**Recycler BPM Sign Convention, System Description, and Signal Path**

Peter Prieto

The BPM upgrade has to resolve positions for 2.5 MHz and 52.8 MHz bunch frequencies with a dynamic range from 5e12 injected particles per batch. Once injected the batches will be slip-stacked making the signal intensity 1e13 per batch. In the 2.5 MHz case a single 4e12 52.809 Mhz batch is injected and then re-bunched into 4 2.514 MHz bunches of 1e12 protons each.



**System Convention:**

The fundamental sign convention for the Recycler BPM System is that measured positions delivered from the VME front-end data acquisition system to ACNET shall be signed positively for beam positions radially outside at horizontal locations and above center at vertical locations. **POSITIVE** measurement values correspond to beam **UP** or **OUT** and **NEGATIVE** measurement values correspond to beam **DOWN** or **IN**. This convention applies to the two Recycler transfer lines as well as to the Recycler Ring itself.

NOTE: the personnel aisle is on the radial INSIDE of the machine in the Recycler tunnel.

**BPM:**

The Recycler BPM pickups are two-electrode devices made with diagonally split elliptical pipes. Vertical pickups have output connectors on the top and the bottom of the pickup body attached to the top and bottom electrodes respectively. Similarly, horizontal pickups have output connectors on the radial inside and the radial outside of the pickup body attached to the inside and outside electrodes respectively.

There are some MI-8 style or 8-GeV style pickups in the Recycler system. These pickups are of the two-electrode, diagonally split cylinder design, may be used in either horizontal or vertical applications, and have both connectors on one side of the pickup body. In vertical installations the upper and lower connectors attach to the top and bottom electrodes respectively. Similarly, in horizontal installations, the radial inside and outside connectors attach to the inside and outside electrodes of the BPM.

1A

Positive Vertical Position when above center line

B

Y

Radially Outward

1B

A

Positive Horizontal Position when beam located Radially out

1A

A

1B

B

**Note: Scale Factor as entered in R43 page section [Channel Params] which has a negative sign. This corrects the crossing of the A and B cables and the transition board channel input channels 1A,1B ; 2A,2B…..**

**Input Cabling:**

Each Recycler has two signals, one for each of two BPM electrode signals. Most of the BPM’s connect to the service building using LDF1-50, a 50 Ohm ¼ inch Heliax cable except at the straight section in MI60 where those BPMs in the proximity of the RF system use LDF2-50, a 50 Ohm 3/8 inch Heliax cable. The Heliax cable connects to the BPM using an SMA connector directly terminated at the BPM pickups. The other end of the cable is connected using an N-Connector which terminates at the rack top plate.



|  |  |
| --- | --- |
| Frequency MHz | Attenuation dB/100 ft. |
| 30 | 0.667 |
| 50 | 0.865 |
| 150 | 1.52 |

**Relay Rack Top Entry Panel:**

The top-entry panel accept the Heliax connection from the tunnel and the signal is passed through an N-Connector 26 dB attenuator feedthrough. The attenuator value is based on the cable length, the attenuation due to the type of cable and the frequency being processed (2.5 MHz or 53 MHz). The signal is then connected to the transition module using Mil 17/ 113-RGS-316 50 Ohm double shielded Coax terminated at one end with an N-connector and an SMA connector at the other end. This SMA connector goes to a transition panel that has an SMA-SMA feedthrough allowing for a short connection between the front plate and the transition module.



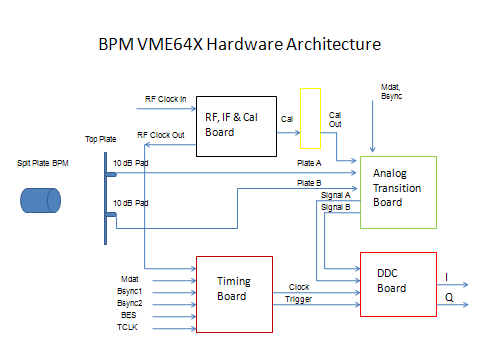
|  |  |  |
| --- | --- | --- |
|  | Material | Diameter(mm) |
| 1．Inner conductor | SCCS | 7/0.17 |
| 2．Insulation | PTFE | 1.52 |
| 3．Outer conductor | 1 : SC | 1.98 |
| 4．Jacket | FEP | 2.49 |

**ELECTRICAL PROPERTIES**

|  |  |
| --- | --- |
| Nom. Capacitance Conductor to Shield(pF/m) | 96.5 |
| Nom. Characteristic Impedance(ohm) | 50 |
| Nom. Velocity of Propagation(％) | 69.5 |
| Min. Bend Radius(Install)(mm) | 13 |
| Voltage Rating(VMS) | 1200 |
| Max. Operating Frequency(MHz) | 3000 |
| Operating Temperature Rating(℃) | -55～+200 |

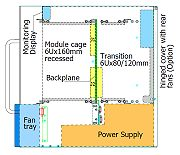
**Nom. Attenuation**

|  |  |
| --- | --- |
| Frequency(MHz) | Nom. Attenuation(≯dB/m) |
| 100 | 0.262 (7.985 dB/100 ft) |
| 400 | 0.531 |
| 1000 | 0.856 |
| 3000 | 1.532 |

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**Transition Module:**

The Transition Module (dwg. 465015) is an eight-channel board receiving signals from four BPMs. Inputs are applied through front-panel SMB connector, one per BPM pickup. The transition board processes the 52.809 MHz by adjusting the gain and sending the signal through a 52.8 MHz, 5MHz BW bandpass filter. The channel output is connected on the front panel to the input of the DDC channel on the echotek digitizer board. The connection is done using Mil 17/ 113-RGS-316 50 Ohm double shielded Coax terminated at each end with an SMB. The same channel input handles the 2.514 MHz signal and processes the signal by filtering the signal with a 2.5 MHz Bandpass filter of 5 MHz BW. The output of the 2.514 MHz channel is summed to the 52.809 MHz signal path using a summing amplifier then driving the common out path to the input of the DDC.



**DDC:**

The EchoTek GC814 digital receiver boards are eight channel boards recycled from the TeV BPM system. The channels are numbered 1 through 8 on the front panel input connectors. Transition module “A” channel output signals connect to odd-numbered EchoTek inputs and transition module “B” channel outputs to the next respectively even-numbered channels. In most, but not all cases, this results in direct physical mapping from the top output of a transition module to the top input of the corresponding EchoTek, second transition module output to second EchoTek input, etc. through all eight channels of each. Specific channel assignments are identified in the last table of this document.

Signal cables between Transition Modules and EchoTek cards are labeled with the BPM and the A or B signal identification, e.g. VP521-A for signal A from vertical BPM at lattice location 521.

**Software:**

The BPM software is based on the Main Injector BPM system.

**NoVA BPM Injection seam:**

The BPM seam in NoVA is located at MI-30 and treated the same as the Main Injector BPM system in hardware as well as software.

**Transition Channel Gain and attenuation Settings:**

Power into DDC input is +4.81 dBm for voltage of +1.1 Vpp.Measured dynamic range of digitizer is ~ 50 dB. In order to have a uniform power level at each DDC input the gain and attenuation for each pickup has to be set to compensate for initial power at the pickup. The heliax cable losses, RG-316 attenuation and transition channel attenuation. The table below shows that for 52.8MHz signal the channel can attenuate the signal between -2.62 dB and -59.6 dB. For 2.5Mhz they are attenuated by -32 dB.

**Attenuation values obtained through the transition board channel**

|  |  |  |  |
| --- | --- | --- | --- |
| 2.5 MHz Channel Components | Attenuation  dB | 52.8 MHz Channel Components | Attenuation  dBm |
| RG-316 attn | **-1.12** | RG-316 attn | **-1.12** |
| Insertion Loss |  | Insertion Loss | **1.82 (swr)** |
| Directional Coupler | **-0.5** | Directional Coupler | **-0.5** |
| Absorptive filter | **-0.5** | Absorptive filter | **-0.5** |
| Fixed Attenuator | **-30.0** | Variable Attenuator | **-31.5 to -0.5** |
| Low Pass Filter | **-0.5** | BandPass Filter | **-3.0** |
| BandPass Filter | **0.0** | Variable Gain Amp | **+19.9** |
| VCA | **0.0** | VCA | **0 to 23dB attn** |
| Total | **-32.62** |  |  |

Standing Wave Ratio or from Reflection coefficient =

Reflection coefficient in terms of power and

The power calculated out of the BPM is in dBm which stands for 0 dBm = 1mW of power so one must convert dBm to Watts and back to dBm when determining the Gain and attenuator settings required.

Both equations needed to calculate transmitted power after the attenuator the HMC542 digital attenuator sees where the measured SWR = 1.82 at each channel input.

Power ( in Watts from dBm ) =

dBm (from Watts )=

Mismatch Loss = a ratio between incident power and power absorbed by the load in units of dB

Return Loss = = is the ratio between forward and reverse power in dB

Insertion Loss = Here loss is as a function of frequency and for a realizable filter network insertion loss and must satisfy the following conditions

where P and Q are even polynomials

= a ratio of even polynomials

; a maximally flat low-pass filter k is passband tolerance and the cut-off frequency

From these terms one can design a low-pass filter and transform to band-pass filter using transformation tables. (G. Matthaei pp. 85-104).

|  |  |  |
| --- | --- | --- |
| Attenuator Setting (HMC542) | dB |  |
| High Gain | 24 |  |
| Medium Gain | 16 |  |
| Low Gain | 4 |  |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **MI-10** | CableLength | CableAtten | PinAttCable | PinPad | PinVSWR | HMCAttnMax | AmpOut | AMpAttn |
| hp628 | 1017.53 | 8.802 | 32.4 | 17.4 | 0.05059367 | -7.0 | 12.9 | 10 |
| vp629 | 919.39 | 7.953 | 33.2 | 18.2 | 0.061515886 | -6.1 | 13.8 | 11 |
| hp630 | 903.96 | 7.819 | 33.4 | 18.4 | 0.063435772 | -6.0 | 13.9 | 11 |
| vp631 | 804.17 | 6.956 | 34.2 | 19.2 | 0.07738425 | -5.1 | 14.8 | 12 |
| hp632 | 788.95 | 6.824 | 34.4 | 19.4 | 0.079766012 | -5.0 | 14.9 | 12 |
| vp633 | 688.78 | 5.958 | 35.2 | 20.2 | 0.097378915 | -4.1 | 15.8 | 13 |
| hp634 | 673.69 | 5.827 | 35.4 | 20.4 | 0.100350093 | -4.0 | 15.9 | 13 |
| vp635 | 574.87 | 4.973 | 36.2 | 21.2 | 0.122179145 | -3.1 | 16.8 | 14 |
| hp636 | 558.51 | 4.831 | 36.4 | 21.4 | 0.126225901 | -3.0 | 16.9 | 14 |
| vp637 | 461.89 | 3.995 | 37.2 | 22.2 | 0.153011749 | -2.2 | 17.7 | 15 |
| hp638 | 445.28 | 3.852 | 37.3 | 22.3 | 0.158158461 | -2.0 | 17.9 | 15 |
| vp639 | 366.25 | 3.168 | 38.0 | 23.0 | 0.185120016 | -1.3 | 18.6 | 16 |
| hp640 | 356.44 | 3.083 | 38.1 | 23.1 | 0.188772632 | -1.2 | 18.7 | 16 |
| vp641 | 281.01 | 2.431 | 38.8 | 23.8 | 0.219374417 | -0.6 | 19.3 | 17 |
| hp100 | 271.83 | 2.351 | 38.8 | 23.8 | 0.223422383 | -0.5 | 19.4 | 17 |
| vp101 | 158.00 | 1.367 | 39.8 | 24.8 | 0.28025904 | 0.5 | 20.4 | 18 |
| hp102 | 158.00 | 1.367 | 39.8 | 24.8 | 0.28025904 | 0.5 | 20.4 | 18 |
| vp103 | 158.01 | 1.367 | 39.8 | 24.8 | 0.280272818 | 0.5 | 20.4 | 18 |
| hp104 | 192.26 | 1.663 | 39.5 | 24.5 | 0.261791011 | 0.2 | 20.1 | 18 |
| vp105 | 263.42 | 2.279 | 38.9 | 23.9 | 0.22719634 | -0.4 | 19.5 | 17 |
| hp106 | 275.09 | 2.380 | 38.8 | 23.8 | 0.221976388 | -0.5 | 19.4 | 17 |
| vp107 | 348.53 | 3.015 | 38.2 | 23.2 | 0.191770226 | -1.2 | 18.7 | 16 |
| hp108 | 358.72 | 3.103 | 38.1 | 23.1 | 0.187917329 | -1.3 | 18.6 | 16 |
| vp109 | 450.22 | 3.894 | 37.3 | 22.3 | 0.156609943 | -2.1 | 17.8 | 15 |
| hp110 | 467.90 | 4.047 | 37.2 | 22.2 | 0.151191066 | -2.2 | 17.7 | 15 |
| vp111 | 564.89 | 4.886 | 36.3 | 21.3 | 0.124632062 | -3.0 | 16.9 | 14 |
| hp112 | 581.72 | 5.032 | 36.2 | 21.2 | 0.120523526 | -3.2 | 16.7 | 14 |
| vp113 | 679.61 | 5.879 | 35.3 | 20.3 | 0.099173806 | -4.0 | 15.9 | 13 |
| hp114 | 694.91 | 6.011 | 35.2 | 20.2 | 0.096197211 | -4.2 | 15.7 | 13 |
| vp115 | 792.08 | 6.851 | 34.3 | 19.3 | 0.079270287 | -5.0 | 14.9 | 12 |
| hp116 | 809.75 | 7.004 | 34.2 | 19.2 | 0.076528972 | -5.2 | 14.7 | 12 |
| vp117 | 906.45 | 7.841 | 33.4 | 18.4 | 0.063121946 | -6.0 | 13.9 | 11 |
| hp118 | 922.86 | 7.983 | 33.2 | 18.2 | 0.061092195 | -6.1 | 13.8 | 11 |
| vp119 | 1020.32 | 8.826 | 32.4 | 17.4 | 0.050313303 | -7.0 | 12.9 | 10 |
| hp120 | 1036.72 | 8.968 | 32.2 | 17.2 | 0.048696397 | -7.1 | 12.8 | 10 |
| vp121 | 1134.14 | 9.810 | 31.4 | 16.4 | 0.040107771 | -8.0 | 11.9 | 9 |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **MI-20** | CableLength | CableAtten | PinAttCable | PinPad | PinVSWR | HMCAttnMax | AmpOut | AMpAttn |
| hp122 | 651.49 | 5.635 | 35.6 | 20.6 | 0.104886787 | -3.8 | 16.1 | 14 |
| vp123 | 554.79 | 4.799 | 36.4 | 21.4 | 0.127164615 | -3.0 | 16.9 | 14 |
| hp124 | 539.19 | 4.664 | 36.5 | 21.5 | 0.131177781 | -2.8 | 17.1 | 15 |
| vp125 | 440.96 | 3.814 | 37.4 | 22.4 | 0.159525175 | -2.0 | 17.9 | 15 |
| hp126 | 425.57 | 3.681 | 37.5 | 22.5 | 0.164490788 | -1.8 | 18.1 | 16 |
| vp127 | 326.08 | 2.821 | 38.4 | 23.4 | 0.200539732 | -1.0 | 18.9 | 16 |
| hp128 | 311.37 | 2.693 | 38.5 | 23.5 | 0.206502151 | -0.9 | 19.0 | 17 |
| vp129 | 215.22 | 1.862 | 39.3 | 24.3 | 0.25008885 | 0.0 | 19.9 | 17 |
| hp130 | 199.74 | 1.728 | 39.5 | 24.5 | 0.257919709 | 0.1 | 20.0 | 18 |
| vp201 | 137.54 | 1.190 | 40.0 | 25.0 | 0.291935917 | 0.7 | 20.6 | 18 |
| hp202 | 153.95 | 1.332 | 39.9 | 24.9 | 0.282548418 | 0.5 | 20.4 | 18 |
| vp203 | 249.42 | 2.157 | 39.0 | 24.0 | 0.233620705 | -0.3 | 19.6 | 17 |
| hp204 | 266.59 | 2.306 | 38.9 | 23.9 | 0.225766386 | -0.5 | 19.4 | 17 |
| vp205 | 362.95 | 3.140 | 38.1 | 23.1 | 0.186340768 | -1.3 | 18.6 | 16 |
| hp206 | 379.27 | 3.281 | 37.9 | 22.9 | 0.18038112 | -1.4 | 18.5 | 16 |
| vp207 | 478.72 | 4.141 | 37.1 | 22.1 | 0.147967668 | -2.3 | 17.6 | 15 |
| hp208 | 493.69 | 4.270 | 36.9 | 21.9 | 0.143620945 | -2.4 | 17.5 | 15 |
| vp209 | 590.98 | 5.112 | 36.1 | 21.1 | 0.118321027 | -3.3 | 16.6 | 14 |
| hp210 | 604.17 | 5.226 | 36.0 | 21.0 | 0.115253091 | -3.4 | 16.5 | 14 |
| vp211 | 705.31 | 6.101 | 35.1 | 20.1 | 0.094225072 | -4.3 | 15.6 | 13 |
| hp212 | 723.54 | 6.259 | 34.9 | 19.9 | 0.090865188 | -4.4 | 15.5 | 13 |
| vp213 | 821.68 | 7.108 | 34.1 | 19.1 | 0.07473197 | -5.3 | 14.6 | 12 |
| hp214 | 837.83 | 7.247 | 34.0 | 19.0 | 0.072366352 | -5.4 | 14.5 | 12 |
| vp215 | 936.26 | 8.099 | 33.1 | 18.1 | 0.059483256 | -6.3 | 13.6 | 11 |
| hp216 | 950.98 | 8.226 | 33.0 | 18.0 | 0.057764621 | -6.4 | 13.5 | 11 |
| vp217 | 1031.23 | 8.920 | 32.3 | 17.3 | 0.049231796 | -7.1 | 12.8 | 10 |
| hp218 | 1042.01 | 9.013 | 32.2 | 17.2 | 0.048186012 | -7.2 | 12.7 | 10 |
| vp219 | 1116.05 | 9.654 | 31.5 | 16.5 | 0.041579224 | -7.8 | 12.1 | 10 |
| hp220 | 1127.72 | 9.755 | 31.4 | 16.4 | 0.04062392 | -7.9 | 12.0 | 9 |
| vp221 | 1212.81 | 10.491 | 30.7 | 15.7 | 0.034290908 | -8.6 | 11.3 | 9 |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **MI-30** | CableLength | CableAtten | PinAttCable | PinPad | PinVSWR | HMCAttnMax | AmpOut | AMpAttn |
| hp222 | 861.21 | 7.449 | 33.8 | 18.8 | 0.069073741 | -5.6 | 14.3 | 12 |
| vp223 | 778.21 | 6.732 | 34.5 | 19.5 | 0.081490687 | -4.9 | 15.0 | 13 |
| hp224 | 765.95 | 6.625 | 34.6 | 19.6 | 0.083505077 | -4.8 | 15.1 | 13 |
| vp225 | 693.64 | 6.000 | 35.2 | 20.2 | 0.09644085 | -4.2 | 15.7 | 13 |
| hp226 | 681.17 | 5.892 | 35.3 | 20.3 | 0.09886614 | -4.0 | 15.9 | 13 |
| vp227 | 602.65 | 5.213 | 36.0 | 21.0 | 0.115602541 | -3.4 | 16.5 | 14 |
| hp228 | 587.01 | 5.078 | 36.1 | 21.1 | 0.119260323 | -3.2 | 16.7 | 14 |
| vp229 | 493.9 | 4.272 | 36.9 | 21.9 | 0.143560886 | -2.4 | 17.5 | 15 |
| hp230 | 482.74 | 4.176 | 37.0 | 22.0 | 0.146787654 | -2.3 | 17.6 | 15 |
| vp231 | 409.59 | 3.543 | 37.7 | 22.7 | 0.169810398 | -1.7 | 18.2 | 16 |
| hp232 | 396.82 | 3.432 | 37.8 | 22.8 | 0.17418483 | -1.6 | 18.3 | 16 |
| vp301 | 396 | 3.430 | 37.8 | 22.8 | 0.174284847 | -1.6 | 18.3 | 16 |
| Hp302 | 317.92 | 2.750 | 38.4 | 23.4 | 0.203825647 | -0.9 | 19.0 | 16 |
| Vp303 | 255.3 | 2.208 | 39.0 | 24.0 | 0.230900637 | -0.4 | 19.5 | 17 |
| hp304 | 204.1 | 1.765 | 39.4 | 24.4 | 0.255689639 | 0.1 | 20.0 | 17 |
| Vp305 | 145.92 | 1.262 | 39.9 | 24.9 | 0.287103727 | 0.6 | 20.5 | 18 |
| Hp306 | 177.04 | 1.531 | 39.7 | 24.7 | 0.269848514 | 0.3 | 20.2 | 18 |
| Vp307 | 259.57 | 2.245 | 39.0 | 24.0 | 0.22894522 | -0.4 | 19.5 | 17 |
| Hp308 | 289.17 | 2.501 | 38.7 | 23.7 | 0.215837837 | -0.7 | 19.2 | 17 |
| vp309 | 360.97 | 3.122 | 38.1 | 23.1 | 0.187077079 | -1.3 | 18.6 | 16 |
| Hp310 | 376.27 | 3.255 | 37.9 | 22.9 | 0.181462162 | -1.4 | 18.5 | 16 |
| vp311 | 449.08 | 3.885 | 37.3 | 22.3 | 0.156965942 | -2.0 | 17.9 | 15 |
| hp312 | 462.23 | 3.998 | 37.2 | 22.2 | 0.152908166 | -2.2 | 17.7 | 15 |
| vp313 | 538.89 | 4.661 | 36.5 | 21.5 | 0.131256186 | -2.8 | 17.1 | 15 |
| hp314 | 554.37 | 4.795 | 36.4 | 21.4 | 0.127271036 | -3.0 | 16.9 | 14 |
| vp315 | 649.92 | 5.622 | 35.6 | 20.6 | 0.105215284 | -3.8 | 16.1 | 14 |
| hp316 | 649 | 5.600 | 35.6 | 20.6 | 0.105744949 | -3.8 | 16.1 | 14 |
| vp317 | 733.77 | 6.347 | 34.9 | 19.9 | 0.089032502 | -4.5 | 15.4 | 13 |
| hp318 | 745.65 | 6.450 | 34.8 | 19.8 | 0.086950559 | -4.6 | 15.3 | 13 |
| vp319 | 814.83 | 7.048 | 34.2 | 19.2 | 0.075758555 | -5.2 | 14.7 | 12 |
| hp320 | 850.09 | 7.353 | 33.8 | 18.8 | 0.070620661 | -5.5 | 14.4 | 12 |
| vp321 | 929.58 | 8.041 | 33.2 | 18.2 | 0.060279956 | -6.2 | 13.7 | 11 |
| hp322 | 965.94 | 8.355 | 32.8 | 17.8 | 0.056068835 | -6.5 | 13.4 | 11 |
| vp323 | 1032.92 | 8.935 | 32.3 | 17.3 | 0.049066359 | -7.1 | 12.8 | 10 |
| hp324 | 1045.6 | 9.044 | 32.2 | 17.2 | 0.047842694 | -7.2 | 12.7 | 10 |
| vp901 | 323.12 | 2.795 | 38.4 | 23.4 | 0.201725514 | -1.0 | 18.9 | 16 |
| hp902 | 292.09 | 2.527 | 38.7 | 23.7 | 0.214586196 | -0.7 | 19.2 | 17 |
| vp903 | 229.47 | 1.985 | 39.2 | 24.2 | 0.243090552 | -0.1 | 19.8 | 17 |
| hp904 | 177.54 | 1.536 | 39.7 | 24.7 | 0.269579914 | 0.3 | 20.2 | 18 |
| vp905 | 119.79 | 1.036 | 40.2 | 25.2 | 0.302441428 | 0.8 | 20.7 | 18 |

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| **MI-40** | CableLength | CableAtten | PinAttCable | PinPad | PinVSWR | HMCAttnMax | AmpOut | AMpAttn |
| open |  |  |  |  |  |  |  |  |
| vp325 | 1229.58 | 10.636 | 30.6 | 15.6 | 0.03316446 | -8.8 | 11.1 | 9 |
| hp326 | 1218.45 | 10.540 | 30.7 | 15.7 | 0.03390786 | -8.7 | 11.2 | 9 |
| vp327 | 1148.9 | 9.938 | 31.3 | 16.3 | 0.038945845 | -8.1 | 11.8 | 9 |
| hp328 | 1091.14 | 9.438 | 31.8 | 16.8 | 0.043694174 | -7.6 | 12.3 | 10 |
| vp329 | 1011.36 | 8.748 | 32.5 | 17.5 | 0.051219252 | -6.9 | 13.0 | 10 |
| hp330 | 995.88 | 8.614 | 32.6 | 17.6 | 0.052823045 | -6.8 | 13.1 | 11 |
| vp331 | 896.94 | 7.759 | 33.4 | 18.4 | 0.06432896 | -5.9 | 14.0 | 11 |
| hp332 | 882.22 | 7.631 | 33.6 | 18.6 | 0.066242899 | -5.8 | 14.1 | 12 |
| vp333 | 782.78 | 6.771 | 34.4 | 19.4 | 0.080752305 | -4.9 | 15.0 | 12 |
| hp334 | 768.27 | 6.646 | 34.6 | 19.6 | 0.083120104 | -4.8 | 15.1 | 13 |
| vp335 | 669.08 | 5.788 | 35.4 | 20.4 | 0.101275741 | -3.9 | 16.0 | 13 |
| hp336 | 654.03 | 5.657 | 35.5 | 20.5 | 0.104357503 | -3.8 | 16.1 | 14 |
| vp337 | 554.49 | 4.796 | 36.4 | 21.4 | 0.127240621 | -3.0 | 16.9 | 14 |
| hp338 | 539.69 | 4.668 | 36.5 | 21.5 | 0.13104721 | -2.8 | 17.1 | 15 |
| vp339 | 460.41 | 3.983 | 37.2 | 22.2 | 0.153463458 | -2.1 | 17.8 | 15 |
| hp340 | 449.8 | 3.891 | 37.3 | 22.3 | 0.156741006 | -2.0 | 17.9 | 15 |
| vp341 | 374.79 | 3.242 | 38.0 | 23.0 | 0.181997859 | -1.4 | 18.5 | 16 |
| hp400 | 365.28 | 3.160 | 38.0 | 23.0 | 0.185478011 | -1.3 | 18.6 | 16 |
| vp401 | 281.81 | 2.438 | 38.8 | 23.8 | 0.219025147 | -0.6 | 19.3 | 17 |
| hp402 | 249.21 | 2.156 | 39.0 | 24.0 | 0.233718441 | -0.3 | 19.6 | 17 |
| vp403 | 166.47 | 1.440 | 39.8 | 24.8 | 0.275589762 | 0.4 | 20.3 | 18 |
| hp404 | 133.61 | 1.156 | 40.0 | 25.0 | 0.294230019 | 0.7 | 20.6 | 18 |
| vp405 | 175.56 | 1.519 | 39.7 | 24.7 | 0.270645138 | 0.3 | 20.2 | 18 |
| hp406 | 189.17 | 1.636 | 39.6 | 24.6 | 0.263407163 | 0.2 | 20.1 | 18 |
| vp407 | 260.21 | 2.251 | 38.9 | 23.9 | 0.228653567 | -0.4 | 19.5 | 17 |
| hp408 | 273.82 | 2.369 | 38.8 | 23.8 | 0.222538589 | -0.5 | 19.4 | 17 |
| vp409 | 363.16 | 3.141 | 38.1 | 23.1 | 0.186262844 | -1.3 | 18.6 | 16 |
| hp410 | 380.58 | 3.292 | 37.9 | 22.9 | 0.179911088 | -1.4 | 18.5 | 16 |
| vp411 | 477.5 | 4.130 | 37.1 | 22.1 | 0.148327655 | -2.3 | 17.6 | 15 |
| hp412 | 493.82 | 4.272 | 36.9 | 21.9 | 0.143583763 | -2.4 | 17.5 | 15 |
| vp413 | 594.62 | 5.143 | 36.1 | 21.1 | 0.117466311 | -3.3 | 16.6 | 14 |

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|  |  |  | MaxPwr | 15 |  | 24 | 19.9 |  |
| **MI-50** | CableLength | CableAtten | PinAttCable | PinPad | TransPWR | HMCAttnMax | AmpOut | AMpAttn |
| hp414 | 1099.32 | 9.5 | 31.7 | 16.7 | 0.042988058 | -7.7 | 12.2 | 10 |
| vp415 | 999.98 | 8.6 | 32.6 | 17.6 | 0.052393442 | -6.8 | 13.1 | 11 |
| hp416 | 985.48 | 8.5 | 32.7 | 17.7 | 0.053928635 | -6.7 | 13.2 | 11 |
| vp417 | 885.69 | 7.7 | 33.5 | 18.5 | 0.065786651 | -5.8 | 14.1 | 12 |
| hp418 | 871.1 | 7.5 | 33.7 | 18.7 | 0.067726422 | -5.7 | 14.2 | 12 |
| vp419 | 771.82 | 6.7 | 34.5 | 19.5 | 0.082534463 | -4.8 | 15.1 | 13 |
| hp420 | 756.94 | 6.5 | 34.7 | 19.7 | 0.085017148 | -4.7 | 15.2 | 13 |
| vp421 | 657.49 | 5.7 | 35.5 | 20.5 | 0.103640806 | -3.8 | 16.1 | 14 |
| hp422 | 642.02 | 5.6 | 35.6 | 20.6 | 0.106883909 | -3.7 | 16.2 | 14 |
| vp423 | 543.54 | 4.7 | 36.5 | 21.5 | 0.130046159 | -2.9 | 17.0 | 15 |
| hp424 | 528.87 | 4.6 | 36.6 | 21.6 | 0.133902005 | -2.7 | 17.2 | 15 |
| vp425 | 429.97 | 3.7 | 37.5 | 22.5 | 0.163055548 | -1.9 | 18.0 | 16 |
| hp426 | 415.85 | 3.6 | 37.6 | 22.6 | 0.167706301 | -1.8 | 18.1 | 16 |
| vp427 | 318.05 | 2.8 | 38.4 | 23.4 | 0.203772878 | -0.9 | 19.0 | 16 |
| hp428 | 301.98 | 2.6 | 38.6 | 23.6 | 0.210400579 | -0.8 | 19.1 | 17 |
| vp429 | 203.59 | 1.8 | 39.4 | 24.4 | 0.255949497 | 0.1 | 20.0 | 17 |
| hp430 | 188.2 | 1.6 | 39.6 | 24.6 | 0.263916553 | 0.2 | 20.1 | 18 |
| vp501 | 136.83 | 1.2 | 40.0 | 25.0 | 0.292349045 | 0.7 | 20.6 | 18 |
| hp502 | 152.43 | 1.3 | 39.9 | 24.9 | 0.283405112 | 0.5 | 20.4 | 18 |
| vp503 | 249.97 | 2.2 | 39.0 | 24.0 | 0.233364924 | -0.3 | 19.6 | 17 |
| hp504 | 265.83 | 2.3 | 38.9 | 23.9 | 0.226108391 | -0.5 | 19.4 | 17 |
| vp505 | 363.63 | 3.1 | 38.1 | 23.1 | 0.186088562 | -1.3 | 18.6 | 16 |
| hp506 | 379.65 | 3.3 | 37.9 | 22.9 | 0.180244649 | -1.4 | 18.5 | 16 |
| vp507 | 475.55 | 4.1 | 37.1 | 22.1 | 0.148904863 | -2.3 | 17.6 | 15 |
| hp508 | 492.63 | 4.3 | 36.9 | 21.9 | 0.143924484 | -2.4 | 17.5 | 15 |
| vp509 | 589.71 | 5.1 | 36.1 | 21.1 | 0.118620699 | -3.3 | 16.6 | 14 |
| hp510 | 607.18 | 5.3 | 35.9 | 20.9 | 0.114564201 | -3.4 | 16.5 | 14 |
| vp511 | 703.71 | 6.1 | 35.1 | 20.1 | 0.094525826 | -4.2 | 15.7 | 13 |
| hp512 | 720.07 | 6.2 | 35.0 | 20.0 | 0.091495362 | -4.4 | 15.5 | 13 |
| vp513 | 816.73 | 7.1 | 34.1 | 19.1 | 0.075472403 | -5.2 | 14.7 | 12 |
| hp514 | 833.81 | 7.2 | 34.0 | 19.0 | 0.072948099 | -5.4 | 14.5 | 12 |
| vp515 | 930.13 | 8.0 | 33.2 | 18.2 | 0.060213959 | -6.2 | 13.7 | 11 |
| hp516 | 948.65 | 8.2 | 33.0 | 18.0 | 0.058033315 | -6.4 | 13.5 | 11 |
| vp517 | 1027.13 | 8.9 | 32.3 | 17.3 | 0.049635475 | -7.0 | 12.9 | 10 |
| hp518 | 1039.6 | 9.0 | 32.2 | 17.2 | 0.048417864 | -7.1 | 12.8 | 10 |
| vp519 | 1113.68 | 9.6 | 31.6 | 16.6 | 0.041775959 | -7.8 | 12.1 | 10 |
| hp520 | 1125.73 | 9.7 | 31.5 | 16.5 | 0.040785255 | -7.9 | 12.0 | 10 |
| vp521 | 1211.65 | 10.5 | 30.7 | 15.7 | 0.034370225 | -8.6 | 11.3 | 9 |

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| **MI-60** | CableLength | CableAtten | PinAttCable | PinPad | #VALUE! | #VALUE! | AmpOut | AMpAttn |
| hp522 | 1004.04 | 8.685 | 32.5 | 17.5 | 0.051971474 | -6.8 | 13.1 | 11 |
| vp523 | 918.97 | 7.949 | 33.3 | 18.3 | 0.061567367 | -6.1 | 13.8 | 11 |
| hp524 | 908.35 | 7.857 | 33.3 | 18.3 | 0.062883525 | -6.0 | 13.9 | 11 |
| vp525 | 834.53 | 7.219 | 34.0 | 19.0 | 0.072843563 | -5.4 | 14.5 | 12 |
| hp526 | 824.72 | 7.134 | 34.1 | 19.1 | 0.074280844 | -5.3 | 14.6 | 12 |
| vp527 | 743.33 | 6.430 | 34.8 | 19.8 | 0.087353273 | -4.6 | 15.3 | 13 |
| hp528 | 729.84 | 6.313 | 34.9 | 19.9 | 0.089732141 | -4.5 | 15.4 | 13 |
| vp529 | 629.16 | 5.442 | 35.8 | 20.8 | 0.109656967 | -3.6 | 16.3 | 14 |
| hp530 | 619.23 | 5.356 | 35.8 | 20.8 | 0.111847345 | -3.5 | 16.4 | 14 |
| vp531 | 532.97 | 4.610 | 36.6 | 21.6 | 0.132812998 | -2.8 | 17.1 | 15 |
| hp532 | 518.64 | 4.486 | 36.7 | 21.7 | 0.136658305 | -2.6 | 17.3 | 15 |
| vp601 | 465.7 | 3.428 | 37.8 | 22.8 | 0.174383115 | -1.6 | 18.3 | 16 |
| hp602 | 430.26 | 3.167 | 38.0 | 23.0 | 0.185177523 | -1.3 | 18.6 | 16 |
| vp603 | 356.95 | 2.627 | 38.6 | 23.6 | 0.209673927 | -0.8 | 19.1 | 17 |
| hp604 | 328.47 | 2.418 | 38.8 | 23.8 | 0.220042064 | -0.6 | 19.3 | 17 |
| vp605 | 253.34 | 1.865 | 39.3 | 24.3 | 0.249920218 | 0.0 | 19.9 | 17 |
| hp606 | 224.17 | 1.650 | 39.6 | 24.6 | 0.262585361 | 0.2 | 20.1 | 18 |
| vp607 | 165.36 | 1.217 | 40.0 | 25.0 | 0.290104637 | 0.6 | 20.5 | 18 |
| hp608 | 212.92 | 1.567 | 39.6 | 24.6 | 0.267639685 | 0.3 | 20.2 | 18 |
| vp609 | 133.42 | 0.982 | 40.2 | 25.2 | 0.306240419 | 0.9 | 20.8 | 18 |
| hp610 | 132.56 | 1.147 | 40.1 | 25.1 | 0.294845993 | 0.7 | 20.6 | 18 |
| vp611 | 219.07 | 1.895 | 39.3 | 24.3 | 0.248178457 | -0.1 | 19.8 | 17 |
| hp612 | 238.85 | 2.066 | 39.1 | 24.1 | 0.238591177 | -0.2 | 19.7 | 17 |
| vp613 | 326.42 | 2.824 | 38.4 | 23.4 | 0.200403974 | -1.0 | 18.9 | 16 |
| hp614 | 341.68 | 2.956 | 38.2 | 23.2 | 0.194404552 | -1.1 | 18.8 | 16 |
| vp615 | 433.23 | 3.747 | 37.5 | 22.5 | 0.162000248 | -1.9 | 18.0 | 15 |
| hp616 | 446.33 | 3.861 | 37.3 | 22.3 | 0.157828046 | -2.0 | 17.9 | 15 |
| vp617 | 518.59 | 4.486 | 36.7 | 21.7 | 0.136671915 | -2.6 | 17.3 | 15 |
| hp618 | 532.42 | 4.605 | 36.6 | 21.6 | 0.132958568 | -2.8 | 17.1 | 15 |
| vp619 | 599.65 | 5.187 | 36.0 | 21.0 | 0.116295358 | -3.3 | 16.6 | 14 |
| hp620 | 633.98 | 5.484 | 35.7 | 20.7 | 0.108609279 | -3.6 | 16.3 | 14 |
| vp621 | 716.05 | 6.194 | 35.0 | 20.0 | 0.092230886 | -4.4 | 15.5 | 13 |
| hp622 | 749.08 | 6.480 | 34.7 | 19.7 | 0.086358568 | -4.6 | 15.3 | 13 |
| vp623 | 820.2 | 7.095 | 34.1 | 19.1 | 0.074952588 | -5.3 | 14.6 | 12 |
| hp624 | 830.22 | 7.181 | 34.0 | 19.0 | 0.073471572 | -5.3 | 14.6 | 12 |
| vp625 | 903.28 | 7.813 | 33.4 | 18.4 | 0.063521746 | -6.0 | 13.9 | 11 |
| hp626 | 915.16 | 7.916 | 33.3 | 18.3 | 0.062036349 | -6.1 | 13.8 | 11 |
| vp627 | 1007.68 | 8.716 | 32.5 | 17.5 | 0.051596047 | -6.9 | 13.0 | 11 |

**List of BPMs in NoVa era listed by House:**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **MI-10** | **MI-20** | **MI-30** | **MI-40** | **MI-50** | **MI-60** | **MI-14** |  |  |  |
| hp628 | hp122 | hp222 | hp326 | hp414 | hp522 | Hp848 |  |  |  |
| hp630 | hp124 | hp224 | hp328 | hp416 | hp524 | HP850 |  |  |  |
| hp632 | hp126 | hp226 | hp330 | hp418 | hp526 | HP852 |  |  |  |
| hp634 | hp128 | hp228 | hp332 | hp420 | hp528 | VP849 |  |  |  |
| hp636 | hp130 | hp230 | hp334 | hp422 | hp530 | VP851 |  |  |  |
| hp638 | hp202 | hp232 | hp336 | hp424 | hp532 | VP853 |  |  |  |
| hp640 | hp204 | Hp302 | hp338 | hp426 | hp602 |  |  |  |  |
| hp100 | hp206 | Hp304 | hp340 | hp428 | hp604 |  |  |  |  |
| hp102 | hp208 | Hp306 | hp400 | hp430 | hp606 |  |  |  |  |
| hp104 | hp210 | Hp308 | hp402 | hp502 | hp608 |  |  |  |  |
| hp106 | hp212 | hp310 | hp404 | hp504 | hp610 |  |  |  |  |
| hp108 | hp214 | hp312 | hp406 | hp506 | hp612 |  |  |  |  |
| hp110 | hp216 | hp314 | hp408 | hp508 | hp614 |  |  |  |  |
| hp112 | hp218 | hp316 | hp410 | hp510 | hp616 |  |  |  |  |
| hp114 | hp220 | hp318 | hp412 | hp512 | hp618 |  |  |  |  |
| hp116 |  | hp320 | Hp001 | hp514 | hp620 |  |  |  |  |
| hp118 | vp123 | hp322 | Hp002 | hp516 | hp622 |  |  |  |  |
| hp120 | vp125 | hp324 | Hp003 | hp518 | hp624 |  |  |  |  |
|  | vp127 | Hp902 | Hp004 | hp520 | hp626 |  |  |  |  |
| vp629 | vp129 | Hp904 |  |  |  |  |  |  |  |
| vp631 | vp201 |  |  | vp415 | vp523 |  |  |  |  |
| vp633 | vp203 |  |  | vp417 | vp525 |  |  |  |  |
| vp635 | vp205 |  |  | vp419 | vp527 |  |  |  |  |
| vp637 | vp207 | vp223 | vp325 | vp421 | vp529 |  |  |  |  |
| vp639 | vp209 | vp225 | vp327 | vp423 | vp531 |  |  |  |  |
| vp641 | vp211 | vp227 | vp329 | vp425 | vp601 |  |  |  |  |
| vp101 | vp213 | vp229 | vp331 | vp427 | vp603 |  |  |  |  |
| vp103 | vp215 | vp231 | vp333 | vp429 | vp605 |  |  |  |  |
| vp105 | vp217 | Vp301 | vp335 | vp501 | vp607 |  |  |  |  |
| vp107 | vp219 | vp303 | vp337 | vp503 | vp609 |  |  |  |  |
| v109 | vp221 | Vp305 | vp339 | vp505 | vp611 |  |  |  |  |
| vp111 |  | Vp307 | vp341 | vp507 | vp613 |  |  |  |  |
| vp113 |  | vp309 | vp401 | vp509 | vp615 |  |  |  |  |
| vp115 |  | vp311 | vp403 | vp511 | vp617 |  |  |  |  |
| vp117 |  | vp313 | vp405 | vp513 | vp619 |  |  |  |  |
| vp119 |  | vp315 | vp407 | vp515 | vp621 |  |  |  |  |
| vp121 |  | vp317 | vp409 | vp517 | vp623 |  |  |  |  |
|  |  | vp319 | vp411 | vp519 | vp625 |  |  |  |  |
|  |  | vp321 | vp413 | vp521 | vp627 |  |  |  |  |
|  |  | vp323 | Vp001 |  |  |  |  |  |  |
|  |  |  | Vp002 |  |  |  |  |  |  |
|  |  | Vp901 | Vp003 |  |  |  |  |  |  |
|  |  | Vp903 |  |  |  |  |  |  |  |
|  |  | Vp905 |  |  |  |  |  |  |  |
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**DDC BPM Channel assignment by House:**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **MI-10** |  | **MI-20** |  | | **MI-30** |  | **MI-40** |  | | **MI-50** |  | **MI-60** |  | |
| Channel | Xmod 1 | Channel | Xmod 1 | | Channel | Xmod 1 | Channel | Xmod 1 | | Channel | Xmod 1 | Channel | Xmod 1 | |
| 1 | hp628 | 1 | hp122 | | 1 | hp222 | 1 | vp325 | | 1 | hp414 | 1 | hp522 | |
| 2 | vp629 | 2 | vp123 | | 2 | vp223 | 2 | hp326 | | 2 | vp415 | 2 | vp523 | |
| 3 | hp630 | 3 | hp124 | | 3 | hp224 | 3 | vp327 | | 3 | hp416 | 3 | hp524 | |
| 4 | vp631 | 4 | vp125 | | 4 | vp225 | 4 | hp328 | | 4 | vp417 | 4 | vp525 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 2 | Channel | Xmod 2 | | Channel | Xmod 2 | Channel | Xmod 2 | | Channel | Xmod 2 | Channel | Xmod 2 | |
| 1 | hp632 | 1 | hp126 | | 1 | hp226 | 1 | vp329 | | 1 | hp418 | 1 | hp526 | |
| 2 | vp633 | 2 | vp127 | | 2 | vp227 | 2 | hp330 | | 2 | vp419 | 2 | vp527 | |
| 3 | hp634 | 3 | hp128 | | 3 | hp228 | 3 | vp331 | | 3 | hp420 | 3 | hp528 | |
| 4 | vp635 | 4 | vp129 | | 4 | vp229 | 4 | hp332 | | 4 | vp421 | 4 | vp529 | |  |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 3 | Channel | Xmod 3 | | Channel | Xmod 3 | Channel | Xmod 3 | | Channel | Xmod 3 | Channel | Xmod 3 | |
| 1 | hp636 | 1 | hp130 | | 1 | hp230 | 1 | vp333 | | 1 | hp422 | 1 | hp530 | |
| 2 | vp637 | 2 | vp201 | | 2 | vp231 | 2 | hp334 | | 2 | vp423 | 2 | vp531 | |
| 3 | hp638 | 3 | hp202 | | 3 | hp232 | 3 | vp335 | | 3 | hp424 | 3 | hp532 | |
| 4 | vp639 | 4 | vp203 | | 4 | vp301 | 4 | hp336 | | 4 | vp425 | 4 | vp601 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 4 | Channel | Xmod 4 | | Channel | Xmod 4 | Channel | Xmod 4 | | Channel | Xmod 4 | Channel | Xmod 4 | |
| 1 | hp640 | 1 | hp204 | | 1 | Hp302 | 1 | vp337 | | 1 | hp426 | 1 | hp602 | |
| 2 | vp641 | 2 | vp205 | | 2 | Vp303 | 2 | hp338 | | 2 | vp427 | 2 | vp603 | |
| 3 | hp100 | 3 | hp206 | | 3 | hp304 | 3 | vp339 | | 3 | hp428 | 3 | hp604 | |
| 4 | vp101 | 4 | vp207 | | 4 | Vp305 | 4 | hp340 | | 4 | vp429 | 4 | vp605 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 5 | Channel | Xmod 5 | | Channel | Xmod 5 | Channel | Xmod 5 | | Channel | Xmod 5 | Channel | Xmod 5 | |
| 1 | hp102 | 1 | hp208 | | 1 | Hp306 | 1 | vp341 | | 1 | hp430 | 1 | hp606 | |
| 2 | vp103 | 2 | vp209 | | 2 | Vp307 | 2 | hp400 | | 2 | vp501 | 2 | vp607 | |
| 3 | hp104 | 3 | hp210 | | 3 | Hp308 | 3 | vp401 | | 3 | hp502 | 3 | hp608 | |
| 4 | vp105 | 4 | vp211 | | 4 | vp309 | 4 | hp402 | | 4 | vp503 | 4 | vp609 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 6 | Channel | Xmod 6 | | Channel | Xmod 6 | Channel | Xmod 6 | | Channel | Xmod 6 | Channel | Xmod 6 | |
| 1 | hp106 | 1 | hp212 | | 1 | Hp310 | 1 | vp403 | | 1 | hp504 | 1 | hp610 | |
| 2 | vp107 | 2 | vp213 | | 2 | vp311 | 2 | hp404 | | 2 | vp505 | 2 | vp611 | |
| 3 | hp108 | 3 | hp214 | | 3 | hp312 | 3 | vp405 | | 3 | hp506 | 3 | hp612 | |
| 4 | vp109 | 4 | vp215 | | 4 | vp313 | 4 | hp406 | | 4 | vp507 | 4 | vp613 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 7 | Channel | Xmod 7 | | Channel | Xmod 7 | Channel | Xmod 7 | | Channel | Xmod 7 | Channel | xmod 7 | |
| 1 | hp110 | 1 | hp216 | | 1 | hp314 | 1 | vp407 | | 1 | hp508 | 1 | hp614 | |
| 2 | vp111 | 2 | vp217 | | 2 | vp315 | 2 | hp408 | | 2 | vp509 | 2 | vp615 | |
| 3 | hp112 | 3 | hp218 | | 3 | hp316 | 3 | vp409 | | 3 | hp510 | 3 | hp616 | |
| 4 | vp113 | 4 | vp219 | | 4 | vp317 | 4 | hp410 | | 4 | vp511 | 4 | vp617 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 8 | Channel | Xmod 8 | | Channel | Xmod 8 | Channel | Xmod 8 | | Channel | Xmod 8 | Channel | Xmod 8 | |
| 1 | hp114 | 1 | hp220 | | 1 | hp318 | 1 | vp411 | | 1 | hp512 | 1 | hp618 | |
| 2 | vp115 | 2 | vp221 | | 2 | vp319 | 2 | hp412 | | 2 | vp513 | 2 | vp619 | |
| 3 | hp116 | 3 |  | | 3 | hp320 | 3 | vp413 | | 3 | hp514 | 3 | hp620 | |
| 4 | vp117 | 4 |  | | 4 | vp321 | 4 |  | | 4 | vp515 | 4 | vp621 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| Channel | Xmod 9 |  |  | | Channel | Xmod 9 | Channel | Xmod 9 | | Channel | Xmod 9 | Channel | Xmod 9 | |
| 1 | hp118 |  |  | | 1 | hp322 | 1 | Hp001 | | 1 | hp516 | 1 | hp622 | |
| 2 | vp119 |  |  | | 2 | vp323 | 2 | Vp001 | | 2 | vp517 | 2 | vp623 | |
| 3 | hp120 |  |  | | 3 | hp324 | 3 | Hp002 | | 3 | hp518 | 3 | hp624 | |
| 4 | vp121 |  |  | | 4 | Vp901 | 4 | Vp002 | | 4 | vp519 | 4 | vp625 | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
|  |  |  |  | | Channel | Xmod 10 | Channel | Xmod 10 | | Channel | Xmod 10 | Channel | Xmod 10 | |
|  |  |  |  | | 1 | Hp902 | 1 | Hp003 | | 1 | hp520 | 1 | hp626 | |
|  |  |  |  | | 2 | Vp903 | 2 | Vp003 | | 2 | vp521 | 2 | vp627 | |
|  |  |  |  | | 3 | Hp904 | 3 | Hp004 | | 3 |  | 3 |  | |
|  |  |  |  | | 4 | Vp905 | 4 | Vp004 | | 4 |  | 4 |  | |
|  |  |  |  | |  |  |  |  | |  |  |  |  | |
| **MI-14** | | | |  | | | | |  | | | | |
| Channel | | | | Xmod 1 | | | | |  | | | | |
| 1 | | | | Hp848 | | | | |  | | | | |
| 2 | | | | Vp849 | | | | |  | | | | |
| 3 | | | | Hp850 | | | | |  | | | | |
| 4 | | | | Vp851 | | | | |  | | | | |
|  | | | |  | | | | |  | | | | |
| Channel | | | | Xmod 2 | | | | |  | | | | |
| 1 | | | | Hp852 | | | | |  | | | | |
| 2 | | | | Vp853 | | | | |  | | | | |
| 3 | | | |  | | | | |  | | | | |
| 4 | | | |  | | | | |  | | | | |

**Number of Items Required to Implement BPM System in RR**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| House | # of BPMs | Number of TransBrds | Number of  Echoteks | Number of VME64X Crates | Number of Cables Top Plate to Transition Brd | Number of Cables Transition Brd to Echotek Brd | Number Timing Boards | Number of Processors MVME5500 and MVME 2430 | Number of PMC MDAT and TCLK Decoder |
| MI-10 | 36 | 9 | 9 | 2 | 72 | 72 | 2 | 2 | 1 |
| MI-20 | 30 | 8 | 8 | 2 | 64 | 64 | 2 | 2 | 1 |
| MI-30 | 40 | 10 | 10 | 2 | 80 | 80 | 2 | 2 | 1 |
| MI-40 | 39 | 10 | 10 | 2 | 80 | 80 | 2 | 2 | 1 |
| MI-50 | 38 | 10 | 10 | 2 | 80 | 80 | 2 | 2 | 1 |
| MI-60 | 38 | 10 | 10 | 2 | 80 | 80 | 2 | 2 | 1 |
| MI-14 | 6 | 2 | 2 | 2 | 16 | 16 | 0 | 2 | 1 |
| total | 227 | 60 | 60 | 14 | 472 | 472 | 12 | 14 | 7 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| House | Number of Calibration Distribution Chassis | Number of RF Boards | Number of Transition cable panels | Number of Calibration Cables |
| MI-10 | 1 |  | 1 | 9 |
| MI-20 | 1 |  | 1 | 8 |
| MI-30 | 1 |  | 1 | 10 |
| MI-40 | 1 |  | 1 | 10 |
| MI-50 | 1 |  | 1 | 10 |
| MI-60 | 1 |  | 1 | 10 |
| MI-14 | 1 |  | 1 | 2 |
| total | 7 | 0 | 7 | 59 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| House | # Timing Boards | Clock Channels(Cables) | Trigger Channels | Control Channels |
| MI-10 | 2 | 9 | 9 | 6 |
| MI-20 | 2 | 8 | 8 | 6 |
| MI-30 | 2 | 10 | 10 | 6 |
| MI-40 | 2 | 10 | 10 | 6 |
| MI-50 | 2 | 10 | 10 | 6 |
| MI-60 | 2 | 10 | 10 | 6 |
| MI-14 | 0 | 2 | 2 | 6 |
| Total | 12 | 59 | 59 | 42 |
| Total Cables | 162 |  |  |  |

**BPM Sensitivity Factor:**

A proportional constant between the beam displacement and the detector signal strength. The units of sensitivity are [%/mm] when using linear processing and [dB/mm] when performing logarithmic processing. (see R. Shafer paper on Beam Position) both cases for small beam displacement. In cases where displacement is large sensitivity factor depends not only on the displacement in the direction of measurement but also on the orthogonal axis as well as frequency [x, y, f].

Accuracy:

Is the ability of measuring a position relative to a mechanical fixed-point, or in general to any known axis. Further, one must include electronics drifts, external coupled noise in the form of electro-magnetic interference.

Resolution:

Is the ability of measuring small displacement variations. Mechanical separation of the BPM plates contribute to the resolution.

**BPM Sensitivity Factor by Type:**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **RR Horizontal BPM** | **RR Vertical BPM** | **8 GeV Style BPM** | **Extra Wide Horizontal BPM** | **Extra Wide Vertical BPM** |
| **Effective Radius** | -61.94 mm | -32.73 mm | -72.6 mm |  |  |
| **Sensitivity Factor Log Ratio** | 0.341dB/mm | 0.725dB/mm | 0.245 dB/mm |  |  |
| **Reff/(1/Sx)** | 21.12 | 23.73 | 17.78 |  |  |

Effective Radius can be obtained from:

Effective radius equals factor (mm/dB) times 40/ln(10)

20

=

,

Sum and Difference corresponds to ,

|  |  |
| --- | --- |
| A=B | =1, |
| A>B | <1, |
| A<B | >1, |

|  |  |  |
| --- | --- | --- |
| If A>B or A<B ,x dB |  |  |
| 0.4 | 0.954 | 1.047 |
| 0.8 | 0.912 | 1.096 |
| 1.2 | 0.871 | 1.148 |
| 1.6 | 0.832 | 1.202 |
| 2.0 | 0.794 | 1.259 |
| 2.4 | 0.759 | 1.318 |
|  |  |  |

**Log (A/B) measurements Horizontal RR BPM**

**Log Ratio Vertical RR BPM**

**Sum and Difference calculation Horizontal RR BPM**

**Sum and Difference Vertical RR BPM**

**DDC Signal Channel Path:**



The signal type into the DDC is type **REAL,** there is only one signal originating from the BPM/Transition module system. This signal is digitized and distributed to four input ports of 14 bits of data in a 2s-complement format, this data is then converted into 19-bit format. The data is digitized at the same rate as the clock rate of the GC4016.

**Signal Path Gain calculation:**

N is the desired decimation and its an integer value between 8 and 4096 but can be shifted to 4 and 2048 in the SPLITIQ mode. The decimation sets the output bandwidth between 4Khz and 3 MHz in the single channel case. The coarse gain has a range of 42 dB in 6 dB steps

The gain of of the CIC filter is compensated by adjusting CIC\_SCALE which sets the gain equal to

The values for SHIFT, Scale, and BIG\_SCALE should be chosen so the CIC Gain ends up being less than one. The range of CIC Gain is

**Sampling Rate and Resulting Spectrum:**



Figure 1. Spectrum of undersampled beam, fbeam = 52.8114 MHz and the resulting spectrum of the beam sampled at 76.343 MHz is 23.5316 MHz.

Fbeam = 52.809e6 and the ADC sampling frequency is. The harmonic number is 588. This new frequency is processed by the numerical controlled oscillator shifting the spectrum to baseband.



**Figure 2.** The NCO is programmed to 23.5316 MHz generating sine and cosine waveforms and modulated the ADC signal producing a DC signal at baseband and upper harmonics.

**CIC Filter Stage:**

The first filter the output of the NCO sees is a 5 stage Cascade Integrator Comb (CIC) filter. The transfer function of this filter given by:

;

Integrator filter section :

Comb filter section:

N -> is the number of filter sections. In the GC4016 N = 5.

R -> is the Decimation ratio

M-> is the differential delay taking the values of 1 or 2.

The magnitude response of the CIC filter is expressed as:

By changing the decimation rate of this filter wideband or narrowband filters can be implemented.

|  |  |  |  |
| --- | --- | --- | --- |
| CIC Decimation Ratio | TBT | NarrowBand |  |
| R | 4 | 1024 |  |
|  |  |  |  |

This filter does not a flat passband response, it droops with a sin(x)/x rolloff. This effect can be compensated by applying a filter that has a frequency response inverse of the CIC filter. This filter can be multirate filter and can have decimation.

This filter is implemented in the CFIR filter.

The CIC/coarse gain outputs are filtered by two stages of filtering. The first stage is a 21-tap decimate-by-two filter with programmable 16-bit coefficients. Because this filter decimates by two, a stopband must be created in that portion of the spectrum that would alias into the signal of interest. This filter has very lax transition-band specifications, so 21 taps are sufficient both to provide the required anti-aliasing stop band and to provide compensation for the droop in the CIC-filter pass band.

Coefficients are assumed to be symmetric, so only the first 11 coefficients (h0 through h10) are loaded into the chip. A non-symmetric mode (NO\_SYM\_CFIR in address 25) allows the user to download an 11-tapnon-symmetric filter as taps h0 through h10. The newest sample is multiplied by h0 and the oldest is multiplied by h10. Filters normally multiply h0 by the oldest data; hence, one may wish to reverse the tap order in the non-symmetric mode.



The coefficients of the CFIR filter which compensate the CIC filter calculated with Fclock 75.4414428e6 and a decimation ratio of 3 machine turns being 1764 gives a clock frequency for the CFIR of 42.76249e3. The CFIR is a 21 tap filter, the first 11 are

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 |
| 5 | 39 | -166 | -1301 | -3009 | -2848 | 1280 | 9009 | 18952 | 28546 | 32762 |

The PFIR filter follows the CFIR and runs at frequency of 21.38363e3 and its made up of 63 taps. The output of the filter is then decimated by 2 so the I and Q pair is produced every 93.529 microseconds.

The 63 coefficients are identified as coefficients h0 through h62, where h31 is the center tap. The coefficients are assumed to be symmetric, so only the first 32 coefficients (h0 through h31) are loaded into the chip. A non-symmetric mode (NO\_SYM\_PFIR in address 26) allows the user to download a 32-tap non-symmetric filter as taps h0 through h31. The newest sample is multiplied by h0 and the oldest is

multiplied by h31.



The first 32 coefficients are

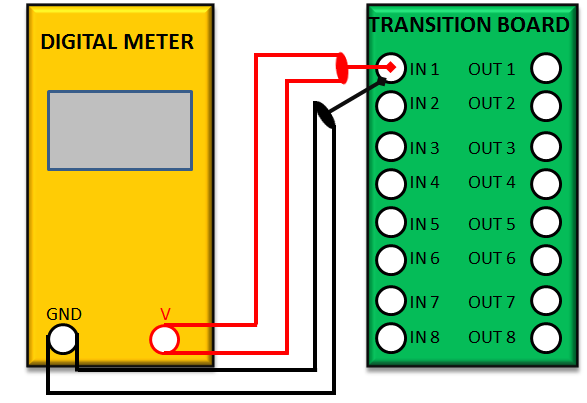
|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| H0 | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 |
| 6 | 17 | 33 | 49 | 54 | 33 | -28 | -132 | -263 | -380 | -424 |
| H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 | H20 | H21 |
| -329 | -49 | 408 | 964 | 1461 | 1690 | 1445 | 597 | -826 | -2589 | -4252 |
| H22 | H23 | H24 | H25 | H26 | H27 | H28 | H29 | H30 | H31 | H32 |
| -5228 | -4098 | -2819 | 1222 | 7006 | 13910 | 20982 | 27118 | 31299 | 32767 |  |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

**Transition Board Measurements**

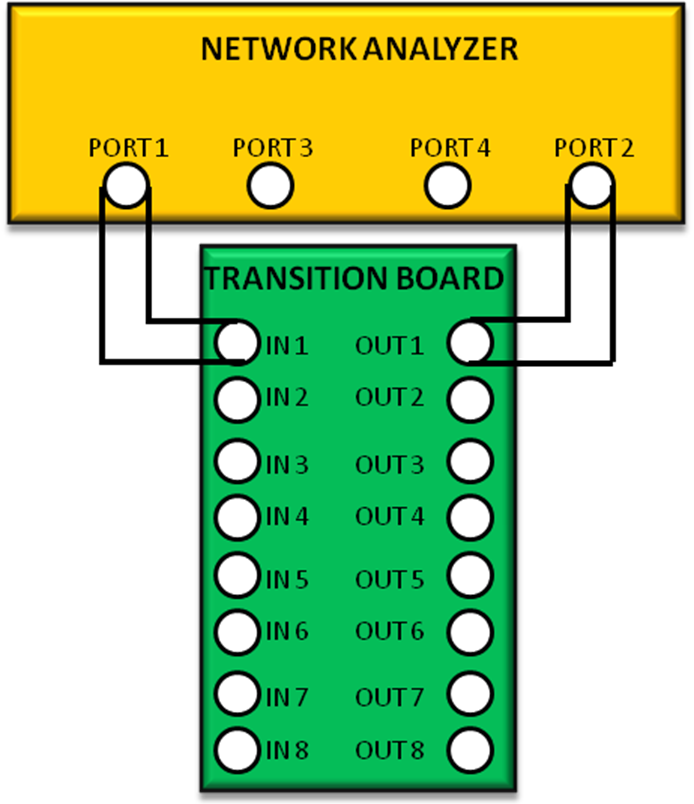
A test procedure was developed to run under Labview controlling a Agilent Network Analyzer. Four types of measurements are performed and recorded for each board and its channels.

**DC Offset Measurements**



|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Brd # | Ch1 A | Ch1B | Ch2A | Ch2B | Ch3A | Ch3B | Ch4A | Ch4B |
| #3 |  |  |  |  |  |  |  |  |
| #4 |  |  |  |  |  |  |  |  |
| #5 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | -1.7e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 |
| #7 | 0.1e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 |
| #9 | 0.2e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 |
| #11 | 0.1e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 |
| #13 | 0.2e-3 | 0.1e-3 | 0.1e-3 | 0.2e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 |
| #15 | 0.3e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.0e-3 | 0.1e-3 | 0.1e-3 | 0.0e-3 |
| #17 | 0.1e-3 | 0.1e-3 | 0.2e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.1e-3 |
| #6 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 |
| #8 | 0.1e-3 | 0.1e-3 | 0.2e-3 | 0.1e-3 | 0.2e-3 | 01.e-3 | 0.2e-3 | 0.1e-3 |
| #10 | 0.2e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.1e-3 |
| #12 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 |
| #14 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.2e-3 |
| #16 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.1e-3 | 0.2e-3 | 0.2e-3 | 0.1e-3 | 0.1e-3 |

**Direct Measurement at 52.809MHz**



|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Brd#* | *Ch1A* | *Ch1B* | *k* | *Ch2A* | *Ch2B* | *k* | *Ch3A* | *Ch3B* | *k* | *Ch4A* | *Ch4B* | *k* |
| *#3* | *0.844* | *-0.423* | *1.267* | *1.25* | *-0.661* | *1.911* | *1.465* | *0.775* | *0.690* | *1.856* | *1.146* | *0.710* |
| *#5* | *0.821* | *0.885* | *0.064* | *1.173* | *0.779* | *0.394* | *0.1778* | *1.578* | *1.40* | *0.867* | *0.532* | *0.335* |
| *#7* | *0.732* | *0.392* | *0.34* | *2.294* | *0.928* | *1.366* | *1.434* | *1.803* | *0.369* | *1.417* | *0.913* | *0.504* |
| *#9* |  |  |  |  |  |  |  |  |  |  |  |  |
| *#11* | *1.278* | *0.407* | *0.871* | *0.114* | *0.685* | *0.571* | *0.497* | *-0.244* | *0.919* | *-0.219* | *0.782* | *1.001* |
| *#13* | *0.904* | *1.243* | *0.339* | *-0.016* | *0.821* | *0.837* | *0.828* | *0.335* | *0.493* | *0.571* | *1.140* | *0.569* |
| *#15* | *-1.226* | *-1.675* | *0.449* | *0.872* | *-0.948* | *1.82* | *1.226* | *1.094* | *0.132* | *1.056* | *-0.281* | *1.337* |
| *#17* | *0.581* | *1.011* | *0.430* | *1.899* | *0.742* | *1.157* | *1.444* | *1.467* | *0.023* | *1.998* | *0.761* | *1.237* |
| *#4* | *1.018* | *0.921* | *0.097* | *1.446* | *1.380* | *0.066* | *1.185* | *0.795* | *0.390* | *1.62* | *1.454* | *0.166* |
| *#6* |  |  |  |  |  |  |  |  |  |  |  |  |
| *#8* | *1.864* | *1.159* | *0.705* | *1.559* | *1.914* | *0.355* | *1.180* | *1.593* | *0.413* | *0.617* | *0.168* | *0.449* |
| #10 | 0.635 | 0.994 | 0.359 | 1.903 | 1.034 | 0.869 | 1.53 | 1.781 | 0.251 | 2.044 | -0.263 | 2.307 |
| #12 | 1.17 | 1.555 | 0.385 | 2.058 | 1.124 | 0.934 | -0.086 | 1.265 | 1.351 | 0.282 | 1.378 | 1.096 |
| #14 | 0.536 | 0.454 | 0.082 | 0.591 | 0.176 | 0.415 | 1.963 | 1.544 | 0.419 | 0.541 | 0.090 | 0.451 |
| #16 |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |

**Cross Coupled Measurement for 52.809 MHz**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Brd # | Ch1A/1B | Ch1B/2A | Ch2A/2B | Ch2B/3A | Ch3A/3B | Ch3B/4A | Ch4A/4B |
| #1 | -58.665 | -53.193 | -59.620 | -99.7133 | -58.800 | -52.981 | -45.546 |
| #3 | -59.618 | -52.589 | -61.033 | -52.7543 | -58.781 | -51.434 | -58.069 |
| #4 | -57.750 | -52.689 | -59.305 | -52.571 | -59.886 | -52.591 | -58.227 |
| #5 | -58.501 | -53.304 | -59.784 | -52.906 | -58.897 | -52.923 | -45.679 |
| #7 | -58.246 | -52.288 | -59.940 | -52.076 | -58.606 | -52.940 | -59.134 |
| #8 | -57.854 | -52.146 | -58.417 | -53.096 | -58.956 | -52.905 | -58.328 |
| #10 | -57.307 | -52.441 | -60.272 | -51.675 | -58.171 | -51.723 | -59.779 |
| #11 | -59.250 | -53.713 | -60.222 | -53.054 | -61.341 | -54.006 | -58.467 |
| #12 | -57.601 | -52.234 | -59.339 | -53.708 | -59.747 | -54.000 | -59.220 |
| #13 | -58.283 | -53.533 | -59.745 | -52.997 | -62.039 | -53.418 | -59.467 |
| #14 | -59.451 | -54.403 | -60.502 | -52.025 | -59.290 | -53.725 | -60.923 |
| #15 | -61.805 | -53.001 | -61.496 | -52.117 | -58.956 | -52.189 | -60.340 |
| #17 | -58.958 | -51.912 | -59.569 | -52.486 | -58.541 | -51.021 | -59.006 |
| #20 | -58.294 | -53.205 | -59.649 | -53.898 | -58.968 | -51.989 | -60.194 |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Brd# | Ch1B/1A | Ch2A/1B | Ch2B/2A | Ch3A/2B | Ch3B/3A | Ch4A/3B | Ch4B/4A |
| #1 | -65.168 | -56.490 | -68.983 | -56.497 | -68.482 | -55.231 | -46.083 |
| #3 | -68.342 | -58.406 | -67.418 | -58.144 | -68.339 | -55.979 | -63.892 |
| #4 | -66.624 | -55.651 | -69.558 | -56.519 | -70.831 | -57.028 | -66.150 |
| #5 | -65.792 | -56.329 | -69.114 | -56.522 | -68.775 | -55.144 | -46.150 |
| #7 | -66.570 | -56.285 | -70.457 | -57.372 | -70.992 | -55.312 | -68.267 |
| #8 | -65.139 | -55.794 | -68.099 | -55.299 | -68.875 | -55.886 | -67.671 |
| #10 | -66.301 | -56.711 | -69.463 | -56.912 | -66.834 | -56.227 | -67.322 |
| #11 | -65.128 | -57.664 | -71.514 | -56.975 | -70.430 | -57.949 | -68.995 |
| #12 | -66.524 | -55.051 | -68.079 | -56.942 | -78.211 | -56.116 | -68.326 |
| #13 | -67.163 | -55.668 | -69.875 | -57.264 | -69.569 | -57.280 | -68.270 |
| #14 | -67.301 | -57.991 | -71.450 | -57.161 | -70.647 | -56.0942 | -69.331 |
| #15 | -71.113 | -59.170 | -71.438 | -58.699 | -70.654 | -56.385 | -67.447 |
| #17 | -65.973 | -57.296 | -69.971 | -56.686 | -68.860 | -56.553 | -66.470 |
| #20 | -66.009 | -56.682 | -71.654 | -56.770 | -70.475 | -56.834 | -67.034 |

Bunch Structures and Beam Intensities

Define four bunch structures to consider:

1. Batch of 30 or more 53 MHz bunches transferred from Booster into RR. Six batches transferred sequentially. An additional 6 batches transferred from Booster into RR and slip-stacked over the existing 6 batches.
2. Single coalesced bunches of protons (i.e. bunches sufficiently isolated from any neighbors so that signal from one bunch dies out in BPM system before arrival of next bunch).

There are then two regimes to consider for each:

1. Specified measurement range intensities

2. Typical operating range intensities

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Structure | Spec. Min | Spec. Max. | Typical |
| 1a. | >30 Bunches | 5e9 ppb | 125e9 ppb |  |
| 1b. | >30 Bunches | 5e9 ppb | 63e9 ppb |  |
| 2. | 5-9 Bunches | 30e9 ppb | 100e9 ppb |  |
| 4. | Single bunch | 5e9 ppb | 400e9 |  |
|  |  |  |  |  |
|  |  |  |  |  |

|  |
| --- |
|  |

Clock Events for Recycler BPMs

Tclk Events (RR BPM):

* $B2 RR BPM - Prepare for Beam
* $B3 RR BPM - Write Profile Memory; multiple events up to 128
* $B4 RRBPM - Write Display Frame, one per cycle
* $B5 RR BPM Flash Trigger, multiple events triggered from Beam Sync and BES

Tclk Events (Recycler):

* $E0 RR Reset for RR Studies
* $E1 RR Reset for MI Studies
* $E2 RR Reset for Fixed Target
* $E3 RR Reset for NuMI
* $E6 RR End of Beam

RR Beam Sync events:

* Booster Extraction Sync (Hardware) Booster to RR transfer
* $A3 8 GeV transfer from RR to MI
* $A6 8 GeV transfer from RR to Muon
* $DA Data Acquisition event, triggers dedicated Turn by Turn acquisition

 RR BPM Test Setup Timeline (with absolute times, use relative times)

1.252449 1.318818

0.533473 0.533704 1.217211 1.283580 1.39423

$E3 $B2 $B3 $19 BES $19 BES $E6

Reset Prepare Profile Reflected Eof Cycle

for Beam from Bsync A7