FRIB

FRIB RF Systems

Dan Morris
Electrical Engineering Department Manager
RF Group Leader

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

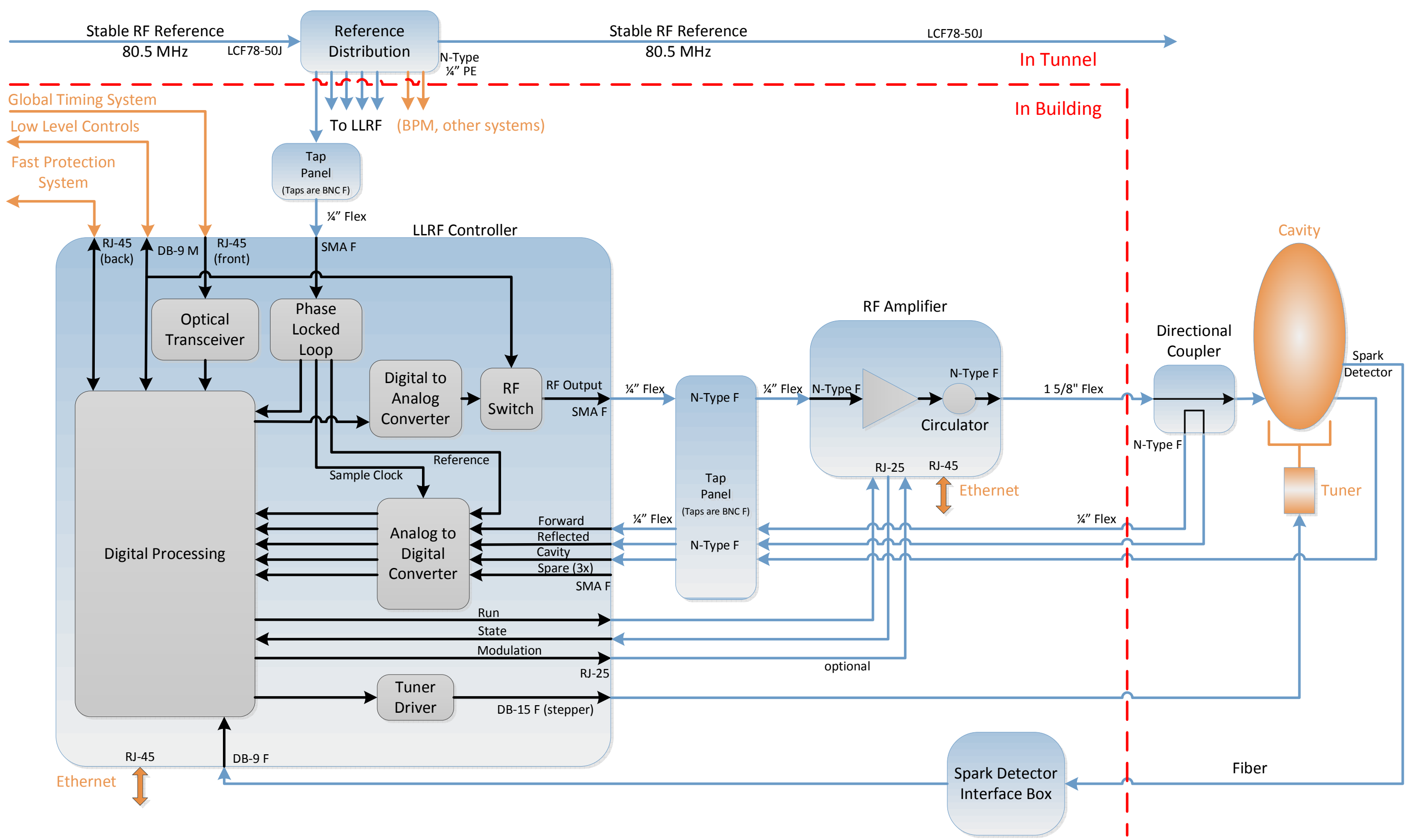
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

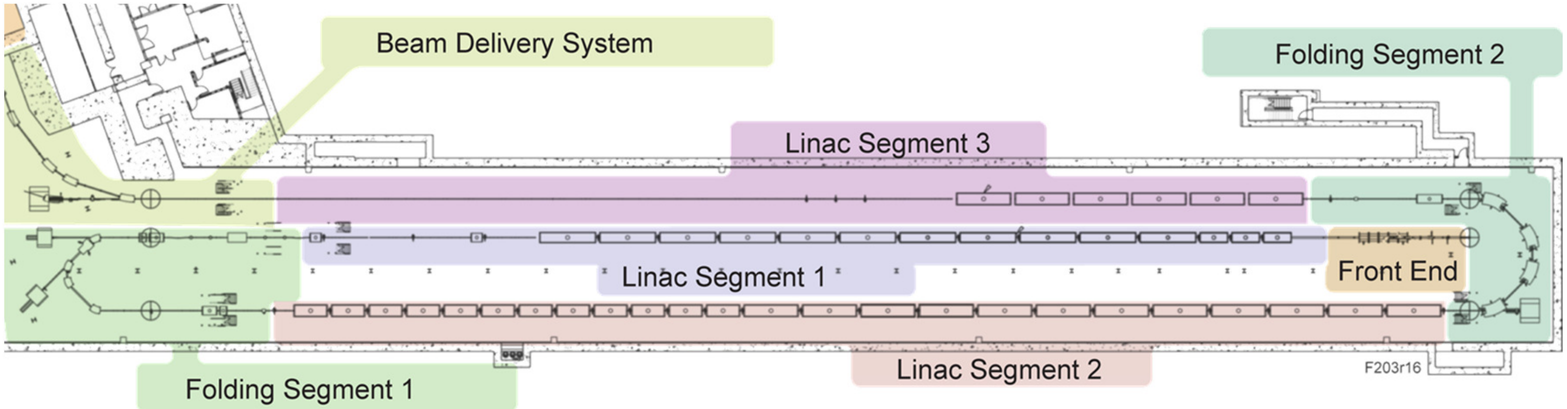
- FRIB RF Systems Introduction
- Front End Commissioning
- RFQ Amplifier Issues Resolved
- Solid-State Amplifiers
- LLRF Controllers
- Summary

Example RF System

RF System – SRF β=0.085

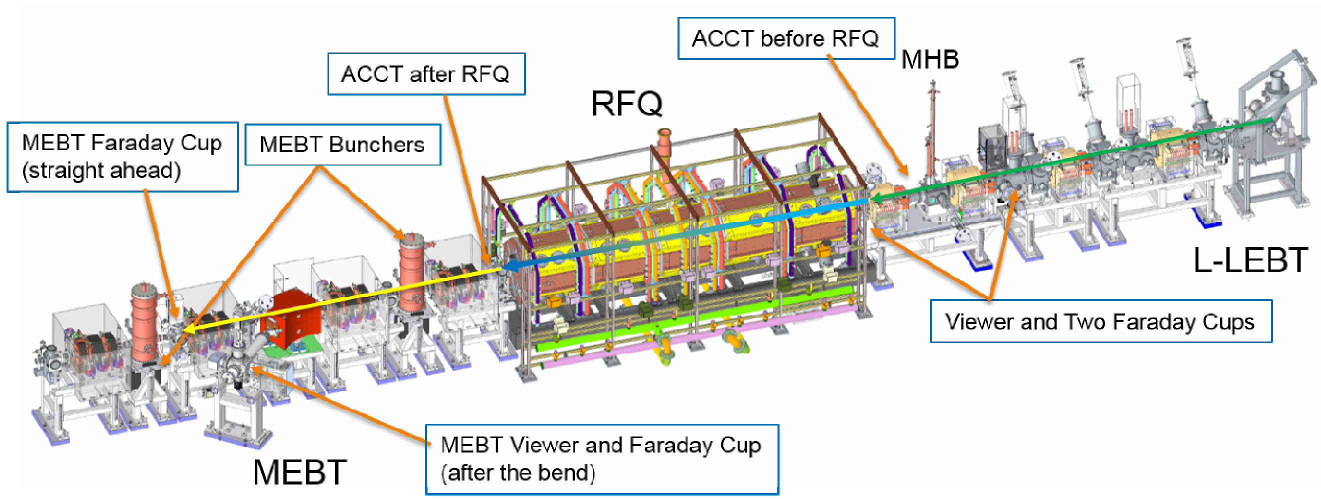


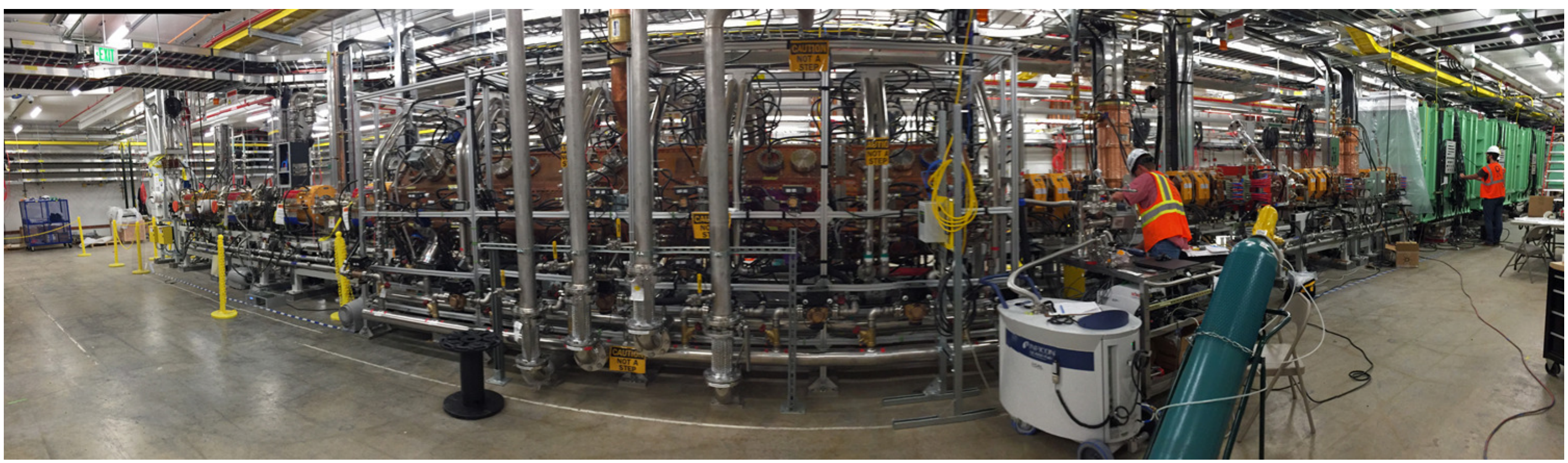
Over 330 RF Systems for FRIB Linac



System	Area	Frequency	Cavity Type	Required RF Power	Amplifier Type	Tuner	Qty
Ion Source	FE	14 GHz	ECR	2 kW	Klystron	N/A	1
LEBT Multi-Harmonic Buncher	FE	40.25 MHz - 120.75 MHz	RT	100 W	SS	N/A	3
RFQ Driver	FE	80.5 MHz	RT	8 kW	SS	N/A	1
RFQ Final (Tetrode)	FE	80.5 MHz	RT	100 kW	Tetrode	Servo (water)	1
MEBT Buncher	FE	80.5 MHz	RT	4 kW	SS	2-phase stepper	2
β=0.041 (accelerating)	LS1	80.5 MHz	SC	700 W	SS	2-phase stepper	12
β=0.085 (accelerating and matching)	LS1 - FS1	80.5 MHz	SC	2.5 kW	SS	2-phase stepper	92
IH Multi-Gap Buncher	FS1	161 MHz	RT	18 kW	SS	5-phase stepper	2
β=0.285 (accelerating and matching)	LS2	322 MHz	SC	3.0 kW	SS	Pneumatic	72
β=0.530 (accelerating and matching)	LS2- LS3	322 MHz	SC	5.0 kW	SS	Pneumatic	148

Front End
Lower LEBT and MEBT Layout



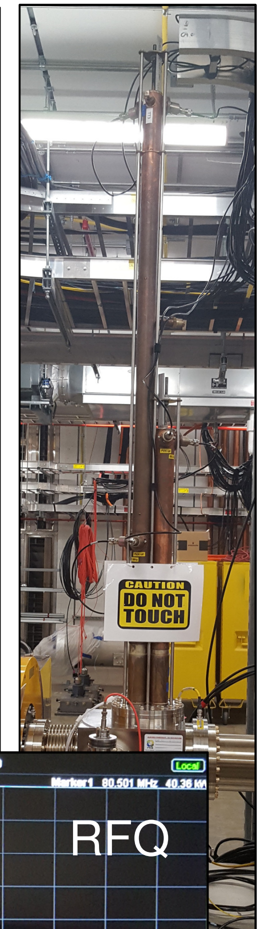


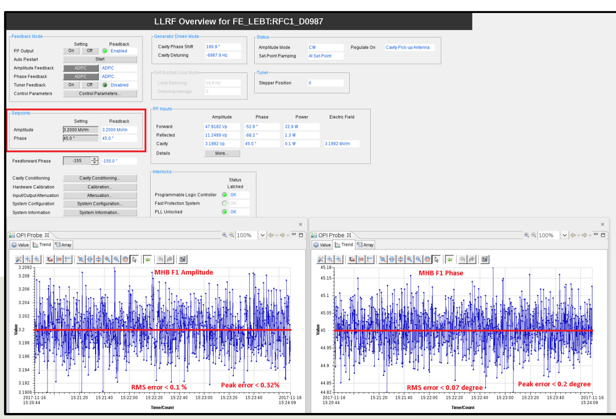
Front End RF Systems Commissioned and Supporting Operations

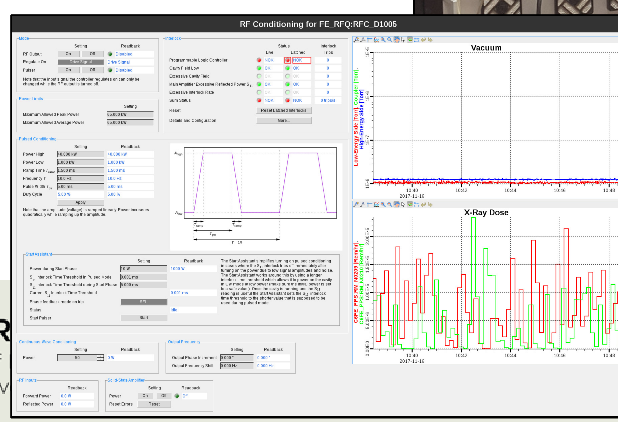
- 14 GHz Klystron commissioned for Artemis ion source
- LLRF controllers and amplifiers installed and tested
  - Drivers and high level controls screens developed
  - Interlocks verified
- Multi-harmonic buncher (MHB) locked all 3 frequencies (100 W amplifiers)
- Medium Energy Beam Transport (MEBT) bunchers commissioned up to 1.6 kW (4 kW amplifiers)
- RFQ in closed loop amplitude and phase with water skids in temperature and frequency control mode
  - RFQ conditioned to 59 kW
  - 40 – 50 kW for argon and krypton
  - 3 of 6 anode power supply modules locked out to limit power
  - Condition to higher power, as needed (100 kW for uranium)
- All systems running with beam at or above KPP

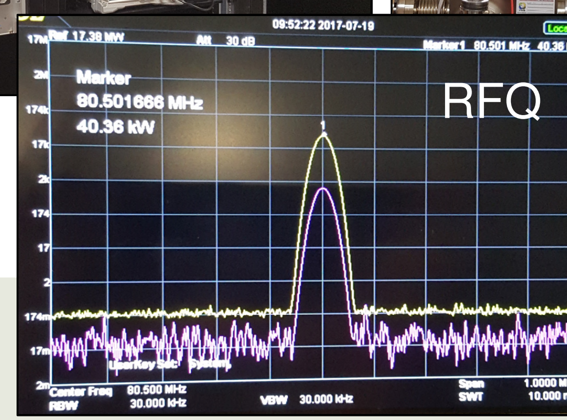
FE RF Amplifiers & LLRF Controllers

MHB









Front End Performance Exceeds Amplitude and Phase Stability Requirements

- Data from January 2018
  - > 3x better than requirements

		MHB F1 (D0987)		MHB F2 (D0987)		MHB F3 (D0987)	
		Amplitude (Vp)	Phase (deg)	Amplitude (Vp)	Phase (deg)	Amplitude (Vp)	Phase (deg)
Set-point		5.2	45.0	9.2	20.0	4.4	10.0
Forward Power (W)		~ 70		~ 20		~ 20	
Peak Error (%, deg)	Meas.	0.294	0.240	0.473	0.336	0.518	0.358
	Spec.	**< 1.5**	**< 1.5**	**< 1.5**	**< 1.5**	**< 1.5**	**< 1.5**
RMS Error (%, deg)	Meas.	0.079	0.049	0.126	0.079	0.137	0.089
	Spec.	**< 0.5**	**< 0.5**	**< 0.5**	**< 0.5**	**< 0.5**	**< 0.5**

		RFQ (D1005)		MEBT (D1066)		MEBT (D1107)	
		Amplitude (Vp)	Phase (deg)	Amplitude (Vp)	Phase (deg)	Amplitude (Vp)	Phase (deg)
Set-point		12.88	20.0	3.56	10.0	6.00	15.0
Forward Power (W)		~ 40000		~ 1500		~ 1500	
Peak Error (%, deg)	Meas.	0.187	0.214	0.480	0.263	0.237	0.223
	Spec.	**< 1.5**	**< 1.5**	**< 1.5**	**< 1.5**	**< 1.5**	**< 1.5**
RMS Error (%, deg)	Meas.	0.025	0.048	0.060	0.055	0.037	0.054
	Spec.	**< 0.5**	**< 0.5**	**< 0.5**	**< 0.5**	**< 0.5**	**< 0.5**

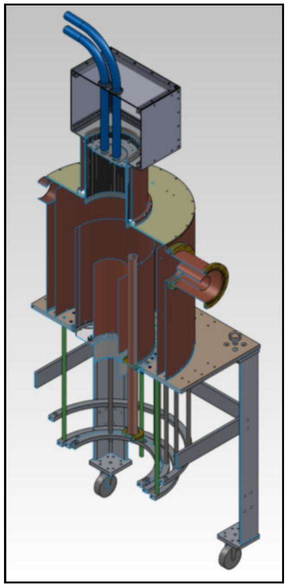
FRIB RFQ Amplifier Based on ReA3

- NSCL ReA3 RFQ amplifier
  - 7 years operation
    - Typical 30 kW average power (90 kW peak)
  - Coaxial resonator (sliding shorts for tuning)
    - TH-781 tetrode
  - Tested up to 160 kW into 50 ohm load
    - Low harmonics, good efficiency
  - Stable design (tested up to 100 kW into short and open circuit with no oscillations)
  - No output circulator (fast LLRF interlocks)
  - Solid-state 1kW pre-amplifier
  - 10 kW triode tube driver amplifier
- Changes for FRIB RFQ amplifier
  - 8 kW solid-state driver amplifier (no pre-amp needed)
  - Switch to Allen Bradley PLC
    - Commonality across FRIB
    - PLC is shared with RFQ amplifier and water skids
    - Supply pressure regulator with PID control
  - No local touch screen (use CS-Studio only)

Final Amp			Final Anode Supply			
P_{in} (kW)	P_{out} (kW)	Gain (dB)	V (kV)	I (A)	VI (kW)	Efficiency (%)
2.6	57.5	13.5	15.6	8.3	129	44%
4.5	102.3	13.6	15.7	11.6	182	56%
5.8	125.9	13.4	15.7	12.9	203	62%
7.0	151.4	13.3	16.0	14.4	230	66%
7.1	158.5	13.5	15.9	14.8	235	67%

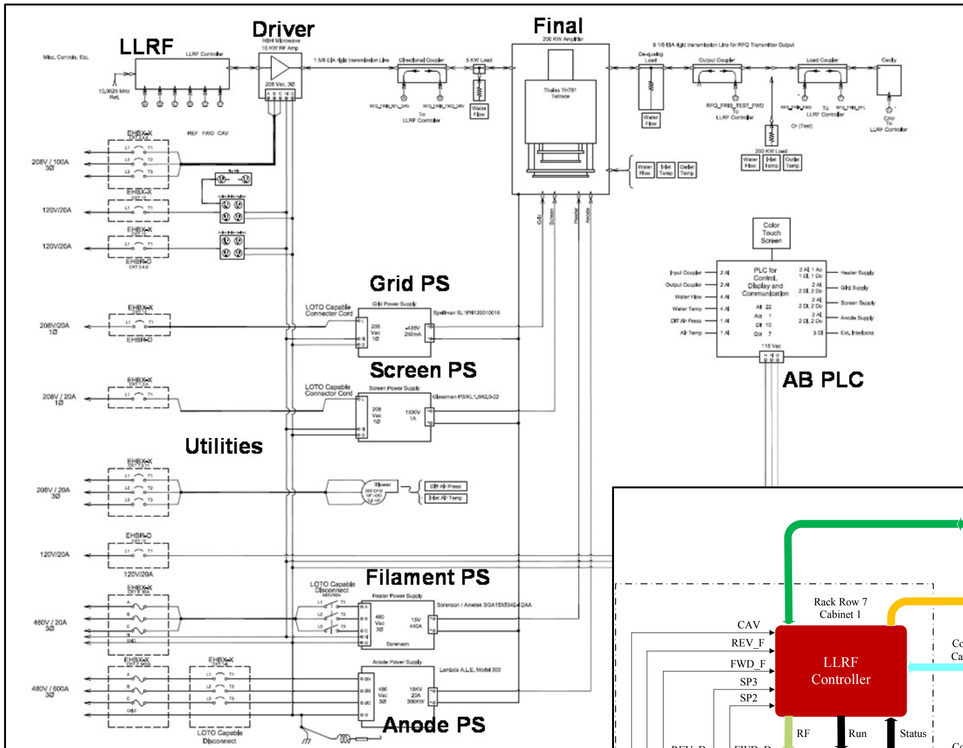
Harmonics at 150 kW (dBc; 80.5 MHz fundamental)

161 MHz	241.5 MHz	322 MHz	402.5 MHz	483 MHz
-63.0	-55.1	-38.6	-46.6	-80.7

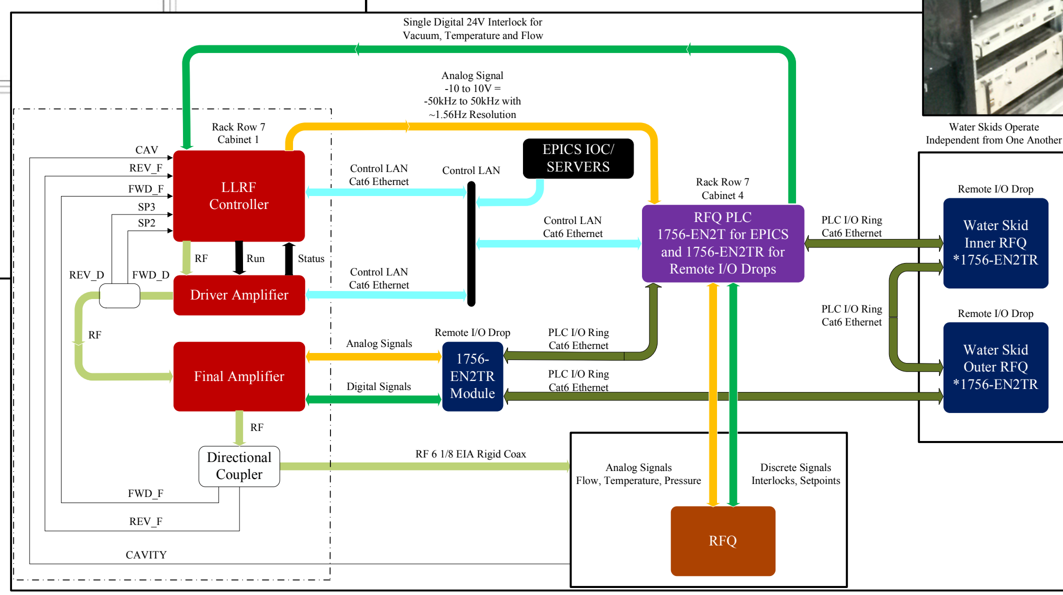


Enclosure not shown

FRIB RFQ Amplifier System



PLC Shared with Water Skids



FRIB RFQ Amplifier Issues Resolved

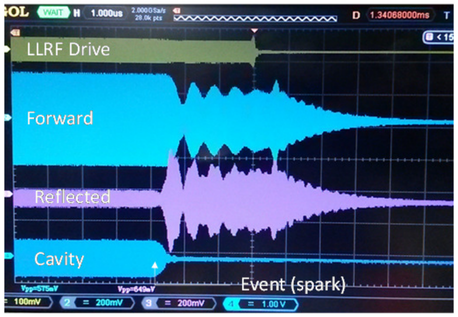
- Stable into dummy load up to 100 kW, but ~1 GHz oscillations occurred ~10 kW when connected to cavity
  - Tuned anode plate sliding shorts for stability and lower gain
  - LLRF interlock response time decreased to 3-4 microseconds to better protect cavity
- RFQ amplifier gain varies with load impedance
  - **No high power circulator**
  - Low cavity impedance during sparking was transformed through the transmission line to a high impedance at the amplifier output
  - Output power increased faster than the LLRF control loop can respond (tube is a voltage-controlled current-source)
  - The spike in RF power caused over-current faults in anode power supply, LLRF forward power high interlock, and vacuum spikes in coupler/cavity
  - **Mitigated by inserting ~¼-wavelength to the transmission line**
  - Now forward power drops in case of spark or multipacting (no trips)

Before line extension

Power increases during cavity events (unstable).

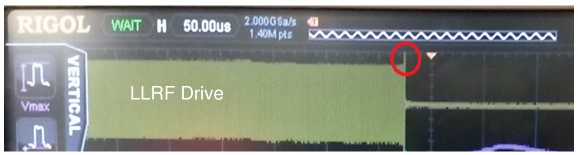
After ~λ/4 line extension

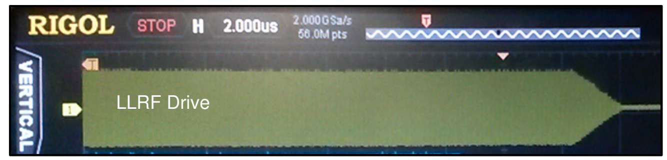
Power decreases during cavity events (stable).



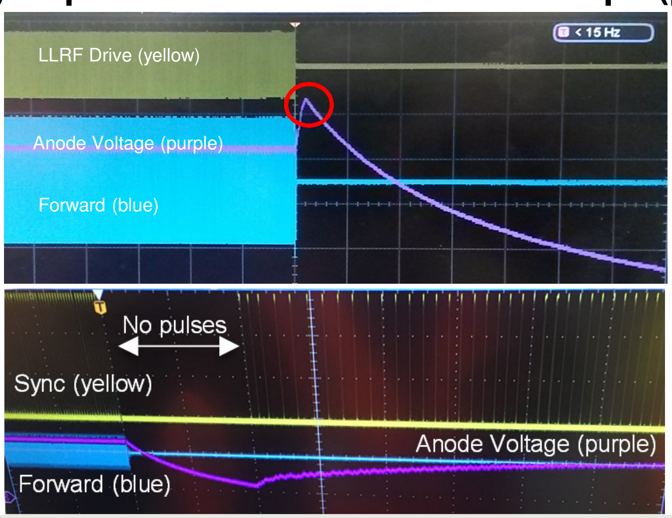
FRIB RFQ Amplifier Issues Resolved [2]

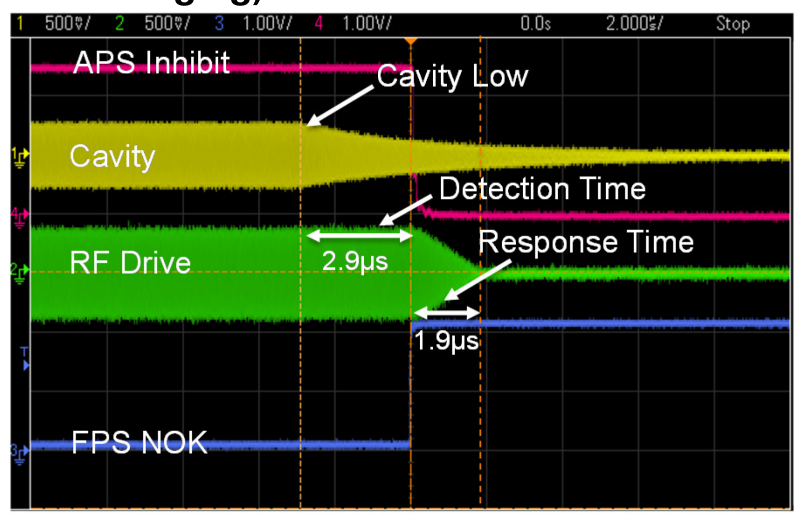
- LLRF turn-off glitch
  - Internal RF switch was used to turn off LLRF output (terminated into 50 ohm load)
  - Glitches occurred due to DC offset, which occasionally tripped anode power supply
  - **Changed firmware to ramp to zero within 2 μs instead of using the RF switch**





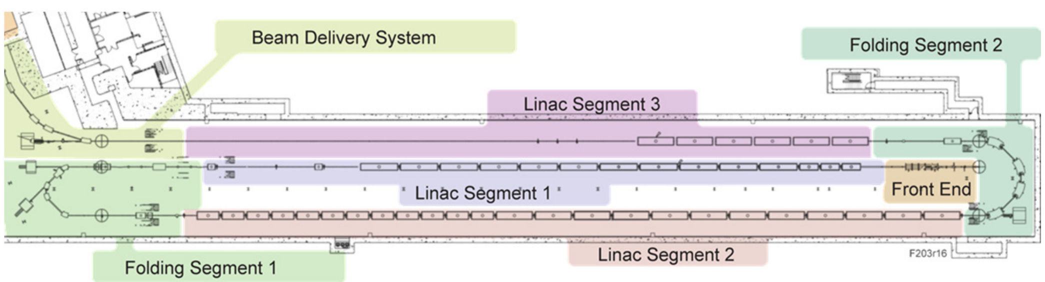
- Anode power supply overvoltage latch when RF drive turns off
  - Voltage increases rapidly due to no load. Trips anode PS overvoltage latch
  - **Increased OV hardware limit (changed resistor value)**
  - **Inhibit sync pulses for >800 ns when RF trips (prevents charging)**





Solid-State Amplifiers Production and Installation On Track

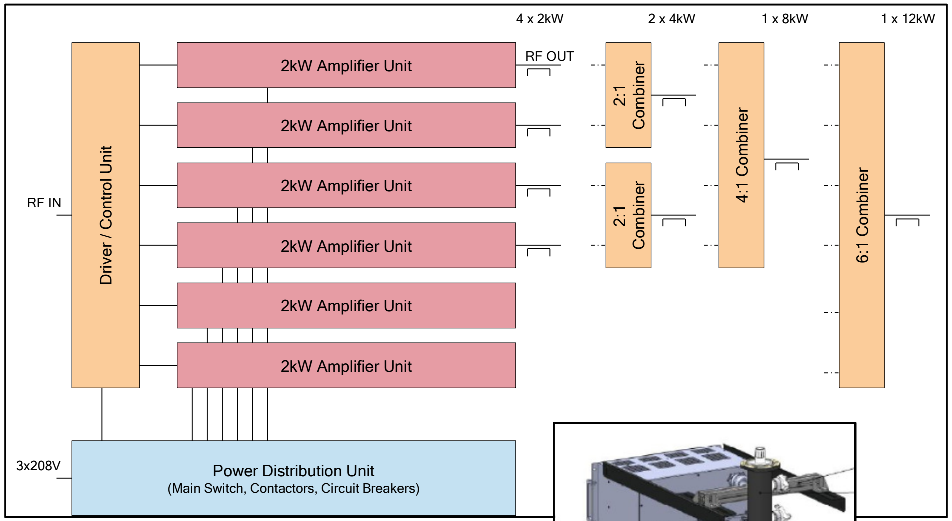
- 80.5 MHz amplifier production completed
  - No pallet or circulator failures during acceptance testing
  - Two controllers failed communication test
    - » Fixed by replacing faulty harness connectors
  - Minor non-conformance for input return loss
    - » Accepted as-is (< -17 dB). Modified design for next units
  - Two drawers with pallet power imbalance on power up
    - » Root cause analysis in progress
- 322 MHz amplifier production in progress. On track to complete in 2018
  - > 50 racks received
- Amplifier installation is on schedule
  - FE and LS1 devices are installed and tested
  - Ready for Device Readiness Review May 2018

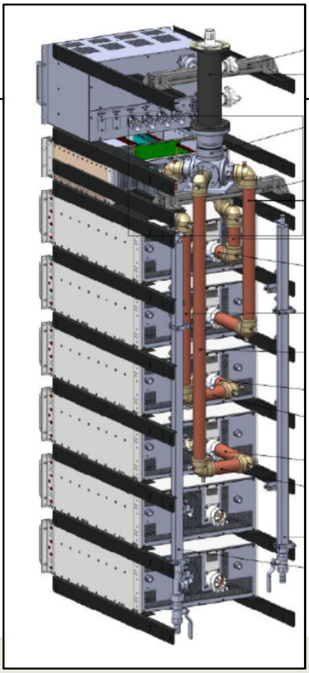


80.5 MHz RF Amplifiers in LS1

Solid-State Amplifier Requirements

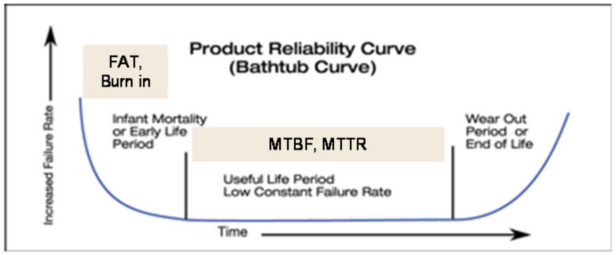
- Key requirements
  - 80.5 MHz, 161 MHz, and 322 MHz
  - 50U modular rack design
  - 2 kW to 8 kW standard
    - » Upgradable to 12 kW (six drawers)
  - Full power CW operation into 100% reflective loads any phase
  - Surge of 4x reflected power (τ < 10ms)
  - Forced water cooling (one GPM per 1 kW)
  - One 208 VAC (100A) 3-phase feed per rack
  - DC power supplies
    - » Active power factor correction
    - » Low conducted and radiated emissions, electromagnetic immunity
    - » UL or equivalent
  - Adjustable drain voltage for efficiency
    - » Upgrade option for modulating power supply (class H)
  - Ethernet interface for controls and monitoring
  - HW interface (RUN PERMIT, STATUS)
  - Serviceability by customer; fully documented





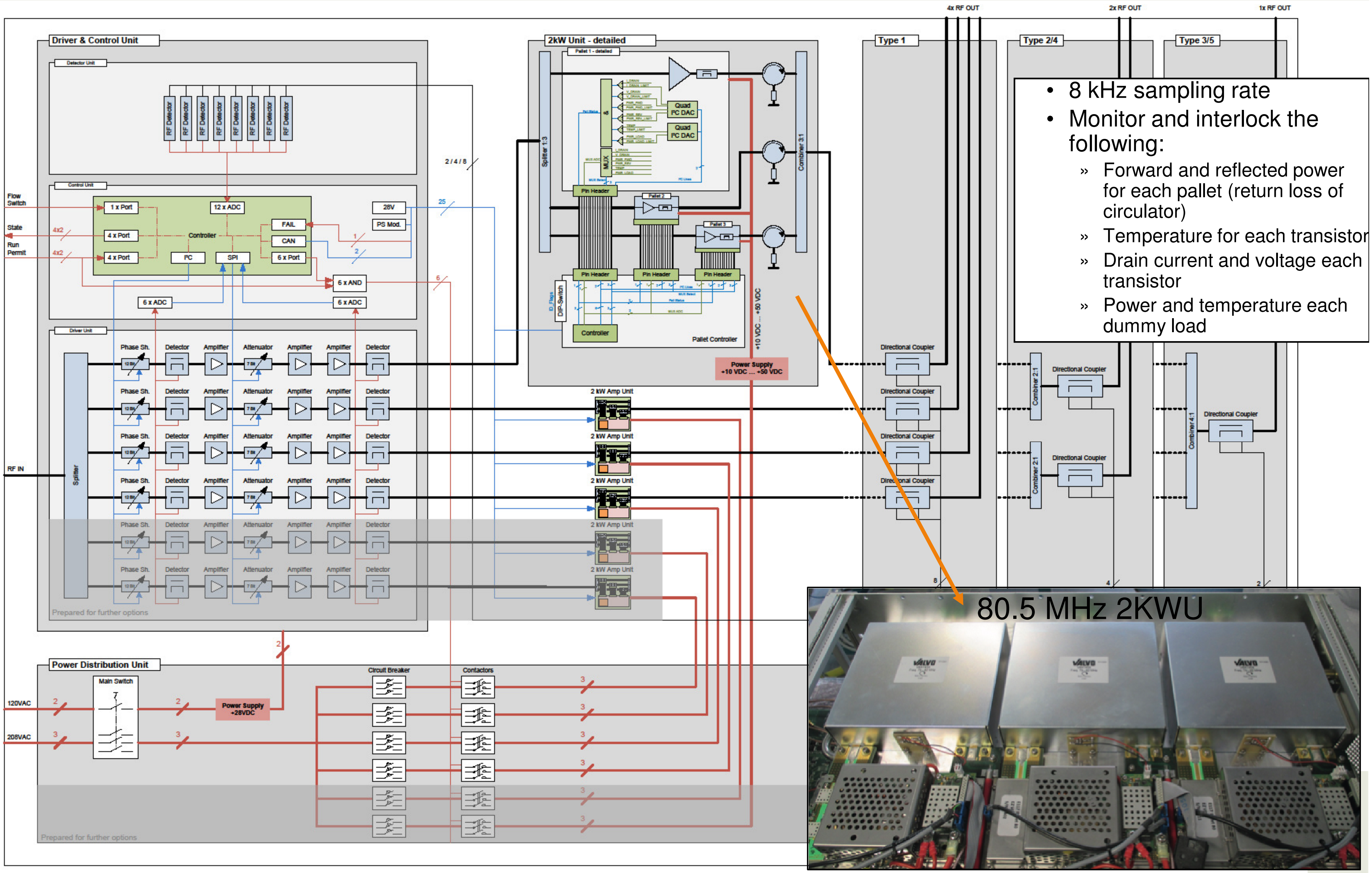
RF Strategy For High Reliability

- With 330+ amplifiers and LLRF controllers, what is strategy for high reliability?
- Definitions:
  - Mean Time Between Failures (MTBF) = Uptime / Number of System Failures
  - Mean Time To Repair (MTTR) = Downtime / Number of System Failures
  - Availability = MTBF / (MTBF + MTTR)



- Need to reduce the MTTR
  - Avoid delays. Keep spares nearby with latest firmware
  - Keep dedicated tools cart stocked and ready
  - Unlike Klystrons and vacuum tube amplifiers that require the RF specialist to repair in-place, the SSAs and LLRF controllers can be swapped by trained operators (and repaired offline)
  - Need good procedures with training and practice sessions
- Need to maximize MTBF (minimize failure rate)
  - We don't have N+1 architecture or ability to continue running with a failed transistor, yet
  - Instead, minimize failure rate by designing in high operating margins for critical parts (circulators, RF pallets / transistors, DC power supplies, RF transmission lines)
  - Fast interlocks protect hardware
- Reduce failures during early ops with thorough screening during supplier FAT (component, 2kW drawer, and rack) and FRIB acceptance testing

RF Amplifier Rack System Interface and Control Diagram



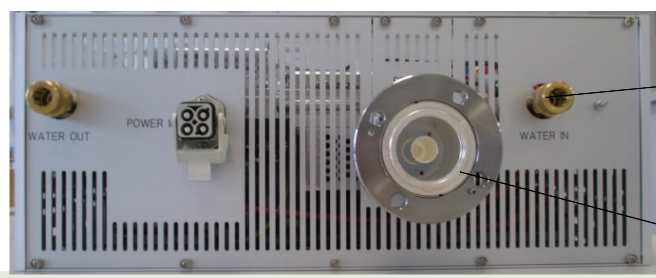
- 8 kHz sampling rate
- Monitor and interlock the following:
  - » Forward and reflected power for each pallet (return loss of circulator)
  - » Temperature for each transistor
  - » Drain current and voltage each transistor
  - » Power and temperature each dummy load

2kW RF Amplifier (322 MHz shown)

- 3 RF pallets gives 50% operating margin
  - Two pallets *could* deliver 2 kW with higher power density and smaller form factor, but…
    - » Too close to voltage breakdown
    - » Sensitive to circulator impedance. Likely to fail during cavity discharge, etc.
    - » Increased junction temperature reduces MTBF
- Design / test drawers > 2.2 kW CW each
  - FRIB baseline operation requires 700 W to 1400 W average power per drawer
  - High operation margin for transistors, circulators and loads
  - Transistors < 60 degrees C at all times
    - » Rule of thumb for electronics: Increasing temperature 10 degrees C reduces MTBF 50%
    - » Lower temperature → better reliability

2 kW Amplifier Unit, 19 inch, 4U
(Top view)

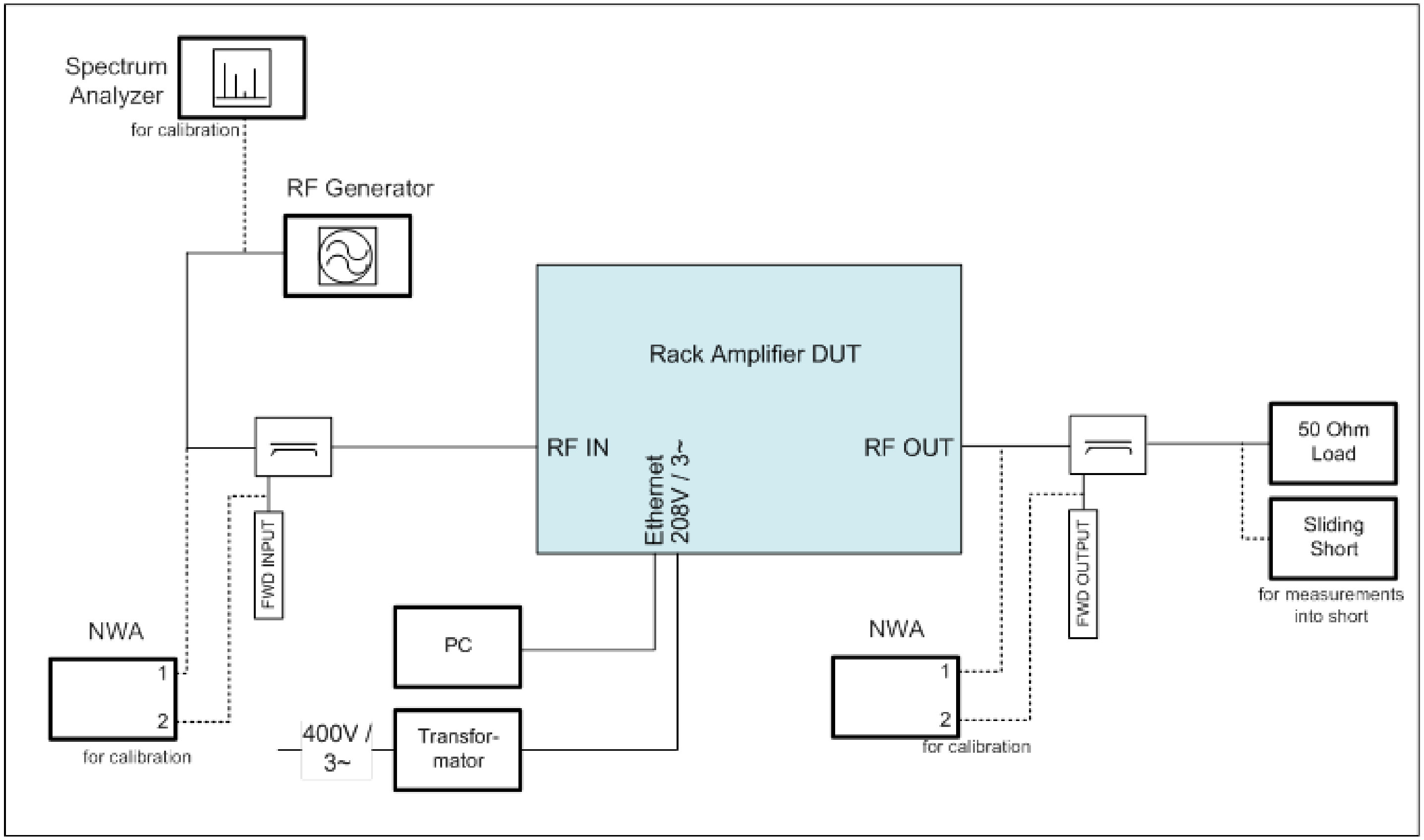
(Front view)



(Rear view)

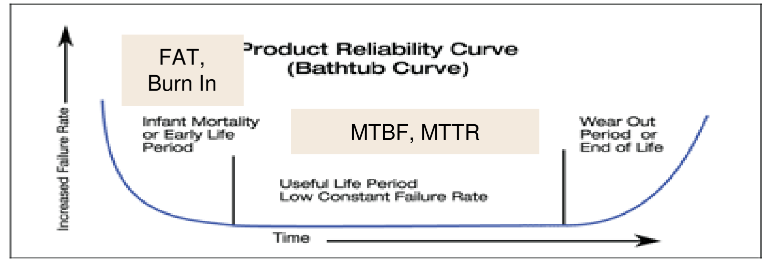
Automated Factory Acceptance Testing

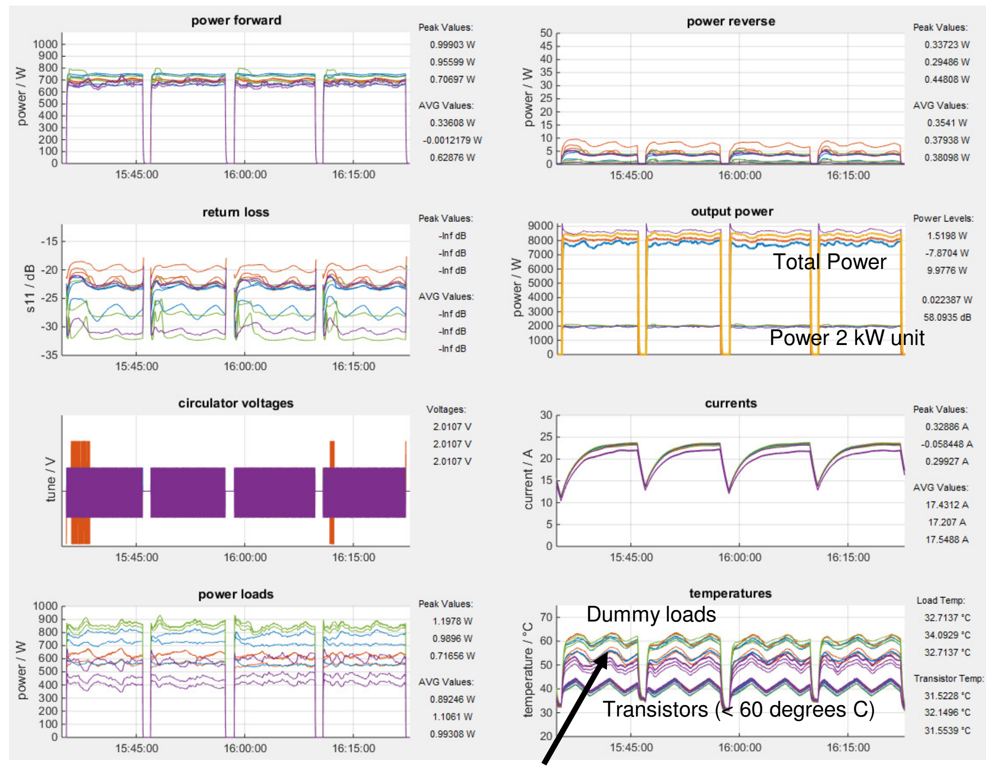
- All amplifiers are tested under short condition, all phases
  - Find worst case phase → 12 hour burn in with 10% overload (Golden units 24 hours)
  - All waveguides rated for 4 x nominal power



Factory Acceptance Testing [2]

- Thorough FAT and acceptance testing at FRIB will detect early failures and improve machine availability during early ops



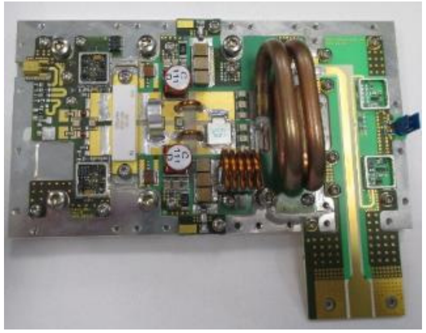


Temperature variation due to chiller cycle

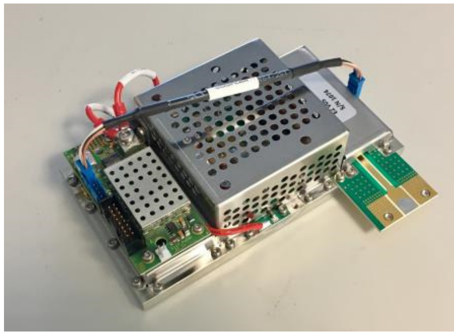
Variable Drain Bias Improves RF Amplifier Efficiency

- Fixed drain bias voltage (conventional approach)
  - Drain voltage is set for maximum available output power
  - Pros: Simple; lowest cost to implement
  - Cons: Lowest efficiency; higher cost to operate
- Variable drain bias voltage (FRIB)
  - Drain voltage is set for peak required power via EPICS
  - Pros: Higher efficiency (up to 20%); **less heat**
  - Cons: Higher cost for power supply and controls; lower gain

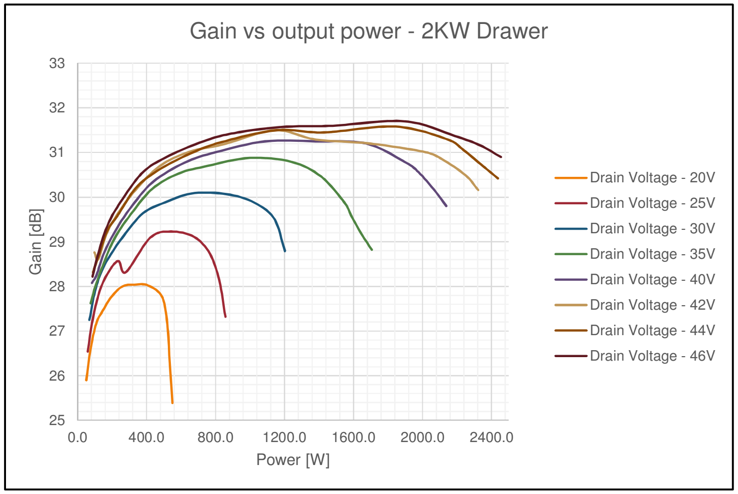
RF Power per 2kW Unit			Fixed Drain Voltage			Variable Drain Voltage			
Max	Avg	Min	Drain Voltage	AC Power	Efficiency	Drain Voltage	AC Power	Efficiency	Delta
2000 W	2000 W	2000 W	46 V	3509 W	57.0%	46 V	3509 W	57.0%	0.0%
1519 W	1287 W	1054 W	46 V	2745 W	47.0%	35 V	2340 W	55.1%	8.1%
1373 W	1092 W	811 W	46 V	2600 W	42.0%	32.5 V	2000 W	54.6%	12.6%
767 W	637 W	507 W	46 V	1924 W	33.0%	25 V	1174 W	54.1%	21.1%

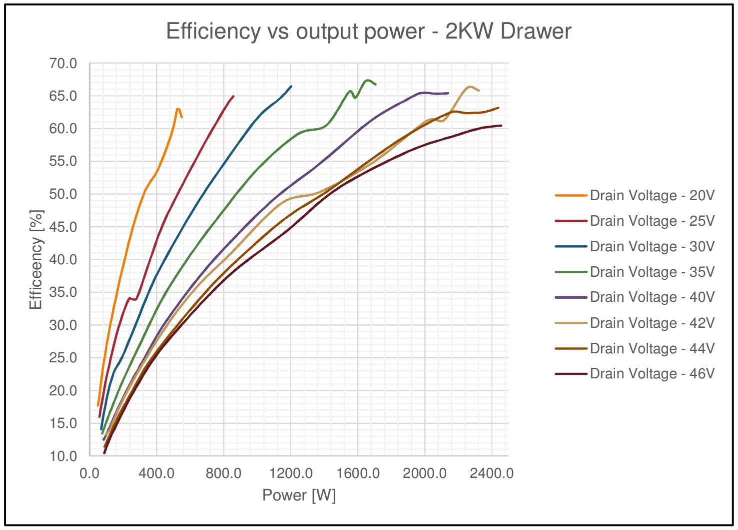


80.5 MHz 1 kW RF Pallet



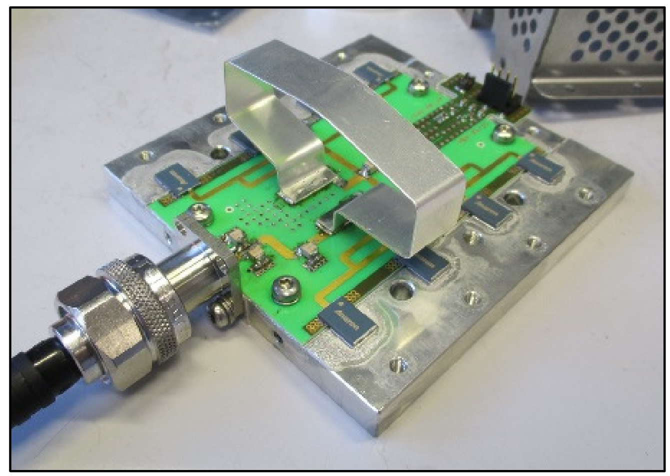
Shielding reduces cross-talk



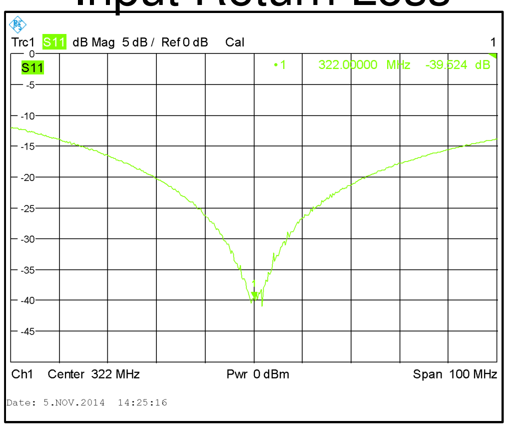


Dummy Loads Improved For Reliability

- Prototype design
  - 2 x 800 W, 100 ohm termination resistors in parallel
  - Load can only hold 1200 W due to heat density too high
- Production design
  - 8 x 200 W resistors
  - Load is designed for 1600 W, but tested up to 3500 W (need 1000 W)
  - All loads are bench tested with power

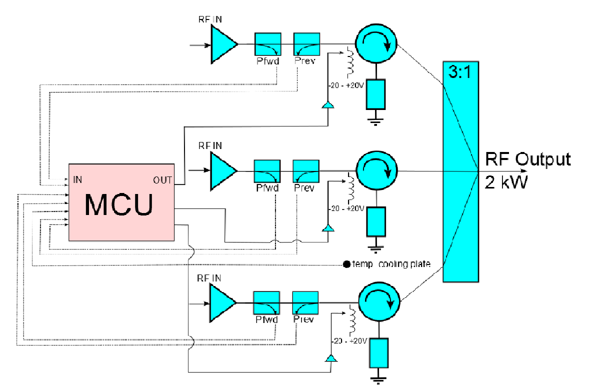


Input Return Loss

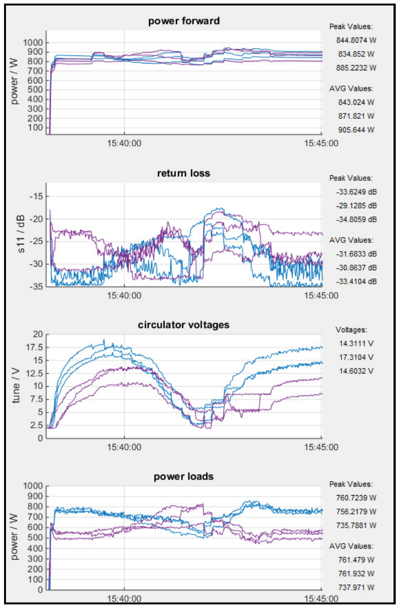


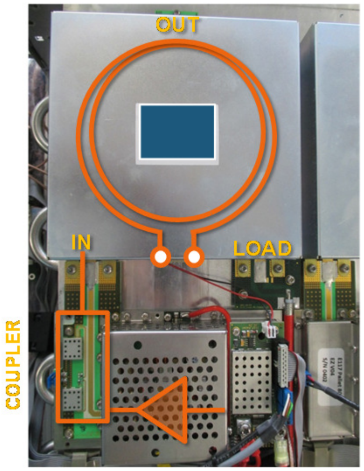
Circulator Tracking

- Circulator tracking developed by supplier for 80.5 MHz (not needed for 161 MHz or 322 MHz)
  - Protection of the amplifier transistors is necessary due to 100% reflection requirement in any phase angle
  - Circulator isolates transistors from output port
  - Circulator return loss, insertion loss and isolation change with temperature and RF power
  - Voltage controlled coil is able to tune the circulator
  - Compensation for RF and temperature effects
  - Tracking algorithm uses S11 and heat sink temperature (defines starting point when RF power is off)

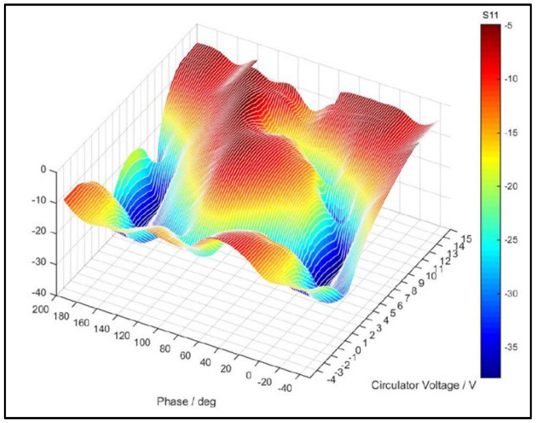


Measured Data

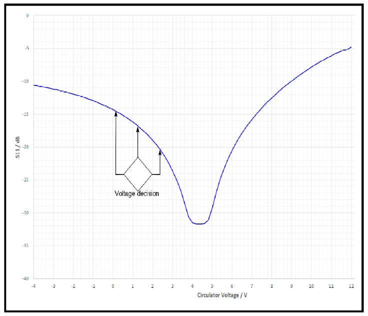




Circulator Characterization



Tracking Algorithm

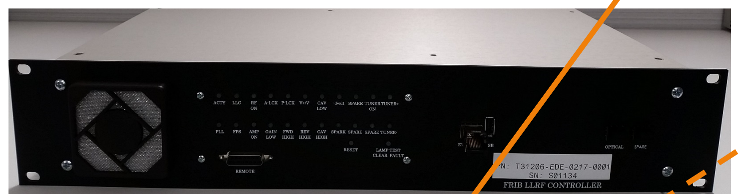


HBH Microwave GmbH

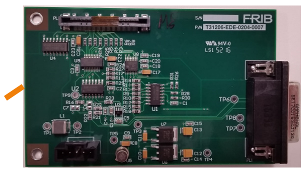
Low-Level RF Hardware

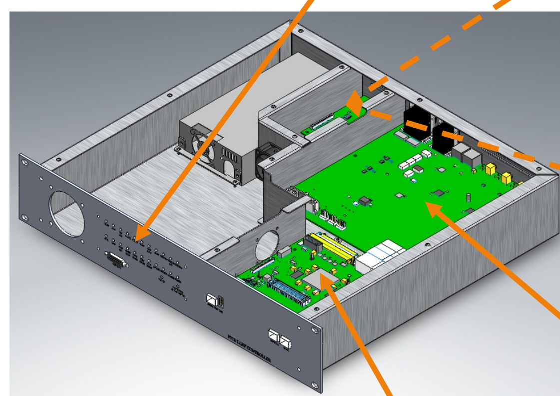
- FRIB general purpose digital board (FGPDB)
  - Xilinx Spartan 6 Field Programmable Gate Array (FPGA)
  - LLRF / Fast Protection System (FPS) / Beam Position Monitor (BPM)
- Radio frequency (RF) board
  - RF inputs/output
    - » 2 Analog-to-Digital Converters (ADCs)
    - » 1 Digital-to-Analog Converter (DAC)
  - Each RF board supports 2 frequencies
  - FPS / External Interlock / Amplifier
  - Spare analog inputs/outputs (slow ADC/DACs)
  - Spare digital inputs/outputs
  - Spark detector circuit
- Front panel board
  - Light Emitting Diodes / Buttons / Connectors
- Tuner boards
  - Stepper tuner board for QWRs
  - Analog tuner board for HWRs (0~5 V) and RFQ (-10~10 V)

Front Panel Board

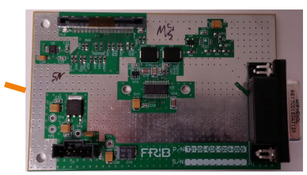


Analog Tuner Board

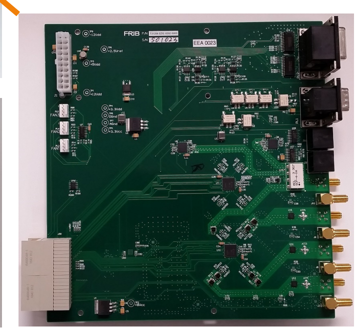




Stepper Tuner Board



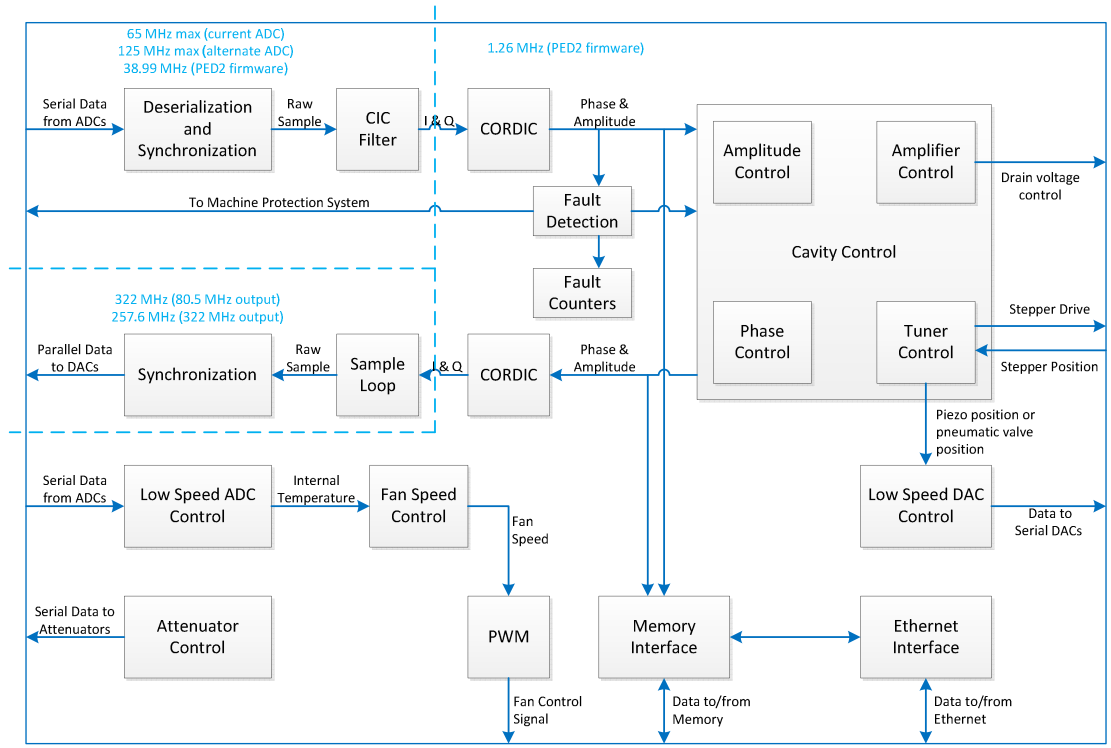
RF Board



FGPDB

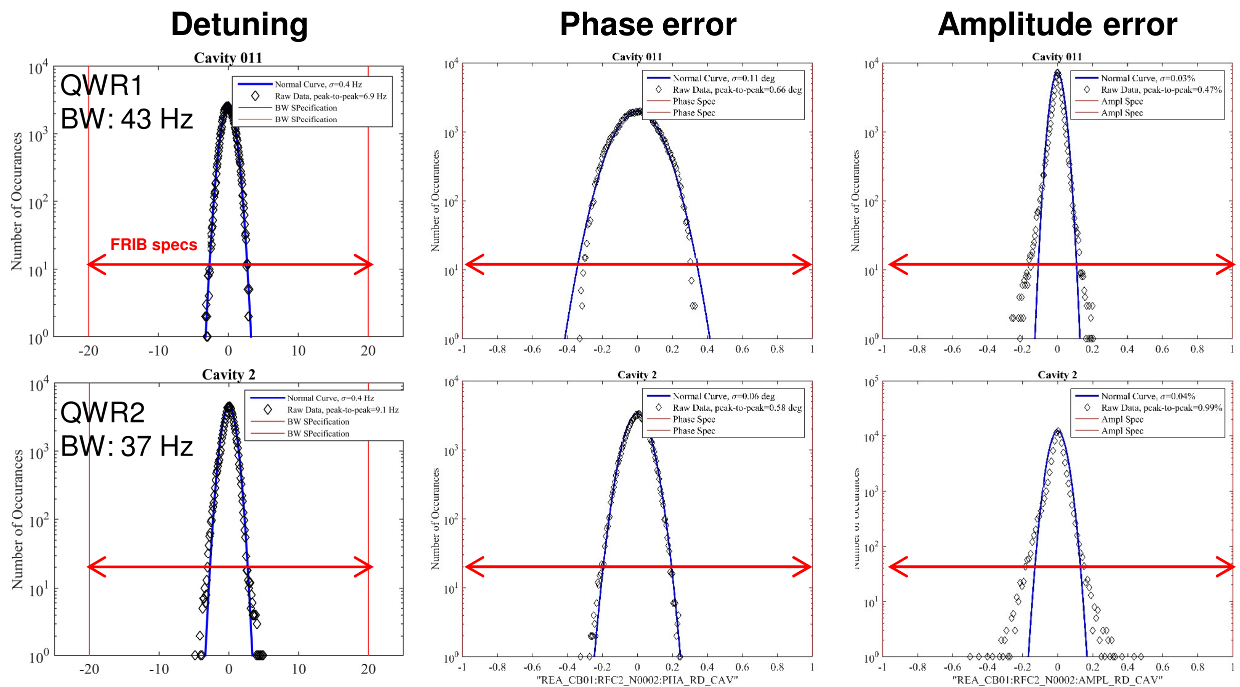
Low-level RF Functionalities

- Firmware Features
  - Amplitude/phase regulation with active disturbance rejection control (ADRC)
  - Tuner control (stepper tuner and pneumatic tuner)
  - RF and analog inputs/outputs
  - Digital self-excited loop (SEL) with +/- 50 kHz range
  - Internal and external interlocks
  - Device and system calibration
  - Remote firmware update
  - Data buffer
- Interfaces
  - Global Timing System (GTS)
  - Fast Protection System (FPS)
  - Low-level Control (LLC)
  - Experimental Physics and Industrial Control System (EPICS)
  - Power amplifier



QWR Validation Test Results
All FRIB Specifications Fulfilled

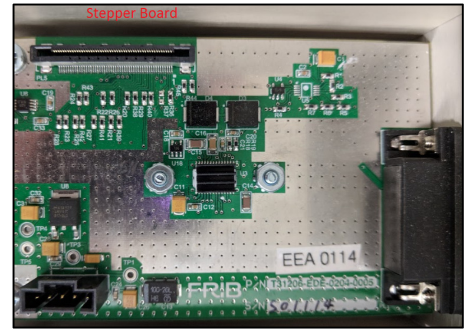
- 2 FRIB QWRs
  - 6.2 MV/m
    - » 10% higher than requirement
  - ~ 40 Hz cavity BW
  - ~ 800 W RF power
  - T=4.2 K
- Microstepping verified
- Locked 24 hours, no trips
  - Phase and amplitude regulation in specification



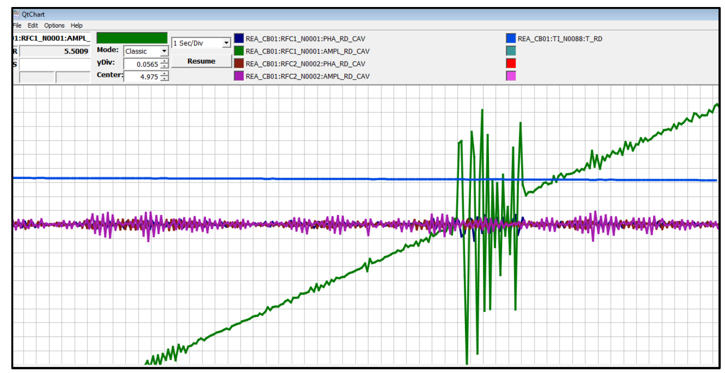
	Gradient	Detuning		Phase		Amplitude	
4.3 K test	E_a (MV/m)	σ (Hz)	pk-pk (Hz)	σ (deg)	pk-pk (deg)	σ (%)	pk-pk (%)
Measured QWR 1	**6.2**	**0.4**	**6.9**	**0.11**	**0.66**	**0.03**	**0.47**
Measured QWR 2	**6.2**	**0.4**	**9.1**	**0.06**	**0.58**	**0.04**	**0.99**
FRIB goal 2 K	5.6	<2.25	<20	<0.25	<2	<0.25	<2

Low Level RF Controller Issues

- Stepper motor driver IC overheating
  - Added fans during initial cavity tests
  - Redesigned stepper board with better thermal management
  - Tested 24 hours continuously with high current (holding, running)

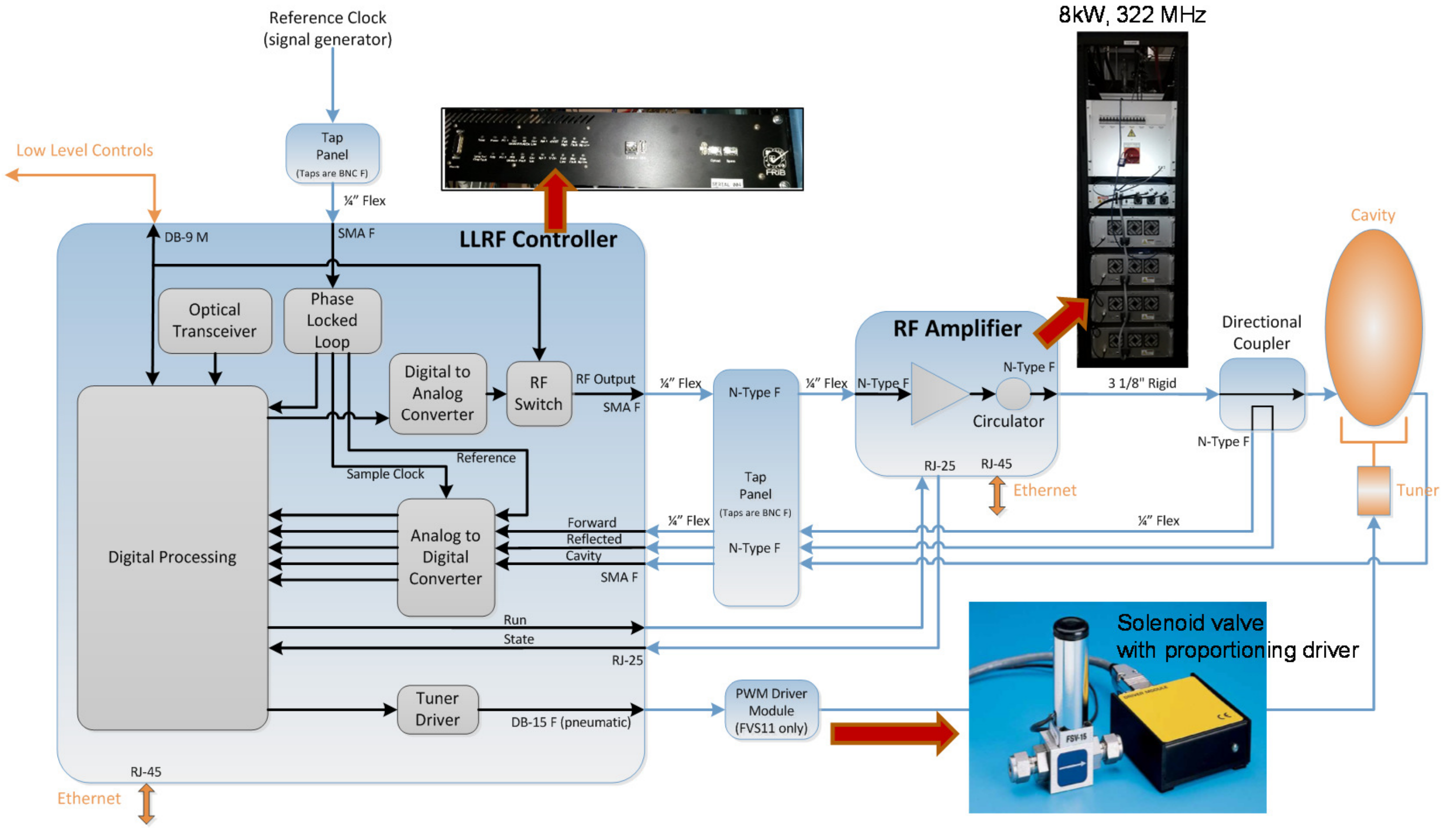


- Control loop internal variable overflow
  - Observed poor control at certain set points and glitches observed during ramping
  - Firmware fixed and verified during cavity tests



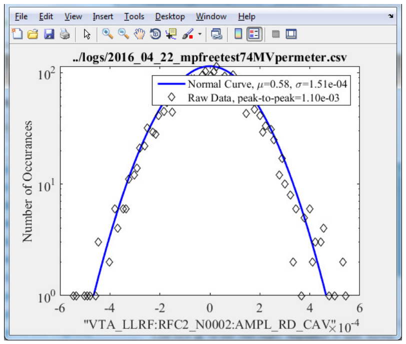
- Amplitude and phase jumps / glitches
  - Infrequent and non-deterministic. Hard to debug
  - Normally fixed by power cycling (resync PLL)
  - Varies with firmware compilation
  - Likely caused by clock domain crossing
    - » All paths need proper timing constraints applied
    - » Make sure all signals crossing clock domains are handled properly (use double latch to avoid race conditions)

HWR Integrated Tests with Pneumatic Tuner

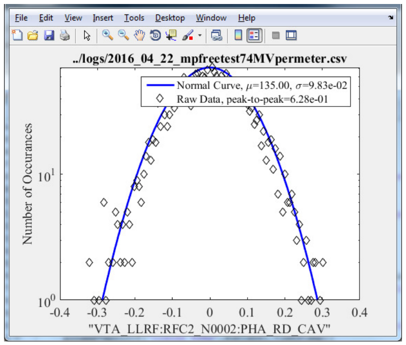


Cavity locked at 7.4 MV/m

Amplitude control
0.17% pk-pk / 0.026% RMS

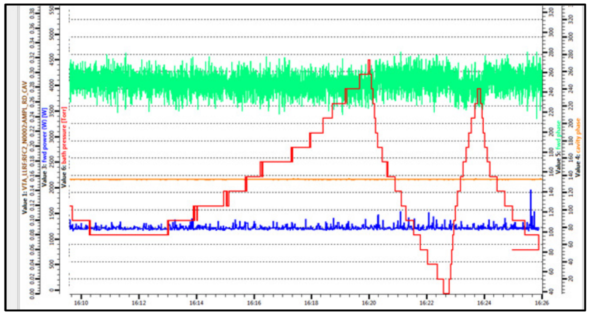


Phase control
0.63 deg pk-pk / 0.1 deg RMS

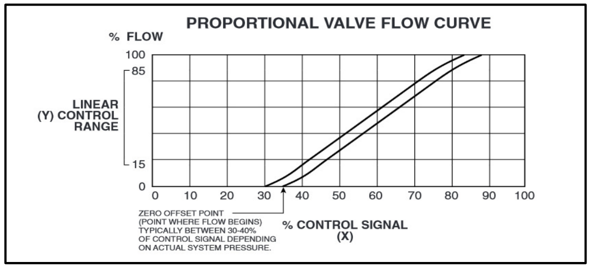


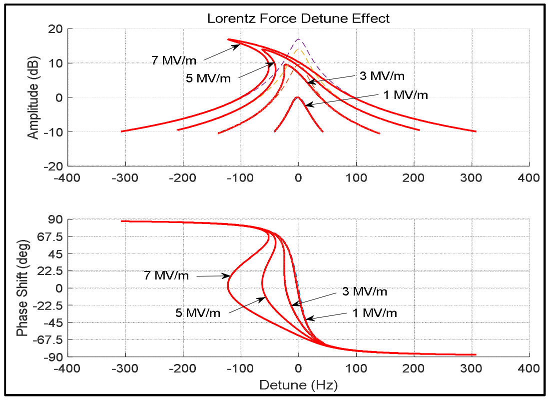
Lessons Learned – HWR Pneumatic Tuner

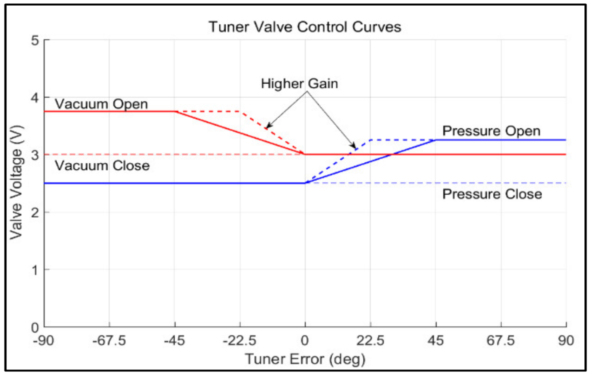
- Tuner tracks changes in pressure; smooth operation
  - No tuner dead zone (stepper motor only)
  - In Dewar, bath pressure is affected by fast changes in RF power
  - Cavities can be locked at high fields directly without ramping
  - Close amplitude loop (in SEL mode) before closing tuner loop
  - Ramp amplitude slowly (up to 2 MV/m/min) with phase locked
  - Phase set point can be changed ±90 degrees without trips



- Valve calibration is based on ANL procedure
  - Minimize dead band with close voltage
  - Adjust to stay near active region (small bleed through)
  - Limit max flow / tuner speed with open voltage
  - Balance vacuum and pressure valves (same speed up/down)

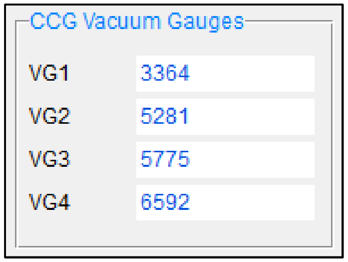




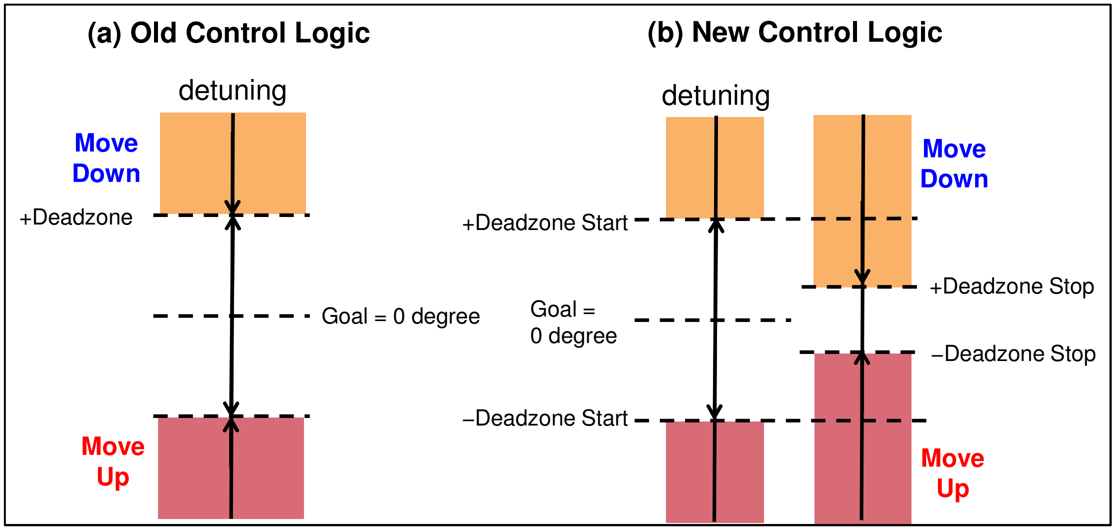


LLRF New Features

- Fast Protection System interface implemented
- Added buffer to Cold Cathode Gauge (CCG) interlock
  - Monitor analog outputs from CCG controllers (0V ~ 10V)
  - Detect increase in pressure due to multipacting in couplers
  - Faster response than Programmable Logic Controller (PLC)
  - LLRF analog input reads ~1.4V if cable is disconnected (indicates good vacuum); not fail-safe
  - Buffer module inverts signal -10V ~ 0V (good range); 1.4V (bad)



- New stepper motor logic
  - Reduce dead zone for stopping
  - More stable operation
  - Tested on SCM811and SCM404

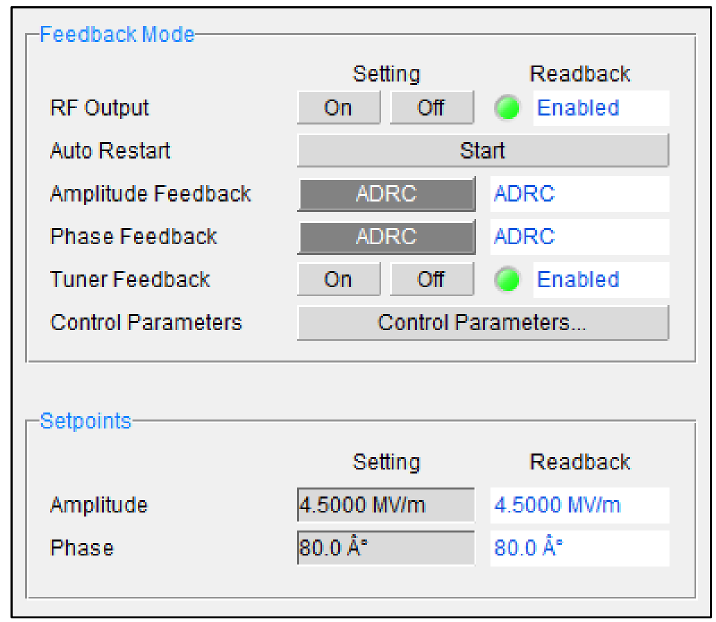


LLRF New Features [2]

- Start assistant
  - Cavity turn on procedure was identified and automated with Start Assistant on the Input / Output Controller (IOC) level to improve operation efficiency
  - For example, Quarter Wave Resonator (QWR) turn on goes through 6 stages automatically, checks for critical interlocks (cavity low, frequency error, etc.), with wait time before ramping to final set-point
  - Verified on ReA3 new LLRF controllers and QWR cryomodule SCM811

QWR Turn On Sequence

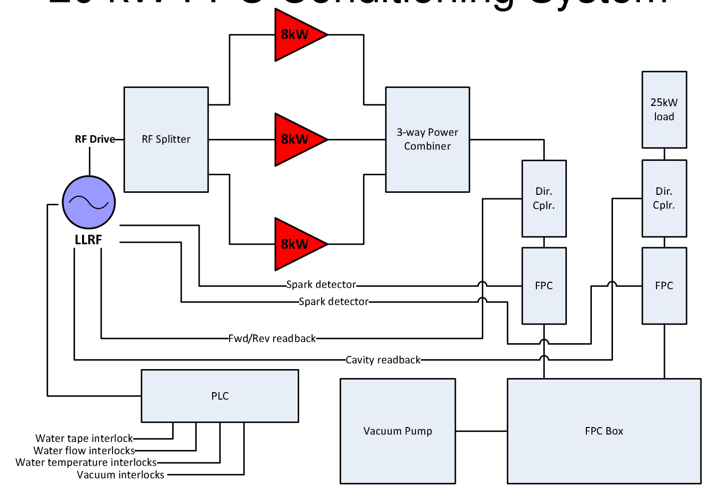
	RF	Amplitude	Amplitude Set-point	Phase	Tuner
Stage 1	**ON**	Open	Initial	SEL	OFF
Stage 2	ON	Open	Initial	SEL	**ON**
Stage 3	ON	Open	Initial	**Open**	ON
Stage 4	ON	**Close**	Initial	Open	ON
Stage 5	ON	Close	Initial	**Close**	ON
Stage 6	ON	Close	**Final**	Close	ON



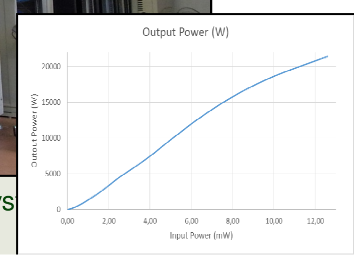
RF Systems Used For SRF Production

- Using FRIB RF amplifiers and LLRF controllers for SRF production
- In cryomodule bunker tests, cavities are locked at least one hour at full FRIB field
  - 15 QWR CMs (104 cavities) tested
    - » 80.5 MHz production completed
  - 5 HWR CMs (32 cavities) tested
    - » 220 HWR cavities total
  - Good opportunity for LLRF and controls development
- Set up two 20 kW fundamental power coupler (FPC) conditioning systems at FRIB and supplier
  - Each system uses three 8 kW amplifiers and an isolated 3-way power combiner
  - FPCs are pulse conditioned up to 20 kW and 20% duty cycle (or 8 kW CW)
  - 220 HWR couplers conditioned in 2 years

20 kW FPC Conditioning System



Installation at Toshiba (Japan)



Summary

- Front end RF systems are commissioned
  - All FE RF devices running simultaneously at or above KPP levels
  - RFQ locked in temperature and frequency control mode
- All 80.5 MHz solid-state amplifiers are installed and tested FE, LS1 and FS1
  - 161 MHz and 322 MHz amplifiers are in production
  - Amplifiers are designed and tested for high reliability
- All low level RF controllers are assembled, programmed, calibrated and installed
- Ready for Device Readiness Review

Thank You!

Acknowledgements

FRIB team, HBH Microwave, John Vincent (Ionetics; formerly at NSCL/FRIB), John Lyles (LANL), Alexander Zaltsman (BNL), Andy Tydeman (TDK-Lambda), Gary Zinkann (ANL), Sergey Sharamentov (ANL), Alberto Facco (INFN), Robert Michnoff (BNL)

Questions?