STOCHASTIC COOLING OF ANTIPROTONS IN THE COLLECTOR RING AT FAIR

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Abstract

In order to reach the required luminosities for the experiments at FAIR, the hot secondary beams (antiprotons or rare isotopes) emerging from the production targets will be efficiently collected and phase-space cooled in the high-acceptance Collector Ring (CR), which is equipped with pertinent stochastic cooling systems. Simulations of the cooling performance are underway in parallel with the finalization of the system design. After an overview of the CR stochastic cooling systems, simulation results for antiproton cooling in the bandwidth 1-2 GHz are presented. The CERN Fokker-Planck code is used for momentum cooling and an analytical model based on "rms" theory for the simultaneous betatron cooling. In the focus is the comparison between the time of flight and the notch filter momentum cooling methods.

SYSTEM OVERVIEW

The Collector Ring (CR) of the FAIR project serves the fast 3D cooling of the hot secondary beams, antiprotons at 3 GeV or rare isotopes (RIBs) at 740 MeV/u. After injection, bunch rotation and adiabatic debunching, the reduced momentum spread of the secondary beams fits into the acceptance of the stochastic cooling system, so that all the particles can be cooled. For maximum antiproton production rate, stochastic cooling of a coasting beam of 10^8 antiprotons must reduce the transverse rms emittances from 45 down to 1.25 mm mrad and the rms momentum spread from 0.35 % down to 0.05 %, within 10 s (for the RIBs see [1]). The CR-precooled beams are delivered to the experiments in the HESR [2, 3]. The CR lattice provides: (i) different ion optical modes for antiprotons and RIBs as well as flexible choice of the transition energy for an optimal compromise for the mixing parameters of the stochastic cooling; (ii) proper betatron phase advance of $\pm 90^\circ$ between pickups and kickers of the transverse cooling systems.

The CR stochastic cooling system will operate in the frequency band 1-2 GHz. It consists of 2 pickup and 2 kicker tanks in straight sections without dispersion, and one Palmer pickup tank at high dispersion (Fig. 1). The foreseen installed microwave power of 8 kW has to cover the simultaneous 3D cooling.

Antiproton cooling makes use of PHL, PVL, KHL, KVL. Each tank consists of two plates, each plate bears 8 arrays of 8 identical broadband slotline electrodes [4]. Cooling is limited by the poor ratio Schottky signal/thermal noise, that is why it is foreseen: (i) to keep the pickup electrodes at cryogenic temperatures (20-30 K), (ii) to strive for large sensitivity by moving (plunging) the pickup electrodes as the beam shrinks, (iii) for momentum cooling, to take the sum signals from both pickups and implement the notch filter technique, which advantageously filters out the thermal noise. The chosen ring slip factor η=-0.011 guarantees optimum momentum acceptance for the notch filter cooling, but slows down the transverse cooling due to the high mixing between kicker and pickup [1].

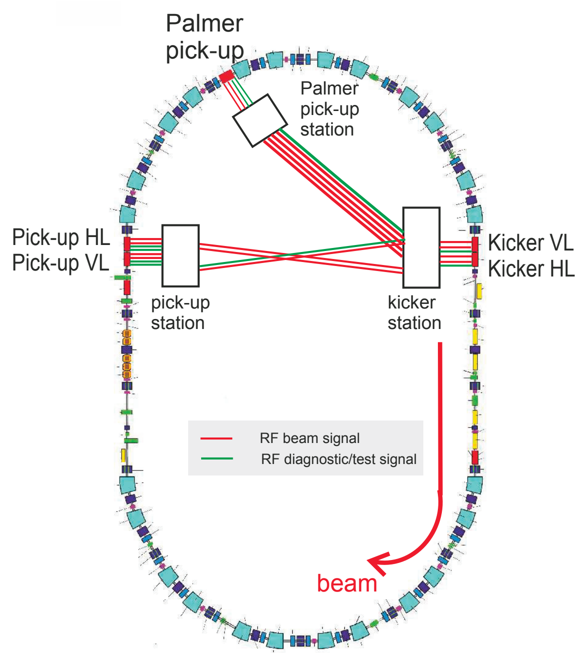

Figure 1: CR layout with stochastic cooling paths of the 1-2 GHz system. PHL, PVL → KHL, KVL: pbar 3D cooling, RIB 3D cooling final stage; Palmer pickup → KHL, KVL: RIB 3D cooling first stage (pre-cooling).

Heavy ion cooling is limited by the undesired mixing. For the hot RIBs, initially the Schottky bands overlap, so that only the Palmer method can be applied. After the momentum spread has decreased so as to fit into the acceptance of the notch filter, it is planned to switch to cooling from PHL and PVL down to the final emittances and momentum spread. For stable ion beams coming with better quality after acceleration in the sysnchrotrons, one-stage cooling by the TOF or notch filter method with PHL, PVL should be sufficient.

COOLING METHODS

Within the standard "rms" theory [5, 6] the cooling rate, e.g. for transverse emittance, is ${\tau_\perp}^{-1} = (W/N)[2gB - g^2(M+U)]$, where W is the system bandwidth, N the particle number, g the system gain, U is the ratio of thermal noise/Schottky signal. The undesired mixing (between pickup and kicker) is $B \approx \cos(m_c\phi_u)$, where m_c is the central harmonic in the band and $\phi_u = -2\pi\chi_{pk}|\eta_{pk}|\delta p/p$. For the maximum ($4\sigma$) initial momentum spread $m_c\phi_u \leq \pi$, otherwise the cooling force changes sign i.e. heats up the beam. The desired mixing (between kicker and pickup) is $M \approx (m_c|\eta|\delta p/p)^{-1}$ for not overlapping Schottky bands, χ_{pk} is the ratio of the flight time from pickup to kicker to the revolution period, η is the ring slip factor and η_{pk} is the slip factor between pickup and kicker.

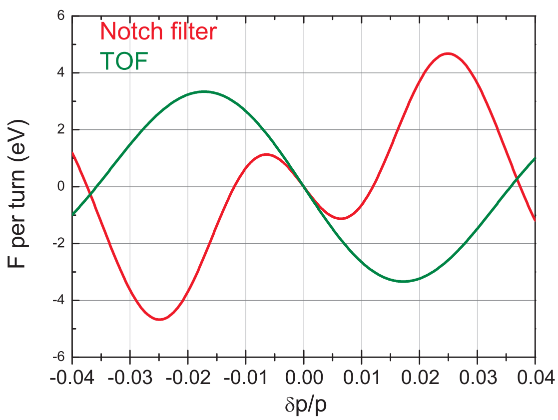

Figure 2: Comparison of the momentum acceptance for notch filter and TOF momentum cooling of 3 GeV antiprotons in the CR. (F is plotted for $G_{||}$=140 dB.)

For momentum cooling, the mixing aspects are similar. The Palmer-Hereward technique [5] is a special case of horizontal cooling. The notch filter method [7] uses the dependence of the particle revolution frequency on its momentum deviation. The signal is splitted, half is delayed by exactly one revolution period and substracted from the other half. The transfer function of the filter with a 90° phase-shifter is ($\delta f/f_0 = m|\eta|\delta p/p$):

$$H = \frac{i}{2}(1 - e^{-i2\pi m|\eta|\delta p/p}) = -\sin(\pi\ \delta f/f_0)e^{-i\pi\ \delta f/f_0}\ .$$

It has no effect at the harmonics mf_0 of the revolution frequency (notches) and pushes particles with wrong revolution frequency to the nearest notch, provided that the Schottky bands do not overlap. The system gain $G = G_{||}He^{im\phi_u} = -G_{||}\sin(\pi\ \delta f/f_0)e^{im\phi_{u,n}}$ yields fast cooling and efficient noise suppression around mf_0, but also higher undesired mixing $\phi_{u,n} = -\pi(2\chi_{pk}|\eta_{pk}| + |\eta|)\delta p/p$ i.e. the momentum acceptance is reduced. The time-of-flight (TOF) method [8] uses for cooling the undesired mixing B after a phase shift by $-90°$ i.e. the kick experienced by a particle is proportional to $\sin(m\phi_u) = -\sin(2\pi m\chi_{pk}|\eta_{pk}|\delta p/p)$. In practice, the TOF method is applied by switching off the delay branch of the notch filter and shifting the phase by $-90°$ i.e. its transfer function is $-i/2$ and system gain $0.5 \cdot G_{||}e^{i(m\phi_u - \pi/2)}$. Compared to the notch filter, the TOF method offers higher momentum acceptance (same as the transverse/Palmer cooling) but no noise suppression. Here, the electronic gain $G_{||}$, real and constant within W, is the variable parameter.

SIMULATION RESULTS

Simulations of the antiproton cooling in the CR are presented, with the parameters given in [1], assuming (conservatively) no plunging of the pickup electrodes. Momentum cooling is described by the Fokker-Planck equation for the particle energy distribution $\Psi(E,t) \equiv \partial N/\partial E$ (see [9]):

$$\frac{\partial\Psi}{\partial t} = \frac{\partial}{\partial E}\left[-F\Psi + \left(D_s\Psi + D_n\right)\frac{\partial\Psi}{\partial E}\right]. \qquad (1)$$

The open loop gain S determines the feedback by the beam. It enters into the coherent effect $F \sim \mathrm{Re}[G/(1-S)]$ and into the diffusion terms $D_s, D_n \sim |G/(1-S)|^2$. The CERN program solves numerically Eq. (1) for $\Psi(E,t)$ and calculates the rms energy (momentum) spread as the 2$^{\text{nd}}$ moment of Ψ. The code yields the maximum total cw power in the bandwidth at the kicker. It is the sum of the initial maximum Schottky power and of the constant (filtered) amplifier power.

Fig. 2 shows that the momentum acceptance of the TOF is 3 times higher ($\pm3.6 \cdot 10^{-2}$) than that of the notch filter method ($\pm1.2 \cdot 10^{-2}$).

As shown in [1], for notch filter cooling, the requirements can be best met with $G_{||}$ =150 dB during 10 s, resulting in a final σ_p/p= $3 \cdot 10^{-4}$, within acceptable power. Systematic simulations of TOF cooling indicate that the best case is with $G_{||} = 138 - 140$ dB during 10-15 s, leading down to σ_p/p= $1.2 \cdot 10^{-3}$. At higher gain, not only the power is unacceptable, but the TOF cooling loop becomes rapidly unstable, as explained below. Characteristic results are given in Fig. 3.

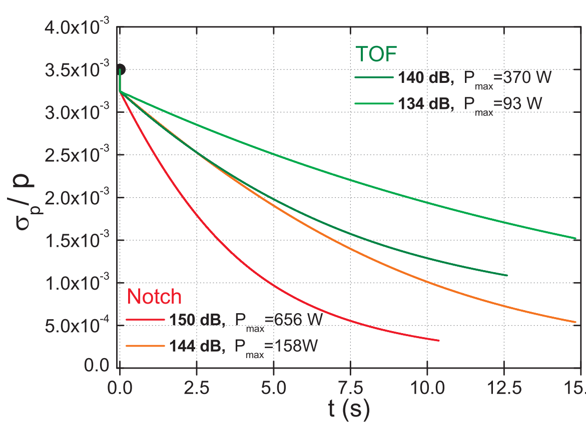

Figure 3: Evolution of the beam rms momentum spread during cooling as well as the maximum cw power. The installed power should be by rule of thumb 4 times higher in order to account for statistical fluctuations.

The best cases are compared in Fig. 4. As expected, since it suppresses both Schottky and thermal noise in the center of the distribution, the notch filter cools the beam core much more efficiently and ultimately leads to lower momentum spreads than the TOF cooling. The TOF method cools the tails faster. These conclusions are consistent with Fig. 5 which compares the calculated cooling

ISBN 978-3-95450-115-1

force for both methods at the end of cooling, illustrating essentially the different behaviour of the open loop gain as seen in Fig. 6. With increasing δp/p within the distribution, $1/|1-S|$ (i) decreases for notch filter, whereas (ii) it slowly increases and reaches a maximum at the edges for TOF. Systematically, after some time (depending on the gain), the diffusion at the steepened beam tails is so high that the loop becomes unstable. By decreasing the gain with time, longer TOF cooling is possible, but obviously cannot meet any better the antiproton cooling requirements.

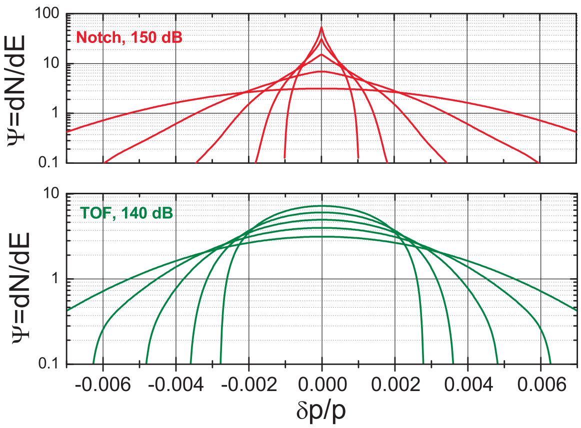

Figure 4: Evolution of the particle density Ψ during cooling. Plots at t=0, 2.5 s, 5 s, 7.5 s and 10 s. The initial distribution is Gaussian with σ_p/p= 0.0035.

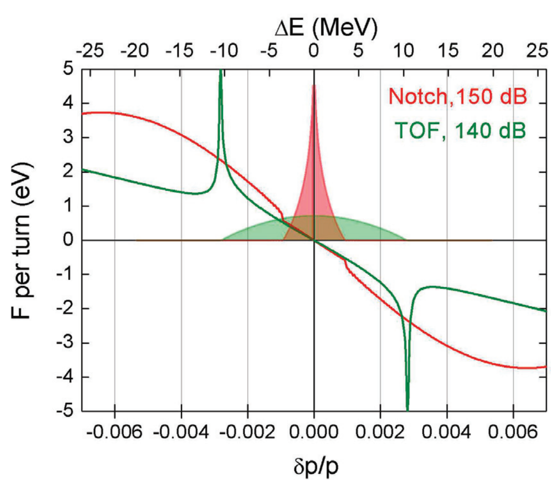

Figure 5: Coherent effect per revolution with the particle distribution in a.u. in the background after t=10 s of cooling, plotted against the relative momentum deviation δp/p and the deviation ΔE of the particles from the nominal kinetic energy of 3 GeV.

OUTLOOK

The results confirm that the notch filter mehod is the choice par excellence for the noise-limited antiproton cooling in the CR. As δp/p shrinks, the ring $|\eta|$ can be slightly increased, so as to control $M \sim (|\eta|\delta p/p)^{-1}$, as required for the simultaneously operating betatron cooling. This optimization procedure will be simulated in the future.

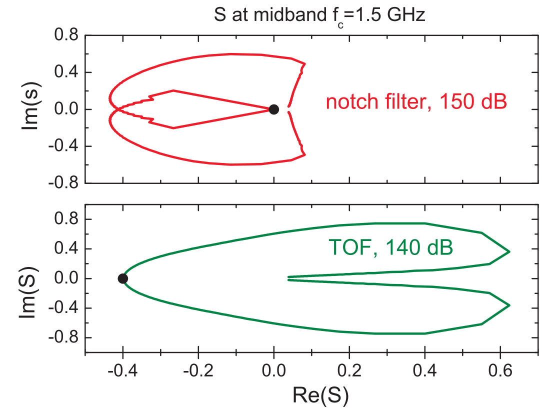

Figure 6: Nyquist plots after t=10 s of cooling. In the TOF case, for t$\geq$ 13 s the loop becomes unstable i.e. the curve encloses the point S=1. The black point indicates the value of S at the center of the distribution δp/p=0.

Nevertheless, the option of TOF cooling is easy to realise and useful for different operation scenarios, e.g.: (i) pre-cooling of the beam tails by TOF if the initial δp/p of the antiproton beam exceeds the acceptance of the notch filter, then switching in a second stage to notch filter cooling for ultimate performance; (ii) TOF cooling alone could be sufficient for antiprotons for moderate requirements on the final δp/p or on the cooling time (e.g. lower particle number). In particular, for transversally hot beams, TOF cooling can operate at a higher ring $|\eta|$, thus allowing faster betatron cooling; (iii) Similar conclusions apply, in principle, for notch filter/TOF cooling of heavy ions, but the quantitative treatment is complicated by Schottky band overlap.

In view of the CR, an optical notch filter was developed at GSI and integrated into the ESR stochastic cooling system. Very recently, notch filter and TOF cooling have been demonstrated for the first time in the ESR with a Au^{79+} beam. The two methods have been compared to each other (and also to the already existing Palmer method). The experimental results [10] qualitatively confirm the conclusions of the above simulations, give confidence for the CR system design and can be used for code benchmarking.

We thank H. Stockhorst, D. Möhl, T. Katayama and L. Thorndahl for their help and many fruitful discussions.

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