Beam Cooling

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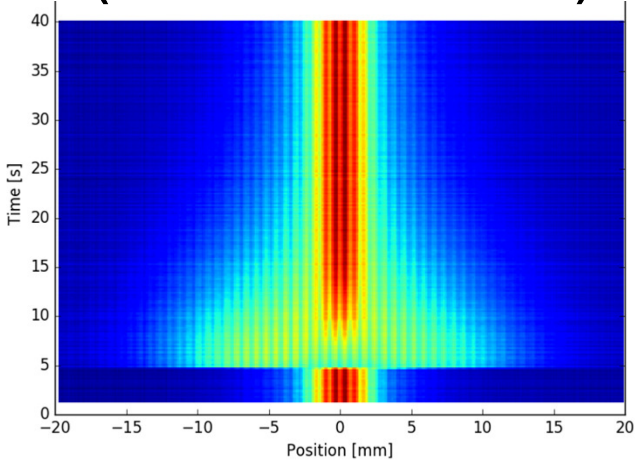
Observation of Cooling

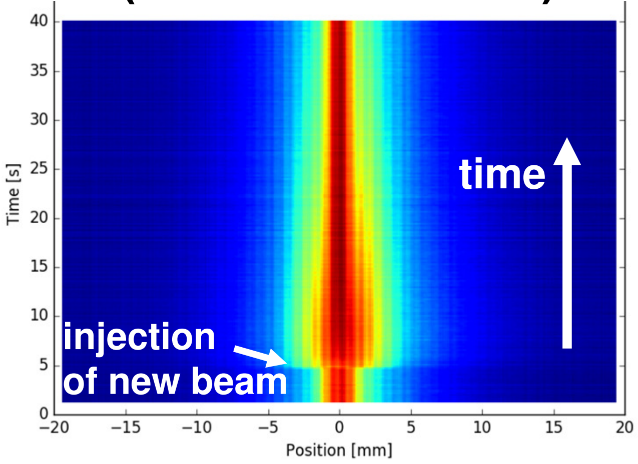
Xe^{54+} beam at 400 MeV/u cooled with electron current 200 mA

cooling in six-dimensional phase space

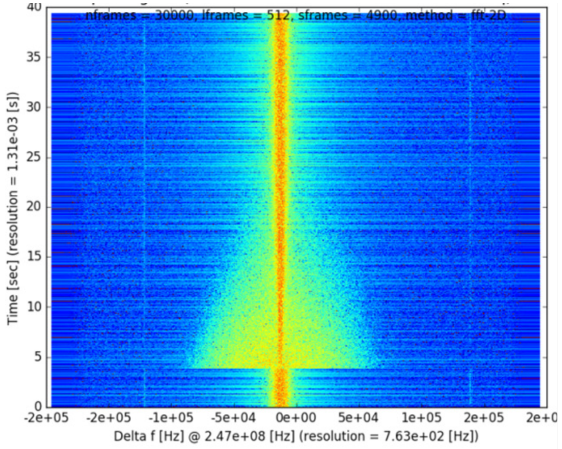
horizontal profile (horizontal emittance)



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 (tomorrow)

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 $f(z, z', t)$

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

$$\frac{df(z, z', t)}{dt} = -\lambda_z f(z, z', t)$$

λ_z cooling (damping) rate

in a circular accelerator:

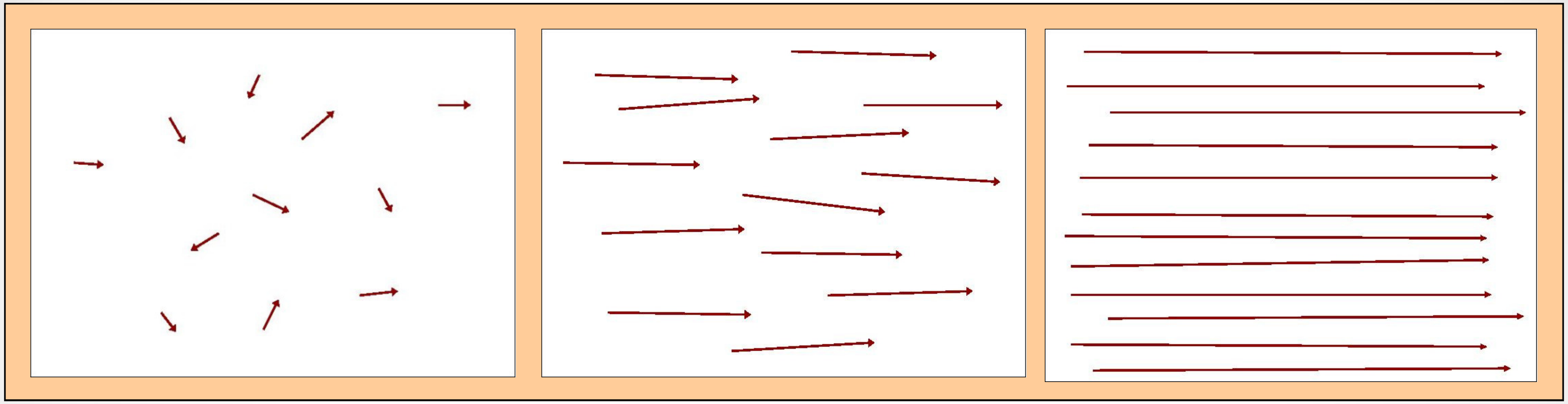
Transverse (emittance) cooling $\epsilon_{x,y}(t_0 + t) = \epsilon_{x,y}(t_0)\ e^{-\lambda_{x,y} t}$

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

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

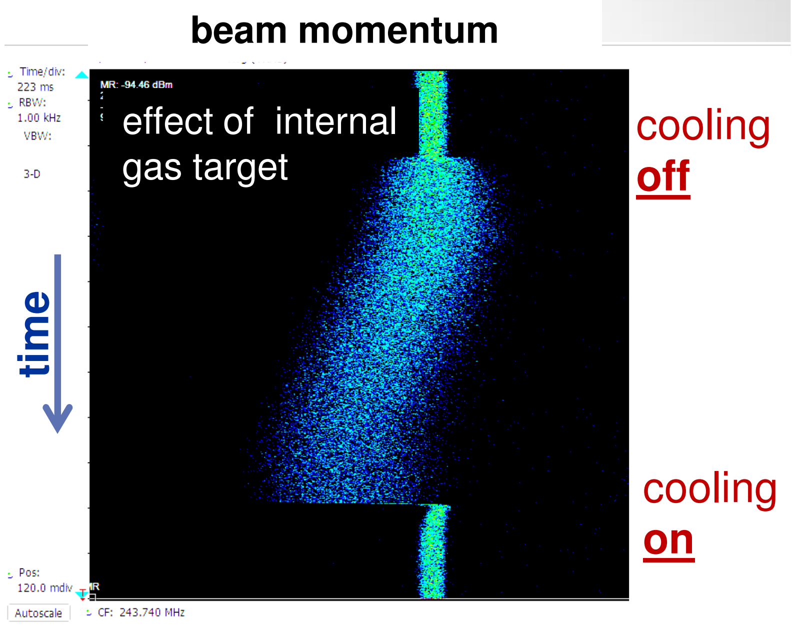
(e.g. a beam of energy 100 GeV can have a temperature of 1 eV)

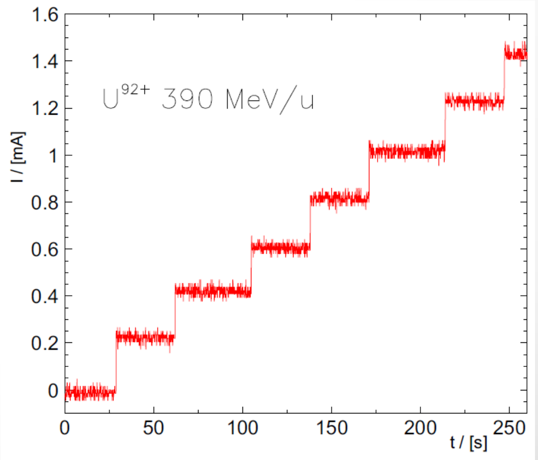
Benefits of Beam Cooling

- Improved beam quality
  - Precision experiments
  - Luminosity increase

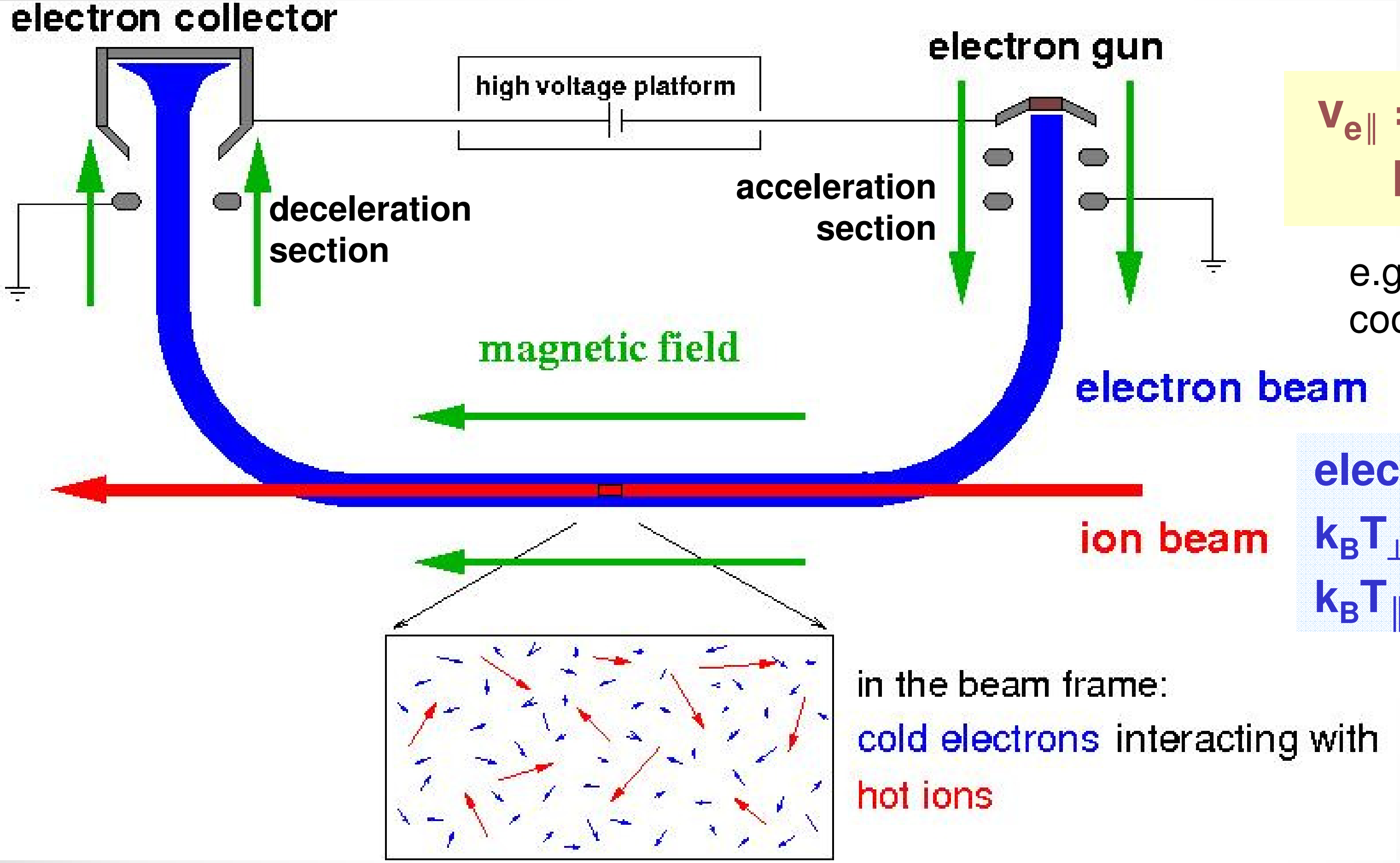
- Compensation of heating
  - Experiments with internal target
  - Colliding beams

- Intensity increase by accumulation
  - Weak beams from the source can be enhanced
  - Secondary beams (antiprotons, rare isotopes)





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

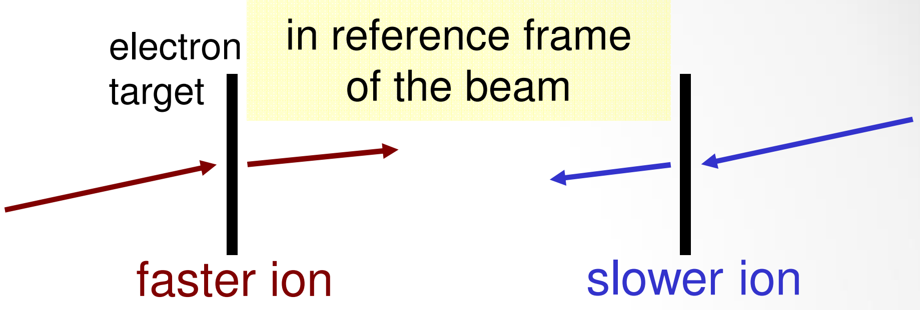
superposition of a cold intense electron beam with the same velocity

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

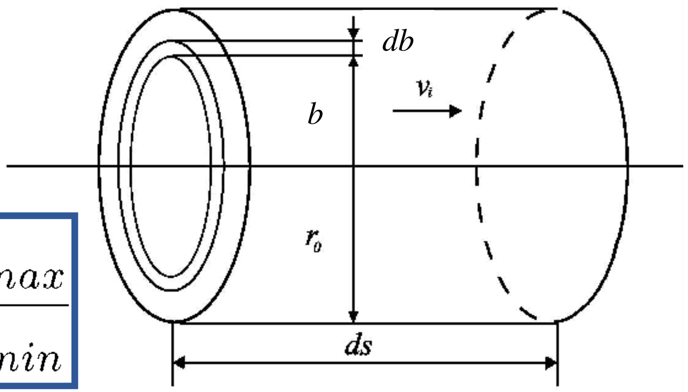
Energy transfer: $$\Delta E(b) = \frac{(\Delta p)^2}{2m_e} \simeq \frac{2Q^2e^4}{(4\pi\epsilon_0)^2 m_e v^2}\frac{1}{b^2} \quad (for\ \ b \gg b_{min})$$

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

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

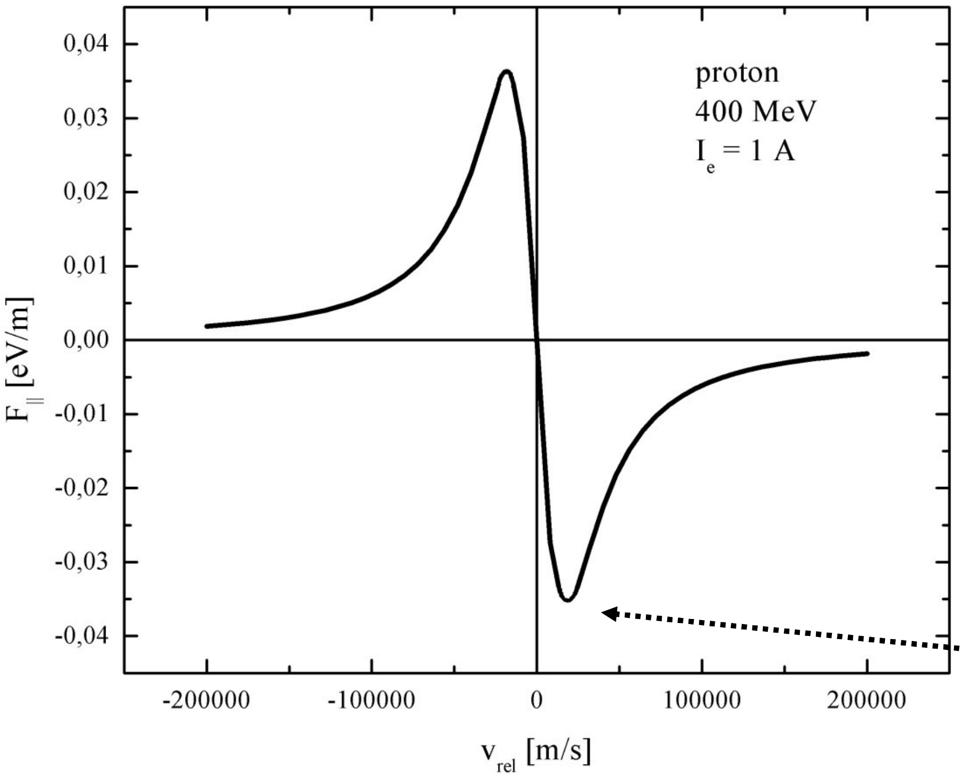
$$\vec{v}_{rel} = \vec{v_i} - \vec{v_e}$$

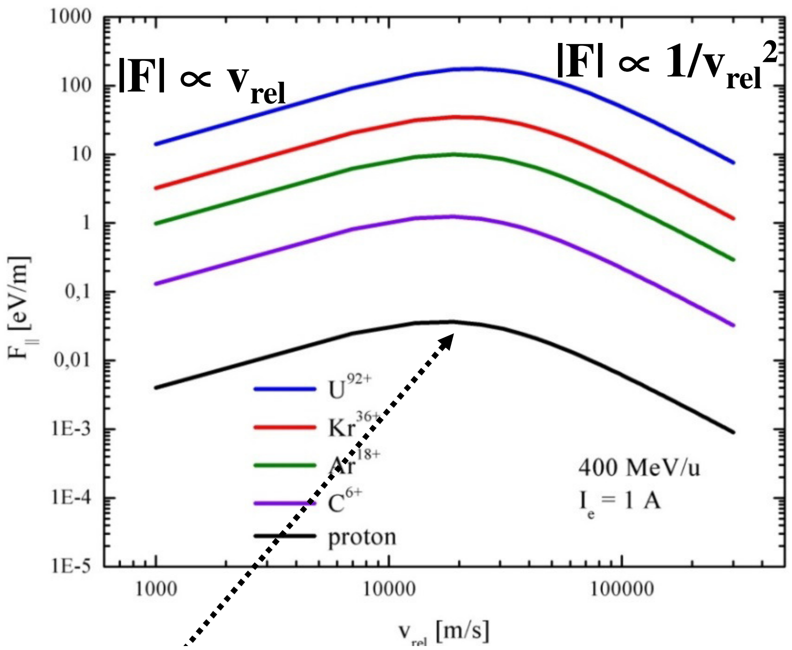
cooling force F

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

Models of the Electron Cooling Force

- binary collision model

description of the cooling process by successive collisions of two particles and integration over all interactions
analytic expressions become very involved, various regimes
(multitude of Coulomb logarithms)

- dielectric model

interaction of the ion with a continuous electron plasma
(scattering off of plasma waves)
fails for small relative velocities and high ion charge

- an empiric formula (Parkhomchuk) derived from experiments:

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

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

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

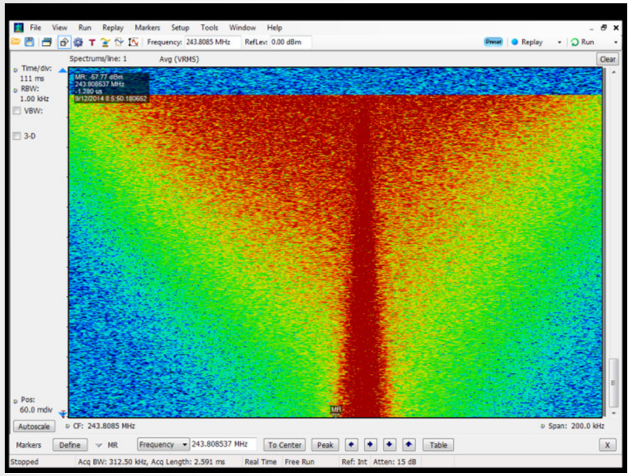
$F \propto v_{rel} \Rightarrow \tau = \Delta t = p_{rel}/F = \text{constant}$

Longitudinal Cooling

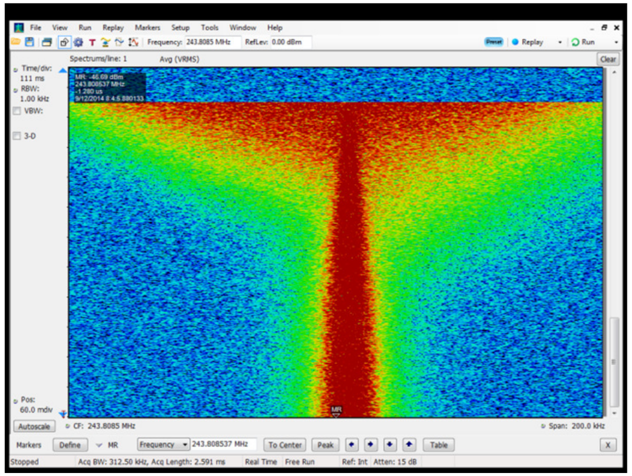
Xe^{54+} 350 MeV/u

measurement time **20 s**

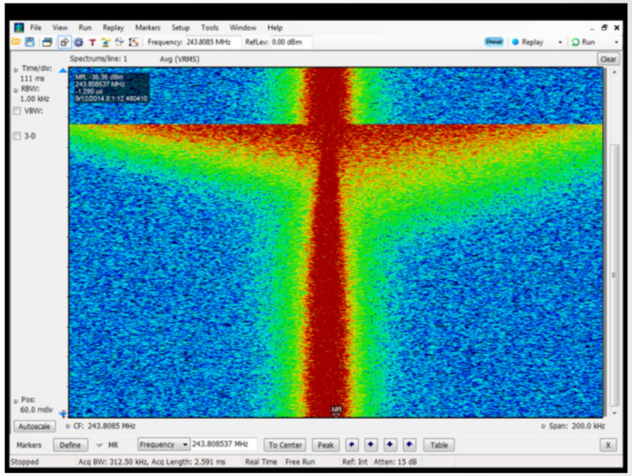
I_e= 100 mA



I_e= 250 mA



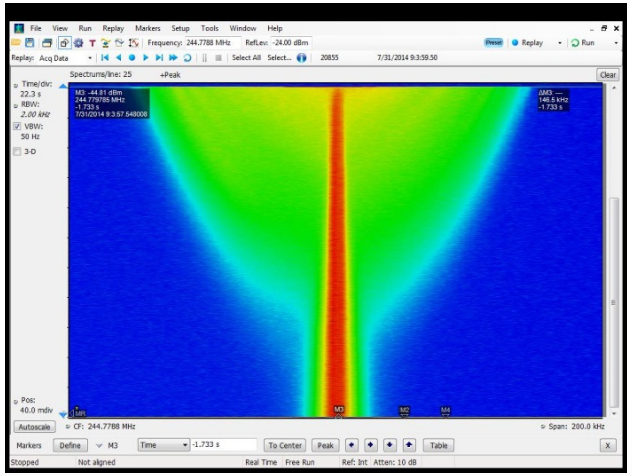
I_e= 500 mA



protons 400 MeV (Q=1)

measurement time **650 s**

I_e= 250 mA



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

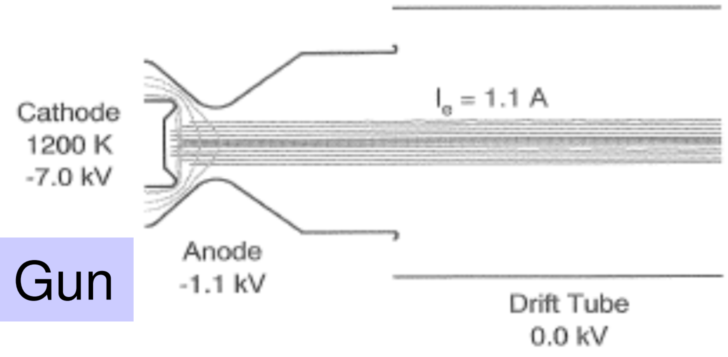
lower limit : $k_BT_\parallel \geq 2e\frac{n_e^{1/3}}{4\pi\epsilon_0}$

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**

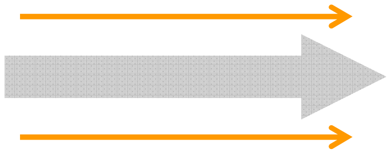
Electron Beam Properties

constant electron beam radius

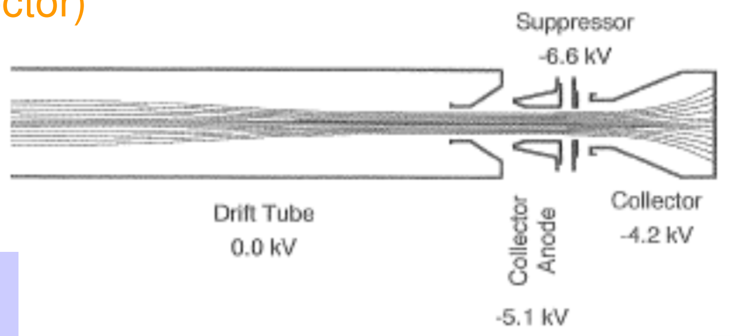


Gun

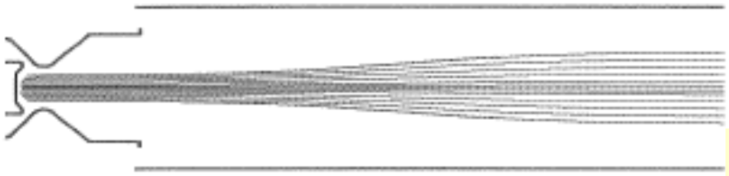
electron beam confined by longitudinal magnetic field (from gun to collector)



Collector

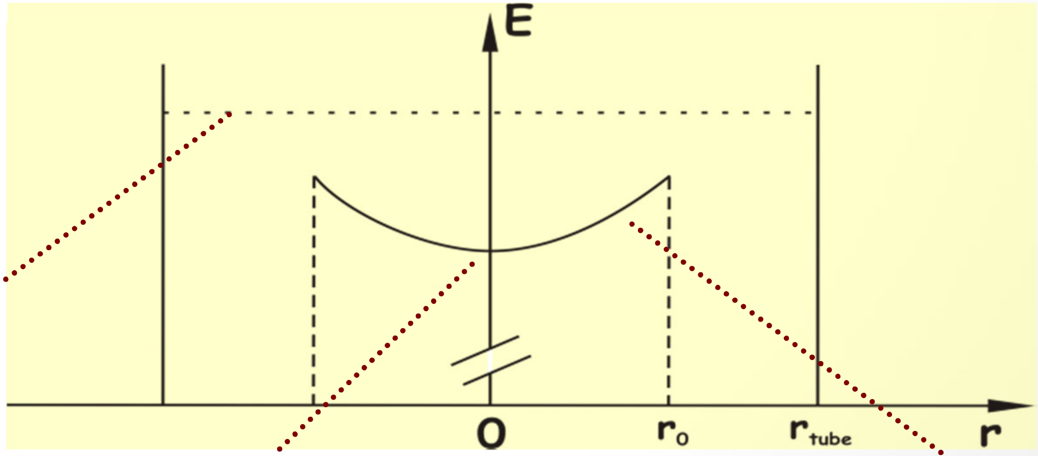


Cooling Section



transversely expanded electron beam

radial variation of electron energy due to space charge

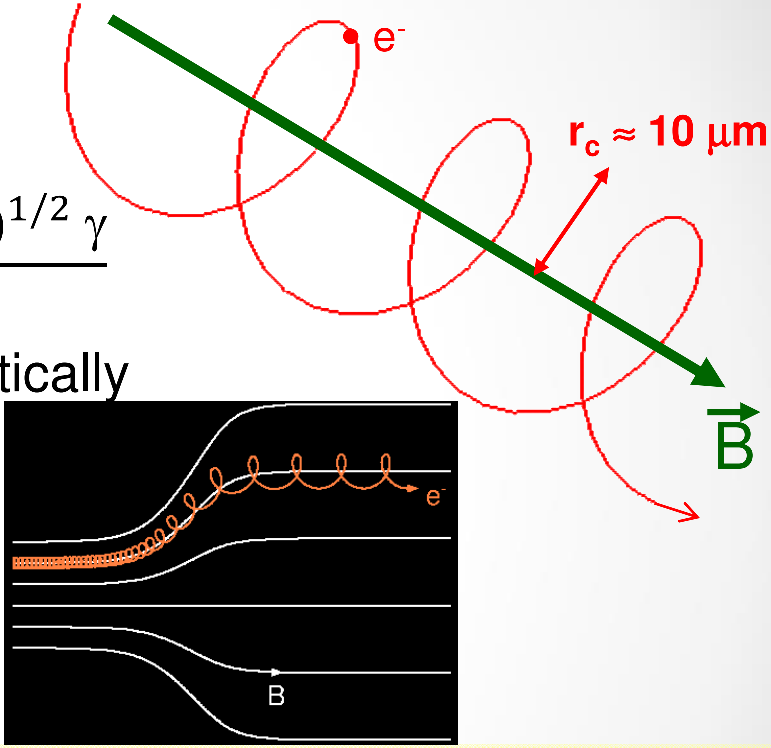


electron current
(space charge limited)

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

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

Electron Motion in Longitudinal Magnetic Field



single particle cyclotron motion

cyclotron frequency $\omega_c = \dfrac{eB}{\gamma me}$

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

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

Some Technical Aspects of Electron Cooling Systems

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

high electron current: up to a few Amperes

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

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

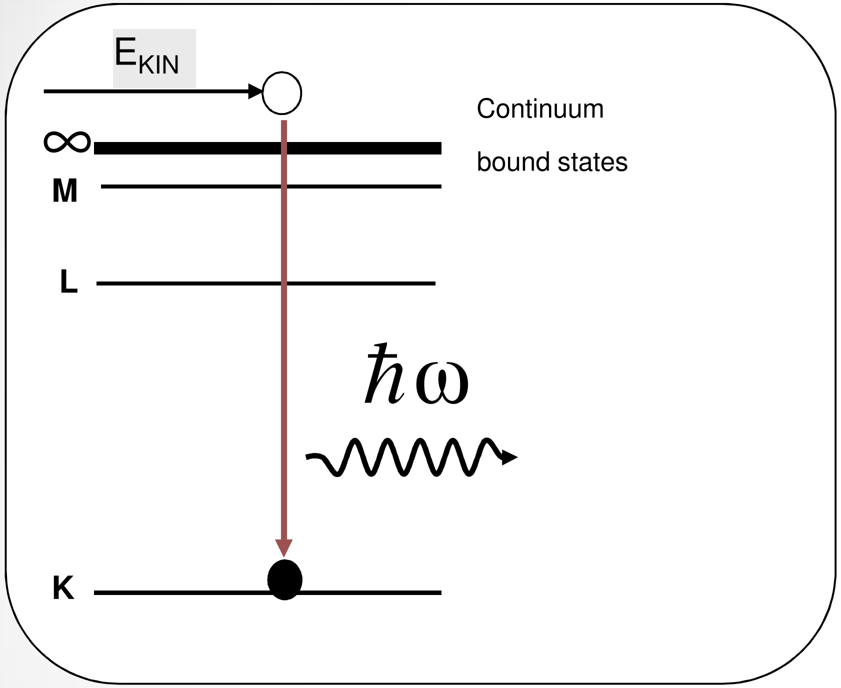
continuous longitudinal magnetic field from electron gun to collector

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

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)

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
$\Rightarrow$ different orbit

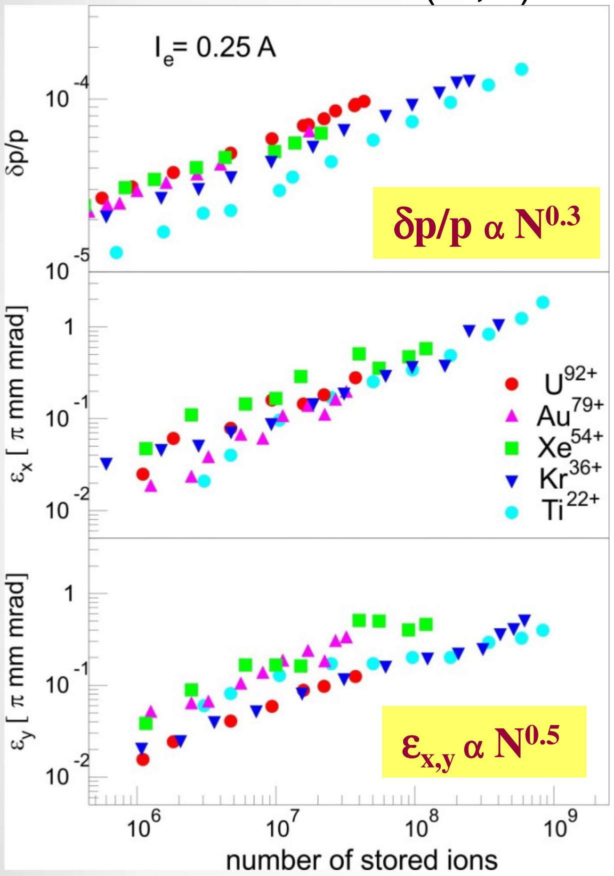
loss rate $\tau^{-1} = \gamma^2 \alpha_{REC} n_e \eta$

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

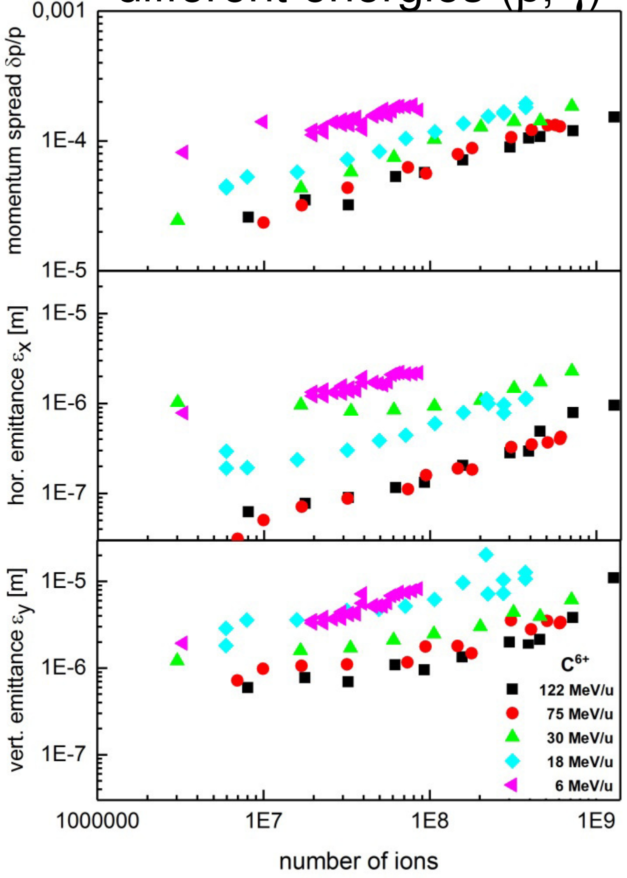
losses by recombination (REC)

Electron Cooled Beams in Equilibrium with Intrabeam Scattering (IBS)

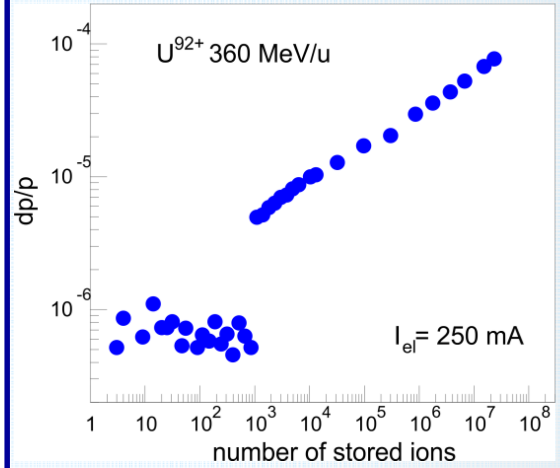
different ions (Q,A)



different energies (β, γ)



suppression of IBS for low intensity (N≤1000)



Beam ordering (crystallization)

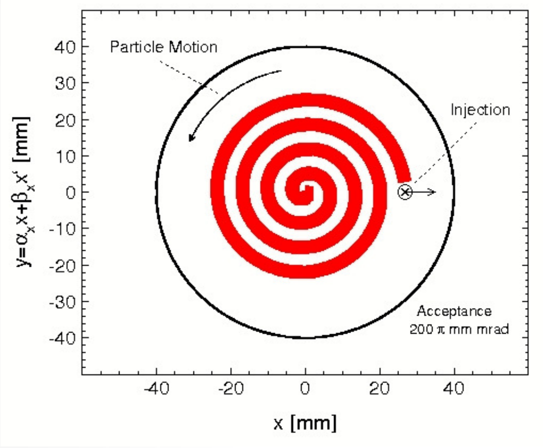
heating rate dominated by Intrabeam Scattering

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

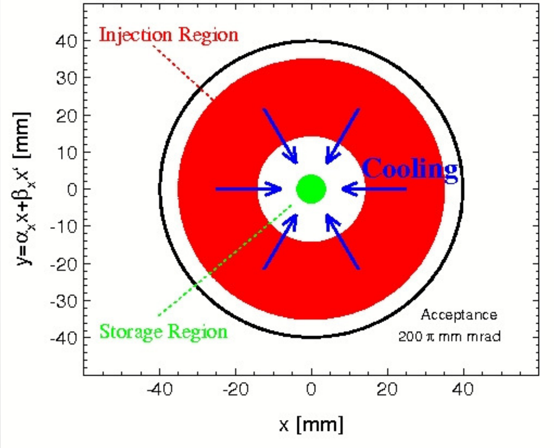
IBS: total phase space volume increases with ion beam intensity and ion charge

Accumulation of Heavy Ions by Electron Cooling

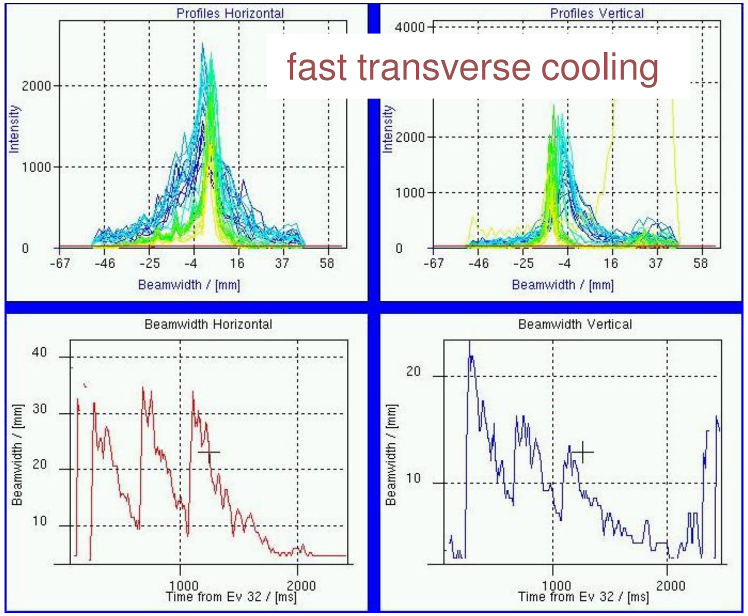
standard multiturn injection



fast accumulation by repeated multiturn injection with electron cooling



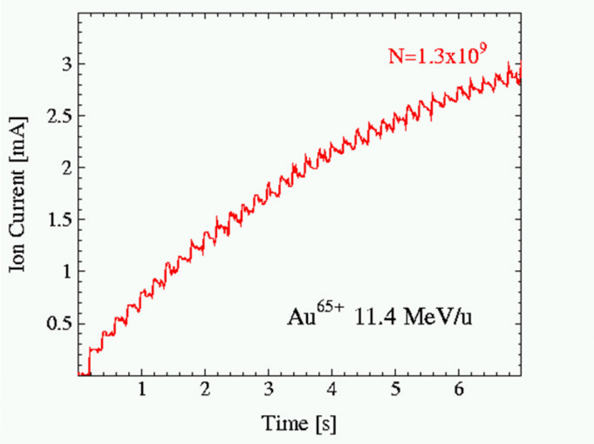
horizontal **vertical**



fast transverse cooling

profile

beam size



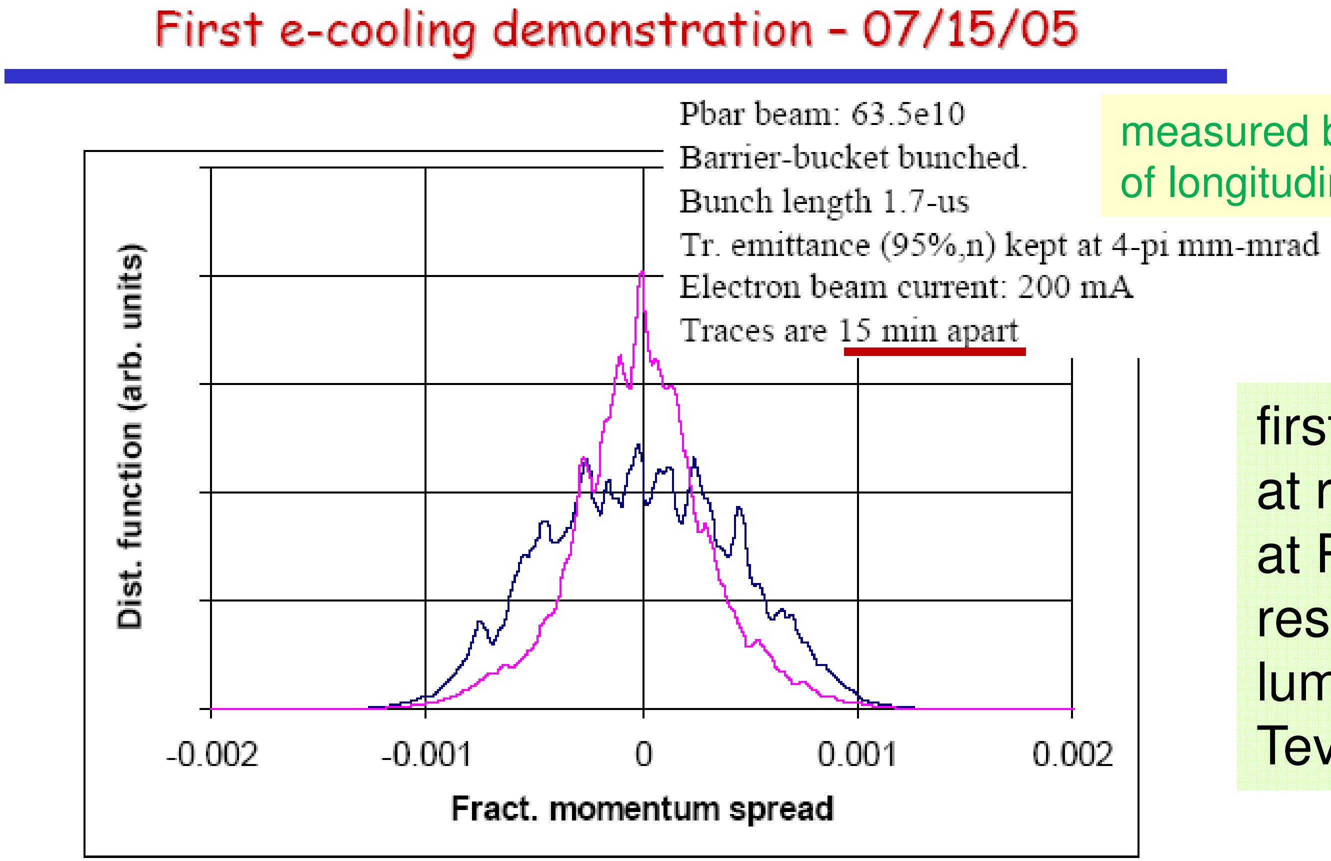
intensity increase in 5 s by a factor of ≈ 10

limitations:
space charge tune shift,
recombination (REC)

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

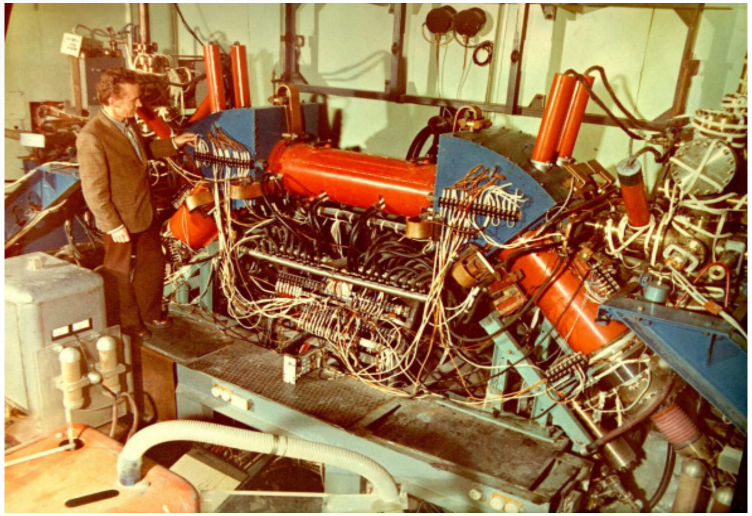
measured by detection
of longitudinal Schottky noise

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

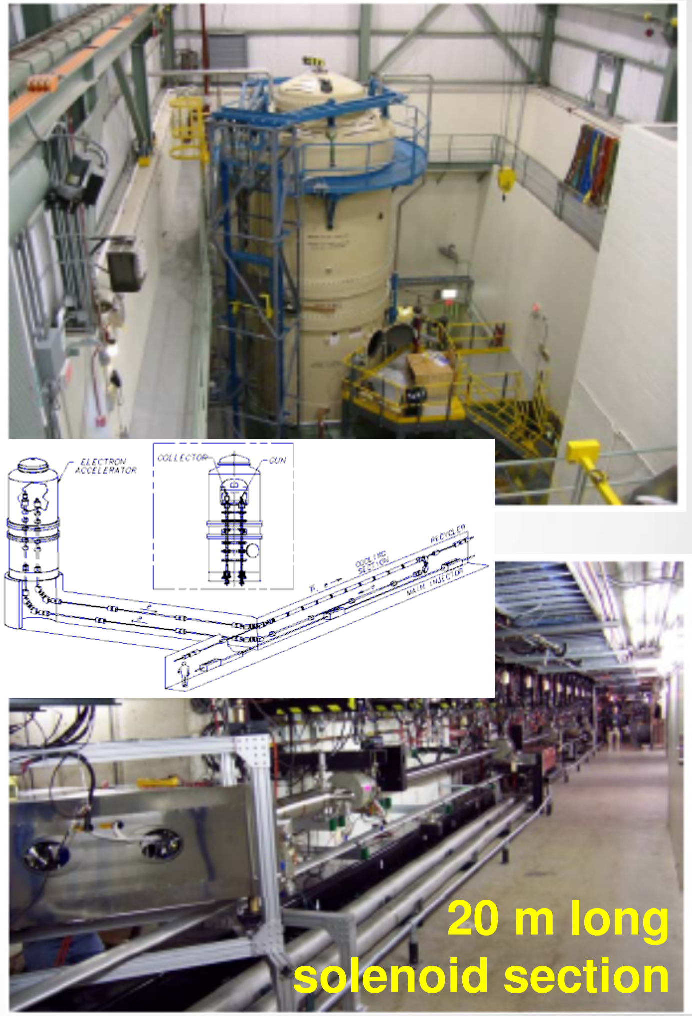
cooling time of some ten minutes has to be compared with the accumulation time of many hours

Electron Cooling Systems

First Electron
Cooling System
NAP-M/BINP
1974



High Energy:
4.3 MeV Recycler/FNAL
2005

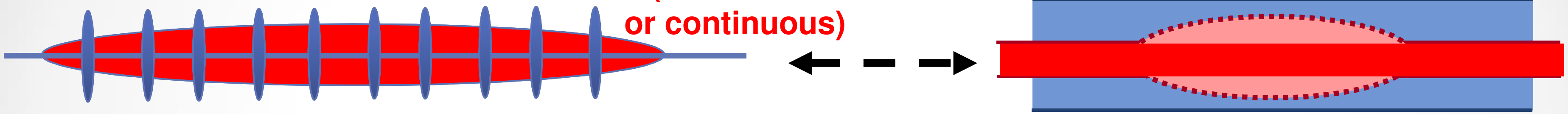


20 m long
solenoid section

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 to increase the electron energy).



new scheme

ion bunch (some ten ns or continuous)

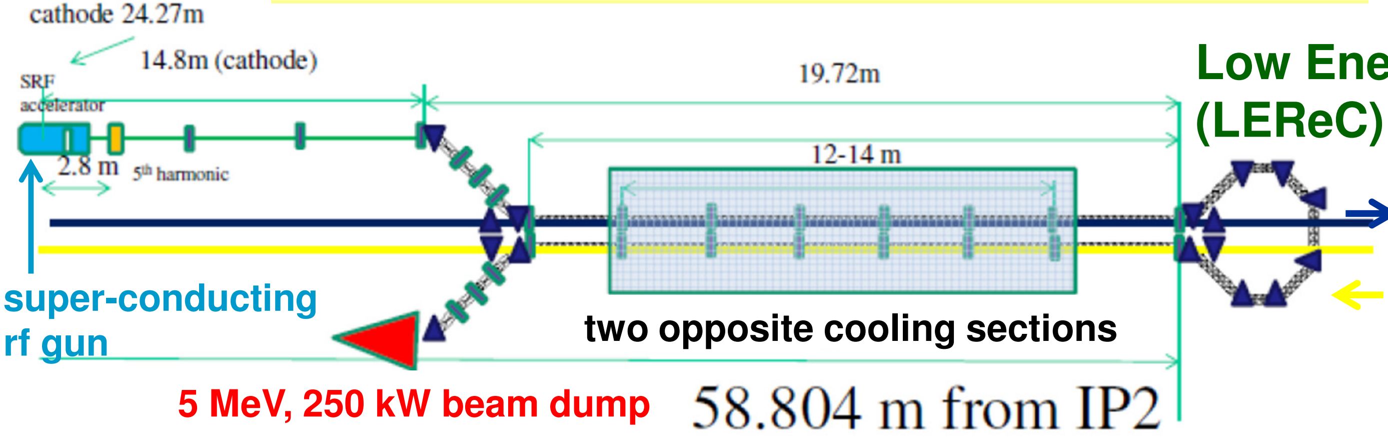
electron bunches (some ns)

traditional

continuous electron beam

continuous (or bunched) ion beam

issues:
- high intensity 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

super-conducting rf gun

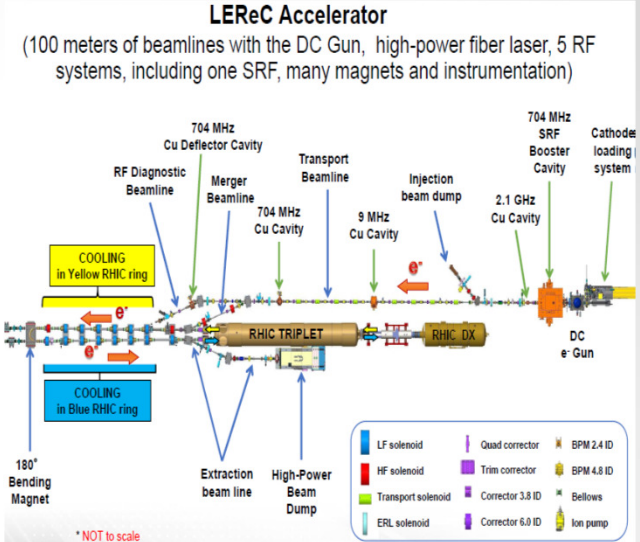
two opposite cooling sections

5 MeV, 250 kW beam dump

two counter-propagating ion beams

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.

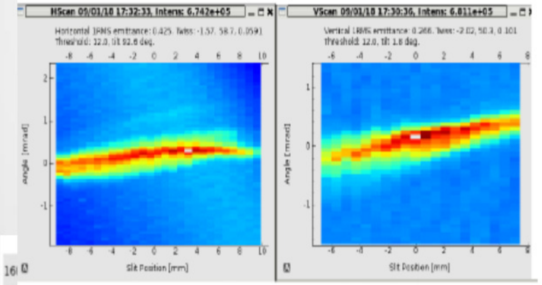

LEReC Accelerator

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

* NOT to scale

RMS normalized emittance in Yellow cooling section

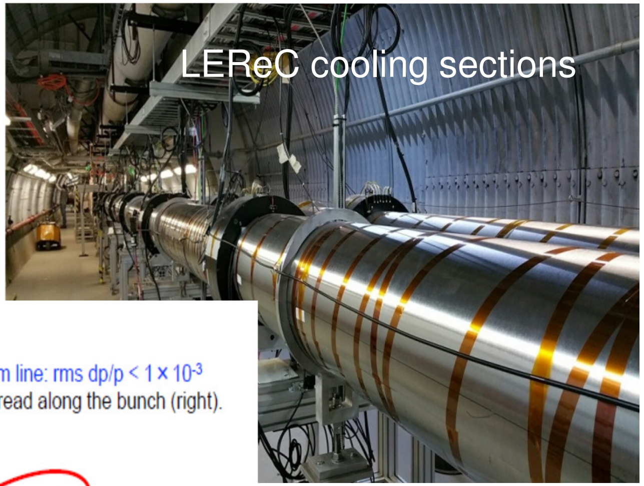
Hor = 1.7 µm; Ver = 1.1 µm


HScan 09/01/18 17:32:33, Intens: 6.742e+05

Horizontal 1RMS emittance: 0.425, Twiss: -1.57, 58.7, 0.0591
Threshold: 12.0, tilt 92.6 deg.

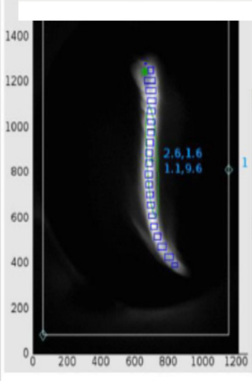
VScan 09/01/18 17:30:36, Intens: 6.811e+05

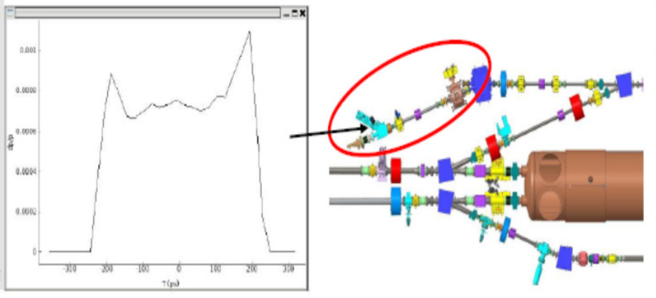
Vertical 1RMS emittance: 0.266, Twiss: -2.02, 50.3, 0.101
threshold 12.0, tilt 1.8 deg.


LEReC cooling sections

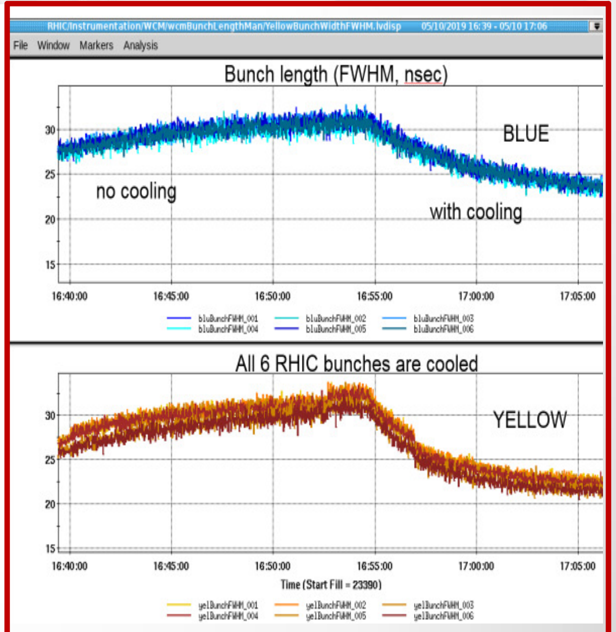
RMS momentum spread in RF diagnostics beam line: rms dp/p < 1 × 10^{-3}

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





A. Fedotov et al.


RHIC/Instrumentation/WCM/wcmBunchLengthMan/YellowBunchWidthFWHM.lvdisp 05/10/2019 16:39 - 05/10 17:06

demonstration of cooling

Electron Cooling Systems

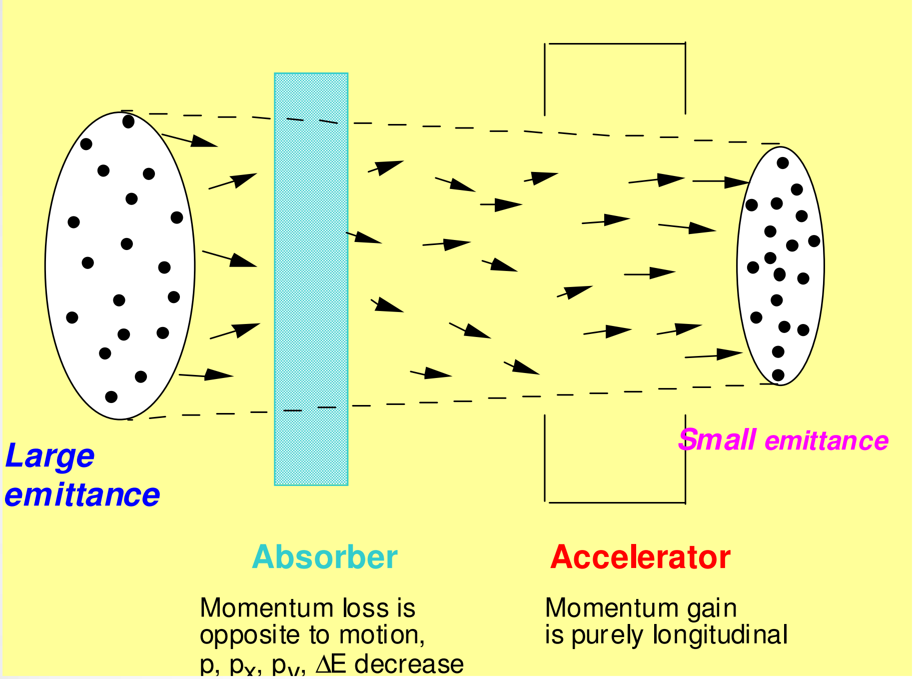
NAP-M, Novosibirsk, Russia, 1974
ICE-Ring, CERN, Switzerland, 1979
Test Ring, Fermilab, Chicago, USA, 1980
LEAR, CERN, Switzerland, 1987
IUCF Cooler, Bloomington, Indiana, 1988
TSR, Heidelberg 1988 and 2004
TARN II, Tokyo, Japan, 1989
CELSIUS, Uppsala, Sweden, 1989
ESR, GSI Darmstadt Germany, 1990
ASTRID, Aarhus, Denmark, 1992
CRYRING, Stockholm, Sweden, 1992, now at GSI
COSY, Jülich, 1993 and 2013
SIS18, GSI Darmstadt, 1998
Antiproton Decelerator (AD), CERN, Switzerland, 1998
HIMAC, Chiba, Japan, 2000
LEIR, CERN, Switzerland, 2005
Recycler, Fermilab, Chicago, USA, 2005
S-LSR, Kyoto, Japan, 2005
CSRm, IMP Lanzhou, China, 2005
CSRe, IMP Lanzhou, China, 2008
ELENA, CERN, Switzerland, 2018
LEReC, BNL, Brookhaven, USA, 2019

decommissioned

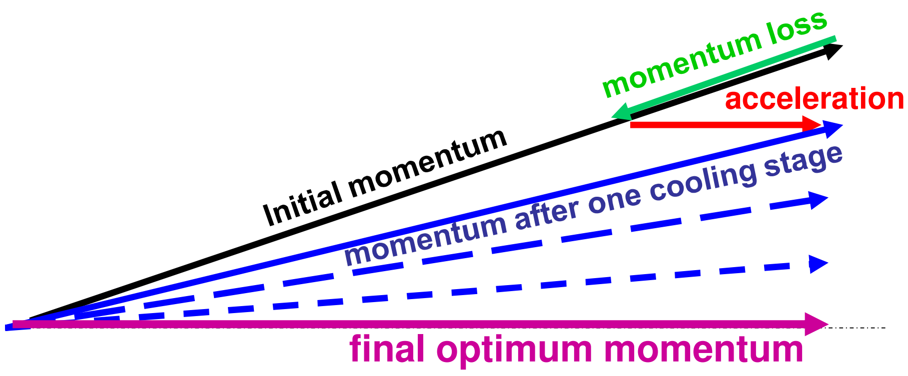
in operation

2. Ionization Cooling

energy loss in solid matter



proposed for muon cooling



not useful for heavy particles due to strong interaction with matter

transverse cooling

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

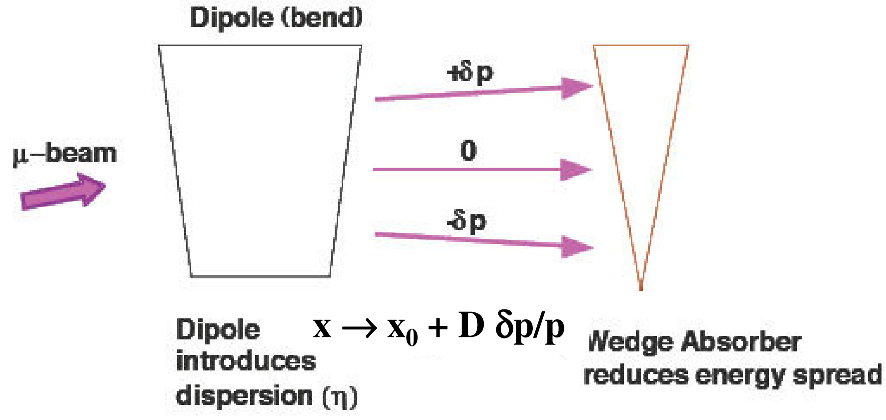
$$= -\frac{1}{\beta^2 E}\frac{dE}{ds}\epsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

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

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

Ionization Cooling

increased longitudinal cooling by longitudinal-transverse emittance exchange



Dipole introduces dispersion (η) $x \rightarrow x_0 + D\,\delta p/p$

Wedge Absorber reduces energy spread

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

cooling term heating term

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

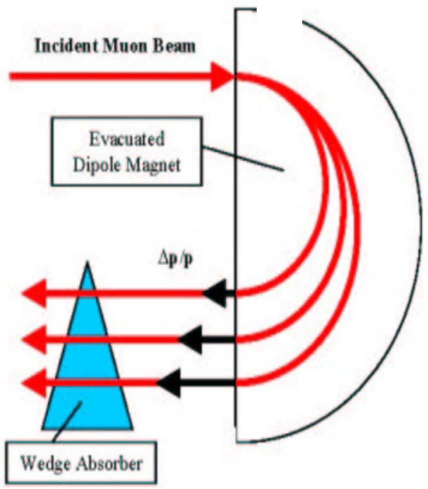


Figure 1. Use of a Wedge Absorber for Emittance Exchange

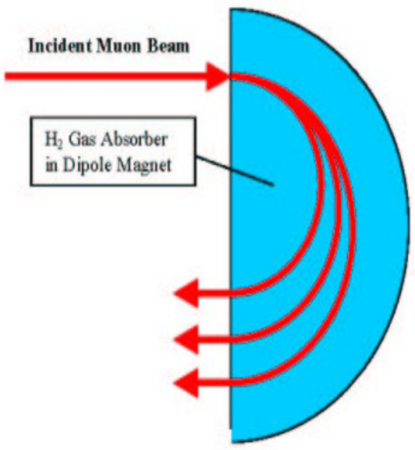


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

emittance exchange

increased longitudinal cooling

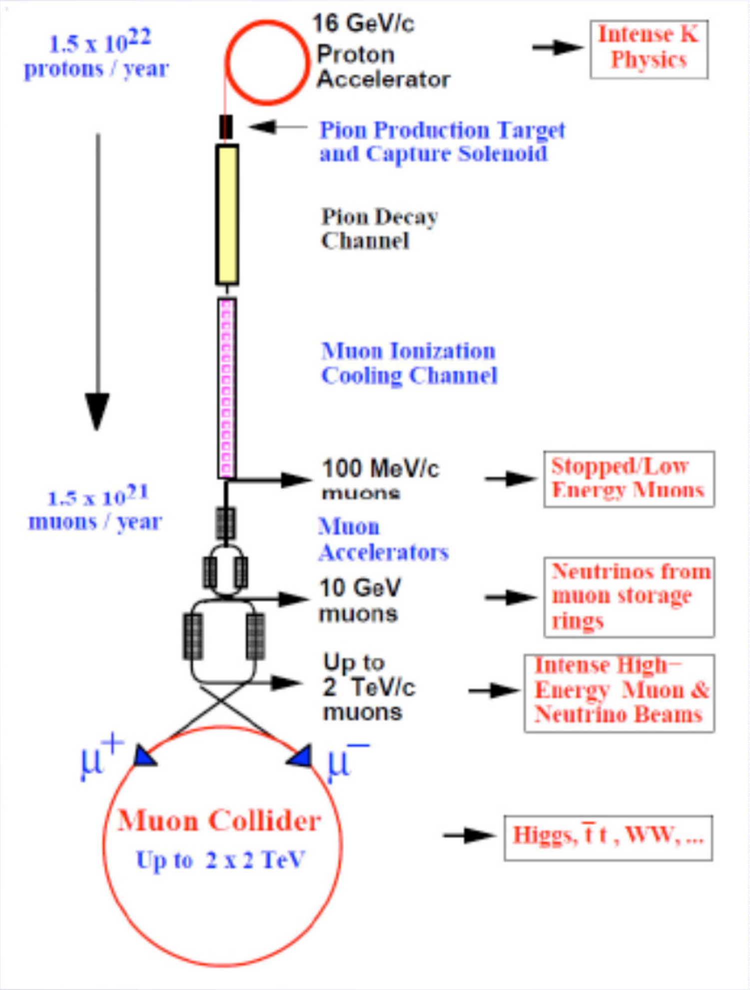
$$\frac{\partial \frac{dE}{ds}}{\partial E} \Rightarrow \frac{\partial \frac{dE}{ds}}{\partial E}\Big|_0 + \frac{dE}{ds}\frac{D\rho'}{\beta c p \rho_0}$$

reduced transverse cooling

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

Scenarios with Ionization Cooling

Muon Collider



1.5×10^{22} protons / year

16 GeV/c Proton Accelerator → Intense K Physics

Pion Production Target and Capture Solenoid

Pion Decay Channel

Muon Ionization Cooling Channel

100 MeV/c muons → Stopped/Low Energy Muons

1.5×10^{21} muons / year

Muon Accelerators

10 GeV muons → Neutrinos from muon storage rings

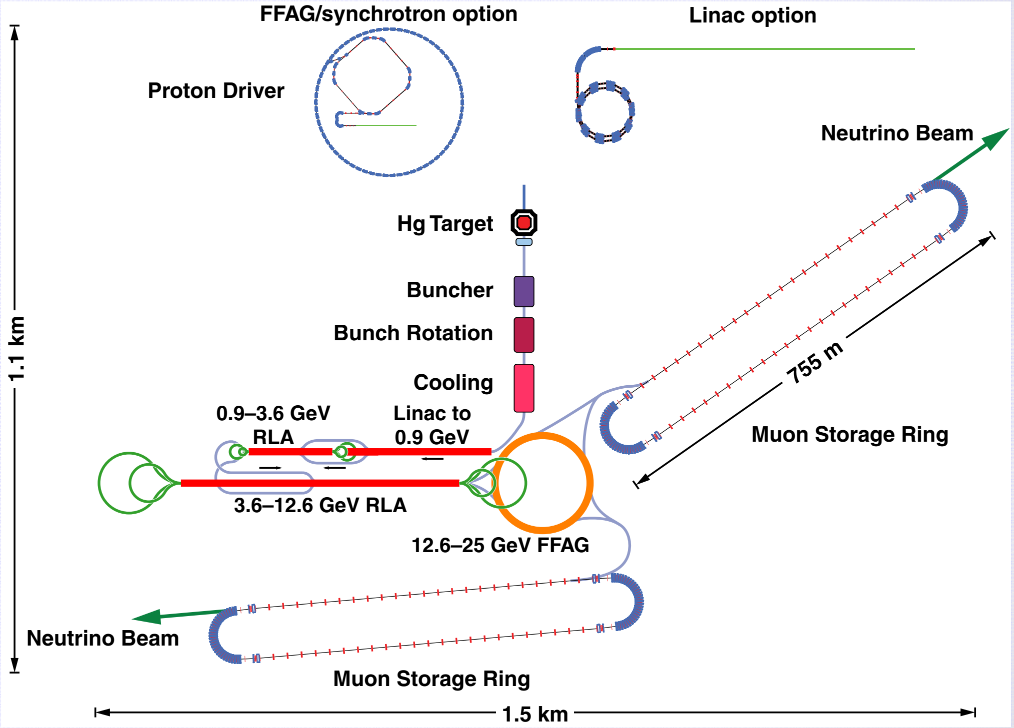
Up to 2 TeV/c muons → Intense High–Energy Muon & Neutrino Beams

μ^+ μ^-

Muon Collider

Up to 2 x 2 TeV → Higgs, $\bar{t}t$, WW, ...

Neutrino Factory



FFAG/synchrotron option

Linac option

Proton Driver

Neutrino Beam

Hg Target

Buncher

Bunch Rotation

Cooling

1.1 km

755 m

0.9–3.6 GeV RLA

Linac to 0.9 GeV

Muon Storage Ring

3.6–12.6 GeV RLA

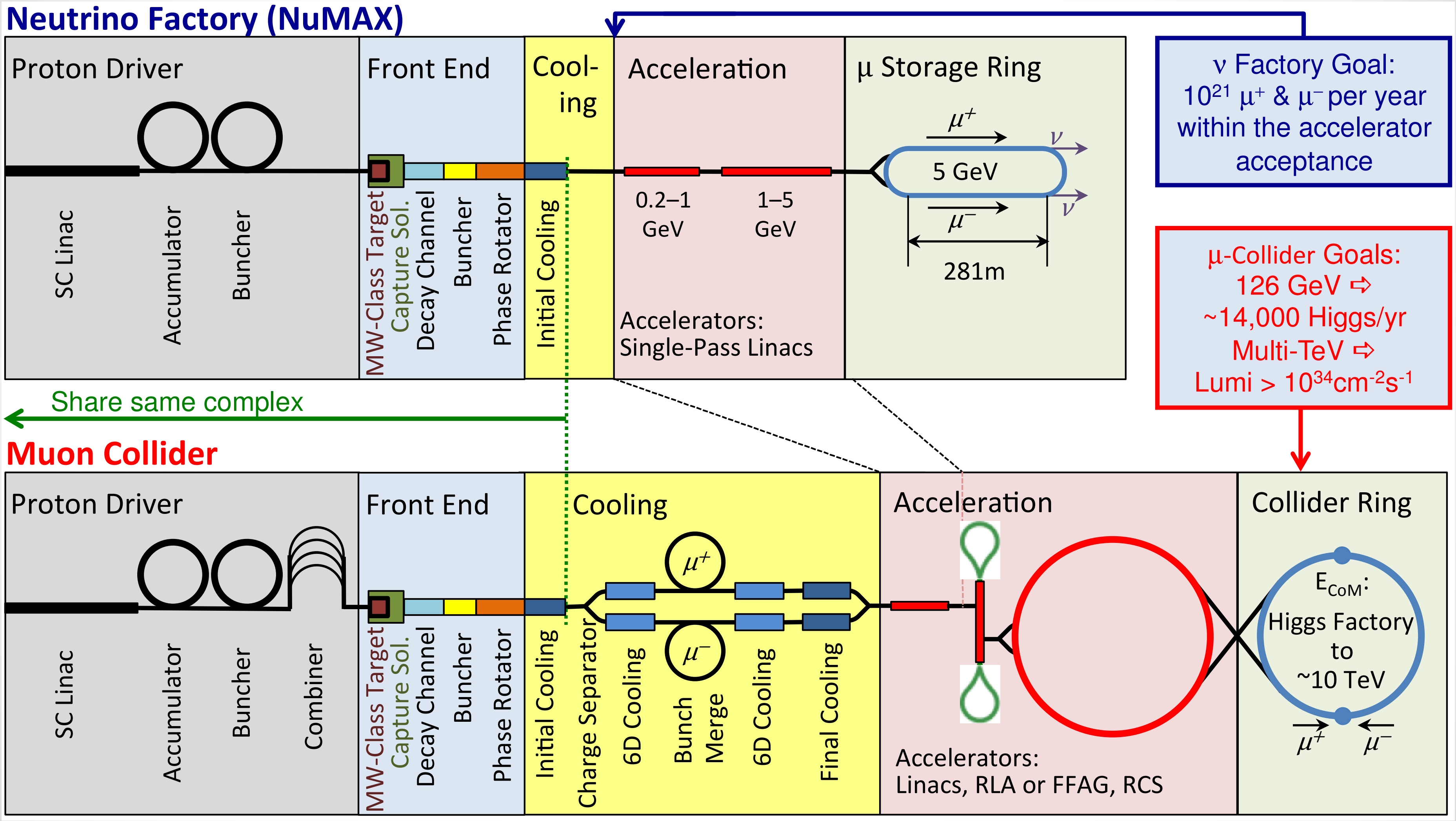
12.6–25 GeV FFAG

Neutrino Beam

Muon Storage Ring

1.5 km

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}

Muon Collider

The Muon Cooling Section

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

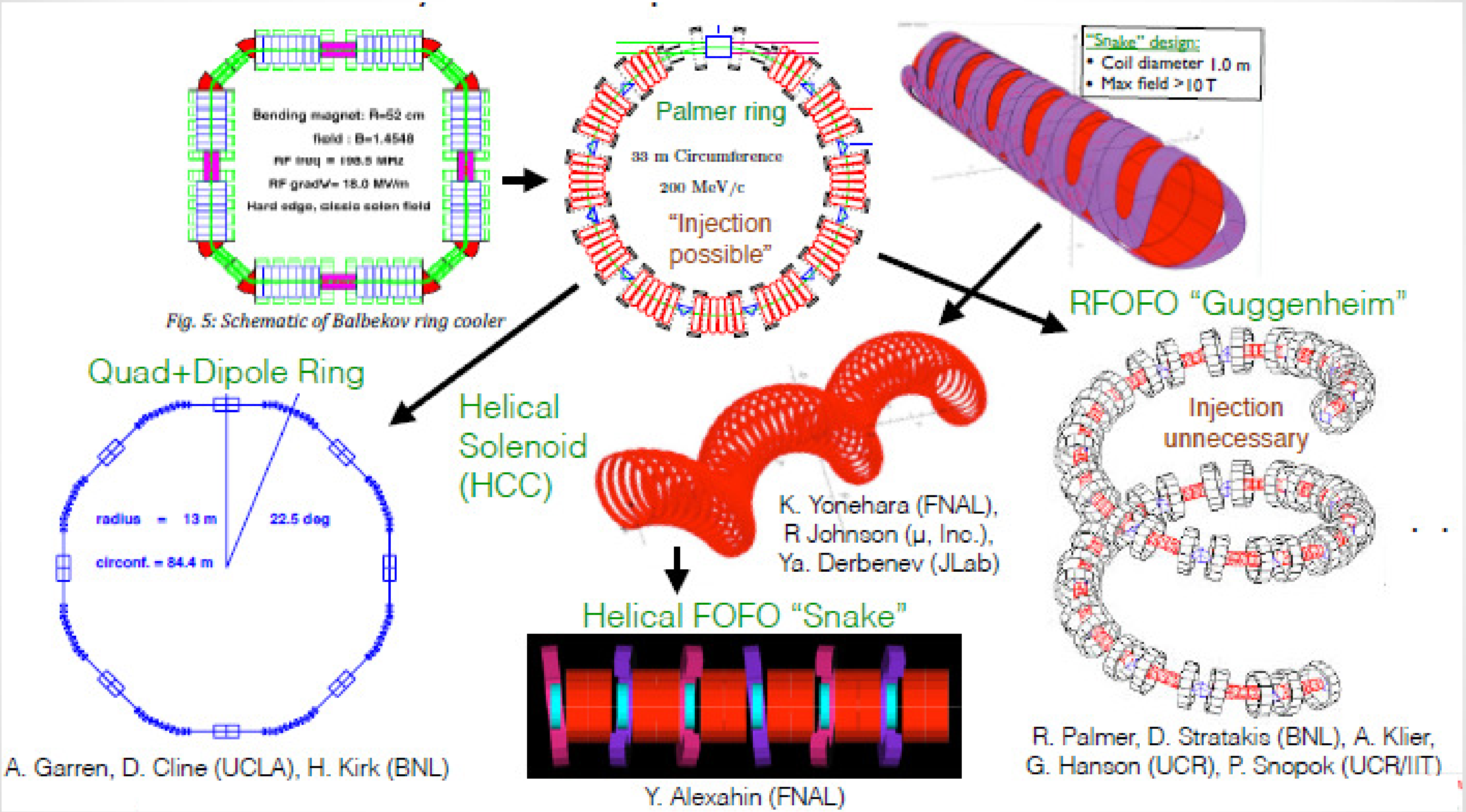


Fig. 5: Schematic of Balbekov ring cooler

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

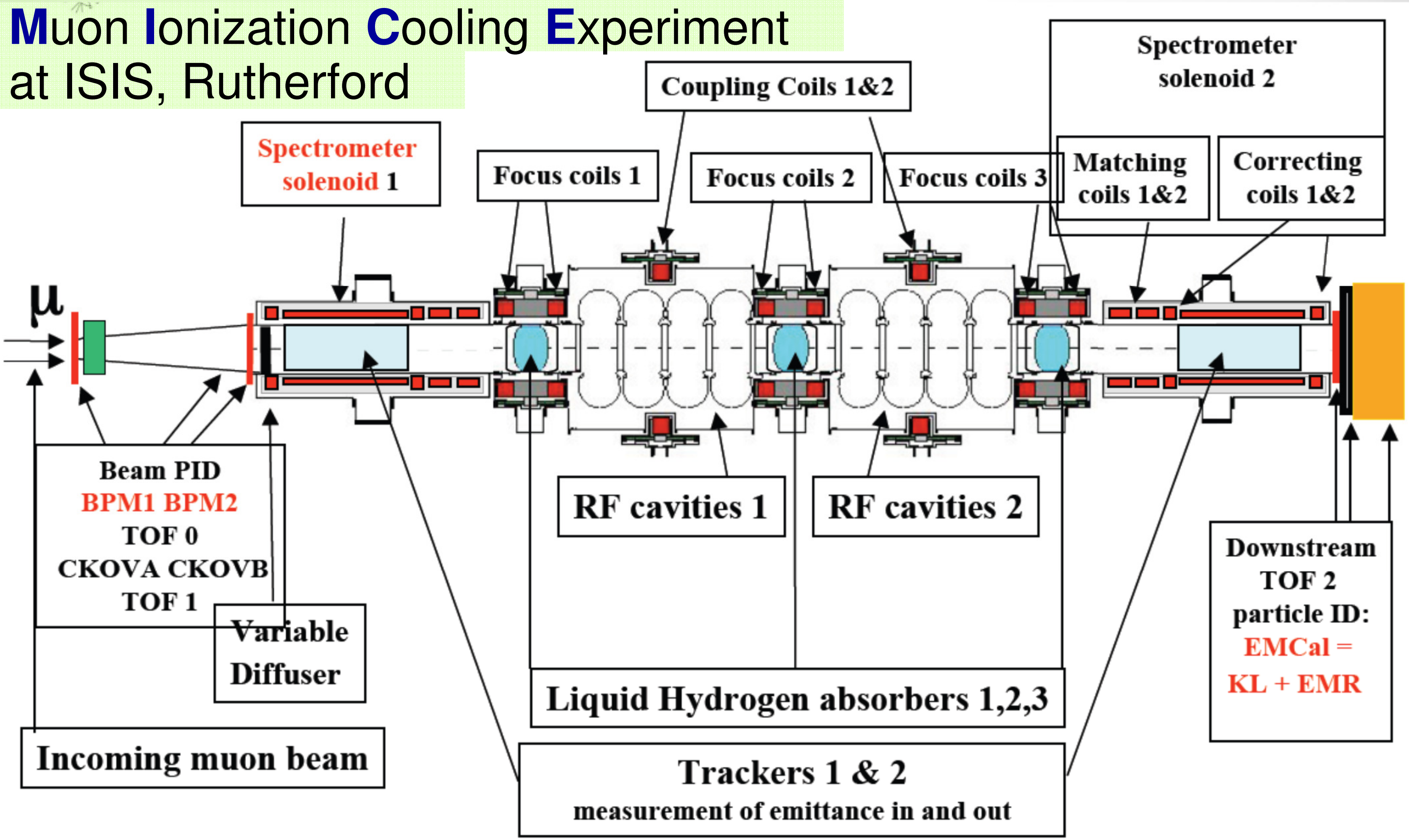
K. Yonehara (FNAL), R Johnson (μ, Inc.), Ya. Derbenev (JLab)

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 1

Focus coils 1

Coupling Coils 1&2

Focus coils 2

Focus coils 3

Spectrometer solenoid 2

Matching coils 1&2

Correcting coils 1&2

Beam PID
BPM1 BPM2
TOF 0
CKOVA CKOVB
TOF 1

Variable Diffuser

Incoming muon beam

RF cavities 1

RF cavities 2

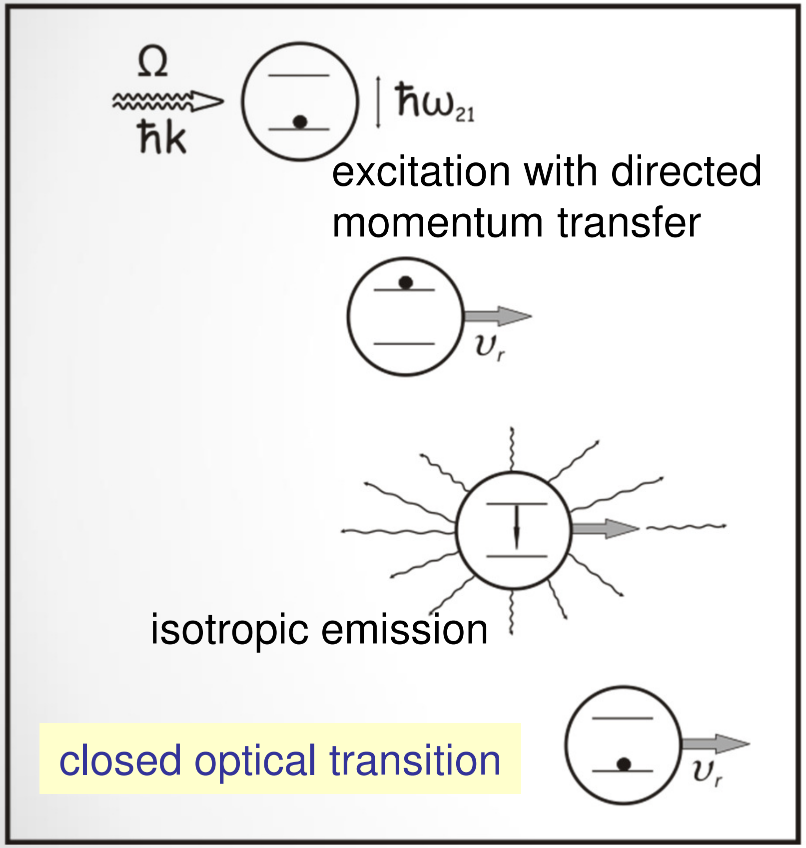
Liquid Hydrogen absorbers 1,2,3

Trackers 1 & 2
measurement of emittance in and out

Downstream
TOF 2
particle ID:
EMCal =
KL + EMR

3. Laser Cooling

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

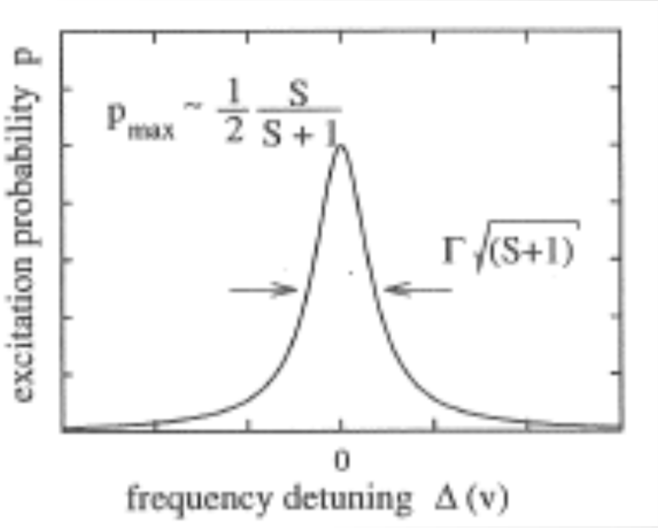


excitation with directed momentum transfer

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

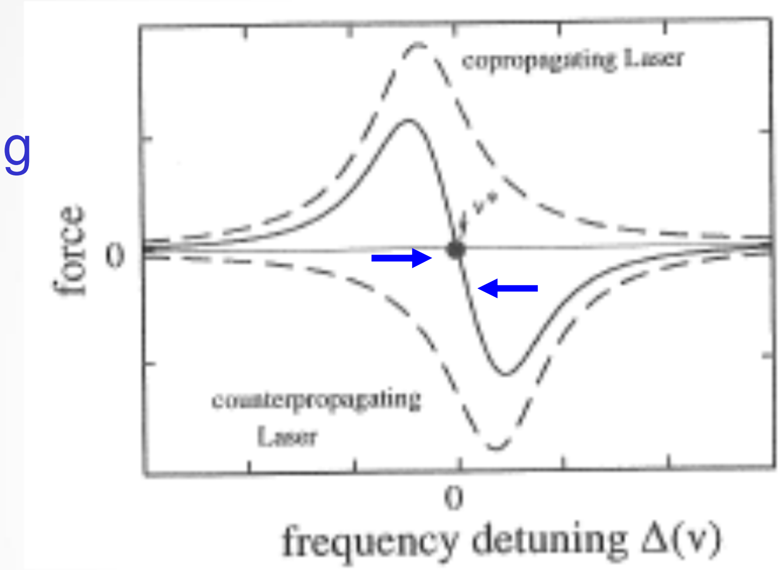
typical cooling time ~ 10 µs

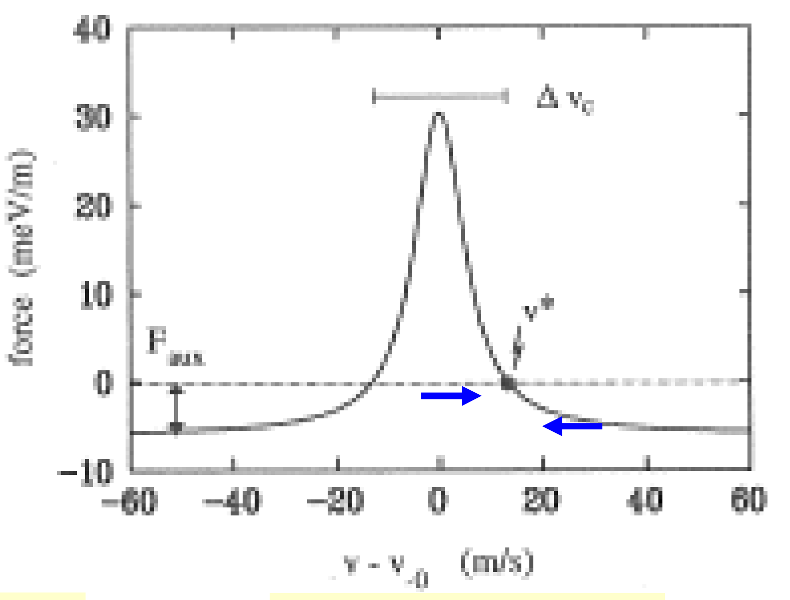
drawback: only longitudinal cooling

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)

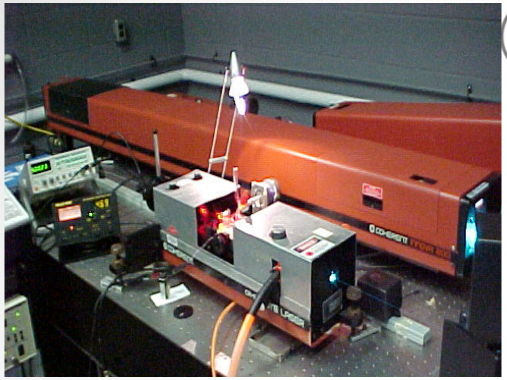
auxiliary force
(betatron core, rf)

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

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

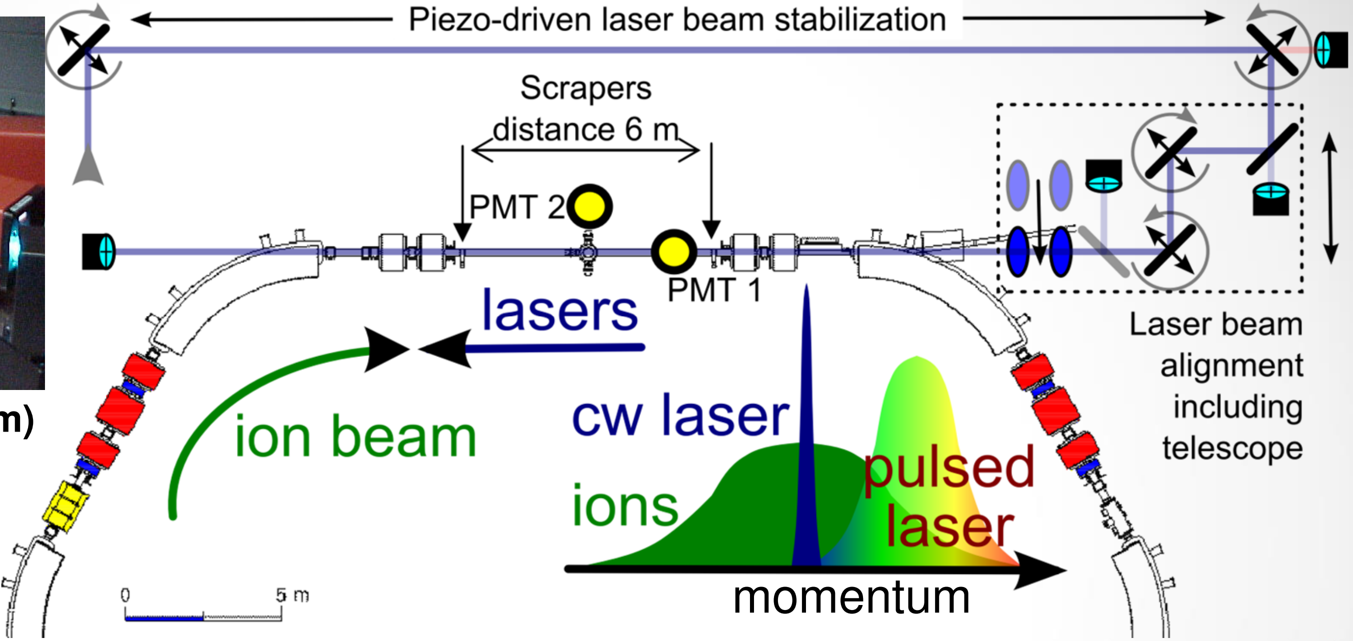
in future: study of Li-like heavy ions at relativistic energies,
cooling rate increases with γ
large relativistic energy ⇒ large excitation energy in PRF

Laser Cooling of C^{3+}



Argon ion laser (257.3 nm) frequency doubled

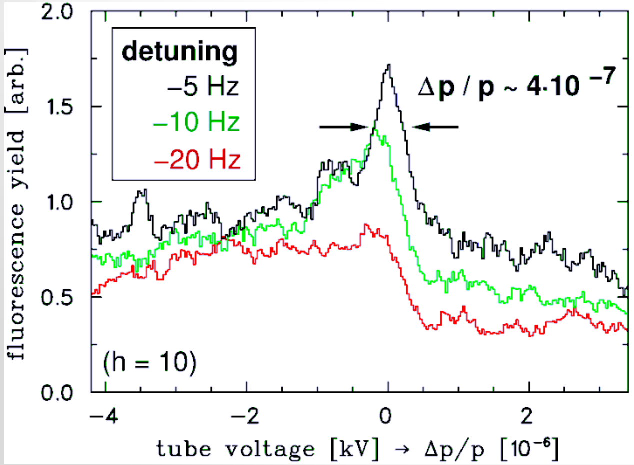
ESR storage ring



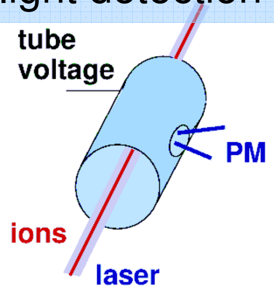
Piezo-driven laser beam stabilization

Scrapers distance 6 m

Laser beam alignment including telescope



fluorescence light detection



probing the velocity distribution