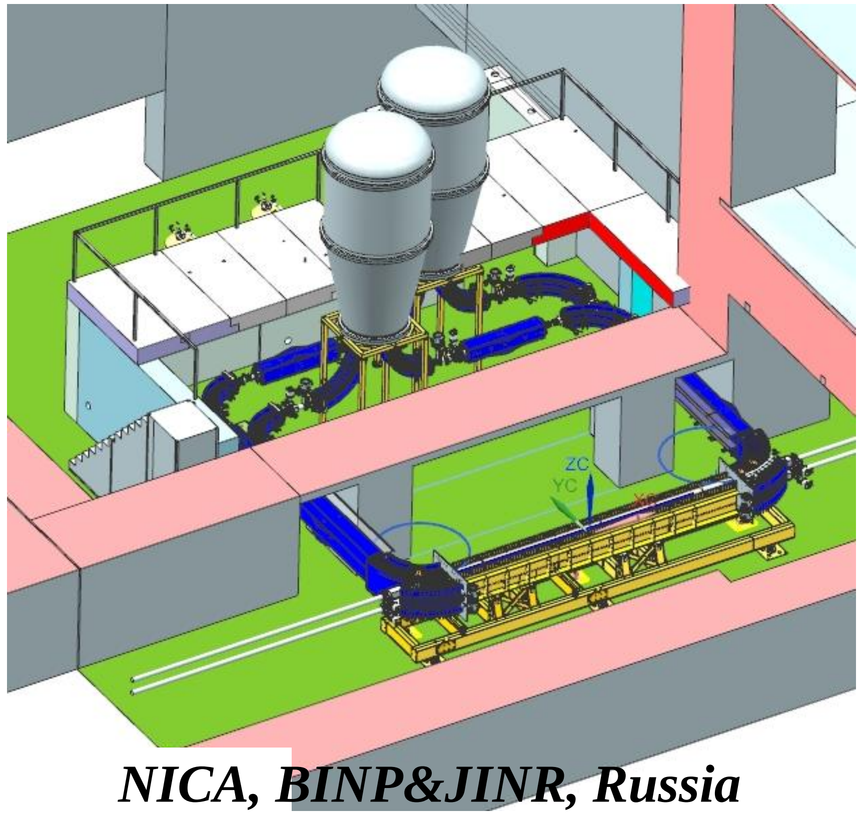
Electron coolers for NICA Booster and Collider

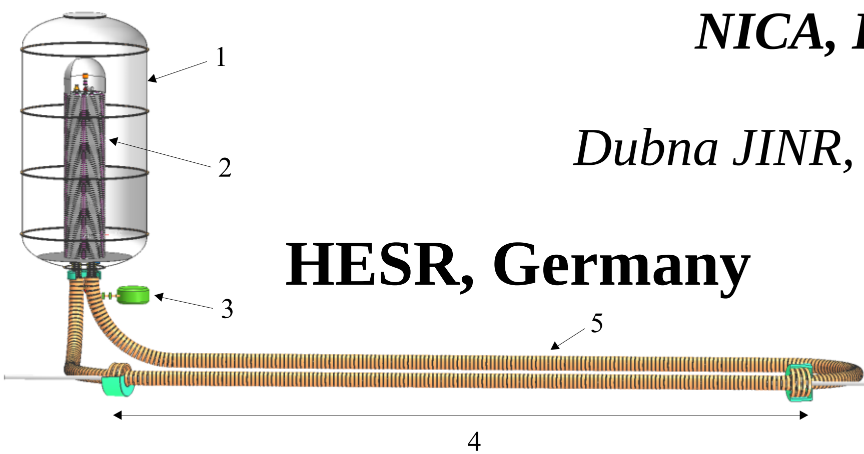
V.B. Reva and BINP team

COSY, Germany



NICA, BINP&JINR, Russia

Dubna JINR, 7-8 June, 2018



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} $см^{-2}\cdot с^{-1}$. 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.

NICA @ Heavy Ion mode

2 electron coolers: NICA booster 60 keV

High Voltage NICA 2.5 MeV

Linac HILac (3.2MeV/u) ← ESIS KRION

Linac LU-20 (5MeV/u) ← Ion sources

Booster (25 Tm)
1(2-3) single-turn injection,
storage of $(2 \div 4) \times 10^9$ ions,
acceleration up to 100 MeV/u,
electron cooling, acceleration
up to 600 MeV/u

Stripping (80%) $^{197}Au^{31+}$ => $^{197}Au^{79+}$

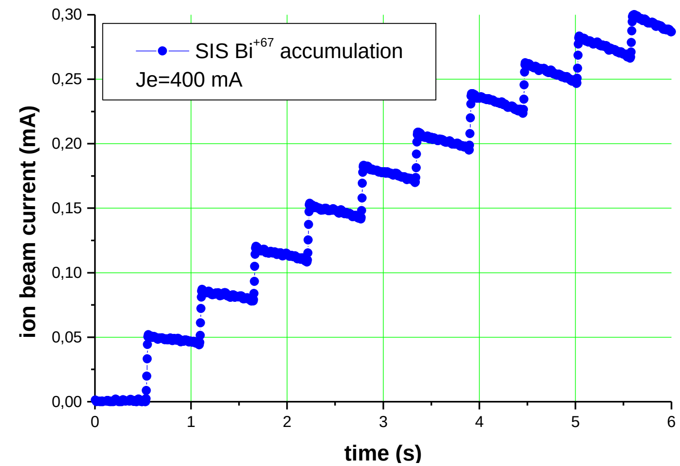
Nuclotron (45 Tm)
injection of one
bunch
of $\leq 2 \times 10^9$ ions,
acceleration up to
1 - 4.5 GeV/u max.

Two SC rings of the collider

~ 2 x 22 injection cycles
22 bunches per ring

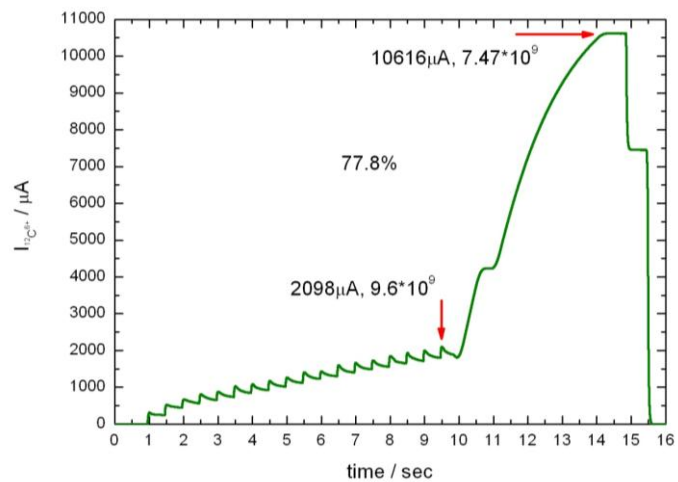
We hope that the low energy electron cooler will be helpful for NICA operation by analogously with others scientific centers

Assembling **NICA** Booster Cooler in JINR

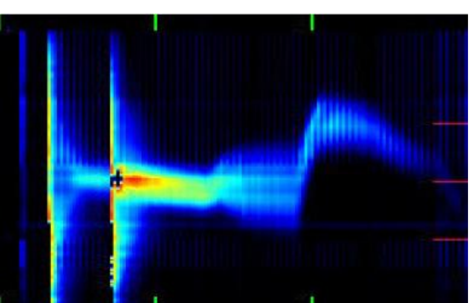


Accumulation Bi beam at **SIS-18**

Vacuum level 10^{-11} is obtained



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



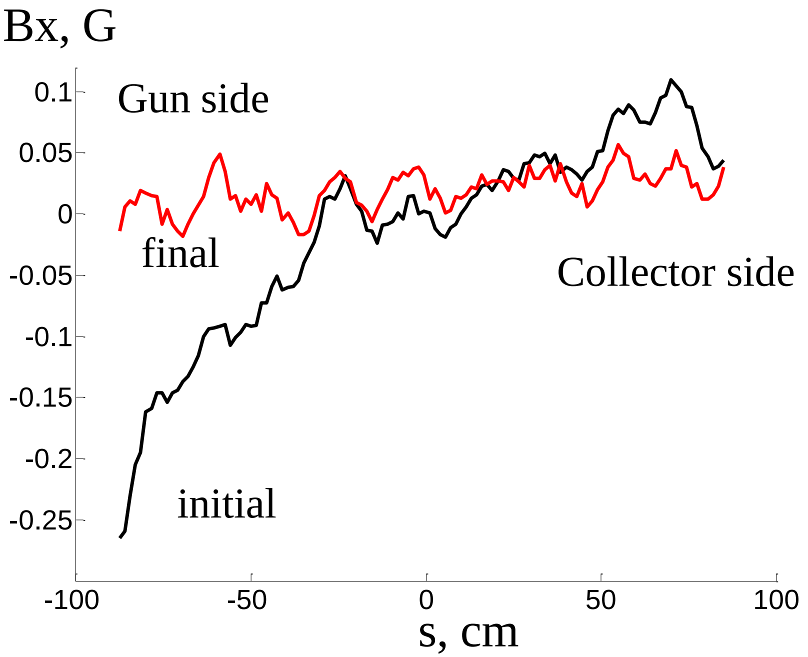
LEIR Lead ion cooling, accumulation, acceleration cooling time about 0.1 c

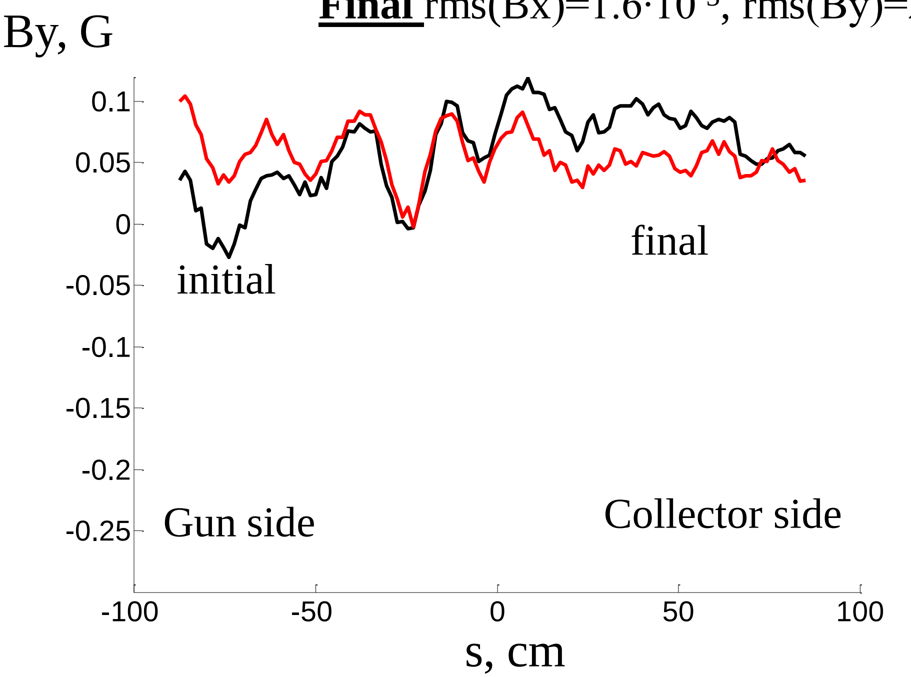
Correction of line straightness of magnetic force line in Dubna

First tuning of coils was done in Novosibirsk, So after the transportation procedure the correction is not very large

Black line is before correction, the Red line is after correction

Initial rms(Bx)=$8\cdot10^{-5}$, rms(By)=$3.5\cdot10^{-5}$
Final rms(Bx)=$1.6\cdot10^{-5}$, rms(By)=$2.0\cdot10^{-5}$

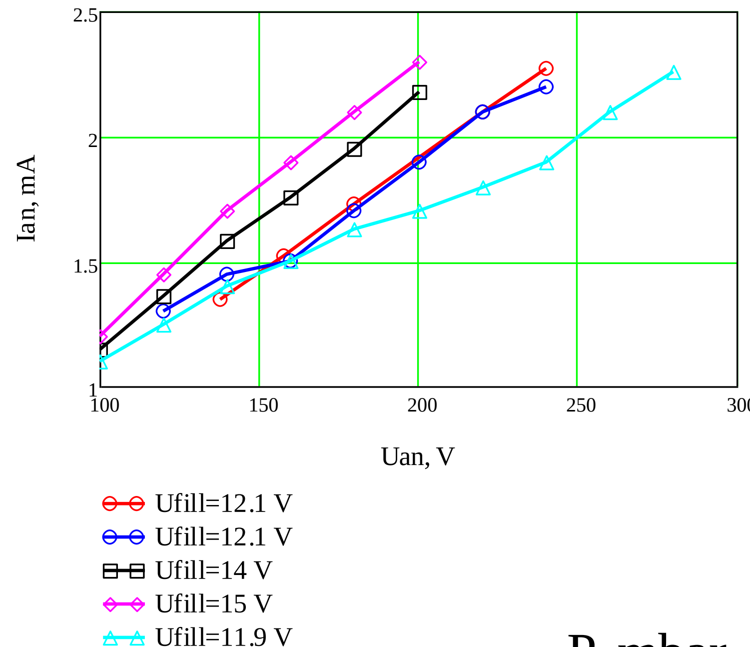


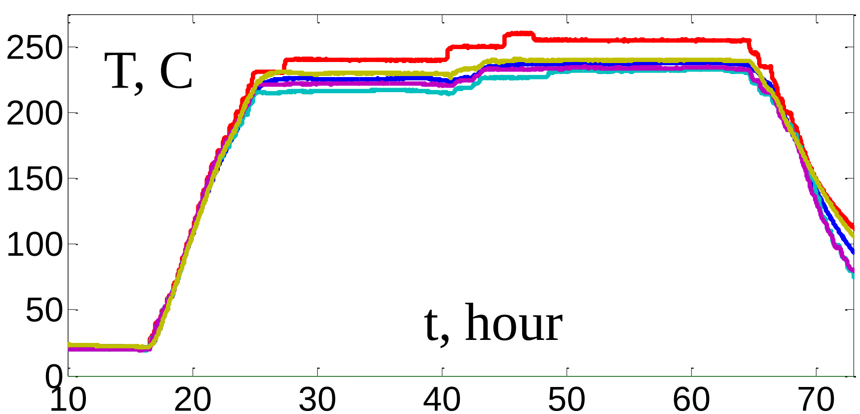


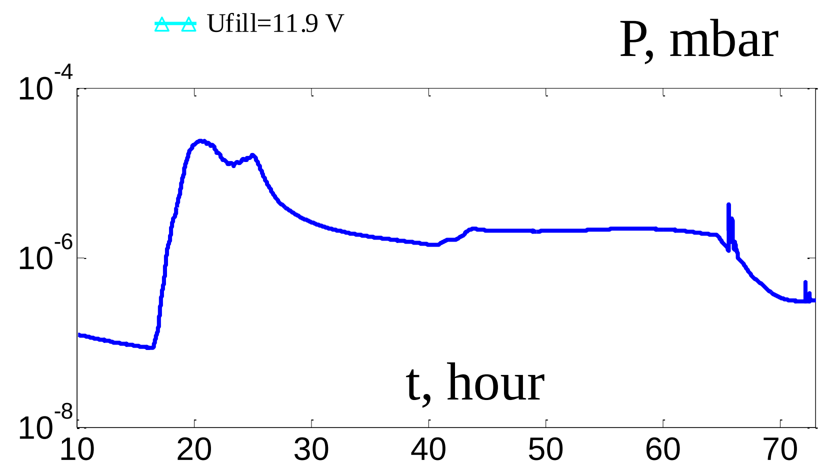
Vacuum baking in Dubna

Assembling of vacuum chamber

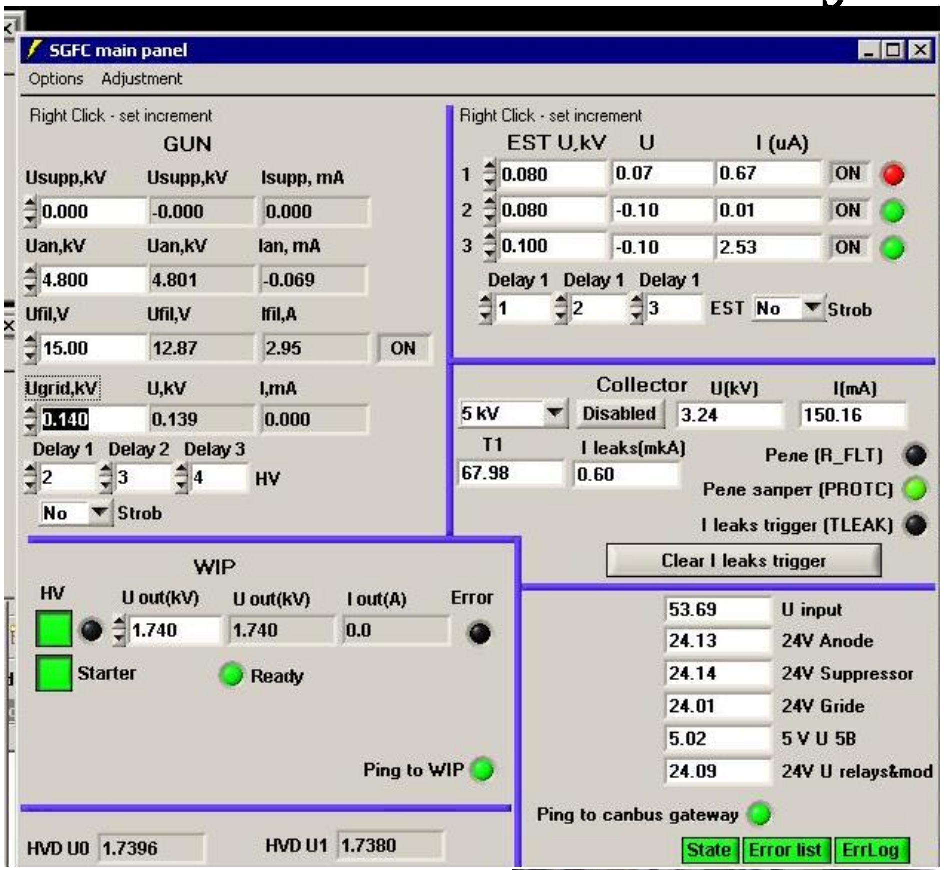
Cathode activation after baking

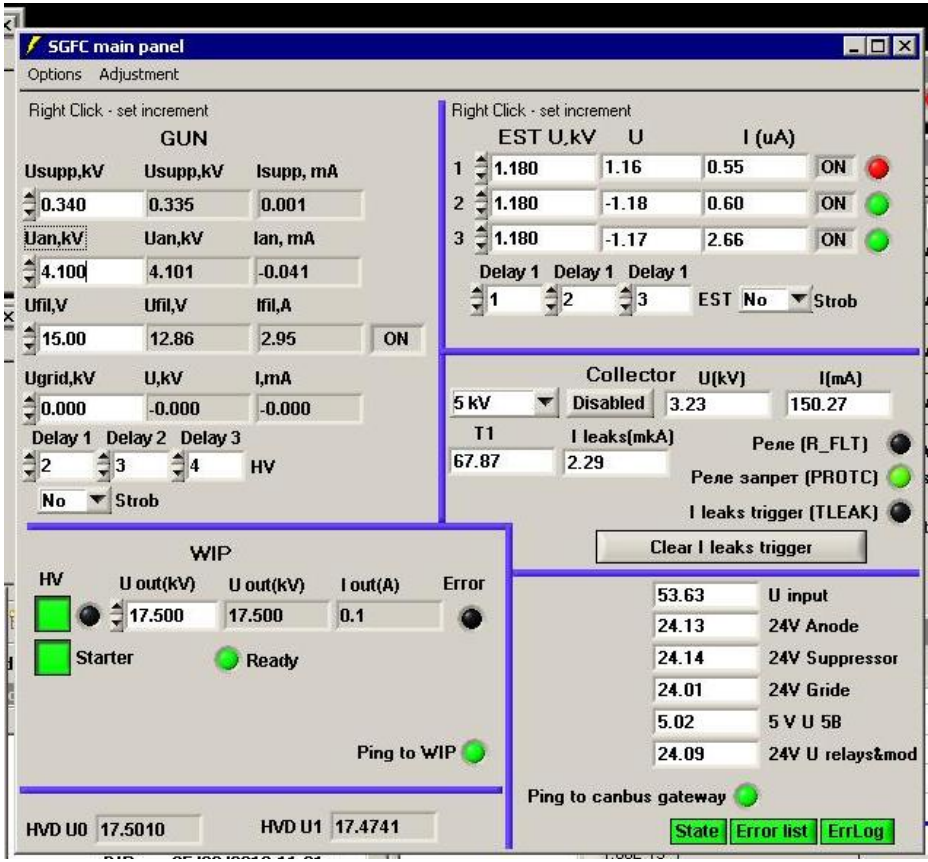




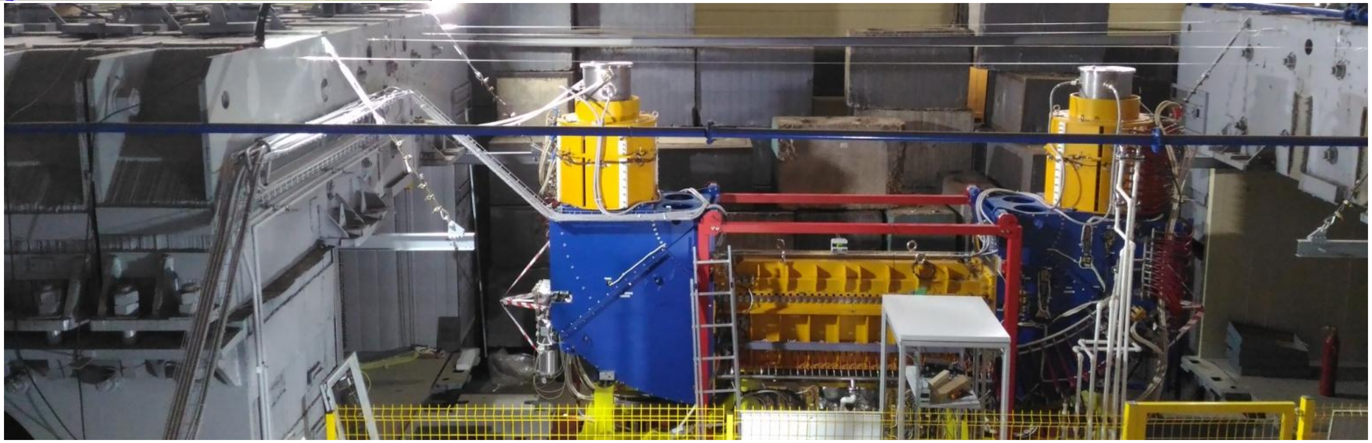


Today situation

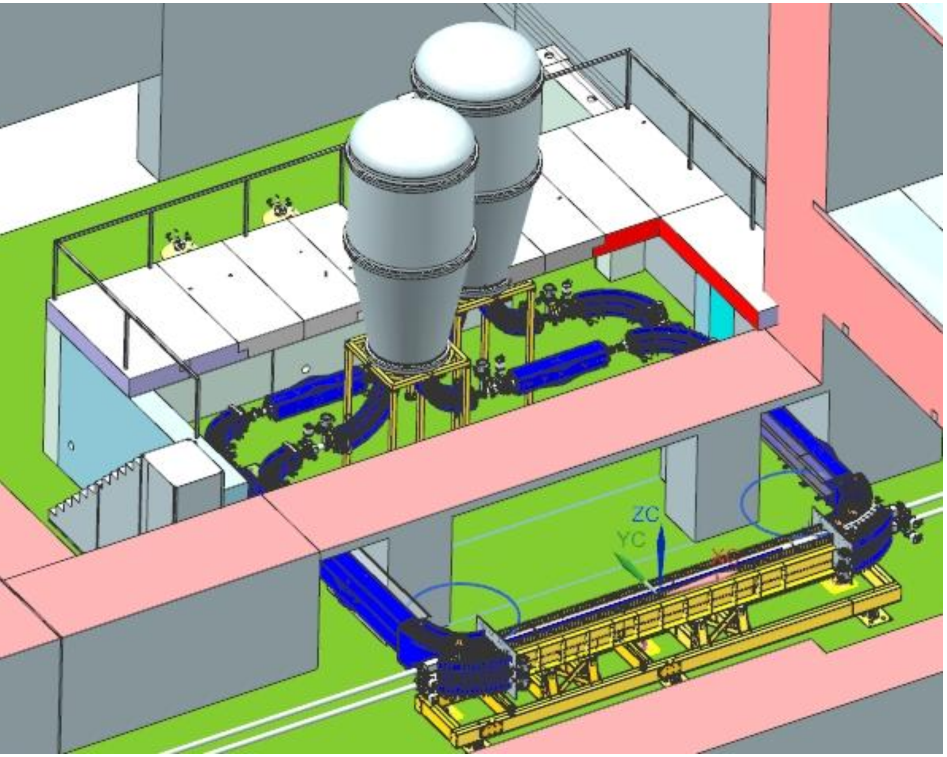


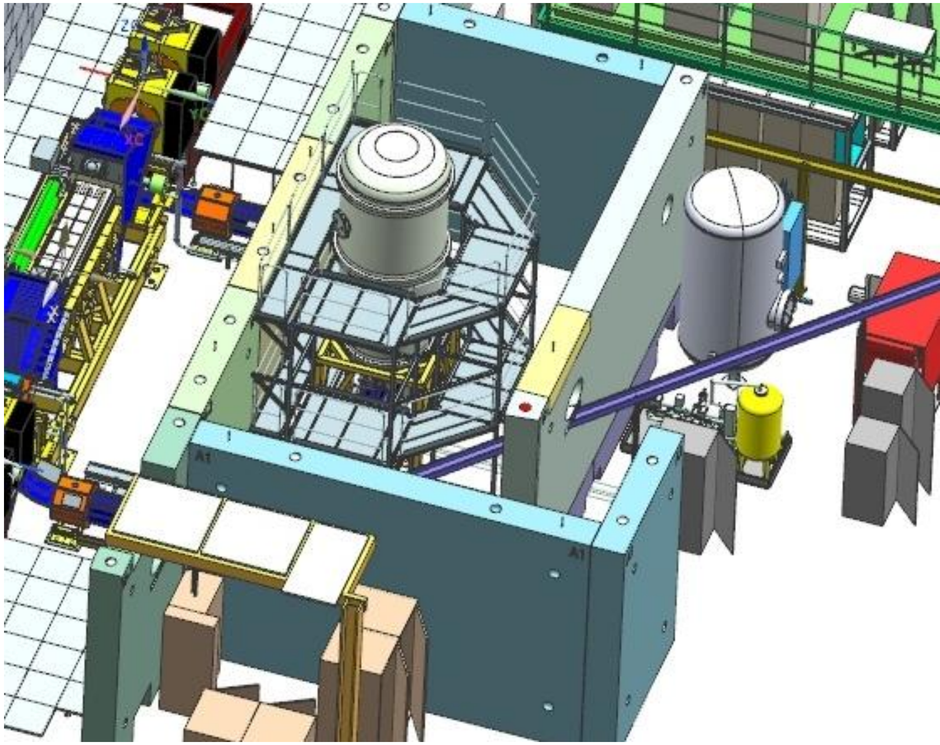


150 mA at energy 1.74 kV and 17.5 kV in JINR, yesterday it was observed 300 mA at 5 kV



Base of High-Voltage cooler for NICA is COSY cooler



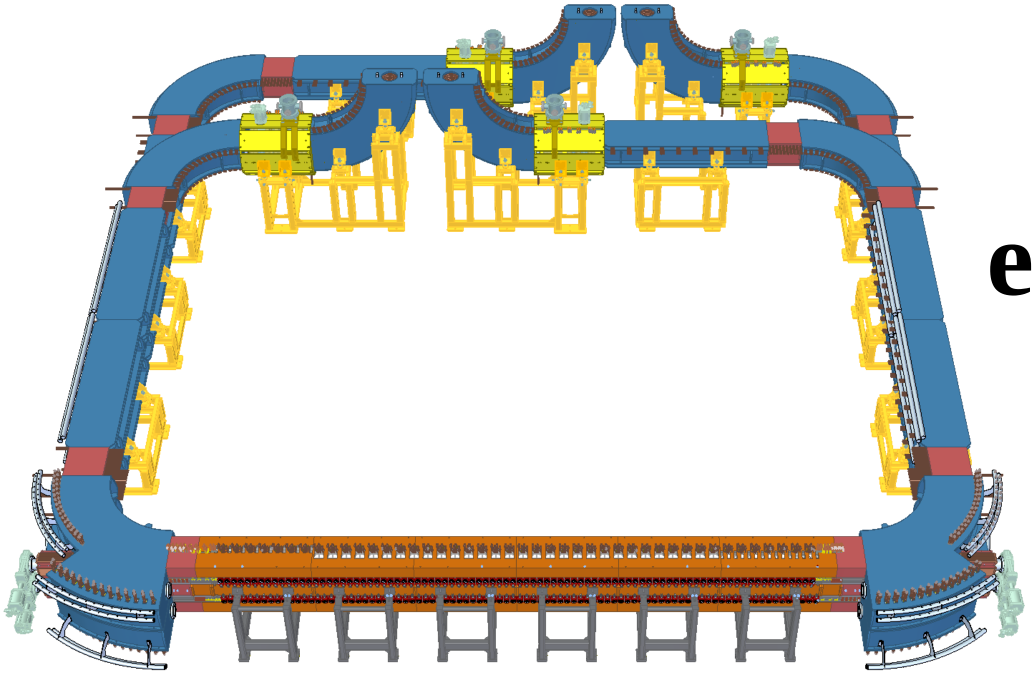


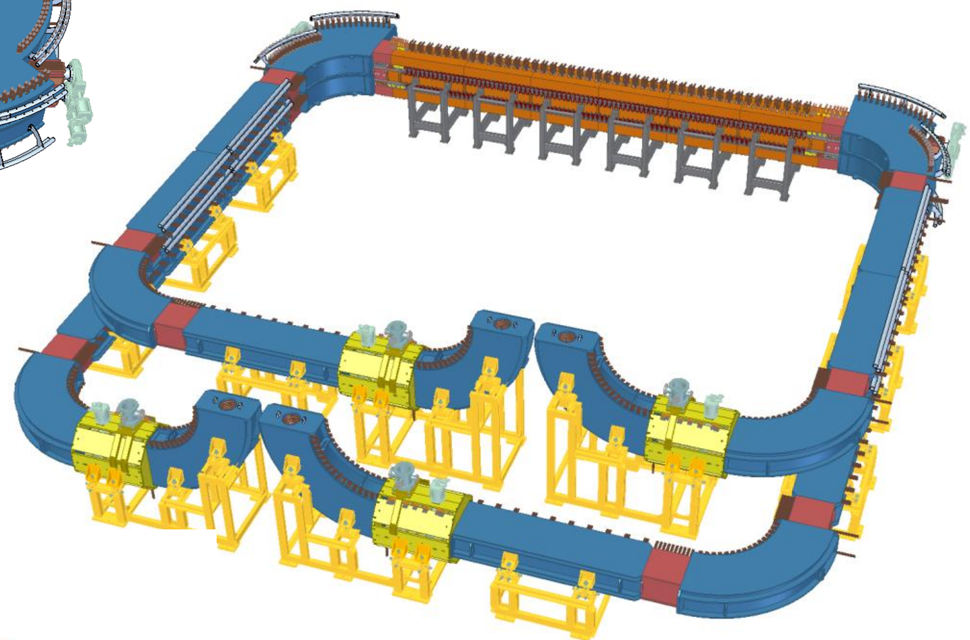
2.5 MeV electron cooler – integration into NICA

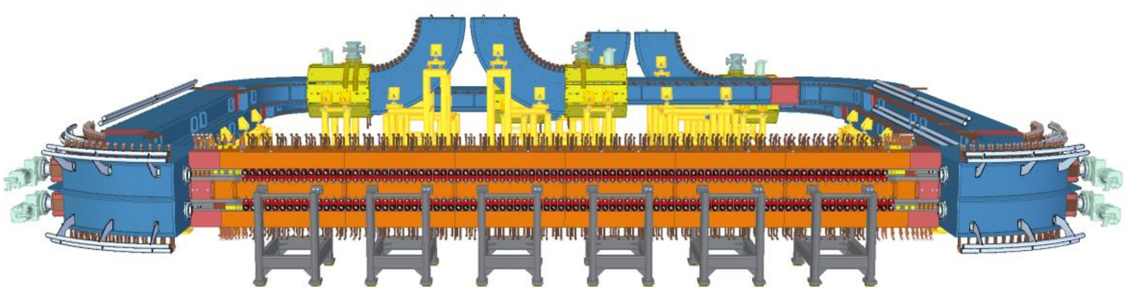
2MeV electron cooler – integration into COSY

The next step is high-voltage cooler for NICA collider

3D design of high energy NICA cooler







Main parameters cooler NICA

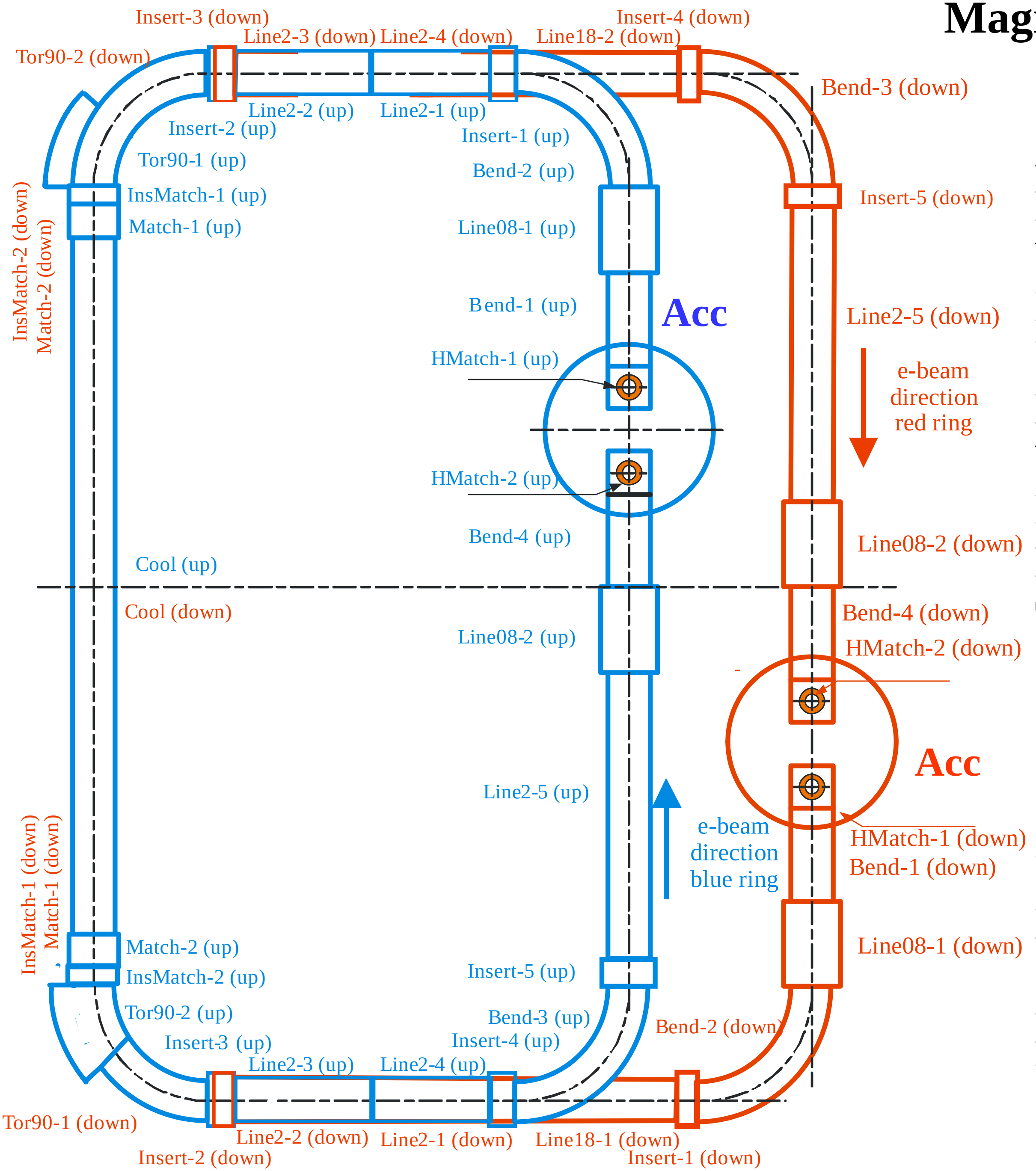
Parameter	Value
Energy range	0.2÷2.5 MeV
Number of the cooling section	2
Stability of energy ($\Delta U/U$)	$\leq 10^{-4}$
Electron current	0.1÷1 A
Diameter of electron beam in the cooling section	5÷20 mm
Length of cooling section	6 m
Bending radius in the transport channel	1 m
Magnetic field in the cooling section	0.5÷2 kG
Vacuum pressure in the cooling section	10^{-11} mbar
Height of the beam lines	1340/1660 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)

HMatch 1 and 2. Transition between different value of the longitudinal magnetic field 0.5-1 kG

Match 1 and 2. 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)

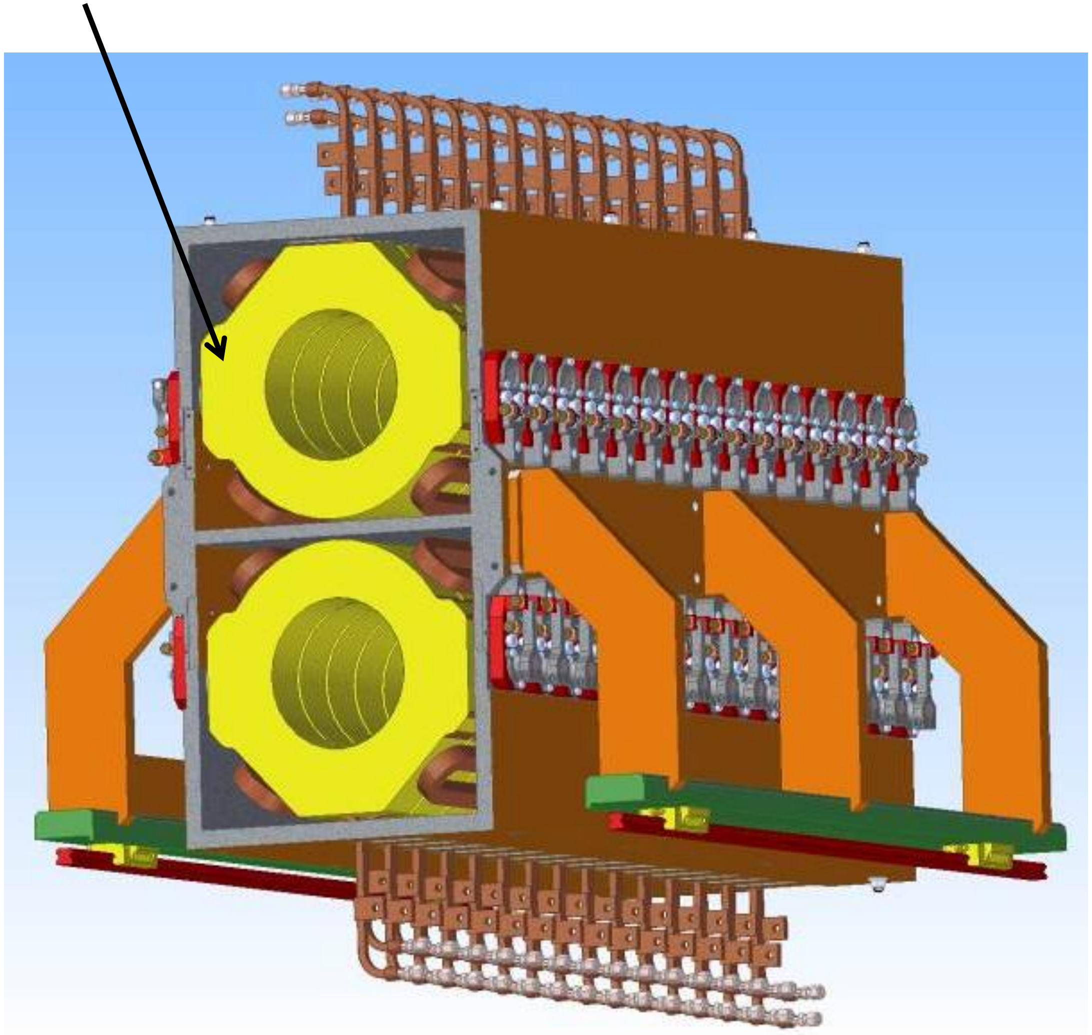
Insert. Magnetic elements for assembling and leading-out wire (1 kG)

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

Line2. Straight transport lines (1 kG)

NICA cooling section

Coils of the longitudinal magnetic field



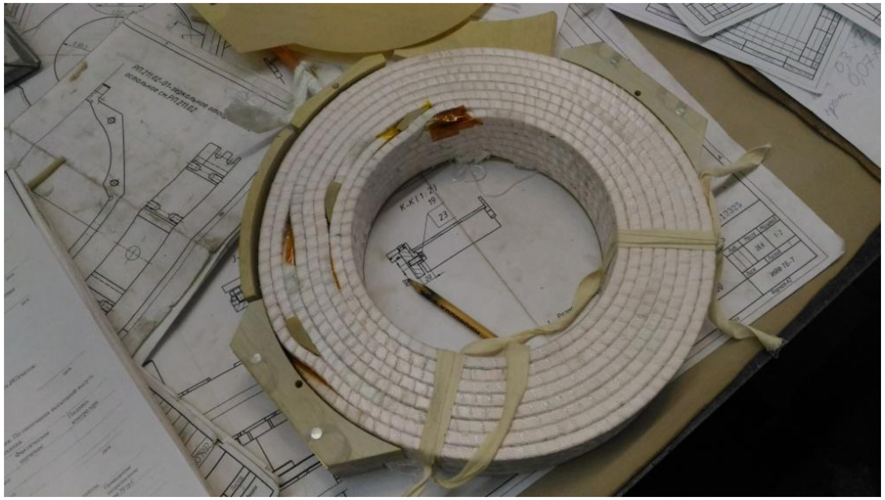
Each vacuum section contains the BPM and the correctors of the transverse magnetic field. So, the rough regulation of the magnetic force line is possible as result measurement of BPM with electron and ion beams. The ion beam is used as base line for the electron beam

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.

Cooling section consists of 6 standard section with length 1 m

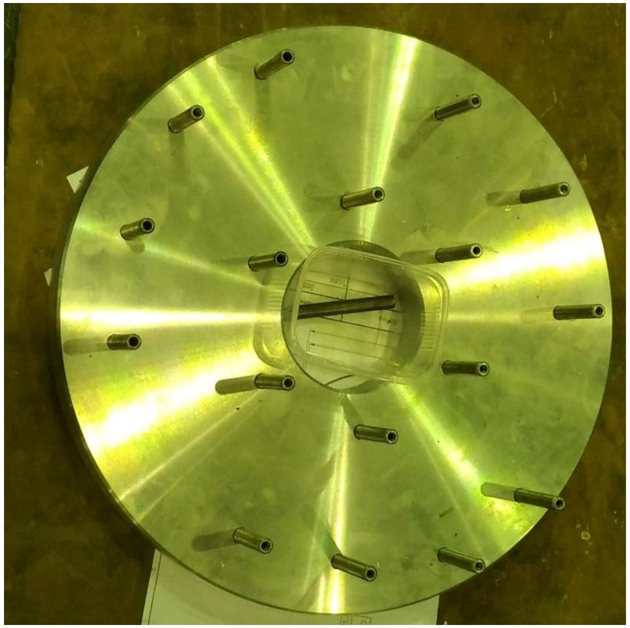
I.N. Meshkov and first cooling section for NICA in BINP

Cover of section is installed on numerically controlled machine tool

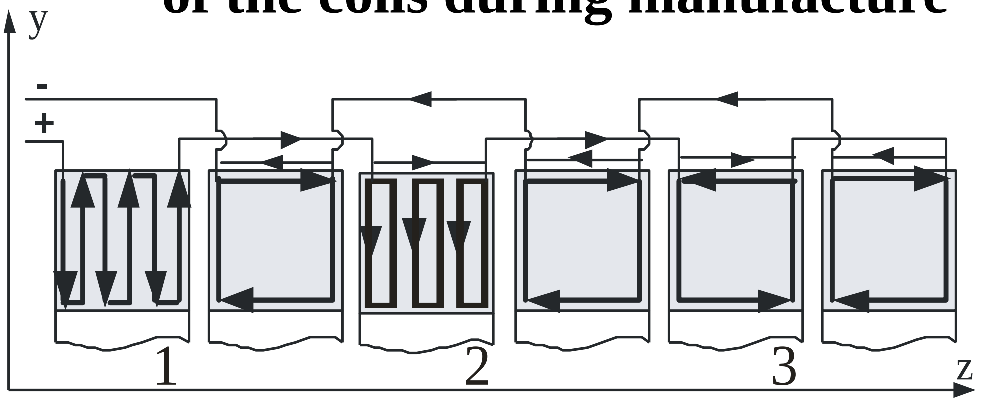


First coil during winding

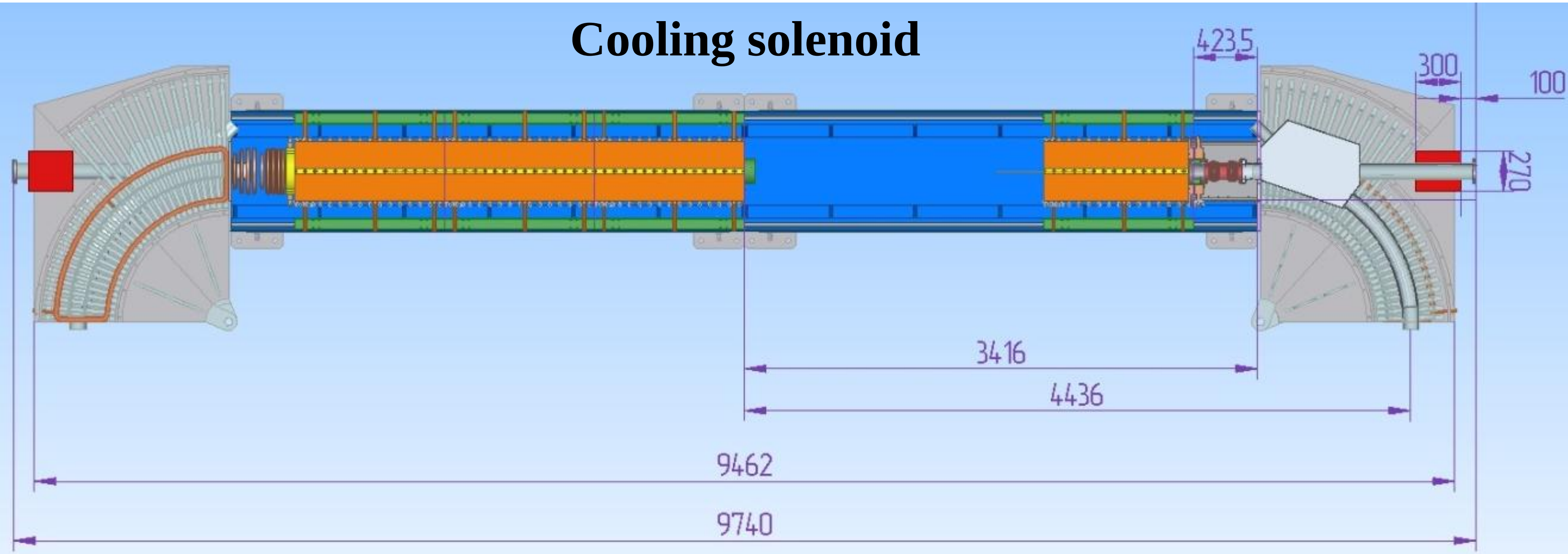
First party of the coils of the cooling section

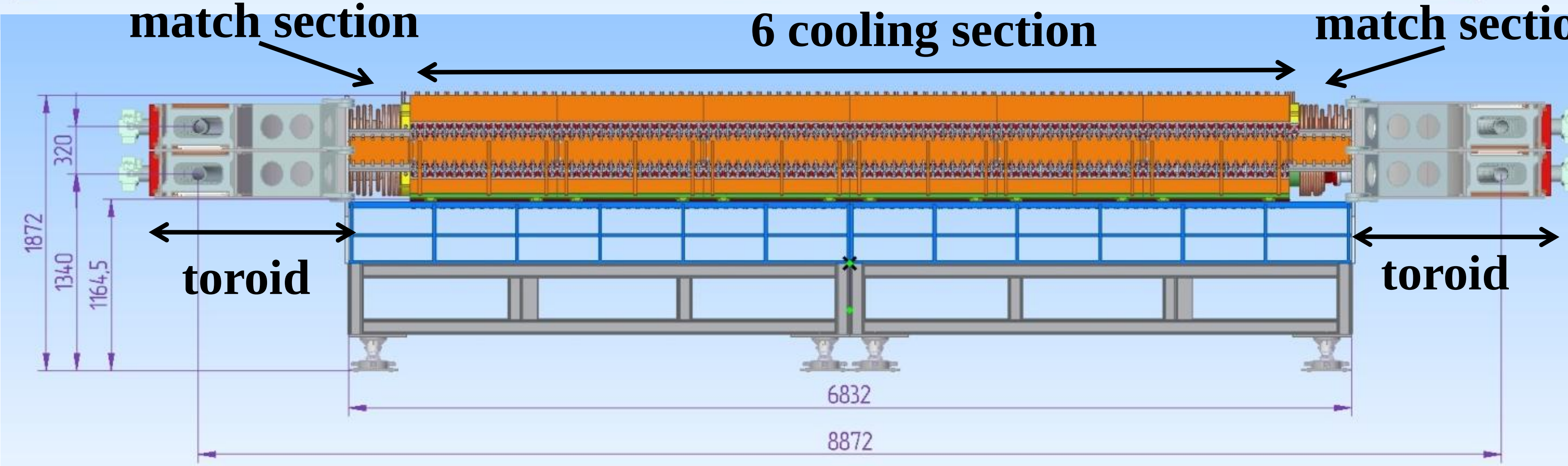


Pattern for on-line checking sizes of the coils during manufacture



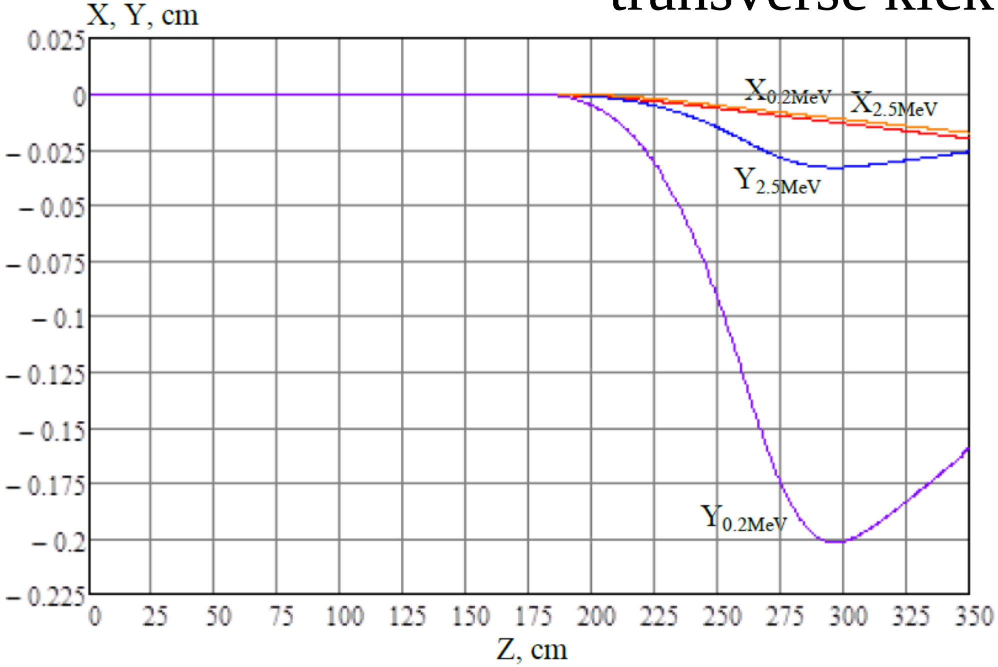
“Left” and “Right” coils like COSY design. The idea is decreasing role of the magnetic field induced by wire splice





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.

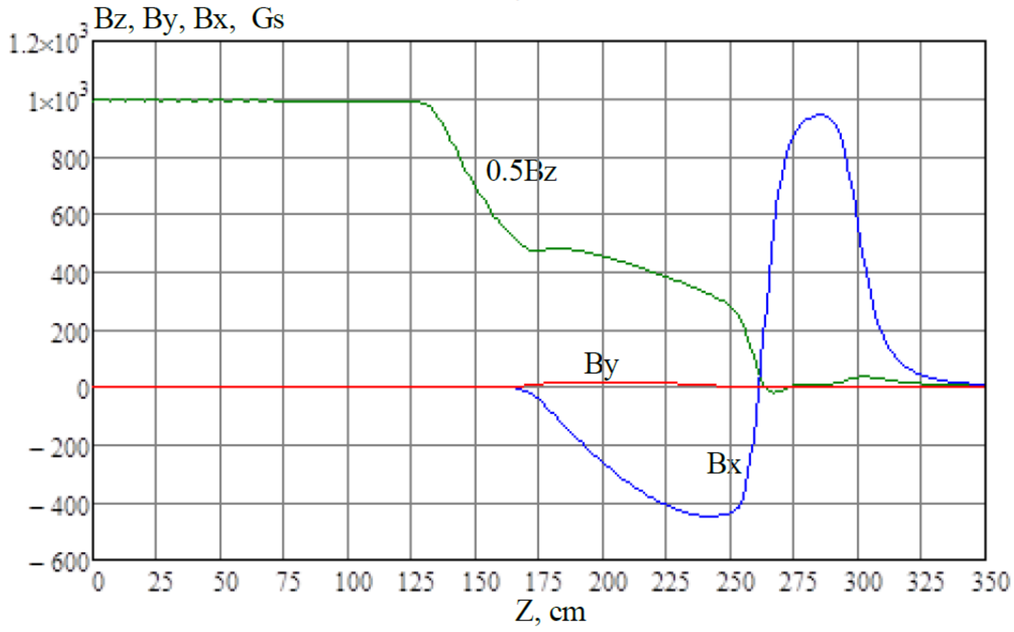
Decreasing magnetic field in the toroid reduces the problem with transverse kick on ion beam.



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

Transverse trajectory of ion at energy 0.2 MeV.

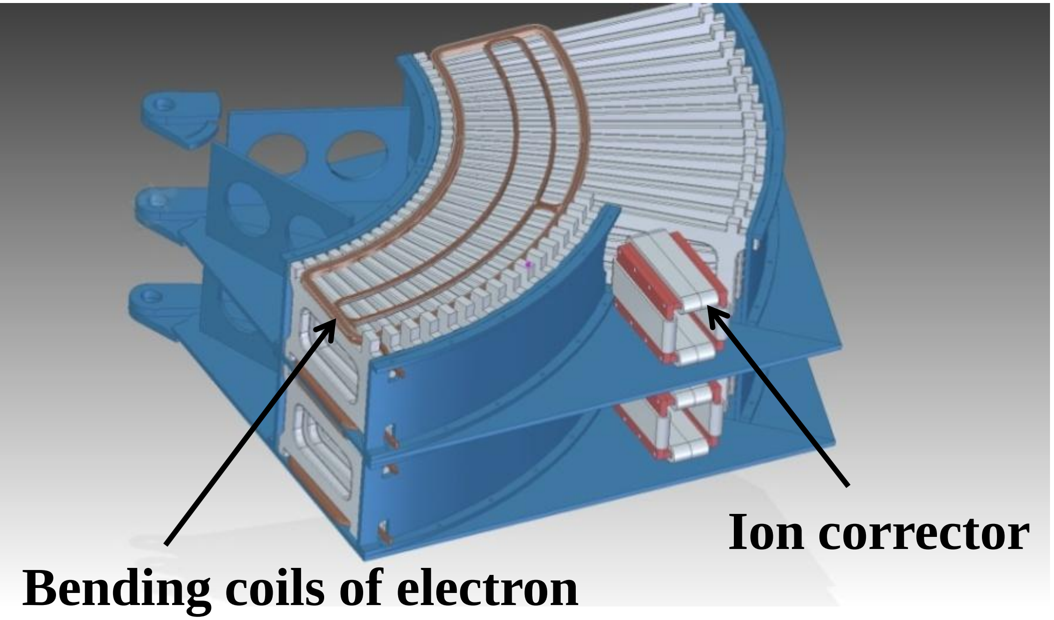
Match section between the different magnetic field is close to the cooling section in order to decrease the longitudinal magnetic field in the toroid. It strongly saves the electrical power and reduce the transverse kick for ion beam.

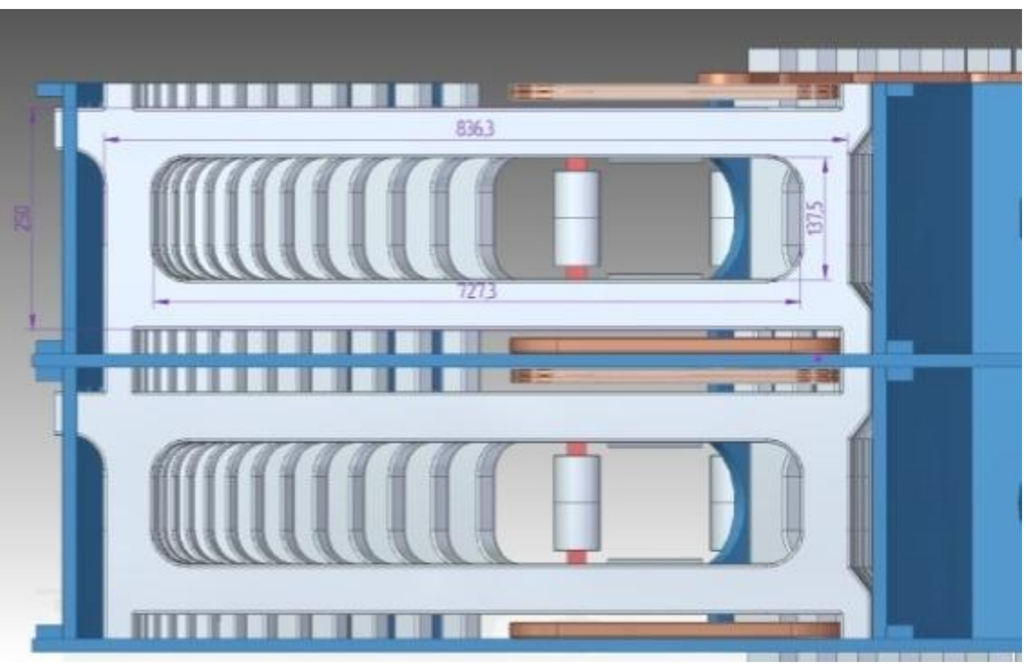


Magnetic field along ion orbit at electron energy Ee=0.2 MeV. Z=282 cm is center of ion corrector, Z=170.8 cm is entrance to the toroid. Integral of the bending field of toroid is 29.4 kG*cm.

Cooling section is 2 kG, toroid is 1 kG.

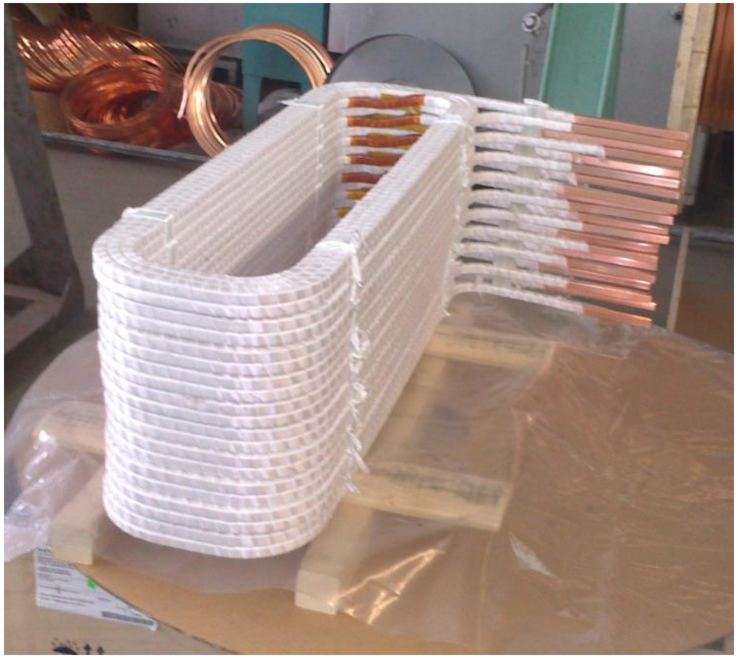
Toroid section





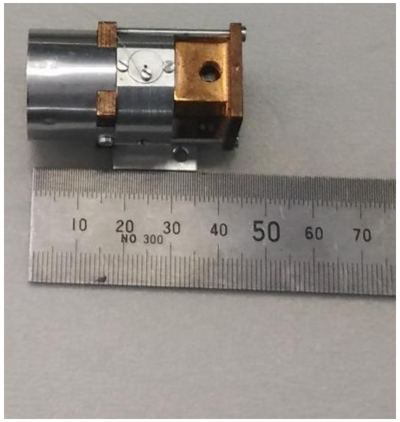
Toroid is the most complicated place where meet together two beam lines: electron and ion. Moreover the ion corrector should be located in this place. Also the it is place for vacuum pumps. The coils for bending field is placed on the toroid side. The power consumption is restricted so the coil should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

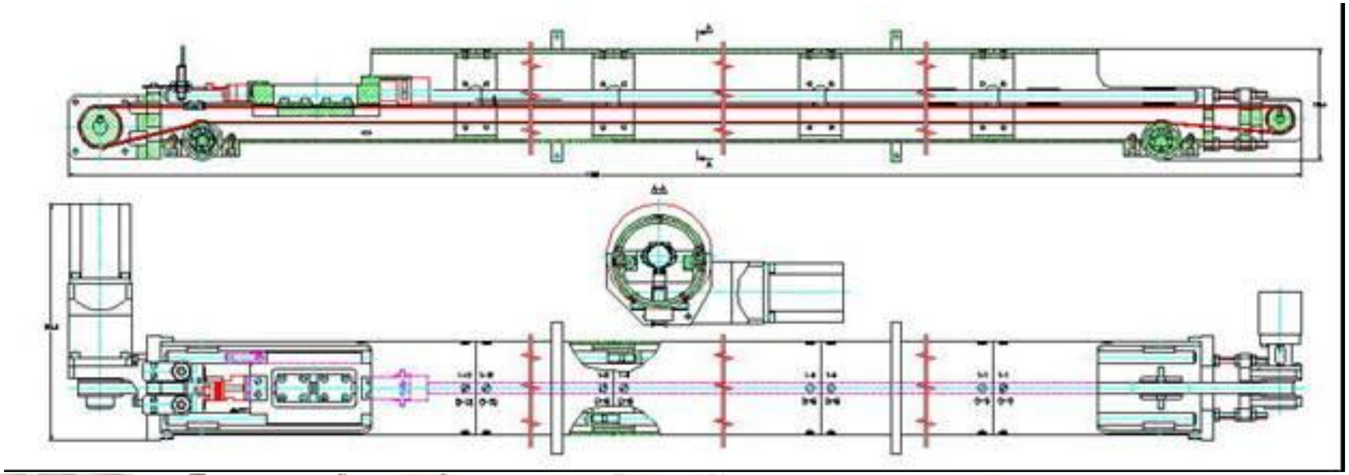
The decision of most of problem is decreasing magnetic field in the toroid. But free cheese only in a mousetrap. The length of the cooling section less (6 m) than the straight section along ion orbit (6.84 m). The distance 0.84 m is spent on the matching section.



Winding process of coils of the toroid section

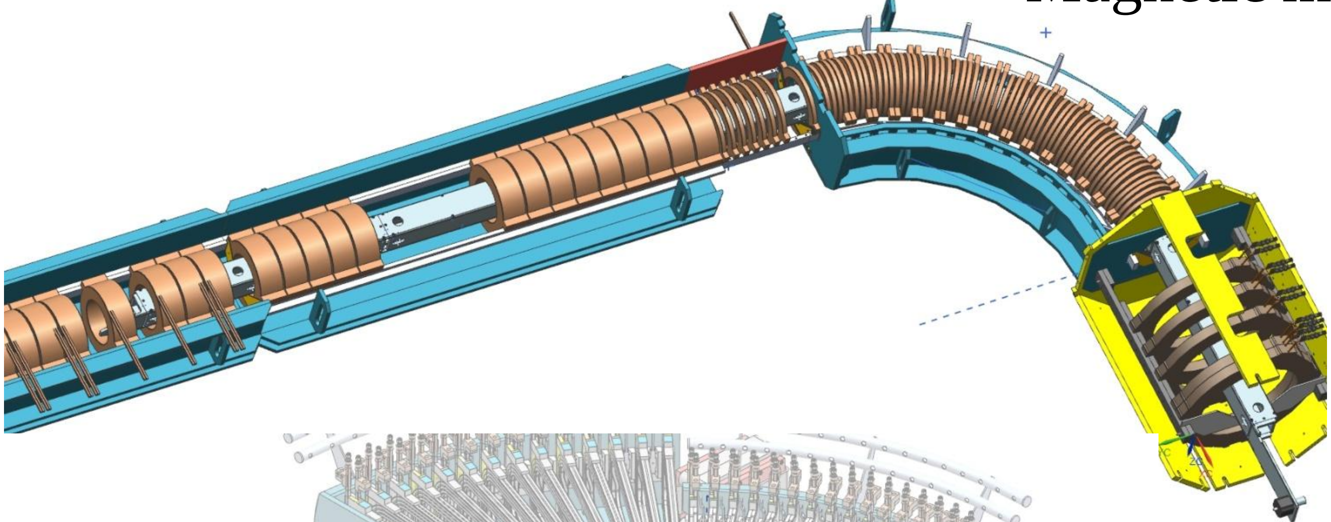
Compass

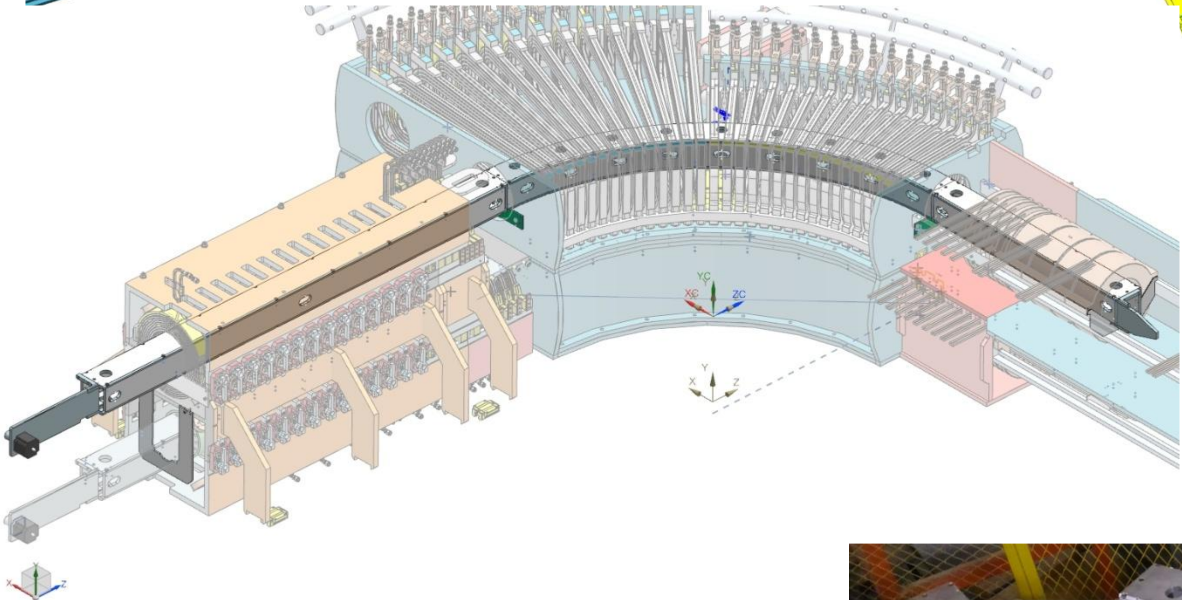


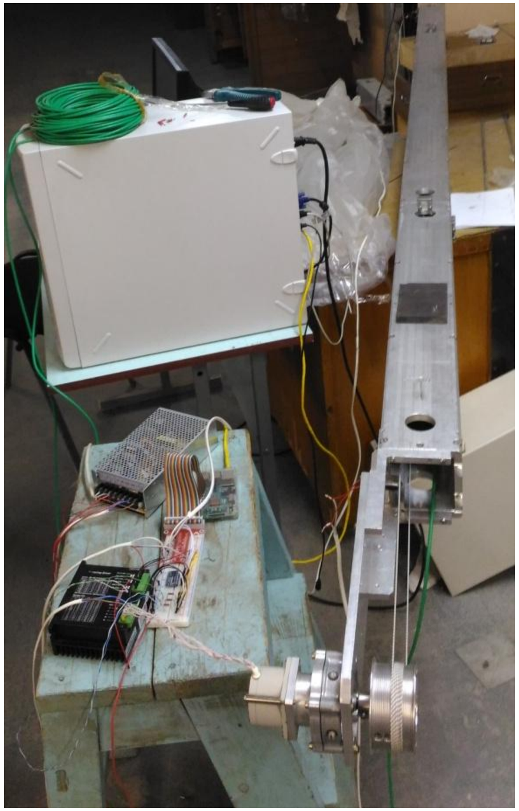


All Magnetic elements of transport channels may be measured with Hall Probes System

Magnetic measurement system

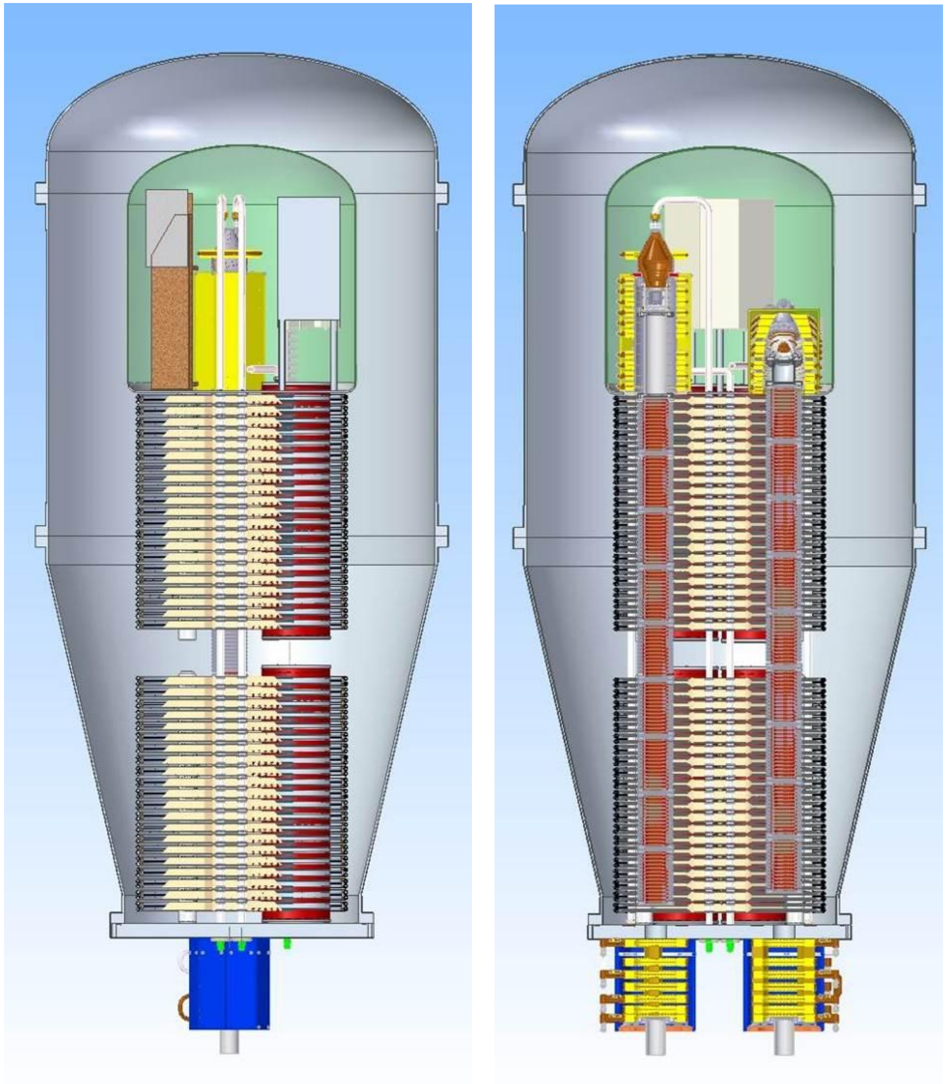




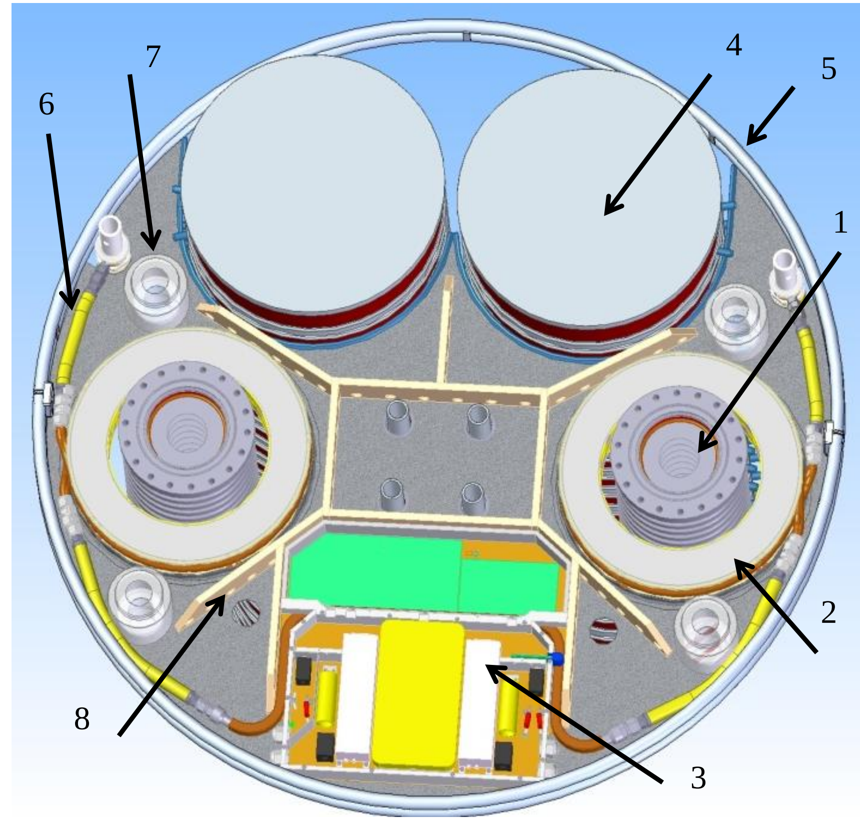


Three or more elements connected together for magnetic measurements in order to accurate measure of one elements (edge effects);

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.



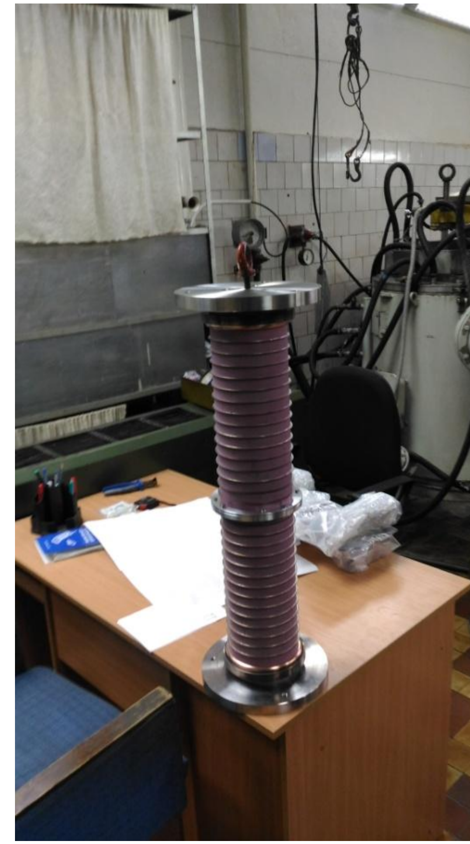
Design of high-voltage section.
1 – accelerator tube, 2 – magnetic coil, 3 – electronics (coils 2.5A, 500 G and HV PS +/- 30 kV), 4 – section of cascade transformer, 5 – safety ring, 6 – oil tube for solenoid cooling, 7 – isolation support, 8 – stiffening rib.

42 high-voltage section (COSY is 33 section)

Central part of high voltage vessel in Novosibirsk workshop

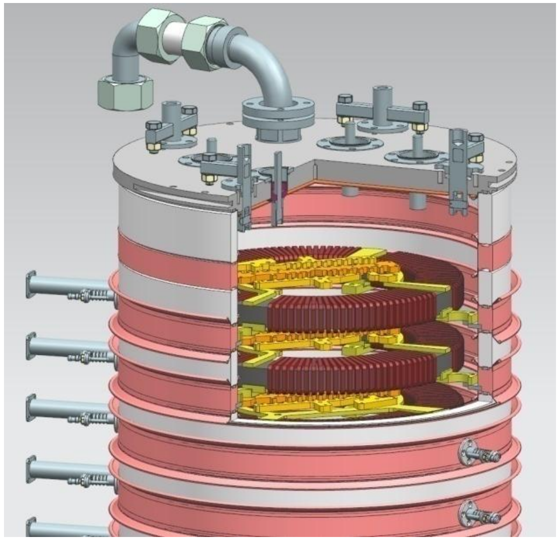
I.N. Meshkov and bottom of high-voltage vessel

Section of electrostatic accelerator

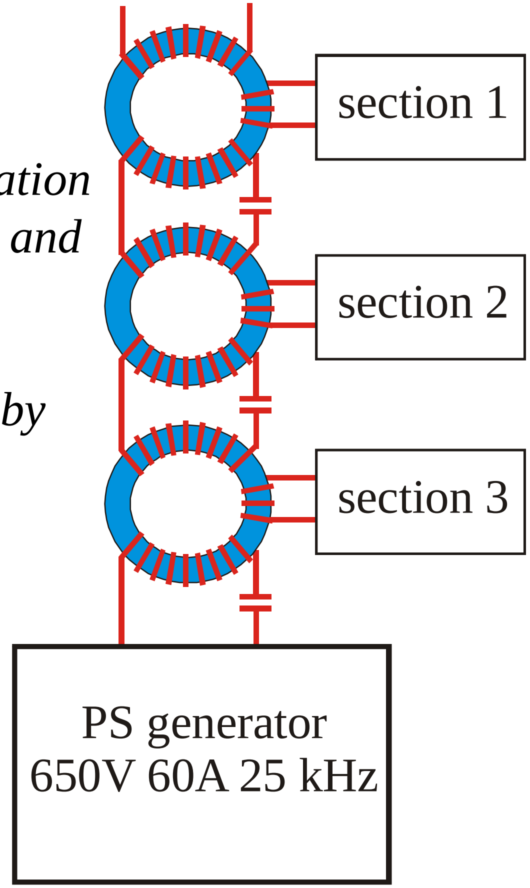


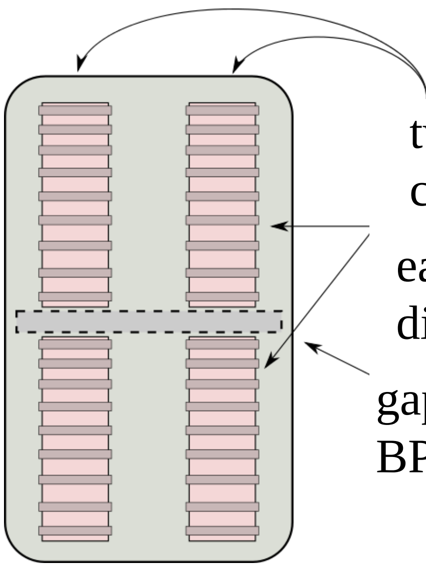
Acceleration tube

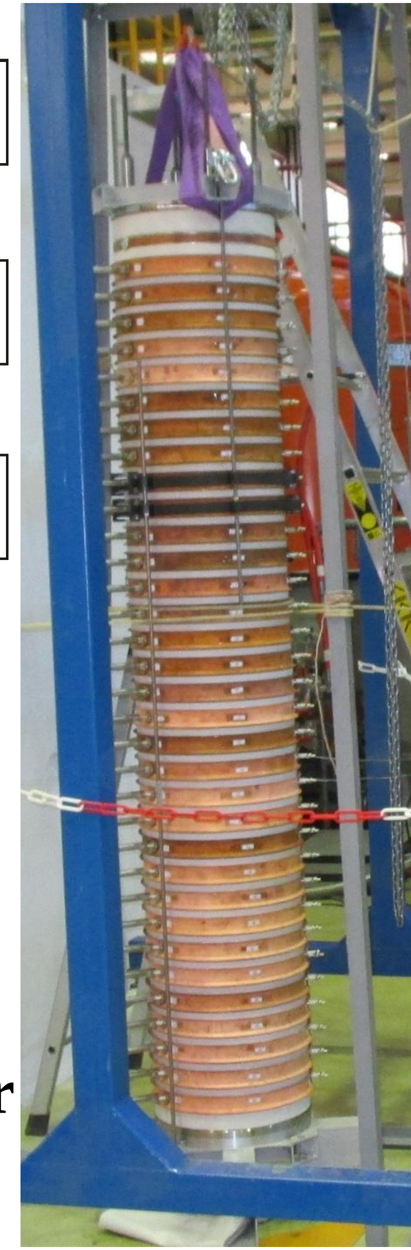
Cascade Transformer as Power Supply



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





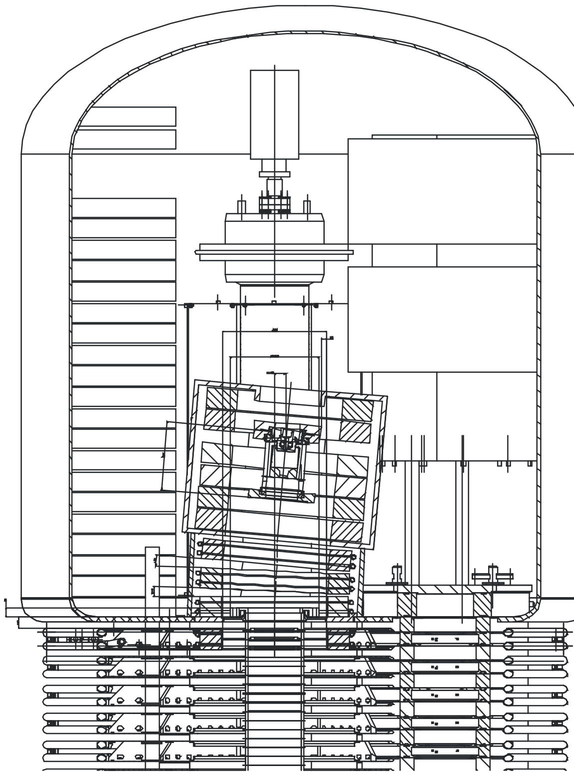


Length of NICA cooler is larger and we decide to use two transformer column. One for collector and the other for the HV

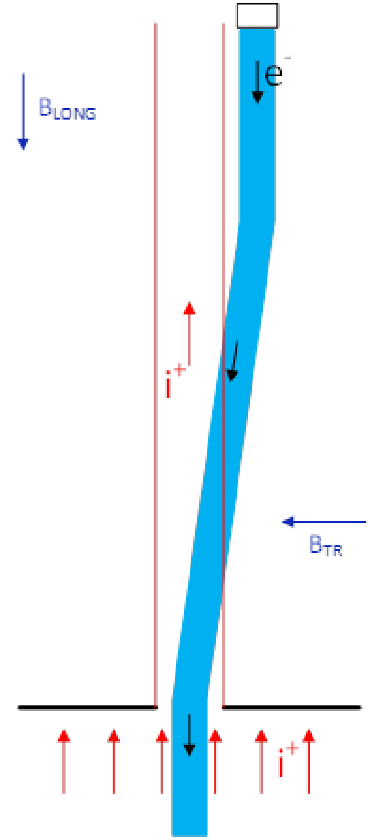
“*Transformers section looks like accelerating tube*”

New section of Cascade Transformer

High voltage terminal – gun and collector

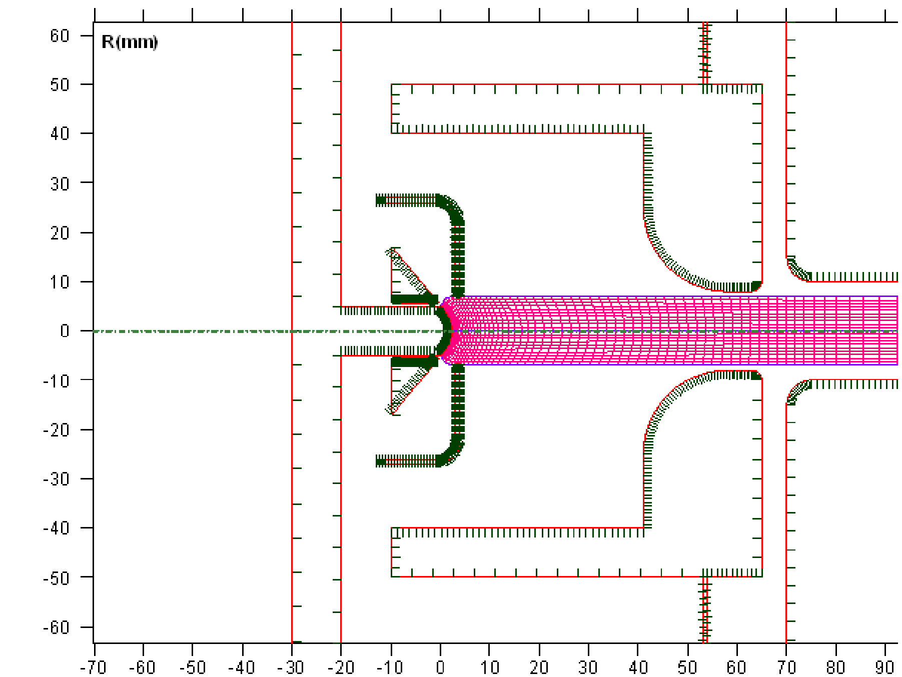


Design of high-voltage terminal of NICA cooler. The left picture shows the electron gun, the right picture shows the collector.

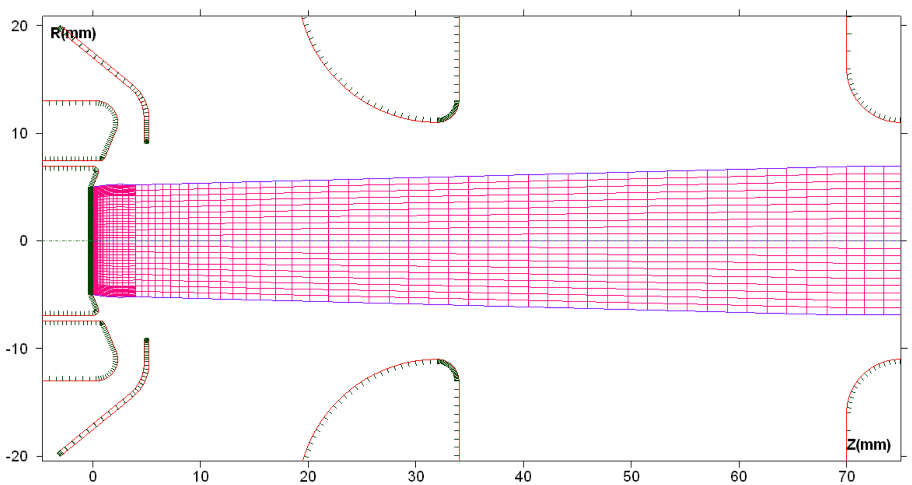


X and Y displacement of electron in the electron gun. The red is ion flow, the blue is flow of the electrons.

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



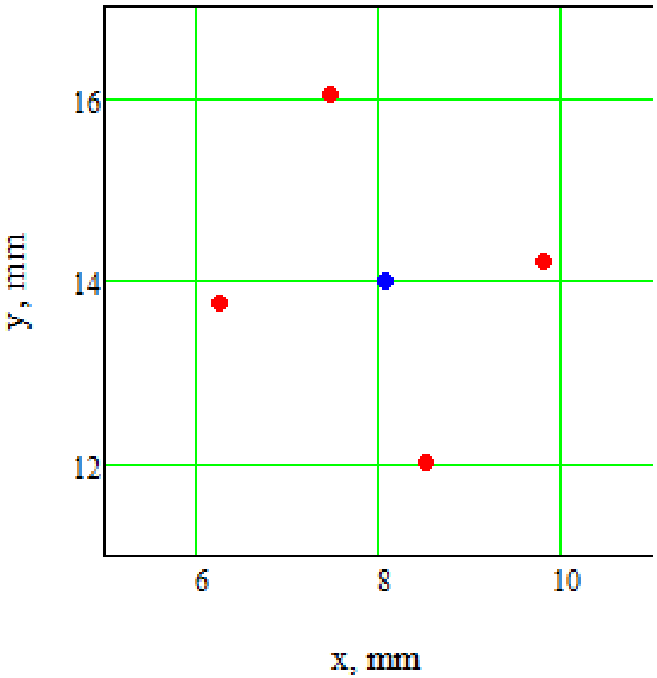
Периметр кольца, м	503,04		
Количество пучков	22		
Ср. кв. длина пучка, м	0,6		
β-функция в точке встречи, м	0,35		
Бетатронные частоты, Q_x/Q_y	9,44/9,44		
Хроматичности, Q'_x/Q'_y	-33/-28		
Аксептанс кольца, π мм·мрад	40		
Импульсный аксептанс, $\Delta p/p$	±0,010		
Фактор критической энергии, γ_{tr}	7,088		
Энергия ионов $^{197}Au^{79+}$, ГэВ/н	1,0	3,0	4,5
Количество ионов в пучке	$2{,}0{\cdot}10^8$	$2{,}4{\cdot}10^9$	$2{,}3{\cdot}10^9$
Ср. кв. импульсный разброс, $\Delta p/p$	$0{,}55{\cdot}10^{-3}$	$1{,}15{\cdot}10^{-3}$	$1{,}5{\cdot}10^{-3}$
Ср. кв. эмиттанс, π мм·мрад	1,1/0,95	1,1/0,85	1,1/0,75
Светимость, см$^{-2}$ с$^{-1}$	$0{,}6{\cdot}10^{25}$	$1{,}0{\cdot}10^{27}$	$1{,}0{\cdot}10^{27}$
Время роста ВПР, с	160	460	1800



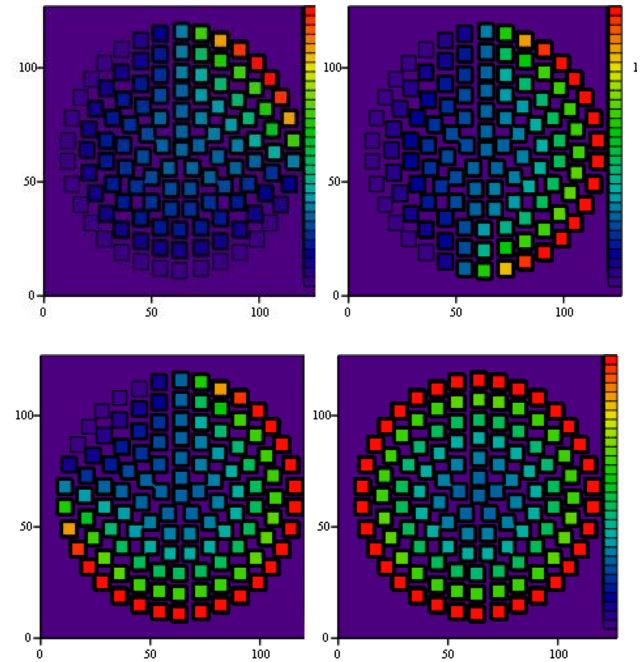
The standard gun of the cooling system designed in BINP has diameter 3 cm. This cathode diameter is useful for low-energy cooling. The size of ion beam is decreased at acceleration so such cathode diameter may be excess value. Table shows the parameter of the collider NICA. The typical r.m.s emittance at energy 3 GeV/u is about 1 π·mm·mrad. So the typical size of the ion beam is 0.3 cm. Therefore we decide to try the gun with smaller diameter of the cathode.

- High density of the electrons at same current;
- Easy transportation of electron beam;
- Possibility to have a large magnetic field in the gun;

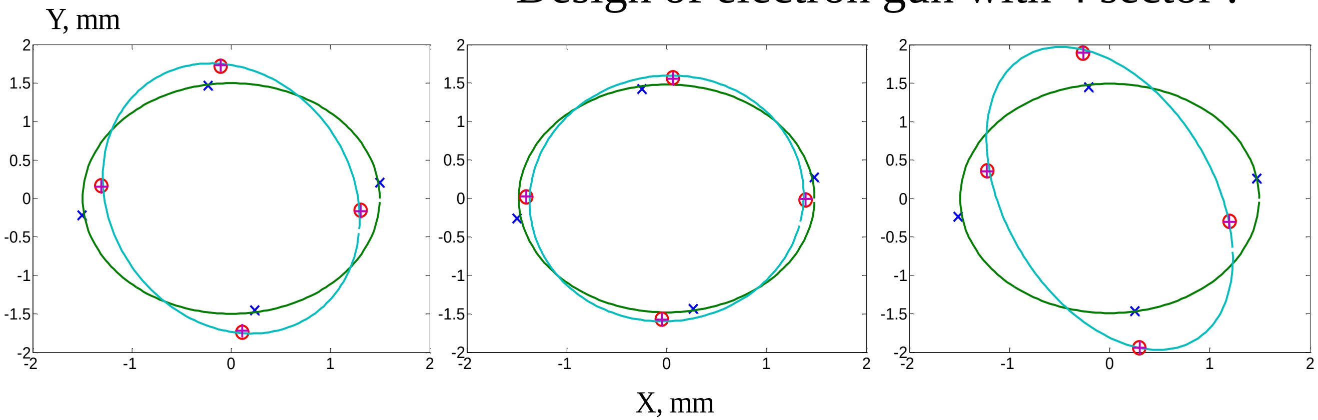
Diagnostics of the shape of the electron beam



Design of electron gun with 4 sector .



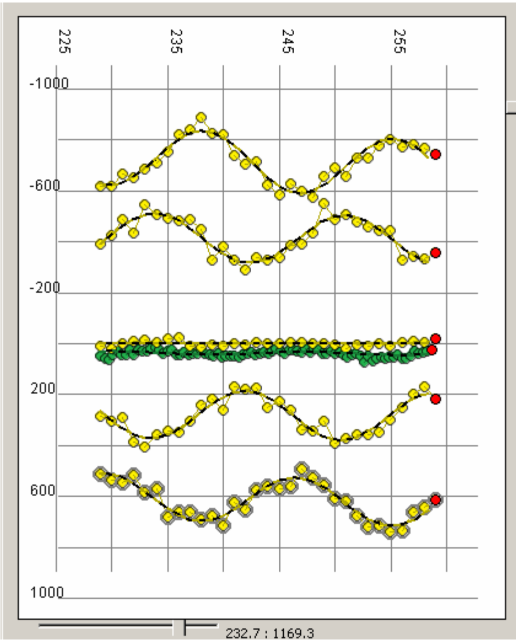
Axial distribution of the electron current density at switching on 1/2/3/4 sectors

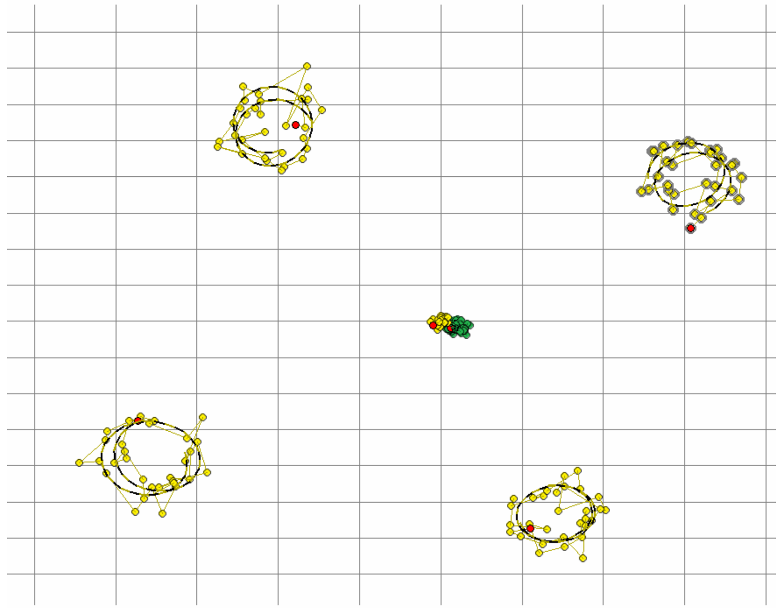


X is first BMP, O is last BPM.

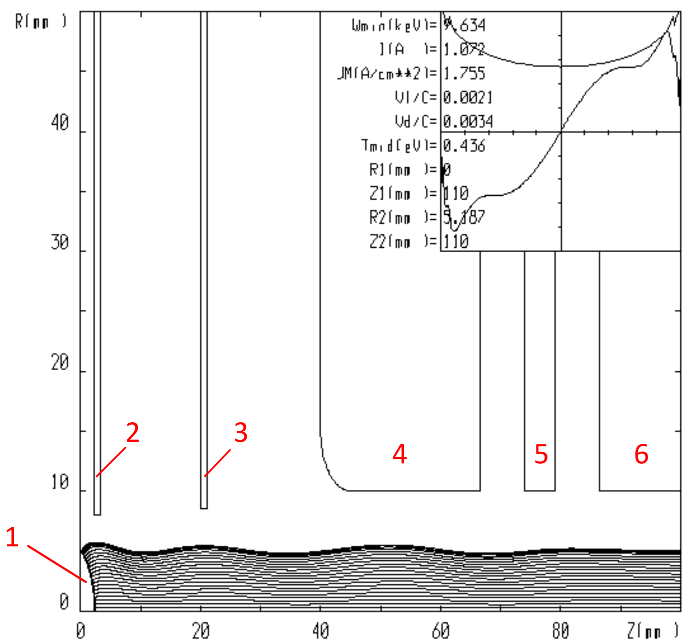
Response of the beam shape induced by quadruple component of the bending magnet (n=0.5 and n≠0.5) . The experimental result from COSY cooler, energy Ee=910 keV.

Radial oscillation of the electron beam





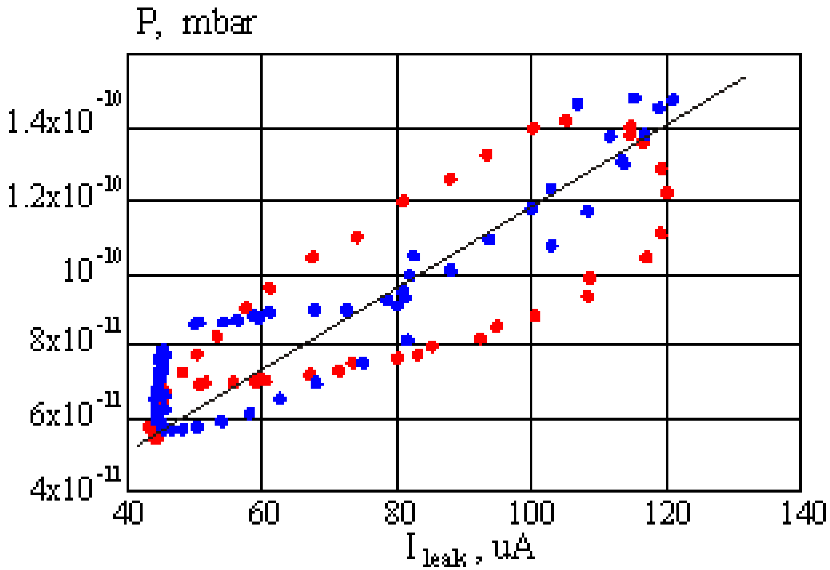
Analyze of the electron trajectory in COSY shows that there is a radial oscillation of the shape of the electron beam (“galloping”). The edge trajectory have Larmour oscillation but the center trajectory is line. It can be different reasons such behavior. It is possible that the main reason is combination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

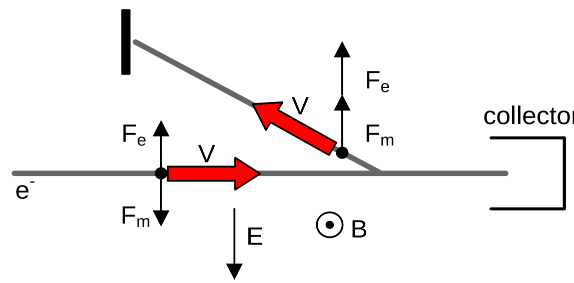
To fit a parameters of electrostatic lens and the value of the magnetic field (phase of Larmour rotation) is possible to control radial oscillation.

Electron collector



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

Principle of the collector work

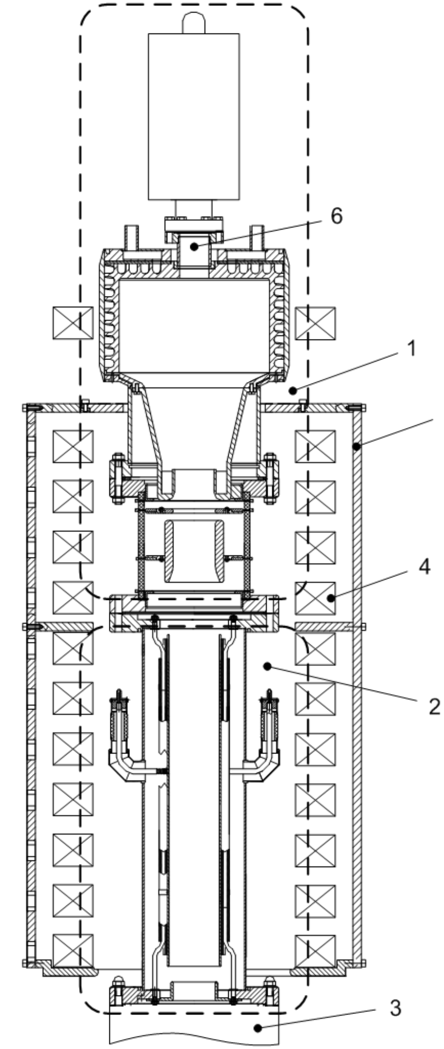


primary beam

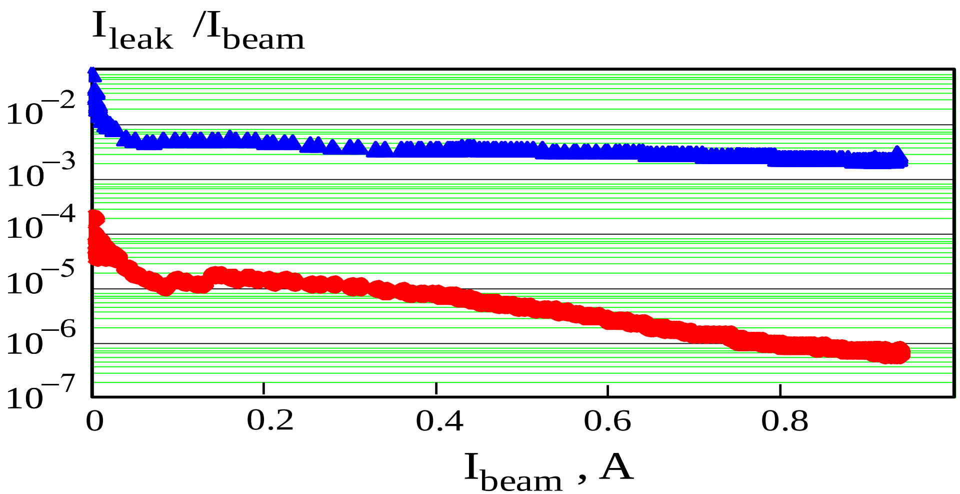
$$\vec{F}_{\perp} = e\vec{E} - \frac{e}{c}\left[\vec{v}\times\vec{B}\right] = 0$$

secondary beam

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

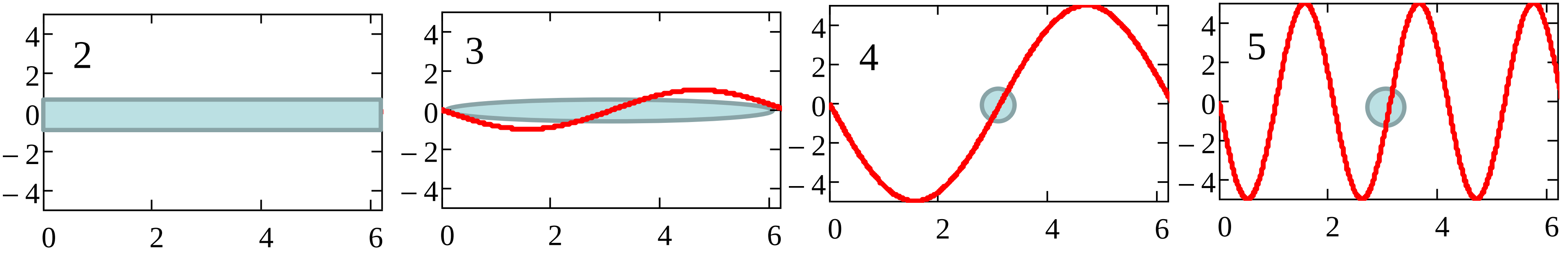


Collector for COSY cooler



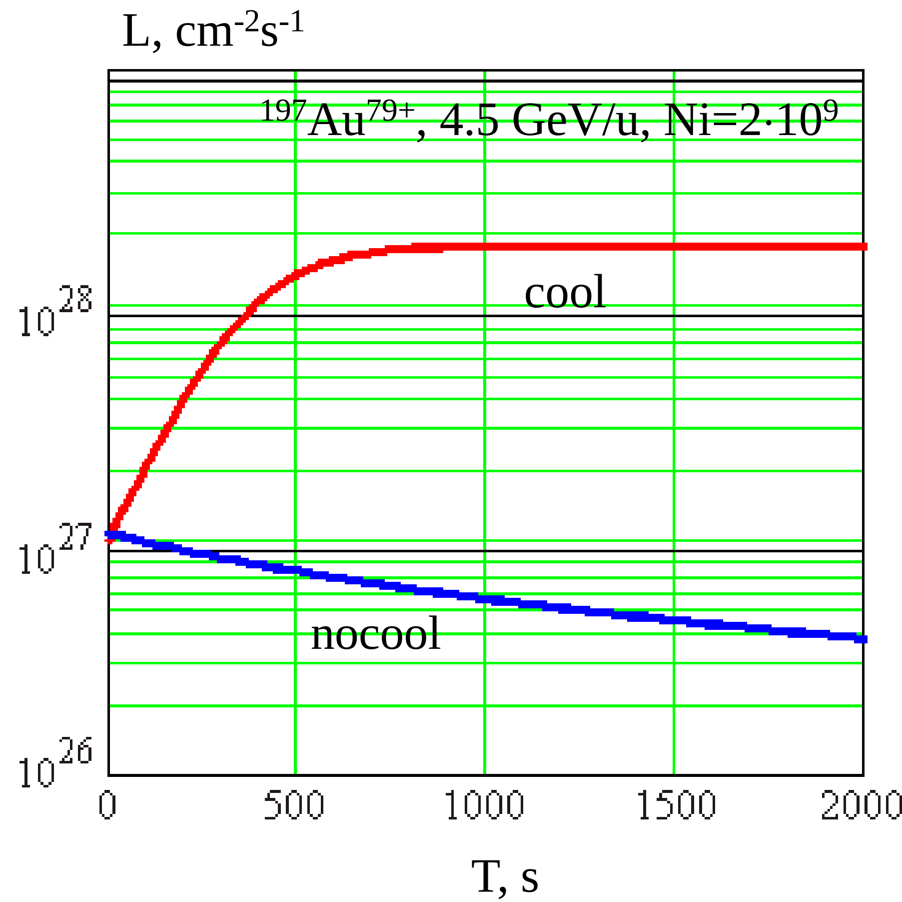
Collector efficiency, measured on COSY cooler at energy 909 kV

RF and e-cooling preparation to collider operation



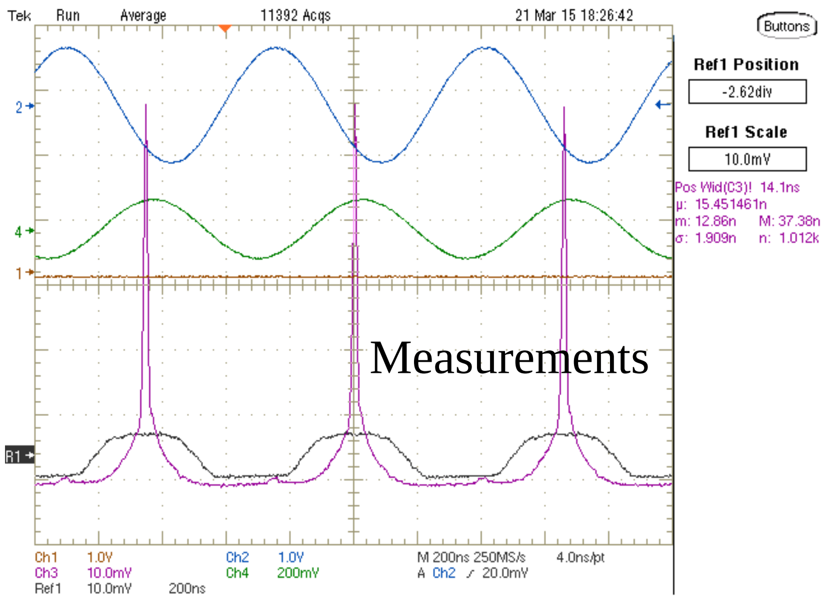
1. Cooling and stacking with RF barrier voltage.
2. Formation of continuous beam
3. RF of 22-nd harmonic, bunching
4. Increase RF voltage and bunch length decreasing
5. RF of 66-nd harmonics, e-cooling

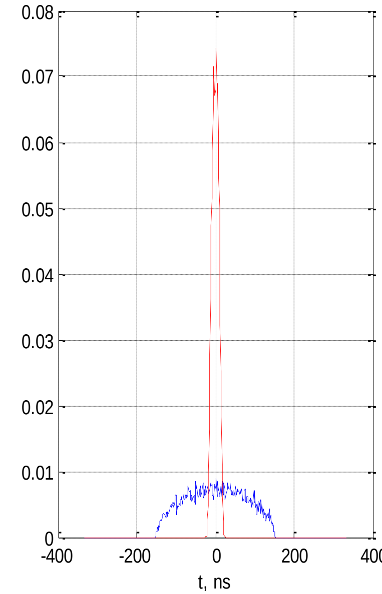
In colliding mode RF has 66 harmonics and the bunch is located in every third separatrix. Electron cooling enables to decrease the transverse emittance and longitudinal length of ion bunch. So, the luminosity may be stable at presence of the electron cooling.



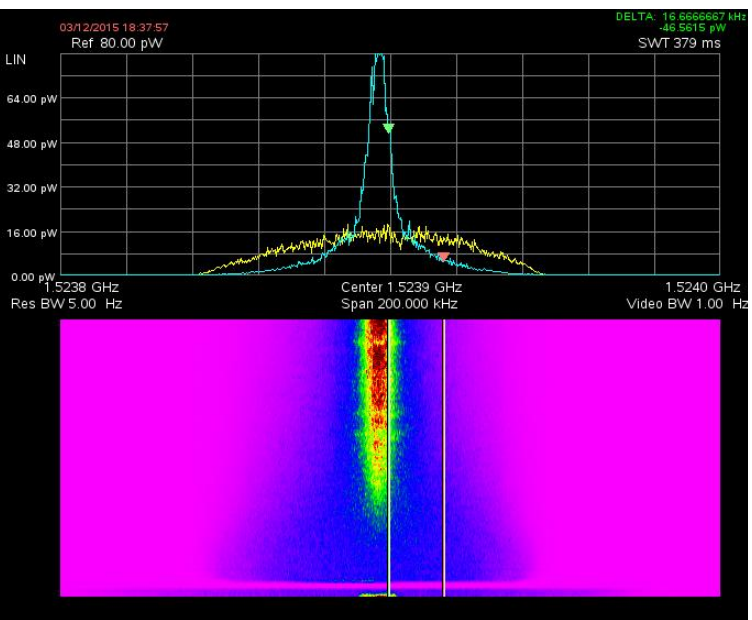
Cooling simulations for COSY

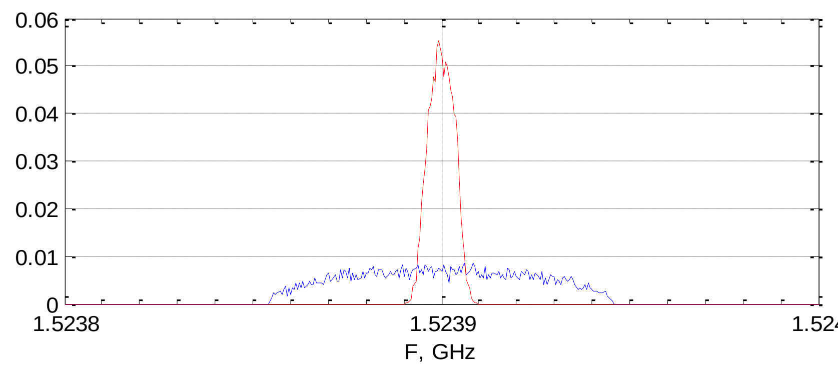
Cooling of bunched proton beam on COSY. Electron energy 908 keV. Electron current 0.5 A.





Simulations with Parkhomchuk's equation and space charge field

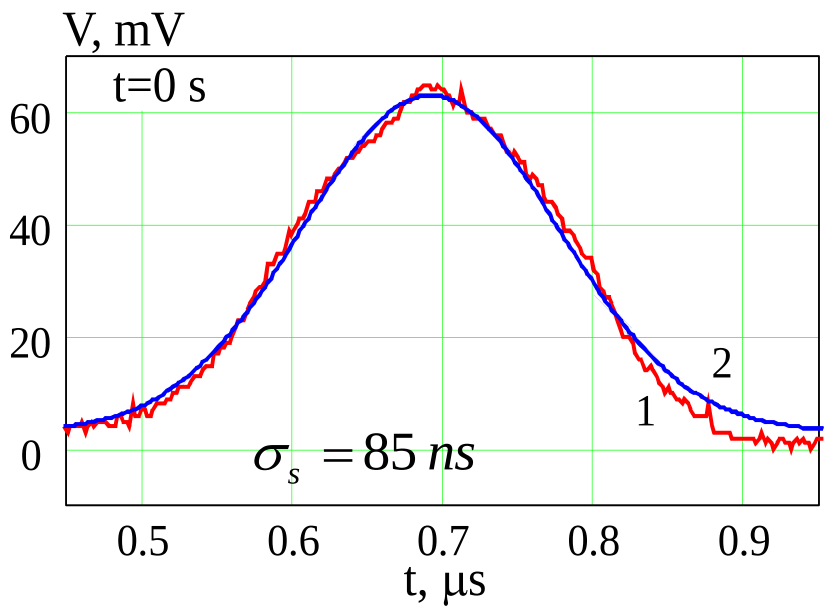


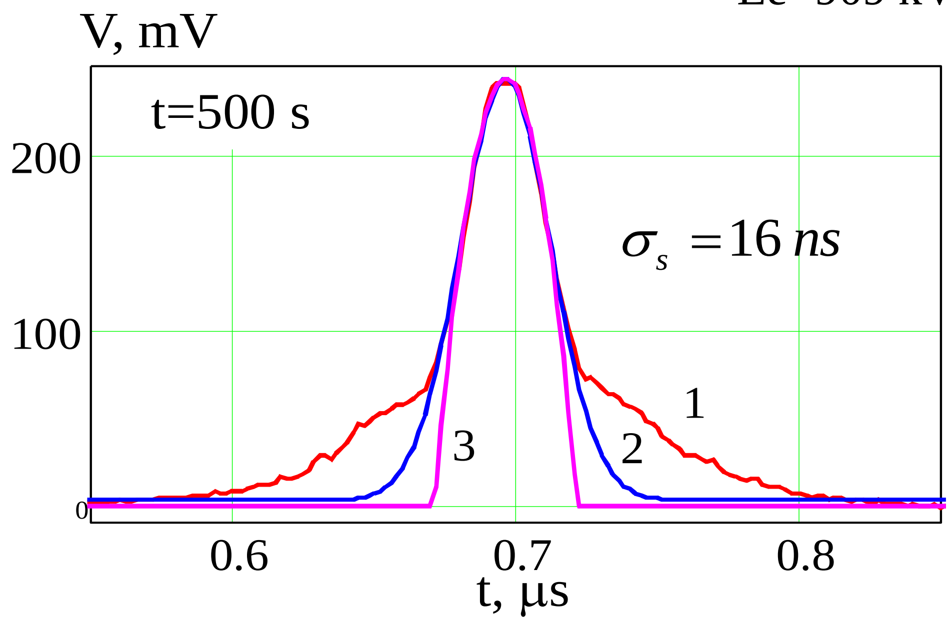


e-cool can well operate with RF harmonic

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, $Np=2\cdot10^9$, Ee=909 kV





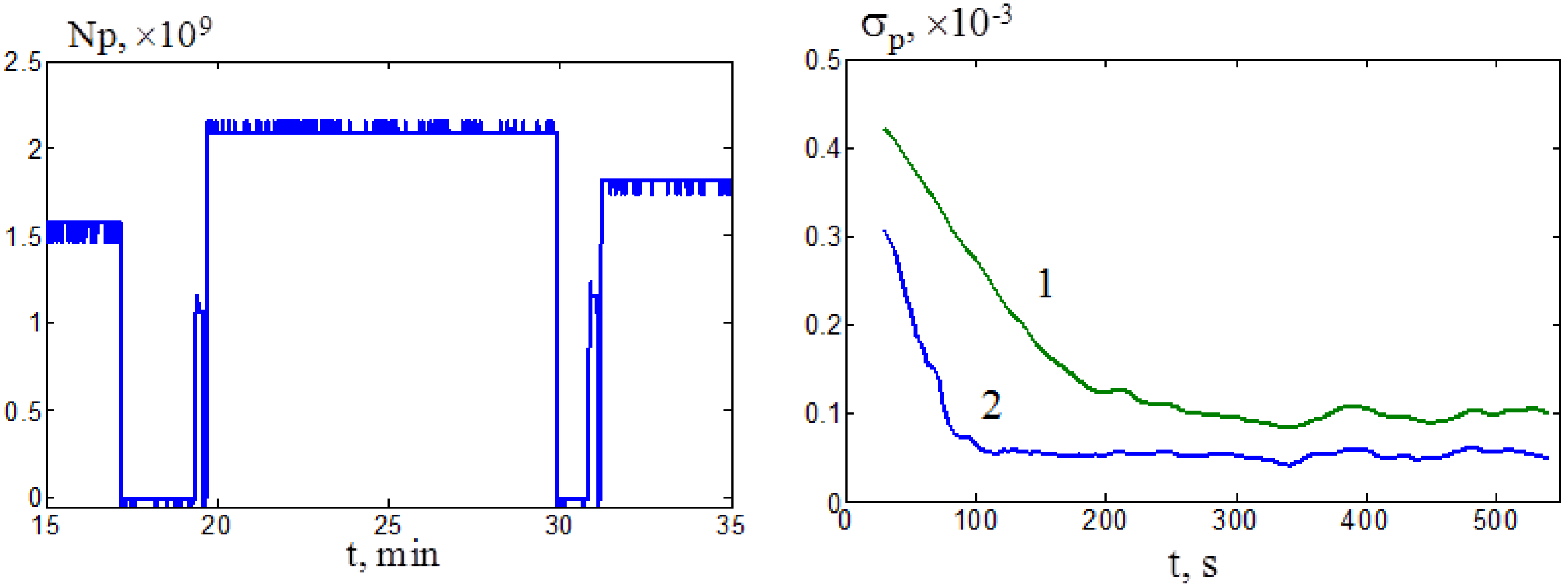
1 is experimental profile, 2 is gauss shape, 3 is parabolic shape

The estimation of the length according equation gives the length 14 ns that is very close to the experimental data. So, the beam core attains equilibrium induced by the space charge force.

$$\sigma_s^3 = \frac{eN_p\left(2\ln\left(\frac{b}{a}\right)+1\right)}{(2\pi)^{3/2}\,\gamma^2 U_{RF}}\Pi^2$$

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

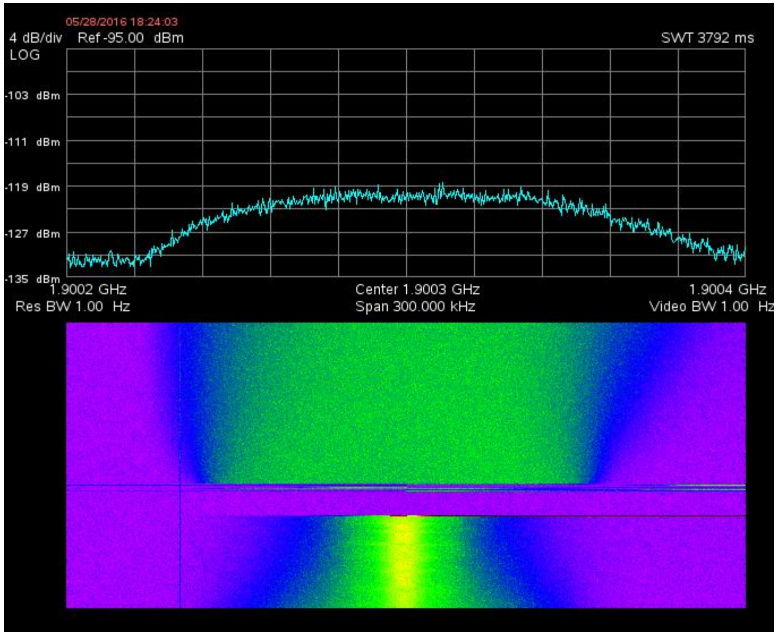
The time of the longitudinal cooling doesn't depend from bunched or continuous mode of the proton beam and the typical value for this experiments were about 100-150 s. In time of the cooling process the typical life-time was good enough. The particle losses were not detected during 600 s period.



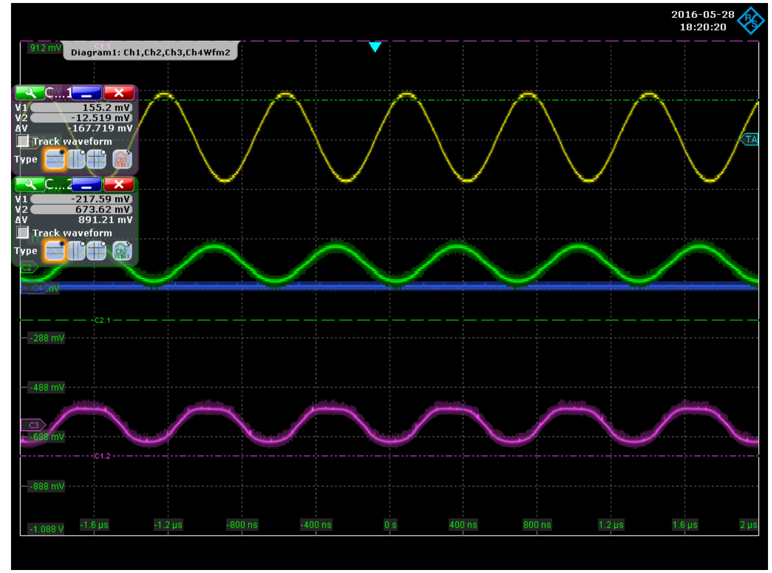
Signal from beam current transformer (left picture) and decrease of the momentum spread (right picture) during cooling process. The curve 1 describes whole distribution function and curve 2 describes only the central core with Gauss shape.

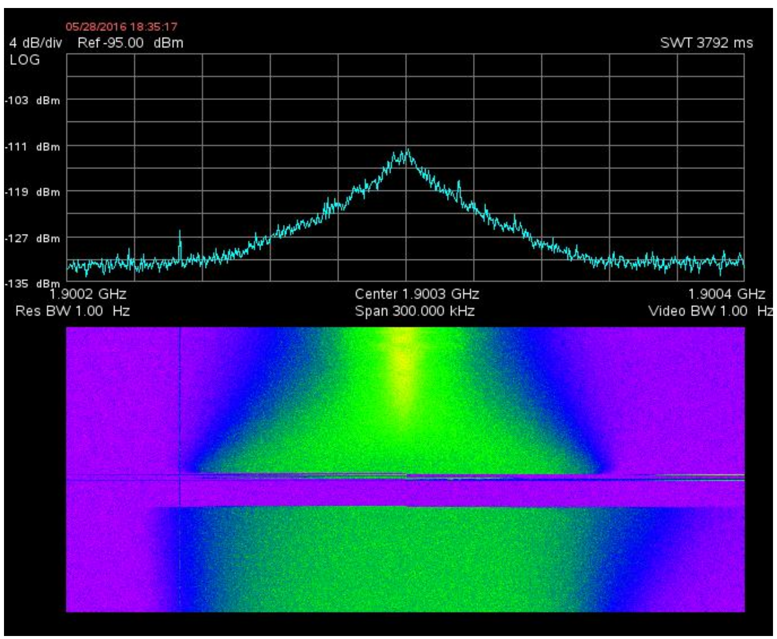
e-cool can well operate with usual RF and target

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

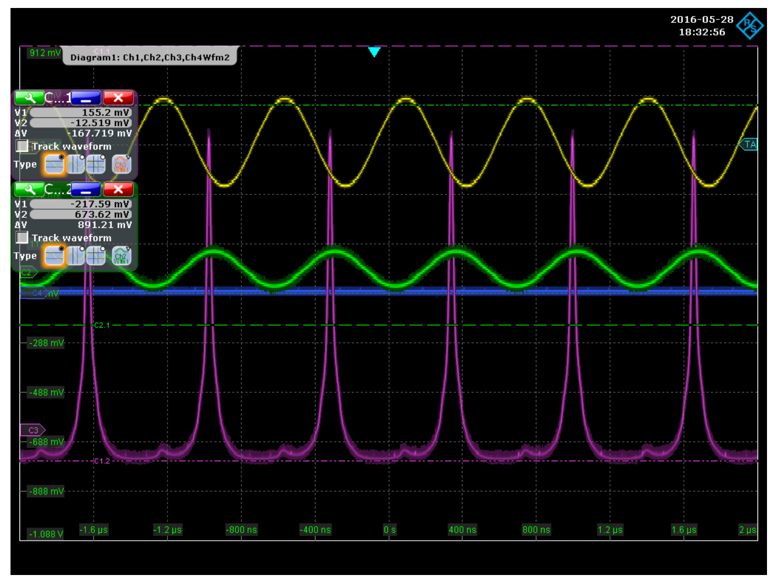


NO COOL



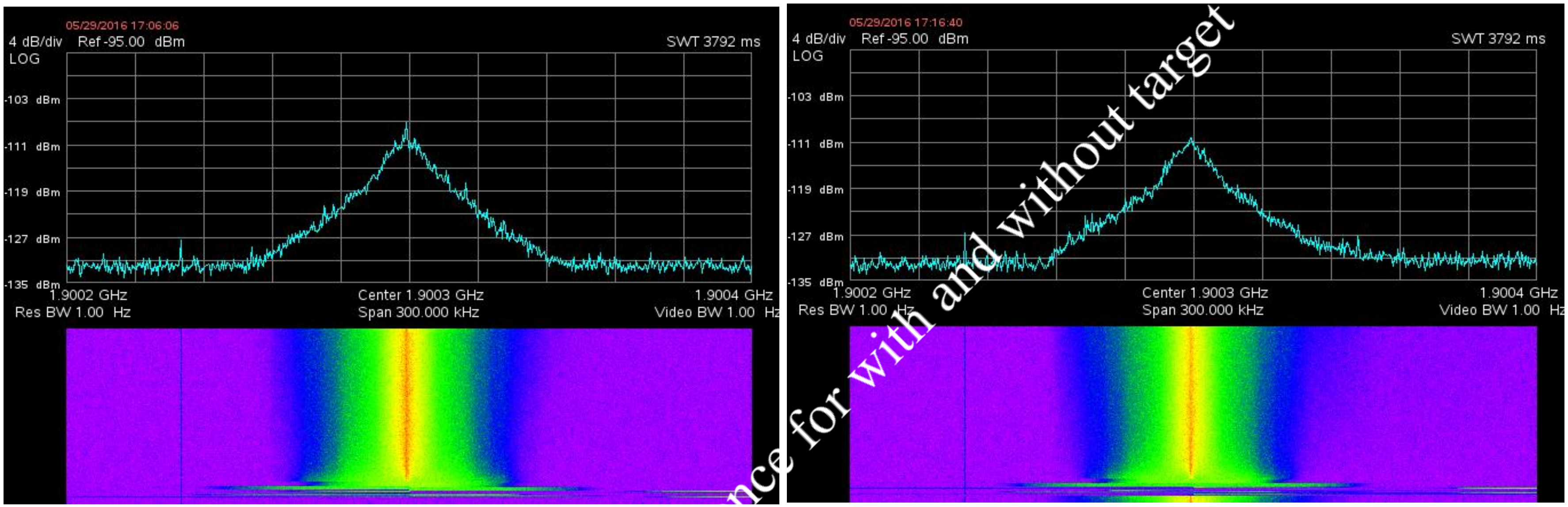


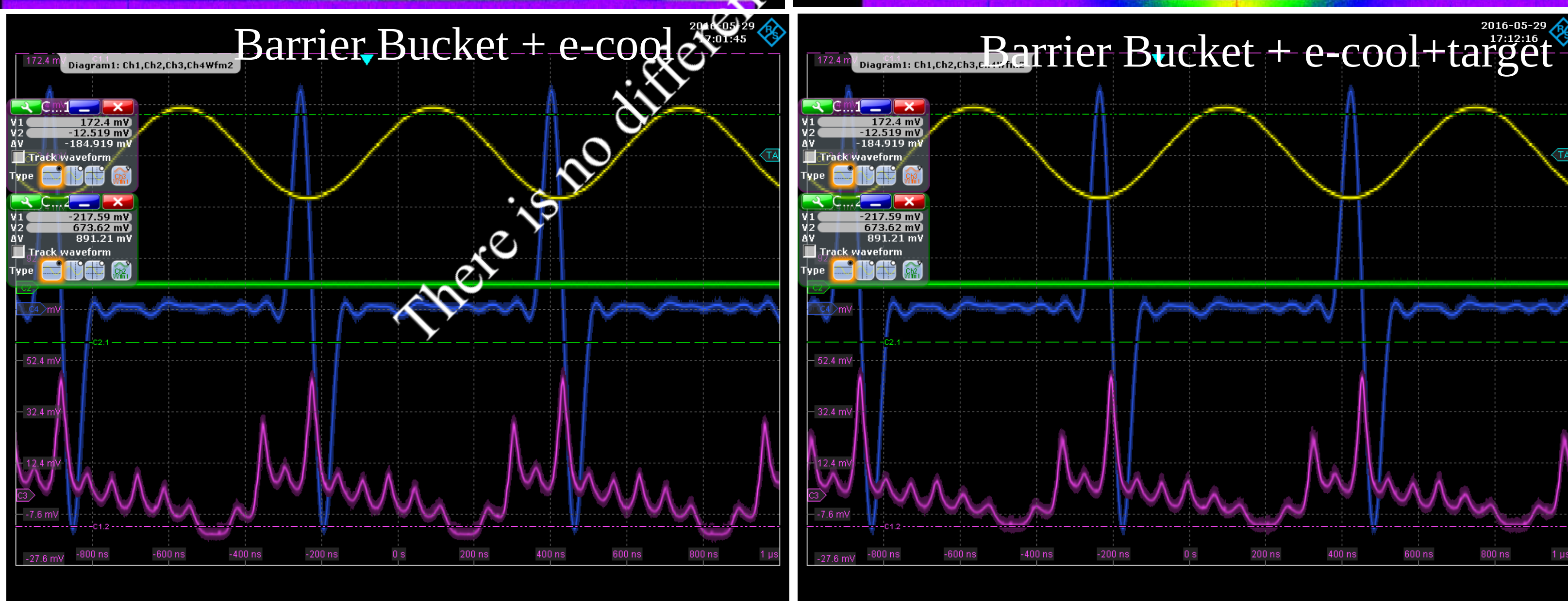
COOL



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}

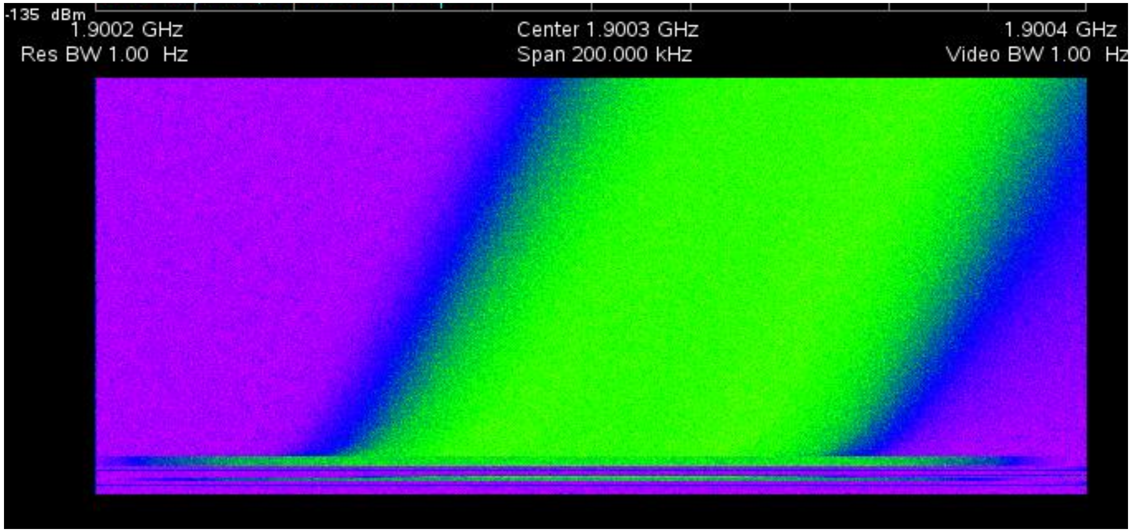




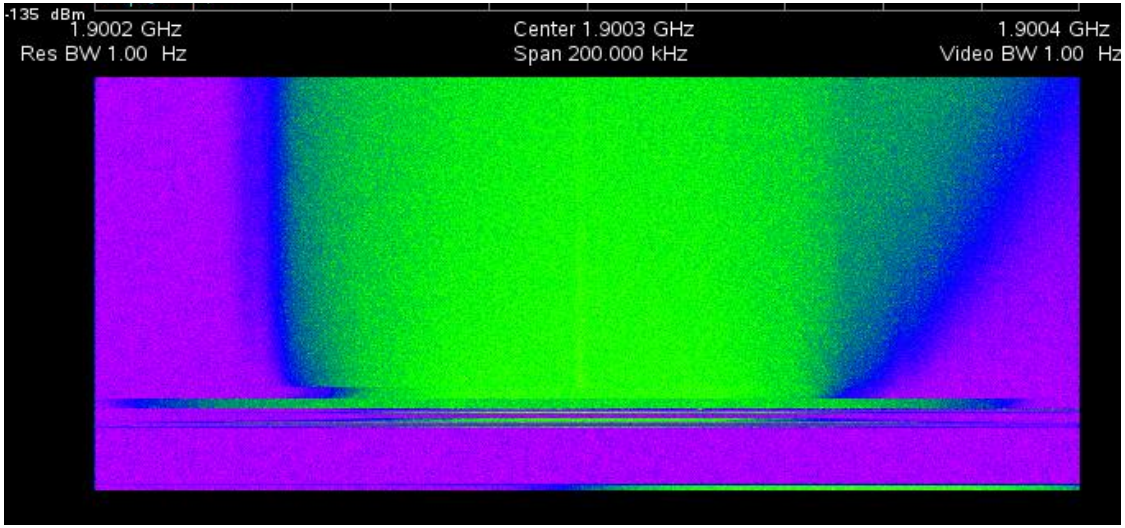
There is no difference for with and without target

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



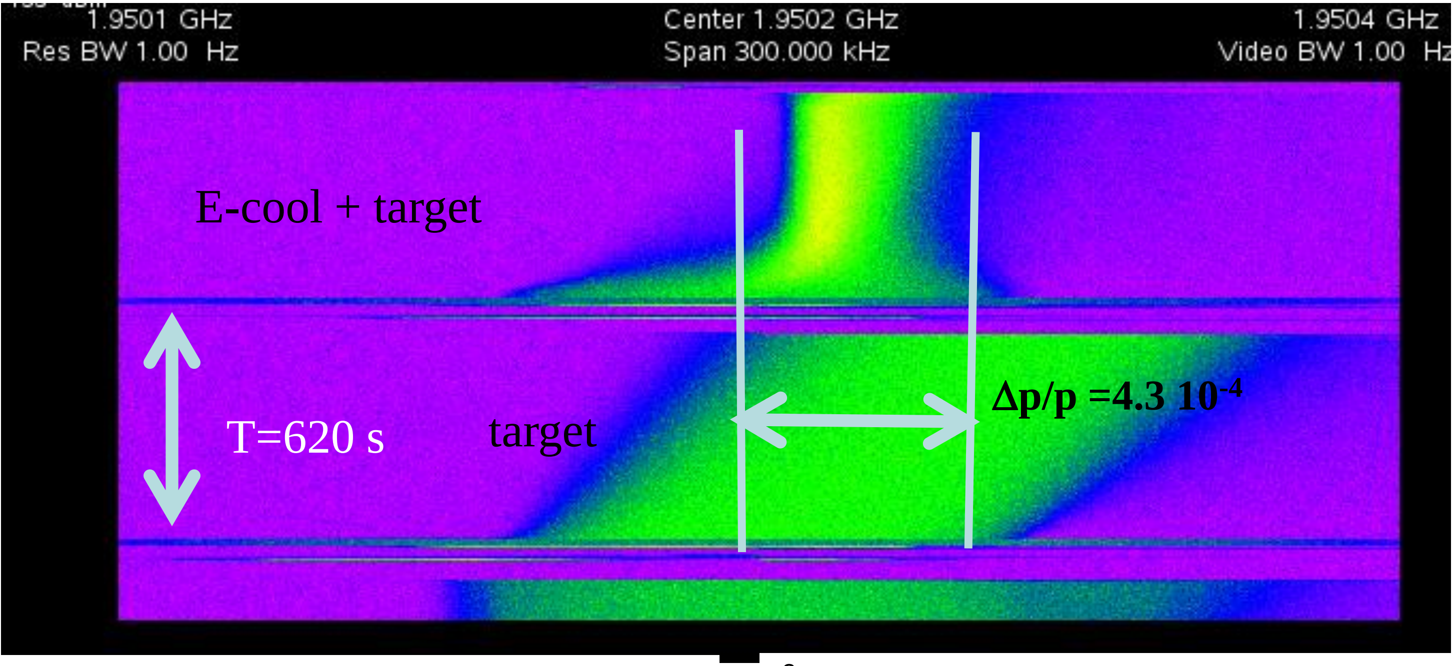
target + barrier bucket

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.

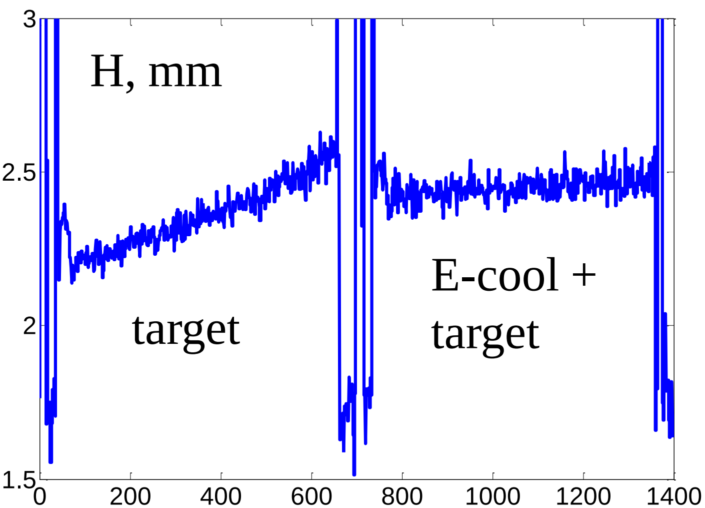
Electron energy 1259.65 kV, Je=500 mA

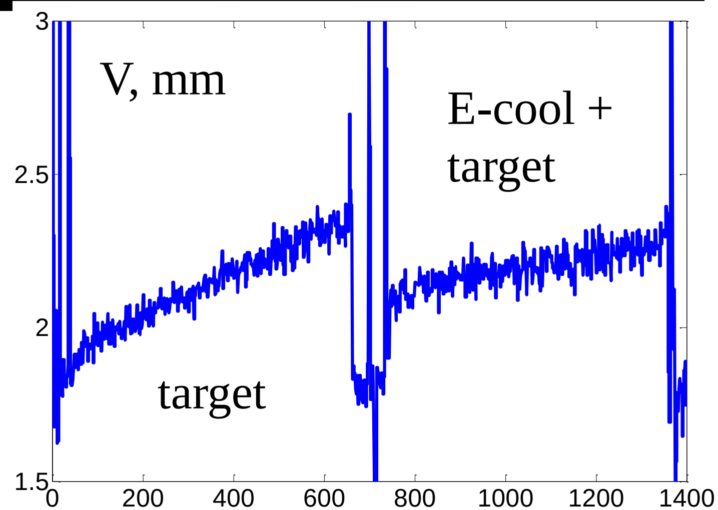
Experiments with e-target

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

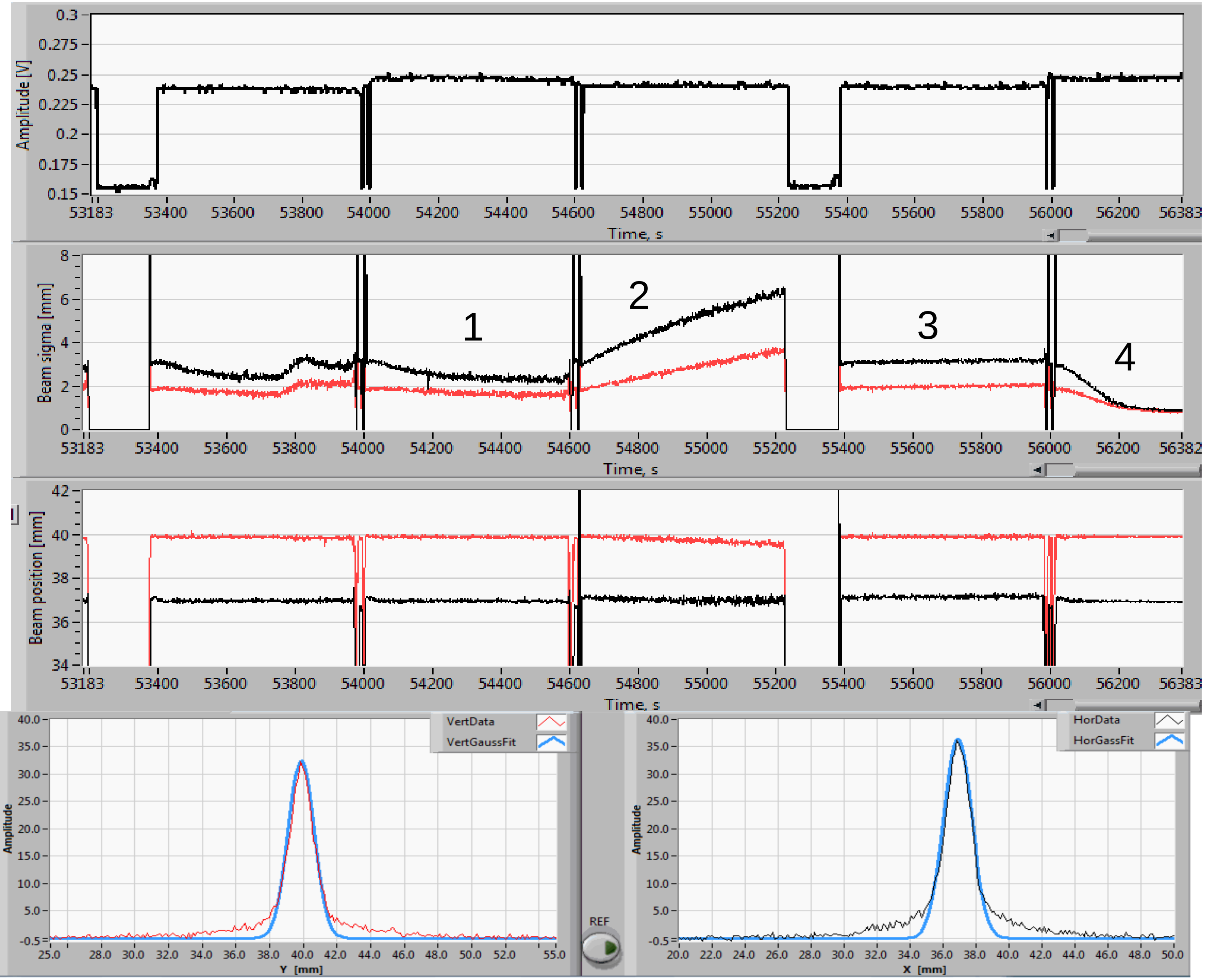


Electron cooling practically suppressed longitudinal and transverse growth induced by target but the more precise tuning storage ring and e-cooler is necessary.





Transverse e-cooling at 909 kV energy



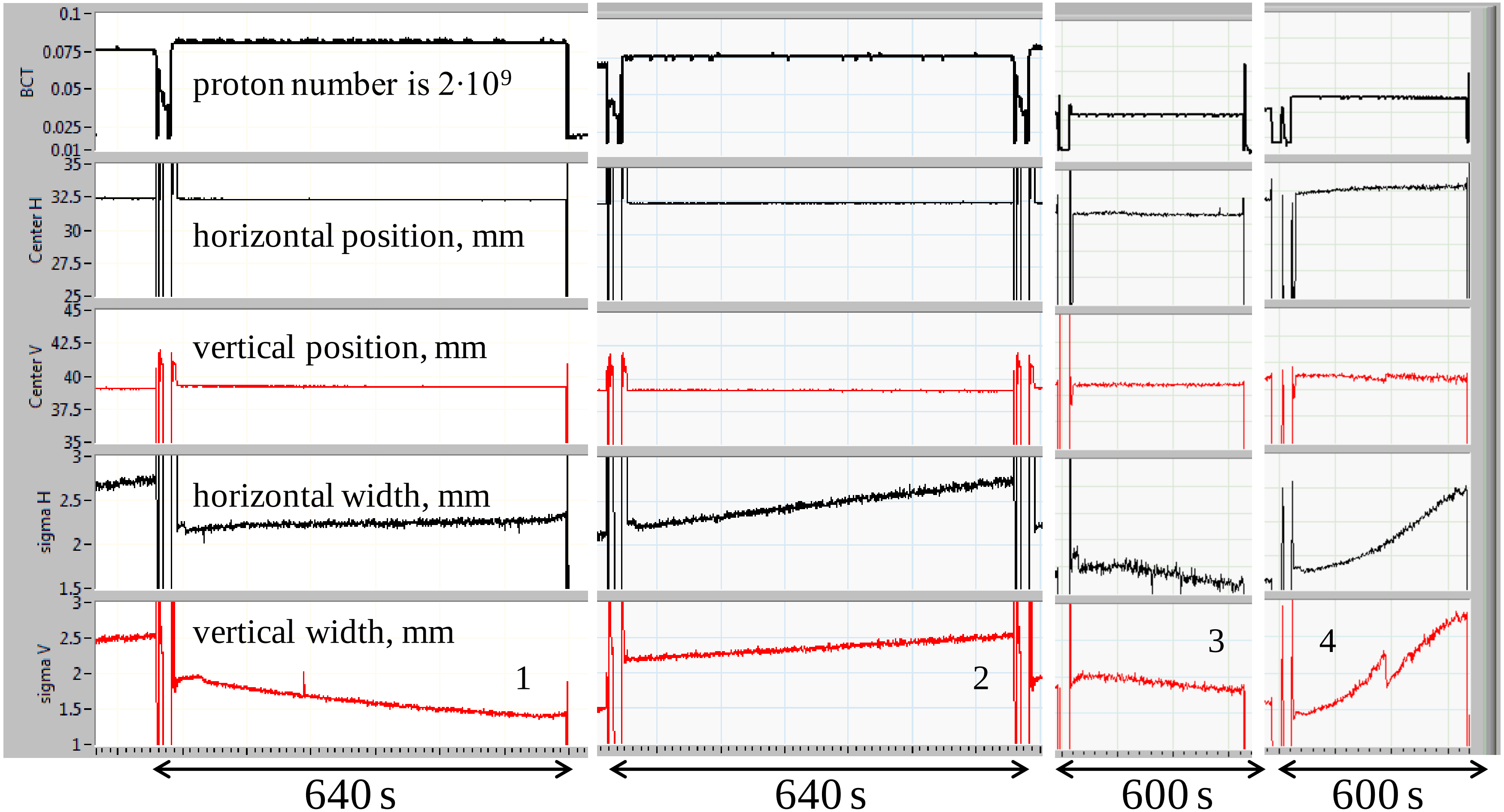
$3.6 \cdot 10^8$ protons
1.66 GeV

$I_e = 0.8$ A
$B_{sol} = 1.3$ kG

1. Noise + EC
2. Noise only
3. Reference
4. EC

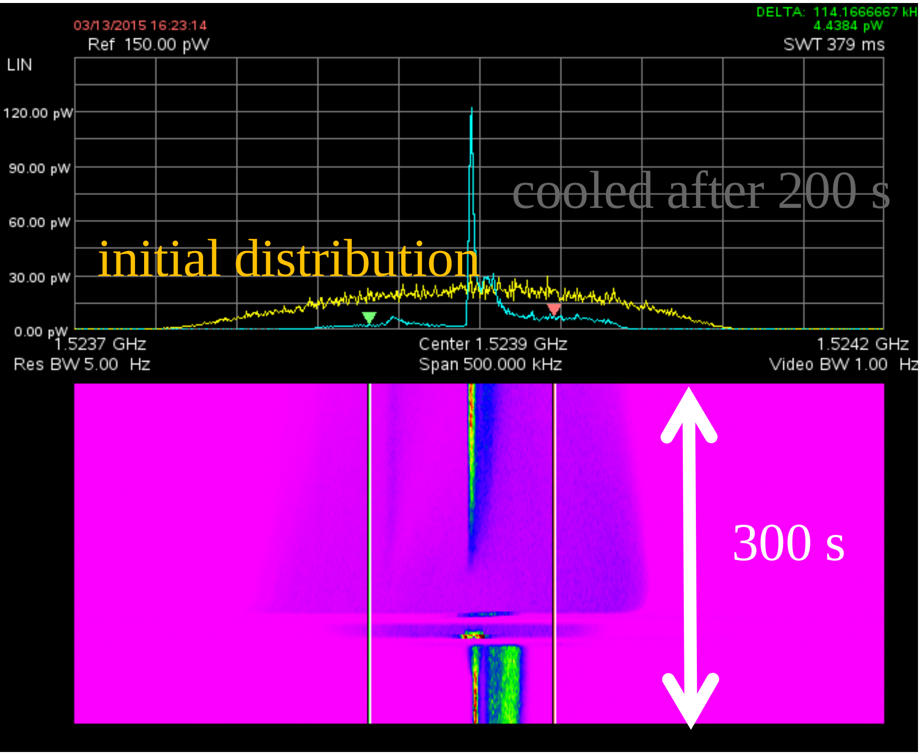
$\varepsilon_x = 1.1 \rightarrow 0.1$
ε_y: $=1.3 \rightarrow 0.2$
mm·mrad,
normalized
beam core
within 200s

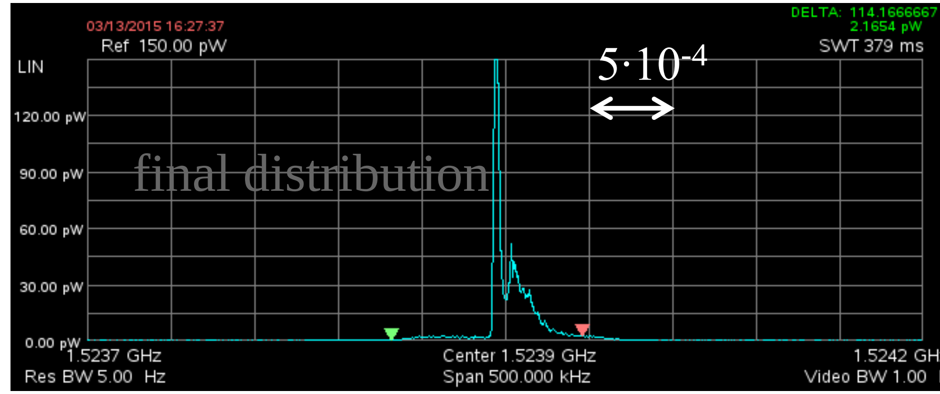
IPM screenshot



Changing transverse size during cooling experiments. Curve 1 is cooling at energy 909 kV, curve 2 is reference cycle without cooling, curve 3 is cooling at energy 1259 keV, curve 4 is growth of the transverse size at changing working point despite of electron cooling action. Tune was shift at $\Delta Qx/ \Delta Qy = 0.02/-0.01$.

Example of the transverse and longitudinal cooling





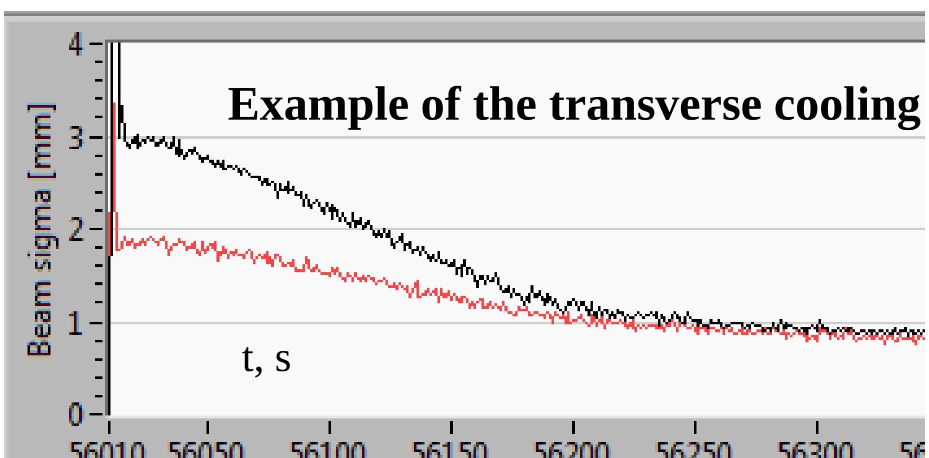
Np=$7\cdot10^8$, Je=400 mA, η=-0.066,

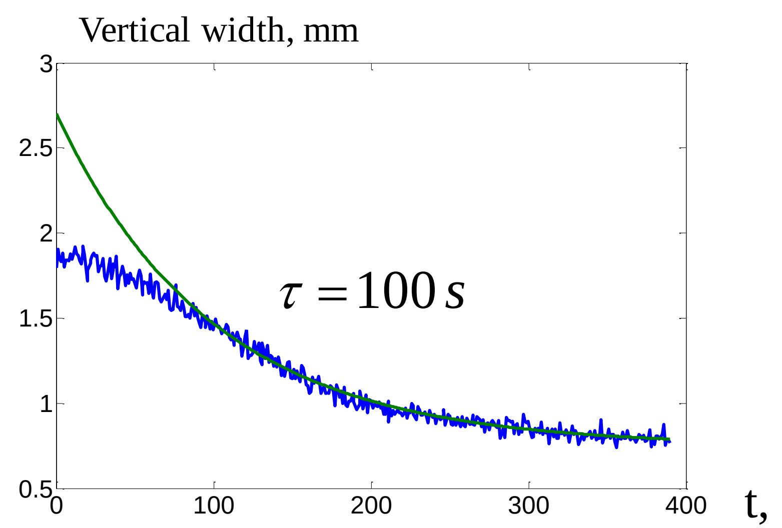
Ee=909 kV, $\gamma=2.77$, $\gamma_{tr}=2.25$, $\gamma>\gamma_{tr}$

The initial proton momentum spread was widened using white noise beam excitation to $\Delta p/p = \pm 2 \cdot 10^{-3}$, and it was cooled down during 100 s.

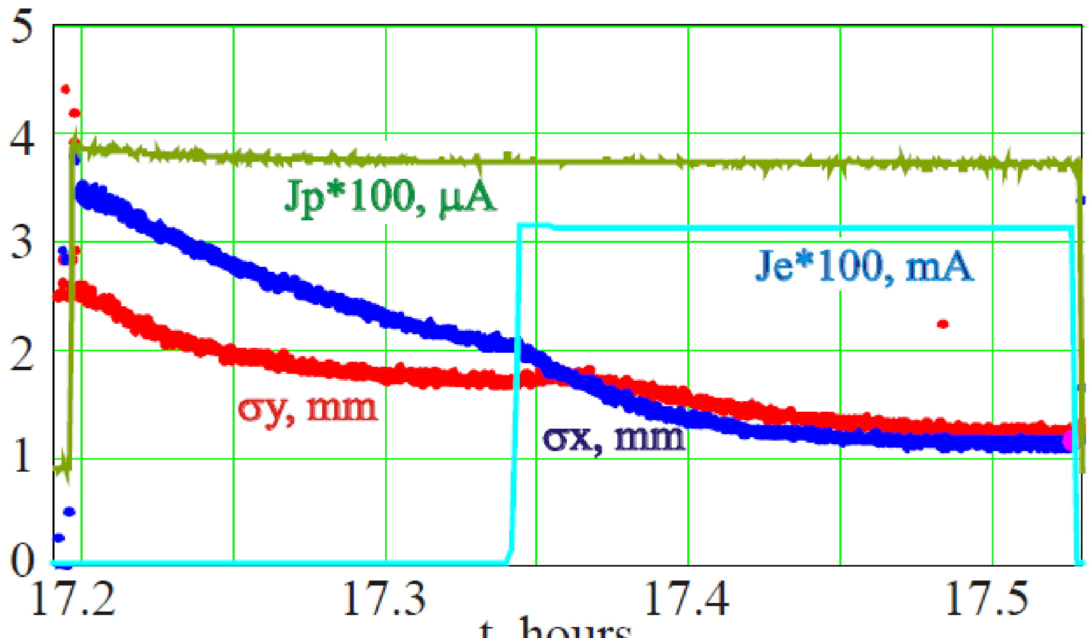
$\Delta p/p = 5.5\ 10^{-3}$

Np=$3\cdot10^8$, Je=800 mA,

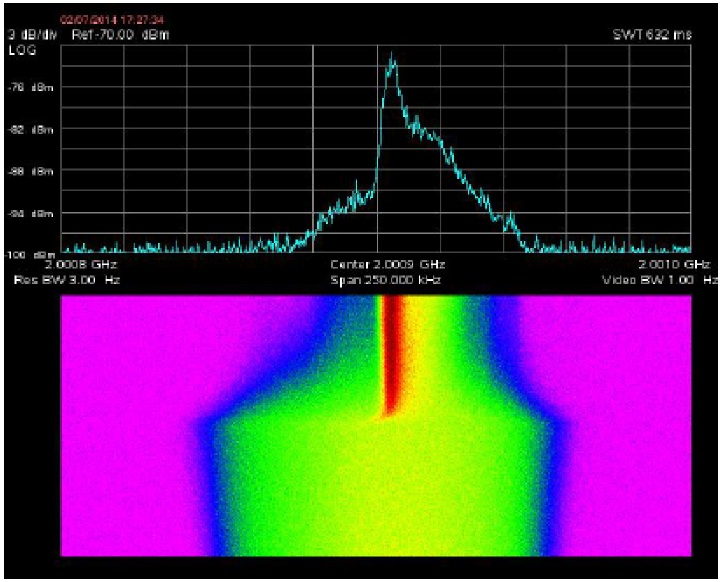




Combined action of stochastic and electron cooling



stochastic only stochastic+e-cooling



initial no longitudinal cool, after e-cooling

Electron energy	0.908 MeV
Proton energy	1.66 GeV
Stochastic cooling	vertical and horizontal
E-cool time	120 s
Stochastic cooling time	400 s
Beta function x/y	4m/3m

February 2014

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) are 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.