Cryogenic Design of FRIB Cryomodule and Distribution System and Present Status

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Background

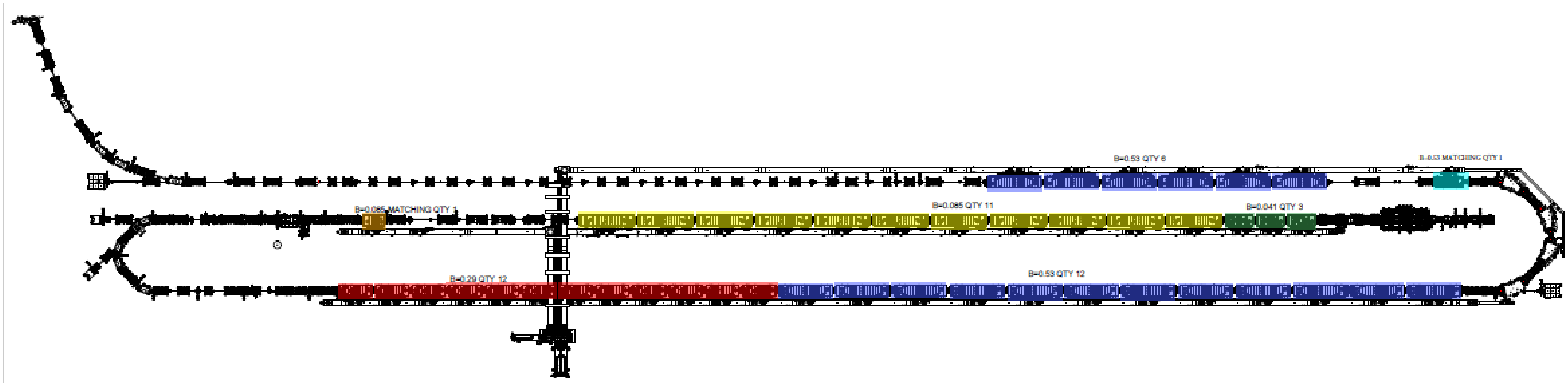
- Layout of the FRIB accelerator was driven by the requirements to:
  - Integrate the existing cyclotron and its experimental areas,
  - While keeping it on the MSU campus within the cyclotron/FRIB site

- Agreement between FRIB and the general contractor at the beginning of the project to install major sub-system components prior to the BOD (March 2017)
  - Items could be put in place as they are received; preventing double-handling
  - This was the case for the large cryo-distribution lines

- Decision in 2012 to divide the Linac into three independent segments

Background (cont.)

- Linac is ‘folded’ into the shape of a ‘paper clip’: three straight sections, LS1, LS2, and, LS3



- Type and number of CM’s in each Linac segment: 6 types

Beta ratio (β)	0.041	0.085	0.085M [a]	0.29	0.53	0.53M [a]	Total
LS1	3	11	1	0	0	0	15
LS2	0	0	0	12	12	0	24
LS3	0	0	0	0	6	1	7
Total CM's	3	11	1	12	18	1	46

- [a] M = ‘Matching’

Cryomodules

- Typical CM is comprised of:
  - Superconducting solenoid magnets
  - Superconducting radio frequency (SRF) Niobium cavities
  - Fundamental power couplers (FPC’s)
  - Cavity tuners
  - Magnet power leads (MPL)
  - Instrumentation
  - Supporting cryogenic components: e.g., valves, heat exchangers, and piping
  - Components surrounded by a thermal radiation shield
  - Everything housed within a rectangular vacuum insulating shell
- Total: 69 solenoid magnets, 324 SRF cavities in 46 CM’s

Cryomodules (cont.)

- CM cryogenic cooled devices by type and quantity

Beta ratio (β)	0.041	0.085	0.085M	0.29	0.53	0.53M
# CM's [a]	3	11	1	12	18	1
# solenoids (4.5 K)	2	3	0	1	1	0
# cavities (2 K) [b]	4	8	4	6	8	4
# FPC	4 [d]	8 [d]	4 [d]	6 [c,d]	8 [c,d]	4 [c,d]
MPL (4.5-300 K) [e]	2	3	0	1	1	0

- [a] Each CM uses a thermal shield at (nominally) 40 to 55 K.
- [b] Niobium cavities for LS1 are at 4.5 K; but, they are at 2 K (31 mbar) for LS2 and LS3
- [c] Fundamental power couplers (FPC) for the Niobium cavities, with a conduction thermal intercept at 4.5 K.
- [d] Fundamental power couplers (FPC) for the Niobium cavities, with a conduction thermal intercept at 40 to 55 K.
- [e] Magnet power leads (MPL) use helium vapor at approx. 4.5 K

Cryomodules (cont.)

- CM operating modes and operating requirements were established in 2013 from a 'bottoms-up' analysis

- Four types of CM loads possible
  - 4.5 K refrigeration (magnets and FPC)
  - 4.5 K liquefaction (magnet power leads; MPL)
  - 2 K refrigeration (cavities), and,
  - 40-55 K thermal shield

Beta ratio (β)	0.041	0.085	0.085M	0.29	0.53	0.53M
2 K refrigeration [W]	10.3	38.8	20.4	27.3	63.2	37.6
4.5 K refrigeration [W]	15.5	30	15	19	21	19
40-55 K shield [W]	123.2	200.6	73	115.6	145.4	77.3

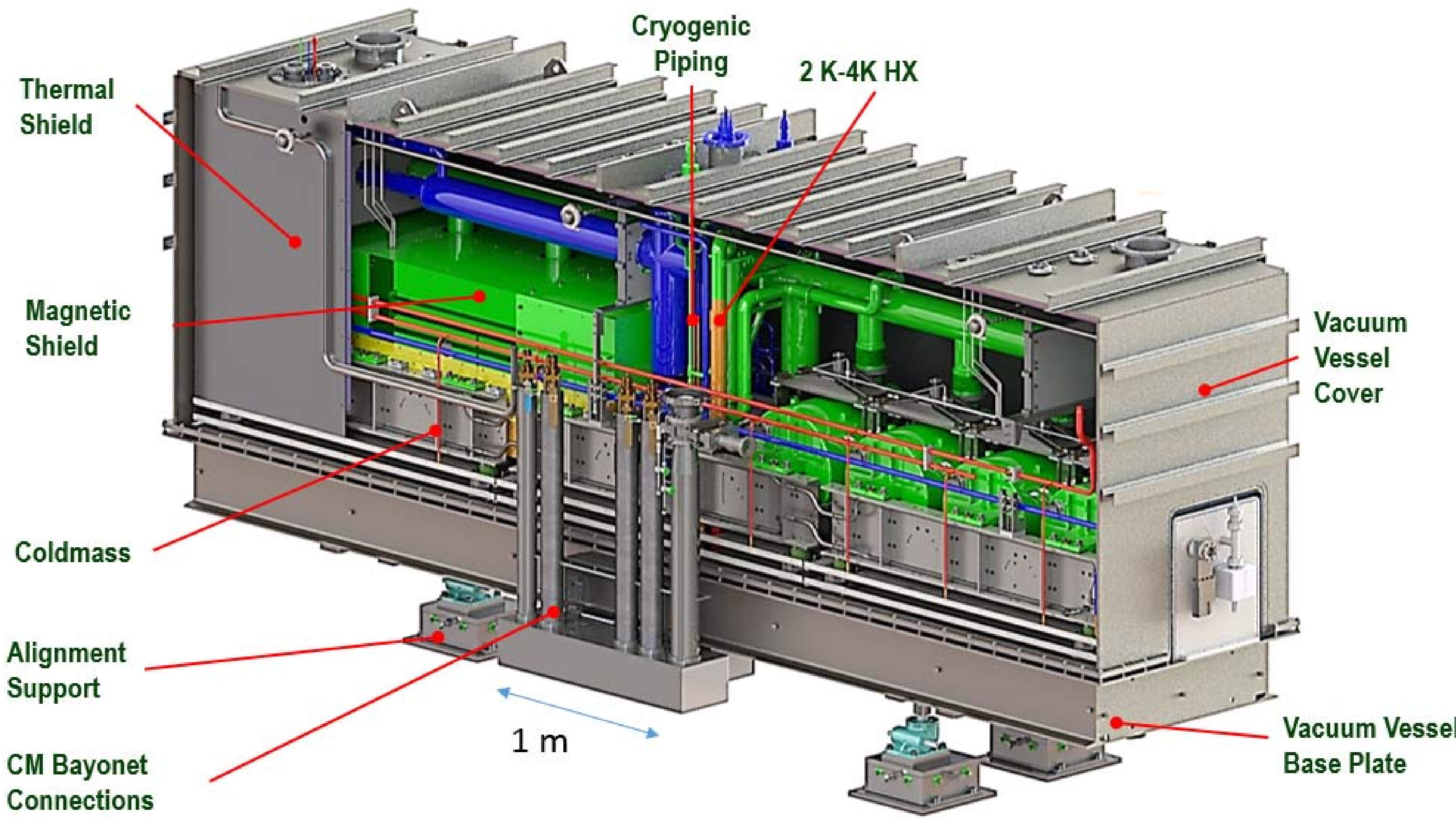
Cryomodules (cont.)

- There are four superconducting magnets (FSD3) in the large 180 degree bend between LS2 and LS3
  - Est. MPL + Shield flow of 0.5 g/s
  - One magnet is connected to LS2, and the other three to LS3 to avoid the TL crossing over the LS2 beam dump
- Expected cryogenic loads from each Linac segment by type
  - Total expected lead flow is 5 g/s (4.5 K liquefaction load)

Beta ratio (β)	0.041	0.085	0.085M	0.29	0.53	0.53M	FS2D3	Total
LS1: 2 K	31	427	20	0	0	0	0	478
LS1: 4.5 K	47	330	15	0	0	0	0	392
LS1: 40-55 K	370	207	73	0	0	0	0	2649
LS2: 2 K	0	0	0	328	758	0	0	1086
LS2: 4.5 K	0	0	0	228	252	0	17	497
LS2: 40-55 K	0	0	0	1387	1745	0	0	3132
LS3: 2 K	0	0	0	0	379	38	0	417
LS3: 4.5 K	0	0	0	0	126	19	51	196
LS3: 40-55 K	0	0	0	0	872	77	0	950

Cryomodules (cont.)

- Typical CM assembly

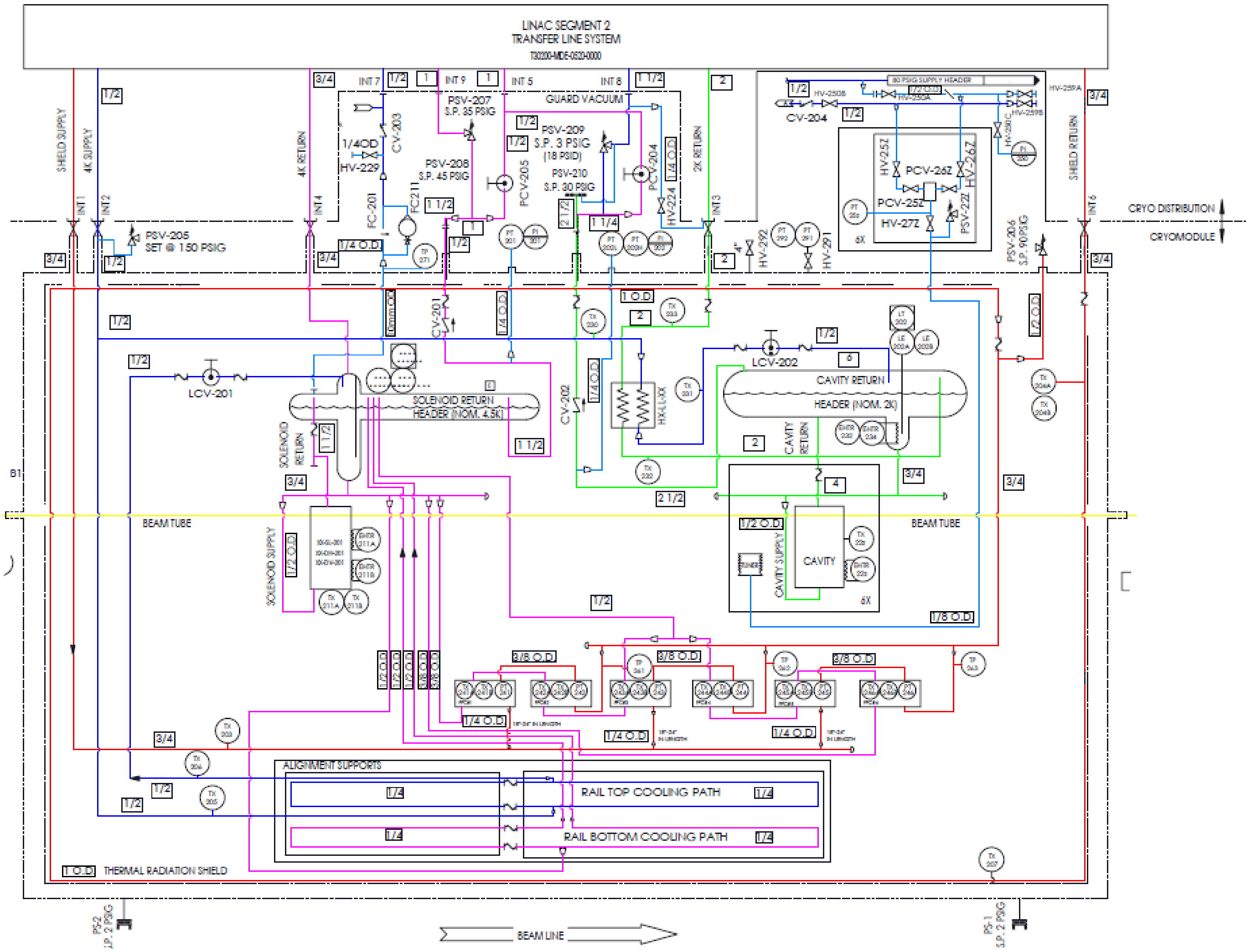


Cryomodules (cont.)

- There are five cryogenic process connections to each CM
  - 4.5 K (saturated liquid or supercritical) supply
  - 5 K 1.2 bar (saturated vapor) return
  - 4 K 31 mbar sub-atmospheric return
  - 40 K shield supply (1.2 to 1.8 bar)
  - 55 K shield return

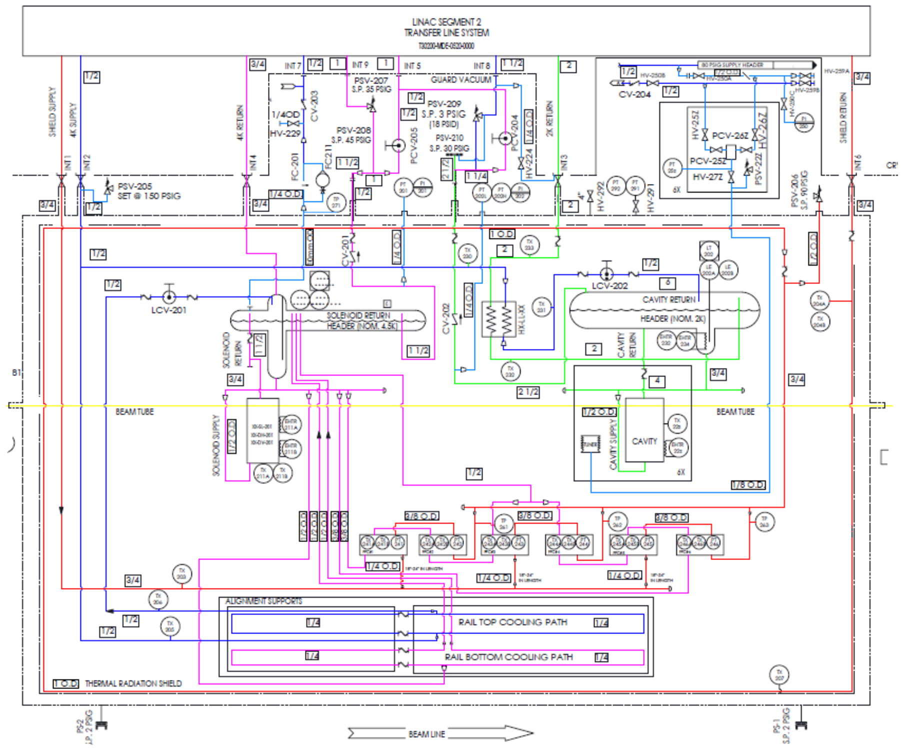
- Each of the cryogenic connections uses a JLab/SNS style cryogenic coupling and is connected to the transfer-line using a line in the shape of an inverted “U”
  - These type of “U” connections, known as “U” tubes, are used throughout the cryogenic system
    - » Permit a physical connection/disconnection that maintains cleanliness, even while the system is at cryogenic temperatures, without relying on a cryogenic valve
    - » Modest heat in-leak to the process, and are reliable and robust

Cryomodules: Typical Flow Diagram



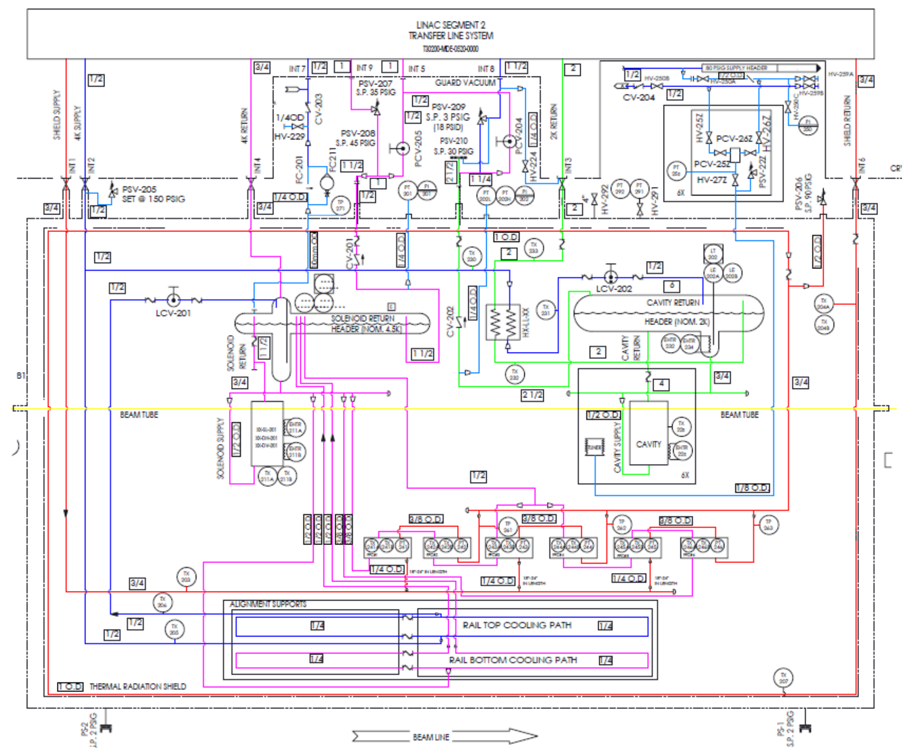
Cryomodules (cont.)

- Typical CM has 4.5 K supply, that can provided as either a supercritical (3 bar) fluid or a saturated liquid by the cryogenic plant
- CM support base is designed with two parallel cooling paths
- Top path is cooled by the 4.5 K supply flow (i.e., forced flow)
- Bottom path by the magnet thermosiphon (i.e., passively)



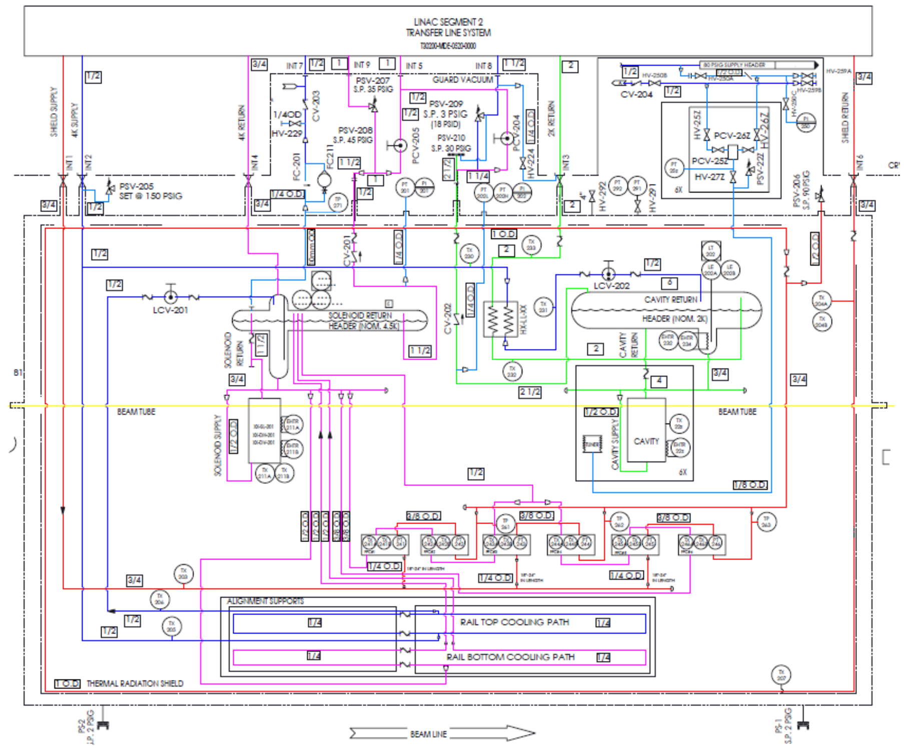
Cryomodules (cont.)

- CM is thermally shielded using the 40-55 K helium flow
- Shielding flow after entering the CM is first used to intercept the FPC heat loads
    - The flow is divided into multiple parallel series paths to reduce the flow induced vibrations and to minimize the pressure drop



Cryomodule: Magnet Cooling

- Since the FRIB CM's are comprised of both cavities & solenoid magnets, 4.5 K supply flow is divided upon entering CM
- Solenoid magnets are cooled using a thermo-siphon
- 100 mm diameter overhead header with a vertical 'cross' serves as a phase separator for the vaporized liquid
- Vertical section houses the liquid level probe
- Magnets are supplied liquid from the bottom and there are separate two-phase returns to the header vapor space
- Heaters are provided for vaporizing the liquid helium in the magnet reservoirs for CM warmup



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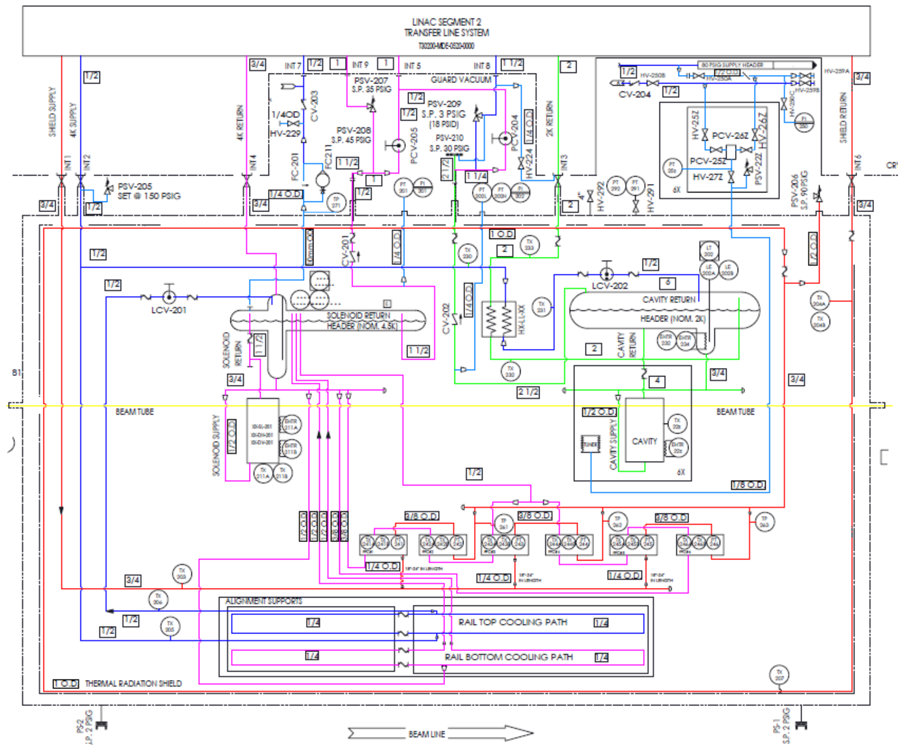
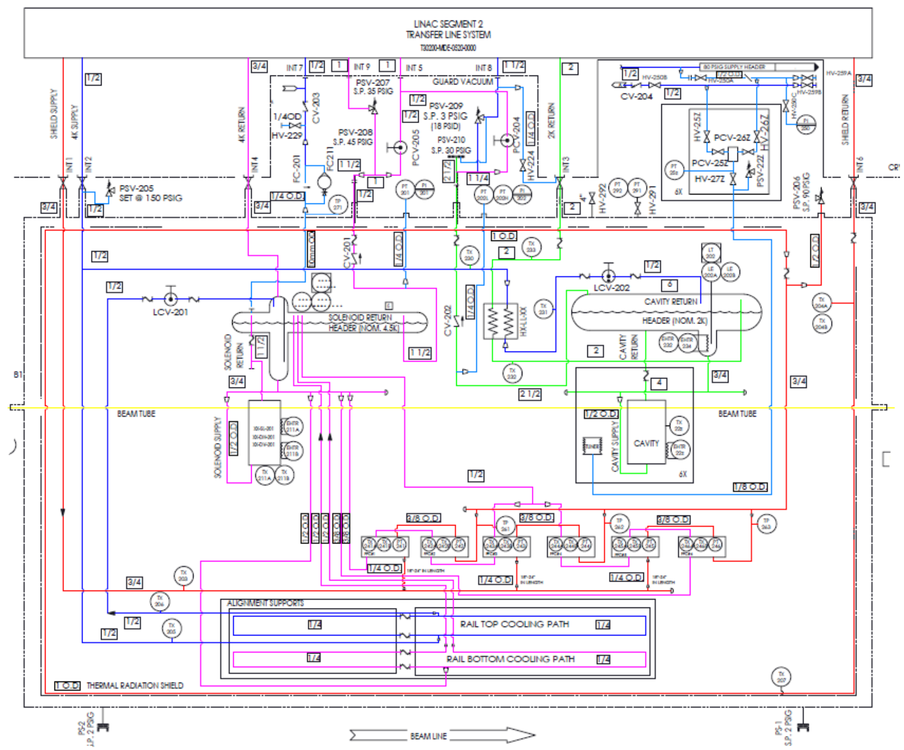
Cryomodule: Cavity Cooling

- Cooling configuration for the SRF cavities is similar to the solenoid magnets
- Liquid helium is supplied to the bottom of the cavity liquid space
- Overhead header is larger, being 150 mm in diameter
- Vertical risers from the top of the cavity volumes are,
  - Generously sized and closely coupled to the header
  - But with sufficient static pressure to ensure a sufficiently high peak heat flux to prevent local boiling when operated at 2 K
- Two sizes of helically coiled finned-tubing (Collins type) 4.5 - 2 K heat exchangers are used in the FRIB CM's



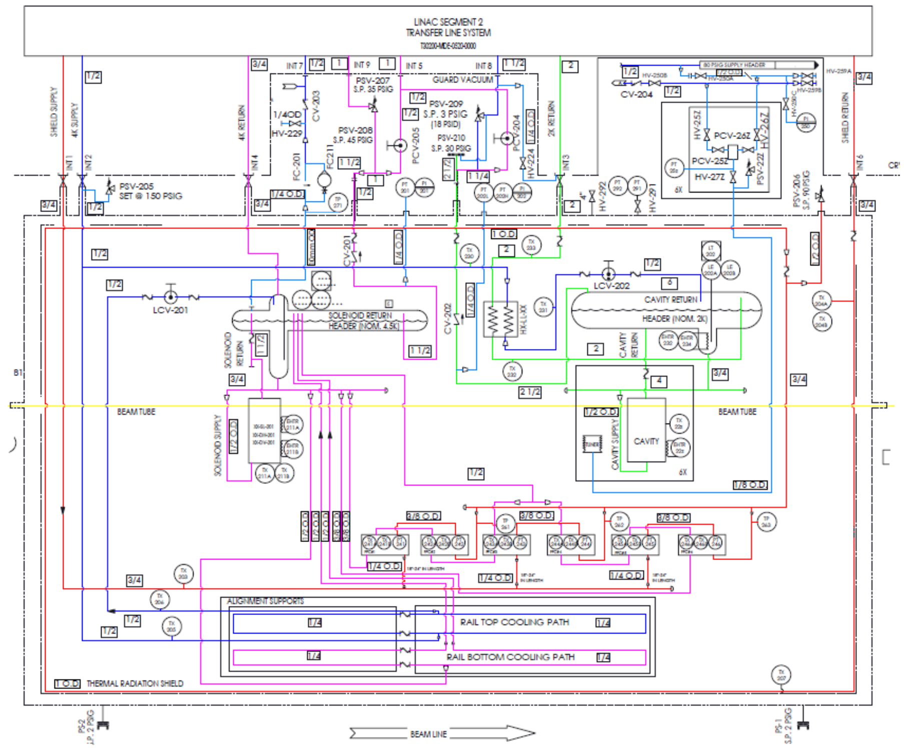
Cryomodule: Electric Heaters

- Electric heaters are provided to add a load to the liquid helium being used to cool the cavities; need to,
  - Compensate for the load change when cavity RF is turned off, so that pressure disturbance to the sub-atmospheric return stream is minimized
- FRIB beta 0.041 and 0.085 CM's use (immersion) heaters mounted within the liquid part of the headers
  - They are away from the cavities, so interaction between the (cavity) RF heat and heater heat is minimized for good performance
  - This design requires a feed-through from the process to insulating vacuum space
  - Band heaters are being used for the beta 0.53 CM's, to eliminate sub-atmospheric feed-through



Cryomodule: Cool-Down Lines

- Two separate cool down paths with valves are provided:
  - One for the magnet and one for the cavity
  - Allows independent cool-down or warmup (of magnet and cavity circuits)
    - » Can be used for degaussing after a quench to recover the CM performance
  - Magnets are equipped with,
    - » 3.4 bara relief, and,
    - » 4.1 bara rupture disk
  - Cavities are equipped with,
    - » 1.24 bar differential pressure relief connected to the guard vacuum system and,
    - » 3.1 bara parallel plate relief with a guard vacuum intercept (in between inner and outer o-rings)



Cryomodule: Production

- Cavities are individually tested and certified
- Then, cold mass assembly is then done
- Since 2014, CM’s have been assembled in up to five parallel bays onsite
- Each CM is individually tested prior to being located in the Linac tunnel
- Presently, 35 of the 46 CM’s have been tested and are in the tunnel
- Remaining CM’s are scheduled to be completed, tested, and installed in the Linac tunnel before the end of 2019

Cryo-Distribution

- Decision in 2012 separate the Linac into three cryo-distribution TL's for LS1, LS2 and LS3 was a major factor permitting the aggressive project schedule to be met
  - Allowing the fabrication, installation and commissioning of the many systems to progress in parallel
- Cryogenic distribution system includes the 46 standardized TL sections in the Linac to interface with each CM
- Each Linac segment has its own vertical shaft line that connects between the cold box room and the Linac tunnel
- Most of non-cryogenic interconnecting piping, the critical parts of the vertical shaft cryogenic TL's, and the Linac tunnel cryo-distribution lines were completed well before the BOD by coordinating with the building contractor

Cryomodules (cont.)

- Typical CM to Cryo Distribution Bayonet Connections

LS1 Transfer Line and the turn around Can

U-Tube connections between CM and cryo Distribution

Cryo-Distribution (cont.)

- Relief sizing and set points were carefully coordinated from the CM to the cryogenic plant
- Each Linac segment has its own relief rack in the cold box room
  - Set-points for these reliefs are lower than the tunnel
  - During an upset condition, if a relief set-point is exceeded, the ones inside the cold box room will discharge, rather than in the tunnel
  - All process lines have replaceable relief valves in the cold box room for re-certification and/or replacement
- Supply from the main 4.5 K cold box can either be super-critical (i.e., approx. 3 bar 4.5 K) or saturated liquid from the 10 kL liquid helium dewar (approx. 1.65 bar)
  - During the commissioning of the CM cavities on LS1 at 4.5 K, it was found that they were to establish a phase lock more easily using the saturated liquid supply
  - Presently, the CM commissioning on LS2 and the (already commissioned) CM's on LS1 are being supplied using the 10 kL dewar

Non-Cryogenic Lines

- There are many non-cryogenic ('warm') lines to support the various modes of operation of the cryogenic devices in the Linac
- This includes:
  - CM cool-down return
  - Magnet power lead flow recovery
  - 3 bar 300 K helium supply for purging
  - Guard vacuum for intercepting air in-leaks into the sub-atmospheric component connections
  - Primary relief connections from the CM to the vent system
- Each of these services and functions are separated by Linac segment and controlled from the cold box room
  - This provides great flexibility for supporting various modes of operation without the need to access the tunnel

Conclusions

- Impact of initial decision to,
  - Provide individual distribution lines to each Linac segment, and,
  - Use JLab/SNS style cryogenic couplings
- These significantly contributed to meet the FRIB's aggressive project schedule by allowing stage-wise commissioning
- Heat load estimates for FRIB have been revised to reflect the updated designs
  - Estimated that the exergy required for the expected loads is approx. two-thirds of the cryogenic plant capacity (1330 kW).
  - As originally planned, these still indicate an appropriate margin to the provided refrigeration capacity
  - This part load operation and/or a change in the load type can be handled efficiently, since:
    - » 4.5 K refrigeration system operates on the Floating Pressure Process
    - » Cold box was designed using equal 'Carnot' steps, and,
    - » Compressors have a very wide operational envelope