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UPGRADING OF THE LEAR STOCHASTIC COOLING SYSTEMS

F. Caspers, M. Chanel, J.C. Perrier

Abstract

After presentation of the actual stochastic cooling systems with a brief historical review, recent improvements are discussed. The usable bandwidth of all systems has been increased mainly by adjustments of phase correctors and hardware modifications of the notch filters used in the longitudinal system. After identification of electromagnetic interferences at low PS-revolution harmonics in the MHz range, an efficient filter has been installed in the power supply path of the cryogenic preamplifier. In addition the power supply units are now situated as close as possible to the amplifiers in order to reduce the coupling due to the interference from the PS, which was acting via intermodulation on a large fraction of the cooling band. A new method using the time-domain function of a network analyzer to check the notch filters without disconnecting cables will be described. In conclusion the performance of all stochastic cooling systems is discussed.

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UPGRADING OF THE LEAR STOCHASTIC COOLING SYSTEMS

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ABSTRACT
After presentation of the actual stochastic cooling systems with a brief historical review, recent improvements are discussed. The usable bandwidth of all systems has been increased mainly by adjustments of phase correctors and hardware modifications of the notch filters used in the longitudinal system. After identification of electromagnetic interferences at low PS-revolution harmonics in the MHz range, an efficient filter has been installed in the power supply path of the cryogenic preamplifier. In addition the power supply units are now situated as close as possible to the amplifiers in order to reduce the coupling due to the interference from the PS, which was acting via intermodulation on a large fraction of the cooling band. A new method using the time-domain function of a network analyzer to check the notch filters without disconnecting cables will be described. In conclusion the performance of all stochastic cooling systems is discussed.

1. INTRODUCTION

The stochastic cooling is an important part of the LEAR machine. It was designed mainly to reduce the beam dimensions before deceleration of the antiprotons towards 100 MeV/c. It has now been working properly for about a decade [1] and may be considered complementary to the electron cooler. The improvements made to this system, which can work for several momenta between 61 MeV/c and 2 GeV/c, are described. Some emphasis is put on the particularities of this system.

2. EVOLUTION OF LEAR STOCHASTIC COOLING SYSTEMS SINCE 1986

The LEAR stochastic cooling system consists of two chains, each working in all three planes, to cover two ranges of particle momentum in the machine. The high-momentum system (Fig. 1) can be adjusted for a momentum range from 200 MeV/c to 2 GeV/c (protons or antiprotons), corresponding to a variation of particle velocity ($\beta = v/c$) by a factor of 4.35.

The low-momentum system (Fig. 2) is adjusted for 105 MeV/c and 61 MeV/c, respectively [2].

Figures 1 and 2 illustrate the configuration used in 1993. Over the years (beginning 1986) the position of stochastic cooling pickups and kickers has been changed together with the type of coupling structure. Initially, the longitudinal cooling systems had ferrite ring pick-ups (24 rings each) and kickers. These ferrite rings were outside the vacuum (outgassing, mechanical dimensions), on a section of the ceramic vacuum chamber. With these units the usable frequency range extended from 30 MHz to 200 MHz, showing a rather poor phase response (dispersion). However, at that time only a momentum cooling (high-energy range) from $\Delta p/p = 0.6\%$ to $\Delta p/p = 0.25\%$ was required.

After the implementation of the "bunch-to-bucket" transfer from the PS into LEAR and the adiabatic debunching in LEAR, the longitudinal stochastic cooling after injection into LEAR turned out to be more important.

Because later LEAR was operated at higher momenta than injection , the increase in bandwidth for the stochastic cooling system became mandatory. Now loop couplers with variable external delays and a horizontal cooling system using the same loop couplers have been installed (BHN 30, Fig. 1). The usable bandwidth extends from 3 MHz to 1.1 GHz. In order to avoid undesired feedback between pick-ups and kickers due to imperfect shielding as well as microwave mode propagation in the beam pipe, pick-ups and kickers were placed as far apart from each other as possible.

3. DESCRIPTION OF THE COOLING SYSTEMS PRESENTLY IN USE

3.1 High-Momentum Systems

At present loop couplers for pick-ups and kickers are in use in all the LEAR stochastic cooling systems. The output of each pick-up plate is followed by a head amplifier and a well-defined delay (combiner delay) before bandwidth is not desirable for the time being as measurements between different pick-ups and kickers have shown the onset of microwave mode propagation at about 1.3 GHz.

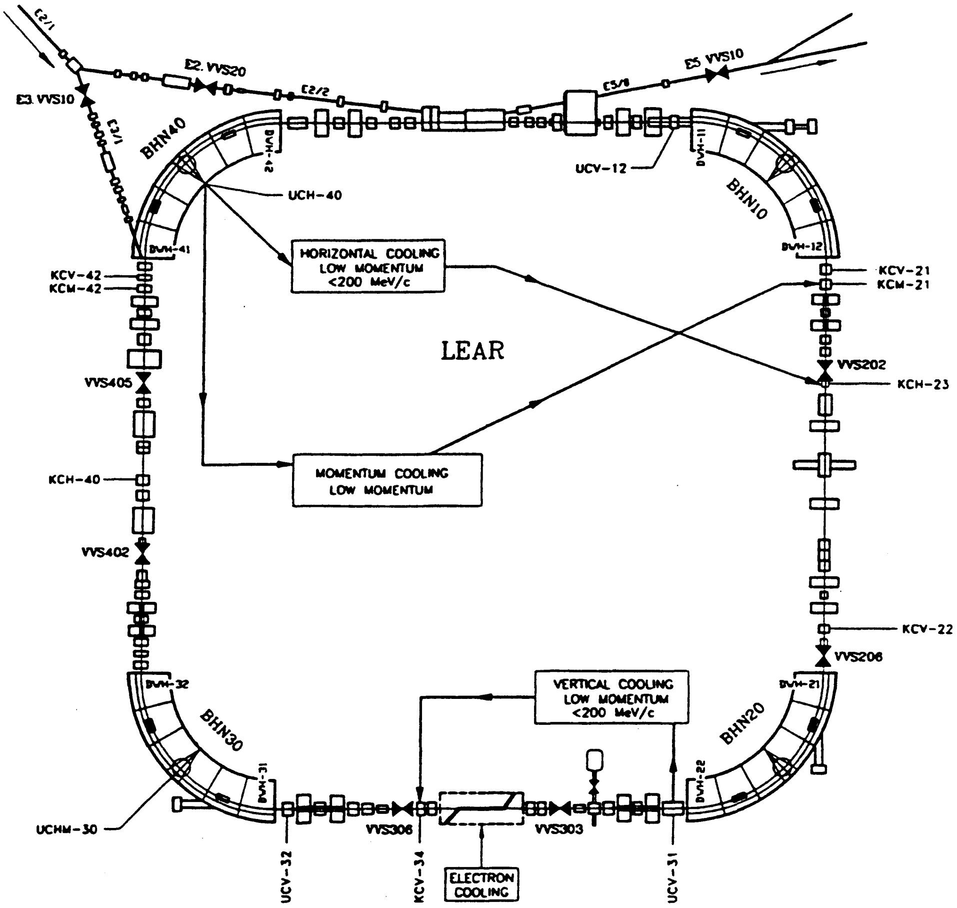

Fig. 2 LEAR low-momentum stochastic cooling systems

3.2 Notch Filters

Both active and passive (notch) filters are in use in the longitudinal cooling systems (Fig. 3). The purpose of the active filters is to increase the steepness of the notch slopes and to provide a better use of the Schottky noise power available from the power amplifier. The principal working points of these cooling systems are 105, 200, 309, 609, 1000, 1500 and 2000 MeV/c for protons and antiprotons. This implies large variations of the required delay settings for both the notch and peak filters as well as for the compensation cables (Fig. 3).

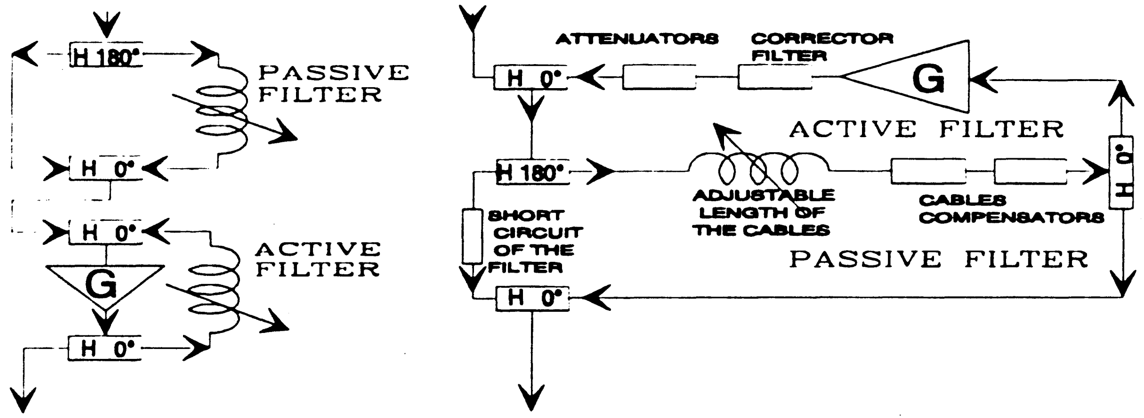

Fig. 3 - Passive and active notch filters used in LEAR. Left: old system, right: improved system.
H = hybrid type power splitter/combiner.

the signals enter a first combiner stage. To satisfy a correct phasing for all required particle momenta, these delay lines are set in steps of 5.7 cm corresponding to 190 ps. The horizontal cooling system (Fig. 1) has 12-loop pairs, also used simultaneously for the longitudinal system, and is located in the bending magnet BHN 30. The vertical system with 8-loop pairs is close to that magnet in position UCV 32 (Fig. 1). Low-noise preamplifiers with a noise figure of 1.4 dB (non-cryogenic) and a frequency range from 5 MHz to 1 GHz ensure a fairly good signal/noise ratio for the pick-up signals. Concerning the kickers, like the pick-ups, an identical coupling loop size is required since different loops could cause unacceptable phase shifts seen by the beam over the complete frequency range of the system.

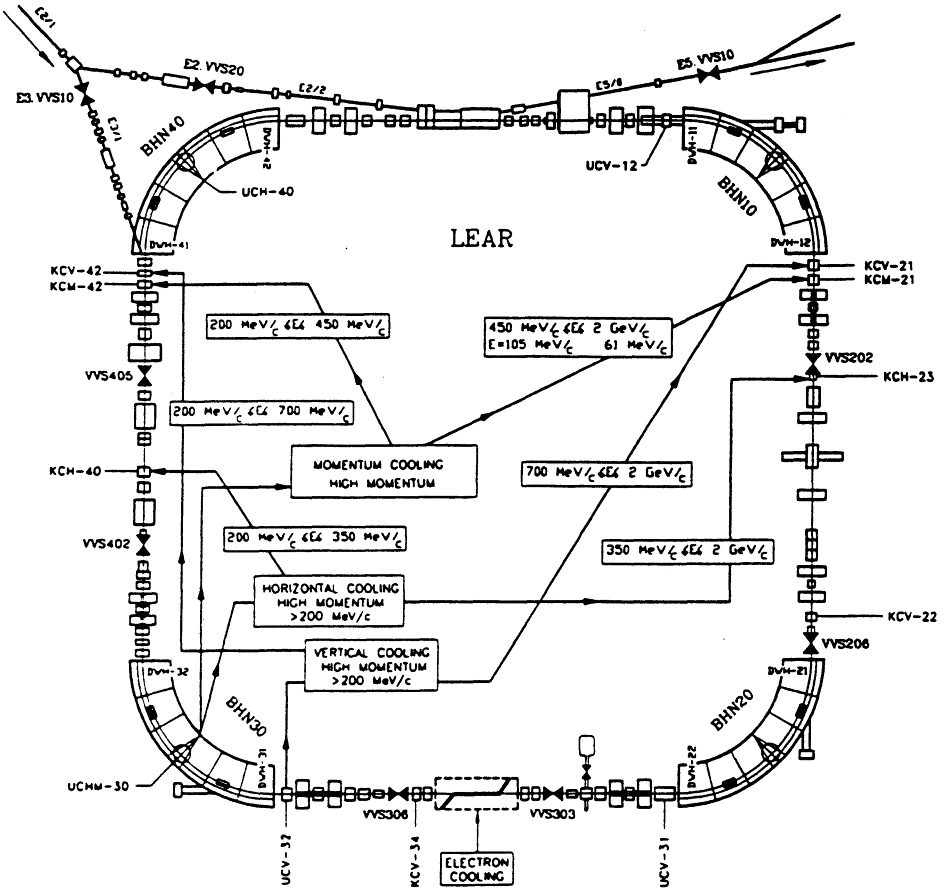

Fig. 1 - LEAR high-momentum stochastic-cooling system

The system delay is digitally set through the control system using a 16-bit data word and can be varied in steps of 41 ps from 0 to 2.7 µs. The short delay variations are implemented as printed circuits (striplines) and extend up to 336 ps. The usable bandwidth of these printed lines is limited to about 1 GHz since beyond that frequency, severe phase distortions appear due to mutual coupling of the striplines.

The maximum system gain defined as the gain sum (in dB) of all amplifiers in the chain corrected by all attenuators (cable losses, combiners, etc.) amounts to about 110 dB. Gain settings are varied by means of a PIN-diode attenuator in steps of 1 dB from 0 to -25 dB.

In some operating conditions, when cooling of particles with a large $\Delta p/p$ is required, overlapping of the Schottky bands towards higher frequencies may occur. In this case the cooling system bandwidth can be limited with an equi-ripple filter, thus allowing for a fast decay in amplitude beyond the cut-off frequency and slight phase distortion.

Until summer 1993 the power amplifier of the longitudinal high-momentum cooling system was a 10 W (CW-sine wave) unit with a passband of 5 MHz-1 GHz. Severe deviation from linear phase beyond 850 MHz led to reduced cooling speed. These phase errors cannot be compensated due to a lack of available electrical delay. A new power amplifier with 4 W output power and a linear phase up to 1.1 GHz has been built. A particular difficulty in these constructions is the requirement of very short electrical length of the unit composed of four commercial amplifier modules and line transformers, for broad-band signal splitting and combination. Practical experience with this improved version showed a considerable increase in the cooling performance, although the usable output power for noise-like signals amounts only to about 1.5 W (4 W CW). A further increase in

Practical and theoretical experience has shown that for the power splitters employed in the filters, hybrid type units should be used, in preference to resistive splitters or just simple split-winding transformers (Fig. 4). As one is aiming for optimum notch depth and periodicity over the band, any asymmetry of signal and reference path will lead to a considerable distortion of notch depth and position.

The tracking of both signal paths in LEAR is within ±1 dB and ±5° of phase corresponding to about 25 dB notch depth in the worst case. If non-hybrid type elements are used for signal splitting and combination, independently of the perfect symmetry in both signal path and reference line, multiple "echos" will occur.

The configuration shown in Fig. 4 (upper part) may be considered as a heavily damped ring resonator with a round trip time corresponding to twice l_1/c. These multiple echos appear as a ripple in the frequency domain response or as a series of "echos" in the time domain. Using 0°/180° hybrid these "echos" are strongly suppressed and a nearly flat response returns. Applying a time-domain gate to a notch filter response with signal and reference paths of different lengths permits the analysis of either path response without the need to disconnect cables.

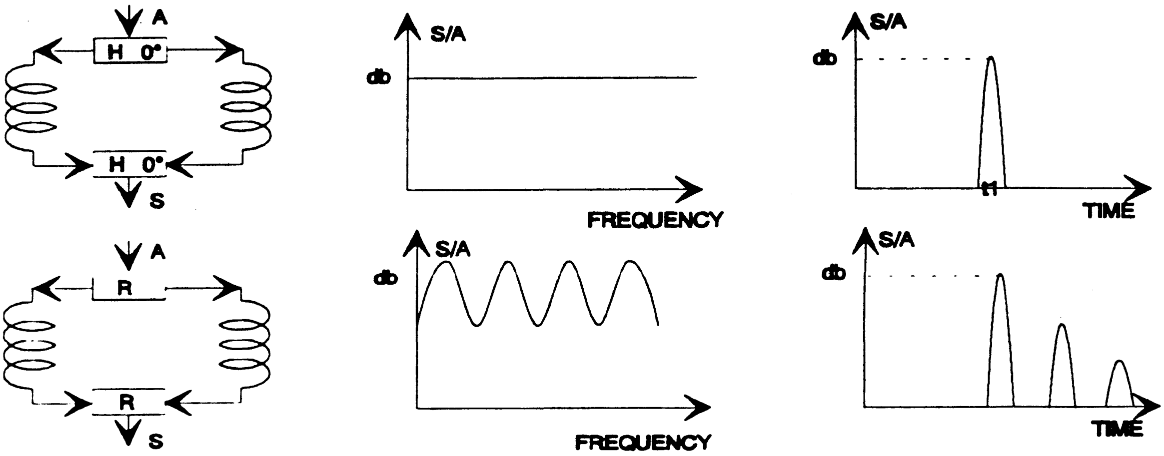

Fig. 4 - Effect of the resistive and hybrid power combiner/splitter

As already mentioned, there is a strong interest to increase the notch filter slopes' steepness, in particular for small $\Delta p/p$. Apart from using peak-filters one can set the periodicity of the notch filter to 1/2 or 1/3, which means that only every second or third notch coincides with a longitudinal Schottky band.

Even when taking into account all the improvements already mentioned, the high-energy LEAR beam fills only 1/10 of the notch width because of its very small η (η = 0.25 at 2000 MeV/c). The use of double and triple notches has significantly increased the cooling speed. It turned out to be very important in this operating condition to maintain steepness, periodicity and depth of the notches to avoid any unnecessary heating of the off-momentum particles.

3.3 Low-Momentum Systems

The low-momentum cooling systems operate at 105 MeV/c and 61 MeV/c. Pick-ups for both the longitudinal and horizontal systems are situated in the BHN 40 bending magnet, with kickers at KCM 21 and KCH 23 (Fig. 2). Similar to the high-energy pick-ups, 12 pick-up plate pairs are also in use here, connected to form a travelling wave structure with delays adapted to 105 and 61 MeV/c, respectively. To increase the signal-to-noise ratio, the termination resistors (50 Ω) are cooled to 20 K in a cryostat and the head amplifiers areoperating at 80 K physical temperature, so that a noise figure below 0.9 dB between 10 MHz and 150 MHz is obtained. There would not be much gain in total signal/noise performance by further reducing the noise figure of the head amplifier to about 0.5 dB. This is because the noise temperature of the pick-up itself (about 1 dB loss, ambient temperature) amounts already roughly to 70 K. It should be mentioned that other types of pick-up structures [3] have been tested, such as the helical and a printed meander pick-up, however with moderate sucess. Another serious problem has been noticed several years ago when interference occurred, linked to the presence of the PS beam. The PS radiates the revolution harmonics in the low MHz range because the skin depth in stainless steel is approaching the material thickness of the PS vacuum chamber. Also, the rf-bypass capacitors foreseen to short-circuit (rf-wise) the dc-isolated sections of the PS-vacuum chamber become less effective at these lower frequencies. It was found that the magnetic-field components of this leakage enter the head amplifiers through the power supply cables and lead to an intermodulation with the stochastic cooling signals. Proper shielding and filtering (cryogenic-compatible components) on this part of the amplifier chain have completely solved the problem. New connectors and vacuum feedthroughs for the cryogenic part (50 Ω resistors, head amplifiers) are at present under construction to simplify mounting and dismantling and to improve the reliability of the contacts.

The longitudinal system uses two different types of notch filter: a conventional one, with coaxial cables and dispersion (loss) compensation is applied for 105 MeV/c; a unique digital filter consisting basically of fast AD converters followed by a digital memory and a DA converter, is applied for the 61 MeV/c range [4].

Pick-up signals from the travelling wave loop couplers with switchable delays outside vacuum (105 MeV/c) are digitized with a fast 200 Megasample 8 bit ADC. The digitized data are transferred through latches into 4 RAMs (random access 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 (500 MHz) for analogue conversion. The subtraction between delayed path and reference path takes place in a broad-band analogue hybrid (180° combiner).

The low-momentum vertical cooling has 5 pairs of coupling loops and the same types of amplifiers and terminations (cryo-pot) as the horizontal system in BHZ 40. Here also, the delays can be dialled for 61 and 105 MeV/c. Kicker signals at KCV 34 can be monitored like on the kicker KCH 23, for proper power settings and intermodulation checks.

4. PERFORMANCE

At high momenta (1 to 2 GeV/c), the stochastic cooling is used in two cases:

1. to retrieve the particles which diffused to lower momenta during the stochastic extraction process, mainly when the extraction time is very long (2 or 3 hours),
2. to get very good beam quality during operation with the Jetset experiment. A hydrogen Jet target of a density of 10^{13} atoms/cm^2 is used and a high number (3×10^{10} to 5×10^{10}) of circulating particles is needed. Then the beam characteristics must be as follows: vertical emittance $<3\pi$ mm·mrad such that the vertical beam dimension at the jet position is smaller than the jet itself (5 mm FWHM), small horizontal emittance ($\sim 3\pi$ mm·mrad) for a good vertex definition of the nuclear reaction, momentum spread $<0.2\%$ at 4π mm·mrad) for a good momentum resolution. These objectives are generally obtained despite the complexity of the operation, where at least one new momentum/day is required by the physicists.

At low momenta (105 to 609 MeV/c) the stochastic cooling has two main goals:

1. to reduce the beam dimensions before deceleration and to compensate the adiabatic emittance increase due to the deceleration. This is still applied for the injection momentum (609 MeV/c) but the electron cooling is used for momenta ≤ 309 MeV/c.
2. to counteract diffusion mechanisms such as intrabeam scattering during the slow extraction process. The need of high fluxes of particles by the experiments and the use of long spills (1 h) necessitate circulating beams of 5×10^{10} to 9×10^{10} particles. In these cases intrabeam scattering becomes important and has to be compensated by stochastic cooling. Transverse emittances of 5π mm·mrad are measured while the momentum spread is maintained below 0.3% at 4π mm·mrad.

5. CONCLUSIONS

The LEAR stochastic cooling systems have undergone several modifications and improvements over the years. Thanks to progress in technologies, better wide-band power amplifiers, the use of BAW (bulk acoustic wave) filters, and printed pick-up and kicker structures, may be considered for the future. For the time being it can be stated that globally speaking all the LEAR stochastic cooling systems work satisfactorily and are reliable. The implementation of further upgrades depends largely on the approval of new experiments and on the extension of the presently scheduled physics antiproton programme.

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