POWER SUPPLY FOR NAL MAIN RING SYSTEM

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Introduction

The NAL main accelerator power system is one of the largest, most powerful, and most sophisticated power supply systems ever developed for accelerators. The system derives it's pulsed power directly from the power lines without the use of energy storage. The power is converted through a large number of widely separated individual phase controlled rectifier supplies and regulated to the accuracy of a reference type supply. It is the hardware, operation, and regulation of this power supply system that is described in this paper.

When evaluating an engineering system, especially one as complicated as the NAL main ring power system, it is important to understand the criteria under which the system was designed, to put into perspective the techniques used in the design. The following is a list of some of the criteria used in developing the system.

1) Generate a basic guide field for the accelerator.
2) Utilize the flexibility of the separated function aspect of the magnet system by separate controls of the bending and focussing magnets.
3) Regulate the bending magnet fields at injection to better than .01%, synchronize with the booster, and maintain a repeatability of .1%, $\Delta B/B$ for the rest of the accelerating cycle.
4) Track the quadrupoles to the bending magnet field to about ±.05 in tune over the accelerating cycle, and regulate the slow extraction tune to better than .003 in tune.
5) Maintain a voltage to ground on all the magnets of approximately 1000 volts maximum.
6) Pulse the system directly from the power lines without the use of rotating equipment.
7) Make the power system from the power lines without the use of rotating equipment.
8) Make it inexpensively.

Each of these requirements were molded into one of the most powerful power systems in accelerators today, as well as a system which is very highly regulated.

An overall prospective of the supply is indicated in the following overall system response.

Maximum peak power	350 megawatts
Maximum current	7000 amps
Maximum overall voltage no load	57,000 volts
Maximum RMS power	120 megawatts

Equipment

Magnet Connections

In order to utilize the flexibility of a separated function accelerator, the bending magnets are powered independently of the quadrupoles. The magnets are connected in series to a folded bus located so as to result in equal and opposite currents flowing in adjacent busses. The bending magnets are interlaced on the two bending magnet busses to minimize the effect of electrical standing waves on the proton beam and allow for a larger number of power supplies to be connected to the bus and at the same time maintain a low voltage to ground with the same number of service buildings. The quadrupoles are also connected to a folded bus. The horizontal focussing quadrupoles are connected to one of the quadrupole busses and the vertical focussing quadrupoles to the other bus. This allows for the possibility of splitting the tune of the accelerator by diverting current from one of the busses to the other across the fold.

Power supplies are installed in the 24 service buildings and connected through knife switches to the bus so that they may be removed or added to the circuit at will. The bending magnets have one supply connected to the "upper" bus and one supply to the "lower" bus in every service building. This results in 48 power supplies interlaced to provide equal numbers of magnets between each power supply. (See Figure 1) The "upper" bus or horizontally focussing quadrupoles are connected to a power supply at every "2" service buildings and the "lower" bus or vertical focussing quadrupoles to a supply in every "3" service buildings. This results in a total of 12 quadrupole power supplies.

The busses are all water cooled and serve the function of not only providing a current conductor but also the water supply for magnets and power supplies. The isolating knife switch for the supplies serves as an easy method of removal of supplies as well as for segmentation of the magnet strings for ground fault isolation.

Power Supplies

The power supplies are 12 phase secondary phase-controlled thyristor rectifier.[1] Each supply is rated for a no-load voltage of 950 volts and a peak power of 6 megawatts at 7000 amps. The RMS rating of each supply is 3 megawatts. The supplies consist of an outdoor substation, indoor rectifier, passive filter, and firing control. (See Figure 2) Supplies are also equipped with Bypass Thyristors designed to bypass the current when the supply is not needed for generating power. The indoor rectifiers consist of a modular design for easy replacement of thyristors. The modules, bus, and filter are all water cooled to minimize the size of the equipment and the cost. The outdoor substation consists of two 1500 kVA extended delta primary, wye secondary transformers in one tank, phased to produce 12 phase rectification. The primary is 13.8 kV 3ϕ with a vacuum breaker, disconnect, and fuses, as the means of isolating the supply and clearing faults. The passive filter consists

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of a series inductor and tuned trap network, tuned for 720 Hz and 1440 Hz.

Ground Monitoring System

Due to the large number of power supplies and their interchangeability, it is difficult to establish and maintain a fixed ground point in the magnet string. A fixed ground is usually used to insure that the voltage to ground on the magnets remains as low as possible and acts as a means of detecting ground faults. To get around the fixed ground problem, a so called " Floating Ground System" is used. Rather than grounding one point in the ring, all terminals of each power supply (after the isolating knife switch) are tied to a common wire via a 50 kΩ resistor. The common wire runs all the way around the ring and is terminated to ground through a ground relay. If the average voltage to ground of all the power supplies is zero, then no current will flow from the common wire to ground. This, of course, is the case when there are no grounds in the magnet system. If, however, a ground develops, the average voltage to ground will not be zero at some time in the cycle, resulting in ground current and a ground trip. The present system is adjusted to trip with an average voltage of 20 volts off ground. This allows for the detection of grounds at one point in the ring of less than 5000 ohms.

The common wire is also an excellent means of high-potting. High-potting the common wire and opening the bus at one point results in a voltage to ground pattern around the ring in which the location of the ground fault can be pin-pointed.

Power System

Individual power supplies are combined at the 13.8 kV side at each service building, and fed by direct buried 750 MÇM tri-plexed aluminum cable. Each half of the ring is fed from a 40/53/66 MVA master substation transformer connected to a 345 kV tie line to Illinois' Commonwealth Edison Comapny's power grid. (See Figure 2) The 345 kV line was used to minimize the effect of the pulsating load on the power lines.[2]

The 345 kV line has a short circuit capacity in excess of 13000 MVA, resulting from a source impedance of .96Ω resistance and 9.15Ω reactive. This means that the effect of the pulsation load on the 345 kV line in terms of voltage drops, is primarily determined by the reactive components of the power.

Control

Each power supply is remotely controlled from the main control room. Individual supplies may be turned on, off, or reset individually or aggregately from the main control computer. (See Figure 3) Also indicated remotely is whether a supply has over-currented or whether the supply is locked out of the circuit by use of the knife switches and disconnect. The phase angle, and therefore the voltage, at which the phased back supply is to operate, is set by a digital firing generator. The only analog signal is a 60 Hz synchronizing signal. The all digital system was used to reduce the possibility of noise in the system and provide for more exact firing pulses than are normally obtained by conventional firing circuit. Phase angles can be set by this firing circuit to an accuracy of .5 electrical degrees with a jitter of approximately ±.2 electrical degrees. The digital nature of the firing generator makes it also directly compatable with the main ring digital multplex system.[3] All supplies, except the fine control supplies, are equipped with an all digital waveform generator designed to generate a simple waveform of a rectify, bypass, and invert from fixed breakpoints. (See Figure 4) Breakpoints for this waveform generator are sent through the main ring multiplex system by the use of the main ring computor.

Fine Control

The fields in the magnets are monitored by a three foot bending magnet installed in service buildings A2 and F3, one for the bending magnets, and one for quadrupoles. The injection field is monitored by a second harmonic field probe.[4] The probe, as well as a hall probe, is mounted in a bucking coil and placed in the three foot magnet's gap. (See Figure 5) The second harmonic probe has a full range of ±4 gauss and a stability of ±.005 gauss. The hall probe is adjusted to read ±300 gauss full scale. The bucking coil is powered by a highly regulated current reference supply capable of maintaining a long term stability of .005%. The bucking field is set to cancel only the nominal injection fields, thereby allowing the second harmonic and the hall probe to operate at about zero field. Pick-up coils are also inserted into the 3 foot magnet and connected to integrators. One coil is used to monitor the absolute field and another to give the difference between the bending magnets and the quadrupole fields. Stability of the integration is .01% over the nominal pulse width. The integrators are zeroed at injection, while the field is being monitored by the second harmonic probes. When the second harmonic probe runs out of range, the integrators take over. The hall probe is used when returning to the injection field as a method of stabilizing into the 2nd harmonics operating region. The analog output of each probe is connected to a multiplexed 15 bit + sign A/D. The selection of the probe to be converted and the transmission of the data to the control room is accomplished by a separated series multiplex system between A2, F3, and the control room. The upper bus F3 and the lower bus A2 supplies are used as fine control supplies, and they are phase controlled directly through the same multiplex system. The quadrupole supplies at A2 and F3 are likewise fine phase controlled.

Regulation and Control

To generate the desired field, and at the same time keep the reactive power seen by the power lines to a minimum, each supply is individually phased to full output voltage before phasing another supply out of bypass. That is, in order to generate the voltage required for ramping the fields of the magnets, individual supplies are phased full "on" in sequential order. In general, one supply will be phased up and the rest will either be fully phased on or bypassed.

The order of turn-on is determined by voltage to ground consideration on the magnets. By so doing, the reactive component of the power required is minimized in all cases, thereby creating the least interference with the power lines. A second reason for turning supplies "on" in sequence is that of regulation. Since the limits of regulation are related to the power line fluctuations, the regulation is related to the number of supplies that are on at the time of the fluctuation. That is, power line fluctuations result in a voltage fluctuation on the magnets of: the number of supplies phased out of bypass, times the magnitude of the fluctuation. If, therefore, the minimum number of supplies are out of bypass at the time of the fluctuation, the magnet voltage fluctuation will be minimized and thereby the field fluctuation will be minimized. The smaller the number of supplies, the better the regulation to line fluctuations.

Determining the power supply turn-on order to minimize the voltage to ground is complicated, therefore, a computer program was developed to determine the best turn-on order from the available power supplies. (See Figure 6) Another program calculated the breakpoints required by the waveform generators from the desired currents and the impedances of the magnetic circuit. All these breakpoint perimeters are calculated off-line, stored, and then sent upon command to the appropriate waveform generators in the order selected by the voltage to ground program. The results of the waveform calculation is a field which is good to about ±3%, depending primarily on the power line voltage and magnet temperature. The breakpoint perimeter calculations also generate a desired field program consisting of numbers representing incrimental changes of field as small as .004 gauss in a time slot of 6 milliseconds. (See Figure 7) The waveform program is transferred to a MAC 16 minicomputer which is the fine control regulator.

The MAC computer acts as the communication link with the field probes and the fine control power supplies as well as the feedback network. The computer is run in real time by interrupts, which occur at at 720 Hz rate. A reset pulse from the main ring cycle timer drives an interrupt level to synchronize the program with the booster. As a result of every 720 Hz interrupt, the computer interrogates the field probes, which monitor the bending magnet and quadrupole fields, converts the data into gauss (depending upon the probe being used), and takes care of the offsets in the integrators. The field measurements obtained are subtracted from the desired program field, resulting in an error signal. The digital numbers are manipulated in double procession in order to generate an error signal that contains the accuracy of the probe being used to monitor the field. The error signal is then normalized to the injection field with the lowest order bit in the computer error signal being .003% of the injection field. The resulting error signal is gain compensated and sent directly to the appropriate fine control supplies in terms of a firing phase angle. The quadrupoles are handled in a similar manner with the field measurements being the difference between the bending magnet field and the quadrupole fields, and the program being a percentage of the bending magnet field. The percentage of "tune" can be modified by a tune program either in terms of energy, corresponding to saturation effects in the magnets, or in terms of time (adjustments in the tune for extraction or tune bumps for better beam survival). The open loop gain from the all-computerized feedback systems is fairly low in the frequency range of interest. A gain of about 20 for the fast feedback is about what is obtained. Such a low gain feedback system would never be sufficient for the type of regulation required by the accelerator. To obtain better regulation, a "self-correcting function generator" technique is used. It is known as the "update" system. There is also an output simulator program, known as "profile", incorporated in the MAC computer's calculations. Updating or self-correcting function generator is a process of utilizing the repetition properties of the accelerator pulse field to extend the systems' bandwidth or overall feedback gain. That is, by looking at the error signal, over many pulses, simulates the repeatable part of the error signal, and adding this simulated signal to the incoming error signal, the real difference between the measured field and the desired field can thereby be reduced toward zero. The limit of this system is related to the low bit accuracy of the update system and the magnitude and frequency of the non-repeating fluctuations. In the NAL case, the low bit accuracy of the measuring A/D, and the firing circuit bit size, is the limiting factor. The profile is a program that remembers the gross characteristics of the fine control phasing program. It is generated at the discretion of the operator, and is used as a backup to the updates. Since it is an output phase program, it does not have the same stability problems of a feedback network.

Operations

The main accelerator has been operated at 200, 300, and a small amount of time at 400 GeV operating levels. The operation of the accelerator at levels of greater than 300 GeV is hampered by two things, at present. The contract with the Commonwealth Edison Company only allows for joint power studies at levels greater than 300 GeV. From studies over 300 GeV, the voltage fluctuation on the 345 kV lines is in excess of the power company's recommendations. The second reason is that the master substation transformers are not rated for the pulsed load required at 400 GeV and beyond. 500 GeV operation would, at present, require more real power out of the substation than it can presently deliver. (See Figure 8) Operation at a 300 GeV level has been continuing for several months and seems to be a reliable mode of operation.

Regulation

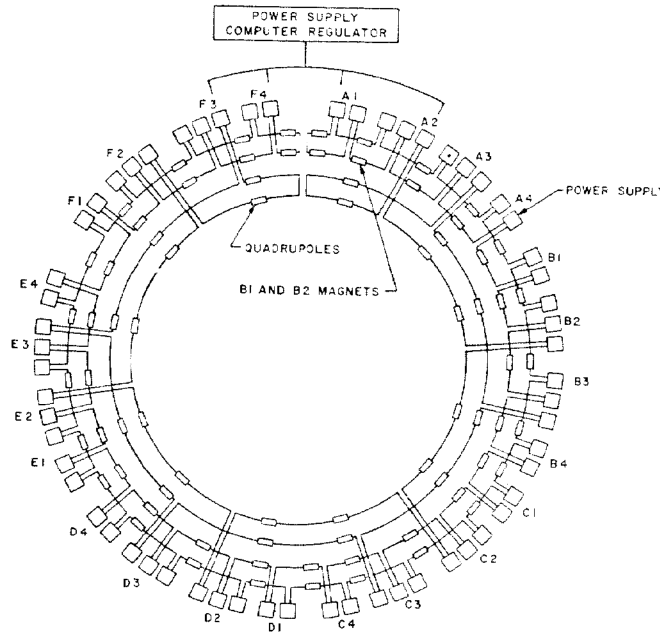
The regulation of the flat-top condition has been better than originally designed in terms of the bending magnets. The field values have been able to be maintained at ±2 gauss for nearly all energy levels. This is primarily due to the A/D minimum bit size, noise in the A/D, and the errors introduced when changing from the second harmonic to the integrators. At injection, the regulation is comparable to the design requirements of .05 in tune for the quadrupole regulation and .01% for the bending, if the interpretation is that .01% means synchronize with the booster. (See

Figure 9) However, at present the magnet's remnant fields, that is the average remnant field, seem to differ, depending upon the exact way in which injection is approached from the invert or the recovery portion of the magnet field waveform. At present, the response to the invert portion of the program is not as reliable as could be expected. Noise has been interferring with the bypass portion of the firing generators in some of the supplies, resulting in erratic behavior in the invert conditions.

At present, the program that calculates the turn-on order has some difficulties in the invert sequence in exactly calculating the invert waveform generator breakpoint times. These problems result in an invert part of the waveform that does not have the stability desired. The instabilities change the way in which injection is approached, and thereby the average injection field in comparison with the one point measurement at the monitoring magnets. At present, this invert instability requires nearly .3 seconds to recover to injection. The flat-top regulation, although it is within the .01% for both the bending and quadrupole fields, still presents difficulties with resonant slow extraction. A very small amount of tune change results in large modulations in the slow extracted beam. Active filters have been installed on all of the quadrupole power supplies in order to reduce the slow extraction ripple.[5] Due to the separated function nature of the accelerator, and the fact that the RF is turned off during extraction, the tune is primarily determined by the quadrupoles and not the ratio between the quadrupoles and the bending magnets. Therefore, during extraction, the measurement of the quadrupoles is switched from that of the difference between the bending and quadrupoles to just the quadrupole fields. An integrator with a resolution of 5 times that of the difference integrator is used. Unfortunately, however, the sextupole component of the bending magnets is not as yet corrected during extraction, resulting in tune changes due to variation in the bending magnet's fields. More work will still be required to reduce the modulation of the slow extracted beam.

References

1. R. Cassel and H. Pfeffer, "The Power Supply System, Control, and Response of the NAL Main Accelerator", IEEE Trans. Nucl. Sci. NS-18, 860, (1971).
2. R. Cassel and J. E. VanNess, "Direct Powering of the 200 GeV Synchrotron Magnets from the Utility System", IEEE Trans. Nucl. Sci. NS-16, 672, (1969).
3. D. F. Sutter, "A Multiplexed Control System for the NAL Main Accelerator", IEEE Trans. Nucl. Sci. NS-18, 432, (1971).
4. R. Yarema, "Main Accelerator Injection Field Monitoring and Regulation", NAL Internal Report, April 1972.
5. R. J. Yarema and R. L. Cassel, "NAL Quadrupole Power Supply Active Filter", This Conference, Paper No. F-24.



MAIN ACCELERATOR POWER SUPPLY DISTRIBUTION

FIGURE 1

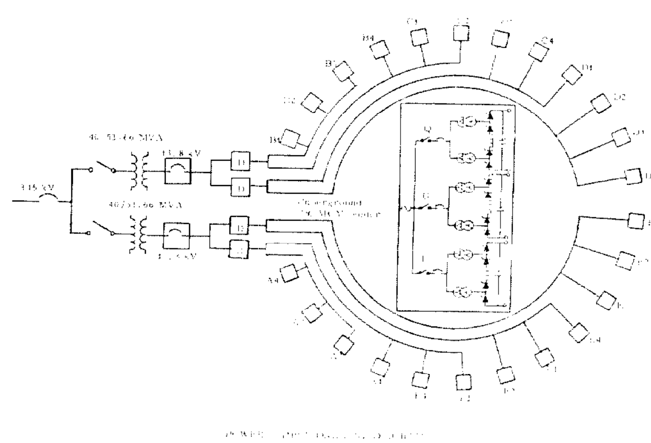


FIGURE 2

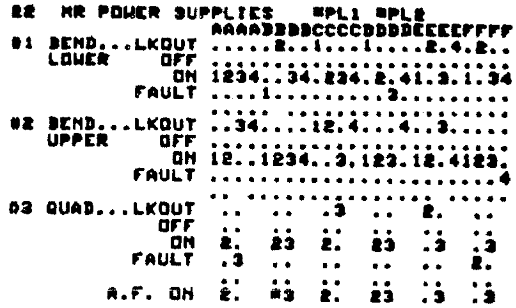
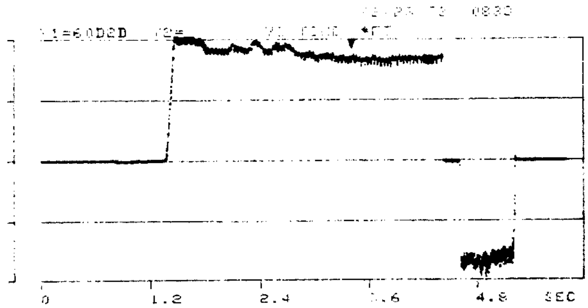


FIGURE 3 POWER SUPPLY AC CONTROL



POWER SUPPLY PROGRAMMED OUTPUT

FIGURE 4

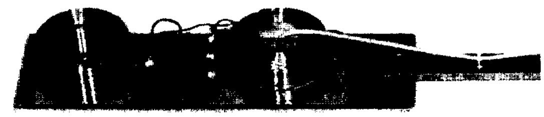
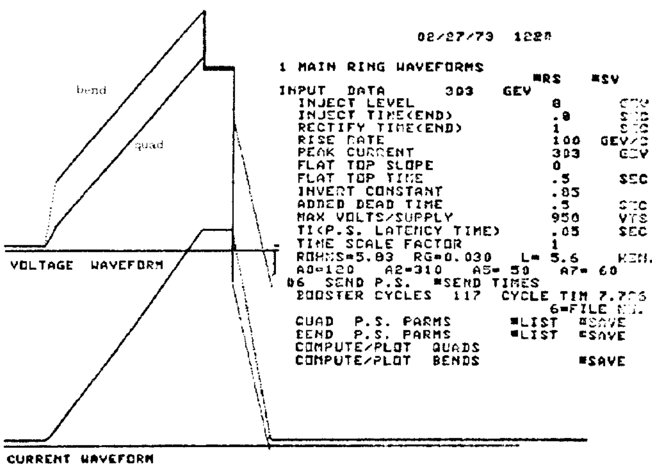
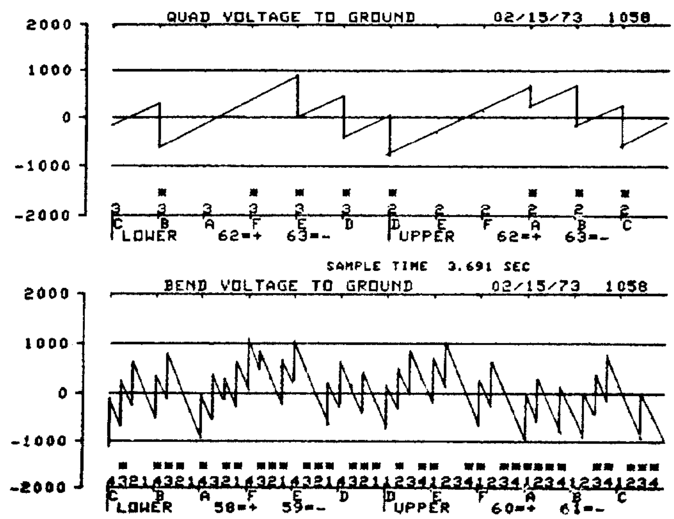


FIGURE 5. 2ND HARMONIC PROBE ASSEMBLY



MAIN RING WAVEFORM PROGRAM

FIGURE 6



VOLTAGE TO GROUND AROUND THE RING AT 300 GEV

FIGURE 7

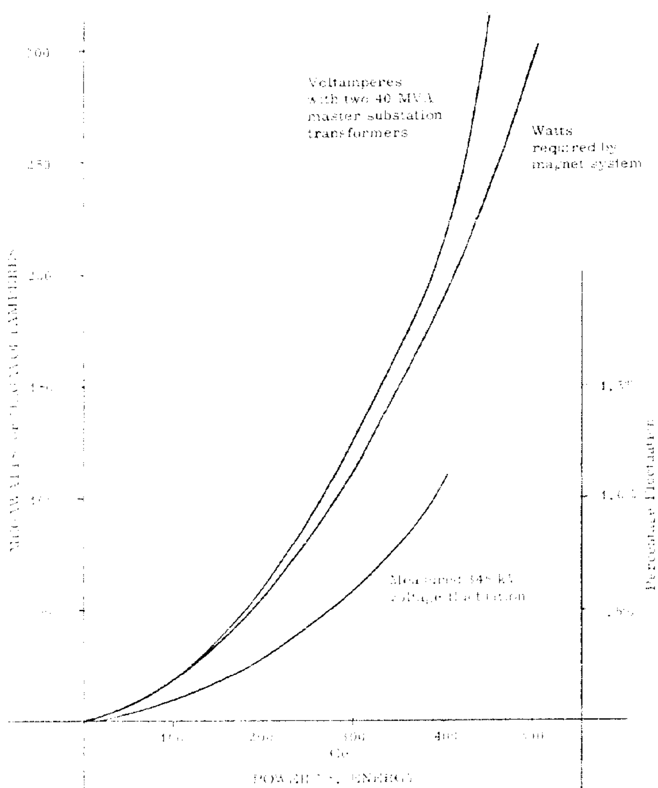
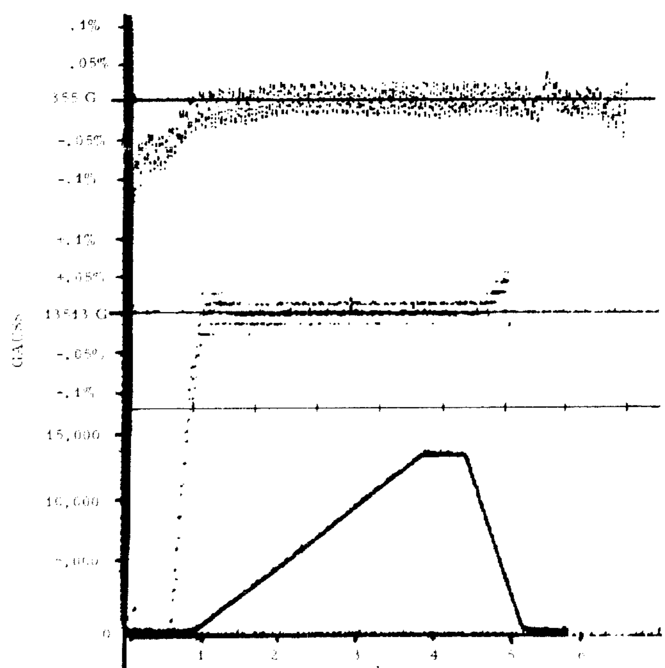


FIGURE 8



REGULATION AT 300 GEV

FIGURE 9