Beam Cooling Techniques

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Introduction: Prehistoric Period

"… In the Beginning was The Word…"

1838 Joseph Liouville (J. De Math. v.3, 1838, p.349)

Theorem of phase space density conservation:

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \sum_{i=1}^{3N}\left(\frac{\partial\rho}{\partial q_i}\cdot\frac{dq_i}{dt} + \frac{\partial\rho}{\partial p_i}\cdot\frac{dp_i}{dt}\right), \quad \frac{dq_i}{dt} = \frac{\partial H}{\partial p_i}, \quad \frac{dp_i}{dt} = -\frac{\partial H}{\partial q_i}$$

The truism saying

"the history does not teach anything"

has no relation to physics. The longstanding history of development of cooling methods is a fascinating "novel" of fighting with famous theorem formulated by Joseph Liouville in 1838:

the theorem of phase space density conservation.

Introduction: Prehistoric Period

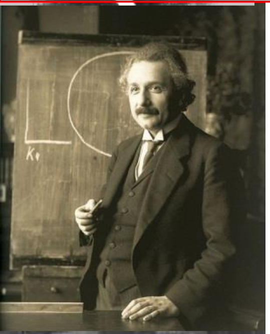
Therefore it is worth to remind that particle beam physics is based on the works of

the Great Predessors

1872 Ludwig Eduard Boltzmann

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\frac{df}{d\vec{r}} + \vec{F}\frac{\partial f}{\partial \vec{p}} = \left.\frac{\partial f}{\partial t}\right|_{coll}$$

Kinetic equation



1906 Albert Einstein, 1913 Marian Smoluchowsky

Equation of Brownian motion

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\frac{df}{d\vec{r}} + \vec{F}\frac{\partial f}{\partial \vec{p}} = \frac{\partial}{\partial p}\xi\left(\frac{p}{m}f + T\frac{\partial f}{\partial \vec{p}}\right)$$

1914 Adrian Fokker, 1917 Max Planck

Equation of dipole rotation in radiation el.-magn. field

Introduction: Prehistoric Period

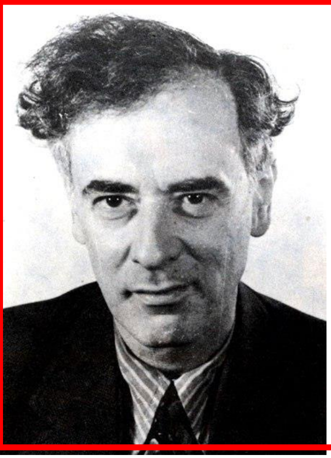
The 30th – Progress in Theory of Plasma Physics

Exactly 1 century after Liouville!

1938 Anatoly A. Vlasov (JETP v.8 (1938) 291)

$$\frac{df_\alpha}{dt} = \frac{\partial f_\alpha}{\partial t} + \vec{v}\frac{df_\alpha}{d\vec{r}} + \frac{q_\alpha}{m_\alpha}\left(\vec{E} + \left[\vec{v},\vec{B}\right]\right)\frac{df_\alpha}{d\vec{v}}$$

Vlasov equation:
Collisionless plasma



1937 Lev D. Landau (JETP v.7 (1937) 203)

$$\frac{df_\alpha}{dt} = \frac{\partial f_\alpha}{\partial t} + \vec{v}\frac{df_\alpha}{d\vec{r}} + \frac{q_\alpha}{m_\alpha}\vec{F}\frac{df_\alpha}{d\vec{v}}$$

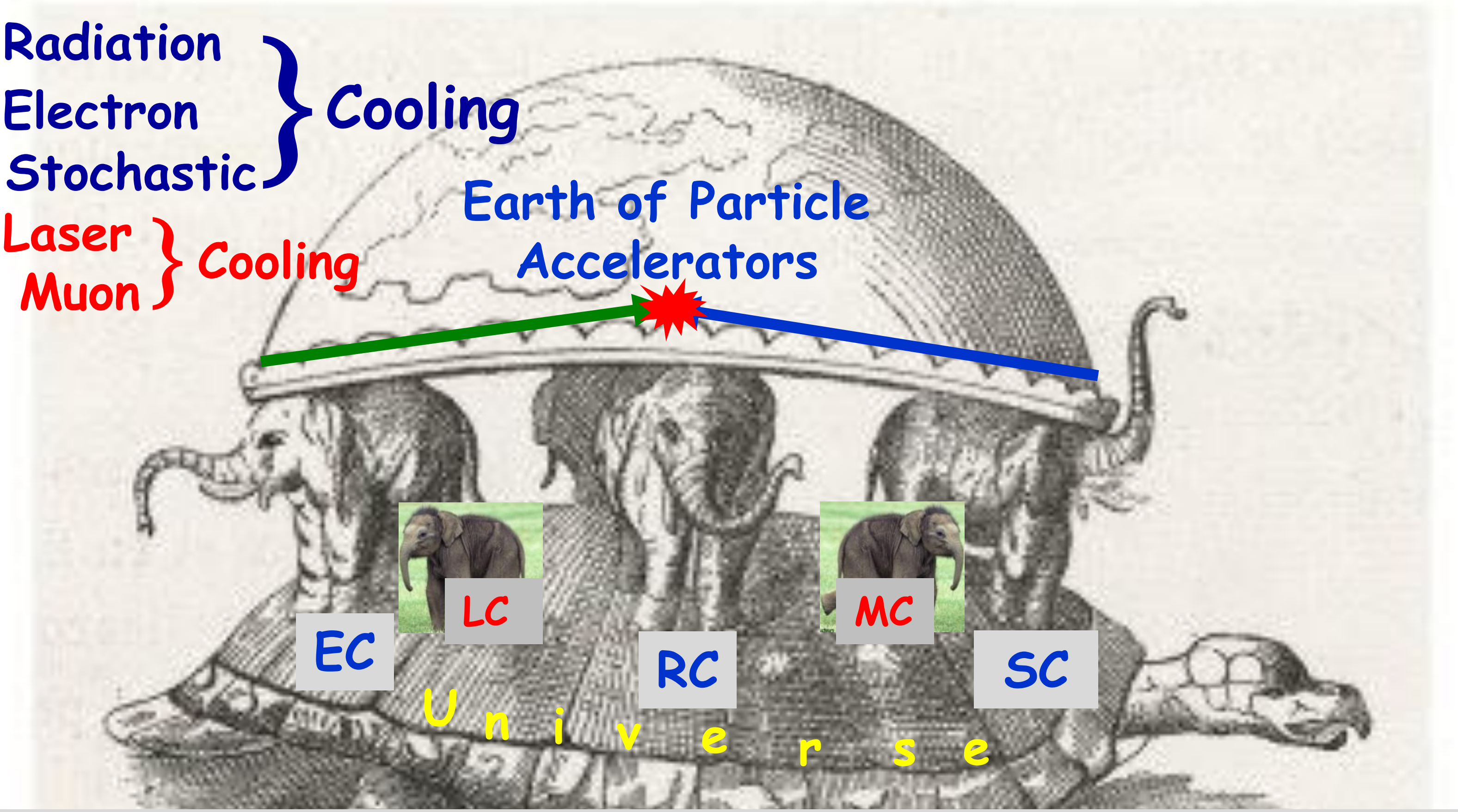
Collision integral in plasma
(F – Coulomb interaction “force”)

The theory developed in plasma physics is used in particle beam physics!

Introduction: Zoo of Beam Cooling Technique

RC – Radiation
EC – Electron
SC – Stochastic
} Cooling

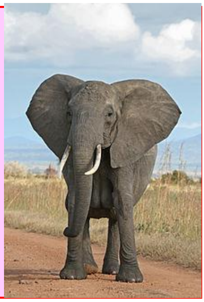
LC – Laser
MC – Muon
} Cooling



What is the "cooling"? ⇒ The methods of reduction of 6D phase space volume occupied by charged particles of a beam in accelerators and storage rings.

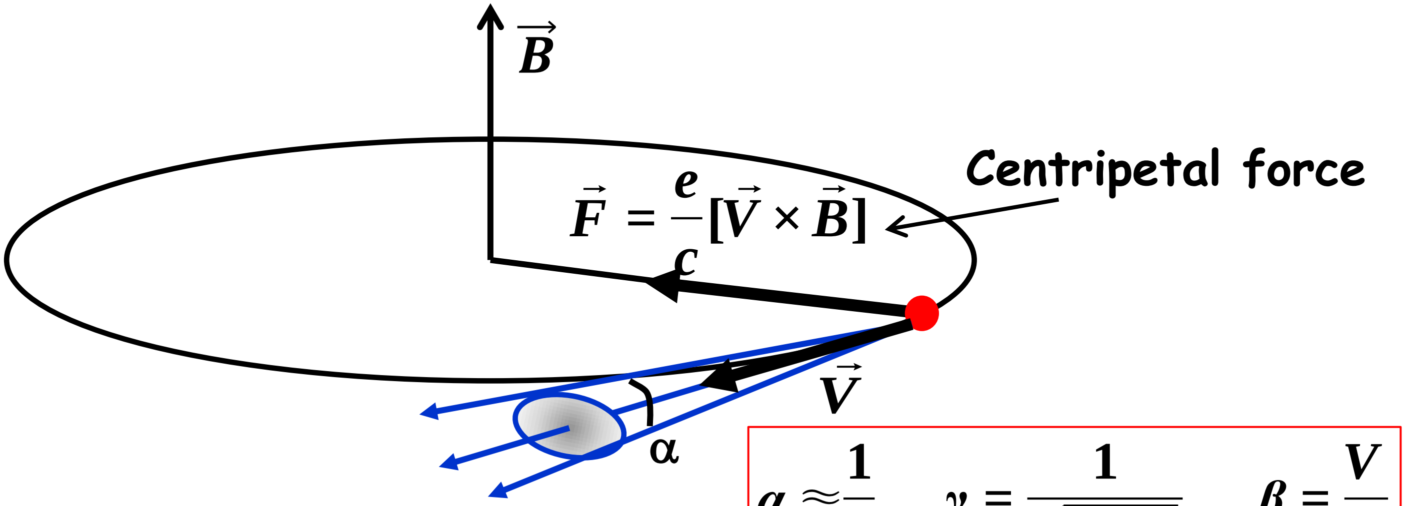
There are also cooling methods for charged particles in traps that we do not consider here.

I. Radiation Cooling Method



I. Radiation Cooling Method

<u>The cooling nature</u>: Magnetic dipole radiation of a charged particle moving in magnetic field



$$\alpha \approx \frac{1}{\gamma}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad \beta = \frac{V}{c}$$

$$\left(\frac{d\vec{p}}{dt}\right)_{recoil} \propto -\vec{V}$$

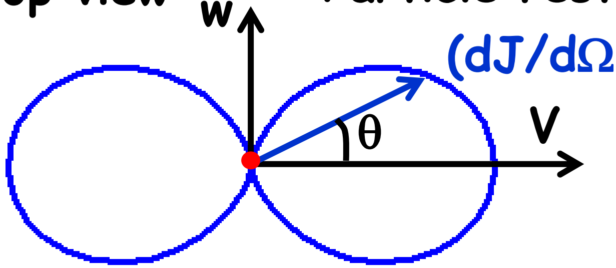
Optional

I. Radiation Cooling Method

The cooling nature: effect of synchrotron radiation of a charged particle moving in magnetic field

Top view

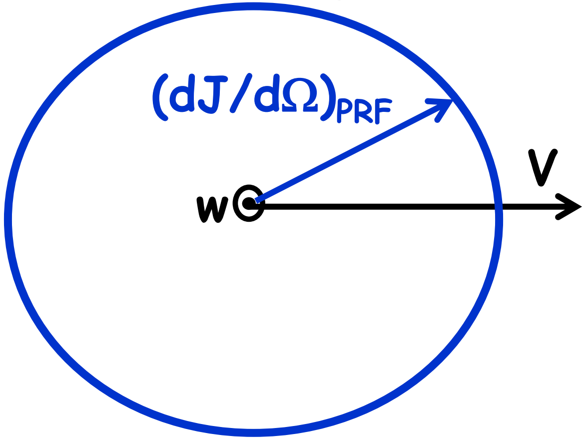
Particle rest frame (PRF)



$(dJ/d\Omega)_{PRF} \propto (\sin\theta)^2$

Radiation flux is normalized by maximum !

Side view (along vector w)

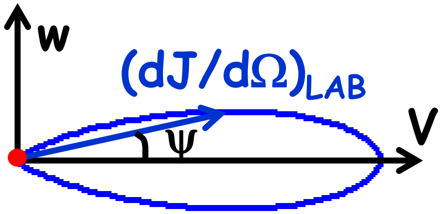


$(dJ/d\Omega)_{PRF}$

Laboratory reference frame (Lab)

Result of Lorenz transformation:

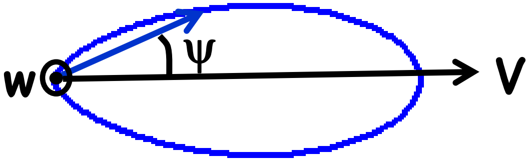
Top view



$(dJ/d\Omega)_{LAB}$

$\beta \equiv V/c = 0.7$

Side view (along vector w)



$(dJ/d\Omega)_{LAB}$

I. Radiation Cooling Method

When Cooling Had Different Name…

1956 A.A.Kolomensky & A.N.Lebedev

(Proc. of the USSR Academy of Sci., 106 (1956) 807)

Synchrotron radiation “friction”

$$\tau_{||} = \frac{3}{2}\cdot\frac{\rho^2}{\gamma^3 r_{cl} c}, \quad r_{cl} = \frac{e^2}{mc^2}$$

Geneva, 1959

1958 Kenneth W. Robinson

Sorry, could not find his photo…

Radiation Effects in Circular Electron Accelerators

(Phys. Rev. v.11 (1958) 373)

PHYSICAL REVIEW VOLUME 111, NUMBER 2 JULY 15, 1958

The main contents Robinson’s paper:

The theorem on sum of decrements and consideration of decrement redistribution between 6 degrees of freedom,

Both papers analysed an influence of quantum fluctuations of radiation on particle dynamics.

I. Radiation Cooling Method

Two Numerical Estimates

Particle energy loss per turn $\Delta\varepsilon_T = \frac{4\pi}{3}\frac{r_{cl}}{\rho}\gamma^4 mc^2$

Collider (CERN)	LEP	LHC
Particle	Electron	Proton
Bending radius ρ, km	2.804	2.804?
Energy	104.5 GeV	7 TeV
γ	2.045×10^5	7.463×10^3
Energy loss per turn	3.8 GeV	6.7 keV
Cooling time	1.6 ms	17 h 6 min.

I. Radiation Cooling Method

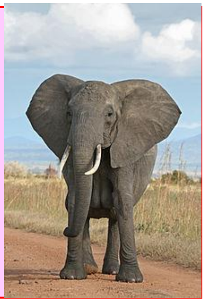
The RC Method Application

1) Formation of intense e^+ and e^- beams of extremely low emittance to reach

- ✓ very high luminosity of cycling (ring) accelerators and colliders;
- ✓ extremely high luminosity of linear collider (using damping rings where SR plays a vital part);
- ✓ Extremely high brightness of Free Electron Lasers (FEL).

2) Formation of polarized e^+ and e^- beams (with application of the effect of "Radiation polarization" (*A.Sokolov and I.Ternov, 1963*).

II. Electron Cooling Method

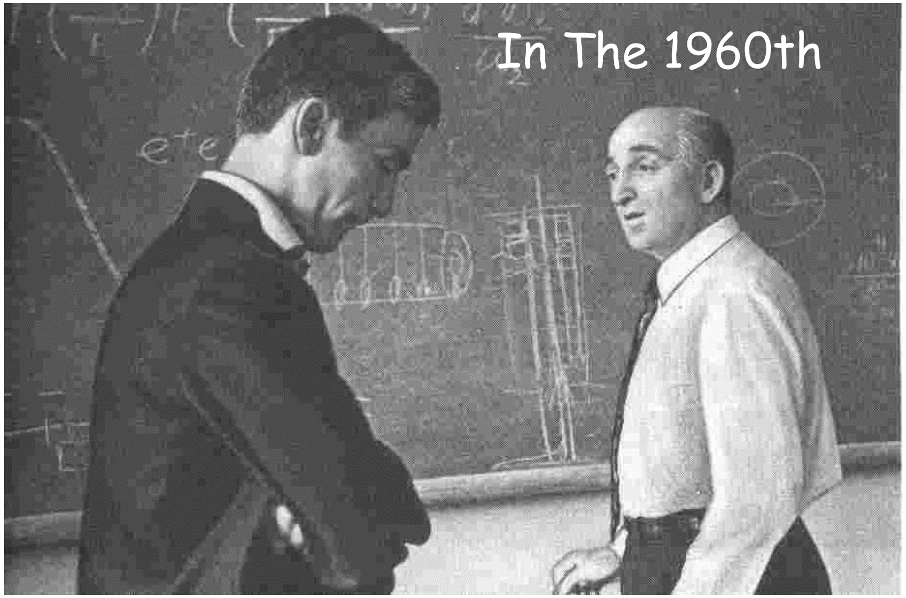


II. Electron Cooling Method

1966 G.I.Budker, Electron cooling

Effective method of particle oscillation damping in proton and antiproton storage rings

Proc. Of The Intern. Symp. on Electron and Positron Storage Rings, Saclay, 1966, p. II-I-I;
Atomnaya Energia 1967, 22, p.346-348 (in Russian).



In The 1960th

Together with A.Skrinsky they developed the Budker's idea!
That was Skrinsky who proposed to use e-cooling for p-bar storage.

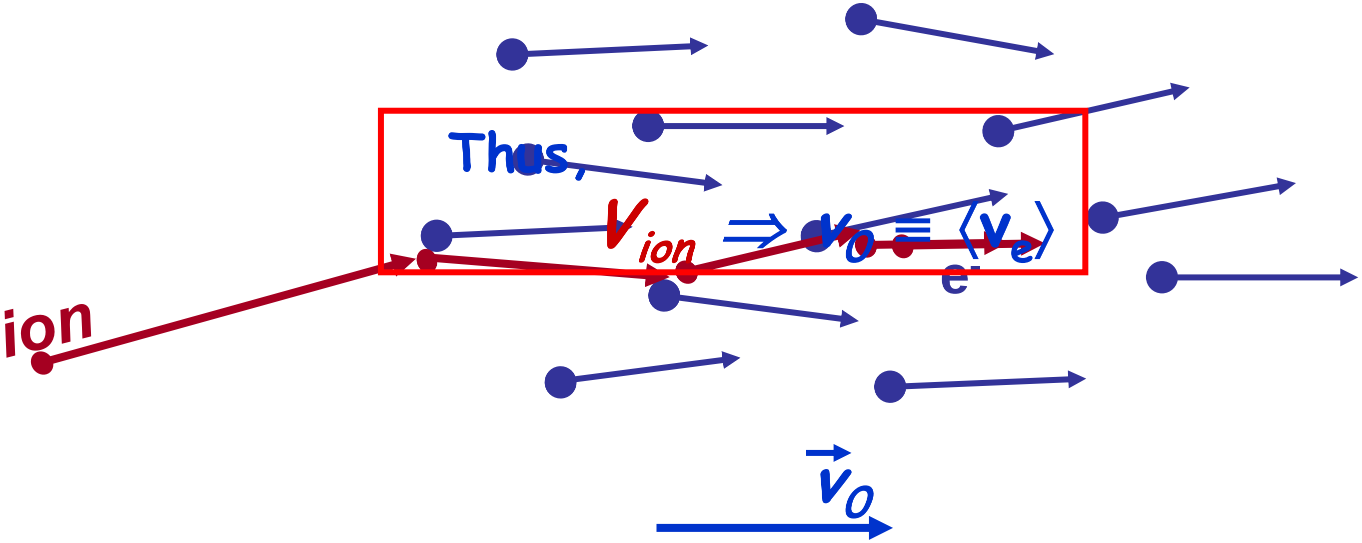
G.Budker and A.Skrinsky
(not PhD yet!)

II. Electron Cooling Method

Physics of Electron Cooling

Simple analogy: heap of sand ("electrons"!) flying with average velocity $\vec{v}_0$ *and a bullet ("ion") shot at the sand heap;*

$$V_{ion} > v_0$$



Thus,

$$V_{ion} \Rightarrow v_0 \equiv \langle \mathbf{v}_e \rangle$$

II. Electron Cooling Method

Physics of Electron Cooling

At cooling $T_{ion} \Rightarrow T_e$ *and equilibrium state corresponds to the equality of ion temperature to electron one in PRF*

$$T_{ion} = T_e\,.$$

It gives us (in PRF!):

$$V_{ion} = \sqrt{\frac{m_e}{M_{ion}}} \cdot v_e \approx \frac{0.023}{\sqrt{A_{ion}}} \cdot v_e$$

Then in LabRF the angle between the ion trajectory and beam axis (equilibrium ion orbit) is equal to

$$\theta \equiv \frac{p_\perp}{p_{||}} = \frac{v_{ion}}{\beta c} = \sqrt{\frac{m_e}{M_{ion}}}\,\frac{v_e}{\beta c} \approx \frac{0.023}{\sqrt{A_{ion}}}\,\frac{v_e}{\beta c} << 1.$$

It is "The plasma approach", which Budker was using in his consideration (invention!) of electron cooling process:
Approximation of homogeneous and isotropic plasma.

Optional

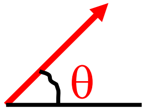
II. Electron Cooling Method: Physics of Electron Cooling

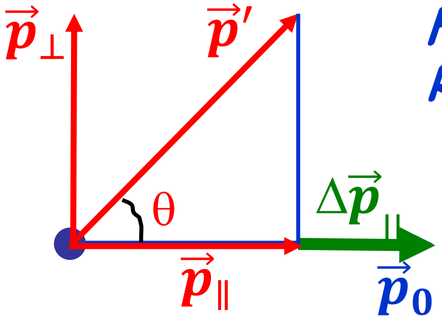
Approximation of spatially homogeneous electron plasma

Cooling (Friction) Force

Binary collision approximation

Coulomb scattering





Formula well known since Rutherford time is:

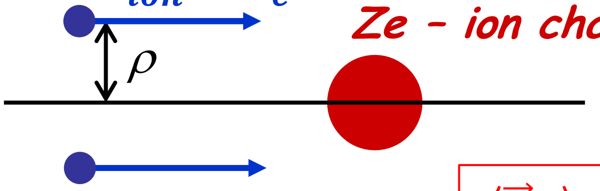
$$\cot\frac{\theta}{2} = \frac{mU^2\rho}{Ze^2}$$

$$\Delta\vec{p}_\parallel = m\vec{U}\cdot(1-\cos\theta)$$

In ion rest frame:

$$\vec{p}_0 = m\vec{U}$$

$$\vec{U} = \vec{V}_{ion} - \vec{v}_e$$



Ze – ion charge

$$\langle\vec{p}_\perp\rangle = 0$$

Summarizing by all impact parameters and by electron velocity v_e (see next slide) we find :

$$\vec{F}_{cool} = -4\pi q\int\frac{\vec{U}}{|U|^3}f(\vec{v}_e)\cdot d^3v_e$$

$$q = \frac{Z^2e^4n_eL_C}{m} = Z^2n_e(r_ec)^2mc^2L_C$$

$$n_e(\vec{r},\vec{v}_e) = n_ef(\vec{v}_e) \qquad L_C = \ln\frac{\rho_{max}}{\rho_{min}}$$

Thus, we came to the Formula for ***cooling force!***

Optional [1]

II. Electron Cooling Method: Physics of Electron Cooling

Approximation of spatially homogeneous electron plasma

Diffusion

Binary collision approximation

Alas, it is not all story! Indeed,

$$\langle p_\perp \rangle = 0.$$

But

$$\langle (p_\perp)^2 \rangle \neq 0\ !$$

It gives diffusion, i.e. heating.

One can obtain the formula for the heating power:

$$Q_\alpha = 2\pi q \cdot \frac{m}{M} \cdot \sum_\beta \int_{-\infty}^{\infty} \frac{U^2 \delta_{\alpha\beta} - U_\alpha U_\beta}{|U|^3} \cdot d^3 v_e$$

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[1] See details in: I.Meshkov, Electron Cooling Status and Perspectives, Physics of Particles and Nuclei, v. 25 (6) (1994) p.p.631- 661

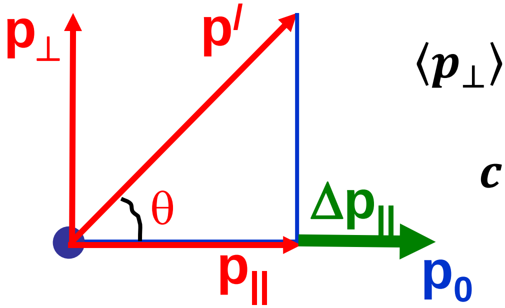
II. Electron Cooling Method: Physics of Electron Cooling

Approximation of spatially homogeneous electron plasma

Optional [1]

Cooling (Friction) Force (Contnd)

How to integrate over impact parameters:



$$\vec{U} = \left(\vec{V}\right)_{ion} - \vec{v_e}, \qquad \vec{p_0} = m\vec{U}$$

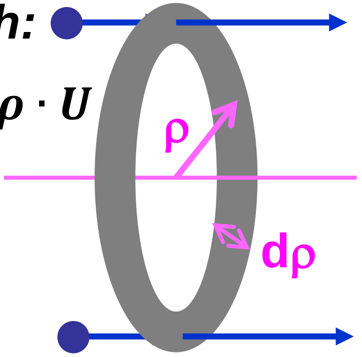
$$\langle p_\perp \rangle = 0 \qquad \Delta p_\parallel = mU\cdot(1-cos\theta)$$

$$cot\frac{\theta}{2} = \frac{mU^2\rho}{Ze^2}$$

From here do find sin²θ/2 and insert into Formula below

Electron flux through the ring of dρ width:

$$dJ = n_e 2\pi\rho\cdot d\rho\cdot U$$



$$\frac{\Delta p_\parallel}{\Delta t} = mU^2 n_e \int_{\rho_{min}}^{\rho_{max}} (1-cos\theta)\cdot 2\pi\rho\cdot d\rho = 2\pi mU^2 n_e \int_{\rho_{min}}^{\rho_{max}} \frac{d\rho^2}{1+\left(\frac{mU^2\rho}{Ze^2}\right)^2}$$

$$F_{cool} = -\frac{\Delta p_\parallel}{\Delta t} = -\frac{2\pi n_e Z^2 e^4}{mU^2} ln\frac{1+\left(\frac{mU^2\rho_{max}}{Ze^2}\right)^2}{1+\left(\frac{mU^2\rho_{min}}{Ze^2}\right)^2} \approx -\frac{4\pi n_e Z^2 e^4}{mU^2} ln\frac{\rho_{max}}{\rho_{min}}$$

II. Electron Cooling Method: Physics of Electron Cooling

Approximation of spatially homogeneous electron plasma

Optional [1]

Cooling (Friction) Force (Contnd)

Coulomb Logarithm and Asymptotics

$$L_C = \frac{\rho_{max}}{\rho_{min}} \qquad \rho_{max} = min\begin{cases} a_e & \text{- electron beam radius} \\ R_D = \sqrt{\dfrac{T_e}{4\pi Z r_e n_e mc^2}} & \text{- Debay radius, } T_e \text{ – electron temperature in PRF} \\ U\tau = UL_{cool}/\beta c & \text{- } L_{cool} \text{ – cooling section length, } \beta c \text{ – electron velocity in Lab.Ref.Frame} \end{cases}$$

$$\rho_{min} \rightarrow \frac{mV^2}{2} = \frac{Ze^2}{\rho_{min}} \rightarrow \rho_{min} = Zr_e\left(\frac{c}{V}\right)^2$$

$r_e = 2.818\ldots\times10^{-13}$ cm is electron classic radius

$$\vec{F}_{cool} = -4\pi q\cdot\begin{cases} \dfrac{\vec{V}_{ion}}{\left|\vec{V}_{ion}\right|^3}, V_{ion} \gg \Delta_e \\ \dfrac{\vec{V}_{ion}}{\Delta_e^3}, V_{ion} \ll \Delta_e \end{cases}$$

$$q = \frac{Z^2e^4n_eL_C}{m} = Z^2n_e(r_ec)^2mc^2L_C$$

$n_e \approx 6\cdot10^7$ cm^{-3}, $L_C = 15 \Rightarrow q \approx Z^2\cdot3.3\cdot10^{10}$ eV·cm/s^2

$$T_e \sim 0.2\text{ eV},\ \Delta_e = \sqrt{\langle v_e^2\rangle} = \sqrt{\frac{T_e}{m_e}} \sim 2\cdot10^7\ cm/s$$

As we see, electron cooling force strongly depends on ion velocity (beam emittance)!

II. Electron Cooling Method: Physics of Electron Cooling

Optional [1]

Langevin Equation and Equilibrium State

$$M\frac{d(V_\alpha)^2}{dt} = P_{cool} + Q_{heat}\,, \qquad P_{cool} = \left(\vec{F}_{cool}\right)_\alpha V_\alpha$$

Q_{heat} is ion heating by electron cloud (see slide 18 and Ref. 1)

Equilibrium: $P_{cool} = - Q_{heat}$. This equality defines minimum ion temperature

Maxwellian Isotropic Ion-Electron Plasma

$$\vec{F}\left(\vec{V}_{ion}\right)_{Maxw} = -4\pi q\cdot\frac{\vec{V}_{ion}}{(V_{ion})^3}\cdot\varphi(x), \qquad \varphi(x) = \sqrt{\frac{2}{\pi}}\cdot\left(\int_0^x e^{-y^2/2}\cdot dy - x\cdot e^{-x^2/2}\right)$$

$$Q_{Maxw} = \frac{4\sqrt{2\pi}qL_C}{M\cdot\left(\frac{T_{ion}}{M}+\frac{T_e}{m}\right)^{1/2}}$$

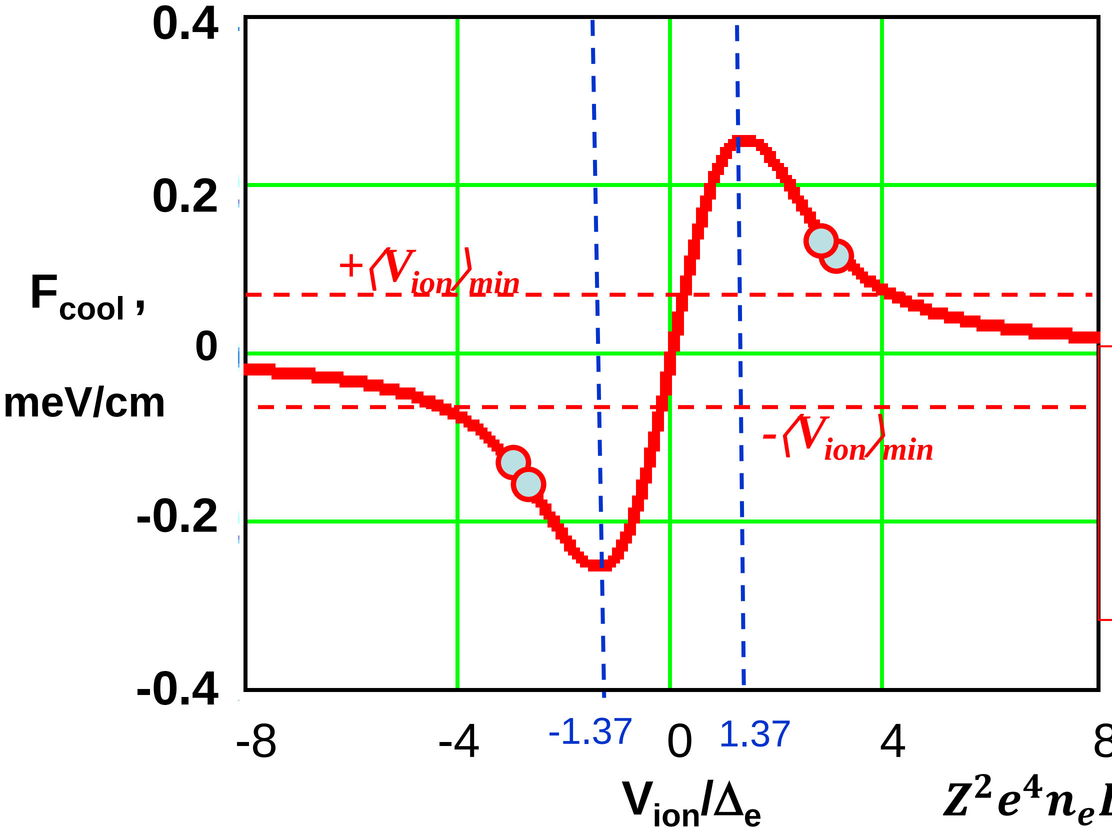
Equilibrium: $T_{ion} = T_e\,,\ \langle V_{ion}\rangle_{min} = \sqrt{\frac{m}{M}}\,\Delta_e$

II. Electron Cooling Method: Physics of Electron Cooling

Approximation of spatially homogeneous electron plasma

Cooling (Friction) Force (Contnd)

Maxwellian Isotropic Electron Gas



$n_e = 6\times10^7$ cm^{-3}
$L_C = 15$
$T_e = 0.2$ eV
$\Delta_e = 1.88\times10^7$ cm/s
$Z = 1$

Equilibrium:

$$T_{ion} = T_e$$

$$\langle V_{ion}\rangle_{min} = \sqrt{\frac{m}{M}}\,\Delta_e$$

$$q = \frac{Z^2 e^4 n_e L_C}{m} = Z^2 n_e (r_e c)^2 m c^2 L_C$$

II. Electron Cooling Method: Physics of Electron Cooling

Optional [1]

Flattened Electron Velocity Distribution

Formation of cooling electron beam with acceleration in electrostatic field *E* leads to decrease of electron velocity spread in PRF.

A simplified explanation: nonrelativistic electrons ($\beta << 1$)

In LabRF we have (energy conservation law) the equality

$$\varepsilon_e = T_{cathode} + eU_0 \equiv \frac{m(v_0 + \Delta v)^2}{2}, \quad \frac{mv_0^2}{2} \equiv eU_0 \equiv \varepsilon_0$$

In nonrelativistic case Δv is electron velocity difference both in LabRF and PRF:

$$\Delta v \approx \frac{T_{cathode}}{mv_0}.$$

Then electron temperature in PRF is equal to

$$T_e\Big|_{PRF} = \frac{m\Delta v^2}{2} \approx \frac{T_{cathode}^2}{4\varepsilon_0}$$

II. Electron Cooling Method: Physics of Electron Cooling

Optional [1]

Flattened Electron Velocity Distribution (Contnd)

In reality one has to take into account several effects:

1) **Electron energy distribution in PRF:** $f(\varepsilon) = e^{-\varepsilon/T_{cathode}}$

2) **Correlation energy of electrons at "fast" acceleration:**

$$T_{correlation} = e^2(n_e)^{1/3}, \; n_e - \textit{electron density in LabRF}\;.$$

3) **Lorenz transformation (β ≈ 1) for energy-momentum of electrons.**

Finally we have: $$T_{||} = \frac{T_{cathode}^2}{\beta^2\gamma^2 mc^2} + e^2 n_e^{1/3}$$

Typical numbers: ε_{ion} = 55 MeV/amu (ε_e = 30 keV), $T_{cathode}$ = 0.1 eV,

$n_e = 3\times10^8$ cm^{-3} (J_e= 0.5 A/cm^2) $\Rightarrow$

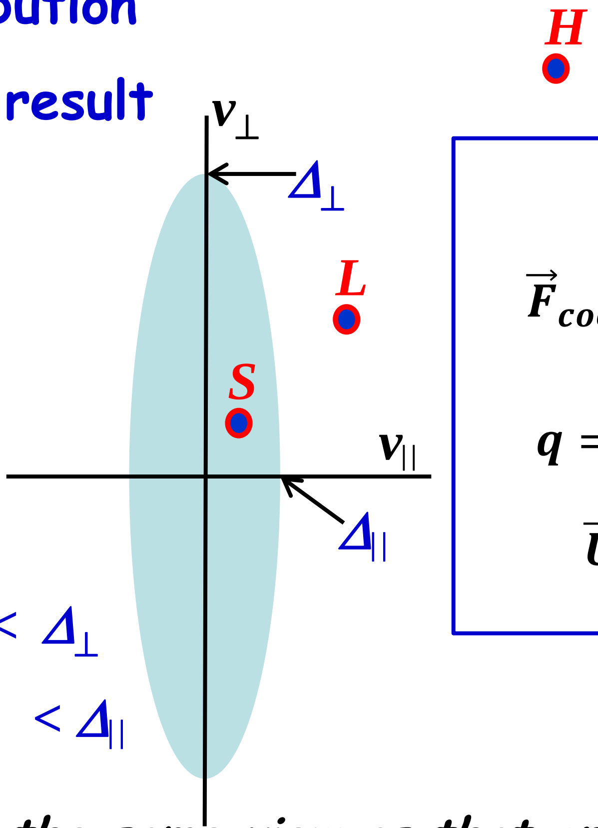
$T_{\perp} \approx 0.2$ eV, $T_{||} = (1.7\times10^{-7} + 0.96\times10^{-4})$ eV

II. Electron Cooling Method: Physics of Electron Cooling

<u>Optional</u> [1]

Flattened Electron Velocity Distribution

Electron density distribution in velocity space – the result of the "flattening":



- **Ion velocity ranges:**

H – *high* $\Rightarrow \Delta_\perp < |V_{ion}|$

L – *low* $\Rightarrow \Delta_{||} < |V_{ion}| < \Delta_\perp$

S – superslow $\Rightarrow |V_{ion}| < \Delta_{||}$

We remind:

$$\vec{F}_{cool} = -4\pi q \int \frac{\vec{U}}{|U|^3} f(\vec{v}_e) \cdot d^3 v_e$$

$$q = \frac{Z^2 e^4 n_e L_C}{m} = Z^2 n_e (r_e c)^2 mc^2 L_C$$

$$\vec{U} = \vec{V}_{ion} - \vec{v}_e$$

The Formula for F_{cool} has the same view as that one for Coulomb law! It means one can use results for calculations of electrostatic field of a charges' system; for instance, here – for a charge ball (H velocity range) and for charged layer (L and S).

II. Electron Cooling Method: Physics of Electron Cooling

Magnetization of Electrons

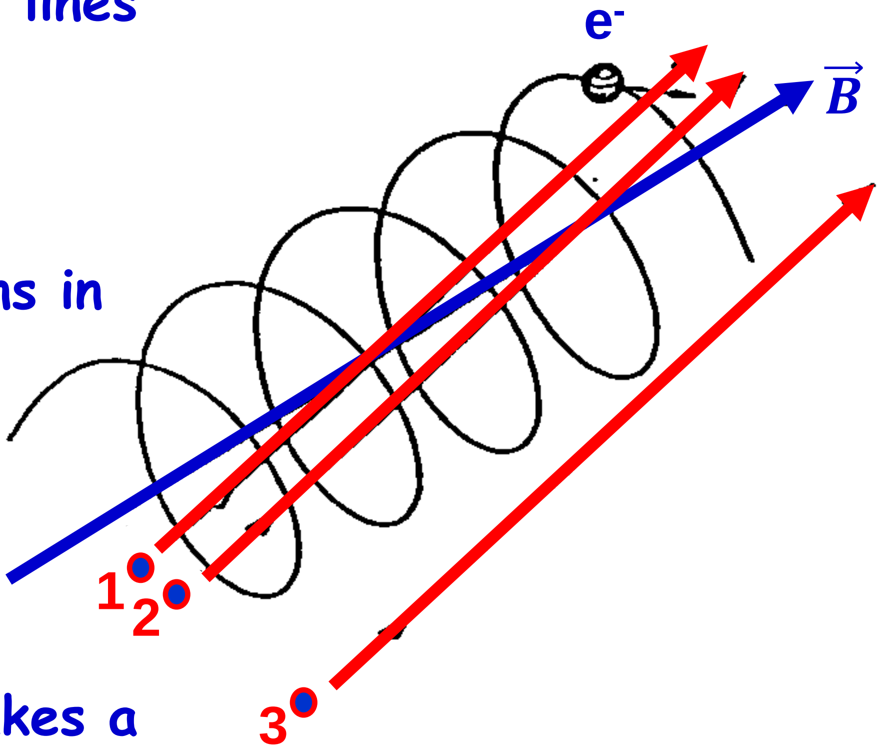
Electrons move along magnetic field lines

on helical trajectories.

One can distinguish

three types of electron-ion collisions in

magnetic field:



1 – fast collisions: electron does not "feel" the magnetic field presence at all;

2 – adiabatic collisions: electron makes a few turns around magnetic field line transferring to the ion impact momentum;

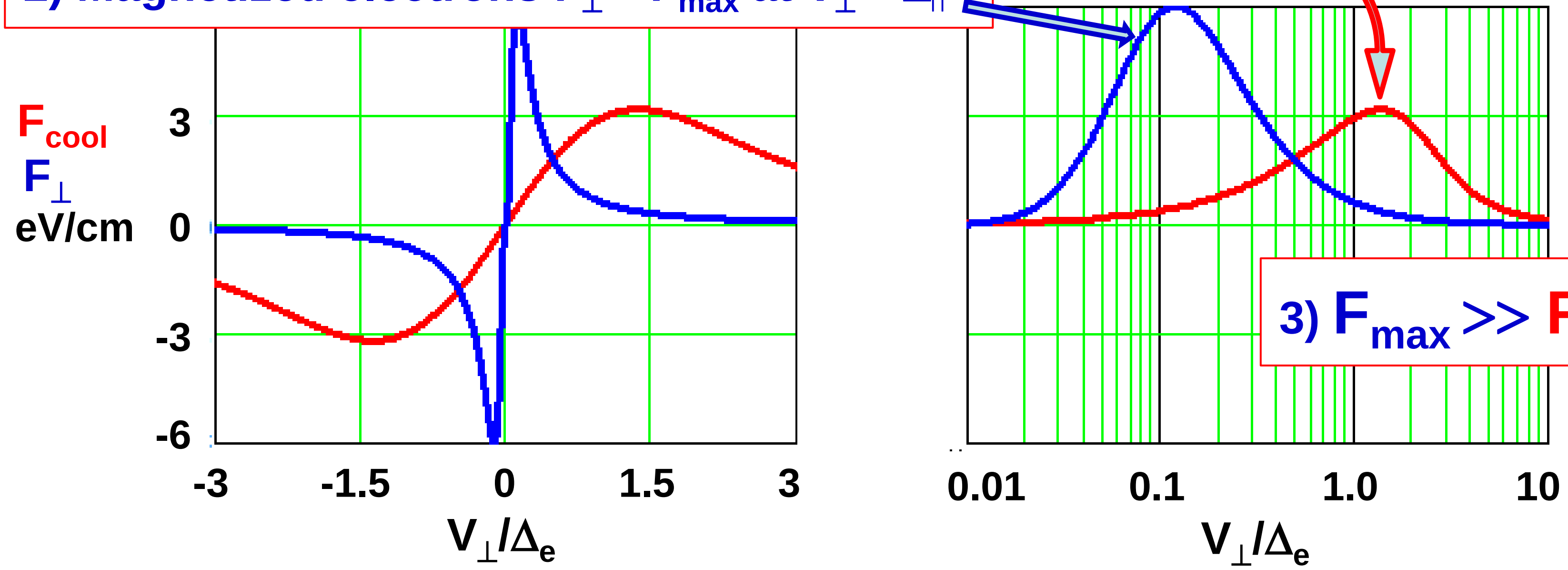
3 – magnetized collisions: electron does not move across the magnetic field transferring mainly momentum in longitudinal direction;

II. Electron Cooling Method: Physics of Electron Cooling

Cooling force has in this case specific characteristics:

1) Maxwellian E-Gas: $F_{cool} = F_{max}$ at $V_\perp = \Delta_\perp$

2) Magnetized electrons $F_\perp = F_{max}$ at $V_\perp = \Delta_{||}$



3) $F_{max} >> F_{max}$!

Parameters in pictures: $Z = 79$ ($^{197}Au^{79+}$), $\varepsilon_{ion} = 55$ MeV/u, $\varepsilon_e = 30$ keV

$n_e = 1.2\times10^8$ cm^{-3} ($J_e = 0.2$ A/cm^2)

$\Delta_e = \Delta_\perp$, $\Delta_{||} = 0.1\times\Delta_\perp$

$L_C = 15$ (Maxw. electron beam)

$T_e = T_\perp = 0.2$ eV ; $T_{||} = 0.01\times T_\perp$ (artificial choice)

$\Delta_e = \Delta_\perp = 1.9\times10^7$ cm/s, $\Delta_{||} = 0.1\times\Delta_\perp = 1.9\times10^6$

5) Equilibrium state:

$(T_{ion})_{min} = T_{||}$

$$\langle V_{ion}\rangle_{min} = \sqrt{\frac{m}{M}}\,\Delta_{||}$$

II. Electron Cooling Method: Physics of Electron Cooling

Magnetized Electron Beam with Flattened Velocity Distribution

Optional [1, 2]

Theory of Electron Cooling with Magnetized Electrons at Flattened Velocity Distribution

Formulae for cooling force based on results of Ref.[2] and adopted for concrete simulations in Ref.[1] (known in The Cooling Community as "DSM-Formulae").

These Formulae describe cooling process rather satisfactory, but require *accurate definition of collision parameters*. They can be used mainly at numerical simulation.

$$\mathbf{F}_\perp \approx -\frac{2\pi q}{m}\mathbf{V}_\perp \begin{cases} \dfrac{1}{V^3}\left(2L_{FH} + \dfrac{V_\perp^2 - 2V_\parallel^2}{V^2} L_{MH}\right), & \text{H} \\ \dfrac{2}{\Delta_\perp^3}\left(L_{FL} + N_L L_{AL}\right) + \dfrac{V_\perp^2 - 2V_\parallel^2}{V^2}\,\dfrac{L_{ML}}{V^3}, & \text{L} \\ \dfrac{2}{\Delta_\perp^3}\left(L_{FS} + N_S L_{AS}\right) + \dfrac{L_{MS}}{V^3}, & \text{S} \end{cases}$$

$$\mathbf{F}_\parallel \approx -\frac{2\pi q}{m}\mathbf{V}_\parallel \begin{cases} \dfrac{1}{V^3}\left(2L_{FH} + \dfrac{3V_\perp^2}{V^2} L_{MH} + 2\right), & \text{H} \\ \dfrac{2}{\Delta_\perp^3 V_\parallel}\left(L_{FL} + N_L L_{AL}\right) + \left(\dfrac{3V_\perp^2}{V^2} L_{ML} + 2\right)\dfrac{1}{V^3}, & \text{L} \\ \dfrac{2}{\Delta_\perp^2\,\Delta_\parallel}\left(L_{FS} + N_S L_{AS}\right) + \dfrac{L_{MS}}{\Delta_\parallel^3}. & \text{S} \end{cases}$$

---

[2] *See details in: Ya.Derbenev and A.Skrinsky, Sov. J. Plasma Phys. v. 4 (1978) p.273*

II. Electron Cooling Method: Physics of Electron Cooling

Magnetized Electron Beam with Flattened Velocity Distribution

Optional [3]

Theory of Electron Cooling with Magnetized Electrons at Flattened Velocity Distribution

Much more useful for practical application is so called

"Parkhomchuk Formula"

derived in the 1970th by V.V.Parkhomchuk during first experiments on electron cooling development at Budker INP (Novosibirsk). In PRF it is

$$F^{\alpha}_{cool} = \frac{Z^2_{ion}}{A_{ion}} \frac{4mc^2(r_e c)^2 n_e V_\alpha}{\left(V_\alpha^2 + V_\parallel^2 + V_{eff}^2\right)^{3/2}} \cdot ln\left(1 + \frac{\rho_{max}}{\rho_L + \rho_{min}}\right)$$

It is empirical Formula [3] for cooling force that approximates very well experimental results and is applicable to the case of cooling with "magnetized e-beam". Here $Z_{ion}e, A_{ion}$ are electric charge and atomic weight of the ion, m, r_e is mass and classic radius of electron, $V_\alpha, V_\parallel$ are ion velocity transverse and longitudinal components, V_{eff} and $\rho_{max}, \rho_L, \rho_{min}$ - see in slide #31.

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[3] If interested do ask your lecturer for copy of manual file.

II. Electron Cooling Method: Physics of Electron Cooling

Optional [1,4,5]

Cooling Time

When cooling force is calculated one can find *cooling decrement* D_{cool} *and cooling time* $\tau_{cool} = 1/D_{cool}$. Formula for cooling decrement follows from Langevin equation [slide #19]:

$$\tau_{\alpha}^{-1}(\vec{V}) = -\frac{1}{M_{ion}} \cdot \frac{\partial F_{\alpha}(\vec{V}_{\alpha})}{\partial V_{\alpha}}$$

[See details in Ref.1]. It is instant magnitude of decrement.

Due to nonlinearity of the function $\vec{F}(\vec{V})$ both decrement and cooling time are functions of vector $\vec{V}$. Therefore calculation of total cooling time requires numerical simulation.

The most advanced code for cooling process simulation is BETACOOL developed at JINR since 1995[4,5]. The code has many options and allows one to include in simulation a lattice of the cooler ring.

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[4] http://betacool.jinr.ru

[5] A.Sidorin, A.Smirnov, Long Term Dynamics Simulation with the BETACOOL Code, Proc. Of RuPAC'2012, http://JACoW

II. Electron Cooling Method: Physics of Electron Cooling

Optional [1]

Cooling Time (Contnd)

For estimates by order of magnitude one can use *approximate cooling time Formula*.

Besides, a practical application requires to find cooling time value in Lab. Reference Frame. Then one needs to make Lorenz transformation of all parameters from PRF to Lab. Ref. Frame. One needs to introduce the following parameters:

$$\theta_{ion\perp} = \frac{\triangle\, p_{ion\perp}}{p_{ion}}, \qquad \theta_{ion\parallel} = \frac{\triangle\, p_{ion\parallel}}{p_{ion}},$$

$$\theta_{e\perp} = \frac{\triangle\, p_{e\perp}}{p_e} = \frac{1}{\gamma\beta}\sqrt{\frac{T_{e\perp}}{mc^2}}, \qquad \theta_{e\parallel} = \frac{\Delta p_\parallel}{p_e} = \frac{1}{\beta}\sqrt{\frac{T_{e\parallel}}{mc^2}},, \qquad \eta_{cool} = \frac{l_{cool}}{C_{Ring}}.$$

Here $\Delta p_\perp$ ($\Delta p_\parallel$) are transverse (longitudinal) components of ion or electron momentum spreads in Lab. Ref. Frame, l_{cool} is cooling section length. Using The "Parkhomchuk Formula" one can derive Formula for cooling time:

$$\tau_{cool} = \frac{A_i}{Z_i^2}\cdot\frac{\beta^4\gamma^5}{4r_p c L_c}\frac{I_0}{J_e}\left(\theta_{i\perp}^2 + \frac{\theta_{i\parallel}^2 + \theta_{e\parallel}^2}{\gamma^2} + \theta_B^2\right)^{3/2}.$$

Here r_p is electron classic radius, J_e is electron beam density (A/cm^2) , θ_B is angular amplitude of solenoid magnetic field deviation.

$$L_c = ln\left(1 + \frac{\rho_{max}}{\rho_{L\perp} + \rho_{min}}\right), \qquad I_0 = \frac{mc^3}{e} \approx 17000\ A,$$

$\rho_{max} = [(\gamma\theta_{ion\perp})^2 + (\theta_{ion\parallel})^2]^{1/2}\, l_{cool}$, $\rho_{min} = Z_i r_e / \beta^2[(\gamma\theta_{ion\perp})^2 + (\theta_{e\parallel})^2]^{1/2}$, $\rho_{L\perp} = \beta\gamma\theta_{e\perp}\, mc^2/eB$ - **electron "transverse" Larmor radius .**

II. Electron Cooling Method: Physics of Electron Cooling

Cooling Time (Contnd)

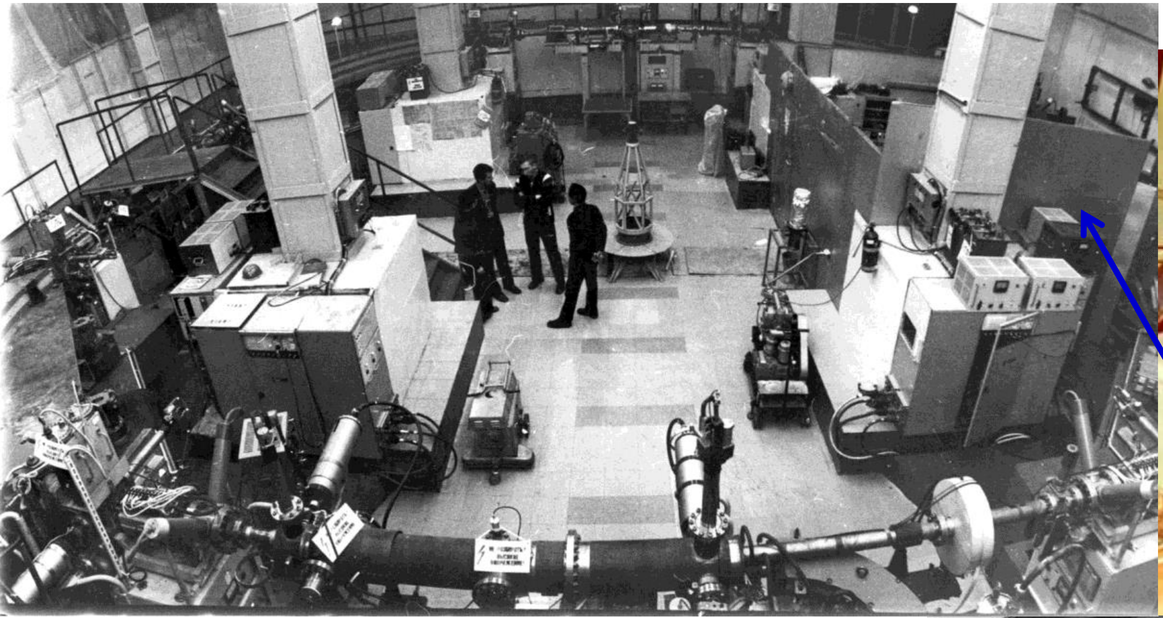
Numerical examples:

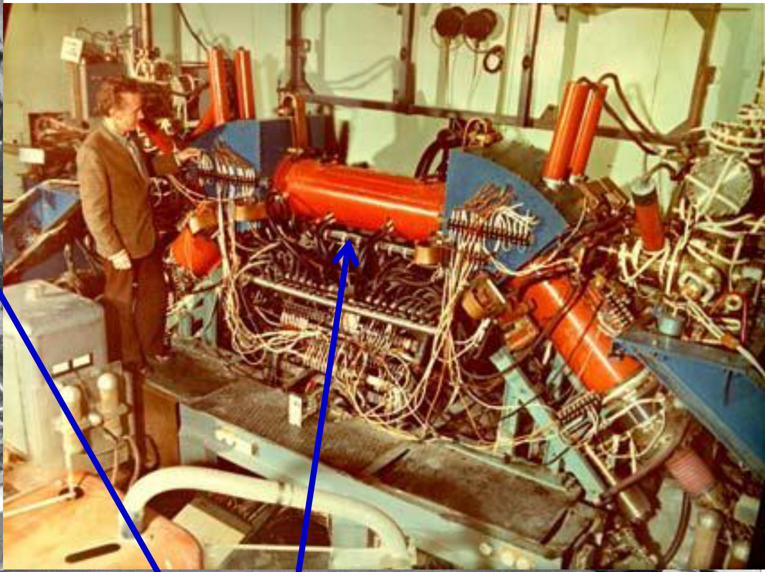
Three Cooler-Rings

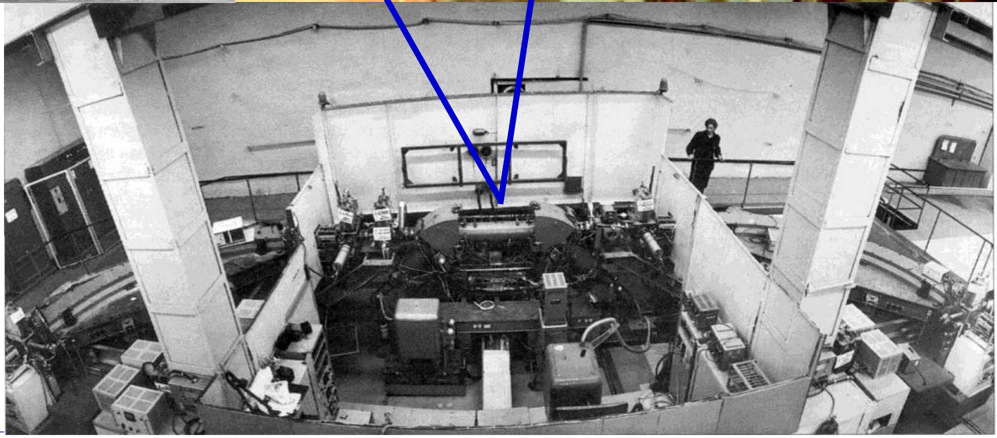
Cooler-Ring	NAP-M (Budker INP)		LEAR (CERN)	Recycler (Tevatron Fermilab)
Particles	p		$^{207}Pb^{54+}$	$\bar{p}$
Energy	80 MeV		4.5 MeV/u	8.0 GeV
C_{Ring}, m	47.0		78.0	3319.4
L_{cool}, m	1.0		1.5	20.0
J_e, A/cm^2	0.2		0.01	0.5
T_e, eV	0.2		0.2	0.2
$\theta_{i\perp}$, mrad	1.0	0.1	0.24	0.1
$\theta_{i\parallel}$, 10^{-3}	1.0	0.1	0.5	0.1
τ_{cool}	3.8 s	9.5 ms$^{*)}$	0.15 s	2.5 h
B, T	0.1		0.06	0.02

$^{*)}$ "Fast electron cooling" at small ion betatron amplitudes

First Experimental Proof: NAP-M Experiment (1974)





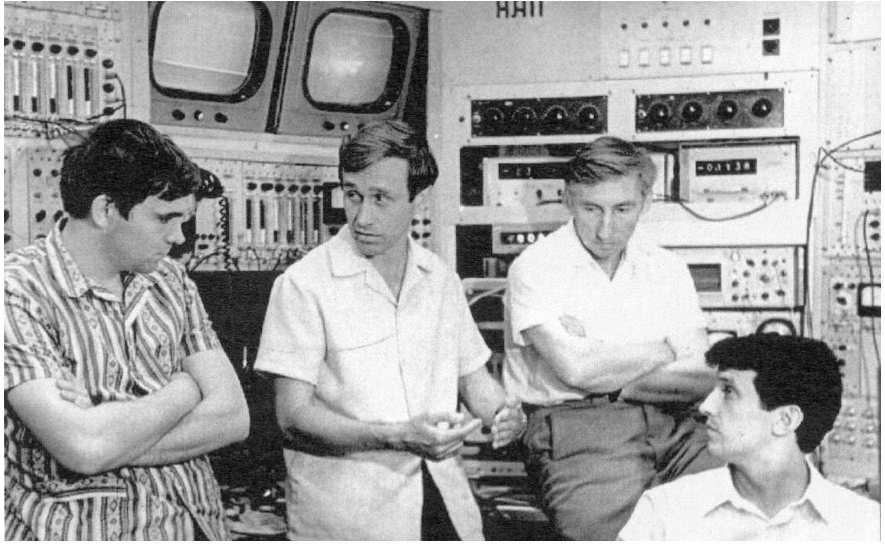


NAP-M :
"Antiproton Storage Ring – Model"
INP Novosibirsk, 1974 - 1984

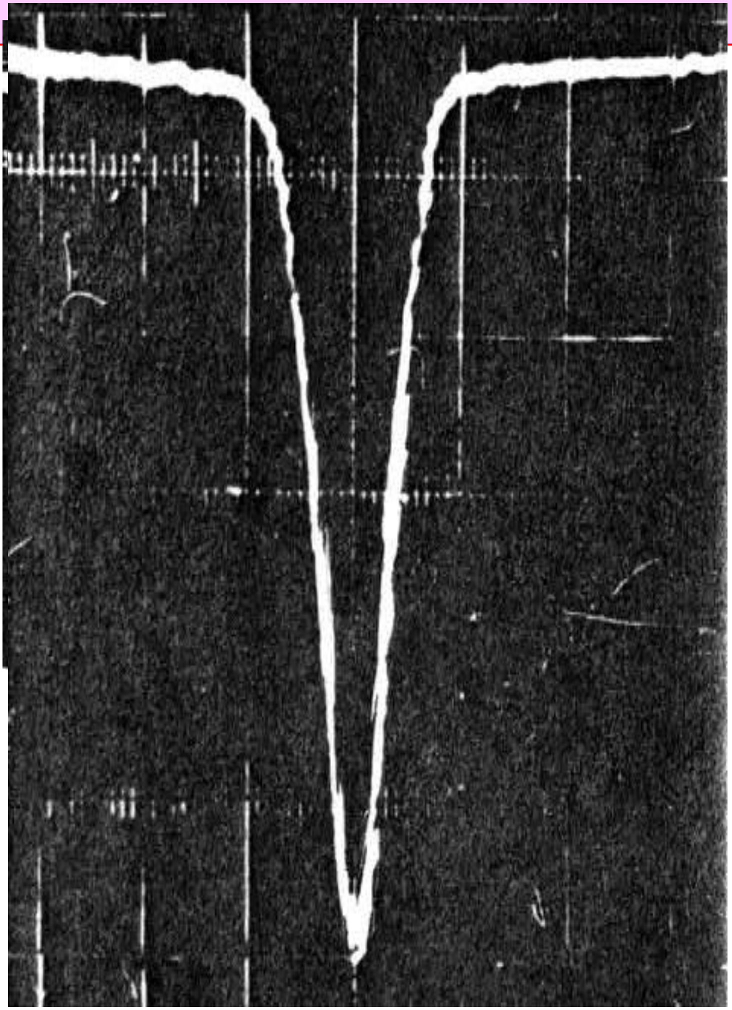
First electron cooler "EPOChA"
("Electron beam for cooling of antiprotons", Rus.)

II. Electron Cooling Method

First Experimental Proves: NAP-M Exper



V.Parkhomchuk, A.Skrinsky, I.Meshkov and N.Dikansky in NAP-M control room (1975)



Dynamics of proton density distribution at electron cooling (BPM based on Mg vapor jet, NAP-M, 1975)

Electron cooling theory in progress: Ya.Derbenev (1977)

Electron Cooling Technique

Two key elements of electron cooler:

1) Electron optic system for "cold" and intense electron beam formation;
2) Electron beam power recovering (recuperation)

<u>Electron optic system</u>: Electron beam immersed into longitudinal magnetic field $B_{||}$.

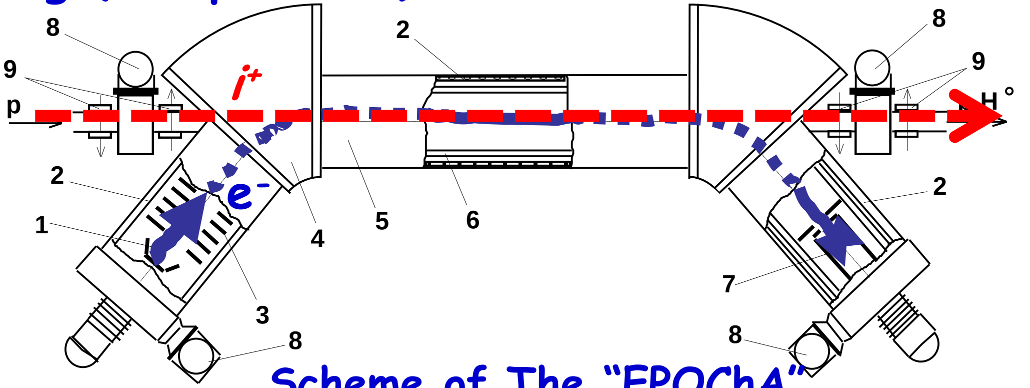
Two kinds of electron optics in $B_{||}$:

- Resonant optics,

$$L_B = 2\pi\rho_L n,\ n = 1,2,\ldots;$$

- Adiabatic optics, $L_B >> \rho_L$.

L_B – length of inhomogeneous $B_{||}$,
ρ_L – electron Larmor radius.



Scheme of The "EPOChA"

1 – electron gun, 2, 4 – solenoids with iron shield, 3 – anodes, 5 – cooling section, 6 – vacuum chamber wall, 7 – electron collector, 8 – ion pumps, 9 – dipole magnets for correction of ion trajectories

Typical electron transverse temperature (due to optic distortion) ~ 0.2 eV in PRF;

Typical el-beam angular spread $\theta \leq 1$ mrad in Lab Ref. Frame.

II. Electron Cooling Method

Electron Cooling Technique

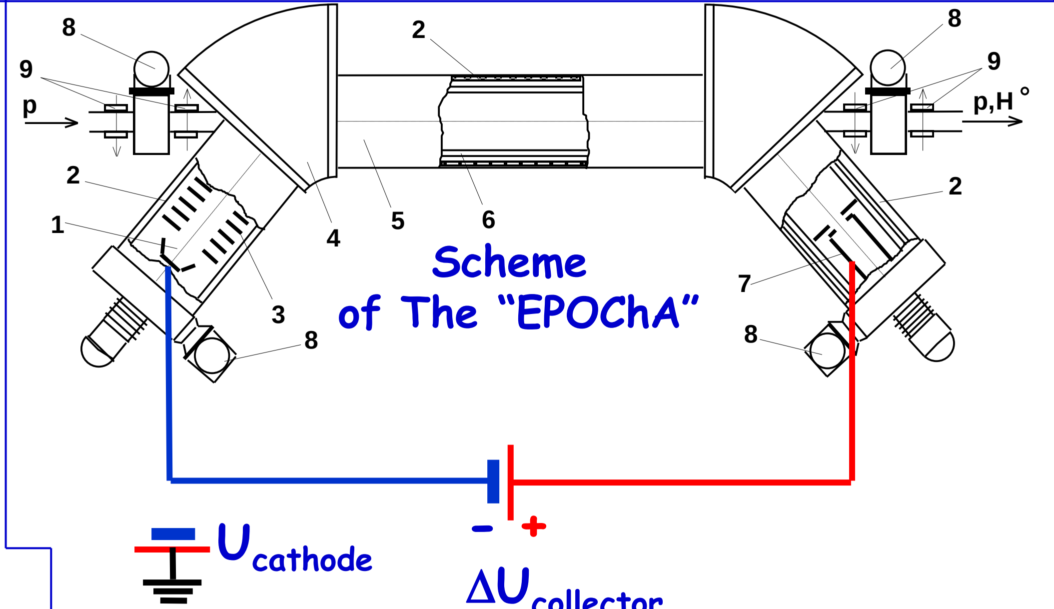
Electron beam power recovering

Electron collector is put on potential close to the cathode one.

Typical beam power recuperation parameters:

1. Electron collection efficiency

$$\Delta I/I \begin{cases} > 3\cdot10^{-3} \Rightarrow \text{bad} \\ \sim 1\cdot10^{-4} \Rightarrow \text{good} \\ < 1\cdot10^{-4} \Rightarrow \text{excellent} \end{cases}$$



Scheme of The "EPOChA"

$U_{cathode}$

$\Delta U_{collector}$

$|\Delta U_{collector}| << |U_{cathode}|$

2. Collector potential and electron beam current

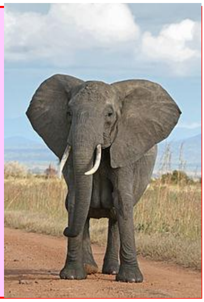
$$I_{max} = P_{collector} \times (\Delta U_{collector})^{3/2},$$

Collector- collector perveance

(from *pervenio*, Latin – to reach).

Typical value $P_{collector} \sim 15\ \mu A/V^{3/2}$, e.g. $I = 1$ A requires $\Delta U_{collector} \geq 1.65$ kV.

III. Stochastic Cooling Method



III. Stochastic Cooling Method

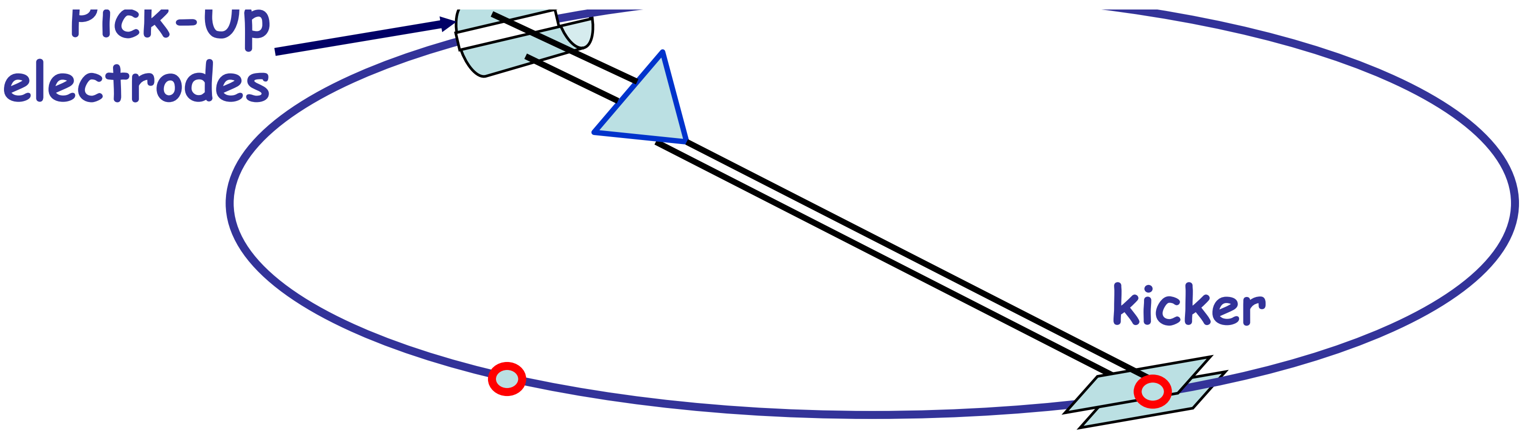
1968 S.van der Meer, Stochastic cooling

"Stochastic damping of betatron oscillations"

> *Such a system resembles Maxwell's demon, which is supposed to reduce the entropy of a gas… violating the second law of thermodynamics…"*
>
> *__Simon van-der Meer__, Nobel Lecture, p.2*

"Demons do not obey 2nd law of thermodynamics"

Boris Chirikov, 1969



III. Stochastic Cooling Method

First Experimental Proof: ISR$^{*)}$ experiment (1975)

1977

monstration of emittance cooling

"...After developing a primitive theory (1968) I therefore did not pursue this subject. However, the work was taken up by others and in 1974 the first experiments were done in the ISR."

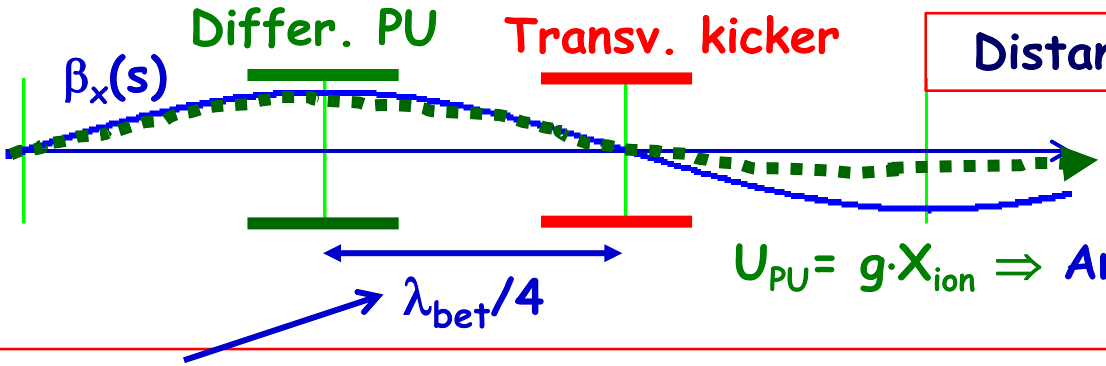
Simon van-der-Meer,
Autobiography of Nobel Laureat

Lars Thorndahl & Dieter Möhl –
– "others" who has done "the work"
(March 1977 – going to Zermatt).

III. Stochastic Cooling Method

Single Particle (Simplified) Approach

Transverse Stochastic Cooling



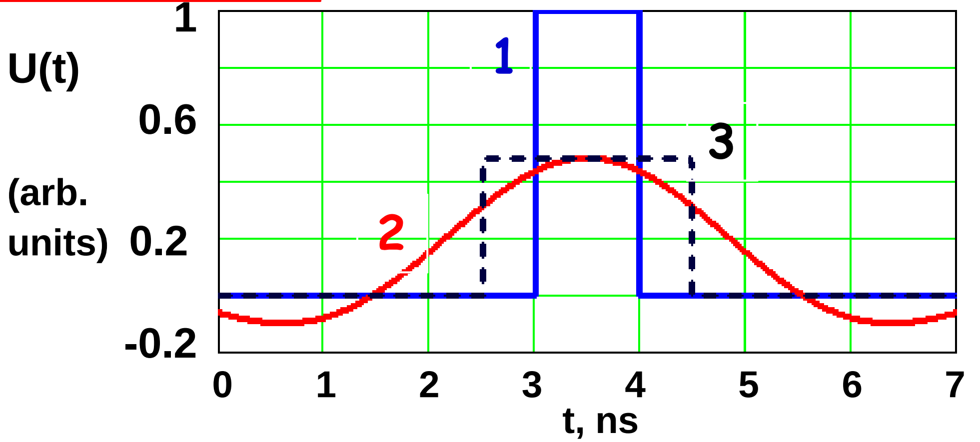
Distance PU – kicker = $\lambda_{bet}/4 + n\lambda_{bet}$

$U_{PU} = g\cdot X_{ion} \Rightarrow$ Amplifier (K) $\Rightarrow U_{kicker} = K\cdot g\cdot x_{ion}$

Owing to Kicker location it decreases ion angular betatron amplitude

Optional [6,7]

Signal transfer from PU to kicker



1 - input signal, τ_{signal} = 1 ns

2 – output signal, W = 0.25 GHz

3 – approximation of output signal

Uncertainty relation (or sampling theorem):

$$\tau_{pulse} \sim 1/2W,$$

where W is bandwidth of transfer line.

III. Stochastic Cooling Method

Multi-Particle Approach

Optional [6,7]

Transverse Stochastic Cooling – Cooling Time

1st approximation

Input signal of the test ion: $\tau_{signal} \approx \frac{L_{PU}}{V} \approx 1\,ns$

Output signal after passing through feed back $T_s = \frac{1}{2W}$

W – bandwidth of the feed back transfer line.

Ion "sample": $N_s = N \cdot \frac{T_s}{T_{rev}} \approx N \cdot \frac{L_{PU}}{C_{Ring}}$, T_{rev} – ion revolution period in the ring.

Test ion is free of influence of other ions in the sample during

$$\Delta t = \frac{T_s}{N_s} = \frac{T}{N}$$

Kicker kick changes ion betatron amplitude by $\Delta x = -\lambda x \equiv -k \cdot \Delta t \cdot x$.

Obviously, $\Delta t \equiv T_s$ and $\lambda_{optimum} = 1$. Then $k_{opt} = 1/T_s = 2W$.

Further, $\frac{dx}{dt} \approx \frac{\Delta x}{T_{rev}} = -\frac{\Delta t}{T_s} \cdot \frac{x}{T_{rev}}$. That gives us

$$\boxed{\tau_{cool}^{-1} = -\frac{1}{x}\frac{dx}{dt} = \frac{2W}{N}}$$

---

[6] D.Möhl, Proc. of CAS'1985 p.p. 453 – 533

[7] D.Möhl Stochastic Cooling of Particle Beams, Springer, Lecture Notes in Physics, v. 866

III. Stochastic Cooling Method

Multi-Particle Approach

Optional [6,7]

Transverse Stochastic Cooling – Cooling Time

2nd approximation: Omitting here detailed description let's contain ourselves here with formulation the result of rigorous analysis (see Ref. [6]) of so called *incoherent effect* – heating of the test ion by "other" ions of the sample. It gives us the cooling time value in 2nd approximation:

$$\boxed{\tau_{cool}^{-1} = \frac{2W}{N}\left(2g - g^2\left(1 + \frac{r_{NS}}{Z^2}\right)\right), \qquad g = \lambda N_s \approx \lambda N \cdot \frac{L_{PU}}{C_{Ring}}}$$

Customary name of g is "gain", λ is "electronic gain",

r_{NS} is noise-to-signal power ratio in feed back system;

for ions: $r_{NS} \Rightarrow r_{NS}/Z^2$, Ze – ion charge.

III. Stochastic Cooling Method

Multi-Particle Approach

Optional [6,7]

Transverse Stochastic Cooling – Cooling Time

3rd approximation: introduction of the "mixing factor" M – "number of turns for ion with average momentum error δp to move by one sample length" (see Ref. [6]). The mixing effect is related to off-momentum function (or "slip factor") :

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma^2_{transition}}\,, \qquad \frac{\delta f}{f} = \eta \cdot \frac{\delta p}{p}$$

Here γ and $\gamma_{transition}$ are Lorenz factors corresponding to ion energy and the ring transition energy, f is particle revolution frequency. It results in the following:

$$\boxed{\tau^{-1}_{cool} = \frac{2W}{N} \cdot \left[2g - g^2\left(M + \frac{r_{NS}}{Z^2}\right)\right], \qquad g_{opt} = \frac{1}{M + r_{NS}/Z^2}\ .}$$

Important to have $M \rightarrow 1$ ("good mixing" at ion travelling from kicker to PU).

III. Stochastic Cooling Method

Multi-Particle Approach

Optional [6,7]

Transverse Stochastic Cooling – Cooling Time

3rd approximation (continued):

"Bad mixing" occurs at ion travelling from PU to kicker and can be account by inserting the "bad mixing factor" $\widetilde{M}$:

$$\widetilde{M} = \frac{T_c}{\Delta t_{PU\to Kicker}}\,, \qquad T_c < T_s\,, \qquad \Delta t_{PU\to Kicker} = t_{PU\to Kicker}\cdot \eta_{PU\to Kicker}\cdot \frac{\Delta p}{p}$$

Then one should change $g \to g\left(1-\widetilde{M}^{-2}\right)$ and we find finally

$$\boxed{\tau_{cool}^{-1} = \frac{2W}{N}\cdot\left[2g\left(1-\widetilde{M}^{-2}\right) - g^2\left(M + \frac{r_{NS}}{Z^2}\right)\right] \ \cdot}$$

It calls The basic cooling rate (τ_{cool}^{-1}) equation [7].

Multi-Particle Approach

Optional [6,7]

Transverse Stochastic Cooling – Cooling Time

3rd approximation (ending):

Cooling time has minimum at

$$g_{opt} = \frac{1 - \tilde{M}^{-2}}{M + r_{NS}/Z^2} \; .$$

and it is equal to

$$\boxed{(\tau_{cool})_{min} = \frac{N}{W} \frac{M + \frac{r_{NS}}{Z^2}}{\left(1 - \tilde{M}^{-2}\right)^2}}$$

An example: $M = 1$, $\tilde{M}^{-2} = 0$, $r_{NS} \ll 1$, $N = 10^{10}$, $W = 2$ GHz $\Rightarrow$

$\Rightarrow \tau_{cool} = N/W = 5$ s.

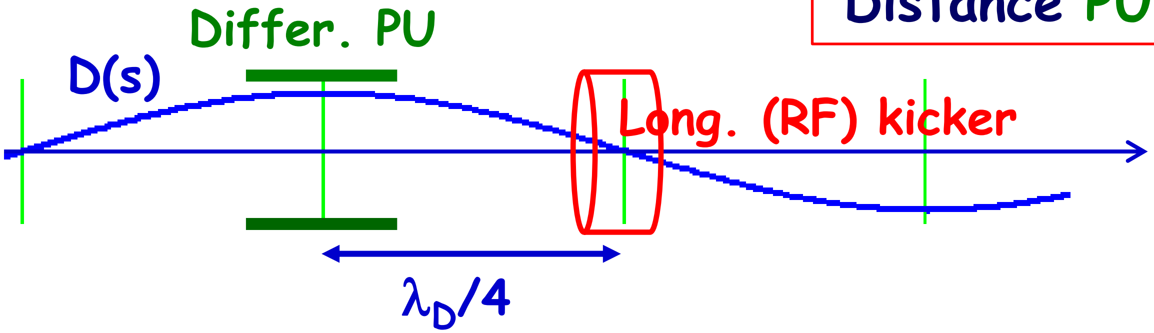
Note: Stochastic cooling time does not depend on ion beam emittance, but proportional to ion number in the beam! Therefore electron cooling and stochastic one are complimentary!

III. Stochastic Cooling Method

Single Particle Approach Longitudinal (Momentum) Stochastic Cooling

Palmer Method (R.B.Palmer, SLAC, 1975)

Distance PU – kicker = $\lambda_D/4 + n\lambda_D$



$$x_{PU}(\Delta p) = D_{PU}\times(\Delta p/p)$$

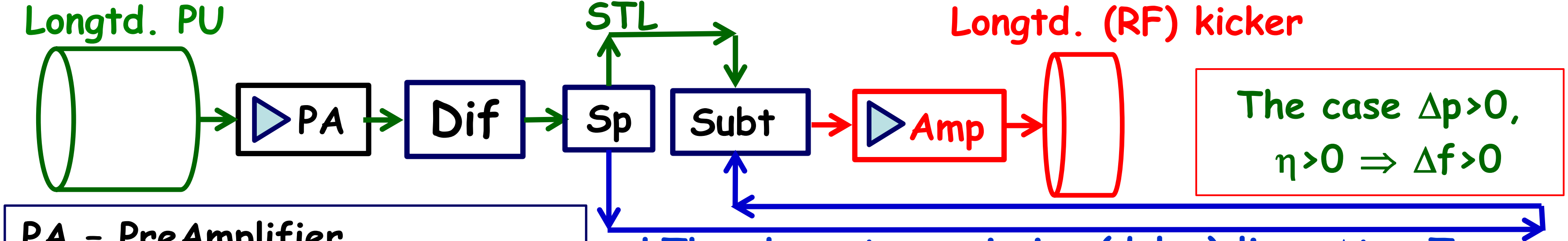
$$U_{PU} = g\cdot x_{PU}(\Delta p) \;\Rightarrow\; \text{Amplifier (K)} \Rightarrow U_{kicker} = K\cdot g\cdot x_{PU}(\Delta p)$$

Note: Owing to proper location of the kicker ($D_{kicker} = 0$) it decreases ion momentum without additional excitation of betatron oscillation – no betatron amplitude increase! (See Ref. [7], § 2.13 “Hereward cooling”).

III. Stochastic Cooling Method

Single Particle Approach Longitudinal (Momentum) Stochastic Cooling

Filter Method (L.Thorndahl & G.Carron, CERN, 1977)

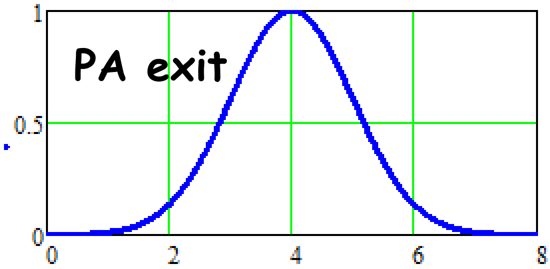


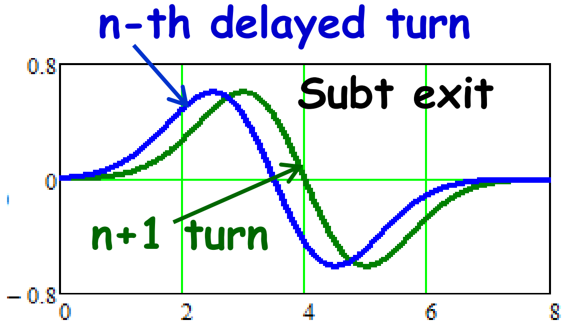
The case $\Delta p>0$, $\eta>0 \Rightarrow \Delta f>0$

LTL – Long transmission (delay) line: $\Delta t = T_{rev}$

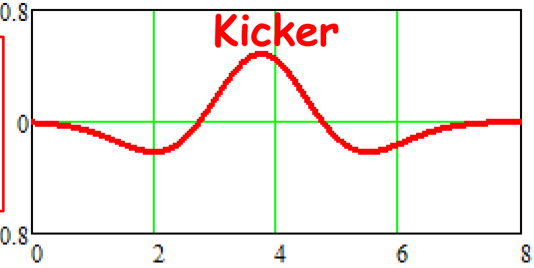
PA – PreAmplifier
Dif – Differentiator ($\pi/2$ phase shifter)
Sp – Splitter
STL – Short transmission line
LTL – Long transmission line
Subt – Subtractor
Amp – amplifier

Important remark:
PU location at filter method is indifferent to D(s) value. But not the Kicker! The condition $D_{ricker} = 0$ remains in force (see remark in previous slide).





at $\Delta p > 0$ ion decelerates
at $\Delta p = 0$ ion p = constant
at $\Delta p < 0$ – ion accelerates

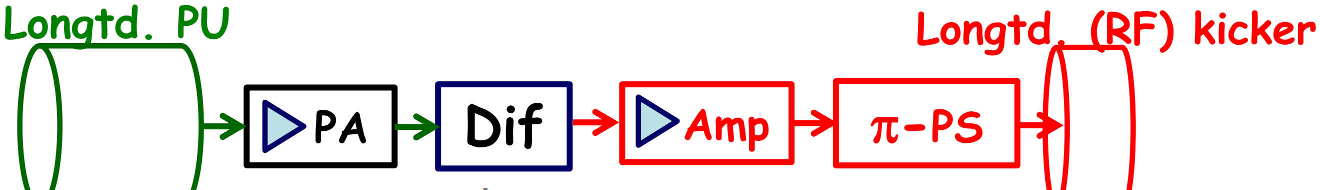


III. Stochastic Cooling Method

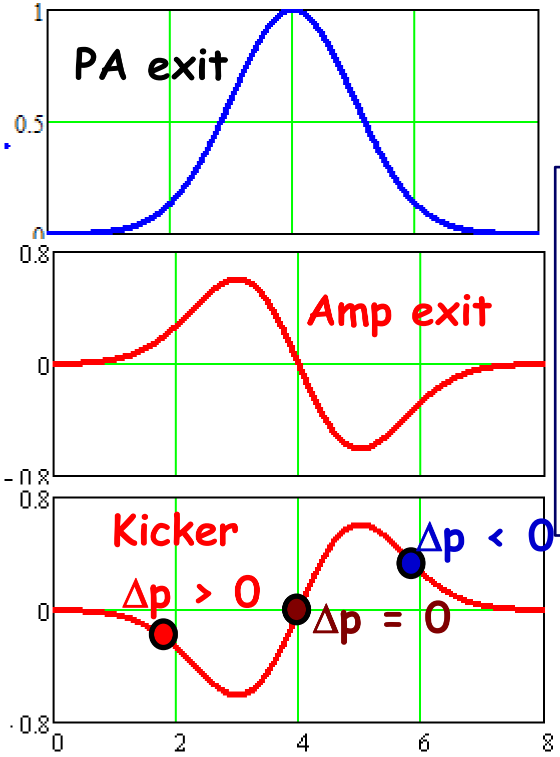
Single Particle Approach Longitudinal (Momentum) Stochastic Cooling

Time of flight (ToF) Method

(W.Kells, Fermilab – initial idea, 1980; R.Stassen, FZ Jülich – first realization, 2012)



PA – PreAmplifier
Dif – Differentiator
(π/2 phase shifter)
Amp – amplifier
π-PS – π-phase shifter



The method has been tested once at COSy cooler ring (2012), but was not implemented yet in operational cooling system[7].

The signal is delayed in feedback transmission line by $\Delta t_{delay} = T_{rev}$ so that ion in kicker
Decelerates, if $\Delta p > 0$,
Accelerates, if $\Delta p < 0$,
Gets zero "kick" if $\Delta p = 0$.

III. Stochastic Cooling Method

Stochastic Cooling Technique – Steady Progress

Amplifiers: From travelling-wave tubes ⇒
⇒ to solid-state powerful microelectronics

Transmission lines: From TEM waveguides ⇒ to optical transmission lines

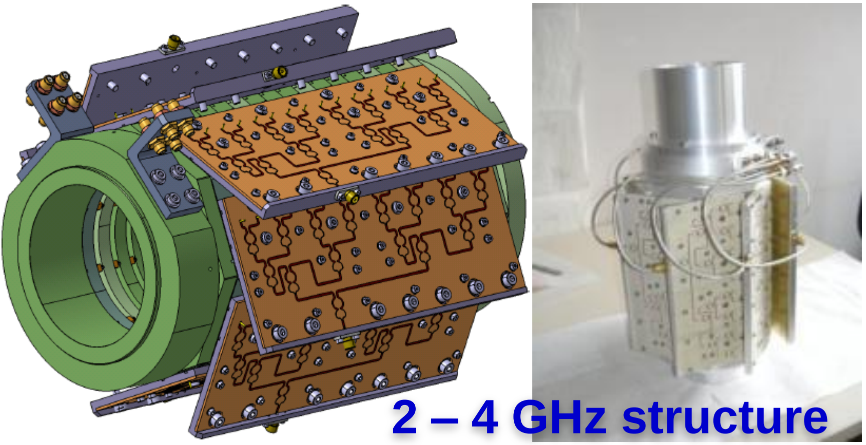
Pick-Ups and kickers ⇒ to wideband devices

"Ring slot coupler"

(L.Thorndahl, CERN and R.Stassen, FZ Jülich)

This sophisticated device can work both as PU and kicker.

It is used at Nuclotron (JINR) and will be used for NICA Collider (JINR) and HESR (FAIR).



2 – 4 GHz structure

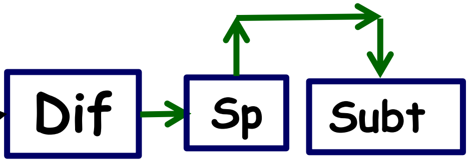
<u>Result</u>: bandwidth of stochastic cooling system increased
from W ~ 300 MHz (150 ÷ 500 MHz)
to 2 and 4 GHz (2 ÷ 4 GHz and/or 4 ÷ 8 GHz).

It led, correspondingly, to shortening of cooling time!

Stochastic Cooling Technique - Steady Progress

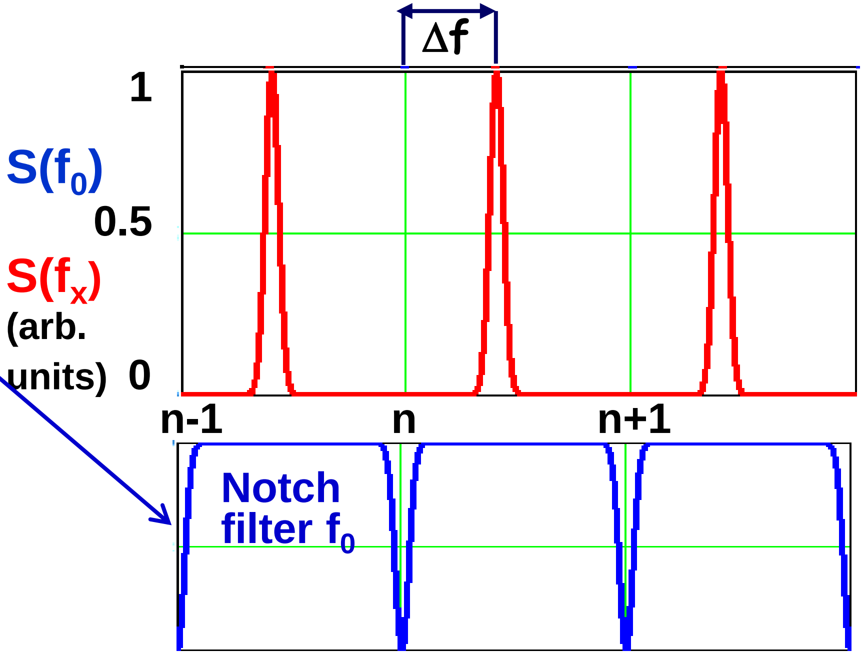
Progress in microelectronics – one example

In early years of the stoch. cooling method development **these three elements** were used with so called
notch filter (“comb”)
that worked for pulse preliminary analysis.



Nowadays it is
one integral circuit (a “chip”),
like “Hybrid coupler 180^0”

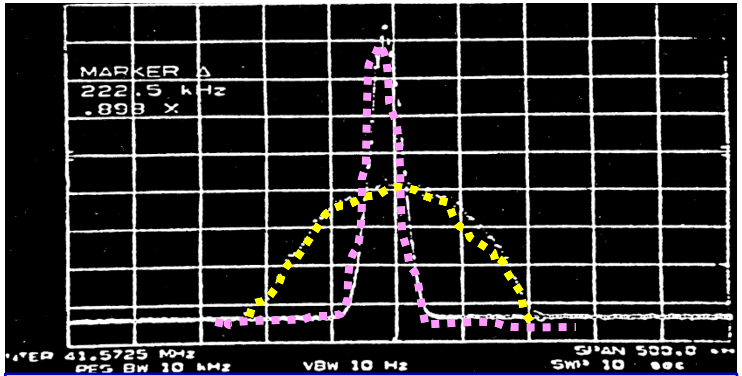
Spectra of equilibrium ion (f_0) and of one shifted by energy (velocity)



III. Stochastic Cooling Method

Stochastic Cooling Technique - Steady Progress

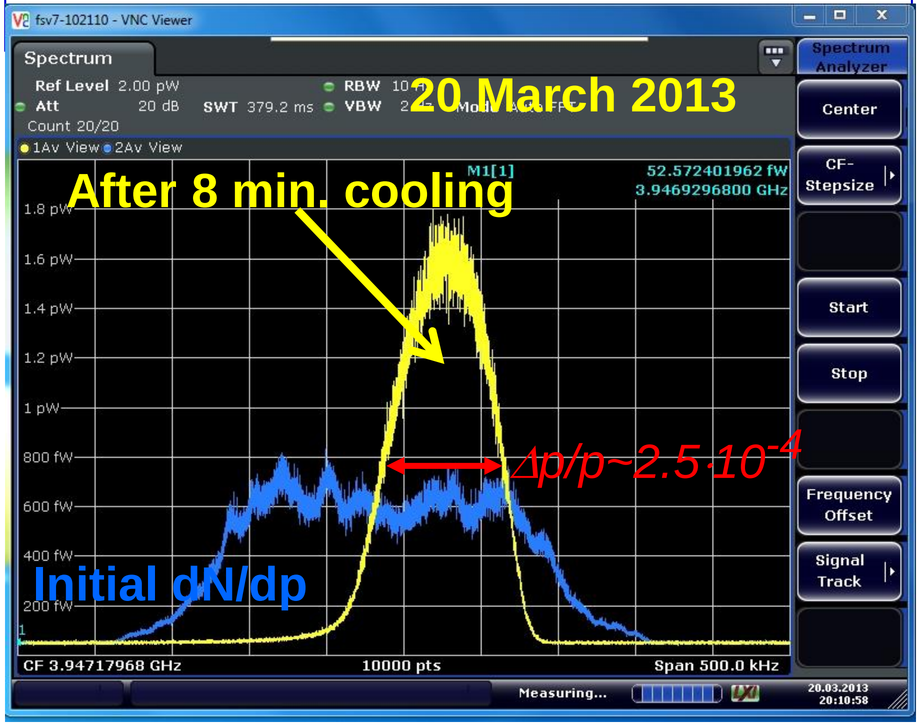
Two Examples



Momentum cooling of antiprotons in Low Energy Antiproton Ring - LEAR, CERN, 1988

Momentum distribution of 3×10^9 antiprotons at injection and after 3 min. cooling, W = 250 MHz.

Momentum Stochastic Cooling Experiment at Nuclotron (JINR)


fsv7-102110 - VNC Viewer

Spectrum

Ref Level 2.00 pW

Att 20 dB

SWT 379.2 ms

RBW 10

VBW 2

Count 20/20

M1[1] 52.572401962 fW 3.9469296800 GHz

CF 3.94717968 GHz

10000 pts

Span 500.0 kHz

Measuring...

20.03.2013 20:10:58

20 March 2013

After 8 min. cooling

$\Delta p/p \sim 2.5\cdot10^{-4}$

Initial dN/dp

IV. Laser Cooling Method

IV. Laser Cooling Method

First laser cooling in co

1990 TSR
(MPI Heidelberg,
Mainz Univ., GSI)

S.Schröder

VOLUME 64, NUMBER 24 PHYSICAL REVIEW

First Laser Cooling of Relativisti

S. Schröder, R. Klein, N. Boos, M. Gerhard, R. Grie
and N. Schmi
Institut für Physik der Universität Mainz, D-6500

T. Kühl and R. Ne
Gesellschaft für Schwerionenforschung, D-6100 Da

V. Balykin,[a] M. Grieser, D. Habs, E. Jaeschke, D. Krä
D. Schwalm, P. Sigray,[c] M. Steck,
Physikalisches Institut der Universität Heidelberg a
D-6900 Heidelberg, Federal Re
(Received 26 Februar

The first successful laser cooling of ions at relativistic
storage ring. A $^7Li^+$-ion beam of 13.3 MeV was overlap
propagating laser beams. The metastable ions were coole

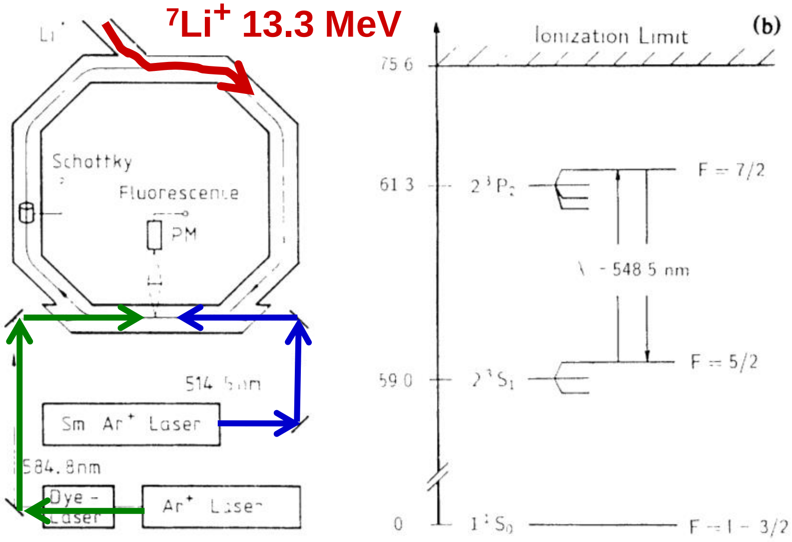


FIG. 1. (a) Experimental setup and (b) partial $^7Li^+$ level scheme. Two counterpropagating laser beams (single-mode Ar$^+$-ion laser and ring dye laser) are merged with the $^7Li^+$-ion beam stored in the TSR at $\beta = 0.064$. The fluorescence signal is detected by a photomultiplier at 90°. The dynamical properties of the stored beam are monitored by a Schottky noise pickup in (a). A schematic $^7Li^+$ level scheme is shown in (b). The closed two-level system $^3S_1(F=\frac{5}{2}) \rightarrow {}^3P_2(F=\frac{7}{2})$ is used for cooling as well as for fluorescence detection.

1991 ASTRID
(Aarhus Univ.)

J.S.Hangst

VOLUME 67, NUMBER 10 PHYSICAL REVI

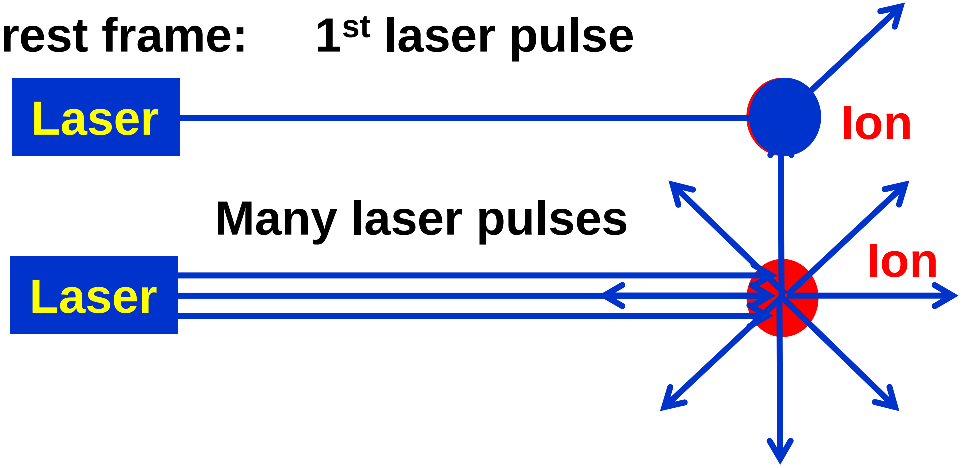
Laser Cooling of a Stor

J. S. Hangst,[a],[b] M. Kristensen, J. S. Nielse
Institute of Physics, University of Aarhus, DK-8000 Aarhus C, Denmark
(Received 5 February 1991)

The interaction of laser-induced and intrabeam forces has been studied in a dense stored beam of 100-keV $^7Li^+$ ions. A fraction of the ions ($\sim 10^{-4}$) exist in the metastable $1s2s\,^3S$ state. Using this state as a laser spectroscopic probe, we observe fast longitudinal heating in the injected, nonequilibrium distribution due to Coulomb scattering. Laser cooling of the metastable ions is ineffective during this heating period. The metastable fraction of the equilibrated beam is subsequently laser cooled to a longitudinal temperature of ~1 mK, the lowest temperature ever reported in a stored ion beam.

Physics of Laser Cooling

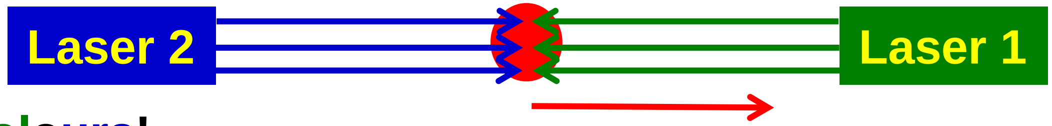
In ion rest frame: 1st laser pulse



Many laser pulses

Directed flux of laser photons forms directed force. However, it is drag force:

one direction force (!) – not a cooling force. The latter one can be formed with two laser beams – co- and counter propagating.



Vector of the ion velocity

Do mind beam colours!

Optional [8,9]

Physics of Laser Cooling

In ion (particle) rest frame laser beams have Doppler shifted frequencies:

$$(\omega_{PRF})_{1,2} = \gamma \cdot (\omega_L)_{1,2} \cdot (1 \pm \beta)$$

Here index 1 denotes counter propagating laser beam, index 2 – co-propagating one. Momentum from single photon absorption is

$$p_{1,2} = \pm\hbar \frac{(\omega_{PRF})_{1,2}}{c}$$

Then laser cooling force can be written as following:

$$F_\omega = \frac{dp_1}{dt} + \frac{dp_2}{dt} = p_1 \frac{d\dot{N}_1}{dS}\sigma(\omega_1) + p_2 \frac{d\dot{N}_2}{dS}\sigma(\omega_2)$$

$\frac{d\dot{N}_{1,2}}{dS}$ **- flux density of lasers' photons, $\sigma(\omega_{1,2})$ – photons' absorption cross section:**

$$\sigma(\omega) \cong \lambda_\omega^2 \frac{(\Gamma/2)^2}{(\omega - \omega_0)^2 + (\Gamma/2)^2},$$

ω_0 – ion transition frequency, Γ - transition line width.

[8] D.Möhl & A.Sessler, NIM A 532 (20014) 1-10; [9] V.Parkhomchuk, Proc. JAS-2000

Optional [8,9]

Physics of Laser Cooling

Laser Cooling Force

For nonrelativistic ions ($\beta << 1, \gamma \approx 1$) and $\dot{N}_1 = \dot{N}_2 = \dot{N}$ one can find

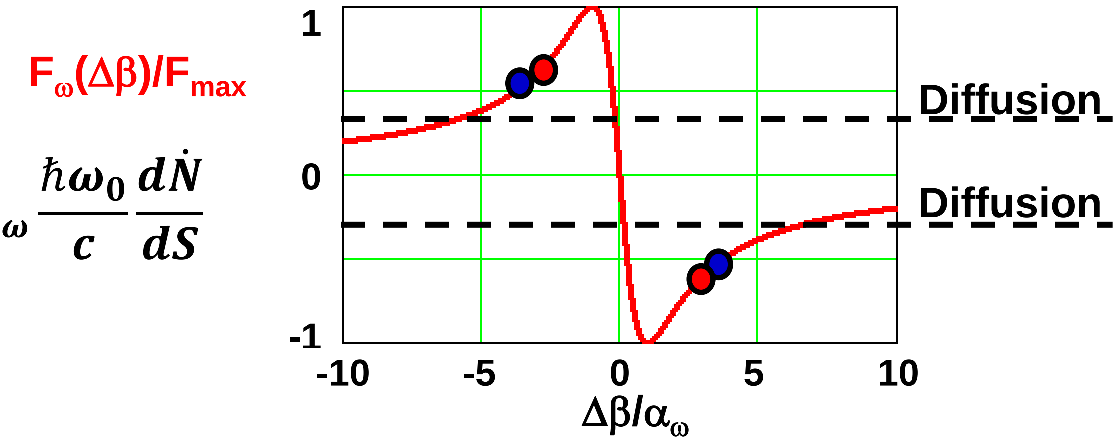
$$F_\omega = -\lambda_\omega^2 \alpha_\omega \frac{\hbar\omega_0}{c} \frac{2\cdot\Delta\beta}{(\Delta\beta)^2 + \alpha_\omega^2} \frac{d\dot{N}}{dS}, \qquad \Delta\beta = \beta - \beta_0,$$

$\beta_0 = V_0/c$, V_0 – **<u>ion equilibrium velocity</u> that follows from the equation**

$$(\omega_{PRF})_1 = (\omega_{PRF})_2 = \omega_0 \quad \text{at } V = V_0 .$$

$$\alpha_\omega = \frac{\Gamma}{2\omega_0}$$

$$F_{max} = \lambda_\omega^2 \alpha_\omega \frac{\hbar\omega_0}{c} \frac{d\dot{N}}{dS}$$



IV. Laser Cooling Method

Optional [8,9]

Physics of Laser Cooling

Laser Cooling Time

$$\tau_{cool}^{-1} = -\frac{2\eta}{M}\frac{dF_{\omega}}{dV} \approx \frac{4\eta}{Mc}\cdot\frac{\lambda_{\omega}^{2}}{\alpha_{\omega}}\frac{\hbar\omega_{0}}{c}\frac{d\dot{N}}{dS}, \qquad \Delta\beta << \alpha_{\omega}, \qquad \frac{d\dot{N}}{dS} = \frac{1}{\hbar\omega_{0}}\frac{dP_{Laser}}{dS}.$$

An example (Parameters of TSR-1990 experiment):

$^{7}Li^{+}$ ions, λ_{ω}= 548.5 nm, ω_0 = $3.44\cdot10^{15}$ s^{-1}, ε_{photon}= 2.19 eV, Γ = 23 MHz, α_{ω} = $3.38\cdot10^{-9}$, P_{laser} = 40 mW, $d^{2}N_{photon}/dS\cdot dt$ = $1.14\cdot10^{9}$ $cm^{-2}\cdot s^{-1}$,

that gives $\tau_{cool} \approx$ 80 ns (!)

One should underline this cooling time value is minimum one (corresponding to cooling time of "fast" electron cooling – slide #32). In practice cooling time is defined by ΔV_{max} ($\Delta\beta_{max}$) and laser scanning time (see references in slide #53).

Optional

Physics of Laser Cooling

3D Laser Cooling

(!) Why can not one to cool ions transversally sending laser beam across ion one? **Because $(\eta_{cool})_{transverse} = \phi_{Laser}/C_{ring} \ll 1$!**

Therefore indirect methods should be applied.

There are presently two methods which use longitudinal-transverse coupling components of ion momenta: ions cooled longitudinally "redistribute" large transverse momentum components to small longitudinal ones

1) "sympathetic" (induced) cooling[10, 11] – using IntraBeam Scattering (IBS) in ion-ion collisions;

2) using coupling at excitation of synchro-betatron resonances in ion motion in the ring (proposed in [12] and demonstrated recently in [13].

---

[10] I. Lauer et al., Phys. Rev. Lett. 81, 2052 (1998); [11] N. Madsen et al., Phys. Rev. Lett. 83, 4301 (1999), [12] H.Okamoto, A.Sessler and D.Möhl, Phys. Rev. Lett. 72, (1994), 397, [13] A.Noda et al., Proc. of IPAC'2014, http://www.jacow.org

Laser Cooling Application

Most promising application of laser cooling is formation of so called crystalline beams

(see below, part VI, slides 83 - 86).

V. Muon Cooling Method

V. Muon Cooling Method

1965 A.A. Kolomensky: Ionization cooling

"On damping decrements in accelerators
under conditions of the arbitrary energy losses"
(*Atomnaya Energiya* v.19 (1965) 534, in Russian)

The concept turned out to be unproductive for heavy and strongly interacting particles like p, p̃, ions due to strong interaction (SI) with a target nuclei (n_0):

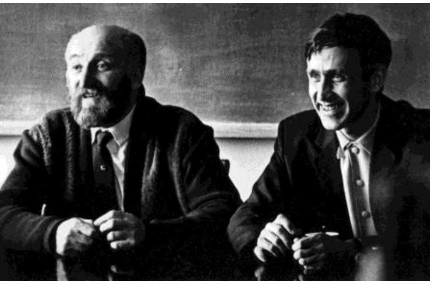
cooling rate ~ $\tau_{cool}^{-1} = 4\pi n_0 c r_e^2 Z_{target} z_p \cdot \dfrac{m_e}{\gamma m_p} \cdot \eta$, sec^{-1}

particle loss rate $\tau_{SI}^{-1} = \sigma_{SI} n_0 c \eta$, sec^{-1}; $\eta = d_{target}/C_{Ring}$.

For protons at E = 5 GeV and carbon target τ_{cool} / τ_{SI} ~ *150.*

Nevertheless, it was a good start idea

V. Muon Cooling Method



The main restriction: $\tau_\mu = 2.2\ \mu s$

But $\tau_{LRF} = \gamma\tau_\mu$ = 22 ms at 1 TeV!

1970 First Proposal of $\mu^+\mu^-$ Collider

G.I. Budker and A.Skrinsky:

Ionization cooling does work

when applied to muon beam formation:

Muons are deprived of Strong Interaction!

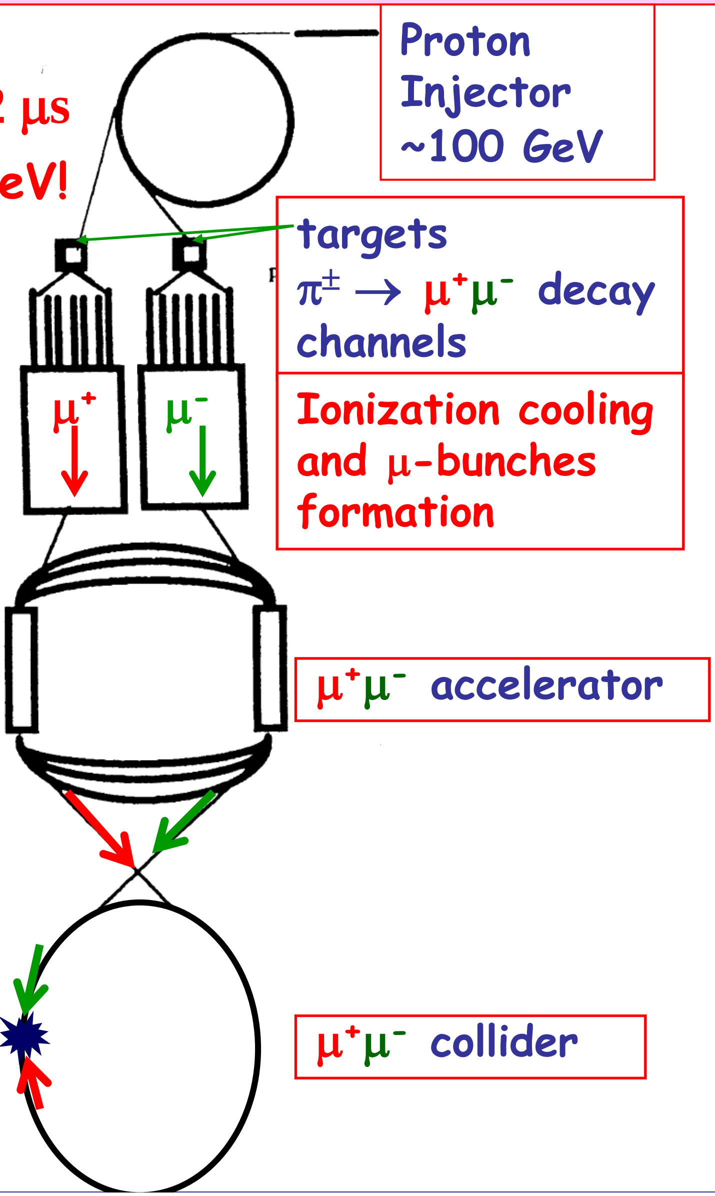
And synch. rad. is less than for $e^\pm$ by factor

$(m_\mu/m_e)^4 = (105.6/0.511)^4 \approx 1.6\times10^9$!

(G.I.Budker, in *Proc. of 15th Intern. Conf. on High Energy Physics.* Kiev, 1970
A.N. Skrinsky, Report at CERN seminar, 1971,
Uspekhi Fizicheskich Nauk, 1982, v.)

Further development – D.V.Neuffer (since 1979), R.B.Palmer (since 1994), and others

R.B.Palmer



Proton Injector ~100 GeV

targets

$\pi^\pm \rightarrow \mu^+\mu^-$ decay channels

Ionization cooling and μ-bunches formation

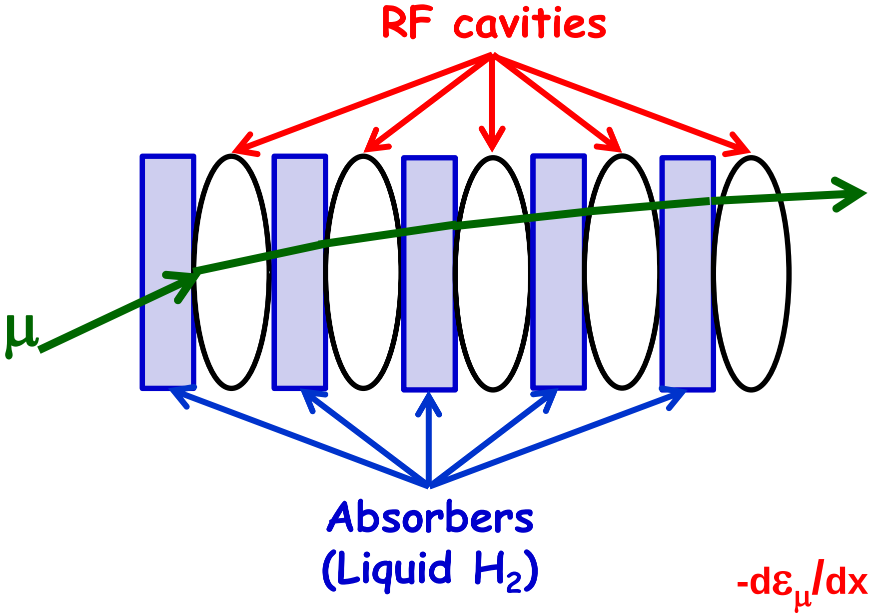
$\mu^+\mu^-$ accelerator

$\mu^+\mu^-$ collider

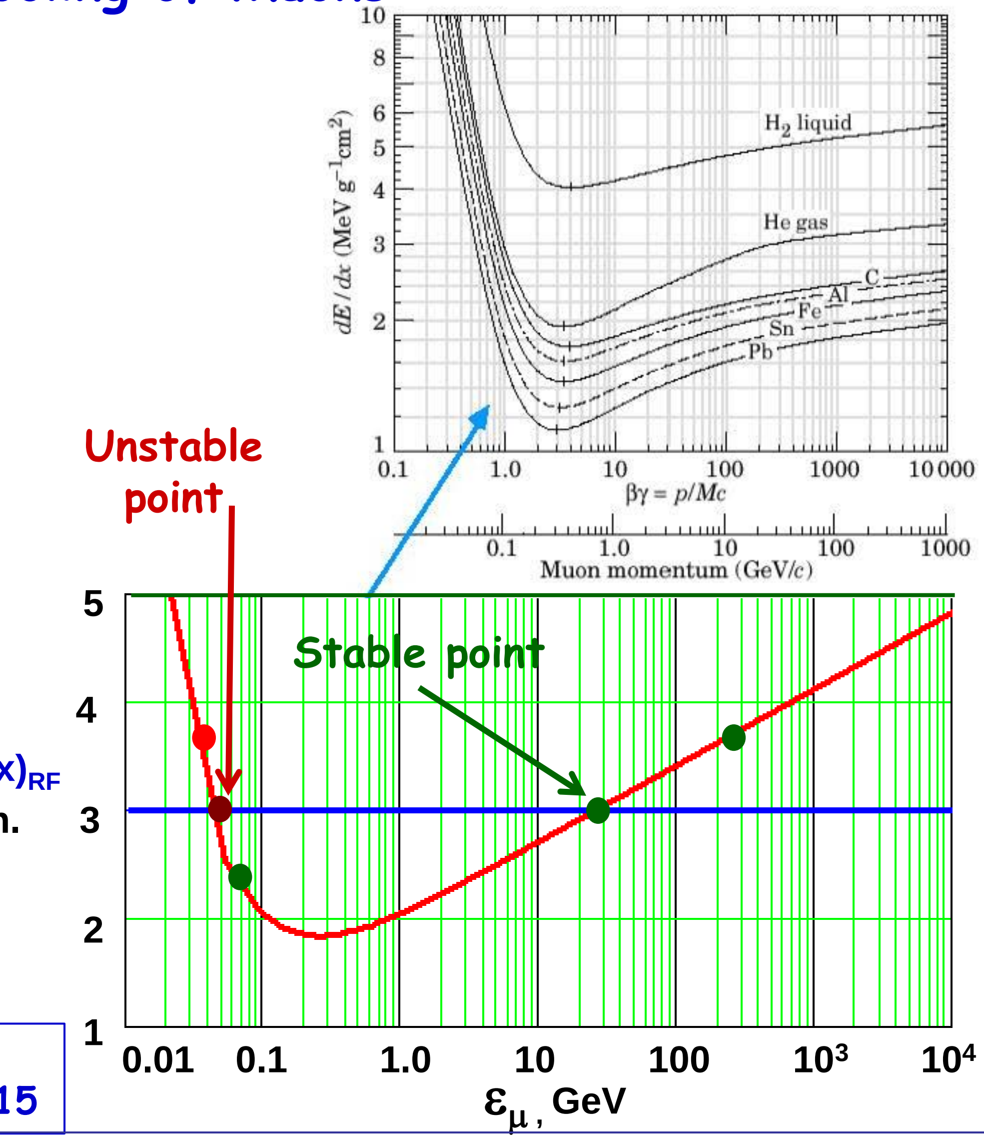
V. Muon Cooling Method

Ionization Cooling of Muons

Muon cooler scheme[14]



Why liquid hydrogen?
See next slide



[14] A.Skrinsky, in Proc. of Joint Accel. School US-CERN-JAPAN-RUSSIA, 2006, p.p.601-615

V. Muon Cooling Method

Optional

Ionization Cooling of Muons

Equilibrium state of muons at mu-cooling

Ionization friction force:

$$F_{cool} = -\frac{d\varepsilon_{\mu}}{ds} = -\frac{4\pi n_{target} Z_{target}\, e^{4}}{mc^{2}\beta^{2}}\left(ln\left(\frac{2mc^{2}\,\gamma^{2}\beta^{2}}{I(Z_{target})}\right) - \beta^{2}\right)$$

Ionization potential $I(Z_{target}) = 12.5 \cdot Z_{target}\ eV$

Ionization cooling time:

$$\tau_{cool}^{-1} = -\frac{\dot{p}_{z}}{p_{z}} = -\frac{F_{cool}}{\beta\gamma mc}\,, \qquad \gamma \gg 1\,.$$

Muon multiple scattering (ms) in the target: Z(Z+1) scattering effect!

$$\left(\frac{d\theta^{2}}{ds}\right)_{ms} = \frac{4\pi n_{target} Z_{target}\,(Z_{target}+1)}{\beta^{4}\gamma^{2}}\frac{z_{\mu}^{2}e^{4}}{m_{\mu}^{2}c^{4}} ln\left(183 Z_{target}^{-1/3}\right)$$

Equilibrium value θ_{equi} *follows from the equation*:

$$\frac{d\theta^{2}}{ds} = -\frac{\theta^{2}}{l_{cool}} + \left(\frac{d\theta^{2}}{ds}\right)_{ms}\,, \qquad l_{cool} \equiv \beta c \tau_{cool}\,,$$

Thus $\theta_{equi}^{2} = l_{cool}\left(\frac{d\theta^{2}}{ds}\right)_{ms} \propto (Z_{target}+1)$, and Z_{target} =1 is preferable.

What is now?

2001 Beginning of
International Muon Ionization Cooling Experiment (MICE)
at Rutherford Appleton Laboratory and Fermilab[15]

Two applications of muon cooling (and MICE goals):

1) $\mu^+\mu^-$ collider
2) neutrino factory – generation of neutrino flux with small divergence angle => increase of the luminosity (!) of long base neutrino oscillation experiment

---

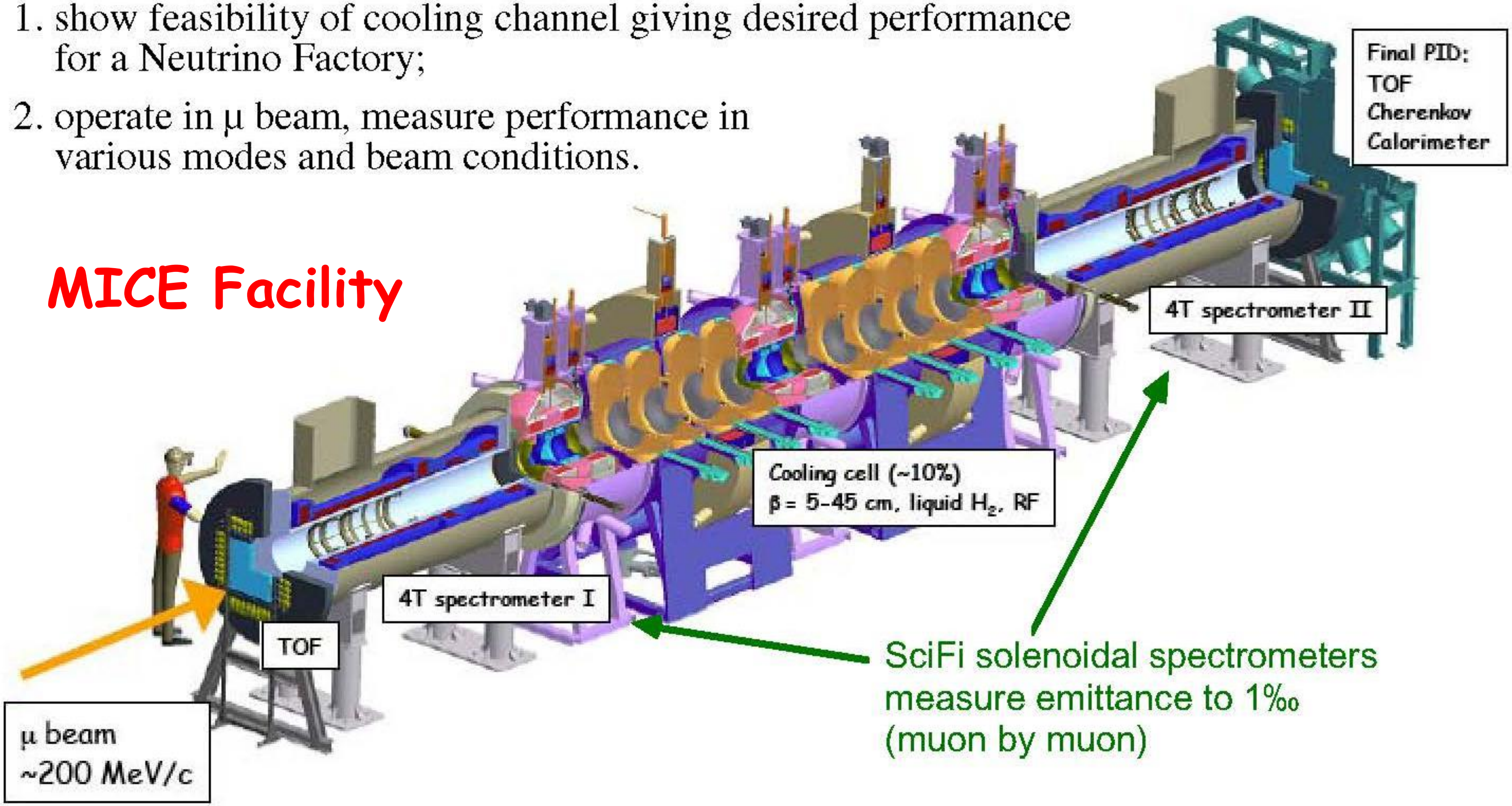
[15] R.Kaplan, in. Proc. Of Int. Conf. on High Energy Physics ICHEP'2006, Moscow

V. Muon Cooling Method

- **Goals:**

1. show feasibility of cooling channel giving desired performance for a Neutrino Factory;
2. operate in μ beam, measure performance in various modes and beam conditions.

MICE Facility



SciFi solenoidal spectrometers measure emittance to 1‰ (muon by muon)

- Large international, interdisciplinary collaboration:
  - >100 particle and accelerator physicists and engineers from Belgium, Bulgaria, China, Italy, Japan, Netherlands, Russia, Switzerland, UK, USA

VI. The Highlights of Cooling Methods' Application

VI. The Highlights of Cooling Methods' Application: Fruitful Years

First Generation of Cooler Storage Rings		Operation years
1	**NAP-M** (Storage Ring for Antiprotons – Model, Budker INP)	1974 - 1984
2	**ICE** (Initial Cooling Experiment, CERN)	1979 - 1980
3	**Test Ring** (FNAL)	1980 - 1982
4	**MOSOL** (MOdel of SOlenoid, BINP)	1986 - 1988
5	**LEAR** (Low Energy Antiproton Ring, CERN)	1988 - 1996
6	**IUCF Cooler** (Indiana Univ. Cyclotron Facility)	1988 - 2002
7	**TSR** (Test Storage Ring, MPI, Heideberg)	1988 => …
8	**TARN-II** (Test Accumulation Ring for Numatron, Tokyo Univ.)	1985 - 2000
9	**ASTRID** (Aarhus STorage RIng in Denmark, Aarhus Univ.)	1989 - 2005
10	**CELSIUS** (Cooling with ELectrons and Storing of Ions from Uppsala Synchrocyclotron, Uppsala Univ.)	1989 – 2005
11	**ESR** (Experimental Storage Ring, GSI)	1990 => …
12	**CRYRING** (CRYebis connected to a small synchrotron RING, MSL, Stockholm Univ. - *See C.J.Harlander and A.Barany, ECOOL'1984*)	1992 - 2009
13	**COSY** (COoler-SYnchrotron, FZJ)	1992 => …

VI. The Highlights of Cooling Methods' Application: Fruitful Years

9 Cooler Storage Rings Operated Presently

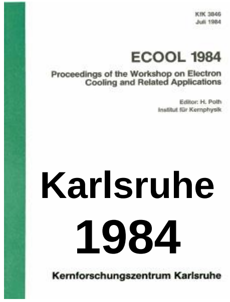
(including 3 listed in previous Table)

	Facility (Lab)	Application	Commissioning
1	**TSR** (MPI, Heideberg)	Nuclear and atomic physics, Accelerators technology	1988
2	**ESR** (GSI)		1990
3	**COSY** (FZJ)	Particle physics	1992
4	**SIS-18** (GSI)	Nuclear physics, Low energy part. phys.	1998
5	**HIMAC** (Chiba-Inage)	Cancer Therapy	2000
6	**AD** (CERN)	Physics of “anti-atoms”	2000
7	**LEIR** (CERN)	Lead ions for LHC	2006
8	**S-LSR** (Kyoto Univ.)	Particle beam physics	2005
9	**CSRm & CSRe** (HIRFL, IMP, Lanzhou)	Nuclear and atomic physics,	2008

10 Pelletron e-cooler at Recycler (Tevatron facility, Fermilab) 2005 - 2012

VI. The Highlights of Cooling Methods' Application: Fruitful Years

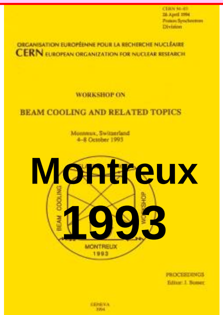
…and developed with the lapse of time:


KfK 3846
Juli 1984
ECOOL 1984
Proceedings of the Workshop on Electron Cooling and Related Applications
Editor: H. Poth
Institut für Kernphysik
Kernforschungszentrum Karlsruhe

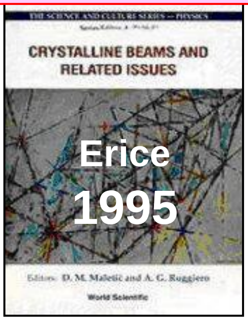
Karlsruhe 1984


Proceedings of the Workshop on
ELECTRON COOLING and NEW COOLING TECHNIQUES
Editors
L. Tecchio
World Scientific

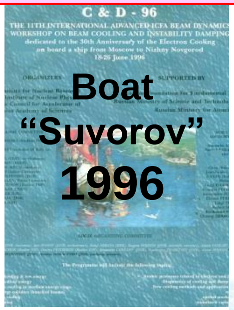
Legnaro 1990


CERN
Workshop on Beam Cooling and Related Topics
Montreux, Switzerland
4-8 October 1993
Proceedings

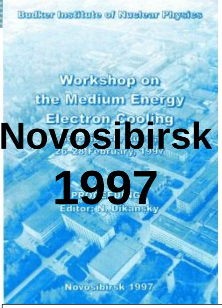
Montreux 1993


The Science and Culture Series — Physics
CRYSTALLINE BEAMS AND RELATED ISSUES
Editors: D. M. Maletic and A. G. Ruggiero
World Scientific

Erice 1995


C & D - 96

Boat "Suvorov" 1996

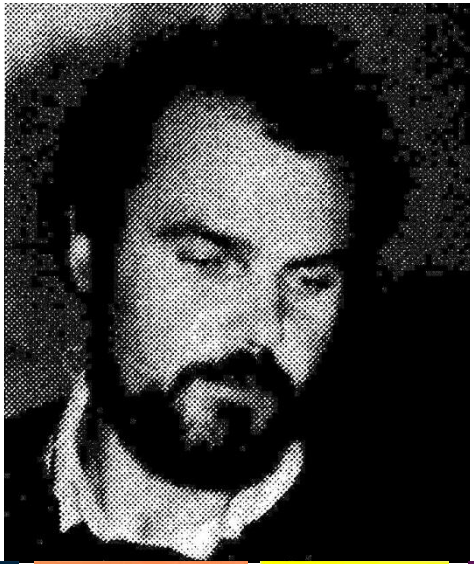

Budker Institute of Nuclear Physics
Workshop on the Medium Energy Electron Cooling
26-28 February, 1997
Editor: N. Dikansky
Novosibirsk 1997

Novosibirsk 1997

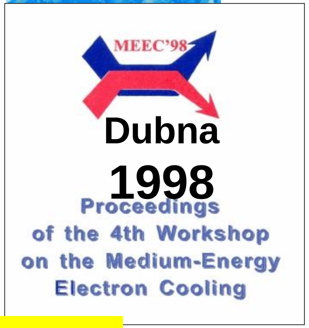
COOL'2015
JLAB, USA

It will be the 16th one

1984 First Cooling Workshop (Karlsruhe)…



…organized by Dr. Helmut Poth… (FZ Karlsruhe – Cern)



Dubna 1998

Proceedings of the 4th Workshop on the Medium-Energy Electron Cooling


COOL 11
Workshop on Beam Cooling and Related Topics
September 12 - 16, 2011
Pansionat "Dnepr", Alushta, Ukraine
hosted by JINR, Dubna
at support of BINP SB RAS, Novosibirsk and Scientific Council of RAS on Charged Particle Accelerators

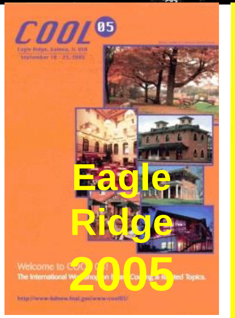
Alushta 2011


COOL'09
Workshop on Beam Cooling and Related Topics
August 31 - September 4, 2009
Lanzhou, China
(Organized By IMP, Lanzhou, China)
The workshop will highlight the state of the art in electron cooling, stochastic cooling, laser cooling, muon cooling, and storage of particles in antiproton and heavy ion traps.
http://cool09.impcas.ac.cn

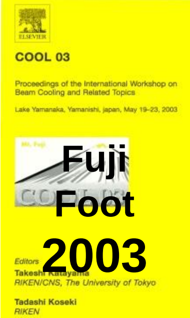
Lanzhou 2009


COOL 07
Workshop on Beam Cooling and Related Topics
September 10-14, 2007
Bad Kreuznach, Germany

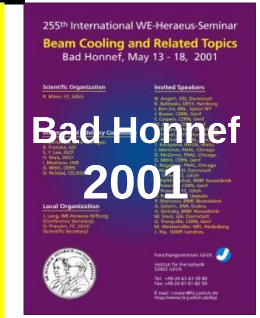
Bad Kreuznach 2007


COOL 05
Eagle Ridge, Galena, IL USA
September 18 - 23, 2005

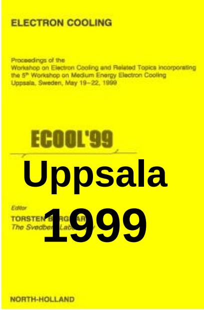
Eagle Ridge 2005


ELSEVIER
COOL 03
Proceedings of the International Workshop on Beam Cooling and Related Topics
Lake Yamanaka, Yamanashi, Japan, May 19-23, 2003
Editors
Takeshi Katayama
RIKEN/CNS, The University of Tokyo
Tadashi Koseki
RIKEN

Fuji Foot 2003


255th International WE-Heraeus-Seminar
Beam Cooling and Related Topics
Bad Honnef, May 13 - 18, 2001
Scientific Organization
Invited Speakers
Local Organization

Bad Honnef 2001


ELECTRON COOLING
Proceedings of the Workshop on Electron Cooling and Related Topics incorporating the 5th Workshop on Medium Energy Electron Cooling
Uppsala, Sweden, May 19–22, 1999
ECOOL'99
NORTH-HOLLAND

Uppsala 1999

VI. The Highlights of Cooling Methods' Application: Fruitful Years

Optional

- ✓ Both electron and stochastic cooling systems became routine tools at cooler storage rings
- ✓ 1993 – 2010 BETACOOL code for cooling processes simulation developed (JINR) and experimentally tested at COSY, ESR, CELSIUS, LEAR, Fermilab Recycler…)
- ✓ 1998 Schwere Ionen Synchrotron [German] (SIS-18, GSI) with E-cooling (E-Cooler has been constructed at BINP)
- ✓ 2000 Heavy Ion Medical Accelerator in Chiba (HIMAC, Chiba-Inage, Japan)
- ✓ 2000 Antiproton Decelerator (AD, CERN) – commissioning with E- and S-cooling

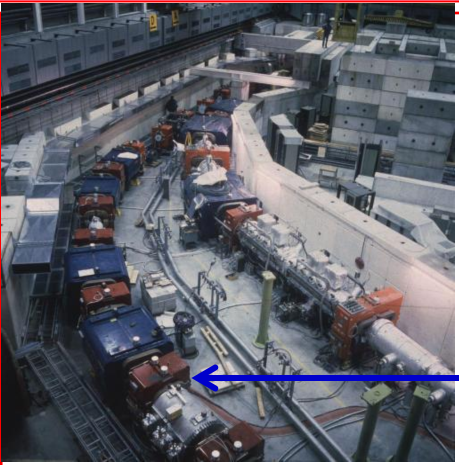
VI. The Highlights of Cooling Methods' Application: Fruitful Years

Optional

- ✓ 2001 Beginning of International Muon Ionization Cooling Experiment (**MICE**) at RAL and Fermilab
- ✓ 2005 S-LSR (**S**mall **L**aser Equipped **S**torage **R**ing, Kyoto Univ.) - commissioning with E-cooling
- ✓ 2005 Recycler (Fermilab) – commissioning of "The Pelletron", HV E-cooler of 4.3MeV and 1 A electron current
- ✓ 2006 Low Energy Ion Ring (LEIR, CERN) - commissioning with E-cooling of Pb ions (E-Cooler has been constructed at BINP)
- ✓ 2008 Heavy Ion Research Facility at Lanzhou (HIRFL, IMP Lanzhou) - - commissioning with E-cooling (E-Coolers have been constructed at BINP)
- ✓ Very recent "Past":

  2013 March S-LSR (Kyoto Univ.) - 3D Laser cooling

VI. The Highlights of Cooling Methods' Application: Particle Physics



$W^{\pm}$ and Z Bosons

Antiproton Generation Complex at CERN based on stochastic cooling application,

Antiproton Accumulator (AA)

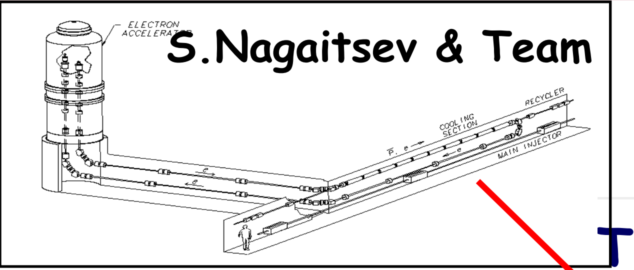
has been constructed ~ 1978.

Owing to this technology construction of first pp collider The Super Proton Antiproton Synchrotron (S$\tilde{\text{P}}$PS) became possible.

It resulted in the discovery of "nobel level".

VI. The Highlights of Cooling Methods' Application: Particle Physics

2000 – 2011: $\tilde{p}p$ Collider Tevatron (Fermilab)

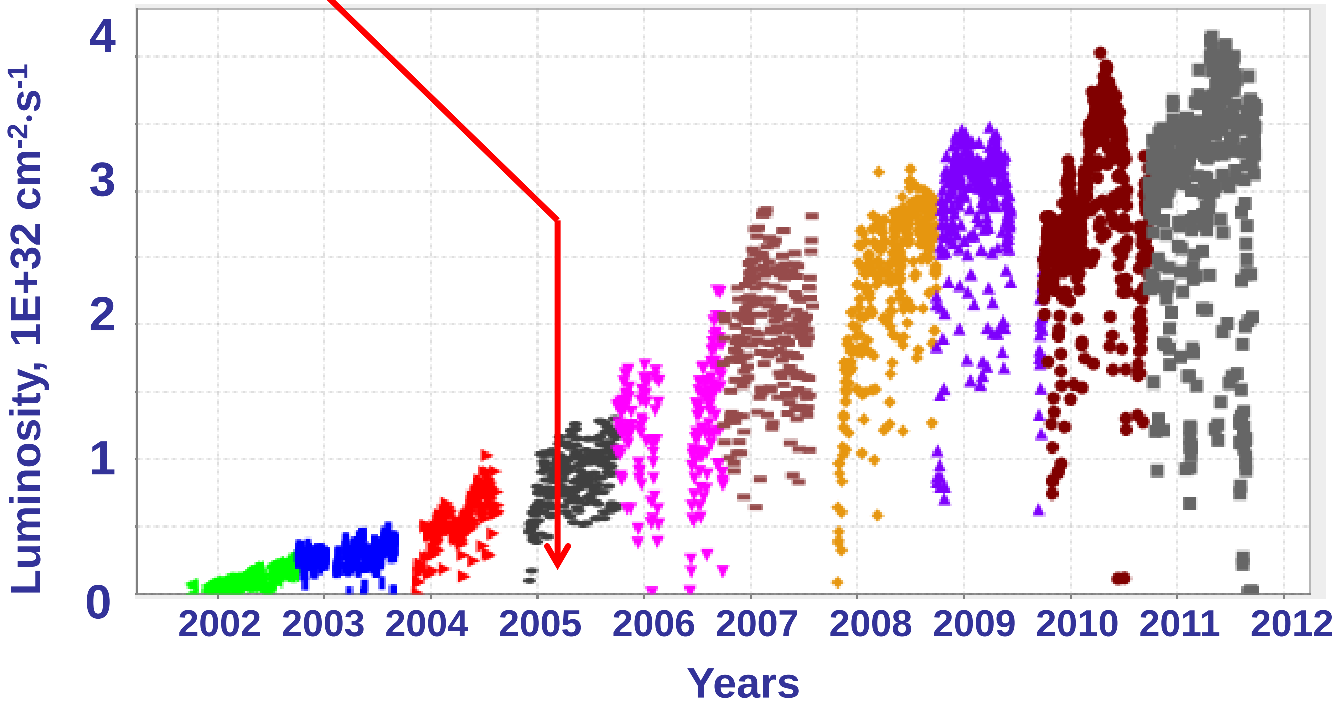


S.Nagaitsev & Team

Steady Progress

Run IIA
$\bar{p}p$ 2x900 GeV
L_{max} = 4×10^{32} $cm^{-2} \times s^{-1}$

Tevatron Peak Luminosity



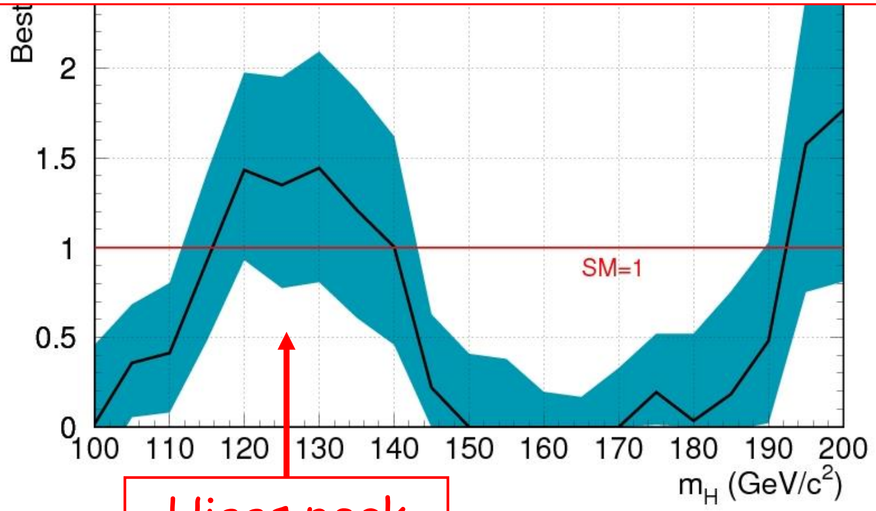
2001 – 2011 Integrated luminosity 11.87103 1/fb ≈ 1.19e39 cm^{-2}

VI. The Highlights of Cooling Methods' Application: Particle Physics

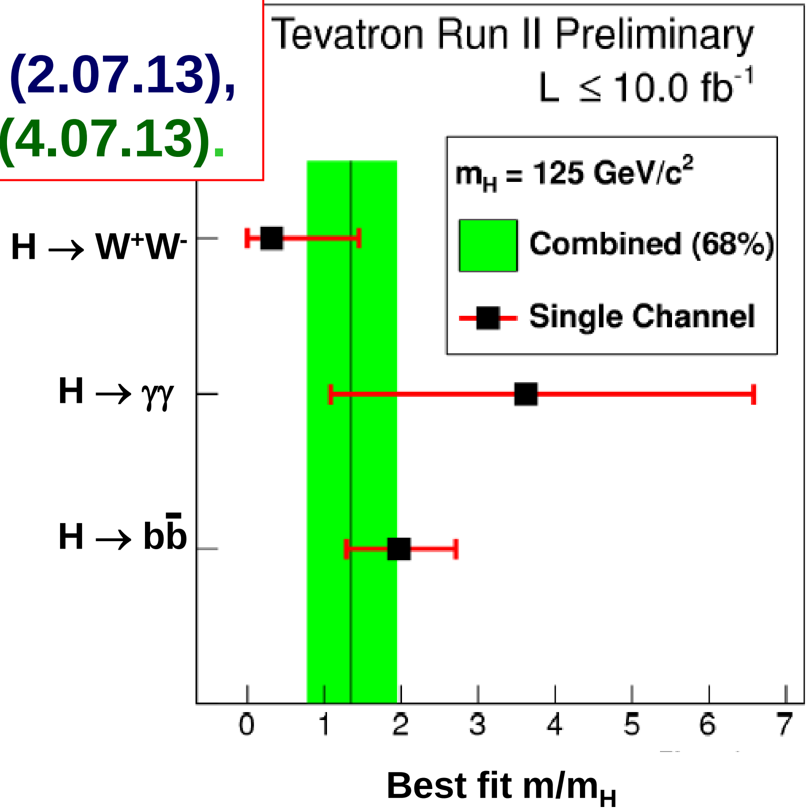
2000 – 2011: $\tilde{p}p$ Collider Tevatron (Fermilab)

2 July 2012, Fermilab seminar

1 sigma => random fluctuations,
3 sigma => an observation => Fermilab (2.07.13),
5-sigma result is a discovery => CERN (4.07.13).



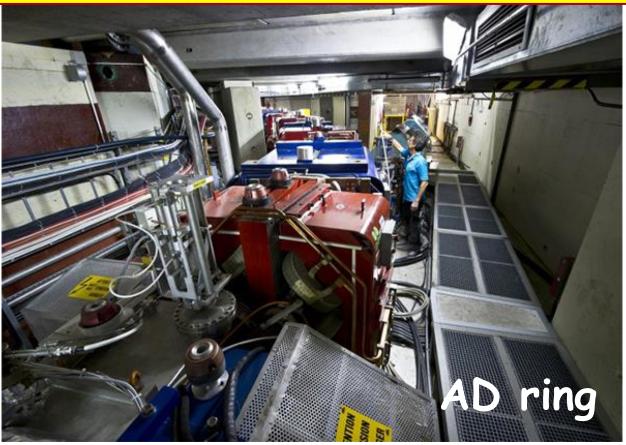
Higgs peak at 126 GeV

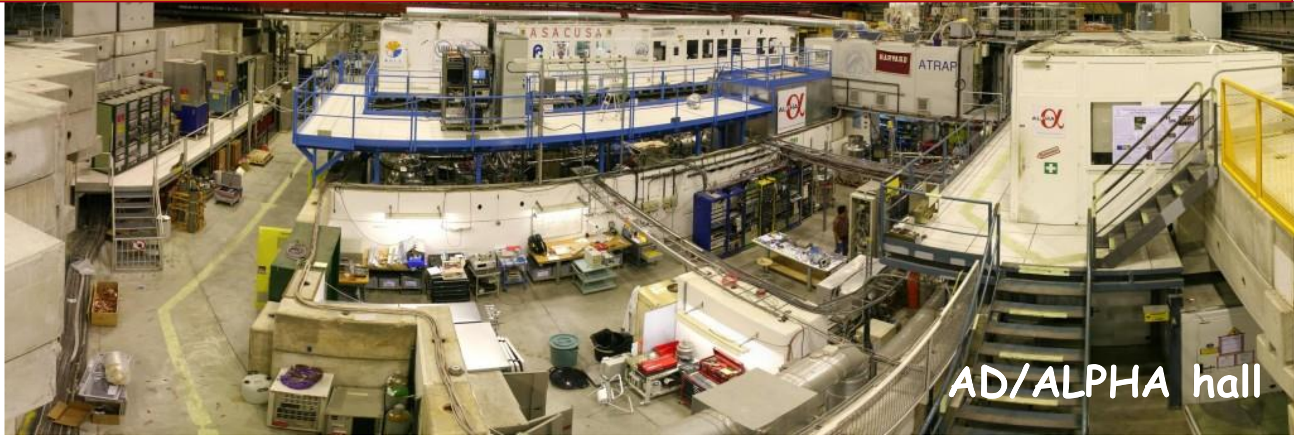


$$\int L\cdot dt \approx 12\ \mathrm{fb}^{-1} = 1.2e40\ \mathrm{cm}^{-2}$$

VI. The Highlights of Cooling Methods' Application: Particle Physics

2010: AD and First H-bar Generation in ALPHA Trap





Stochastic and electron cooling in AD allows to store and decelerate sufficient number of p-bars for 3 experiments – ALPHA, ASACUSA & ATRAP

Antihydrogen Laser PHysics Apparatus (ALPHA)

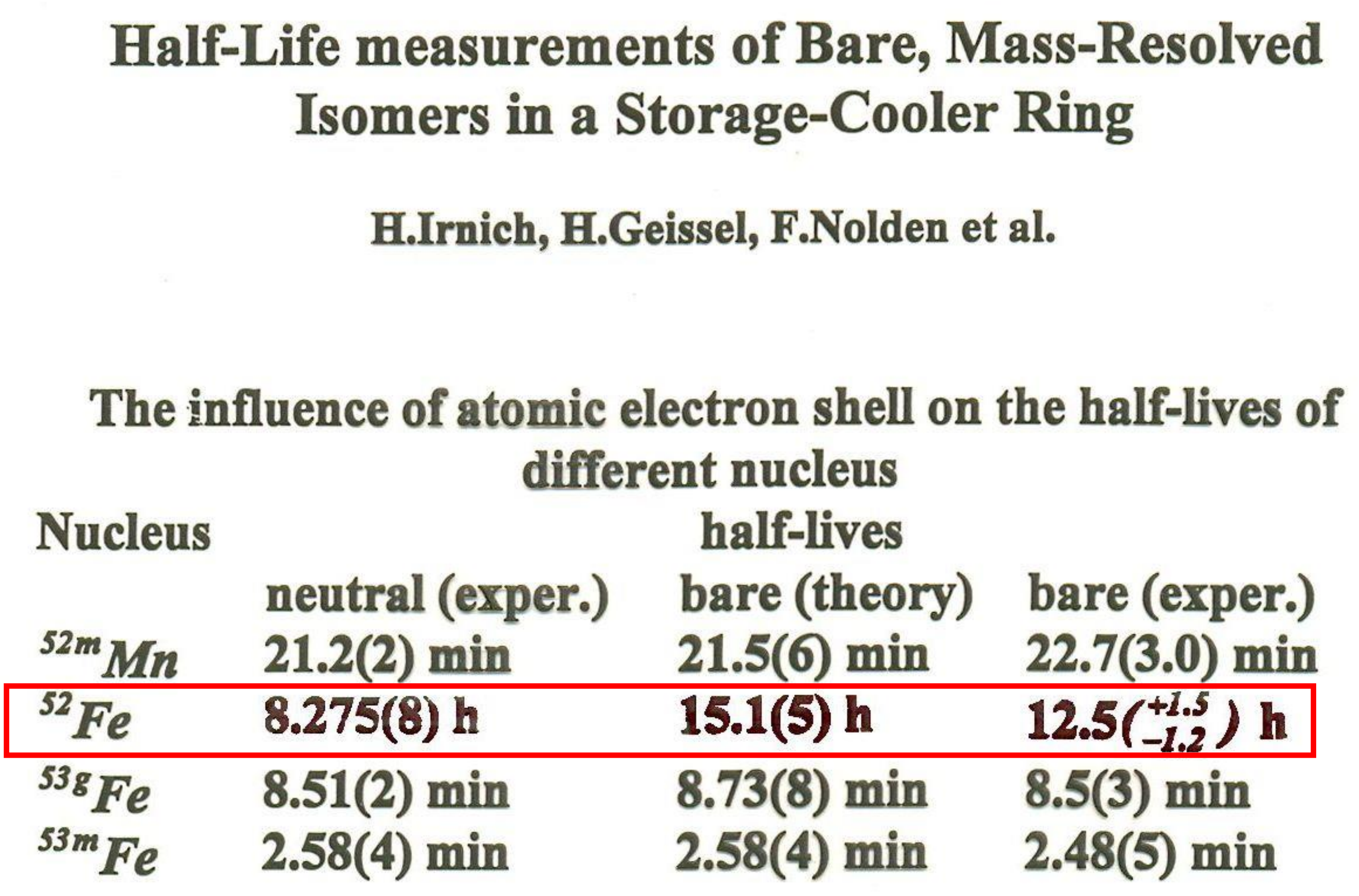
ALPHA Experiment

17 November 2010 - the first to capture and store 38 antihydrogen atoms for about 170 ms.

26 April 2011 - 309 antihydrogen atoms trapped and kept, some for as long as 1,000 seconds (about 17 minutes)

VI. The Highlights of Cooling Methods' Application: Nuclear Physics

1996 ESR (GSI)



Half-Life measurements of Bare, Mass-Resolved Isomers in a Storage-Cooler Ring

H.Irnich, H.Geissel, F.Nolden et al.

The influence of atomic electron shell on the half-lives of different nucleus

Nucleus	half-lives		
	neutral (exper.)	bare (theory)	bare (exper.)
^{52m}Mn	21.2(2) min	21.5(6) min	22.7(3.0) min
^{52}Fe	8.275(8) h	15.1(5) h	$12.5(^{+1.5}_{-1.2})$ h
^{53g}Fe	8.51(2) min	8.73(8) min	8.5(3) min
^{53m}Fe	2.58(4) min	2.58(4) min	2.48(5) min

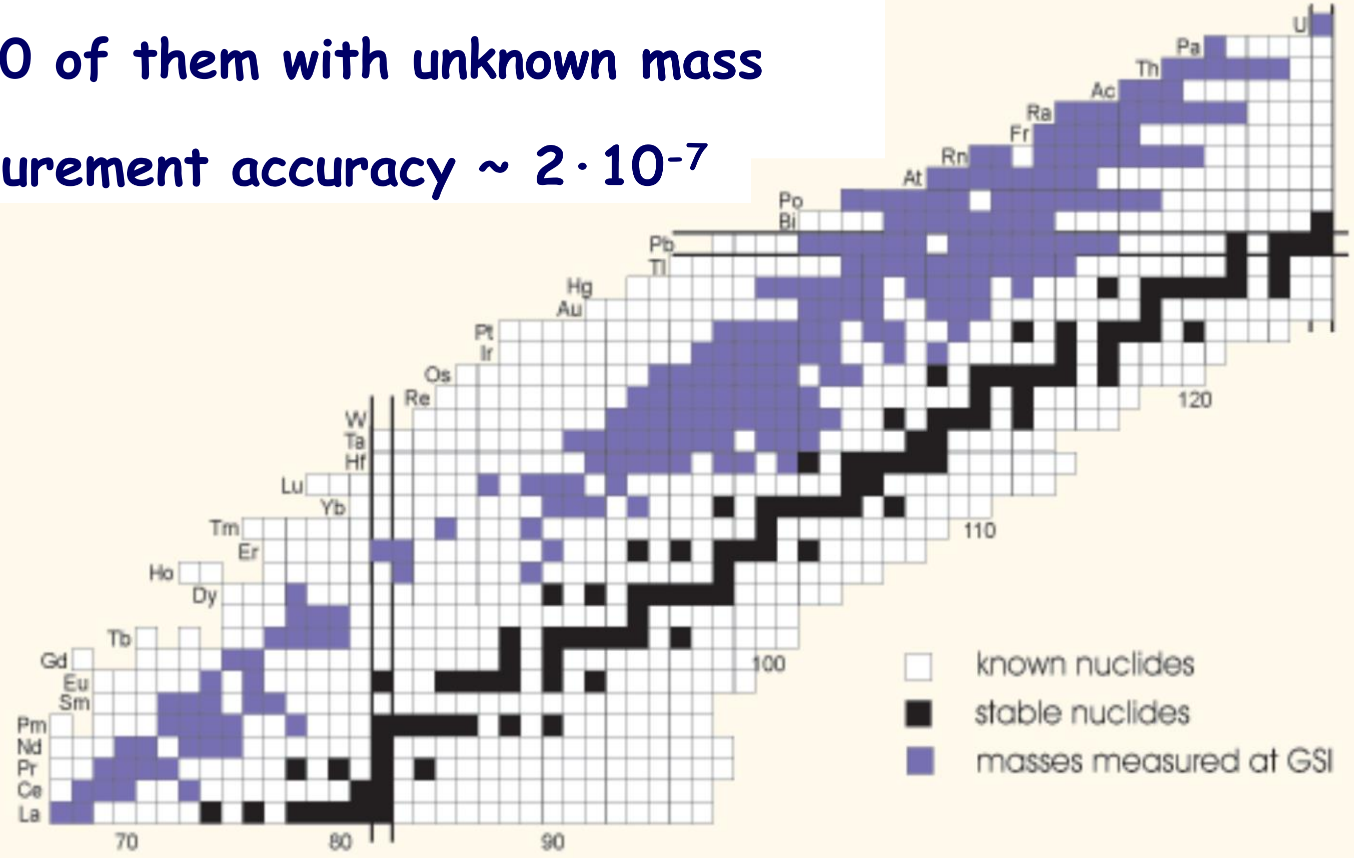
VI. The Highlights of Cooling Methods' Application: Nuclear Physics

1994 -2014 - …   ESR (GSI)

High Precision Schottky Mass Spectroscopy

- 194000 peaks identified
- 500 different nuclei
- about 200 of them with unknown mass

Mass measurement accuracy ~ $2 \cdot 10^{-7}$



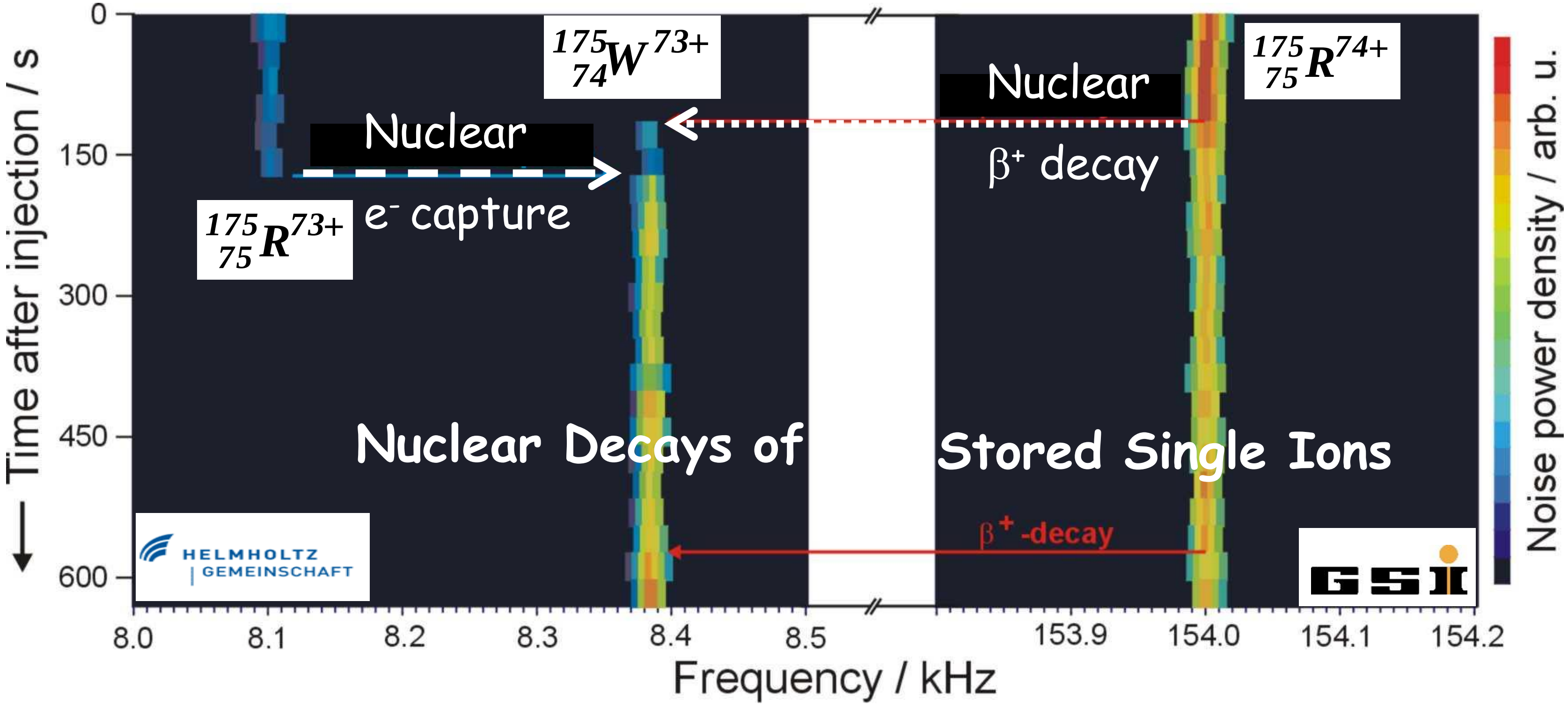
VI. The Highlights of Cooling Methods' Application: Nuclear Physics

1996 -2014 - … ESR (GSI)

High Precision Time-Resolved Schottky Mass Spectroscopy (TR SMS)

May 10, 2013 Courtesy of Yuri Litvinov and Markus Steck

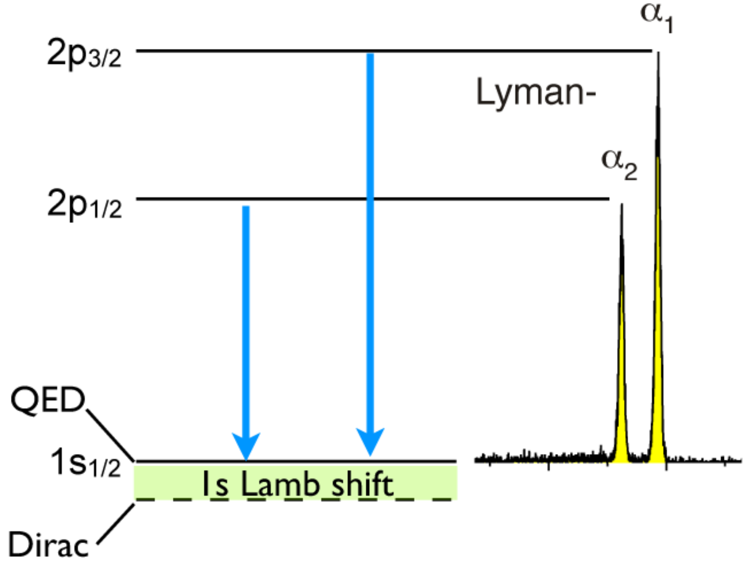
TR SMS is a perfect tool to study nuclei decays in the ESR

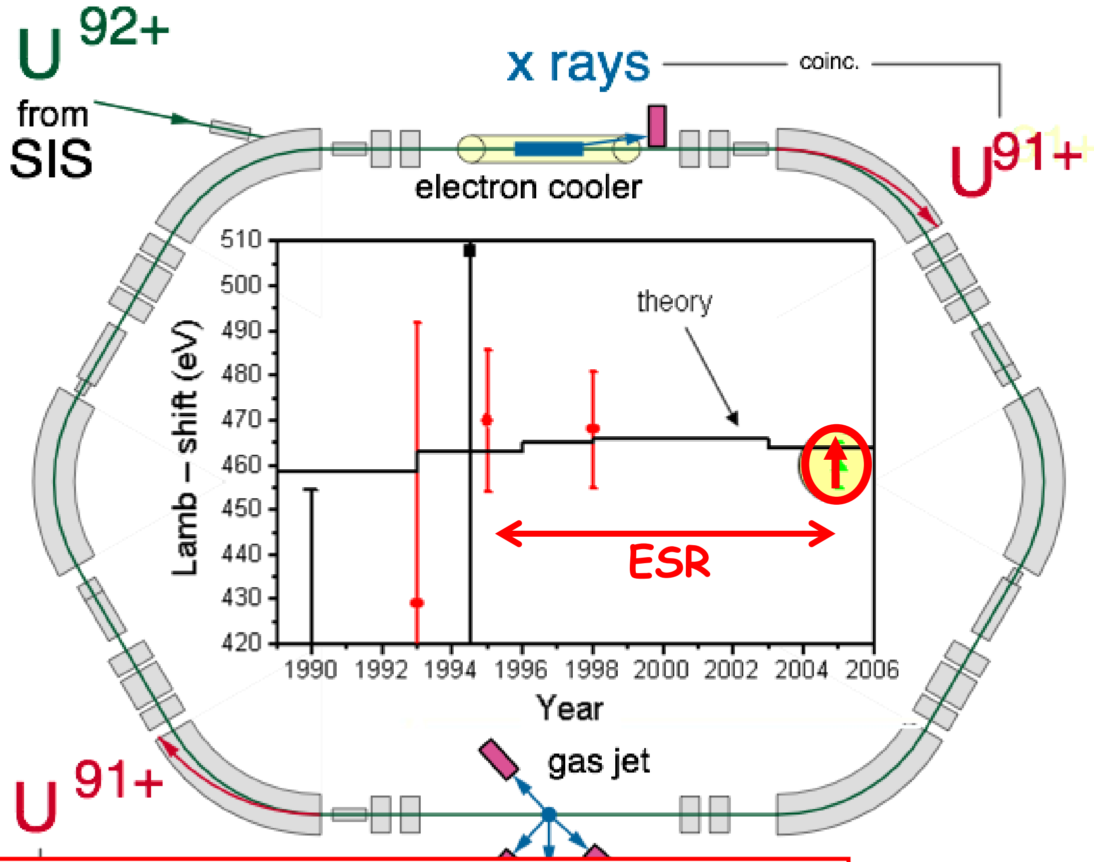


VI. The Highlights of Cooling Methods' Application: Atomic Physics

1994 - 2005 ESR (GSI)

High Precision Measurement of U^{91+} 1S Lamb Shift





Theory (2001) 460.26 ± 0.5 eV

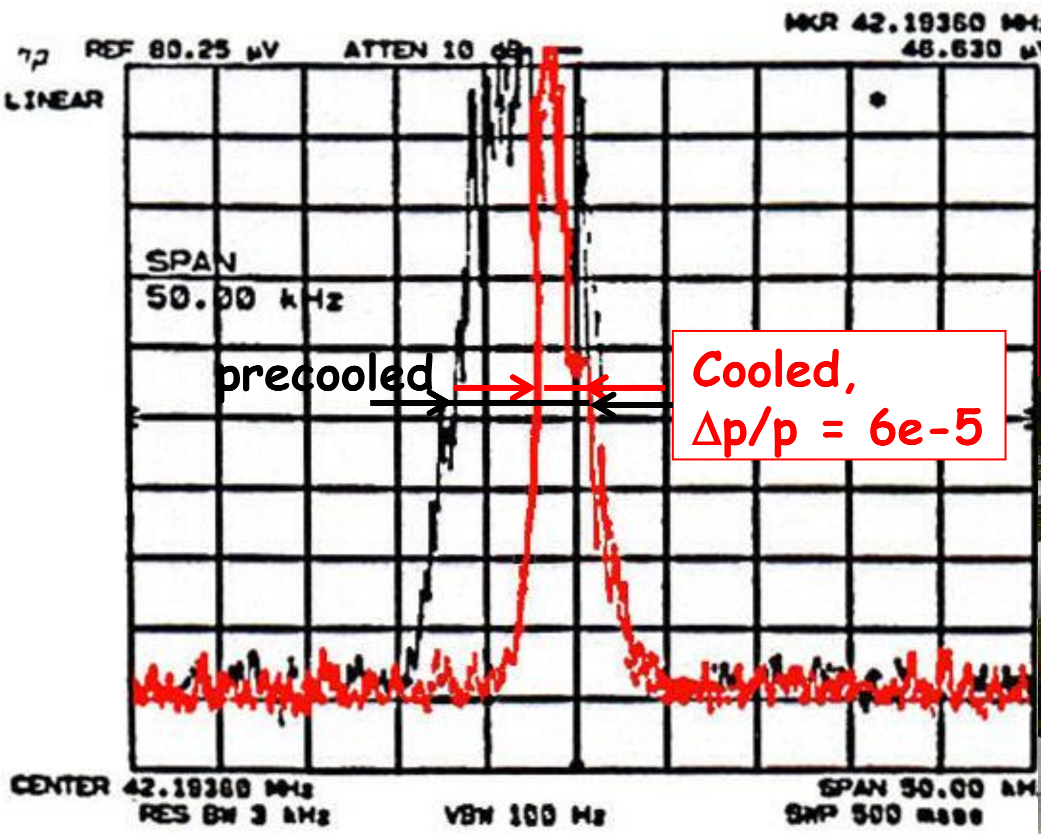
ESR (1995) 470 ± 16 eV

ESR (2005) 460 ± 4.6 eV

QED related studies => to be continued at FAIR

(Th. Stoehlker et al., NIM B 205 (2003) 156)

December 14, 1988 First Electron Cooling of Antiprotons



precooled

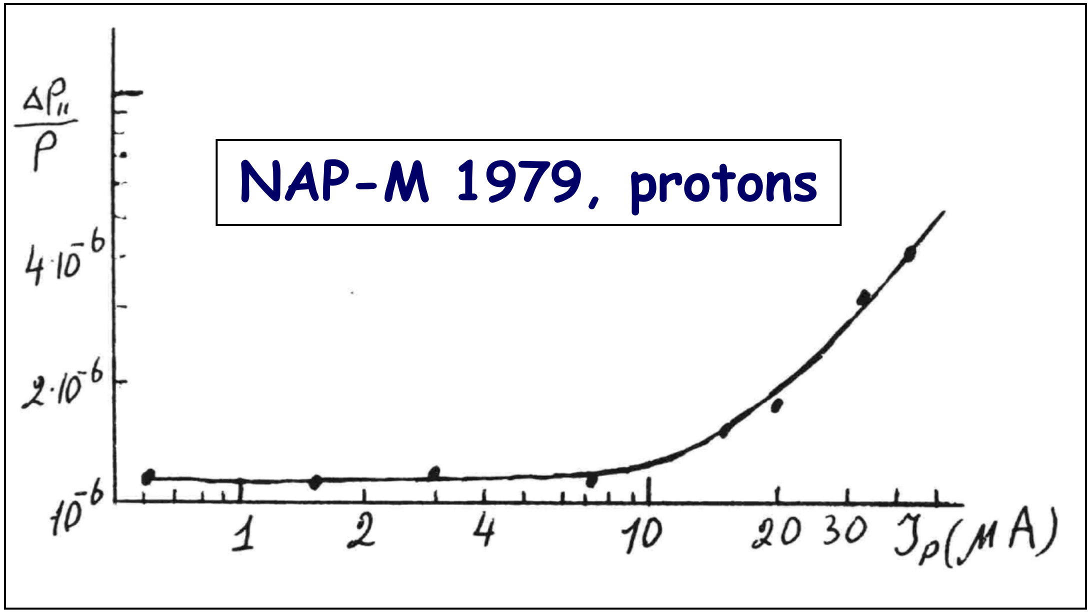
Cooled, $\Delta p/p$ = 6e-5

LEAR (CERN)

Hot Jokes for Cold Antiprotons (December 1994)

VI. The Highlights of Cooling Methods' Application: Particle Beam Physics

1979 – 2013 => ???? Crystalline Beam



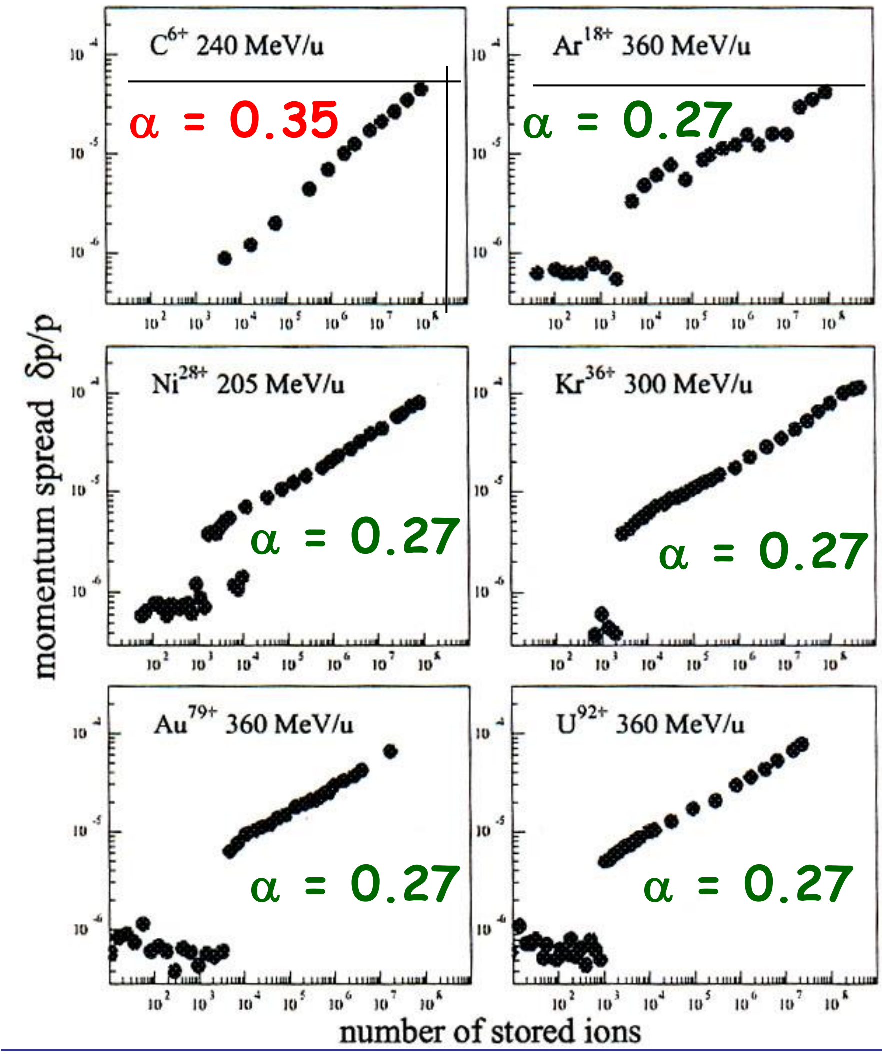
(E.Dementiev, N.Dikansky, V.Parkhomchuk et al., Preprint 79-70 BINP (1979); Preprint 79-41, CERN/PS/AA (1979))

1984 V.Parkhomchuk, Concept of Crystalline Beam

(in Proc. of the Workshop on Electron Cooling and Related Applications, FZ Karlsruhe, 1984, p.71)

VI. The Highlights of Cooling Methods' Application: Particle Beam Physics

$\Delta p/p \propto N^\alpha$ 1979 – 2013 => ???? Crystalline Beam



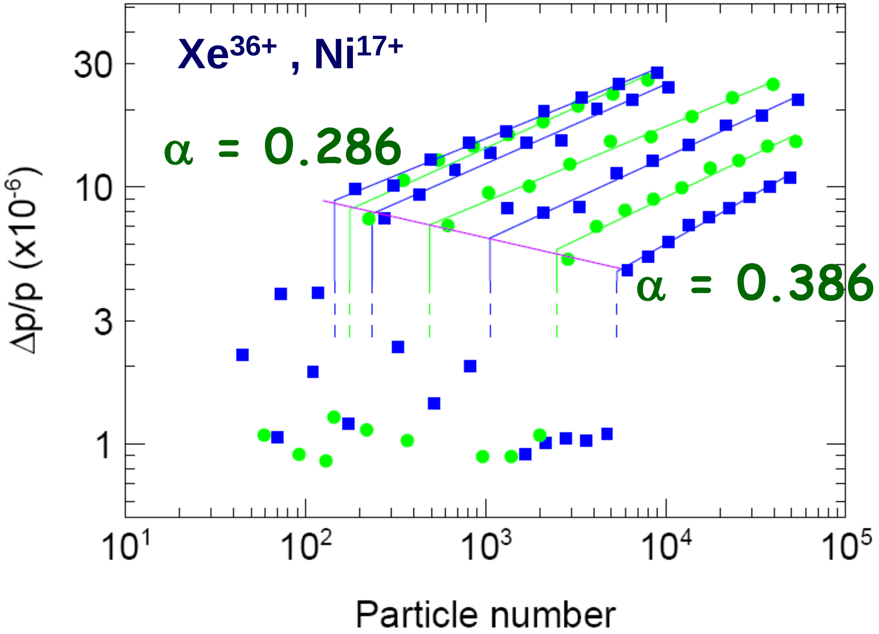
1996 New Stage: Experiments at ESR

M. Steck, *et al.*, PRL 77 (1996) 3803

Phase transition in ion beam: <u>ordering</u>

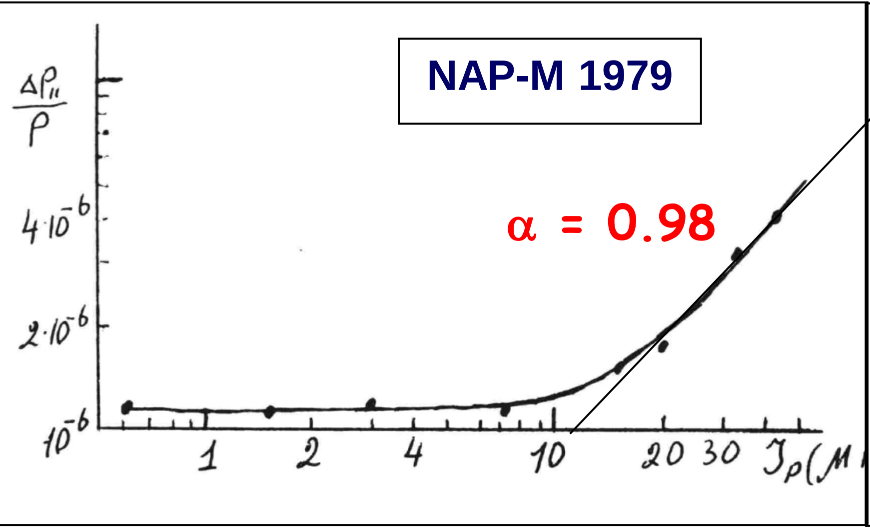
Confirmed at CRYRING

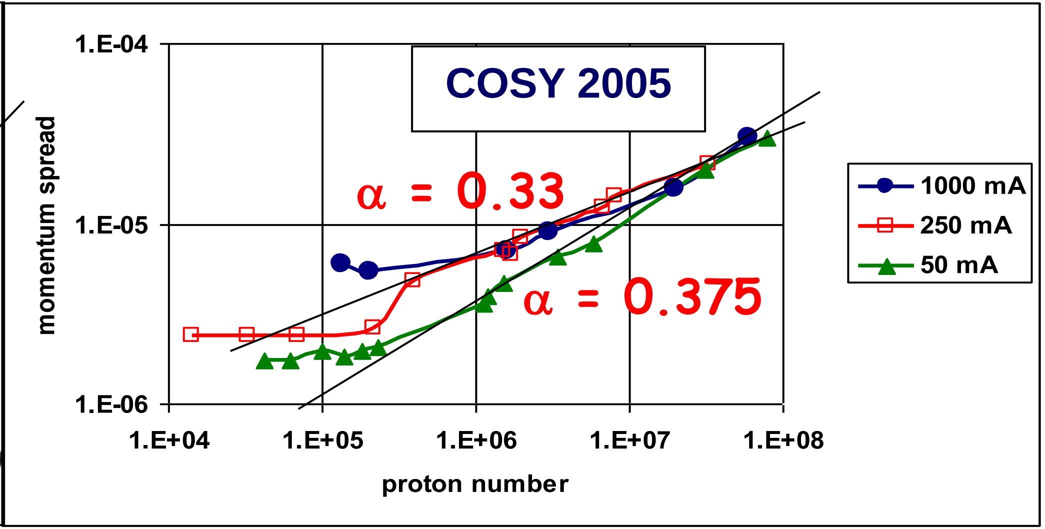
H.Danared et al., PRL 88 (2002) 1003

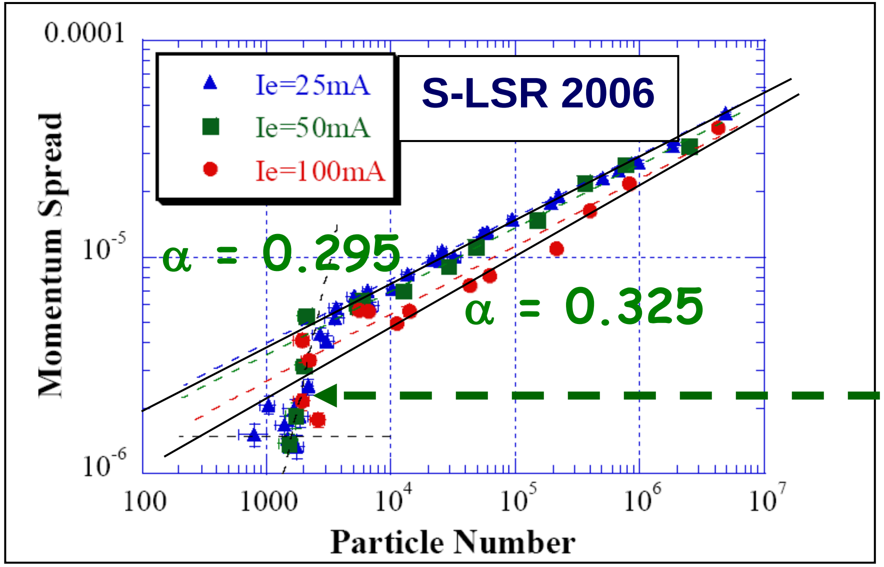


VI. The Highlights of Cooling Methods' Application: Particle Beam Physics

NAP-M / COSY / S-LSR , Proton Ordering







Phase transition

VI. The Highlights of Cooling Methods' Application: Particle Beam Physics

Optional

Crystalline Beams: Numerical Simulation

A.Smirnov: BETACOOL Code (2005 -2013)

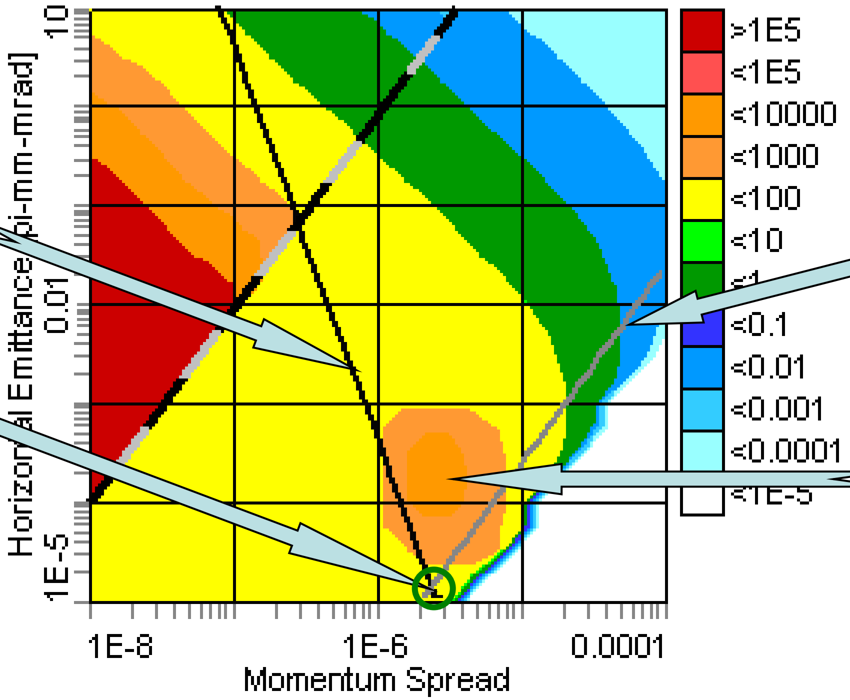
"3D" Dependence of IBS longitudinal heating rates (in colours) vs horisontal emittance and momentum spread of proton beam (S-LSR, 7 MeV, N_p = 10^3)

Ordering criterion (I.Meshkov, COOL'03)

$$\Gamma_2 = \frac{Z^2 e^2}{T_{||}\sigma_\perp} > \pi$$

Criterion line

Ordering point



Proton cooling "trajectory"

Anomalous ("Smirnov") island of IBS heating of longitudinal momentum component

VI. The Highlights of Cooling Methods' Application: Particle Beam Physics

Stability of Cooled Proton Beam: CELSIUS / COSY / HIMAC

CELSIUS (Uppsala, Sweden):

Injection energy 48 MeV, H^{2+}, stripping injection

Intensity 25 mA (bunched beam), cooling at 400 MeV

COSY (Juelich, Germany): Vertical acceptance 24 $\pi\cdot$mm$\cdot$mrad

Injection energy 45 MeV, H^-, stripping injection

Intensity 8 mA: 10^{11} protons (coasting beam)

HIMAC (Chiba, Japan): Vertical acceptance 24 $\pi\cdot$mm$\cdot$mrad (also!)

Injection energy 6 MeV/u, Ar^{18+}

Intensity $1.5\cdot10^9$ ions (coasting beam)

V.Parhomchuk: Concept of "electron heating"

(in Proc. of JAS'2000, p.53; Uspekhi Fiz. Nauk, v.170 (2000) 473)

All three rings are subjected to "the electron heating"!

VI. The Highlights of Cooling Methods' Application: Present for Future

Projects with Cooling Application under Development

1) Prototyping/Construction/Commissioning Stage

Project (Lab)		**Application**	**Status**
1	**CSR** (MPI, Heidelberg)	Atomic & molecular physics	Commissioning
2	**NICA** (JINR, Dubna)	Particle physics	Construction
3	**FAIR** (Darmstadt)	Particle, nuclear and atomic physics	Design & construction
4	**MICE** (RAL/Fermilab)	ν_μ-fabric, Muon collider	Prototyping
5	**Bunched beam Stochastic Cooling** (RHIC, BNL & NICA, JINR)	Particle physics	Development
6	**LEPTA** (JINR)	Particle physics	Commissioning with positrons

Projects with Cooling Application under Development

1) Prototyping/Construction/Commissioning Stage

Ultra Low Particle Energy: Cryogenic Storage Ring (CSR) at MPI, Heidelberg

CSR at Assembling

Projects with Cooling Application under Development

1) Prototyping/Construction/Commissioning Stage

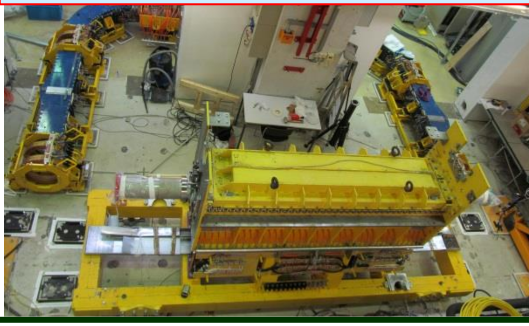
Electron Coolers for Future Colliders – NICA and HESR

Electron Cooler for COSY:
2.0 MeV, 1.0 A
(Prototype for HESR)

Dec. 2011,
Assembling
at BINP

May 2013,
Assembling
at COSY

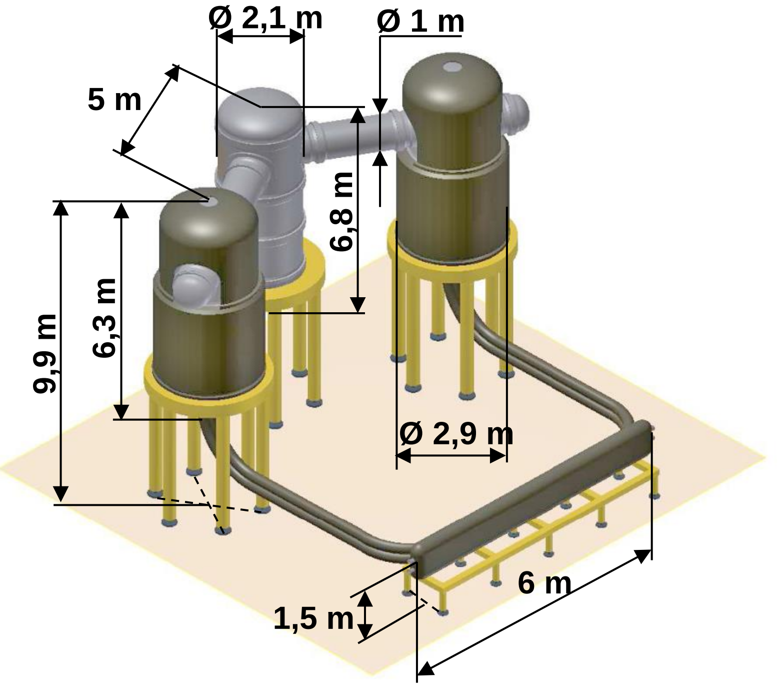
Commissioning now



BINP Version

Two Versions
of
Electron Cooler for
2.5 MeV, 0.5
NICA project

JINR Version



VI. The Highlights of Cooling Methods' Application: Present for Future

Projects with Cooling Application under Development

2) Conceptual Design ("Paperwork") Stage

	Project (Lab)	Application	Status
1	**ELENA** (CERN)	Antihydrogen physics	Approved
2	**Electron-Ion Collider** (JLab)	Particle physics	Concept development
3	**eRHIC** (BNL)		
4	**Coherent electron cooling** (BNL/JLab)	Particle, nuclear, atomic physics	

New requirements to synchrotron radiation cooling efficiency appeared with development of

- ✓ SuperB-fabric
- ✓ e^+e^- linear collider
- ✓ Electron-Ion Colliders (JLab, BNL, FAIR (?), …)
- ✓ SLHC in ep-mode

Super LHC: $C_{ring} \approx 100$ km

Conclusion

Pelletron
(4.3 MeV electron energy)

Cooling methods were developed for cooling with

300 keV electron cooler (Lanzhou)

synchrotron radiation,
electrons,
microwave frequency stochastic signal,
ionization in medium…
…and the development continues at new level.

Particle beams being cooled:
electrons, protons, antiprotons, ions… ⇒ muons

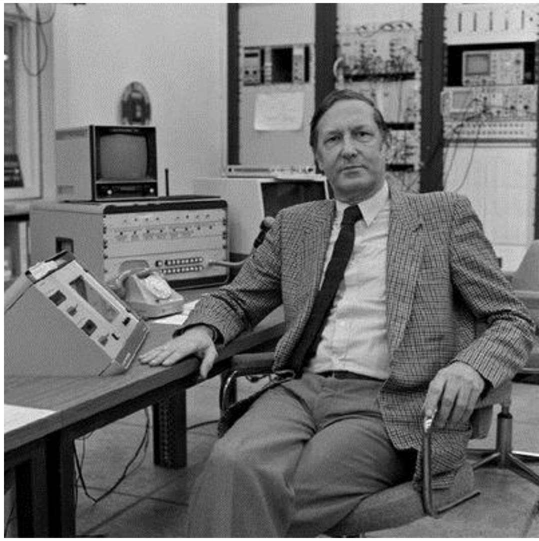
Energy Range: 40 keV/u (ions) ÷ 8 GeV (p-bars)

Cooling method	Particles/Ring	Energy	$T_{\parallel}$, K	$T_{\perp}$, K
Electron cooling	$^{40}Ar^{18+}$ / ESR protons / S-LSR	360 MeV/u 7 MeV	10 1.9	2000 11
Laser cooling	$^{9}Be^{+}$ /TSR $^{24}Mg^{+}$/S-LSR	7.3 MeV 40 keV	$5 \cdot 10^{-3}$ 0.4	- 7.0 (hor.) / 2.1 (ver.)

Thank you for your attention!

Back up

III. Stochastic Cooling Method



1968 S. van der Meer, Stochastic cooling

Stochastic damping of betatron oscillations

Internal Report CERN/ISR-PO/72-31 1972.

"The S-Cooling ideology"

(or "How to fight Liouville theorem")

"Such a system resembles Maxwell's demon, which is supposed to reduce the entropy of a gas by going through a very similar routine, violating the second law of thermodynamics in the process. It has been shown by Szilard that the measurement performed by the demon implies an entropy increase that compensates any reduction of entropy in the gas. Moreover, in practical stochastic cooling systems, the kicker action is far from reversible; such systems are therefore even less devilish than the demon itself."

Simon van-der Meer, Nobel Lecture, p.2