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ACOUSTIC BREAKDOWN LOCALIZATION IN RF CAVITIES*

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Abstract

Current designs for muon cooling channels require high-gradient RF cavities to be placed in solenoidal magnetic fields in order to contain muons with large transverse emittances. It has been found that doing so reduces the threshold at which RF cavity breakdown occurs. To aid the effort to study RF cavity breakdown in magnetic fields it would be helpful to have a diagnostic tool which can detect breakdown and localize the source of the breakdown inside the cavity. We report here on acoustic simulations and comparisons with experimental acoustic data of breakdown from several RF cavities. Included in this analysis are our most recent results from attempting to localize breakdown using these data.

INTRODUCTION

Muon beams are desired for use in future particle physics experiments. Muon colliders could compliment hadron machines like the LHC without the need for prohibitively long accelerators that are proposed for electron-positron machines such as the ILC or CLIC. Neutrino physics would also benefit from having a neutrino factory which generates a neutrino beam from the decay of muons.

The main challenge with using muons for colliders and neutrino factories is creating tight muon beams. Muons are created from the decay of pions which themselves come from proton collisions with fixed targets. The resultant spray of muons must be collected, focused, and accelerated well within the muon lifetime (2.2 μs in the rest frame). The only feasible method that has been conceived for reducing the beam size prior to accelerating it is ionization cooling [1].

Ionization cooling uses low-Z materials as energy absorbers to reduce the overall momentum of muons. The muons are then subjected to electric fields which accelerate them only along the beam axis. To corral the muons as they are cooled transversely, strong solenoidal magnetic fields are used [1]. Unfortunately it has been found that the maximum accelerating gradient a cavity can produce without breaking down is significantly reduced in the presence of strong magnetic fields [2].

In order to improve the performance of accelerating cavities in strong magnetic fields, it would be useful to have a diagnostic tool that would indicate where breakdown sparks are occurring without having to shutdown the experiment and open the cavity to inspect damage. Acoustic data has been collected on the Muon Ionization Cooling Experiment's (MICE) 201.25 MHz RF cavity and the Modular Cavity at the MuCool Test Area (MTA) at Fermilab. We have demonstrated the feasibility of acoustic localization of breakdown spark sources with other cavities, and we present here experimental and simulation results as well as our path forward towards the goal of acoustic localization of breakdown.

EXPERIMENTAL SETUP

The experimental setup for the MICE 201.25 MHz cavity at the MuCool Test Area (MTA) at Fermilab was previously described in detail [3]. Additional details on previous cavity setups was also previously presented [4]. Since then we have instrumented a newly built, cylindrical cavity, the Modular Cavity, with 10 passive, piezoelectric microphones. These microphones are nearly identical to those on the MICE cavity, with the main difference being added strain relief for the cable where it attaches to the microhpone housing. Four are placed on each end plate. The remaining two were placed on the underside of the waveguide. An additional variable gain amplifier box was installed in the MTA experiment hall for these new microphones. Connections to our DAQ system were simplified by the existance of enough spare capacity that no rearrangement of MICE cavity connections was necessary. Finally, our LabVIEW software has been rewritten for stability and to be easily configurable for multiple cavity setups.

EXPERIMENTAL RESULTS

MICE Cavity

The MICE cavity was run at the end of last year in no magnetic field. The signals are characterized by large spikes at the beginning that correspond with the RF pulse followed by oscillations that have an amplitude less than a volt (Fig. 1). This is true for both spark and non-spark signals, making it difficult to tell the difference on visual inspection between the two. Given that our experience with previous cavities shows a much larger response from spark than from normal RF pulse noise (referred to as the RF hammer), it was thought that the microphones might have been ruined during the cavity bakeout in preparation for evacuation. After the Fall running completed the Cu end plates on the MICE cavity were removed along with the 12 microphones attached to them (leaving 12 on the main body at a constant radius of 41 cm). We took the opportunity to test the microphones again by tapping on the cavity with a makeshift hammer that triggers the DAQ on contact with the cavity's conductive surface. All but two microphones were behaving normally. Since this cavity dissipates much more energy than previous cavities it was assumed that the acoustics in general would be much louder. We have put considerably more effort towards

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simulations and theoretical work in hopes of explaining these results.

One early hypothesis was that the large spike in the signals was from the RF hammer despite very little reverberation. This was tested by leaving a microphone dangling that had come loose in the vacuum vessel that surrounds the cavity. When cavity operation resumed this year in preparation for running in a magnetic field we continued to observe a spike on the channel attached to this unattached microphone. We concluded that a large amount of EM interference from the RF system is leaking into the DAQ system. In an attempt to partially isolate the source of the interference, 20 dB L-Pad attenuators were created and placed on the inputs to the amplifiers. A noticable reduction in the interference was observed meaning that the interference is entering between the microphones and the amplifiers. Unfortunately this also dampens already weak acoustic signals coming from the microphones. Further investigation has not been possible due to tight experimental schedules.

Though we subtract out the average RF hammer noise before attempting to isolate the acoustic wavefront in the signals, an additional complication of the EM interference from the RF system limits our ability to localize breakdown in the MICE cavity. When an RF pulse is cut short by breakdown, subtraction of the average RF hammer leaves an artifact that is due to the average RF hammer being longer in duration than noise from the short RF pulse hammer. In tests on the High Pressure RF (HPRF) cavity we observed some of this interference as well. Fortunately, given the smaller size of the resonant chamber and the thickness of the cavity walls, this interference died out before the acoustic wavefront reached any microphones. The MICE cavity, on the other hand, has very thin walls and has an RF pulse ten times longer in order to fill the much larger resonant chamber. This means that the acoustic wavefronts are embedded in the region where incorrect RF hammer noise subtraction occurs. Unless a method of eliminating this interference is devised, even with additional amplification of the weak acoustic signals, there will likely be a practical limit based on cavity size to acoustic breakdown localization.

Modular Cavity

In the past month we have collected and begun to analyze a small amount of data from brief runs of the Modular Cavity. These signals are relatively weak, but they are so far not plagued by RF pulse noise (Fig. 2). To boost the signal we have connected an additional amplifier. We await further Modular Cavity runs in a month or so to continue our analysis.

SIMULATION RESULTS

MICE Cavity

Time-domain simulations using a naïve spark source impulse were done to gain information on what signals from the MICE cavity ought to look like. Two main conclusisons were drawn using the results of these simulations.

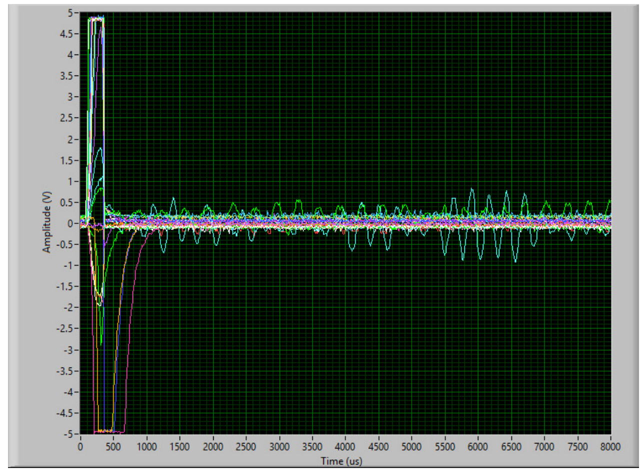

Figure 1: 8 ms of a typical MICE cavity non-spark signal.

Figure 2: Strongest Modular Cavity spark signal (1 ms).

First, the signals had relatively large amplitudes at the beginning for around 50 μs and decayed quickly to zero in around 300 μs. The RF pulse duration for the MICE cavity is around 400 μs. A typical breakdown event will have an RF pulse cut short by about 100 μs. Given the noise subtraction artifact issue, this 100 μs is enough time to completely hide any meaningful acoustic signal from the MICE cavity. This potentially expalains why we don't see strong acoustic signals in the captured data.

Secondly, the frequency of the signals changes significantly with distance from the spark location. Figure 3 shows the correlation between frequency and microphone distance from the spark using the most prominent frequency component of the simulated signals. This makes it difficult to use Accumulated Correlation to calculate time delays between microphones since this algorithm depends on cross correlations between signals [5]. Timing information from cross correlations are only valid for similar waveforms. While smaller cavities may not be hindered by this effect, this has forced us to consider alternative localization algorithms.

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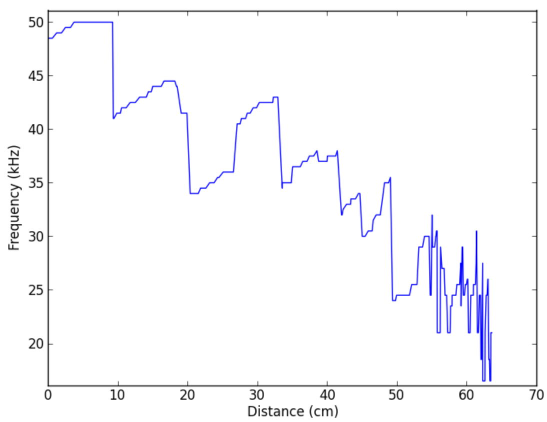

Figure 3: Most Prominent Frequency vs. Microphone Distance from Breakdown Spark Source.

FUTURE LOCALIZATION ALGORITHMS

As mentioned above, and has been necessary since our first experiments with the HPRF cavity, we would like a way to compare the arrival of wavefronts that are part of dissimilar acoustic signal waveforms. To compare signals that are dissimilar we are exploring two types of waveform decomposition analysis. The intent is to either find similar scale features in each signal that can be directly compared or to compare timing information from differently scaled features in each signal.

Wavelet analysis involves convolving the signal with a wave packet of finite width at different scales and times. The resultant matrix is an indication of where features of certain scales begin [6]. This can be used to identify when the oscillations caused by a spark first appear in the signal.

The Hilbert-Huang transform is the term used for applying the Hilbert transform to the results of Empirical Mode Decomposition (EMD). EMD, as the name suggests, empirically decomposes a waveform into Intrinsic Mode Functions (IMF). The IMF have properties that make them well-behaved for a Hilbert transform. The Hilbert transform analytically completes the IMF from which oscillitory phases can be calculated. The instanteous frequency is then obtained by the time derivative of the phase function [7]. Though each signal is decomposed differently, timing information can be obtained and compared to determine the relative time of arrival of the respective wavefronts.

CONCLUSION

RF pulse noise continues to be a major concern, and mitigation will be of critical importance for large cavities with long RF fill times. We have also found that large cavities are not good candidates for the use of the Accumulated Correlation algorithm for localization due to changes in wavelengths with distance from the spark source. We are actively looking into the feasibility of using wavelet and Hilbert-Huang transforms to obtain time-frequency information that could lead to a better localization scheme. Finally, we hope to get better data from future Modular Cavity tests with additional signal amplification. Data from this cavity is crucial to refine our localization techniques on smaller RF cavities.

ACKNOWLEDGMENT

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