Analysis of the Electrical Noise from the APS Kicker Magnet Power Supplies*

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Abstract

The APS kicker magnet power supplies deliver damped sinusoidal currents in excess of 2400A peak with a half-period of 300ns to the kicker magnets. Conducted and radiated electromagnetic interference (EMI) is created by this system in the low megahertz range. This interference affects a number of beam diagnostics in the APS injector. The sources and coupling mechanisms for the EMI generated by this system are described and solutions discussed.

I. INTRODUCTION

Systems producing high amplitude current pulses with fast risetimes generate significant levels of electromagnetic interference (EMI) [1]. These high levels mean that special care must be taken with the implementation and installation of the noise-producing system itself, and with ‘hardening’ of equipment operating in its vicinity.

Conducted EMI can be a problem because of the high current levels, thus special care must be taken to control the current paths and to prevent current flow into other parts of the facility. Radiated EMI is typically low impedance (i.e. magnetic), and can be difficult to shield, especially close to the source where fields are highest.

The kicker power supplies in the APS deliver fast high-current pulses to magnets which deflect a positron beam during its injection to, or extraction from, the APS rings. They operate in an environment where beam diagnostics are required to detect low-level analog signals, and interlock systems protect against events such as arcing in the rf cavities. The levels of EMI generated by the kicker magnets have limited the usability of some of these diagnostics.

Most kicker noise investigation work in the APS has been carried out on kickers in the positron accumulator ring (PAR) [2]. These operate at a repetition rate of 60Hz, have voltages on their pulse-forming networks (PFNs), and produce larger current pulses than the other APS kickers, therefore offering the worst case.

Measurements have been made of both conducted and radiated EMI, and while most of these were done at a PFN voltage of 5kV rather than the nominal level of 25kV, insight has been obtained into the EMI sources and their coupling mechanisms. Data was processed using the Self-Describing Data Sets (SDDS) toolkit [3].

II. KICKER OPERATION

The PAR kicker power supplies are designed to deliver a nominal 2400A peak, half-sinusoidal current with a rise time of ~160nS to the kicker magnets [4]. A simplified schematic of the power supply is shown in Figure 1.

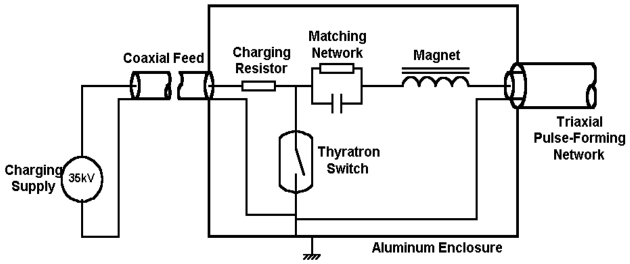

Figure 1: Simplified Schematic of PAR Kicker Power Supply

Prior to a current pulse, the open-ended PFN is charged to a nominal 25kV. When a current pulse is required, the thyratron switch is triggered, causing energy stored in the PFN to discharge through the magnet winding. The pulse duration is determined by the time constant of the PFN which forms a quarter-wave transmission line.

Physically, the PAR kicker system is comprised of three separate chassis: the magnet and PFN; the thyratron switch assembly; and the high voltage charging supply/control chassis. The magnet and thyratron assembly sit close together in the PAR enclosure, however the charging supply/control unit is located outside the PAR radiation shield and is connected to the thyratron assembly by several meters of cable. This arrangement differs from the other APS kickers where both the charging supply/control unit and thyratron assembly are located outside the radiation shield in the same cubicle.

The grounded aluminum enclosures for the magnet and thyratron assembly provide protection from high voltage hazards, are intended to provide some shielding against radiated EMI, and act as a ground plane for the system. The outer shield of the PFN and the shield of the high-voltage feed are connected to these enclosures.

A typical magnet current pulse is shown in Figure 2.

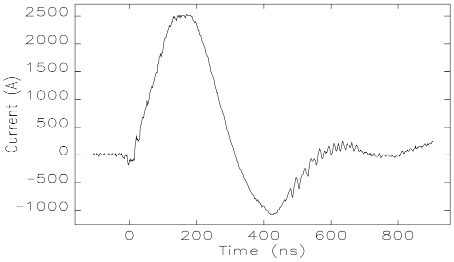

Figure 2: Kicker Magnet Current Pulse at 25kV

III. EMI CONSIDERATIONS

Figure 1 shows a near ideal situation where all components are contained within a Faraday enclosure. However, the concept is compromised in several ways (see Figure 3).

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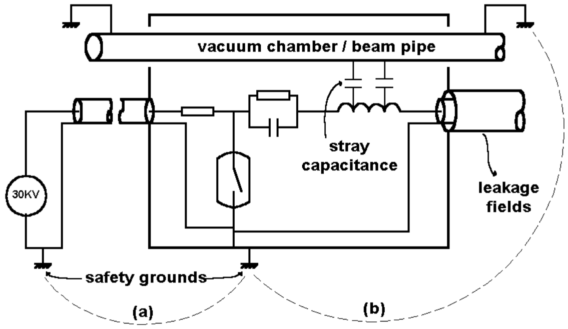

Figure 3: Modified Power Supply Schematic

First, since the high voltage supply is located some distance from the remainder of the system, it requires a local safety ground. This creates an additional return path (‘ground loop’) for the charging supply current since all of the local grounds are part of the overall facility ground system.

Second, while the magnet winding is completely contained within the enclosure, the vacuum chamber which it surrounds must pass through the enclosure. Since there is capacitive coupling between the magnet winding and the vacuum chamber, current can flow from the magnet to the vacuum chamber and hence to the outside world (forming another ‘ground loop’).

Third, the Faraday shield is not perfect, and possibilities exist for radiated fields to leak through the enclosure boundaries and through cable shields.

In many situations, the above-described weaknesses may be of little consequence. However, they contribute significantly to the EMI generated by the APS kickers because of the magnitude of the currents involved.

IV. CONDUCTED INTERFERENCE

Conducted EMI is a direct consequence of there being current loops outside of the kicker enclosures. The existence of loops (a) and (b), shown in Figure 3, means that part of the magnet current pulse flows through the facility ground system and hence through any equipment connected to it.

The magnitude of the current flowing in any given loop depends on its impedance relative to that of the primary current path. The fact that surprisingly large currents have been measured in apparently unrelated cables clearly means that the loop impedance is not high enough (based on the nominal magnet current, even a path isolated by 100dB from the main circuit would see a 12mA current pulse).

The conducted EMI problem is widespread because of the mesh of parallel paths formed by the mass of “ground” cables and busbars. Any equipment connected into the ground system experiences voltage and/or current transients (depending on how it is configured relative to the ground system). The closer the equipment is (electrically) to the kicker system, the larger the transient it will experience.

The net current in the charging supply cable is effectively the total current flowing through loop (a) (if the supply and return currents are equal, there is no net current flow). The measured current is shown in Figure 4. As expected, the dominant frequency is the same as that of the current pulse.

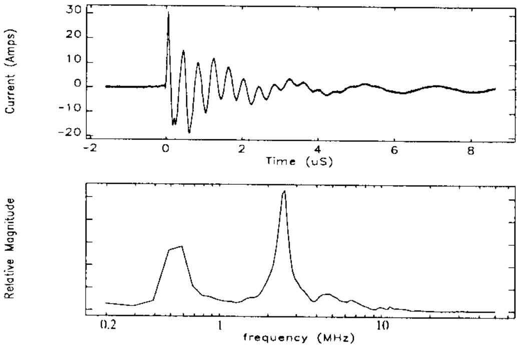

Figure 4: Current on the Charging Cable at 5kV

This current has been traced through various cables connected to the charging supply/control unit. Significant currents have been measured on the 480V power feed, the charging supply safety ground, and on cables to the APS control system.

Current flowing in loop (b) is believed to be the most disruptive to the beam diagnostics which connect directly to the vacuum chamber. It is difficult to measure the bulk current flowing in this loop, since the physical layout of the kicker system and the large number of ground connections to the vacuum chamber make it impossible to select a single conductor which carries all of the loop current.

In order for loop (b) to exist there must be capacitive coupling between the magnet winding and the vacuum chamber. The measured capacitance is 50-100pF, which offers an impedance of around 1kΩ to the main current flow. The main circuit impedance is 16Ω which means that if this capacitance were to dominant the loop impedance, more than 1% of the current pulse could be coupled through the vacuum chamber.

Measurements were made during checkout of a synchrotron kicker in order to look at this coupling path using a dummy beam pipe. Figure 5 shows the current measured in the ground connection of the dummy beam pipe at a PFN voltage of 15kV. While a direct comparison cannot be made with the installed PAR kicker, the fact that such a large current was measured demonstrates the significance of this coupling path.

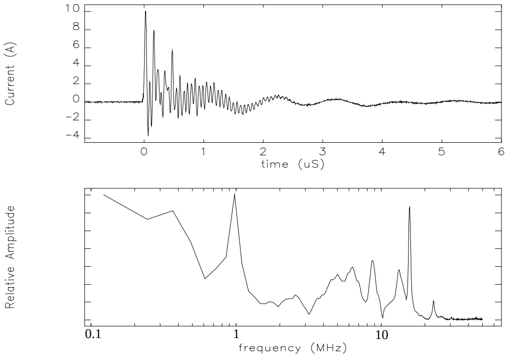

Figure 5: Beam-Pipe Current in Test Configuration

V. RADIATED INTERFERENCE

The single most significant source of radiated EMI has been found to be the PFN cables. This was not entirely surprising given the magnitude of the currents they carry, their length (12 meters), and the fact that braided shields were chosen to give some flexibility to the bulky cables. A triaxial cable was chosen for the APS kicker systems in order to provide additional shielding over a coaxial design.

Since the PFN shields are only grounded at one end, at a distance the cable would appear as if it were a simple E-field antenna. However, in the case of the kicker system, the near-field situation is of greater interest because of the close proximity of other equipment. In this case, the PFN cables appear to be a long wire and they behave like a magnetic source. The leakage field through the shield gives the impression of a net current flow along the cable. Measurements at 5kV, using a close-field probe, indicated leakage fields equivalent to a 1-2A current flow (~0.5% of the total current). Assuming a simple long wire model, this would produce a magnetic field of 50-100mA/m [5] which agrees well with measured radiated magnetic fields under the same conditions (shown in Figure 6).

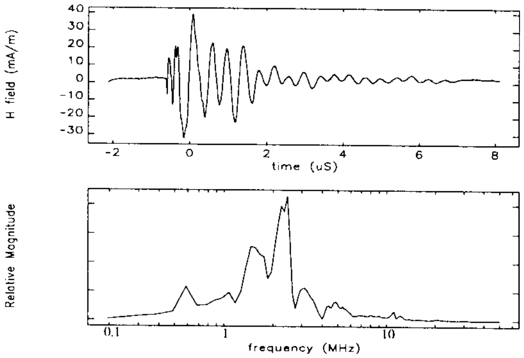

Figure 6: Magnetic Field, 3 meters from Source at 5kV

Similar measurements of the radiated electric field were also made. By taking the ratio of the E and H fields, the source impedance was determined to be around 12Ω indicating a strongly magnetic source.

VI. SOLUTIONS

Initially, EMI levels were high enough that the kicker supply itself would trip on noise well below its nominal operating level, and signals on the PAR beam current monitor were large enough to trip the safety interlock.

The current flowing around loop (a) in Figure 3 was reduced by installing EMI filters on the cables connecting the thyratron assembly and the charging unit. These increased the relative impedance of the loop and reduced the amplitude of the current by around 20dB. This alone was sufficient to allow the kicker systems to operate without tripping on noise.

The most promising approach to reducing the current in loop (b) is considered to be the addition of an electrostatic shield around the magnet winding. Tests have been carried out on a mock-up which indicate that reductions of 20dB or more could be achieved in the coupling to the beam pipe. However, care is needed in providing a very low impedance path from the shield back to the energy source, since the degree of coupling can be increased by a wrong connection.

In order to reduce the radiated fields, additional shielding is required around the PFN cables. Since the radiated fields are magnetic and the shield material would be installed close to the field source, a material with good absorption loss is required. Thick-walled steel conduit is ideal for this type of application. In theory, a 2mm thickness of steel provides in excess of 200dB absorption loss at 2MHz, and the material is readily available. A low cost improvement in the radiated fields was obtained by wrapping the PFN cables in aluminum baking foil. The measured attenuation was 3dB, consistent with the theoretical absorption loss for 1mil of soft aluminum at 2MHz.

VII. SUSCEPTIBILITY

In parallel with the investigations of the EMI source, attempts have been made to reduce the susceptibility of diagnostics affected by the noise. Clearly any improvement in their susceptibility will complement reductions in the magnitude of the EMI sources.

An example is the PAR beam current monitor which consists of a current toroid encircling the PAR vacuum chamber. Considerable attention had been given to protecting the current monitor against radiated EMI, the sensor being housed in a multi-layer electromagnetic shield which is bonded to the vacuum chamber. Nevertheless, unacceptably large pulses appeared on the current monitor signal every time a kicker fired. Originally the toroid was electrically floating inside its electromagnetic shield with the low-level signal being transmitted over a coaxial cable. By bonding the shield of the coaxial cable to the electromagnetic shield of the toroid, the noise coupled to the current monitor was reduced by 20dB. Kicker currents flowing in the ground system develop voltages between different locations all deemed to be at ground potential. By bonding the toroid and its shield, the voltage between them is reduced. This effect is believed to be the cause of the improvement in the noise on the current monitor.

The fact that these mechanisms are not fully understood illustrates the difficulties in predicting EMI effects and emphasizes the need for experimentation.

VIII. REFERENCES

[1] J. Carwardine, G. Pile, T. Zinnerman, "Management of High Current Transients in the CWDD Injector 200kV Power System," *Proceedings of the 1993 IEEE Particle Accelerator Conference,* p. 3210, 1993.

[2] M. Borland,"Commissioning of the Argonne Positron Accumulator Ring," these proceedings.

[3] M. Borland, "A Self-Describing File Protocol for Simulation Integration and Shared Postprocessors," these proceedings.

[4] J. Wang, "Design and Test Results of Kicker Units for the Positron Accumulator Ring at APS," these proceedings.

[5] D. White and M. Mardiguian, "EMI Control Methodology and Procedures," (Interference Control Technologies Inc.,1989).