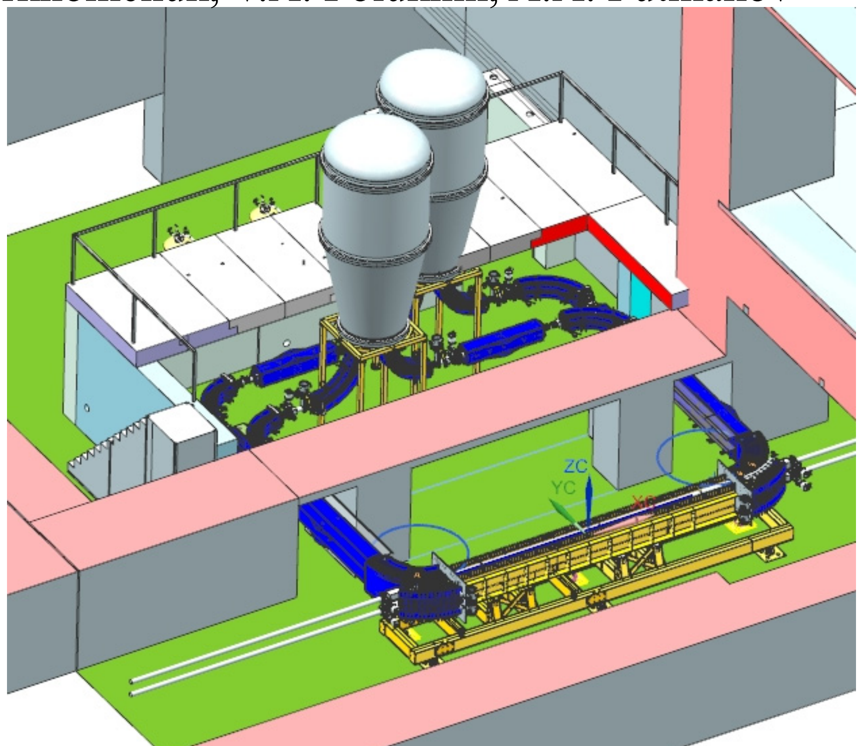
High voltage cooler NICA: Status and ideas

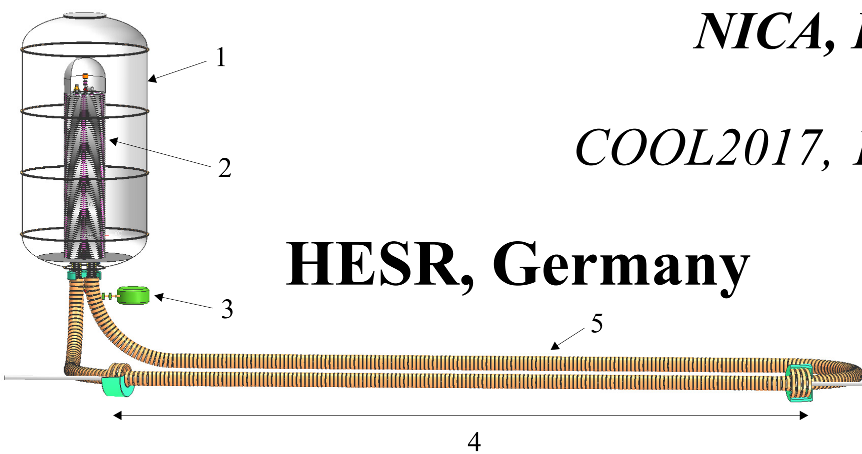
V.B. Reva, M.I. Bryzgunov, A.V. Bubley, A.D. Goncharov, N.S. Kremnev, V.M. Panasyuk, V.V. Parkhomchuk, V.A. Polukhin, A.A. Putmakov

COSY, Germany



NICA, BINP&JINR, Russia

COOL2017, 18-23 September, 2017

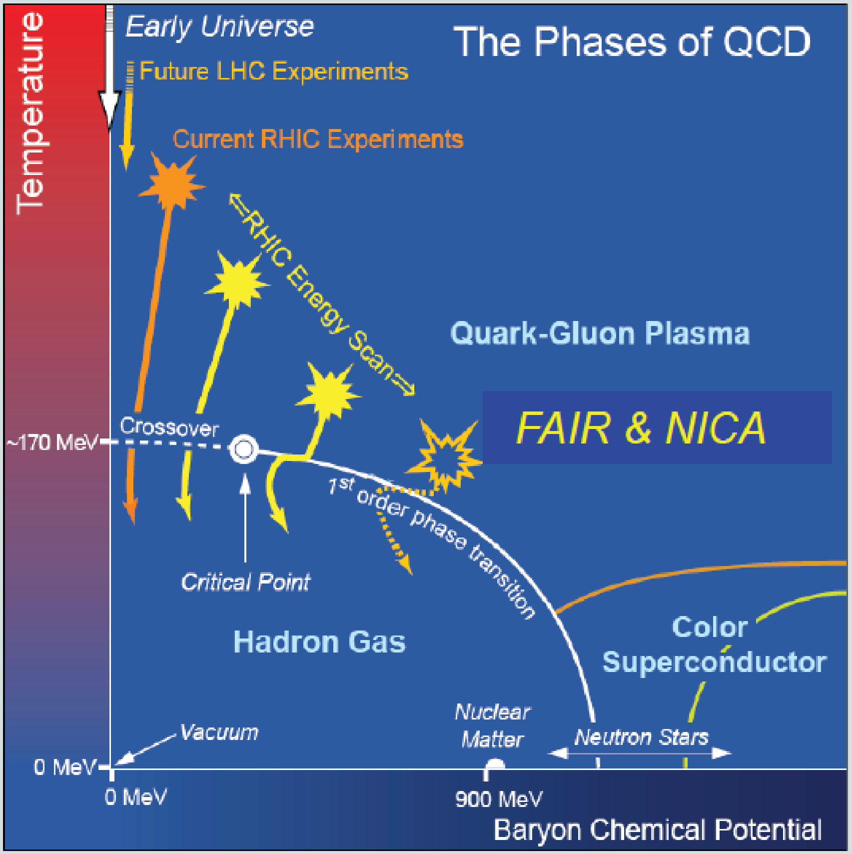


HESR, Germany

FERMILAB, USA

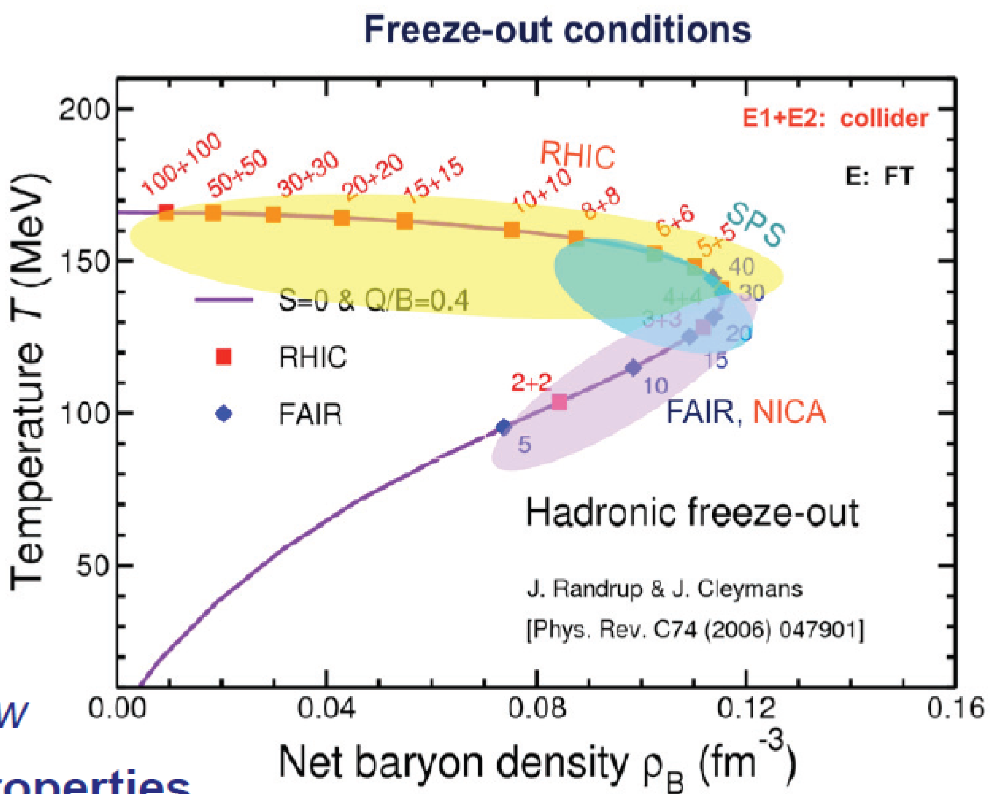
The new accelerator complex NICA is designed at the Joint Institute for Nuclear Research (JINR, Dubna, Russia) to do experiment with ion-ion and ion-proton collision in the range energy 1-4.5 GeV/u. The main regime of the complex operation is ion collision of heavy ion up to Au for study properties of dense baryonic matter at extreme values of temperature and density. The planned luminosity in these experiments is 10^{27} $см^{-2}·с^{-1}$. This value can be obtained with help of very short bunches with small transverse size. This beam quality can be realized with electron and stochastic cooling at energy of the physics experiment. The subject of the report is the problem of the technical feasibility of fast electron cooling for collider in the energy range between 0.2 and 2.5 MeV.

Physics



QCD matter at NICA :

- *Highest net baryon density*
- *Energy range covers onset of deconfinement*
- *Complementary to the RHIC, FAIR and CERN experimental programs*

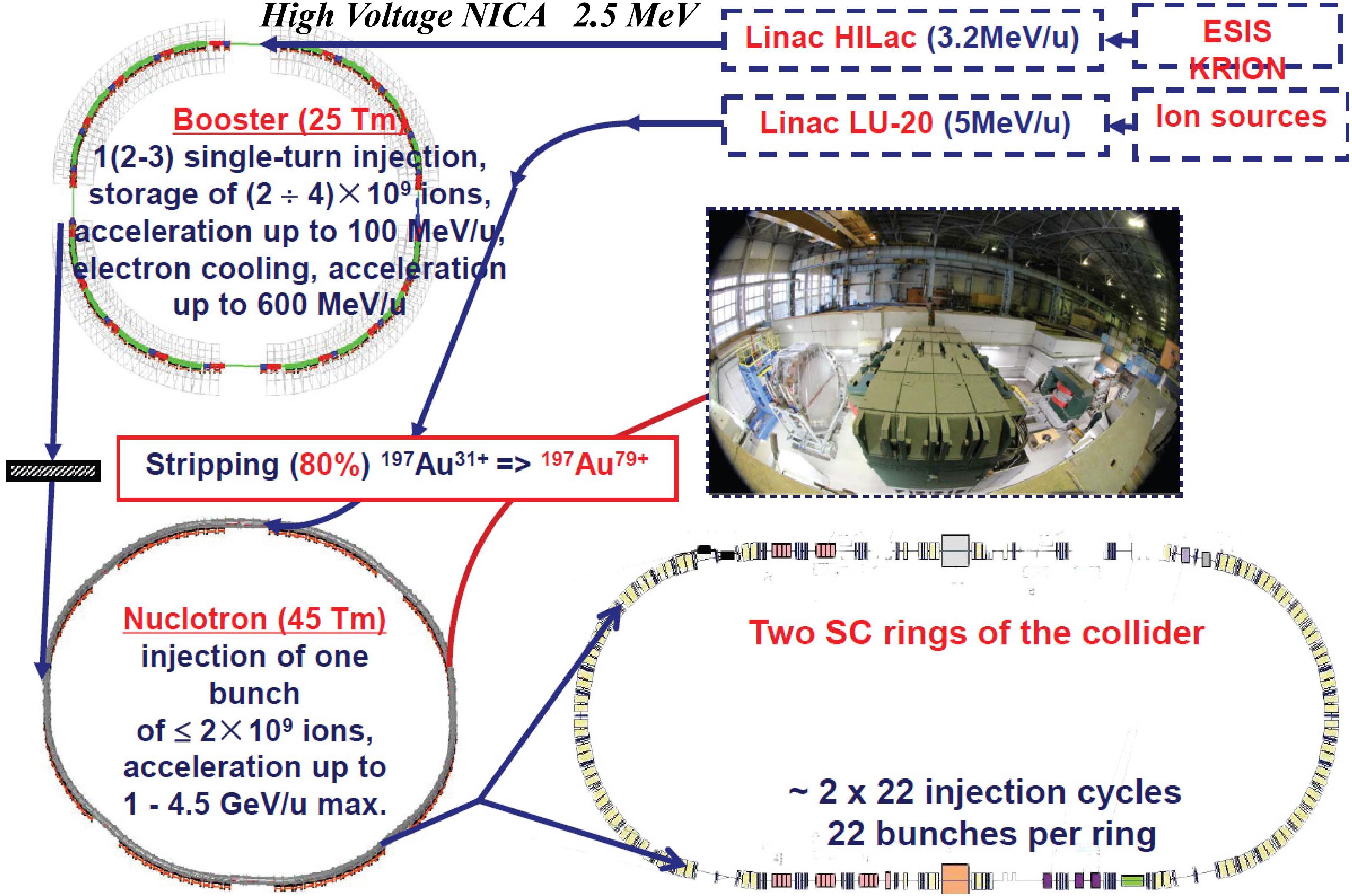


- **Bulk properties, EOS -** *particle yields & spectra, ratios, femtoscopy, flow*
- **In-Medium modification of hadron properties**
- **Deconfinement, phase transition at high ρ_B** - *enhanced strangeness production*
- **QCD Critical Point -** *event-by-event fluctuations & correlations*
- **Strangeness in nuclear matter** - *hypernuclei*

NICA @ Heavy Ion mode

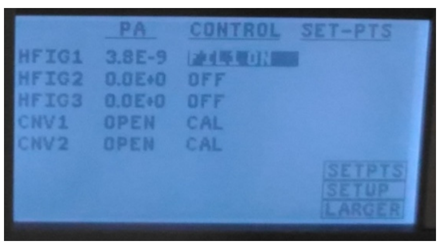
2 electron coolers: NICA booster 60 keV

High Voltage NICA 2.5 MeV

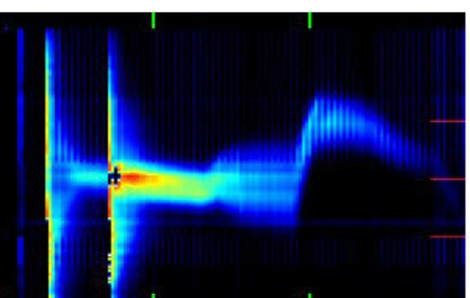


We hope that the low energy electron cooler will be helpful for NICA operation by analogously with others scientific centers

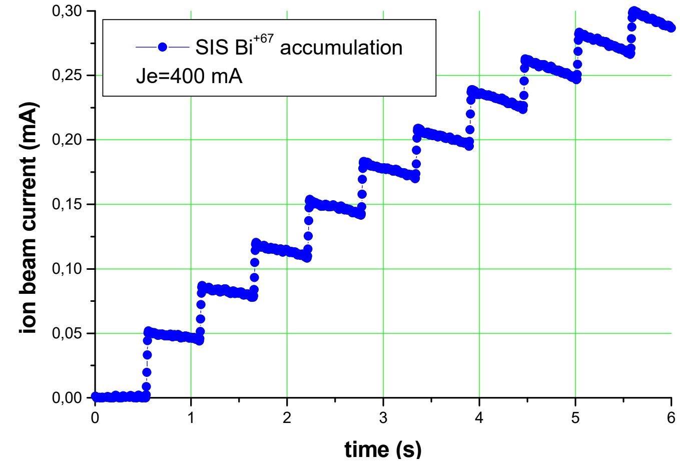
Assembling **NICA** Booster Cooler in JINR



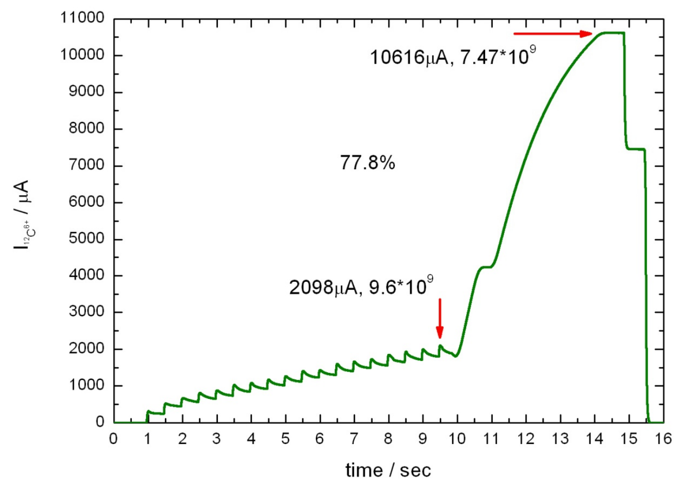
Vacuum level 10^{-11} is obtained



LEIR Lead ion cooling, accumulation, acceleration cooling time about 0.1 c

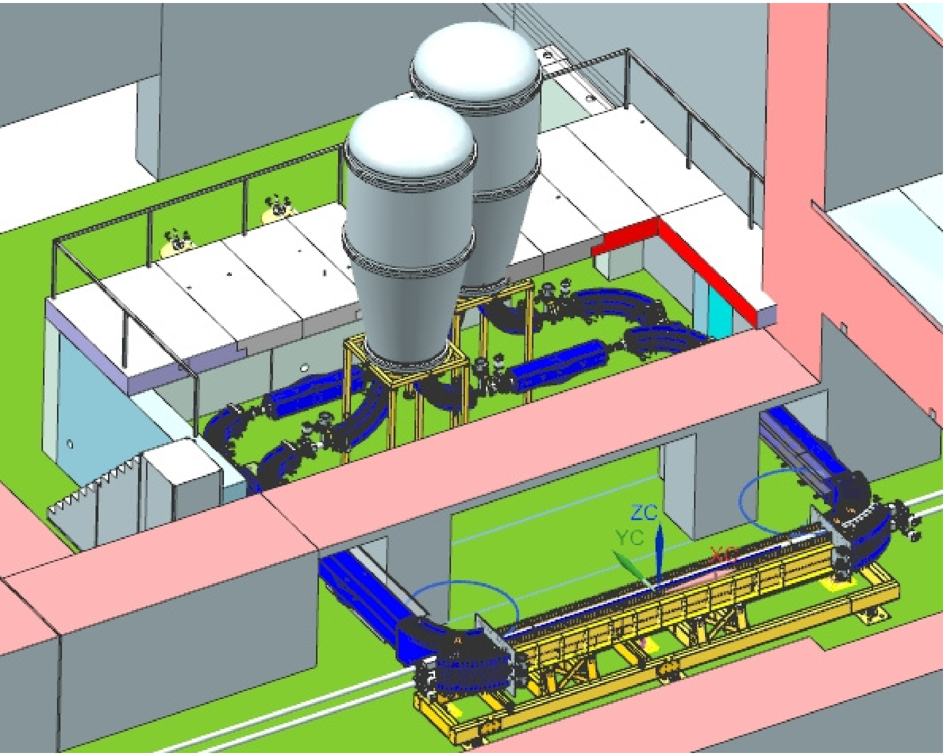


Accumulation Bi beam at **SIS-18**

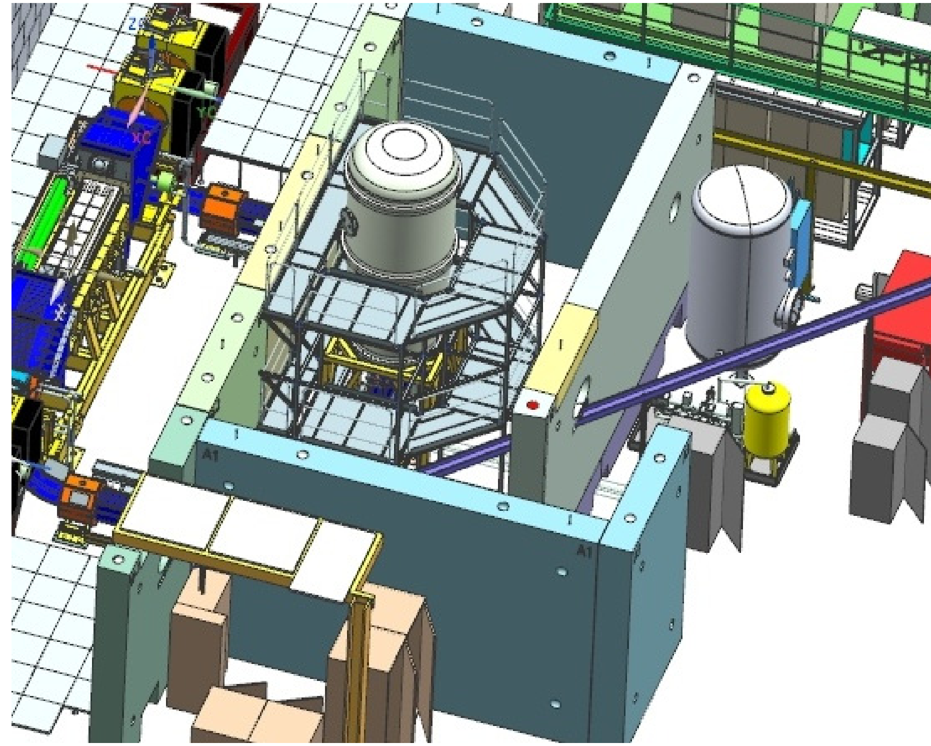


Accumulation of carbon ion at energy 7 MeV/u in **CSRm**

Base of High-Voltage cooler for NICA is COSY cooler



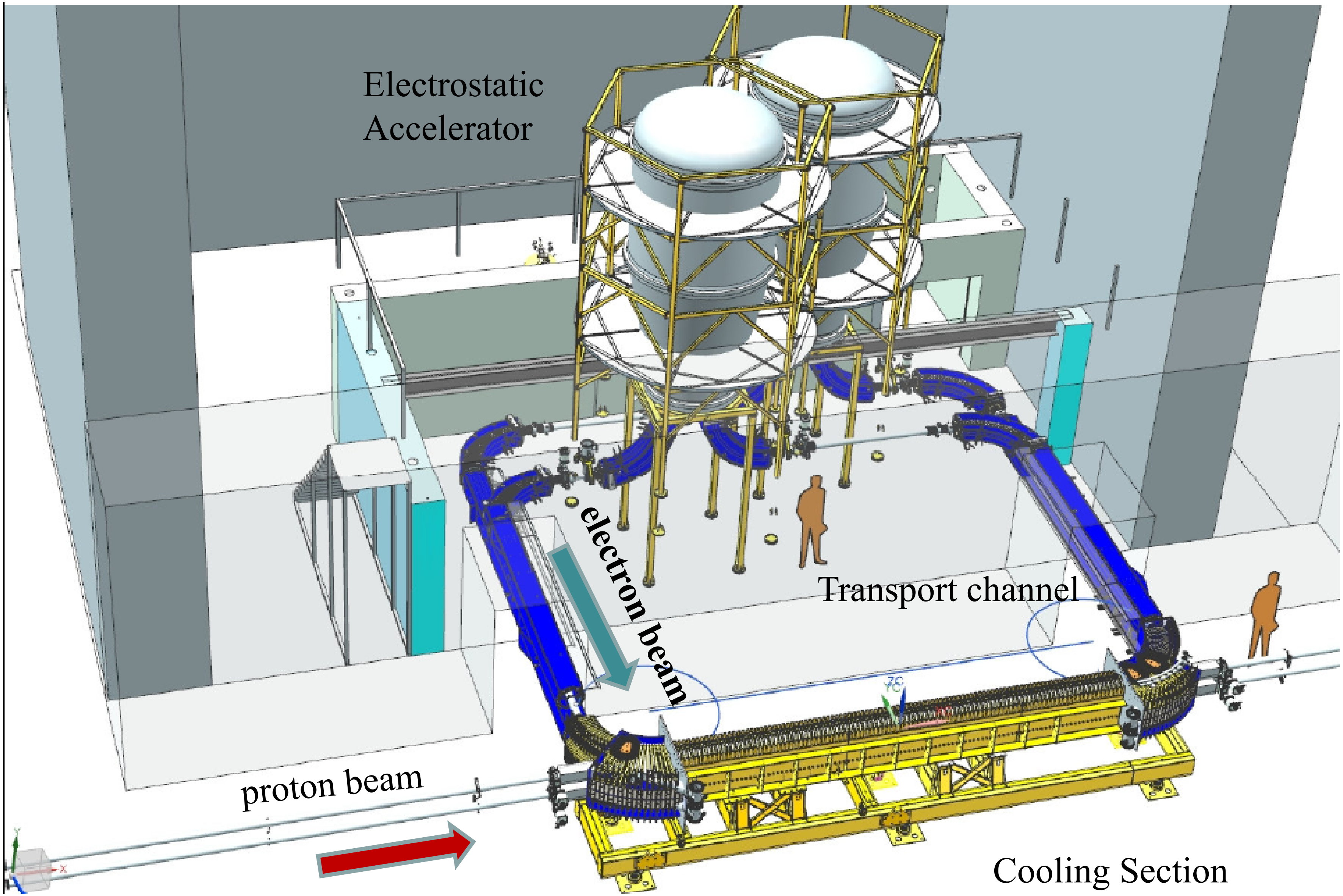
2.5 MeV electron cooler – integration into NICA



2MeV electron cooler – integration into COSY

The next step is high-voltage cooler for NICA collider

3D design of high energy COSY cooler



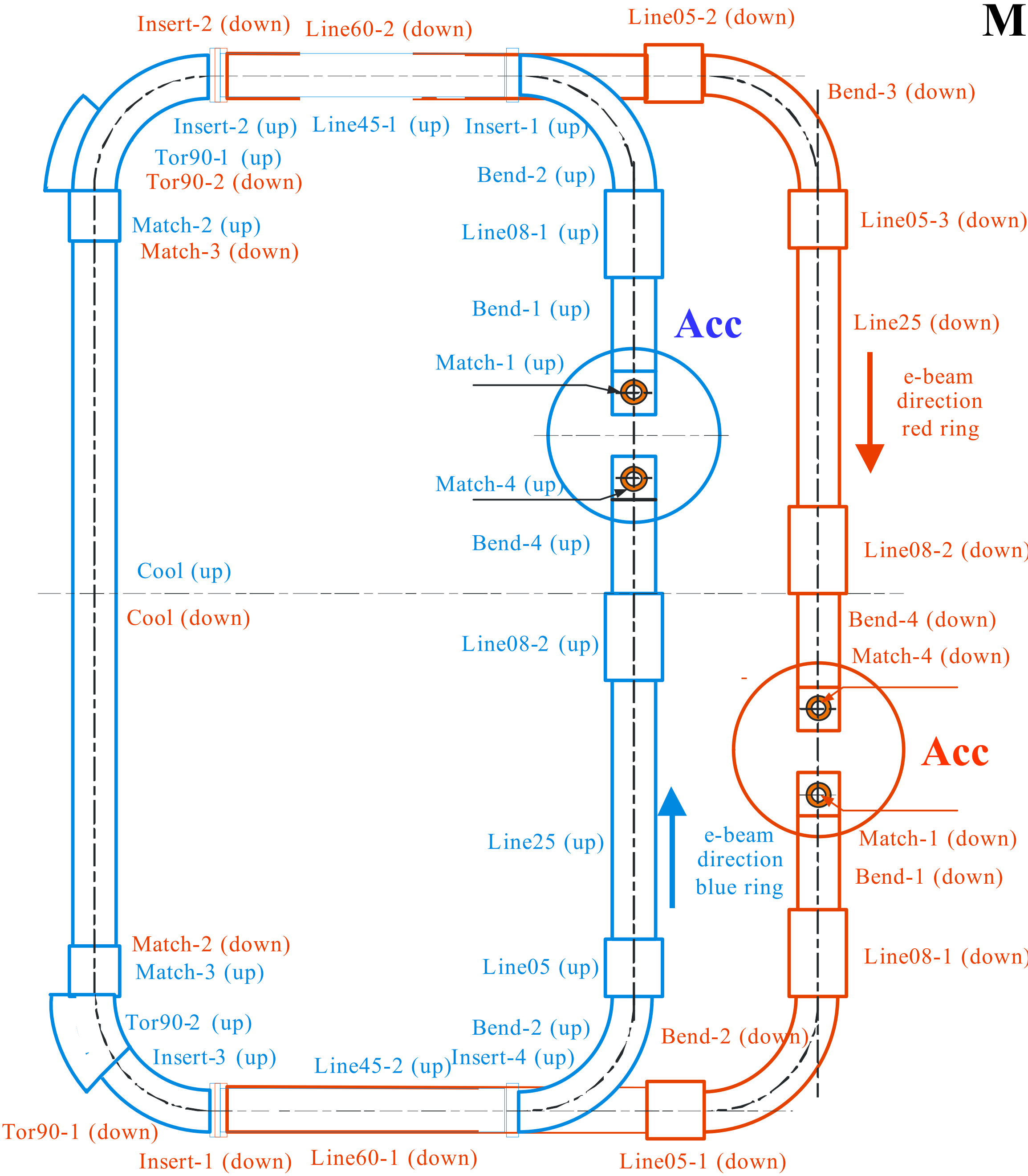
Main parameters cooler NICA

Parameter	Value
Energy range	0.2÷2.5 MeV
Number of the cooling section	2
Stability of energy (ΔU/U)	$\leq 10^{-4}$
Electron current	0.1÷1 A
Diameter of electron beam in the cooling section	5÷20 mm
Length of cooling section	6 m
Bending radius in the transport channel	1 m
Magnetic field in the cooling section	0.5÷2 kG
Vacuum pressure in the cooling section	10^{-11} mbar
Height of the beam lines	1500/1820 mm
Total power consumption	500-700 kW

Comparison COSY and NICA coolers

1. Both system have classical design with longitudinal magnetic field, but NICA cooler has two line and small distance (32 cm) between ion beams;
2. Both system have section-module principle of the design of the accelerator column
3. NICA has a section-module principle for the cooling section (as Fermilab) but with continuous magnetic field. COSY has one and indivisible cooling section.
4. NICA cooler will have possibility of the online magnetic measurements with BPM method. COSY cooler was equipped by the vacuum compass probe for the magnetic measurement.
5. Cascade transformer for power supply of the magnetic coils for both;
6. Electron collector with Wien filter for both
7. “Magnetized” electron motion for both
8. “4-sectors” electron gun for diagnostics of the electron beam motion for both

There are a lot of common and different features



Magnetic elements of NICA cooler

Acc. Accelerating column (500 G)

Match 1 and 4. Transition between different value of the longitudinal magnetic field 0.5-1 kG

Match 2 and 3. Transition between different value of the longitudinal magnetic field 1-2 kG

Bend. 90° bending (1 kG)

Tor90. Combination ion and electron beam together (1 kG)

Cool. Cooling section (2 kG)

Insert. Magnetic elements for assembling and leading-out wire (1 kG)

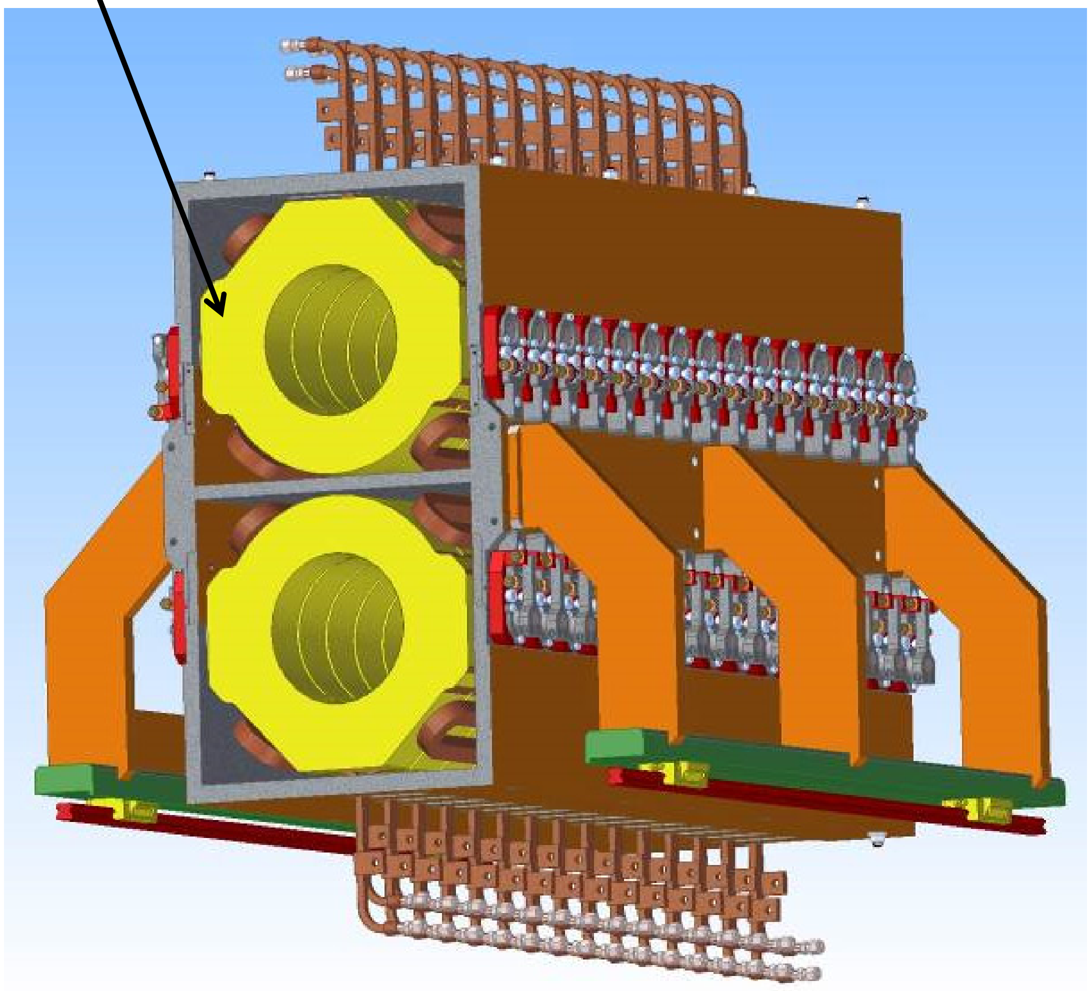
Line08. Place for vacuum valves and ion pumping (1 kG)

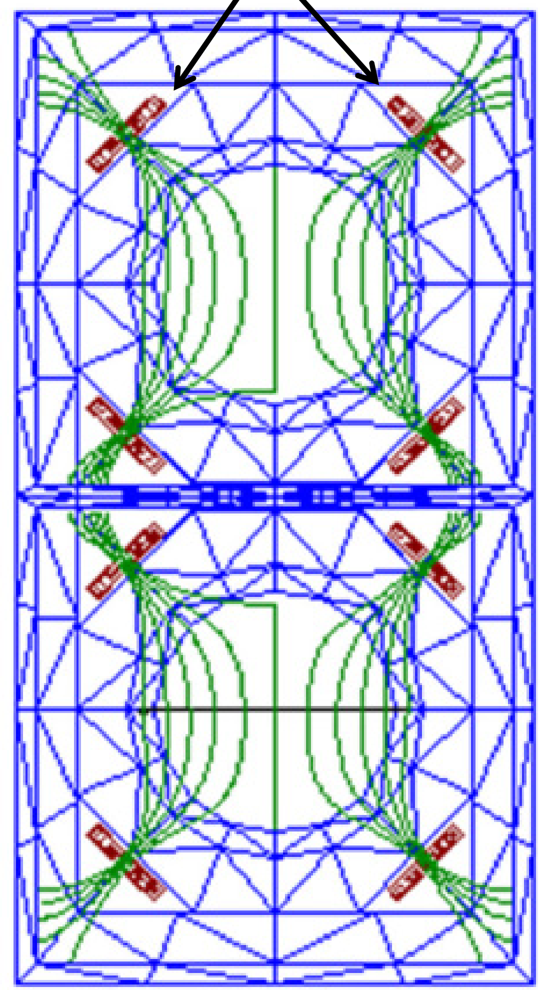
Line. Straight transport lines (1 kG)

NICA cooling section

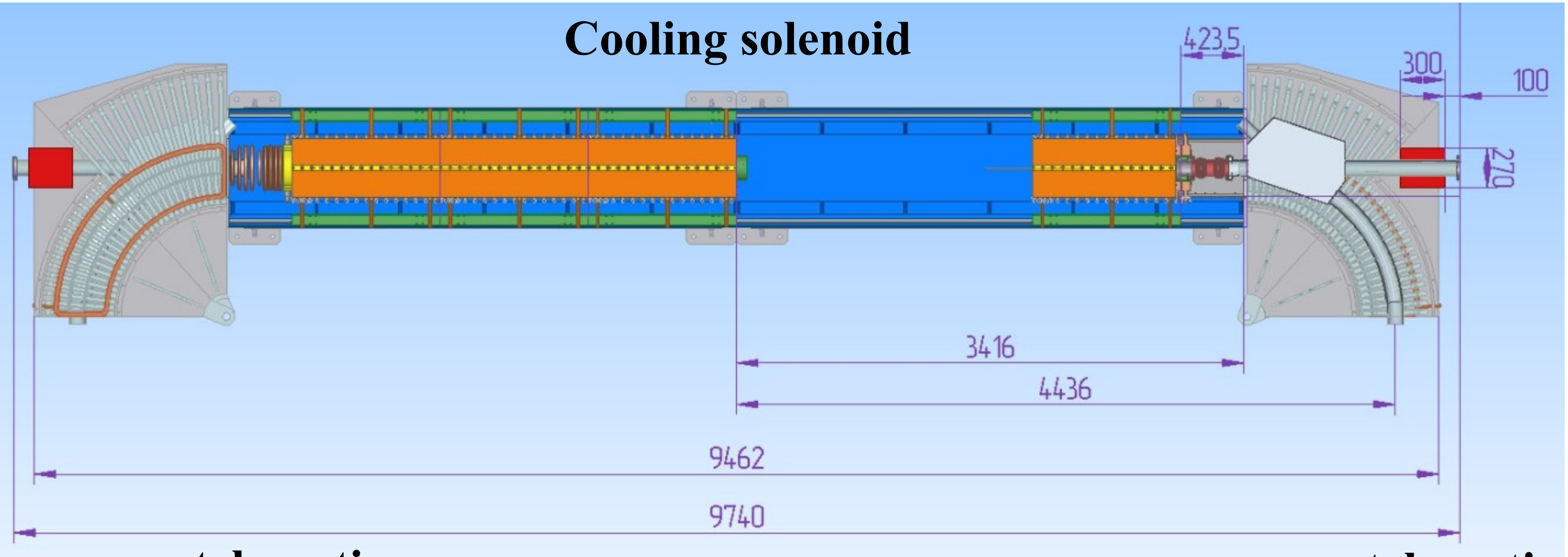
Coils of the longitudinal magnetic field

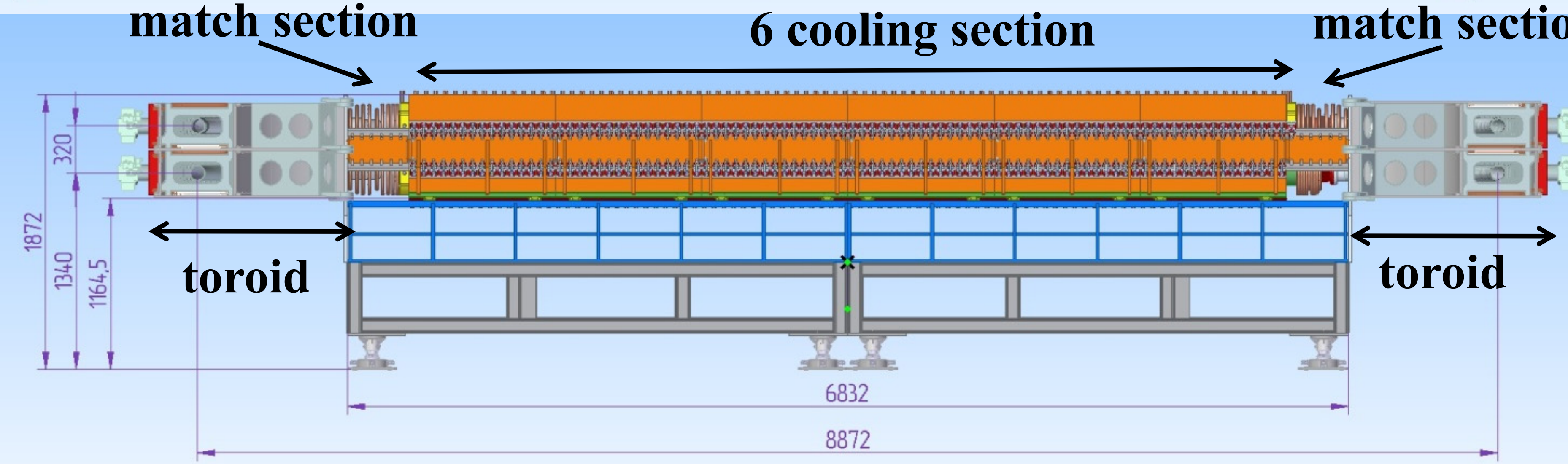
transverse magnetic correctors





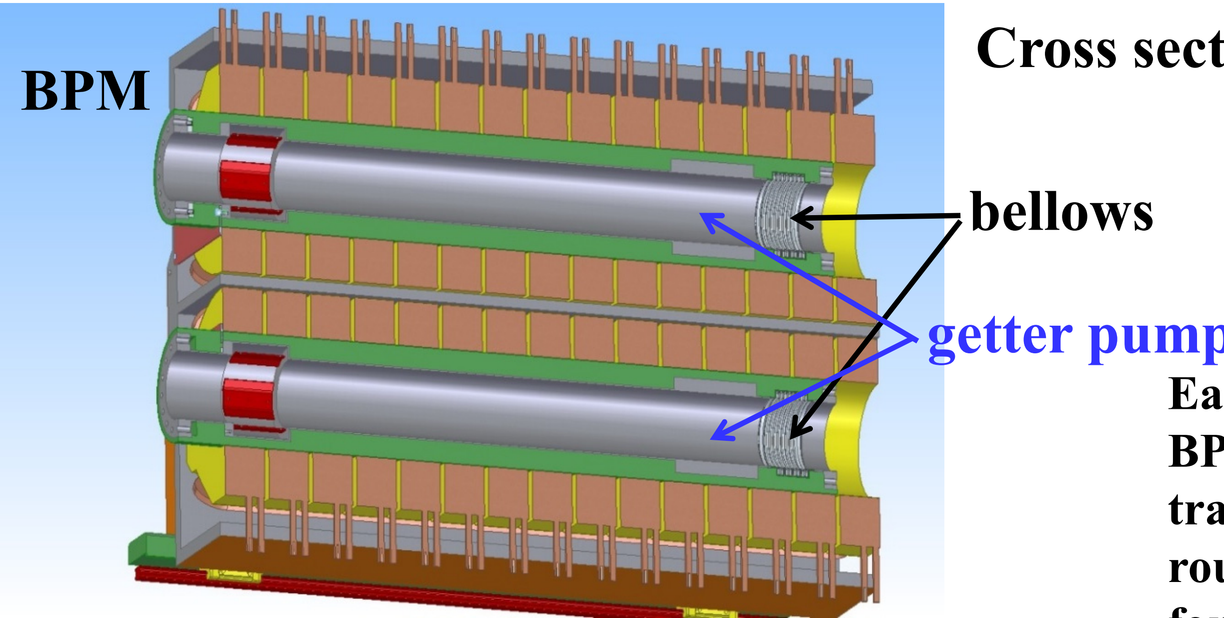
Cooling section consists of 6 standard section with length 1 m





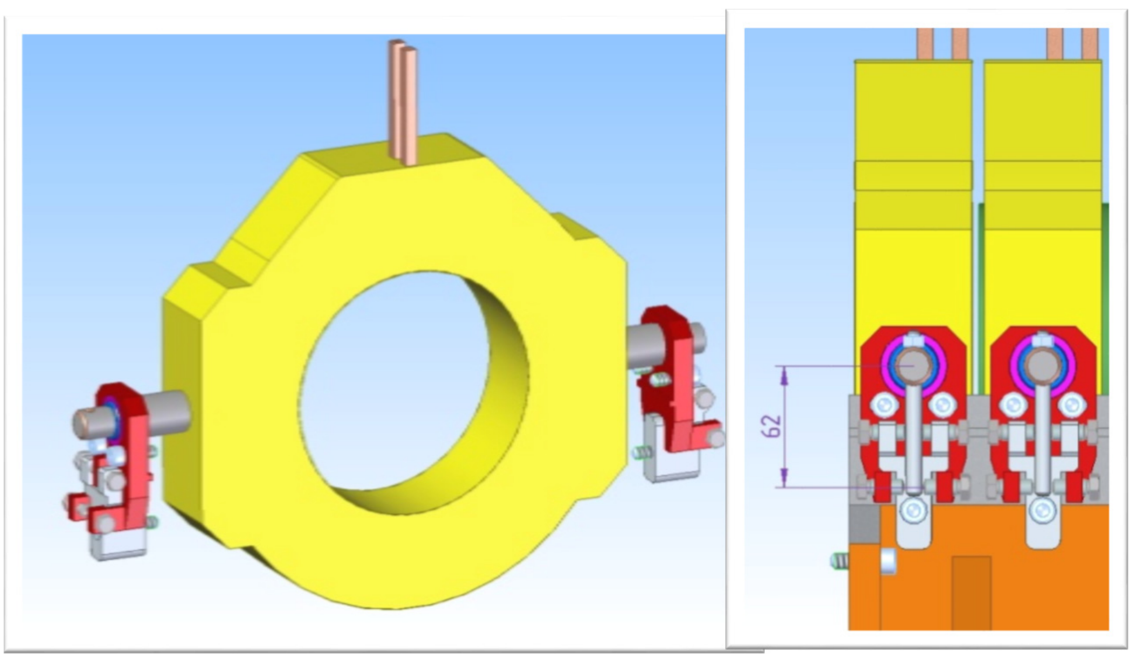
Match section between the different magnetic field is close to the cooling section in order to decrease the longitudinal magnetic field in the toroid. It strongly saves the electrical power and reduce the transverse kick for ion beam.

Cross section of the cooling section



The cross section of coil copper is maximum as possible in order to decrease the power consumption

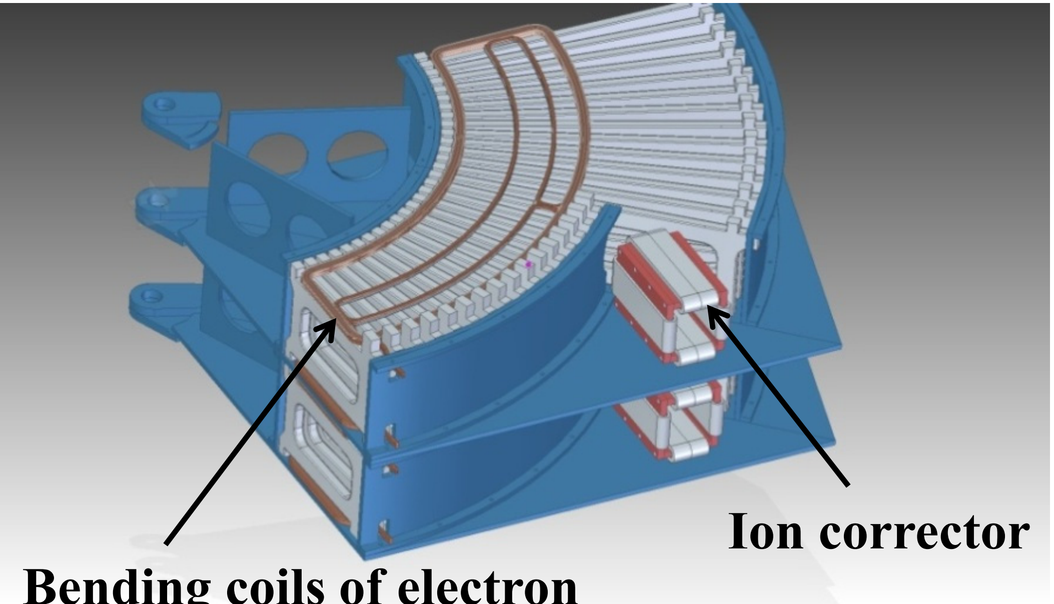
Each vacuum section contains the BPM and the correctors of the transverse magnetic field. So, the rough regulation of the magnetic force line is possible as result measurement of BPM with electron and ion beams. The ion beam is used as base line for the electron beam

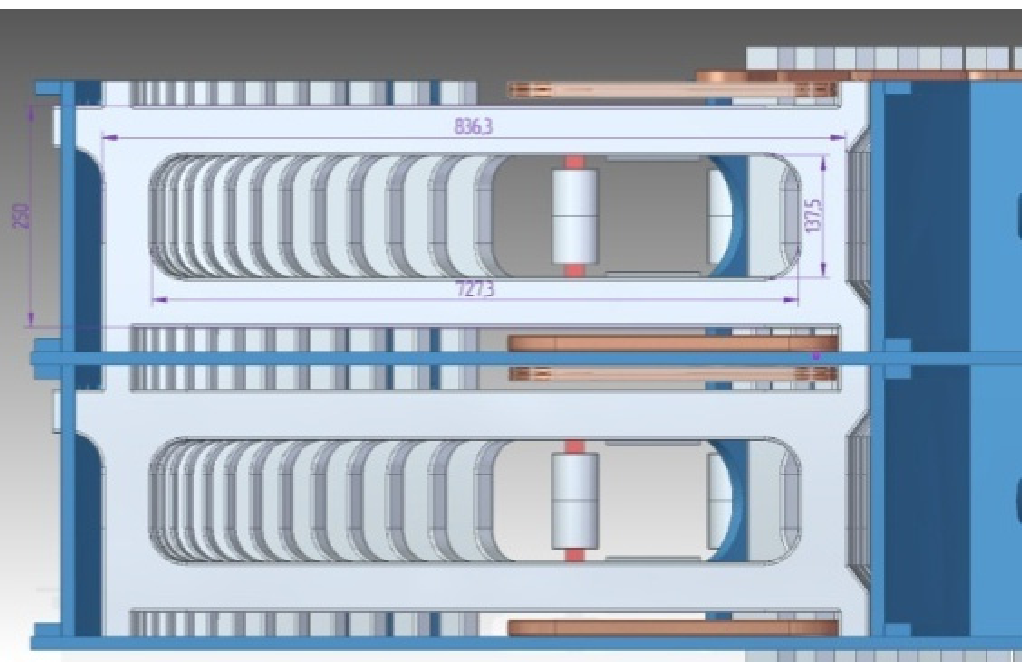


Coils of the cooling section with adjusting elements

Requirements to the magnetic field is very strong – 10^{-5}. The adjustment elements should provide regulation with 10um accuracy. In the present construction the coil have possibility incline and rotate changing angle in two direction.

Toroid section

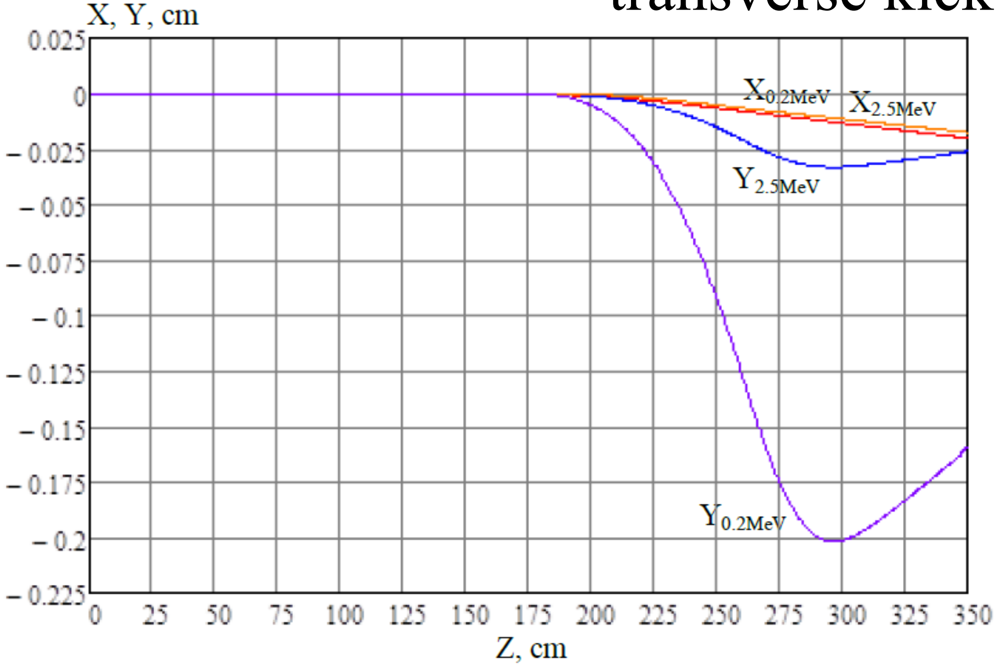




Toroid is the most complicated place where meet together two beam lines: electron and ion. Moreover the ion corrector should be located in this place. Also the it is place for vacuum pumps. The coils for bending field is placed on the toroid side. The power consumption is restricted so the coil should contains maximum value of copper. In addition to all problem two electron beam should be located with distance 32 cm.

The decision of most of problem is decreasing magnetic field in the toroid. But free cheese only in a mousetrap. The length of the cooling section less (6 m) than the straight section along ion orbit (6.84 m). The distance 0.84 m is spent on the matching section.

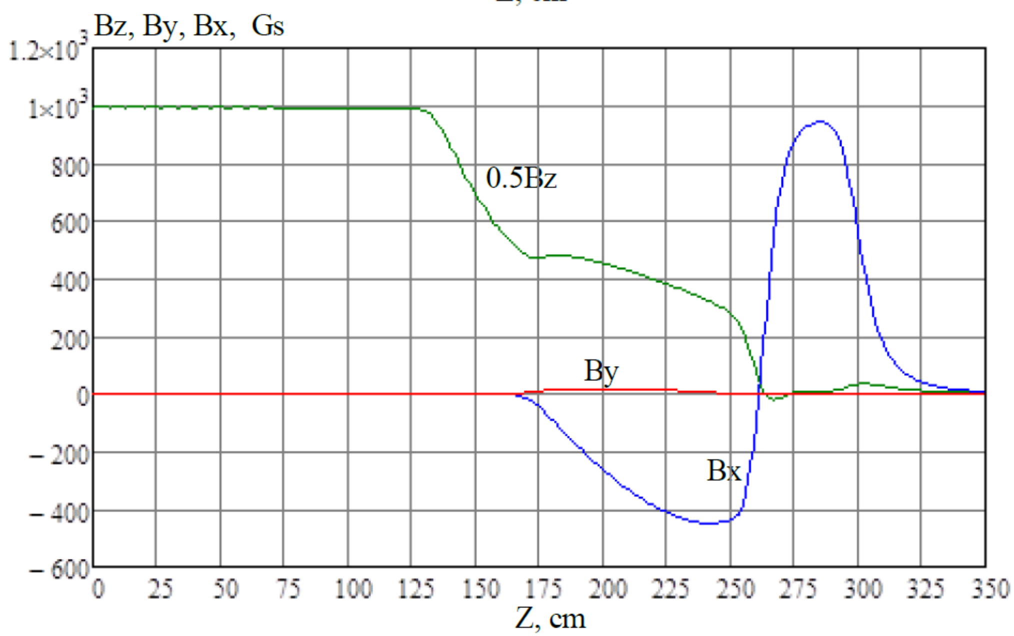
Decreasing magnetic field in the toroid reduces the problem with transverse kick on ion beam.



${}^{79}Au^{197}$ at energy 72.4 GeV (Ee=0.2 MeV)

Transverse trajectory of ion at energy 0.2 MeV.

Match section between the different magnetic field is close to the cooling section in order to decrease the longitudinal magnetic field in the toroid. It strongly saves the electrical power and reduce the transverse kick for ion beam.

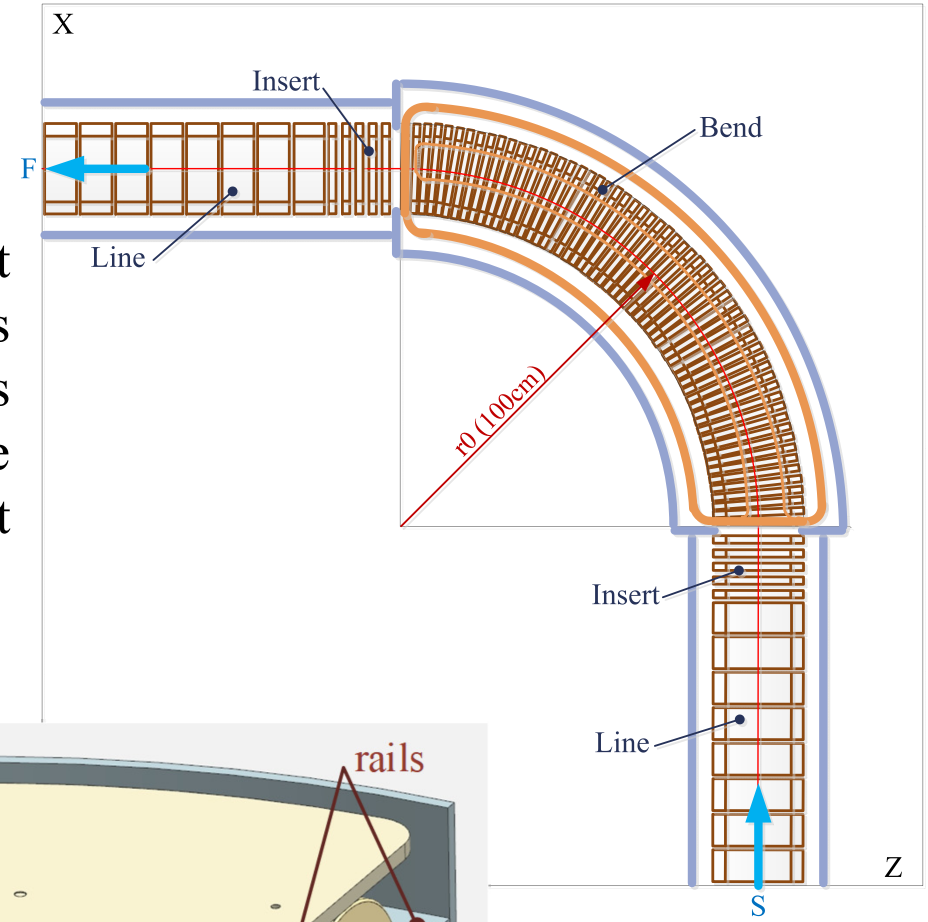


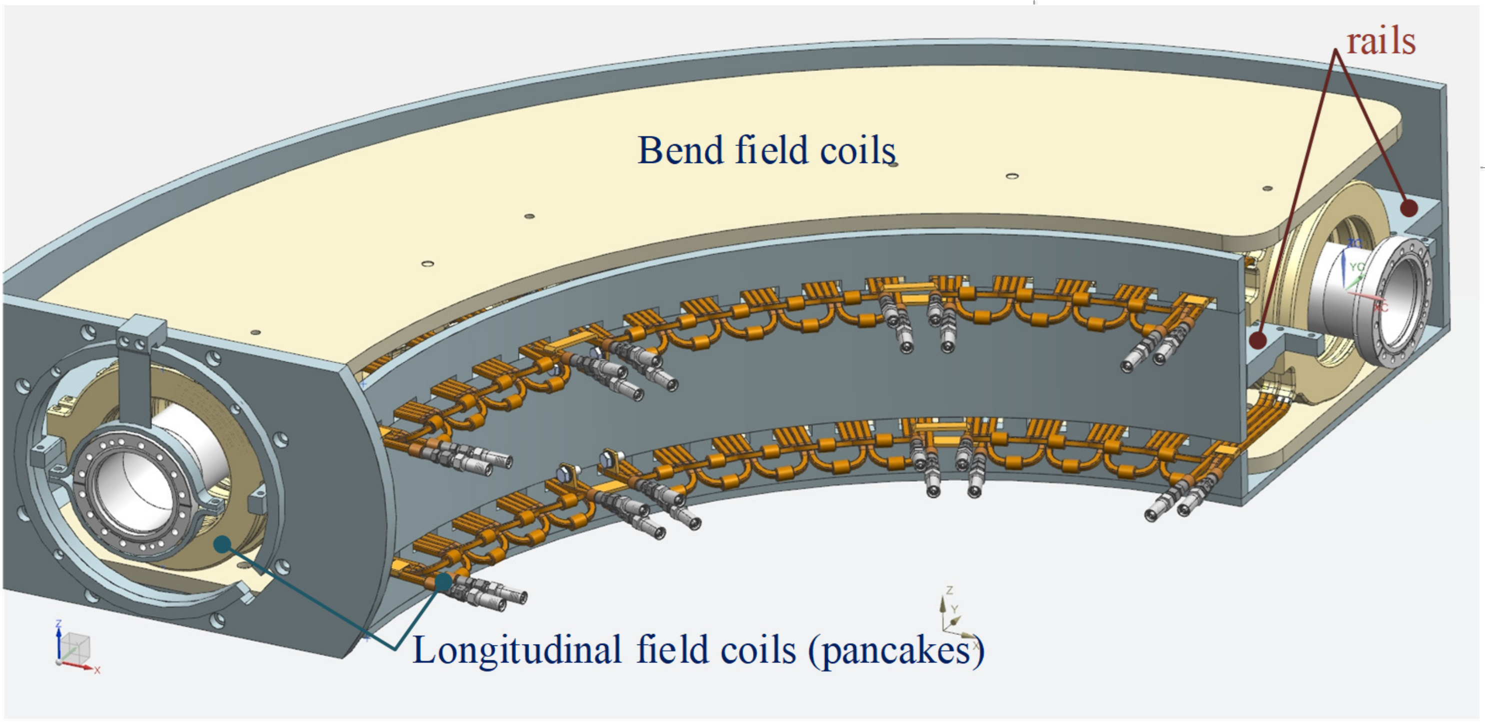
Magnetic field along ion orbit at electron energy Ee=0.2 MeV. Z=282 cm is center of ion corrector, Z=170.8 cm is entrance to the toroid. Integral of the bending field of toroid is 29.4 kG*cm.

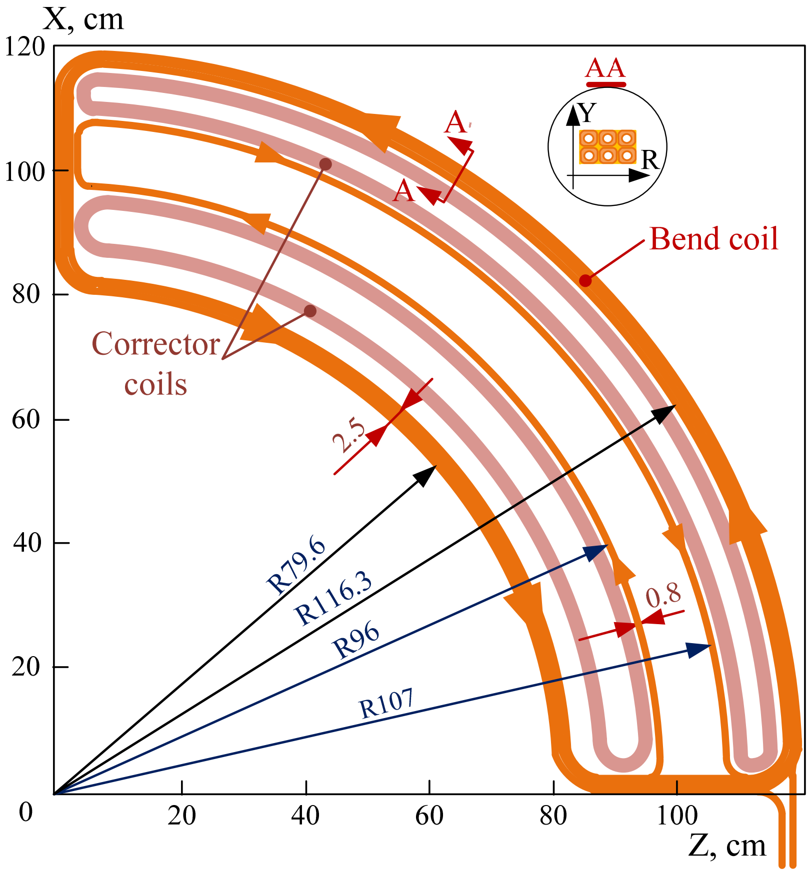
Cooling section is 2 kG, toroid is 1 kG.

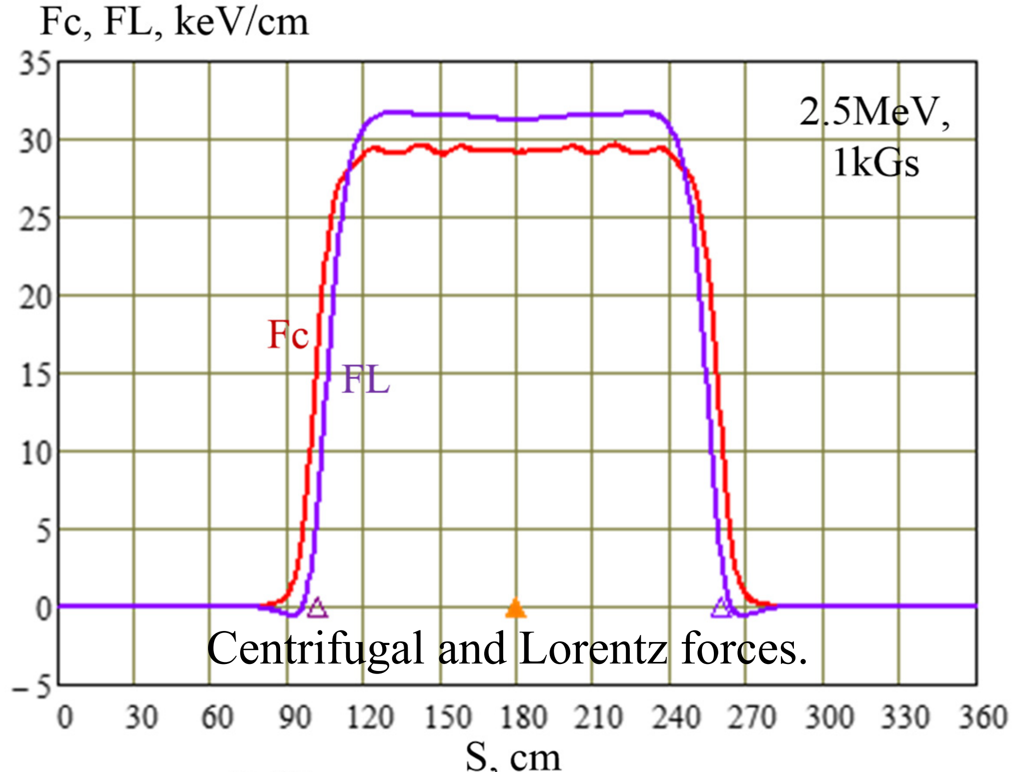
90 bend of transport channel

Another problem place is the bending magnet of the transport channel. The problem is similar to toroid section. Two transport line is located together, there is lack of space. The power consumption is restricted and amount of copper should be maximum.

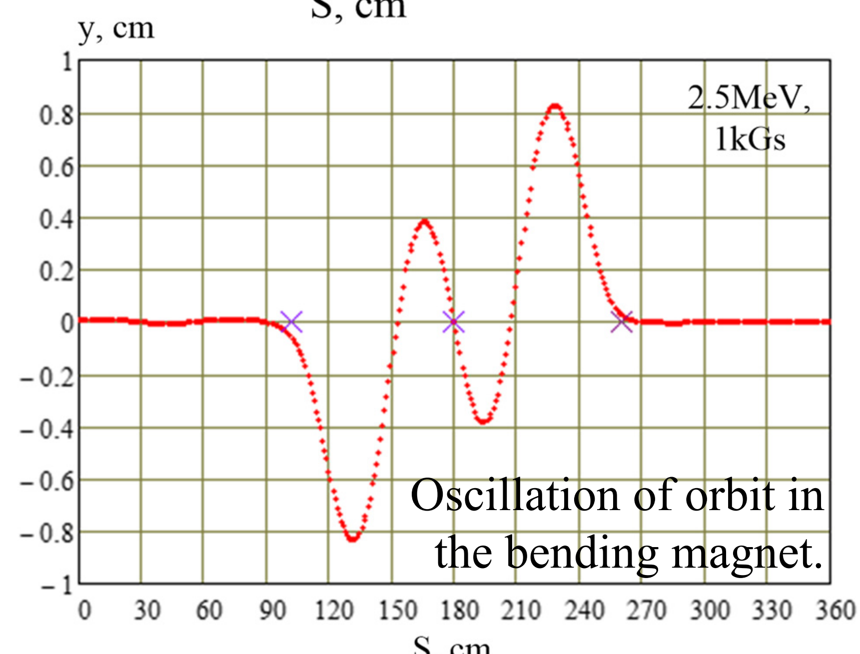




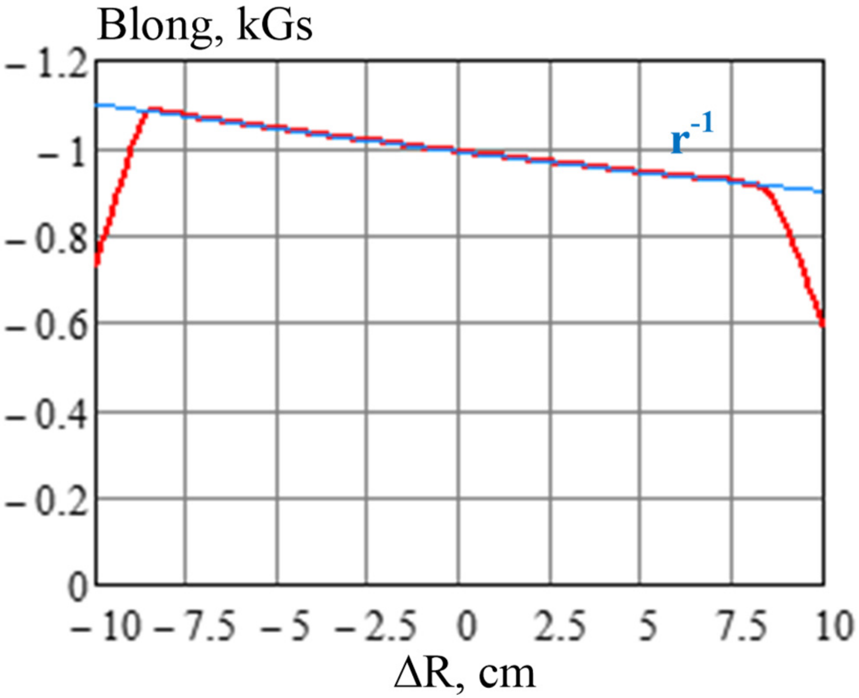




The curve of the bending field should be very close to the centrifugal force. In this case the oscillation of the transverse motion of electrons is minimal. Also field index n=0.5 is required in order to prevent changing transverse shape of the electron beam. The field index is produced with help of bend coils with special fshape.

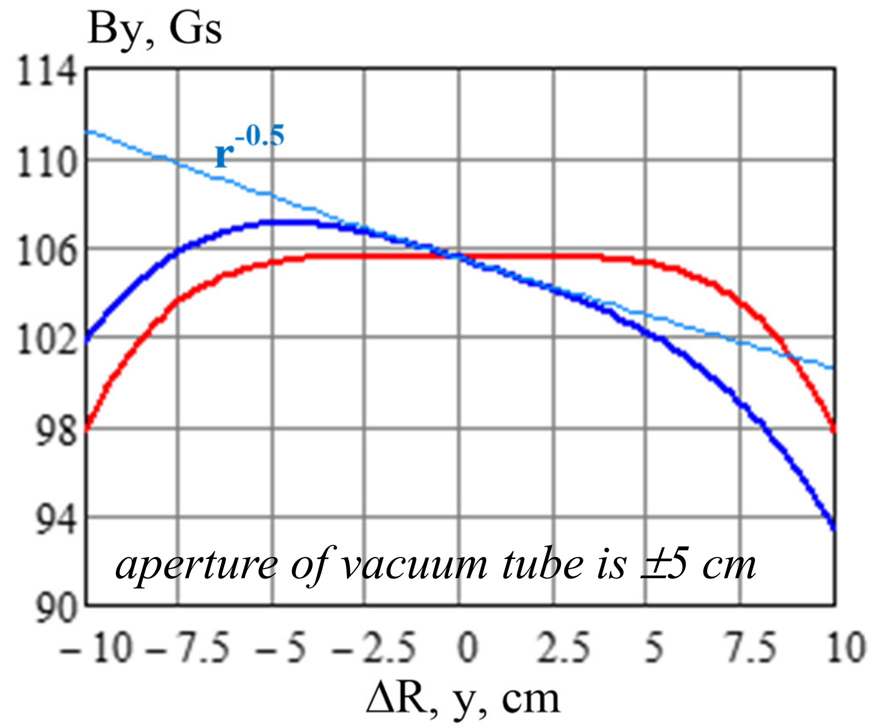


Natural slope of the longitudinal magnetic field



Longitudinal magnetic field versus radius in the center of bending magnet.

Field index of the transverse magnetic field



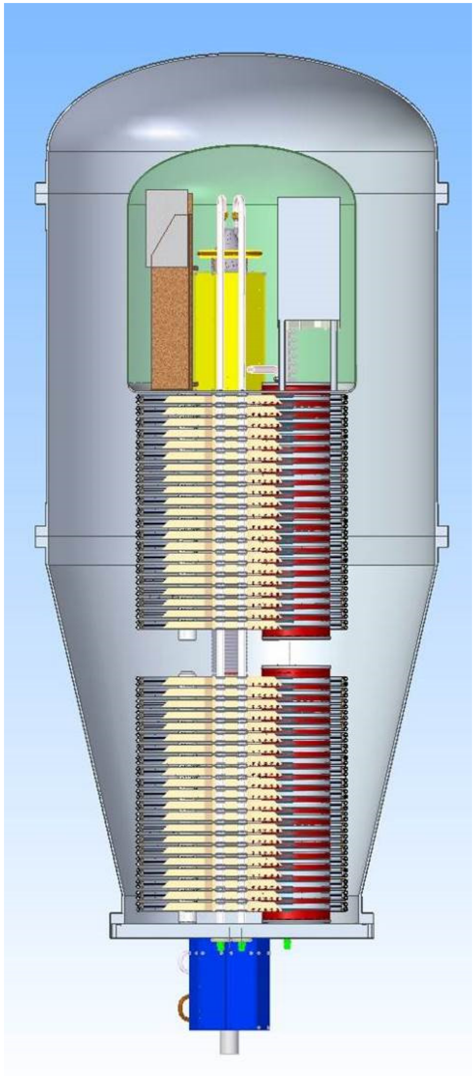
Bending magnetic field versus radius and vertical coordinate (perpendicular of bending plane).

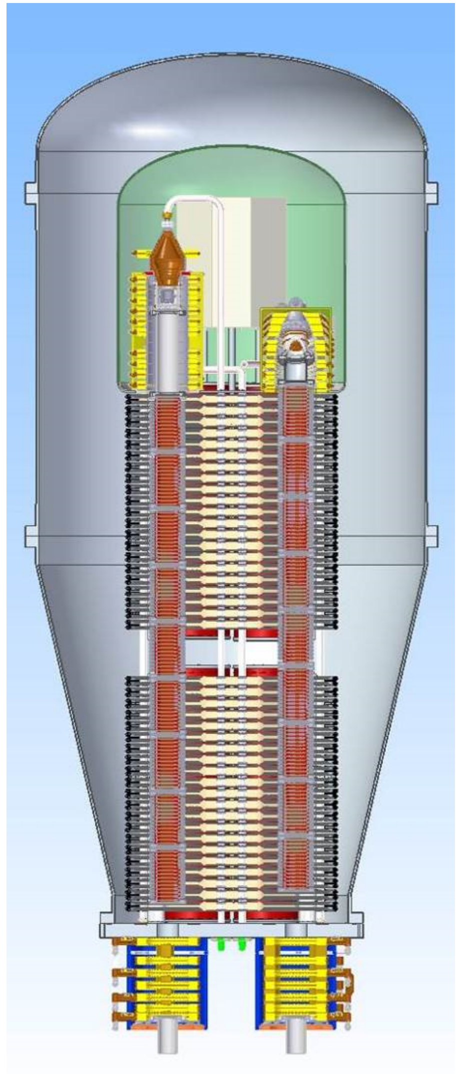
$$x'' + y'/R_L + (1-n)\,x/R^2 = 0$$
$$y'' - x'/R_L + n \cdot y/R^2 = 0$$

Only field index n=0.5 provide the preservation of the beam shape

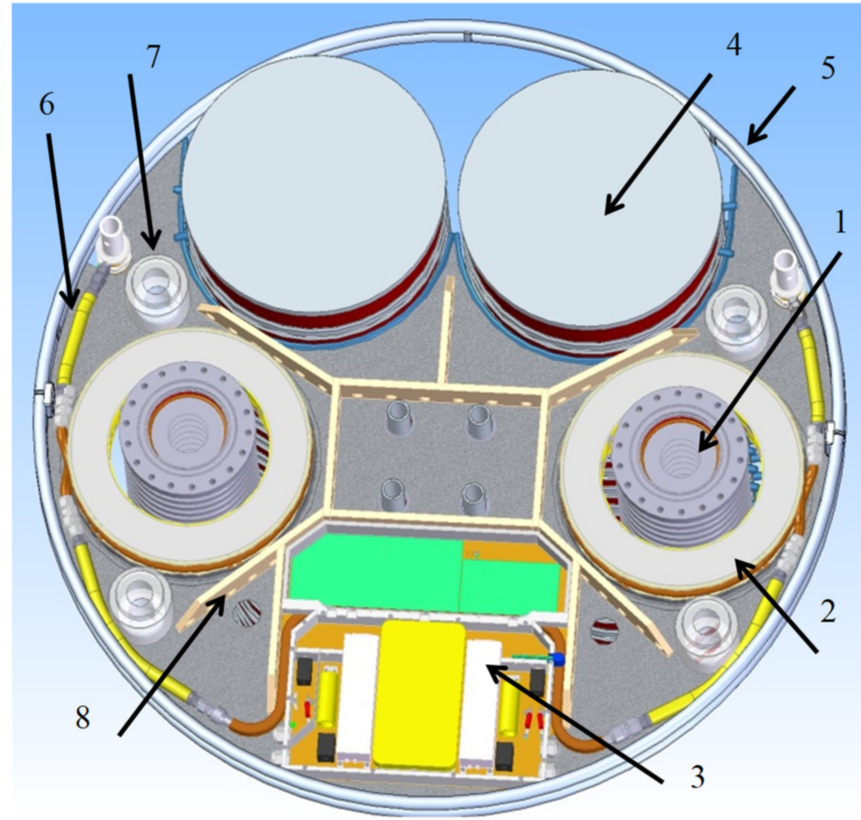
R – bending radius, $R_L = pc/eB$

3D design of Accelerating Column



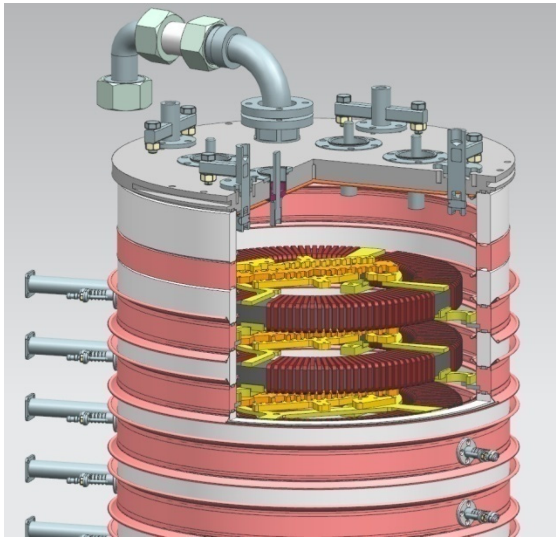


Electrostatic accelerator of NICA cooler. It is divided on two part. The middle section contains of vacuum pumping, BPM, correctors and mechanical support.

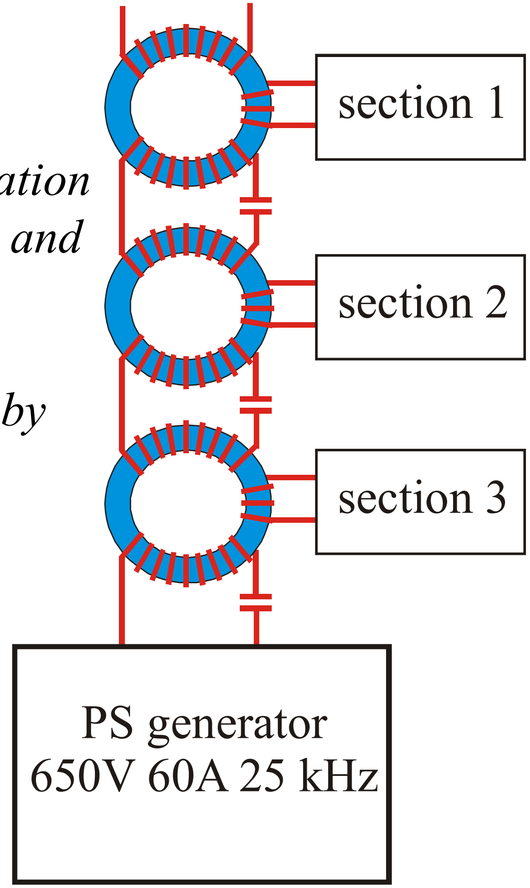


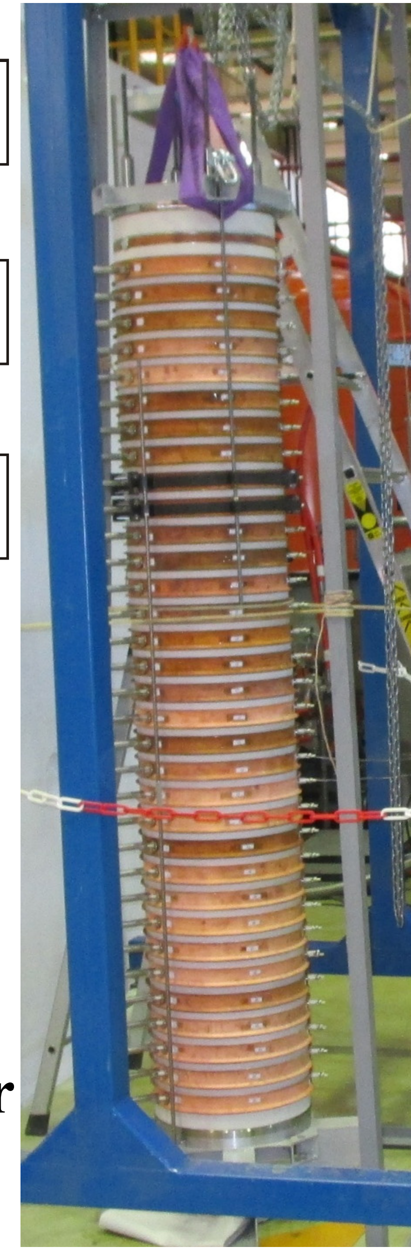
Design of high-voltage section.
1 – accelerator tube, 2 – magnetic coil, 3 – electronics (coils 2.5A, 500 G and HV PS +/- 30 kV), 4 – section of cascade transformer, 5 – safety ring, 6 – oil tube for solenoid cooling, 7 – isolation support, 8 – stiffening rib.

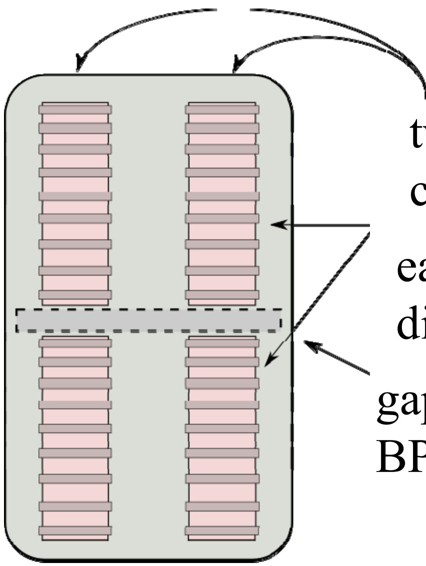
42 high-voltage section (COSY is 33 section)



-transformers connected to series;
-tube is alternation of the ceramic and metal rings (sections);
- tube is filled by oil;
- section has special spark-gaps;







two transformer column

each column is divided by two part

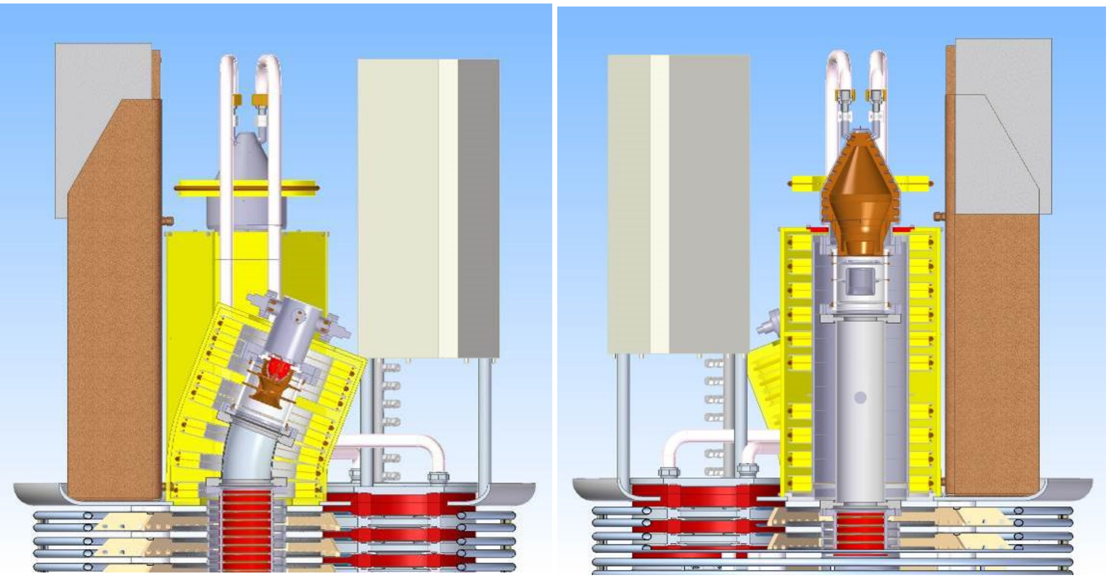
gap for correctors, BPM, vacuum pump

Cascade Transformer as Power Supply

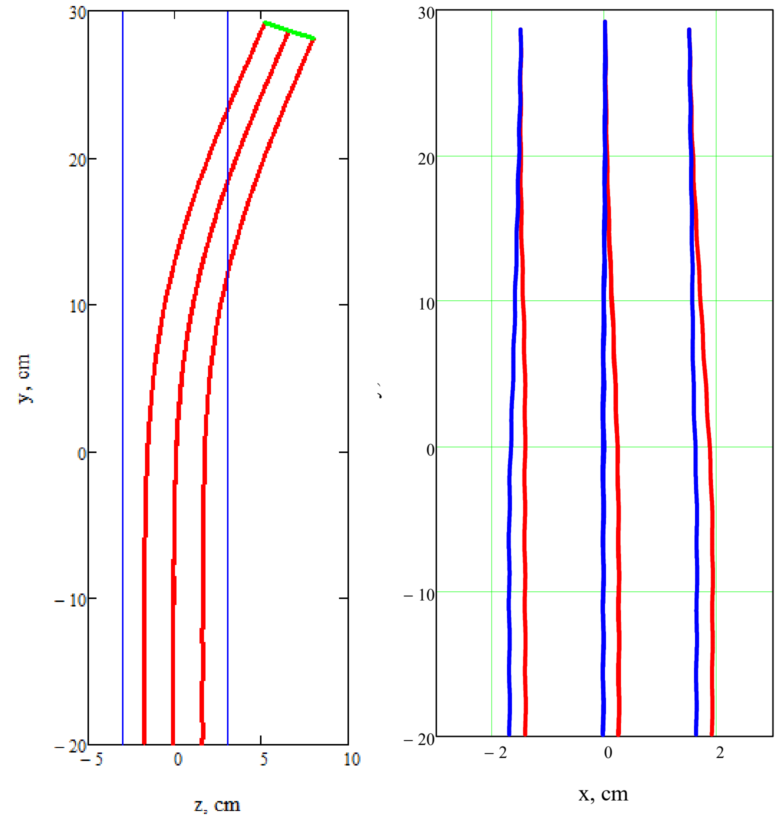
Length of NICA cooler is larger and we decide to use two transformer column. One for collector and the other for the HV

"*Transformers section looks like accelerating tube*"

High voltage terminal – gun and collector



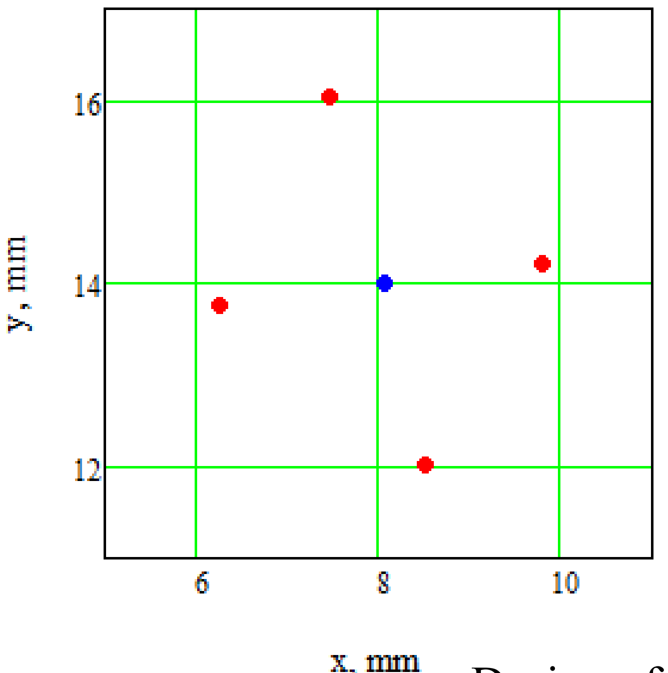
Design of high-voltage terminal of NICA cooler. The left picture shows the electron gun, the right picture shows the collector.

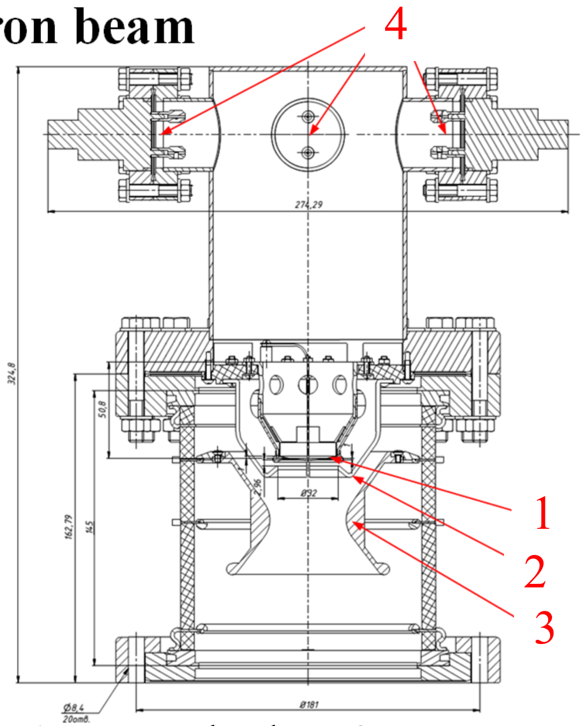


X and Y displacement of electron in the electron gun. The left picture shows the electron trajectory (red) versus apperyre of accelerating tube (blue). Right picture shows the electron trajectory at with and without compensation of centrifugal drift.

This design of magnetic system of electron gun is proposed in order avoid ion bombarding of cathode by the secondary ions.

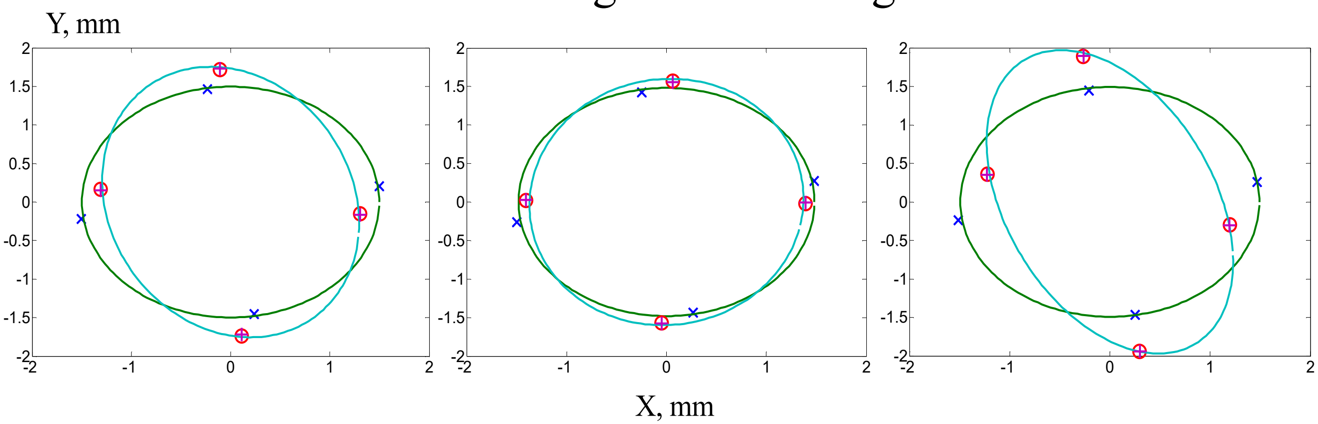
Diagnostics of the shape of the electron beam





Design of electron gun with 4 sector .

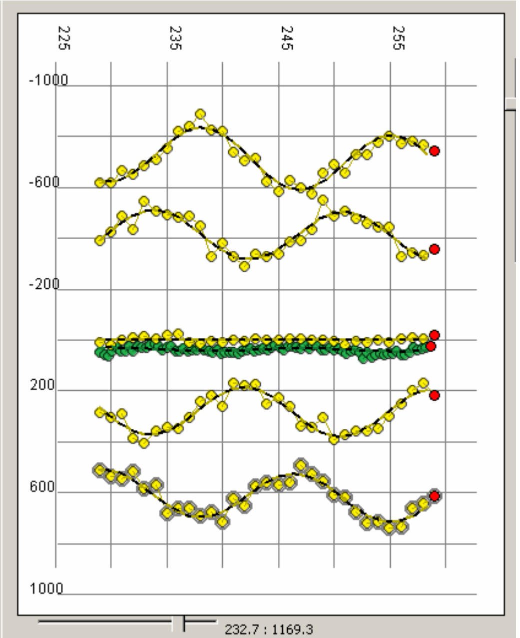
1 – cathode, 2 – control electrode, 3 anode, 4 – feedthrough for filament and control electrodes.

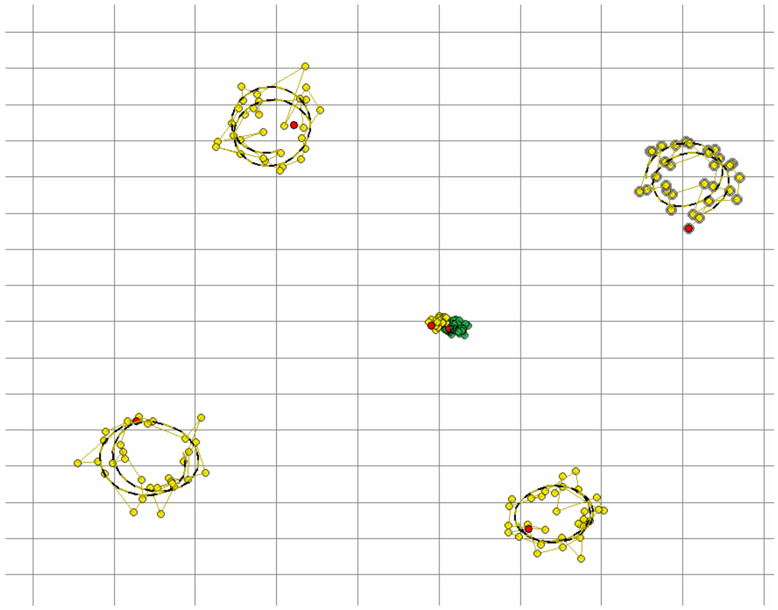


X is first BMP, O is last BPM.

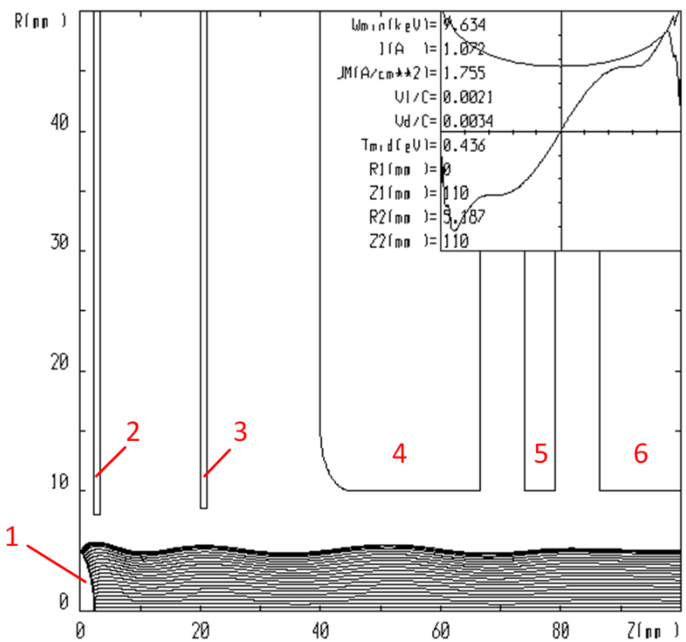
Response of the beam shape induced by quadruple component of the bending magnet (n=0.5 and n≠0.5) . The experimental result from COSY cooler, energy Ee=910 keV.

Radial oscillation of the electron beam





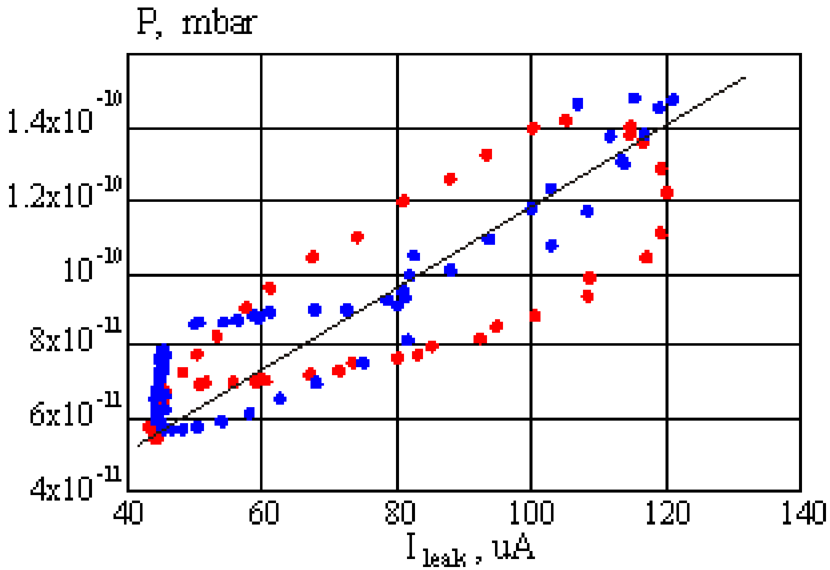
Analyze of the electron trajectory in COSY shows that there is a radial oscillation of the shape of the electron beam (“galloping”). The edge trajectory have Larmour oscillation but the center trajectory is line. It can be different reasons such behavior. It is possible that the main reason is combination of the electrical lens from the control and anode electrode.



The special design of the electron gun can control “galloping” mode. 1 – cathode, 2 – control electrode, 3 – anode, 4,5,6 – anode with electrostatic lens.

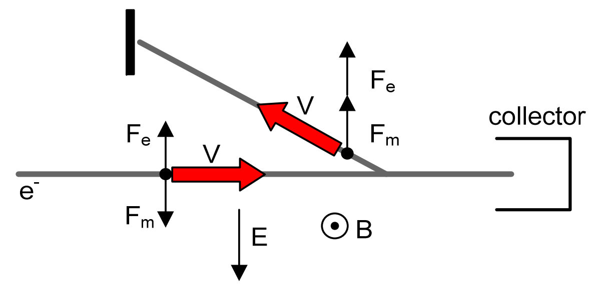
To fit a parameters of electrostatic lens and the value of the magnetic field (phase of Larmour rotation) is possible to control radial oscillation.

Electron collector



Influence of electron beam on vacuum, NICA Booster Cooler, Ee=6 kV.

Principle of the collector work

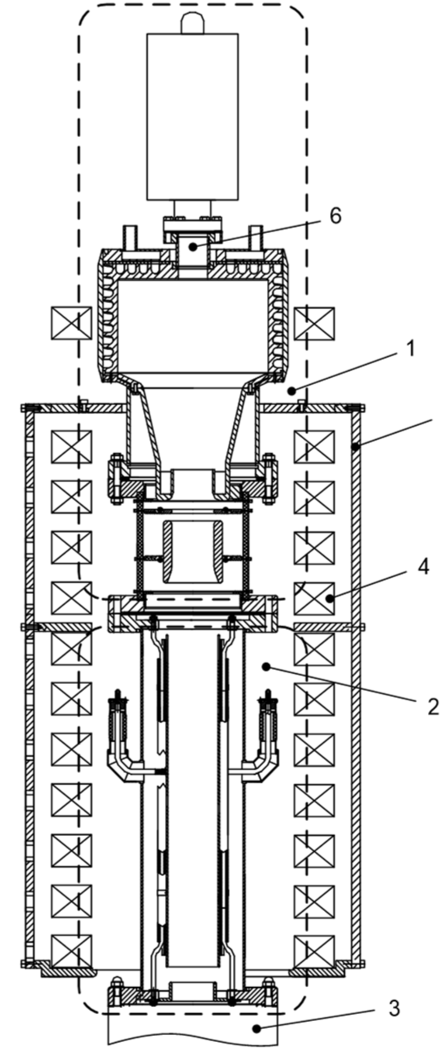


primary beam

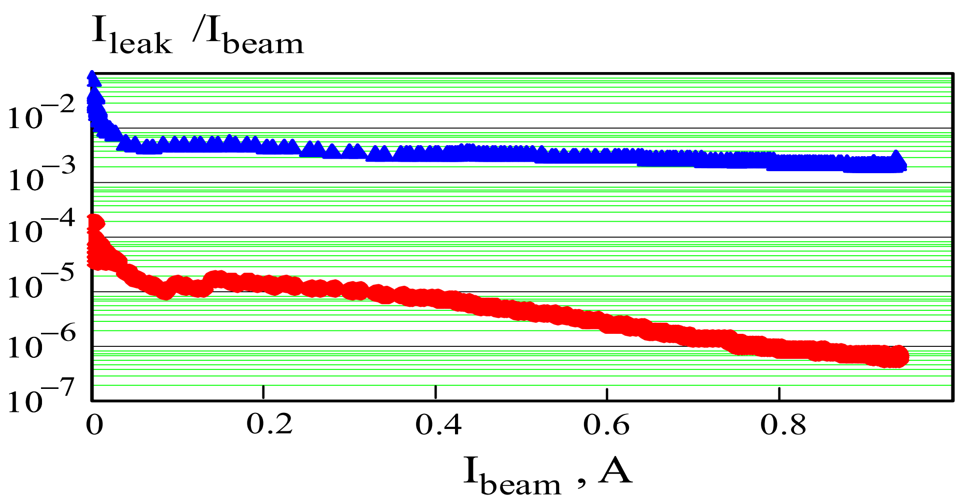
$$\vec{F}_{\perp} = e\vec{E} - \frac{e}{c}\left[\vec{v} \times \vec{B}\right] = 0$$

secondary beam

$$\vec{F}_{\perp} = e\vec{E} + \frac{e}{c}\left[\vec{v} \times \vec{B}\right] \neq 0$$

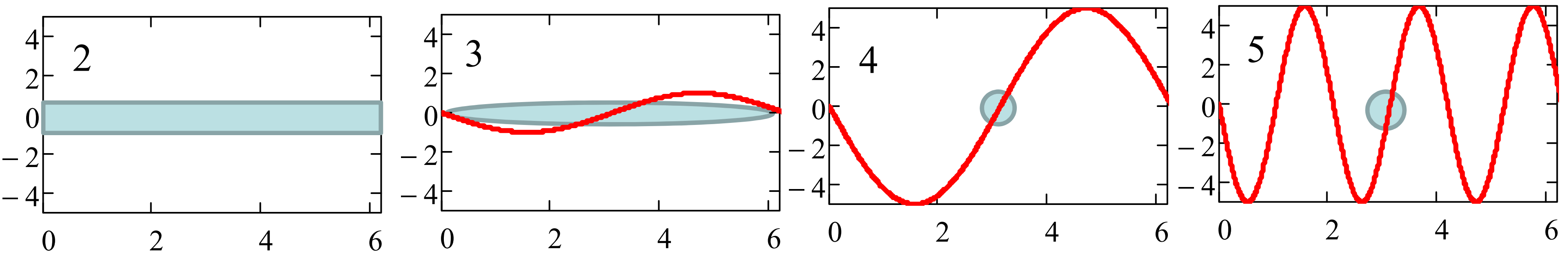


Collector for COSY cooler



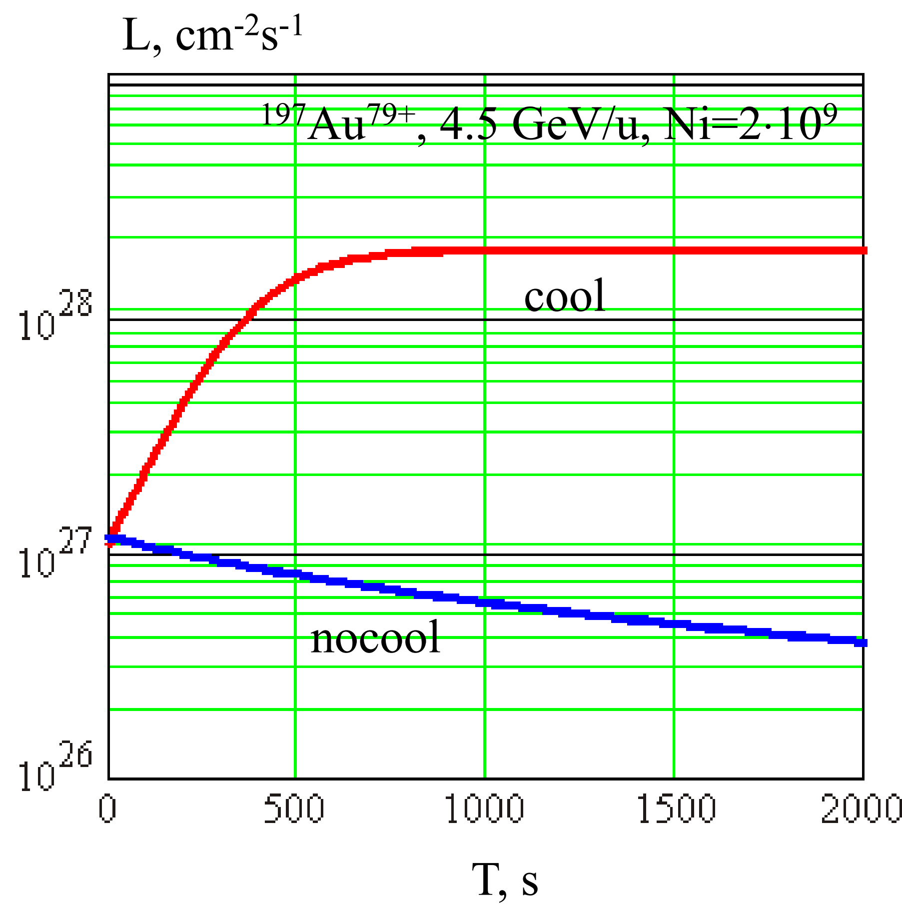
Collector efficiency, measured on COSY cooler at energy 909 kV

RF and e-cooling preparation to collider operation



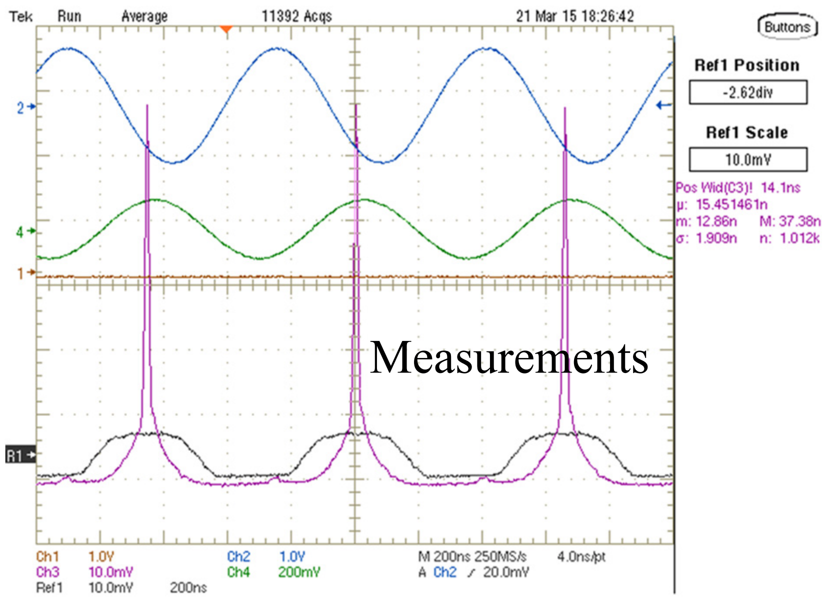
1. Cooling and stacking with RF barrier voltage.
2. Formation of continuous beam
3. RF of 22-nd harmonic, bunching
4. Increase RF voltage and bunch length decreasing
5. RF of 66-nd harmonics, e-cooling

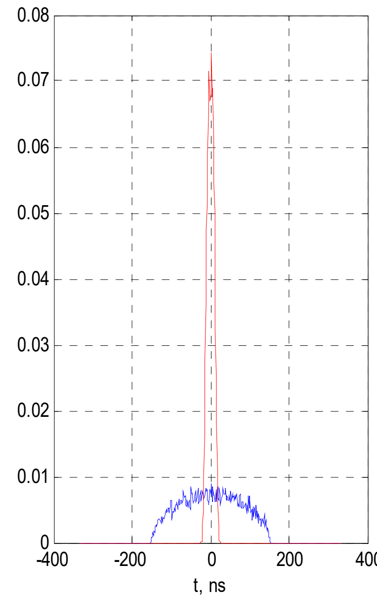
In colliding mode RF has 66 harmonics and the bunch is located in every third separatrix. Electron cooling enables to decrease the transverse emittance and longitudinal length of ion bunch. So, the luminosity may be stable at presence of the electron cooling.



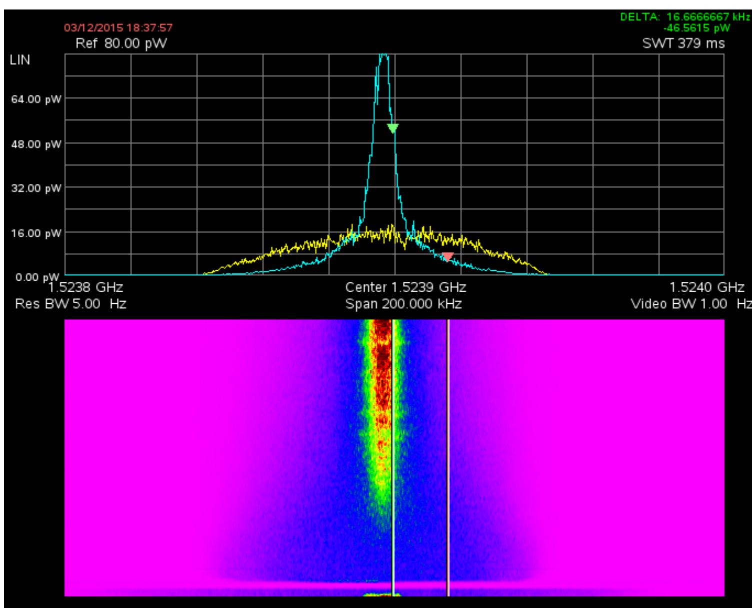
Cooling simulations for COSY

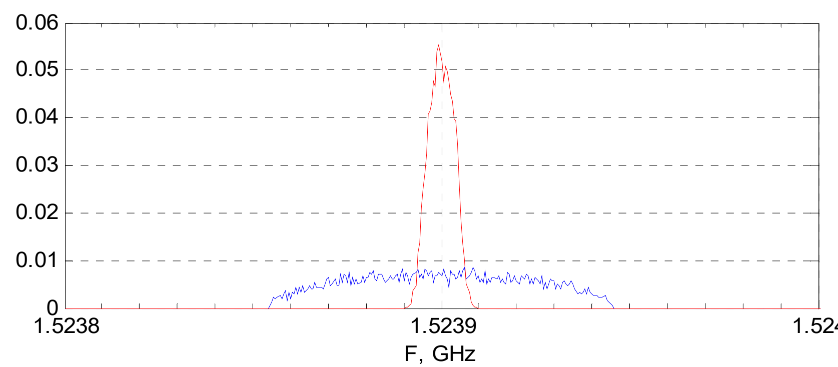
Cooling of bunched proton beam on COSY. Electron energy 908 keV. Electron current 0.5 A.





Simulations with Parkhomchuk's equation and space charge field

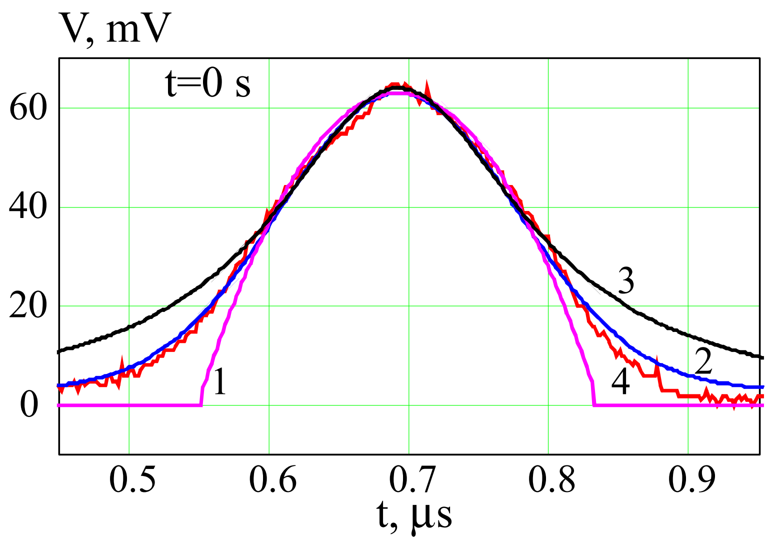


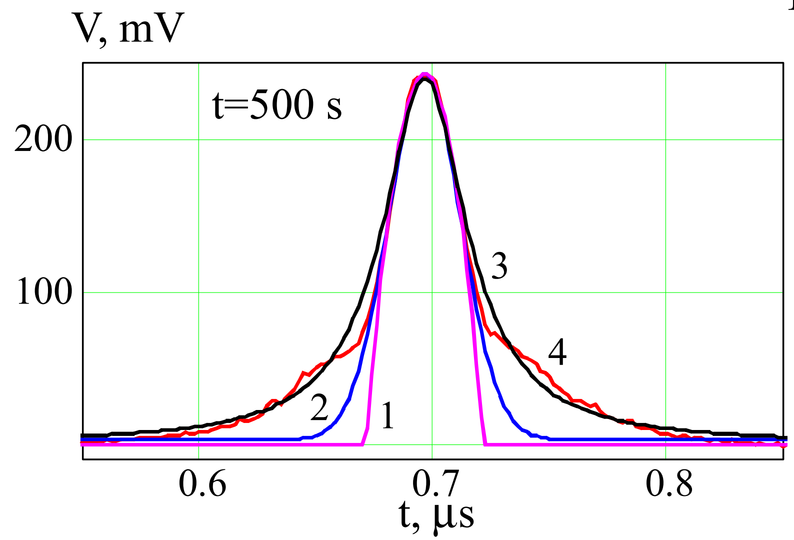


e-cool can well operate with usual RF

Fitting curves of the shape of the proton bunch for the start (left picture) and the end (right picture) of the cooling process.

RF on, e-cooling with 570 mA, $N_p=2\cdot10^9$, E_e=909 kV





t=0 s		t=500 s	
1. Parabolic shape 140 ns	(magenta)	1. Parabolic shape 25 ns	(magenta)
2. Gauss shape120 ns	(blue)	2. Gauss shape 22 ns	(blue)
3. Lorentz shape 110 ns	(black)	3. Lorentz shape 22 ns	(black)
4. Experimental data	(red)	4. Experimental data	(red)

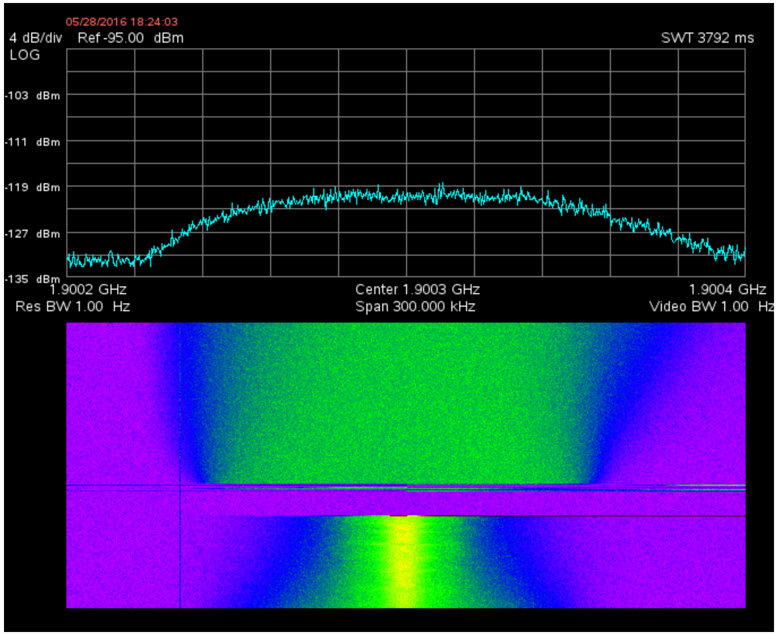
The estimation of the length according equation gives the length 20 ns that is very close to the experimental data. So, the beam core attains equilibrium induced by the space charge force.

$$\sigma_s\left(J_i\right)=\left[\frac{3}{2\gamma^2\beta}\Pi^3\frac{J_{ion}\left(1+2\ln\left(b/a\right)\right)}{cU_{RF}}\right]^{1/3}$$

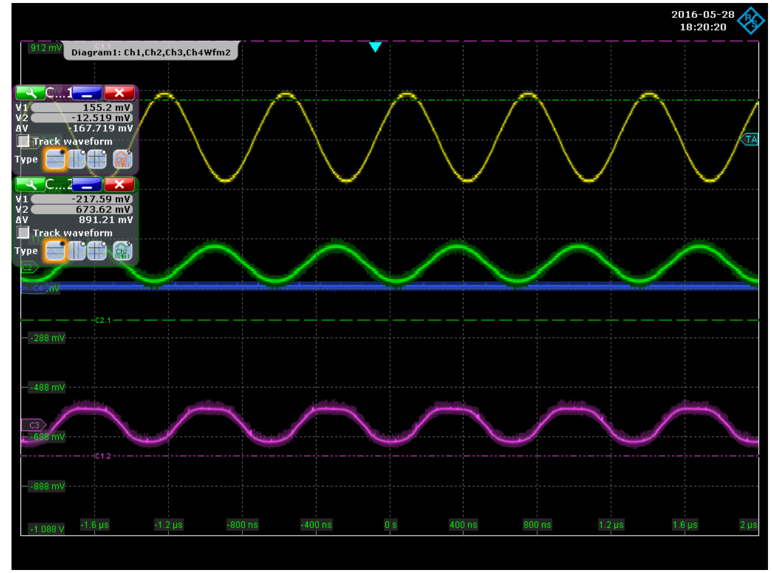
e-cool can help to obtain the space-charge limit

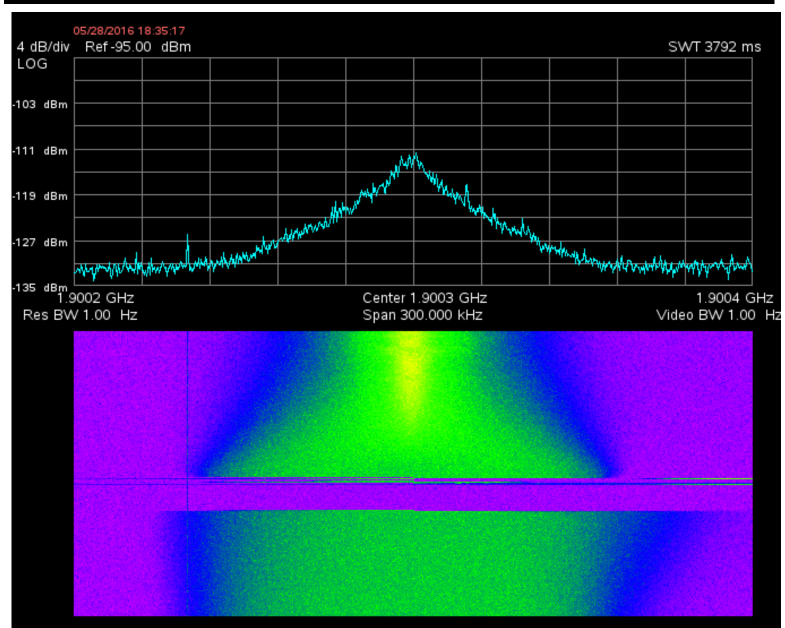
e-cool can well operate with usual RF and target

Ee=909 kV, Np=$2\cdot10^9$, $n_a=2\cdot10^{14}$ cm^{-2}

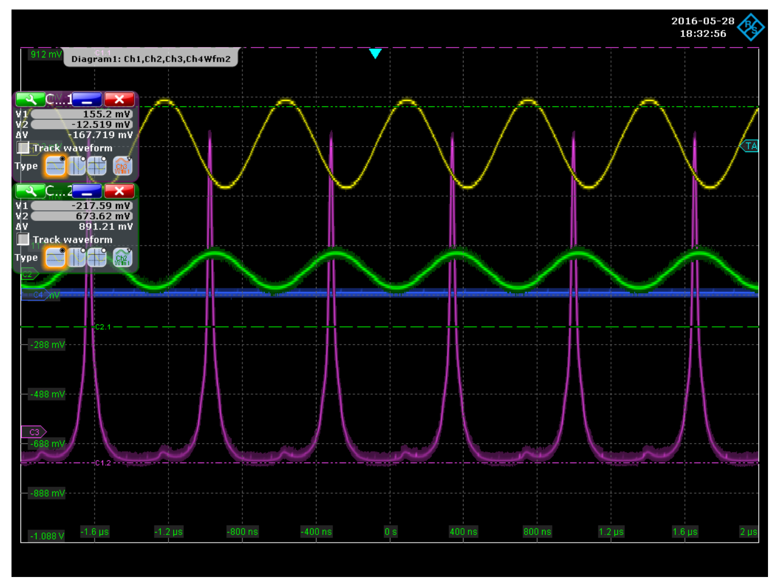


NO COOL



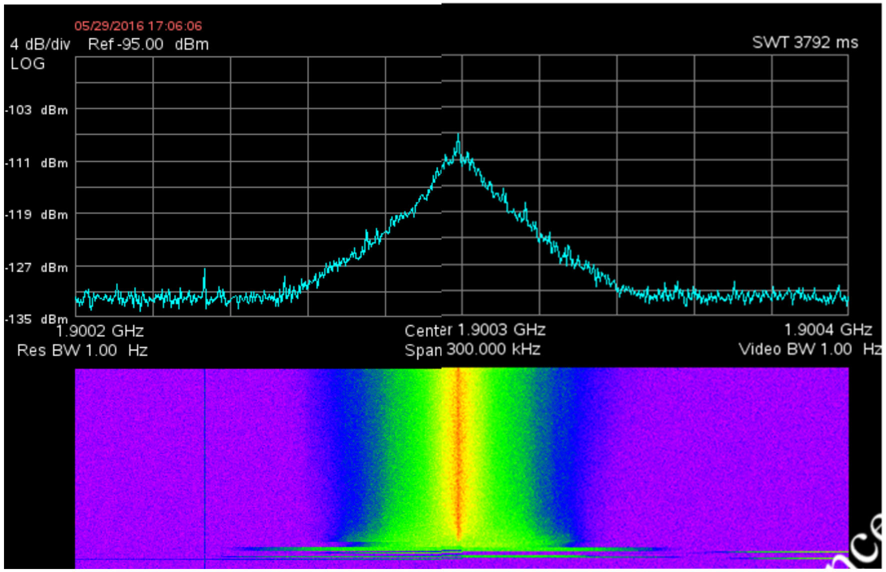


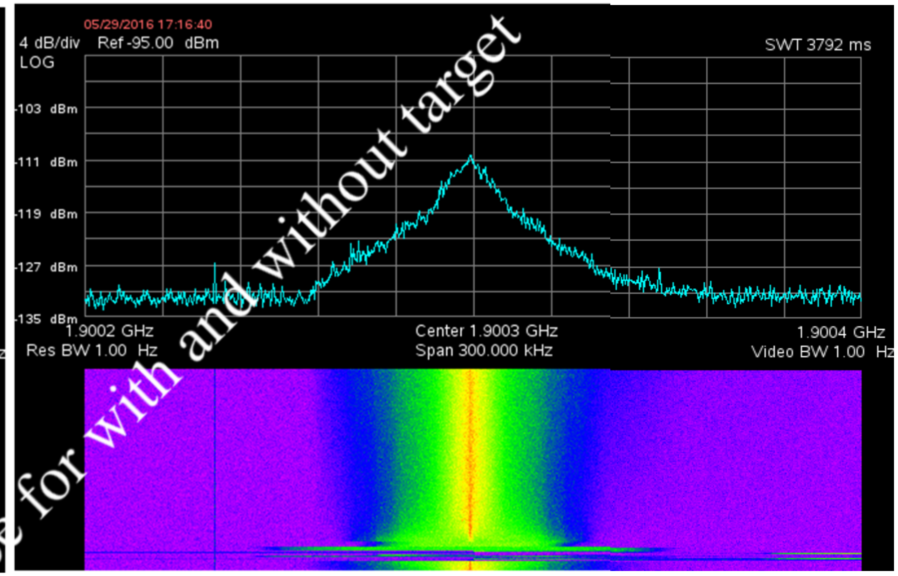
COOL

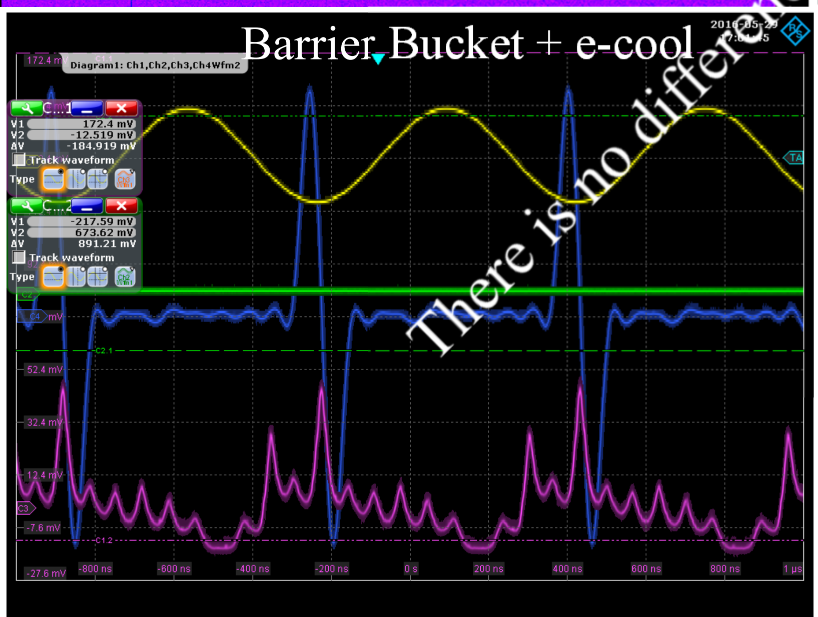


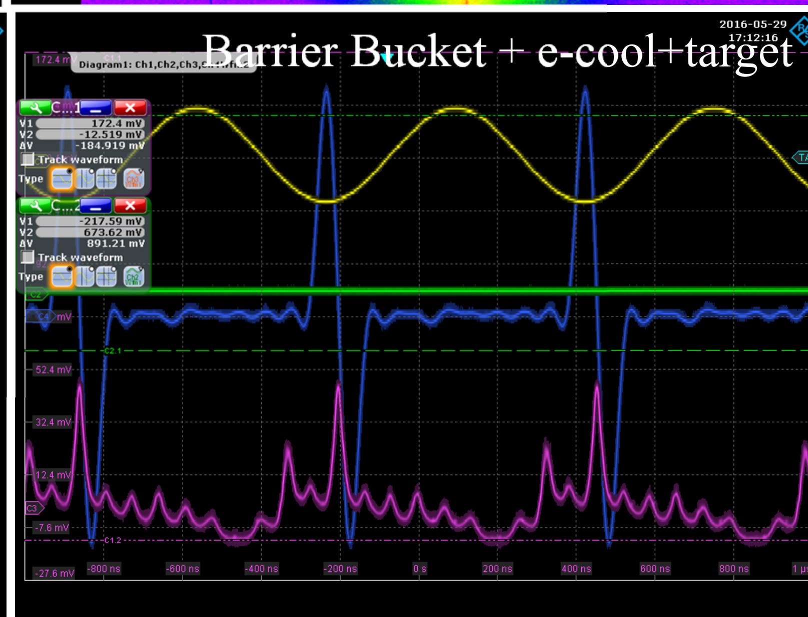
e-cool can well operate with barrier bucket and target

Electron cooling with barrier bucket and target with density Ee=1259.5 kV, $n_a = 2 \cdot 10^{14}$ cm^{-2}





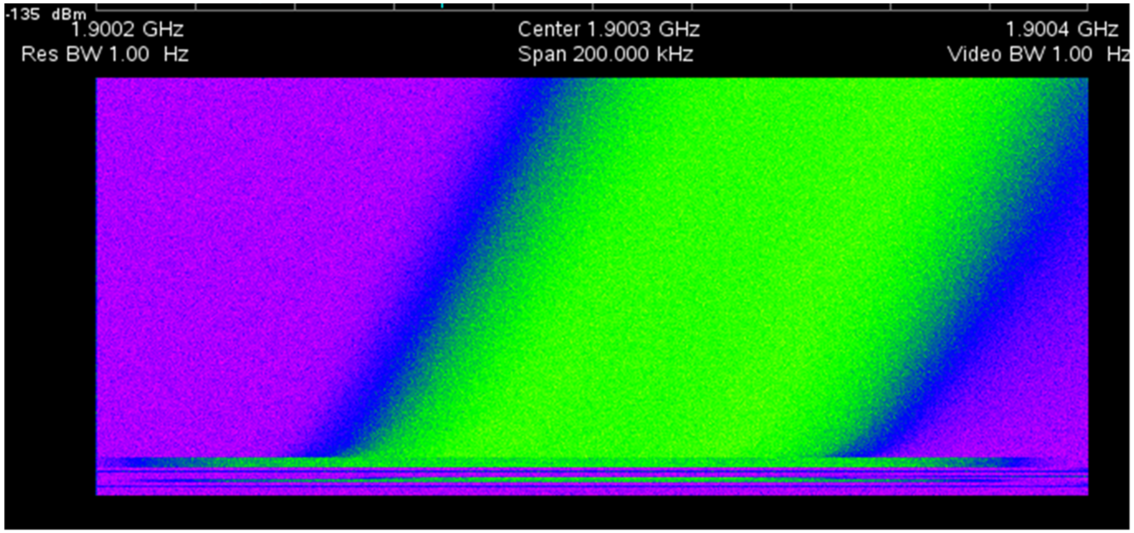




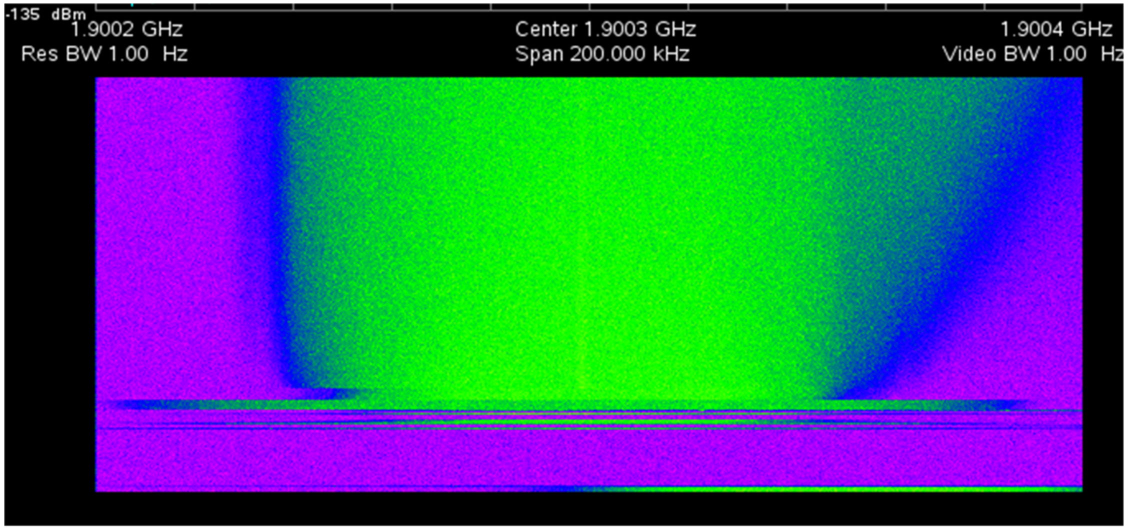
There is no difference for with and without target

Experiments with target without electron cooling

Target has a significant influence on the dynamic of the proton $n_a = 2 \cdot 10^{14}$ cm^{-2}



target



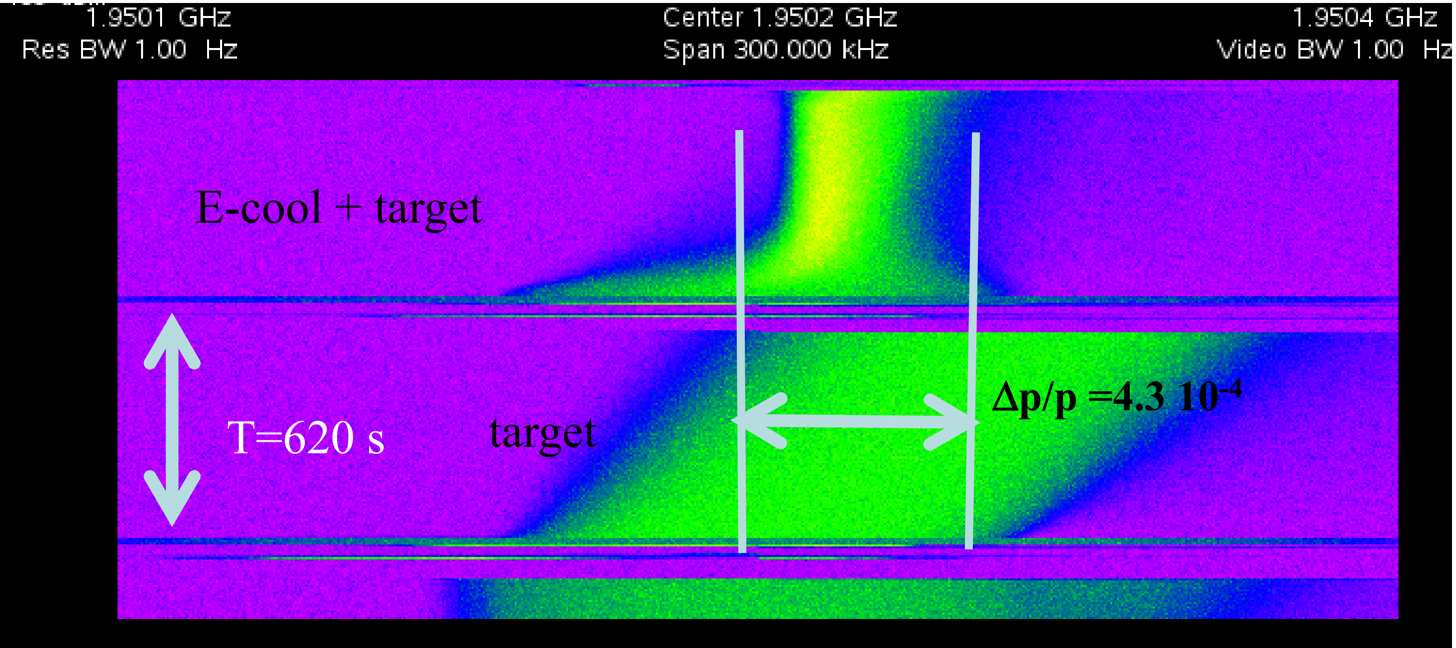
target + barrier bucket

Spectrogram of Schottky noise at target action. The top picture shows ionization loss in cluster target corresponding to hydrogen density $n_a = 2 \cdot 10^{14}$ cm^{-2}. The bottom picture shows the simultaneously action barrier bucket and target. All spectrum duration is about 550 s.

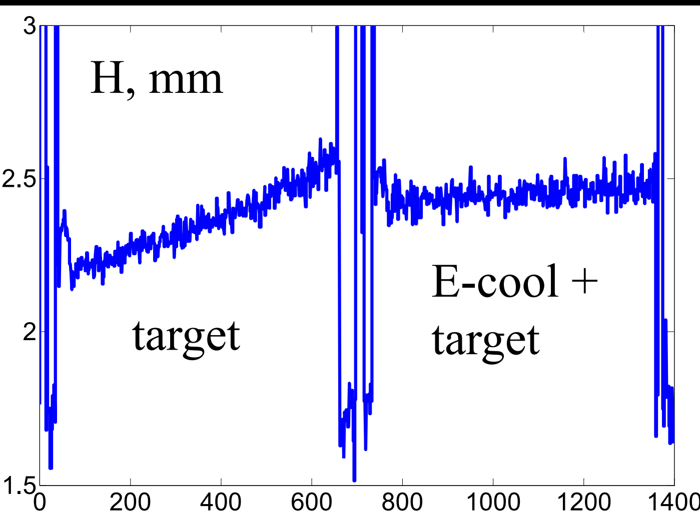
Electron energy 1259.65 kV, Je=500 mA

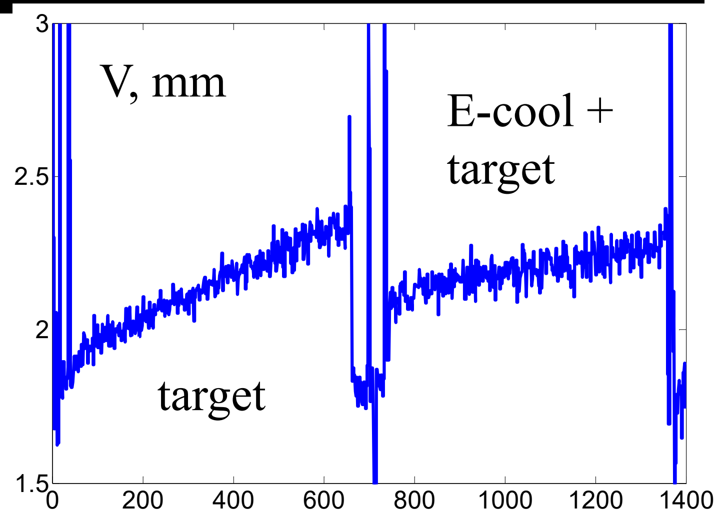
Experiments with e-target

Electron cooling suppressed the longitudinal action of the target with density $n_a = 2\cdot 10^{14}$ cm^{-2} without help RF.



Electron cooling practically suppressed longitudinal and transverse growth induced by target but the more precise tuning storage ring and e-cooler is necessary.





Summary

1. The many problems of the electron cooler at 2.5 MeV (modular approach of the accelerator column, the cascade transformer, the design of the electron gun with 4-sectors control electrode, Wien filter etc) is experimentally verified during commissioning in COSY.

2. But there is enough new decision for future hard works. At the end of work the NICA collider will obtain a powerful system of the electron cooling.