Design and Simulation of Fast Pulsed Kicker/Bumper Units for the Positron Accumulator Ring at APS*

Ju Wang and Gerald J. Volk
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

Abstract

In the design of fast pulsed kicker/bumper units for a positron accumulator ring (PAR) at APS, different pulse forming networks (PFN) are considered and different structures for the magnet are studied and simulated. This paper describes some design considerations and computer simulation results of different designs.

I. INTRODUCTION

Three fast pulsed kicker/bumper magnets are required in PAR for the beam injection and/or extraction at 450 MeV. These magnets have the same design because they have identical specifications and are expected to produce identical magnetic fields. Each kicker/bumper magnet is required to generate a magnetic field of 0.06 T with a rise-time of 80 ns, a flat-top of 80 ns and a fall-time of 80 ns.

A fast pulsed magnet system normally consists of a high voltage dc power supply, charging/discharging switches, a PFN, and a magnet assembly consisting of a ferrite magnet, a matching capacitor or capacitors and a load (termination) resistor. The primary objective of this study is the design of the PFN and magnet assembly.

II. PULSE FORMING NETWORK

There are various configurations for pulse forming networks [1]. The simplest one is to use coaxial cables (transmission lines) as the PFN. For this kind of PFN, the duration of the pulse waveform is equal to twice the cable length divided by the propagation velocity of the cable. It is usually used for pulses with durations under 100 ns.

The second way is to use equal inductors and capacitors to construct PFNs. This type of PFN is actually a lumped equivalent to coaxial cables and, hence, behaves similarly to coaxial cables. They are normally used to generate pulses with durations over several hundred nanoseconds.

Another type of PFN is called a type-C Guillemin network. For a type-C Guillemin network, Fourier analysis is used to calculate the frequency components of the desired waveform. Then multiple L-C branches are connected in parallel with each L-C branch generating one frequency component. The number of the L-C branches depends on the requirement of the waveform. There are other types of Guillemin networks. Some of them are different variations of the type-C network.

Among many types of PFNs, the best candidates for the PAR kicker/bumper are coaxial cables and the equal L-C network. In the design, a combination of coaxial cables and an equal L-C network with damping resistors is used. The cable section of the PFN consists of two 12 meter paralleled cables. The cable impedance is approximately 13 Ω, the inductance is 101.7 nH/m and the capacitance is 377.3 pF/m. The propagation velocity of the cable is 0.161 m/ns. The equal L-C section of the PFN is made of the magnet and the matching capacitors. Since a capacitor or capacitors have to be added to the magnet to match the cable impedance in order to minimize the reflections between the cables and the magnet, it will be advantageous if the magnet can contribute to the pulse forming network. With the capacitors matching the above cables, the magnet is equivalent to two 4.15 meter paralleled cables. It takes 25.7 ns for the current and voltage to pass through the magnet.

III. MAGNET

A window-frame magnet has been proposed in the design. This magnet is 35 cm long and has an air gap of 11 cm by 5.3 cm. The air gap size is determined by the sizes of the vacuum chamber and copper conductors with the insulations. The cross section of the magnet is shown in Figure 1.

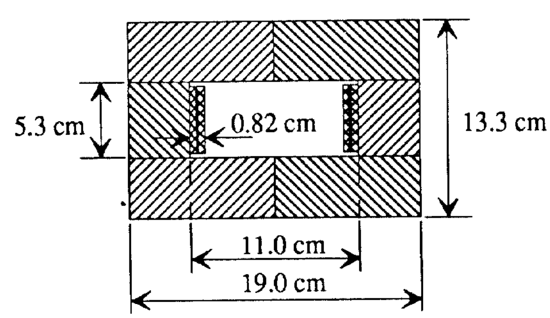

Figure 1. Cross section of the PAR kicker/bumper magnet

Assuming that the magnetic field inside the air gap is uniform and the magnetic field intensity inside the ferrites is negligible compared with that in the air gap, the flux density, **B**, in the air gap can be calculated as

* Work supported by U.S. Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38.

$$\mathbf{B} = \frac{\mu_0 I}{g} \qquad (1)$$

where I is the current in the coil and g is the air gap length. Equation (1) can be solved for I when $\mathbf{B}$ is given. For the magnet in Figure 1, to generate a magnetic field of 0.06 T, the required current will be 2530.56 A.

The inductance of the coil can be calculated as

$$L = \frac{\mu_0 w l}{g} \qquad (2)$$

where w is the air gap width, the distance between the centers of two conductors, and l is the magnet length if the end effect is ignored. For the given geometry, the magnet inductance, L, is equal to 844.8 nH.

Since the rise-time of the current, hence the rise-time of the magnetic field, mostly depends on the magnitude of the inductance, the inductance of the magnet needs to be as small as possible. The total inductance is fixed for the given geometry of the magnet. The only way to reduce the inductance is to divide the single-turn coil into two half-turn coils. In doing so, the inductance seen by the cables is reduced to one half. However, the number of required cables is increased by a factor of two.

The magnet will be constructed with ferrite CMD5005, by Ceramic Magnetics, Inc. The thickness of the ferrite blocks is selected as 4 cm. This results in a magnetic field of about 764 Gauss inside the ferrites, below its saturation field. Thin copper films will be inserted into the top and the bottom ferrites to completely decouple two half-turn coils.

IV. IMPEDANCE MATCH OF THE MAGNET AND THE COAXIAL CABLES

To match the magnet with the cables, the ideal way is to build the magnet with a coaxial structure. However, the size of the required aperture for the beam is relatively large and the cable impedance is relatively small, so it is very difficult to build a coaxial magnet that has a large air gap and a small impedance. Therefore a window-frame magnet is chosen and a lumped capacitor or capacitors will be added to the magnet to match the cable impedance. Since the magnet is a lumped element, to better match the cables the magnet can be divided longitudinally into several sections with multiple capacitors. Ideally, the more sections the magnet is divided into, the better it matches the cables. However, the number of sections cannot be very large due to the limitation of the physical sizes of the magnet and the capacitors. In this design, the magnet is divided into 4 sections.

Now that the magnet is divided by the capacitors, it can be part of the pulse forming network and is precharged to the PFN voltage. When the discharge switch (thyratron) is closed, the current will travel through the magnet back to the input of the PFN. The minimum rise-time of the current in the termination resistor is approximately equal to

$$T_{r,term} = \frac{\pi\sqrt{L_{1/2}C}}{8} \qquad (3)$$

where $L_{1/2}$ is the half-turn magnet inductance and C is the total capacitance of the capacitors added to one half of the magnet. With the given cable and magnet parameters, a total capacitance of 6.26 nF will be required. Each capacitor is 1.56 nF and each section of the magnet is 105.6 nH.

Substituting $L_{1/2}$ and C into equation (3) gives the minimum rise-time of the current in the termination resistor as 20.2 ns. The minimum rise-time of the magnetic field of the whole magnet will be the sum of $T_{r,term}$ and the time required for the current to pass through the magnet, and will be 45.9 ns.

Even if the magnet is divided into multiple sections, it still cannot match the cables perfectly. There exist voltage and current oscillations between the capacitors and the magnet, which destroy the flat-top of the magnetic field. Hence, resistors need to be added to the capacitors to damp the oscillations. But, the damping resistors slow down the rise-time of the current, especially when the circuit is critically damped. Because the damping resistors are unavoidable, a compromise has to be made between the rise-time and the flat-top. According to the computer simulations, the best result is obtained when the circuit is slightly under damped and the corresponding resistance of the damping resistors is 6.5 Ω.

V. COMPUTER SIMULATION OF THE CIRCUIT

A basic circuit diagram of the kicker/bumper unit is shown in Figure 2. This circuit has been simulated with PSpice program, by MicroSim Corporation, Irvine, CA.

In the simulation two different cases were considered for the cables. One assumed that the cables were lossless. The other took into consideration the copper losses of the cables. In the case of the copper losses, the skin effect was taken into account by using equation (4) to estimate the resistance [2].

$$r = 8.3(f)^{1/2}\left(\frac{1}{d}+\frac{1}{D}\right) \quad \mu\Omega/\mathrm{m} \qquad (4)$$

In equation (4), f is the frequency, d and D are the cable diameters in centimeters at the inner conductor and the outer conductor, respectively. According to the required pulse width, f is approximately 4 MHz. Diameters d and D are 3.64 and 2.25 cm, respectively. The estimated cable resistance is 0.0119Ω/m, about five times the dc resistance.

The simulations show no significant effect on the rise-time and the flat-top due to the copper losses. Only the PFN voltage needs to be slightly higher when the copper losses are considered. The losses in the dielectrics could not be included in the simulation because no data are available.

The thyratron is represented by a 100V dc voltage source and a 20 nH inductor (suggested by the manufacturer). This may have over simplified the turn-on process of the

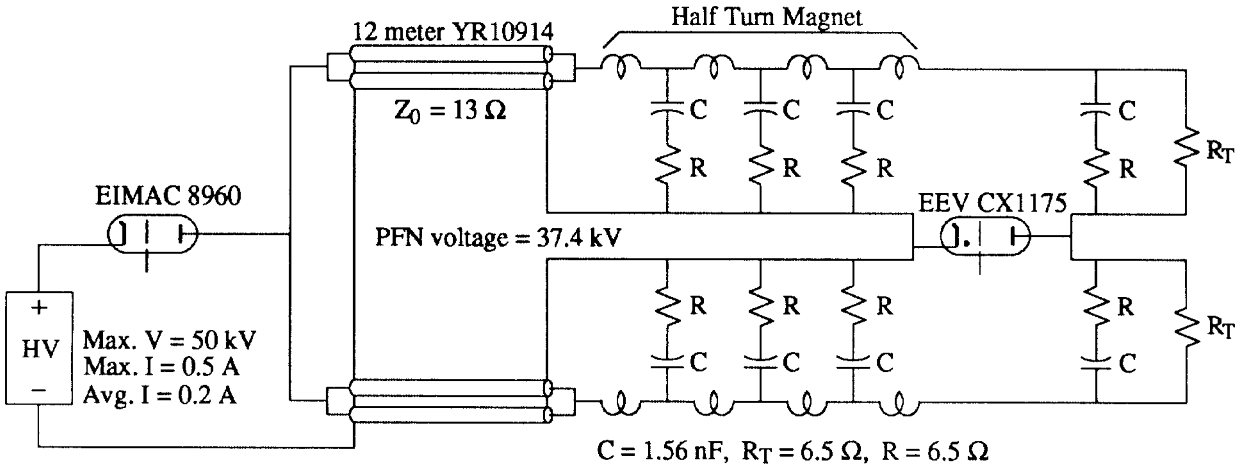

Figure 2. Circuit diagram of the kicker/bumper unit for PAR

thyratron. In reality, the turn-on process may take a longer time than that due to a 20-nH inductor. If a longer turn-on process does happen, a saturable magnet can be added to the anode (or cathode) of the thyratron. This technique can significantly reduce the turn-on time. Furthermore, it may also extend the life time of the thyratron [3,4].

The simulations were also done for the circuit with only one matching capacitor for each half-turn magnet, and the circuit with the magnet divided by multiple capacitors but no damping resistors. The results show that the circuit shown in Figure 2 produces the best current waveform.

Figures 3 through 6 show some simulation results.

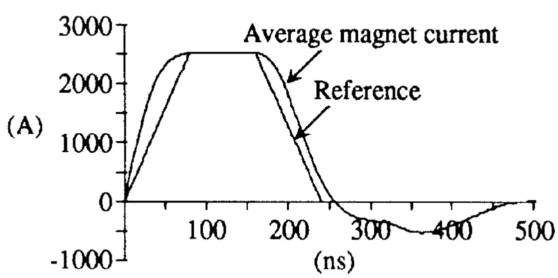

Figure 3. Simulation result for the circuit in Figure 2.

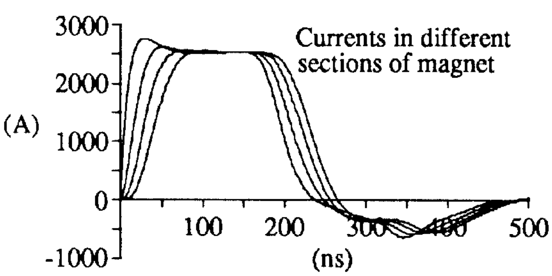

Figure 4. Simulation result for the circuit in Figure 2.

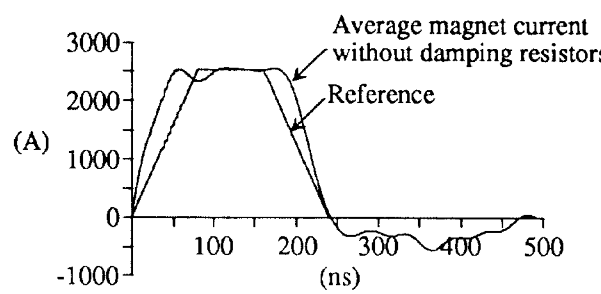

Figure 5. Average magnet current for magnet without damping resistors.

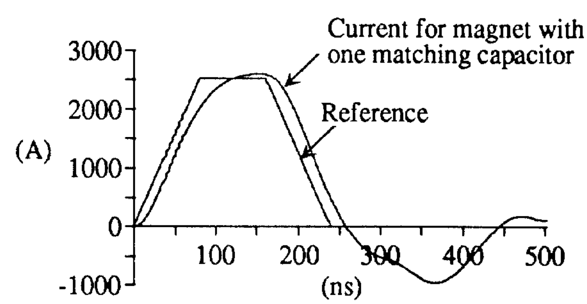

Figure 6. Currents for one half-turn magnet with only one matching capacitor.

VI. References

[1] Sarjeant, James W. and Dollinger, R. E., "*High-Power Electronics*," TAB BOOKS Inc., 1989.

[2] Giacoletto, L. J., "*Electronics Designers' Handbook*," Second Edition, McGraw-Hill Book Company.

[3] Ducimetière, L. and Fiander, D. C., "Commutation Losses of a Multigap High Voltage Thyratron," *19th Power Modulator Symposium*, San Diego, CA, June 26-28, 1990.

[4] Rust, Ken and McDuff, Glen, "Life Extension of Thyratrons in Short Pulse Circuits with the Use of Saturable Magnetic Sharpeners," *19th Power Modulator Symposium*, San Diego, CA, June 26-28, 1990.