BOOSTER MAIN MAGNET POWER SUPPLY IMPROVEMENTS FOR NASA SPACE RADIATION LABORATORY # AT BNL *

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Abstract
The NASA Space Radiation Laboratory (NSRL), constructed at Brookhaven National Laboratory, under contract from NASA, is a new experimental facility, taking advantage of heavy-ion beams from the Brookhaven Alternating Gradient Synchrotron (AGS) Booster accelerator, to study radiation effect on humans, for prolonged space missions beyond the protective terrestrial magnetosphere. This paper describes the modifications and operation of the Booster Main Magnet Power Supply (MMPS) for NSRL applications. The requirement is to run up to 1 sec flattops as high as 5000 Amps with 25 % duty cycle. The controls for the Main Magnet Power Supply were modified, including the Booster Main Magnet application program, to enable flattop operation with low ripple and spill control. An active filter (AF) consisting of a +/- 120 volts, +/-700 Amps power supply transformer coupled through a filter choke, in series with the Main Magnet voltage, was added to the system to enable further ripple reduction during the flattops. We will describe the spill servo system, designed to provide a uniform beam current, during the flattop. Results from system commissioning will be presented.

PARAMETERS

The Booster MMPS consists essentially of six pairs of thyristor controlled power supplies connected in series (the actual implementation is in 2 stations). Each pair is a 24 pulse controlled rectifier, rated at +/- 1000 volts dc, see Figure 1. For NSRL application only IAB and IIAB power supplies are used, because they are rated for 5000 Adc, while the rest of the units are rated for 2800 Adc. During the flattop only IAB unit will be on while IIAB is in bypass. The key parameters for the Booster MMPS are shown in Table 1.

Table 1: Booster MMPS ratings

Voltage dc max at 2800 amps dc max	+/- 6 kV
Voltage dc max at 5000 amps dc max	+/- 2 kV
Current dc max at +/-6000 V dc max	2800 A
Current dc max at +/-2000 V dc max	5000 A
Fundamental Ripple Frequency	1440 Hz
Magnet Resistance (R)	0.107 Ω
Magnet Inductance (L)	0.145 H
Nominal pulse rep. Rate for NSRL	4 sec
Nominal Flattop for NSRL	1 sec
3600 KVA Transformer primary current rms	150 A

Even though the units are operated as 24-pulse controlled rectifiers, the ripple requirement at flattop is very stringent. Note that running the power supply for NSRL application at 5000 A, with 1 sec flattop and a repetition rate of 4 sec, the 3600 KVA transformer's primary current was measured to be 145 A rms, which is very close to the rating of the transformer see Table 1. For that reason the Nominal pulse repetition Rate for NSRL was set to 4 sec with a Nominal Flattop of 1 sec, under the worst case flattop current of 5000 A.

ALGORITHM MODIFICATIONS

As noted in the previous paragraph, the Booster MMPS consists essentially of six pairs of thyristor controlled power supplies connected in series. There are bypass SCR's across every pair, except pair IAB. There is a Booster application program that calculates 6 voltage references and one current reference, based on a required magnetic field pulse. If the required magnet voltage is 2000 volts as it is the case for NSRL application, only pairs IAB and IIAB are used. The rest of the pairs are in bypass mode, meaning that the bypass SCR's are turned on automatically. During the 5000 A flattop however, the flattop voltage is 535 volts dc. With the original algorithm of the Booster application program, unit IIAB was firing at 0 volts during the flattop, and unit IAB was firing at 535 volts. As a result the ripple from unit IAB was added to the ripple from unit IIAB and this resulted in unnecessary voltage ripple during the flattop. Note that the most contribution to beam spill modulation, is due to the voltage ripple of the Booster MMPS during the flattop. The Booster application program, was as a result modified, to place unit IIAB in bypass mode during the flattop, since the total voltage needed 535 volts dc, was accommodated by unit IAB. At the end of the flattop however, unit IIAB had to be turned on to ramp down the current, using –1000 volts. For that reason the Booster application program was also modified, so that unit IIAB's voltage reference was becoming positive for 50 msec with an amplitude of 100 volts to commutate the bypass SCR off and then was going negative to –1000 volts.

ACTIVE FILTER DESIGN

As mentioned above, one of the most critical contributions to beam spill modulation, is due to the voltage ripple during the flattop of the Booster MMPS. The fundamental frequency at flattop is 1440 Hz.

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However we have harmonics mostly at 60 HZ, some at 120 Hz, 180 Hz, 240 Hz, 300 Hz and 360 Hz, see Table 2. The damped passive filter at the output of the MMPS is a 40 db per decade filter with the 3-db point set to 400 Hz. As a result this filter attenuates frequency harmonics above 400 Hz without any attenuation at frequency harmonics below 400 Hz. The MMPS voltage ripple requirement by the spill, is an order of magnitude of 1 to 3 volts peak, for frequencies below 500 Hz. Therefore, in order to create a filter with the robustness required by the continuous and flexible operation of the Booster, it was decided to use a series transformer/choke as the coupling element to the MMPS circuit. Note that this design is already implemented as part of the AGS MMPS for the same reasons, with great success. The idea was to derive the ac component of the Booster MMPS voltage ripple during the flattop and inject it, 180 degrees out of phase as a voltage reference, into a voltage regulated power supply, connected to the series transformer/choke with the Booster magnets. As a result the coupled voltage through the transformer/choke would cancel out the actual Booster MMPS voltage ripple. A voltage regulated power supply rated at +/-120 Vdc, +/-700Adc, drives the series transformer/choke. The ac ripple during the flattop of the Booster MMPS, is fed into tuned filters with adjustable gains and phases, and the output of the tune filters drives the power supply. The tuned filters are tuned to correct 60 Hz, 120 Hz, 180 Hz, 240 Hz, 300 Hz, and 360 Hz. The power driver is a commercial, bipolar, 4-quadrant, switch mode power supply. The switching frequency is ~44 kHz, which results in a constant voltage full power bandwidth of 1.5 kHz. The input voltage is 480V three phase and can be disabled through a fuse disconnect switch. The back EMF from the Booster MMPS while the Booster MMPS is pulsing at +/- 6000 Vdc, is 20 Vdc peak-to-peak. The inductance of the transformer/choke was measured to be 25 mH and the resistance of it was measured to be 100 mΩ. Figure 1 is a block diagram of the overall system.

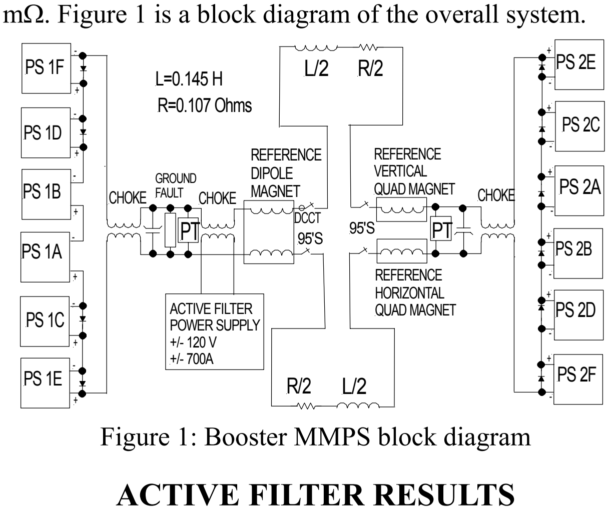

Figure 1: Booster MMPS block diagram

ACTIVE FILTER RESULTS

The active filter power supply system was fully commissioned with very encouraging results. We run a 3000 amps NSRL cycle for the Booster MMPS, with 0.5 sec flattop and a repetition rate of 5 sec. This cycle was being used to commission the NSRL extraction line. With the active filter power supply off, we measured 55 volts peak to peak, magnet voltage ripple during the flattop. See oscilloscope Figure 2. Then we turned on the active filter power supply and independently adjusted the gain and phase of the tune filters feeding the active filter power supply for 60 Hz, 120 Hz, 180 Hz, 240 Hz, 300 Hz and 360 Hz. Oscilloscope Figure 3, shows the magnet voltage ripple during the flattop to be 27 volts peak to peak from 55 volts previously stated. Figure 3 also shows the active filter power supply voltage of 230 volts peak to peak, coupled through the transformer/choke into the main magnet voltage. The major component as can be seen is 60 Hz. Table 2, shows the magnet peak voltage ripple as a function of frequency, as measured by a spectrum analyzer with the active filter on and off, at the flattop current of 3000 A. Note that the MMPS 60 Hz harmonic was improved by a factor of 10. The rest of the MMPS harmonics were improved by a factor of 4 to 7 depending on the frequency component. Figure 4, shows a $1x10^{10}$ protons, 300 msec extracted beam as measured by an ion beam chamber, with the active filter power supply off. Figure 5 shows the $1x10^{10}$ protons 300 msec extracted beam as measured by the same ion beam chamber, with the active filter power supply on. Note that the 60 Hz ripple on the extracted beam was improved by a factor of 4.5.

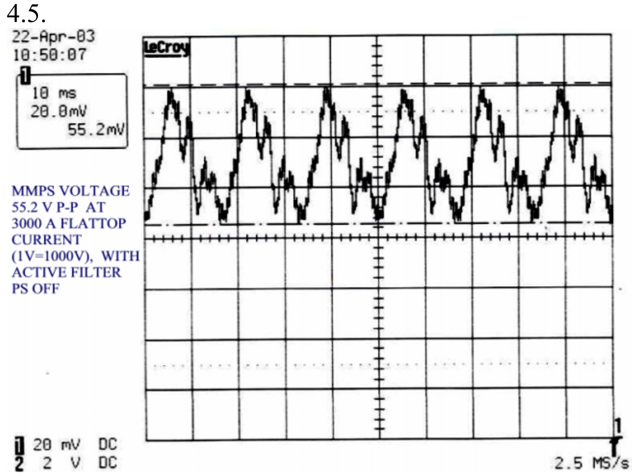

Figure 2: MMPS Flattop voltage, Active filter OFF

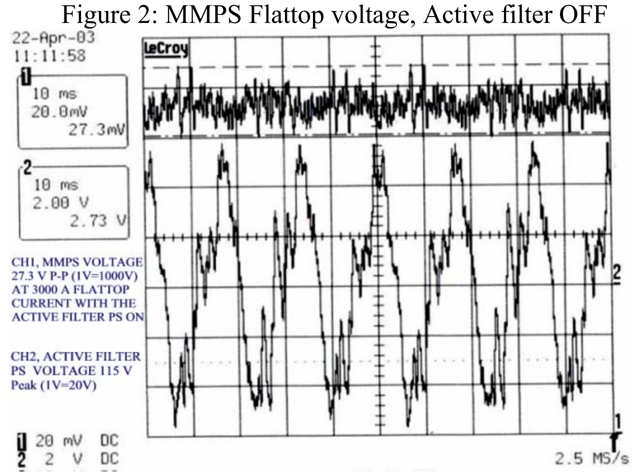

Figure 3: MMPS Flattop voltage and Active filter power supply voltage, Active filter ON

Table 2: MMPS Flattop voltages, Spill harmonics, Active filter ON and OFF (BLUE= Corrected frequencies)

Frequency (Hz)	MMPS Flattop Voltage Peak, At 3000A, Active filter OFF	MMPS Flattop Voltage Peak, At 3000 A, Active filter ON
60	16.38	1.56
120	7.0	0.96
180	3.06	0.48
240	3.78	0.54
300	2.4	0.54
358	0.84	0.12
378	1.95	0.48
420	2.4	1.2
720	0.84	1.32
1082	2.4	4.2
1440	4.44	6.3

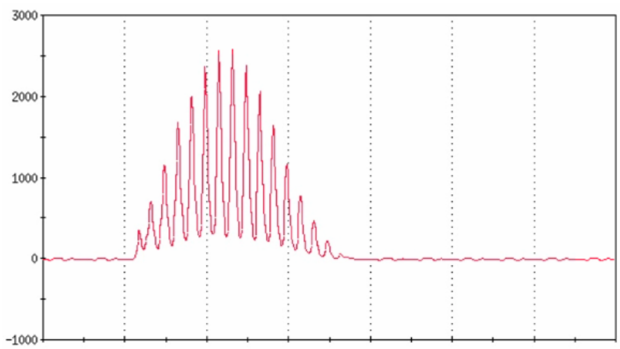

Figure 4: 1x10[10] protons, 300 msec Beam spill, AF OFF

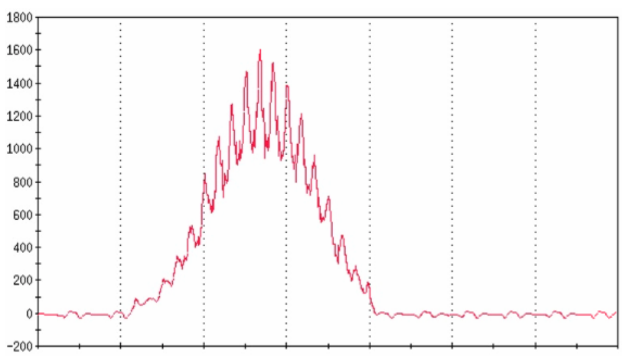

Figure 5: 1x10[10] protons, 300 msec Beam spill, AF ON

SPILL SERVO

The spill servo is a feedback loop used to dynamically adjust the MMPS flattop current in order to ensure a uniform beam spill with constant spill length. Figure 6 is a block diagram of the system. The Booster spill servo is identical to the AGS spill servo. It has been built but not been fully commissioned yet. Since the Booster MM time constant is 1.35 seconds, it has a corresponding load breakpoint frequency of 0.12 Hz and thus can control very well the average spill rate and spill length. There is a 0 to 10 volts Booster Circulating Beam monitor (CBM) signal, coming to a sample and hold circuit in the spill servo. The CBM signal is sampled at the timing event called spill start, which is usually 50 to 100 msec after the beginning of the flattop. The sample and hold, retains this value until another timing event comes in, called the end of flattop. This square wave signal is then multiplied by another 0 to 10 volts signal called spill rate. This signal through some amplifier gain, constitutes the actual spill reference of the spill servo loop. Once extracted beam is established, an ion chamber spill monitor intensity signal is used for measurement and for feedback. An error amplifier is then used to subtract the ion chamber spill monitor signal from the spill reference. The error signal is multiplied with another 0 to 10 volts signal, coming in the spill servo called the spill gain, which sets the gain of the loop remotely. This error signal is switched in only during the flattop and is being added to another signal coming in the spill servo, called the spill function. This signal is a 0 to – 10 volts square wave signal. The addition of these two signals goes through an integrator, which starts integrating at the beginning of the flattop and is being reset at the end of the flattop. The output of this integrator through some gain, is being added to the current error of the current loop of the Booster MMPS. Thus the MMPS flattop current is dynamically adjusted, in order to ensure a uniform beam spill during the flattop. Provisions are also made to learn what the spill error signal is through a data acquisition device and then play it back into the spill servo, without using the spill monitor feedback signal. This requirement, was set by NASA. Note that this provision does not exist in the AGS spill servo.

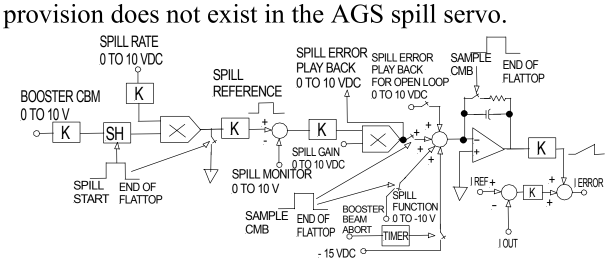

Figure 6: Booster MMPS Spill Servo

CONCLUSION

The algorithm modifications and the active filter have been fully commissioned. The 60 Hz ripple on the extracted beam was improved by a factor of 4.5. The 120 Hz, 180 Hz, 240 Hz, 300 Hz and 360 Hz components, were improved by a factor of 5 to 7 depending on the frequency. The spill servo has been built and is in the process of being fully commissioned.

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REFERENCES

[1] The active filter voltage ripple correction system of the Brookhaven AGS Main Magnet Power Supply. (WAR11) 1995 Particle Accelerator Conference.