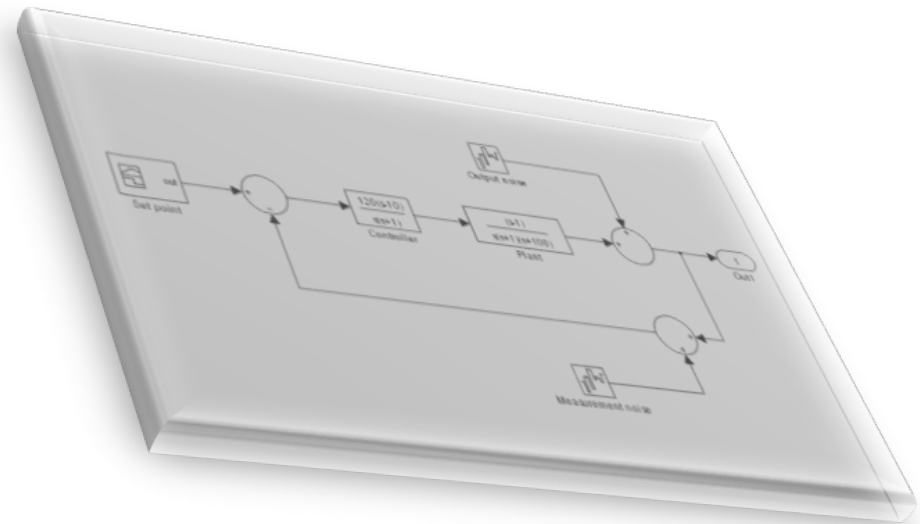


# Operational Experience of the SELAP Algorithm for LLRF Control at JLAB



Rama Bachimanchi – Jefferson Lab , Newport News, VA

On behalf of LLRF Group at JLAB

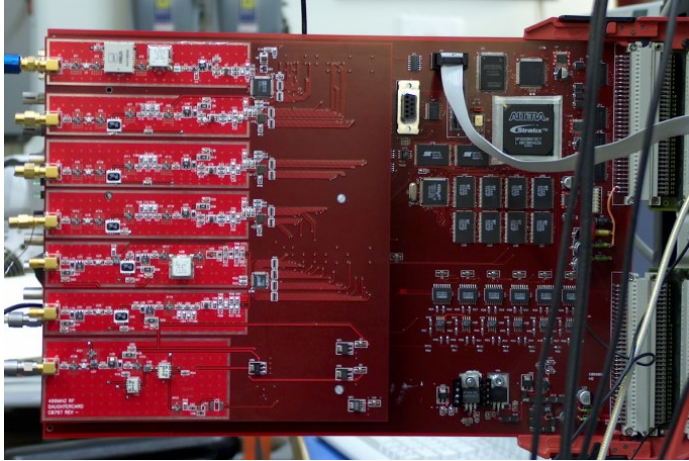
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# RF Team

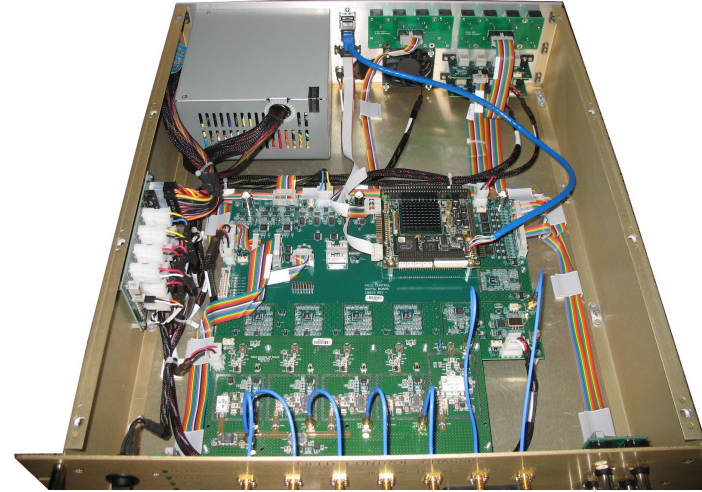
- LLRF Team
  - Curt Hovater
  - Rama Bachimanchi
  - Tomasz Plawski
  - James Latshaw
  - Dave Seidman (coordinator)
  - Clyde Mounts (operations)
- Controls/Software
  - Jianxun Yan (ORNL)
  - Scott Higgins
  - Kyle Hesse
- Many more

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# Where We Have Been ...Digital



VXI Motherboard & 499 MHz Transceiver

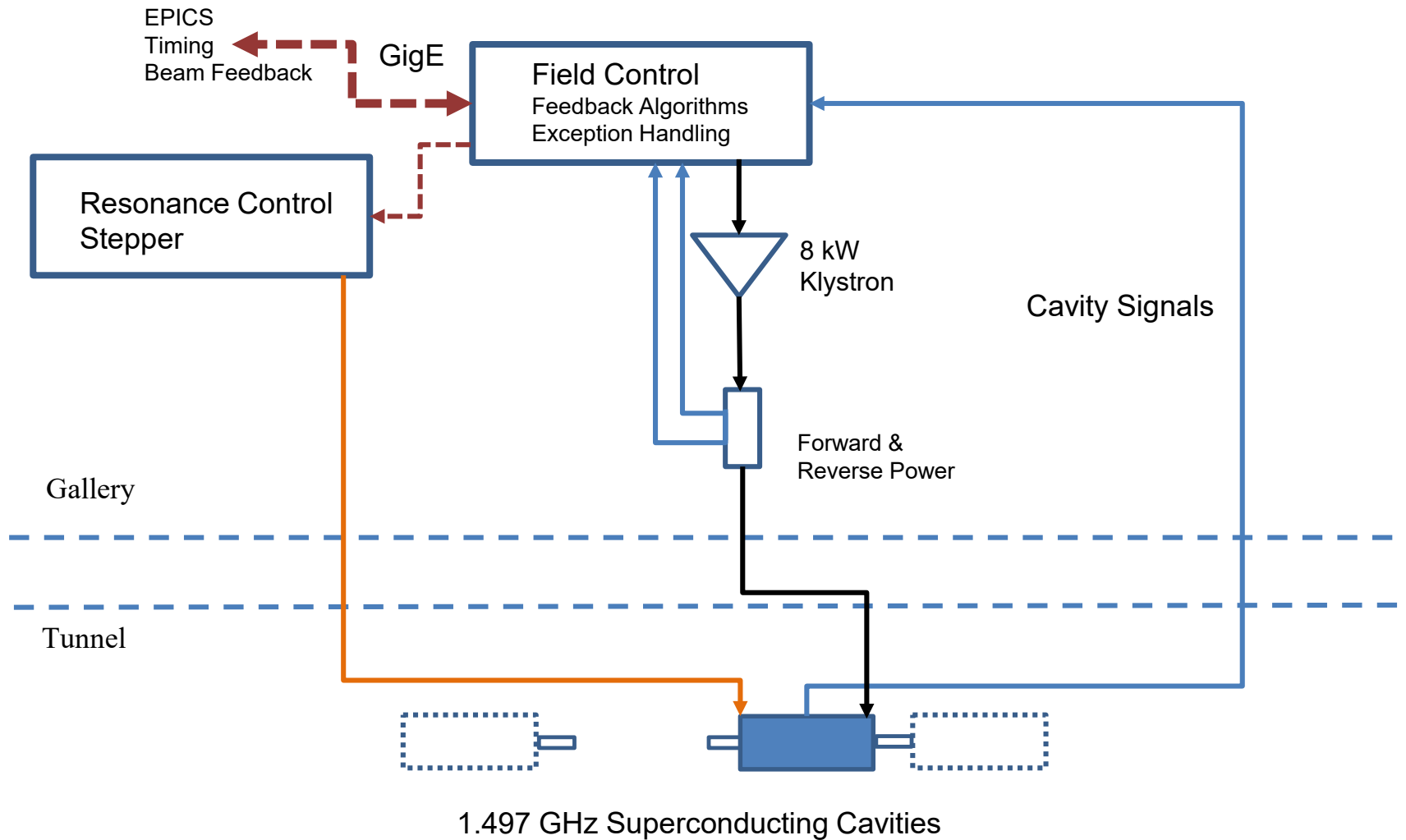


C100 Field Control Chassis (LLRF 2.0)



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# LLRF 3.0



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# Cyclone 10GX FPGA Carrier

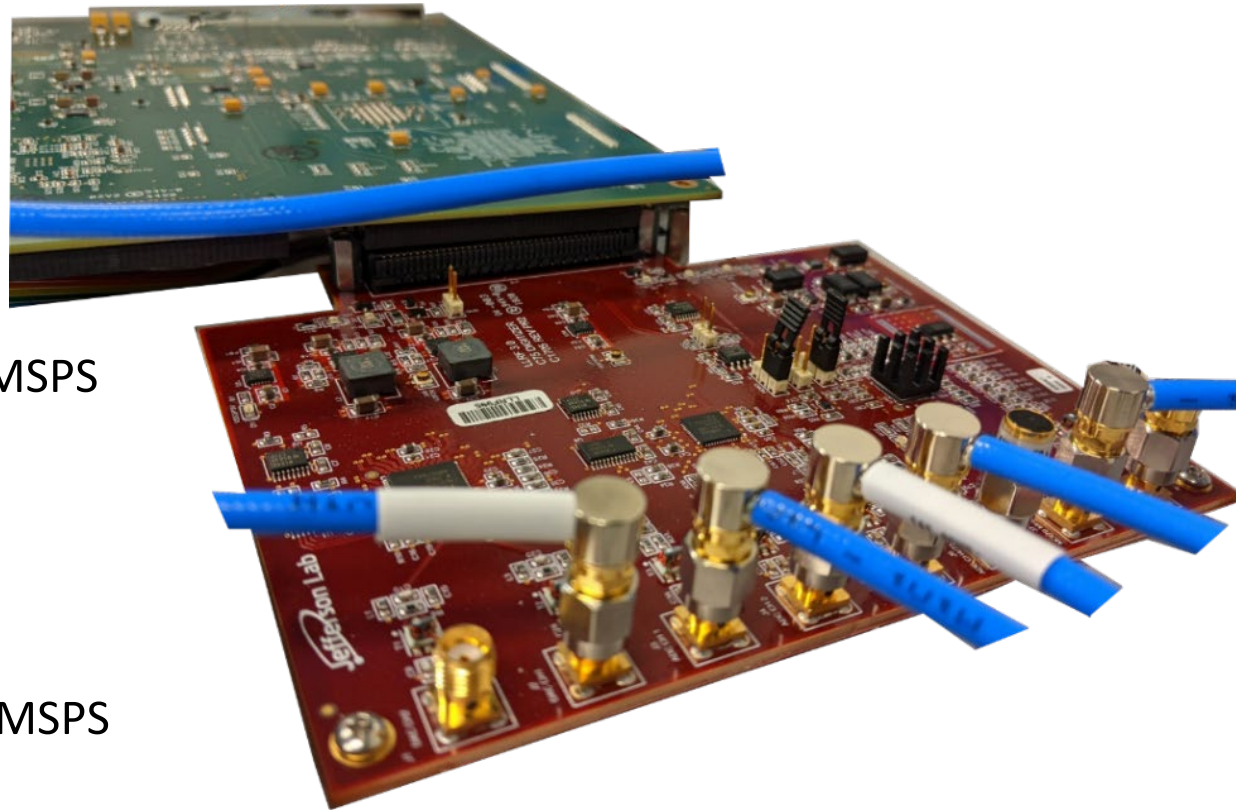
- Cyclone 10GX
  - 10CX105YF672
  - 152,000 FF (pin compatible with 220k FF/320k FF)
  - 10x12.5Gbps transceiver
- MAX10 FPGA
  - Power management
- Dual LPC FMC
  - LPC – 34 LVDS pairs
- 2xQSFP, 1xSFP, 1xRJ-45
- GPIO headers
  - 2x40 pin (20 signals)



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# Digitizer

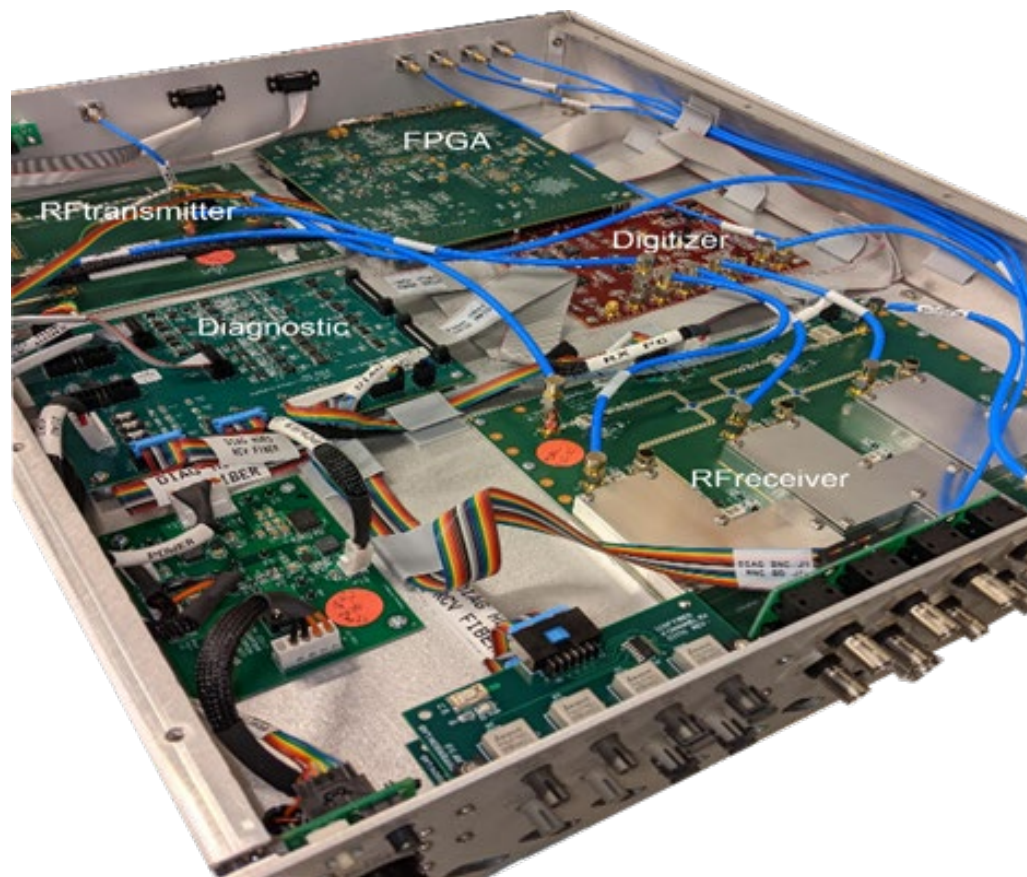
- Based on LCLS-II
- Single LPC FMC
- LMK03328
  - Dual PLL (VCO)
- AD9653
  - 16-bit, 4 channel 125MSPS ADC
  - IF – 70 MHz
  - ADC clock – 93 MHz
- AD9781
  - 14-bit, 2 channel 500 MSPS DAC
  - IF - 70 MHz
  - DAC clock – 186 MHz



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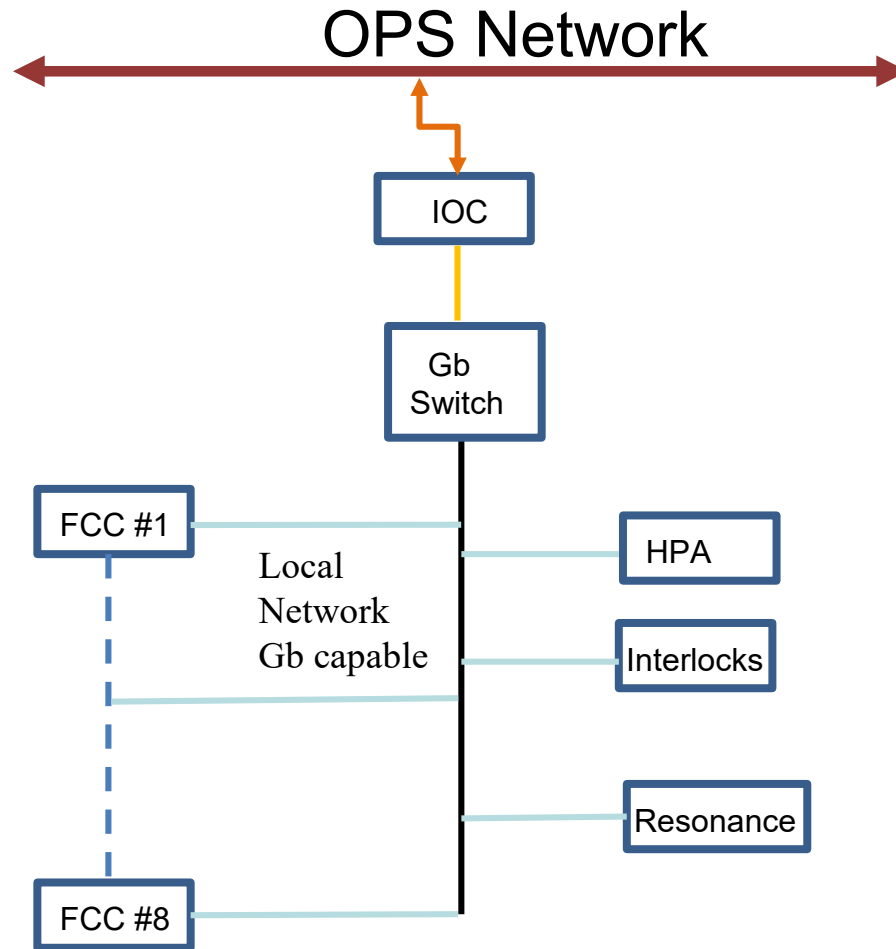
# LLRF 3.0

- Cyclone 10GX FPGA carrier
- Modular design
- UDP Ethernet interface (1 Gbps)
- RF Downconverter
  - ~80 dB isolation
- One IOC per CM (8 cavities)
  - 8 Field Control
  - 1 HPA controller
  - 1 Interlocks control
  - 1 Resonance control (stepper)
  - All use the same FPGA board



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# Network Architecture



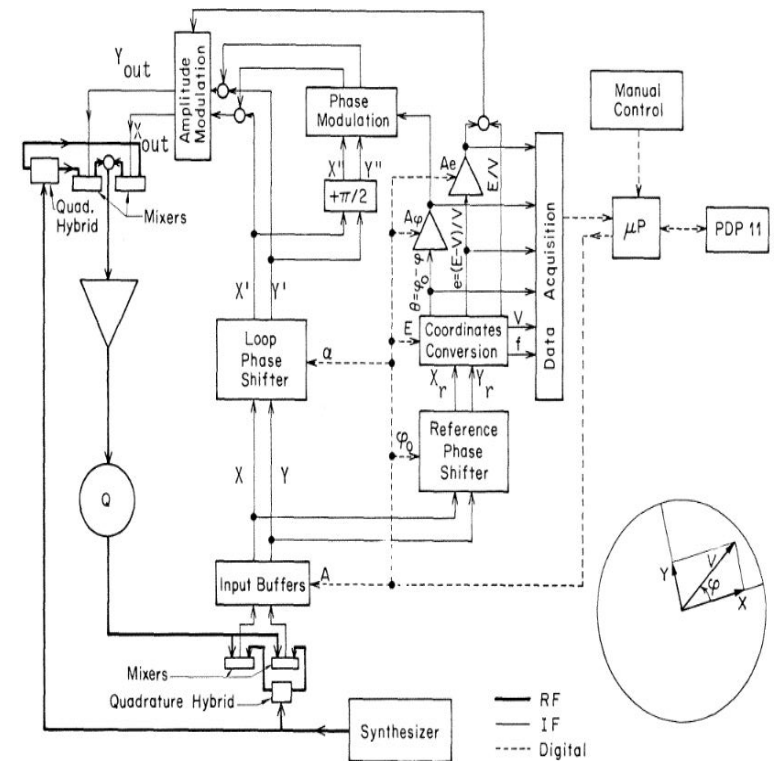
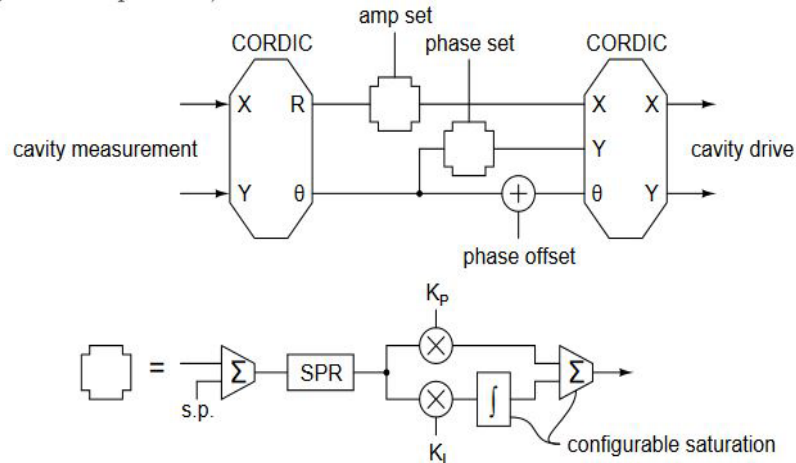
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# SEL and SELAP

## SEL'78 and digital SELAP today

- 1978 J. Delayen, PhD thesis - locked analog SEL concept
- 2012 Digital SEL, US Patent for JLAB LLRF team
- 2014 L. Doolittle

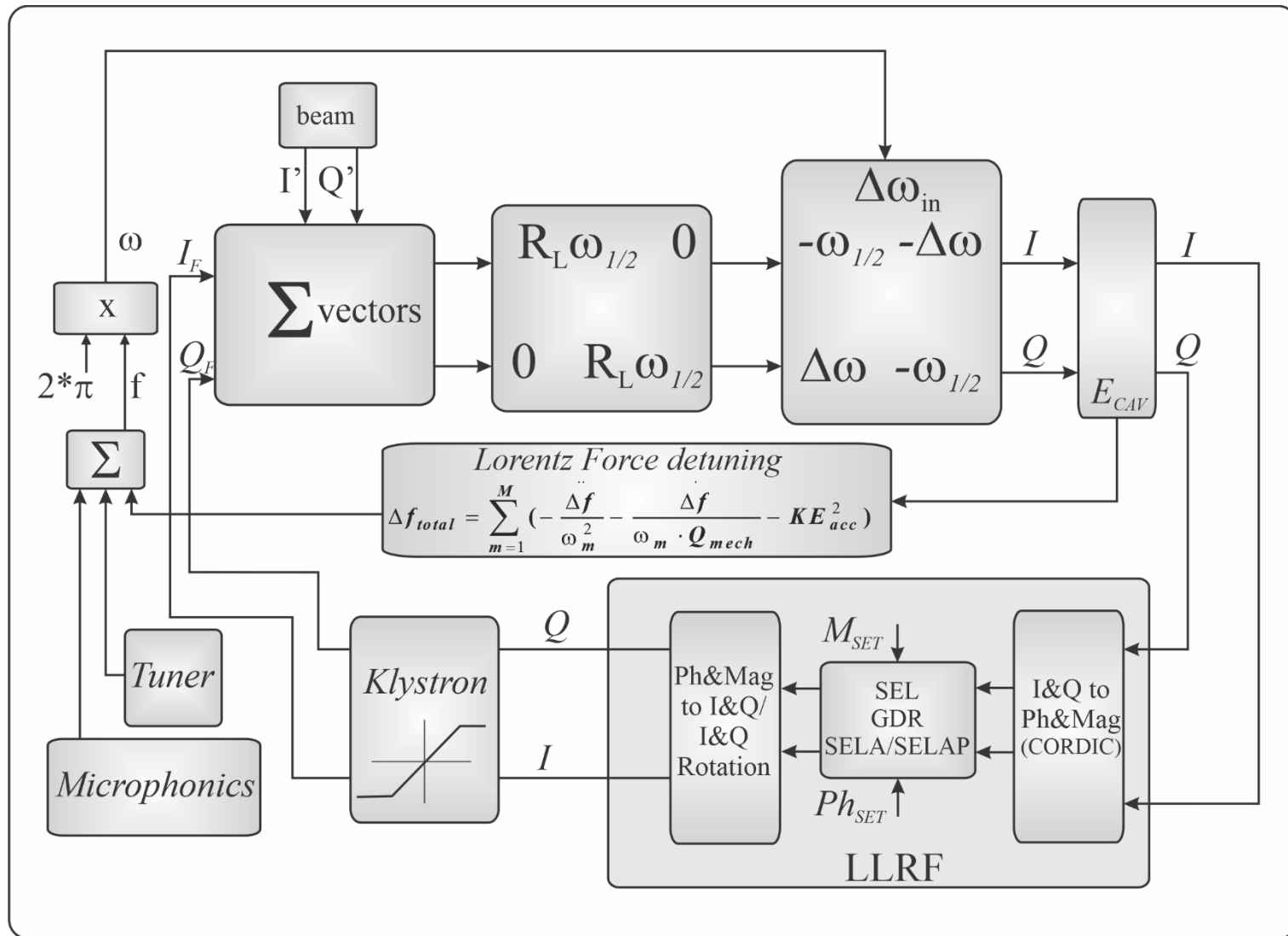
The important features of an SEL data path were clearly laid out in 1978, although using analog terminology. A modern rendition of the block diagram in the digital domain, loosely following JLab's experience, is shown here:



Where SPR stands for stateful phase resolver, and it is only used in the phase channel.

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# SELAP Algorithm Test on UITF



nd

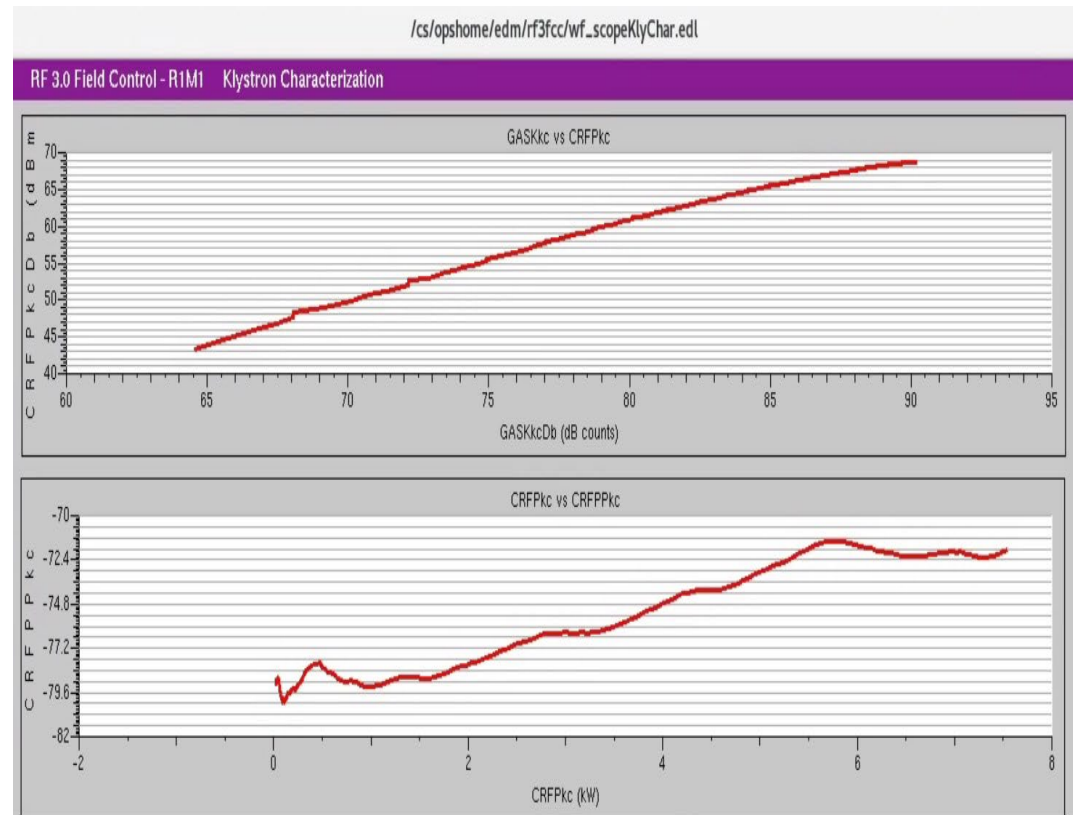
# SELAP Algorithm Test on UITF

- SEL (self excited loop)
  - Amplitude is not regulated
- SELA
  - Amplitude is regulated
- GDR
  - Amplitude and phase are regulated
- SELAP
  - Amplitude is regulated
  - GDR alike, if detuning is within the power limits
  - Phase spins at residual frequency if detuning is outside the power limits

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# Klystron Characterization

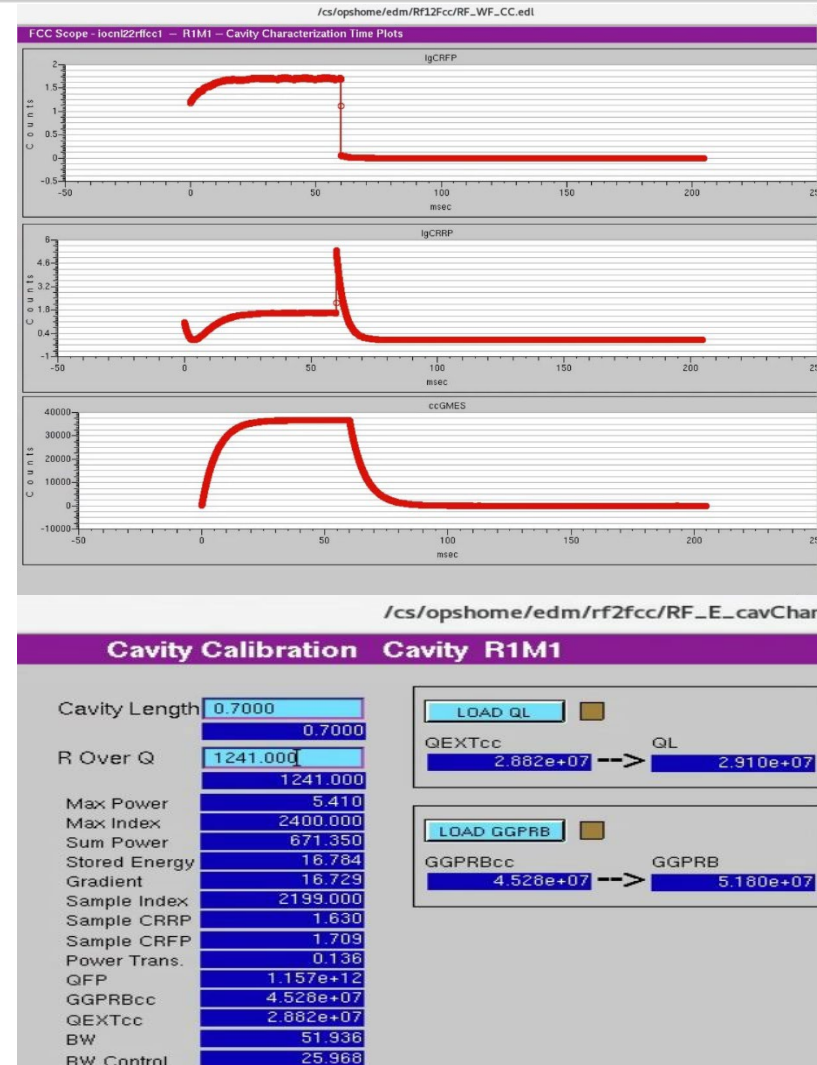
- Ramps the klystron input to max drive in 200  $\mu$ s
- Cavity sees little to no gradient
- Measures the klystron response to input (DAC drive from FPGA)
- Phase response
- Max power



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# Cavity Characterization

- Cavity in pulse mode
- Stored energy
- Gradient (MV/m)
- $Q_{\text{ext}}$
- Bandwidth
- $Q_{\text{FP}}$  (field probe Q)



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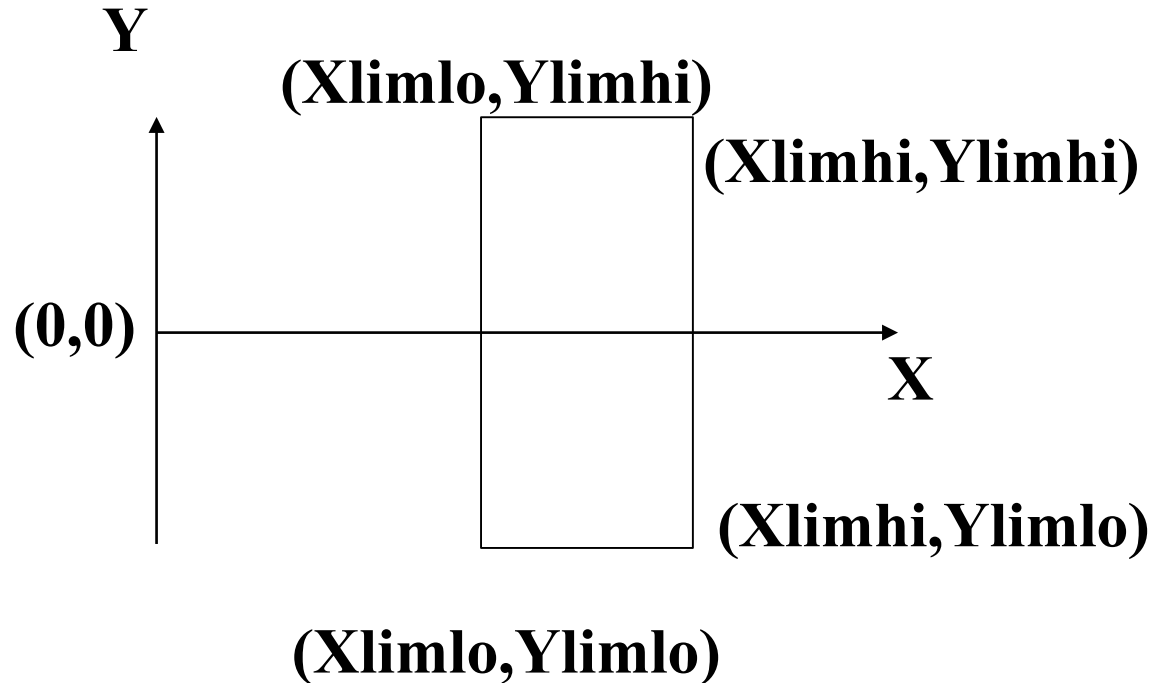
# Power requirements for the cavity

- Xpower – power required for gradient
  - $P_{kly} = (L * E^2 / (4 * Q_{ext} * r / Q))$
- Xpowerbeam
  - $P_{klybeam} = L * (E + (I_0 * Q_{ext} * r / Q))^2 / (4 * Q_{ext} * r / Q)$
- Ypower – reactive power available for detuning
  - $P_{klydf} = P_{kly} * \tan(dA) * \tan(dA)$
- Total power no beam = Xpowerbeam + Ypower ( $I_0 = 0$ )
- Total power with beam = Xpowerbeam + Ypower ( $I_0 =$  beam current)
- Resultant voltage limits for the power

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# Power limits for the cavity

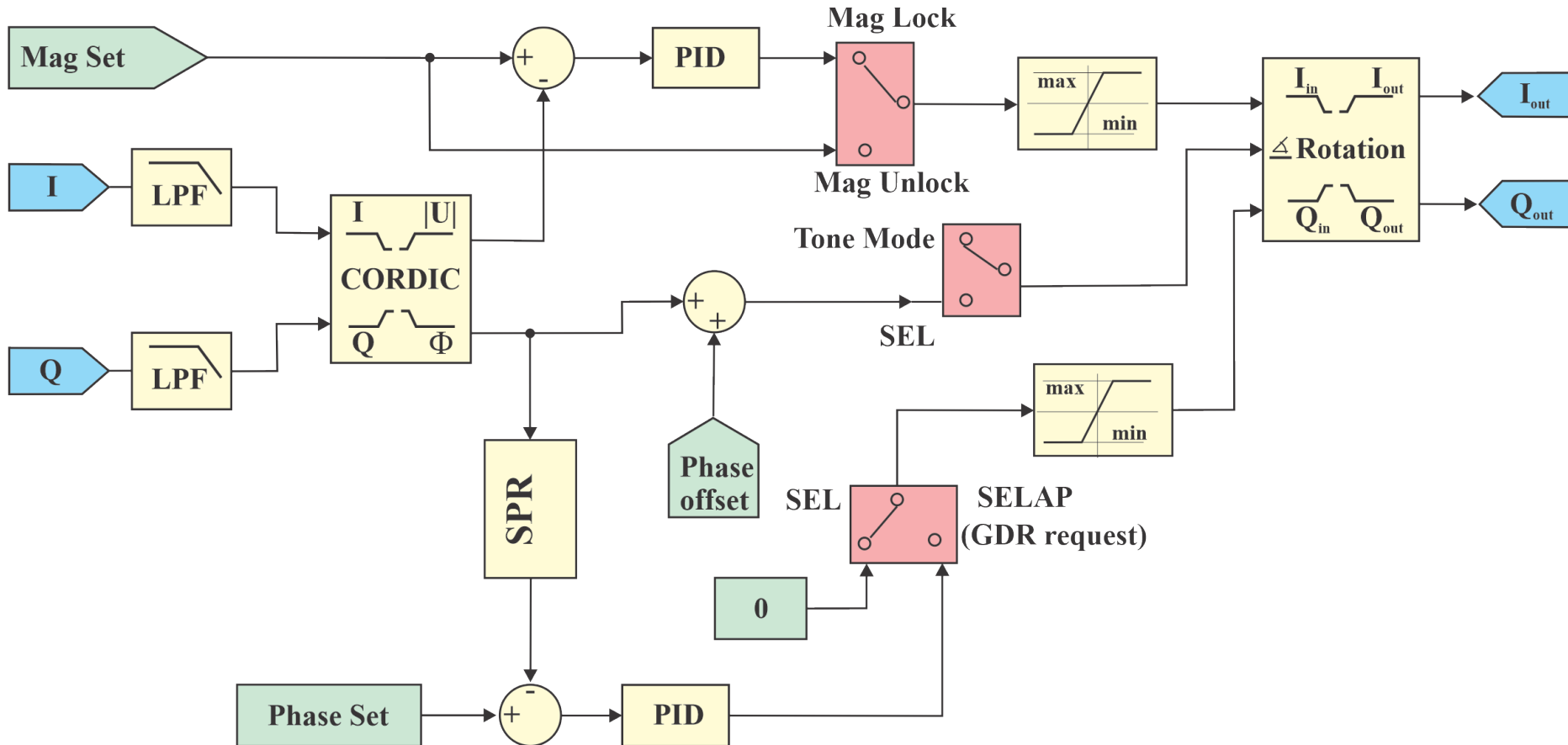
- Power limits translated to drive voltage for FPGA
- $X_{lim}$  are the main power
- $Y_{lim}$  are the detuning budget
- $Y_{limlo}$  is the same as  $Y_{limhi}$  with opposite sign
  - Detuning on either side



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# New Algorithm Test on UITF

## New Controller



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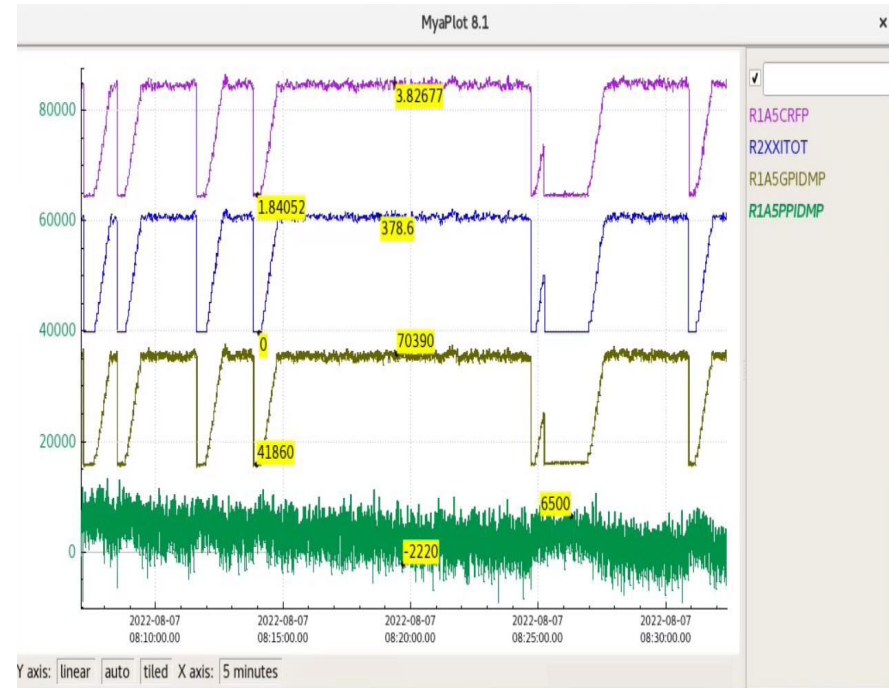
# RF Test on UITF Booster 7-cell Cavity

The screenshot displays the CMTF Field Control software interface, titled "CMTF Field Control - Operational Values - RM12". The interface is divided into several functional areas:

- Modulation (G/PSET):** Controls for ADC2 (0.000), GSET (0.300), GRMF (7701), PSET (-32.00), PRMF (0.000), ISET (0), QSET (0), and IQ PID (GLDE: 3.27e+04, PLDE: -180, GLDER: 0.000e+00, PLDER: 0.000, ILDE: 0, OLDE: 0).
- Grad & Phase Set:** Includes ESET & total (gset \* 0.7) (0.00) and SELAP PVs.
- Gradient Control:** Features M PID, Gradient Pulse, Grad Loop Open Set (GLOS: 2.22, 2.22), Grad Clamp (GDCL: 10.000, GDAL: 9.000), Gradient CORDIC (GCRDC: 0.000), Phase CORDIC (PCRDC: 0.000), Phase Loop Open Set (PLOS: 0.000, 0.000), Phase Offset (POFF: 161.883, 161.884), Phase Spin, and P PID.
- RF Switch and Power:** Includes RF Switch (Open/Close), Cavity Drive (IASK: -5556, QASK: -6656, GASK: 2.222, PASK: 72.285), Forward Pwr (CRFPI: -1, CRFPG: -3, CRFP: 0.000, CRFP: -71.812), Reflected Pwr (CRRPI: -2, CRRPG: -3, CRRP: 0.000, CRRP: -105.396), and Variable Attenuator (RATN: 0.0 dB).
- Diagnostics and Status:** Shows EMES (0.000), GLOW (0.500), GMES Fault (Lvl: 1.000, Tr: 0.000, GMFL: 283, GMFL: 0.000), Discriminator (RMS: 26857.823), Detune Angle (CFQE: 27.45, DETA: -169.043, CFQEA: 71.647, TDOFF: -128.309), and Stepper Tuner (ZPQE: -268.50, ZPID: 0.000, VOFF: 10.000, PZTS: 1.000, PZT: 0.000, DMUX: 1).
- Waveforms and Scopes:** A "CRFP vs. DETA2" plot is visible, along with a "Digital Scopes" section and a "Heartbeat" indicator (Firmware: 100).
- Calibration and Warnings:** Includes a "Calibration Table Warnings" section with FCC ID (360) and Temperatures (TMPR: 0.000, TMPD: 0.000).
- RF Test Results:** On the right, three plots show the RF signal: "L" (0 to -2000), "GMES" (0 to 1), and "FMES" (0 to 200). The FMES plot shows a red signal between 0 and 300 msec.
- Diagnostic DACs:** DMUX12 (0), DMUX34 (0).
- Other Parameters:** LOPW 1427 MHz (101.400), IF Pwr 70 MHz (IFPW: 0.122, PSifpw: 43.423, IIRKM: 8, IIRKQ: 7), and various filter and button settings.

# LLRF 3.0 in the LINAC

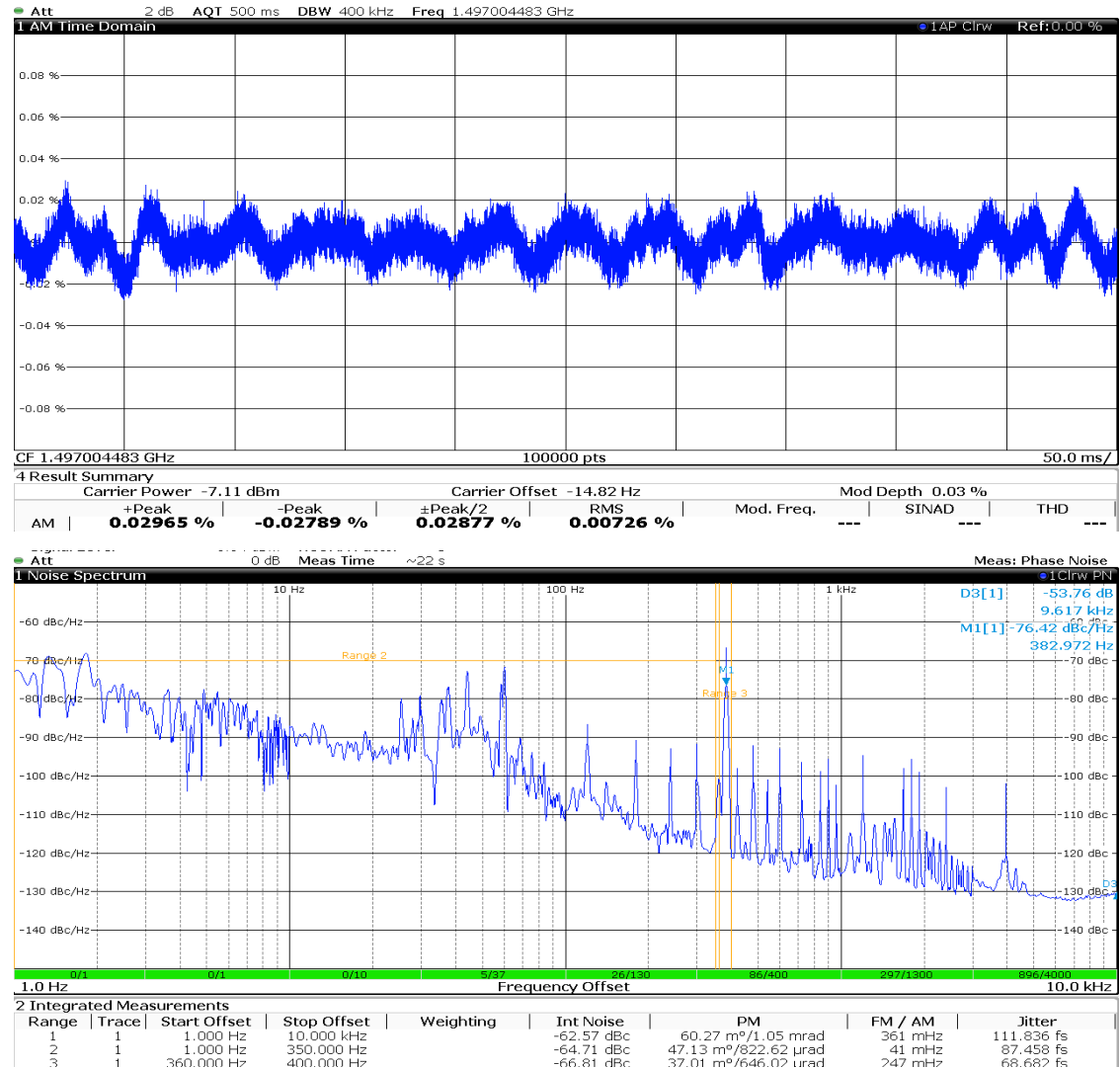
- Installed on two C75 cryomodule(16 cavities)
  - July 2021, May 2022
- Klystron Characterization
- Cavity Characterization
- SRF commissioning
- SELAP without beam
- SELAP with 400 uA beam
- Beam current through EPICS
- Adjust the limits with beam



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# Field and Phase regulation

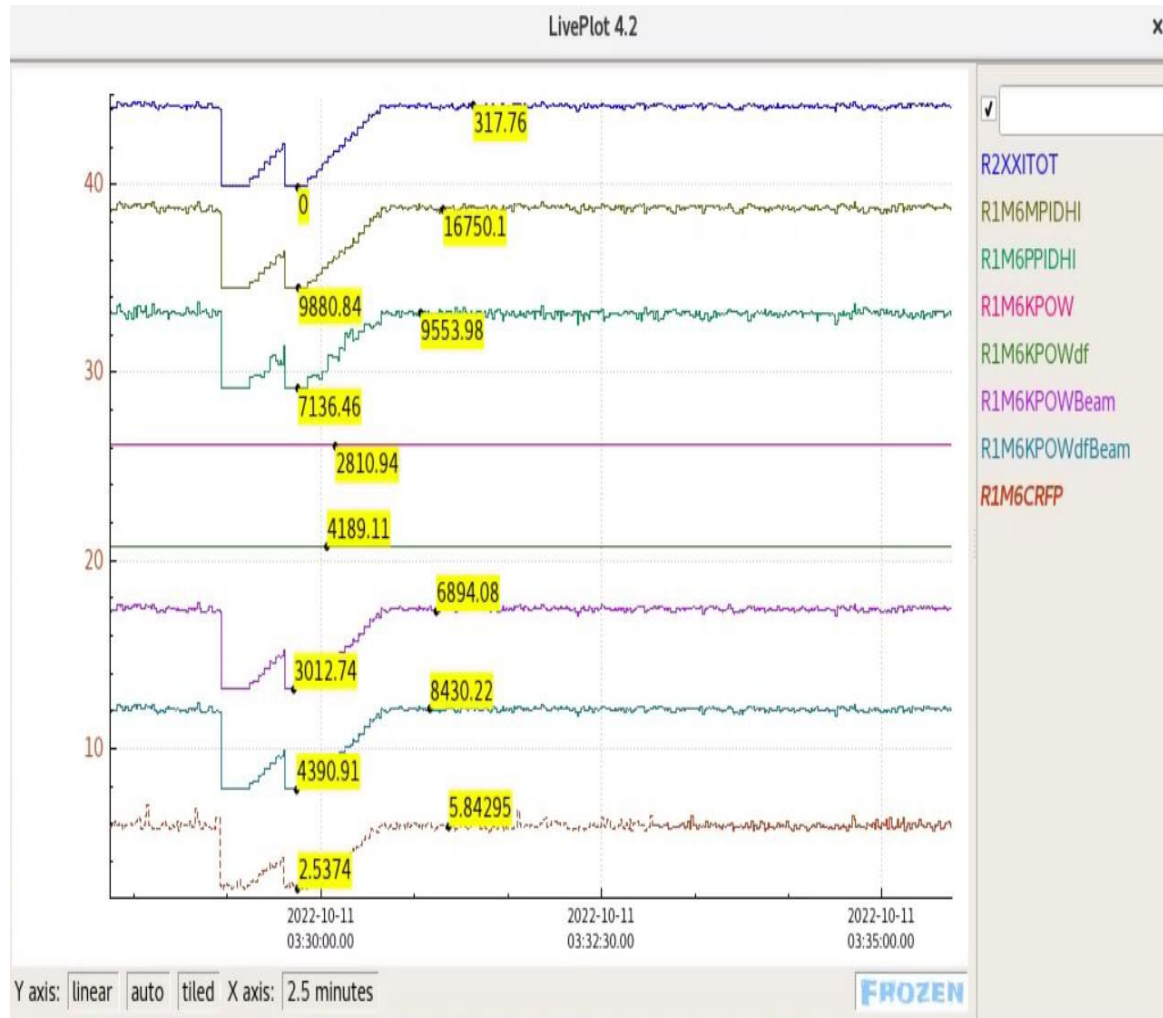
- Requirements
  - Gradient
    - .045%
  - Phase
    - .5 deg
- Measured
  - Out of the loop measurement
  - Gradient
    - .007%
  - Phase
    - 60 mdeg
    - 1 Hz – 10 kHz



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# Power Limits with Beam Loading

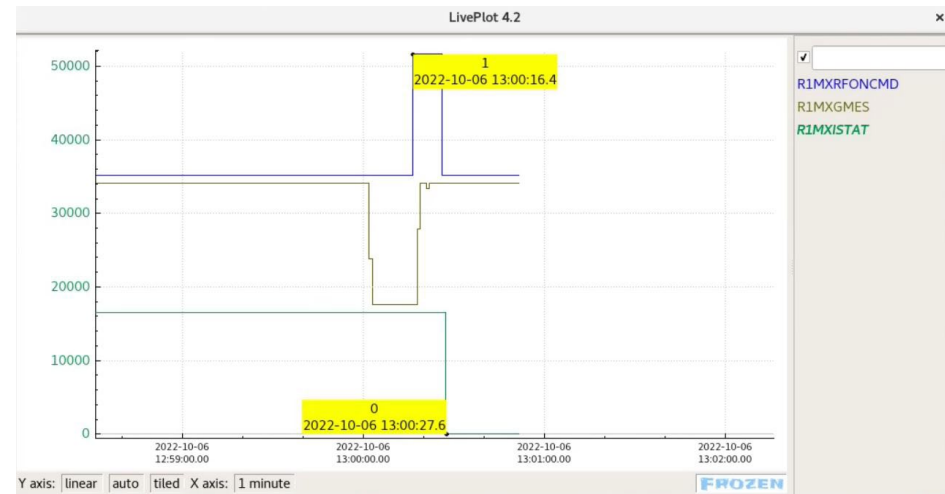
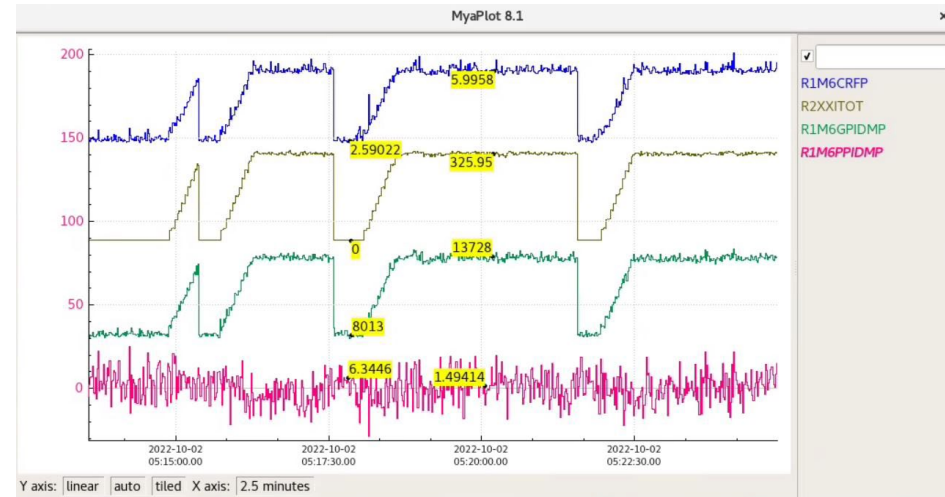
- R2XXITOT- Beam in uA
  - EPICS
- KPOW –pwr reqd with no beam, no detuning
- KPOWdf – pwr reqd with no beam, detuning
- KPOWBeam – pwr reqd with beam
- KPOWBeam – pwr required with beam, detuning
- MPIDHI - xlimhi
- PPIDHI – ylimhi
- CRFP – fwd pwr in kW
- Limits are as good as calibration
- Initial Beam Current of 50 uA
  - Feed forward is slow
- False trips on beam transients
  - Operating gradient is close to quench limit



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# SELAP in LLRF 2.0

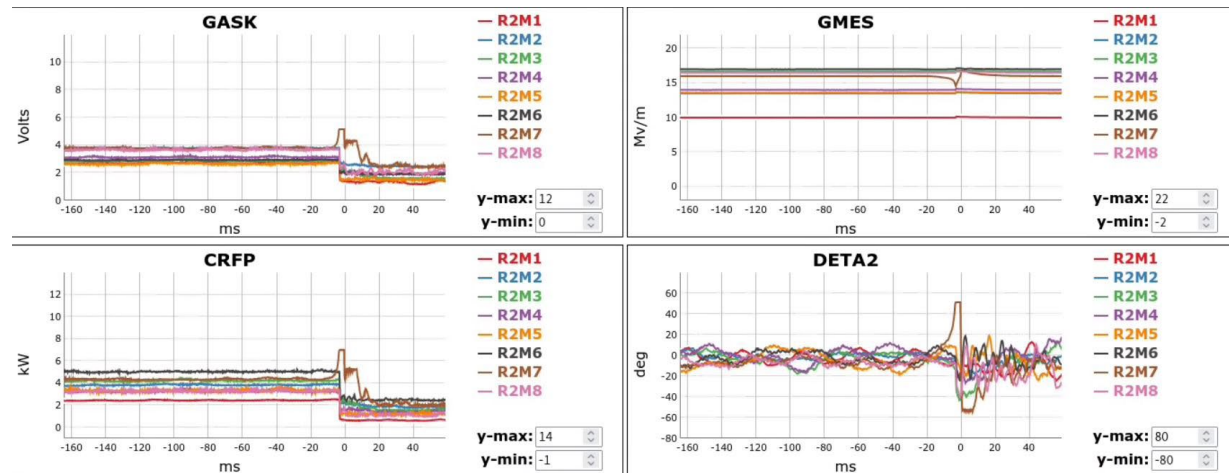
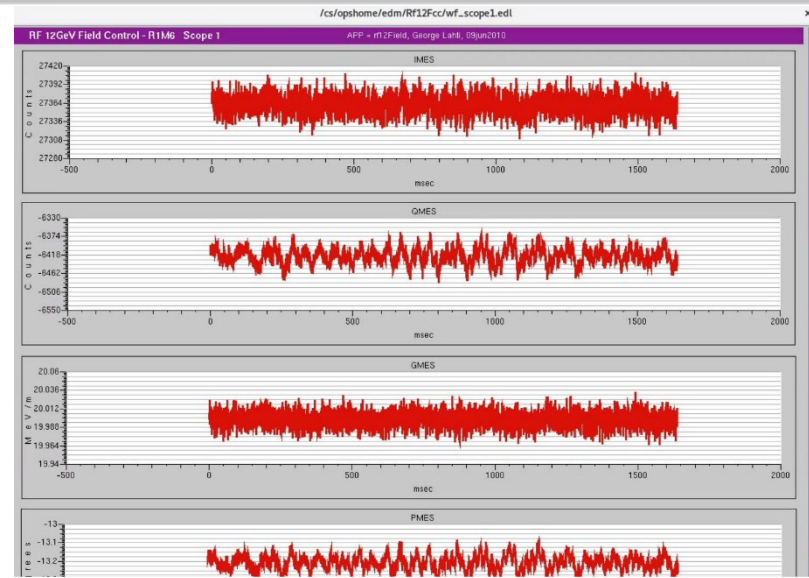
- Installed in three C100 cryomodules (24 cavities)
  - May 2022, Sep 2022
- Klystron Characterization
- Cavity Characterization
- SELAP without beam
- SELAP with 400  $\mu$ A beam
- Eliminated cavity fratricide
  - $\sim$ 800 Hz Lorentz force detuning
  - 10% mechanical coupling
- Faster recovery
  - 1.5 minutes vs 10 secs
- Channel isolation 55-60 dB
  - Impacts the loop gain



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# Dual Data Buffers

- Live data for diagnostics
  - Time and frequency domain
  - min, max, rms, stddev
- Fault data for offline analysis
  - Synchronized across the cryomodule
  - AI/ML



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# Future Work and Conclusions

- Upgrade all C100 zones with SELAP
  - Nine more cryomodules (72 cavities)
- Fine tune the algorithm to eliminate any false trips
- Data acquisition on beam trip
  - Capture the data in digital LLRF zones
- SELAP is an efficient algorithm to operate the srf cavities
  - Gradient is regulated, phase gets unlocked
  - Eliminates cavity fratricide
  - Doesn't saturate the amplifier
- Faster recovery
  - Whole zone is recovered in ~5 sec
  - Recovery can be instantaneous
- Collaborations are great
  - LCLS-II collaboration
- Special Thanks to L. Doolittle

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