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AUTOMATIC RF CONDITIONING OF S-BAND CAVITIES FOR COMMERCIAL PROTON THERAPY LINACS

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Abstract

The CERN spinoff company ADAM owned by Advanced Oncotherapy plc (AVO-ADAM) is completing the construction and testing of its first LIGHT (Linac for Image-Guided Hadron Therapy) system. Each LIGHT machine is composed by 20 accelerating modules: one 750 MHz RFQ, four 3 GHz Side-Coupled Drift Tube Linac (SCDTL) and 15 3 GHz Coupled-Cavity Linac (CCL). The company aims at delivering several similar LIGHT machines in the next years. A prerequisite to achieve such goal is the capability to complete the RF conditioning of the accelerating modules in a systematic and automatic way, with minimal inputs from RF engineers. In the past years ADAM developed an automatic conditioning system capable of increasing the main conditioning parameters – RF power, pulse width, repetition rate – while controlling the cavity breakdown rate and vacuum level. The system has been so far tested on about twenty accelerating structures with different brazing methodologies and RF accelerating voltages, proving its robustness. This paper discusses the ADAM automatic conditioning system design and its implementation.

INTRODUCTION

RF accelerating structures must undergo a process of conditioning before being accepted for operation in an accelerator facility. The conditioning is considered finished when the breakdown rate (BDR) meets the requirements and the RF parameters – pulse width and repetition rate – are nominal. The conditioning process consists of an iterative algorithm that smoothly increases the average power in the cavity until the working conditions are reached. During this process, the BDR and other parameters, such as the cavity vacuum pressure, are acquired to characterize the conditioning status. A fast RF inhibit is recommended to protect the cavity from clusters of breakdowns that could damage the inner surface of the cavity. A schematic of an RF system suitable for accelerating cavity conditioning is sketched in Fig. 1.

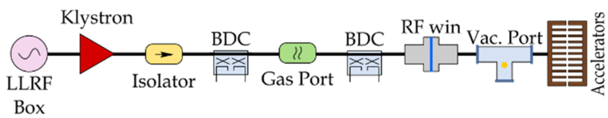

Figure 1: Overview of an RF network layout for cavities conditioning.

Such systems are typically composed of a low-level RF (LLRF) box or RF generator, a modulator and klystron system (MKS), an RF network (RFN), vacuum system and gauges, temperature sensors and thermos-switches, SF6 gauge and reading, a cooling system and a trigger system to synchronize the LLRF, the MKS and the acquisition system.

AVO-ADAM developed in the past years an automatic tool for conditioning its accelerating cavities, called Event Detection System (EDS), building on the initial work discussed in [1]. The EDS permitted to condition more than 19 accelerating cavities so far with a reproducible and standardized process.

SYSTEM COMPOSITION

The Event Detection System (EDS) is a system consisting of software and hardware. It monitors the RF signals in the RF network and in the accelerating cavity. If any of the signals exceeds predefined limits, the EDS marks it as an event. After a user-defined number of consecutive events, it can inhibit the trigger of the RF generator to protect the RF cavity from physical damage. In addition, the EDS accepts external digital inhibit signals from the cooling and vacuum systems.

EDS is fully controlled by a supervisory control system, where also sends the data for monitoring, archiving and further processing. Triggers arrive from the trigger generator and are conditionally forwarded to the RF generator.

When the EDS detects a trigger, it will perform data acquisition on 8 analogue inputs, process the acquired waveforms, detect whether some of those processed values are out of preconfigured limits and appropriately flag this data. Typically acquired signals are the MKS voltage and current, the MKS and accelerating cavity bi-directional coupler (BDC) forward and reflected power as well as the accelerating cavity pickups (PKPs). This system capability proved very useful during the data postprocessing to discern between recorded events originating from breakdowns in the accelerating cavities, rather than in the RFN or in the klystron.

If the number of consecutive events is higher than a user-defined limit, an internal inhibit signal is raised. EDS also detects externally produced inhibit signals, typically those coming from the cooling and the vacuum systems. If an inhibit signal is raised, the EDS will no longer forward the triggers from its input to its power output.

The EDS computes the rate of recognized events in a dynamic way, as 2 divided by the number of pulses since the second to last event to the present time. This number is the accelerating cavity BDR monitored by the system, though as explained above during the data postprocessing several recorded events can be discarded as breakdowns non-originating from the accelerating cavity.

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SIGNAL ACQUISITION AND ANALYSIS

Analogue signal acquisition and processing are carried out in an FPGA to ensure deterministic operation at 200 Hz and no lost triggers as well as to immediately react to multiple detected events.

Upon a trigger signal, each of the eight channels performs pulse analysis on the acquired waveform. The analysis measures three parameters of the pulse: its mean and peak amplitude and area (Fig. 2). The measurements are performed between time window delimiters window begin and window end (marked red in the three figures). Each of the three parameters has independent time window delimiters.

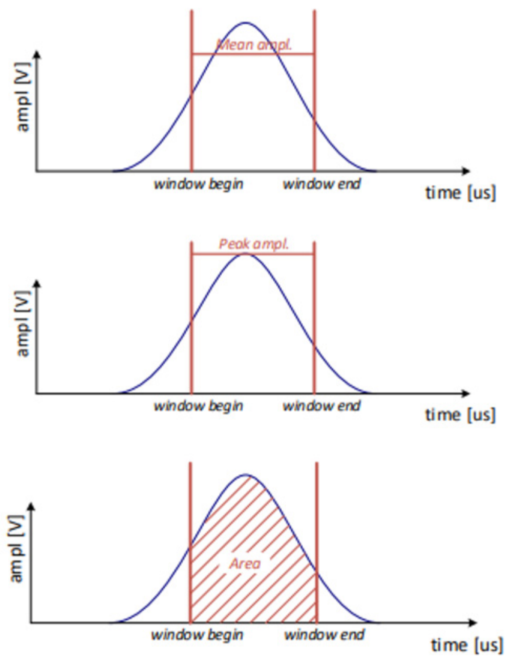

Figure 2: Sketch of the three types of measurements applicable to the acquired signals.

When pulse analysis is complete, the results are evaluated. If any of the parameters is outside the limits, this pulse is marked as an event (otherwise it is referred to as a nominal pulse). The user can set three types of limits: a low, a high and a maximum deviation from the moving average. Each of the three limits may be turned on or off. The deviation is set in percent change with respect to the value averaged from the last N nominal pulses (events are excluded). N is set by the user and can be either 1, 2, 4, 8, 16 or 32. The data sent to the software include the flags reporting which of the limits was reached on which channel. Event detection also includes a counter of consecutive events. If the number of consecutive events exceeds a user-defined limit, a register is set to inform the trigger logic that an EDS inhibit has been triggered.

The EDS keeps in a buffer the RF signals of the most recent nominal pulse. In such a way, all the RF pulses recognized as “Events” can be compared with their previously nominal RF pulse, as shown in Fig. 3.

Amongst the different detection systems available, the one that proved to be the most effective is the possibility to flag as events the RF pulses where the pulse area, peak or mean value differs more than a user-defined percentage from the averaged values of the last N pulses. This type of threshold has been applied to all the LIGHT-conditioned cavities BDC FWD pulses and PKP signals, together with the most common maximum peak threshold on the BDC RFL signals.

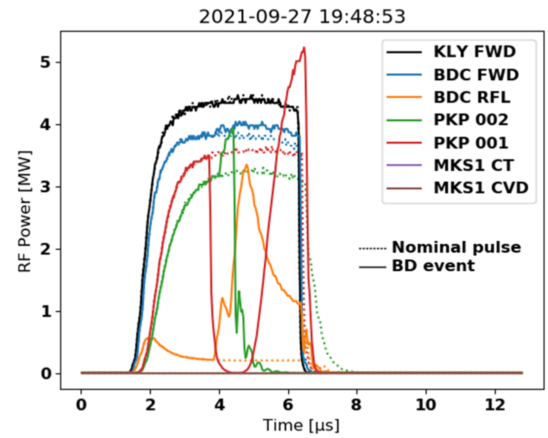

Figure 3: Example of acquired signals. Breakdown event in solid lines and previous nominal pulse in dotted lines.

CONTROL AND LOGGING

A complementary layer to the EDS oversees controlling the GUI, archiving data, monitoring the EDS, managing the inhibits and their recovery, and regulating the RF frequency to keep minimum the cavity reflected power.

GUI Control and Data Archiving

This part of the application permits to control:

- The RF generator amplitude, phase, frequency, and repetition rate.
- The MKS status.
- The EDS thresholds and the enabling of the inhibit conditions.
- The vacuum and cooling status.

The application can display the RF signals, the computed values (peak/mean/average of the RF signals), the BDR, and the vacuum and temperature signals at a maximum repetition rate of 2 Hz. The user can retrieve all the data in CSV files over a defined time window.

When enabled, events are logged into binary files at a rate up to 200 per second and stored on a remote server. Once a file size has been reached, a new file is created and populated as events occur.

EDS Monitor

Once an event has been recognized by the EDS, this is displayed together with the most recent nominal pulse before it. The conditions that trigger the event are shown, together with the number of pulses accumulated since the last recognized event.

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Inhibits and Automatic Recovery

When the functionality is enabled, the EDS can restart the output trigger after an inhibit blocks it. When an inhibit occurs, the EDS tries to resume the conditioning for a user-defined number of times. If the inhibit root cause was cleared in the meantime, the EDS restarts the conditioning, else it stops it. Typical examples of external inhibits not recoverable by the EDS are high/low SF6 pressures in the RFN and MKS interlocks.

Cavity Resonance Feedback

During the RF conditioning, the average power in the cavity changes, so the optimum resonance condition changes as well. This part of the application monitors the cavity temperature, and it reacts when this changes more than a user-defined value – typically 0.2 deg. The RF generator frequency is changed automatically by a user-defined ratio, typically 50 kHz/deg. As a result, a matched cavity at the start of the RF conditioning – with low RF power, pulse width, and repetition rate – remains matched also when the nominal RF conditioning parameters are reached.

CONDITIONING LOGIC

The conditioning is driven by the Cavity Conditioning Algorithm (CCA) algorithm, which decides when and how to increase the RF power delivered to the cavity. This works similarly to systems previously developed, e.g., in [2], namely, the CCA is capable of 1. Automatically increasing the RF power at a user-defined rate when the BDR is below a user-defined low threshold, 2. Keeping the RF power constant when the BDR is above the previous threshold but below an upper one, and 3. Decrease the RF power by a user-defined amount when the BDR exceeds the upper limit.

The CCA allows the user to enable, disable, pause, and resume the conditioning process. The user shall define the RF conditioning goal parameters – RF power, pulse width and repetition rate – together with the corresponding increase steps. The CCA increases first the RF power. Once the RF power reaches the goal one, the CCA reduces the RF power by a user-defined percentage and increases the repetition rate by the same percentage. Once both the RF power and the repetition rate reach the goal values, the CCA starts increasing the pulse width with the same logic as above.

During the increase of the pulse width, the system modifies the moving thresholds (average and mean) accordingly, such that the sample values maintain their statistical significance.

Once the system has reached all the goal parameters – RF power, pulse width and repetition rate – the CCA keeps on operating at those values until the BDR fall to a user-defined goal. Once this is reached, the CCA can either stop the conditioning or continue it, depending on the user settings. An e-mail notification can be sent either when the conditioning ends successfully or when the conditioning stops.

The CCA publishes live, at a slow monitoring rate of 2 Hz, the RF power in any of the eight acquired signals, together with the vacuum reading, the pulse width, the repetition rate, the RF generator power, and the BDR in the cavity according to the thresholds set in the EDS. The operator has thus a quick way to monitor the main conditioning parameters and their trends.

SYSTEM CAPABILITIES EXAMPLE

An example of the full history conditioning data of one of the LIGHT accelerating cavities conditioned with the EDS is shown in Fig. 4. In the case shown, the repetition rate was set from the beginning at 200 Hz, and one can appreciate the initial RF power ramp-up – driven by the CCA BDR thresholds set by the operator – followed by the increase of the pulse width. More than 1600 breakdowns were detected during the cavity conditioning, which lasted less than 2 weeks in total. After the setup of the EDS events recognition thresholds, the operator intervention was minimal and limited to stopping and restarting the CCA once activities such as SF6 refill were needed.

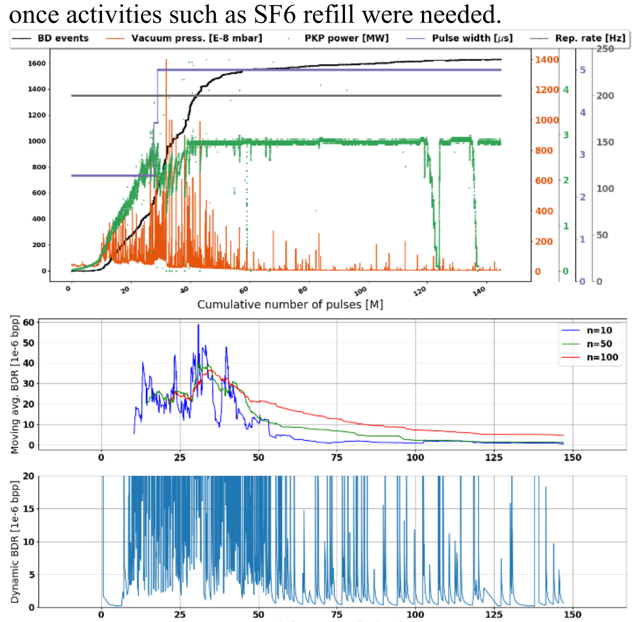

Figure 4: Full conditioning history of one LIGHT accelerating cavity. The top picture shows the cumulative number of breakdowns, the pulse width, the repetition rate, the RF power, and the vacuum pressure across the cumulative number of RF pulses. The bottom picture shows the BDR moving average and the dynamic BDR across the cumulative number of RF pulses.

SUMMARY

The EDS system permitted to complete the automatic conditioning of the 4 SCDTL modules and the 15 CCL modules composing the first LIGHT accelerator in a systematic and efficient way, along with several RFN components such as isolators and RF windows.

The system has been first tested and it is in use since late 2019. More than 130 GB of data have been collected and post-processed, corresponding to a total of almost 1 million breakdowns identified.

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REFERENCES

[1] M. Jacewicz *et al.*, "Instrumentation for the 12 GHz Stand-Alone Test-Stand to Test CLIC Accelerating Structures", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper TUPC133, pp. 1335-1337.

[2] N. Catalan-Lasheras *et al*, "Experience Operating an X-band High-Power Test Stand at CERN", in *Proc. IPAC2014,* Dresden, Germany, 15-20 Jun 2014, pp. 2288. doi:10.18429/JACoW-IPAC2014-WEPME016