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AN ENGINEERING SOLUTION TO THE RHIC BEAM ABORT KICKER UPGRADE*

W. Zhang[ξ], **T. Roser, J. Sandberg, Y. Tan**
Brookhaven national Laboratory
Upton, NY 11973
A. Welleman, K. Stephenson
ABB Switzerland Ltd, Semiconductors

Abstract

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the world largest superconducting accelerator for nuclear energy research. Particle beams traveling in opposite directions in two accelerator rings, Blue and Yellow, collide at six interaction regions to create phenomena of the early universe. There are more than 1700 superconducting magnets and very sophisticate and delicate large detectors inside the RHIC tunnel. With high beam intensity and ultra high beam energy, an inadvertent loss of beam can result severe damage to the superconducting magnets and detectors. Beam abort kickers are used to remove beam safely from the ring.

The large inductive load, high current capability, short beam gap, and high reliability are the challenging issues of this system design. With high intensity and high momentum beam operation, it is desirable to have all high voltage modulators located outside of RHIC tunnel. However, to generate 22 kA output current per modulator with fast rise time, a conventional low impedance PFN and matched transmission cable design can push the operation voltage easily into 100 kV range. The large quantity of high voltage pulse transmission cables required by conventional design is another difficult issue. Therefore, the existing system has all ten high voltage modulators located inside RHIC tunnel. More than a hundred plastic packaged mineral oil filled high voltage capacitors raise serious concerns of fire and smoking threats. Other issues, such as kicker misfire, device availability in the future, and inaccessibility during operation, also demand an engineering solution for the future upgrade.

In this paper, we investigate an unconventional approach to meet the technical challenges of RHIC beam abort system. The proposed design has all modulators outside of the RHIC tunnel. It will transmit output pulse through high voltage cables. The modulators will utilize solid-state switches, and operate at a maximum voltage in 30 to 50 kV range.

I. SYSTEM UPGRADE REQUIREMENT

The performance of the RHIC beam abort kicker systems has been greatly improved over the last few years. However, to continually provide superior scientific research at RHIC, all systems must meet higher safety standards of operation. A legacy issue of the RHIC beam abort kicker systems is the large quantity of mineral oil filled, plastic packaged high energy pulse capacitors used in the high voltage modulators. These capacitors are being used in close proximity of the beam pipes. Additional fire protection systems were installed above high voltage modulators, and capacitor inspections are conducted frequently.

The primary reason of this study is to look into possible technical solutions to have an upgrade of RHIC beam abort kicker high voltage modulator system with following features:

1. It will be located outside of the RHIC tunnel to reduce fire and smoke threat to RHIC magnets and experimental detectors;
2. It will offer higher stability to reduce un-commanded beam abort events;
3. It will have better serviceability and maintainability.
4. It will have predictable device availability in the future.

The basic parameter specifications are similar to the existing systems as listed in Table 1.

Table 1. Main Parameter Specification.

Magnetic Rigidity at top energy	839.5 T-m
Beam Energy Range, Au	7-100 GeV/u
Beam Energy Range, Proton	28-250 GeV
Deflection Angle	1.6 mrad
Deflection Strength	1.2 T-m
Kicker Magnetic Length	6.1 m
Horizontal Aperture	50.8 mm
Vertical Aperture	76.2 mm
Minimum Current at Top Energy	13.3 kA
Maximum Current at Top Energy	20.2 kA

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ξ email: arling@bnl.gov

Field Rise Time to Minimum Current Amplitude	900 ns
Number of magnet sections	>= 5

II. DESIGN CHALLENGES

It is always desirable to have high voltage modulators located in the service building rather than in the beam tunnel. Several factors, such as very high peak current, fast current rise time, and large inductive load, limited the design choice of the present system.

At top beam energy, the required peak output current of beam abort kicker is 20.2 kA. To generate a 20 kA pulse with conventional pulse-forming network, 200 kV will be needed for a 5 ohm matched system, and at least 100 kV for 5 ohm PFN with un-terminated load. Therefore, the original system used very low impedance PFNs to drive mismatched loads.

To deliver high current, high voltage pulse through long transmission cables would need many high voltage cables in parallel to reduce the transmission impedance. This can be very expensive and often unaffordable.

Comparing with other systems, like CERN LHC beam abort kicker, the RHIC system has a similar peak current requirement. The beam abort kicker rise time requirement of RHIC is 0.9 μs, while the CERN LHC allows 2.7 μs.

The RHIC beam abort kicker magnet has a total mechanical length of 6.1 meters in each ring. Each kicker magnet is divided into five sections, and five L-shaped high voltage modulators are attached to the front of the vacuum chamber and extended underneath beam pipes.

To provide an engineering solution to these challenging problems, an unconventional design is being proposed.

The new design is based on a capacitor discharge circuit, a short length transmission line, a resonance capacitor, and the magnetic load. The principle schematic is given in Figure 1.

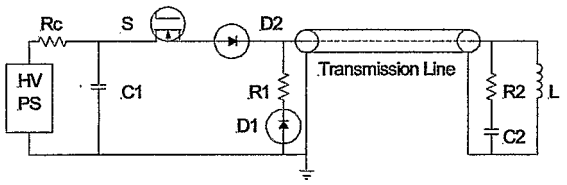

Figure 1. Principle circuit.

In this circuit, the capacitor C1 is for energy storage, and switch S is for the main discharge. Diode D1 is a freewheel diode for pulse length extension, and resistor R1 can be varied to control current amplitude ramping down to produce the required 30-40% amplitude span at the first 12.6 us of the pulse flat-top. The transmission line is shorter than the wavelength of the pulse front. It acts more like a semi-lumped circuit. The reflection caused by the short transmission line will produce a saw-tooth waveform. It can be utilized for sweeping effect on the pulse top. The resonate capacitor C2 can change the saw-tooth oscillation and speed up pulse rise time, and resistor R2 can be used to damp the saw-tooth amplitude. The saw-tooth sweeping and amplitude change are required to disperse beam on a wide area of beam absorber to preserve its material integrity.

Key issues that require investigation for the new design include the transmission line length vs. pulse rise time, the transmission line impedance vs. pulse rise time, the transmission line impedance vs. charge voltage, the resonance effect, and the switching delay effect.

III. DESIGN SIMULATION

The present RHIC beam abort kicker magnets have five sections each. The load inductance is 1.1μH per magnet section, plus 0.5 μH stray inductance of coil, vacuum feed-through and external circuit loop. Therefore, we assume an inductive load of 1.6μH, and insert an additional stray inductance of 200 nH at power supply side. The main switch has a 200 ns turn on delay to allow initial current build up inside semiconductor switch. The transmission line has 5 ohm impedance and 300 ns one-way transmission time. Depending on the transmission cable characteristic, this is equivalent to 180 feet of cable with 1.67 ns per foot of transmission speed, or 154 feet of cable with 1.95ns per foot. Other parameters are as listed in Figure 2.

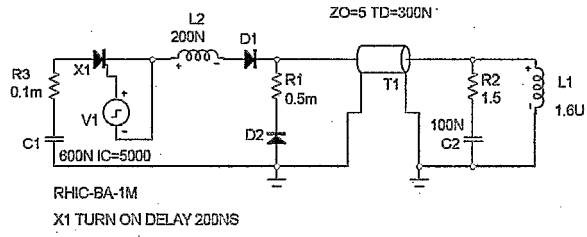

Figure 2. Design Example 1.

A scale-down simulation of one tenth voltage and current amplitude was performed, as given in Figure 3. The simulation result of this circuit, shown that the load magnet current rise time from 2% to the required minimum current amplitude at top energy is about 678 ns, much faster than 900 ns specification.

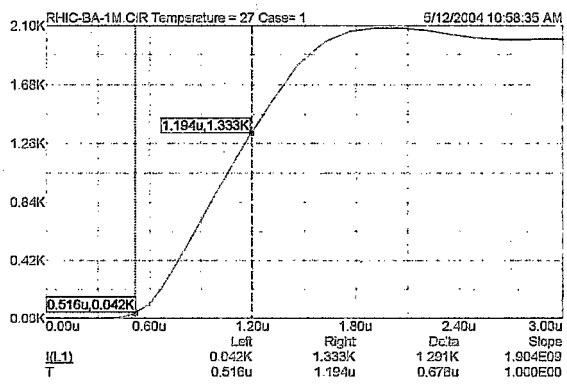

Figure 3. Load magnet current rise time from 2% to the required minimum amplitude at top beam energy.

The Figure 4 is the simulation result of design example 1 with 5 kV initial capacitor charging voltage and near 2.1 kA peak load current.

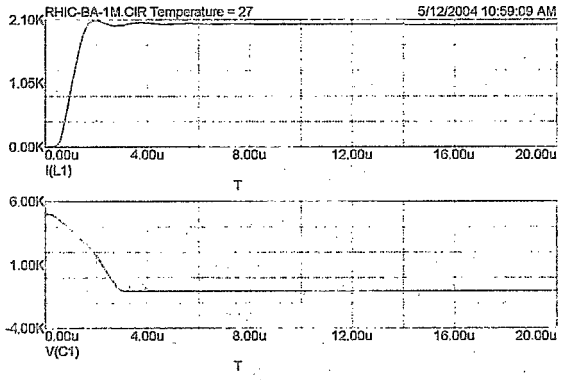

Figure 4. Load current waveform and storage capacitor voltage waveform of design example 1.

In Figure 5, the effect of resistor R1 on load current decay rate is shown. The Load current oscillation damping by the resistor R2 is illustrated in Figure 6. The waveforms in figure 7 are the effect of capacitor C2 on load current oscillation amplitude and frequency.

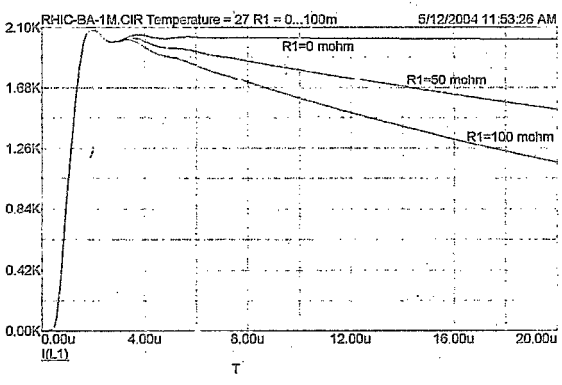

Figure 5. Load current decay vs. R1.

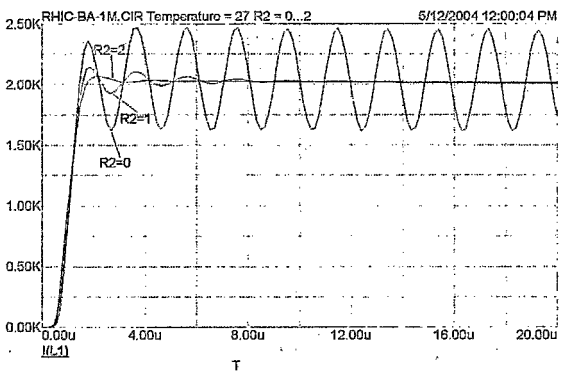

Figure 6. Load current oscillation damping vs. R2.

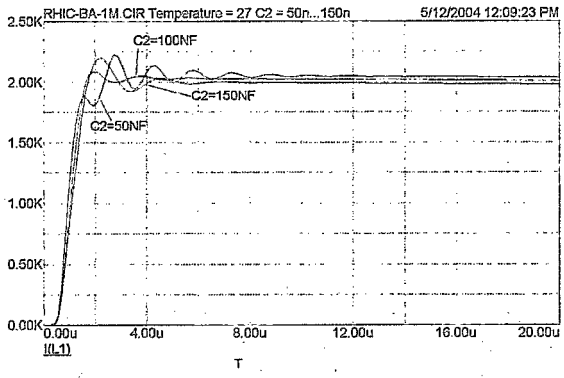

Figure 7. Load current oscillation vs. C2.

In Figure 8, we see that the transmission line length affects the load current rise time, flatness, and amplitude. The impedance of the transmission line also affects the load current rise time, flatness and amplitude, which are shown in Figure 9.

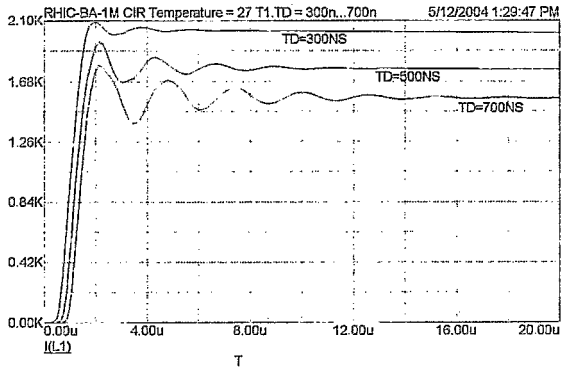

Figure 8. Load current waveform vs. transmission line delay.

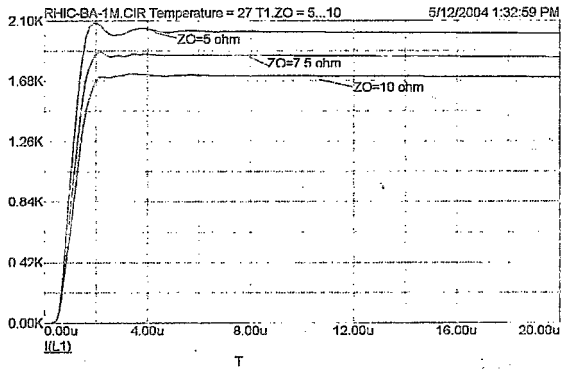

Figure 9. Load current vs. transmission line impedance.

From above results, we see there is a wide range of parameters can be used to achieve our design goal. The following two design examples, shown in Figure 10 and Figure 12, are demonstrations of possible parameters.

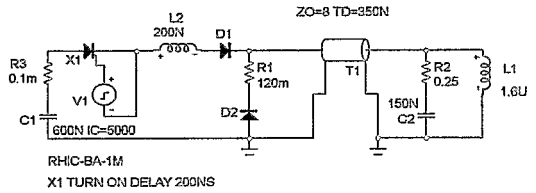

Figure 10. Design example 2.

The simulation of design example 2 is given in Figure 11. The load current rise time is about 890 ns, and the peak load amplitude is about 2.1 kA with 5 kV initial charging voltage. The load inductance used in this example is 1.6 μH. Note that the transmission line impedance used here is 8 ohm, much larger than the charging voltage over peak load current ratio. Also, the equivalent transmission line length of 350 ns one-way delay is 180 feet with 1.95 ns/ft.

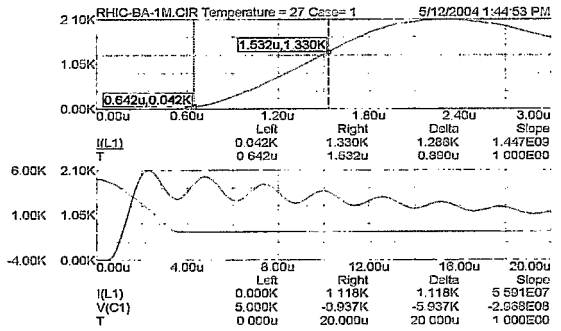

Figure 11. Upper - Load current rise time; Lower – Load current waveform and storage capacitor voltage waveform of design example 2.

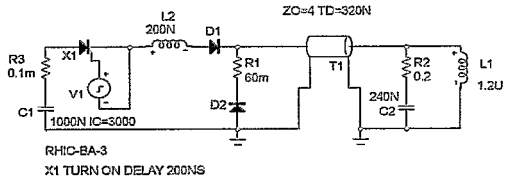

Figure 12. Design example 3.

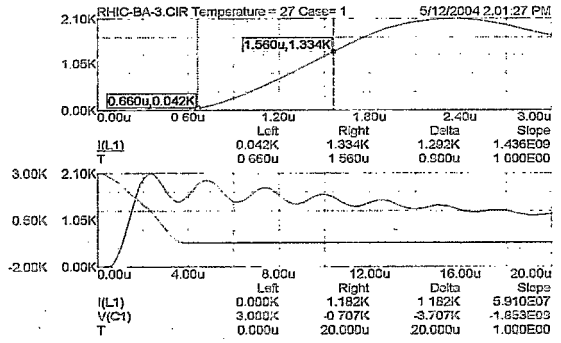

Figure 13. Upper - Load current rise time; Lower – Load current waveform and storage capacitor voltage waveform of design example 3.

The design example 3 is assuming a smaller load inductance of 1.2 μH. In this case, a 30 kV initial charging voltage corresponds to 21 kA load current. As shown in Figure 13, the rise time of the load current is about 900 ns. The lower initial charging voltage used here can ease the transient voltage on the transmission cable, vacuum feed-through, magnet, and other high voltage components.

IV. SUMMARY

The critical components used in the proposed design upgrade include the high-energy pulse capacitors, the main discharge switch, fast diode, and transmission lines.

Since the modulators will be away from the beam tunnel, the solid-state switch can be used. The ABB Pulsed Power Semiconductor ASPY-20H45-20-CC-PP discharge switch assembly is proposed for this application. It offers a 90 kV blocking voltage, 50 kV maximum charge voltage, a 22 kA peak current, and a 30 kA/μs current slew rate. The current waveform, with 200 ns switch turn on delay used in the design examples, can be matched by the ABB switch.

The tri-axial high voltage cable DS2241 of Dielectric Sciences can be used for transmission line. It is rated for 75 kV DC application, and has a characteristic impedance of 16 ohm, and 1.95 ns/ft propagation time. Two to four cables in parallel will give the required impedance. Since RHIC is a storage ring, its radiation level is much lower than AGS. Hence, the survivability of flexible high voltage cables is higher.

In this new design, the energy storage is much lower. The storage capacitors used in design examples are 1 μF or less, much smaller than the 8.55 μF used in existing modulator [1]. At the operating voltage of 30 kV, the energy storage in design example 3 is only 11.7% of the existing modulator.

This new design is significantly different than the one given in reference [2] by allowing much higher transmission line impedance and much longer transmission line length, and moderate charging voltage for the large load current.

A simulation of inserting transmission cables in between load and the existing modulator has been performed. The result is very encouraging. Engineering test will be performed when the resource is available. This can be the first step toward the future upgrade.

V. REFERENCES

[1] H. Hahn, et. al., "The RHIC Beam Abort kicker System," Proceedings of the 1999 Particle Accelerator Conference, pp. 1100-1102, 1999.

[2] E. Vossenberg, et. al., "Dual Branch High Voltage Pulse Generator for The Beam Extraction of The Large Hardon Collider," Conference Record of the Twenty-Fifth International Power Modulator Symposium, pp. 114-117, 2002.

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