ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-MOB03

# DESIGN AND FABRICATION OF FRIB NORMAL CONDUCTING CAVITIES*

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## *Abstract*

At FRIB, five unique designs of normal conducting cavities were developed for a 40.25-MHz Multi-Harmonic buncher (MHB), 80.5-MHz quarter-wave cavity MEBT bunchers, 161-MHz H-type cavity bunchers, 322-MHz H-type bunchers, and a quarter-wave 161-MHz buncher for a ReAccelerator (ReA). The paper will cover the main parameters for each type of bunchers, their design/fabrication, cooling design, RF contact design/effectiveness, tuning process, brazing design and fabrication challenges, coupler design, copper-to-stainless steel transitions, etc. The operation status of these bunchers will also be discussed.

## INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) started user operation in May 2022 after ~10 years of project design and construction. FRIB since then has been used for scientific experiments for ~3 years successfully [1, 2], with recent achievement of 20 kW Uranium-238 beam on target, which is currently work record [3].

Eight normal conducting cavities with 5 unique designs are under operation along FRIB beamlines, primarily located within the Front End and Folding Segment 1 regions. Six cavities are under operations, and two more are planned summer of 2026.

Figure 1 shows the location of these normal conducting copper cavities: each type and locations.

Normal conducting cavities are made of high-purity copper using high-temperature furnace brazing. They are equipped with motorized tuners for real-time frequency control. An efficient water cooling is provided for CW operation. We have developed and applied a multi-step brazing technique to achieve high dimensional accuracy, reliable RF contacts, and accommodate large stainless steel-to-copper joints.

Superconducting cavities are the primary choice for acceleration because of their distinct advantages. Normal conducting cavities can still be beneficial due to their distinct characteristics and benefits depending on the application:

- Simpler Construction and Infrastructure
  - No cryogenics required
  - If far from other cryogenics devices
- Compact Size: Suitable for Front End

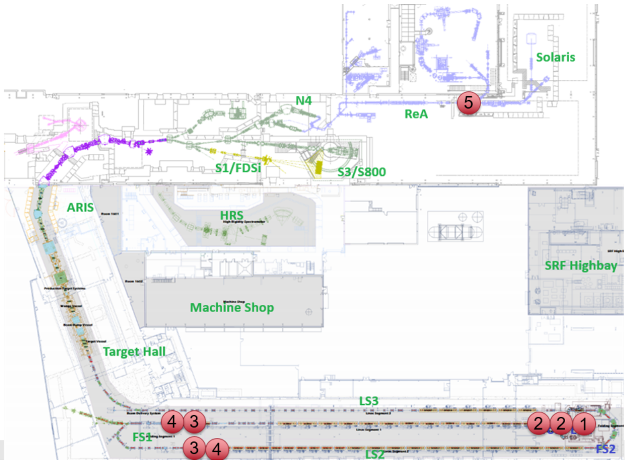

Figure 1: Layout of FRIB Normal Conducting Cavities. Mark 1: MHB at Front End; Mark 2: MEBT Buncher (X2) also at Front End; Mark 3: IH Buncher (X2) at Folding Segment 1 (FS1); Mark 4: 2H Buncher (X2) also at FS1; Mark 5: ReA Buncher.

- Better Protected against Intended or Un-intended Beam Loss
  - Less sensitive to mechanical vibrations
- Lower Cost
  - Drawing count is fewer for lower design cost
  - Fabrication generally quicker
  - Fabrication also generally less expensive
- Quicker Testing and Commissioning
  - Faster testing and conditioning cycles allow for quicker deployment and troubleshooting
- More Potential for RF Power Increase
  - Easy target to be requested for higher RF power
- Benefits for low beta, low duty cycle machine or at low frequency

## DESIGN PARAMETERS

Table 1 shows major design parameters for four types of normal conducting cavities, including operating frequency, geometrical beta, aperture diameter, resonator diameter, calculated Q factor, vacuum level, and each cavity's max RF power.

For MHB, model frequencies are 40.25, 80.5 and 120.75 MHz, with total power for MHB is up to 100 Watts [4]. MHB has 3 couplers and 3 tuners. Differences to other cavities are that MHB cavity is on air side, with ceramic break as vacuum interface. Q values measured for MHB are 515, 325 and 244 for the three harmonic. The MHB buncher was manufactured, assembled, tested, installed and commissioned.

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[*] This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

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Table 1: Main Parameters of FRIB MEBT/IH/2H/ReA Normal Conducting Cavities

| Parameter | | Units | MEBT | IH | 2H | ReA |
|---|---|---|---|---|---|---|
| Frequency | $f$ | MHz | 80.5 | 161.0 | 322 | 161.0 |
| Geometrical $\beta$ | $\beta_G$ | - | 0.0328 | 0.185 | 0.186 | 0.1 |
| Aperture diameter | $2a$ | mm | 30 | 36 | 36 | 30 |
| Resonator Dia. | $D$ | m | 0.20 | 0.49 | 0.24 | 0.30 |
| Q-factor | $Q$ | - | 7300 | 15620 | 13037 | 12855 |
| Tuning Range | | MHz | 1 | 1.5 | 1.8 | 1.5 |
| Vacuum Level | | Torr | $10^{-8}$ | $10^{-8}$ | $10^{-8}$ | $10^{-8}$ |
| RF Power | | kW | 2.5 | 30 | 4.6 | 2.7 |

Tuning of the buncher showed that the two resonators are well decoupled making tuning of the modes easier.

Operation showed that the buncher is able to reach the desirable electrode voltage with available RF power and is stable under a high RF power load, as well as mechanical disturbances.

### MEBT Buncher and ReA Buncher

MEBT buncher and ReA buncher are similar type, quarter-wave cavity with center drift and beam ports drift tubes forming 2 gaps, with one motorized tuner, and one fixed tuner. There is mesh at bottom to protect vacuum pump. Cooling to center drift tube through a deep-drilled hole (~900 mm).

Main differences between these two types are that MEBT buncher has 5 radially brazed circular cooling channels, with each ID on the cooling rings smaller from vertical up. And ReA buncher has 4 side vertically brazed cooling plates (cooling of resonator main body also for IH bunchers and 2H bunchers).

### IH Buncher and 2H Buncher

IH buncher and 2H buncher are similar Inter-digital H-Mode (IH) drift tube type radio frequency (RF) resonant structure, shown in Fig. 2. Vertical Copper cylindrical resonator with a number of drift tubes to form multiple gaps, so called Multi-Gap Buncher, MGB (7 gaps for IH cavity; 4 gaps for 2H cavity).

2H cavity is needed to eliminate LS2 loss by linearizing the effective voltage of IH Buncher [5]. Each 2H cavity is right downstream of IH cavity.

As operating frequency for 2H cavity is higher, 2H resonator is smaller in dimensions, and at the same time has higher sensitivities due to dimension errors.

### Cooling Design

Multi-physics analysis is done to get power density to different heating area, then to optimize cooling design, with investigation on deformation, stress as well frequency change due to temperature increase of the cavity and center stem is conducted. A unique feature for drift tube design is Helix like cooling channel design on center drift tube for max cooling capacity.

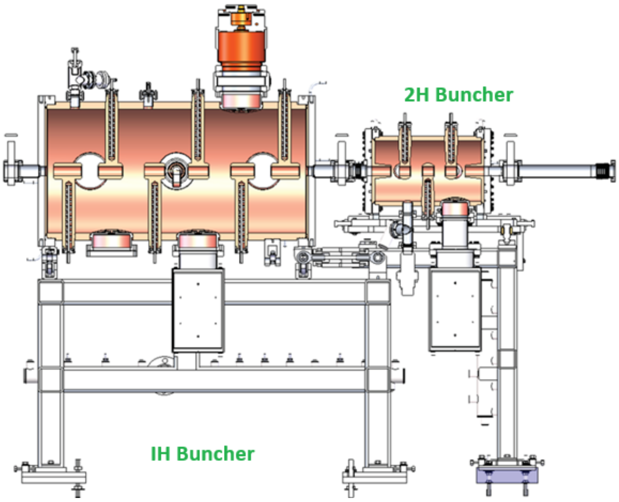

Figure 2: Cross Section View of IH Buncher (left) and 2H buncher (right).

### RF Contact

Three types of RF contact are used between non-continuous Copper surfaces: canted coil spring, RF fingers and flapper with C seal. All three types works well, with different applications for each type.

## FABRICATION

Overall strategy for FRIB normal conducting cavity fabrication is to locate a qualified vendor with vertical integration of major fabrication processes and be responsible for final product, with capacity to do field tuning as well.

Risk involving brazing is high and many factors can lead to not leak tight after brazing: low quality plating; dimension out of tolerance; improper brazing design; missing brazing alloy, inaccurate over temperature, etc. As for one overall brazement, close to 100 brazing joints need to be leak tight at once.

To help vendor with better understanding dimensional error's impact to the cavity performance, a table of tolerances based on each value's sensitivity is provided to vendor. This also help the cost to be reasonable.

### *Material*

Major components shall be Oxygen Free High Conductivity C101.2 (ASTM F68-10) or equivalent. It is preferred that fabrication vendor to buy the material, and with three material checks (material vendor, fabrication vendor, as well as FRIB). Material from Asia, Europe and US were both used and worked out fine.

End wall functions as both vacuum interface, and RF contact and both functions are critical. Different vacuum seal were used: O ring, Conflat, Delta seal. Normally Stainless Steel portion provides vacuum interface and Copper portion functions as RF contact. Both bi-metal material and brazing are used to form joint in between Stainless Steel portion and Copper portion. Both method work fine (bi-metal may not available in some markets) and cost/risk for bi-metal is slight lower.

### *Brazing*

As a large brazement has many brazing joints what need to be sealed at the same time, it is beneficial to divide brazing into multiple steps. Benefits includes reduce final number of brazing joints and lower brazing risk, able to check each brazing step, allows use of brazing alloys with descending melting points, and greater flexibility in manufacturing work flow.

Different vendors seem to have different preference related to brazing between circular surfaces or flat surfaces. Both have high success rate with good Q/A process.

Due to planned multi-step brazing, or unexpected repair, a Copper structure may be brazed more than one time. FRIB experience shows max of 4 brazing cycles. There can be risks for multiple brazing cycles: gain size growth with each brazing; each brazing cycle functions as annealing process, and material becomes softer each time; thermal cycling at this high temperature may cause cumulative stress relief and distortion; if brazing oven temperature control is off, earlier joints may experience creep of diffusion, which will reduce joint strength.

Brazing joints between Copper and Copper have much higher success rate than between Copper and Stainless Steel, especially at relatively large dimension. FRIB experiences shows 67% success rate at brazing of Stainless Steel and Copper at 0.5 meter diameter. For the failed brazing resonator, re-brazing doesn't solve the problem. This issue was mitigated by establishing a different vacuum interface resolved the leak issue.

To protect Cryomodule and Superconducting Magnets, it is good practices to avoid water-to-vacuum brazing joints. One way is to move the joints on the airside (e.g. center stem/tuner cooling doesn't have interface to vacuum, and cavity body cooling or end wall cooling from outside, also no interface to vacuum). Another way is to add additional brazing joints, such that one joint is air-to vacuum, and the other joint is air-to water). Couple is only device that can't avoid water-to-vacuum brazing joint.

### *Cleaning*

Cleaning surfaces prior to brazing are key to ensure strong, void-free joints and prevent contamination, with initial mechanical cleaning, degreasing and organic removal, and acid cleaning in ultrasonic bath, rinse and dry.

Cavity right after brazing is as clean as it can get. Machining the cavity after brazing should be avoided. It is a good practice to apply clear paint on outer surface right after leak checking, for cosmetic purpose only and will not impact functionality.

Ultrasonic cleaning was applied to IH buncher once. Results are mixed: Q value increased to higher than calculation, but oxidation happened quickly after cleaning shown in Fig. 3.

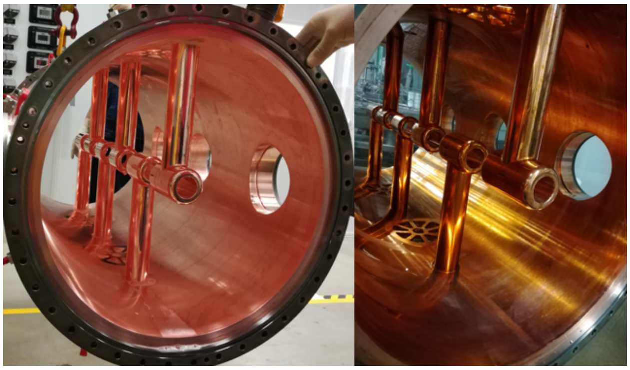

Figure 3: IH buncher cavity right after ultrasonic bath (left), and after another 10 minutes (right).

## TUNING PROCESS

A device for each cavity is designed to have extra material to cut during final tuning process, usually fixed tuners, also a plug threaded at bottom of long center stem.

During final tuning, FRIB representative is present at vendor site to witness leak checking (with cavity inside a plastic bag with no leak for at least 15 minutes), and frequency tuning (tuning range by motorized tuners, Q factor value measurement with at least 80% of calculated Q value as target). Usually three steps of tuning are done to cut different length of the tuning device. Normally the intended cut length and actual cut length is within 1 mm, with consideration of vacuum, gravity and ambient temperature.

## OPERATIONAL STATUS

The installed normal conducting cavities support FRIB facility beam operation during last few years. There are couple of minor issues during installation, and improvements have been implemented in next device design. These devices have caused no downtime.

AIP project was completed last year to upgrade IH buncher from 18 kW to 30 kW [6]. The upgrade is on RF system only and no changes to cavity side (which shows the advantage of such normal conducting cavity).

Critical spare is identified (IH buncher assembly, motorized tuner assembly, RF contact parts, coupler, motors, etc.) Periodical maintenance is also scheduled to reduce mean time between down.

## SUMMARY

This paper presents an overview of the normal-conducting cavities employed at FRIB, including key design parameters, functional characteristics, and principal features of the MHB, MEBT buncher, IH buncher, 2H buncher, and ReA buncher. The discussion also includes insights into their fabrication processes, as well as operational performance and experience gained during commissioning and routine operation.

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