Development of a New Generation of Coolers with a Hollow Electron Beam and Electrostatic Bending

V.V. Parkhomchuk
BINP, Novosibirsk,630090,Russia

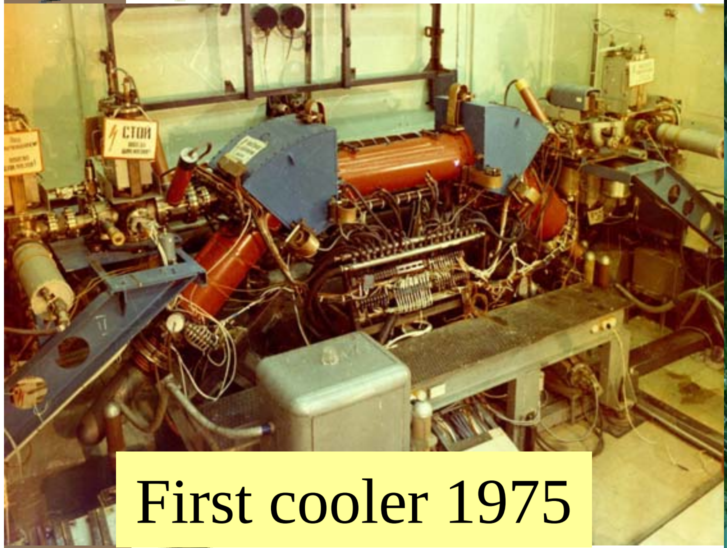
Electron cooling stages *(path from first cooler(1975) to LEIR cooler(2005)*

Problems of cooling intensive electron beam*(electron heating or why we need the new generation of cooler)*

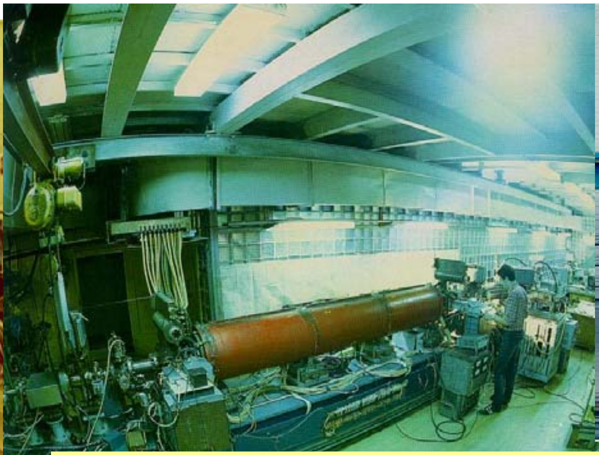
Electron gun with variable electron beam profile *(how to produce good for cooling electron beam profile)*

Electrostatic bending *(continue of discussion about optimal configuration cooler U- shape EPOHA (BINP) or S-shape ICE (CERN))*

BINP coolers from idea at 1967, to first cooler at 1975 and to LEIR cooler 2005



First cooler 1975



Single pass stand for study magnetization

SIS-18 cooler 1998

CSRm 35 kV cooler 2003

CSRe 300 kV 2004

LEIR cooler 2004 still at BINP

New coolers was appointed electron gun with variable profile electron beam and the electrostatic bending plate for the electron and ion beams convergence.

At LEIR cooler was used very powerfully vacuum system pumping base on NEG absorbers and NEG coating vacuum chamber.

Table 1. Basic parameters new generation of electron coolers

	EC35	EC300	EC40
Max. voltage (kV)	35	300	40
Max. electron current (A)	3	3	3
Cooling length (m)	4	4	2.5
Mag. field at cooling (kG)	1.5	1.5	1.5
Vacuum at cooler (Torr)	2E-11	2E-11	5E-12
Storage ring	CSRm	CSRe	LEIR

Cooling force

$$\vec{F}(\vec{V}) = \frac{4e^4 Z^2 n_e}{m} \frac{\vec{V}}{(\sqrt{(V^2 + V_{eff}^2)})^3} \ln\left(\frac{\rho_{\max} + \rho_L + \rho_{\min}}{\rho_L + \rho_{\min}}\right)$$

No magnetization Veff is thermal electrons velocity Vt
Budker calculation 5-10 sec cooling time

Experiments NAP-M cooler cooling time 0.1 sec!

Magnetization:

$$V_{eff} = c\frac{E_\perp}{B} = \frac{2\pi q n_e x}{B} << V_t$$

is drift electron by space charge : spiraling motion change only ρ_L under ln()
for FNAL cooler, ρmax=0.13 cm, ρ_L=0.008 cm ($\theta=0.5\times10^{-4}$) tcool=6000 , ρ_L=0.033 cm ($\theta=2\times10^{-4}$) tcool=11000

Problems of cooling intensive electron beam

$$\delta p = -\int F dt \approx -F * \tau$$

Momentum loss at single pass cooling section

How large exited zone at the electron beam by action single ion?

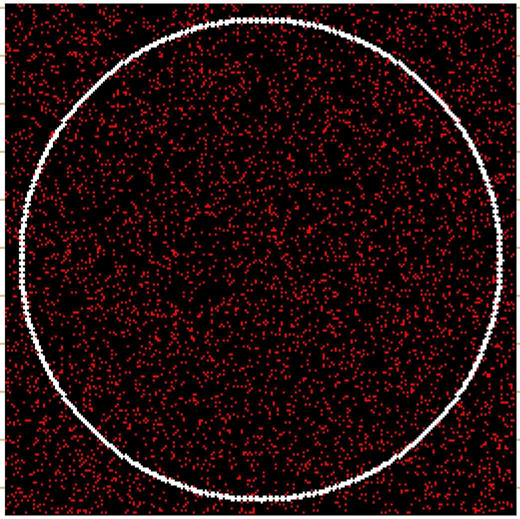
$$\rho_{\max} = \tau\sqrt{V^2 + V_{eff}^2}$$

$N = n_i \rho_{\max}^3 4\pi / 3$

ρmax=0.2 cm N=8000

$n_{ion}=10^6$ 1/cm^3

How large kick from neighboring ions that generate the same kick field but for itself do not worry about others ions?



$$\Delta p^2 = -2\delta p p + \delta p^2 n_i \frac{4\pi}{3} \rho_{\max}^3$$

cooling

$$\frac{\delta p}{p} < \frac{2}{N}$$

Heating from neighbor ions

$$\left(\frac{\Delta p}{p}\right)^2 = -2\frac{F\tau}{p}(1-\omega_e^2\omega_i^2\tau^4 g)$$

Single turn cooling decrement
and
heating term

$$\omega_e = \sqrt{\frac{4\pi e^2 n_e}{m_e}} = c\sqrt{4\pi r_e n_e},$$

$$\omega_i = \sqrt{\frac{4\pi e^2 Z^2 n_i}{M_i}} = c\sqrt{4\pi r_i n_i}$$

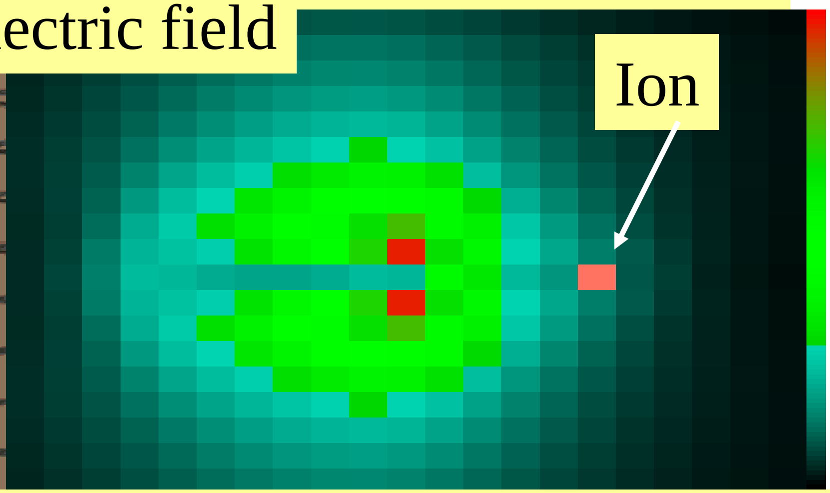
Electron and ion beams plasma frequency
τ is time of flight cooling section at beam system of reference

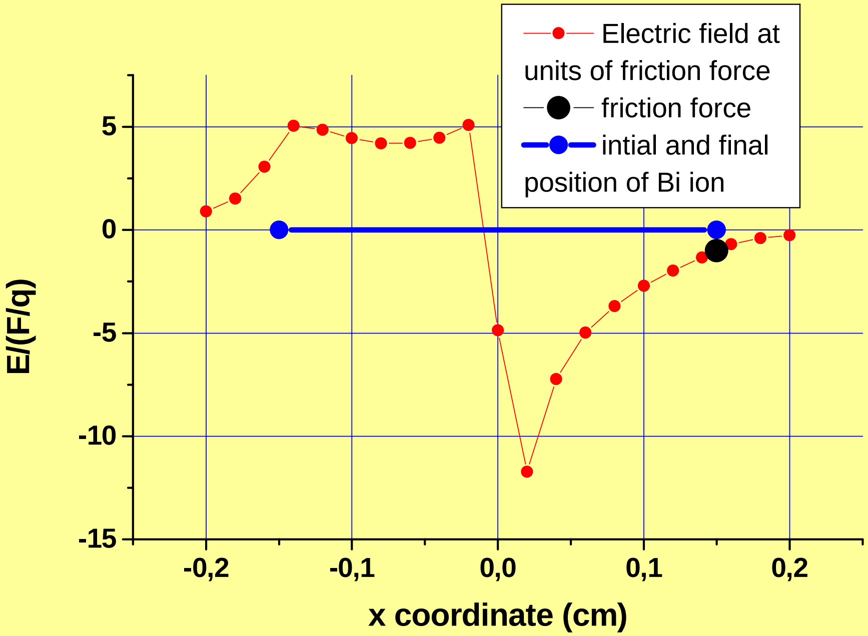
$$g = \int E^2 dV/(4\pi\rho^3_{\max}/3)/(F/qZ) \approx 1.4$$

g is numerical factor that can calculated by computer simulation.
Example of calculation was made for Bi^{+67} ion moves with velocity 4.6E6 cm/s at an electron beam with density 1E6 1/cm^3, time of interaction 6.5E-8s, length of path is $\rho_{\max} = V\tau$ 0.3 cm

Wave at electron beam by moving Bi ion

Electric field





Red boat (as Bi ion) exit visual wave

Electric field around moving ion Bi at plane (color map) and along axis (down figure)

CELSIUS experiments

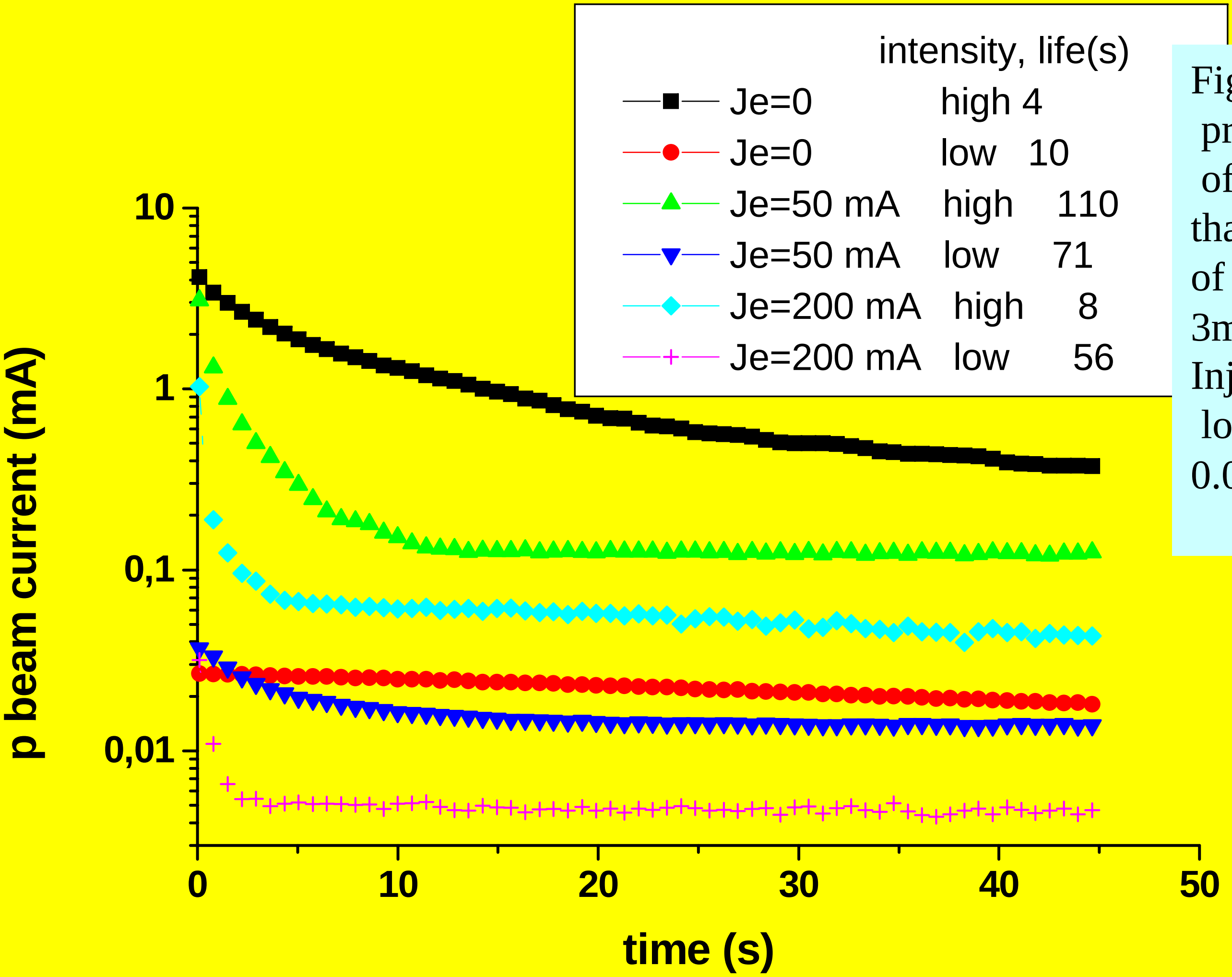
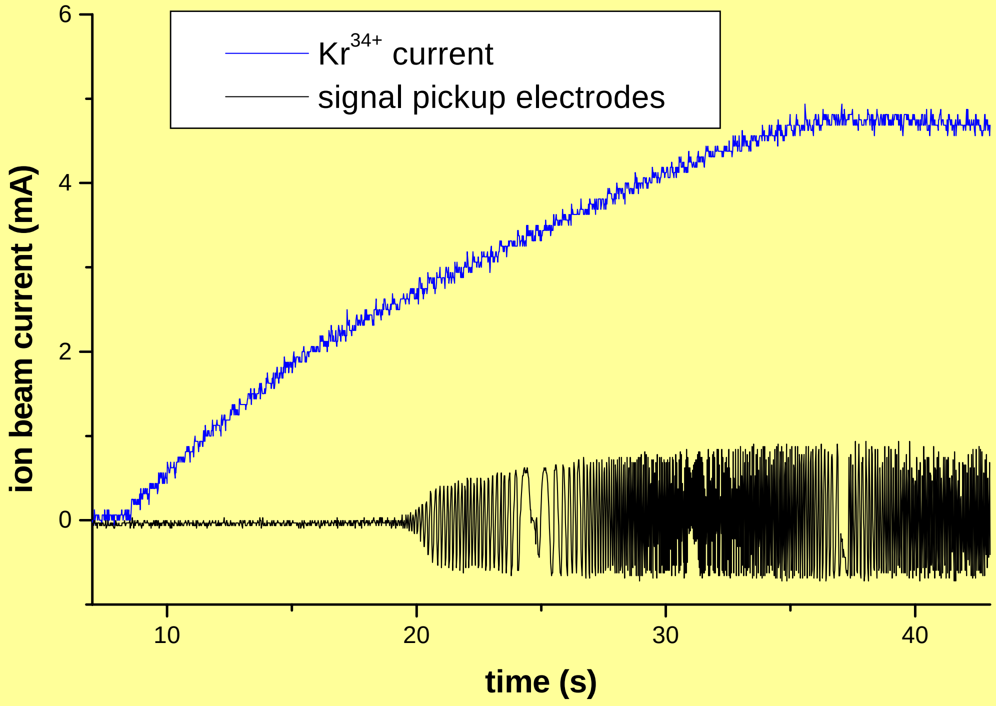


Fig. show that after injection intens
proton beam presents
of electron beam made losses so hi
that after cooling only small fractio
of initial intensity of the beam cool
3mA→0.1-0.07 mA 30-40
Injection low intensive beam show
losses not so high.
0.03mA→0.02-0.007 mA 1.5-4

Instability for intensive electron and ion beam (SIS)



Experiments
show that:
down electron beam
density results
increasing ion beam
threshold current but
by slowing
accumulation rate

Basic idea of new cooler to have high electron current but low density at accumulation zone (center).

Parameters of interaction for two plasma model are:

$$\lambda = \omega_{ee}^{2}\omega_{ii}^{2}\tau^{4}$$

ω_{ee} Electron beam plasma frequency

ω_{ii} Ion beam plasma frequency

τ Time of flight cooling section

$$\lambda_0 = f_0 \frac{4 r_e r_i n_e c \tau}{(V/c)^3} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) =$$

$$\frac{4 r_e r_i \eta_e}{\gamma^5 \beta^4 \theta^3} \frac{J_e}{q\pi a_e^2} Ln_c = \frac{4 r_e r_i \eta_e \beta_{cool}^3}{\gamma^5 \beta^4 a_i^3} \frac{J_e}{q\pi a_e^2} Ln_c$$

Cooling rate for low intensity

How to proceed for cooling high ion beam current?
→Hollow electron beam!

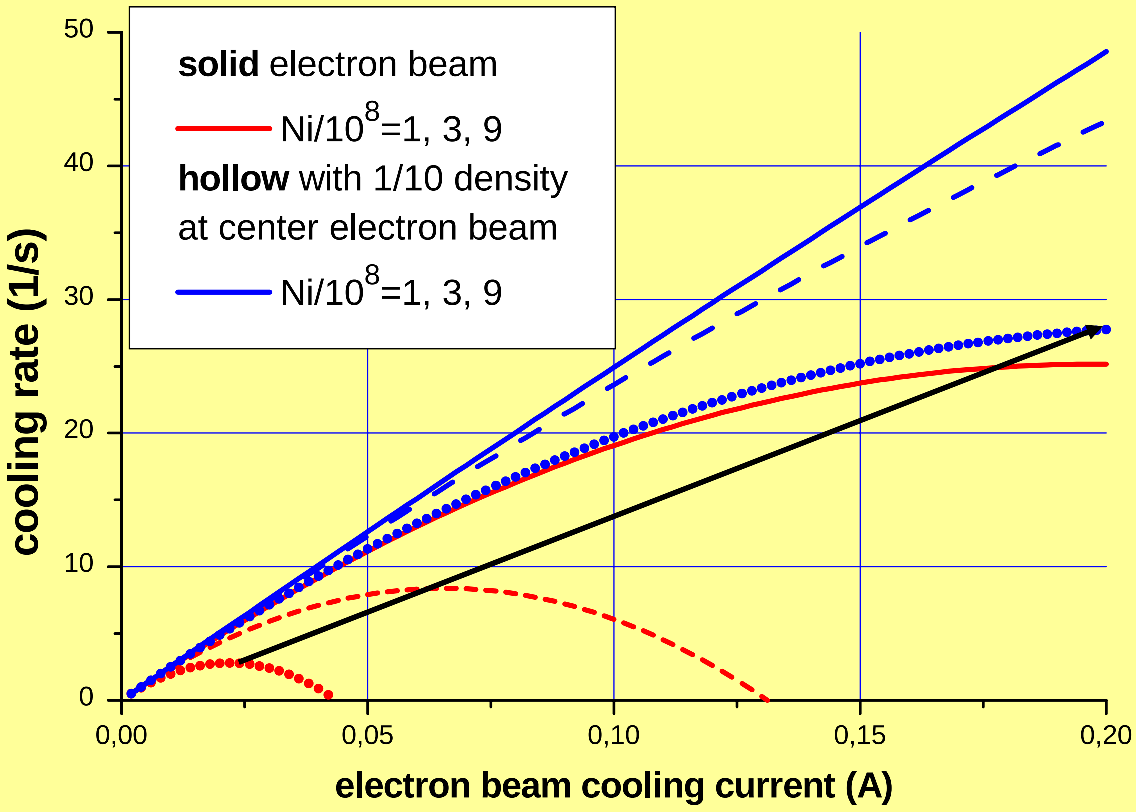
$$\lambda = \lambda_0 (1 - \omega_i^2 \omega_e^2 \tau^4 * k)$$

k=1 N=9E8 optimum
cooling 0.025 A only
k=0.1 optimum 0.2 A

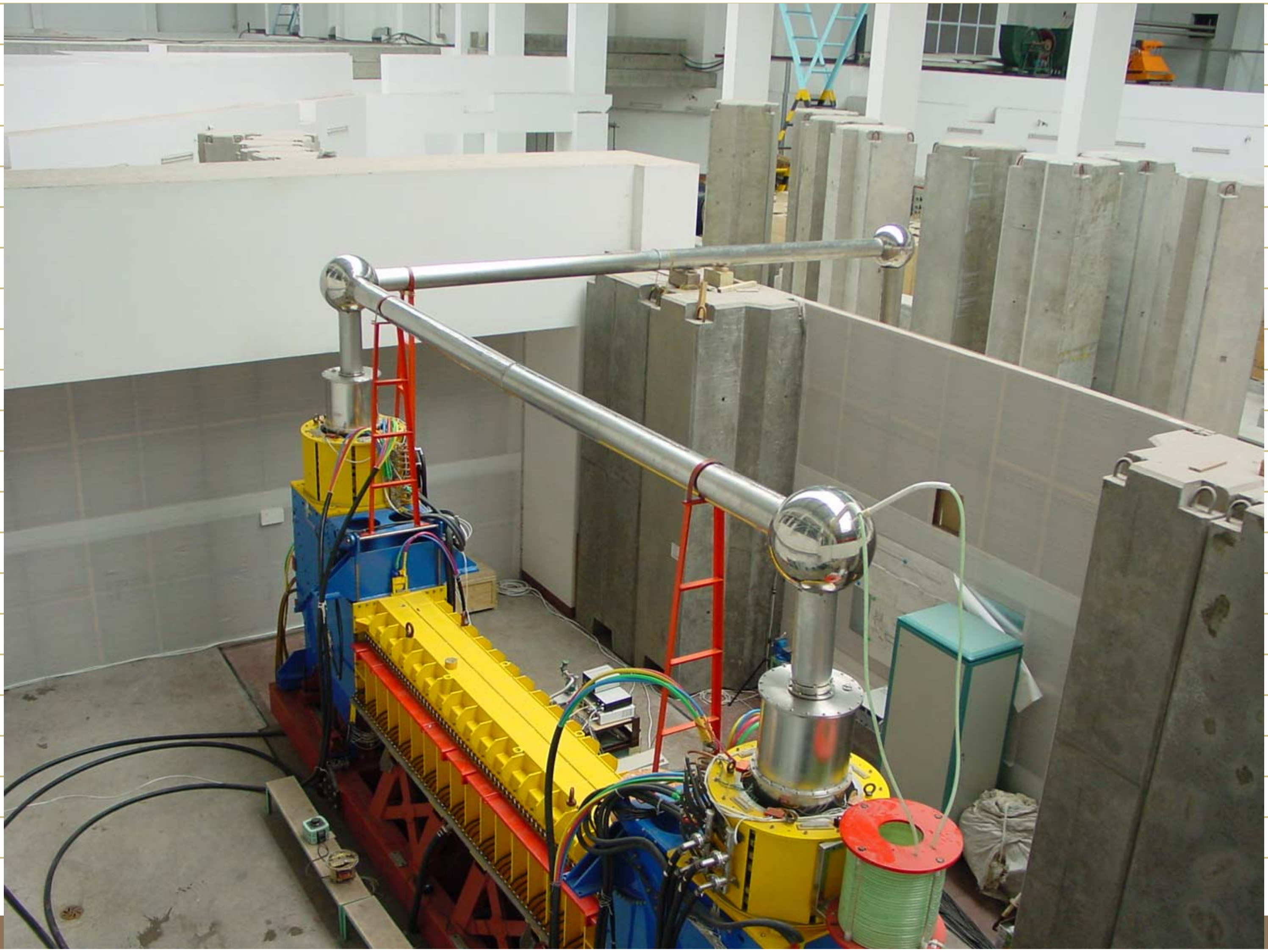
$\omega_e^2 - \downarrow$

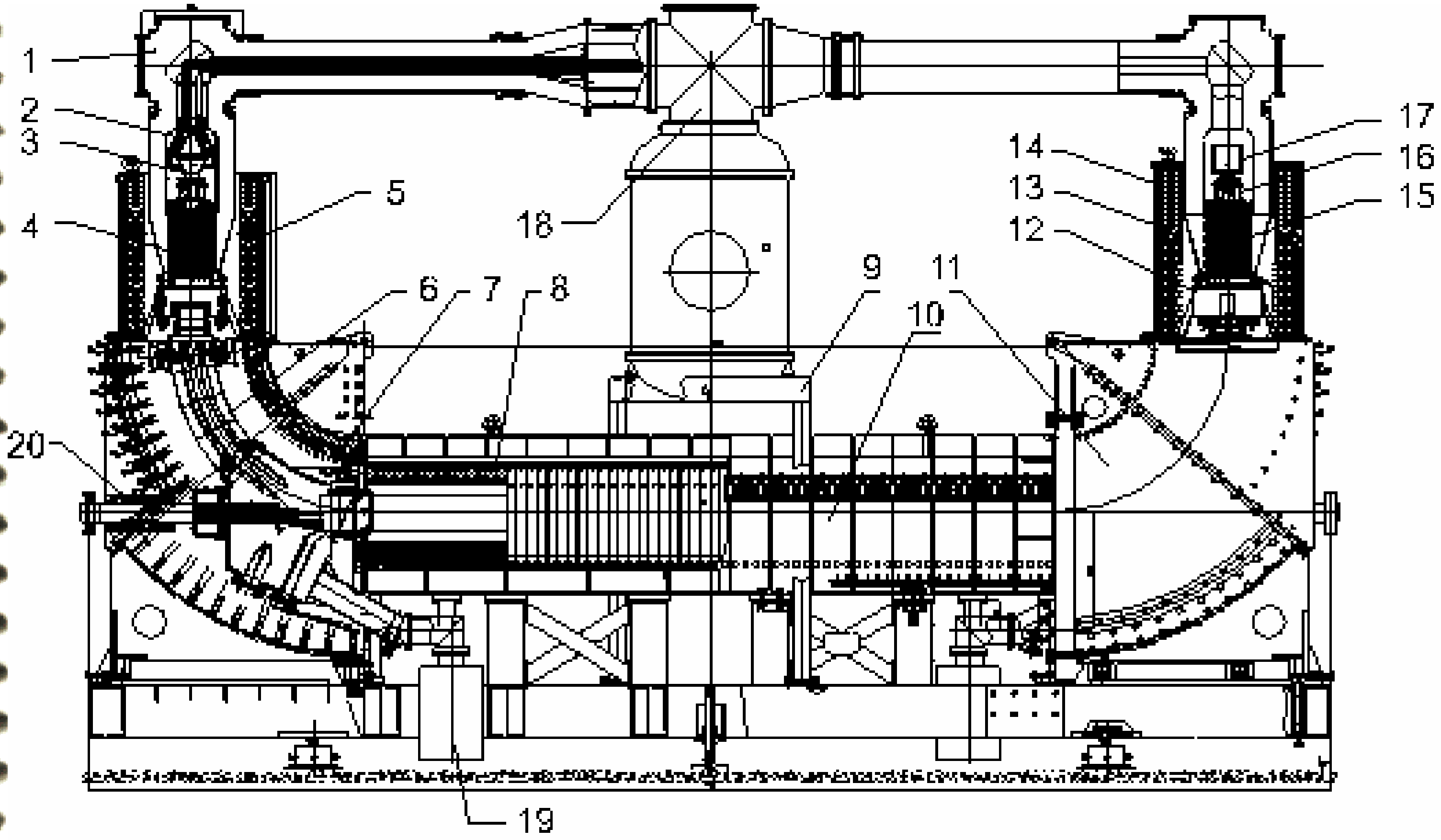
$\omega_i^2 - \uparrow$

Decreasing electron
beam density
results to
Increasing threshold
ion beam density



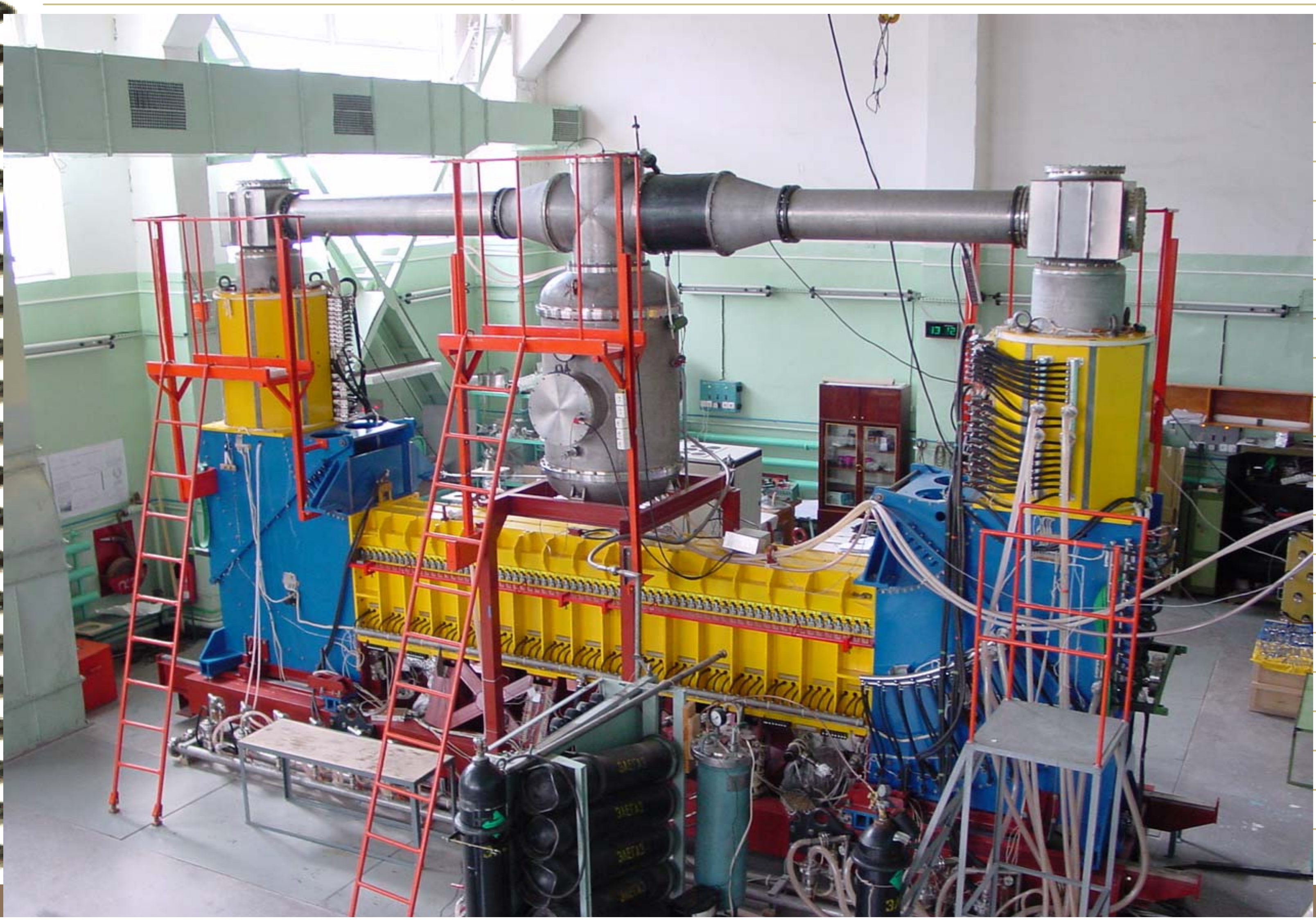
CSRm (IMP) cooler EC35





EC-300 1-high voltage line, 2-collector magnet shilding, 3-collector, 4-de accelerator tube, 5-magnet filed coils, 6-electrostatic bending, 7-toroidal coils, 8-coils cooling section, 9-high voltage vessel, 10-magnet yoke, 11- Ti pumping, 13-gun solenoid coils, 14-gun solenoid yoke, 15-acceleration tube, 16-electron gun, 17-concentrator of magnet field of electron gun, 18- high voltage terminal, 19-ion pump, 20- dipole corrector

Electron cooler EC-300
300 kV at Novosibirsk



EC-300
at IMP
6.05.2004
after commissioning
with
max. voltage 250 kV
max. current 3 A

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}) 610^{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.

Cooler at LEIR ring EC40

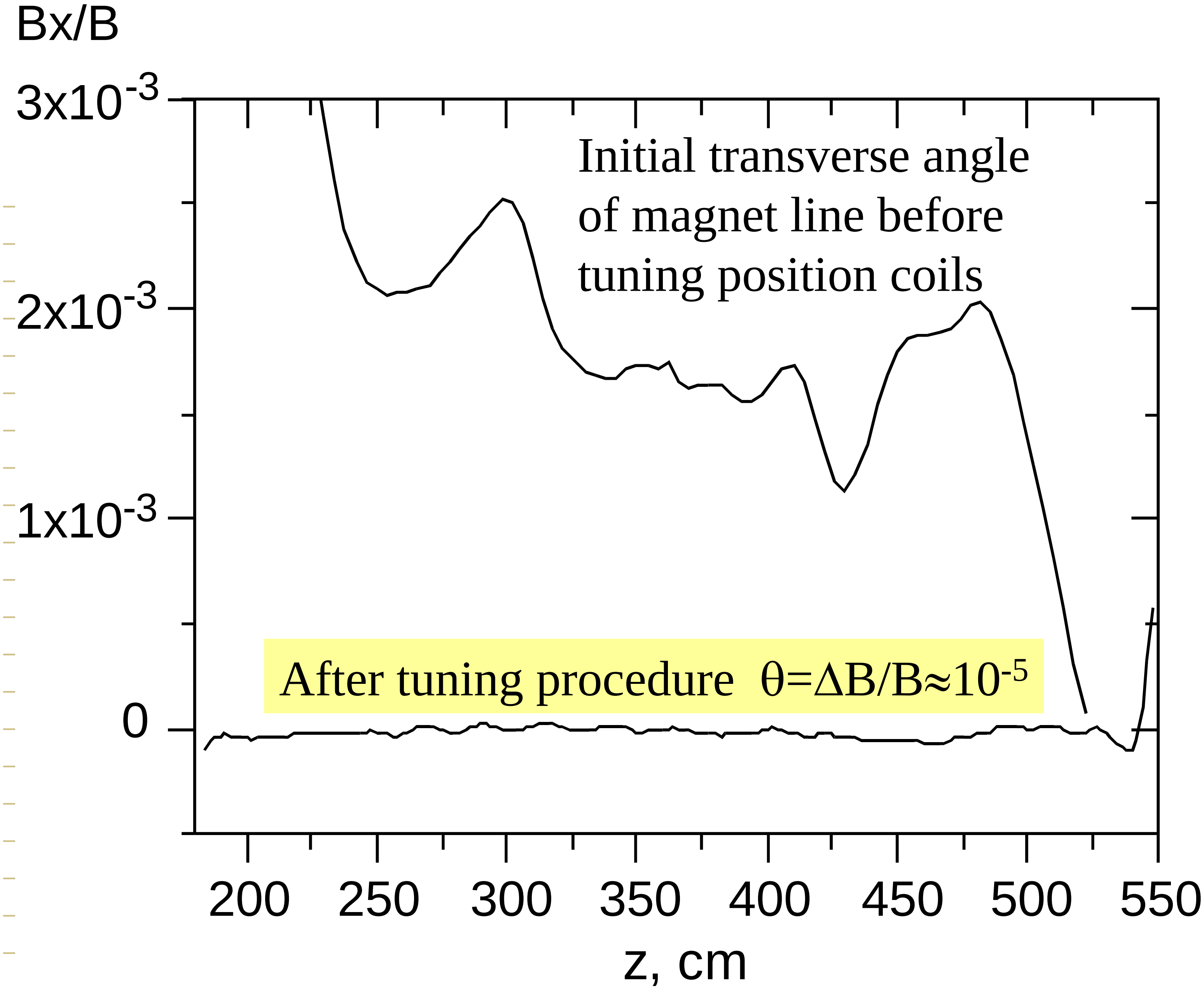
Basic features of new generation of coolers made at BINP

1. Tunable of the coils position for generation precise magnet field at cooling section with straightens better 10^{-5}

Example of tuning position of #42 coil with optical tube

Coil after measuring magnet axis

ready for installing



Initial transverse angle of magnet line before tuning position coils

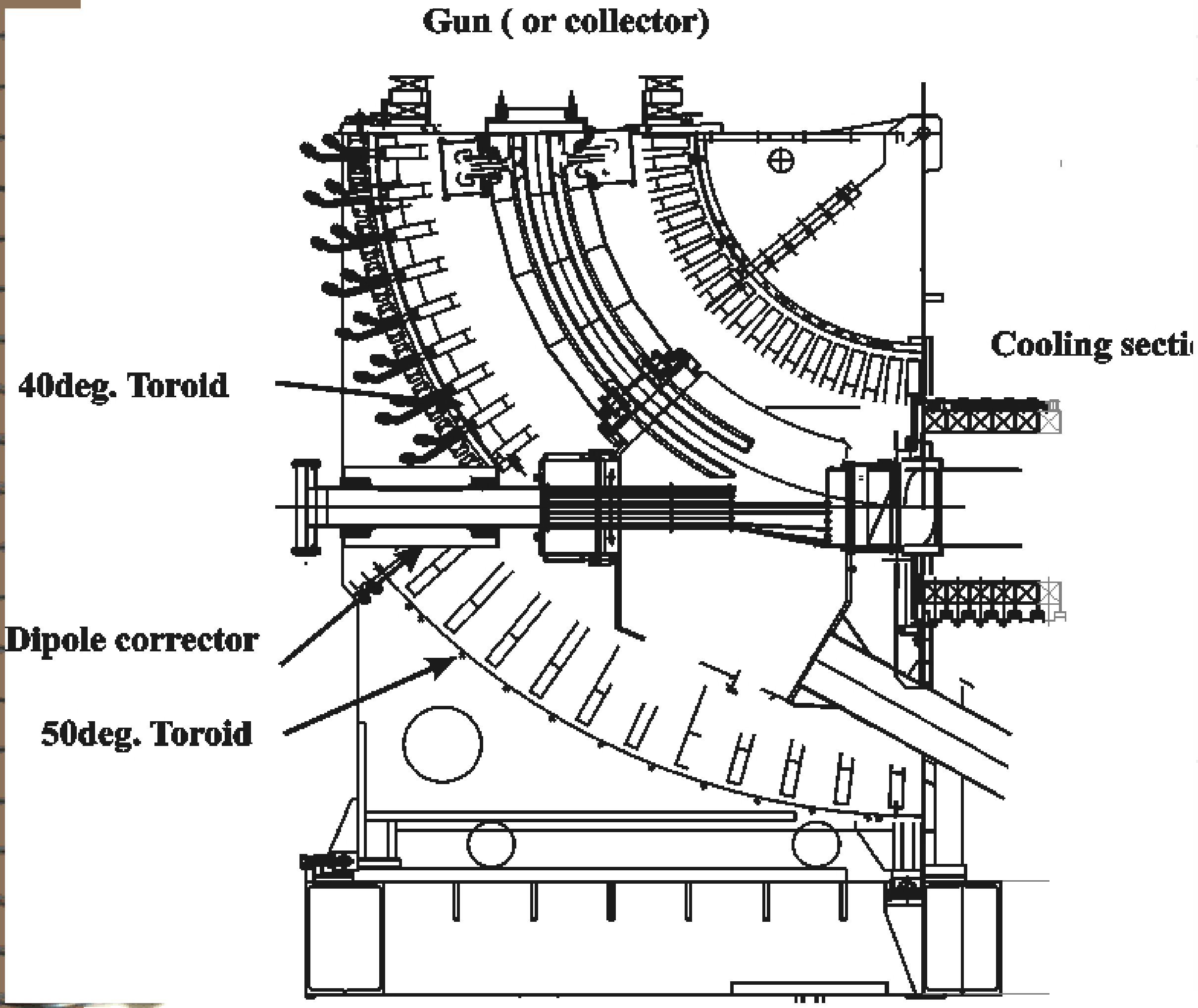
After tuning procedure $\theta = \Delta B/B \approx 10^{-5}$

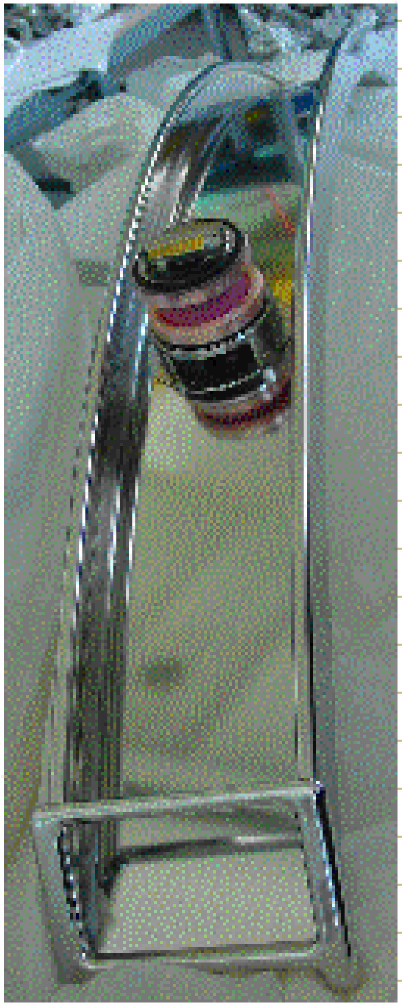
2. Electrostatic bending for compensation drift electrons

$$F = \frac{mV^2}{R} = eE + e\frac{[V \times B]}{c} = const$$

E=0 magnet bending B=pc/eR

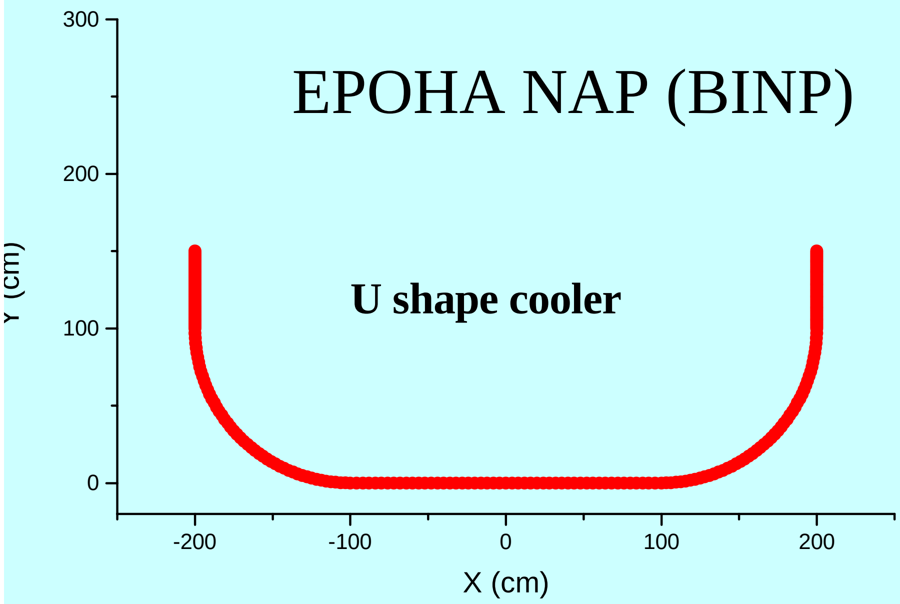
B=0 electrostatic bending E=pV/eR

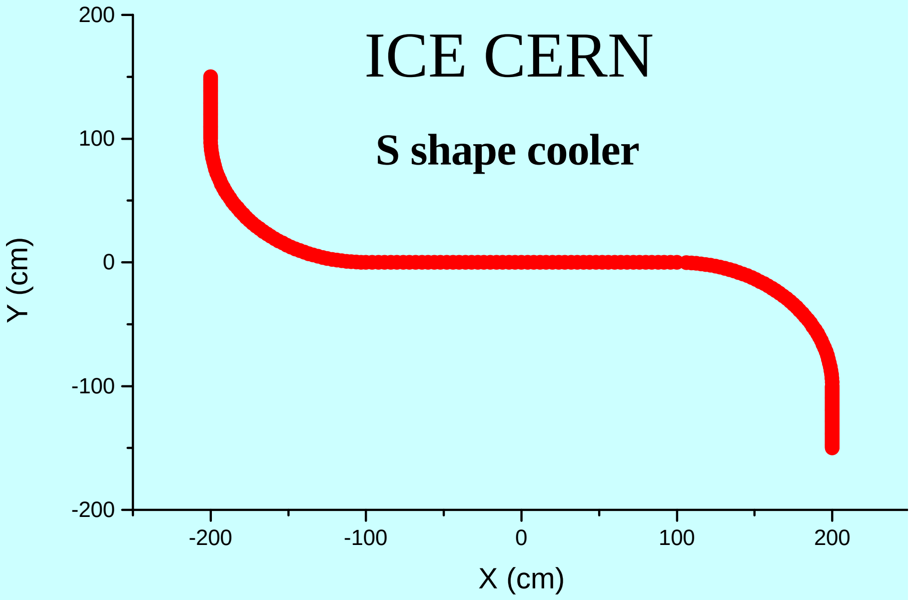




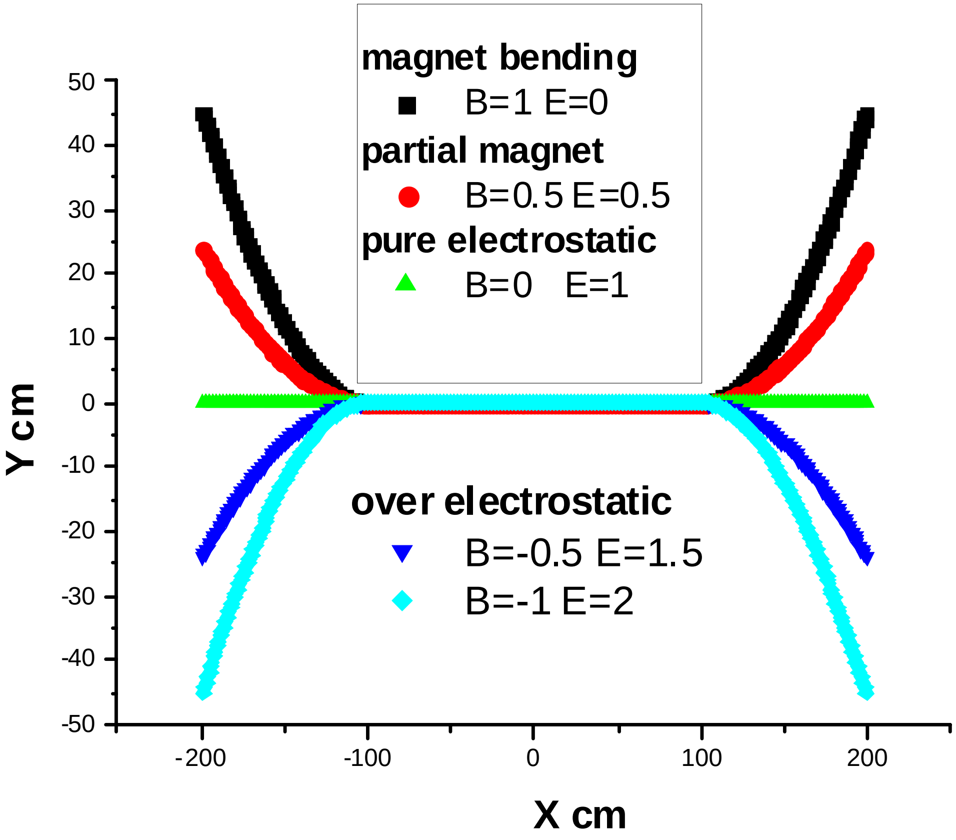
What is better U-shape EPOHA NAP cooler or S-shape ICE cooler (CERN)?

New coolers is U shape for magnet bending (drift and S-shape for electrostatic bending (no drift)





Geometry from point of view drift



$$\frac{B}{B_{opt}} + \frac{E}{E_{opt}} = 1$$

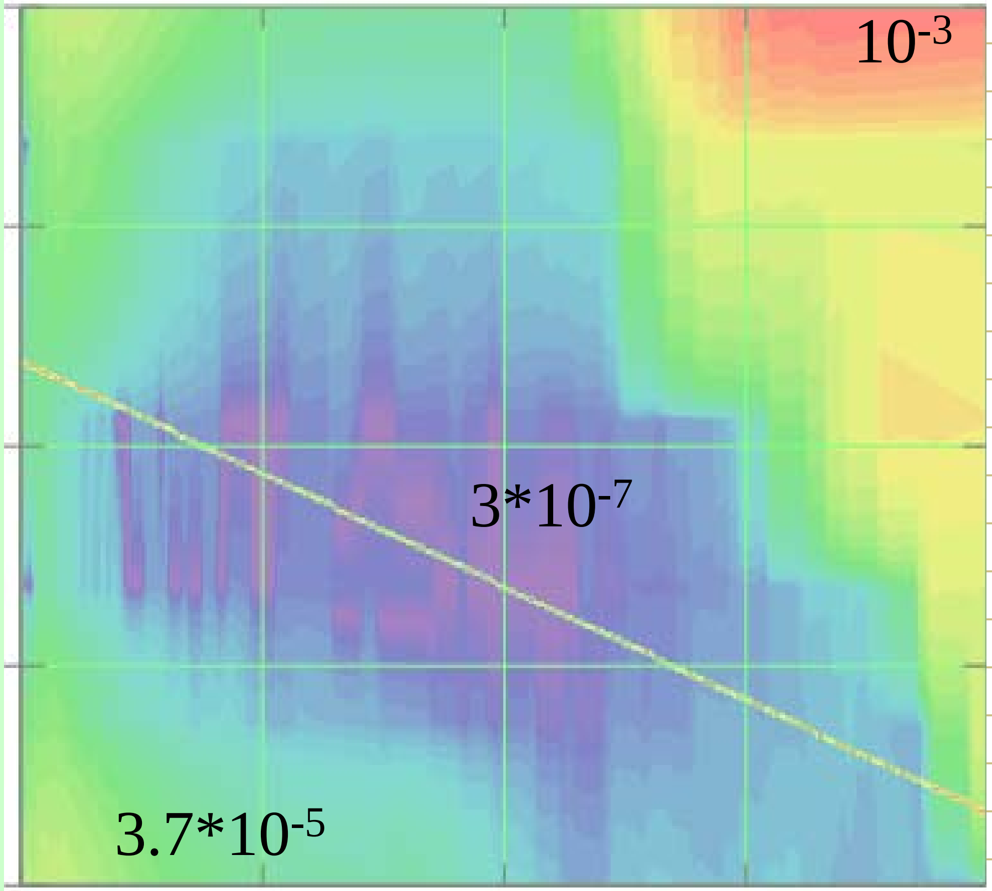
Condition of save trajectory for main electron beam but drift is

E/Eopt	B/Bopt	V/Vopt
E=0	B=1	1
E=0.5	B=0.5	0.5
E=1	B=0	0 no drift
E=1.5	B=-0.5	-0.5
E=2	B=-1	-1

Optimization of bending plate voltage for LEIR cooler

$$U_{bend} = \frac{d}{R_{bend}} * 2 * \left(\frac{mV^2}{2} - eU_{space.charge}\right)$$

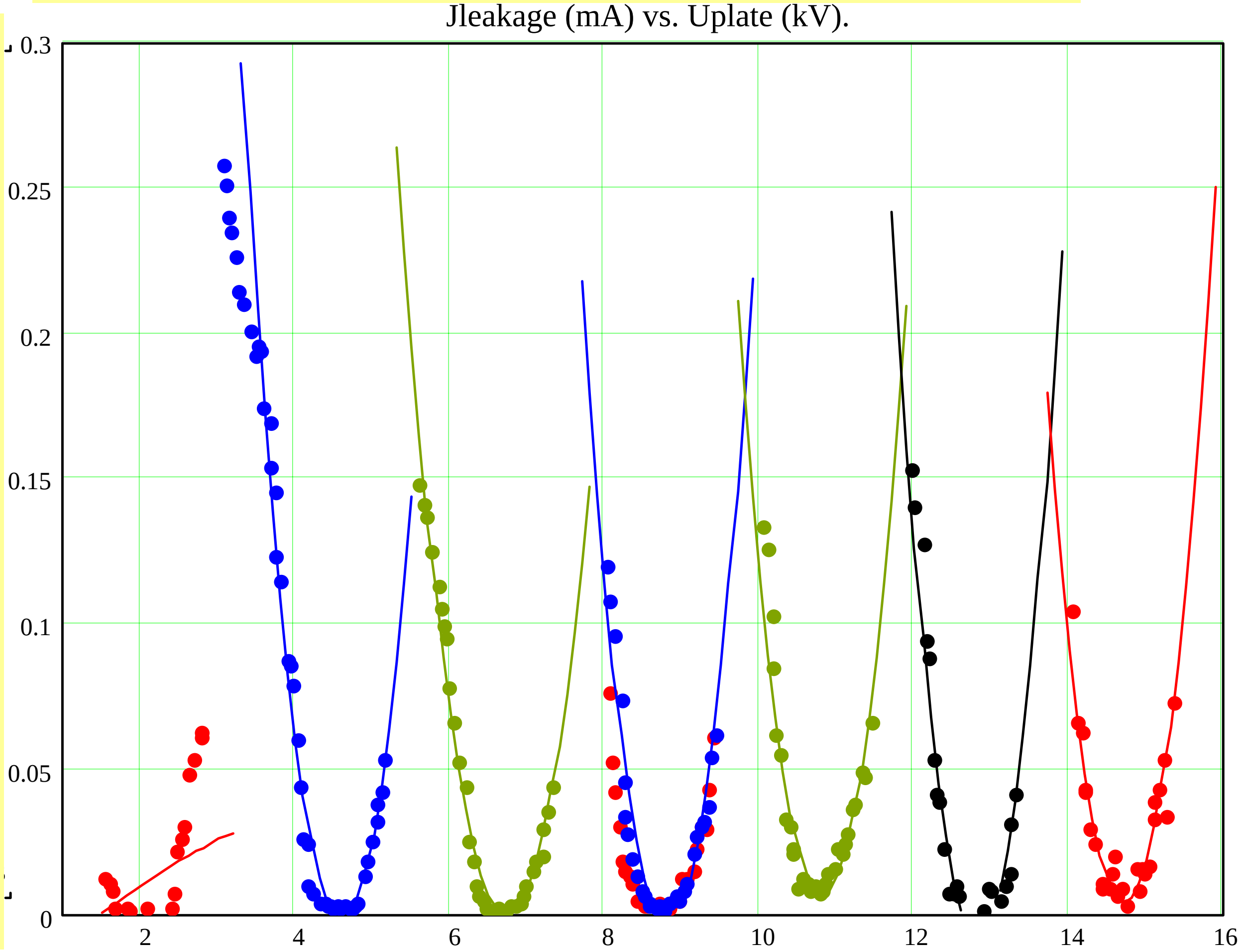
losses



Line-change of optimal bending voltage by space charge voltage

Loss currents for different beam energy
25,50,75,100,125,150,175 keV

Jloss
(mA)

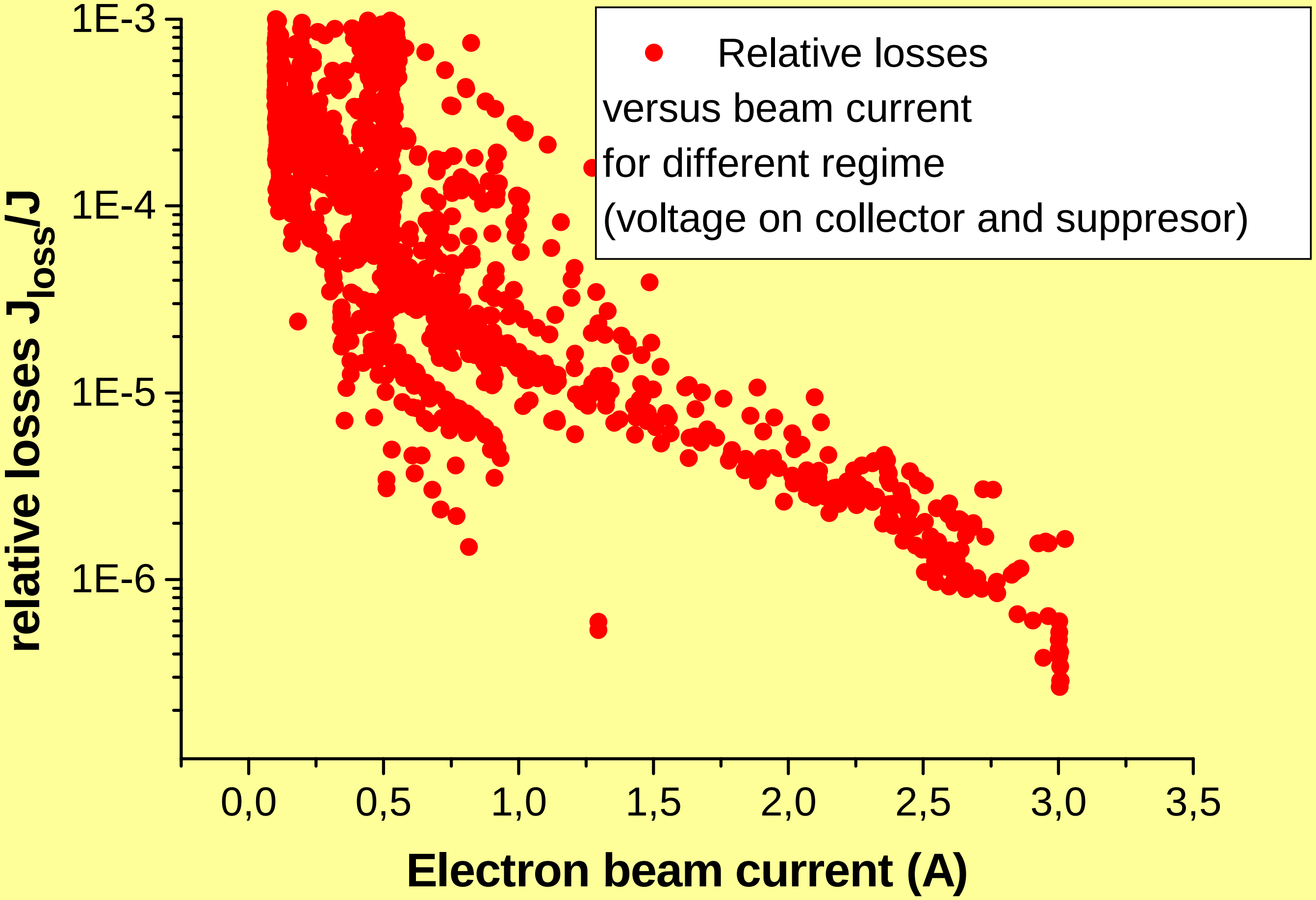


Voltage on bending plates (kV)

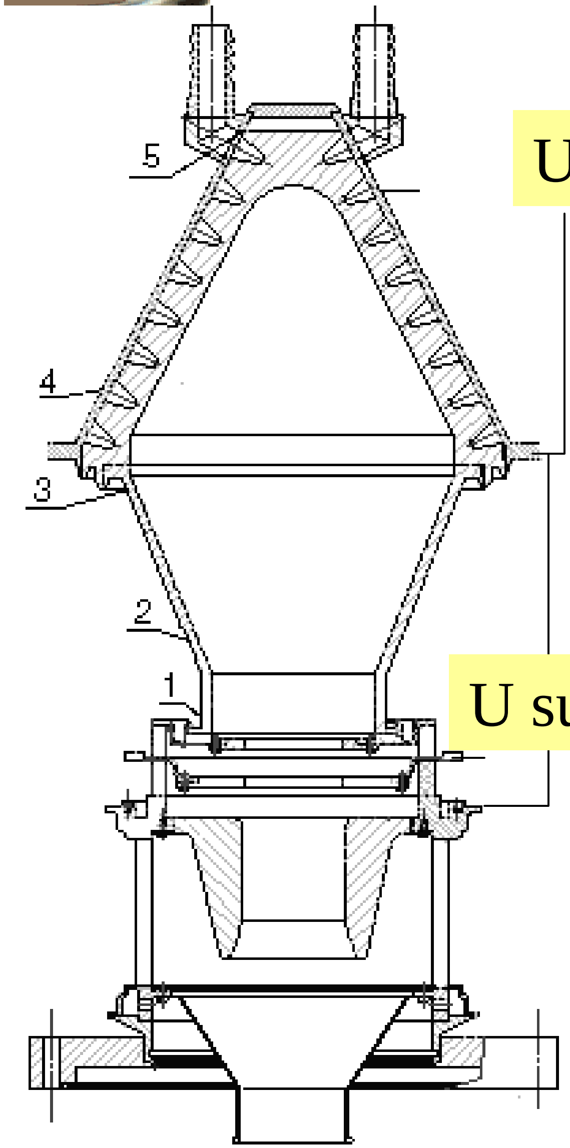
E(→) increased B(←) decreased but position of main beam keep the same

losses at optimum drop down >1000 from fraction mA to fraction μA

Suppressing losses by the space charge of electron beam

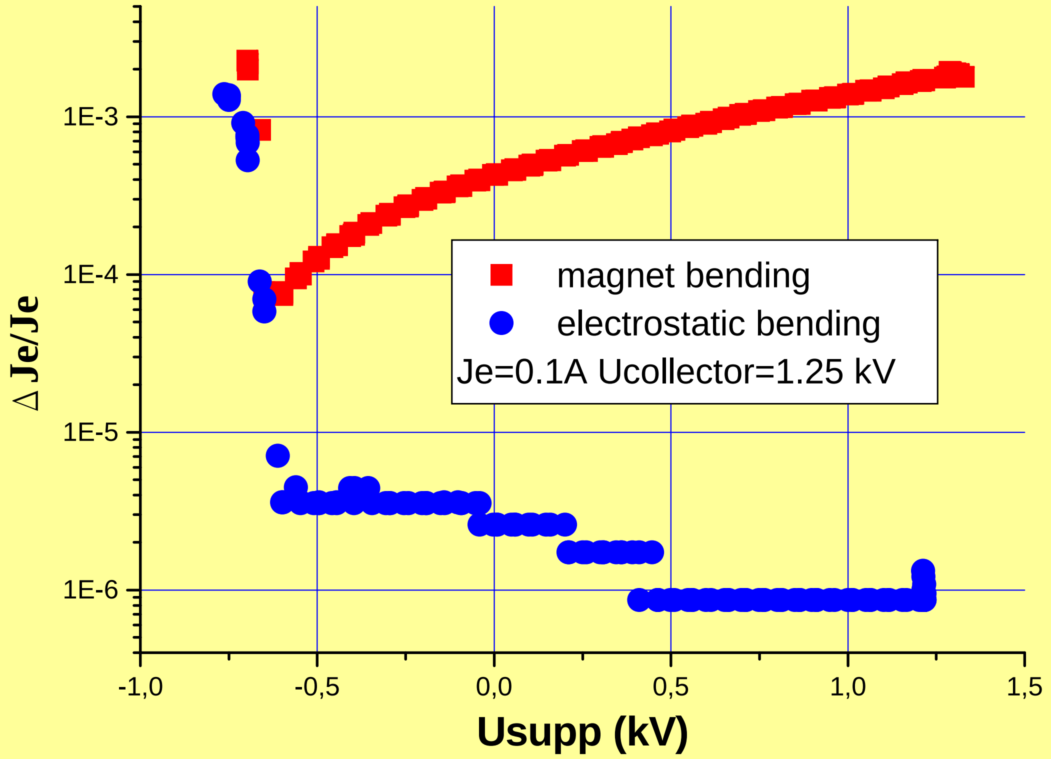


Optimization of recuperation

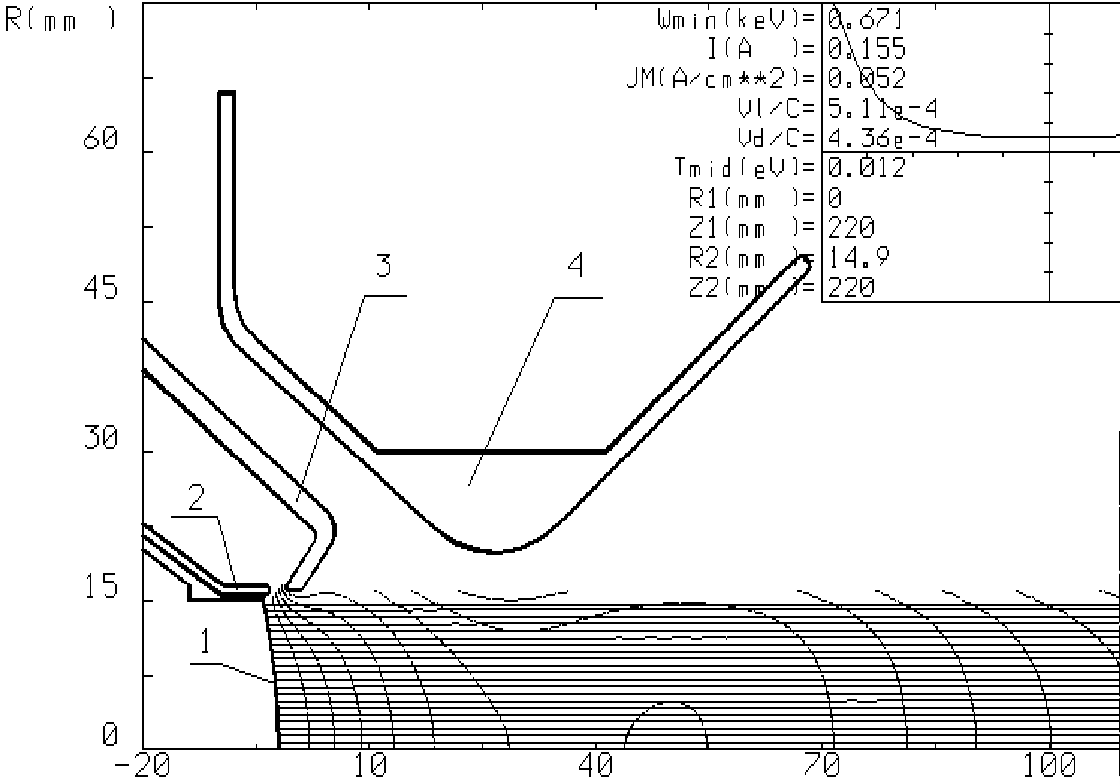


U collector

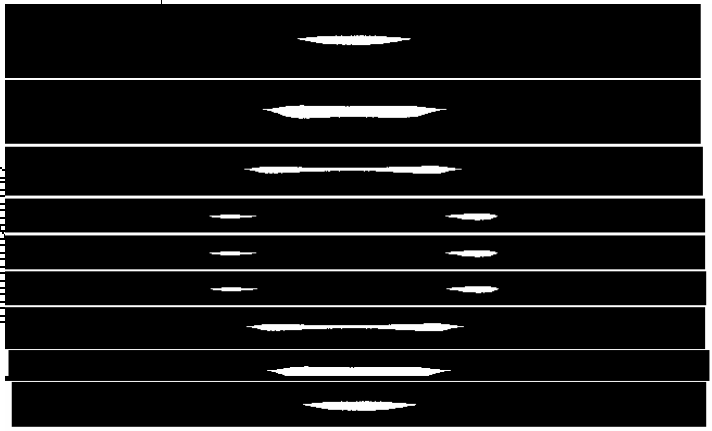
U suppresser



3. Electron gun with variable profile

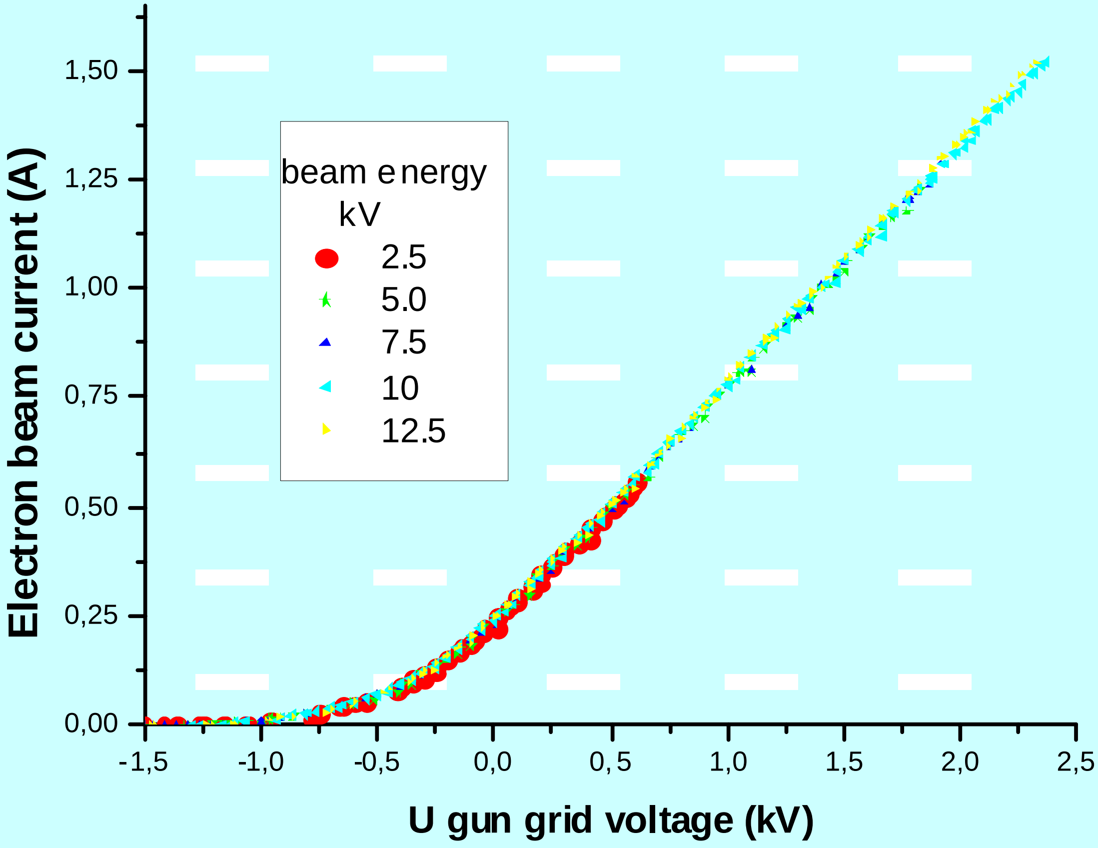


1-cathode
2-forming electrode
3-control electrode
4-anode

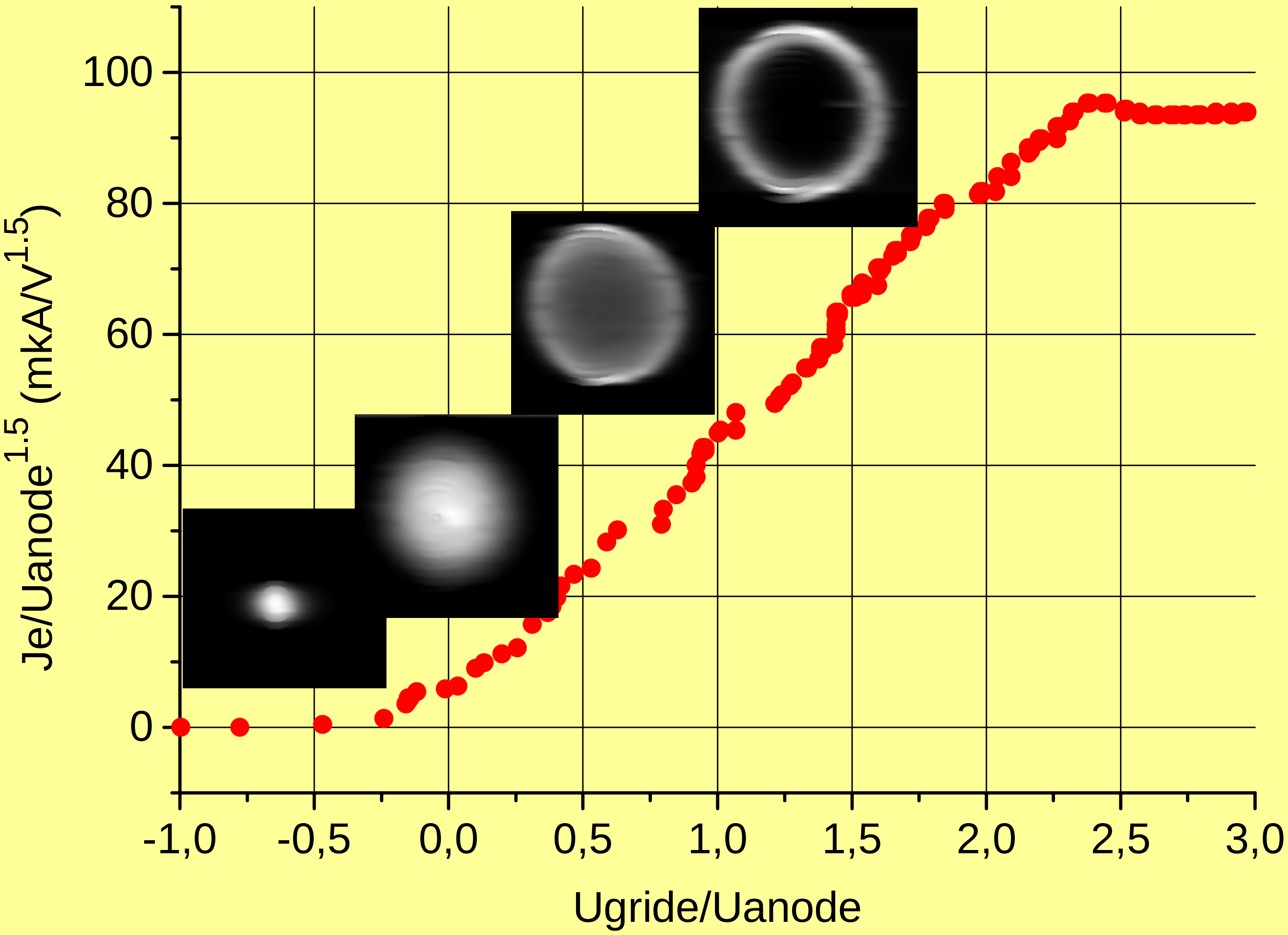


Photos of tungsten wire at different position inside electron beam

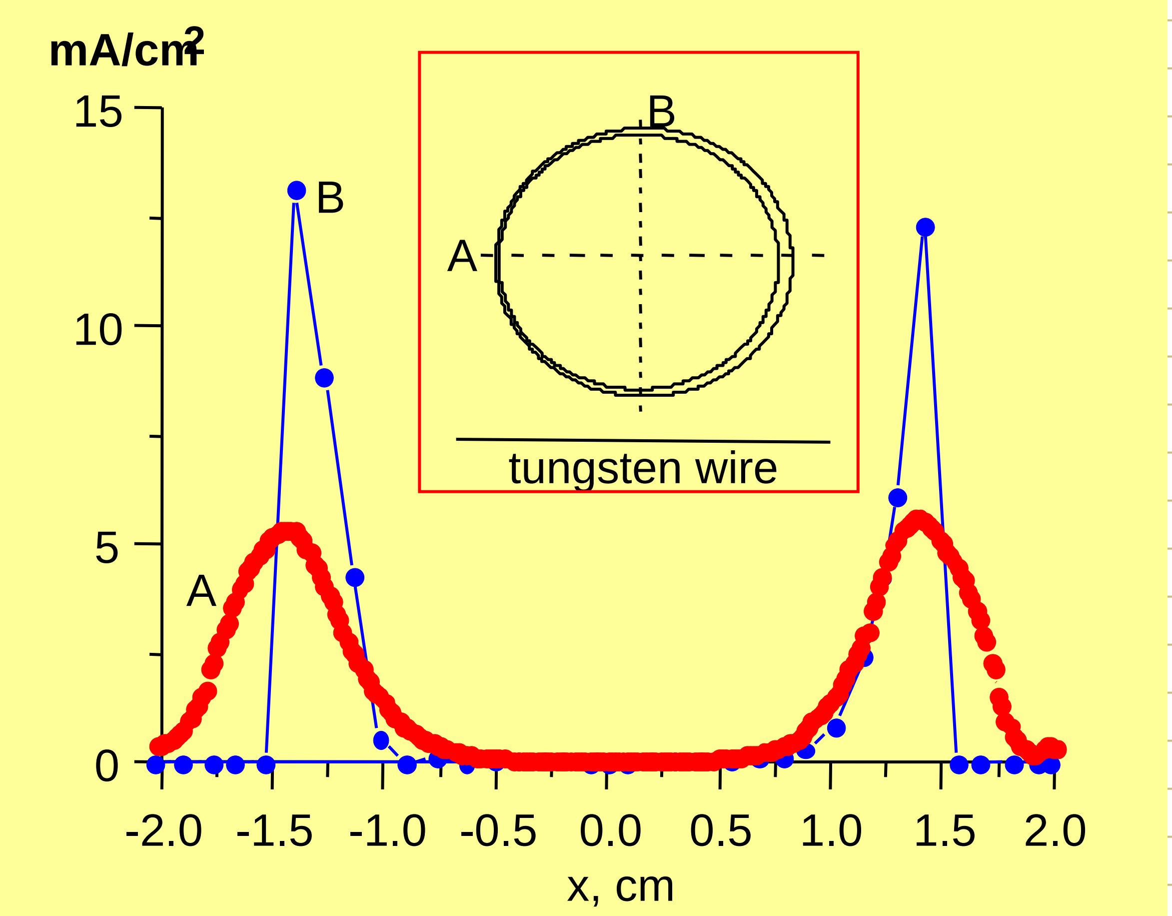
LEIR cooler
electron gun measuring

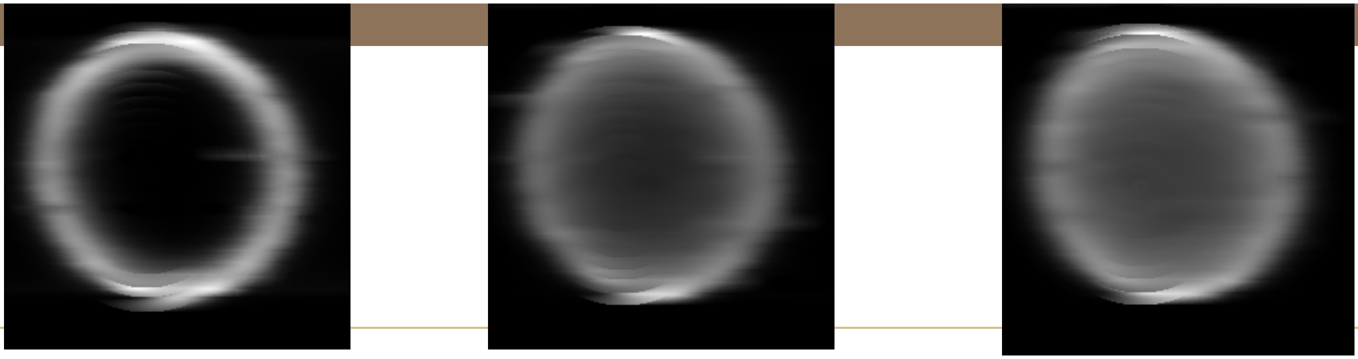


Perveance of gun and electron beam profile $Je(\mu)/Uanode(V)^{3/2}$



Measuring with tungsten wire current blue and emission measurement red (thermal conductivity along wire limited space resolution)

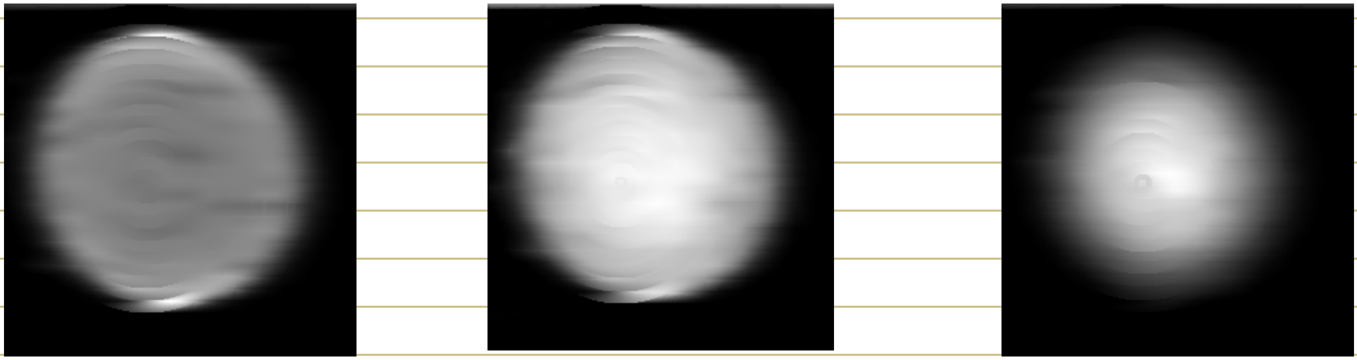




$U_{\text{contrrol}}/U_{\text{anode}}$= 0.6/0.9 kV

$U_{\text{contrrol}}/U_{\text{anode}}$= 0.3/0.9 kV

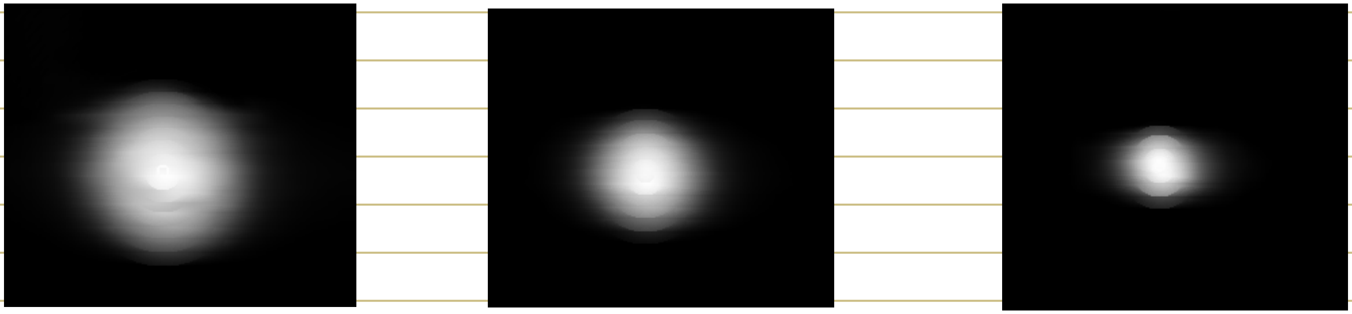
$U_{\text{contrrol}}/U_{\text{anode}}$=0.2/0.9 kV



$U_{\text{contrrol}}/U_{\text{anode}}$=0.1/0.9 kV

$U_{\text{contrrol}}/U_{\text{anode}}$= 0.05/0.9 kV

$U_{\text{contrrol}}/U_{\text{anode}}$= 0/1.4 kV



$U_{\text{contrrol}}/U_{\text{anode}}$= –0.2/2.8 kV

$U_{\text{contrrol}}/U_{\text{anode}}$= -0.4/2.8 kV

$U_{\text{contrrol}}/U_{\text{anode}}$= –0.6/2.8 kV

Electron beam distribution for different voltage on the control electrode and the anode.

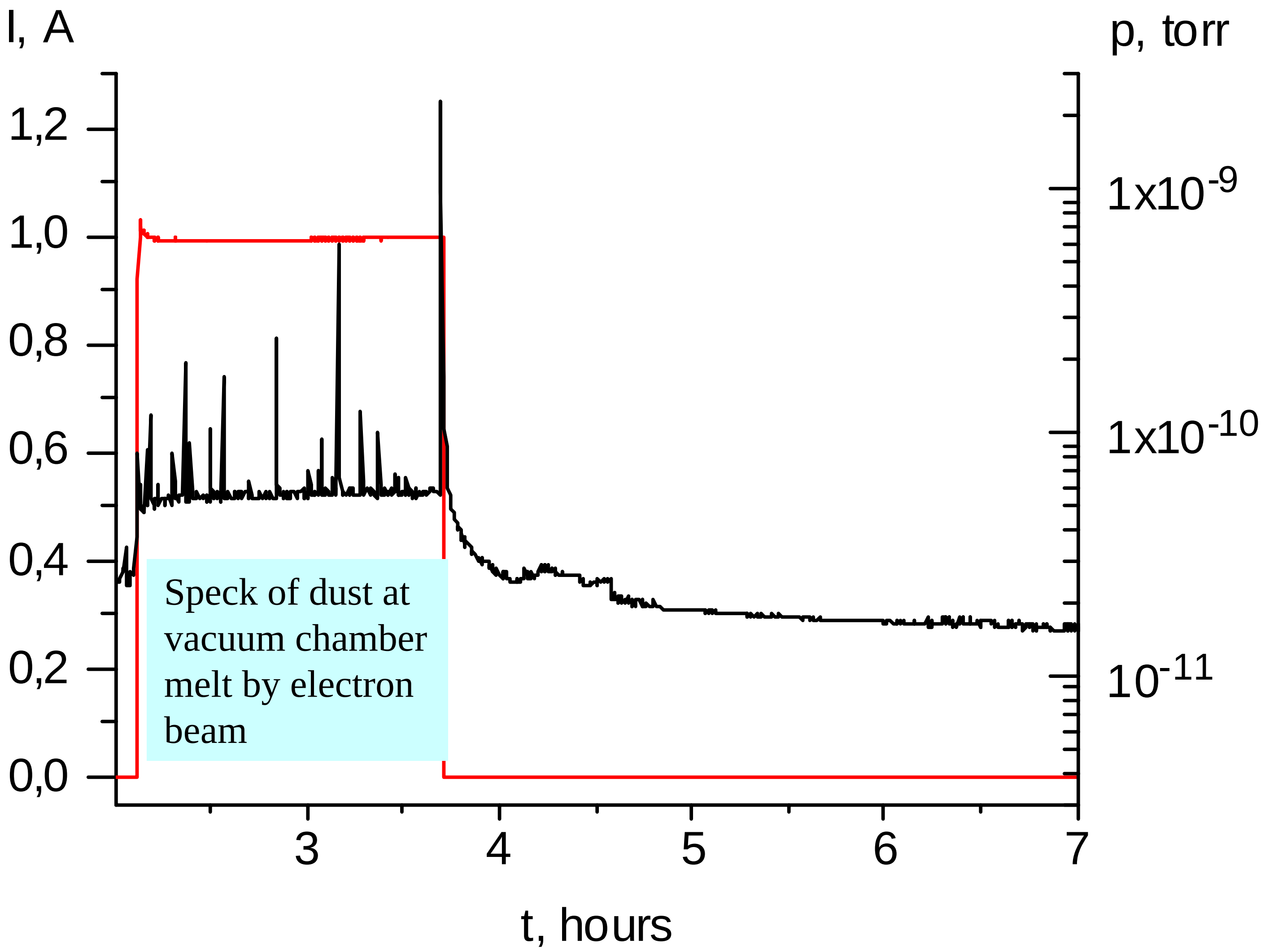
Ions at electron beam from residual gas and vacuum requirements

At time of commissioning at IMP
at moment of initial beam with energy 50 kV
strong outgasing with preassure >3E-9 Torr

After backing electron beam with energy 50 keV was used for final clearing vacuum chamber.

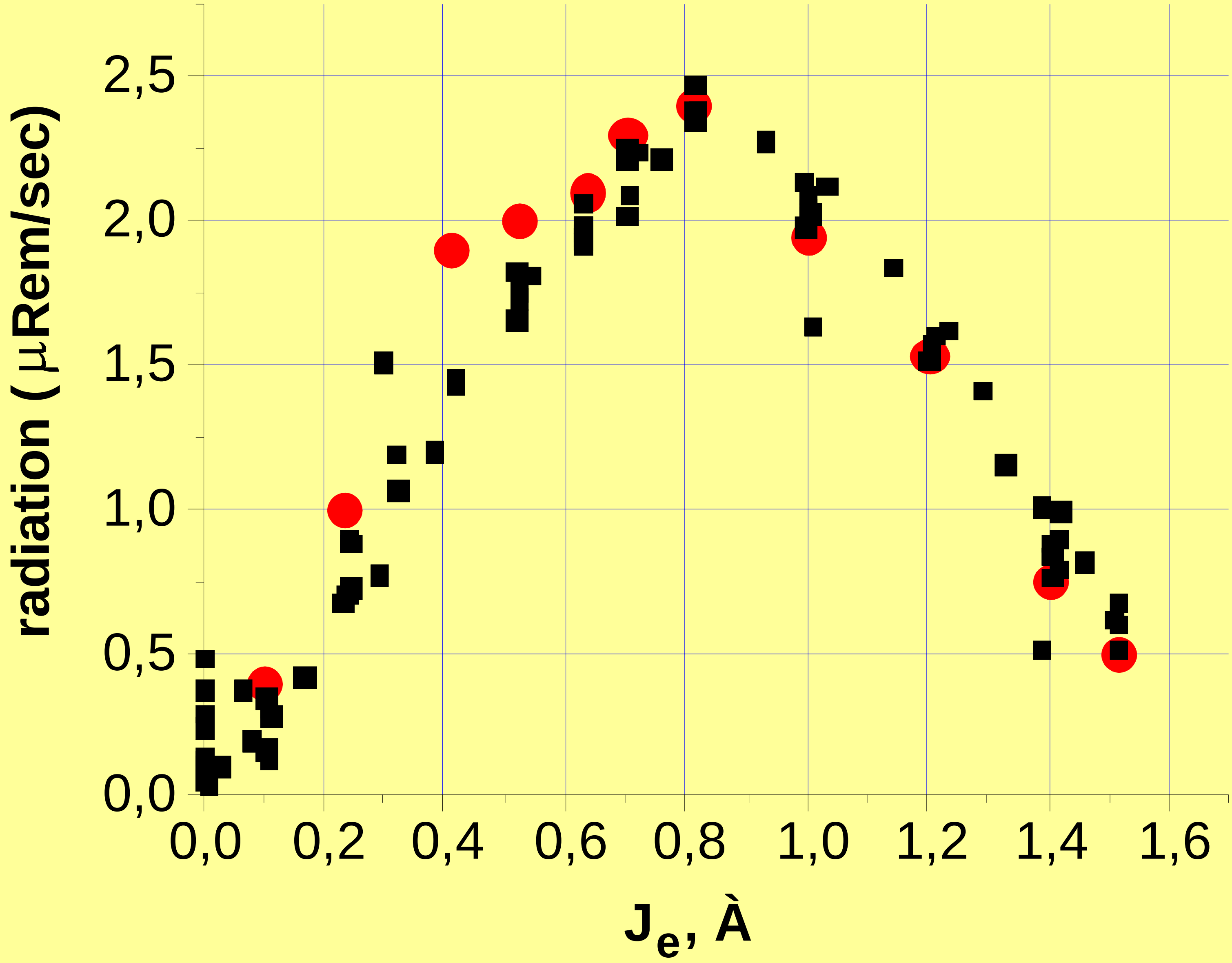
Initial vacuum 2E-9 Torr and for beam 0.25A the same oscillations at pickup electrodes was found. After few hours training vacuum pressure go to 5E-10 Torr and oscillations disappear for current >1 A. The threshold electron current change inverse proportional vacuum pressure.

Vacuum with electron beam

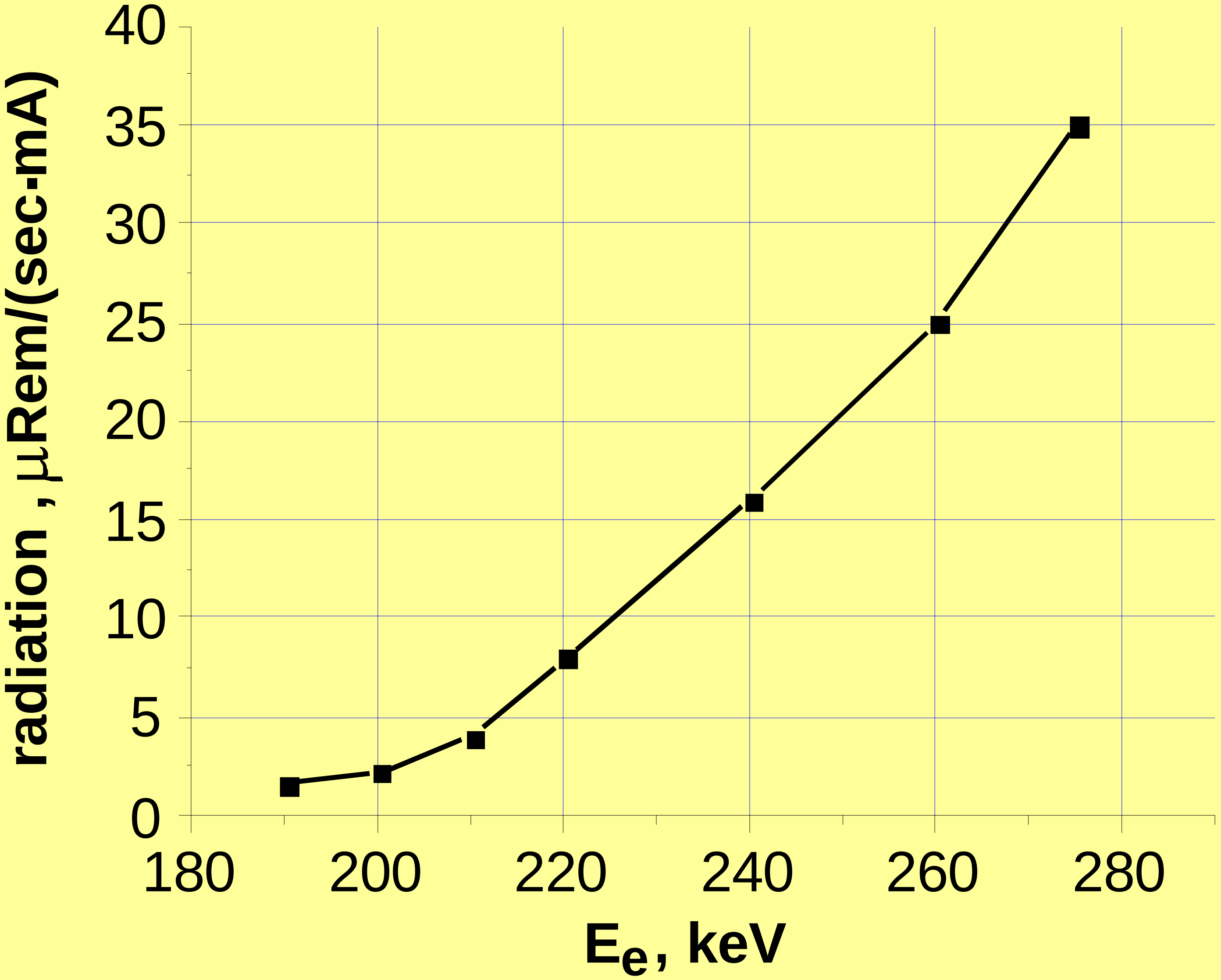


Speck of dust at vacuum chamber melt by electron beam

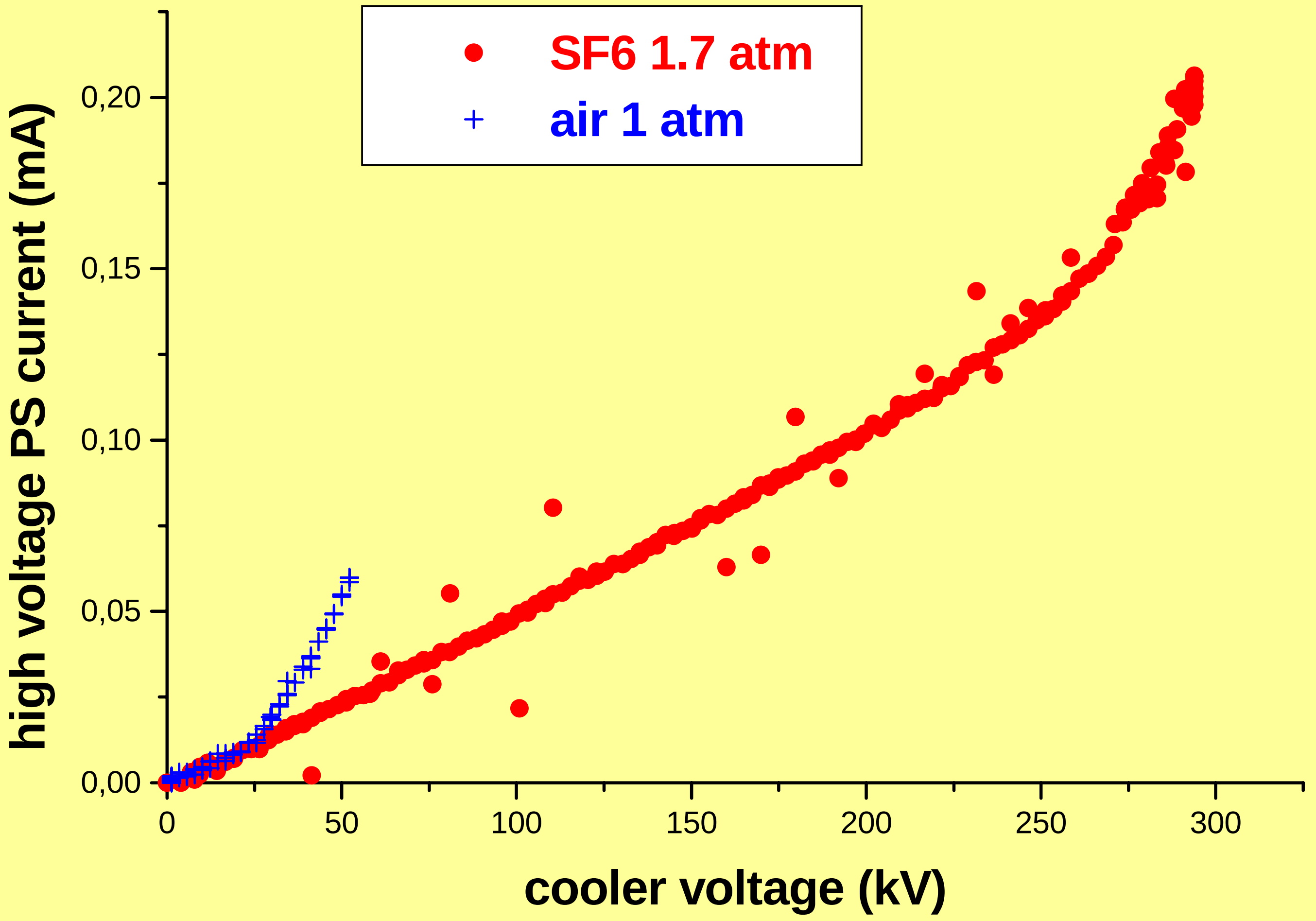
Radiation for different electron current (260 kV)



Radiation at 1 m from collector at gap magnet system



Problems high voltage



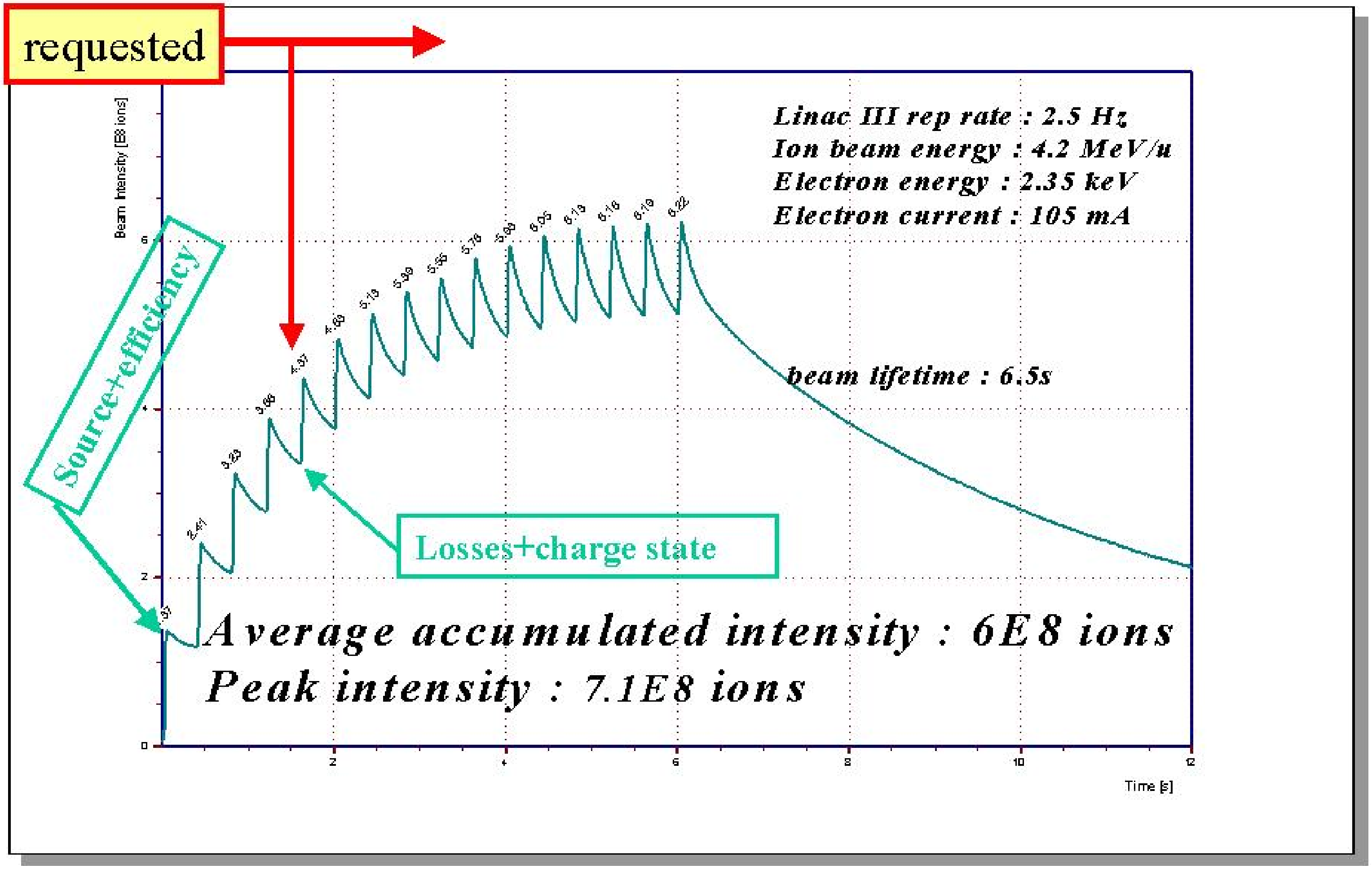
- Commissioning with electron beam both IMP coolers was successful
- Electrostatic bending means: low noise, better vacuum.
- High perveanse electron beam with hollow beam will help
- optimized cooling and decreased losses ion beam by recombination
- Pancake design of magnet system showed reasonable accuracy
- Gas isolation should calculated with more maximal voltage +30%
- (for not perfect gas)!
- Resistive damper at collector PS for operation with current more 1 A.
- High level oscillations without this damping resistor.
- Important to have commissioning with electron beam before
- using at ion ring.

LEIR cooler at CERN

At June 2005 was commissioned with low energy electron beam 300 V and current 40 mA. **Baking was did with electron beam switch on for clearing vacuum chamber and collector.** Idea was that after baking and activation NEG coating not to be overload NEG cartridge outgasing at moment first switch on electron beam. After backing vacuum was 5E-12 Torr but was found leak at electron gun that increased pressure to 7E-12 Torr. More about today situation with LEIR cooler we will know from Gerard Tranquille report.

LEAR Pb ion experiments

Stacking tests of lead ions



requested

Source+efficiency

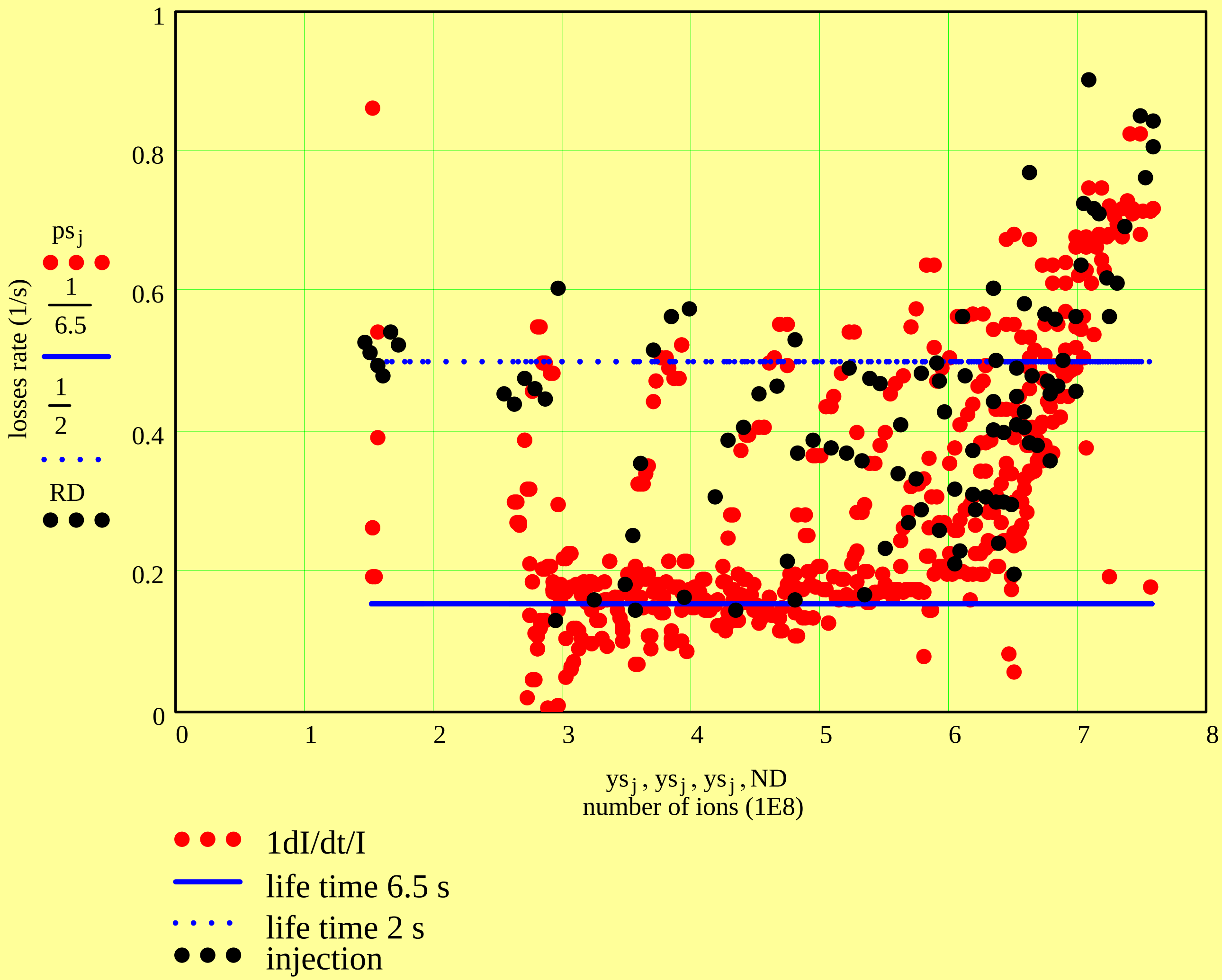
Losses+charge state

Linac III rep rate : 2.5 Hz
Ion beam energy : 4.2 MeV/u
Electron energy : 2.35 keV
Electron current : 105 mA

beam lifetime : 6.5s

Average accumulated intensity : 6E8 ions
Peak intensity : 7.1E8 ions

LEAR accumulation show only high gas desorption or +electron heating?



Conclusion

The commissioning of coolers with electron beam demonstrated high performance of new electron coolers. The electron current up to 3 A was obtain that few times high that can used for the cooling ion beams. The nearest future these coolers will tested at experiments with cooling ion beam and it can open many interesting physics pheromones. Most interesting will be optimization of cooling the high intensive ion beam. It will be very interesting for next cooler for the high luminosity hadron colliders as RHIC or HESR.

Acknowledgments

The development new generation of the electron coolers are result of effort high intellectual team scientists, engineers, workers at BINP with using world experience technique of the electron cooling. Especially I want mention important contribution to cooler techniques the general designer of these coolers Boris Smirnov.