# CONTROL OF THE BEVATRON/BEVALAC MAIN GUIDE FIELD POWER SUPPLY FOR FAST ION SWITCHING OPERATION*

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## Abstract

The Bevatron/Bevalac Main Guide Field Power Supply stores 680 Megajoules in the flywheel-shaft systems of two independent motor-generator sets. During the normal acceleration cycle of various heavy ion beams the energies of the rotating shafts is converted to energy stored in the main magnet guide field. At the end of the acceleration cycle the magnet energy is inverted back to the shafts. Generally this takes place from 10 to 15 times per minute. The rapid switching of ions, energy and beam lines at the Bevalac has required various control techniques for fast switching between all operational Bevalac Fields within one minute.[1] The Power Supply control systems and operating parameters are described.


## Introduction

Ideally, the heavy-ion radiotherapy program at the Bevalac complex should be transparent to the nuclear science program.[2] This means that most of the operating time should be spent in the non-therapy mode, with operations transferred to the therapy mode only at the time of patient treatment. The Bevalac day to day operation exhibits fast reproducible changes of:

1) target area/beam line,
2) energy, and
3) ion.

Making these changes in less than one minute defines the fast switching operation at the Bevalac. Beam line switching with no energy or ion change was accomplished first and has been in regular use for several years. A different energy, or a different ion, or both is required to use the interpatient time effectively.

The Bevatron magnet is a weak focusing magnet 100 feet in diameter. It is constructed of 88 turns of 1750 MCM. copper cable. The unsaturated magnet inductance of 5.6 Henry and the resistance of 0.250 ohms results in a 22 second time constant. To fast-switch with this load a total of seven closed-loop control systems are required. Figure 1. is a one line diagram of the power supply showing all feedback loops except for the generator voltage control loop.

## The System - Physical Plant

The Bevatron/Bevalac main guide field power supply includes two motor-generator sets that energizes the Bevatron magnet. Each set includes...

1. A 46 MVA. Synchronous Generator.
2. A 67 Ton Flywheel (Total shaft weight = 128 Tons).
3. A 3600 horsepower motor powered at 12,000 VAC.

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The electrical outputs of the generators are rectified by Ignitron Rectifiers. In original Bevatron operation the rectified peak power was about 128 Megawatts: 8333 amperes at 15,500 volts. This peak power value is no longer scheduled at the Bevatron/Bevalac and a peak of 80 Megawatts is more the rule.

The blocks labeled 1A through 4A and 1B through 4B each represent 3 phase 1/2 wave Ignitron rectifier power supplies rated at 16 MVA (4000 volts DC at a peak current of 4000 amperes). The circuit shown in Figure 1. provides the minimum speed range change, for the shafts, during two MG Set operation. Synchronization of the two MG Sets is required in this configuration. The power distribution system is a conventional 12,000 VAC. industrial power system rated at 29 MVA.

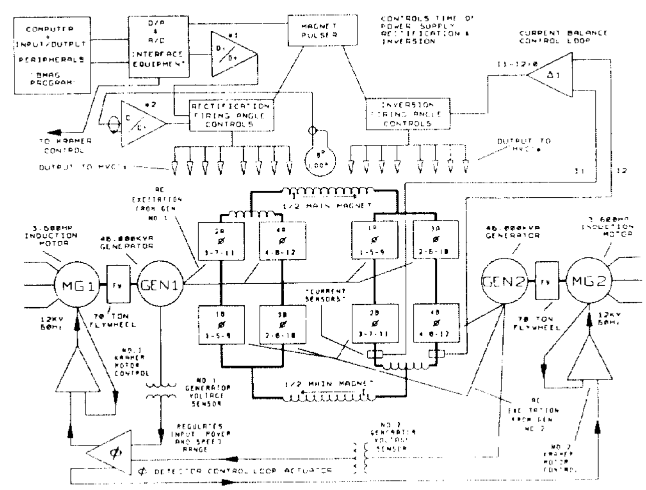


Fig. 1 Bevatron Magnet Power Supply - System Block Diagram.

## Description of Operation

The present day operation of the Bevalac calls for the following operational cycle:

Acceleration:
As the rectified current from the generators to the Bevatron Main Magnet increases, the MG Sets slow down. Stored energy in the shaft is converted to energy stored in the magnet field. Figure 2. illustrates the Current, Voltage and Generator Speed Range for the 12,575 Gauss Flattop Pulse at the Bevatron.

Flattop:
When the required magnet field is reached, and in order to provide a longer period for spilling the particle beam, a Flattop Field is provided. The Flattop is developed by switching 1/2 of the rectifiers into an inversion mode which subtracts from the voltage of the remaining rectifying units. The difference voltage is programmed to insure there is enough driving voltage to just equal the magnets resistive voltage drop. The magnet current and field can then be maintained for a time determined by the RMS value of the pulse. A typical Bevatron 12.575 Kilogauss field flattop is 1.7 seconds, with a 10 pulse per minute repetition rate .

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Full Inversion:

At the end of the flattop period the remaining rectifiers are programmed as inverters. This returns most of the energy stored in the magnet to the shaft system. The power provided by the motors must make up for the losses in the system.

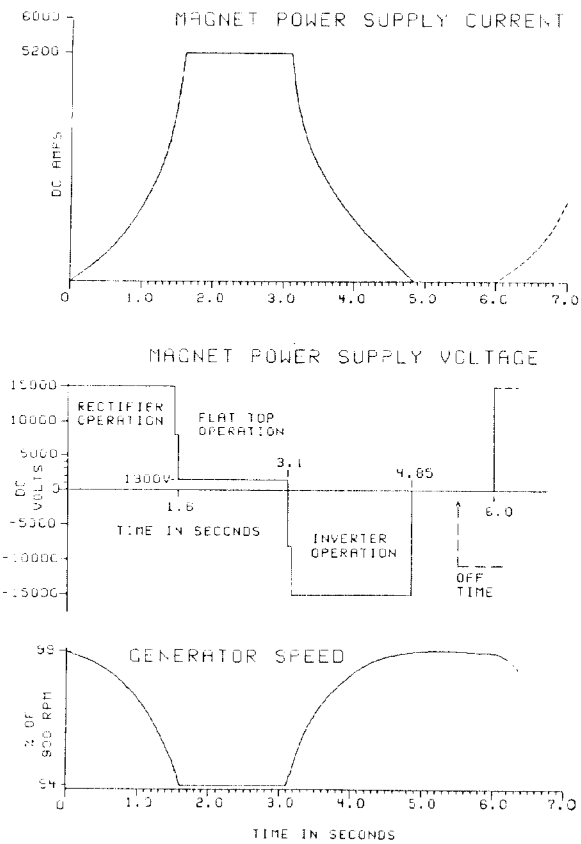


Fig. 2 Bevatron Magnet Power Supply - Current, Voltage and MG Set Speed

Table 1. shows some of the electrical parameters of the Bevatron Pulse while the magnet field builds to the flattop level. "TIME" is time into the magnet pulse. The table is derived for 2 MG SET operation. Each MG Set is supplying 1/2 the energy total (Ut).

| Time sec. | I amps | Mag E. kv | Field gauss | L hy | Power mva | Ut mj |
|---|---|---|---|---|---|---|
| 0 | 0 | 15.0 | 0 | 5.65 | 0 | 0 |
| 0.250 | 710 | 15.1 | 2,150 | 5.65 | 10.7 | 1.4 |
| 0.500 | 1440 | 15.1 | 4,398 | 5.55 | 21.7 | 5.8 |
| 0.750 | 2200 | 15.5 | 6,717 | 5.26 | 34.1 | 13.3 |
| 1.000 | 3050 | 15.3 | 9,822 | 4.58 | 46.7 | 24.0 |
| 1.200 | 3960 | 15.2 | 10,872 | 3.68 | 60.2 | 29.3 |
| 1.584 | 5133 | 15.3 | 12,575 | 2.15 | 78.5 | 49.9 |

The inductance of the Bevatron Magnet is approximately 5 Henry at the start of the pulse and 2.15 Henry at the peak due to magnet saturation.

## Pulse Scenario
## Closed Loop Systems

The loading of the two generators must be closely balanced as the magnet pulse is developed. Synchronization of the two shafts is held to ± 1.5 electrical degrees when the outputs of the two generators are compared. Synchronization is a requirement to insure:

- Minimum speed change ($\Delta$RPM) during the pulse.
- Minimum voltage ripple components.
- Power balance between the two systems.
- All control systems operate in the middle of their operating range.

The following scenario outlines the fast switch from a low to a high field. Just prior to the request for the change the operating field might be 4,398 Gauss. With this field the Bevatron usually pulses with a 15 Pulse Per Minute (PPM) repetition rate and a 1.5 second flattop length. The speed range of the two shafts, during the pulse, is monitored and displayed as:

Speed range (RPM):

| Mag on | Flattop on | Flattop off | End of Inv |
|---|---|---|---|
| 889 | 885 | 884 | 889 |

When the request is made to fast switch to 12,575 Gauss, the Power Supply Operator inputs to the computer the name of a previously defined pulse profile, in this case 12575.2T5. The extension tells the operator it is a 2 MG Set operation on Tap 5. Tap 5 is a Generator Voltage Reference that defines the field slope during the beam acceleration period.

**1. Computer Control Loop** The computer has field, repetition rate, and flattop length data in a field profile data base. The computer has displayed the operating parameters in the following form...

Analysis of Profile 12575.2T5

| t to field (msec.) | field (gauss) | t at field (msec.) | current (amperes) | opt |
|---|---|---|---|---|
| 1584 | 12575 | 1250 | 5133 | B |

Pulse length = 4684 msec.

Speed range (RPM):

| Magnet on | Flattop on | Flat top off | End of Inv |
|---|---|---|---|
| 880 | 849 | 844 | 878 |

Two machine operation only:

| | |
|---|---|
| 6.0 PPM | 3556 KW |
| 8.6 PPM | 4404 KW |
| 10.0 PPM | 4863 KW |

During the next Bevatron pulse the computer changes the repetition rate to 10 PPM, and the new value of 12575 gauss is loaded into a field comparing scaler. The Option B designation has preset, via a control microprocessor, the firing angle of the Ignitron rectifiers for both the rectification and inversion modes. This data has been logged during an initial operating period for the requested field. These values are seldom changed after the initial entry. A voltage to frequency converter continuously counts at a rate proportional to the change in magnet field. When the total counts equal the scaler value the power supply is switched to the flattop mode. Figure 3. shows a block diagram of the components in the Computer Control Loop.

During this first high field pulse, the rectification period has been lengthened by more than a full second. Table 1 shows that peak power from the generators has gone from approximately 22 MW to 78 MW. The speed range of the two MG sets has now changed. In this scenario the closed loops would be active in the following modes...

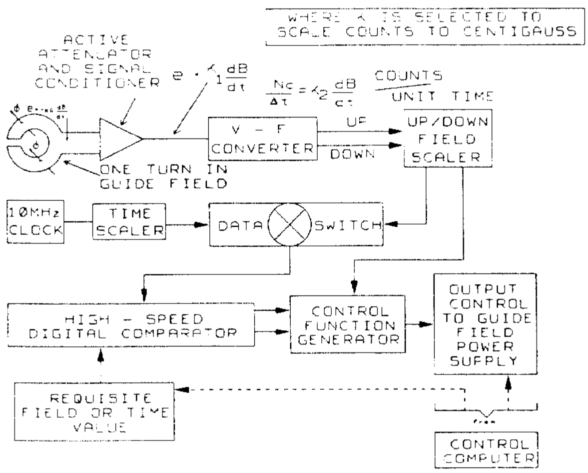


Fig. 3 Bevatron Magnet Power Supply - Computer Control Loop

**2. Kramer Control Loops (2)** The two Kramer control loops define the speed-torque curves that the MG sets will traverse during the pulse. These loops regulate the shaft torque by controlling the rotor currents of the 3600 horsepower motor. The main components of the Kramer control loops are shown in Figure 4.

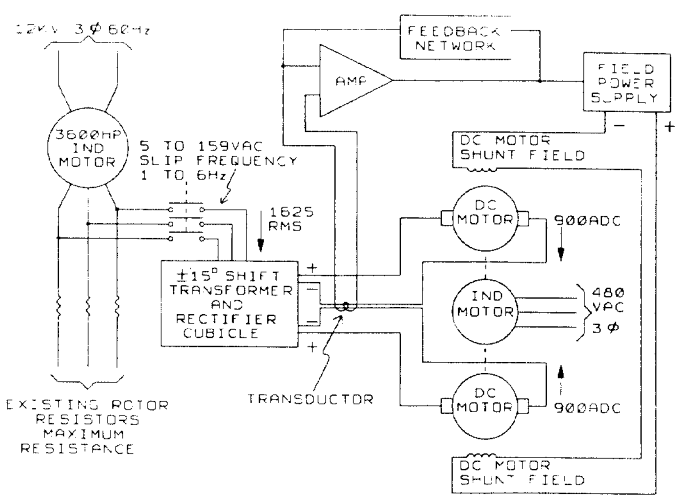


Fig. 4 Bevatron Magnet Power Supply - Kramer Control Loop

**3. Synchronizing Phase Loop** It would be desirable, while changing from the first shaft loading to the second, to have the two MG sets track without error. A second closed loop, the Synchronizing Phase Loop, is added to the overall system to reduce any tracking error. This control loop synchronizes the speeds of the two MG Sets by comparing the phase error between the outputs of the two generators. This phase error is fed back into the two Kramer control systems.

**4. Generator Voltage Control Loop** - This control system monitors the output voltages of the two generators and insures that the sum of the two outputs are regulated to a reference value. Control limits also require the output of the two generators to be equal. Thus, the control parameters of this loop are...
(Gen 1. AC) + (Gen 2. AC) = A Constant.
(Gen 1. AC) - (Gen 2. AC) = Zero.

**5. Current Balance Control Loop** - It is desirable to have the DC. currents in the parallel branches balanced. The Current Balance control loop provides an error proportional to the difference in these currents. This error feeds into the firing circuits that control the output voltages of the Rectifiers and balances the currents in the parallel paths.

**6. Flattop Field Slope Control (DI/DT) Loop** - After the field at Flattop is established to an accuracy of 1 Gauss the resultant voltage on the Bevatron Magnet must be regulated to provide the proper field slope. The DI/DT loop is closed by feeding a voltage from a single turn B-dot winding and regulating this voltage to a constant. This loop regulates constant field slopes from a 1 gauss per second rate to 300 gauss per second rates. This loop controls the firing angle and the resulting output voltage of the rectifying units during flattop.

## Control Simplification
## 1 MG Set Operation

In order to provide power savings the system can be powered by only one MG Set for magnet fields below 7650 Gauss. This is a significant reduction in the complexity of the control system. Field changes are usually stabilized in 3 or 4 Bevatron pulses.

## Conclusion

The necessity for providing the controls to allow the Bevatron/Bevalac Power Supply to quickly change field levels has made the system more reliable and efficient. Each control loop that was described has been optimized to make it possible to operate in the fast switch mode.

In terms of the present day operation of the Bevalac it allows two different ions such as neon and helium, at different energies, to be delivered to two different patient treatment areas within 1 minute.

In summary, the control loops maintain the operating parameters to the following precision.

- Field: ± 1 Gauss @ 12, 575 Gauss.
- Field Slope during Flattop: ± 0.5 Gauss per second.
- Power balance between the two MG Sets: (each motor loaded to 2.5 Megawatts) ± 80 Kilowatts.

Note - The two Generators are each loaded to 41.2 Megawatts at the peak of the 12,575 Gauss pulse.

- Output voltage differential between the two Generators: ± 16 VAC @ 5600 $VAC_{L-L}$.
- Balance of current in the parallel branches: ± 10 Amperes @ 2600 Amperes per branch.
- Synchronization of the 2 MG Set shafts: ± 1.5 degrees (electrical) for the 8 pole Generators.

## References


[1] F. Lothrop, et al, "Mixing and Matching Bevalac Programs - A Progress Report on Rapid Switching of Ions and Other Operational Highlights." Presented at the 1987 Particle Accelerator Conference, Washington, DC, March 16-19, 1987.

[2] F. Lothrop, et al, "Achievement of Bevalac Rapid Mode Switching." Presented at the 1985 Particle Accelerator Conference, TRIUMF, Vancouver, B.C., Canada May 13-16, 1985.