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A 1–2 GHz STOCHASTIC COOLING SYSTEM FOR ANTIPROTONS AND RARE ISOTOPES

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Abstract

A 1–2 GHz stochastic cooling system is being developed to provide fast 3D cooling of hot secondary beams (antiprotons at 3 GeV and rare isotope ions at 740 MeV/u) at intensities up to 10^8 particles per cycle. For antiproton cooling, cryogenic plunging pick-up electrodes will be used to improve the ratio of Schottky signals to thermal noise. To cool hot rare isotope beams quickly, a two-stage cooling (pre-cooling by the Palmer method and main cooling by the notch-filter method) has been decided. This paper presents the recent R&D highlights of this unique stochastic cooling system especially the main sub-systems i.e. two cryogenic plunging slotline pick-ups, one Palmer pick-up, and two slot-ring kickers.

OVERVIEW

To reduce the transverse emittance ε_t and the momentum spread ($\delta p/p$) of high-energy and high-intensity antiproton ($\bar{p}$) beams and rare isotope beams (RIB), a stochastic cooling system working in the bandwidth of 1–2 GHz is under construction for the Collector Ring (CR) of the future FAIR facility [1-3]. The required performance of the CR stochastic cooling system is listed in Table 1.

Table 1: Required Cooling Performance in the CR

	$\bar{p}$	RIB
Particle number	10^8	10^8
Kinetic energy [MeV/u]	3000	740
$\delta p/p$ (rms) [%] before cooling	0.35	0.2
$\delta p/p$ (rms) [%] after cooling	<0.05	<0.025
ε_t (rms) [mm mrad] before cooling	40	35
ε_t (rms) [mm mrad] after cooling	1.25	0.125
Cooling time [s]	≤ 9.7	≤ 1.4
Cycle time [s]	10	1.5

For $\bar{p}$ cooling, the following special concepts have been adopted to improve the ratio of Schottky signals to thermal noises: 1) to keep the pick-up (PU) electrodes at 30–40 K; 2) to move the electrodes as the beam shrinks; 3) to implement the notch-filter method for the longitudinal cooling for filtering out thermal noises.

For RIB cooling, the undesired mixing between the slot line PUs and kickers limits the momentum acceptance of the notch-filter method, so only the Palmer method with a PU closer to the kickers can be applied at the beginning of the cooling. As soon as $\delta p/p$ is within the acceptance of the notch-filter method, one can switch to the more effective filter cooling. In principle, the TOF (Time of Flight) method using the signals from the slotline PUs can also be applied as the first stage of the cooling, however the TOF cooling is slower.

As shown in Fig. 1, the CR stochastic cooling system mainly consists of the following sub-systems:

- Two cryogenic plunging slotline PUs (one for horizontal and longitudinal cooling; one for vertical and longitudinal cooling).
- One Palmer PU.
- Two slot-ring kickers (one for transverse cooling; one for longitudinal cooling) being developed by Forschungszentrum Jülich (FZJ), Germany.
- The RF signal processing chains between the tanks.

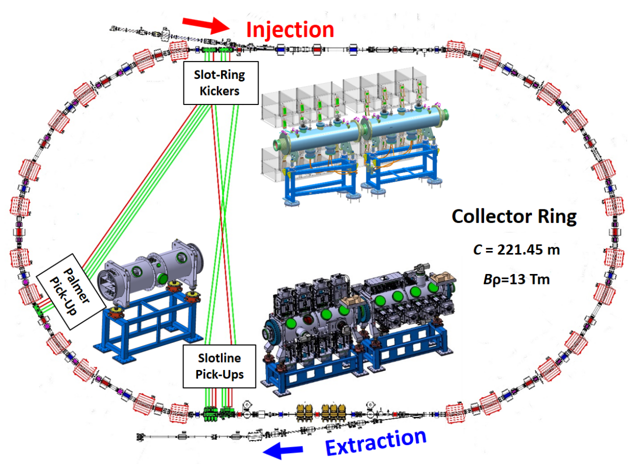

Figure 1: Overview of the CR stochastic cooling system.

CRYOGENIC PLUNGING SLOTLINE PU

After many years of R&D studies, ~90% of components of the cryogenic plunging slotline PUs have been constructed [4, 5]. This section will focus on the recent progress with the key components i.e. the slotline electrodes. Each slotline PU tank contains 2 (sides) × 4 double modules. Each double module has 2 × 8 slotline electrodes.

Figure 2 shows the manufactured prototype of a double module. This design is mainly based on an earlier version which detailed parameters can be found in [6], but with some new concepts to simplify fabrication and to improve frequency response. For example, the 4 large expensive aluminum oxide ceramic boards with low production yield

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have been replaced by 2 smaller combiner boards and 16 small pick-up boards. And some other mechanical changes have been made to avoid parasitic resonances.

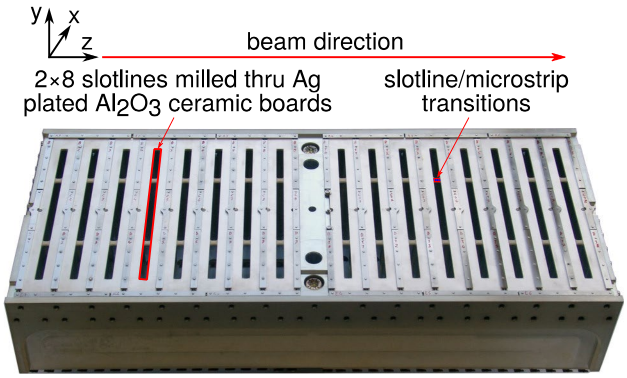

Figure 2: Prototype of the slotline PU double module.

To check the frequency response and field distribution of the prototype, we have made 4D (x, y, z, f) field measurements using a small electrical near-field probe moved by a CNC machine.

Figure 3 shows the voltage U integrated along the beam direction in different heights y above the center of the slotlines as a function of the frequency f. The plotted value is the integral of the transmission from the pick-up to the near-field probe with the design velocity for antiprotons (β = 0.97). The properties of the probe and all cables are calibrated out from the results. The value is proportional to U over the square root of power loss P_v:

$$\frac{U}{\sqrt{P_V}} \propto \int_{-\infty}^{\infty} S_{21} \cdot e^{i\frac{\omega}{\beta \cdot c}} dz \,. \tag{1}$$

And it is also proportional to the square root of the shunt impedance. The voltage at y = 10 mm stays flat within ±1.2 dB and ±9° in the operating band 1–2 GHz. The out-of-band response is also very good. There is no frequency point with high sensitivity and wrong phase nearby the operating band, which can heat up the beam.

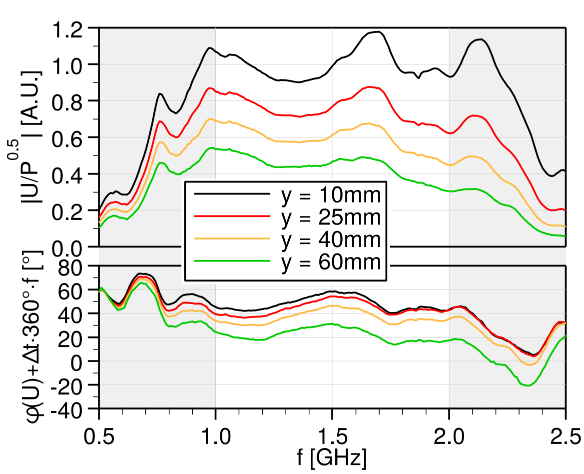

Figure 3: Normalized voltage and phase in different heights versus frequency.

PALMER PU

Using Faltin-type structures for coupling, the Palmer PU serves for the pre-cooling of very hot RIBs. To archive an octave bandwidth, the 4 long rails of the Palmer arrangement are equally divided into upstream and downstream parts. The design parameters of the Palmer PU based on the HFSS FEM field calculation can be found in [7].

The Palmer PU has been built and tested with β = 0.83 proton beams provided by Cooler Synchrotron (COSY) at FZJ in October, 2021. For the beam test, the Palmer tank was equipped with all 8 Faltin rails and the low noise amplifiers (LNAs), but without the subsequent signal processing.

Figure 4 compares the measured longitudinal pick-up shunt impedance of the 4 upstream Faltin rails in circuit convention with the HFSS calculation results, which shows a good agreement. The measured longitudinal shunt impedance $R_{||}$ of the two bottom rails is closer to the HFSS values, while those of the two top rails are slightly higher than the HFSS values. This could be caused by gain drift of the LNAs.

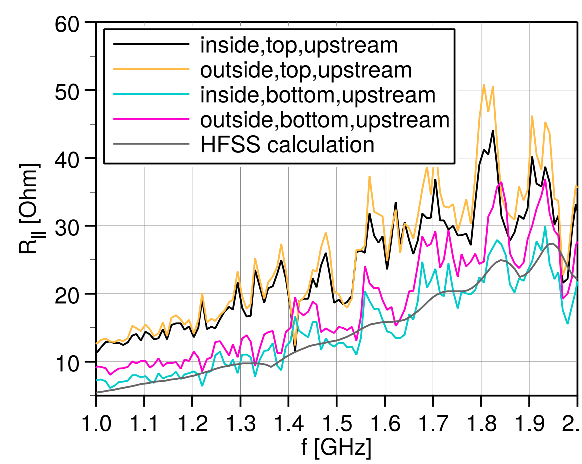

Figure 4: Measured longitudinal shunt impedance.

To archive a higher signal-to-noise ratio, the input end of each Faltin rail is loaded by an input of a LNA, which acts as an artificial cold load, instead of a resistor.

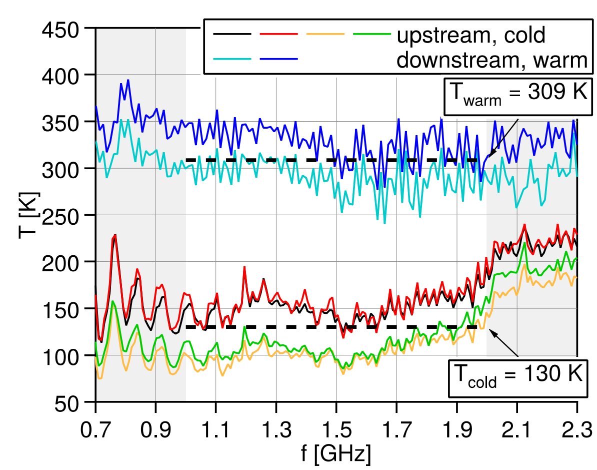

Figure 5: Noise temperature at output (upstream rails with LNAs vs. downstream rails with terminators).

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Figure 5 shows the noise temperature seen at the outputs of the Faltin rails. The 4 upstream rails are loaded by LNAs. Their average noise temperature is 130 K. For verification, two of the downstream rails were loaded by normal terminators at room temperature. As expected, their noise temperature is around room temperature.

SLOT-RING KICKER

For the kickers, we will use the slot-ring structure which was originally developed for the 2–4 GHz HESR stochastic cooling system of FAIR [8] and has already been well proven by the beam cooling experiments at COSY [9].

For the CR stochastic cooling system, two 1–2 GHz slot-ring kicker tanks (one for transverse cooling and one for longitudinal cooling) have been adopted. The main design parameters of the slot-ring kickers are listed in Table 2.

Table 2: Parameters of Each Slot-Ring Kicker Tank

Parameter	Value
Aperture [mm]	140
Length [m]	1.6
Total power loss [W]	960
$R_{\|\|}$ at $\beta = 0.97$ [Ω]	1280
$R_{\perp}$ at $\beta = 0.97$ [Ω]	896

Unlike the slotline PUs, the cooling for both transverse planes can be operated at the same beam position due to the static aperture. Each kicker tank contains 128 slot-rings. Every 16 rings are hard-wired with ceramic divider-boards as a stack (see Figure 6).

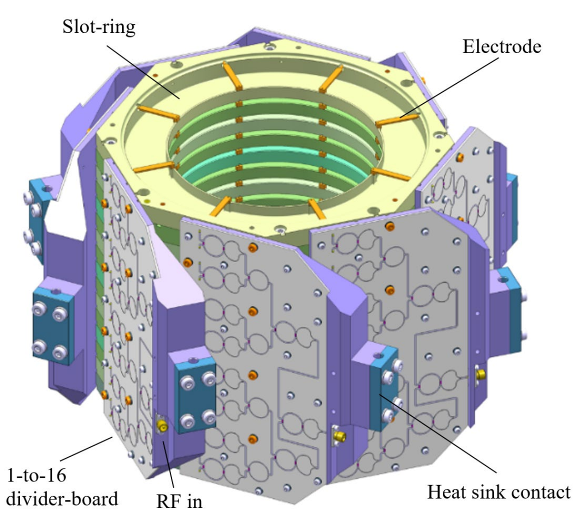

Figure 6: One hard-wired stack with 16 slot-rings (drawing by R. Greven, ZEA-1, FZJ).

The delay lines on the boards have been matched to the design velocity for $\bar{p}$ ($\beta = 0.97$). In the longitudinal cooling tank, all eight boards of a stack will be operated in the same phase and thus produce accelerating or decelerating electric fields to the beam. The boards of the transverse tank will be operated in pairs and in push-pull mode. The beam will experience a deflecting electromagnetic field in the vertical plane caused by the opposite sign of the RF signal on the two rows of electrodes above, and likewise the two rows below in the horizontal plane.

The slot-ring structures have been optimized with CST Studio Suite for a high shunt impedance of antiprotons at a velocity of $\beta = 0.97$. The impedances are defined according to [10]. Shown in Fig. 7, the electric fields were simulated for one excited slot-ring in the middle of a long structure. The obtained impedances were multiplied by the number of slot-rings to give the total impedances listed in Table 2.

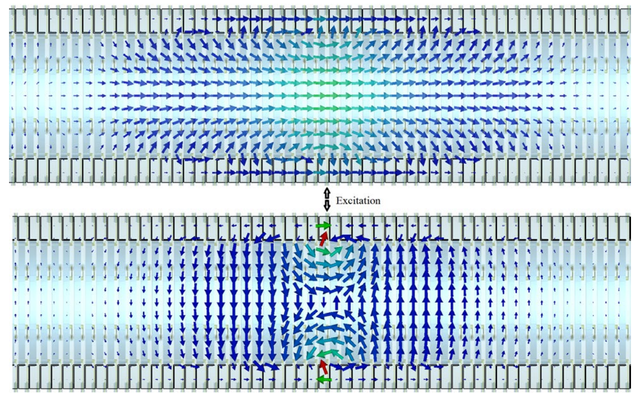

Figure 7: Simulated electric fields of one excited slot-ring in the middle of the structure at 1 GHz (top: longitudinal excitation; bottom: transverse excitation).

SUMMARY

The status of the CR stochastic cooling system can be summarized as follows:

- ~90% of components of the cryogenic plunging slotline pick-ups have been constructed. A cryo-test at 30–40 K for one slotline PU tank with real components has been foreseen.
- The Palmer PU has been built and successfully tested with $\beta = 0.83$ proton beams at COSY, FZJ in October, 2021.
- The slot-ring kickers have been designed.
- The RF signal processing scheme has been designed. ~50% of the components has been constructed or purchased.

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