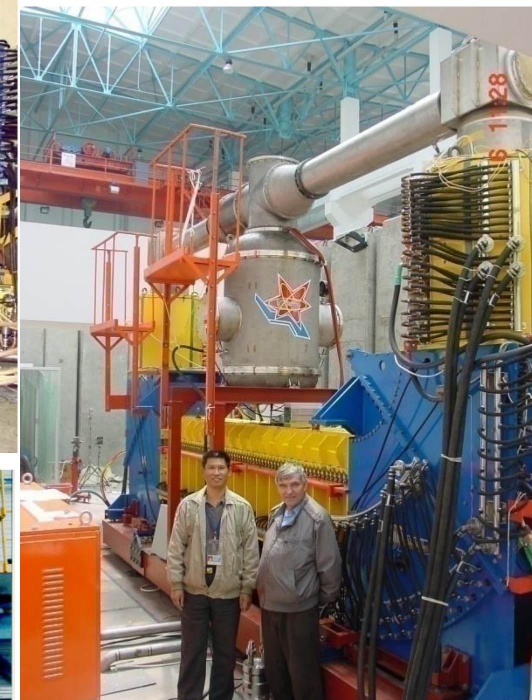
Low Energy Cooler for NICA Buster

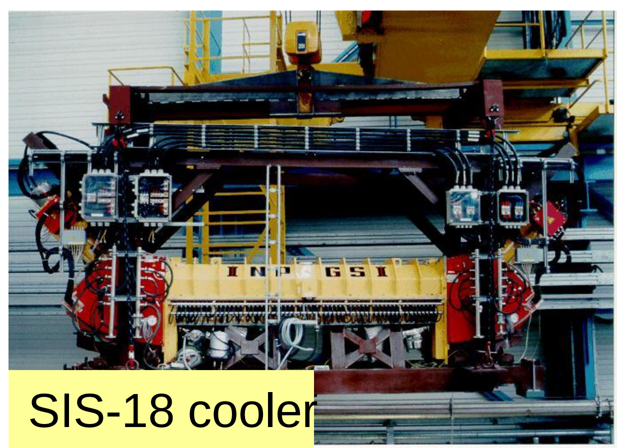
speaker Vladimir Reva, team of Budker Institute of Nuclear Physics
(BINP SB RAS, Novosibirsk)


COSY 2 MeV


LEIR cooler


CSRe 300 kV


CSRm 35 kV cooler

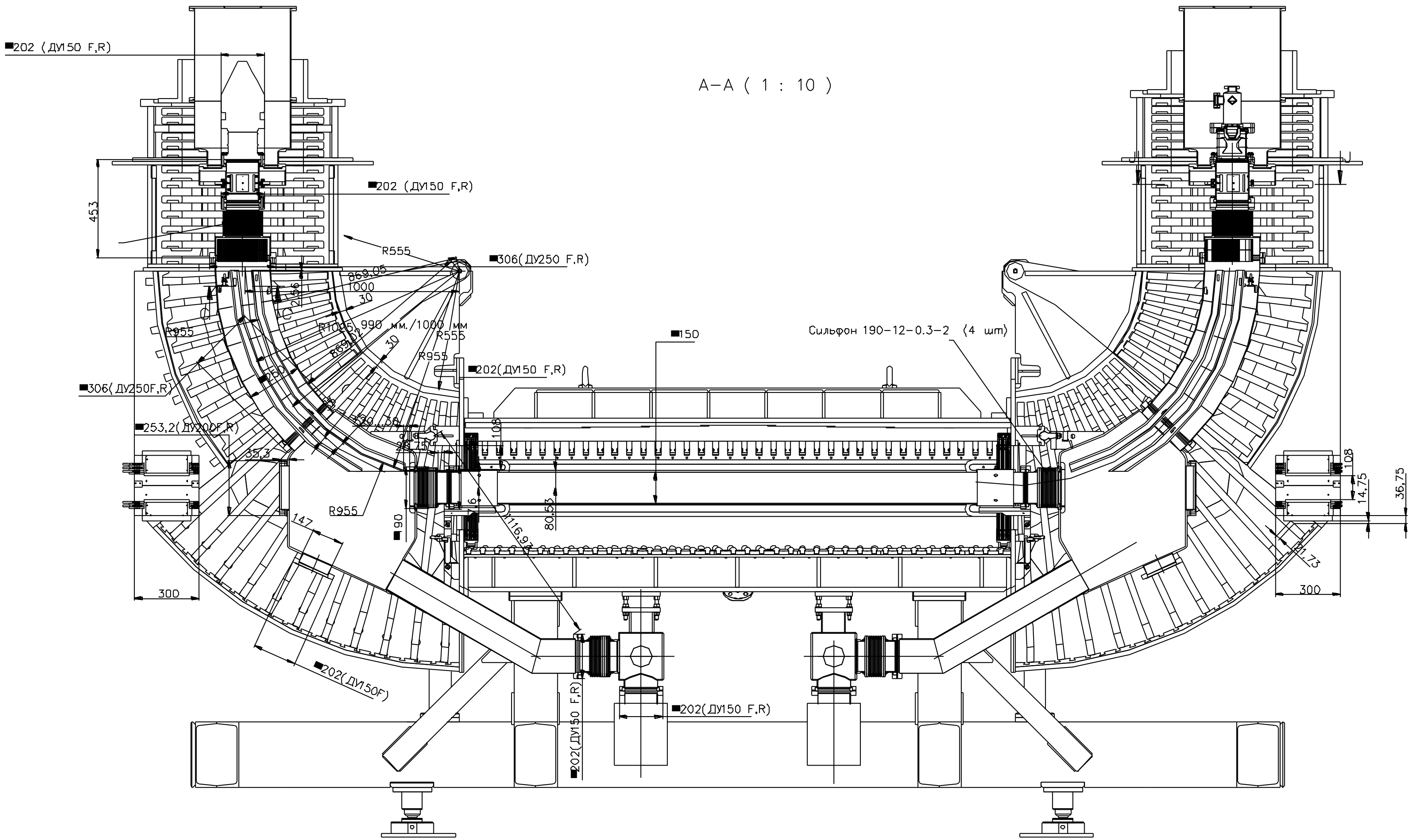

SIS-18 cooler

Technical requirements:

the Installation of Electron Cooling is to provide efficient cooling of heavy charged ions from protons to $^{197}Au^{31+}$ and have the following basic parameters:

Electron energy *E*, keV possibility of tuning the energy in this range;	$1{,}5 \div 50$
Electron beam current *I*, A	$0{,}2 \div 3{,}0$
Accuracy of electrons energy and its stability, $\Delta E/E$	$\leq 1\cdot10^{-5}$
The stability of the beam current, $\Delta I/I$	$\leq 1\cdot10^{-4}$
Recovery mode of the electron beam energy Leakage current of the electron beam, $\delta I/I$	$\leq 3\cdot10^{-5}$
The intensity of the longitudinal magnetic field, T	$0{,}1 \div 0{,}2$
Magnetic field inhomogeneity at the cooling section, $\Delta B/B$	$\leq 3\cdot10^{-5}$
Ion orbit correction (input and output)	displacement, ≤ 1,0 mm angular deviation, ≤ 1,0 mrad

Cooler design

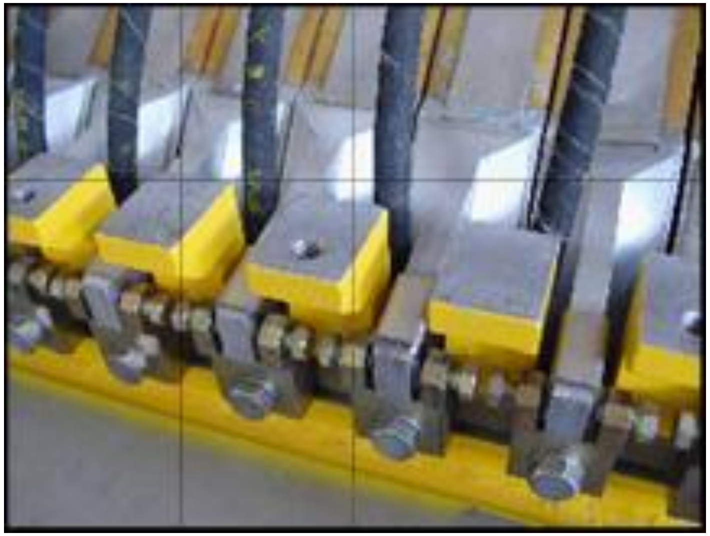


Cooling section 2,5 m

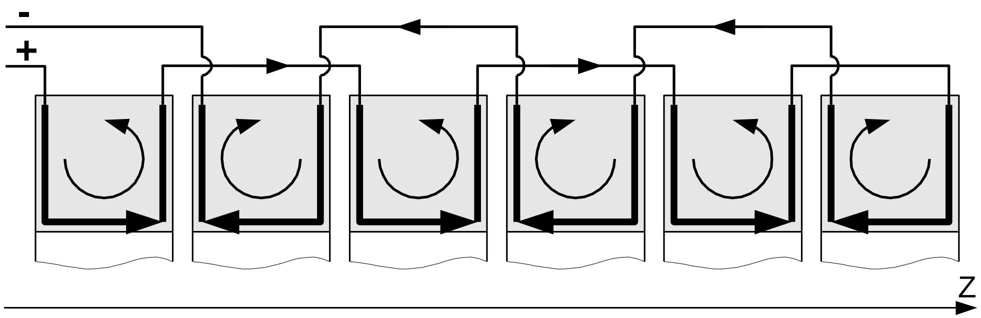
Some new and old features implemented in the cooler

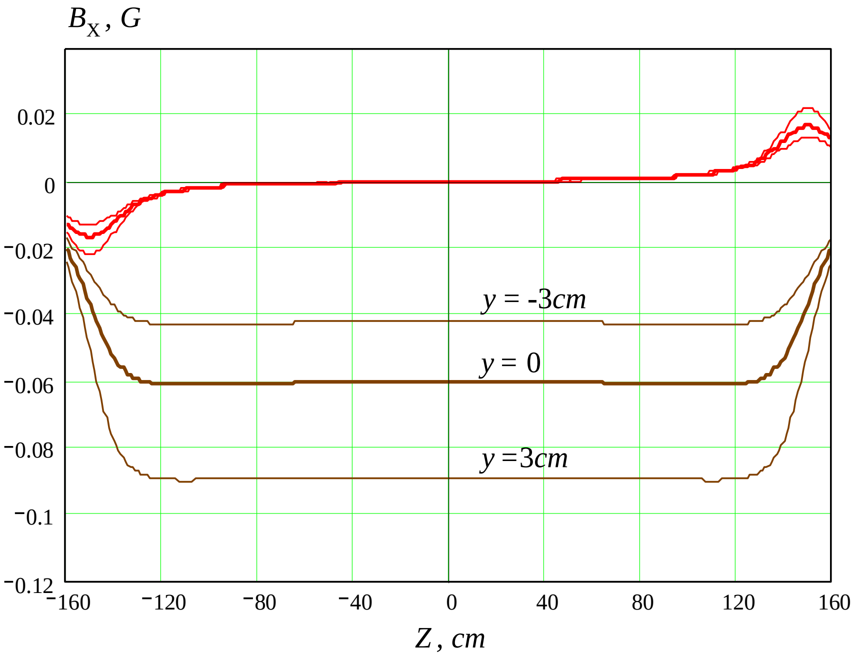
1. Solenoid of the central section without return busline
2. Electrostatic bending with an extra electrode combined with magnetic field correction. Provides compensation of the electron beam centrifugal drift along the bend
3. Operation regime for buster
3. Four – sector control electrode for the electron gun combined with BPMs at the gun and collector. Provides diagnostic of the electron beam shape and position
4. Advanced magnet structure at cooling section. Provides expansion of the good field region for cooling
5. Getter modules in gun and collector chambers for an extra pumping

Photo of the standard coils of the cooling section.



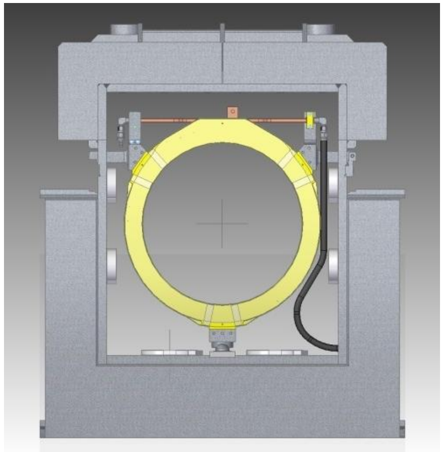
Magnetic dipoles are produced by the finite size of the magnetic coils and cross-bar connections

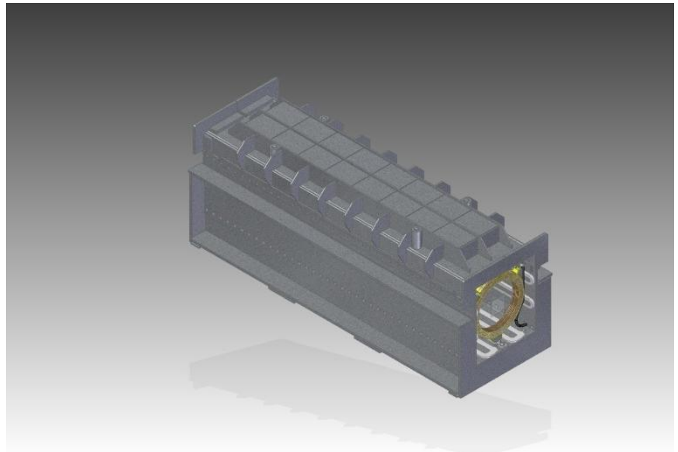


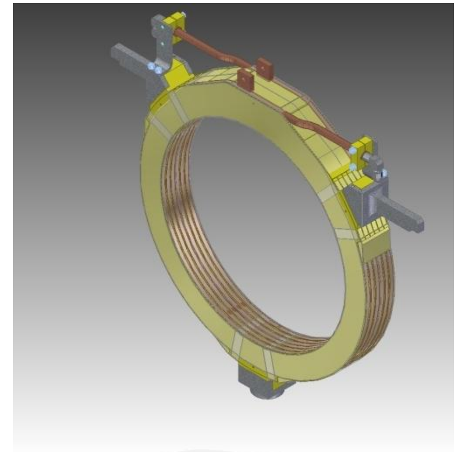


Transverse magnetic field at alternation of left/rind winded coils (red curve) and only left winded coils

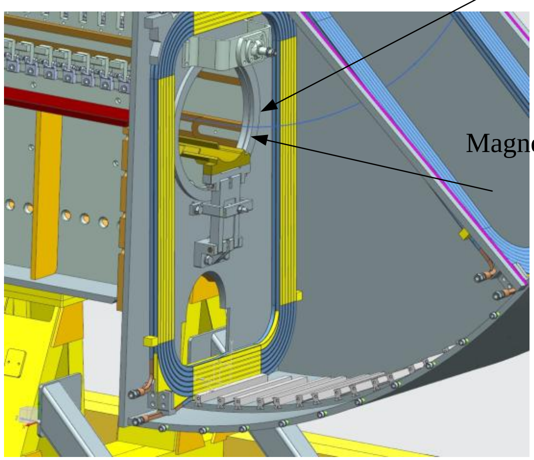
Central solenoid (cooling section)

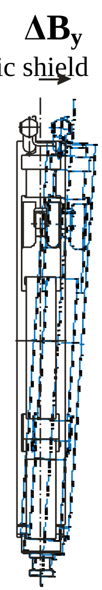


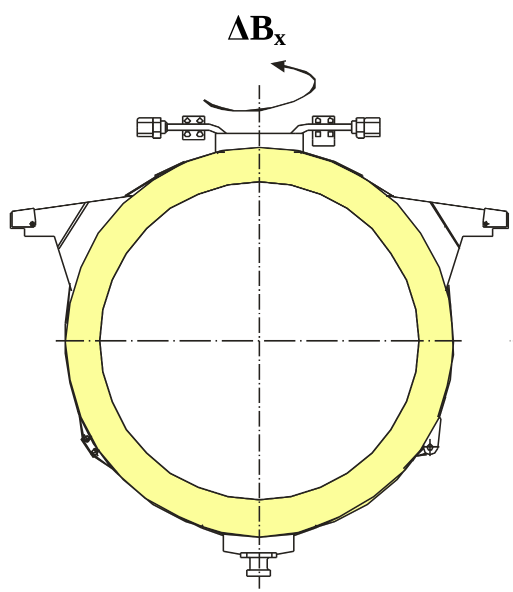




Magnetic shield and correction coil on the solenoid edge make good field region longer



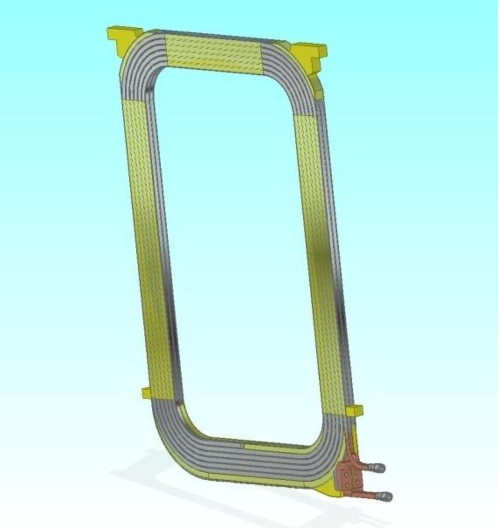


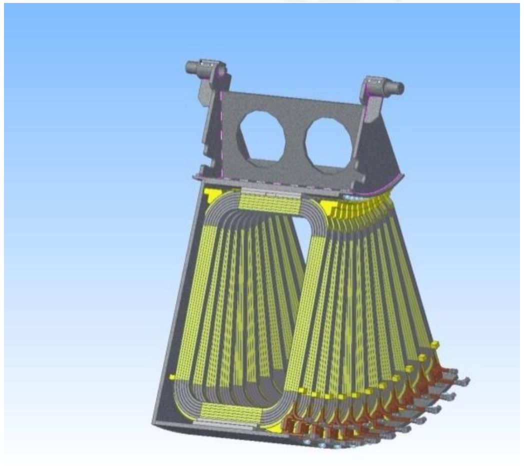


The magnetic iron of the central solenoid is similar to the previous version of the electron coolers, but the difference in the coil step, length of the central section, displacement of the mechanical supports leads to the efforts of the designer and technologist.

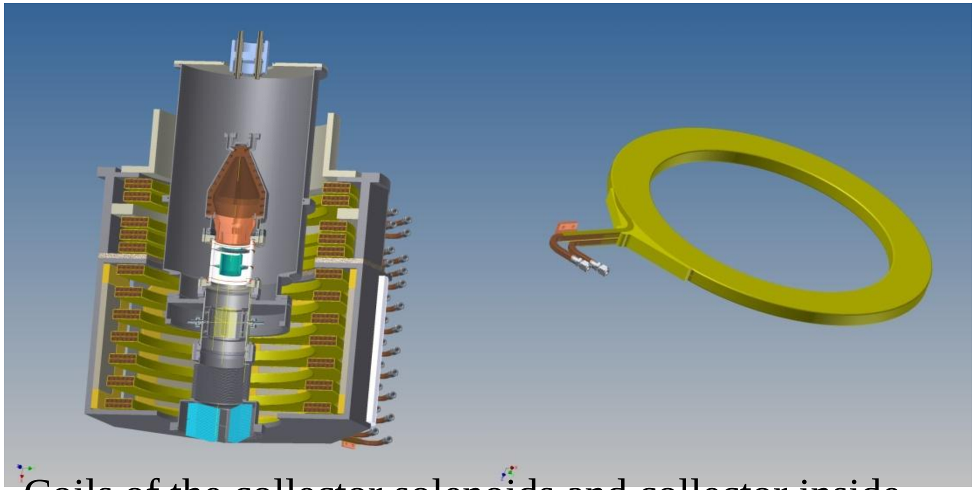
Parameters of the power supplies of the magnetic elements of COSY cooler

Магнитные системы с общим источником	Поле kG	Ток A	V	kW
1. Соленоид охлаждения	**до 2**	**350**	**290**	**100**
2. 50°тороид и 40° тороид пушки Соленоид перехода пушки 50°тороид и 40° тороид коллектора Соленоид перехода коллектора	**1.5**	**800**	**240 (120+ 120)**	**192**
3. Соленоиды пушки и коллектора	**~2**	**1100**	**50**	**55**
4. Диполь пушки и коллектора	**~3**	**300**	**130**	**40**





Coils of the toroids solenoids and toroid assembling



Coils of the collector solenoids and collector inside magnetic system

Coils production

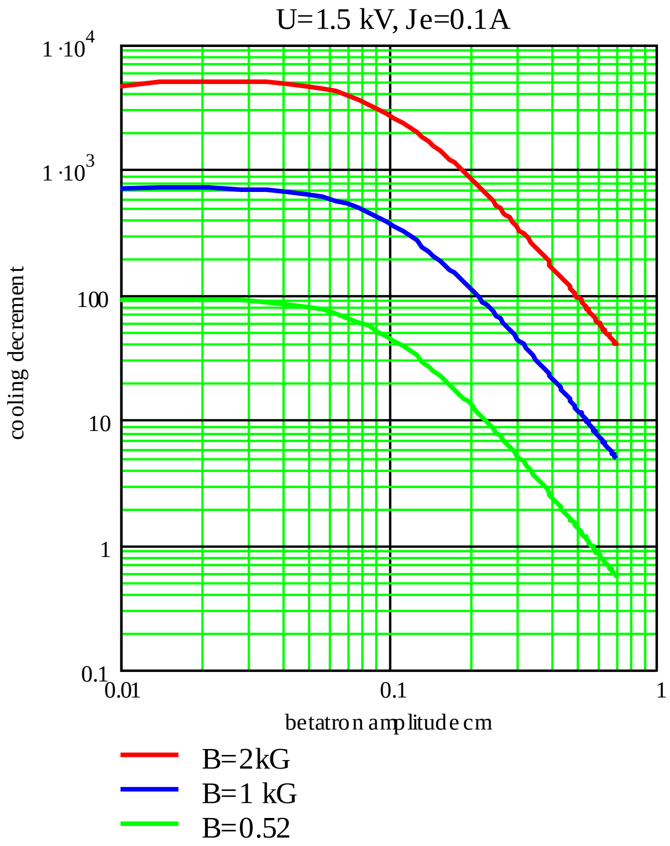
Cooler manufacturing at BINP workshop

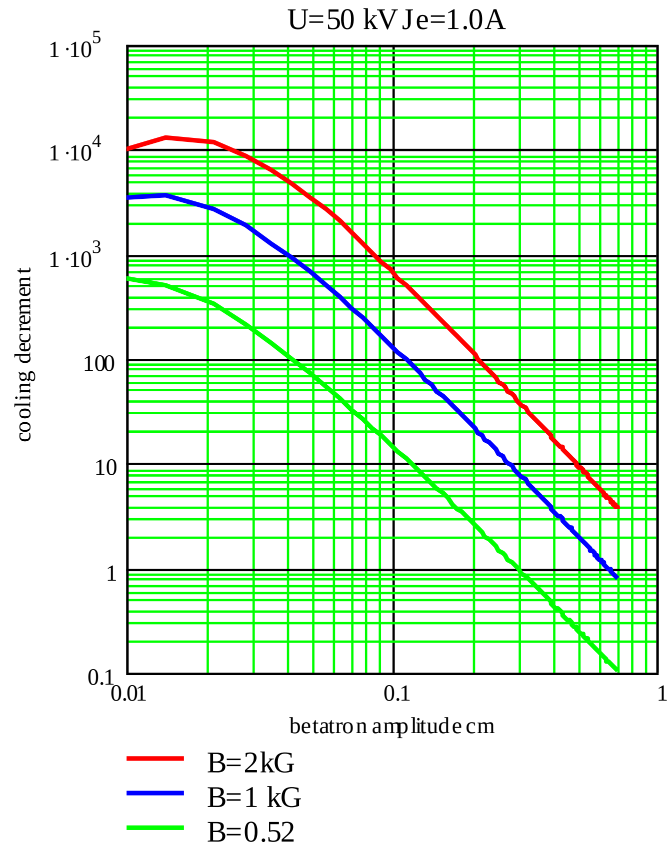
support frame (upside- position)

cooling section magnet yoke at welding area

adjustable supports

bent workpieces for toroid magnets



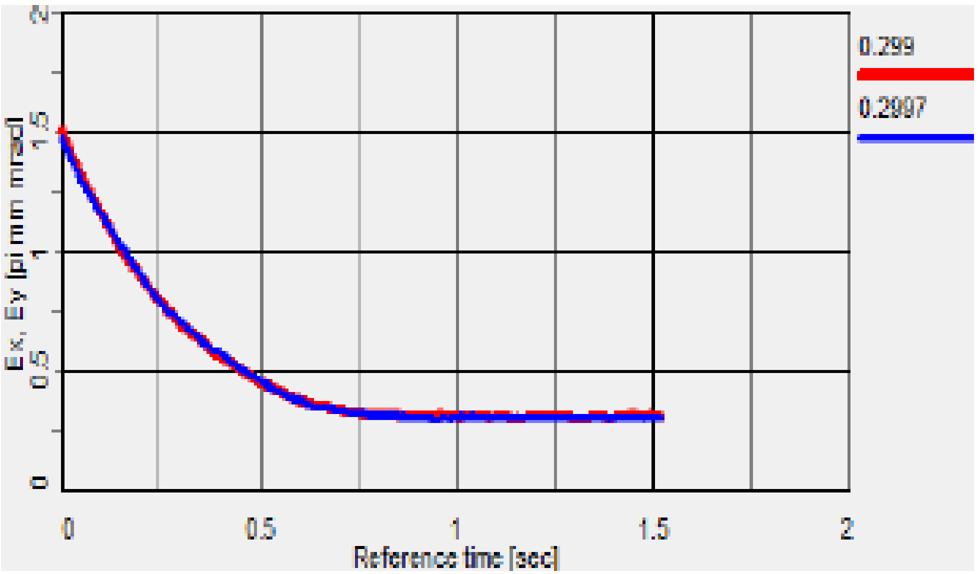


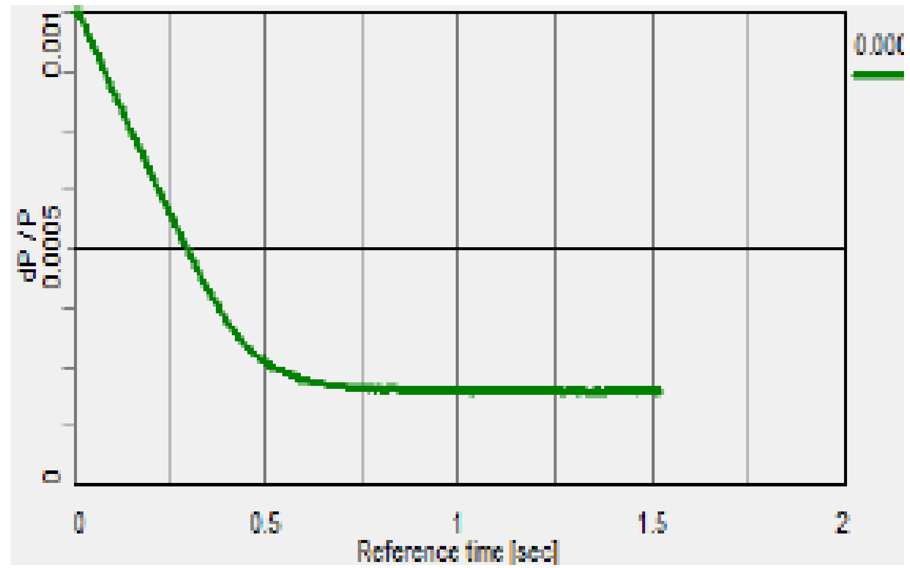
Operation regime

Comparison of the cooling rates at the electron energy 1.5 and 50 kV.

One can see that the cooling time better than 1 s is possible to Au(197,+31) with emittance 5 mm*mrad.
The principal question is the space charge and the injection capability of the injector and ion source. There is probability to have electron cooling a few times. The first is cooling at the injection energy the second is cooling at high-energy.

During 1 sec the cooling is possible at the injection energy.





Evolution of the parameters of the bunching beam in time of the electron cooling. The energy of ion $^{197}Au^{32+}$ is 3 Mev/n,The left picture is horizontal(red curve) and vertical (blue curve), the right picture is momentu, spread. The calculation was done with taking into account effects electron cooling and IBS.

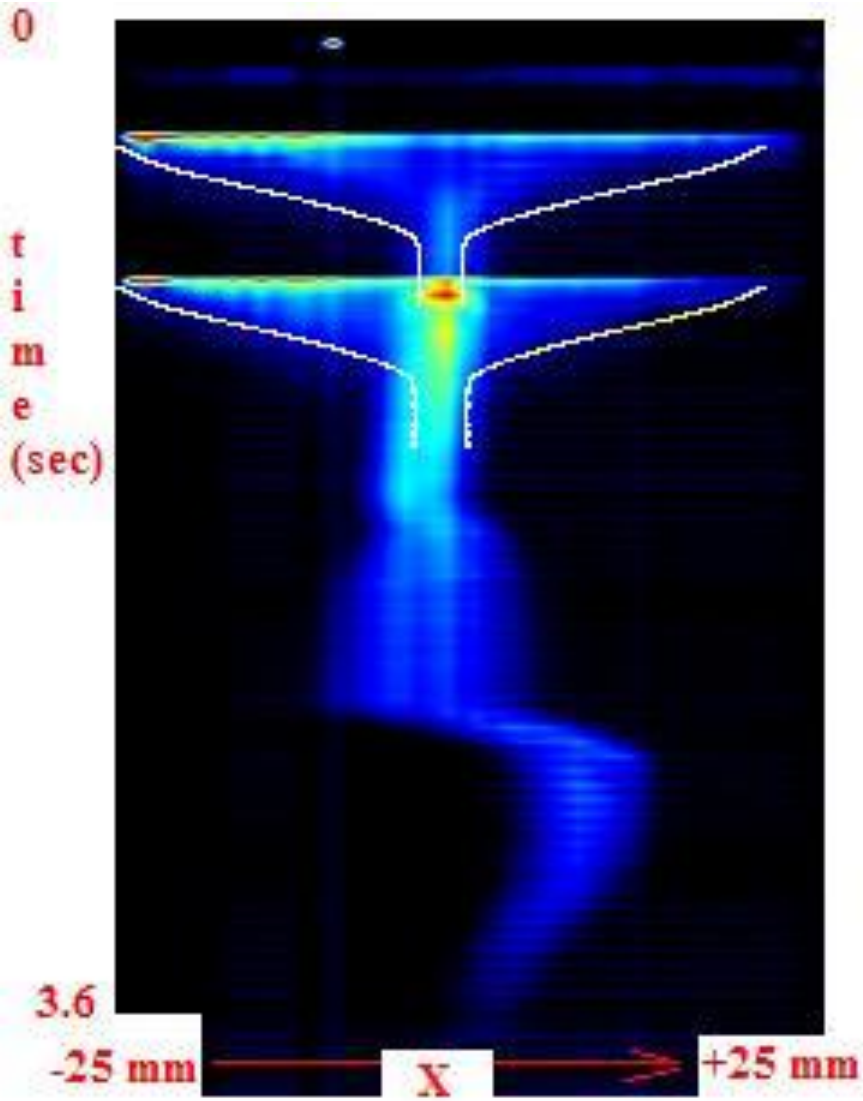
Trubnikov G.V. Synchrotron of relativistic heavy-ion NUCLOTRON in acceleration complex NICA

Working cycle of the LEIR (CERN)

LEIR try to have a few injection cycle

Green line – electron current at the cooler. (It is on just before injection and off after ion beam accumulation).
Yellow line – number of ions captured in storage ring.
Pink curve – magnetic field at the ring during cycle (injection, storage, RF, acceleration).

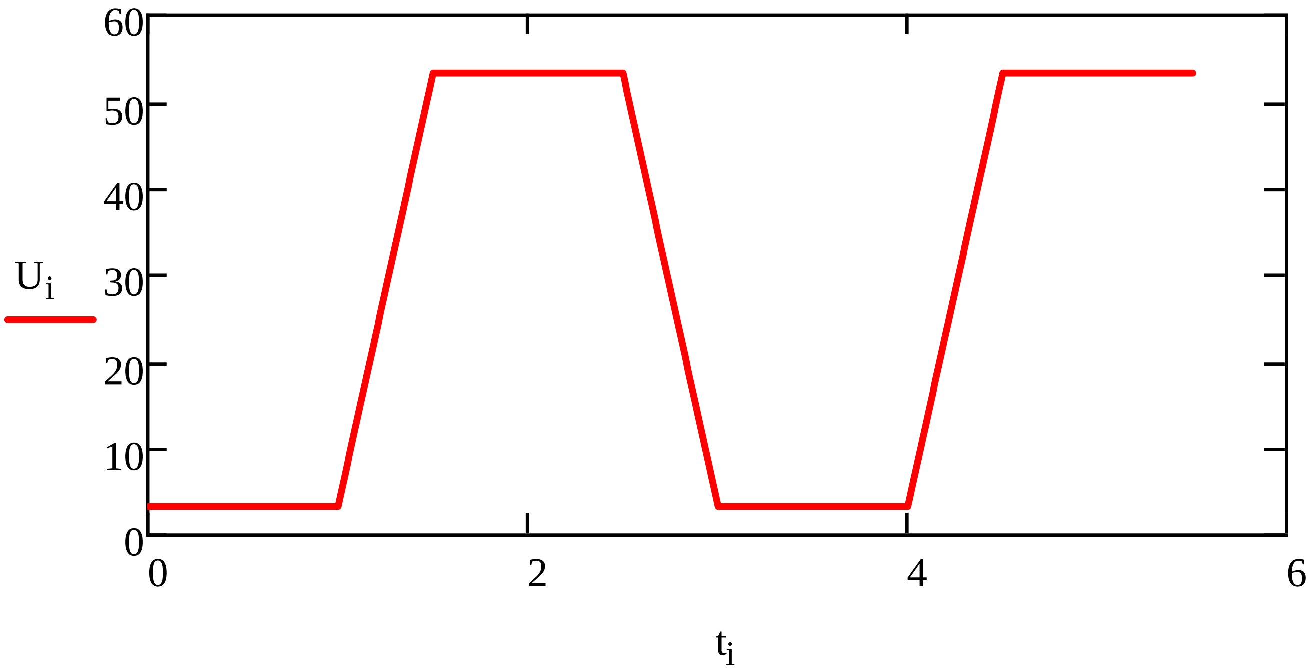
Lead ion beam cooling process at injection energy (LEIR)



After every of two injection pulses ion beam shrinks dramatically forming narrow “cord”.
It gets wider after the cooling is off due to intrabeam scattering.
During acceleration the ion beam gets narrower again due to adiabatic “cooling”.

This picture proves that cooling at injection energy provides reliable operation of the NICA booster since its parameters are similar to LEIR.

Proposed cycle of the electron beam energy at the cooler



BINP team popularizes the idea to have two cooling plato.

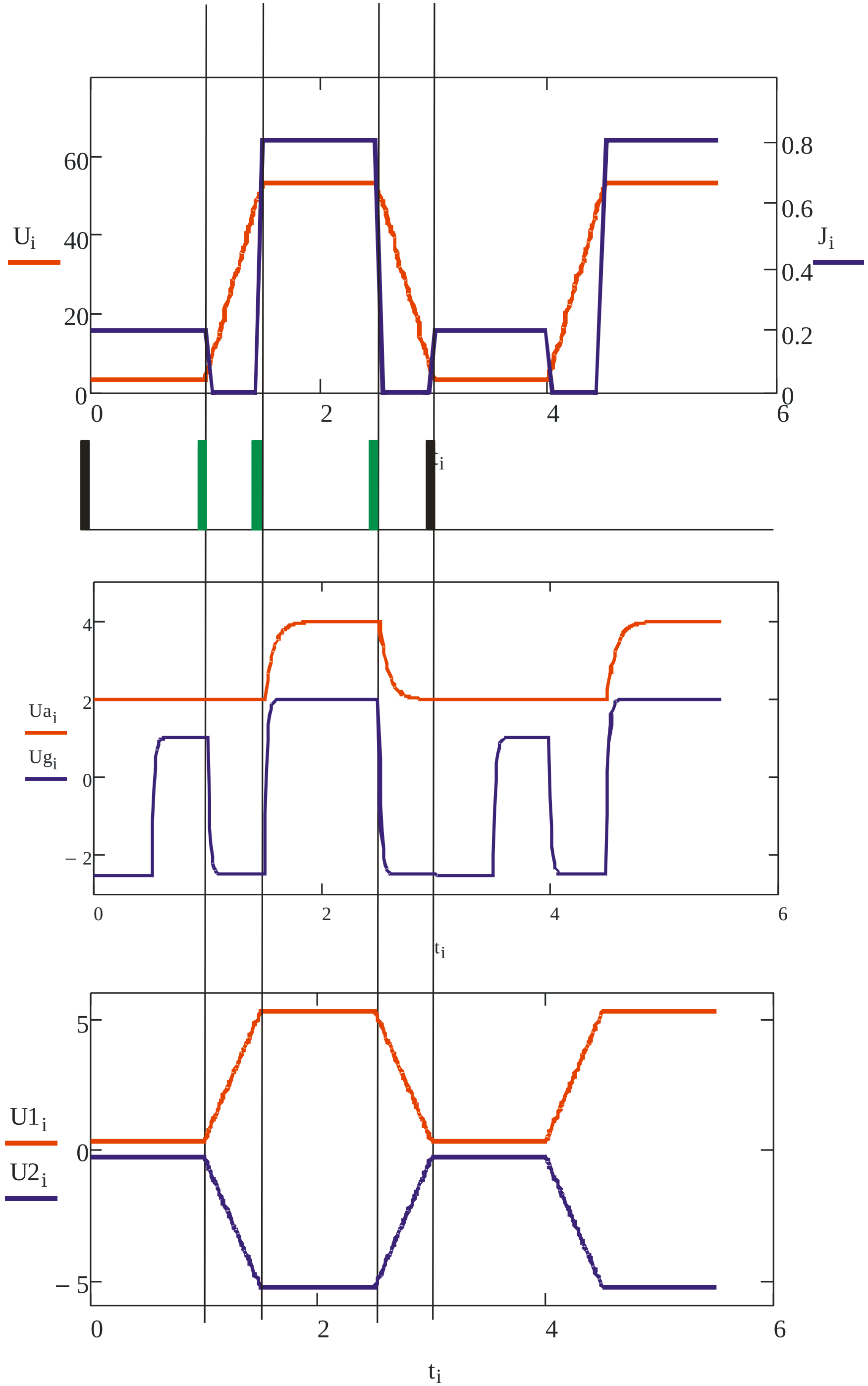
It requires essential efforts in the electronics but it give more flexibility to cooler operation.

Correspondent working cycle of the NICA Booster contains following:

Plato at injection energy sufficiently long for **cooling** (about 3 keV electron energy)
Preacceleration up to about 100 MeV/u
Plato for cooling (about 54 keV electron energy)
Acceleration up to final energy

Such a double-step scheme provides accumulation of ions even if there is a problem with ion source intensity. On the other hand this scheme demands complicated electronics for the Cooler.

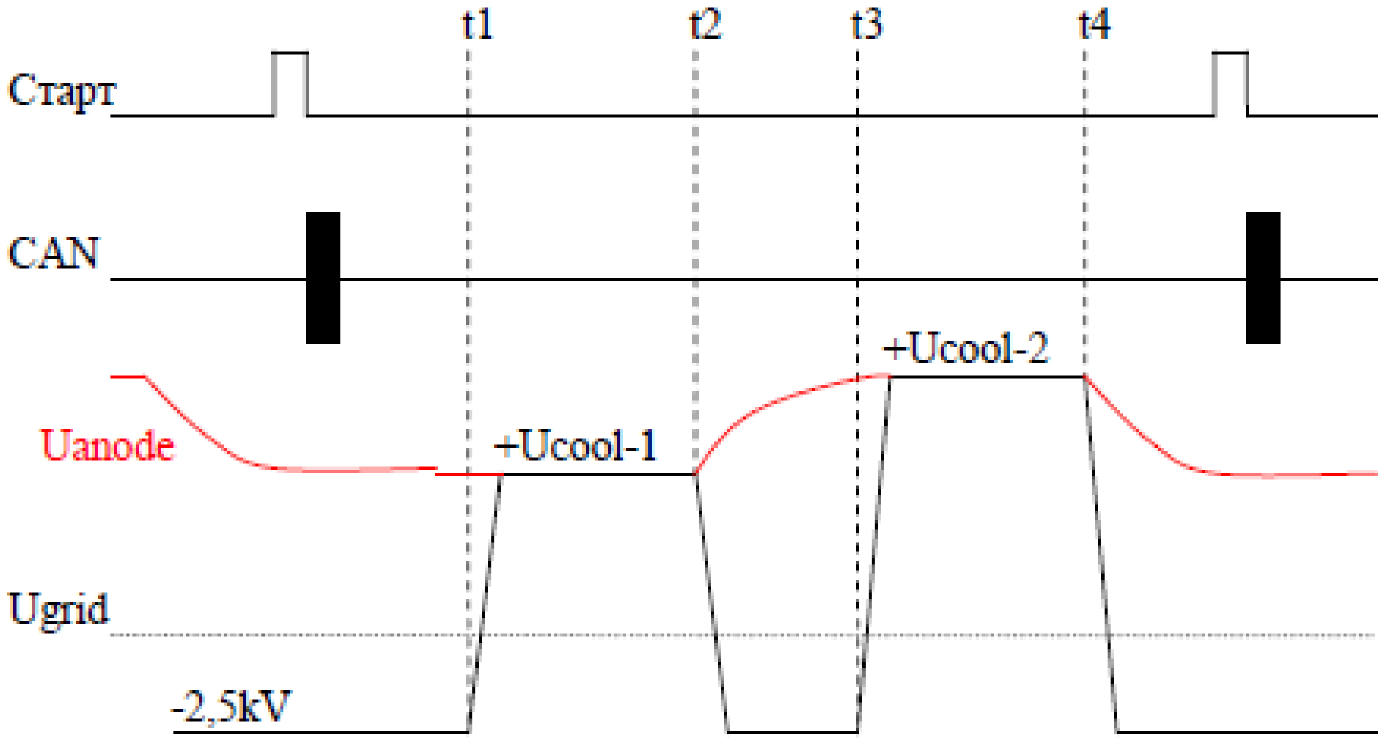
Synchronization of the different subsystem of the cooler



High-voltage and electron current

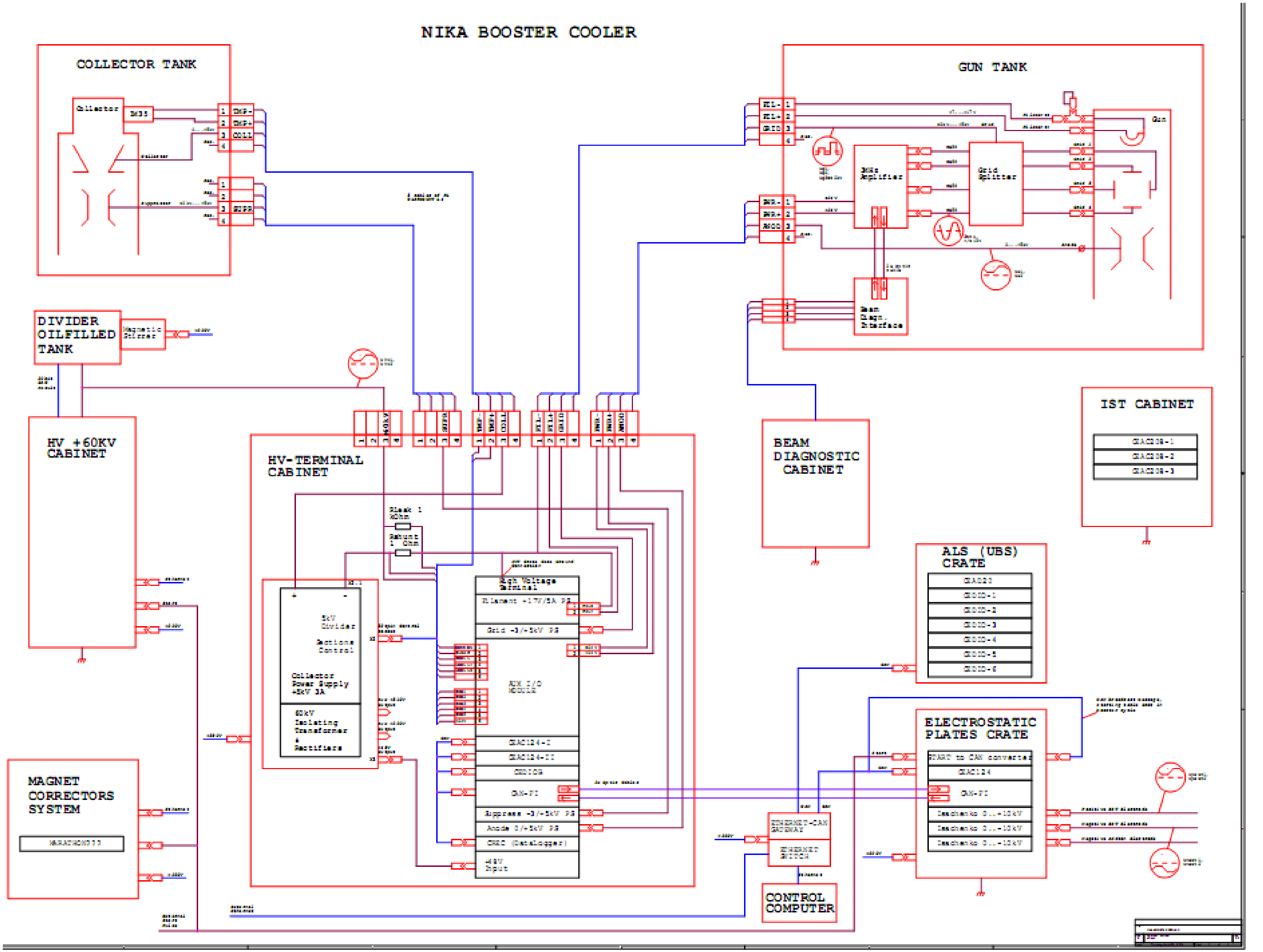
Grid and anode potentials

Electrostatic plates



The time diagram of the voltage in the cooler can be realized with the mechanism of the table operation of DAC device of CAN-modules. All CAN modules is started by one broadcasting data packet. For example, the figure shows the time diagram of gun power supplies. So, it needs a block that can send the start CAN message at time of the analog start impulse. There is a prototype of such block that can be modernize to necessary regime. The expected jitter is about 10-20 ms that is enough for this purpose.

Electronic scheme

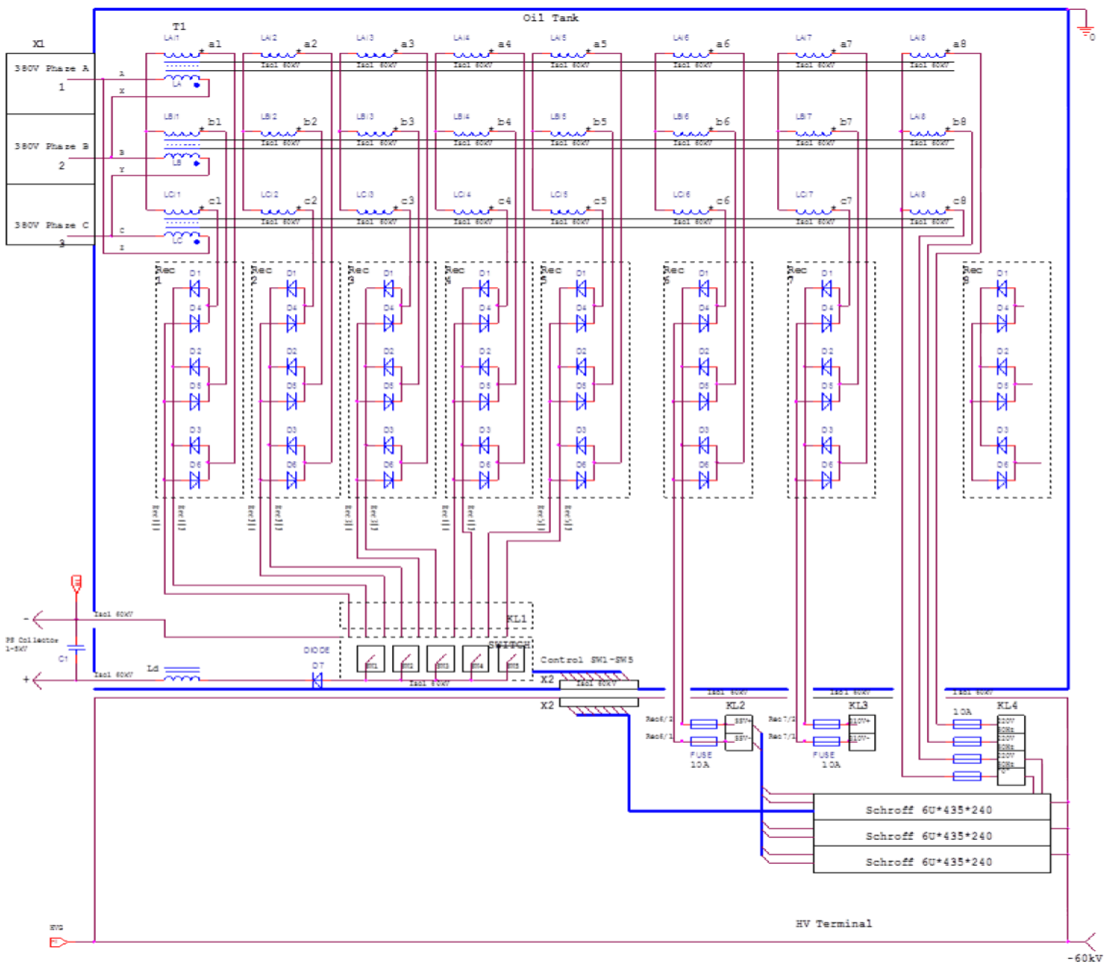


Requirements for the high voltage power supply

1	polarity	negative
2	max. voltage	60 kV (100 MeV/u; 54 keV)
3	max. current	10 mA
4	min. voltage	1.5 kV (6.2 MeV/u; 3.3 keV)
5	long term stability of the energy (54 keV) at current losses 100 μA	$\pm 10^{-5}$
6	voltage adjustment precision (54 keV)	$\pm 10^{-5}$
7	voltage ripple (54 keV) less than	$\pm 10^{-6}$
8	voltage stability at current losses 10 mA	10^{-2}
9	stability of the energy (3.3 keV)	10^{-3} or better
10	energy adjustment precision(3.3 keV)	10^{-3} or better
11	energy ripple (3.3 keV)	10^{-3} or better
12	voltage adjustment time	0.5 s
13	стабильность привязки к заданному времени цикла бустера	50 ms
14	Working cycle	Cycles with period of 2-6 s, two voltage platos (одно в районе инжекции, другое в области E-cooling).

High-voltage power supply of the collector and the others power supplies of the high voltage terminal is designed on base high power 3 phase transformer 3*380V, 50 Hz. The high voltage rectifier is combined with 5 high-voltage non-regulate rectifiers with voltage 1 kV. This rectifiers may connected in series with high-voltage switch. In order to avoid voltage jumps on the filter inductance the commutation of the switch is possible only at zero electron current.

The magnetic circuit of the transformer is made with anisotropic electro-technical bend 3408 with thickness 0.3 mm and technology UNICORE. The transformer submerge in oil for cooling and high-voltage isolation with 60 kV.



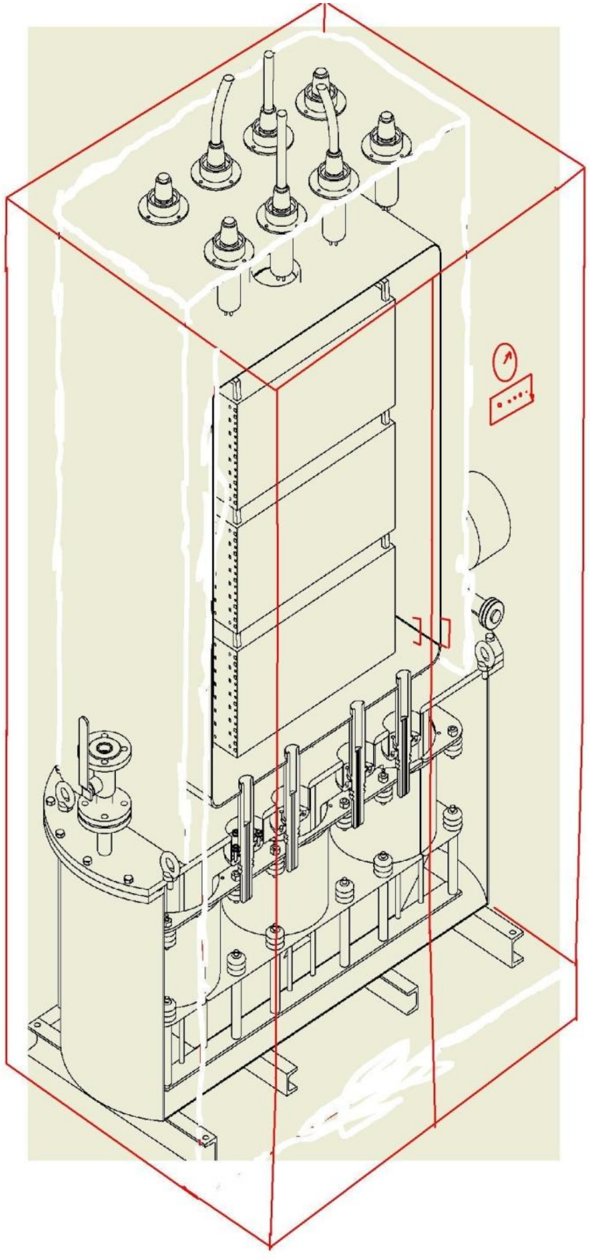
D7	Diode (Urev 6-10kV, I for RMS 3A)
X2	2PMG24B19H1E2
X1	2PMG22B4H3E2
SW1-5	G41C-334
FUSE 1-8	DVP4-4V
Ld Drossel	K ripple suppres =10, For Ld=1H 500 Vitkov PETV-2, 1.30/1.41
C1	K75-47 2.2mkF*6.3kV
	Rectifiers 1-8 Most 3Phase 15A,1400V tipe TBR1514
	LA/8, LB/8, LC/8 41 Vitka, PETV-2, 1.30/1.41
	LA/7, LB/7, LC/7 25 Vitka, PETV-2, 1.30/1.41
	LA/6, LB/6, LC/6 4 Vitka, Shinka 1.6*4.75
	LA/1-LA/5, LB/1-LB/5,LC/1-LC/5 79 Vitka, PETV-2, 1.30/1.41
	LA, LB, LC 64 Vitka, Shinka 1.6*4.75
T1	MNT3-220*190*140*140 ST3408 GOST 214271-1-83 8.36 V/Vitok

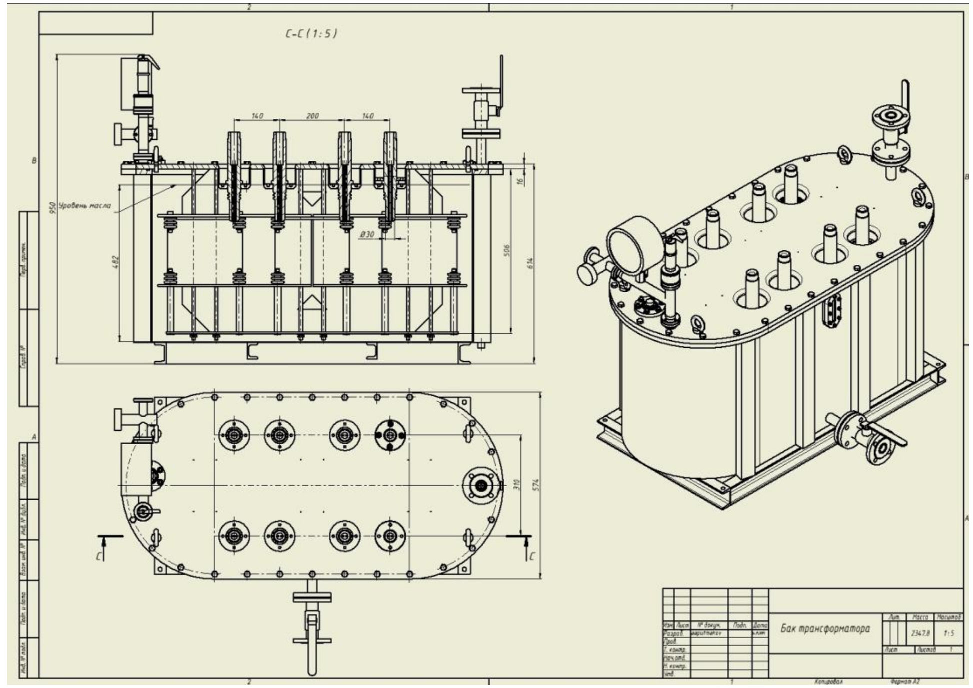
A.D.Goncharov

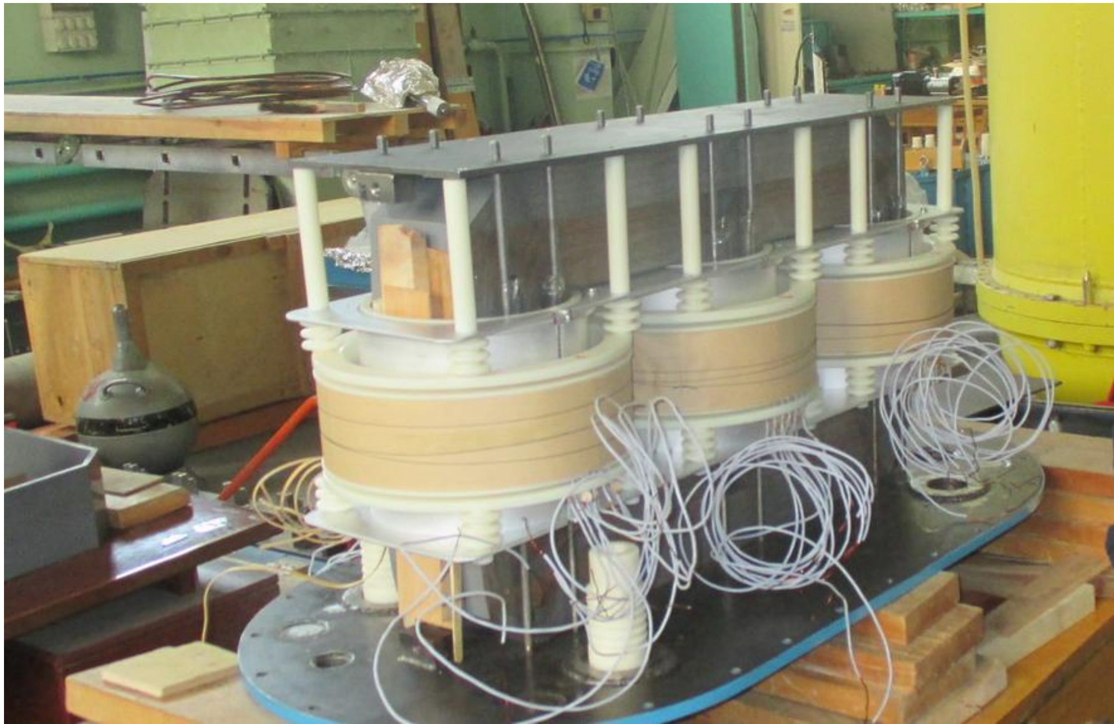
Title <Title> Rectifier 5kV, 15kWt, Isolate 60kV

Size A3 Document Number <Doc> Rev <RevCode>

Date: Tuesday, November 26, 2013 Sheet 1 of 1



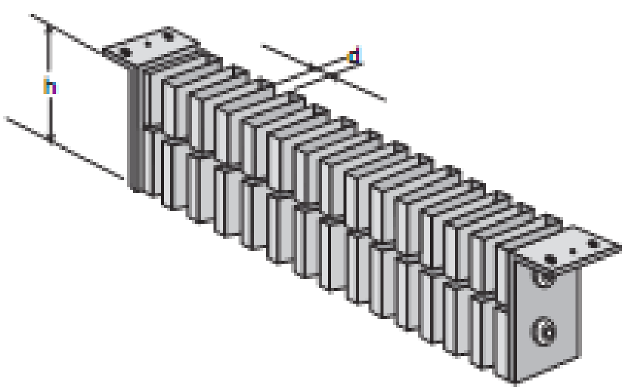

C–C (1:5)
Уровень масла
140
200
140
Ø30
950
482
506
614
16
310
574
Бак трансформатора
Лит.
Масса
Масштаб
2347.8
1:5
Лист
Листов 1
Изм.
Лист
№ докум.
Подп.
Дата
Разраб.
Пров.
Т. контр.
Нач. отд.
Н. контр.
Утв.
Копировал
Формат A2



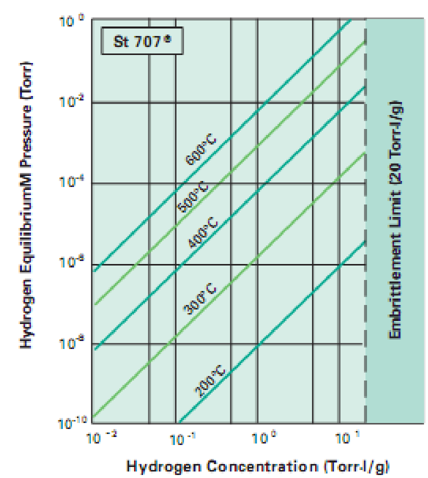
The tradition of the heavy-ion storage rings is high requirement to the vacuum condition. LEIR storage ring has requirement to vacuum $p<1\text{-}2*10^{-12}$ Torr Pb^{+54}. The reason is high-outgasing capability of heavy-ion. Pb^{+54} 1 ion release from vacuum chamber by desorption 10^4 atoms, for comparison 1 electron release only $0.1\text{--}10^{-7}$ atoms. So, the beam losses to the vacuum chamber can lead to explosive degradation of the vacuum, because the vacuum degradation. The loss of ion leads results in decrease of the life time and increase of the ion flux to the vacuum chamber.

The vacuum chamber is close to LEIR, COSY, CSRe design but there is some features. The vacuum chambers of the gun and collector are supplied by the pick-ups for more accurate measurement of the electron beam dynamics. The vacuum pumping of the gun and collector is done with by the getter wafer modules. The toroids chambers are equipped by titanium evaporable getter pumps, two ion pumps are connected with toroids chambers.

The pressure increase within cooler results mainly from the electron current losses, which therefore should be kept as low as possible in a good collector. The ecooler will be entirely bakeable to 200-300ºC and designed according criteria for ultra-high vacuum (special steel, vacuum firing etc.). Planning level of the vacuum is 10^{-11} torr.



	WP 750
Surface of the strip (cm^2)	870
Substrate thickness (mm)	0.2
Powder Coating thickness on each side (microns)	70
Total mass of St 707® alloy (g)	33
Electrical resistance (Ω)	0.16
Approximate total weight (g)	295
Overall dimensions (mm): total length	207
active length	145
width	50
height	30



Getter wafer modules WP750 are used (three ones for each chamber) are used for pumping gun and collector vacuum chambers

Vacuum in collector

Bombardment of the collector surface by an intensive electron beam leads to outgassing. For the electron current of J_e=1 A and the pumping output of the vacuum system (ions pump and NEG) of 10^4 l/s a vacuum of 1×10^{-11} torr can be obtained only in the case of desorption efficiency equal to:

$$N_{des}/N_e = \eta_d = 1\times10^{-11}/(1/1.6\text{x}10^{-19})\ 3.29\times10^{16}\times10000\times1000 = 3\times10^{-7}$$

Such a low value of desorption efficiency may be found only with a collector trained for many hours with bombardment by an intensive electron beam. The practice of electron coolers shows that the desorption efficiency of a good baked stainless steel wall may be evaluated as

$$\eta_d = \frac{10^{-2}}{(1 + D_e / 10^{16})^{0.68}}$$

where D_e is the dose of electrons (1/cm^2) stored in the time interval of surface training. A dose of 1.6x10^{24} 1/cm^2 is accumulated in 3 days at 1 A electron current on a surface of 10 cm^2, and the desorption efficiency drops down to 2.6×10^{-7}

Vacuum in cooler

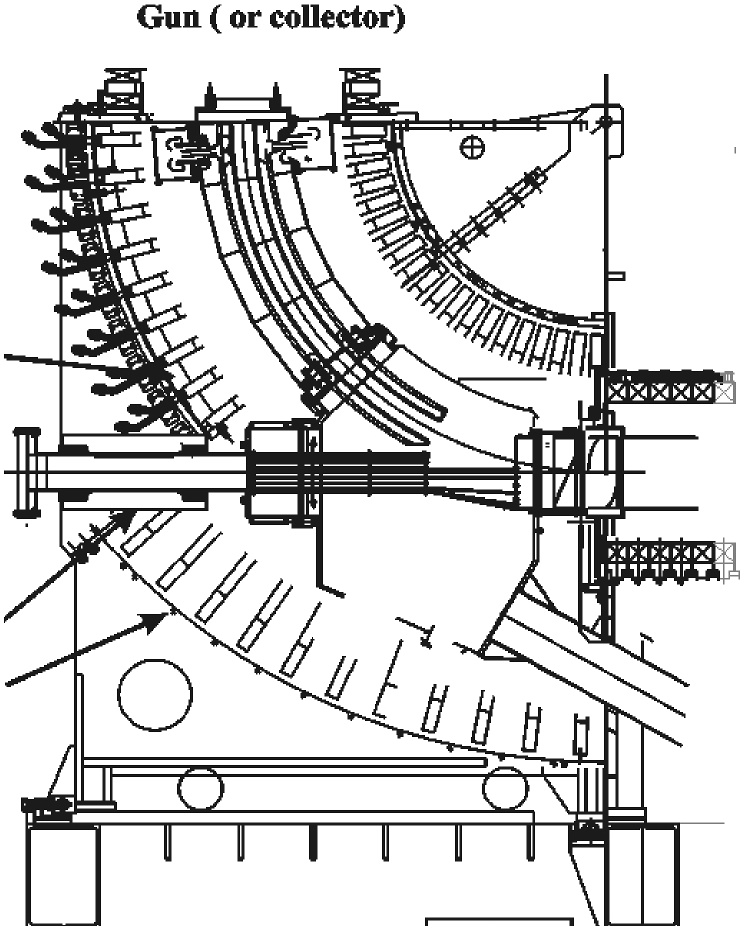
The cooling section surface is too large to obtain a low desorption. The high intensity of the cleared electron beam determines its high losses. This value usually makes about 5 mA. If this current is distributed along all the surface of the cooling section of 3m*π (0.1m)^2 =0.1 m^2 =10^3 cm^2, the 10 days dose will comprise about 2.7x10^{19} 1/cm2 and the desorption efficiency will be 5x10^{-5}. For a current of 1 mA the dynamic pressure corresponds to 10^{-11} Torr. To reach such a value, it needs many days of cleaning the vacuum chamber. A low energy electron beam with magnetic field variation along the beam may be used to make this procedure more effective. It is possible to switch off part of the magnetic system and clear a specific part of the vacuum chamber by electron beam. This technology has been tested at FNAL for the high voltage electron cooler.

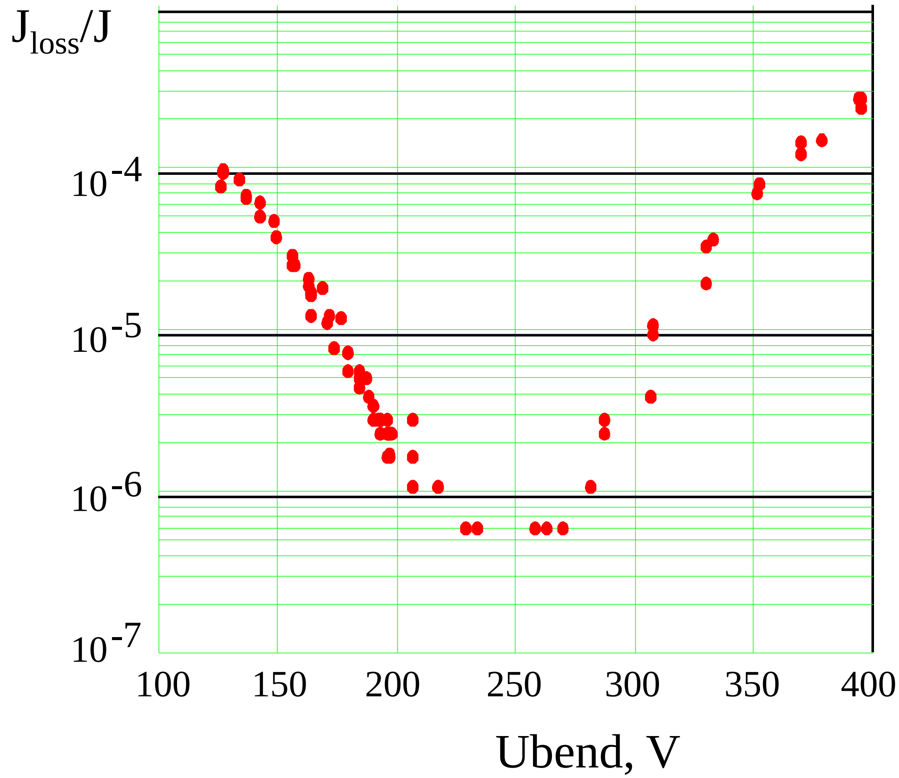
Electrostatic bending for compensation drift electrons

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

E=0 magnet bending B=pc/eR

B=0 electrostatic bending E=pV/eR

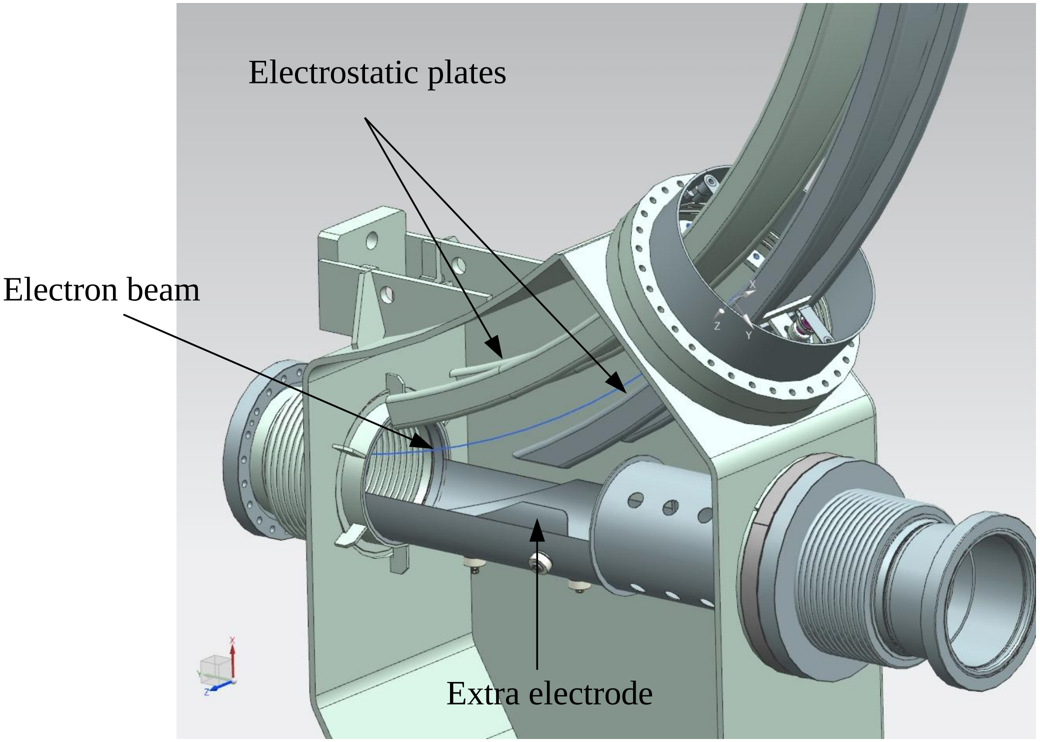




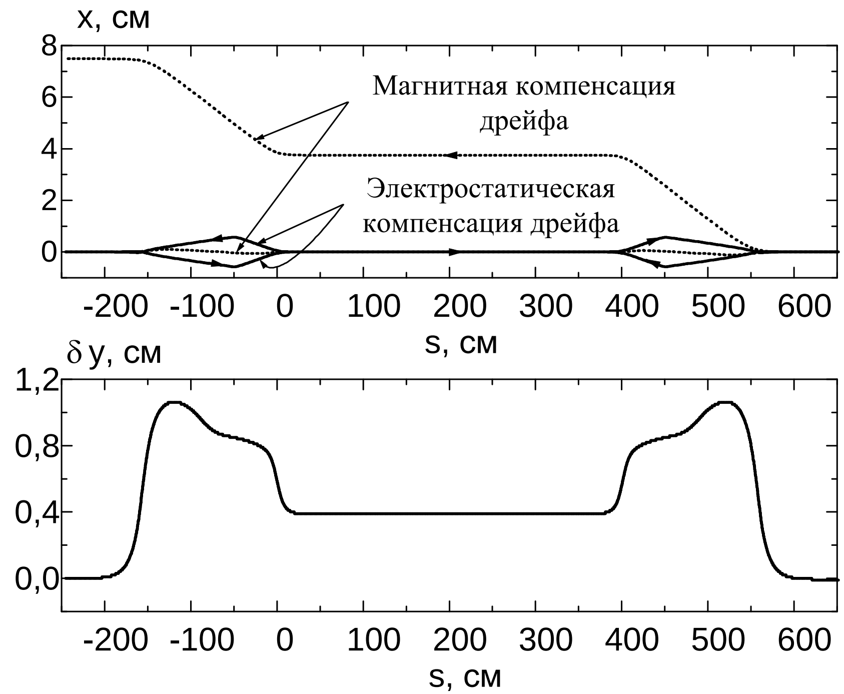
0 - voltage is magnet field bending, 250 V- pure electrostatic bending. we keep position of electron beam the same increasing voltage and decreasing magnet field

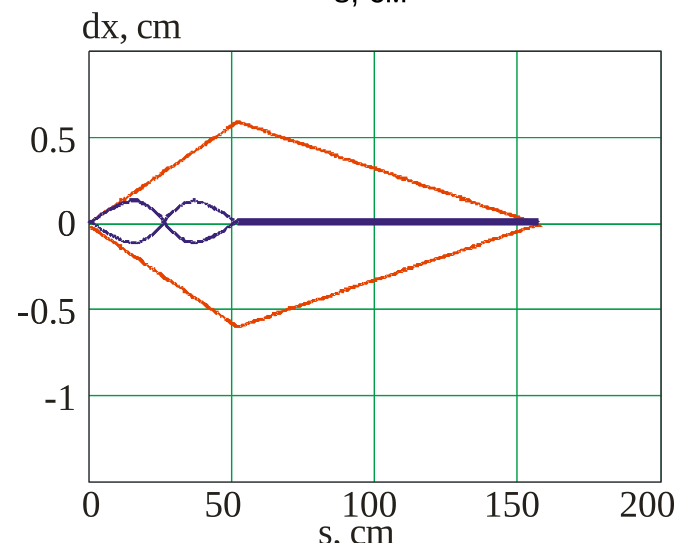
small leakage current means a good vacuum

Electrostatic bending with an extra electrode



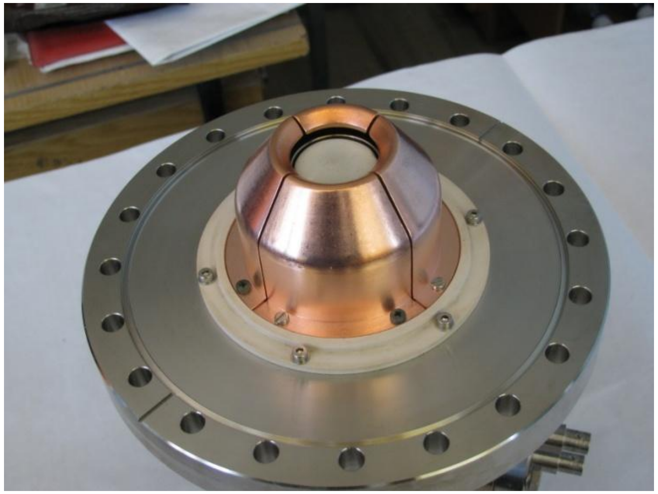
Up to 12kV voltage applied to electrode

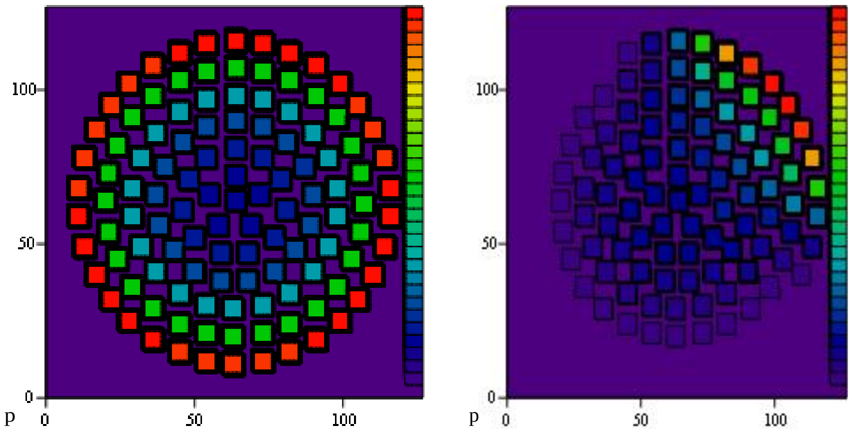




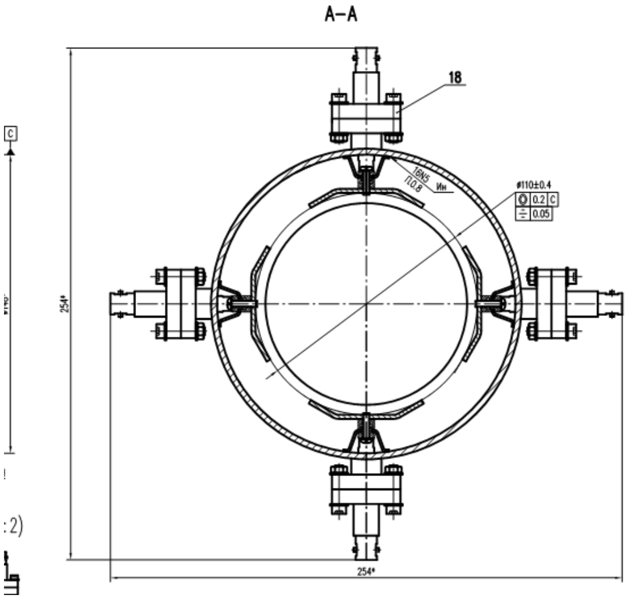
Main goal is reducing transverse shift of the rejected electrons for improving of the recuperation coefficient

Four – sector control electrode for the electron gun





3D simulation of the electron beam profile for DC current: four sectors on the left, one sector on the right.



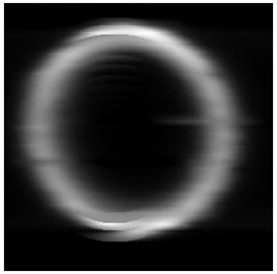
Main purpose is the proper shape and position near collector. Precise fall into the collector – small leakage current and good vacuum condition.

The recombination of heavy-ions is a problem of the electron cooler devices. The change of the charge state results change equilibrium orbit of the particle and losses it. The recombination rate depends from the charge state of ions, transverse temperature of the electrons and the density of the electron beam. The recombination can be suppressed by the different ways.

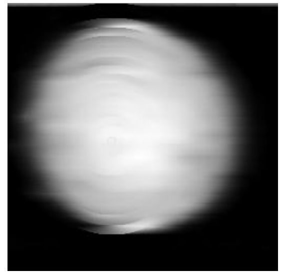
1. Avoid the charge state with resonance recombination
2. Excitation of the transverse motion of the electrons
3. Standard decision proposed by BINP team is the variable beam profile of electron beam

1999 Idea of variable profile electron gun:

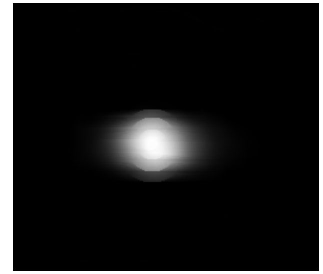
THE ELECTRON GUN WITH VARIABLE BEAM PROFILE FOR OPTIMIZATION OF ELECTRON COOLING,



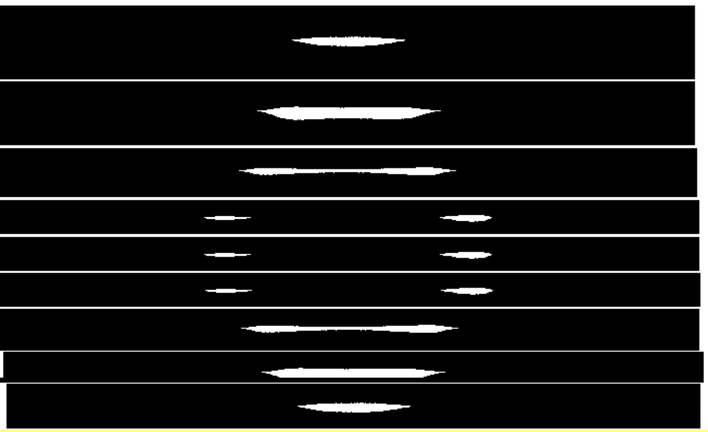
+2kV



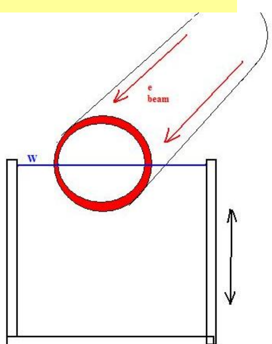
0 kV

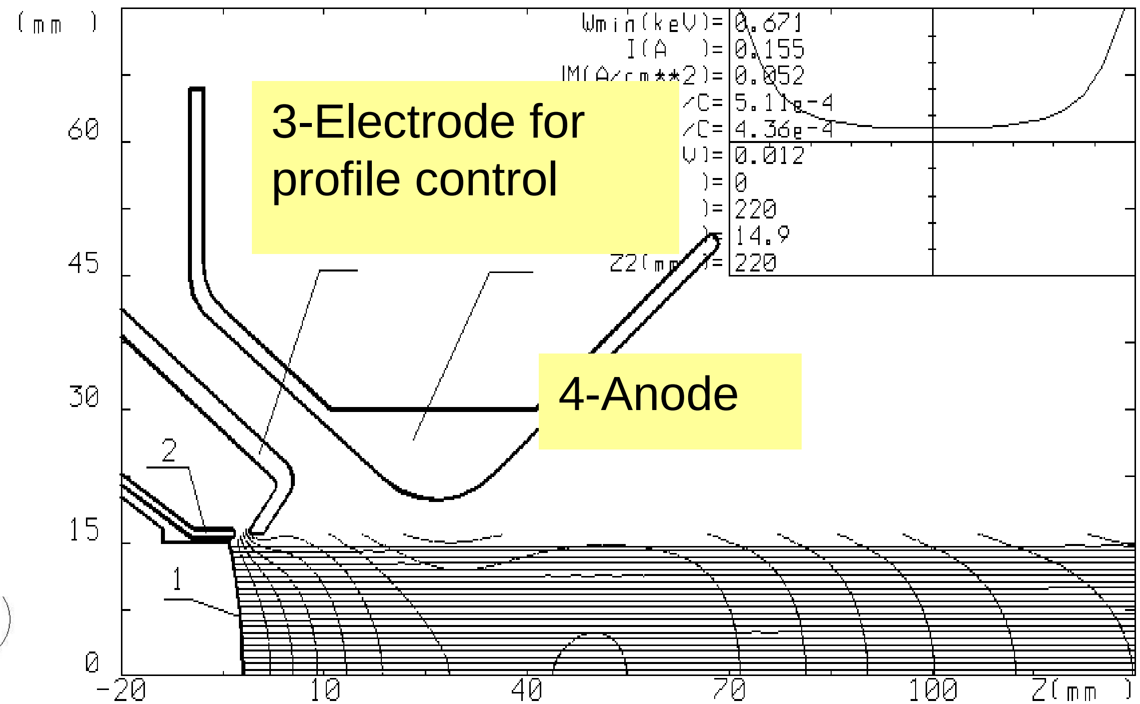


-0.5 kV



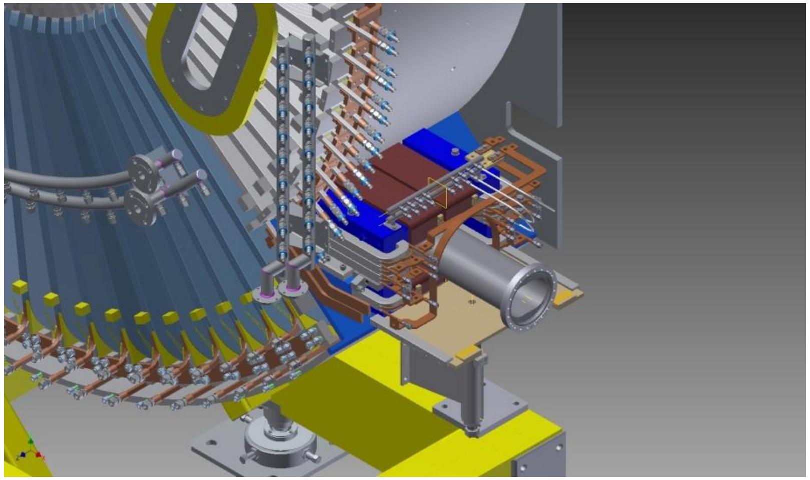
Photos of tungsten wire at different position inside electron beam

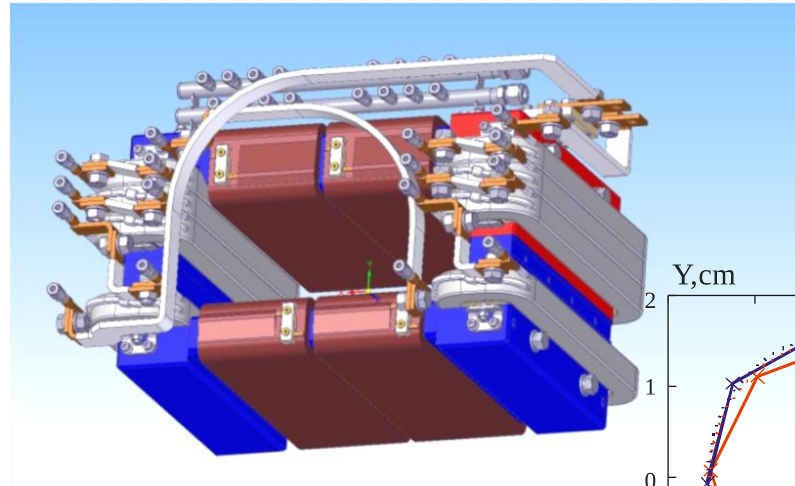


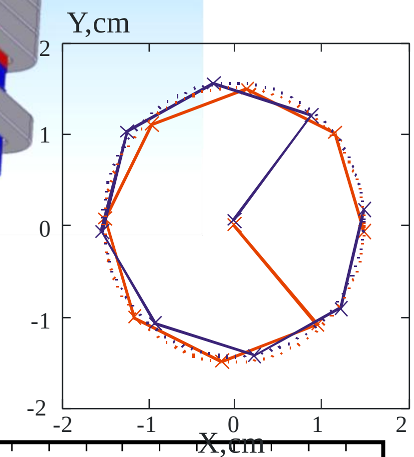


Positive voltage on electrode 3 increases emission at external hoop.

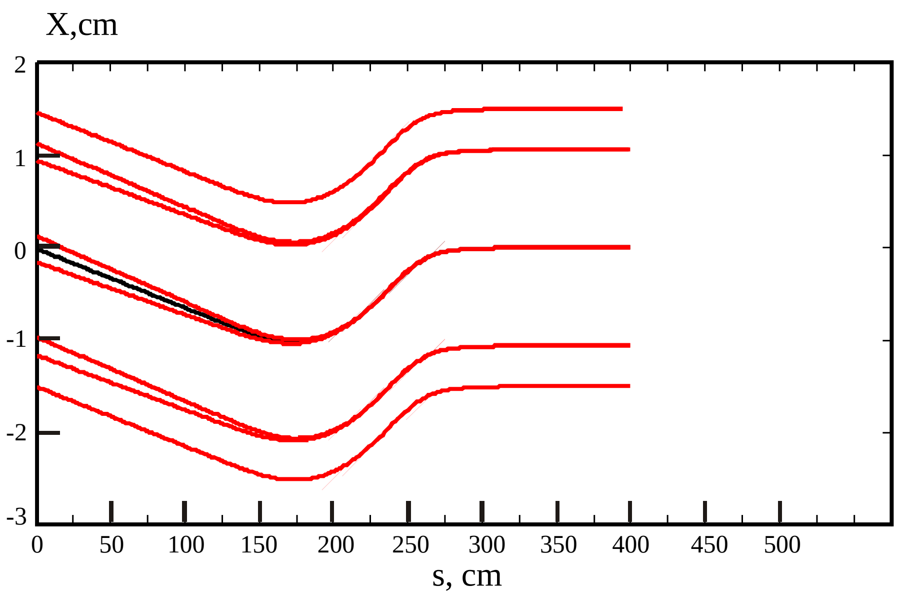
Ion beam correction

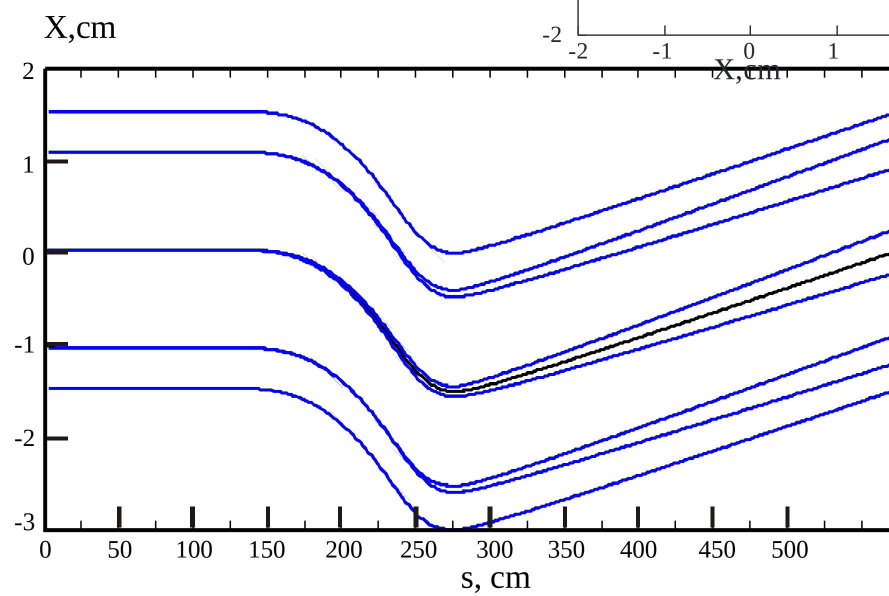




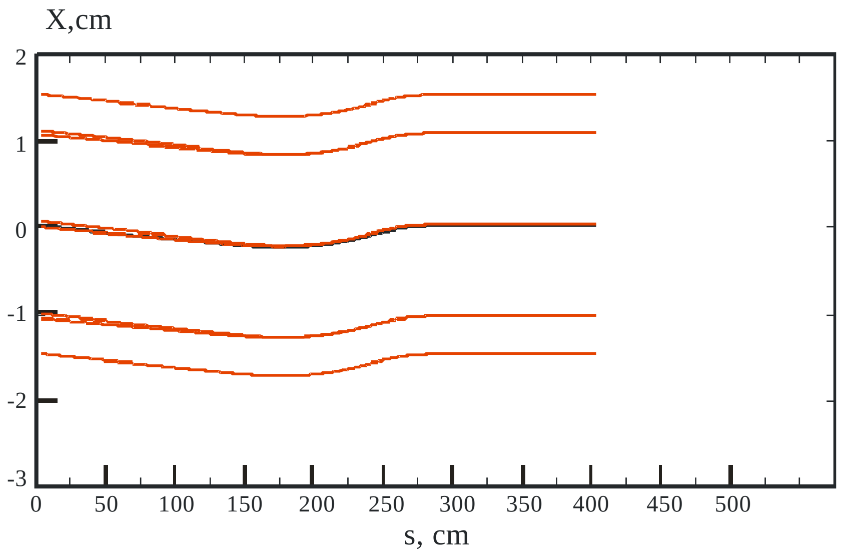


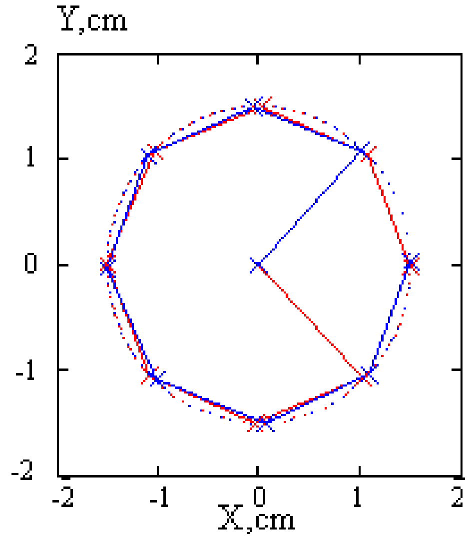
$^{197}Au^{31+}$, 6 MeV/n, injection energy





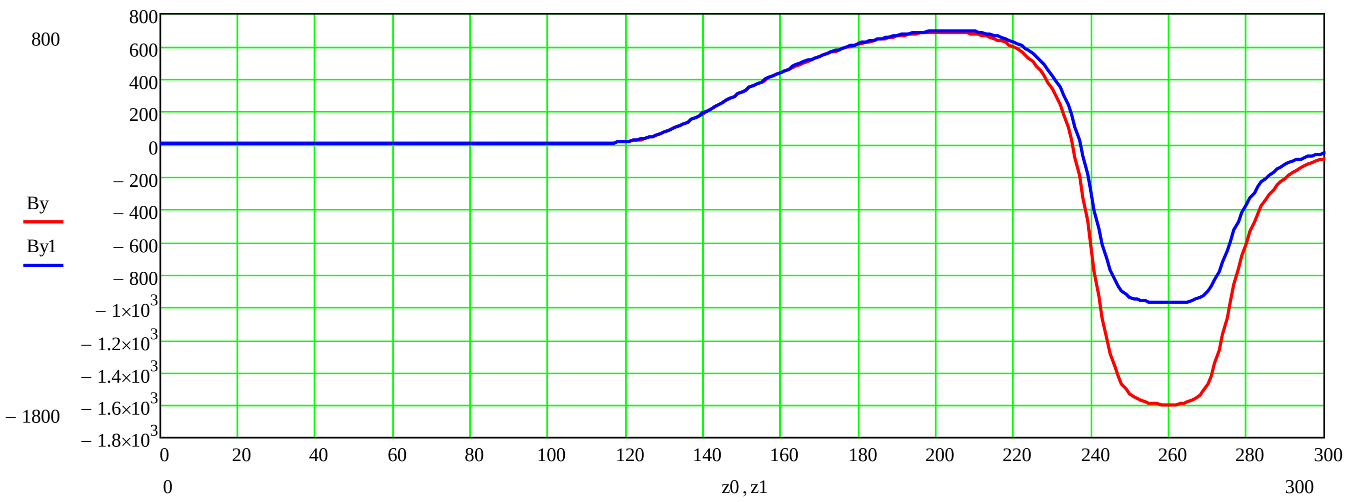
$^{197}Au^{31+}$, 92 MeV/n, injection energy





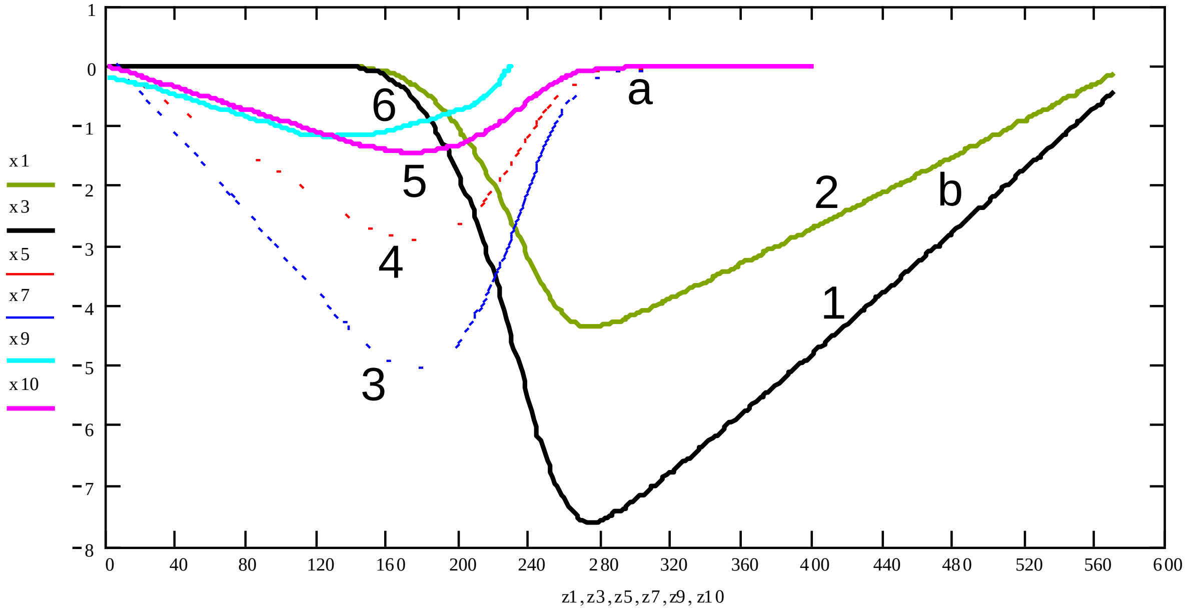
Trajectory of the particle at the energy 92 MeV/n

Magnetic field of the cooler is not ramping because it is tuning if the equilibrium orbit during acceleration cycle



Profile of the vertical magnetic field along axis of the electron cooler

Поле соленоида Bsol=1,5kG, поле пушки Bgun=2.5kG.
Конец соленоида z=128cm, центр диполя z=258cm



Вариант a – вход в диполь по оси, прохождение соленоида под углом к его оси. Поле диполя Bdip=1.025kG. 1 – протон 10MeV, 2 – протон 30MeV.

Вариант b – вход в диполь со смещением и под углом к его оси, прохождение соленоида по оси. Поле диполя Bdip=1.945kG. 3 – протон 10MeV, 4 – протон 30MeV, 5 – дейтон 60MeV, 6 - электроны из пушки.

Summary

1. The key problems of the electron cooler for NICA is experimentally verified in the different experimentally devices.
2. The strong surprises aren’t observed and the elements of cooler are successfully manufactured in BINP for furter continue assembly and commissioning.