FRIB Cryogenic System Status

F Casagrande[1], *V Ganni*[1], P Knudsen[1], M Wright[1], S Jones[1], C Nguyen[1], A Fila[1], N Hassan[1], G Vargas[2], N Joseph[1], S Stanley[3]

[1] Facility for Rare Isotope Beams (FRIB), Michigan State University (MSU), East Lansing, MI 48824 USA
[2] Jacobs, Houston, TX 77058 USA
[3] Black & Decker, New Britain, CT 06053 USA

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Background of Cryogenic System

- Initial plan of a “turn-key” approach for the cryogenic helium system from industry exposed the project to serious risk due to budgetary constraints
  - Approach failed since a large-scale, non-standard system is not any one manufacturer’s standard product
  - Nor are there any manufacturers that have adequate experience and successful integration expertise in these particular systems, as reflected by the proposal costs to offset risk
- This lead the FRIB management to utilize the design and operational experience and expertise found from similar systems like those at Jefferson Lab (JLab) and the Spallation Neutron Source (SNS)
- FRIB cryogenic design team was formed in February of 2012
  - FRIB and JLab cryogenic engineering groups to plan, design, procure, install and commission the sub-systems and the overall system

Planning

- Main challenges in planning the cryogenic system:

- An understanding of the load requirements of the superconducting devices which must be supported
  - Includes normal steady and transient loads, such as commissioning, cool-down/warmup, and maintenance.

- Process and mechanical design of the cryogenic system to support these loads
  - One which is both cost effective and efficient, and one that can reasonably be expected to be executed on schedule and budget – based on experience

Planning (cont.)

- To achieve the project over all goals, the FRIB cryogenic design team made the following major decisions in conjunction with the FRIB management in February of 2012
- Decision-1: Lab will assume the responsibility for the planning, process design, integration, and commissioning of the sub-systems
- Decision-2: Lab will assume the responsibility for the design of most of the sub-systems
  - In most cases, this is a build-to-print design procured from industry
  - Other sub-systems would be procured using an comprehensive equipment specification based on the FRIB process design
  - This approach provided the initial information needed by FRIB conventional facilities (CF) for the building and the cryogenic system utilities without waiting for vendor supplied designs
    - » i.e., Building layout, foundations, trenches, door openings, cranes, utilities, conduits and equipment installation strategy

Planning (cont.)

- Decision-3: Revise the CM design based on a bottoms-up detailed approach
  - Incorporate:
    - » JLab/SNS style cryogenic couplings, and,
    - » Individual 4.5 K to 2 K heat exchangers in each CM
  - Divide the cryo-distribution system in the tunnel in to three Linac segments to support
    - » Step-wise commissioning, and,
    - » If required, to support operation at different operating conditions
- Decision-4: An overall bottoms-up cryogenic system design plan developed based on the revised CM cryogenic design requirements
  - By the end of 2012, plan for long lead items and the sub-system procurements to:
    - » Meet the overall project schedule, and,
    - » Taking into account of the building availability and funding profile provided by the project team

Initial Critical Planning Time Line

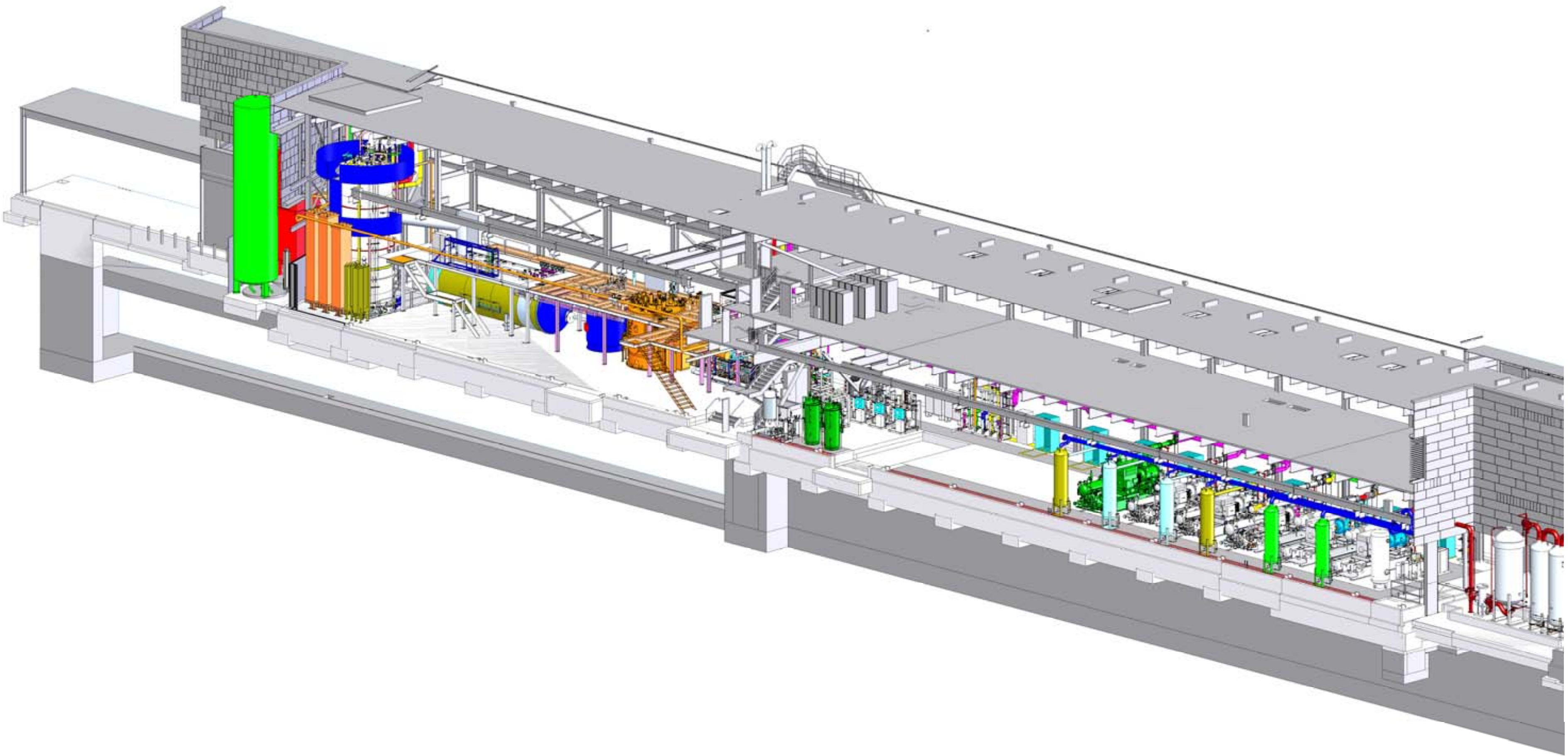
Item	Date
Decision to move away from turnkey approach	January 2012
CM requirements and process & instrumentation diagram development	February 2012
Start of bottoms-up process study	March 2012
Establishment of cryogenic system requirements	June 2012
TL prototype design concept	June 2012
System process study	October 2012
Preliminary equipment layout within building	November 2012
4.5 K cold box specification development	December 2012
Preliminary cryo distribution system concept and layout	December 2012
Release 4.5 K cold box purchase order	March 2013
Start cryogenic design of CM's	May 2013
Requirements to CF	May 2013

Planning: Conventional Facilities (CF)

- One of the initial critical path requirements was to provide the information needed by CF for the building and the utilities to support the cryogenic system
- Power:
  - 8.3 MW of facility power with dual transformers to main compressors
  - Facility power seamless supplied by local power company and/or MSU power plant
  - 3 MW of backup power from MSU power plant to main compressors (using gas turbine generators)
  - Two 800 kW diesel generators (1.6 MW) for utility systems (e.g., helium purifier compressors, vacuum pumps)
  - UPS (using flywheels) for control systems (until 1.6 MW is online)
  - After commissioning of the 4.5 K cold box was completed all the main compressors required to support the cold box operation were verified on each of the power sources
- Close coordination with CF was maintained in planning and during construction to ensure on-schedule installation of the all the cryogenic sub-systems

Planning: Plant Layout

- Overall cryogenic plant layout



Planning: Equipment

- Equipment order was prioritized based on:
  - Time required to design the equipment
  - Supplier delivery time
  - Building availability to avoid double handling and storage
  - Funding profile
  - Manpower availability.
- Cryogenic refrigeration system and the cryo-distribution system have a number of sub-systems…so, the design, procurement, installation were very carefully planned and coordinated to stay on the planned path and project goals
  - 4.5 K cold box was identified as the long lead item
  - Process study and the specifications were developed by the end of 2012
  - Followed by the order for the cold box placed in March 2013

Planning: Equipment (cont.)

- Refrigeration main sub-system procurements

Sub-system	P. O. Date
Main 4.5 K cold box	March 2013
Main warm helium compressors, 6 units	March 2015
Tunnel TL sections, 49-units	January 2015
Gas helium storage tanks, 6 units	June 2015
10 m^3 liquid helium storage dewar	June 2015
57 m^3 liquid nitrogen (LN) storage dewar	June 2015
Cold (cryogenic) compressors	September 2015
Compressor oil removal equipment	October 2015
Helium purifier cold box	February 2016
Helium purifier compressor	March 2016
Compressor oil processer skid	April 2016
Instrument air skid	September 2016

Planning: Fabrication

- FRIB cryogenic engineering team was responsible for the fabrication oversight of equipment provided by industry
  - Build-to-print drawings were done by the FRIB cryogenic design team for the Linac cryogenic TL section and for the prototype fabricated at Jlab
  - After testing, 49 sections were procured from industry
  - LS1 and LS3 tunnel horizontal roof level TL sections and the three vertical ‘shaft’ TL sections between the cold box room and Linac tunnel were also fabricated at JLab and then installed during the FRIB building construction.
  - Concurrently with the efforts at JLab, a facility was setup at FRIB for the fabrication of many of the needed components
    - i.e., interconnecting warm piping, helium gas tank piping, warm piping in the Linac, interconnecting cryo-distribution lines in the cold box room, the three Linac segment ‘tee’ sections (in the tunnel), the turnaround end-cans at the end of each Linac segment TL, the cryo-distribution lines and connecting (cold) boxes to the four superconducting magnets in the bend between LS2 and LS3, and the sub-atmospheric cold box (for 2 K operation)
  - FRIB engineers were responsible for the fabrication of all onsite equipment

Planning: Installation

- All the equipment was received just in time to avoid double handling and storage and to meet the project schedule
- FRIB cryogenic engineering group was responsible for:
  - Procurement of the materials
  - Onsite piping installation oversight of the contractors to ensure the specifications were met
  - Development the receiving and rigging plans in coordination with the building contractor
  - Routing verification, code compliance, code leak/pressure check, sensitive helium leak check, and the cleanliness of the warm and cryogenic interconnecting piping
    - » Lines and valves providing gaseous nitrogen, 3 bar 300 K clean helium, and compressor oil from the processing skid were routed and located next to the equipment requiring these services for commissioning and maintenance

Planning : I&EC

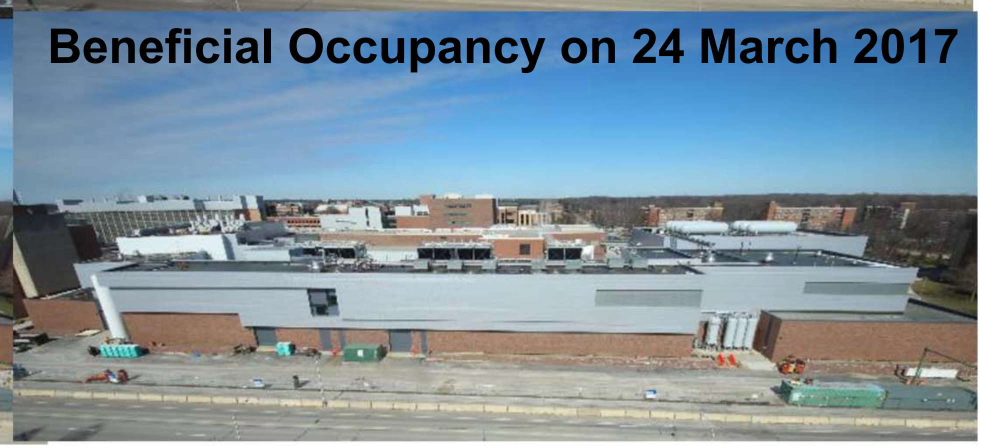
- Instrument selection included proper span and over-pressure protection to cover the intended measurement range
- Instruments were field calibrated and/or verified with end to end checks
- Control systems were baselined on experience obtained from other recent similar projects like the JLab 12 GeV upgrade and James Webb cryogenic system with additional improvements
- Dedicated cryo-control room and cryo-network are fully operational and have supported the step-wise commissioning of each sub-system, as well as supporting the operation of the commissioned systems
- Normal operating and special HMI screens were developed for the commissioning of each sub-system

Conventional Facilities: Progress


Groundbreaking –March 2014


March 2015


March 2016

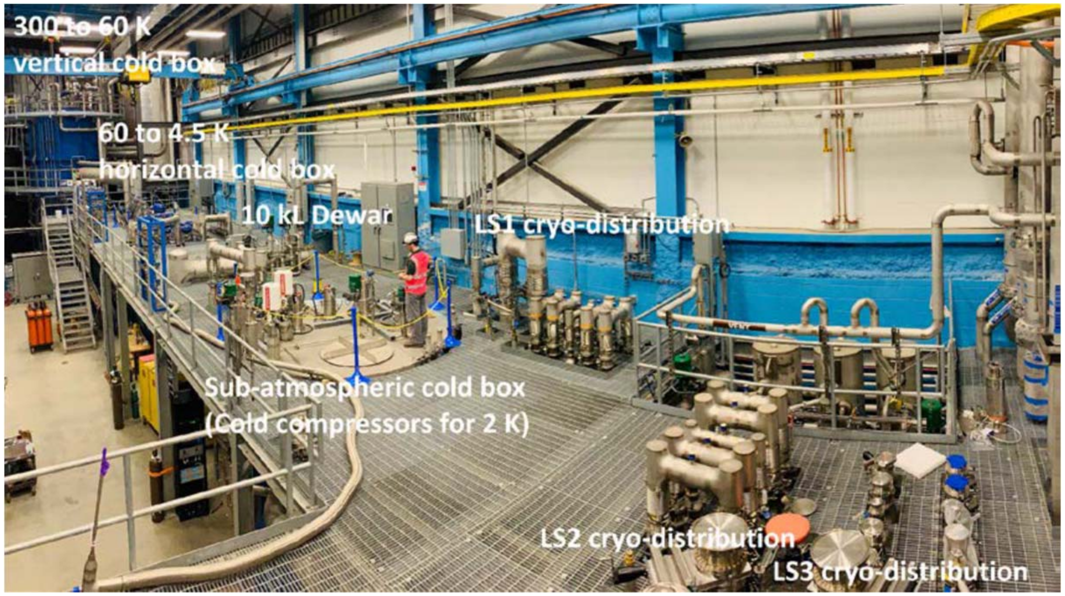

Beneficial Occupancy on 24 March 2017

Installation and Commissioning

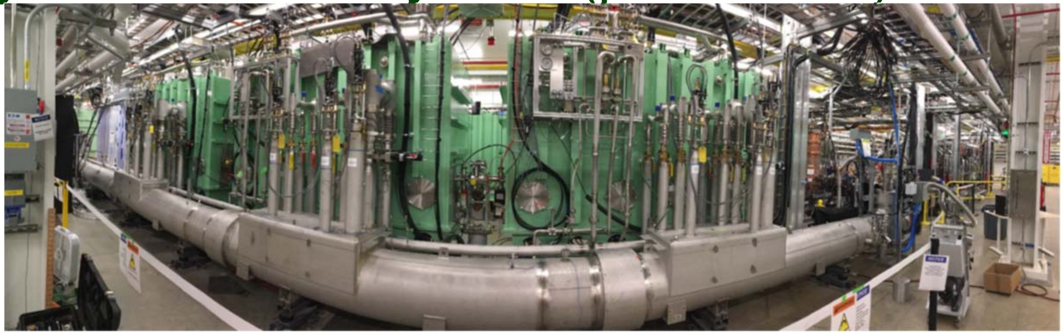
- Substantial progress in bringing the FRIB cryogenic system to operation has been made from the conference
- Main compressors were tested and their performance mapped
- 4.5 K cold box system has been tested and partially mapped
  - It met or exceed the design goals and has been continuously operating since April 2018
- 2 K system was commissioned in December 2018 and partially mapped in early 2019
  - It met or exceeded all the design goals and is ready to support the Linac commissioning at 2 K
- Papers on this will be presented in this session

Installation and Commissioning (cont.)

- Cryo-plant supporting Linac at 4.5 K and at 2 K



- FRIB LS1 cryo-distribution system (panoramic)



Installation and Commissioning (cont.)

- LS1 with it's 15 CM's has been commissioned at 4.5 K
- LS2 with 6 CM's (plus LS1) is present being commissioned at 4.5 K, followed by 2 K in August-September 2019 (planned)
- LS3 is planned follow later in the fall (2019) with the four 180 deg. arc superconducting magnets (designated as FS2D3)
- Fourth TL to support the target and separator area superconducting magnets is scheduled to be commissioned at the end of 2020

- The cryogenic system is presently supporting the 15 CM's on LS1, and 6 CM's on LS2 at a 7 bar supply pressure to the cold box with a nominal input power of 1.3 MW and 5 g/s of LN usage

Installation and Commissioning (cont.)

- Since the three Linac segments are independent…the operational experience of LS-1 at 4.5 K and at the design gradient gives additional flexibility and cryogenic capacity margin (and/or a reduction in the operating costs)

- This is possible since the cryogenic plant is:
  - Designed to operate on the floating pressure process, and,
  - Cold box design is based on equal Carnot steps, and,
  - Compressor system is capable of a wide range of operation

- Consequently, the system has the inherent flexibility to adopt to various types and sizes of loads at maximum efficiency

Installation and Commissioning (cont.)

- Dates for sub-systems

Sub-system	Date
Building ground breaking	March 2014
Tunnel ceiling TL's [a]	October 2015
Partial building occupancy	January 2016
Main compressors [a]	March 2016
Main 4.5 K cold boxes [a]	Jul. & Oct. 2016
Shaft (vertical) TL's [a]	August 2016
Beneficial occupancy	March 2017
Main non-cryogenic piping	Jun. 2016 - 2017
Utility systems: power, LN, cooling water, instrument air	Mar. to Jun. 2017
LN storage	March 2017
Helium purifier compressor	March 2017
Helium warm piping	March 2017
LN/gaseous nitrogen piping	March 2017
Electric power (4160V/ 480V/ 208V)	March 2017
Cooling water	March 2017
Instrument air	March 2017
Compressor oil processor	April 2017
Helium purifier system	May 2017
Helium purifier cold boxes	May 2017
ODH validation	August 2017

Sub-system	Date
4.5 K cold box	Oct. to Dec. 2017
Liquid helium storage	November 2017
Cold box room cryo-distribution lines	February 2018
LS1 TL cool down	March 2018
LS1: operation of first 3 CM's	May 2018
First beam through first 3 CM's	July 2018
Cryogenic plant control system	December 2018 [c]
LS1: operation of 15 CM's	December 2018
Sub-atmospheric cold box and cold compressors	December 2018
Beam through all 15 LS1 CM's	February 2019
LS2: cool-down of TL	March 2019
LS2: operation of FS2D3 superconducting magnet	March 2019
Install guard vacuum skid [a]	March 2019
Tunnel shaft and cryo-distribution lines	LS1 March 2018
	LS2 March 2019
	LS3 August 2019 [b]
CM controls	Progressing [d]

[a] Installed.
[b] Planned.
[c] Mostly complete, supporting cont. unattended operation
[d] Progressing with stage-wise CM installation.

Conclusions

- FRIB cryogenic system has faced all the project constraints typical to an accelerator project
- Initial plan to move away from an industry supplied turnkey system and for the lab to take full responsibility and control is the major factor for remaining within the budget and schedule
- The revised plan allowed for the progressive stage-wise commissioning of the accelerator in an efficient, reliable, and stable manner
- Compressor design, cold box design, and floating-pressure process have proved essential in meeting the cryogenic system project goals
- Careful planning, and a management and technical team that is dedicated and competent have also proven to be essential
- The 15 CM's operating at 4.5 K on LS1, accelerated the heavy ion beam to above the design goal of 20 MeV/u, setting the record for the highest energy continuous-wave hadron Linac in February 2019, without waiting for the completion other two Linac segments