C2Or3D-06: Characterization of centrifugal compressors operating in FRIB's sub-atmospheric system

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U.S. DEPARTMENT OF ENERGY | Office of Science

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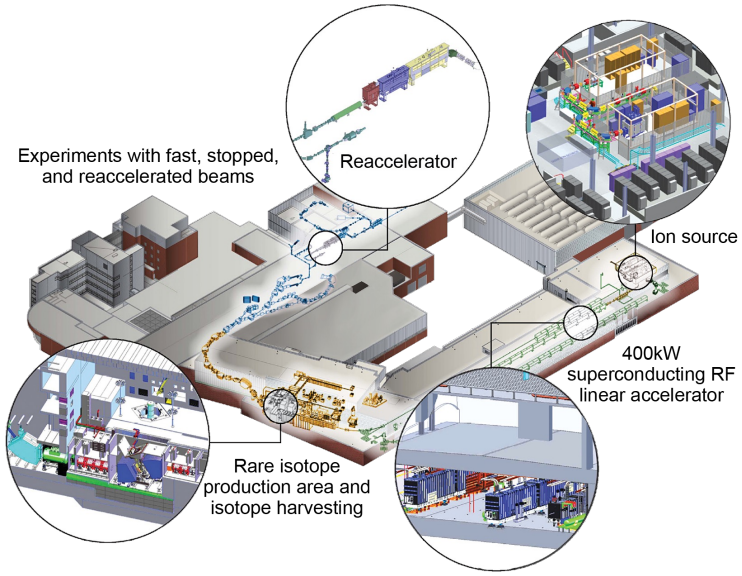
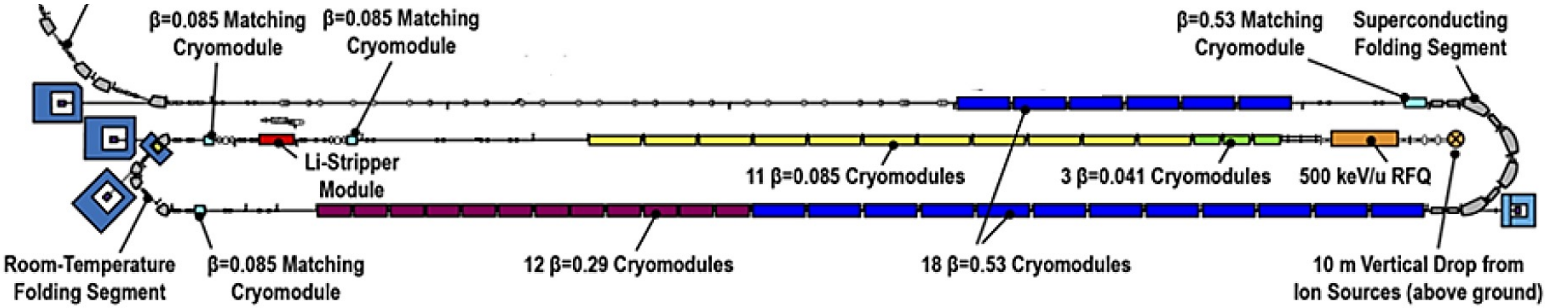
Background [1]

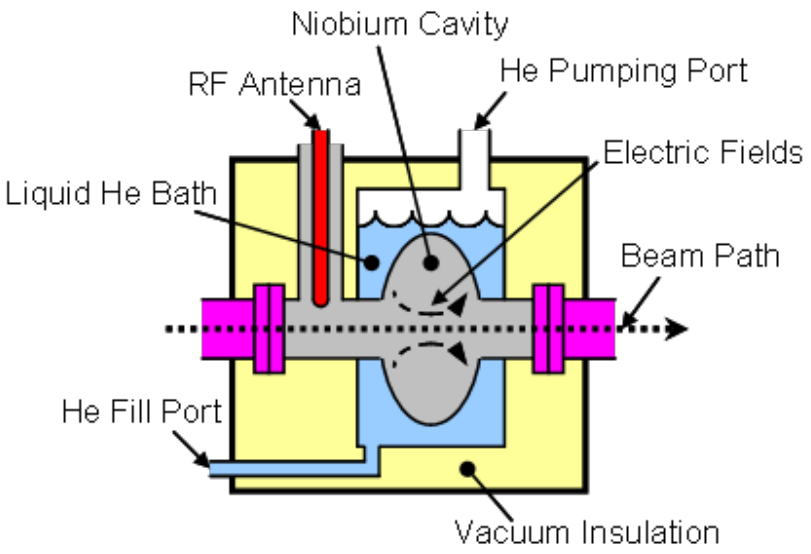
- Facility for Rare Isotope Beams
  - User facility for the U.S. Department of Energy Office of Science
  - Produces rare isotopes utilizing the worlds most powerful heavy-ion accelerator
  - Built to enable discoveries in the following areas:
    - » Properties of rare isotopes
    - » Nuclear astrophysics
    - » Fundamental particle interactions
    - » Medicine, homeland security

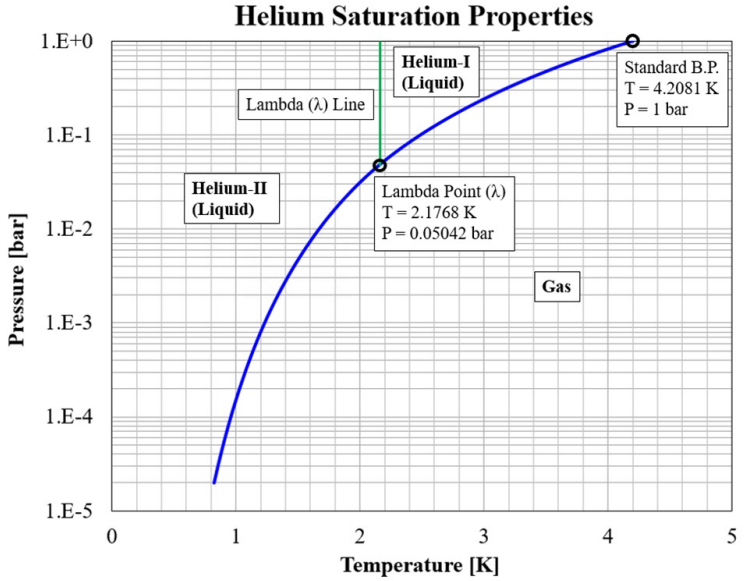




Background [2]

- Heavy ions are accelerated in the linear segments of the beam line by employing superconducting radio-frequency (SRF) cavities
- SRF cavities operate at temperatures below the standard boiling point of helium (4.2 K @ 1 bar), at FRIB this temperature is ~ 2 K
- A reduction of bath pressure is require to reach saturation conditions which meet the temperature requirements (pressure ~ 30 mbar)

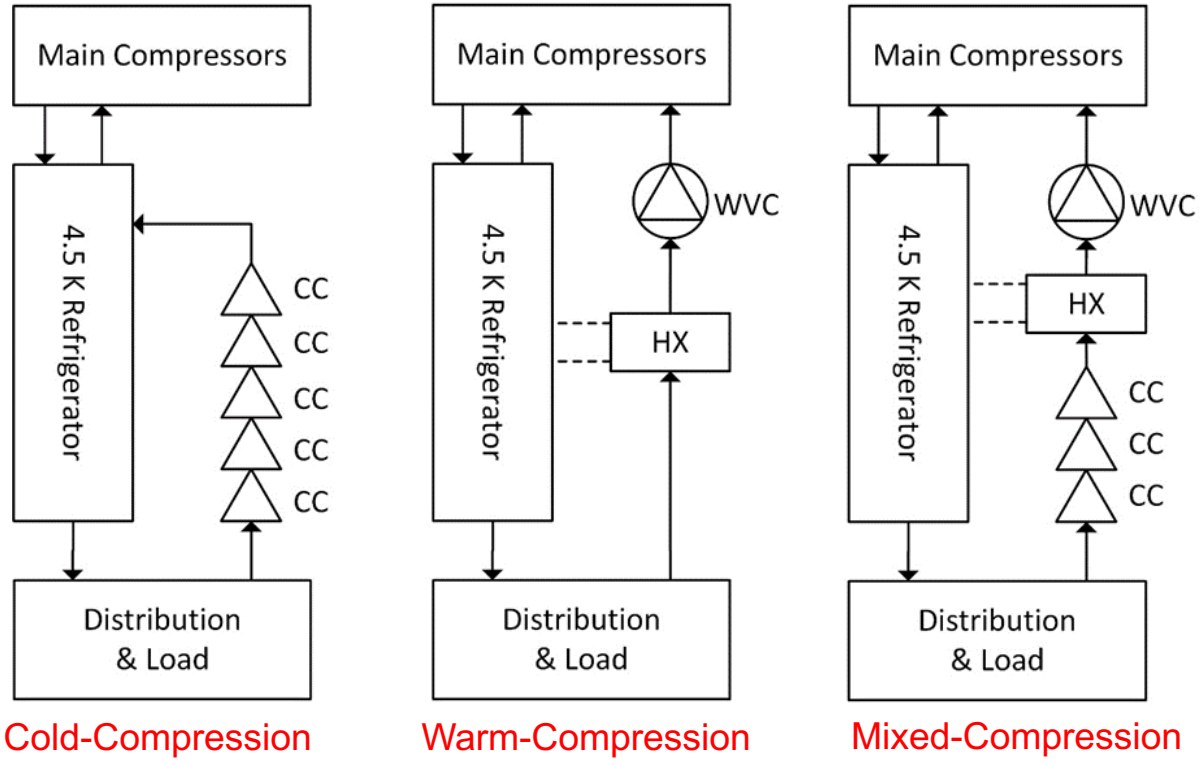




Background [3]

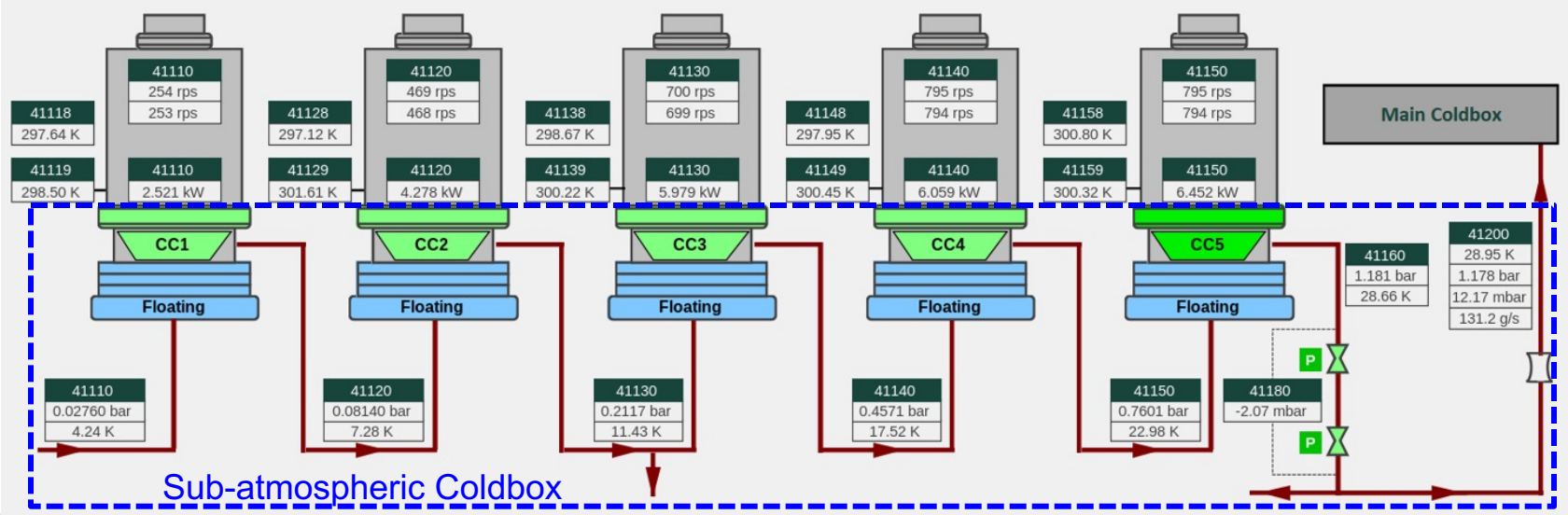
- Common methods for reducing the helium bath pressure involve systems with centrifugal compressors, warm vacuum compressors, or a combination using both types

- Selection based on:
  - Performance
    - » Efficiency
    - » Turndown
  - Complexity
  - Contamination risk
    - » In-leak
    - » Compressor oil
  - Equipment size
    - » Compressors
    - » Heat exchangers



FRIB Cryogenic System [1]

- FRIB utilized a full cold-compression system
- Cold-compression typically involves multiple centrifugal-type compressor in series, with isentropic efficiencies near 75%
- FRIB cold-compressor system consists of 5 centrifugal type compressors with 5-axis magnetic bearings (Knudsen et al., 2019)



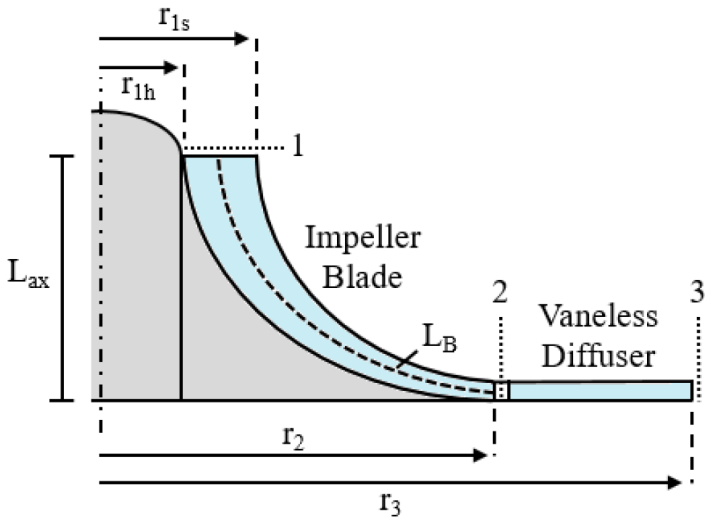
FRIB Cryogenic System [2]

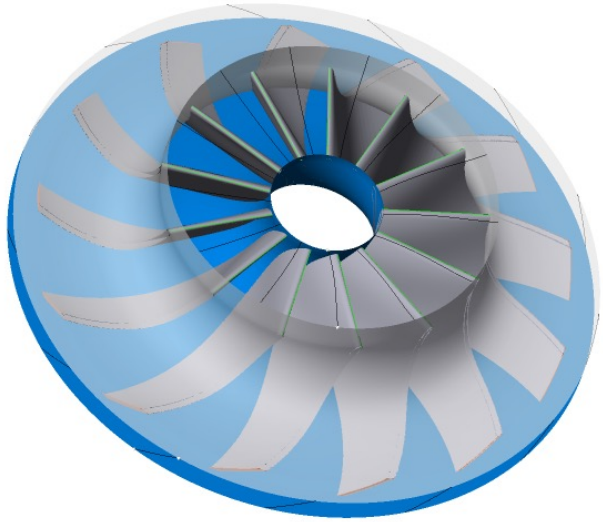
- Centrifugal cold-compressor train control
  - Currently based on compressor characteristics found through experimentation
  - Compressor rotational speeds are electronically coupled to each other through specified gearing ratios derived from experimentation
  - Requires actively exploring new operational regions of interest, limiting the flexibility of the 2 K cryogenic system

- Accurate prediction of cold-compressor performance will allow for high-efficiency and reliable wide range operation of the 2 K helium cryogenic system
  - Rotational speeds
  - Total pressure ratio
  - Anticipated efficiencies
  - Surge and choke margin estimation

Model Development [1]

- Different methods for performance prediction vary in complexity
  - One-dimensional station-based models
  - Three-dimensional computational fluid dynamic models





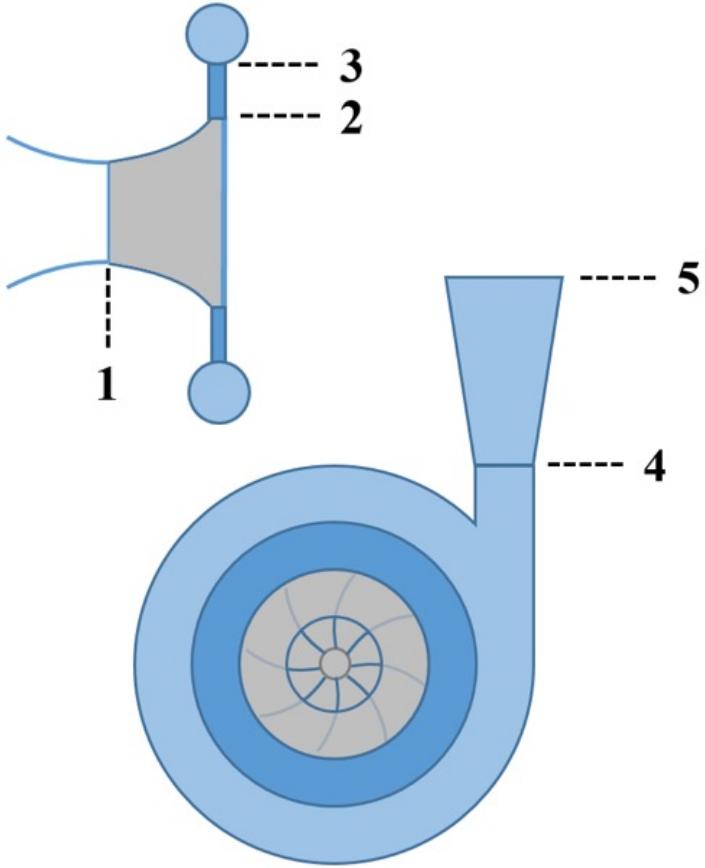
- Cryogenic cold-compressor performance prediction constraints:
  - Minimal computational cost/time
  - Limited required geometrical information
  - Simple model interface

Model Development [2]

- Constraints lead to the development of a one-dimensional model used to estimate performance of the cold-compressors (Howard et al., 2023)

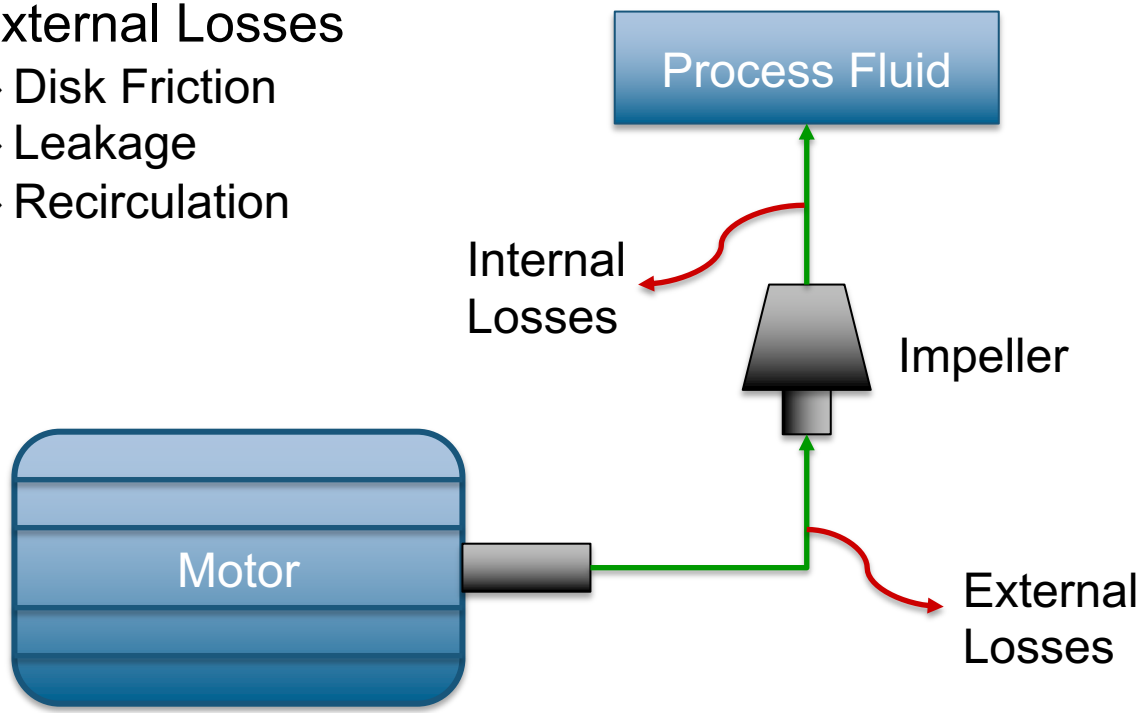
- Basis of 1-D model:
  - Laws of thermodynamics
  - Momentum Conservation
  - Compressible flow equations
  - Ideal gas equation of state

- One-dimensional model is segmented with 5 distinct station locations:
  - Impeller Inlet
  - Impeller Outlet / Diffuser Inlet
  - Diffuser Outlet / Volute Inlet
  - Volute Outlet / Exit Diffuser Inlet
  - Exit Diffuser Outlet



Model Development [3]

- Pressure and efficiency calculations at the impeller outlet implemented empirical models for individual enthalpy loss mechanisms present in the compression process
- Loss employed are split into two separate categories:
  - Internal Losses
    - » Blade loading
    - » Choking
    - » Clearance
    - » Incidence
    - » Mixing
    - » Skin Friction
  - External Losses
    - » Disk Friction
    - » Leakage
    - » Recirculation



Model Development [4]

- Each loss mechanism described have empirical correlations available in open literature, with many of the losses having many correlations
- Recommended set of loss correlations:

Loss Mechanism	Air (Howard et al., 2023)	Helium (Present Study)
Blade Loading	*Coppage et al.*	*Aungier*
Choking	*Aungier*	*Aungier*
Clearance	*Jansen*	*Jansen*
Disk Friction	*Daily & Nece*	*Daily & Nece*
Incidence	*Galvas*	*Aungier*
Leakage	*Aungier*	*Aungier*
Mixing	*Johnston & Dean*	*Aungier*
Recirculation	*Oh et al.*	*Oh et al.*
Skin Friction	*Aungier*	*Coppage et al.*

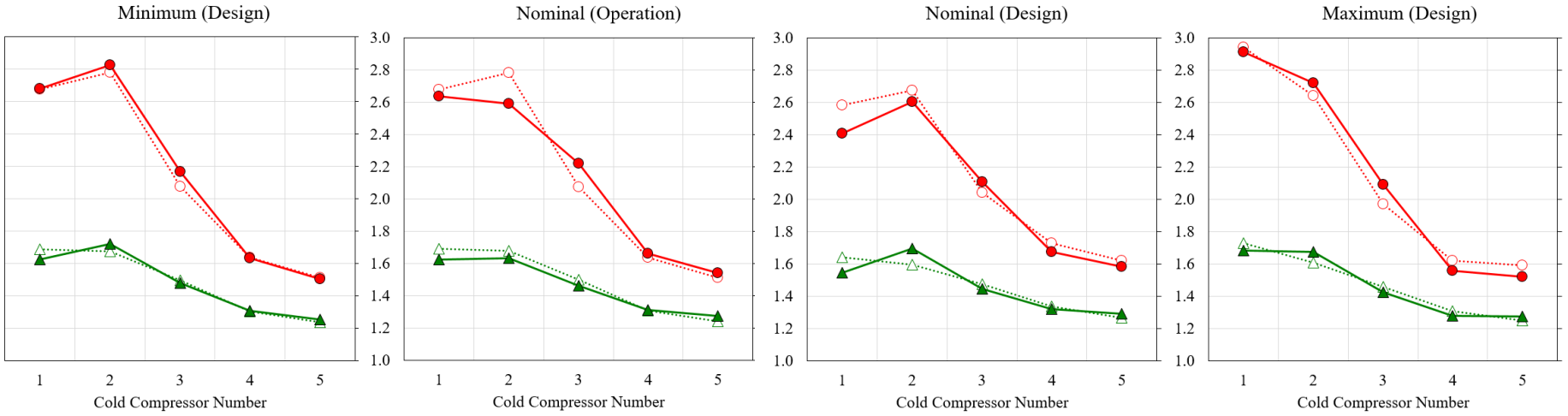
FRIB Measured Data

- Operational modes that were chosen to compare against the developed model included:

Operating Modes:		Minimum (Design)	Nominal (Operational)	Nominal (Design)	Maximum (Design)
$\dot{m}$	[g/s]	104.5	128.3	151.0	180.4
P_i	[bar]	0.029	0.029	0.029	0.029
T_i	[K]	4.166	4.206	4.094	4.015
N_1	[Hz]	234	240	235	257
N_2	[Hz]	465	457	468	490
N_3	[Hz]	663	667	671	695
N_4	[Hz]	761	776	808	816
N_5	[Hz]	762	776	809	817

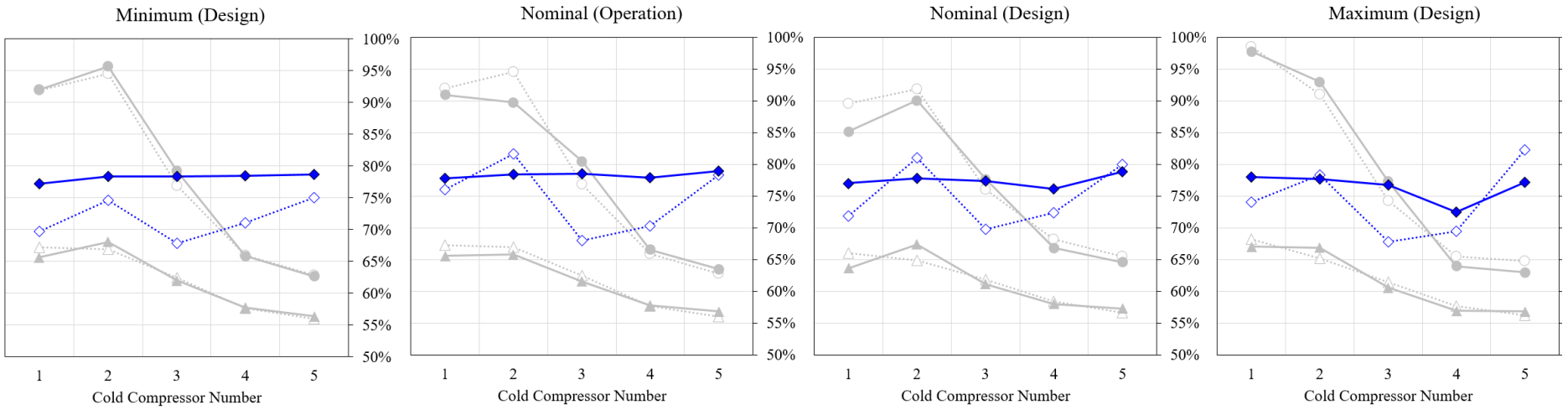
Model Results [1]

- Individual cold compressor performance prediction
  - Cold compressor performance was independently tested for each of the cold compressors given measured inlet conditions
- Pressure ratio (red circles) and temperature ratio (green triangles) generally follow the trends observed during testing
  - Largest pressure ratio error observed for CC3
  - Largest temperature ratio error observed for CC2



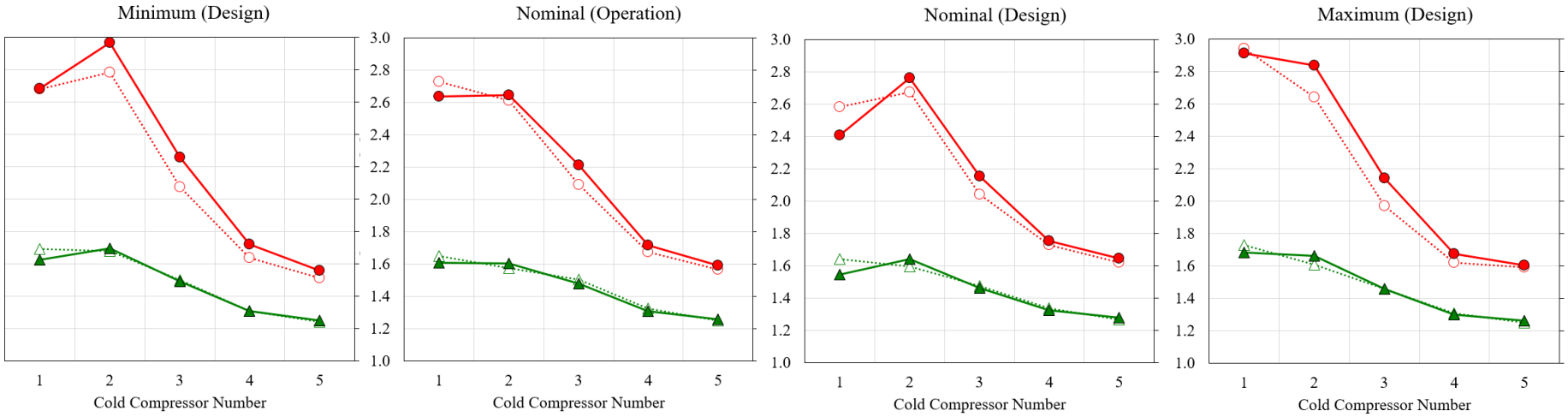
Model Results [2]

- Isentropic efficiency of the cold compression process was calculated based on input and output parameters
- Efficiency estimation (blue diamonds) were predicted to be nearly constant between 75% and 80%
  - Prediction of the efficiency did not properly follow calculated efficiency from the measured data
  - More investigation into loss model selection and methodology is necessary



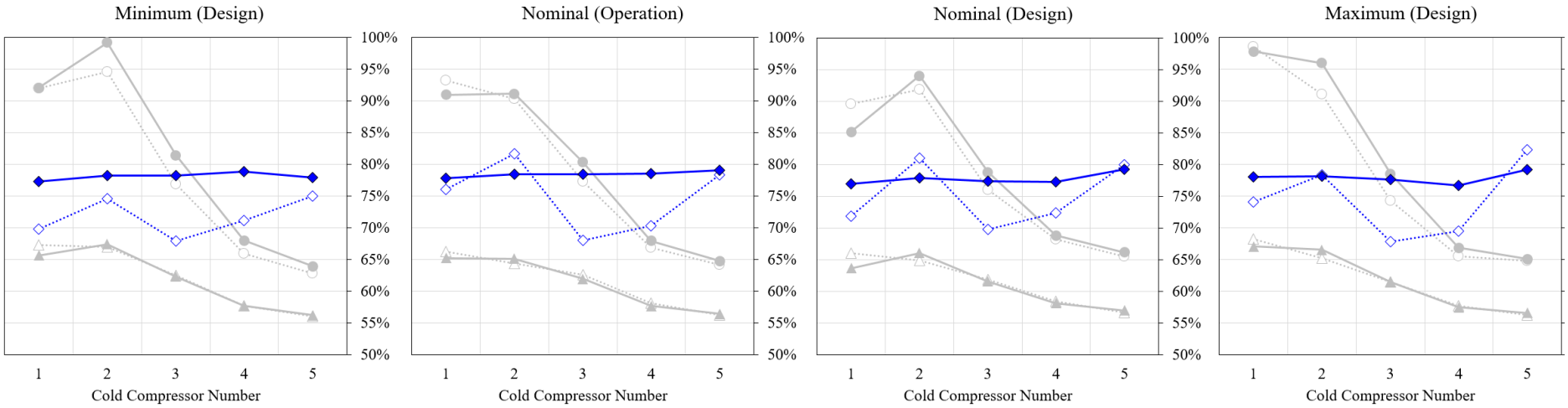
Model Results [3]

- Cold compressor train performance prediction
  - Inlet conditions were provided to CC1, but subsequent cold compressor inlet conditions were taken from the previous cold compressor calculated outlet
  - CC1 tended to underpredict the pressure ratio (red circles), while the rest of the compressor train overpredicted pressure ratio
- Temperature ratio (green triangles) was consistent with trends observed in the measured data



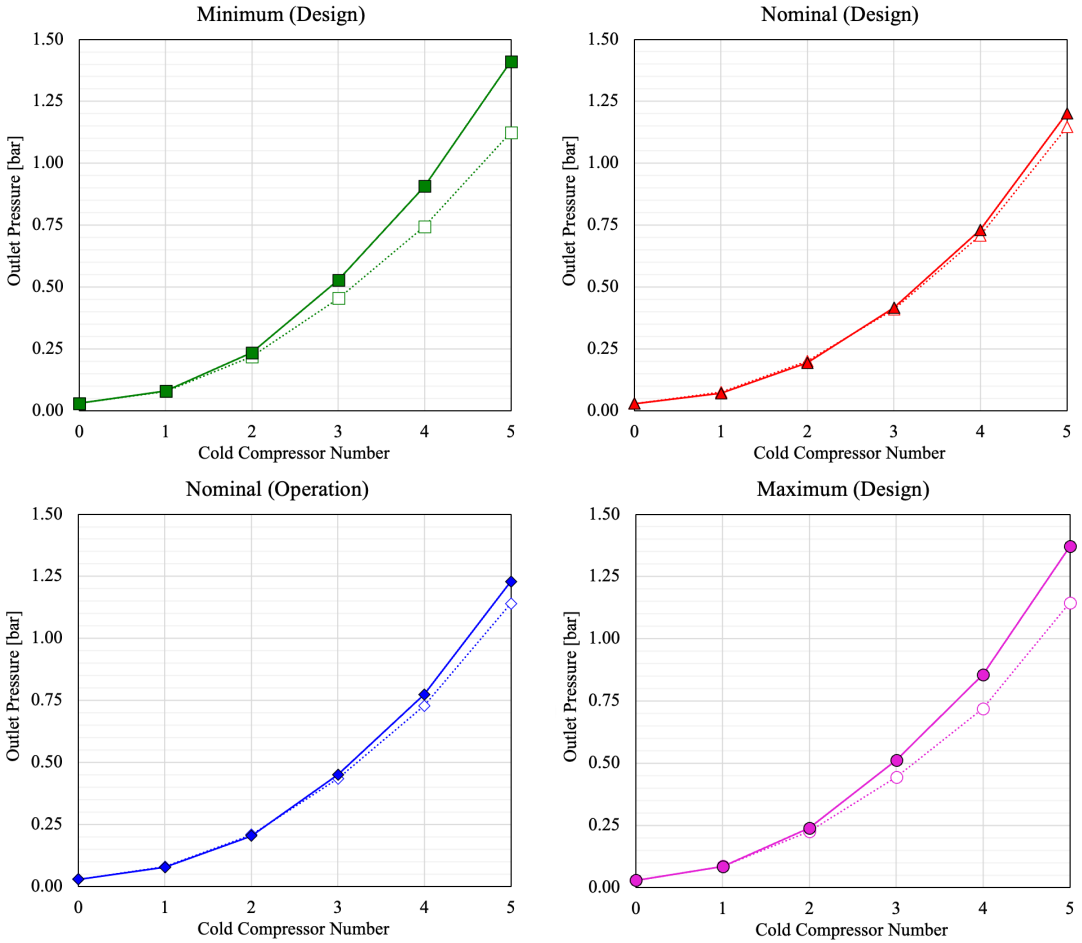
Model Results [4]

- Isentropic efficiency estimation (blue diamonds) were again predicted to be nearly constant between 75% and 80%
  - The largest error was observed for CC3



Model Results [5]

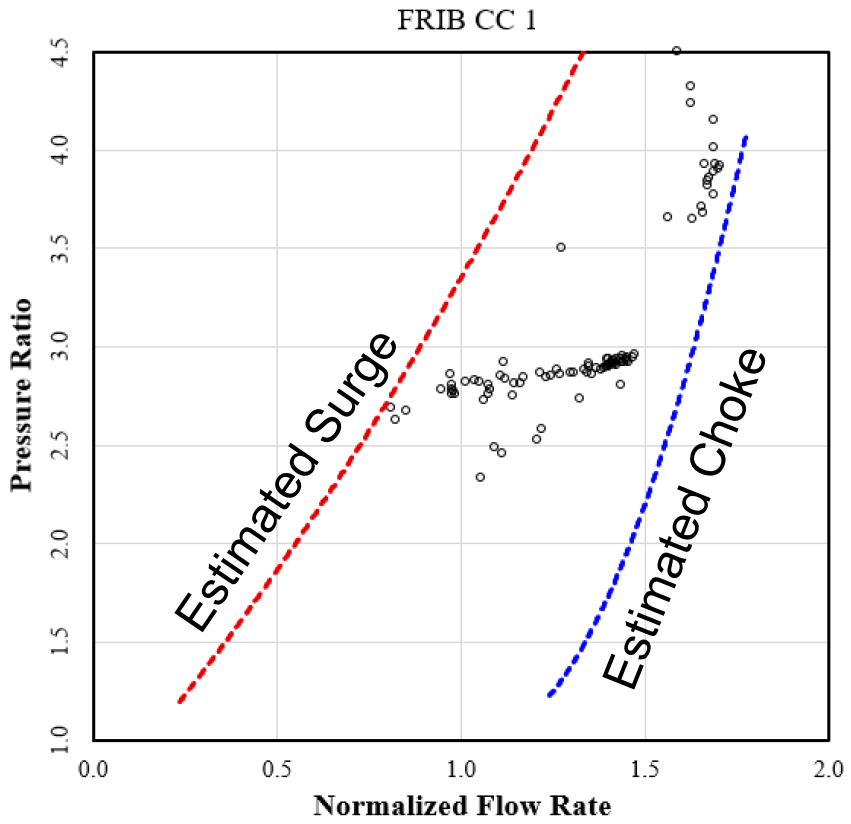
- Compressor train outlet static pressure prediction

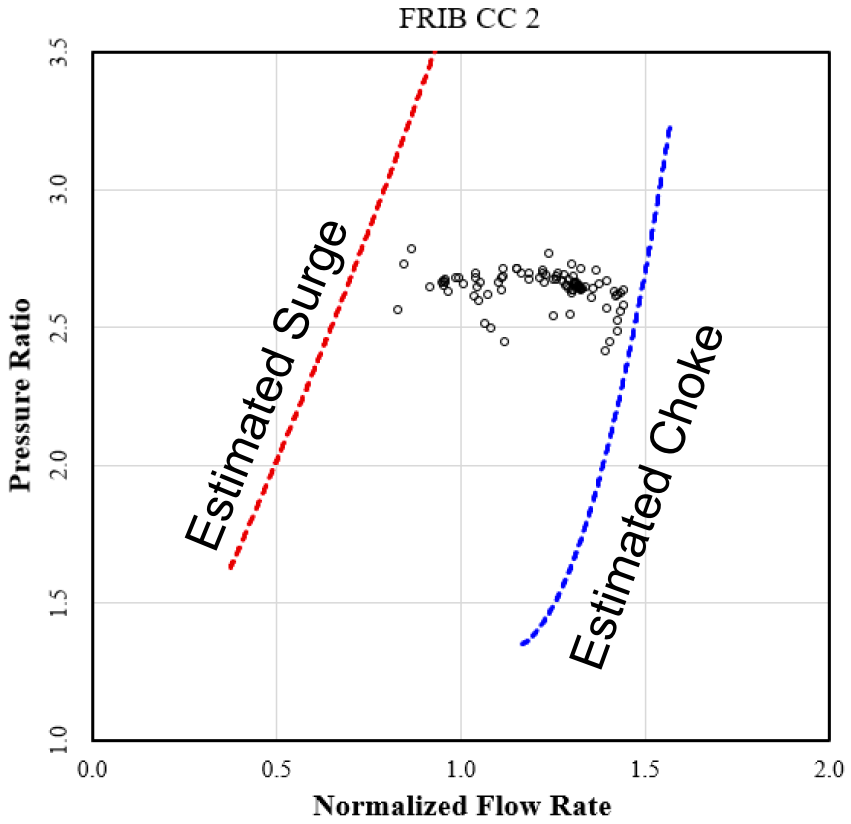


- Pressure rise across the compressor train was compared to measured data
- Nominal condition estimation agrees well with the measured data
- Minimum and maximum design conditions both over-predicted the pressure ratio over the compressor train

Model Results [6]

- Surge and choke estimation for CC1 and CC2





Summary

- Accurate prediction of cold-compressor performance will enable more robust and efficient control and operation of the sub-atmospheric cryogenic system at FRIB

- Modifying a previously developed centrifugal compressor performance methodology, performance characterization of cold-compressors operated at FRIB was enabled

- Performance estimation was compared to measured data captured during FRIB compressor testing
  - Pressure ratio and temperature ratio estimation showed reasonable agreement over the range of operation considered
  - Isentropic efficiencies were inconsistent with measured efficiencies, and require further investigation into loss correlation selection and methodology
  - Surge and choke estimation showed reasonable agreement

Acknowledgements

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Questions?

Thank you!

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