AWA RF Modulator Upgrade Using Solid State Thyratron Replacement*

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Abstract

The recently built 12us long pulse RF modulator at Argonne Wakefield Accelerator (AWA) facility was having many performance problems until the thyratron used in the modulators were replaced with pulsed power solid state switches. Detail of both the problems experienced with the thyratrons and the results of successful upgrade with solid state switches are presented in this paper. The design of the solid state switches will also be discussed.

I. AWA Facility

The mission of the Argonne Wakefield Accelerator Facility (AWA) is to develop technology for future accelerator facilities. The AWA facility has been used to study and develop new types of accelerating structures based on electron beam driven wakefields. In order to carry out these studies, the facility employs a photocathode RF gun capable of generating electron beams with high bunch charges and short bunch lengths. This high intensity beam is used to excite wakefields in the structures under investigation.

The facility is also used to investigate the generation and propagation of high brightness electron beams, and to develop novel electron beam diagnostics.

The AWA high intensity electron beam is generated by a photocathode RF gun, operating at 1.3 GHz. This one-and-a-half cell gun typically runs with 12 MW of input power, which generates an 80 MV/m electric field on its Magnesium photocathode surface. A 1.3 GHz linac structure increases the electron beam energy, from the 8 MeV produced by the RF gun, to 15 MeV. The linac is an iris loaded standing-wave structure operating in the $\pi/2$ mode with an average accelerating gradient of 7 MV/m; it has large diameter irises to minimize the undesirable wakefields generated by the passage of high charge electron bunches.

The charge of the electron bunches can be easily varied from 1 to 100 nC, with bunch lengths of 2 mm rms, and normalized emittances of 3 to 100 πmm mrad. The AWA laser system consists of a Spectra Physics Tsunami oscillator followed by a Spitfire regenerative amplifier and two Ti:Sapphire amplifiers (TSA 50). It produces 1.5 mJ pulses at 248 nm, with a pulse length of 2 to 8 ps FWHM and a repetition rate of up to 10 pps. A final KrF Excimer amplifier is optionally used to increase the energy per pulse to 15 mJ.

The generation of electron bunch trains (presently up to 16 bunches) requires each laser pulse to be divided by means of beam splitters into a laser pulse train. The charge in each electron bunch is determined by the energy in each laser pulse and the quantum efficiency of the photocathode material. Typically, single bunches of 100 nC can be produced (with a maximum of 150 nC occasionally reached).

AWA have had several major upgrades in the past few years. Now the facility maintains the world's two highest charge RF photoinjectors, both capable of 100 nC per bunch. The drive RF photoinjector beamline generates a 75 MeV, GW-class drive bunch train of variable pulse length and the witness RF photoinjector produces a 15 MeV, high-quality 1nC@1um witness bunch. A new beamline switchyard is illustrated in Fig. 1 and has been constructed to allow concomitant experiments: (a) collinear wakefield acceleration; (b) RF power generation and two beam acceleration; (c) phase space manipulation (emittance exchange, etc); (d) high brightness beam generation; (e) beam diagnostic development. This flexible beamline switchyard allows a quicker and more efficient transition among several concurrent experimental setups.

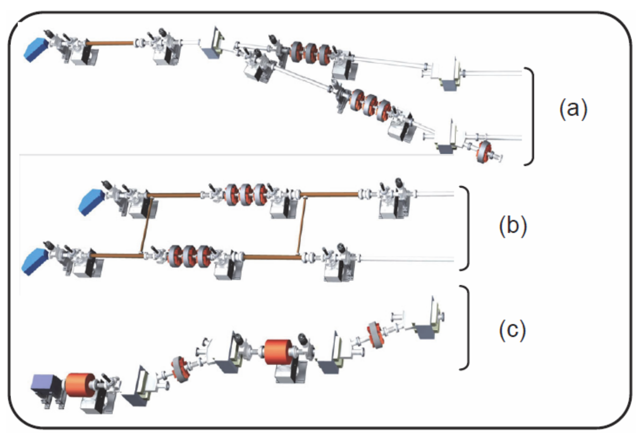

Figure 1. Different legs of the new AWA beamline switchyard will be dedicated to specific types of experiments: (a) collinear wakefield acceleration; (b) twobeam- acceleration and RF power generation; (c) phase space manipulation (emittance exchange) and beam diagnostic development.

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II. AWA RF system upgrade

For years, AWA facility was operating with only one RF power station. This RF power station had being upgraded several times. First its PFN has been modified to extend the flap top from 3.5us to 5.5us. Then its high voltage power source has been upgraded to a commercial 40kV capacitor charging power supply. This RF power station has been driving our RF photo-injector gun and RF linac and witnessed many successful experiments at AWA.

In order to explore higher accelerating gradient and generate longer RF pulses at higher intensity, the drive beam energy needs to be upgraded and thus more RF power stations are needed. As part of the recent AWA facility upgrades, three additional L-band RF power stations have been added to AWA RF system. These three additional RF power stations are dedicated for powering the 6 L-band RF linacs on the drive beam line to accelerate the drive beam up to 75MeV. The Q factor of these 6 linacs is about 25000 and thus require about 9us RF pulse [1].

The modulators of the three additional RF stations are all identical. They all have a PFN capable of 40kV with FWHM pulse length of about 11us. At the beginning, all three modulators were equipped with a CX1725 thyratron and they all have some performance issues. It took us a while before we figured out that the problems were all caused by the thyratron. We asked around and found out that there is a solid state alternative for thyratrons and Advanced Photon Source (APS) at Argonne National Lab has replaced some of their thyratron with the solid state switches developed by Applied Pulsed Power (APP). With help from APP, we borrowed one solid state switch from APS and tested it in our modulators. It solved all the problems we have had with our new RF stations. Now all the thyratrons in the AWA RF power stations have been replaced with solid state switches and the AWA RF system is now functioning flawlessly ever after.

A. The puzzle of intermittent excessive klystron reverse voltage

Since the day one of the turning on the first new RF power station, we started to experience some sort of intermittent problems with the modulators and strong noises in all scope traces monitoring the RF signals when new modulators were running. As shown in Fig. 2 and Fig. 3, we observed excessive reverse klystron voltage from time to time. We did not suspect the thyratron for causing these problems at the beginning. We tried snubber circuits, we tried high frequency choke, we tried to reroute and optimizing the PFN connections and finally realized that it is the thyratron itself having problems.

As shown in Fig 3, when the klystron reverse voltage is climbing up, the thyratron voltage is climbing up as well while the thyratron current drops to zero which indicates that the conduction through thyratron has been terminated before the stored energies have been completely dissipated. It is clearer in Fig. 4. As shown in Fig. 4, the klystron reverse voltage climbs up when the thyratron voltage climbs and then collapses when the thyratron voltage collapses. On our ways of trying to solve the thyratron problem, we also found out that those spikes on the thyratron voltage scope trace were indeed the due to the quenching of thyratron.

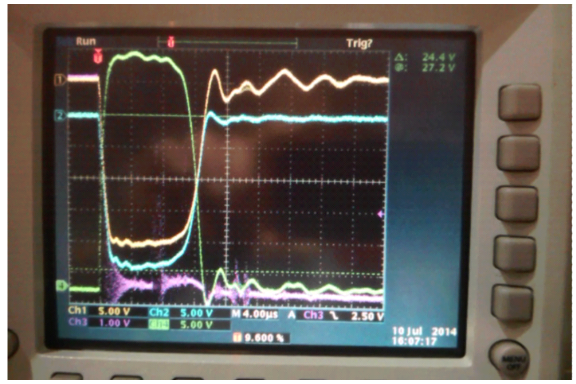

Figure 2. Typical scope traces showing normal klystron votage and current. Ch1 is the klystron voltage; ch2 is the klystron current; ch3 is the thyratron voltage and ch4 is the thyratron current.

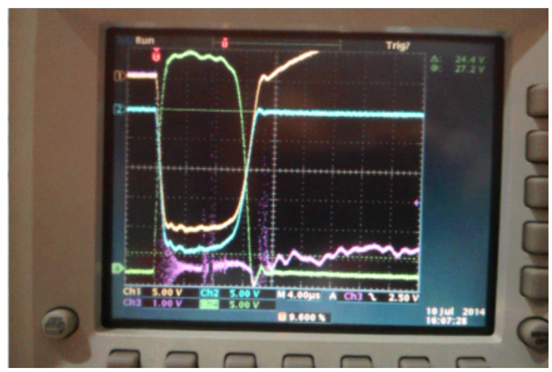

Figure 3. Typical scope traces showing intermittent problem with excessively high klystron reverse votage. Ch1 is the klystron voltage; ch2 is the klystron current; ch3 is the thyratron voltage and ch4 is the thyratron current.

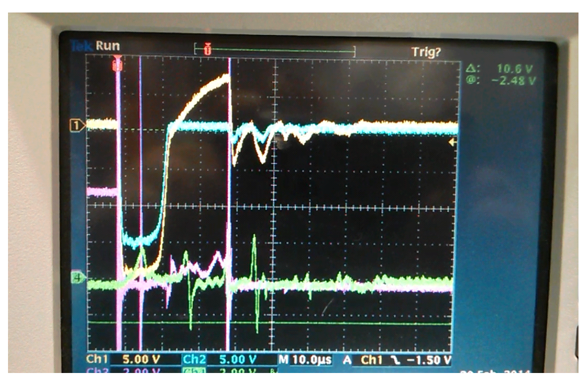

Figure 4. Scope traces clearly indicate the problem is from thyratron. Ch1 is the klystron voltage; ch2 is the klystron current; ch3 is the thyratron voltage and ch4 is the EOL current.

In order to solve the problem, we even changed the thyratron reservoir heater to a point where the thyratron begins to self-fire at our nominal PFN voltage and still couldn't solve the problem completely. The thyratrons just couldn't handle the long pulse length and high peak currents even though our operating points are within the spec of the thyratron. The problems were worse with used thyratrons repurposed from the Intense Pulsed Neutron Source at Argonne National Laboratory but also occurred with brand new thyratrons provided by E2V.

B. The cure, solid state thyratron replacement

APP has provided solid state thyratron replacement switches since 2009. One of the first places to install these switches was APS at Argonne National Laboratory. The results of this work have been previously reported [2,3]. APS LINAC Modulator uses a 704 nF, 4 Ω PFN comprising two parallel sets of 8 stages. This system operates at 30 Hz. Originally operating using a E2V CX1836, the thyratron has been replaced with a model S56-12 from APP. Modulator cabinet L3, the first to be upgraded, has now been operating without failure for more than 17500 hours with the solid state switch.

APP model S56-12 is comprised of twelve CCS TA 14N40 thyristors from Silicon Power Corporation connected in series with integrated trigger, snubber, and resistive balance circuitry. Fig. 5 shows a picture of the S56-12 and Fig. 6 shows the dimensions. As can be seen, the S56-12 has similar dimensions to the E2V CX1725 and the CX1836. The operational parameters of the S56-12 can be seen in Table 1.

Table 1. APP Model S56-12 Operational Parameters

Parameter	Value	Units
Peak Voltage	60	kV
Maximum DC Voltage	48	kV
Repetitive Forward Current	7	kA
Peak Forward Current	14	kA
Rate of Current Rise Time	40	KA/μs
On-State Resistance	0.1	Ω
Turn-on Delay	200	ns
Timing Jitter	2	ns

The AWA modulator cabinets were based on the APS design where the S56-12 was already proven. While the new AWA modulators have a longer pulse width, 12 μs rather than 6 μs, they operate at much lower frequency 10 Hz rather than 30 Hz. The problems in the AWA modulators only got solved after we replaced the thyratron with solid state switch. AWA upgraded using the S56-10 rather than the S56-12, the main difference being a lower maximum DC voltage rating of 40kV rather than 48kV. The S56-10 would also cost less and have a slightly higher efficiency than the S56-12. Another benefit from this thyratron to solid state switch upgrade is that the noises produced by the modulators are greatly reduced. Fig. 7 shows the scope traces monitoring the RF signals when a solid state switch has been installed in the modulator. As can be seen comparing Fig. 7 with Fig. 2 in the trace for Ch3, the thyratron voltage, where in Fig. 2 it has significant high frequency noise which is not seen in Fig. 7. Now all of the RF modulators at AWA are operating with the solid state switch.

Figure 5. Image of an APP Model S56-12 solid state thyratron replacement.

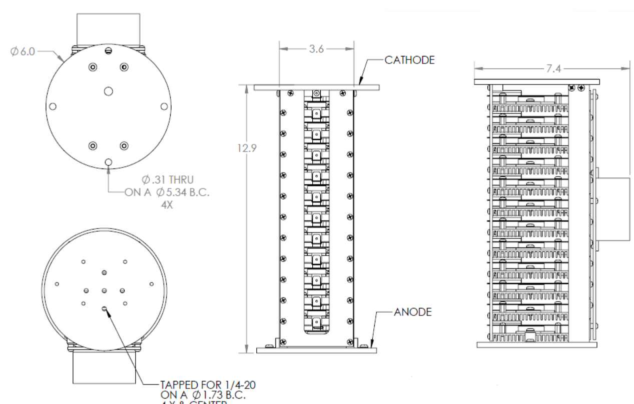

Figure 6. APP Model S56-12 dimensions.

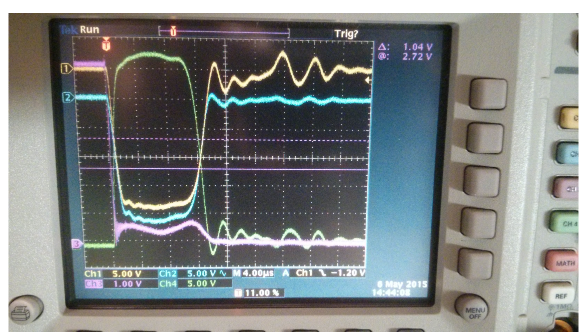

Figure 7. Typical scope traces when a solid state switch is installed in the modulator. Ch1 is the klystron voltage; ch2 is the klystron current; ch3 is the solid state switch voltage and ch4 is the solid state switch current.

III. SUMMARY

AWA facility upgrade would never being successful if the intermittent performance issues with the three additional RF power stations were not solved by replacing the thyratrons with the solid state switches. After the upgrade from thyratron to solid state switches, all the modulators have being operating flawlessly and the upgraded AWA facility is now completely back in service.

IV. REFERENCES

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