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Introduction to electron cooling

2. September 2015 | Vsevolod Kamerdzhiev, Forschungszentrum Jülich, IKP-4, COSY

Belgian Dutch German graduate school in particle physics 2015

Outline

- Idea and Motivation
- Electron beam properties
    - Temperature
    - Electron motion in longitudinal magnetic field
- Cooling force and cooling time
- Generation of electron beam
    - Electron guns
    - E-beam transport
- Applications and limitations
- Beam diagnostics
- Comparison with other beam cooling methods (stochastic, ionization and laser cooling)
- History and existing facilities
- Recent developments in high energy EC, experimental results
- Summary

Why beam cooling

What it does

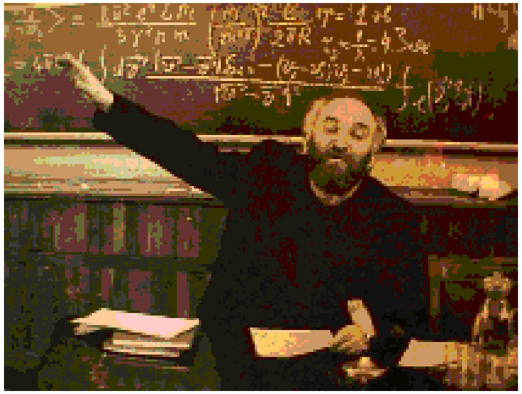
- Reduces beam emittance $\Rightarrow$ transverse beam size and divergence
- Reduces momentum spread

Applications

- Compensation of various heating effects acting on a circulating beam (mismatch, space charge, intra-beam scattering, internal targets, residual gas, external noise)
  - Compensate or reduce momentum spread growth ⇨ better energy resolution
  - Compensate or reduce emittance blow up ⇨ higher luminosity for experiments
  - Makes beam accumulation possible (stacking) ⇨ higher luminosity for experiments

Also see: Hans Stockhorst, slide 2, 6 and Mei Bai, slides 27-28

Idea of electron cooling



G.I. Budker is discussing electron cooling

Electron cooling was proposed by G.I.Budker in 1965 as a method for preparing of the beams for a hadron collider. The electron beam moving with the same average velocity as proton beam absorbs the kinetic energy of heavy particles (protons or ions).

AN EFFECTIVE METHOD OF DAMPING PARTICLE OSCILLATIONS IN PROTON AND ANTIPROTON STORAGE RINGS

A method is proposed for the damping of synchrotron and betatron oscillations of heavy particles, which makes use of the sharp increase in the cross section for the interaction of these particles with electrons at small relative velocity. It is shown that it is possible by this method to compress strongly the proton and antiproton bunches in storage rings, and also to achieve multiple storage of these particles.

Budker, G. I. (1967), *Soviet Atomic Energy* **22** (5): 438–440

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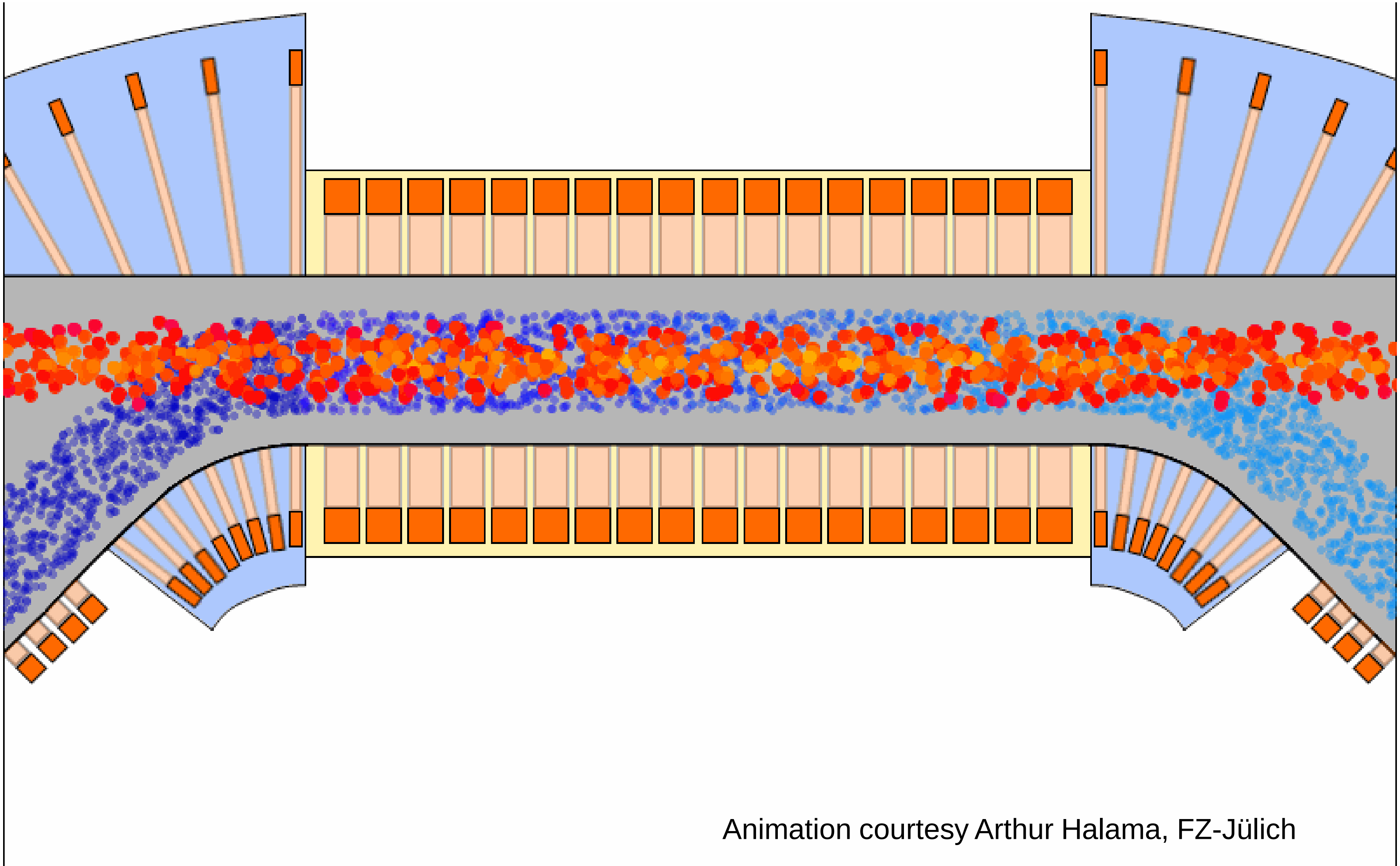
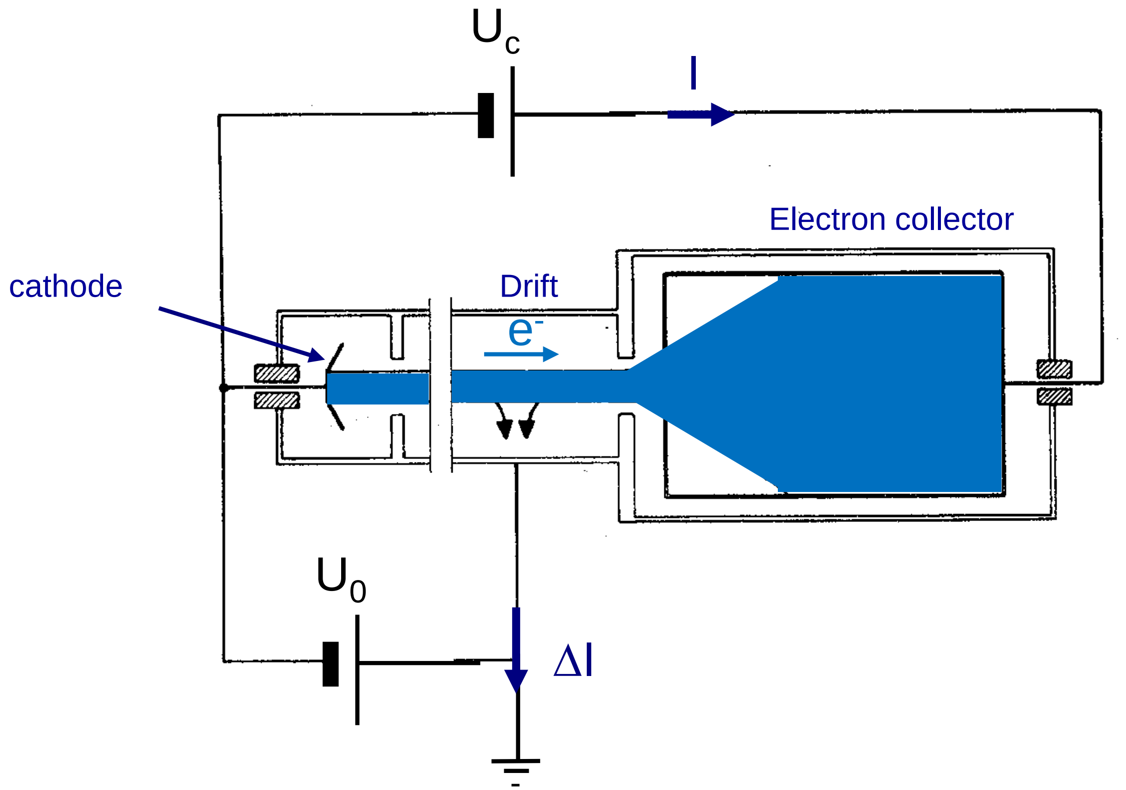
Idea of electron cooling

- The circulating ion beam and an intense electron beam share the same orbit on a small fraction of a circular accelerator
- Average velocities of the two beams are (nearly) equal
- Coulomb interaction between ions and electrons
- The electrons interact with ions only once (single pass)
- The electron beam is guided by the longitudinal magnetic field (besides from the beam transport *B* leads to enhanced cooling)



Animation courtesy Arthur Halama, FZ-Jülich

HV system, energy recovery



Beam temperature

When considering electron cooling it is convenient to use the theory of ideal gases. In the particle frame an e-beam can be represented by “electron gas”. A hot ion gas interacts with a colder e-gas (cooling). In this picture beam temperature is similar to terms like emittance and momentum spread.

Longitudinal

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

Transverse

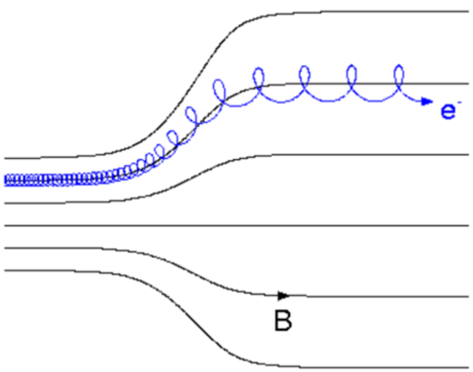
$$\frac{1}{2}k_B T_{\perp} = \frac{1}{2}mv_{\perp}^2 = \frac{1}{2}mc^2\beta^2\gamma^2\theta_{\perp}^2$$

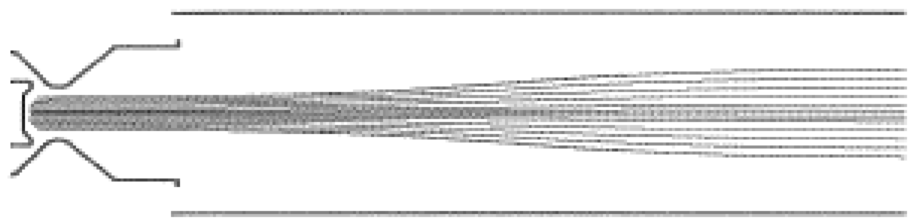
$$\theta_{\perp} = \frac{v_{\perp}}{\beta c}, \qquad \theta_{\perp}(s) = \sqrt{\frac{\epsilon}{\beta_{\perp}(s)}}$$

Electron beams typically used for cooling are anisotropic

$$T_{\|} < T_{\perp}$$

e-beam properties





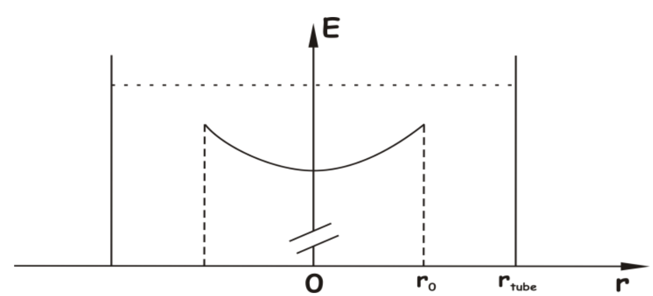
transversely expanded electron beam

transverse electron beam temperature of the expanded beam $k_BT_\perp \propto B_c/B_{gun}$

typical values for low energy coolers: $k_BT_\perp \approx 0.1$ eV (1100 K), $k_BT_{//} \approx 0.1 - 1$ meV

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

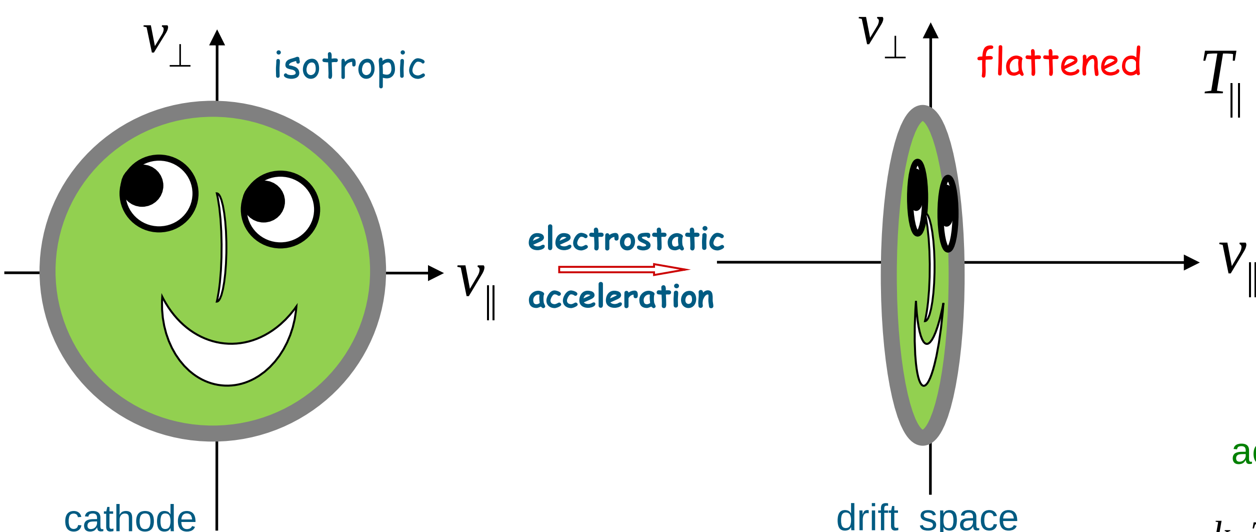
radial variation of electron energy due to space charge



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

Flattened distribution

electron-velocity distribution at the cathode and after acceleration in the drift space



$$T_\parallel = \frac{(k \cdot T_c)^2}{\gamma_e{}^2 \beta_e{}^2 m_e c^2} << T_c$$

Example: $kT_{c||}$ = 0.1eV
acceleration voltage U_0=27 kV

$$k \cdot T_{e\parallel} = 1.7 \cdot 10^{-7} eV << k \cdot T_c \cong 2k \cdot T_{e\perp}$$

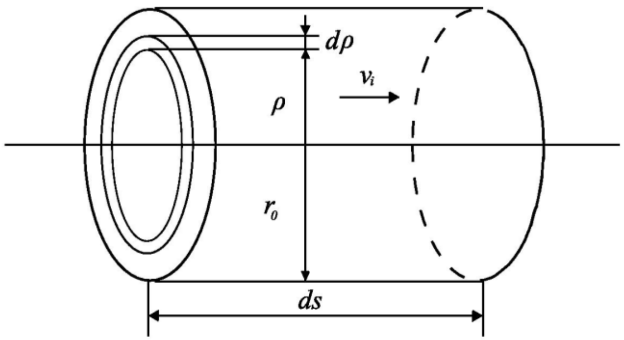
Cooling force

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

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

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



Energy loss:

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

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

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Cooling force behavior

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

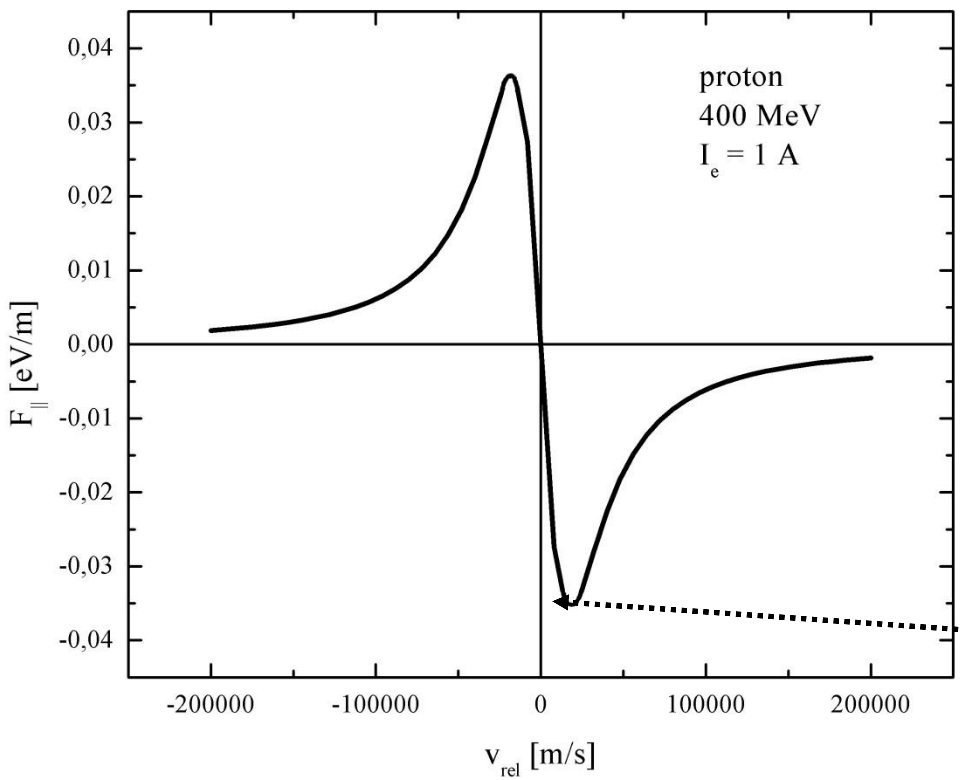
$$\vec{v}_{rel} = \vec{v_i} - \vec{v_e}$$

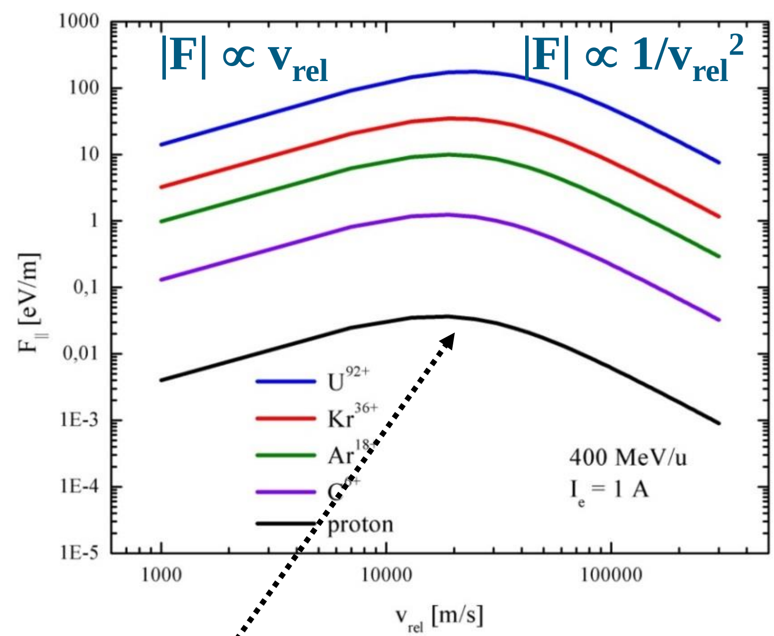
cooling force F

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

for large relative velocities

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

$$\Theta_{x,y} = \frac{v_{x,y}}{\gamma\beta c}$$

$$\tau_z \propto \frac{A}{Z^2} \frac{1}{n_e \eta} \beta^3 \gamma^5 \Theta_z^3$$

$$\Theta_{\|} = \frac{v_{\|}}{\gamma\beta c}$$

increases with energy
slow for hot beams
linear dependence on electron beam intensity n_e and cooler length $\eta = L_{ec}/L_{ring}$
short for highly charged ions
independent of ion beam intensity

for small relative velocities

cooling rate is constant and maximum at small relative velocity

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

Models of 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

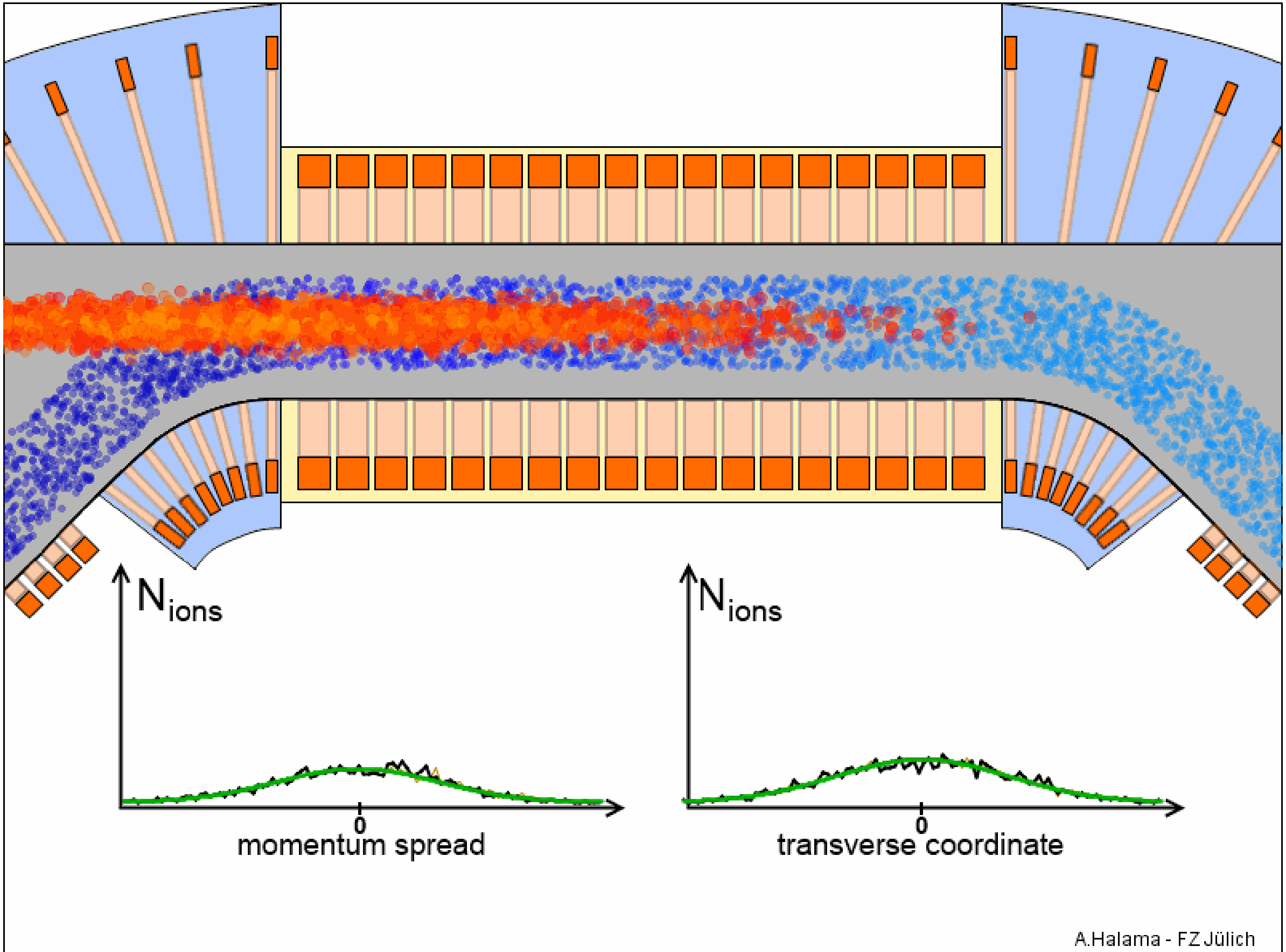
interaction of the ion with a continuous electron plasma (scattering off of plasma waves)

fails for small relative velocities and high ion charge

an empiric formula derived from experiments by V. Parkhomchuk

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

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



N ions
0
momentum spread
N ions
0
transverse coordinate
A.Halama - FZ Jülich

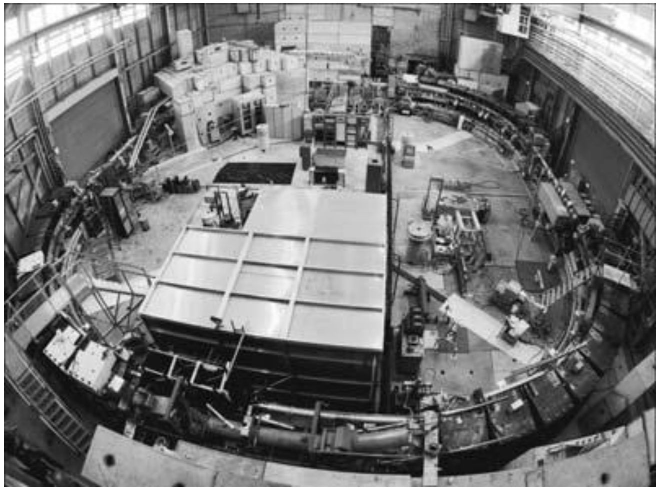
First experimental demonstration at NAP-M

Electron cooling pioneers in Novosibirsk in 1974 left to right: V Parkhomchuk, A Skrinsky, I Meshkov, N Dikansky.

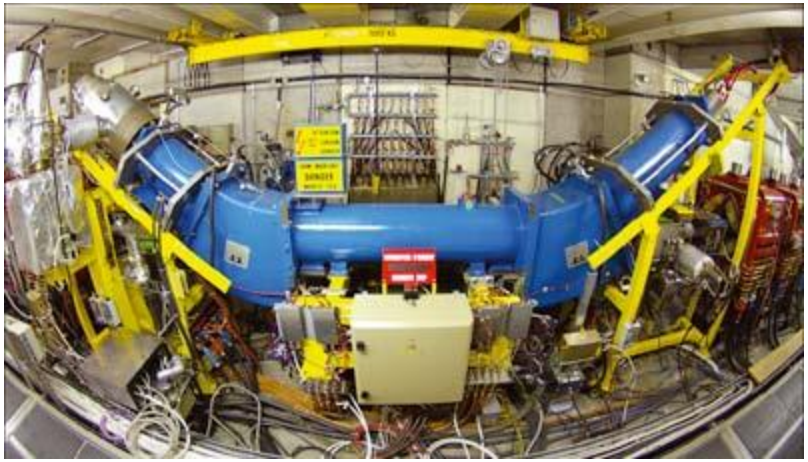
First electron cooler

The first experiments carried out in Novosibirsk in 1974 demonstrated the high efficiency of this method and triggered the development of heavy particle cooling methods. First electron cooler had cooling length of 1 m.

Initial Cooling Experiment (ICE) at CERN

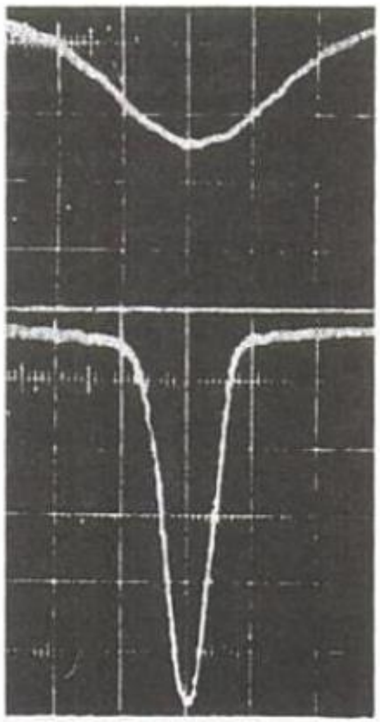


The storage ring of the Initial Cooling Experiment (ICE). The cooler is visible just behind the concrete blocks in the foreground.



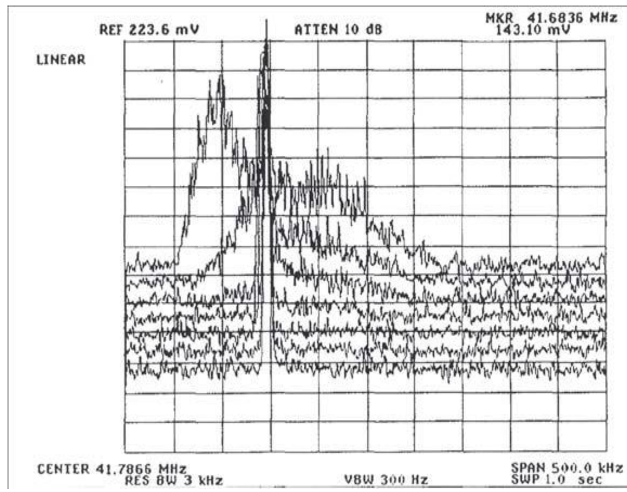
Ice e-cooler upgraded for use in LEAR

Cooling results



Vertical beam profile at NAP-M without and with electron cooling

1974



The first electron cooling of protons in LEAR is shown in this scan – a frequency analysis of the Schottky noise. The spectrum becomes narrower as the cooling process takes effect.

From the archives

Electron cooling tests started in the ICE (Initial Cooling Experiment) storage ring at CERN in May and the results obtained so far are very encouraging. Beam quality can be greatly improved (for example, the six-dimensional phase space density can be improved by a factor of 10^7), cooling times are short (0.3 s and 1.2 s in momentum spread and betatron amplitude, respectively) and beam losses are down to the level corresponding to scattering on residual gas.

The construction of the electron gun started at CERN in the summer of 1977. It was installed in the ring in April 1979 and the first test started in May. Cooling effects, both in longitudinal and transverse dimensions, were observed on the first day as soon as the electron and proton beams were aligned and their velocities matched. Further optimization was obtained by adjusting the gun parameters to minimize the microwave radiation produced by the electrons. Cooling was then strong enough to produce longitudinal bunching of the proton beam. Finally the betatron frequencies of the ICE ring were modified to move the transition energy above the operating energy. The bunching effect disappeared and the best cooling conditions were obtained. The proton beam reduced from 2 cm to less than 1 mm and the momentum spread from 2×10^{-3} to 4×10^{-5}.

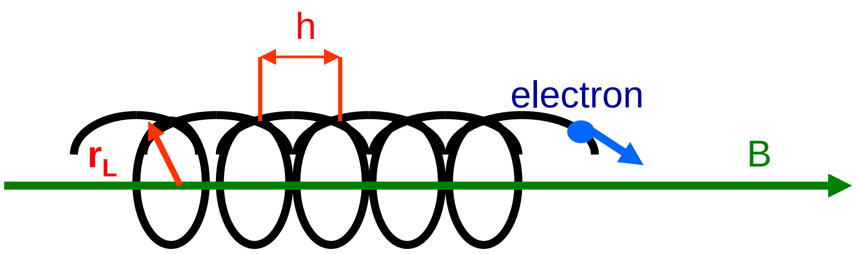
- *CERN Courier* October 1979 p309.

Magnetized electron beam

The magnetic field limits the transverse motion of the electrons which appear to be frozen in this plane.

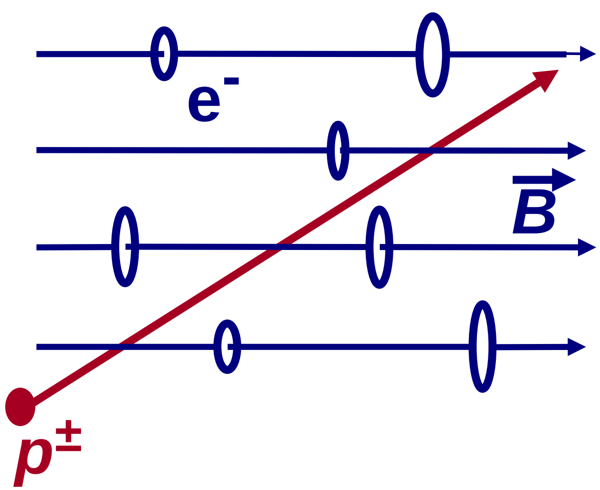
The electrons rotate around their axis at the cyclotron frequency ω_L with a radius equal to r_L.

$$r_L = \frac{v_\perp}{\omega_L} \qquad \omega_L = \frac{eB}{m_e} \qquad h = v_\parallel \cdot T_L = v_\parallel \frac{2\pi}{\omega_L} = v_\parallel \frac{2\pi m_e}{eB}$$

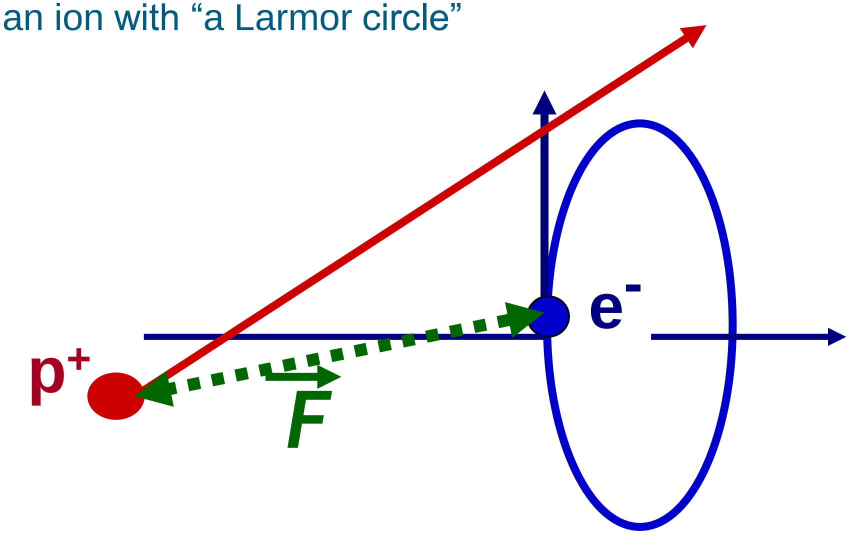


Magnetized electron beam

In addition the whole beam rotates around the axis, which is given by the magnetic field B, with the substantially smaller frequency $\omega_d = en_e/(2e_0B)$.



Interaction of an ion with "a Larmor circle"



e-coolers around the world

Low and medium energy

SIS18 35keV
ESR 320keV
TSR 20keV
CRYRING 20keV
CSR 35, 300keV
TARN 2 110keV
ASTRID 2keV
COSY 100kV
IUCF 270
LEAR 30keV
CELSIUS 300 keV

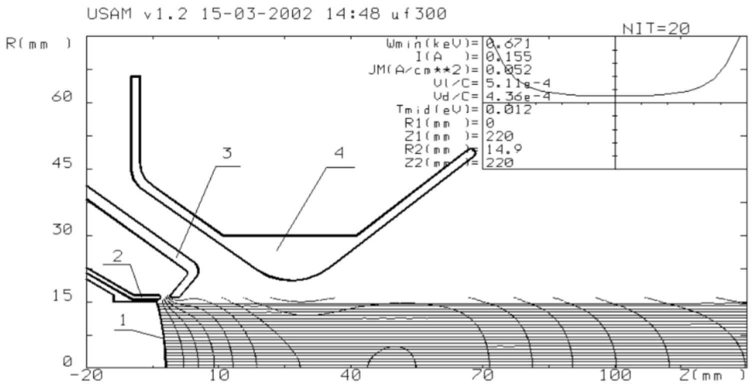
H.Danared, EPAC96

High energy

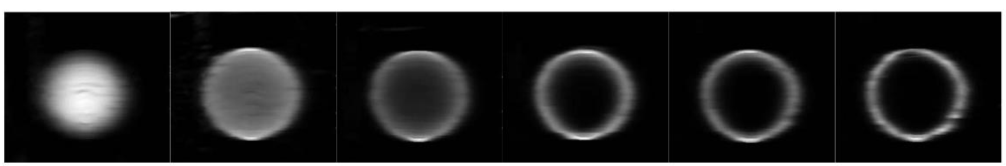
FNAL Recycler
record energy 4.3 MeV
non-magnitized

FZ-Jülich COSY
2 MeV magnitized

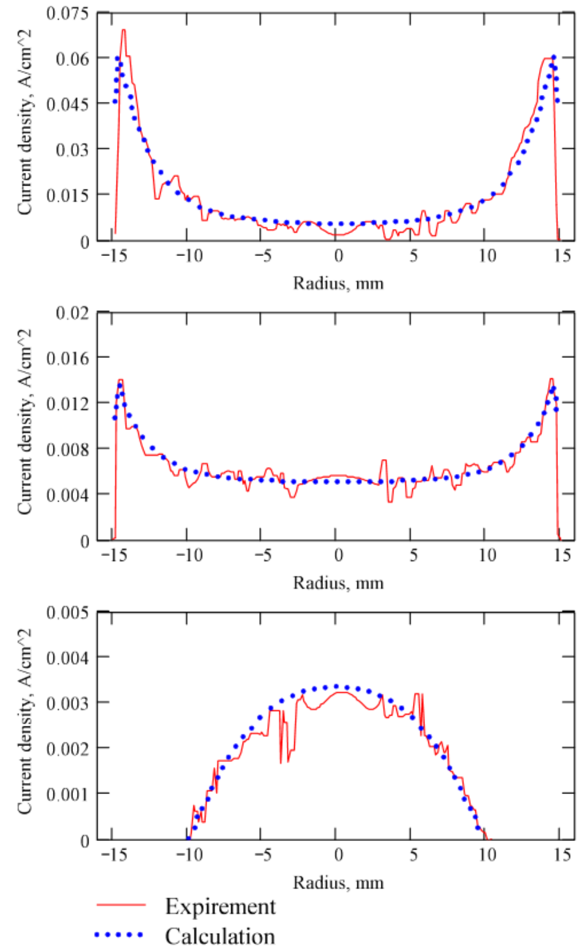
Optimized electron gun



Geometry of electron gun with variable beam profile: 1 – cathode, 2 – forming electrode, 3 – control electrode, 4 – anode



Electron beam profiles at control electrode potential Uc = 0V, +100V, +200V, +350V, +400V, +600V and anode potential Ua=500V

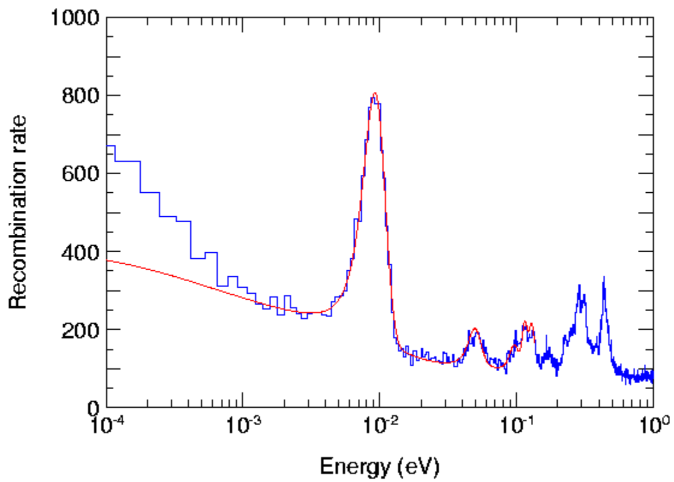


Calculated and measured beam profiles at control electrode potential Uc = +300V, +100V, -100V and anode potential Ua=500V.

A. Bubley et al. Proceedings of EPAC 2002

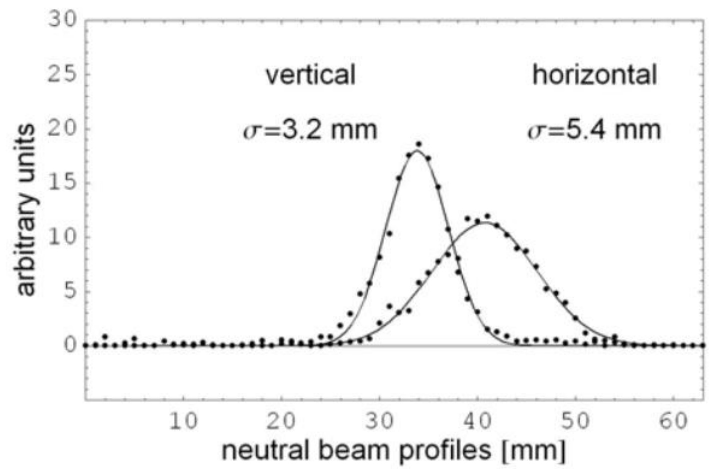
Beam diagnostics based on recombination

CRYRING



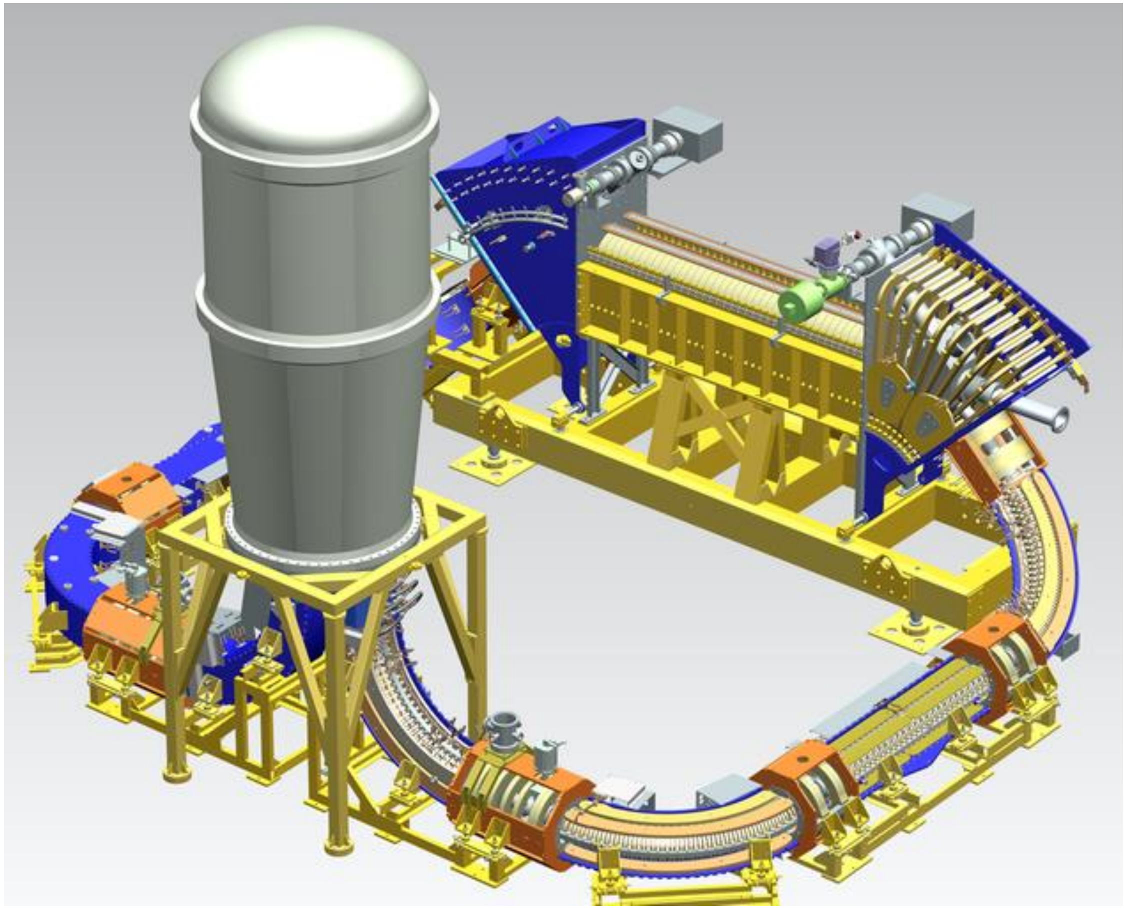
Measured rate coefficient for dielectronic recombination of F6+. The red curve was obtained by fitting a theoretical cross section calculated by Eva Lindroth at Stockholm University to the large peak at 10-2 eV, the shape of which is sensitive to both transverse and longitudinal electron temperatures. This fit gave kTperp = 1.5 meV and kTpar = 0.10 meV. The rate is in arbitrary units and the calibration of the experimental energy scale is only approximate. (CRYRING webpage)

COSY

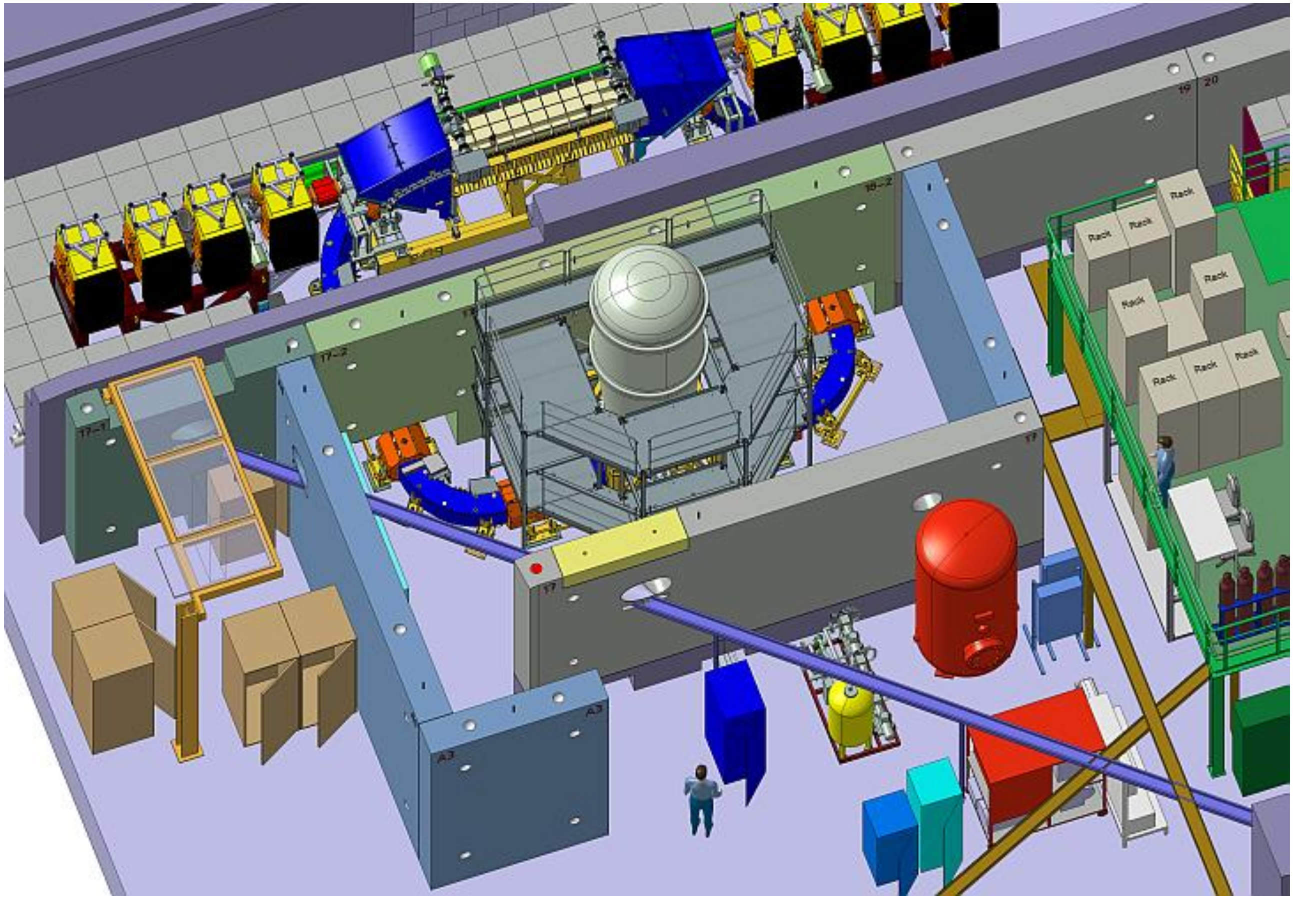


Horizontal and vertical H 0 profiles with a 0.35 mrad horizontally misaligned electron beam. Electron beam current 130 mA.

Design of the 2 MeV electron cooler



Integration into COSY



Design parameters of the 2 MeV e-cooler

Energy range:	0.025 - 2 MeV
High voltage stability	$< 10^{-4}$
Electron current	up to 3 A
Electron beam diameter	10 - 30 mm
Cooling section length	2.7 m
Toroid radius	1 m
Magnetic field	
(cooling section solenoid)	0.5 - 2 kG
Vacuum at cooler	10^{-9} - 10^{-10} mbar

Designed and built at BINP, Novosibirsk

Current status of the 2MeV cooler

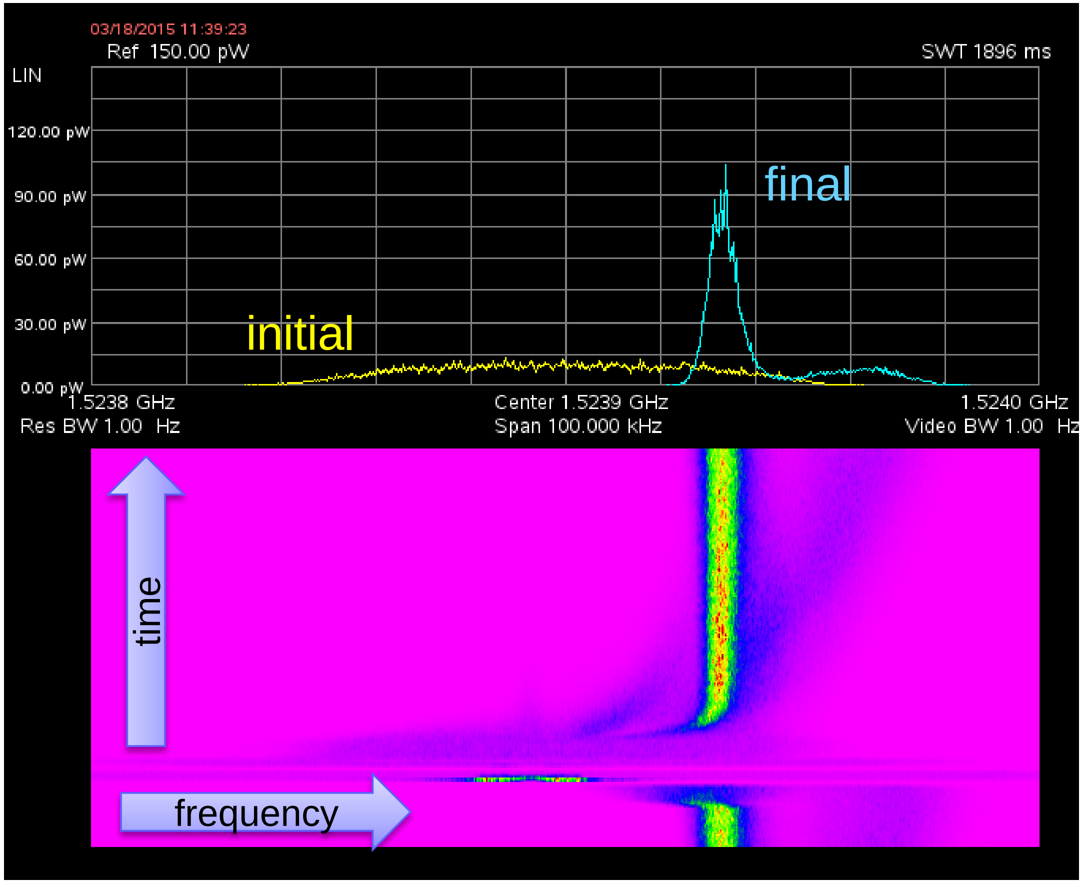
Electron cooling of the proton beam

Proton energy, MeV	Electron energy, MeV	Max. electron current, A
200	0.109	0.5
353	0.192	0.5
580	0.316	0.3
1670	0.908	**0.9**

Maximum electron current and energy so far demonstrated

Electron energy, MeV	Electron current, A
0.024	**1**
1.25	0.2
1.5	**0.09**

Experimental results, dc beam & e-cooling



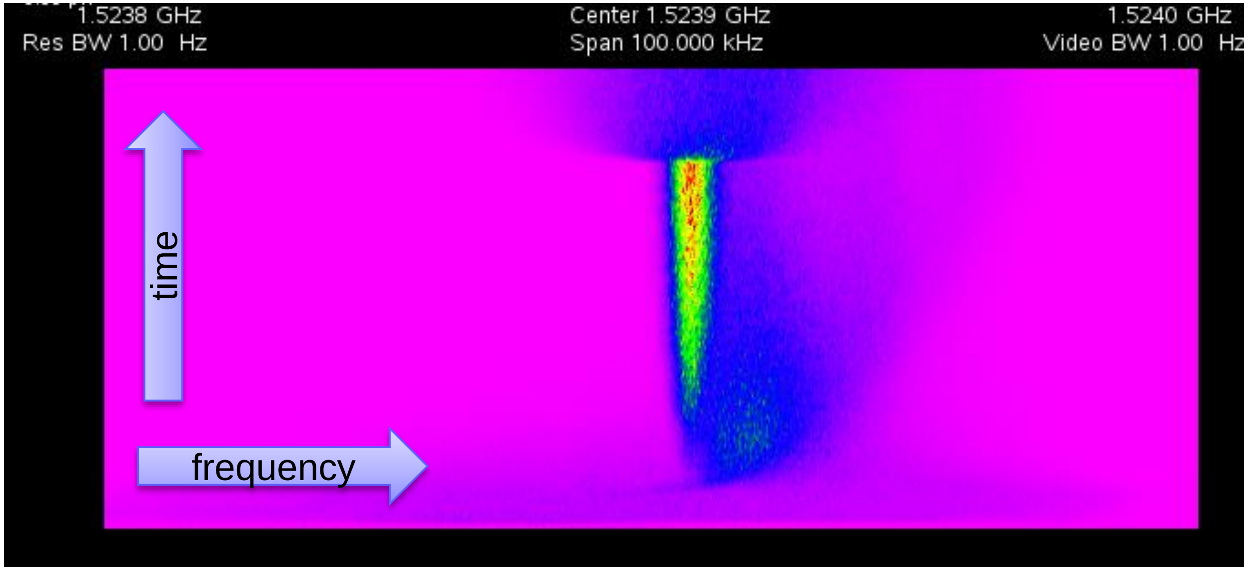
final $\Delta p/p$ = 5e-5

Time span of the color spectrogram 550 s

Vertical pickup of the SC system was used to measure the spectra

5e8 protons, 2425 MeV/c, electron current 0.8 A

Experimental results, turning off EC



Time span of the color spectrogram 550 s

Longitudinal electron cooling process. e-beam turned off leading to fast Δp/p growth. 5e8 protons, 2425 MeV/c, electron current 0.8 A

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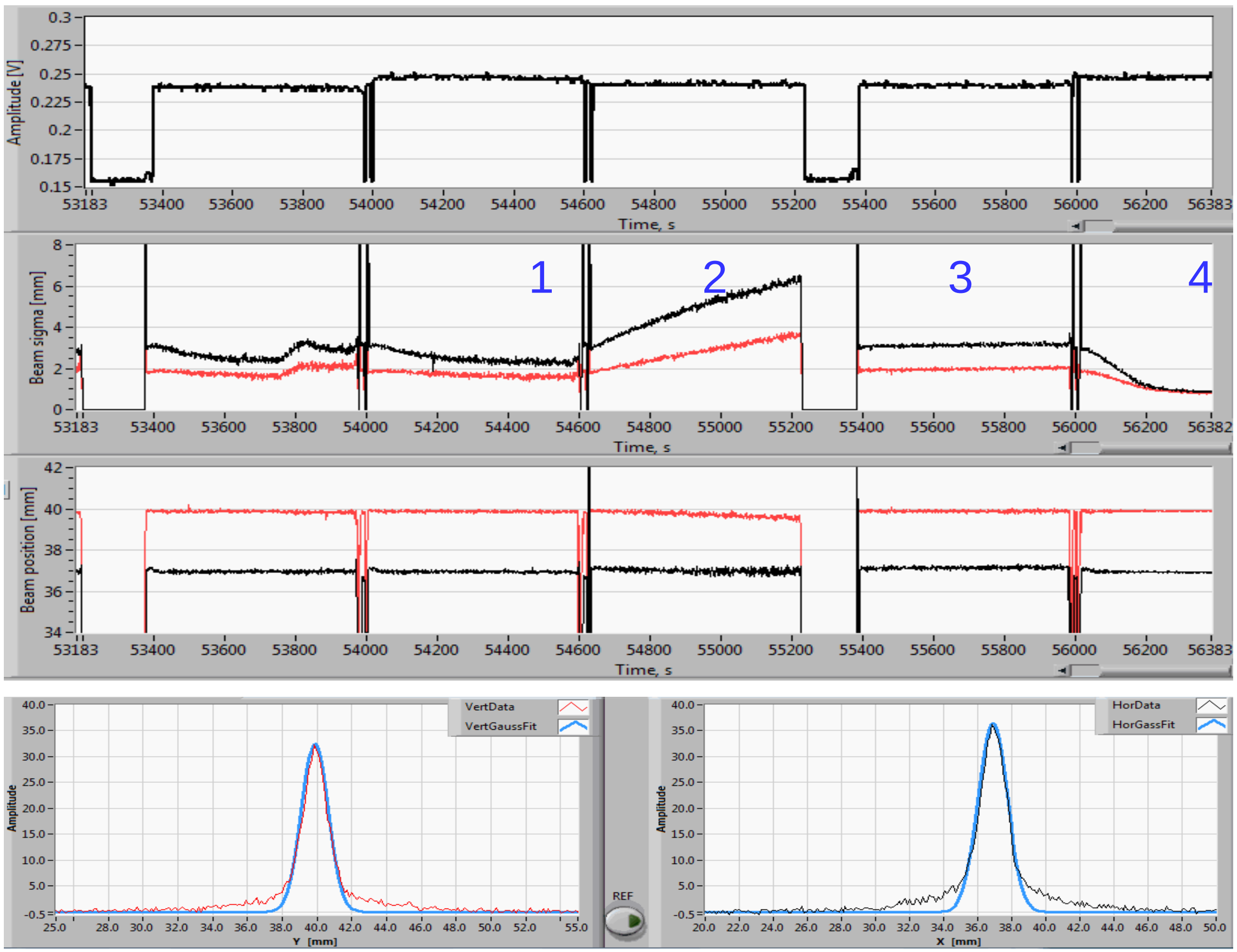
Transverse e-cooling



3.6e8 protons
2425 MeV/c

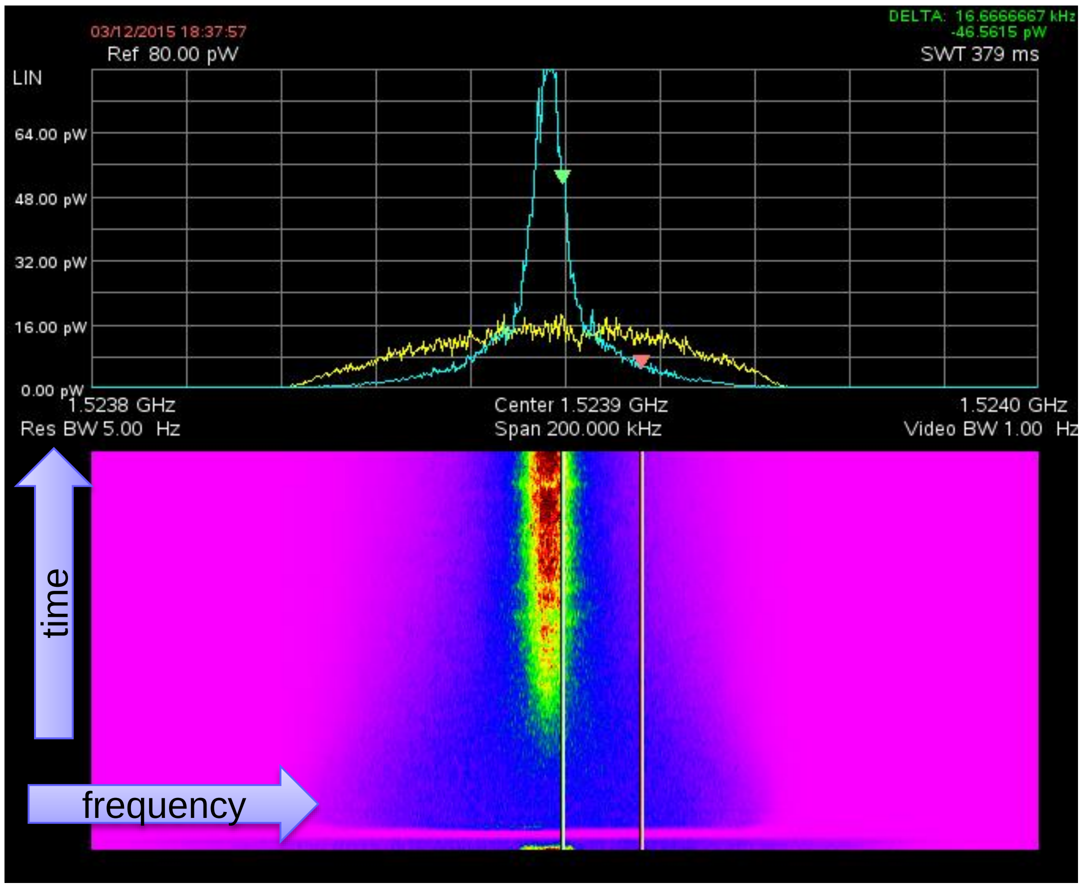
Ie = 0.8 A

1. Noise + EC
2. Noise only
3. Reference
4. EC

$\varepsilon_x = 1.1 \rightarrow 0.1$
ε_y: $=1.3 \rightarrow 0.2$
(mm·mrad, rms normalized)
within 200s

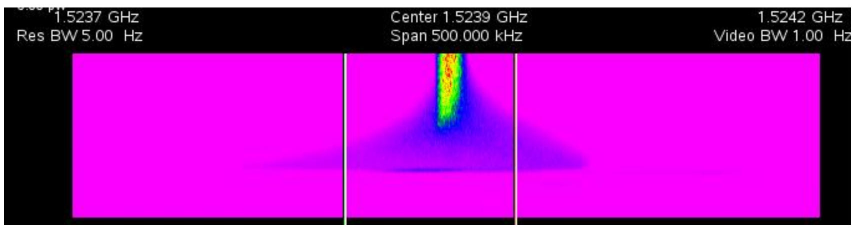
IPM screenshot

RF & e-cooling

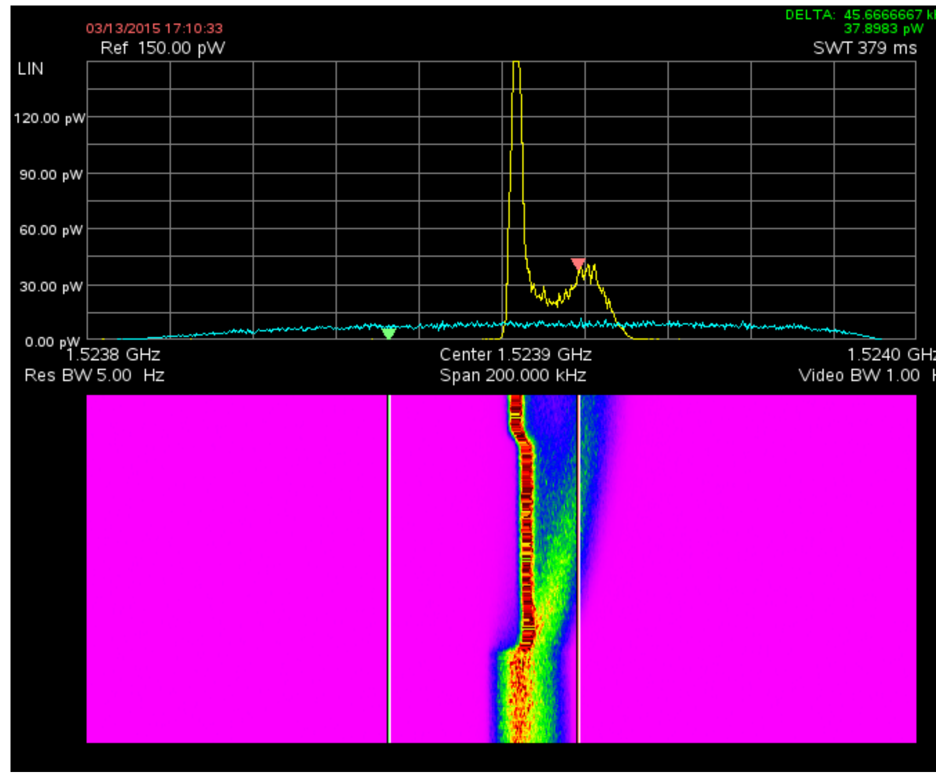


RF on, e-cooling with 550 mA

Electron and stochastic cooling



initial noise + e-cooling at 400 mA + stochastic cooling. Time span 220 s.



e+st. cooling. SC off, e-beam energy changed by +30 V (909.03 kV)

Performance limiting factors

- Magnetic field imperfections (straightness of longitudinal magnetic field in the cooling section, kicks in the transport line)
- Ripple of accelerating voltage
- Recombination (is also used for beam diagnostics)
- Beam control (alignment, requires good diagnostics)

- Technical/technological (manufacturing issues incl. tolerances etc.)
- Reliability issues with increasing complexity

Comparison of different cooling methods

Stochastic and electron cooling are most commonly used in particle accelerators

method	phenomena	dimensions	particles	τ vs energy	τ vs intensity	Impact on the machine
electron	coulomb	3d	hadrons	increases		high
stochastic	Detect and correct beam samples	3d easy to separate	hadrons		increases	moderate

Other methods are radiation (electrons), laser (ions) and ionisation (muons) cooling

Summary

- Even after 50 years of development electron cooling is an active field of research
  - Commissioning of the 2MeV e-cooler at COSY in Jülich
  - New projects making use of bunched e-beam (BNL)
  - Theory of e-cooling under active development
- A brief introduction to the principles of electron cooling was given
- A short history of electron cooler development was presented
- The most recent developments in electron cooling and experimental results were discussed
- Limitations of the electron cooling method as well as its comparison with the other cooling methods were presented
- Current problems in the field of electron cooling were discussed

References

Material used (journal articles, lectures, conference proceedings, private communication)

G.I. Budker, V.V. Parkhomchuk, D.I. Pestrikov, A.N. Skrinsky, V.B. Reva, J. Dietrich, M.Steck, H. Stockhorst, R. Stassen, D. Prasuhn, H.J. Stein, M.I. Bryzgunov, H. Poth, I.N.Meshkov, S. Nagaitsev, A. Shemyakin, M. Beutelspacher, H.Danared

in no particular order