Development of Electron Coolers in Novosibirsk

on behalf of

Vasily Parkhomchuk

(Budker INP SB RAS, Novosibirsk)

May 23, 2012, IPAC12, New Orleans

What is beam cooling?

- Cooling is reduction of the phase space occupied by the beam (without the reduction of beam intensity).
- Equivalently, cooling is reduction of the random motion of beam particles.
    - Cooling process violates Liouville's theorem

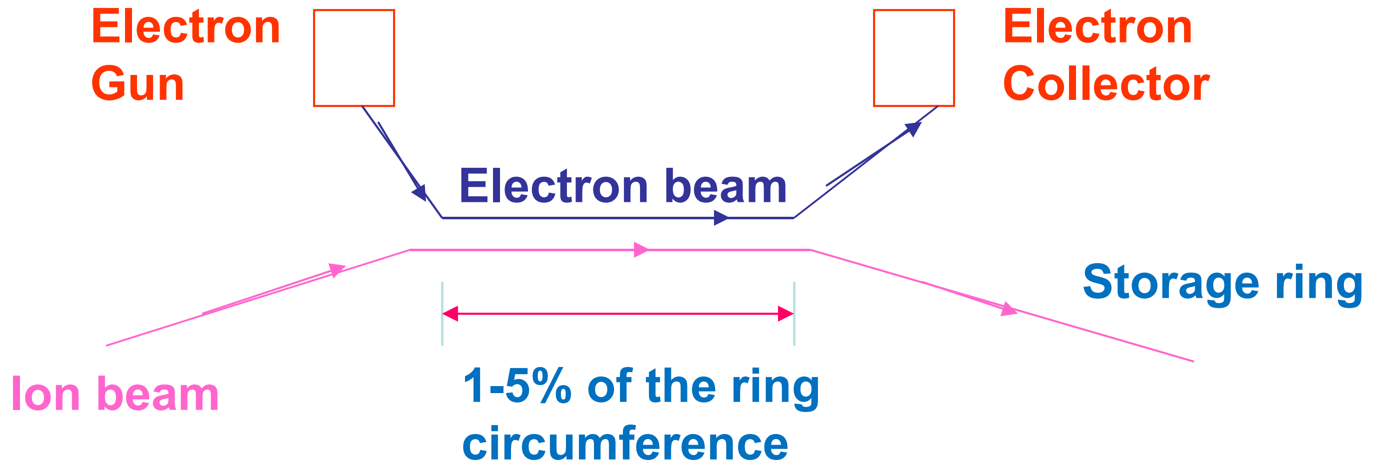
Need for cooling

- Injection help: stacking, accumulation, phase-space manipulation etc.
- Rare isotope and antiparticle production: accumulation of many pulses of antiparticles
- Internal fixed target: emittance growth from target scattering
- Colliding beams: beam-beam effects, residual gas scattering, intra-beam scattering, rf noise
- Precise Energy Resolution: narrow states, threshold production

How does electron cooling work?

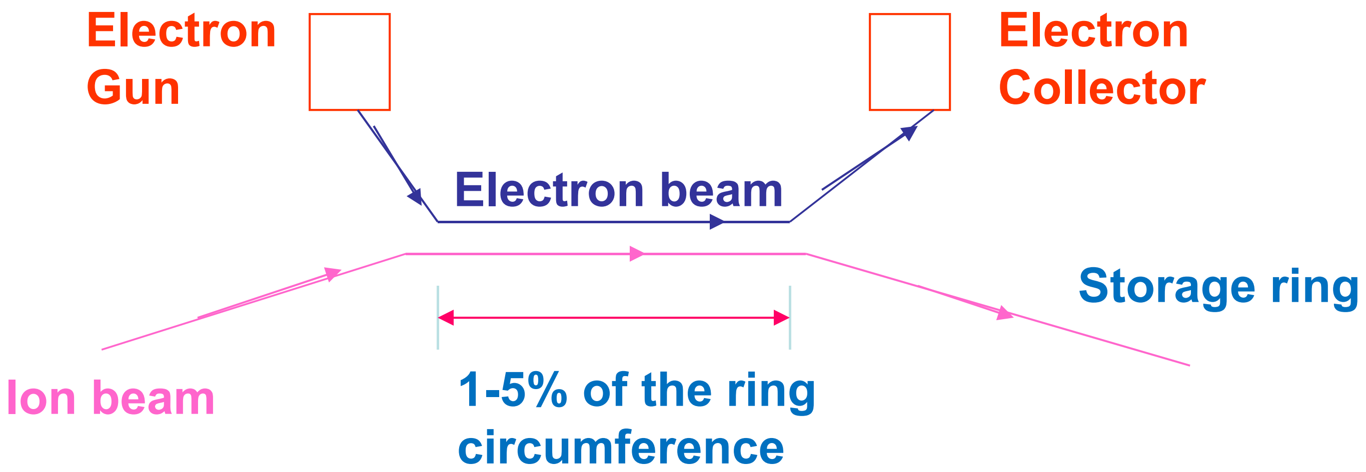
The velocity of the electrons is made equal to the average velocity of the ions.

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.

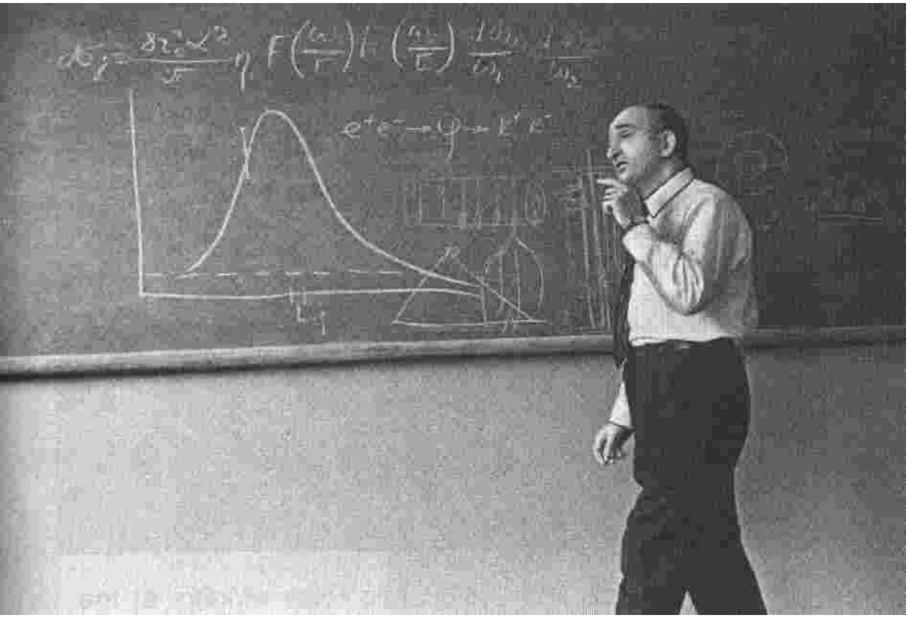


How does electron cooling work?

- Typical parameters of all existing low-energy electron coolers:
  - electron kinetic energy: ~keV to ~MeV
  - ion kinetic energy: ~MeV/u to ~GeV/u
  - electron beam current: up to 5 A



Invention electron cooling 1966



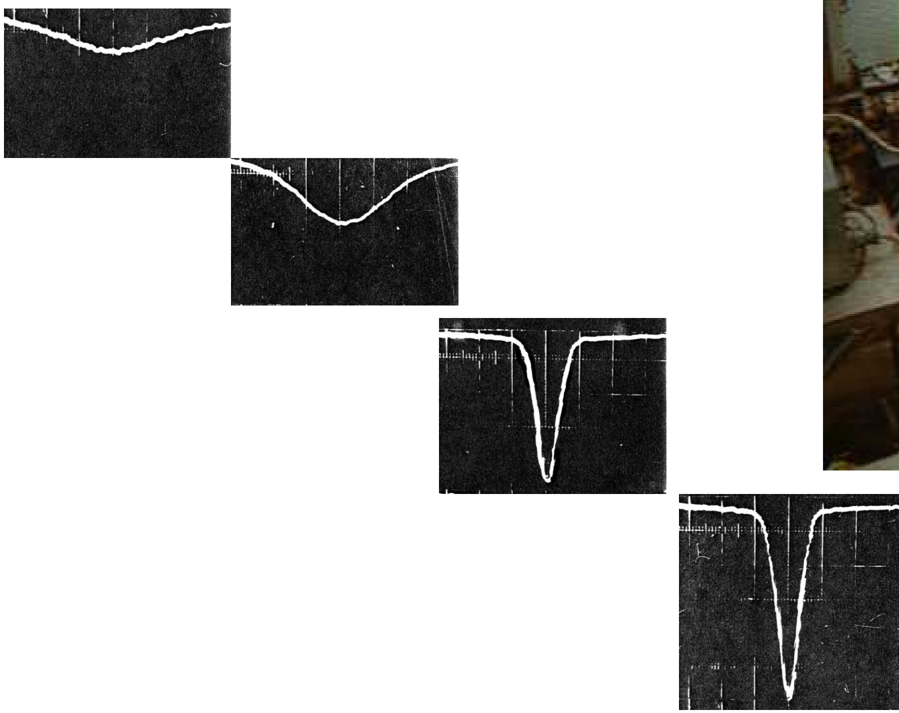
- Was invented by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.
- First publication at Symp. Intern. sur les anneaux de collisions á electrons et positrons, Saclay, 1966: "Status report of works on storage rings at Novosibirsk"

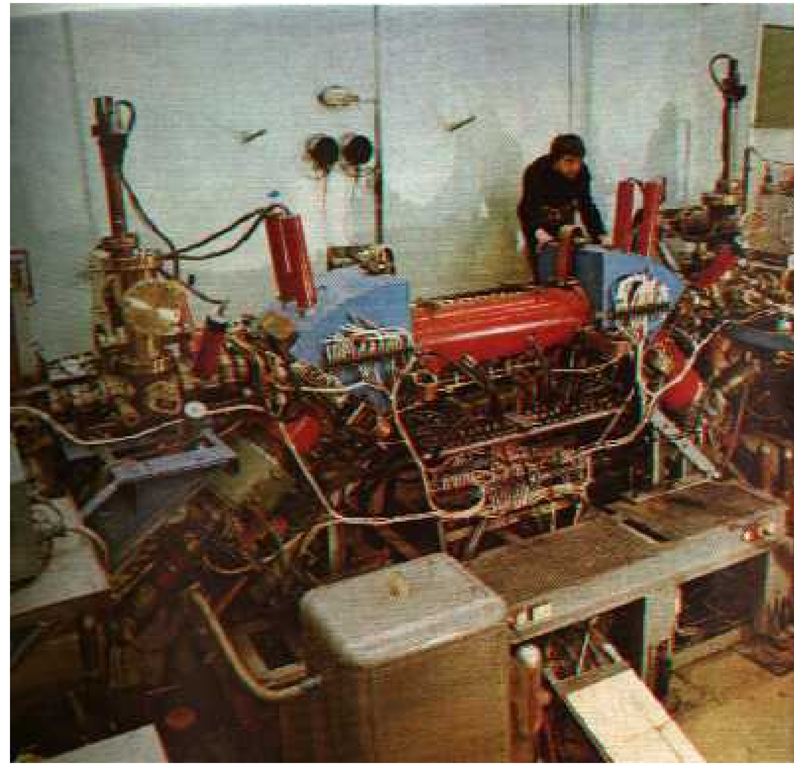
Budker's formula

$$\tau_{Maxwellian} = \frac{3}{8\sqrt{2\pi}} \cdot \frac{A}{Z^2} \cdot \frac{m_p m_e}{e^4 n_e} \cdot \left(\frac{T_i}{A m_p} + \frac{T_e}{m_e} \right)^{3/2}$$

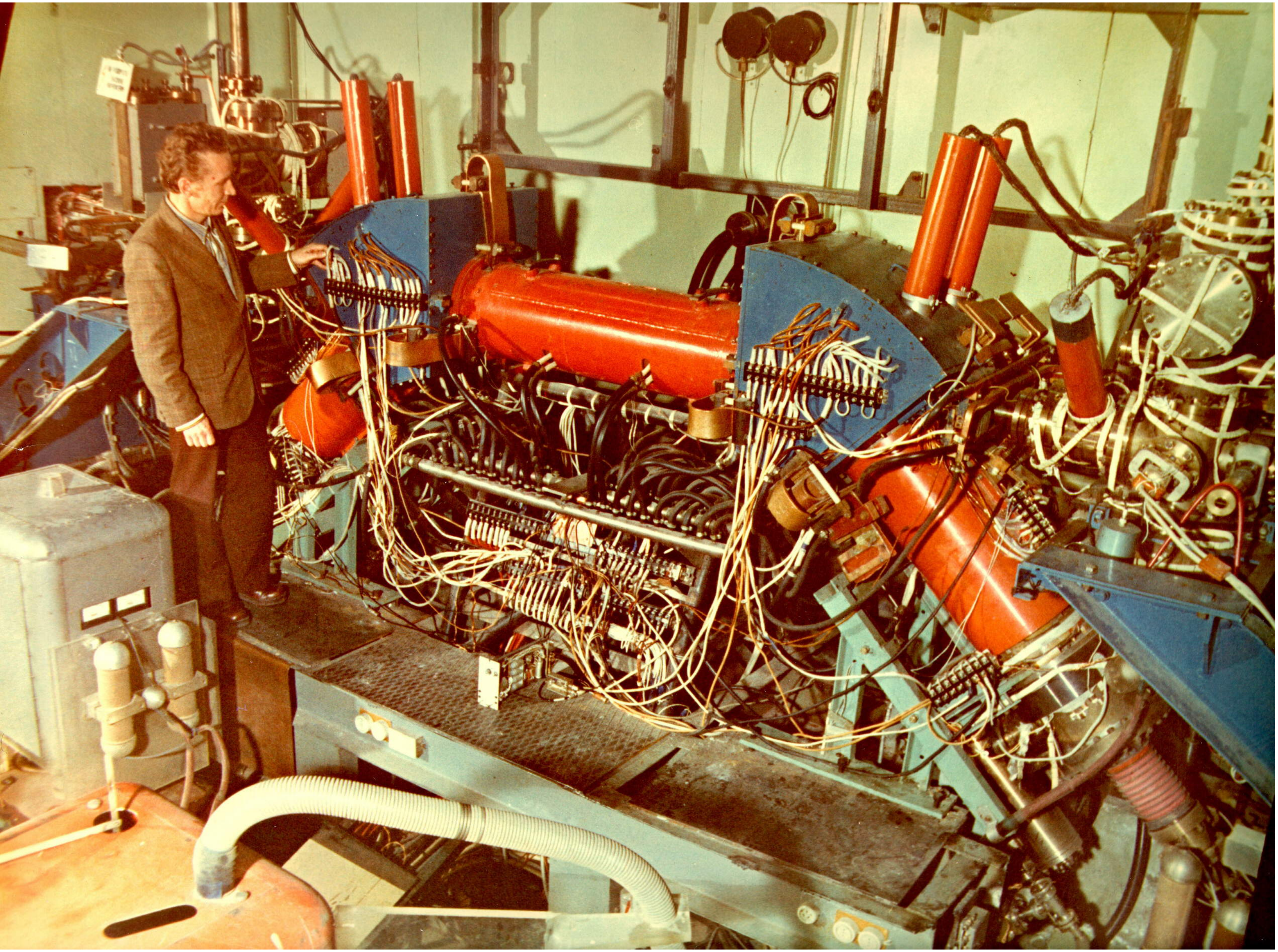
First Cooling Demonstration

- Electron cooling was first tested in 1974 with 68 MeV protons at NAP-M storage ring at INP(Novosibirsk).

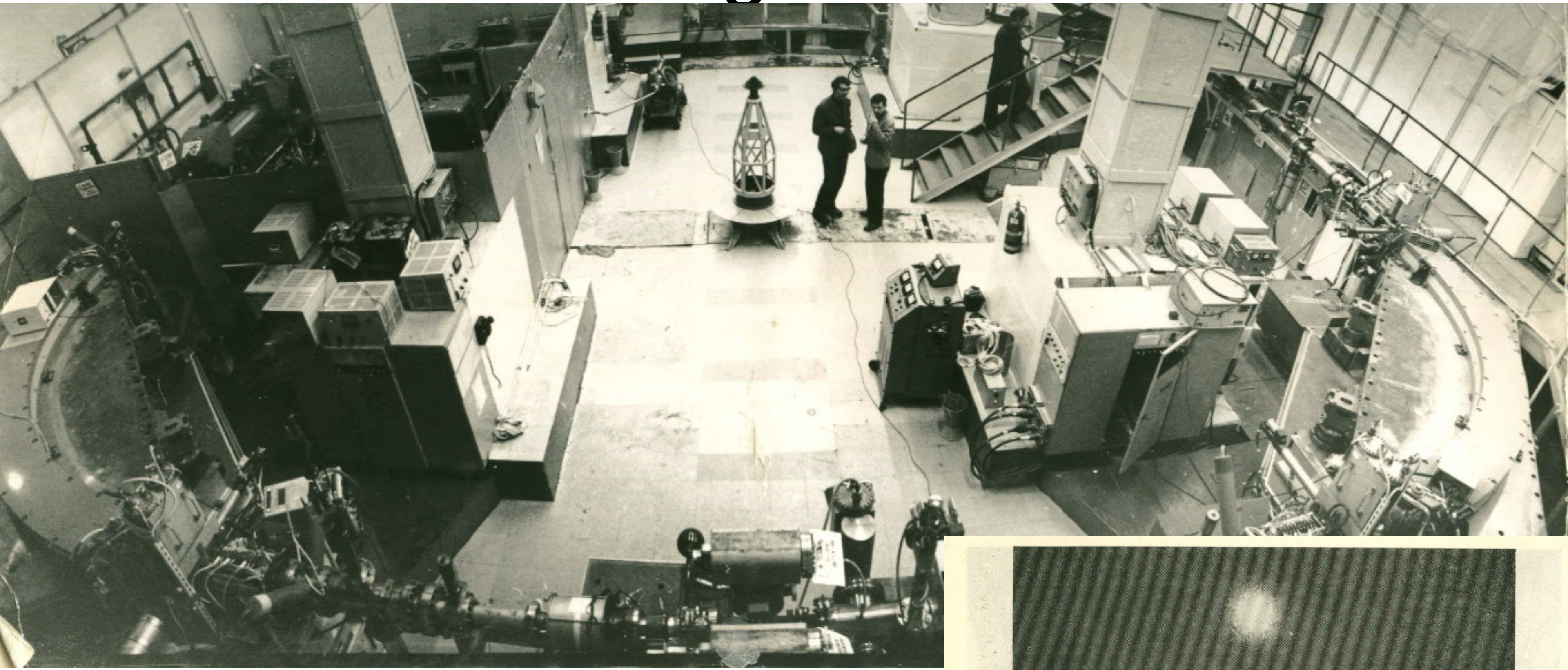




First electron cooler for NAP-M



Storage ring for testing electron cooling NAP-M



The foot print of H0 beam at nuclear emulsion (after recombination proton with electrons) after electron cooling of 65 MeV proton beam , grid lines are 1 mm apart, distance from center of cooler to emulsion foil 10 m. →

$$\Delta p / p = 10^{-5}, ... \Delta E = 65 \times 10^{6} * (10^{-5})^{2} == 65 * 10^{-4} = 65K, Temperature!$$

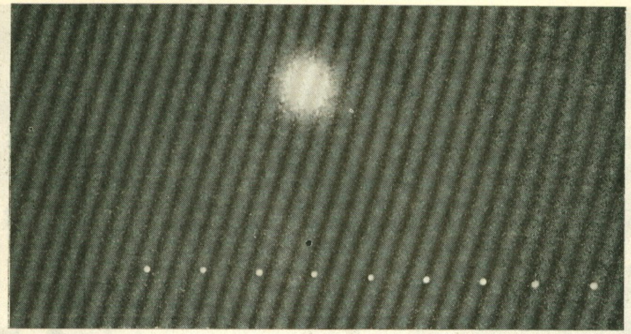
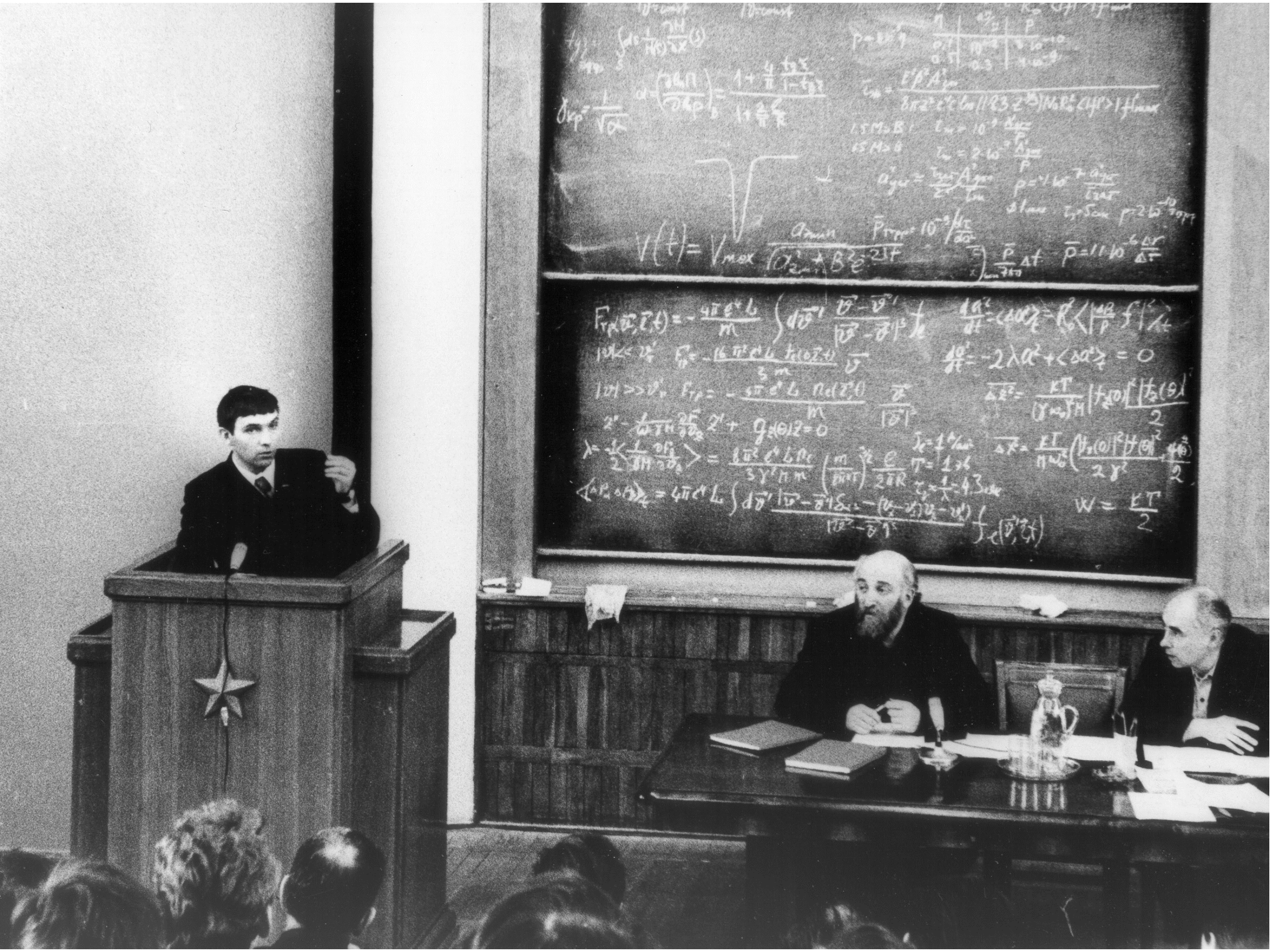


Рис. 4. Фотография ядерной фотоэмульсии, экспонированной пучком быстрых атомов водорода ($v/c = 0{,}35$), возникающих при рекомбинации протонного и электронного пучков на участке охлаждения

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

Presentation of a PD thesis
“First experiment with electron cooling”



G.I. Budker,
N.S.Dikansky,
V.I. Kudelainen,
I.N. Meshkov,
V.V. Parkhomchuk,
A.N. Skrinsky,
B.N. Sukhina,
“First experiments on electron cooling”,
IEEE Trans. Nucl. Sci. **22**, 2003-7,1975.

IEEE Transactions on Nuclear Science, Vol.NS-22, No.5, October 1975

EXPERIMENTS ON ELECTRON COOLING

G. I. Budker, Ya. S. Derbenev, N. S. Dikansky, V. I. Kudelainen
I. N. Meshkov, V. V. Parkhomchuk, D. V. Pestrikov, B. N. Sukhina
A. N. Skrinsky

Institute of Nuclear Physics
Siberian Division
USSR Academy of Sciences

IVth All-Soviet Conference on Part. Accelerators, Moscow, 1974

The electron cooling method was suggested by one of the authors in the middle sixties. The original idea of electron cooling published in 1966[1] is the following: An electron beam is put into one of the straight sections of a storage ring of heavy particles (protons, for example). The average velocity of electrons is the same as that of protons both in amount and direction. Then, in the rest frame system, two beams running through each other are equivalent to a two-component plasma. If the effective electron temperature is low enough, the proton temperature will increase to the electron temperature (when the multiple scattering on the residual gas is not appreciable). That means the angular divergence of the proton beam θ_p is decreased down to the value

$$\theta_p \sim \sqrt{\frac{m}{M}}\,\theta_e \qquad (1)$$

where θ_e is the temperature angular spread of electrons, m is the electron mass, M is the proton mass. Similarly an energy spread in the proton beam is

$$\frac{\Delta E_p}{E} \sim \sqrt{\frac{m}{M}}\,\beta^2\,\gamma\,\theta_e \qquad (2)$$

Damping time is determined by the following expression

$$\tau = \frac{3}{2\sqrt{2\pi}}\left(\frac{mc^2}{e^2}\right)\left(\frac{Mc^2}{e_p^2}\right)\frac{\gamma^2}{nc\eta L}\begin{cases}\left(\frac{T_e'}{mc^2}\right)^{3/2} & \theta_p \ll \theta_e \\ \theta_p^3\beta^3\gamma^3 & \theta_p \gg \theta\end{cases} \qquad (3)$$

where n is the density of electrons in the laboratory system, T_e' is the electron temperature in the particle system, e and e_p are the electron and proton charges respectively, η is the ratio between the length of the orbit section occupied by the electron beam and its circumference, $L \simeq 20$ is the Coulomb logarithm, c is the velocity of light.

Naturally, the cooling process kinetics is more complex. One should take into account the peculiarity of the proton beam motion in a storage ring as well as

Table I (Continued)

Betatron wave numbers:	
ν_z	1.24
ν_z	1.34
Momentum compaction factor	0.8
Transition energy	110 MeV
Average pressure	$5\cdot10^{-10}$ Torr
Acceleration time	30 sec

The electron beam installation (Fig. 3,4) is located in one of the storage ring straight sections and has the parameters given in Table 2.

Table 2 Parameters of the Electron Beam Installation

Interaction region length	1 m
Electron energy	up to 100 keV
Electron current	up to 1 A
Temperature angular spread	$2\cdot10^{-3}$
Energy stability	$2\cdot10^{-4}$
Longitudinal magnetic field	1 kG

Formation of the intense beam with the small transverse velocities was performed with the special three electrode gun placed into an homogeneous longitudinal magnetic field[6]. The electron energy recovering is used. In the installation the collector potential is higher than the cathode potential by 1-2 kV. The use of electron energy recovering is especially important for the high energy region.

Typical experimental conditions and the best previous results are given in Table 3.

Table 3 Typical Conditions of the Experiment and Main Results

p	50 MeV;	50 μ A
e	27 keV	0.1 A
Electron beam temperature		0.2 eV
Temperature angular spread		$2\cdot10^{-3}$
Damping time of protons		3 sec
The proton beam equilibrium dimension		1 mm

G.I.Budker, Ya.S.Derbenev, N.S.Dikansky, V.I.Kudelainen, I.N.Meshkov, V.V.Parkhomchuk,D.V.Pestrikov, B.N.Sukhina, A.N.Skrinsky, First experiments on electron cooling, in Proc. of IVth All-Soviet Conference on Part. Accel., v.2, p.302, 1975; IEEE Trans. Nucl. Sci., NS-22 (1975) 2093; Part. Accelerators 7 (1976)197; Rus. Atomic Energy 40 (1976) 49.

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E_p 50 MeV Ip 50 μA

E_e 37 keV Ie 0.1 A

$\phi_{p\_equilibrium}$ 1 mm

where n is the density of electrons in the laboratory system, T_e is the electron temperature in the particle system, e and e_p are the electron and proton charges respectively, η is the ratio between the length of the orbit section occupied by the electron beam and its circumference, L≃20 is the Coulomb logarithm, c is the velocity of light.

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$\phi_{p\_equilibrium}$ 1 mm

τ_{cool} 3 sec - in full agreement with Budker's theory (classic plasma formulae).

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G.I.Budker, Ya.S.Derbenev, N.S.Dikansky, V.I.Kudelainen, I.N.Meshkov, V.V.Parkhomchuk, D.V.Pestrikov, B.N.Sukhina, A.N.Skrinsky, First experiments on electron cooling, in Proc. of IVth All-Soviet Conference on Part. Accel., v.2, p.302, 1975; IEEE Trans. Nucl. Sci., NS-22 (1975) 2093; Part. Accelerators 7 (1976)197; Rus. Atomic Energy 40 (1976) 49.

1975 – Unexpected results after e-cooler improvement

Provisional text
not revised by CERN
Translation Service

NUCLEAR PHYSICS INSTITUTE
SIBERIAN BRANCH OF USSR ACADEMY OF SCIENCE

PS/DL/Note 76-25
October 1976
Preprint N.P.I. 76-32

G.I. Budker, A.F. Bulyshev, N.S. Dikansky, V.I. Kononov, V.I. Kudelainen, I.N. Meshkov, V.V. Parkhomchuk, D.V. Pestrikov, A.N. Skrinsky, B.N. Sukhina

NEW EXPERIMANTAL RESULTS OF ELECTRON COOLING

Presented to the All Union High Energy Accelerator Conference, Moscow, October 1976

(Translated at CERN by O. Barbalat)

* * * * *

Improvements:

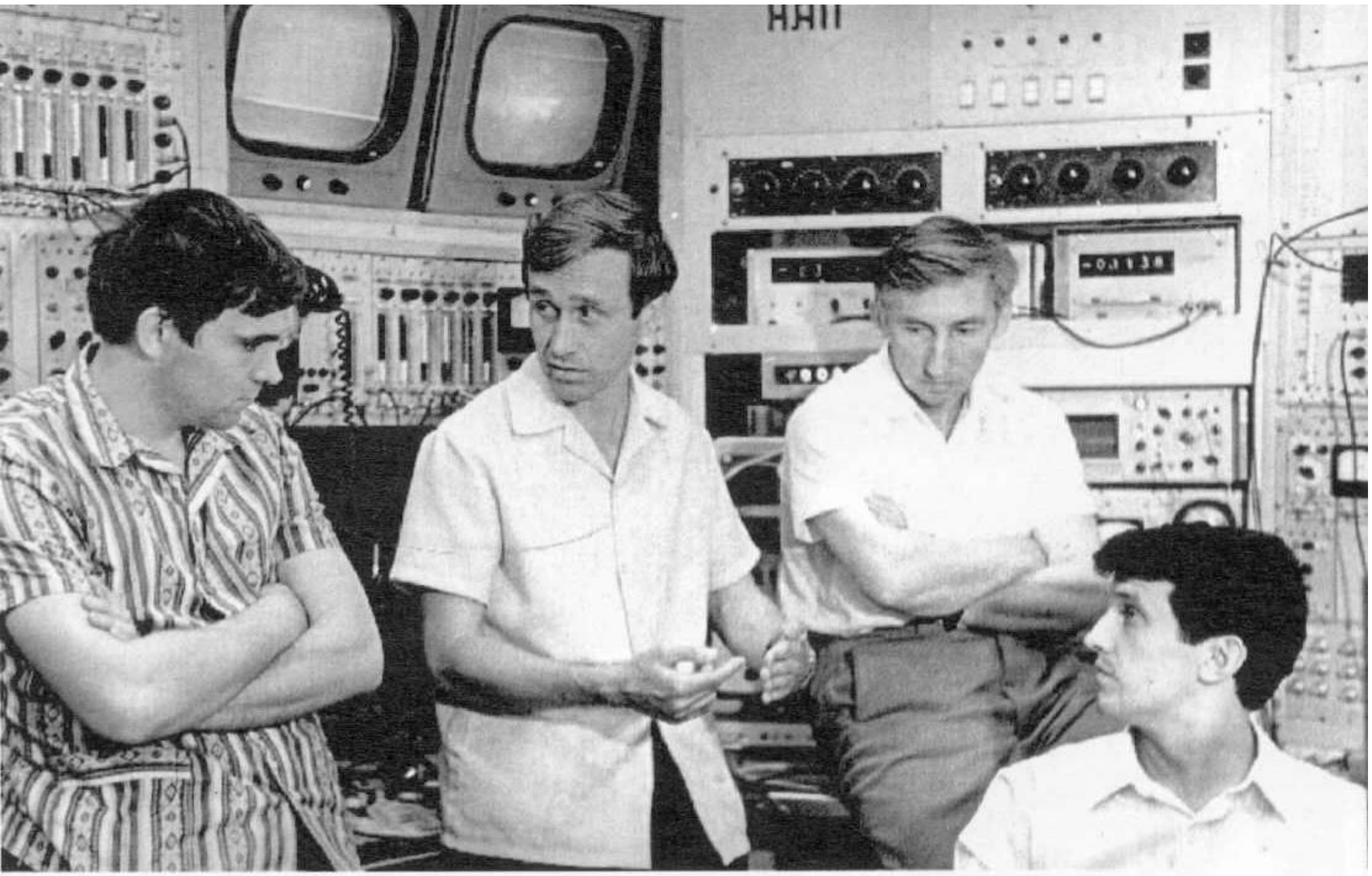
B-field homogeneity in the cooling section – about 10^{-4},

Electron energy stability – better than 10^{-5}.

For the electron current of 0.8 A the measured cooling time was 83 ms (proton energy of 65 MeV) –

-much shorter of “The Budker’s numbers!”

Fast electron cooling with magnetized electron beam was born in the control room NAP-M as results measuring cooling force and discussion “strange” results with Y.S.Derbenev and A.N.Skrinsky



Академик А. Н. Скринский и созвездие будущих членов Российской академии: ст. инженер В.В. Пархомчук, кф-мн, снс И.Н. Мешков, кф-мн, снс Н.С. Диканский в пультовой НАП-М. 1975 г.

Derbenev Ya.S.
Skrinsky A.N.
“Magnetization effects in electron cooling”

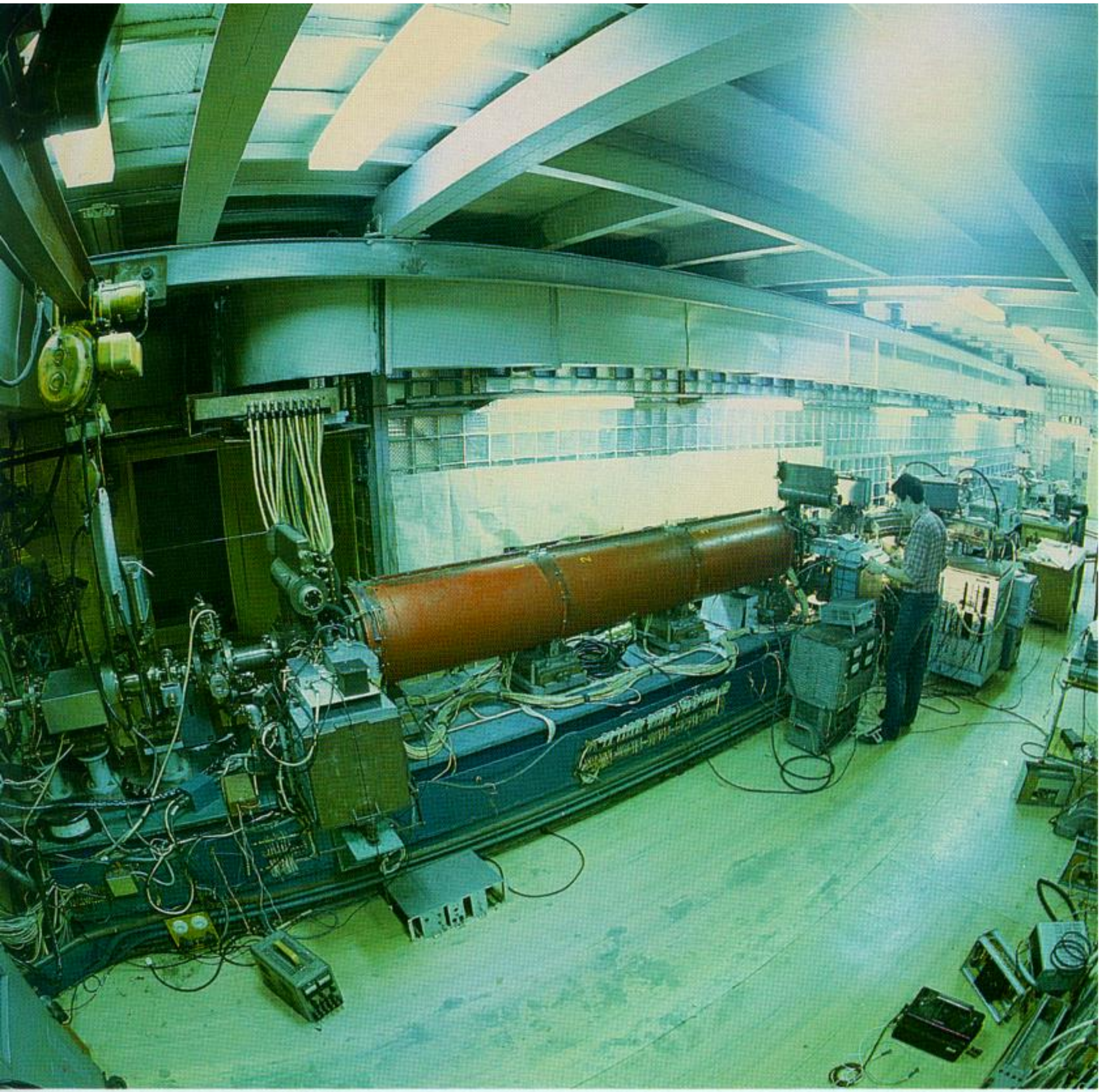
Fizika Plasmy v.4 pp. 492-500, 1979

Test bench for investigation magnetized cooling

Схема измерения замагниченной силы трения на установке МОСОЛ
1 МеВ H-, 3 м соленоид 1-4 кГс,
выходной спектрометр для измерения потерь энергии при проходе электронного пучка 400-500 эВ

Fig. 6. Schematic diagram of installation «Model of Solenoid»; *1*—a source of H^-; *2*—electrostatic accelerator; *3*—paramagnesium target; *4*—electron gun; *5*—solenoid; *6*—collector; *7*—spectrometer; *8*—additional solenoid.

Single-pass cooling section to study magnetized cooling



Andrei Seryi adjusting the final energy spectrometer for measuring cooling force at solenoid with
magnet field values up to 1-4 kG

Proton/ion energy variation after the 2.5-m cooling section (electron beam -- 3 mA). Proton/Ion energy – 1 MeV

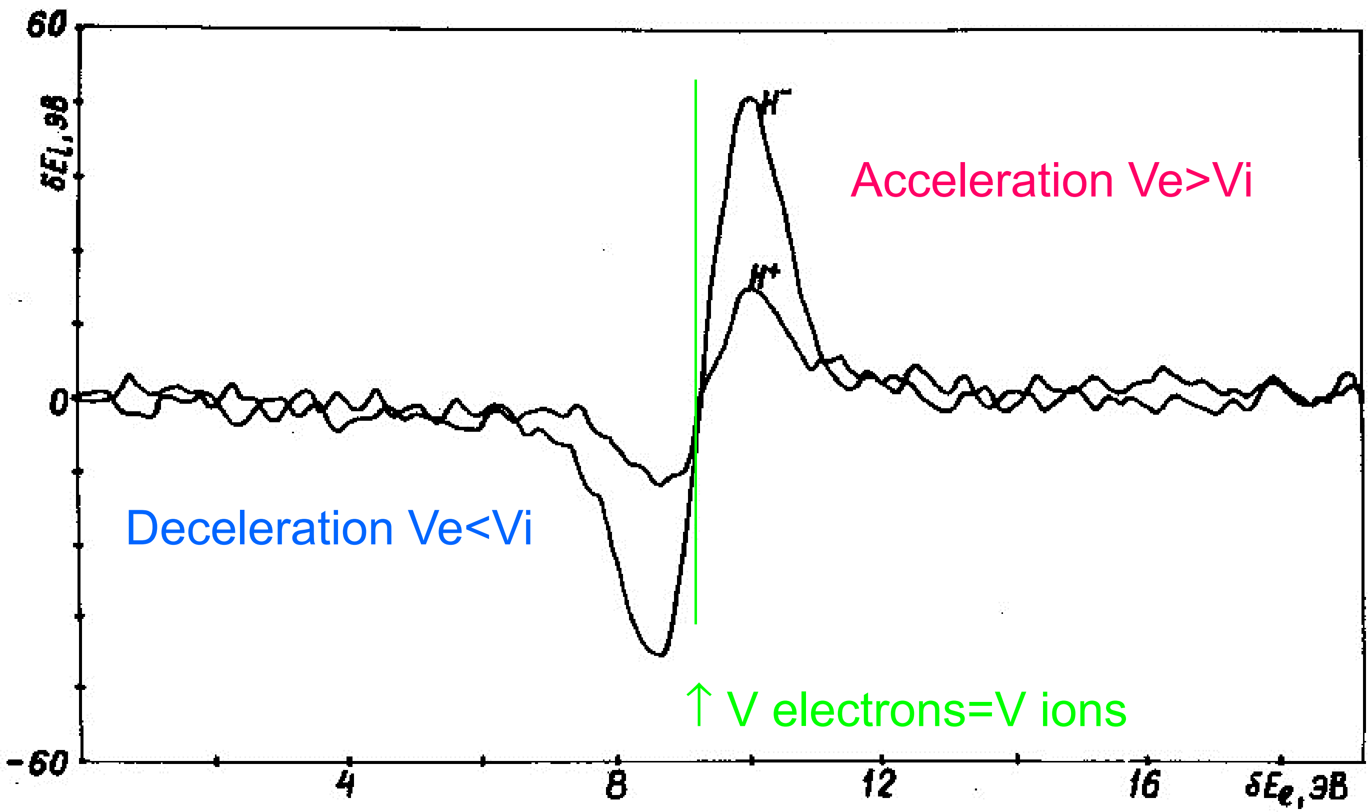
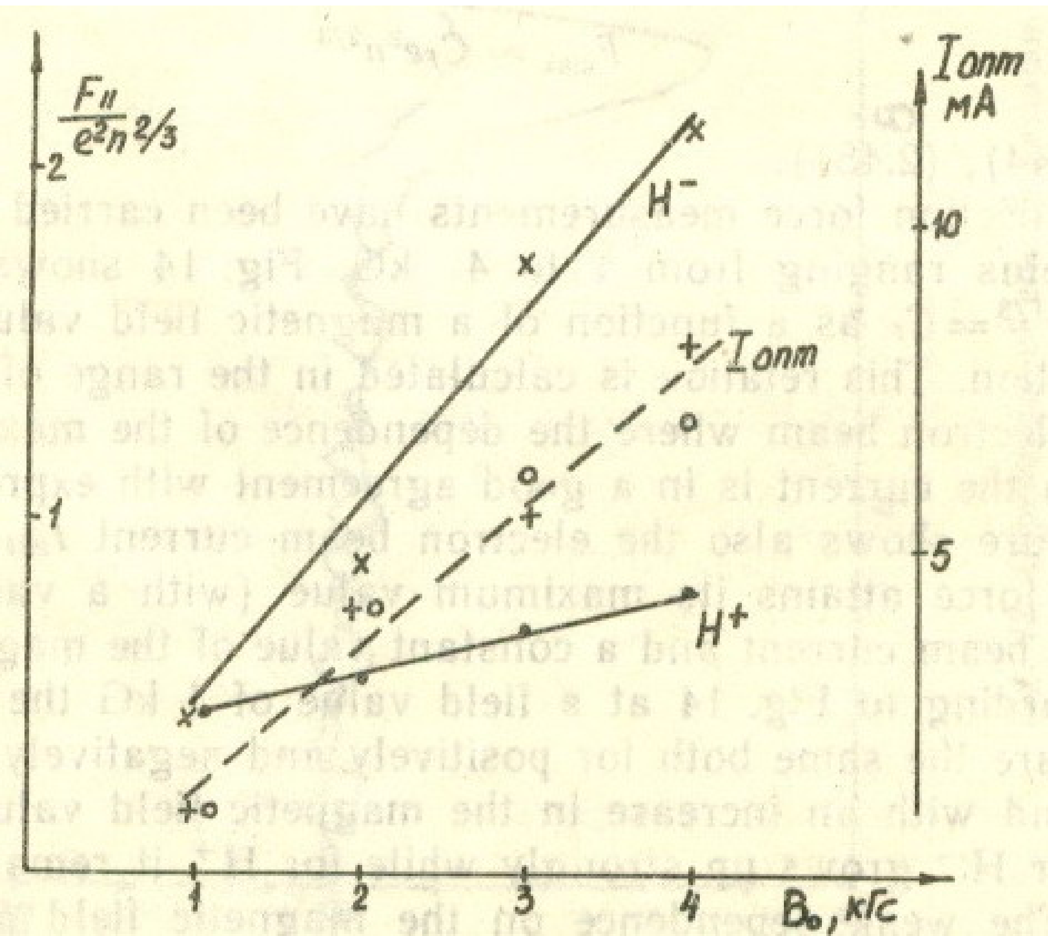


Fig. 12. Dependence of energy variation for ions of various charge signs on electron energy, $B=4$ kG, $I_e=3$ mA.

Magnetic field and optimal electron beam current and cooling force

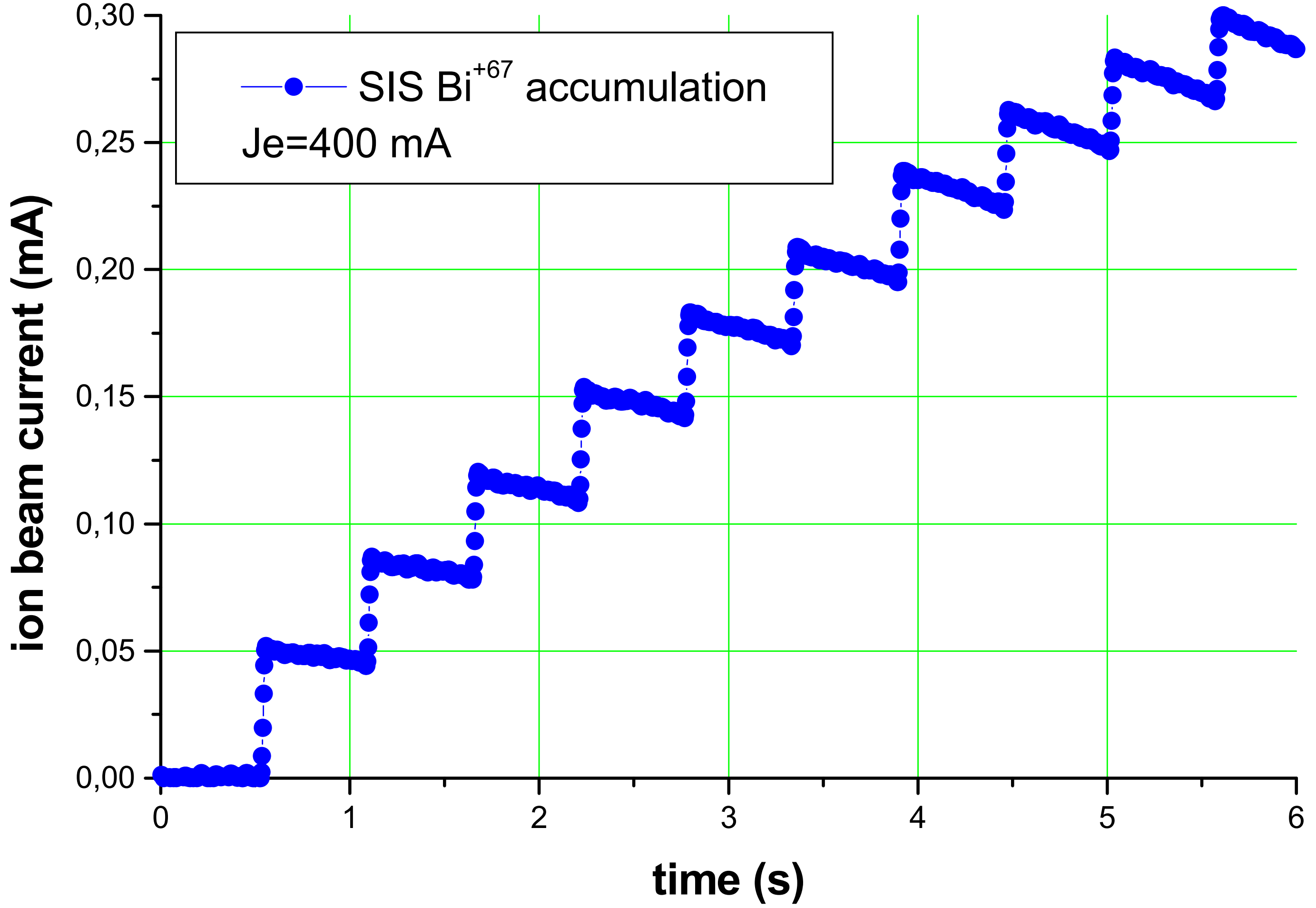


Maximal cooling force increased as F~B$^{1.6}$ for low ion velocity and as F~B^{1} for high velocity by mainly suppression drift motion at electron beam

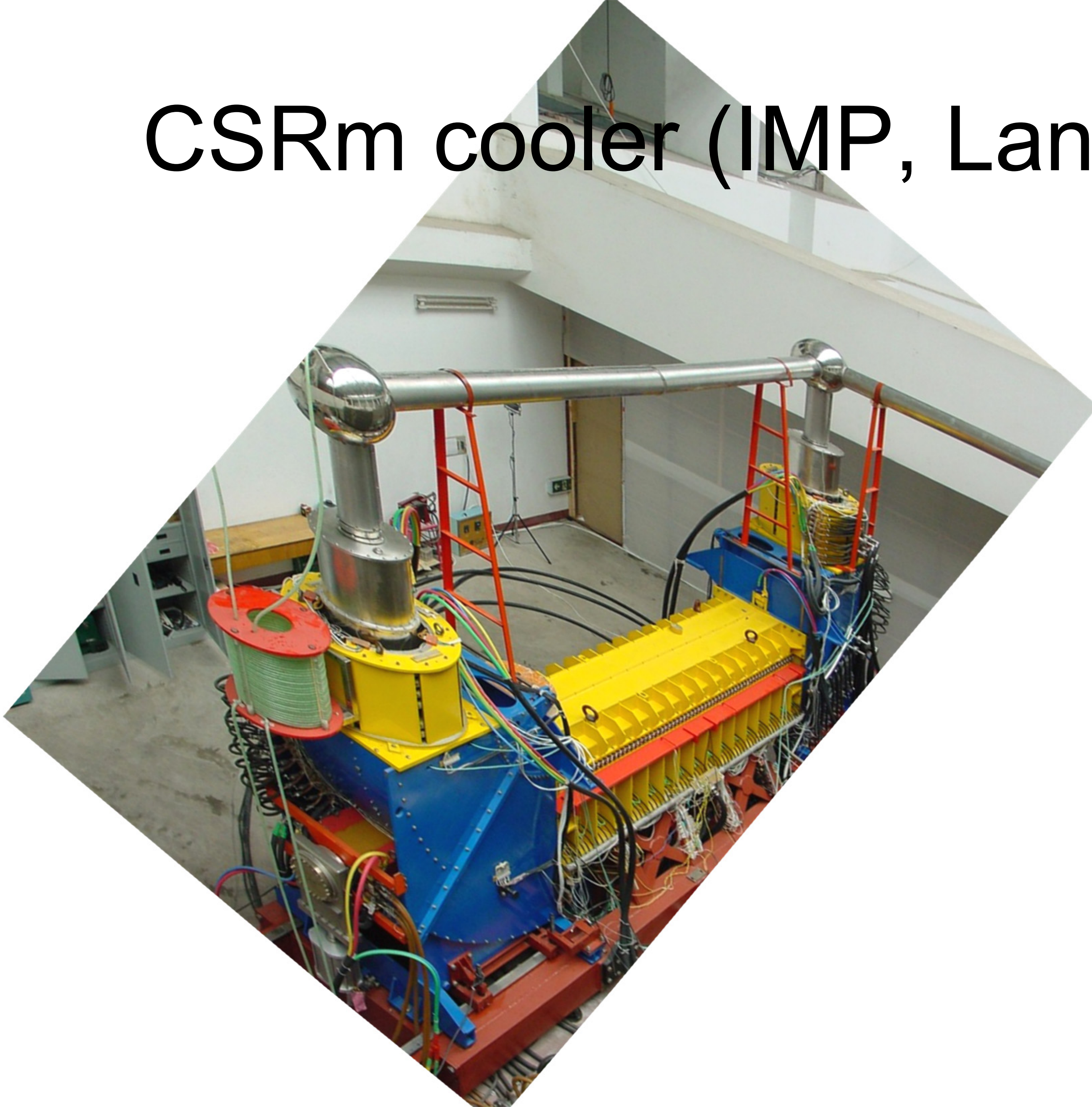
$$V_{drift} = c\frac{E}{B} = c\frac{2\pi e n_e a_e}{B}$$

Cooler for synchrotron SIS-18 GSI 1998

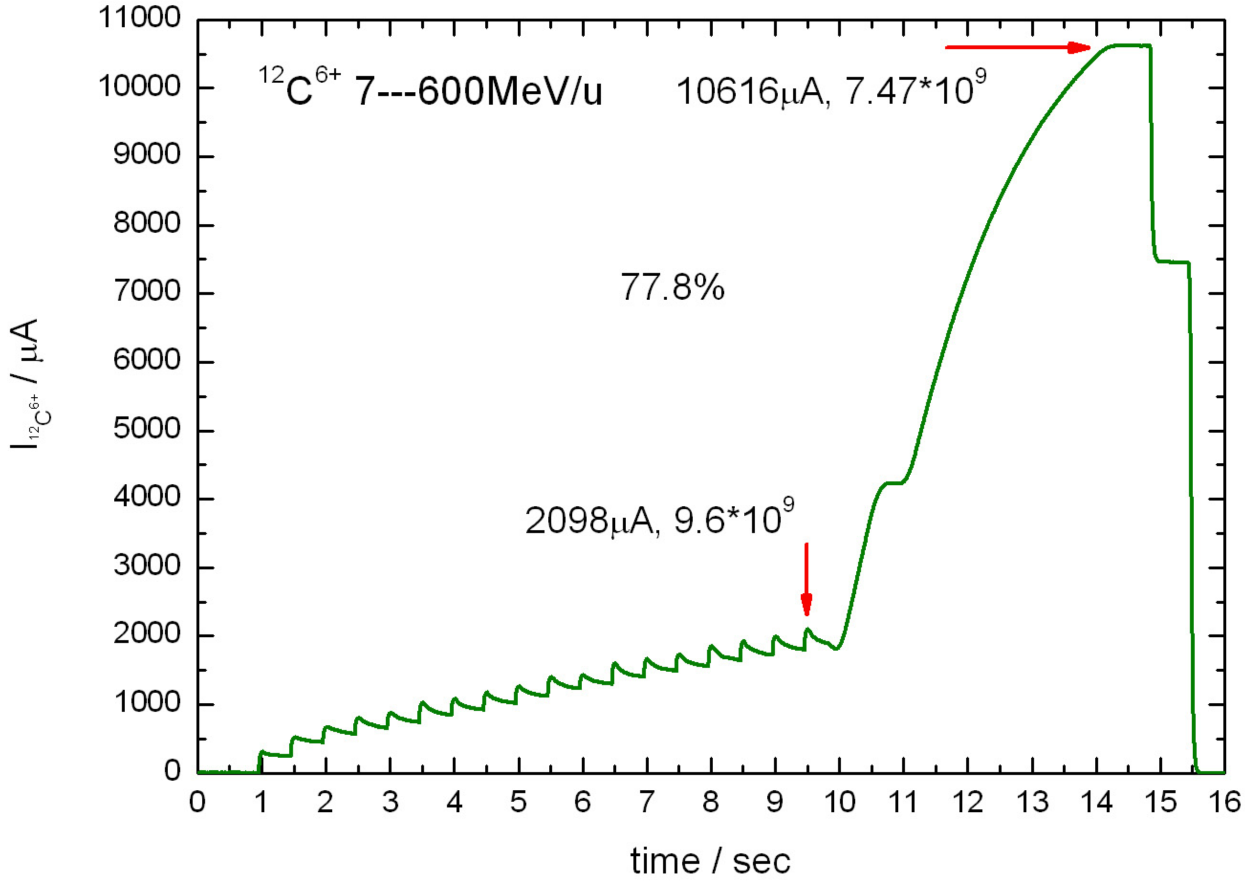
Accumulation Bi beam at SIS-18



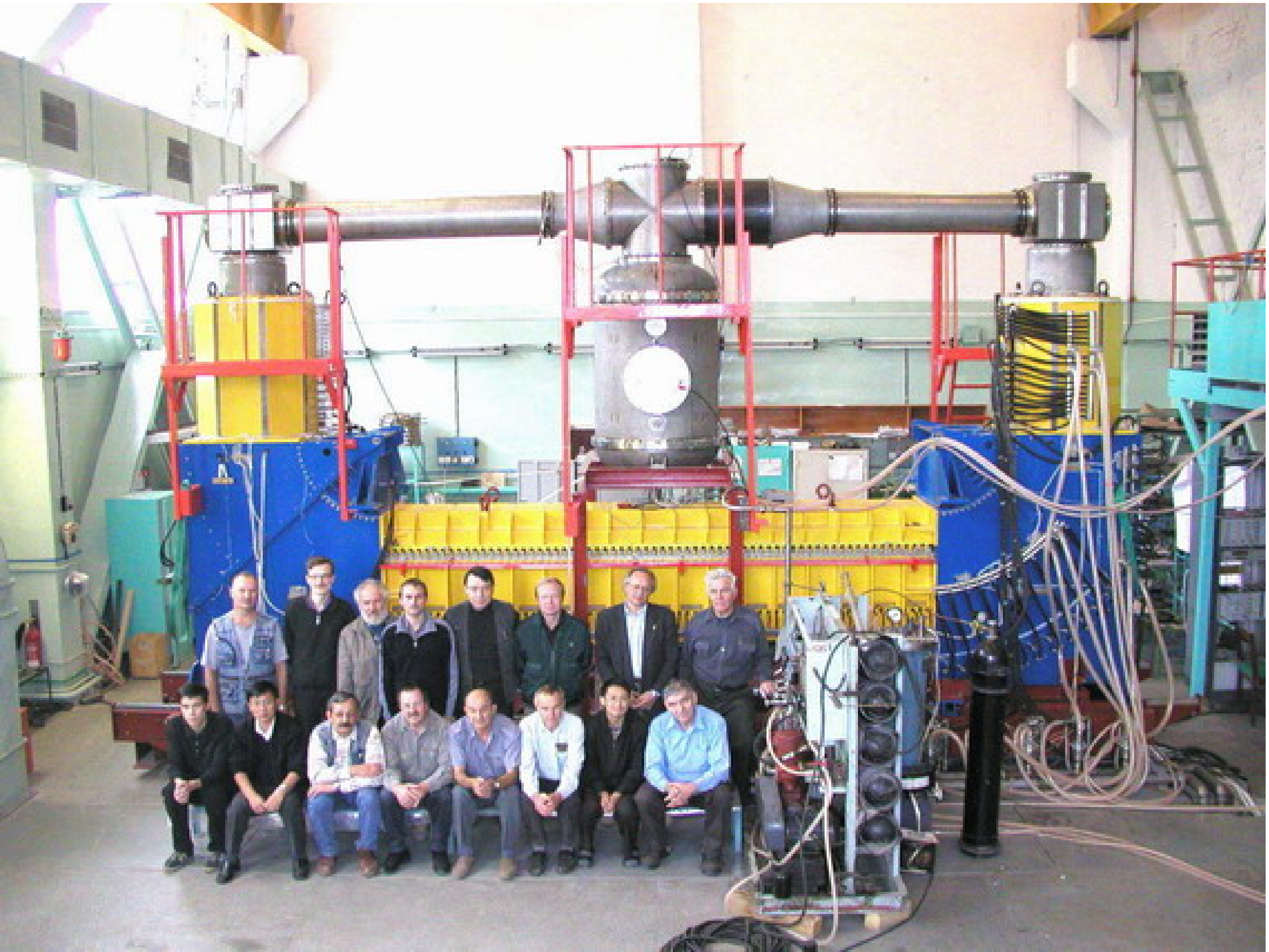
CSRm cooler (IMP, Lanzhou)



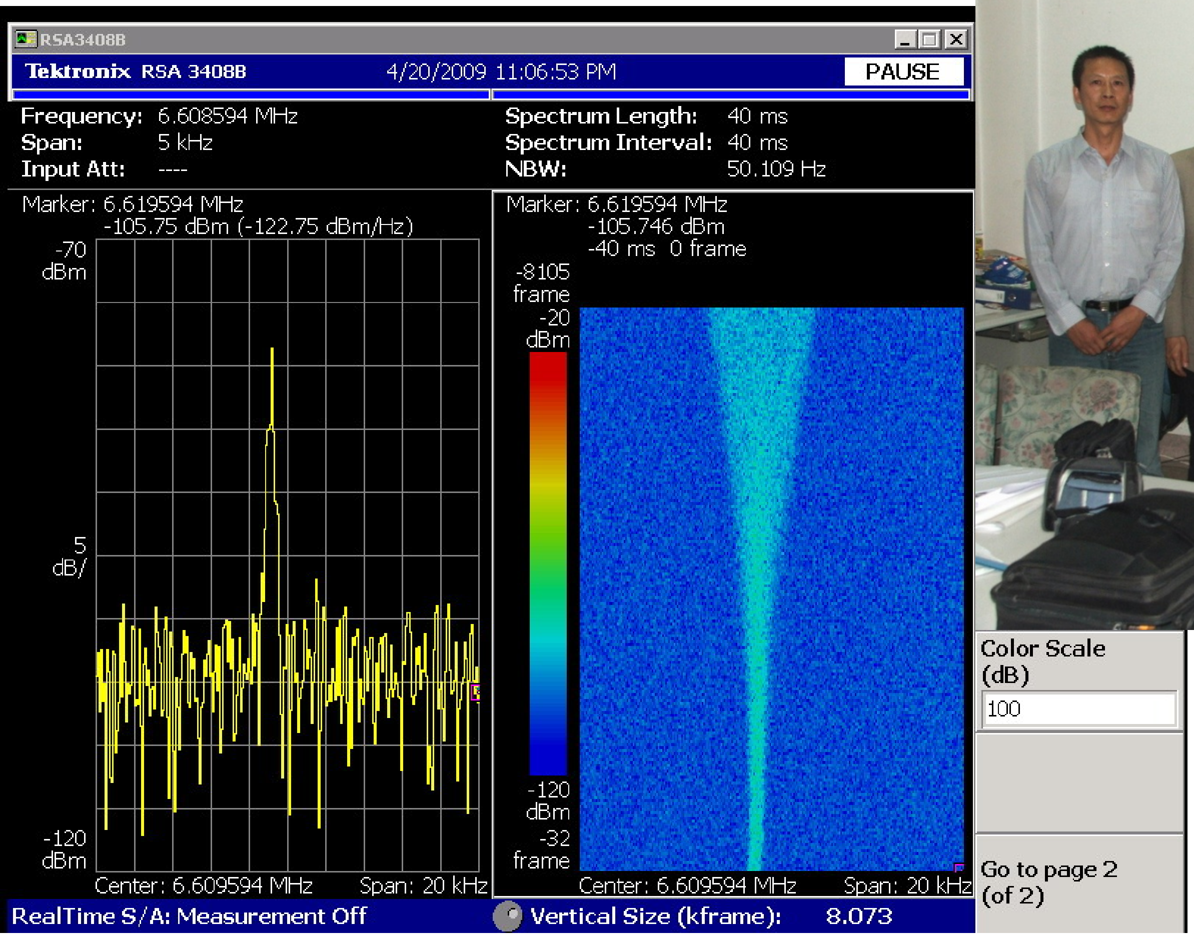
Accumulation with electron cooling of Carbon beam and acceleration to 600 MeV/u



Cooler for CSRe 2002



Cooling of 400 MeV/u carbon beam at CSRe (IMP-BINP team)



LEIR cooler 15 Nov.2004
Before packing for trip at CERN

Design features of LEIR cooler

Vacuum 1E-12 Torr

10^9 Lead ion/3.6 s 70% efficiency release

(η(a/ion)=10^4) desorbtion gases 10^{11} atoms/s

A standard cooler with magnet bending losses

current 0.1-0.3 mA release (η(a/electron)=10^{-3}) $6 10^{11}$ atom/s

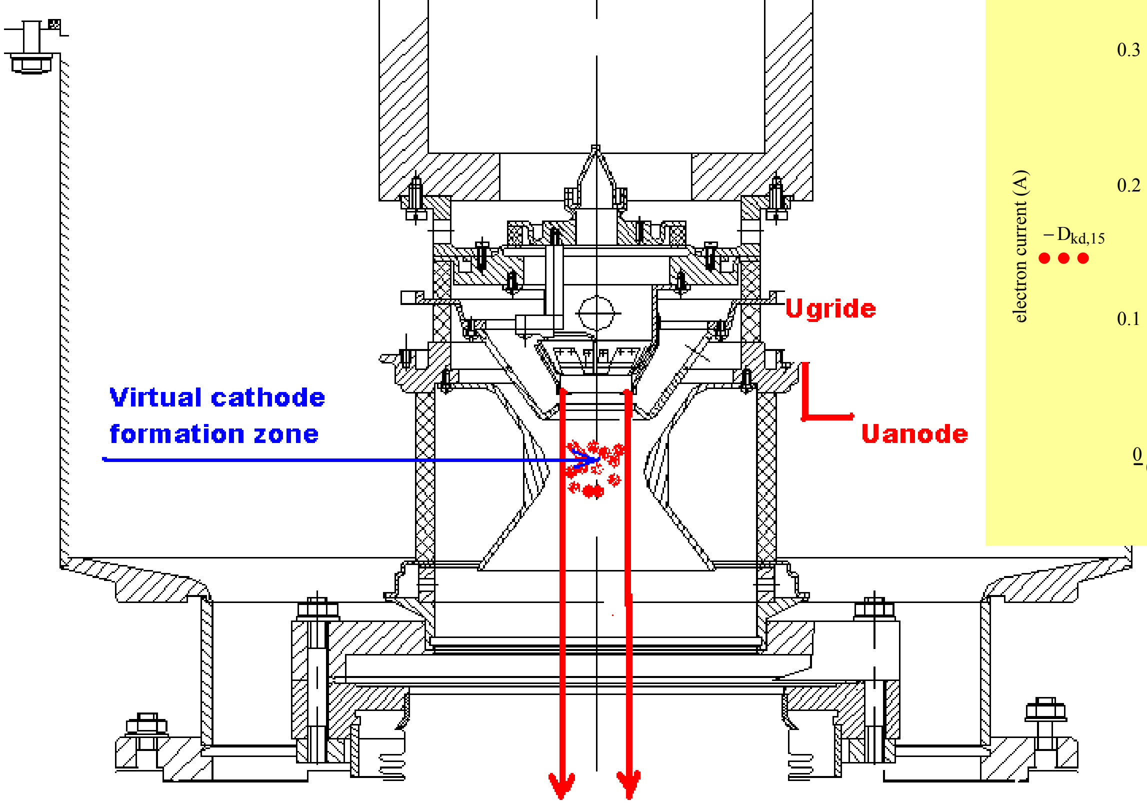
To obtain 1E-12 Torr

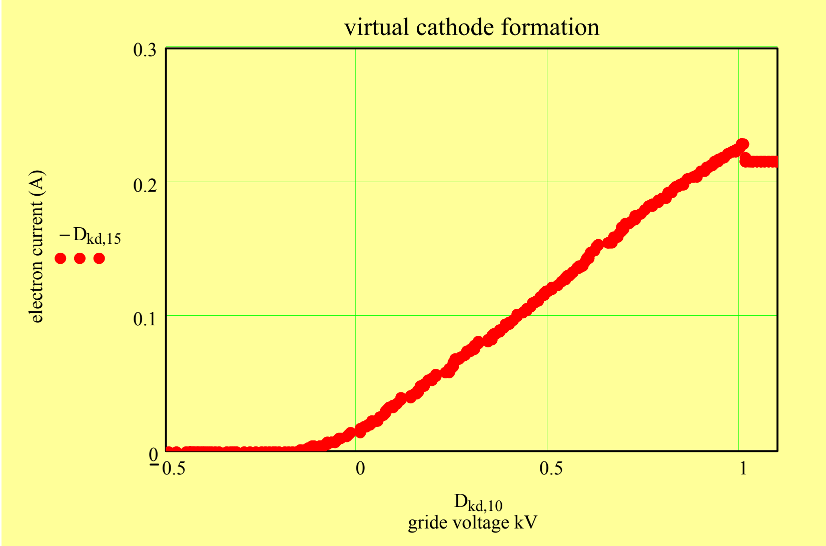
pumping power should be 15000 l/s

or decreased losses at both ion and electron beams

For cooler with electrostatic bending losses current near 0.1-0.3 μA (at 1000 time less!) was obtained.

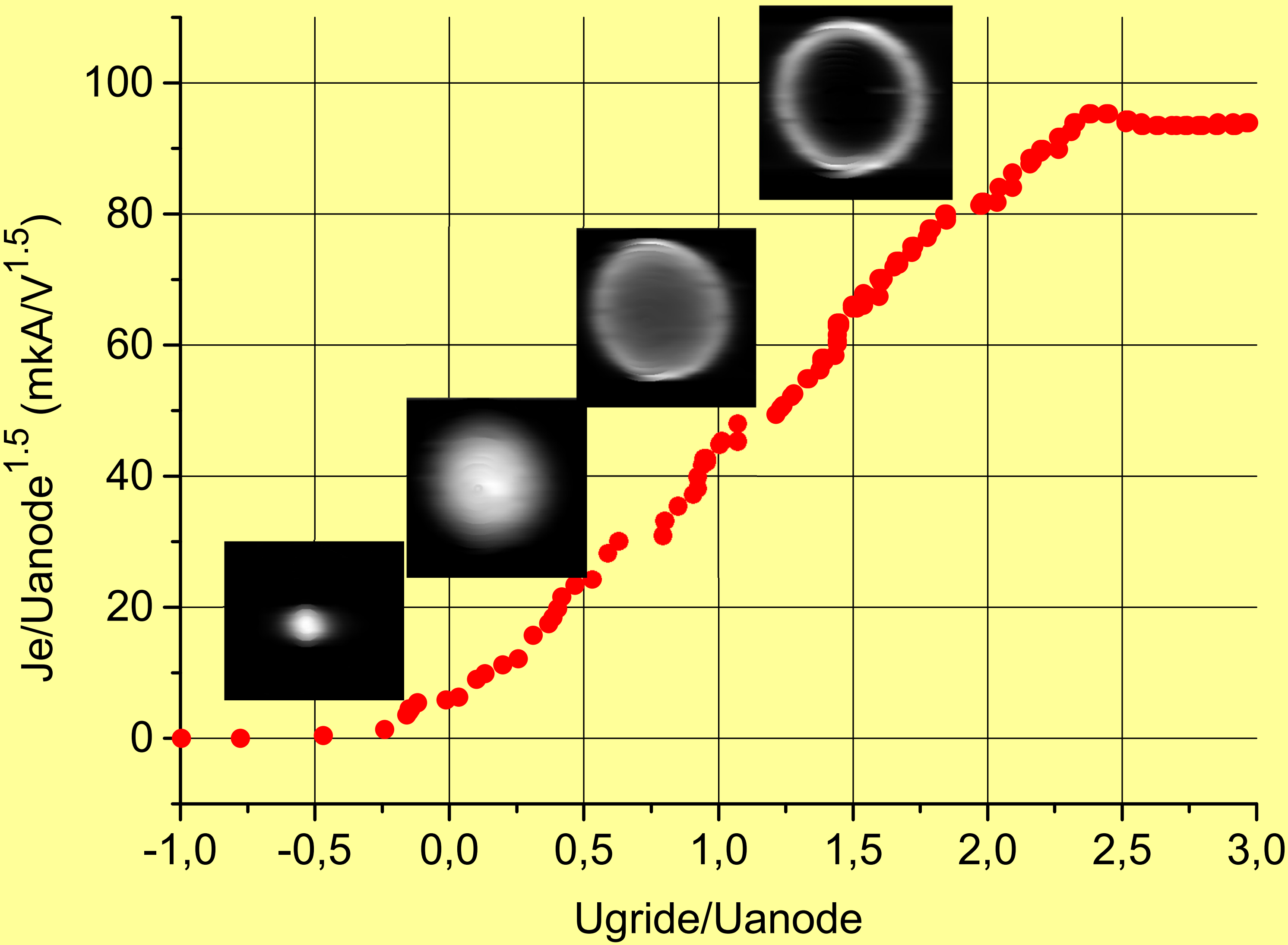
Commissioning at Novosibirsk (BINP) was done using "second hand" NEG cartridges just for testing performance of cooler from magnet system and electron gun and collector





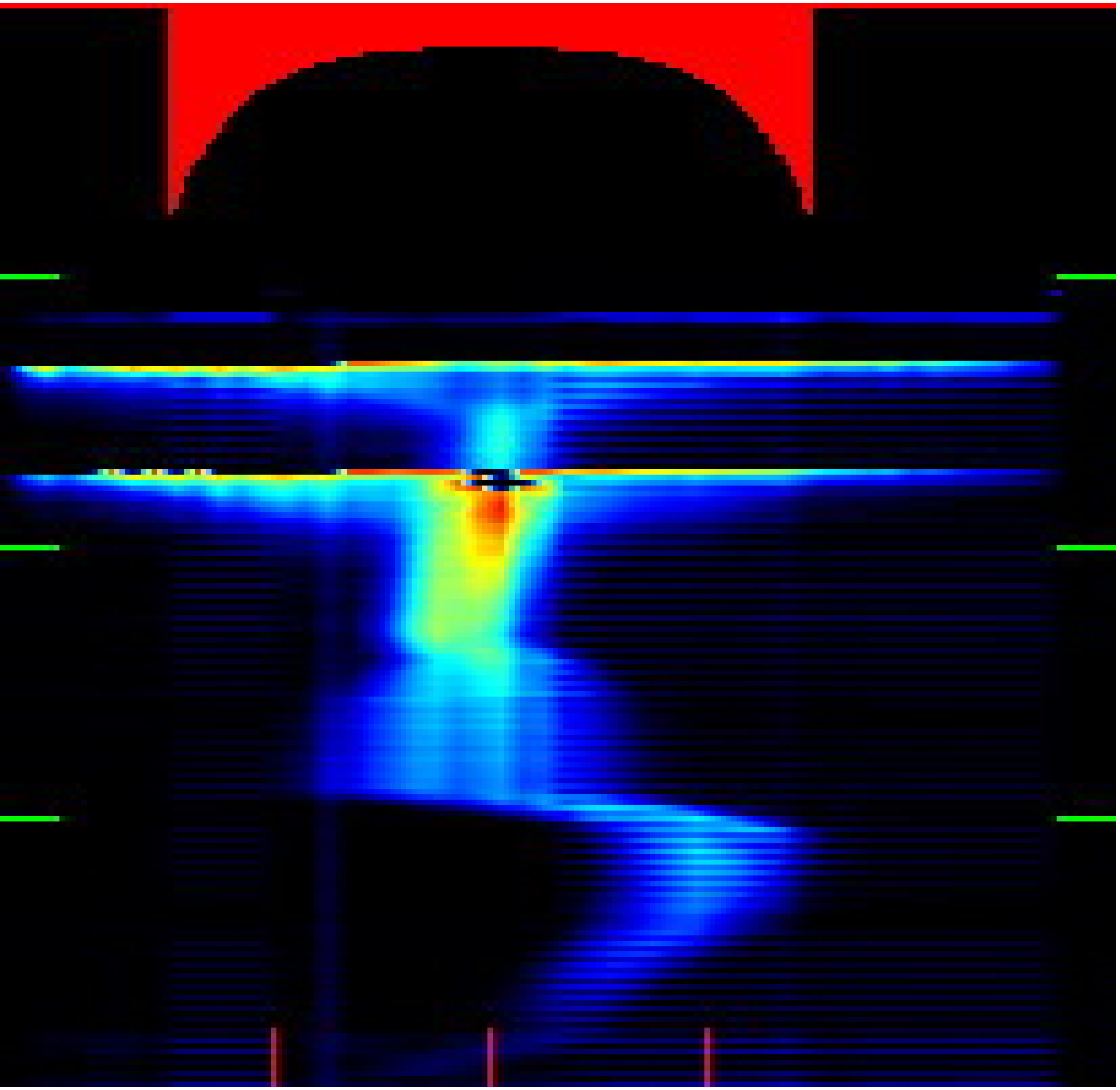
The electron current is extracted from the cathode by voltage on a “grid” or “control” electrode and anode voltage. For negative voltage on grid the emission from edge part of cathode is suppressed- narrow parabolic shape profile, for low positive Ugride<<Uanode the electron beam have flat profile close to classical Pierce optics, but for Ugride-->Uanode we have ring profile beam and finally for Ugride>Uanode the empty at center electron beams are formed

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



Cooler installed at LEIR ring

The cycle of LEIR: 2 injections with electron cooling, switch off cooling and beam bunching and acceleration



The red color show the electron Beam profile, vertical- time 3 sec down, horizontal 50 mm

Clear see Intra Beam Scattering at increasing the ion beam size after cooling second injection and at increasing beam size after switch off electron cooling.

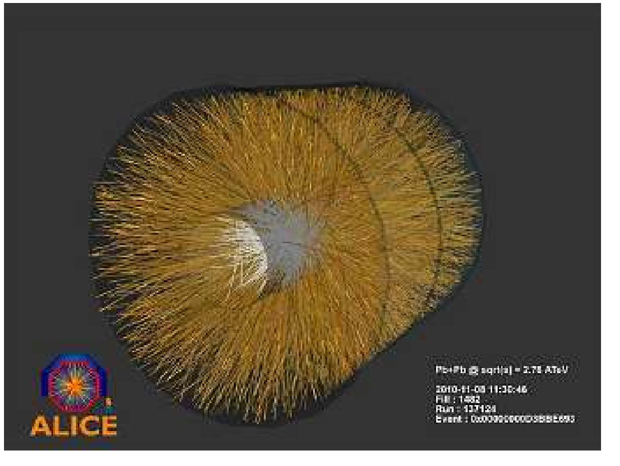
At time of acceleration ion beam size decreased by adiabatic “cooling”.

Gerard Tranquille information about cooler at LEIR

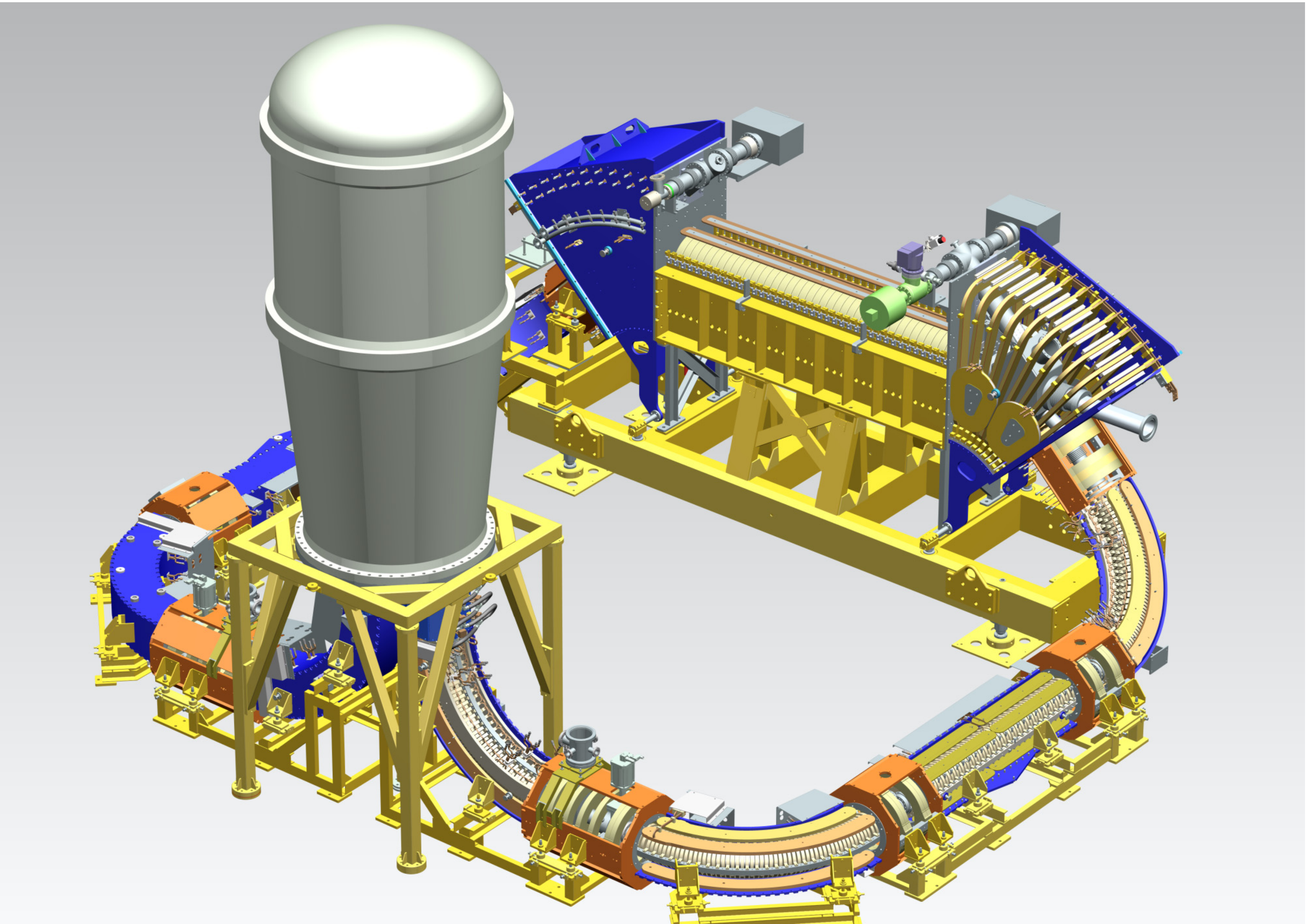
The LEIR machine has performed exceptionally well these past two years. Despite the Linac 3 current still being very low (<20 uA) we have managed to obtain the early beam without much difficulty and we have even produced the nominal beam (1.2 10e9 particles) by increasing the repetition rate to 5 Hz with an electron current between 300 and 350 mA to cool faster. The emittances are well below the LHC requirements (I measure on the IPMs 0.1 um in the horizontal plane and 0.2 um in the vertical plane) for the early beam and closer to the LHC characteristics (but still smaller) for the nominal beam. We haven't had much time to make any experiments as we have had to provide the beam for the upstream machines for their setting up and they do not like it when we start to play in LEIR and change the beam characteristics. Now that LHC is running with Pb ions it might be easier to get MD in between fills.

Best regards to you and your group at BINP.

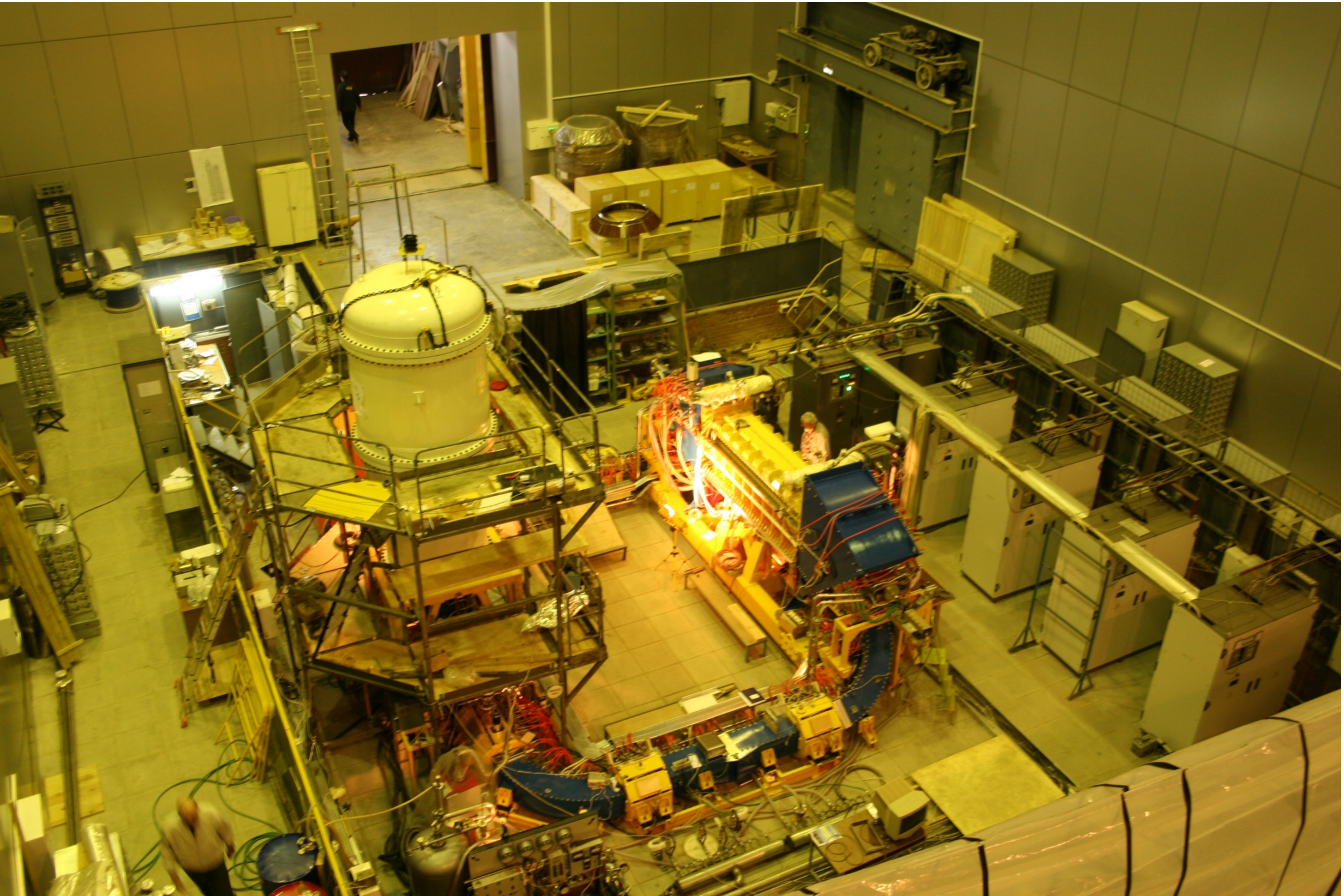
Gerard



COSY 2 MeV cooler



Cooler for COSY under commissioning at BINP 2012



Summary of all BINP coolers

1. NAP-M 0.5-120 kV, 0-1 A
2. Test bench 0.5 kV, 0-0.02 A
3. SIS-18 3-30 kV, 0-1 A
4. CSRm 2-30 kV, 0-3 A
5. CSRe 50-300 kV, 0-3 A
6. LEIR 3-50 kV, 0-3 A
7. COSY cooler 30-2000 kV 0-1 A

   Commissioning status: May 2012 30-1500 kV 0-0.5 A

- Future projects:
  - NICA booster cooler (~10's kV)
  - NICA collider cooler (~MV)

ACKNOWLEDGMENT

It is good a occasion for remembering the inventor of the electron cooling, G.I. Budker.
He was my advisor at BINP and many coolers continue his ideas.

Author thanks the BINP team for the opportunity to participate in such an
interesting research as electron cooling: A.N.Skrinsky, N.S.Dikansky, I.N.Meshkov, D.V.Pestrikov, B.N.Suhina, B.M. Smirnnov and the new generation of cooler physicists: V.B.Reva, A.V.Bubley and M. Brizgunov.

This report was presented by S. Nagaitsev (FNAL)