STOCHASTIC COOLING OF HEAVY IONS IN THE HESR

R. Stassen, B. Breitkreutz, G. Schug, H. Stockhorst, Forschungszentrum Jülich, Germany

Abstract

Due to the Modularized Start Version (MSV) of the FAIR project with the postponed New Experimental Storage Ring (NESR), the High Energy Storage Ring (HESR) became very attractive for experiments with heavy ions. Although the HESR is optimized for the storage of antiprotons it is also well suited for heavy ion beams with slight changes in the optics. Within the MSV only stochastic cooling and no electron cooling will be available, but even the main 2 - 4 GHz stochastic cooling system will be capable to fulfil the beam requirements for heavy ions. Most critical parts of the active elements are the high power amplifiers. The stochastic cooling amplifiers for the HESR will be based on new GaN devices. Nonlinearities of these devices necessitate a dedicated analysis of the use in stochastic cooling systems.

STOCHASTIC COOLING SYSTEM OF HESR

The stochastic cooling system of the HESR is based on completely new structures especially designed for the HESR [1]. Each beam surrounding slot of these so called slot-ring couplers covers the whole image current without a reduction of the HESR aperture. Each resonant ring structure is heavily loaded with eight 50 Ω electrodes for a broadband operation. The single rings are screwed together to a self-supporting structure in stacks of 16 rings. Four of these stacks will build the spindle for one tank.

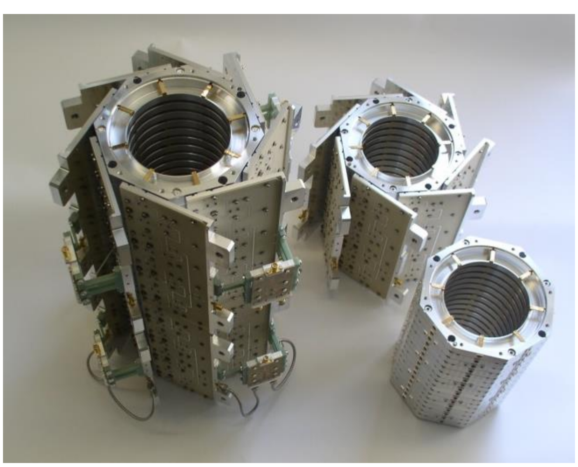

Figure 1: Stacks of slot ring couplers with and without 16:1 combiner-boards and two stacks mounted together including 2:1 combiner with heat-trap.

These structures have the great advantage that they can be simultaneously used in all three cooling planes (horizontal, vertical and longitudinal) just by skilful combining the signals of the electrodes. Another advantage in the case of the HESR is the fact that no movable parts in the vacuum are needed to obtain a good signal to noise ratio. The basic parameters of the main stochastic cooling system are summarized in table 1.

Table 1: Basic Parameters of Main System

Main system	**Based on slot-ring couplers**	
Bandwidth	2 - 4	GHz
Cooling methods	transverse, longitudinal filter cooling, longitudinal ToF cooling	
β-range	0.83-0.99	
Pickup:	**2**	**tanks**
No. of rings /tank	64	
Shunt impedance Z_{pu} / ring	9	Ohm
Total impedance	1152	Ohm
Structure temp.	30	K
Kicker	**3**	**tanks**
	2 tanks for transverse **or** longitudinal cooling, 1 tank longitudinal cooling only	
No. of rings /tank	64	
Shunt impedance Z_k / ring	36	Ohm
Impedance /tank	2304	Ohm
Installed power/tank	640 (longitudinal cooling) 320 (transverse cooling)	W W

Beside extensive test as pickup in the Cooler Synchrotron COSY Jülich [2] one small pickup and one kicker each equipped with 16 rings were installed into the Nuclotron in Dubna. This experimental stochastic cooling setup was initiated as a preparatory work for the NICA collider [3, 4]. During a few runs in 2013 and 2014 the system was commissioned and D^+ and C^{6+} beams were successful longitudinal cooled [5].

Cooling of Heavy Ions using Existing Design

The HESR stochastic cooling system was designed to cool pbars in the whole momentum range of the HESR lasting from 1.5 GeV/c to 15 GeV/c. Two operation modes have been analysed: first, the High-Resolution mode (HR) with 10^{10} pbars and a momentum spread of $\Delta p/p \approx 5\times10^{-5}$ and second, the High-Luminosity mode (HL) with 10^{11} pbars and a momentum spread of Δp/p

ISBN 978-3-95450-174-8

less than 1×10^{-4}. Due to the MSV with the postponed Recycled Experimental Storage Ring (RESR) a concept of longitudinal beam accumulation with moving barrier buckets and strong longitudinal stochastic filter cooling has been worked out [6,7] and the design of the stochastic cooling slightly changed to achieve the requirements for a pbar accumulation in the HESR of up to 10^{10} particles. A proof-of-principle experiment was done at the GSI in Darmstadt [8].

Extensive simulations carried out in [9] give the following demands concerning Schottky-power and the system gain:

- Accumulation pbars:
  $P \leq 70$ W, $G_a = 130$ dB, $N = 10^{10}$
- Longitudinal cooling @ 3 GeV pbars, (hydrogen-target $N_T = 4\times10^{15}$ /cm²)
  $P \leq 5$ W, $G_a = 110$ dB, $N = 10^{10}$
- Transversal cooling @ 3 GeV pbars
  $P \leq 35$ W, $G_a = 130$ dB, $N = 10^{10}$

Regarding safety margin, cable attenuation and noise peaks the installed power at each tank is sufficient (rule of thumb: factor 5 - 10 between Schottky-power and P_{1db}).

The shielding of the HESR was planned regarding a pbar production rate of 2×10^7 / s. This will limit the numbers of heavy ions in the HESR. The average loss-rate should not exceed 10^6 particles per second. Together with the cycle-length this will limit the number of particles to $N = 10^8$ per cycle. As example fully stripped uranium ions were simulated to define maximum Schottky-power and gain [10]:

- Longitudinal ToF cooling @ 740 MeV/u, $^{238}U^{92+}$ (hydrogen-target $N_T = 4\times10^{15}$ /cm²) $P \leq 13$ W, Ga = 85 dB, $N = 10^8$ (limited due to radiation safety)
- Longitudinal filter cooling @ 2 GeV/u, $^{238}U^{92+}$ (hydrogen-target $N_T = 4\times10^{15}$ /cm²) $P \leq 60$ W, Ga = 108 dB, $N = 10^8$ (limited due to radiation safety)

The power and gain requirements can easily be fulfilled with the designed system without any changes. But all combiner stages limit the useful operation of the stochastic cooling system to a minimum energy. In a first stage 16:1 combiners will add the signals of 16 rings within the vacuum tank. The dependence of the combiner losses from the energy of pbars can be found in Fig. 2 together with a comparison when the smallest group will be changed to 8 rings.

These rigidly combined groups define the lowest possible cooling energy given by the velocity of the species. In the case of the 16:1 combiner the lowest β is 0.83. This corresponds to the injection energy of uranium (740 MeV/u). The lowest energy for pbars will change from 0.7 GeV to 0.38 GeV only by changing the groups to 8 rings each combined within the tank. But this will significantly increase the costs because this measure will double the number of combiner-boards, vacuum feed-troughs and preamplifiers and the additional heat load demands a re-design of pickup-tank and a new power distribution at the kicker.

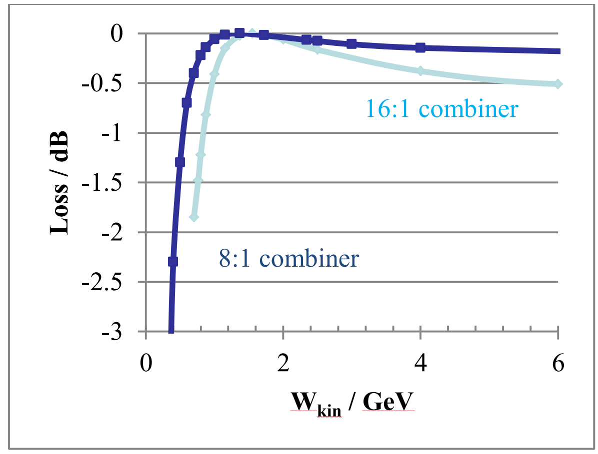

Figure 2: Losses of 16:1 combiner compared to 8:1 combiner.

The signal combination for each cooling plane outside the tanks takes place in 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). The Wilkinson couplers, which combine two input signals after the switching stages, are already included. 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 of pbars in the whole energy range of the HESR (0.8 - 14 GeV).

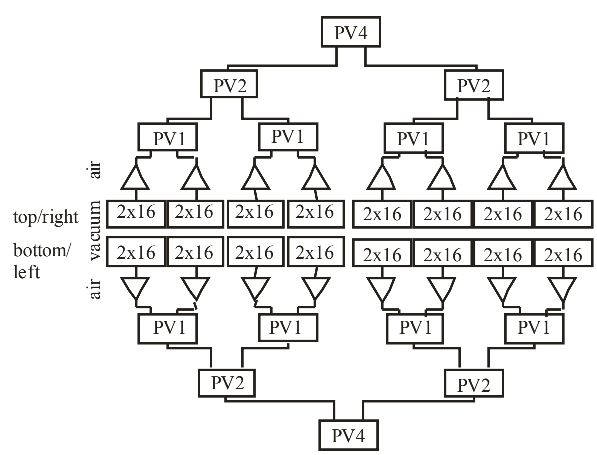

Figure 3: Double tank signal combination; PV1, PV2, PV4 programmable delay lines including Wilkinson couplers for optimum signal combination at different energies.

ISBN 978-3-95450-174-8

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. Further, each signal-path of the delay-lines contains the same number of switches, and has therefore a similar amplitude-frequency characteristic which is compensated in the last stage of delay-lines. The change to 8:1 combiners inside the tank requires the installation of a fourth stage of programmable delay-lines.

The designed stochastic cooling system is already well prepared to cool bare uranium from injection energy 740 MeV/u to maximum energy 5 GeV/u. Cooling of heavy ions at energies lower than the injection energy is only possible with significant change of the whole system design.

One possible solution for stochastic cooling of heavy ions below the injection energy will be to add a system dedicated to lower energies. The signal to noise ratio is proportional to the square of the charge ($S/N \sim Z^2$). Thus the numbers of rings can be significantly reduced. Units of 16 rings seem feasible. Figure 4 shows the combiner losses of a 16:1 combiner-board optimized for uranium at 10 Tm ($\beta = 0.77$) versus the kinetic energy of uranium. Such a small unit is only effective in a kinetic energy-range of about 0.4 GeV/u to nearly 1 GeV/u.

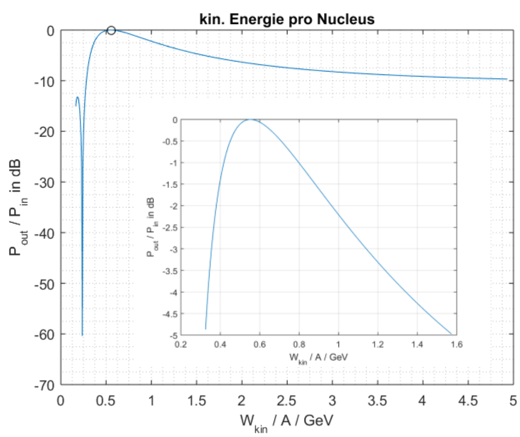

Figure 4: P_{out}/P_{in} of 16:1 combiner optimized for uranium at 10 Tm vs. kinetic energy of uranium.

Stochastic cooling of particles below a velocity of $\beta = 0.69$ is not useful with the designed structure because the decrease of the shunt impedance is too high (see table 2).

Table 2: Change of Shunt Impedance at 2 GHz

β-value	0.99	0.89	0.79	0.69
Z_k / Ω	30	20	11	6

HIGH POWER AMPLIFIERS

One of the most critical parts in the active chain will be the high power amplifiers. Several decades ago GaAs (gallium-arsenide) was the first choice to build high power solid-state amplifiers in the GHz-range. Since some years GaN (gallium-nitride) technology became very attractive not only for expensive military applications [11]. Higher voltages and higher heat-densities allow much higher power with better efficiencies.

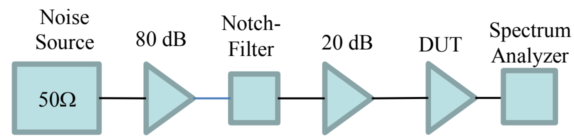

Figure 5: Setup to determine intermodulation products due to non-linearities with the aid of a notch-filter.

Stochastic cooling is mostly dominated by highly amplified noise. Noise-peaks can easily drive amplifiers into saturation. Due to non-linearities intermodulation products (IMD) will always occur even far below the 1 dB compression point (P_{1dB}). Normally, these IMD products are not visible, but with a notch-filter (comb-filter) where the noise is significantly reduced at the notch the IMDs lead to a filling up of the notch-depths. Figure 5 and 6 show a corresponding measurement. Starting with a 50 Ω load as noise-source, two low-noise preamplifiers boost the noise level (blue curve) to -80 dBm. After the notch-filter one can clearly see the noise reduction by the notch (notch-depth: about 35 dB). The insertion loss of the notch-filter can be compensated by an additional medium power amplifier (green curve). After the high-power amplifiers (DUT: device under test) the notch-depths are reduced. The results of one 50 W GaAs amplifier and an 80 W GaN based prototype already optimized for the HESR cooling system are shown.

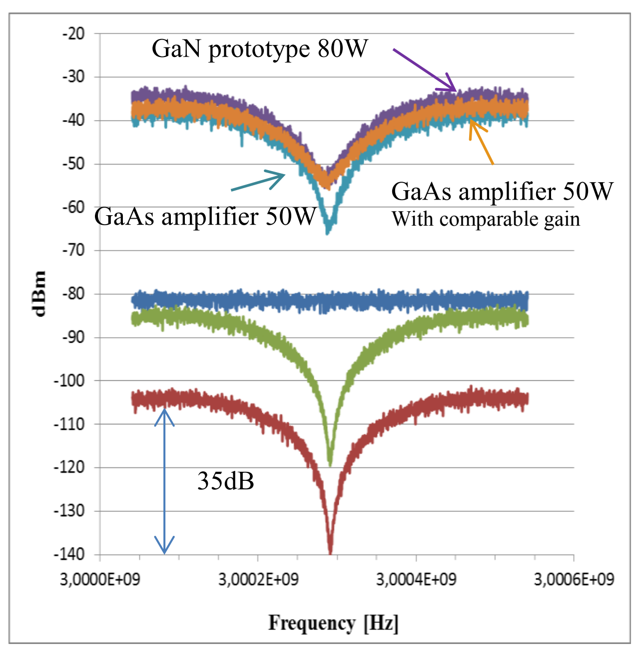

Figure 6: Filling up the notches due to IMDs-products of noise by non-linearities of power-amplifiers.

ISBN 978-3-95450-174-8

In a first view the GaAs amplifier looks better than the GaN prototype. But when the input level was increased to a comparable gain regarding the 1 dB compression point, no great difference could be realized. One has to keep in mind here that the noise level is far away from the 1dB compression point.

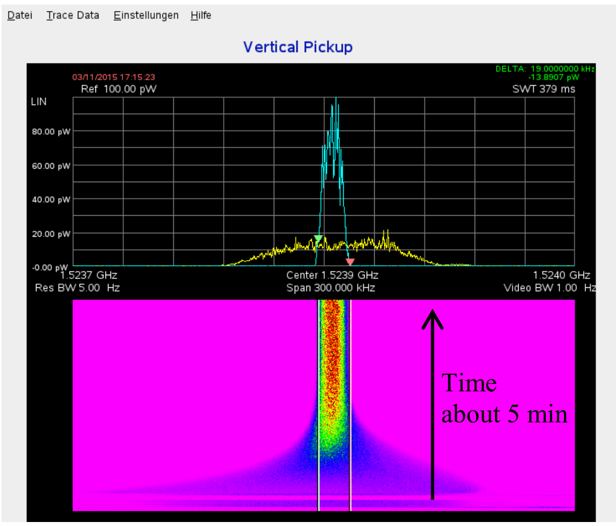

Figure 7: Starting and final beam distribution with a notch-depth of more than 30 dB.

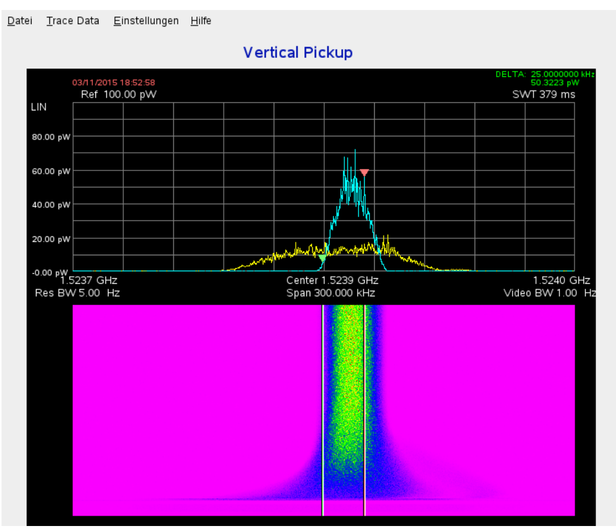

Figure 8: Starting and final beam distribution with a notch-depth of about 15 dB.

High notch-depths are essential for a good stochastic filter cooling. IMD products will create additional noise which acts as an additional heating term to the beam particles. The cooling time and particularly the equilibrium momentum spread will be increased. The existing stochastic cooling system of COSY was used to demonstrate this. The notch-depth of the optical notch-filter can be easily changed. Figure 7 shows the normal longitudinal cooling of $5{\times}10^8$ protons at 2.6 GeV/c with the initial momentum distribution (yellow) and the final distribution (blue). The average notch-depth was in the order of 30 dB and better.

The equilibrium momentum spread was reached after about 200 seconds. After changing the notch-depth to about 15 dB the equilibrium value was doubled (Fig. 8).

The same behaviour can be found in the simulations as demonstrated in Figure 9.

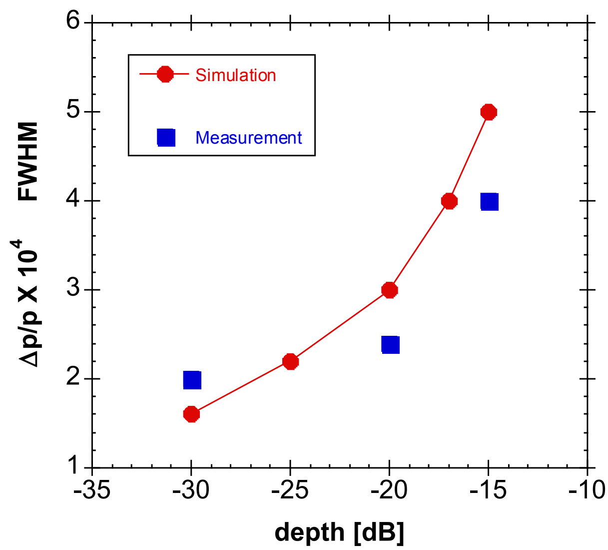

Figure 9: Simulated and measured beam equilibrium as function of different notch-depths.

OUTLOOK

The main stochastic cooling system for the HESR is now in the production phase. To test the performance of the cooling system the first pickup with 64 slot-coupler rings will be installed in COSY during the Christmas shutdown 2015/2016. The first kicker is scheduled to be installed in COSY in the middle of 2016 and commissioning of the whole system is expected at the end of 2016.

REFERENCES

[1] R. Stassen, P. Brittner, R. Greven, H. Singer, H. Stockhorst, L. Thorndahl, “Recent Developments for the HESR Stochastic Cooling System”, Proceedings COOL07, Bad Kreuznach, Germany, 2007

[2] R. Stassen, F.J. Etzkorn, R. Maier, D. Prasuhn, H. Stockhorst, L. Thorndahl, “COSY as Ideal Test Facility for HESR RF and Stochastic Cooling Hardware”, Proceedings PAC09, Vancouver, Canada, 2009

[3] G. Trubnikov et al., “Project of the Nuclotron-based Ion Collider Facility (NICA) at JINR”, Proceedings of EPAC08, Genoa, Italy, 2008

[4] G. Trubnikov, A. Sidorin, N. Shurkhno, “NICA Cooling Program”, Cybernetics and Physics Journal, Vol. 3, No. 3, 2014

ISBN 978-3-95450-174-8

[5] N. Shurkhno et al., "Study for Stochastic Cooling at Nuclotron", JINR, Proceedings of COOL13, Murren, Switzerland, 2013
[6] H. Stockhorst, R. Maier, D. Prasuhn, R. Stassen, "Status of Stochastic Cooling Predictions at the HESR", Proceedings of IPAC11, San Sebastian, Spain, 2011
[7] T. Katayama, T. Kikuchi, R. Maier, I. Meshkov, D. Prasuhn, R. Stassen, M. Steck, H. Stockhorst, "Beam Accumulation with Barrier Voltage and Stochastic Cooling", Proceedings of IPAC10, Kyoto, Japan, 2010
[8] M. Steck et al., "Demonstration of Longitudinal Stacking in the ESR with Stochastic Cooling", Proc. of COOL11, Alushta, 2011
[9] H. Stockhorst, T.Katayama, B. Lorentz, R. Maier, D. Prasuhn, R. Stassen, "Stochastic Beam Cooling in the Storage Rings COSY and the Future HESR with Internal Target Operation", ICFA Beam Dynamics Newsletter No. 64, p121 ff, 2014
[10] H. Stockhorst et al., "Heavy Ion Storage and Acceleration in the HESR with Stochastic Cooling and Internal Target", Proceedings STORI14, St. Goar, Germany, 2014
[11] P. Saad et al., "Design of a Highly Efficient 2-4GHz Octave Bandwidth GaN-HEMT Power Amplifier", IEEE Transactions on Microwave Theory and Techniques, Vol. 58, No7, July 2010

ISBN 978-3-95450-174-8