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Design, Fabrication, Commissioning and Testing of FRIB 2 K Cold Compressor System

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Background

- Cryogenic process which provides 2 Kelvin (31 mbar) to the SRF cavities in the FRIB Linac uses a series of five cryogenic centrifugal ("cold") compressors ("CC")
  - Brings the helium from ~29 mbar 4 K up to 1.2 bar ~30 K
  - i.e., "Full" cold compression (sub-atm. to positive pressure)
  - CC discharge injected back into the 4.5 K cold box
  - Housed within an insulating vacuum vessel, or sub-atmospheric cold box
- This type of 2 K system is superior to 'partial' (or 'mixed') cold compression systems; e.g.,
  - More efficient, less expensive, and requires a smaller equipment 'foot-print'
  - More reliable since the sub-atmospheric condition is dealt with in the most immediate manner
    - » i.e., risk of air in-leak contamination is reduced
  - And the CC's are substantially more robust and require less maintenance than sub-atmospheric warm compression equipment

Background (cont.)

- Often the limited turn-down is cited as a significant drawback to full vs. partial (or mixed) cold compression
  - Underlying motivation usually driven by assumptions regarding commissioning schedule of the accelerator, and/or uncertainties in the accelerator load
  - In practice, the turn-down for partial cold compression (of large systems) has been demonstrated for approximately a 3 to 1 ratio
  - <u>Energy savings for this kind of turn-down can only be realized if the 4.5 K refrigeration system can also turn-down efficiently over this range</u>
  - Prudent?...2 K load capacity requirements strongly driven by a relatively short term commissioning activity vs. the long term science program needs
- It is fundamental to stable and reliable 2 K operations that the 4.5 K system refrigeration system be capable of,
  - Wide capacity range, and load type
  - Handling transient processes – including upsets and those required for normal operations

Background (cont.)

- To achieve a sub-atmospheric condition from an initial positive pressure (say, 1.2 bar), the system must be 'pumped-down'
  - Full cold compression pump-down is a more complex and challenging process than a partial cold compression process
  - Latter allows operators a wider margin when pumping-down the system
    - » Since the vacuum pumps (in such a system) can reduce a significant portion of the pressure ratio which the cold compressors must handle
  - For these processes…many,
    - » Many control elements (e.g., compressor speeds, compressor bypasses, cryomodule liquid level control valves, cryomodule heaters, etc.)…
    - » Across a number of sub-systems (main compressors, 4.5 K cold box, sub-atmospheric cold box, cryogenic distribution, cryomodules, etc.) and,
    - » Many possible process parameters (e.g., pressures, temperatures, speed, liquid levels, etc.) with which to regulate the control elements
    - » And, often the initial-starting conditions are typically different

Background (cont.)

- Despite complexity, with the implementation of,
  - Floating Pressure Process for the 4.5 K refrigerator, and,
  - Simple process control developed (by one of the authors, 1994) for the JLab sub-atmospheric cold boxes
- …the full cold compression process is efficient and stable for these transient operations (and upsets)
  - This process ensures a steady acceleration of the cold compressors during the critical part of the pump-down process
  - Has been well established for the past 25 years (since 1994) at JLab, and for the past 15 years at SNS
- FRIB is one of five sub-atmospheric 2 Kelvin helium systems of its kind in the world
  - However, only the two at Jefferson Lab (JLab) are of comparable capacity
  - i.e., the upgraded original system, and the 12 GeV refrigerator
  - System at SNS and XFEL are roughly two-thirds the capacity of the FRIB and JLab systems

Process Design Requirements

- FRIB cryogenic staff performed process studies, preliminary analysis, and developed the specification for the cold compressors

	CC Mass Flow Rate [g/s]	CC1 Suction Temperature [K]	CC1 Suction Pressure [mbar]	CC5 Discharge Temperature [K]	CC5 Discharge Pressure [bar]
Maximum Capacity	180	3.9	≤ 28	< 30	1.20
Nominal Capacity	120	4.2	29	< 30	1.20
Minimum Capacity	110	4.3	29	< 30	1.20

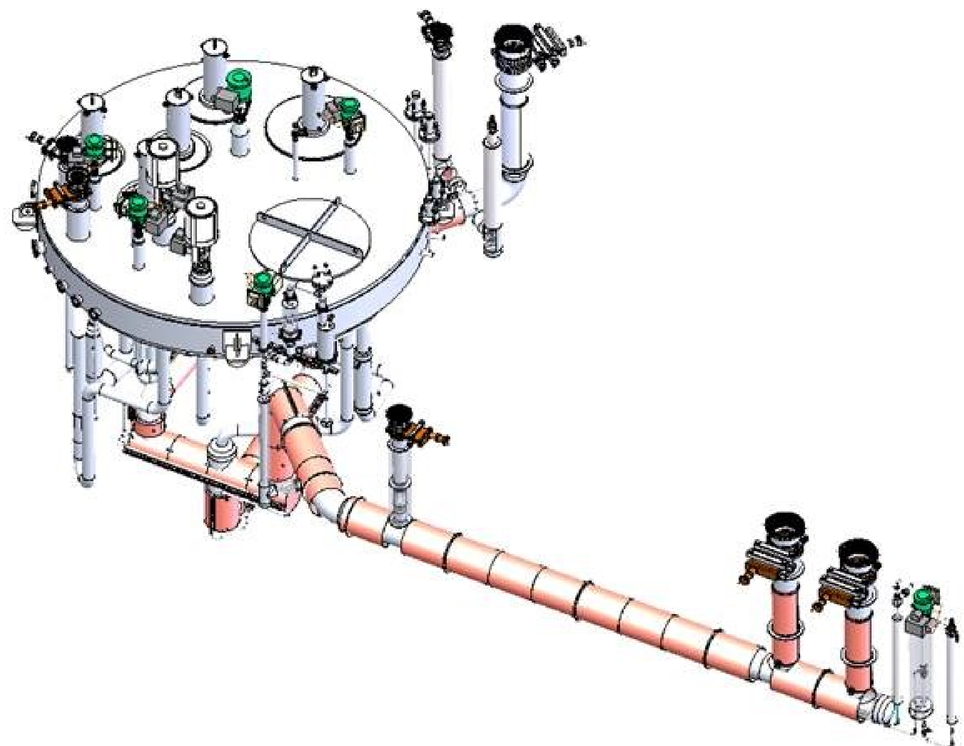
- Specification also included requirements for the start of pump-down, pump-down peak, and an upgrade provision
- RFP was awarded in October 2015 and delivered to FRIB December 2016

Cold Compressors

- 2 K system uses five stages of cold compressors
  - Stage 1 (CC1) is the largest and handles the flow returning from the Linac
  - Stage 5 (CC5) is the smallest and its discharge is injected to the 4.5 K helium refrigerator (at the 30 K temperature level)
  - Compressor wheel diameters range from about 200 mm to 85 mm; with maximum speeds ranging from ~300 to over 800 Hz
  - Stages 4 and 5 are interchangeable; this was intentional
  - All the compressor wheels are ‘three dimensional’ and use a vanless volute design
- Compressors
  - Bearings: 5-axis AMB – with touch-down mechanical bearings
  - Motors: 2 pole 100 V synchronous permanent magnet
    - » CC1/2 higher torque – lower speed motor; as compared to stages CC3/4/5
    - » Mounted externally (not within the cold box vacuum)
    - » Motors and wheels can be removed from casings, while maintaining an insulating vacuum
    - » Water cooled and guard vacuum intercept to prevent air in-leaks
    - » Separate electrical cabinet that houses the variable frequency drive (VFD), AMB controller, and local controller
    - » <u>There are no other 2 K helium cryogenic plants in the world which use these compressors/motors</u>

Sub-Atmospheric Cold Box: Design

- Except for CC’s, entire design of sub-atmospheric cold box was led and performed by the FRIB cryogenic group; includes,
  - Process design and analysis; i.e., performance, stability, sizing, etc.
  - Mechanical design; i.e., piping, components, stress, etc.
  - Electrical design; i.e., instruments, wire/cabling, power supplies, etc.
  - Controls design; i.e., programming, communications, human-machine-interface, etc.
- Internal piping and top plate of sub-atmospheric cold box

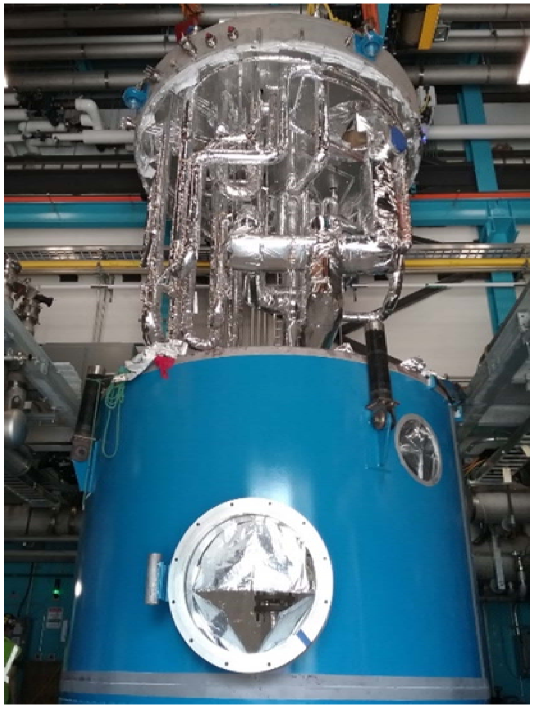


Sub-Atmospheric Cold Box: Design (cont.)

- Design includes the following features:
  - Shield (approx. 35 K) of suction line to CC1
  - Back-filling from 10 kL LHe dewar (vapor), or Linac 4.5 K (return) vapor
  - Back-filling from 30 K injection on 4.5 K helium cold box
  - Forward-filling from Linac
  - Process heater on 4.5 K vapor injection to regulate CC1 suction temperature
  - CC overall ‘train’ bypass (i.e., CC5 to CC1)
  - CC2 to CC1 bypass
  - Ability to prevent Linac over-press. & min. boil-off during a power outage
  - Ability to warm-up, clean-up and then (re-)cool-down any individual compressor or the entire cold box without affecting 4.5 K operations
  - Instruments (pressure, temperature, mass flow, power, speed) necessary to characterize performance of individual compressors and overall ‘train’
  - Any combination of the three Linac segments (LS1 to LS3) can be connected, and operated at 2 K
  - Provision to prevent back-flow (and in-leakage) of air into helium process from a sub-atmospheric relief valves

Sub-Atmospheric Cold Box: Fabrication

- Except for cold compressors (including motors and electrical cabinets) and vacuum shell, entire cold box was fabricated ‘in-house’ at FRIB
  - Mechanical and I&EC
  - Vacuum shell and top plate was fabricated by local supplier
- Installation of the top plate in the vacuum shell

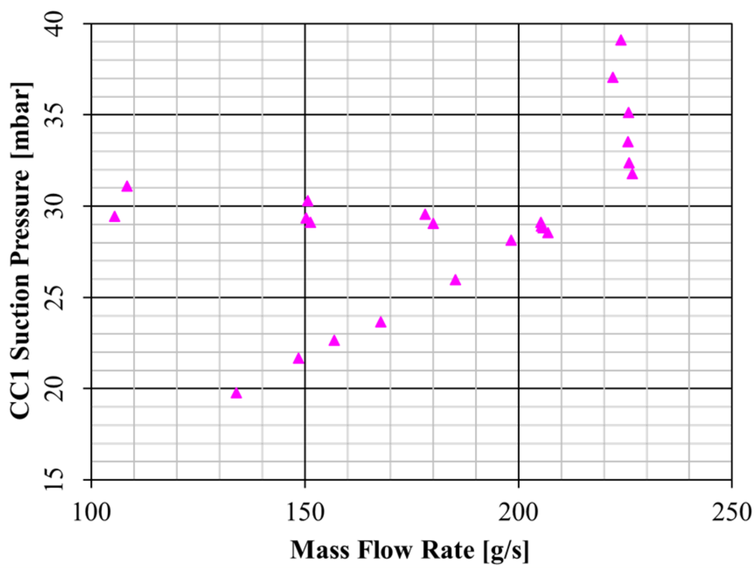


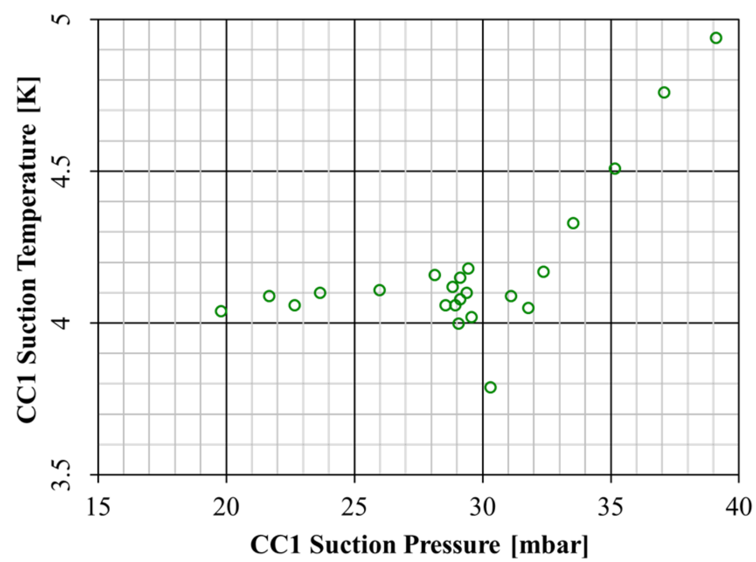
Sub-Atmospheric Cold Box: Preparations for Commissioning (cont.)

- Mechanical preps included:
  - ASME code (piping) leak ('pressure') test
  - Sensitive helium leak check: piping to vacuum, external piping
  - Valve leak-through test
  - Insulating vacuum check
  - Clean-up
  - Spin check at maximum speed under vacuum at ambient temperature, 14-Dec-2018
  - Diode calibration at 4.5 K ('flood' with liquid), 17-Dec-2018
  - Partial warm-up (for u-tubes)
  - Connection to Linac (LS-1), 18-Dec-2018
  - Cool-down (to 4.5 K)
- I&EC preps included:
  - Simulated funct. & oper. check-outs
  - Valve operation
  - Test heater verification
  - Insulating vacuum system
  - CC communications interface
  - CC enable, run/stop/reset
  - CC hard landing logic
  - Permissives
  - Trips (safety shut-downs)
  - Alarms
  - PID loops
  - Pump-down sequencer and logs
  - Install power measurement in vendor AMB/VFD cabinets
  - Fix transformer grounding
  - Fix/connect wiring terminations to motors

Commissioning and Testing

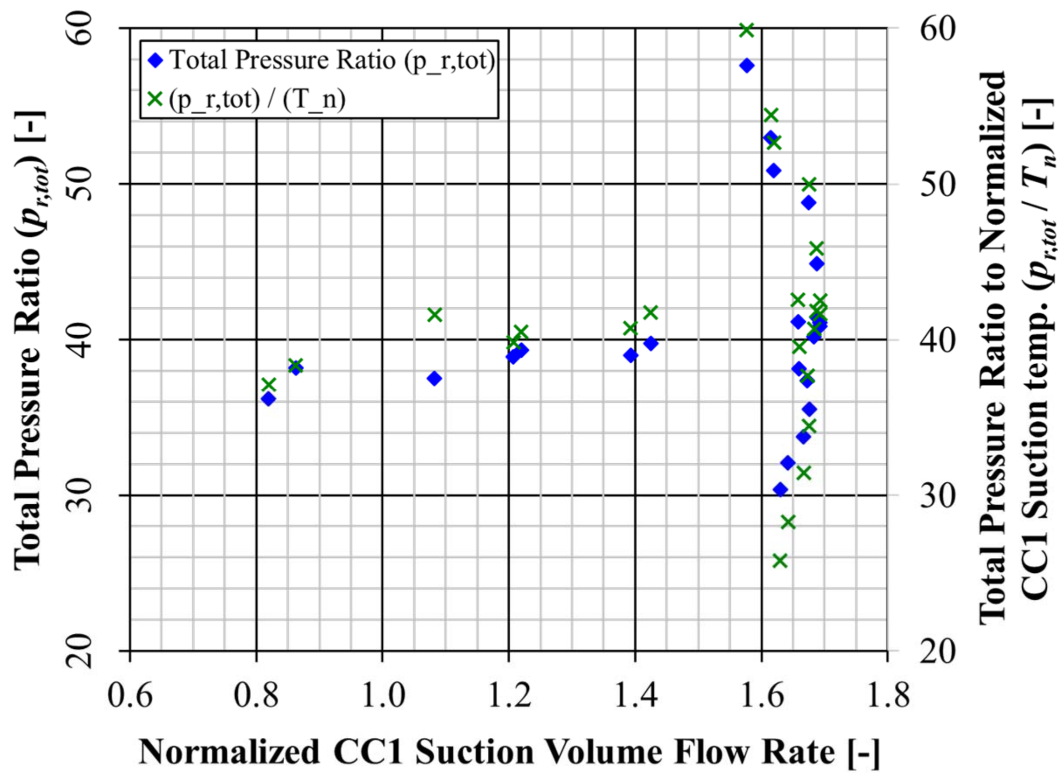
- System successfully pumped-down & operated at 2 K on the third attempt (19-Dec-2018, which was the second day of commissioning)
  - To provide adequate suction volume for stability: connected to the first Linac segment
- Further testing performed in Jan. and Feb. 2019 for several days each time; objectives to,
  - Verify the design basis (max., nominal, and min. capacity), and,
  - Characterize the operating boundaries





Commissioning and Testing (cont.)

- LHS *y*-axis: total (or overall) pressure ratio
- RHS *y*-axis: total pressure ratio divided by the normalized CC1 suction temperature
  - 'Normalized' – i.e., relative to nominal design condition (4.2 K)
  - Correction is done, as it is known that stability limit is a function of both the pressure ratio and suction temperature
- *x*-axis: normalized CC1 suction volume flow
  - CC1 suction volume flow calculated from measured pressure, temp. & mass flow rate
  - 'Normalized' – i.e., divided by normal design condition vol. flow



Commissioning and Testing (cont.)

- As can be seen this system has a considerable operating range…
- And a *turn-down of nearly 2 to 1 at the operating condition* (i.e., at a total, or overall pressure ratio of approx. 38 to 40)
- Operation of these cold compressors was very stable
- Further testing-mapping is planned

- Three significant but minor issues occurred during commissioning
  - CC mass flow measurement initially indicated lower than actual – corrected on 20-Dec-2018 (i.e., the third day of commissioning, before the second successful pump-down)
  - CC motor power calculation and CC AMB parameter (for indication of rotor clearance) were corrected during subsequent testing-mapping in Jan. and Feb. 2019

Conclusions

- FRIB cryogenic staff led and were responsible for the specification, design, fabrication, and commissioning of sub-atmospheric cold box
- Entire design of the sub-atm. cold box was led and performed by FRIB cryogenic group: i.e., process, mechanical and electrical (except CC's)
- Entire cold box was fabricated 'in-house' at FRIB – mechanical and I&EC (except for CC's, and vacuum shell)
- FRIB cryogenic group achieved successful CC pump-down to 31 mbar (i.e., 2 Kelvin) on Linac segment one (LS1) on the third attempt
- All commissioning issues were quickly resolved
- Testing-mapping has demonstrated a very wide range of stable operation
- FRIB expresses it appreciation to Air Liquide and MECOS for their contribution to the success of this project