Phase Space Cooling in Storage Rings

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Abstract

An introductory overview is given of the history, the status and future trends of storage rings with beam cooling. Achievements obtained with cooling rings are outlined, the main cooling methods operational in circular machines are recalled and some features of the “ion coolers” now under construction or planned are briefly discussed.

It is concluded that the combination of the storage and beam cooling techniques will continue to lead to new discoveries and surprises.

1. Introduction

The title of this introductory talk refers to the aspect of storing particles in circular “machines” and to the related one of cooling them.

I would therefore like to take a few minutes to share with you the amazement about beam stability in storage rings before turning to the — may be even more surprising — subject of beam cooling.

2. Beam stability in storage rings

2.1. Of stars and storage rings

Particles have been stored and kept in rings like the CERN Intersecting Storage Rings (ISR), the experimental Cooling Ring (ICE), the Antiproton Accumulator (AA) or the Low Energy Antiproton Ring (LEAR) for days or weeks. Yet, when the ISR was planned it was by no means clear that beams could be held in order for more than a few minutes. Confronted with the scepticists, Kjell Johnsen, the ISR project leader, would regularly invoke the stability of the universe as an “existence proof”. Let us try to quantify his considerations:

Assuming that our solar system exists for 5 billion years, the earth has made some 5×10^9 revolutions about the sun and the moon some 6×10^{10} turns around the earth. On the other hand particles in a storage ring make 10^{11} or 10^{12} turns per day or per week. Hence we are led to the conclusion that

beam stability in a storage ring is (at least) as surprising as the stability of the solar system. I am indebted to my colleague Michel Martini who drew up these numbers in a recent talk on chaotic behaviour of particle beams.

Continuing our simple-minded “criterion of the number of stable turns”, nature has even more surprising records to offer: Take for instance the hydrogen atom (Bohr’s model) where the electron orbits some 10^{16} times per second around the proton . . . This situates our storage ring problem somewhere between the stability question of the solar system and the hydrogen atom.

2.2. Stellar- and beam-dynamics

The comparison between stars and storage rings is not quite so far-fetched as it might seem on first sight. The mathematical methods both in stellar dynamics and in accelerator physics are very much the same. One has just to replace the gravitational forces prevailing in the universe by the electromagnetic field of the storage ring.

There are numerous sources of perturbation that threaten the order in both beams and galaxies. Resonant build up of orbit errors driven by imperfections of the guiding fields can rapidly destroy a beam. Imagine a 0.1 mm kick per turn as occurs even in carefully designed storage rings. Added up systematically over 10^{11} turns it would lead to a displacement comparable to the diameter of the earth (1.2×10^7 m).

Clearly such resonances have to be avoided. But as the focusing fields of the storage ring are concentrated in quadrupoles or gradient magnets with field-free regions in between, particles “see” their restoring force modulated as they go around. Thus resonances occur at a large number of perturbing frequencies which correspond to the unstable bands of a frequency modulated oscillator (the stop-bands of Hill’s equation).

In addition, unavoidable field nonlinearities lead to higher order “subharmonic resonances” and other field errors introduce coupling between horizontal, vertical and azimuthal motion. The well known general resonance condition [1] is:

$$n_h Q_h + n_v Q_v + n_s Q_s = \text{integer}$$

$$n_h, n_v, n_s = 0, \pm 1, \pm 2 \dots$$

(where the “tunes”, Q , are the horizontal, vertical and longitudinal “eigenfrequency” of the particle in the storage ring field, normalized to revolution frequency).

This relation indicates a threefold infinite number of resonances. It exhibits the difficulty of finding a stable range for the working point $P = (Q_h, Q_v, Q_s)$.

I was told that at the time when strong focusing was invented someone made a statistical analysis and concluded that with overwhelmingly high probability, machines with alternating gradient focusing would be unstable. In fact this

Table I. *Some history of beam cooling by synchrotron radiation*

1907	Classical theory of radiation by electrons in a magnetic field to explain Bohr's model (Schott).
1944–46	Radiation loss in circular electron accelerators (Ivanenko & Pomerantchuk, Schwinger. . .).
1946–47	First experimental observation of "Synchrotron radiation" (Blewett, Pollock <i>et al.</i>).
1949–55	Theory of "Quantum Effects". Beam heating by "quantum fluctuations" (Vladimirsky, Schwinger, Sokolov & Ternov, Sands. . .).
1955–58	Theory of beam cooling (all three planes), theorem on the sum of the decrements, semi-classical theory of equilibrium with "radiation damping" and "quantum excitation" (Robinson, Kolomensky & Lebedev, Sands. . .).
1962	Complete quantum theory giving both "radiation damping" and "quantum excitation" (Gutbrod).
1963	First electron-positron storage ring based on radiation damping (Ada, Frascati).

conjecture is valid assuming that one chooses the working point at random. The reason why strong focusing machines nevertheless work is that the tune values are carefully chosen to avoid dangerous resonances.

There will be more to say on beam stability during the panel discussions at this conference: space-charge forces between the beam particles, coherent instabilities due to direct Coulomb forces or coupling with the beam environment, intra-beam interactions or reactions with the residual gas as well as with internal targets of co-moving beams . . . to name only some intensity, brightness and/or beam lifetime limitations which can be harmful especially in the low energy rings to be discussed at this symposium.

To conclude our detour to the sky let me quote a sentence from one of the very first and by now classical papers on coherent instabilities in storage rings [2]: "... The stability properties of circulating rings of interacting particles were first analysed by Maxwell in his famous essay on the stability of Saturn's rings . . .". Clearly accelerator physics has since long profited from the look at the stars.

Table II. *Some history of electron cooling*

1966	First report by G. Budker (Saclay symposium), proposal of a p-pbar collider using E-cooling.
1967–70	Experimental study on the electron gun (Meshkov).
1974	First experimental demonstration (Novosibirsk group).
1976–77	Observation of "fast cooling", theory of "flattened velocity distribution" and "magnetised electron-beam".
1977–82	Electron-cooling experiments at CERN and FNAL.
1979–...	Proposals of low energy p-bar and ion storage rings with electron cooling (more than 12 proposals to date, at least 8 authorised. . .).
1984	Report on beam-crystallisation in ultra-cold beams (Novosibirsk group).
1987/88	Planned start-up of several storage rings with electron cooling.

Table III. *Some history of stochastic cooling*

1968	Idea of stochastic cooling (van der Meer).
1972	Observation of proton beam Schottky noise (ISR staff), first publication of cooling idea (van der Meer).
1972–75	Hardware studies (Thorndahl, Schnell).
1975	First experimental demonstration (ISR staff). First proposal of pbar accumulation with stochastic cooling.
1977–83	Cooling tests at CERN, FNAL, Novosibirsk, INS-Tokyo.
1980–82	Start-up of the CERN-pbar complex (AA, SPS-collider, ISR-pbar-programme, LEAR).
1982–84	Observation of intermediate vector bosons, Nobel prize 1984 to Rubbia and van der Meer.
1986/87	Start-up of Fermilab pbar facility based on stochastic cooling.

3. Beam cooling

3.1. Overview

We have seen that beams in a storage ring are highly ordered and hence delicate ensembles. Beam cooling aims at an even further increase – or at least a longer preservation – of this surprising orderliness.

Three methods are operational in storage rings:

- Cooling of electron beams *by synchrotron radiation*.
- Cooling of proton and ion beams *by electrons*.
- *Stochastic cooling* of proton and ion beams.

Some dates in the history of their development are given in Tables I–III. In all three cases one notes the relatively long time interval from the first idea or publication to a practical application.

3.2. Some achievements with cooling

Examples of beam cooling are illustrated by Figs. 1–3 which show the reduction in vertical beam size (Fig. 1) or momentum spread (Figs. 2 and 3) and the concurrent increase in beam density during cooling. The essence of beam cooling is thus to increase the beam density and this has been used for at least

Fig. 1. Vertical beam profile before (lower trace) and after electron cooling of a 65 MeV proton beam. Results from the NAP-M ring in Novosibirsk, 1976.

Fig. 2. Stochastic momentum cooling of 5×10^7 particles. Longitudinal Schottky noise signals after 0, 1, 2 and 4 min showing $\sqrt{dN/dp}$ vs. momentum p . The momentum spread is reduced from 3.5×10^{-3} to 5×10^{-4} . Results from the cooling experiment ICE at CERN, 1977.

three purposes:

- (1) the accumulation of rare particles (like positrons, antiprotons and — in the future — exotic ions);
- (2) the compensation of emittance increasing mechanisms;
- (3) the preparation of highly monochromatic and sharply colimated beams for precision studies.

It is the combination of beam cooling with storage ring techniques which has opened new horizons in particle physics research. This development started with the electron positron rings in the 1960s followed by proton-antiproton rings in the 1980s and now by the ion cooling rings to be discussed during this symposium. Electron-positron rings from AdA to LEP (see Tables IV and V) have a remarkable record of producing not only fine beams but also superb physical results. The design has turned from craftsmanship to almost art as documented e.g., by M. Sands classical text on “the physics of electron storage rings” [4]. Although the trend in very large electron-positron machines now-a-days seems towards single pass-colliders, these linear machines need “damping rings” in the injection system to produce the extremely high density beam required. An important fall out of the e^+e^- -ring technology are the synchrotron radiation facilities which provide researchers from a wide variety of fields with the unique light emitted by relativistic leptons bent in a magnetic field.

Achievements with cooling of antiprotons are illustrated

Fig. 3. Longitudinal scan, like Fig. 2, taken during the operation of LEAR in 1985. The momentum spread of 3×10^9 particles at 180 MeV is reduced from 4×10^{-3} to 1.2×10^{-3} in 3 minutes of stochastic cooling.

Table IV. The smallest and the largest e^+e^- collider

	AdA (1963)	LEP 1 (1989)
Circumference	4 m	27 km
Energy	250 MeV	55 GeV
Radiation loss per turn	540 eV	260 MeV
Luminosity	$10^{27} \text{ cm}^{-2} \text{ s}^{-1}$	$10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
Injection system	synchrotron	Linac, accumulator, PS, SPS
Typical radiation damping time constant ($J = 1$)	12 ms	36 ms

by the two examples of Figs. 4 and 5 which show how by storing and cooling 5 to 8 orders of magnitude are gained in intensity and beam quality.

Other results obtained already in the experimental cooling rings NAP-M at Novosibirsk and ICE at CERN include:

- the preparation of ultra cool beams with 10^7 to 10^8 particles with emittances of $1 \pi \text{ mm mrad}$ and a momentum spread of 10^{-4} ;

Table V. Electron positron storage rings (adapted from [3])

Device	First operation	Type	Energy per beam (GeV)
AdA (dismantled) Nat. Lab. of C.N.E.N., Frascati	1963	Single ring	0.25
Princeton-Stanford Storage Rings (dismantled) Stanford Univ.	1964	Tangent rings	0.56
VEPP-2 Novosibirsk, USSR	1965	Tangent rings	0.04
ACO Orsay Lab. Paris	1966	Single ring	0.5
ADONE Nat. Lab. of C.N.E.N., Frascati	1965	Single ring	1.5
SPEAR Stanford Linear Acc. Center	1972	Single ring	4.2
DORIS DESY, Hamburg	1974	Single ring	4.5
VEPP-2M Novosibirsk, USSR	1975	Single ring	1.3
DCI Orsay Lab. Paris	1975	Interlaced rings	3.7
VEPP-3 Novosibirsk, USSR	1977	Single ring	3
VEPP-4 Novosibirsk, USSR	1978	Single ring	7
PETRA DESY, Hamburg	1978	Single ring	19
CESR Cornell Univ.	1979	Single ring	8
PEP Stanford Linear Acc. Center	1980	Single ring	18
TRISTAN KEK, Tokyo	1986	Single ring	30
LEP CERN	1989	Single ring	55

Fig. 4. The Antiproton Accumulator AA. Sketch of layout and table of design performance, comparing the properties of the $\bar{p}$ -pulse from the target injected every 2.6 s and the beam at the end of stacking.

- the non-destructive observation of as few as 50 particles, after cooling their spread in revolution frequency to 10^{-5} ;
- the increase of the lifetime of stored low energy beams by a factor of 50 by compensating for the heating due to scattering on the residual gas.

Many of these results had long been anticipated by the Novosibirsk group [5].

3.3. Ion cooling ring projects

In the light of the achievements of $\bar{p}$ cooling rings (Table VI), it was natural to consider the application of similar techniques

to other rare particles like heavy-ions and/or polarized beams.

In 1980, R. Pollock *et al.* [6] proposed adding a cooling ring to the Indiana Cyclotron. This proposal was followed by at least ten other ion cooler ring projects (Table VII). Three are now in an advanced stage of construction.

Although these projects cover a wide range both in physics goals and parameter space, a few common features can be discerned [7]:

a typical cooler ring is a storage ring of 50 to 150 m circumference with:

- two or several relatively long straight sections to include beam cooling devices and apparatus for physics with the circulating beam;
- different families of straight sections or variable optics to adapt to the requirements of different experiments;
- ultra-high vacuum, a low frequency RF system with large frequency swing, densely packed straight sections . . . ;
- electron cooling (in all) and provision for stochastic cooling (in most of the projects);
- internal targets in conjunction with phase-space cooling for high resolution studies;
- different modes of operation of the same machine (storage ring, accelerator, recirculator, accumulator, duty-cycle stretcher, post-stripper, comoving or collider beams);
- different types of stored particles;

New possibilities opened up with these cooling rings include:

- the accumulation of rare ions;
- post stripping to obtain higher charge states;
- the provision of high quality extracted beams;
- high resolution experiments with circulating beam and internal target;
- high resolution experiments with the internal beam and a co-moving ion or laser beam or with colliding beams;
- long time beam storage for special experiments at low energy;
- accelerator research.

More details will be discussed in B. Franzke's talk [8] at this conference.

4. Cooling methods

The two cooling methods for heavy particles [9, 10] tested with protons (and protons and Alpha particles at TARN) seem well suited for other ions. Cooling by electrons [9]

Cooled beam from LEAR.
Several 10^5 antiprotons/s
Typical beam size $5 \times 5 \text{ mm}^2$

300 MeV/c beam from
production target:
200 antiprotons/s +
several 10^4 conta-
minants
Beam size $4 \times 4 \text{ cm}^2$

Fig. 5. Progress with LEAR. Sketch of the size and performance figures of a secondary 300 MeV/c antiproton beam from a target as used prior to 1979. Comparison with the beam extracted from LEAR.

Table VI. Proton, and antiproton cooling rings

Machine	First operation as cooling ring	Function	Circumference (m)	Max energy (MeV)	Type of cooling*
<i>Cooling experiments</i>					
NAP-M Novosibirsk, USSR	1974	Experimental cooling ring	47	65	E
ISR, CERN	1975	P-P-Collider used for cooling exp.	960	26 000	S
ICE, CERN	1977	Experimental cooling ring	72	1 400	S E (1978)
Cooling ring Fermilab	1980	Experimental cooling ring	135	200	S E
TARN I INS-Tokyo	1982	Experimental cooling ring storage ring	33	7	S
<i>Antiproton cooling rings</i>					
AA, CERN	1980	Antiproton accumulator	165	2 800	S
ISR, CERN	1981	Antiproton physics	960	25 000	S
LEAR, CERN	1982	Low energy antiproton physics	78	1 300	S E (1987)
Fermilab P-source Debuncher ring accumulator	1986	Antiproton accumulator	505	8 000	S
			474	7 900	S
ACOL	1987	Antiproton collector to upgrade AA	182	2 800	S

* E: Electron cooling, S: Stochastic cooling.

uses — as you known — an electron beam which travels together with the ions over part of the storage. The electrons absorb transverse and longitudinal energy deviation of the ions by Coulomb interaction. Viewed in the “electron rest frame” moving with the electrons, ions are “stopped” similarly to the slowing down of particles in matter by virtue of their energy loss to the atomic electrons. A simple estimate of the cooling time can be made using the binary collision model in which the ion interacts only with one electron at a time. This permits the scaling of the results from protons to ions, noting that the energy transfer per collision and hence the cooling rate scale like:

$$1/\tau \propto q^2/A$$

This suggests fast cooling for highly charged ions. However, these ions can more easily pick up cooling electrons and get lost from the storage ring, owing to the change of their charge state. In fact, the recombination rate due to radiative electron capture scales approximately like:

$$1/\tau_r \propto q^2$$

For protons, typical cooling and recombination times are $\tau = 50\text{ ms to }10\text{ s}$, $\tau_r = 10^5\text{ s to }10^6\text{ s}$ both strongly dependent on proton and electron beam parameters. Scaling to heavier ions, one concludes that electron cooling of heavy ions seems feasible with at worst a few percent recombination loss per

Fig. 6. The principle of (horizontal) stochastic cooling: The pick-up measures horizontal position; the kicker corrects angular deviation. They are spaced by a multiple plus one quarter of the betatron wavelength. A positron error at the pick-up transforms into an error of angle at the kicker. This angular error is corrected.

Table VII. *Ion cooling rings*

Machine	First operation as cooling ring	Function	Circumference (m)	Max energy (MeV/u)	Type of cooling
IUCF cooler Bloomington USA	1988	Light ion cooler	87	500	E
TARN II INS-Tokyo	1988	Light ion cooler	76	1300	E, S
TSR, Heidelberg Germany	1988	Light and medium ion cooler	55	25	E, S
CELSIUS Upsalla, Sweden	1989	Light ion cooler	82	1200	E
ASTRID Aarhus, Denmark	1989	Light and heavy ions, electrons	40	38	E, (S)
CRYRING Stockholm, Sweden	1990	Light and heavy ion cooler	49	24	E, (S)
ESR, GSI Darmstadt Germany	1990	Heavy ion cooler	108	830	S, E
COSY KFK Jülich, Germany	1992	Light ion cooler	184	2500	E, S
OSAKA COOLER RCNP, Osaka, Japan	1992	Light ion cooler	125	1500	E, (S)
HISTRAP ONRL, Oak Ridge USA	Proposal	Heavy ion cooler	47	47	E, (S)
SR LBL, Berkeley	Study	Heavy ion cooler	~ 100	~ 700	S, E
BCR BNL, Brookhaven USA	Study	Low energy heavy ion cooler	~ 50	~ 30	S, E

cooling time. However, if one wants to apply cooling for long periods, one will have to reduce the electron current, which of course also reduces the cooling strength.

More details will be given in A. Sørensen's [11] and A. Wolf's talks [12] on electron cooling during this conference.

Stochastic cooling [10] uses an electronic feedback system as indicated in Fig. 6 to correct the momentum deviation and the betatron oscillations of each individual particle. A set of pick-up electrodes senses the error of a particle; the signal is amplified in a high-gain wide-band amplifier and applied on a corrector down-stream in the storage ring. Accepting a fair amount of simplification, cooling may be viewed as the competition between two effects: the action of a test particle upon itself via the cooling system ("coherent effect") and the perturbing action of the other particles on the test particle ("incoherent heating effect"). Owing to the finite bandwidth (W) of the cooling system, the correction signal of a particle will be present during a time $T_s = 1/2W$, where T_s is the response time of the system. All particles passing during this time interval will influence the test particle. To minimize their heating effect, it is important to have large bandwidth and a small number of particles.

These qualitative considerations may help to understand the cooling-rate expression, which can be written as:

$$1/\tau = (W/N) \cdot \text{"const"}$$

In the best of all cases, "const" = 1. For practical systems "const" $\approx 1/10$ at the start of cooling with a tendency to decrease as the beam shrinks. In our simple model, the cooling rate is independent of the ion properties. More elaborate models indicate a greater ease in bringing "const" closer to 1 for highly charged ions.

Present day systems work with cooling times of 1 s for 10^7 particles or 1 day for 10^{12} . A factor of 10 will be gained in the near future by pushing the bandwidth into the gigahertz region. This imposes, however, other severe constraints (e.g., the choice of transition energy and the cooling system power) on the storage ring design. A discussion is beyond the scope of this introduction. All we want to retain here is that fast stochastic cooling is restricted to relatively small intensity beams.

Comparing the two cooling methods, one notes a certain complementarity: electron cooling works best for beams which are already cool: the transfer of energy is most efficient when ion and electron cross each other slowly. Stochastic cooling works best for a large beam which induces strong error signals on the pick-up. The two can then be combined for strong "core cooling" by electrons and "halo cleaning" by the stochastic method.

Fig. 7. The principle of cooling by synchrotron radiation: A relativistic electron moving in the magnetic field of a storage ring emits synchrotron radiation which is sharply peaked in the forward direction. The corresponding energy loss leads to a friction force (F) opposite to the direction of motion. For a "nominal particle" (a) the energy loss is restored (and hence F compensated) by the RF-system. For a real particle (b) the residual friction force (dF) is proportional to its deviation from nominal conditions and tends to damp out the deviation.

The third cooling method, namely damping by synchrotron radiation [4], [12] works due to the fact that the radiation emitted by a relativistic particle moving in a magnetic field is sharply peaked in the forward direction. The continuous emission of synchrotron light leads to a "friction force" F opposite to the direction of motion. For a nominal particle moving on the design orbit (Fig. 7) the energy loss is restored (and hence F compensated) by the RF-system. For a real particle the residual friction force (dF) therefore tends to damp out the deviation from the nominal orbit.

The energy loss per turn can be written as:

$$eU_0 = 9.54 \times 10^{-10} \text{ eV m} \left[\frac{E}{m_0 c^2} \right]^4 \int \frac{ds}{\rho^2}$$

where ρ is the radius of curvature of the orbit and the integral is taken once around the ring. Thus the loss depends very strongly on the rest-mass of the particle and this explains why radiation damping is (so far) only important for light particles.

In terms of this energy loss the cooling rate in any of the three planes (x : horizontal, z : vertical, s : longitudinal) is:

$$1/\tau_i = \frac{1}{T_0} \left[\frac{eU_0 J_i}{E} \right]$$

where T_0 is the revolution period and the damping partition numbers J_i depend on the details of the storage ring ion optics. The three partition numbers are related by Robinson's theorem [14]:

$$J_x + J_z + J_s = 4$$

Two examples are included in Table IV.

All three cooling methods have stimulated a rich development of both physics ideas and hardware. The flattened distribution and the magnetised electron effects leading to unexpectedly fast electron cooling [11], [12] or potential ordering effects in ultra cold beam (beam liquefaction or crystallisation) [15] are examples of the first kind. The special technology of low temperature electron beams and the energy recuperation in a collector device essential in the electron cooler [12] are examples of technological developments as are the low-noise high-power wideband "Hi Fi" systems [16] needed for stochastic cooling.

The ion cooling rings planned or under construction will no doubt lead to further achievements in cooling theory and practice. In addition to the established methods, new cooling principles for ions like laser cooling and inelastic intra-beam scattering look promising as we will hear from O. Poulsen [17] and K. Kilian [18] during this workshop.

5. Conclusions

– Beam stability in a storage ring is as surprising as the stability of the universe, beam cooling is – maybe – even more surprising.

– Cooling of circulating electron-positron and more recently antiproton beams has opened, . . . and cooling of ion beams will open, spectacular new possibilities.

– The three cooling methods used to date in storage rings are operative. Theory and hardware are adequate to cover the more direct applications foreseen in the near future. New cooling methods for heavy ions are on the horizon.

– The physics of beam cooling is very rich in itself and holds the promise of further surprises.

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