THE STOCHASTIC COOLING SYSTEM OF HESR

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Abstract

The HESR is the High Energy Storage Ring (1.5 - 15 GeV/c) for antiprotons at the FAIR facility (Facility for Antiprotons and Ion Research) in Darmstadt (GSI). Stochastic cooling in the HESR is necessary not only during the experiments to fulfill the beam requirements, but also during the accumulation due to the postponed RESR. Extensive simulations and prototype measurements have been carried out to optimize the HESR stochastic-cooling system with the new slot-ring couplers. The system design is now in the final construction phase for the mechanical tank layout and all active RF-components. First results of the optical notch-filter with automated frequency control and the 4-6 GHz slot-ring couplers will be presented.

Stochastic cooling tanks

The main system of the HESR [1] stochastic cooling (SC) system [2] will operate in the frequency range from 2-4 GHz. In total, 5 SC-tanks will be installed, each tank housing 64 slot coupler rings and each ring is coupled out by eight electrodes [3]. Two tanks will be used as pickups, each cryogenically cooled by two cold heads on top of the tank. Support bars and rings connect the combiner-boards with the second stage of the cryo-pumps. Thus the lowest temperature of about 20 K will be found at the Wilkinson resistors which are the main noise sources.

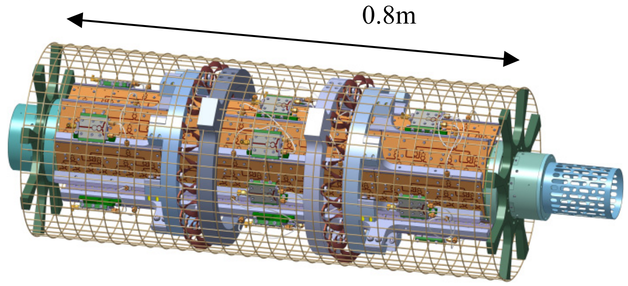

Fig. 1: Inner part of one pickup tank with combiner-boards and support bars for the cryogenic connections.

Each pickup will be used to detect the signals of all three cooling planes (horizontal, vertical and longitudinal). The 16:1 combiners join the electrodes in beam direction, while the 2:1 combiners join neighboring electrode-rows to get the upper, lower, right and left signals for the transverse cooling. These combiners are designed as heat trap for the heat flow coming from the RF lines. The inner part of one pickup tank including all combiner-boards is shown in Fig.1. The design phase of the pickup tanks including the x-y support to adjust the inner structure according to the beam centre is now in the final stage and production can start in 2012.

The kicker-tank layout will be similar to the pickup-tank layout except that no cryogenic cooling system will be installed and the electrode combination within the tank and thus the number of feed troughs will be adjusted according to the RF power needed for the new accumulation scheme [4, 5]. Here three tanks will be installed, one for each cooling direction. Nevertheless all tanks will be fully installed to ensure that each tank can be used for any cooling plane. This gives a good compromise to meet the necessary phase advance at the different foreseen optics. During the accumulation all tanks will be used for longitudinal cooling, where a higher RF power is needed. A relay-matrix will be used to switch between the different operation modes. This concept provides an installed RF power of about 250 W for each transverse cooling direction (horizontal/vertical) at each tank, or 500 W per tank when used for longitudinal cooling.

RF components outside the tanks

The combined power of the pairs of 16 electrodes in beam direction are coaxially fed through the vacuum envelope and put in 32 low-noise octave-band pre-amplifiers. These commercial available amplifiers will gain around 20 dB and will work outside the tank at ambient temperature. The compact design of this highly integrated amplifier minimized the fabrication tolerances. Nevertheless each amplifier will be measured and paired to reduce amplitude and phase errors of the corresponding channels. The 16:1 combiner has been optimized for a best signal combination at injection energy (ß = 0.96). Combiner losses at higher energies are negligible while at the lowest HESR energy a loss of 2.5 dB is still tolerable (Fig. 2).

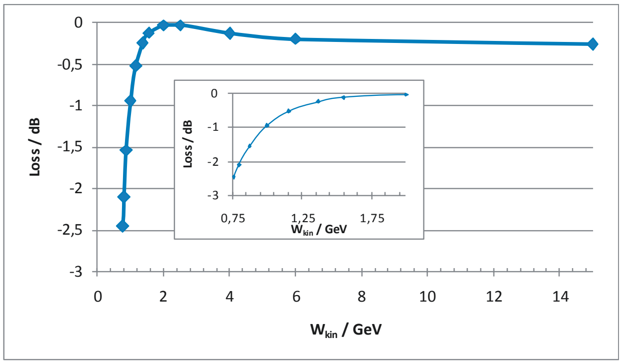

Fig. 2: Losses of the 16:1 combiner at different energies. The shown losses are upper limits occurring at 4 GHz.

The pre-amplified signals will be combined in further 3 layers (Fig. 3). Hereby, switchable delay lines are required to compensate for the energy-dependent beam drift time. The delay lines will be switched in steps of 10 mm of electrical length at the first layer (PV1) and 20 mm at the further layers (PV2, PV4). Each programmable delay-line includes a Wilkinson coupler which combines the two input signals after the switching stage. A deviation of 10 mm from the ideal length leads to a phase difference between the Wilkinson inputs that causes at 4 GHz an additional attenuation of nearly 0.8 dB. The last Wilkinson layer adds the power of both adjoining tanks. This allows stochastic cooling in the whole energy range of the HESR (0.8 - 14 GeV). To minimize the number of switches, the reference plane is shifted at different energies but this can be easily compensated by adjusting the delay-line between pickup and kicker. Prototypes of each delay line were built and tested and fulfilled all RF requirements.

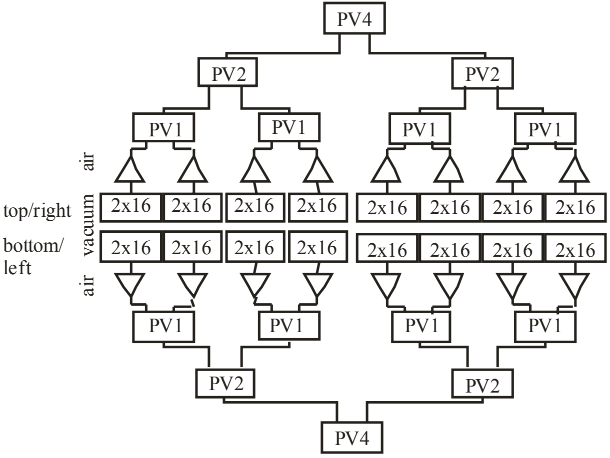

Fig. 3: Pickup section with programmable delay-lines (PV) to provide stochastic cooling in the whole energy range of the HESR (lengths are not to scale).

One important element in the active cooling chain are the high power amplifiers. Power amplifiers in the 2-4 GHz range are nowadays commercially available. But the specific requirements concerning group-delay and phase behavior demands a dedicated design. In collaboration with IMST [6] a first prototype of a 25 W amplifier was built. All requirements have been nearly reached but the modular design with separately housed stages showed some restrictions. The final version will have a compact one-board design with separated caves for each GaN transistor similar to the design of the delay lines.

4-6 GHz System

Besides the main 2-4 GHz system, an additional 4-6 GHz system is planned which is needed to reach the desired momentum spread in the high resolution mode at higher energies. This system will be used for longitudinal cooling only. The higher frequencies required at least 12 electrodes instead of 8. 12 Combiner-boards around the structure are no longer mountable. Thus the circuitry of the electrodes has been changed that 2 electrodes will already be combined within the structure. The combination of the rings is similar to the 2-4 GHz design. Each structure is closed by the next ring which gives the ground plane of the microstrip electrodes. Special mechanical tolerances guarantee the desired connections of the rings.

Simulations have shown that the longitudinal coupling impedance of the 4-6 GHz structure is much lower than that of the 2-4 GHz one [7]. While the 2-4 GHz structure has a shunt impedance of $Z_k \approx 36\ \Omega$ constant over the whole frequency band, the impedance of the 4-6 GHz structure decreases from about $Z_k \approx 27\ \Omega$ at 4 GHz down to $Z_k \approx 6.5\ \Omega$ at 6 GHz.

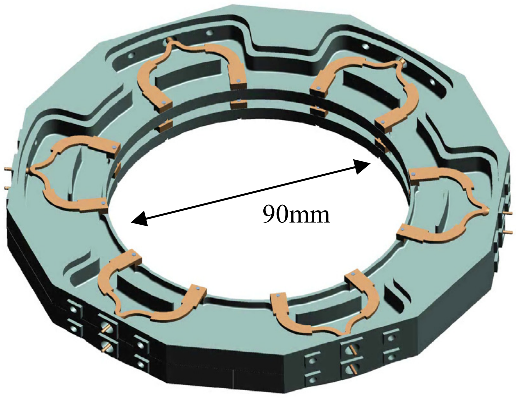

Fig. 4: Two slot coupler rings with combined electrodes for the 4-6 GHz longitudinal cooling.

A part is compensated by the smaller dimension in beam direction. 80 rings instead of 64 in the 2-4 GHz system can be installed in the same tank. The lower sensitivity is tolerable because only longitudinal cooling in the 4-6 GHz range is needed [5]. The first measurements show great resonances above 4.8 GHz. The strongest one can be interpreted as an E31 mode in a corrugated wave guide along the beam direction. This sextupole mode especially interacts with the sixfold electrode structure and degenerates the coupling impedance. We got a partial improvement of the signal transmission by shifting the resonances with metal pieces introduced into the ring slots. The combiner boards contain further error sources. We have chosen to use a substrate with a lower permittivity ($\varepsilon_r = 6$) in order to get the nearly the same dimensions of the circuit elements as at the proven 2-4 GHz band ($\varepsilon_r = 9.2$). But the signals are less guided and show parasitic ways introducing phase errors. Therefore, we are going to redesign the combiner boards.

Optical Notch-Filter with active frequency control

The principle of the notch filter for the HESR is shown in Fig. 6. Similarly to the COSY design [8], both signal paths will operate in the optical range. This eliminates phase noise and amplitude variation from the laser. The fluctuations of each notch frequency over the time must be within 0.5 Hz. The main source for such changes is the high temperature sensitivity of the fibre-optic delay line. An active temperature control of the coil can only minimize the temperature dependence, but not additional sources and is limited by the achievable precision of the temperature control. That's the reason why for the HESR the following control system has been chosen (Fig. 6):

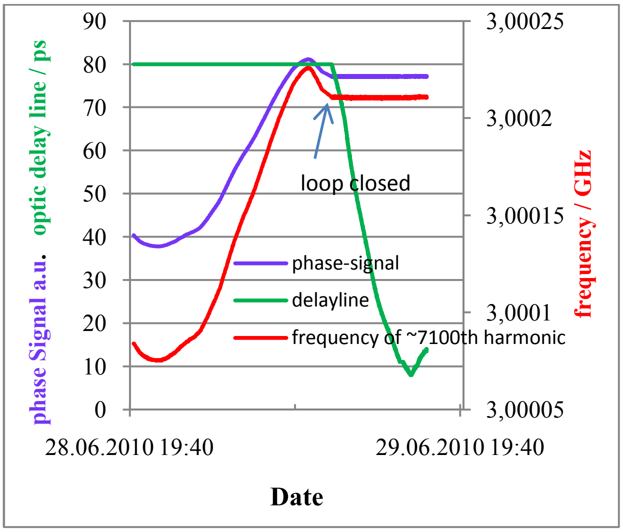

Fig. 5: Frequency change (red) of the 7100th harmonic of the first HESR notch-filter during one night (left part) and after closing the control loop.

Besides the signal from the pickup (In), a fixed frequency pilot signal will be added and transmitted through both optical paths. Directional couplers after the photo-detectors take band-pass-filtered parts of the transmitted signals to a phase detector. Any differences between the lengths of the two signal paths and thus any change of the notch frequencies will be detected by the phase detector. The controller closes this active loop by driving the fibre optic delay line according to the phase change of the pilot signal.

The drift of the 7100th notch frequency over one night is shown in the left part of Fig. 5. This corresponds to a change of the fundamental notch frequency of 25 Hz during the night. This relates to a deviation of 5E-5, which is far too high for the required cooling. At 8:30 in the morning, the phase loop was closed and the frequency-change due to the day's warming up was completely compensated by the phase loop.

The length of the optic delay line (green curve in Fig.5) was changed by about 70 ps (= 21 mm electrical length) during the day. The setting range of the used delay line is 560ps, thus one delay line gives enough margin for a full compensation. The amplitudes of both optical paths and thus the stability of the notch-depths are automatically controlled by the new optical attenuators. The included power measurements in these attenuators allow a fast control of the amplitudes.

A similar system can be used to control the optical fibre link from pickup to kicker either by sending a portion back via an additional fibre line or by using the BuTis (bunch phase timing) system to generate a phase stable pilot signal at the kicker side.

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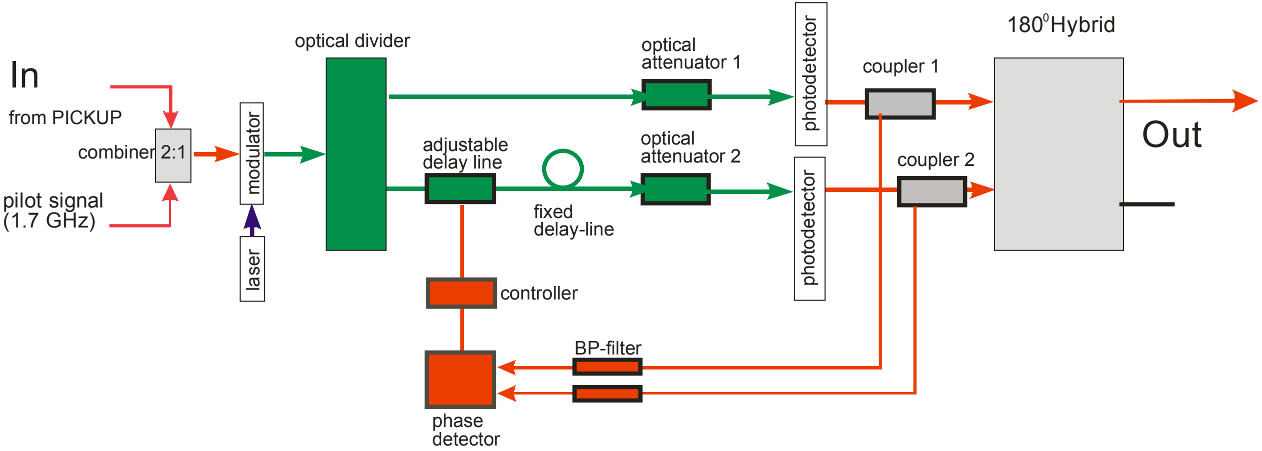

Fig. 6: Optical notch filter with active frequency control