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ZERO GRADIENT SYNCHROTRON BOOSTER INJECTION*

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Introduction

Due to the large radial aperture of the Zero Gradient Synchrotron (ZGS), it seems reasonable to stack two booster beam bunches in the radial betatron phase space. This requires some manipulation of timing and intermediate kicks to accomplish the task.

Fourth harmonic operation was selected which fitted best the kicker flux rise times and the injector energy spread. The accelerating voltage frequency will be 5.3 MHz, which gives a beam bunch every 188 ns. The beam length will be 94 ns.

Injection Phase Space

Fig. 1 is the phase space diagram illustrating the injection of two booster beam bunches into one ZGS rf bucket. The expected highest and lowest energy beams are shown to illustrate how each contributes to the final beam width. The first booster beam is bumped onto the equilibrium orbit in the straight section three-eighths of a revolution from the injection point. For $\nu_x = 0.833$ the kicker is at 112° in betatron phase. To achieve the minimum beam width ($\phi = 90^\circ$) the booster beam is injected at a slight positive angle. For betatron motion:

$$x \text{ (amplitude)} = x_o \cos\left(\nu_x \frac{z}{R} - \theta_o\right)$$

where:
x_o = maximum betatron amplitude
ν_x = radial tune = 0.833
z = linear distance from injector
R = beam path radius
θ_o = phase angle resulting from injection angle being other than zero

$$x' \text{ (slope)} = \frac{dx}{dz} = -\frac{x_o \nu_x}{R} \sin\left(\nu_x \frac{z}{R} - \theta_o\right)$$

If injection is eight inches outside the equilibrium orbit, then

$$x_o = \frac{8}{\cos 22^\circ} = 8.6 \text{ inches.}$$

To kick the beam onto the equilibrium orbit we have

$$x' = -\frac{(8.6)(0.833)}{1076} = -6.7 \text{ mR}$$

Therefore, a +6.7 mR kick is required.

Three machine revolutions (two and one half betatron oscillations) before the second booster beam is injected, the resident bunch is kicked + 2.7 mR and with the arrival of the booster beam, both bunches are kicked - 4.7 mR. The betatron amplitudes of each bunch are then equal and if they are equally populated the net amplitude is zero.

By detection of the coherent betatron oscillation of a particular bunch, one is able to diagnose proper injection.

The other three rf buckets will be filled in the same manner.

Booster - ZGS Synchronization

The booster has a radius one-fourth that of the ZGS; but since some manipulation of beam steering via the rf is needed, the frequencies cannot be locked. Instead a coincidence anticipate mode will be used whereby the coincidence zero crossing of the frequencies is detected, when enabled by the booster extraction ready pulse. A countdown toward the next coincidence will begin which will program pulses to trigger the kicker magnets. A jitter of less than 4 ns is achievable in the zero crossing determination.

Kicker Magnet Configuration

Fig. 2 shows a front view of the kicker magnet. The radial aperture of the kicker magnet must be sufficiently large to allow injection of 50 MeV beam and extraction of the high energy beam. The ZGS beam orbits are different in the long and short straight sections at high energy. The kicker magnets will be in the S2 short section where the beam runs inside.

Although the equilibrium orbit for the 500 MeV beam will be optimized by experiment, +6 inches outside center in the long straight section seems reasonable. This is -1 inch in the short section so the kicker magnets will be centered at -1 inch.

The magnet has a design flux width of 10 inches. The maximum kick expected is 9 mR so that at 500 MeV, $B\ell = 0.0327$ T-m. Total magnet length is 0.84 m. Because of the fast rise and fall times necessary, a matched transmission line magnet will be used.

Inductance

$$L = \frac{\mu_o A_g}{\ell_g} \text{ assumes } \mu_{Fe} = \infty$$

$$L = 2.2 \times 10^{-6} \text{ H for 0.84 m length.}$$

To keep the magnet voltage within reason, an impedance of 14 ohms will be used. The magnet will be completely shielded with conducting material to minimize the leakage flux. Even with this precaution the inductance for a 0.28 m long magnet is 1.1×10^{-6} H as opposed to a theoretical value of 0.73×10^{-6} H. Although one can compensate somewhat for the leakage inductance, it results still, in leakage flux and slower rise times.

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The total capacitance needed for a 14 ohm magnet 0.84 m long is equal to

$$\frac{L}{Z^2} = \frac{2.2 \times 10^{-6}}{196} = 1.13 \times 10^{-8}\ \mathrm{F}.$$

A single 0.84 m magnet would thus have a propagation time of 158 ns which is much too long. To achieve shorter propagation times the magnet length is split into three separate parts; each with its own firing circuit and termination. This approach was taken rather than increase Z and the magnet voltage. An added advantage is that only one section is used to make the small kick so that 3 μs later the other two sections are ready for the last kick.

The buildup of large amounts of capacitance for a large high frequency magnet poses a real problem. Conventional approaches such as building capacitors into the magnet sections were tried but had intolerable inductance and resonances. This construction also added to already tight magnet length requirements.

The method with which we have had reasonable success is shown in Fig. 4. Aluminum oxide ceramic (K = 9) is used for its high dielectric constant and high dielectric strength. Tests performed on the 0.28 m magnet show a flux rise time of 70 ns. There is still a resonance causing a 5% undershoot at 50 ns into the pulse flattop. The wire grid capacitor was made by winding a large diameter solenoid with No. 30 wire, impregnating the solenoid with epoxy and then cutting sections at right angles to the turns. The gridlike construction is necessary to reduce eddy currents.

Fig. 5 shows a computer simulated plot of the magnet flux for a one-fourth section sample.

Switches

Spark gap vs thyratron arguments have been going on for sometime and the comparisons have been summarized by others.[1] 100 kV triggered pressurized spark gaps (manufactured by Maxwell Laboratories, Incorporated, San Diego, California) were selected for the ZGS kickers. The spark gap has an expectant life of 10,000 shots for a charge transfer of 0.3 C at 50 kA. The kicker magnet requires a maximum charge transfer of 7×10^{-4} C at 5 kA. Under equal voltage conditions, the expected lifetime should be 4.3×10^6 pulses. Tests have been run with up to 1.5×10^6 shots under actual kicker magnet conditions and timing jitter was still less than 5 ns.

Timing Line

The problem of the best configuration for a timing line has not been resolved but it will probably be a shielded strip line folded in such a way as to reduce required real estate. Following are the requirements: Z = 14 ohms; V_{max} = 150 kV dc between plates; 75 kV to ground and propagation time 94 ns.

Line Charging and Firing

The charging and firing circuit diagram is shown in Fig. 6. The system is electrically symmetrical with respect to ground to minimize ground potential. The gate signals to the grids of the triodes are coupled in via optical cables with appropriate transducers. The charging circuit will operate closed loop with the error signal derived from a voltage comparator. The system will charge the lines to within ± 1% repeatability in 25 ms. Each line can be charged to two different potentials during each rf bucket fill, via logic which selects the comparator. The magnet lengths are chosen such that the extent of voltage change is small so that spark gap pressure changes are not needed.

Magnet Terminations

Under worst case conditions, the 14 ohm load dissipation is 589 W average assuming 10 pps. Actual pulsing will consist of eight pulses every 33 ms per ZGS cycle. The loads will be split into two 28-ohm sections which will be insulated electrically with a heat sink into the magnet supports. This will alleviate the need for high vacuum feedthroughs to an external load.

Summary

Although all of the milestones have not been achieved yet, it is anticipated that they will be by July 1976 when it is expected that the ZGS-Booster interface will be ready. Already under consideration is the possibility of trying fifth harmonic operation. This gives, of course, another 20% of booster beam assuming acceptance by the ZGS, but making the injection kicker rise times 20% shorter.

Acknowledgments

Credit is due to N. Oki for the magnet test models and results. Thanks to R. Lari for the computer simulated magnet data, A. Rauchas and W. Chyna for the synchronizer work, to R. Kliss for the charging and firing circuits.

Reference

1. E. B. Forsyth and M. Fruitman, "Fast Kickers", Particle Accelerators, 1970, Vol. 1, pp 27-39.

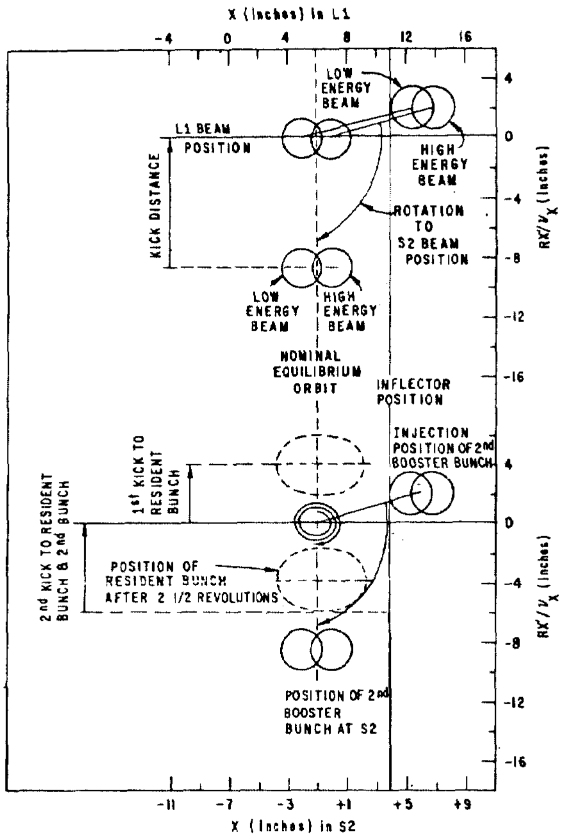


Fig. 1. Phase Space Considerations for Injection of Two 500 MeV Beam Bunches into ~~One~~ ZGS RF Bucket

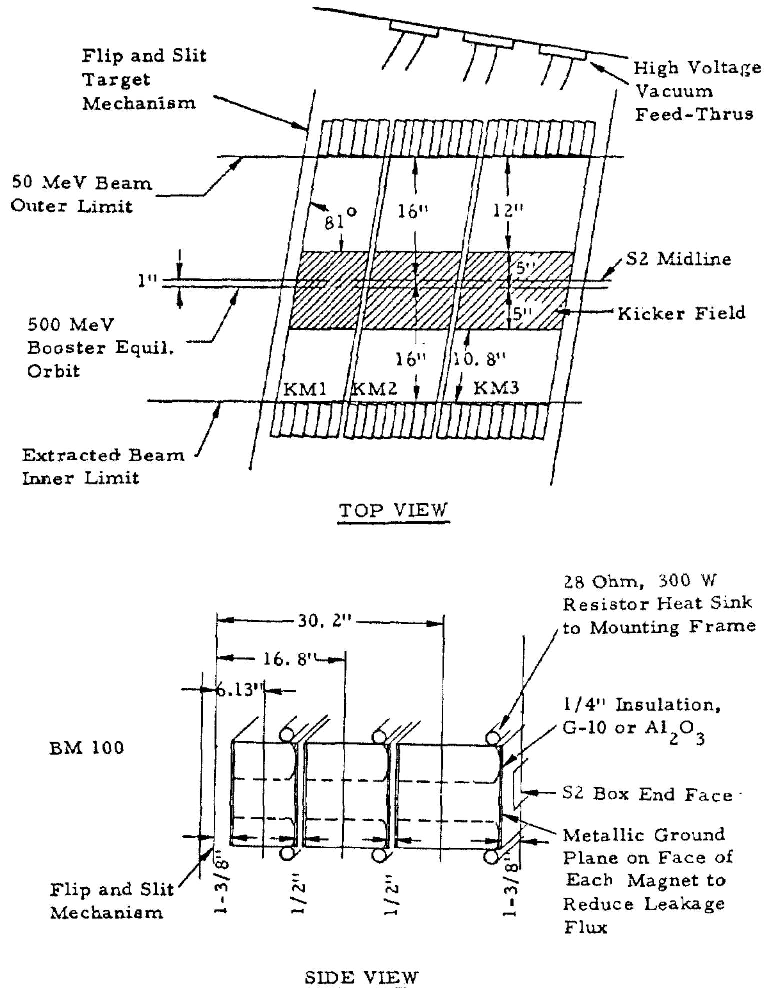
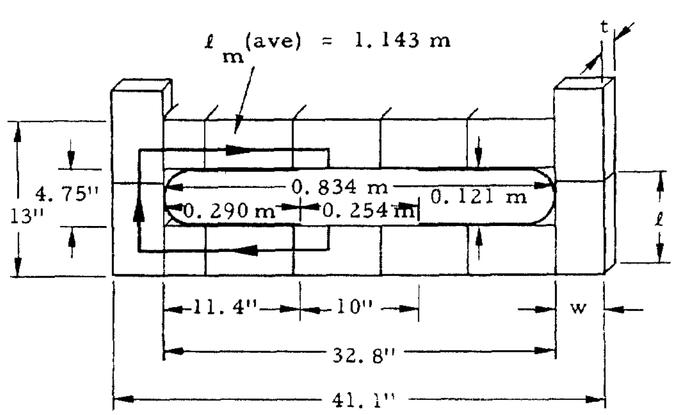


Fig. 3. Magnet Orientation in S2 Box



Block Size

ℓ = 185 mm = 7. 88"

w = 105 mm = 4. 13"

t = 35 mm = 1. 38"

Fig. 2. Magnet Frame Dimensions

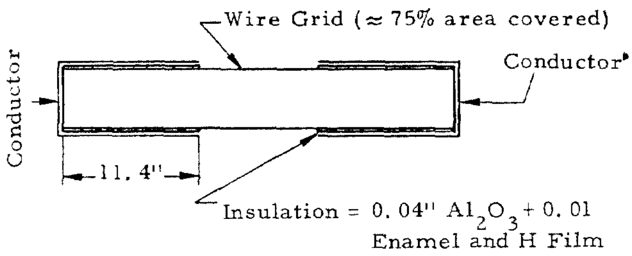


Fig. 4. Magnet Capacitance

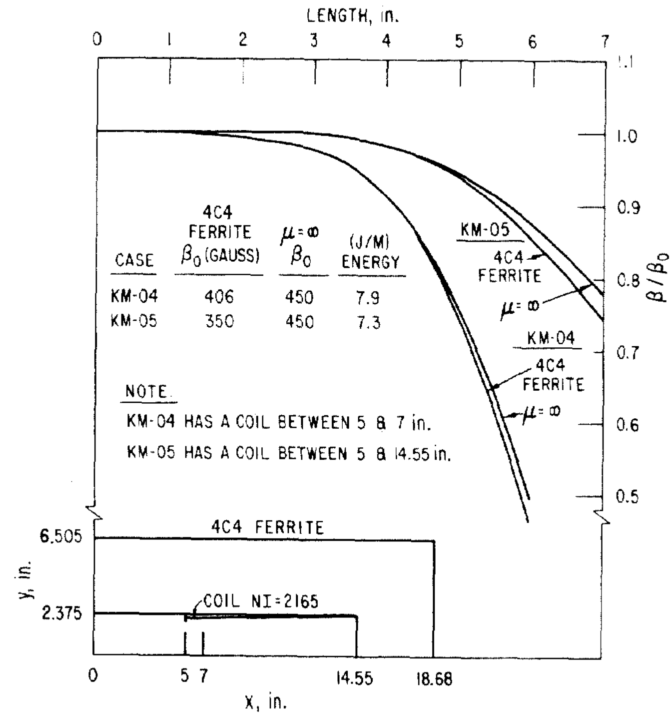


Fig. 5. Plot of Results from Computer Model of Kicker Magnet

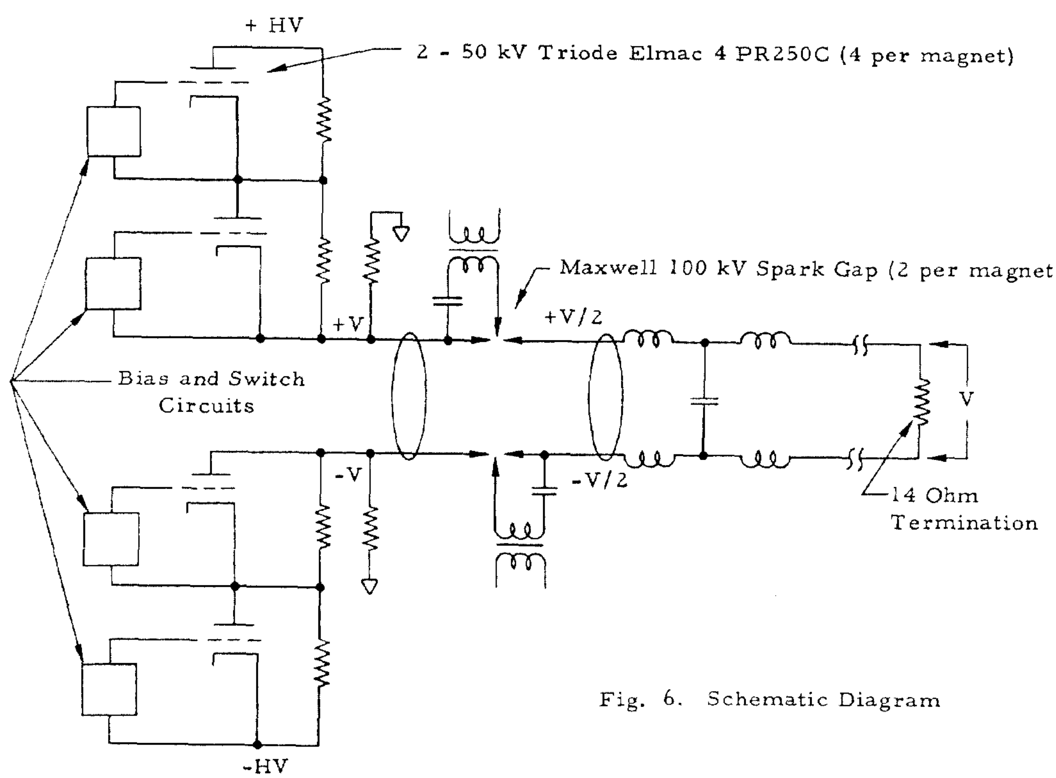


Fig. 6. Schematic Diagram