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FEbreak: A COMPREHENSIVE DIAGNOSTIC AND AUTOMATED CONDITIONING INTERFACE FOR ANALYSIS OF BREAKDOWN AND DARK CURRENT EFFECTS

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Abstract

This work is a part of an ongoing research to develop a high gradient test stand called the C-band engineering research facility New Mexico (CERF-NM) at Los Alamos National laboratory (LANL). Our team has developed the software called FEbeak (a part of the FEmaster series) which allows to analyse breakdown in real time. This software will be able to provide high accuracy breakdown analysis while coupling it to the field emission dark current effects and breakdown *in situ* imaging software diagnostics. FEbreak has shown a 97% efficiency for pulse acquisition and analysis when processing1 µs long pulses at 100 Hz repetition rate, which is a standard setting for testing many normal conducting cavities for high gradient.

INTRODUCTION

The ability to measure the breakdown rate is the cornerstone of high gradient research. Breakdown rate characterizes the ability of the structures to handle high electromagnetic power under long-term operation [1]. Therefore, the ability to measure the breakdown rate accurately and consistently is paramount. If a breakdown analysis software is not a real-time measurement it will not be able to recognize and analyze every pulse and therefore will not accurately compute the breakdown rate [2, 3]. This will result in an artificially low breakdown rate. Furthermore, if these measurements are not done in real-time, timely control of the klystron is impossible.

The work presented here is a new attempt to fill the existing gap in diagnostics. To this end, a real time breakdown analysis software called FEbreak was developed. It enables active klystron tuning, while also providing a parallel computing option for data processing to analyze the field emission characteristics and then directly tie them to a future *in situ* imaging system to be able to determine the locations of breakdowns within the structure during the commissioning process.

CERF-NM FACILITY

In brief, the CERF-NM facility is a C-band (5.712 GHz) high gradient test facility. It is based around a 50 MW Canon klystron that can produce peak powers up to 50 MW and couple the power into the structures under test (see Fig. 1a). The accelerating structures under test produce dark current that can be accelerated up to the beam energies of 5 MeV in a three-cell design. (See other papers in this proceedings collection for more details on CERF-NM.)

The waveguide line of the CERF-NM has seven vacuum pumps which can maintain vacuum at 10^{-10} Torr. A series of temperature controls are implemented using thermocouples on key components including both bidirectional couplers inside and outside of the lead box enclosure (see Fig. 1b) and the RF window which is temperature control by using a chiller. The two Faraday cup allow for the dark current measurements. When combined with the forward or reflected power measurements that come the bidirectional coupler it allows us to determine the Fowler-Nordheim parameters for the field enhancement in the cavity. All of these diagnostics are used to analyze breakdown in real-time. The commissioning procedure of cavity can be completely automated.

(a)

(b)

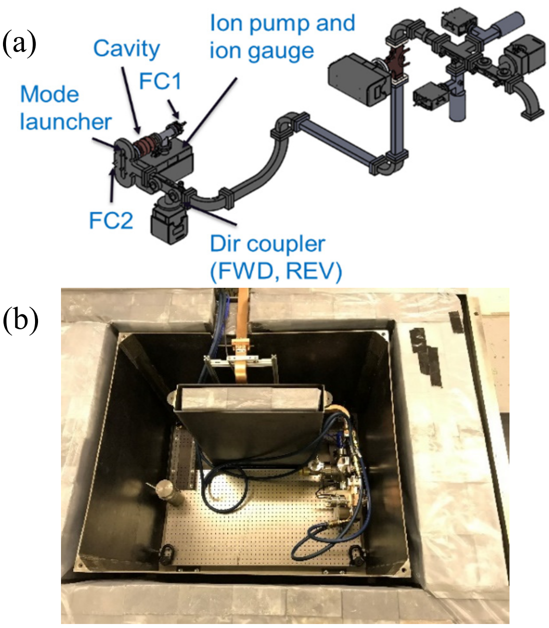

Figure 1: (a) CAD model of waveguide components and diagnostics, (b) a photograph of the current state of the part of the CERF-NM facility in lead box enclosure.

FPGA SCOPE FOR REAL-TIME BREAK-DOWN ANALYSIS

Our controls system is based on the National Instruments PXI Express system. This system consists of a crate which allows multiple modules to be inserted into the system in order to customize the configuration and capabilities of the entire system. Currently our configuration consists of the main PXIe chassis, a PXIE-8840 controller with Windows

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installed onto it, a PXIE-6341 DAQ card, a PXIE-5654 RF signal generator, and a PXIE-5172 Oscilloscope with built in FPGA see Fig. 2. This system can be broken down into two main sections, the controller and the FPGA. Currently the majority of the decision-making processes are done within the controller section, however it is planned to off-load significant portions of the decision making onto the FPGA in the near future.

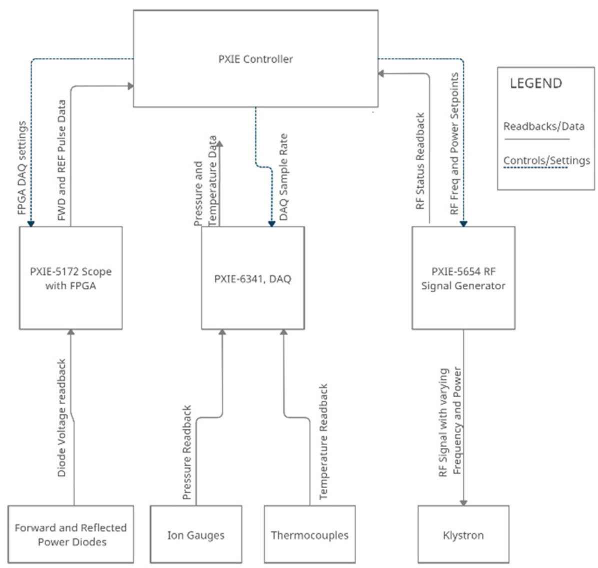

Figure 2: Block diagram of FEbreak.

Within the controller section of our DAQ system, we perform several operations. First, we initialize the crate modules. The controller first initializes our RF signal generator with a set power and frequency and waits for the module to confirm that it is sending out the appropriate signal. During this time, the controller also initializes the DAQ module to begin recording vacuum and temperature data. Once the RF signal is being generated and the pressure and temperature readings start being recorded, the rest of intricate parts of FEbreak is initialized.

The FPGA module runs mostly independently from the crate controller. It begins by waiting for a initialize command from the controller, and once it receives this initialization command it grabs configuration information from the current experimental settings. This information includes the number of channels to read, the trigger settings in order to synchronize it with RF generation, how many datapoints to record, and at what sample rate it should record them. The FPGA itself then proceeds to run in its own loop, constantly triggering, recording data, and then sending that data to a pool of shared memory between itself and the controller. Currently the FPGA does not make any decisions on its own with this data, but future plans will offload some of the computational logic with the recorded data from the controller to the FPGA.

Once the controller has received the data from the FPGA it performs a series of operations. First, it displays the data in real time, which allows an operator to select what parts of the reflected power they are interested in analysing (see Fig. 3).

Once this selection is completed, the controller will automatically determine the breakdown threshold and analyze each pulse to determine if a breakdown has occurred. If the breakdown rate is acceptable the controller will increase the RF power by a set amount after the required number of pulses have been sent down the waveguide. However, if the breakdown rate is too high, then the controller will decrease the RF power to reduce the breakdown rate, before resetting its pulse count and continuing with the conditioning process. This data is saved in real-time after each pulse in order to prevent any data loss. This process repeats itself until stopped by an operator, or it reaches the end power goal of conditioning with an acceptable breakdown rate.

Figure 3: Display window of FEbreak with all the indicators and controls for user inputs.

Currently, a breakdown is defined when the Faraday cup exceeds a tolerance limit set by the user. The tolerance limit it was decided for this case was 25 mV see Fig. 4. The reason for the Faraday cup is used to determine breakdowns is due to the short pulse lengths (300 nC) currently being used which comparable to the field time of the cavity. The increase in the reflected power that would normally be observed happens later in the pulse and therefore is inconsistent and leads to false positives or missing break down pulses that may be able to detect due to their variation. Future generations will hope to analyze both the Faraday cup and the reflected power for higher accuracy in the breakdown determination.

The first single-cell cavity at CEFR-NM was tested up to 500 kW of input power into the cavity with no breakdowns detected. Hence, the dummy/test signals were used to evaluate algorithm functioning. Conditioning of the same cavity is underway up to 4 MW which will correspond to 161 MV/m accelerating gradient. This experiment will act as an actual proof of concept for FEbeam's algorithm, analysing the breakdown rate , as well as the field emission and dark current effects.

Future work includes integration of FEbreak into the FEmaster series along with analyzing the breakdown rate. It is paramount to not forget that breakdowns are dark

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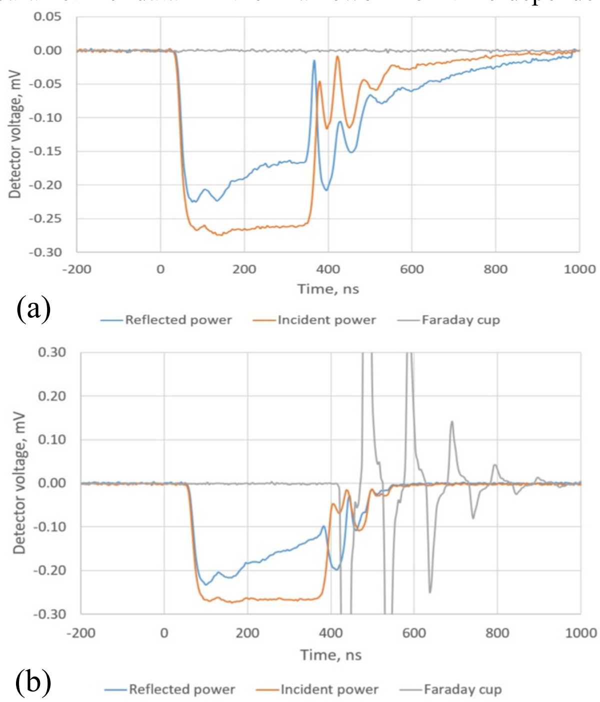
current/field emission effects. Therefore for a comprehensive analysis, the field emission characteristics must be taken into account when analyzing the performance of these high gradient structures. The data extracted from FEbreak will record the forward and reflected power as well as the Faraday cup measurements throughout the conditioning process. This data then would be directly imported into the FEbeam [4] software to parametrize data in the framework of time-dependent



Fowler-Nordheim equation.

Figure 4: Nominal (a) and breakdown condition (b) pulses showing the forward, reflected, and Faraday cup signals

Additional hardware upgrades are underway to build an in situ imaging system. Such upgrades will allow for imaging breakdown events/locations. Further coupling of field emission parameters to the modelling software FEgen [5] and image processing software FEpic [6] would allow to backtrack the geometry and location of a breakdown inside of the cavity, that can further be confirmed with autopsy/post-mortem analysis. It is this combination that will allow for high resolution cavity design (see Fig. 5). Work is currently underway to allow for parallel computing on a separate CPU system independent of the PXIE crate to do data processing and data acquisition in parallel.

This upgrade will be done in coordination with current upgrades to the PXIE configuration the first of which is to include the internal triggering instead of external triggering by an external circuit which is currently being built. Second, work has shown in the past that having a phase in amplitude modulated forward pulse is better for conditioning as it will rapidly fill the cavity but then reduce the gradient for the rest the pulse. A second function generator can be used to produce this pulse and it will be done in real time using the FPGA code in future. Third, the current breakdown software is being programed in the LabVIEW platform and therefore is subject to slowdowns from running other codes in parallel such as the pressure and temperature monitoring code. Therefore, ongoing work is to completely include the breakdown logic into the FPGA functionality. It is the author's opinion that including this functionality completely inside of the PXIE crate will improve efficiency to above 99%.

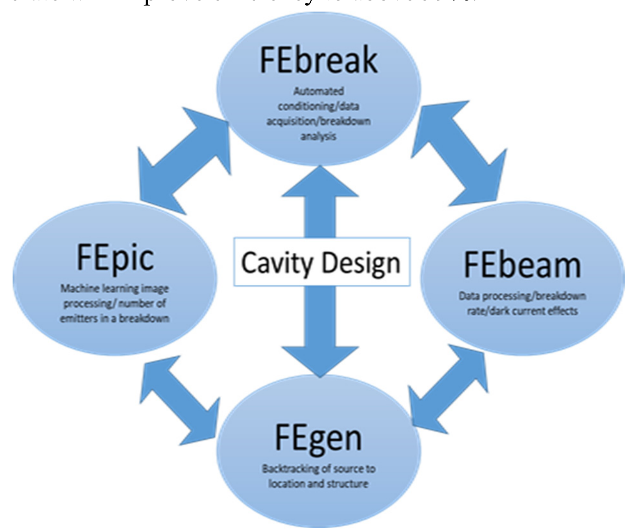


Figure 5: Block diagram of the fully integrated FEmaster.

REFERENCES

[1] E. I. Simakov *et al.*, "Advances in high gradient normal conducting accelerator structures", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 907, pp. 221-230, Nov. 2018. doi:10.1016/j.nima.2018.02.085

[2] V. A. Dolgashev, "Progress on high-gradient structures", *AIP Conference Proceedings*, vol. 1507, pp. 76-84, Dec. 2012. doi:10.1063/1.4773679

[3] A. Palaia *et al.*, "Diagnostics of RF breakdowns in high-gradient accelerating structures", SLAC, Menlo Parl, CA, USA, SLAC-PUB-16089, Sep. 2014.

[4] M. Schneider *et al.*, "FEbeam: Cavity and Electron Emission Data Conversion, Processing and Analysis. A Freeware Toolkit for RF Injectors", *Rev. Sci. Instrum.*, vol. 92, p. 053305, May 2021. doi:10.1063/5.0048630

[5] E. Jevarjian *et al.*, "FEgen (v. 1): Field Emission Distribution Generator Freeware Based on Fowler-Nordheim Equation", Sep. 2020. arXiv:2009.13046

[6] T. Y. Posos, "Fast Pattern Recognition for Electron Emission Micrograph Analysis", Dec. 2020. arXiv:2012.03578