# Design and Test Results of Kicker Units for the Positron Accumulator Ring at the APS*

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*Abstract*

Three fast kicker units have been designed, tested, and installed in the positron accumulator ring (PAR) at the Advanced Photon Source (APS) for beam injection and extraction. The performance of these kicker units has been satisfactory. This paper presents the design and test results.

## I. INTRODUCTION

Three fast kicker units are required in the PAR at the APS. Two of them, named P1K and P2K, are used for both beam injection and extraction with injection as the main function. A third unit, named P4EK, is required for beam extraction only. Based on the ring size and the beam length, the time specifications for the kicker's magnetic field are listed in Table 1.

Table 1. Kicker Specification

| | | |
|---|---|---|
| Rise time | 0 to 100%<br>20% to 100% | < 190 ns<br>< 100 ns |
| Fall time | 94% to 50% | < 70 ns |
| Flat top | 3% flatness | > 35 ns |
| Ringing | % of peak | < 30% |

The required kicker field strengths are 283 Gauss for injection and 435 Gauss for extraction.

In the original design, three kickers had identical circuit configurations in order to reduce the amount of design work and the number of spare parts. However, during initial test it was found that it was the best to tune the kickers differently based upon their main function, i.e., beam injection or beam extraction, to meet the different requirements.

## II. KICKER CIRCUIT

*Kicker Magnet*

The kicker magnet has a window-frame structure with an 11 cm by 5.3 cm aperture to accommodate the coil and the vacuum chamber. The magnet is 35 cm long and constructed with ferrite CMD5005 by Ceramic Magnetics, Inc. The magnetic field inside the ferrites is kept well below the saturation point even under maximum current. The total inductance of the magnet, not including the inductance due to the connections, is about 844.8 nH. This inductance is too high for the fast rise-time and fall-time requirements. In order to reduce the inductance, the magnet is divided into two half-turn magnets, each having a separate pulse forming network (PFN). The magnet is also divided longitudinally into multiple sections to make it a distributed magnet.

*Pulse Forming Network*

The pulse forming network consists of two parts. Part one is made of AA7949 triaxial cables by Times Microwave Systems, Inc. Each cable is made 12 meters long and then trimmed to the proper length during the test to give the desired rise time. The nominal characteristic impedance of the cables is 16.4 Ω, calculated from the nominal inductance and capacitance per unit length. However, the manufacturer specifies it as a 13-Ω cable. The test shows that its impedance is around 15 Ω. In the computer simulation 16.4 Ω is used. The propagation velocity of the cable is 0.16 m/ns. For each half-turn magnet, there are two cables connected in parallel to form an 8.2-Ω PFN.

Part two of the PFN is the magnet itself. Since each half-turn magnet has an inductance of 422.4 nH, it would have a time constant of 55.3 ns if terminated with an 8-Ω resistor. This time constant would be too large for the required rise times, especially for the rise time between 20% and 100%. To reduce the effect of the magnet inductance on the field rise time it was decided to make the magnet a distributed magnet instead of a lumped one. Each half-turn magnet is divided into multiple sections by lumped capacitors. Apparently, the more sections the magnet is divided into, the closer it is to a true transmission line. However, because of the limit of the physical size of the capacitors, the number of sections cannot be too big. In reality it has to be a compromise between the time requirement and the sizes of the magnet and the capacitors.

With a distributed magnet, the rise time of the field in the magnet gap is determined by the sum of the time that is required for the current in the load resistors to reach the peak and the time that is required for the current wave to travel through the magnet. The rise time of the current depends on the overall inductance in the connections between the magnet and the resistor load, in the resistor load assembly, and in the thyratron assembly. The speed at which the field wave travels through the magnet is given by

$$v = 1/\sqrt{L_0 C_0}$$

where $L_0$ and $C_0$ are the inductance and the capacitance of

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each section. Then for a magnet that has N sections the traveling time through the magnet is $T = N / v = N\sqrt{L_0 C_0}$.

In the design $C_0$ is chosen first because not many capacitors are available for this type of applications. The TDK UHV-12A high-voltage ceramic capacitor was chosen for its high voltage rating and relatively small physical size. It has a nominal capacitance of 1.72 nF and is rated at 50 kV. Using these values, N is determined to be 4 and $T$ is equal to 53.9 ns. The characteristic impedance of the half-turn magnet, given by $Z_o = \sqrt{L_0 / C_0}$, is then equal to 7.84 Ω which is close to the characteristic impedance of the cable portion of the PFN.

Since four sections are not enough to make the magnet behave like a true transmission line, there will be ringing between the sections if no damping is introduced. The SPICE computer simulation showed that adding a resistor with the same value as the PFN impedance to each capacitor eliminated the ringing without slowing the speed significantly.

*HV Power Supply*

The high-voltage power supplies used for the kicker units are rated at 50 kV and 6 kJ/s. This power supply operates in the constant-current-charging mode before the output voltage reaches the set point, then it switches into the constant-voltage-regulating mode. The output can be easily controlled by an HV ON/OFF TTL logic signal. The output voltage level can be controlled by the reference voltage within ±0.5% (though the HV power supply's specification is better) from shot to shot even for a load less than 30 nF. This is very important to our application since the injection kickers require different voltage levels at the beam injection and the beam extraction.

The HV power supply also has a built-in 100-200 µs dead time after the load is suddenly discharged to give enough time for the thyratron to recover. This type of power supply is ideal for capacitive loads that are charged and discharged repeatedly. It eliminates the need for an external high voltage regulator and makes the control simple.

A circuit diagram of a half-turn magnet and its PFN is shown in Fig. 1. This circuit is used in the computer simulation. The capacitor, $C_T$, is not included in the simulation and there is only one capacitor at the end of the half-turn magnet. The PFN cable length used in the simulation is 12 meters one way. The simulation showed this circuit would produce a waveform with 80-ns rise time and fall time and 80-ns flat top [1].

## III. TEST RESULTS OF THE KICKER UNITS

A prototype kicker, shown in Fig. 2, was built according the circuit shown in Fig. 1. During the test a few problems were found with the original design.

First, the current and the magnetic field had a rise time close to 120 ns—much longer than what the simulation showed. The fall time was even longer, more than 200 ns. Second, looking at the currents or voltages at different sections of the magnet, the propagation of the field along the magnet was not clear. There was some time delay among the first three sections, but very little delay between the last two sections. The test showed that the inductance of all the connections, the thyratron assembly, and the resistor load was greater than the original estimate, 50 to 100 nH. Also, there was some magnetic coupling between adjacent magnet sections. In the design, there is a 1/8 inch gap between two sections. The test showed that this gap is not big enough to stop magnetic flux flowing from one section to another. The result is a magnetic coupling between two adjacent sections which makes the magnet act more like a lumped magnet. According to J. Dinkel, et al. [2], the space between adjacent sections can be up to 40% of the ferrite width without significant effect on the field. Some effort was spent on inserting copper plates between magnet sections to prevent

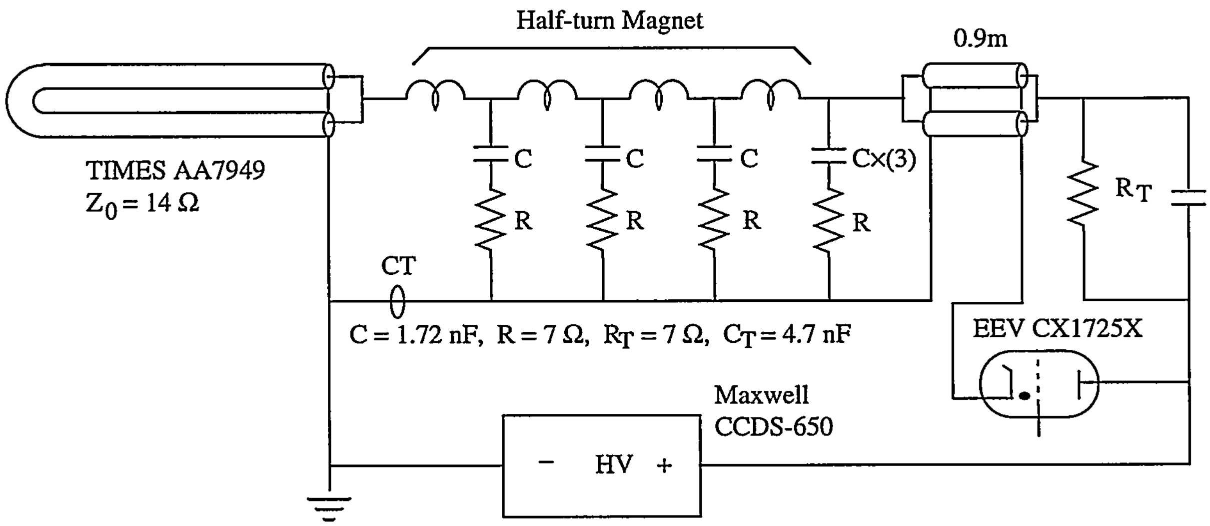


Figure 1. Circuit diagram of the kicker unit for the PAR

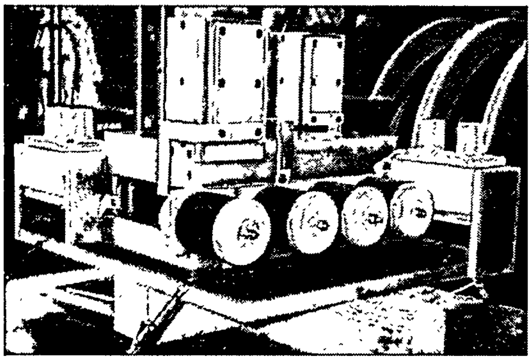

Figure 2. Prototype kicker magnet

the flux from crossing the gaps. However, because of size limitations, the copper plates could not stop the flux effectively.

Because of the schedule, it was not possible to redesign the magnet. Much effort was spent on making adjustments in the circuit to compensate for the slow magnet. For the injection kickers, the total rise time satisfied the requirement, but the rise time from 20% to 100% exceeded the limit. Its fall time also needed to be greatly reduced.

To reduce the rise time, a capacitor, $C_T$, was added to the load resistor. This capacitor not only reduced the rise time and the fall time, but also increased the ringing at the end of the pulse. Therefore, $C_T$ could not be too big. A 4.7-nF capacitor was found to be the optimal choice, providing the needed time reduction without an excessive increase in the ringing.

To further reduce the fall time, the capacitor value at the output of the magnet was tripled. This greatly reduced the fall time, but the rise time increased as a side effect. To compensate, the PFN cables were shortened so the traveling wave from the PFN would come back early and the magnetic field would reach the peak early. The negative side of shortening the PFN was that greater PFN voltage would be needed to produce the required current. After extensive tests, the best configuration for the injection kickers was achieved. For the best configuration, the PFN cables were shortened to 8 meters and the third R-C branch from the input of the magnet was removed. Figure 3 shows the field waveform obtained.

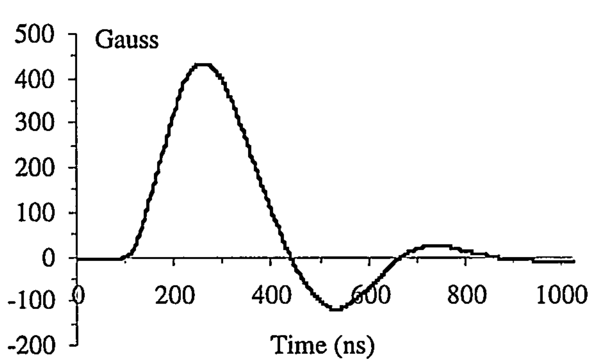


Figure 3. The magnetic field of the beam injection kicker

For the extraction kicker, the fall time and the ringing are not important since the PAR is empty after beam extraction. The flat top can be narrower because of a much smaller beam size, less than a nanosecond, at the extraction. The important parameter is the rise time. After some adjustment, the best configuration was found. Its cable PFN is 9 meters, and the half-turn magnet only needs the first and the last R-C branches (with only one C in the last branch). The 4.7-nF capacitor, $C_T$, is also required. Figure 4 shows the magnetic field of the extraction kicker, and Table 2 shows the achieved parameters of the injection and extraction kickers.

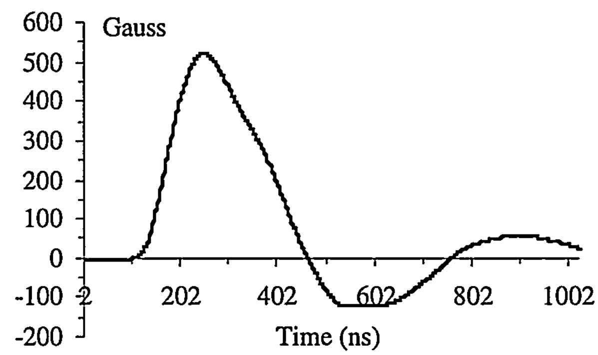


Figure 4. The magnetic field of the beam extraction kicker

Table 2. Achieved Kicker Parameters

| | | Injection | Extraction |
|---|---|---|---|
| Rise time | 0 to 100% | 160 ns | 142 ns |
| | 20% to 100% | 98 ns | 88 ns |
| Fall time | 94% to 50% | 70 ns | |
| Flat top | 3% flatness | 60 ns | 46 ns |
| Ringing | % of peak | 26% | |

## IV. CONCLUSION

Since the prototype, three kicker units have been built. Their PFNs and the magnet configurations were adjusted according to the test results from the prototype. These kicker units have been installed in the PAR for more than a year, with each injection kicker accumulating more than 25 million pulses. The performance of these kickers has been satisfactory—near 100% beam injection and extraction efficiency has been achieved.

## V. REFERENCES

[1] J. Wang and G. Volk, "Design and Simulation of Fast Pulsed Kicker/Bumper Units for the Positron Accumulator Ring at APS," *1991 IEEE Particle Accelerator Conference*, San Francisco, CA, May 6-9, 1991.

[2] J. Dinkel, et al., "Development of a High Quality Kicker Magnet System," FERMILAB-TM-1843, Fermi National Accelerator Laboratory, May, 1993.

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