8. Phase-space cooling

Liouville's theorem states that "*the particle density in 6-dimensional phase-space of non-interacting particles is constant in the presence of conservative forces*". A change of the phase-space distribution can only be caused by **dissipative forces**, as there are:

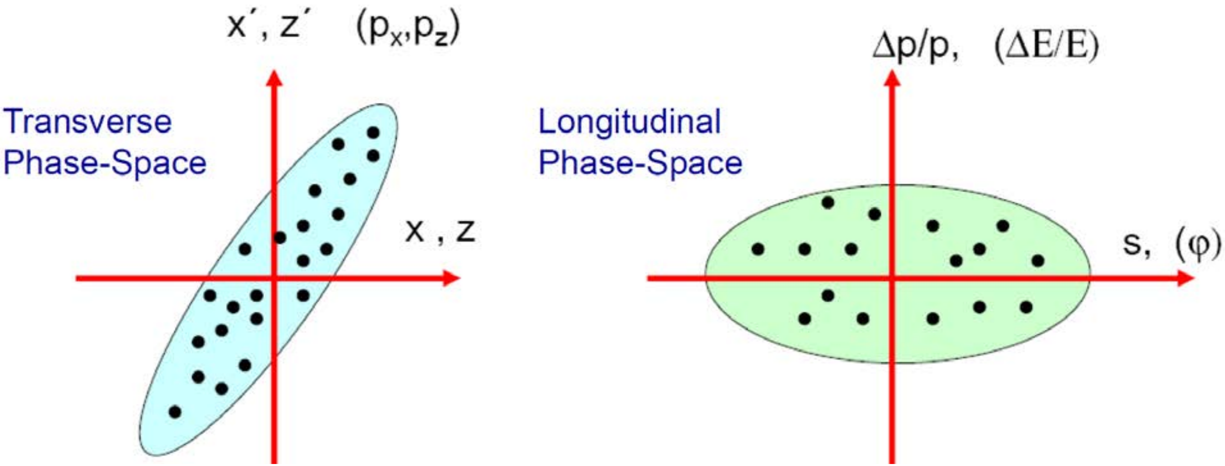
- **residual gas scattering**
- **beam-beam and beam-target interaction**
- **intra-beam scattering**
- **synchrotron radiation**
- **phase-space cooling**

So far, we have treated the influence of synchrotron radiation on electrons, leading to an equilibrium distribution in phase-space (natural emittances and energy spread). Due to the γ^4-scaling, its effect on protons and ions is completely negligible! Here, we will concentrate on cooling methods for protons/ions based on dissipative forces:

- **electron cooling**
- **stochastic cooling**
- ionization cooling
- laser cooling

8.1. Beam emittance and temperature

The particle distributions in the transverse and longitudinal phase-spaces is



The beam quality can be characterized by the are in phase-space or by the temperature of a particle beam which depends on the particle's average speed v* in the centre-of-mass frame of the particle beam moving with the average speed $\beta_r c$:

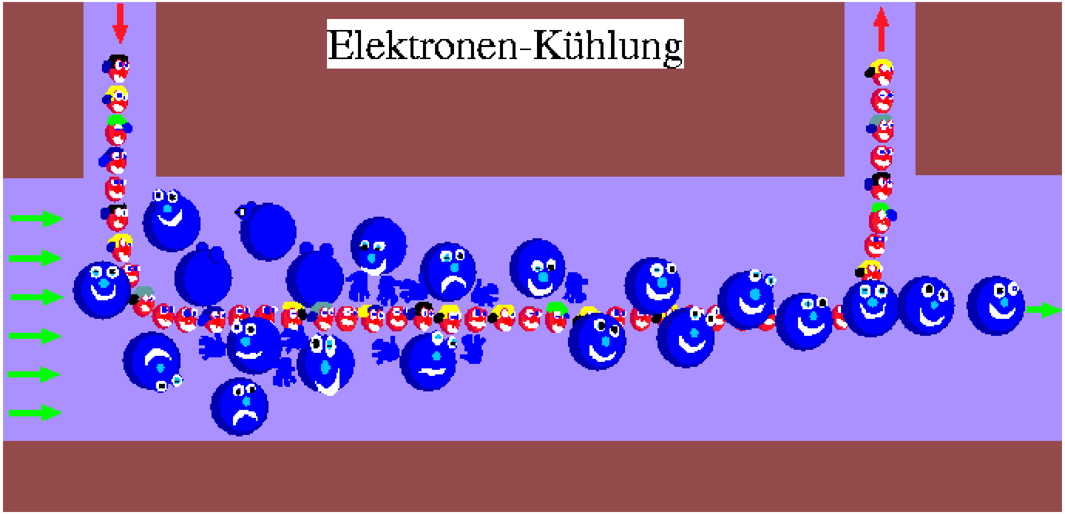
$$\frac{3}{2}k_B T = \frac{1}{2}m\overline{\mathrm{v}^{*2}} = \frac{1}{2}m\left(\overline{\mathrm{v}_x^{*2}} + \overline{\mathrm{v}_z^{*2}} + \overline{\mathrm{v}_s^{*2}}\right)$$

After applying the Lorentz transformations, we get approximately

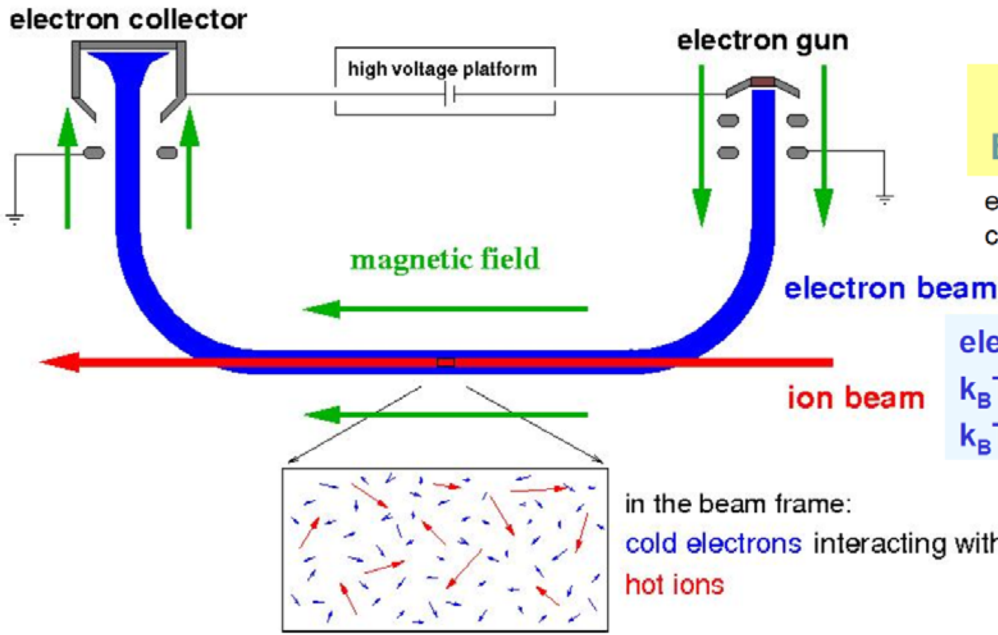
$$\frac{3}{2}k_B T = k_B T_\perp + \frac{1}{2}k_B T_\parallel \approx \frac{1}{2}mc^2\left(\beta_r\gamma_r\right)^2\left\{\left(\frac{\varepsilon_x}{\langle\beta_x\rangle} + \frac{\varepsilon_z}{\langle\beta_z\rangle}\right) + \frac{1}{\gamma_r{}^2}\left(\frac{\sigma_p}{p}\right)^2\right\}$$

8.2. Electron cooling

Invented by Gersh Budker in 1966, first published in Sov. Atomic Energy 22, 1967:



8.2.1. Typical set-up of an electron cooler



$v_{e//} = v_{i//}$

$E_e = m_e / M_i \cdot E_i$

e.g. :220 keV electrons
cool 400 MeV/u ions

electron temperature

$k_B T_\perp \approx 0.1$ eV

$k_B T_{//} \approx 0.1 - 1$ meV

in the beam frame:
cold electrons interacting with
hot ions

superposition of a cold intense electron beam with the same velocity

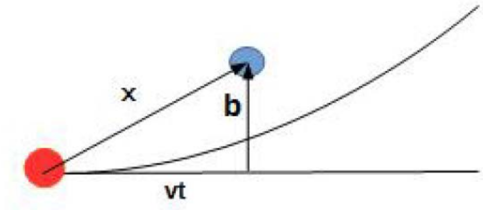
momentum transfer by Coulomb collisions

cooling force results from energy loss in the co-moving gas of free electrons

8.2.2. Cooling force

The force experienced by an ion when passing a single electron is

$$\vec{F} = \frac{d\,\vec{p}}{dt} = -\frac{Ze^2\vec{x}}{4\pi\varepsilon_0\left|\vec{x}\right|^3} = -\underbrace{\frac{Ze^2\vec{\mathrm{v}}t}{4\pi\varepsilon_0\left|\vec{x}\right|^3}}_{F_\parallel} - \underbrace{\frac{Ze^2\vec{b}}{4\pi\varepsilon_0\left|\vec{x}\right|^3}}_{F_\perp}$$

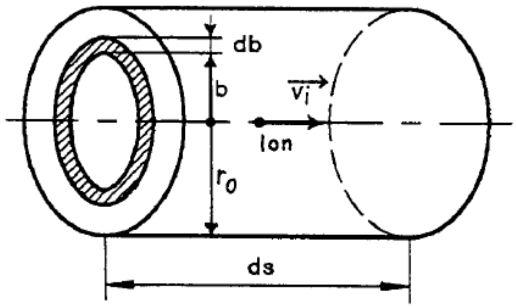


The longitudinal momentum change can be neglected for small angle scattering (integral of an odd function), whereas the transverse momentum change is given by

$$\Delta p = \int_{-\infty}^{\infty} -\frac{Ze^2}{4\pi\varepsilon_0}\frac{b}{\sqrt{(\mathrm{v}t)^2+b^2}^{\,3}}\,dt = -\frac{Ze^2}{2\pi\varepsilon_0 \mathrm{v} b}$$

The energy loss of the ion which is that gained by the electron is then

$$\Delta E = \frac{(\Delta p)^2}{2m_e} = \frac{2e^4Z^2}{(4\pi\varepsilon_0)^2 m_e b^2 \mathrm{v}_i^{\,2}} = \frac{2Z^2\cancel{e}^4}{m_e b^2 \mathrm{v}_i^{\,2}}$$



Now we will regard multiple collisions with all possible impact parameters *b*. The number of electrons in the volume $\pi b^2 ds$ will be $\pi b^2 n_e ds$ and $dn = 2\pi b n_e ds\, db$ is the number of electrons between *b* and *b*+d*b* in ds. The energy loss per unit length can then be obtained by integrating over all possible impact parameters:

$$\frac{dE}{ds} = 2\pi \int_{b_{\min}}^{b_{\max}} b n_e \Delta E \cdot db = \frac{4\pi Z^2 \cancel{e}^4}{m_e \mathrm{v}_i^2} n_e \underbrace{\ln\left(\frac{b_{\max}}{b_{\min}}\right)}_{L_C \approx 10}$$

where $b_{\min} = Z\cancel{e}^2 / m_e \mathrm{v}_i^2$ can be determined from the maximum possible momentum transfer to the electron ($= 2m_e \mathrm{v}_i$, head-on collision) and $b_{\max} = \min(r_e, \lambda_D)$. In general, the electrons are not mono-energetic and we have to weight over the electron distri-

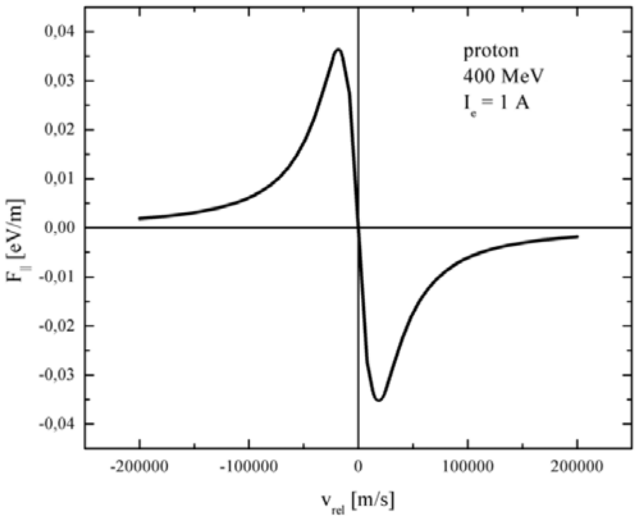
bution function $$f(\mathrm{v}_e) = \frac{m_e}{\sqrt{2\pi k_B T_{e,\|}}} \left(\frac{m_e}{\sqrt{2\pi k_B T_{e,\perp}}}\right)^2 e^{-\frac{m_e \mathrm{v}_{e,\|}^2}{2k_B T_{e,\|}}} \cdot e^{-\frac{m_e \mathrm{v}_{e,\perp}^2}{2k_B T_{e,\perp}}}$$

and obtain for $T_{\|} \ll T_{\perp}$ the friction or cooling force

$$\vec{F} = -4\pi \left(\frac{Ze^2}{4\pi\varepsilon_0} \right)^2 \frac{n_e L_C}{m_e} \int f(\mathrm{v}_e) \frac{\vec{\mathrm{v}}_i - \vec{\mathrm{v}}_e}{\left| \vec{\mathrm{v}}_i - \vec{\mathrm{v}}_e \right|^3} \cdot d^3\mathrm{v}_e$$

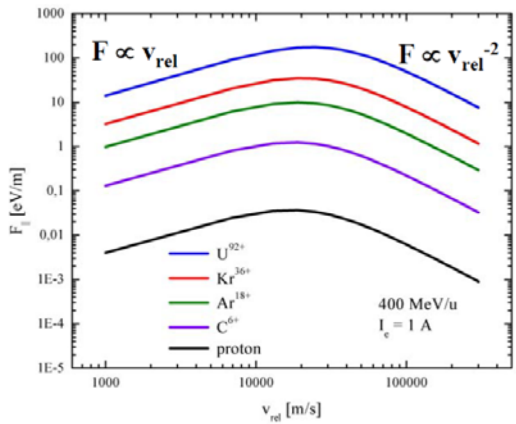
where $T_{\|,\perp}$ is the electron transverse and longitudinal temperature, respectively.

8.2.4. Characteristics of the cooling force



increases with charge: ∝ Q²

maximum at electron temperature



Assuming an exponential decrease of the ion velocity we get for the cooling time

$$\frac{1}{\tau_{\mathrm{v}_i}} = -\frac{1}{\mathrm{v}_i}\frac{d\mathrm{v}_i}{dt} = -\frac{1}{\mathrm{m}_i \mathrm{v}_i}\left(m_i \frac{d\mathrm{v}_i}{dt}\right) = -\frac{F(\mathrm{v}_i)}{p_i}$$

for large relative velocities

cooling time $\tau_z \propto \frac{A}{Q^2}\frac{1}{n_e \eta}\beta^3\gamma^5\theta_z^3 \begin{cases} \theta_{x,y} = \frac{v_{x,y}}{\gamma\beta c} \\ \theta_{\|} = \frac{v_{\|}}{\gamma\beta c} \end{cases}$

cooling rate:

- slow for hot beams $\propto \theta^3$
- decreases with energy $\propto \gamma^{-2}$ ($\beta\gamma\theta$ is conserved)
- linear dependence on electron beam intensity n_e and cooler length $\eta = L_{ec}/C$
- favorable for highly charged ions Q^2/A
- independent of hadron beam intensity

for small relative velocities

cooling rate is constant and maximum at small relative velocity

$F \propto v_{rel} \Rightarrow \tau = \Delta t = p_{rel}/F = \text{constant}$

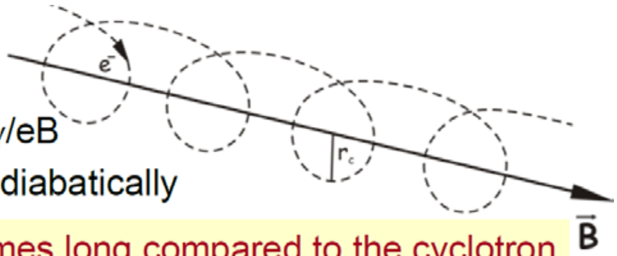
8.2.5. Magnetized cooling

single particle cyclotron motion

cyclotron frequency $\omega_c = eB/\gamma m_e$

cyclotron radius $r_c = v_\perp/\omega_c = (k_B T_\perp m_e)^{1/2}\ \gamma/eB$

electrons follow the magnetic field line adiabatically



important consequence: for interaction times long compared to the cyclotron period the ion does not sense the transverse electron temperature

magnetized cooling ($T_{eff} \approx T_{//} << T_\perp$)

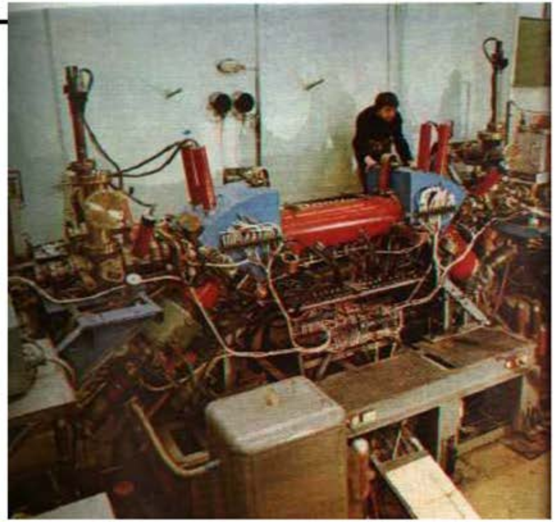
<u>Conclusions:</u>

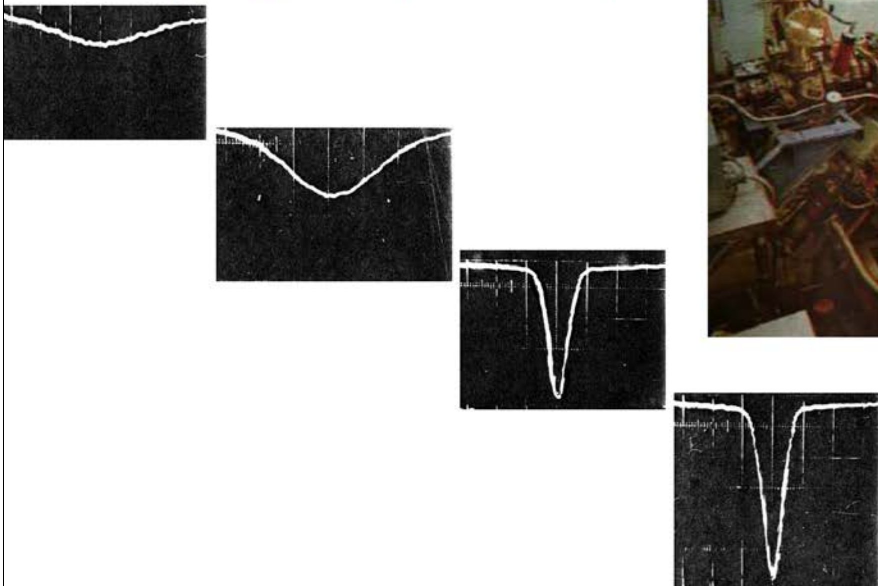
- ecool rate is linearly dependent on electron density and cooler length
- ecool rate is more effective for highly charged heavy ions (A/Z^2)
- ecool rate is independent of ion beam intensity
- ecool is most effective to cool the core of the beam
- ecool for high energy ions is challenging, because:
  - size of momentum spread of the ion beam is rather limited
  - electron beam energy needs to be significantly high ($\gamma_e = \gamma_i$)

8.2.6. Examples

First Demonstration Electron Cooling

- Electron cooling was first tested in 1974 with 68 MeV protons at NAP-M storage ring at INP(Novosibirsk).





Cooling at the GSI

ESR Electron Cooler
300 keV

Cooling for Internal Experiments

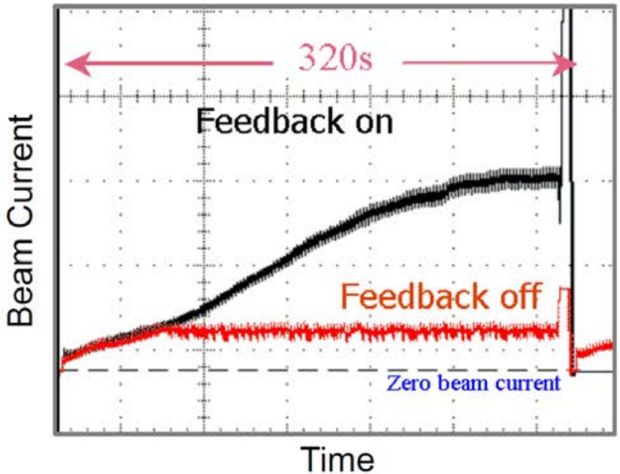
SIS Electron Cooler
35 keV

Cooling at Injection Energy of Synchrotron
Accumulation in transverse phase space
By Multiple Multiturn Injection (MMTI)

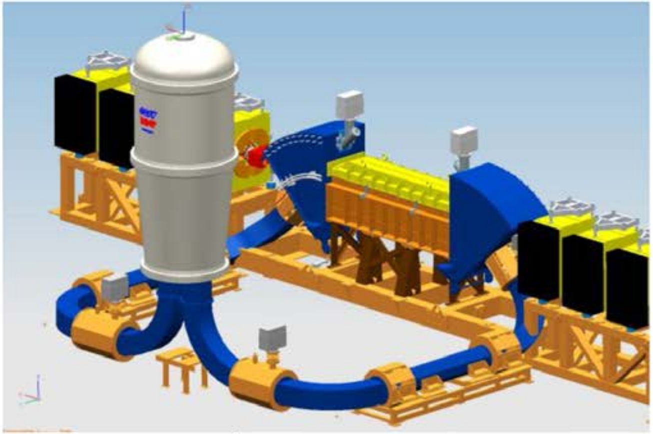
Cooling at COSY / FZJ

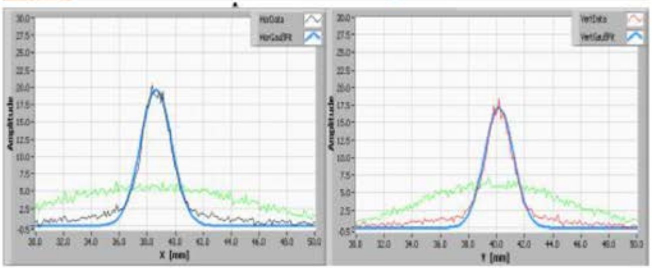
Electron Energy:
< 100 kV (24.5 kV)
Electron Current:
< 4 A (200 mA)

Beam Accumulation at Injection



COSY 2 MeV Cooler



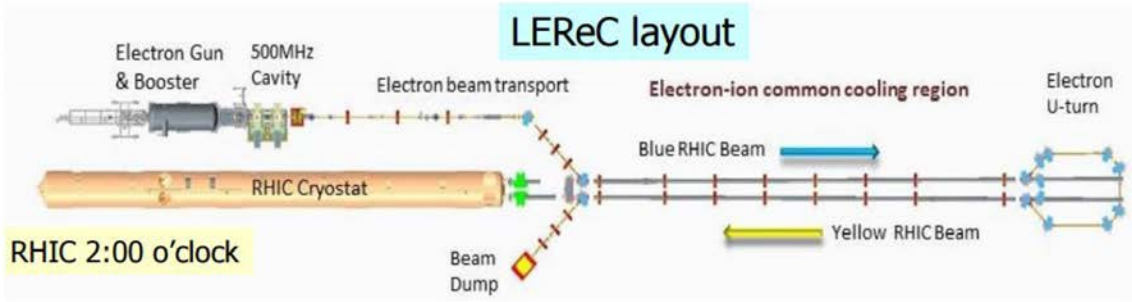


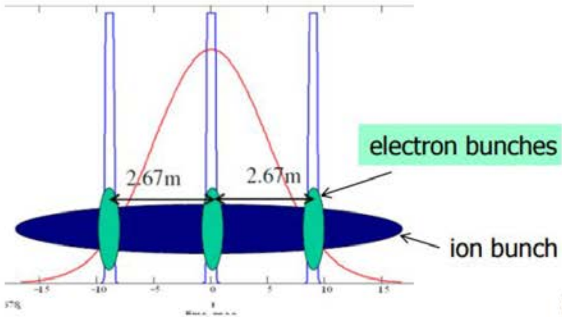
COSY 2 MeV Electron Cooler	Parameter
Energy Range	0.025 ... 2 MeV
High Voltage Stability	$< 10^{-4}$
Electron Current	0.1 ... 3 A
Electron Beam Diameter	10 ... 30 mm
Length of Cooling Section	2.69 m
Toroid Radius	1.00 m
Magnetic Field (cooling section)	0.5 ... 2 kG
Vacuum at Cooler	10^{-9} ... 10^{-10} mbar
Available Overall Length	6.39 m
Maximum Height	5.7 m
COSY Beam Axis above Ground	1.8 m

Table 1: Beam Parameters used for Cooling

Proton energy, MeV	Electron energy, keV	Max. electron current, mA
200	109	500
353	192	500
580	316	300
1670	908	340

8.2.7. Future Options



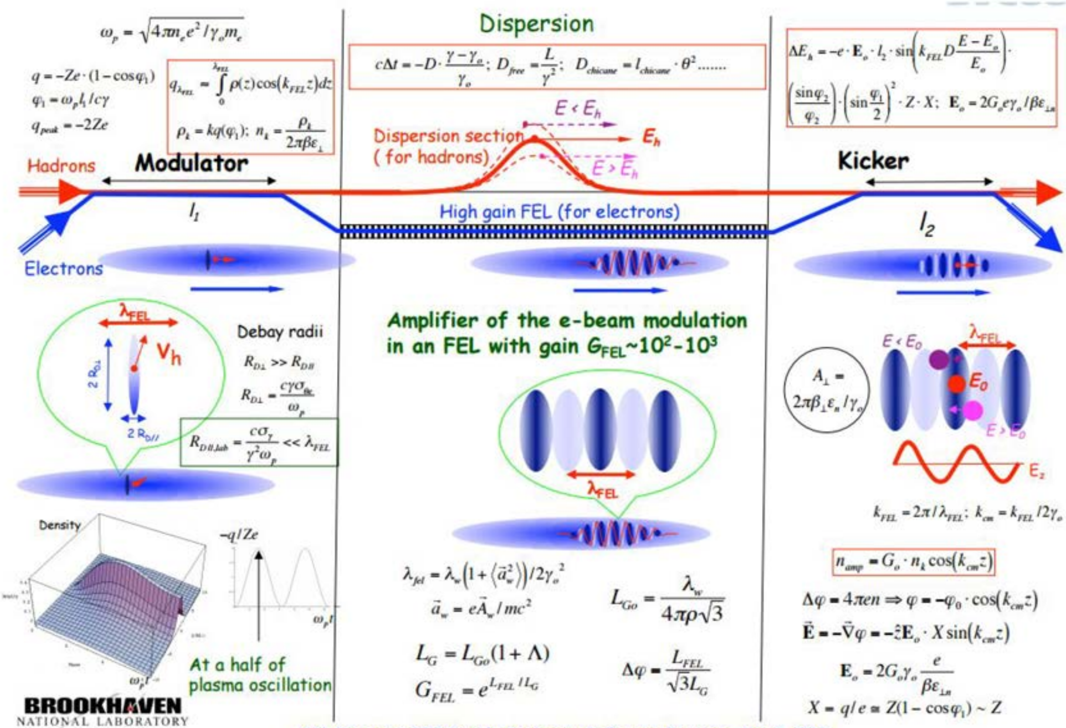


84.5 MHz SRF gun to generate 2.5MeV e beam

- 84.5MHz SRF gun to produce 2.5MeV e beam
- 507 MHz RF cavity for energy correction
- correction solenoids(200Gauss) located in the cooling section

Coherent electron cooling

- originally proposed by Y. S. Derbenev in the 80s
- further developed by V. Litvinenko(SUNY/BNL)

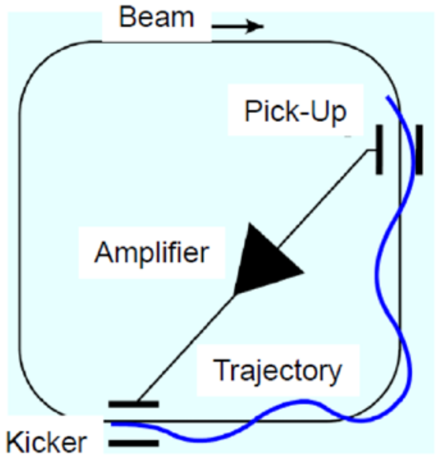


V.N. Litvinenko, 2009 Particle Accelerator Conference, Vancouver, May 8, 2009

8.3. Stochastic cooling

Simon van der Meer at CERN invented the technique in the late 1970's. The required technology was developed there, and applied to the CERN proton-antiproton collider.

S. van der Meer
Nobel prize 1984



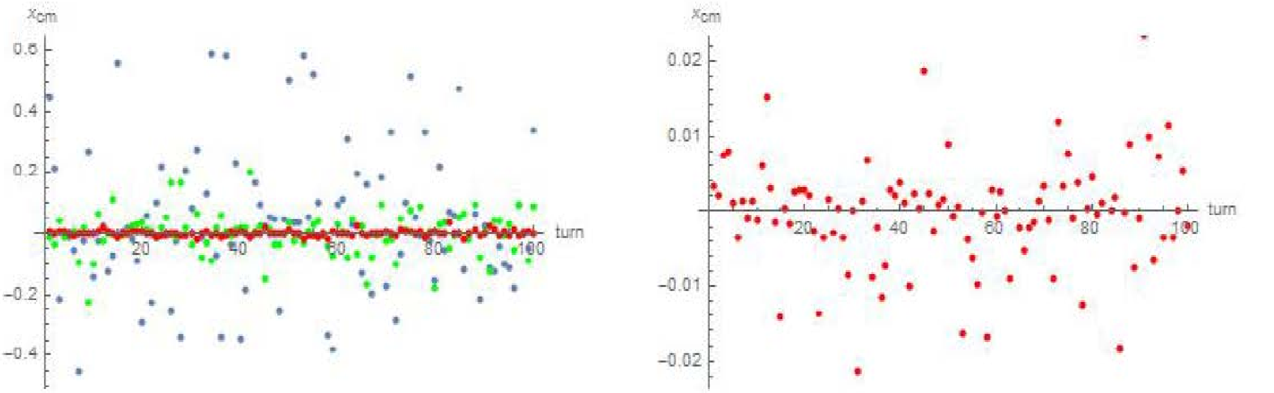
A feedback loop uses an electrical signal from a pick-up that an ensemble of particles generates to reduce the tendency of individual particles to move away from the other particles of the beam.

It is important to mention here that the phase advance between pick-up and kicker should be an odd multiple of $\pi/2$, so that a maximum transverse offset at the pick-up can be counteracted by a transverse kick in the kicker reducing only the transverse momentum of a particle.

8.3.1. Schottky noise

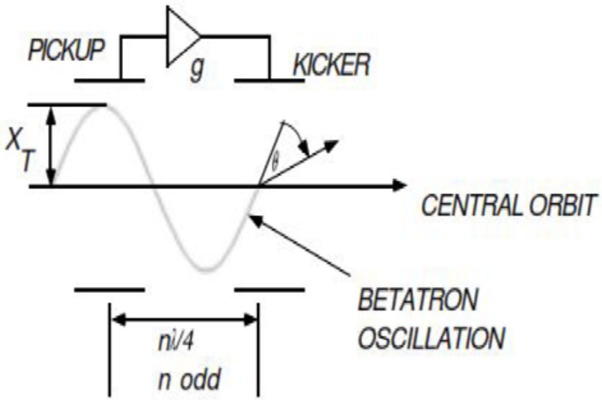
Measurement of the charge center of an ensemble of particles:

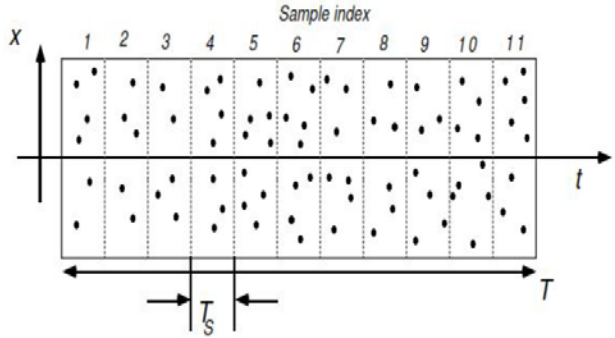
$$\langle x \rangle = \frac{1}{N_S}\sum_{i=1}^{N_S} x_i = \frac{1}{N_S}\sum_{i=1}^{N_S} A_i \cos\phi_i$$



Beam position for a beam with 10 (green), 100 (blue) and 10.000 (red) particles

Due to the finite sampling time interval T_S, we will always record mean positions of sub-samples of particles:





Due to the relatively small number of particles in our sub-sample we have important changes in the statistics! Given a beam of N particles, we get for the expectation values $\mathbf{E}[...]$ of a random sub-sample of N_S particles (note the remarkable difference in the last term!):

beam with N ($\to \infty$) particles	random sample with N_S particles
$\bar{x} = 0$	$\mathbf{E}[\bar{x}] = \mathbf{E}\left[\frac{1}{N_S}\sum_{i=1}^{N_S} x_i\right] = 0$
$\overline{x^2} = x_{rms}^2 = \sigma_x^{\,2}$	$\mathbf{E}\left[\overline{x^2}\right] = \mathbf{E}\left[\frac{1}{N_S}\sum_{i=1}^{N_S} x_i^{\,2}\right] = x_{rms}^2 = \sigma_x^{\,2}$
$\bar{x}^2 = 0$	$\mathbf{E}\left[\bar{x}^2\right] = \mathbf{E}\left[\left(\frac{1}{N_S}\sum_{i=1}^{N_S} x_i\right)^2\right] = \frac{1}{N_S} x_{rms}^2 = \frac{1}{N_S}\sigma_x^{\,2}$

8.3.2. Betatron cooling

Let's assume when a particle passes through a Stochastic cooling system, i.e. pick-up and kicker, the position at the pickup at $(k+1)^{th}$ orbital revolution

$$x_{i,k+1} = x_{i,k} - g \cdot x_{i,k}$$

where $x_{i,k}$ is the particle's position at the pick-up in the previous turn k, and $g \cdot x_{i,k}$ is the equivalent change of position due to the deflection of the kicker, g is called the **gain** of the system.

Now, let's look at the case of N_s particles passing the pick-up within the same sampling period T_s, as illustrated by the right figure. In general, T_s is way shorter than the revolution period of a particle. In this case, the effective deflection of the kicker after one orbital revolution is $g \cdot \overline{x}$, where $\overline{x} = \frac{1}{N_S}\sum_{i=1}^{N_S} x_i$

is the mean position of this sample of the beam. In this case, the i^{th} particle position is

$$x_{i,k+1} = x_{i,k} - g \cdot \overline{x}$$

and the variance of its amplitude is

$$x_{i,k+1}^2 = x_i^2 - 2gx_{i,k}\overline{x} + g^2\overline{x}^2$$

and the change of the variance of the sample is

$$\Delta x_i^2 = x_{i,k+1}^2 - x_{i,k}^2 = -2gx_{i,k}\overline{x} + g^2\overline{x}^2$$

Averaging over one sample, one gets

$$\overline{\Delta x^2} = -2\frac{g}{N_s}\sum_{i=1}^{N_S} x_i \cdot \overline{x} + \frac{g^2}{N_s}\sum_{i=1}^{N_S}\overline{x}^2 = -2\frac{g}{N_s}\sum_{i=1}^{N_S} x_i \cdot \overline{x} + g^2\overline{x}^2$$

Stochastic cooling is a slow process, which requires many turns. Since we are only interested in the long-term behaviour, we regard the average over many turns. Doing so, we replace the sample averages by their expectation values for random samples and obtain the "expected cooling rate / change per turn":

$$\Delta\sigma_x^2 = \mathbf{E}\left[\Delta x^2\right] = -2g\cdot\mathbf{E}\left[\frac{1}{N_s}\sum_{i=1}^{N_S} x_i\left(\frac{1}{N_S}\sum_{i=1}^{N_S} x_i\right)\right] + g^2\cdot\mathbf{E}\left[\left(\frac{1}{N_s}\sum_{i=1}^{N_S} x_i\right)^2\right]$$

and using the above findings for uncorrelated particles

$$\boxed{\Delta\sigma_x^2 = \left(-2g + g^2\right)\frac{x_{rms}^2}{N_S} = \left(-2g + g^2\right)\frac{\sigma_x^2}{N_S}}$$

8.3.3. Cooling rate and bandwidth

The number N_S of particles in the ensemble is determined by the sampling time Δt of the pick-up electronics. It is connected to the frequency bandwidth W by

$$W = \frac{1}{2\Delta t}$$

If the ring is filled with N particles revolving in the revolution time T_0, we have

$$\frac{N_S}{N} = \frac{\Delta t}{T_0} \qquad \Rightarrow \qquad N_S = N\frac{\Delta t}{T_0} = \frac{N}{2WT_0}$$

So, the cooling rate of the beam emittance, i.e. $\sigma_x^2 = \sigma_{x,0}^2 \cdot e^{-t/\tau_{x^2}}$, is

$$\frac{1}{\tau_{x^2}} = \frac{2g - g^2}{N_S T_0} = \frac{2W}{N}\left(2g - g^2\right)$$

We conclude the following points:

- the maximum cooling is when $g = 1$, i.e. $\dfrac{1}{\tau_{x^2,\max}} = \dfrac{2W}{N}$

- to keep the same cooling rate, higher bandwidths are required for more particles. Hence, high frequency signal processing and large bandwidth are preferred. Common values are 2-8 GHz.

8.3.4. Electronic noise

Appears as additional, uncorrelated contribution to $\langle x\rangle$ such that $\langle x\rangle \rightarrow \langle x\rangle + x_n$. Therewith we have to modify the correction to:

$$x_{i,k+1} = x_i - g\overline{x} - gx_n \quad \rightarrow \quad x_{i,k+1}^2 = x_i^2 - 2gx_i\left(\overline{x} + x_n\right) + g^2\left(\overline{x} + x_n\right)^2$$

$$\left\langle \Delta x^2 \right\rangle = 2g\left\langle x\overline{x}\right\rangle + 2g\left\langle xx_n\right\rangle + g^2\left\langle \overline{x}^2 + 2\overline{x}x_n + x_n^2\right\rangle$$

Using $\left\langle xx_n\right\rangle = 0$, $\left\langle \overline{x}x_n\right\rangle = 0$ and defining $U = \left\langle x_n^2\right\rangle \Big/ \left\langle \overline{x}^2\right\rangle$ we obtain straightforward

$$\frac{1}{\tau_{x^2}} = \frac{2W}{N}\left\{2g - g^2\left(1+U\right)\right\}$$

8.3.5. Mixing

Mixing is caused by the different speeds of the individual particles. It is absolutely essential! Without mixing and assuming "complete" correction, we would get almost no Schottky signal after one turn! The cooling would stop more or less immediately! This does not happen due to mixing: In a coasting beam with finite momentum spread, the difference in revolution period is

$$\frac{\Delta T}{T} = -\eta \frac{\Delta p}{p}$$

Defining the mixing factor $M = \frac{T_S}{\Delta T}$, we get using

$$-\eta \frac{\Delta p}{p} = \frac{\Delta T}{T} = \frac{1}{M} \frac{T_S}{T} = \frac{1}{M} \frac{1}{2WT} \quad \rightarrow \quad M = \frac{1}{2WT} \frac{1}{|\eta| \cdot \Delta p / p}$$

An individual particle remains M turns with its noise neighbors! Therefore, the "in-coherent" effect is enhanced by *M*, leading (assuming g << 1!) to

$$\frac{1}{\tau_{x^2}} = \frac{2W}{N}\left\{2g - g^2\left(M+U\right)\right\}$$

Mixing has as well an impact on the "coherent" effect, as it occurs as well between pick-up and kicker. Defining L as the distance between pick-up and kicker and C as the circumference of the ring, we can define an "unwanted" mixing factor $\tilde{M}$ by

$$\frac{\Delta T}{T_C} = \frac{L}{CM} = \frac{1}{\tilde{M}} \qquad \Rightarrow \qquad \tilde{M} = \frac{C}{L}M$$

And using a parabola model, the coherent effect decreases according to

$$2g \quad \rightarrow \quad 2g\left(1-\frac{1}{\tilde{M}^2}\right)$$

We then get finally for the cooling rates

$$\boxed{\begin{aligned}\frac{1}{\tau_{x^2}} &= \frac{2W}{N}\left\{2g\left(1-\frac{1}{\tilde{M}^2}\right) - g^2\left(M+U\right)\right\},\\ \frac{1}{\tau_x} &= \frac{W}{N}\left\{2g\left(1-\frac{1}{\tilde{M}^2}\right) - g^2\left(M+U\right)\right\}\end{aligned}}$$

8.3.6. A more thorough treatment of mixing

We will try a more comprehensive treatment, assuming that the cooling feedback acts on an unchanged ensemble for *M* turns, which, after *M* turns, is replaced by a (statistically) new one. We then obtain for the mean displacement after the last turn

$$x_{i,k+1} = x_{i,k} - g \cdot x_{i,k} \quad \rightarrow \quad \bar{x}(k+1) = \{1-g\} \cdot \bar{x}(k)$$

and the mean quadratic displacement

$$x_{i,k+1}^2 = x_i^2 - 2g x_{i,k} \bar{x} + g^2 \bar{x}^2 \quad \rightarrow \quad \overline{x^2}(k+1) = \overline{x^2}(k) - \{2g - g^2\} \cdot \bar{x}^2(k)$$

But this can be related to the correction which has happened one turn before, using

$$\bar{x}^2(k) = \left(1-g\right)^2 \cdot \bar{x}^2(k-1)$$

$$\overline{x^2}(k) = \overline{x^2}(k-1) - \{2g - g^2\} \cdot \bar{x}^2(k-1)$$

thus giving

$$\overline{x^2}(k+1) = \overline{x^2}(k-1) - \left[1 + \left(1-g\right)^2\right]\{2g - g^2\} \cdot \bar{x}^2(k-1)$$

The generalisation to *M* turns is straightforward, giving

$$\overline{x^2}(M) = \overline{x^2}(0) - \sum_{j=1}^{M} (1-g)^{2j-2} \cdot \{2g - g^2\} \cdot \overline{x}^2(0)$$

Again, we rewrite this as the overall change in the quadratic displacement, which now has happened over M turns (which approximately equals M identical changes $\Delta\overline{x^2}$ per turn)

$$M \cdot \Delta\overline{x^2} = \overline{x^2}(M) - \overline{x^2}(0) = -\sum_{j=1}^{M} (1-g)^{2j-2} \cdot \{2g - g^2\} \cdot \overline{x}^2(0)$$

and get, after building the expectation values

$$\Delta\sigma_x^2 = -\frac{1}{M} \sum_{j=1}^{M} (1-g)^{2j-2} \cdot \{2g - g^2\} \cdot \frac{\sigma_x^2}{N_S}$$

Straightforward we derive for the cooling rate (without signal noise and unwanted mixing)

$$\frac{1}{\tau_{x^2}} = \frac{2W}{N} \frac{1}{M} \sum_{j=1}^{M} (1-g)^{2j-2} \cdot \{2g - g^2\}$$

In case of weak amplification $g \ll 1$, we can express the sum as follows:

$$\sum_{j=1}^{M}(1-g)^{2j-2}\cdot\left\{2g-g^2\right\}\approx\left[M-2g\sum_{j=1}^{M}j\right]\cdot\left\{2g-g^2\right\}=\left[M-M\left(M-1\right)g\right]\cdot\left\{2g-g^2\right\}$$

$$=M\left\{2g-g^2\left[1+2\left(M-1\right)\right]\right\}$$

Thus giving approximately

$$\frac{1}{\tau_{x^2}}\approx\frac{2W}{N}\left\{2g-g^2\left[1+2\left(M-1\right)\right]\right\}$$

Now, we have overestimated the effect, assuming that the ensemble will remain unchanged for M turns, which leads to an additional "incoherent" contribution (g^2 term) of $2\left(M-1\right)$. In fact, after $M/2$ turns already half of the ensemble has been replaced.

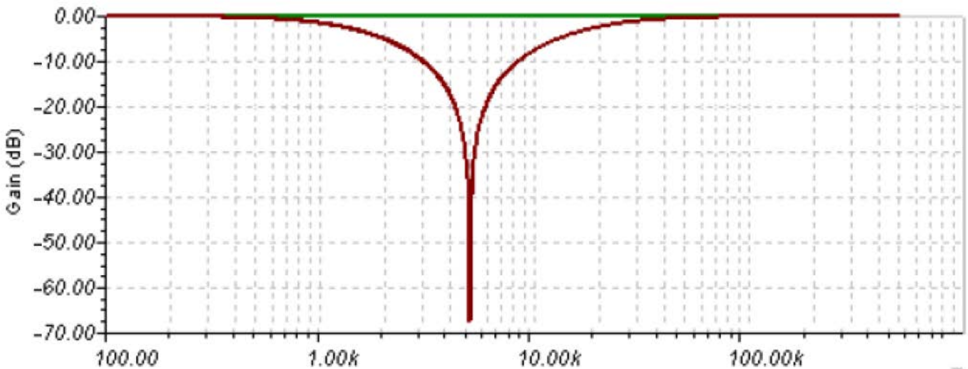
A more realistic approach would therefore assume about half of this additional contribution and – there we are:

$$\frac{1}{\tau_{x^2}}\approx\frac{2W}{N}\left\{2g-g^2M\right\}$$

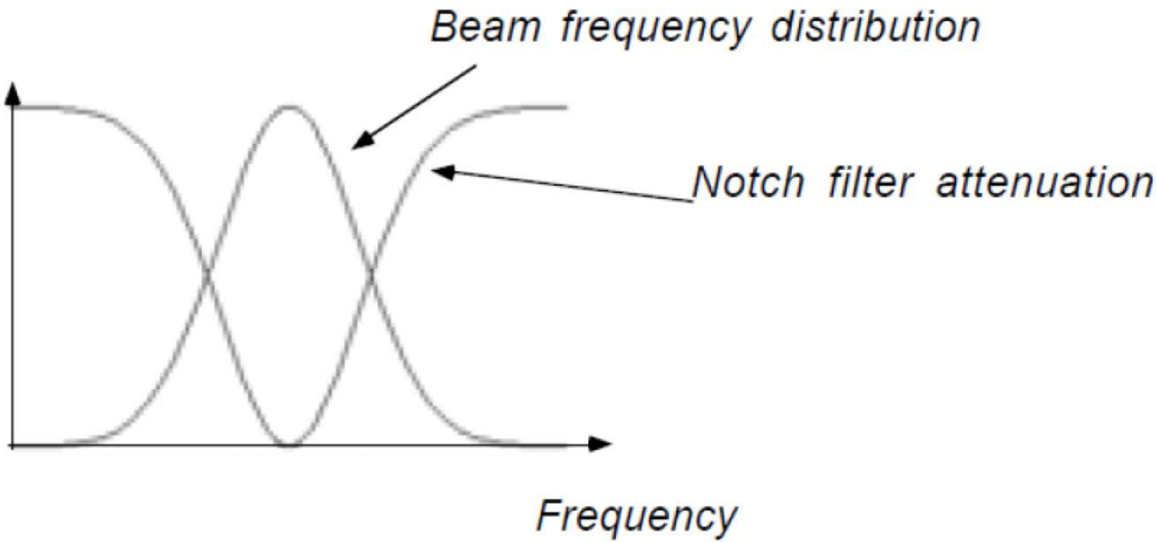
8.3.7. Longitudinal stochastic cooling

Palmer cooling (Robert Palmer): Correlation between position and momentum → pick-up at position with large dispersion function Difference signal of the pick-up is used. Longitudinal kicker at position with zero dispersion kicks the whole momentum distribution → acceleration/deceleration kick.

Filter cooling: Correlation between circulation frequency and particle momentum is used. The sum signal is attenuated by a notch filter which creates harmonics of nominal revolution frequency



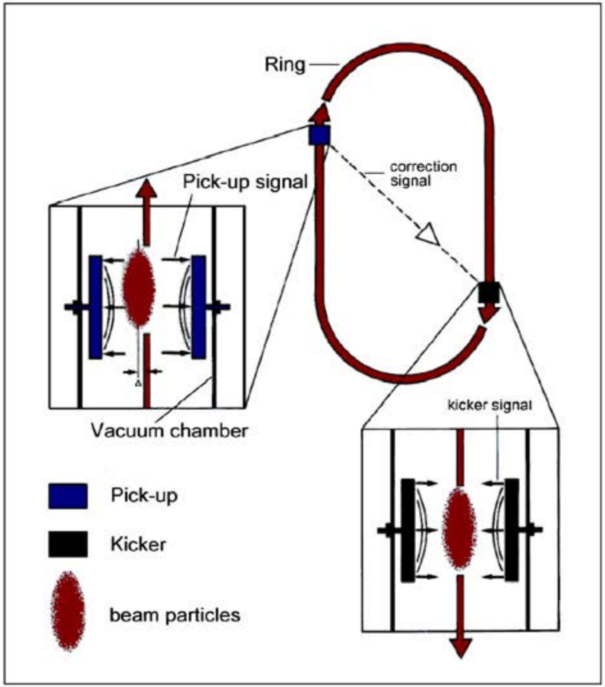
Particles with correct energy are not affected due to gain suppression by the notch filter → particles are forced to circulate at the nominal frequency:



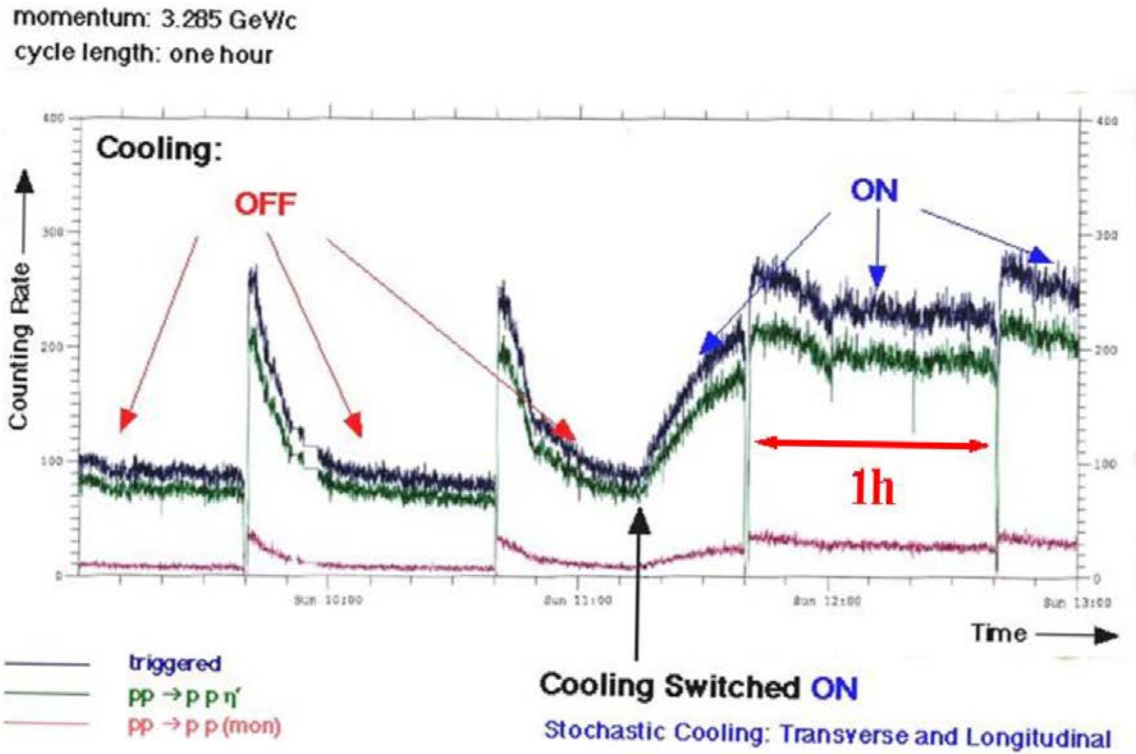
$$\frac{\Delta f}{f} = -\eta_C \frac{\Delta p}{p}$$

8.3.8. Examples

Stochastic cooling at COSY / FZJ:



- Transverse and longitudinal
- Frequency range: 1-3 GHz 2 bands
- RF power: 500 W per plane

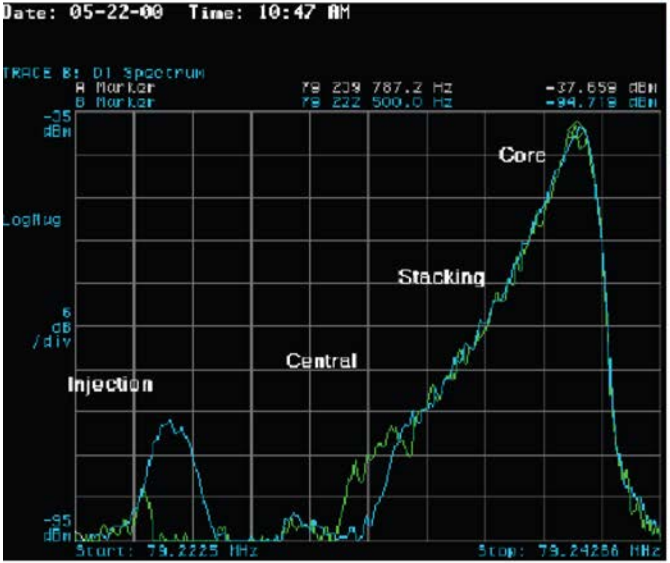


Compensation of emittance growth and increase of momentum spread due to internal targets

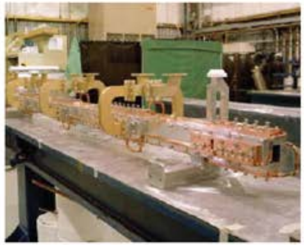
Antiproton Accumulation by Stochastic Cooling

M. Steck
CAS 2009
Darmstadt

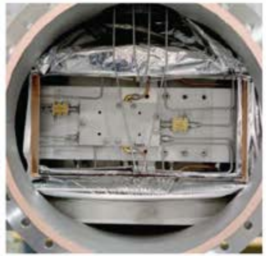
accumulation of 8 GeV antiprotons at FNAL



momentum distribution of accumulated antiproton beam



kicker array



cryogenic microwave amplifier

microwave electronics

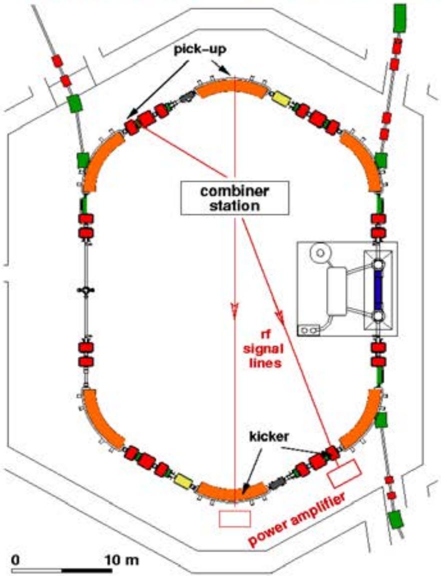
power amplifiers (TWTs)

Stochastic Cooling at GSI

M. Steck
CAS 2009
Darmstadt

fast pre-cooling of hot fragment beams

energy 400 (-550) MeV/u
bandwidth 0.8 GHz (range 0.9-1.7 GHz)
$\delta p/p = \pm 0.35\ \% \rightarrow \delta p/p = \pm 0.01\ \%$
$\varepsilon = 10 \times 10^{-6}$ m $\rightarrow \varepsilon = 2 \times 10^{-6}$ m



electrodes installed inside magnets

combination of signals from electrodes

power amplifiers for generation of correction kicks

Table 1. A list of stochastic cooling systems and basic parameters.

Site	Machine	Type	Frequency (MHz)	Beam Momentum (GeV/c)
CERN	ISR	H & V	1000-2000	26.6
	ICE	H, V, ΔP	50-375	1.7 & 2.1
	AA	PreCool ΔP ST H, V, ΔP Core H, V, ΔP	150-2000	3.5
	LEAR	2 systems H, V, ΔP	5-1000	<0.2 & 0.2-2.0
	AC	H, V, ΔP	1000-3000	3.5
	AD	H,V, ΔP	900-1650	2.0 & 3.5
FNAL	ECR	V, ΔP	20-400	0.2
	Debuncher	H, V, ΔP	4000-8000	8.9
	Accumulator	ST ΔP Core H, V, ΔP	1000-8000	8.9
KFA Julich	COSY	H, V, ΔP	1000-3000	1.5-3.4
GSI Darmstadt	ESR	H, V, ΔP	900-1700	0.48/nucleon
Tokyo	TARN	ΔP	20-100	0.007
BINP	NAP-M	ΔP	100-300	0.062

J. Marriner,
http://arxiv.org/ftp/physics/papers/0308/0308044.pdf