Fermi National Accelerator Laboratory

FERMILAB-TM-2074

Report on Booster High Pulse Repetition Rate Operation Tests Conducted on March 29, 1998

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March 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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Compiled and Edited by Robert C. Webber

Introduction

The proposed MiniBooNE experiment requires pulses of 8 GeV beam from the Fermilab Booster at an average repetition rate of 5 Hz and expects to run simultaneously with both Tevatron Collider and NUMI experiment operation[1]. NUMI and antiproton production for the Tevatron Collider together require Booster beam on six consecutive 15 Hz cycles each 1.867 seconds (i.e. every twenty-eight 15 Hz cycles)[2]. In this same interval, nine to ten beam pulses are necessary to satisfy MiniBooNE. Booster is therefore expected to accelerate beam on sixteen of every twenty-eight 15 Hz cycles, corresponding to average beam pulse operation of 8.6 Hz.

The Booster cycle rate is nominally 15 Hz although not all Booster equipment is capable of pulsing continuously at that rate. The Booster gradient magnets are cycled continuously at 15 Hz, but the RF systems and pulsed injection and extraction devices are not. These devices are triggered on each beam cycle and on one or two 15 Hz cycles immediately prior to each beam cycle (or burst of 15 Hz beam cycles). This "pre-pulsing" is done to establish a fresh charge on energy storage elements in the power supplies and to reset remnant fields in preparation for beam. The pre-pulses result in an average pulse repetition rate for the power equipment somewhat higher than that of the beam.

A high pulse repetition rate test of all Booster systems was conducted on March 29, 1998, to identify equipment in need of modification, upgrade, or replacement in order to satisfy the expectations identified above. In general, Booster beam was not run during these tests. The procedure and results of the tests are described in this note.

Set-up

The accelerator timeline was set up with a repetitive cycle of 1.93 seconds (twenty-nine 15 Hz periods) to simulate the Collider/NUMI/MiniBooNE cycle. Limitations in the TimeLine Generator software were encountered at the time of the tests preventing setup of the exact cycle described in the introduction. Two timeline configurations were used during the tests. The first simply established a pulse repetition rate of approximately 7.5 Hz; the second more closely simulated the expected MiniBooNE operation cycle. The first timeline configuration was comprised of two Booster pre-pulse cycles (TCLK Booster reset event $12’s), followed by six Booster beam type cycles (TCLK Booster reset event $14’s), followed by two more $12’s, then four more $14’s, and finally fifteen null cycles (TCLK Booster reset event $11’s). For the second timeline configuration, the number of $14's in second group was increased from 4 to 10 to fully represent the MiniBooNE pulses. These timeline setups are shown in Figures 1 and 2.

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[1] A proposal for an experiment to measure $\nu_\mu \rightarrow \nu_e$ oscillations and ν_μ disappearance at the Fermilab Booster: BooNE, December 7, 1997.

[2] Private communication: Steve Holmes.

Different Booster equipment responds to different TCLK events. The 400 MeV chopper, injection orbit bump (ORBMP), RF bias supplies, extraction kickers, extraction septa are triggered on all pre-pulse ($12) and all beam type (e.g. $14) cycles. RF is applied to the accelerating cavities on all $14 cycles and on all but the first of successive $12 cycles. The ramped correction element magnets are programmed to run only on beam (e.g. $14) cycles.

The Tests

TimeLine #1

With the first timeline configuration, the RF bias supplies, extraction kickers, ORBMP, extraction septa, and 400 MeV chopper operate at 7.24 Hz (14/29 duty cycle), RF power amplifiers and cavities at 6.72 Hz (13/29 duty cycle), and Booster correction elements at 5.17 Hz (10/29 duty cycle). This timeline was installed at 10:55 hrs on March 29.

About 13 minutes after the timeline was loaded, the 480 VAC breaker in the transformer yard substation for RF station #15 tripped. This was not totally unexpected; these breakers were known to be marginal for high duty cycle RF operation. In fact, #15 was the only station that did trip even after nearly two hours of running at this rate. Inspection of #15 station showed that its bias supply needed to run about 100 amps higher than the typical station.

After 30 minutes operation at 7.24 Hz, the MP01 extraction septum at Long 13 was manually shut down due to high magnet temperature readings on both MP01 and ML01 magnets. MP02 extraction septum at Long 3 ran for 60 minutes before tripping on magnet temperature interlocks. Figures 3 and 4 show the temperature rise of the MP01 and MP02 magnets. The temperature sensors, exact placement unknown, are attached to the magnets internal to the vacuum box. The septum magnets were known to be weak links for high repetition rate operation. Due to the magnet heating problems, we were unable to further test the septa power supplies themselves. However, design specs for the power supplies rate them only for 50%, i.e. 7.5 Hz, operation.

Also after 30 minutes of operation, vacuum interlocks shut down ORBMP and GMPS power supplies and closed beam valves at the injection girder. This trip was reset and the supplies were brought back on without problem. Heating and outgassing of the ORBMP magnets is suspected to have caused the trip. The conductors and laminations of these magnets are internal to the vacuum system.

Figures 5 and 6 show plots of the ring vacuum early in the tests and one hour into the tests respectively. Notice higher pressures around MP01 and the Long 13 area early in the tests before MP01 was turned off and then higher pressures around the injection region in the later plot as the ORBMP magnets heated. After two hours of operation with this timeline no additional vacuum problems were identified. Approximately 90 minutes into the test period, beam was momentarily switched on and observed to still accelerate through the Booster; this, of course, is the true test of all the systems.

TimeLine #2

At 13:00 hrs, the second timeline configuration was loaded with the six additional $14 cycles to simulate the full NUMI plus 10 pulse MiniBoone cycle each 1.93 seconds. This increased the RF bias supply, extraction kicker, 400 MeV chopper and ORBMP pulse rate to 10.34 Hz (20/29 duty cycle), the RF power amplifiers and cavities to 9.83 Hz (19/29 duty cycle), and the correctors to 8.28 Hz (16/29 duty cycle).

With this timeline, both East and West Booster RF Anode supplies quickly tripped on AC Input Overload indications. Dave Wildman suggested this settable trip limit might be increased without endangering the RF equipment, but it was decided to not make any changes at that time. RF was reset and operated minus two modulators in each gallery to avoid the Anode Supply trips. All bias supplies except #15 ran at 10.34 Hz for about 30 minutes without breaker trips.

After only six minutes on this timeline, vacuum interlocks around the injection region took down ORBMP and GMPS, and closed gate valves at the stripping foil, VB-24, and VB-03. The problems again were believed to be due to ORBMP magnet heating and outgassing. Figure 7 records the ORBMP magnet temperature rise during the tests. The ORBMP temperature sensors are attached to the outside of the magnets, insulated from the core temperature by the electrical insulation between the core and the outer skin. GMPS was reset and ran for another 30 minutes with the injection area valves closed. GMPS then tripped again and was left off.

ORBMP was reset after each of the vacuum trips and allowed to run at 10.34 Hz until, after running nearly an hour at this rate, a burning smell was detected at the ORBMP AC transformer.

The 400 MeV Chopper and the Booster extraction kickers ran throughout the testing period without apparent problems.

At 14:17 hrs the high pulse repetition rate test was ended.

Summary and Conclusions

The Booster power equipment was operated at repetition rates up to about 10 Hz, pulsing each 20 of 29 15Hz cycles. Many devices performed well, but numerous problems were evident, some at significantly lower pulse rates.

The 400 MeV Chopper and Booster extraction kickers manifested no apparent problems even up to 10.34 Hz (20/29 duty cycle). Booster ramped correction elements, not normally cycled on the $12 pre-pulse cycles, showed no apparent problems up to 8.28 Hz (16/29 duty cycle). A follow-up remains to be done to assess the capability of the pulsed sextupole magnets. They ran during the tests, but there were no temperature monitors on these magnets to be monitored. The wire size used to fabricate the magnets should be checked to determine allowable RMS current.

ORBMP ran well for two hours at 7.24 Hz (duty cycle of 14/29). There was one vacuum trip in the ORBMP magnet region at that rate, but the vacuum recovered quickly and then held its own. Even at 10.34 Hz (20/29 duty cycle) the ORBMP PFN and discharge circuits ran well for an hour, however the AC transformer for the supply exhibited definite signs of overheating. The transformer must be replaced with one of higher capacity and more careful determination of power supply internal temperatures must be made before continuous operation at this rate is possible.

At 10.34 Hz the ORBMP magnets exhibited serious, but hopefully temporary, vacuum problems. The limitations of the transformer did not permit sufficient conditioning time.

Achieved magnet temperatures were not excessive, though they had not reached equilibrium before tests were ended. Presently 7 Hz operation of ORBMP appears satisfactory from the vacuum pressure perspective, but acceptable performance at 10 Hz was not achieved in the conditioning time possible during the test.

Heating problems of the extraction septum magnets are known to be a limitation at 3 Hz or higher operation. It was a surprising result of the tests however that MP01/ML01 temperature monitors indicated excessive temperatures earlier than those on MP02. The power supply designs are different such that capacitor charge recovery pulse current flows through the MP02 magnet whereas that for MP01 flows through a separate charge recovery reactor. Thus MP02 sees effectively twice the pulse rate as MP01! This inconsistency requires further investigation, but does not alter the fact that both systems suffer from unacceptably elevated magnet temperatures at the desired pulse rates. The heating in turn leads to vacuum problems since the magnet conductors and laminations are internal to the vacuum system. Plans are being developed to continue investigation of the magnet heating problems by running a spare magnet in the gallery powered by the MP02 supply. Substantial modifications to or redesign of the magnets is expected to be necessary. The capability of the septa power supplies has not been established; their design rating is 7.5 Hz.

Except for anticipated circuit breaker limitations, the RF systems exhibited no apparent problems at 7.24 Hz (14/29 duty cycle). At 10 Hz, Anode Power Supply trips did not permit operation of the full complement of power amplifiers, though the yard breakers for all stations except #15 did survive with the bias supplies pulsing. No cavity temperature measurements were possible during these tests. Such measurements should be done before discarding the possibility of cavity heating problems. All 480 VAC RF substation breakers should be upgraded to 225 amp rated breakers (some already are) for reliable operation at the high repetition rates. The condition and capacity of wiring between the substation breakers and gallery equipment must be established to determine if wiring replacement is necessary. The rating of components in the anode supplies must be investigated to determine the wisdom of raising the anode supply overload trip settings.

During 1998, new heat exchangers for the Booster 95 degree water system were specified and procured to replace aging equipment in the Central Utility Building. This equipment was sized with the anticipated higher pulse repetition rate in mind. Most of the heat absorbed by the water system is in fact from static rather than pulse rate sensitive loads. Water system capacity should not be a concern.

Finally, the present maximum pulse rate for selected essential Booster components and fixes necessary for improvement are summarized in Table 1.

Component	Maximum Pulse Rate	Limitation	Fix
MP01, ML01, MP02 magnets	2.5 Hz	Magnet heating and vacuum	Charge recovery reactor for MP02; new magnets with better cooling design to achieve 15 Hz
RF Station #15	5-7 Hz	Substation breaker due to high bias supply current	Replace breaker and, if necessary, AC wiring; possibly re-tune cavity mechanically
MP01 and MP02 Power Supplies	7.5 Hz	Design spec, and ?? power supply component heating at <15 Hz ??	To be determined; may require new power supply design for 15 Hz
ORBMP Power Supply	7.5 Hz	Design spec, AC transformer overheating at 10 Hz, and ?? power supply component heating at <15 Hz ??	Replace transformer; other modifications to be determined for 15 Hz
RF Anode Power Supplies	7.5-10 Hz	AC Input Overload, and ?? power supply component heating at <15 Hz ??	Adjust trip level; other modifications to be determined for 15 Hz
ORBMP magnets	10-15 Hz??	Magnet overheating and vacuum	To be determined; maybe simply conditioning
RF Stations	10-<15 Hz	Substation breaker overcurrent trips	Replace breakers and, if necessary, AC wiring
RF Cavities	<15 Hz??	Cavity heating??	To be determined

Table 1. Limiting pulse rates for selected devices

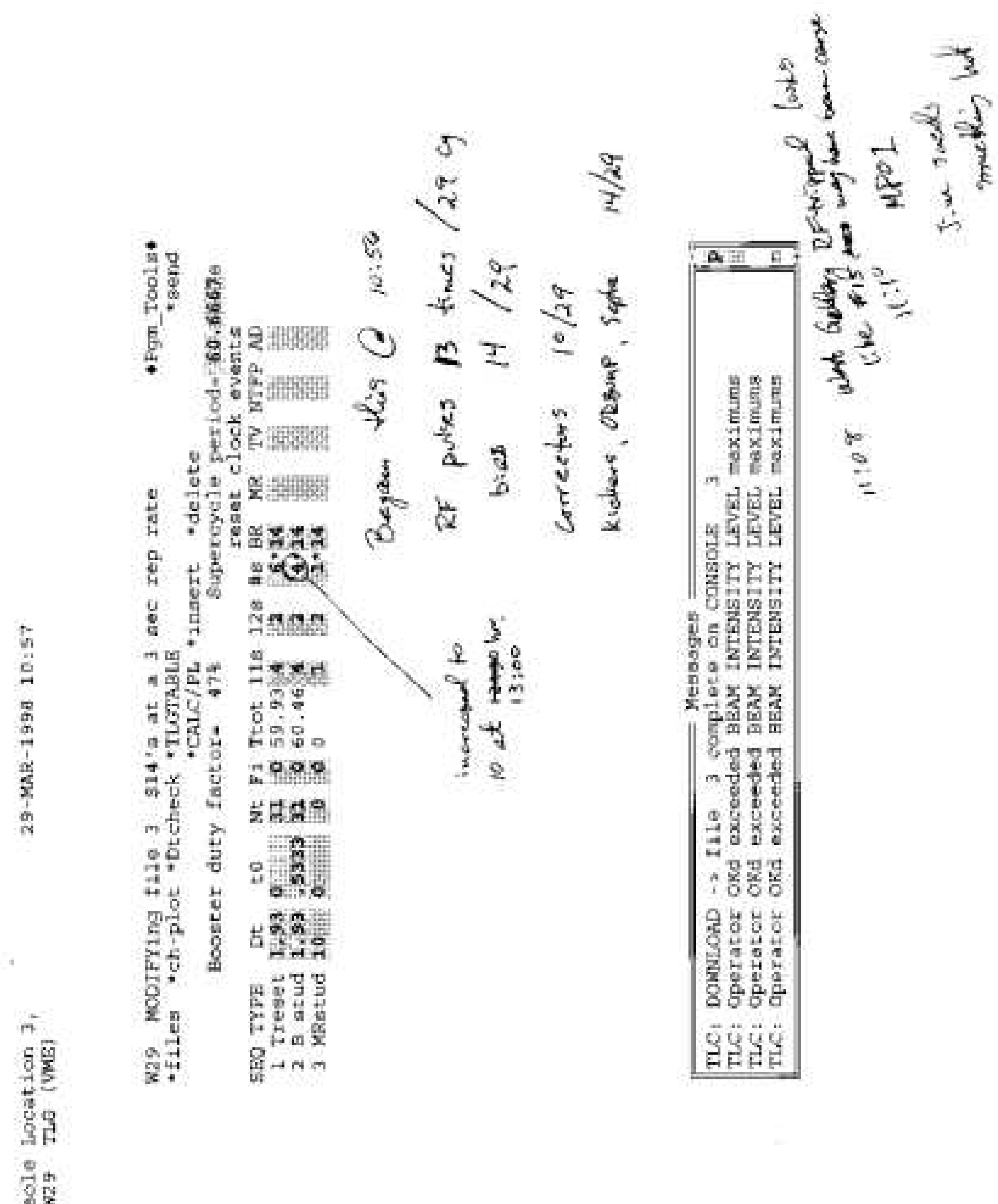


Figure 1. Timeline configuration for first two hours of Booster high pulse repetition rate test.

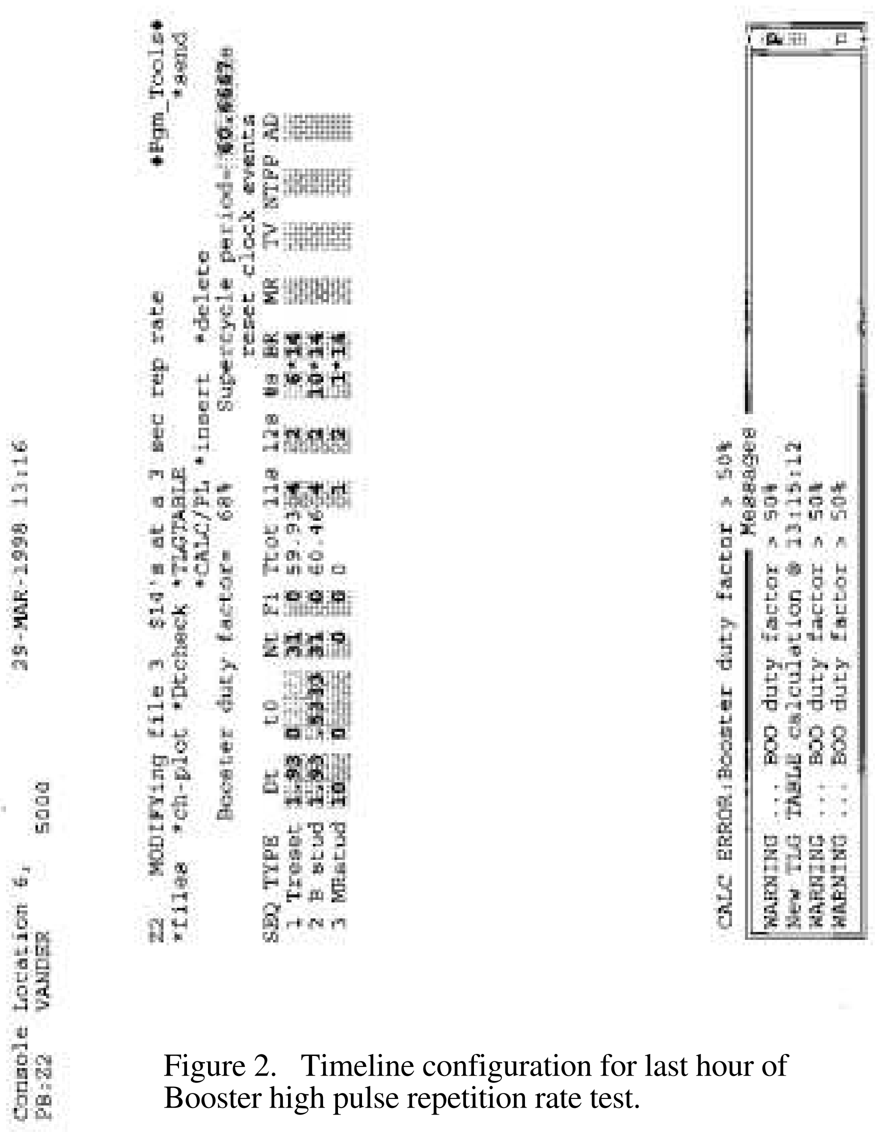
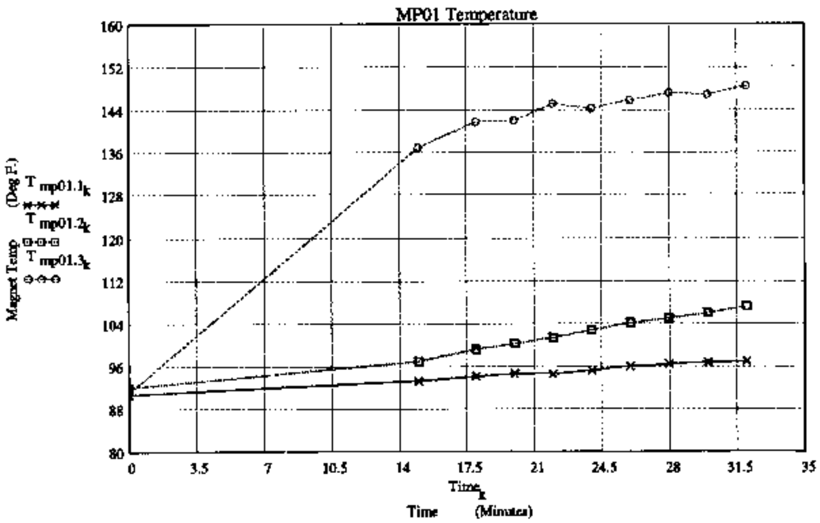
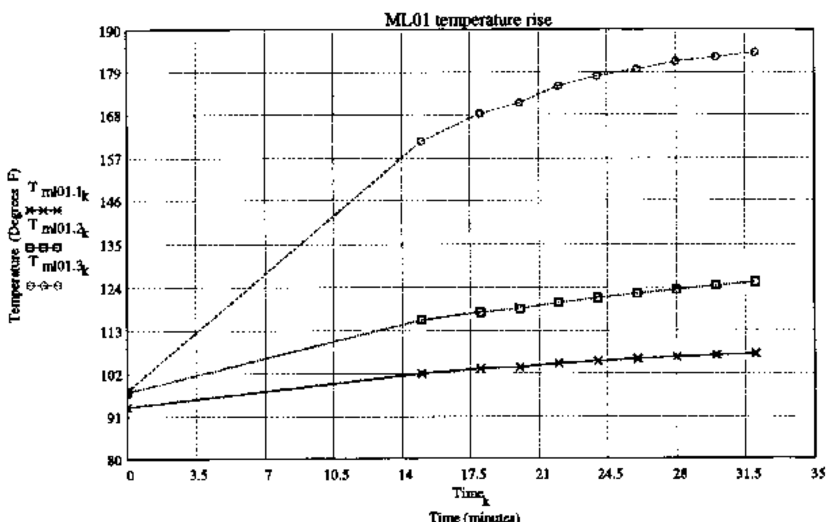


Figure 2.   Timeline configuration for last hour of Booster high pulse repetition rate test.





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Plots of the temperature rise measurements on MP01 and ML01 during the hi rep rate run of3/26/98. The highest temperature is on the power feed end of the magnet. The PS was shut off after 30 minutes because of fear of damaging the ML01 magnet.

Figure 3. MP01 magnet temperatures during Booster high pulse repetition rate test.

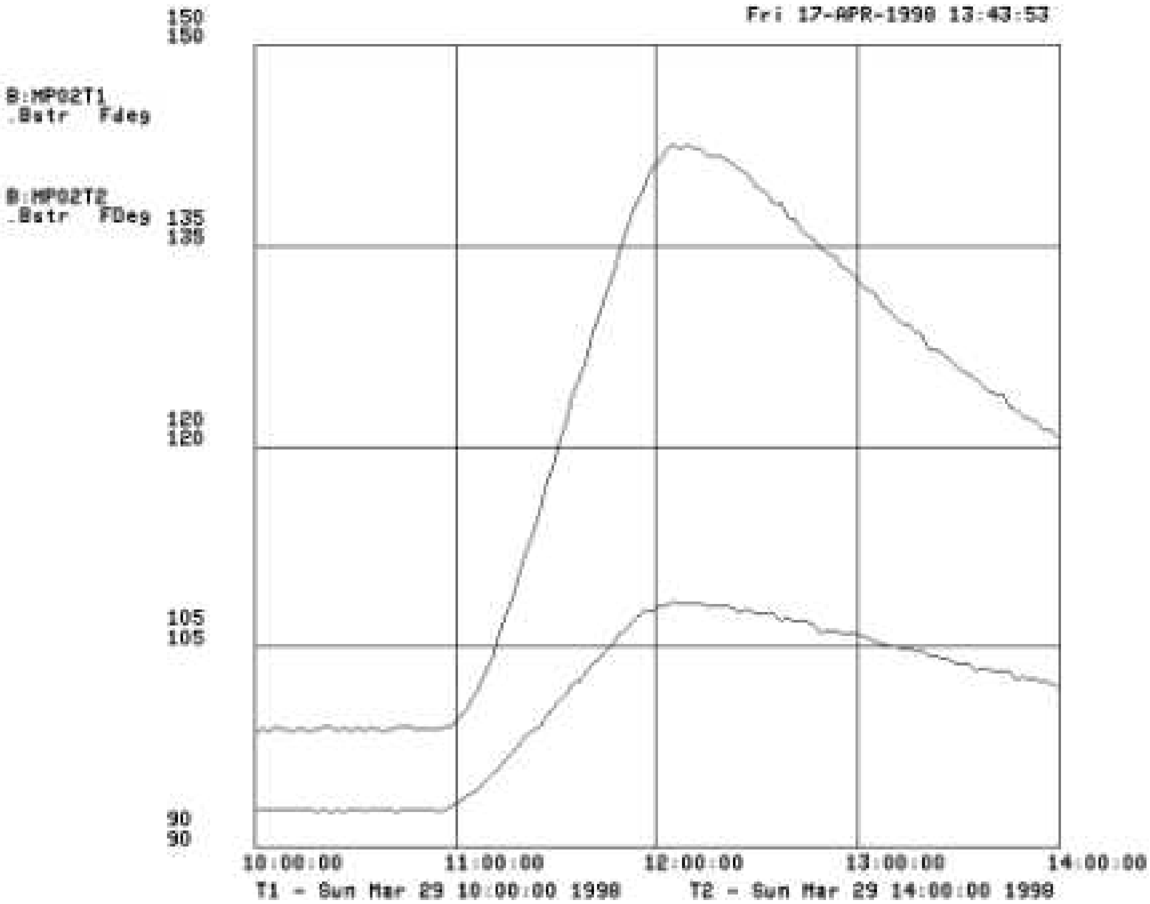

Figure 4. MP02 magnet temperatures during Booster high pulse repetition rate test.

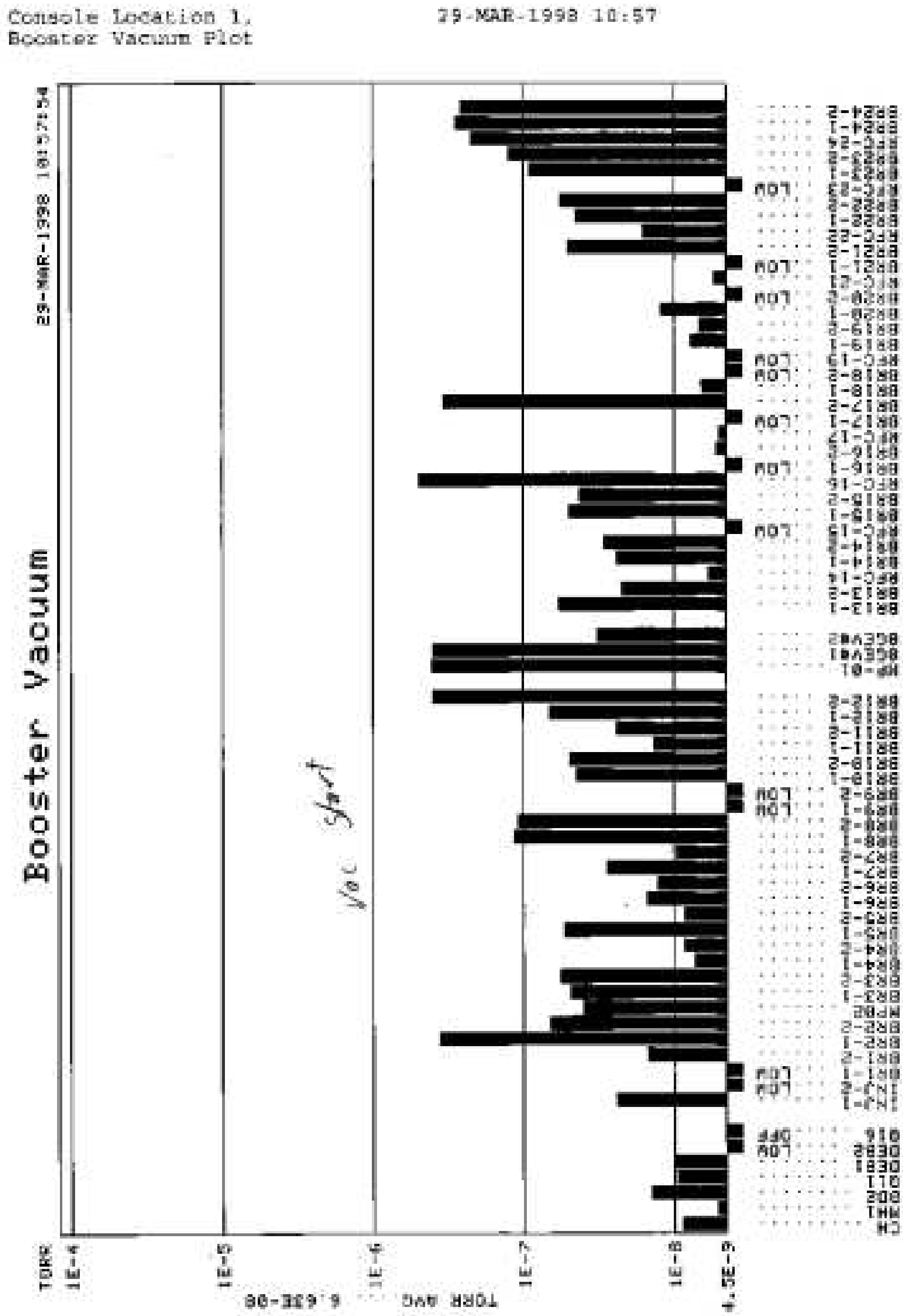

Figure 5. Booster vacuum two minutes into Booster high pulse repetition rate test.

Console Location 1,   29-MAR-1998 11:48
Booster Vacuum Plot

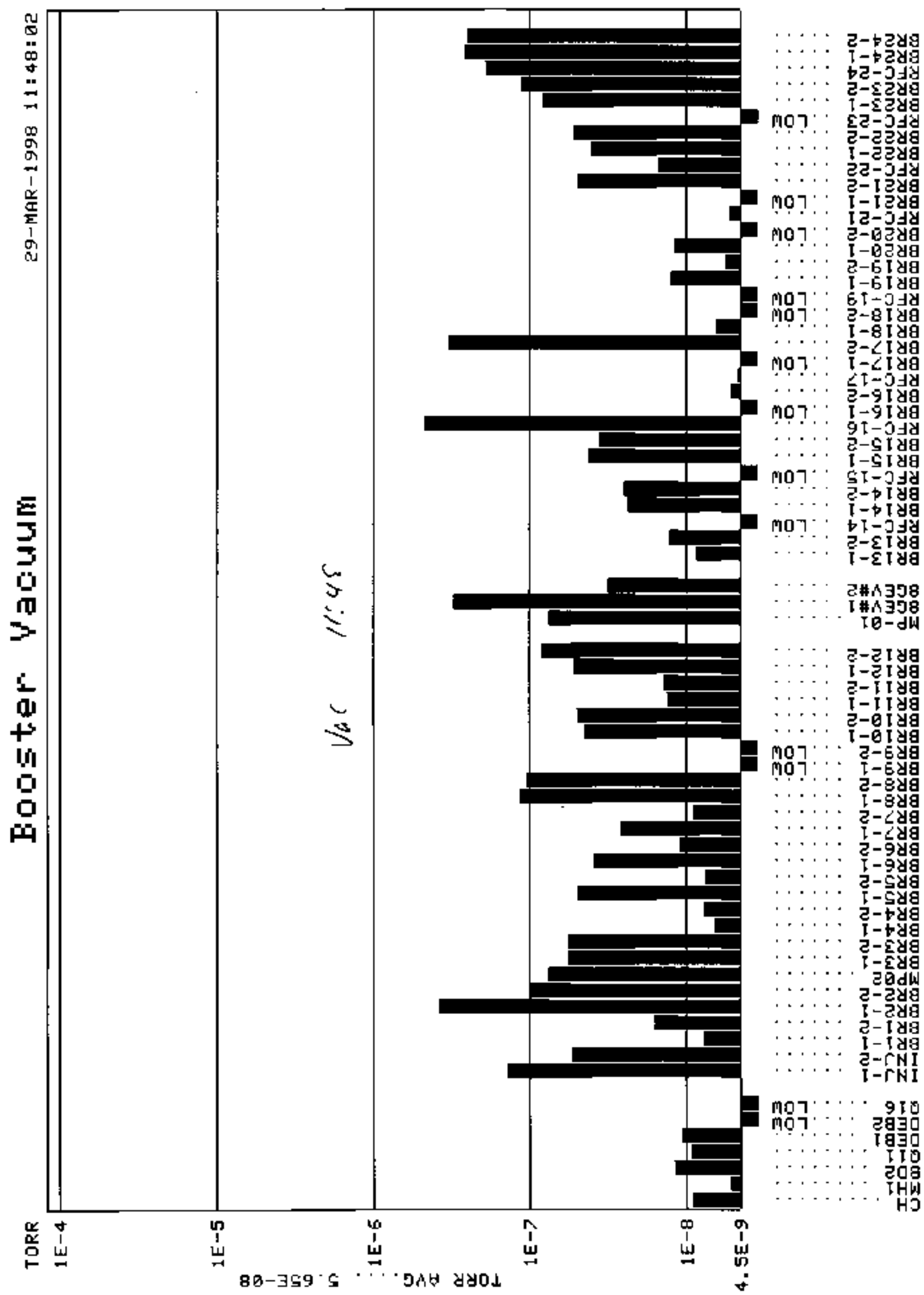

Figure 6. Booster vacuum one hour into Booster high pulse repetition rate test.

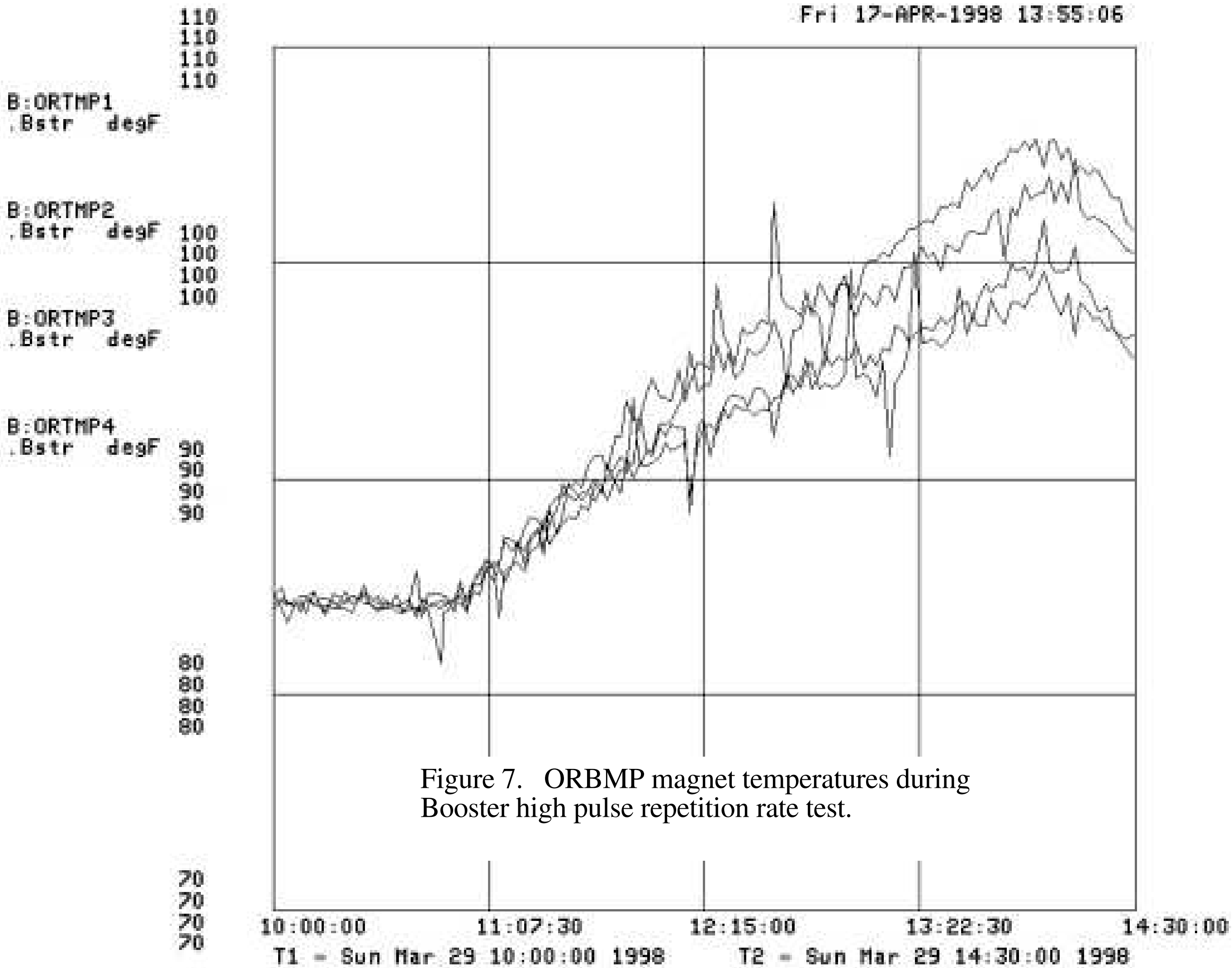

Figure 7. ORBMP magnet temperatures during Booster high pulse repetition rate test.

Appendix 1

Booster High Pulse Repetition Rate Operation Tests Logbook Text

Booster Electronic Log 2

Entry Title High Pulse Rep Rate Author Webber

Entry Date Sun, Mar 29, 1998 11:14 Entry Number 490

Contents

At 10:55 AM we loaded a time line with 2 $12's, 6 $14's, 2 $12's, and 4 $14's each 1.93 sec, that is 14 pulses each 29 15Hz cycles. Testing how power supplies handle 50% duty cycle pulsing.

Observe bias supplies pulsing at 14/29 duty cycle, RF at 13/29, correctors at 10/29, kickers, ORBMP, septa and chopper at 14/29.

At about 11:08 West Gallery RF tripped. Looks like it was taken down by Station #15. Station #15 480 V breaker tripped.

At about 11:10 Jim Lackey at MP01 called to report smell of something hot. He will stay there and try to identify cause while also monitoring MP01 magnet temps.

At 11:24 Jim Lackey reports temps on MP01 magnet rising beyond his comfort level, he is shutting off MP01!

At about 11:25 ORBMP tripped on vacuum interlock. Vacuum looks OK, reseting and turning back on.

At 11:33 West Gallery RF being turned back on.

At 11:35 noticed GMPS tripped on vacuum interlocks (probably at same time as ORBMP), also noticed vacuum valves around stripping foil closed.

At 11:39 GMPS back on and valves opened. Beam still accelerates.

AT 11:44 beam still accelerates.

At 11:49 Station #15 tripped again. Dave Wildman had reported that #15 bias supply runs about 100 amps more than other stations. We will reset RF leaving Station #15 off.

At 11:54 MP02 tripped on magnet temperature interlock.

AT 11:59 West Gallery RF back on sans #15.

Ray Tomlin reports measuring MP02 RG220 cables at 116F eight minutes after it had shut off. ORBMP resistors at 157F.

At 12:13 beam still accelerates.

At 12:26 beam still accelerates.

Plan to add 6 more $14's at 12:30 to make rate 20/29. Having problems with TLG calc and loading, seems to limit things to 50% duty cycle.

At 13:00 we sent out time line with 6 additional $14's. So now bias supplies at 20/29, RF at 19/29, correctors at 16/29, and kickers, chopper, ORBMP at 20/29.

At 13:13 RF back on except two stations in each gallery left off. Still accelerate some beam. Dave Wildman believes trip caused by anod AC overcurrent trip level setting.

At 13:19 got GMPS vacuum trip and foil area valves closed. ORBMP did not trip. GMPS back on at 13:26, leaving valves FOIL, VB-03, and VB-23 closed!

Within a minute of loading new time line, the East Anode supply tripped with no indication, reset it once and it quickly tripped again. West Anode supply tripped shortly thereafter on AC input OL. Investigating.

At 13:39 turned on 4 bias supplies which had been off (did not turn on those modulators). See if yard breakers trip.

Outside temperature is 80F!

13:44 RF #15 tripped breaker. We knew that would happen,shouldn't have turned on #15 bias supply.

13:47 Turned on all West bias supplies except #15.

13:50 GMPS tripped on vacuum interlock.

At 13:53 West RF back on except #15 bias supply, and #15 and 16 modulators.

At 1403 ORBMP has been turned off. Jim and Ray report burning smell coming from ORBMP AC transformer and 140F air measured from transformer cabinet.

At 1417 experiment over, slow rep rate time line re-established.

1430 normal beam re-established.