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PREVENTION OF DUAL-MODE EXCITATION IN 9-CELL CAVITIES FOR LCLS II-HE*

P. Owen†, Jefferson Lab, Newport News, VA, USA

Abstract

Dual-Mode Excitation, also referred to as mode-mixing, is a superposition of two modes in an SRF cavity. In 9-cell TESLA cavities, the π mode of the cavity (1300.2 MHz) is driven with an RF source to determine the gradient and corresponding quality factor. However, above a certain gradient, the 7/9 π mode (1297.8 MHz) becomes self-excited while the RF is only supplying power at the π mode frequency. In this scenario, the RF power measurement system is unable to differentiate between the superimposed modes on the reflected and probe signals, which invalidates the resulting measurements. This paper demonstrates a new RF control solution which suppresses the 7/9 π mode during the measurement without impacting the quality measurement itself. The system has been successfully implemented at Jefferson Lab and is now routinely used to test a cavity for the LCLSII-HE project.

BACKGROUND

As part of the LCLSII-HE project, about 200 1.3-GHz 9-cell SRF cavities have to be tested in vertical dewars cooled with liquid helium to about 2 K. Each cavity is tested to determine the maximum achievable gradient and resonant quality factor, and to observe any field emission. In addition to LCLSII, this cavity design is in use at XFEL and ILC research. The phenomenon of mode-mixing begins with multipacting in the cavity at gradients above 17 MV/m [1, 2]. As a consequence, a self-excitation of the 7/9 π mode in the cavity may appear above this gradient.

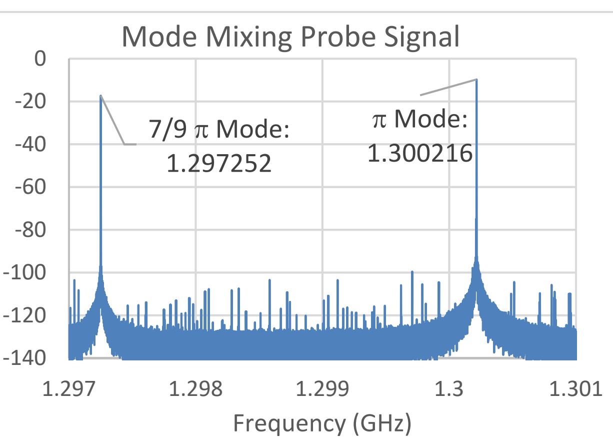

Figure 1: Spectral data from field probe showing mode mixing.

There is a positive feedback loop which allows the mode to grow until it is equal in strength to the π mode, limited by the incident power (Fig. 1). The cavities are equipped with HOM couplers to remove unwanted modes. However, the frequency of the 7/9 π mode is close enough to the π mode that it is not strongly damped by these notch filters. Mode mixing does increase power in the HOM filters, but it is not sufficiently attenuated to prevent the positive feedback loop.

This behavior is only observed during vertical testing of cavities, not in an assembled cryomodule. This is caused by the significantly lower loaded Q of the fundamental power coupler used in the module compared to the high Q antennas ($1\text{-}3 \times 10^{10}$) in the dewar and the correspondingly higher bandwidth.

Mode-Mixing Effects

The RF measurement systems used during vertical test are unable to differentiate between the superimposed modes, making any data recorded during mode-mixing invalid. The presence of mode mixing causes reflected power to increase because of the additional uncontrolled energy in the cavity. Previously, the only way of taking data at high gradients during mode mixing was to power cycle the cavity. As the coupling to the cavity is near critical and the cavity itself has a high Q_0 (>2.5×10^{10}), it takes several seconds to let both modes decay. Once both modes have died away, the operator can turn power back on and the cavity returns to the desired gradient. However, there is only a short window of time where the π mode gradient is stable, and/or the 7/9 π mode has not yet grown enough to interfere with the measurement. This leads to longer testing times and reduces the accuracy of Q_0 measurements. At higher gradients, the superposition of the second mode can cause the cavity to prematurely quench when both fields are present. This prevents RF processing of some high-gradient multipacting barriers.

OFF-RESONANCE POWER

A new RF system layout was designed to prevent the 7/9 π mode from being-self excited by providing a negative feedback loop specifically at that frequency.

RF System Layout

In the Jefferson Lab Vertical Test Area (VTA), there are five RF systems which are available to test cavities in any one of eight liquid-helium dewars. The exact specifications of the systems vary based on the RF bands in which they operate. Despite this, they all share the same general topology. The control of amplitude, phase, and precise frequency lock are all handled by a field control chassis

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† powen@jlab.org

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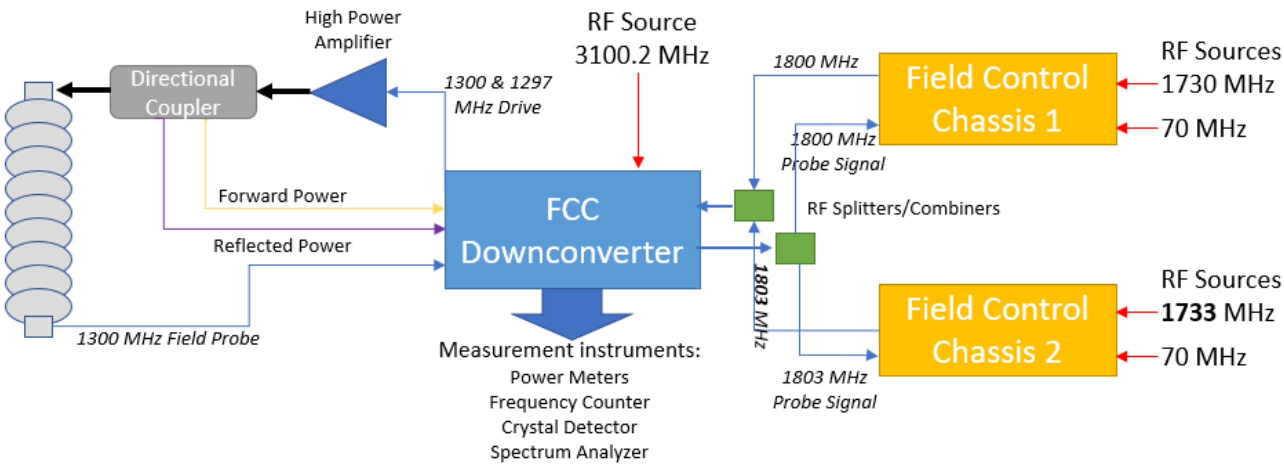

Figure 2: Layout of the RF control system with two field control chassis.

(FCC). This is an FPGA-based computer designed for operating Jefferson Labs' CEBAF accelerator. The FCC locks onto a frequency of 1800 MHz based on a 70-MHz reference Master Oscillator (MO) and 1730-MHz Local Oscillator (LO). In order to test a wide range of cavity frequencies in the VTA, this 1800-MHz signal is mixed in another chassis, the FCC Converter Chassis. A third RF source (3100 MHz for L2-HE) is connected to down-convert the 1800-MHz signal to 1300-MHz for cavity testing. The FCC Converter Chassis also up-converts the 1300-MHz probe signal coming from the cavity to the appropriate frequency for the FCC to use for frequency and phase locking. The chassis also handles the incident and reflected power signals from the directional coupler, routing them as needed to the power meters for measurement, and the crystal detectors for immediate monitoring. Figure 2 is a block diagram of the system used for this measurement.

Reversing the Phase

Attempting to replicate the results of Zhenghui Mi [3], an analog filter circuit was added to the Converter Chassis to reduce the effects of mode mixing. The circuit was designed to isolate the unwanted mode in the probe signal using narrow bandpass filters. The signal phase would then be shifted manually and combined with the π mode drive signal. This was found to be ineffective either because the off-resonance power was too low, or an exact phase offset could not be found. Due to the narrow bandwidth of these modes (< 1 Hz), using a simple RF source is not sufficiently precise to drive the cavity.

Building off of that failed attempt, a second FCC (FCC 2) was connected to the Converter, parallel to the first one, using RF splitters/combiners. The new layout can be seen in Figure 2. In order to prevent the 7/9 π mode from being self-excited, the following procedure was used.

Power from the first FCC (FCC 1) was turned off so the π mode was no longer excited; the second FCC is then turned on. The LO frequency is adjusted so FCC 2 generates power at 1803 MHz and locks onto the 7/9 π mode. At low power (~1 W), the optimal group phase is determined by minimizing reflected power. This phase is then shifted by 180°, causing the mode to die away. The output power from FCC 2 is set to 10 mW at the cavity in order to reduce interference at the 1297 MHz frequency while the power from FCC 1 is restored to drive the π mode, and RF testing continues.

With higher power (2-5 W), the off-resonance system is strong enough to interrupt a fully developed state of mode mixing. Enabling this power causes the 7/9 π mode to decay over a few seconds. The power can then be reduced from a few watts down to milliwatts, but will still prevent the mode from returning. This sequence is depicted in Figure 3.

By testing the limits of the off-resonance control, the LO of FCC 2 sets the chassis within 10 kHz of the 7/9 π frequency. The optimal phase must be determined within 5 degrees before reversing the phase. If either of these parameters is outside the specification, the 7/9 π mode may grow during testing. Increasing the off-resonance power from FCC 2 could increase the bandwidth of these parameters, but that also introduces unnecessary error to the measurement. Implementing other systems of frequency and phase control could increase the stability and reliability of the system even further.

EFFECTS ON CAVITY TESTING

Once the second FCC is in place, has been locked in frequency, and has been reversed in phase, the 7/9 π mode is no longer excited during cavity testing. When a cavity is in the mode-mixing region of gradient and power and FCC 2 is turned off, mode mixing may begin to grow as before. This shows that the system, even with minimal power, is able to prevent the positive feedback loop which drove the undesired mode.

Additionally, the presence of off-resonance power in the RF loop does not severely affect measurement of the π mode itself. The power from FCC 2 is set to the minimum allowed by the chassis. This has been measured to be less than 10 mW at the cavity i.e., near the noise floor of the measurement system. For gradients above 4 MV/m, the incident power in the π mode is generally above 1 W. Hence, the presence of off-resonance power adds 0.1-1% of error

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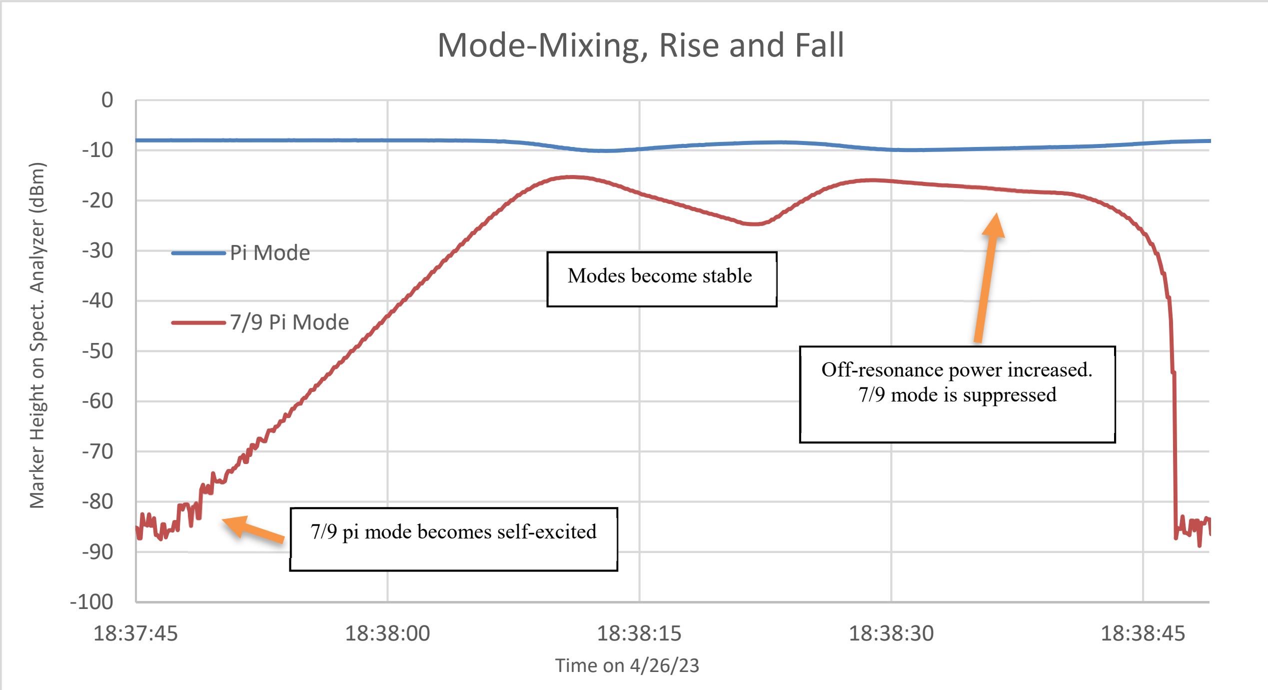

Figure 3: Strength of modes measured from spectrum analyzer on field probe.

to the measurement of Q_0. The typical preexisting systematical errors for this measurement are already in the order of 10%, so the additional error is negligible. Because the 7/9 π mode is not excited and theoretically has no gradient, the measurement of accelerating gradient based on the field probe power is not affected at all. These estimates have been verified through testing. Several cavities have been tested using the traditional power-cycling method of mode-mixing mitigation, as well as with the new FCC 2 power enabled to suppress the 7/9 π mode. On average, Q_0 remains equal between the measurements and well within the standard error of the system.

CONCLUSION

The system of off-resonance power is now in routine use at Jefferson Lab. It greatly reduces the time needed to test a cavity and increases accuracy. With only one mode present, CW processing of high-field multipacting barriers is now possible. As noted by G. Kreps and others at DESY [3], other π modes can begin to mix in the cavity. The system described here could be extended to suppress those modes as needed. These methods used for mode suppression can also be used for dual-mode excitation. This is useful in some cases of quench studies, using second-sound time-of-flight sensors.

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