ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV002

HOM EXCITATION IN SPOKE RESONATOR FOR SRF STUDIES

D. Longuevergne, N. Bippus, F. Chatelet, V. Delpech, N. Hu, C. Joly, T. Pépin-Donat, F. Rabehasy, L. Renard, Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
E. Cenni, M. Baudrier, L. Maurice, CEA-IRFU, Gif-sur-Yvette, France

Abstract

The excitation of Higher Order Modes (HOM) or Lower Order Modes (LOM) has been performed for years on multi-cell superconducting accelerating cavities as a mean to coarsely locate a quench, a defective area or ignite a plasma for surface cleaning. Moreover, such multi-mode testing is very useful to understand more accurately the frequency dependence of the surface resistance in a wide range of surface magnetic fields (0<B<150mT). In that sense, several type of dedicated non-accelerating resonators like Quadrupole Resonator (QPR), Half- or Quarter-Wave resonators have been built to specifically study new superconducting materials or new surface or heat treatments. What is proposed in this paper is to perform such multi-mode analysis (352 MHz, 720 MHz and 1300 MHz) in an existing accelerating cavity, in particular a Spoke Resonator. Baseline results will be presented and perspectives of such technique will be discussed.

INTRODUCTION

SRF cavities are nominally operated between 50 MHz and 4 GHz depending on their position in accelerators and on their mode of operation (accelerating, bunch corrections, crabbing, …). The most used frequency for particle acceleration and R&D purposes corresponds to the Tesla type 1.3 GHz elliptical cavity developed for light sources like the EU-XFEL and LCLS-II, and eventually used for next generation linear colliders like ILC. Years of intense R&D have been carried out worldwide through the Tesla Technology Collaboration (TTC) to reach the very ambitious specifications in term of accelerating gradient (Eacc) and quality factor (Qo). Most of models on surface resistance, optimization of surface treatment recipe is based on data collected at 1.3 GHz. However, the growing business of low beta structures for ion accelerators tends to show that recipes optimized at 1.3 GHz structures is not necessarily optimal at lower or higher frequencies [1]. More importantly, the field dependence of the surface resistance appears to be very dependent on the frequency. In an attempt to gain more insight in the frequency dependence, several studies [2, 3] have been performed and new dedicated SRF structures [4, 5] have been built. These studies are very delicate to carry out and interpret as the frequency dependence is studied in multiple cavity geometries requiring to proceed with identical surface treatments to be representative. On the other hand, the fabrication of dedicated SRF structures in which multiple modes can be excited is very expensive, time consuming and risky. Only one structure is built with no guarantee that it will be suitable for this kind of studies. What is suggested in this paper is to perform multi frequency analysis in low-beta accelerating cavities built during prototyping phase for accelerator projects. These cavities are typically numerous, not used on the linac and thus available for further studies.

At IJCLab, several Spoke resonators have been developed, built and optimized for Spiral2, ESS and MYRRHA projects. Multi-mode testing has been developed for MYRRHA prototypes as these cavities are easy to process and show very good performances like high achievable accelerating gradient, low surface resistance and low field emission. The cavity is externally coupled with a movable antenna with a stroke of 50 mm. The pick-up antenna is however fixed.

This paper aims at describing firstly all the RF simulations performed to characterize suitable modes and obtain important parameters. Secondly, all necessary room temperature measurements prior to cold test will be presented. Finally results of first cryogenic tests will be shared and discussed.

SIMULATIONS

RF Simulations

RF Simulations have been performed with CST Microwave Studio. The main goal of the simulations is to identify which modes could be easily operated with regular RF system. First the mode would need to be easily coupled with an antenna with a simple geometry and critical coupling at 2K should be achieved within the 50-mm stroke of the system. Moreover, the fixed pick-up antenna should show coupling factors, denoted Qt, compatible with Qo of all operational modes (typically Qt > 10·Qo). Secondly, the frequencies of modes should be close to standard frequencies like 700 MHz and 1.3 GHz so as to be compatible with existing RF equipment.

At the sight of all these constraints, several modes have been identified by simulation, important parameters are shown in Table 1 and field distributions in Fig. 1. So as to evaluate the peak magnetic field in the cavity during vertical testing, the specific parameter U/Bpk^2 can be used to translate the stored energy into peak magnetic field.

Table 1: Modes Parameters Estimated by Simulation

Id	Frequency (MHz)	U/Bpk^2 (J/mT^2)	G (Ohms)	Bpeak @1J (mT)
1	353	8.9e-3	109	15.8
2	719	7.75e-4	255	36.1
3B	1300	1.8e-3	396	24
3D	1312	6.6e-4	431	40
3E	1333	1.6e-3	483	25.4

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV002

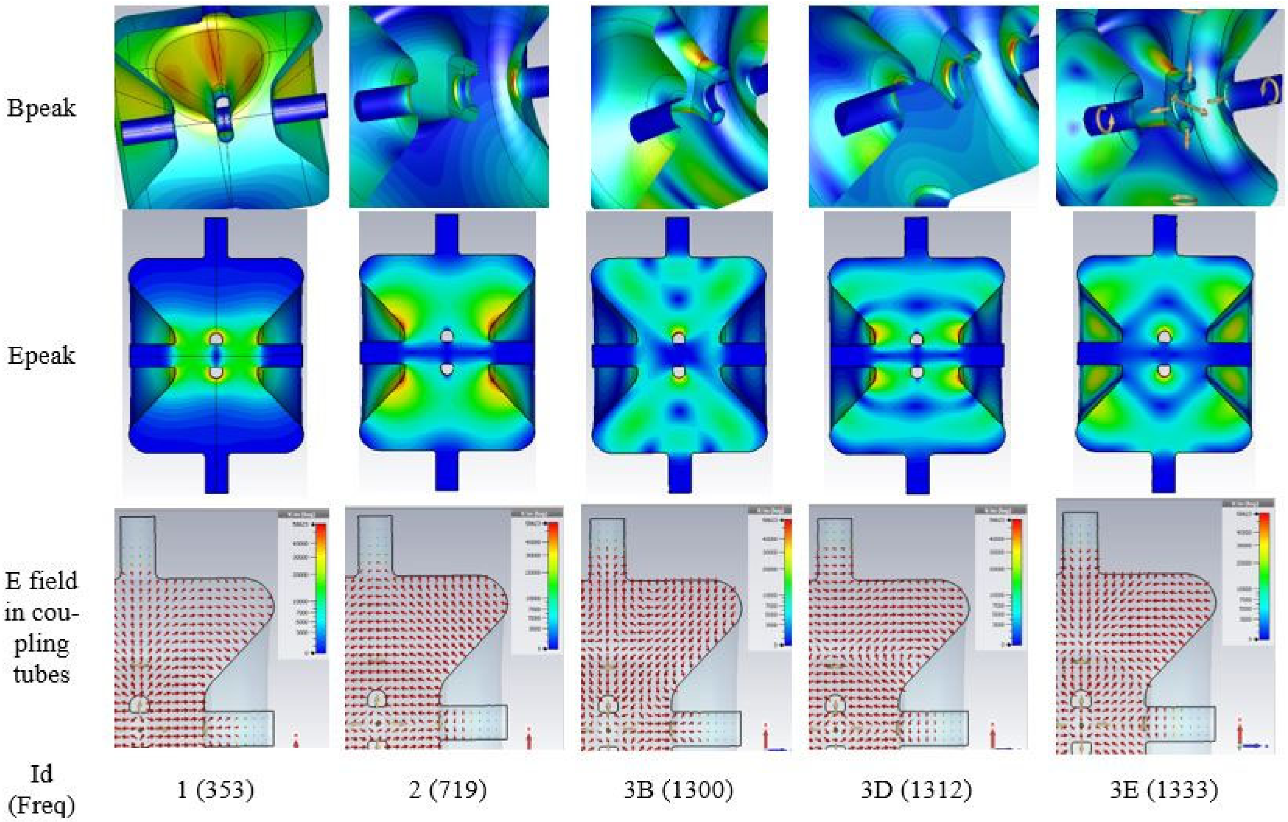

Figure 1: From top to bottom: Magnetic field distribution, electric field distribution and electric field vectors in coupling tubes for the five identified modes.

Electric field orientations in beam ports (horizontal) and coupler ports (vertical) are suggesting:

- The way electric field is decaying in coupler ports (penetration of field is more pronounced at higher frequencies) imposes the use of a movable coupler to allow tuning of the coupling factor. This port is thus suitable for unity coupler.
- The way electric field is decaying in beam ports (penetration of field is rather similar whatever the frequency) allows to use a fixed coupling.
- Orientation of electric field in coupling ports could be longitudinal or radial. A straight antenna centred would not allow to couple all the modes efficiently. A specific geometry has to be found.

Multipacting Simulations

Spoke resonators typically show numerous multipacting barriers for the fundamental accelerating mode. These could be significantly difficult to process. Multipacting simulations have been performed with CST Spark3D [6] so as to identify which modes would be difficult to operate. The secondary Emission Yield (SEY) considered is for clean baked Niobium after some conditioning time [7]. The growth rate (noted α) versus magnetic field is defined in Eq. (1):

$$N(t) = N_0 e^{\alpha t}. \tag{1}$$

With N and N_0 respectively the number of electrons at time t and t=0. A growth rate above zero indicates the existence of multipacting: the electron population is growing exponentially. As depicted in Fig. 2, the five modes are subject to multipacting but two of them (719 MHz and 1312 MHz) tend to be multipacting-free respectively up to 120 mT and 80 mT. On the contrary, the two other modes close to 1.3 GHz exhibit very high growth rates and might not be convenient to operate. As it will be discussed later in the test results, these simulations are in very good agreement with observations done during cavity testing.

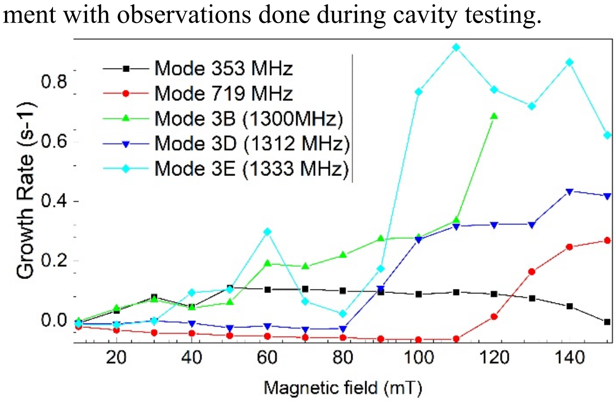

Figure 2: Growth rate versus maximum magnetic field for the five modes 353 MHz, 719 MHz, 1300 (3B), 1312 (3D) and 1333 MHz (3E).

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV002

EXPERIMENTAL SET-UP AND MEASUREMENTS

This section will describe the specific points addressed to allow HOM coupling and testing during a single cryogenic test without any cavity disassembly. Moreover, the intrinsic quality factor (Q_0) and thus the surface resistance (R_s) are evaluated thanks to power levels (P_{ext}, P_r, P_t), coupling factors (Q_{ext}, Q_t) and geometrical factors (G, U/B_{pk}^2) depending on the field distribution of the HOM mode.

Identification of modes is thus of first importance, especially for those above 1 GHz, as they are numerous and their frequencies and thus their orders are very sensitive to fabrication deviations and uncertainties.

Identification of Modes

Several methods have been tried to identify efficiently modes above 1 GHz, as many of them are only few MHz away from the others as depicted in Fig. 3.

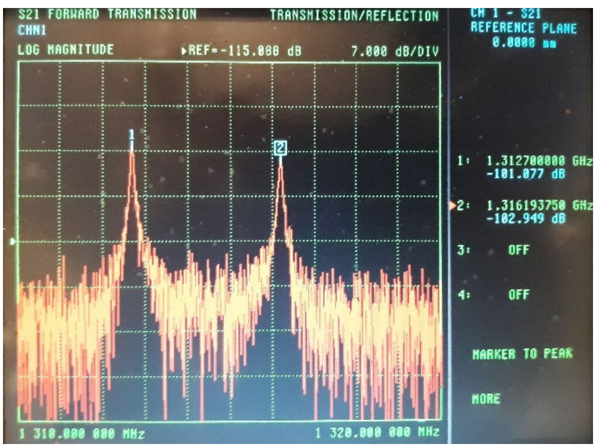

Figure 3: Screenshot of a network analyser showing 2 HOM modes close to 1.31 GHz and separated of about 3 MHz. Measurement done at room temperature on the MYRRHA Spoke resonator just before cool-down in vertical cryostat.

Direct measurement of the field distribution along beam axis by bead pulling has been performed but the analysis happened to be complicated as some modes have very weak fields in this region. The best identification method found is to evaluate the geometrical factor G during coupling measurements and compare to simulation values. From Table 1, G factors of modes are different enough to be resolved by RF measurements at room temperature.

So as to evaluate coupling factor of unity coupler (Q_{ext}) and pick-up antenna (Q_t), a network analyser is used to measure the resonance frequency, the bandwidth and $S_{11}=P_r/P_f$ and $S_{21}=P_t/P_f$ parameters where P_r, P_f and P_t are respectively the reflected, forward and transmitted powers. Coupling factors can be directly evaluated as explained in [8] as well as Q_0. G factor can be deduced thanks to Eq. (2) by considering that parameters of the fundamental mode are well-known and the surface resistance of a normal conductor scales with the square root of the frequency:

$$G_{HOM} = Q_{0,HOM} \cdot \frac{G_{Fund}}{Q_{0,Fund}} \cdot \sqrt{\frac{F_{HOM}}{F_{Fund}}} \qquad (2)$$

Where $Q_{0,HOM}$ and $Q_{0,Fund}$ the intrinsic quality factors of the HOM and the fundamental modes, F_{HOM} and F_{Fund} the resonance frequencies of HOM and fundamental modes and G_{Fund} the geometrical factor of the fundamental mode.

Table 2 below summarizes the main parameters of the modes measured at room temperature. This identification process was clearly justified as position of modes 3B and 3D have been inverted.

Table 2: Measured Parameters

Id	**Measured frequency (MHz)**	**G (Ohms)** measured	**G (Ohms)** simulated
1	351.6	109	109
2	721.5	264	255
3B	1315.1	391	396
3D	1314.4	429	431
3E	1337.9	480	483

Coupling of Modes

The next challenge for the HOM testing is to find the appropriate antenna geometries to couple the five modes during the same cryogenic test with following constraints:

- Unity coupler is movable with 50 mm stroke and can only operate vertically
- Pick-up antenna is fixed
- Unity coupler should be close to critical coupling for all modes between 4.2K and 2K.
- Pick-up antenna should have weak coupling with all modes $Q_t > 10 \cdot Q_0(T=1.8K)$.

At the sight of these constraints and the field distribution in tubes as depicted in Figure 1 the unity coupler could only be installed on a coupler port and pick-up antenna on a beam port. To couple modes 2, 3B and 3D, the antennas should be bended as the electric fields are transverse. In that sense, 3 parameters could be adjusted as the antenna length, the length and orientation of the bended tip.

Figure 4 is showing the geometries of the two antennas offering very good coupling capabilities as detailed in Table 3. Indeed, modes 1, 2 and 3D can be perfectly coupled whatever the temperature between 4.2K and 2K. However, modes 3B and 3E are respectively too highly coupled with unity coupler and too weakly coupled by pick-up antenna.

Figure 4: From left to right: Unity coupler fully out, fully in and pick-up antenna.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV002

Table 3: Ranges of Coupling Factors Obtained with Unity Coupler and Pick-Up Antenna

Mode Id	Measured frequency (MHz)	Expected Q_0 @ 4.2K @ 2K	Q_{ext} (fully-in)	Q_{ext} (fully-out)	Q_t
1	351.6	2E9 4E10	3.6E9	2.6E13	4.7E11
2	721.5	1.2E9 3.8E10	6.8E8	1.1E12	4.6E11
3B	1315.1	6.6E8 2.5E10	5.9E6	2.1E9	2.1E11
3D	1314.4	7.2E8 2.7E10	1.5E7	4.3E10	3.7E11
3E	1337.9	8E8 3E10	1.4E7	1.7E10	5.2E12

RF Equipment and Configuration

The fundamental mode is excited and controlled by a self-excited loop (SEL) available at IJCLab whereas a Phase-Lock Loop (PLL) from IRFU is used for all HOMs. For each mode different bi-directional couplers, amplifier and circulator are used. Cable and RF system attenuations are measured for each mode. When possible, coupling factor of unity coupler is adapted to reach critical coupling so as to reduce the reflected power and thus measurement errors.

BASE-LINE TEST RESULTS

Figures 5, 6 and 7 are respectively detailing the quality factor Q_0 versus the peak magnetic at various temperatures for the fundamental mode (1) and HOM modes (2) and (3B).

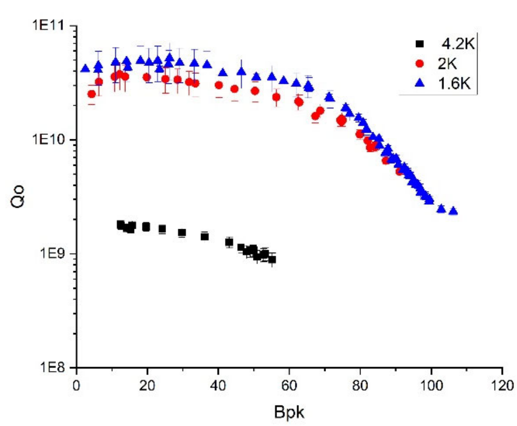

Figure 5: Quality factor of fundamental mode (1) versus peak magnetic field between 4.2K and 1.6K.

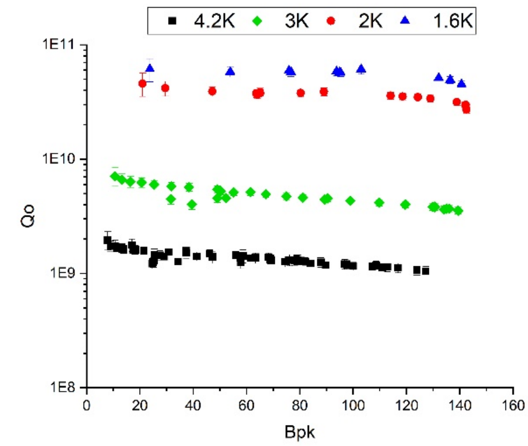

Figure 6: Quality factor of HOM mode (2) versus peak magnetic field between 4.2K and 1.6K.

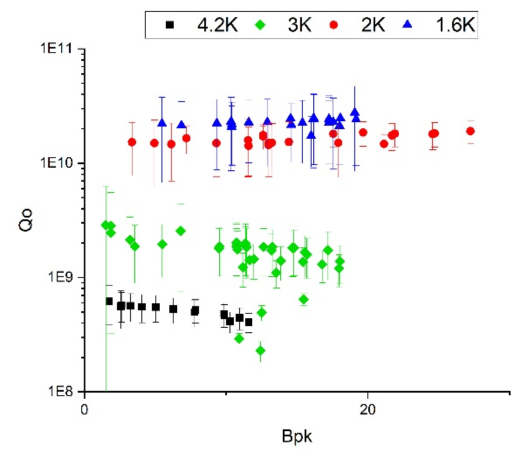

Figure 7: Quality factor of HOM mode (3B) versus peak magnetic field between 4.2K and 1.6K.

The quality factors measured for the fundamental mode at low fields (see Fig. 5) are validating the high quality of surface preparation of this cavity. However, at higher fields above 60 mT a very strong Q-slope can be observed attributed to multipacting [7]. This prevents any surface resistance analysis to be performed at high field. This multipacting origin is as well confirmed by results obtained with HOM (2). Indeed, no field emission has been observed up to the maximum field although maximum electric fields are distributed close to the same location as the fundamental mode (see Fig. 1).

Quality factors measured for HOM (2) are as well confirming the high quality of surface preparation and this up to 140 mT. As plotted in Fig. 2, this mode is showing no anomalous dissipations inducing Q-slope and is multipacting-free up to 120 mT (Fig. 2).

Finally, more difficulties have been encountered with HOM close to 1.3 GHz. HOM (3D) couldn't be locked due to instabilities of the RF loop. HOM (3B) was also difficult to lock but measurements of the quality factor were possible only up to 20 mT. Additional tests have to be performed so as to resolve these instabilities and allow reliable measurement at higher fields.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV002

Analysis and Discussions

One of the main motivation of HOM test is to highlight and evaluate any frequency dependence of the surface resistance. The total average surface resistance R_s of the cavity can be evaluated thanks to Eq. (3) and its dependence in temperature can be fitted by Eq. (4).

$$Q_0 = \frac{G}{R_S} \tag{3}$$

$$R_S(T) = R_{res} + C \cdot F^2 \cdot x \cdot e^{-D \cdot x} \qquad x = \frac{Tc}{T} \tag{4}$$

With R_{res} the residual surface resistance, C and D two fitting parameters related to material properties, F the frequency of the mode in GHz.

It has to be pointed out that Eq. (3) is a good approximation at low field (< 20 mT) in a region where the surface resistance (i.e the quality factor) does not depend on the amplitude of the magnetic field. At higher fields (>20 mT), geometrical corrections are required especially in low beta cavities to take into account the field distribution inside the geometry [9].

Figure 8 depicts how the low field surface resistances are changing versus temperature for the fundamental mode and two HOMs. Table 4 summarizes fitting parameters and standard errors.

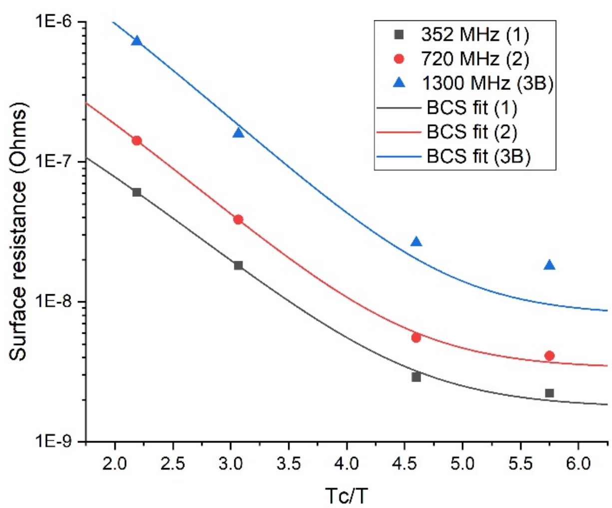

Figure 8: Surface resistance dependence versus temperature for the fundamental mode and two HOM. The surface resistance is for a peak magnetic field below 20 mT.

Table 4: Fitting Parameters and Standard Errors in Brackets for the Three Modes Measured

	352 MHz (1)	720 MHz (2)	1300 MHz (3B)
R_{res} (nΩ)	1.8 (0.3)	3.3 (0.5)	8 (23)
C (Ω·s²)	1.13(0.09) E-4	0.80(0.05) E-4	1.44(0.7) E-4
D	1.84(0.04)	1.95(0.03)	2(0.25)

CONCLUSION

The methodology and technical difficulties to test HOMs in the MYRRHA Spoke cavity have been exposed and addressed. Preliminary tests showed that several modes are adequately coupled to measure the quality factor with good accuracy. Some modes could show instabilities. Additional tests should be performed to understand if these are technical (from RF loop) or are from multipacting.

The investigation of frequency dependences is now possible in a single cavity and could be extended in any low-beta structures.

ACKNOWLEDGEMENTS

The authors would like to thank all the experimental works and efforts of Supratech team and the accelerator department at IJCLab to allow such specific studies to happen on prototypes cavities dedicated to projects.

Part of this study (MYRRHA SSR) happened during MYRTE project, which has received funding from the EUR-ATOM research and training programme 2014-2018 under grant agreement N◦662186.

REFERENCES

[1] D. Longuevergne, “Review of Heat Treatments for Low Beta Cavities: What's So Different from Elliptical Cavities”, in *Proc.* SRF’17, Lanzhou, China, July 2017, pp. 708-714. https://doi.org/10.18429/JACoW-SRF2017-THXA08

[2] M. Martinello *et al.*, “Field-enhanced superconductivity in high-frequency niobium accelerating cavities”, *Phys. Rev. Lett.*, vol. 121, iss. 22, p. 224801, 2018. https://doi.org/10.1103/PhysRevLett.121.224801

[3] M. Checchin *et al.*, “ Frequency dependence of trapped flux sensitivity in SRF cavities”, *Appl. Phys. Lett.*, vol. 112, p. 072601, 2018. https://doi.org/10.1063/1.5016525

[4] P. Kolb *et al.*, “Coaxial multimode cavities for fundamental superconducting rf research in an unprecedented parameter space”, *Phys. Rev. Accel. Beams*, vol. 23, p. 122001, Dec. 2020. https://doi.org/10.1103/PhysRevAccelBeams.23.122001

[5] H. Park *et al.*, in *Proc. SRF’15*, Whistler, Canada, September 2015, paper MOPB003, pp. 70-73.

[6] Spark3D, https://www.3ds.com/products-services/simulia/products/spark3d/

[7] N. Hu *et al.*, “Multipactor Simulations for MYRRHA Spoke Cavity: Comparison Between SPARK3D, MUSICC3D, CST PIC and Measurement”, *in Proc. IPAC’21*, Virtual Edition, Campinas, Brazil, May 2021, paper WEPAB381.

[8] D. Longuevergne *et al.*, “Troubleshooting and performances of Type–B SPIRAL2 series cryomodule”, in *Proc. 27th Linear Accelerator Conf. (LINAC’14)*, Geneva, Switzerland, Aug.-Sept. 2014, paper THPP078, pp. 1037-1040.

[9] D. Longuevergne, “Geometrical corrections for accurate fitting of the field dependent surface resistance for superconducting accelerating cavities”, *Nucl. Instrum. Methods, Sect. A*, vol. 910, pp. 41-48, 2018. https://doi.org/10.1016/j.nima.2018.08.005