

# Beam Cooling

M. Steck, GSI Darmstadt

CAS Advanced Accelerator Physics,

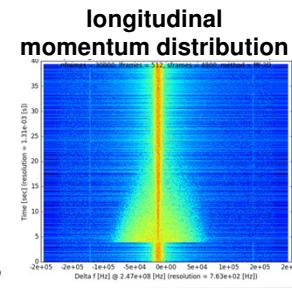
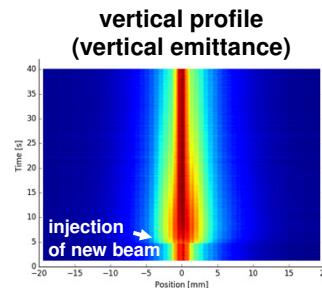
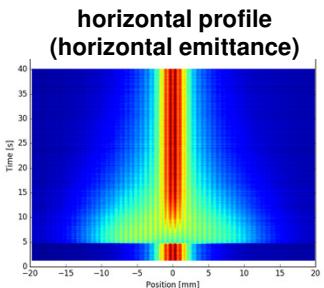
Royal Holloway University of London,

3 - 15 September 2017

## Observation of Cooling

Xe<sup>54+</sup> beam at 400 MeV/u cooled with electron current 200 mA

cooling in six-dimensional phase space



measured with residual gas ionization beam profile monitor

longitudinal Schottky noise

# Beam Cooling

## Introduction

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

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# 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)

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## Cooling Force

**Generic (simplest case of a) cooling force:**

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

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

non conservative, cannot be described by a Hamiltonian

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

$$F_z = -\alpha_z v_z \quad z = x, y, s \quad v_z = v_0 \cdot z' \\ \frac{df(z, z', t)}{dt} = -\lambda_z f(z, z', t) \quad \lambda_z \text{ cooling (damping) rate}$$

**in a circular accelerator:**

**Transverse (emittance) cooling**

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

**Longitudinal (momentum spread) cooling**

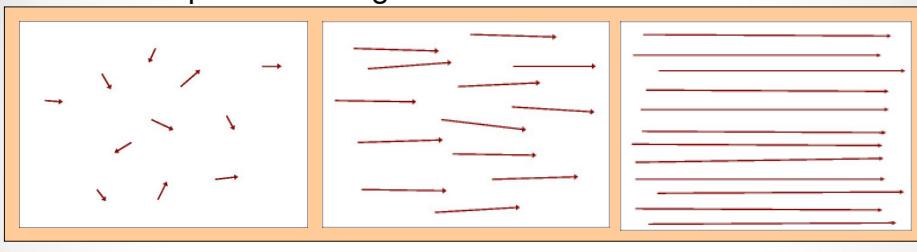
$$\frac{\delta p_{\parallel}}{p_0}(t_0 + t) = \frac{\delta p_{\parallel}}{p_0}(t_0) e^{-\lambda_{\parallel} t}$$

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## 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

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## Beam Temperature Definition

Longitudinal beam temperature

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

Transverse beam temperature

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

Distribution function

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

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

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

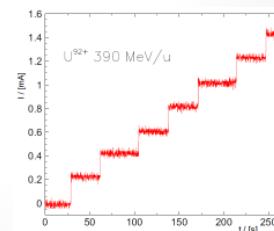
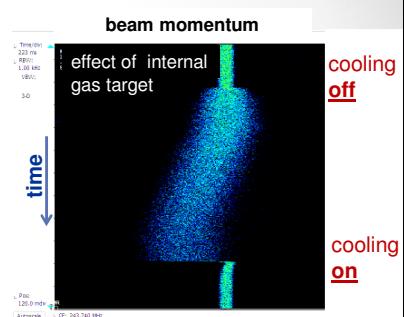
Don't confuse: beam energy  $\leftrightarrow$  beam temperature

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

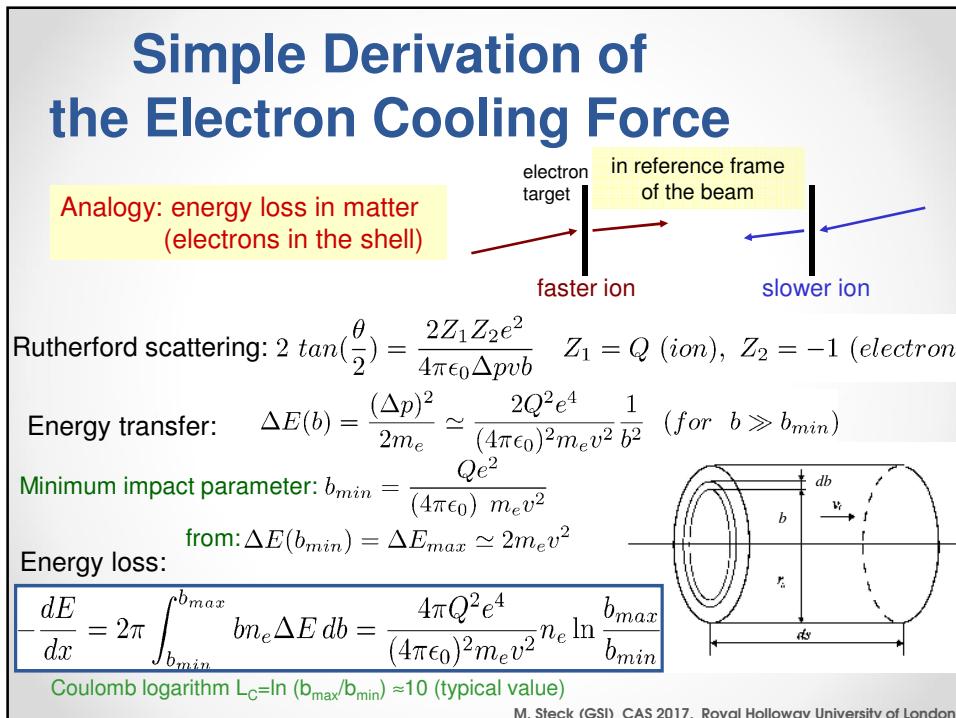
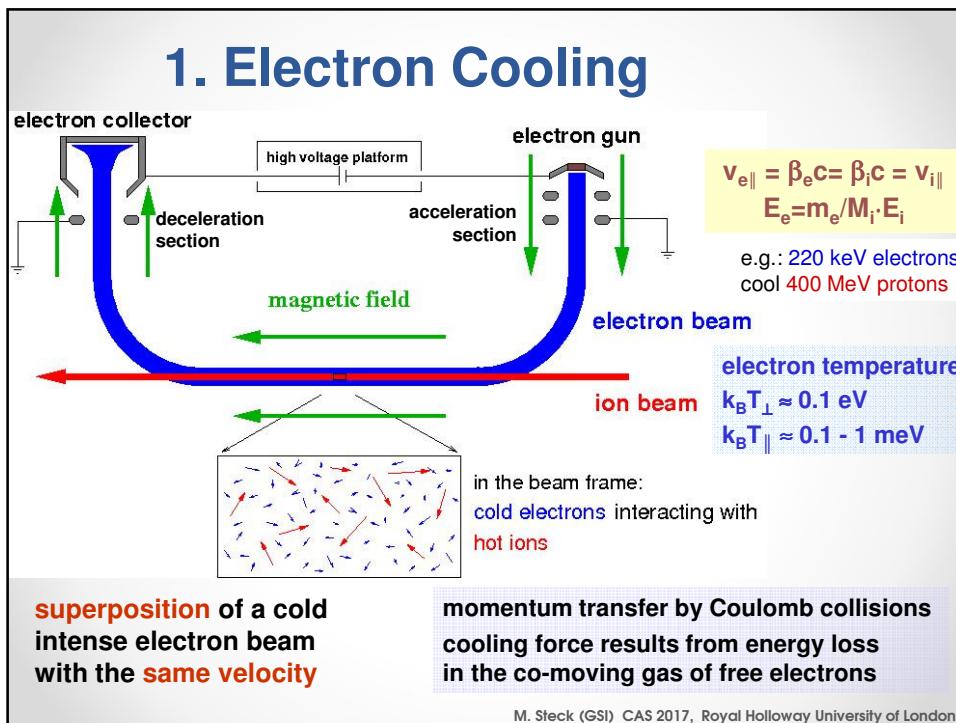
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## Benefits of Beam Cooling

- 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)



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# Characteristics of the Electron Cooling Force

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

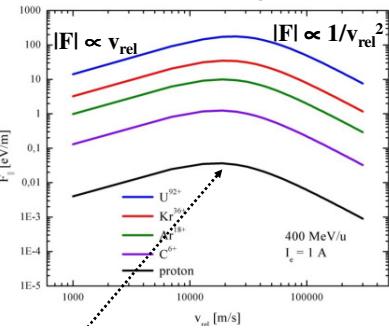
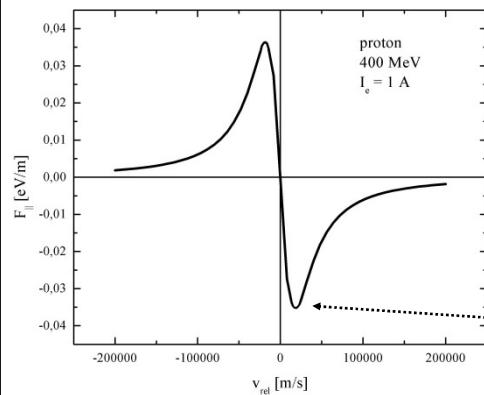
$$\vec{v}_{rel} = \vec{v}_i - \vec{v}_e$$

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

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# 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:

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

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

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# Electron Cooling Time

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

**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 ( $\tau^1$ ):**

- slow for hot hadron 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

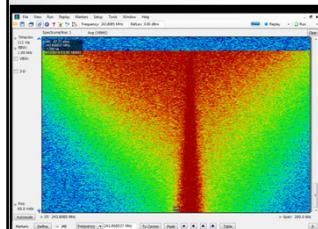
$$F \propto v_{rel} \Rightarrow \tau = \Delta t = p_{rel}/F = \text{constant}$$

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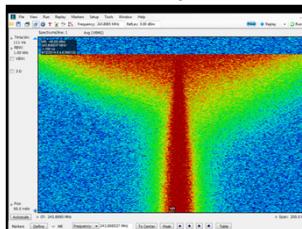
# Longitudinal Cooling

Xe<sup>54+</sup> 350 MeV/u

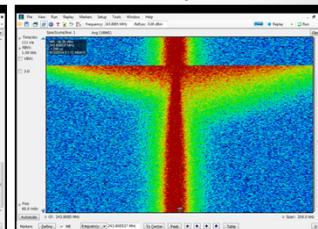
I<sub>e</sub> = 100 mA



I<sub>e</sub> = 250 mA

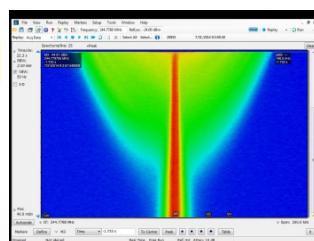


I<sub>e</sub> = 500 mA



measurement time 20 s

protons 400 MeV (Q=1)



measurement time 650 s

I<sub>e</sub> = 250 mA

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# Electron Beam Properties

**electron beam temperature**

is determined by the thermal cathode temperature  $k_B T_{cat}$

transverse temperature  $k_B T_{\perp} = k_B T_{cat}$ ,

can be reduced by transverse magnetic expansion with ( $\propto B_c/B_{gun}$ )

longitudinal temperature  $k_B T_{\parallel} = (k_B T_{cat})^2 / 4E_0 \ll k_B T_{\perp}$

$$\text{lower limit : } k_B T_{\parallel} \geq 2e \frac{n_e^{1/3}}{4\pi\epsilon_0}$$

**typical values:**

transverse  $k_B T_{\perp} \approx 100 \text{ meV (1100 K)}$

with magnetic expansion  $k_B T_{\perp} \approx 1 \text{ meV}$

longitudinal  $k_B T_{\parallel} \approx 0.1 - 1 \text{ meV}$

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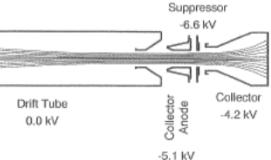
# Electron Beam Properties

constant electron beam radius



electron beam confined by longitudinal magnetic field (from gun to collector)

Collector



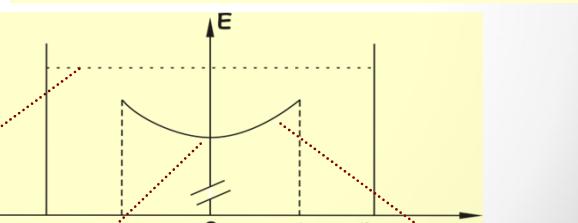
Cooling Section

transversely expanded electron beam

electron current (space charge limited)

$$I_e = PU_{an}^{3/2}$$

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



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## Electron Motion in Longitudinal Magnetic Field

single particle cyclotron motion

$$\text{cyclotron frequency } \omega_c = \frac{eB}{\gamma m_e}$$

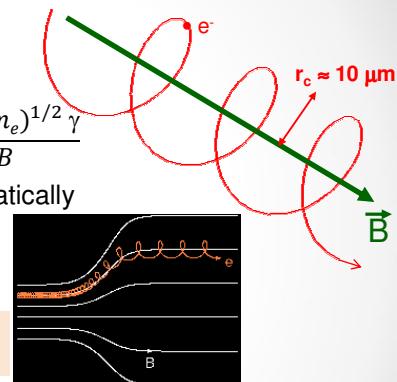
$$\text{cyclotron radius } r_c = \frac{v_\perp}{\omega_c} = \frac{(kBT_\perp m_e)^{1/2} \gamma}{eB}$$

electrons follow the magnetic field line adiabatically

$\Rightarrow$  transverse magnetic expansion

results in a reduction of the

$$\text{transverse temperature } \frac{mv_\perp^2}{B} = \text{const.}$$



another important consequence:

for interaction times which are long compared to the cyclotron period the ions do not sense the transverse electron temperature

$\Rightarrow$  magnetized cooling ( $T_{\text{eff}} \approx T_{\parallel} \ll T_{\perp}$ )

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## Optimized Electron Cooling

minimize relative velocity between ions and electrons

electron beam space charge:

transverse electric field + longitudinal B-field  $\Rightarrow$  azimuthal drift

$$v_{azi} = r\omega_{azi} = r \frac{2\pi r_e n_e c^2}{\gamma \omega_c}$$

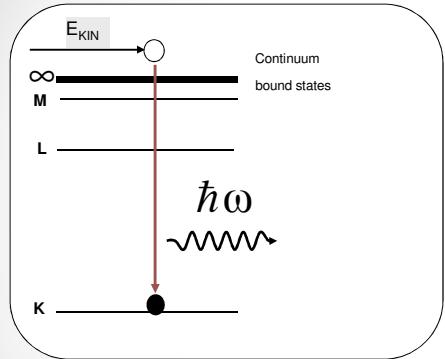
$\Rightarrow$  • electron and ion beam should be well centered

Favorable for optimum cooling (small transverse relative velocity):

- parallel adjustment of ion and electron beam
- high parallelism of magnetic field lines  $B_\perp/B_\parallel$  in cooling section
- large beta function (small divergence) in cooling section

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# Atomic Physics Limitation of Electron Cooling



## Radiative Electron Capture (REC)



emission of a photon

change of the ion charge  
results in particle loss  
⇒ different orbit

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

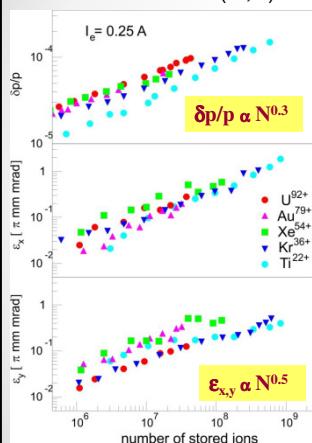
$$\alpha_{\text{REC}} = \frac{1.92 \times 10^{-13} Q^2}{\sqrt{k_B T}} \left( \ln \frac{5.66 Q}{\sqrt{k_B T}} + 0.196 \left( \frac{k_B T}{Q^2} \right)^{1/3} \right) [cm^3 s^{-1}]$$

## losses by recombination (REC)

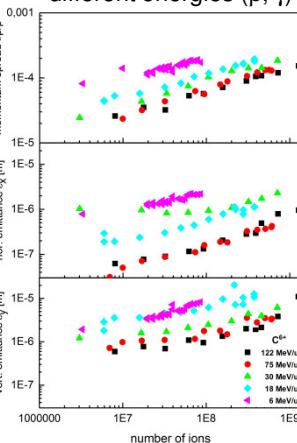
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# Electron Cooled Beams in Equilibrium with Intrabeam Scattering (IBS)

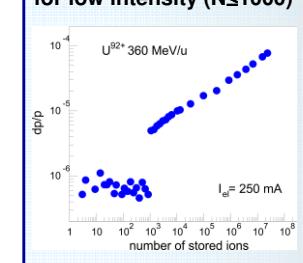
different ions ( $Q, A$ )



different energies ( $\beta, \gamma$ )



## suppression of IBS for low intensity ( $N \leq 1000$ )



Beam ordering  
(crystallization)

## heating rate dominated by Intrabeam Scattering

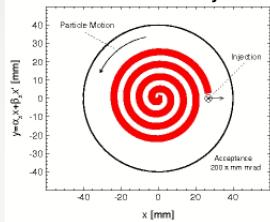
$$\tau_{\text{IBS}}^{-1} = \frac{Q^4 e^4}{(Am_i)^2} \cdot \frac{N}{C \epsilon_h \epsilon_v \delta p / p} \cdot \frac{1}{(\gamma^4 \beta^3 c^3)} \cdot 4\pi \mathcal{L}_C^{\text{IBS}}$$

IBS: total phase space volume increases with ion beam intensity and ion charge

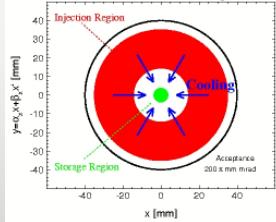
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## Accumulation of Heavy Ions by Electron Cooling

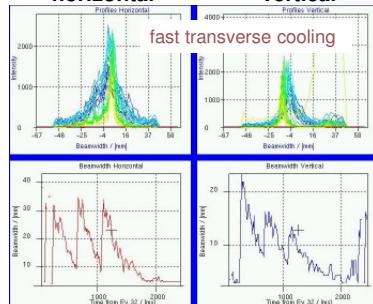
standard multturn injection



fast accumulation by repeated multturn injection with electron cooling



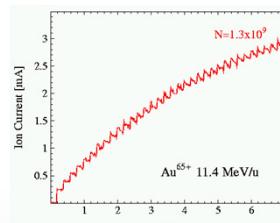
horizontal



vertical

profile

beam size



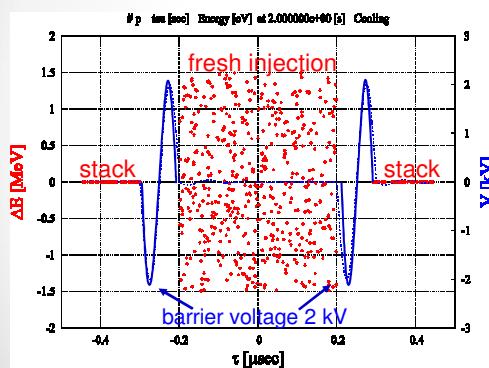
intensity increase in 5 s by a factor of  $\approx 10$

limitations:  
space charge tune shift,  
recombination (REC)

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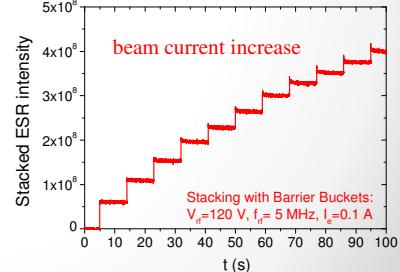
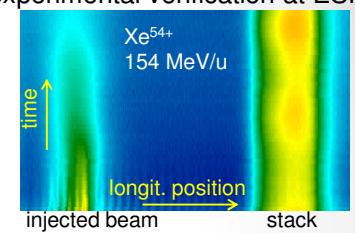
## Accumulation of Secondary Particles

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



simulation of longitudinal stacking with barrier buckets and electron cooling

experimental verification at ESR



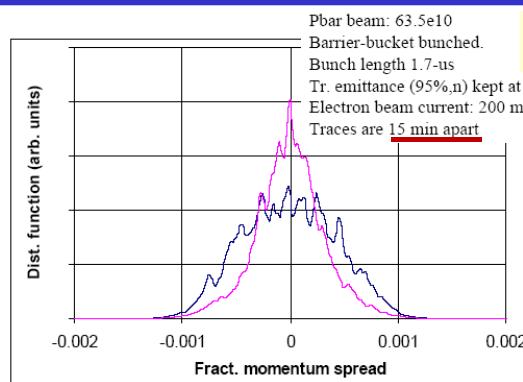
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# High Energy Electron Cooling

electron cooling of 8 GeV antiprotons

longitudinal cooling with 0.2 A, 4.4 MeV electron beam

First e-cooling demonstration - 07/15/05



measured by detection of longitudinal Schottky noise

first electron cooling  
at relativistic energy  
at Recycler, FNAL  
resulting in increased  
luminosity in the  
Tevatron collider

cooling time of some ten minutes has to be compared  
with the accumulation time of many hours

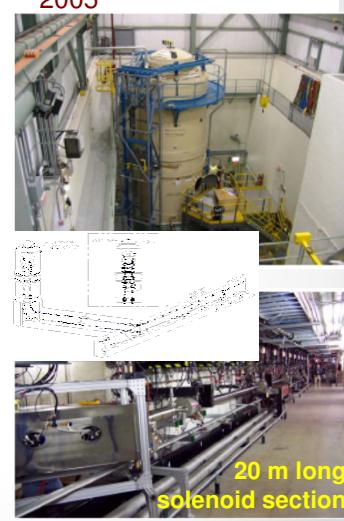
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## Electron Cooling Systems

First Electron  
Cooling System  
NAP-M/BINP  
1974



High Energy:  
4.3 MeV Recycler/FNAL  
2005



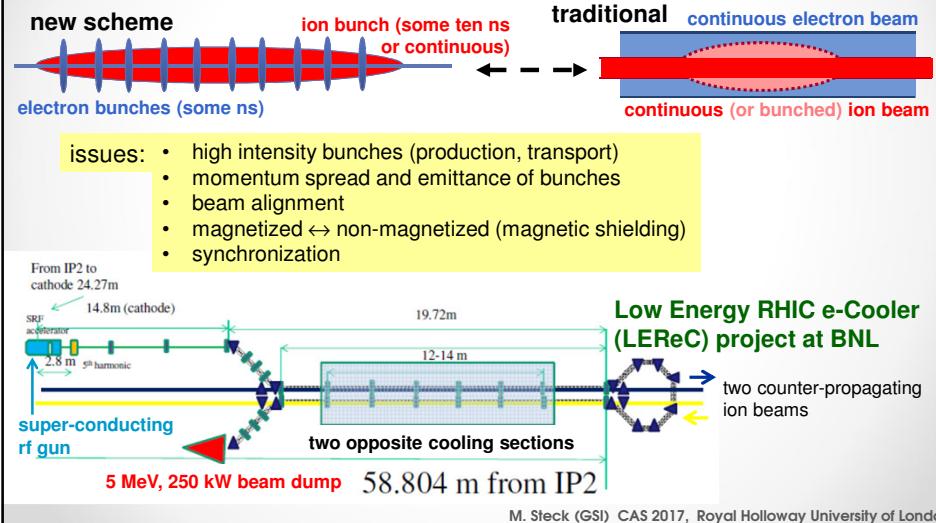
Medium Energy:  
300 keV  
ESR/GSI  
1990



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## Bunched Beam Electron Cooling

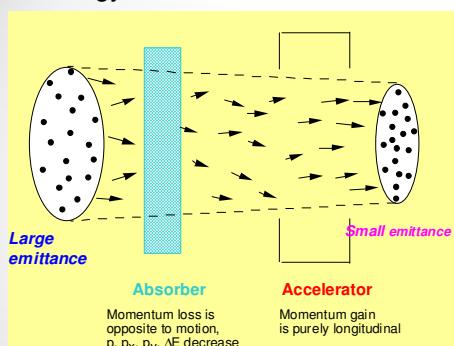
Electron cooling with electrostatic acceleration is limited in energy (5-10 MeV). A bunched electron beam offers the extension of the electron cooling method to higher energy (linear rf accelerator).



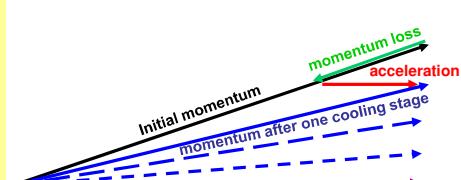
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## 2. Ionization Cooling

energy loss in solid matter



proposed for muon cooling



not useful for heavy particles due to strong interaction with matter

transverse cooling

$$\begin{aligned} \frac{d\epsilon_N}{ds} &= -\frac{1}{\beta^2 E} \frac{dE}{ds} \epsilon_N + \frac{\beta \gamma \beta_\perp \langle \theta_{rms}^2 \rangle}{2} \frac{ds}{ds} \\ &= -\frac{1}{\beta^2 E} \frac{dE}{ds} \epsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_R E} \end{aligned}$$

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

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

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# Ionization Cooling

increased longitudinal cooling  
by longitudinal-transverse emittance exchange

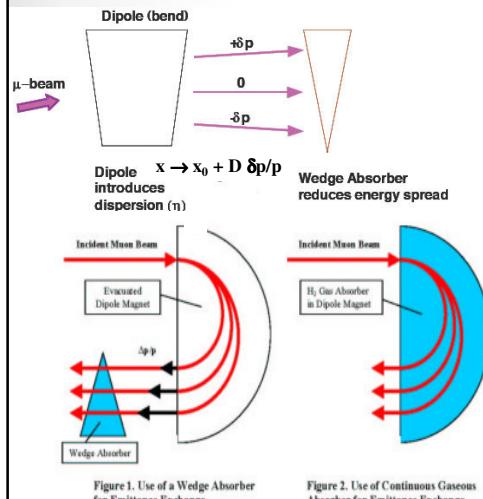


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

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

cooling term      heating term

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

## emittance exchange

increased longitudinal cooling

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

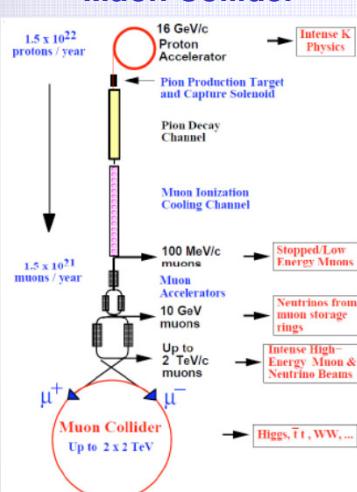
reduced transverse cooling

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

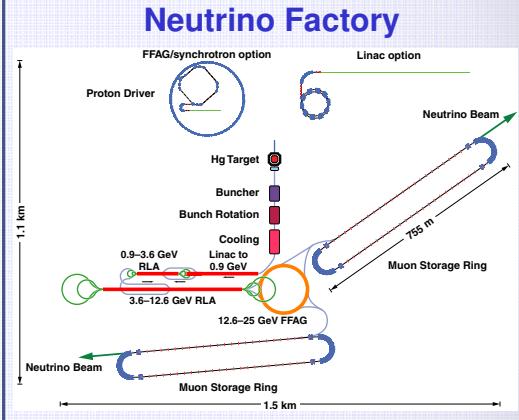
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# Scenarios with Ionization Cooling

## Muon Collider

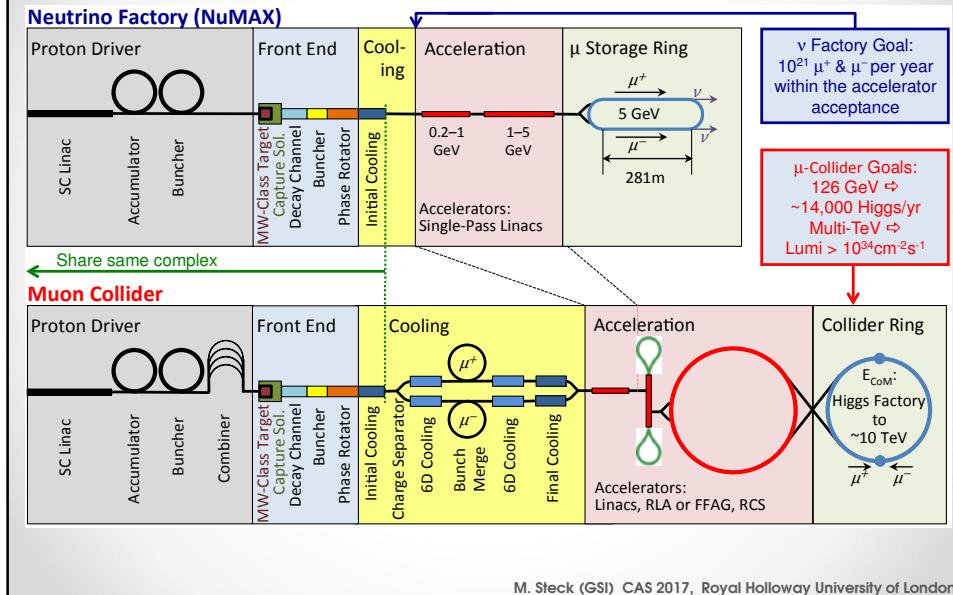


## Neutrino Factory



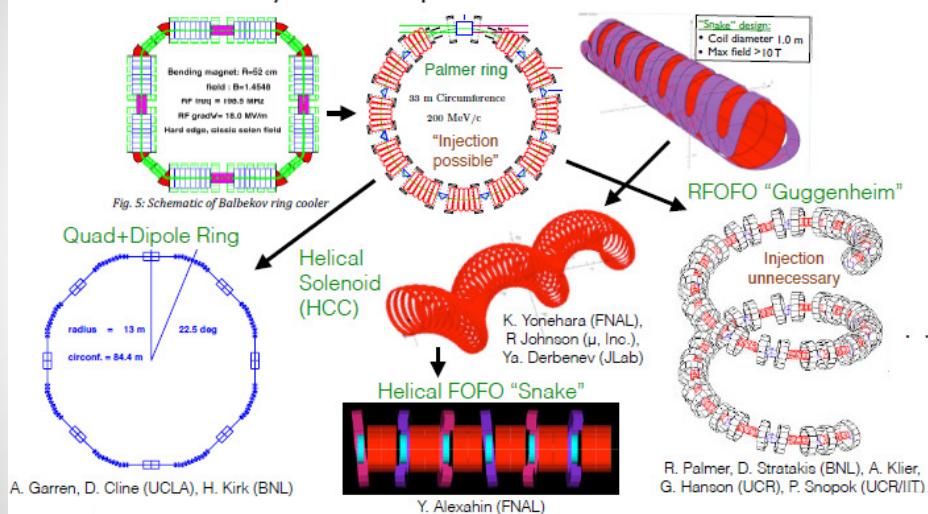
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## Scenarios with Ionization Cooling

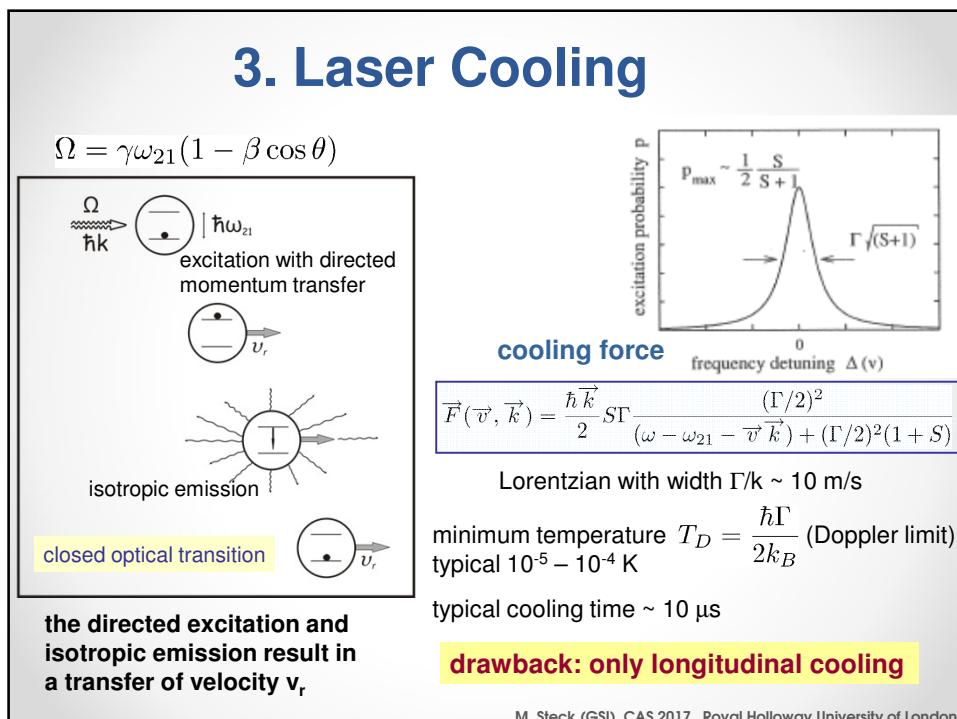
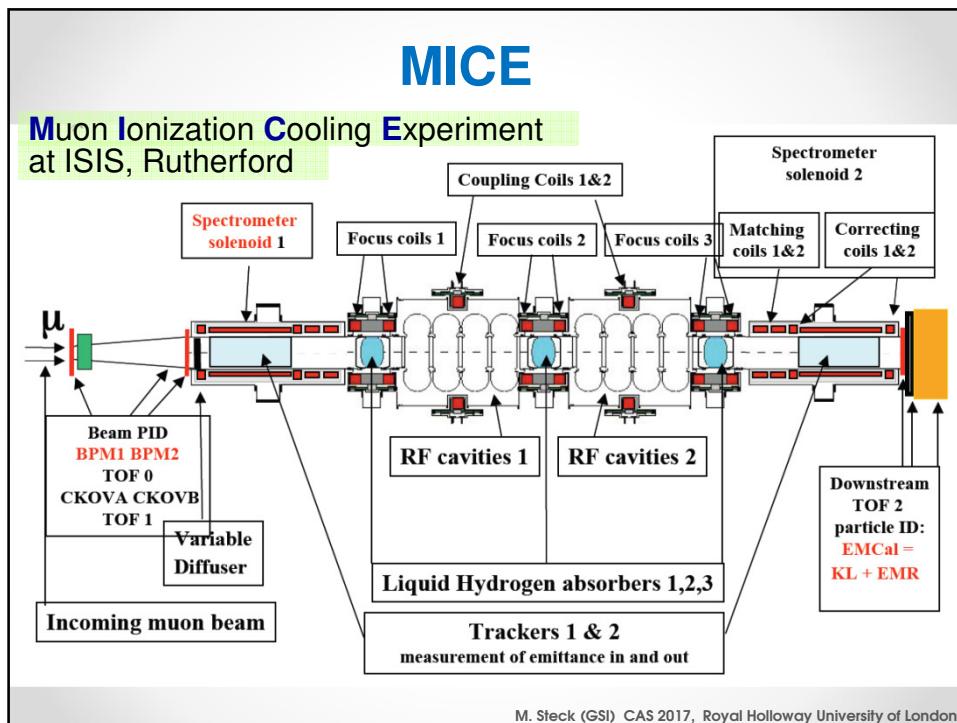


## The Muon Cooling Section

studies for the arrangements of ion optical structure, absorber and rf section



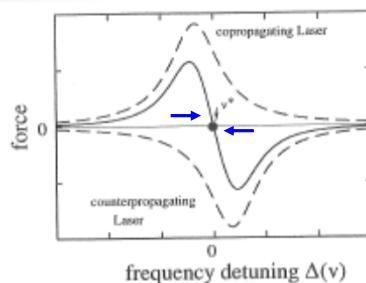
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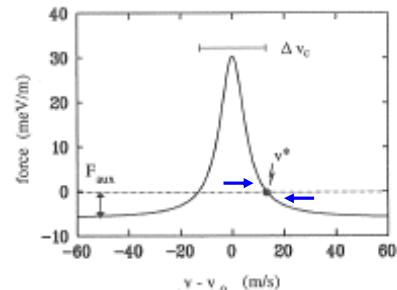
# Laser Cooling

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)  
or pulsed laser with large spectral width  
ions studied so far:  $^7\text{Li}^{1+}$ ,  $^9\text{Be}^{1+}$ ,  $^{24}\text{Mg}^{1+}$ ,  $^{12}\text{C}^{3+}$

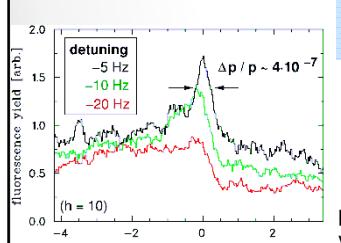
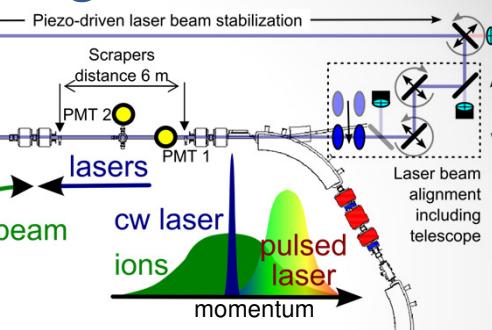
in future: Li-like heavy ions at relativistic energies, cooling rate increases with  $\gamma$   
large relativistic energy  $\Rightarrow$  large excitation energy in PRF

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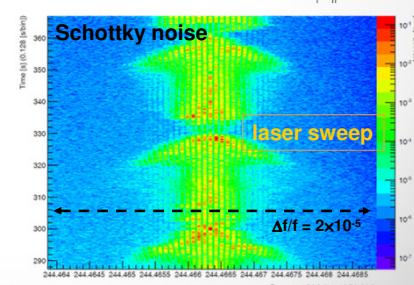
# Laser Cooling of $\text{C}^{3+}$



Argon ion laser (257.3 nm)  
frequency doubled



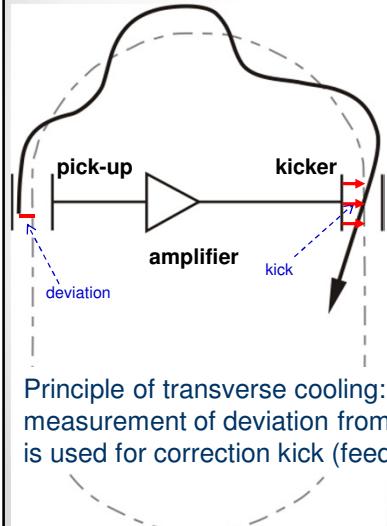
fluorescence light detection  
tube voltage  
ions  
laser  
probing the  
velocity distribution



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## 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):  $(n + \frac{1}{2})\pi$

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

Sampling of sub-ensemble of total beam

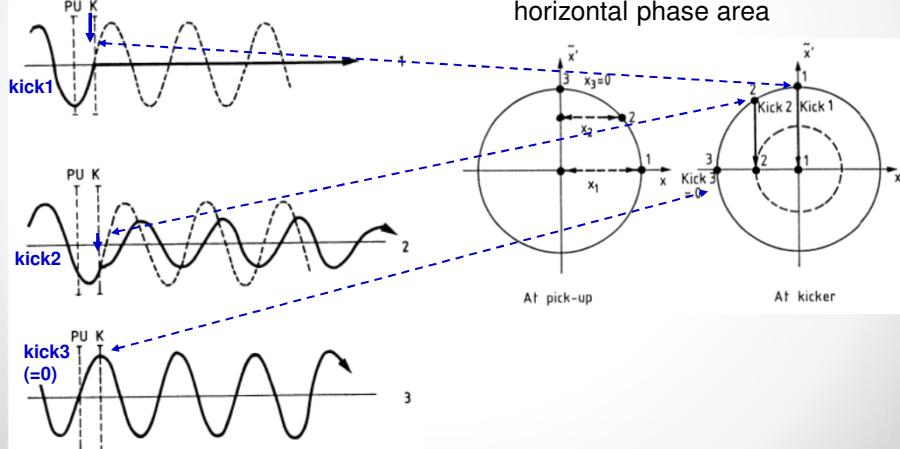
Principle of transverse cooling:  
measurement of deviation from ideal orbit  
is used for correction kick (feedback)

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## Stochastic Cooling

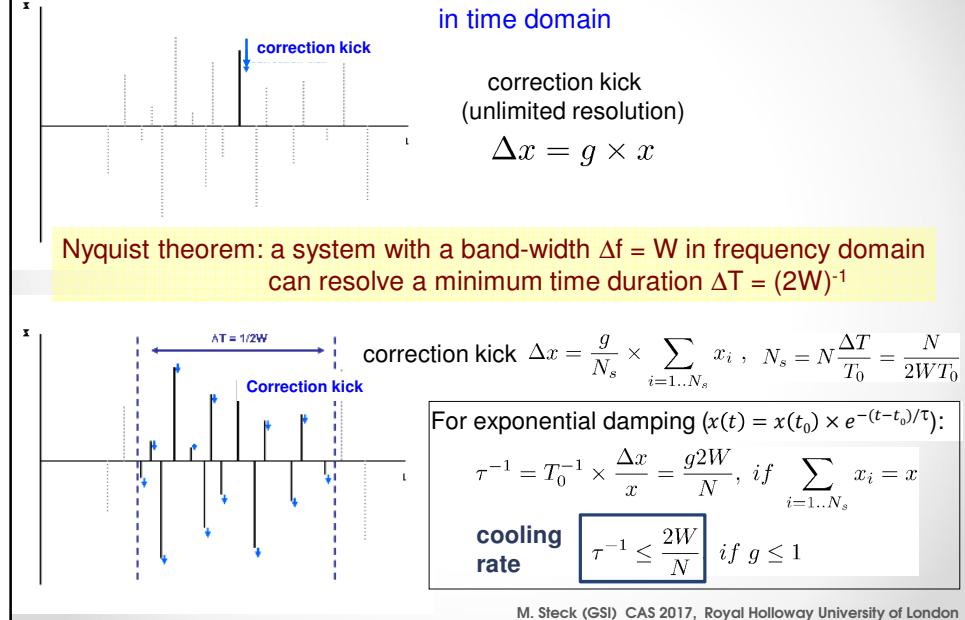
single particle betatron motion  
along storage ring  
without (dashed) and with (full)  
correction kick

projection to two-dimensional  
horizontal phase area



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# Stochastic Cooling



# 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

$$\text{cooling rate } \lambda = \tau^{-1} = \frac{2W}{N} \left( \frac{2g}{\text{cooling}} - \frac{g^2(M+U)}{\text{heating}} \right) \quad \begin{matrix} M \text{ mixing factor} \\ U \text{ noise to signal ratio} \end{matrix}$$

**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)  $\lambda = \tau^{-1} = \frac{2W}{N} (2g(1 - \tilde{M}^2) - g^2(M+U))$   
and unwanted mixing  $\tilde{M}$  (pick-up to kicker)

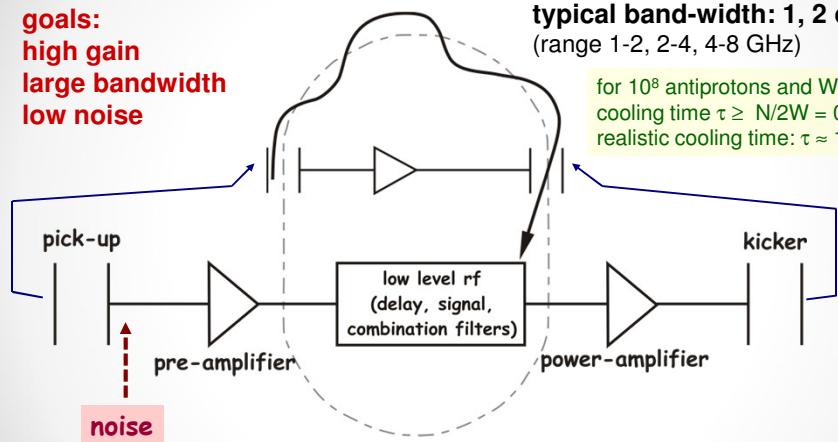
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# Stochastic Cooling Circuit

**goals:**  
**high gain**  
**large bandwidth**  
**low noise**

**typical band-width: 1, 2 or 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 cooling time:  $\tau \approx 1$  s



Transfer Function:

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

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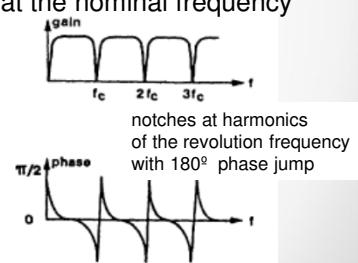
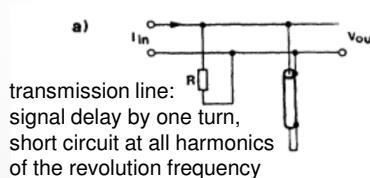
# Longitudinal Stochastic Cooling

## 1) Palmer cooling

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

## 2) Notch filter cooling

filter creates notches at the harmonics of the nominal revolution frequency  
 $\Rightarrow$  particles are forced to circulate at the nominal frequency



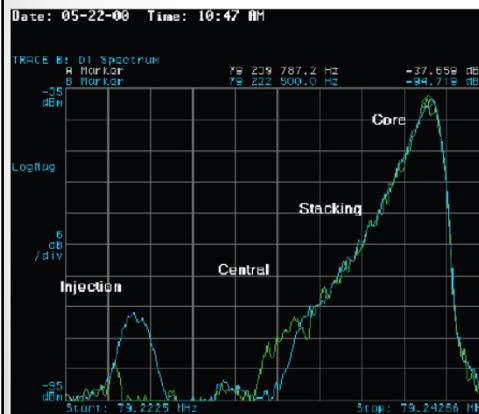
## 3) ToF cooling

simplified scheme without notches allows efficient pre-cooling

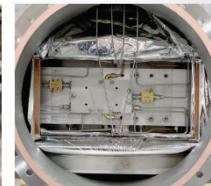
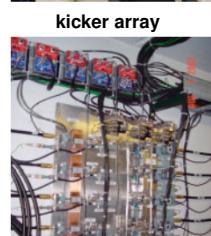
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# Antiproton Accumulation by Stochastic Cooling

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



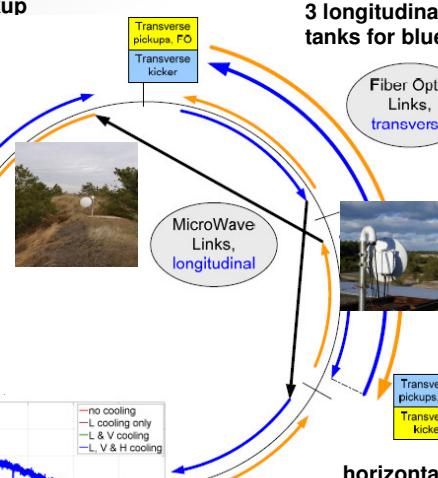
momentum distribution of accumulated antiproton beam



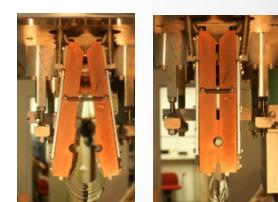
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## RHIC – 3D stochastic cooling for heavy ions

longitudinal pickup

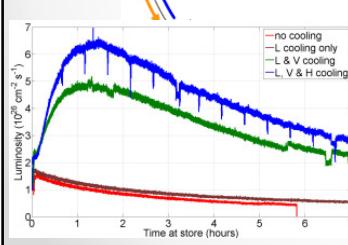


3 longitudinal kicker tanks for blue ring



longitudinal kicker open for injection and ramping (left), closed during cooling (right)

increase of luminosity by a factor of five

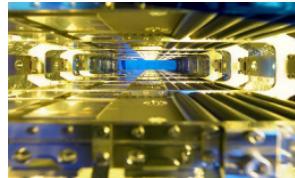
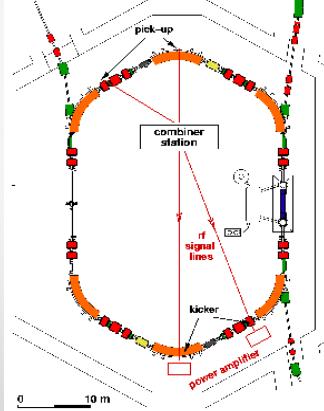


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## Stochastic Cooling of Rare Isotopes at GSI

**fast pre-cooling of hot fragment beams**

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



electrodes  
installed  
inside magnets



combination of  
signals from  
electrodes



power amplifiers  
for generation of  
correction kicks

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## Comparison of Cooling Methods

### Stochastic Cooling

**Useful for:** low intensity beams

hot (secondary) beams  
high charge  
full 3D control

### Electron Cooling

low energy  
all intensities  
warm beams (pre-cooled)  
high charge  
bunched beams

**Limitations:** high intensity beams  
/problems beam quality limited  
bunched beams

space charge effects  
recombination losses  
high energy

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

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