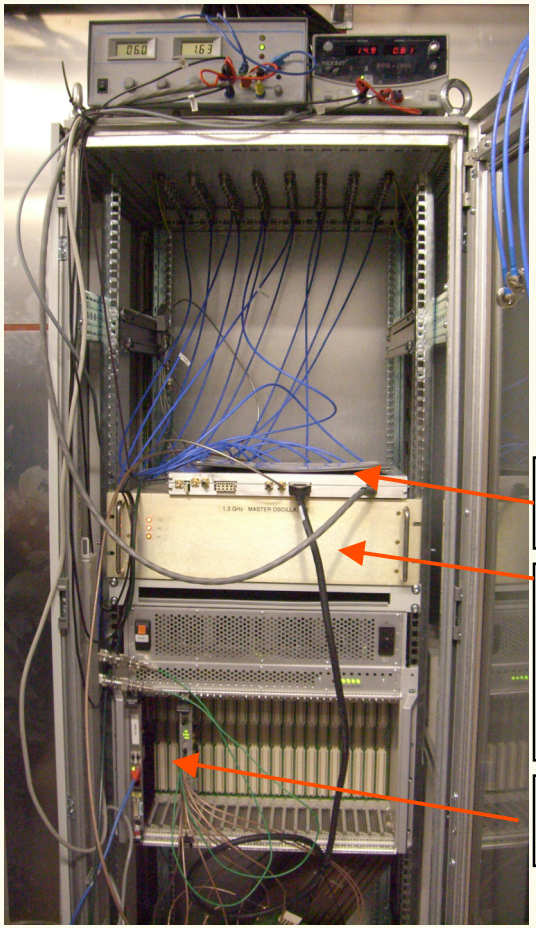
LLRF Team

- AD/RF/LLRF Group:
  - Julien Branlard, Paul Joireman, Uros Mavric, Vitali Tupikov, Philip Varghese, Barry Barnes, Dan Klepec
- TD
  - Ruben Carcagno, Warren Shappart, Yuriy Pischalkov, Darryl Orris
- CD
  - Gustavo Cancelo, Ted Smuda, Ken Treptow
- Collaborations
  - DESY- Stephan Simrock, Frank Ludwig and many more
  - KEK - Shinichiro Michizono
  - LBNL- Alessandro Ratti, Larry Doolittle
  - SNS - Mark Crawford
  - BNL - Hengie Ma

Measurements on ACC1 at DESY







8 Channel Rc/Tx

Master Oscillator

LO Generation

ESECON

Summary

- Project X shares many of the same control issues as the ILC (by design)
- The High Power Vector Modulators and their bandwidth are key to regulation
- There are no show stoppers that we see
- Project X RF control has and will continue to benefit from collaborations

- Thank you for your attention!