Debuncher Transverse Cooling Measurements of November 8 and November 28, 2007

and

A Comparison with the Transverse Cooling Measurements of Fall 2006

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Updated November 30, 2007

During this study measurements of signal to noise and cooling rate were performed on all transverse cooling bands and sub-bands. The measurement data is summarized in this memo.

Signal to Noise Measurements

The signal to noise ratio (SNR) was measured at the FIL signal point of each system. Tables 1 and 2 below give the SNR from band power measurements on spectrum analyzer 1.

Table 1: Horizontal SNR Measurements

System	Measured Band Power (dBm) Beam	No Beam	Int. BW (GHz)	SNR (dB)
HB1L	-48.3	-54.0	1.2	5.7
HB1U	-45.3	-51.7	1.2	6.4
HB1 Both	-43.3	-49.7	1.2	6.4
HB2L	-48.6	-54.8	1.2	6.2
HB2U	-52.1	-56.5	1.2	4.4
HB2 Both	-47.2		1.2	
HB3L	-42.5	-45.1	1.7	2.6
HB3U	-43.9	-48.2	1.7	4.3
HB3 Both	-40.3	-43.5	1.7	3.3
HB4L	-48.5	-52.4	1.7	3.9
HB4U	-45.8	-47.7	1.7	1.9
HB4 Both	-44.2	-46.8	1.7	2.7

Table 2: Vertical SNR Measurements

System	Measured Band Power (dBm) Beam	No Beam	Int. BW (GHz)	SNR (dB)
VB1L	-54.2	-57.0	1.2	2.8
VB1U	-50.1	-55.1	1.2	5.0
VB1 Both	-48.7	-53.7	1.2	5.0
VB2L	-53.9	-58.4	1.2	4.5
VB2U	-51.3	-55.9	1.2	4.6
VB2 Both	-49.6	-54.8	1.2	5.2
VB3L	-41.8	-44.2	1.7	2.4
VB3U	-43.4	-48.1	1.7	4.7
VB3 Both	-39.8	-43.0	1.7	3.2
VB4L	-46.2	-49.2	2.0	3.0
VB4U	-43.8	-45.2	2.0	1.5
VB4 Both	-42.1	-44.1	2.0	2.0

The Debuncher beam intensity was somewhat variable over the course of these measurements (see Figure 1). I did not attempt to correct for this variability for any of the analysis that follows. The Debuncher beam intensity for the SNR measurements was approximately 5 μA.

The horizontal data is given in Figures 2 and 3. The SNR for sub-bands 3 lower and 4 upper are significantly below that of the other bands.

The vertical data is given in Figures 4 and 5. Again, the SNR for sub-bands 3 lower and 4 upper are below that of the other bands. Vertical band 1 lower also has a low SNR.

Figures 6 and 7 show the SNR when both sub-bands of each system are on. The measurement of horizontal band 2 was inadvertently skipped due to operator error.

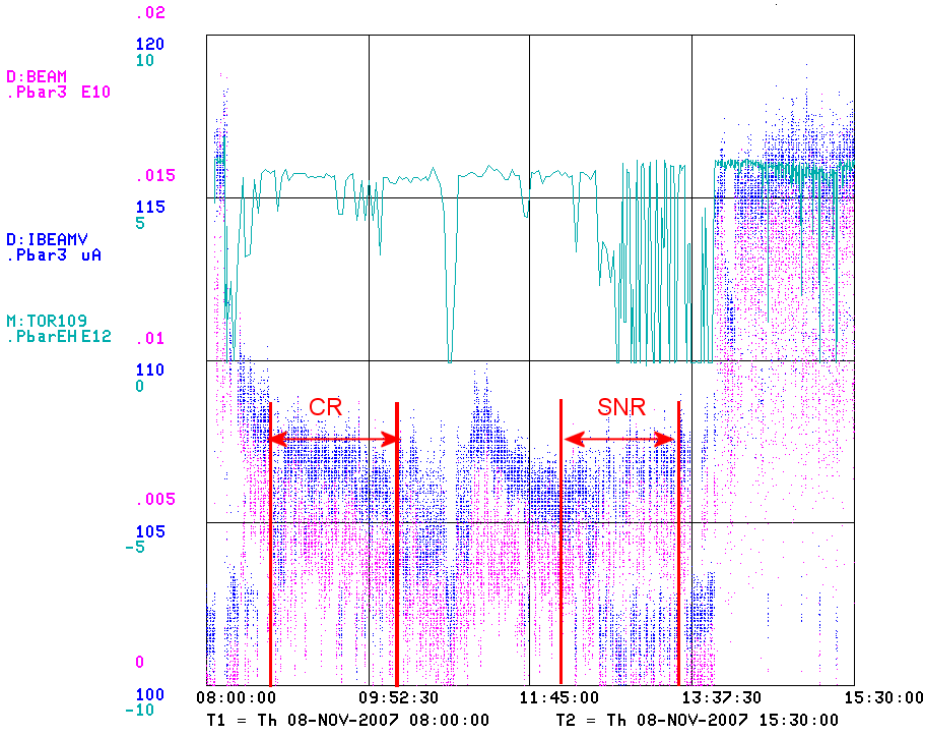


Figure 1 D:BEAM and D:IBEAMV during the cooling rate (CR) and SNR measurements of November 8, 2007. Note that D:IBEAMV has a no-beam offset of approximately 102 μA. NOTE: the cooling rate measurements that are included in this memo were performed November 28.

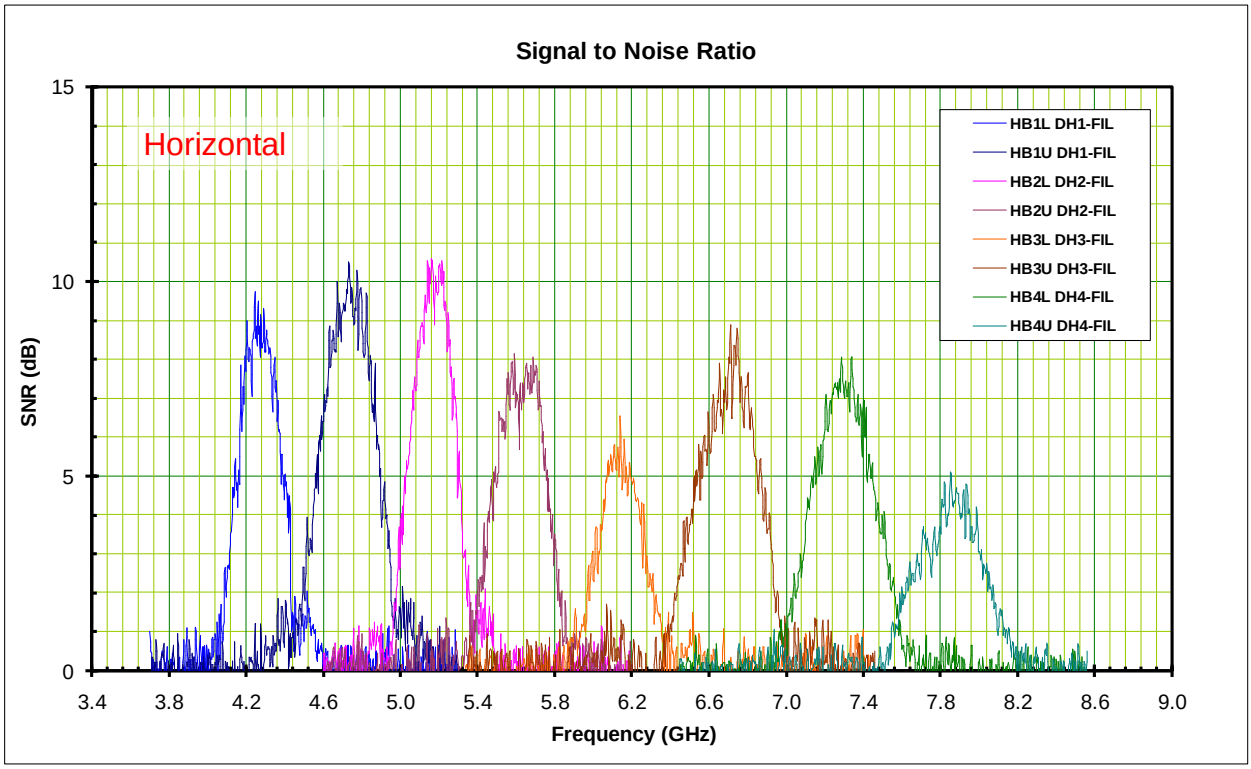


Figure 2 Horizontal SNR calculated from beam and no-beam response spectra. The raw data for this calculation is given in Figure 3.

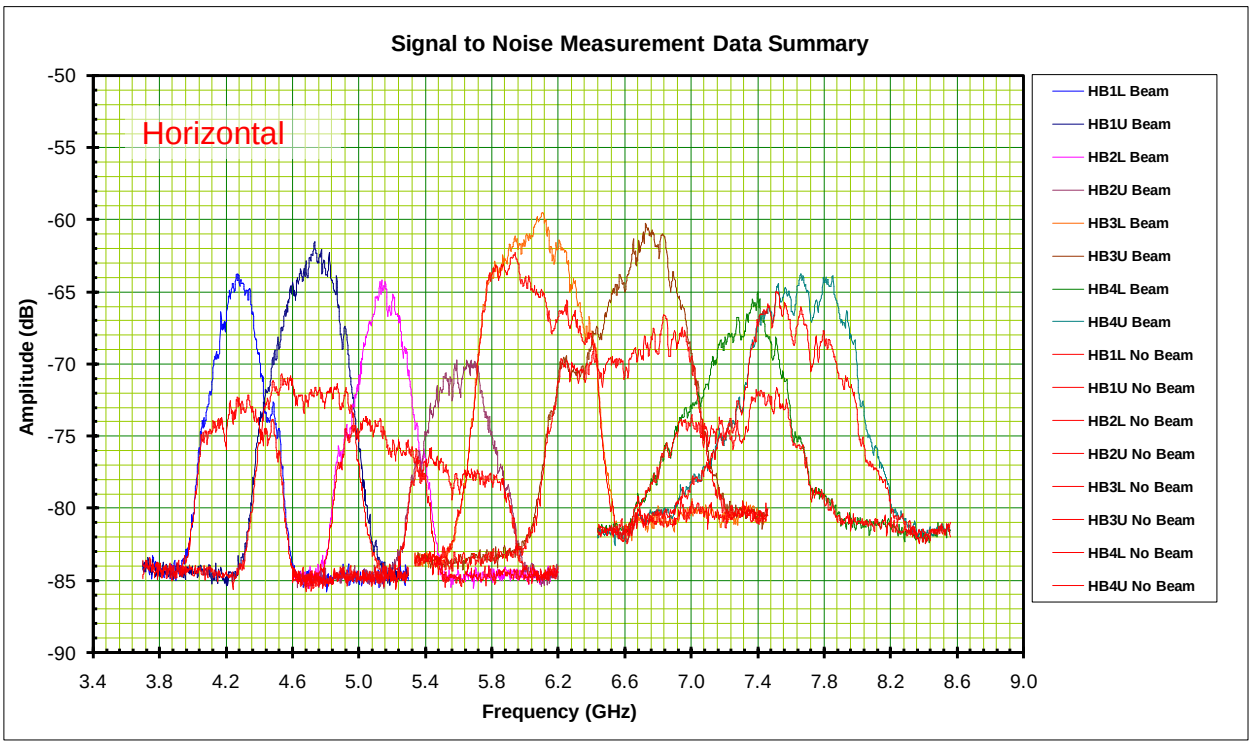


Figure 3 Horizontal raw data for the SNR calculation of Figure 2.

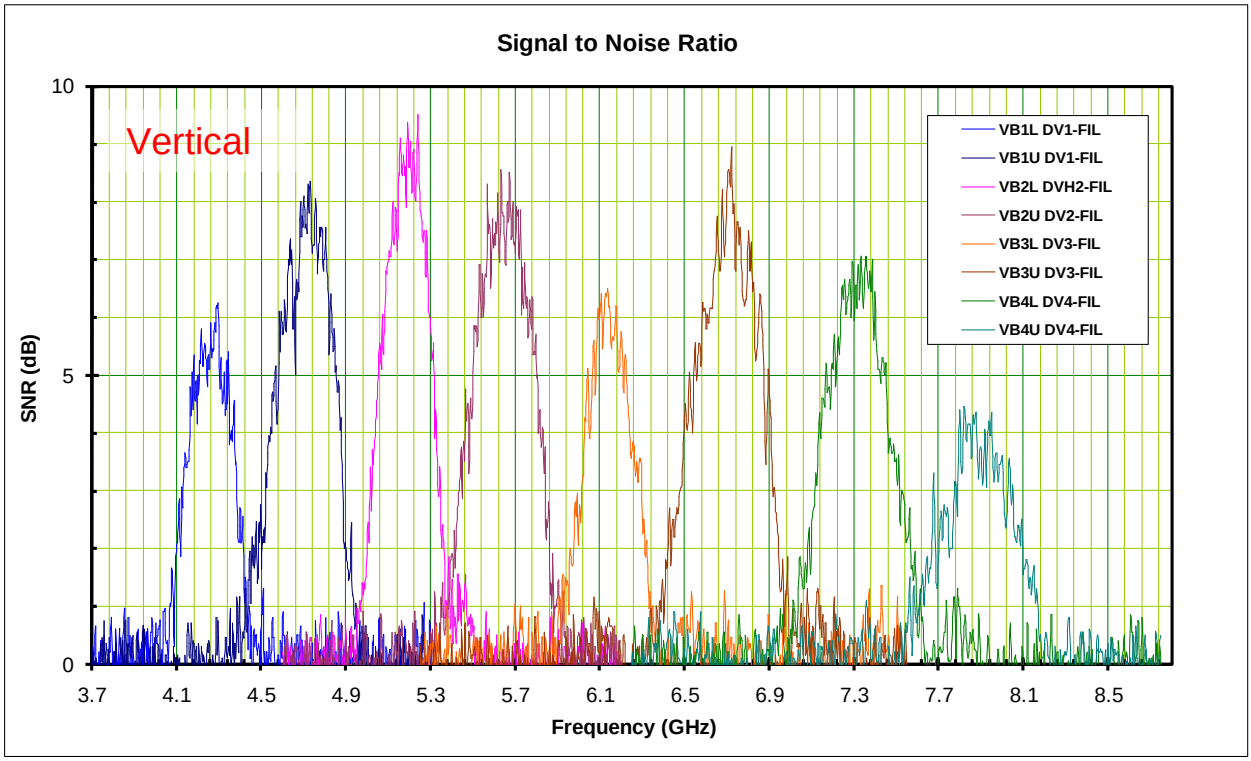


Figure 4 Vertical SNR calculated from beam and no-beam response spectra. The raw data for this calculation is given in Figure 5.

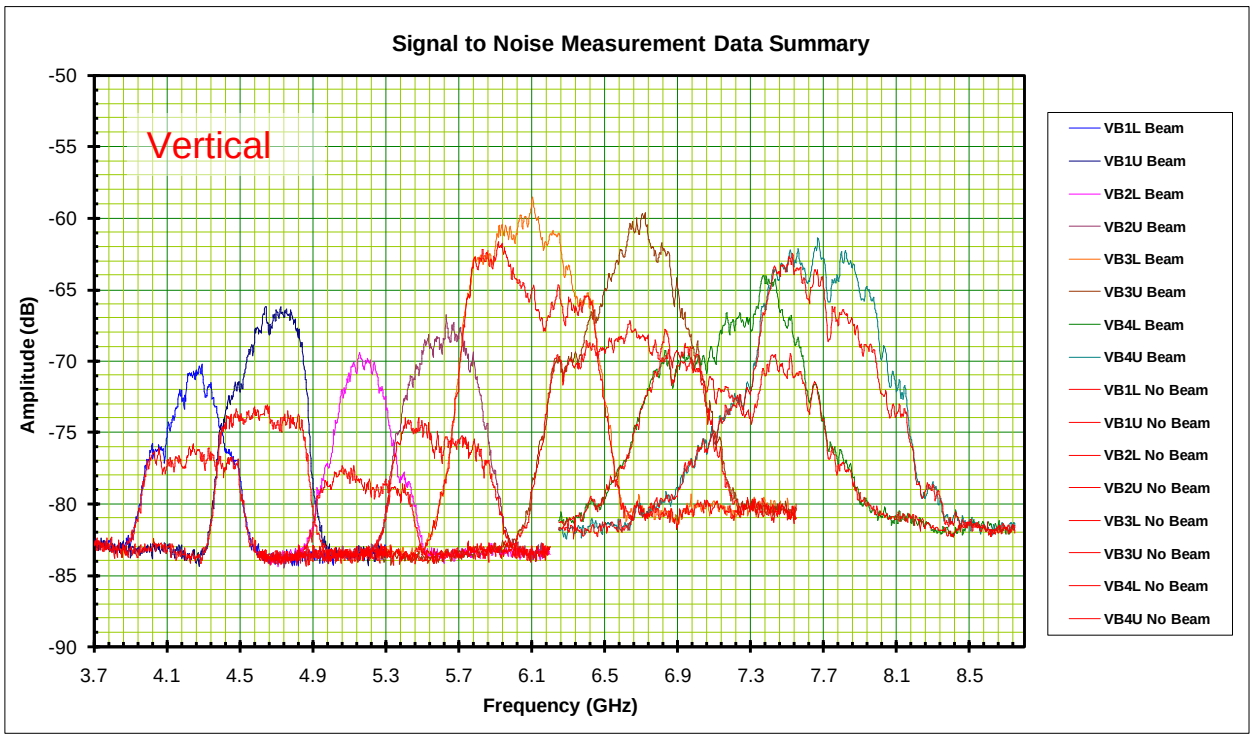


Figure 5 Vertical raw data for the SNR calculation of Figure 4.

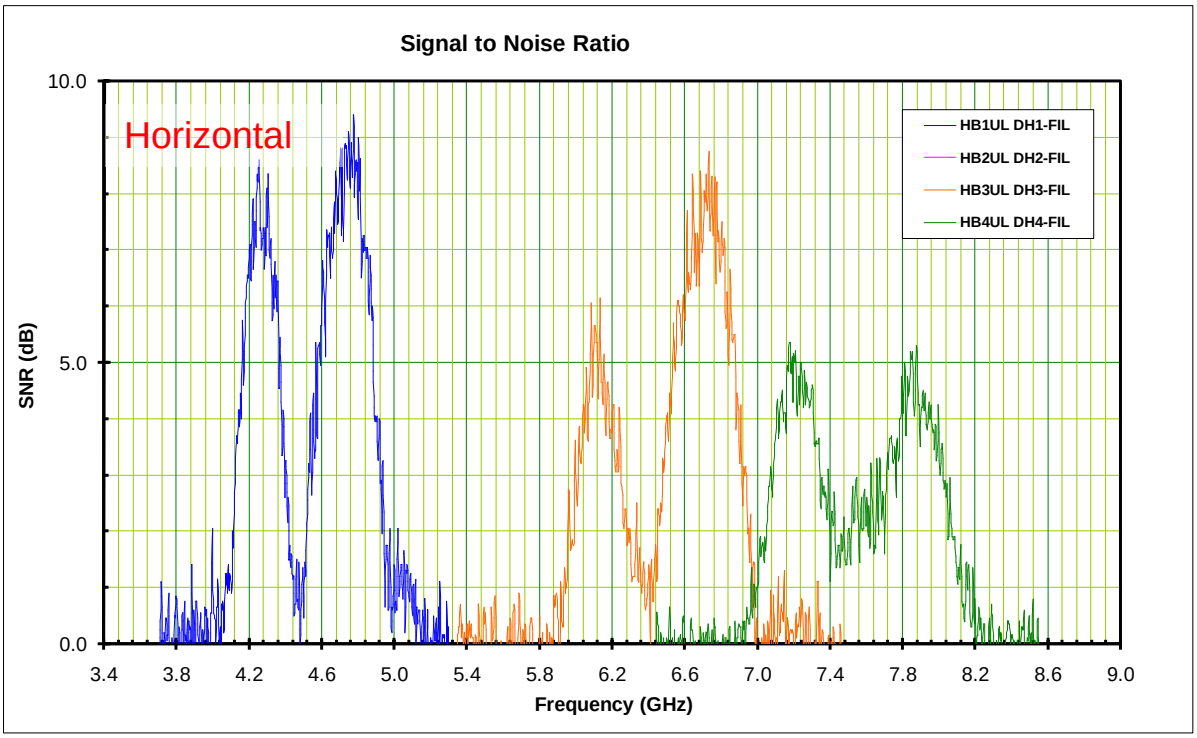


Figure 6 SNR for all horizontal bands. The upper and lower sub bands were both on for each measurement. The band 2 measurement was inadvertently skipped.

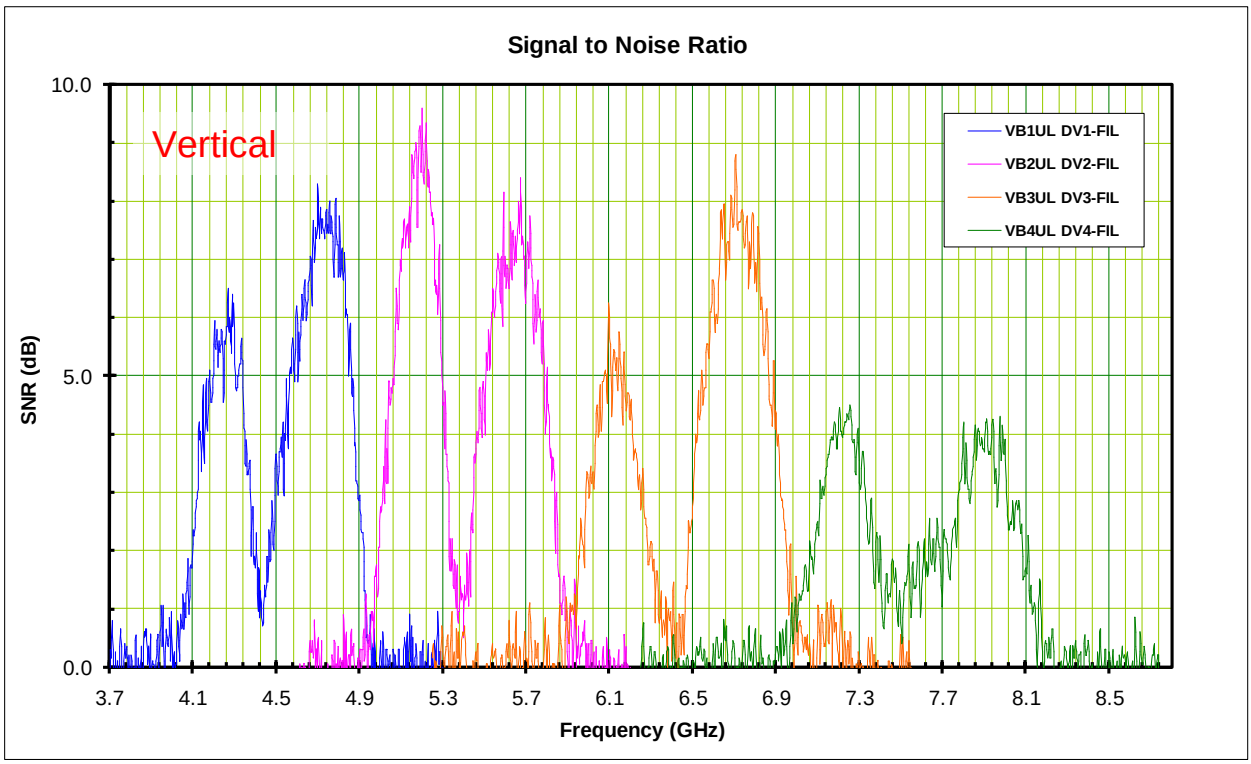


Figure 7 SNR for all vertical bands. The upper and lower sub bands were both on for each measurement.

Cooling Rate Measurements

The cooling rate measurements presented here were performed on November 28, 2007. The Debuncher beam intensity was somewhat variable over the time the data was taken (see Figure 8). The average beam intensity was approximately 10 μA.

The cooling rate was measured for each sub-band by connecting spectrum analyzer 1 to the SCH signal points of HB1L and VB1L and tuning it to a betatron sideband near the center of these sub-bands*. The spectrum analyzer is then set to zero-span with a resolution bandwidth that is wider than the betatron sideband being observed (RBW = 30 kHz). These measurements were made while stacking with a very long cycle time (30 sec). All transverse cooling gain ramps were turned off for these measurements.

The transverse cooling was set to come on 1.00 sec after the spectrum analyzer sweep starts, which is also 1.00 sec after the momentum cooling is gated on. The last 24 seconds of each trace were fit to an exponential. The resulting cooling times are given in Table 3.

The table below describes the timing of these measurements.

* When HB1 or VB1 cooling rates were being measured, the spectrum analyzer was tuned to the center of HB2L or VB2L to avoid signal suppression effects.

Stacking cycle time	30 sec
SA Sweep time	25 sec
Injection	\$80 + 1.03 sec
Δp cooling on time	\$80 + 1.03 sec
Δp cooling off time	\$80 + 1.01 sec
Transverse cooling on time	\$80 + 2.03 sec
Transverse cooling off time	\$80 + 1.01 sec
SA 1 external trigger	\$80 + 1.03 sec

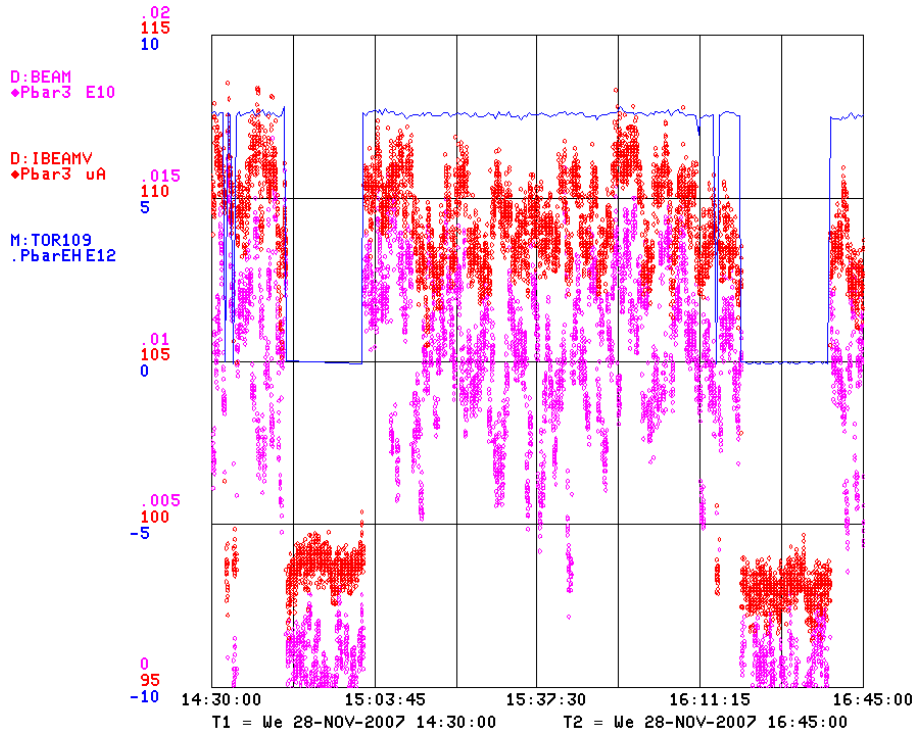
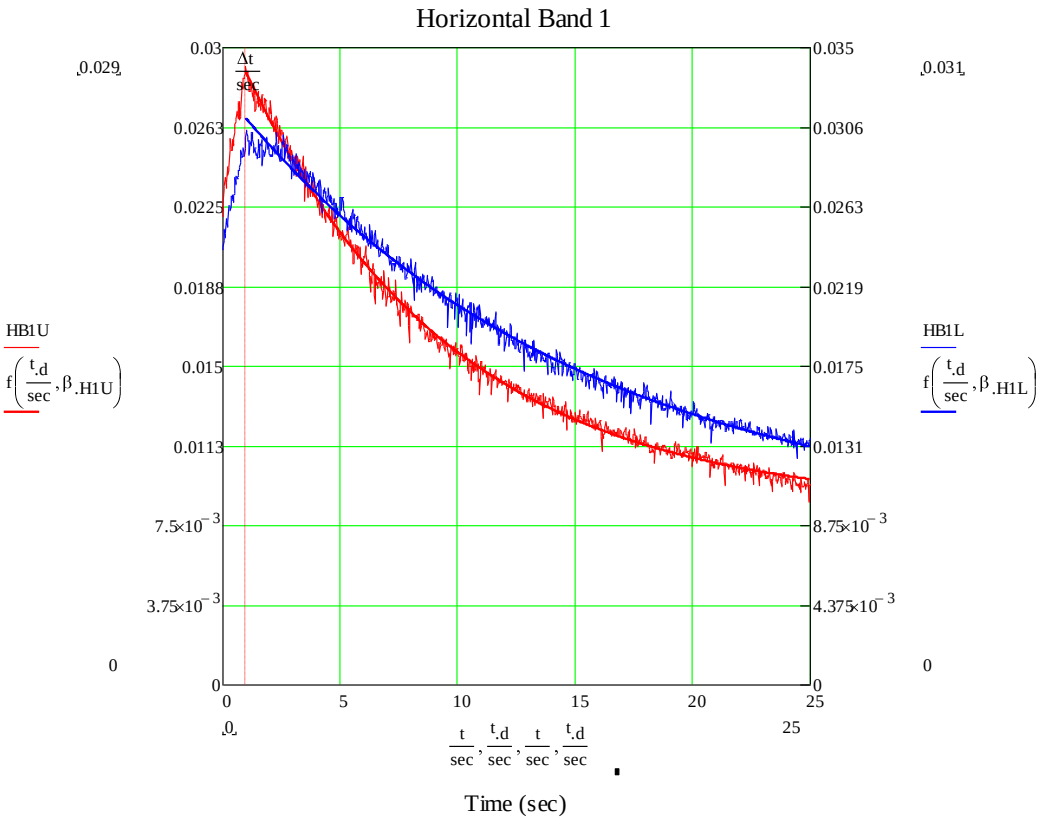


Figure 8 D:BEAM and D:IBEAMV during the cooling rate measurements of November 28, 2007. Note that D:IBEAMV has a no-beam offset of approximately 98 μA.

Table 3: Transverse Cooling Times

Band	Horizontal	Vertical
1 Lower	14.70 sec	Not Measured
1 Upper	8.73 sec	18.09 sec
2 Lower	35.28 sec	33.92 sec
2 Upper	21.55 sec	11.27 sec
3 Lower	28.21 sec	26.47 sec
3 Upper	14.95 sec	20.53 sec
4 Lower	31.48 sec	54.41 sec
4 Upper	38.06 sec	44.80 sec

The fits are shown in the plots below.



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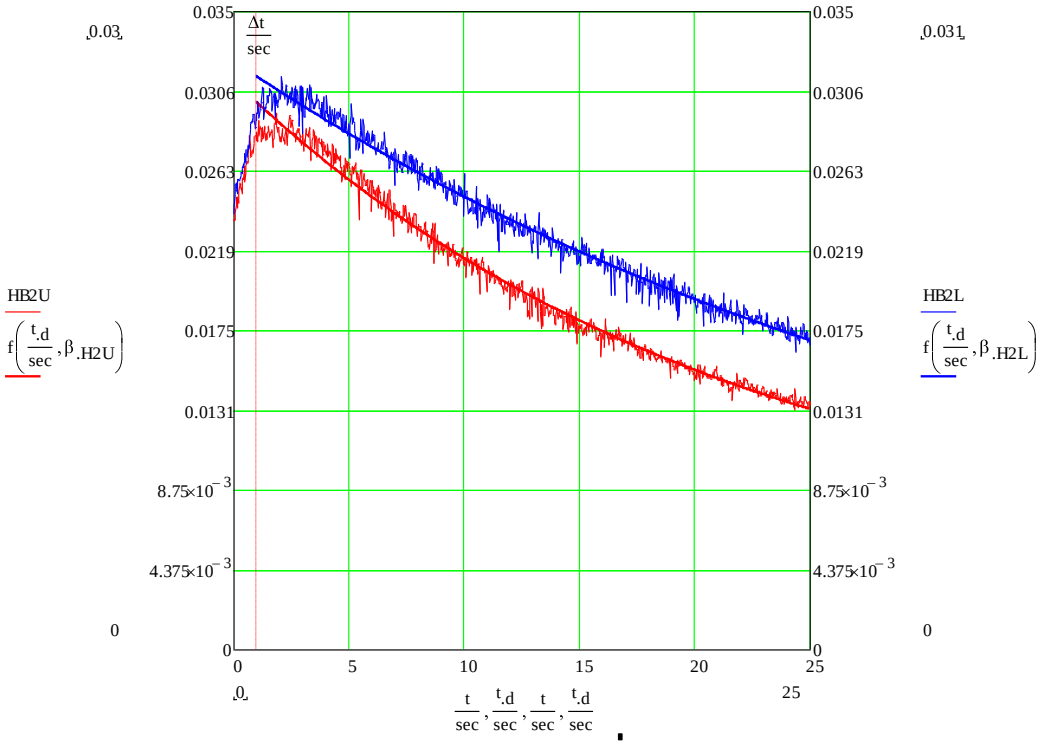
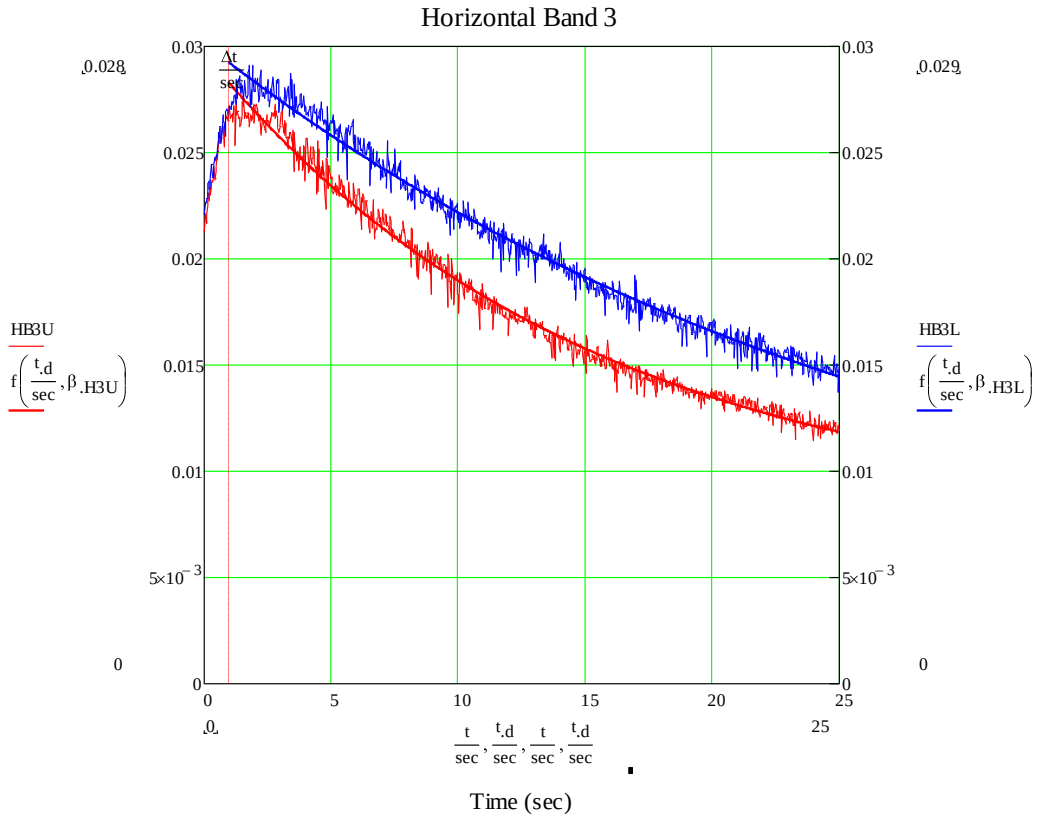
Horizontal Band 2



Horizontal Band 3



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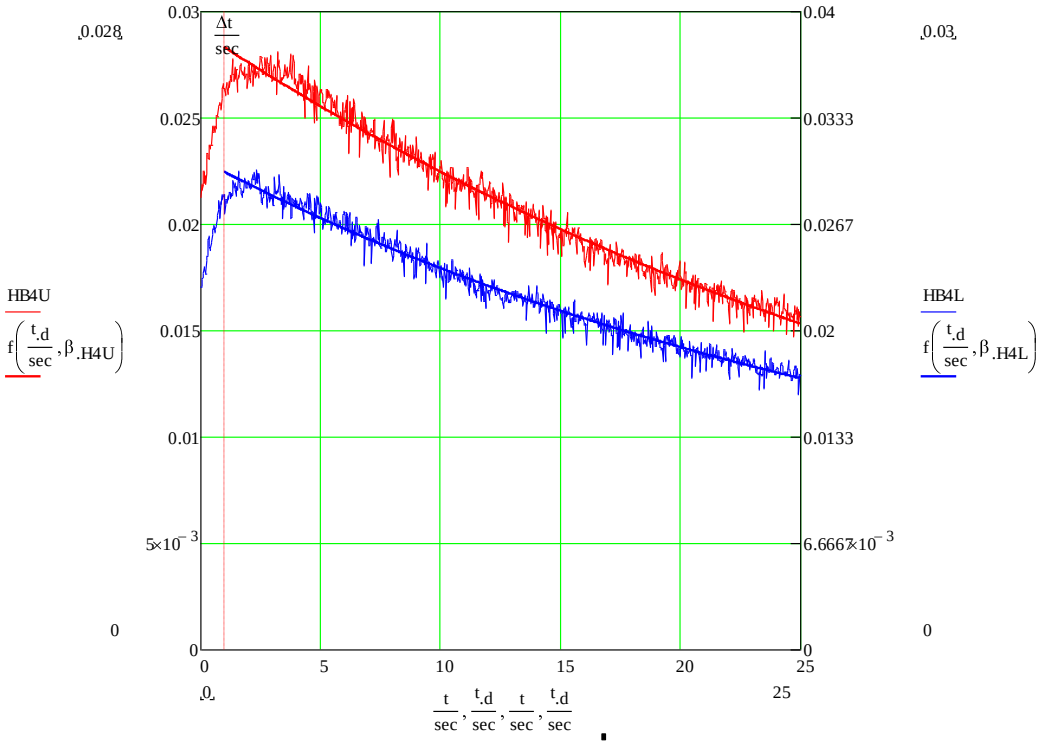
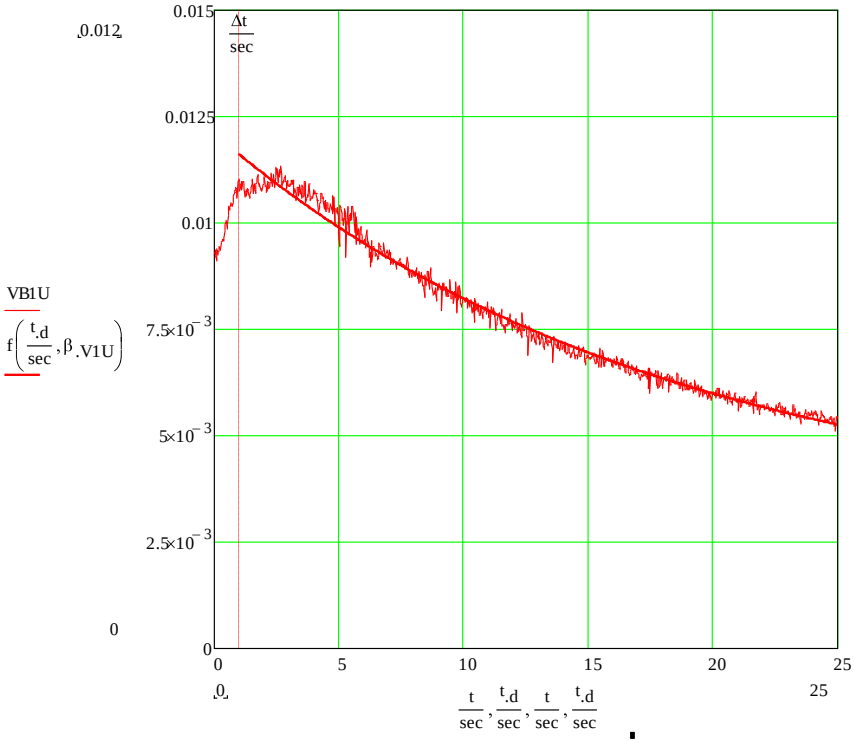
Horizontal Band 4



Time (sec)

Vertical Band 1



Time (sec)

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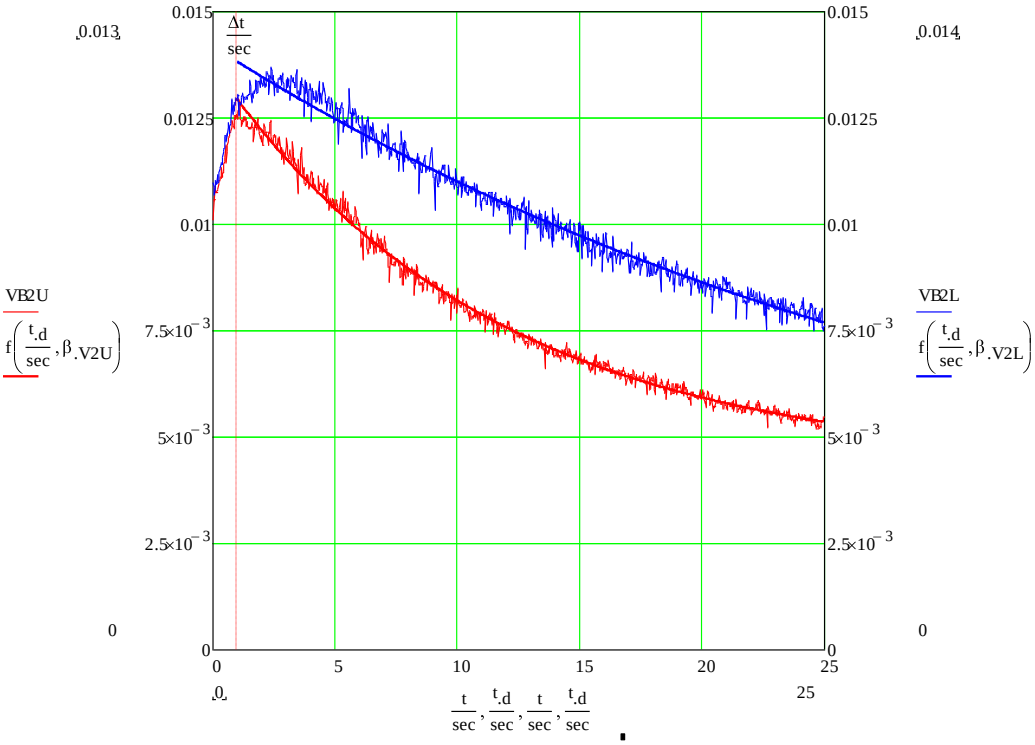
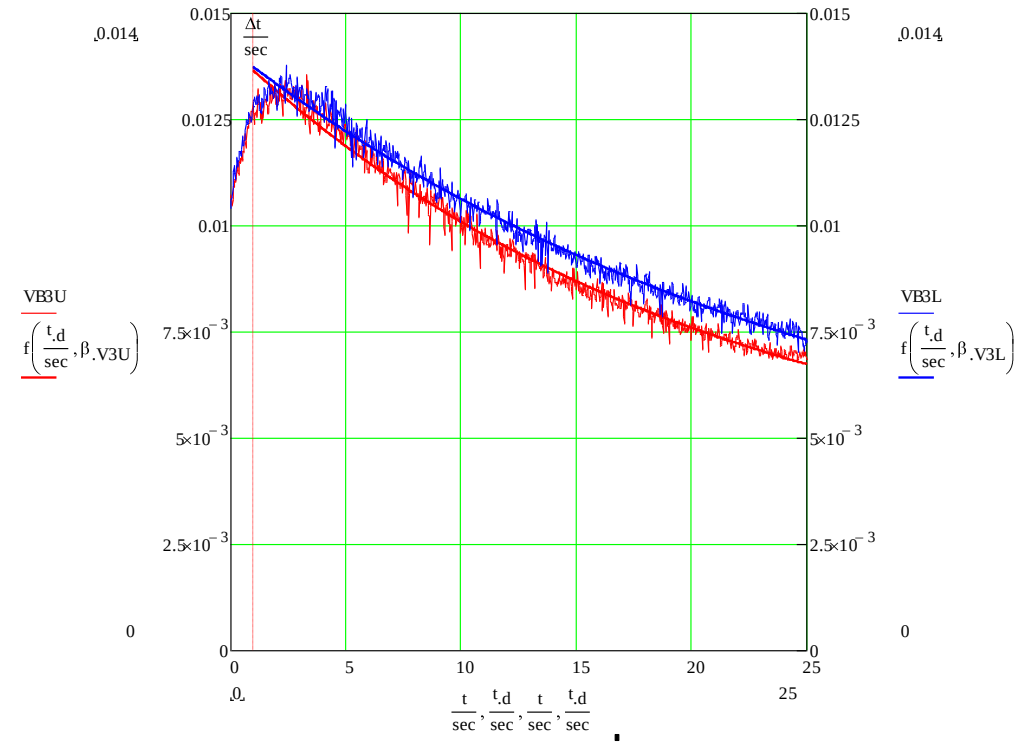
Vertical Band 2

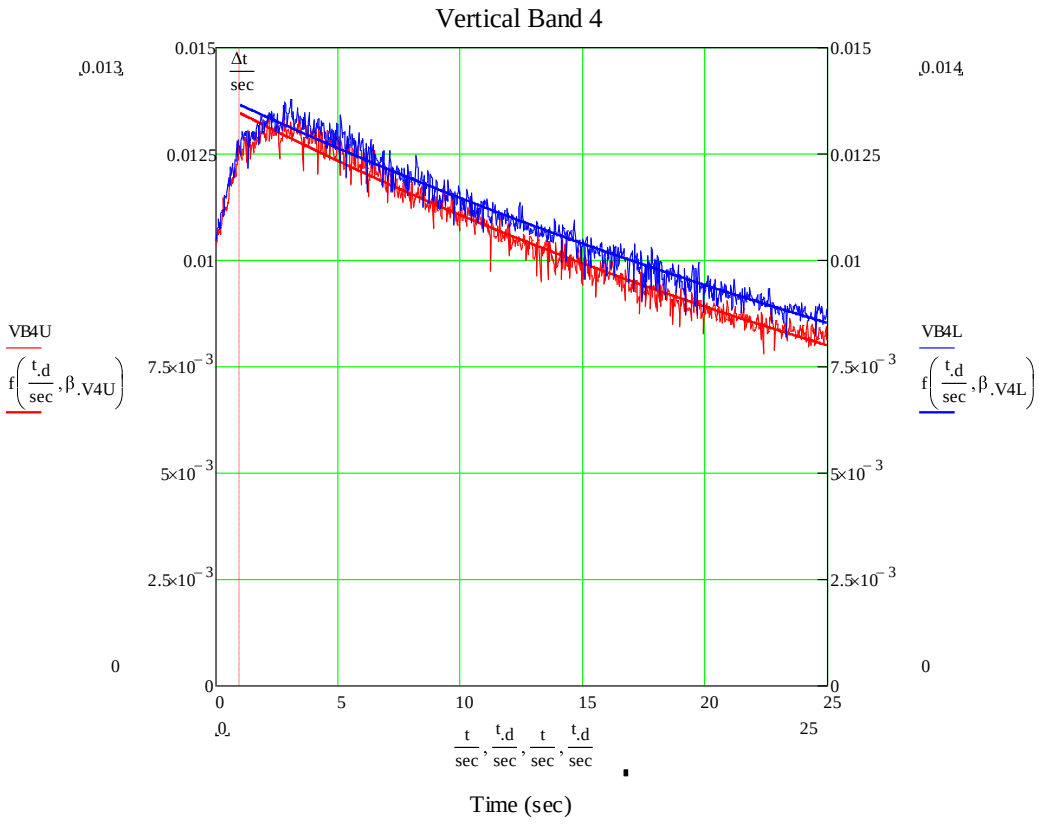


Time (sec)

Vertical Band 3



Time (sec)



Combined upper + lower sub band cooling rates

The cooling rate and SNR was measured for each band with both upper and lower low level sub bands on. The cooling rates were measured with and without the notch filters. The gain was increased by 3 dB for the no-notch measurements. The plots showing the cooling time fits (notch filter in measurements only) are shown in Figures 9 and 10 below. The results are shown in Table 4.

Table 4: SNR and Cooling Rates

System	SNR (dB)	Int. BW (GHz)	τ (sec)	
			w/ Notch Filter	No Notch Filter
HB1	6.4	1.2	8.05	10.40
HB2	Not Meas.	1.2	11.19	16.43
HB3	3.3	1.7	8.68	12.19
HB4	2.7	1.7	15.41	55.49
VB1	5.0	1.2	9.90	14.35
VB2	5.2	1.2	10.45	13.94
VB3	3.2	1.7	10.68	12.24
VB4	2.0	2.0	17.32	27.22

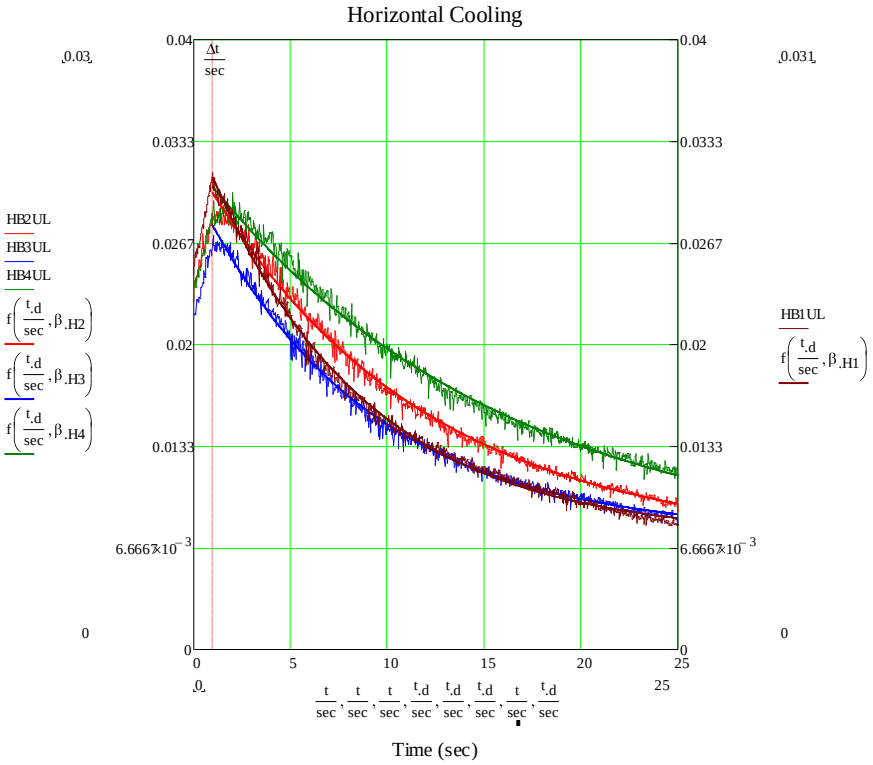


Figure 9 Exponential fits to horizontal betatron sideband power vs. time. Both low level sub-bands were on when each system was measured. The notch filters were in for these measurements.

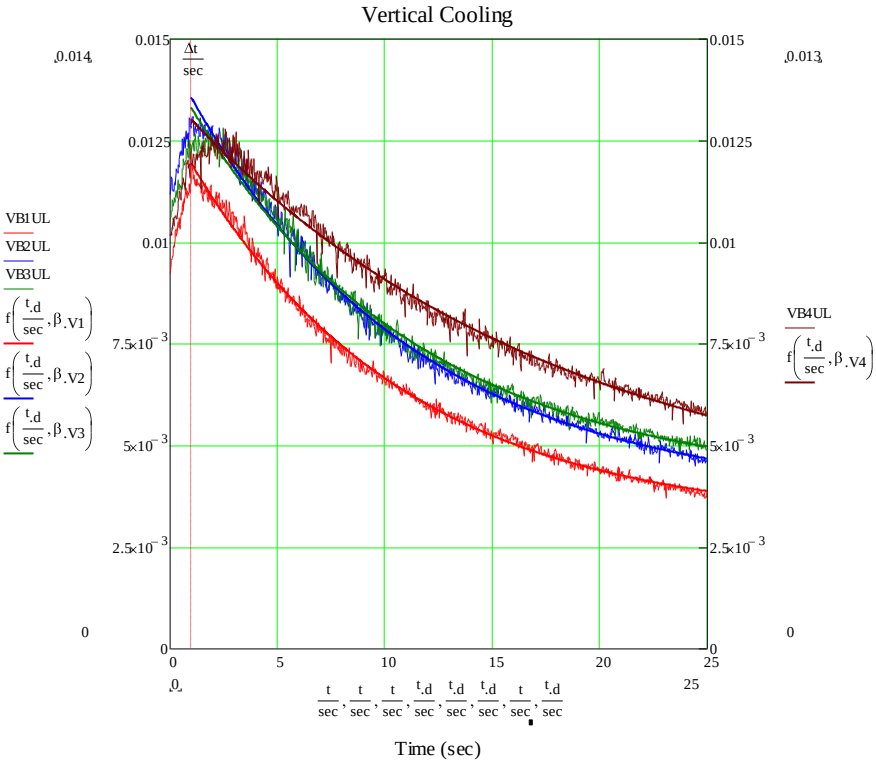


Figure 10 Exponential fits to vertical betatron sideband power vs. time. Both low level sub-bands were on when each system was measured. The notch filters were in for these measurements.

Analysis

The measured cooling rates span a rather wide range. A variety of parameters were examined in an attempt to determine what causes this variation in cooling rate. Table 5 contains a summary of the various parameters that were studied. The red entries are quantities that are significantly different from what is expected. The quantities in Table 5 are defined as follows:

β_{pu} = beta-function at the pickup

β_k = beta-function at the kicker

$\Delta\phi$ = pickup to kicker betatron phase advance (modulo 360°)

$$\beta_{eff} = \sqrt{\beta_{pu}\beta_k}\sin(\Delta\phi)$$

Table 5: Parameters affecting cooling

System	β_{pu} (m)	β_k (m)	$\Delta\phi$ (deg)	β_{eff} (m)	SNR (dB)	τ (sec)
HB1L	12.38	16.20	94.24	14.13	5.7	14.70
HB1U	19.10	16.20	90.73	17.59	6.4	8.73
HB2L	9.49	6.49	92.23	7.84	6.2	35.28
HB2U	5.53	6.49	80.91	5.92	4.4	21.55
HB3L	9.54	10.98	91.87	10.23	2.6	28.21
HB3U	13.69	10.98	84.72	12.21	4.3	14.95
HB4L	5.36	4.65	102.64	4.87	3.9	31.48
HB4U	3.44	4.65	83.29	3.97	1.9	38.06
VB1L	11.89	12.35	87.29	12.11	2.8	----------
VB1U	18.27	12.35	81.76	14.87	5.0	18.09
VB2L	6.96	7.95	91.41	7.43	4.5	33.92
VB2U	5.69	7.95	78.35	6.59	4.6	11.27
VB3L	8.41	9.60	93.75	8.97	2.4	26.47
VB3U	13.72	9.60	86.14	11.45	4.7	20.53
VB4L	6.79	5.38	87.26	6.04	3.0	54.41
VB4U	4.37	5.38	72.13	4.61	1.5	44.80

The parameters that best correlate to cooling rate are β_{eff} and SNR. Figure 11 shows a plot cooling rates versus SNR. The correlation is far from perfect. Figure 12 shows a plot of cooling rates versus β_{eff}. There is a general correlation with some exceptions.

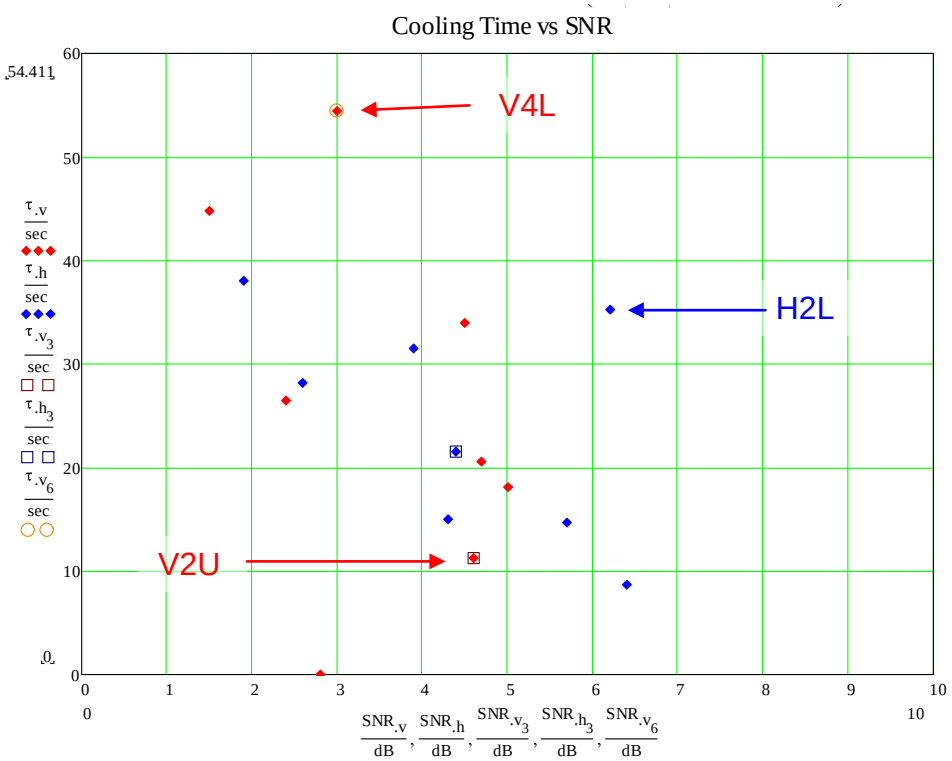


Figure 11 Exponential cooling time (τ) versus signal to noise ratio (SNR) for all cooling sub bands. ♦ is horizontal and ♦ is vertical.

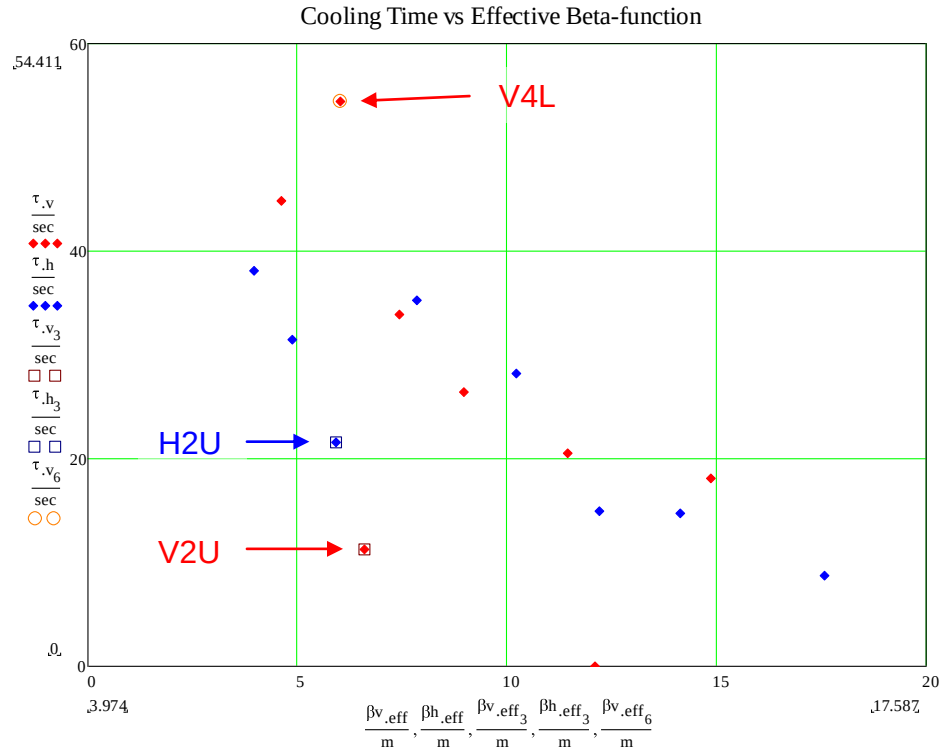


Figure 12 Exponential cooling time (τ) versus β_{eff} for all cooling sub bands. ♦ is horizontal and ♦ is vertical.

Comparison of the Fall 2006 and November 2007 measurements

A set of SNR and cooling rate measurements were made in October and November of 2006. The results are summarized in a document in the Accelerator Division document database at the following link: https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=2913.

SNR Comparison

The comparison of signal to noise measurements is difficult due to the large uncertainty in the Debuncher beam intensity. For the October 2006 analysis I used the Debuncher DCCT readout (D:IBEAMV) as the measure of beam intensity. Subsequently it has been determined that this quantity has a large and variable no-beam offset. Using the lumberjack archive of D:IBEAMV the offset corrected beam intensity was determined to be 16.5 μA during the October 17, 2006 SNR measurements*. The Debuncher beam intensity for the November 8, 2007 SNR measurements was 5.0 μA. To compensate for the difference in beam intensity, a correction given by $10\log\left(\frac{16.5}{5.0}\right) = 5.2$ dB is added to the 2007 measurements.

The 2006 and corrected 2007 measurements are shown in the Tables 6 and 7:

Table 6: Horizontal SNR Comparison

Band	October 2006 SNR (dB)	Corrected Nov. 2007 SNR (dB)
H1L	10.1	10.9
H1U	9.5	11.6
H2L	10.7	11.4
H2U	9.4	9.6
H3L	4.2	7.8
H3U	6.3	9.5
H4L	6.4	9.1
H4U	4.2	7.1
H1 L&U	9.3	11.6
H2 L&U	9.9	----
H3 L&U	4.8	8.5
H4 L&U	4.8	7.9

* Note: the chart headings in the 2006 document indicate that the SNR plots were corrected to a beam intensity of 2.2×10^8 particles. This is not true. The correction was set to zero (so the plots would match the band power measurements) but the plot headings were not updated.

Table 7: Vertical SNR Comparison

Band	October 2006 SNR (dB)	Corrected Nov. 2007 SNR (dB)
V1L	8.2	8.0
V1U	10.1	10.2
V2L	10.5	9.7
V2U	10.0	9.8
V3L	4.5	7.6
V3U	7.1	9.9
V4L	5.1	8.2
V4U	3.5	6.7
V1 L&U	8.0	10.2
V2 L&U	8.5	10.4
V3 L&U	5.5	8.4
V4 L&U	4.0	7.2

Cooling Rate Measurement Comparison

A comparison of the cooling rates measured in October-November 2006 with the November 2007 measurements lends great support to the hypothesis that we don't know how to measure a transverse cooling rate. Despite SEM 806 measurements that show the Debuncher transverse cooling is working better now than in the Fall of 2006[*], the present measured cooling times are significantly greater than those of a year ago.

Tables 8 and 9 show the cooling times derived from the Fall 2006 and the November 2007 measurements.

[*] SEM 806 measurements from August 24, 2006 and December 28, 2006 show an average σ_x of 3.12 mm and an average σ_y of 2.90 mm for a 2.4 sec cycle time. SEM 806 measurements November 21 and 27, 2007 show an average σ_x of 2.86 mm and an average σ_y of 2.63 mm for a 2.2 sec cycle time.

Table 8: Horizontal Cooling Rate Comparison

Band	Oct. – Nov. 2006 Cooling Rate (sec)	Nov. 2007 Cooling Rate (sec)
H1L	8.60	14.70
H1U	7.25	8.73
H2L	12.32	35.28
H2U	8.91	21.55
H3L	14.66	28.21
H3U	10.10	14.95
H4L	12.21	31.48
H4U	22.56	38.06
H1 L&U	4.63	8.05
H2 L&U	5.58	11.19
H3 L&U	6.64	8.68
H4 L&U	9.89	15.41

Table 9: Vertical Cooling Rate Comparison

Band	Oct. – Nov. 2006 Cooling Rate (sec)	Nov. 2007 Cooling Rate (sec)
V1L	6.58	----
V1U	6.61	18.09
V2L	12.65	33.92
V2U	8.59	11.27
V3L	13.06	26.47
V3U	12.19	20.53
V4L	16.02	54.41
V4U	15.07	44.80
V1 L&U	4.40	9.90
V2 L&U	7.27	10.45
V3 L&U	6.92	10.68
V4 L&U	8.78	17.32

Observations

1. The shape of SNR versus frequency in Figures 2 – 7 is very similar to the shape measured in Fall 2006.
2. For bands 1 and 2 the SNR corrected for beam intensity from the band power measurements in Tables 6 and 7 is within 1 dB of what was measured in Fall of 2006. For bands 3 and 4 there is a 3 dB improvement in SNR over the Fall 2006 measurements. This is likely due to the new notch filters in these bands.
3. The SNR for horizontal and vertical band 3 lower is relatively small. Also the band width of these bands is narrower than any other sub-band.
4. When the sub-bands of band 4 (horizontal and vertical) are measured separately, the peak SNR of band 4 lower is 2 – 3 dB greater than the peak SNR for band 4 upper (see Figures 2 and 4). When the band 4 sub-bands are measured together the upper and lower peak SNRs are approximately equal (see Figures 6 and 7).
5. Band 2 lower has the best SNR for both the horizontal and the vertical systems, but has anomalously large measured horizontal and vertical cooling times.
6. HB4U and VB4U are practically useless.
7. The November 2007 cooling times are significantly longer than those measured in October 2006. Possible explanations: transverse gain ramping was on in 2006 but off in 2007; momentum cooling may be better in 2007 than in 2006; we don't know how to measure cooling rates.
8. For most systems it appears as if it takes a couple of seconds after the transverse cooling is gated on for exponential cooling to begin. This was not the case for the Fall 2006 cooling rate measurements. An example of a proper turn-on is HB1U (page 7). An example of an especially poor turn-on is VB1U (page 9). While this causes the fitted cooling time to be longer, it does not explain the significantly longer cooling times measured in November 2007 compared to Fall 2006.
9. All pickup to kicker betatron phase advances are within 15° of 90° except VB4U, which is 18° off.

Appendix: Setup and conditions

November 8, 2007 Measurements			***November 28, 2007 Measurements***	
D:H1PA1	7.00		D:H1PA1	6.00
D:H2PA1	22.00		D:H2PA1	25.00
D:H3PA1	15.50		D:H3PA1	17.00
D:H4PA1	17.00		D:H4PA1	17.50
D:V1PA1	12.50		D:V1PA1	13.50
D:V2PA1	17.00		D:V2PA1	15.00
D:V3PA1	13.00		D:V3PA1	13.00
D:V4PA1	15.50		D:V4PA1	17.00

The SNR measurements for all bands were done on November 8, 2007.

The cooling rate measurements for all bands were done on November 28, 2007.