SNS LLRF Design Experience and its Possible Adoption for the ILC

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Why Consider the SNS System for ILC R&D at SMTF

- Close to state of the art components (2 yrs old)
- System is operational and meeting SNS specs
- The design team is fresh from the current design and can easily modify for 1300 MHz
- The Epics interface is complete and there is state control for startup and exception handling
- Lots of commonality with FNAL LLRF systems, Such as VXI and VxWorks OS running on PPC

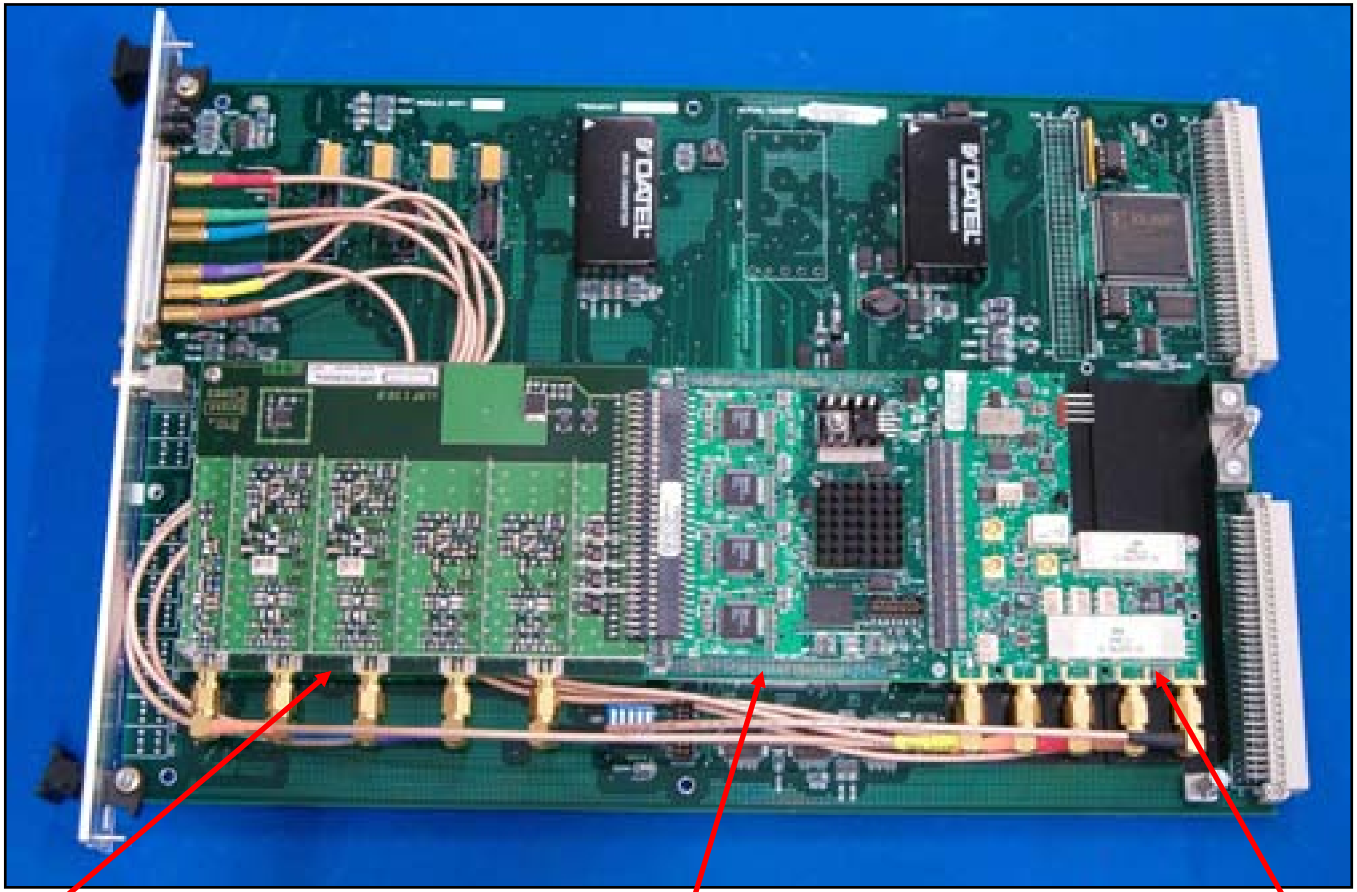
Each Rack in the Superconducting Linac Contains LLRF Hardware for Two RF Systems

Typical LLRF control rack installation in the superconducting linac.

The VXI crate contains:

- Input/Output Controller: PowerPC running VxWorks
- Utility Module: Decodes events from Real Time Data Link
- Timing Module: Generates RF Gate timing signal
- Two FCM/HPM pairs

The Field Control Module (FCM) consists of a motherboard and three daughterboards

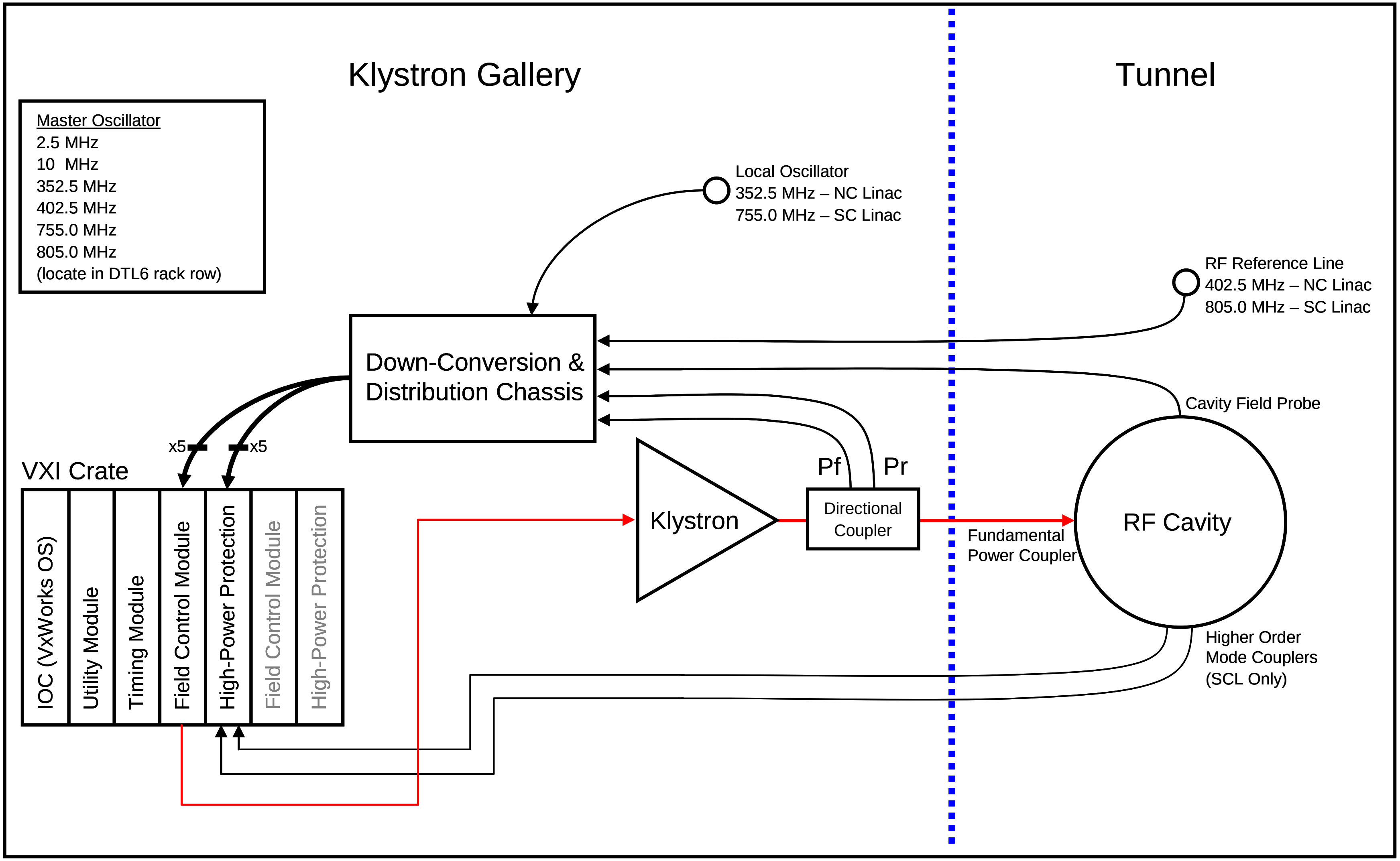


Analog Front End (AFE)
Down-converting channels:
Incident and Reflected RF
(402.5 or 805 MHz)
IF channels:
Cavity and Reference (50 MHz)

Digital Front End (DFE)
Four 14 bit, 40 MHz ADC channels
One Virtex II FPGA
(XC2V1500 – 1.5M gates)

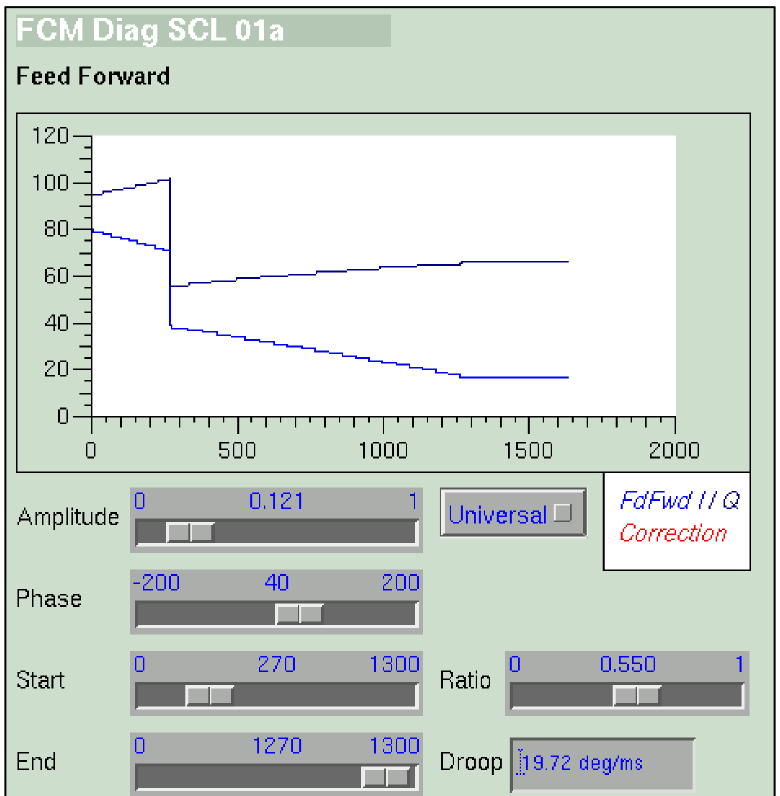
RF Output (RFO)
Clock & PLL circuitry
One 14 bit, 80 MHz DAC
Up-Conversion to 402.5/805 MHz
Filtering

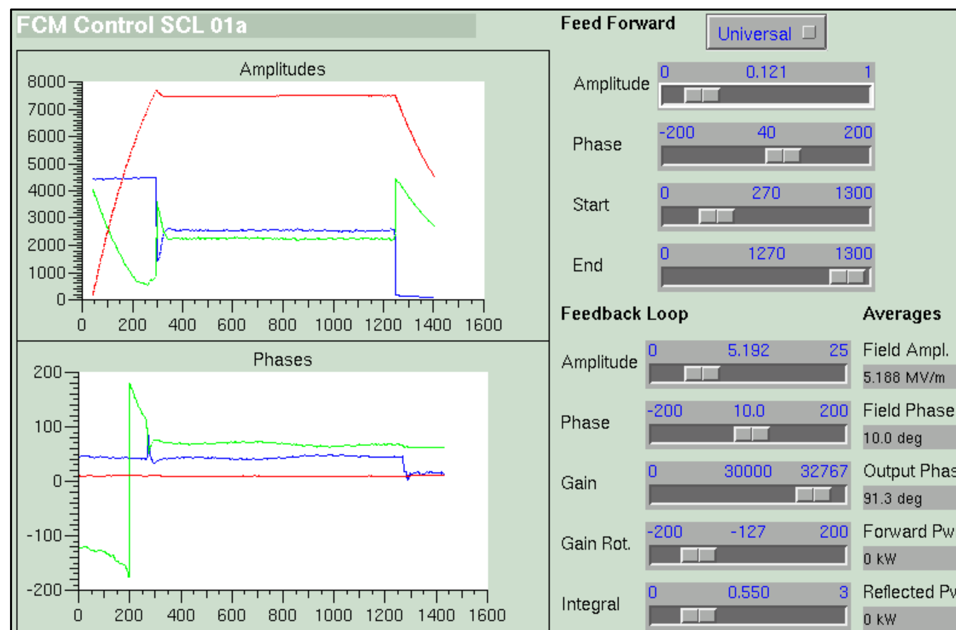
Block Diagram of the SNS Linac LLRF Control System



Advanced FeedForward techniques are being developed to maximize performance

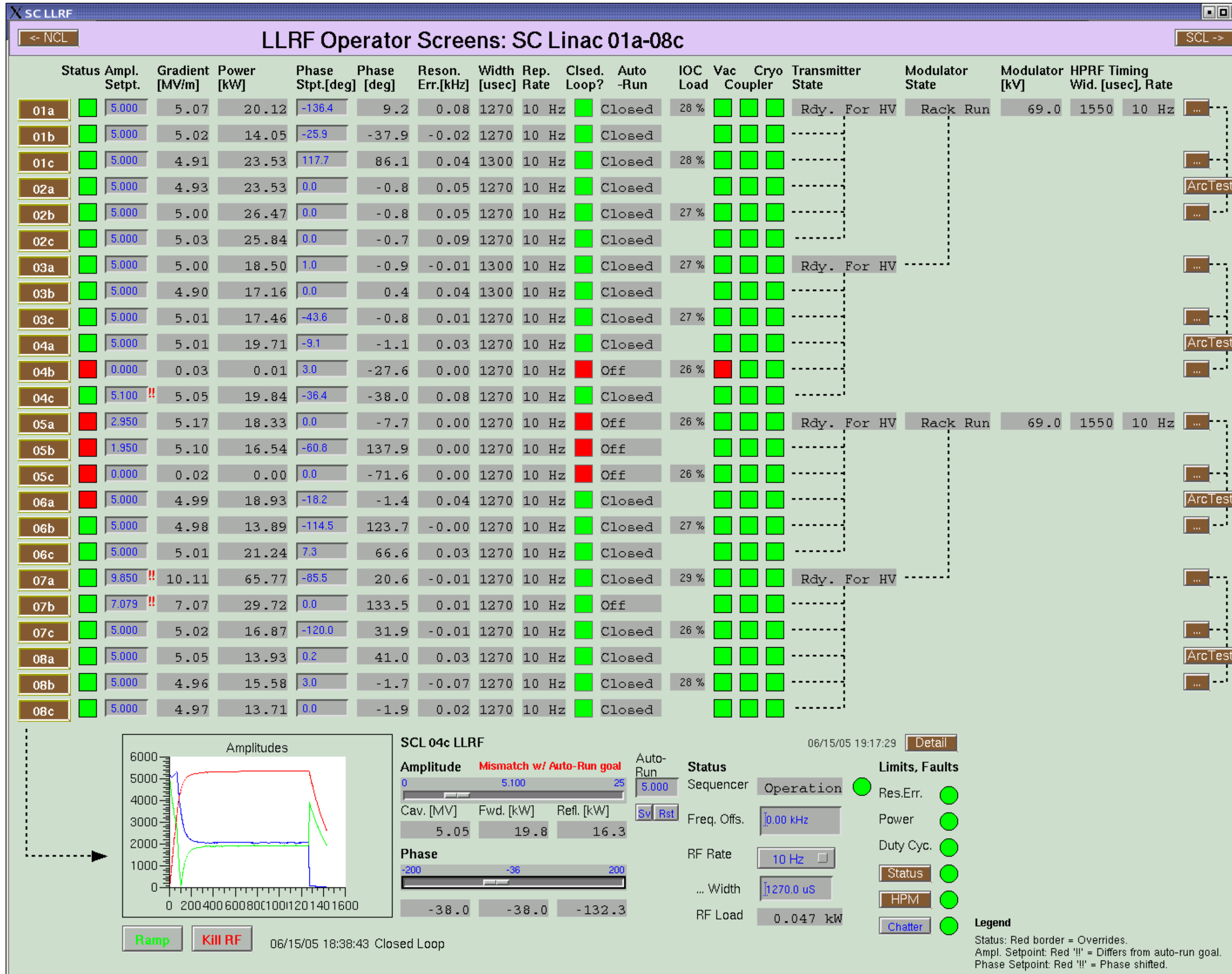
- Cavity fill is best achieved using feedforward techniques.
- Feedback control is reserved for maintaining the cavity field after the desired operating point has been reached.
  - Allows for higher gain settings and tighter regulation
- In this example, the incident RF power is highest during the cavity fill so that the target field can be achieved within a fill time of 300 us.
- The phase push is being compensated by a ~20 deg/ms compensatory slope on the feedforward curve.





One-button turn-on has been tested on the SCL cavities

- Auto-Run sequencer ramps up cavity field under open-loop conditions.
- Auto-Tune sequencer maintains correct cavity frequency.
- Upon reaching the desired gradient, the feedback control loop is engaged.
- In this example, all available cavities (19) for cryomodules 1-8 were turned on automatically.



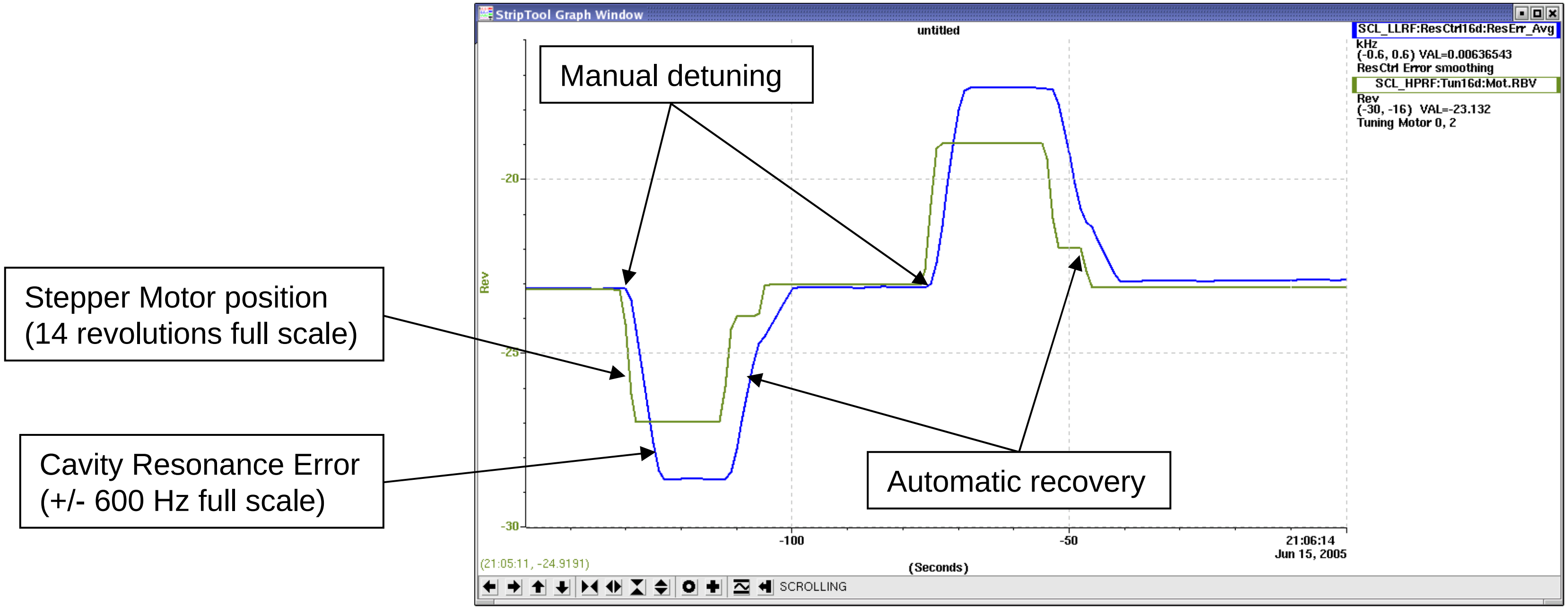
The **Cavity Tuning System** has been tested and is ready to support the SCL beam commissioning run

The LLRF Control System calculates the resonance error based on the cavity field decay.

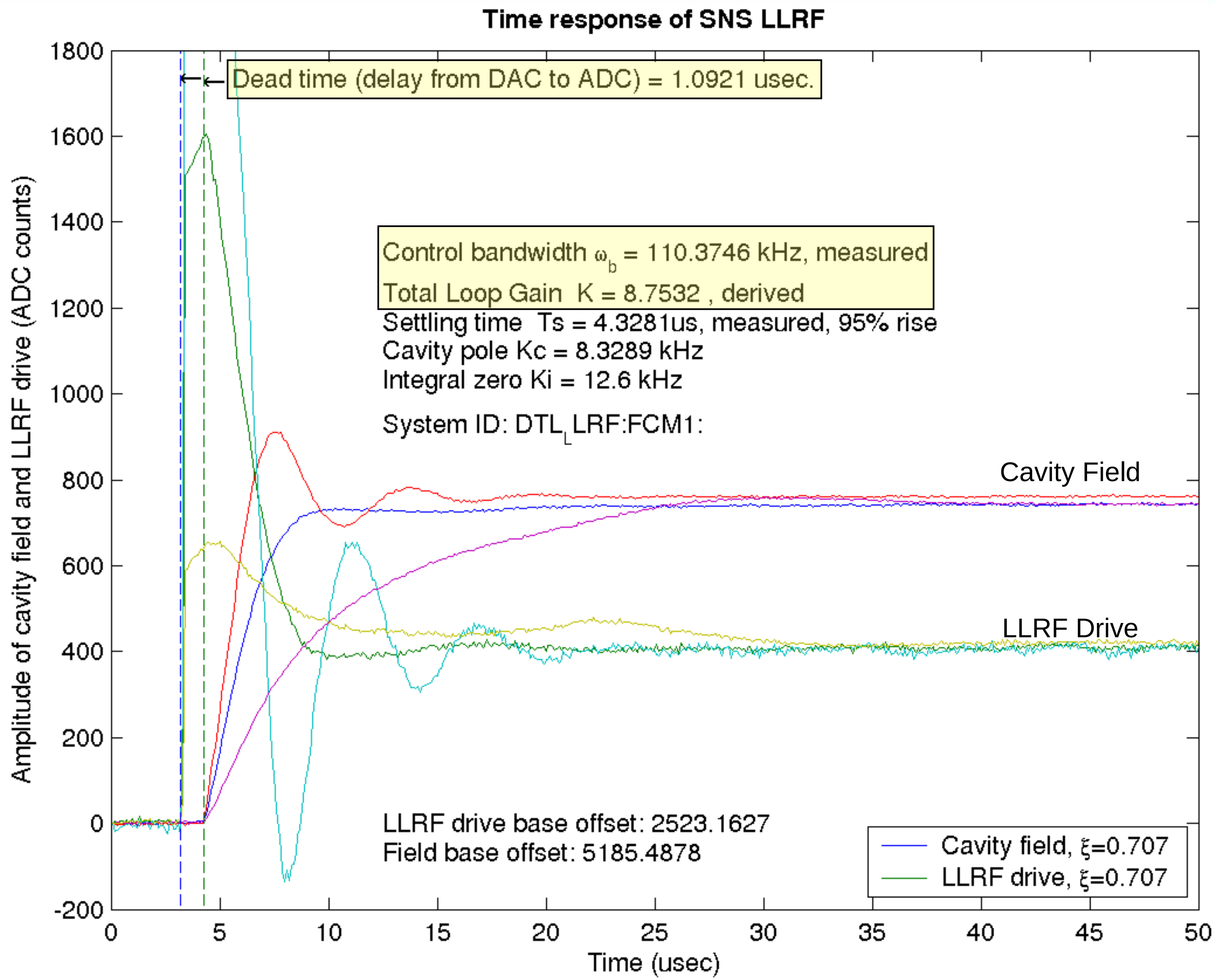
The Cavity Tuning System drives the stepper motor inside the cryomodule to tune the cavity.

Manual and Automatic modes of operation have been tested.

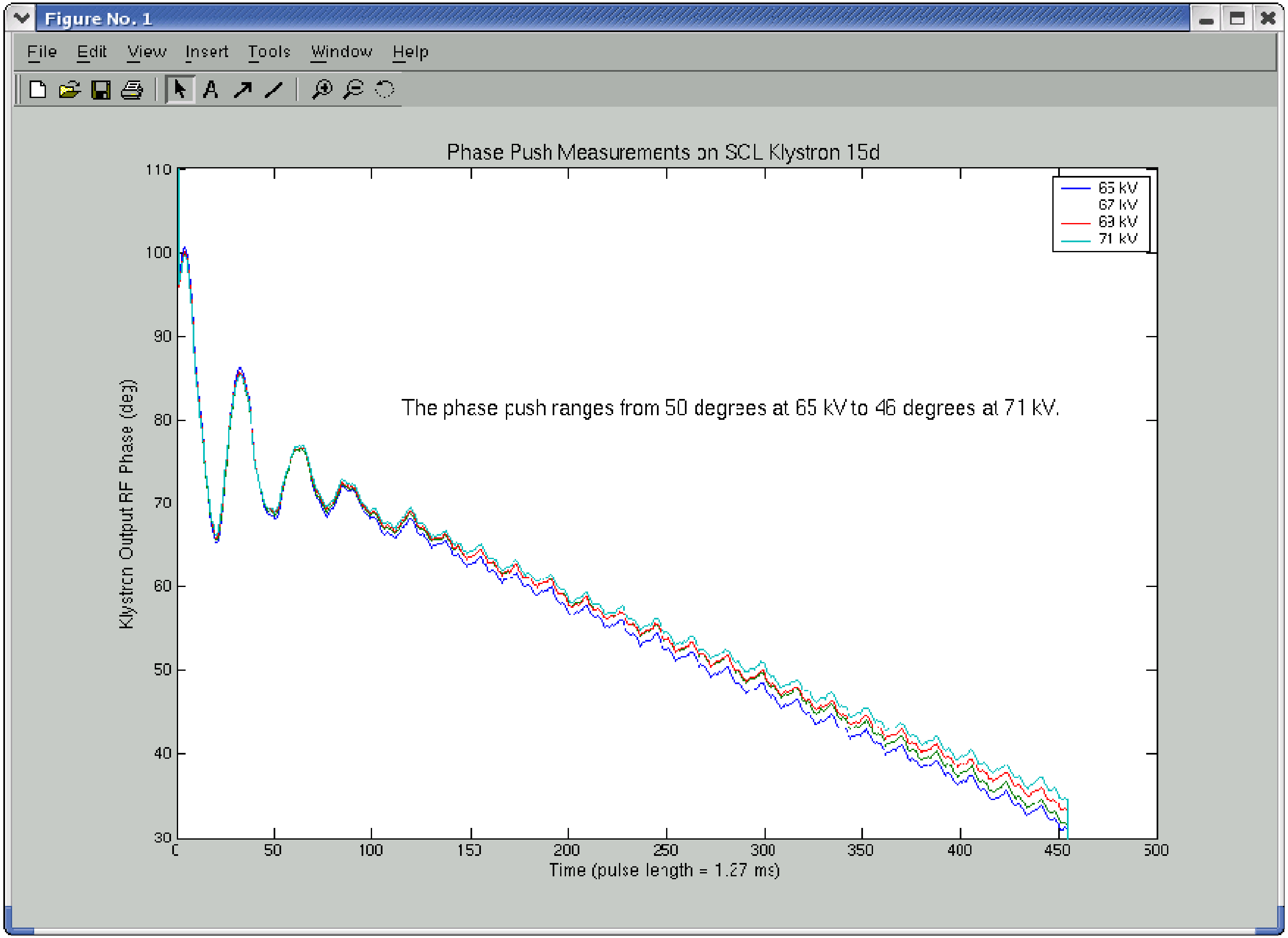
In Automatic mode, the cavity frequency is maintained within a configurable deadband (+/- 100 Hz typical).



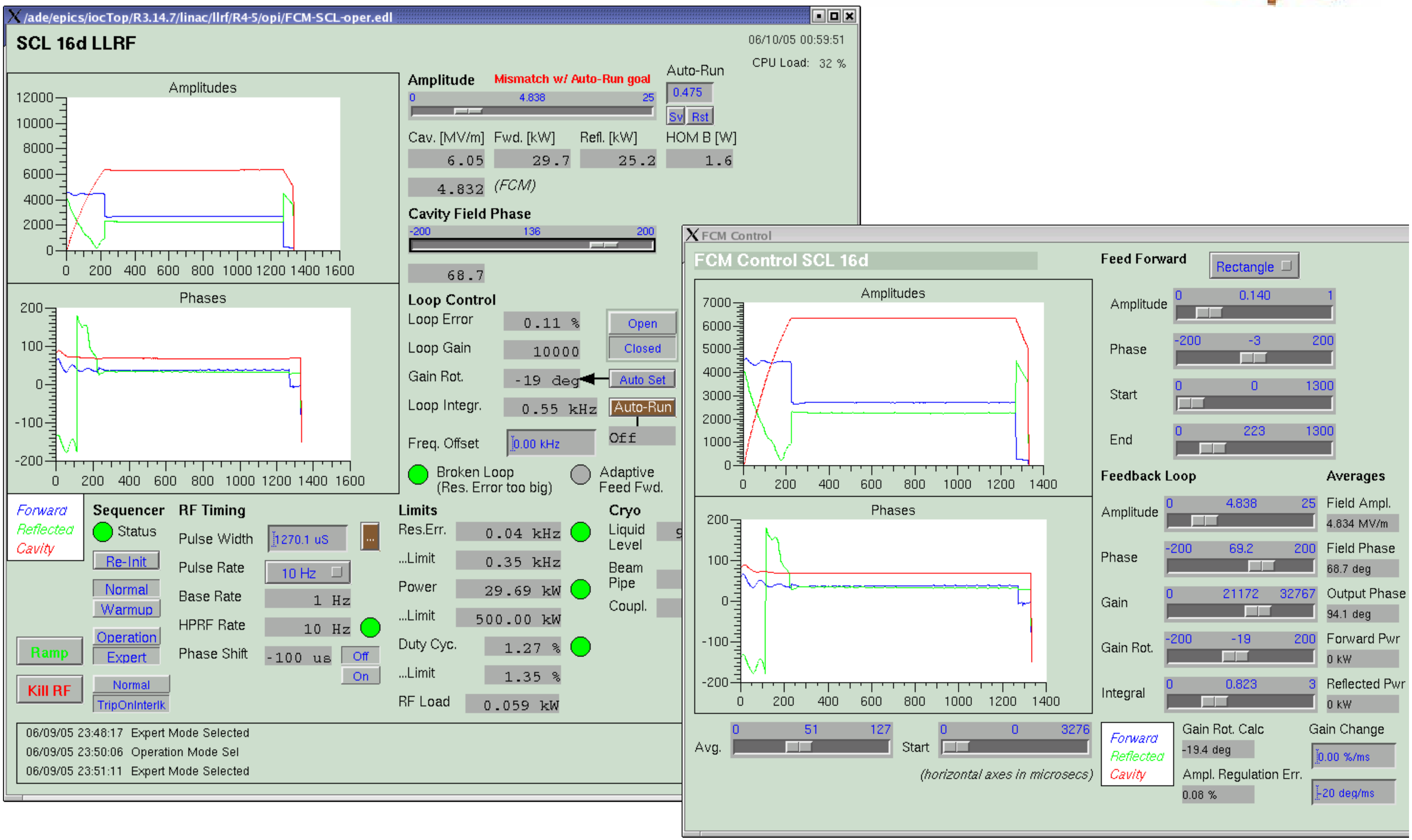
Transient Response of Feedback Control on DTL1
(Courtesy of H. Ma)



Droop on the SCL klystron high-voltage pulse induces phase push of ~50 deg (worst case)
→ LLRF must compensate this effect



Implementation of a Gain Rotation Ramp provides for Compensation of the Phase Push



Adaptive FeedForward Beam Compensation was Deployed during SNS NC Linac Commissioning

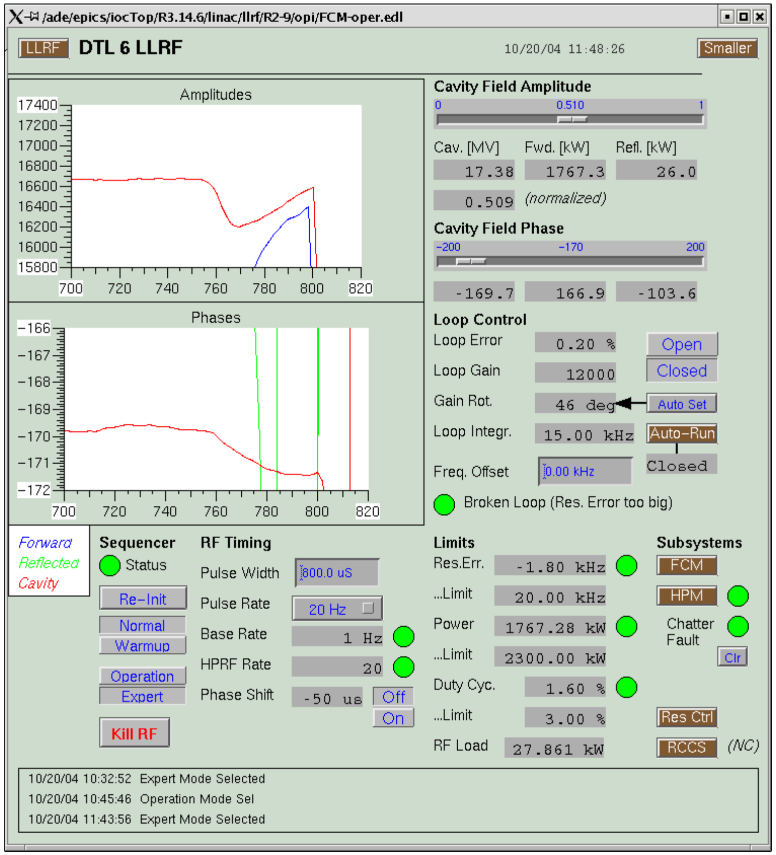


Fig. 1 Beam loading in DTL6 with ~40 us, 20 mA beam induced error of 2.7% and 2 deg in amplitude and phase.

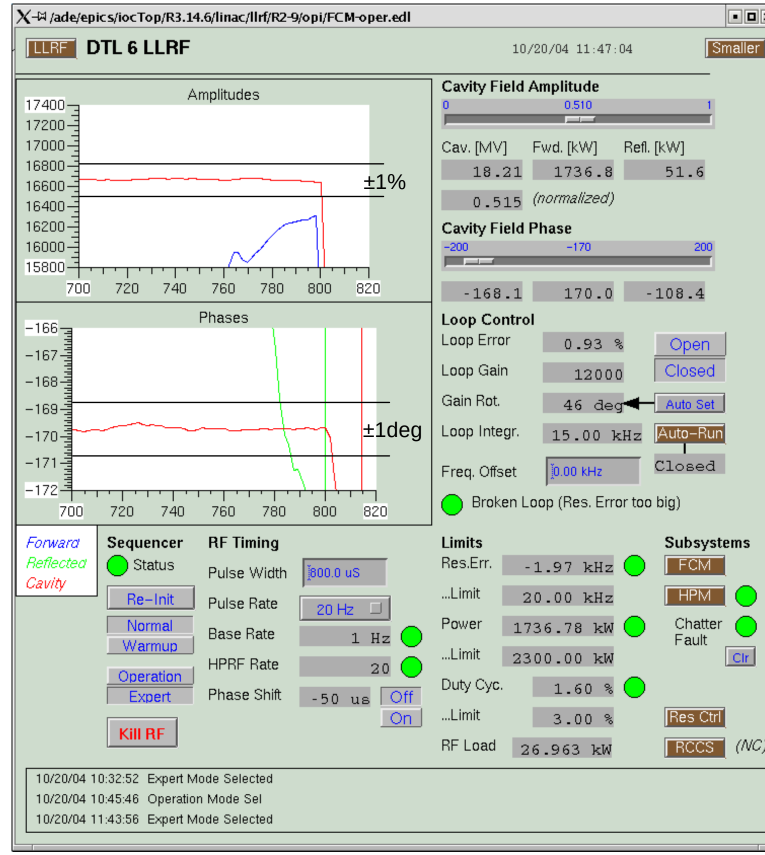


Fig. 2 Beam loading eliminated by means of Adaptive FeedForward.

SNS Design Experience

- The first design effort failed schedule requirements and the project was restructured late in the game. There are many reasons why this project got into trouble.
- Recommendations for ILC
  - Treat LLRF as a core competency, not a commodity!
  - On site team must have project control
  - Build and plan to keep a strong team on site as they will be key to many modifications and upgrades over the life of the machine

RF Parameters

Parameter/ System	Main Linac	Bunch Compressor	SNS Linac
Uncorrelated Amplitude	0.5%, 0.5 deg	0.08%, 0.03 deg	0.3%, 0.3 deg
Correlated	0.03%, 0.1 deg	0.03%, 0.03 deg	
Bunch to Bunch Energy	0.05%		
Stored Energy W	144J/m		
Gradient	35MV/m		
Beam Current	9.5mA		
Uncorrelated / Klystron	0.5%		
Klystrons/Linac	286		
Cavities/Klystron	24 or 36		
Loaded Q	2.6E6		

SNS LLRF at FNAL

- FNAL will supply a VXI crate and a slot 0 controller to SNS
- SNS is ordering the needed RF and IF filters
- Multi-cavities can be supported with an analog vector sum of the 50 MHz IF signals now, with an FNAL 36 channel 12 bit 65 MHz ADC module in the future
- Hopefully we will have two operational LLRF systems to compare and contrast!

ILC LLRF Design Cycle

- LLRF is based on computer and communication technology and has been following Moore's law. Eight years = 2^5
- Design algorithms and topologies now and repeat prototype hardware design cycle every 2.5 years. Production at 18 months before commissioning
- Continued R&D at test and operational facilities

Structure of an LLRF Collaboration for the ILC

- There are many labs worldwide that have experienced LLRF teams that could contribute to the ILC.
- These teams could be productively involved in the specifications, design, production of hardware, firmware and software.
- Parallel design paths for several years of R&D
- 1% luminosity at the ILC is worth many $ millions
  - There are many ways to optimize performance with control systems - LLRF is a key controller for the ILC and should be highly optimized!

Conclusions

- SNS LLRF can meet the present needs for ILC R&D at FNAL SMTF and the SNS team is very interested in being involved
- Parallel design efforts are a good thing at this point in the project
  - We would benefit from a common IF frequency (52.00 MHz?)
  - Beam instrumentation might use the same IF?
- High performance electronic system designs such as LLRF, instrumentation and controls should not be frozen like the basic machine design. They need to stay "just in time" and continue to evolve with new technologies.