FRIB Helium Compression System Commissioning & Performance Test Results

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Background: FRIB Compressor System

- Three streams interface with 4.5 K main helium cold box system:
  - LP stage suction
  - MP stage suction
  - HP stage discharge
- Medium-pressure-high (MPH) header: discharge from the LP and MP stages; also the HP stage suction
- Swing stage discharge is common with the HP stage
  - Its suction can be aligned with the LP, MP or MPH headers
- Gas management, process control valves: interconnect the four headers (LP, MP, MPH, and HP)
- Arrangement is identical to that used for JLab's 12 GeV compressor system; except, based upon operating experience:
  - Inlet to the HP bypass is connected downstream of the final oil removal
  - MP-to-LP bypass uses a 2.5 IPS control valve and 3 IPS venturi flow meter

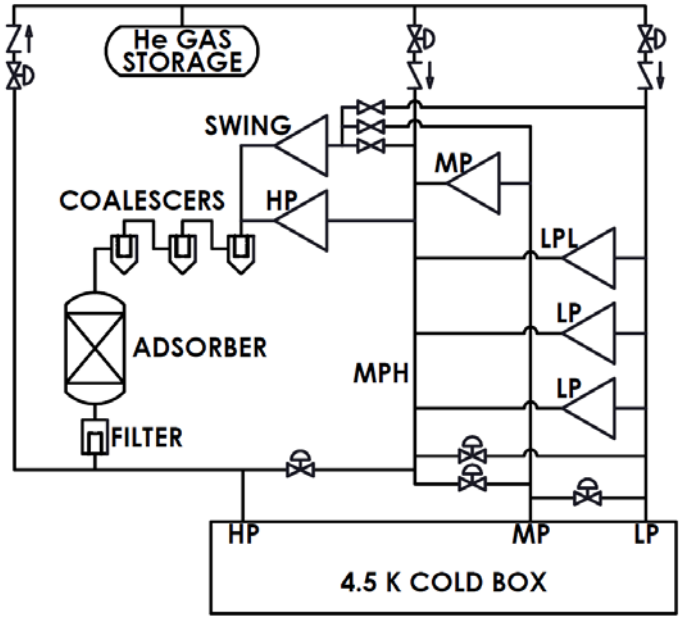
Background: FRIB Compressor System (cont.)

- Due to the expected cryogenic load, one of the three LP stages is different from the other two
  - Designated as “LPL”; its rotor length is 14 percent (%) longer than the others
  - This is different than Jlab 12 GeV system
- ‘Swing’ compressor has the same design as the HP stage
- All of the compressors have a variable built-in volume ratio (BVR, or, “Vi”) adjustment
- FRIB system uses CP 4601-68 as the lubricant
  - Same as do the compressors for the NASA helium compressor system
  - JLab 12 GeV system uses UCON LB-170X.

Background: FRIB Compressor System (cont.)

- Summary of main helium compressors

	LPL Stage	LP Stage	MP Stage	HP Stage
No. of Units	1	2	1	2
Compressor Model No.	WLVi 321/220	WLVi 321/193	WLVi 321/165	WLViH 321/193
Suction Swept Volume	35.526 l/rev	29.979 l/rev	26.649 l/rev	29.979 l/rev
Motor Frame	4009	3508	3508	4512
Full-load amperage (FLA)	124	99	99	305
Motor Rating	746 kW	597 kW	597 kW	1864 kW



Background: FRIB Compressor System (cont.)

- Design of FRIB compressor skids is essentially the same as used for the JLab 12 GeV system but with some improvements
  - Helium system for NASA James Webb project that was the prototype for these very successful designs
  - Design was accomplished by one of the authors, and was provided to industry as a build-to-print package for each project
  - This approach for design & procurement proved quite successful at JLab & FRIB
  - Skids are capable of efficient & automatic operation over very wide range of process conditions, without concern of excessive oil carry over, or component damage
  - Allow a full implementation of the Ganni-Floating Pressure Process
- Level of effort is warranted on the following basis:
  - Typically ~50% input power is wasted in compressor system irreversibilities - even for large systems that are well-matched with refrigerator system
  - ~50% margin is typical in refrigeration system design capacity due to uncertainties in experimental program it supports and progressive commissioning requirements
  - Sub-system is critical for a reliable helium refrigeration system

Performance Mapping

- January to February of 2018, performance mapping of several of the FRIB compressors was accomplished
  - FRIB compressors are designated C1 to C6
    - » C1: LPL stage
    - » C2 and C3: LP stages
    - » C4: MP stage
    - » C5: HP stage
    - » C6: Swing stage
- Gas management
  - Not only comprised of the mass-in, mass-out, and compressor bypass (process control) valves…
  - But also flow venturi meters
    - » Used to measure the compressor helium mass flow rate
    - » Checked for through helium leakage at operating conditions & adjusted leak tight
    - » Pressure & temperature measurements were calibrated
    - » An addition low range pressure transmitter used for testing; an independent suction pressure verification

Performance Mapping (cont.)

- Volumetric efficiency: ratio of measured flow rate (venturi flow meter) to theoretical mass flow rate at the measured suction density
  - Density calculated from measured pressure and temperature
- Isothermal efficiency: ratio of reversible-isothermal input power to the actual compressor input power
  - Assumed ideal gas (reversible-isothermal input power)
  - Measured mass flow rate was used
  - Each compressor MCC was equipped with an Eaton XPM 4000 series power meter
  - Assumed that motor efficiency (vs. motor load fraction) provided by the manufacturer was accurate
- Performance testing occurred before this system was required for the commissioning of the helium refrigeration system
- Several of the compressors where tested over a wide range of conditions, and BVR's; and, one was tested at part loading

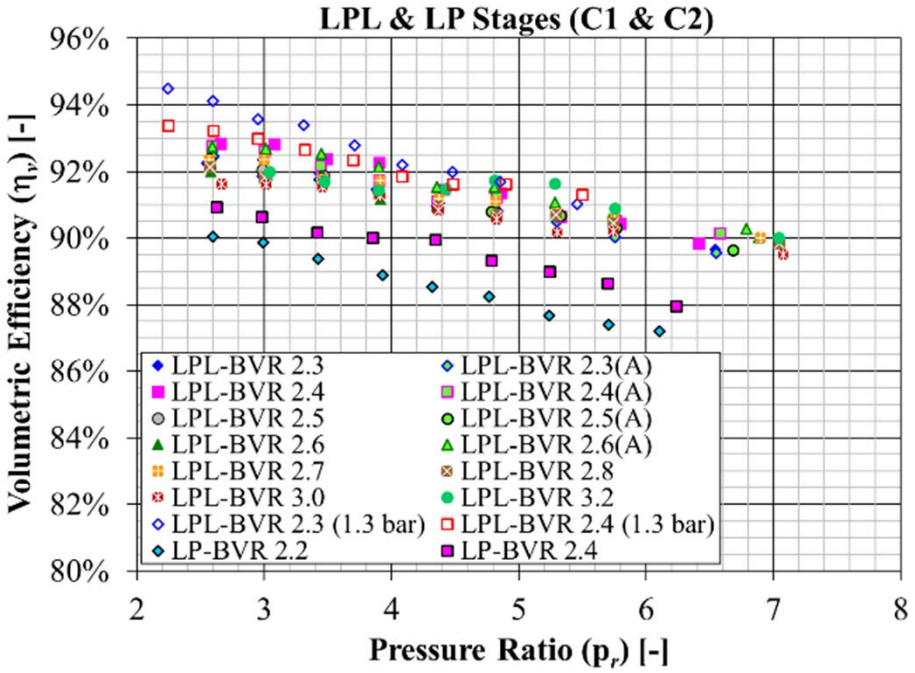
Performance Testing: Fully Loaded

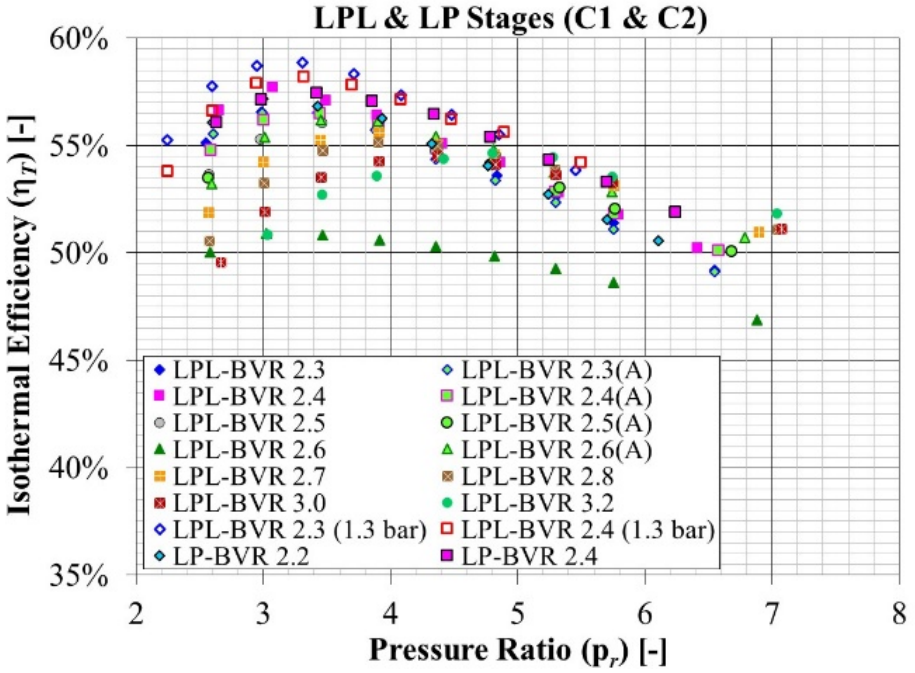
- Summary of ranges covered for full load compressor testing
  - LPL and swing stages were extensively tested over a wide BVR range
  - Unless otherwise indicated, the nominal suction pressure for the LPL, LP, and swing stage tests where as indicated (below)
  - However, pressures in parentheses serve to clarify the suction pressure for a particular data set
  - Letter in parenthesis to the right of the BVR value indicates that the data set was re-measured (i.e., 'A' is the first time, 'B', the second time, etc.)
  - For expediency, no attempt was made to change or manipulate the cooling oil injection valves during the full load testing (thus the range of discharge temperature values)

Compressor Stage	BVR	Suction Pressure [bar]	Discharge Pressure [bar]	Pressure Ratio	Discharge Temperature [K]
LPL	2.3 to 3.2	1.05 to 1.3	2.7 to 7.5	2.2 to 7.1	363 to 374
LP	2.2 to 2.4	1.05	2.8 to 6.7	2.6 to 6.2	365 to 372
MP	2.2	1.2 to 2.2	3.2 to 7.2	2.0 to 5.7	363 to 370
HP	2.2	2.9 to 4.9	8.5 to 18	2.6 to 6.3	363 to 366
Swing	2.2 to 5.0	1.05	6.1 to 18	5.7 to 17	358 to 366

Performance Testing: Fully Loaded (cont.)

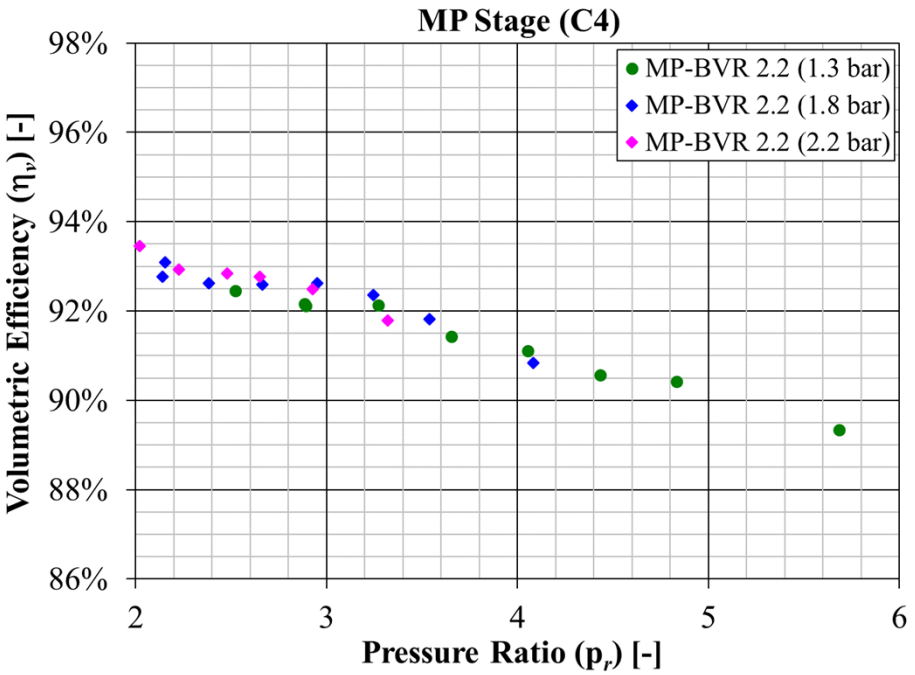
- LPL and LP stage volumetric and isothermal efficiency, fully loaded

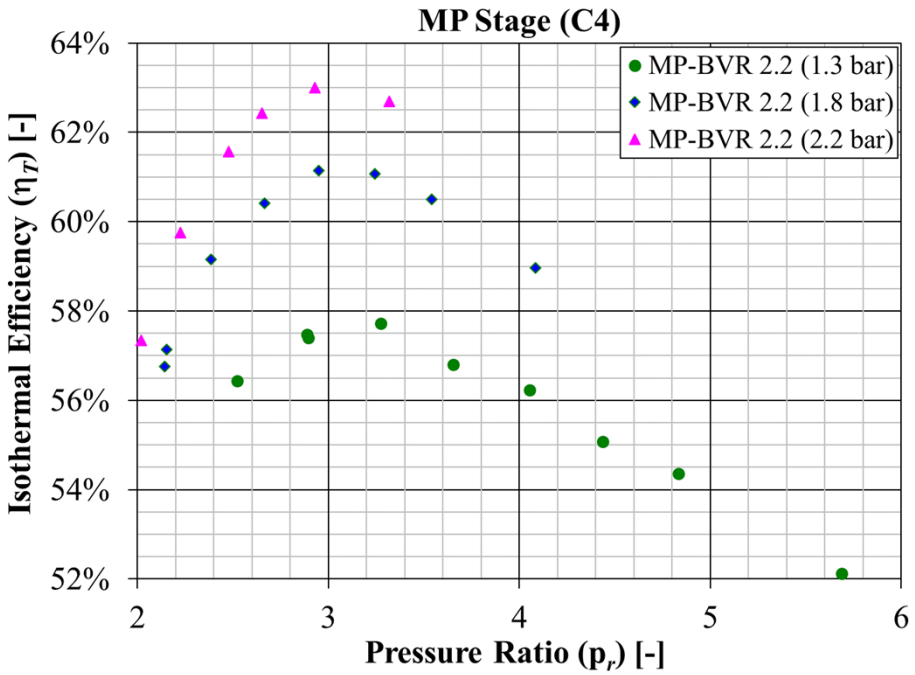




Performance Testing: Fully Loaded (cont.)

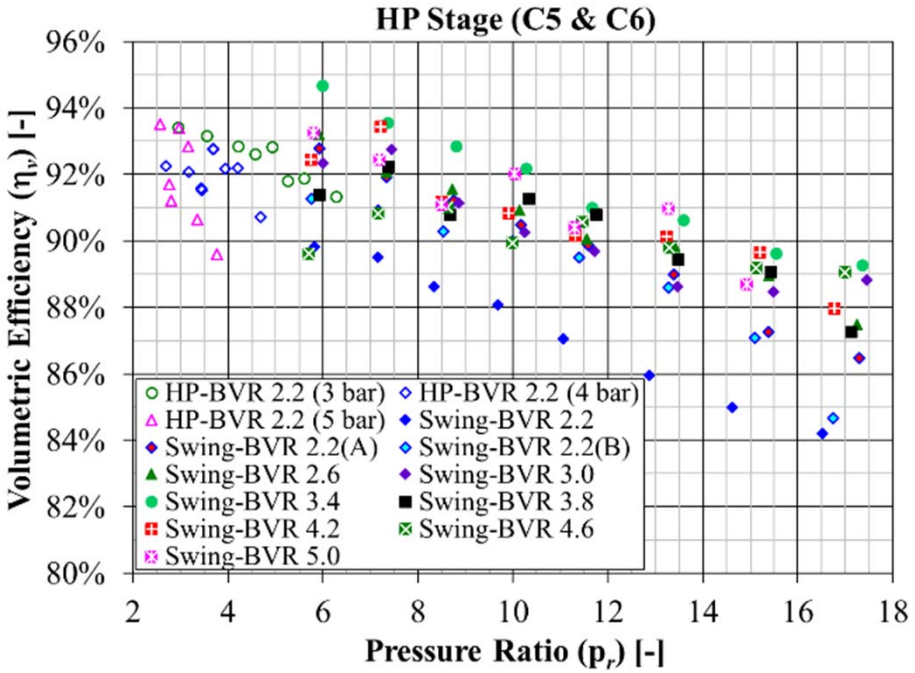
- MP stage volumetric and isothermal efficiency, fully loaded

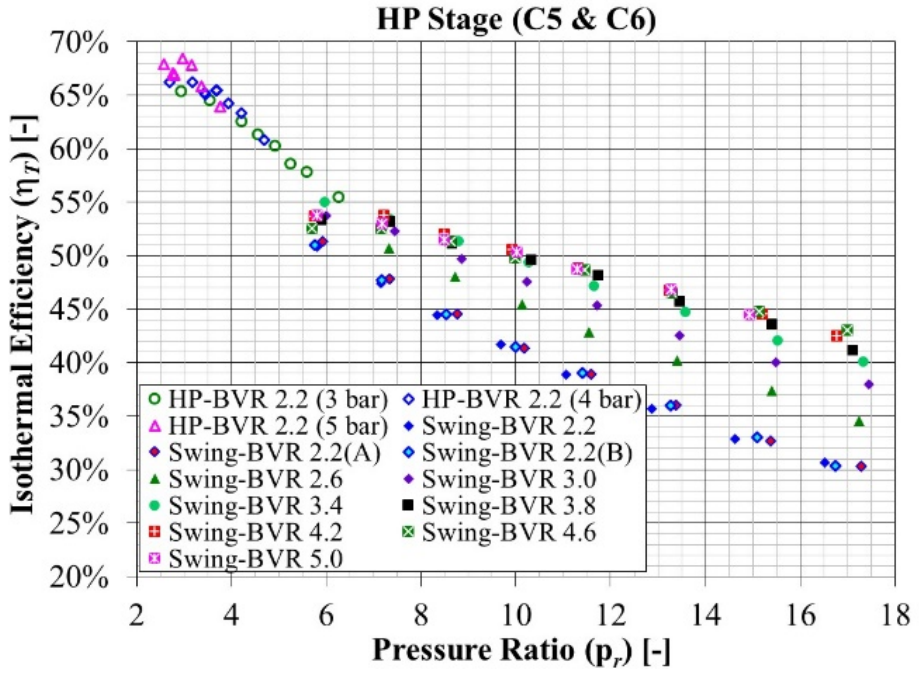




Performance Testing: Fully Loaded (cont.)

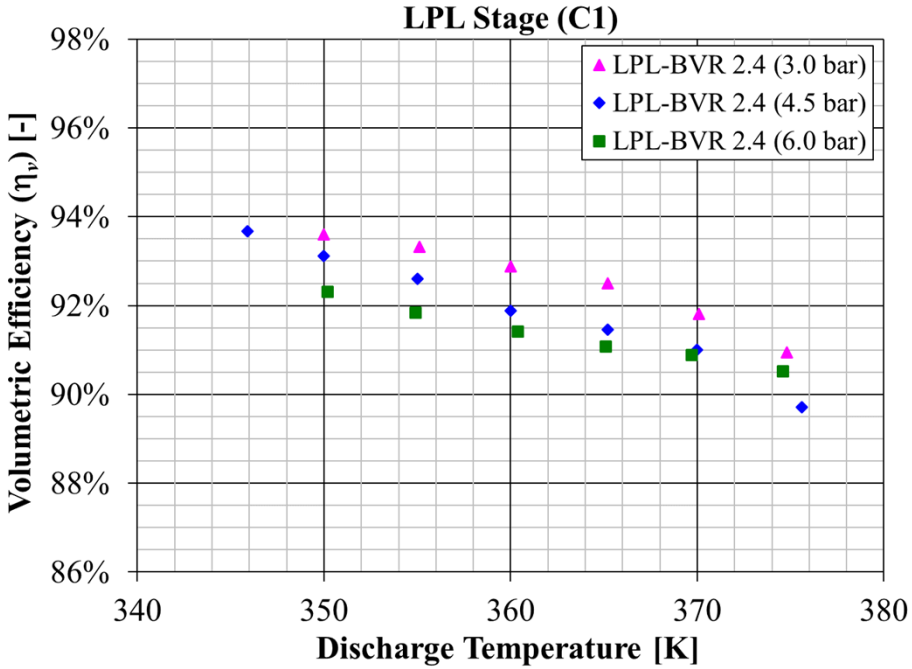
- HP and swing stage volumetric and isothermal efficiency, fully loaded

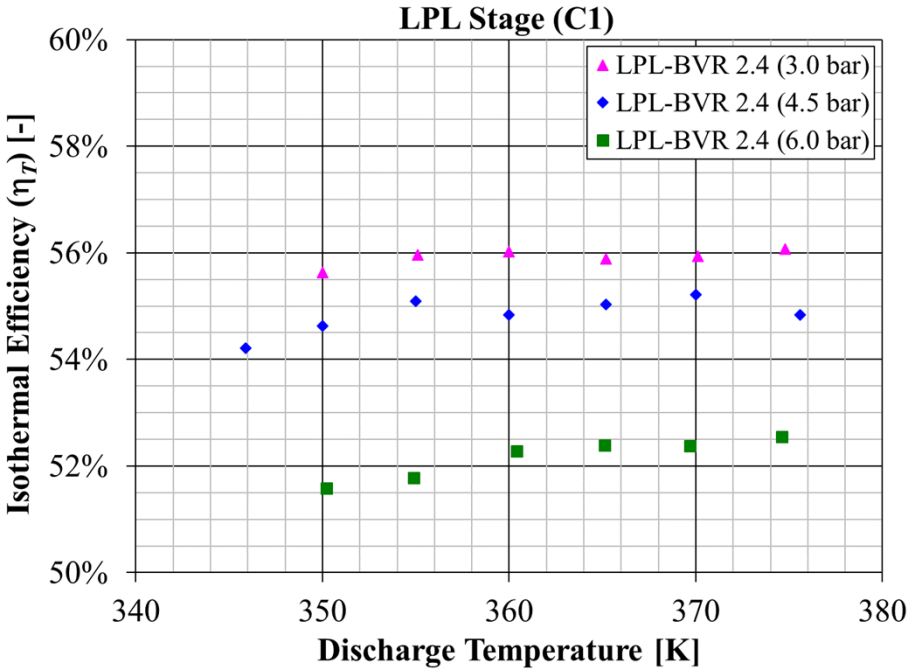




Performance Testing: Fully Loaded (cont.)

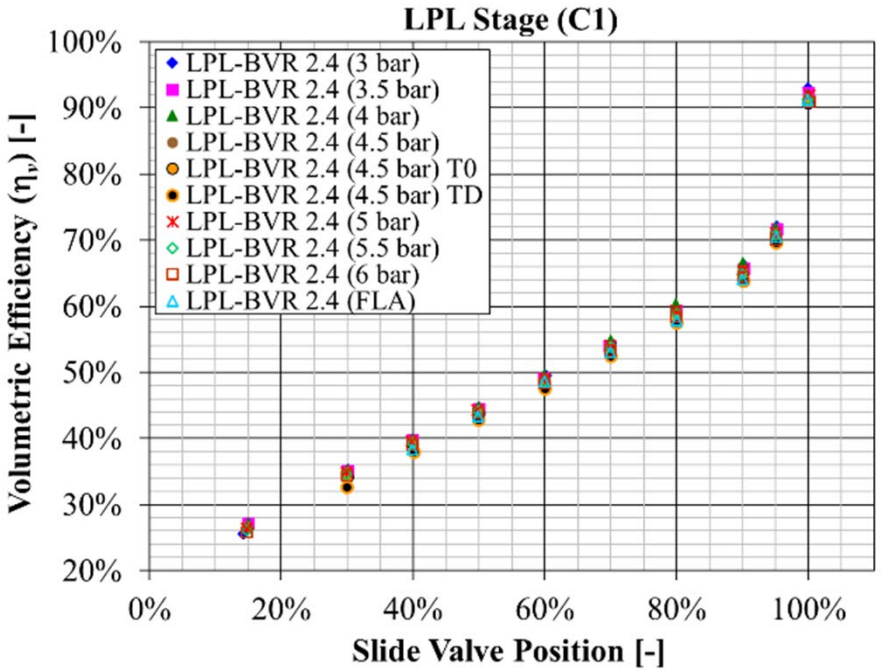
- Tests were also done on the LPL stage where the discharge temperature was varied for a given (fixed) BVR, suction pressure and discharge pressure
  - Accomplished by manipulating the cooling oil injection (valves)
  - For these tests compressor was fully loaded, BVR was 2.4, nominal suction pressure was 1.06 bar, and the discharge pressure was varied from approximately 3 to 6 bar.
  - Volumetric and isothermal efficiency varies approximately 1% and 0%, respectively, between 360 to 375 K

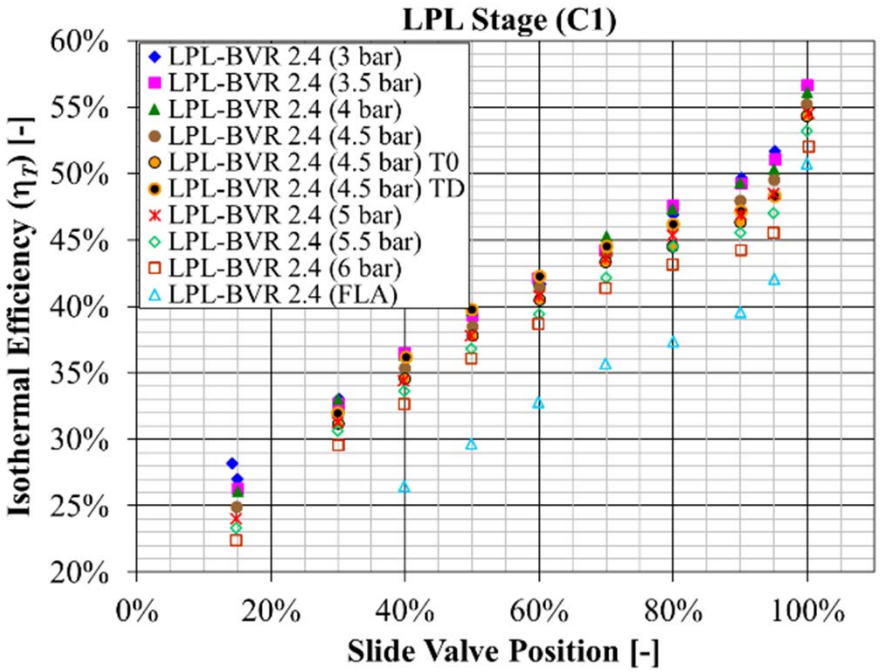




Performance Testing: Part Load

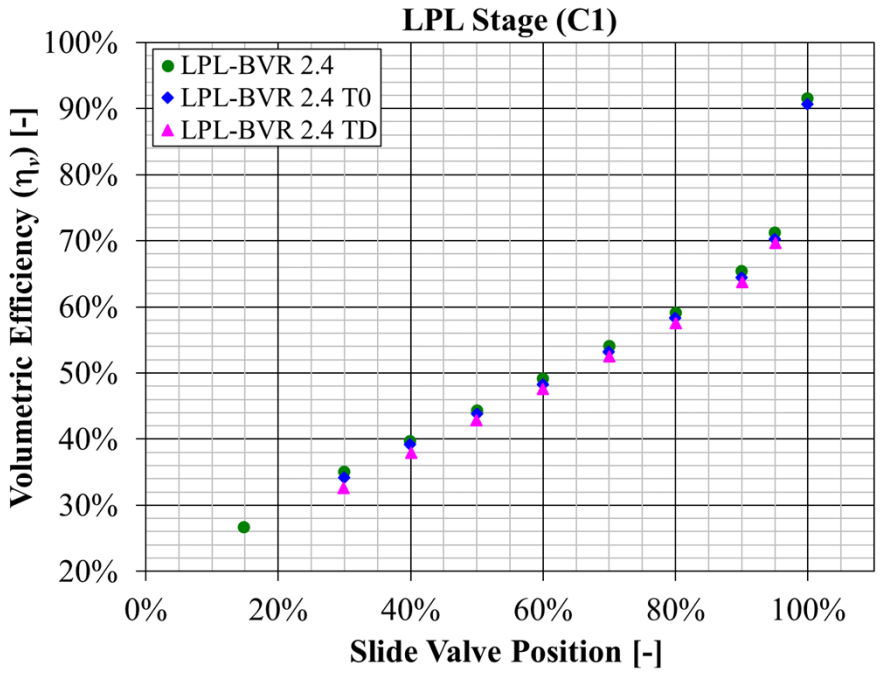
- Part load testing on the LPL stage
  - BVR of 2.4, and 1.06 bar nominal suction pressure
  - Slide valve varied from 15% to fully loaded
  - Discharge pressure varied from 3.1 to 11 bar
  - Pressure ratio varied from 2.8 to 10.2

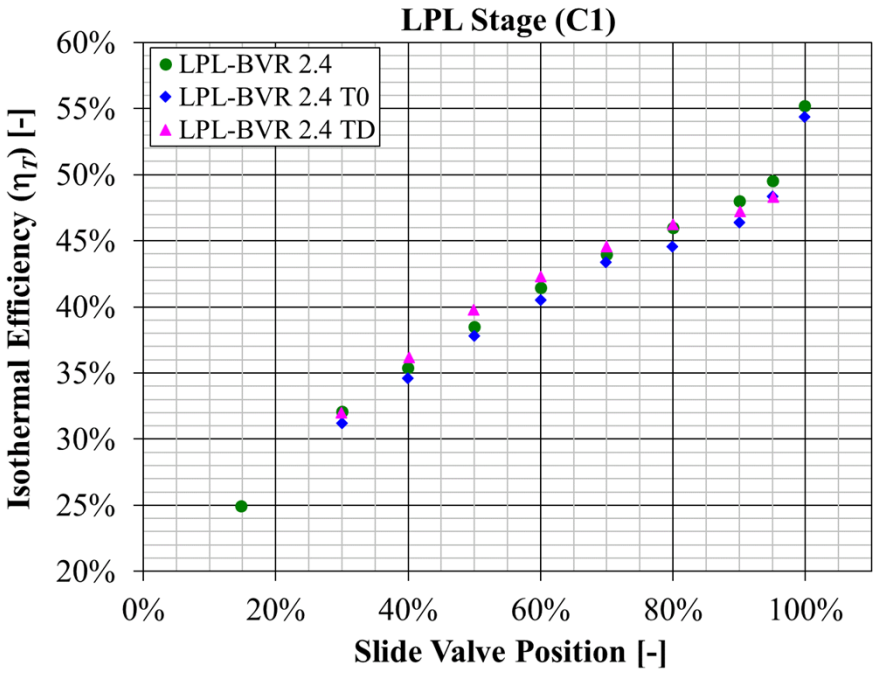




Performance Testing: Part Load (cont.)

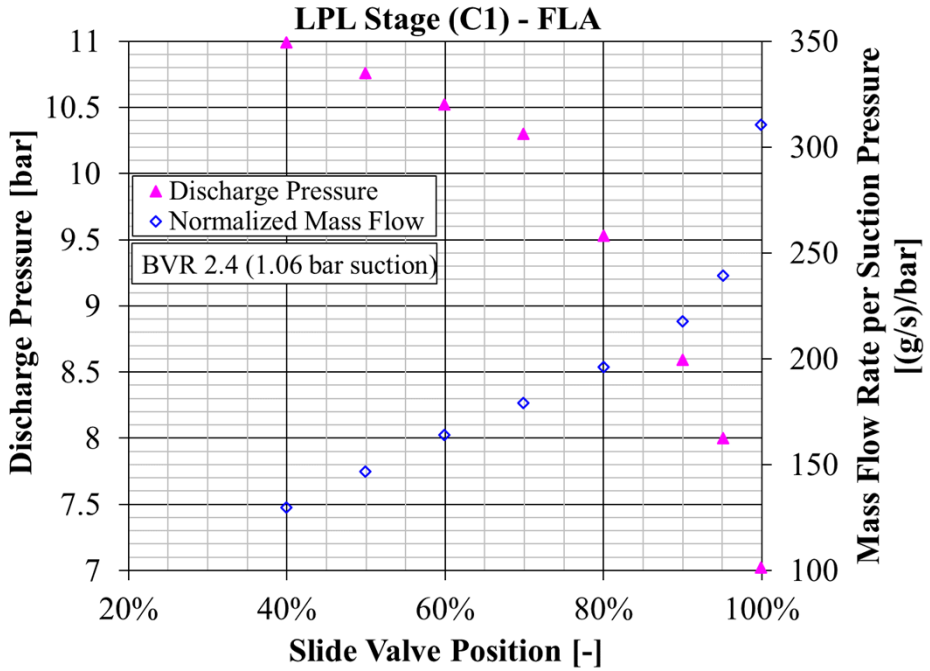
- Also, two sets of part load tests on the LPL stage were done
  - 1st set ("TD" label): cooling oil injection (valves) manipulated at each slide valve position to maintain a fixed discharge temperature of approximately 365 K
  - 2nd set ("T0" label): cooling oil was not manipulated at each slide valve position; injection valves were set so that at a fully loaded condition, the discharge temperature was approximately 365 K
  - Slide valve varied from 15% to fully loaded, BVR was 2.4, nominal suction pressure was 1.06 bar, and nominal discharge pressure was 4.5 bar





Performance Testing: Part Load (cont.)

- LPL stage at the FLA condition, from a part to fully loaded condition
  - Left-hand side *y*-axis is discharge pressure
  - Right-hand side *y*-axis is (measured) normalized mass flow rate; i.e., mass flow rate divided by suction pressure
  - All compressor motors have a service factor of 1.15…so, they can be operated at their FLA condition



Conclusions

- FRIB compressor system successfully commissioned and tested
- It has been supporting incremental commissioning of the other FRIB cryogenic systems without incident
- In the beginning of the project, vibration from these in the Linac was a concern…however, as measured, no difference can be detected whether the compressors in any combination are running or off
- Design allows for safe, reliable, and easy maintenance, while supporting a wide range of cold box operation conditions with a supply pressure anywhere between 6 to 21 bar
- For 4.5 K cold box testing, the BVR for the LPL, LP, MP, HP and swing stages were set at 2.4, 2.4, 2.2, 2.2, and 3.5, respectively
- Most of the compressors have a run time greater than 11,000 hours (by mid-July 2019)
- FRIB expresses it appreciation to PHPK for their contribution to the success of this project