RF Note #083

MI RF Solid State Drive Power Supply Upgrade for Proton Plan

T. Berenc, S. Kotz

12/8/2006

Introduction:

The Proton Plan design increases the Main Injector (MI) beam intensity from the present 3.2×10^{13} protons to a system design of 5.5×10^{13} protons. Associated with this is an increase in the 'moving average' solid-state drive (SSD) power requirements. The estimate is approximately 3.6kW for a 75° de-tuning angle. Allowing for lower de-tuning angles requires even more power. Current measurements [1] indicate that the SSD 'moving average' power requirement could approach 4kW – 5kW. The present 10kW rated power supplies can only provide about 4.2kW of average power, so the limits of these supplies have been reached. Additionally, having more drive power offers the capability to operate the PA tube more efficiently. Therefore, an upgrade to a higher rated power supply is warranted.

A comparison of the capabilities of the existing 10kW supply versus the proposed 15kW supply was conducted using the SSD racks of the MI-60 RF test station. Several tests were conducted to provide a means of comparison of the two supplies. These tests included a power sweep to find the useful steady state operating range, a pulse burst test to determine the peak and average pulsed power limits, a short pulse test to simulate beam loading effects and a frequency sweep to measure the bandwidth of the SSD rack.

A brief summary of the power supply upgrade comparison is shown below in table 1. It can be seen that the proposed 15kW supply will provide indefinitely the same peak power that the 10kW supply can supply for only 4ms. Also, the average and maximum transient free power of the 15kW supply is almost twice that of the 10kW supply.

	10kW Supply	15kW Supply
Peak Power / Duration (kW/ms)	~8 / 4	8 / indefinte
Average Power (kW)	~4.2	8
Maximum Power (kW) (w/o PS Turn-on problems)	3.7	6.9

Table 1. Comparison of Existing 10kW and Proposed 15 kW SSD Rack Power Supplies

Test Set-up:

A diagram of the measurement test set-up is shown in figure 1. The RF test station was configured to use the Station RF Controller and SSD driver rack along with the HP8656B signal generator to provide the RF drive signal. A pulse generator connected directly to the RF switch of the station RF controller was used to modulate the pulse width of the RF drive signal. An Agilent 8753ES network analyzer (NWA) was connected between the feed-forward (FF) input of the station RF controller and the output of one of the eight dual directional couplers of the SSD rack amplifiers.

The power supply under evaluation had a 100A/50mV shunt connected in series with the negative output terminal in order to directly monitor the power supply current without incurring the delays and noise problems associated with the current monitoring signal of the test rack. This necessitated the use of an isolated oscilloscope (by means of an isolation transformer) in order to avoid ground loops that could cause inaccurate or incorrect measurement of the supply current.

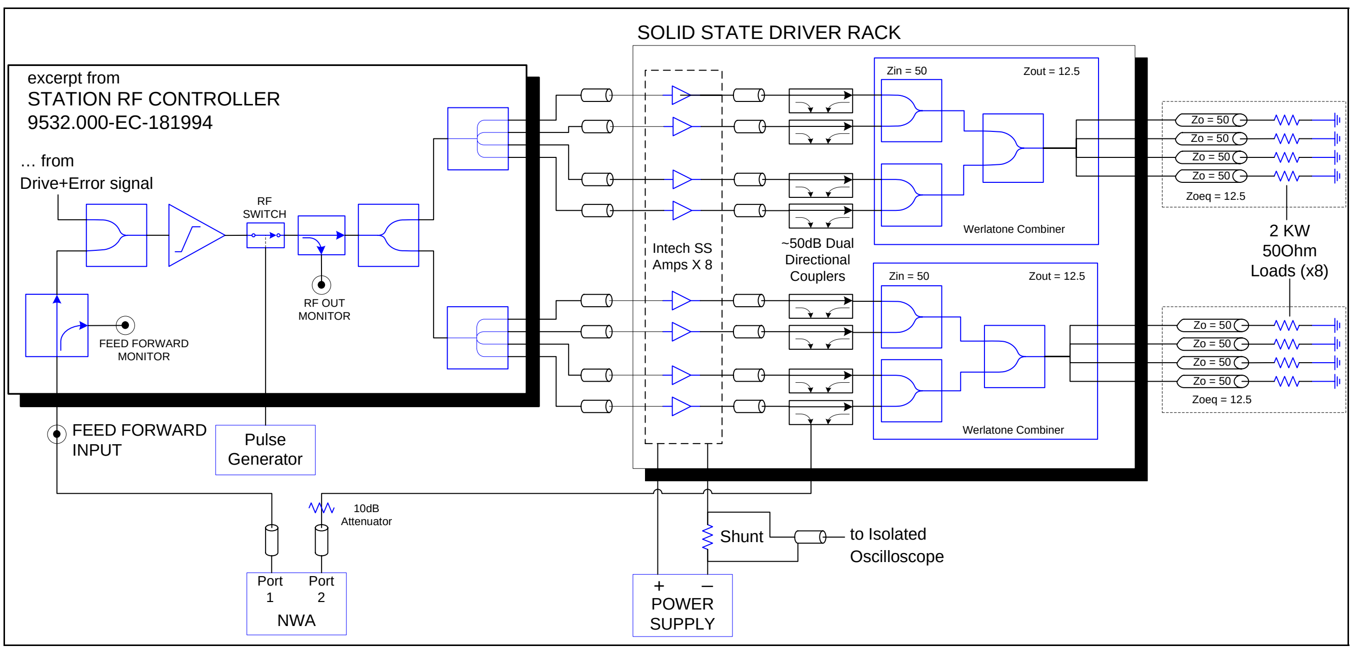


Figure 1. RF Test Station Measurement Set Up

Power / Time Sweep:

The power sweep is used to determine two characteristics of the supply under test. First, the power sweep is used to determine the useful operating range by finding the maximum amount of delivered power before a supply protection mode such as over current limit or under voltage lock out is encountered. The measurements are taken with a NWA set to 'power sweep' mode. Next, by using a NWA time sweep at a fixed drive level, a time swept plot of forward power and voltage at a particular drive level is produced on the oscilloscope. This reveals the transient nature of the supply at those various drive levels.

Figure 2 shows the NWA power sweep measurement for the existing 10kW power supply. The maximum average power is shown at marker 4 and corresponds to a total forward RF drive level of 4.2kW from the SSD amplifier stack. After this point the supply enters constant current mode and can not deliver the demanded power as seen by the sharp drop-off between marker 4 and 5. By contrast, the proposed 15kW supply, as shown in figure 3, allows an average power of 7.8kW from the SSD amplifier stack.

The results of the power sweeps are summarized in table 2 for the original 10kW supply and table 3 for the proposed 15kW supply. The tables show the determined RF output power for the corresponding NWA drive level, the total supply current, the calculated supply power for a supply voltage of 46.2V and the calculated efficiency of the supply (η). The second to last row shows the maximum power from the SSD stack without causing the supply to momentarily transition to constant current mode upon turn-on. The final row shows the power at which the supply will enter constant current mode.

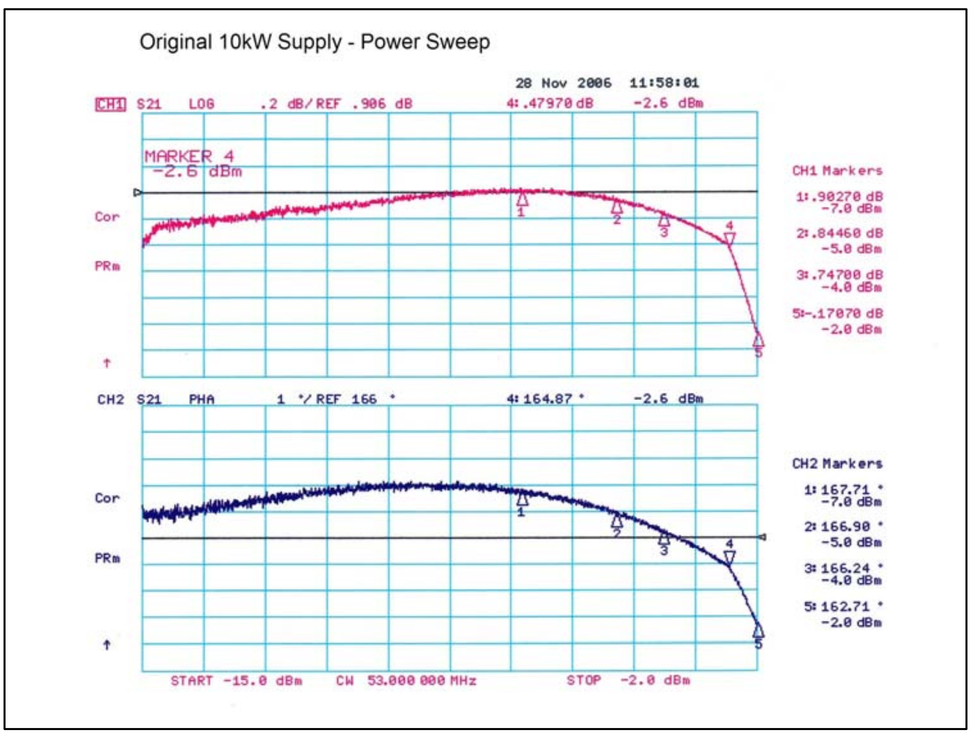


Figure 2. 10kW Supply Power Sweep (-15 dBm to -2 dBm)

P_{OUT_RF} (kW)	NWA Pwr (dBm)	I_{SUPPLY} (A)	P_{SUPPLY} (kW)	η (%)
1.7	-7	132	6.1	28
2.7	-5	162	7.5	36
3.3	-4	178	8.2	40
3.7	-3.45	188	8.7	43
4.2	-2.6	202	9.3	45

Table 2. 10kW Supply Efficiency

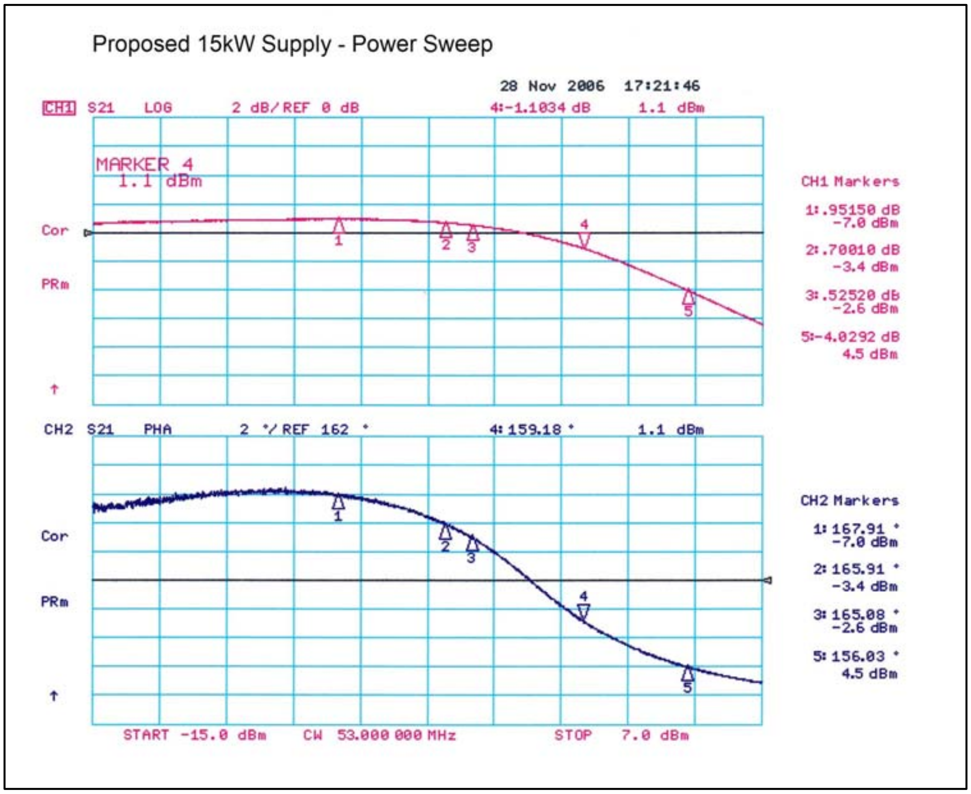


Figure 3. 15kW Supply Power Sweep (-15 dBm to +7 dBm)

P_{OUT_RF} (kW)	NWA Pwr (dBm)	I_{SUPPLY} (A)	P_{SUPPLY} (kW)	η (%)
1.7	-7	132	6.1	28
3.9	-3.45	188	8.7	43
4.3	-2.6	206	9.5	45
6.9	1.1	272	12.6	55
7.8	4.5	292	13.5	58

Table 3. 10kW Supply Efficiency

Figures 4 and 5 below show the oscilloscope display for the power sweep. The point where the 10kW supply enters constant current mode and the supply voltage monitor begins to drop or ‘foldback’ is clearly seen in figure 4a. The maximum current supplied by the 10kW supply is approximately 200A as shown in figure 4b. The 15kW supply voltage does not exhibit ‘foldback’ and the maximum supplied current is approximately 300A as shown in figures 5a and 5b respectively.

10 kW Supply Power Sweep (-15dBm to -2dBm)

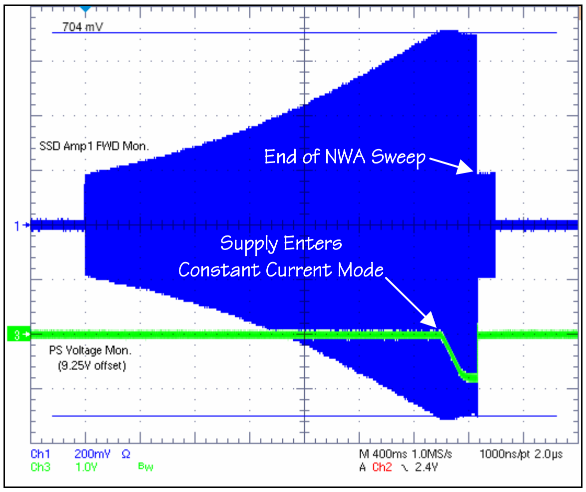


Figure 4a. Forward Power (blue) and Voltage (green).

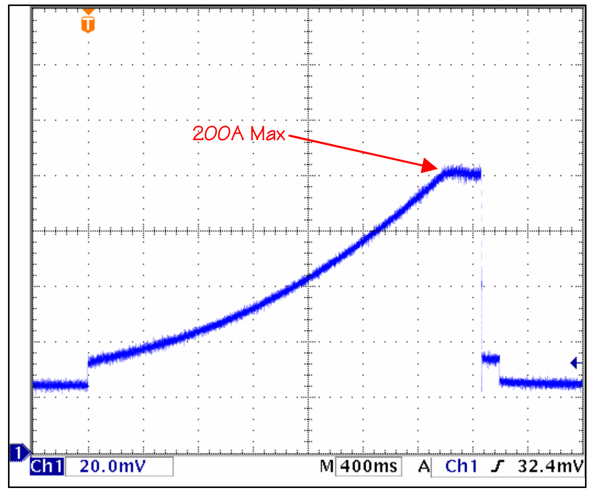


Figure 4b. Shunt monitored Supply Current (40A/div).

15 kW Supply Power Sweep (-15dBm to +7dBm)

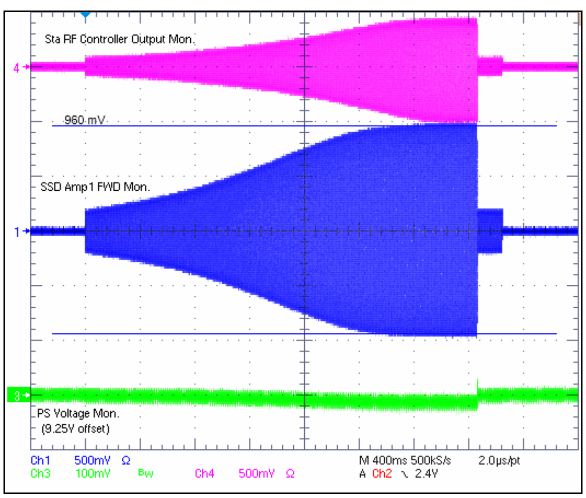


Figure 5a. Forward Power (blue), Voltage (green) and RF controller output (magenta).

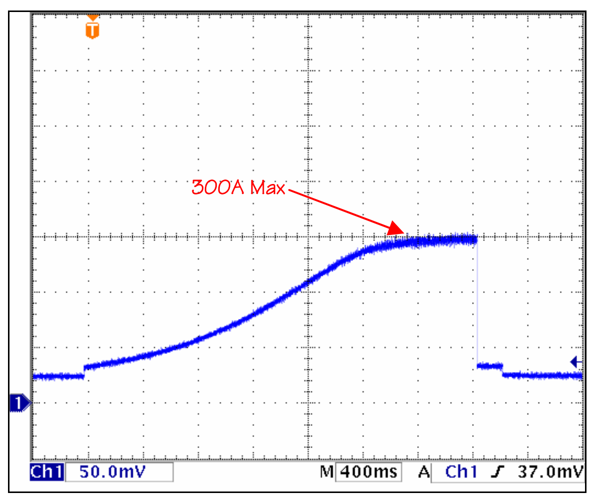


Figure 5b. Shunt monitored Supply Current (100A/div).

10 kW Supply Time Sweep (140ms)

SSD Forward Power (blue) and Voltage (green)

Note: Vertical Axis expanded to show transients

Shunt monitored Supply Current (40A/div)

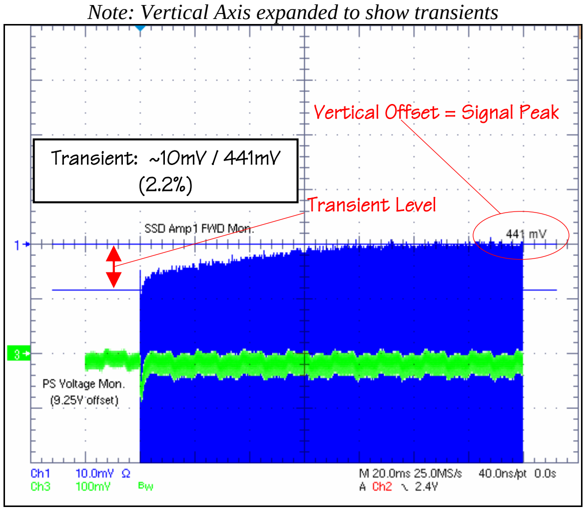


Figure 6a. 1.7kW Output Power

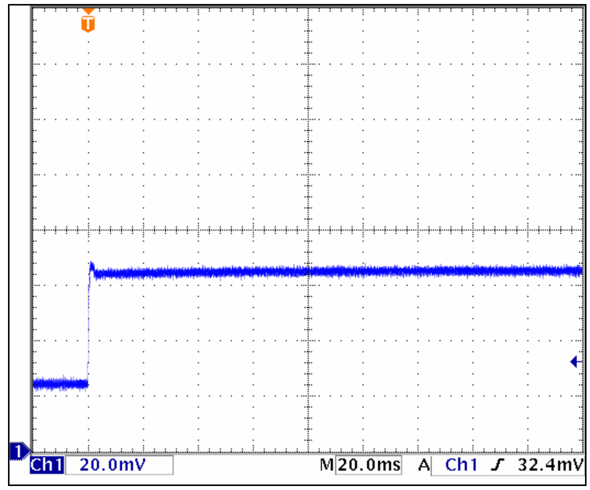


Figure 6b. 1.7kW Output Power

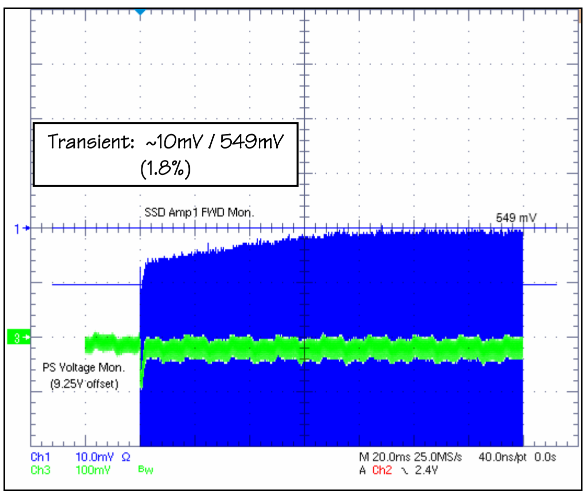


Figure 7a. 2.7kW Output Power

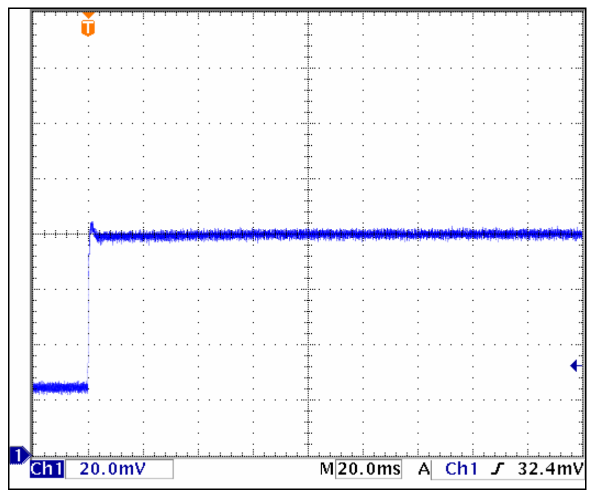


Figure 7b. 2.7kW Output Power

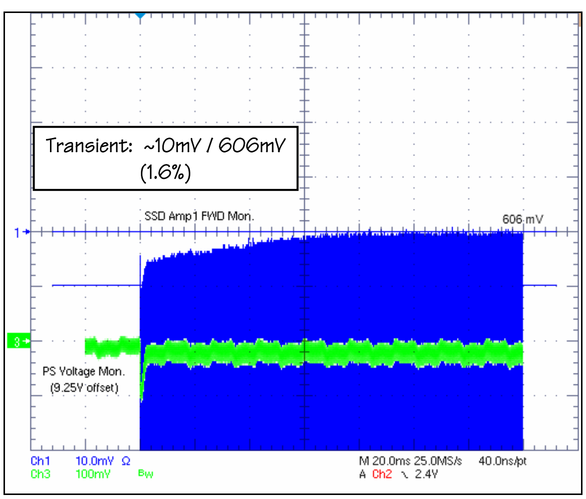


Figure 8a. 3.3kW Output Power

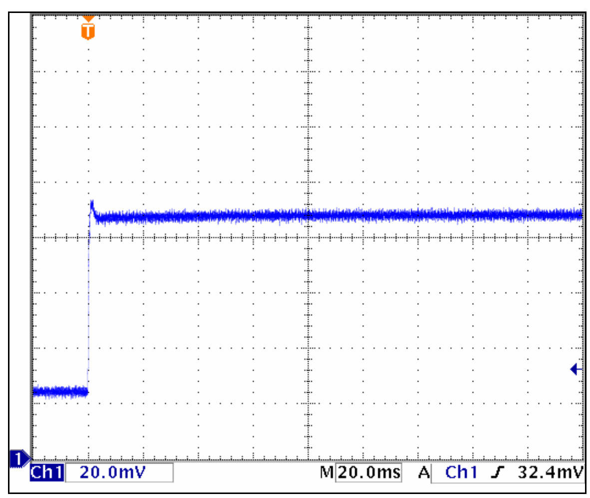


Figure 8b. 3.3kW Output Power

10 kW Supply Time Sweep (140ms)

SSD Forward Power (blue) and Voltage (green)

Note: Vertical Axis expanded to show transients

Shunt monitored Supply Current (40A/div)

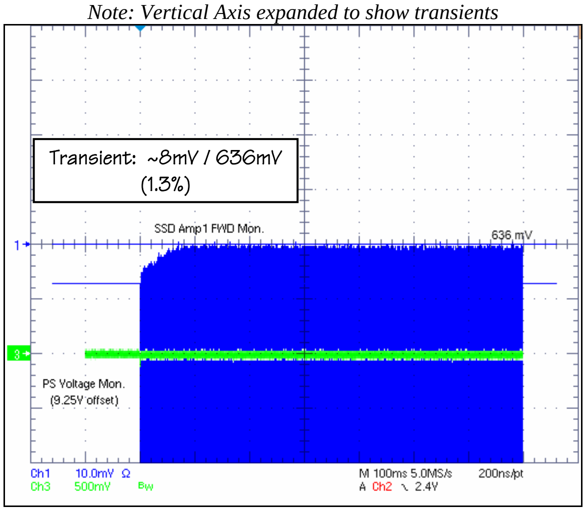


Figure 9a. 3.7kW Output Power

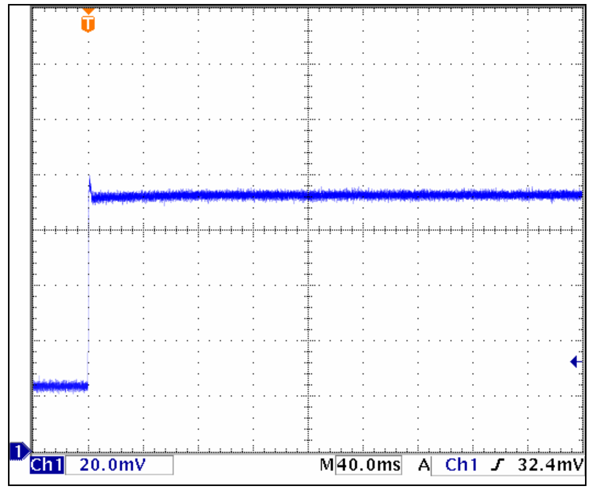


Figure 9b. 3.7kW Output Power

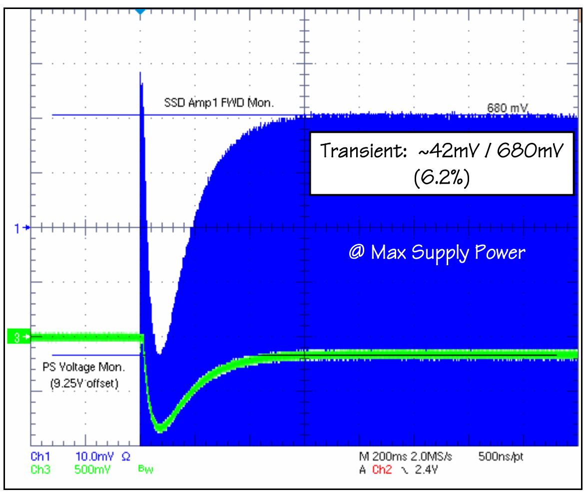


Figure 10a. 4.2kW Output Power

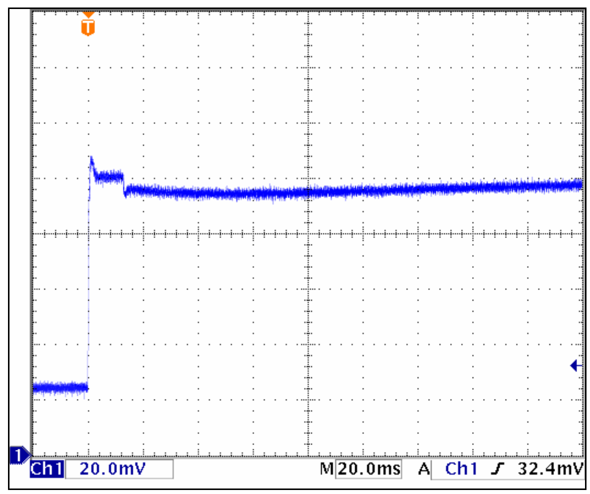


Figure 10b. 4.2kW Output Power

15 kW Supply Time Sweep (140ms)

SSD Forward Power (blue) and Voltage (green)

Note: Vertical Axis expanded to show transients

Shunt monitored Supply Current (100A/div)

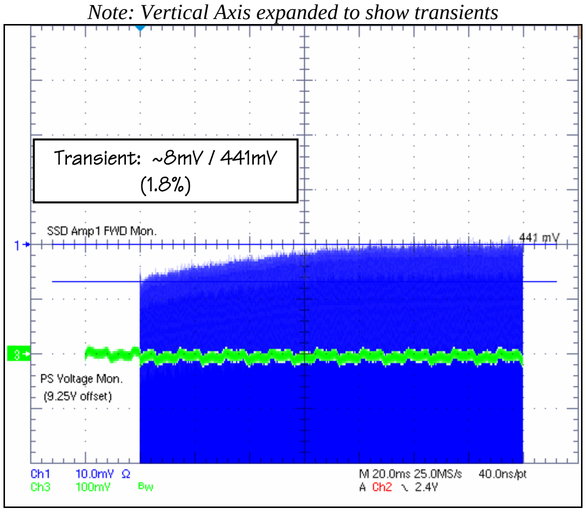


Figure 11a. 1.7kW Output Power

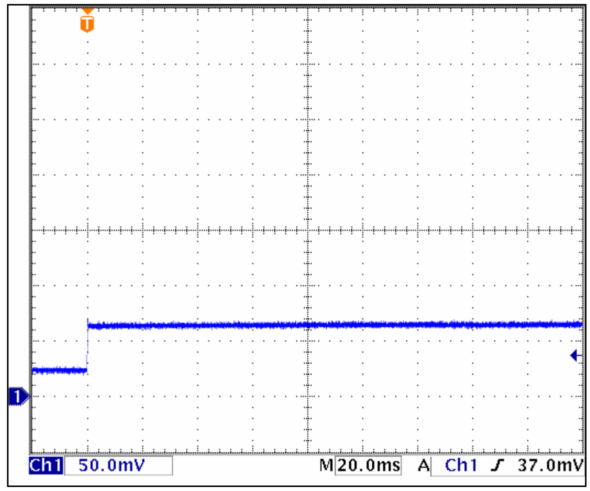


Figure 11a. 1.7kW Output Power

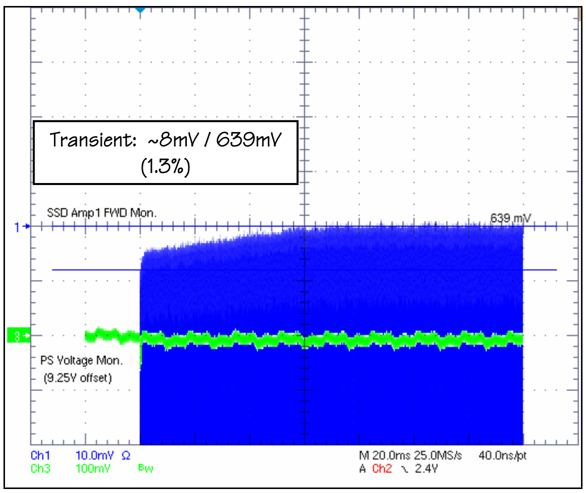


Figure 12a. 3.7kW Output Power

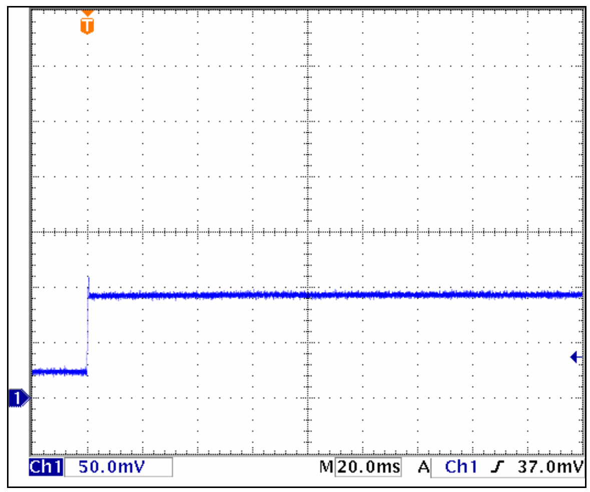


Figure 12a. 3.7kW Output Power

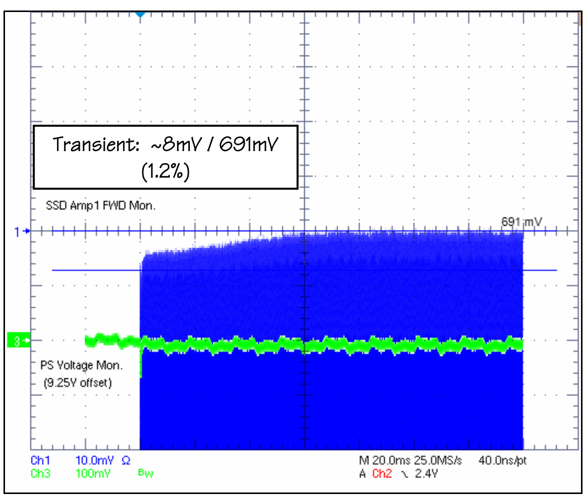


Figure 13a. 4.2kW Output Power

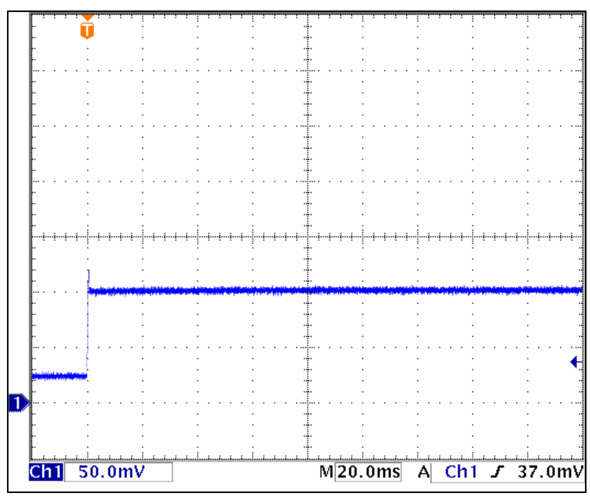


Figure 13a. 4.2kW Output Power

15 kW Supply Time Sweep (140 ms)

SSD Forward Power (blue) and Voltage (green)

Note: Vertical Axis expanded to show transients

Shunt monitored Supply Current (100A/div)

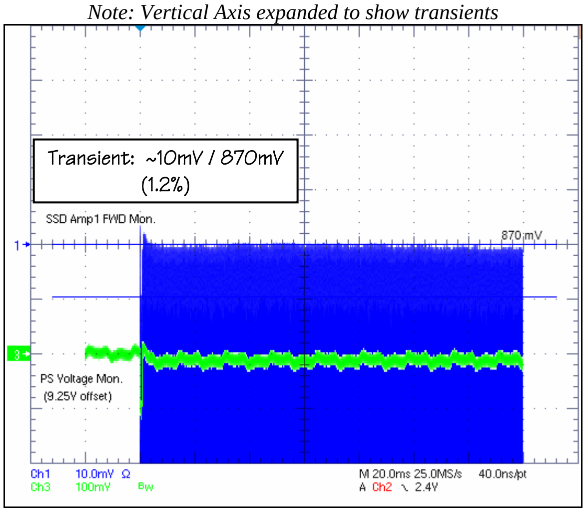


Figure 14a. 6.9kW Output Power

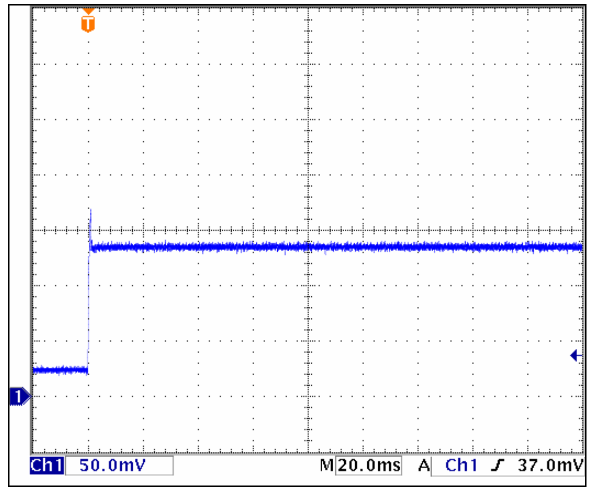


Figure 14a. 6.9kW Output Power

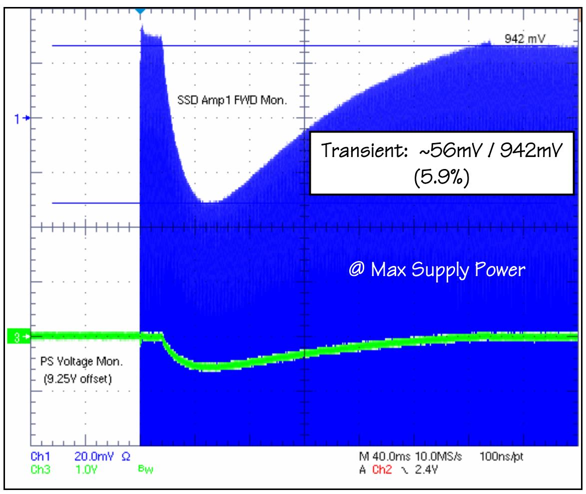


Figure 15a. 7.8kW Output Power

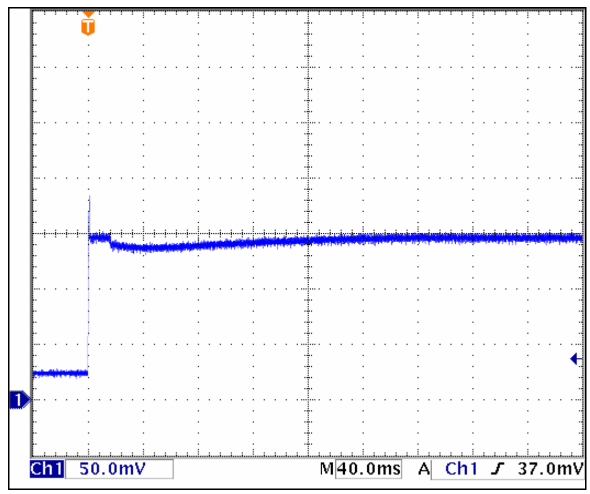


Figure 15a. 7.8kW Output Power

Burst Mode Pulsing:
The burst mode test is used to determine the amount of time the supply allows the full 8kW RF power from the SSD stack. Figure 16 shows that the output voltage of the10kW supply begins to droop severely after about 6 ms and trips the undervoltage lockout mode at about 8 ms. So, a constrained estimate of the pulse time is chosen as 4 ms. In contrast, the 15kW supply allows the 8kW power indefinitely after its initial turn-on transient, see figure 17.

10 kW Supply Burst Mode Pulse

SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)

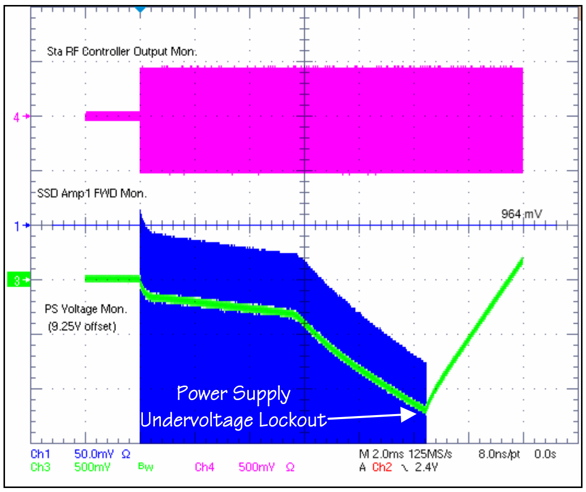


Figure 16a. 8kW Power Burst

Shunt monitored Supply Current (2A/mV)

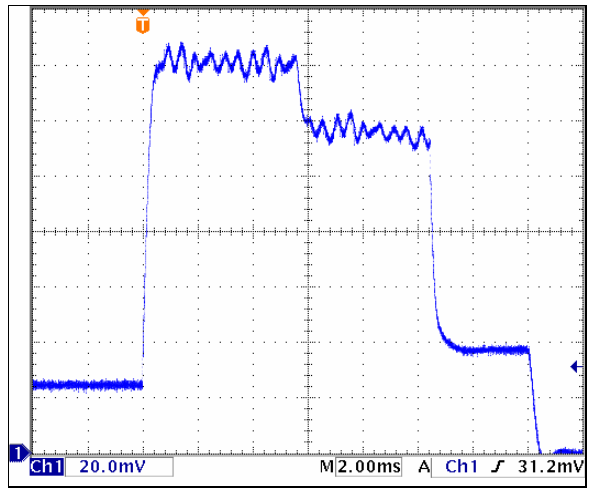
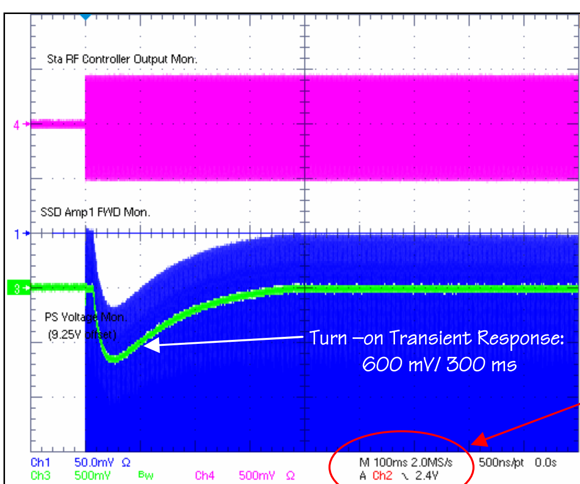


Figure 16b. 8kW Power Burst

15 kW Supply Long Burst Mode Pulse

SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)



Note
the expanded
Timebase

Shunt monitored Supply Current (2A/mV)

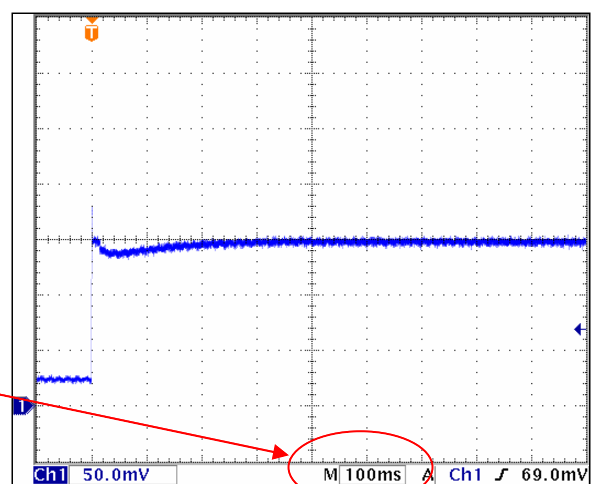


Figure 17a. 8kW Power Burst

Figure 17b. 8kW Power Burst

Figures 18 and 19 are plots of the SSD forward power and voltage as well as the shunt monitored supply current for a pulsed drive signal that has an 8ms period and 50% duty factor. This results in an RF output power of 8kW peak and 4kW average. Both supplies can allow 8kW peak at 50% duty factor, however, the 10kW supply suffers from higher ripple voltage and RF power sag than the 15kW supply.

10 kW Supply Repeated Burst Mode Pulse

SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)

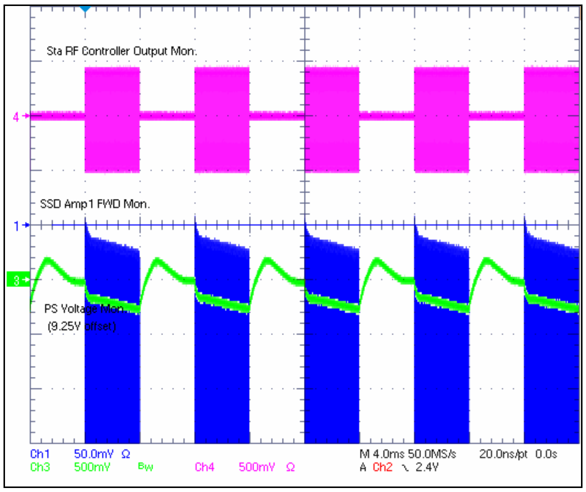


Figure 18a. 8kW peak / 4kW average

Shunt monitored Supply Current (2A/mV)

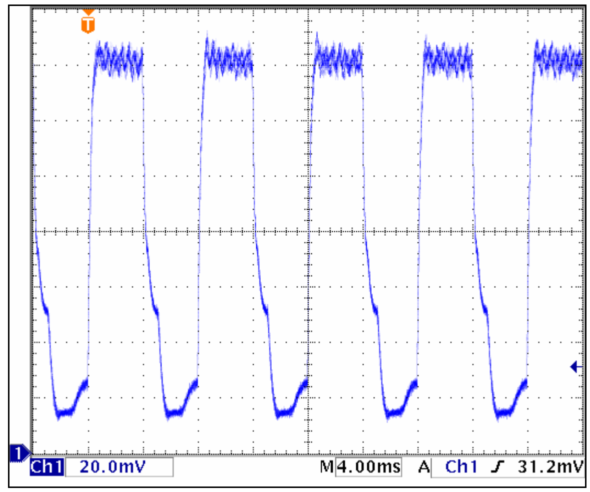


Figure 18b. 8kW peak / 4kW average

15 kW Supply Repeated Burst Mode Pulse

SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)

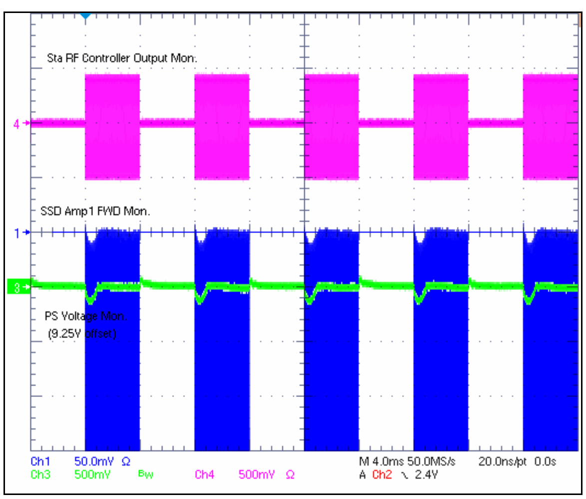


Figure 19a. 8kW peak / 4kW average

Shunt monitored Supply Current (2A/mV)

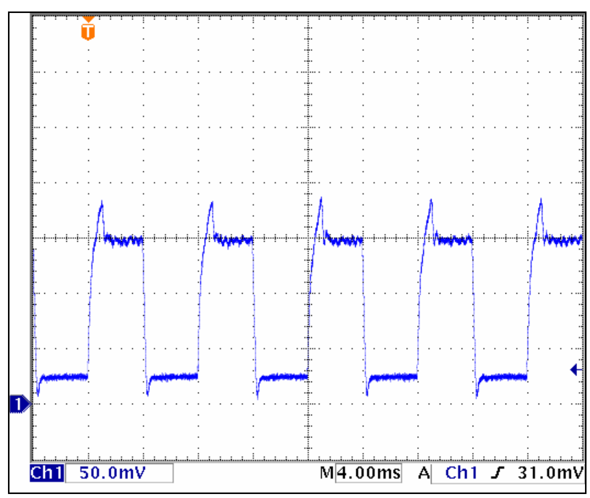


Figure 19b. 8kW peak / 4kW average

Short Pulse Testing:

Short pulse testing is used to simulate beam loading by progressively increasing the pulse width of the RF drive. The beam revolution period of the MI is 11µS with a maximum ring filling factor of 6/7. The pulse width was varied in integer increments of 1.57µS (11µs period / 7 batches). The following figures show the oscilloscope plots for the pulse width progression. Note that the 10kW supply can not support the full 8kW peak for 5/7 and 6/7 duty factor. As shown previously, the 15kW supply allows the full 8kW power indefinitely, thus it can provide the 8kW peak power at any duty factor up to 100%.

10 kW Supply Short Pulse
SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)

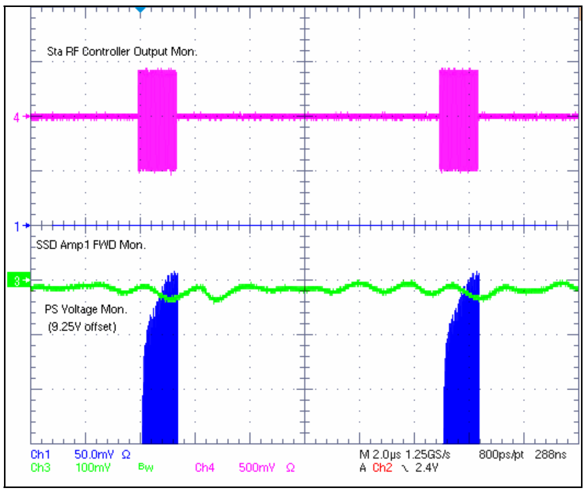


Figure 20. 1/7 Duty Factor

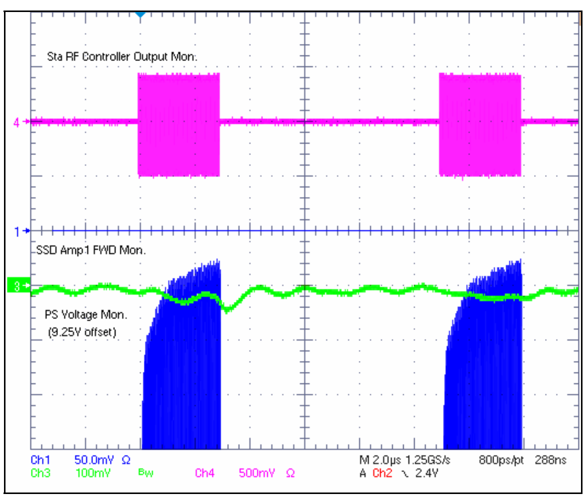


Figure 22. 2/7 Duty Factor

15 kW Supply Short Pulse
SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)

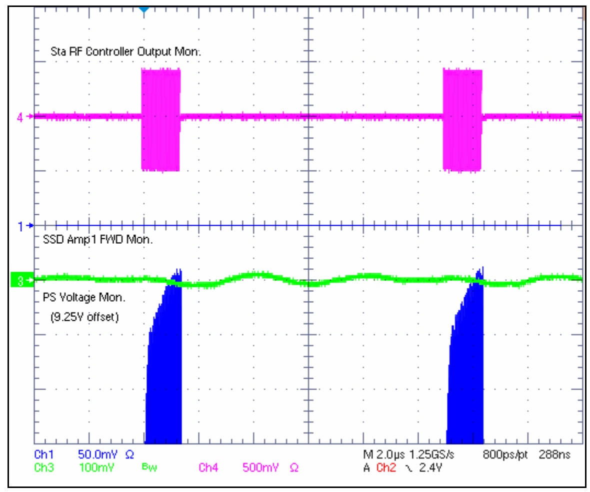


Figure 21. 1/7 Duty Factor

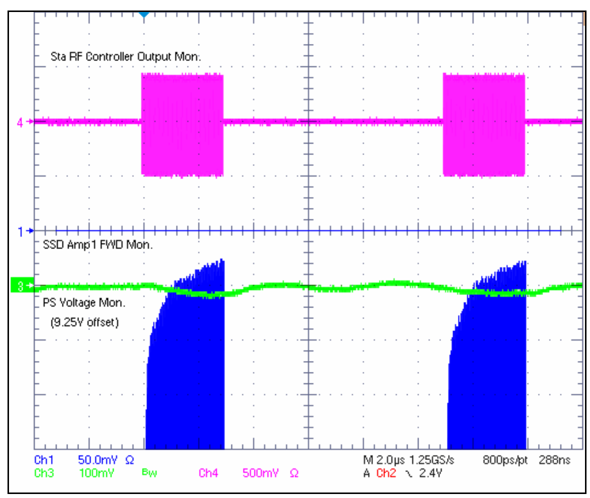


Figure 23. 2/7 Duty Factor

10 kW Supply Short Pulse
SSD Forward Power (blue), Voltage (green) and
Station RF Power (magenta)

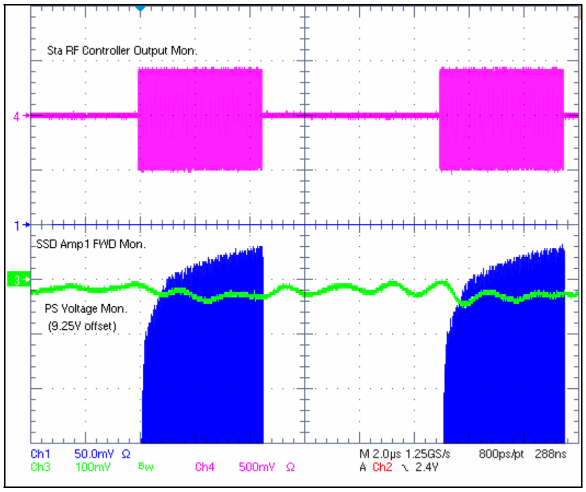


Figure 24. 3/7 Duty Factor

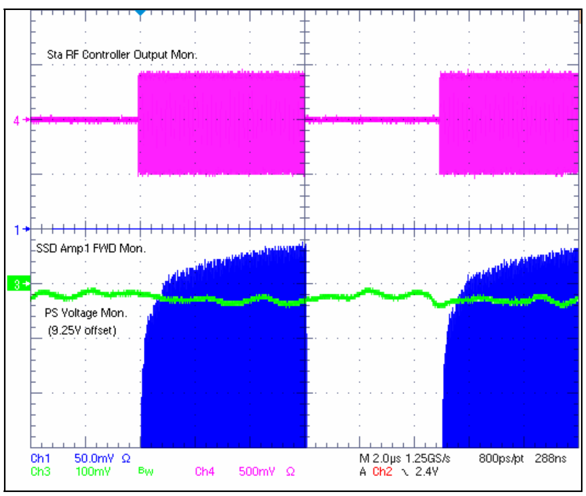


Figure 26. 4/7 Duty Factor

15 kW Supply Short Pulse
SSD Forward Power (blue), Voltage (green) and
Station RF Power (magenta)

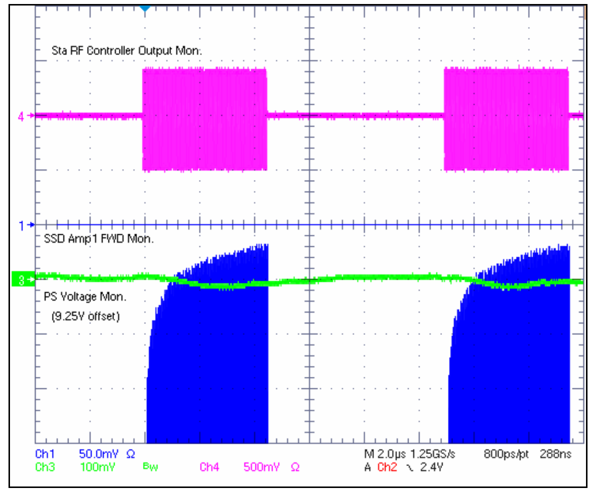


Figure 25. 3/7 Duty Factor

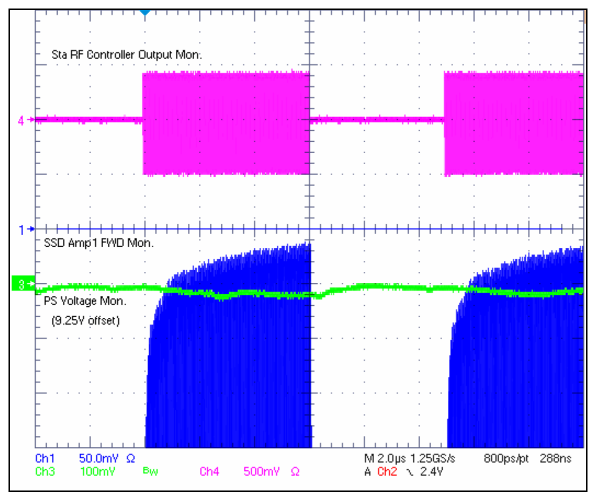


Figure 27. 4/7 Duty Factor

10 kW Supply Short Pulse
SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)

N/A with 5/7 Duty Factor

N/A with 6/7 Duty Factor

15 kW Supply Short Pulse
SSD Forward Power (blue), Voltage (green) and Station RF Power (magenta)

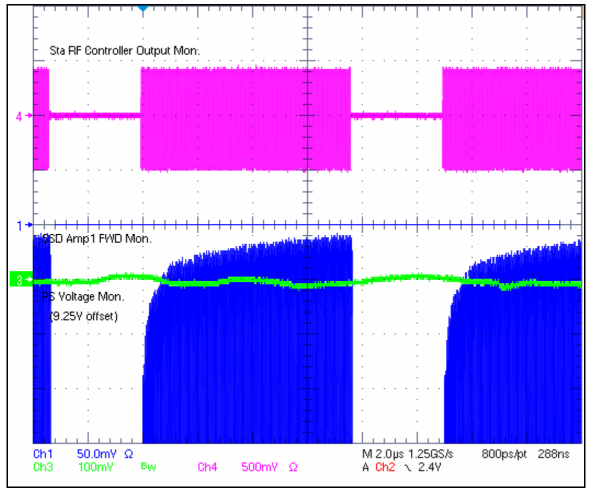


Figure 28. 5/7 Duty Factor

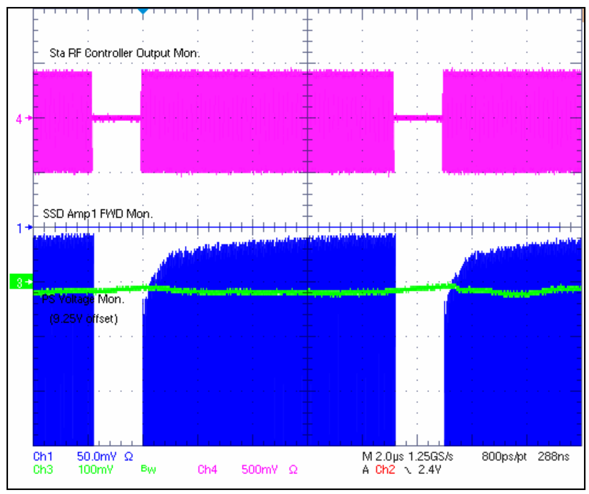


Figure 29. 6/7 Duty Factor

10 kW Supply Short Pulse
Shunt monitored Supply Current (40A/div)

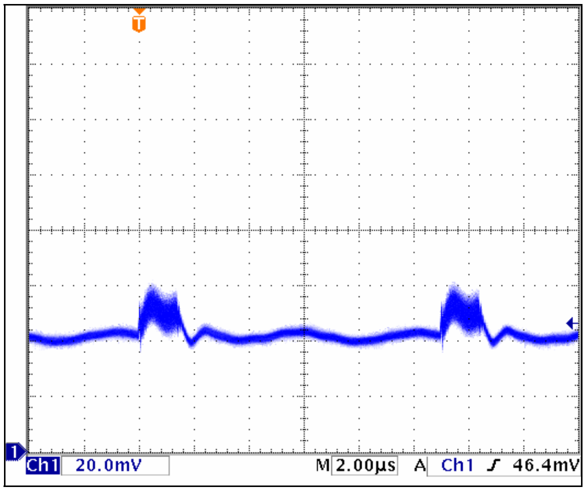


Figure 30. 1/7 Duty Factor

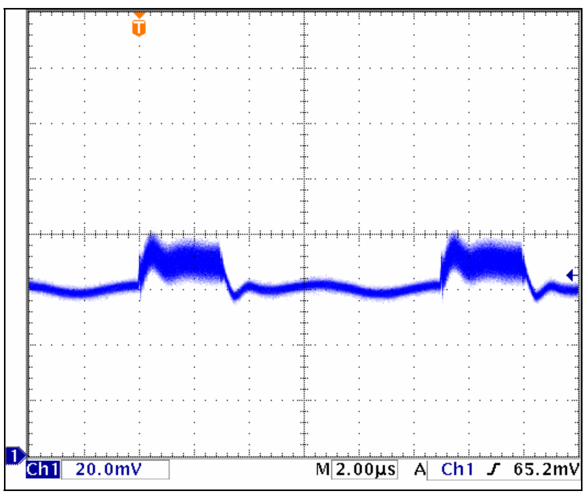


Figure 32. 2/7 Duty Factor

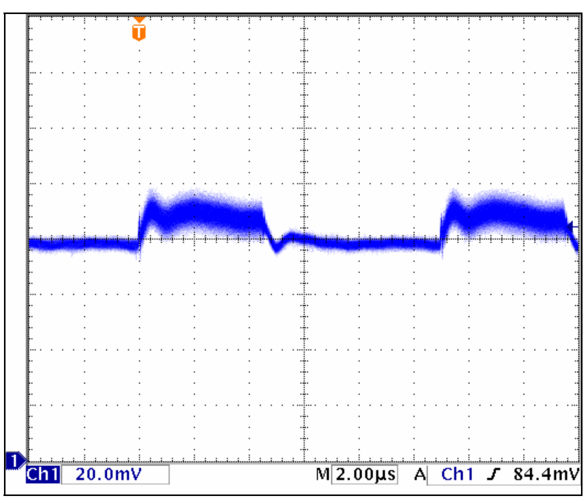


Figure 34. 3/7 Duty Factor

15 kW Supply Short Pulse
Shunt monitored Supply Current (100A/div)

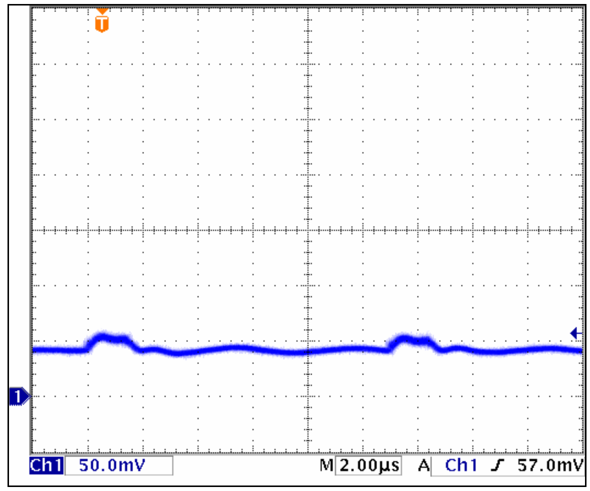


Figure 31. 1/7 Duty Factor

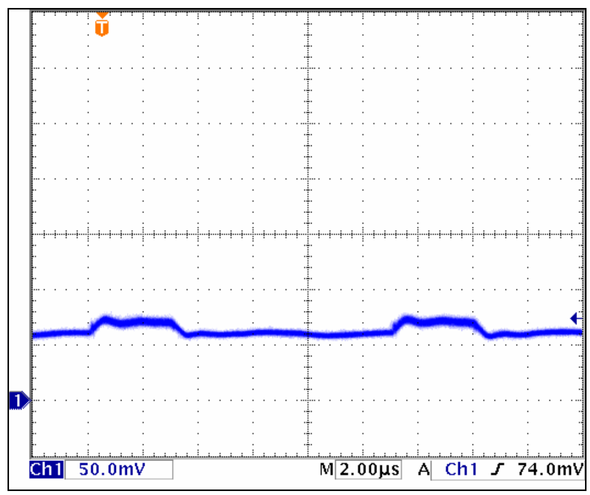


Figure 33. 2/7 Duty Factor

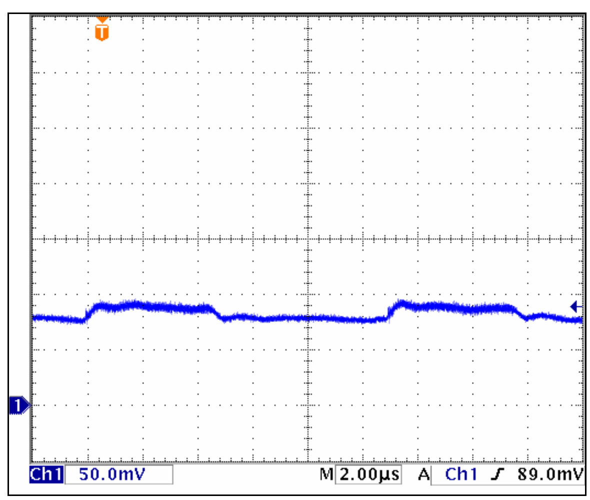


Figure 35. 3/7 Duty Factor

10 kW Supply Short Pulse
Shunt monitored Supply Current (40A/div)

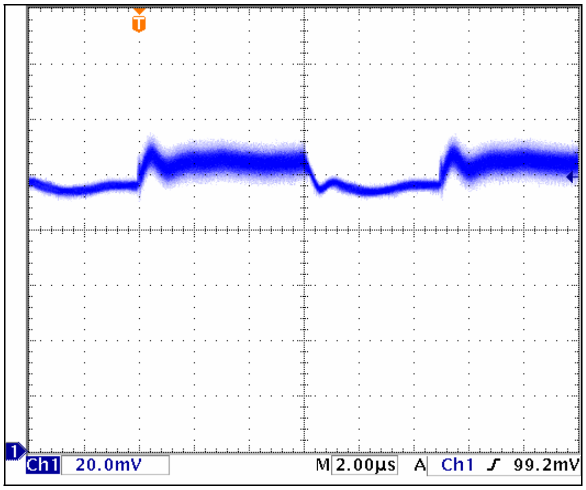


Figure 36. 4/7 Duty Factor

N/A with 6/7 Duty Factor

N/A with 6/7 Duty Factor

15 kW Supply Short Pulse
Shunt monitored Supply Current (100A/div)

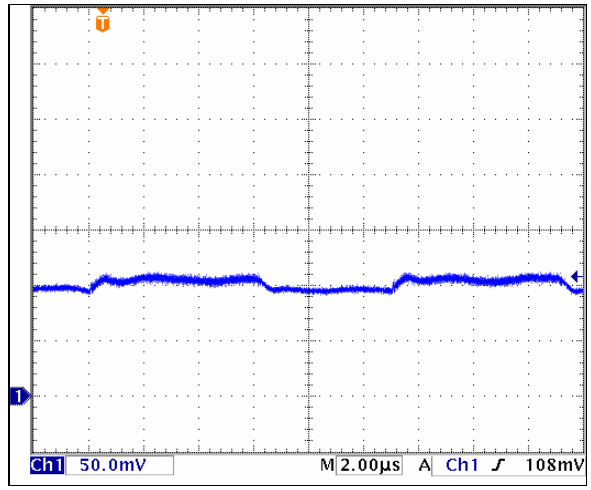


Figure 37. 4/7 Duty Factor

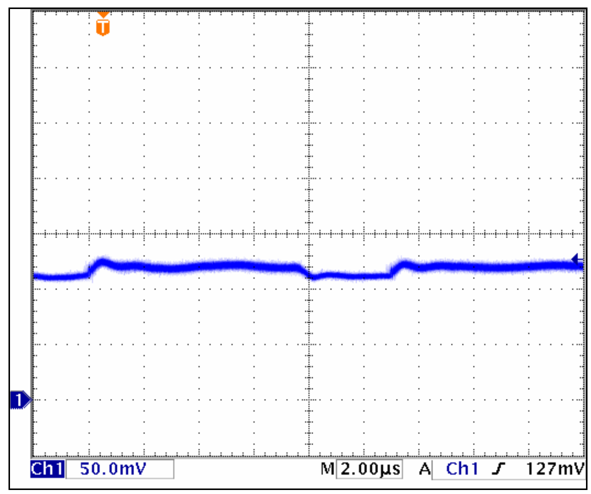


Figure 38. 5/7 Duty Factor

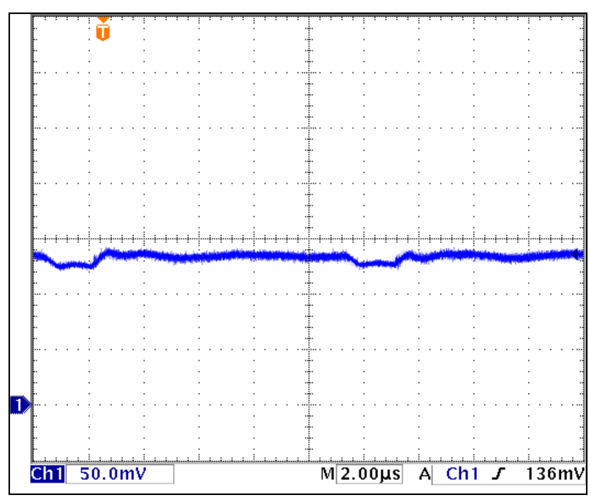


Figure 39. 6/7 Duty Factor

Frequency Sweep:
The frequency sweep measures the useable bandwidth of the feed-forward (FF) path and SSD rack. The bandwidth information is used to help determine the characteristics for the comb filter in the cavity tuning control loop. The plots in figures 40 and 41 show the magnitude and phase relationship of the FF path and SSD rack. The 15kW power supply was used during this testing. The phase plots utilized the electrical delay feature of the NWA to display the non-linear phase response of the path. As seen in the two figures, the distortion free zone is from 49 MHz to 57 MHz for a bandwidth of approximately 8 MHz. This value does not vary much over the RF power output range as seen in the plots with the two power levels.

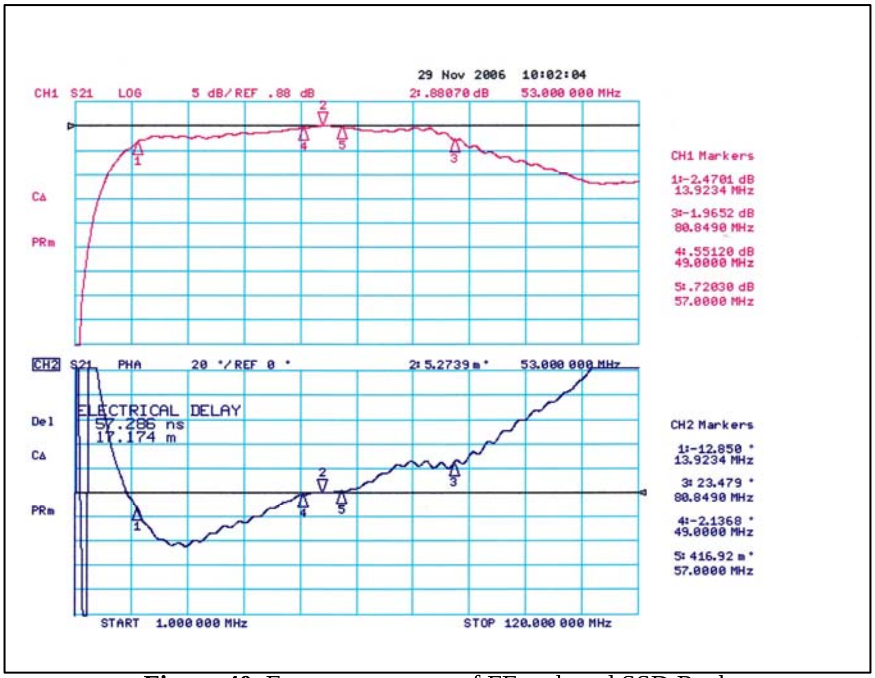


Figure 40. Frequency sweep of FF path and SSD Rack
(Output Power = 2.7kW, ϕ offset = 180°)

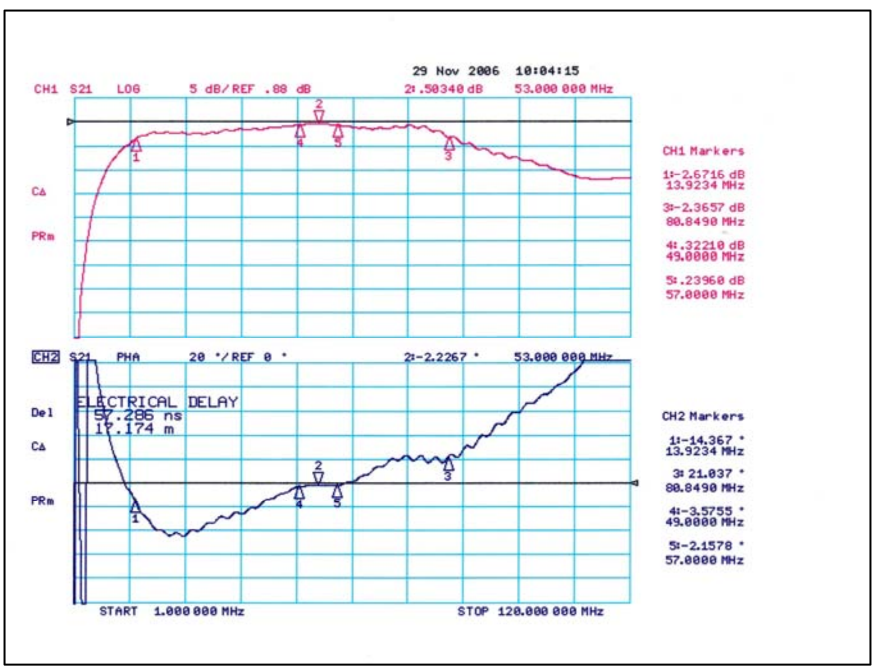


Figure 41. Frequency sweep of FF path and SSD Rack
(Output Power = 4.2kW, ϕ offset = 180°)

Conclusion:

This power supply comparison has shown that the approximate 4.2 kW average SSD RF power limit with the present 10kW model offers little to no headroom for the expected 4kW to 5kW moving average SSD RF power for the Proton Plan. It is recommended that the SSD power supply be upgraded to the 15kW version which was evaluated here. The 15kW version allows for (1) ~8kW of average SSD RF power; almost twice that allowed with the 10kW supply, (2) greater headroom for transients required by turn-on, the longitudinal damping system, and comb filters, (3) the capability to use full Feed Forward beam loading compensation across the entire cycle if needed, (4) increased flexibility in biasing the RF Power Amplifier tube for more efficient operation, and (5) reuse of the present 10kW supplies for the Booster SSD upgrade.

References:

[1] T. Berenc, "Main Injector HLRF Measurements for Proton Plan", Fermilab beams-doc #2331 v1, July 2006.

[2] T. Berenc, I. Kourbanis, D. McGinnis, J. Reid, "Main Injector RF Power Requirement Calculations for the Proton Plan", Fermilab beams-doc #2311, June 2006.