Stochastic Cooling

Aim of Cooling:

⇒ Reduction of emittances
   (transverse and longitudinal).
⇒ Increase of phase space density.

• Basic principle of stochastic cooling

• History

• Simple theory in time domain

• Stochastic cooling at AC/AA

• Stochastic cooling at AD

• Hints for operation
Stochastic Cooling

Basic principle of (transverse) stochastic cooling

Measure position and apply a correction.

One particle passing with maximal position at PU

Particle crossing the reference orbit at PU

⇒ Phase from PU to Kicker: 90° plus a multiple of 180°
Basic principle

A sample of particles passing the cooling system - correction of the mean position.

Cooling is hampered by ... noise:
- from other particles 'in the sample slice'.
- noise from pick-up and electronics.

Longitudinal cooling:
- Palmer cooling (not used for AD): Measure mean energy with a PU at a location with dispersion and correct for it.
- Filter method (quantitative description difficult in time domain).
History of stochastic cooling

1968  Idea of stochastic cooling by van der Meer.
1972  First observation of Schottky noise at ISR.
1972  Theory of transverse stochastic cooling.
1975  First experimental demonstration at ISR.
1975  $\bar{p}$ accumulation schemes for ISR and SPS.
1975  Filter method for momentum cooling.
1977 & 1978  Refinement of theory and detailed experimental verification at ICE.
1981 & 1982  Accumulation of several $10^{11}$ $\bar{p}$’s in AA from batches of several $10^6$ $\bar{p}$’s.
1986 & 1987  Construction of AC.
1983  Observation of W and Z bosons (carriers of the electro-weak force) in Sp$\bar{p}$S
1995  Observation of top-quark at Fermilab.
Schottky scan for $2 \times 10^8$ protons at 2.0 GeV/c in AD

Particles in normalized phase space
Simple theory in time domain
Bandwidth and Kicker response

- Transmission in frequency range $f_1 - f_2$
  i.e. bandwidth: $W := f_2 - f_1$
  nominal for AD: 900 - 1600 MHz (amplifiers)
  realistic: 1200 - 1500 MHz (entire system)

- Arrival at the kicker with a delay $t_d$ (.315µs in AD at 3.57 GeV/c)

- Response in time domain

Band from 0 MHz to 700 MHz

Band from 900 MHz to 1600 MHz
Simple theory in time domain

- One sample contains \( N_S = N(1/2W)/t_{rev} \) out of \( N \) ions (\( t_{rev} \) is the revolution period).

- Measurement (normalized phase space \( \Rightarrow < \xi^2 > = < \xi'^2 > = \varepsilon_\sigma \)) gives \( \tilde{\xi} + \xi_n \), where \( \xi_n \) is due to noise.

- With a correction \( g(\tilde{\xi} + \xi_n) \) (\( g \) is the a factor) the relative emittance change is:

\[
\frac{\Delta \varepsilon_\sigma}{\varepsilon_\sigma} = \frac{< (\xi - g(\tilde{\xi} + \xi_n))^2 > - < \xi^2 >}{< \xi^2 > + < \xi'^2 >} = \frac{-2g\tilde{\xi}^2 - 2\tilde{\xi}\xi_n + g^2(\tilde{\xi} + \xi_n)^2}{< \xi^2 > + < \xi'^2 >}
\]

- Cooling rate is the mean relative emittance decrease per turn divided by \( t_{rev} \):

\[
\frac{1}{\tau} = \frac{1}{t_{rev}} \frac{-\Delta \varepsilon_\sigma}{\varepsilon_\sigma} = \frac{1}{t_{rev}} \left[ \frac{g}{N_S} - \frac{g^2}{2N_S} (1 + U) \right]
\]

with \( U := < \xi_n^2 > / < \tilde{\xi}^2 > \) the noise power to signal power ratio. Note \( < \tilde{\xi}^2 > = < \xi^2 > / N_S \)

- Optimum \( g = (1 + U)^{-1} \) (neglecting mixing) gives:

\[
\frac{1}{\tau} = \frac{W}{N} \frac{1}{1 + U}
\]
The theory in time domain:

- Correct dependancy on number of ions \( N \) and bandwidth \( W \).

- Importance (qualitative) of mixing:
  - Good (wanted) mixing \( M \) Kicker \( \rightarrow \) PU.
  - Bad (unwanted) mixing \( \tilde{M} \) PU \( \rightarrow \) Kicker.

- Mixing difficult to evaluate numerically.

- Filter method for longitudinal stochastic cooling difficult to explain.

A more precise theory in frequency domain:

- Includes filter method for longitudinal cooling.

- Explains attenuation of Schottky sidebands when the cooling loop is closed.

- Transverse cooling time \((M \text{ and } \tilde{M} > 1)\) :
  \[
  \frac{1}{\tau} = \frac{W}{N} \left[ 2g(1 - \tilde{M}^{-2}) - g^2(M + U) \right]
  \]

- Optimum: \[
  \frac{1}{\tau} = \frac{W}{N} \frac{(1 - \tilde{M}^{-2})^2}{M + U}.
  \]
Transverse cooling time for AD at 3.5 GeV/c using the simple formula without mixing

- Bandwidth $W = 300$ MHz (more realistic than the nominal 700 MHz).

- Number of $\bar{p}$: $N = 5 \times 10^7$

- Noise to signal ratio: $U = 1$ to 30 (at large and small emittances respectively).

- Expect to cool from $200 \pi \, \mu m$ to $5 \pi \, \mu m$:
  \[
  \ln \left( \frac{200 \pi \, \mu m}{5 \pi \, \mu m} \right) \frac{5 \times 10^7}{300 \times 10^6 \, s^{-1}} (1 + 10) = 7 \, s. \\
  \]

  Optimistic Value not including effect of mixing.

- Gives correct order of magnitude - design report states 20 s. But we were lucky to obtain such a good result with the simple theory.

- Be careful applying this formula !!!

- Effect of mixing can lead to significantly different results !!!
Stochastic Cooling at AAC
History of first large scale application

• Increase of (6-dimensional) phase space density by a factor \( 10^9 \)!

• \( \bar{p} \) collection in AC:
  – Large acceptances in all 3 planes.
  – Fast cooling of \( \bar{p} \) beam.
  ⇒ Large bandwidth overlapping 3 bands with distinct hardware.
  – Operated at only one energy.

• Accumulation in AA:
  – Accumulation of batches injected from AC.
  – Separation in momentum of stack (in AA) and batch coming from the AC.
  – Cooling of newly injected \( \bar{p} \) into stack.
  – Deceleration (with RF) to bring new batch close to stack.
  – Stack-tail system cools new batch into stack
  – Stack-core system keeps stack small
Stochastic cooling systems in AC

- Band 1: 1.0 - 1.65 GHz
- Band 2: 1.65 - 2.4 GHz
- Band 3: 2.4 - 3.0 GHz

H: horizontal
V: vertical
p: momentum
PRECOOLING
on injection orbit
momentum: 0.8 - 2.4 GHz

STACK-TAIL COOLING
momentum: 0.9 - 1.65 GHz

STACK-CORE COOLING
momentum: 1 - 4 GHz
horizontal: 2 - 8 GHz
vertical: 2 - 8 GHz

Systems in AA
Stochastic Cooling at AD

• Slower Cooling w.r.t. AC can be accepted
  ⇒ Band 1 out of three in AC is sufficient.

• Three cooling systems using two PU and two kickers (horizontal and vertical). Both PU’s
  and both kickers for longitudinal system.

• Cooling at two distinct momenta (and thus ion velocities) implies:
  – Two distinct delays necessary (for all three system) ⇒ (partly) distinct transmission
    paths.
  – Different revolution harmonics ⇒ two distinct notch filters for long. cooling.
  – PU constructed for injection momentum:
    ⇒ at 2.0 GeV/c : lower sensitivity and thus reduction of signal/noise
  – For 2 GeV/c delay correction power amplifiers grouped in 3 blocks

• Programmable PU and Kicker movement as in the AC. (Only PU movement used now)

• Programmable phase invariant attenuators (static and dyn.) to optimize gain.

• Programmable delays (gain invariant) to optimize phase.
Stochastic cooling systems in AD
Hints for Operation
Setting of following example such that:

⇒ Cooling in all three planes at 3.5 GeV/c and at 2.0 GeV/c.

• Check optics of AD, e.g. orbits and working point (tunes).

• Are amplifiers o.k. (DC current) ? They should be used in adjacent pairs.

• Check system switches on stochastic cooling control display.

• Pick-up movement. Closes slowly during 3.5 GeV/c flattop, closed at 2.0 GeV/c and open otherwise. Position reading possible via display ("knob").

• Dynamic attenuators: function increases with time to decrease gain. No way to check execution of programmantion from ACR.

• Check timings and make sure that the system works only during the plateaus required.