Summary

- Beam temperature, emittance; Liouville’s theorem
- Beam cooling; Non-Liouvillean processes
- Electron cooling theory
- Electron cooling: practical implementations

- In my lecture I will use the Gaussian units:
  \[ e = 4.8 \times 10^{-10} \text{ G.U.}, \quad c = 3 \times 10^{10} \text{ cm/s} \]
Beam sources

- The simplest conceptual model of an electron beam source is a planar diode.
  - Cathodes typically operate at 1400K ($kT \approx 0.12$ eV)
  - An effective work function is about 1.6 eV
- Ion sources are generally more complex. The ions are typically extracted from the plasma of a gas discharge.
Beam temperature

- The electrons in the tail of the Fermi-Dirac distribution inside a cathode and the ions in the plasma source have a Maxwellian velocity distribution given by

\[
f(v_x, v_y, v_z) = f_0 \exp \left[ - \frac{m(v_x^2 + v_y^2 + v_z^2)}{2kT} \right]
\]

- For electrons: \( v_{rms} = \sqrt{kT} \approx 6 \cdot 10^7 \sqrt{T_e} \text{[cm/s]} \)

- The thermal velocity spread of electrons (or ions) remains present in the beam at any distance downstream of the source. However, it may increase or decrease as will be discussed later.

- Let’s assume that the beam propagates in the z-direction
Beam acceleration

- Suppose that the initial state, which we will denote by $i$, corresponds to the distribution emerging from the particle source:

$$f_i(v_i) = f_0(v_x, v_y) \exp \left[ -\frac{m(v_i^2)}{2kT_i} \right]$$

where $v_i, T_i$ stand for initial $v_z, T_z$.

- After acceleration the distribution will be:

$$f_f(v_f) = f_0(v_x, v_y) \exp \left[ -\frac{m(v_f^2 - v_0^2)}{2kT_f} \right], \text{ where } v_f^2 = v_i^2 + v_0^2$$

and $\frac{mv_0^2}{2} = eV_0 = E_k$
Beam acceleration (cont’d)

- The new temperature: \( kT_f = m\left(\frac{v_f^2}{2} - \left[\frac{v_f}{2}\right]^2\right) \)

\[
\bar{v}_f^2 = \left(\bar{v}_i^2 + v_0^2\right) = \bar{v}_i^2 + v_0^2
\]

\[
\left(\bar{v}_f\right)^2 = \left(\sqrt{\bar{v}_i^2 + v_0^2}\right)^2 = v_0^2 \left(1 + \frac{1}{2} \frac{\bar{v}_i^2}{v_0^2} - \frac{1}{8} \frac{\bar{v}_i^4}{v_0^4} + \ldots\right)^2
\]

\[
\left(\bar{v}_f\right)^2 = v_0^2 + \bar{v}_i^2 + \frac{1}{4} \frac{\left(\bar{v}_i^2\right)^2}{v_0^2} - \frac{1}{4} \frac{\bar{v}_i^4}{v_0^4} + \ldots
\]

Finally, we have

\[
kT_f \approx \frac{m}{4v_0^2} \left(\frac{\bar{v}_i^4}{2} - \left[\frac{\bar{v}_i^2}{2}\right]^2\right) \approx \frac{(kT_i)^2}{2E_k}
\]
The cooling effect predicted by this equation is very dramatic. Take, for example, an electron beam with an initial temperature of \( kT = 0.1 \text{ eV} \). After acceleration to \( E_k = 10 \text{ keV} \), the longitudinal temperature drops, while transverse does not change:

\[
kT_f \approx 6 \times 10^{-7} \text{ eV}
\]

- Relativistic expression:

\[
kT_f \approx \frac{(kT_i)^2}{\beta^2 \gamma^2 mc^2}
\]
Beam density effect on long. temperature

- Let’s estimate the mean potential energy of electrons after acceleration:

\[ E_p \approx Ce^2 n^{1/3} = Cmc^2 r_e n^{1/3} \]

where \( C \) is a numeric constant (\( \sim 2 \)), \( n \) - particle density, \( r_e \) - classical electron radius (2.8e-13 cm)

- Example: 1-Amp electron beam at 10 keV, beam radius \( a = 1 \text{-cm} \):

\[ n = \frac{I_b}{\pi a^2 \beta ce} \approx 3.4 \cdot 10^8 \text{ cm}^{-3} \]

Thus, \( E_p \approx C \cdot 10^{-4} \text{ eV}!!! \)

- After acceleration, the long. temperature dramatically drops, but then starts increasing due to electron-electron interactions. The rate of increase depends on beam density and other factors.

S. Nagaitsev – Electron Cooling
## Emittance

- Typically, $T_i$ is much smaller than the kinetic energy after acceleration. Thus, each particle has a velocity only slightly different from $v_0$. In the lab. frame a particle velocity has angles w.r.t. the $z$-direction:

$$\theta_x \equiv x' = \frac{v_x}{v_0} \quad \quad \theta_y \equiv y' = \frac{v_y}{v_0}$$

- Let’s define the *rms emittance* as:

$$\epsilon_x = \left( \frac{1}{2} xx'^2 - xx'^2 \right)^{1/2}$$

Similarly, for $y$...

- Emittance is a measure of the beam’s phase-space area (or volume)
Emittance (cont’d)

- Electron beam: 1-cm radius \((a)\), uniform density, kinetic energy \(E_k = 10\) keV, emitted from a cathode with \(kT_i = 0.1\) eV

\[
\varepsilon_{\text{rms}} = \frac{a}{2v_0} \left( \frac{kT_i}{m} \right)^{1/2} = \frac{a}{2\beta} \left( \frac{kT_i}{mc^2} \right)^{1/2}
\]

(*home work problem)

- Relativistic expression:

\[
\varepsilon_{\text{rms}} = \frac{a}{2\beta\gamma} \left( \frac{kT_i}{mc^2} \right)^{1/2}
\]

- Let’s define the normalized emittance:

\[
\varepsilon_n = \beta\gamma \varepsilon_{\text{rms}}
\]

- This quantity is independent of beam energy.

- For the above example \(\varepsilon_n = 2.2\) \(\mu\)m
Liouville’s theorem

(1) Historical Background

- Joseph Liouville 1838
  - proof of a result on the material derivative of the “Jacobian” of the transformation exerted by the solution of an ordinary differential equation on its initial condition
  - “Nachlaß” of Liouville ... 340 notebooks at approximately 50,000 pages

- → Transport Theorem

- → Liouville Equation (LE)

- → Fokker–Planck Equation (FPE)

- → Liouville Theorem (LT)
Ces considerations generales deviennent beaucoup plus claires lorsqu'on les applique au cas particulier où $n = 3$. On a alors

$$
\begin{align*}
2 &= \frac{dx}{da} \frac{dx}{db} \frac{dP}{dc} \\
+ \frac{dx}{da} \frac{dx}{db} \frac{dP}{dc} \\
+ \frac{dx}{da} \frac{dx}{db} \frac{dP}{dc}
\end{align*}
$$

et par le calcul direct, on trouve, en omettant les termes qui se detruisent, et en remplaçant $x^m$ par $P$,

$$
\begin{align*}
\frac{du}{da} &= \frac{dx}{da} \frac{dx}{db} \frac{dP}{dc} \\
+ \frac{dx}{da} \frac{dx}{db} \frac{dP}{dc} \\
+ \frac{dx}{da} \frac{dx}{db} \frac{dP}{dc}
\end{align*}
$$

expression qui devient nulle en effet, lorsqu'on met au lieu de

$\frac{dP}{dx}$, $\frac{dP}{db}$, $\frac{dP}{dc}$ leurs valeurs respectives.

Tomes III. - Janvier 1838.
Liouville’s paper

(3) The result of J. Liouville 1838

- **Liouville’s proof.** He considered the differential equation, assuming solution existence:

\[ x''' = P(t, x, x', x'') \quad \rightarrow \quad x = x(t, a, b, c) \quad (2.0.1) \]

He defined \( u \), the determinant of the Jacobian:

\[ u = u(a, b, c, t) = \det \begin{pmatrix}
\frac{\partial x(t, a, b, c)}{\partial a} & \frac{\partial x(t, a, b, c)}{\partial b} & \frac{\partial x(t, a, b, c)}{\partial c} \\
\frac{\partial x'(t, a, b, c)}{\partial a} & \frac{\partial x'(t, a, b, c)}{\partial b} & \frac{\partial x'(t, a, b, c)}{\partial c} \\
\frac{\partial x''(t, a, b, c)}{\partial a} & \frac{\partial x''(t, a, b, c)}{\partial b} & \frac{\partial x''(t, a, b, c)}{\partial c}
\end{pmatrix} \quad (2.0.2) \]

He showed that it is true that (while noting the chain rule differentiation):

\[
\frac{\partial u}{\partial t} = u \frac{\partial P}{\partial x''} 
\]

\[
\frac{\partial x'''}{\partial a} = \frac{\partial P}{\partial a} = \frac{\partial P}{\partial x} \frac{\partial x}{\partial a} + \frac{\partial P}{\partial x'} \frac{\partial x'}{\partial a} + \frac{\partial P}{\partial x''} \frac{\partial x''}{\partial a} \quad (2.0.3)
\]

He generalized the result to \( n \)-th order equations and to a system of first-order equations.
In physics, Liouville's theorem, is a key theorem in classical statistical and Hamiltonian mechanics. It asserts that the phase-space distribution function is constant along the trajectories of the system - that is that the density of system points in the vicinity of a given system point travelling through phase-space is constant with time.

\[
N = \int d^d q \, d^d p \, \rho(p, q)
\]

\[
\frac{d \rho}{dt} = \frac{\partial \rho}{\partial t} + \sum_{i=1}^{d} \left( \frac{\partial \rho}{\partial q^i} \dot{q}^i + \frac{\partial \rho}{\partial \dot{p}_i} \dot{p}_i \right) = 0.
\]

In the simple case of a non-relativistic particle moving in Euclidean space under a force field \( F \) with coordinates \( x \) and momenta \( p \), Liouville's theorem can be written as

\[
\frac{\partial \rho}{\partial t} + \frac{p}{m} \cdot \nabla_x \rho + F \cdot \nabla_p \rho = 0.
\]
In simple words

No system of magnets or electro-magnetic fields can reduce the phase-space density of beam

The density of particles in phase-space, or the phase-space volume occupied by a given number of particles remains invariant under Hamiltonian forces.
Consequence of Liouville’s theorem

- While the volume in phase space remains constant, the shape generally does not. In fact, nonlinearities (aberrations) in the field configurations may cause considerable distortions (filamentations)
  - Examples: spherical aberrations; synchrotron motion
Emittance and Liouville’s theorem

- Normalized emittance is an *approximate* (but very convenient) measure of the phase-space volume.
- In an ideal linear accelerator with a perfect vacuum and no interactions between particles the emittance should remain constant.
- However...
**Why cool beams?**

- Particle accelerators, by imparting high energies to charged particles, create a beam in a state with a virtually limitless reservoir of energy in one (longitudinal) degree of freedom. This energy can couple (randomly and coherently) to other degrees of freedom by various processes, such as:
  - scattering;
  - improper bending and focusing;
  - interaction with environment (e.g. vacuum chamber);
  - radiation;

- Normally, it is necessary to keep energy spreads in the transverse degrees of freedom at $10^{-4}$ of the average longitudinal energy.
**What is beam cooling?**

- Cooling is a reduction in the phase space occupied by the beam (of same number of particles).
- Equivalently, cooling is a reduction in the random motion of the beam.
Examples of NON-COOLING

- Beam scrapping (removing particles with higher amplitudes) is NOT cooling.
- Expanding the beam transversely would lower its transverse temperature. This is NOT cooling.
- Coupling between degrees of freedom may lead to exchange of energies. If the dynamics is Hamiltonian, this is NOT cooling.
- We carefully reserve the term “beam cooling” for non-Hamiltonian processes where Liouville’s theorem is violated; i.e., where there is an increase in phase-space density.
Need for cooling

- Injection help: stacking, accumulation, phase-space manipulation etc.
- Antiparticle production: accumulation of many pulses of antiparticles
- Internal fixed target: emittance grows from target scattering
- Colliding beams: beam-beam effects, residual gas scattering
- Precise Energy Resolution: narrow states, threshold production
Types of beam cooling

- Stochastic cooling
- Synchrotron radiation
- Electron cooling
- Laser cooling (of certain ion beams)
- Ionization cooling (not yet tested)
- A technique for rapid transverse cooling in a straight transport line has yet to be found.
How does electron cooling work?

The velocity of the electrons is made equal to the average velocity of the ions.
The ions undergo Coulomb scattering in the electron “gas” and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.
Binary collisions

Let's consider the simplest case of a single stationary Coulomb center, interacting with a monochromatic beam of particles, moving in z-direction.

Consider only “binary collisions”.

The trajectory is a hyperbola, such that,

\[ \tan \left( \frac{\theta}{2} \right) = \frac{\rho_\perp}{\rho} \]

where \( \rho_\perp = \frac{e_\alpha e_\beta}{mu^2} \) is the 90-degree impact parameter.
The “friction” force

- Let’s now find the friction force, \( F \), acting on the scattering center, \( \alpha \).
- From symmetry \( F \) can only be along z-direction
  \[
  \vec{F} = -\frac{\vec{u} m}{u} \frac{d}{dt} \sum_{\beta} u_{z}^{\beta}
  \]
- Scattering is elastic – only direction of \( u \) changes!
The friction force

- The z-projection of particle velocity:
  \[
  \Delta u_{z}^{\beta} = -2u \sin^{2} \frac{\theta}{2} = -2u \frac{\rho_{\perp}^{2}}{\rho_{\perp}^{2} + \rho^{2}}
  \]

- Thus, the force \( F \)
  \[
  \vec{F} = -\frac{u}{u} \int m \Delta u_{z}^{\beta} n_{\beta} u d\sigma = \frac{u}{u} \left( 4\pi m n_{\beta} u^{2} \rho_{\perp}^{2} \right) \int_{0}^{\infty} \frac{\rho d\rho}{\rho^{2} + \rho_{\perp}^{2}}
  \]

- The integral diverge logarithmically
- Let’s introduce a “cut-off”, the maximum impact parameter \( \rho_{\text{max}} \gg \rho_{\perp} \)
- Then
  \[
  \Lambda \equiv \int_{0}^{\rho_{\text{max}}} \frac{\rho d\rho}{\rho^{2} + \rho_{\perp}^{2}} \approx \ln \left( \frac{\rho_{\text{max}}}{\rho_{\perp}} \right)
  \]
The friction force

- Finally, we obtain

\[ \vec{F} = \frac{4\pi}{m} e_\alpha^2 e_\beta^2 n_\beta \Lambda \frac{\vec{u}}{u^3} \]

where \( \Lambda \) is the so-called Coulomb log

- Truncating the integral is not a “trick”. There is always some “cut-off” (i.e. beam radius or Debye shielding)

- Debye shielding (homework problem):
  - At impact parameters greater than Debye radius, \( D \), the coulomb potential decays exponentially

\[ D \approx 740[\text{cm}] \sqrt{\frac{T[\text{eV}]}{n[\text{cm}^{-3}]}} \]
Moving foil analogy

- Consider electrons as being represented by a foil moving with the average velocity of the ion beam.
- Ions moving faster (slower) than the foil (electrons) will penetrate it and will lose energy along the direction of their momentum (\(dE/dx\) losses) during each passage until all the momentum components in the moving frame are diminished.

\[ \vec{F}^* = -\nabla^* E^* = -\frac{4\pi n^* (r_e mc^2)^2 \Lambda}{m v_p^*} \cdot \frac{\vec{v}_p^*}{v_p^*} \]

* represents rest frame
Friction force (cont’d)

• For an arbitrary electron distribution function (for example):

\[
f(\vec{v}_e) = \frac{1}{(2\pi)^{3/2} \sigma_{ex} \sigma_{ey} \sigma_{ez}} \exp\left(-\frac{v_{ex}^2}{2\sigma_{ex}^2} - \frac{v_{ey}^2}{2\sigma_{ey}^2} - \frac{v_{ez}^2}{2\sigma_{ez}^2}\right)
\]

a moving ion experiences the following force:

\[
\vec{F}_b(\vec{V}_p) = -4\pi \cdot m_e r_e c^4 n_{eb} \eta \cdot \Lambda \cdot \int \frac{\vec{V}_p - \vec{v}_e}{|\vec{V}_p - \vec{v}_e|^3} f(\vec{v}_e) d^3 v_e \equiv A \int \frac{\vec{V}_p - \vec{v}_e}{|\vec{V}_p - \vec{v}_e|^3} f(\vec{v}_e) d^3 \vec{v}_e
\]
Electron cooling

- Was invented by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.

- First mentioned at Symp. Intern. sur les anneaux de collisions à électrons et positrons, Saclay, 1966: “Status report of works on storage rings at Novosibirsk”

SYMPOSIUM INTERNATIONAL
SUR LES ANNEAUX DE COLLISIONS
A ELECTRONS ET POSITRONS

Sous la présidence de
Monsieur Alain Peyrefitte
Ministre délégué chargé de la recherche scientifique
et des questions atomiques et spatiales

tenu à
Institut National des Sciences et Techniques Nucléaires, Saclay
26-30 Septembre 1966

Édité par
H. ZYGIER
ORSAY
S. NAGAITSEV - Electron Cooling
STATUS REPORT OF WORKS ON STORAGE RINGS AT NOVOSSIBIRSK

SHORT SUMMARY OF THE TALK GIVEN BY:

G.I. Budker

During the year elapsed since our last meeting in Frascati, the work in our Institute on colliding beams has been developed in three directions.

On electron-electron storage ring VEP-1 were performed high energy physics experiments: electron-electron elastic scattering (1) and double bremsstrahlung production for energies up to 2 x 160 MeV (2).

On electron-positron ring VEPE-2, we investigated the storing of electrons and positrons. After a first stage devoted to the understanding of numerous beam instabilities (3-7), experiments on electron-positron interaction at 2 x 380 MeV were undertaken (8). Currents as high as 2 A of electrons and 20 mA of positrons were obtained with single beams, and 70 mA of electrons and 10 mA of positrons with interacting beams. At present time we already have detected some elastic scattering events at large angle and creations of \(\pi\)-meson pairs.

We have started working on the construction of our third set-up designed for proton-antiproton colliding beam experiments at energies up to 2 x 25 GeV. We are looking into the possibility of using this set-up also for electron-positron colliding beam experiments up to 2 x 6 GeV. It was decided that a second ring allowing proton-proton collisions will not be built since CERN undertook the construction of such a machine at a similar energy. The main tunnel for the machine is under completion. We are now experimenting different components of the system.
Fig. 1 shows the general lay-out of the set-up, with the accelerator-injector, the small and the big storage rings. The injector is an ironless proton synchrotron accelerating protons up to 500 MeV. Experiments on charge exchange injection into such a synchrotron have shown the possibility of obtaining currents near the space-charge limit (9).

Lack of radiation damping for heavy particles somewhat complicates their accumulation. We are working out in our institute a method of artificial damping through interaction between the proton beam and an electron beam. In discussions with prof. O’Neill, I found out that they also contemplated such a method several years ago, and named it "electron cooling".

The stacking process in the proton-antiproton machine can be divided into several stages. The first one is the stacking of protons in the big storage ring. The length of the proton bunch in the synchrotron injector allows its capture in the large ring without loss of particles in one bucket of the 300th harmonic of the revolution frequency. After filling of the 300 buckets, the RF frequency is switched to the first harmonic. The particles are then accelerated to the maximum energy, and this reduces the bunch length approximately to the length of the small ring. Then the protons are ejected towards a special target to create antiprotons which are injected into the small ring.

According to our estimations, electron cooling will take about 100 seconds. Then, for the lifetime of one day, we can have about 1000 cycles of antiproton injection. After that, antiprotons will be re-injected into the big ring where colliding beam experiments will be performed.

- Was a professor of physics at Princeton University (1965-1985). He invented and developed the technology of storage rings for the first colliding-beam experiment at Stanford. He served as an adviser to NASA. He also founded the Space Studies Institute.
Budker's formula

\[
\tau_{\text{Maxwellian}} = \frac{3}{8\sqrt{2\pi}} \cdot \frac{A}{Z^2} \cdot \frac{m_p m_e}{e^4 n_e} \cdot \left( \frac{T_i}{A m_p} + \frac{T_e}{m_e} \right)^{3/2}
\]

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ORSAY

S. Nagaitsev – Electron Cooling
Electron cooling was first tested in 1974 with 68 MeV protons at NAP-M storage ring at INP(Novosibirsk).
1974 - First experimental success and first report on electron cooling of protons in NAP-M:

- $E_p = 50$ MeV, $I_p = 50 \mu A$
- $E_e = 37$ keV, $I_e = 0.1$ A
- $\phi_{p\_equilibrium} = 1$ mm
- $\tau_{cool} = 3$ sec - in full agreement with Budker's theory (classic plasma formulae).

NEW EXPERIMENTAL RESULTS OF ELECTRON COOLING

Presented to the All Union High Energy Accelerator Conference, Moscow, October 1976

(Translated at CERN by O. Barbalat)
Improvements: B-field homogeneity in the cooling section – about 10^{-4},
electron energy stability – better than 10^{-5}.

As result - “... the betatron oscillation damping time is inversely proportional to the electron current
and for a current of 0.8 A it amounts to 83 ms (proton energy of 65 MeV) –
much shorter of “The Budker’s numbers!”

What a puzzle!
Puzzle explained...

- “Flattened” electron velocity distribution

\[ T_{||} = \frac{T^2_{\text{Cathode}}}{\beta^2 \gamma^2 mc^2} \]

- The role magnetic field - magnetized cooling

Interaction of an ion with “a Larmor circle”
The role of the solenoidal field

The solenoidal magnetic field allows to combine strong focusing with the requirement (for efficient cooling) of low electron transverse temperature in the cooling interaction region;

Cooling rates with a "strongly" magnetized electron beam are ultimately determined by the electron longitudinal energy spread only, which can be made much smaller than the transverse one.
Effects of a strong magnetic field

• It is obvious that the influence of magnetic field becomes important when the duration of an ion-electron interaction exceeds the Larmor oscillation period:

\[ \rho > \frac{v_r}{\omega_L} \equiv \frac{mcv_r}{eH} \]

• If the ion velocity is small compared to the electron velocity spread and the impact parameter is large, the ion practically interacts with a Larmor “circle” moving only along the magnetic field. This might lead to an order of magnitude enhancement in the cooling force.
Friction force for various degrees of magnetization


Figure 2. Behaviour plotted against friction force at different values of magnetic field. Curve 1: in the absence of magnetic field, curve 2: under the condition of partial magnetization, curve 3: complete magnetization of transverse electron motion.
First cooler rings

Europe – 1977 – 79, Initial Cooling Experiment at CERN

M. Bell, J. Chaney, H. Herr, F. Krienen, S. van der Meer,

USA – 1979 – 82, Electron Cooling Experiment at Fermilab

T. Ellison, W. Kells, V. Kerner, P. McIntyre, F. Mills, L. Oleksiuk,

S. Nagaitsev – Electron Cooling
Stochastic cooling was invented by Simon van der Meer in 1972 and first tested in 1975 at CERN in ICE (initial cooling experiment) ring with 46 MeV protons. FNAL - 1980.

-- Simon van der Meer

1984 Nobel Laureate in Physics
Fermilab
Electron Cooling Experiment
Design Report

Participants: J. Bridges, J. Gannon, E.R. Gray, J. Griffin, F.R. Huson,
D.E. Johnson, W. Kells, P.E. Mills, C. Moore, G. Nicholls,
L. Oleksiuk, T. Rhoades, D.E. Young, Fermilab; P.M.
McIntyre, C. Rubbia, Harvard; W.B. Herrmannsfeldt, SLAC;
D. Cline, J. Rhoades, Wisconsin.

Fermi National Accelerator Laboratory
Batavia, Illinois

August, 1978

Operated by Universities Research Association Inc.
Under Contract with the United States Department of Energy

S. Nagaitsev - Electron Cooling
APPENDIX I

FERNILAB $\vec{P} \times P$
$\sqrt{s} = 500/2000$ GeV

GOALS:
- Proton "cooling" experiment
  1. Electron "cool" 200 MeV proton (11/78)
  2. Accumulate 200 MeV protons (11/78)
  3. First $\bar{P}$ into cooling ring (3/79)
  4. First $P$ into main ring (3/79)

STEP 1. PRODUCE $\bar{P}$, DECCELERATE $\bar{P}$, COOL $\bar{P}$ (6 sec.)
- Accelerate 200 MeV H$^-$ in Linac and inject into booster (normal operation).
- Strip H$^-$ at injection into booster to load booster with p (normal operation).
- Inject 5 GeV p into main ring and accelerate to 100 GeV (normal operation).
- Extract 100 GeV p into target and produce 5.2 GeV $\bar{P}$.
- Inject 5.7 GeV $\bar{P}$ into booster and decelerate to 200 MeV.
- Inject 200 MeV $\bar{P}$ into cooling ring and "cool" with 110 KeV a.
Fred Mills, one of the Fermilab physicists working on the electron cooling tests in 1980, writes:

One of our regular visitors at Fermilab was Kolya Dikansky, who had so brilliantly constructed NAP-M and carried out the INP cooling experiments. When we were close to cooling at Fermilab, Kolya brought us a bottle of vodka. He had written on it simply, “Don’t open without cooling.”

The first cooling took place at 4:40 AM one morning. Don Young and Peter McIntyre had tuned the ring and electron system all night and I came in at 4:00 AM for the next 12 hour shift. I noticed that although the conditions favored resonance crossing, the beam loss pattern was not usual, so I asked for a few minutes to check the RF. I simply turned down the RF from several kV to 10-15 V, and after a slight frequency adjustment, observed the beam (all 100,000 protons!) cool into a tiny bucket. We immediately called Russ Huson. When Russ arrived, we and others who happened along, opened and drank the vodka according to Kolya’s instructions.
Fermilab’s legacy: Cool Before Drinking...
Second Generation of Cooler Storage Rings

1988 - IUCF Cooler Ring (Bloomington, IN, USA)

1988 - Test Storage Ring (MPI, Heidelberg, Germany)

1988 - Low Energy Antiproton Ring (CERN)

1989 - TARN-II (“Test Accumulator Ring for NUMATRON, Tokyo University, Japan)

1989 - CELSIUS (Uppsala University, Sweden)

1990 - Experimental Storage Ring (GSI, Darmstadt, Germany)
Second Generation of Cooler Storage Rings

1992 - COoler-SYnchrotron (FZ Juelich, Germany)

1992 - CryRing (MSI, Stockholm, Sweden)
1993 - ASTRID (Aarhus University, Denmark)

1998 - SIS (GSI, Darmstadt, Germany)

2000 - Heavy Ion Medical ACcelerator (NIRS, Japan)

2000 - Antiproton Decelarator (CERN)

2002 - Electrostatic cooler storage ring at KEK (KEK, Tsukuba, Japan)
ESR Electron Cooler at GSI (Darmstadt)

electron beam parameters

- energy: 1.6–250 keV
- current: 1 mA – 1 A
- diameter: 50.8 mm
- gun perveance: 1.95 μP
- collection efficiency: > 0.9998

- temperature
  - transverse: 0.1 eV
  - longitudinal: ~ 0.1 meV

magnetic field

- strength: 0.015 – 0.2 T
- straightness: 1 × 10^{-4}

vacuum

- 2 × 10^{-11} mbar
2005 - Recycler Electron Cooler (Fermilab, USA)

2006 - Two cooler rings complex (IMP, Lanzhou, China)

2006 - Low Energy Ion Ring (CERN)

20?? - TARN-II-renovated (RIKEN, Japan)

2005 - S-LSR : Solid magnet Laser equipped cooler Storage Ring (Kyoto University, Japan)
Electron cooling applications

- Particle physics with “electron cooled” protons, deuterons and antiprotons:

  ✓ Antiproton physics => LEAR

  ✓ $\pi$-meson physics => IUCF, COSY, CELSIUS

  ✓ First antihydrogen generation in-flight => LEAR (stochastic cooling)

  ✓ Antihydrogen generation in traps => AD => ATHENA and ATRAP
Electron cooling applications

- Nuclear physics

✓ Studies of radioactive nuclei and rare isotopes, exotic nuclei states (like bare nuclei decay, etc.) =>
  => ESR

✓ High precision mass spectroscopy => ESR

- New stage of experiments in atomic and molecular physics =>
  => TSR, CryRing, ASTRID
Mass-spectrometry of radioactive nuclei at GSI
Mass spectrometry of excited nuclear states

Schottky Spectra of Ground and Isomeric State of $^{145}$Gd$^{63+}$

$^{145m}$Gd$^{63+}$ (1 particle)
$E_{ax} = (748.7 \pm 0.1)$ keV
$T_{1/2}(^{145m}$Gd$^{0+}) = 85$ s
$J^e = 11/2^-$
$\beta^+ = 5.7$

$^{145g}$Gd$^{63+}$ (1 particle)
$E_{ax} = (750 \pm 50)$ keV
$T_{1/2}(^{145g}$Gd$^{0+}) = 23.0$ min
$J^e = 1/2^+$
$\beta^+ = 100$

$m/\Delta m = 700 000$
Detection of single cooled ion at GSI

high sensitivity due to well defined revolution frequency and high ion charge (Schottky noise $\alpha q^2$)
Energy loss by the beam due to residual gas after electron cooling is turned OFF
Ordering effects in coasting and bunched ion beams

CRYRING, Manne Siegbahn Lab
Phase transition to a 1D crystal (string). Min. dist. btw. ions 4 mm

More information in
Most recent addition to the electron cooling family - a 300-kV cooler at IMP, Lanzhou

- Built and commissioned by Budker INP
- Has implemented several novel ideas:
  - Electrostatic electron beam bends
  - Variable-profile electron beam
  - Extra-uniform (1ppm) guiding magnetic field
1 - electron gun; 2 - main “gun solenoid”; 4 - electrostatic deflectors; 5 - toroidal solenoid; 6 - main solenoid; 7 - collector; 8 - collector solenoid; 11 - main HV rectifier; 12 - collector cooling system.
Schematic of Fermilab's Electron Cooler
Electron beam parameters

- Electron kinetic energy \(4.34\ \text{MeV}\)
- Absolute precision of energy \(\leq 0.3\ %\)
- Energy ripple \(\leq 10^{-4}\)
- Beam current \(0.5\ \text{A DC}\)
- Duty factor (averaged over 8 h) \(95\ %\)
- Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms \(\leq 0.2\ \text{mrad}\)
Where do we get antiprotons?

The Antiproton Source is made up of three parts. The first is the Target: Fermilab creates antiprotons by striking a nickel target with protons. Second is the Debuncher Ring: This triangular shaped ring captures the antiprotons coming off of the target. The third is the Accumulator: This is the storage ring for the antiprotons. Recently, we have added another ring, the Recycler, for additional antiproton storage.
The Recycler is a fixed-momentum (8.9 GeV/c), permanent-magnet antiproton storage ring.

The Main Injector is a rapidly-cycling, proton synchrotron. Every 1.5-3 seconds it delivers 120 GeV protons to a pbar production target. It also delivers beam to a number of fixed target experiments.
Electron cooling system setup at Fermilab

Pelletron
(MI-31 building)

Cooling section solenoids
(MI-30 straight section)
Electron cooling: long. drag rate

- For an antiproton with zero transverse velocity, electron beam: 500 mA, 3.5-mm radius, 200 eV rms energy spread and 200 μrad rms angular spread

\[ F_p \approx -\lambda p \]

Non-magnetized cooling force model

\[ F = 4\pi n_e m_c^2 \Lambda \int_{-\infty}^{+\infty} f(v_e) \frac{v_e - v_p}{|v_e - v_p|^3} d^3 v_e \]

Linear approx.

\[ f(v_e) = \frac{1}{(2\pi)^{3/2} \sigma^2} \exp \left[ -\frac{v_{e\perp}^2}{2\sigma_{\perp}^2} - \frac{v_{e\parallel}^2}{2\sigma_{\parallel}^2} \right] \]

\[ \sigma_{\perp} = \beta \gamma \theta_e c \]

\[ \sigma_{\parallel} \approx \frac{\delta E}{\beta \gamma mc} \]

\[ n_e = \frac{J_{CS}}{\gamma e \beta c} \]

S. Nagaitsev - Electron Cooling

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Cooling force - Experimental measurements

- Two experimental techniques, both requiring small amount of pbars, coasting (i.e. no RF) with narrow momentum distribution and small transverse emittances
  - 'Diffusion' measurement
    - For small deviation cooling force (linear part)
    - Reach equilibrium with ecool
    - Turn off ecool and measure diffusion rate
  - Voltage jump measurement
    - For momentum deviation > 2 MeV/c
    - Reach equilibrium with ecool
    - Instantaneously change electron beam energy
    - Follow pbar momentum distribution evolution
Cooling rate for small amplitudes

- For small momentum deviations (< 1 MeV) the cooling force is linear: \( F \approx -\lambda p \). The distribution function in momentum is close to being Gaussian.

\[
\sigma_{rms}^2 = \frac{D}{2\lambda}
\]

- Cooled by 500 mA electron beam on axis
- RMS spread: 0.17 MeV/c
- 5x10^{10} pbars, 2 mm mrad (n, 95%)
By turning the electron cooling OFF and ON again one can determine both the diffusion and cooling rates. 

Cooling OFF:

$$\sigma(t) = \sqrt{\sigma_0^2 + Dt}$$

Cooling ON:

$$\sigma(t) = \sqrt{\left(\frac{\sigma_0^2}{2\lambda} - \frac{D}{2\lambda}\right) \exp(-2\lambda t) + \frac{D}{2\lambda}}$$

$$D \approx 2.5 \text{ MeV}^2/\text{hr}$$

$$\lambda \approx 43 \text{ hr}^{-1}$$

5x10^{10} \text{ pbars, 2 mm mrad (n, 95%) }
Drag force measurements: electron energy jump by +2 keV

Momentum distribution (log scale)

Evolution of the weighted average of the pbar momentum distribution function

Beam emittance was measured by Schottky: 1.5 μm (n, 95%).
In the cooling section this corresponds to a 0.9 mm radius (rms), electron current 500 mA

Cooling force is in reasonable agreement with predictions
Conclusions

- Beam cooling is widely used, but each cooling technique has a limited range of applicability.
- Low energy electron cooling (for ions below 500 MeV/nucleon) found many excellent experimental applications in nuclear and atomic physics.
- Fermilab now has a world-record operational electron cooling system:
  - Since the end of August 2005, electron cooling is being used on (almost) every Tevatron shot.
  - Electron cooling allowed for the latest advances in the Tevatron luminosity.