RECENT DEVELOPMENTS IN STOCHASTIC COOLING

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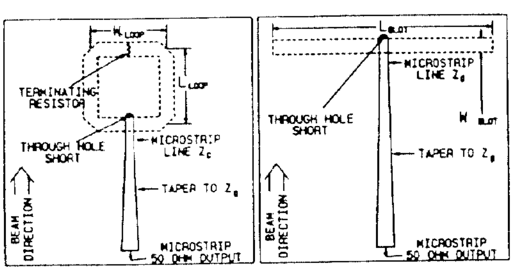
Abstract

A comparison of developments in different machines using the stochastic cooling method is presented. Examples include planar pick-up and kicker structures at Fermilab using printed circuit techniques, a novel digital delay line for LEAR, experience with bunched beam cooling equipment in the SPS and the AAC improvement and performance. As an interesting component from TARN, the helical coupler for slow beams is discussed. Machines presently under construction and planning to use stochastic cooling are COSY at KFA Jülich for light ions and ESR at GSI for heavy ions. In order to reduce experimental cut and try bench work for high frequency pick-up and kicker construction, the development of appropiate computer codes for systematic design of such structures has started. As a future application, the possible stochastic cooling (AAC or PS) of lead ions at CERN for LHC is discussed.

Planar stochastic cooling pick-ups and kickers

One important ingredient in the recent progress of stochastic cooling was the development of new pick-up and kicker structures. Until 1988 directional loop couplers have been used for all stochastic cooling pick-ups and kickers at Fermilab. As cooling frequencies are pushed up to the point where the beam aperture and the pick-up dimensions are of the order of one wavelength, the theoretical description of these devices starts to deviate from simple directional coupler theory. The three-dimensional nature of these directional coupler structures, where the width of the coupler may be bigger than its length makes them very complicated to design at high frequencies [1]. Here two planar structures shall be considered which can be understood more easily and are certainly not so difficult to fabricate. These structures are the "planar loop" and the "transverse half-wave slot". Both were fabricated using standard printed circuit board processes.



(a) (b)

Fig. 1: Solid lines are microstrip and dashed lines are slots in ground plane (a), planar loop geometry (b), transverse half wave slot pick-up geometry (from [1].

The planar loop shown in Fig. 1 is similar to the traditional directional coupler pick-up. The usual stripline structure is replaced with a coplanar waveguideline, made up of two slots running parallel to the beam. The front and back edges are considered as slotlines [1].

A half-wave slot pick-up is shown in Fig. 1b. Consider a slot impedance of twice the Z_0 and a length L_{slot}. A single charged particle travelling close to the slotline side of the pick-up and centered on the microstrip transition induces an image current, which creates a voltage across the slot. Half of the pulse travels down the microstrip line to the receiver. The other half splits again into two pulses which travel in opposite directions on the slotline. At the shorted ends of the slot the pulses invert and reflect back toward the microstrip transition. At the microstrip transition the inverted pulses add and travel out along the microstrip line. If losses in the slotline are ignored the signal output is a pulse followed by an inverted pulse of the same amplitude, at time L_{slot}/vs_{slot}. This is exactly the same response as the traditional coupled loop [1]. The main difference is that the transverse half-wave slot is not directional.

The planar loop is similar in performance to traditional quarter wave loop pick-ups. However, for the mechanical tolerances required at high frequencies the planar loop is much easier to fabricate than the traditional loops. In applications in which directionality is important, quarter wave loops are superior to half-wave slots since a half-wave slot is not directional. Unlike quarter wave loops half wave slots do not have termination resistors. This may cause complications in the design of kicker combiner networks. For many applications, the half-wave slot pick-up outperforms quarter wave loops. It has the same sensitivity at the centre as do quarter wave loops, but it shows a better coverage. The half-wave slot pick-up also has a better rejection of of the unwanted transverse beam mode. A question that still needs further investigation is the minimum spacing between adjacent printed loops and slots. The mutual coupling as a limiting factor allows spacing less than half a wavelength for the loops but for the slots serious deterioration may then occur [8].

CERN AAC improvements and performance

During the SPS collider runs, the performance of the AAC is of crucial importance for the collider luminosity. During operation for LEAR a high production rate permits intermittent stacking which lowers the operation costs and reduces power consumption. The stacking rate evolved from $1.2*10^{10}$ p-/h in early 1988 to $5.8*10^{10}$ p-/h in May 1989. So far a maximum stack intensity of $1.31*10^{12}$ p- has been obtained, which exceeds the ACOL project design goals.

For the AC stochastic cooling systems additional cyrogenic cooling systems were installed in early 1989 reducing the temperature of the signal combiner boards from 100°K to 30°K and thus the thermal noise by 4 dB. Furthermore the function governing the the pick-up and kicker movement was modified such that the loop gain is increased during the later part of the cycle, without affecting the initial 200 π mm.mrad acceptance. These modifications increased the capabilities of the AAC to run at 2.4 s cooling cycle time. After 2.4 s of stochastic cooling in the AC, the mea- sured transverse emittances were about 13 π mm.mrad and 70% of the antiproton produced in the target reached the injection orbit of the AA. Under these conditions, the AA precooling and stacktail systems were found to be the limiting factor in the 2.4 s repetition scheme. It has been proposed to improve the stochastic cooling speed by a factor two by means of a new cryogenic system installed in the AA [2].

This would yield a further 10% improvement in stacking rate at 2.4 s. The present 4.8 s cycle stochastic cooling reduces the transverse emittances to 4 π mm.mrad in both planes. For the AA the precooling system has been improved by installing preamplifiers with lower noise figures and additional band II (1.65-2.4 GHz) power amplifiers

The band I and band II power amplifiers are combined with a frequency diplexer before the signals enter the kicker tank. In the 4-8 Ghz core cooling systems (transverse), the hardware coupling has been reduced and clean BTFs (beams transfer functions) have been measured. Also the sensitivity of the vector network-analyzer for the BTF measurements could be increased by about 15 dB using a tracking YIG-filter in the receiver path. This YIG- filter rejects the broadband noise coming in from the amplifier chain. Since the receiver in the network-analyzer is not only sensitive at its nominal frequency but also over a comb-spectrum, this method permits lowering the noise floor or decreasing the sweep time.

Due to the high $\eta \approx 0.1$ ($\eta = 1/\gamma_{tr}^2 - 1/\gamma^2$) in the AA, problems occurred exploring the full 4-8 GHz bandwidth. To compensate transverse particle heating at extreme momenta (stack edges) caused by excessive mixing between observation and correction at the upper band end, the lower band limit was reduced from 4 GHz down to 2 GHz. In a similar way the Δp (2-4 GHz) system for the stack had its lower band limit reduced to 1 GHz in order to improve the cooling at the stack edges. This measure also improves the transfer from the stack tail to the stack-core system. However the improvements in the cooling systems would not have permitted to obtain a high stack intensity without using a technique known as "beam shaking". Shaking of the beam (near 500kHz) modifies the ion amplitude distribution and reduces the excitation of higher order resonances.

A Digital Notch Filter for LEAR

An interesting technological development for the LEAR stochastic cooling systems is a digital notch filter with 100 MHz bandwidth and a notch depth of 40 dB. Pick-up signals from travelling wave loop couplers with switchable delays outside vacuum (105 MeV/c and 61.2 MeV/c) are digitized with a fast 200 Megasample 8 bit ADC. The digitized data are transferred via latches into 4 RAMs (random access memory memory). After storage in the RAMs for the required delay time (adjustable from 50 ns to 1280 ns) the data are read and sent to a fast DAC (500MHz) for analog conversion. The subtraction between delayed path and reference path takes place in a broadband analog hybrid (180° combiner) [3].

For the present application, where a momentum range of 50 to 500 MeV/c should be covered, the digital solution is certainly easier than 1.5 km of coaxial delay line with switchable length. In the future, one might also consider BAW (BAW=bulk acoustic wave [9] elements for certain signal delay line applications. The stochastic cooling system (with the digital filter) installed increased the lifetime of a 105 MeV/c beam to 3 hours and for 61.2 Mev from 7 minutes to 25 minutes. This improved the low momentum performance significantly, permitting slow extraction spills of 1 hour at 105 Mev/c and 15 minutes at 61.2 MeV/c.

Bunched beam stochastic cooling experiment

To test the possibilities of bunched beam cooling in high energy colliders, an experiment is under way at the CERN SPPS . The short bunches and the large inter bunch spacing in the CERN collider lead to techniques radically different from those used in coasting beam machines. Although the total bandwidth necessary is very high (8-16 GHz), only a small number of narrow band channels within this range are required [4] and hence narrow band pick ups and kickers can be used. To test the ideas, a high frequency kicker and pick up (10 GHz center frequency, 1 GHz bandwidth) have been installed in the SPS. In parallel with the development of the kickers, a digital transmission system using an atmospheric laser link across an arc of the SPS has been developed. Preliminary tests on the signals obtained from the pick-up using low intensity proton bunches have revealed a restriction whose implications are at present being studied. It seems that even at these very high frequencies, the true Schottky noise of the beam is contaminated by coherent signals related to the synchrotron frequency. This contamination reflects a macrostructure within the bunch which depends upon the past RF history of the bunch and which does not seem to disappear completely. Measurements will be continued during the collider run starting in September 1990.

Stochastic Cooling at COSY (KFA Jülich)

The cooling in COSY will work in the ranges: Band I: 1 to 1.8 GHz, Band II: 1.7 to 3 GHz. The upper limit is given by the various cut-off frequencies of EH and HE deflecting waves in the beam-envelope components. The tranverse stability (Schnell-Zotter criterion) is kept in mind because of the low injected momentum spread (1.10^{-3} at 40 MeV).

There will be separate systems for both transverse planes. The longitudinal cooling will be performed using Thorndahl filters (notch filters) in the sum paths of the transverse equipment. Different cooling paths are envisaged for low and high energies (around 0,6 and 2 GeV) in order to overcome the mixing in the telescope sections at low energies .

The working point near $(Q_x, Q_y)=(3.37,3.39)$ will meet the optical constraints for transverse stochastic cooling. An overview over the COSY lattice is given in [5]. As compared to other machines the initial transverse emittance of the beam becomes low due to acceleration. AT T > 1.5 GeV, the time required to cool the proton beam from an initial emittance of 5 π mm mrad to the final emittance of 1 π mm mrad will be of the order of 30s for $N=10^{10}$ ppp. Cooling times of about 3 s are expected for low intensities ($N = 10^8$ ppp) [6].

In the mechanical concept the main characteristics of the pick-up and kicker tanks for COSY are:

beam-interaction structures: loop couplers, movable electrode supports, driven by 4 stepping motors
beam aperture: 140 mm * 20 to 140 mm,
tank diameter * length: 500 mm * 2 m,
number of RF-feed-through domes: 4.

Many design features will be taken over from the CERN AC structures. The pick-up structures will be cooled to g 25° K using the cryopanels of two-stage He cryopumps [2]. The vacuum requirements of COSY (10 nPa) will be fulfilled applying the following steps: bakeout at 300°C for the tank walls 100°C for the pick-up structure and 150-200°C for the complete kicker tank with extensive use of NEG pumping materials.

The modularity of the electrode support allows the construction of 2 m long tanks having 1 m of Band I and Band-II structure each.

In order to damp the electromagnetic resonances of the tanks (there are more than 30 deflecting ones) ferrite plates of low conductivity (static charge) are used. Tapers of the beam tube to the electrode supports will be replaced by additional ferrite plates at the tank end walls. The transverse coherent stability is problematic without an active damping system.

The signals of the single electrodes in COSY are combined in a first step allowing an energy range of 0.6 to 2.6 GeV. That results in a number of RF vacuum feed- throughs of 8 per electrode support bar. The signals of each feed-through is then amplified in a low noise FET amplifier. The further signal-processing steps will be performed after amplification to a level of some dBm. The scheme used in the AC, has been modified because of the large particle velocity range in COSY. Thus the second step of signal combination will be performed outside of the the tank. The length of phase shifting transmission lines is switched as a function of the actual particle energy.The power amplifiers will provide a capability of about 400 W per tank and per cooling plane fed in 2 * 8 tanks inputs.

A prototype low-noise GaAs-FET (MFG 4301) amplifier was build for the Band-I range. A power gain of at least 12 dB has been measured. A noise figure of about 0.7 dB (corresponding to a noise temperature of 50 deg K) was reached operating at room temperature.

Stochastic cooling at GSI (Darmstadt)

In the ESR at GSI stochastic (pre) cooling will be applied to (exotic) heavy ions prior to RF stacking. For the momentum cooling, the Palmer method was chosen . The intensity ratio of the stack to the injected beam does not exceed 10. Electron cooling finally reduces the phase space of the stack. Beams of different charge states from carbon to uranium will be used at a fixed β = 0.76, with beam intensities between 10^5 and10^8 particles. The full momentum spread (FWHM) will be cooled from 0.7% to 0.2% and both emittances from 20 π mm mrad to below 2.5 π mm mrad before stacking.

The ESR has not been built as a dedicated machine for stochastic cooling. Thus with the rather large eta=0.28 certain compromises had to be accepted. This eta value assures the required good mixing between kicker and pick-up but the mixing between pick-up and kicker is so large (+150° at 1.6 Ghz) that compensation is required. This compensation is obtained by introducing individual delays for inner and outer electrodes. For the cooling system, the CERN Band I has been chosen (0.9-1.6 GHz) because of the mixing problems and to reduce development work. Since there will a stack present in the beampipe, all active cooling elements are placed in high dispersion regions. This implies installation in dipole and quadruploe magnets. In order to carry out stacking, all pick-up and kicker electrodes have to be oriented horizontally.

By subtraction of the signals from different pick-ups purified position signals can be produced which are not influenced by momentum deviations. Cooling based on this scheme is of course only possible for a good signal/noise ratio. Highly stripped ions even at a moderate intensity should fulfil this requirement [7].

Stochastic Cooling at TARN

Stochastic cooling experiments were conducted at TARN 1 (Test Accumulation Ring for the NUMATRON) from Feb 1984 through May 1985. TARN 1 was discarded in June 1985 and replaced by a new cooler-synchrotron TARN 2. Electron cooling experiments are now going on at TARN 2 In the future , stochastic precooling may be applied. The number of ions (7 MeV protons and 28 MeV alpha particles) was of the order of 10^7 with a relative velocity β = 0.12 and a revolution frequency of 1.1MHz. With TARN's η value of 0.7 Schottky bands start overlapping at 140 MHz and thus the range of the cooling system was fixed from 20 Mhz to 95 MHz.

In this context, the helical travelling wave pick-up/kicker was developped. It could find applications in other slow beam stochastic cooling systems. As the beam velocity at TARN 1 was so low, a helical line with a pitch angle of 0.12 radian was a very efficient pick-up/kicker structure. In the helical structure the phase velocity can be matched to the beam velocity (=0.12 c). Pick-up and kicker had the same structure with a length of 70 cm.

The pick-up impedance (sensitivity) has been derived experimentally from Schottky power measurements on a spectrum analyzer. The resulting frequency dependence was 250 Ohm (40 MHz), 400 Ohm (80 MHz) and 290 Ohm (120 MHz). These impedances are the ones normalized in a 50 Ohm system. The pick-ups characteristic impedance was 100 Ohm. A theory based on a sheath helix model explains well the experimentally obtained data. These measurements as well as cooling experiments confirmed that the travelling wave coupler is advantageous to a slow beam. Other features are that the structure is simple and that careful signal summation as for the loop coupler or ferrite ring arrays is not necessary. However as a disadvantage the range of applicable beam velocity is rather limited, since the phase velocity has to match closely the beam velocity.

Cooling experiments showed that an initial momentum spread of 1.2% (FWHM) was reduced to 0.06 % final value in 7 minutes cooling time on α particles. (system gain at the pole of a notch filter = 99 dB). For protons with a system gain of 99 dB the 1/e cooling time turned out to be 85 s with a final momentum spread of 0.08%. In consistency with theory for 109 dB gain the 1/e time constant and final momentum spread were 26 s and 0.13% respectively. It should be mentioned that a related structure, the meander line coupler,has been designed and build for transverse cooling in LEAR at CERN. This is in a way a printed circuit version of the helix coupler [10]. It consists of two alumina plates ,each metallized (thick film technology) on the back side and bearing a printed meander-shaped microstrip on the other side (towards the beam). In that case the beta was 6.6% and the frequency range 20 MHz 120 MHz.

Numerical Calculations of Pick-up/Kicker structures

With increasing operating frequencies, the quarter wavelenth stripline loops are becoming very short, and in certain cases, their width is more than twice their length. In such cases many approximations, which are commonly used for "long" stripline couplers (e.g. 70 MHz Schottky signal observation), are no longer justified and one has to take into account fringing field capacitance, coupling to waveguide modes (radiation), mutual coupling and other effects. So far, the usual approch in designing high frequency (>1GHz) pick-ups was to start with the very simple quarter wavelenth directional coupler and build models , which had to be tested on the bench. This method may turn out to be a very tedious cut and try approach and thus more sophisticated models for the electromagntic fields and subsequently for structure syntheses are desirable. In the following, two independent approaches (P. Raabe, TH Darmstadt [8] and D. McGinnis FNAL [9] are discussed.

Assuming beam propagation in z-direction (Fig. 2) inside an infinitely long and perfectly conducting pick-up structure, the resulting electromagnetic field distribution is calculated using a special mode matching technique. The exited fields are analytically expanded into the eigenfunctions of the waveguide structure, which is subdivided in areas of rectangular shape.Integration of the tangential magnetic fields yields the conductive currents of electrodes and inner wall as functions of the beam position, frequency and pick-up geometry.

Due to the proximity of the plates signal-cross talk occurs. Thus the "beam free" electrode array can be characterized as a system of coupled transmission lines, requiring an electrical termination network. The mathematical description is done by a 4x4 matrix equation. In this equation, the coupling capacitances between the electrodes are found by solving the two dimensional Laplace equation in the transverse plane of the pick-up geometry. Assuming total conversion of the beam induced currents into TEM waves at the input and output ports of a pick-up device with fixed length i.e. neglecting the excitation of higher order waveguide modes, the transfer characteristics and pick-up frequency response can be calculated using the theory of electrical transmission lines.

The other approach mentioned uses for the field description inside a beampipe with rectangular crossection magnetic current sources (Mc Ginnis, FNAL)

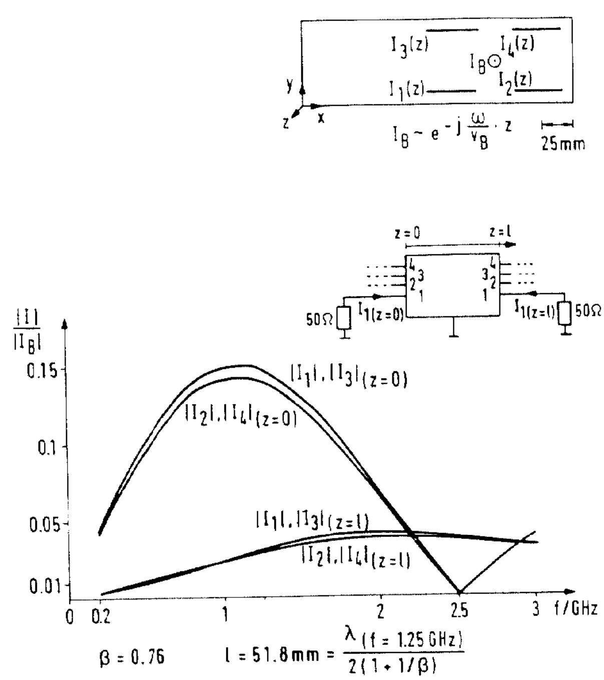


Fig. 2: Geometry and calculated results for a pick-up configuration [8]

The inner part of the rectangular beampipe (Fig. 2) is defined as region 1, the outer part as region 2. These regions may have different dieletric constants or backing plate configurations. It should be pointed out that this approach is mainly foreseen to be applied on printed loop or slotline structures. The beam travels in the z-direction somewhere in region 1. The two regions are connected by a hole or aperture in the screen. The purpose of the moment method program is to find the tangential electric and magnetic fields in the aperture and in region 1.

As the tangential electric field is zero on the conducting screen that separates the two regions, this approach is best formulated using magnetic current sources. If the aperture is not a perfect conductor, electric currents are also used. Electric and magnetic currents are defined by the equivalence principle. The fields in region 1 may be considered as the superposition of the "incident" field from the beam and the fields from the magnetic currents at the walls. Application of the continuity condition for E and H in region 1 leads to an integral equation. In this integral equation the E-and H-fields are given as the sum of orthogonal expansion functions.

Lead ion cooling

In the context of considerations to provide lead ions for the Large Hadron Collider), three possible stacking scenarios (PS, AA, LEAR) with the associated cooling systems are in discussion [11]. For LEAR, only electron cooling of the lead ions would apply.

Stochastic cooling of Pb ions in the CPS

The required horizontal and momentum cooling is obtained using common pick-ups ,power amplifiers and kickers. A large bandwidth will be necessary to achieve the cooling of 10^8 ions in less than 1 second. Pick-up and kicker electrodes have a quarter wavelength at midband and should be retractable for injection in the PS and subsequent acceleration to a flat top at 1 GeV, where the cooling takes place. The choice of the filter method is proposed, because the initial horizontal width due to momentum spread is about 30 times smaller than the width due to betatron oscillations. For the calculations a single periodic filter has been assumed, since at midband initially the longitudinal Schottky signal width equals half the revolution frequency.

Pick-ups and kickers are essentially the same structure. They consist of pairs of directional coupler loops and combiner/splitter boards. Possibly planar structures (printed on alumina substrate) as for the Fermilab bunched beam cooling systems could be considered. The kickers are placed only a quarter machine circumference downstream of the pick-ups to minimize the mixing between observation and correction. For the assumed β(0.875), the spare electrical length is ≈ 19m.

For the momentum cooling of Pb ions in the CPS calculations have been carried out assuming an initial rms width of $0.49 10^{-4}$ $\Delta p/p$ and a cooling time of 0.5 s ($=2.10^5$ turns) with a maximum power applied to the kicker of 80 Watts. The feedback effect on the Schottky signal and the mixing between observation and correction were taken into account during the integration of the Fokker-Planck equation. For the horizontal betatron cooling, the signal to noise ratio at midband, neglecting the feedback effect, becomes S/N=75. This justifies neglecting ther- mal noise power. The reason for this favorable value are the 53 elementary charges/ion(signal power increases proportional to n^2). The total required power for correction in this case will be then 235 W.

The kicker with a total active length of 1.5 meter with movable electrodes could be similar to the kickers in the Antiproton Collector (AC). The pick-up of a total active length of 0.15 meter would be a shorter version of the existing ones in the AC. For the periodic filters for momentum cooling, it seems reasonable to use optical fibers for the 720 meter long delay. Such a delay has been build with good precision at Fermilab for the 2-4 GHz band. The installed RF power should be 3 to 4 times higher than the mean noise-like signal power to reduce effects of saturation. An appreciable increase in correction strength can be obtained by reducing the the kicker gap as the horizontal beam dimension decreases due to the cooling. Nevertheless, as a precaution, a reserve up to 1 s for the cooling time should be reserved to allow for imperfections such as phase and amplitude errors in the feedback chain. In case of a larger initial $\Delta p/p$, it becomes necessary to cool at a higher energy, where both eta and deltap/p are reduced, such that no overlaps of revolution harmonics occur inside the 4-8 GHz working band. In case of momentum cooling the RF power scales proportionally with $(\Delta p)^2$.

An advantage of the CPS cooling scheme would be compatibility with anti-proton operation. However weak points are the need for a new RF dipole in the PSB-PS transfer line, the long LHC filling time and significant hardware installations in the CPS.

Lead Ion Cooling in the AAC

Considering the AAC complex for cooling and stacking the lead ions one has already experimentally with Antiprotons obtained a $\Delta p/p$ reduction by a factor 10 with pick-ups and kickers at a position of 25pimm mrad in a time of 1.1 seconds. It should be noted that the initial energy spread of 3 MeV/ nucleon (lead ions) is about 23 times smaller than the 70 MeV of the p-.

	Pb	p-
deltap/p	0.11%	1.5%
gamma	1.8	3.94
DeltaT/T	0.17%	1.88%
T	about 1.8 GeV/nucl	3.9 GeV
DeltaT	about 3 MeV/nucl	70 MeV
eta	0.26	0.02

The charge per nucleon is however 82/208 times e. The required correction for the ions will be 3/70*208/82=0.11 of the correction for p- (amplitudewise) corresponding to about a factor 100 in microwave power at the kickers. Therefore one can envisage cooling the transverse emittances also by a large factor simultaneously with the $\Delta p/p$ cooling. Furthermore the signal to noise ratio will be better by 82**2=6724 for the same number of pick-up electrodes. Thus in practice one would use a much smaller number of electrodes than for pbars. The smaller microwave power required and the better signal to noise ratio would allow the AC to cool a somewhat wider $\Delta p/p$ by a factor exceeding 10. With the excellent signal/noise ratio of the highly charged ions some of the mixing between pick-up and kicker could be overcome applying anti-peak filters, which have a positive phase slope at revolution harmonics. Thus larger $\Delta p/p$ initial can be treated.

Advantages of the AAC cooling scheme are the highest possible extraction energy (fully stripped ions in the PS). As disadvantages delicate and cumbersome beam gymnastics in the PS have to be mentioned, the need of a new RF dipole in the PSB-PS transfer line and dedicated AAC operation (no pbars available)

Conclusion

The number of machines, where stochastic cooling is used, increases steadily. During the last years, not only cooling of antiprotons (Fermilab, CERN) but also protons and heavy ions became attractive. This shows that this method after its proof of principle and the contribution to the discovery of the W- and Z-Bosons finds a wider range of applications. Other cooling schemes, like electron and laser cooling are under rapid development and will become a serious competitor in particular for heavy ion cooling.

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