Beam Cooling

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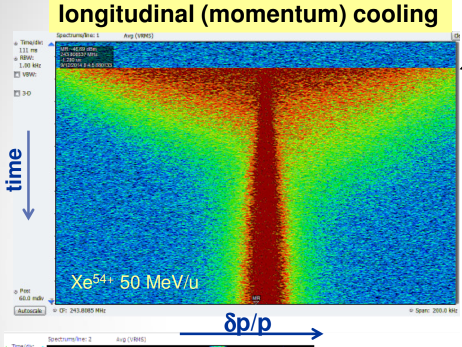
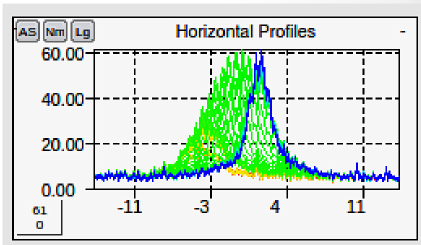
Cooling

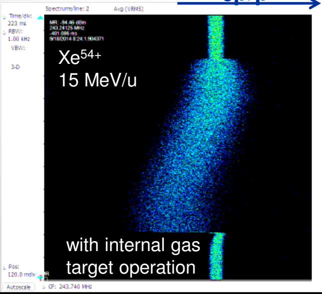
longitudinal (momentum) cooling



injection into the storage ring

transverse cooling





cooling **off**

heating (spread) and
energy loss (shift)

cooling **on**

cooling:
good energy definition
small beam size
⇒ highest precision

Beam Cooling

Introduction

1. Electron Cooling
2. Ionization Cooling
3. Laser Cooling
4. Stochastic Cooling

Beam Cooling

Beam cooling is synonymous for a reduction of beam temperature.

Temperature is equivalent to terms as phase space volume, emittance and momentum spread.

Beam Cooling processes are not following Liouville's Theorem:

\`in a system where the particle motion is controlled by external conservative forces the phase space density is conserved´

(This neglects interactions between beam particles.)

Beam cooling techniques are non-Liouvillean processes which violate the assumption of a conservative force.

e.g. interaction of the beam particles with other particles (electrons, photons, matter)

Cooling Force

Generic (simplest case of a) cooling force:

$$\boxed{F_{x,y,s} = -\alpha_{x,y,s} v_{x,y,s}}$$

$v_{x,y,s}$ velocity in the rest frame of the beam

non conservative, cannot be described by a Hamiltonian

For a 2D subspace distribution function $f(z, z', t)$

$$F_z = -\alpha_z v_z \qquad z = x, y, s \qquad v_z = v_0 \cdot z'$$

$$\frac{df(z, z', t)}{dt} = -\lambda_z f(z, z', t) \qquad \lambda_z \text{ cooling (damping) rate}$$

in a circular accelerator:

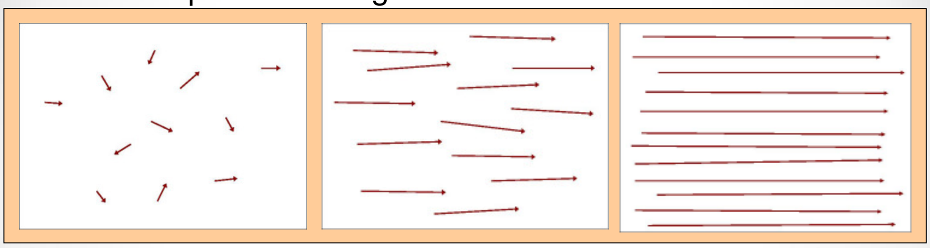
Transverse (emittance) cooling rate $\epsilon_{x,y}(t_0 + t) = \epsilon_{x,y}(t_0)\ e^{-\lambda_{x,y} t}$

Longitudinal (momentum spread) cooling rate $\frac{\delta p_\parallel}{p_0}(t_0 + t) = \frac{\delta p_\parallel}{p_0}(t_0)\ e^{-\lambda_\parallel t}$

Beam Temperature

Where does the beam temperature originate from?

The beam particles are generated in a 'hot' source



at rest (source) **at low energy** **at high energy**

In a standard accelerator the beam temperature is not reduced (thermal motion is superimposed the average motion after acceleration)

but: many processes can heat up the beam

e.g. heating by mismatch, space charge, intrabeam scattering, internal targets, residual gas, external noise

Beam Temperature Definition

Longitudinal beam temperature

$$\boxed{\frac{1}{2}k_B T_{||} = \frac{1}{2}mv_{||}^2 = \frac{1}{2}mc^2\beta^2(\frac{\delta p_{||}}{p})^2}$$

Transverse beam temperature

$$\boxed{\frac{1}{2}k_B T_{\perp} = \frac{1}{2}mv_{\perp}^2 = \frac{1}{2}mc^2\beta^2\gamma^2\theta_{\perp}^2} \quad \theta_{\perp} = \frac{v_{\perp}}{\beta c}, \quad \theta_{\perp}(s) = \sqrt{\frac{\epsilon}{\beta_{\perp}(s)}}$$

Distribution function

$$f(v_{\perp}, v_{||}) \propto \exp\left(-\frac{mv_{\perp}^2}{2k_B T_{\perp}} - \frac{mv_{||}^2}{2k_B T_{||}}\right)$$

Particle beams can be anisotropic: $k_B T_{||} \neq k_B T_{\perp}$

e.g. due to laser cooling or the distribution of the electron beam

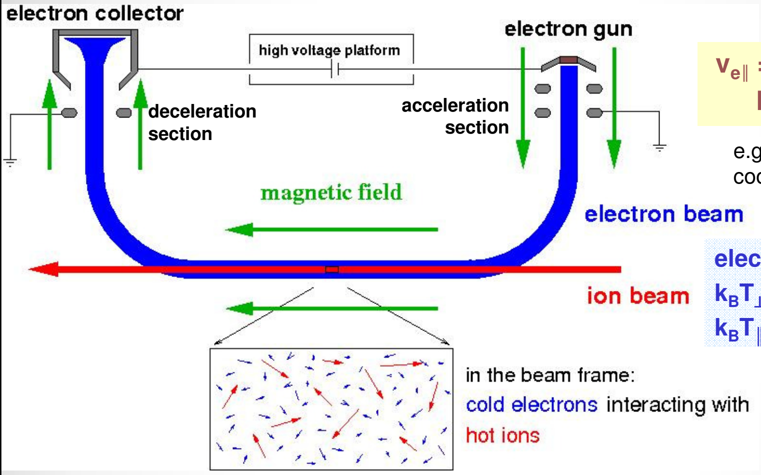
Don‘t confuse: beam energy $\leftrightarrow$ beam temperature

(e.g. a beam of energy 100 GeV can have a temperature of 1 eV)

Benefits of Beam Cooling

- Improved beam quality
  - Precision experiments
  - Luminosity increase
- Compensation of heating
  - Experiments with internal target
  - Colliding beams
- Intensity increase by accumulation
  - Weak beams from the source can be enhanced
  - Secondary beams (antiprotons, rare isotopes)

1. Electron Cooling



$v_{e\parallel} = \beta_e c = \beta_i c = v_{i\parallel}$

$E_e = m_e/M_i \cdot E_i$

e.g.: 220 keV electrons
cool 400 MeV protons

electron temperature

$k_B T_\perp \approx 0.1$ eV

$k_B T_\parallel \approx 0.1$ - 1 meV

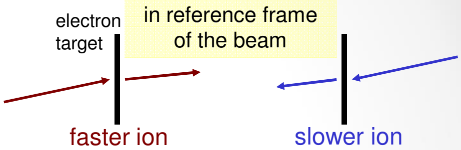
superposition of a cold intense electron beam with the same velocity

momentum transfer by Coulomb collisions

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

Simple Derivation of the Electron Cooling Force

Analogy: energy loss in matter
(electrons in the shell)

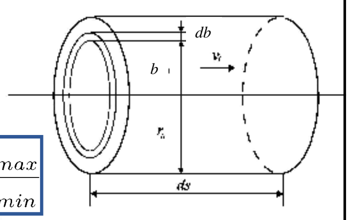


Rutherford scattering: $2\,tan(\frac{\theta}{2}) = \frac{2Z_1Z_2e^2}{4\pi\epsilon_0 \Delta p v b} \quad Z_1 = Q\ (ion),\ Z_2 = -1\ (electron)$

Energy transfer: $\Delta E(b) = \frac{(\Delta p)^2}{2m_e} \simeq \frac{2Q^2e^4}{(4\pi\epsilon_0)^2 m_e v^2}\frac{1}{b^2} \quad (for\ \ b \gg b_{min})$

Minimum impact parameter: $b_{min} = \frac{Qe^2}{(4\pi\epsilon_0)^2 m_e v^2}$

from: $\Delta E(b_{min}) = \Delta E_{max} \simeq 2m_e v^2$



Energy loss:

$$\boxed{-\frac{dE}{dx} = 2\pi \int_{b_{min}}^{b_{max}} b n_e \Delta E\, db = \frac{4\pi Q^2 e^4}{(4\pi\epsilon_0)^2 m_e v^2} n_e \ln\frac{b_{max}}{b_{min}}}$$

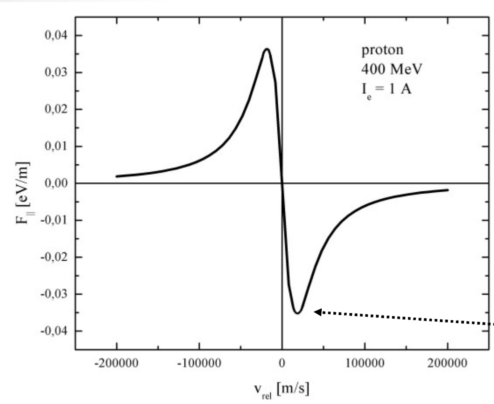
Coulomb logarithm $L_C = \ln(b_{max}/b_{min}) \approx 10$ (typical value)

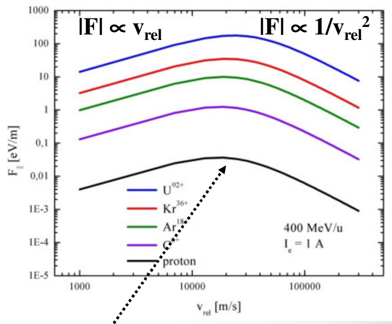
Characteristics of the Electron Cooling Force

$$\boxed{\vec{F}(\vec{v_i}) = -\frac{4\pi Q^2 e^4 n_e}{(4\pi\epsilon_0)^2 m_e}\int L_C(\vec{v}_{rel}) f(\vec{v_e}) \frac{\vec{v}_{rel}}{v_{rel}^3} d^3\vec{v_e}}$$

$$\vec{v}_{rel} = \vec{v_i} - \vec{v_e}$$

cooling force F
for small relative velocity: $\propto v_{rel}$
for large relative velocity: $\propto v_{rel}^{-2}$
increases with charge: $\propto Q^2$





maximum of cooling force
at effective electron temperature

Electron Cooling Time

first estimate:
(Budker 1967)

$$\tau = \frac{3}{8\sqrt{2\pi} n_e Q^2 r_e r_i c L_C}\left(\frac{k_B T_e}{m_e c^2} + \frac{k_B T_i}{m_i c^2}\right)^{3/2}$$

for large relative velocities

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

cooling rate (τ^{-1}):

- slow for hot beams $\propto \theta^3$
- decreases with energy $\propto \gamma^2$ ($\beta \cdot \gamma \cdot \theta$ 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

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

Models of the Electron Cooling Force

• binary collision model

description of the cooling process by successive collisions of two particles and integration over all interactions

analytic expressions become very involved, various regimes (multitude of Coulomb logarithms)

• dielectric model

interaction of the ion with a continuous electron plasma (scattering off of plasma waves)

fails for small relative velocities and high ion charge

• an empiric formula (Parkhomchuk) derived from experiments:

$$\boxed{\vec{F} = -4\frac{n_e}{m_e}\frac{(Qe^2)^2}{(4\pi\epsilon_0)^2}\ln\left(\frac{b_{max}+b_{min}+r_c}{b_{min}+r_c}\right)\frac{\vec{v}_{ion}}{(v_{ion}^2+v_{eff}^2)^{3/2}}}$$

$$b_{min} = \frac{Qe^2/4\pi\epsilon_0}{m_e v_{ion}^2};\quad b_{max} = \frac{v_{ion}}{min(\omega_{pe}, 1/T_{cool})},\quad v_{eff}^2 = v_{e,\parallel}^2 + v_{e,\perp}^2$$

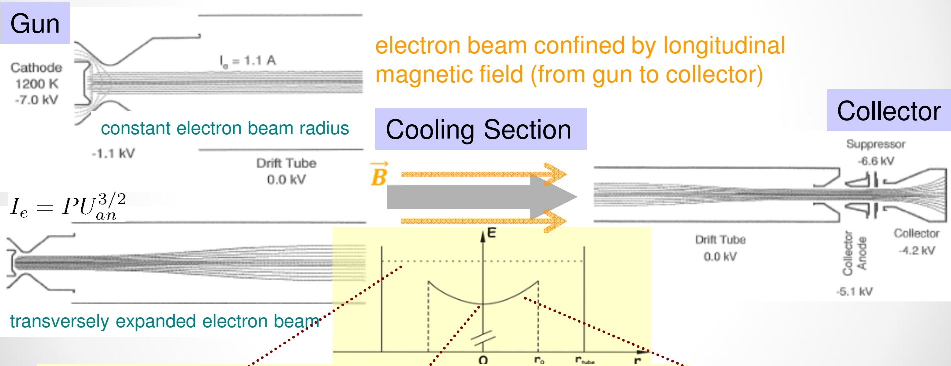
Electron Beam Properties

electron beam temperature

transverse $k_B T_\perp = k_B T_{cat}$, with transverse expansion ($\propto B_c/B_{gun}$)

longitudinal $k_B T_\parallel = (k_B T_{cat})^2/4E_0 \ll k_B T_\perp$ lower limit : $k_B T_\parallel \geq 2e\frac{n_e^{1/3}}{4\pi\epsilon_0}$

typical values: $k_B T_\perp \approx 0.1$ eV (1100 K), $k_B T_\parallel \approx 0.1 - 1$ meV



radial variation of electron energy due to space charge:

$$E(r) = eU_{cat} - \underline{n_e}\pi r_0^2 r_e m_e c^2[1 + 2\ln(r_{tube}/r_0)] + \underline{n_e}\pi r_e m_e c^2 r^2$$

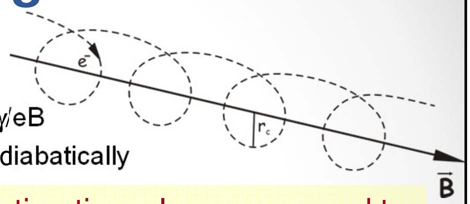
Electron Motion in Longitudinal Magnetic Field

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 $\Rightarrow$ **magnetized cooling ($T_{eff} \approx T_\parallel << T_\perp$)**

electron beam space charge:

transverse electric field + B-field $\Rightarrow$ azimuthal drift $v_{azi} = r\omega_{azi} = r\dfrac{2\pi r_e n_e c^2}{\gamma\omega_c}$

$\Rightarrow$ electron and ion beam should be well centered

Favorable for optimum cooling (small transverse relative velocity):

- high parallelism of magnetic field lines $\Delta B_\perp/B_0$
- large beta function (small divergence) in cooling section

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Imperfections and Limiting Effects in Electron Cooling

technical issues:

ripple of accelerating voltage

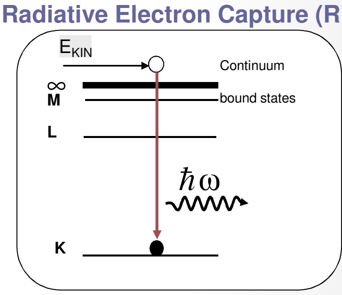
magnetic field imperfections

beam misalignment

space charge of electron beam and compensation

physical limitation:

Radiative Electron Capture (REC)



losses by recombination (REC)

loss rate $\tau^{-1} = \gamma^{-2}\alpha_{REC} n_e \eta$

$$\alpha_{REC} = \frac{1.92\times10^{-13}Q^2}{\sqrt{k_B T}}\left(\ln\frac{5.66Q}{\sqrt{k_B T}} + 0.196\left(\frac{k_B T}{Q^2}\right)^{1/3}\right)[cm^3 s^{-1}]$$

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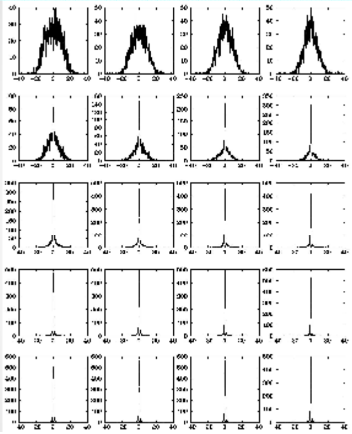
Examples of Electron Cooling

fast transverse cooling at TSR, Heidelberg

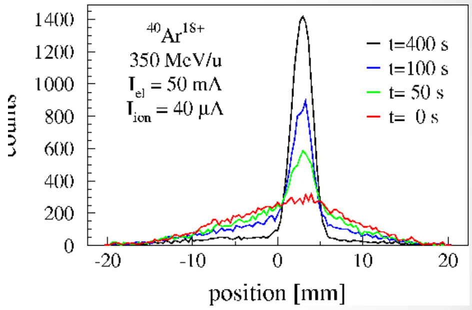


profile every 0.1 s. x [mm]

cooling of 6.1 MeV/u C^{6+} ions
0.24 A, 3.4 keV electron beam
$n_e = 1.56 \times 10^7$ cm^{-3}

measured with residual gas ionization beam profile monitor

transverse cooling at ESR, Darmstadt

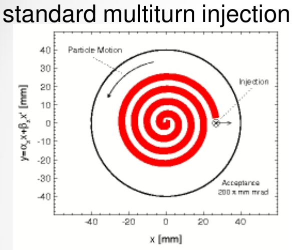


cooling of 350 MeV/u Ar^{18+} ions
0.05 A, 192 keV electron beam
$n_e = 0.8 \times 10^6$ cm^{-3}

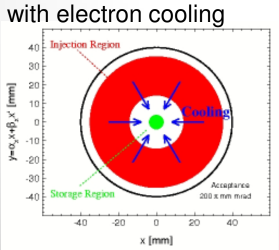
note! time scale, cooling time varies strongly with beam parameters

Accumulation of Heavy Ions by Electron Cooling

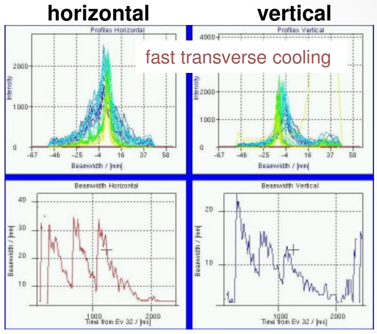
standard multiturn injection



fast accumulation by repeated multiturn injection with electron cooling

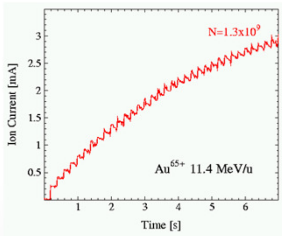


horizontal vertical



profile

beam size



intensity increase in 5 s by a factor of ≈ 10

limitations:
space charge tune shift, recombination (REC)

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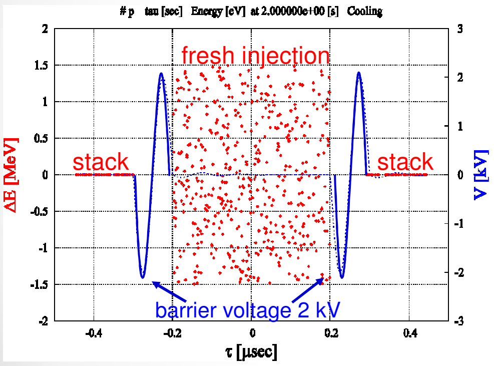
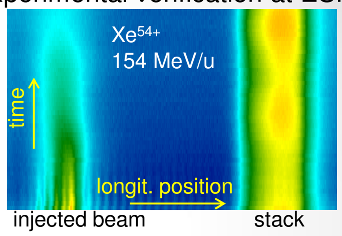
Accumulation of Secondary Particles

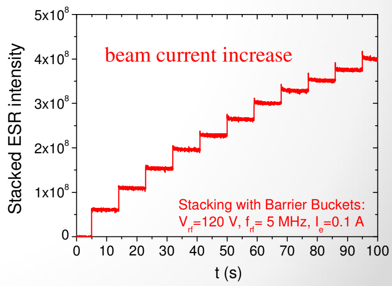
basic idea: confine stored beam to a fraction of the circumference, inject into gap and apply cooling to merge the two beam components
⇒ fast increase of intensity (for secondary beams)



simulation of longitudinal stacking
with barrier buckets and electron cooling

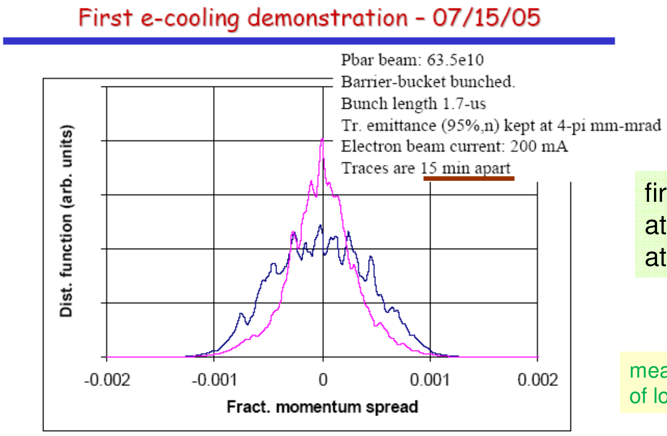
experimental verification at ESR





Examples of Electron Cooling

high energy electron cooling of 8 GeV antiprotons
longitudinal cooling with 0.2 A, 4.4 MeV electron beam



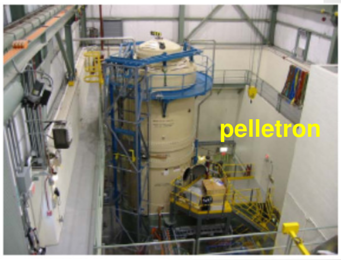
first electron cooling at relativistic energy at Recycler, FNAL

measured by detection of longitudinal Schottky noise

Electron Cooling Systems

Low Energy: 35 keV SIS/GSI

High Energy:
4.3 MeV Recycler/FNAL



Medium Energy:
300 keV
ESR/GSI

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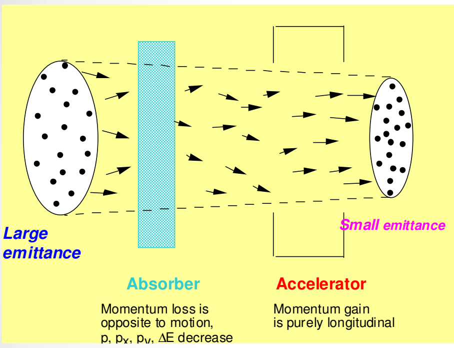
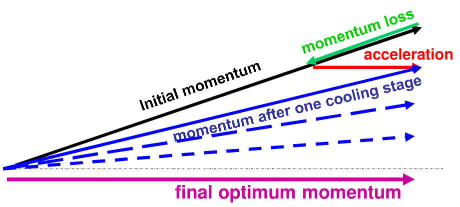
2. Ionization Cooling

energy loss in solid matter



proposed for muon cooling



not useful for heavy particles
due to strong interaction with matter

transverse cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\epsilon_N + \frac{\beta\gamma\beta_\perp}{2}\frac{\langle\theta_{rms}^2\rangle}{ds}$$

$$= -\frac{1}{\beta^2 E}\frac{dE}{ds}\epsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

small $\beta_\perp$ at absorber in order
to minimize multiple scattering

large L_R, (dE/ds) $\Rightarrow$ light absorbers (H_2)

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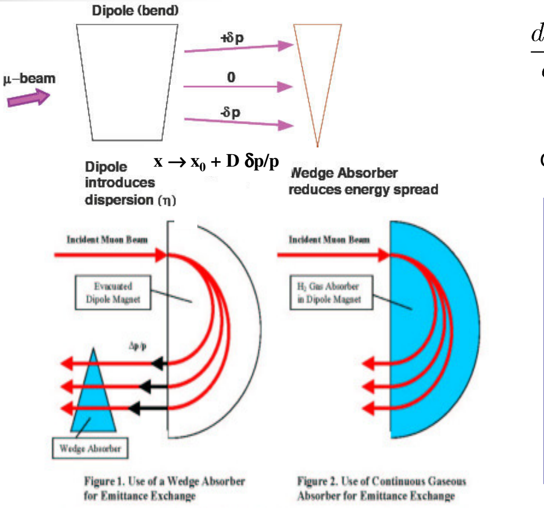
Ionization Cooling

increased longitudinal cooling
by longitudinal-transverse emittance exchange



$$\frac{d\sigma_E^2}{ds} = -2\frac{\partial(dE/ds)}{\partial E}\sigma_E^2 + \frac{d\langle\Delta E_{rms}^2\rangle}{ds}$$

cooling term   heating term

cooling, if $\frac{\partial(dE/ds)}{\partial E} > 0$

emittance exchange

increased longitudinal cooling

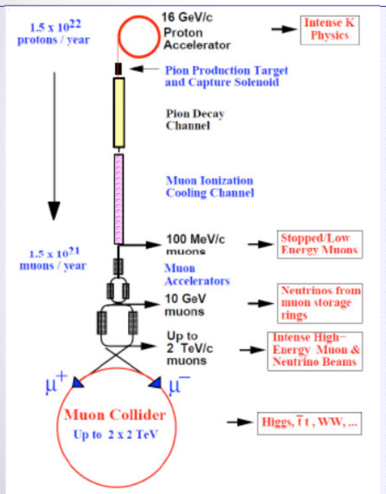
$$\frac{\partial \frac{dE}{ds}}{\partial E} \Rightarrow \frac{\partial \frac{dE}{ds}}{\partial E}\Big|_0 + \frac{dE}{ds}\frac{D\rho'}{\beta c p \rho_0}$$

reduced transverse cooling

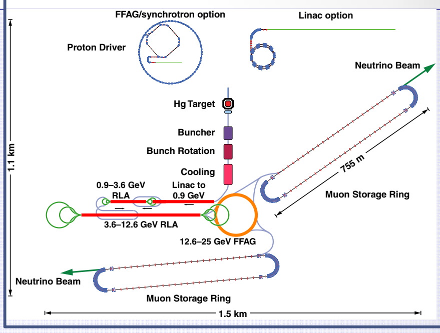
$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\left(1 - \frac{D\rho'}{\rho_0}\right)\epsilon_N$$

Scenarios with Ionization Cooling

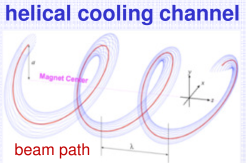
Muon Collider



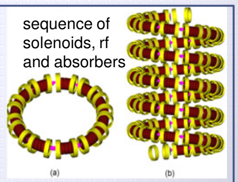
Neutrino Factory



helical cooling channel

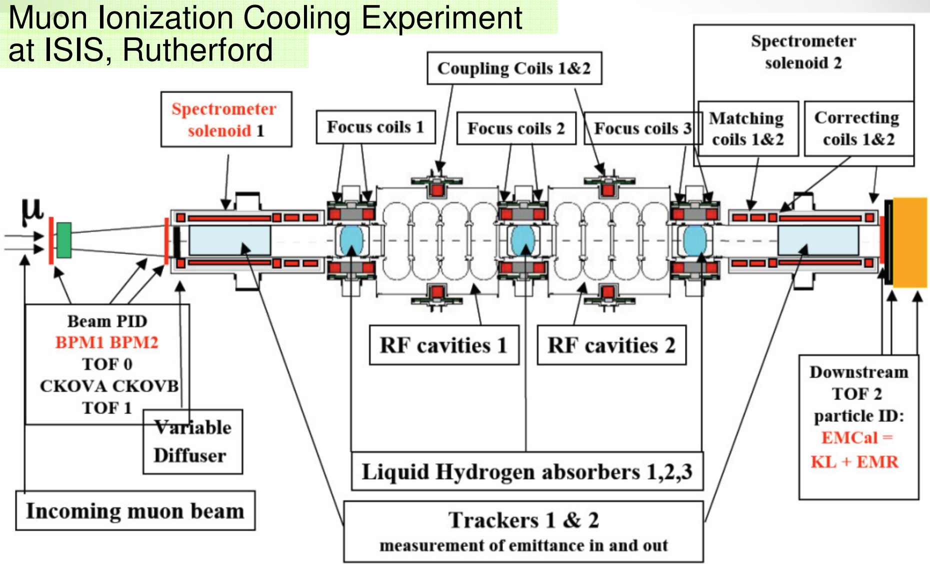


sequence of solenoids, rf and absorbers



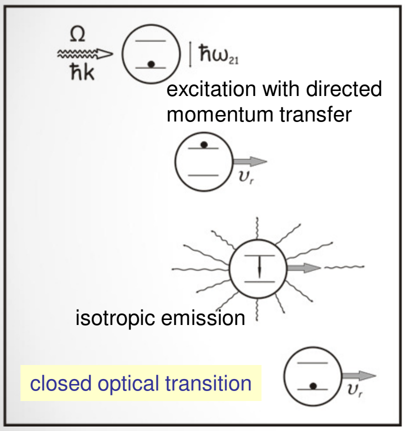
MICE

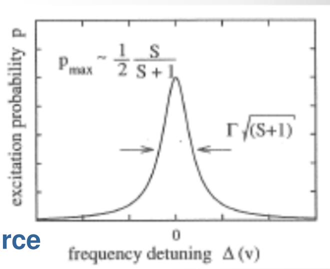
Muon Ionization Cooling Experiment
at ISIS, Rutherford



3. Laser Cooling

$$\Omega = \gamma \omega_{21}(1 - \beta \cos\theta)$$





the directed excitation and isotropic emission result in a transfer of velocity v_r

cooling force

$$\vec{F}(\vec{v}, \vec{k}) = \frac{\hbar \vec{k}}{2} S\Gamma \frac{(\Gamma/2)^2}{(\omega - \omega_{21} - \vec{v}\,\vec{k}) + (\Gamma/2)^2(1+S)}$$

Lorentzian with width Γ/k ~ 10 m/s

minimum temperature $T_D = \frac{\hbar\Gamma}{2k_B}$ (Doppler limit)
typical 10^{-5} – 10^{-4} K

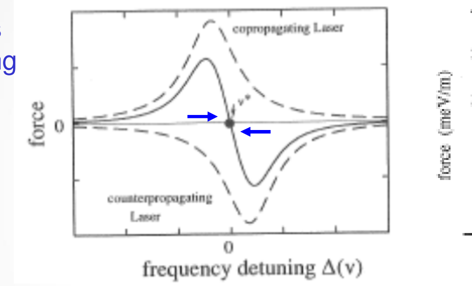
typical cooling time ~ 10 μs

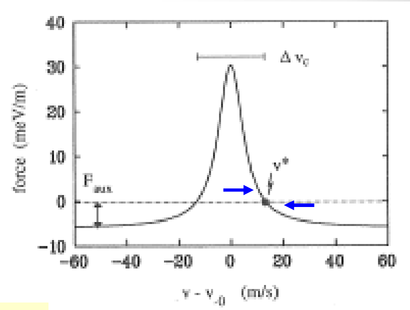
drawback: only longitudinal cooling

Laser Cooling

a single laser does not provide cooling (only acceleration or deceleration)

schemes for cooling





two counter-propagating lasers (matched to beam velocity, but slightly detuned)

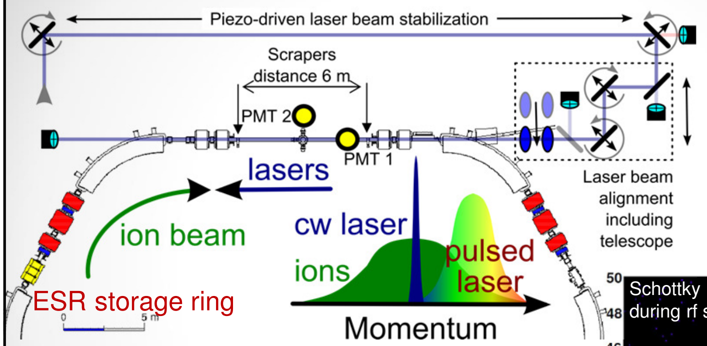
auxiliary force (betatron core, rf)

capture range of laser is limited $\Rightarrow$ frequency sweep (snowplow)

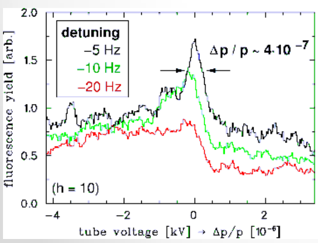
ions studies so far: ^{7}**Li**$^{1+}$, ^{9}**Be**$^{1+}$, ^{24}**Mg**$^{1+}$, ^{12}**C**$^{3+}$

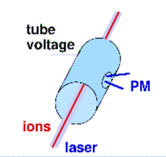
in future: Li-like heavy ions at relativistic energies
large relativistic energy $\Rightarrow$ large excitation energy in PRF

Laser Cooling of C^{3+}

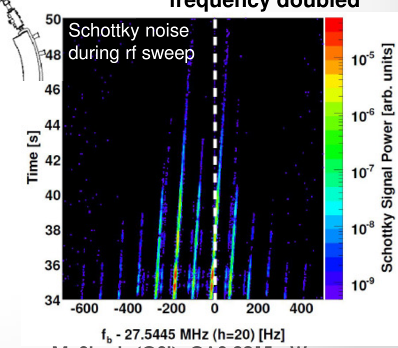


Argon ion laser (257.3 nm) frequency doubled



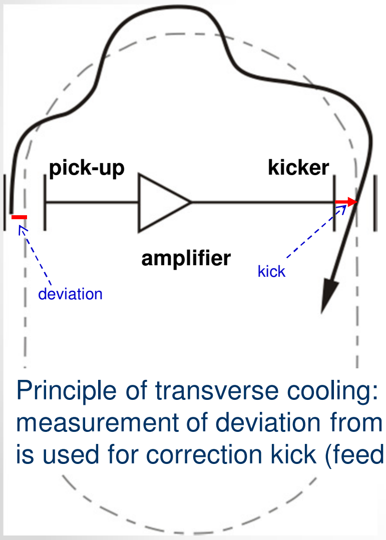


fluorescence light detection



4. Stochastic Cooling

First cooling method which was successfully used for beam preparation



S. van der Meer, D. Möhl, L. Thorndahl et al.
(1925 – 2011) (1936-2012)

Conditions:

Betatron motion phase advance (pick-up to kicker): (n + ½) π

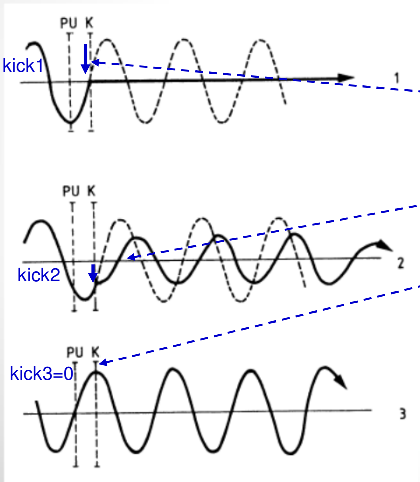
Signal travel time = time of flight of particle (between pick-up and kicker)

Sampling of sub-ensemble of total beam

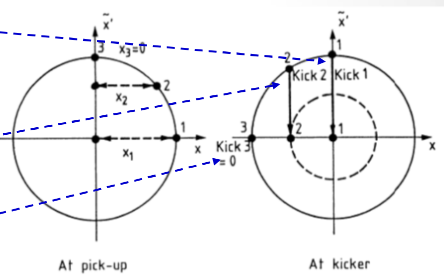
Principle of transverse cooling:
measurement of deviation from ideal orbit is used for correction kick (feedback)

Stochastic Cooling

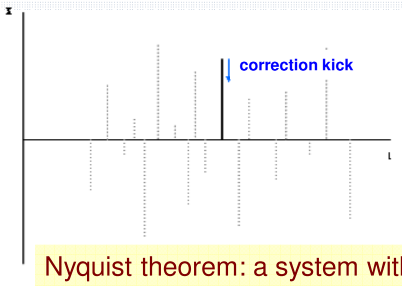
single particle betatron motion
along storage ring
without and with correction kick



projection to two-dimensional
horizontal phase area



Stochastic Cooling

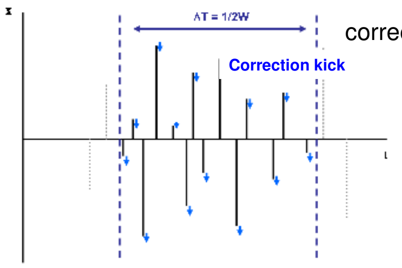


in time domain

correction kick
(unlimited resolution)

$$\Delta x = g \times x$$

Nyquist theorem: a system with a band-width Δf = W in frequency domain can resolve a minimum time duration ΔT=1/(2W)



correction kick $\Delta x = \frac{g}{N_s} \times \sum_{i=1..N_s} x_i \;,\; N_s = N\frac{\Delta T}{T_0} = \frac{N}{2WT_0}$

For exponential damping ($x(t)=x(t_0)\cdot\exp(-(t-t_0)/\tau)$):

$$\tau^{-1} = T_0^{-1} \times \frac{\Delta x}{x} = \frac{g2W}{N}, \; if \; \sum_{i=1..N_s} x_i = x$$

cooling rate $\boxed{\tau^{-1} \leq \frac{2W}{N}}$ $if \; g \leq 1$

Stochastic Cooling

some refinements of cooling rate formula

noise: thermal or electronic noise adds to the beam signal

mixing: change of relative longitudinal position of particles due to momentum spread

cooling rate $\lambda = \tau^{-1} = \frac{2W}{N}(\underbrace{2g}_{\text{cooling}} - \underbrace{g^2(M+U)}_{\text{heating}})$

M mixing factor
U noise to signal ratio

maximum of cooling rate

$$\lambda_{max} = \frac{2W}{N}\frac{1}{M+U}$$

$$\frac{d\lambda}{dg} = 0 \Rightarrow g = \frac{1}{M+U}$$

further refinement (wanted ↔ unwanted mixing):

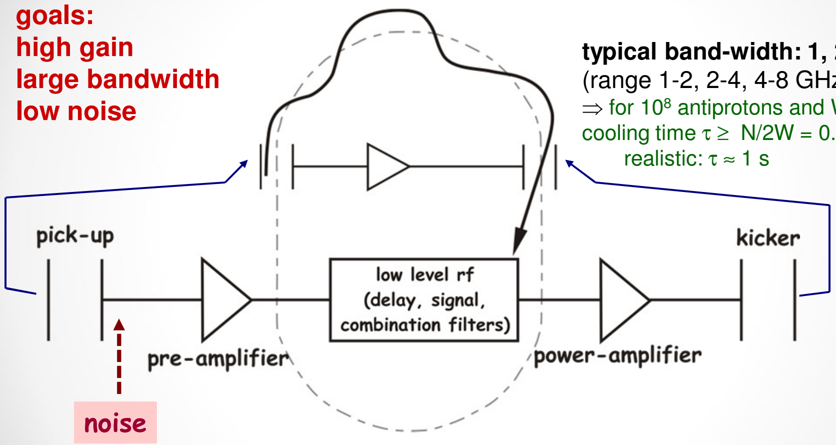
with wanted mixing M (kicker to pick-up)
and unwanted mixing $\tilde{M}$ (pick-up to kicker)

$$\lambda = \tau^{-1} = \frac{2W}{N}(2g(1-\tilde{M}^2) - g^2(M+U))$$

Stochastic Cooling Circuit

goals:
high gain
large bandwidth
low noise

typical band-width: 1, 2, 4 GHz
(range 1-2, 2-4, 4-8 GHz)
⇒ for 10^8 antiprotons and W = 1 GHz
cooling time $\tau \geq$ N/2W = 0.05 s
realistic: $\tau \approx$ 1 s



Transfer Function:

$$Z_{pick-up} \cdot G_{pick-up}(E) \cdot H(t_{delay}) \cdot F(E) \cdot G \cdot G_{kicker}(E) \cdot Z_{kicker}$$

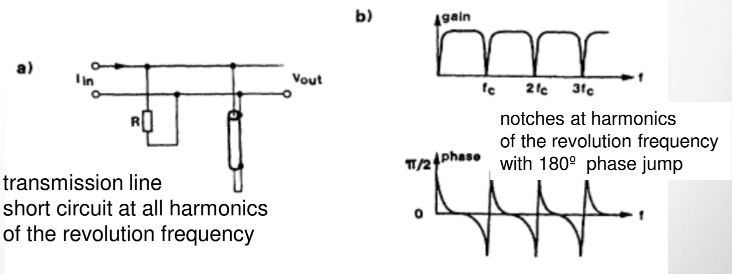
Longitudinal Stochastic Cooling

1) **Palmer cooling**

pick-up in dispersive section detects horizontal position
⇒ acceleration/deceleration kick corrects momentum deviation

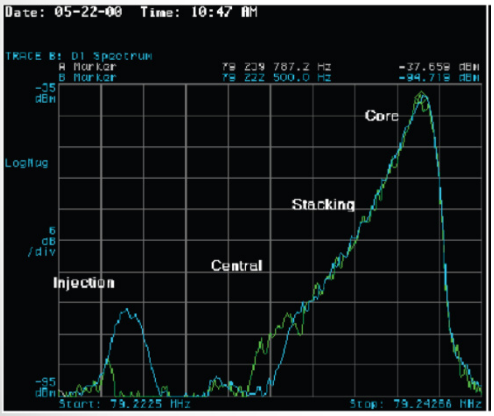
2) **Notch filter cooling**

filter creates notches at the harmonics of the nominal revolution frequency
⇒ particles are forced to circulate at the nominal frequency

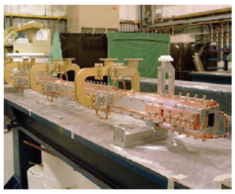


Antiproton Accumulation by Stochastic Cooling

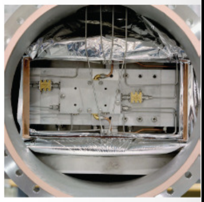
accumulation of 8 GeV antiprotons at accumulator ring, FNAL, shut down 09/2011
a similar facility AC/AA at CERN was shut down 11/1996



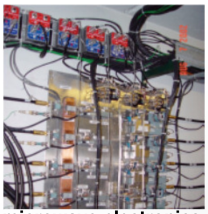
momentum distribution of accumulated antiproton beam



kicker array



cryogenic microwave amplifier



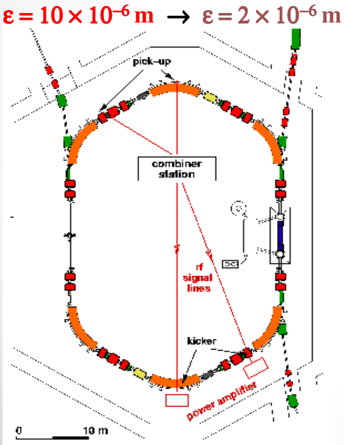
microwave electronics

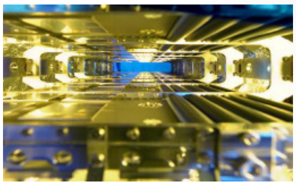
power amplifiers (TWTs)

Stochastic Cooling of Rare Isotopes at GSI

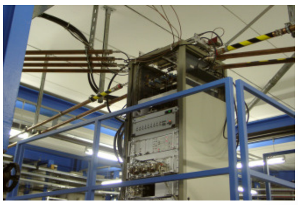
fast pre-cooling of hot fragment beams

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





electrodes installed inside magnets



combination of signals from electrodes

power amplifiers for generation of correction kicks

Comparison of Cooling Methods

	Stochastic Cooling	Electron Cooling
Useful for:	**low intensity beams**	**low energy**
		all intensities
	hot (secondary) beams	**warm beams (pre-cooled)**
	high charge	**high charge**
	full 3 D control	**bunched beams**
Limitations: /problems	**high intensity beams**	**space charge effects**
	beam quality limited	**recombination losses**
	bunched beams	**high energy**

laser cooling (of incompletely ionized ions) and ionization cooling (of muons) are quite particular and not general cooling methods

Trends in Beam Cooling

Stochastic cooling was mainly developed for the production of high intensity antiproton beams for colliders (CERN, FNAL, 1972 – 2011). It is still in operation at AD (CERN), COSY (FZJ) and ESR (GSI). It will also be used in the FAIR project (Germany) for cooling of antiprotons and rare isotope beams.

First demonstration of bunched beam stochastic cooling (2008) with ions (BNL) made it also attractive for ion colliders. Now it is proposed for the collider of the Russian NICA project.

Electron cooling was and still is used in low energy storage rings for protons, ions, secondary beams (antiprotons, rare isotopes).

Electron cooling is interesting for low energy storage rings, but also application at higher energies (MeV electron energies) is envisaged after the successful demonstration of the 4 MeV electron cooler at FNAL.

Other cooling methods, like muon (ionization) cooling or coherent electron cooling are under investigation, but are still far from implementation in a full scale machine.

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Biannual Workshops on Beam Cooling: e. g. COOL'15, Jefferson Lab, USA