INCREASING THE ENERGY OF THE FERMILAB BOOSTER

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Summary

The Fermilab booster accelerator was originally conceived for acceleration of protons with an injection energy of 200 MeV to an extraction energy of ten GeV (to the 500 GeV main accelerator). Early booster operation has been limited to eight GeV. The booster beam will be more acceptable to the main accelerator if extraction is at ten GeV, thus we are now modifying the booster magnet system for ten GeV acceleration.

Regulation of the booster magnetic field for injection at 200 MeV was a task even when operating to eight GeV. This paper outlines the approach which was adopted and how it relates to the ten GeV attempt. Further, it highlights the problems encountered in the design of any AC magnet system.

Introduction

The booster magnetic field can be described as

$$B(t) = B_{dc} - B_{ac} \cos 2\pi ft \quad (1)$$

If the magnetic circuit is linear then the energizing current is

$$I(t) = I_{dc} - I_{ac} \cos 2\pi ft \quad (2)$$

where f is the 15 Hz resonant frequency. The complete magnet system in simplified form is shown in Fig. 1. The 48 magnet girders or cells are powered by four power supplies which are each connected to power 12 cells or one quadrant of the circuit, for equalization of the voltage-to-ground. A typical cell consists of a D and an F magnet. The magnets and capacitors constitute a series resonant circuit while the bypass choke in conjunction with the same capacitance constitute a parallel resonant circuit.

The four power supplies provide a biased ac voltage to the magnet circuit. The power supplies are controlled with a precision servo[1]. Fig. 1. contains the simplified diagram of the servo. The servo monitors and regulates the current valley (I_{MIN}) and the current peak (I_{MAX}) which correspond to the injection and extraction fields respectively. The servo employs a transductor[2] for current feedback and resistive dividers on each supply for voltage feedback. The servo regulates slow magnet and environmental variation via the current loop and the voltage loop compensates for fast variations. The servo controls the I_{MAX} and I_{MIN} current values, so equation (2) can be rewritten in terms of these values

$$I(t) = \left(\frac{I_{MAX} - I_{MIN}}{2} + I_{MIN}\right) - \frac{I_{MAX} - I_{MIN}}{2} \cos 2\pi ft \quad (3)$$

The power supplies voltage output can be also described employing equation (2)

$$E(t)_{ps} = I_{dc} R_{dc} - I_{ac} R_{ac} \cos 2\pi ft \quad (4)$$

The power supplies only provide energy to overcome circuit losses, since in a resonant circuit the major energy is exchanged between the inductors and capacitors. The circuit losses are R_{dc} and R_{ac} in equation (4). R_{dc} is merely the dc resistance of the magnet circuit and is independent of frequency. R_{ac} identifies the losses in the circuit which are frequency dependent. R_{ac} is composed of copper and core losses. The R_{ac} value would appear as the real term in a complex number, but it stands alone during resonance because the imaginary terms cancel.

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Operation at 8 GeV

The system as described suffered from extremely poor current regulation. The injection field varied by ±5% which made it extremely difficult to operate the booster. The poor regulation at injection also affected the extraction field regulation which was about ±1%.

The problem was traced to the power supplies output. If the value of I_{MAX} were decreased from 1023 A (8 GeV extraction current) to around 800 A the system operated satisfactorily. The regulation of I_{MIN} and I_{MAX} were improved by a factor of 10. The power supplies were responsible because as the output voltage swing was increased, the voltage for I_{MIN} approached a clamp condition near zero volts. The ac voltage swing was considerably larger than the dc voltage offset for the eight GeV operating conditions. The ac losses and dc losses had been calculated giving[3] R_{ac} = 1.120 Ω/quadrant, and R_{dc} = 0.654 Ω/quadrant. The current for 8 GeV operation is shown in Fig.3a. The voltage waveform based on equations (3) and (4) is shown in Fig.3b. The voltage had to go to negative, but it could not because of the freewheeling diodes across the output of each supply. Refer to Fig.2. but for now ignore (short-out) the SCR's shown in series with the diodes. Fortunately, the actual value of R_{ac} was not as large as the calculations indicated. In fact R_{ac} was only 25% larger than R_{dc}, not the calculated 42%. This difference accounted for why the system almost worked, but precise voltage control during I_{MIN} was not possible. The voltage was entering the clamped condition. The R_{ac} value could only be measured when the ac voltage was reduced by 20%. At the full voltage swing required for operation the non-linearity introduced by the diodes changed the R_{ac} value. Fig.3c. illustrates what the ac swing was at the output of one supply during eight GeV operation. The gain of the system (and hence its response) was severely attenuated during I_{MIN} and consequently the regulation was very poor.

The regulation of I_{MIN} or the magnetic field at injection could be improved if the magnet circuit could be modified so that R_{dc} were increased or so that R_{ac} were decreased. Increasing R_{dc} would raise

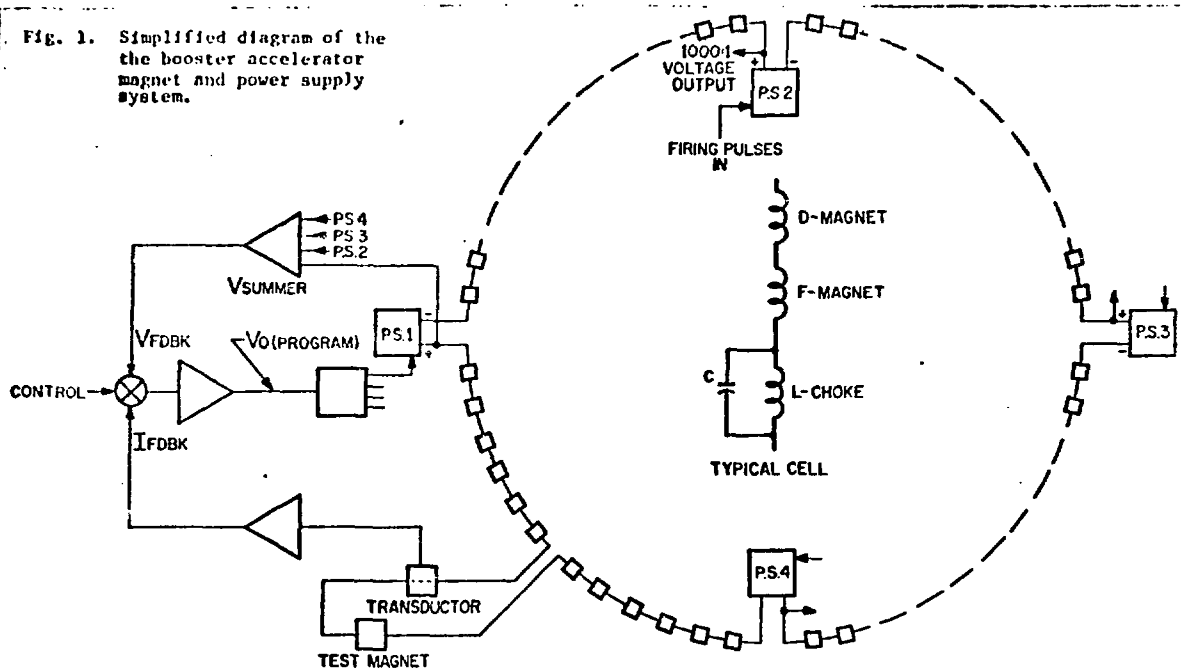

Fig. 1. Simplified diagram of the the booster accelerator magnet and power supply system.

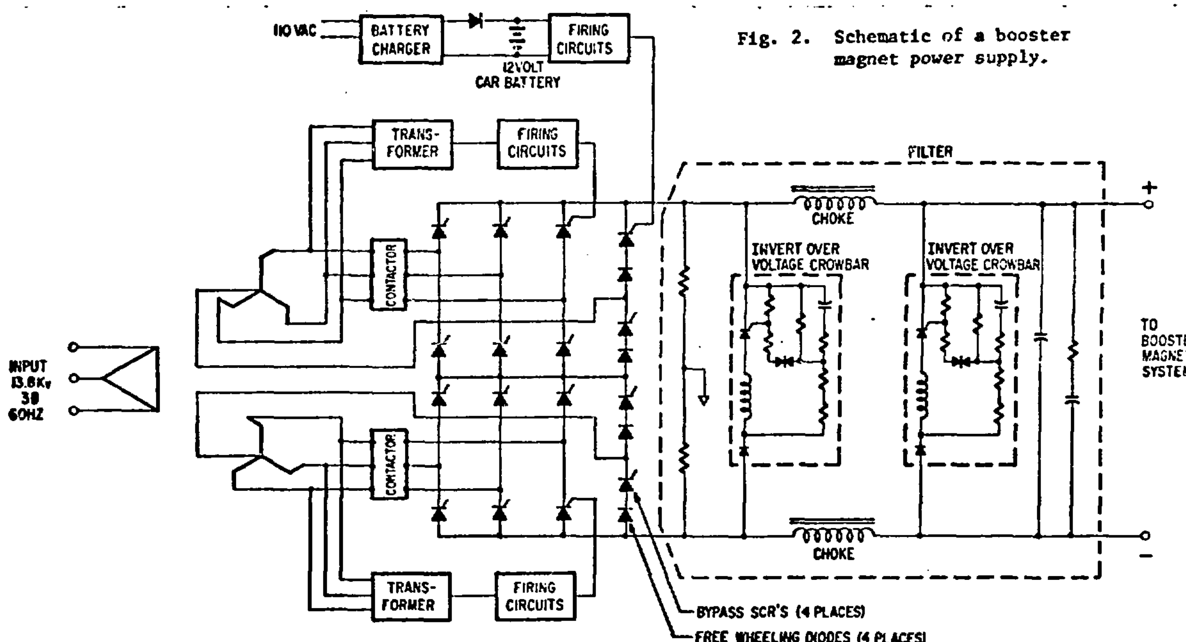

Fig. 2. Schematic of a booster magnet power supply.

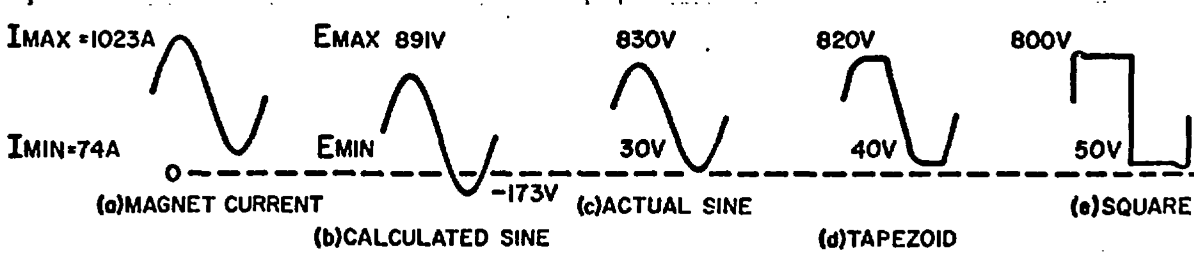

Fig. 3. Power supply output waveforms as a function of programming.

the dc voltage on the magnet circuit and allow I_{MIN} regulation above clamp. The alternative, decreasing R_{ac} would decrease the ac voltage swing while maintaining the same dc operating voltage.

The R_{dc} value could be increased by the addition of a small water-cooled resistor to each resonant cell. However, this resistive addition would also require a fifth power supply in the magnet system and consequent rebussing of the system. Therefore, we began working on techniques to decrease R_{ac}. Detuning via waveform harmonic content affects the parallel resonant circuit by decreasing its resistance. The detuning also, decreases the ac resistance in the series resonant circuit but by not as large a percentage. Since the circuit has a high Q (Q ~40) this detuning is possible.

A square wave at 15 Hz would offer the highest harmonic (odd) content, but initially square wave operation was not possible because of a 100 Hz resonance in the power filter. A trapezoidal filter was designed with a very low seventh harmonic content and was used to replace the sinusoidal filter between the servo output and the firing circuits. With trapezoidal programming the ac voltage swing was further reduced. See Fig.3d. The regulation of I_{MIN} was definitely improved.

Following this improvement, the power filters were redesigned to eliminate the 100 Hz resonance so that square wave programming could be employed. The result is shown in Fig.3e. The ac voltage swing was further reduced with immediate improvement in the current regulation. Magnet field regulation was improved by a factor of 100.

Modification to Attain Ten GeV

Increasing the extraction energy of the booster can improve the proton intensity in the main accelerator. This intensity increase can be accomplished because the effective acceptance of the main accelerator is better at a higher injection energy.

The magnet circuit and power supplies were delivered for operation at ten GeV. The system with square wave programming can regulate to approximately nine GeV. Above nine GeV the ac voltage swing must go negative for I_{MIN} regulation. The free-wheeling diodes must be disconnected to allow a negative voltage output.

Controlled negative voltage operation[4] from a power supply is termed inversion. Fig. 4. compares the transfer functions for a non inverting (curve-a[5]) and an inverting (curve-b[6]) power supply. Inverting power supplies are capable of producing well controlled negative outputs with ac loads. The conversion to the invert mode required circuit additions and modifications. Bypass SCR's were placed in series with the free-wheeling diodes to permit control of the power supply mode. The bypasses provide an initial conduction path from the 15^0 phase retard rectifiers (see Fig.2.) to the 15^0 phase advance rectifiers until the angles overlap at 30^0 and then the bypasses are opened. Another important aspect of the bypasses are for supply protection at turn-off. The bypasses are energized prior to turn-off to provide a discharge path for the current flowing in the magnet system. If the bypasses are not energized, then the last conducting SCR in the supply carries the full discharge current which generally results in its failure. The uninterruptable power supply for the bypass firing circuit (Fig.2.) insures that upon a power failure the bypasses are energized. Initial tests in the invert mode with one power supply were successful and a controlled negative excursion was produced. Two of the four power supplies were equipped with the invert circuitry in an attempt to provide the -200 V excursion required for ten GeV operation. Unfortunately, the two non-inverting power supplies cancelled the intended effect. Referring to Fig.4., we see that curve-b provides a -200 V output at a phase angle of 100^0, but curve-a indicates for the same angle a +200 V output. The inverting supplies which were not negatively limited tried to produce the necessary -200 V at phased back angle of greater than 120^0 and consequently failed because of limited reverse recovery time. The plan for ten GeV operation requires modification of the other two supplies for inversion.

An Alternative Ten GeV Plan

The booster now accelerates 3 x 10^{13} protons per main accelerator cycle. It requires 18 operational R.F. cavities to handle this intense beam loading while 14 are sufficient to provide the acceleration voltages for minimal beam. It would require more cavities to accelerate the full beam intensity to ten GeV at 15 Hz.

By retuning the booster to a 12 Hz cycle time, only slightly longer time (small compared to the accelerator ramp time) is required for filling the accelerator, but the lower dB/dt by 12/15 compensates for the increased accelerating voltage required to go to ten GeV. Therefore, the present number of cavities will suffice to accelerate the intense beam and the lower ac voltage swing will allow ten GeV with a voltage program similar to that required for eight GeV.

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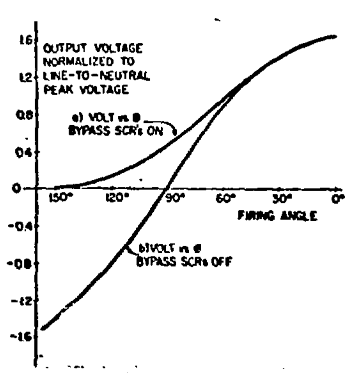

Fig. 4. Voltage vs ϕ Angle