STUDIES OF BREAKDOWN IN HIGH GRADIENT X-BAND ACCELERATOR STRUCTURES USING ACOUSTIC EMISSION*

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Abstract

X-band accelerator structures meeting the Next Linear Collider (NLC) design requirements have been found to suffer damage due to RF breakdown when processed to high gradients. Improved understanding of these breakdown events is desirable for the development of structure designs, fabrication procedures, and processing techniques that minimize structure damage [1]. Acoustic emission sensors attached to an accelerator structure can detect both nominal and breakdown RF pulses [2]. Using an array of acoustic sensors, we have been able to pinpoint both the cell and azimuth location of individual breakdown events. This allows studies of breakdown time and position sequences so that underlying causes can be determined. The technique provided a significant advance in studies of breakdown in the structure input coupler. In this paper we present acoustic emission sensor data and analysis from the breakdown studies in several x-band accelerator structures.

1 BREAKDOWNS IN RF STRUCTURES

Damage due to breakdowns is a significant limitation to high gradient operation of room temperature RF structures. Materials damage is observed in regions of high electric field, presumably due to electron or ion bombardment, and in regions of high magnetic field presumably due to peak current surface heating. The portion of microwave energy absorbed by a breakdown (as opposed to reflected or transmitted) can be as high as 90% [3]. The NLCTA (Next Linear Collider Test Accelerator) is used for testing structure designs.

Table 1: Structures: typical operating parameters

Frequency	11.424 GHz
Structure Length	30-90 cm (typical test structure)
Number of cells	30-100
Test accelerating gradient	60-85 MeV/M unloaded
RF pulse width	50-400ns
RF pulse power	10-100 MW
Repetition rate	60Hz
Breakdown Rate	~1/hour after processing
Test duration	~1000 hours

2 ACOUSTIC SIGNALS

The high power pulsed RF in the accelerator structures produces acoustic signals, presumably through pulse heating and thermal expansion. For typical operating parameters (20 Joule RF pulse) the estimated peak pressure from pulse heating is ~10^7 Pa, consistent with measured signals. On a pulse where a RF breakdown occurs, larger amplitude acoustic signals (~X10 amplitude) are detected near the breakdown point.

2.1 Acoustic Sensors

For both normal and breakdown pulses the acoustic signals have frequency content up to about 1 MHz. Figure 1 shows typical acoustic signals for normal and breakdown pulses. Note that the frequency response of the detector has not been subtracted from the data.

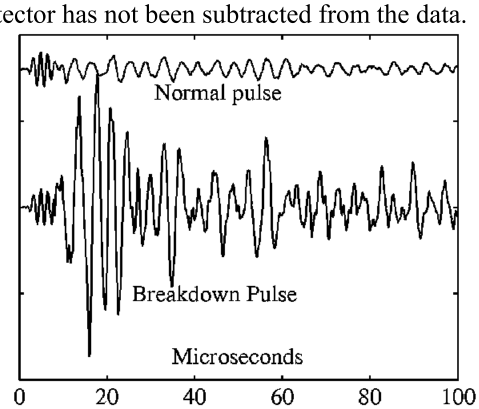

Figure 1: Acoustic signals

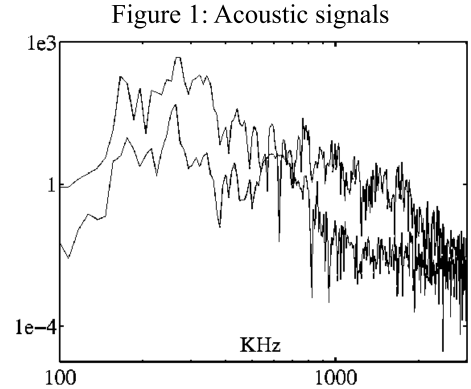

Figure 2: Power spectra for acoustic signals. Upper trace is breakdown pulse, lower is normal.

The acoustic spectra are fairly smooth, and drop at roughly 12dB/Octave above 300KHz. Note that the approximately 600KHz peak in the "normal" signal is believed to be due to electrical pickup from the modulator pulse. No correlation has been found between the energy deposited in a breakdown and the spectral content of the acoustic signals. However, by measuring the amplitude and arrival times at an array of acoustic sensors attached to the structure the location of breakdowns can be determined.

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2.2 Breakdown Location

Ideally the arrival time of acoustic signals at an array of sensors could be used in a straightforward fashion to determine the location of a breakdown. Unfortunately the signals generated by the RF heating complicate the analysis. In particular since the maximum currents and heating occur near the outer radius of the cavity, these signals arrive before the breakdown signals from the iris. (figure 3).

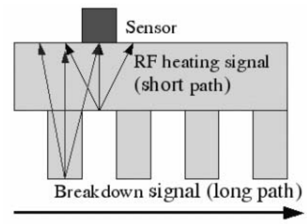

Figure 3: Signals from normal RF pulse heating of cavity outer radius arrive before signals from breakdown at iris.

RF breakdowns change the distribution of RF power in the structure, often absorbing all power downstream of the breakdown. The resulting change in acoustic signal from the RF heating of the structure prevents using background subtraction to obtain a "pure" breakdown signal.

The existence of 3 relevant wave speeds in copper (Pressure wave: 5000M/s, Shear wave: 2300M/s, and Surface wave: 1900 M/s) complicates analysis. In addition the accelerator structure has internal dimensions comparable to the wavelength of the acoustic waves.

2.3 Acoustic Sensors

Piezoelectric ultrasonic sensors are available from commercial vendors. Sensors for acoustic amission testing have high sensitivities in the 100 KHz – 1MHz range, but are fairly expensive (~100 USD). Lower sensitivity general-purpose sensors are available for ~20 USD. Due to our requirement for a large number of sensors, we used ITC-9070 4MHz general-purpose sensors from *International Transducer Corporation*.

3. ELECTONICS AND DAQ SYSTEM

An array of up to 64 sensors (limited by DAQ channels) is attached to the accelerator structure to locate breakdowns. Radiation in the accelerator tunnel prevents the use of local electronics, and the sensors are transformer coupled to drive differential pair cables. A differential receiver and amplifier are used in the control area, followed by a 12 bit 10Ms/s ADC.

3.1 Analog Electronics

The acoustic sensors act approximately as current sources in parallel with about 1000 pF of capacitance. For 300KHz signals this corresponds to ~500 Ohms impedance. The sensor is connected to a 400:100 Ohm transformer driving 100 Ohm twisted pair (Cat-5 Telecom) cable, with impedance matching to 50 Ohms at the receiver. A variable gain amplifier is used to match the signal level into the digitizer input.

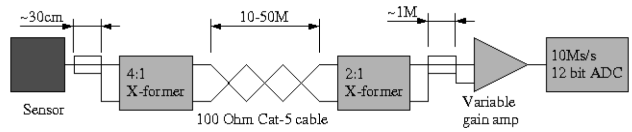

Figure 4: Electronics block diagram

3.2 Digital Electronics and Software

The Digitizers used are *Joerger* VTR812-10, 8 channel, 12 bit, 10Ms/s VME modules. Eight modules were used for a total of 64 channels. The modules are operated in circular buffer mode to record the last 3 events, with 1024 points per event.

The control system is based on EPICS and operates both the RF level control for processing and the acoustic data acquisition. When the processing system detects a RF breakdown, the next RF pulse is disabled and the data from all of the digitizers for the last three pulses is recorded.

Data is processed offline using *Matlab*. Typically the RMS of the first 200 points (20us or ~10 mm at copper P-wave velocity) is used to determine the breakdown location.

4 MEASUREMENTS

For each breakdown, a series of waveforms similar to figure 5 is produced.

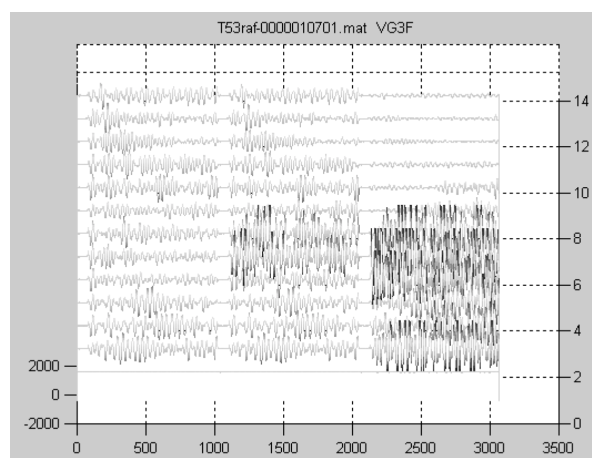

Figure 5: Sequence of 3 pulses

In this example, the RF was normal on the first pulse, and there was a small breakdown on the second pulse, which failed to trip the RF. On the third pulse there was a large breakdown. The front of the structure is on the bottom of the graph. Note that the timescale of the graph is compressed: the waveforms represent ~100us, with a 16 millisecond gap between the three waveforms.

4.1 Breakdown measurements on structure body

Measurements were conducted on a 60-cell traveling wave structure. The breakdowns occurred primarily in the input and output couplers, with a fairly even distribution throughout the body of the structure (Figure 6). This matches the distribution deduced from RF data, although one to one matches of breakdowns were not done. [4]. Acoustic sensors have also been used to locate breakdowns in the Tesla Test Facility gun where the larger size of the RF structure produced very clean data [5].

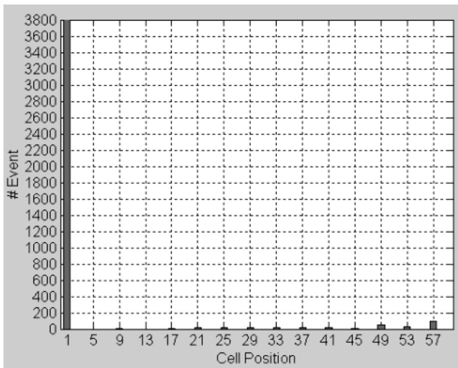

Figure 6 Breakdown locations in traveling wave structure

In addition to providing longitudinal location of breakdowns in the structure, the acoustic sensors also provide azimuthal information. When the sensors are arranged around a single cell, the acoustic signal appears to be "beamed" with an angular resolution of ~60 degrees.

4.2 Coupler Breakdown Diagnostics

The acoustic location system has proven very useful in diagnosing the high rate of breakdowns in the RF couplers. Figure 7 shows the input coupler, which has RF feeds from the sides. The 4 "horns" on the 2 RF feeds are located in a region of low electric field, but high magnetic field. An array of sensors was placed on the coupler to localize the RF breakdowns (Figure 8).

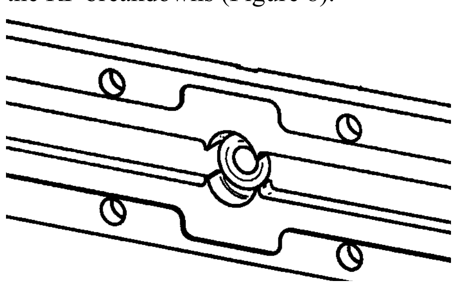

Figure 7: Input coupler. Note 4 "horns" on feeds.

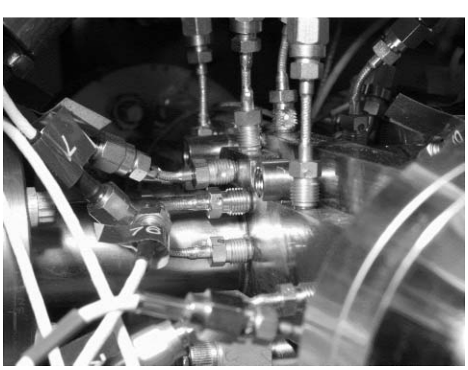

Figure 8: Acoustic sensors attached to coupler

Data from a number of breakdowns was recorded and binned based on the ratios of power detected by the acoustic sensors in the first 20 microseconds of the pulse. The breakdown pulses were found to fall into 4 distinct types (figure 8). These were correlated with breakdowns occurring in the high magnetic field region on the coupler "horns". Examination of the structure after operation found damage in the areas predicted by the acoustic measurements.

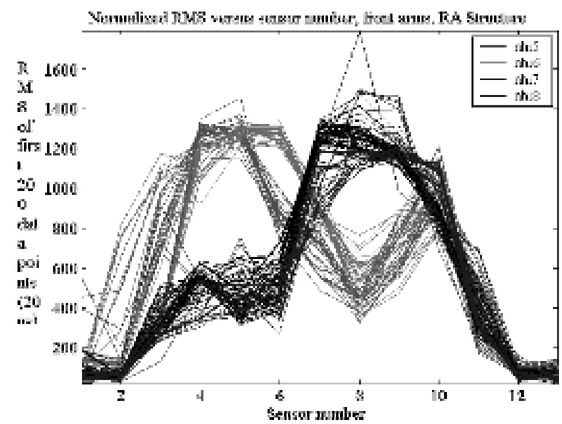

Figure 9: Coupler breakdowns occur in 4 types.

5 FUTURE PLANS

The present data acquisition system is limited to 64 channels, insufficient to process azimuthal data. A system with ~300 channels (50 cells X 6 sensors / cell) is being developed. The present system is also limited to a few cm resolution due to a combination of acoustic wavelength (1.3cm at 300KHz) and structure feature size (~1cm). Work is under way to understand the propagation of higher frequency acoustic signals in the structures.

6 ACKNOWLEDGEMENTS

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