Beam Cooling

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Beam Cooling

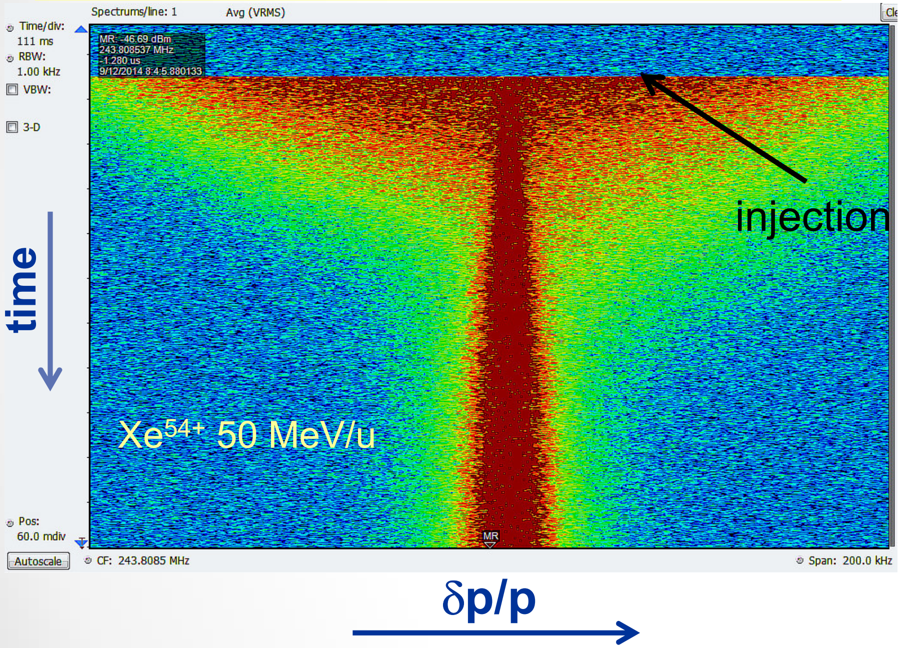
Introduction

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

Cooling

reduction of momentum (energy) spread due to cooling

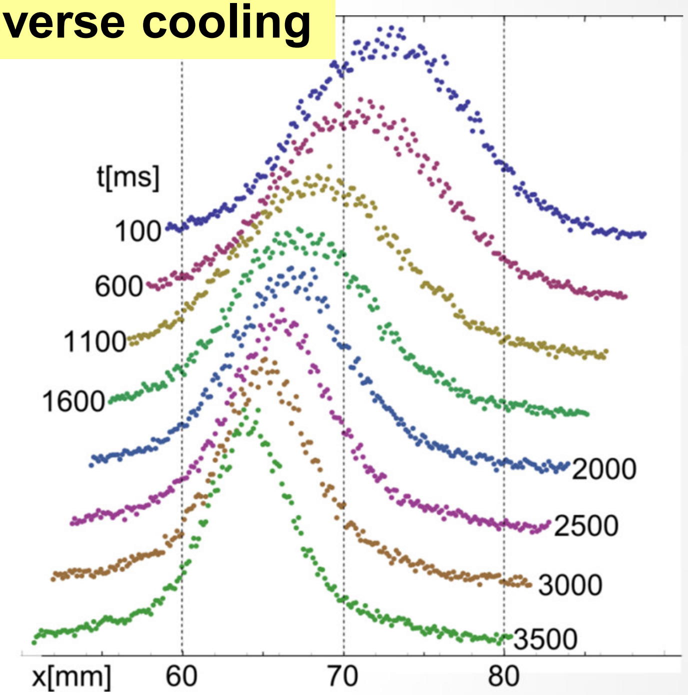
longitudinal (momentum) cooling



Time/div: 111 ms
RBW: 1.00 kHz
Pos: 60.0 mdiv
CF: 243.8085 MHz
Span: 200.0 kHz

reduction of beam size (emittance) due to cooling

transverse cooling



cooling

good energy definition, small beam size
⇒ highest precision for experiments

Xe^{54+} 15 MeV/u

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 neglect interactions between beam particles.)

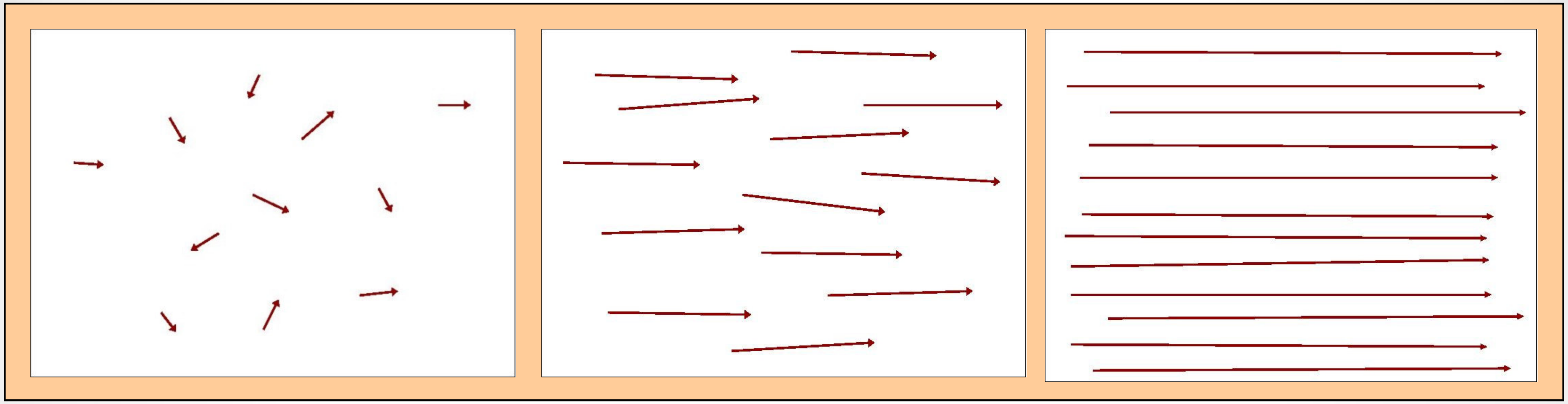
Beam cooling techniques are non-Liouvillean processes which violate the assumption of a conservative force.

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

Beam Temperature

Where does the beam temperature originate from?

The beam particles are generated in a 'hot' source



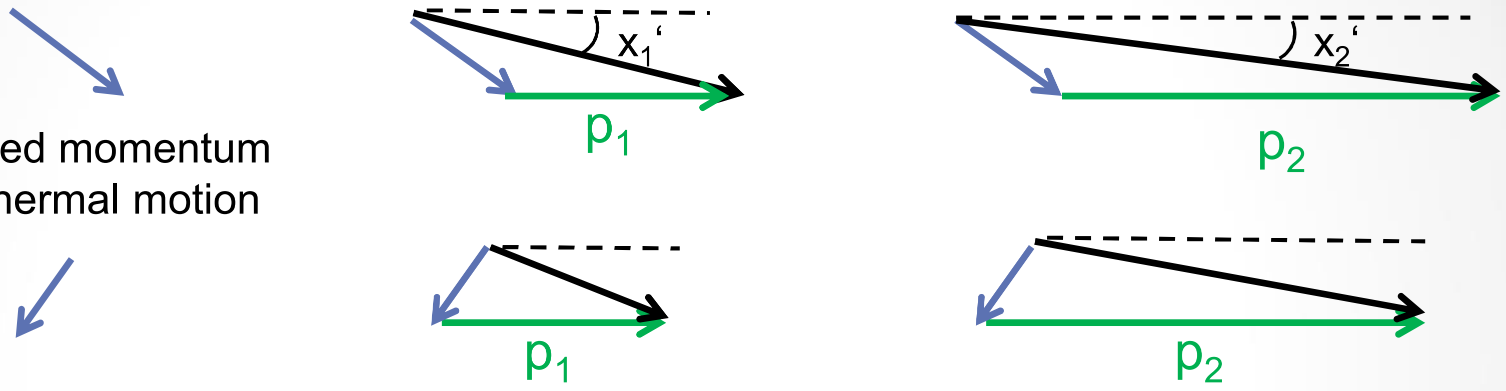
at rest (source) **at low energy** **at high energy**

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

Adiabatic Shrinking



at rest ($p=0$)

acceleration to p_1

acceleration to p_2

undirected momentum
due to thermal motion

after acceleration from p_1 to p_2: $x_2' < x_1'$

adiabatic shrinking of emittance: $\varepsilon_2 = x_2 \cdot x_2' < \varepsilon_1 = x_1 \cdot x_1'$

$\varepsilon_1 \beta_1 \gamma_1 = \varepsilon_2 \beta_2 \gamma_2$ **(normalized emittance)** **momentum:** $p_{1,2} = m_0 c \beta_{1,2} \gamma_{1,2}$

$\varepsilon_2 = \varepsilon_1 \times \beta_1 \gamma_1 / \beta_2 \gamma_2 = \varepsilon_1 \times p_1 / p_2$
(reduction of emittance due to acceleration)

6D Particle Coordinates

Particle coordinates

(longitudinal)

$$z = s - s_0 = R\Delta\phi / h$$

$$\frac{\Delta p}{p_0} = \frac{\Delta W}{\beta_0^2 W_0}$$

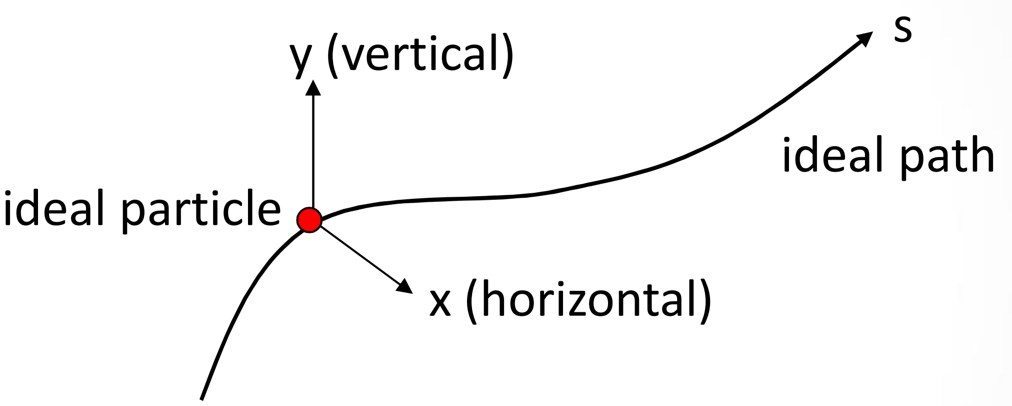
(transverse: horizontal)

$$x,\, x' = \frac{dx}{ds} \approx \frac{p_x}{p_0} < 1$$

(transverse: vertical)

$$y,\, y' = \frac{dy}{ds} \approx \frac{p_y}{p_0} < 1$$

particle trajectory is determined by external fields (magnets)



$$\vec{r} = \left(z, \frac{\Delta p}{p}, x, x', y, y' \right)$$

the motion in the longitudinal (z,Δp/p) and the transverse phase plane (x,x´) (y,y´) are decoupled and the phase space areas are conserved independently

Beam Temperature Definition

Longitudinal beam temperature

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

Transverse beam temperature

$$\boxed{\frac{1}{2}k_BT_\perp = \frac{1}{2}mv_\perp^2 = \frac{1}{2}mc^2\beta^2\gamma^2\theta_\perp^2}$$

$$\theta_\perp = \frac{v_\perp}{\beta c}, \qquad \theta_\perp(s) = \sqrt{\frac{\epsilon}{\beta_\perp(s)}}$$

Distribution function

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

Particle beams can be anisotropic: $k_BT_\parallel \neq k_BT_\perp$

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

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

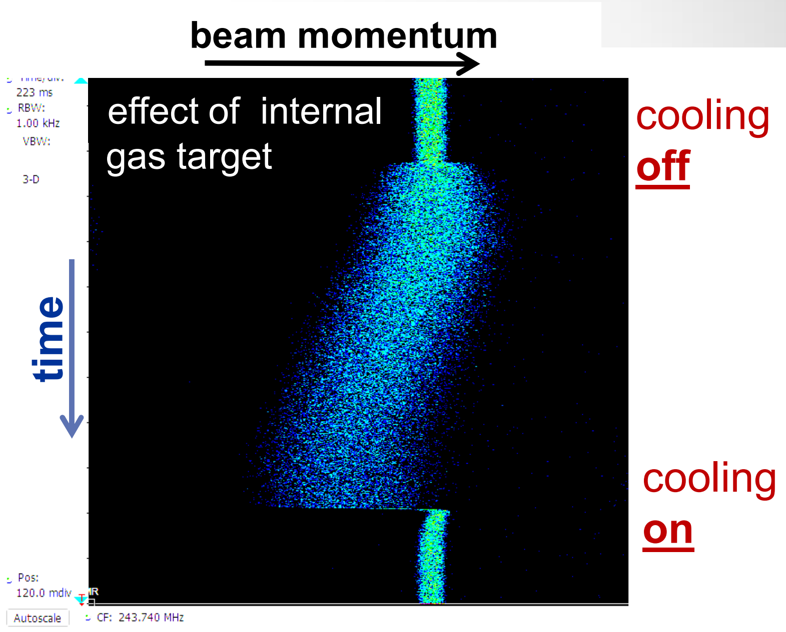
(e.g. a beam of energy 100 GeV can have a temperature of 1 eV)

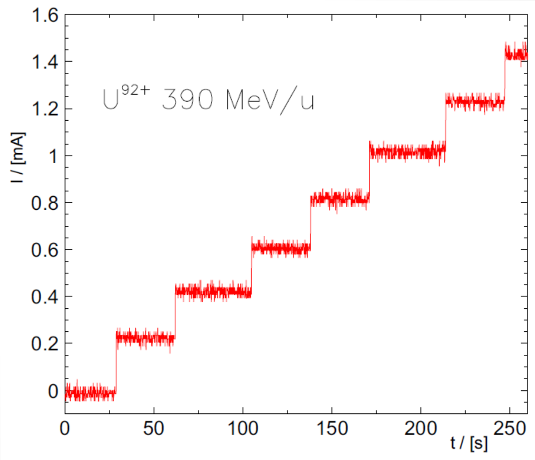
Benefits of Beam Cooling

- 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)

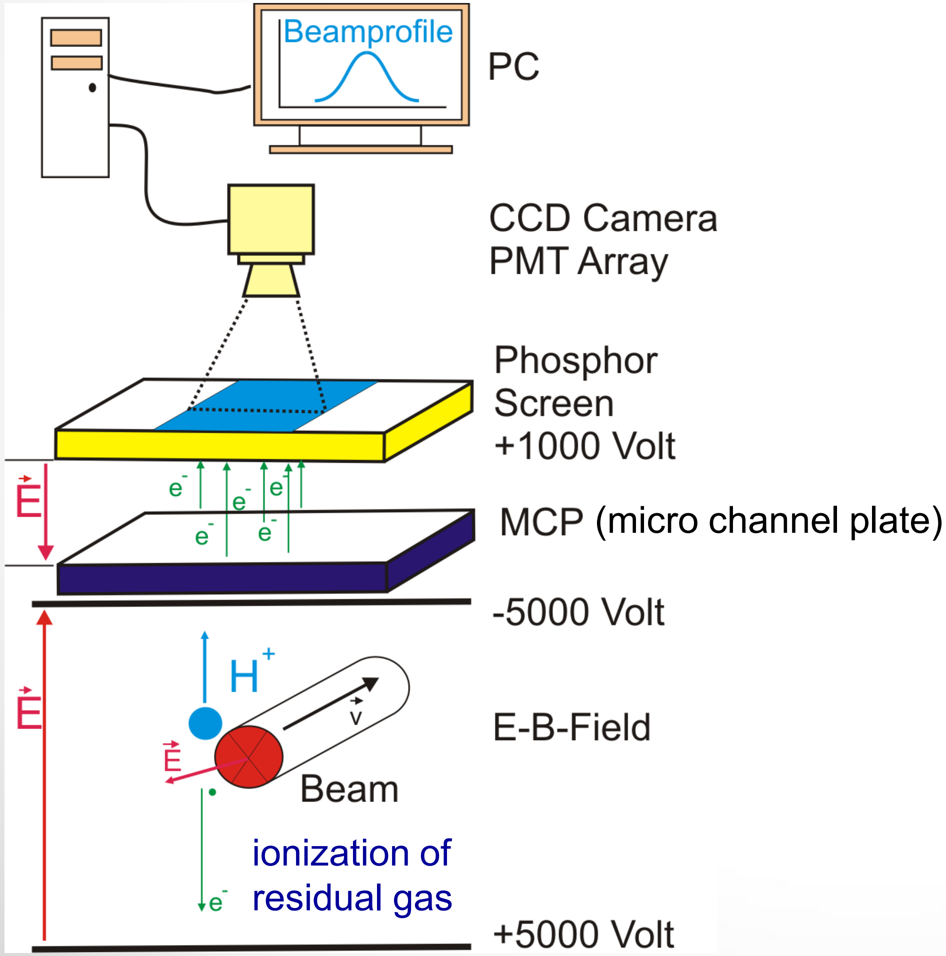




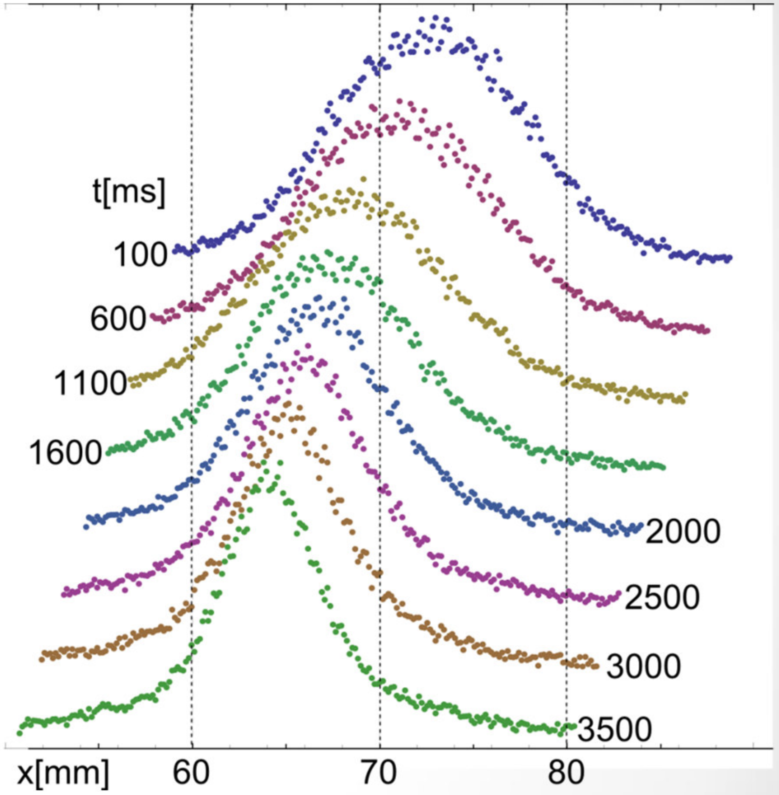
Non-destructive Diagnostics

transverse

Profile of transverse distribution
from ionization of the residual gas



horizontal beam profile



Cooling of the beam
after injection into ESR

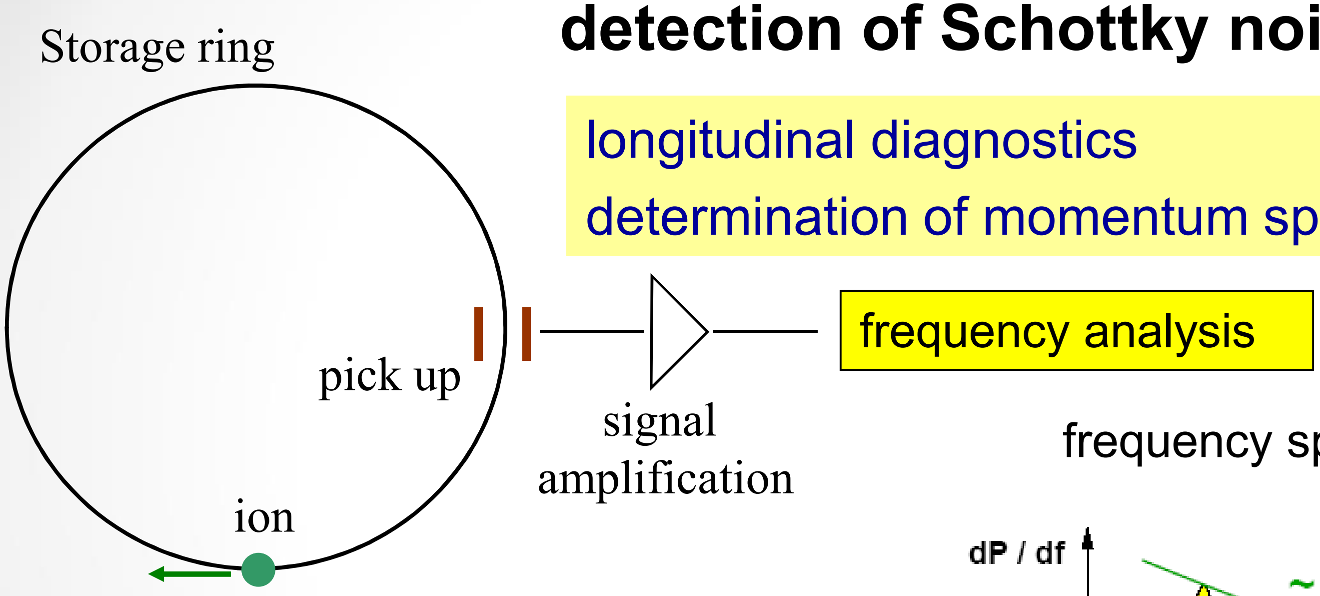
Non-destructive Diagnostics

longitudinal

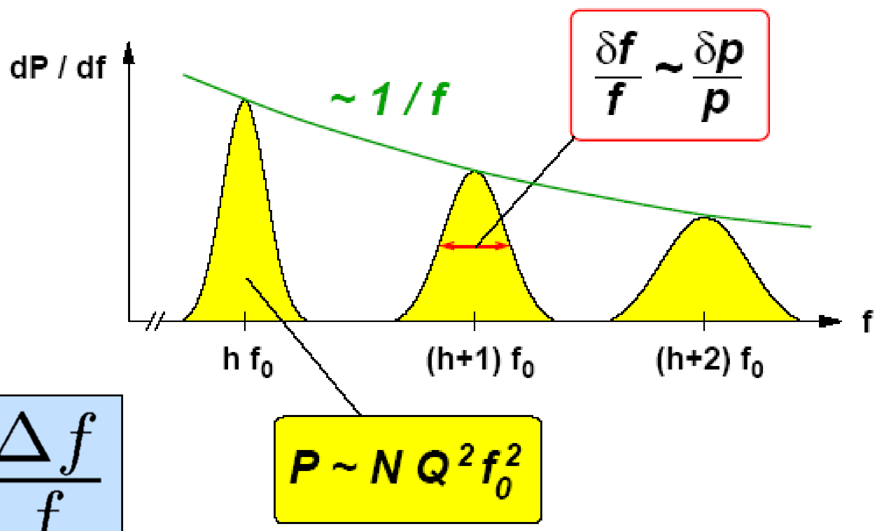
detection of Schottky noise (also used for stochastic cooling)

longitudinal diagnostics

determination of momentum spread



frequency spectrum



$$\frac{\delta f}{f} \sim \frac{\delta p}{p}$$

$$P \sim N Q^2 f_0^2$$

momentum compaction factor η

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}$$

transition energy γ_t
(ion optical parameter)

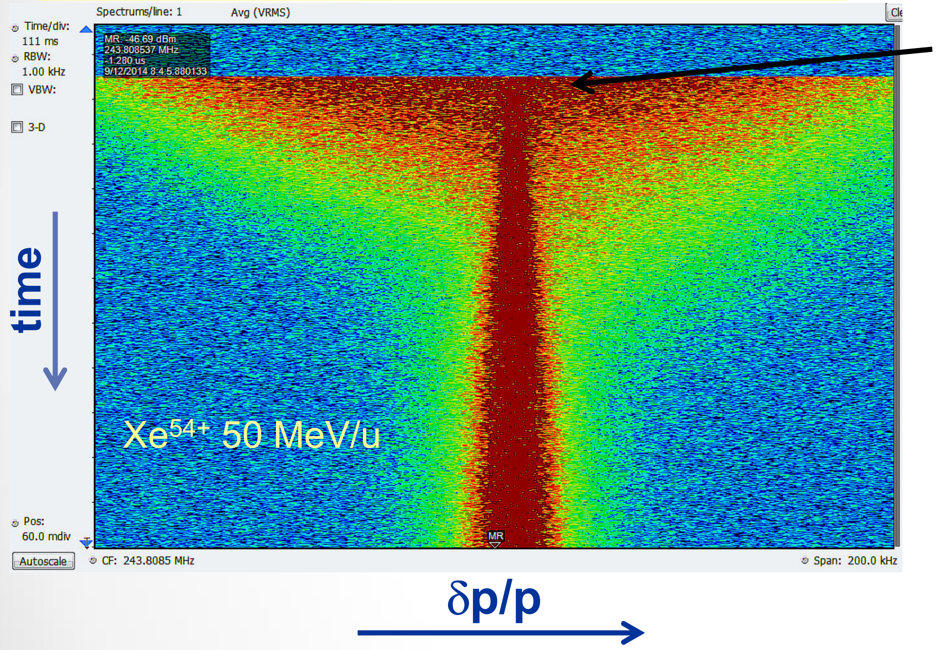
$$\frac{\Delta p}{p} = \frac{1}{\eta} \frac{\Delta f}{f}$$

Cooling

reduction of momentum (energy) spread due to cooling

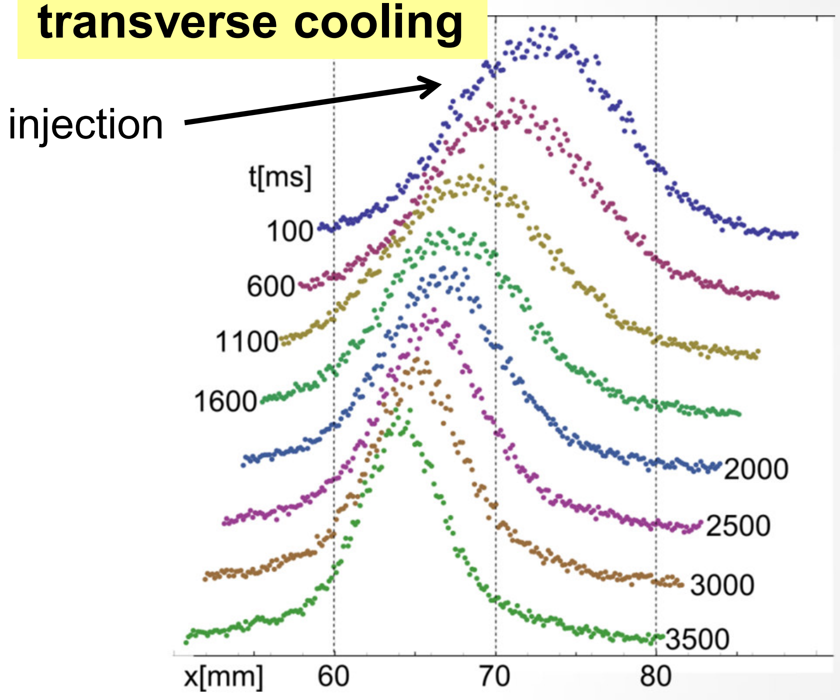
reduction of beam size (emittance) due to cooling

longitudinal (momentum) cooling



Spectrums/line: 1
Avg (VRMS)
Time/div: 111 ms
RBW: 1.00 kHz
☐ VBW:
☐ 3-D
MR: -46.69 dBm
243.808537 MHz
-1.280 us
9/12/2014 8:4:5.880133
Pos: 60.0 mdiv
CF: 243.8085 MHz
Span: 200.0 kHz

transverse cooling



cooling

good energy definition, small beam size

⇒ highest precision for experiments

Xe^{54+} 15 MeV/u

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 $f(z, z', t)$

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

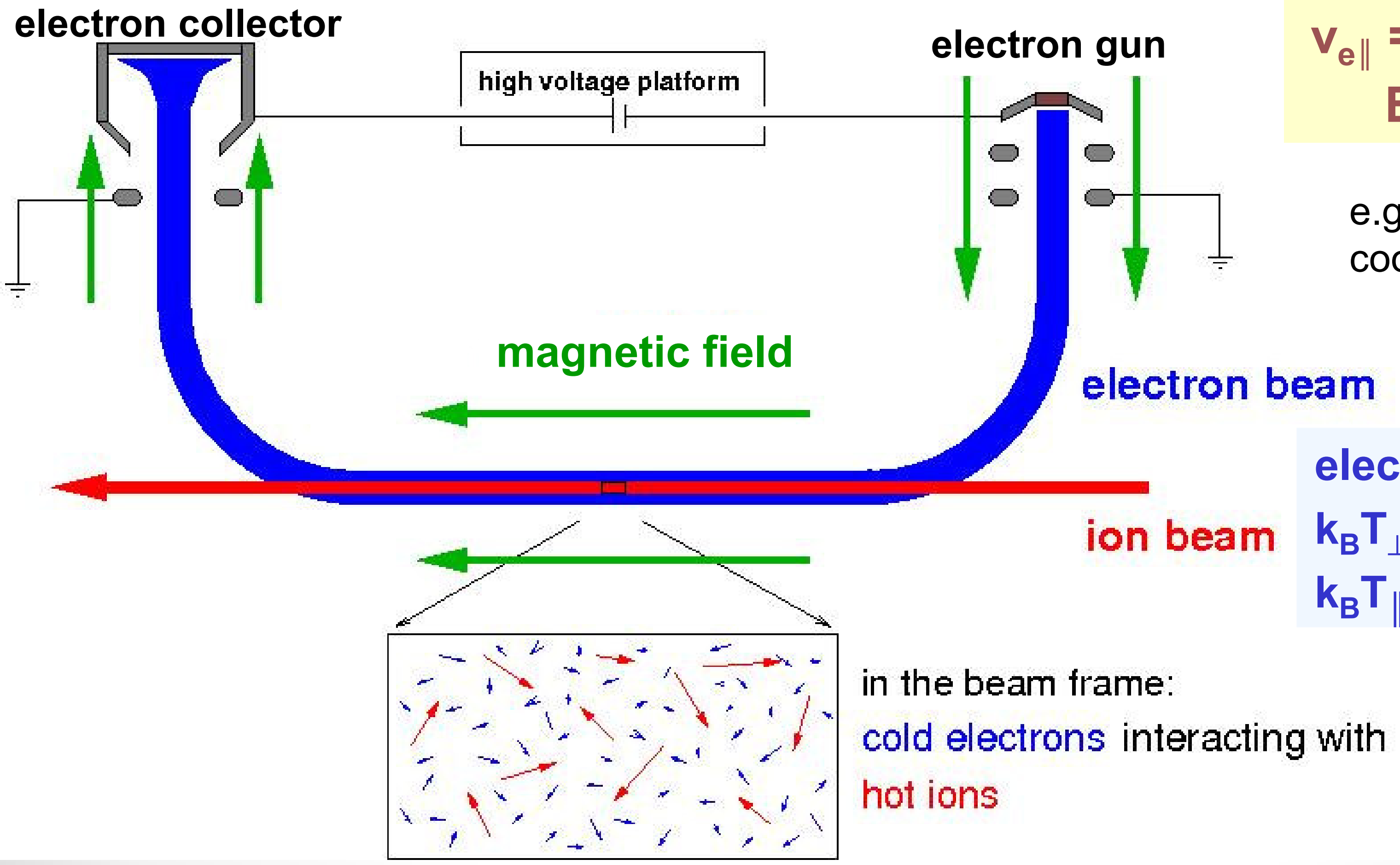
$$\frac{df(z, z', t)}{dt} = -\lambda_z f(z, z', t) \qquad \lambda_z \quad \text{cooling (damping) rate}$$

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

1. Electron Cooling



in the beam frame:
cold electrons interacting with
hot ions

$v_{e\parallel} = \beta_e c = \beta_i c = v_{i\parallel}$
$E_e = m_e/M_i \cdot E_i$

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

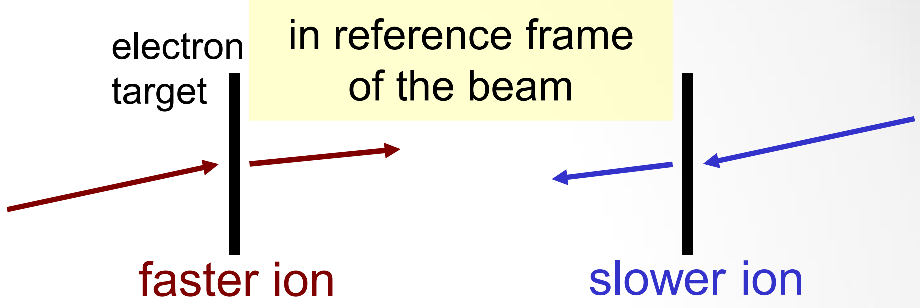
electron temperature
$k_B T_\perp \approx 0.1$ eV
$k_B T_\parallel \approx 0.1 - 1$ meV

superposition of a cold intense electron beam with the same velocity (in the lab system)

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)



electron target

in reference frame of the beam

faster ion

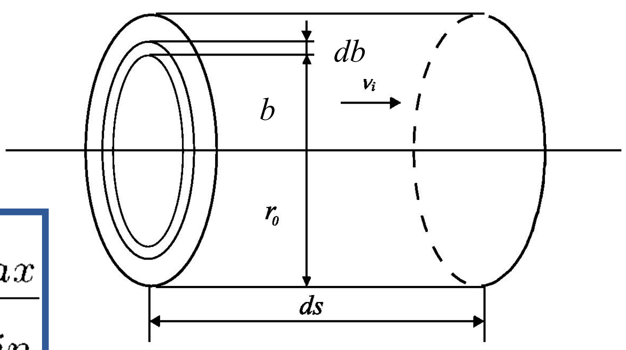
slower ion

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:

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

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

Characteristics of the Electron Cooling Force

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

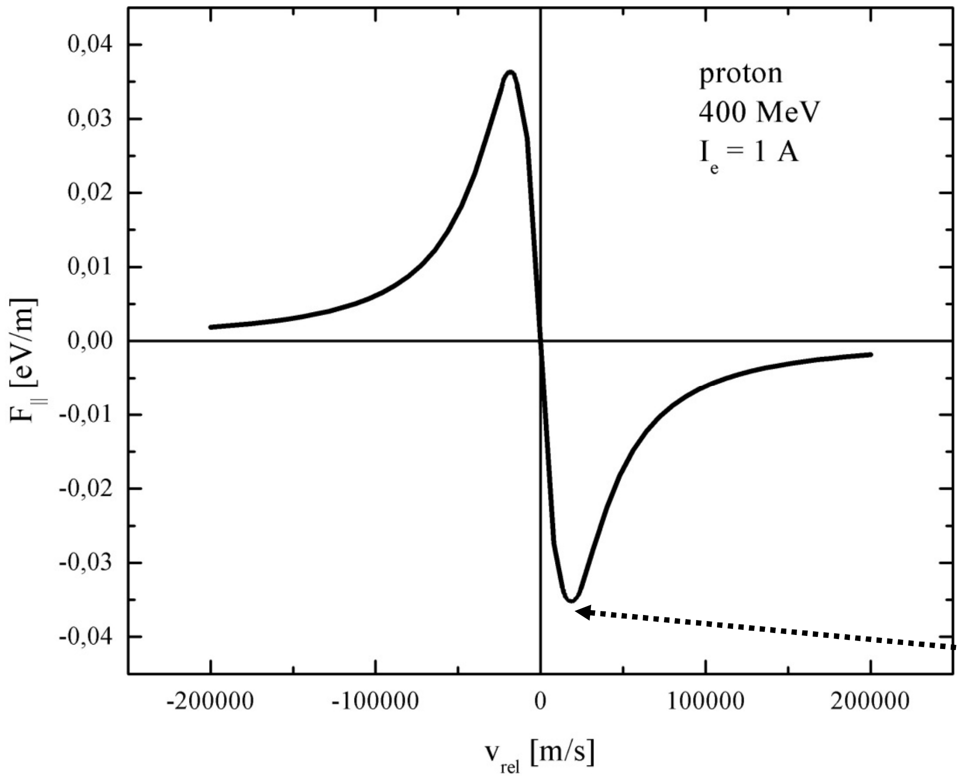
$$\vec{v}_{rel} = \vec{v_i} - \vec{v_e}$$

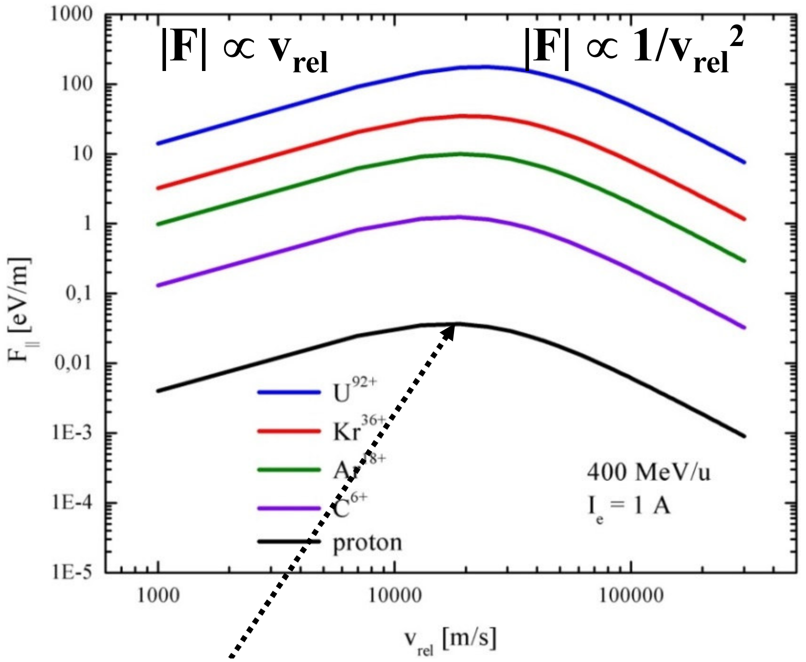
cooling force F

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

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

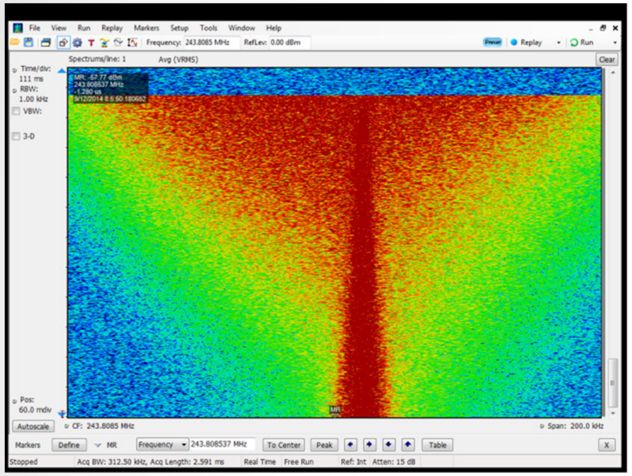
cooling rate is constant and maximum at small relative velocity

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

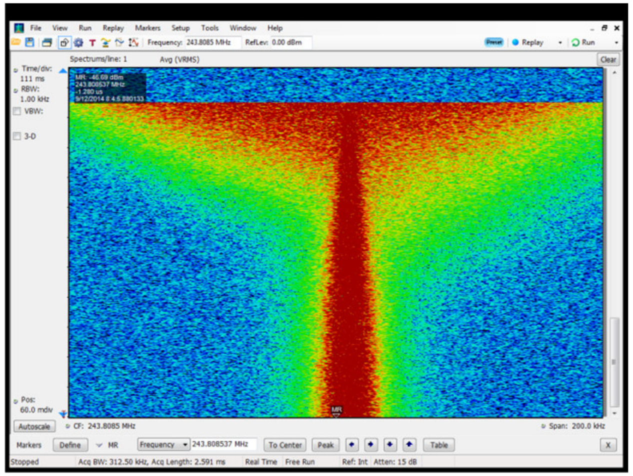
Longitudinal Cooling

Xe^{54+} 350 MeV/u

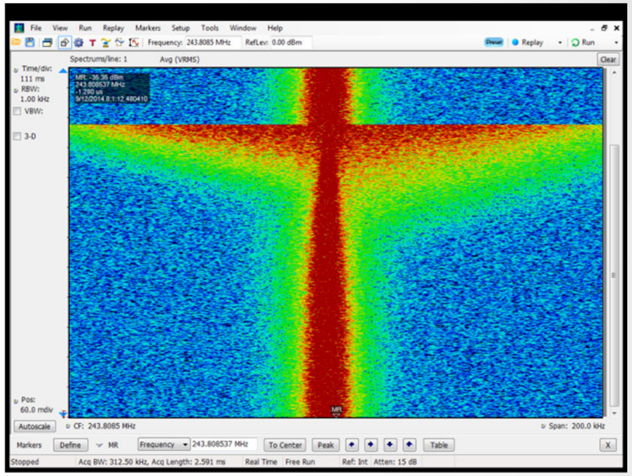
I_e= 100 mA



I_e= 250 mA

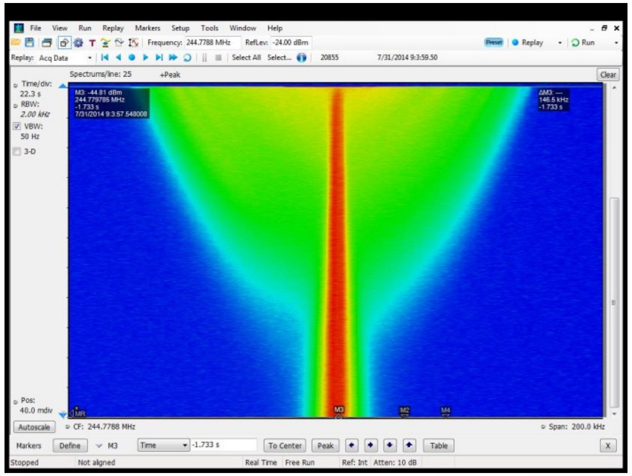


I_e= 500 mA



measurement time **20 s**

protons 400 MeV (Q=1)



I_e= 250 mA

measurement time **650 s**

Electron Beam Properties

electron beam temperature

is determined by the thermal cathode temperature k_BT_{cat}

transverse temperature $k_BT_\perp = k_BT_{cat}$,

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

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

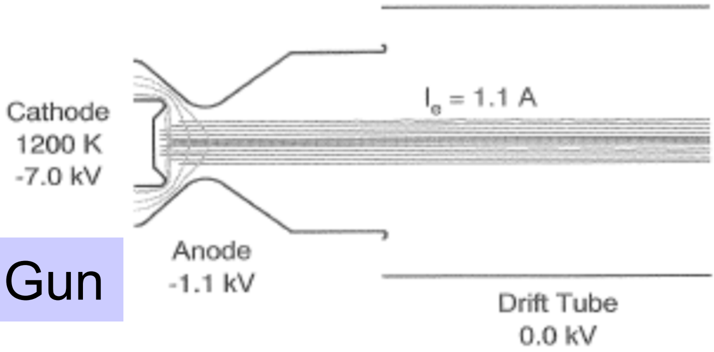
lower limit : $k_BT_\parallel \geq 2e\dfrac{n_e^{1/3}}{4\pi\epsilon_0}$

typical temperature values:

transverse	**$k_BT_\perp \approx$ 100 meV (1100 K)**
with magnetic expansion	**$k_BT_\perp \approx$ 1 meV**
longitudinal	**$k_BT_\parallel \approx$ 0.1 - 1 meV**

Electron Beam Properties

constant electron beam radius

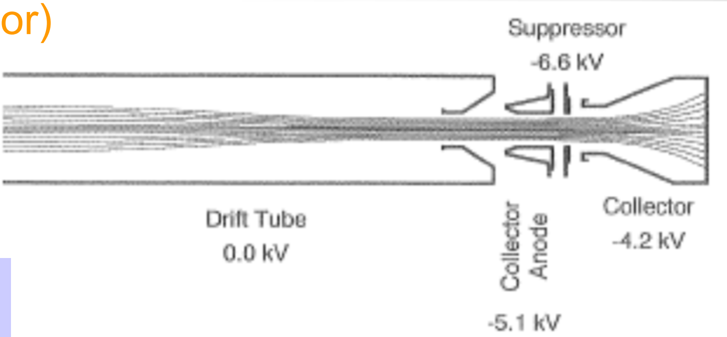


Gun

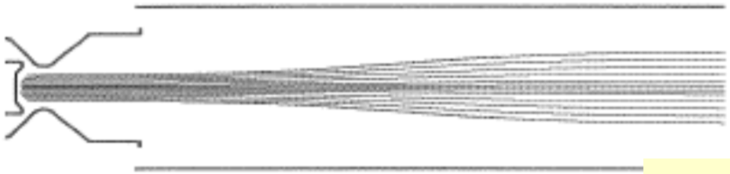
electron beam confined by longitudinal magnetic field (from gun to collector)

Collector

efficient capture of electrons $I_{loss} \sim 10^{-4} I_{el}$

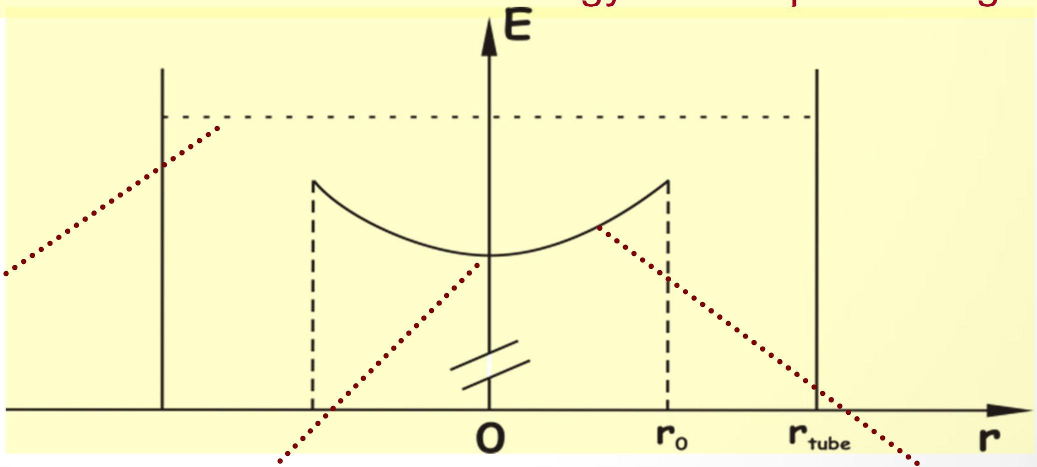


Cooling Section



transversely expanded electron beam

radial variation of electron energy due to space charge



electron current
(space charge limited)

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

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

Electron Motion in the Longitudinal Magnetic Field

single particle cyclotron motion

cyclotron frequency $\omega_c = \dfrac{eB}{\gamma m e}$

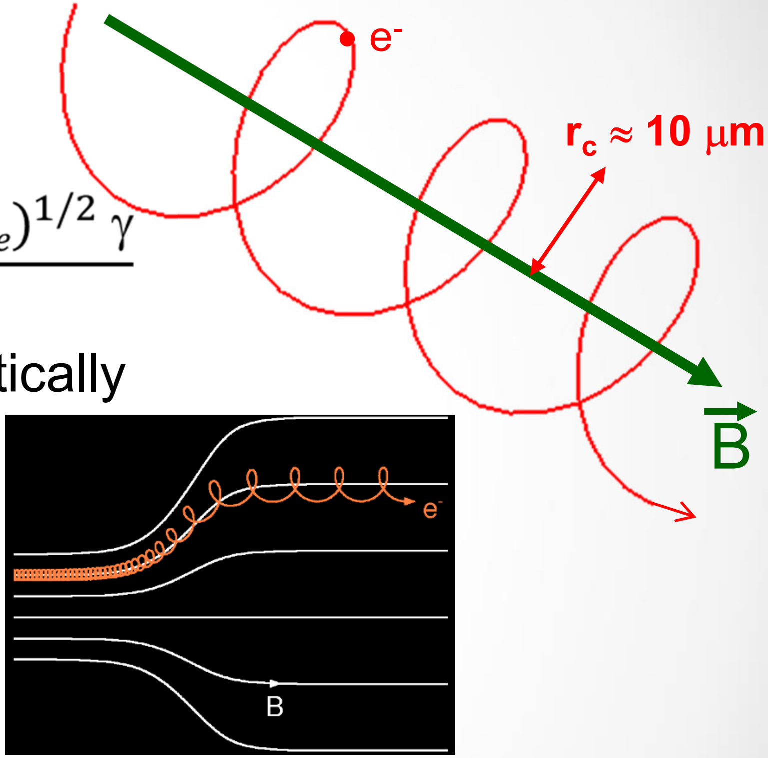
cyclotron radius $r_c = \dfrac{v_\perp}{\omega_c} = \dfrac{(k_B T_\perp m_e)^{1/2}\,\gamma}{eB}$

electrons follow the magnetic field line adiabatically

$\Rightarrow$ transverse magnetic expansion

results in a reduction of the

transverse temperature $\dfrac{m v_\perp{}^2}{B} = const.$



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

Optimized Electron Cooling

minimize relative velocity between ions and electrons

electron beam space charge:

transverse electric field + longitudinal B-field ⇒ azimuthal drift

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

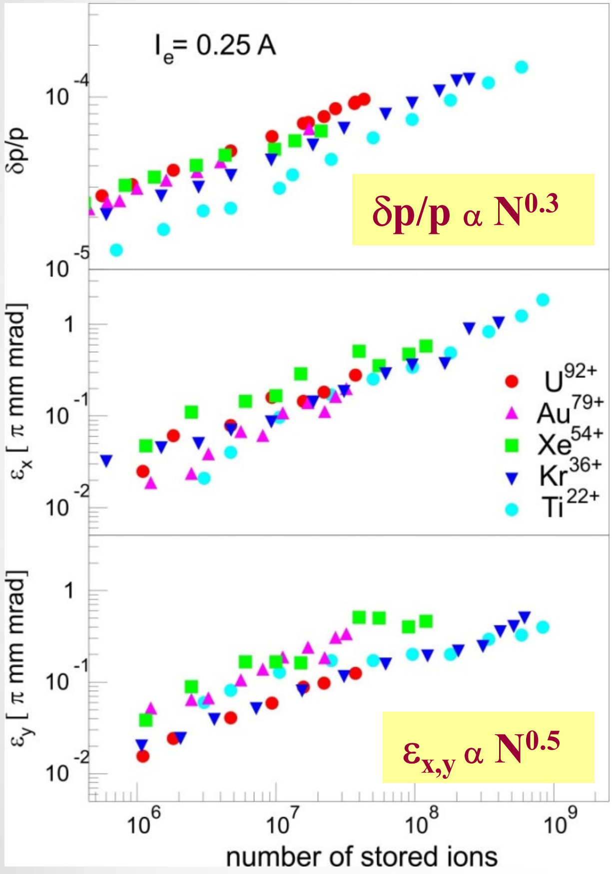
⇒ electron and ion beam should be well centered

Favorable for optimum cooling (small transverse relative velocity):

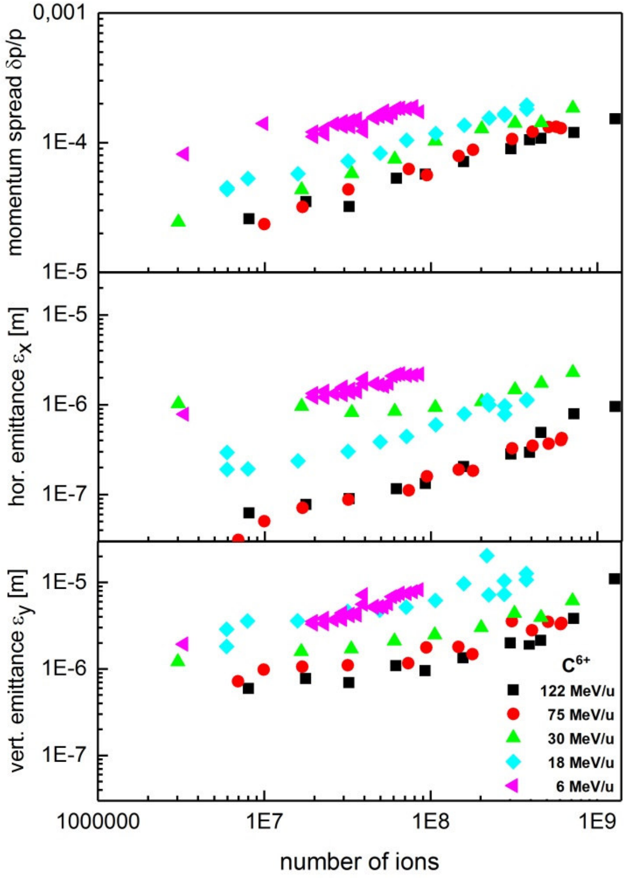
- parallel adjustment of ion and electron beam
- high parallelism of magnetic field lines $B_\perp/B_\parallel$ in cooling section
- large beta function (small ion beam divergence) in cooling section

Electron Cooled Beams in Equilibrium with Intrabeam Scattering (IBS)

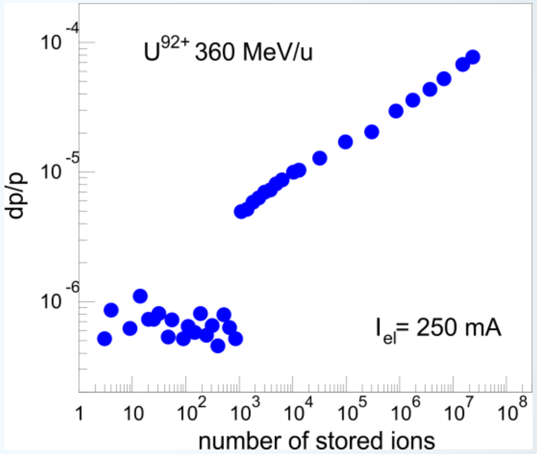
different ions (Q,A)



different energies (β, γ)



suppression of IBS for low intensity (N≤1000)



Beam ordering (crystallization)

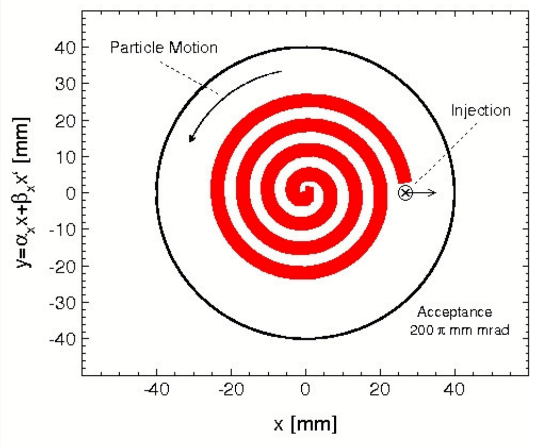
heating rate dominated by Intrabeam Scattering

$$\tau_{IBS}^{-1} = \frac{Q^4 e^4}{(A m_i)^2} \cdot \frac{N}{C \varepsilon_h \varepsilon_v \delta p / p} \cdot \frac{1}{(\gamma^4 \beta^3 c^3)} \cdot 4\pi L_C^{IBS}$$

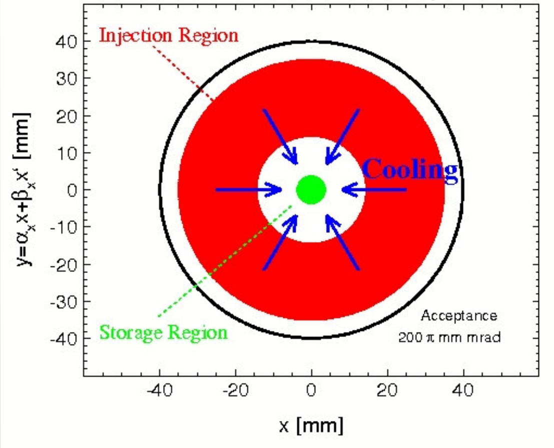
IBS: total phase space volume increases with ion beam intensity and ion charge

Accumulation of Heavy Ions by Electron Cooling

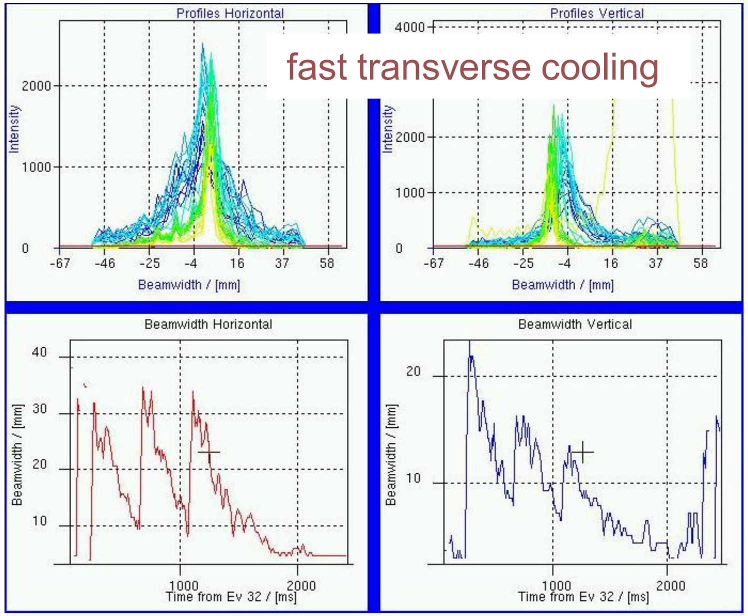
standard multiturn injection



fast accumulation by repeated multiturn injection with electron cooling



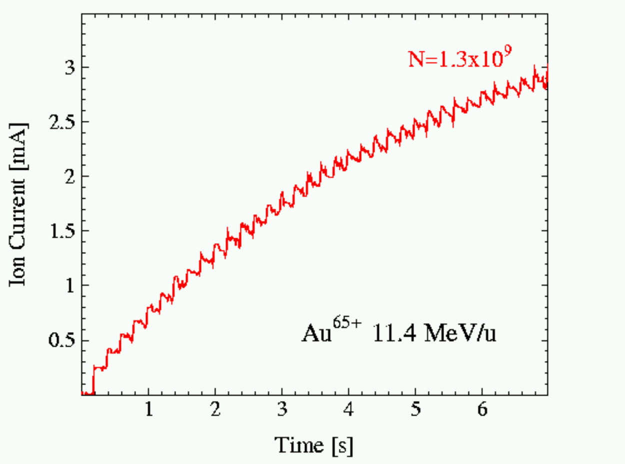
horizontal **vertical**



fast transverse cooling

profile

beam size



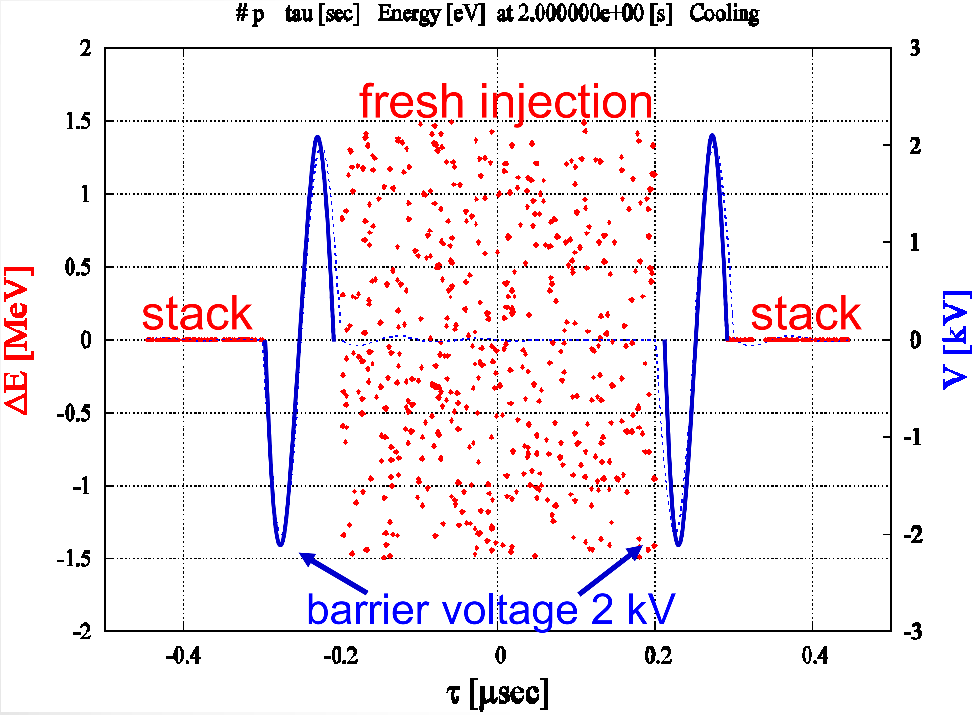
intensity increase in 5 s by a factor of ≈ 10

limitations:
space charge tune shift
recombination (REC)

Accumulation of Secondary Particles

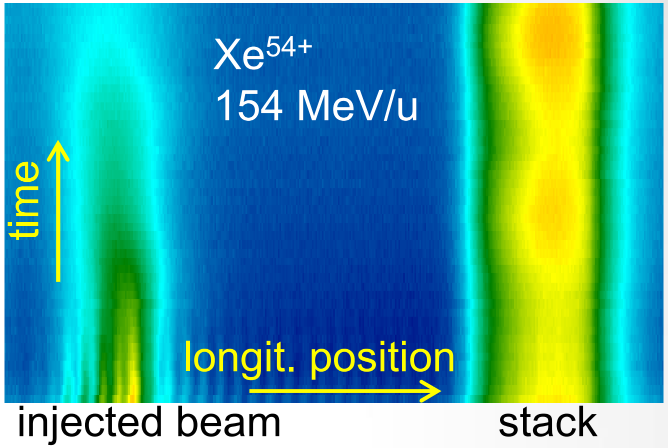
basic idea: confine stored beam to a fraction of the circumference, inject into gap and apply cooling to merge the two beam components

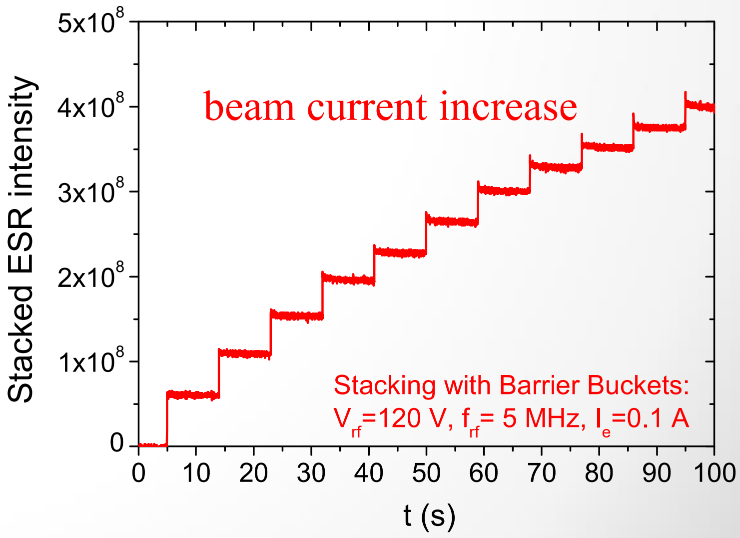
⇒ fast increase of intensity (for secondary beams)



simulation of longitudinal stacking with barrier buckets and electron cooling

experimental verification at ESR





Some Technical Aspects of Electron Cooling Systems

cold electron beam: thermal cathode at about 1000-1200 degrees C

high electron current: up to about 1 A

small current losses at full energy: $\leq 10^{-4}$ relative to electron current

ultrahigh vacuum operation: 10^{-11} mbar range

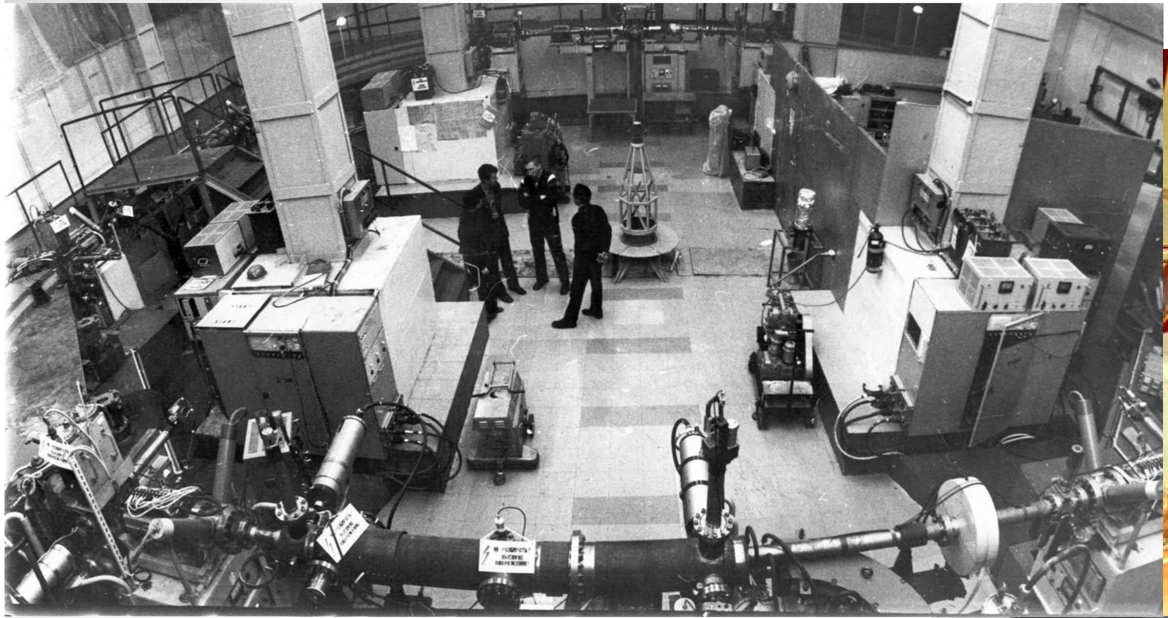
continuous longitudinal magnetic field from electron gun to collector

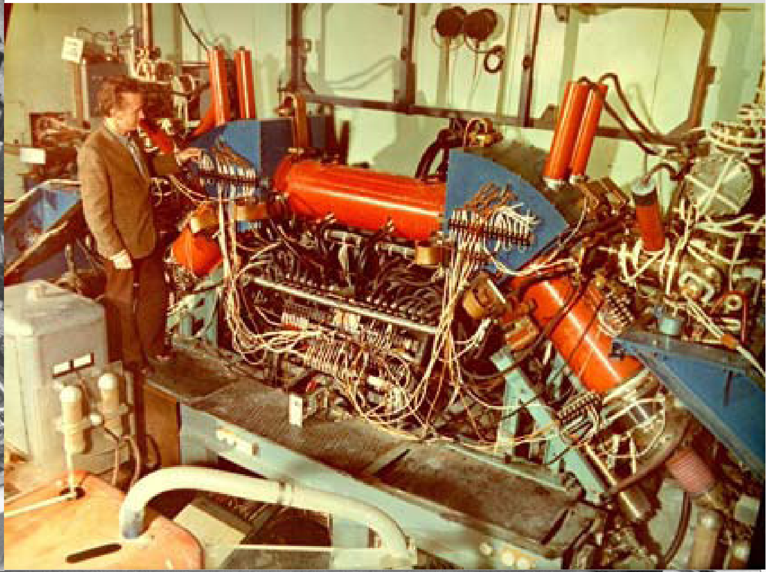
straight magnetic field (parallel field lines): $\langle B_\perp / B_\parallel \rangle \leq 10^{-5}$ - 10^{-4}

stable accelerating voltage (electron energy): variations $\delta U/U \approx 10^{-6}$ - 10^{-5}

control of space charge compensation (capture of residual gas ions in the negative potential of the electron beam)

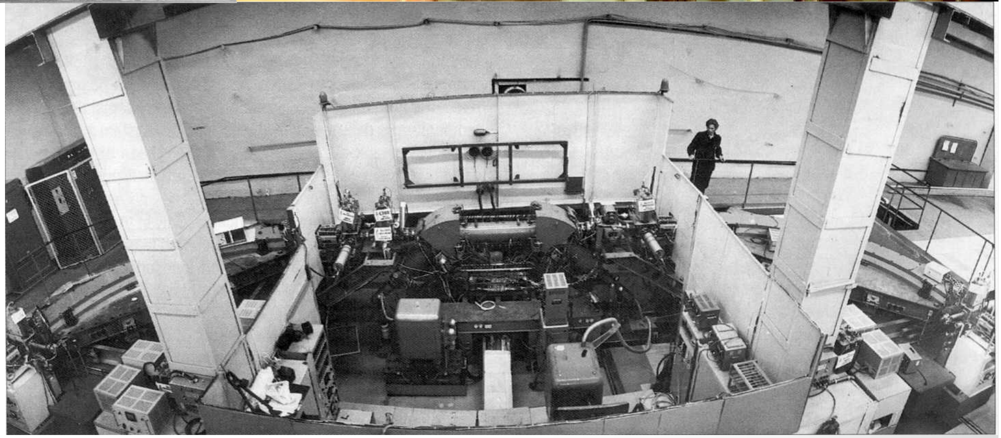
First Experimental Proof: NAP-M Experiment (1974)





NAP-M :
“Antiproton Storage Ring – Model”
INP Novosibirsk, 1974 - 1984

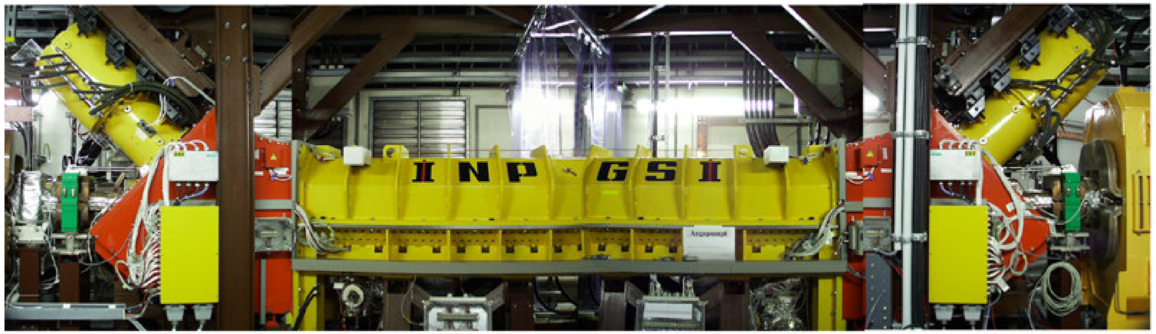
First electron cooler
“EPOChA”
(“Electron beam for cooling of antiprotons”, Rus.)



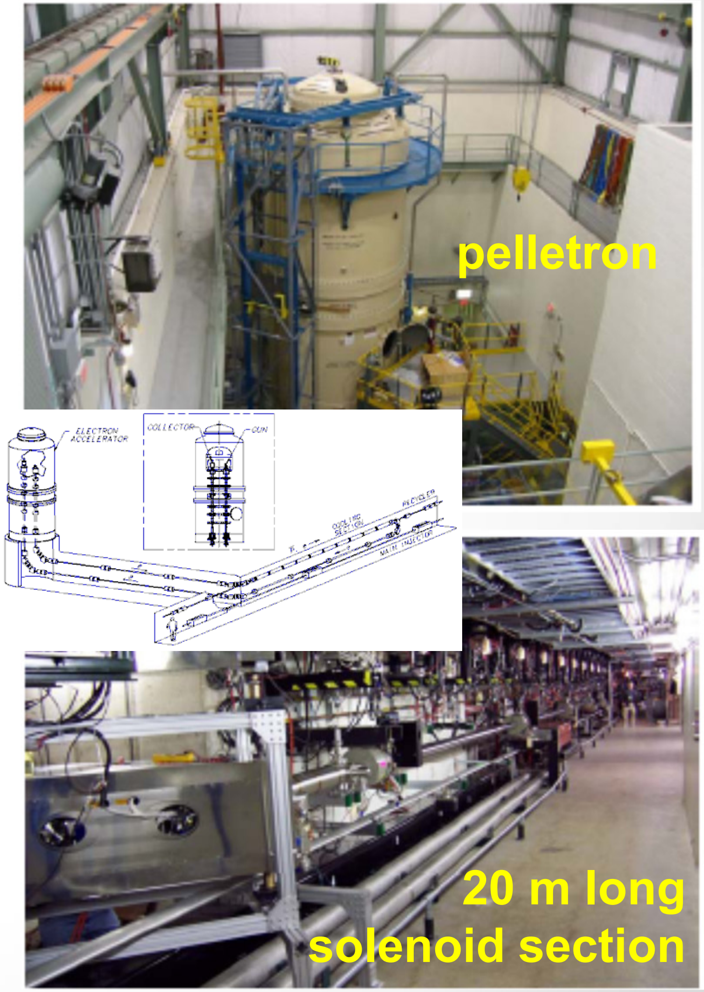
courtesy I. Meshkov, JINR Dubna

Electron Cooling Systems

Low Energy: 35 keV SIS/GSI



High Energy:
4.3 MeV Recycler/FNAL



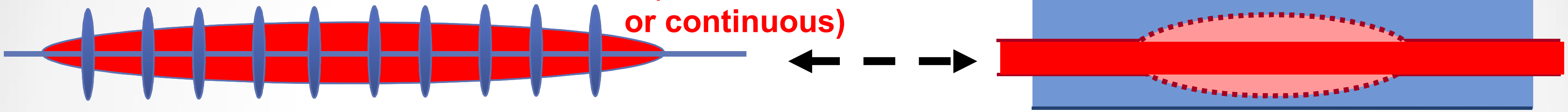
pelletron

20 m long solenoid section

Medium Energy:
300 keV
ESR/GSI

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 to increase the electron energy).



new scheme

ion bunch (some ten ns or continuous)

electron bunches (some ns)

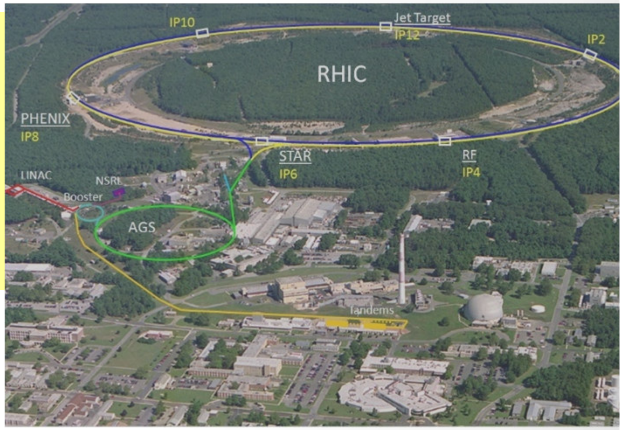
traditional

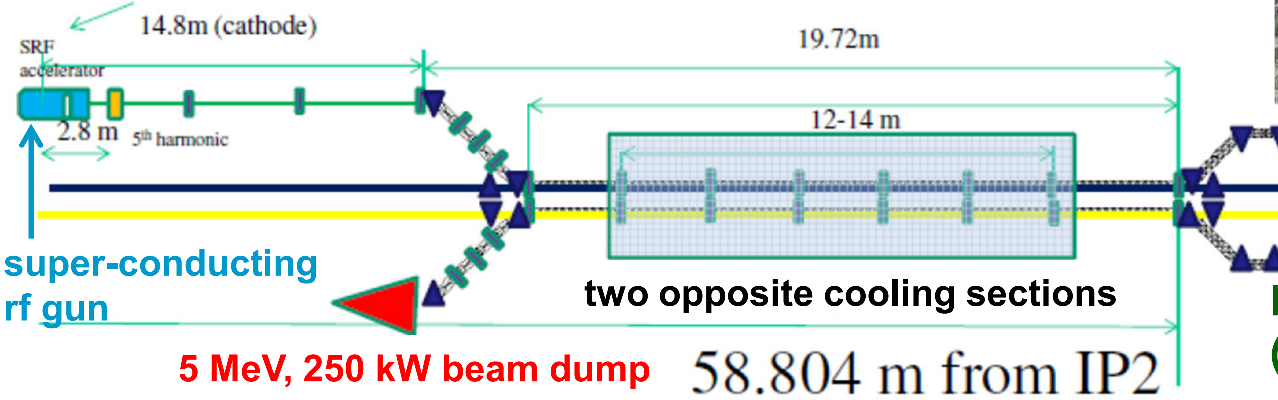
continuous electron beam

continuous (or bunched) ion beam

issues:

- high intensity e-bunches (production, transport)
- momentum spread and emittance of e-bunches
- beam alignment
- magnetized ↔ non-magnetized (magnetic shielding)
- synchronization of ion-electron bunches





super-conducting rf gun

two opposite cooling sections

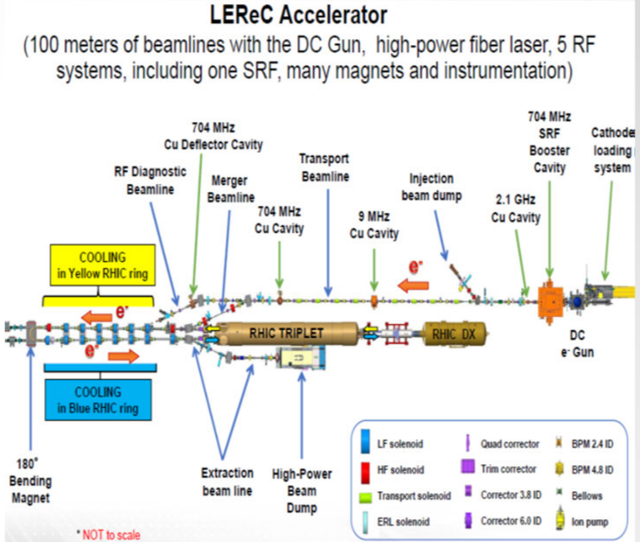
5 MeV, 250 kW beam dump

two counter-propagating ion beams

Low Energy RHIC e-Cooler (LEReC) project at BNL

Low-Energy RHIC electron Cooler (LEReC) at BNL

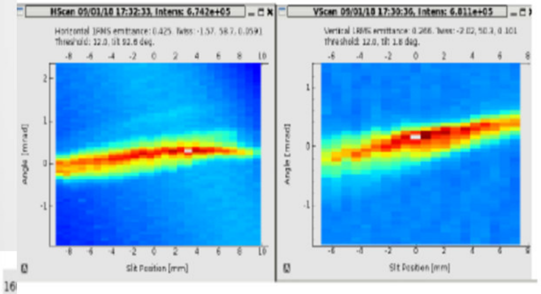
- LEReC is the first electron cooler based on the RF acceleration of electron beam .
- State of the art electron accelerator which uses photocathode high-current gun, high-power laser and several RF cavities.
- Electron beam parameters suitable for cooling were successfully generated and transported to the cooling sections in RHIC.
- First electron cooling of hadron beams using a bunched electron beam was demonstrated on April 5, 2019.
- Both longitudinal and transverse cooling was achieved.
- Cooling of ion bunches in two separate RHIC rings (Yellow and Blue) using single electron beam was demonstrated.

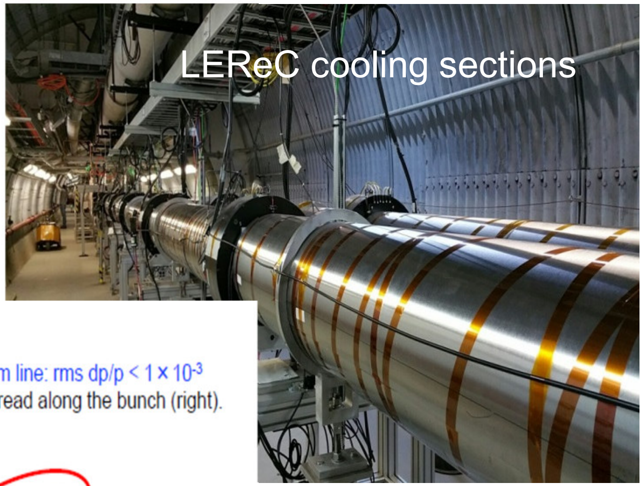

LEReC Accelerator

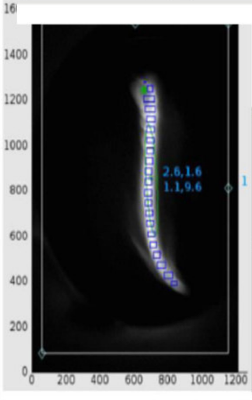
(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)

RMS normalized emittance in Yellow cooling section

Hor = 1.7 µm; Ver = 1.1 µm

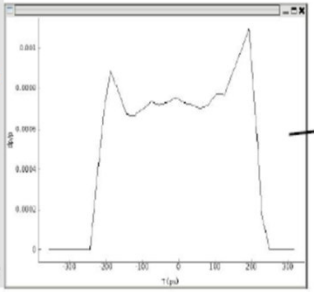


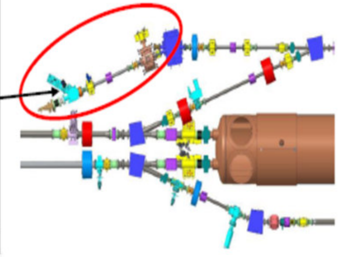




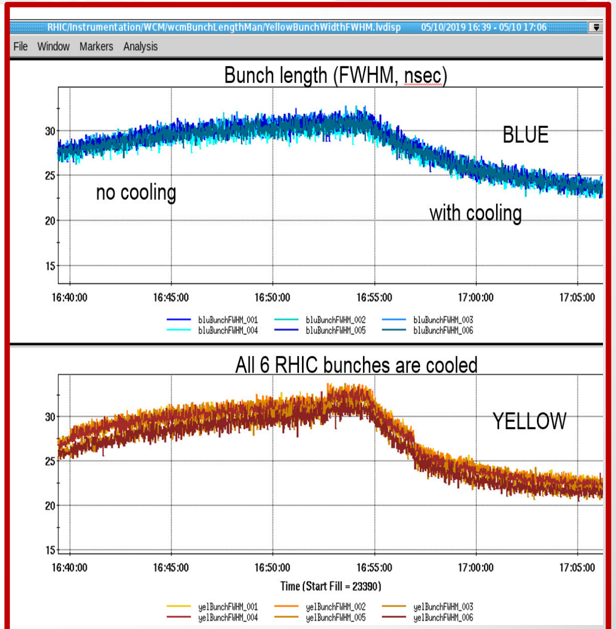
RMS momentum spread in RF diagnostics beam line: rms dp/p < 1 × 10^{-3}

Image on profile monitor (left), sliced energy spread along the bunch (right).





A. Fedotov et al.

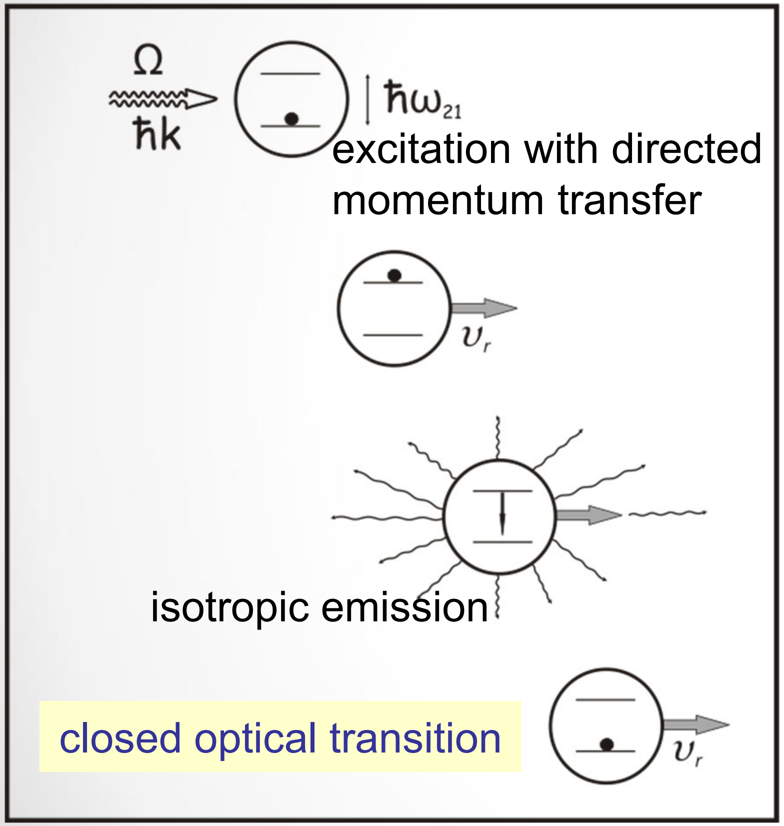


demonstration of cooling

2. Laser Cooling

fast ions interact with laser light

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

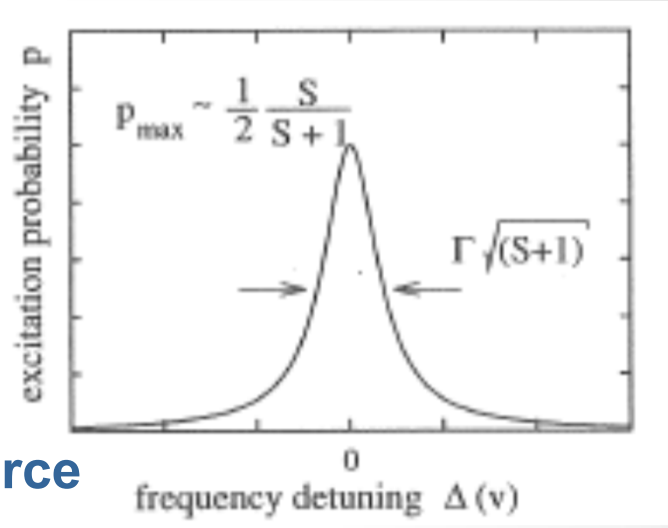


excitation with directed momentum transfer

isotropic emission

closed optical transition

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 distribution with width Γ/k ~ 10 m/s

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

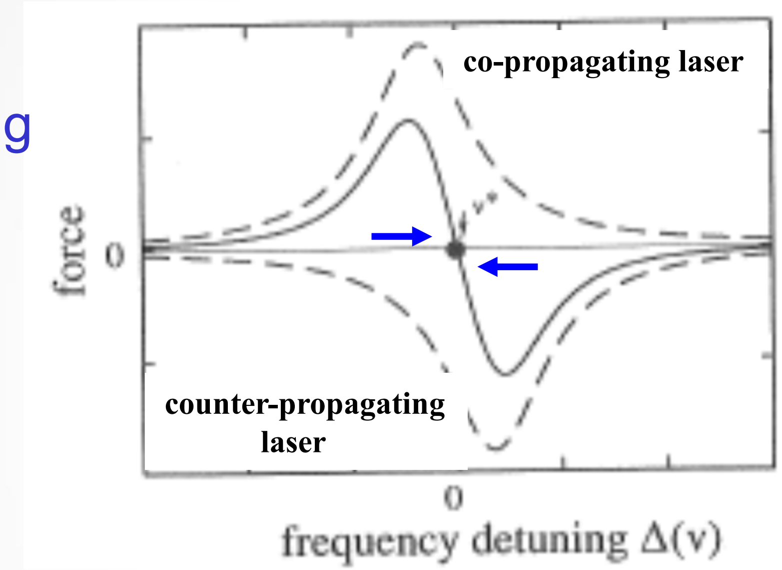
typical cooling time ~ 10 μs

drawbacks: only longitudinal cooling
extremely small cooling range

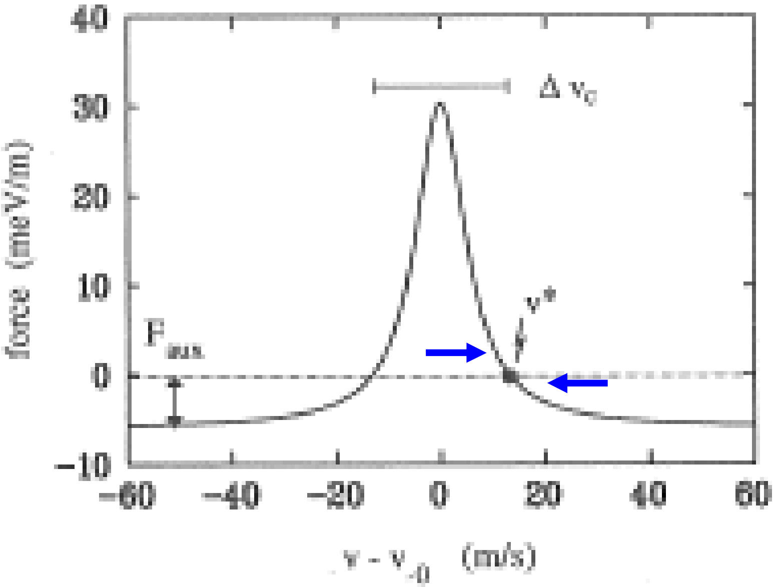
Laser Cooling

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

schemes
for cooling



two counter-propagating lasers (matched to beam velocity)



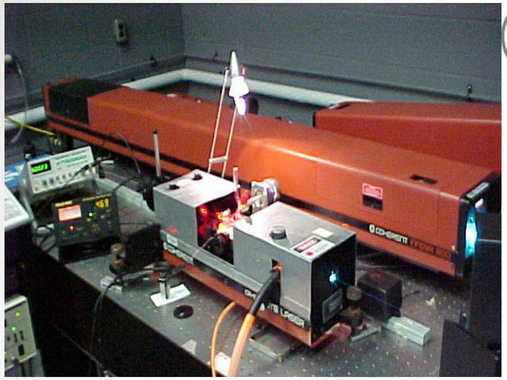
auxiliary force (betatron core, rf)

capture range of laser is limited ⇒ frequency sweep (snowplow)

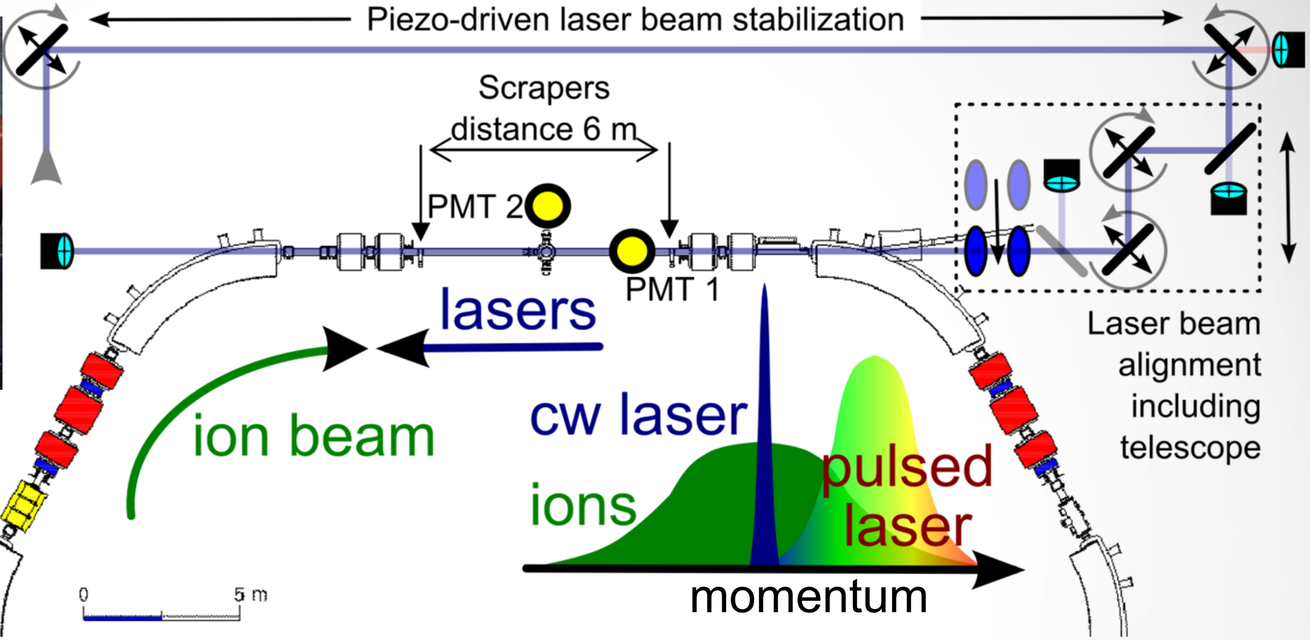
ions studied so far: $^{7}\mathrm{Li}^{1+}$, $^{9}\mathrm{Be}^{1+}$, $^{24}\mathrm{Mg}^{1+}$, $^{12}\mathrm{C}^{3+}$

in future: laser cooling of Li-like heavy ions at relativistic energies at SIS100
large relativistic energy ⇒ large excitation energy in particle rest frame

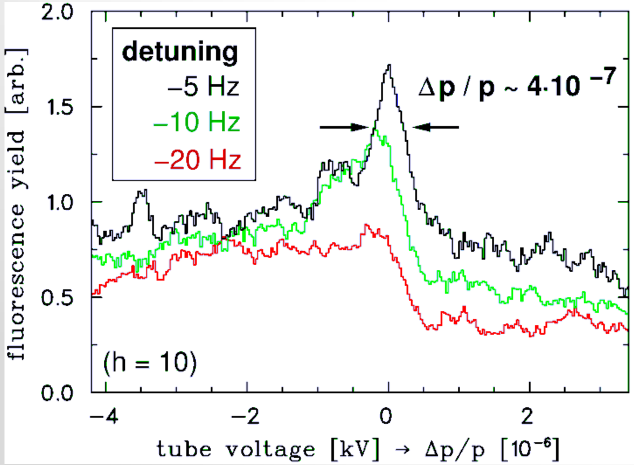
Laser Cooling of C^{3+}



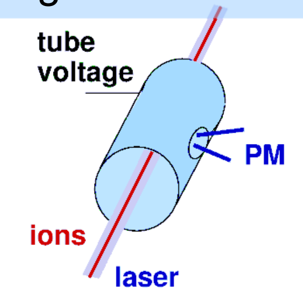
Argon ion laser (257.3 nm) frequency doubled



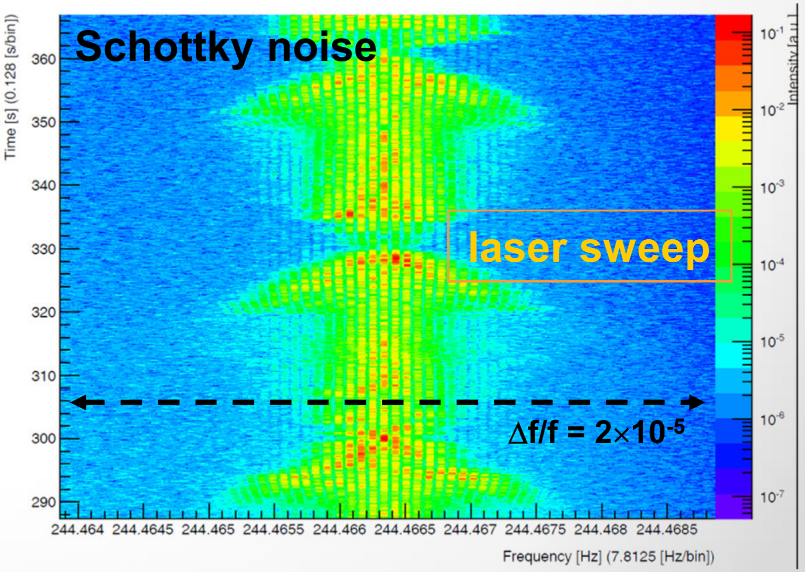
ESR storage ring



fluorescence light detection

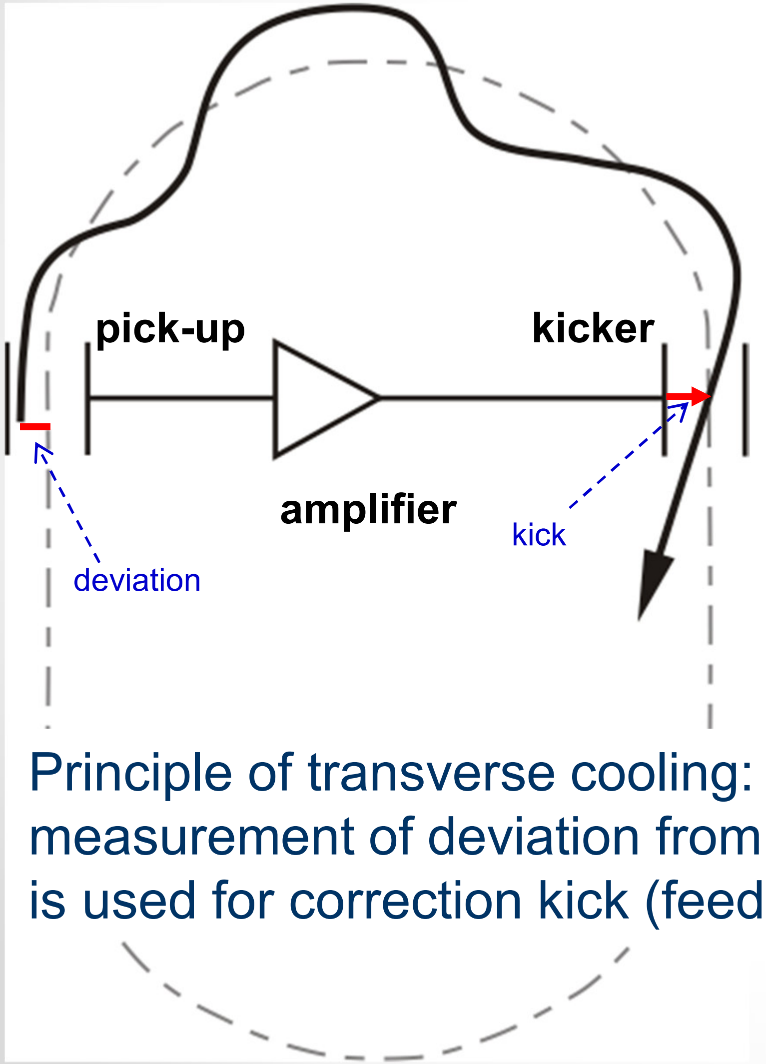


probing the velocity distribution



3. 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

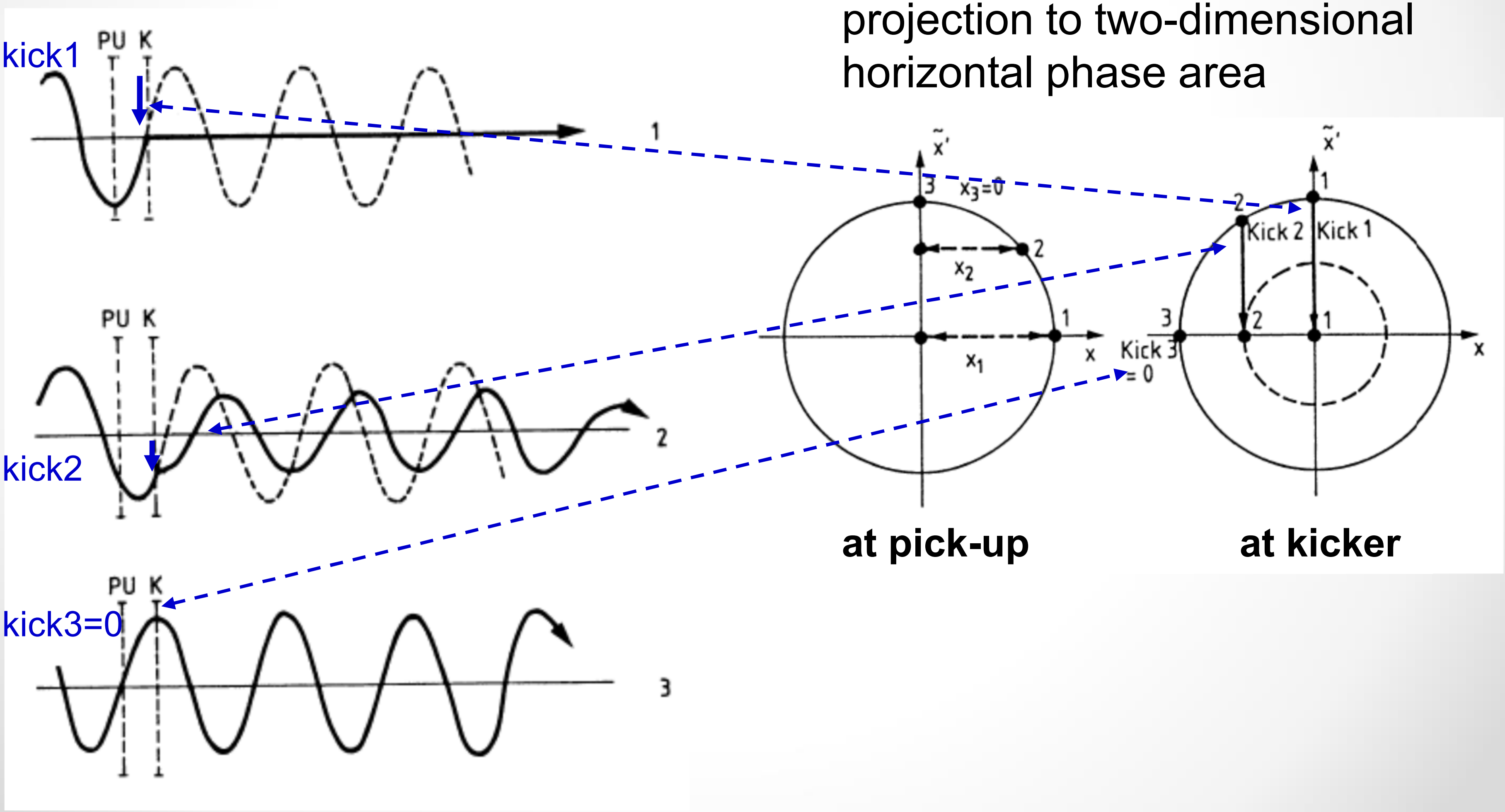
Signal travel time = time of flight of particle
(between pick-up and kicker)

Sampling of sub-ensemble of total beam

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

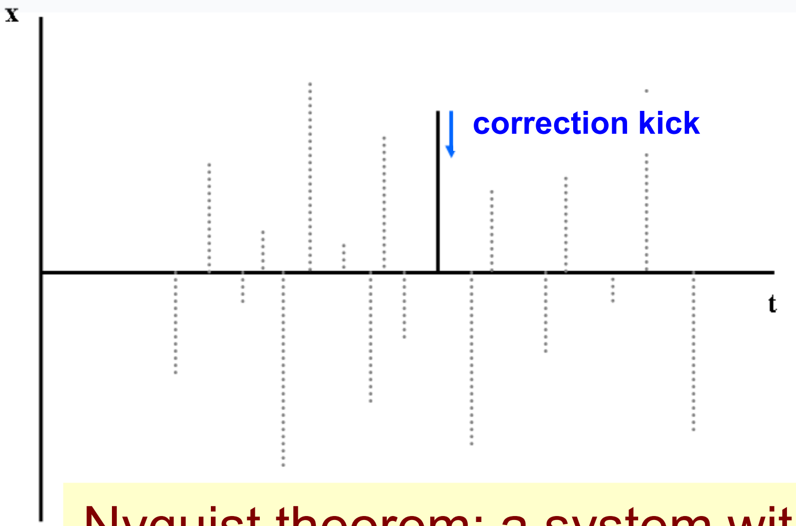
Stochastic Cooling

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



projection to two-dimensional
horizontal phase area

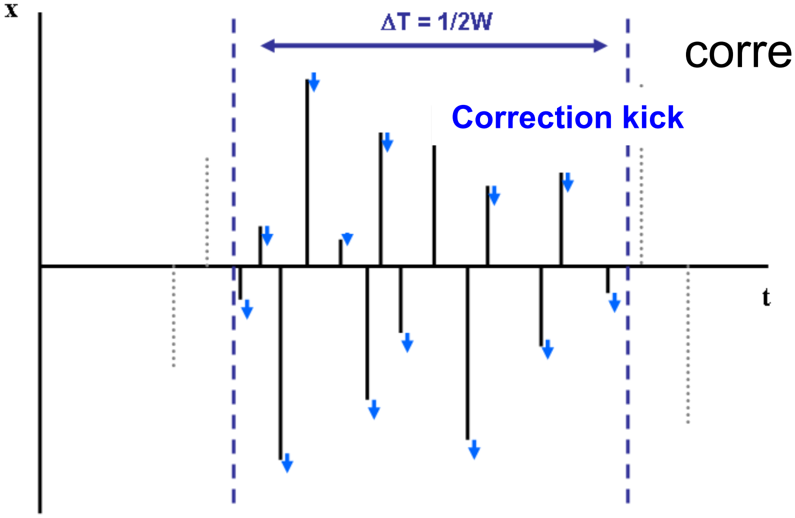
Stochastic Cooling



correction kick
(unlimited resolution)

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

Nyquist theorem: a system with a band-width $\Delta f = W$ in frequency domain can resolve a minimum time duration $\Delta T = 1/(2W)$



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

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

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

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 beam signal

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

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

M mixing factor

U noise to signal ratio

maximum of cooling rate

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

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

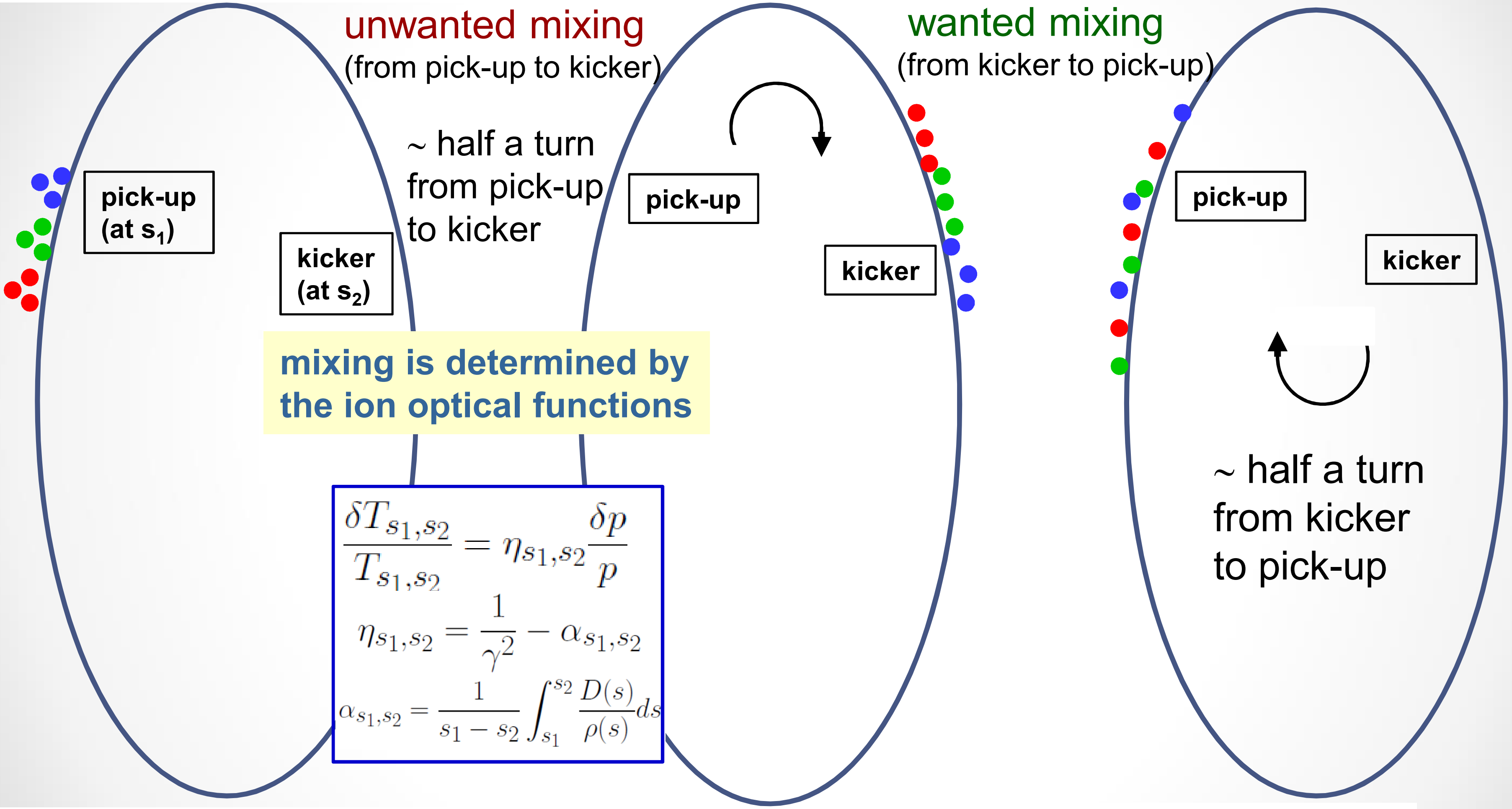
further refinement (wanted ↔ unwanted mixing):

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

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

Mixing

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



unwanted mixing
(from pick-up to kicker)

~ half a turn
from pick-up
to kicker

wanted mixing
(from kicker to pick-up)

~ half a turn
from kicker
to pick-up

mixing is determined by the ion optical functions

$$\frac{\delta T_{s_1,s_2}}{T_{s_1,s_2}} = \eta_{s_1,s_2}\frac{\delta p}{p}$$

$$\eta_{s_1,s_2} = \frac{1}{\gamma^2} - \alpha_{s_1,s_2}$$

$$\alpha_{s_1,s_2} = \frac{1}{s_1 - s_2}\int_{s_1}^{s_2}\frac{D(s)}{\rho(s)}ds$$

$$1 - \widetilde{M}^{-2} \approx \cos\left[0.5\pi\ \eta_{eff}\ n_{max}(\Delta p/p)_{rms}\right]$$

$\Rightarrow \eta_{eff} \sim 0$

$$M = (2WT\eta(\Delta p/p)_{rms})^{-1}$$

$\Rightarrow \eta_{k\text{-}pu} > 0,\ (T\eta\cdot\Delta p/p_{rms})^{-1} \sim\ 1$

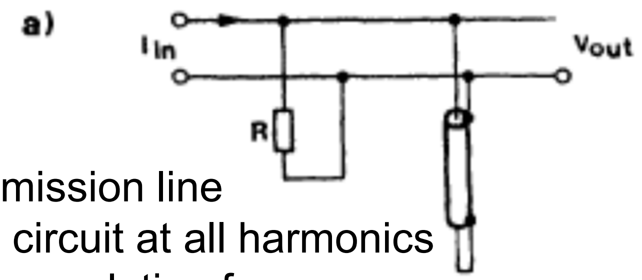
Longitudinal Stochastic Cooling

1) **Palmer cooling**

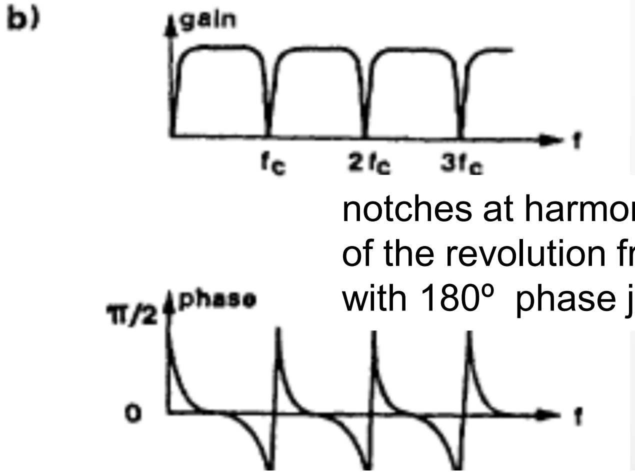
pick-up in dispersive section detects horizontal position
⇒ acceleration/deceleration kick corrects momentum deviation

2) **Notch filter cooling**

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



transmission line
short circuit at all harmonics
of the revolution frequency



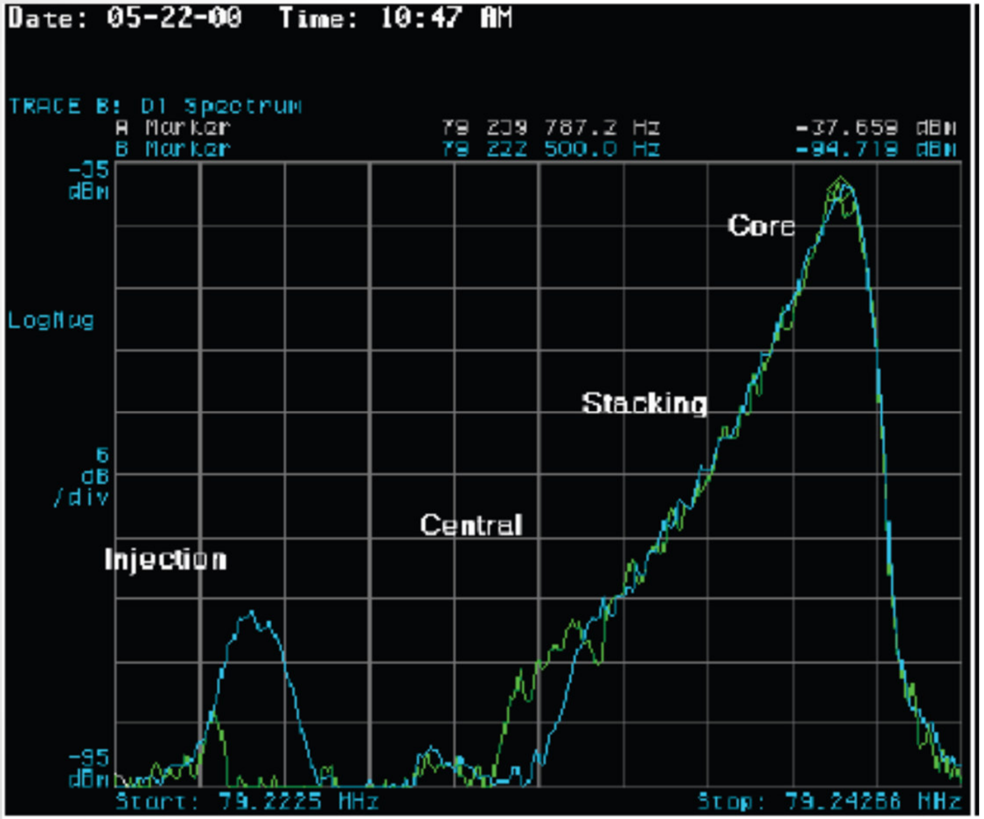
notches at harmonics
of the revolution frequency
with 180° phase jump

3) **ToF cooling**

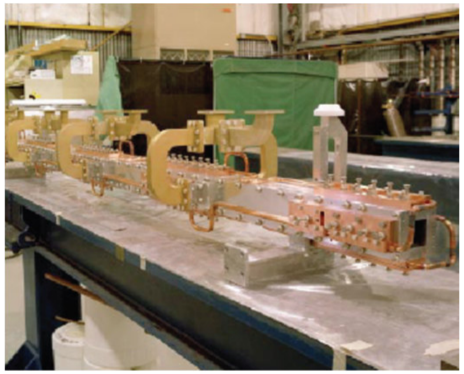
simplified scheme without notches allows efficient pre-cooling

Antiproton Accumulation by Stochastic Cooling

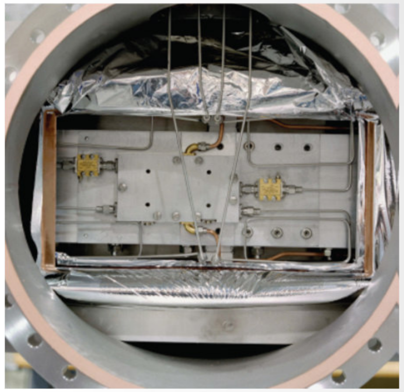
accumulation of 8 GeV antiprotons at Accumulator, FNAL, shut down 09/2011
similar facility AC/AA at CERN, shut down 11/1996



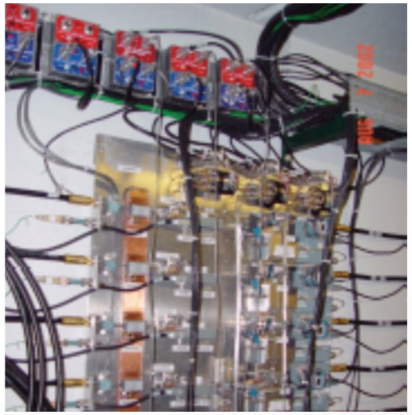
momentum distribution of accumulated antiproton beam



kicker array



cryogenic microwave amplifier



microwave electronics

power amplifiers (TWTs)

Stochastic Cooling of Rare Isotopes at GSI

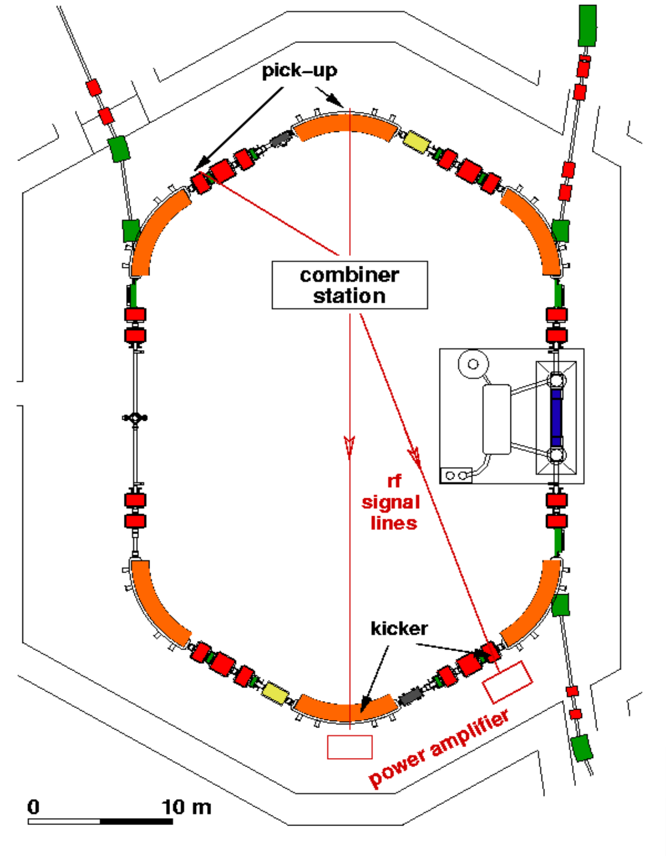
fast pre-cooling of hot fragment beams

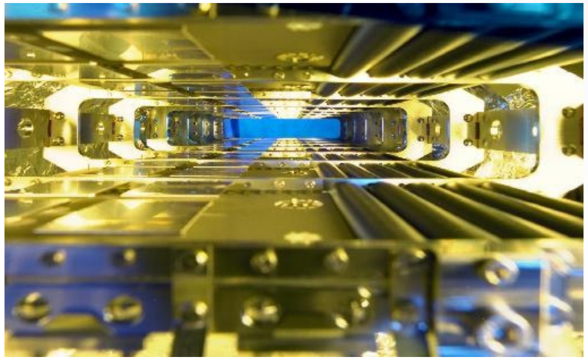
energy 400 (-550) MeV/u

bandwidth 0.8 GHz (range 0.9-1.7 GHz)

$\delta p/p = \pm 0.35\ \%$ → $\delta p/p = \pm 0.01\ \%$

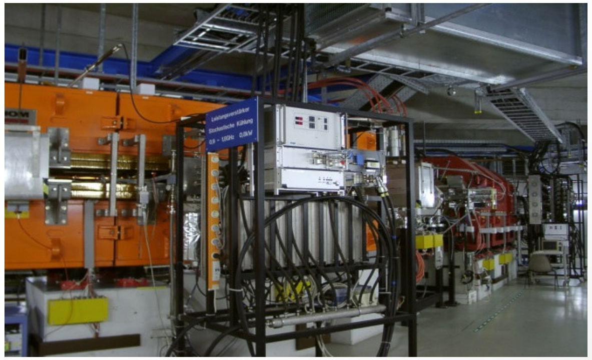
$\varepsilon = 10 \times 10^{-6}$ m → $\varepsilon = 2 \times 10^{-6}$ m





electrodes
installed
inside magnets

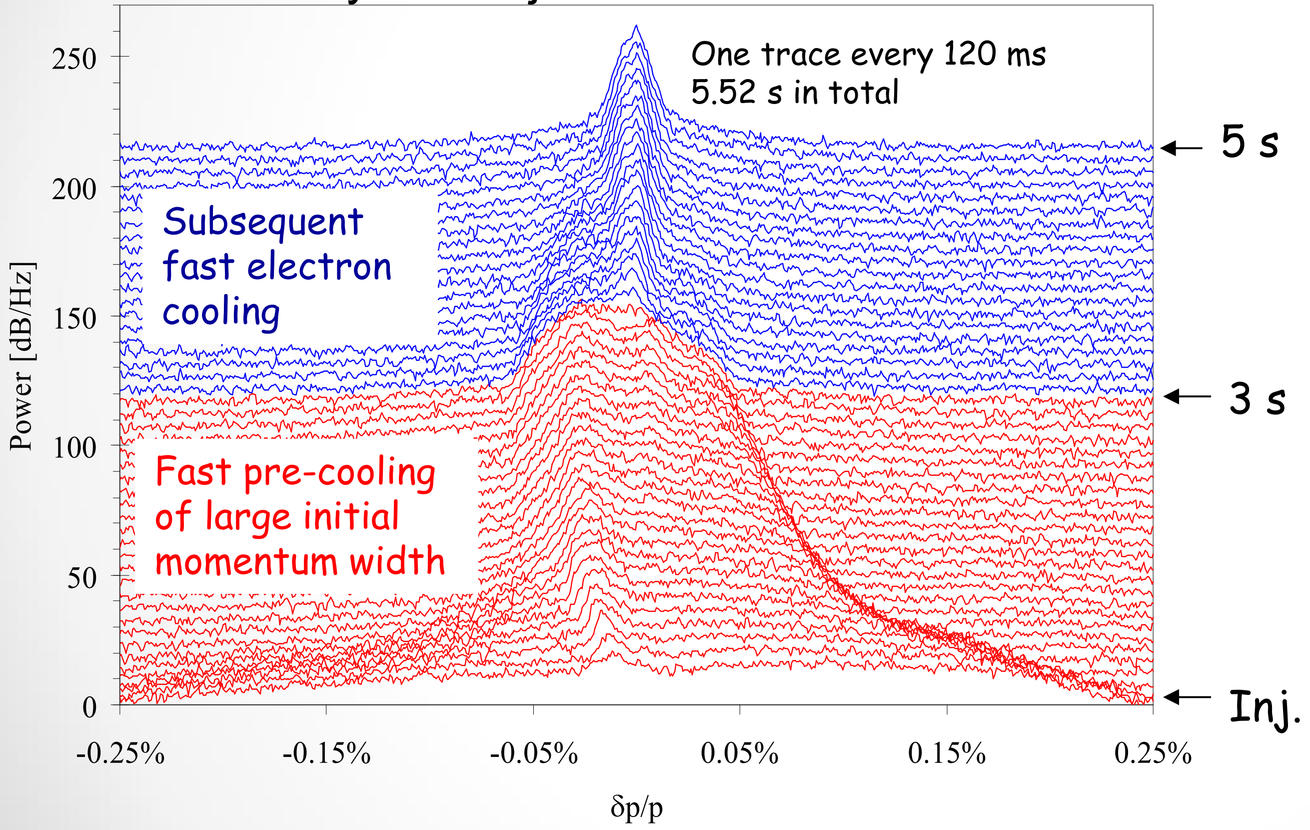
combination of
signals from
electrodes



power amplifiers
for generation of
correction kicks

Combination of Stochastic and Electron Cooling

stochastic pre-cooling + final electron cooling
immediately after injection



Primary Uranium beam heated after passage of a thick target

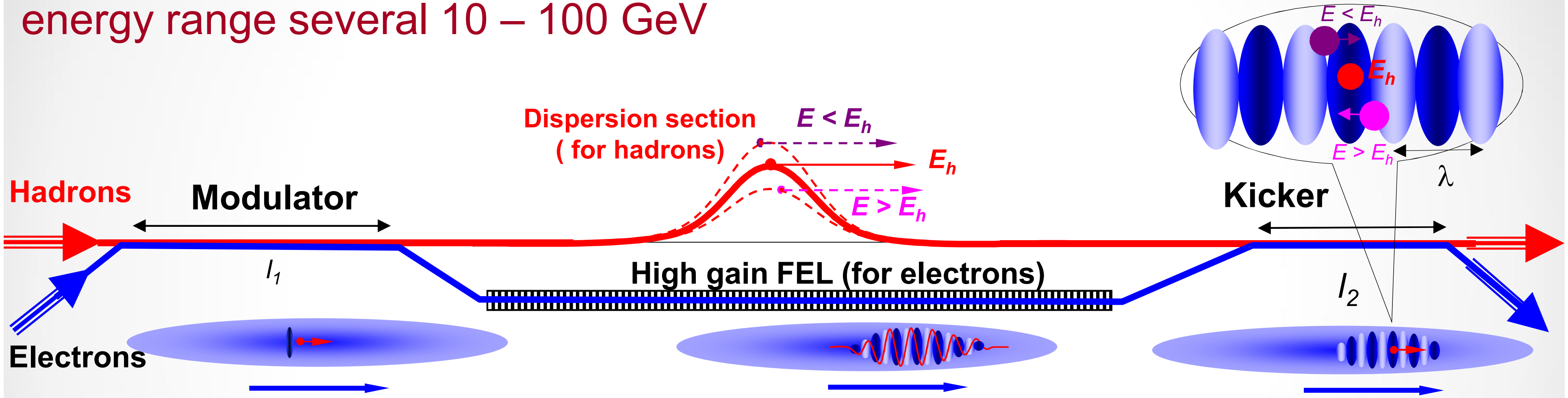
hot secondary beams can be cooled in reduced total time

Coherent Electron Cooling

A combination of electron and stochastic cooling concepts

proposed for fast cooling at highest energies

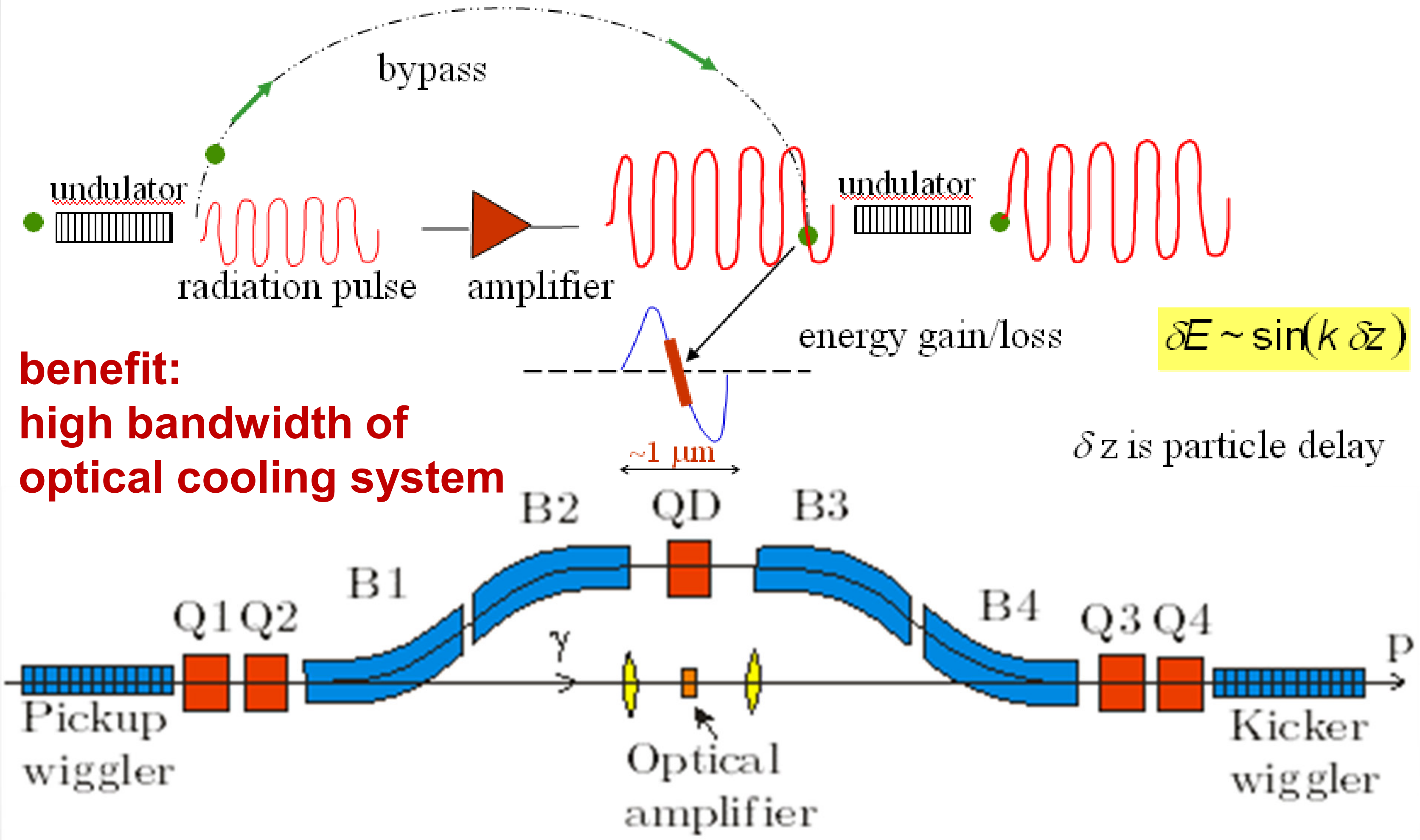
energy range several 10 – 100 GeV



- The Coherent Electron Cooling system has three major subsystems
    - **modulator**: the ions imprint a "density bump" on the electron distribution
    - **amplifier**: FEL interaction amplifies the density bump by orders of magnitude
    - **kicker**: the amplified & phase-shifted electron charge distribution is used to correct the velocity offset of the ions

investigated for the planned electron-ion collider EIC at BNL

Optical Stochastic Cooling Concept



benefit:
high bandwidth of optical cooling system

first experimental demonstration with 100 MeV electron beam in IOTA

Nature 608 287-292 (2022)

option for cooling hadron beams of highest energy

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 only cools in the longitudinal degree of freedom
and can only be applied to very specific ions
(with bound electrons and associated atomic transitions)

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Biannual Workshops on Beam Cooling: e. g. COOL'19, Novosibirsk, Russia