RF CAVITY SPARK LOCALIZATION USING ACOUSTIC MEASUREMENT*

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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 progress towards developing a diagnostic tool for detecting and localizing sparks in an RF cavity by using piezoelectric transducers.

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 achieving this is ionization cooling.

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 before they are cooled transversely, strong solenoidal magnetic fields are used. 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.

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. We address here our efforts to use an array of microphones attached to the outside of various cavity bodies to localize sparks inside the active area of the cavity.

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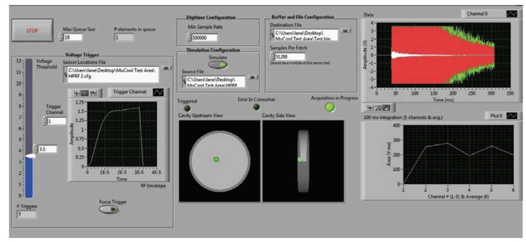

Figure 1: LabVIEW Virtual Instrument interface for spark localization.

EXPERIMENTAL SETUP

The six sensors being used (individually referred to as S0 through S5) are acoustic transducers originally designed for the COUPP dark matter experiment. They are comprised of a piezoelectric crystal and a preamplifier encased in a Cu jacket that acts as a Faraday cage. The piezo is soldered to a thin Cu membrane that is roughly circular with an average radius of about 3 cm. The membrane is also soldered to the Cu jacket, and the vessel containing the piezo/preamp assembly is filled with epoxy.

Signal data is collected using a National Instruments PCI-5105 card installed in a PC. This card has 8 analog inputs and has a maximum sampling rate of 60 MHz. One of the free inputs is connected to the RF envelope signal. The localization software is written in LabVIEW (Fig. 1).

Three different cylindrical cavities have been used in developing this spark localization system. Each cavity is comprised of a wide central ring and two end cap disks. Bench tests were conducted on a copper-coated, stainless steel cavity dubbed the high-pressure RF cavity (HPRFC) as well as a mock aluminum cavity built to the same dimensions (minus some holes) as the HPRFC. Powered cavity tests were conducted on the HPRFC as well as a larger copper-coated, stainless steel cavity called the all-seasons cavity (ASC). When operated, the HPRFC is pressurized with various gases and has hemispherical buttons attached to the inner surface of the end caps centered at the axis. The ASC is evacuated during operation and has a more complicated end cap design.

POWERED CAVITY DATA

HPRFC Tests

After being installed in the MTA hall, the HPRFC was pressurized with Nitrogen to 300 PSI and powered by 40 μs RF pulses spaced 100 ms apart. Fig. 2 shows a typical acoustic signal from an RF pulse just below the breakdown

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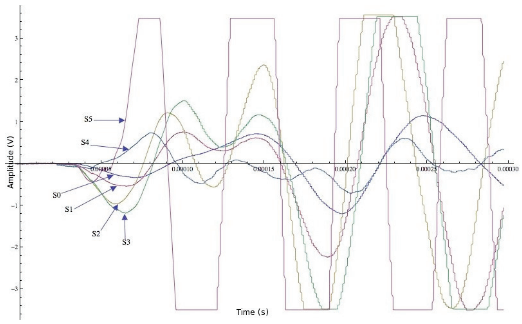

Figure 2: 300 μs RF pulse with channels labeled.

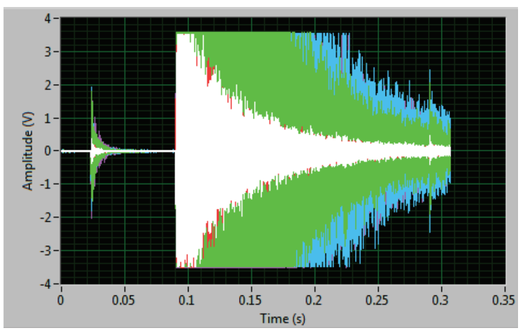

Figure 3: RF hammer versus spark acoustic signals.

gradient threshold (around 29 MV/m). The sound is loud enough to saturate some of the transducers.

At about 20 μs (half of the RF pulse duration) all of the transducers start to react at the same time. Given the time resolution for these tests of 100 ns (sampling rate of 50 MS/s), the significantly different distances of the transducers from the cavity's active volume, and the shape of the displacements this is unlikely to be acoustic in nature. It appears more dramatically in later tests and will be discussed in more depth there.

The DAQ software was converted to use lower level data streaming code which stored arbitrarily long, continuous data on disk after it was discovered that some crucial RF data was not captured. After that another set of data was taken using the HPRFC. This allowed for better analysis of the signal and ultimately lead to the development of an automated localization technique using actual cavity spark acoustic signals. Fig. 3 shows a signal plot of an RF hammer (the sound of RF with no spark) event along with a spark event. One can also make out a second RF hammer event at the tail end of the spark (0.29 s). Three other RF hammer events occurred but are completely masked by the spark event.

An interesting feature of these signals is the more pronounced electrical disturbance that occurs in these tests from the start of the RF pulse. Fig. 4 shows the beginning of an RF hammer event.

The orange trace in Fig. 4 is the RF envelope. The disturbance is almost a mirror image of the RF envelope in the RF hammer signal. The disturbance was considered an artifact that could be ignored since it did not affect the part of the acoustic signal generated by the spark.

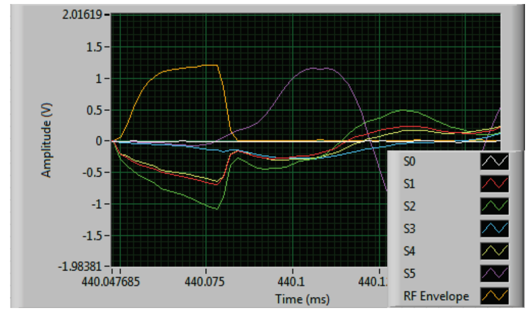

Figure 4: Electrical disturbance in RF hammer and spark signals from the HPRF cavity.

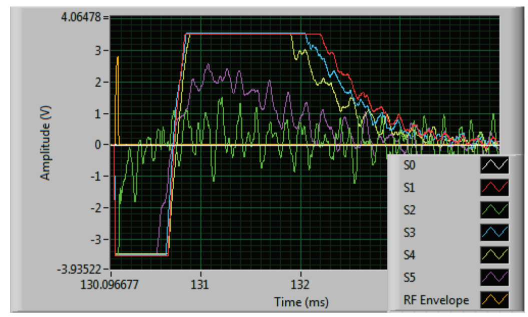

Figure 5: All-seasons RF cavity signal, severe clipping is observed.

ASC Tests

After significant progress was made on creating code to localize spark sources based on the later HPRFC data, the transducers were reinstalled onto the ASC. This cavity was also placed in a 3 T solenoid magnetic field. A wide view of the signals generated looked similar to the HPRFC signals. Upon closer examination severe clipping was observed (Fig. 5).

Note that the time scale is different. The orange trace can still be seen as a spike on the left of the plot. Like the HPRFC electrical disturbance this clipping begins immediately upon initiation of the RF pulse. This suggests a related cause to both disturbances. Unfortunately this clipping makes it impossible to apply the localization algorithm developed using the HPRFC signals. Considering that the acoustic signals get much more complicated after the clipping has subsided, it is unlikely that an effective localization algorithm can be developed for these signals. Therefore an effort is underway to find the cause of the clipping and to hopefully find a mitigation strategy. This includes using transducers with lower gain that are currently in production.

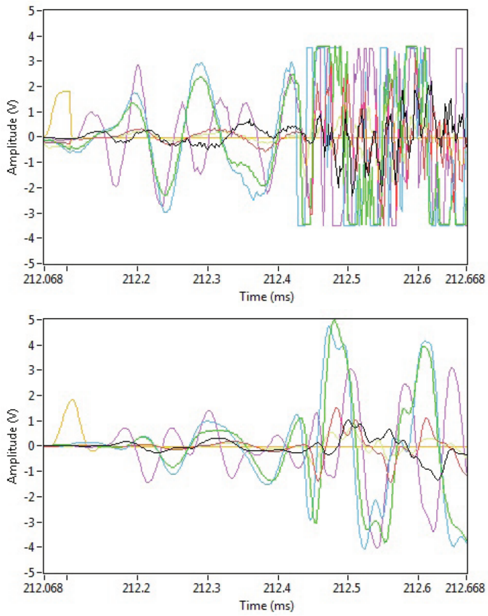

Figure 6: 600 μs of spark before and after signal conditioning.

LOCALIZATION

Signal Conditioning

Before applying the localization algorithm three modifications are made to the spark signals. First, the RF hammer background is removed. This is done by taking the average of the last few RF hammer waveforms, aligning the average with the spark waveform, and then subtracting the RF hammer waveform from the spark waveform.

Second, to smooth out high-frequency modulation and artifacts from background subtraction, a digital filter is applied. Analyzing the frequency spectrum a low-pass filter was used with a cutoff frequency of 25 kHz.

Third, the initial response of the end cap transducers were negative while all of the initial ring transducer responses were positive. To normalize the signals even more in order for the localization algorithm to work well, the end cap signals were flipped so that all initial transducer responses were positive. Fig. 6 shows a spark signal before and after signal conditioning.

Algorithm

Accumulated correlation (AC) is a form of time delay estimation (TDE) which starts by forming cross-correlation vectors between each pair of signals. The main difference from traditional TDE techniques is that it uses the principle of least commitment by using the entire cross-correlation vector instead of only one of its peaks.

Like in beamforming, an array of candidate locations (limited by the sampling rate of the DAQ system) is created. For each candidate location the difference of arrival time is computed between each pair of transducers. The cross-correlation vector elements corresponding to each set of sensor pairs and time differences is summed to create an overall likelihood that the sound originated from the chosen location:

$$L_{AC}(\mathbf{q}) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} R_{ij}(\tau_{j,\mathbf{q}} - \tau_{i,\mathbf{q}}). \qquad (1)$$

In terms of its use in localizing sound inside an RF cavity, the propagation times from candidate source locations and the sensors can be adjusted to account for the more complicated geometry and propagation characteristics. In effect the more complicated geometry of the cavity is being mapped onto the uniform geometry of the cross-correlation vector [1].

Analysis

The final form of the conditioned signal reveals some interesting pieces of information. First, the downstream end cap is louder than the upstream end cap. The downstream end cap is connected to the RF coupler. This suggests that the downstream end cap is receiving the brunt of the RF hammer.

Second, the downstream end cap signal arrives slightly before the upstream end cap. This suggests that these transducer responses are from separate sub-events. Field emission generates an acoustic wave on the downstream end cap, and then about 6 μs later the impact of the electrons on the upstream end cap generates a second acoustic wave. The time between when the spark occurs (taken to be the end of the RF envelope) and the beginning of the downstream end cap signal is consistent within uncertainties with a p-wave traveling through the Be button, down the attaching bolt, and then mode converting to an s-wave and traveling through the end cap to the transducer. Given that electric field enhancement is required to liberate electrons from the surface, it is difficult to determine the speed of the electrons traveling between the end cap buttons.

SUMMARY

A set of algorithms and tools were developed to capture and analyze the acoustic signal potentially indicating the source of spark in RF cavities of different geometries. The interface can be adjusted easily to accommodate a new geometry. The ASC test indicates that the gain of the available sensors may be too large causing significant clipping that obstructs the actual signal. A potential mitigation strategy is using transducers with lower gain.

ACKNOWLEDGMENT

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