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ADVANCES OF THE FRIB PROJECT*

J. Wei†, H. Ao, S. Beher, N. Bultman, F. Casagrande, J. Chen, S. Cogan, C. Compton, J. Curtin,
L. Dalesio, K. Davidson, A. Facco[1], V. Ganni, A. Ganshyn, P. Gibson, T. Glasmacher, Y. Hao,
L. Hodges, K. Holland, H.-C. Hseuh, A. Hussain, M. Ikegami, S. Jones, T. Kanemura, P. Knudsen,
R.E. Laxdal[2], J. LeTourneau, S. Lidia, G. Machicoane, I. Malloch, F. Marti, S. Miller,
Y. Momozaki[3], D. Morris, P. Ostroumov, J. Popielarski, L. Popielarski, J. Priller, H. Ren, T. Russo,
K. Saito, S. Stanley, T. Xu, Y. Yamazaki,
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA
K. Dixon, M. Wiseman, Thomas Jefferson National Laboratory, Newport News, VA, USA
M. Kelly, Argonne National Laboratory, Argonne, IL, USA
K. Hosoyama, KEK, Tsukuba, Japan
S. Prestemon, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[1] also at INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
[2] also at TRIUMF, Vancouver, Canada
[3] also at Argonne National Laboratory, Argonne, IL, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) Project has entered the phase of beam commissioning starting from the room-temperature front end and the superconducting linac segment of first three cryomodules. With the newly commissioned helium refrigeration system supplying 4.5 K liquid helium to the quarter-wave resonators and solenoids, the FRIB accelerator team achieved the sectional key performance parameters as designed ahead of schedule. We also validated machine protection and personnel protection systems that will be crucial to the next phase of commissioning. FRIB is on track towards a national user facility at the power frontier with a beam power two orders of magnitude higher than operating heavy-ion facilities. This paper summarizes the status of accelerator design, technology development, construction, commissioning, as well as path to operations and upgrades.

INTRODUCTION

The FRIB project started technical construction at the Michigan State University in August 2014 [1]. Three years later, the project entered the stage of phased commissioning with the heavy ion beams (Ar and Kr) following the completion of the room temperature part of the front end, as shown in Fig. 1 and Table 1. In this paper, we present the main results of the first two stages of beam commissioning that have been completed covering nearly all major accelerator systems including the electron cyclotron resonance (ECR) ion source, the Radio-frequency quadrupole (RFQ), the cryomodules of β=0.041 quarter-wave resonators, the liquid helium refrigeration plant operating at 4 K temperature, and supporting systems including RF, power supply, diagnostics, vacuum, hardware and high level controls, machine protection, personnel protection, physics applications and integration.

Figure 1: FRIB driver linac viewed from the lower LEBT towards the superconducting linac in the accelerator tunnel at the beginning of beam commissioning in 2017.

Table 1: Stages of Accelerator Readiness (ARR) for the Phased Beam Commissioning of the FRIB Accelerator

Phase	Area with beam	Date
ARR1	Front end	2017-7
ARR2	Plus β=0.041 cryomodules	2018-5
ARR3	Plus β=0.085 cryomodules	2019-2
	Plus lithium charge stripper	2020-7
ARR4/5	Plus β=0.29, 0.53 cryomodules	2020-12
ARR6	Plus target and beam dump	2021-9

Subsequently, we discuss resolutions to some leading technical issues including low-sensitivity loss detection and machine protection, charge stripping with liquid metal, and microphonics suppression. We continue with status reports on infrastructure build-up of the MSU cryogenics initiative and the superconducting RF (SRF) Highbay. We conclude with challenges in the beam power ramp up and the path forward of beam energy upgrade.

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† wei@frib.msu.edu

PHASED COMMISSIONING

Front End Beam Commissioning

The main purpose of Front End (ARR1) commissioning was to integrate room-temperature accelerator systems together with the newly built civil infrastructure including electricity and water. For simplicity, we avoided cryogenics and focused on establishing needed processes for a newly constructed accelerator facility. Emphases were on hazard mitigation for personnel safety (electrical hazard from the high voltage platform and radiation hazard from the source plasma) and conduct of operations.

The ARR1 commissioning goals were promptly achieved with both Ar and Kr beams produced from the ion source, transported through the low energy beam transport (LEBT) with pre-bunching, and accelerated by the RFQ to beam energy of 0.5 MeV/u with full design transmission efficiency of about 85% [2] (Fig. 2).

Figure 2: Front End (ARR1) beam commissioning in 2017.

First Three Cryomodule Beam Commissioning

The main purpose of ARR2 commissioning was to perform integrated tests of nearly all accelerator systems with emphasis on cryogenics and cryomodules. Figure 3 shows the beamline layout extending from the ion source at the surface to the linac tunnel underground including three β=0.041 cryomodules and a temporary diagnostics station. After establishing the oxygen deficiency hazard control system [3], we first started the commissioning of the FRIB cryoplant at 4 K temperature (Fig. 4), followed by the commissioning of the cryo-distribution and the cool down of the cryomodules [4]. The tunnel access control system is activated for radiation hazard mitigation before we proceed with RF conditioning of the SRF cavities. As cryomodules have been 100% tested at multiple stages (cavity/couple/solenoid individual tests and cryomodule bunker tests), the conditioning in tunnel proceeded rapidly.

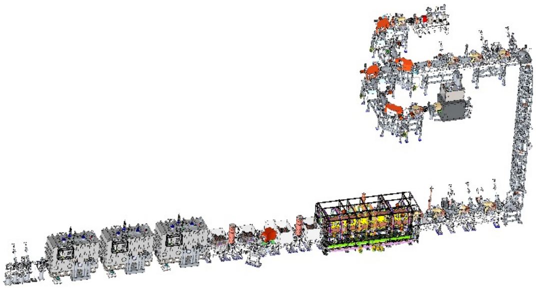

Figure 3: Scope of ARR2 beam commissioning in 2018 including the front end and the first three cryomodules.

Figure 4: Commissioning of the FRIB cryoplant at 4 K.

The ARR2 commissioning goals were again promptly achieved with both Ar and Kr beams from the Front End accelerated by the three cryomodules to beam energies above 2 MeV/u with 100% transmission efficiency (Fig. 5). The beam duty factor was gradually increased to 30% limited by the temporary beam dumping Faraday cup. The Ar^{9+} beam power of 66 W at 1.5 MeV/u would correspond to about 38 kW of power on the target had the beam been accelerated to the full energy of 285 MeV/u at 100% duty cycle. An unexplained observation was the neutron signal detected at unexpected low energy of 1.8 MeV/u [5].

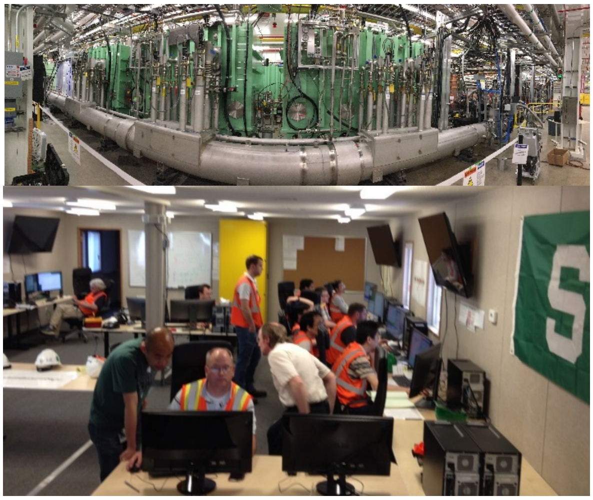

Figure 5: ARR2 beam commissioning in 2018 including both the front end and the first three cryomodules.

Forthcoming Beam Commissioning

ARR3 aims at accelerating the beams to ~ 20 MeV/u energy passing the charge stripper. All 15 cryomodules needed for ARR3 have been installed and being cooled down to 4 K temperature (Fig. 6). Subsequently, the carbon charge stripper installed for commissioning is planned to be replaced by the liquid lithium stripper. A warm up period of about 8 months is planned in-between facilitating installation, system reconfiguration and improvements.

ARR4/5 aims at further acceleration above 200 MeV/u meeting the facility requirements with SRF cavities operating at 2 K temperature. ARR6 integrates the driver linac accelerator with the target and beam dump of the experimental systems.

Figure 6: Cryomodules installed for ARR3 commissioning.

TECHNICAL ISSUE RESOLUTION

Major technical issues have been the focus of R&D since project start. These issues are being resolved and demonstrated during the staged beam commissioning.

Machine Protection and Low-sensitivity Beam Loss Detection

The issue of poor detection sensitivity of low energy heavy ions and the consequent challenges in machine protection is addressed by multi-layer, multi-time scale machine protection system designs [6]. The initially installed beam attenuator for machine protection was removed after the beam chopper was validated and monitored limiting the beam duty cycle before the interim beam dump. The fast machine protection based on the differential beam current signal was demonstrated mitigating the stray beam within the required 35 μs time duration (Fig. 7). In addition, the halo monitor rings installed between the cryomodules were highly sensitive to both ion and electron signals at nA level (Fig. 8). The fast thermometry sensors installed inside the cryomodule detected beam loss induced heating at 0.1 K level.

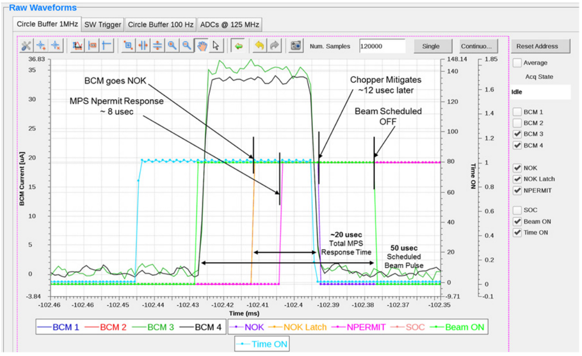

Figure 7: Demonstration of fast machine protection with the differential current monitor signal.

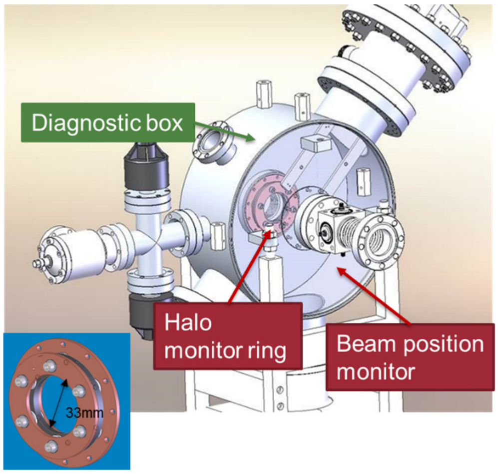

Figure 8: Halo monitor rings installed in the warm section between the cryomodules.

High-power Charge Stripping

Development of liquid lithium charge stripper capable of withstanding high beam power of heavy ions proceeded with demonstration of continuous lithium circulation with the electromagnetic pump. Lithium film was established inside the primary chamber housed inside the secondary vessel [7] (Fig. 9). Credited controls are implemented to ensure configuration management and conduct of operations.

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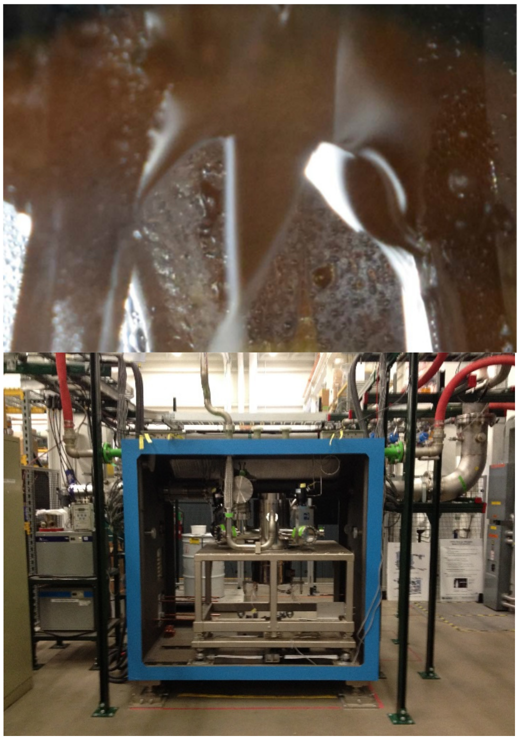

Figure 9: Liquid lithium charge stripper module (bottom) and the established lithium film (top).

Microphonics Suppression

Microphonics is known to compromise the performance of SRF resonators. The situation is more challenging for FRIB as the cryoplant containing noisy compressors is located in the same building of the FRIB accelerator (Fig. 10). Precautions in compressor design & installation is key to microphonics mitigation. Design of the innovative "bottom-up" cryomodule carefully incorporated microphonics suppressing considerations including top suspended cryogenic headers for vibration isolation [8 – 10]. Effectiveness of microphonics mitigation is monitored by tunnel measurement of vibrational spectrum (Fig. 10). SRF cavity locking issues that occurred at initial cool down were promptly resolved by iteration on valve controls logic and by provisions for liquid helium supply from a 10,000 liter Dewar.

INFRASTRUCTURE GROWTH

Michigan State University has heavily invested in the infrastructure necessary for FRIB development and for future research including funding of the cryogenics initiative, establishing the SRF Highbay for SRF resonator processing and certification at mass production capacity, and recruitment of subject matter experts from over the world covering all disciplines of accelerator physics and engineering needed for the development of high-power hadron accelerators.

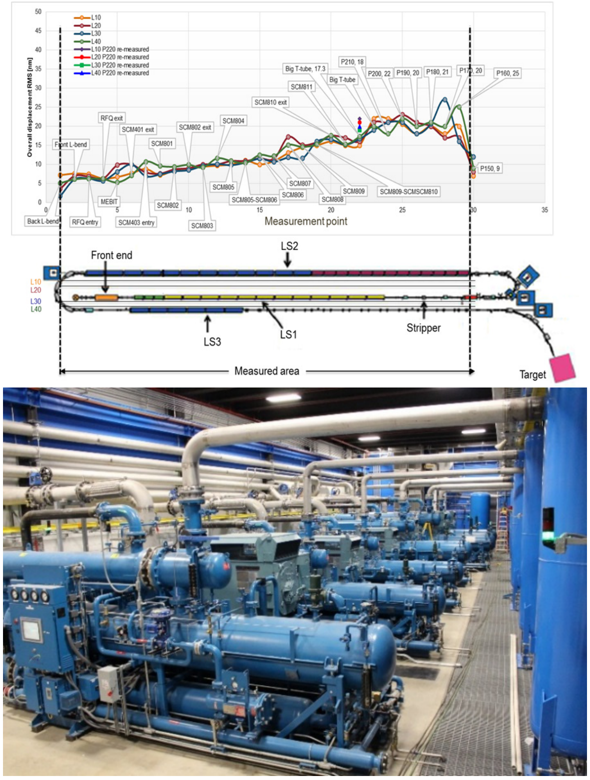

Figure 10: Cryoplant compressors located in the FRIB building (bottom) and the measured tunnel vibration (top).

The MSU Cryogenics Initiative

The MSU cryogenics initiative directed by R. Ganni aims at building up the national cryogenic knowledge base through education and training of cryogenic physicists and engineers, pursuing advanced cryogenic process design and state-of-the-art technology development, and supporting large-scale cryogenic systems associated with major accelerator facilities. Both regular university courses and condensed US Particle Accelerator School courses are offered along with traineeship programs. The initiative's primary R&D areas are main compressor efficiency improvements, low level impurity removal, and small 2 K system for laboratory use (Fig. 11) [11].

SRF Highbay & Cryogenics Assembly Building

To meet the FRIB project schedule, MSU has built up the capacity of mass production and certification of > 1 cryomodules per month. The 2500 m^2 "SRF Highbay" houses areas for material inspection, cavity mechanical coordinate measurements, vacuum furnace degassing, chemical etching, high-pressure water rinsing, SRF coupler conditioning, cold mass assembly, and cryomodule testing (Figs. 12). This facility, together with the cryomodule assembly area and the machine shop, supports the production throughput of testing five cavities per week and one cryomodule per month [12]. In addition to the buffered chemical polishing (BCP) used for FRIB cavities, the electro-polishing (EP) facility is being established to support FRIB upgrade. Furthermore, a new 1440 m^2 cryogenic assembly building is under constructed to house future cryomodule and superconducting magnet developments and production.

Figure 11: The MSU cryogenics initiative programs.

Figure 12: The SRF Highbay (top) and the cryomodule assembly area (bottom) housing six parallel assembly lines delivering more than one cryomodule per month.

POWER RAMP UP & UPGRADE

FRIB expects to ramp up beam power to 400 kW in about four years after the completion of the construction project (Fig. 13), which is about two order-of-magnitudes higher than any existing heavy ion accelerator in the power frontier [13]. Challenges include establishing the 28 GHz superconducting ECR ion source, the liquid lithium charge stripper, and the high-power charge selector, facilitating beam halo cleaning and collimation, and improving the reliability and availability of the facility.

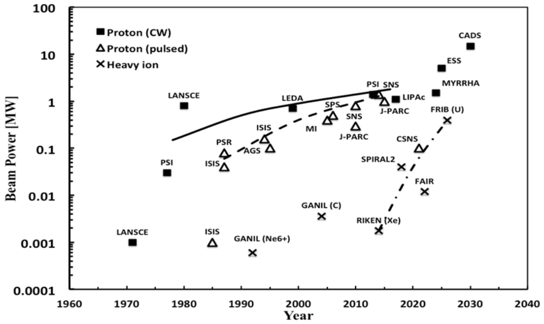

Figure 13: Evolution of hadron accelerator beam power.

The first step of FRIB upgrade is to double the driver linac output energy from the baseline to above 400 MeV/u. Space reserved in the FRIB tunnel will be filled with additional 11 cryomodules of β=0.65 elliptical cavities. Prototype cavities are being fabricated by the industrial vendors. In house BCP processing and certification results (Fig, 14) are to be benchmarked with those from Argonne using EP processing. The cryogenic distribution is configured so that the prototype cryomodule for FRIB upgrade can be readily connected after it is built. The raised energy is expected to significantly enhance the rare isotopes yield. It will also reduce the stress on the production target and the beam dump.

Figure 14: SRF cavity for FRIB upgrade being processed at MSU and Argonne National Laboratory.

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FRIB accelerator systems design and construction have been facilitated under work-for-others agreements with many DOE-SC national laboratories including ANL, BNL, FNAL, JLab, LANL, LBNL, ORNL, and SLAC, and in collaboration with institutes worldwide including BINP, KEK, IHEP, IMP, INFN, INR, RIKEN, TRIUMF, and Tsinghua University. The cryogenics system is developed in collaboration with the JLab cryogenics team. The recent experience gained from the JLab 12 GeV cryogenic system design is utilized for both the refrigerator cold box and the compression system designs. The liquid lithium charge stripping system is developed in collaboration with ANL.

BNL collaborated on the development of the alternative helium gas stripper. The SRF development benefited greatly from the expertise of the low-β SRF community. FRIB is collaborating with ANL on RF coupler and tuner developments, assisted by JLAB for cryomodule design, and by FNAL and JLab on cavity treatments. FRIB collaborated with LBNL on the development of VENUS type ECR ion source.

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