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THE LOS ALAMOS PROTON STORAGE RING (PSR) INJECTION DEFLECTOR SYSTEM*

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Summary

We describe a pulsed magnetic deflector system planned for the injection system of the PSR.^{1,2} Two sets of magnets, appropriately placed in the optical systems of both the ring and the injection transport line, provide control of the rate at which particles are injected into a given portion of transverse phase space and limit the interaction of stored beam with the injection stripping foil. High-current modulators that produce relatively complex waveforms are required for this purpose. Solid-state drivers using direct feedback to produce the necessary waveforms are discussed as replacements for the more conventional high-voltage tube technology.

Inflector Magnet System

Two pulsed magnet systems comprise the PSR injection inflector system. Their placements are shown in Fig. 1, which shows a plan view of the ring injection section. A stripper magnet converts the 800-MeV H^- beam to H^0 , which then passes through a ring bend and onto a stripper foil for conversion to protons.²

Vertical Orbit Bump System

Vertical inflection is accomplished by an orbit bump system consisting of six single-turn air-core magnets. The injected beam, with emittance much less than the stored beam, is focused on the horizontal-edged stripper foil at a constant vertical displacement (relative to the ring equilibrium orbit) equal to the extreme coordinates of the stored beam. At the start of injection, the bump system deflects the equilibrium orbit at the foil to the injected beam coordinates. Outside the bump region, the orbit follows its nominal course. As injection proceeds, the deflection decreases at a rate appropriate to production of the desired transverse beam-density distribution. Because accumulation occurs at the beam surface, interaction with the foil is minimized. After injection is complete, the orbit perturbation is zero and the beam no longer interacts with the foil. A more detailed description of the phase-space manipulation procedure has been published.²

A ray trace of the extreme orbit deformation is shown in Fig. 2. The ring tune is an integral part of the bump system; other settings of the ringquads change the required magnet deflections. From an optical viewpoint it is preferable to bump in the horizontal direction. However, the stored beam would then pass through the foil with coordinates greater than the injected beam because of horizontal dispersion in the ring. Four magnets are required to produce a given deflection at the foil and return beam to the ring orbit. However, six magnets are used to limit the peak current needed by an individual magnet to 2.3 kA (~ 1 mrad deflection). The magnet positioning shown is not the most efficient for beam deflection purposes; placement of other elements was a constraint.

Despite a complex frequency response and higher required currents, the air-core magnets were preferred over a ferrite system to maintain low reactances as seen by the beam. Each magnet is kept identical to the others so that magnet frequency response, and

Fig. 1. A plan view of the PSR injection section showing the inflector magnets' position.

Fig. 2. Ray trace of equilibrium orbit deflection in vertical plane. Ring sections viewed are the same as Fig. 1.

hence pulse shape, is affected similarly by magnet environment and construction. Details of the air-core magnet design are contained in another publication.³

Horizontal Deflection

Horizontal manipulation of the beam is accomplished by two sets of steering magnets in the injection transport line. The two sets of magnets are sufficient to produce required phase-space coordinate at the foil. Additionally, the transport quadrupole shown in Fig. 1 forms part of the deflection system as well as providing beam focus onto the foil.

The injected beam is moved in a programmed sequence as implied by the magnet waveforms shown in Fig. 3. Each sweep over the extent of horizontal phase space is repeated several times during the vertical sweep, thus cycling over the spatial phase-space projection. The combined horizontal and vertical motions can be shown to completely fill the four-dimensional volume of phase space.

Because wall reactance is unimportant here, ferrite magnets are used with single-turn excitation. Magnet inductances are somewhat higher for the 0.5-m-long ferrite magnets ($>0.5 \mu H$ as compared to $\sim 0.3 \mu H$ for the air-core magnets) but with correspondingly smaller current requirements for a given deflection.

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Fig. 3. Current waveforms required for horizontal injection steering. Vertical waveforms have the same timing but decrease monotonically from 2.3 kA after the start of injection.

Magnet Driver Systems

Multiturn injection into the ring will last $\sim 100 \mu\text{s}$ for PSR short-bunch operation and as long as 1 ms for the long-bunch operational mode.¹ Figure 3 shows the horizontal-steering current requirements, where at the beginning of the cycle an 800-A peak current is required. The waveform has a programmable oscillating structure to accomplish the desired horizontal sweep. The vertical bump-drive timing is similar except that the corresponding waveform decreases monotonically after the initial rise and peak currents up to 2.3 kA are required.

Drivers for both the horizontal and vertical systems use solid-state techniques rather than the conventional hard-tube, high-voltage technology. Because requirements for the two systems differ, a different type of modulator is to be used for each system. The horizontal magnets have higher inductance and require smaller peak currents than do the vertical magnets and also require an oscillating waveform. Hence the horizontal drivers use a bipolar drive with direct feedback from the output to provide the necessary waveform. The vertical drivers on the other hand are unipolar to manage higher currents (using available transistors) and use techniques other than direct feedback to maintain the requisite pulse fidelity.

Horizontal Driver Design

The horizontal driver schematic is shown in Fig. 4. A number of semiconductors are arranged in parallel so that each can supply some fraction of the total magnet current, where the amount of total current is adaptively created by feedback.

The feedback system is drawn in block diagram form. The four major interconnected parts of the system shown are (1) a current or field sensor, whose output is a measure of the controlled variable (current/field); (2) a feedback amplifier, G_2 , which permits the scale factor of the current/field quantity to be set; (3) a differencer, d , which computes the deviation between the desired current/field and the actual current/field in the load; and (4) a forward acting power amplifier, G_1 , connected to the load terminals, which furnishes the required voltage and current wave to the load and controls the accuracy of the input and output relationship. The system functions as follows: With application of the desired quantity E_{in} , defined in Fig. 3, the differencer

Fig. 4. Horizontal steering-magnet-driver schematic using solid-state and feedback techniques.

compares the applied input with a feedback sample of the current/field quantity through G_2 . Any error is amplified by the power amplifier G_1 so that the newly developed wave produced will force a correspondence between the desired and actual load quantities.

The node voltages, at points 1, 2, 3, 4 in Fig. 4, together with the load voltage differential equation, may be used to determine the overall load current, $I_L(s)$, in complex form, as

$$I_L(s) = E_{in}(s) \frac{G_1}{(sL + R) + kG_1G_2}$$

where k is the current-sensor transfer function in Fig. 4 (that is, the ratio of the feedback voltage E_b to the load current, I_L). The circuit implementation allows $kG_1G_2 \gg (sL + R)$, giving by inverse transformation the output-current, $I_L(t) = \alpha E_{in}(t)$, where α is the net transconductance constant of the circuit (explicitly equal to $1/kG_2$). The load current thus is directly proportional to the programmed input $E_{in}(t)$, and therefore the magnet current can be programmed with relative ease by a voltage representation of the desired current function rather than the more complex time-derivative programming usually associated with other methods.

The complex nature of the load current and the reactive load impedance make the system's peak voltage requirement the sum of the inductive and resistive components of load voltage. For PSR programmable magnets, this total is 40 V, peak maximum.

The added inductive component of the connection cables (between points X-Y in Fig. 4) would be appreciable and a serious technical drawback for a low-voltage design, except that a special transmission line with negligible inductance and loss was devised especially for this application. The line consists of a 20-layer ribbon conductor, each layer 1.86 in. wide by 0.012 in. thick, 60 ft long. Molded Mylar insulation provides a 0.008-in.-layer separation and 1-kV operational voltage. The total added inductance for the 20-m line is 5.6 nH. Line impedance is 0.073 Ω .

The basic current-driver concept shown in Fig. 4 has been implemented by using 30 field-effect transistors (FET), 15 IRF-150 devices in parallel, and 15 IRI-9130 in parallel, arranged as a bipolar follower amplifier. The follower was combined in tandem connection with a 1-MHz bandwidth, gain of 50, bipolar gain stage to form the G_1 part of the circuit. A unity gain, 10-MHz bandwidth differential amplifier was used as the differencer, and a coaxial 10-nH shunt was used to sense the magnet current. The gain of element $G_2 = 1$.

Figure 5 shows the system's overall current-driving capability (that is, the combined performance

Fig. 5.
Horizontal steering mag-
net-driver performance.
The vertical scale top
trace is 50 V/div, bot-
tom, 200 A/div. Time in
each trace is 50 μ s/div.

of driver, line, and 0.5- μ H magnet). To date the model system has undergone testing for ~ 500 h with the 2% duty-cycle wave shown in Fig. 5. However, many other current waveforms to 1-kA peak and with rise and fall times as low as 7 μ s have been used in magnet-current drive experiments with this equipment.

Vertical Driver Design

Figure 6 shows a simplified circuit of a pulsed driver for an orbit bump magnet, using a single-ended common-source n-channel VMOS output stage. The magnet load has been made "acceptable" for the inherently current-source drive circuit by incorporating the magnet inductance into a constant-impedance network, which presents a resistive (and well-behaved) load to the driver. An additional benefit is that the resistive load now can be driven at a distance through a matched transmission line without additional waveshape distortion from line reactance. Another advantage is that the load network, being resistive, does not present the "kickback" hazard inherent in inductive loads, where a sudden cessation of the driver current results in a potentially damaging voltage transient.

The load network shown is one form of a constant-resistance network. It can be shown that if two resistances are equal and $L/R_L = R_L C$, then the impedance presented by the network is constant (independent of frequency), resistive, and equal to R_L . Note that inductive and capacitive leg time constants are equal. If a square-wave voltage signal is put across the network, the total network current will be a square wave, but the inductive and capacitive leg currents will have the usual time-varying exponential shapes.

The magnet current in such a system will have a shape and magnitude like that of the driver output but modified in its time response by the L/R_L time

constant. In practice, R_L is made so that the peak magnet current multiplied by R_L equals the supply voltage minus the transistor and transmission-line voltage drops. The supply voltage is chosen to be the transistor-voltage rating minus a safety margin. It can be shown that if V_L is defined as the maximum allowable load-network voltage, $V_L = I_L R_L$, then the magnet time constant, L/R_L , is determined by $\tau = L/R_L = LI_L/V_L$ and is a function of the magnet inductance, the required maximum magnet current, and the allowable load-network voltage.

The circuit of Fig. 6 shows, in simplified form, a drive circuit for the output common-source transistors, which is similar in concept to the "current mirror" often used in monolithic integrated circuits with either bipolar or MOS transistors. A current i_D , proportional to the input voltage signal v_s , is produced by the p-channel transistor Q_D driven by operational amplifier A_1 , which compares the voltage drop across R_D with the input voltage. Current i_D in turn is passed through n-channel VMOS transistor Q_M , which has the gate and drain tied together. The gate-source voltage drop will be that required to pass current i_D through Q_M . This voltage also is applied to all the paralleled output transistors. If all the transistors have identical characteristics, the output current i_L will be equal to $N i_D$, where N is the number of output transistors. A small external source resistor is added to each transistor to improve the current-sharing.

The current-mirror drive has the advantages of "linearizing" the output transistor-drive characteristics (which otherwise are quite nonlinear) and making the output current linear with input voltage to a first-order approximation. The current-mirror drive also provides a very low impedance voltage source to drive the large input capacitance of the paralleled output transistors.

Operation of this driver circuit has been demonstrated with a scaled-load network to 500-A peak, using ten paralleled drive transistors. The observed current wave shapes in the circuit were as predicted, with no damaging "turn-off" voltage spikes even with an abrupt end of the drive signal.

Acknowledgments

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Fig. 6. Simplified schematic for the vertical bump-magnet driver showing matched transmission line and constant-impedance load network.