THE LOS ALAMOS PROTON STORAGE RING FAST-EXTRACTION KICKER SYSTEM*

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Summary

We describe the kicker system used by the Los Alamos Proton Storage Ring[1] (PSR) for fast extraction of accumulated 800-MeV proton beam. The system has several severe constraints in terms of rise time, field quality, and magnet dimensions. These are, in turn, defined by characteristics of the stored beam, ring lattice, and the allowable activation of ring components. Design methods to meet the constraints are outlined here and we describe the novel modulators that produce the fast pulses required.

Introduction

The PSR, which circulated first beam in April 1985, is part of the upgraded Weapons Neutron Research (WNR) spallation neutron source. The PSR accumulates a 750-μs-long chopped macropulse of H^- ions from LAMPF into a single, 270-ns-long proton bunch, which has a suitable structure for condensed-matter research.

The nominal cycle rate is 12 Hz, and the design average extracted current is 100 μA. Extraction immediately follows the accumulation cycle of some 2100 turns. Hence, the average circulating current in the ring is 105 mA. The peak current is 46 A (assuming a parabolic distribution), and 5.2×10^{13} particles are injected during each cycle with injected vertical and horizontal emittances of 2.0 cm•mrad. The nominal operating tunes are just below 3.25 horizontally and 2.25 vertically.

The 270-ns bunch is maintained throughout accumulation by a low-impedance, 2.8-MHz bunching system. This pulse structure leaves a 90-ns gap during which the extraction kicker must attain full amplitude to provide single-turn extraction, including structure fill time. The horizontally kicked beam is captured by a pair of septum magnets for transfer to the extraction line and, thence, to the WNR target.

Kicker Magnet

The magnet consists of two electrodes that form a terminated transmission line as shown in Fig. 1. A 50-Ω line impedance was chosen, primarily because of the availability of electronics components. Additionally, this impedance translates into convenient dimensions for the magnet structure. A bipolar pulse sent down the line propagates in the TEM mode with the speed of light c. The electric and magnetic fields

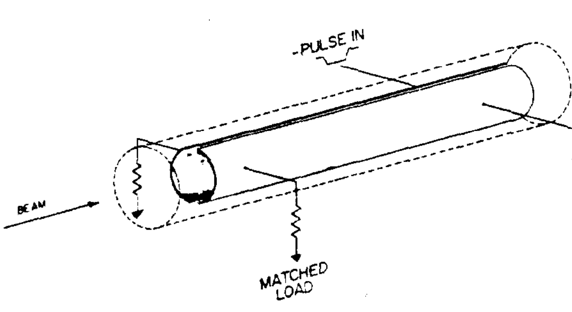

Fig. 1. Kicker electrode configurations.

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deflect particles in the same direction if the particles travel opposite the wave. The ratio of magnetic-to-electric deflection is equal to the ratio of particle velocity to that of light, β = 0.841. Hence, the total angular deflection, for a constant electrode separation, is

$$\theta = \frac{BL}{B\rho}\left(\frac{1}{\beta} + 1\right) \quad , \tag{1}$$

where $B\rho$ is the beam rigidity, 4.869 Tm, and B is the magnetic field produced by the wave over a distance L, the magnet length. A structure length of 3.95 m was chosen so that the magnet would fit within a PSR straight section. As shown below, two magnets are necessary, each capable of deflecting the beam by about 6 mrad. Assuming a parallel-plate structure and a magnet gap of 10 cm, a magnetic field of 33 G, and an electric field of 10^6 V/m, a pulse amplitude of about 50 kV at each magnet terminal is implied by Eq. (1). The magnet fill time is 13 ns.

The magnet aperture was an important design consideration. Although pulse-amplitude minimization by a decreased electrode separation is desirable, it is necessary to maintain an adequate aperture to avoid beam losses from halo interception. An aperture 2.8 times the beam-core diameter was chosen as consistent with other apertures in the ring. Because the beam diameter varies along the kicker length, a tapered magnet gap was the logical consequence of these constraints. The electrode separation varies linearly from 10 to 6.2 cm in the upstream magnet and from 14.8 to 5.8 cm in the downstream structure.

Further design constraints were imposed by requirements on the magnets' field homogeneity and impedance. Field nonlinearity, as represented by the integrated sextupole content, was required to be less than 2% of the dipole moment, a figure derived from second-order transport calculations and consistent with the nonlinearities achieved in the remainder of the extraction transport line. The impedance was required to be within ±1 Ω of the nominal 50 Ω to avoid significant pulse distortion.

The magnet design code POISSON was used to determine appropriate electrode shapes. To minimize difficulties in fabricating electrodes, the simple cross-sectional shape shown in Fig. 2 was used. Field-harmonic analysis was given directly by the code, and the impedance was calculated from the stored energy. The chamber walls and electrodes were set at constant vector potentials so that a definite current was sent through the electrodes. The code established the stored energy per unit length and, hence, the inductance L per meter. For a TEM wave, the relation Z = Lc gives the impedance Z.

By a first-order solution, chamber diameters of 7 and 11 in. were specified for the upstream and downstream magnets, respectively. The electrode thickness was set to a convenient 0.93 in., and the plate separation was set to the aperture requirement for the particular cross section under study. For a given angle α and a linear taper in dimension h over the electrode length, the flange projection a (Fig. 2) was determined as a function of length to minimize the sextupole moment. Several iterations at five cross sections served to produce an acceptable field nonlinearity and an impedance varying from 52 to 60 Ω. The impedance was next trimmed by the structure, on the back of the electrode, with dimensions b and c.

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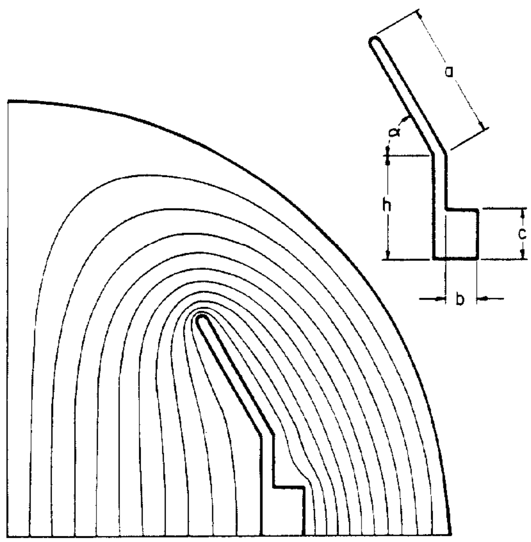

Fig. 2. Field lines for a quadrant of magnet's cross section. Electrode dimensions are parametrized in the electrode cross section, which is repeated on the right of the figure.

Originally, b was to be adjustable through ports in the vacuum, but this proved to be awkward. Instead, b was fixed, and dimension c was varied along the electrode length. This fixed configuration proved to have the correct impedance to within 1 Ω, as determined by time-domain reflectometry.

The electrodes were made from copper sheet bent on a large brake, and the flange projection a was cut by a numerically controlled milling machine to a semicircular edge. The electrodes are supported by Macor insulators at four points along the magnet length and by their connection to the vacuum feedthroughs at the magnet ends. The insulators fit closely into accurately bored tubes welded to the chamber. By means of a threaded fixture inserted in the tubes, the electrode positions can be accurately adjusted. The magnet is shown in Fig. 3.

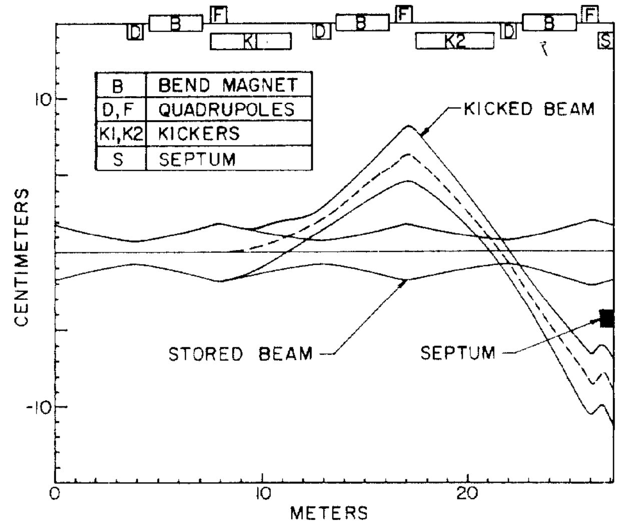

Fig. 4. Kicked beam trajectory relative to the stored beam. Elements of the PSR lattice are shown.

a deflection of about 8.3 cm at the septum magnet entrance is required. The optical phase separation of the two magnets is 132°. The ideal separation is 180°, but this could not be achieved without extending K1 into a 36° bend magnet. An optimal configuration was found to use the same voltage and length for each magnet. The pulse voltage necessary is a decreasing function of tune, with 45.25 kV required for a 3.2 horizontal tune and for a 2.2 vertical tune. At this voltage, the upstream and downstream kickers have respective strengths (BL) of 149 and 125 Gm. The two strengths differ because of the wider aperture required in the downstream magnet to allow adequate clearance for both the kicked and stored beams.

Because of the substantial separation of the stored and kicked beams in both magnets, they are placed off-center with respect to the stored beam by tilting the vacuum chamber horizontally so that the magnet axes lie between the two beams.

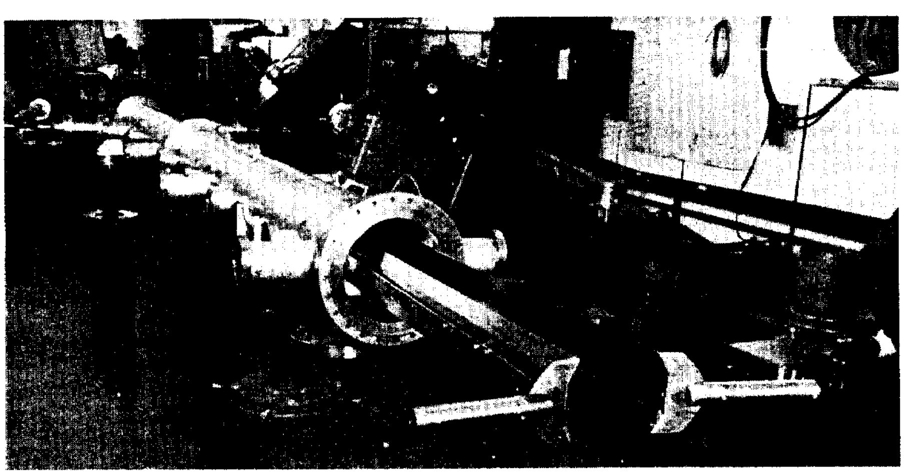

Fig. 3. Upstream kicker magnet; vacuum tank is partially removed to show electrode structure.

Beam Optics

Beam trajectories and kicker placement in the ring lattice are shown in Fig. 4 along with core-beam envelopes. To adequately clear the extraction septum,

Modulators

The modulators produce pulses over 46 kV that drive 50-Ω loads at 920 A. A similar design for modulators that produce shorter pulses for an alternate PSR mode has been described.[2,3] Peak power produced is near 85 MW, with an average power of 860 W for a 360-ns pulse at the specified 24-Hz repetition rate. During a year's operation at half-duty, 3.6×10^8 pulses are produced. To limit activation by beam spill, the firing reliability must be high, with fault rate approaching 10^{-4}. Additionally, the (expensive) switch tubes should have a long lifetime for tolerable operating costs.

The final design uses a specially developed pulse-forming network (PFN) switched by a fast hydrogen thyratron. A schematic of the PFN, a variation of the dual Blumlein-line circuit, is shown in Fig. 5. This configuration produces dual pulses of opposite polarity, using a single-polarity charging supply with voltage equal to the desired pulse amplitude. One switch is used to discharge the two parallel lines, which must

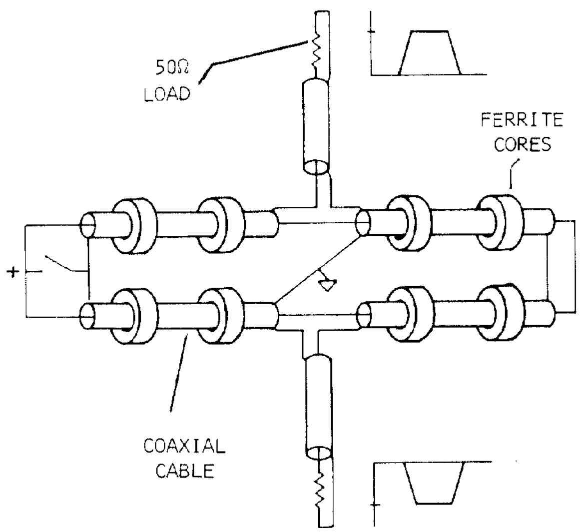

Fig. 5. Dual ferrite-isolated Blumlein.

be inductively isolated to prevent immediate discharge. Isolation is done by threading the line cables (23 Ω, 17/14) through Type C38 Ferrocube ferrite toroids; 104 ft of cable coiled inside the modulator tanks is used for each of the four sections, with 200 toroids per section.

A two-stage resonant and pulse-transformer circuit charges the PFN. The intermediate-storage capacitor (C1 in Fig. 6) is charged (to 5 kV for 46 kV output) through inductor L1 by the power supply. The voltage across C1 is monitored, and at the appropriate level, switch S1 closes, which immediately halts the charging process. S2, an EG&G HY-5751 thyratron, then is closed to transfer energy in 10 μs through the 10:1 transformer T1 and diode D2 to the Blumlein lines represented by C2. The cycle requires a total of 2.5 ms. Severe requirements are placed on D2, which is an assembly of 20 Unitrode KX-50 diodes in series. Overall voltage regulation of the charging system is 0.03%.

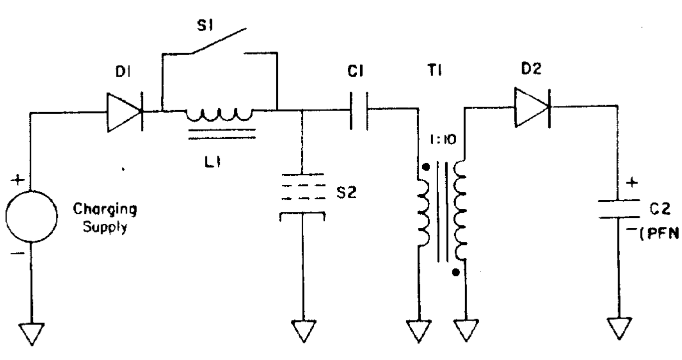

Fig. 6. Simplified schematic of two-stage Blumlein charging circuit. C2 represents the line capacitance, about 35 nF. Representative values for L1 and C1 are 210 mH and 3.5 μF, respectively.

After extensive tests, the Blumlein-line switch selected was an EG&G HY-5353 thyratron mounted in an isolated low-inductance shroud and with regulated dc filament and reservoir power supplies to reduce output jitter. The line is fired by an HY-8 thyratron in a standard PFN configuration that is, in turn, triggered by an optically coupled solid-state source.

The output current is monitored by a specially designed ferrite core transformer that is coupled to a portion of the output coaxial-cable shield current. This unit is located outside the modulator enclosure to eliminate high noise backgrounds. A simpler resistive measurement was not desirable because of excessive radiated noise.

Each modulator is mounted on a hydraulic lift table inside a 4- by 8- by 4-ft-high tank filled with circulating transformer oil. A circulating solution of copper sulfate provides the 50-Ω loads that terminate the kicker magnets.

The modulators have been run at 46 kV and 24 Hz for 300 h without thyratron failure. Peak-to-peak time jitter for 10 000 pulses is about 5 ns, and the amplitude stability is 0.1% with 5×10^{-6} misfire rate as determined by a computer-controlled monitoring system. An oscilloscope trace of the output current pulses is shown in Fig. 7.

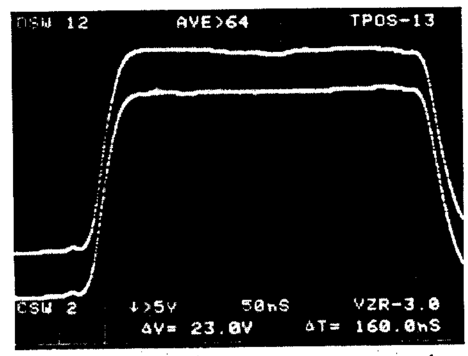

Fig. 7. Digital storage-scope tracing of modulator output pulses. The pulses rise to 46 kV, and the horizontal scale is 50 ns/division.

Timing and Synchronization

PSR extraction timing is referenced to a 2.8-MHz signal synchronous with the 2.8-MHz fundamental-mode bunching system. A ready pulse derived from the angular position of the WNR mechanical neutron chopper (which must be synchronized with beam extraction) initiates charging. After a fixed delay, when charging is complete, and at the 2.8-MHz timing-signal zero crossing, a fire pulse is initiated. The pulse passes through a computer-controlled delay adjustable in 0.5-ns increments up to the ring period. This latter delay allows synchronization of each extraction pulse to passage of the beam through the kicker magnets. Drifts in modulator firing time automatically are adjusted for by computer monitoring and adjustment. If drift or jitter becomes excessive, injection is inhibited.

References

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