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The Booster to AGS Beam Transfer Fast Kicker Systems*

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ABSTRACT

The Brookhaven AGS Booster had a very successful commissioning period in June 1991. The third phase of that commissioning was a beam extraction test. The Booster extraction fast kicker (F3) deflected a 1.2 Gev proton beam from the Booster circulating orbit into the extraction septum aperture, partially down the extraction line to a temporary beam stop. Now, the Booster is committed to the AGS operations program for both heavy ion and proton beams. Thus, the Booster extraction and the corresponding AGS injection systems must operate routinely up to a pulse repetition frequency of 7.5 Hertz, and up to a beam energy of 1.5 Gev. The injection fast kicker is located in the A5 section of the AGS ring and is used to deflect the proton or heavy ion beam into its final AGS closed orbit.

The Booster extraction and the AGS injection fast kickers are both multi-module systems. Also, they both serve the dual-function of deflecting the proton or heavy ion beams, which require a change in pulse rise time, amplitude, flat top duration, and the fall time. For each system, the multiple modules are arranged electrically in parallel. Each module drives one lumped inductance picture frame magnet section, and the magnets are arranged mechanically in series. The pulsed current delivered from the modulator creates a pulsed magnetic field in the magnet aperture which imparts an angular deflection to the passing particle beam from/into the machine orbit.

A distinctive feature of the AGS injection fast kicker modulators is the tail-bitting function required for proton beam injection. This enables the system to produce a fast current fall time (<140 ns) to go along with the high current pulse amplitude (1100 Ampere/module) with a fast rise time (<120 ns). The AGS injection fast kicker system has three pulse modulators, and each modulator consists of two thyratrons. The main PFN thyratrons switch on the current, and the tail bitting thyratrons are used to force the magnet current to decrease rapidly. Two digital pulse delay generators are used to align the main thyratrons and the tail bitting thyratrons respectively. The system has been tested and installed. The final commissioning of the Booster to AGS beam transfer line and injection is currently being undertaken.

In this article, the system design, realisation techniques and performance data will be presented.

INTRODUCTION

The AGS-Booster operation undertaken this spring has successfully accelerated silicon ions, gold ions, and protons, which marks the beginning of the new era of the AGS high energy physics and nuclear physics programs. As a major part of the operating program, the Booster to AGS transfer fast kicker systems have been running satisfactorily.

The Booster extraction fast kicker (F3) deflects the particle beam from the deformed Booster orbit into the extraction septum aperture. The particle beam is then transported and matched through the Booster to AGS transfer line and arrives at the AGS injection septum aperture, which inflects the beam into the AGS ring. The AGS injection fast kicker (A5) deflects the particle beam into the proper AGS closed-orbit.

The modulators of the AGS injection and the Booster extraction fast kickers are basically E-type pulse forming networks. R-C compensations are used to shape the front edge of the pulse, which improves the pulse rise time significantly. Pulse

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length change is accomplished by mechanically switching in or out additional PFN sections. In the Booster extraction fast kicker, when used for proton extraction, the terminating resistor is matched to the PFN impedance thus enabling a fast pulse rise time. For heavy ion extraction, the requirement is for a higher peak current (about 1600 A/module) but a slower rise time, therefore the resistor is switched to a smaller value mismatching the PFN impedance to gain more current. The AGS injection fast kicker incorporates a tail biting section, which is required only during proton injection to obtain a fast pulse fall time as well as a fast rise time. The basic principle of the hard tube tail biting circuit is to apply an opposing high voltage across the load magnet near the end of the pulse flat top, to force a fast decrease of the magnet current. The inductively stored energy in the magnet will be extracted rapidly and dissipated in the load resistor. The main circuit diagram of one of the AGS injection fast kicker modulator is shown in Figure 1.

MULTIPLE MODULE SYSTEM CONSTRUCTION AND INTEGRATION

The AGS injection fast kicker and the Booster extraction fast kicker are both multi-module systems. There are three PFN modules in the AGS injection kicker system, which are connected to three independent magnet sections. The Booster extraction kicker consists of four PFN modules one for each of four magnet sections. The magnets are lumped inductance picture frame type. The core material is ferrite and the single turn conductor is made of copper.

The requirement for a full aperture picture frame magnet is necessary to permit passage of the large size high intensity beams through its window during injection, acceleration, and extraction. This results in a relatively high inductance magnet. Several techniques were used to minimize the inductance. The Booster extraction fast kicker is located in the Booster F3 straight section, which is about 2.4 meter long. In this distance, the beta function β_x and the dispersion function D_x change rapidly, which determines the horizontal emittance of the beam according to the equation $[\epsilon_x \frac{\beta_x}{\pi} + (D_x \frac{dp}{p})^2]^{1/2}$. The horizontal aperture requirement is 3" at the upstream end of the F3 section and 4.6" at the downstream end. To reduce the magnet inductance, this emittance varying effect has been taken into consideration in the designing the magnet. The first two sections of the F3 magnet have a window width of 4.0" and the other two have a window width of 4.8". (This was first suggested by A.V. Soukas, and Y. Y. Lee). Their length are also made different by the same ratio to result in a nearly constant inductance per section. The AGS injection fast kicker occupies less than a meter in the AGS A5 straight section, where the emittance of the beam varies slightly. Hence, the three sections of the AGS injection kicker magnet have been made identical.

Multiple Module Construction

In our application, the multiple module system has the advantage of lowering the peak voltage per module compared to a single module scheme. Thus, the modulators can be operated in air without use of dielectric agents. However, it requires a lot of attention in the construction to ensure the overall system performance. In our cases, every attempt was made to produce modules that were uniform in construction techniques. In the Booster case a prototype was built, and this was copied four times by a construction crew. This resulted in satisfactory performance. The AGS injection fast kicker modulators have much more stringent requirement on the construction, because of the rise and fall time requirements and because of the tight space requirement. Each module is constructed in a box of approximate 12.5"x48"x60". These modules have shown high reliability. The waveforms generated from the multiple modules are fairly close to each other. In Figure 2, the magnet currents as seen on current transformer pickups on the output are obtained from the three AGS injection fast kicker modulators. The first and the third modules have the waveforms almost identical. The second one, located in the middle of the three, is slightly different from the others, because the magnet in the middle section has more coupling inductance. This phenomenon has also been observed in the Booster fast kicker modulators. Physically, the modules are mounted as close as possible to the magnets in the accelerator tunnel.

The System Integration

The multiple modules are electrically linked together at their control unit. The control racks and the high voltage power supplies are located in the service buildings outside the accelerator rings. The master control unit is an Allen Bradley programmable logic controller (PLC), which receives status commands from a local panel or from the AGS main control computer system. The PLC generates the command chain to control the high voltage power supplies, trigger power supplies, thyratron auxiliary control power, and the modulators. It also monitors, processes, and reports the status of the equipments to the AGS main control center and the local display panel.

To minimize the coupling between the modules and between the power supplies, it is necessary to eliminate all ground loops and multiple commons. The AGS injection kicker system exhibits more sensativity, due to the complexity of the tail biting circuitry. In its control design, the whole system is considered as one circuit. This helps the design by developing on the principle of single point grounding. As seen by our results, this proved to be effective. Both the AGS injection and the Booster extraction kicker systems have achieved multiple module decoupling. Each module can be triggered independently, while others show no misfiring, even though they are fully charged. The magnet coupling, in these situations, does not affect the thyratron holding ability.

The Multiple Module Synchronization and Trigger Generators

The high voltage trigger generators for the AGS injection fast kickers are designed and built in the Lab. Each trigger generator consists of basically a storage capacitor, charged up to 400Vdc, two power MOSFETs in parallel as the switch, and a 2:1 pulse transformer which steps up the pulse to 800V maximum and isolates the input and output circuitries. Two types of power MOSFETs are used to compare the device reliability. Four trigger modules are made of Motorola MTM13N50E TMOS, which is rated at V_{DSS}=500*Vdc*, and I_{DM}=60*Apulse*. And, the other two trigger units use the Advanced Power Technology APT1001R1AN MOSFETs, which is rated at V_{DSS}=1000*Vdc*, and I_{DM}=38*Apulse*. The six trigger generators have been operated for 5 months, 24 hours/day. Up to date, there is no failures on neither type of MOSFETs. The pulse rise time of these trigger units are in the order of 40 ns.

Two SRS DG535 precision digital pulse and delay generators are used to synchronize the output pulse of the multiple modules. Each digital delay generator has four output channels. One unit is used to synchronize all three main thyratrons, and the other is used to synchronize the three tail biting thyratrons. The pre-ionization grid of the tail biting thyratron is pulse charged, which produce a longer anode delay. Therefore, the trigger pulse to the tail biting thyratrons are set in advance of the main thyratron trigger, although the main thyratrons are turned on about 700 ns earlier than the tail biting thyratrons. In this way, time jitter is more dependent on each individual thyratron. The three main thyratrons, CX1168B type, are the new devices, and the three tail bite thyratrons, CX1168's, are previously used devices. One of the CX1168's is probably more than 10 years old, and it is the only thyratron which required adjustment on the time delay after the initial setup. All other thyratrons have been stable. Several CX1168 thyratrons have arrived recently, the old ones will be replaced probably after this AGS operating period is complete.

THE DEVELOPMENT OF THE TAIL BITE CIRCUIT

When the Booster is operating at an extraction energy of 1.5 Gev for protons, the AGS RF system will be running at 4.114 MHz frequency, which corresponds to 243 ns time spacing between the center to center of the beam bunches. The nominal bunched beam length is 80 ns, and the maximum bunch length is less than 100 ns. Therefore, the space between the end of one bunch and the beginning of the other bunch is 143 ns minimum. The AGS injection fast kicker pulse has to rise up between the bunches, then keep flat in order to deflect the passing beam bunches into the AGS ring, and then fall down before the earlier injected circulating beam bunches come back. Hence the bunch spacing and length set the upper limit of the pulse rise and fall time. This fast fall time requirement demands the development of the tail biting circuitry for the AGS proton injection.

The development work started with a literature search, then proceeded to computer simulation, and then to hardware realization. In the implementation of the tail biting circuit, it is very important to minimize the noise at its source, isolate the noise paths, and shield the tail biting thyratron from other radial electromagnetic fields, such as from the fields of the main thyratron. In 1988, we built a test model to study the system feasibility. This unit used CX1154 type thyratron as the switching device. It was very carefully packaged and constructed. With some modifications, this unit soon reached design expectations. In testing a module we charged both the main and the tail biting section capacitors up to 25 KV, and the unit worked in a relatively stable manner.

The first prototype module was designed and built in late 1989. It employed either an CX1168B or CX1168BD two-gap double ended thyratron as the switching device, and added other components. The intent was to increase the operating range to the full extent of the specification of the injection kicker, and in addition, to add the function of the pulse length change to accommodate the requirement for either proton or heavy ion injection. However, in some aspects, the design became overcomplicated, and the packaging and the auxiliary circuit design were improper. After several design and construction modifications, it was improved to an operating range up to 500 Ampere in proton mode, less than half of the specified range. The basic problem was a false triggering of the tail bite thyratron, due to noise generated at the initial conduction of the main thyratron. This problem was due to several reasons such as the elimination of the thyratron shielding, massive grounding loops, low signal to noise ratio of the triggering scheme applied at the tail bite thyratron control grid, etc. In the end, almost the entire high voltage section of this unit was disassembled, and work was stopped.

The development of the tail biting circuit resumed after the early commissioning period of the AGS Booster in June 1991. We learned several lessons from the test model and the first prototype module, namely the importance of proper grounding, shielding and noise reduction techniques. A second prototype was built under the strict guidelines of taking precautions in the detailed grounding and shielding of all areas.

In the second prototype, the main thyratron high voltage section and the tail biting section are separated into two compartments. The two thyratrons are mounted at right angles and shielded from each other by a 1/4 inch thick aluminum plate. The two high voltage isolation transformers, which are used to supply the filament, reservoir, and grid power to the tail bite thyratron and the main thyratron, are located 3 feet away from the respective tubes. Therefore, all the wires from their secondary leads are run within 5/8 inch diameter copper pipes to the thyratron. The pipes are connected at one of their ends to the thyratron cathode or anode common.

We also used tri-axial cables, with one end of the outer shield grounded, for all high voltage triggers and current monitors. All power and control wires are twisted and double shielded. All equipment grounds are individually grounded to a single building ground point by use of 3/4 inch wide copper braid.

The high voltage trigger pulse to the tail bite thyratron is coupled through a dry type high voltage isolation pulse transformer. This type of trigger transformer is not available on the commercial market, therefore we decided to build our own. We used an Arnold AL 248 as the transformer core, and an aluminum can as the case. All the sharp edges on the core are machined to be rounded and then wrapped it completely with fiber glass tape and impregnated under vacuum with a thin epoxy. The primary winding has 20 turns of #18 AWG PVC insulated wire which is covered by a layer of mylar tape, then shielded completely by a layer of copper tape. This electrostatic shield was electrically connected to the core, and from there a wire is brought to the outside. Several layers of insulation are placed over the copper tape to isolate the primary and secondary windings. The secondary winding is also 20 turns, and covered by more insulation material to separate it from the case. A very critical step in building this potted transformer is to make sure that it is free of air voids. For this transformer, we utilized a thin two part room temperature curing epoxy with a setting time of at least a half hour, and pumped it down to -29" Hg. The transformers were high potential tested to 40 KVDC, while their insulation requirement is in the 30 KV pulsed range.

During the initial conduction of the main thyratron, the floating side of the magnet will jump to a transient negative high voltage, equal to approximately the magnitude of the main PFN charging voltage. This transient lasts about one hundred nanoseconds, which means that a sharp high voltage pulse up to 30 KV is seen by the tail biting thyratron cathode. Although the tail biting thyratron is floating, even a small fraction of this pulse coupling could cause an instability of the thyratron. By moving the tail biting damping resistor from the anode side to the cathode side, it isolates the tail biting thyratron cathode from the direct connection to the high voltage end of the magnet. This seemed effectively eliminate the transient pulse coupling. The maximum operating voltage in proton injection is about 30 KV in the main PFN. We tested it in excess of 42 KV in main PFN, and the tail bite thyratron is stable without mistriggering. We also tested it with the summation of the main PFN voltage and the tail bite capacitor voltage up to the maximum tube rating 70 KV. The system is stable and operates properly.

Every step we described above has improved the system performance significantly. The construction units duplicated from this prototype were all tested to the peak rating and work properly. This system has been in operating since early this spring. The photographs in figures 2, 3, 4, and 5 show some of the results.

The result of the tail biting performance would be better if the main switch is a single ended thyratron, which could keep the undershoot at the end of the pulse within about 10 percent. In Figure 6, the waveform of the tail biting circuit is obtained using the CX1168 thyratrons as both main and tail biting switches. The undershoot at the end of the pulse is due to PFN mismatch and pulse reflection. Although the double ended thyratron has the advantage of bidirectional conduction of current for a mismatched network, it might not be the best choice when the pulse undershoot is of the concern. In the present status, the pulse undershoot is tolerable, and it will be compensated by the bunch-to-bunch transverse damper kicker which is under construction and test. In addition, the tail biting section alternately could be a multiple section R-C network, which might result in a cleaner waveform.

CONCLUSION

This project has really been one of team work. We have received expert advice from many people who work in the Lab, and from the pulse power society. We would like to thank Mr. C. Eld, Mr. D. Warburton, and Mr. J. Addessi for their dedicated work in the scheduling, construction, installation and operation of the systems. The great management support from the AGS Department and the Power Supply Group head Mr. J. Sandberg, and the support from the Physics Group and Mechanical Group are deeply appreciated.

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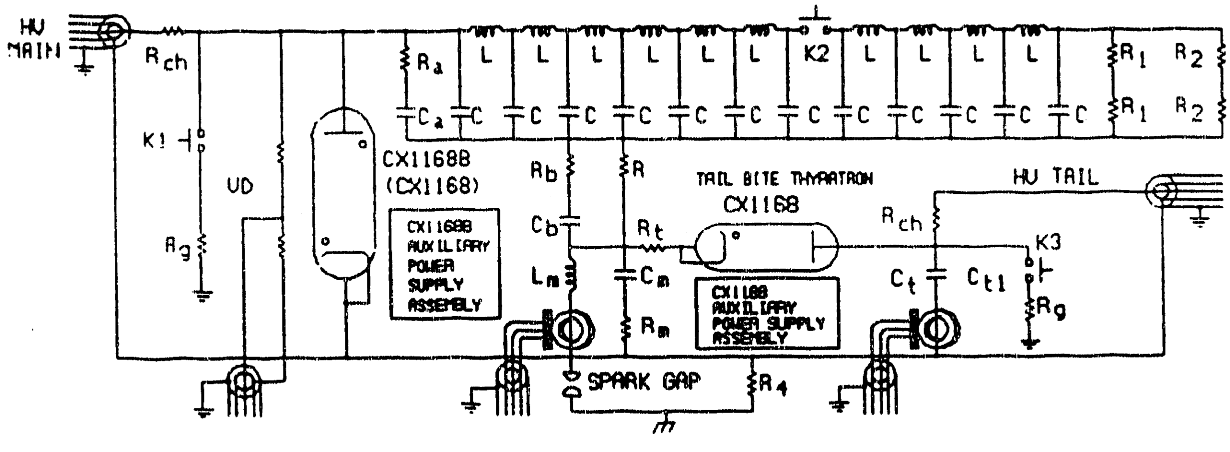

Figure 1. The main circuit diagram of the AGS injection fast kicker modulator.

DISCLAIMER

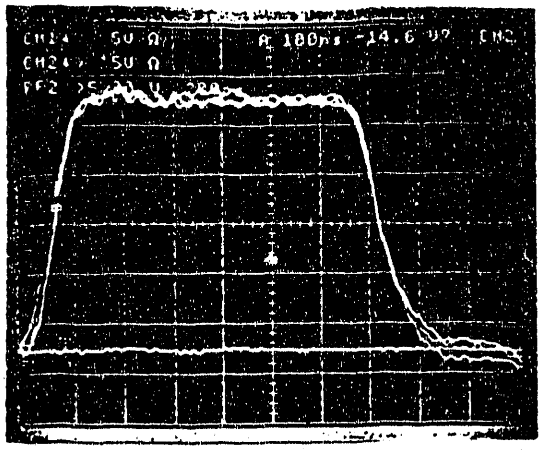

Figure 2. The current waveforms of the AGS injection fast kicker module A, B, and C.

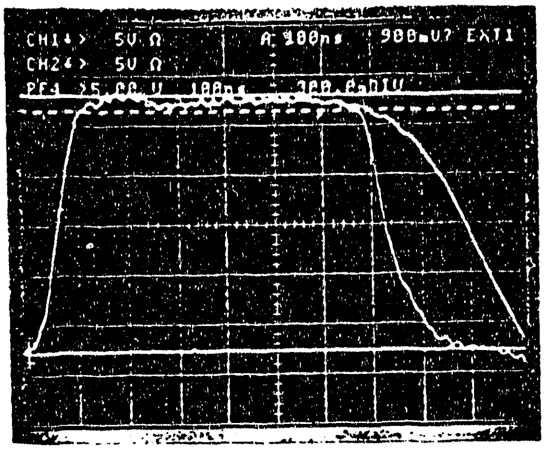

Figure 3. The typical current waveforms with or without tail bite.

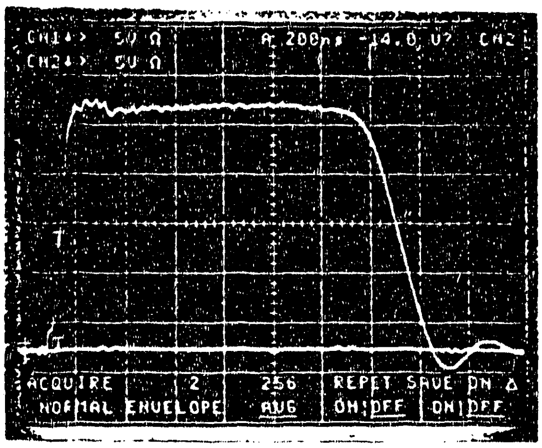

Figure 5. The magnet current waveform in heavy ion mode.

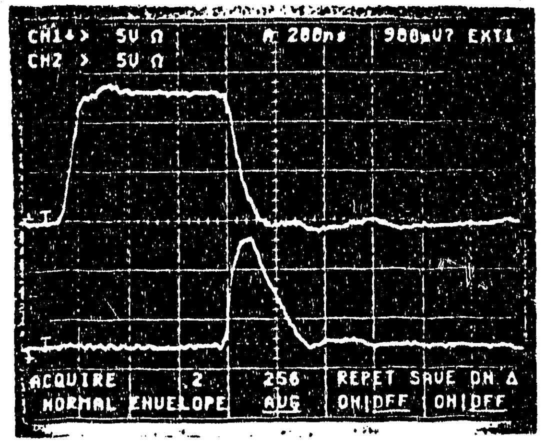

Figure 4 (a). The main current with tail bite and the tail biting current.

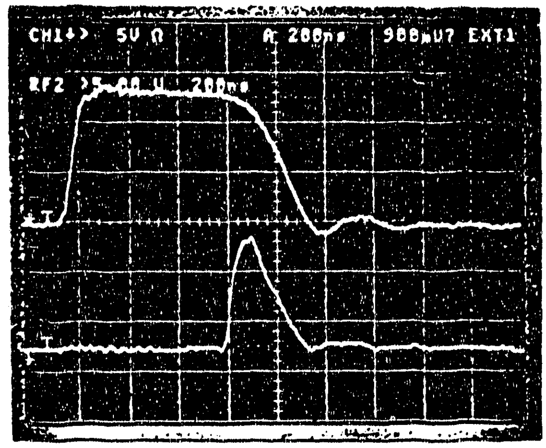

Figure 4 (b). The main current without tail bite and the relevant position and magnitude of the required tail biting current.

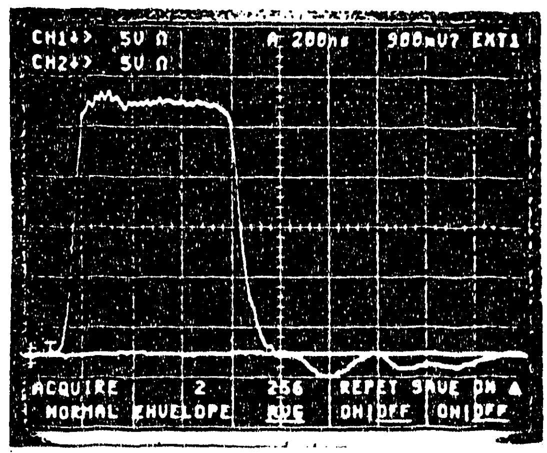

Figure 6. The current waveform obtained when using CX1168 thyratrons as both the main and tail biting switches.

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