Recent HPRF Efforts at FRIB

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Outline

- RFQ solid state amplifier (SSA)
  - Design and Testing of Solid State Amplifier for the FRIB RFQ, CWRF 2024
    - » Design, single rack testing, combiner installation
  - The 120 kW solid state amplifier system for the FRIB RFQ, HIAT 2025
    - » All eight racks combined tested into a dummy load at 120 kW
  - Operation since October 2025

- Dual sources for the ion sources to boost performance
  - Added a 28 GHz gyrotron for HP ECR
  - Adding a 10 ~ 13 GHz solid state amplifier for the ARTEMIS B

FRIB Linac Uses Solid State Amplifier Only

- FRIB SSA Types
  - Total number of drawers: 960 (80.5 MHz: 200; 161 MHz: 24; 322 MHz: 736)
  - Number of years in service: ~6 years on average
  - High availability
    - » 2021: 99.9%; 2022: 99.8%; 2023: 99.7%; 2025: 99.7%

Type	Frequency (MHz)	# of drawers per amplifier	Cavities	Note
1	80.5	1	QWR (0.041)	CA
2	80.5	2	QWR (0.085)	CB, CH
3	80.5	4	RFQ	Driver amplifier for the tetrode
4	322	2	HWR (0.29)	CC
5	322	4	HWR (0.53)	CD, CG
6	161	4	MGB	Upgraded to type 8 in Sep. 2024
8	161	6	MGB	Two more drawers in each rack
9	**80.5**	**6**	**RFQ**	**8-rack system (120 kW)**
10	644	4	Upgrade elliptical cavity	New drawer/rack design (20 kW)

Mean time between failure (MTBF)

$$MTBF_{Rack} = 166,750 \ [h]$$

$$MTBF_{PA\ Unit} = 952,857 \ [h]$$

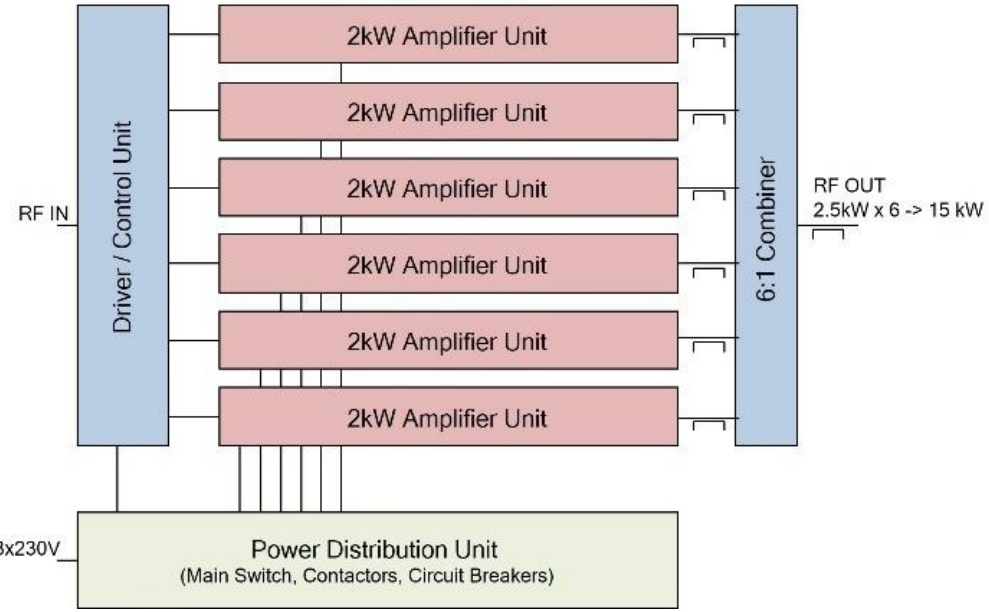
$$MTBF_{DCU} = 833,750 \ [h]$$

$$MTBF_{PDU} = 1,667,500 \ [h]$$

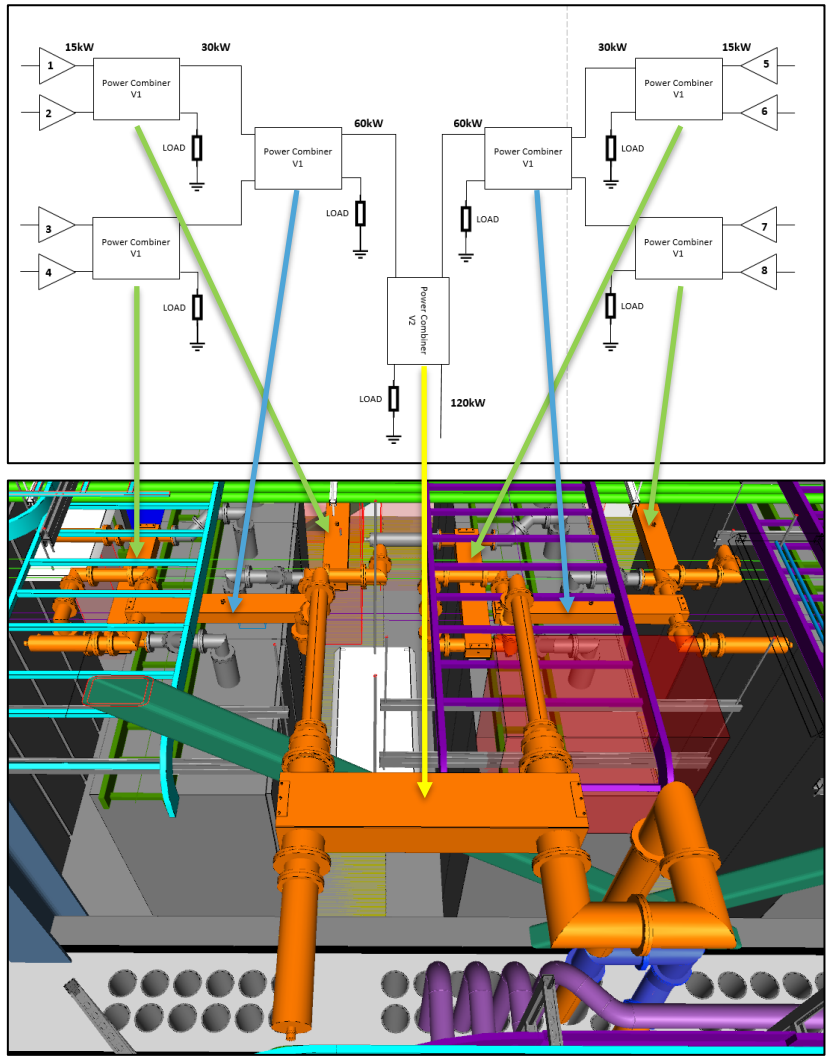
PA: Power Amplifier
DCU: Drive Control Unit
PDU: Power Distribution Unit

The RFQ SSA Design

- Rack level
  - Total power of 15 kW
  - Six drawers per rack
  - 2.5 kW per drawer (into matched load)



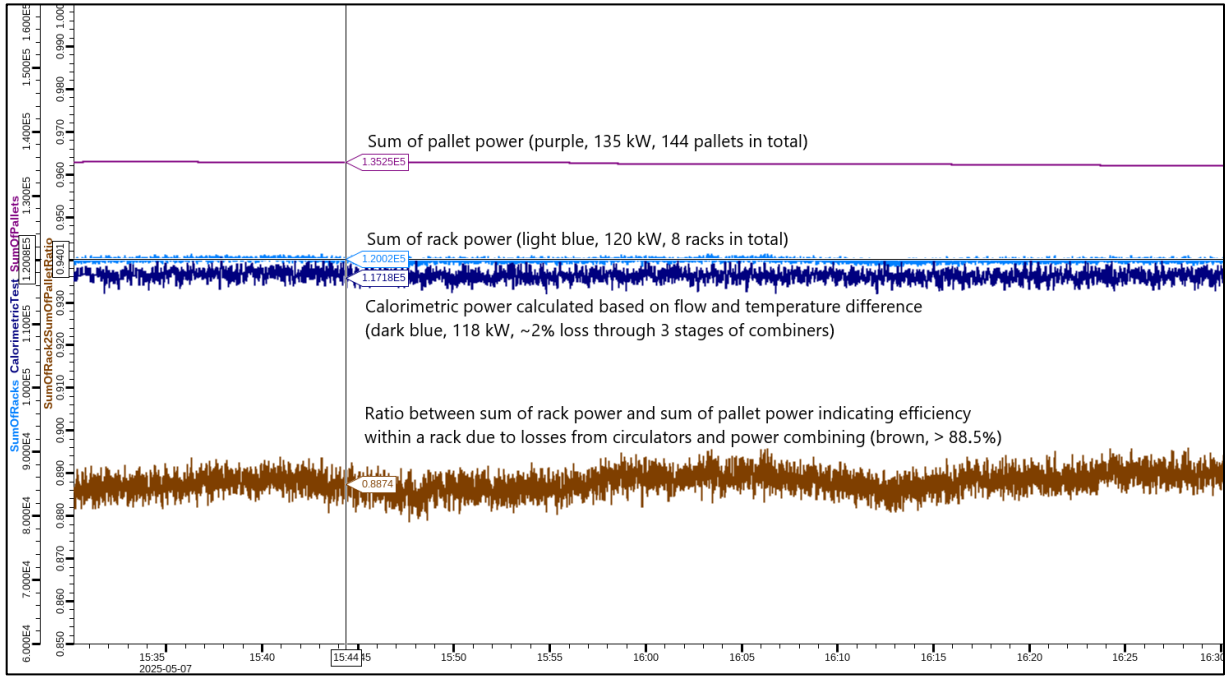
- System level
  - Total power of 120 kW
  - Eight racks in total
  - Three stages of combining



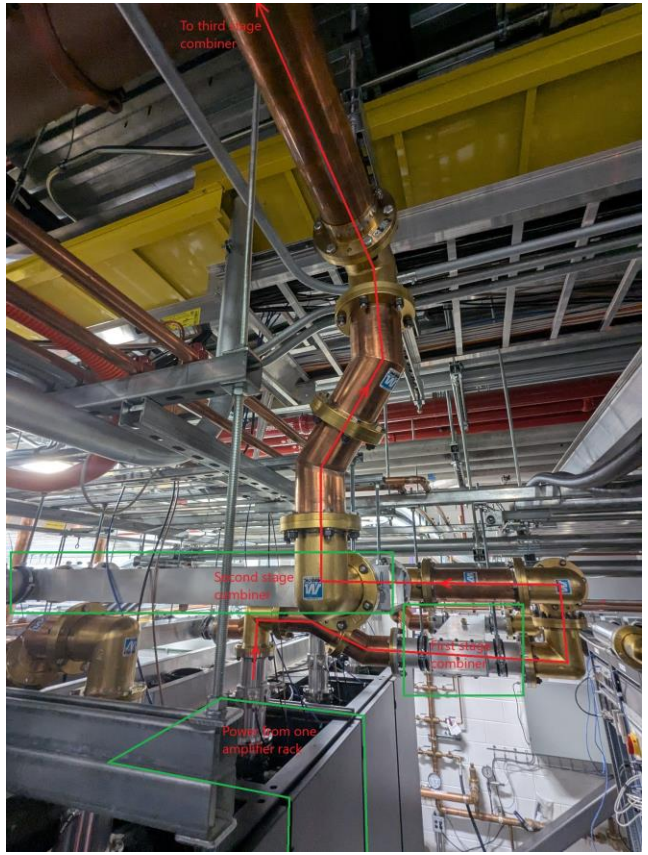
RFQ SSA Tested into a Load

- RFQ solid state amplifier has been tested into a dummy load at 120 kW output power
  - U^{35+} beam needs 92.5 kW, U^{34+} beam needs 98 kW

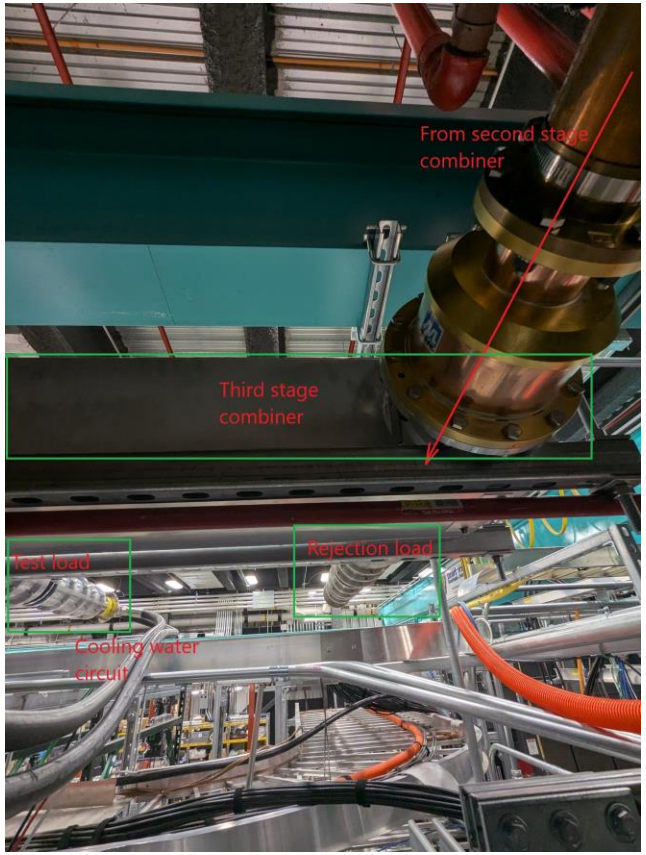
SSA with total combiner efficiency > 86.7%



Stage I / II Combiners



Stage III Combiner



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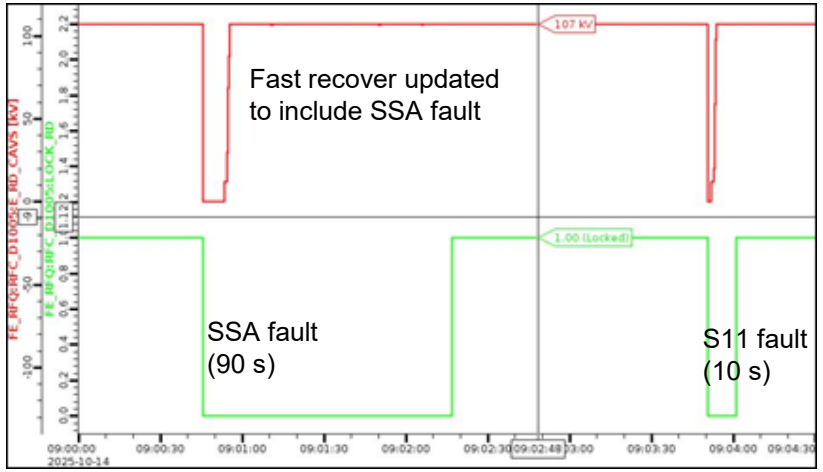
Early Issues Addressed Before Operation Started

- Drawer drain voltage low interlock
  - Nine instances from Oct. 4th to Oct. 7th caused a total of two hours and 48 minutes of downtime (table below)
    - » 20 minutes on average for each instance due to RFQ slow frequency control
  - Resolution
    - » Fast-recover update (deployed on October 14th)
      - Previously only recover for S11 and reverse power high cases
      - Now add SSA fault, reduce recover time from 20 minutes to two minutes
    - » Call emergency meeting with vendor
      - Lowered the drain voltage low threshold from 95% to 85% of nominal value (48 V)
      - Not a single drain voltage low interlock afterward
      - Still exploring software filtering solution

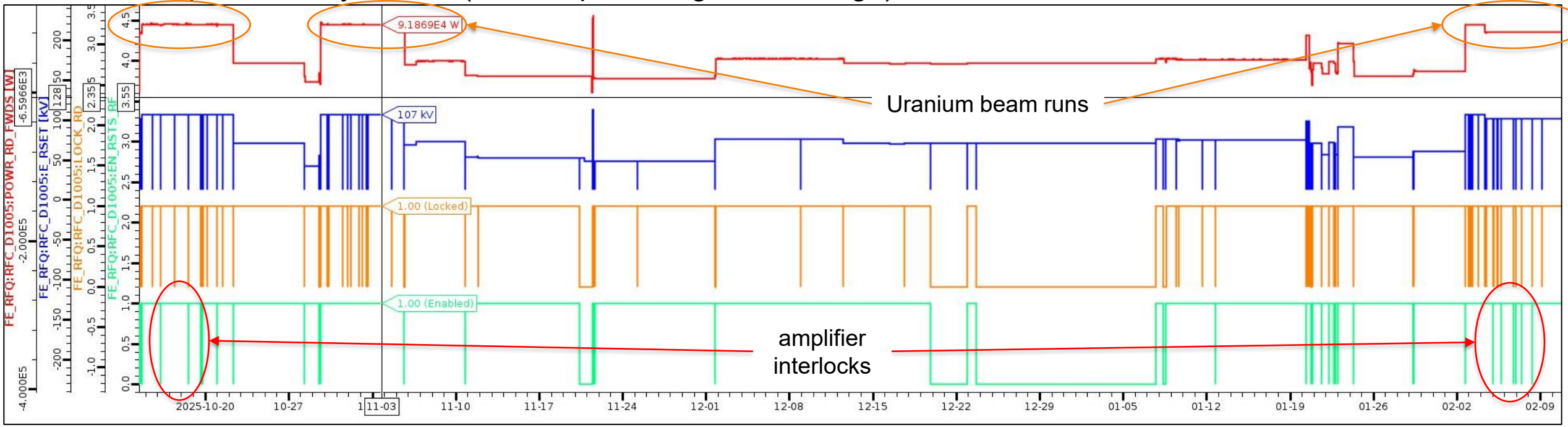


- Drawer drain current high interlock
  - Two instances as of Oct. 11th
- ReA RFQ tetrode issues
  - Anode power supply (48 hrs)
  - RF fingers burnt (31 hrs)

Start Date/Time	End Date/Time	Duration	D#	TR	Category	Description
10/4/2025 14:56	10/4/2025 15:29	0:33:00	D1005	61281	HPRF	RFQ SSA rack 8 drawer 1 pallet 3 drain voltage low interlock
10/4/2025 21:33	10/4/2025 21:50	0:17:00	D1005	61281	HPRF	RFQ SSA rack 4 drawer 1 pallet 3 drain voltage low interlock
10/5/2025 0:36	10/5/2025 0:48	0:12:00	D1005	61281	HPRF	RFQ SSA rack 8 drawer 1 pallet 3 drain voltage low interlock
10/6/2025 4:06	10/6/2025 4:29	0:23:00	D1005	61281	HPRF	RFQ SSA rack 2 drawer 2 pallet 3 drain voltage low interlock
10/6/2025 6:53	10/6/2025 7:11	0:18:00	D1005	61281	HPRF	RFQ SSA rack 5 drawer 6 pallet 3 drain voltage low interlock
10/6/2025 8:45	10/6/2025 9:01	0:16:00	D1005	61281	HPRF	RFQ SSA rack 5 drawer 1 pallet 3 drain voltage low interlock
10/6/2025 18:39	10/6/2025 18:56	0:17:00	D1005	61281	HPRF	RFQ SSA rack 2 drawer 2 pallet 3 drain voltage low interlock
10/7/2025 8:16	10/7/2025 8:32	0:16:00	D1005	61281	HPRF	RFQ SSA rack 4 drawer 5 pallet 3 drain voltage low interlock
10/7/2025 11:21	10/7/2025 11:37	0:16:00	D1005	61281	HPRF	RFQ SSA rack 6 drawer 5 pallet 3 drain voltage low interlock

Operation Experience Since October 2025

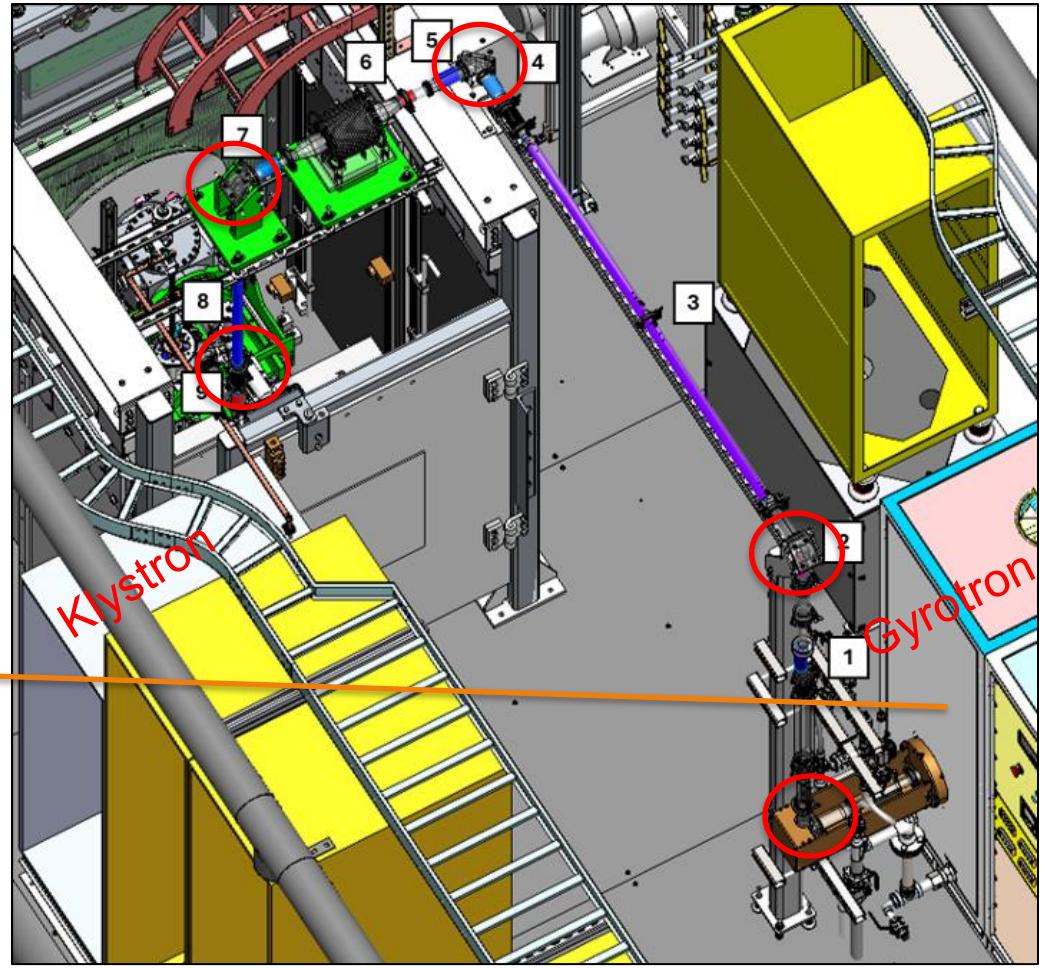
- October 14th until today
  - 120 calendar days including 19 days of winter shutdown/maintenance, 2424 hours of operation
  - 9 trips due to amplifier interlock (drain current high, likely noise) causing less than 20 minutes (0.015%) downtime in total with the help of auto-recovery
    - » All happened during Uranium beam runs (power > 90 kW)
    - » Other trips are cavity related (reverse power high or S11 high)



A 28 GHz Gyrotron was Installed as a Second RF Source for the HP ECR

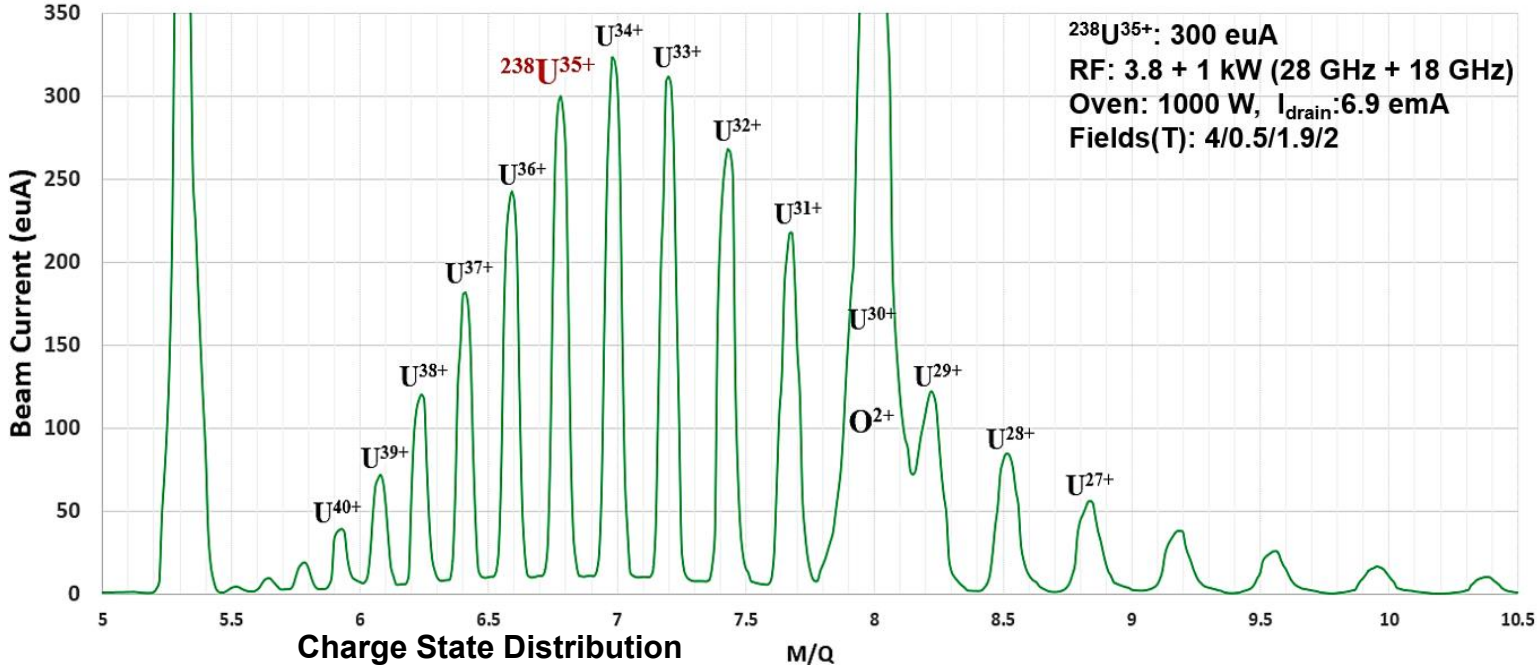
- FRIB has two ion sources
  - HP ECR
  - ARTEMIS B (ARTEMIS A is for the K500 cyclotron)
- To fit the HPECR high voltage platform layout, five bends are used from the gyrotron to the ion source, 28 GHz transmission line is more complex than other facilities
- Dual RF sources
  - 28 GHz gyrotron
    - » 10 kW, CPI turn-key
  - 18 GHz klystron
    - » 2 kW, in-house system design

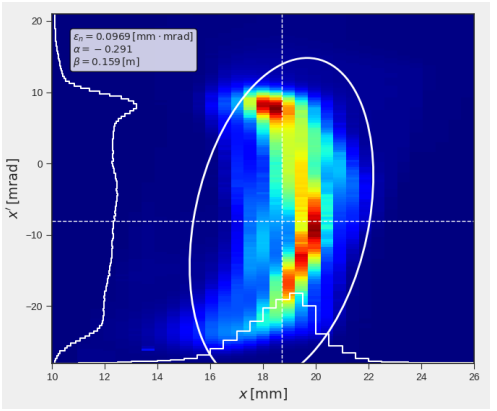
Gyrotron Transmission Line Layout



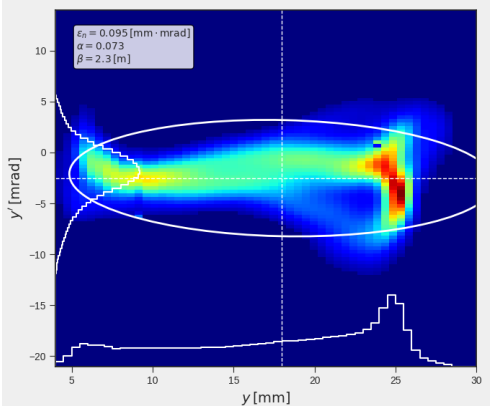
Demonstrated 300 eμA of U^{35+} Meet FRIB 400 kW Operations

- 300 eμA U^{35+} was produced with 3.8 kW of 28 GHz plus 1 kW of 18 GHz
  - 323 eμA U^{34+}, 310 eμA U^{33+}
- Meet 200 kW (one charge state) and 400 kW (two charge states) operations
- Emittance meets the requirements by optimizing ion source parameters
  - 28 GHz, 260 eμA, X: 0.097 (< 0.1) π mm-mrad Y: 0.095 (< 0.1) π mm-mrad





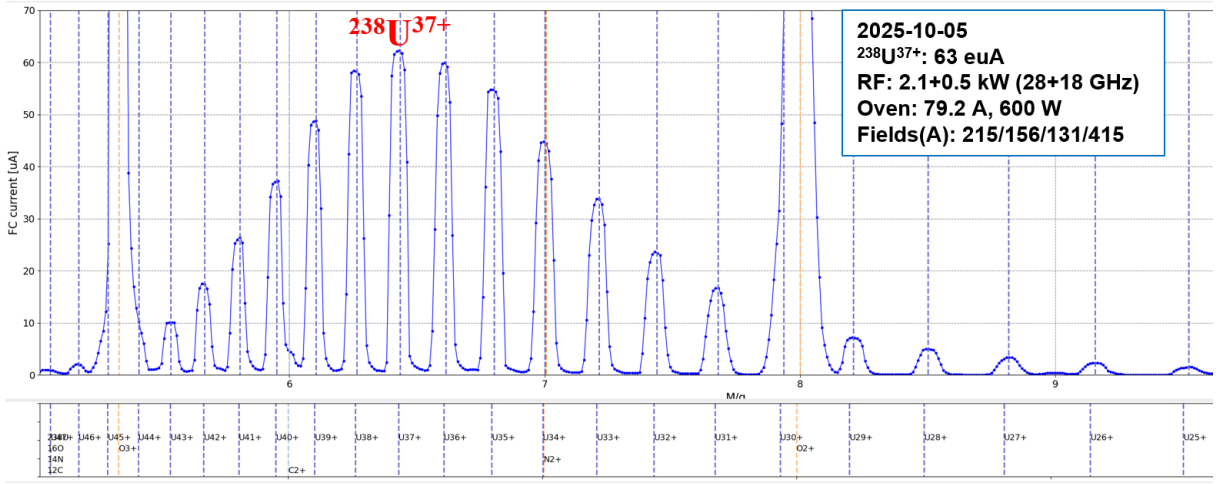
X: 0.097 π mm- mrad



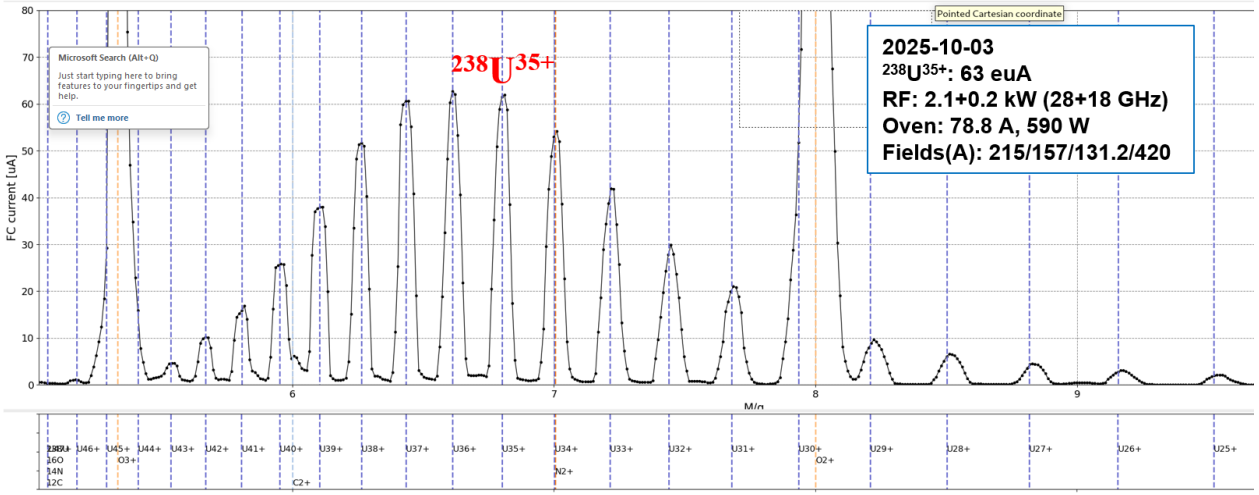
Y: 0.095 π mm-mrad

HP ECR Started 28 GHz Operations Since September 2025 Demonstrated Excellent Stability

- HPECR operates in a dual-frequency mode at 28 GHz + 18 GHz, typical power of 2.1 + 0.5 kW
- Provided 60 eμA of $^{238}U^{37+}$ supported FRIB operation at 20 kW with 194 MeV/u
- Provided 60 eμA of $^{238}U^{35+}$ supported FRIB operation at 30 kW with 177 MeV/u
- Had one hour downtime, the issue has been addressed with improvements
  - The gyrotron tripped due to a water flow spike in the waveguide
    - » The interlock delays have been optimized; increased water flow by adjusting the configuration



Charge State Distribution



Charge State Distribution

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Second RF Source for ARTEMIS B

- Solid state amplifier
  - Frequency: 10 GHz ~ 13 GHz
  - Power: 400 W
  - Gain: 56 dB min
  - Mode: continuous wave only
  - Cooling: air-cooled, internal coolant circulation
  - Dimension: 19” rack 8U
- Tests completed
  - Full power (400+ W) at various frequencies
  - Interlock
    - » **External interlock**
    - » **Over forward**
    - » Over current
    - » Over input
    - » **VSWR alarm**
    - » Voltage alarm
    - » Temperature alarm
- To be installed within two months (April 2026)

Control

	Setting		Readback
Power On/Off	On	Off	ON
Error			OK
Clear Error Log	Clear		
ALC On/Off	On	Off	ON
ALC (dBm)	40.000 dBm		40.000 dBm
Attenuation (dB)	20.000 dB		20.000 dB
Frequency (MHz)	10000.000 MHz		10000.000 MHz
Sys Restart	Restart		
Sys Fault Function	On	Off	ON
Verbose			OFF

Readings

	Readback		C
Voltage HPA	42.450 V	Sys Temp	29.120 C
Voltage +5V	5.030 V	Heatsink Temp	32.070 C
Current Drive	0.850 A	HPA 1 Temp	34.640 C
Current HPA 1	8.830 A	HPA 2 Temp	0.000 C
Current HPA 2	8.920 A	HPA 3 Temp	34.440 C
Current HPA 3	8.730 A	HPA 4 Temp	0.000 C
Current HPA 4	9.470 A		
Input Power (dBm)	-11.970 dBm	OK	
S11	0.048	OK	
Forward Power (W)	9.990 W	OK	
Reflected Power (W)	0.020 W	OK	