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DEVELOPMENTS TOWARDS FRIB UPGRADE TO 400 MeV/u FOR THE HEAVIEST URANIUM IONS

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Abstract

High-Q_0 medium-velocity ($\beta_{opt} \approx 0.6$) 5-cell elliptical cavities for superconducting linacs are critical technology for current and future hadron linac projects such as Fermilab's Proton Improvement Plan II (PIP-II) and the proposed energy upgrade of Michigan State University's Facility For Rare Isotope Beams (FRIB400). Previous work established the validity of the novel geometry of the FRIB400 prototype 644 MHz 5-cell elliptical β = 0.65 superconducting rf cavities for future high-Q_0 development. In collaboration with Fermilab, two leading-edge high-Q_0 recipes, N-doping and furnace/medium-temperature baking (FMTB), were tested in the 5-cell cavity. N-doping ("2/0") + cold electropolishing was successful at achieving the FRIB400 and PIP-II requirements for Q_0, achieving an unprecedented 3.8×10^{10} at 17.5 MV/m, which is 1.75 times higher than the FRIB400 requirement for Q_0. With FMTB, Q_0 was 1.4 times higher than the FRIB400 requirement. Additionally, systematic studies of bulk Nb material parameters suggest a relationship between the flux pinning force measured in a sample and the flux expulsion properties of a cavity fabricated from the same material.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU), a first-in-class nuclear research facility, was fully commissioned in January 2022, and has successfully provided beam to three user experiments, with 34 more having been approved [1]. The FRIB accelerator consists of 3 linac segments and 2 folding segments, with a total of 324 superconducting radio-frequency (SRF) cavities (divided among quarter-wave and half-wave resonators) in 46 cryomodules. The FRIB400 project proposes to double the energy of the current superconducting FRIB linac for the heaviest uranium ions from 200 MeV per nucleon (MeV/u) to 400 MeV/u [2]. The increased rare isotope production from higher-energy drive beams would bring many important foci of nuclear physics research within reach of FRIB, including the ability to probe parameters of the nuclear matter equation of state to new levels of precision, which would provide critical information for the study of neutron star mergers. Further, the facility's reach along the neutron drip line would be significantly increased. [2].

In support of the FRIB400 proposal, a design study identified the novel β_{opt} = 0.65 5-cell elliptical 644 MHz SRF cavity with an accelerating gradient (E_{acc}) of 17.5 MV/m as the best candidate for the upgrade accelerator [3]. Of the three frequencies studied for elliptical cavities, the 644 MHz 5-cell β_{opt} = 0.65 case was the only one capable of delivering the necessary accelerating voltage within the 80 m of space available in the FRIB linac tunnel without increasing the current standards for the peak surface electric field, around 40 MV/m [3]. This design also has the lowest cryogenic heat load and the largest longitudinal acceptance [3]. The principal cavity design parameters and operating goals can be found in Table 1, and Figure 1 shows the cavity design.

Table 1: FRIB400 Cavity Parameters

Frequency	644 MHz
Geometric β	0.61
Optimal β	0.65
Aperture diameter	83 mm
Effective length L_{eff}	71.0 cm
Number of cells	5
Geometric shunt impedance R/Q	368 Ω
Geometry factor G	188 Ω
E_{peak}/E_{acc}	2.28
B_{peak}/E_{acc}	4.42 mT/(MV/m)
2 K operating goals	
Accelerating gradient E_{acc}	17.5 MV/m
Peak surface electric field E_{peak}	40 MV/m
Peak surface magnetic field B_{peak}	77.5 mT
Intrinsic quality factor Q_0	2×10^{10}

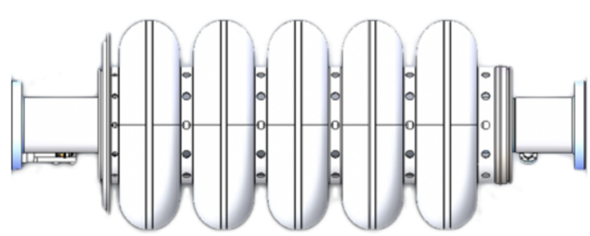

Figure 1: Drawing of the FRIB400 5-cell cavity.

The proposed 5-cell cavity operating at medium gradient bridges a hitherto unfilled gap from low-β TEM-type cavities to β = 1 elliptical-type cavities for continuous wave (CW) operation. Requiring a minimum Q_0 of 2×10^{10}, these large, sub-GHz cavities pose novel rf surface processing challenges. The European Spallation Source (ESS) and the Spallation Neutron Source (SNS), both of which operate in pulsed mode, employed buffered

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chemical polishing (BCP) with a Q_0 requirement nearly an order of magnitude lower than that of FRIB400. In order to limit FRIB400 to a modest upgrade to the FRIB cryogenic facilities and provide broader benefit to the field of SRF in this velocity and frequency range, our R&D efforts for rf surface processing aim higher than the FRIB400 minimum Q_0 of 2×10^{10}.

Two prototype 5-cell cavities were fabricated and vertically tested at MSU/FRIB under various "conventional" rf processing recipes, such as Electropolishing (EP) and buffered chemical polishing (BCP), to demonstrate that the novel 644 MHz geometry was valid, had no confounding multipacting or microphonic resonance issues, and thus was a reasonable vehicle for high-Q_0 development [4]. EP was the most successful of the conventional recipes, achieving $Q_0 = 2.3 \times 10^{10}$ in the best trial.

We now move to explore the potential of advanced and highly promising rf surface processing recipes of nitrogen doping (N-doping) [5] and furnace/medium temperature baking [6] for FRIB400 cavities. Though well-developed at frequencies greater than 1 GHz, complex physics makes the translation of these techniques to lower-frequency, larger-area cavities not obvious.

RF SURFACE PROCESSING

N-doping classically consists of heat treating a freshly electropolished cavity to 800 C in vacuum, profusing nitrogen for some time at that temperature, annealing at that temperature without nitrogen for some time, and then cooling. Afterwards, the cavity must undergo light EP to remove the detrimental layer of niobium nitrides. The EP tool we used for the large FRIB400 cavities is described in [4]. A "2/6" recipe (2 minutes of doping, 6 minutes of annealing) was explored for PIP-II high-β 650 MHz cavities [7], where 7 µm of post-doping EP was found to be optimal. Subsequent work for LCLS-II found a "2/0" recipe (2 minutes doping, 0 minutes annealing) improved upon those results, in part by reducing the temperature-dependent component of the rf resistance, the BCS resistance (R_{BCS}) [8].

Furnace/medium temperature baking consists of a relatively short, low-temperature baking period, followed by high-pressure rinsing (HPR), then assembly to the vertical test insert. It is important to note that this differs from other "mid-T" baking methods in which a similar temperature is applied to the cavity for a similar amount of time, but *in situ*, avoiding post-treatment exposure of the cavity surface to air. Based on past results [6], we elected to apply the 300 degrees C bake for 3 hours to a FRIB400 5-cell cavity.

The cavity cold tests were performed at MSU/FRIB and Fermilab. Both facilities use magnetic field cancellation during cooldown to ensure the background magnetic field at transition is generally less than 1 mG. The results of these trials are shown in Fig. 2. Both recipes improved cavity performance over the EP baseline (green); the 2/0 doping recipe delivered the best performance of $Q_0 = 3.8 \times 10^{10}$ at $E_{acc} = 17.5$ MV/m (magenta) with a low background magnetic field. Post-EP tests were limited by available amplifier power; the N-doped tests were limited by quench; and the FMTB test reached the administrative limit of 26 MV/m.

A few interesting points emerge from these initial trials. The first 2/6 N-doping of S65-001 (blue) caused a slightly decreased Q_0 compared to the EP baseline despite similar background magnetic fields. Given the challenges of conducting EP on this cavity, it is possible that the post-doping EP did not remove enough material; cavity performance can be highly sensitive to the depth of post-doping EP. Additional EP improved the performance of that cavity in a subsequent test (red) where the background magnetic field may have even been slightly higher. In testing of the cavity at 1.5 K at Fermilab, we found that the temperature-independent component of the surface resistance, the residual resistance (R_0), decreased by nearly 1 nΩ at 17.5 MV/m after further EP; hence the improvement can be attributed to fuller removal of the Nb nitride layer produced during N-doping.

The second prototype cavity was also EP-baselined to a very similar performance level to the first cavity, then treated with 2/0 N-doping. With a low background magnetic field in the MSU vertical test dewar, this cavity had very strong performance achieving an unprecedented $Q_0 = 3.8 \times 10^{10}$ at $E_{acc} = 17.5$ MV/m (magenta). As is typical in N-doped cavities, 1.5 K testing revealed that R_0 was the primary performance limitation. Hence further pursuit of N-doping development for these cavities will focus on mitigating known contributors to R_0. In particular, we aim to quantify the increased magnetic flux sensitivity of N-doped cavities and develop methods of promoting flux expulsion, for vertical testing, with an eye toward practical solutions for flux expulsion in a cryomodule.

After an EP-reset and re-baselining (black), the first prototype cavity underwent FTMB at 300 C for 3 hours, high-pressure rinsed, and then cold tested (cyan). The resultant performance, while elevated, was not significantly different from the immediately-prior EP baseline. The effect of the treatment became more obvious in the decomposition of R_{BCS} and R_0 in low-temperature testing, where the FMTB'ed cavity had elevated R_0 and low R_{RCS}, in contrast to the elevated R_{BCS} and low R_0 of the EP-treated cavity.

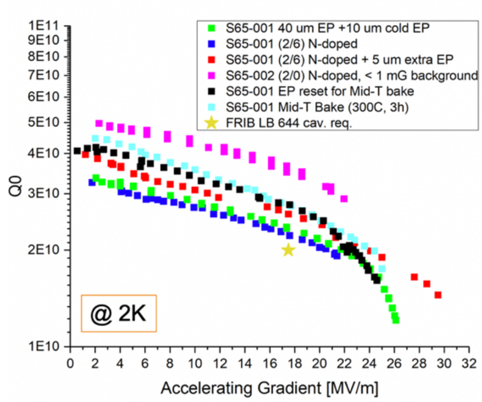

Figure 2: Cold tests at 2 K for the FRIB400 prototype cavities (S65-001, -002) before and after N-doping or FMTB. The yellow star marks the FRIB400 minimum goal.

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CAVITY FLUX SENSITIVITY

The residual resistance R_0 clearly dominates the loss mechanisms for N-doped and FMTB'ed cavities. Magnetic flux trapping in the Nb cavity walls increases R_0, so efforts have been made to understand flux trapping and how to minimize it [9].

Three single-cell cavities of the same β_{opt} = 0.65 design at 644 MHz were fabricated for FRIB400 upgrade R&D, including a more detailed study of magnetic flux expulsion. To begin quantifying the flux sensitivity of the FRIB400 cavity, a baseline electropolished single-cell cavity was subjected to a slow-cooldown in an imposed 20 mgauss ambient magnetic field. By immersing the cavity in a known field, we can directly measure the change in surface resistance resulting from the trapped flux, usually referred to as the flux sensitivity. Results for a baseline electropolished single-cell cavity are shown in Fig. 3. With low ambient field the Q_0 is high at 2 K (black), as expected; with 20 mGauss ambient field, Q_0 at 2 K decreases significantly (blue). The 1.5 K performance with 20 mGauss of imposed field (pink) makes it clear that the performance degradation is mainly due to increased R_0, as expected. We infer a flux sensitivity of 0.45 nΩ/mGauss from these measurements. Future experiments will repeat this measurement in an N-doped cavity, for which we expect significantly higher flux sensitivity. Quantifying the flux sensitivity for the FRIB400 cavity will help us to understand the magnetic shielding and cool-down speed requirements for electropolished and N-doped cavities in a future FRIB400 cryomodule.

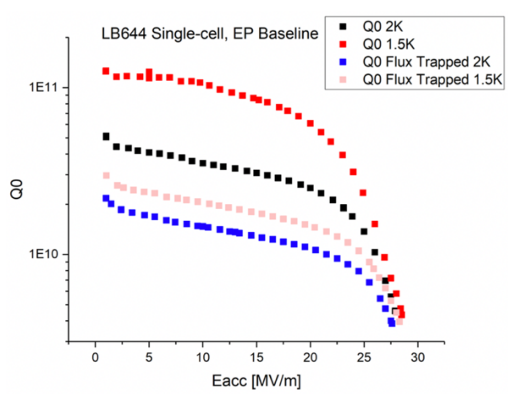

Figure 3: Flux sensitivity measurement in an electropolished single-cell FRIB400 cavity.

CAVITY FLUX EXPULSION

Given the likely high flux sensitivity of the highest-performing N-doped recipes, it is highly desirable for cavities to expel as much background magnetic flux as possible during cooldown. The flux expulsion performance of cavities is measured as a ratio of the magnetic field measured at the cavity equator after the superconducting transition and before the transition in an imposed magnetic field (B_{SC}/B_{NC}). Simulations can be used to predict the theoretical maximum flux expulsion ratio; for the FRIB400 cavity, the theoretical value is $B_{SC}/B_{NC} \approx 1.8$. We can expect to measure a ratio near the theoretical value in a best-case scenario.

In the course of rf testing, single-cell β_{opt} = 0.65 cavities fabricated from Nb material from Ningxia (NX) for INFN/PIP-II (650 MHz) showed significantly improved expulsion performance after a 900 C, 3 hour heat treatment, as shown in Fig. 4. The ratio B_{SC}/B_{NC} is the most enhanced for 900 C-treated NX material (green), compared to the previous 800 C-treated performance.

Since flux expulsion properties have been found to vary by Nb vendor, and even by lot number for material from the same vendor, we began to investigate whether material from a different vendor would respond similarly to 900 C heat treatment. The FRIB400 single-cell cavity was fabricated from Tokyo-Denkai (TD) material, and despite a significant difference in average grain size (around 130 μm for the TD material vs. 40 μm for the NX material), performed similarly in flux expulsion testing (blue). The cavity has since been heat treated at MSU at 900C for 3 hours, and we plan to repeat the flux expulsion test on the heat-treated cavity.

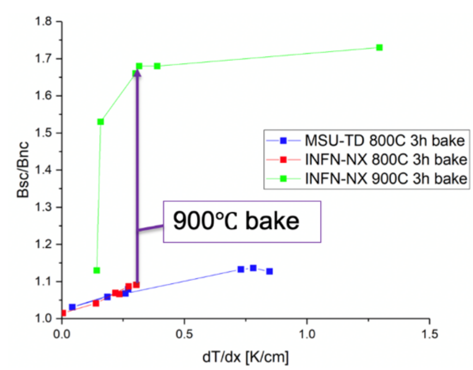

Figure 4: Measured single cell cavity flux expulsion as a function of the spatial temperature gradient along the cell surface.

It is worth noting that challenges remain in determining whether it is feasible to apply high-temperature heat treatment to the 5-cell cavities. Studies are currently underway at Fermilab to determine the mechanical stability of the cavities during heat treatment.

SAMPLE FLUX PINNING FORCE

For cavity mass production runs requiring Nb material from multiple vendors or multiple lots from the same vendor, it would be desirable to understand the flux expulsion properties of a given lot of Nb without having to first fabricate and test a cavity. The Fermilab Material Science Laboratory has a Physical Property Measurement System (PPMS) which allows us to measure the flux-pinning force (F_p) in small (3 mm × 8 mm) samples of niobium. At 9 K, just below the superconducting transition, the PPMS applies a magnetic field on the order of many gauss in two opposite directions and measures the resulting irreversible magnetization of the sample, from which the flux pinning force may be calculated [10]. The imposed field in this measurement is obviously well beyond that which a cavity

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will experience, since a typical background magnetic field is of order a few mGauss. However this PPMS measurement is still informative, as will be described below.

We measured F_p on samples from TD and NX, as shown in Fig. 5. Initial measurements were done without heat treatment (black, gray). After heat treatment for 3 hours at 800 C, there is a reduction in F_p (red, blue). After further heat treatment for 3 hours at 900 C (mimicking the heat treatment of the INFN-NX cavity which had the dramatic flux expulsion improvement with 900 C treatment), we saw an additional decrease in F_p for the NX material (green). A similar decrease in F_p was observed in the MSU-TD material (magenta). A wider sample set is needed to fully understand the relationship between F_p measurements on samples and cavity performance, but these preliminary results are encouraging. Based on our results, we hypothesize that the TD cavity will have an improved flux-expulsion ratio after 900 C treatment, similar to that seen in the NX cavity.

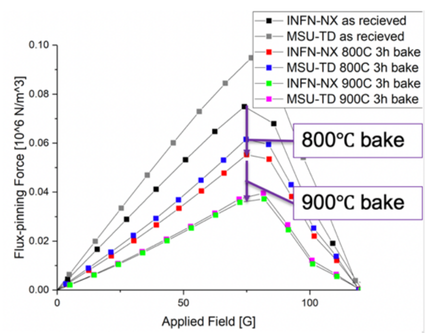

Figure 5: Flux-pinning force as a function of applied magnetic field measured on Nb samples using the PPMS.

If the hypothesis above is confirmed, it will provide motivation to continue development of a practical understanding of how F_p measurements in Nb samples correlate with flux-expulsion performance in cavities. If we find that there is a good correlation between the flux pinning force in samples and flux expulsion in cavities, this would be beneficial both for evaluating treatments to improve cavity performance and for evaluating lots of Nb material from material suppliers for their potential to produce good cavities.

CONCLUSION

The high-Q_0 development for the medium-β 644 MHz FRIB energy upgrade cavity is progressing well, as demonstrated by our current world-record of $Q_0 = 3.8 \times 10^{10}$ at an accelerating gradient of 17.5 MV/m in an N-doped 5-cell FRIB400 cavity. Initial tests suggest that the highest Q_0 is obtained via N-doping for the FRIB operating temperature (2 K) and gradient (17.5 MV/m). Furnace/medium-temperature baking provides some improvement in Q_0 with a simpler treatment, but does not yet show potential to equal or exceed the results of N-doping, even prior to refinement of the N-doping recipe for FRIB400.

We anticipate that the ultimate limit to Q_0 for real cryomodules will be the residual resistance, and we are developing multiple approaches to minimize its adverse impact. Efforts to establish a connection between cavity flux expulsion and the bulk material property of flux-pinning force (which can be measured with small samples) show promise; however, further study is needed to refine our understanding of the correlation between the two. Overall, we expect significant progress in improving cavity performance, and look forward to extending it to a fully dressed cavity by the time we receive project funding for FRIB400.

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REFERENCES

[1] P. Ostroumov, "FRIB Commissioning", presented at HIAT'22, Darmstadt, June 2022, paper WE1I3.

[2] A. Gade *et al.*, "FRIB400 The Scientific Case for the 400 MeV/u Energy Upgrade of FRIB", FRIB, MA, USA. https://indico.frib.msu.edu/event/2/attachments/57/292/FRIB400_Final.pdf

[3] P. N. Ostroumov *et al.*, "Elliptical superconducting RF Cavities for FRIB energy upgrade", *Nucl. Inst. Methods Phys. Res. A*, vol. 888, pp. 53-63, 2018. doi:10.1016/j.nima.2018.01.001

[4] K. McGee *et al.*, "Medium-Velocity Superconducting Cavity for High Accelerating Gradient Continuous-Wave Hadron Linear Accelerators", *Phys. Rev. Accel. Beams*, vol. 24, p. 112003, 2021. doi: 10.1103/PhysRevAccelBeams.24.112003

[5] A. Grassellino *et al.*, "Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures", *Supercond. Sci. Technol.*, vol. 26, p. 102001, 2013. doi:10.1088/0953-2048/26/10/102001

[6] H. Ito, H. Araki, K. Takahashi, K. Umemori, "Influence of furnace baking on Q–E behavior of superconducting accelerating cavities", *Prog Theor. Exp. Phys.*, p. 071G01, 2021. doi:10.1093/ptep/ptab056

[7] M. Martinello *et al.*, "Q-factor optimization for high-beta 650 MHz cavities for PIP-II", *J. Appl. Phys.*, vol. 130, p. 174501, 2021. doi:10.1063/5.0068531

[8] S. Posen *et al.*, "High gradient performance and quench behavior of a verification cryomodule for a high energy continuous wave linear accelerator", *Phys. Rev. Accel. Beams*, vol. 25, p. 042001, 2022. doi:10.1103/PhysRevAccelBeams.25.042001

[9] M. Martinello, "The Path to High Q-factors in Superconducting Accelerating Cavities: Flux Expulsion and Surface Resistance Optimization", Ph.D. thesis, Illinois institute of Technology, IL, USA, 2017.

[10] M. Martinello, "Microscopic Investigation of Flux Trapping Sites in Bulk Nb", presented at the 19th Int. Conf. on RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper TUFUB4, unpublished.