APS Wilson Prize Lection
13 OCT (2016)

For crucial contributions in the proof of principle of electron cooling, for leading contribution to the experimental and theoretical development of electron cooling, and for achievement of the planned parameters of coolers for facilities in laboratories around the world.

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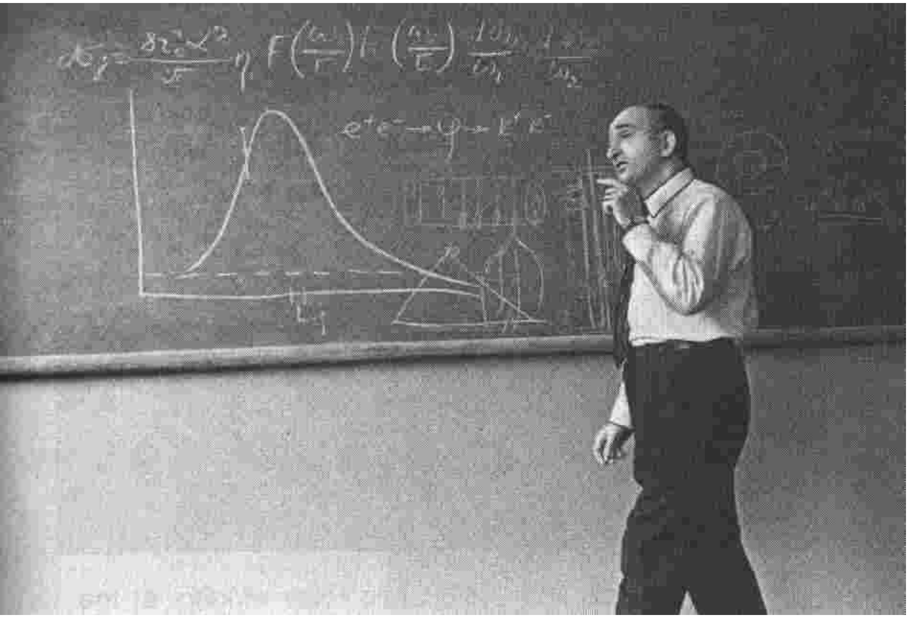
Abstract

The development of electron cooling started at 1966 from proposal G.I.Budker
To try used this system for proton-proton colliders. Now the electron cooling used for many ions accelerators for shrinking ion beam emittance and for accumulation rare ions beam at very broad energy range.
Many ideas was used for improved the cooling power and many problems was opened. The new ideas for extended the energy of cooled beam will discuss at report. The energy of cooler up to 8 GeV still required for HESR for suppress the scattering antiproton in inner target. The experience obtain at time of the commissioning 2 MeV cooler for COSY are used. These results are practical test bench for estimation different solutions for new the cooling systems.

Few keys ideas of the electron cooling

1966 – Effective method cooling at p*p storage rings. G.I. Budker, Atomic Energy 1967 v.22. #5 p.346-349
1974- First experements with electron cooling, G.I. Budker, N.S.Dikansky, V.I.Kudelainen, I.N.Meshkov, V.V.Parkhomchuk, D.V.Pestrikov, A.N.Skrinsky, B.N.Sukhina, IEEE Trans.Nucl.Sci. VS-22 pp2093-7 T=1000 K
1977- The magnetization effects in electron cooling, Derbenev Ya.S., Skrinsky A.N. 1978 Fizika Plasmy v.4, pp.492-500 (1978)
1984 Study of fast electron cooling Parkhomchuk V. ECOOL 1984, Karlsruhe
1980- Coherent electron cooling -**Amplification the electron cooling by instability inside electron beam**, Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980), **Coherent electron cooling -perfect tool for EIC** Vladimir N. Litvinenko,C-AD, Brookhaven National Laboratory, Upton, NY, USA Department of Physics and Astronomy, Stony Brook University, Yaroslav S. Derbenev, Thomas Jefferson National Accelerator Facility,Newport News, VA, USA
http://casa.jlab.org/viewgraphs/2007/Derbenev,etal_EICMtg_Dec07.pdf
1986 Compass for precise solenoid, 13 Inter. Conf. on high energy accelerators Novosibirsk 1986, v.1 p341343
1997- Accumulation at SIS18 high charge ions (recombination) Steck … M. EPAC98
2001 Electron cooling for RHIC Low frequency RF linac recycler for electron beam
http://www.agsrhichome.bnl.gov/AP/ap_notes/ap_note_47.pdf
2002- Hollow electron beam for cooling
2003- Electrostatic bend for CSRm,CSRe coolers
2006- LEIR cooler for Lead ions.
2004- Storage ring with longitudinal magnet field LEPTA I.N.Meshkov
http://www1.jinr.ru/Pepan_letters/panl_2012_4-5/11_ah.pdf
2006- 4 MeV electron beam cooling (TEVATRON) S. Nagaitsev
2007- Start design 2 MeV magnetized cooler for COSY
2008 -Cascade transformer for power solenoids around acceleration tubes
2009 -4 electrodes electron gun for measuring rotation electron beam at system
2012 –Electron beam commissioning COSY cooler in Novosibirsk
2016 –New coolers for NICA project

Invention electron cooling 1966



Budker G.I., Effective method of damping particle oscillations at proton antiproton storage rings, Atomic Energy 1967, v.22, №5, p.346
plasma model with electron plasma having temperature cathode.

$$\frac{MV_i^2}{2} = \frac{mV_e^2}{2} = T_{equilibrium}$$

$$\frac{\Delta p_\perp}{p} = \theta_i = \sqrt{\frac{m}{M}}\theta_e$$

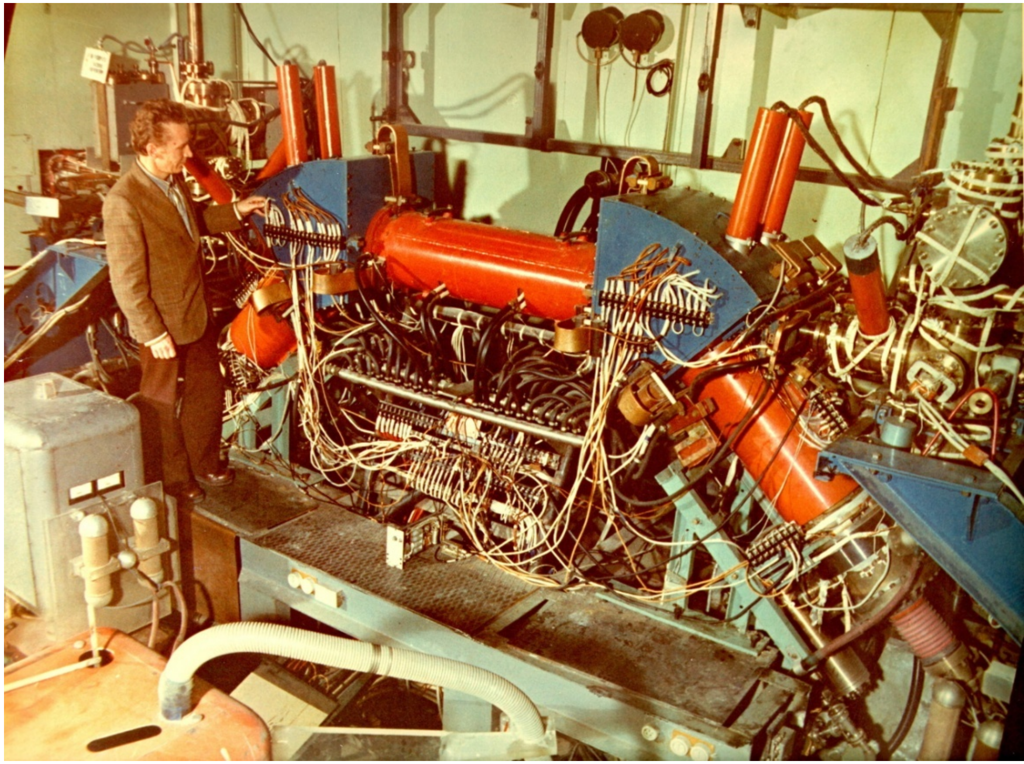
$$\theta_e = 3\times10^{-3}$$

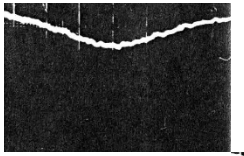
$$\theta_p = 1\times10^{-4}$$

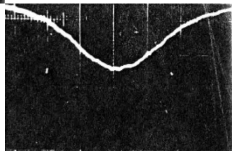
$$T_{equilibrium} = 1000 - 2000K$$

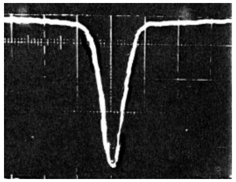
First Cooling Demonstration

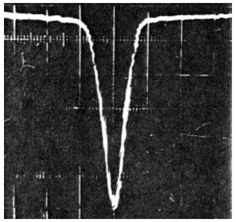
- Electron cooling was first tested in 1974 with 65 MeV protons at NAP-M storage ring at INP(Novosibirsk).









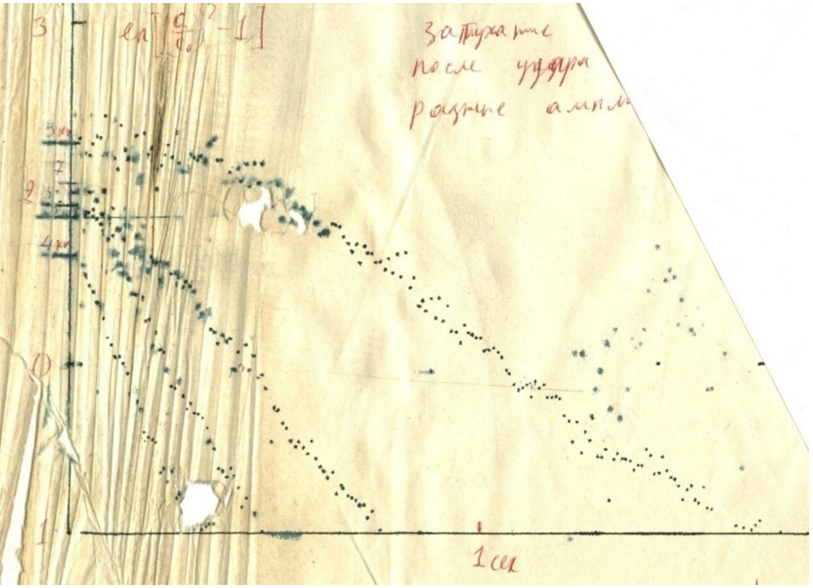


Cooling time ~17 sec.

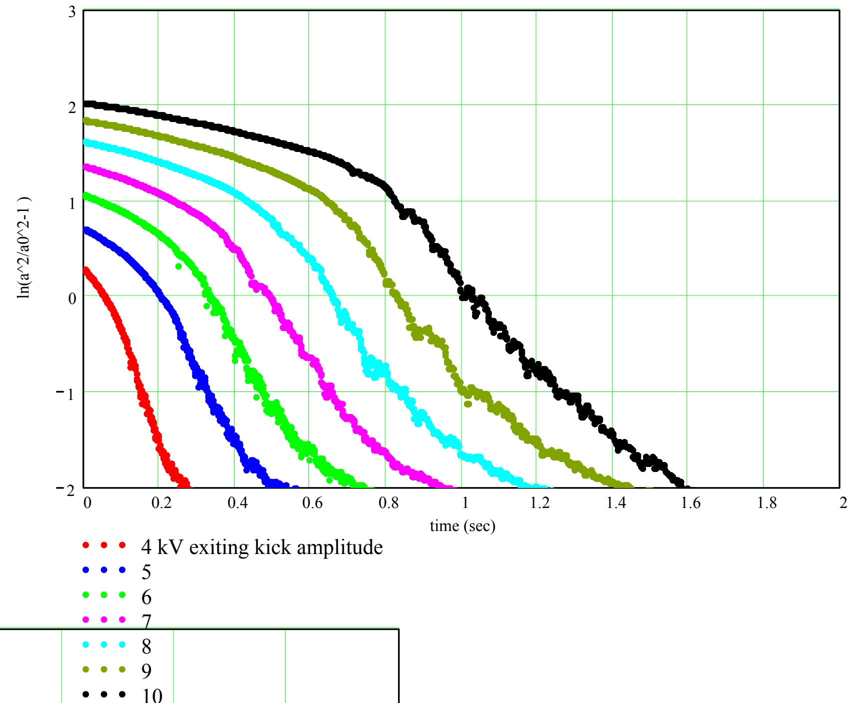
First experiments on electron cooling Proceeding 4 All- Union accelerator conference 1974,v.2. p 309., 1975,IEEE Trans. Nucl. Sci. VS-22, pp. 2093-7

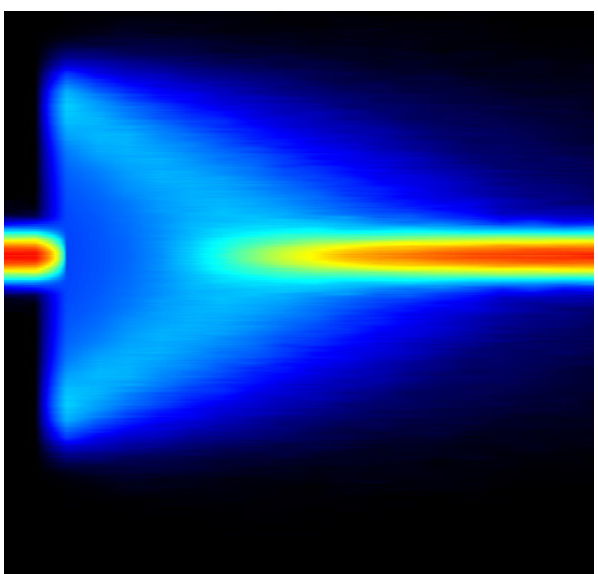
After modernization of the cooler magnet system cooling time go to 0.05 s!

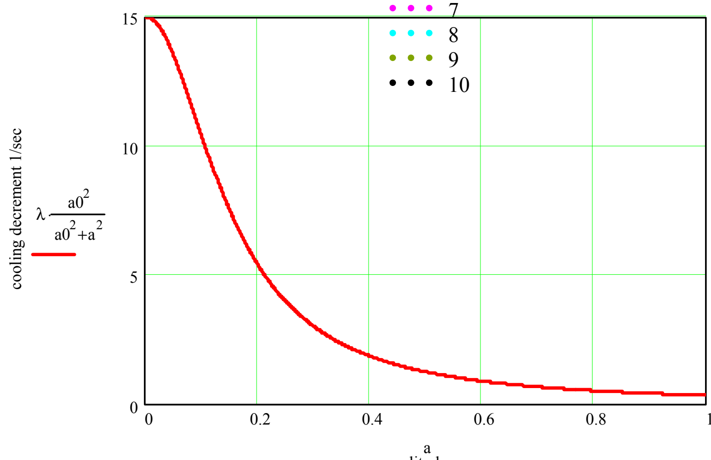
Measuring NAP-M cooling
after different amplitude of kick (1977)



Computer simulation cooling with
differ initial amplitude of kick 2013

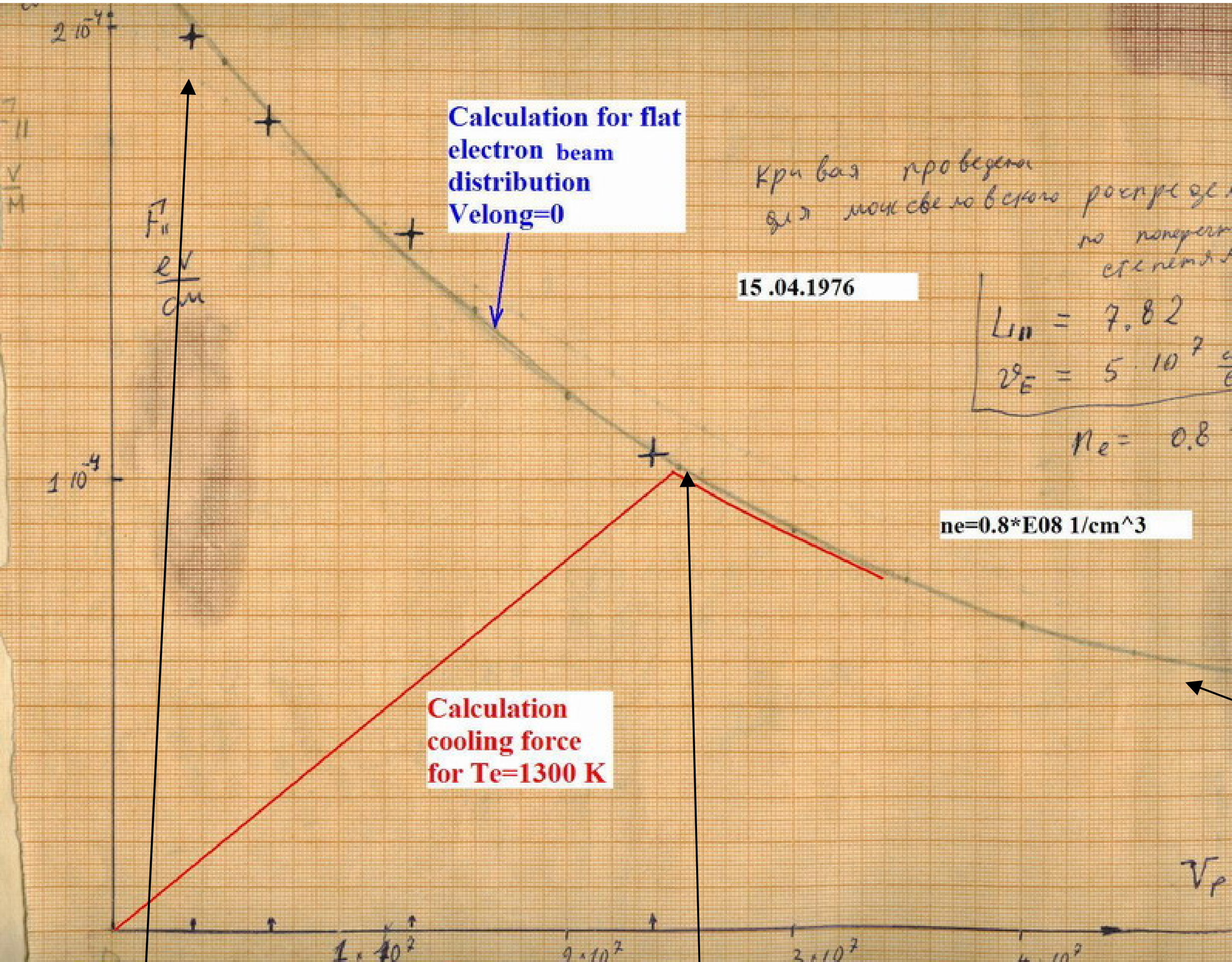






Cooling rate vs.
amplitude of kick

Magnetized electron cooling



Puzzle of increasing cooling force for small difference at velocity was cleared for idea magnetized cooling:

Y.S. Derbenev, A.N.Skrinsky The magnetization effects in electron cooling, 1978 Fizika Plasmy v.4, pp.492-500
effective temperature of electrons beam at magnet field 1 K

Improved the straightness magnet fields give results as cooling time 0.05 s and the temperature cooled proton beam 1K

$$F = m_e c^2 \int d\vec{V} * f(\vec{V}) \frac{4\pi r_e^2 c^2 n_e \eta}{V^2} Ln(\rho \max / \rho \min)$$

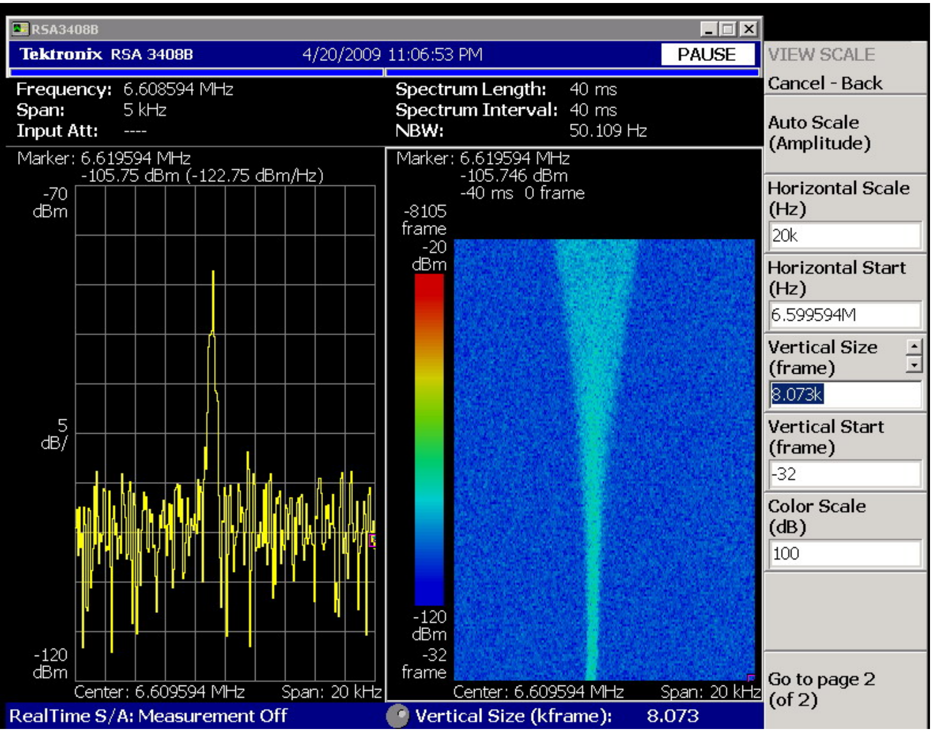
$$\vec{F} = 2*10^{-4}\left(\frac{eV}{cm}\right) * \frac{\vec{V}}{0.5*10^7\,(cm/s)}$$

$$\lambda = \frac{F}{MV} = \frac{Fc^2}{Mc^2 V} = \frac{2*10^{-4}*9*10^{20}}{0.938*10^9*0.5*10^7} = 40(1/s)$$

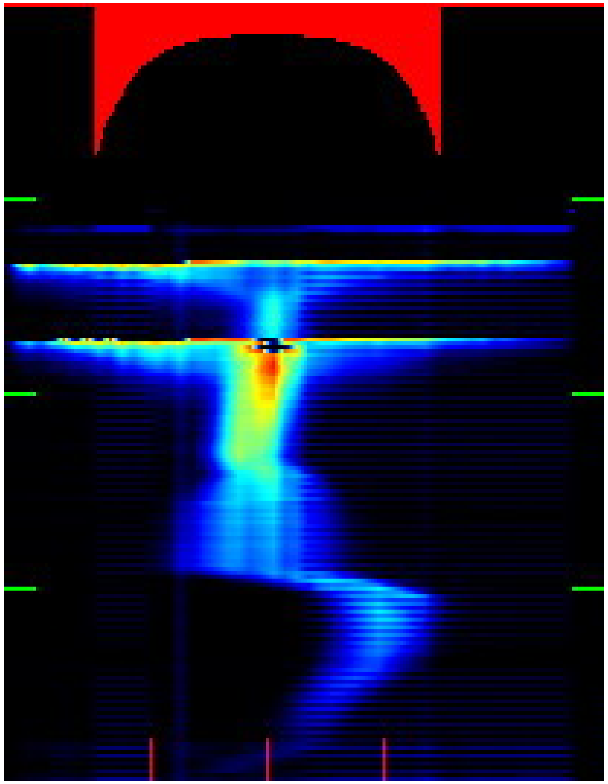
$$\vec{F} = 1*10^{-4}\left(\frac{eV}{cm}\right) * \frac{\vec{V}}{2.5*10^7\,(cm/s)}$$

$$\longrightarrow \lambda = 4(1/s)$$

SIS-18,CSRm, CSRe, LEIR coolers as example of realization ideas of magnetized cooling



CSRe Carbon 400 MeV/u



LEIR Lead ion cooling, accumulation, acceleration

Electron heating

WORKSHOP ON

BEAM COOLING AND RELATED TOPICS

Montreux, Switzerland
4–8 October 1993

MEASUREMENTS OF ELECTRON COOLING AND "ELECTRON HEATING" AT CELSIUS

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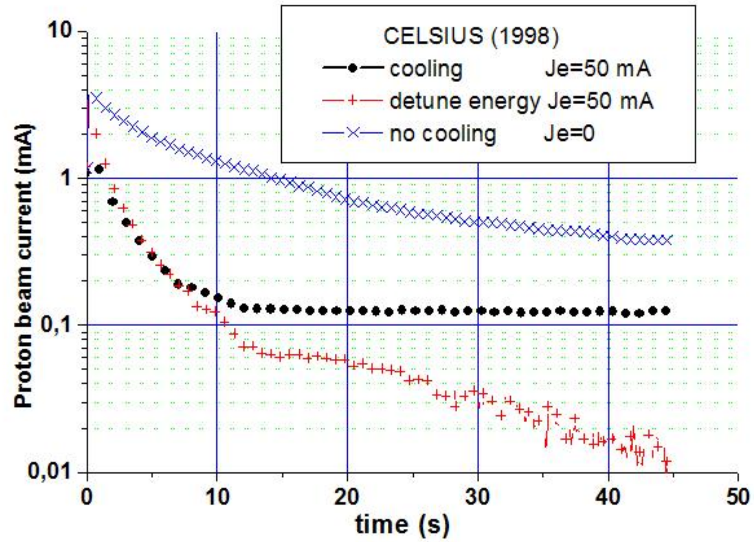
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

3. "ELECTRON HEATING"

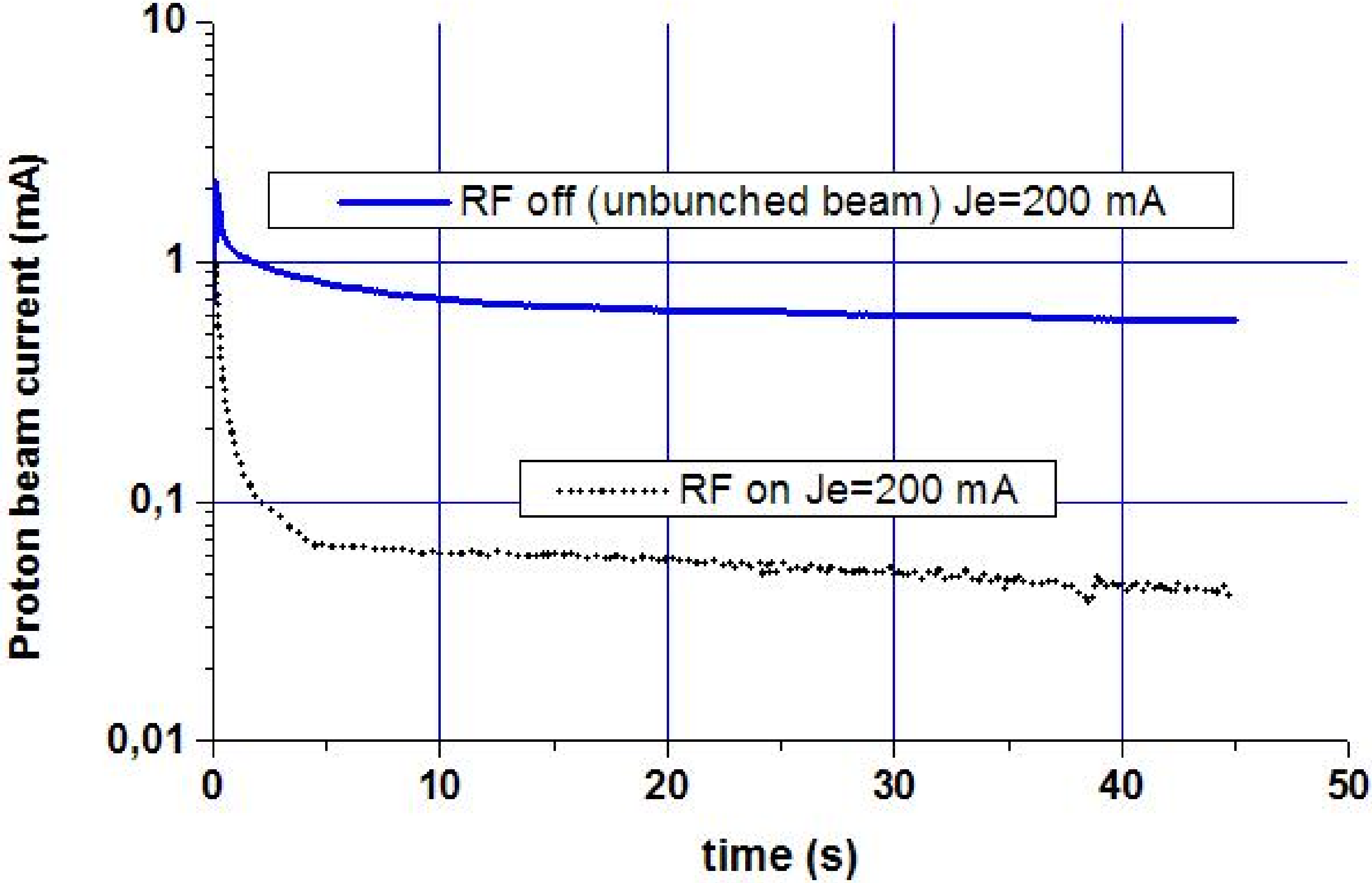
When turning on the electron beam in the presence of a 48 MeV stored and bunched proton beam for the rst time in 1988, the accelerator staff at Uppsala were disturbed to find that the stored beam lifetime became uch shorter than before it was exposed to the electron beam. This phenomenon, which we have nick-named lectron heating," has been the subject of study for some time, however without obtaining a complete under-anding.



With electron beam on measured initially fast decay proton beam with detune electron beam energy. With proper energy for cooling decay stopped for small ion curre and show high life time

Today this phenomena called "electron cloud"

For bunched proton beam the cooled intensity low at comparison for RF off and beam not bunch



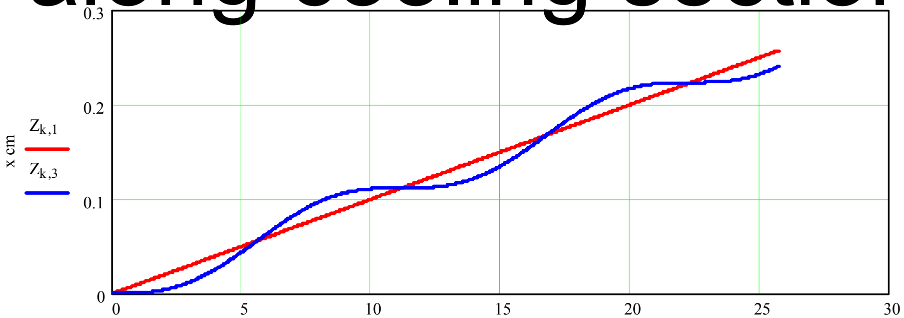
Plasma oscillations along cooling section

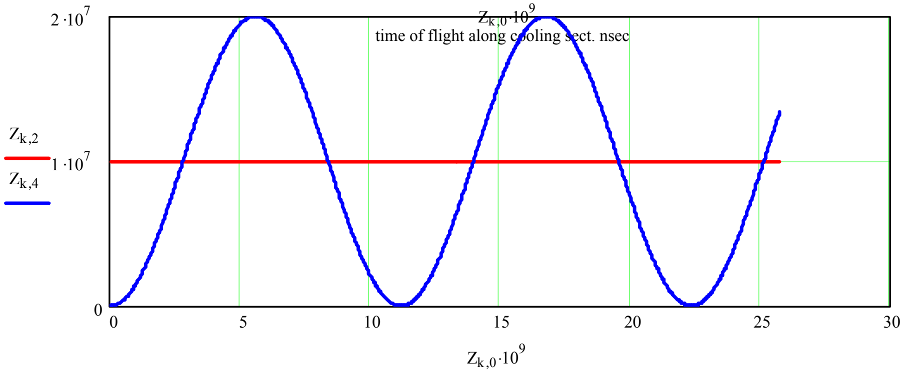
$$\frac{d^2 x_e}{dt^2} = -\frac{e}{m} E_p$$

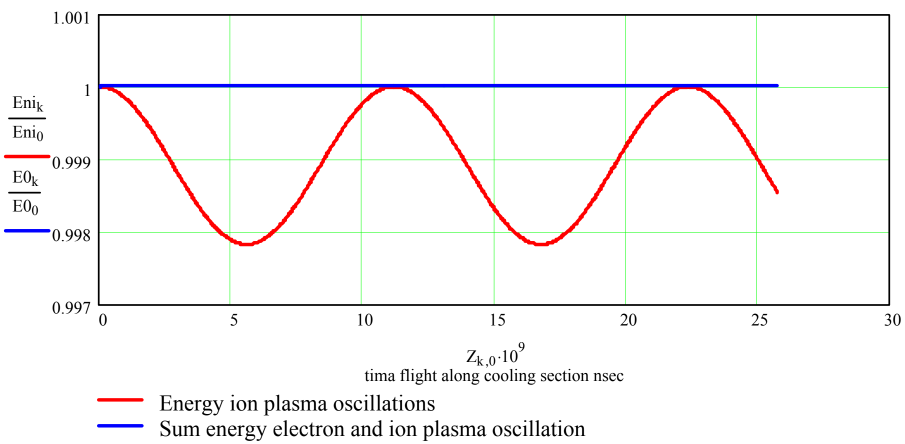
$$\frac{d^2 x_i}{dt^2} = -\frac{Ze}{M} E_p$$

$$E = 4\pi q n_e * x_e - 4\pi q n_i x_i$$

Electrons oscillated near slow moved ions







Limits on ion beam intensity

$$\Delta p_{cool} = -eE_{cool}\tau = -\lambda\tau p$$

Single pass cooling

$$E_{cool} = \frac{4\pi}{m_e V^2} n_e e^3 Z_i^2 Ln_c$$

Friction field at electron beam from single Ion moved with velocity V

$$\lambda = \frac{4\pi n_e e^4 Z_i^2}{m_e M_i V^3} Ln_c$$

Cooling rate for single ion moved with electron beam

$$\delta p^2 = -2p\Delta p_{cool} + \Delta p_{cool}^2 N_i^*$$

$$N_i^* = \frac{4\pi}{3}(V\tau)^3 n_i$$

Change energy single ion with taking at account fields from neighbors ions that moved inside radius V*τ

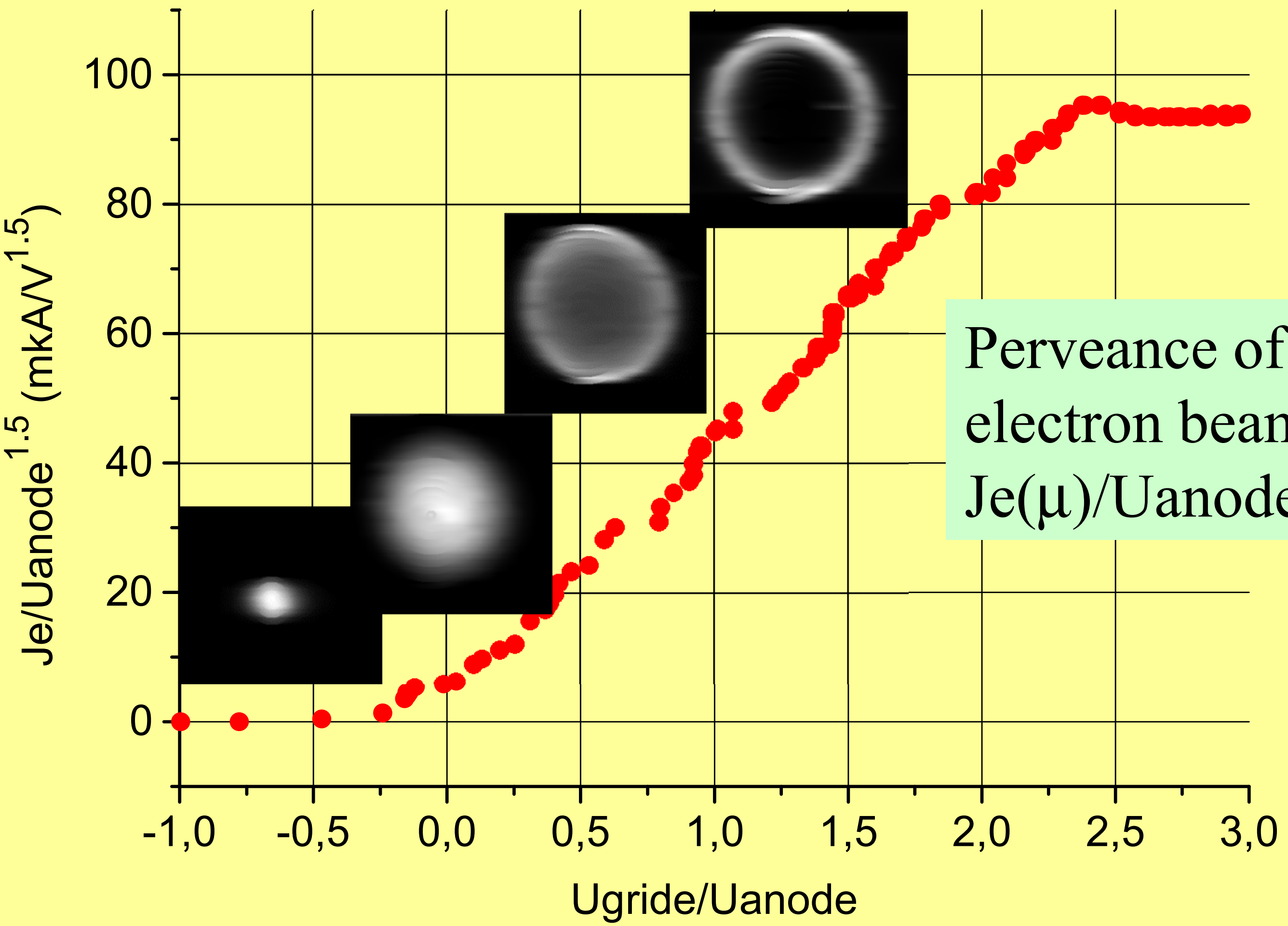
$$\frac{\delta p^2}{p^2} = \lambda\tau(-2 + (\frac{4\pi e^2 n_e}{m_e})(\frac{4\pi e^2 Z_i^2 n_i}{M_i})\tau^4 \frac{Ln_c}{3})$$

$$\omega_e^2 \omega_i^2 \tau^4 << \frac{6}{Ln_c}$$

$$\frac{\delta p^2}{p^2} = \lambda\tau(-2 + \omega_e^2 \omega_i^2 \tau^4 \frac{Ln_c}{3})$$

Condition for cooling-Linits on density ion beam ne*ni<limits

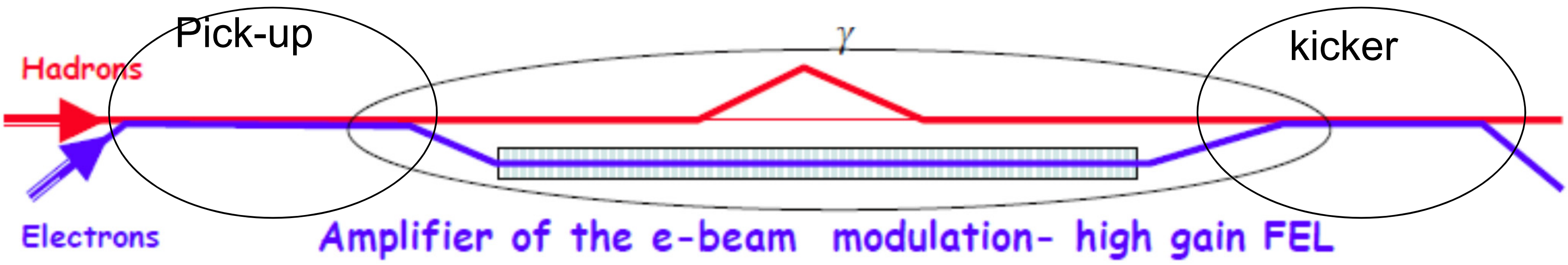
Hollow electron beam for opimization cooling



Perveance of gun and electron beam profile Je(μ)/Uanode(V)$^{3/2}$

Coherent cooling

1980- Coherent electron cooling -**Amplification the electron cooling by instability inside electron beam**, Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980), **Coherent electron cooling -perfect tool for EIC** Vladimir N. Litvinenko,C-AD, Brookhaven National Laboratory, Upton, NY, USA Department of Physics and Astronomy, Stony Brook University, Yaroslav S. Derbenev, Thomas Jefferson National Accelerator Facility,Newport News, VA, USA
http://casa.jlab.org/viewgraphs/2007/Derbenev,etal_EICMtg_Dec07.pdf



How to converse heating at powerful cooling?
Very simple: just take amplification g under control!
when cooling more powerful then heating

$$\delta p^2 = -2p\Delta p_{cool} * g + \Delta p_{cool}^2 N_i^* * g^2$$

Synthesis of stochastic and electron cooling at simplest realization

ELECTRON BEAMS AS STOCHASTIC 3D KICKERS V.V. Parkhomchuk, V.B. Reva, A.V. Ivanov, BINP, Novosibirsk, Russia, THM2I06 Proceedings of COOL 2007, Bad Kreuznach, Deutschland

http://accelconf.web.cern.ch/AccelConf/cl07/PAPERS/THM2I06.PDF

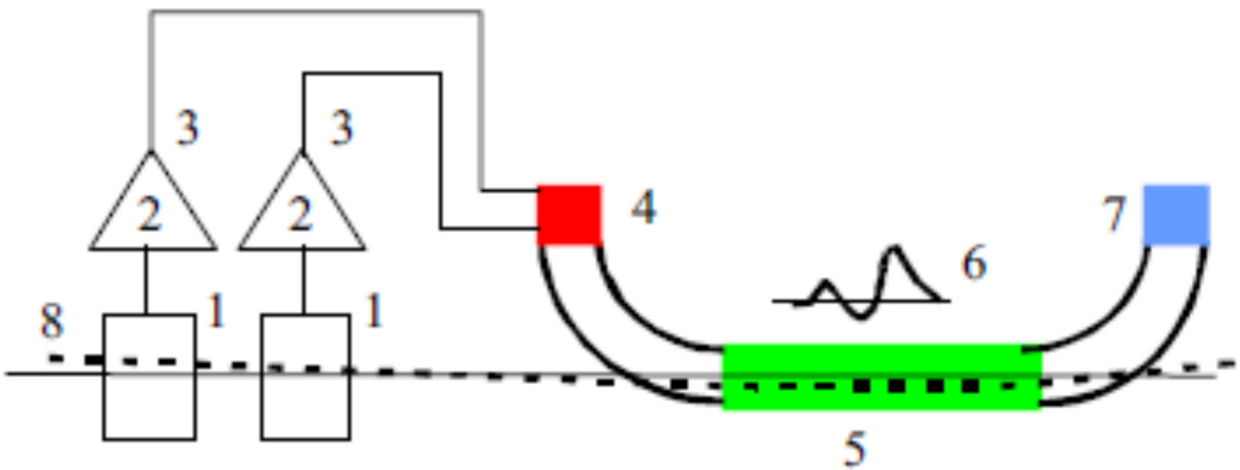


Figure 1: Scheme of stochastic cooling with electron cooler as 3D kicker. 1 – pick-up system, 2 – hybrid and amplifier, 3 – cable system, 4 – electron gun with the current modulation, 5 – cooling section, 6 – modulation of the space-charge density in the cooling section, 7 – collector of the electron beam, 8 – ion trajectory.

Electron gun with electrodes for generation 3D kick was produced for COSY cooler

Electron gun

The design of electron gun for cooler base on concept of the "hollow" electron gun [4] with special ring near cathode (grid electrode) for changing profile of the electron beam. Main news is using 4 sectors ring that can generate for AC beams with different position relative centre/

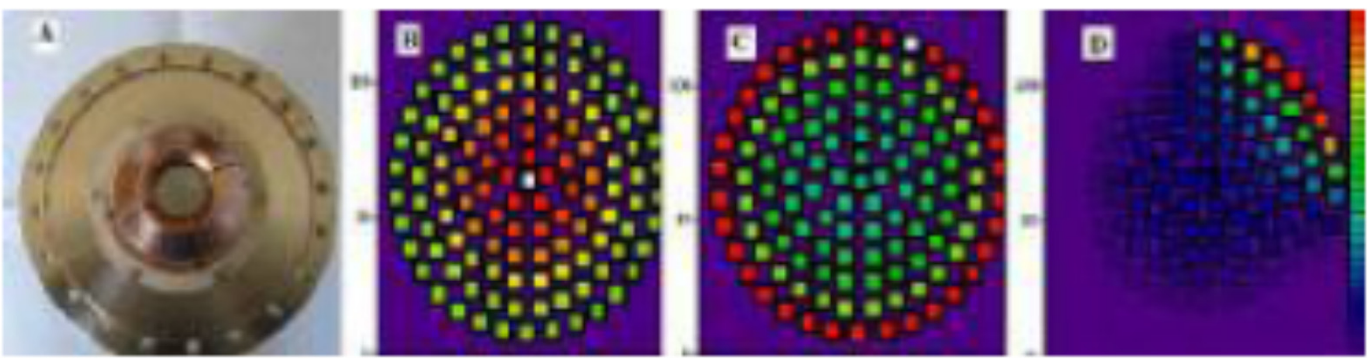


Figure 5: A is-photo cathode with grid electrodes, B is parabolic shap beam with maximum at centre C is "hollow" beam with minimum at centre, D is AC component of beam with RF voltage on single sector.

STATUS OF THE 2 MEV ELECTRON COOLER FOR COSY / HESR

J. Dietrich, V. Kamerdzhiev, FZJ, Jülich, Germany
M.I. Bryzgunov, A.D. Goncharov, V.M. Panasyuk, V.V. Parkhomchuk,

http://accelconf.web.cern.ch/AccelConf/COOL2011/papers/moio05.pdf

The 2 MeV electron cooling system for COSY-Jülich is being built to boost the luminosity in presence of strong heating effects of high-density internal targets in the entire energy range. The 2 MeV cooler is also well suited in the start up phase of the High Energy Storage Ring (HESR) at FAIR in Darmstadt.

The basic idea of this cooler is to use high magnetic field along the orbit of the electron beam from the electron gun to the electron collector. In this case high enough electron beam density at low effective temperature can be achieved in the cooling section.

$$V_{\perp} = c\frac{E}{B} = c\frac{2\pi e n_e a_e}{B}$$

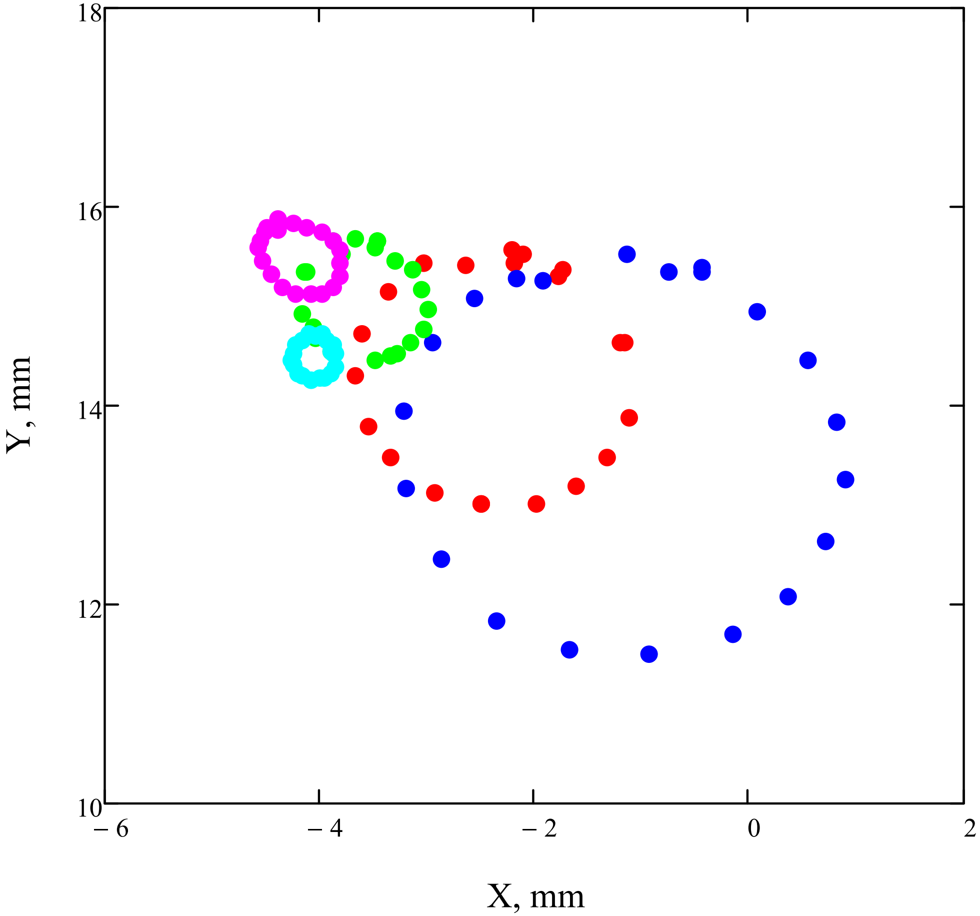
For ne→increase
B→increase
B magnet field control
Effective temperature electron beam

2 MeV cooler arriving at COSY

http://cool11.jinr.ru/presentations/4_2_Reva.pps

Optic features of COSY cooler

Control of the dipole component of electron motion



Energy 1000 keV, pick-up 10, Scanning of the magnetic field in the cooling section 250-270 A (about 1 larmour oscillations)

Current at dipole corrections

X (A)	Y (A)
3.0	0
0.0	0
-3.0	0
-4.0	0
-4.5	2

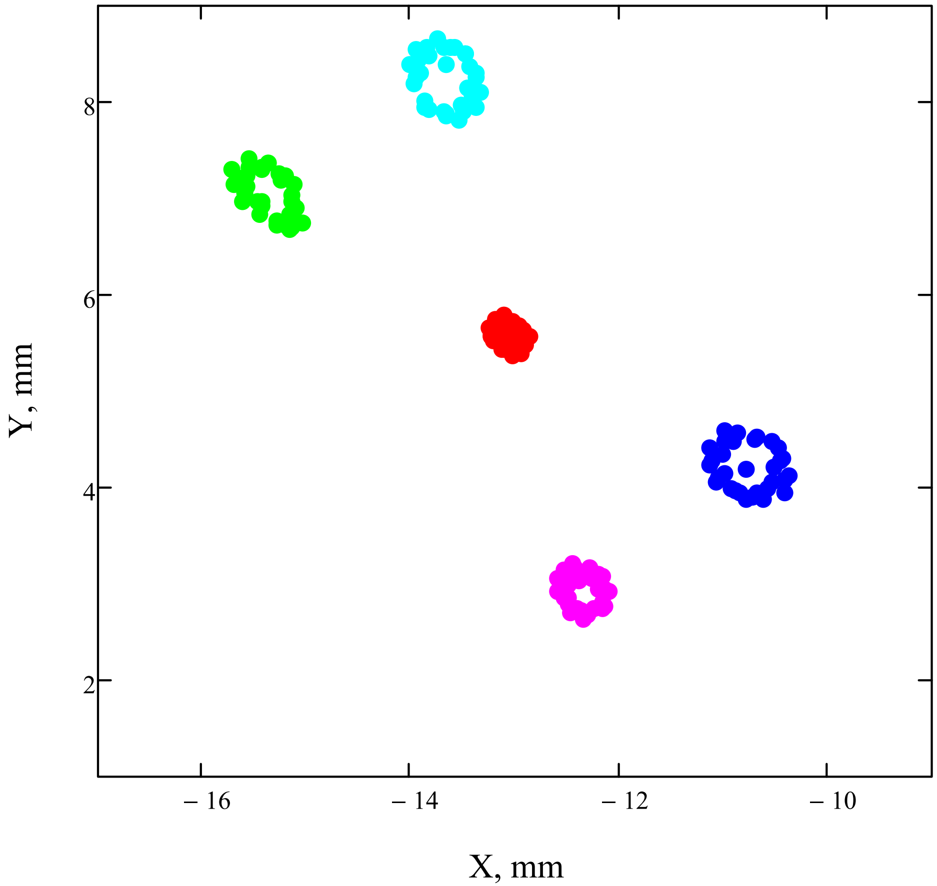
Radius rotation 1.5 mm → 0.1 mm

The energy of transverse rotation 4 kV→ 17 eV

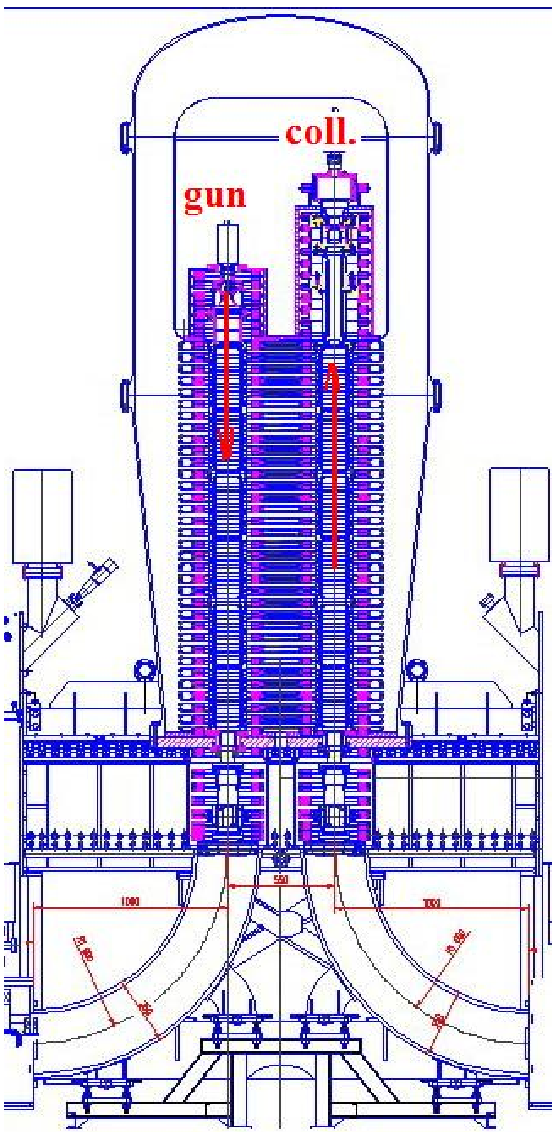
Optic features of COSY cooler

demonstration of the quadruple components of the electron motion

Energy 150 keV, pick-up 10,
Scanning of the magnetic field in the cooling section130-145 A (about 2.5 larmour oscillations)

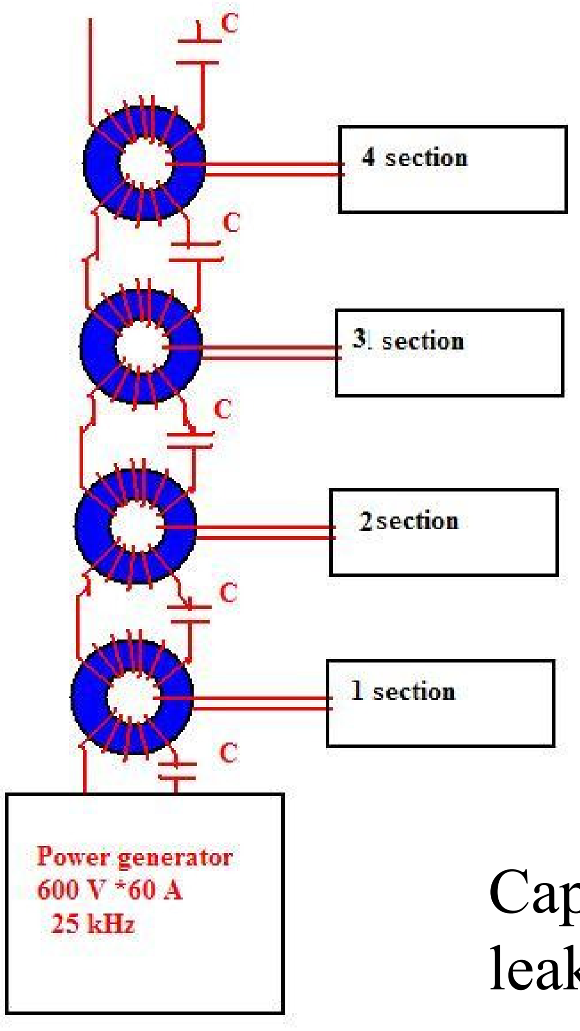


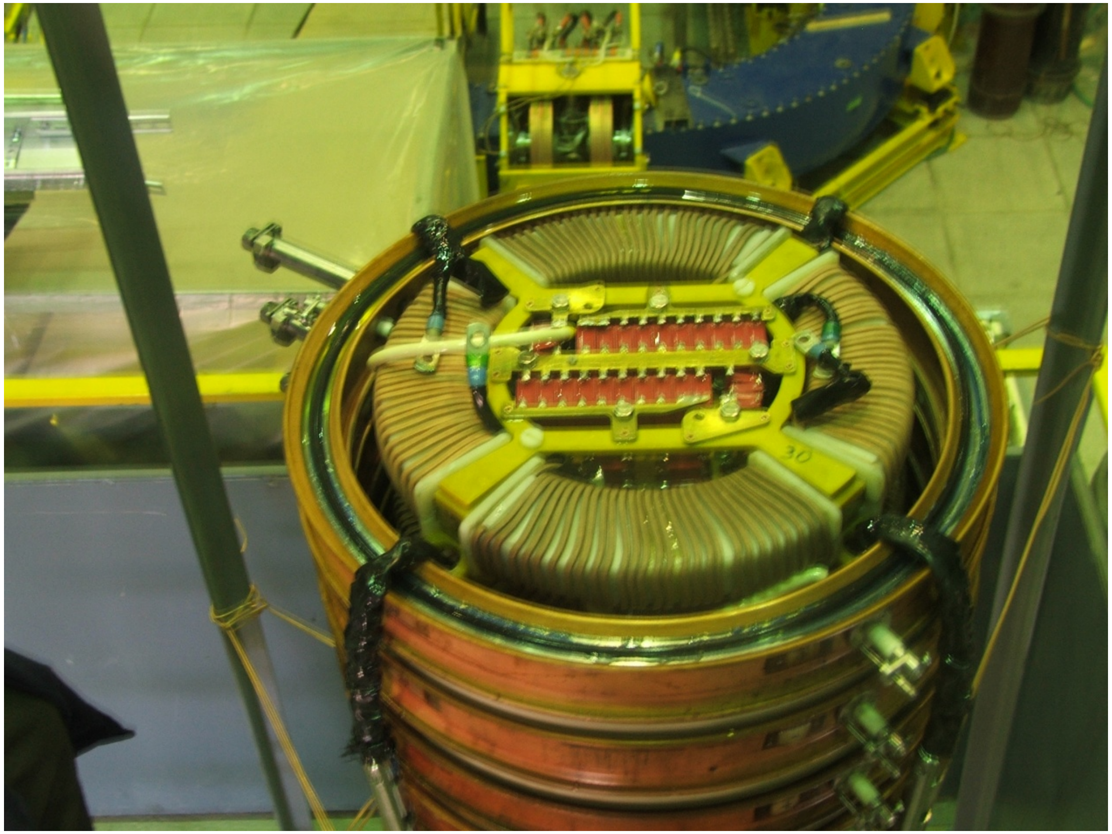
High voltage vessel



1. Cascade transformer sending power from ground to High voltage terminal.
2. Individual solenoid sections around acceleration tube
3. +30 and -30 kV PS at each sections *33
4. Gun with 4 sectors modulations electron beam
5. Collector with suppression reflected electrons

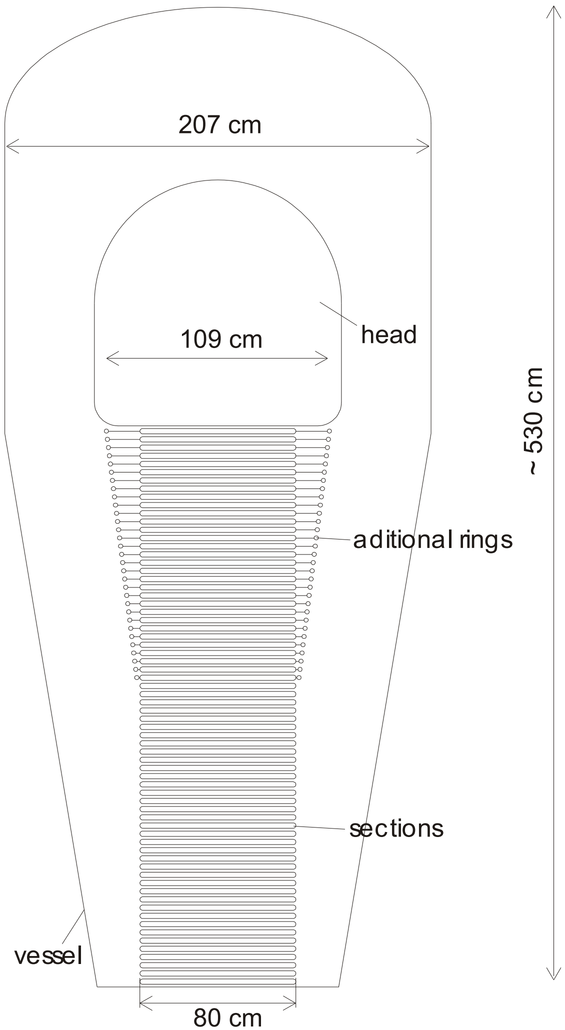
Cascade of serial transformers with amorphous Fe core for powering sections

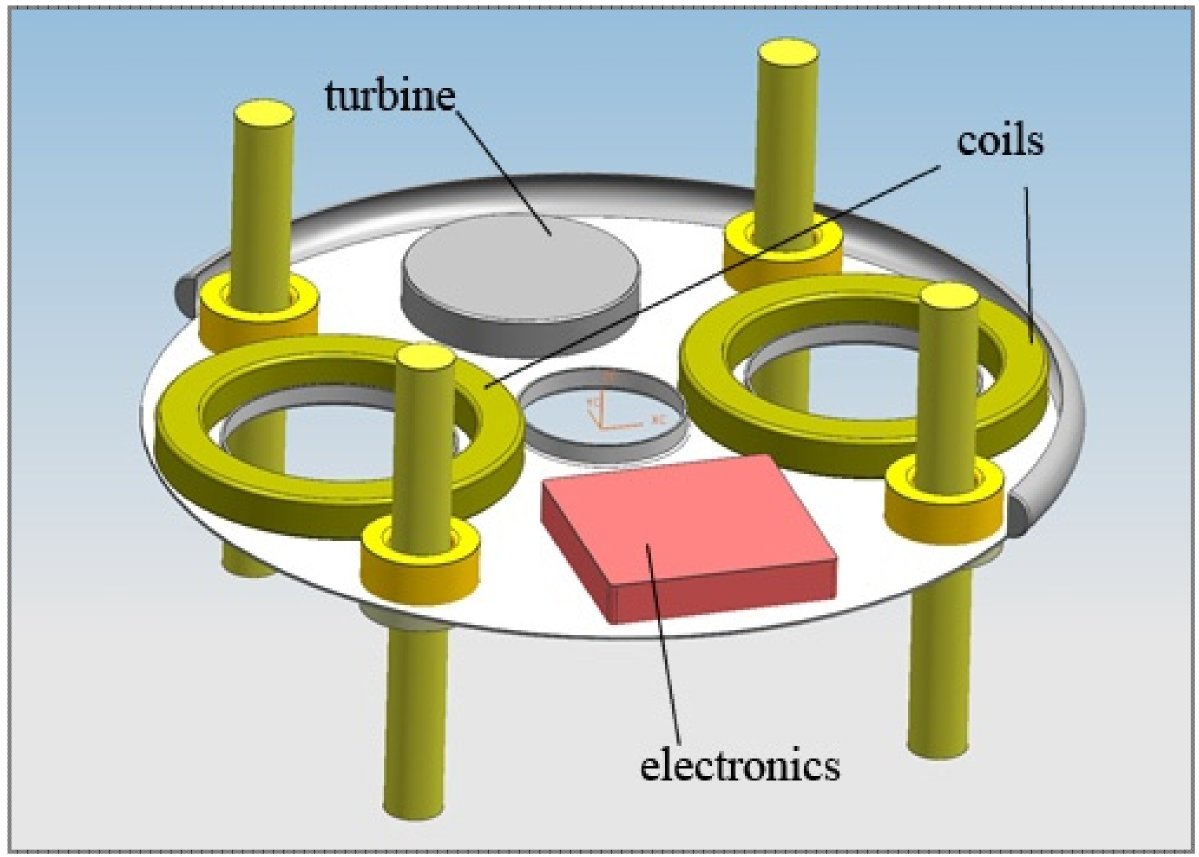




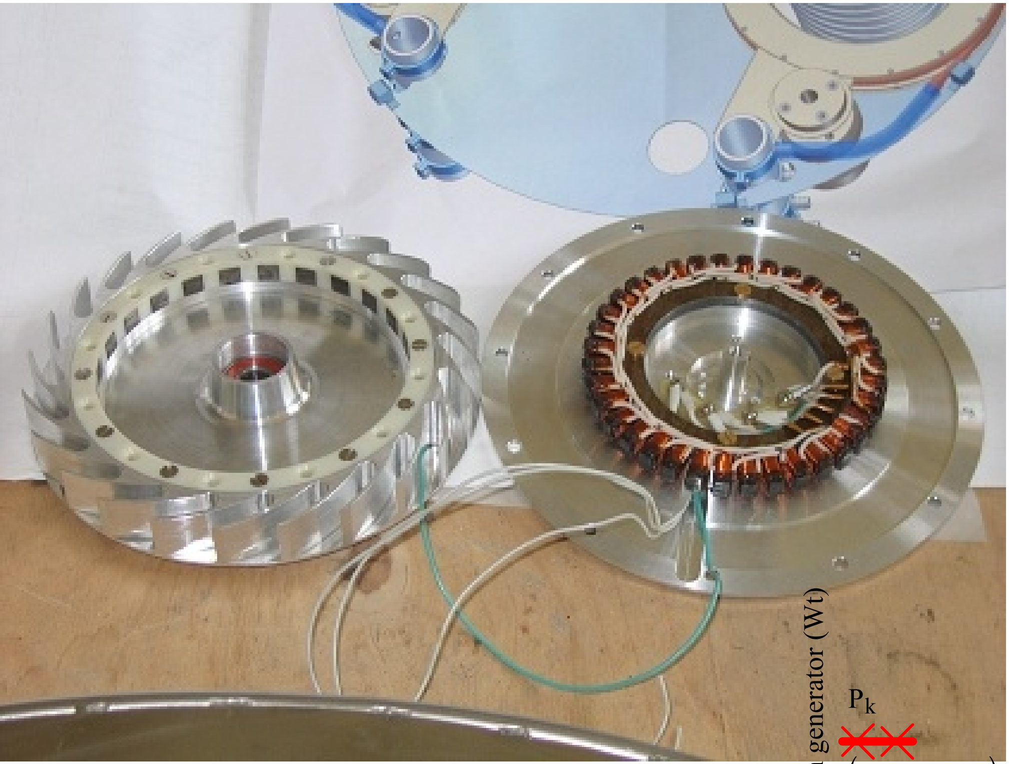
Capacitors used for compensation leakage inductance

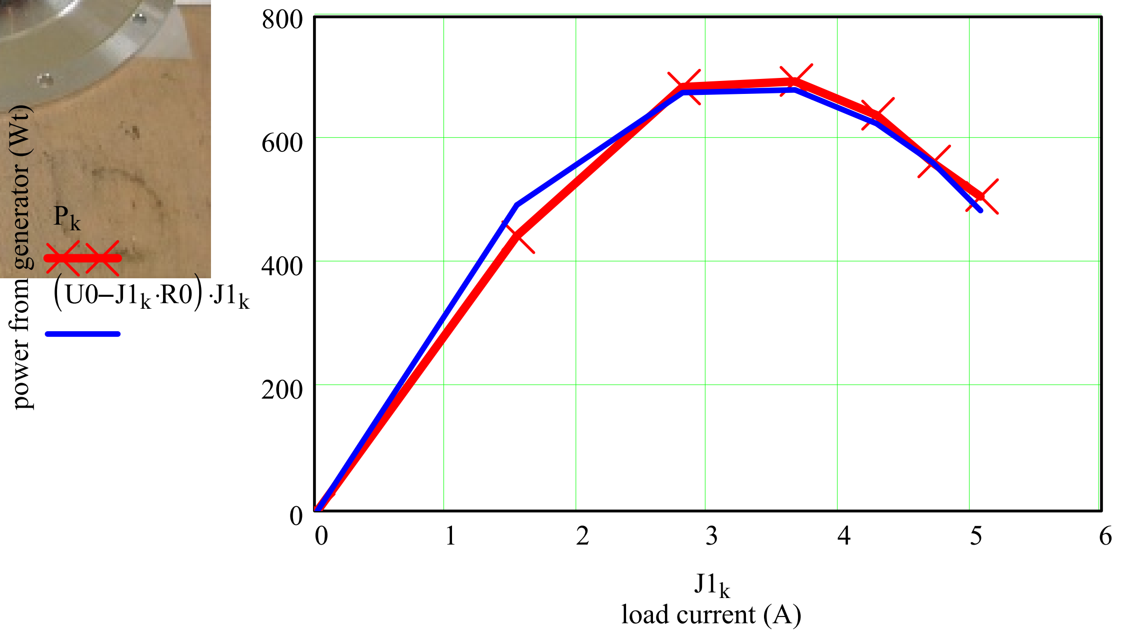
From 2 MeV to 4 MeV



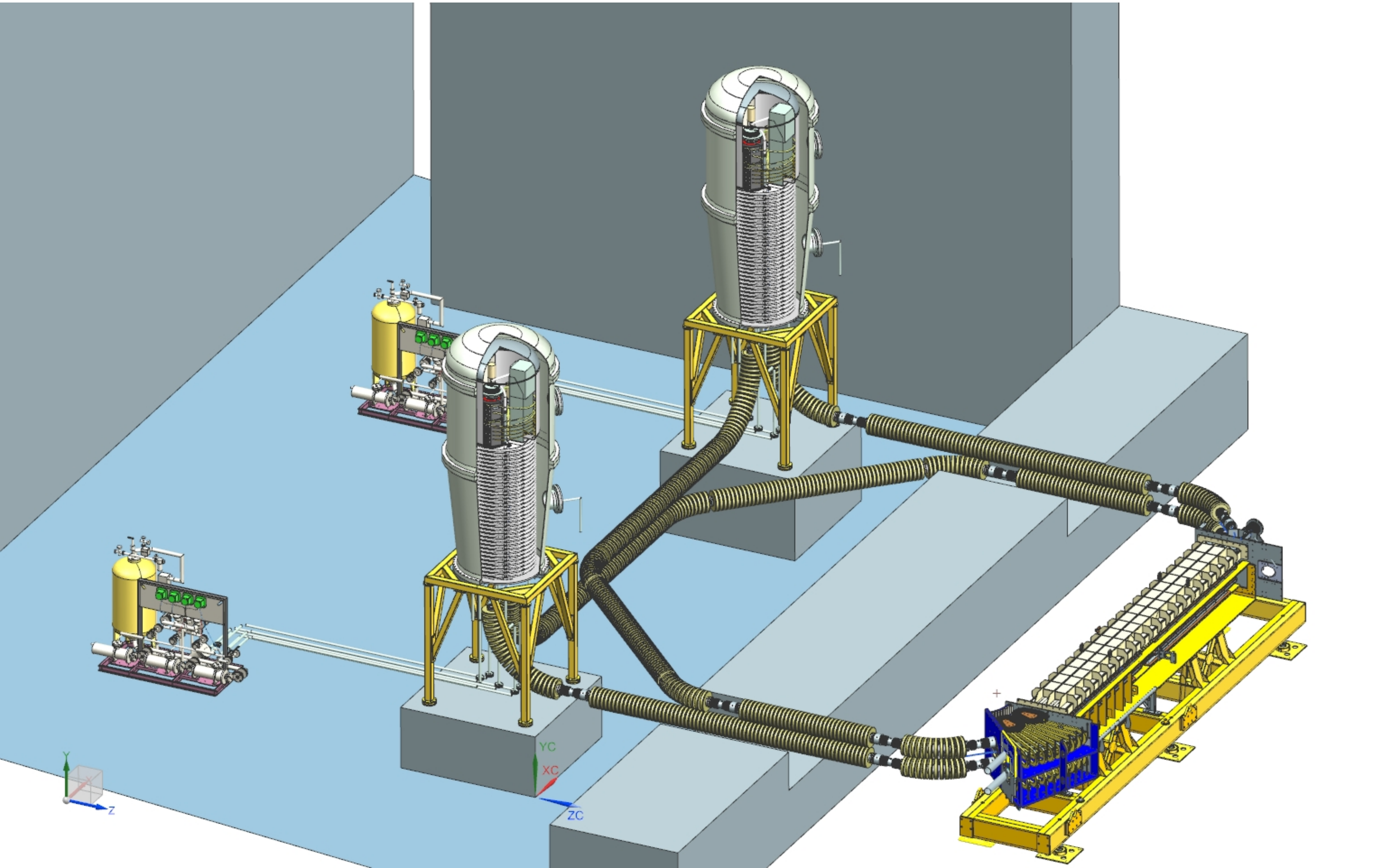


Turbine parameters





Today activity: Cooler for NICA collider



CONCLUSION

Electron cooling demonstrate high potential for obtain high brightness ion beams and high luminosity at collider.
From proposal G.I.Budker in 1966 up to 2016 this idea continue generated new and new applications

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ACKNOWLEDGMENT

At the electron cooling technology are contributed many world laboratories. I had collaboration with few of them: Initial Cooling Experiment (F.Krienen, CERN), ESR (Markus Steck, GSI), First cooling experiment (P.M.McIntyre,FNAL), CELSIUS (D.Reistad), RECYCLE cooling (S.Nagatsev,FNAL), CSRm,CSRe (Yang Sheadong, Mao),2MeV COSY cooler (J. Dietrich, S. Kamerziev) and many others.
And I especially thanks my teachers – G.I.Buder, A.Skrinsky, I.Meshkov, N.Dikansky, R.Salimov and my colleges A.Bubley, V.Reva, M.Bryzgunov and many others from BINP

Thanks for attentions

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