RF Project Status at FNAL

Brian Chase

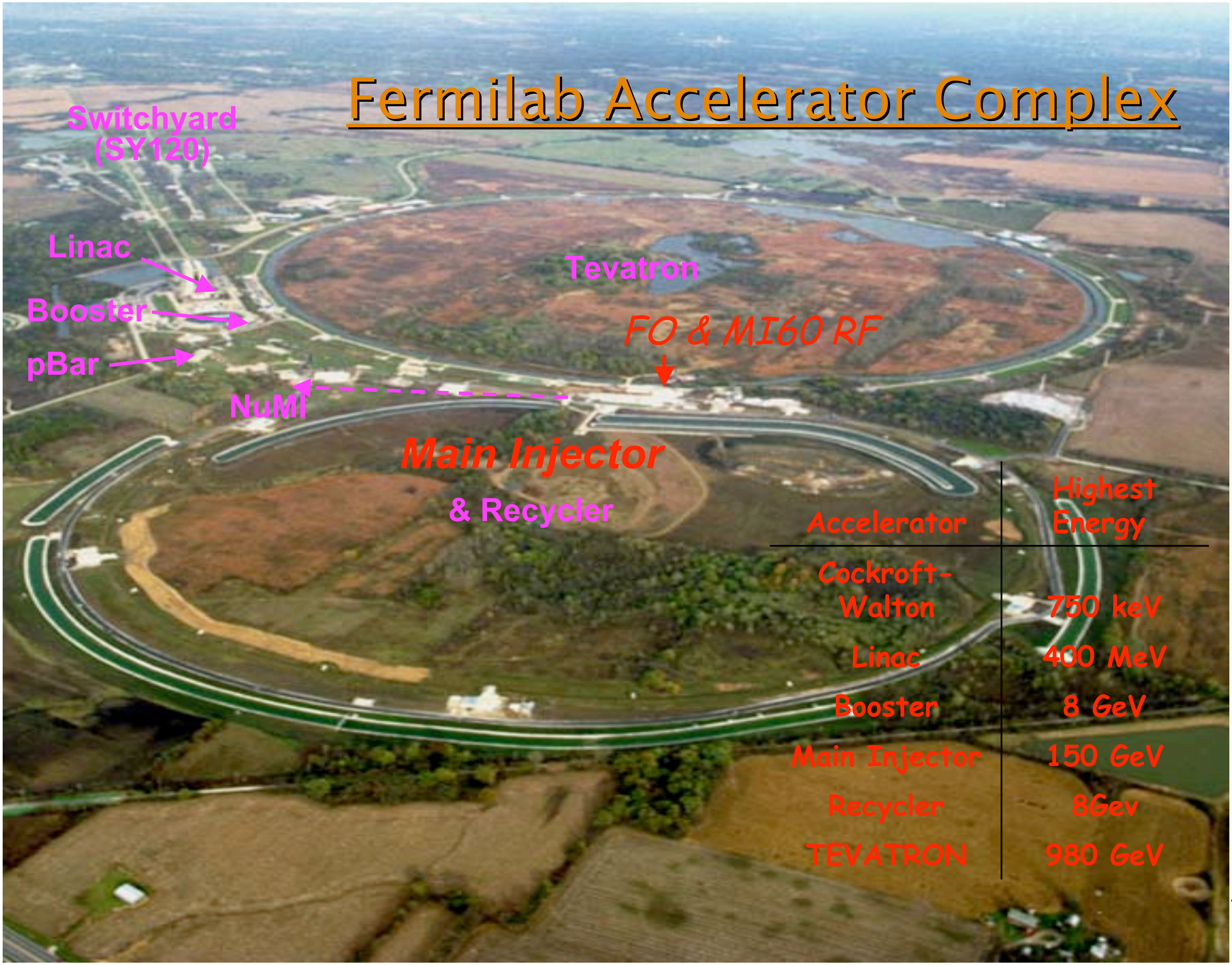
FNAL LLRF Team

- 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,
- 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, Hengie Ma

Overview

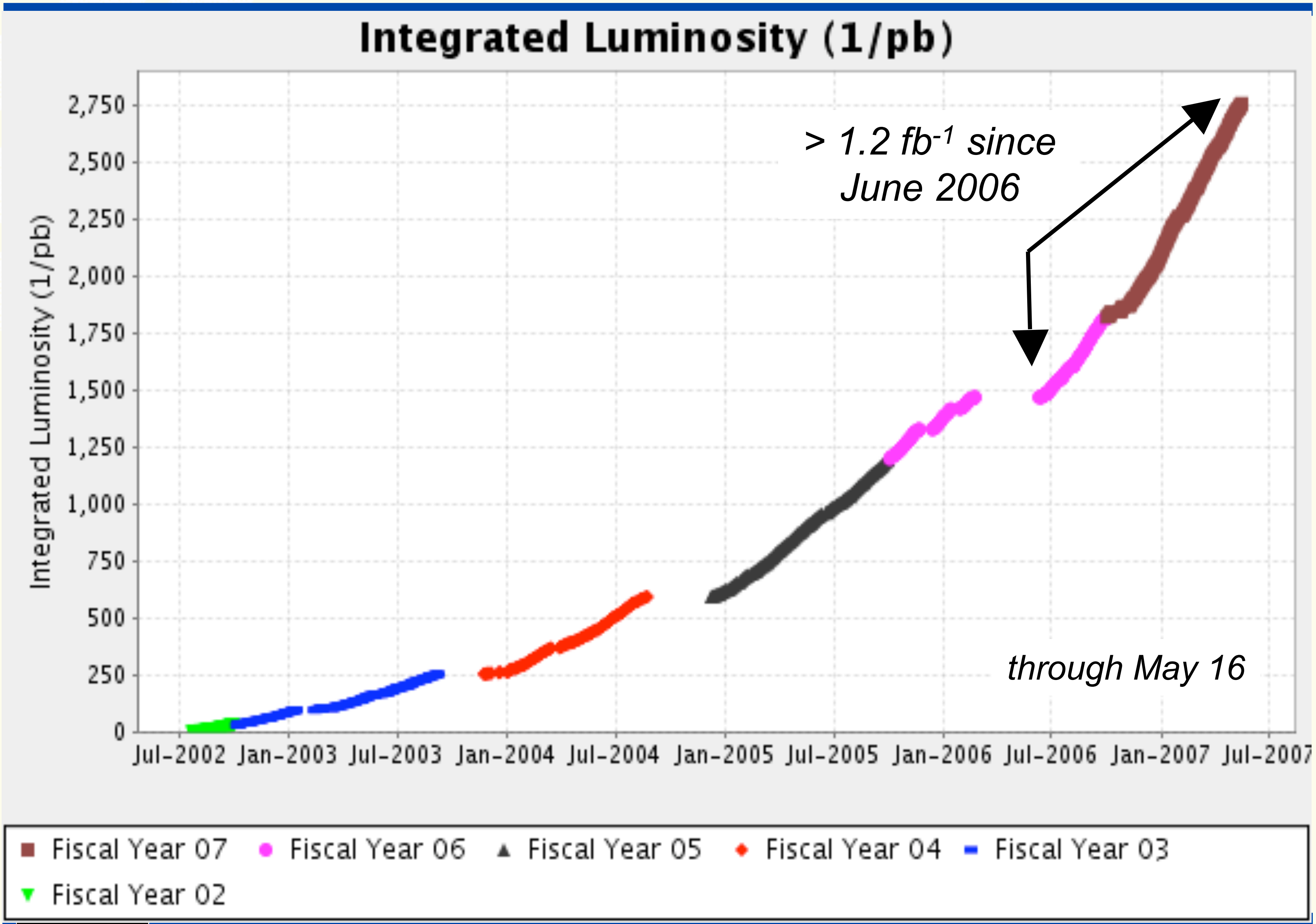
- Current operations
- RF Upgrades
- New directions
  - 8 GeV SRF linac
  - ILCTA
- Developments in LLRF Hardware

Fermilab Accelerator Complex

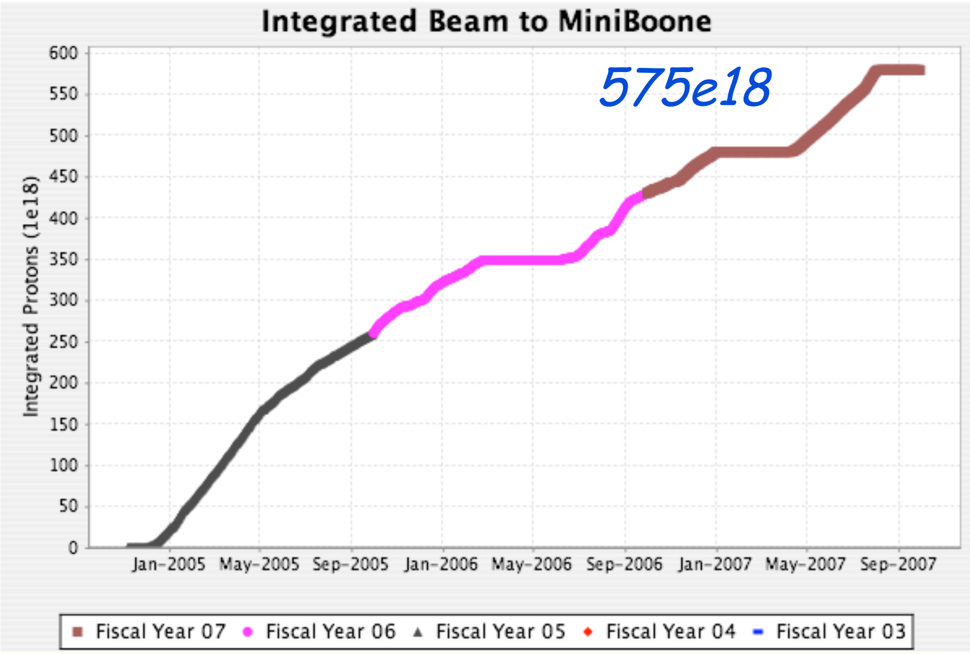


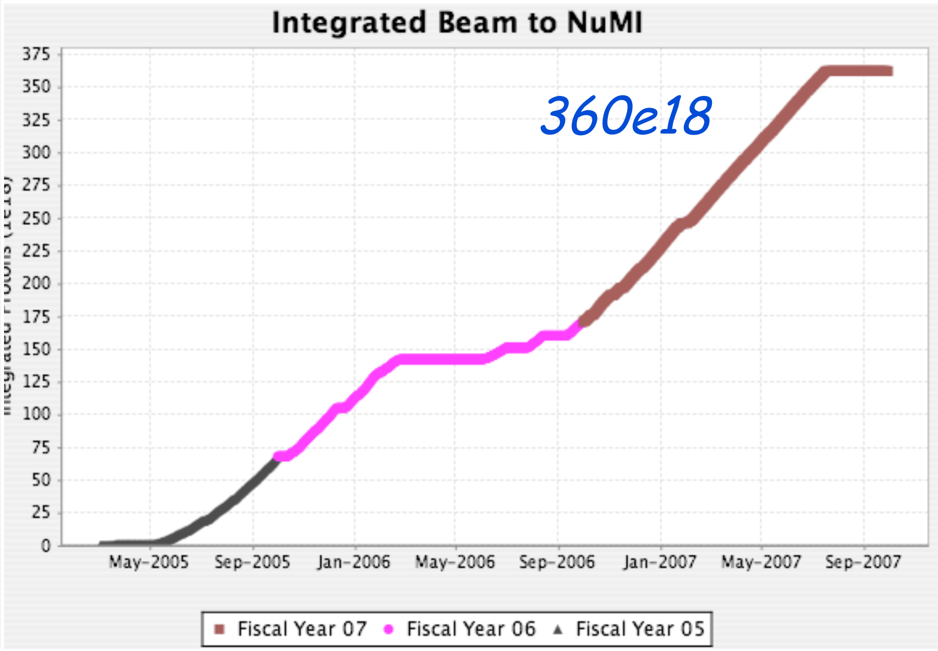
Accelerator	Highest Energy
Cockroft-Walton	750 keV
Linac	400 MeV
Booster	8 GeV
Main Injector	150 GeV
Recycler	8Gev
TEVATRON	980 GeV

Tevatron Run 2 Delivered Luminosity



Beam to Neutrino Program





RF Projects for Run II

- Recycler RF Upgrades
  - HLRF Feedback (comb filter) to flatten Pbar bunches to TeV
  - Bucket Morphing to lower longitudinal emittance
- Main Injector Upgrades

2003: Feed-Forward beam loading compensation added to HLRF fanout

2004-2005: (Slip-stacking for pBar production becomes operational)

Mid-Level RF (MRF) system bridges the gap between LLRF and HLRF

- True Global amplitude and phase control of HLRF system (previous A/B balancing)
- Fundamental shifts in HLRF station operations influenced by MRF

2005-Present: LLRF tools used to develop multi-batch slip-stacking for Neutrino Program

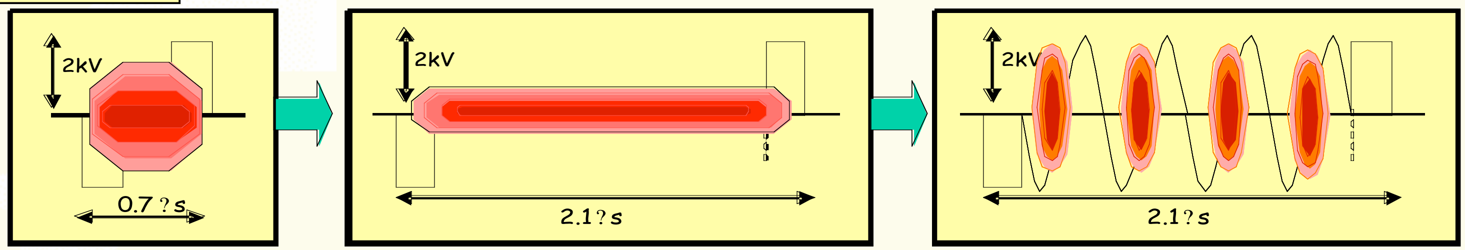
2007: Comb Filter Feedback development at the HLRF station level begins (FPGAs coming to HLRF stations)

- 201 MHz Digital Linac LLRF upgrade
  - Lower energy spread of beam to the Booster
  - Lower beam losses in the Linac

Recycler LLRF – 2.5 MHz pbar bunches by Morphing (frequency chirp)

Before March 20, 2007

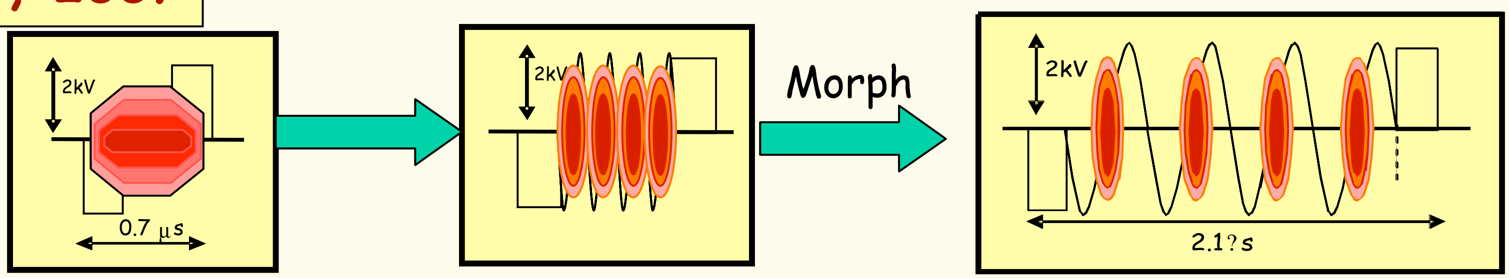
RR HLRF- (4) 50 Ohm broadband cavities
500 Vpk each



Mini-bunch after mining — Stretch — 2.5 MHz Bunches

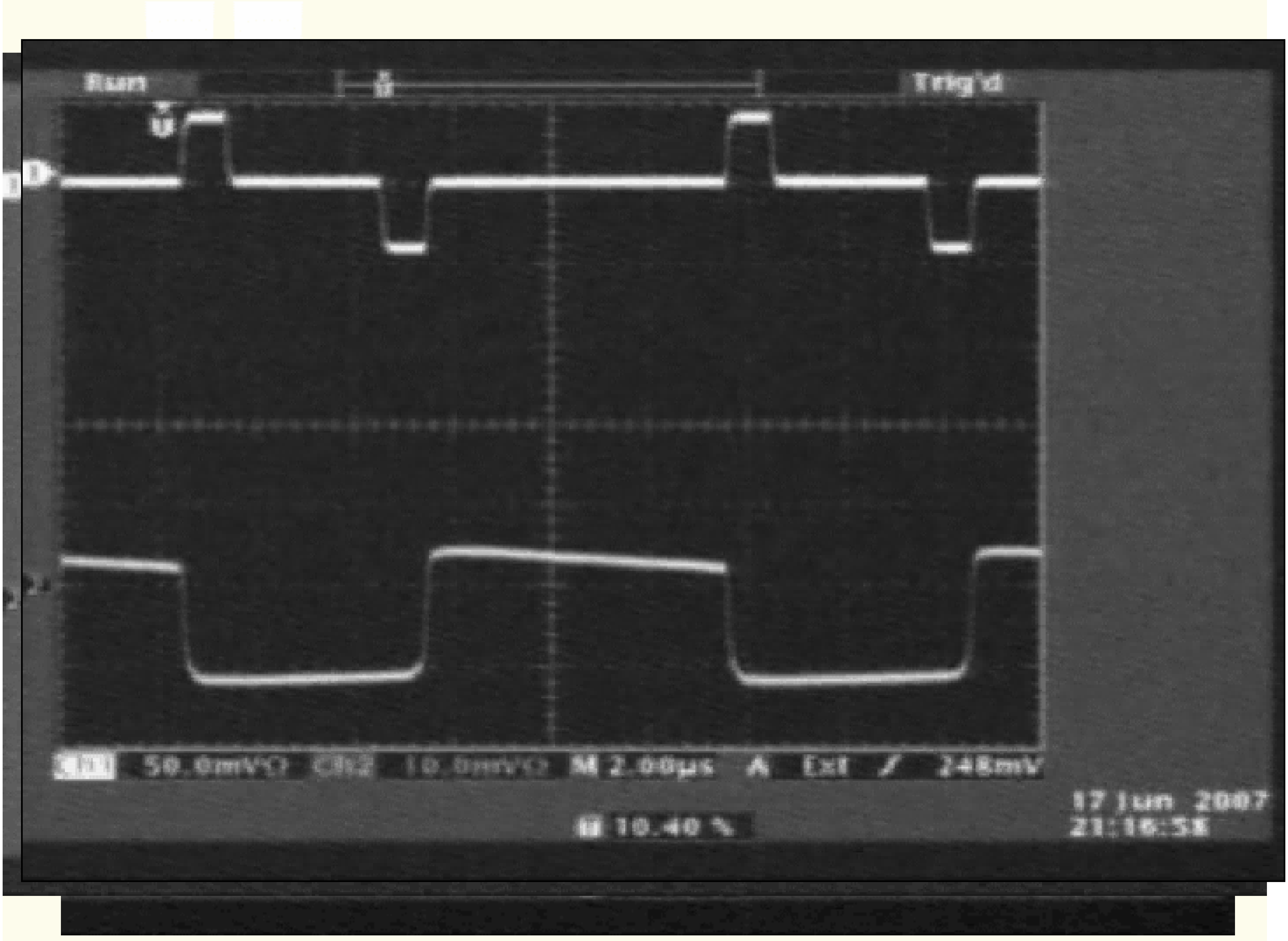
⟹ 20-30% longitudinal emittance growth; takes ~75 sec

Since March 21, 2007



Mini-bunch after mining — Capture in 7.5 MHz — 2.5 MHz Bunches

⟹ <10% longitudinal emittance growth and takes ~60 sec


Run
Trig'd
Ch1 50.0mV Ω Ch2 10.0mV Ω M 2.00µs A Ext ∕ 248mV
10.40 %
17 Jun 2007
21:16:58

RF Projects for Run II

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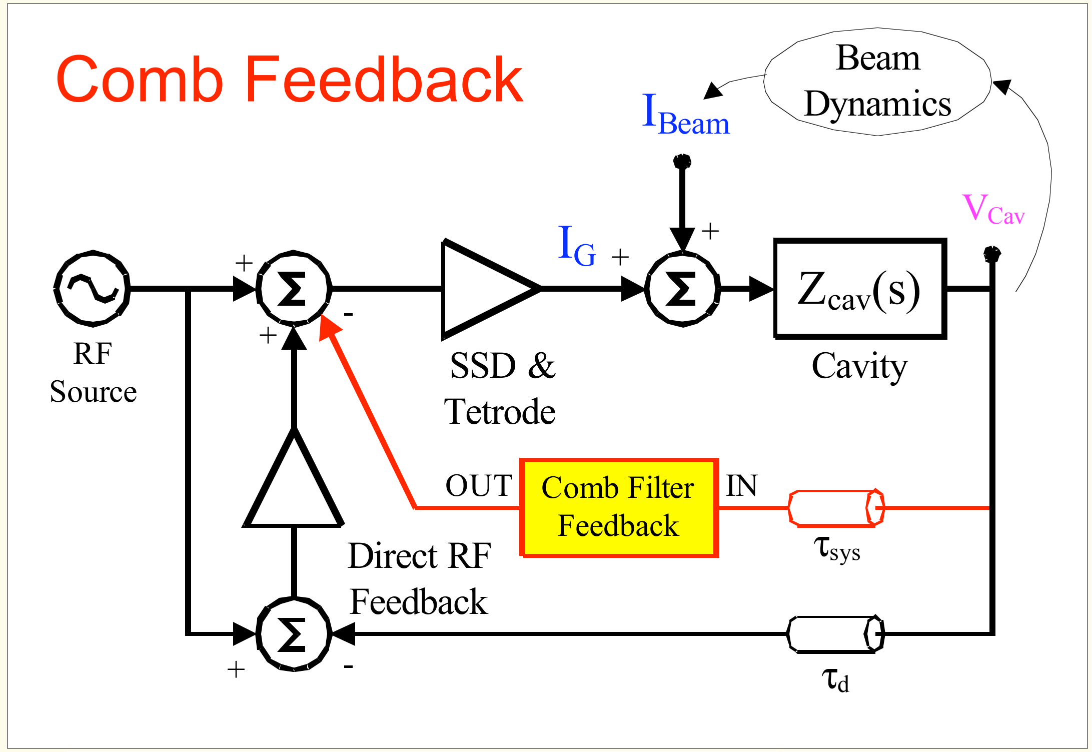
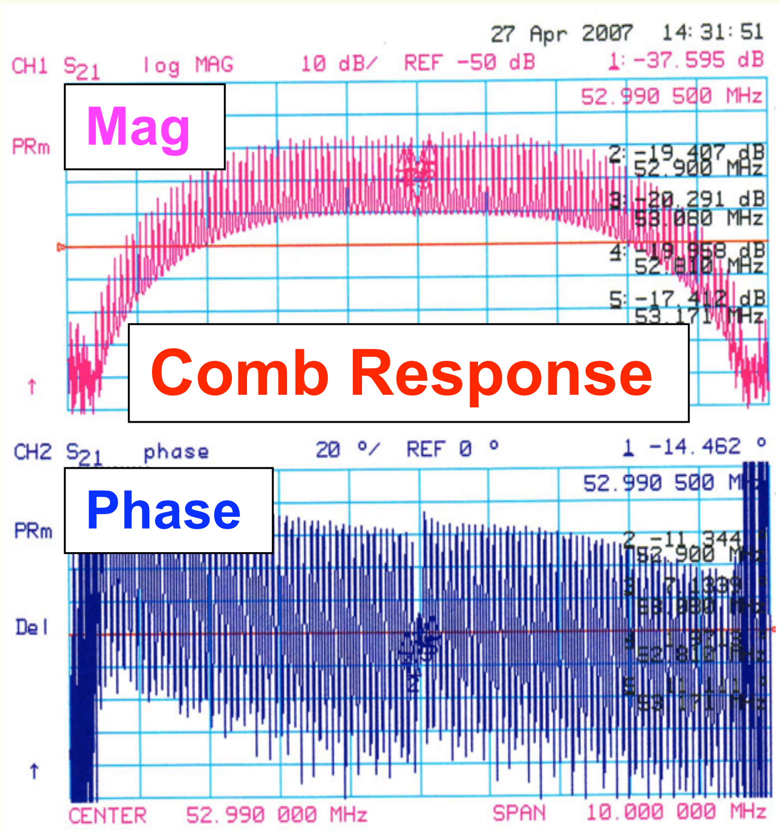
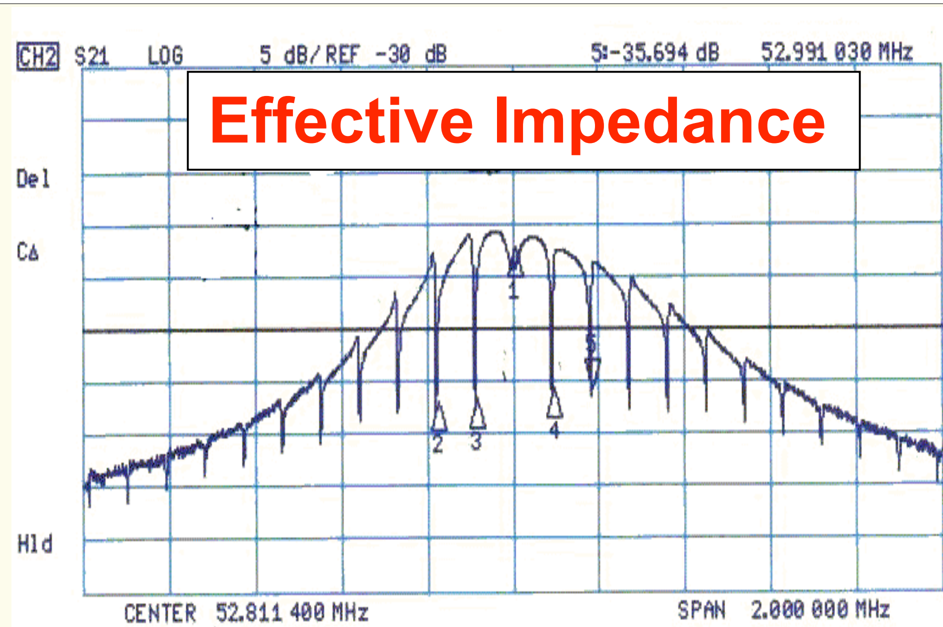
Single Peak Comb Filter Feedback:

$$H(s) = \frac{G}{1 - K e^{-sT_{rev}}} \cdot e^{-sT_{rev}}$$

- Pioneered by Boussard (CERN)
- Provides loop gain at revolution harmonics
  - Reduces periodic beam loading
  - For low Q_s reduces growth rates







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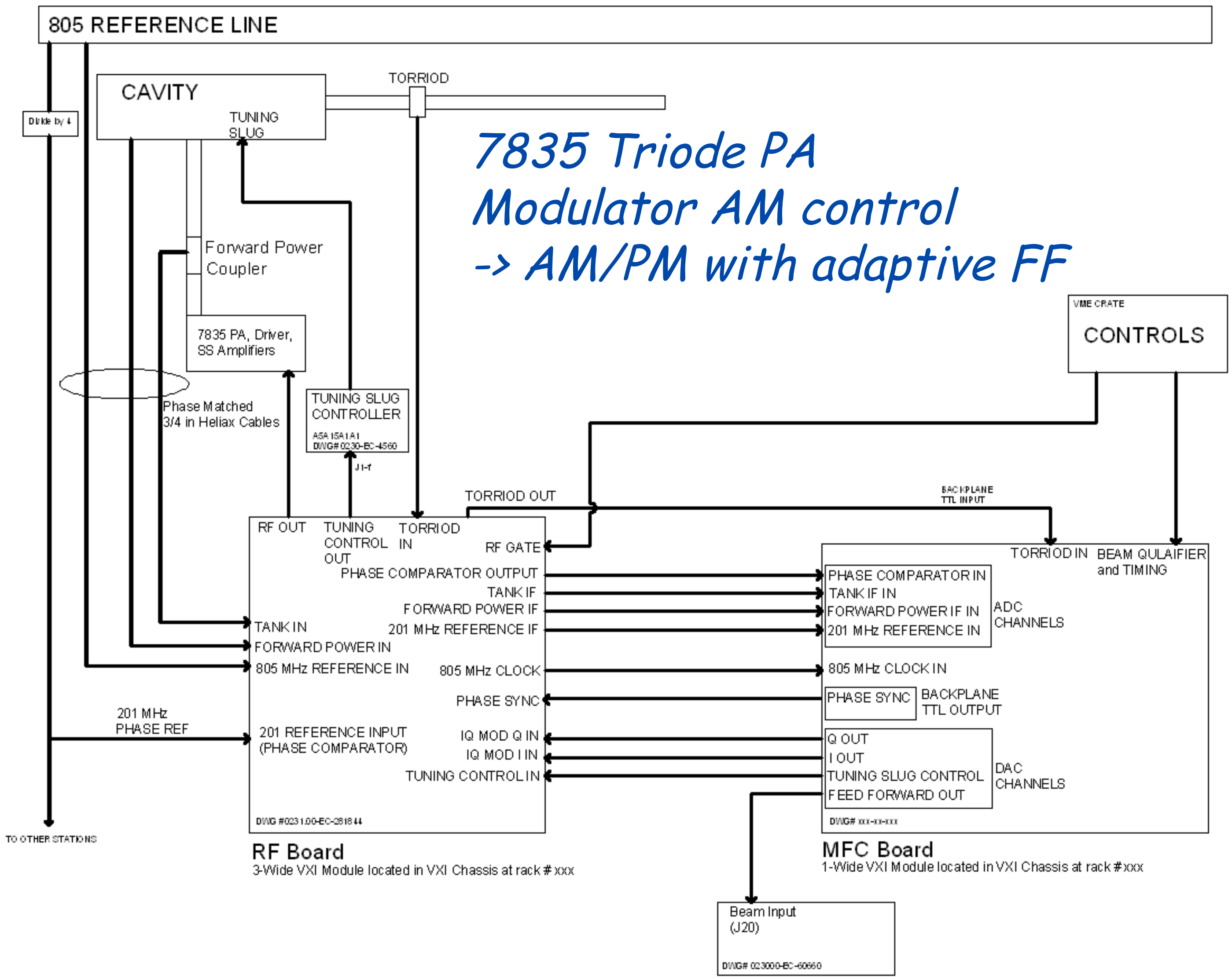
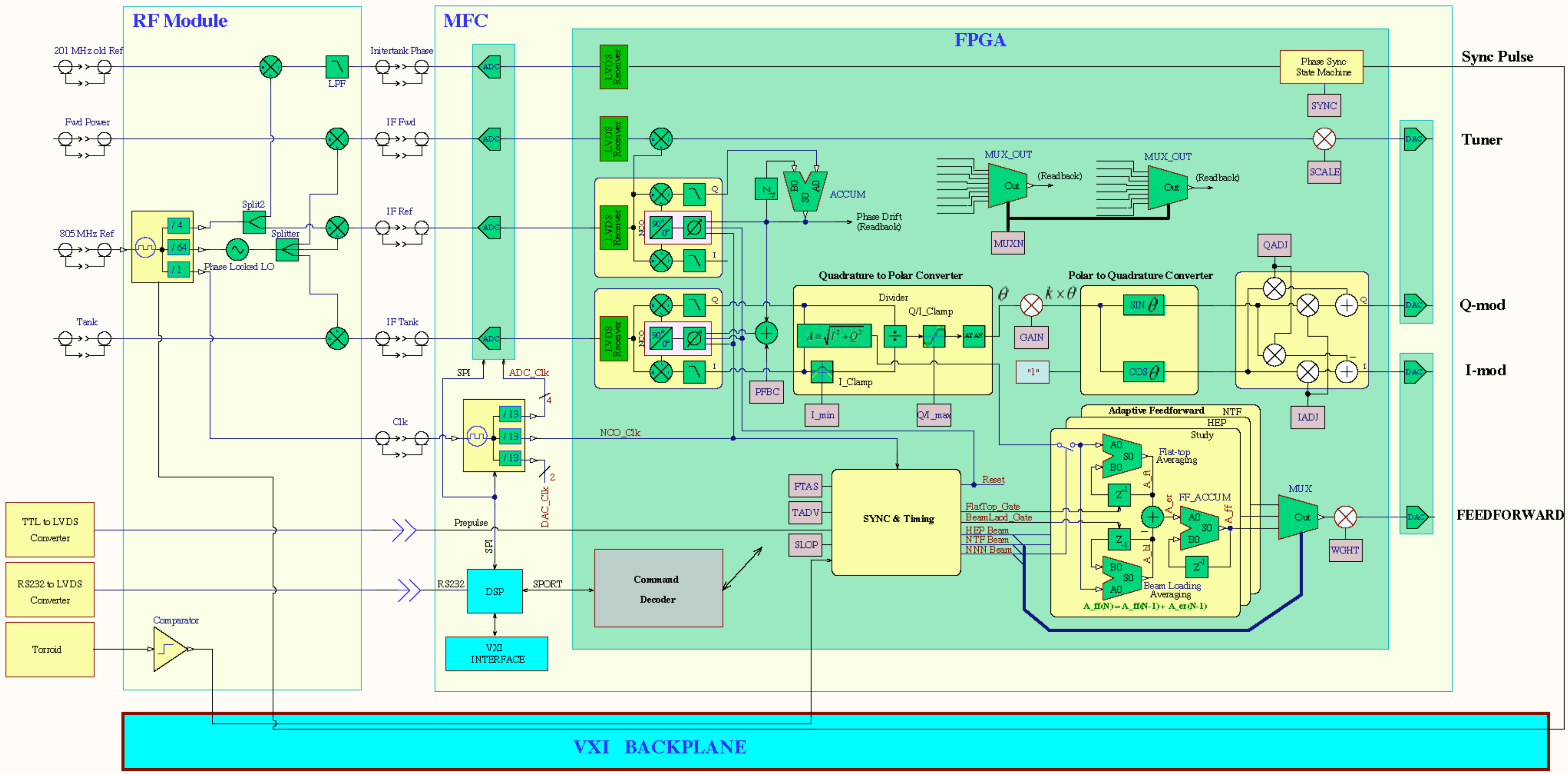
- 201 MHz Digital Linac LLRF upgrade
  - Improve stability and reliability
  - Lower energy spread of beam to the Booster
  - Lower beam losses in the Linac

201 MHz DTL Linac LLRF Upgrade

7835 Triode PA
Modulator AM control
-> AM/PM with adaptive FF



Linac Processing Block Diagram



Phase loop: Clamp I to > .2 FS -> no phase chatter!

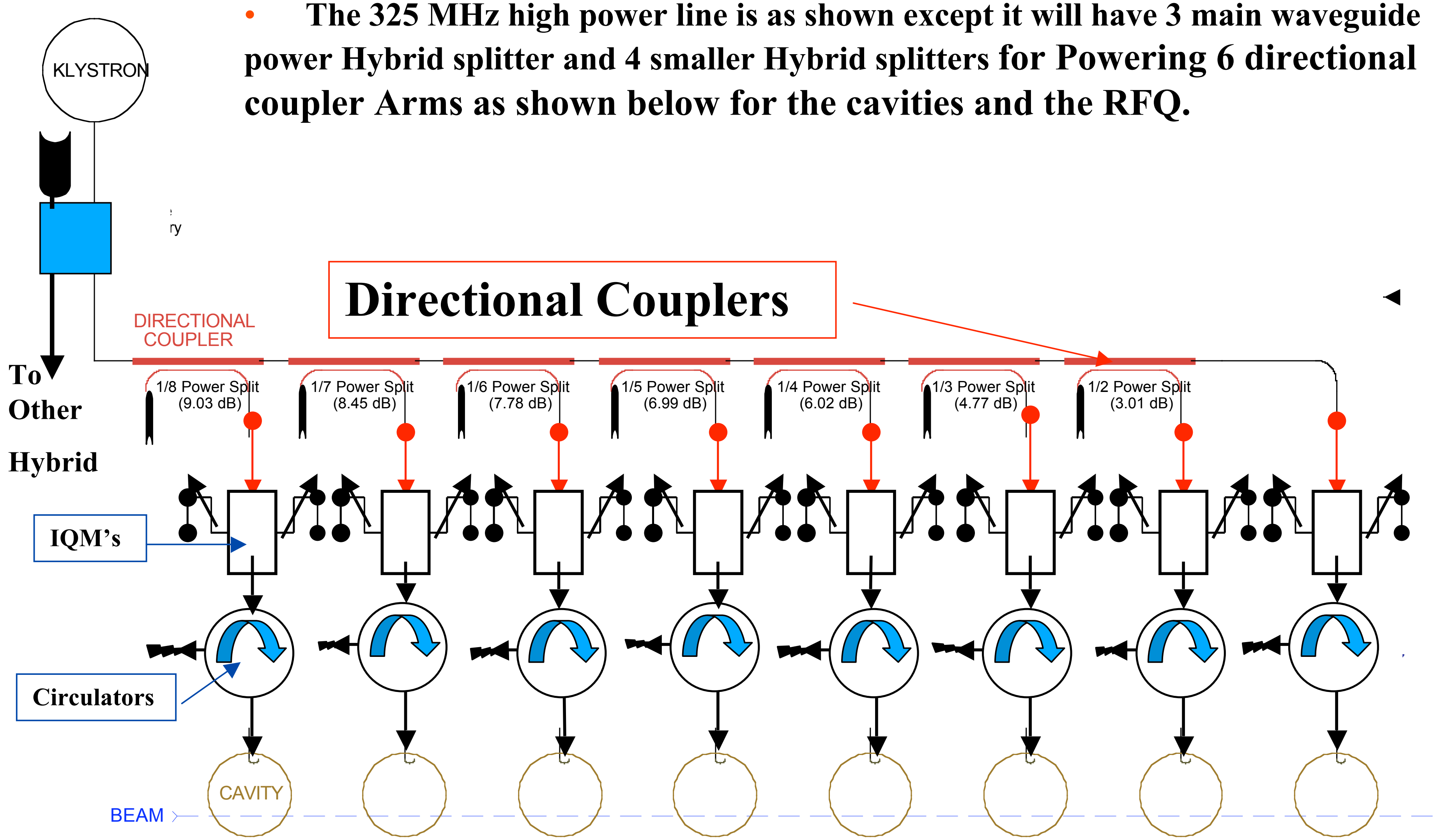
Fermilab's New Directions

- High Intensity Neutrino Source
  - HINS
  - Project X - AKA Proton Driver
    - *8 GeV SRF proton linac with ILC like RF stations*
- ILC Development
  - Vertical test stand, Horizontal test stand
  - ILCTA-NML test string
  - Fermilab is the America's choice of ILC site
    - LLRF efforts are on the ILC Engineering Design Report

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

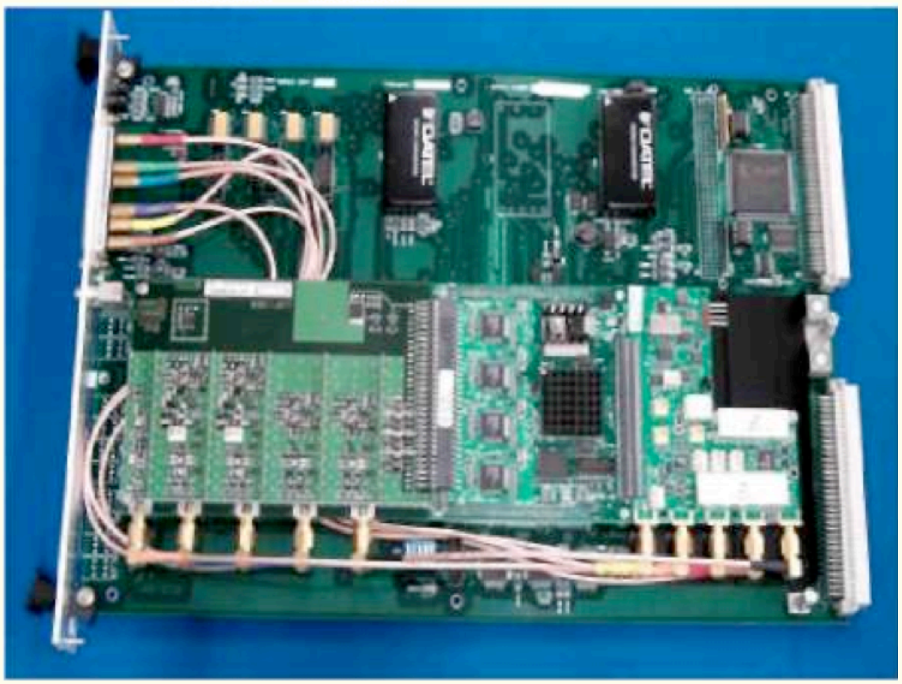
This is simplified Layout of the high power RF distribution system

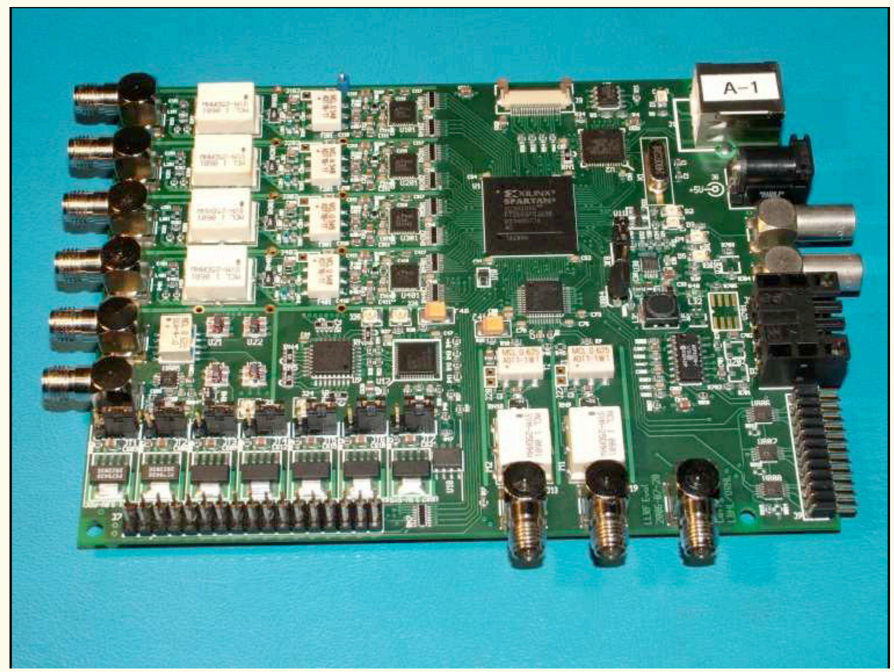
- The 325 MHz high power line is as shown except it will have 3 main waveguide power Hybrid splitter and 4 smaller Hybrid splitters for Powering 6 directional coupler Arms as shown below for the cavities and the RFQ.



HINS LLRF –near term

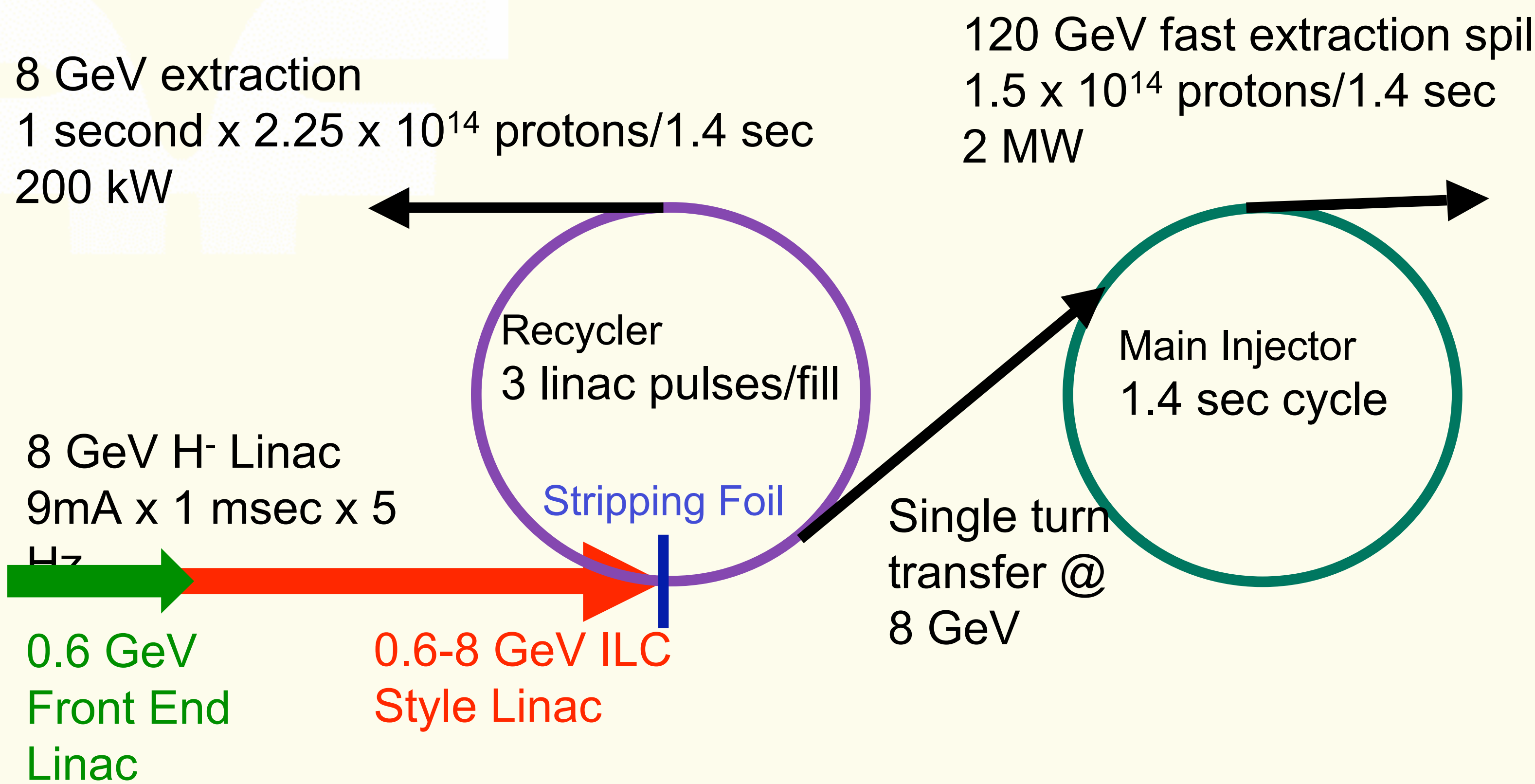
- SNS System modified for 325MHz
  - Complete, operation proven
  - Will not support multi-cavities/klystron
- LBNL - LLRF4
  - Has some field testing and is a proof of principle design
  - Will take further hardware and software development



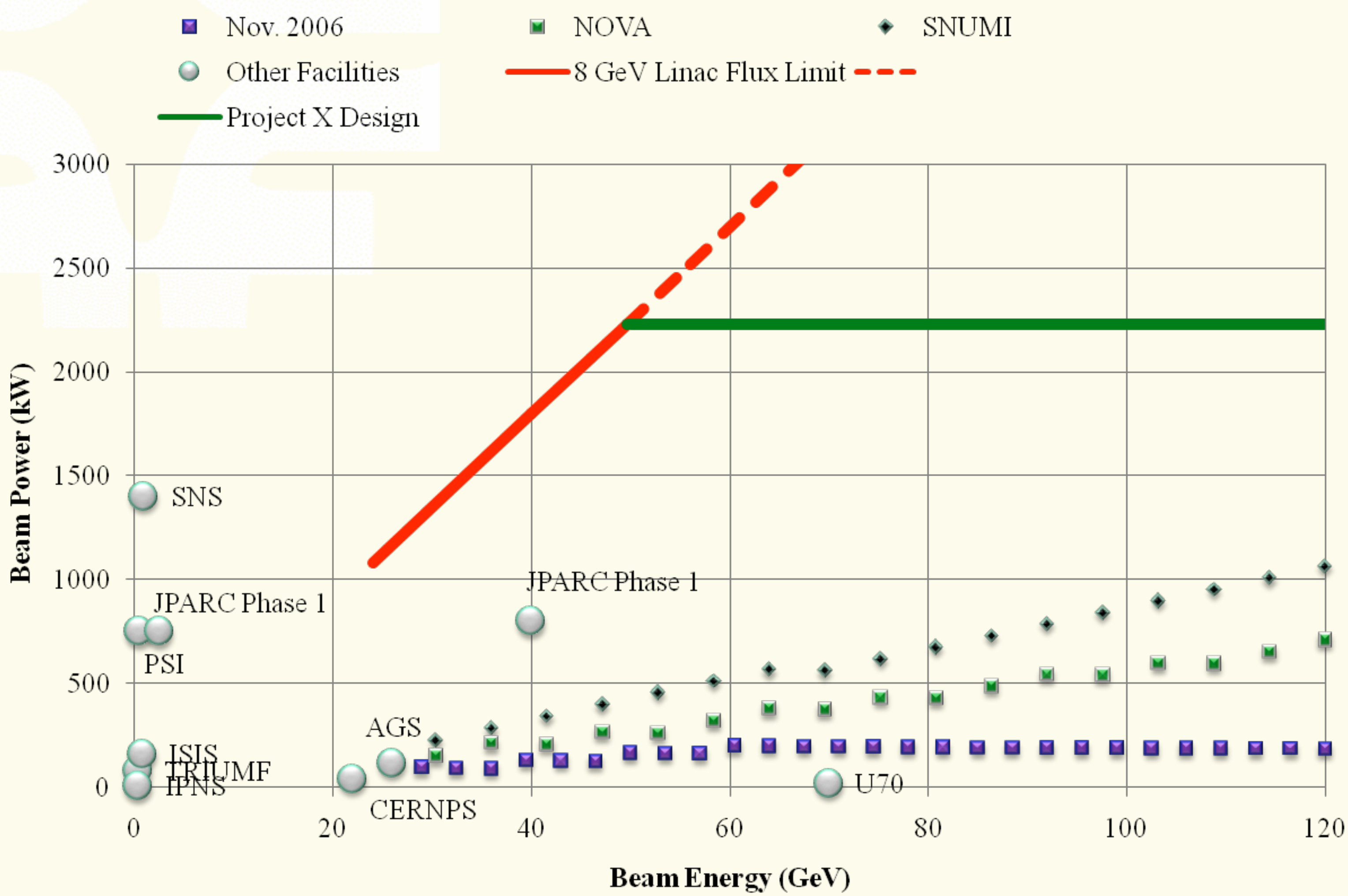


Project X Layout

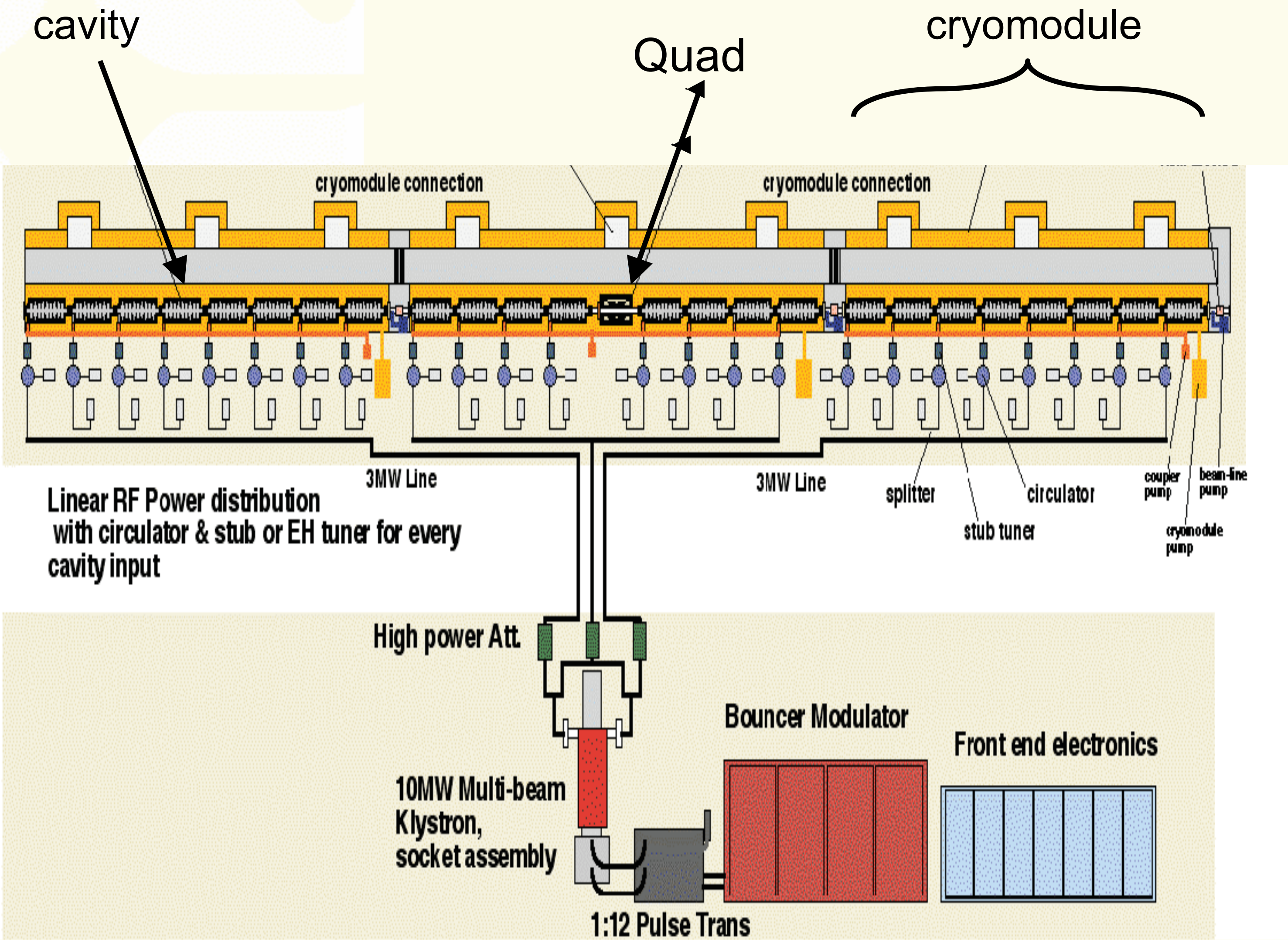
Proton linac and ILC test string



Proton Beam Power



One ILC RF Unit



Acceleration in the Main Injector – RF System

Project X

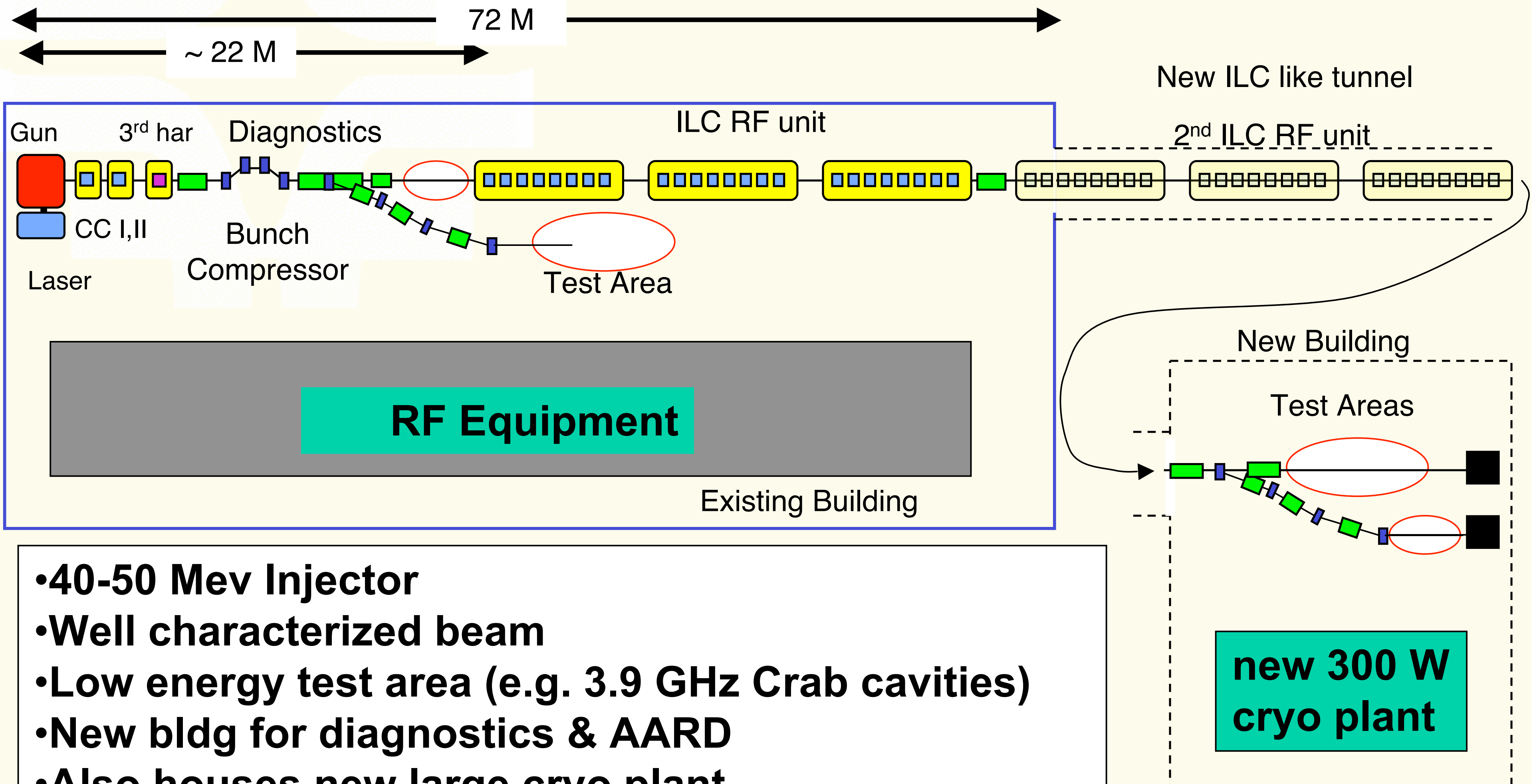
	Present	MI upgrade
Harmonic number	588	
Frequency swing from injection to extraction, MHz	52.811 - 53.103	
Number of cavities	18	18
Shunt impedance per cavity, (R/Q)*Q, kΩ	500	100
Loaded Q	4000	4000
Maximum operating parameters		
RF voltage, MV	4.2	4.2
Peak RF power, MW	3.2	13
Average RF power, MW	0.8	5
Operating parameters required by the presented accelerating scenario		
RF voltage, MV		3.43
Maximum RF power, MW		10.59
Maximum power transferred to the beam, MW		7.32
Maximum power lost in the cavity walls, MW		3.27
Average RF power, MW		4.1

Table 5.2 Parameters of the first harmonic RF system.

	Present	MI upgrade
Frequency swing from injection to extraction, MHz	105.622 - 106.206	
Number of cavities		5
Shunt impedance per cavity, (R/Q)*Q, kΩ		100
Loaded Q		4000
Maximum operating parameters		
RF voltage, MV		1.2
Peak RF power, MW		1.5
Average RF power, MW		0.9
Operating parameters required by presented accelerating scenario		
RF voltage, MV		1.16
Maximum RF power, MW		1.34
Maximum power transferred to the beam[3], MW		-1.83
Maximum power lost in the cavity walls, MW		1.34

Table 5.3 Parameters of the second harmonic RF system

ILCTA_NML



- •40-50 Mev Injector
- •Well characterized beam
- •Low energy test area (e.g. 3.9 GHz Crab cavities)
- •New bldg for diagnostics & AARD
- •Also houses new large cryo plant

Purpose of ILCTA_NML

- Provide ILC like beam for SCRF cavity tests
  - Full Beam loading at Buncher section
- Provide a facility for use by ILC collaborators
  - Crab cavities
  - Diagnostics
  - Personnel training
  - Accelerator R&D

LLRF Focus for ILCTA_NML

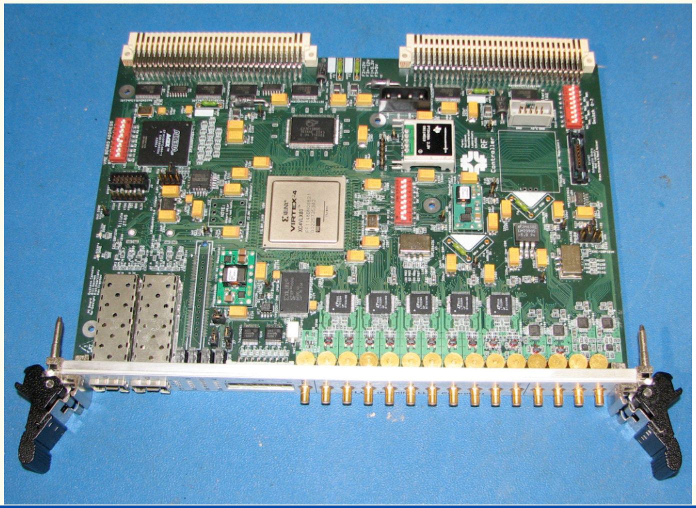
- Demonstrate vector control that meets the Main Linac and Buncher Section
  - Requires Reference Line, LO, FF,FB, piezo control
  - Vector Sum Calibration
- Demonstrate the baseline design and cost model

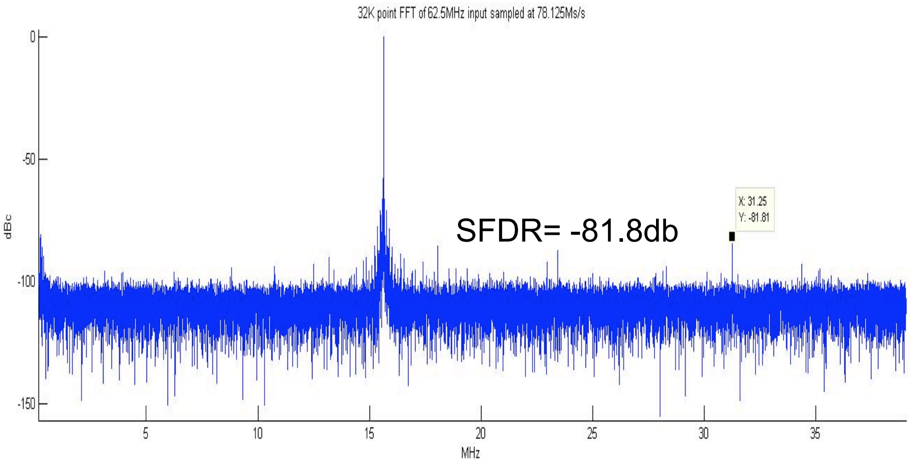
TABLE 3.9-1
Summary of tolerances for phase and amplitude control. These tolerances limit the average luminosity loss to <2% and limit the increase in RMS center-of-mass energy spread to <10% of the nominal energy spread.

Location	Phase (degree)		Amplitude (%)		limitation
	correlated	uncorr.	correlated	uncorr.	
Bunch Compressor	0.24	0.48	0.5	1.6	timing stability at IP (luminosity)
Main Linac	0.35	5.6	0.07	1.05	energy stability $\leq 0.1\%$

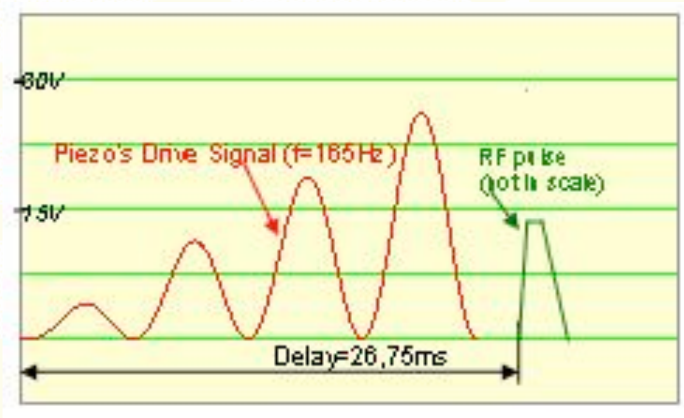
ILCTA LLRF

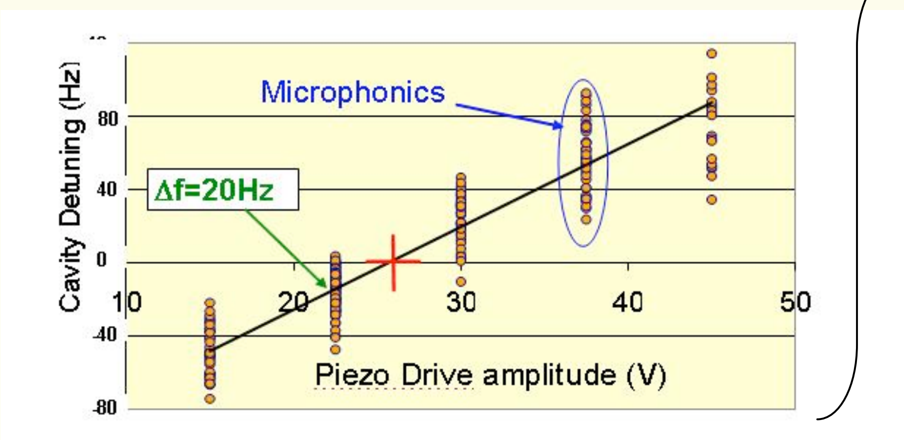
- Started with DESY Simcon3.1 cards at the AO Photo-injector and Capture Cavity 2
- Replaced by Fermilab ESECON cards
- Talk by Gustavo Cancelo
  - Hardware and firmware design overview.
  - ESECON functionality.
  - Firmware design tools: Simulink/Matlab/SysGen.
  - ESECON noise measurements.
  - ESECON integration in A0 LLRF systems.
  - Measurements done at DESY-FLASH with cryomodule ACC1.

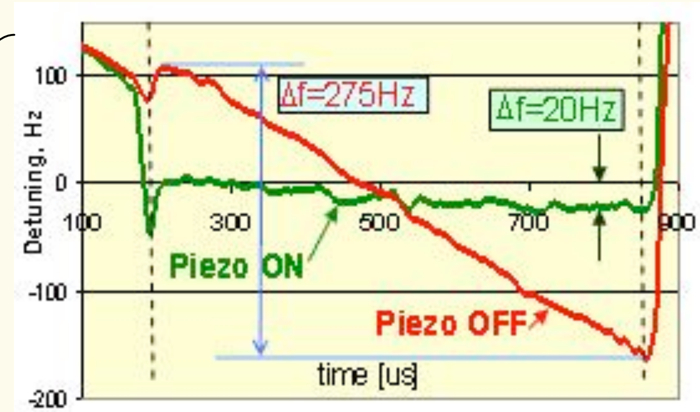


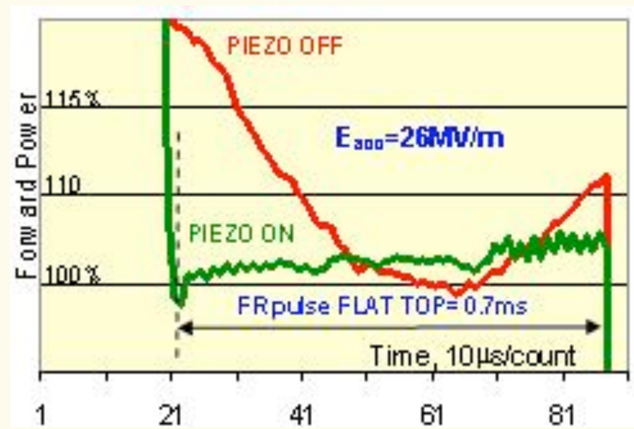


Lorentz Force Compensation in CCII





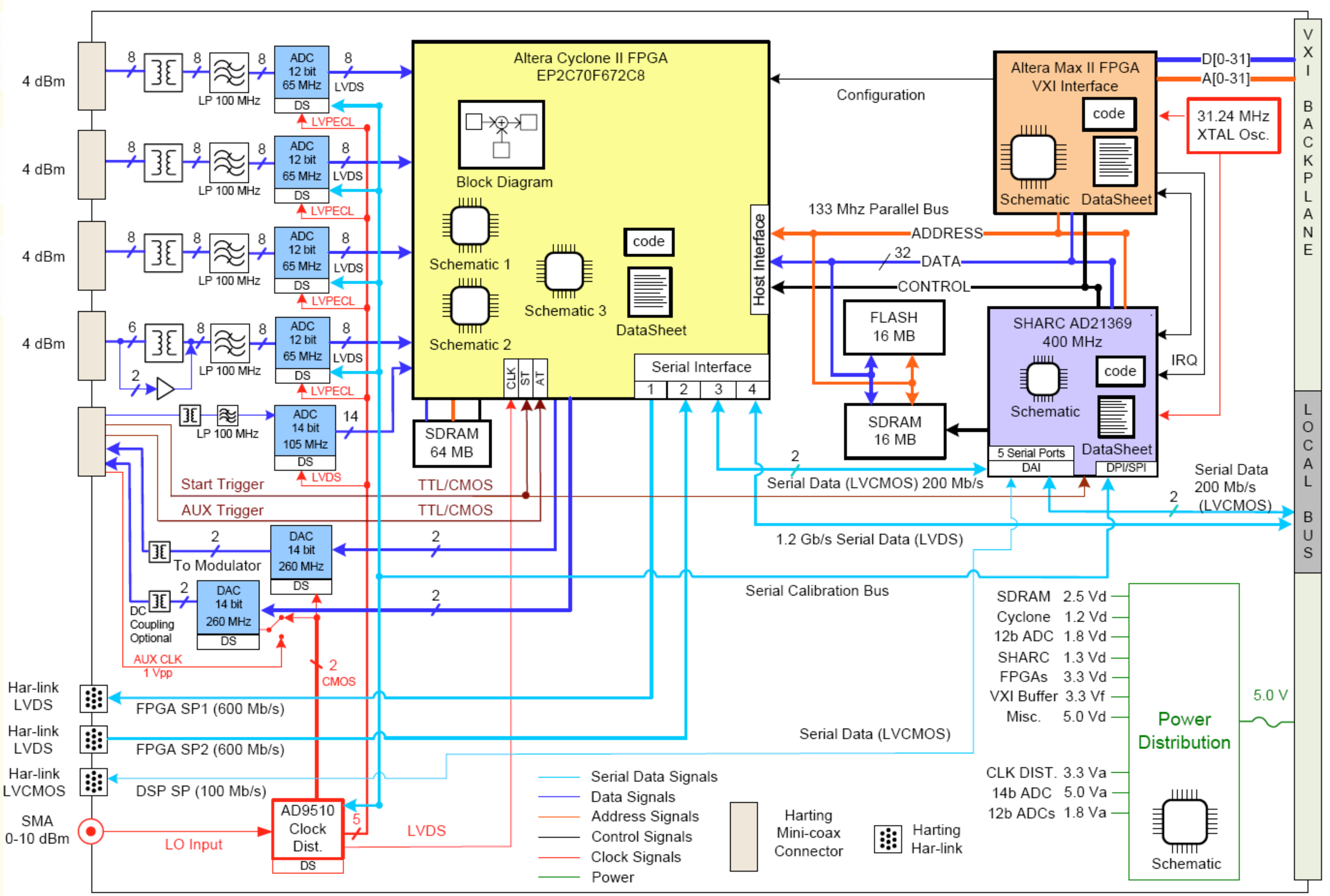




Management of Workload

- Issues:
  - Many projects developed concurrently
    - *Linac Upgrade, Main Injector Comb Filter, HINS, Project X, NML RF Station*
  - Partial overlapping of requirements
    - *Multiple channels of high speed RF processing(90)*
    - *Multiple sample clocks*
    - *Multi-channel control of piezo tuners or ferrite modulators*
  - Past FNAL LLRF projects are DSP based
    - *LLRF05 convinced us of the need to switch to high performance FPGAs.*
- Solution:
  - Develop ESECON for high precision or low cavity count stations
  - Develop a high channel count system that will work for many projects
    - *32 channel MFC - (4) 8 channel 12 bit ADCs, LVDS output*
    - *96 channel down-converter chassis*

33 Channel Controller (MFC)

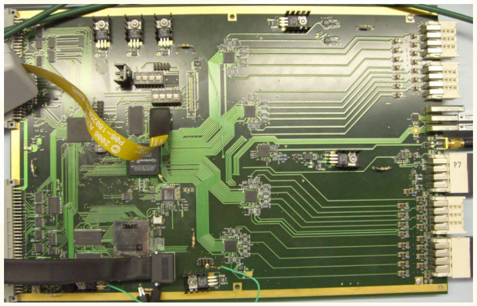


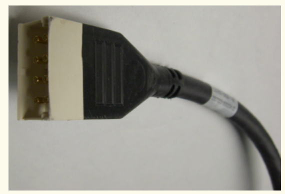
ADCs with LVDS Interfaces

- LVDS - the interface of choice for ADC's?
  - Available today
    - AD9222 Octal, 12-Bit, 40/50/65 MSPS Serial LVDS
    - AD9259 Quad, 14-Bit, 50 MSPS Serial LVDS
    - ADC14DS105 - Dual 14-Bit, 105 MSPS Serial LVDS and 7 other parts from National
    - ADS5242 4-Channel, 12-bit, 65MSPS Serial LVDS (TI)
    - Ads6445 4 channel 14 bit 125MSPS
  - Advantages
    - *High channel count on ICs - 4 to 8 -> Small board area*
    - *Small pin count on FPGAs*
    - *Serial interface control with test patterns*
    - *Low cost and low power*
  - Disadvantages
    - *800 MHz digital signals*
    - *Will probably never be the highest performance parts*

8 Ch Receiver and MRF

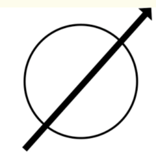
Multi-Channel Field Control Module



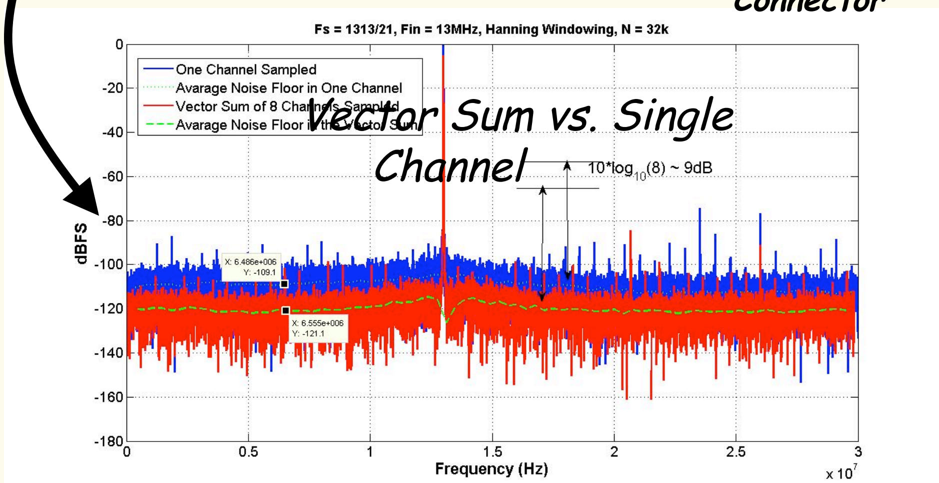


Harting IF Mini-coax Connector

8 Channel Rc



Phase Adjustment



Vector Sum vs. Single Channel

<u>Measured SNR for one channel</u>

<u>(12bit ADC):</u>

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

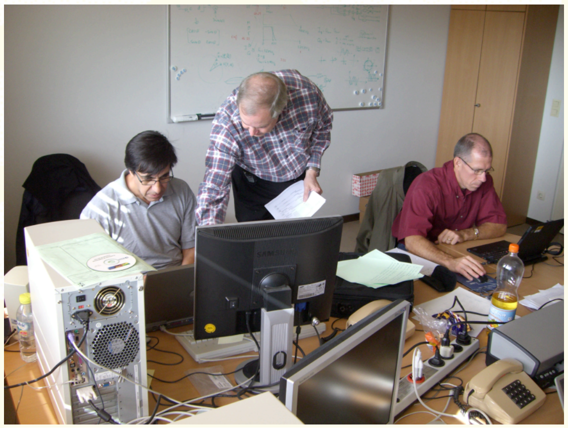
<u>Measured SNR for vector sum</u>

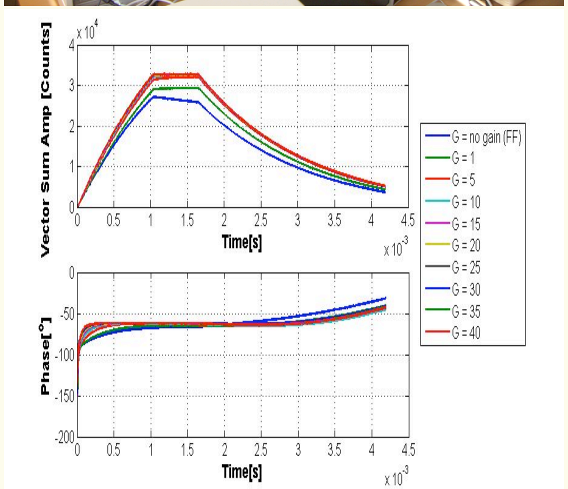
<u>(8x12bit ADC):</u>

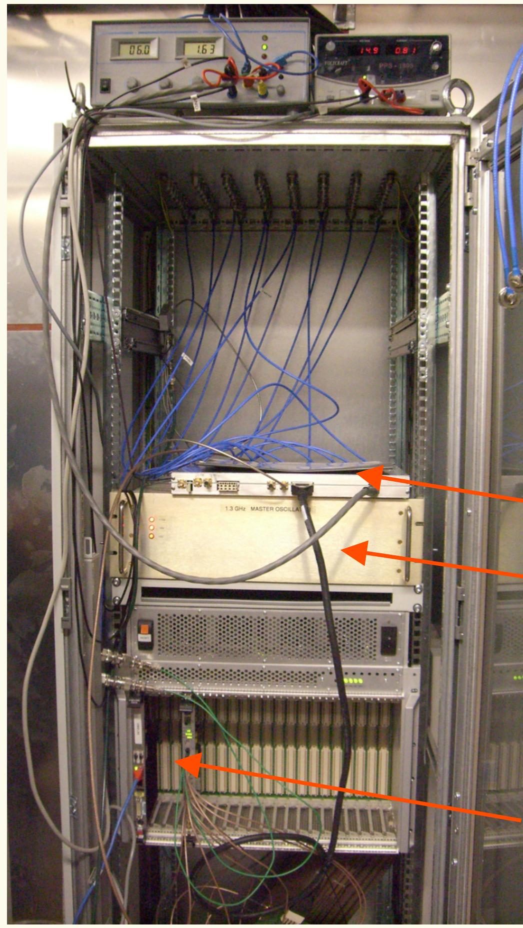
SNR@fs/2 + 10log10(8) = 79dB

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

Measurements on ACC1 at DESY







8 Channel Rc/Tx

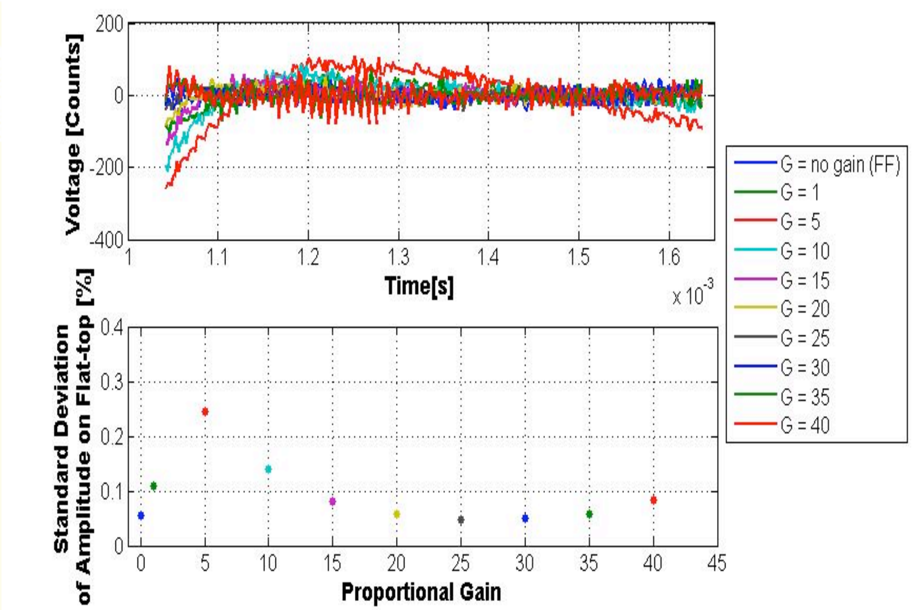
Master Oscillator

LO Generation

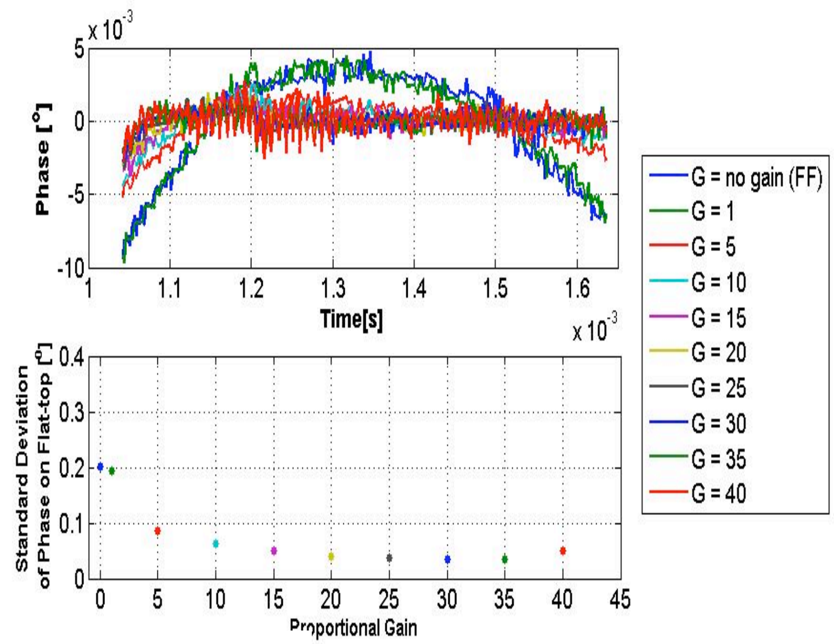
ESECON

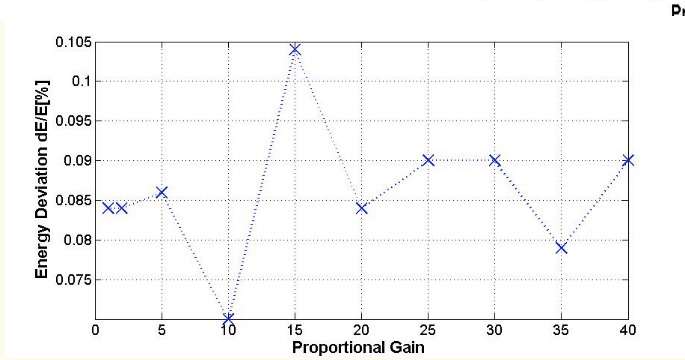
Measurements on ACC1 at DESY

Amp dev. Vs. Loop Gain



Phase dev. Vs. Loop Gain





Related Talks

- Wed 17:10: A prototype RF Comb Filter Feedback for the Fermilab Main Injector (Tim Berenc)
- Thursday 8:30: ESECON, 14-channel LLRF Controller (Gustavo Cancelo)
- Thursday 8:50: Measurements of the 8-Channel Down-Converter Module for the New Muon Laboratory (Uros Mavric)
- Poster on LFD on CC2 (Yuriy Pischalkov, Warren Schappert)