Novel Ideas in Electron Cooling

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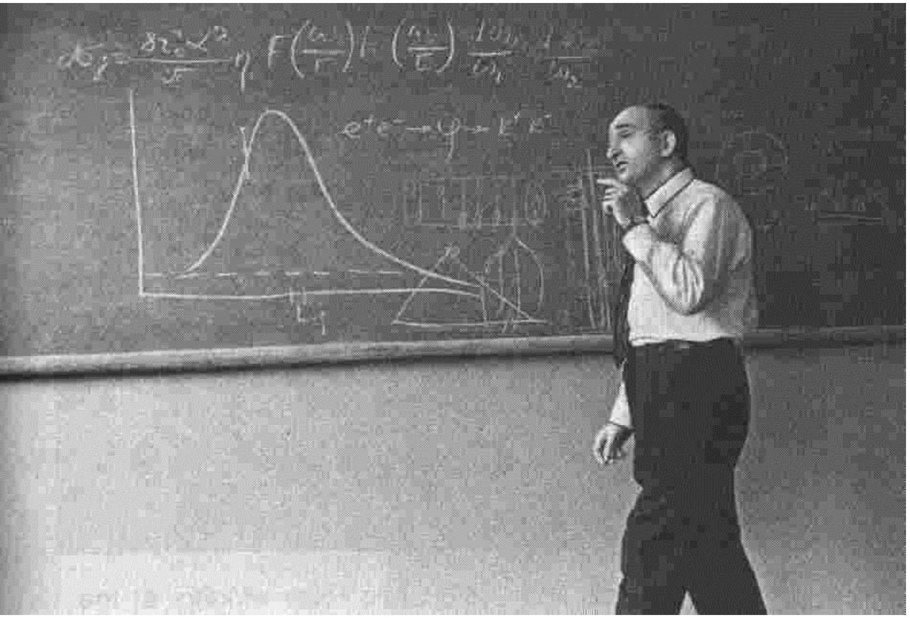
Mürren, Switzerland

Abstract
The development of electron cooling started at 1966 from proposal G.I.Budker 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 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
future 4—8 MeV coolers for HESR?

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

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

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

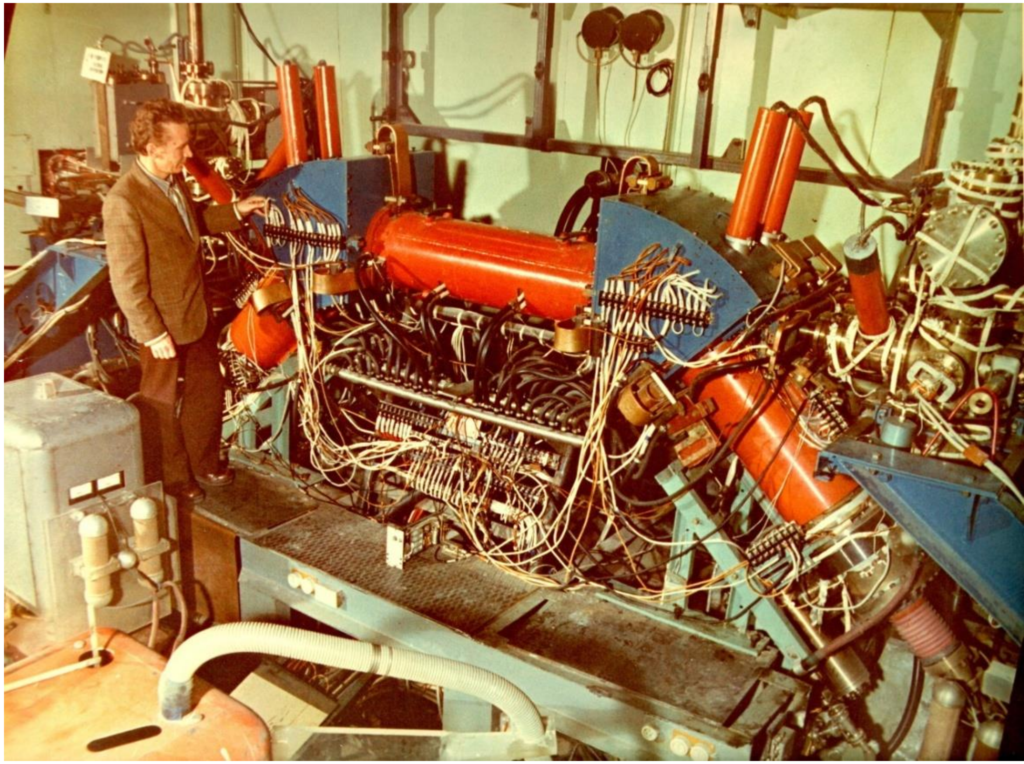
$$\theta_e = 3\times10^{-3}$$

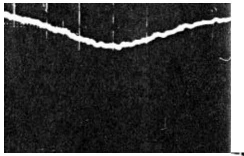
$$\theta_p = 3\times10^{-4}$$

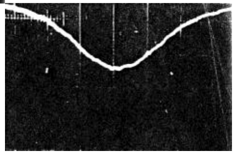
$$T_{equilibrium} = 1000 - 2000K$$

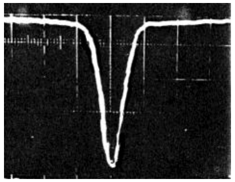
First Cooling Demonstration

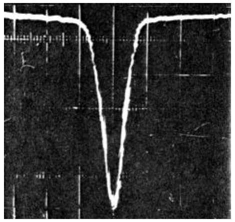
- Electron cooling was first tested in 1974 with 65 MeV protons at NAP-M storage ring at INP(Novosibirsk).











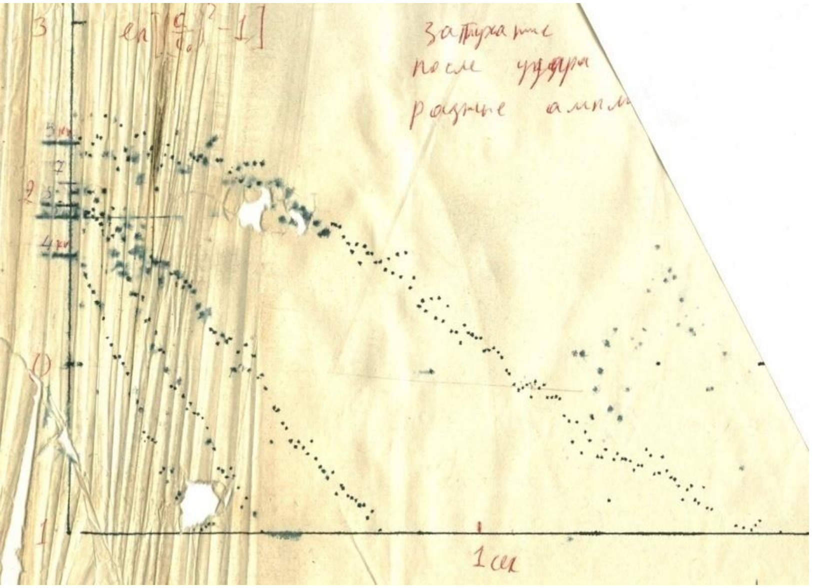
Cooling time
Few seconds

Cooling time ~17 sec.

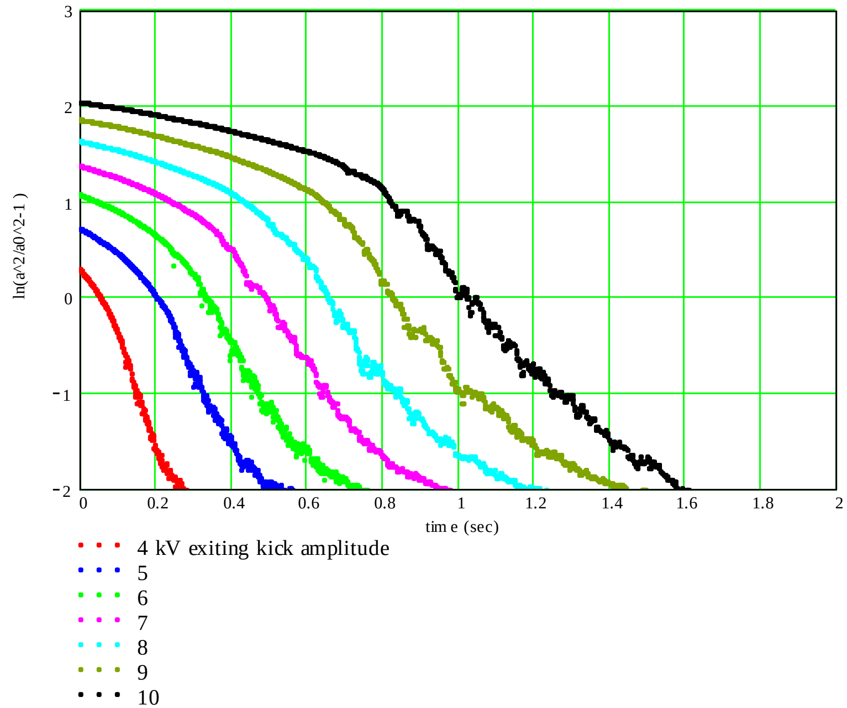
First experiments on electron cooling Proceeding 4 All- Union accelerator conference 1974,v.2. p 309., 1975,IEEE Trans. Nucl. Sci. VS-22, pp. 2093-7

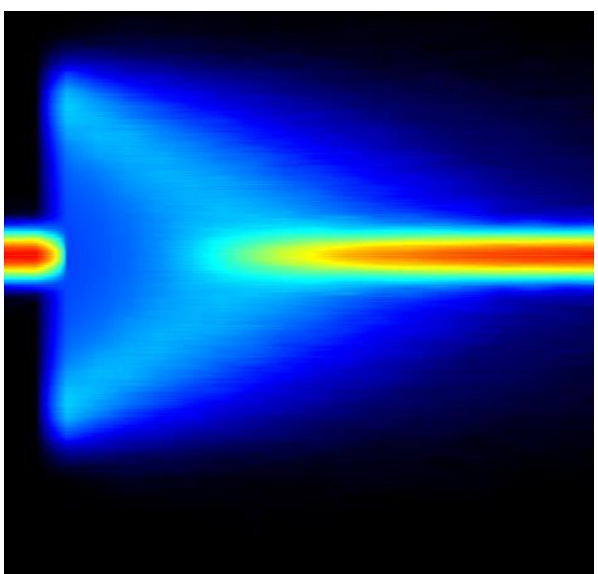
After modernization of the cooler magnet system cooling time go to 0.05 s!

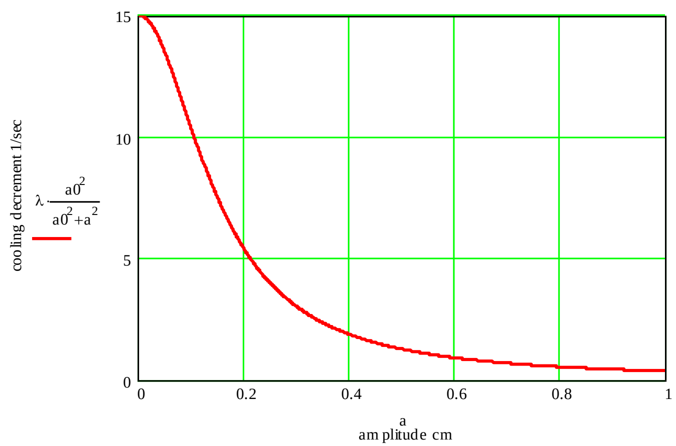
Measuring NAP-M cooling
after different amplitude of kick (1977)



Computer simulation cooling with
differ initial amplitude of kick 2013

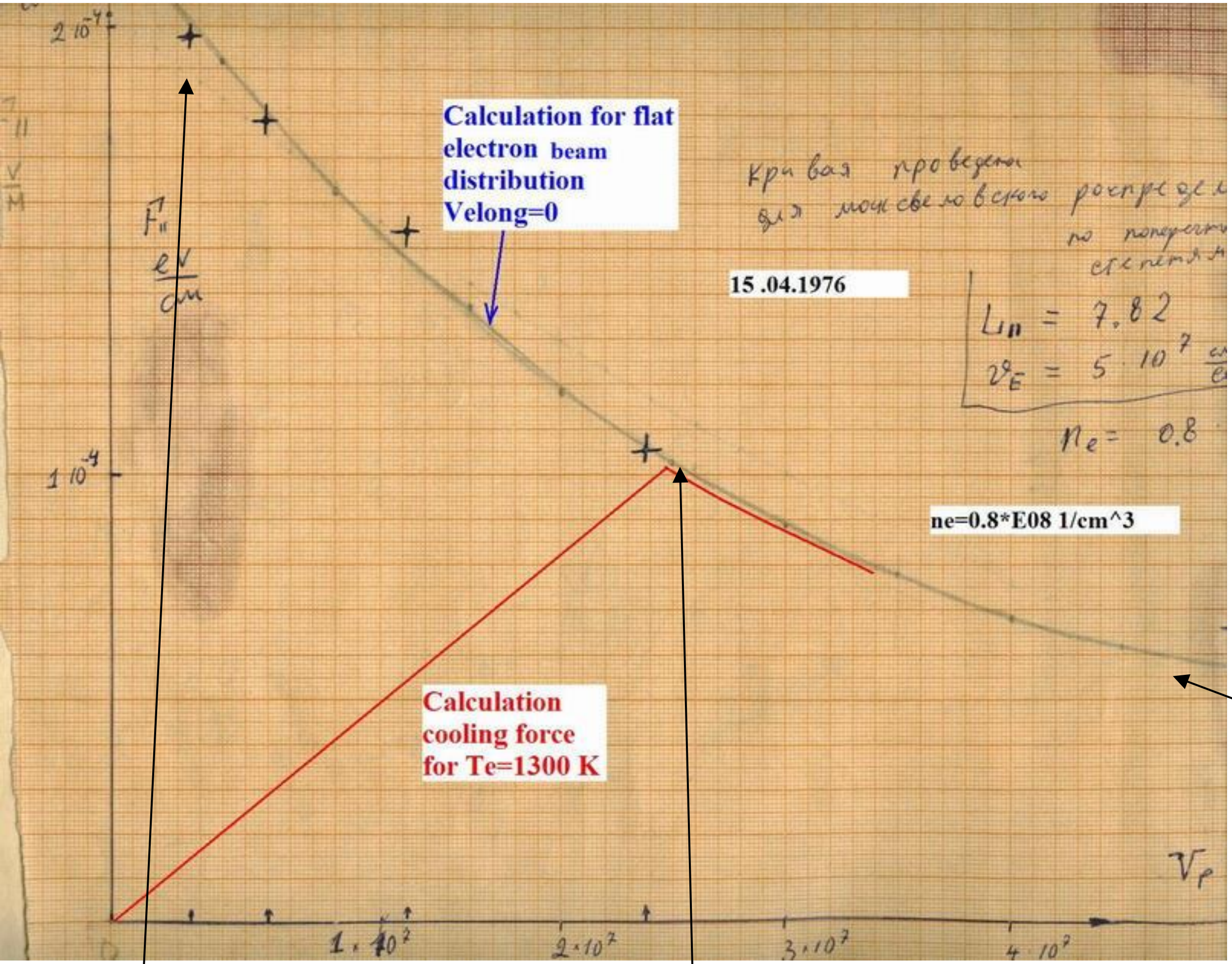






Cooling rate vs.
amplitude of kick

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

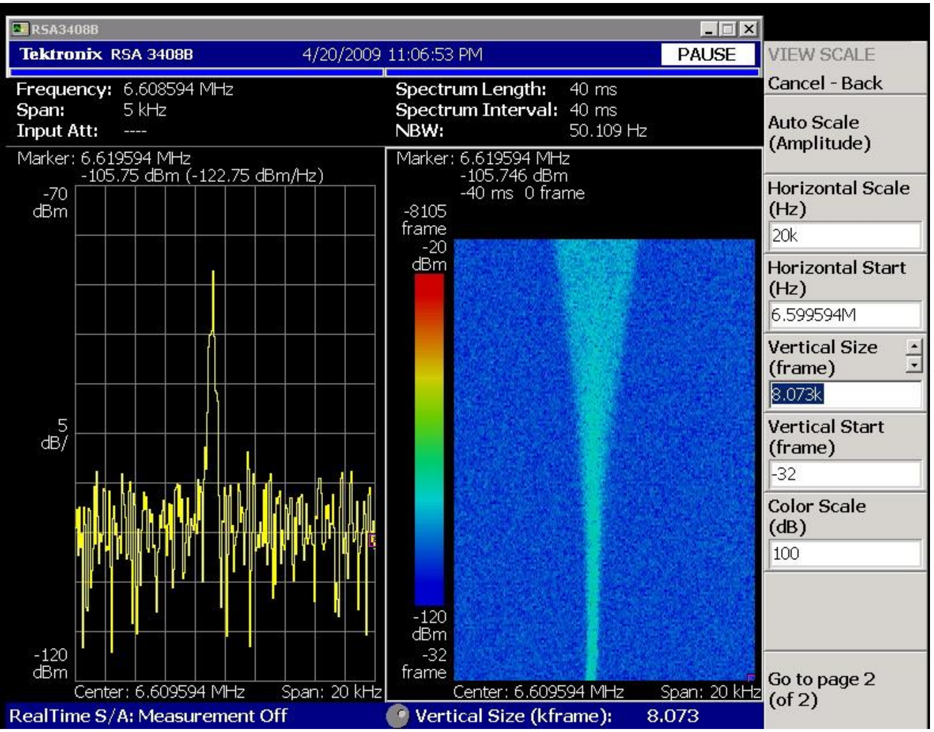
$$F = m_e c^2 \int d\vec{V} * f(\vec{V}) \frac{4\pi r_e^2 c^2 n_e \eta}{V^2} Ln(\rho \max / \rho \min)$$

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

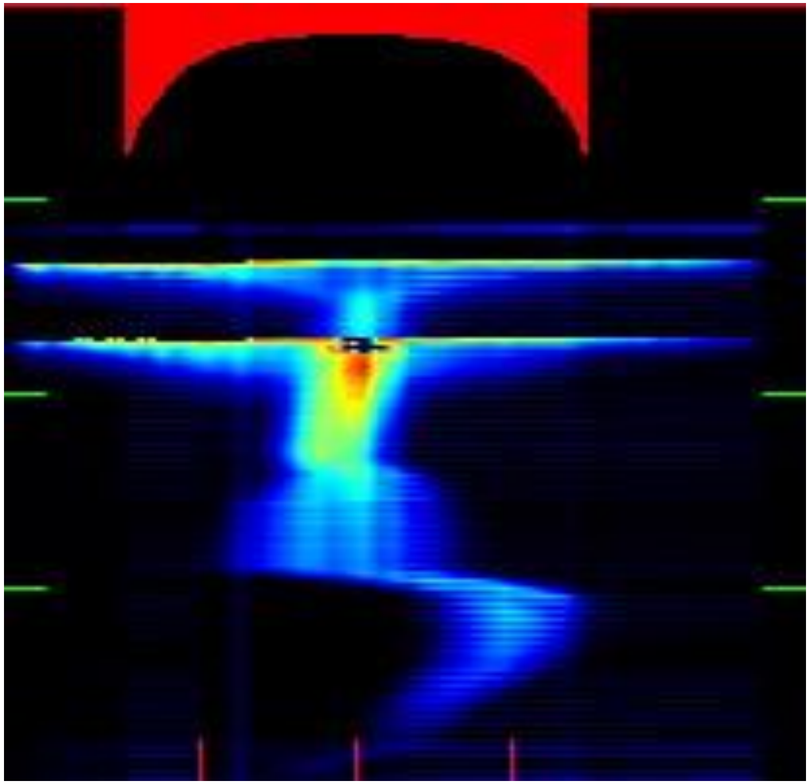
$$\lambda = \frac{F}{MV} = \frac{Fc^2}{Mc^2 V} = \frac{2*10^{-4} * 9*10^{20}}{0.938*10^9 * 0.5*10^7} = 40(1/s)$$

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

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

Cooling for carbon beams for cancer therapy

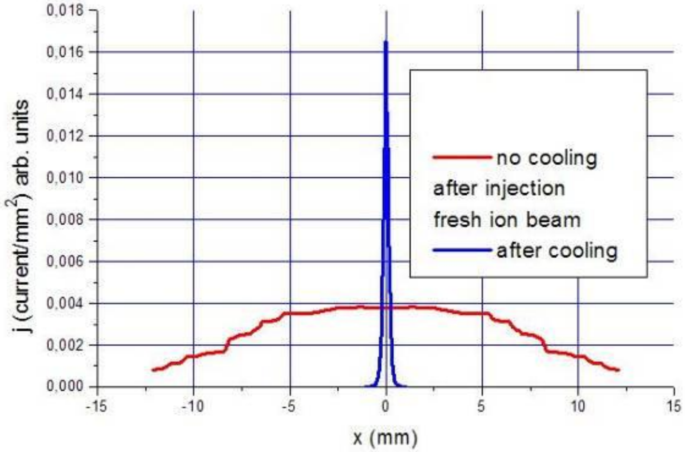


Fig.3 The profile of the carbon ion beam (700 μA)measured at CSRe . Before cooling r.m.s. radius ion beam is σ=8 mm, after cooling σ=0.15 mm,

In Lanzow institute IMP medical application of CSRm carbon beam very active and used for medical help real patients

$$N_i = 0.44 * 10^9$$

$$\delta\upsilon = 0.08$$

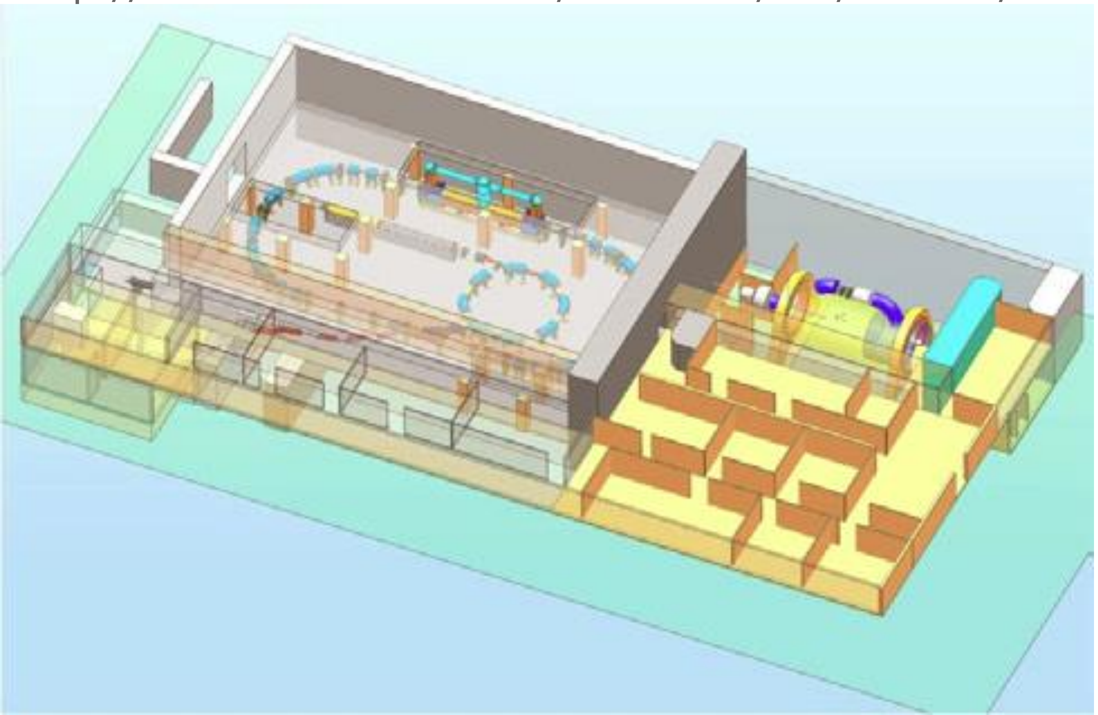
The Advance Technology Extraction for Therapy Ions Beam from Carbon Storage Ring with Electron Cooling [Adobe PDF]
The electron cooling because of increasing the 6D phase space density of ion beams is the path for development compact accelerator ions beam therapy.
Authors: V. V. Parkhomchuk, V. B. Reva, BINP SB Size: 1MB Date: 26/10/2011
RAS, Novosibirsk

http://accelconf.web.cern.ch/AccelConf/COOL2011/papers/thioa03.pdf

CARBON ION ACCELERATOR FACILITY FOR CANCER THERAPY [Adobe PDF]
A carbon ion or proton beams are a superior tool to xrays in both physical and biological doses in treating a cancer.

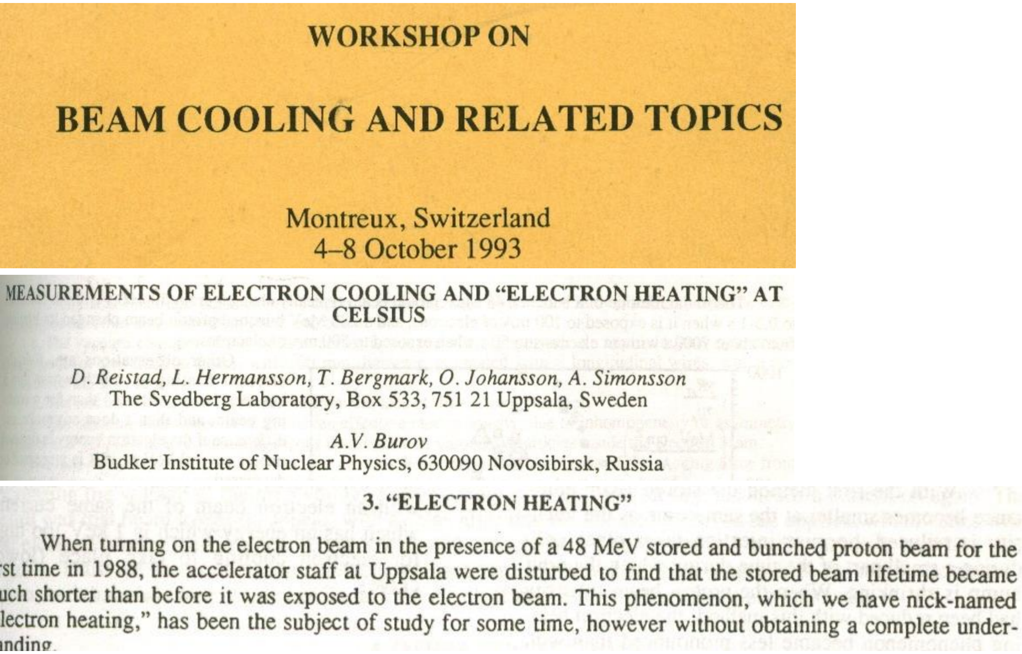
Authors: E.Levichev, V.Parkhomchuk, S.Rastigeev, A.Skrinsky, V.Vostrikov (Budker Institute of Nuclear Physics, Novosibirsk, Size:
347KB Date: 11/04/2007 Russia), M.Kumada (NIRS, Chiba, Japan)

http://accelconf.web.cern.ch/AccelConf/r06/PAPERS/MOLP13.PDF



Still only dream for BINP

Electron heating



WORKSHOP ON

BEAM COOLING AND RELATED TOPICS

Montreux, Switzerland
4–8 October 1993

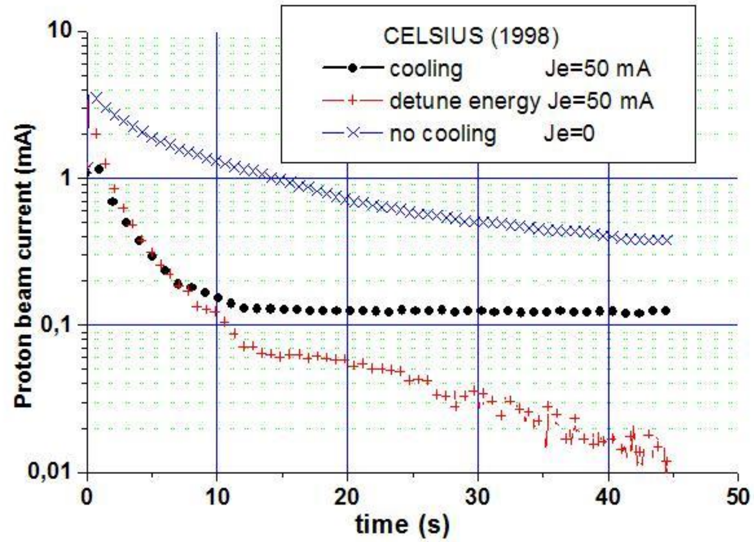
MEASUREMENTS OF ELECTRON COOLING AND "ELECTRON HEATING" AT CELSIUS

D. Reistad, L. Hermansson, T. Bergmark, O. Johansson, A. Simonsson
The Svedberg Laboratory, Box 533, 751 21 Uppsala, Sweden

A.V. Burov
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

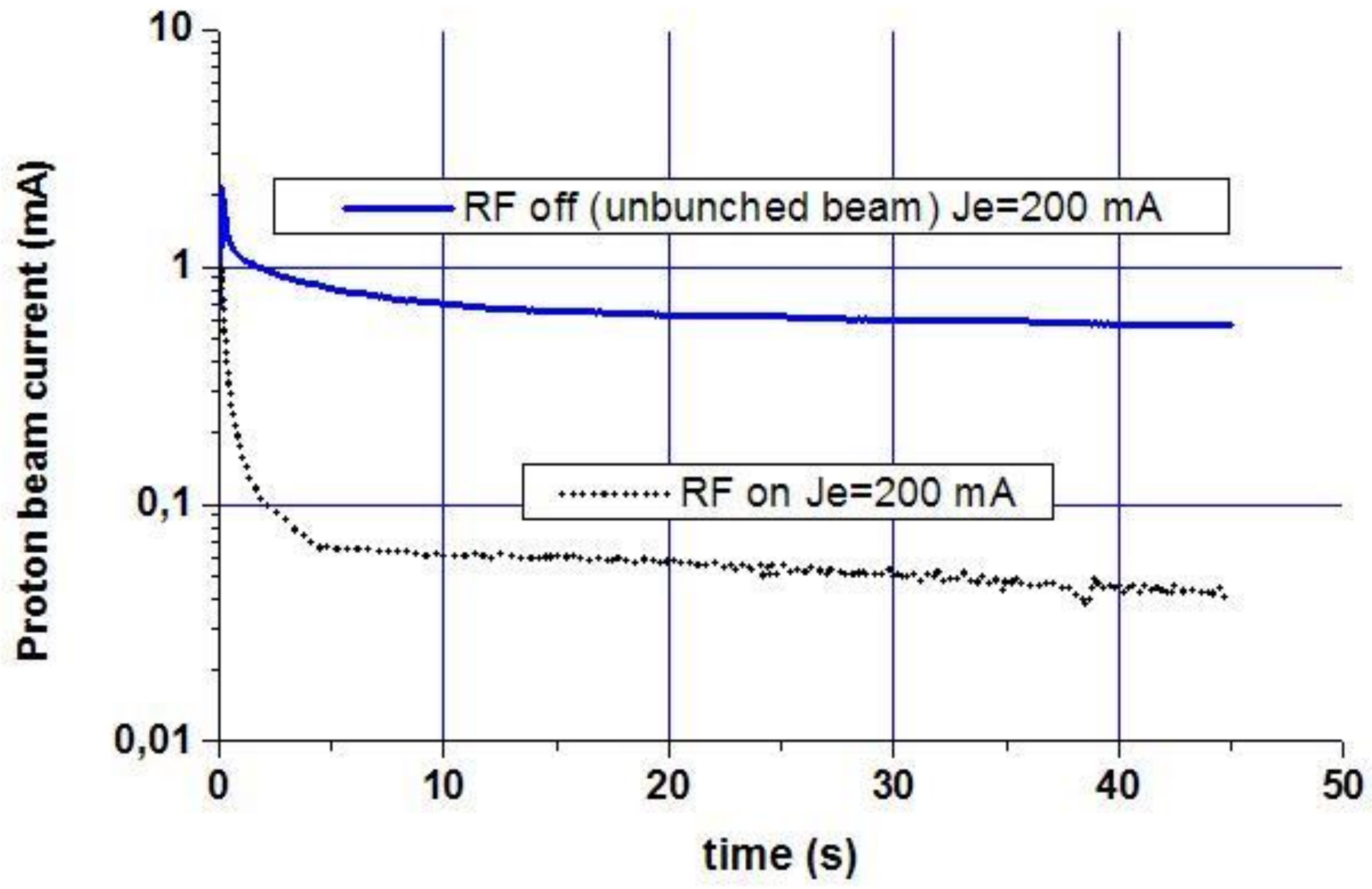
3. "ELECTRON HEATING"

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-nding.



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

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



Experiments with detune beam

Chinese Physics C Vol. 37, No. 1 (2013) 017004

Research on the detuning system of a cooling electron beam for the dielectronic recombination experiment at CSRm

MENG Ling-Jie(孟令杰)[1,2;1)] MA Xin-Wen(马新文)[1;2)] V. V. Parkhomchuk[3] YANG Xiao-Dong(杨晓东)[1]
V. B. Reva[3] LI Jie(李杰)[1] MAO Li-Jun(冒立军)[1] MA Xiao-Ming(马晓明)[1]
YAN Tai-Lai(晏太来)[1] XIA Jia-Wen(夏佳文)[1] YUAN You-Jin(原有进)[1]
XU Hu-Shan(徐瑚珊)[1] YANG Jian-Cheng(杨建成)[1] XIAO Guo-Qing(肖国青)[1]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
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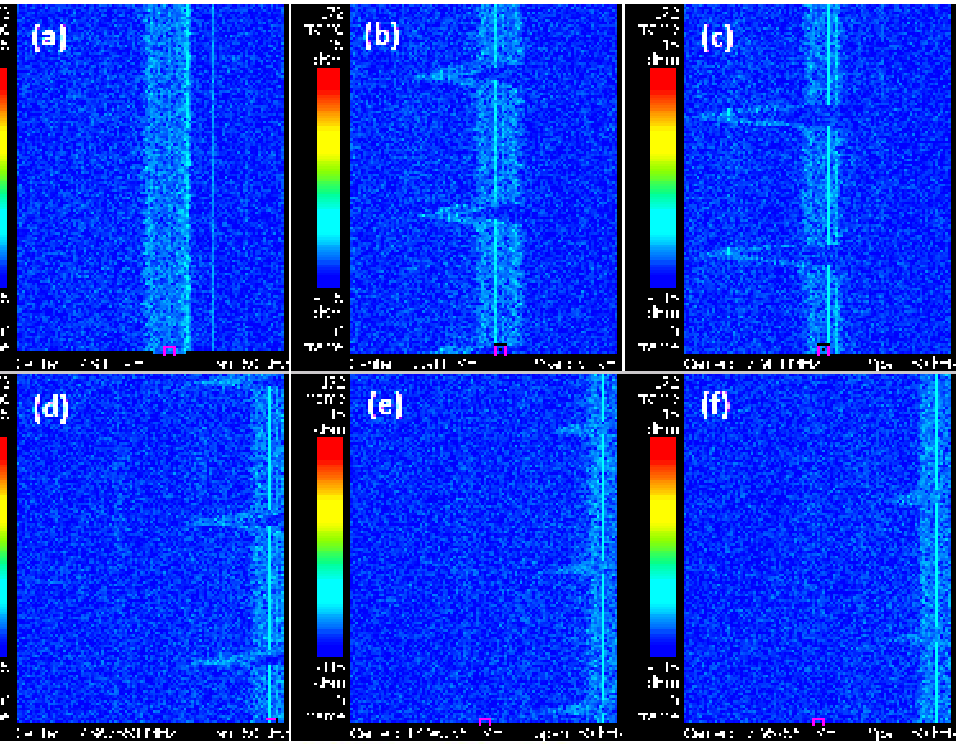
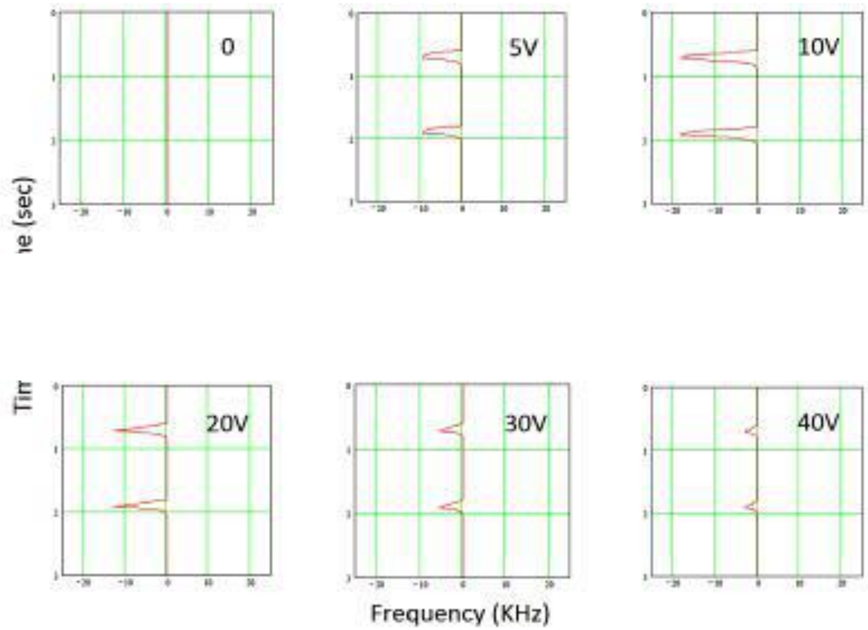
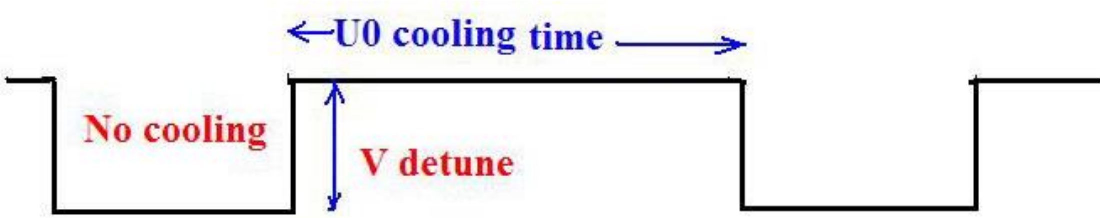
[3] Budker Institute of Nuclear Physics, Laverentyeva 11, 630090 Novosibirsk, Russia

Cooling force at CSRm



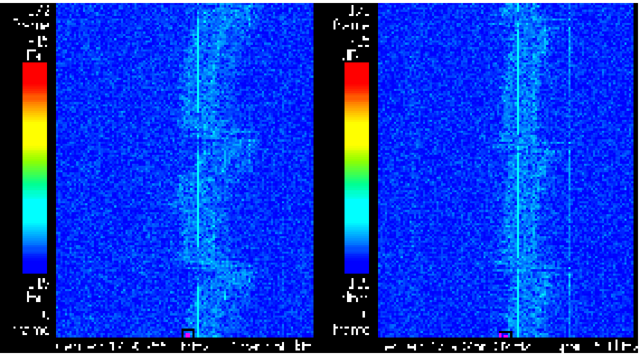




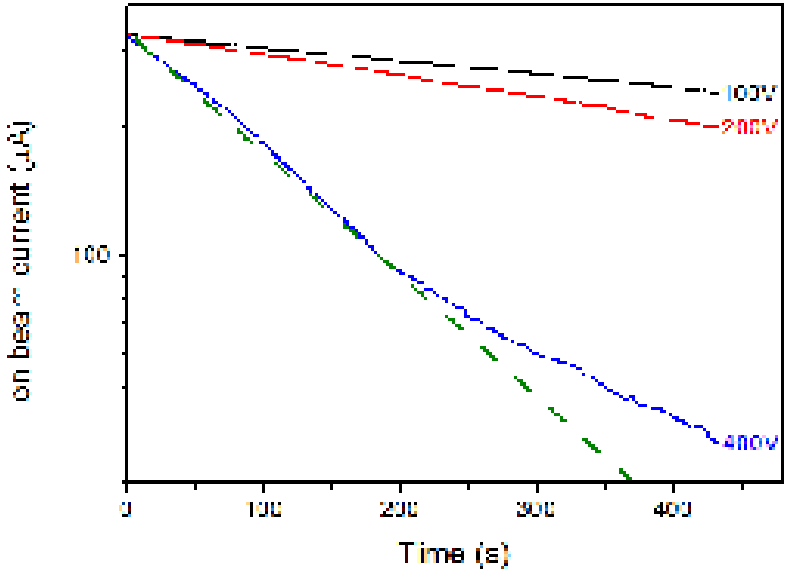
$$U(t) = U0 + \Delta U(t)$$

the electron energy was detuned away from cooling point by positive pulse then cooling energy then negative pulse.

Life time at CSRm



Recorded Schottky spectrum. The pulse height is 700V and the interval is 1s for the pulse width of 100ms (left) and 20ms (right), respectively



Decay ion beam intensity with amplitude detune energy $\Delta U(t)$>400 V

Direct experiments showing that naïve idea decreasing interaction with increasing different velocity between ion and electron beam are wrong

Model is two beams instability

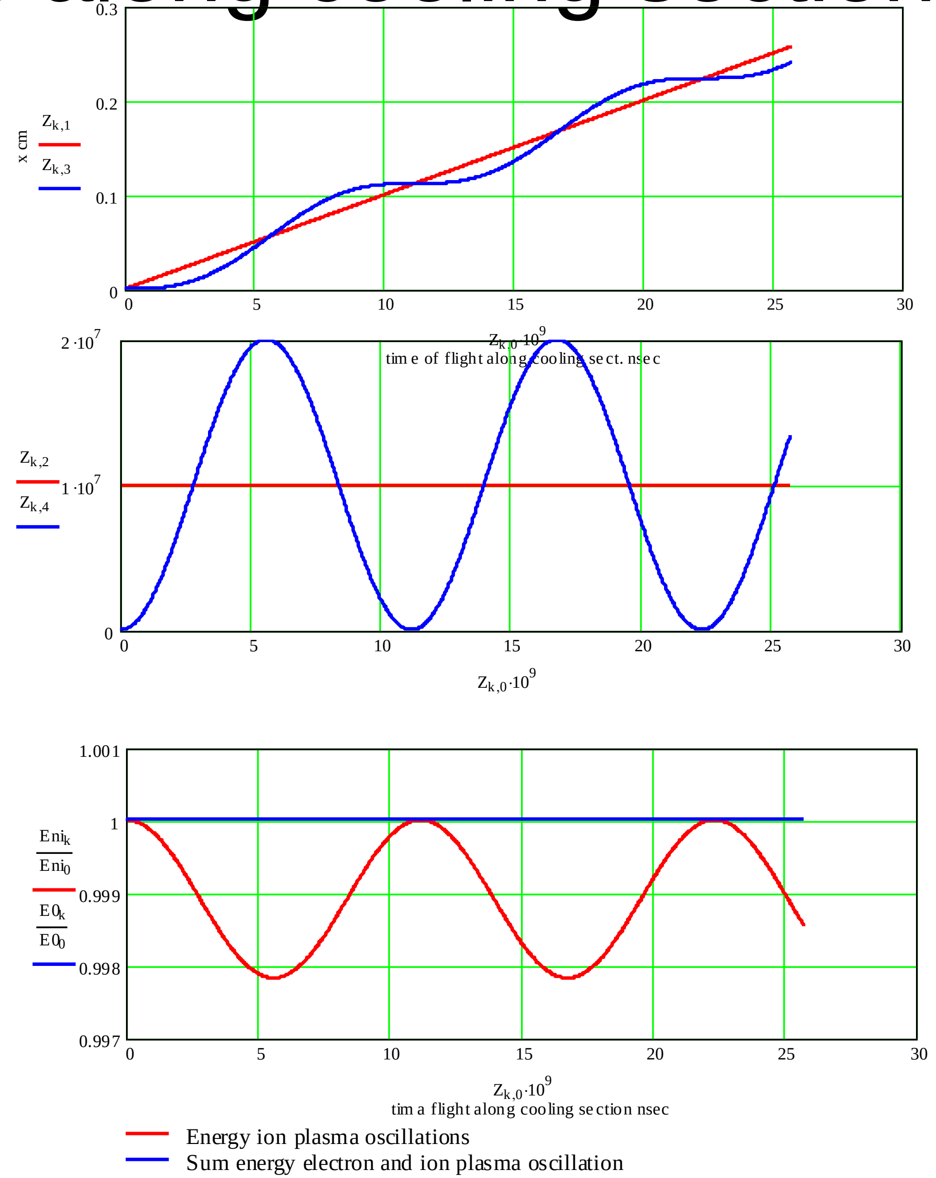
Plasma oscillations along cooling section

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

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

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

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

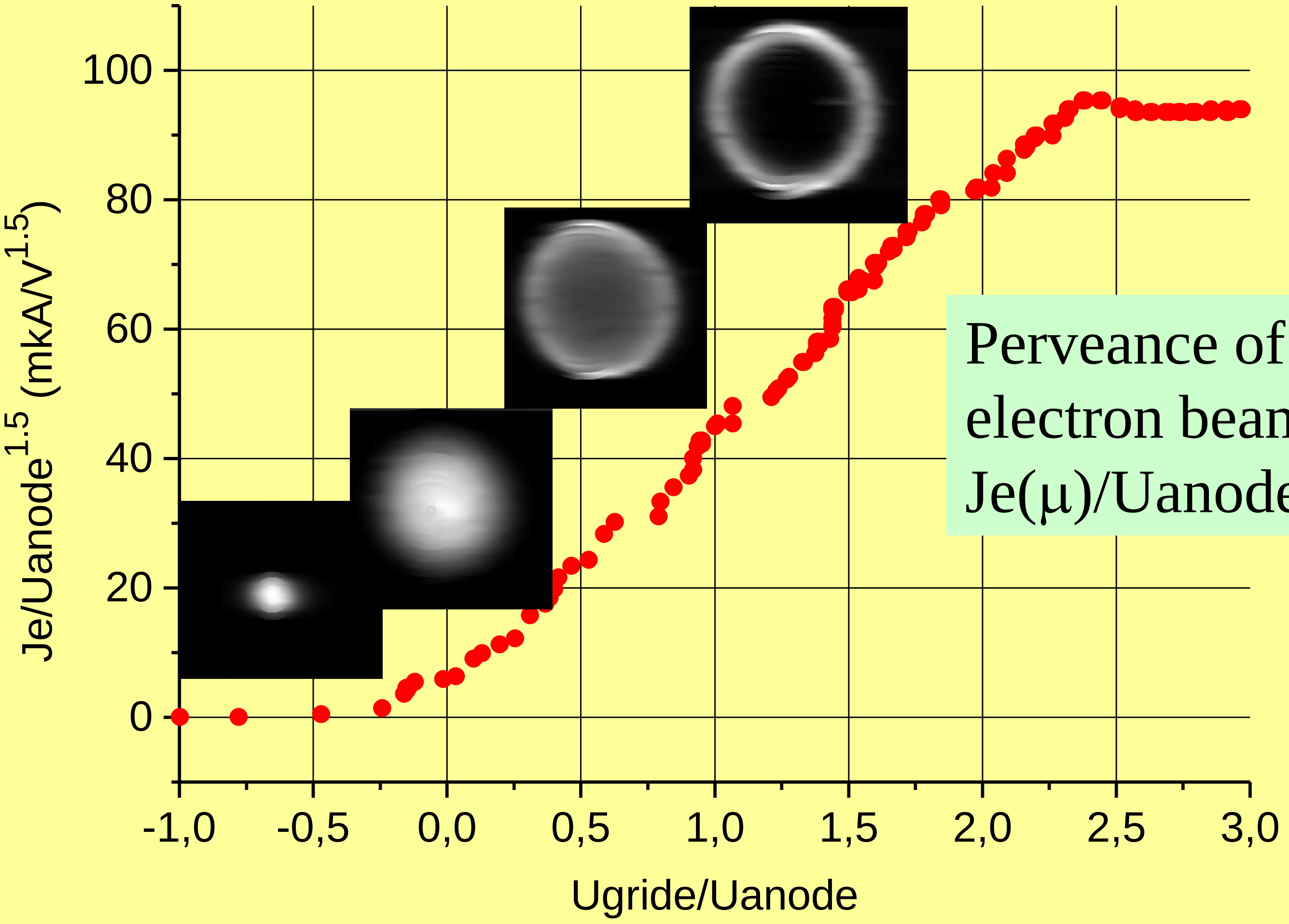
$$\frac{\delta p^2}{p^2} = \lambda\tau(-2 + (\frac{4\pi e^2 n_e}{m_e})(\frac{4\pi e^2 Z_i^2 n_i}{M_i})\tau^4 \frac{Ln_c}{3})$$

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

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

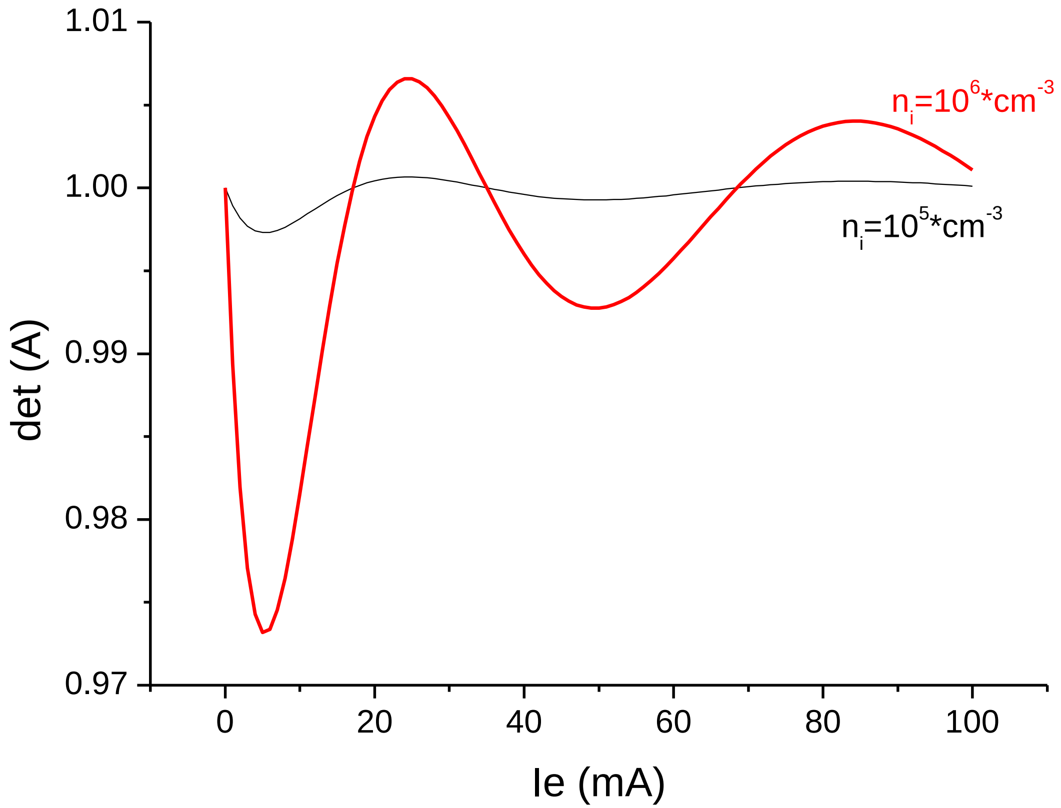
Condition for cooling- Linits on density ion beam ne*ni<limits

Hollow electron beam for opimization cooling



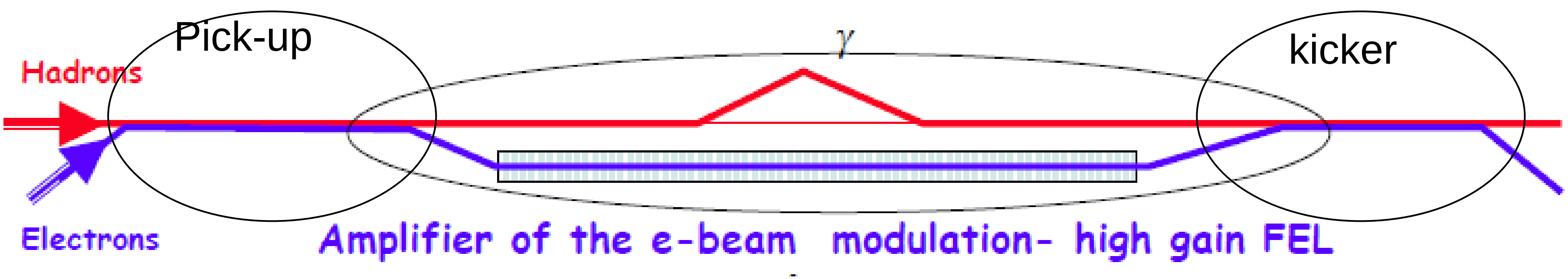
Perveance of gun and electron beam profile Je(μ)/Uanode(V)$^{3/2}$

Coherent cooling det<1 or heating det>1 versus electron current



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

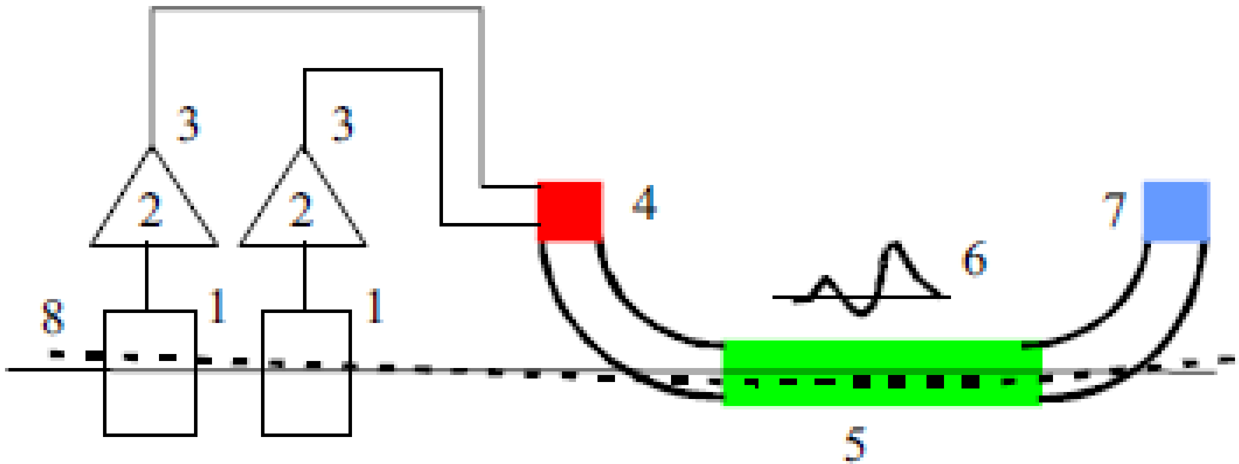
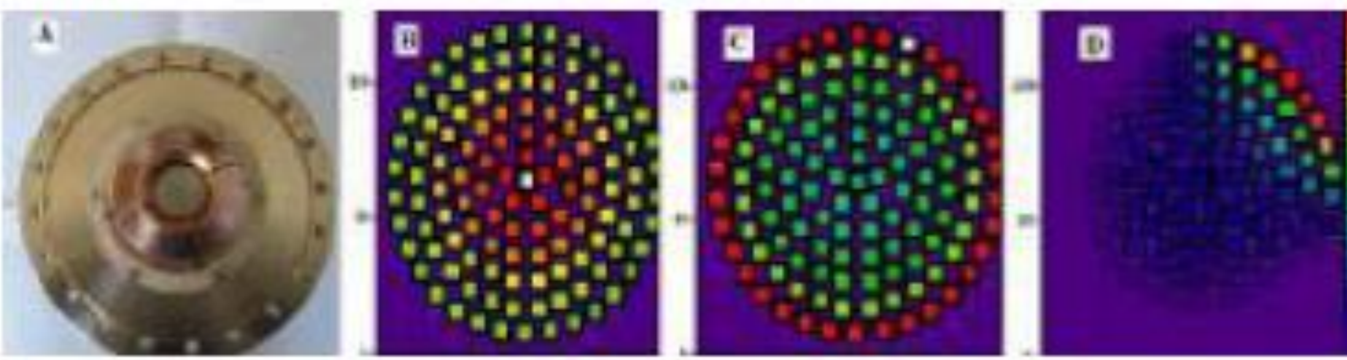


Figure 1: Scheme of stochastic cooling with electron cooler as 3D kicker. 1 – pick-up system, 2 – hybrid and amplifier, 3 – cable system, 4 – electron gun with the current modulation, 5 – cooling section, 6 – modulation of the space-charge density in the cooling section, 7 – collector of the electron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



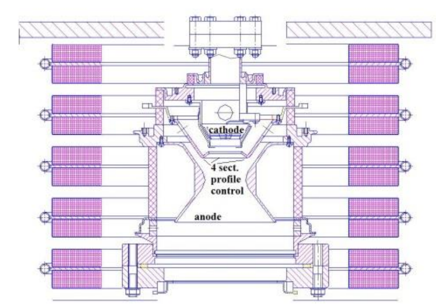
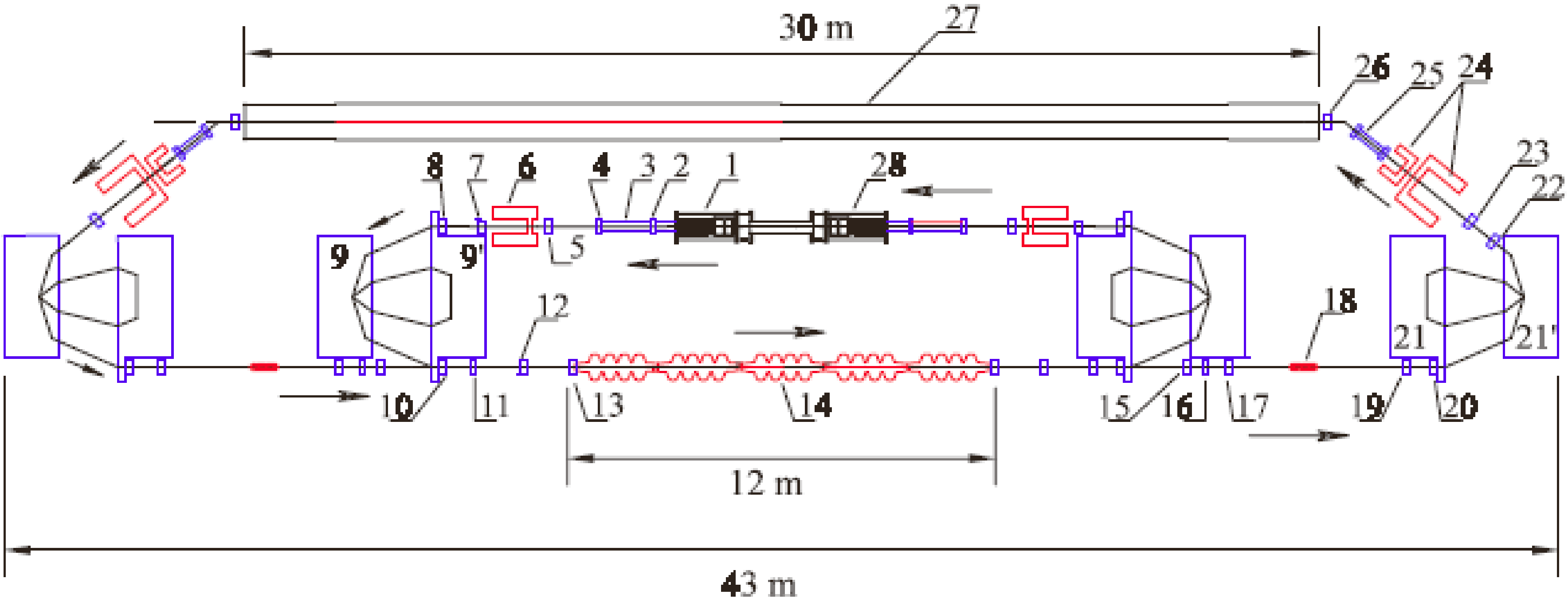


Figure 5: A is-photo cathode with grid electrodes, B is parabolic shap beam with maximum at centre C is “hollow” beam with minimum at centre, D is AC component of beam with RF voltage on single sector.

Project cooler for RHIC



Storage rings low energy electron

Idea very interesting
but solution for stable
motion still not clear

$$Q_{\perp} = Circ/(pc/eBs)$$

Q=700 !!!!

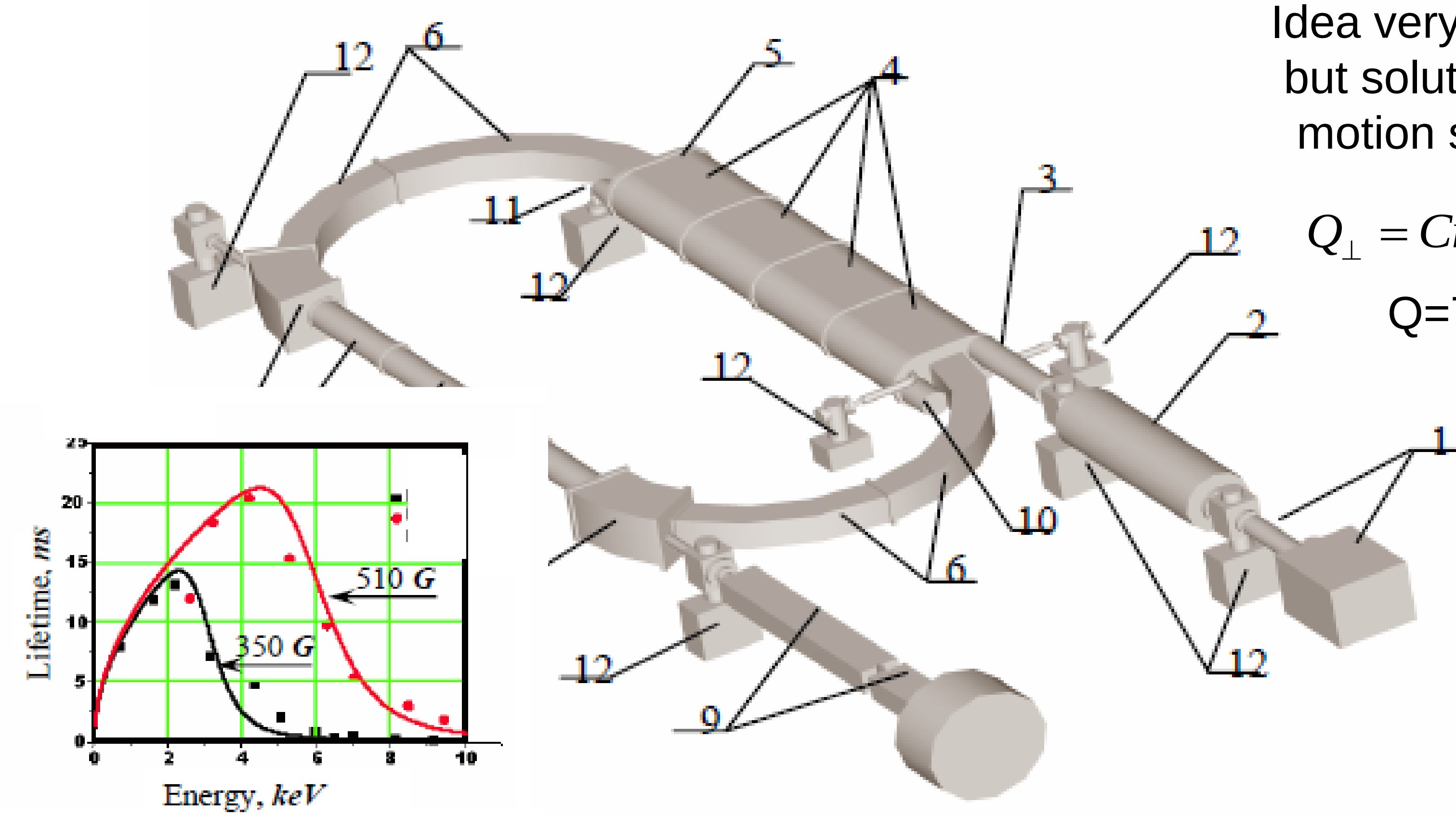


FIGURE 1. Design of the LEPTA. 1 – positron source, 2 – positron trap, 3 – positron transfer section, 4 – septum solenoids, 5 – kicker (inside septum solenoid), 6 – toroidal solenoids, 7 – solenoid and helical quadrupole inside it, 8 – electron cooling section, straight solenoid, 9 – channel for experiments with positronium in-flight, 10 – electron gun of cooling electron beam, 11 – collector of the electrons coming in to it after complete turn around the ring, 12 – vacuum pumps.

Problems ⟹ Working Session

Juergen Dietrich 2005

Importance of an intermediate energy electron cooler (2 MeV) between existing and 8 MeV HESR-cooler !?

Importance of interaction studies between high density targets (WASA at COSY, pellet target) and electron cooling !?

Relevance of magnetized cooling for HESR-GSI-FAIR project ?
Technical differences between magnetized and non-magnetized electron cooling.
Could we study a solution of magnetized cooling at existing electron coolers?
Importance of combination of high energy electron cooling and stochastic cooling against target heating.
How important is to have hands -on direct experience before committing oneself to irreversible construction ?
The role of intra beam scattering in the case of magnetized cooling?
Is the experience gained with the Fermilab cooler is already sufficient to plan for the 8 MeV cooler of HESR?
Is it necessary to investigate scaling laws in the case of high energy electron cooling (cooling time dependence of ß and γ, benchmarking etc.) ?

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.

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

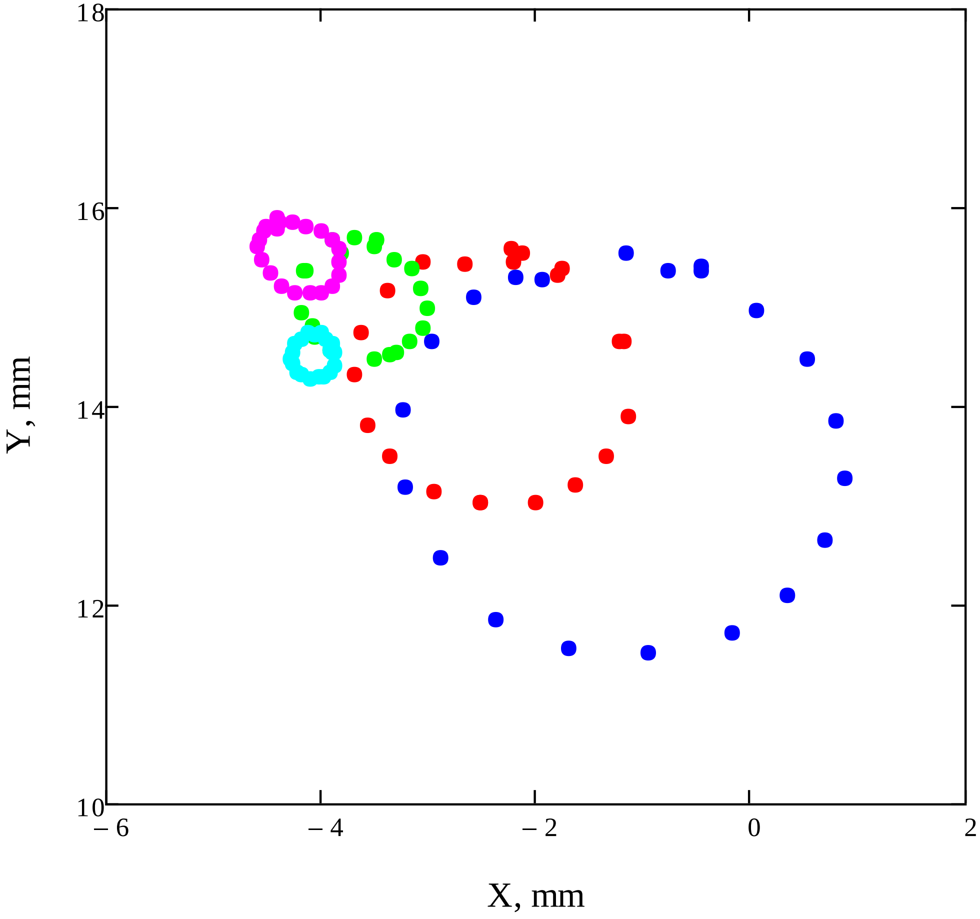
For ne→increase
B→increase
B magnet field control
Effective temperature electron beam

2 MeV cooler arriving at COSY (2012)

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

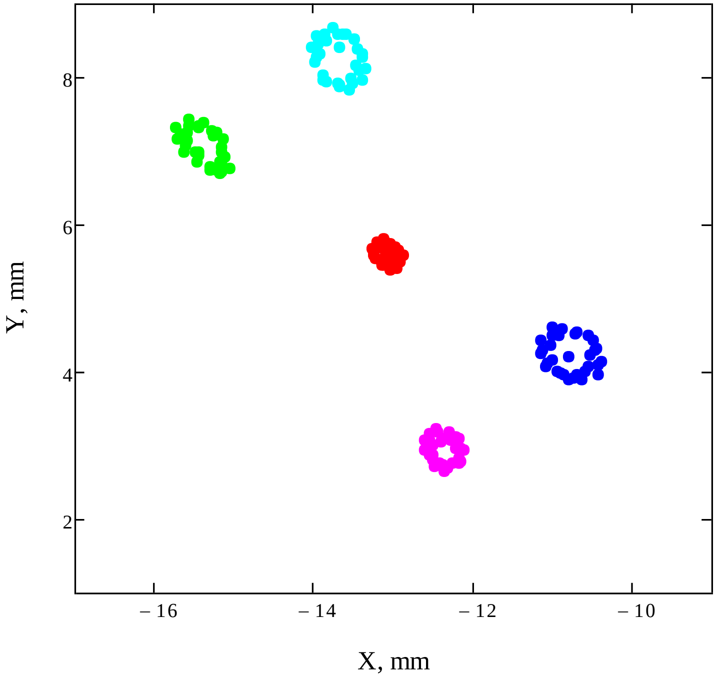
Radius rotation 1.5 mm → 0.1 mm

The energy of transverse rotation 4 kV→ 17 eV

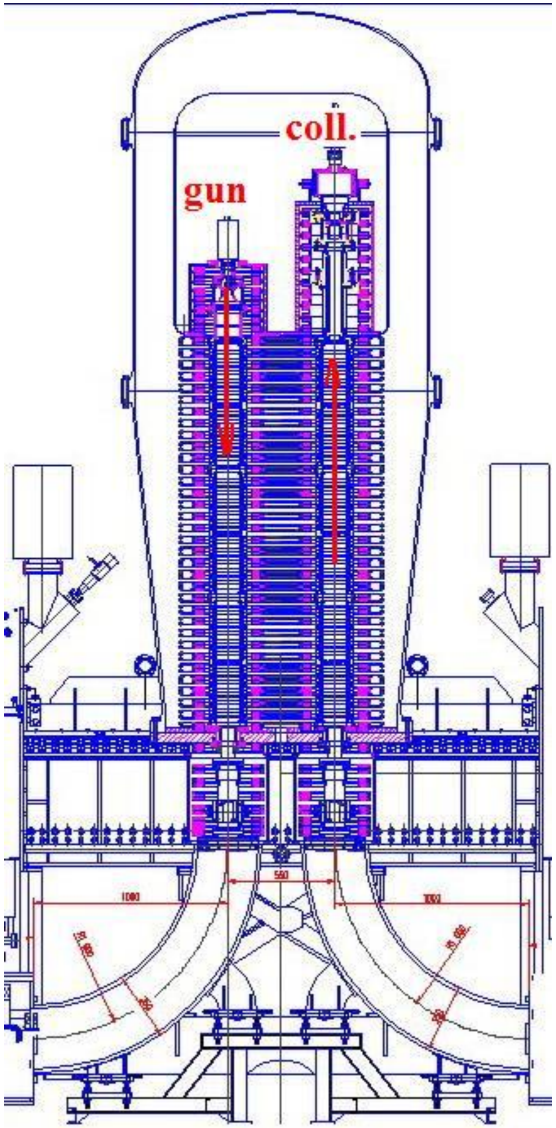
Optic features of COSY cooler

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)



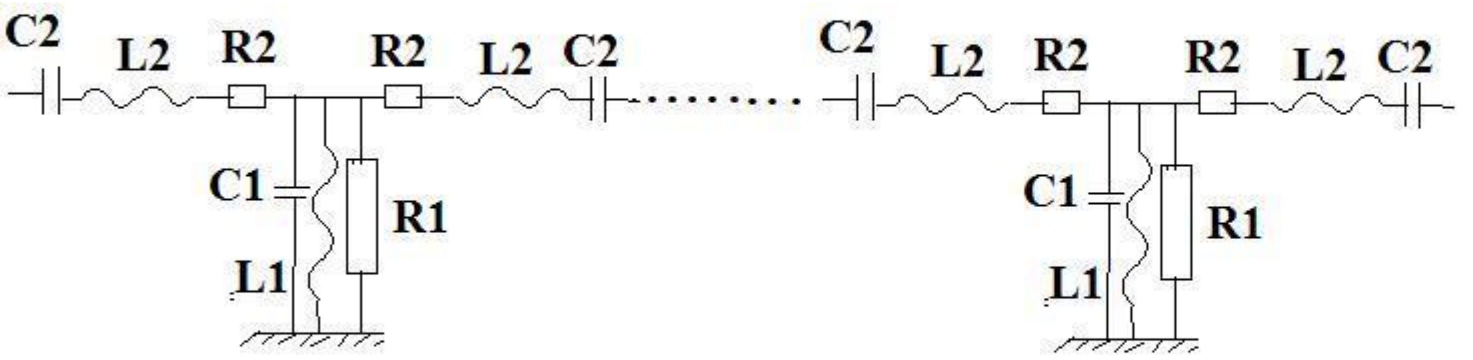
High voltage vessel



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

For details see reports:
TUPUM2HA01- Reva,
TUPUM2HA02-Kamerdziev.
WEPO12- Bryzgunov,
WEPO07-Panasuk

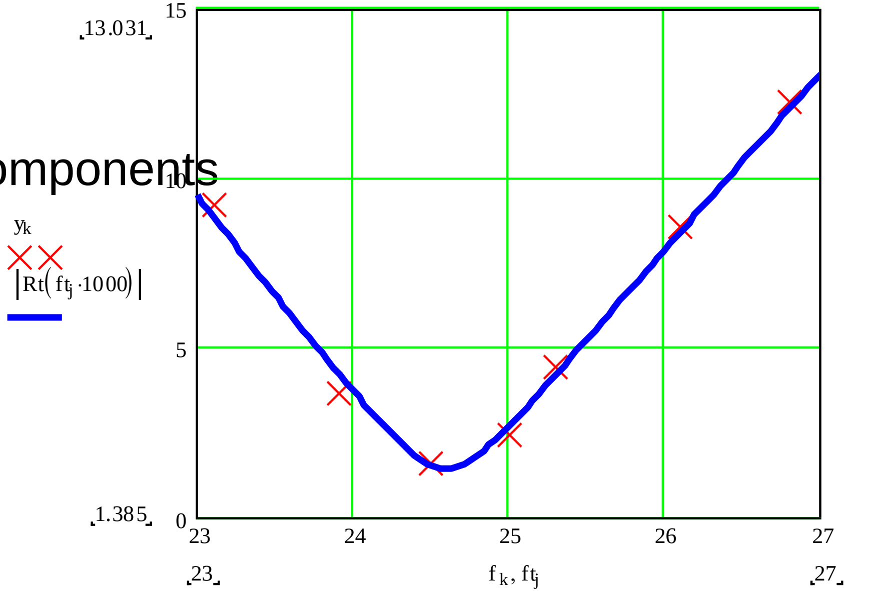
Basic scheme of cascade transformer



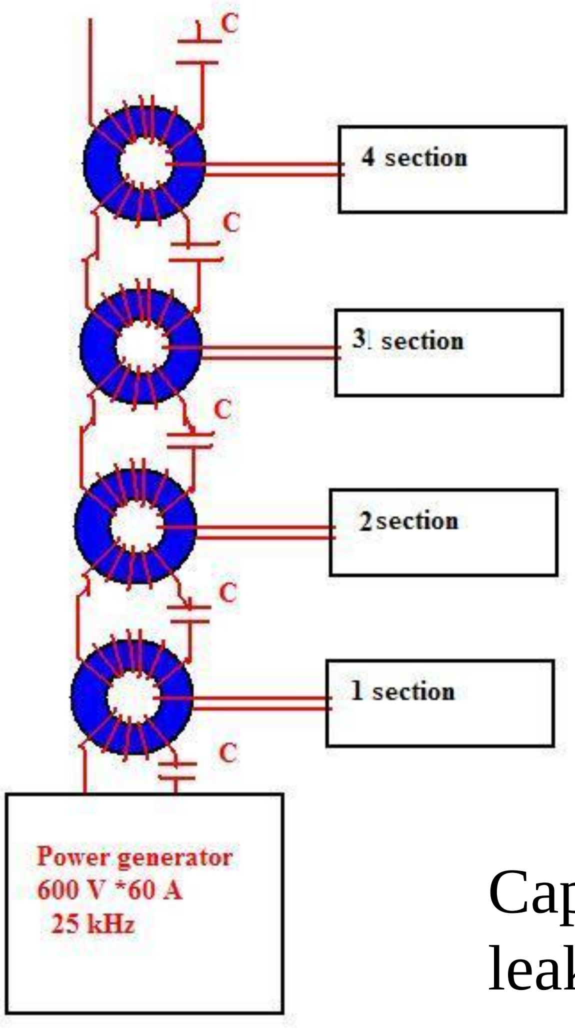
$$\frac{1}{i\omega C2} + i\omega L2 = 0 ... and ... \frac{1}{i\omega C1} = i\omega L1$$

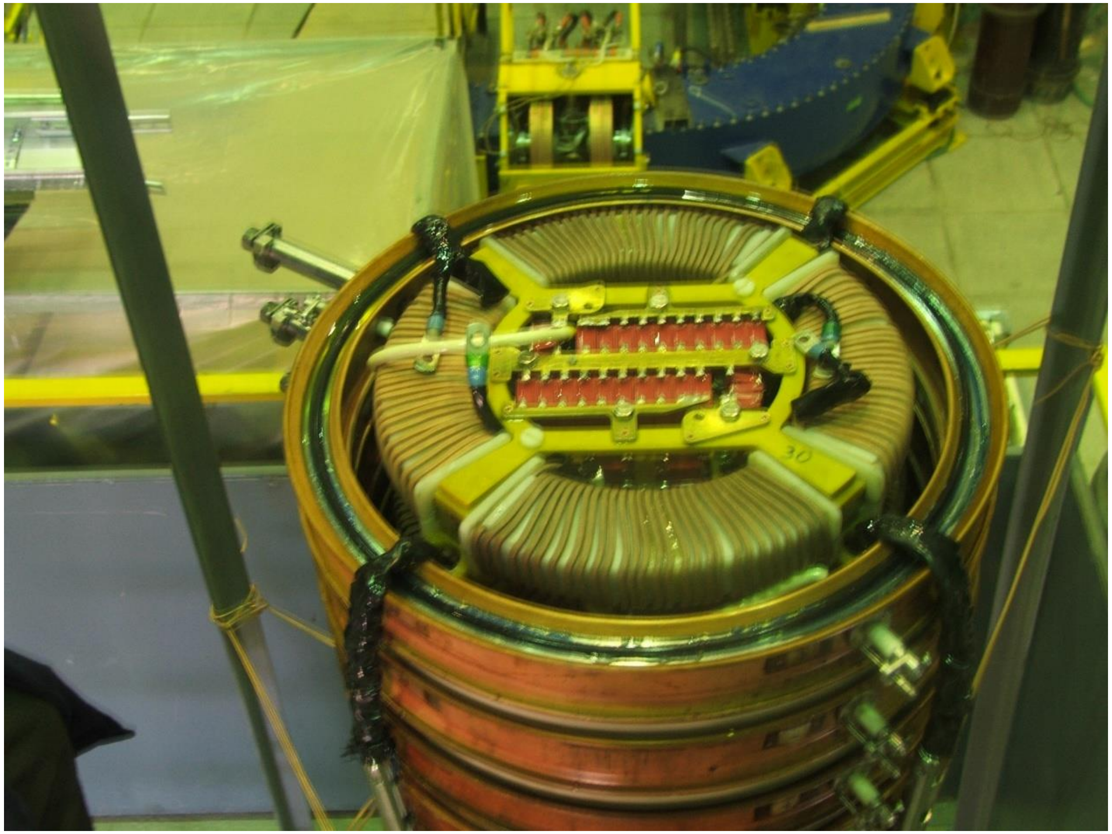
L1-inductive without loading
(L2+L2) –inductive bonding
R1-resistive loading in section
R2-resistive loses for bonding output coils

For resonance frequency 24.6 kHz resistive components
 limits maximal power at loading resistor
 For 33 sections was obtain 33*2R=2-3 ohm
For 700 V amplitude Wmax at end
of cascade 40 kWt
 but with 2 times decreasing
voltage that was not practical!



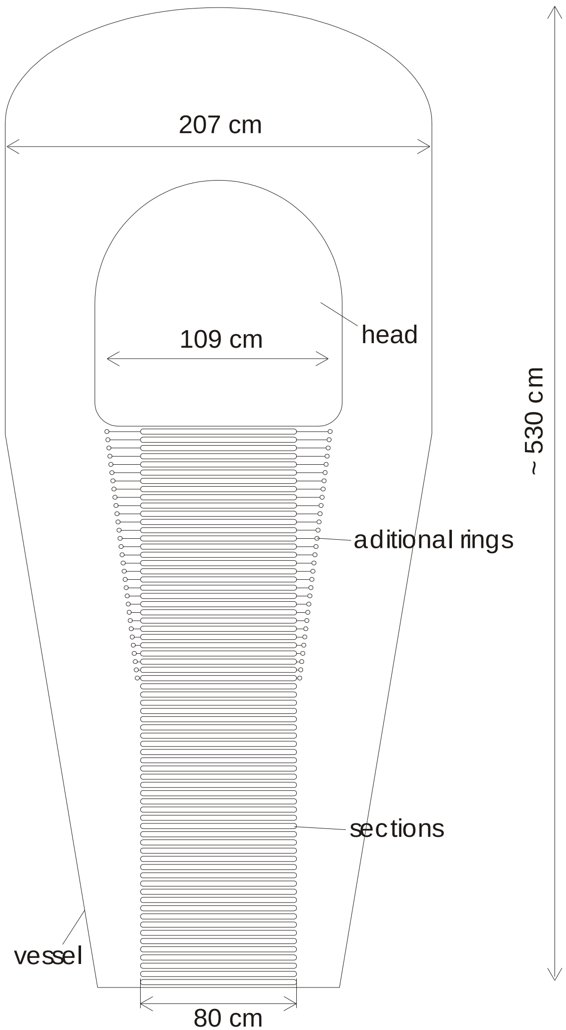
Cascade of serial transformers with amorphous Fe core for powering sections

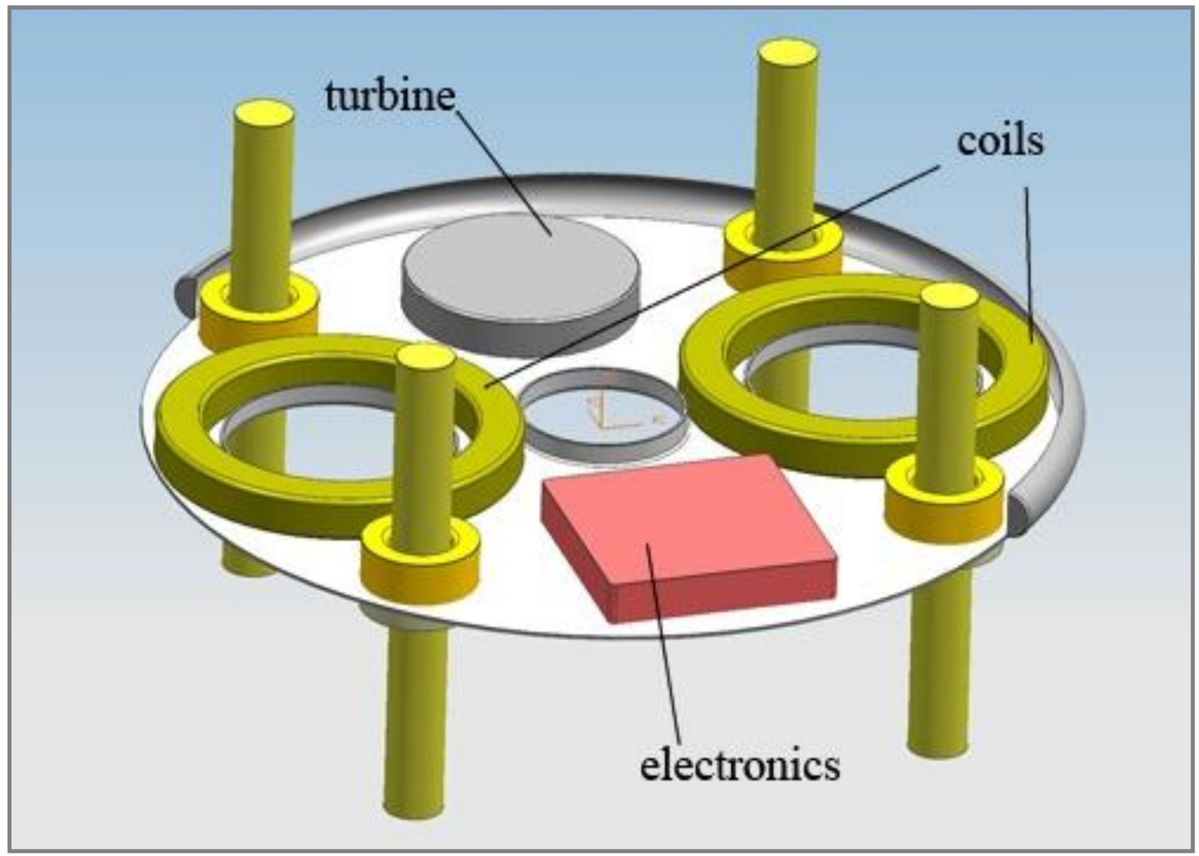




Capacitors used for compensation leakage inductance

From 2 MeV to 4 MeV

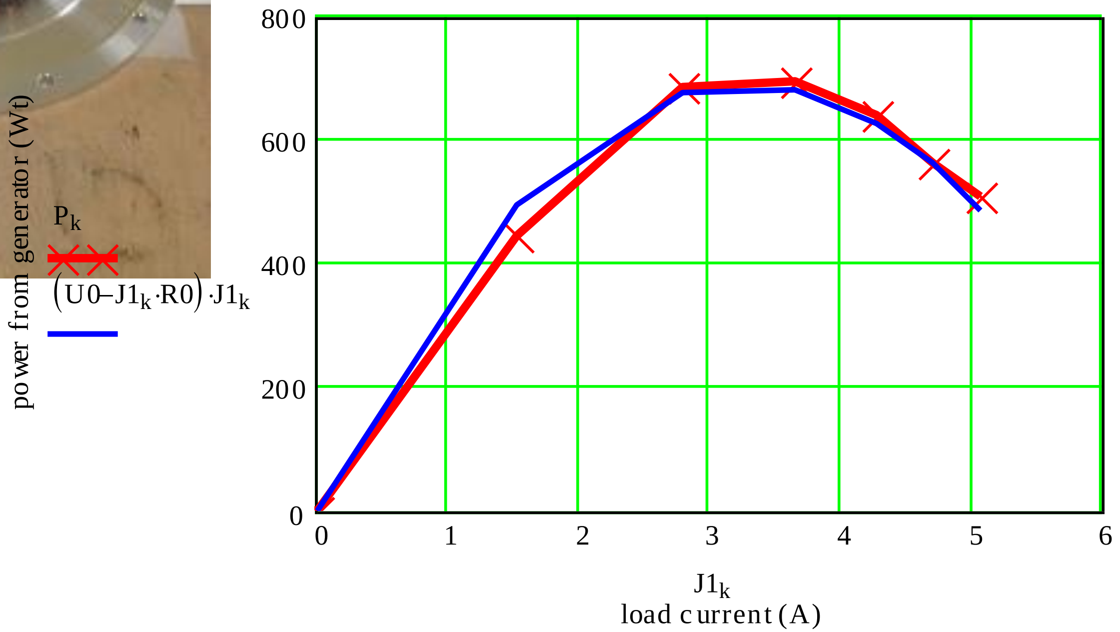




Turbine parameters

4 MeV/60 keV=66 sections
66 turbines looks to many

But it is possible to used industrial
turbines with power near 5 kWt
and local cascade transformer
That power 10 sections (on 0.6 MeV)
At this case we need about 7 turbines



How construct DC electron cooler for 8 MeV?

It will subjects of next step investigations in collaboration:

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CONCLUSION

Electron cooling demonstrate high potential for obtain high brightness ion beams.

The energy range of ion beams from 0 to 8 GeV was used.

Exist many not realized ideas that can increased potential of using electron cooling.

I hope most interesting ideas will be found at nearest future, may by discussion at our COOL"13 workshop .

Thanks for attentions

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COOL'13
10th - 14th June 2013
Mürren, Switzerland