Beam Cooling

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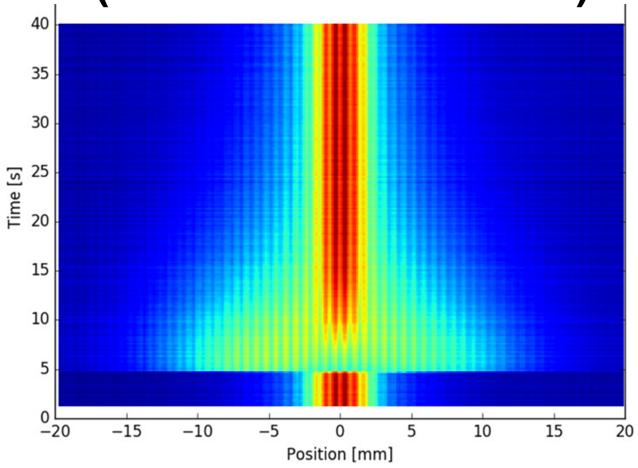
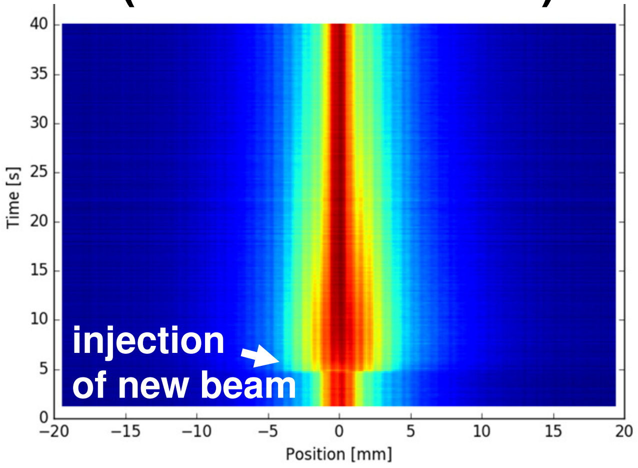
Observation of Cooling

Xe^{54+} beam at 400 MeV/u cooled with electron current 200 mA

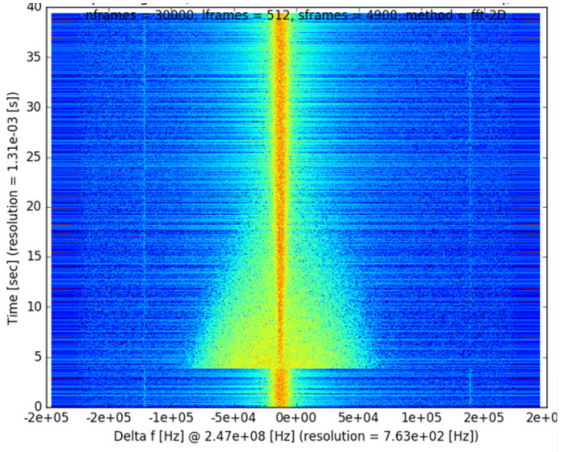
cooling in six-dimensional phase space



horizontal profile (horizontal emittance)



vertical profile (vertical emittance)



longitudinal momentum distribution

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

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:

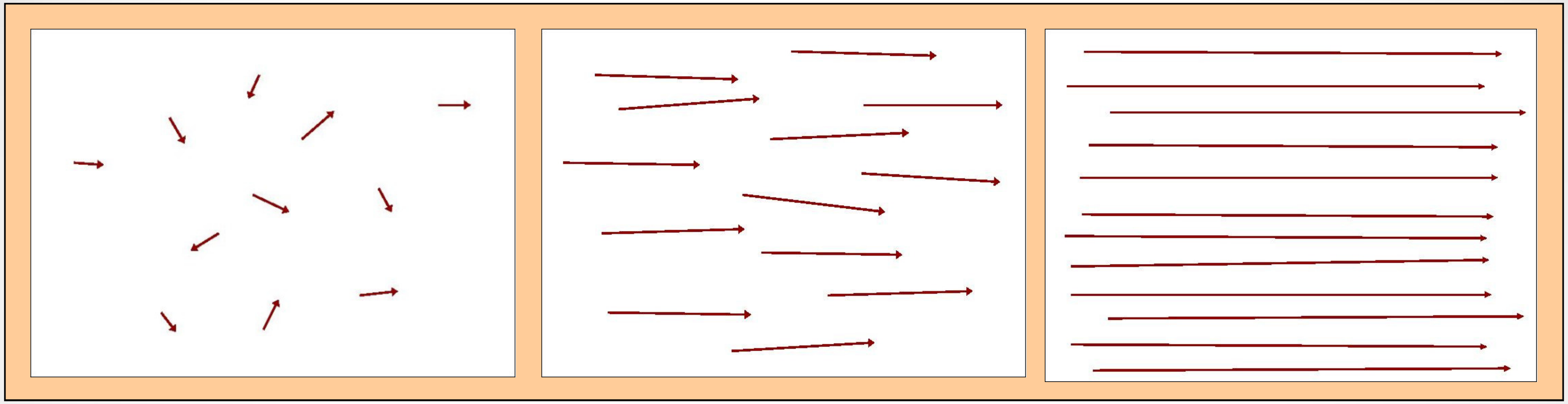
Transverse (emittance) cooling $\quad \epsilon_{x,y}(t_0 + t) = \epsilon_{x,y}(t_0)\ e^{-\lambda_{x,y} t}$

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

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

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

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

dependent on s

Distribution function

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

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

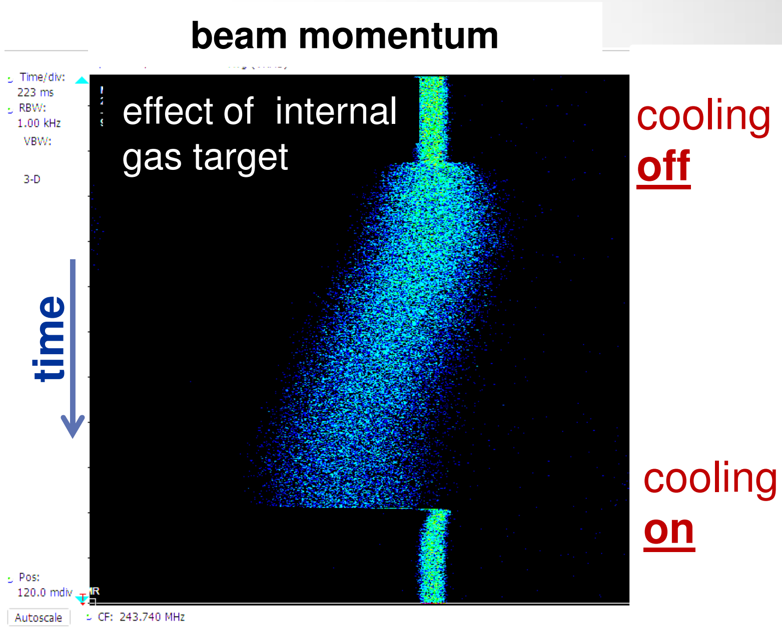
e.g. due to laser cooling or the distribution of the electron beam

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

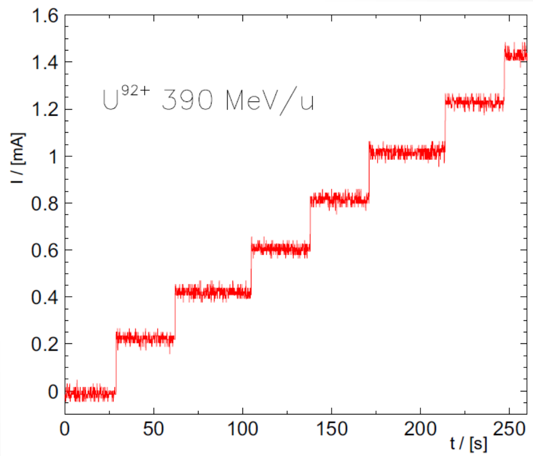
(e.g. a beam of energy 100 GeV can have a temperature of 1 eV)

Benefits of Beam Cooling

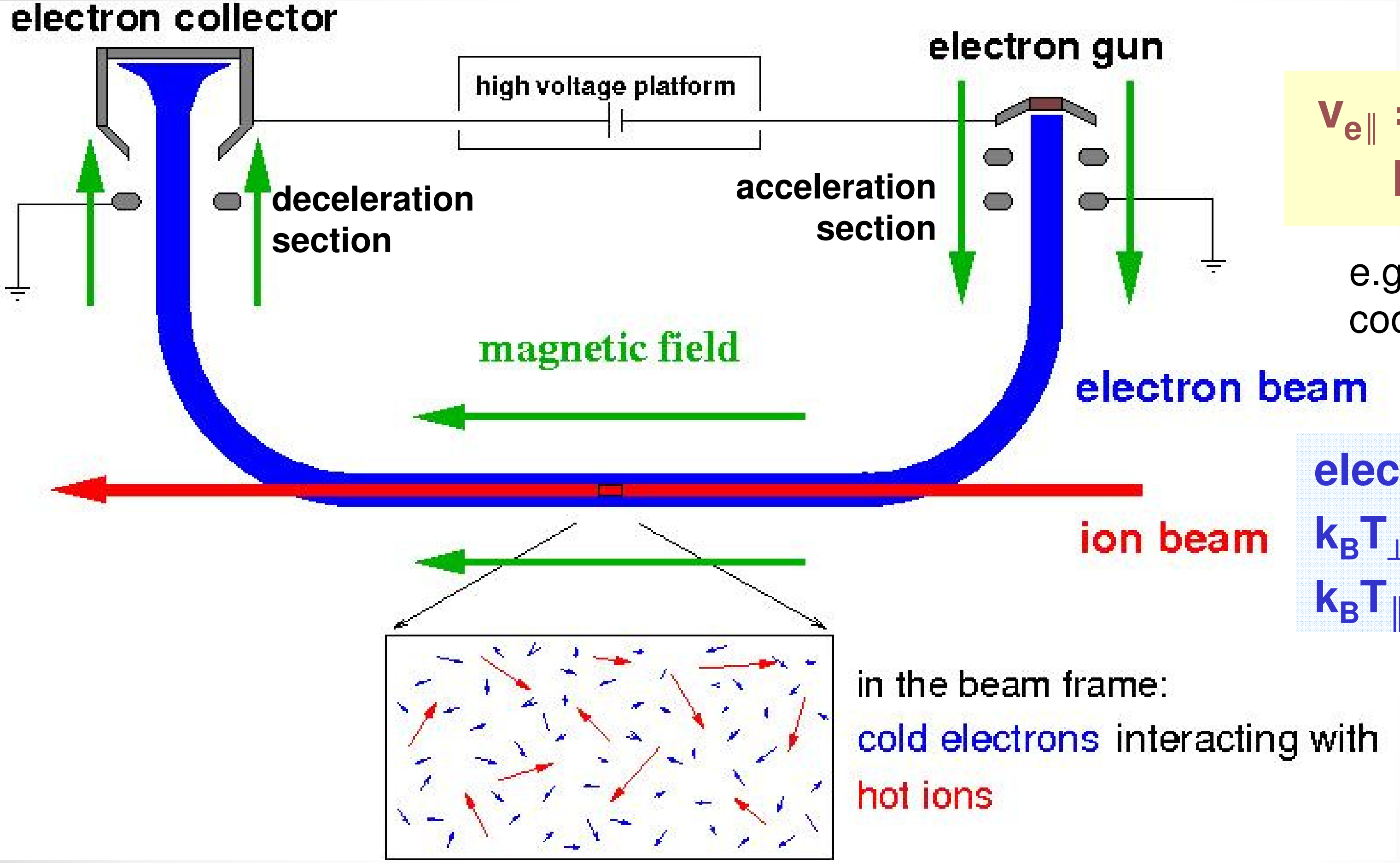
- Improved beam quality
  - Precision experiments
  - Luminosity increase
- Compensation of heating
  - Experiments with internal target
  - Colliding beams
- Intensity increase by accumulation
  - Weak beams from the source can be enhanced
  - Secondary beams (antiprotons, rare isotopes)



Time/div: 223 ms
RBW: 1.00 kHz
VBW:
3-D
Pos: 120.0 mdiv
Autoscale
CF: 243.740 MHz



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 protons

electron temperature

$k_B T_\perp \approx 0.1$ eV

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

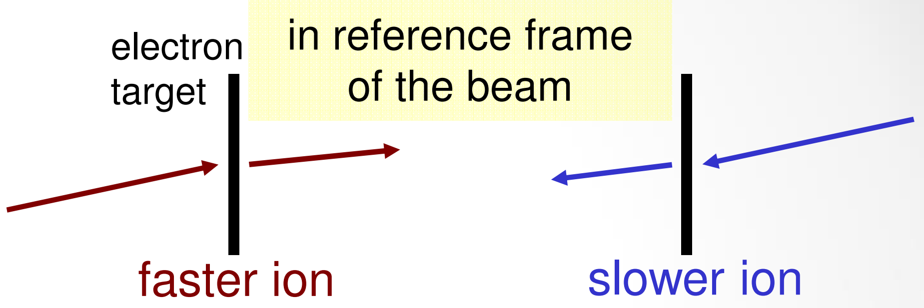
superposition of a cold intense electron beam with the same velocity

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

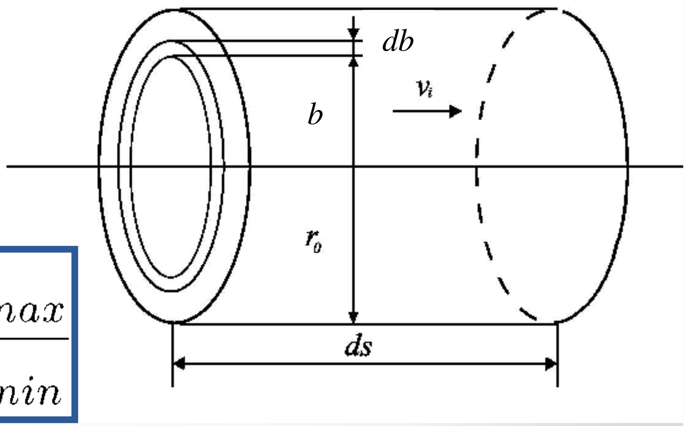
Energy transfer: $\Delta E(b) = \frac{(\Delta p)^2}{2m_e} \simeq \frac{2Q^2e^4}{(4\pi\epsilon_0)^2 m_e v^2}\frac{1}{b^2}$ $\quad (for\ \ b \gg b_{min})$

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

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

Characteristics of the Electron Cooling Force

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

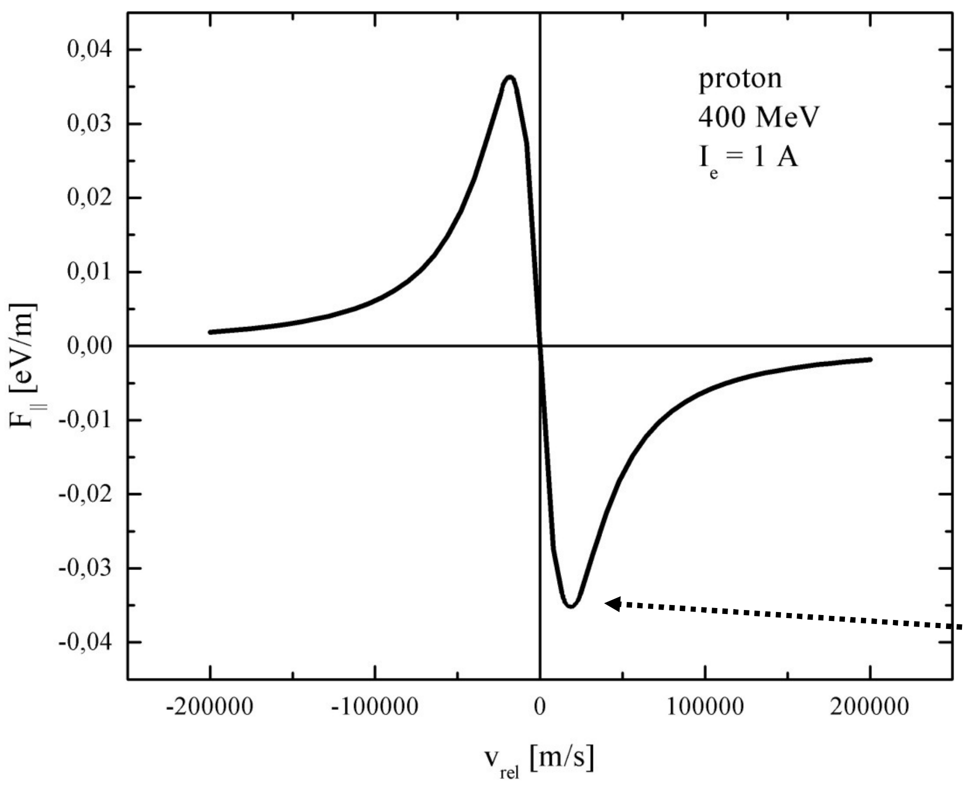
$$\vec{v}_{rel} = \vec{v_i} - \vec{v_e}$$

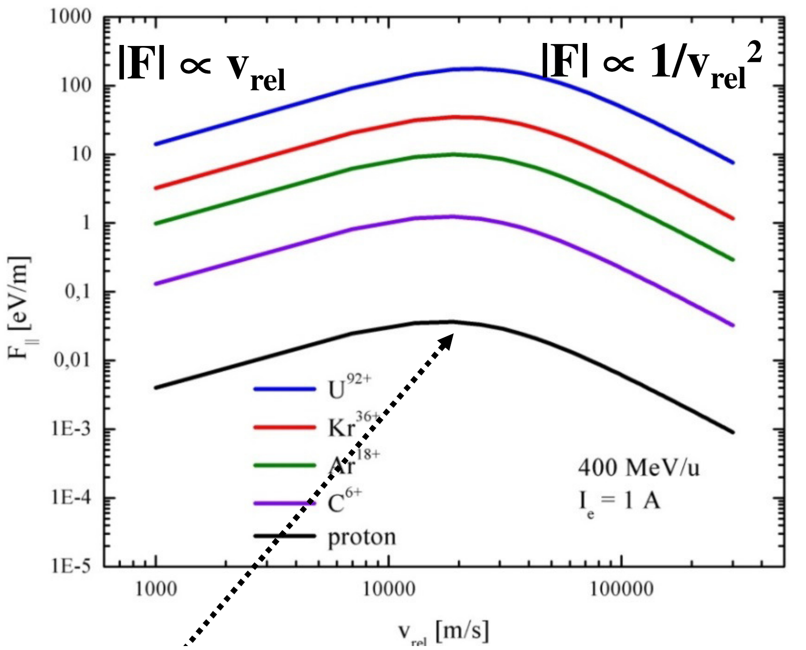
cooling force F

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

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 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

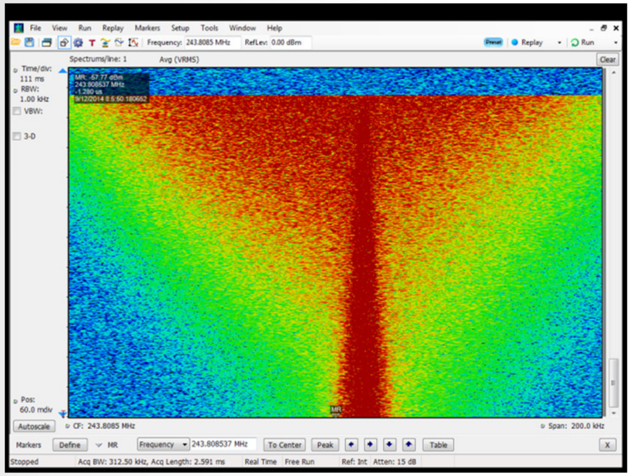
cooling rate is constant and maximum at small relative velocity

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

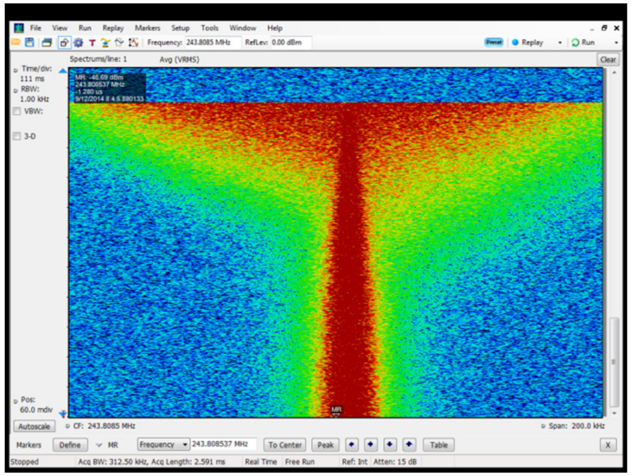
Longitudinal Cooling

Xe^{54+} 350 MeV/u

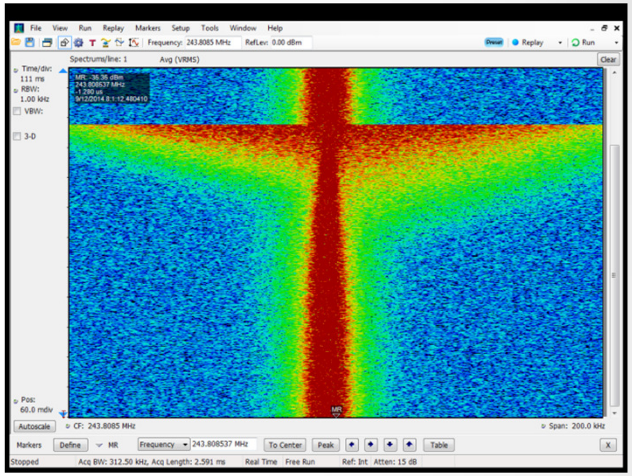
I_e= 100 mA



I_e= 250 mA

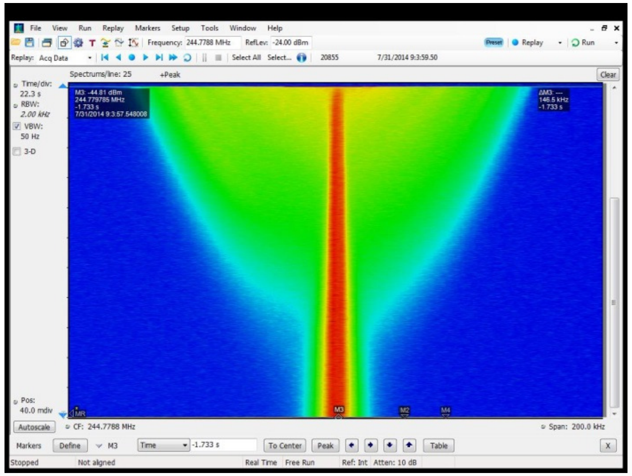


I_e= 500 mA



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

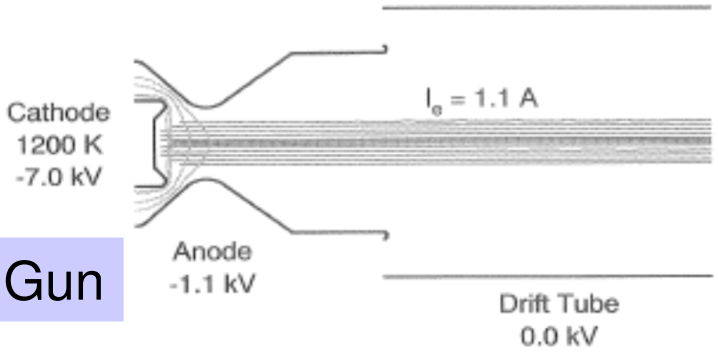
lower limit : $k_BT_\parallel \geq 2e\frac{n_e^{1/3}}{4\pi\epsilon_0}$

typical 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**

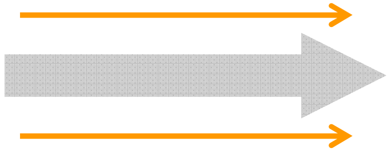
Electron Beam Properties

constant electron beam radius

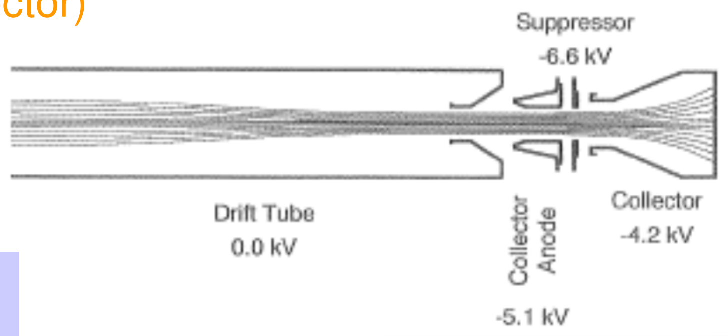


Gun

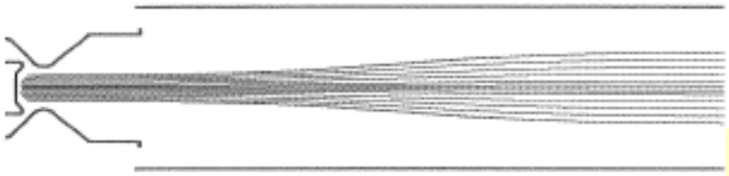
electron beam confined
by longitudinal magnetic
field (from gun to collector)



Collector

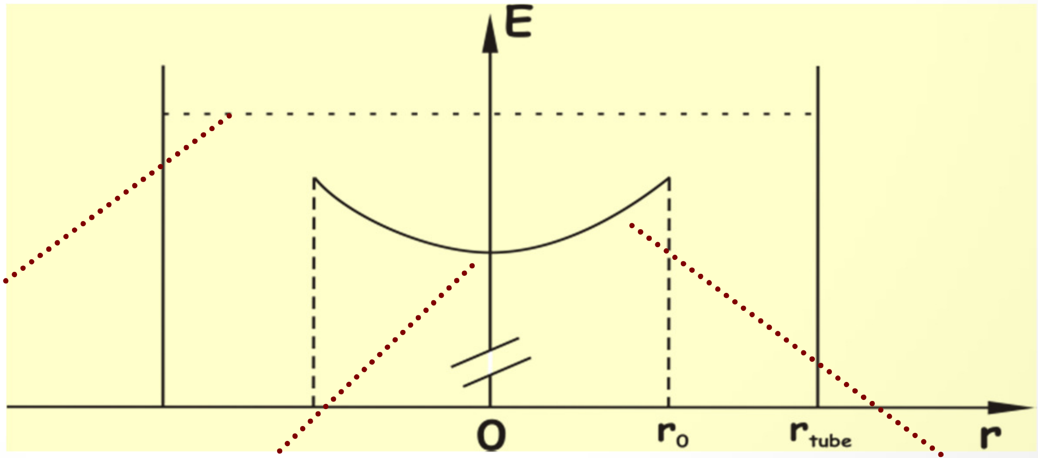


Cooling Section



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 Longitudinal Magnetic Field

single particle cyclotron motion

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

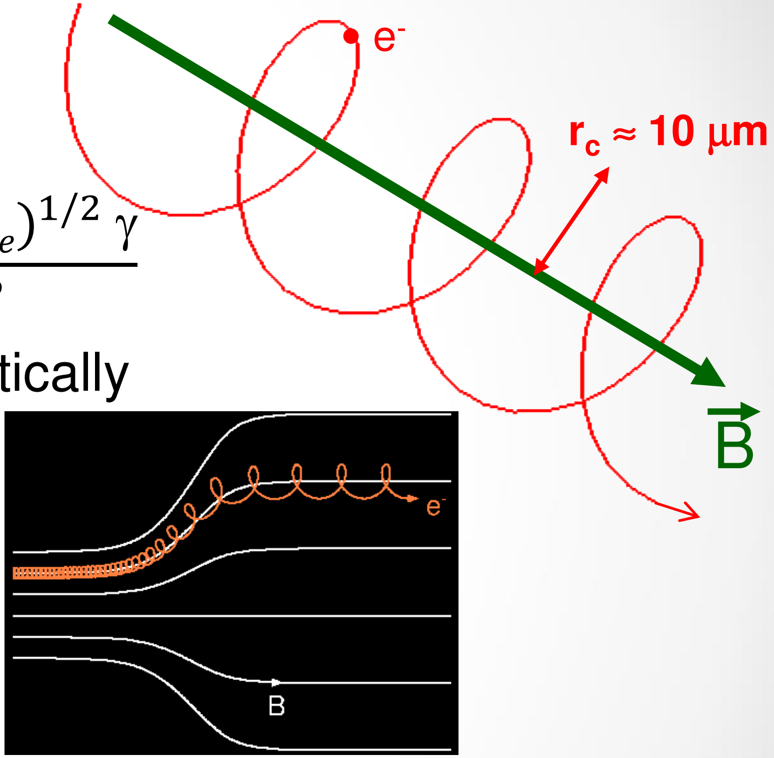
cyclotron radius $r_c = \dfrac{v_\perp}{\omega_c} = \dfrac{(kBT_\perp m_e)^{1/2}\,\gamma}{eB}$

electrons follow the magnetic field line adiabatically

⇒ transverse magnetic expansion

results in a reduction of the

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



another important consequence:
for interaction times which are long compared to the cyclotron period the ions do not sense the transverse electron temperature
⇒ **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

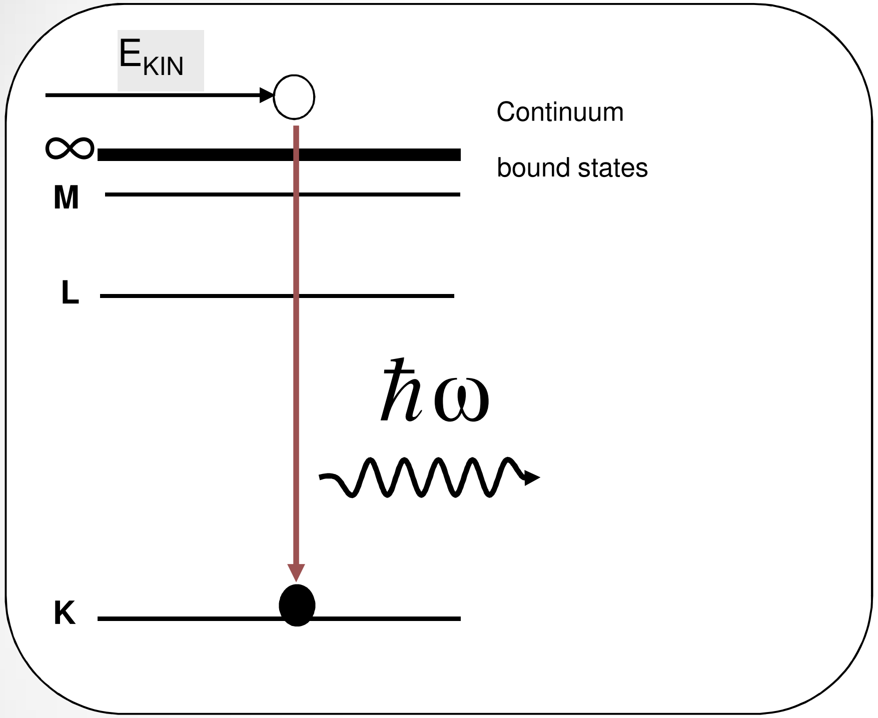
$$v_{azi} = r\omega_{azi} = r\frac{2\pi r_e n_e c^2}{\gamma\omega_c}$$

⇒ • 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 divergence) in cooling section

Atomic Physics Limitation of Electron Cooling



Radiative Electron Capture (REC)

$A^{Q+} + e^{-} \quad A^{(Q-1)+} + h\nu$

emission of a photon

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

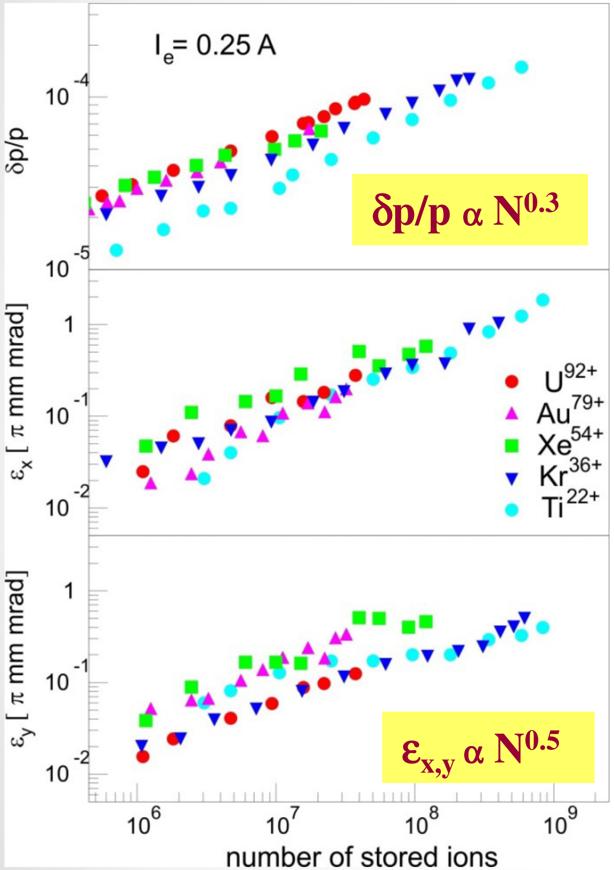
loss rate $\tau^{-1} = \gamma^{2}\,\alpha_{REC}\, n_{e}\eta$

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

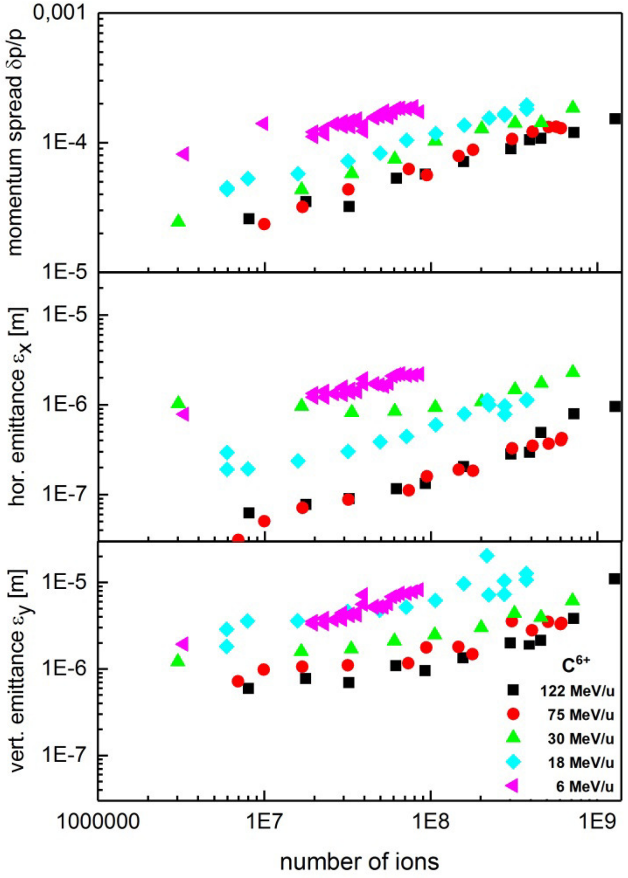
losses by recombination (REC)

Electron Cooled Beams in Equilibrium with Intrabeam Scattering (IBS)

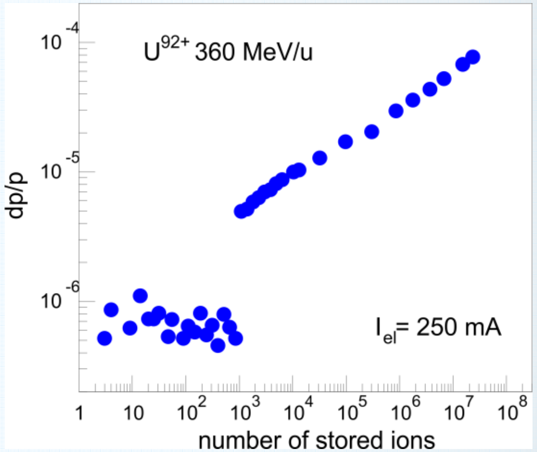
different ions (Q,A)



different energies (β, γ)



suppression of IBS for low intensity (N≤1000)



Beam ordering (crystallization)

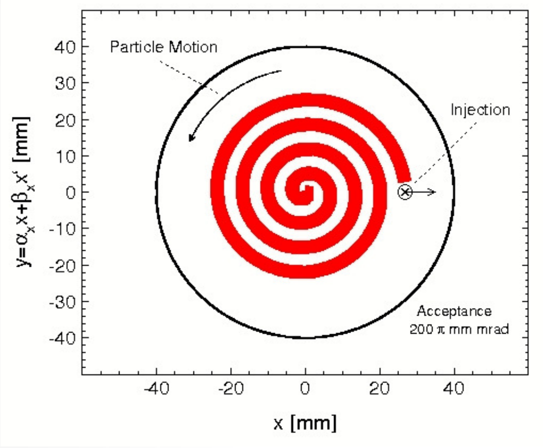
heating rate dominated by Intrabeam Scattering

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

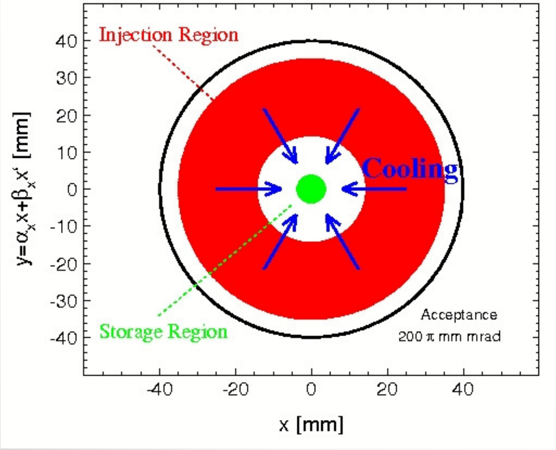
IBS: total phase space volume increases with ion beam intensity and ion charge

Accumulation of Heavy Ions by Electron Cooling

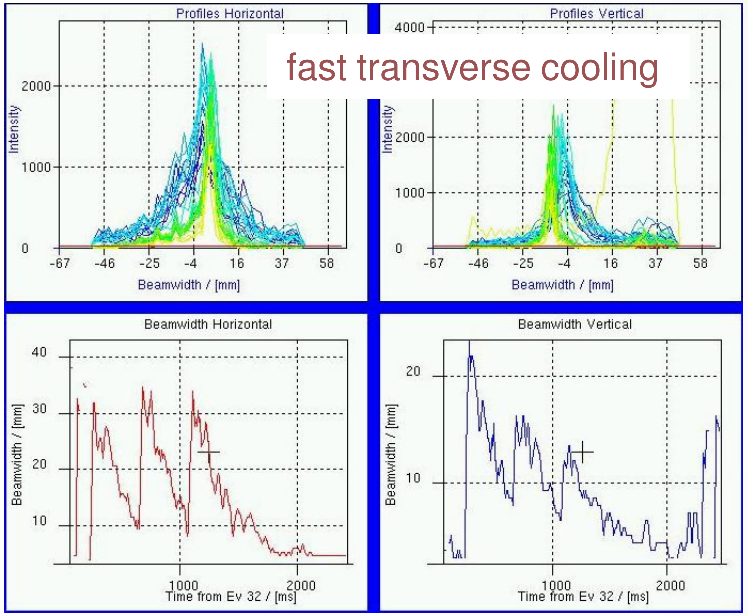
standard multiturn injection



fast accumulation by
repeated multiturn injection
with electron cooling



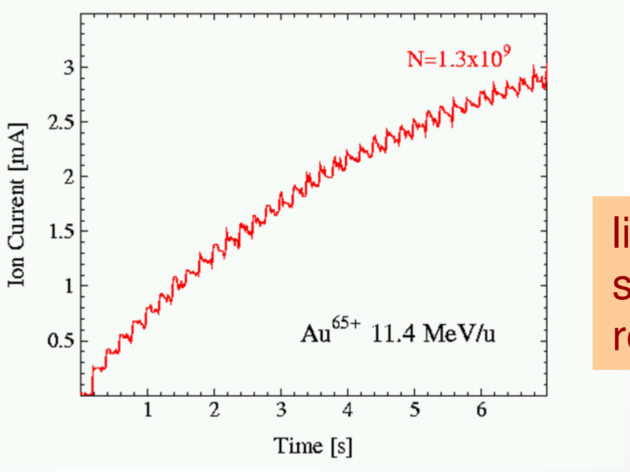
horizontal **vertical**



fast transverse cooling

profile

beam size

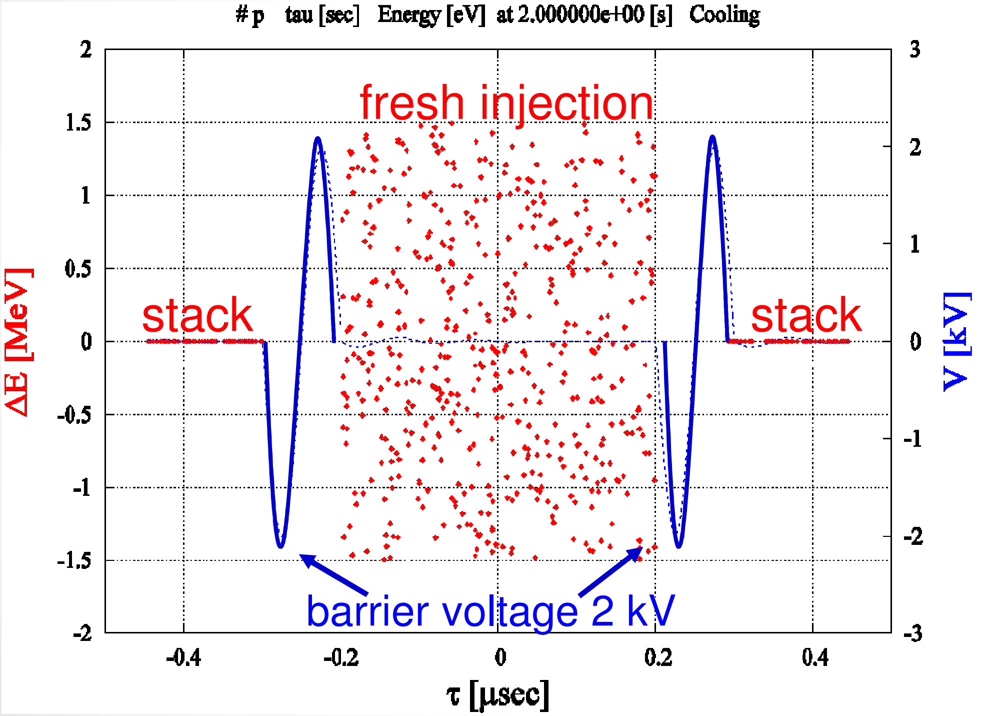


intensity increase in 5 s by a factor of ≈ 10

limitations:
space charge tune shift,
recombination (REC)

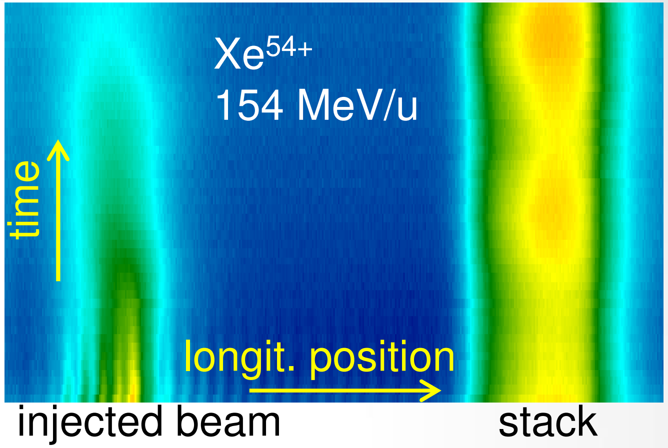
Accumulation of Secondary Particles

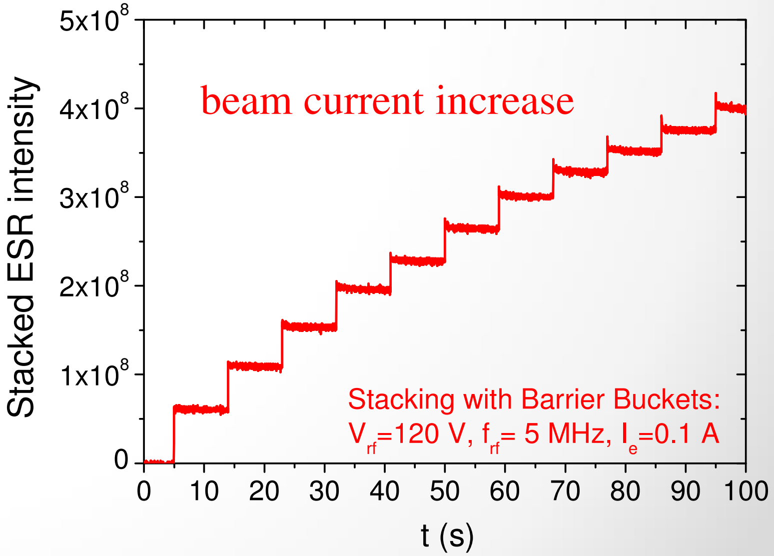
basic idea: confine stored beam to a fraction of the circumference, inject into gap and apply cooling to merge the two beam components
⇒ fast increase of intensity (for secondary beams)



simulation of longitudinal stacking
with barrier buckets and electron cooling

experimental verification at ESR



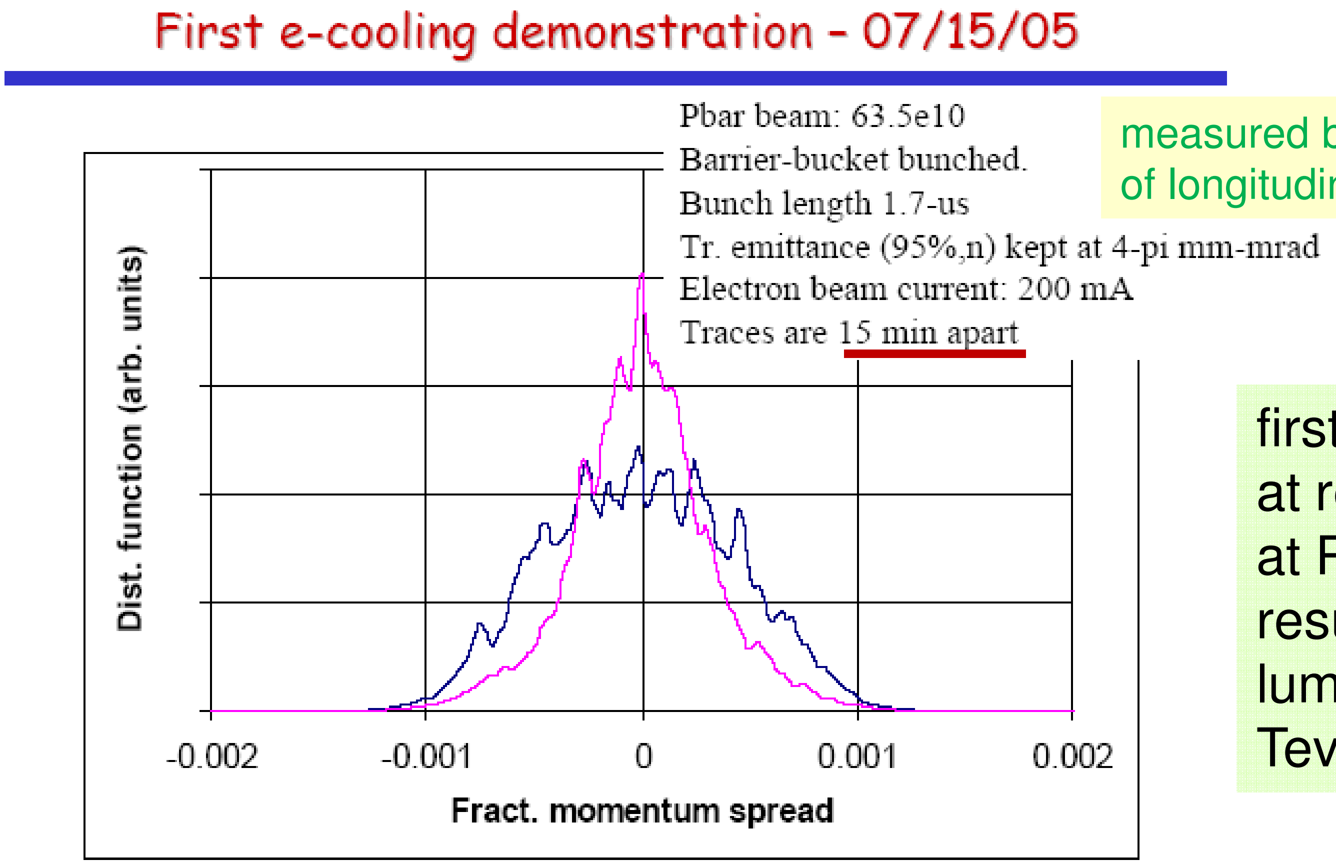


Stacking with Barrier Buckets:
V_{rf}=120 V, f_{rf}= 5 MHz, I_e=0.1 A

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

Pbar beam: 63.5e10
Barrier-bucket bunched.
Bunch length 1.7-us
Tr. emittance (95%,n) kept at 4-pi mm-mrad
Electron beam current: 200 mA
Traces are 15 min apart

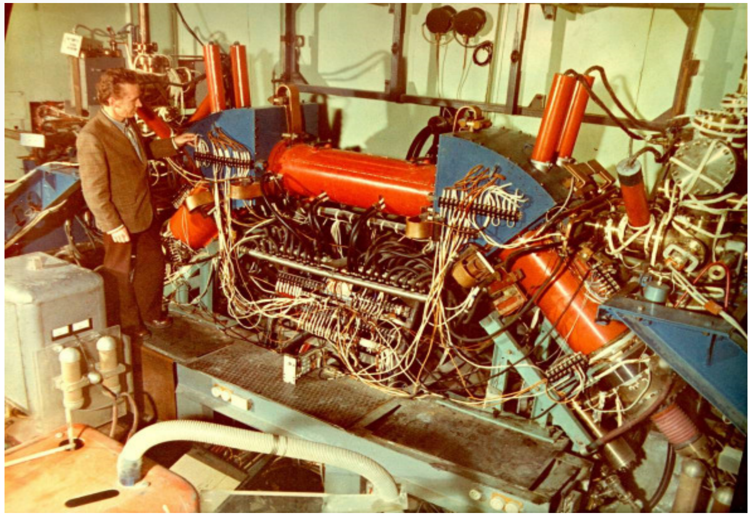
measured by detection
of longitudinal Schottky noise

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

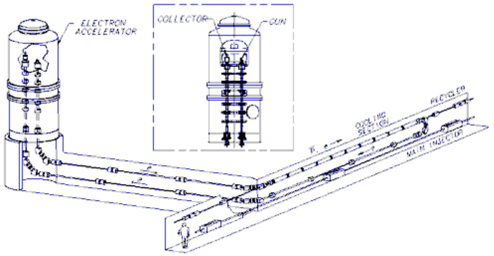
cooling time of some ten minutes has to be compared with the accumulation time of many hours

Electron Cooling Systems

First Electron
Cooling System
NAP-M/BINP
1974



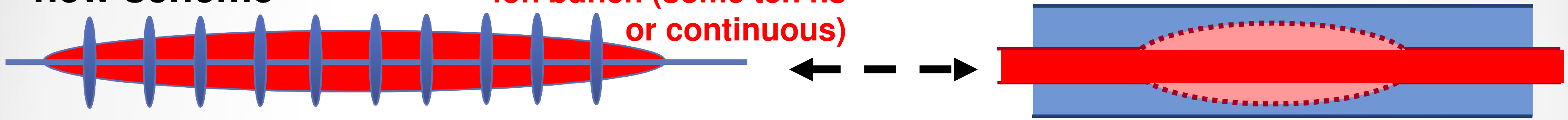
High Energy:
4.3 MeV Recycler/FNAL
2005



Medium Energy:
300 keV
ESR/GSI
1990

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).



new scheme

ion bunch (some ten ns or continuous)

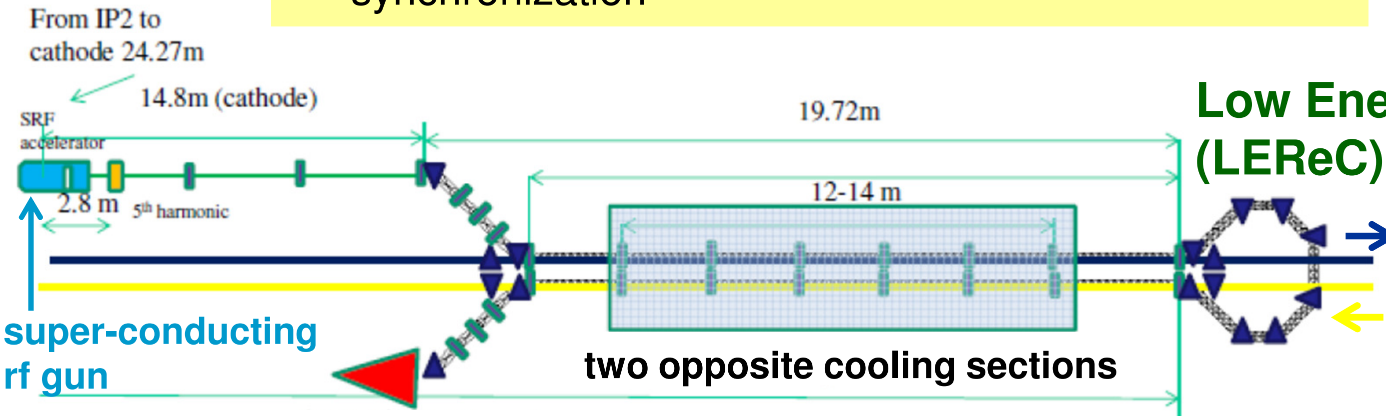
electron bunches (some ns)

traditional

continuous electron beam

continuous (or bunched) ion beam

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



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

two counter-propagating ion beams

super-conducting rf gun

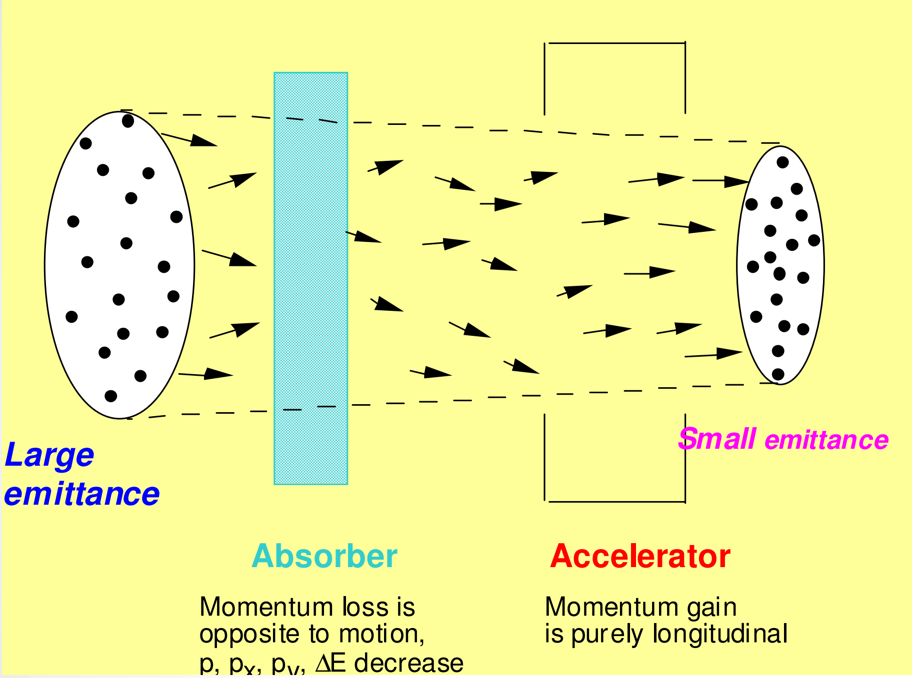
two opposite cooling sections

5 MeV, 250 kW beam dump

58.804 m from IP2

2. Ionization Cooling

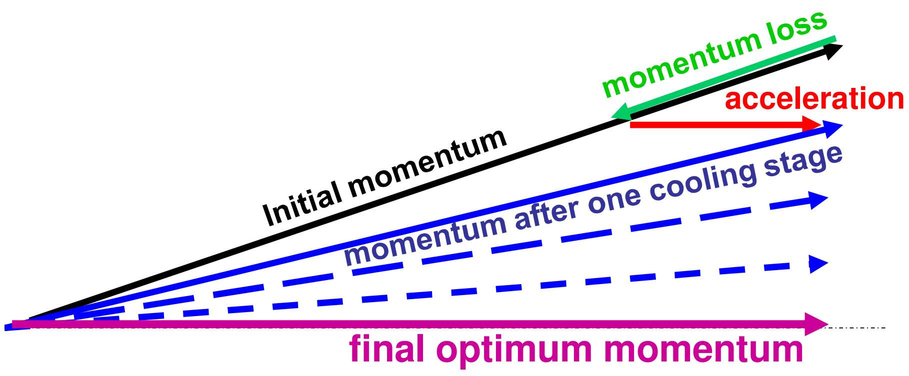
energy loss in solid matter



Momentum loss is opposite to motion, p, p_x, p_y, ΔE decrease

Momentum gain is purely longitudinal

proposed for muon cooling



not useful for heavy particles
due to strong interaction with matter

transverse cooling

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

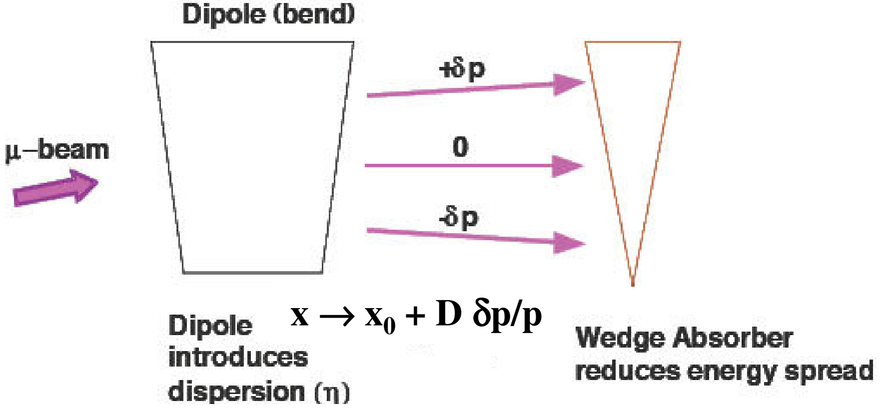
$$= -\frac{1}{\beta^2 E}\frac{dE}{ds}\epsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

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

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

Ionization Cooling

increased longitudinal cooling
by longitudinal-transverse emittance exchange



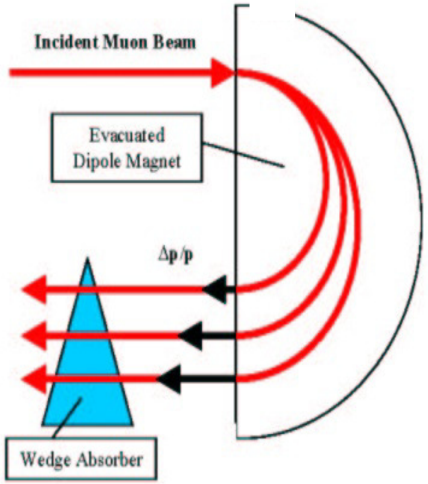


Figure 1. Use of a Wedge Absorber for Emittance Exchange

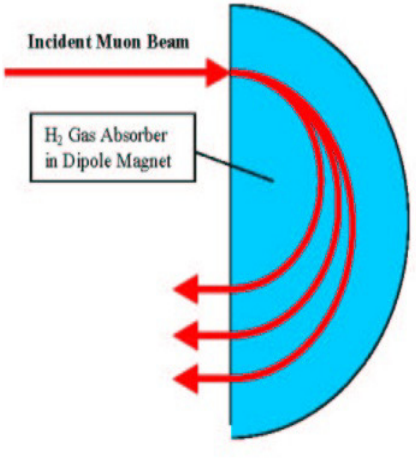


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

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

cooling term heating term

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

emittance exchange

increased longitudinal cooling

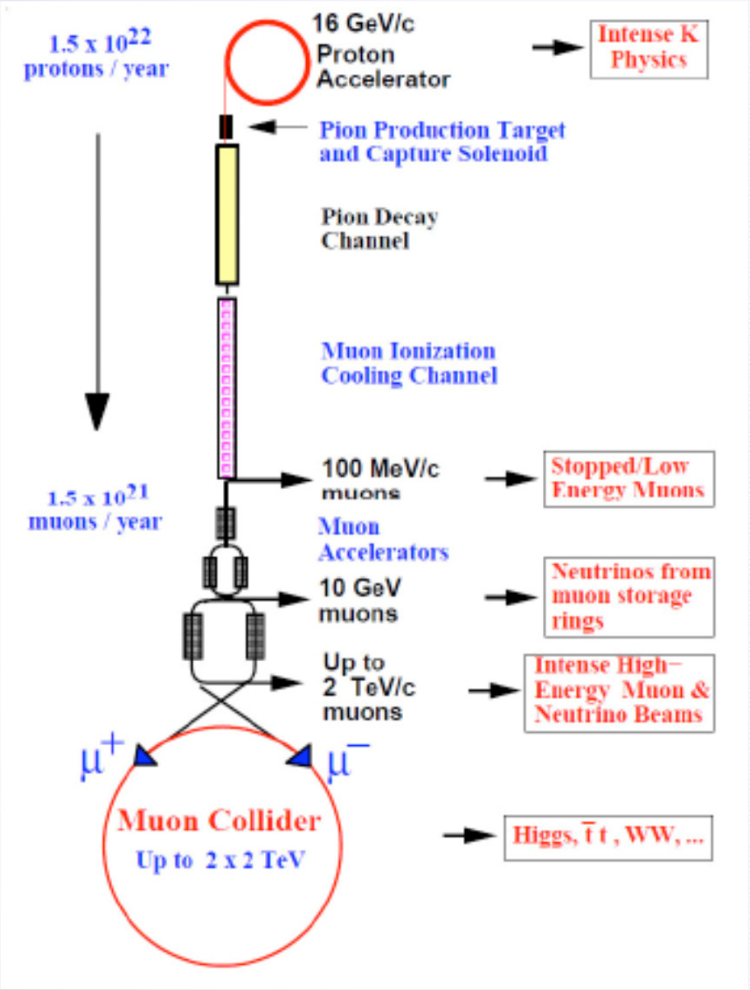
$$\frac{\partial\frac{dE}{ds}}{\partial E} \Rightarrow \frac{\partial\frac{dE}{ds}}{\partial E}|_0 + \frac{dE}{ds}\frac{D\rho'}{\beta c p\rho_0}$$

reduced transverse cooling

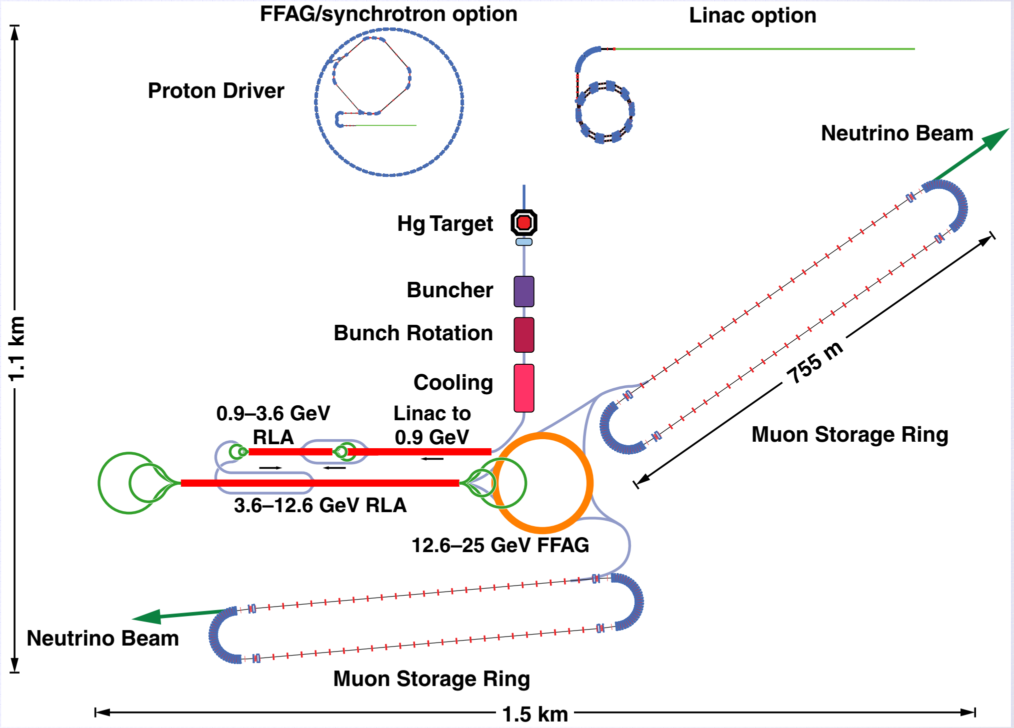
$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}(1-\frac{D\rho'}{\rho_0})\epsilon_N$$

Scenarios with Ionization Cooling

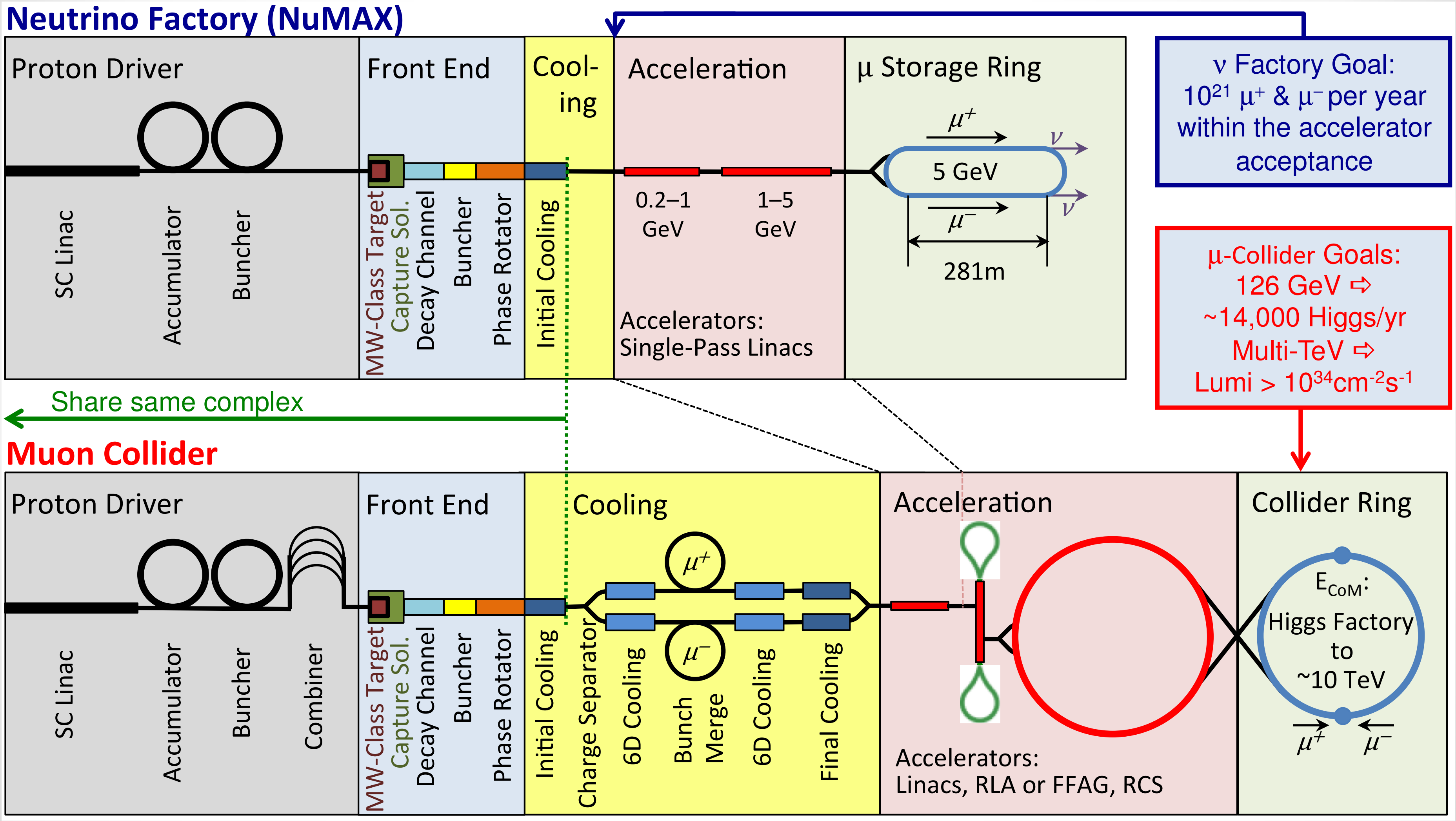
Muon Collider



Neutrino Factory



Scenarios with Ionization Cooling



Neutrino Factory (NuMAX)

ν Factory Goal:
10^{21} μ^+ & μ^- per year
within the accelerator acceptance

μ-Collider Goals:
126 GeV ⇨ ~14,000 Higgs/yr
Multi-TeV ⇨ Lumi > 10^{34}cm^{-2}s^{-1}

Share same complex

Muon Collider

The Muon Cooling Section

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

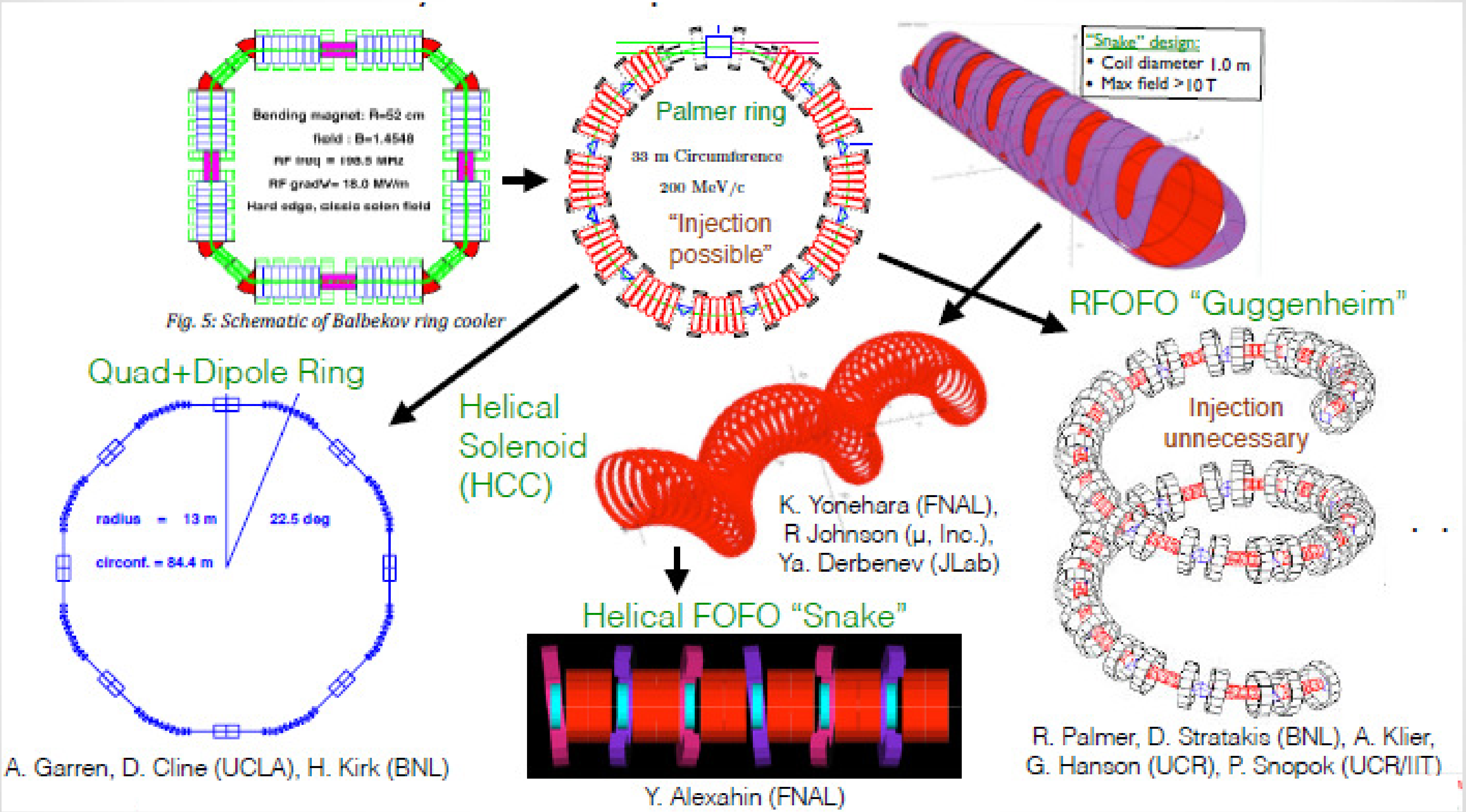


Fig. 5: Schematic of Balbekov ring cooler

Palmer ring

"Injection possible"

RFOFO "Guggenheim"

Injection unnecessary

Quad+Dipole Ring

Helical Solenoid (HCC)

K. Yonehara (FNAL), R Johnson (μ, Inc.), Ya. Derbenev (JLab)

Helical FOFO "Snake"

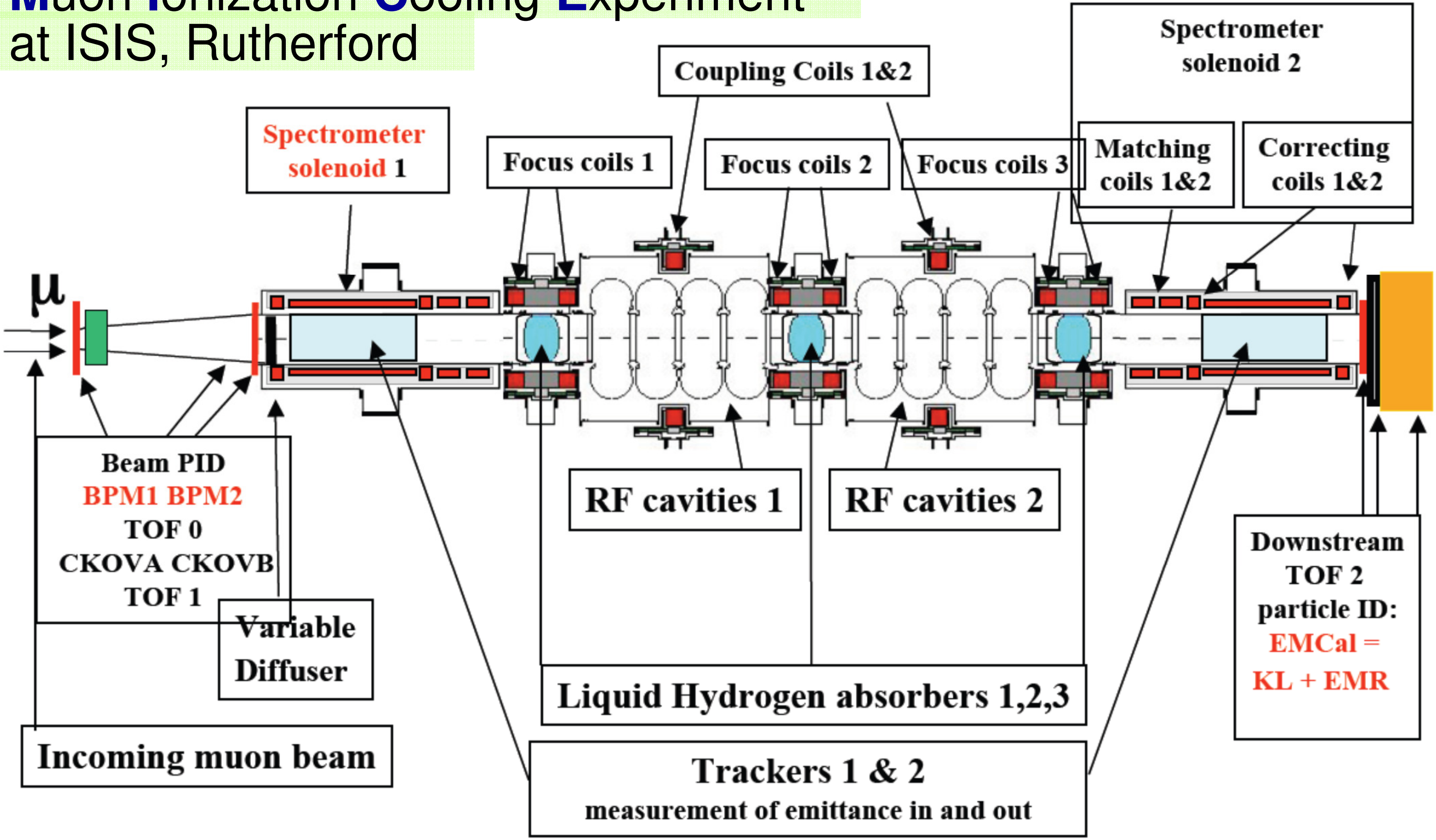
A. Garren, D. Cline (UCLA), H. Kirk (BNL)

Y. Alexahin (FNAL)

R. Palmer, D. Stratakis (BNL), A. Klier, G. Hanson (UCR), P. Snopok (UCR/IIT)

MICE

Muon **I**onization **C**ooling **E**xperiment
at ISIS, Rutherford



Spectrometer solenoid 2

Coupling Coils 1&2

Spectrometer solenoid 1

Focus coils 1

Focus coils 2

Focus coils 3

Matching coils 1&2

Correcting coils 1&2

Beam PID
BPM1 BPM2
TOF 0
CKOVA CKOVB
TOF 1

Variable Diffuser

RF cavities 1

RF cavities 2

Downstream
TOF 2
particle ID:
EMCal =
KL + EMR

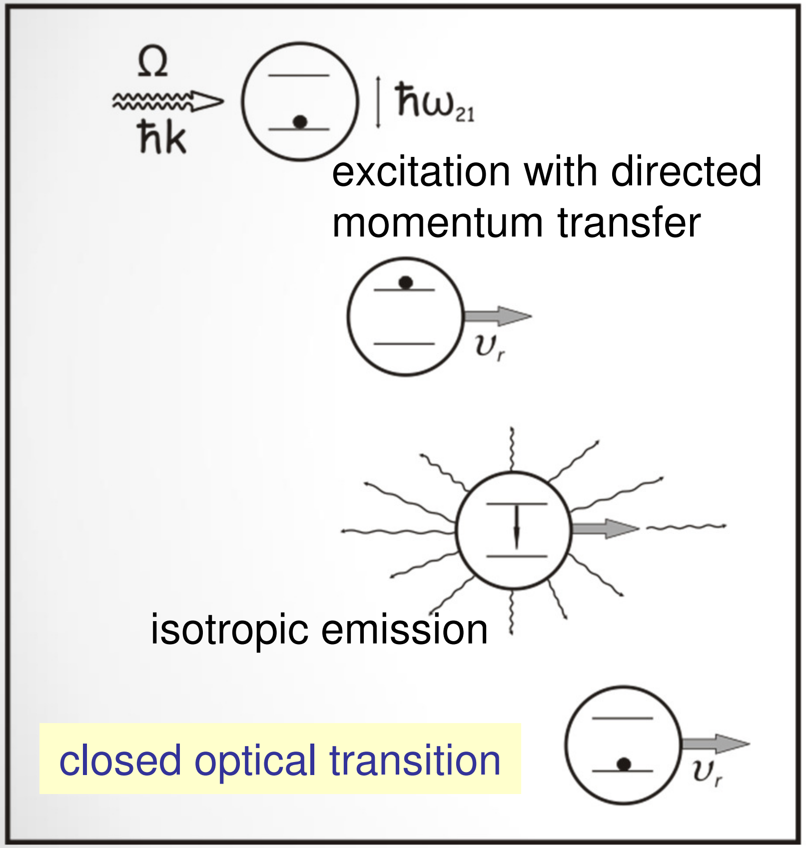
Liquid Hydrogen absorbers 1,2,3

Incoming muon beam

Trackers 1 & 2
measurement of emittance in and out

3. Laser Cooling

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

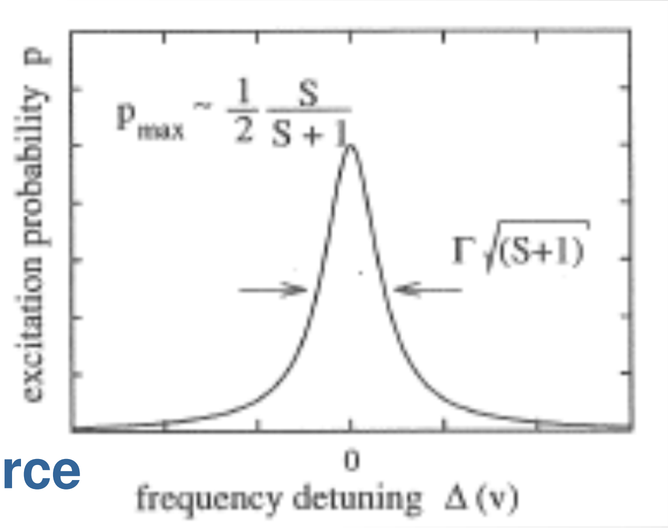


excitation with directed momentum transfer

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 with width Γ/k ~ 10 m/s

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

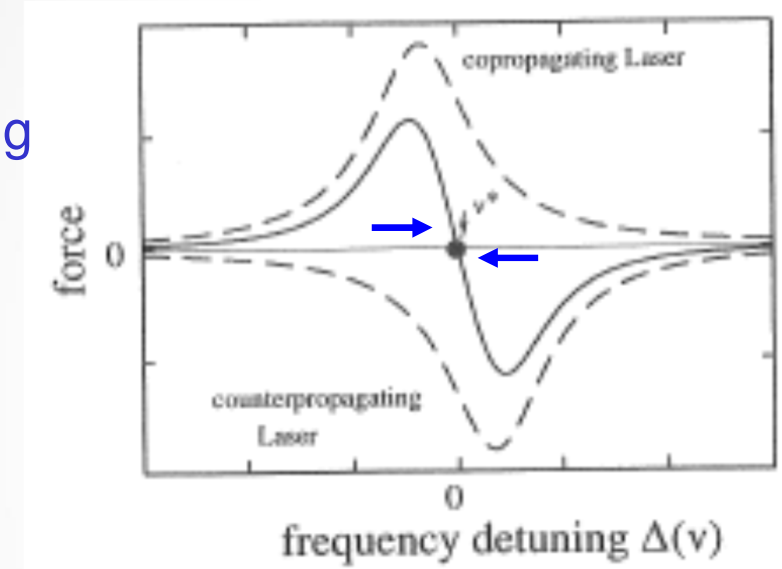
typical cooling time ~ 10 µs

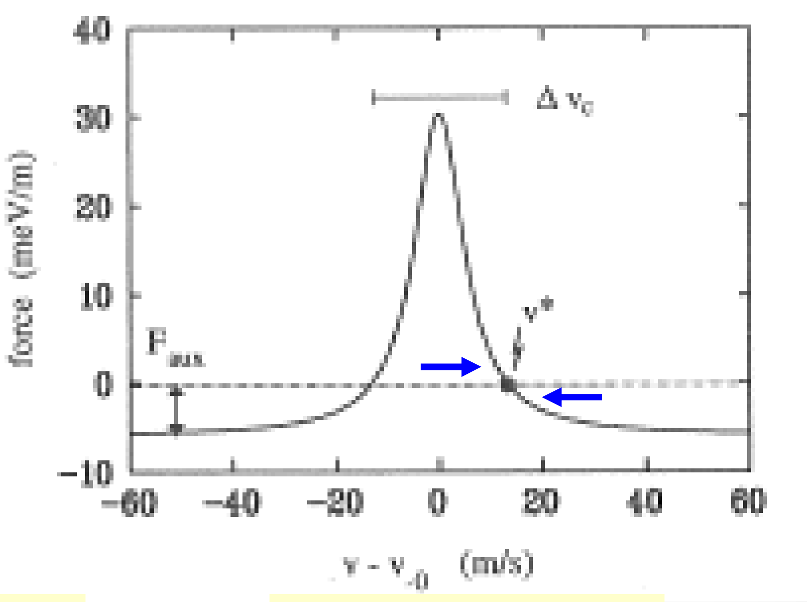
drawback: only longitudinal cooling

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)

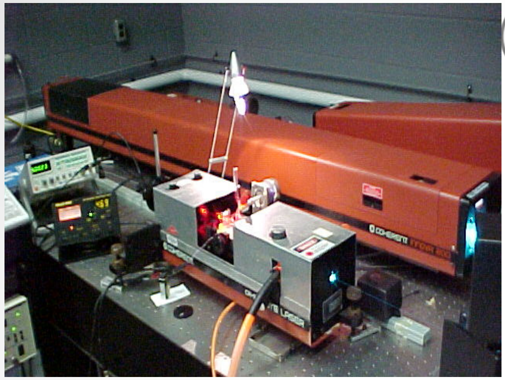
auxiliary force
(betatron core, rf)

capture range of laser is limited ⇒ frequency sweep (snowplow)
or pulsed laser with large spectral width

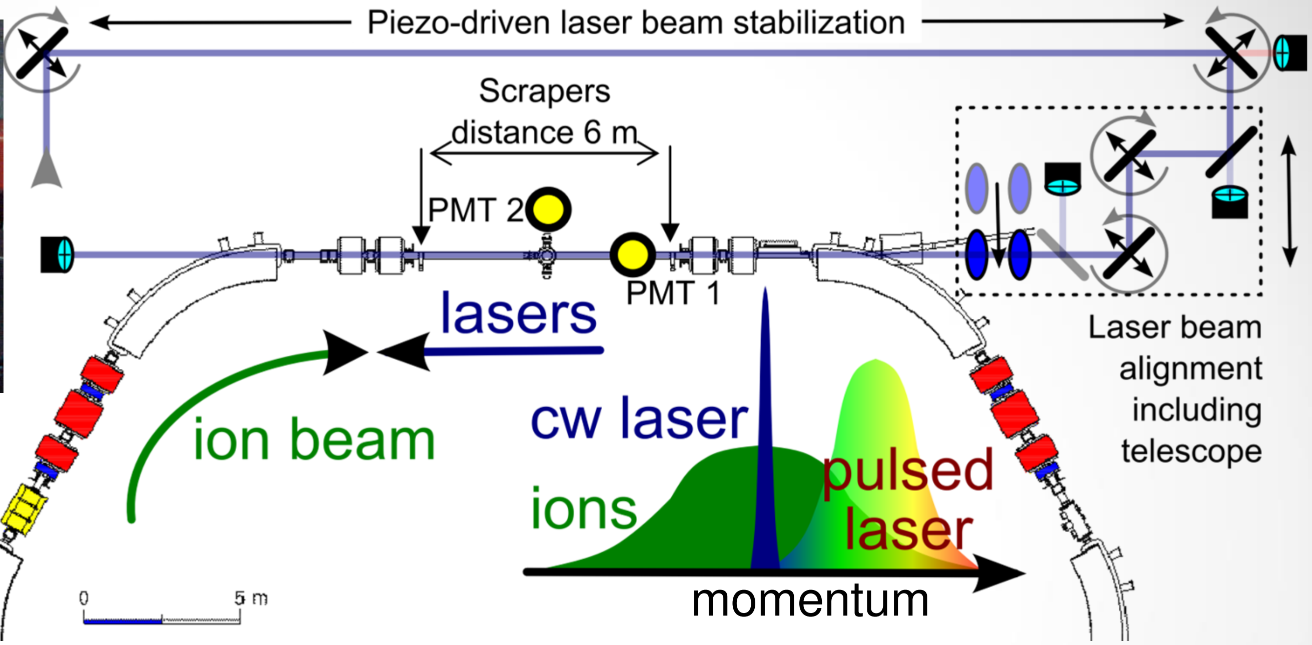
ions studied so far: **^{7}Li^{1+}, ^{9}Be^{1+}, ^{24}Mg^{1+}, ^{12}C^{3+}**

in future: Li-like heavy ions at relativistic energies, cooling rate increases with γ
large relativistic energy ⇒ large excitation energy in PRF

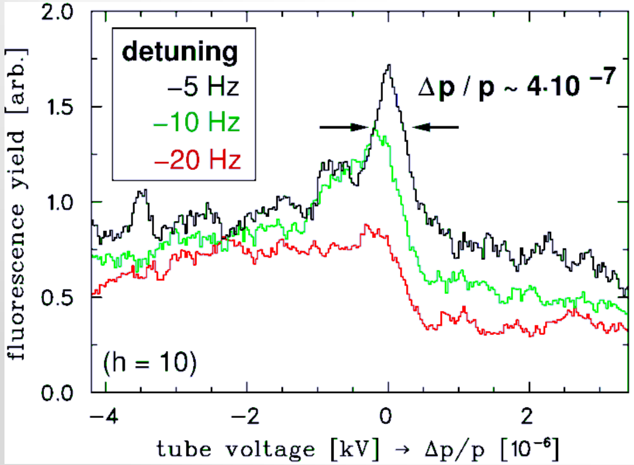
Laser Cooling of C^{3+}



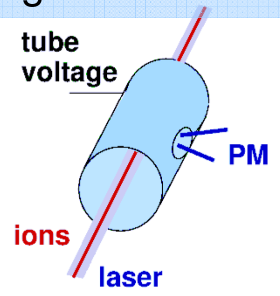
Argon ion laser (257.3 nm)
frequency doubled



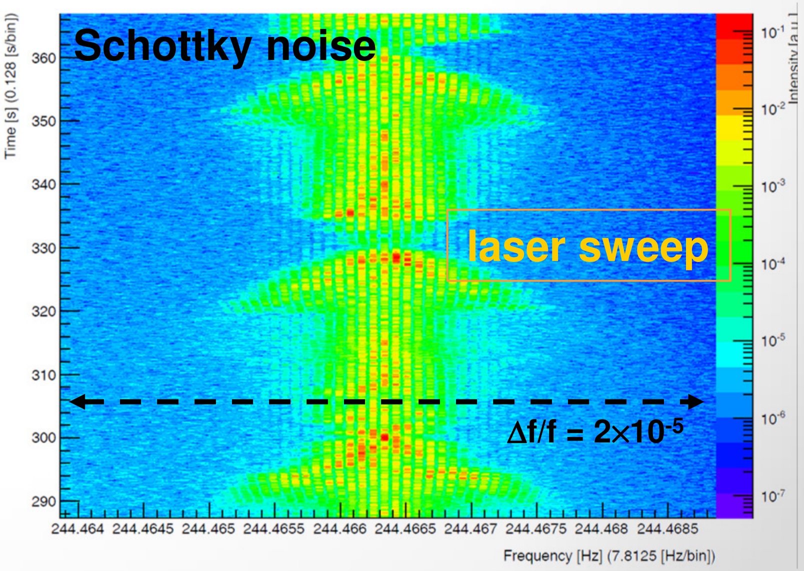
ESR storage ring



fluorescence light detection

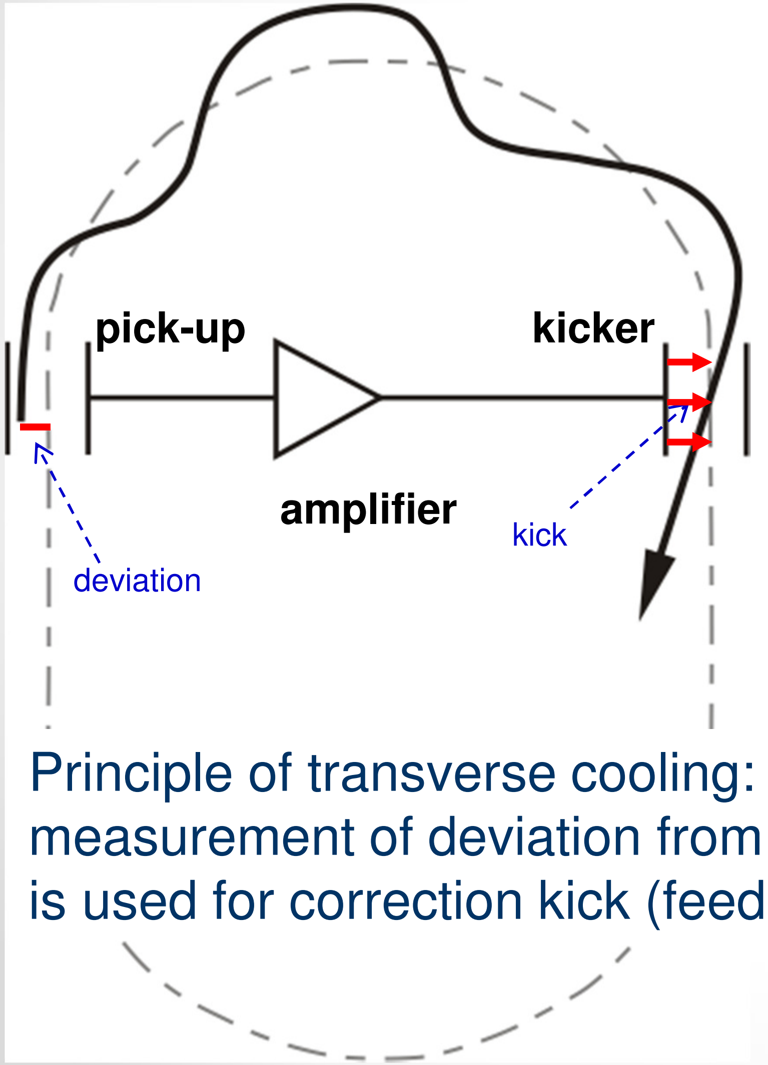


probing the velocity distribution



4. Stochastic Cooling

First cooling method which was successfully used for beam preparation



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

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

Conditions:

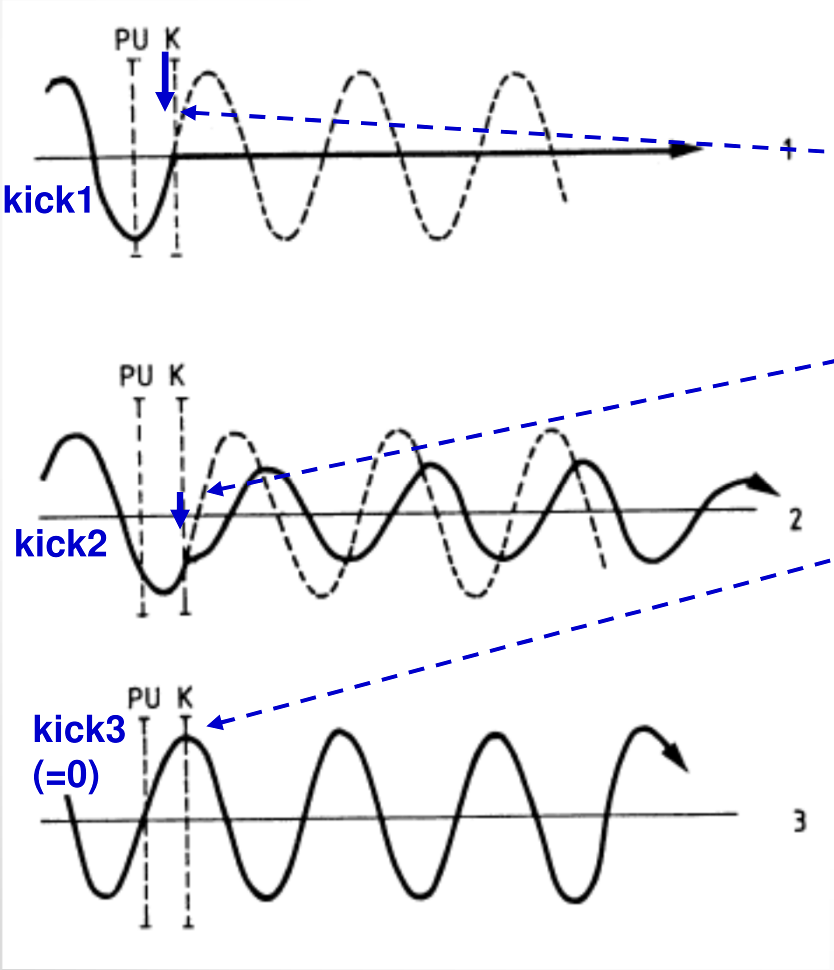
Betatron motion phase advance
(pick-up to kicker): $(n + ½)\ \pi$

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

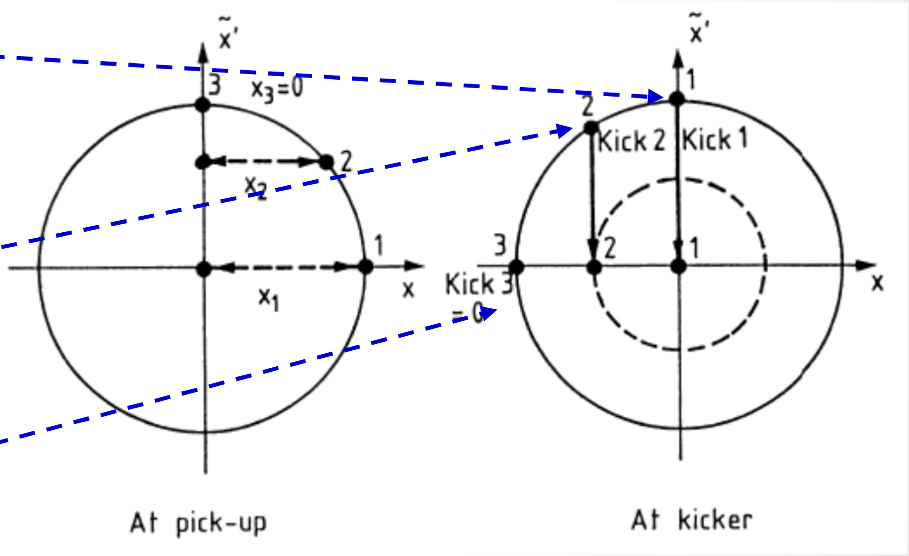
Sampling of sub-ensemble of total beam

Stochastic Cooling

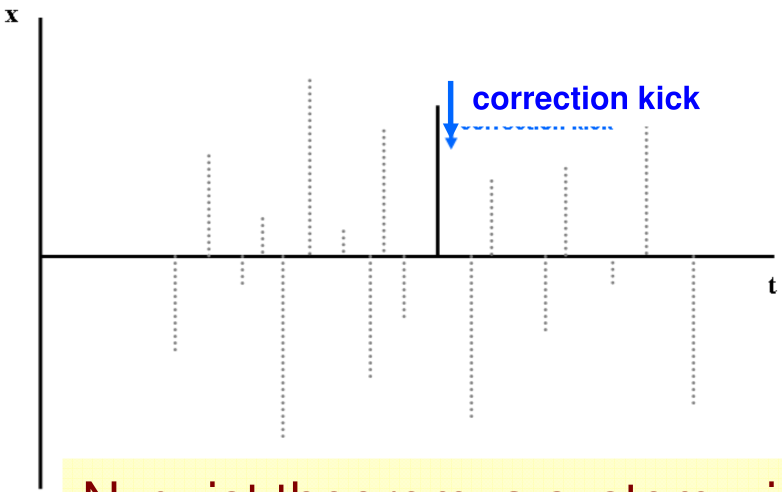
single particle betatron motion
along storage ring
without (dashed) and with (full)
correction kick



projection to two-dimensional
horizontal phase area



Stochastic Cooling

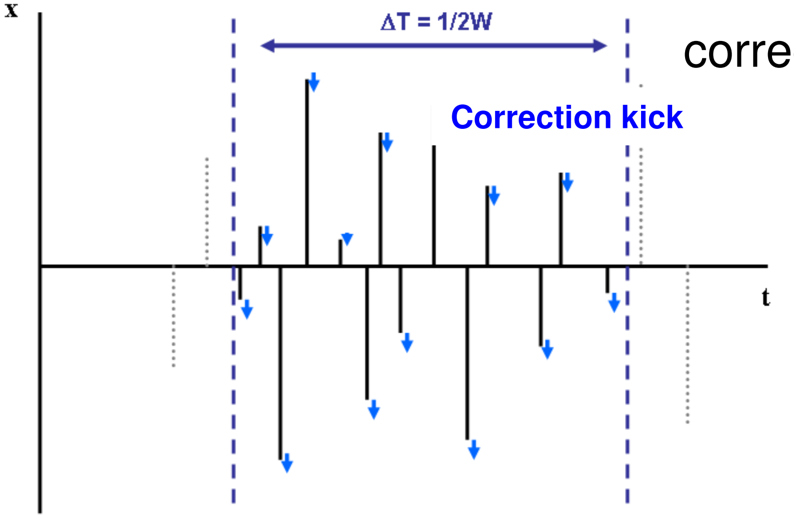


in time domain

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 $\Delta T = (2W)^{-1}$



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 ($x(t) = x(t_0) \times e^{-(t-t_0)/\tau}$):

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

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

M mixing factor

U noise to signal ratio

maximum of cooling rate

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

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

further refinement (wanted ↔ unwanted mixing):

with wanted mixing M (kicker to pick-up)

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

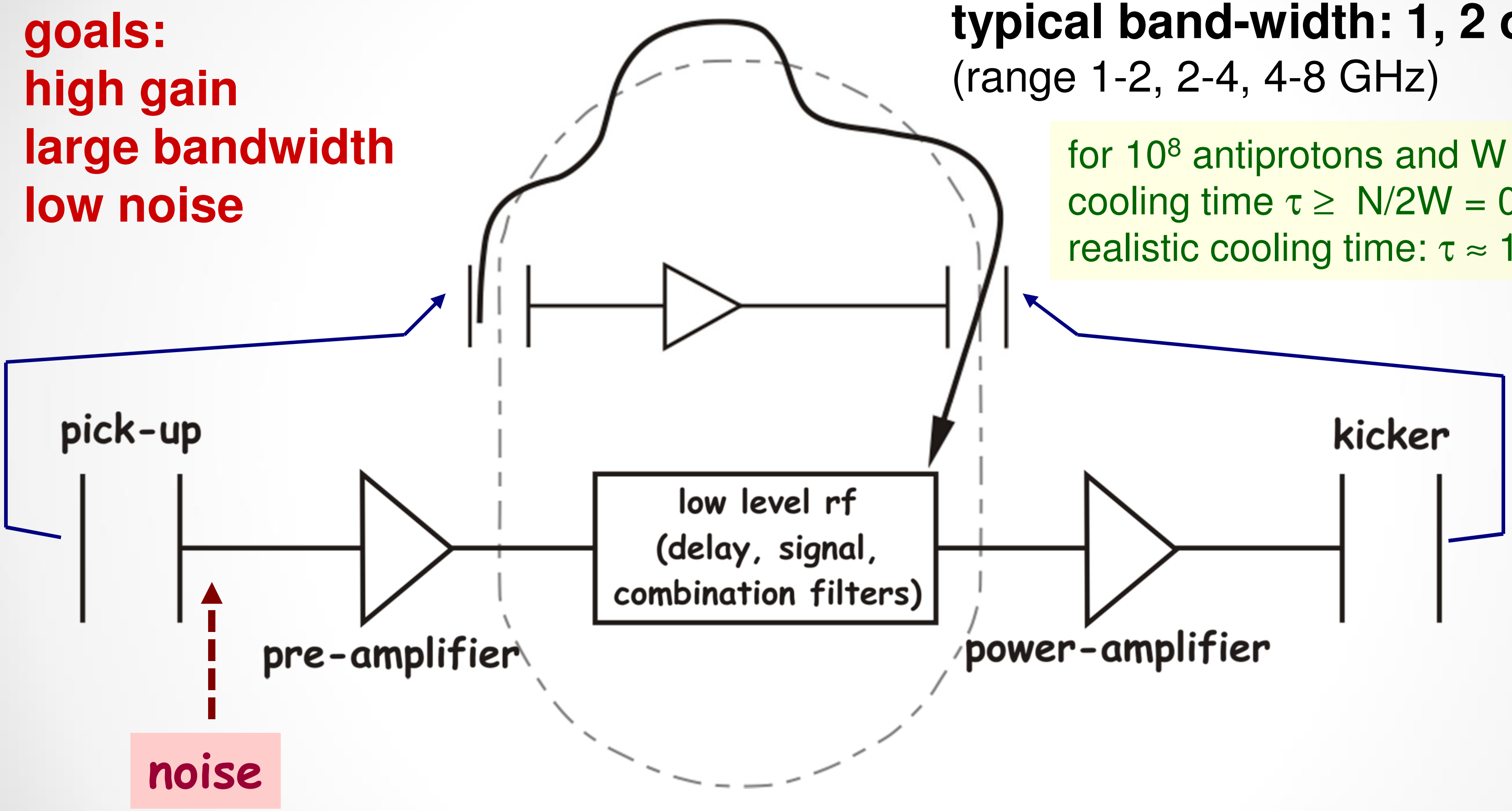
$$\lambda = \tau^{-1} = \frac{2W}{N}(2g(1-\tilde{M}^2) - g^2(M+U))$$

Stochastic Cooling Circuit

goals:
high gain
large bandwidth
low noise

typical band-width: 1, 2 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:

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

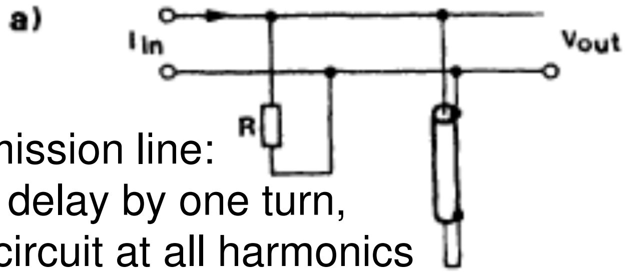
Longitudinal Stochastic Cooling

1) **Palmer cooling**

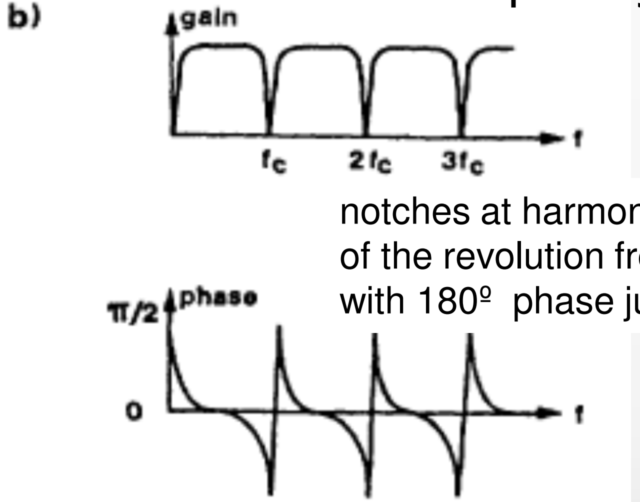
pick-up in dispersive section detects horizontal position
⇒ acceleration/deceleration kick corrects momentum deviation

2) **Notch filter cooling**

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



transmission line:
signal delay by one turn,
short circuit at all harmonics
of the revolution frequency



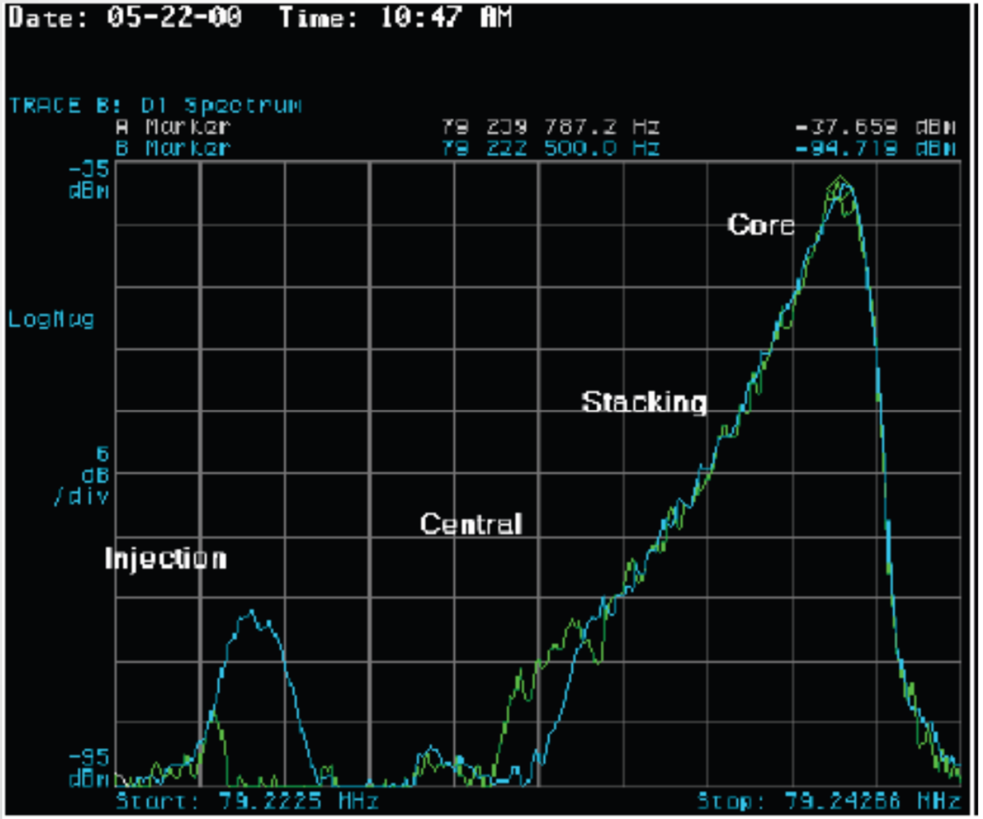
notches at harmonics
of the revolution frequency
with 180º phase jump

3) **ToF cooling**

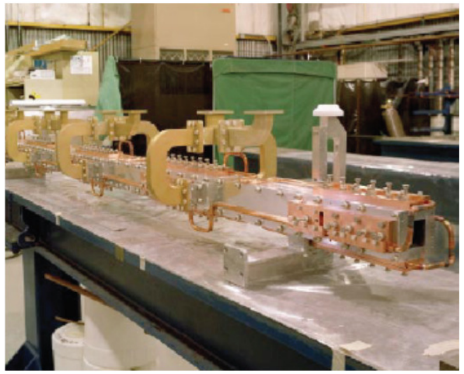
simplified scheme without notches allows efficient pre-cooling

Antiproton Accumulation by Stochastic Cooling

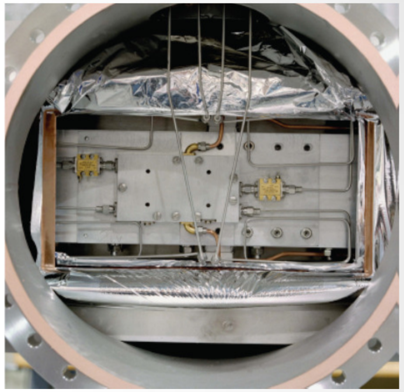
accumulation of 8 GeV antiprotons at accumulator ring, FNAL, shut down 09/2011
a similar facility AC/AA at CERN was operated until 11/1996



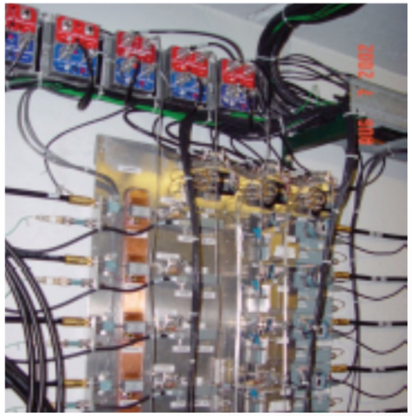
momentum distribution of accumulated antiproton beam



kicker array



cryogenic microwave amplifier

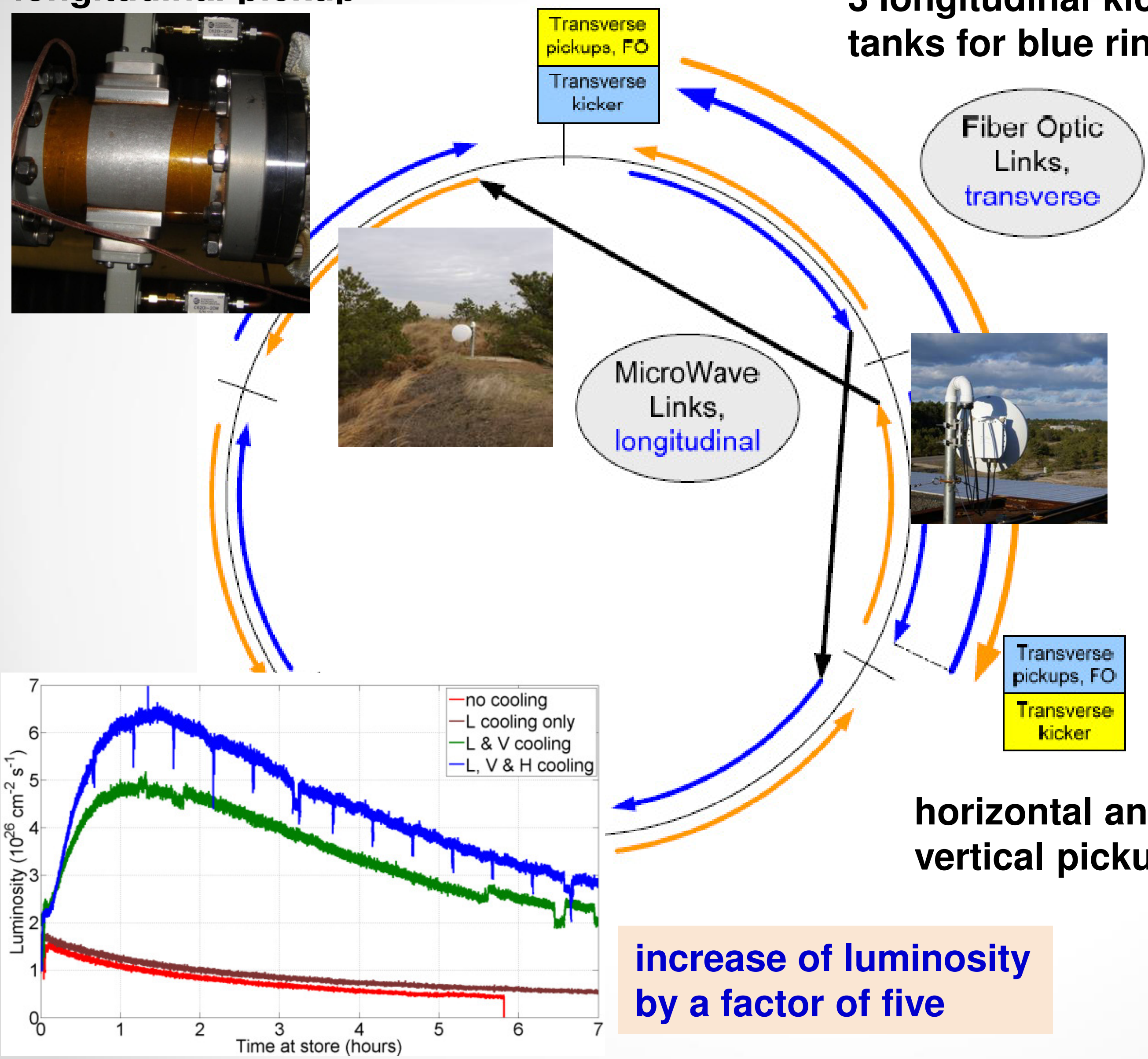


microwave electronics

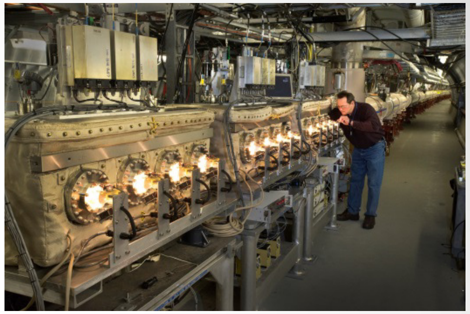
power amplifiers (TWTs)

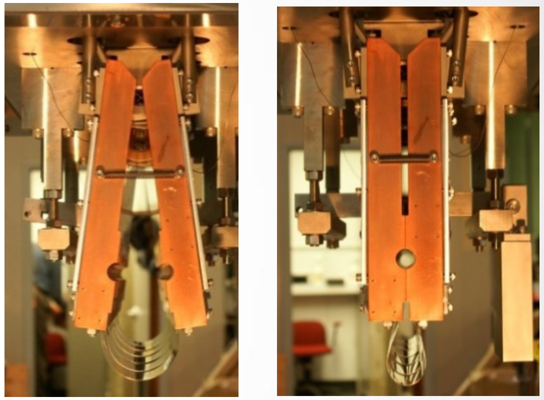
RHIC – 3D stochastic cooling for heavy ions

longitudinal pickup



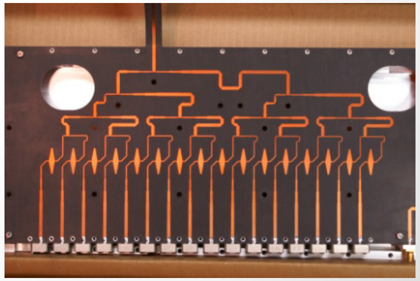
3 longitudinal kicker tanks for blue ring





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

horizontal and vertical pickups



increase of luminosity by a factor of five

Stochastic Cooling of Rare Isotopes at GSI

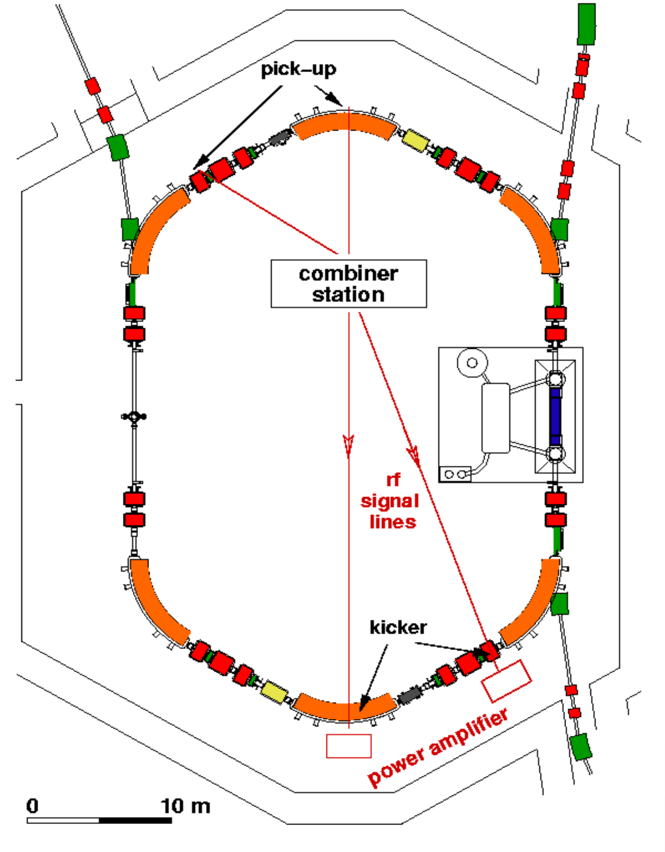
fast pre-cooling of hot fragment beams

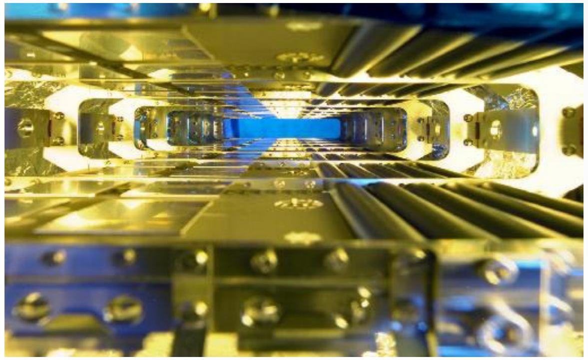
energy 400 (-550) MeV/u

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

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 3D control	bunched beams
Limitations:	high intensity beams	space charge effects
/problems	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

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