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RF CONDITIONING OF THE PHOTO-CATHODE RF GUN AT THE ADVANCED PHOTON SOURCE – NWA RF MEASUREMENTS*

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Abstract

A new S-band photo-cathode (PC) gun was recently installed and RF conditioned at the Advanced Photon Source (APS) Injector Test-stand (ITS) at Argonne National Lab (ANL). The APS PC gun is a LCLS type gun fabricated at SLAC [1]. The PC gun was delivered to the APS in October 2013 and installed in the APS ITS in December 2013. At ANL, we developed a new method of fast detection and mitigation of the gun's internal arcs during the RF conditioning process to protect the gun from arc damage and to RF condition more efficiently. Here, we report the results of RF measurements for the PC gun and an Auto-Restart method for high power RF conditioning.

INTRODUCTION

RF measurements performed on the gun at the APS before installation confirmed the measurements made at SLAC before the gun was shipped to ANL. After the gun was fully RF conditioned and photo-electron beam commissioned in the ITS, the gun was baked to improve vacuum and then installed into the APS linac tunnel in August 2014 (Figure 1).

During the PC gun conditioning at the APS, three different protection systems were used to disable RF in order to prevent gun damage that could be caused by sustained or continuous arcing: 1) vacuum pressure interlock, 2) reflected RF power interlock, and 3) arc detector interlock. Arcing is a common phenomenon during RF conditioning and typically it is not required to disable the RF on every single random arc, however, it is prudent to disable the RF on all sustained arcs. A new Auto-Restart method has been developed that limits the number of arcs associated with the PC gun, which is interlocked to both the RF reflected power (~4μs trip) and the arc detector (~3μs trip) systems. During Auto-Restart, both protective systems will shut off RF to the gun every time there is a reflected power or an arc detected. The Auto-Restart scripts will turn the RF back on automatically in < 20ms if it is a single-arc event and not a sustained arc. With the APS linac operating at a maximum of 30 Hz repetition rate, the RF will turn back on easily before the next RF pulse. The Auto-Restart system is "fail-safe" in that if the Auto-Restart script would quit working, both protective circuits are hard-wire interlocked and the RF would trip off at the next arc event and will remain off.

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PC GUN OVERVIEW AND MEASUREMENT RESULTS

The photo-cathode RF gun and its magnets are identical to the LCLS gun system. The 1.6 cell S-band RF gun has dual RF feeds to mitigate the dipole field [1]. The basic requirements from the RF gun design include ~15MHz mode separation between the zero and π modes, 120 MV/m accelerating gradient on axis, and a cavity quality factor Q0 > 11500 [2]. The gun and focusing magnets are critical in order to generate high-brightness beams. After gun conditioning in the ITS, the gun and the solenoid assembly were baked for five days at 150ºC in order to improve the gun base pressure. The PC gun and its beam line components were installed in the APS linac tunnel in August 2014 after completion of the bake. The vacuum conditions of the PC gun after linac installation are gun cathode cell (cold cathode gauge) = 7 x 10^{-9} Torr and gun waveguide = 2 x 10^{-10} Torr.

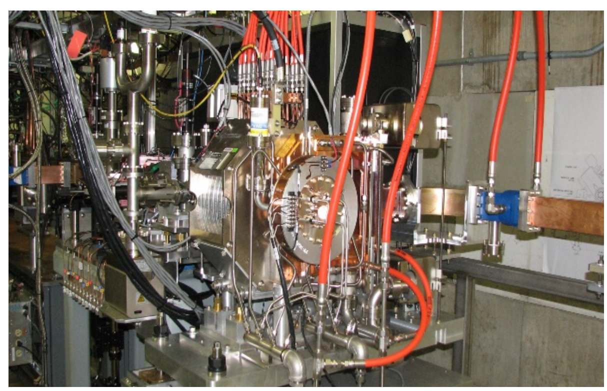

Figure 1: PC Gun Installed in the APS Linac Tunnel.

Initial network analyzer measurements were completed at SLAC, including bead drop measurements. Upon receiving the gun at the APS, RF measurements were performed using a closed water system to control the gun temperature such that the π-mode frequency was set to 2856.0 MHz. Resonant frequencies of the zero and π modes, quality factors, and coupling coefficients were made using a network analyzer. The gun body temperature was varied by ± 4ºC and the above measurements were repeated.

Unloaded Q, External Q and Loaded Q were measured using the Impedance Method [3]. To characterize the PC gun before installation, the following measurements were performed (see Table 1).

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Table 1: PC Gun LLRF Results

APS PC Gun @ 36.5°C	Pi Mode	Zero Mode
Frequency (MHz)	2,856.0	2,841.1
Q zero	12,836	12,490
Q loaded	4,218	5,430
Q ext	6,384	9,605
Beta	2.01	1.30
Mode Spacing = 14.91		
Cathode cell - upper probe coupling (dB) = -76.23		
Cathode cell - lower probe coupling (dB) = -89.18		
Coupler cell - Inner probe coupling (dB) = -86.25		
Coupler cell - outer probe coupling (dB) = -82.61		

RF CONDITIONING WITH AUTO-RESTART

In the past, PC gun RF conditioning relied on vacuum pressure interlock and operators' patience, or by using fast detection (reflected power and/or arc detector) protection. Implementing an Auto-Restart procedure allows random arcs in a pre-defined time window to occur without unnecessary interruption of the gun RF processing. A random arc is an arc that may occur during one RF pulse duration, may not damage the gun's internal surfaces, and may not occur again for a period of time afterward. The Auto-Restart script is also implemented in a way that protects the gun from repeated or sustained arcs by quickly disabling the RF.

In Figure 2 we show a captured screen for the PC gun reflected power Auto-Restart conditioning script. Notice that the script allows for variable time scale (between 10 to 500 seconds) and the number of trip events (between 2 to 10 events). When the PC gun was conditioned at the APS ITS, the script was set to allow 3 arcs in a 30-second window. Operating at a 30 Hz repetition rate, there are 900 RF pulses in a 30-second period and the Auto-Restart script will not restart the RF after a third arc during those 900 pulses.

The steps of the Auto-Restart procedure are described below for a specific example of the PC gun conditioning that is shown using figure 2.

If a trip would occur, the trip tally (count) would be set to 1 and the timer would start counting toward a 30-second time window. If in 10 seconds after the first trip, another trip would occur, the trip tally would count up to 2. If in the remaining 20 seconds a third trip would occur, then the Auto-Restart would not be re-activated and the RF would not restart automatically. However, if a third trip would not occur in the last 20 seconds of the 30-second window, the trip tally would be reset to 1. This allows for a rolling 30-second period to be continuously monitored.

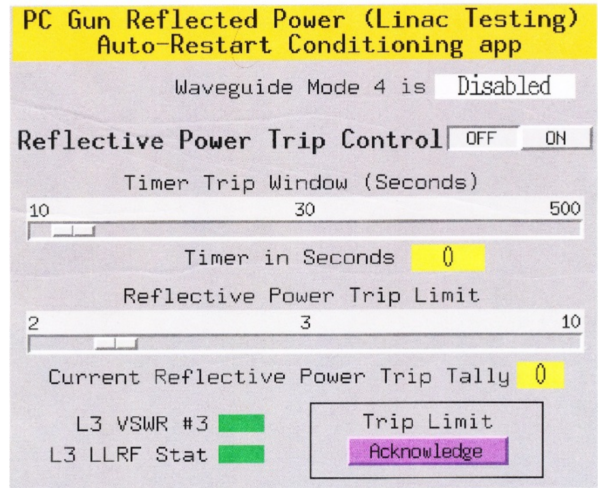

Figure 2: Reflected power Auto-Restart.

If the trip tally above (see Figure 2) is constantly changing between 0, 1 and 2, the RF conditioning continues without a trip and the RF drive level is set at the optimum spot for efficient RF conditioning. This provides a way to view the optimum drive level while the RF is on and conditioning. A lower RF drive level would not condition the gun in a timely fashion; likewise, increasing the RF power level manually would trip the RF, thus slowing down the conditioning process. In addition to the reflected power, a second Auto-Restart script is utilized at the same time for the arc detector interlock circuitry.

This optimum RF drive level would not be known if a fast detection circuit (reflected power and/or arc detector) would trip the RF at every event. During RF conditioning, if the number of the trip tally is kept as described above, a steady RF drive is maintained that allows incremental drive power increases without tripping the RF system.

Under these operating conditions, when a sustaining or continuous arc occurs, the RF will be shut off in three RF pulses. At a 30Hz rate the RF would be off in ~ 100ms. Thus operating with a pulse width of 2.5μs, this allows only a maximum of 7.5μs of arcing, therefore providing gun protection.

STATE NOTATION LANGUAGE AND SEQUENCER

An Acromag 9440 digital I/O board with interrupts is used to process trip events under 20ms. This module is controlled by the Experimental Physics and Industrial Control Systems (EPICS), which runs the "Auto-Restart Arc Detector" and the "Auto-Restart Reflected Power" scripts. These scripts are written in "State Notation Language and Sequencer" provided by EPICS.

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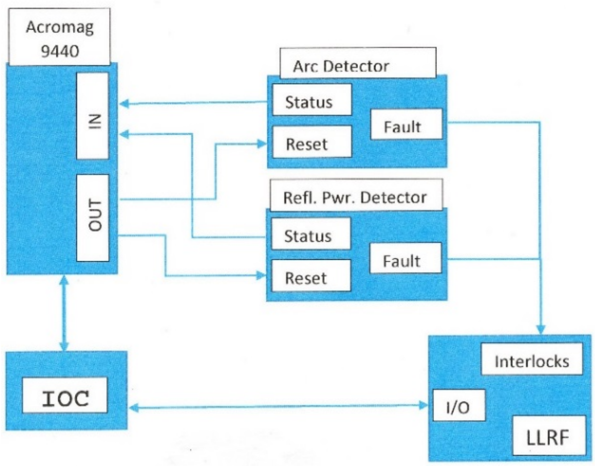

Figure 3: SNL / Acromag 9440.

Figure 3 is a simplified diagram showing the interface between the Auto-Restart script and the hardware. Both the arc detector and the reflective power detector will trip the interlock of the LLRF system, which will switch the RF to the OFF state. The Input Output Controller (IOC) in Figure 3 is a VME system with a MVME3100 as the main CPU and using EPICS as control software. An Acromag 9440 was installed in the VME system - a digital Input/Output module - for its interrupt capability, which is needed for 30Hz operation. If either detector senses a fault condition, the hardware interlock is tripped and a status is sent to the Acromag 9440 module, which causes an interrupt to be generated. The CPU acknowledges the interrupt and updates the associated Process Variable (PV). The State Notation Language (SNL) running on the IOC responds to the PV changing, resets the appropriate detector, and then waits for the status to be cleared. Once cleared, the SNL program will turn ON the LLRF system all within a 30Hz cycle. The SNL program adjusts the time stamps as was described above and waits for the next fault status.

ITS CONDITIONING PROCESS

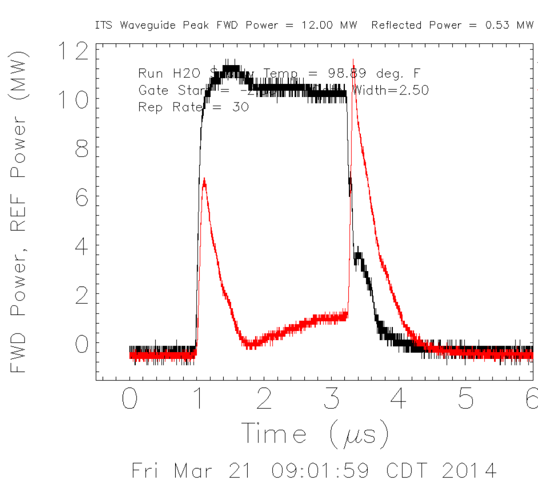

Figure 4: Forward and Reflected RF Waveforms. (Measured at PC Gun Waveguide).

RF conditioning the gun using the prescribed procedure maintains a level of RF drive to the gun without causing any unnecessary trip of the RF system. Employing this procedure allowed us to fully RF condition the PC gun in < 80 hours without any sustained or continuous arcs.

The ITS RF conditioning sequence allows effective RF processing of the gun starting from low peak power, low repetition rate and short pulse width to 12MW peak power, 2.5µs and 30Hz repetition rate with the solenoid current between 0 and 250 amps.[4].

The goals of RF conditioning, including 12MW forward power, 2.5µs pulse width, and a 30Hz repetition rate, were achieved (see Figure 4). The gun solenoid can operate at any current from 0 to 250 amps. The maximum accelerating gradient achieved was ~125 MV/m on the photo-cathode (at 12MW forward power) [5]. During the RF conditioning, the gun vacuum trip level was set at 3 x 10^{-8} Torr and the reflected power trip level was set at 1.6MW.

SUMMARY

During PC gun RF conditioning at the APS in March 2014, a reflected power Auto-Restart conditioning script and an arc detector Auto-Restart conditioning script were used to prevent possible gun damage from continuous arcs. The PC gun was able to be conditioned quickly and in a manner that protected the gun.

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