http://ab-ws-llrf05.web.cern.ch/ab-ws-llrf05/

Curt Hovater, Tom Powers, John Musson, Kirk Davis
&
The LLRF Community

Workshop Facts

- 125 Participants
- Focus was on LLRF control for Linacs and Synchrotrons
- 35 Invited Talks, 20 Contributed + 17 Posters

T. Powers: LLRF Work at JLAB

K. Davis: Transient Microphonics

J. Musson: Linear Recievers

C. Hovater: Four years of LLRF

- Four Working Groups
  - WG1: Synchrotrons and LHC, Mike Brennan
  - WG2 : LINACS ILC, Mark Champion
  - WG3 : RF System Modeling & Software : Stefan Simrock
  - WG4: Hardware/Implemenation/DSP, Brian Chase

Scientific Programme Committee

Kazunori Akai KEK
Mike Brennan BNL
Mark Champion SNS
Brian Chase FNAL
Larry Doolittle LBL
Roland Garoby CERN
Curt Hovater JLAB
Matthias Liepe Cornell
Trevor Linnecar (Chair) CERN
Patricia Shinnie (Secretary) CERN
Stefan Simrock DESY
Dmitri Teytelman SLAC

Local Organizing Committee

Maria Elena Angoletta
Philippe Baudrenghien
Alfred Blas
Roland Garoby
Lidia Ghilardi (Secretary)
Trevor Linnecar
Flemming Pedersen (Chair)
Patricia Shinnie

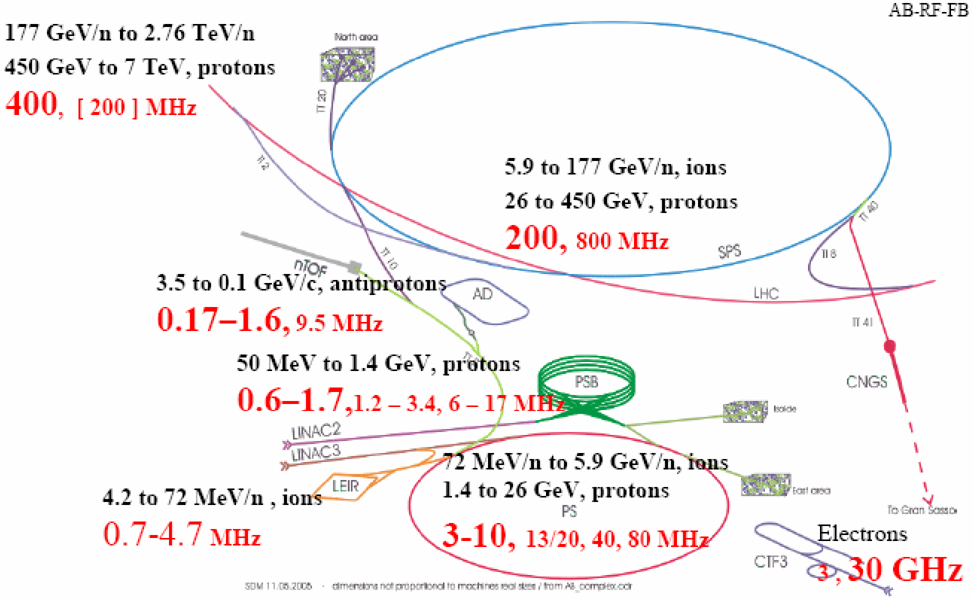
Overview of CERN LLRF

Fleming Pederson

Outline

- Overview of RF aspects of current and future CERN Accelerators
- Evolution of LLRF technologies: Analog, Semi-digital, Master and Slave DDS, All-digital.
- Coping with beam loading: Direct RF feedback, one-turn delay feedback
- Developments by accelerator: PSB, PS, AD, LEIR, SPS, LHC. History and challenges ahead
- What has been left out?

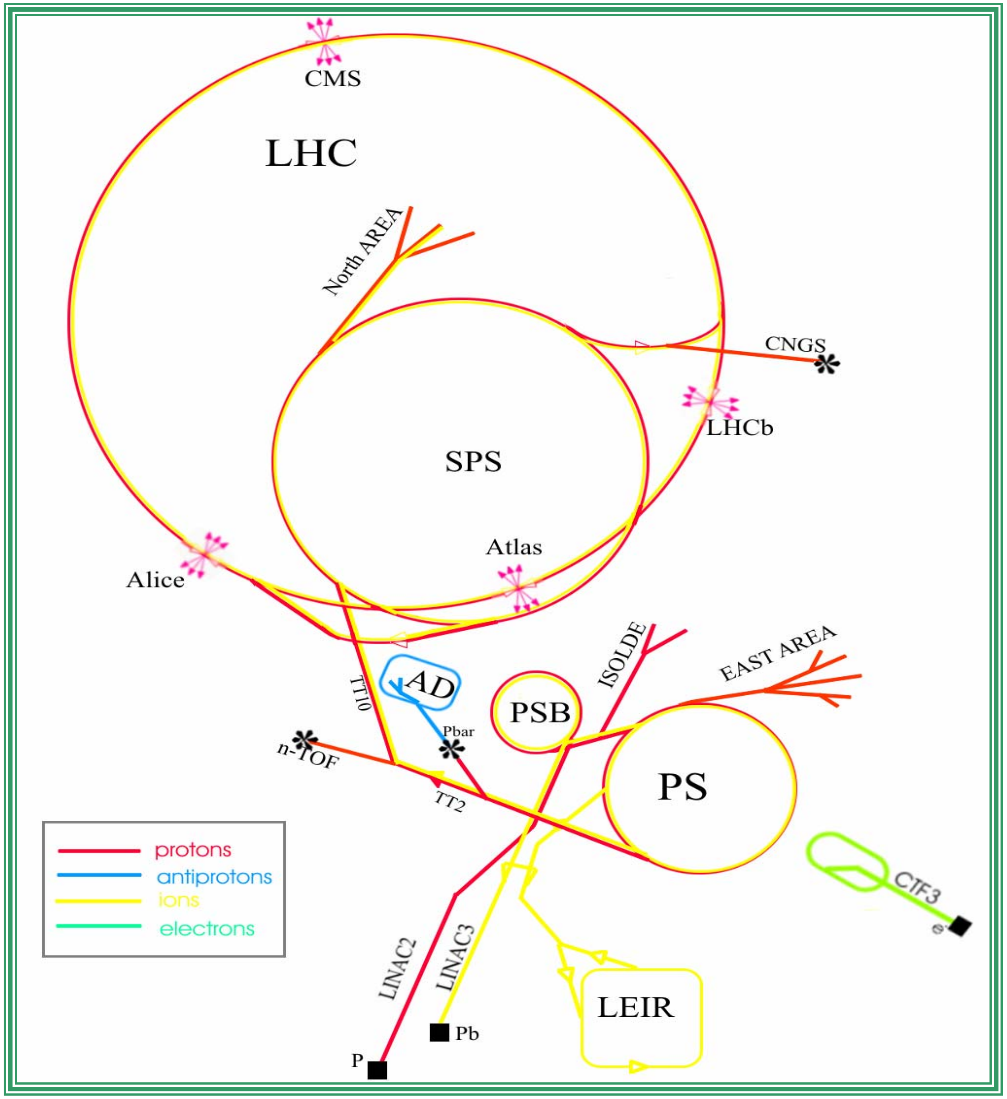
CERN Accelerators



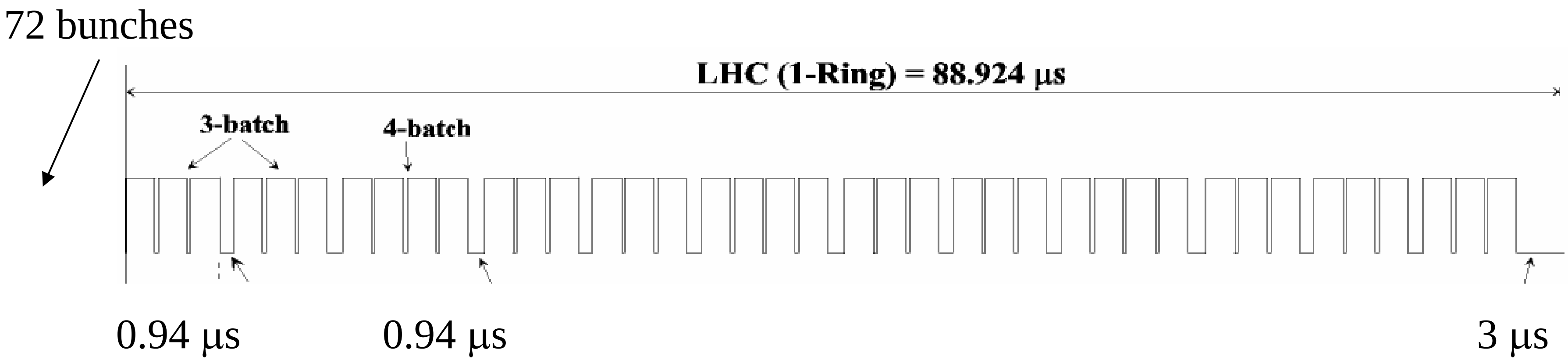
The LHC Low Level RF

Andy Butterworth
Daniel Valuch
Donat Stellfeld
Gregoire Hagmann
Joachim Tuckmantel
John Molendijk
Philippe Baudrenghien
Pierre Maesen
Ragnar Olsen
Urs Wehrle
Vittorio Rossi

Reported by P. Baudrenghien



The LHC beam



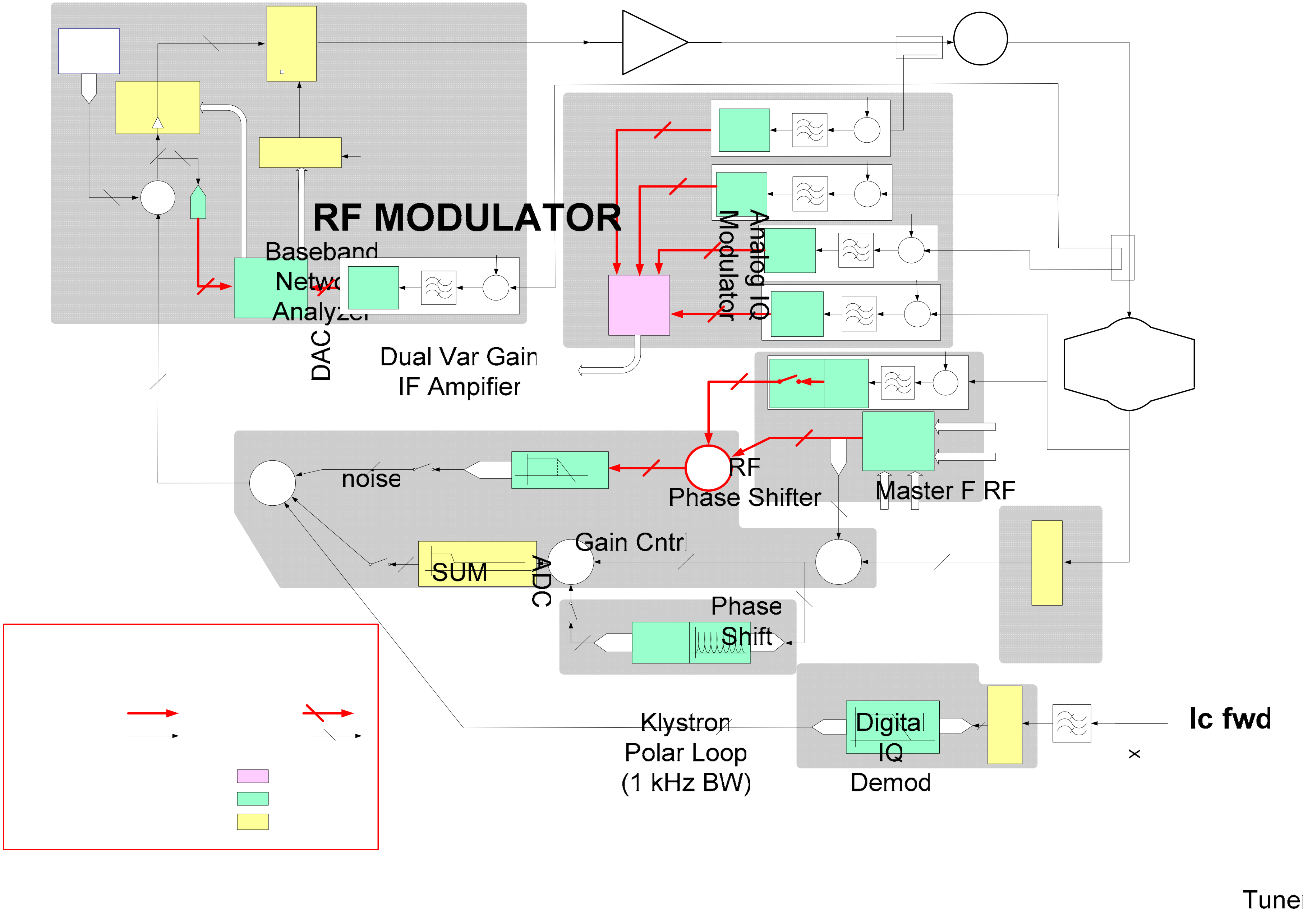
- High beam current: 0.6 A DC (nominal)
- Very unevenly distributed around the ring: many gaps …
- 2808 bunches, 25 ns spacing, 400 MHz bucket
- bunch length (4σ): 1.7 ns at injection, 1 ns during physics.
- Longitudinal emittance: 1.0 eVs (injection), 2.5 eVs (physics)
  - growth time due to IBS: 61 hours (physics)
  - damping time due to synchrotron radiation: 13 hours (physics)
- Frequency swing (450 Gev -> 7 TeV):
  - < 1 kHz for protons
  - 5.5 kHz for Pb

Bottom line: high beam current, low noise electronics…

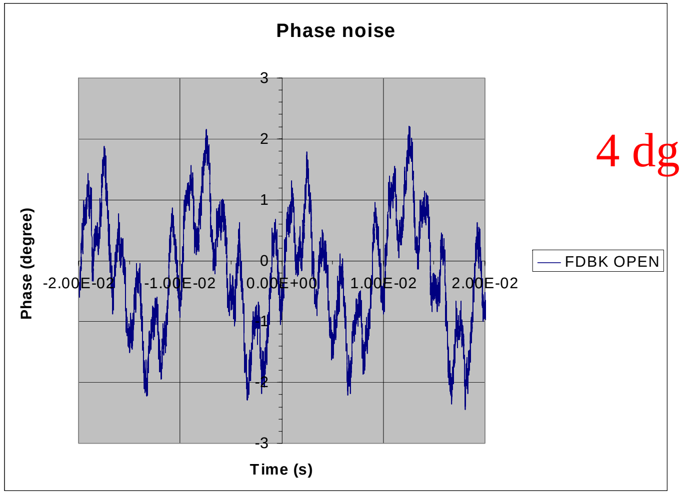
The LHC RF

- Two independent rings
- 8 RF cavities per ring at 400.790 MHz [2]:
  - Super Conducting Standing Wave Cavities R/Q = 45 ohms, 6 MV/m nominal
  - Movable Main Coupler (20000 < Q_L < 180000)
    - 1 MV /cavity at injection with Q_L = 20000
    - 2 MV/cavity during physics with Q_L = 60000
  - 1 klystron per cavity
    - 300 kW max
    - 130 ns group delay (~ 10 MHz BW)
  - Mechanical Tuner range = 100 kHz

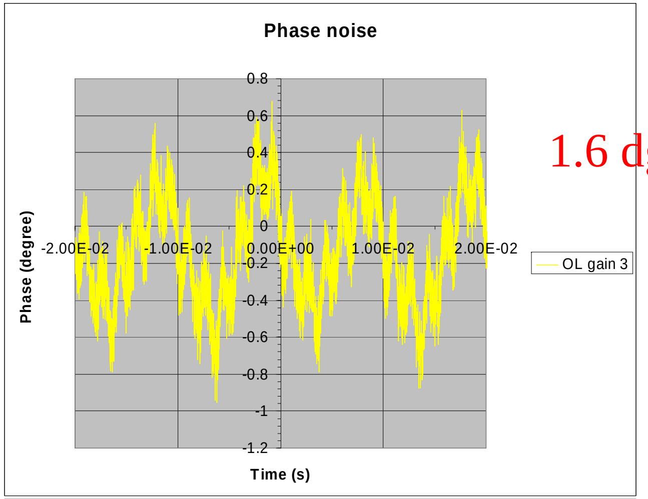
LHC LLRF Block Diagram



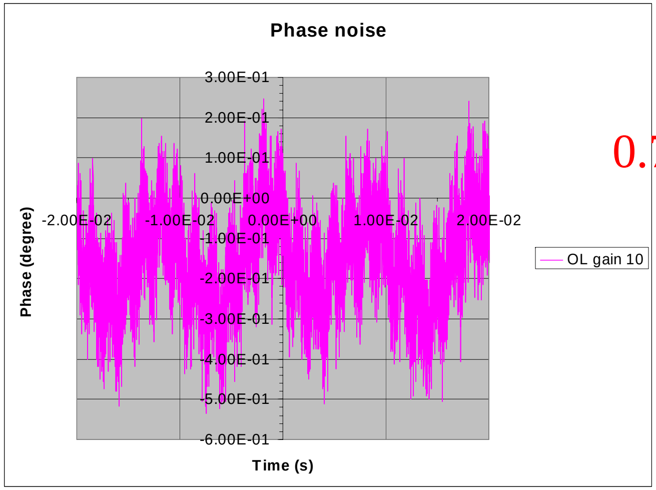
Phase noise reduction with fdbk



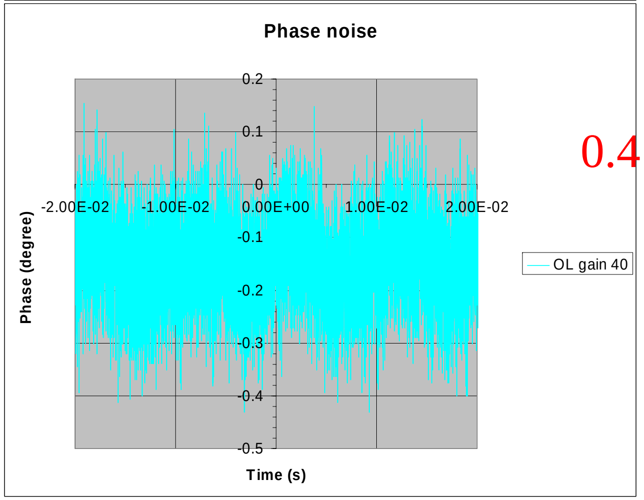
4 dg pp



1.6 dg pp



0.7 dg pp



0.4 dg pp

Measurement of phase noise Vcav/Synth with ZLW-1W mixer and 100 MHz LPF.Q60000, 2 MV Vacc

Bunch Lengthening in Tevatron due to RF noise

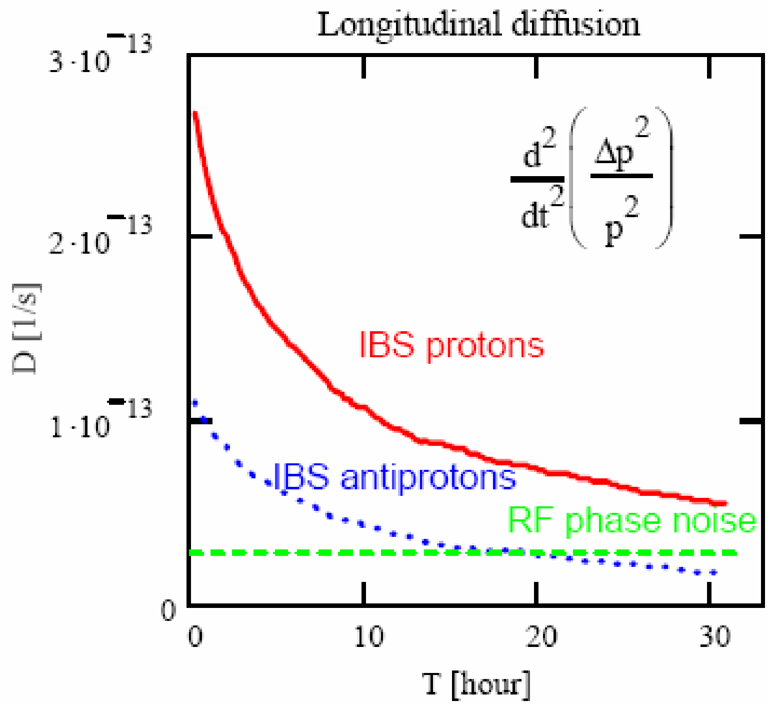
Valeri Lebedev, FNAL

1. Introduction

- Hadron colliders (storage rings) require high quality RF to prevent growth of longitudinal emittance
- Modern "master oscillators" are good enough to satisfy high requirements of phase and amplitude stability
- Microphonics in cavities is a major source of the problems in Tevatron
  - Local feedback systems stabilizing phase and amplitude in the cavities relative to the master oscillator (phase feedback)
  - Longitudinal feedback suppressing synchrotron oscillations (longitudinal damper)
- Tevatron has 8 cavities phased so that 4 of them accelerate protons and other 4 antiprotons
  - Phase feedback for antiproton beam
  - Phase feedback and longitudinal damper for antiproton beam

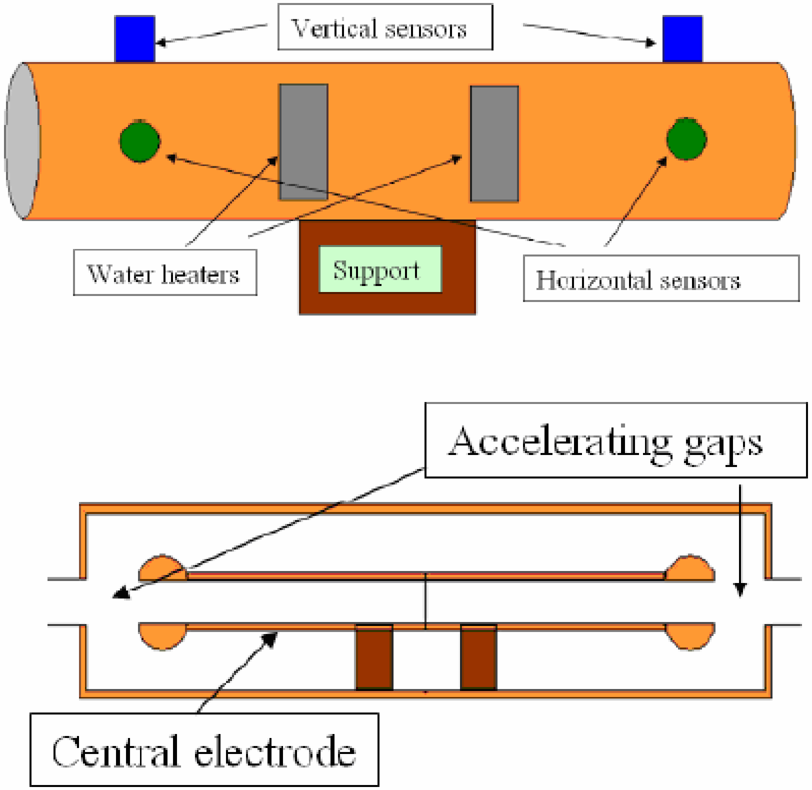
How strong effect of the RF noise on Tevatron Beam

- Sources of the longitudinal emittance growth
  - Intrabeam scattering (IBS)
    - Multiple and single scattering
  - RF noise
    - Phase
    - Amplitude
- IBS dominates during
  - entire store duration for p
  - first half of store for $\bar{p}$
- Spectral density of RF noise is not controlled during Tevatron operation
  - a value not easy to measure directly
  - not much easier with the beam
- RF voltage stability satisfies present Tevatron operation,
  - low priority for further improvements



Diffusion coefficients due to IBS and RF noise computed for store 4301 (Sep. 27, 2005)

3. Microphonics in the RF cavities



- Microphonics is a major source of the phase noise
  - It is excited by water flow
- Two vertical and two horizontal geo sensor were mounted on the cavity assemble
- There are many mechanical modes with frequencies close to the synchrotron frequency of 34 Hz

The prototype cavity with 4 geo sensors HS1 installed

Conclusions

- Tevatron RF system was well designed for Run I (1992-1996) and was not subjected to any major modifications since that time
  - Run II upgrades include
    - Better suppression of HOMs
    - Installation of longitudinal damper
    - Higher amplification in the global phase loop stabilization
    - Reducing mechanical vibrations due to water heaters (1 of 8 cavities are done)
- Studies performed during Run II allowed us to achieve better understanding of RF system operation and its interaction with beam
  - The main conclusion is: while further decrease of RF system noise could produce measurable improvements of the bunch lengthening it hardly could produce measurable improvements in the luminosity integral.
  - Decent coincidence of the beam based measurements and the direct RF noise measurements was obtained

Klytsron Linearizer: John Fox

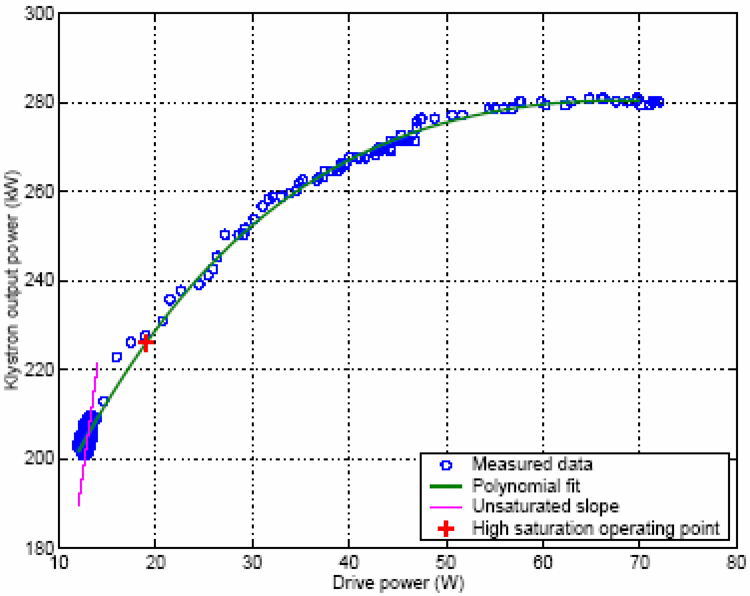
September 2005

PEP-II fast impedance control loops -Limitations of cavity impedance control due to klystron saturation

A major effort by the group involves understanding the high-current instability limits in PEP-II. Our machine physics measurements have led to a better understanding of the limitations of impedance control in the PEP-II RF systems. Due to klystron saturation a linear impedance control model is not applicable.

For the HER at 1 A the growth rates rise from linear prediction of 0.12 ms^{-1} to actual 1-1.8 ms^{-1}.

These high growth rates were limiting HER currents above 1380 mA.



We are attacking this limitation through a new RF woofer channel in the longitudinal feedback paths, and a novel klystron linearizer within the low level RF processing. The Low Group Delay Woofers were commissioned in PEP-II during the year, and allowed an increase in HER current to 1650 (plus) mA. This channel improves the damping possible with feedback.

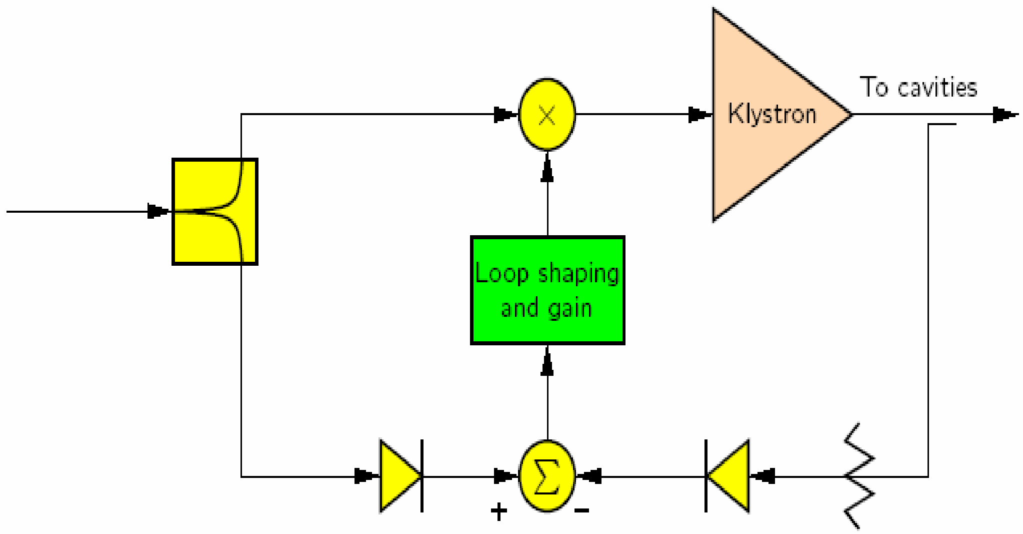
The Klystron Linearizer is a technique to improve the impedance control (increasing direct loop gain)

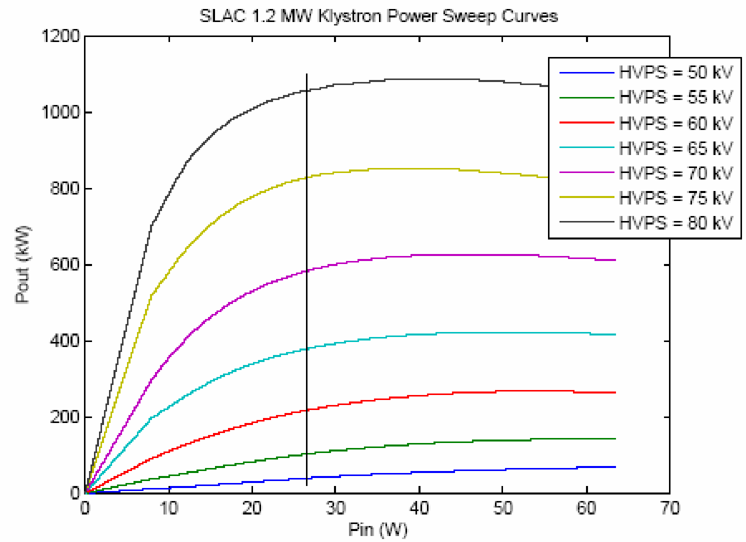
Klystron linearizer: block diagram

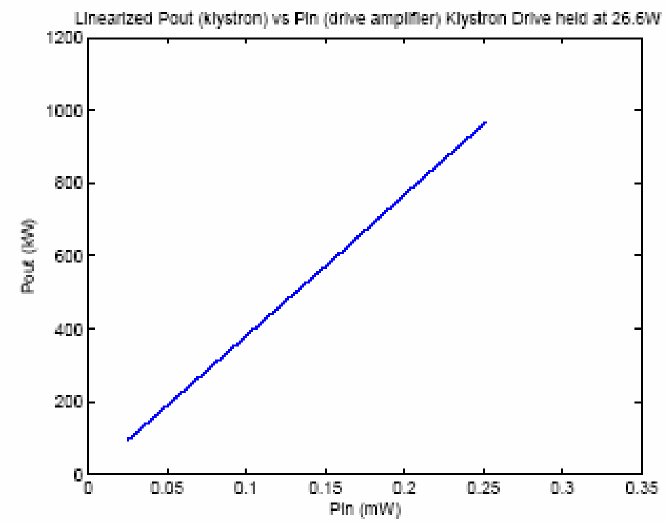
Suggested by S. Gallo. Why not inearize the amplitude response?

Compare the input of the klystron and the output, use amplitude modulator to make the two match. Linearizes the klystron so that large- and small-signal gains are identical. Feedback does increase the effective klystron delay.

Commericial approaches,too-Kalhn EER, Inverse lookup, Polar and I/Q feedback



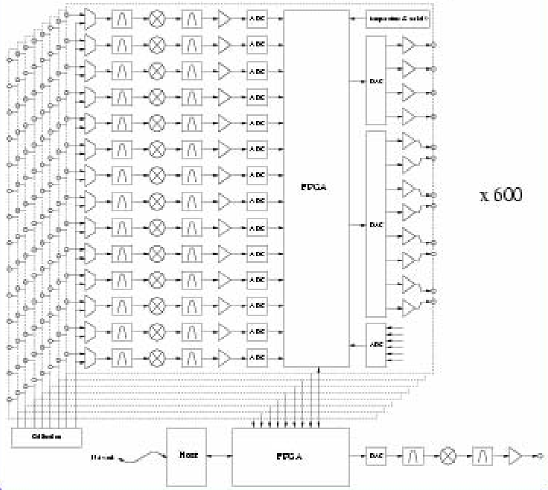




Conceptual Design for ILC LLRF Hardware

Larry Doolittle, LBNL

Start: October 2004 ILC workshop: block diagram



ILC Needs:

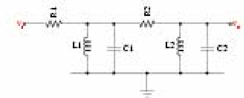
- Support 3 x 12–cavity cryomodules
- 3 precision 1300 MHz RF inputs per cavity
- One Klystron RF output
- 0.1°, 0.1% stability over 30 km

Assume: Complex electronics kept away from radiation

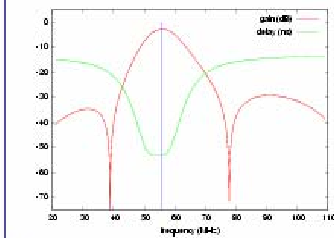
Philosophy:

- Digital IF measurement & control
- Keep It Simple, Stupid!
- Cable drift measured in–band with pulsed cal source

IF Filter Design



Include $(1-z^{-2})$ digital filter



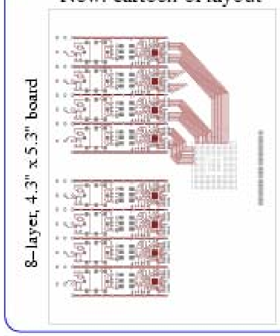
Infrastructure needs:

- 50 Watts DC and air cooling
- Cat–5 cable to fast EPICS computer
- Clean 1244.1718 MHz LO

Feedback latency (group delay):

150ns	40m cable
50ns	analog input filter
75ns	ADC pipeline delay
50ns	4 cycles on 1st FPGA
25ns	2 cycles board–board
50ns	4 cycles on 2nd FPGA
50ns	analog output filter
160ns	Klystron chain
190ns	40m waveguide
800ns	Total

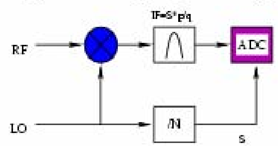
Now: cartoon of layout



Selection of ADC

part	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
resolution	14	12	12	14	14	14	bits
speed	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	MS/s
input BW	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	MHz
aperture jitter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	ps rms
latency	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	cycles
min. latency	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	ns
power	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	mW
power (idle)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	mW
gain tempco	[illegible]	1	[illegible]	[illegible]	[illegible]	1	ppm/°C
analog Vcc	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	V
digital Vcc	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	V
pins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
size	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	mm
cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	US$
stock	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
reputation	[illegible]		[illegible]	[illegible]			

Digital LLRF Frequency Numerology



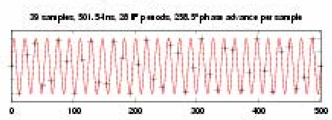
IF ~ 50 MHz (clock jitter vs. RF filter)

S/4q ~ 100 kHz (closed loop BW of cavity)

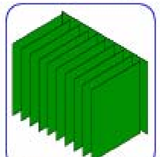
p/q ~ 1/4 + m/2 (center in Nyquist zone m–1)

RF	1300.0000 MHz
LO	1244.1718 MHz
N	16
S	77.7607 MHz
p	28
q	39
IF	55.8282 MHz

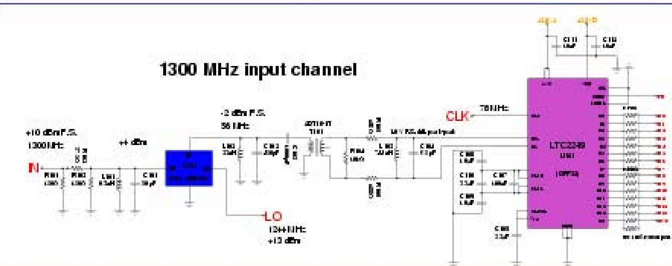
LO/2 is 9.5ppm away from 622.08 MHz



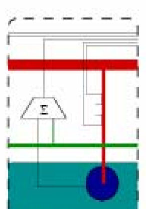
Enhances linearity of ADC by factor of 10 vs. I/Q sampling



1300 MHz input channel

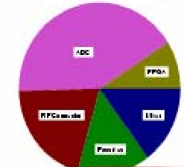


Calibrate critical cables between each pair of pulses!



Component costs:

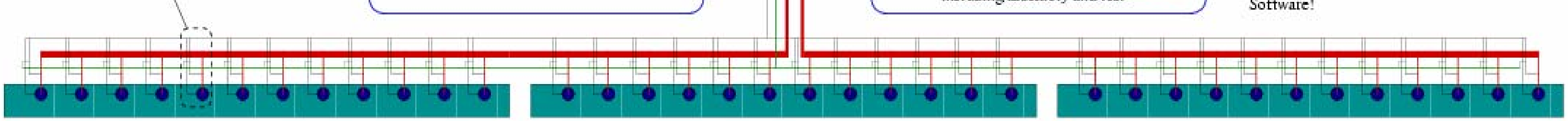
US$844 per 14–channel RF input board



Estimate US$18K per 36–cavity module including assembly and test

Goal: Provoke and frame questions

- Support robotic module swap?
- Install calibration line in cryomodule?
- FPGA resources enough to simulate hardware for full–up software test?
- Integration with related hardware:
  - Wire Position Monitors
  - Piezo drivers
  - Waveguide tuners
  - Phase distribution system
  - Interlocks
- Software!



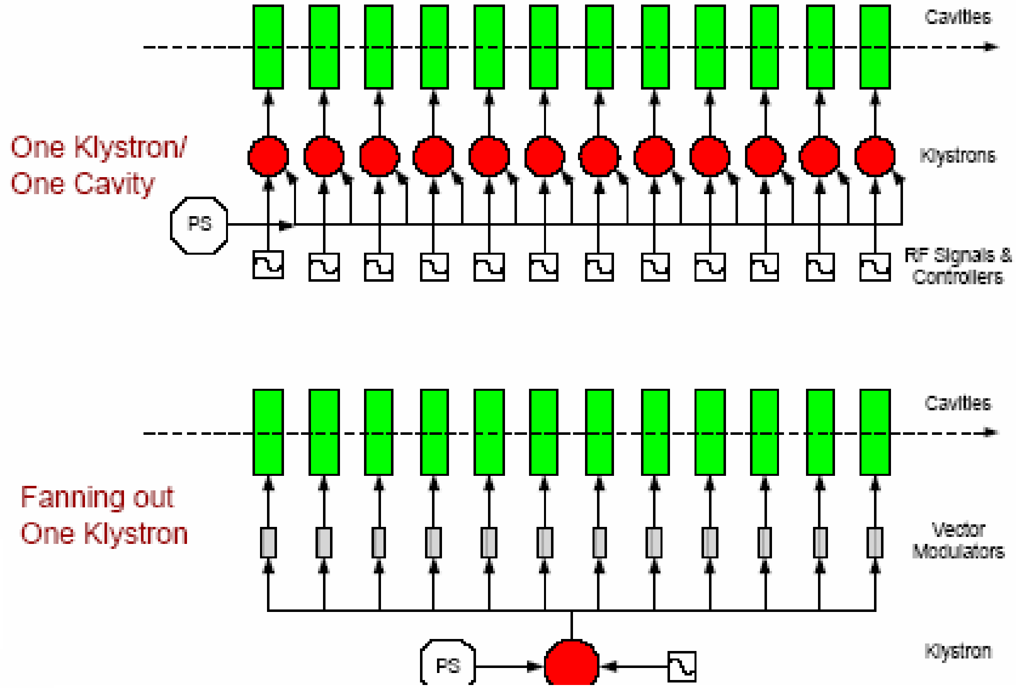
Vector Modulation of High Power RF

Y. Kang
J. Wilson, M. McCarthy, M. Champion
and RF Group

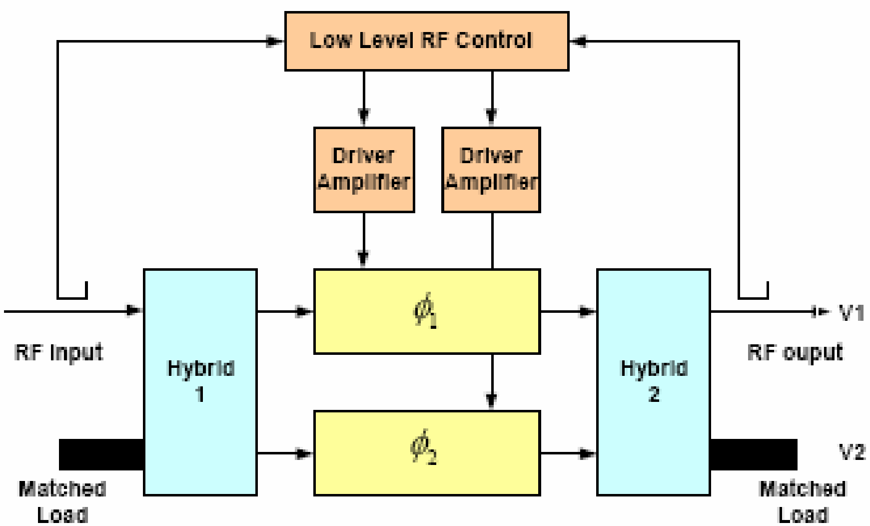
Spallation Neutron Source
Oak Ridge National Laboratory

LLRF05 Workshop, CERN
10-13 October, 2005

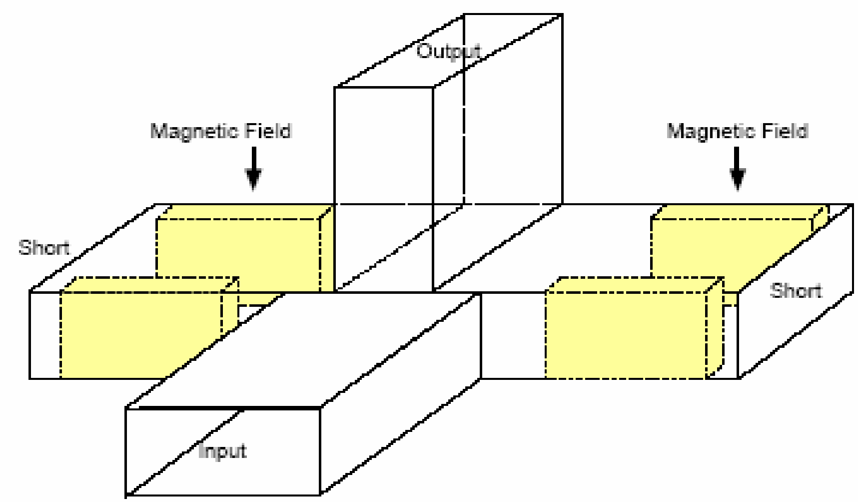
Comparison of Two Configurations



Vector Modulation



Waveguide Vector Modulator (FNAL)



Vector Modulation Cont.

Linac RF Cost for a 805 MHz System

(non-official estimate for a linac with100 cavities)

	One/one			Fan out (1:20)			Savings
	Quantity	Unit Price ($k)	Total ($k)	Quantity	Unit Price ($k)	Total ($k)	($k)
Klystron	100	150	15,000	5	700	3,500	11,500
Transmitter + Power Supply	5	700	3,500	5	700	3,500	0
Circulator + Loads	100	50	5,000	100	50	5,000	0
RF Controls	100	105	10,500	100	135	13,500	-3,000
Waveguide	100	46	4,600	5	250	1,250	3,350
Gallery	40,000	0.20	8,000	5,000	0.20	1,000	7,000
Labor for WG/Klystron	10,000	0.10	1,000	2,000	0.10	200	800
Subtotal ($)			47,600			27,950	19,650
Other Items							Can be more

SNS Reference System
Chip Piller

- **SNS system the "high water" mark for coax!**
- **Tight Reference line requirements**

+/- 0.1 degrees between Cavities

+/- 2.0 degrees between linac points

- **Employs temperature stabilized Reference lines and down converters**
- **Measurements over the short term (< hour) did not reveal any drifts!**

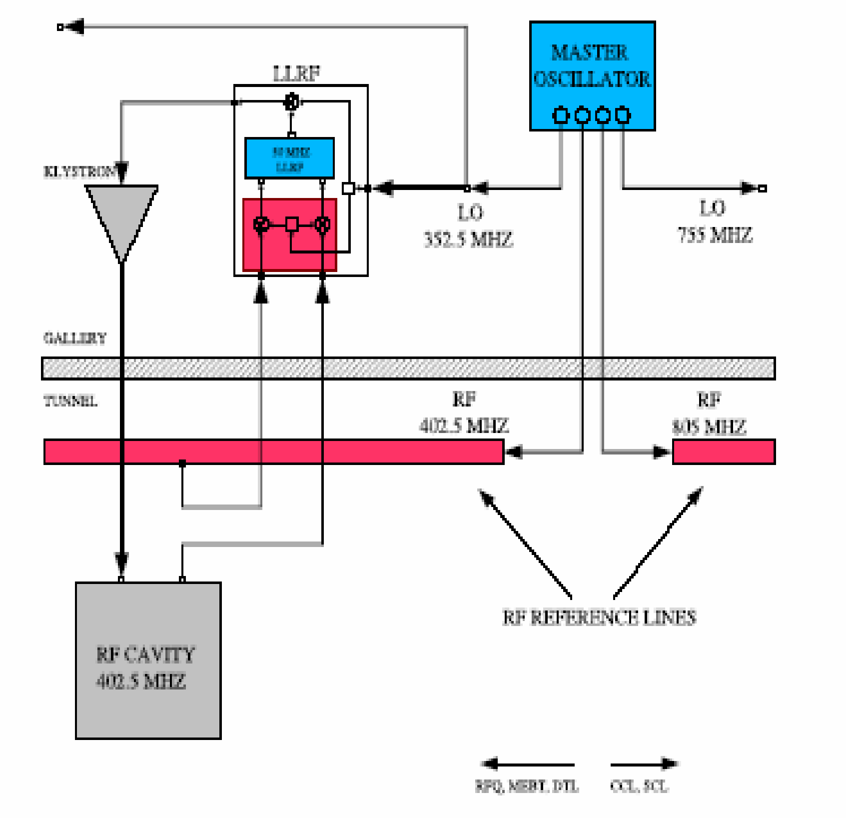


Diagram of the SNS RF Reference System
C. Piller, PAC05

Femto-Second Stable Timing and Synchronization Systems

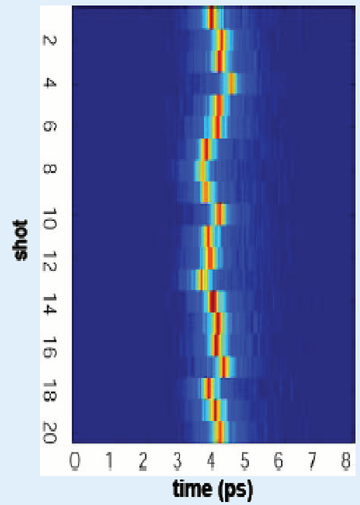
Volker Schlott, PSI

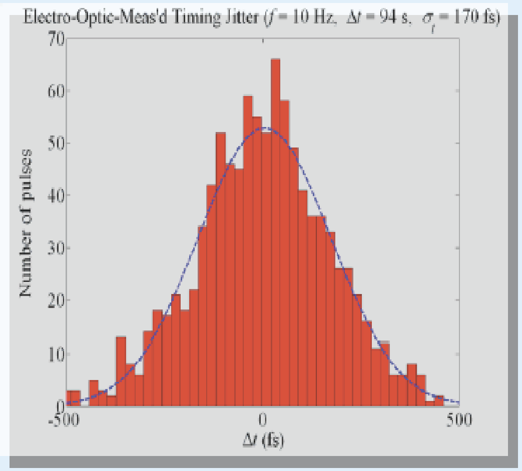
- **Motivation** – Future XFELs and Time Resolved Experiments on fs-Lev
- **Architecture of Optical Synchronization Systems**
  - Fiber Lasers
  - Optical Master Oscillator
  - Optical Timing Distribution
- **First Experimental Results**

Motivation: electron beam – laser arrival time jitter measurements

EO cross-correlation-measurements performed by A.L.Cavalieri et al. @ SPPS, SLAC

Timing Jitter Data (20 successive shots)





courtesy of A.L.Cavalieri

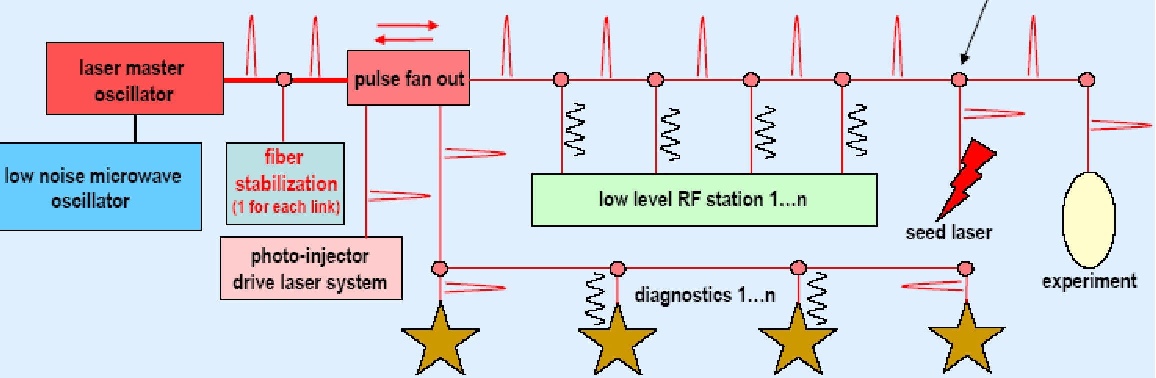
Motivation – Future XFELs and Time Resolved Experiments on fs-Level

- <u>Stability of RF and RF Distribution</u>
  - arrival time jitter of electron beam in undulator ≤ bunch length (~ 30 - 50 fs)
    - ⇨ RF amplitude stability ~ 10^{-4}
    - ⇨ RF phase stability ~ 0.01 ° (21 fs @ 1.3 GHz)

    } in injector, booster and bunch compressor
- <u>Single Bunch Beam Diagnostics along Accelerator</u>
  - single bunch and "sliced" beam parameters are relevant for SASE process (not rms!)
  - measurement locations are spread over kilometers along LINAC
    - ⇨ highly stable timing / sync distribution on fs-level
- <u>Laser-Electron Beam and Laser-Photon Beam Interaction on a fs-Level</u>
  - stable reference for seeding and HGHG generation
  - time-resolved ("pump-probe") experiments at user end stations
  - synchronization for today's "femto-second slicing sources" in storage rings
    - ⇨ highly stable timing / sync distribution on fs-level

Schematic Layout of Optical Synchronization System

(as proposed by Winter et al. (DESY) in collaboration with MIT)



Optical Synchronization Layout based on:

- low noise microwave master oscillator as stable low frequency reference (DC to < 10 kHz)
- mode-locked Er-doped fiber lasers as "new" optical master oscillator
- RF can be re-generated locally by photo-detection (n^{th} harmonic of laser rep.-rate)
- other lasers (for gun, diagnostics, seeding and experiments) can be linked directly

- optical fiber distribution: length stabilization over kilometers achi

Passively Mode-Locked Fiber Lasers

Noise characteristics:

< 10 kHz ⇨ worse than microwave oscillators due to thermal and vibrational disturbances

> 10 kHz ⇨ low-pass characteristic of pump source due to long (ms) upper state lifetime of Er

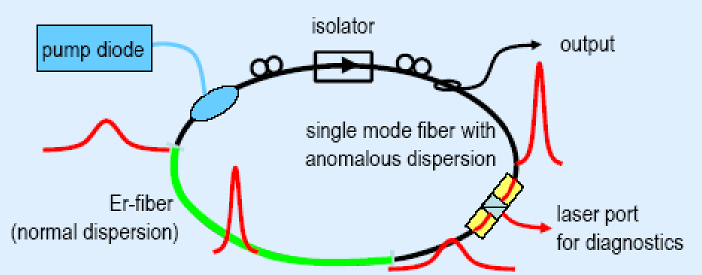
Er-fiber lasers

⇨ sub 100 femto-second to pico-second pulse durations

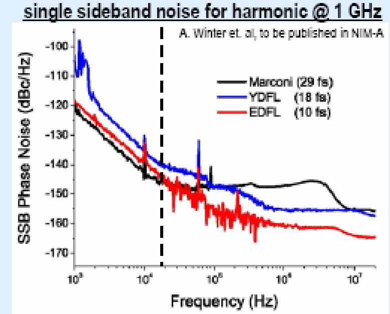
⇨ high availability of fiber-optic components @ 1550 nm (telecom)

⇨ 30 – 100 MHz repetitions rates (lockable to accelerator RF)

⇨ high reliability and long term stability (commercial systems available)



single sideband noise for harmonic @ 1 GHz



First Experimental Results by Winter (DESY) and MIT co-workers

- tests in real accelerator environment @ MIT Bates laboratory
- Er-doped fiber laser locked to Bates master oscillator
- laser pulses transmitted through a total fiber length of 1 km
- "passive" temperature stabilization of fiber link
- stabilization of fiber length by RF feedback

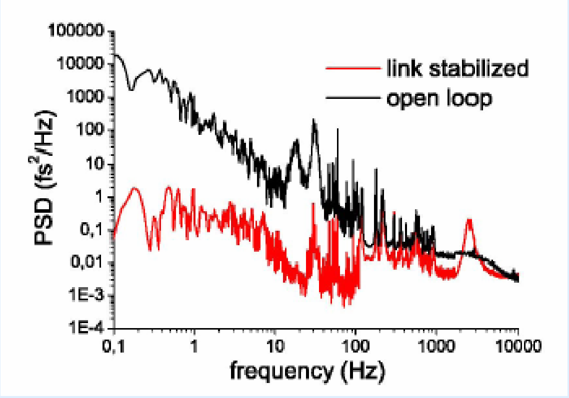
First Experimental Results by Winter (DESY) and MIT co-workers

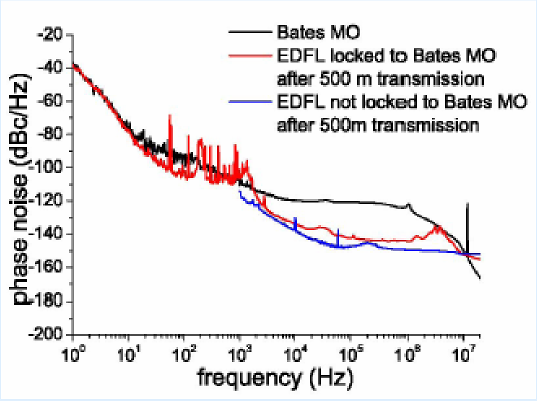
open / closed loop performance

- open loop stability ⇨ 60 fs (0.1 Hz – 5 kHz)
- closed loop stability ⇨ 12 fs (0.1 Hz – 5 kHz)
- stability achieved with "simple" RF feedback
- no significant noise added at high frequencies

transmited RF-signal (2.856 GHz)

- phase lock jitter ⇨ 30 fs (10 Hz – 2 kHz)
- total jitter added ⇨ 50 fs
- overall improvement 272 fs vs. 178 fs (up to 20 MHz)
- spurs are technical noise (pump diode PS)





Technology: Platforms .....in.....Transition

- **VME/VXI Crates have been the traditional method of housing and communicating with LLRF**
- **Easy to proto-type and install, well supported**
- **Can be expensive in large quantities**
- **Installations:**
  SNS, JLAB, J-PARC ring RF, FERMI, TTF

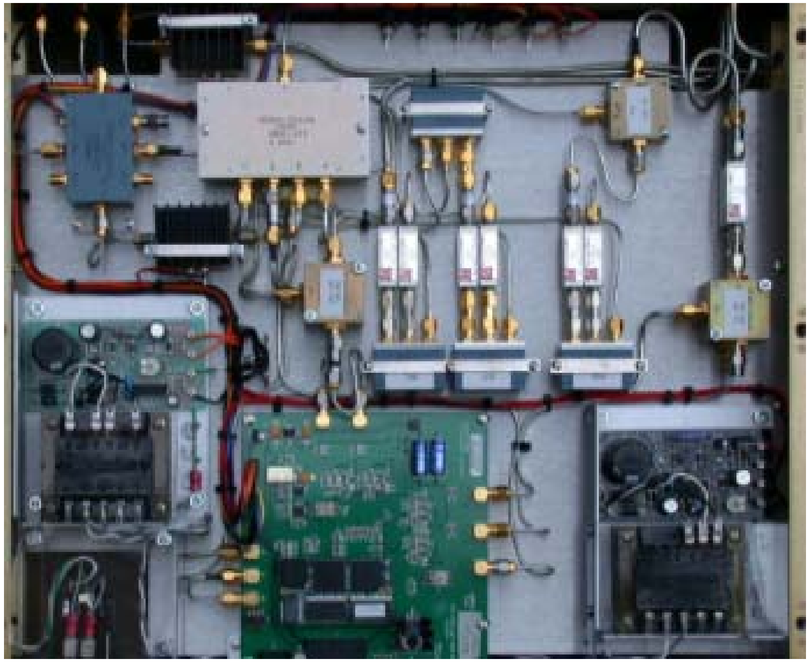
SNS LLRF System using VXI Crate
B. Chase, Snowmass05

Technology: Platforms.….in.….Transition

Networked based systems:

Control what you want, where you want, when you want!

- Ethernet
- PCI
- CAN (Controller Area Network)



LBL LLRF using embedded StrongARM CPU and Ethernet. L. Doolittle et al, LINAC02

- **PCI**

Well supported

Installations: SNS (BPM), J-PARC (linac)

- **Embedded Ethernet**

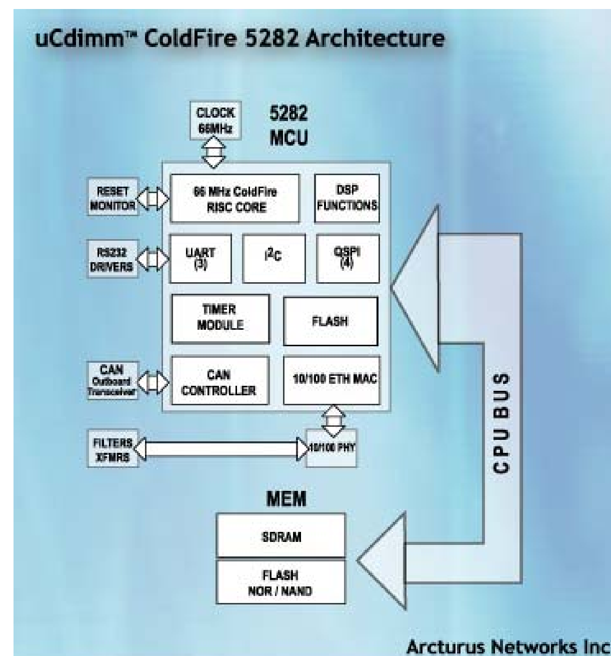
Inexpensive & Flexible

Many COTs boards ready to support your project.

LCLS RF Control System

Dayle Kottouri

- Only the Coldfire uCdimm 5282 processor had the communication speed and power to meet our data requirements. Cost is $150 per processor plus the development of the board it sits on
- By choosing the Arcturus Coldfire uCdimm 5282 processor, we are able to make use of the port of the operating system, RTEMS, which has already been done.
  - RTEMS is the standard for the real-time operating system chosen for LCLS by the Controls Group
  - EPICS, the standard for the control system software for LCLS runs on RTEMS
  - With these choices, the LLRF control system will be fully integrated into the rest of the LCLS EPICS control system and can speak to other devices and applications such as control panels, alarm handlers and data archivers, using Channel Access protocol, the standard communication protocol for this project.

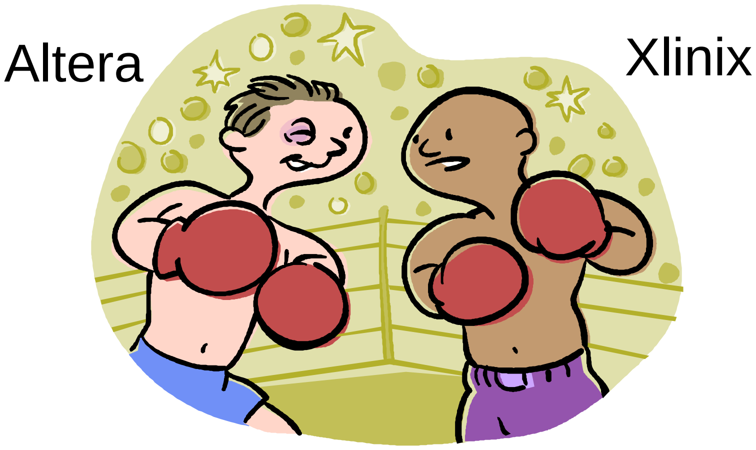


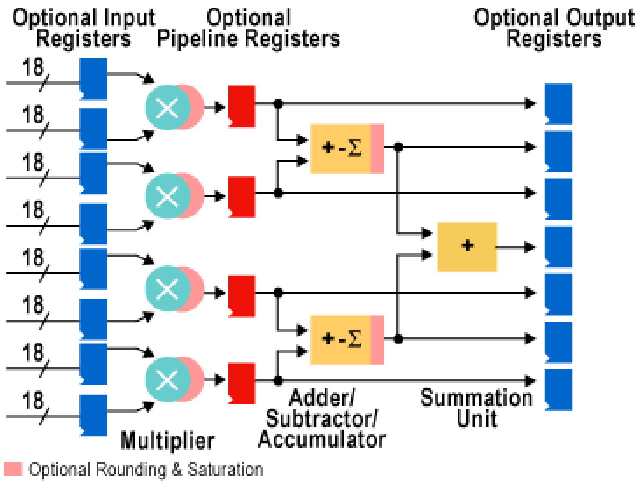
Technology: FPGA's

- Most new LLRF designs incorporate a large Xlinix or an Altera FPGA.

- Manufactures have added new features that make it easier to perform DSP manipulations in the IC.

- Uncharted and new territory: hard and soft processor cores in the FPGA may allow complete system on chip with network connections.





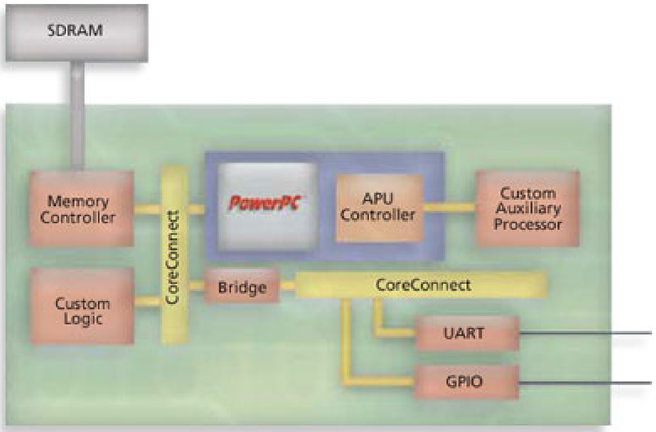
Altera DSP Block Architecture

http://www.altera.com/

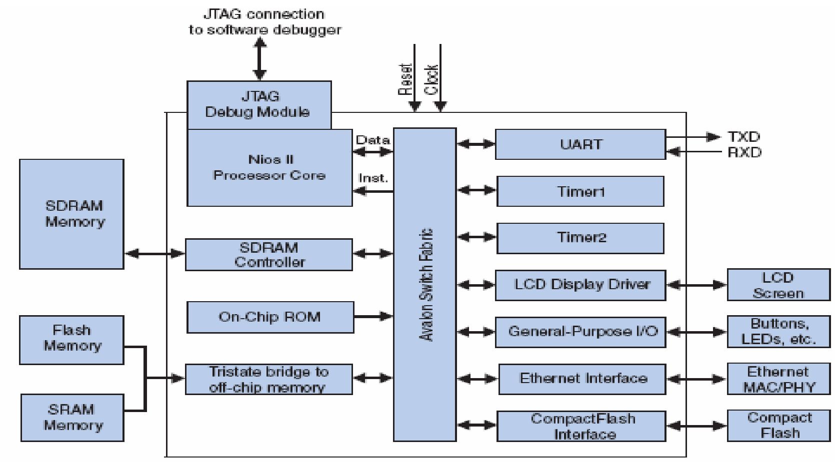
Traditional Processors …DSP ….FPGA….

- **Large multi-core Processors could possibly run dedicated feedback, communication and house keeping.**
- **Blended system DSP/FPGA, large processor/DSP etc. Example is Cornell's LLRF system which uses a DSP and a FPGA.**
- **Large FPGA's with soft or hard processor cores can run dedicated feedback while running LINUX and EPICS.**

Your options are endless!



Xilinx FPGA with hardcore Power PC
http://www.xilinx.com/

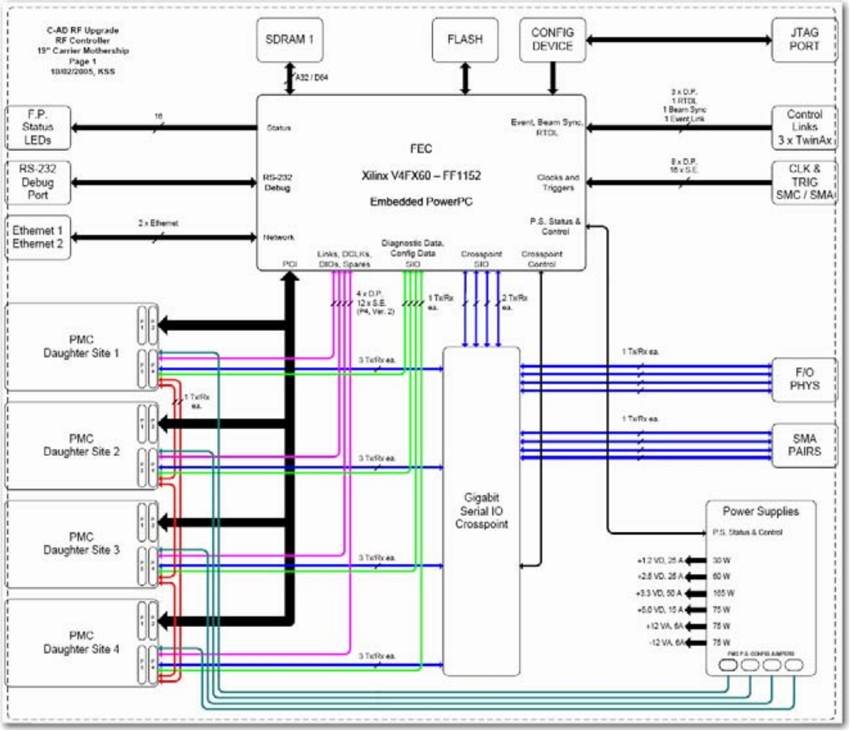


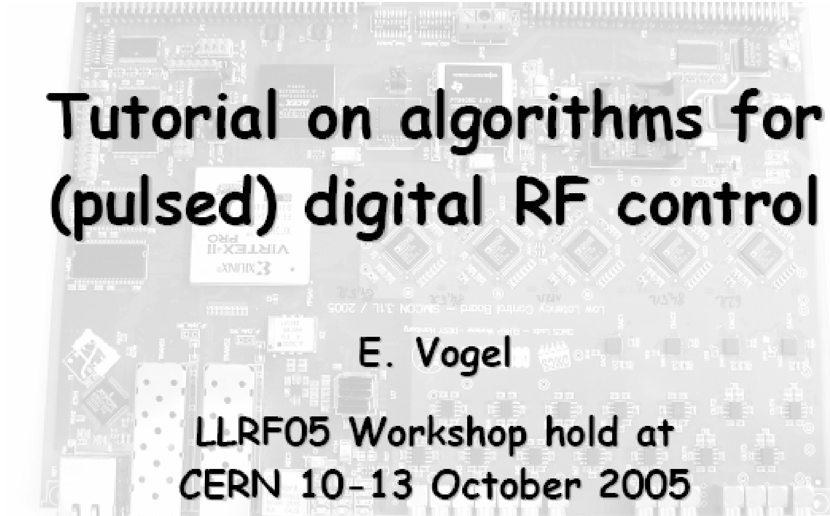
Altera FPGA with softcore NIOS processor
http://www.altera.com/

BNL LLRF Super Board

Kevin Smith

- Design a generic, modular LLRF control architecture which can be configured to satisfy all of the LLRF control demands we currently have, and which will be supportable and upgradeable into the foreseeable future.
- Architecture has evolved from design and operational experiences with digital LLRF control hardware for RHIC, and more recent experience with the AGS, Booster, and SNS Ring LLRF design efforts.
- Two major components:
  - System Carrier Board
    - Self supporting (stand alone) LLRF system controller and control system interface.
  - Custom Daughter Modules
    - Provide system specific data acquisition capability and processing horsepower.
    - DSP, ADC, DAC, etc.
  - Obviously other support modules around this (primarily NIM analog).
- Huge engineering challenge, but the potential benefits justify it.





Tutorial on algorithms for (pulsed) digital RF control

E. Vogel

LLRF05 Workshop hold at
CERN 10-13 October 2005

Outline of the talk

We will go through algorithms applied at the new TTF RF gun control as one example for digital RF control of (pulsed) accelerating cavities.

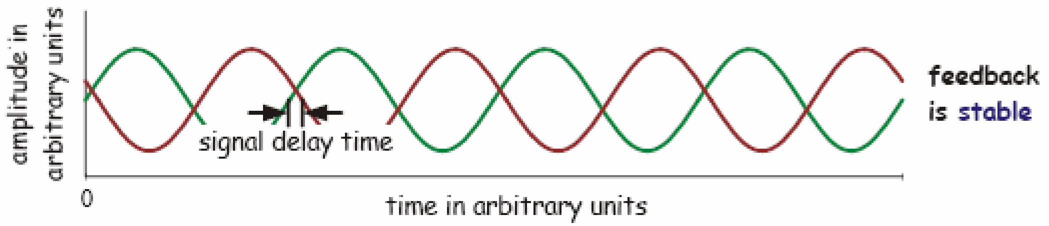
To list separately:

- proportional control
- IQ loop phase determination
- effects of signal propagation times
- two concepts for digital filters: FIR and IIR
- feed forward algorithms
- cavity tuning determination
- CORDIC algorithms
- exception detection and handling
- summary

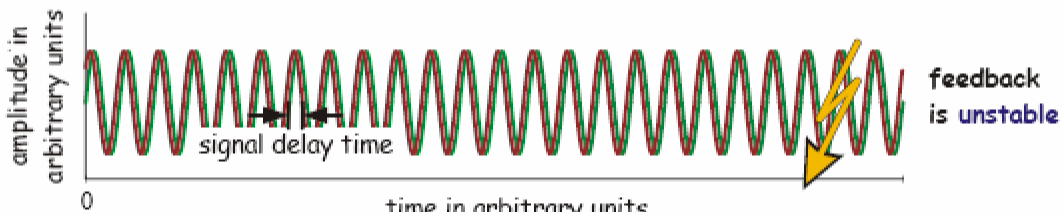
Latency restricts proportional gain and loop stability

A time delay leads to an unwanted positive feedback for higher frequencies

negative feedback for low frequencies



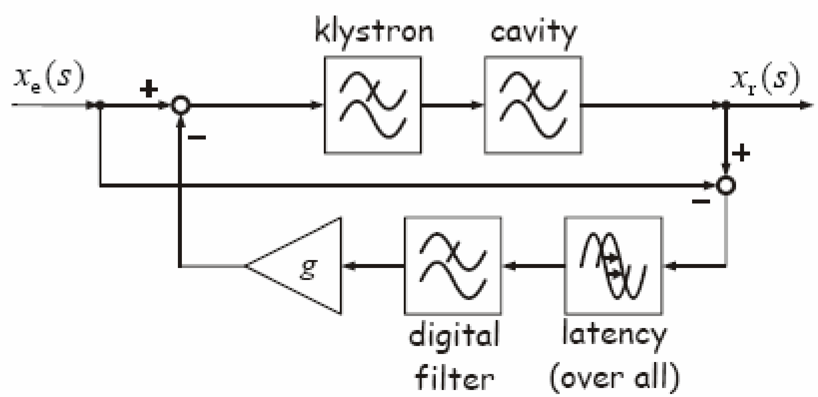
positice feedback for high frequencies



Cure: suppression of high frequencies

Suppression of high frequencies by

- the cavity bandwidth
- the restricted bandwidth of high power RF (e.g. klystron)
- and digital low pass filters in the LLRF.

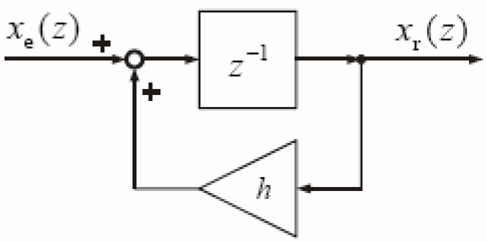


Recursive or Infinite Impulse Response (IIR) filter

- IIRs are usually digital copies of analog filters
- impulse response of an analog low pass is an exponential decay
- to model this we reduce the output of a one step delay by

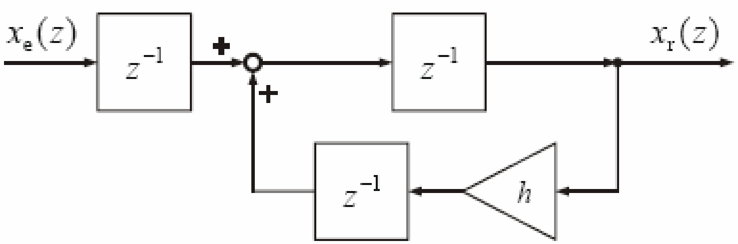
$$h \approx 1 - \frac{2\,\pi\, f_{3\mathrm{dB}}}{f_{\mathrm{samp}}}$$

- and add it to the next input for the delay



Concession to real life

- multiplication and sum can hardly be performed together in a FPGA

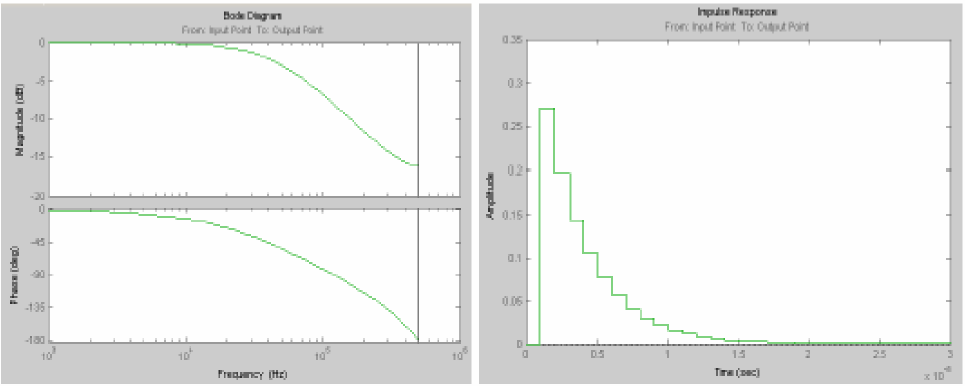


➢ additional delays double reduction value

$$h \approx 1 - \frac{4\,\pi\, f_{3\mathrm{dB}}}{f_{\mathrm{samp}}}$$

➢ Bode diagram and the impulse response are similar to previous version

Response of 50 kHz IIR with 40 MHz sample frequency



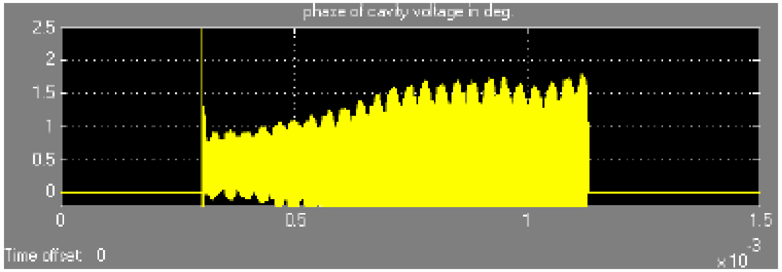
Advantage: the signal delay is only one sample step (25 ns)

Disadvantage: nonlinear phase response ⇒ different group delay
⇒ signal distortion

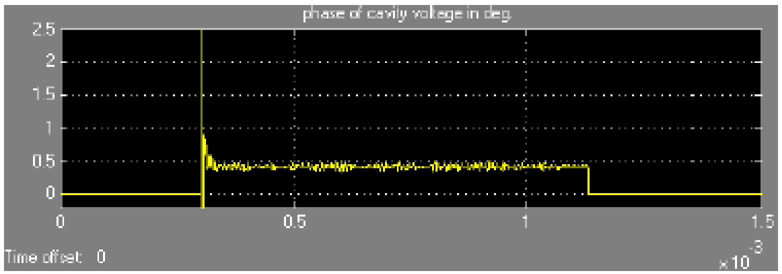
Example: proportional control at TTF RF gun

Proportional IQ control with gain 5, gun 2.3 kHz detuned

without IIR



with 50 kHz LP IIR



System Model Extraction

Dmitry Teytelman

Stanford Linear Accelerator Center
Stanford, CA, USA

Low-level RF Workshop, 2005

Model extraction: WHAT

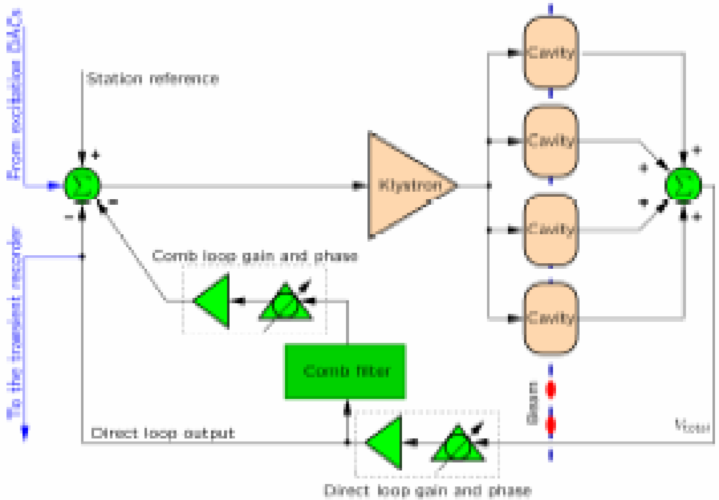
Basic procedure:

- Measure dynamic response of a physical feedback system.
- Fit the parameterized linear system model to the response.
  - Time domain
  - Frequency domain
- Compare estimated parameters to known "gold configuration".
- Apply the adjustments to the system.
  - Maybe even automatically?

Model extraction: WHY

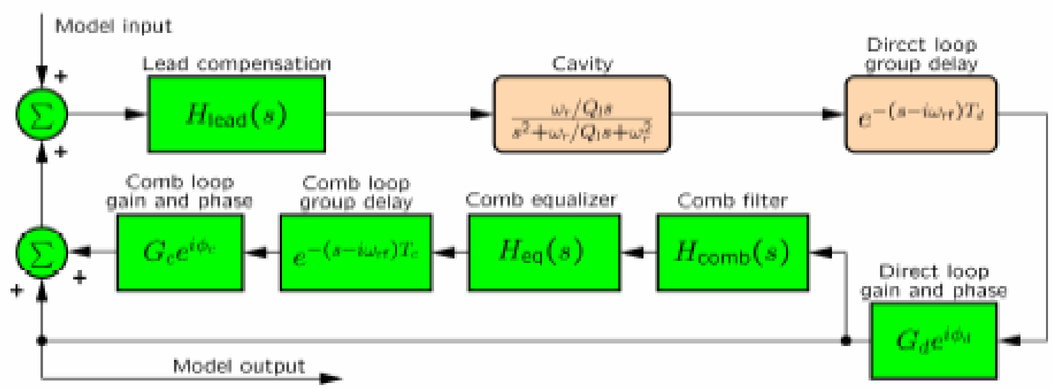
- All systems have imperfections.
- If we knew the system perfectly we would not need the feedback.
- Loop dynamics change with the operating point - need to quantify.
- Open-loop transfer function measurement:
  - Not always applicable.
  - Open-loop system is unstable.
  - Operating point shift in the open-loop mode.
  - Parasitic measurement desired.

Fast feedback loops



- Two fast feedback loops:
  - Direct
  - Comb
- Baseband I&Q processing
- Mixed analog and digital implementation

Loop model



Assumptions:

- Replace multiple cavities with a macromodel
- Ignore integrator loop
- Klystron is "perfect"

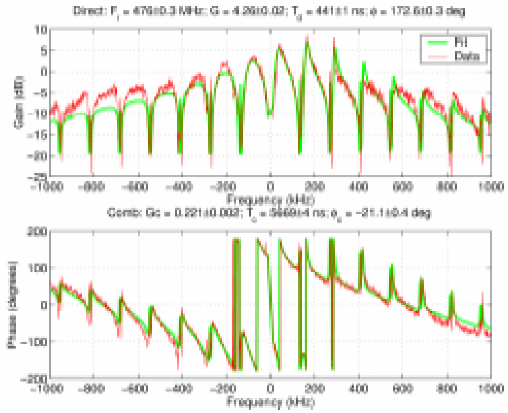
Fitting parameters

- Eight parameters
- ω_r and Q_l are not fitted.
  - Unreliable results seen when fitting these.
  - Resonant frequency computed from measured tuner positions.
  - Use nominal quality factor

Model parameters

ω_r	Resonant frequency
Q_l	Loaded Q
G_d	Direct loop gain
T_d	Direct loop delay
ϕ_d	Direct loop phase
G_c	Comb loop gain
T_c	Comb loop delay
ϕ_c	Comb loop phase

Station tuning sequence

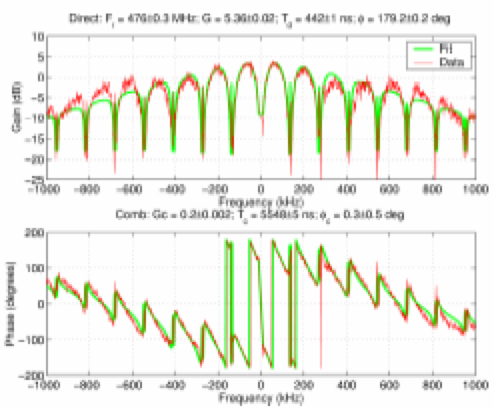


Start with a badly mistuned station.
Iteratevely apply model-based corrections.

Model errors

G_d	+2 dB
ϕ_d	+7 deg
G_c	-0.8 dB
T_c	+100 ns
ϕ_c	+21 deg

Station tuning sequence



Start with a badly mistuned station.
Iteratevely apply model-based corrections.

Model errors

G_d	+1 dB
ϕ_d	+0.9 deg
G_c	0 dB
T_c	+13 ns
ϕ_c	-0.3 deg

Summary

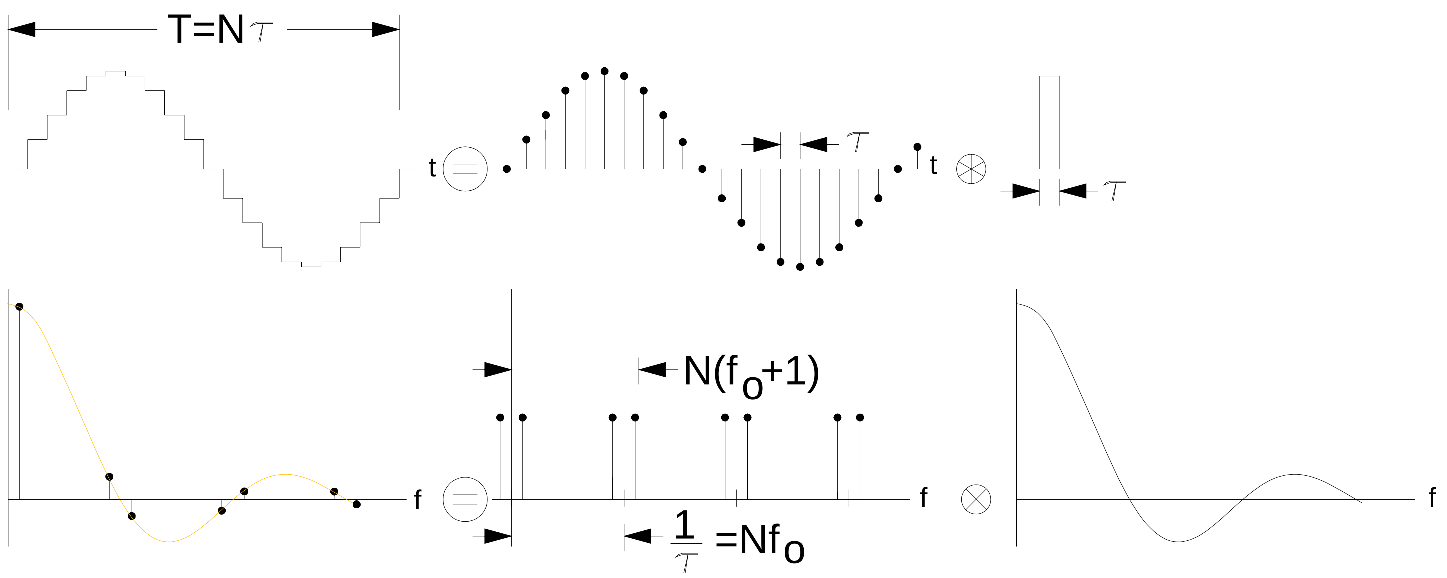
- Non-invasive tuning of LLRF systems is very important for reliable operation.
- Linear model fitting methods have been successfully used in PEP-II since 2001.
- Selection of fitted parameters is key for trustworthy model extraction.

- Wish list
  - Better placement of the test points.
  - Time-domain fitting including klystron nonlinearity.

RF Field Control for 12 GeV Upgrade

Tom Powers
K. Davis, J. Delayen, H. Dong, A, Hofler,
C. Hovater, S. Kauffman, G. Lahti,
J. Musson, T. Plawski,

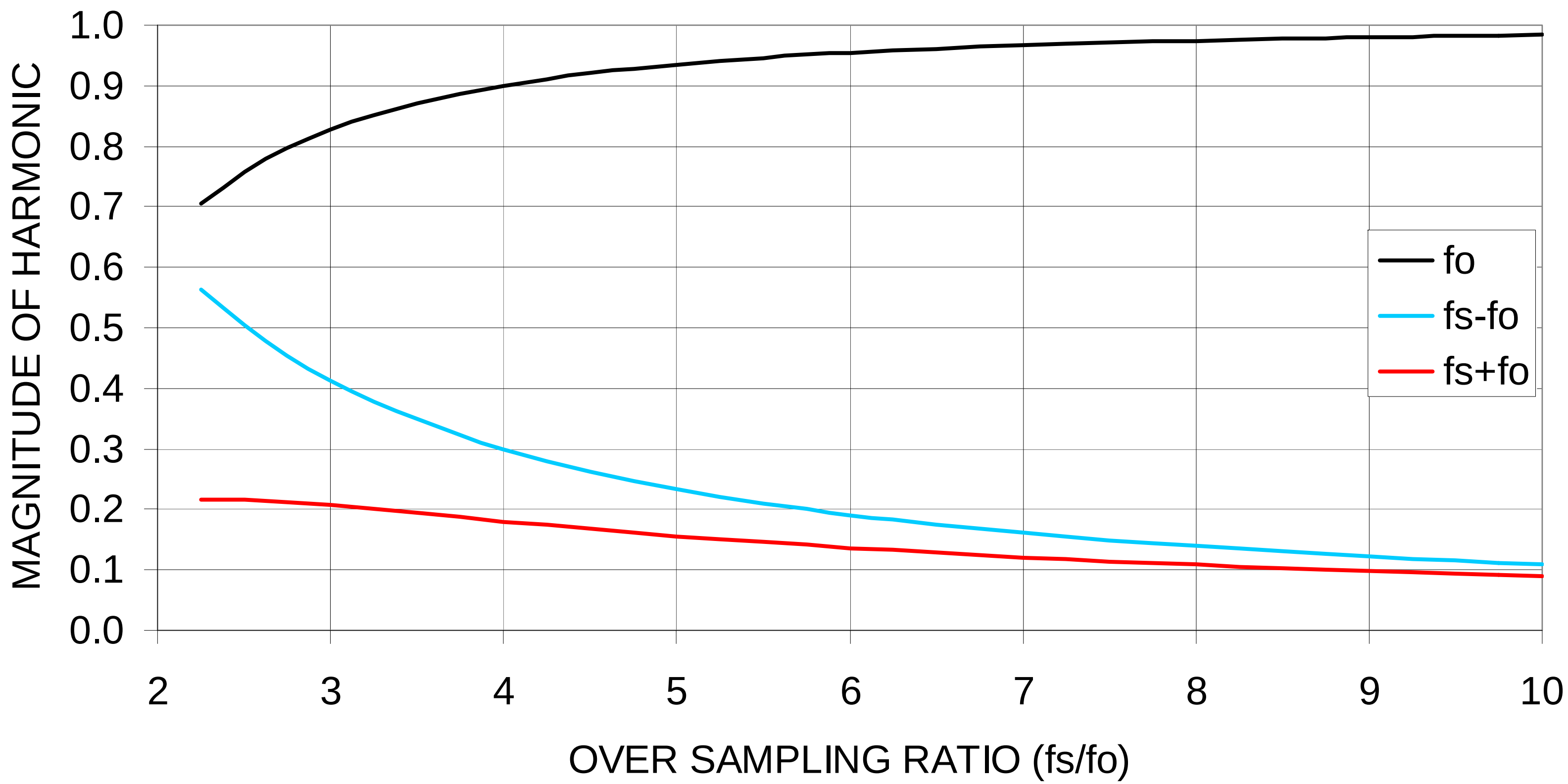
Direct Digital IF Signal Generation



- Concept use one of the harmonics out of your ADC for your IF frequency.

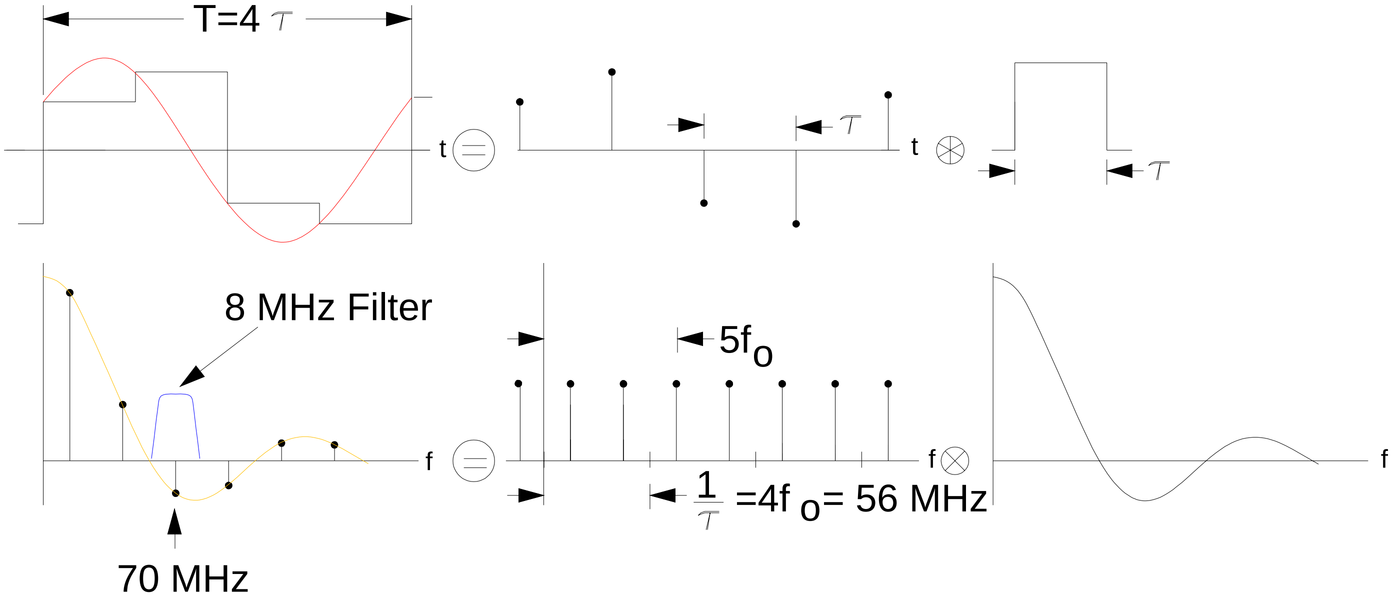
- For a 10-X system two disadvantages to using second or third harmonic frequencies are:
  — Small signal content.
  — Analog filter requirements.

Relative Magnitude of Harmonics



- **Relative magnitude of the three harmonics out of an ADC when the sampling frequency, fs, is near the signal frequency, fo.**

3-X DDS



- **Ratios of f3 to f1 is 1:5.**
- **70 MHz component is 14 MHz away from nearest neighbor.**
- **Commercial drop in 8 MHz BW filter available for $30.**
- **One can show that the harmonic contains the proper phase signal and is:** $A\sin(2\pi f_0 + \varphi) \Rightarrow B_k A\sin(2\pi(kf_S \pm f_0)t + \varphi)$ where $k = 0, 1, 2 \ldots$

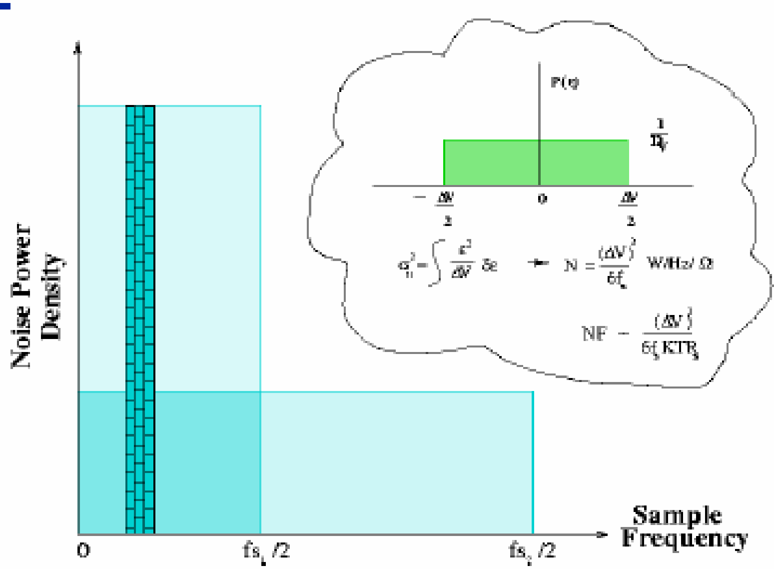
Ultra-Linear Receivers for Digital LLRF Control Systems

John Musson
(and Colleagues!)
TJNAF

All Math Aside....or a Toolbox Smorgasbord

- $To = 290\ K$ (IEEE)
- $KTo = -174\ dBm$
- $NF = Tsys / 290 + 1$
  - $F = 10 \log NF$
- $IIP3 = \frac{Supression}{(Order - 1)} + Ptone$
- $Pim = 3Ptone - 2PIIP3$
- $NFnet = F1 + \frac{(F2-1)}{G1} + \frac{(F3-1)}{(G2 * G1)} + \ldots$
- $Processing\ Gain = 10 \log(\frac{fs}{BW})\ x\ Eff$
- $SFDR3 = 2/3\ (IIP3 + 174 - F - 10 \log BW)$
- $SFDR2 = ½\ (IIP2 + 174 - F - 10 \log BW)$
- $P_{phase\ noise} = P_{unwanted} + 10 \log BW + P_{rx\ phase\ noise}$

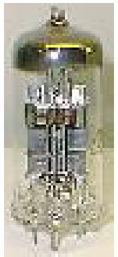
Quantization Noise in A/D Converters



- Courtesy "Digital Signal Processing in Communication Systems," Frerking, M., Chapman a
- "Digital Communications," Proakis, J., McGraw-Hill, 1994

Summary

- Life for the Analog RF Engineer is STILL interesting!
- Back-to-basics design and testing
  - — Made much easier with modern ($$) test equipment
  - — Models are quite reliable for first-cuts
- Narrowband techniques can improve most parameters (ala Genesys)
- If LLRF becomes more demanding.......(?)
- 73, DE WD8MQN

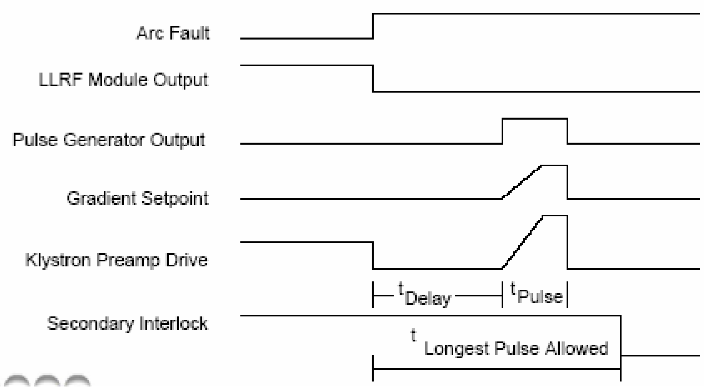


Transient Microphonic Effects In Superconducting Cavities

Kirk Davis
Tom Powers

Experimental Overview

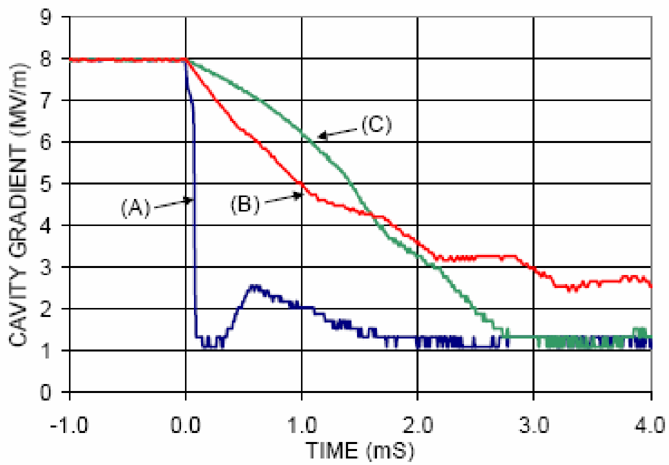
- Induce arc events using the existing LLR Fsystem
- Apply a secondary R Fpulse following a delay
- Measure system response
- Vary delay and ramp-up time of secondary R Fpulse
- Maintain machine protection via hardware interlocks



Background

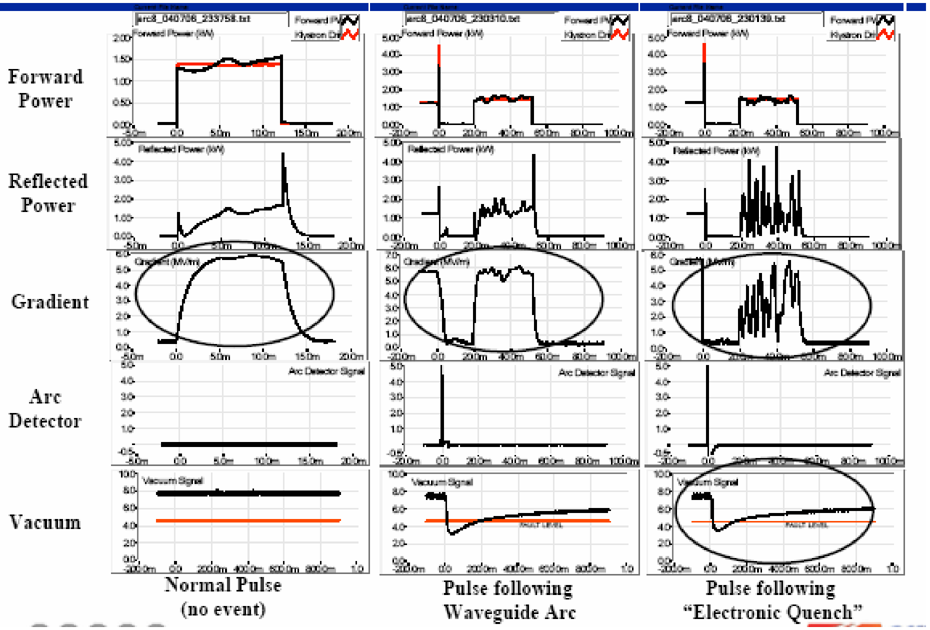
- Arcs in the vicinity of the cold RF waveguide window cause occasional cavity trips.
- On cavities that arc, the trip rate increases with gradient once the field emission onset gradient has been exceeded.
- The cumulative effect of these trips in 338 SRF cavities reduces CEBAF performance especially at beam energies 30% to 50% over the design value.
- Presently, beam recovery following a trip takes approximately 30 seconds. The first ten seconds is to restore gradient.
- The cryotargets used by physics require beam restoration within a few hundred milliseconds to remain at thermal equilibrium.
- The waveguide vacuum signal decays in about 2 seconds.

Question. With a temporary mask on the vacuum interlock, how quickly could a "fast recovery" algorithm restore a cavity to service following an arc trip?

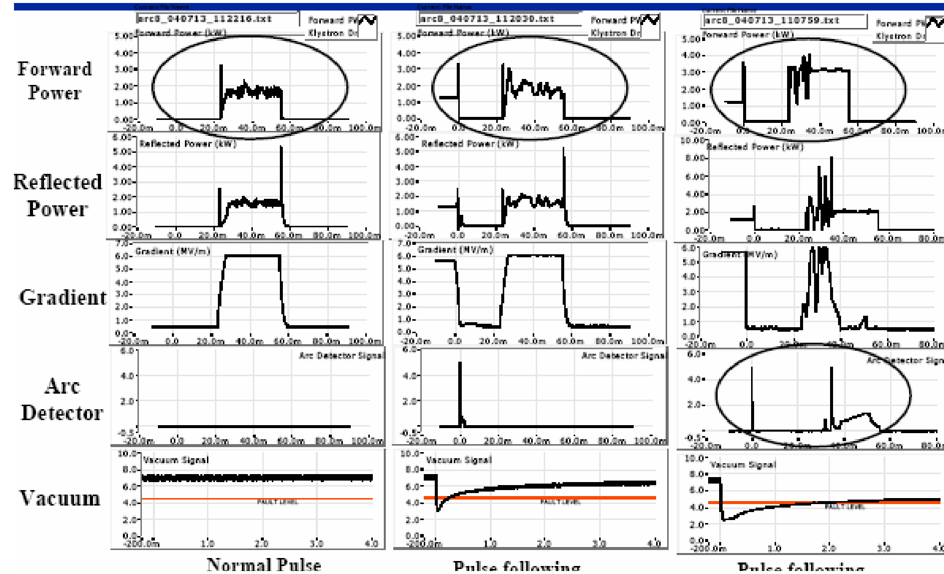


A. "Electronic Quench"
B. Waveguide Arc
C. Normal Response

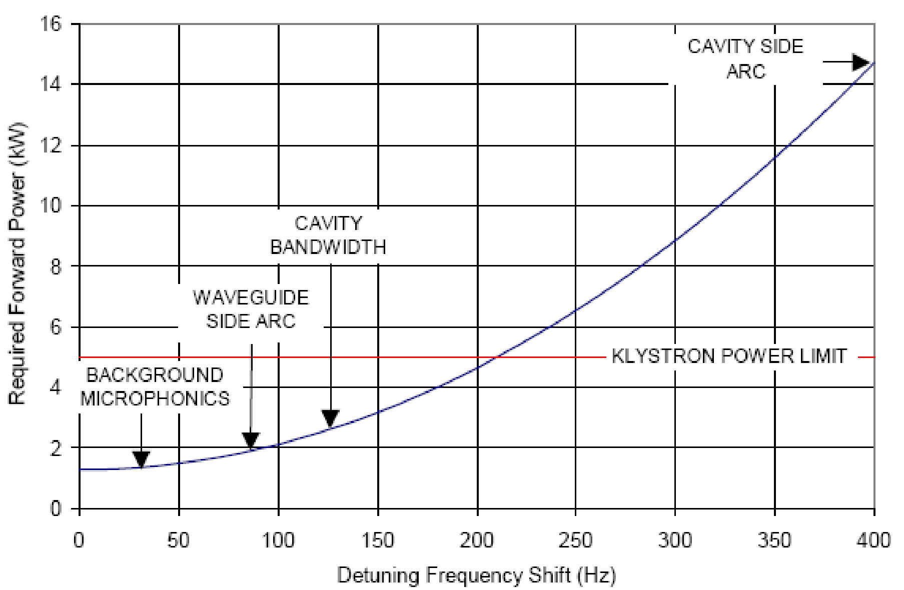
Open Loop Test Results at 7.7 MV/m



Closed Gradient Loop Test Results at 7.7 MV/m



Calculated Power vs. Detuning at 7.7 MV/m



Conclusions

- There are cavity vibration modes that, coupled with beam-loaded klystron power margins, limit the recovery of CEBAF cavities after an arc event.
- The most likely source of the vibration excitation is the dynamic Lorentz force detuning which occurs when the cavity gradient is rapidly reduced by an arc event. This effect is substantially worse for an arc which occurs on the cavity side of the cold window where the gradient decays in less than 100μs.
- Using the existing RF system, one would probably have to wait for at least 500 ms prior to applying R F and about 1.5 seconds prior to loading the system with beam.
- Power levels exceeding 10 times the nominal level (that is 3 times the CEBAF klystron capacity) would be required in order to maintain closed loop gradient control following an electronic quench.
- Vibration Modeling, testing, and control are important aspects of cryomodule design cycle for accelerators that are susceptible to microphonic

Other Talks Of Note

- Fermilab LLRF Software Architecture and Development: Paul W. Joireman
- Tutorial on Optimal Controller: Stefan Simrock
- RF for large heavily loaded rings: limiting factors and promising new developments: Dmitry Teytleman
- Complex digital circuit design for LHC Low Level RF: John Molendijk
- CERN LEIR LLRF: Maria Elena Angoletta
- LLRF Future Thoughts: Larry Doolittle
- Beam based feedback for control: Holger Schlarb
- Characterization of SNS low-level RF control system : Hengjie Ma,

See web: http://indico.cern.ch/conferenceTimeTable.py?confId=a050

Working Group 1
Synchrotrons/LHC

Summary Report

Mike Brennan
Philippe Baudrenghien

Four Talks, and much discussion
(LHC)

Issues of particular interest to LHC

1. RF noise and longitudinal emittance control
2. Klystron gain saturation and phase noise remedies
3. Beam Control topics (not presented in talks)

LLRF05

WG-2 *Linac Applications*

Summary

Mark Champion

&

Participants

Summary WG3

Modelling, Software, Algorithms, Automation

S. Simrock, DESY

Conclusions

- Cavity Simulator and Controller offers great potential for development of software on all levels.
- Beam Instability Modelling quite advanced.
- Potential of SysID (black box model for cavity)
- Technical performance goals for European XFEL-Linac are achieved with VUV-FEL LLRF, other objectives not yet. Injector requires tighter control.
- Downconverter IF frequency of 10 MHz compared to 80 MHz appears to be favorable with respect to SNR and SFDR
- LANSCE-R has tight requirements for Amplitude and phase control which can be met with Adaptive Feedforward Techniques.
- Novel concept to measure 2 cavity probe signals with 1 ADC with 2 different IF frequencies added.
- Use cavity simulator for software development.
- Internal interface provide generic mapping between signal names and hardware registers. Comparison with simpler interface by Larry Doolittle.
- Conceptual LLRF Design for ILC. Hardware can be made compact at low cost. Cabling problems need to be solved.
- Automation for Accelerators will be important for large accelerators such as European X-FEL and ILC. State machines have been demonstrated for subsystems but not yet for complexity equivalent for ILC.

Hardware WG4

Brian Chase

WG4 - Hardware

Tuesday

- Platforms - Larry Doolittle
- ADCs - Curt Hovator
- DSP - combined with WG3

WG4 - Hardware

Wednesday

- Swept Frequency Systems, Receivers and Master Oscillators - Flemming Pedersen
- Thoughts on DSP - Dmitry Teytelman
- Control of Ferrite Phase Shifters - Yoon Kang
- SNS LLRF Reference System (Chip Piller)
- Optical Stabilization (Axel Winter - DESY)
- System Software/Verification - Paul Joireman

Summary

- **LLRF work continues to be a changing and challenging field.**
- **New projects and even the refurbishment of older systems will keep the community busy for the foreseeable future.**

The growth (120 people) of this workshop is testament to the strong need and interest in LLRF!

- **Next LLRF Workshop, 2007 in Knoxville**