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THE HESR STOCHASTIC COOLING SYSTEM, DESIGN, CONSTRUCTION AND TEST EXPERIMENTS IN COSY

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Abstract

The construction phase of the stochastic cooling tanks for the HESR has started. Meanwhile two pickups (PU) and one kicker (KI) are fabricated. One PU and one KI are installed into the COSY ring for testing the new stochastic cooling system with real beam at various momenta. Small test-structures were already successfully operated at the Nuclotron in Dubna for longitudinal filter cooling, but not for transverse cooling and as small PU in COSY. During the last COSY beam-time in 2017 additional transverse and ToF cooling were achieved. The first two series high power amplifiers were used for cooling and to test the temperature behaviour of the combinerboards at the KI. The system layout includes all components as planned for the HESR like low noise amplifier, switchable delay-lines and optical notch-filter. The HESR needs fast transmission-lines between PU and KI. Beside air-filled coax-lines, optical hollow fiber-lines are very attractive. First results with such a fiber used for the transverse signal path will be presented.

STOCHASTIC COOLING SYSTEM OF HESR

Stochastic cooling at HESR is not only used to reduce beam size and momentum spread during the experiment, but also to accumulate antiprotons due to the postponed Recuperated Experimental Storage Ring (RESR) [1, 2] of the modularized start version of the FAIR project.

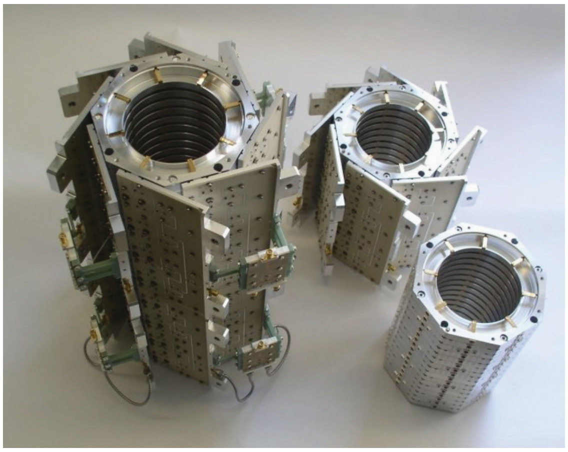

Figure 1: Stacks of slot ring couplers with and without 16:1 combiner-boards and two stacks mounted together including 2:1 combiner with heat-trap.

The system is based on dedicated structures. Each beam-surrounding slot of these so called slot-ring couplers covers the whole image current without a reduction of the HESR aperture [3]. Each resonant ring structure is heavily loaded with eight 50 Ω electrodes for a broadband operation. The rings are screwed together to a selfsupporting structure in stacks of 16 rings. Four of these stacks will build the spindle for one tank. Figure 1 shows these stacks; one without combiner one with combinerboard and a combination of two stacks including additional 2:1 combiner especially designed to minimize the heat flow to the 16:1 combiners. Meanwhile a new structure has been designed for a special cooling system operating in the frequency range 350 – 700 MHz [4].

Beside the main 2 – 4 GHz system a 4 – 6 GHz system was planned for additional longitudinal cooling. This system will be substituted by an additional 2 – 4 GHz system with modified combiner-boards to cool heavy ions at lower energies [5].

The first HESR series pickup was installed into COSY during the winter-shutdown 2015/2016 and is used to measure routinely Schottky spectra for several experiments. Two cryo-pumps are installed to cool down the pickup and increase the signal to noise ratio. The inner structure of the pickup was cooled down to less than 20 K within 10 h and although the tank is not bakeable, the vacuum reached already $5 * 10^{-10}$ mbar. During the summer shutdown 2016 the first HESR kicker tank was installed in COSY at the position of the old vertical kicker.

First commissioning started in February 2017 after installing the new notch-filter, measurement system and prototype of the GaN power amplifiers.

The automated frequency adjustment of the notch-filter was successfully tested and takes less than a minute for frequency and gain - whereas with the old system the typical setup time was in the order of one hour. The program determines also the frequency error for each notch with respect to the fundamental frequency. The fluctuations of the Notch-frequency were within ±10 Hz taking into account the harmonic number. This is pretty small and does not influence the cooling time and power, but can still increase the equilibrium momentum spread due to the small eta-value in the HESR. These fluctuations are dominated by the transimpedance amplifiers in the optical receivers and can be further reduced by pairing the receivers.

The algorithms for automatic open-loop measurements and system delay adjustment were also successfully tested and refined. The open-loop measurements now can be carried out for the full bandwidth within single sweep or by

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separate measurements of each harmonic. The latter had a problem of random phase jumps near ±180°, which made it impossible to calculate phase in the center of the harmonic. The problem was solved with the fairly simple trick: for each harmonic the algorithm iteratively finds (by minimizing the standard deviation) the artificial delay that would shift the phase to zero, then it calculates the phase and restores the phase to its original value [6].

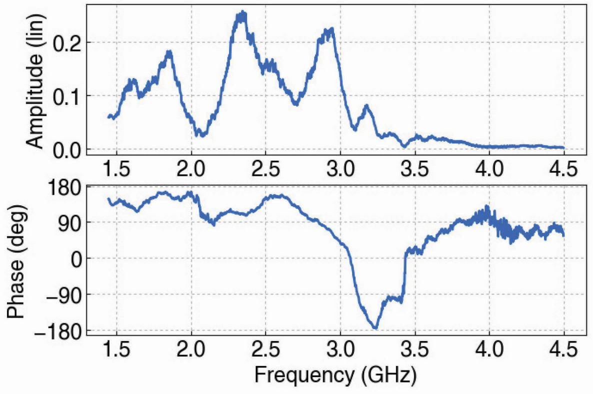

Figure 2: Amplitude (top) and phase (bottom) of system's hardware transfer function.

A lot of open-loop measurements were performed during first commissioning. The relative hardware transfer function from PU to K - derived from these open-loop measurements – is plotted in Fig. 2. Regions with high amplitude and good phase behaviour alternate with good phase and smaller gain and above 3 GHz with strong phase change and very low amplitude. The reason for this strange behaviour was found in a wrong orientation of the kicker with respect to the beam direction. Simulations of a rotated structure with CST Microwave Studio [7] have shown a similar behaviour.

Nevertheless first longitudinal cooling has been carried out using the ToF [8] cooling method and filter cooling (Fig. 3). The beam was initial heated and the particle numbers was about N = $1*10^9$. Figure 3 shows one longitudinal Schottky spectrum at about 3 GHz (blue: before cooling, green: after several minutes of cooling).

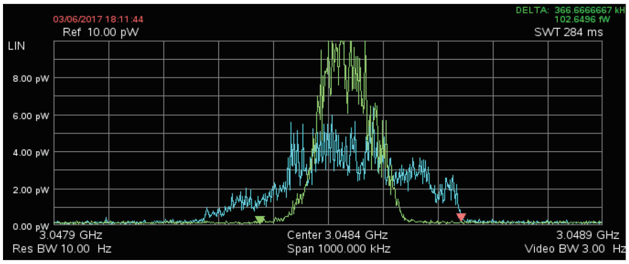

Figure 3: Longitudinal cooling with Filter method, blue: initial heated beam before cooling, green: after cooling.

The 180° phase shift between ToF and filter cooling was realized by adding a delay of 130 ps instead of an additional 180° phase shifter. Due to the small amplitude above 3 GHz the cooling works like a system with reduced bandwidth. Cooling simulations show similar cooling times when the measured hardware transfer function is included into the simulations. The kicker tank has a symmetric layout and was easily rotated in the next shutdown. Figure 4 shows an open-loop measurement of the rotated tank. The plot shows the results for one group (group D) separated for both directions in sum-mode. Old Schottky measurements of the pickup tank have already shown that the maximum sensitivity is not at 3 GHz - as simulated with HFSS [9] - but at 2 GHz. Nevertheless the sensitivity in the whole frequency range is high enough for good cooling results. The constant decrease in the desired frequency range can be compensated by simple filter in a later stage.

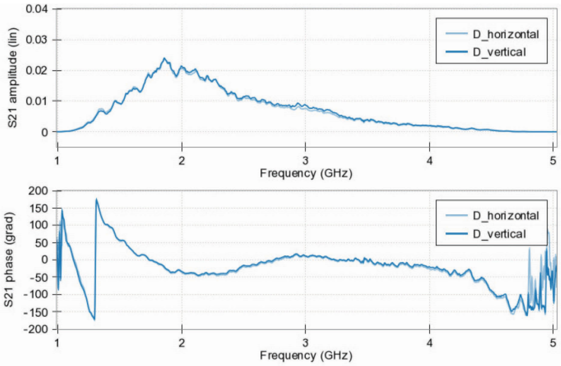

Figure 4: Open loop measurement with rotated kicker.

During the last beam-time in August 2017 a lot of different cooling experiments have been done with protons at a momentum of 2.425 GeV/c. The standard optic with zero dispersion in the straight sections was used. This gives an eta value of $\eta = -0.07$. This setting is comparable to the HESR working point taking into account the higher revolution frequency at COSY.

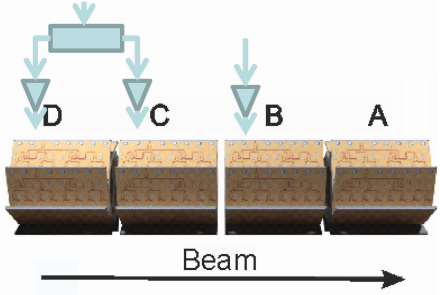

Figure 5: Kicker setup during last commissioning.

Two different signal paths were used. Group B with one high power amplifier was used for longitudinal cooling, while group D and C (each with one amplifier) combined with adjustable delay-lines were used to cool the beam in one transverse direction (Fig. 5).

LONGITUDINAL COOLING WITH DIFFERENT PARTICLE NUMBERS

After reassembling the modified notch-filter and measurement system first open-loop measurements were carried out using modified programs for a fast setup of notch frequency and system delay. Within several hours notch-frequency and system delay were adjusted using optical delay-lines. Even without phase-shifter to adjust the optimum phase, cooling was immediately visible after closing the loop. The momentum spread was reduced by a factor of 3 within about 2.3 min and $7*10^9$ particles (Fig. 6a) even without optimizing the gain. Figure 6b shows the longitudinal cooling of $2*10^8$ particles with the same setting of delay and gain. The cooling is only slightly faster than with $7*10^9$ particles, but the equilibrium is significantly smaller.

In both cases we can see instabilities in the cooled beam but without beam losses. The slight fast momentum change of some particles will be cooled again by the longitudinal cooling. It's the strongest stochastic cooling in COSY ever seen, although the system is not optimized. The use of one group with one amplifier limits the power and additional heating from Schottky noise outside the band was not reduced by additional filters.

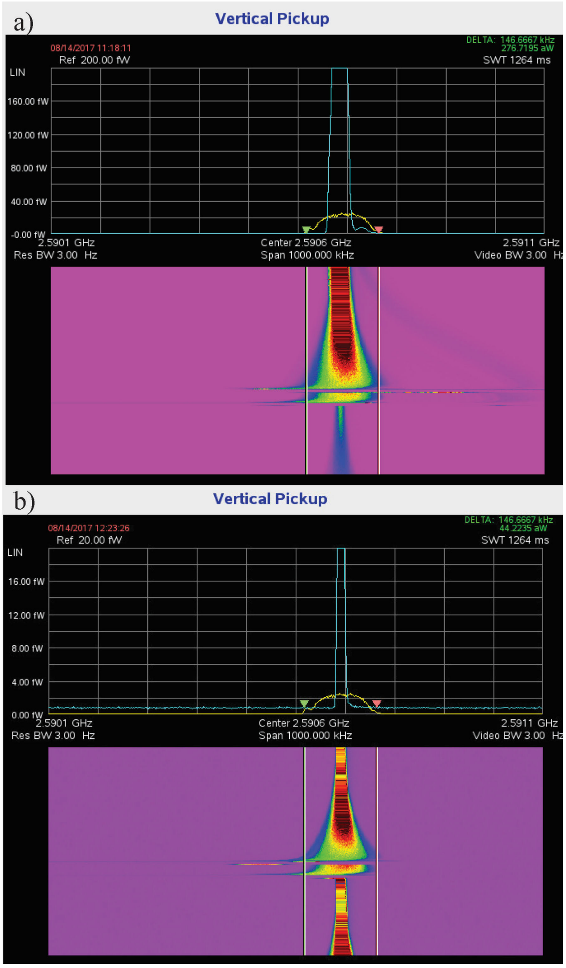

Figure 6: Longitudinal cooling of $7*10^9$ (a) and $2*10^8$ particles (b).

Even ToF [7] cooling was demonstrated after switching off the notch-filter and removing 150 ps delay to substitute the missing 180° phase shift.

FIRST TRANSVERSE COOLING

Longitudinal cooling with this structure was already demonstrated 2013 at the Nuclotron in Dubna [10], but so far no transvers cooling. First transverse cooling was achieved by switching the hybrids of the first signal path from sum-mode to difference-mode.

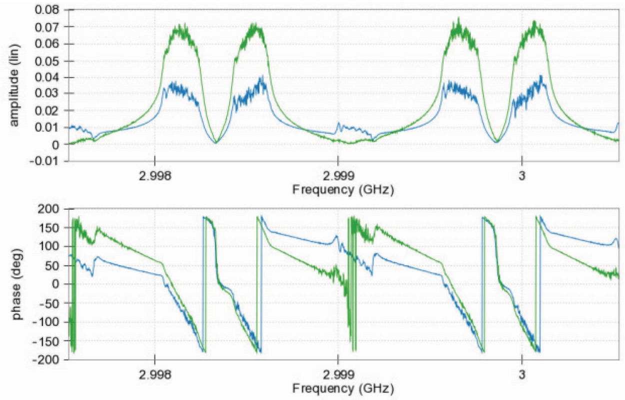

Figure 7: First transverse open loop measurement with and without notch-filter.

The sidebands are clearly visible in the open loop measurement (Fig. 7) with and without notch-filter. The notch-filter here helps to eliminate the unwanted longitudinal part – which is always there, even when the beam is centred – and reduce partly the Schottky noise. Only a few system delay corrections were needed to achieve horizontal cooling.

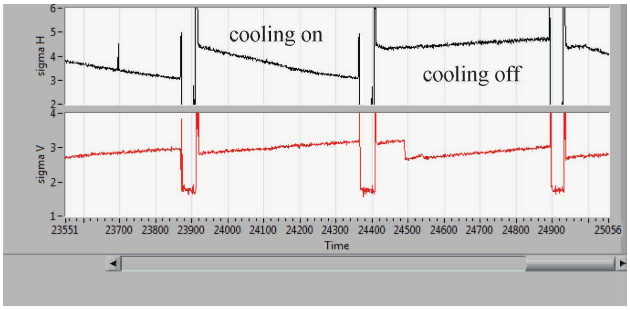

Figure 8: Profile measurements of horizontal cooled beam.

Profile measurements with the ion profile monitor (IPM [11]) verified the transverse cooling during the 5 minutes cycles (Fig. 8). Without cooling the beam is slightly heated by rest-gas scattering.

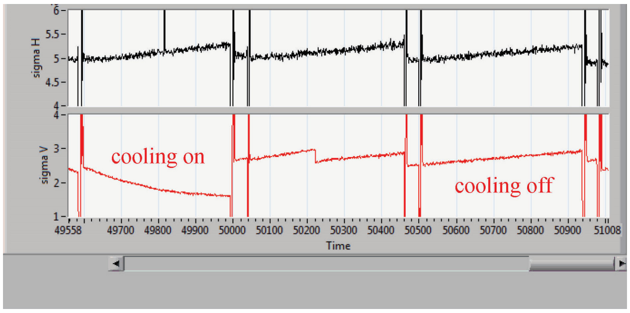

Figure 9: Profile measurement of vertical cooled beam.

Figure 9 represents the other direction by switching manually from the horizontal into the vertical plane. A similar transvers cooling was measured without influence to the other plane.

SECOND SIGNAL PATH WITH HOLLOW FIBER LINE

Optical fiber lines are very attractive to transmit broadband RF-signals over a wide distance. They are easy to install, have low attenuation and zero dispersion. But standard fibers have some disadvantages: The signal speed is only about 60% of speed of light and these lines have a high temperature-gradient. An alternative are hollow fiber lines, where the light is guided in a hollow core which is surrounded by a microstructured cladding [12]. 50 m of such a line was installed as transmission-line between pickup and kicker. The line acts very sensitive against movements, but once installed a stable operation was possible.

This second path was used for transverse cooling of the vertical plane. One original switchable delay-line – especially designed for the HESR including divider – was used to feed two amplifiers for two groups.

Single measurements of signal suppression at each of the two groups have shown that the delay difference between the groups is not optimized, but both groups show cooling.

Different gain settings were used to find the best cooling rate. Higher gains decreased the cooling rate (Fig. 10), but the equilibrium will be higher. Thus a gain control during cooling is useful and will be installed for the next beam time.

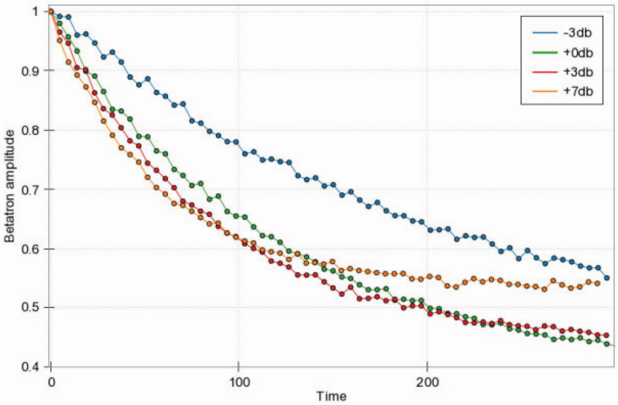

Figure 10: Vertical cooling with different gain settings.

With the second path it was possible to cool the beam in the longitudinal and vertical plane simultaneously. Figure 11 represents the difference signal of the vertical plane during cooling (blue curve: before cooling, yellow curve: after 5 min of cooling). The longitudinal parts demonstrate the longitudinal cooling with system one. Without transverse cooling the betatron sidebands would increase as well, but due to the vertical cooling with the second system the amplitudes decreased. Thus, first 2d cooling (longitudinal and vertical) was achieved although not all groups of the kicker were used.

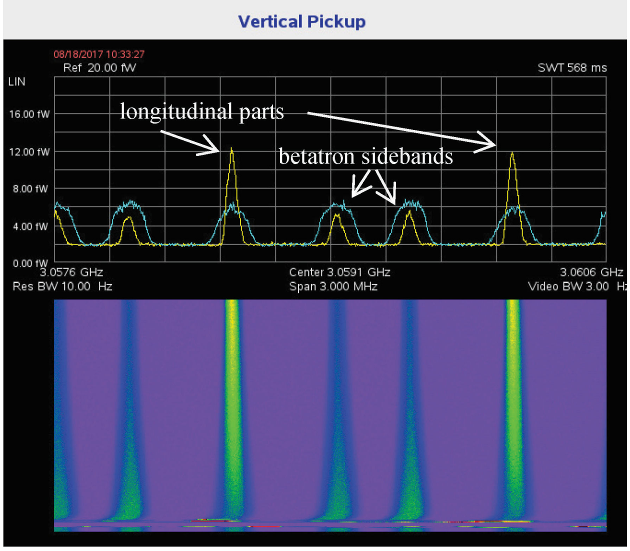

Figure 11: Difference signal of vertical plane.

Most of the power from the GaN amplifiers is dissipated in the Wilkinson resistors of the combiner-boards located inside the vacuum tank. Each combiner-board is connected to a fixed water-cooled pipe by thick copper ribbons. During the 2d cooling with three amplifiers the temperature at the combiner-boards rises only about 1-2°C. Thus the passive thermal cooling of the combinerboards is sufficient.

During the last hours of the beam-time a new measurement scheme was tested (see Fig. 12). The notch filter can be measured as well as an open loop measurement of the whole system. Most attractive is the possibility to perform measurements during cooling. Notch filter frequency and system delay can be checked without great influence of the cooling.

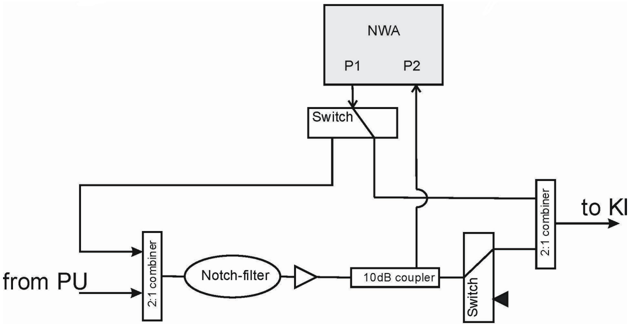

Figure 12: New measurement setup.

SUMMARY

One pick-up and one kicker of the HESR stochastic cooling system can now be tested under real beam condition. Besides longitudinal cooling with filter and ToF method, transverse cooling in both directions has been achieved. A hollow fiber line as transmission line between pick-up and kicker was successfully used for the first time.

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OUTLOOK

The production of the high power amplifiers is ongoing with 2 amplifiers per month. We expect a full equipped kicker with eight amplifiers end of this year. First tests of a full 3d stochastic cooling with HESR pick-up and kicker can start beginning of 2018.

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