Workshop To Workshop: Four Years of Low Level RF

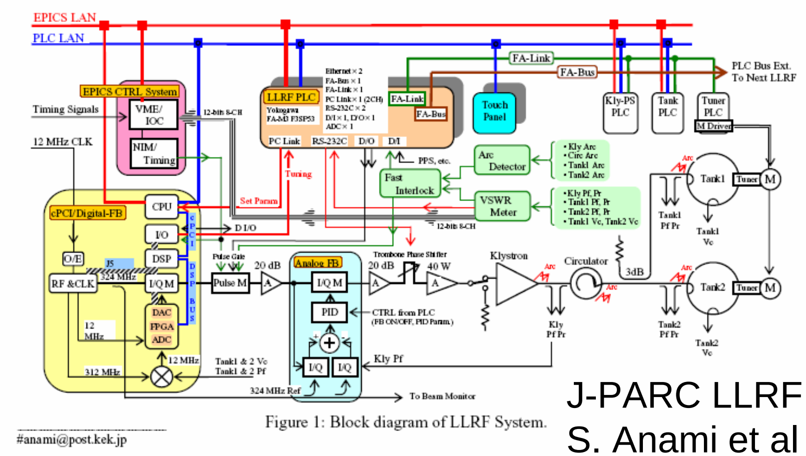
Curt Hovater
&
The LLRF Community

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Past…. Present…. Future….

- **Last Workshop 2001**

ELBE LLRF board
A. Buechner,
LLRF01



J-PARC LLRF
S. Anami et al
LINAC04

- **What has gone on in the four years since**

- **What the future may hold**

First LLRF Workshop at Jefferson Lab

- **April 25 – 27, 2001**
- **70+ Participants**
- **Focus was on LLRF for Superconducting Linacs**

  It was JLAB's idea to have a similar workshop as CERN is doing for the LHC RF systems i.e. bring people in to review our design and direction.
- **Three Working Groups**
  - **Working Group 1 (WG1): Application Specific Issues and Conceptual Designs: Alban Mosnier**
  - **Working Group 2 (WG2): RF Field Control Schemes, RF System Modeling, RF: Stefan Simrock**
  - **Working Group 3 (WG3): Implementation/Design: Tony Rohlev**

The Great Debate: Self Excited Loop (SEL) vs. Generator Driven Resonator (GDR)

- **We heard talks on a number of LLRF systems where each technique was used**
- **Self Excited Loop:**

Design and Operational Experience with the LLRF at the S-DALINAC
Markus Platz (Darmstadt)

Basic Rules for the Design of RF Control Systems in High Intensity SC Proton Linacs M. Luong – A. Mosnier (CEA)

Self Excited Loop Jean Delayen (JLAB)

- **Generator Driven Resonator**

TESLA RF Control System Stefan Simrock (DESY

SNS LLRF Control System Amy Regan (LANL)

Self Excited Loop

Advantages

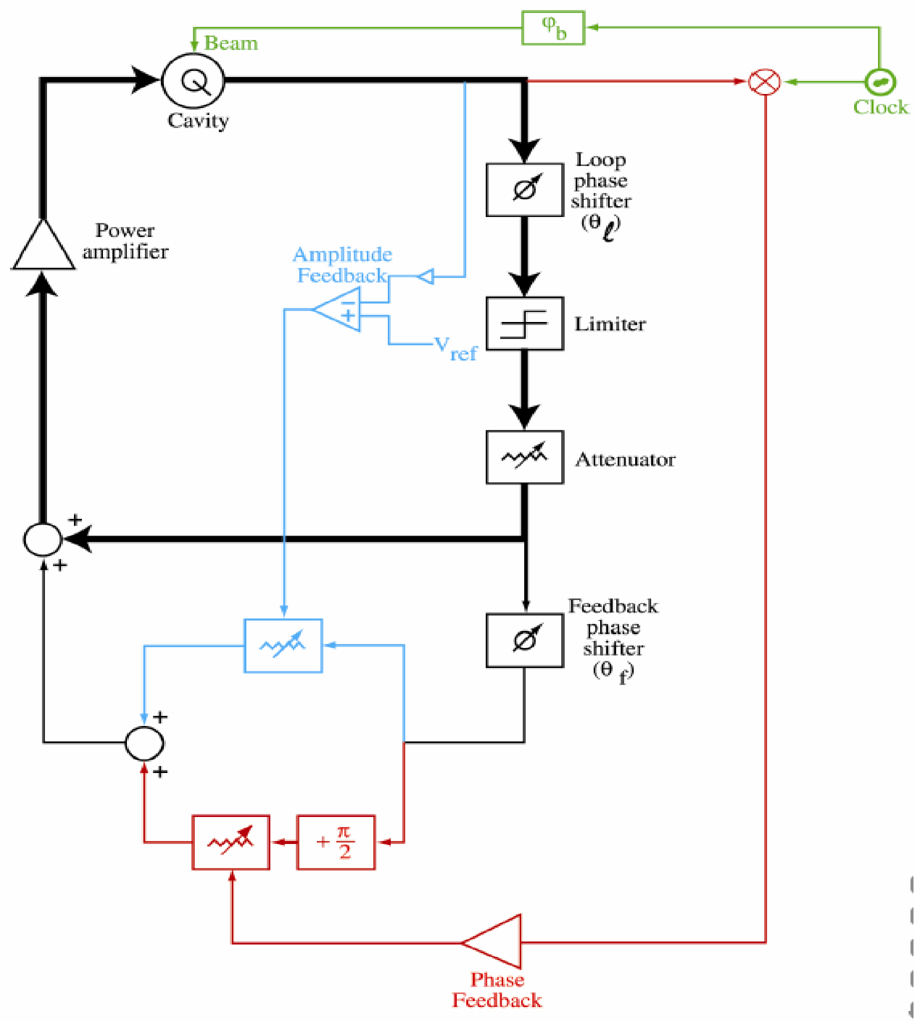
- CW Accelerators
- High Q_L Cavities
- Systems with large Lorentz detuning

Disadvantages

- Pulsed Accelerators (slow lock up up time)

- Installed Systems:

ANL, Darmstadt, TRIUMF, low β accelerators



J. Delayen LLRF01

Generator Driven Resonator

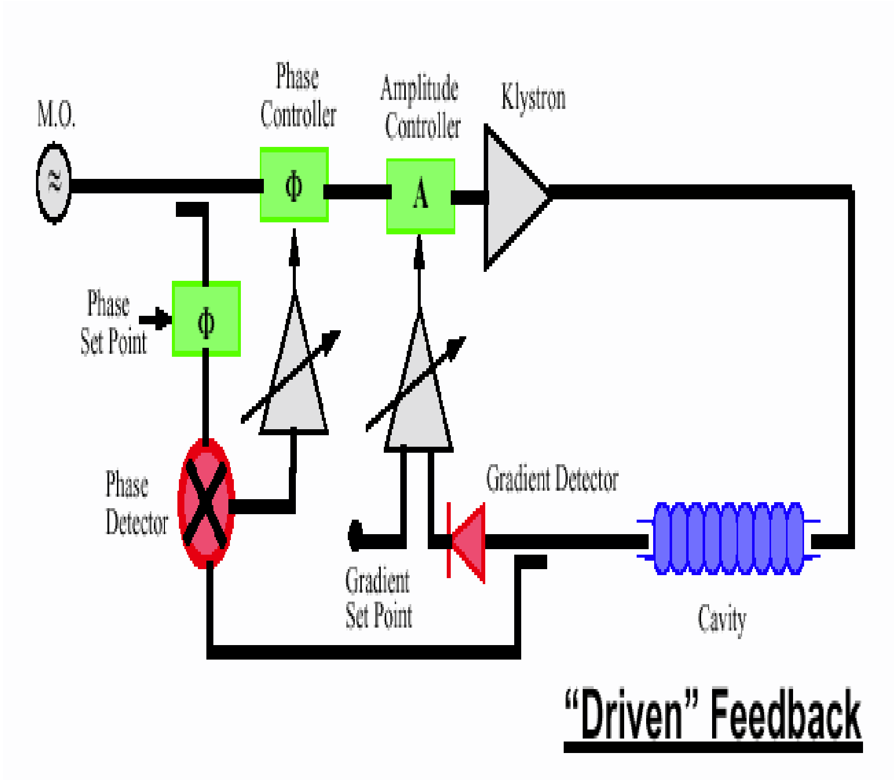
Advantages

- - Pulsed machines where lock up times are critical

Disadvantages

- - High Q_L machines with high microphonic content

- Installed Systems: CEBAF, TESLA, SNS



S. Simrock LLRF01

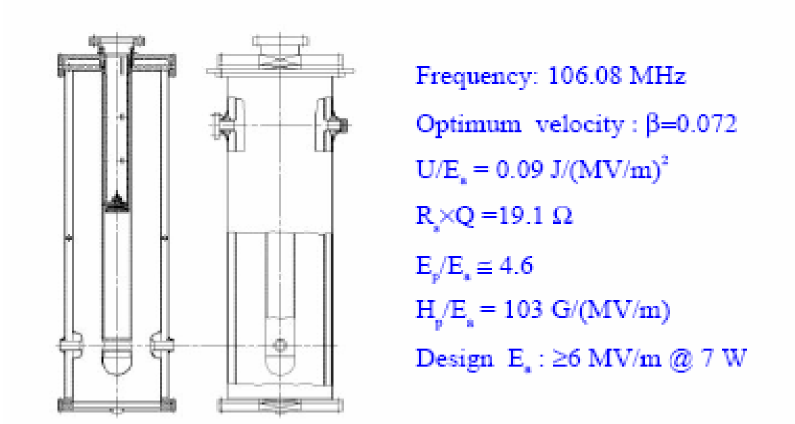
SEL vs. GDR at the end of the Conference

"Which method is greatly application dependent"

- **SEL**

High Loaded Q_L (> 10^8)

Lightly beam loaded CW machines



1/4wave SC cavity for ISAC-II at TRIUMF
R. Laxdal, PAC2001

- **GDR**

Pulsed Accelerators

Heavily beam loaded

Low Q_L (< 10^7)

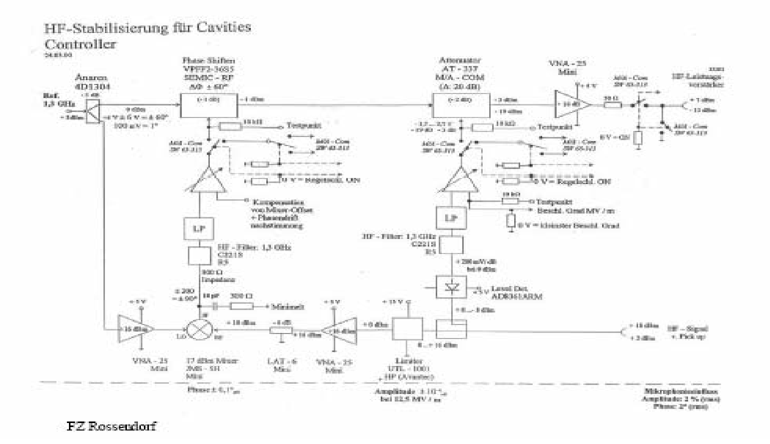
Vector Sum

SNS Cavities, b = 0.61 (a) and b = 0.81 (b)
P. Kneisel, PAC01

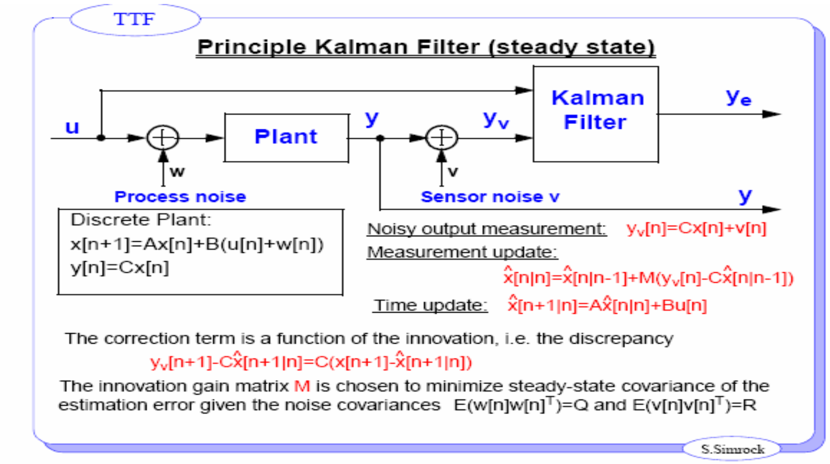
Grey Area: Q_L 10^7 - 10^8

Analog vs. Digital

- **The flexibility of Digital vs. the simplicity of Analog.**
- **Small installations with “set and forget” controls still should consider analog.**
- **Large complicated systems Digital is the best method.**



ELBE Analog LLRF System
A. Buechner, LLRF01

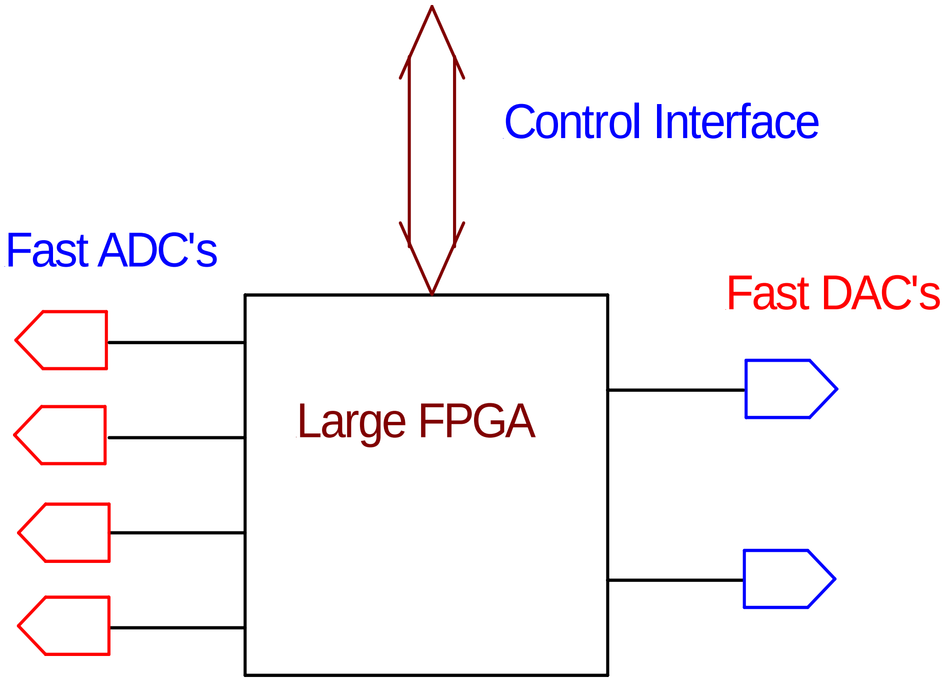


TTF Feedback Algorithm, S. SImrock, LLRF01

The "Standard Design" Emerges

- **A standard Design begins to emerge for control of one or more cavities**
- **One large FPGA & four or more channels**

Transmitted power
Forward Power
Reflected Power
Reference
More Cavities ……???



First Work Shop Summary

and how we got here ………..

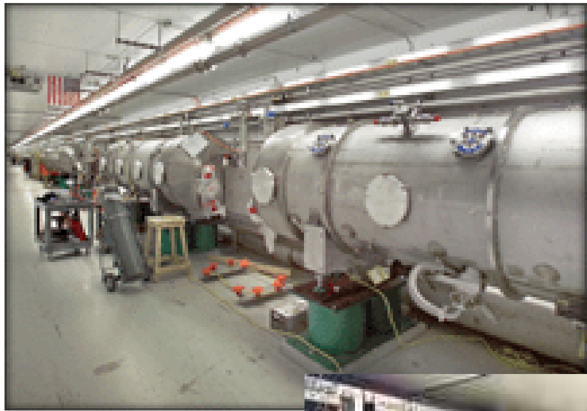
- GDR/SEL application dependant. Use what meets your specifications …..almost a religion type argument.

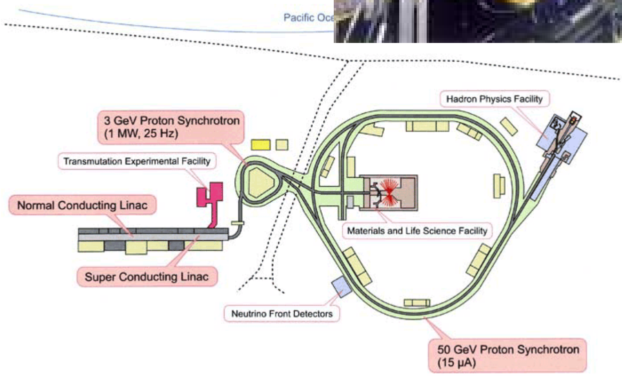
- Digital systems become the norm. Most of the future (at the time) to center around one large FPGA or DSP.

- Marion White gladly proposes the next workshop to be held at the SNS in 2003 ……….early 2004 I begin to harass Mark Champion! Roland and Trevor suggest we have it at CERN …..and here we are!

The Past Four Years

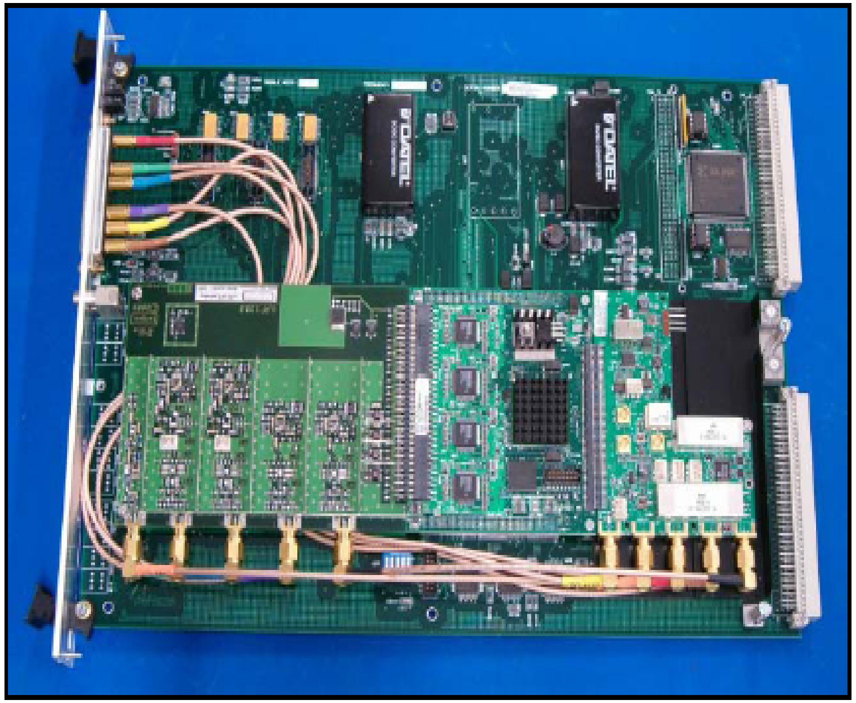
- **Projects: SNS, TTF, J-PARC, FELs, rings, many more …..**
- **The FPGA the heart of a design**
- **The Platform dilemma….. *Pick a crate or make it a network device***
- **New Challenges**
- – **RF Reference/ Distribution systems**
- – **Control of Vector Sum systems**
- – **SRF Microphonic minimization**





SNS LLRF System

- **Design grew out of a simple/minimalist prototype developed by L. Doolittle.**
- **Uses unique quadrature DDS to generate RF**
- **GDR system 1 source/1 cavity**
- **VXI based mother board (large Xlinix FPGA) with multiple daughter cards for receiver (*Bergoz*) and transmitter.**
- **Design controls both superconducting and normal conducting systems.**
- **System is operating and has accelerated pulsed beam to 900+ MeV.**

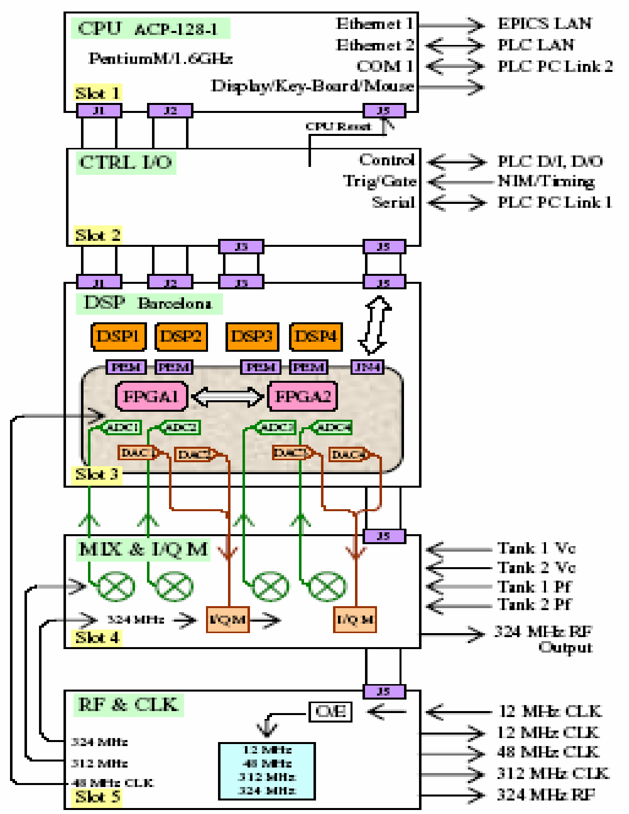


SNS LLRF mother and daughter boards
M. Champion et al, pick your PAC03 or '05

J-PARC LINAC LLRF

- **GDR based system**
- **Uses Analog I&Q Demodulators and Modulators**
- **Blended digital system with FPGA's controlling the fast feedback and DSP's used for resonance.**
- **Uses PCI bus.**
- **System Status:**

  LLRF system has been tested on 60 MeV beam line. J-PARC is being assembled and commissioning to start in June 2006

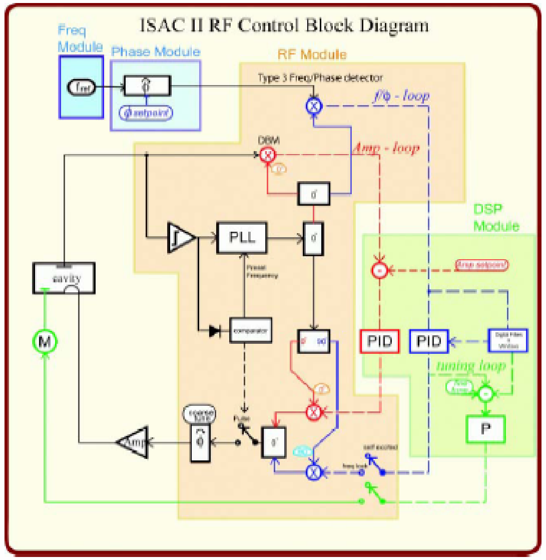


Block Diagram of LLRF using cPCI modules
S. Anami, et al, LINAC04

LLRF Systems Cont.

ISAC II RF Control System

- Uses Self Excited Loop, SEL
- Unique hybrid Analog/Digital system
- Incorporates PLL for phase & frequency stabilization
- VXI DSP (Motorola DSP560002) Module is controlled by a PC using FireWire



Block Diagram of RF control System
K. Fong, PAC03

VUV-FEL TTF DESY

- LLRF System: Pulsed GDR using Vector Sum to control 32 cavities
- Tight Field Requirements
- **Phase: 0.1 degree**
- **Amplitude: 10^{-4}**
- Uses one TI DSP card connected with Gigalink to four ADC (x8) cards
- Incorporates both feedback and feed forward (for Lorentz compensation)

VUV LLRF VME Board
V. Ayvazyan et al, PAC05

LLRF Systems Cont.

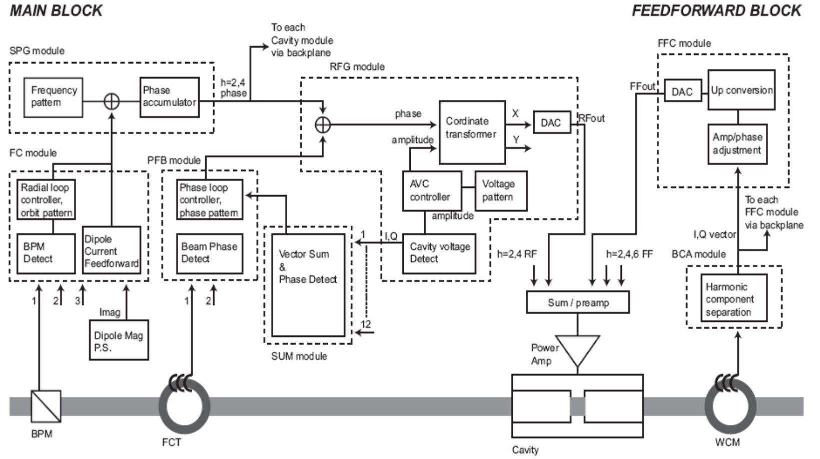
SNS Ring

- Cavity controller Uses a commercial card with four AD DSP for process control.
- Daughter cards support Direct I&Q Demod/modulation
- System supports Feed forward and beam based feedback.

SNS Ring Cavity Controller card
S. Peng, PAC05

J-PARC Synchrotron

- Vector Sum control (11 cavities)
- Multi-harmonic DDS (No PLL)
- VME Based system incorporating Xlinx FPGA

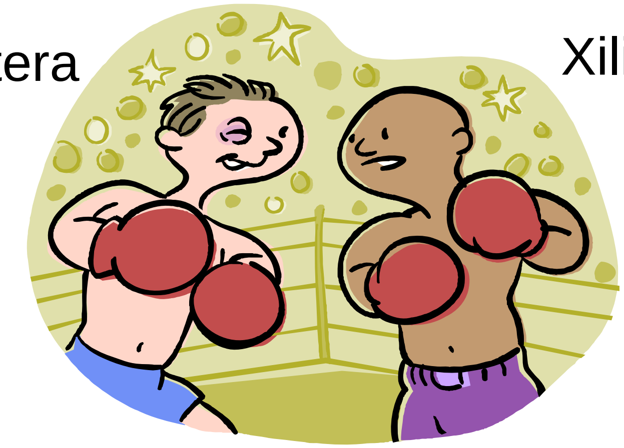


Block Diagram of J-PARC Synchrotron RF System
F. Tamura et al, PAC05

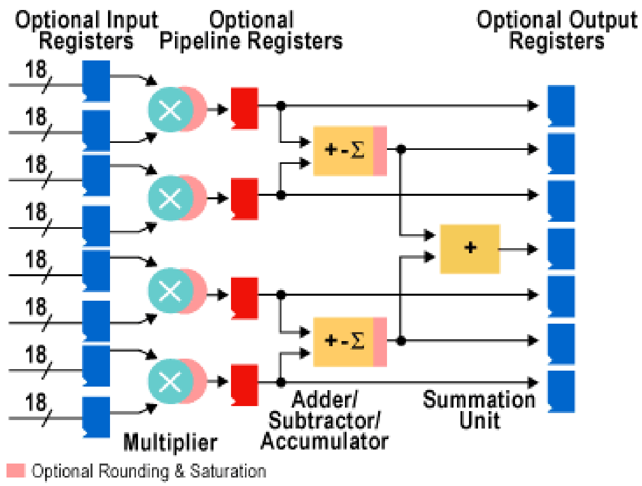
Technology: FPGA's

- **Many new LLRF designs incorporate a large Xilinx 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



Xilinx



Altera DSP Block Architecture

http://www.altera.com/

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)

- **PCI**

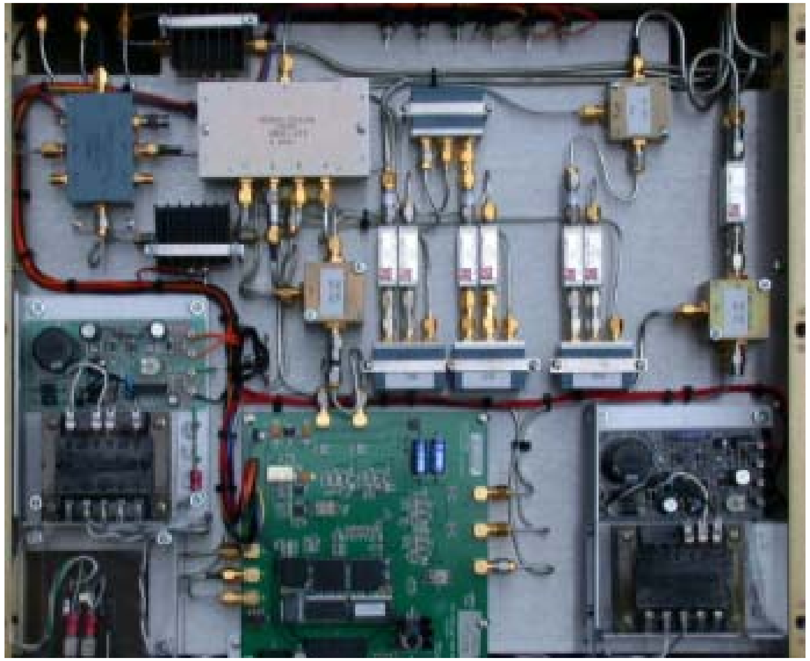
Well supported

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

- **Embedded Ethernet**

Inexpensive & Flexible

Many COTs boards ready to support your project.



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

RF Reference Systems

- **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!**

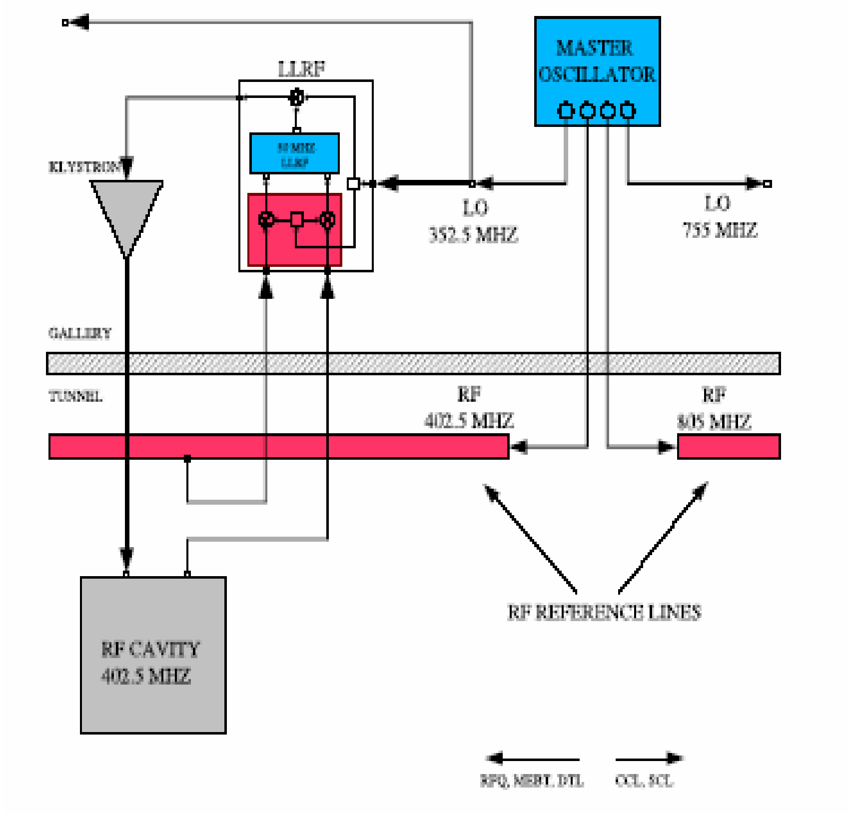
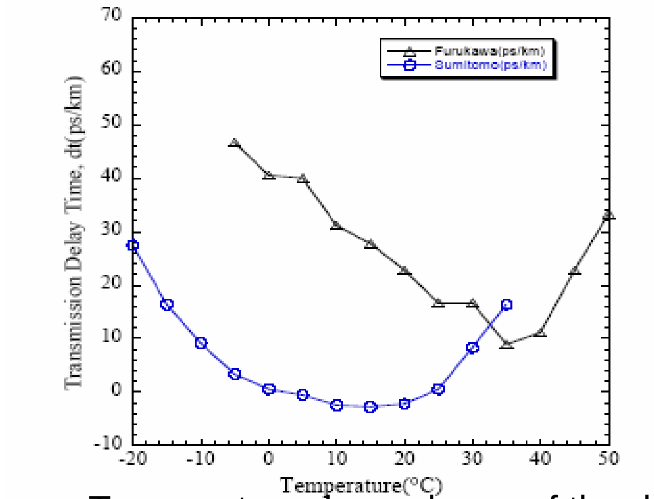


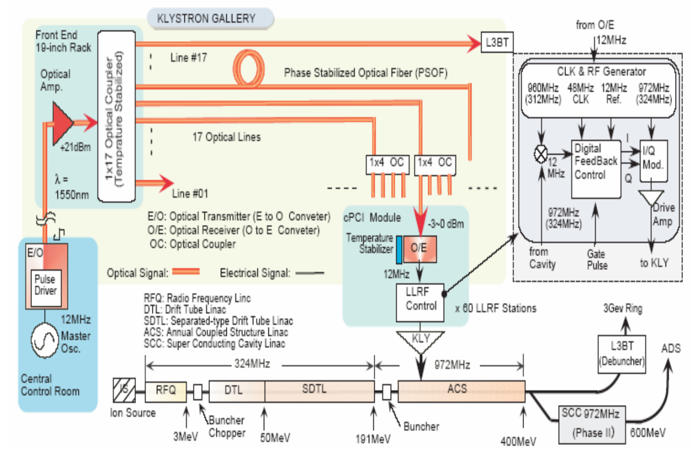
Diagram of the SNS RF Reference System
C. Piller, PAC05

RF Reference Systems Cont.

- **Fiber based systems are the future!**
- **Cost/Size/Flexibility/Installation comparable if not better than Coax**
- **Phase Stabilized Optical fibers available ~ 0.4 ppm/C (compare to coax ~ 5 ppm/C)**
- **Installations: LEP (the first?) KEKB, J-PARC ….**
- **Size of the ILC will demand a fiber system**



Temperature dependence of the delay of Two commercial fibers. Naito et al PAC01



J-PARC Fiber Reference system.
T. Kobayashi et al, LINAC04

One Source: Multiple Cavity Control

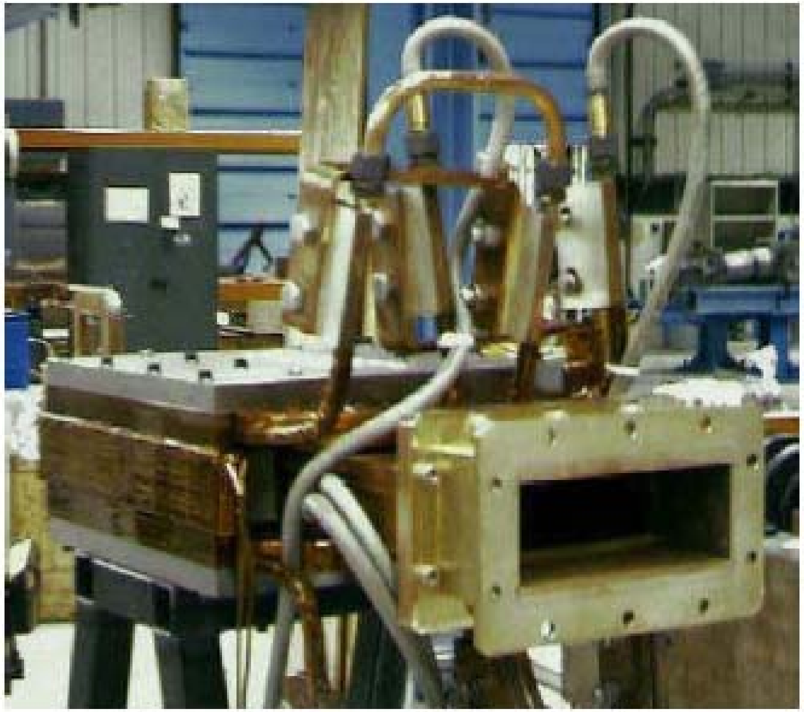
- **Need method to control cavity field of individual cavities relatively fast ~ 1 ms**
- **Solution: High Power Fast Ferrite Phase shifters & tuners**
- **An attractive alternative (and possibly economical) to one cavity/one tube**
- **Questions Concerning**

  - Cost

  - Complexity

  - Reliability

Still need answers ………



Fermi Lab's High Power Phase shifter for Proton Driver Linac.
I. Terechkine et al, PAC05

Active Mechanical Control of Cavity Microphonics

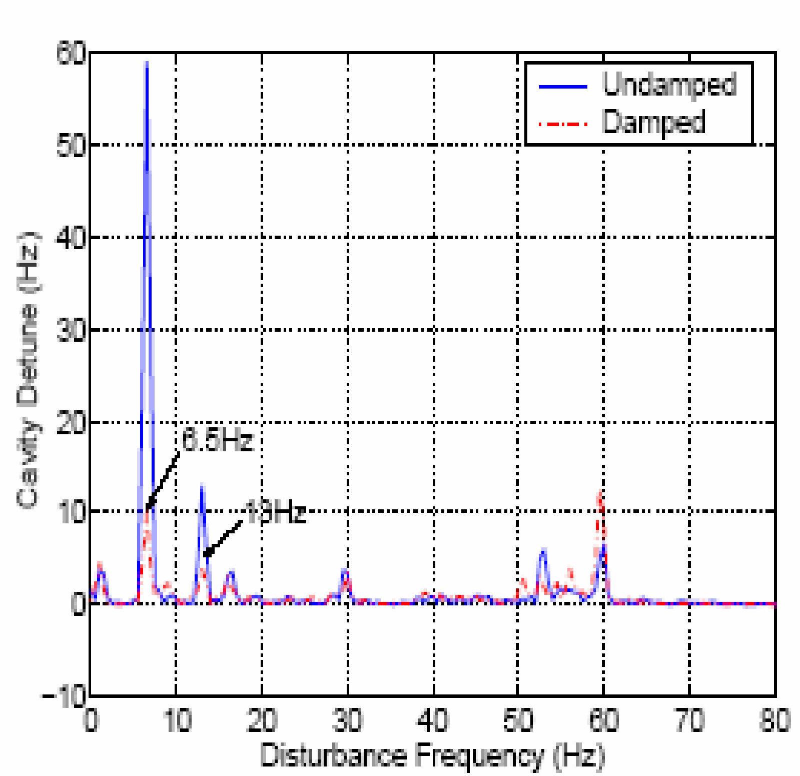
- **Feed forward pulsed RF control of microphonics has been demonstrated.**

  - Simrock, Leipe et al.

- **Feed forward control of well known mechanical modes has been tested.**

  - Grimm, MSU et al.

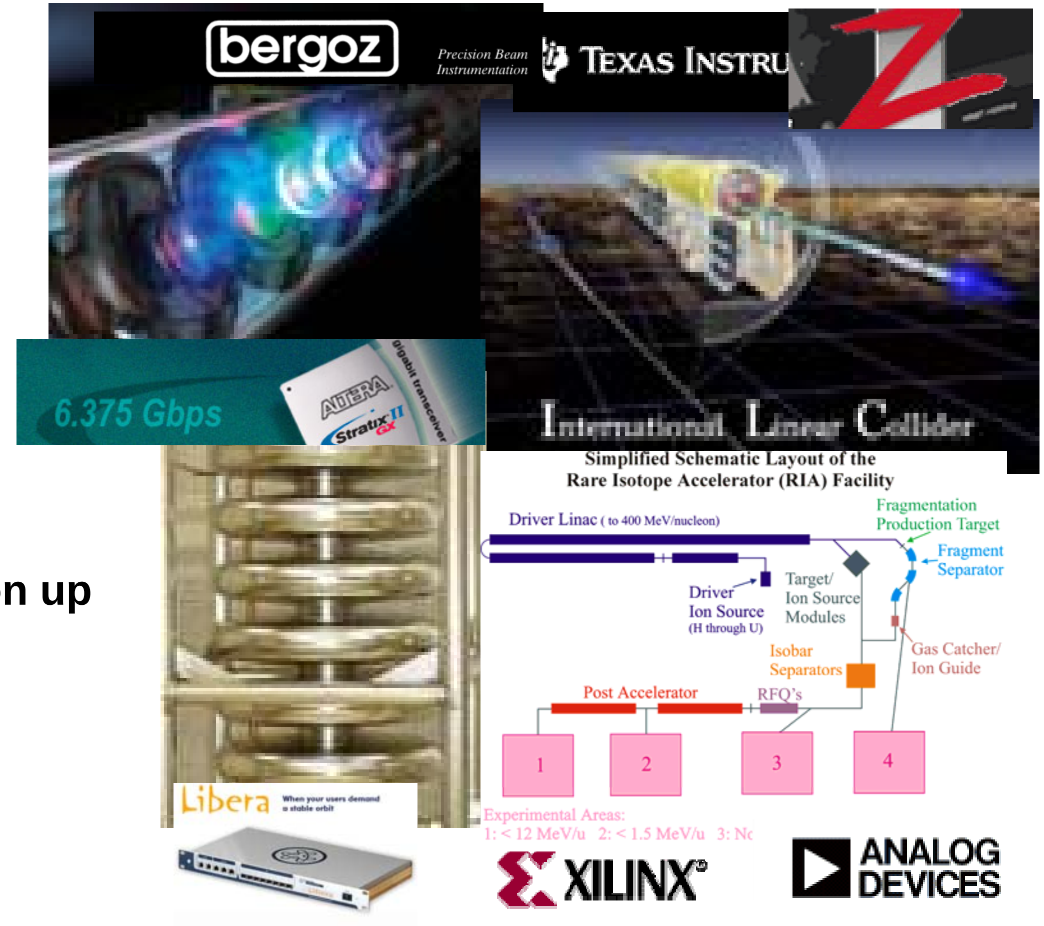
- **Is Mechanical Feedback next?**



Active damping of helium oscillations at 2K
MSU, Grimm et al, LINAC04

Future LLRF Work

- **Projects:**
  - ILC
  - RIA
  - FEL's: X-FEL, LCLS, Bessy
  - JLAB upgrade
  - ERLs: Cornell, eRHIC



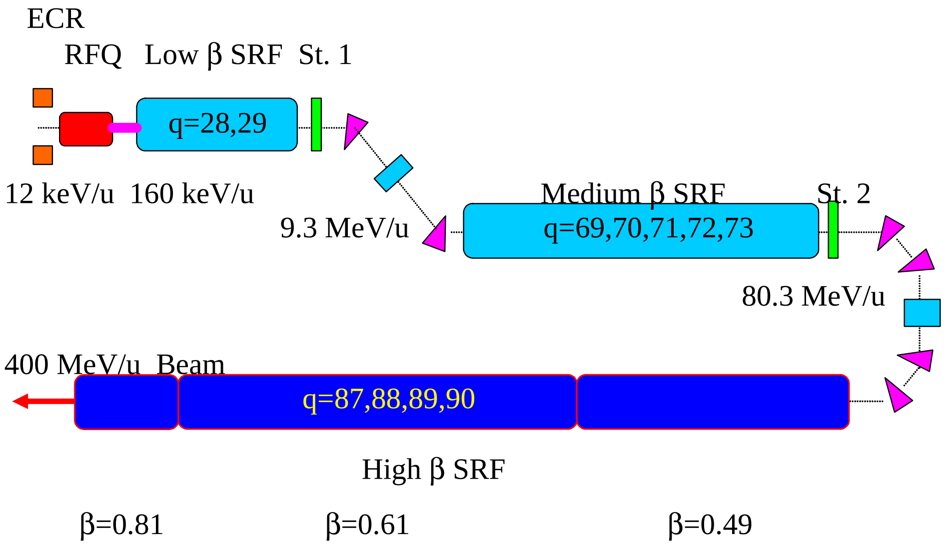
- **Technology**
  - Platforms: embedded network devices and processors
  - Hardware (DSP vs. FPGA)
  - Transceivers: Direct conversion up and down
  - Extremely low jitter reference systems

- **Industrial Participation**

- **Lab Collaboration**

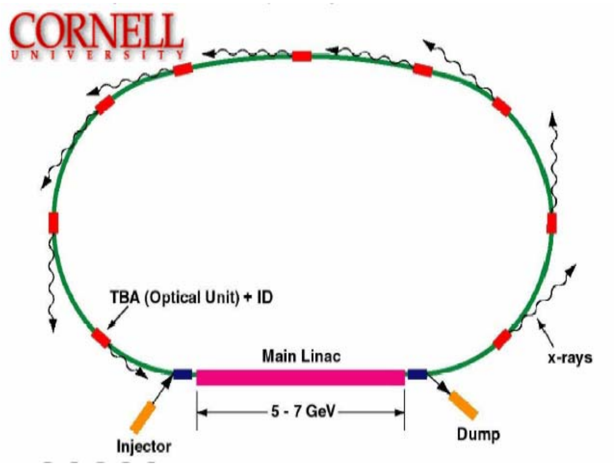
Rare Isotope Accelerator

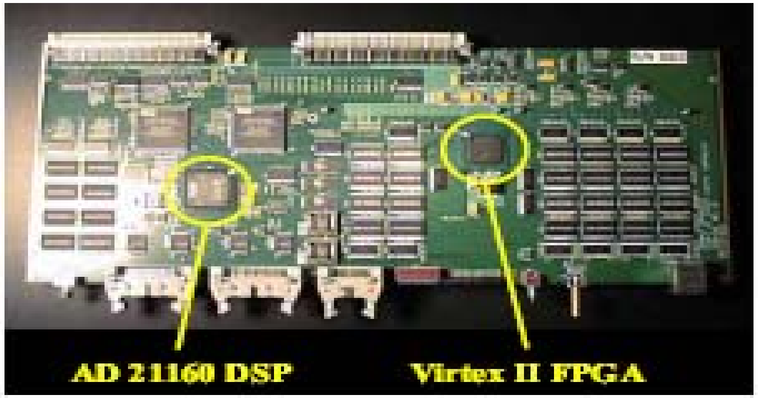
- **Relatively Low current accelerator ~ 100's uA**
- **Many Charge States: protons to Uranium**
- **Max Energy ~ 1 GeV**
- **Present Plans call for 1 tube/cavity**
- **Phase and Amplitude control ~ 1%/1°**
- **Number of Systems : ~ 300**
- **Status: awaiting site selection and funding (*this could be a while!)***



Cornel Energy Recovery Linac (ERL)

- **Large System ~ 300 RF systems.**
- **1v1 Source/cavity**
  - Tesla style cavities
  - Power requirements depend on Q_L (tube or solid state: $ impact)
- **Prototype LLRF system built and tested**
  - GDR based system
  - Operating in CESR
- **Status: Injector Linac is funded and prototype cryomodules are being built.**





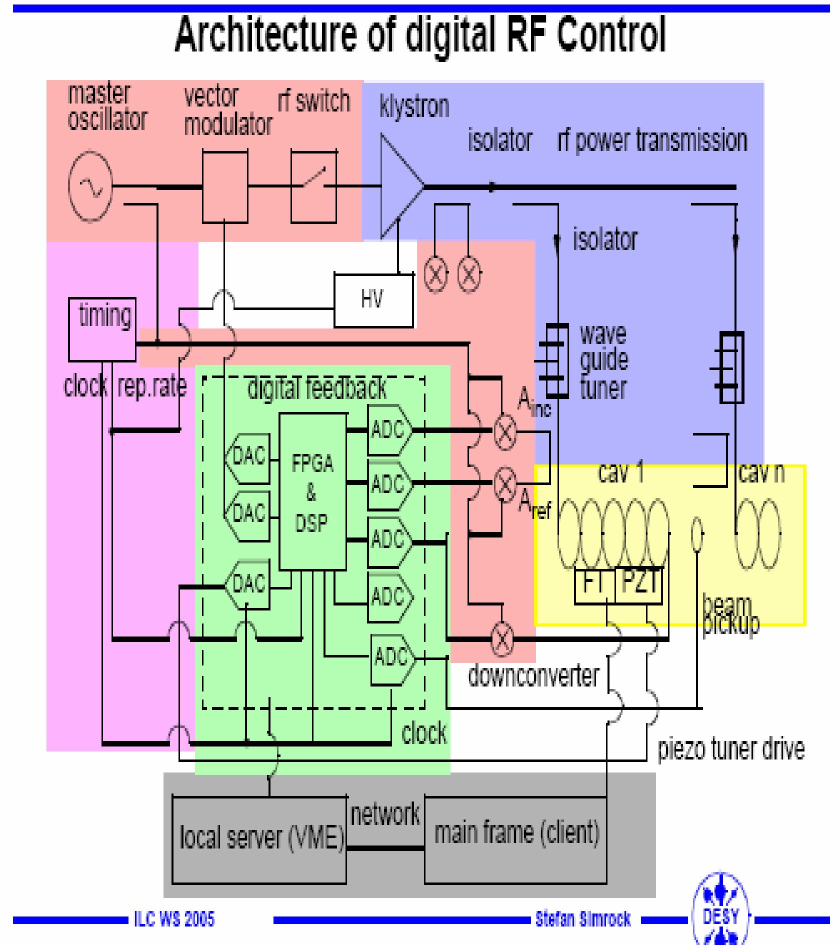
Digital Mother Board,
M. Liepe et al, PAC03

International Linear Collider

Snowmass Highlights

- **VUV/X-FEL should be prototype design for ILC**
- **Design Drivers**
  - **- Automation**
  - **- Beam based feedback**
  - **- Build-in Diagnostics**
  - **- Exception Handling**
- **R&D Issues**
  - **- Software architecture chosen to spur on collaboration**
  - **- Continued algorithm development with beam (multiple sites)**
  - **- Many systems …. Availability Issues**

Status: Global Project Getting Organized.

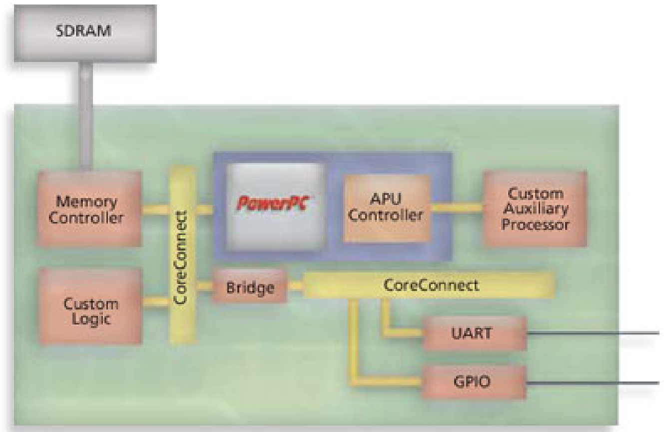


S. Simrock, Snowmass 2005

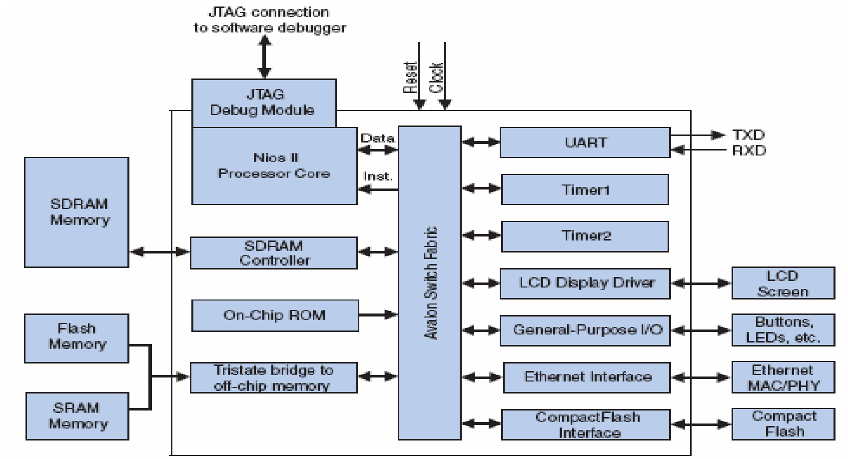
Traditional Processors …DSP ….FPGA….

- **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!



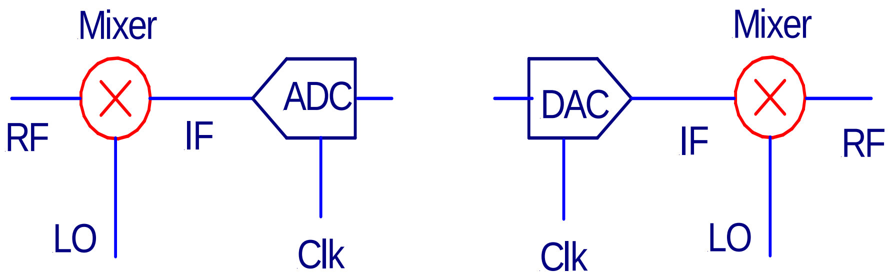
Xilinx FPGA with hardcore Power PC
http://www.xilinx.com/



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

Direct Conversion Transceivers

- Direct conversion receivers are already being considered by BPM folks.
- Eliminates much of the RF section, potentially reducing drifts and non-linear effects
- ADC's are approaching the frequencies to use direct conversion.
- Direct Up conversion using DACs is ready for F < 1 GHz.
- Potential Problems
  - SNR
  - Aperture Jitter/Phase noise

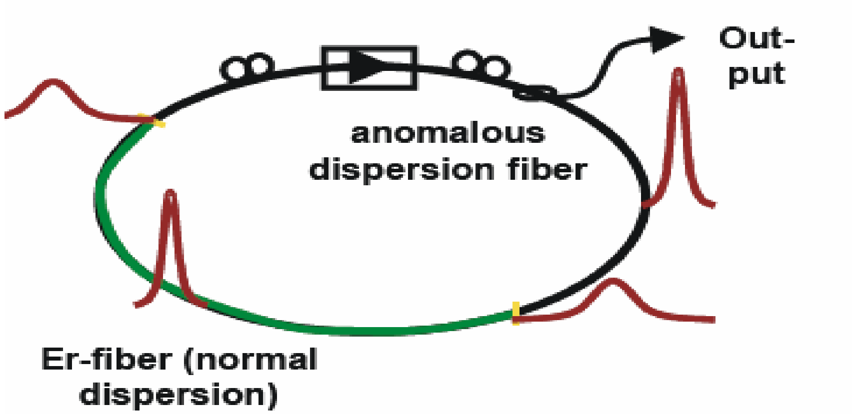


Traditional Super-heterodyne Transceiver

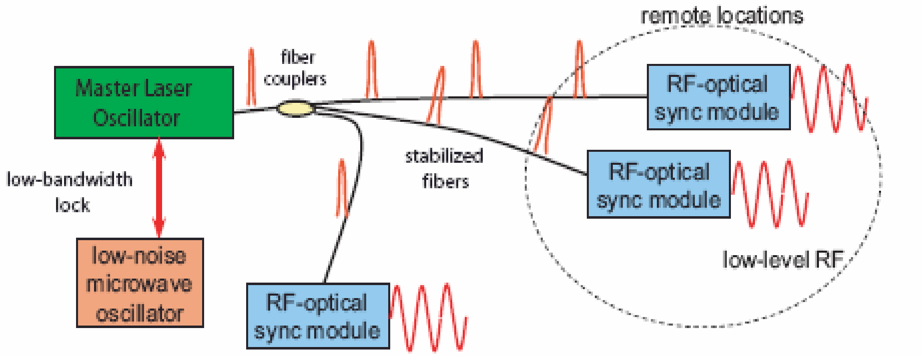
Direct Conversion Transceiver

Fs Synchronized Reference systems

- **FELs are demanding timing signals distributed over large distances with timing jitter on the order of 10's of fs.**
- **Mode locked optical master oscillators synchronized to microwave oscillators using fiber lasers promise < 20 fs of jitter.**
- **They complement fiber distribution.**
- **Attosecond systems next?**



Optical Master Oscillator using a fiber laser, Kartner el al, PAC05



Optical Synchronization Scheme
A. Winter et al, PAC05

Commercial and Industrial Utilization

- **Industrial Collaboration**

  Beam diagnostics folks are already doing this (Bergoz, Instrument Technologies….etc.)

  LLRF Industrial Collaboration

  – **SNS used Bergoz for their receivers**

  – **LANL has used Ztec for DSP modules in the past**

  The ILC's size will probably demand it.

- **Commercial Off The Shelf (COTS) hardware**

  – **Most accelerators are doing this. Makes sense especially for small focused projects.**

Insert Company Advertisement Here

SNS RING LLRF Controller
Bittware Hammerhead –PMC module

Lab Collaboration

- **In my opinion it has improved since the first LLRF workshop recent examples:**

ERL's: JLAB – Cornell

ILC: SNS – Fermi – DESY …..more?

TTF: DESY – JLAB

RIA: LBL – ANL – JLAB – MSU

SNS: BNL – LBL – LANL- JLAB – ORNL

Lots More …….!!!

- **Hey! ….. We're all here so lets Collaborate!**

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!

Thank you for allowing me to spend some time learning about other LLRF systems and projects.