FRIB Construction, Commissioning, and Operation Status Update

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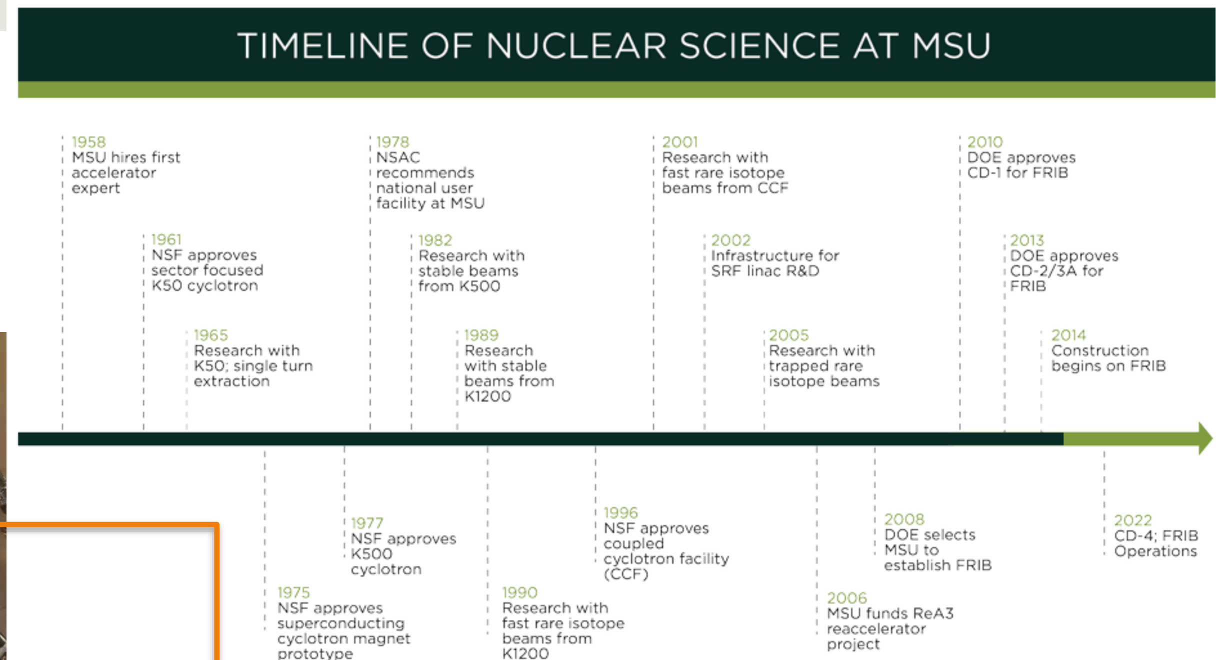
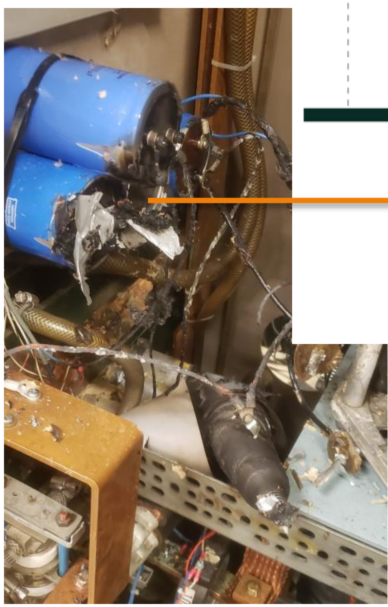
Outline

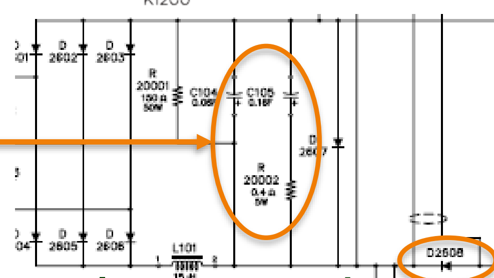
- History
  - NSCL
  - FRIB construction and commissioning
- FRIB Operations
  - Scope
  - Priorities
  - Availability and breakdowns
  - Improvement and mitigation plans
- FRIB Power Supply (PS) approach to high availability
- PS installation and testing procedures, training, and checklists
- Miscellaneous project updates

NSCL History

55 Years of Beam Prior to Nov 2020 Reconfiguration to FRIB







- Sept-Oct 2020, K1200 Cyclotron Main Magnet Power Supply
  - Repeated intermittent DC bus filter cap failures, ~1 week total downtime
  - Root cause determined to be intermittent blocking diode short, 30 MJ in magnet

FRIB User Operations Started in May 2022

CD-4 in April 2022 Followed by Ribbon Cutting on May 2, 2022

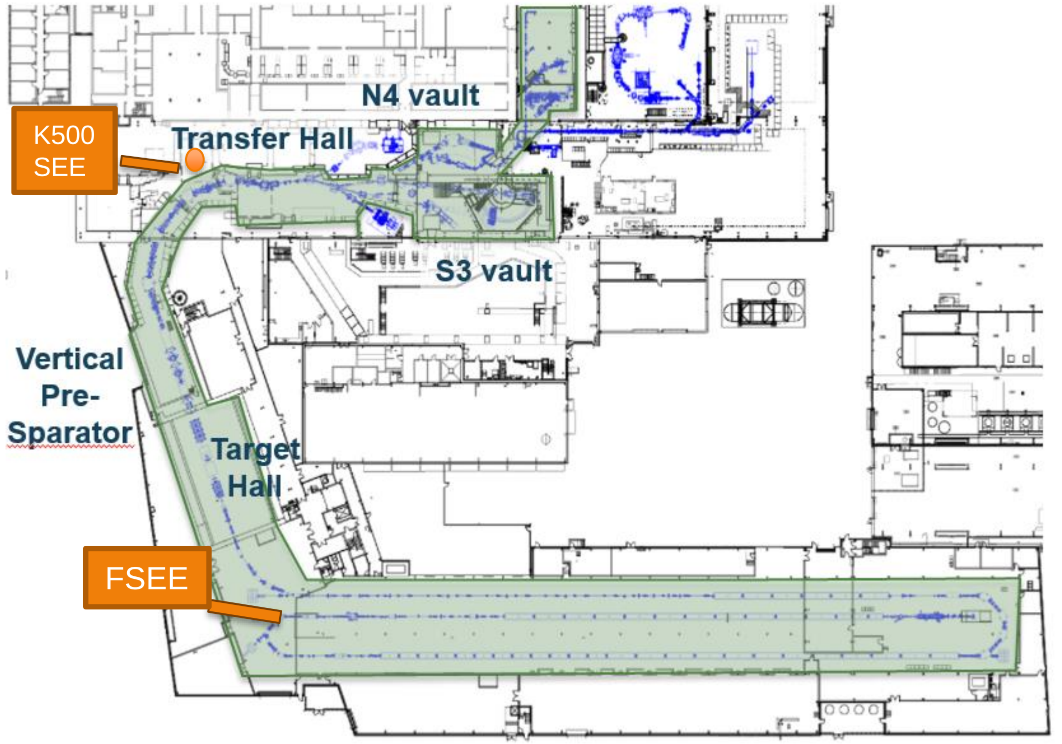
FRIB driver linac in accelerator tunnel

Milestones	Date
DOE and MSU cooperative agreement	Jun 2009
CD-1: preferred alternatives decided	Sep 2010
CD-2/CD-3a: performance baseline, start of civil construction & long lead procurement	Aug 2013
CD-3b: start of technical construction	Aug 2014
FRIB linac construction completion	May 2021
Project technical construction completion	Jan 2022
CD-4: project completion	Apr 2022
Start of scientific user experiments	May 2022

FRIB ribbon cutting ceremony

FRIB Operations
Power Supply Scope and FRIB Priorities

- Over 1500 power supplies (PS) and PS ancillary equipment
- FRIB Overall Priorities
  - Safe operations
  - Operate with >85% availability to maintain user satisfaction
    - » Steadily increase machine availability at planned operating hours
    - » Keep PS availability high to support FRIB meet availability requirements
  - Support ramp up of beam power and automation
    - » Provide engineering and maintenance support
  - **Additional FSEE ~ 2000 hours yearly
    - » Revive K500 for SEE users in coming years



Year	FY23	FY24	FY25	FY26	FY27	FY28
Beam power [kW]	10	20	50	100	200	400
Operating hours [hour]**	4100	4250	4350	4400	4400	4400
Availability [%]	80	82	84	85	85	85

Power Supplies Achieving High Availability

Addressing PS Breakdowns

Power Supplies (PS) Operational Availability

FY	Operational Time (hrs)	# Incidents	PS Downtime (hrs)	PS Availability (%)
2019	895	7	2.6	99.7
2020	1201	5	5.5	99.5
2021	1749	6	8.1	99.5
2022	4518	20	23.3	99.5
2023	2941	4	5.4	99.8

Note: the number of PS in operations has grown exponentially in the past 5 years

System	PS Systems Breakdowns (2022-2023)	UOF (minutes)	Improvements / Preventive Action
SCM PS	**(6) Suspected PS re-boots (4 TRs for 1 PS, 2 for others)**	**500**	**TBD pending root cause. Recently swapped 1 PS.**
RTM PS	**(3) PS internal network PCB failures**	**386**	**1) Monitor failure rates to determine if these are pre-mature failures or systemic. 2)Received replacement PCBs, repair in house.**
SCM PS	(1) Internal bulk AC/DC PS failure (2 trouble reports for same PS)	93 + 226	Spare bulk PS received. Improve operator training.
RTM PS	(1) Blank screen	131	Verified adequate spares
HV PS	(1) Chopper HV PS DOA	120	Increase spare Qty
Legacy SCM PS	(1) Tripped off during lab wide AC power brown out	61	Replace legacy PS with FRIB type PS
SCM PS / RTM PS	(1) Communication to several PS not re-established after IOC restart	51	Verify communication is re-established after IOC restart
RTM PS	(1) Breaker left in off position after maintenance	29	Verify PS operational
RTM PS	(1) multiple PS ramped to 0 A	27	IOC bug fixed
RTM PS	(1) Internal over temperature interlock	24	Verified adequate spares
SCM PS	(1) Employee bumped PS on/off switch	14	Rope off rack isles

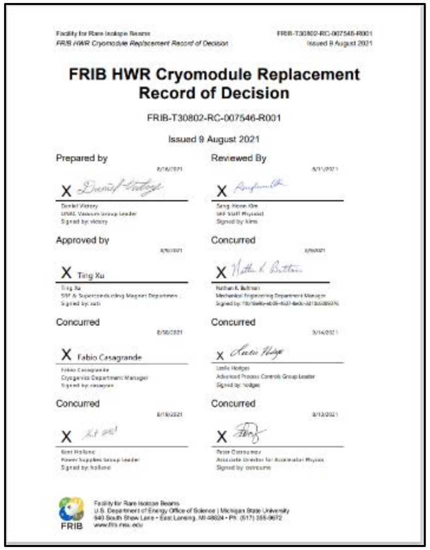
Improving PS Reliability, Safety, Cost of Ownership, and Digital Hygiene for Operations

- Replace legacy NSCL PS to FRIB standard types with goal of maximizing reliability, lowering cost of ownership, and improving digital hygiene
  - Commissioned 91 PS over the past year
    - Transfer tall, S800 beamline, N4 Vault
  - Installation of 23 PS in progress
    - S1/S2 vault and S800 Dipole PS
  - 62 power supplies procured for upcoming projects
    - Cyc Stopper, ReA
  - Planning for remaining legacy RTM and HV PS
    - 80 PS for K500 SEE project - legacy replacements procurement imminent
    - Consolidate using FRIB types where possible and eliminate obsolete power supplies
- CM slow dump diodes prototyped
  - Prevent energy dissipating into cold diodes (faster recovery)
- Improvements
  - Simplify by eliminating parallel polarity reversal switches and parallel ground fault detection (hard to troubleshoot)
  - Planning water system improvements (replace barb + hose clamp with compression fittings)

S800 Beamline PS (located in S800 Vault)

Mitigating Operations Single-point Failures
Example: Magnet Raft

- Mitigation for cryomodule (CM) failure (T30802-RC-007546)
  - If a CM fails, room-temperature (RT) magnet raft will be installed in place of first CM
  - First CM then spare. Subsystems at first CM need to accommodate the raft
    - » This includes power supplies, control systems, water lines, etc.
- PS and DC cable installation in progress to accommodate the RT magnets
  - DC cables and tunnel DC junction, install summer 23
  - Magnet raft terminal blocks and magnet wiring in process
  - PS installed



FRIB HWR Cryomodule Replacement Record of Decision

FRIB-T30802-RC-007546-R001

Issued 9 August 2021

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Concurred — X

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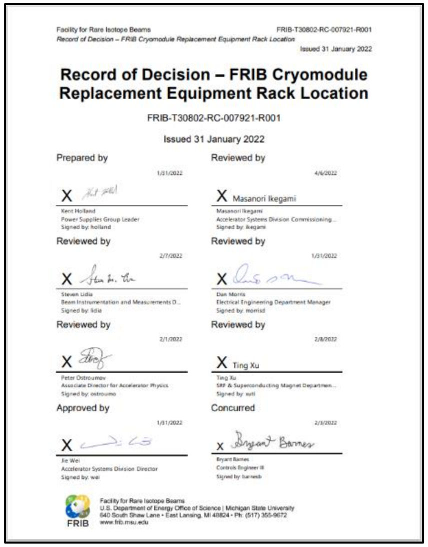

Facility for Rare Isotope Beams FRIB-T30802-RC-007921-R001
Record of Decision – FRIB Cryomodule Replacement Equipment Rack Location
Issued 31 January 2022

Record of Decision – FRIB Cryomodule Replacement Equipment Rack Location

FRIB-T30802-RC-007921-R001

Issued 31 January 2022

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RT Magnet Raft

Fast MPS DCCTs for Higher Power Operation

Monitor Current on Dipole Magnet PS Mitigating Mis-Steering

DCCTS

Name	DCCT Mode	FPS Alarm	Enable/Disable Acquisition Setting	Enable/Disable Acquisition Readback	FPS Alarm Clear	Possitive Threshold Setting	Possitive Threshold Readback	Negative Threshold Setting	Negative Threshold Readback	Current Actual	Current Base	
FS1 CSS DCCT D2163	OSC	NOT-OK	ARM DISARM	DISARMED	CLR	0.00000	0.00000	0.00000	0.00000	0.00000 A	0.00000 A	More...
FS1 BBS DCCT D2394	OSC	NOT-OK	ARM DISARM	DISARMED	CLR	0.00000	0.00000	0.00000	0.00000	0.00000 A	0.00000 A	More...
FS2 BBS DCCT D3979	FPS	OK	ARM DISARM	ARMED	CLR	0.63000	0.63000	0.63000	0.63000	-115.84874 A	-115.84647 A	More...
FS2 BBS DCCT D4034	FPS	OK	ARM DISARM	ARMED	CLR	0.63000	0.63000	0.63000	0.63000	-116.30619 A	-116.30526 A	More...
FS2 BBS DCCT D4072	FPS	OK	ARM DISARM	ARMED	CLR	0.63000	0.63000	0.63000	0.63000	-115.22385 A	-115.22151 A	More...
FS2 BBS DCCT D4127	FPS	OK	ARM DISARM	ARMED	CLR	0.63000	0.63000	0.63000	0.63000	-115.65178 A	-115.64647 A	More...
BDS BBS DCCT D5578	FPS	OK	ARM DISARM	ARMED	CLR	0.10340	0.10340	0.10340	0.10340	-54.78240 A	-54.93647 A	More...
FS F1S1 DCCT D1064	FPS	OK	ARM DISARM	ARMED	CLR	0.26860	0.26860	0.26860	0.26860	134.25253 A	134.25378 A	More...

- Precision fast DCCTs monitor PS current, trip beam off
  - Fast MPS DCCTs for dipoles
    - » DCCTs can be armed when PS reaches set-point
    - » Once armed the DCCT sets a baseline based on average current
    - » Thresholds, sampling rate, and sensitivity are pre-programmed
      - Sampling rate can be set as low as 10 us
      - Sensitivity is the number of consecutive bad samples before triggering MPS
      - Thresholds are set around the baseline current, if the actual current exceeds the thresholds a signal is sent to trigger MPS
    - » Commissioned FS2 to target beam dump
    - » Installed (not yet connected to MPS) FS1
    - » Recently added post-mortem waveform

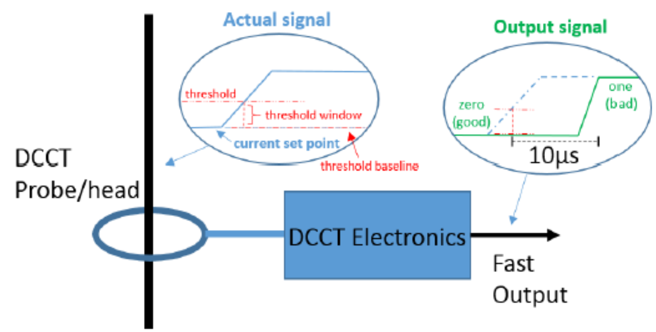
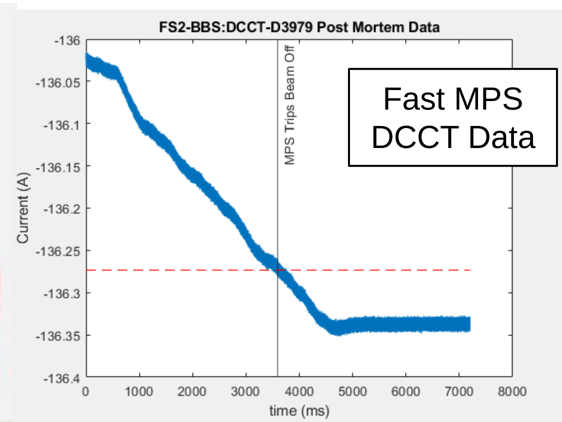


Figure 4-2 Signal Latency Requirement (10µs)



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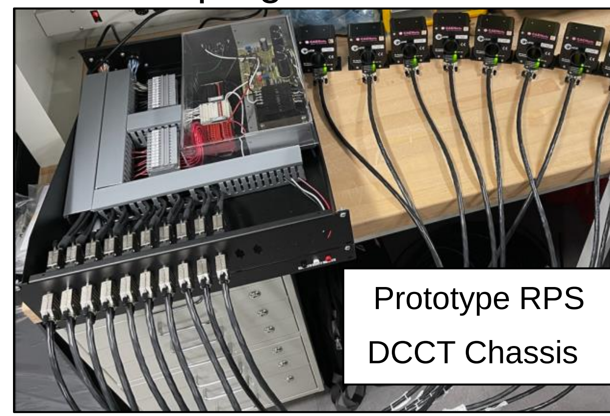
U.S. Department of
Michigan State Univ

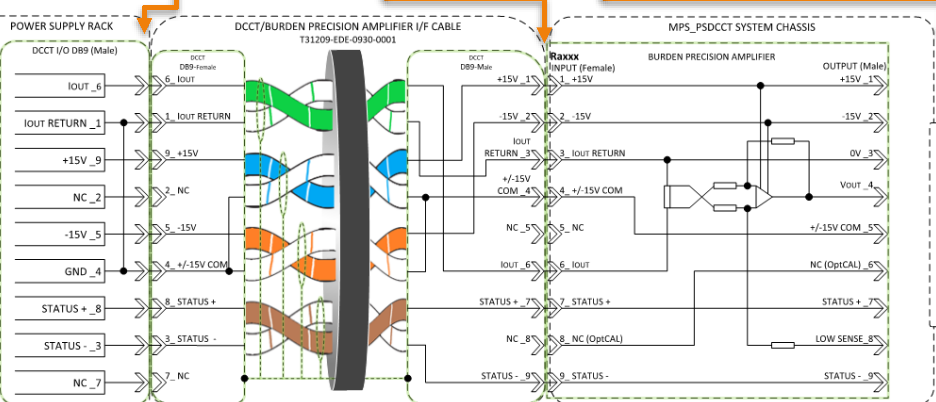
RPS DCCTs for Higher Power Operation

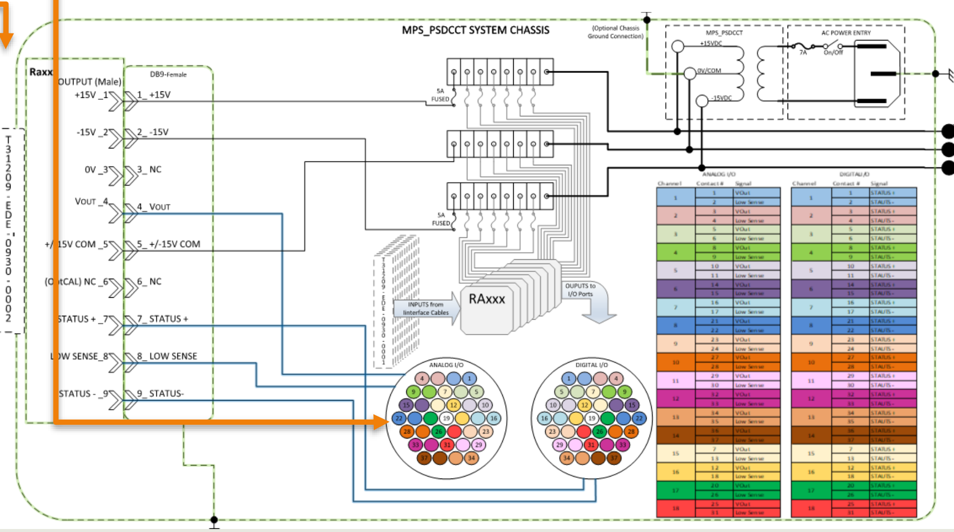
Preparing Current Monitoring on Multipole Magnet PS to Mitigate Mis-Focusing

- Run Permit System (RPS) DCCTs for multipoles
  - Extending magnet current monitoring, first BDS dipole through target beam dump, summer 2023
  - Monitored by PLC (not part of MPS), PLC logic and CSS screens will be programed to mimic the fast MPS DCCTs
    - » Sampling rate ~100 ms (PLC scan time) vs 10 us
    - » Removes run permit if threshold crossed
  - Current output DCCTs
    - » PS are scattered far from PLC, current output for signal integrity
    - » Current output also upgradable to fast MPS
  - 16 Ch. Burden resistor chassis marshal signals at the PLC
    - » Precision Burden resistor amplifiers convert to +-10 Vdc
  - Test boxes; before DCCT/PLC connection, troubleshoot ops
    - » TPs to measure/inject: +/-15V, I/V signal, status. 3 selectable shunts. Push buttons test status. Pass-thru.
    - » DCCT, Burden in, Burden out, Marshal chassis out.



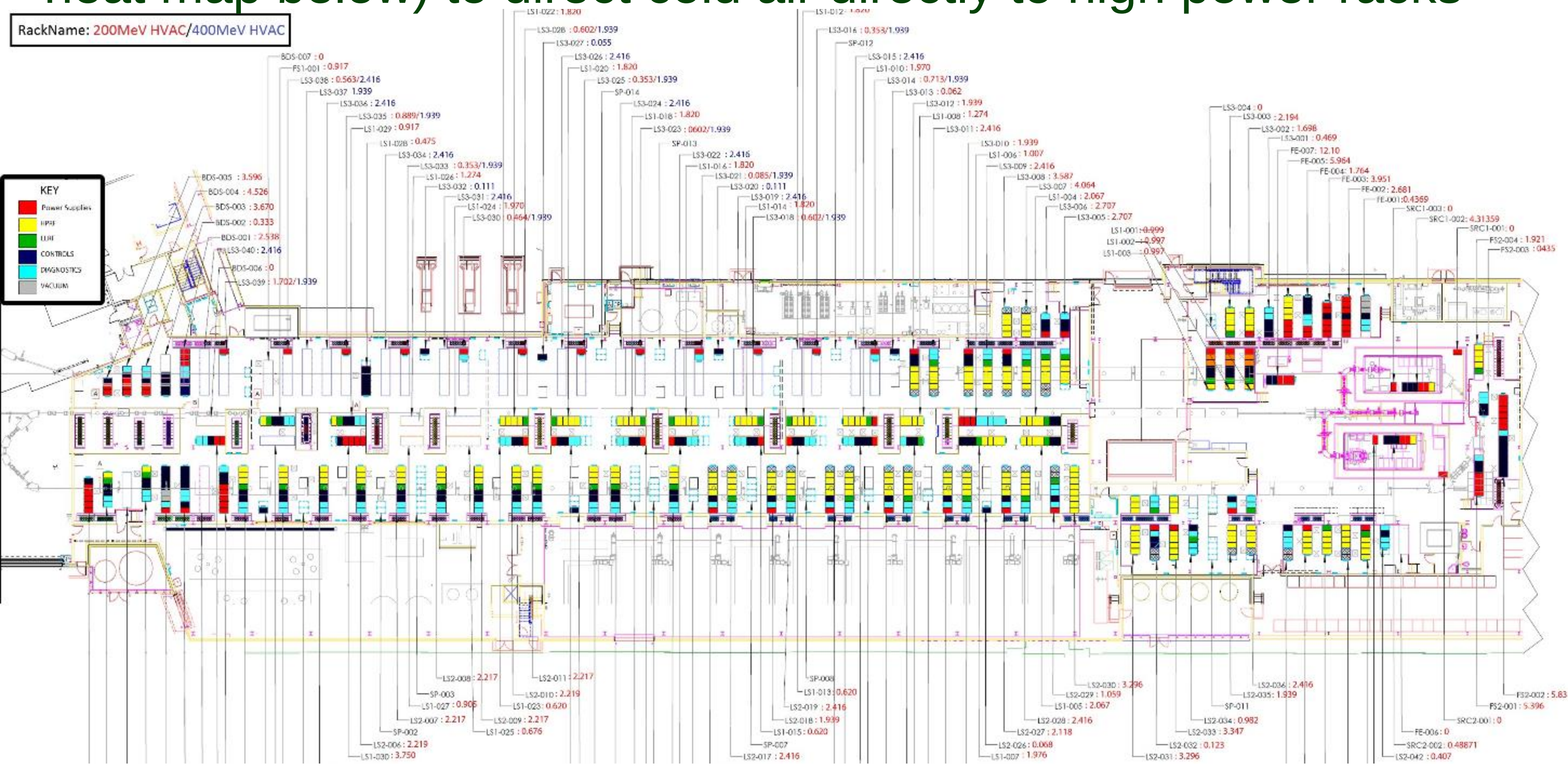
Prototype RPS DCCT Chassis





FRIB Approach to High Availability
Design: Rack Room Cooling

- Server room type raised floor with vents strategically located (per heat map below) to direct cold air directly to high power racks



FRIB Approach to High Availability
Design: Stakeholder Agreement on Margin

- Margin included in the parameter list / requirements documents
  - Physicist 'Tuning margin'
    - » Typically 10% added to multipoles, and 5% added to dipoles
    - » Added to the field requirement, as necessary, to ensure project specifications are met. Important for magnets that operate with saturated steel, where 10% >current ≠ 10% field
  - 'Magnet design margin'
    - » Magnet design margin is added as necessary to account for slight differences in as built magnet, from steel performance, etc.
    - » Magnet engineer provides current and voltage requirements, which include 'built-in' tuning and magnet margin.
  - PS 'Operational margin'
    - » Operational margin is added as necessary to the voltage and current to improve long term reliability.
      - RT magnet PS are off the shelf, and should run at <80% max power to increase long term reliability.
        - » <80% of max power, 'rule-of-thumb' for 5 year warranty
        - » Increase margin for shorter warranties
      - SC magnet PS are custom build to spec.
        - » FRIB specifies built-in operational margin to run continuously at maximum power (see next slide)
        - » SC magnet PS only run at max power during ramping, the power drops off significantly when regulating at low voltage
- Recent margin example in backup

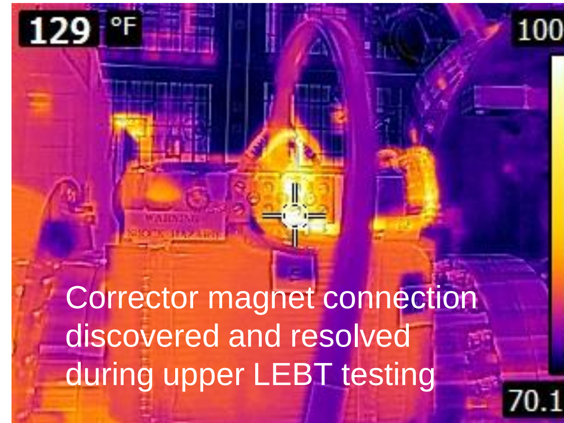
FRIB Approach to High Availability
Design: FRIB Specifies Built-in Margin for Custom PS

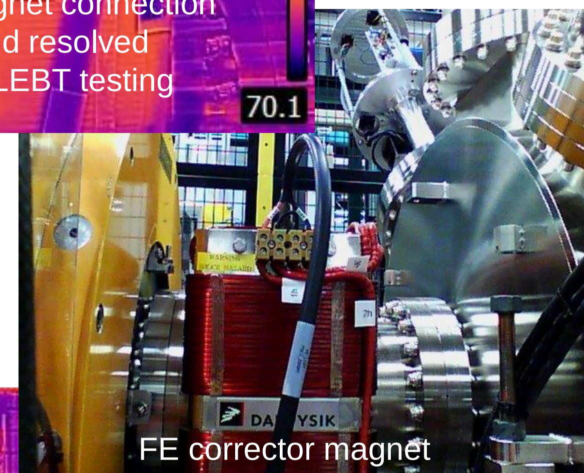
- PS Statement of Work (SOW)
  - Custom PS
    - Clearly define operating conditions (DC, pulsed, etc.)
    - Include margin in specifications, examples from recent SCM PS SOW
      - Dump resistor: shall be rated to dissipate the stored energy in the magnet plus ≥20% margin, thermal calculations shall be proven by testing without airflow. Include methods to prevent repetitive energy dumps which could potentially overheat and damage the resistors. Include thermal switch.
      - Hardwired fail safe external interlock. Redundant functions to guarantee the output of the PS is off when interlocked off.
      - PS Self-protection: PS shall have internal interlocks suitable to protect itself against adverse conditions such as over temperature, over voltage, over current, high output ripple, ground fault, DCCT status, etc.
      - PS response to fault scenarios: loss of network watchdog, AC power hold-up-time, AC line fluctuations
      - DC output withstand voltage ≥50% margin on dump voltage
      - Worst case environmental conditions: air temperature and humidity range, air filters, air flow direction. LCW temperature range, pressure, documented pressure testing ≥ 1.5x, water conductivity, acceptable materials, blown dry with dry nitrogen prior to shipping
      - Maximum junction temperatures shall not exceed 100° C, and verify the components thermal and power cycling lifetimes are >>25 years (conservatively the power supply will thermal cycle [full power/off] once per day).
      - FAT: 24/8 h burn-in/stability vs. air temp. Worst case thermal; verify cap lifetime, dump R temp, and j-temp calcs. Linearity, resolution, reproducibility, accuracy. AC/DC voltage holding. **Sink mode test**. General function, network, internal interlocks, external interlock and dump switch time. Calibrated test equipment, record of SN and NIST cert.
    - Include design review in spec: component margin line by line (2014 SCM PS example in backup)

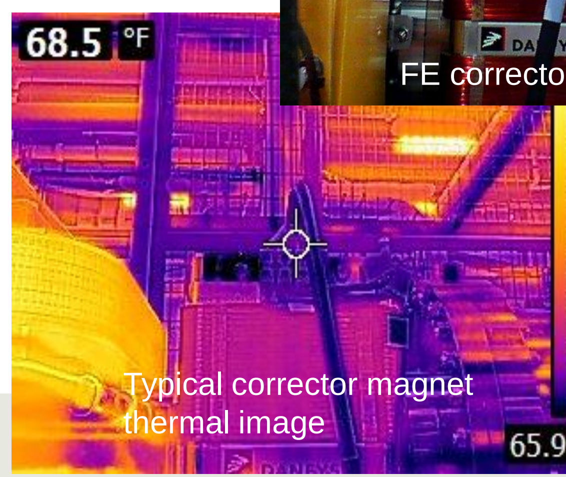
- Maintainability: modular approach vs. standalone high power PS
  - Avoid week-long downtime (K1200 MMPS example slide 3) to repair standalone PS in place
  - Where possible use modular PS, or spare standalone PS
    - Exe; 500 A, 750 A, 1250 A SCM PS are parallel combinations of 250 A modules with an external controller

FRIB Approach to High Availability
Installation, Testing, and Maintenance

- FAT (previous slide)
- ACL (recent example in backup)
  - Test a sample of PS to ensure specs are met, with rigorous test of first article
- Installation (see next slides)
  - Procedures and training
  - Checklists to track installation and testing
- Initial test
  - Functionality test all PS in situ
  - Micro Ohm measurements ensure low resistance connections
- Final test
  - Polarity testing to verify correct magnet polarity
  - PS and magnet thermal imaging during first power ramp up →
- Maintenance
  - Database for periodic maintenance
  - Spares: tracked, testing, mitigation plans







PS Installation and Testing
Follow FRIB Procedures and Training

- Procedures completed for
  - PS and cabling installation and testing (T31209-PR-000491)
    - Includes hazard analysis and mitigations
    - Cabinet completion progress report tracker completed, based on steps in this procedure
  - DC cable lug crimping (T31209-PR-000457)
  - Making PS and magnet connections and µ-ohm testing (T31209-PR-000380)
  - High frequency grounding (T31209-PR-000444)
  - Water manifold installation (T31209-PR-000443)
  - Labeling (T31209-PR-000442)
  - High potential testing (T10401-PR-000065)
  - Magnet polarity testing (T30102-PR-000437)
  - Thermal Imaging PS and Magnet Connections(T31209-PR-000924)
  - PS Energy Control Procedures, and Maintenance Procedures (T31209-PR-000448)
  - Electrical Equipment Inspection Procedure (S10300-PR-000291)
  - Electrical Equipment Checklist (S10300-FM-000128)

- Critical Steps to be Signed off on Trackers
  - Authorization to start work
  - Verify correct PS type, location, cables
  - Safety inspection; Inspect Alternating Current (AC) connections, ground, covers, cable type, breaker size, and labels
    - Electrical Inspection Procedure S10300-PR-000291
    - Electrical Equipment Checklist S10300-FM-000128
  - Initial testing into dummy load
  - Device Readiness Review (DRR)
  - Final integrated testing

- Installation broken into four tasks
  - Pull cables from racks to equipment locations
    - Relatively independent of status of equipment at each end
  - Install PS and supporting systems in rack
    - AC power, controls, cooling water
  - Initial test of PS and supporting systems into dummy load
    - Install and initially test power supplies independent of magnet schedule
  - Final PS testing
    - Cannot start until all supporting systems are complete
      - Magnets, Low Conductivity Water (LCW), controls, interlock testing, magnet terminal covers, traveler signatures, etc.

PS Installation and Testing Checklist

Example – Micro Ohm and Coil Resistance

- Analyzing trends in these measurements helped identify multiple issues;
  - Magnet supplier connection quality issues found by u-ohm coil connections
  - Stagnate water due to crossed water lines found by low coil to yoke resistance, finding this prior to magnet energization prevented potentially overheating magnets
  - Magnet manifold ground missing, ‘flow electrification’ of tubing

		DC Connections Terminal A				Coil Interconnect Hardware re-install				Coil to Magnet Yoke Resistance			Coil Resistance		
Magnet Type	Device	Terminal A, Copper Adaptor Plate to Magnet Terminal (M ohm)	Terminal A, Outside Lug to Copper Adaptor Plate (M ohm)	Terminal A, Inside Lug to Copper Adaptor Plate (M ohm)	Date Measured	4 Screws Micro Ohm (furthest away from 1/2" bolt)	B, 4 Screws closest to 1/2" bolt) Micro Ohm	B, 1/2"x 1.5" bolt Micro Ohm	Date of hardware re-install	4 Wire: Coil to Magnet Yoke resistance (Meg ohm)	4 Wire: Coil to Magnet Stand resistance (Meg ohm)	Date Measured	Coil resistance 4 Wire(ohms) Red Probe (A) Black Probe (B)	Coil resistance 4 Wire(ohms) Red Probe (B) Black Probe (A)	Date Measured
Q1	FS1_CSS:QH_D2194	5/5	7/7	5/5	12/7/2018	11/14	3/2	5/5	10/30/2018	49.0	49.0	10/31/2018	0.086	0.010	10/31/2018
Q1	FS1_CSS:QV_D2202	6/6	7/6	5/4	12/7/2018	7/13	4/5	6/4	10/30/2018	101.0	101.0	10/31/2018	0.097	0.014	10/31/2018
Q1	FS1_CSS:QH_D2215	6/10	5/4	6/6	12/7/2018	6/9	4/3	7/8	10/30/2018	49.2	49.2	12/7/2018	0.090	0.013	10/31/2018
Q1	FS1_CSS:QV_D2220	4/4	6/5	5/5	12/7/2018	11/11	3/4	4/5	10/30/2018	65.0	66.0	10/31/2018	0.095	0.011	10/31/2018
Q1	FS1_CSS:QH_D2254	4/5	6/6	8/7	3/23/2021	10/10	4/5	6/7	3/23/2021	OL	OL	3/23/2021	0.081	0.052	3/23/2021
Q1	FS1_CSS:QV_D2260	5/4	5/5	7/7	3/23/2021	8/7	9/10	4/6	3/23/2021	55.9	55.9	3/23/2021	0.089	0.039	3/23/2021
Q1	FS1_CSS:QH_D2272	2/2	5/4	4/3	12/7/2018	10/11	5/5	7/6	10/30/2018	164.0	164.0	10/31/2018	0.104	0.023	10/31/2018
Q1	FS1_CSS:QV_D2280	6/5	5/5	4/5	12/7/2018	12/7	4/5	9/3	10/30/2018	43.0	43.0	10/31/2018	0.099	0.024	10/31/2018
Q1	FS1_CSS:QH_D2356	6/2	5/5	9/10	12/7/2018	9/8	2/5	8/6	10/30/2018	40.8	40.8	12/7/2018	0.102	0.020	10/31/2018
Q1	FS1_CSS:QV_D2362	9/8	5/5	5/5	12/7/2018	10/9	2/3	5/5	10/30/2018	64.0	64.0	10/31/2018	0.101	0.022	10/31/2018
Q1	FS1_CSS:QH_D2372	8/7	4/4	4/4	12/7/2018	8/8	4/4	5/5	10/30/2018	68.0	68.0	10/31/2018	0.101	0.023	10/31/2018
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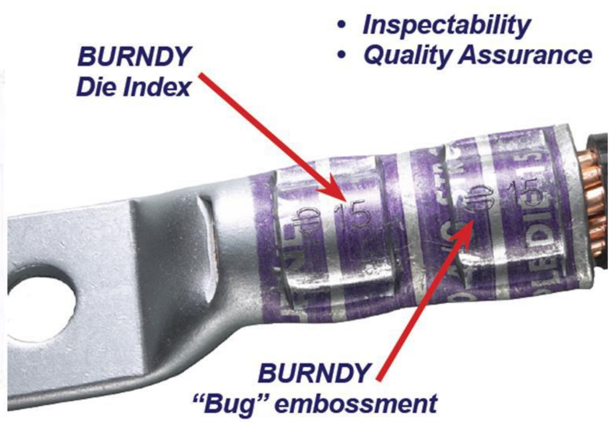
Q1	FS1_BTS:Q_D2409	6/8	6/5	3/4	12/7/2018	13/9	4/4	10/6	10/30/2018	129.0	129.0	10/31/2018	0.094	0.024	10/31/2018
Q1	FS1_BTS:Q_D2413	7/5	5/5	4/5	12/7/2018	8/9	3/4	6/4	10/30/2018	45.0	45.0	10/31/2018	0.098	0.011	10/31/2018
Q1	FS1_BBS:Q_D2445	5/7	5/5	4/4	12/7/2018	10/8	5/4	6/9	10/30/2018	56.0	56.0	10/31/2018	0.095	0.005	10/31/2018
Q1	FS1_BMS:QV_D2511	5/5	4/4	6/6	10/17/2019	6/10	5/3	5/6	1/4/2019	Open Load	Open Load	1/8/2019	0.058	0.058	1/8/2019
Q1	FS1_BMS:QH_D2515	6/7	5/4	10/6	10/17/2019	10/10	3/3	8/3	1/4/2019	Open Load	Open Load	1/8/2019	0.072	0.075	1/8/2019
Q1	FS1_BMS:QV_D2539	7/5	6/5	6/6	10/17/2019	12/9	4/5	3/3	1/4/2019	Open Load	Open Load	1/8/2019	0.071	0.070	1/8/2019
Q1	FS1_BMS:QV_D2563	8/7	5/6	6/5	10/17/2019	8/3	5/4	3/6	1/4/2019	Open Load	Open Load	1/8/2019	0.073	0.071	1/8/2019
Q1	FS1_BMS:QH_D2590	6/7	6/6	5/5	10/17/2019	13/7	5/5	4/4	1/4/2019	Open Load	Open Load	1/8/2019	0.076	0.071	1/8/2019
Q1	FS1_BMS:QV_D2597	3/6	5/4	4/5	10/17/2019	4/4	4/4	7/3	1/4/2019	Open Load	Open Load	1/8/2019	0.074	0.072	1/8/2019
Q1	FS1_BMS:QH_D2645	4/7	3/5	6/6	10/17/2019	14/29	6/4	6/4	1/4/2019	Open Load	Open Load	1/8/2019	0.064	0.062	1/8/2019
Q1	FS1_BMS:QV_D2654	7/6	5/4	4/4	10/17/2019	11/19	4/3	8/6	1/4/2019	Open Load	Open Load	1/8/2019	0.069	0.066	1/8/2019
Q1	FS1_BMS:QH_D2666	6/7	5/4	6/6	10/17/2019	7/8	4/4	10/7	1/4/2019	Open Load	Open Load	1/8/2019	0.069	0.065	1/8/2019
Q1	FS1_BMS:QV_D2679	7/5	5/5	6/6	10/17/2019	3/4	4/4	6/4	1/4/2019	Open Load	Open Load	1/8/2019	0.062	0.062	1/8/2019
Q1	FS1_BMS:QH_D2693	5/6	5/5	6/6	10/17/2019	11/11	3/4	7/6	10/2/2019	Open Load	Open Load	1/8/2019	0.064	0.064	1/8/2019
Q1	FS1_BMS:QV_D2698	3/8	5/5	5/7	10/17/2019	14/14	4/4	4/4	10/2/2019	Open Load	Open Load	1/8/2019	0.065	0.065	1/8/2019

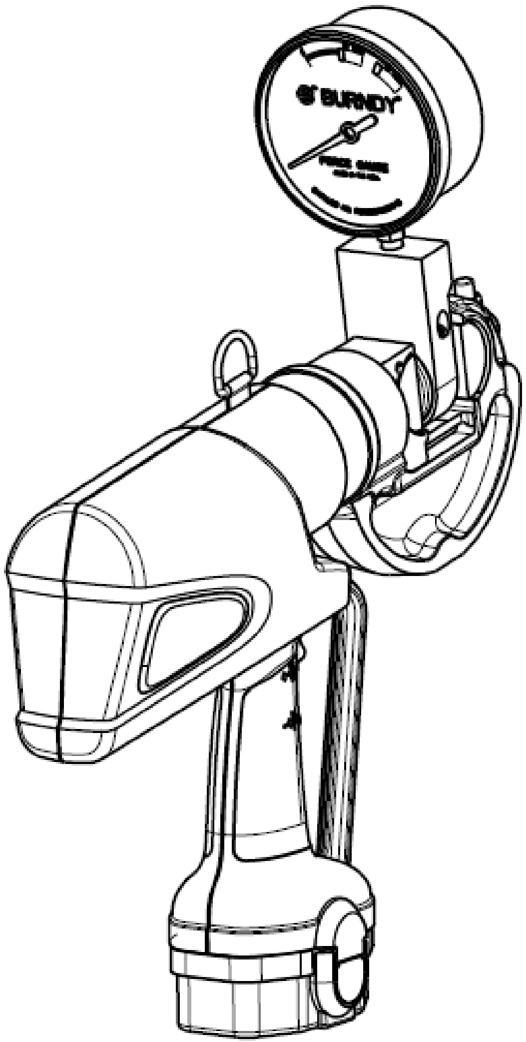
DC Cables
Design, Installation, and Testing

- Preferred design
  - UL listed cable tray rated flex cable - UL tray rated as required by the NEC
  - UL 2-hole lugs and standard electrical grade silicon bronze hardware
    - 2-hole lugs reduce magnet damage risk from a broken bolt
  - UL Long barrel lugs where possible to get multiple crimps (mitigate 1 bad crimp)
  - Cable ampacity following NEC for routing in cable tray and conduits
  - Mutual heating effects for multi-conduit banks (see backup slide)
  - FRIB approval for use by area to address radiation hardness, flammability, etc.

- Installation following supplier guidelines for making UL crimps

- Daily testing, inspection, and record keeping
  - Train technicians on lug selection (size, code vs flex), strip length, etc.
  - Test crimp tool with calibrated force gauge, verify crimp tool embossment, test torque wrenches on calibrated torque gauge
    - Clearly mark tools that fail testing and remove from service for repair
  - Mark torqued hardware

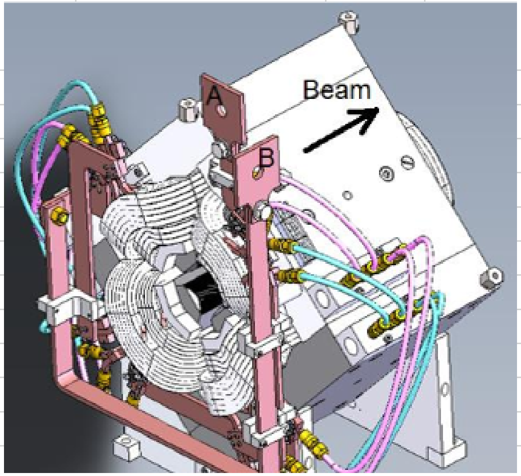




Magnet Polarity
Definition, Connection, and Testing

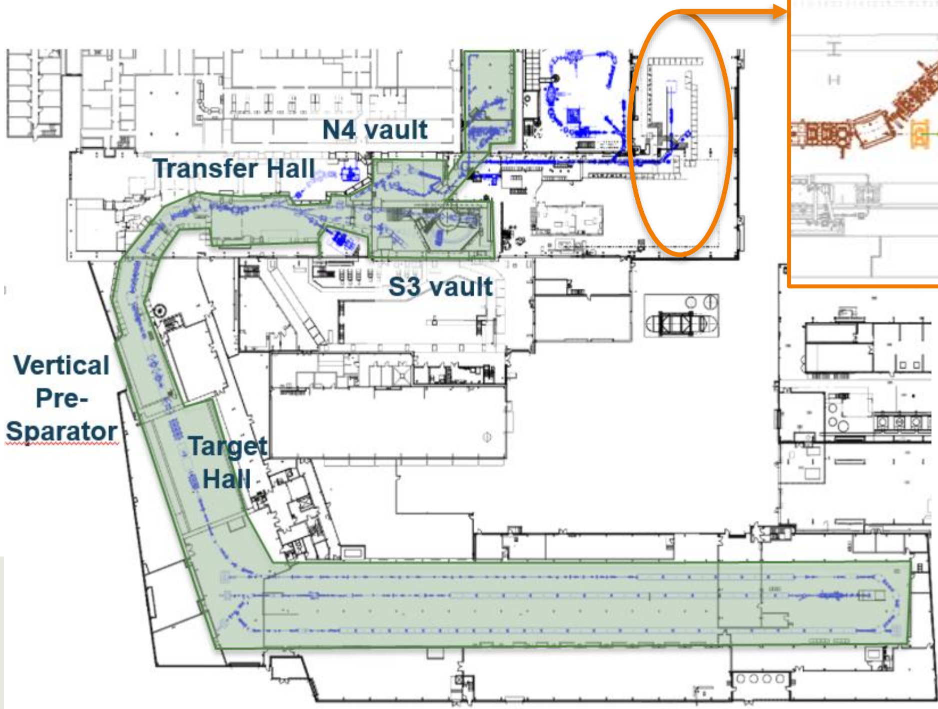
- FRIB Magnet Polarity Definition (S30000-SP-000494)
  - Defines magnet polarities for the FRIB Laboratory in the local user coordinate system
- A “hook up table” is provided by Beam Physics
  - Provides the necessary information to connect PS and lead drop monitors
  - Example below for single quadrant RTM PS
    - » PS Engineer enters cable numbers, PS technician makes connections according to table
  - SCM PS are typically 4-quadrant, so PS ’+’ to magnet ‘A’
    - » For vertical focusing, PS provides negative current
    - » Exception; if magnet is rotated 180 degrees (“flipped” in example below), then PS ’+’ to magnet ‘B’
- SC Magnet group responsible for clearly labeling polarity during magnet mapping
  - Measure terminal voltage to verify polarity if field measurement is not possible
- Polarity is confirmed by NMR or hand held hall probe during final integrated testing (T30102-PR-000437)

Number	Physics name	Control name	Type	Polarity	"+" cable to Terminal	Location	Orientation	"+" cable #	"-" cable #
1	ReA6_Q1Y	REA_BTS41:Q_D1380	Q1	Negative	A	6MeV	Flipped		
2	ReA6_Q2X	REA_BTS41:Q_D1385	Q1	Positive	B	6MeV	Flipped		
3	ReA6_Q3X	REA_BTS42:Q_D1400	Q1	Positive	A	6MeV			
4	ReA6_Q4Y	REA_BTS42:Q_D1405	Q1	Negative	B	6MeV			
5	ReA6_AQ1X	REA_BTS44:Q_D1425	Q1	Positive	A	Achromat			
6	ReA6_AQ2X	REA_BTS44:Q_D1437	Q1	Positive	A	Achromat			
7	ReA6_tpcQ1Y	REA_BTS46:Q_D1458	Q1	Negative	B	TPC			
8	ReA6_tpcQ2X	REA_BTS46:Q_D1463	Q1	Positive	A	TPC			
9	ReA6_tpcQ3Y	REA_BTS46:Q_D1513	Q1	Negative	A	TPC	Flipped		
10	ReA6_tpcQ4X	REA_BTS46:Q_D1518	Q1	Positive	B	TPC	Flipped		
11	ReA6_tpcQ5Y	REA_BTS46:Q_D1533	Q1	Negative	A	TPC	Flipped		
12	ReA6_tpcQ6X	REA_BTS46:Q_D1538	Q1	Positive	B	TPC	Flipped		



ReA6 Project Update
Completed 2021

- ReA6 energy upgrade of ReA with two experimental beamlines
  - 35 FRIB Type PS installed
  - Challenge due to global supply chains, Covid safeguards, and resource conflicts with FRIB project



SECAR Project Update

Project Completed: Managed PS Issues to Minimize Impact

- 47% (14 out of 30) PS have experienced failures, several PS multiple failures
  - Typical pre-mature failure rate ~ 2-5%
- Two supplier service visits to go through corrective actions – resulting in a stabilized failure rate, very few repeat failure modes
  - Prior to September 2018 supplier visit - 9 failures, 5 failure modes
  - Between September 2018 and June 2019 supplier visits – 4 failures, 2 new failure modes
- Since the last supplier service visit in June 2019 – 3 failures, 1 new failure mode. 1 global 'bug'
  - 2 Failures – Failed power module, repaired in house with spare modules
  - 1 Failure – Communication error (repeat symptom). Loose ribbon cable connection (new failure mode), after >1000 hours of PS operation. Repaired in-house. Path forward, If we have any repeat failures, open all PS and use electronics grade RTV to hold connectors in place.
  - 1 bug – PS reproducibility issue, not affecting operations. Identified on multiple PS while performing magnetic field reproducibility tests, repeatedly ramped PS current and ~5% of the time the PS read-back would change by ~200 ppm (on a 10 ppm class PS) and the magnetic field would change by ~0.1%.
  - Supplier able to recreate the bug at their facility and isolated the problem to the digital current slope setting, and is currently working on a software fix.
  - Supplier continues to work with us to resolve any issues!

SECAR PS Issues
Mitigation Plans Implemented

- Short term plan; existing spares from an alternate PS supplier have been installed.
  - These PS were used twice to keep SECAR commissioning on track. Remain on standby.
- Medium term; replaced (6) multipole PS with FRIB type PS
  - FRIB type PS current stability ±500 ppm_full scale exceeds SECAR requirement
  - Number of existing PS spares increased
    - Reconfigured all (5) 50 A PS and existing spare parts into (4) 200 A PS
      - Resulting in 6 spare 200 A PS (5 + 1 existing) for 23 remaining in service = 26% spares
- Spare for standalone velocity filter PS received, installation in process
  - Repair in place mitigation plan could lead to long mean-time-to-repair (MTTR)

Power Supply Type	Total Quantity	Current Stability Requirement (ppm_full scale)
Dipole PS	8	±10
Velocity Filter	2	±10
Quad	15	±100
Hex/Aux/ Oct	6	±1000
Total	31	

Multipole Magnet	SECAR Magnet Requirement (with DC cable drop)	FRIB PS Type Replacement
Q1_Hex	3 V, 33 A	12 V 70 A
Q1 Dipole	8 V, 100 A	12 V 140 A
Hex1	6 V, 15 A	12 V 70 A
Hex2	8 V, 18 A	12 V 70 A
Hex3	11 V, 20 A	12 V 70 A
Oct1	11 V, 21 A	12 V 70 A

SECAR PS Issues
Additional Mitigation Plans

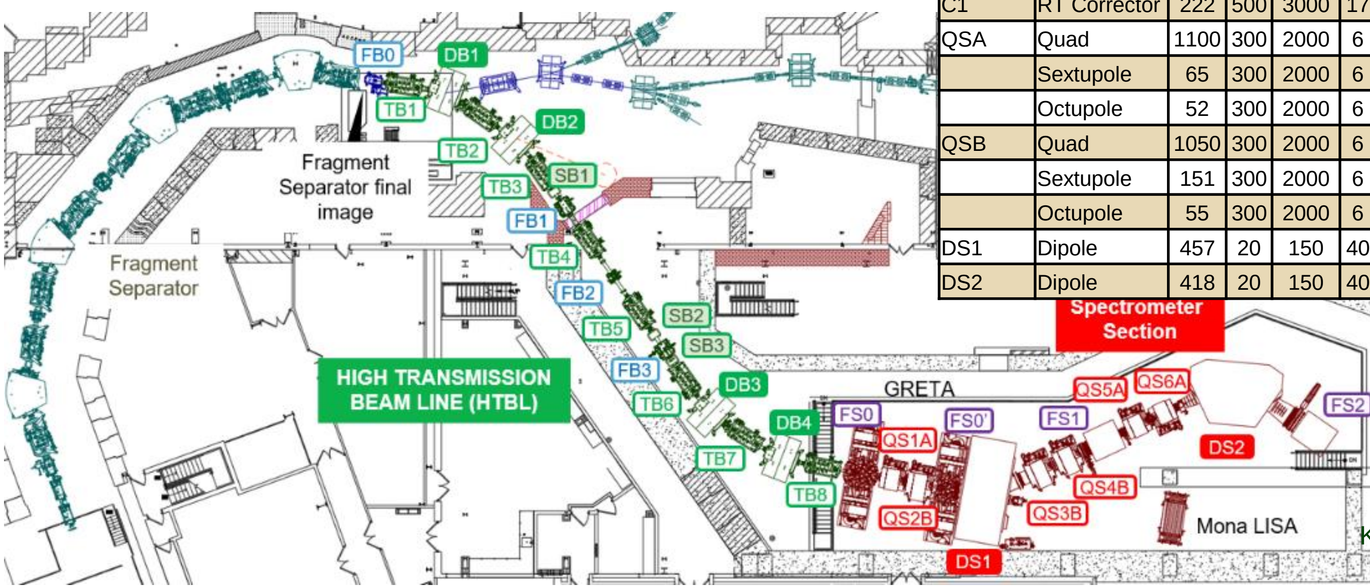
- Options if PS continue to cause issues
  - Replace Quad PS with existing FRIB air cooled RTM PS type (preferred)
    - » Requires documentation that ±500 ppm_full scale current stability and additional HVAC load are acceptable.
  - Replace Quad PS with PS similar to FRIB room temperature dipole PS
    - » ±100 ppm current stability class, water cooled. Physical space issue.
  - Replace Dipole PS with alternate supplier ±10 ppm current stability PS

Power Supply Type	Total Quantity	Current Stability Requirement (ppm_full scale)
Velocity Filter	2	±10
Dipole PS	8	±10
Quad	15	±100
Hex/Aux/ Oct	6	±1000
Total	31	

HRS Project Status

- Scope: 99 PS and cabling, in two families
  - 96 SCM PS, 3 RTM PS
- PS requirements documented →
- CD1 achieved fall 2020
- DOE comments addressed (see following slides)
- 90% HTBL and 30% HRS design reviews completed November, 2021

Magnet type	Magnet Description	Current (A)	PS stability ppm_fs*	Required PS stability ppm_fs**	Voltage (V)	Number of Quadrants	E_stored (kJ)	L (H)	Total PS needed	Dump Voltage (V)	Delta V Circuit Required	Quench Protection Topology
HTBL-D	Dipole	182	20	150	6	2 (or 4)	339.5	21.5	4	80	no	Self-protecting
HTBL-QB(Q)	Quad	76	300	2000	6	4	87.7	30.4	16	80	no	Self-protecting
HTBL-QB(S)	Sextupole	40	300	2000	6	4	0.3	0.37	16	80	no	Self-protecting
HTBL-QB(O)	Octupole	20	500	3000	6	4	0.1	0.59	16	80	no	Self-protecting
HTBL-QC(Q)	Quad	98	300	2000	6	4	196.6	41	8	80	no	Self-protecting
HTBL-QC(S)	Sextupole	40	300	2000	6	4	0.6	0.71	8	80	no	Self-protecting
HTBL-QC(O)	Octupole	20	500	3000	6	4	0.3	1.38	8	80	no	Self-protecting
C1	RT Corrector	222	500	3000	17	2	1.1	0.045	3	NA	NA	NA
QSA	Quad	1100	300	2000	6	4	824.0	1.4	3	80	no	Self-protecting
	Sextupole	65	300	2000	6	4	7.9	3.7	3	80	no	Self-protecting
	Octupole	52	300	2000	6	4	2.4	1.8	3	80	no	Self-protecting
QSB	Quad	1050	300	2000	6	4	2294.0	2.7	3	80	no	Self-protecting
	Sextupole	151	300	2000	6	4	65.1	5.7	3	80	no	Self-protecting
	Octupole	55	300	2000	6	4	15.8	7.5	3	80	no	Self-protecting
DS1	Dipole	457	20	150	40	2 (or 4)	9307.0	86.33	1	200	no	Self-protecting
DS2	Dipole	418	20	150	40	2 (or 4)	2545.0	30.1	1	200	no	Self-protecting



HRS Recommendations Addressed [1]

- PS design review recommendations are tracked and have been addressed
- Comments from the August 2021 DOE Status Review;
  - The magnet and power supply design is encouraged to continue to refine and identify how stored energy will be handled in the event there is an event rendering the power supply connection or operability unable to provide the dissipation of stored energy
  - The quench protection of magnets, in particular those with large stored energy, should incorporate redundant measures to minimize the risk of arcing under fault scenarios. A detailed analysis of fault scenarios, including failure modes of current leads, should be performed, and the protection system detection and response clarified
- These comments were evaluated in detail following FRIB processes, the results and mitigations were presented at the Magnet and PS design reviews
  - Environmental, Safety, Health, and Quality Impact Assessment (S10300-QMS-000051)
    - » Determined the severity of a potentially **unmitigated failure**, assessed the probability of the failure occurring, determined Impact Magnitude / Level of Care, and listed ESH&Q requirements
  - Results and mitigations presented, proposed design was found to adequately address ES&H
  - Self-protecting magnets, no fast quench detection or fast energy extraction systems required
    - » HTBL magnet leads; current decays well within required time to protect leads after cooling stopped
    - » SC magnet with parallel dump resistor topology
      - Identical to nearly all existing SC magnets at FRIB
      - Alarms and interlocks will be documented in DCC along with interlock test results
      - If a threshold is exceeded, PLC interlocks off PS, magnet stored energy to dumps into the parallel resistor

HRS Recommendations Addressed [2]

Safety Integrated and Hazards Mitigated for Activities

Activity	Aspect	Unmitigated Level of care	Mitigation
Disconnecting dump resistor	Safety, Health	High	See below
	Quality	High	See Below (Following device specific LOTO procedure ensures proper dissipation of stored energy, mitigating magnet failure)
Working near AC power	Safety, Health	High	See below
	Quality	None	NA

- Safety, Health, and Quality mitigation
  - Severity crisis (catastrophic threat to mission), probability frequent (could occur annually), high level of care
  - FRIB Electrical Safety Program (S10300-MA-000093)
    - Provides rules for working around hazardous electrical systems or sources (greater than 50 Vrms AC or DC, 5 mA, or 10J of stored energy)
    - Addresses training, hazard thresholds, approach boundaries, Personal Protective Equipment (PPE), equipment design / documentation, guards, test equipment, labeling
    - In compliance with MIOSHA, NEC and follows DOE Guidelines
  - Device specific LOTO procedures
    - PS Energy Control Procedures, and Maintenance Procedures (T31209-PR-000448)
      - Includes SCM PS LOTO procedure – high current, high stored energy, multiple energy sources, and discrepant conditions
      - Wait times for dissipation of stored energy are posted on rack safety instruction labels
      - Requires all PS with inductively coupled loads to be LOTO'd prior to performing maintenance on any PS or magnets
    - Lockable disconnecting means and zero voltage indicators with safe test points will be installed
  - Training
    - All electrical workers - general electrical safety awareness and lock out/tag out (LOTO)
    - Lockout/Tagout Superconducting Magnet Power Supplies training in Intra
      - Only experienced PS Group Qualified Electrical Workers are trained and authorized
  - Work is planned and authorized for Qualified Certified Personnel using Work Control Plan system
    - Laboratory Work Control Program (S10300-PL-000263) covers safety issues and discrepant conditions

HRS Recommendations Addressed [3]

Safety Integrated and Hazards Mitigated for Equipment

Equipment	Aspect	Unmitigated Level of care	Mitigation

Dump resistor / cable / lug / bolt failure	Safety, Health	Medium	• Severity crisis (catastrophic threat), probability remote (not more than once in ten years), medium level of care
			  ◦ Lesson learned, brass bolt (improper hardware) failed resulting in magnet loss
			• HRS Superconducting Magnet Power Supplies Specifications (M41800-SP-000809)
			  ◦ Dump resistor design, thermal simulation and measurement results will be reviewed and verified
			  ◦ Dump resistor energy rating contains at least 20% margin
			  ◦ Dump resistor thermal interlock prevents repeated energy dumps
			  ◦ Dump resistor time delay to allow cool-down redundantly prevents repeated energy dumps
			• UL listed components and procedures following National Electric Code
			  ◦ Using properly rated UL listed DC cables, installed per NEC, protected in cable in cable tray / conduit
			  ◦ Insulation and continuity test DC cable after installation
			  ◦ Using UL 2 hole lugs where possible to reduce risk of a single bolt failure (lesson learned)
			  ◦ Using UL long barrel lugs where possible following manufacturer instructions resulting in multiple UL hydraulic embossed crimps to reduce risk of a single crimp failure
			  ◦ Using UL electrical grade silicon bronze hardware (multiple if 2 hole lugs possible) (lesson learned)
			  ◦ Proper design of strain relief of DC cable and jumper to lead can
			  ◦ Magnet termination boxes shall be UL enclosure type rated for use in location, with hazard and safety instruction labels.
			• Following QA steps in FRIB crimp, connection procedures, and training
			  ◦ DC cable lug crimping (T31209-PR-000457)
			  ◦ Making PS and magnet connections and µ-ohm testing (T31209-PR-000380)
			  ◦ Attach fasteners to magnets and power supplies training course on Intra
			• Micro ohm and thermal imaging measurements ensure connections are good
			  ◦ Thermal Imaging PS and Magnet Connections (T31209-PR-000924)
			• PS racks are configuration controlled – locked, connections covered, hazard and safety instruction labels.
			• Controls lead drop wiring, isolation modules, PLC modules covered, hazard and safety instruction labels.
			• Grounding magnet, cable tray, rack, PS, Laboratory Technical Grounding Guidelines (S20102-MA-005062)
			• Electrical inspections require AHJ approval prior to energization
			  ◦ Electrical Equipment Procedure (S10300-PR-000291)
			  ◦ Electrical Equipment Checklist (S10300-FM-000128)
			• Work Control Program (S10300-PL-000263) covers safety issues and discrepant conditions
			• PS Energy Control Procedures (T31209-PR-000448) covers hazards and discrepant conditions
			• Thermal imaging preventative maintenance campaigns to ensure long term reliability
			• Likely failure modes mitigated, unlikely events (earthquake, fork truck severing cables, etc.) are at an acceptable level of risk

	Quality	Medium	

Backup

FRIB Example: SCM PS Detailed Design [1]
Component Margin Reviewed

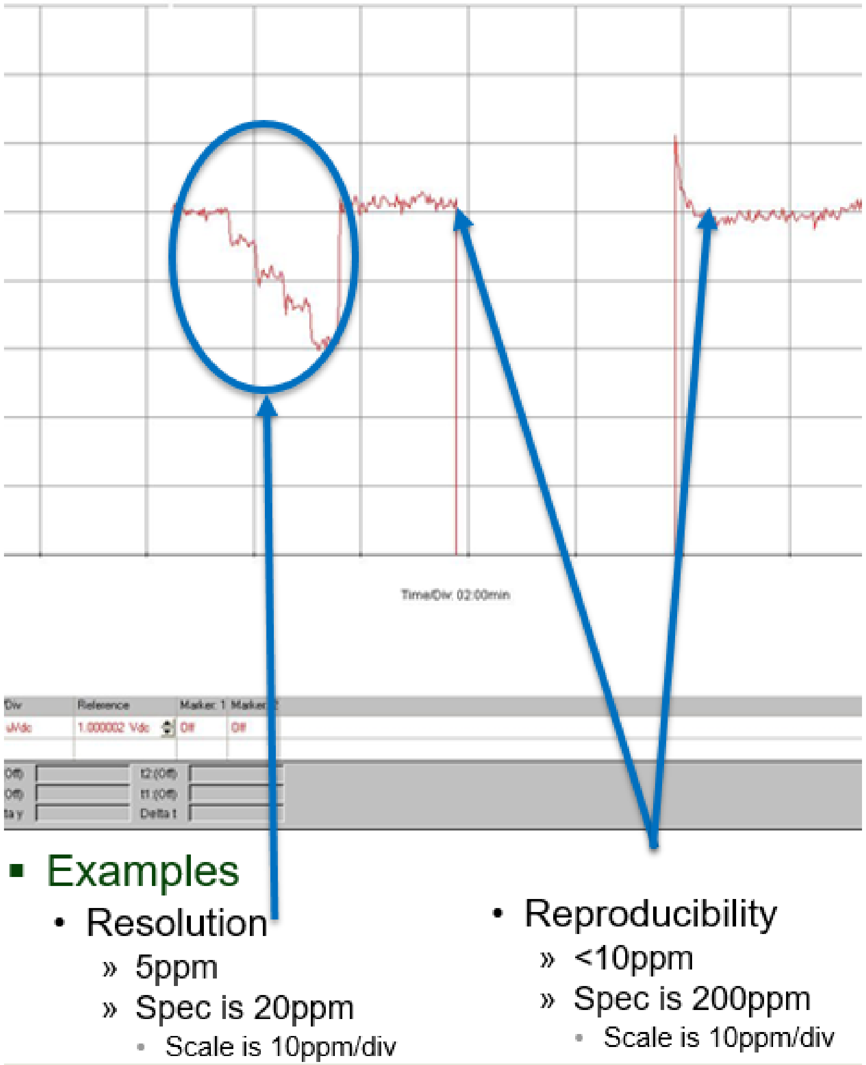
- DC link AC/DC max power calculated = 1.1kW
  - AC/DC PS = 2 // 24V 27A = 24V 54A = 1.3kW, 18% margin
    - » Note that DC link power drops while regulating,18% is only while ramping
  - AC/DC input max = 1.42kVA
    - » 2 // 24V 27A PS, input 7.1A @ 100V, =~ 14.2A (~12.9A at 110V)
    - » 14.2A is at 1.3kW, while max DC link power is 1.1kW
    - » ~10.9A at 110V and max 1.1kW DC link
      - Again note that the DC link input current drops while regulating
  - Line filter – 16A
    - » 13% margin using the worst case 14.2A
    - » 46% at 10.9A
  - Contactor
    - » Rated for 20A
    - » 40% margin using the worst case 14.2A
    - » 80% at 10.9A
    - » 10M cycles
- Insulated-Gate Bipolar Transistor (IGBT)
  - Tj calculated 75C, rated 150C
  - >>20k thermal cycles, ~54 years, non-issue
  - Rated 300A @ 80C operating Tc case temperature.
  - Tc is ~ 40C heatsink temp
  - Limited to 70C by the thermal switch.
  - Case is rated for 100C max
- D1 and Chopper elements
  - No thermal issues during FAT
- DC filter inductor – 125A, 15A @ 20kHz
  - ~45C measured
- DC filter caps
  - rated 200V, dump voltage 80V
  - rated at magnet current
  - 11k hrs @ 85C, Supplier claims 8X expected lifetime at 55C, 88k hrs = ten years
  - Ambient air inside chassis measured ~40C, > ten years expected

FRIB Example: SCM PS Detailed Design [2]
Component Margin Reviewed

- Dump Resistor
  - 20% margin added to stored energy
  - Simulations showed the housing temp = 115C (peak housing temp is ~3min after t0), and wire = 750C
    - » 'Compact Brake Resistor' rated for 1200C
    - » Datasheet states 'if temperature rise is less than 900-1000K the resistor should work for your application'…'However it is recommended to verify the results of the simulation'
    - » The simulation was verified as part of the FAT
      - 3 min after t0, the housing temp = 72C which is better than the simulation
- DCCT - 200A
- Cables
  - AC = 14AWG,
    - » rated 32A for chassis wiring
    - » worst case 14.2A
    - » ~10.9A at 110V and max 1.1kW DC link
  - DC link 1 = 12AWG
    - » rated 41A for chassis wiring
    - » worst case 27A
    - » ~23A (from Sigma Phi calculation)
  - DC link 2 = 8AWG
    - » rated 73A for chassis wiring
    - » worst case 54A
    - » ~46A (from Sigma Phi calculation)
  - DC Out = 2AWG
    - » rated 181A for chassis wiring
    - » worst case 107.5A
- Summary of component review
  - The 100A power supply is built to run at 6V / 100A continuously
  - Running at 2V / 95A continuously for operations is not desired, but acceptable
    - » Fallback position is to run solenoids at lower fields (95A is for 8T, 7T is acceptable)

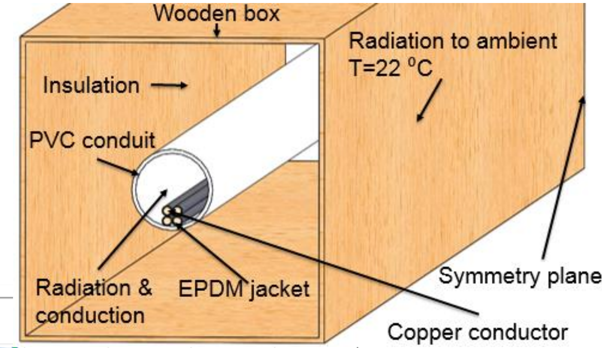
ACL Plans

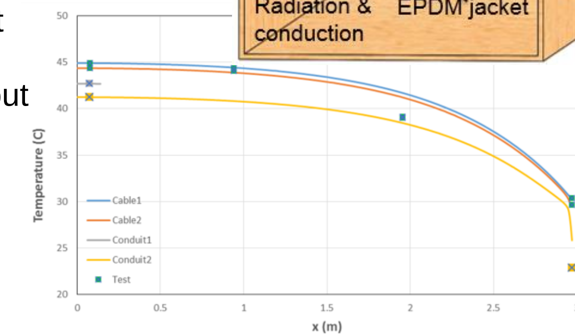
- Draft HRS SCM PS ACL Plan (M41800-VP-001965)
  - Following successful FRIB ACL Plans
    - » SCM PS ACL Plan (T31209-VP-000114)
    - » RTM PS ACL Plan (T31209-VP-000095)
- Verify factory acceptance test report for each PS
- 5-10% of each PS model (minimum 1 of each) is tested in house for payment acceptance and verification results documented. Example FRIB results;
  - SCM PS ACL Results (T31209-VR-000114)
  - RTM PS ACL Results (T31209-VR-000095)
- Also each PS is tested in place after installation. Example FRIB results;
  - FRIB LS2 Power Supply Initial Testing Results (T31209-RC-004258)

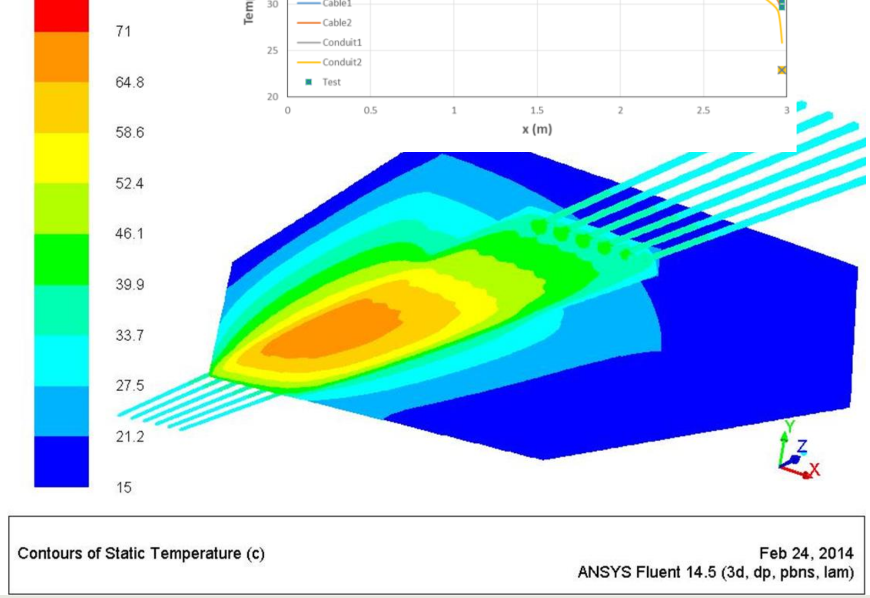


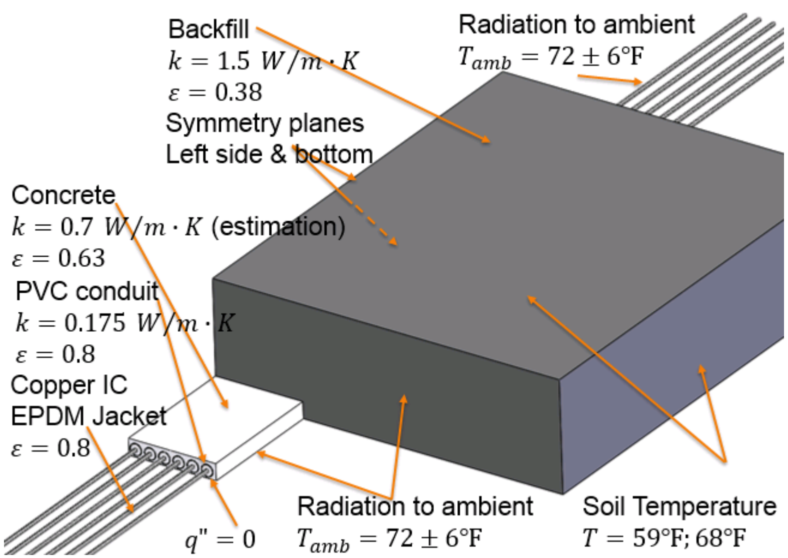
FRIB DC Cable Conduit Heat Mock Up Test and Simulations – Ensures Properly Rated Cables

- Mutual heating between conduits has been verified
  - A mock up test has been completed
  - Simulation model has been verified by comparing results from the mock up →
  - The verified model is fed into a worst-case multi-conduit chase model ↓
  - Results show that only a few of the largest cables, in highly congested areas, needed to be spread out or use larger cables
  - In house thermal simulations verified by comparison to commercial duct bank software results and NEC Informative Annex B calculations
  - Final design review conclusion, FRIB DC cable sizing is conservative, but not overly so









HRS Margin

PS Operational Margin Nearly Identical to Linac and Pre-Separator

- *Assume 10% tuning margin used and new 40 A PS type (vs 100 A) (both worst case)
- HTBL-QC(Q), Sextupoles and Octupoles low / no current or peak power margin
- HTBL (S) and (O) 200% operating power margin, and very short peak (ramp time ≤ 5 s)
- HTBL-QC(Q) 206% operating power margin, ramp time 11 min

Magnet type	Magnet Description	Max operating Current (A)*	PS Current (A)	Current Margin (%)	Max Operating Voltage (V)	PS Voltage (V)	Voltage Margin (%)	Expected Operating Voltage (V)	Expected Operating Power (W)	PS Power (W)	Expected Operating Power Margin (%)	Peak Operating Power (W)	Expected Peak Power Margin (%)	L (H)	Ramp time (s)	Ramp time (minutes)
HTBL-D	Dipole	182	250	**37%**	6	6	0%	2	364	1500	**312%**	1092	**37%**	21.5	652	11
HTBL-QB(Q)	Quad	76	100	**32%**	6	6	0%	2	152	600	**295%**	456	**32%**	30.4	385	6
HTBL-QB(S)	Sextupole	40	40	**0%**	6	6	0%	2	80	240	**200%**	240	**0%**	0.37	2	0
HTBL-QB(O)	Octupole	20	20	**0%**	6	6	0%	2	40	120	**200%**	120	**0%**	0.59	2	0
HTBL-QC(Q)	Quad	98	100	**2%**	6	6	0%	2	196	600	**206%**	588	**2%**	41	670	11
HTBL-QC(S)	Sextupole	40	40	**0%**	6	6	0%	2	80	240	**200%**	240	**0%**	0.71	5	0
HTBL-QC(O)	Octupole	20	20	**0%**	6	6	0%	2	40	120	**200%**	120	**0%**	1.38	5	0
C1	RT Corrector	133	300	**126%**	43	50	**16%**	43	5719	15000	**162%**	5719	**162%**	0.16	0	0
QSA	Quad	1100	1250	**14%**	6	6	0%	2	2200	7500	**241%**	6600	**14%**	1.4	257	4
	Sextupole	65	100	**54%**	6	6	0%	2	130	600	**362%**	390	**54%**	3.7	40	1
	Octupole	52	100	**92%**	6	6	0%	2	104	600	**477%**	312	**92%**	1.8	16	0
QSB	Quad	1050	1250	**19%**	6	6	0%	2	2100	7500	**257%**	6300	**19%**	2.7	473	8
	Sextupole	151	250	**66%**	6	6	0%	2	302	1500	**397%**	906	**66%**	5.7	143	2
	Octupole	65	100	**54%**	6	6	0%	2	130	600	**362%**	390	**54%**	7.5	81	1
DS1	Dipole	457	500	**9%**	40	40	0%	2	914	20000	**2088%**	18280	**9%**	86.3	986	16
DS2	Dipole	393	500	**27%**	40	40	0%	2	786	20000	**2445%**	15720	**27%**	30.1	296	5