Developments in LLRF control of SRF Cavities

LDRD Program Review Meeting

Jefferson Lab

16 September 2026

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Jefferson Lab

U.S. DEPARTMENT of ENERGY

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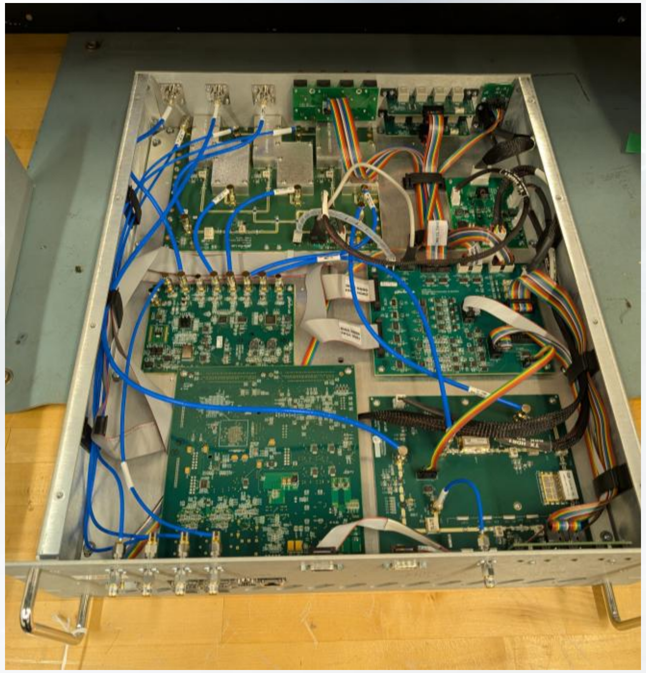
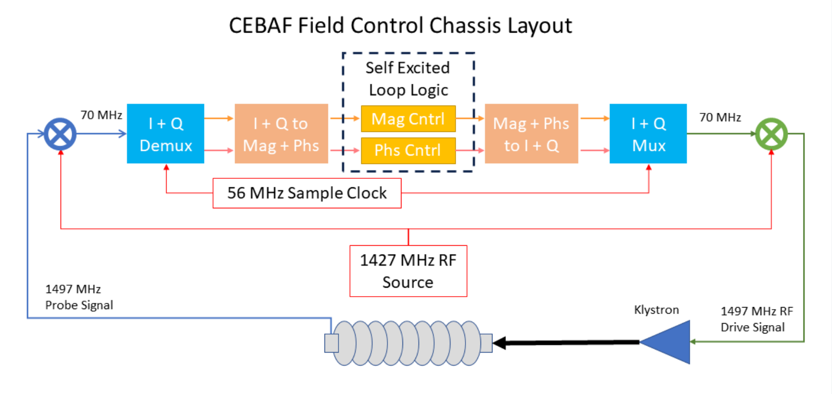
RF Control Systems

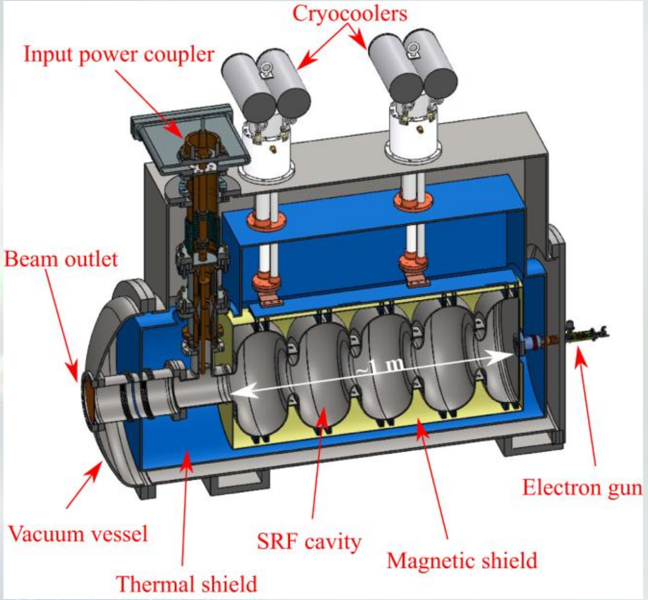
- LDRD project for FY 25/26 to develop new LLRF control and measurement methods
- Perform measurement and control of RF signals to and from cavity
- CEBAF FPGA, tuned for one frequency of operation
- Connections and interlocks to external systems (tuners, RF permit, master oscillator, EPICS)
- FPGA Performs Self Excited Loop controls
  - Regulation of Amplitude and Phase (SELAP)
  - Other control modes (SEL, Pulse)
- Excellent LLRF system at CEBAF, contributing to record machine uptime



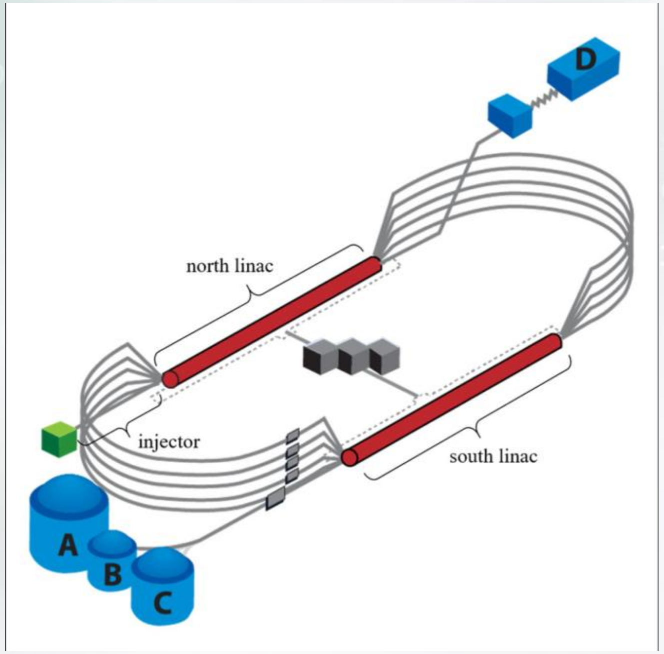


LLRF control and measurement systems in CEBAF

New Applications of SRF



Compact, Conduction-Cooled Accelerator



High-Energy Physics

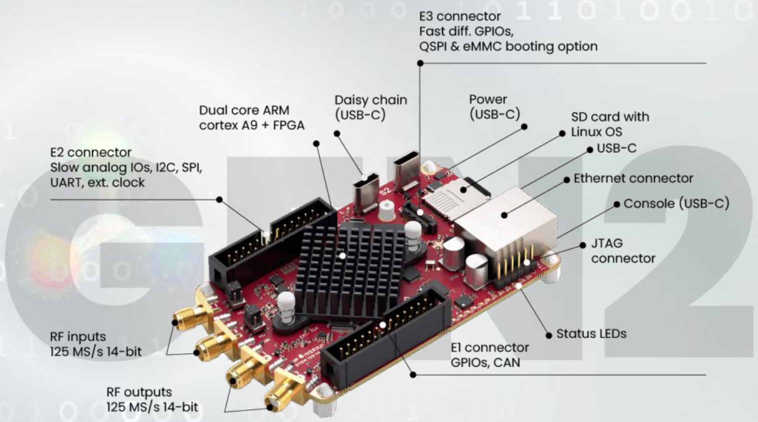
Quantum Physics

https://www.agilent.com/en/solutions/vacuum-solutions/particle-plasma-physics/particle-accelerators

https://sqmscenter.fnal.gov/

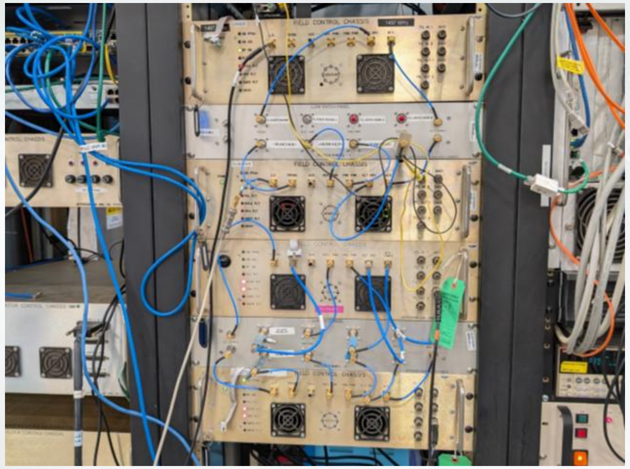
New RF Controllers for SRF

Compact, Conduction-Cooled Accelerator



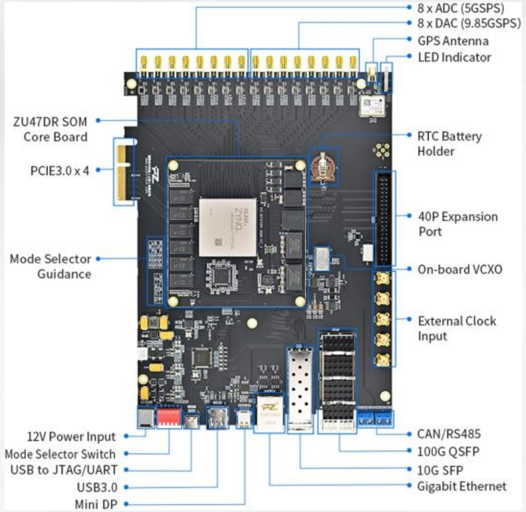
Low cost, low volume
Relaxed requirements for stability
Commercially available

High-Energy Physics



Scalable (100’s of cavities)
Interlocks and MPS
Low noise
Stable operation
Custom system designs

Quantum Physics

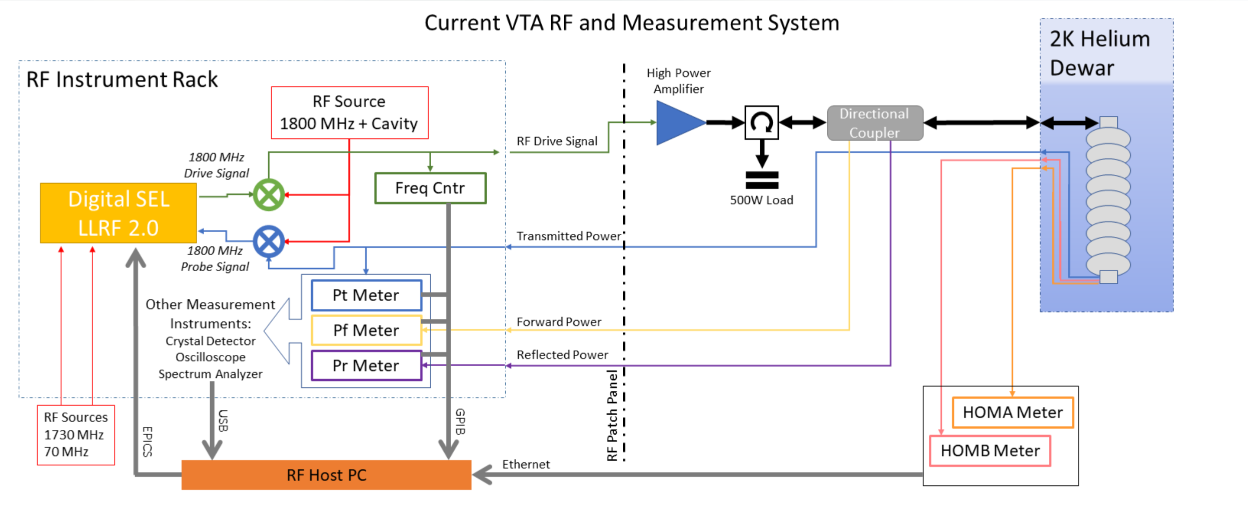


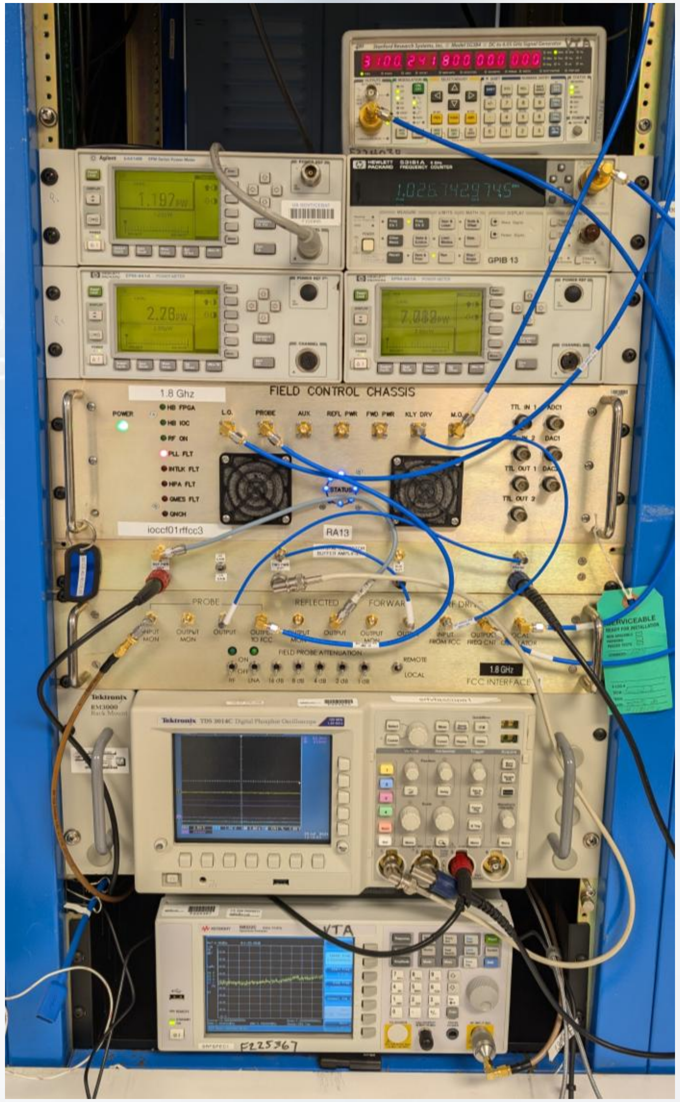
Ultra fast (>5GSps)
Very low noise
Wide bandwidth
More expensive

redpitaya.com

RF Control Systems - VTA

- Wide range of cavities and frequencies, 0.2 – 7 GHz
- Up to 100W of power, critically coupled cavities
- High throughput, up to 400 cavity tests per year
- Cavity control (SEL) from CEBAF LLRF2.0 system, adapted through interface chassis
- Measurement done with power meters

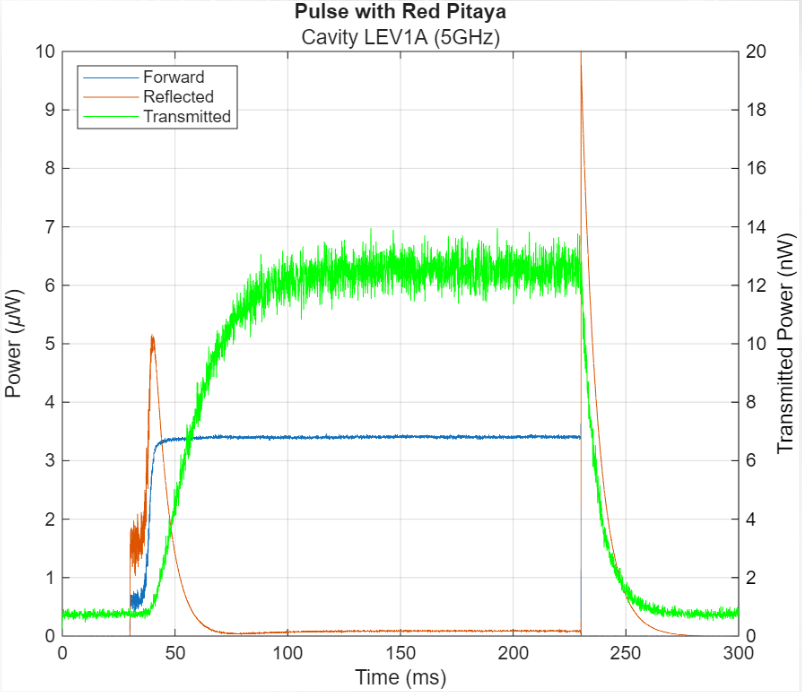




LLRF control and measurement system in the VTA

New RF System Design

- Red Pitaya FPGA
  - 2x Rx and Tx channels
  - Perform SEL control, easily programmable
- NI Software Defined Radio
  - Digital acquisition of cavity signals
  - Wide frequency range and bandwidth
  - FPGA to process signals
  - Computer interface, no other external systems needed
- All commercially available
  - Improve system flexibility at the cost of amplitude and phase stability
  - Less than $40k for a very flexible system, 0.1 – 7 GHz

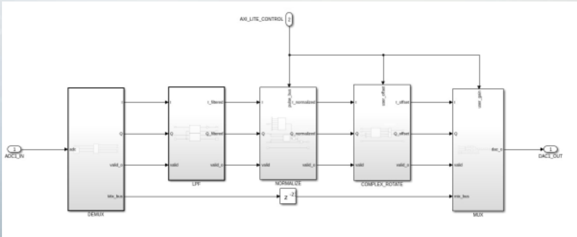


New RF System Design

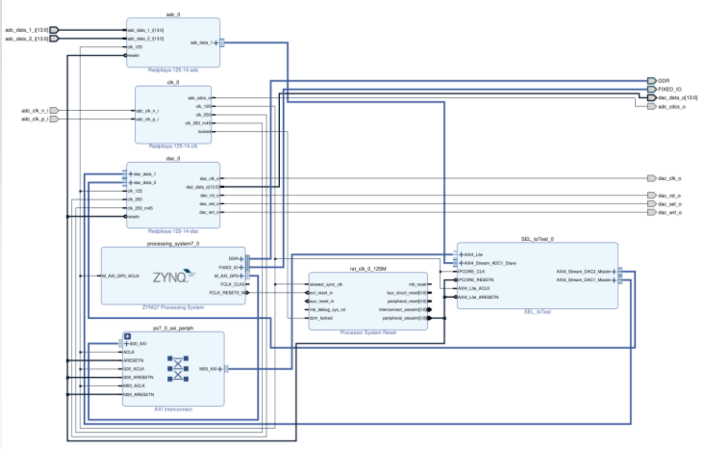
Control
Jupyter Notebook

- Red Pitaya FPGA
  - 2x Rx and Tx channels
  - Perform SEL control, easily programmable

- Developed a workflow to take Simulink model, compile VHDL in Vivado, and run the code on Red Pitaya
- Access to control variables through Jupyter Notebook server
- Allows for new control methods to be easily designed and tested in the field



Design
MathWorks Simulink

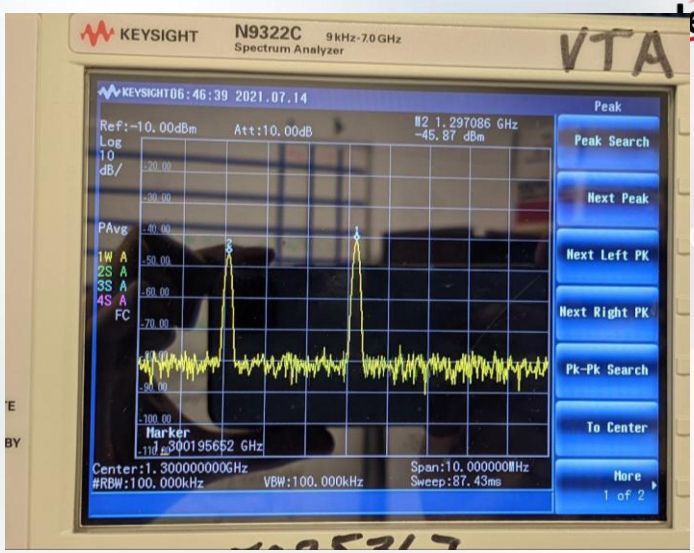


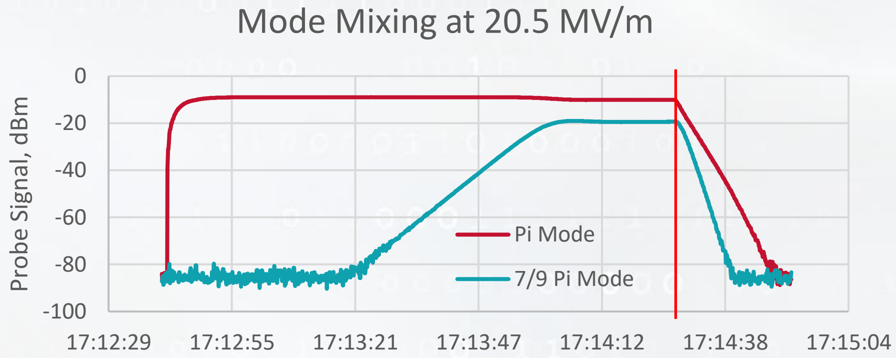
Build
AMD Vivado

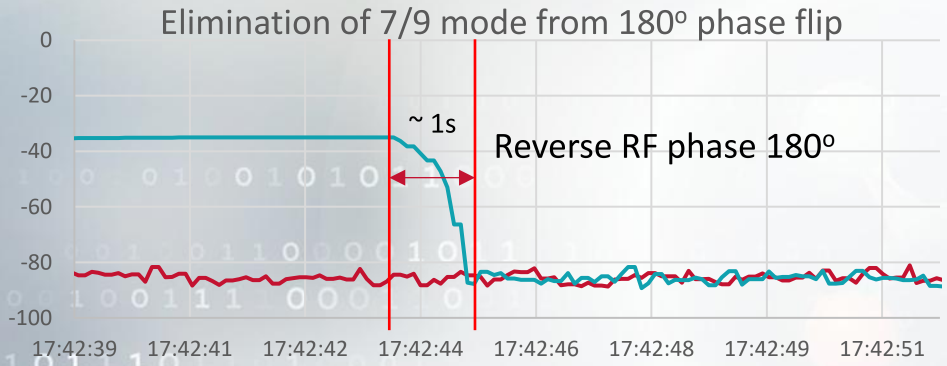
Execute
Red Pitaya

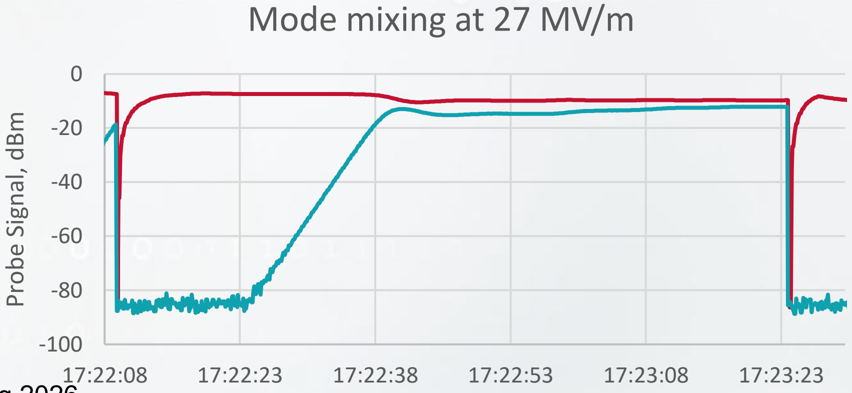
LCLS-II Mode Mixing

- Vertical Cavity testing, RF control system exciting the pi mode (1300 MHz)
- At high gradients (>18 MV/m) the 7/9 pi mode (1297 MHz) becomes self-excited
- Power Meters can only measure the sum of both modes, data points are invalid
- New RF Control scheme suppresses 7/9 mode: Setup a second SEL 180 degrees off resonance

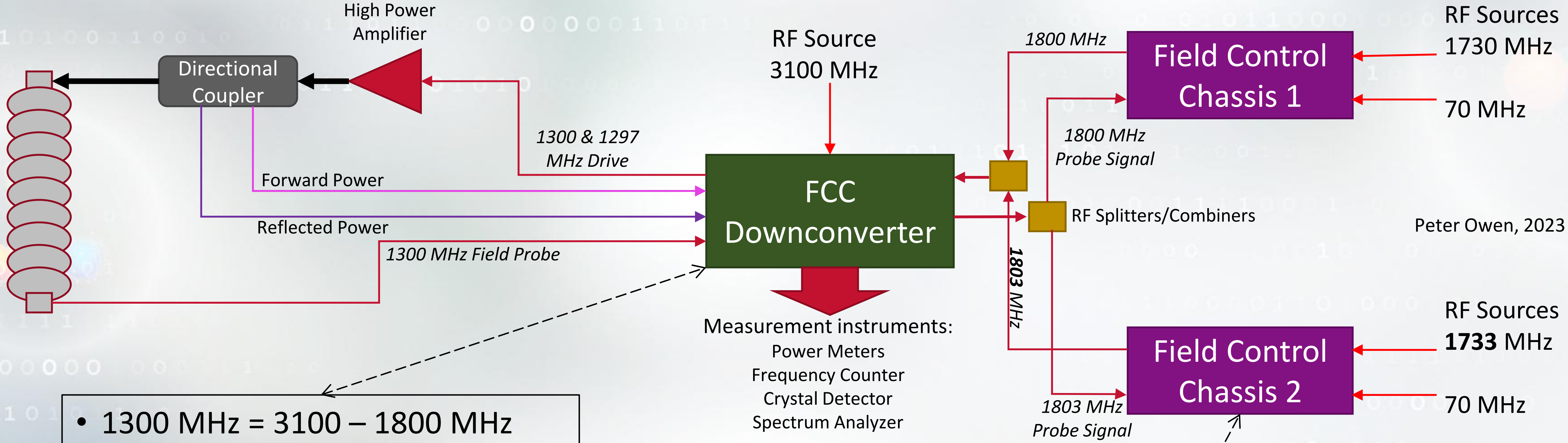








Anti-Mode Mixing System (AMMS)

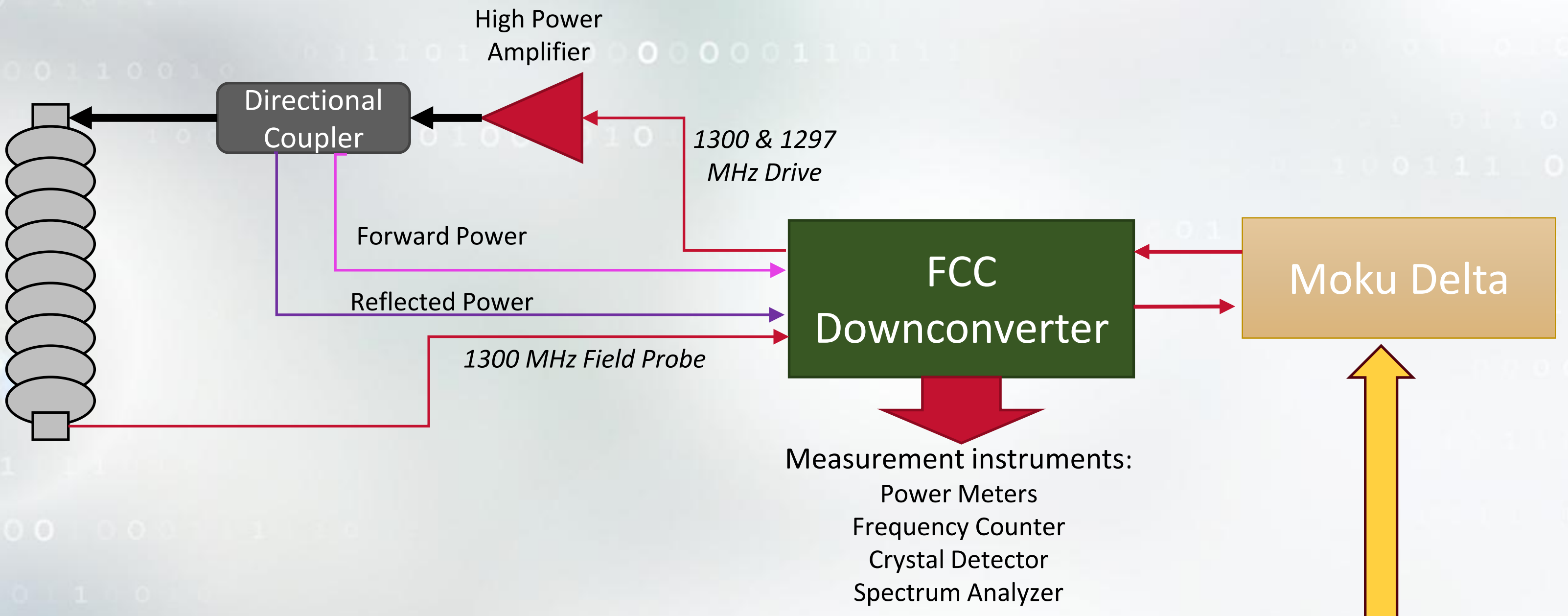


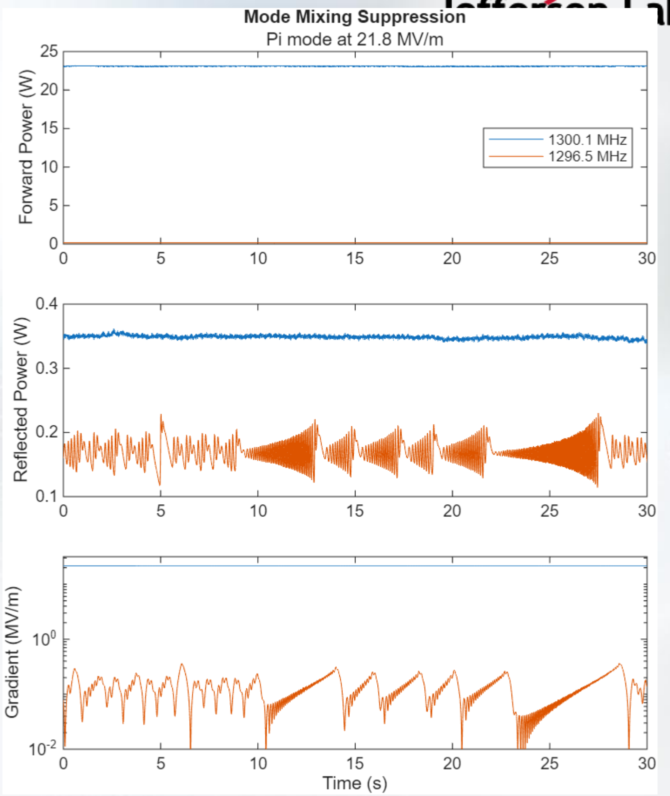
Peter Owen, 2023

- 1300 MHz = 3100 – 1800 MHz
- Conversion done with RF Mixer in FCC downconverter
- Allows easy switching between cavity types and frequencies

- 1297 MHz = 3100 – 1803 MHz
- FCC #2 is locked onto 7/9 mode

LDRD Anti-Mode Mixing System





Moku Delta:
Commercially available RFSoC
8x input and output
5 GSps sample rate allows direct measurement of SRF cavity signals
Manufacturer's software allows for rapid testing of RF control and measurement

With 180º shift on PLL, second mode is suppressed orders of magnitude below primary mode

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Enabling RF measurements

- Attempted in-situ RF measurement of Q0 in a cryomodule
  - Complex signals acquired with SDR
  - Work is ongoing, disentangling errors from RF crosstalk
  - Need to measure signals to less than 0.1% accuracy to determine Q0 in a cryomodule

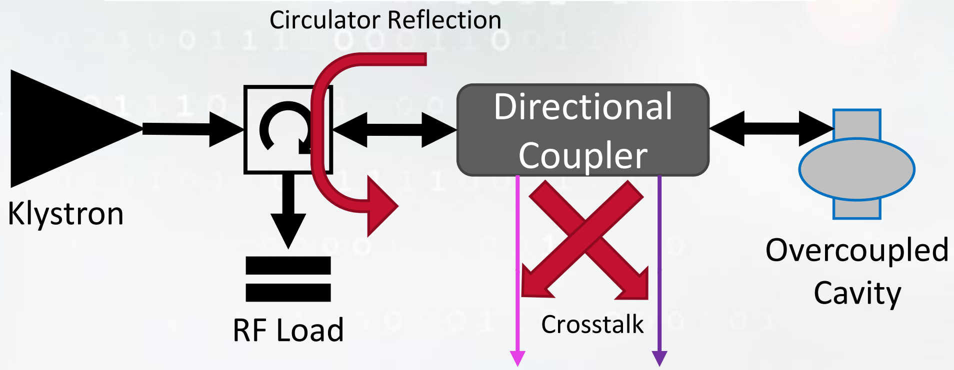
- Measure Q0 of 5 GHz ‘LEV’ cavities for another LDRD project
  - Attain high Q0 at low temperatures for magnetic levitation
  - Complex signals acquired with SDR
  - High frequency signals
  - Low temperature for quantum measurements (<1.8K)
  - Low power, short pulses

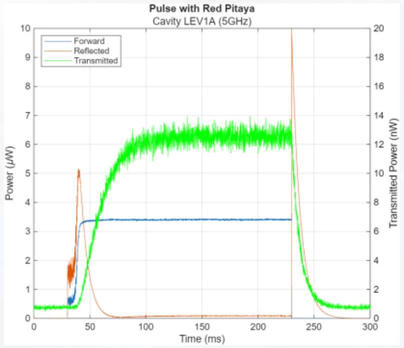
$$\begin{pmatrix} \frac{dV_r}{dt} \\ \frac{dV_i}{dt} \end{pmatrix} = \begin{pmatrix} -\omega_{12} & -\Delta\omega \\ \Delta\omega & -\omega_{12} \end{pmatrix} \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} \omega_E R & 0 \\ 0 & \omega_E R \end{pmatrix} \begin{pmatrix} I_r^+ \\ I_i^+ \end{pmatrix}$$

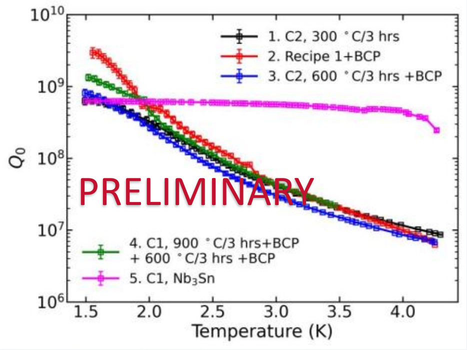
A new method to measure the unloaded quality factor of superconducting cavities

Volker Ziemann, Uppsala University, 75120 Uppsala, Sweden

March 4, 2024

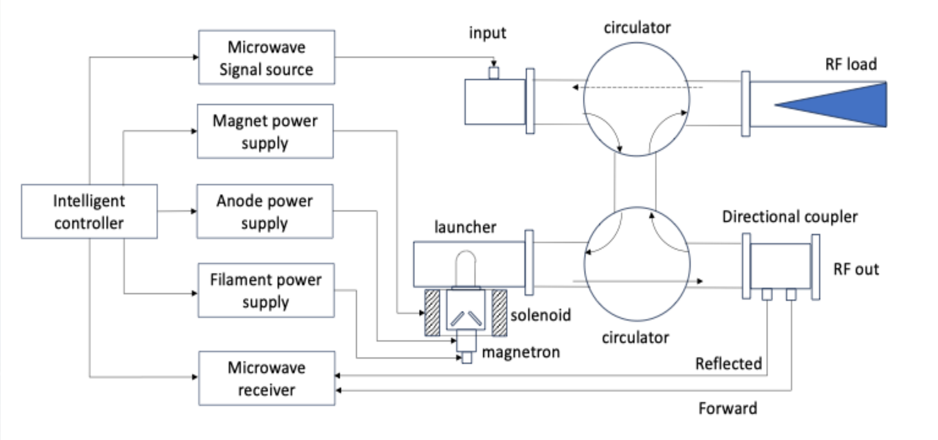






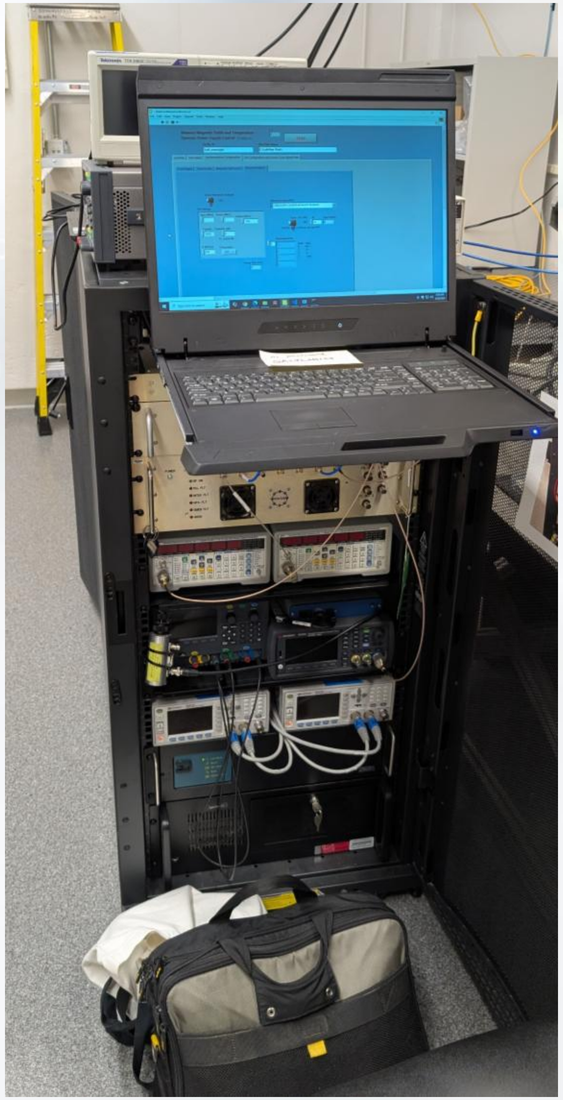
Future Work

- Demonstrate SRF Operation at smaller scales (conduction-cooled, compact)
- Operation of non-linear amplifiers with complex feedback mechanisms (magnetron)
- Integrate commercial LLRF controllers into accelerator RF system
- Capturing raw signal data for new measurement methods and AI training for fault detection

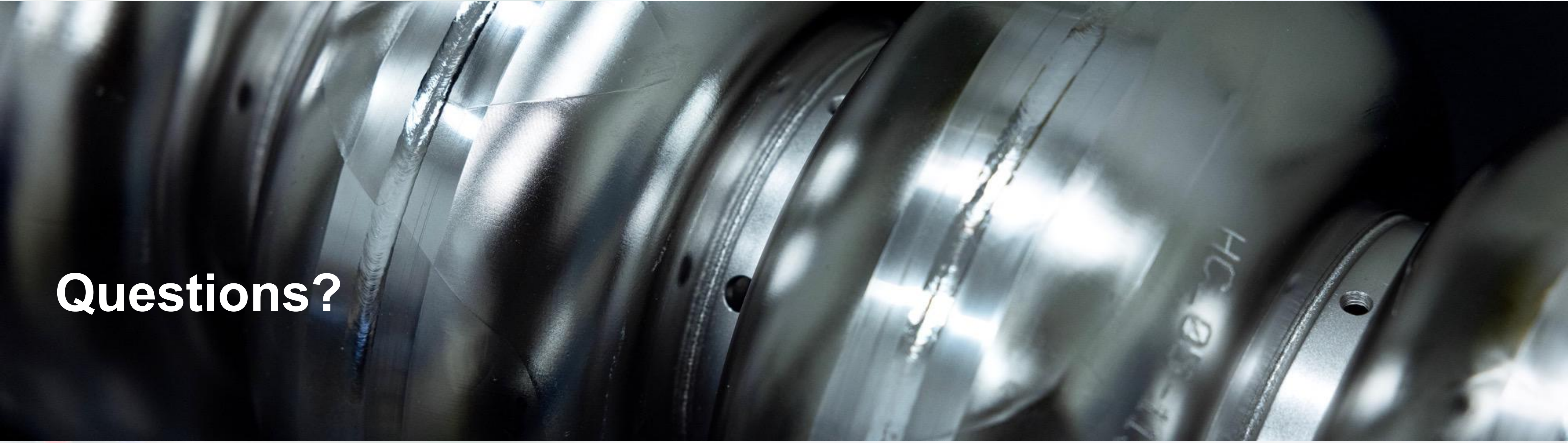


Proposed Magnetron Controller layout

- R. Rimmer



LLRF control and measurement system ported from VTA to General Atomics



Questions?

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