PROGRESS OF THE RF-SYSTEM DEVELOPMENTS FOR STOCHASTIC COOLING OF THE FAIR COLLECTOR RING

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Abstract

An overview of the recent developments regarding the RF signal processing for the stochastic cooling system of the Collector Ring is given. In focus are the developments of RF components which can be used at different locations within the signal paths between the pickup and kicker tanks in the frequency band (1-2 GHz). Two of these components are discussed in detail, a directional power meter with high dynamic range (9 dBm to −68 dBm) , low phase distortion (±0.75 °(max)) and low attenuation (≤0.4 dB) and a variable phase shifter with exceptionally flat amplitude (±0.4 dB(max)) and linear phase response (±3.5 °(max)). Furthermore, we present the status and the newest enhancements of other components with stringent specifications, such as optical notch filters, pickup module controllers and the power amplifiers at the kickers.

INTRODUCTION

The main components of a stochastic cooling system are certainly the pickup and kicker devices. The signal processing between the pickup and kicker tanks has a great influence on the cooling performance as well. To achieve a high cooling efficiency a precise phase and amplitude control of the signals is necessary. Therefore it is crucial to monitor and affect these values according to the requirements of the integral system. The need to monitor and adjust certain values in the signal processing paths is typically not bounded to one particular point, instead there are multiple locations where phase and amplitude correction can be necessary. Standard RF components available at the market often do not fulfill crucial requirements (i.e. bandwidth, linear phase response etc.) for stochastic cooling. Therefore, the approach is to develop own RF components which meet our requirements and can be used at different locations without changing the design parameters of the respective devices. The next two sections cover the status of two in-house RF developments: a directional embedded power meter and a variable phase shifter. The subsequent sections present the development status of non-universal (i.e. fixed position, specialized purpose etc.) stochastic cooling components: notch filter, pickup module controller and power amplifies at the kickers.

EMBEDDED POWER METER

The embedded power meter consists out of two main components, a 20 dB broadband directional coupler with low insertion loss and low phase distortion and a power level detector with a high accuracy and wide dynamic range. The power level detector is a true RMS (Root Mean Square) device with a linear and temperature-compensated output voltage. It can measure any broadband signal with arbitrary waveform and crest factor changes over time [1]. The power meter should be used as a feedback to adjust the power levels and prevent gain compression. Additionally, a diagnostic I/O port was incorporated into the design, therefore the power meter can not only be used for measuring the power level of the input signal, but also to direct diagnostic signals into/out of the signal path. The diagnostic I/O port can be used to determine beam and system parameters which affect the cooling setup and performance. All components were dimensioned to work within the 1-2 GHz band of the stochastic cooling system. However, the system is also somewhat sensitive to out of band signal components in the 0.7 – 2.3 GHz range, therefore the power meter must also fulfill less stringent specifications within this extended band. Figure 1 shows a schematic of the power meter. To guarantee a reliable operation of the device several selftest circuits are embedded: a 10 MHz test signal generator which can be used to perform RF tests of the 20 dB amplifier, the Wilkinson power divider (resistive splitter), the RMS power detector and the “RF1” and “RFC” connection of the solid state relay. Three DC test points can be used to perform resistance and leakage current measurements. They can be used to check the DC characteristics of the 15 MHz low pass filter, directional coupler and “RF” connections of the solid state relay.

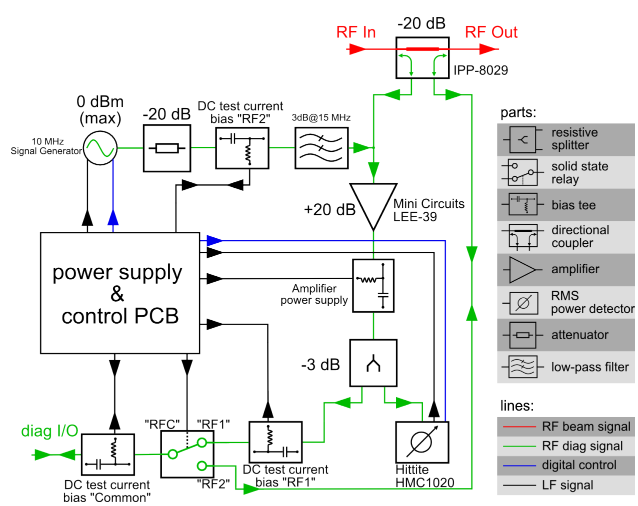

Figure 1: Block diagram of the embedded power meter.

A prototype (Fig. 2) of the power meter was build and the S-parameters were recorded. The determined electrical parameters of the prototype are given in Table 1[1].

[1] Phase distortion is defined as the deviation from the ideal linear phase response.

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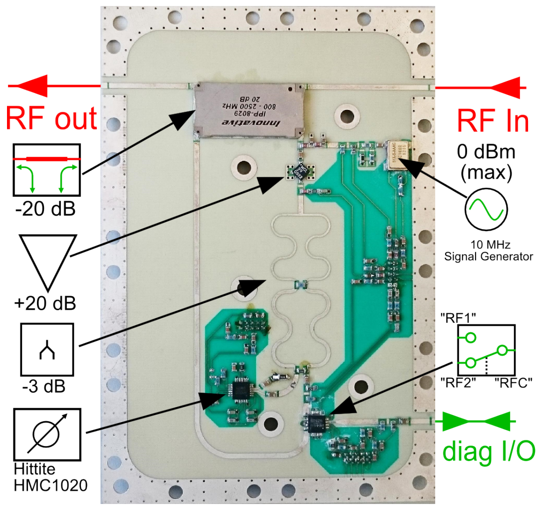

Figure 2: Prototype of the RF PCB of the power meter.

Table 1: Measured RF Values of the Power Meter

Parameter	Frequency	Values
Insertion Loss	0.7 - 2.3 GHz	0.2 dB - 0.55 dB
Insertion Loss	1 - 2 GHz	0.3 dB - 0.4 dB
Phase Distortion	0.7 - 2.3 GHz	±0.6 °
Group Delay	0.7 - 2.3 GHz	0.86 ns
Return Loss	0.7 - 2.3 GHz	≥ 14 dB
Dynamic Range	1.5 GHz	−68 dBm - 9 dBm
Detector Accuracy	1 - 2 GHz	≤ ± 1 dB

The data show that the critical values: insertion loss, amplitude response, phase distortion and group delay are within acceptable limits. Therefore, the device poses only a small imperfection to the signal path, which was a critical design aspect. At the same time, the dynamic range is quite high which provides versatile application possibilities for the power meter.

VARIABLE PHASE SHIFTER

Feeding the kicker modules with a correctly phase-shifted signal is crucial for the stochastic cooling system. A continuously variable phase shift is necessary to compensate position-dependent phase errors of the movable pickups. Therefore, the development of a variable phase shifter has begun. Simulations of the design show promising results, the prototype is underway. The basic concept of the phase shifter is a vector modulator (Fig. 3), the benefits of which are: high bandwidth (mainly dependent on the used 90 ° hybrid couplers), precise amplitude control, precise phase control and a simple structure with few active components (this guarantees a long lifetime and easy maintainability). Drawback of the design is an inherent 3 dB loss of the RF signal which increases the insertion loss of the device.

Basic principle of the vector modulator is to split the incoming RF signal into two components using a 90 ° hybrid coupler: an in-phase component (I component) and

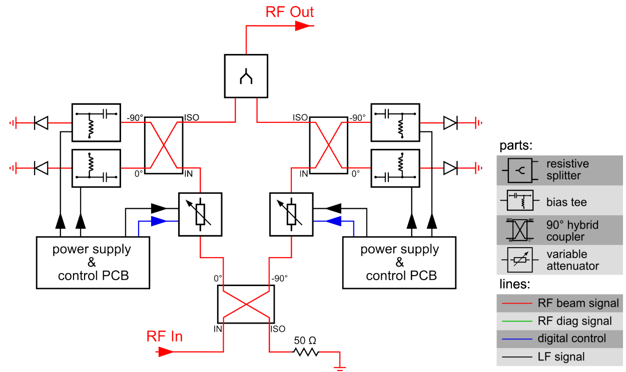

Figure 3: Block diagram of the variable phase shifter.

a 90° phase-shifted quadrature component (Q component). These two components can then be fed independently into a 0 °/180 ° phase shifter. In this case the 0°/180° phase shifter is constructed by using a 90 ° hybrid coupler with PIN diodes connected to the *coupled* and *through* ports. The impedance of the two PIN diodes can be changed from short circuit ($Z_L \approx 0\ \Omega$) to open circuit ($Z_L \approx \infty\ \Omega$). Depending on the status of the PIN diodes the signal than recombines at the *isolation* port of the respective hybrid coupler with a specific phase shift compared to the phase at the *input* port, 0 ° if Z_L is at maximum ($Z_L \gg Z_0 = 50\ \Omega$) and 180 ° if $Z_L \ll Z_0 = 50\ \Omega$). The 0 °/180 ° phase shifters can be used to determine in which quadrant of the constellation diagram the signal should be located. However, additional variable attenuators are necessary to achieve a fine phase adjustment. Any possible phase shift can be achieved by adjusting the magnitude of the I and Q components and recombining them using an in-phase (Wilkinson) combiner [2]. The actual phase resolution depends on the step size and accuracy of the used attenuators.

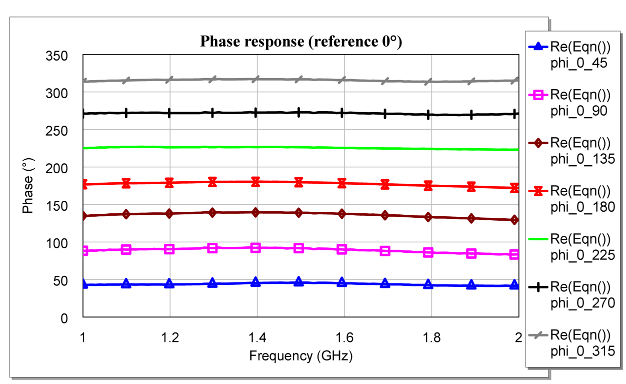

Figure 4: Phase Response (in 45 ° steps) of the phase shifter (in relation to 0 °).

The simulated S-parameters show satisfying results, especially regarding amplitude and phase response (Fig. 4). Table 2 shows the determined RF parameters.

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Table 2: Simulated RF Values of the Phase Shifter

Parameter	Frequency	Values
Insertion Loss	1 - 2 GHz	7.25 dB - 8.75 dB
Amplitude Response	1 - 2 GHz	±0.4 dB
Amplitude Response	0.7 - 2.3 GHz	±1.5 dB
Phase Distortion	1 - 2 GHz	±3.5 °
Phase Distortion	0.7 - 2.3 GHz	±7.5 °
Average Group Delay	1 - 2 GHz	1.818 ns ± 7 ps
Return Loss	1 - 2 GHz	≥ 15 dB
Phase Resolution	1 - 2 GHz	≤ ± 1 °
Switching Freq.	1 - 2 GHz	25 kHz

OPTICAL NOTCH FILTER

Longitudinal stochastic cooling with the notch filter method is essential in the CR. Two notch filters (one for antiprotons at v=0.97 c, revolution frequency=1.315 MHz; one for RIBs at v=0.83 c, revolution frequency=1.124 MHz) have been developed and built.

The initial design was similar to the notch filter prototype in the ESR [3]. The first optimization was to substitute the symmetric optical splitter by an asymmetric one (Fig. 5). The asymmetric splitter makes additional attenuation on the short branch redundant. The short branch determines the propagation delay t_0 (i.e. the electrical length) of the filter, in our case $t_0 = 3.45$ ns. Each branch (the short and the long one) is demodulated to a RF signal (Fig. 5). The second optimization was to use a 180 ° power combiner (ZAPDJ-2-S) instead of the previously used 180 ° hybrid (ANZAC H 183-4) to substract those signals and provide the notch filter transfer function. The power combiner is linear (in amplitude and phase) in a broader frequency range that the hybrid.

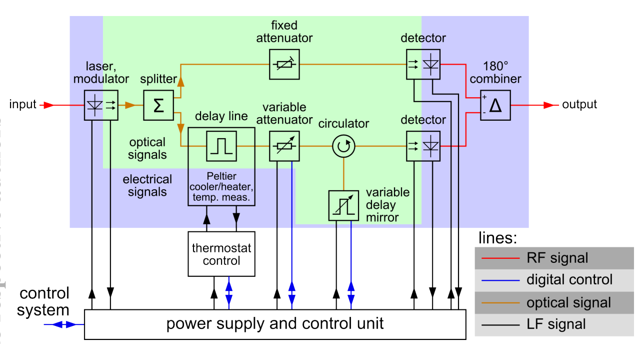

Figure 5: Block diagram of the CR optical notch filter.

In practice, within the bandwidth, a real filter has a finite (i.e. non-zero) low transmission (notch depth) at all harmonics nf_0. Because of non-linearity there is also a small deviation $f_n - nf_0$ between the frequencies f_n at which the transmission minima occur and the harmonics nf_0 (frequency periodicity error). Both effects affect the filter performance and lead to an increase of the equilibrium momentum spread of the cooled beam with respect to the ideal filter case.

We measured the transfer function of the notch filter in the pass band 1 to 2 GHz according to the CR requirements. The notch filter is mainly defined by the length of its optical delay line, for a fibre length of 160 m a time delay of 460 ps was necessary to setup a notch distance of $f_{0,set}$=1.234 966 MHz. The lower and higher harmonic number of $f_{0,set}$ in the bandwidth are $n_1 = 810$ and $n_2 = 1619$ respectively. As an example, the response at midband is shown in Fig. 6.

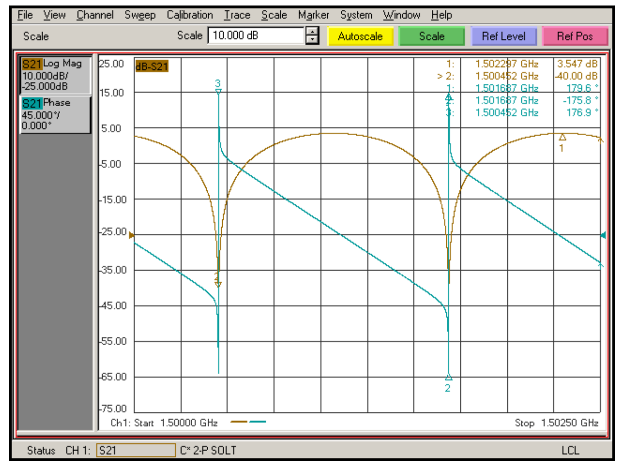

Figure 6: Measured response of the notch filter close to 2 notches at midband (1.5 GHz). The notch distance is 1.235 MHz. Because of the finite notch depth, the phase jump at each notch was less (177 °) than the 180 ° expected in the ideal case. The variable attenuator was set at 0.99 dB. (Due to temperature dependence of the setup later measurements vary in attenuation.)

In Fig. 7 the envelope (bottom line) of the measured amplitude $|S_{21}|$ at all in-band minima of the transfer function is displayed. In comparison, the envelope of $|S_{21}|$ at all in-band maxima (top line) represents the insertion loss mainly caused by the components in the long branch of the notch filter. It was found to be practically constant close to 3.5 dB within the whole band. All in-band notches have a depth $|S_{21}|_{\min} - |S_{21}|_{\max}$ lower than -30 dB. A vector network analyser and an automated test setup were used for these measurements (see [3] for details).

In order to quantify the periodicity error in the band, a linear regression fit was applied to the measured frequencies f_n (position of notches) for all harmonics n within the bandwidth: $f_n = f(n) = f_0 \times n + b$ = (1.234832 MHz) ×n-35.7 kHz. The slope f_0 represents a mean notch distance within the band. Because of the non-linearity it is slightly different than the setup notch distance $f_{0,set}$ given above. In the storage ring, the beam will be ultimately cooled by the notch filter to the revolution frequency f_0. So, optimally, f_0 has to be tuned at the beginning to the nominal revolution frequency of the beam. The ordinate intercept point b expresses the mean periodicity error. The difference between the measured notch positions f_n of the notch filter transfer function and the ascending linear regression line nf_0 , scaled to the harmonic number n of the notches in the

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pass band represents an absolute periodic frequency error $\Delta f = (f_n - nf_0)/n$ (Fig. 8).

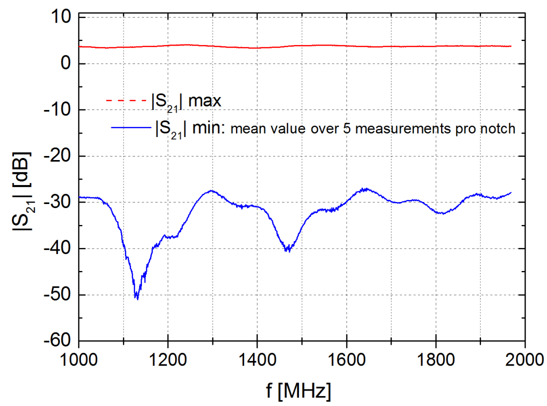

Figure 7: Envelopes of max. and min. $|S_{21}|$ for all notches in the bandwidth 1-2 GHz.

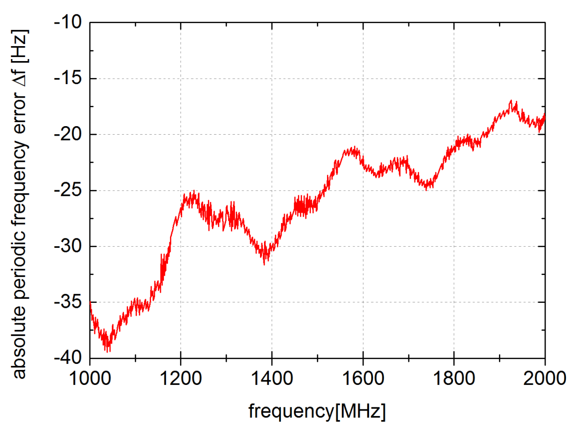

Figure 8: Absolute periodicity error for all notches in the bandwidth 1-2 GHz. The relative periodicity error $\alpha = |\Delta f|/f_0$ within the full band 1-2 GHz was always below 32 ppm.

PICKUP MODULE CONTROLLER

A pickup module controller is implemented, to control the slotline electrode arrays along the beam in the pickup tanks of the CR stochastic cooling system [4]. Four pickup module controllers are needed, 2 for the horizontal pickup tank (left/ right arrays of 64 slots in total) and 2 for the vertical pickup tank (top/ bottom arrays of 64 slots in total).

The pickup module controller consists of a power supply unit, a microcontroller unit, 8 channel controller cards, a 4-channel temperature measurement card and an RF input card. The switching power supply converts 230 V AC to 50 V/ 600 W and 18 V/100 W and in a second stage to 5 V digital and 8 V analog supply voltage. The analog supply voltage is reduced to 5 V by a linear controller at each specific analog card to reduce supply noise. The 50 V supply provides the 50 W power for each of the eight channel controller cards to heat up the module for vacuum purposes. It could be switched off to avoid distortion during beam time. The channel controller cards feed the amplifier boards or the switch boards in the pickup module with −5 V to 15 V respectively by an adjustable switching power supply. Each of these power supplies are fed with 18 V from the power supply unit. All system voltage levels and settings are controlled by the microcontroller unit. The communication between the units is transmitted by I²C Bus or SPI. The temperature of each of the 8 slotline arrays per tank side is monitored by one of the corresponding 8-channel controller cards in a four-wire measurement setup.

For test purposes a RF Signal ($f \in [0.5, 2.5\,\text{GHz}]; P < -10\,\text{dBm}$) from an external signal generator (e.g. of the network analyzer) is fed to the SMA plug at the RF attenuator card of the pickup module controller. The signal can be reduced by a step attenuator. Additional amplification with a driver amplifier is implemented to keep a proper level for the following signal splitter. Via the backplane the signal is split to the channel cards. From the channel cards the RF signal is fed in transmitting antennas in the slotline arrays. The loop is closed by measuring the signal with the pickup slotline arrays and sending it through the diagnostic signal processing chain to the network analyzer.

POWER AMPLIFIERS AT THE KICKERS

The procurement contract for the water cooled 1-2 GHz power amplifiers at the kickers has been awarded. Because of the very demanding antiproton cooling a total cw microwave power of 8 kW (= 32 × 250 W units) is required. This is in combination with stringent requirements on amplitude flatness and phase linearity within the 1-2 GHz band i.e. ≤ 1 dB amplitude response and ≤ 10 ° phase distortion at 10 dB below OP_{-1dB} as well as very short (≤ 4.8 m/16 ns) allowed electrical length for each unit. The preseries unit is under development.

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