

# PROGRESS OF THE STOCHASTIC COOLING SYSTEM OF THE COLLECTOR RING

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## Abstract

An overview of the recent achievements and ongoing developments for the stochastic cooling system of the Collector Ring is given. In focus are the hardware developments as well as the progress in predicting the system performance. The system operates in the frequency band 1-2 GHz, it has to provide fast 3D cooling of antiproton, rare isotope and stable heavy ion beams. The main challenges are (i) the cooling of antiprotons by means of cryogenic movable pick-up electrodes and (ii) the fast two-stage cooling (pre-cooling by the Palmer method, followed by the notch filter method) of the hot rare isotope beams (RIBs). Recently, a novel code for simulating the cooling process in the time domain has been developed at CERN. First results for the momentum cooling for heavy ions in the CR will be shown in comparison with results obtained in the frequency domain with the Fokker-Planck approach.

## INTRODUCTION

The overview of the CR stochastic cooling system, its design criteria and the required physics performance, especially for the antiprotons, are described elsewhere [1].

Heavy ion cooling is limited by the undesired mixing. After injection and bunch rotation of the hot RIBs only the Palmer method can be applied with a dedicated pick-up (pre-cooling stage). In a second stage, after the momentum spread has decreased, it is planned to switch to cooling with the slotline pick-ups and the notch filter until the final beam quality is reached. For stable ion beams coming with better quality after acceleration in the synchrotrons, one-stage cooling by the TOF or notch filter method with the slotline pick-ups should be sufficient.

Table 1: Cooling Requirements for RIBs in the CR

740 MeV/u, $10^8$ ions, coasting beam		
	$\delta p/p$ (rms)	$\epsilon_{h,v}$ (rms) $\pi$ mm mrad
Before cooling	0.2 %	45
After cooling	0.025 %	0.125
Cooling down time		$\leq 1$ s
Cycle time		1.5 s

The design value for the maximum stored beam current in the CR corresponds to  $10^9$   $U^{92+}$  ions. The cooling requirements for  $10^8$  ions are given in Table 1. Originally, the phase space reduction in Table 1 was dictated by the

need for fast electron cooling in the NESR. At present, the experiments envisaged in the HESR are the only users of heavy ion beams from the CR: in this case, the final beam phase space requirements are rather  $\delta p/p(\text{rms})=0.025$  % and  $\epsilon_{h,v}(\text{rms})\approx 1 \pi$  mm mrad, taking into account the rebunching for transfer from the CR to the HESR and the matching to the acceptances (momentum acceptance  $\pm 2.5 \cdot 10^{-3}$ , transverse  $7 \pi$  mm mrad) of the HESR [2].

## PICK-UP ELECTRODES AND TANKS

### Developments at the Prototype Pick-up Tank

The prototype pick-up tank (Fig. 1) has been modified in the mechanical workshop in order to accommodate the two novel water-cooled linear motor drive units (Fig. 1). Their synchronous operation remains to be tested after re-assembly in the tank. These units are easier to maintain and are made of aluminium which is lighter and cheaper to manufacture than the previously used stainless steel. Their maximum range of plunging is now 70 mm so as to follow the size of the shrinking beams during cooling. After cooling, the motor drive units must move out back to the initial maximum aperture within 200 ms, before new beam is injected.

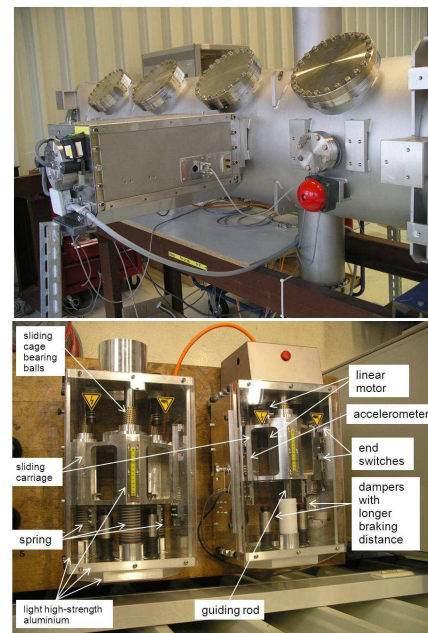


Figure 1: The prototype pick-up tank where the mechanical and thermal concepts will be tested. The new linear motor drive unit.

In order to enhance the signal to noise ratio, the movable pick-up slotline electrode modules are thermally coupled to flexible Ag/BeCu sheets which are cooled by helium cryoheads to about 20-30 K (Fig. 2). Very recently, the intermediate cryoshield at 80 K inside the pick-up tank has been designed, ordered and assembled. It consists of 4 half-shells, each 1 m long and has holes for the motor drives and openings for assembly purposes, it is made of oxygen-free copper (Fig. 2). It will be gilded galvanically so as to reach very low thermal emissivity. From measurements performed on gilded specimens in our lab, an emissivity lower than 2% (at 100°C; 7-16  $\mu\text{m}$ ) is expected.

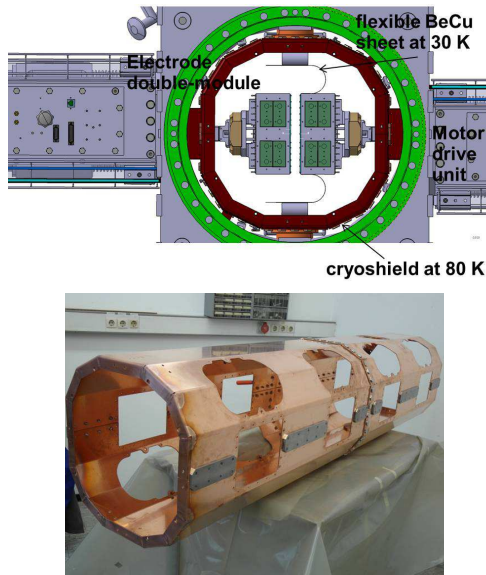


Figure 2: Section of the prototype pick-up tank showing the cryoshield at 80 K and the cooled movable electrode modules. Photo of the cryoshield.

In parallel, a testing chamber for linear motor drives is being manufactured. It will be used for long-term mechanical tests at room temperature (robustness, force measurements, also under pre-vacuum, effects of gravitation, acceleration profiles a.o.). Later it can be used for RF power tests on kicker electrodes.

### Slotline Electrodes

The cryogenic movable pick-up slotline electrodes were further optimized, the first ceramic electrode plates have been delivered. The electrode module has been slightly modified to integrate a circuit housing (i) an antenna-switch permitting to test the slots without beam and (ii) a cryogenic low-noise amplifier as a future option [3]. RF tests of this circuit, also at cryogenic temperatures, are underway. Consequently, the combiner boards will be finalized.

### Faltn Electrodes for the Palmer Pick-up

Dedicated electromagnetic simulations with the HFSS code are underway in order to design the electrodes of the Palmer pick-up. The geometry of the proposed Faltn rail

structures is being optimized in the band 1-2 GHz in order to achieve (i) maximum pick-up impedance coupled to the beam, (ii) linear output signal phase with respect to the particle pulse and (iii) flat frequency response  $S_{21}(f)$ , avoiding resonances [4]. Plunging of the electrodes is not needed for pre-cooling of RIBs, but the sensitivity of the Palmer pick-up is limited because of the large vertical aperture ( $\pm 66$  mm with respect to the beam axis) required, so as not to intercept the injected beams (before the bunch rotation).

## RF SIGNAL PROCESSING

A flexible RF signal processing scheme (RF block diagram) of the complete stochastic cooling system has been laid out [3]. It covers the transverse (horizontal, vertical) cooling branches as well as the longitudinal cooling using the notch filter, the time of flight (TOF) or the Palmer method. The electrical length of the components in the cooling paths from pick-up to the kicker should be as short as possible. Refinement is underway taking into account the design of the CR lattice and building as well as the beam operation modes.

The experience gained from the successful tests of the prototype optical notch filter with beam in the ESR [5] is being used to optimize the setup in view of the CR [3].

The call for tender for the water cooled 1-2 GHz power amplifiers has started. Because of the very demanding anti-proton cooling a total cw microwave power of 8 kW (32 250 W units) is required, in combination with stringent requirements on amplitude flatness and phase linearity as well as very short ( $\leq 4.8$  m i.e. 16 ns) allowed electrical length for each unit.

## SIMULATIONS OF HEAVY ION COOLING

The longitudinal cooling performance for ions in the CR with the notch filter and TOF methods was investigated using a Fokker-Planck approach (CERN code). Since the thermal noise was much lower than the particle noise and the latter scales with  $Q^2$ , we obtained the same results for ions with  $Q=50+$  and 6 dB higher gain than for  $U^{92+}$ . Therefore, we only show results for coasting beams of  $U^{92+}$  ions. The expected impedance and frequency response of the slotline electrodes is included as in [1]. An example is shown in Fig. 3.

The initial rms momentum spread  $\sigma_p/p$  of the ion beam was chosen: (i) as expected after bunch rotation and adiabatic debunching. (ii) within the notch filter/TOF momentum acceptance. For the RIB lattice the former is  $\sigma_p/p = 5 \cdot 10^{-4}$  and the latter is 3 times larger. (iii) small enough so as to avoid band overlap between the harmonics and the betatron sidebands (effects not included in the Fokker-Planck approach). This band overlap occurs already at  $\sigma_p/p = 2.7 \cdot 10^{-4}$  at 2 GHz and  $5 \cdot 10^{-4}$  at 1 GHz.

A new code to simulate the cooling process in the time domain (t-domain), based on ab initio calculations of the cooling and diffusion effects, has been developed at CERN [6]. This work was motivated by bunched beam

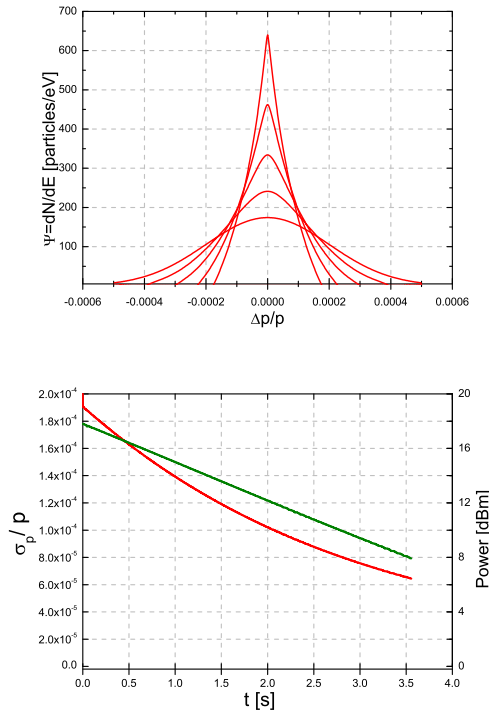


Figure 3: Notch filter cooling of  $10^8$   $U^{92+}$  in the CR at 78 dB gain. Up: Evolution of the particle density, plots at  $t=0$ , 0.9 s, 1.8 s, 2.6 s and 3.5 s. Bottom: Evolution of the rms momentum spread (red line) and of the total cw power in the bandwidth (green line).

cooling. Nevertheless, even for coasting beams the method is useful for benchmarking the standard Fokker-Planck treatment in the frequency domain. Here, we present first results of this comparison for the CR case. The t-domain simulation does not consider the thermal noise, which is anyway negligible compared to the particle noise. In the t-domain a 'gain' parameter is defined as the fraction of the coherent energy removed per turn (without the undesired mixing term). It has been matched to the corresponding pure coherent effect expected for the given electronic gain in the frequency domain. The undesired mixing and the feedback by the beam appear naturally in the t-domain treatment. In order to save computation time, in these preliminary simulations, a beam of  $10^8 - 10^9$  ions is typically simulated by 20000-50000 superparticles, each one is tracked turn by turn. As a result, the Schottky signals are averaged within a few thousand turns only. Even so, the tendencies are clear as shown for example in Fig. 4. At a gain of 74 dB, the Fokker-Planck simulation predicts that the notch filter and the TOF method take 2.8 s and 7 s, respectively to cool  $10^8$   $U^{92+}$  ions from  $\sigma_p/p = 5 \cdot 10^{-4}$  down to  $3 \cdot 10^{-4}$ . In general, the evolution of  $\sigma_p/p$  predicted by the t-domain simulation agrees within a few percent.

The incoherent effect due to Schottky noise is expected to be more important at higher particle number. Figure 5 shows that the peaked shape of the distribution function at the end of cooling comes essentially from this effect.

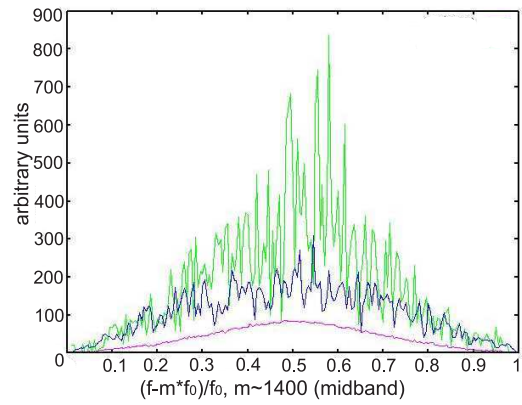


Figure 4: Effect of the feedback by the beam in a t-domain simulation of TOF cooling of  $10^8$   $U^{92+}$  ions. The Schottky signal for the closed loop (blue line) is clearly reduced compared to the open loop case (green line).

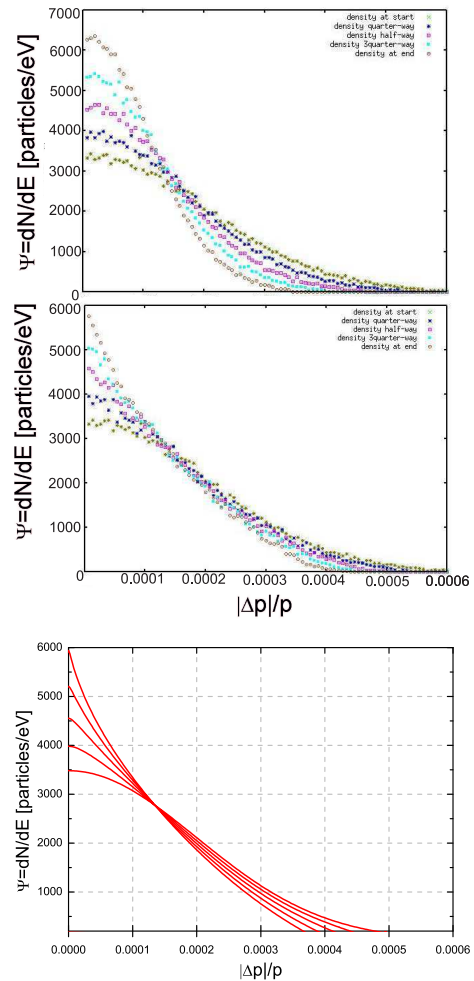


Figure 5: Notch filter cooling of  $10^9$   $U^{92+}$  (at a gain parameter equivalent to 76 dB). Evolution of the particle density, plots at  $t=0$ , 0.5 s, 1.0 s, 1.5 s and 2.0 s. Up, middle: t-domain results without and with Schottky noise incoherent effect, respectively. Bottom: frequency-domain (Fokker-Planck) result including Schottky noise and negligible thermal noise.

As an outlook, the longitudinal cooling of hot RIBs with the Palmer method will be simulated with the CERN code taking into account the response of the Faltin structures which are currently being designed [4]. Consequently, the performance of the Palmer pre-cooling and its handover to the fast notch filter cooling will be optimized in future simulation work.

In [7], simulations of Palmer cooling of RIBs as well as its handover to notch filter/TOF cooling are presented, assuming loop couplers for all pick-up and kicker electrodes in the CR.

### *Numerical 2D Fokker-Plank Approach*

A numerical algorithm solving the 2D Fokker-Plank equation has been written [8]. This is a first effort towards a powerful treatment of the Palmer stochastic cooling of ions where, typically, the longitudinal and transverse phase space planes are strongly coupled (aforementioned band overlap).

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