Development and implementation of pulse summing amplifier modules for the MPRu fusion neutron spectrometer at JET.


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A set of high-frequency pulse summing amplifiers (PSA) are installed at the Joint European Torus (JET) as part of the Magnetic Proton Recoil upgrade (MPRu) fusion neutron spectrometer. This paper describes the development of such devices and their implementation for MPRu. Tests showed that PSA are capable of good performance and wide bandwidth for a relatively large range of input signals. The reliability of the devices was also proved by laboratory tests at Uppsala University and through several years of operation at JET.

I. INTRODUCTION

The Magnetic Proton Recoil upgrade (MPRu) [1] is a 2.5 MeV / 14 MeV neutron spectrometer at the Joint European Torus (JET). Each of the 32 MPRu scintillation detectors is equipped with a pair of photomultiplier tubes (PMTs), one for each end, and their signals are actively summed to reduce statistical fluctuations. This requires 32 pulse summing amplifier (PSA) modules described in this paper. Passive solutions are not suitable for this because of the relatively long distance (∼110 m) between the detectors in the Torus Hall and the digitizing cards (TRC), which are installed in the data acquisition computers (DAC) in the Diagnostic Hall. The long cables are known to attenuate the signal and to introduce pick-up noise which significantly degrades the signal-to-noise ratio (SNR). Besides the summing function, the PSA must also provide a possibility for remote enabling and disabling of the left and right channels for diagnostic purposes, e.g. single PMT tests, without affecting the PMT high voltage power supply. A block diagram of the MPRu data acquisition is presented in Fig. 1. This paper describes the design and implementation of the MPRu PSA modules.

II. DEVELOPMENT

During PSA development and MPRu installation (2003-2004) the signals from the PMTs were expected to be of ∼100 – 300 mV (negative amplitude) and a few ns full-width-half-maximum (FWHM). Preliminary analysis of the transmission line between the Torus Hall and Diagnostic Hall suggested that a net amplification of about 6 was necessary for good SNR. The amplifier design thus was aimed towards accurate high-frequency operation, large slew rate and a relatively large output voltage range. Several configurations and devices were tested for this purpose and the one allowing for good and stable performance was a simple two-stage non-inverting configuration using the OPA695 operational amplifiers from Texas Instruments [2]. Although these were not the ones featuring the widest bandwidth (1.4 GHz vs. 2GHz of some other devices), they were found to be very stable for pulse amplification.

The schematic for each of the 32 PSA channels is illustrated in Fig. 2. The labels IN1, IN2 and OUT indicate the left/right inputs and the output, respectively, while EN1 and EN2 represent logic input signals that enable or disable each channel. All components are surface-mounted to minimize parasitic capacitance and improve high-frequency performance. A pair of 6.8 μF tantalum capacitors was found to be effective for power supply bypass. Two 0.1μF polypropylene capacitors for each amplifier, one for each power supply pin, were sufficient to ensure stable operation even for large signals. Finally, a
10 nF capacitor (C9) was used across the power supplies to optimize harmonic distortion. The gain on the input block was set to +2 while the second stage was fixed to approximately +6. The lower gain in the former stage was chosen not to saturate the input of the latter. The relatively large amplification for each channel is due to the 50 Ω coupling of the device. This explains the choice \( R_8 = R_9 = 100 \, \Omega \), yielding approximately 50 Ω output impedance of the PSA module. Once a 50 Ω load is connected to \( OUT \), the drop on \( R_8 \) and \( R_9 \) is about 75% of \( v_{21} \) or \( v_{22} \) thus giving about a factor +3 net amplification per channel \( (2 \cdot 6 \cdot (1 - 0.75)) \) and a factor +6 for the sum.

The OPA695 nominal operating point uses a ±5V balanced power supply for \( +V\text{DC} \) and \( -V\text{DC} \). This ensures low offset but it is not an optimal choice for the application, in which the signals are mostly negative. To improve the output swing in the negative region, a pair of asymmetric power supplies was used with \( +V\text{DC}=+4V \) and \( -V\text{DC}=-7V \). This also increased the difference between the two values from 10V to 11V, which is above the recommended operation point but still within maximum ratings (13 V). A series of stress tests was performed to test these operating conditions. The results provided no indication that the shifted and increased supply voltage window would negatively affect the device stability or reliability.

SPICE [3] simulations were performed for the PSA design using the Texas Instruments OPA695 SPICE model included in TINA-TI v.7 [4]. It was found that the model is in good agreement with experimental results with the exception of the enable-disable functionality of the amplifier. While experiments show that the device output lies in high-impedance state while disabled, this does not seem to be the case with the TINA-TI model. This functionality has thus been corrected and further investigation on the subject is in progress with Texas Instruments. Tables I and II report on SPICE simulations of DC offset analysis of the PSA board with symmetric and asymmetric power supplies. It can be seen that the latter case shows an increased offset from a few mV to 37-66 mV. The experimental values found for each of the 32 boards were close but not identical to these values. The deviations are likely due to errors in the resistors and differences between each individual OPA695. The choice of asymmetric power supplies and the DC offset is discussed in Section IV.

**TABLE I: SPICE DC offset analysis for balanced ±5 VDC power supplies.** The nodes reported in the table refer to Fig. 2.

<table>
<thead>
<tr>
<th>Enabled</th>
<th>( v_{11} ) (mV)</th>
<th>( v_{12} ) (mV)</th>
<th>( v_{21} ) (mV)</th>
<th>( v_{22} ) (mV)</th>
<th>( V_{OUT} ) (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN1</td>
<td>0.7</td>
<td>-5.3</td>
<td>4.1</td>
<td>15.2</td>
<td>2.49</td>
</tr>
<tr>
<td>EN2</td>
<td>4.1</td>
<td>15.2</td>
<td>0.7</td>
<td>-5.3</td>
<td>2.49</td>
</tr>
<tr>
<td>EN1 + EN2</td>
<td>0.7</td>
<td>-5.3</td>
<td>0.7</td>
<td>-5.3</td>
<td>-2.64</td>
</tr>
</tbody>
</table>

**TABLE II: SPICE DC offset analysis for asymmetric +4/−7 VDC power supplies**

<table>
<thead>
<tr>
<th>Enabled</th>
<th>( v_{11} ) (mV)</th>
<th>( v_{12} ) (mV)</th>
<th>( v_{21} ) (mV)</th>
<th>( v_{22} ) (mV)</th>
<th>( V_{OUT} ) (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN1</td>
<td>-15.9</td>
<td>-132.9</td>
<td>3.19</td>
<td>-18.6</td>
<td>-37.9</td>
</tr>
<tr>
<td>EN1</td>
<td>3.19</td>
<td>-18.6</td>
<td>-15.9</td>
<td>-132.9</td>
<td>-37.9</td>
</tr>
<tr>
<td>EN1 + EN2</td>
<td>-15.9</td>
<td>-132.9</td>
<td>-15.9</td>
<td>-132.9</td>
<td>-66.5</td>
</tr>
</tbody>
</table>

Table III reports an analysis of a \( A_{in}=-300 \) mV proton pulse in each of the PSA inputs. Both peak-to-peak amplitude (\( A_{p-p} \)) and net gain with respect to the input (\( G_{NET} = |A_{p-p}/A_{in}| \)) are displayed. It can be seen that the nodes \( v_{21} \) and \( v_{22} \) must be capable of adequate negative voltage swing. In particular, with ±5 V power supply the amplifier was found to start saturating at about -3.9 V. With the +4 / −7 V supply scheme this was extended to -5.8 V without any apparent loss of stability, accuracy or reliability. In these conditions the PSA can ensure linearity up to -490 mV input signals.

Analysis in the frequency domain of the PSA showed another possible issue with the SPICE model and/or the analysis code. The SPICE simulation highlighted a high-frequency pole giving a -3dB intersection at about 350 MHz. Experimental tests performed with a 500 MHz spectrum analyzer on a fully assembled board failed to detect such an intersection within the instrument frequency range. The gain loss at 500 MHz was within -1dB suggesting a -3dB frequency around 800-900 MHz. The model also failed to reproduce the frequency plots from the OPA650 data sheet in various configurations, providing further evidence that the model should be reviewed in the future for best accuracy.
TABLE III: SPICE analysis for a -300 mV proton pulse using asymmetric +4/ – 7 V DC power supplies. Both channels enabled. The polarity of the signal is negative.

<table>
<thead>
<tr>
<th>IN1, IN2</th>
<th>v11, v21</th>
<th>v12, v22</th>
<th>VOUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_{peak} (V)</td>
<td>-0.300</td>
<td>-0.591</td>
<td>-3.553</td>
</tr>
<tr>
<td>( G_{NET} )</td>
<td>1.00</td>
<td>1.97</td>
<td>11.84</td>
</tr>
</tbody>
</table>

controller board developed for the application, visible on the bottom right. The addition of a 40 mm fan ensured proper cooling of these devices although this was not strictly necessary. A 10 wire ribbon cable connector is used to interface all PSA boards in a daisy-loop scheme. Ethernet communication with the device is provided by a HD1100 [7] logic interface connected to the PSA cards through each controller board. This permits for remotely enabling the left and right channels of the PSA from the DAC computer through TCP/IP socket programming. A single HD1100 is physically mounted on the MPRu bipolar nanosecond LED driver (BLD) [8] and interfaced to all PSA modules with D-SUB connectors on the back side (bottom right of the figure).

Fig. 6 shows the crate currently installed on the MPRu service balcony in the JET torus hall. This is at ≈8 m distance (RG58 cables) from the MPRu PMTs. The four PSA modules can be seen on the left side. In each module the left and right arrays of BNC connectors are used for the left and right input channels, while the center one is the output. Also shown in the picture are the two BLDs (right side) used for calibration and monitoring of the MPRu and TOFOR [9] neutron spectrometers at JET [10].

IV. DISCUSSION

The use of asymmetric power supply to optimize the voltage swing in current feedback amplifiers such as OPA695 is possible although generally not recommended due to the increase in offset, as reported in Section II. For the present application, however, this was not an issue since the signal is fed into the TRC digitizing cards which have a built-in offset compensation input stage.
There are several possibilities to compensate the offset if necessary, of which one of the simplest is illustrated in Fig. 7 for channel 1 only. The scheme for channel 2 is identical. The offset compensation is achieved through AC coupling between the first and second stage using a decoupled bias network for the non-inverting pin of $A_2$. This creates a single zero at DC and a low-frequency pole at about 48 Hz ($\sim 1/(2\pi C_{in} R_{in})$). The ratios between $R_{in}$, $R_A$ and $R_B$ control the amplifier offset which in this case becomes <1 mV at the OUT node. SPICE simulations on this scheme suggested that this is a possible solution for a revised PSA version, although the device should be tested in the laboratory to optimize the values of the resistors and capacitors. The relatively small time window of the TRC (up to 5.12 $\mu$s) indicates that a single zero in DC is adequate as long as the low-frequency pole is kept as low as possible, preferably well below 1kHz. More sophisticated filters are possible, for instance by using AC coupling at the output and a series capacitor installed between $R_6$ and ground.

The original design of the PSA was based on negative proton pulses around 100-300 mV but results collected at JET on the fully installed MPRu generally showed lower signal amplitudes. Furthermore, the preliminary survey on the attenuation by the cables between the torus hall and diagnostic hall was found to be rather conservative. This means that the PSA values for the feedback and gain resistors for $A_2$ and $A_3$ should be updated in the future based on such information to optimize the SNR.

The use of current feedback amplifiers (CFB) is usually not recommended for precision applications. Voltage feedback amplifiers (VFB) are typically used instead of CFB. Additionally, the summing of the signals is usually performed on the inverting node which is at virtual ground and very stable. Although VFB amplifiers were tested in both inverting and non-inverting configurations it was found that the OPA695 (CFB) in non-inverting configuration was a better choice due to the large bandwidth, voltage swing and output current sourcing / sinking capabilities. This was the case at the time the PSA were developed.

Up to the present (2009) there has been only one incident with the PSA modules and in particular with the left channel 1 on module 1. This happened following an insulation failure of the corresponding PMT which is believed to have produced a high voltage spike ($\sim 1200$V) on the signal cable before tripping the high voltage power supply. In these conditions the damage of the input stage of the $A_1$ amplifier was inevitable.
V. CONCLUSION

This paper has described the development and the implementation of the pulse summing amplifiers modules for MPRu at JET. SPICE simulations were performed on the circuit which was then built and extensively tested both at Uppsala University and at JET over several years. Although some choices in the implementation were not following the typical guidelines for high-frequency amplifiers, results showed that the PSA was capable of wide-band accurate and reliable performance over a relatively broad range of signals.

Acknowledgement

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