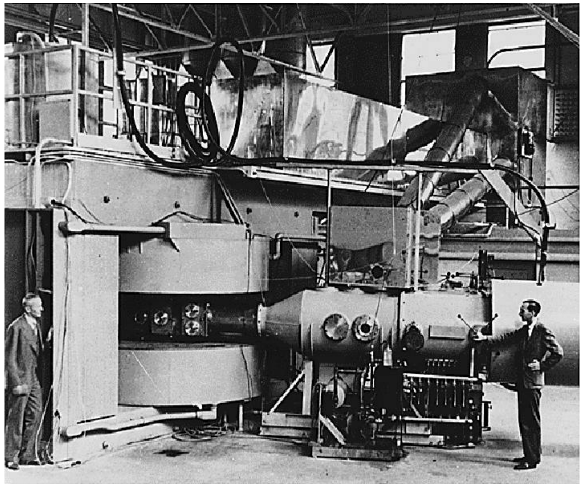
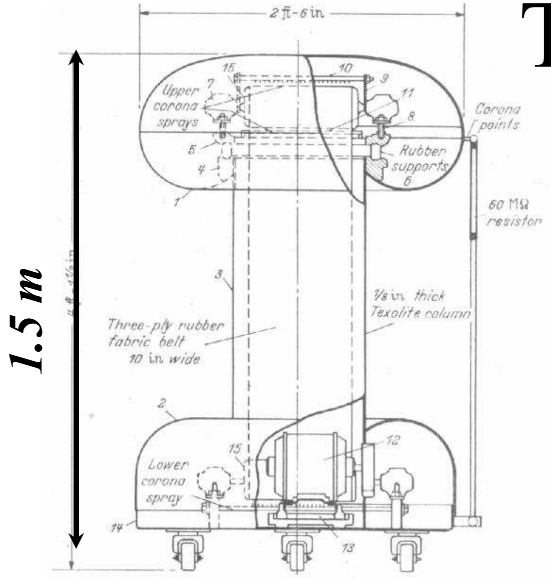
V.B Reva.
Electron cooling.

6 November 2019

To high energy ….



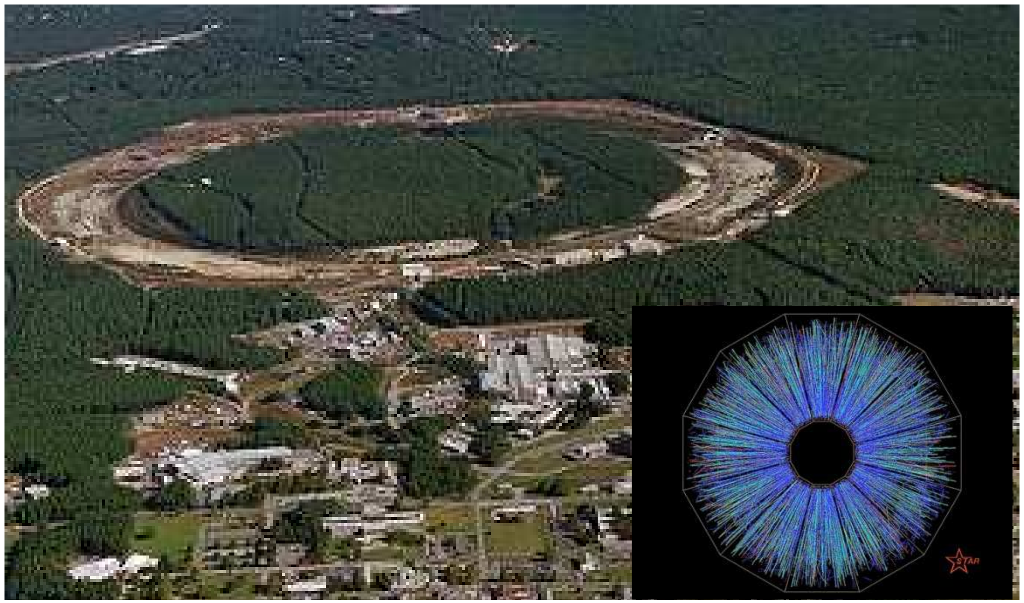
Ernest Lawrence's 60-inch cyclotron, 1939



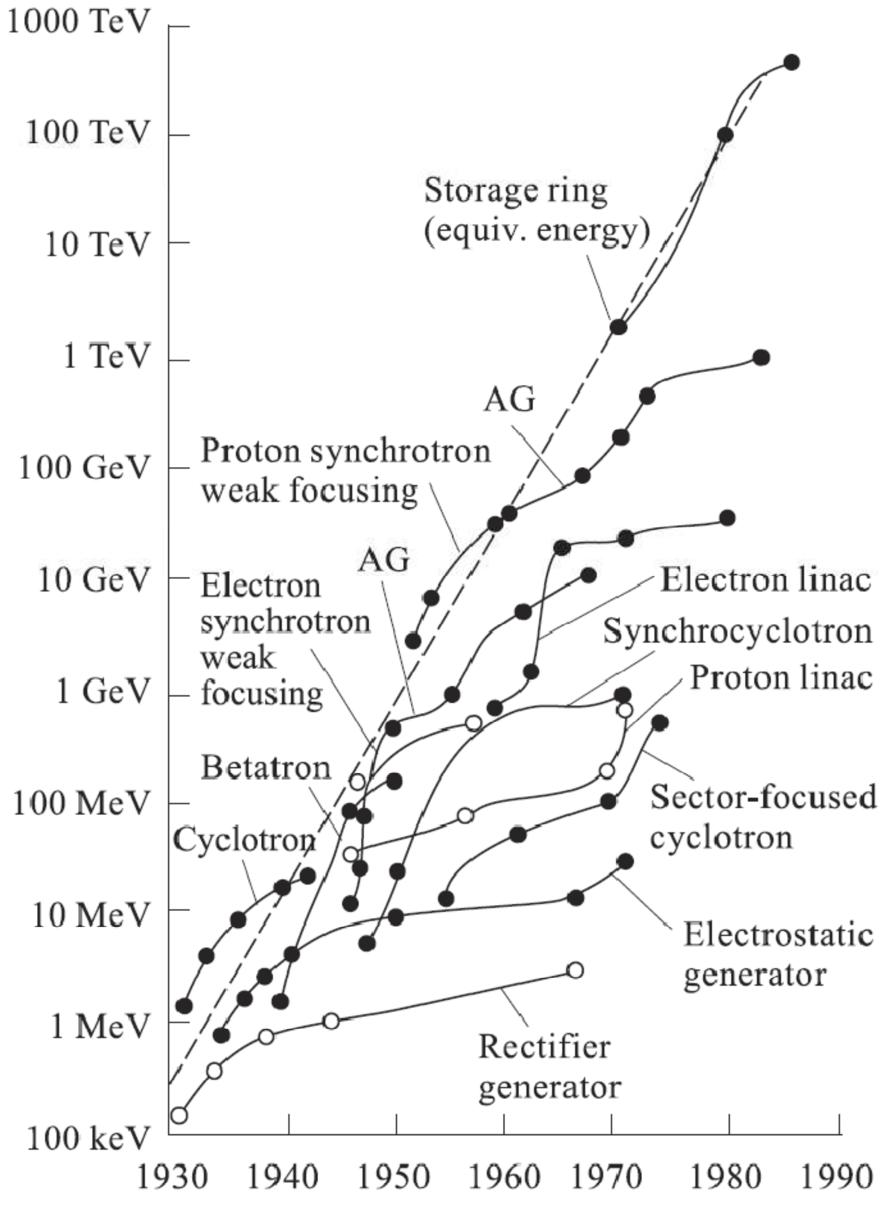
Van de Graaff generator 1938

Okridge pelletron up to 25 MeV

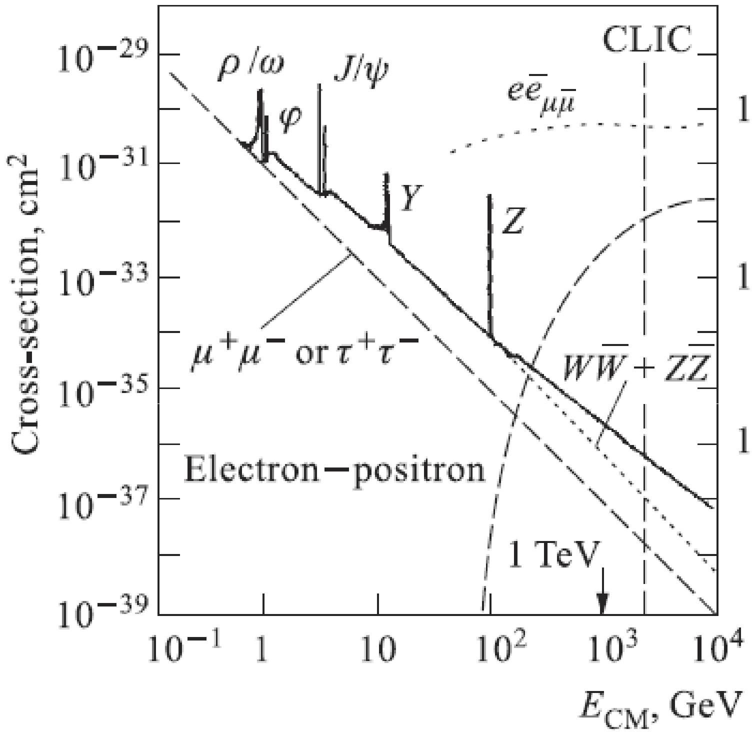
Brookhaven National Laboratiry 100 GeV per nucleon



Large Hadron Collider 7 TeV protons



New construction and ideas leads to higher energy for electrons, protons and ions

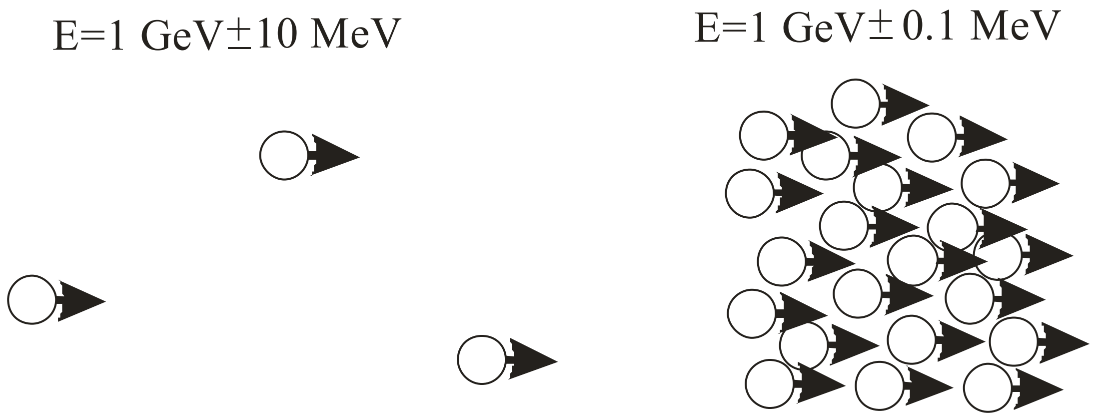


Improving design for obtaining more and more energy

With energy growth the more and more particle and effects in the physics of the elementary particle can be investigated are observed

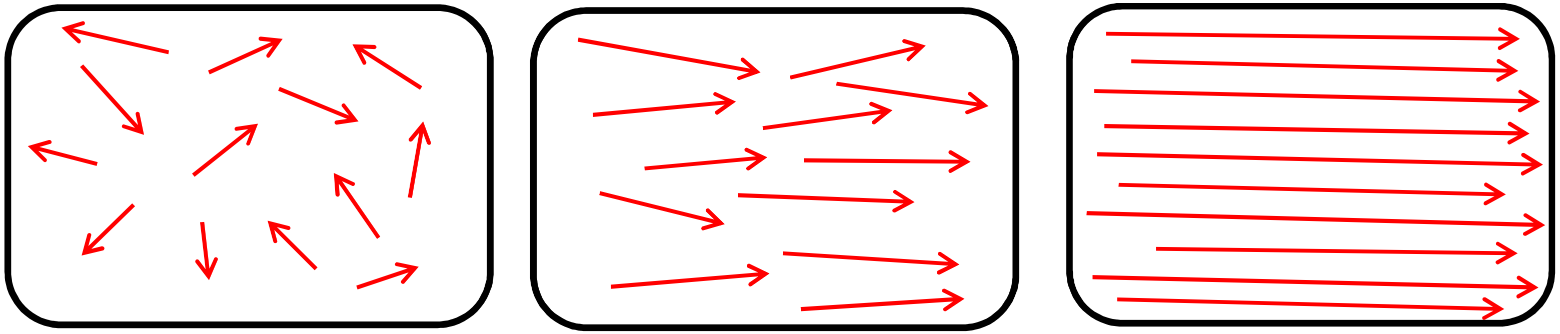
But energy is not ultimate parameter, the quality of the beam should be good enough …

1. The particles should be many
2. The momentum spread of the particle should be small



A few particle with large energy deviation is worse than many particle with equal energy

What is the temperature of the beam



The charge particles are generated in the source and have initial momentum and coordinate spread

After acceleration this ensemble of particles preserve chaos in the parameters despite of the strong increase of particles energy. This allows us to introduce the conception of temperature of the beam especially for co-moving frame of reference.

$$T_{II} \propto m\left\langle v_{II}^2 \right\rangle = mc^2\beta^2\left(\frac{\delta p_{II}}{p_0}\right)^2$$

$$f\left(v_\perp, v_{II}\right) \propto \exp\left(-\frac{mv_\perp^2}{2T_\perp} - \frac{mv_{II}^2}{2T_{II}}\right)$$

$$T_\perp \propto mv_\perp^2 = mc^2\gamma^2\beta^2\vartheta_\perp^2 = mc^2\gamma^2\beta^2\left(\frac{a_\perp(s)}{\beta_\perp(s)}\right)^2$$

$$T_\perp \neq T_{II}$$

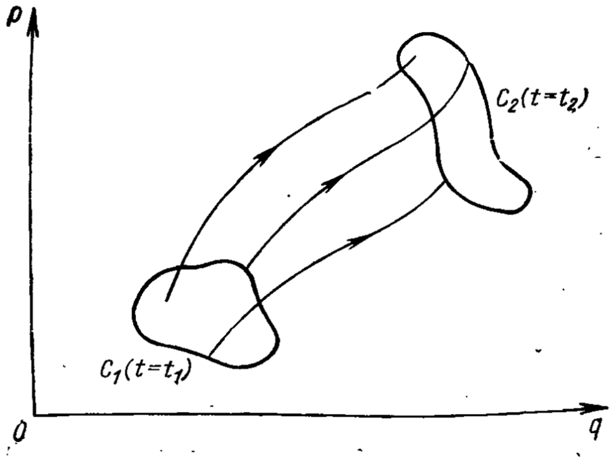
$$\vartheta_\perp = \frac{v_\perp}{\beta c} \qquad \vartheta_\perp(s) = \sqrt{\frac{\varepsilon}{\beta_\perp(s)}}$$

$a_\perp(s)$ Transverse size of the beam

$\beta_\perp(s)$ Beta function of the beam

ε beam emittance

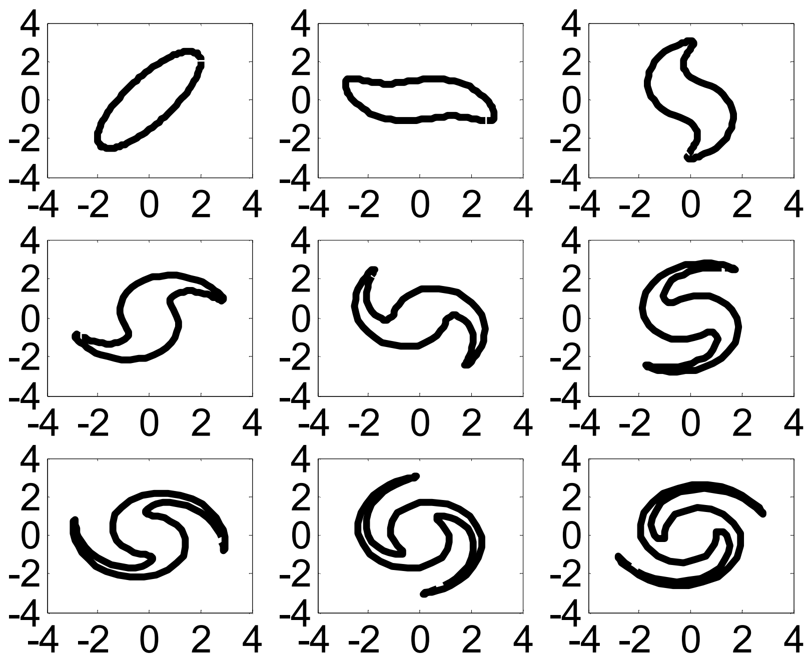
Liouville's theorem



The very important feature of the particle motion in the accelerator is fact that it can be described by some Hamiltonian. This Hamiltonian provides the equation of motion that have the special invariant – phase-space volume. The particle traveling through phase-space along individual trajectory and the phase-space distribution function is constant along them.

$$\widehat{H}\Gamma_0 = \Gamma_0$$

This fact forbids the decrease of the momentum spread without the increase of the space size of the beam. It means that the emittances of the beam is constant during beam transportation along accelerator structures. Unfortunately there are mechanisms that can extend the effective phase-space volume of the beam even when Hamiltonian's laws exist. The idea of such motion is shown in right Figures. Stretching and mixing leads to increase of the space volume occupied by the particles.



Reason that leads to increase of the space volume (“temperature”) of the beams

- non-linearity of the electromagnetic field during transportation and revolution particles in accelerator
- noise of the electromagnetic field
- interaction with internal target
- interaction with the other beam in colliding experiments (beam-beam effect)
- interaction with residual gas in the vacuum system
- intrabeam scattering
- resonances
- space-charge effects

Shrinking space volume = Beam Cooling

Methods of Beam Cooling

- synchrotron radiation (electron)
- electron cooling (proton, antiproton, ions)
- stochastic cooling (proton, antiproton, ions)
- ionization cooling (muon)
- laser cooling (Doppler cooling) (cooling for a few kinds of atomic ions)

“Pseudo” cooling of particle isn’t “true” cooling

1. “scrapping” – remove particle with high value of betatron amplitude and momentum impulse
2. Expanding the beam transversely or longitudinally with decrease the momentum spread (transverse or longitudinally)
3. Exchange of energy between degrees of freedom (horizontal ↔ vertical) induced by the coupling in accelerator

True cooling is non-Hamiltonian processes where Liouville’s theorem is violated and the phase-space density is increased.

Profit from particle cooling

• improving the quality of experiment
– precise energy resolution
– increase luminosity of the experiment because the increase of phase-space density

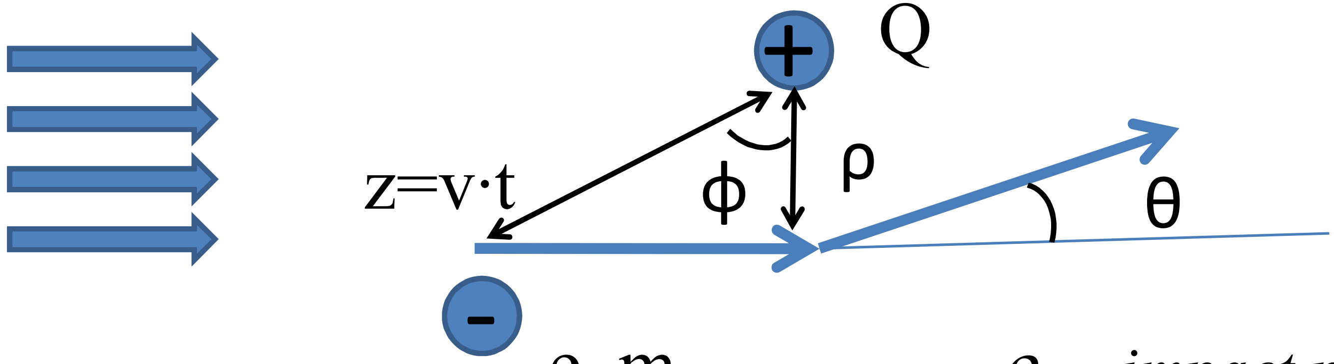
• compensation of “heating” processes
– experiments with internal target
– beam-beam effects
– intrabeam scattering

• increase of effectiveness of particle accumulation
– accumulation of many pulses
– accumulation of secondary beams (pbars, rear isotopes, radioactive beams)

Simple way of cooling is friction at interaction of charge particle with a media

The friction force between moving charge particle and immovable gas of charge particle

Moving flow of particle with flow density j=n*v



ρ *- impact parameter*

$$\delta F = \frac{dp_{II}}{dt} = p_{II} \cdot (1-\cos(\vartheta)) \cdot \frac{dN}{dt} =$$ for flow of particle with given ρ

$$= p_{II}(1-\cos(\vartheta)) \cdot j \cdot \delta S = p_{II}(1-\cos(\vartheta)) \cdot n \cdot v \cdot \delta S$$

for flow with arbitrary ρ $$F = \int_0^\infty p_{II}(1-\cos(\vartheta)) \cdot n \cdot v \cdot 2 \cdot \pi \cdot \rho \cdot d\rho =$$

$$\equiv p_{II} j \sigma_{tr}$$

The transport cross section

$$\sigma_{tr} \equiv \int_0^{\infty} (1 - \cos(\theta(\rho))) \cdot 2 \cdot \pi \cdot \rho \cdot d\rho$$

the transport cross section – is the area of transverse cross-section of scattering center that completely absorbs the particle impulse

For small angle θ one can see find equation for θ(ρ)

$$\theta(\rho) = \frac{\Delta p_{\perp}}{p_{II}} = \frac{1}{p_{II}} \int_{-\infty}^{\infty} F \cdot dt = \frac{1}{p_{II}} \int_{-\infty}^{\infty} \frac{e \cdot Q}{z^2 + \rho^2} \cdot \cos(\phi) \cdot dt =$$

$$= \frac{1}{p_{II}} \int_{-\infty}^{\infty} \frac{e \cdot Q}{\left(z^2 + \rho^2\right)^{3/2}} \cdot \frac{\rho}{v} \cdot dz = \frac{1}{p_{II}} \cdot \frac{2 \cdot e \cdot Q}{\rho \cdot v}$$

The transport cross section

For small angle θ $\cos(\theta)=1-\theta^2/2$

$$\sigma_{tr} \equiv \int_0^{\infty}\left(\frac{1}{p_{II}}\cdot\frac{2\cdot e\cdot Q}{\rho\cdot v}\right)^2\cdot\frac{1}{2}\cdot 2\cdot\pi\cdot\rho\cdot d\rho = \frac{4\cdot\pi\cdot e^2\cdot Q^2}{p_{II}^2\cdot v^2}\int_{\rho\min}^{\rho\max}\frac{d\rho}{\rho} = \frac{4\cdot\pi\cdot e^2\cdot Q^2}{p_{II}^2\cdot v^2}Ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right)$$

It is divergent integral but the physics model for cross-section has natural restriction for values of impact parameters

small impact parameters $\theta \approx 1$ $\rho_{\min} \approx \dfrac{eQ}{m_e v^2}$

Large impact parameters – a specific features of specific problem: Debay shielding, size of the electron beams, the path length of moving particle in gas …

$$\rho_{\max} \approx V\ \tau$$

Why estimation of ρ_{min} and ρ_{max} is so unpunctual because it is the LOG approximation. The function Ln is insensitive to error.

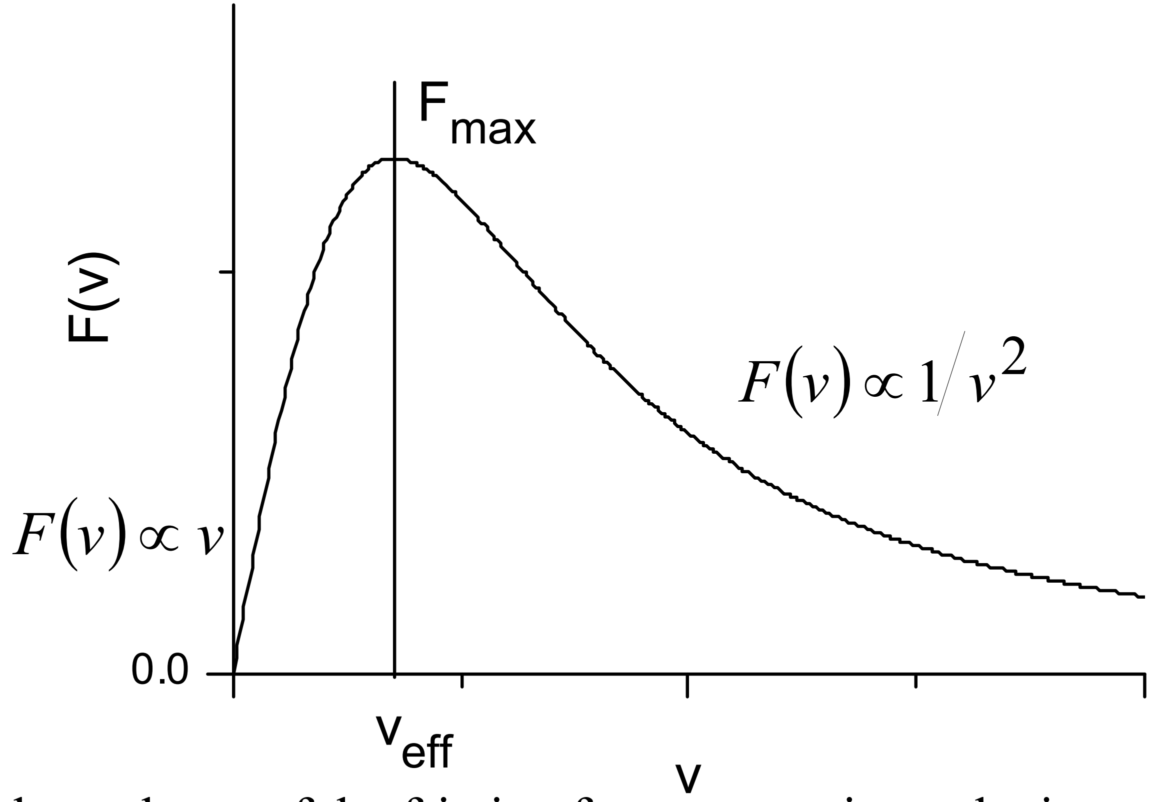
Friction force

Friction force for proton in electron gas. Electron gas is best choice for friction medium because the mass of particles is small (see equation below)

$$\vec{F} = -m_e n_e \sigma_{tr} v \vec{v} = -\frac{4\pi n_e e^4}{m_e} L_C \int \frac{\vec{v}_i - \vec{v}_e}{\left|v_i - v_e\right|^3} f(v_e) d^3 v_e$$

Here n_e – density of electron gas, $L_C = \int d\rho/\rho$ – Coulomb logarithm, $f(v_e)$ – distribution function of electron in velocity phase-space.

One can see that the friction force is maximum when the ion velocity is about some "effective" velocity.



The qualitative dependence of the friction force versus ion velocity

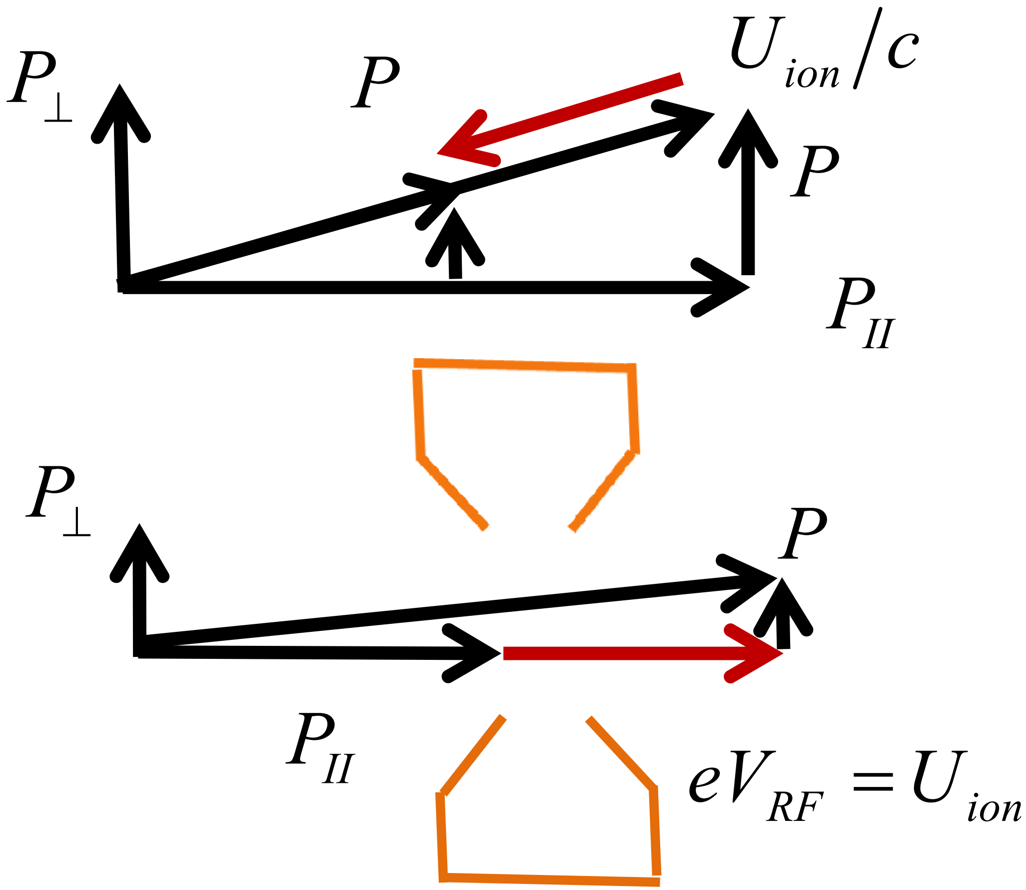
$$\vec{F} = -m_e n_e \sigma_{tr} v \vec{v} = -\frac{4\pi n_e e^4}{m_e} L_C \int \frac{\vec{v}_i - \vec{v}_e}{\left|v_i - v_e\right|^3} f\left(v_e\right) d^3 v_e$$

At small velocity of ion relatively to average electron velocity the friction force has linear growth $F(v) \propto v$, at large velocity between ion and the average velocity of electron gas the friction force decreases as $F(v) \propto 1/v^2$

Principle of ionization cooling – simple idea of interaction with a medium, the solid target is large density of electrons

$n_e \sim 10^{23}$ cm^{-3} for condensed matter, but v_i much larger than optimum value, friction force is far away from maximum value

1. At interaction with target the charge particles loss the impulse and energy
2. After passing RF system the losses of longitudinal impulse is restored but the decrease of transverse impulse is preserved. So, the transverse cooling is realized. The realization of longitudinal cooling demands the specific decisions.



A.A,Kolomensky, Atomnaya Energiya 19, (1965) 534.

Imperfection – strong scattering on the nucleus in target

Electron cooling

The idea of collider with proton-antiproton collision lead to new idea of beam cooling. The ionization cooling was known by that time, but the nuclear interaction and scattering with target lead to fast degradation of beams. In 1965 G.I.Budker proposed to cool the particle by the pure electron beam. The density of such beam should be small because of the strong action of space-charge. The typical electron density in the beam is 10^7 -10^9 cm^{-3} so factor of decrease density is about 10^{14} -10^{16} . It just seems like that the friction force should be negligible small but the electron beam can move with the same velocity relatively to ion beam. Thus it is possible to reach the peak of the function of friction force. This fact may compensate reducing decrease of electron density.

Budker G I, Skrinskii A N “Electron cooling and new possibilities in elementary particle physics” Sov. Phys. Usp. 21 277–296 (1978);
Report of VAPP-NAP Group, in: Proc. of the 8th Intern. Conference on High-Energy Accelerators, Geneva, CERN, 1971, p. 72.

Scheme of the electron cooling

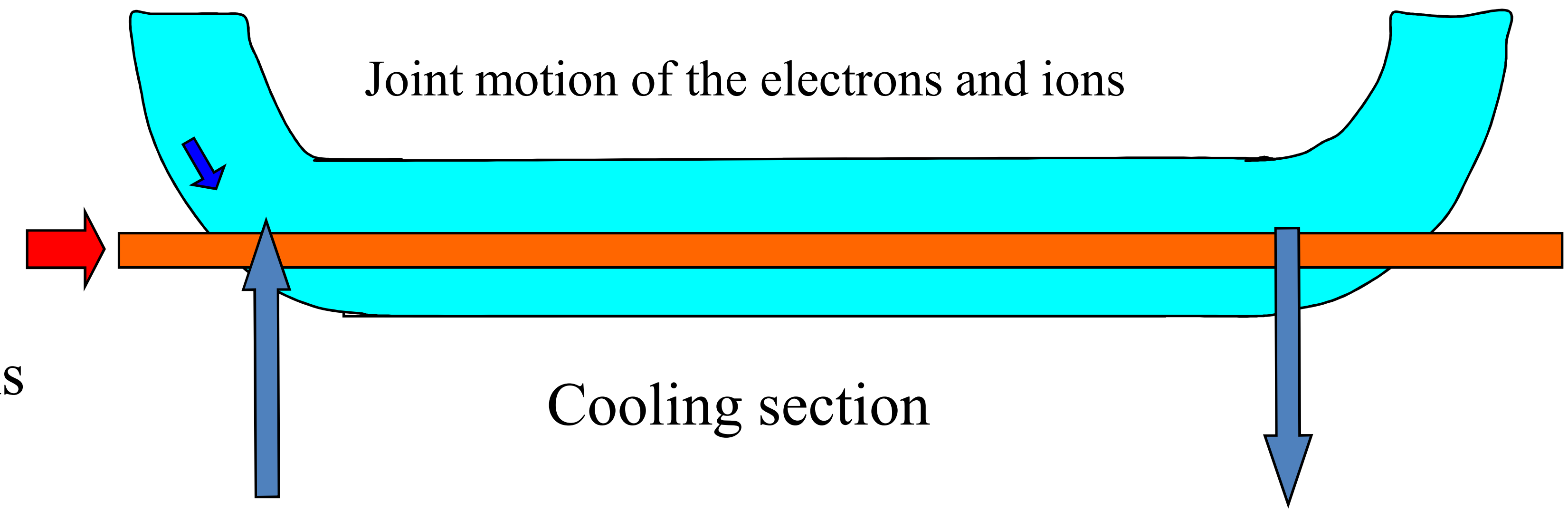
The velocity of the electrons is made equal to the average velocity of the ions. The ions undergo Coulomb scattering in the electron “gas” and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.

Always “fresh” electron from electron gun

<u>The energy transfer from the hot ions to the cold electrons</u>

the relative velocity of ions and electrons in the co-moving system is very slow

electrons



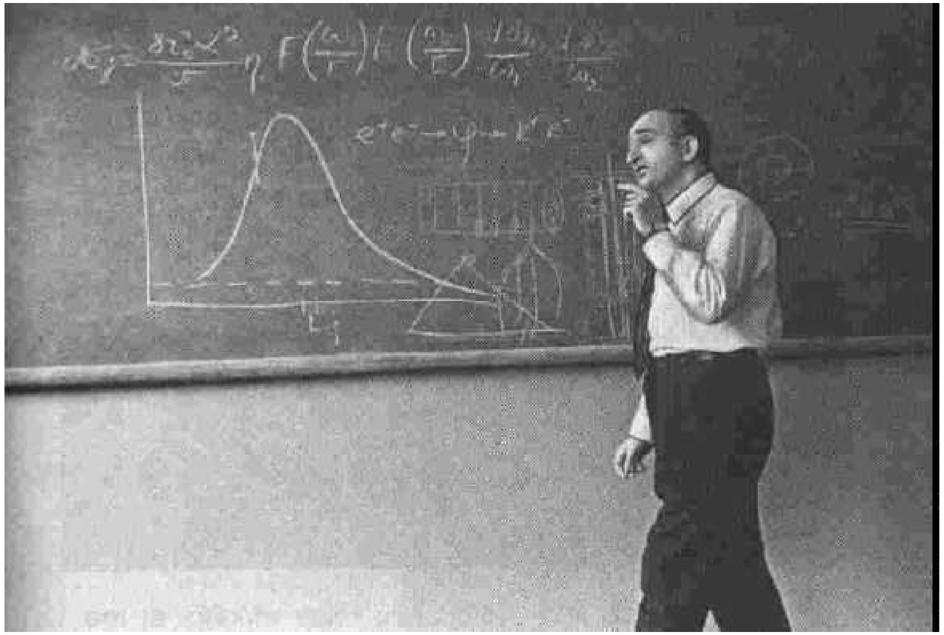
ions

Start point of the interaction

Final point of the interaction

Usually the velocity spread in the ion beam is about $|V/c| \sim 10^{-3}$, that is enough for compensation of effectiveness decrease connected with density reduce in the method of ionization cooling. Removing of nucleus from friction medium is very useful because it remove scattering and reaction processes with the ions of the beam. The physics reason of cooling is very simple. It is heat exchange between cold and heat gases. At initial stage of proposal of experiment with electron cooling the researchers propose that the electron will have the temperature about 1000 Celsius degrees that corresponds to cathode temperature. The pbar beam with energy 1 GeV and angle spread $\theta = 10^{-3}$ has temperature $T = Mc^2\gamma^2\beta^2\theta^2 = 4 \cdot 10^3$ eV $= 4 \cdot 10^7$ °C. One can see that the electron beam from cathode has very low temperature (~0.1 eV or 1000 °C) with compare to pbar. The factor is 40000 and cooling process looks very probable.

The estimation of the cooling time was based on the classical equation for the relaxation time in two-component plasma

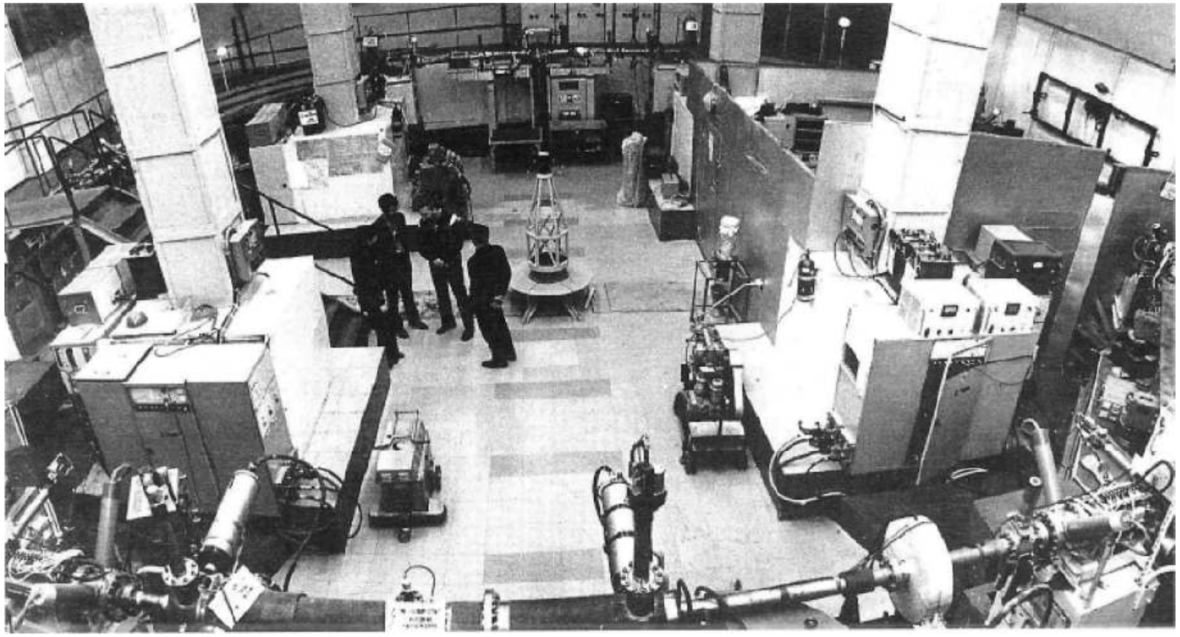


$$\frac{dT_p}{dt} = -\frac{T_p - T_e}{\tau}$$

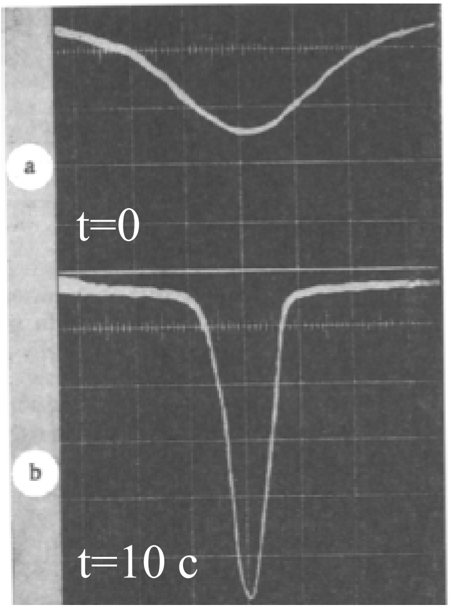
$$\tau \approx 5 \cdot 10^{-2} \frac{M}{m} \cdot \frac{\gamma^5 \left(\beta \vartheta_e^3\right)}{L r_0^2 N c \eta}$$

Despite of the idea of electron cooling was reported on few accelerator conference and was published in scientific journal there was no-one in the world who was going to do it. The main problem was transportation and focusing of intensive electron beam with large space-charge. The resolve of this problem defined success or failure the experiment. The first proposal of experiment contains the electron current 1 A and the energy 500 kV that corresponds to power 500 kW of electron beam. It was clear that the electron beam should be decelerated and absorbed at lowest energy. In 1967-1970 the test-bench of electron cooling device with magnetic field for compensation space-charge effect was designed in INP, Novosibirsk, Russia. This experience allowed to start the design of storage ring NAP-M with electron cooling in 1972. The name NAP-M indicated development path to pbar storage ring. In Russian N="nakopitel" (storage) AP="AntiProton" (pbar) M="model" (test-bench). The perimeter of NAP-M was 47.2 m. The straight section of this storage ring contains the electron cooling device with effective length 1 m.

First demonstration of electron cooling process

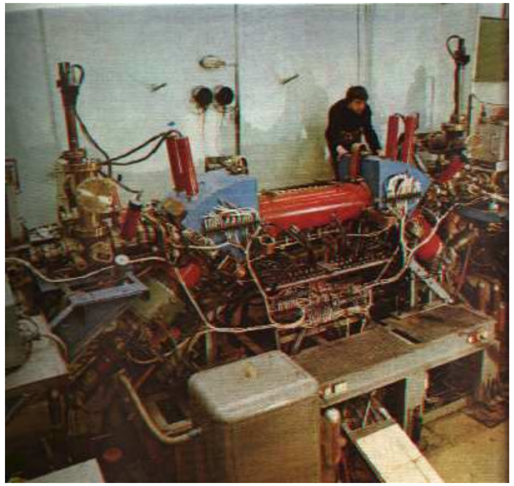


NAP-M is the first storage ring for investigation of electron cooling of ions. The injector is electrostatic accelerator with use Van de Graaff generator at 1.5 MeV. The range of energy of protons is 1.5 – 90 MeV, the proton current is up to 300 mkA. The electron cooler was named EPOCHA ("Electron Beam to Cool Antiprotons“) and had parameters: energy – 50 keV, electron current – up to 1 A.



First experiments show the cooling time τ~3 s that was in accordance with plasma base estimations (1974)

But after modernization of electron cooling device (1976) the cooling time was improved to 83 ms (the proton energy 65 MeV, the electron current is 0.5 A). It was better than the big assumption of anybody.



- **stabilization of electron energy – better than 10^{-5}**
- **straightness of force line of magnetic field not worse than 10^{-4}**

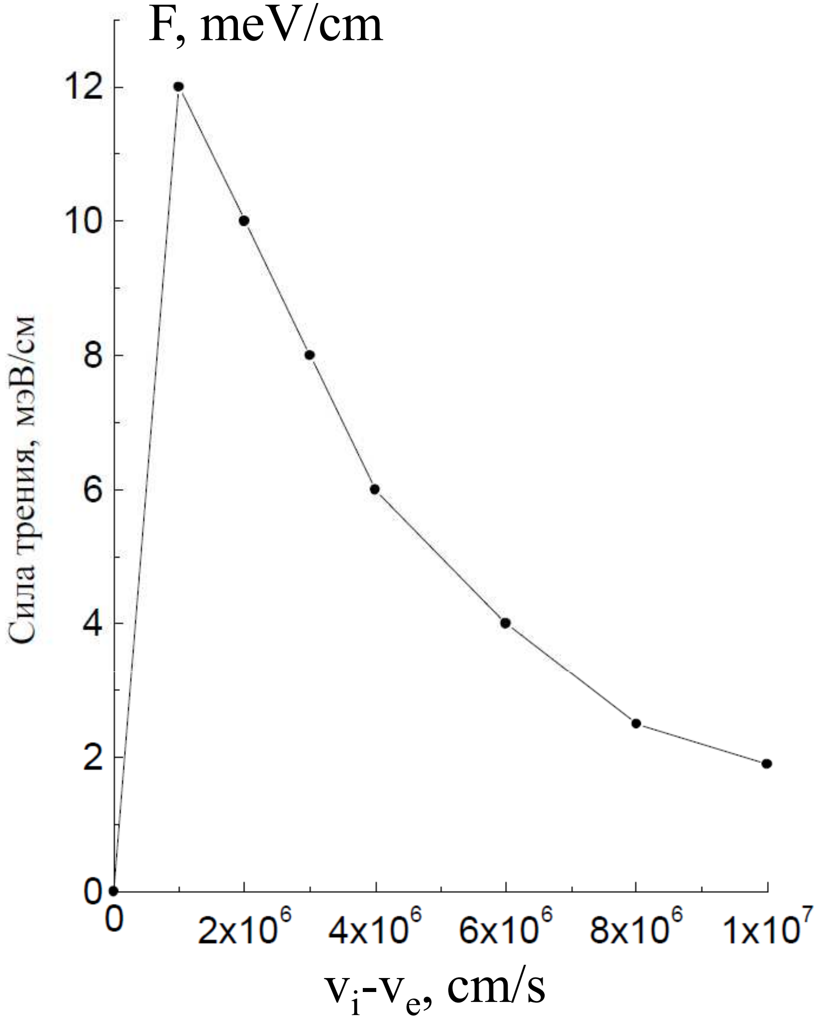
First cooling proton beam on NAP-M 1975

Рис. 4. Фотография ядерной фотоэмульсии, экспонированной пучком быстрых атомов водорода ($v/c = 0{,}35$), возникающих при рекомбинации протонного и электронного пучков на участке охлаждения

Фотоэмульсия расположена на расстоянии 10 м от участка взаимодействия. Метки нанесены через 1 мм. Размер изображения соответствует диаметру протонного пучка 0,5 мм и угловой расходимости $3 \cdot 10^{-5}$ рад

Slow extraction from the ring with using recombination proton with electron

Protons after recombination at cooler and passing 10 m to nuclear emulsion. Distance between points mark 1 mm.



Experimental data from NAP-M. Friction force versus relative velocity between ion and electron. The proton beam energy is 65 MeV, electron current is 0.3 A.

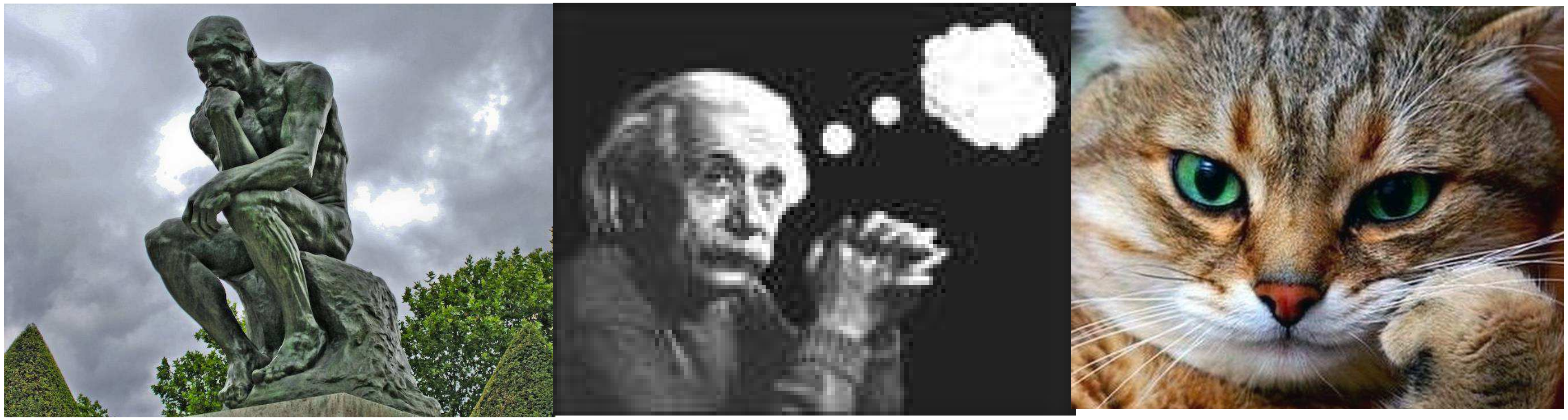
After improving of some elements NAP-M storage ring and electron cooling device EPOCHA the accuracy of measurement was improved significantly. The researchers   expects that the velocity distribution function of electrons will be spherically symmetric in co-moving frame. The typical width of the distribution function will be 0.2 eV that corresponds to cathode thermal temperature.

$$V_e = \sqrt{T_e / m_e} = 2 \cdot 10^7 \; cm/s$$

Expected that this is threshold value after which the cooling force will be to decrease. But the experimental data shows that the maximum of friction force located at essential small velocity.

$$\Delta V_e = 1.5 \cdot 10^6 \; cm/s$$

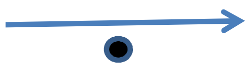
The friction force is more amazing that it was thinking before …



The problem of the classical way to cooling force

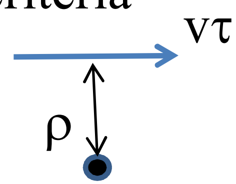
- **the electron does not move along line during collision**
- **the distribution function of the electron in velocity space is not Maxwellian**
- **the ion has the finite time for interaction in the cooling section (fixed length, not infinite)**

classical collision (particle move about from -∞ to + ∞)



no collision

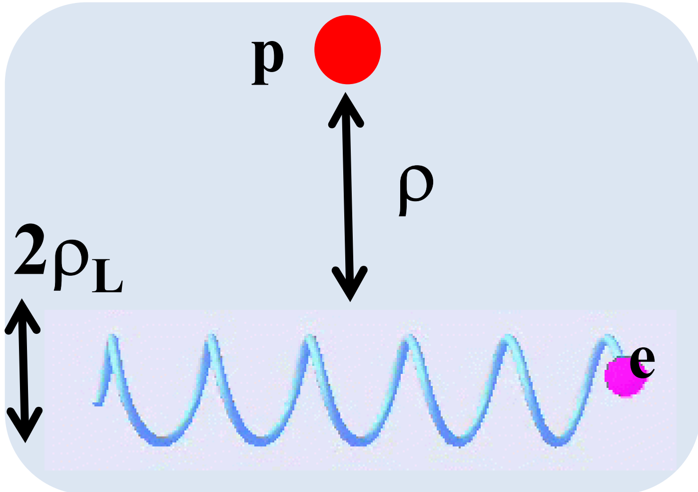
criteria



ρ~vτ

magnetized collision

magnetized plasma – plasma located in the strong magnetic field. The Larmour frequency of the rotation of charged particle is larger than the typical collision time.

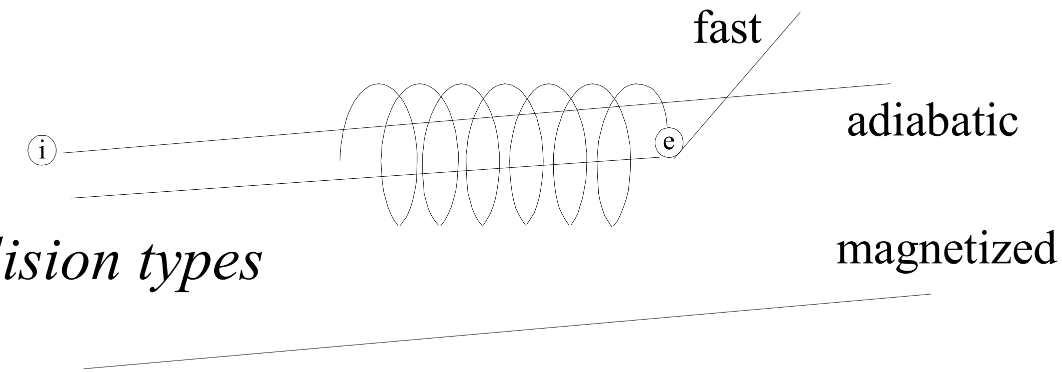


At interaction of magnetized electron with the ion the new typical value of impact parameter is appear. It is Larmour radius ρ_L. If the proton moving at distance $\rho \gg \rho_L$ than the collision occurs with Larmour circle, but not with single electron.

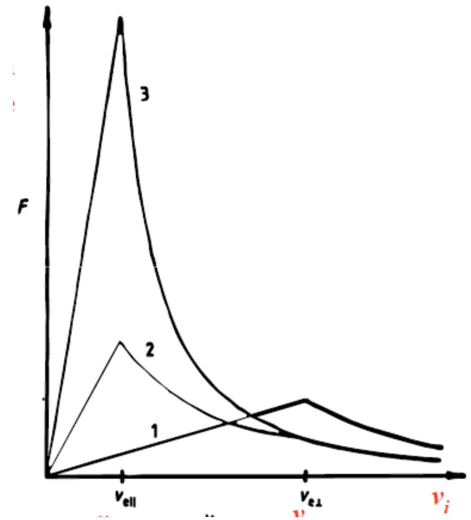
Result of the investigation of magnetized collision

N.S. Dikansky, V.I.Kudelainen, V.A.Lebedev, I.N.Meshkov, V.V.Parkhomchuk, A.A.Sery, A.N.Skrinsky, and B.N.Sukhina, "Ultimate Possibilities of Electron Cooling," INP, Novosibirsk, USSR Report, Preprint 88-61 (1988)

All collision may be divided to the different types in the magnetic field with finite strength: fast, adiabatic and magnetized. All collision have the different impact distances and give in result the diferent dependence from the ion velocity.



Collision types



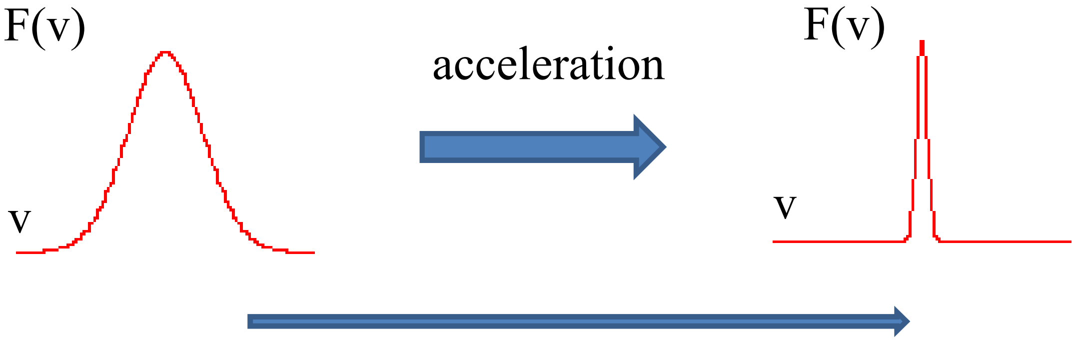
$$\vec{F}_F = \frac{4n_e e^4 L_F}{m_e}\frac{\vec{v}}{v_{e\perp}^3} \qquad \frac{e^2}{m v_e^2} < \rho < \frac{V}{\omega_H}$$ fast (free) Coulomb collsions

$$\vec{F}_A = \frac{4\pi n_e e^4 L_A}{m_e}\frac{\vec{v}}{\left(v^2 + v_{e\parallel}^2\right) v_{e\perp}} \qquad \frac{V}{\omega_H} < \rho < \rho_L$$ adiabatic or multiply

$$\vec{F}_\perp^A = -\frac{2\pi n Z^2 e^4}{m} L^A(v) \frac{v_\perp^2 - 2v_{II}^2}{v^2}\frac{\vec{v}_\perp}{v^3}$$

$$\vec{F}_{II}^A = -\frac{6\pi n Z^2 e^4}{m} L^A(v) \frac{v_\perp^2}{v^2}\frac{v_{II}}{v^3}$$

$$\rho_L < \rho < V \cdot \tau$$ magnetized



$$T_f \to \frac{T^2}{2E_k}$$

$$T_f \to \frac{T^2}{\gamma^2 \beta^2 mc^2}$$

$$v \to \sqrt{v^2 + v_0^2} \qquad dv \to \frac{vdv}{\sqrt{v^2 + v_0^2}}$$

$$dv \downarrow \quad dl \uparrow$$

After acceleration the spread of longitudinal velocity is smaller than the spread of the transverse velocity. It is result of Liouville's theorem. The electron bunch is stretched in the longitudinal direction, so the momentum spread is shrunk. If the start temperature of electron gas is about T=0.1 eV (cathode temperature), then the longitudinal temperature of electron gas in co-moving reference system is $T=6\cdot10^{-7}$ eV= $6\cdot10^{-3}$ K.

Really it is not the whole truth. The fluctuation of electron density in the electron beam becomes essential and the estimation of the longitudinal velocity can be write as

$$T_p \approx Ce^2 n_e^{1/3} = Cmc^2 r_e n_e^{1/3}$$

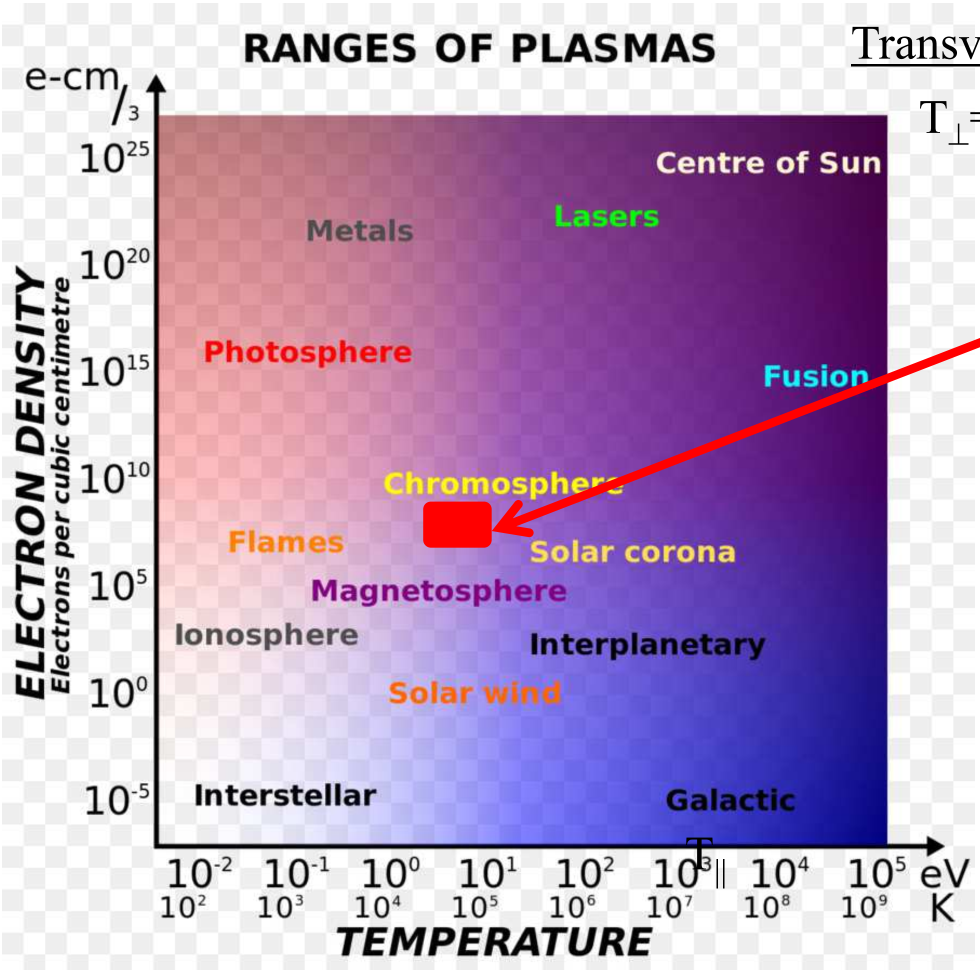
$$T_p \approx 2\cdot10^{-4}\ \text{эВ=2 K}$$

$$n_e = \frac{I}{\pi a^2 e\beta c} = 3.4\cdot10^{8}\ \text{cm}^{-3}$$

I = 1 A, E=10 кВ, a=1 см

The next problem is “flattened” electron velocity distribution

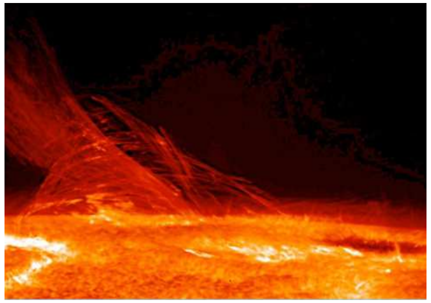
For the electron gas for electron cooling the transverse and longitudinal temperatures is very different



$T_\parallel$

Transverse temperature

$T_\perp$=1 000-1 0000 °C



$$= \frac{T_c^2}{2E_0} + e^2 n_e^{1/3} =$$

1 mK -1 K

Longitudinal temperature

$$\vec{F} = -\frac{4\pi n_e e^4}{m_e} L_C \int \frac{\vec{u}}{u^3} f(v_e)\, d^3 v_e \qquad u = \vec{v}_i - \vec{v}_e \qquad \rho_e = \frac{4\pi n_e e^4}{m_e} L_C f(v_e)$$

The main feature of the equation for the friction force in the electron gas is the full analogy with the equation for the electrostatic field. The same integral is derived for Coulomb's law and charge density ρ_e. This analogy allow to make the qualitative analyze of the integral property. For example, for isotropic distribution of distribution function in the velocity space v_i is

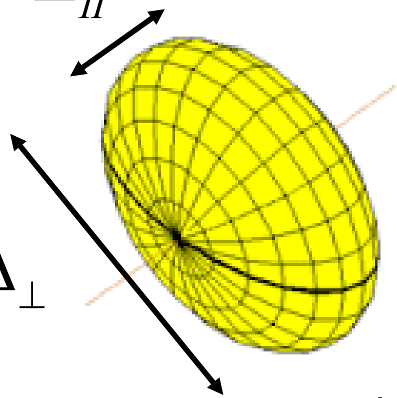
$$\vec{F} \propto \frac{\vec{v}_i}{v_i^3} \qquad v_i >> v_e$$

"electrostatic field" inside "charge sphere"

$$\vec{F} \propto \frac{\vec{v}_i}{v_e^3} \qquad v_i << v_e$$

outside

Δ_{II}



$\Delta_\perp$

$$\left[\begin{array}{c} v_i > \Delta_\perp \\ \Delta_{\mathrm{II}} < v_i < \Delta_\perp \\ v_i < \Delta_{\mathrm{II}} \end{array}\right.$$

magnetized case, very flatten distribution

$$\vec{F}_\perp = -\frac{4\pi n_e e^4}{m_e} L_C \vec{v}_\perp \begin{cases} 1/v_i^3 \\ 1/\Delta_\perp^3 \\ 0 \end{cases}$$

$$\vec{F}_{\mathrm{II}} = -\frac{4\pi n_e e^4}{m_e} L_C \vec{v}_{\mathrm{II}} \begin{cases} 1/v_i^3 \\ 1/\left(v_{\mathrm{II}} \Delta_\perp^2\right) \\ 1/\left(\Delta_{\mathrm{II}} \Delta_\perp^2\right) \end{cases}$$

non magnetized case, very flatten distribution

Empirical equation is useful for estimation of electron cooling

$$\vec{F} = -\frac{4\, n_e\, e^4}{m_e} \frac{\vec{v}_i}{(v_i^2 + v_{eff}^2)^{3/2}} \ln\left(\frac{\rho_{\max} + \rho_{\min} + \rho_L}{\rho_{\min} + \rho_L} \right)$$

$\rho_L = m v_{Te} / eB$ - Larmour radius

$\rho_{\max} = \dfrac{v_i \tau}{1 + \omega_{pe} \tau}$ - maximal impact parameter

τ - flight time through cooling section (interaction time)

ω_{pe} - plasma frequency

$\rho_{\min} = \dfrac{e^2}{m v_i^2}$ - minimal impact parameter

v_{eff} - all parasitic velocities of electrons respectively ions

$v_{eff}^2 = v_{\Delta\Theta}^2 + v_{E\times B}^2 + v_{\mathrm{II}e}^2$

$v_{IIe} = C e^2 n_e^{1/3}$ - spread of longitudinal velocities of electrons

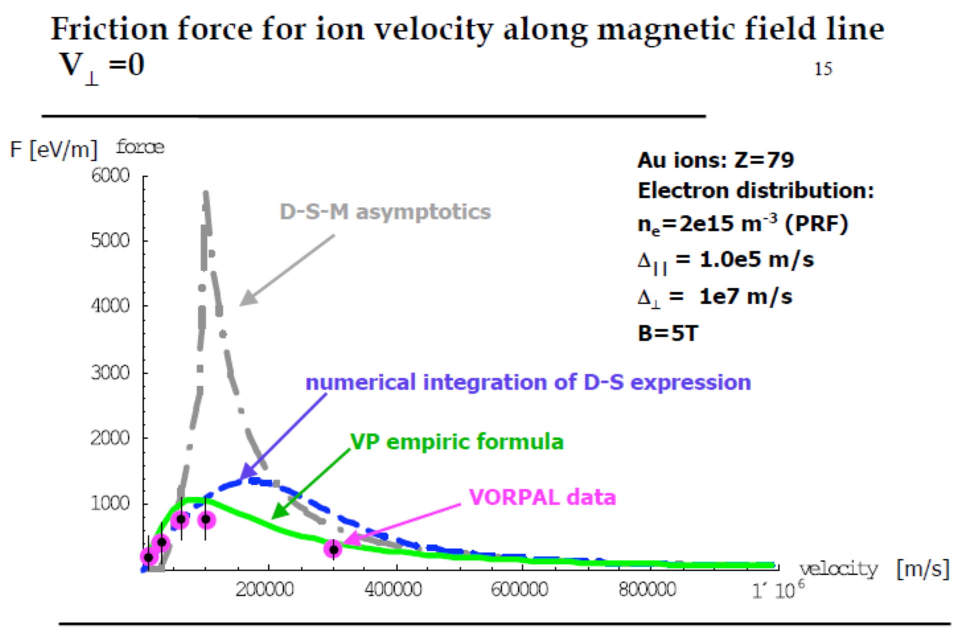
$v_{\Delta\Theta} = \gamma\beta c \sqrt{\langle \square B^2 \rangle}$ - waviness of magnetic force line

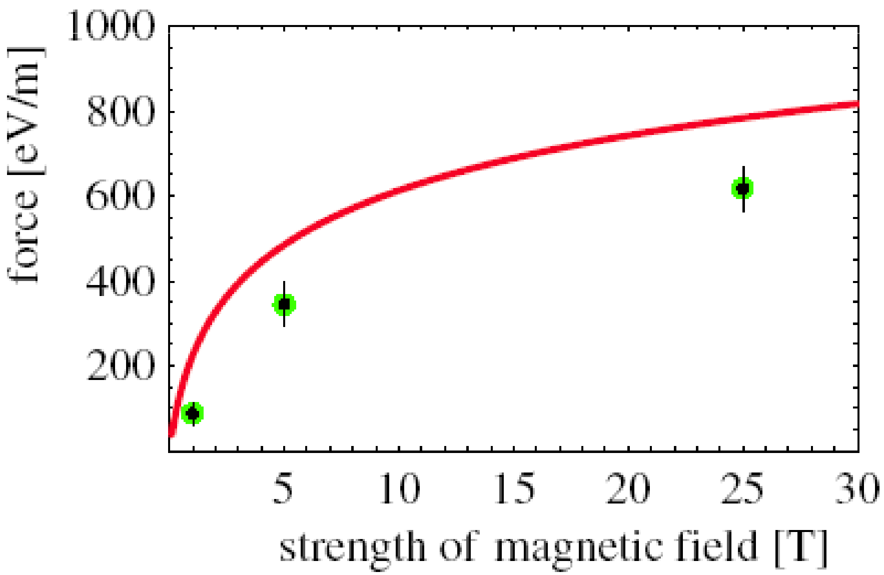
$v_{E\times B} = c\, \dfrac{E_{sp\_charge}}{B}$ - drift of electrons induced by space charge

V. Parkhomchuk's empiric formula for magnetization cooling

$$\Delta\vec{p} = \vec{F}\cdot\tau = -\frac{4e^4 n_e \vec{V}\tau}{m_e(\sqrt{V^2+V_{eff}^2})^3}\ln\left(1+\frac{\rho_{\max}}{\rho_L+\rho_{\min}}\right)$$

Parkhomchuk's empirical formula is much better agreement with computer simulations and experiment measurements of ***fully magnetized cooling and contains (embodies) this idea.***

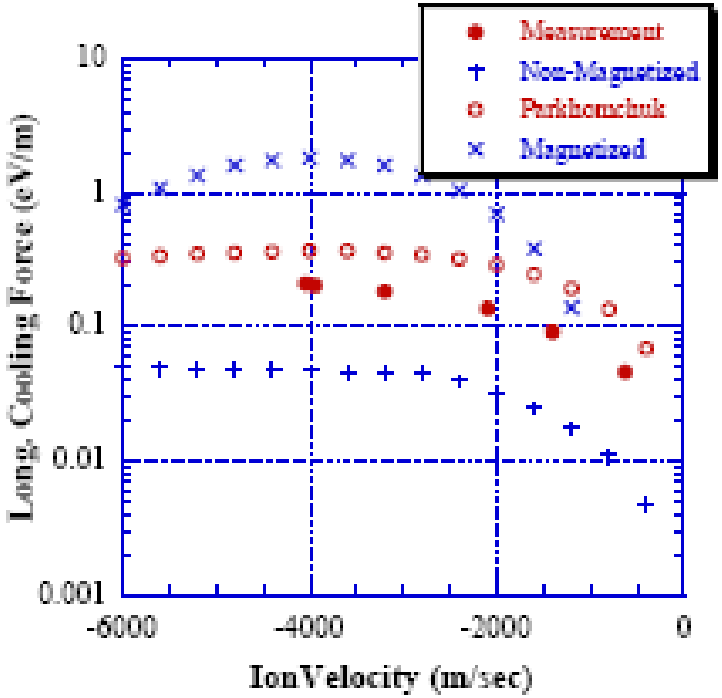




Direct calculation with VORPAL code by A. Fedotov, D. Bruhwiler, A.Sidorin,D. Abell, I. Ben-Zvi, R. Busby, J. Cary and V. N. Litvinenko
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9, 074401 (2006)**

Solid curve—Parkhomchuk equation; dots with error bars—VORPAL results.

The maximum friction force versus the magnetic field



Comparison between the measured longitudinal cooling force and the cooling force models, such as nonmagnetized, Parkhomchuk and magnetized cooling model. The electron current is 100 mA (8.8×10^{6} e^{-}/cm^{3}), COOL-05, CELSIUS

ELECTRON COOLING EXPERIMENTS AT S-LSR

T. Shirai, S. Fujimoto, M. Ikegami, H. Tongu, M. Tanabe, H. Souda, A. Noda, K. Noda, T. Fujimoto, S. Iwata, S. Shibuya, E. Syresin, A. Smirnov, I. Meshkov, H. Fadil, M. Grieser,

Proceedings of COOL 2007, Bad Kreuznach, Germany THM1I02

Experimental Benchmarking of the Magnetized Friction Force

A.V. Fedotov[1], B. Galnander[2], V.N. Litvinenko[1], T. Lofnes[2]

A.O. Sidorin[3], A.V. Smirnov[3], V. Ziemann[2]

March 2 data: B=0.1T, electron current Ie=250 (pink color), 100 (red), 50 (blue) mA

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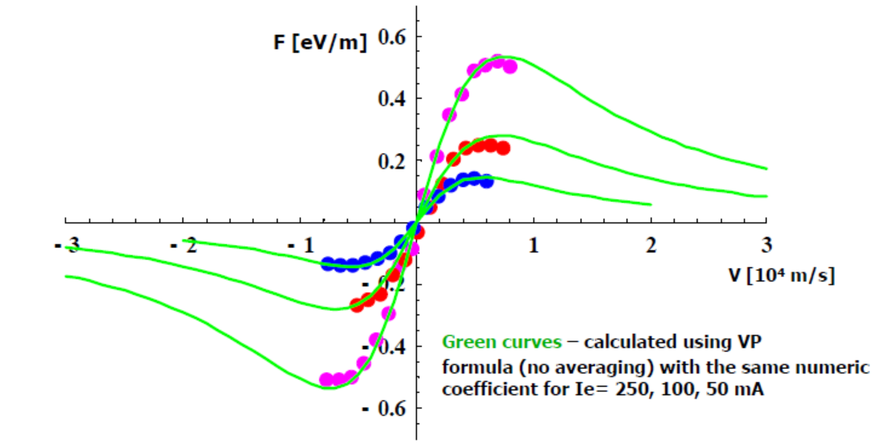


Technical realization of electron cooling
Magnetic field for strong focusing of electrons

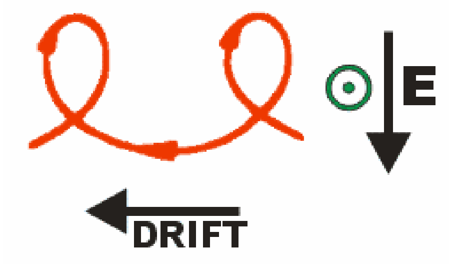
For electron cooling realization the cooling (straight) section should contains the electron beam with high density. The first obvious problem is divergence of particle induced by the space charge force. Defocusing length l_{def} of pure electron beam with density n_e is:

$$\frac{1}{l_{def}} = \sqrt{\frac{2\pi r_e n_e}{\beta^2 \gamma^3}}$$

Here re is classical radius of electron, are γ, β relativistic parameters of the beam. At density of the electron beam n_e=10^8 cm^3 and energy 54 keV for cooling proton beam 100 MeV the defocusing length is 37 cm, that much less than the typical length of the cooling section. The simplest way to solve this problem is use of the longitudinal magnetic field.

At presence of longitudinal magnetic field the transverse electrical field of space – charge induces the drift motion around beam axis. The value of drift motion increase with distance from axis.

$$E'_{\perp} = 2\pi n'_e e r \qquad v'_{\perp} = c\frac{E'_{\perp}}{B}$$



in co-moving frame

The subject to sufficiency of value of magnetic field is smallness of electron velocity to compare the velocity of ion in the cooling section.

$$v'_i = \gamma\beta c\frac{r}{\beta_{cool}}$$

v'_i - ion velocity

β_{cool} - beta function

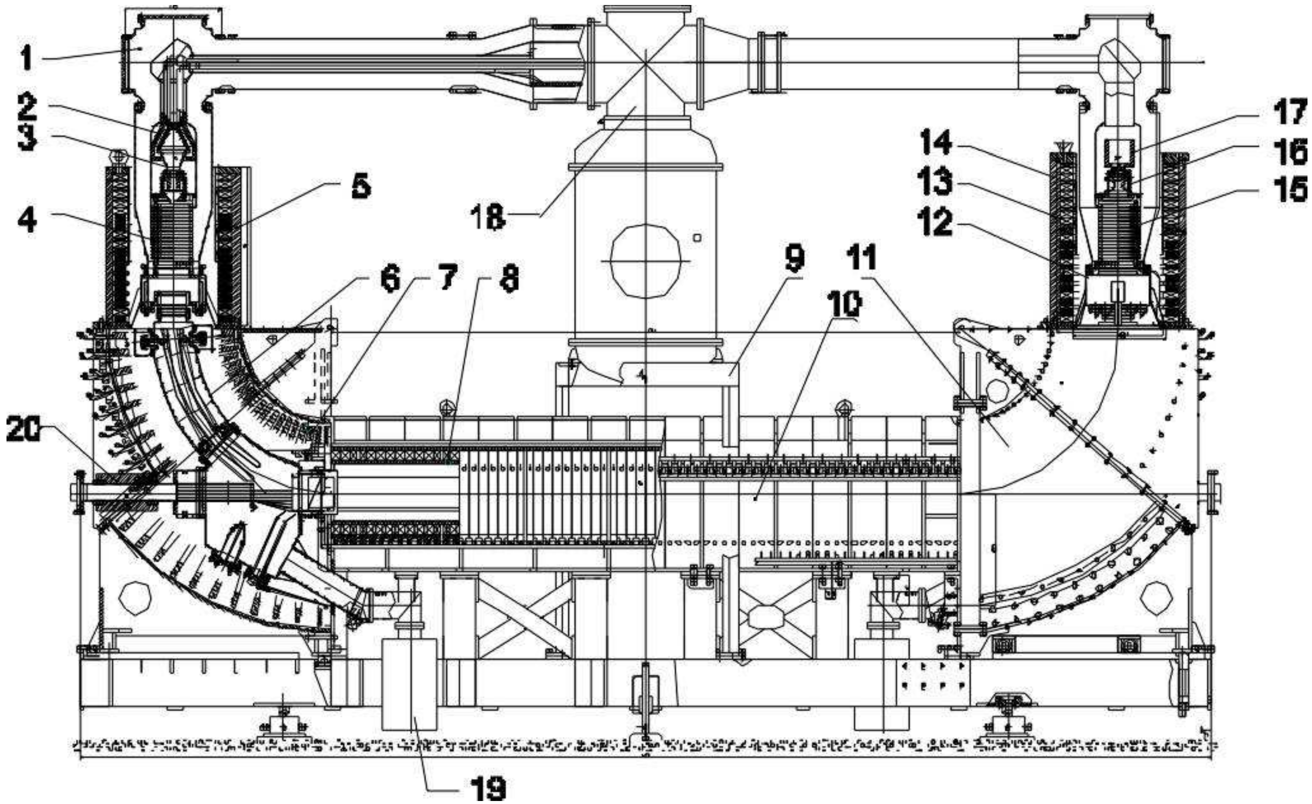
$$B = \frac{2}{\gamma^2\beta^2}\frac{\beta_{cool} I}{c a_e^2}$$

At electron current I=1 A, electron radius ae=1 cm and energy 54 keV for cooling proton beam 100 MeV with beta function in the cooling section b=1 m the estimation of the magnetic field is B=900 G.

So the solenoidal magnetic field allows to combine strong focusing with the requirement (for efficient cooling) of low electron transverse velocity in the cooling interaction region;

300 kV electron cooler as example of technical design

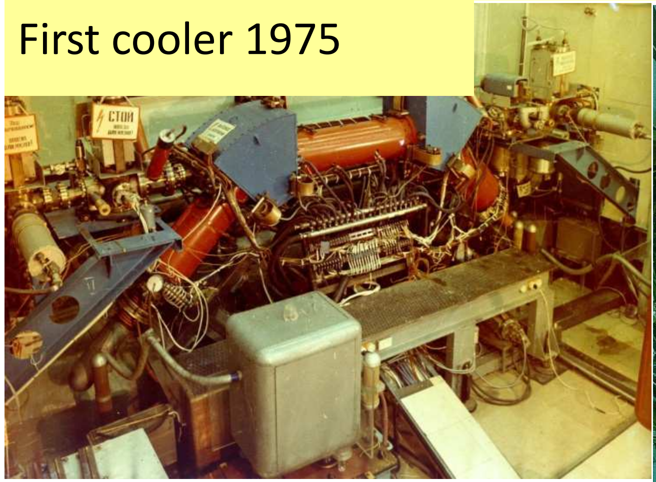
1. Tunable of the coils position for generation precise magnet field at cooling section with straightens about 10^{-5}
2. Magnetized motion of the electron beam from cathode to collector.
3. Variable beam profile of the electron beam
4. High collector efficiency in order avoid the problem with vacuum, radiation, high-voltage stability e t.c.
5. Recuperation energy of the electron beam



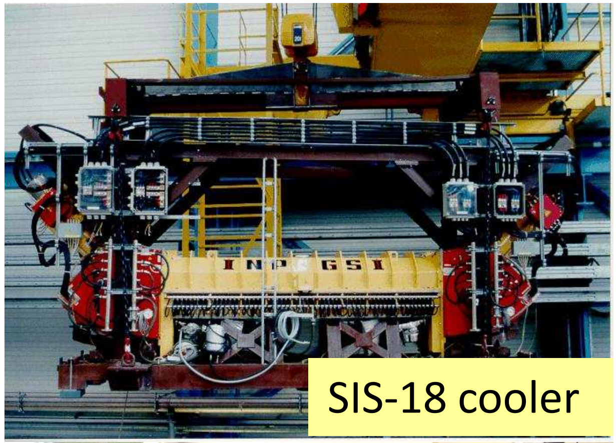
1 – high voltage feeder, 3 – collector, 4 – decelerator tube of collector, 5 – coils of the collector magnetic field, 6 – bend with electrostatic plates, 9 – vessel of the high voltage generator, 15 – accelerator tube of the electron gun, 16 – electron gun, 18 –high voltage terminal

EC-300 electron cooler for CSRe storage ring (Lanzhou, China)

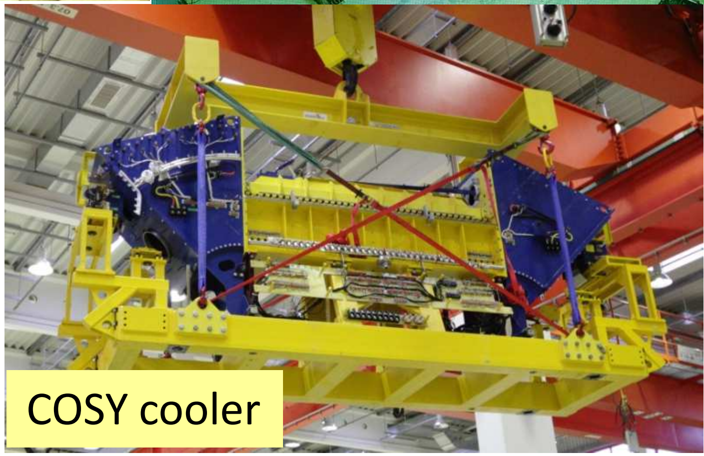
BINP coolers from 1967 to 2016


First cooler 1975


MOSOL


SIS-18 cooler


CSRm 35 kV cooler


COSY cooler

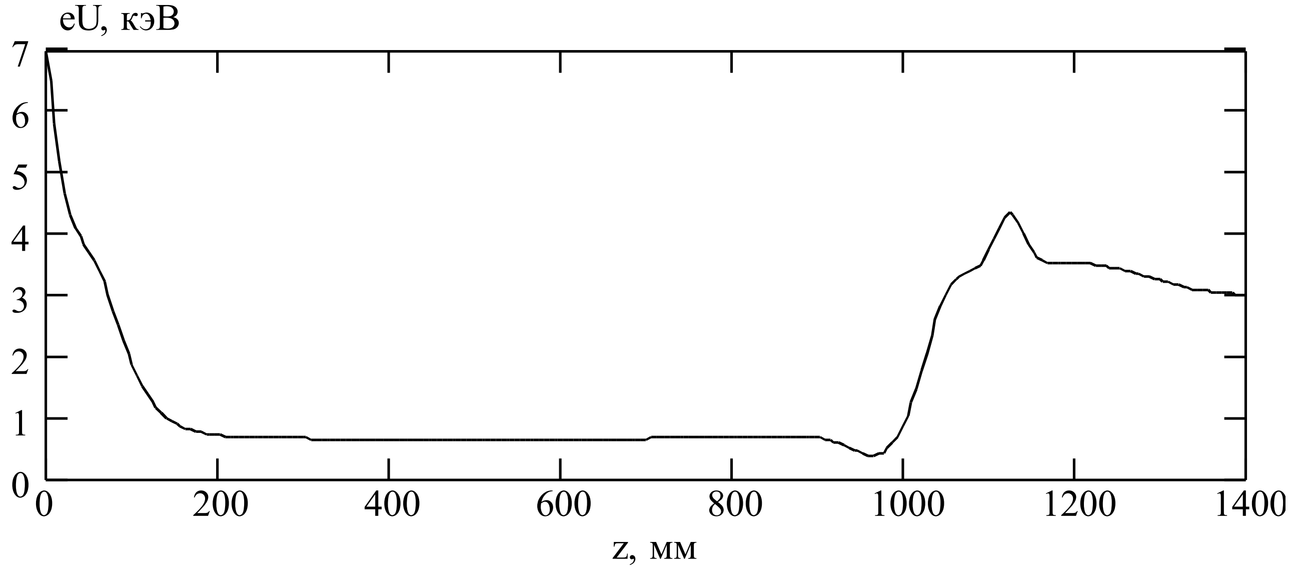

LEIR cooler


CSRe cooler


Booster Dubna cooler

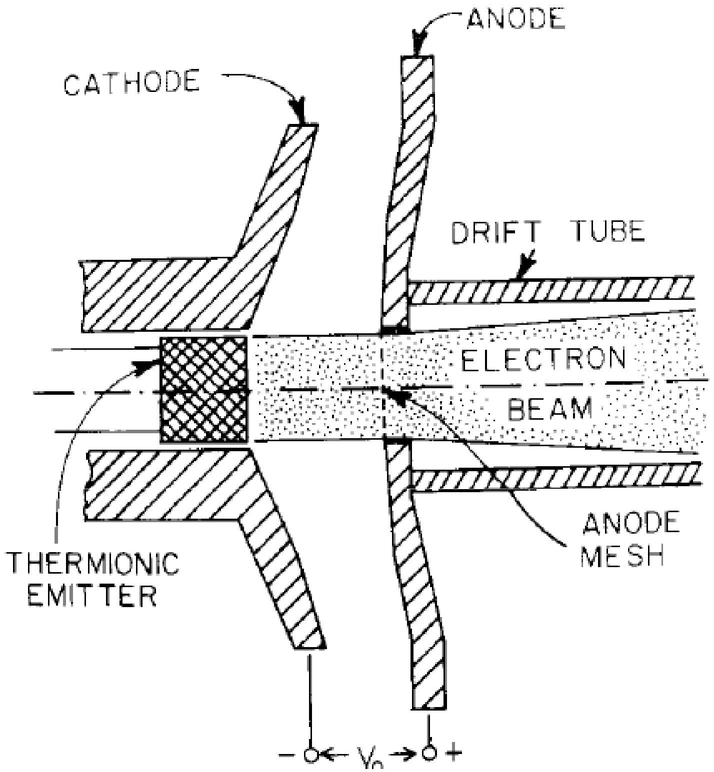
Recuperation energy

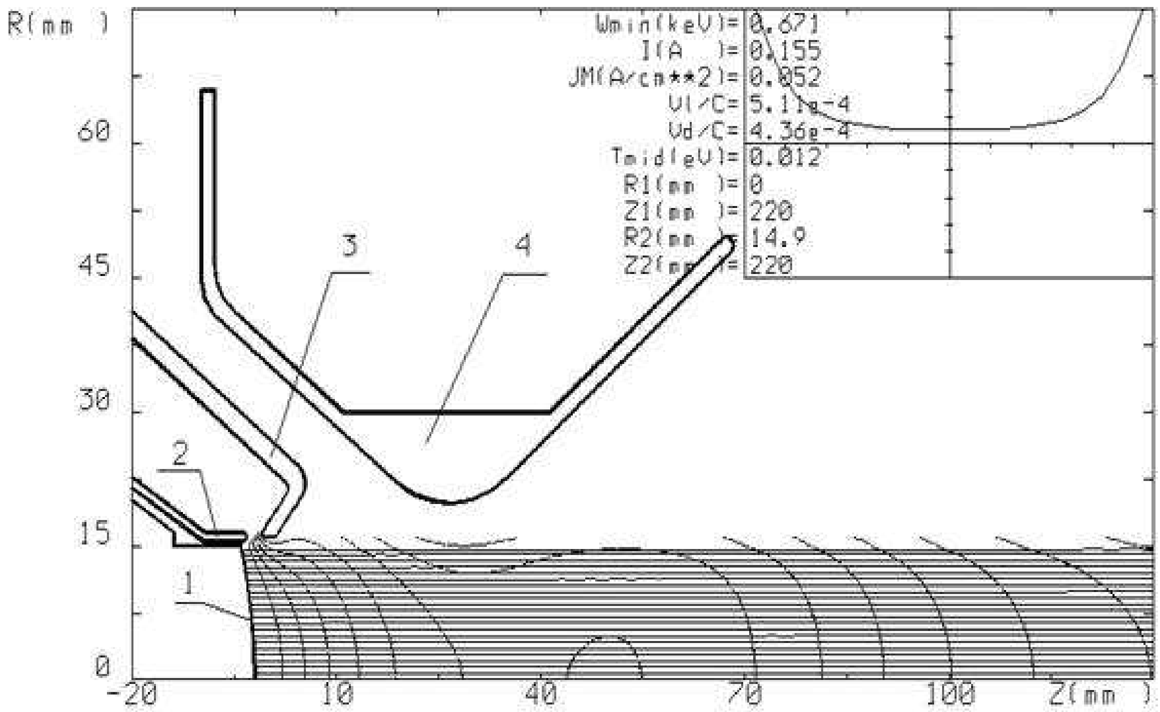
For small energy of electron beam (up to 5 MeV) the simplest way of electron beam acceleration is the direct electrostatic acceleration. The power of such electron beam is eU_0I_e , where U_0 is potential of cathode, $Ie=e \cdot n_e \cdot V_p \cdot a_e^2$ is the current of electron beam. For cooling 100 MeV proton beam with electron current 1 A and energy $e \cdot U_0$ =54 keV the required power is 54 kW. The electron beam density is $n=1.4 \cdot 10^8$ 1/см^3 at electron beam radius 1 cm. Absorbing such value of power in the vacuum chamber may result the problem with cooling vacuum elements, X-ray radiation, vacuum pressure. The recuperation of energy is based on use of two power supply. The first power supply provides the energy for the circuit cathode – collector. The second power supply applies the potential between the cathode and ground.



Technical features of the realization of the electron cooling

Gun



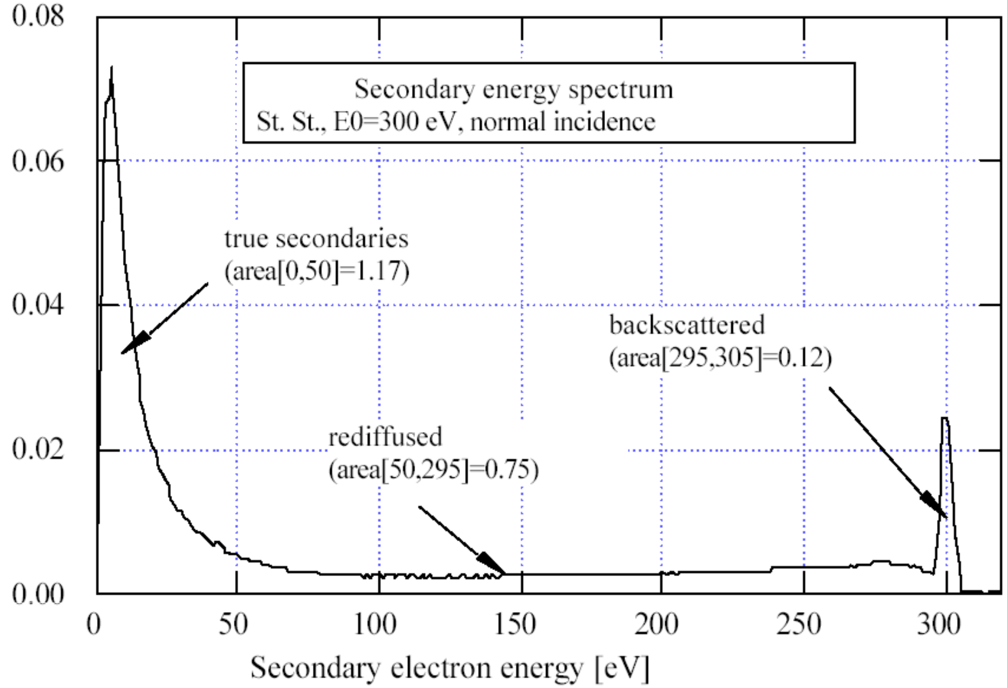


The simple variant of Pierce optic. Axial symmetric electron gun. No profile changing

Electron gun for EC-35 BINP, it sis possible to profile changing

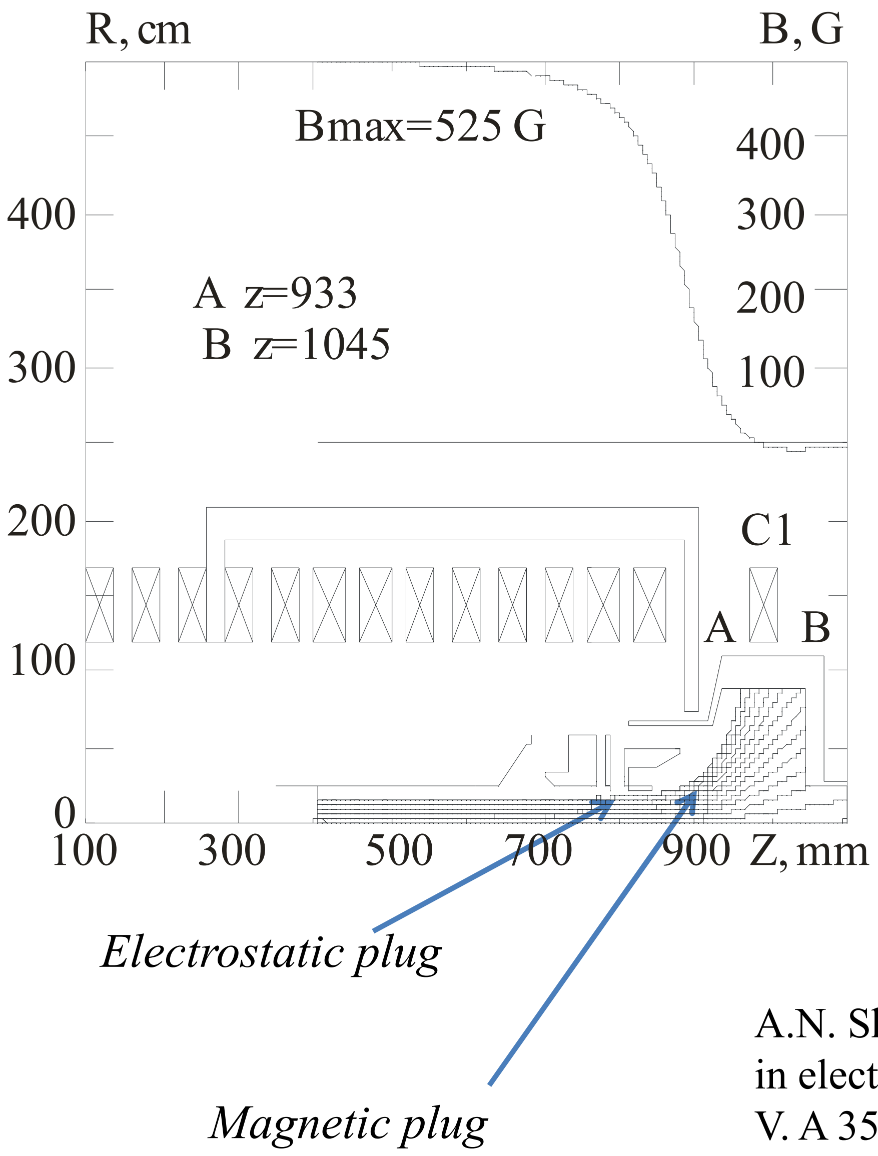
1 – cathode, 2 – beam-forming electrode, 3 – control electrode, 4 – anode.

Collector of electron



The spectrum of secondary electrons that produces by the primary electron beam at normal falling on stainless steel surface (Ee=300 eV).

The total coefficient of secondary emission is the number of whole number secondary electrons to the number of primary electrons. This coefficient depends from material type and may be 0.1-1.5 for the different material of surface and electron energy. The secondary electrons can move from the place of their origin to the collector entrance and escape from it. So the flux of secondary electrons from collector can be essential.



The main parameter of the collector is efficiency parameter that is ratio between the electron current escaping from collector to primary electron current:

$$\sigma_{coll} = \delta I / I_0 .$$

Here δI is the current of secondary electrons, I_0 – the current of primary beam. There is a simple estimation of this value σ_{coll}:

$$\sigma_{coll} = k \cdot \left(\frac{U_m}{U_{coll}} \right)^2 \cdot \frac{H_{coll}}{H_{out}} ,$$

Here k – the coefficient depending from collector material and vacuum, U_m – potential minimum about axis, H_{coll} – magnetic field on the collector surface, H_{out} – magnetic field on collector entrance. According this equation for collector parameters $k = 0.2$, $U_m = 1.5\,KV$, $U_{coll} = 2.5\,KV$, $H_{coll} = 15\,Gs$ и $H_{out} = 1000\,Gs$ the collector efficiency is $\sigma_{coll} = 1.1 \cdot 10^{-3}$, that is reasonable according experimental facts.

A.N. Sharapa, A.V. Shemyakin. Secondary electron current loss in electron cooling devices. Nucl. Instrum. and Methods. 1994. V. A 351. P. 295-299.

Cooling section.

Decreasing of the distortion of the force line of the magnetic field increases the maximal value of the friction force. This effect is essential for small difference of ion momentum from equilibrium value. So, this effect may is keyword parameter for the experiment with intrinsic target.

$$\Delta\vec{p} = \vec{F}\cdot\tau = -\frac{4e^4 n_e \vec{V}\tau}{m_e(\sqrt{V^2 + V_{eff}^2})^3}\ln\left(1 + \frac{\rho_{\max}}{\rho_L + \rho_{\min}}\right)$$

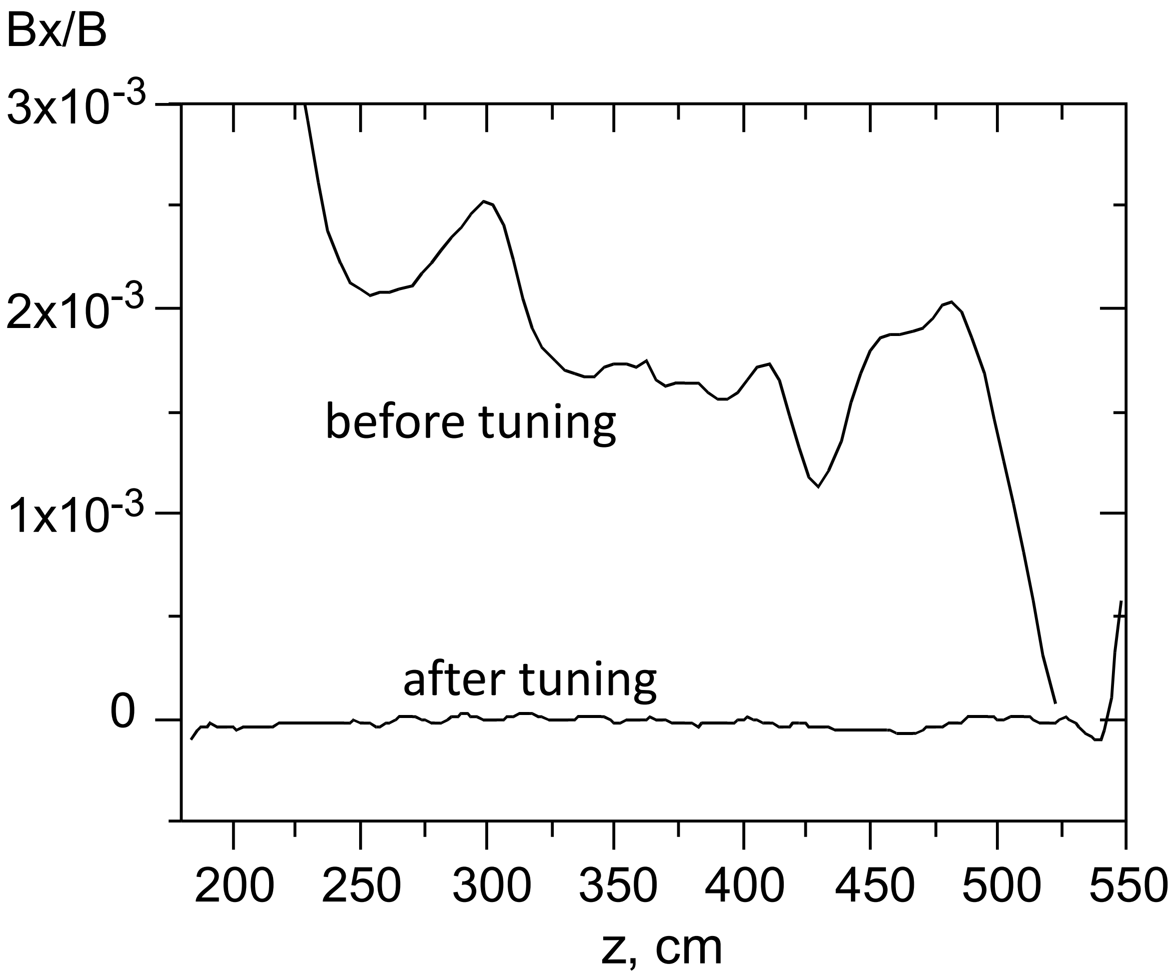
$$V_{eff}^2 = V_{\Delta\Theta}^2 + V_{E\times B}^2 + V_e^2$$ *effective temperature*

$$V_{\Delta\Theta} = \gamma\beta c\sqrt{\left\langle \Delta B^2 \right\rangle} \quad \left\langle \Delta B^2 \right\rangle -$$ *ripple of the magnetic field*

$\gamma_E\beta_E/\gamma_{30}\beta_{30}$	E, кэВ
1.9	100
8.0	1000
13.8	2000

Cooling section – standard BINP decision with pan-cake coils

Tuning of the magnetic force line



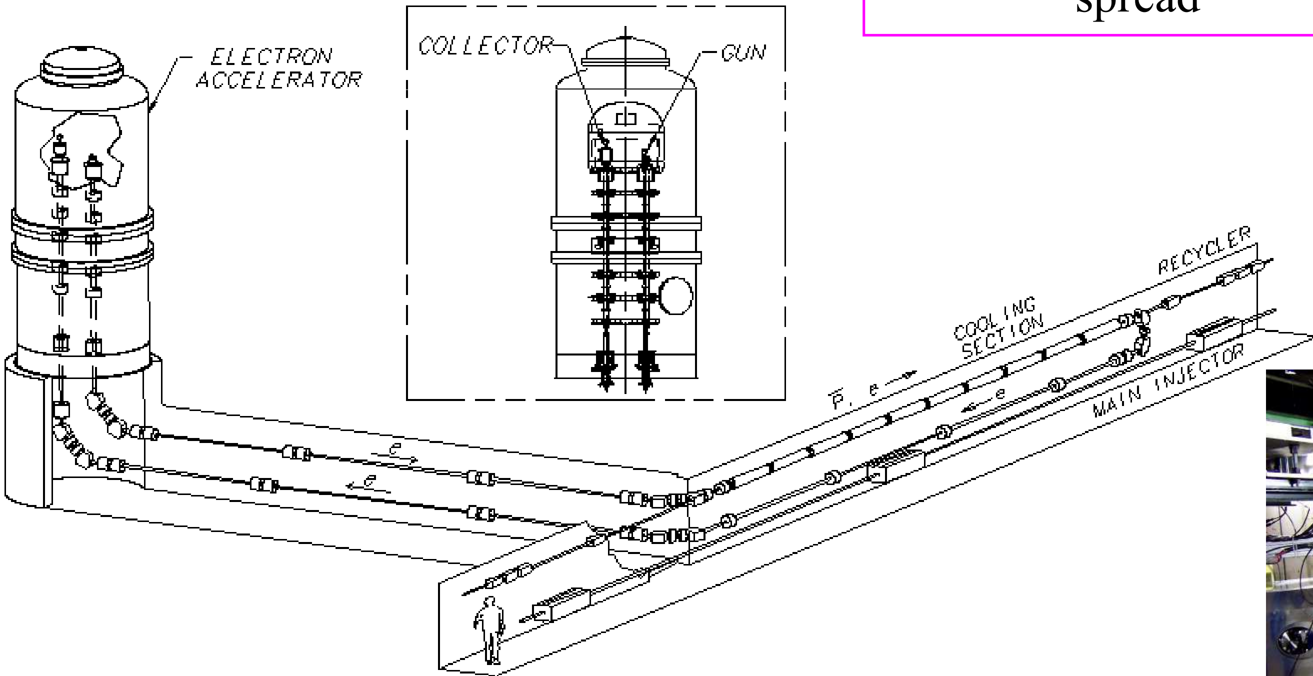
Transverse component of the magnetic field

Steps to high energy

Cooler in the Recycler at 4.3 MeV (Fermilab National Laboratory)

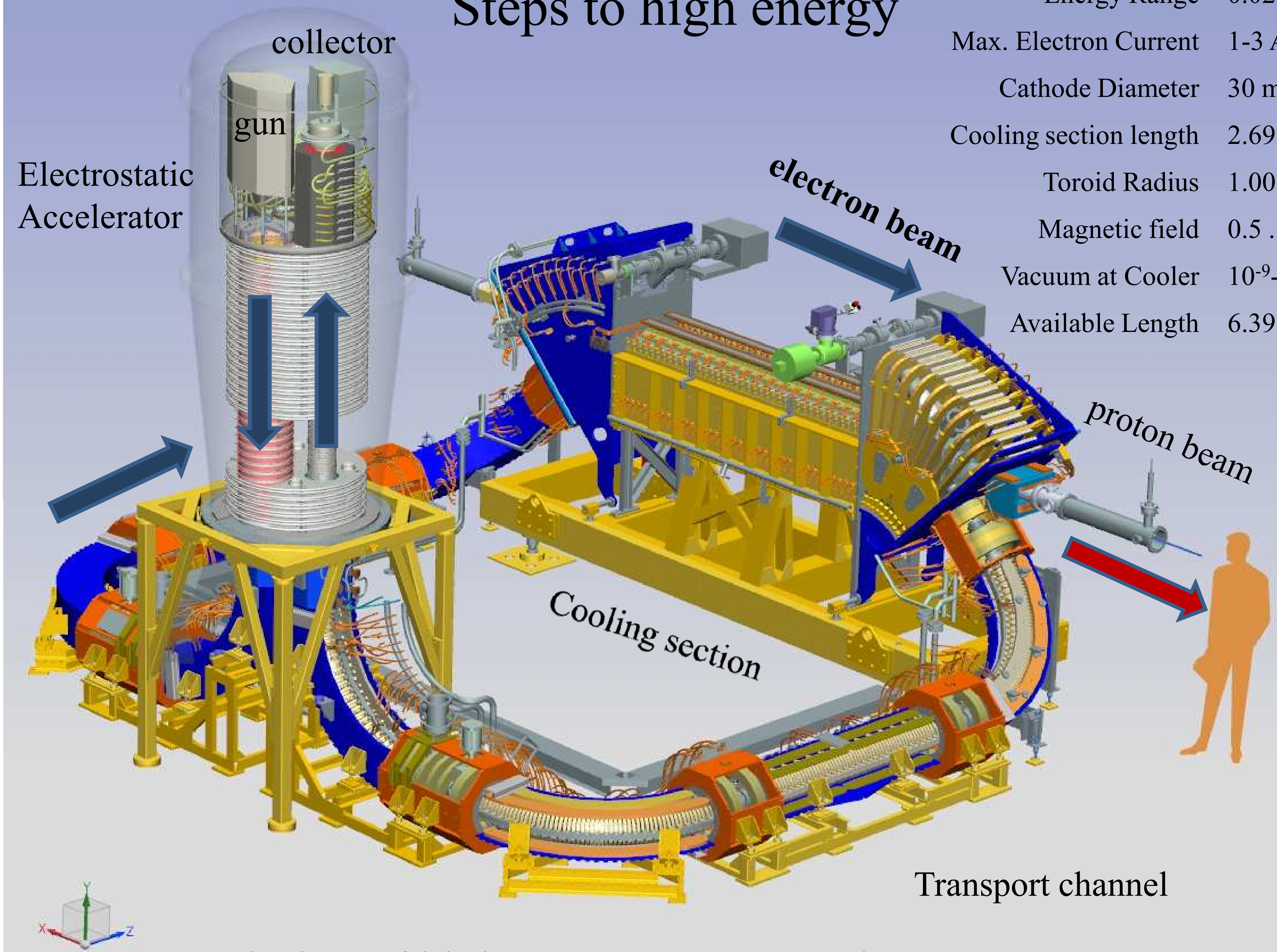
Design parameters of the ECool beam

Energy	4.34 MeV
Beam current	0.5 Amps DC
Angular spread	0.2 mrad
Effective energy spread	300 eV



Steps to high energy

Energy Range	0.025-2 MeV
Max. Electron Current	1-3 A
Cathode Diameter	30 mm
Cooling section length	2.69 m
Toroid Radius	1.00 m
Magnetic field	0.5 ... 2 kG
Vacuum at Cooler	10^{-9}-10^{-10} mbar
Available Length	6.39 m

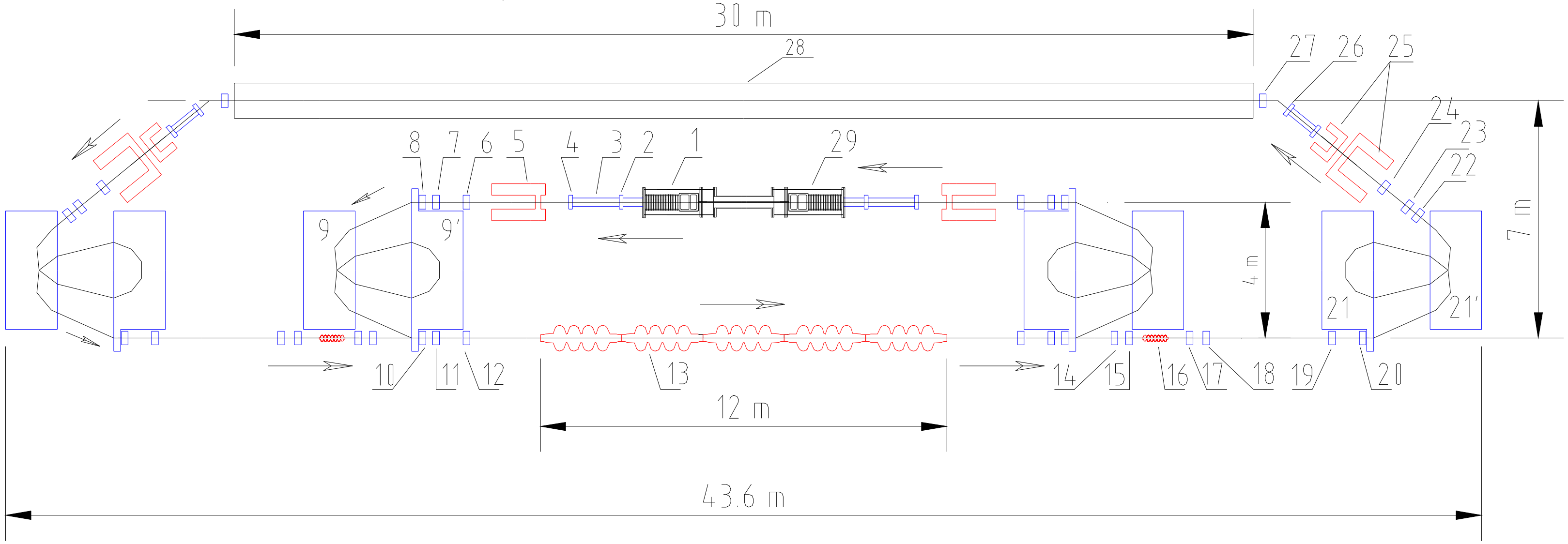


3D design of high energy COSY cooler

Steps to high energy

Project of the next step of the cooling technique for high energy

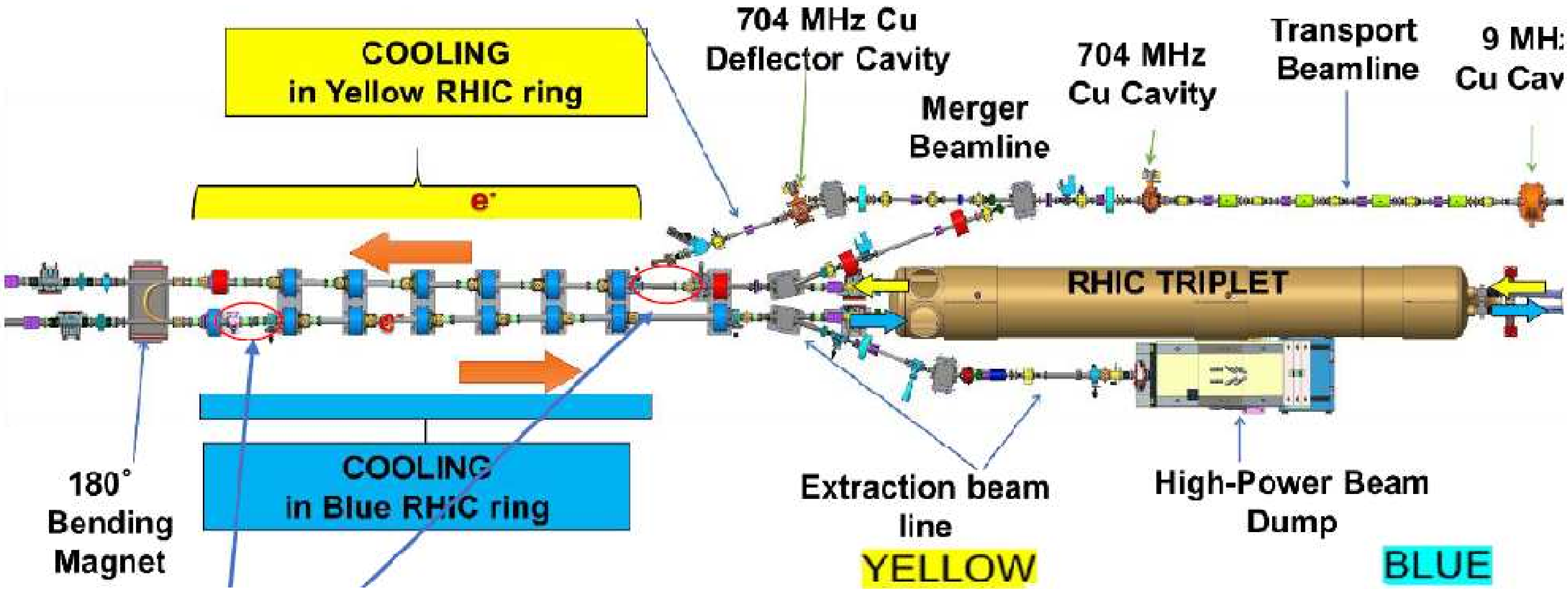
Project cooler for RHIC, Ee=50 MeV



1 – 2 MeV injector with magnetized cathode (the magnetic field into the injector 100 G); 3 – Extension of longitudinal magnetic field of the injector by a solenoid (100 G); 2,4 – Skew quadrupoles for transformation of magnetized beam to the flat beam; 5 – Energy modulating cavity for shrinking of an electron bunch from 4 ns to 0.06 ns. It consists of two 70 MHz RF-cavity (the gap voltage is 350 kV into everyone) and one 210 MHz (36 kV) RF-cavity; 6,7,8 – Adjust optic for bunching system; 9,9' – Magnetic buncher (α-magnet, the radius of bend is 1m); 10,11,12 – Adjust optic for bunching system;13 – RF linac structure (350 MHz LEP structure); 14 – Bend magnet for the compensation of action of last bend magnet (9'') at the high energy (50 MeV); 15,17 – Optic elements for transfer from the flat beam after injector (100 G) to the flat beam before the input to the main solenoid (104 G); 16 – Third harmonic of the RF linac (1.05 GGz) for the compensation of the non-linearity of base accelerating field; 18,19,20 – Adjust optic elements for debunching system; 21,21' – Magnetic debuncher (α -magnet, the radius of bend is 1m). 22,23,24 – Adjust optic elements for debunching system; 25 – RF-cavity for eliminate of linear dependence of longitudinal momentum from longitudinal position of electron. It consists of 80 MHz RF cavity (the gap voltage is 4.6 MV) and 240 MHz (0.24 kV). This cavity should be superconductive; 26 – Optic element for transfer of electron beam from flat to round beam for the injection into the main solenoid; 27 – Bend magnet; 28 – Main solenoid (10^4 G); 29 – Beam dump or system of beam recuperation.

Steps to high energy

A.V. Fedotov. Cooling commissioning results of first RF-based cooler. Brookhaven National Laboratory. ECOOL-19, Russia, Novosibirsk - 2019



LEReC electron beam parameters

Two energies commissioned ✓

Electron beam requirement for cooling			
Kinetic energy, MeV	1.6	2	2.6
Cooling section length, m	20	20	20
Electron bunch (704MHz) charge, pC	130	170	200
Effective charge used for cooling	100	130	150
Bunches per macrobunch (9 MHz)	30	30	24-30
Charge in macrobunch, nC	4	5	5-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5
Average current, mA	36	47	45-55
RMS energy spread	< 5e-4	< 5e-4	< 5e-4
RMS angular spread	<150 urad	<150 urad	<150 urad

ENERGY A. Fedotov et al., COOL19, Novosibirsk, Russia, September 23-27 2019 BROOKHAVEN NATIONAL LABORATORY 8

Ee=1.6 and 2 MeV

Conclusions

1. The cooling process is very useful for the accelerating physics and physics of the elementary particle
2. Electron cooling is the base cooling technique used at low energy storage rings (protons, ions, secondary beams (antiprotons, rare isotopes).
3. Electron Cooling still is also application at higher energies (MeV electron energies) that is clear after the successful demonstration of the 4 MeV electron cooler at FNAL, 2 MeV electron cooler at COSY and 1.6-2 MeV LEReC at BNL.