PROBING THE FUNDAMENTAL LIMIT OF NIOBIUM IN HIGH RADIOFREQUENCY FIELDS BY DUAL MODE EXCITATION IN SUPERCONDUCTING RADIOFREQUENCY CAVITIES*

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Abstract

We have studied thermal breakdown in several multi-cell superconducting radiofrequency cavity by simultaneous excitation of two TM_{010} passband modes. Unlike measurements done in the past, which indicated a clear thermal nature of the breakdown, our measurements present a more complex picture with interplay of both thermal and magnetic effects. JLab LG-1 that we studied was limited at 40.5 MV/m in $8\pi/9$ mode, corresponding to B_{peak} = 173 mT in the end cells. Dual mode measurements on this quench indicate that this quench is not purely magnetic, and so we conclude that this field is not the fundamental limit in SRF cavities.

INTRODUCTION

Multi-cell cavities have multiple pass-band modes. The surface field distribution in each cell is the same among all pass-bands, but relative field strengths between different cells vary from mode to mode. Hence, if two pass-band modes in a cell are excited at the same time their vector fields are collinear, however, the field strengths do not sum up coherently, because resonant frequencies vary among different modes.

In 1980 D. Proch exploited this fact to distinguish between thermal and magnetic breakdown in SRF cavities at that time [1]. π and $\pi/2$ modes were excited simultaneously in several 2-cell cavities. By bringing cavities into repetitive quench with varying relative field strengths between two modes, quench dependence on mode mixture was measured. The conclusion was that "The data unambiguously supports the thermal model."

Today elliptical niobium SRF cavities are reaching above bulk lower critical field of niobium, and in a few cases cavities reaching above niobium thermodynamical critical field have been reported. At this point we start asking ourselves if the niobium material finally hit the hard limit, the superconducting critical field, or if the cavities are still limited by a local imperfections on the surface. In order to address this question, we implemented dual mode excitation technique to distinguish purely magnetic quench from other quenches.

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EXPERIMENTAL SETUP

For the dual mode excitation, all the pass-band modes of a cavity are measured first and the maximum gradient for each cell is determined. During pass-band measurements quench locations are measured with OSTs [2] and the cells responsible for quench in each mode are identified. After the data is analyzed, two modes that are quenching on the same defect of interest are chosen.

Drive signals from two independent voltage-controlled oscillators (VCO), each oscillating at one of the modes of interest, with independent phase-lock loops (PPL) are combined with power combiner and fed into power amplifier. From the power amplifier through the conventional RF system, the signal is fed into the cavity via the input coupler. Phase locking is accomplished by splitting transmitted power from the pick-up probe with power dividers and feeding the transmitted signal into respective phase lock loops. Part of the transmitted signal is sampled by the spectrum analyzer.

The spectrum analyzer that we use to measure each field level is calibrated in the following way. Two markers are placed on the respective resonance frequencies and the marker measurement mode is set to band power measurement. The spectrum analyzer is connected to PC via Ethernet cable and a continuous data acquisition with DAQ time of about 5 msec is done. The data is recorded continuously to a file on the computer. One of the VCOs then locked onto resonance frequency, while PPL of the other VCO is open, and the cavity is brought into quench. From the known quench field of this mode, measured earlier during the pass-band measurement, the calibration factor from the spectrum analyzer data to the field level is calculated. The procedure is repeated for the second mode with the other VCO. After the calibration factors have been measured, the both VCOs are locked onto respective resonance frequencies and the dual mode excitation measurements is performed by varying field amplitudes of the pass-band modes.

Fig. 1 shows an example of the measurements. The stored energy rises as a function of time on about 1 sec scale determined by high intrinsic quality factor of the cavity ($\approx 10^{10}$). When the field at the quench location exceeds the critical condition the location becomes normal conducting causing rapid drop in quality factor and energy dissipation on the order of 1 msec. In quench the quality factor of the cavity drops by several orders of magnitude. The resulting mismatch at the input coupler leads to field drop in the cavity. The quench area becomes superconducting again, which causes coupling to match again and the cavity starts to fill with energy again. The process repeats itself. Field levels of two modes in Fig. 1 at the time pf quench give us a single (x,y) data point for dual mode measurement plot.

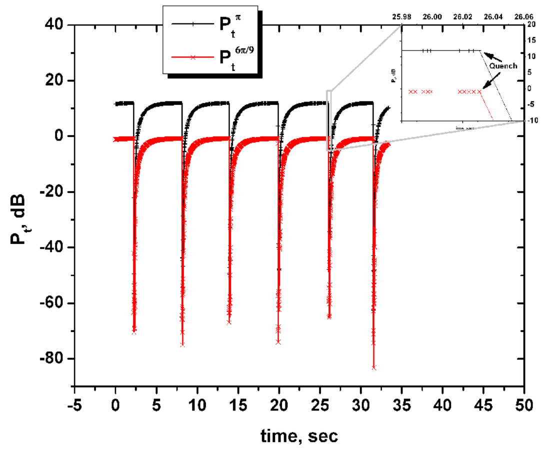

Figure 1: An example of mode mixing data. Each trace represents field in different modes. Data is acquired in real-time from the spectrum analyzer. The inset shows data points close to quench. The typical data acquisition rate is 200 Hz.

The measured dual mode measurement data is normalized to the quench field mode of each mode and presented on x-y plot. The data is then characterized by a fit with $H_1^{\alpha} + H_2^{\alpha} = const$ dependence, where α is a fitting parameter. We expect α to be between 1 and 2, where the exponent of 1 would represent pure magnetic breakdown, whereas the exponent of 2 would be expected for a thermal one.

We distinguish between different quenches during dual mode excitation measurements by the data from second sound transducers. During the quench a thermal wave propagating from the quench location causes vibrations in the oscillating superleak transducers. The time elapsing between the quench time and onset of the signal in OST is uniquely determined by the distance from the quench location to the transducers. By monitoring the second sound signals on OSTs during dual mode measurements we ensure that we collect the data from the same quench location each time.

RESULTS

PKU #2

Three cavities have been measured with dual mode excitation at Jefferson Lab. The first cavity we measured was PKU #2. This is a large grain 9-cell ILC cavity that initially received 100 μm of buffered chemical polishing (BCP), followed by 600 °C for 10 hours furnace treatment. After that the cavity was treated with 80 μm BCP, 800 °C for 2 hours, 30 μm electropolishing (EP), and, finally, 120 °C baking for 48 hours. OST measurements indicated that cell #9 limited the gradient in π,8π/9, 7π/9, 6π/9 modes at about 22 MV/m. A defect in cell #3 limited the gradient in 5π/9, 2π/9, and π/9 modes, at 21 MV/m, and a defect in cell #8 limited this cell to about 26 MV/m in 4π/9, 3π/9. It was noted during the data analysis that if the cell #3 was limited to about 21 MV/m, then π mode should be limited by this gradient as well, and the cavity could not reach 22 MV/m in π mode. However, this discrepancy is within generally accepted 5 percent error bars for π mode measurements, and for pass-band modes that are not tuned to theoretical prefect profile, it is not surprising to see such discrepancy for close gradients.

For the dual mode measurements of the defect in cell #9 we chose π and 7π/9 modes. In Fig. 2 we plot the result for this measurements. The best fit exponent is 1.69 ± 0.01. For defects in cells #3 and #9 we used 5π/9 & 2π/9 modes and 4π/9 & 3π/9 modes respectively. In table below we summarized the results for these defects in PKU #2.

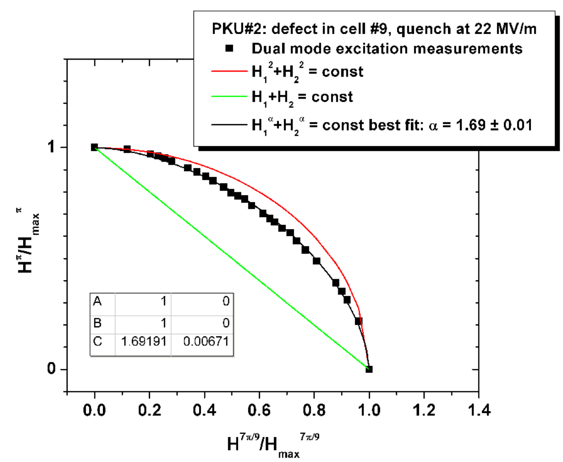

Figure 2: PKU #2 mode mixing results for defect in cell #9. Black dots present the data for π and 7π/9 mode mixing. Black line is the best fit with the exponent of 1.69 ± 0.01. The red line is the theoretically expected result for a pure magnetic quench, the green line is expected for a pure thermal quench.

PKU2	Cell #9	Cell #3	Cell #8
E_{acc}^{max}	22 MV/m	21 MV/m	26 MV/m
α	1.69 ± 0.01	1.50 ± 0.01	1.40 ± 0.02

TB9NR001

TB9NR001 is a fine grain 9-cell ILC cavity that was processed at JLab: 80 μm EP, 800 °C for 2 hours furnace treatment, another 50 μm EP, and 120 °C baking for 48 hours. The cavity was limited in π mode by a defect in the cell #5. A twin cat-eye feature on the weld at the identified quench location was found with the optical inspection system after the test. For dual mode excitation measurement π

and $7\pi/9$ mode were used. The results of this measurement are plotted in Fig. 3. The best fit exponent is 1.91 ± 0.03.

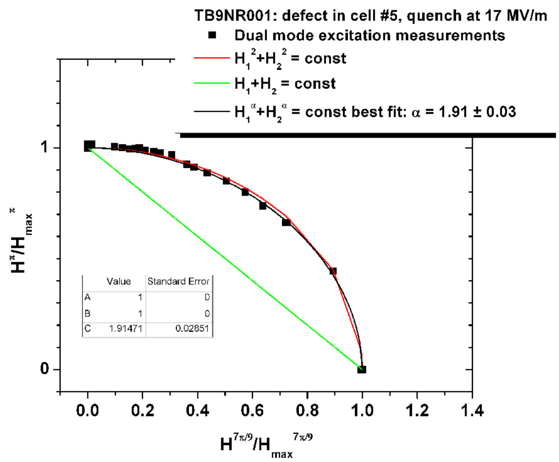

Figure 3: Dual mode measurement of twin cat-eye defect in cell #5 of TB9NR001. Black dots present the data for π and $7\pi/9$ mode mixing. Black line is the best fit with the exponent of 1.91 ± 0.03. The red line is the theoretically expected result for a pure magnetic quench, the green line is expected for a pure thermal quench.

JLab LG-1

JLab LG-1 is a 9-cell ILC cavity produced at JLab from large grain material. After initial BCP treatment the cavity received 35 μm EP, 120 °C for 48 hours, then the defect in cell #5 was locally ground at KEK, and the cavity further received 85 μm EP and 120 °C for 48 hours. The cavity was limited by a quench in cell #6 at 20 MV/m in π mode. $8\pi/9$ mode was limited by a defect in cell #9 at 40.5 MV/m. This defect was studied with dual mode excitation. No other mode was limited by this defect, so the whole parameter space investigation was not possible. It was still possible to measure dual mode mixing with $8\pi/9$ mode dominating. We excitated $8\pi/9$ and $5\pi/9$ modes and motintored OST signals on the oscilloscope to ensure that $8\pi/9$ mode defect is limiting the cavity and not the defect limiting $5\pi/9$ mode. In Fig. 4 we plot dual mode measurements results. The best fit gives exponent of 1.50 ± 0.04.

After the test the cavity received 1000 °C for 3 hours furnace treatment and 30 μm EP. In RF test the cavity was limited by the same defect in cell #6 at 24 MV/m. This defect also limited $6\pi/9$, $4\pi/9$, and $\pi/9$ modes. $8\pi/9$, $7\pi/9$, and $5\pi/9$ modes were limited by a defect in cell #9 at 30 MV/m. $3\pi/9$ was limited by a defect in cell #8 at 39 MV/m, $2\pi/9$ was limited by a defect in cell #3 at 34 MV/m. In this test we measured defects in cells #6 and #9 with dual mode excitation. π and $6\pi/9$ modes were excited to measure the defect in cell #6. In Fig. 5 we plotted dual mode measurements results for this defect. The best fit exponent is 1.35 ± 0.03.

In table below we summarized the results for defects in JLab LG-1.

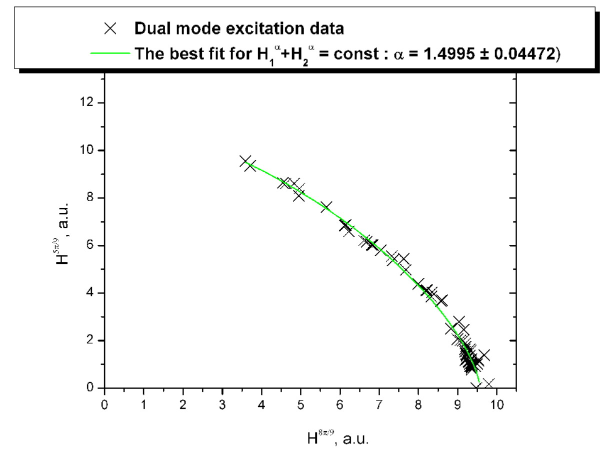

Figure 4: $8\pi/9$ and $5\pi/9$ dual mode excitation result. It was not possible to investigate the whole parameter space, because $5\pi/9$ mode was limited by a defect other than the one limiting $8\pi/9$ at 40.5 MV/m. Black dots are measurement data. The green line is the best fit. The best fit exponent is 1.50 ± 0.04.

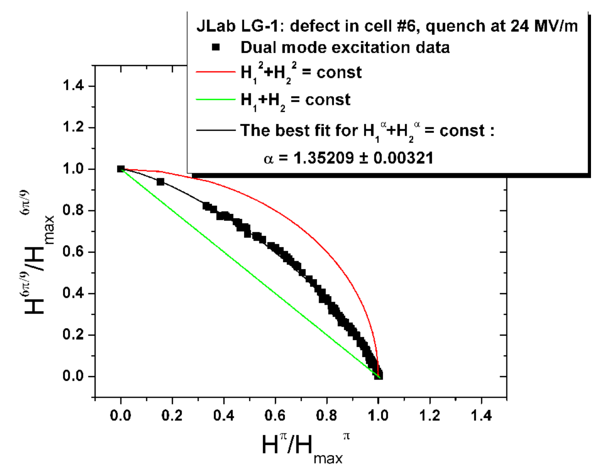

Figure 5: Dual mode excitation result for JLab LG-1 defect in cell #6. Black dots are measurement data. The red line is the expectation for a pure thermal quench. The green line is the expectation for a pure magnetic quench. Black line is the best fit. The best fit exponent is 1.35 ± 0.03.

JLab LG-1	Cell #9[1]	Cell #9[2]	Cell #6
E_{acc}^{max}	40.5 MV/m	30 MV/m	24 MV/m
α	1.50 ± 0.04	1.60 ± 0.01	1.35 ± 0.01

DISCUSSION

The best fit exponent for the defects that we've measured vary between 1.35 and 1.91. The highest exponent of 1.91 was measured in TB9NR001. This cavity is known to be limited by a twin cat-eye feature on the equator weld in cell #5. The dual mode excitation on this defect gives the result closest to a pure thermal quench we have measured. We speculate that a contamination on the weld prior welding could be the cause of the twin cat-eye feature.

The lowest exponent of 1.35 was measured in JLab LG-1 cavity. The feature which is responsible for the quench at 24 MV/m in π mode was identified on the inner surface. It is a outstanding irregularity on the weld with a complex shape. The best exponent on this feature is the closest to the pure magnetic feature, for which we infer that field enhancement on the weld feature plays the major role in inducing the quench.

During RF test JLab LG-1 was limited at 40.5 MV/m in $8\pi/9$ mode, corresponding to B_{peak} = 173 mT in the end cells. This is the highest magnetic field we measured with dual mode excitation method. The best fit exponent of 1.5 is not among the lowest we measured, which lead us to conclude that B_{peak} = 173 mT is not the critical magnetic field limitation.

CONCLUSION

We have studied thermal breakdown in several multicell superconducting radiofrequency cavity by simultaneous excitation of two TM_{010} pass-band modes. Unlike measurements done in the past, which indicated a clear thermal nature of the breakdown, our measurements present a more complex picture with interplay of both thermal and magnetic effects. The dual mode excitation data was fit for each defect with one parameter, the best fit exponent. The defects we measured were limiting cells in the range between 17 MV/m and 41 MV/m. The best fit exponents for the defects range from 1.35 to 1.91. JLab LG-1 that we studied was limited at 40.5 MV/m in $8\pi/9$ mode, corresponding to B_{peak} = 173 mT in the end cells. Dual mode measurements on this quench indicate that this quench is not purely magnetic, and so we conclude that this field is not the fundamental limit in SRF cavities and higher gradients can be expected.

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