Title
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Abstract

The stochastic beam cooling amplifier front end consists of 180° hybrids, cables, directional couplers, power dividers/combiners and low noise preamplifiers. Most front ends will be operating at near liquid nitrogen (LN) temperature. Components used in the front ends should be able to operate at this temperature satisfactorily. Since the noise performance of the front end is of utmost importance to the beam cooling process, the insertion losses of cables, 180° hybrids, directional couplers and power combiners have been measured at room temperature and near liquid nitrogen temperature. The purpose of this report is to describe and present some measurements and data on the components mentioned, with the exception of the 1-2 and 2-4 GHz preamplifiers, which have been described elsewhere.1,2

Introduction

The bunched particles in a high energy accelerator tend to spread with time. Systems for reducing this spreading, known as cooling systems, have been developed.3,4 The anti-proton source (which consists of a debuncher ring and an accumulator ring) of the Fermi National Laboratory will employ a stochastic beam cooling system to reduce the emittance and spreading of the particle beam. This beam "cooling" system includes pick-up electrodes coupled to very low-noise preamplifiers through a component system that is discussed in this report. The feedback system picks up signals from the beam bunches with pick-up electrodes, amplifies them and feeds them back to the beam through kicker electrodes with proper amplitude, phase and propagation delay to keep the particle beam "cooled".

Figure 1 shows a typical front end of the amplifier systems; there will be three to four variations of this configuration in the anti-proton source. Most front ends will be operating near liquid nitrogen temperature. The preamplifiers used in those front ends will be those described in References 1 and 2. They will be operating at about 80 K with noise figures in the 0.2-0.6 dB range. Since the hybrids, directional couplers, power combiners, and interconnecting cables are mostly situated ahead of the preamplifiers, any insertion loss due to these components degrades the signal to noise ratio of the whole system. Therefore it is imperative that such losses be kept at minimum. In some front ends, where the output signals from the pick-up electrodes are higher, no liquid nitrogen cooling is necessary. In such cases, commercially available preamplifiers with noise figures in the range 1.5-2 dB are used. Those front ends will be operating at room temperature.

The pick-up electrode consists of arrays of 32 pairs of electrodes.7 The signal picked up by each electrode is combined by a primary combiner whose outputs are in turn combined by a secondary combiner which has a single output port. Both the upper and lower pick-up electrodes are configured in the same way. The signals picked up by this array of 32 pairs of electrodes was calculated to be approximately equal to 1.4 pW in the stack tail system. By combining four such arrays the signal power will double, yielding a signal to noise ratio of better than one at 80 K. The average loss of a combiner is approximately 0.6 dB at 80 K. The output signals from the upper and lower secondary combiners either go into the two input ports of a 180° hybrid or into a power combiner depending on which system the front end is located. The output of the delta and/or the sum port of the 180° hybrid or the power combiner, as the case may be, is connected to a bidirectional coupler whose two coupling ports are used for monitoring purposes. When one of these two ports is being used for signal injection, the other unused port must be terminated with a high quality 50-ohm termination. The output of the direction coupler is then connected to the low noise preamplifier which has a gain of 30 dB. The output of this preamplifier then goes through the portion of the amplifier system which contains filters, drivers, phase shifters, power amplifiers and power splitters. Finally, the amplified signals with the correct phase, delay and amplitude are used for cooling the particle beam by means of the kicker electrodes.

Components Characteristics Measurements

All insertion loss measurements were made with the HP 8409 network analyzer using HP's 12-term calibration procedure. Accuracy of the measurement system was estimated to be ± 0.03 dB, but it became worse when measurements were made on components installed inside a liquid nitrogen-cooled chamber. In such cases the losses of the interconnecting cables must be subtracted to obtain the losses of the cooled devices. As a result, the accuracy of the 80 K data was estimated to be ± 0.06 dB. The loss in the semi-rigid cables which were part of the input system operating at 80 K was measured by using a 5 foot piece of cable immersed in liquid nitrogen. Two stainless steel buffer cables were used between the test ports of the network analyzer and the cable under test to minimize heat loss. The decrease in loss of the stainless steel cables at low temperature was taken into account in the final semi-rigid cable loss data. Low temperature insertion loss measurements of all other components were made by using a liquid nitrogen-cooled copper plate which was installed in a vacuum chamber. Heatsink compound was used between the copper plate and the components to obtain good thermococonductivity. The lowest temperature obtained by this cold plate was approximately 90-95 K.

Since a large number of measurements have to be made other than the insertion loss measurement on the 180° hybrids, directional couplers, power combiners and 50-ohm terminations, it was not practical to make all these measurements using the liquid nitrogen-cooled plate inside the vacuum chamber. The cool-down and warm-up cycle of the LN-cooled plate took ~8 hours and a large amount of LN had to be used for each cycle. As a result, components were instead lowered into an LN bath very slowly for cool-down, with the measuring cables connected to the device through 90° swept right angle assemblies which were also included in the calibration procedures. The LN bath enabled components
to cool down a lot faster, although it also subjected components to a much higher stress than they will encounter in the intended application.

Results of Insertion Loss Measurements

Table 1 shows the losses of all components measured at room temperature and at 90-95 K in the 1-2 GHz and the 2-4 GHz band. Since the uncertainty of the low temperature data was ± 0.06 dB, numbers below 0.1 dB should be regarded as typical rather than absolute.

Table 2 shows the total loss of different front ends between the output of the secondary combiner and the input of the preamplifier. At 3 GHz the front end loss (without combiner losses) with 180° hybrid was 0.99 dB at room temperature and 0.6 dB at 90 K for a system using 141 semi-rigid cables. At 1.5 GHz, the front end loss with the 180° hybrid and 141 semi-rigid cables was 0.68 dB at room temperature and 0.49 dB at 90K. Insertion losses of other front ends can be obtained from Tables 1 and 2.

Results of 50 Ohm Termination Measurements

A few 50-ohm terminations were tested. The return loss of one of the terminations is shown in Fig. 2 at room and LN temperature. 50-ohm terminations similar to these units should be used in the front ends. It is helpful to point out that the mechanical stress put on the terminations by ordinary wrenches could cause the device to fail; hence it is advisable to use a torque wrench when tightening the connections.

Results of 180° Hybrid Measurements

Figure 3 shows the 1-2 GHz hybrid's delta port to output port 1 and port 2 response at room temperature, and Fig. 4 shows the same response at LN temperature. Figures 5 and 6 give the same response of the 2-4 GHz hybrid at room temperature and at LN temperature, respectively. The voltage output of the delta port of the 1-2 GHz hybrid, as a function of the difference of two voltages of the same frequency and phase but different amplitude feeding into ports 1 and 2, is presented in Fig. 7 while Fig. 8 shows the response of the 2-4 GHz hybrid under the same testing procedures. The deviation from linear phase was within ± 1.2 degrees for both 180° hybrids. The isolation between the sum and the difference ports was better than 24dB for both units across their frequency bands of operation.

Hybrid Problems and Solutions

When the hybrids were cooled down to LN temperature, one out of sixteen connections opened in the 1-2 GHz hybrid and three out of sixteen connections opened in the 2-4 GHz hybrid. Such failure was not acceptable for this application. The opening of the connections was due to the shrinkage of the aluminum of the 2-4 GHz hybrid under the same testing procedures. The deviation from linear phase was within ± 1.2 degrees for both 180° hybrids. The isolation between the sum and the difference ports was better than 24dB for both units across their frequency bands of operation.

Acknowledgment

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

Results of Directional Coupler Measurements

The 1-2 GHz and the 2-4 GHz directional couplers are both bidirectional couplers. Figures 10 and 11 show the coupling response of the 1-2 GHz and the 2-4 GHz directional coupler at room and LN temperature. The directivity of both directional couplers were in the order of 50 dB or better at room and LN temperature. The coupling responses in the other direction on both devices were similar to those shown in Figs. 10 and 11.

Results of Power Combiner Measurements

The 1-2 GHz in-phase two-way power combiner is internally isolated with two resistors which limit the maximum operating power level to 6 W at room temperature. Figure 12 shows the response of one of the two output ports at room and LN temperature and Fig. 13 shows the same response of the other port at room and LN temperature.

Conclusion

During measurements some analyzer calibration drift was experienced. The error was minimized by doing calibration checks before, after, and in between data taking. Recalibrations were done whenever necessary.

Putting a minute amount of gallium-indium-tin alloy on the connecting surfaces of the circuits and the connector tabs provides a good cure for problem joints and an insurance for performing joints for the 180° hybrids. The failure rate of connections after this treatment was zero with 10 cycles of rigorous LN testing.

At liquid nitrogen temperature the center conductor and the teflon dielectric recede from the cold end of the 141 semi-rigid cables. The amount of shrinkage in some cases may be enough to open up connections. With the very short length of cable used in the front ends, this may not cause any problem provided the center conductor, which also serves as the pin for the connector, is not marginally short to start with. In all amplifier front end assemblies SMA couplers and SMA swept right angle assemblies will be used to interconnect components. The VSWR of a swept right angle assembly is in the order of 1.01-1.05 across the 1-4 GHz band. Short pieces of 141 semi-rigid cables will also be used.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.
References


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TABLE 1: DEVICE INSERTION LOSS AT 80-90 K

<table>
<thead>
<tr>
<th>DEVICE</th>
<th>1 GHz</th>
<th>1.5 GHz</th>
<th>2 GHz</th>
<th>3 GHz</th>
<th>4 GHz</th>
<th>5 GHz</th>
</tr>
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<tbody>
<tr>
<td>1/4&quot; cable</td>
<td>(0.06 dB)</td>
<td>(0.11 dB)</td>
<td>(0.13 dB)</td>
<td>(0.16 dB)</td>
<td>(0.18 dB)</td>
<td>(0.22 dB)</td>
</tr>
<tr>
<td>40 CM</td>
<td>(0.03 dB)</td>
<td>(0.05 dB)</td>
<td>(0.06 dB)</td>
<td>(0.08 dB)</td>
<td>(0.09 dB)</td>
<td>(0.13 dB)</td>
</tr>
<tr>
<td>141 cable</td>
<td>(0.15 dB)</td>
<td>(0.18 dB)</td>
<td>(0.23 dB)</td>
<td>(0.29 dB)</td>
<td>(0.35 dB)</td>
<td>(0.39 dB)</td>
</tr>
<tr>
<td>40 CM</td>
<td>(0.065 dB)</td>
<td>(0.09 dB)</td>
<td>(0.11 dB)</td>
<td>(0.13 dB)</td>
<td>(0.16 dB)</td>
<td>(0.175 dB)</td>
</tr>
<tr>
<td>180° HYBRID</td>
<td>(0.35 dB)</td>
<td>(0.45 dB)</td>
<td>(0.52 dB)</td>
<td>(0.54 dB)</td>
<td>(0.56 dB)</td>
<td>(0.58 dB)</td>
</tr>
<tr>
<td>2-4 GHz</td>
<td>(0.32 dB)</td>
<td>(0.35 dB)</td>
<td>(0.36 dB)</td>
<td>(0.37 dB)</td>
<td>(0.38 dB)</td>
<td>(0.39 dB)</td>
</tr>
<tr>
<td>DIR. COUPLER</td>
<td>(0.15 dB)</td>
<td>(0.18 dB)</td>
<td>(0.21 dB)</td>
<td>(0.24 dB)</td>
<td>(0.27 dB)</td>
<td>(0.30 dB)</td>
</tr>
<tr>
<td>2-4 GHz</td>
<td>(0.1 dB)</td>
<td>(0.13 dB)</td>
<td>(0.16 dB)</td>
<td>(0.19 dB)</td>
<td>(0.22 dB)</td>
<td>(0.25 dB)</td>
</tr>
<tr>
<td>POWER COMBINER</td>
<td>(0.15 dB)</td>
<td>(0.22 dB)</td>
<td>(0.29 dB)</td>
<td>(0.34 dB)</td>
<td>(0.40 dB)</td>
<td>(0.45 dB)</td>
</tr>
<tr>
<td>180° HYBRID</td>
<td>(.2 dB)</td>
<td>(.3 dB)</td>
<td>(.4 dB)</td>
<td>(.5 dB)</td>
<td>(.6 dB)</td>
<td>(.7 dB)</td>
</tr>
<tr>
<td>2-4 GHz</td>
<td>(.13 dB)</td>
<td>(.25 dB)</td>
<td>(.34 dB)</td>
<td>(.43 dB)</td>
<td>(.52 dB)</td>
<td>(.61 dB)</td>
</tr>
<tr>
<td>DIR. COUPLER</td>
<td>(.08 dB)</td>
<td>(.1 dB)</td>
<td>(.13 dB)</td>
<td>(.16 dB)</td>
<td>(.19 dB)</td>
<td>(.22 dB)</td>
</tr>
<tr>
<td>1-2 GHz</td>
<td>(.07 dB)</td>
<td>(.1 dB)</td>
<td>(.12 dB)</td>
<td>(.14 dB)</td>
<td>(.16 dB)</td>
<td>(.18 dB)</td>
</tr>
<tr>
<td>POWER COMBINER</td>
<td>(.11 dB)</td>
<td>(.13 dB)</td>
<td>(.15 dB)</td>
<td>(.17 dB)</td>
<td>(.19 dB)</td>
<td>(.21 dB)</td>
</tr>
<tr>
<td>1-2 GHz</td>
<td>(.07 dB)</td>
<td>(.08 dB)</td>
<td>(.10 dB)</td>
<td>(.12 dB)</td>
<td>(.14 dB)</td>
<td>(.16 dB)</td>
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ESTIMATED RESULT ACCURACY = ± .06 dB

TABLE 2: FRONT END INSERTION LOSS

<table>
<thead>
<tr>
<th>OPERATING TEMPERATURE</th>
<th>1 GHz</th>
<th>1.5 GHz</th>
<th>2 GHz</th>
<th>3 GHz</th>
<th>4 GHz</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td>(.76)</td>
<td>(.99)</td>
<td>(1.27)</td>
<td>w/180° Hybrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°K</td>
<td>(.5 dB)</td>
<td>(.6 dB)</td>
<td>(.74 dB)</td>
<td>w/180° Hybrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Room Temperature</td>
<td>(.5 dB)</td>
<td>(.66 dB)</td>
<td>(.89 dB)</td>
<td>w/180° Hybrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°K</td>
<td>(.5 dB)</td>
<td>(.6 dB)</td>
<td>(.74 dB)</td>
<td>w/180° Hybrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Room Temperature</td>
<td>(.4 dB)</td>
<td>(.5 dB)</td>
<td>(.67 dB)</td>
<td>w/Power Combiner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°K</td>
<td>(.29 dB)</td>
<td>(.49 dB)</td>
<td>(.61 dB)</td>
<td>w/Power Combiner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Room Temperature</td>
<td>(.24 dB)</td>
<td>(.32 dB)</td>
<td>(.4 dB)</td>
<td>w/Power Combiner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°K</td>
<td>(.19 dB)</td>
<td>(.25 dB)</td>
<td>(.34 dB)</td>
<td>w/Power Combiner</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1  Block diagram of a typical front end

Fig. 2  Return loss of a 50 ohm termination.
Fig. 3  1-2 GHz hybrid delta port - port 1 and port 2 response at room temperature

Fig. 4  1-2 GHz hybrid delta port - port 1 and port 2 response at LN temperature
Fig. 5 2-4 GHz hybrid delta port - port 1 and port 2 response at room temperature

Fig. 6 2-4 GHz hybrid delta port - port 1 and port 2 response at LN temperature
Fig. 7 1-2 GHz hybrid delta port output as a function of input voltages
Fig. 8 2-4 GHz hybrid delta port output as a function of input voltages
MODIFICATION ILLUSTRATION
1-2 GHz 180° HYBRID

NOTE:

Fig. 9 Modification illustration diagram for the 1-2 GHz 180° hybrid
Fig. 10  Coupling between the input port and the coupled port of the 1-2 GHz directional coupler at room and LN temperature

Fig. 11  Coupling between the input port and the coupled port of the 2-4 GHz directional coupler at room and LN temperature
Fig. 12 Response of one of the two output ports of the 1-2 GHz power divider at room and LN temperature.

Fig. 13 Response of the second output port of the 1-2 GHz power divider at room and LN temperature.
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