Система электронного охлаждения на высокую энергию для коллайдера NICA

В.Б.Рева и команда ИЯФ СО РАН

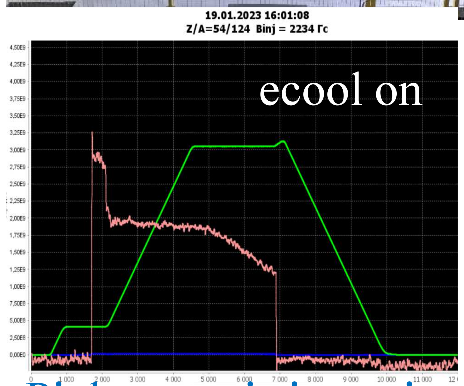
XV МЕЖДУНАРОДНЫЙ СЕМИНАР ПО ПРОБЛЕМАМ УСКОРИТЕЛЕЙ ЗАРЯЖЕННЫХ ЧАСТИЦ ПАМЯТИ ПРОФЕССОРА В.П.САРАНЦЕВА:

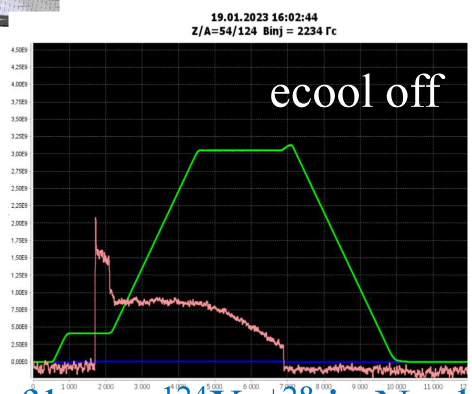
15-20 сентября 2024 г.

High voltage electron cooling in the NICA collider

Parameter	Value		
Number of bunches	22		
RMS length of a bunch, m	0.6 m		
β-function at the IP, m	0.6 m		
Energy Au^{79+}, GeV / n	1.0	3.3	4.5
Number of ions in the bunch	$2 \cdot 10^{8}$	$2.4 \cdot 10^{9}$	$2.3 \cdot 10^{9}$
RMS momentum spread, Δp/p	$0.6 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$
RMS emittance, π·mm·mrad	1.10/1.1	1.10/0.9	1.10/0.8
Time of growth due IBS, s	160	530	1700
Luminosity, $cm^{-2} \cdot c^{-1}$	$0.6 \cdot 10^{25}$	$1.0 \cdot 10^{27}$	$1.0 \cdot 10^{27}$

Electron cooling system for NICA booster



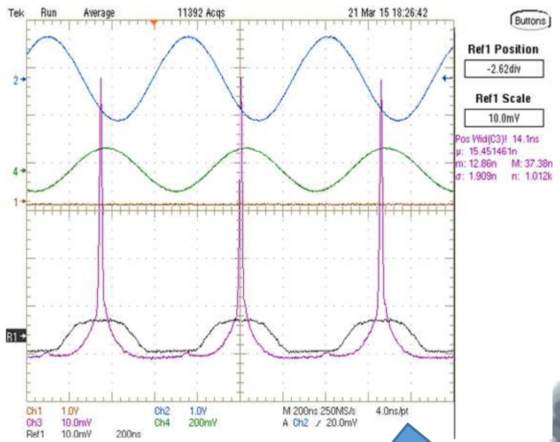


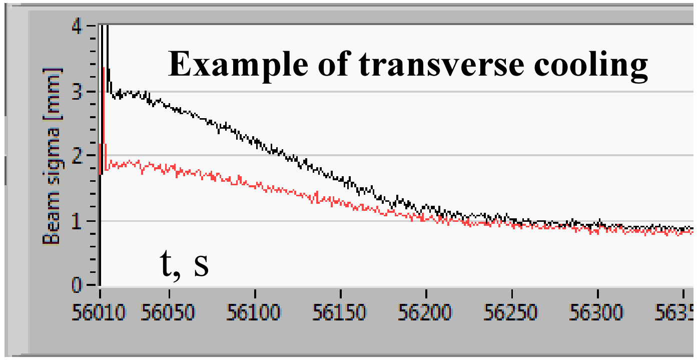
Pink curve is intensity of beam $^{124}Xe^{+28}$ in Nuclotron

Two cooling systems (electron and stochastic) will work both during beam accumulation and during experiment.

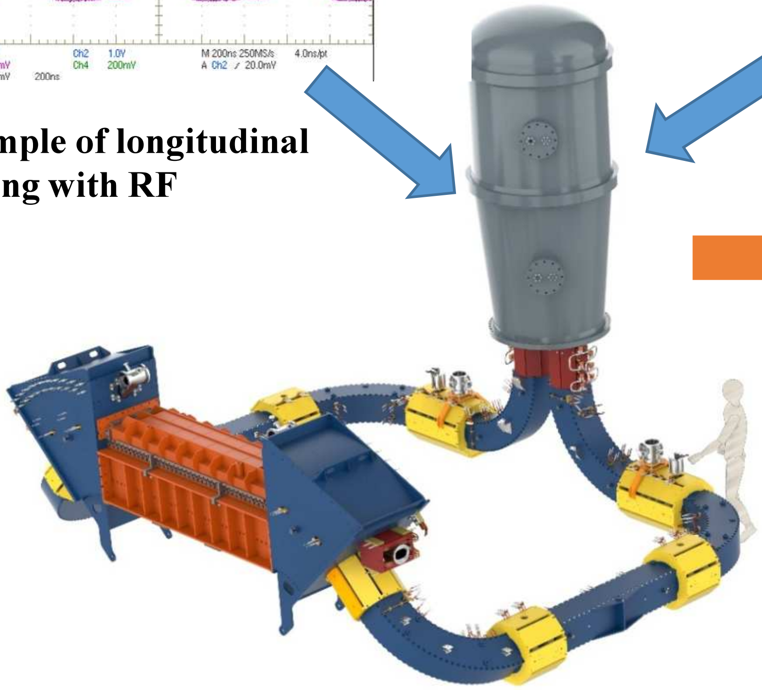
From COSY to NICA

The NICA high voltage cooler construction is based on 2 MeV cooler for the COSY synchrotron (Juelich, Germany).

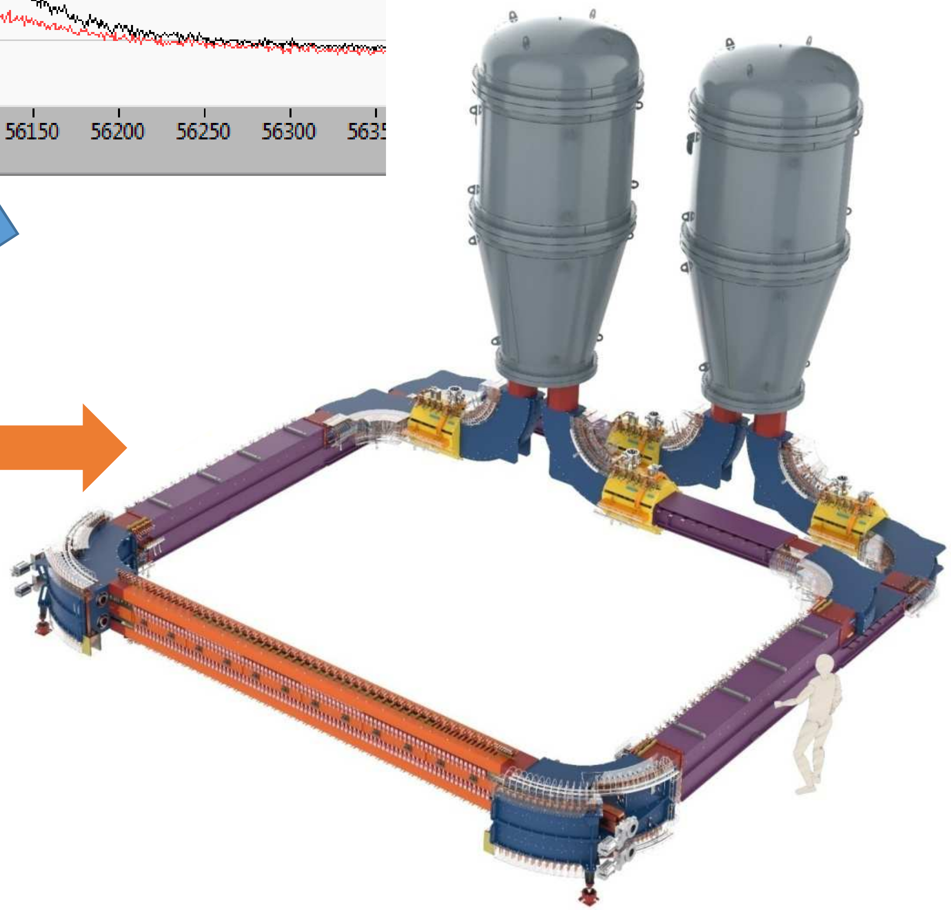




Example of longitudinal cooling with RF



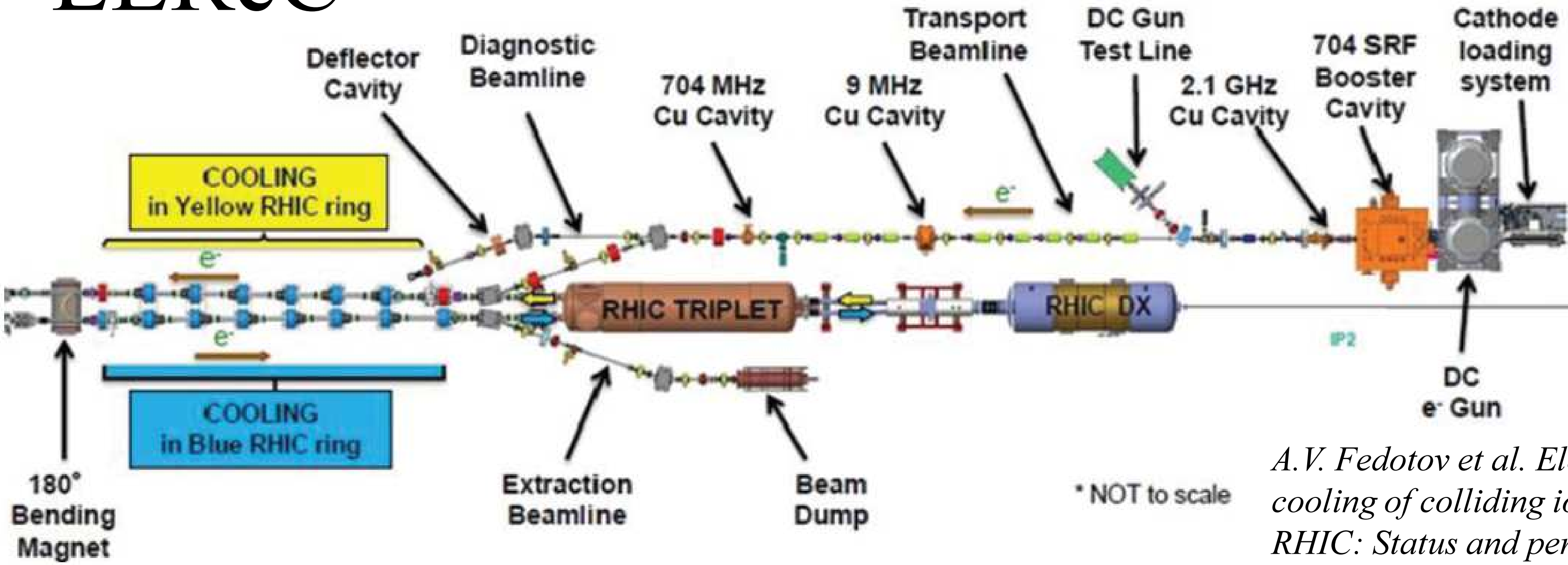
COSY cooler (2 MeV)



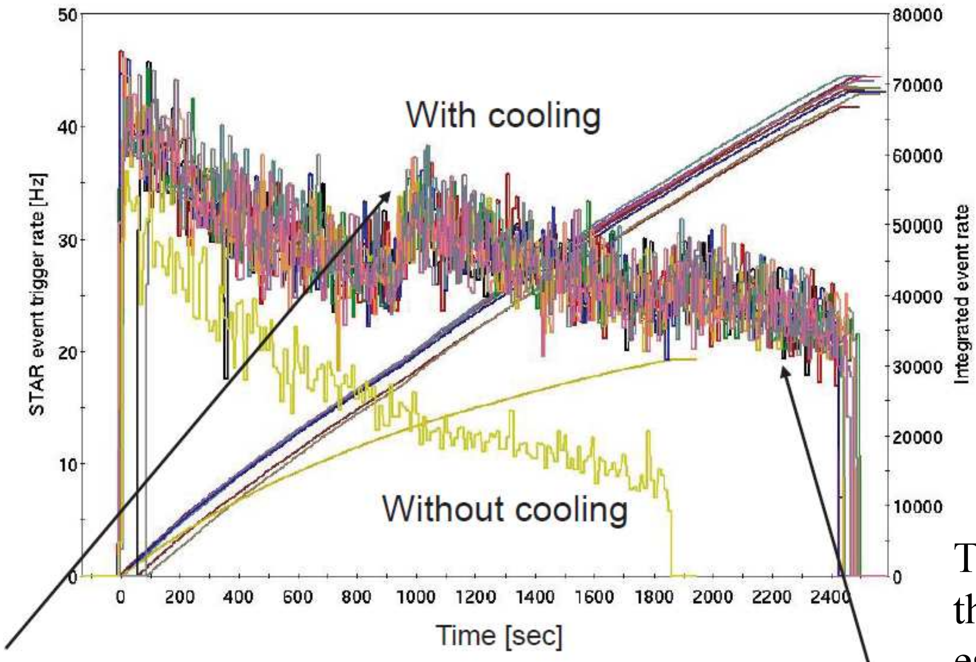
NICA cooler (2.5 MeV)

LEReC

E$_e$=1.6 and 2 MeV



A.V. Fedotov et al. Electron cooling of colliding ion beams in RHIC: Status and perspectives. COOL2021, Novosibirsk, Russia

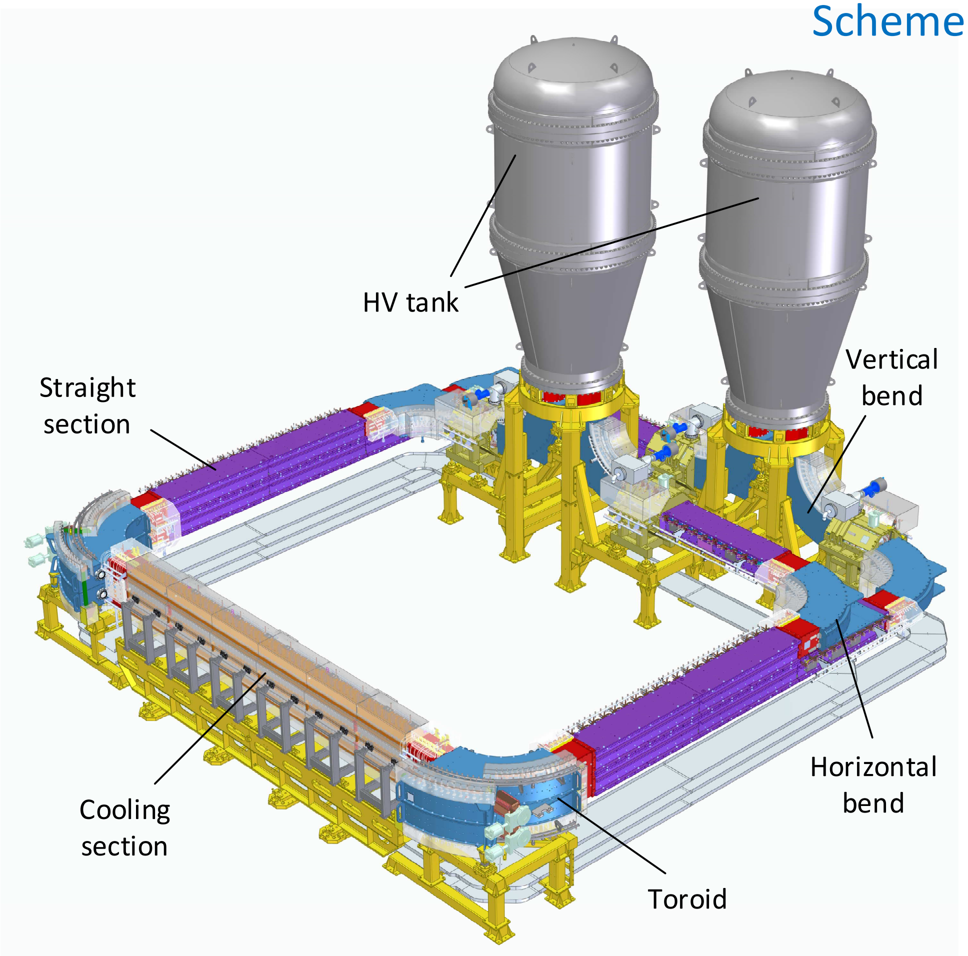


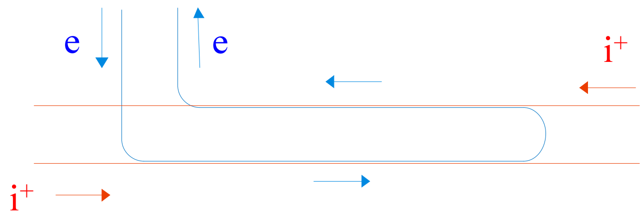
LEReC is based on state-of-the-art accelerator physics and technology: reproducibly high quantum efficiency photocathodes with a sophisticated delivery system which can hold up to 12 cathodes simultaneously (specifically designed to support long-term operation with up to one cathode exchange per day); a high-power laser beam with laser shaping and stabilization; a high-voltage high-current DC gun; RF gymnastics using several RF cavities; instrumentation, controls and a machine protection system.

The electron cooler LEReC successfully operated for the RHIC physics program in 2020 and 2021 and was essential in achieving the required luminosity goals.

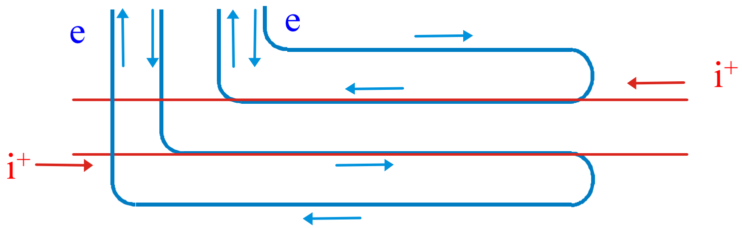
High voltage electron cooling in the NICA collider

The HV ECS for NICA consists of two almost independent coolers.
Scheme with one electron beam looks very complicated





Electron energy	0.2 - 2.5 MeV
Energy stability (ΔU/U)	$<10^{-4}$
Electron current	0.1 - 1 A
Cooling section length	6 m
Magnetic field in cooling section	0.5 - 2 kG
Vacuum	10^{-11} mbar



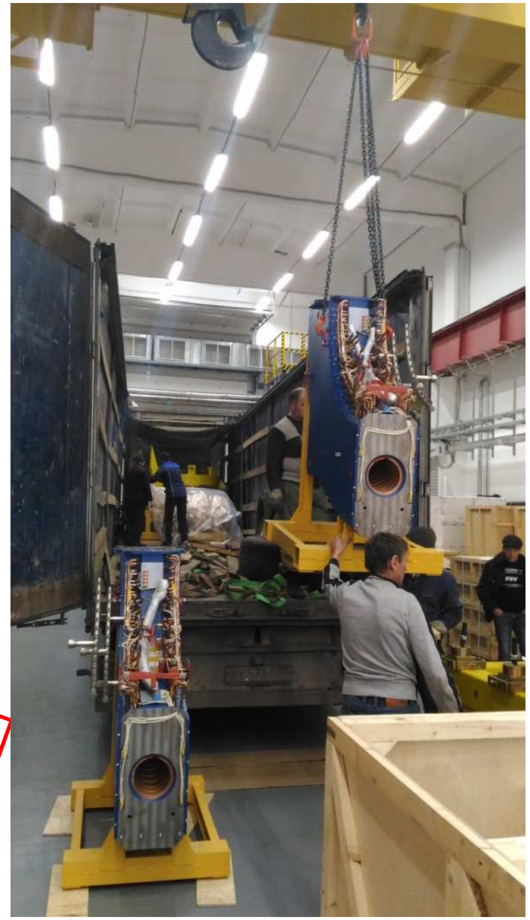
Main problems:

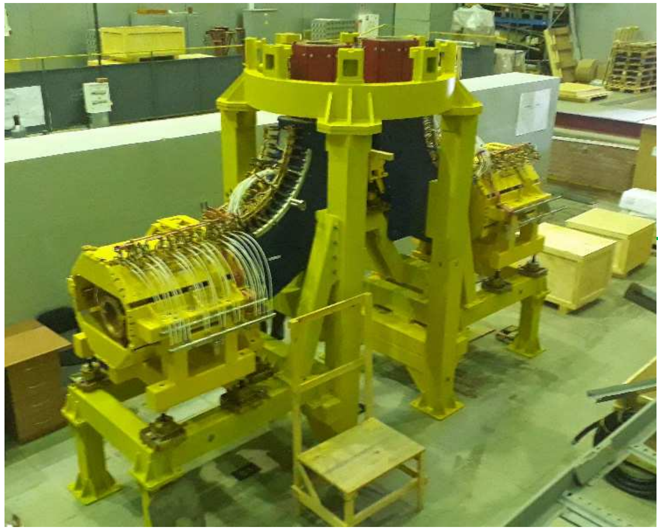
- High energy (up to 2.5 MeV);
- Small distance between beams (320 mm);
- Limited power consumption of the system (not more then 700 kW).

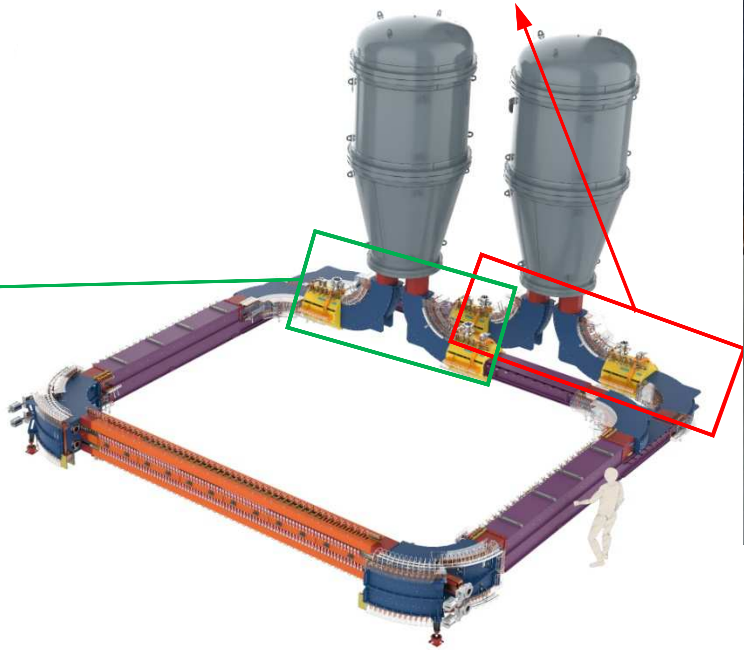
Assembling of transport channel elements

Partial assembling of elements under the HV vessels.

After test it was disassembled and sent to JINR

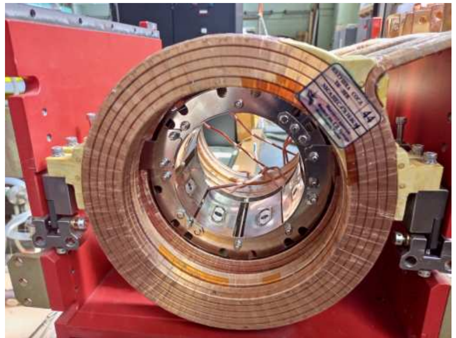


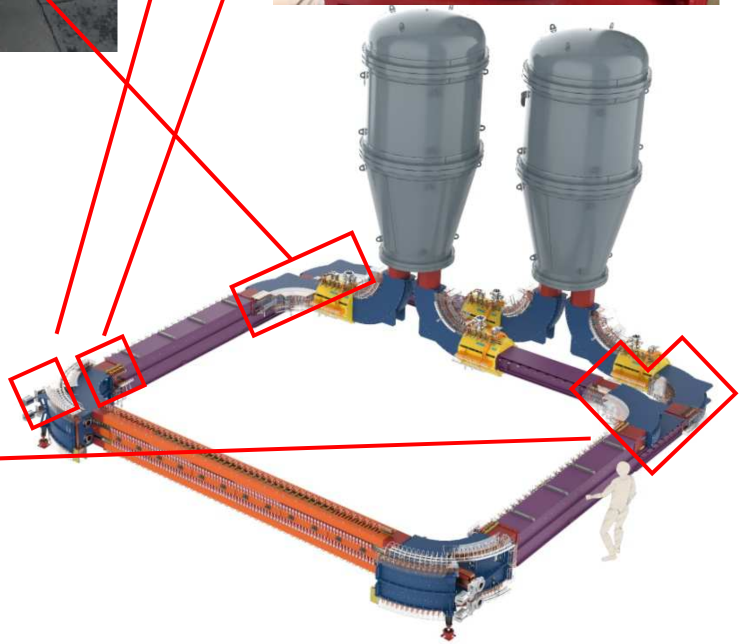




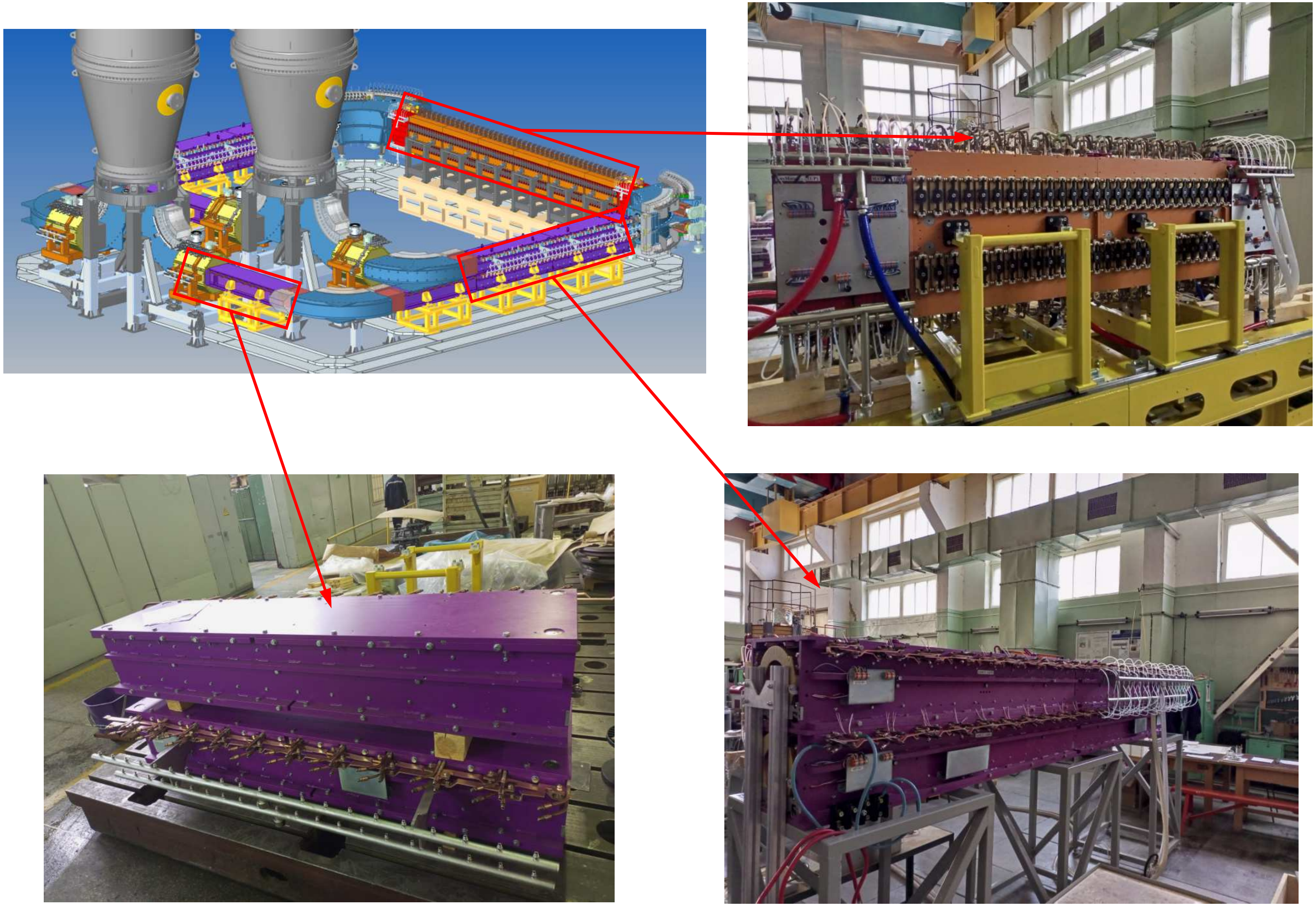
Partial assembling of elements of transport channel in JINR

Continue assembling of transport channel elements in BINP

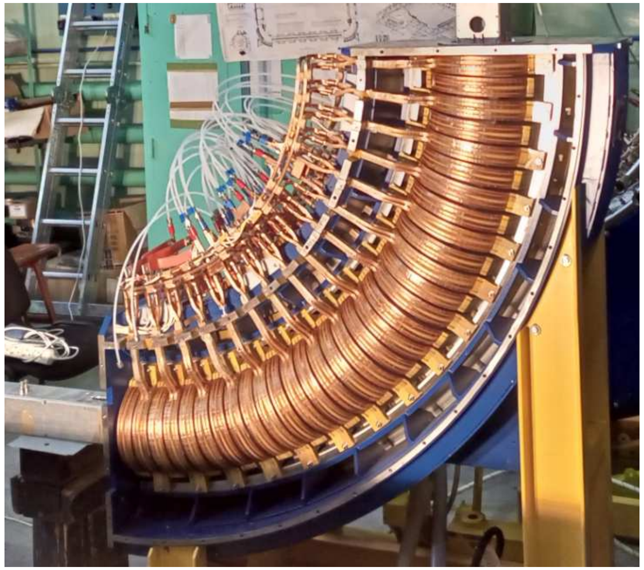




Assembling of transport channel elements and cooling section



Conception of magnetized motion requires many coils



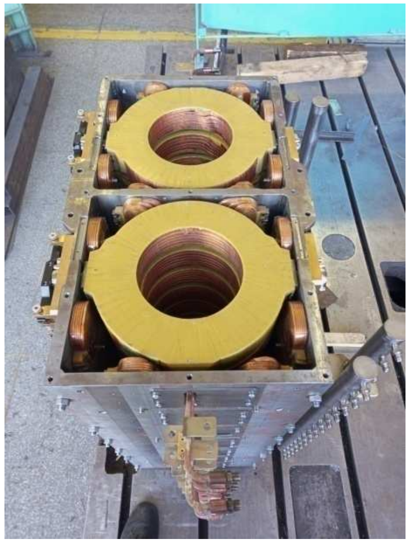
Longitudinal magnetic field

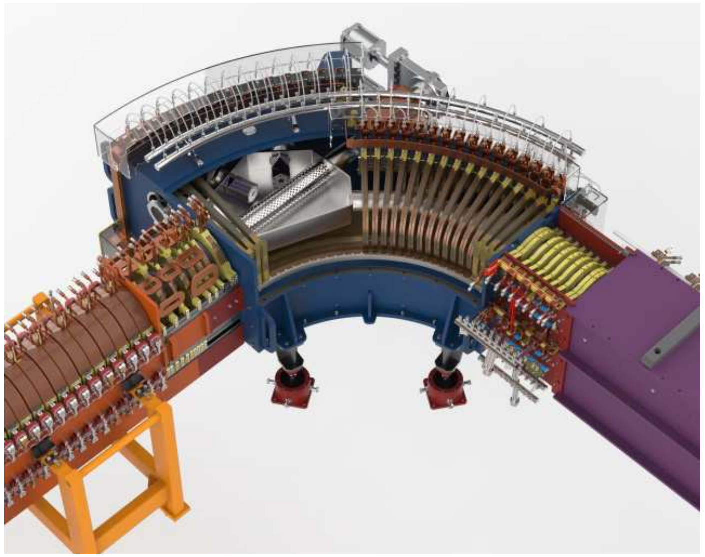
Cooling section –	180
Small toroids coils –	66
Large toroids coils –	60
Match sections –	48
Insert section –	110
Line transport section –	250
Bend section –	260
Line08 –	30
Hmatch section –	28
High Voltage Section –	180
HV Terminal –	46

And plus many correctors coils of the vertical and horizontal magnetic fields

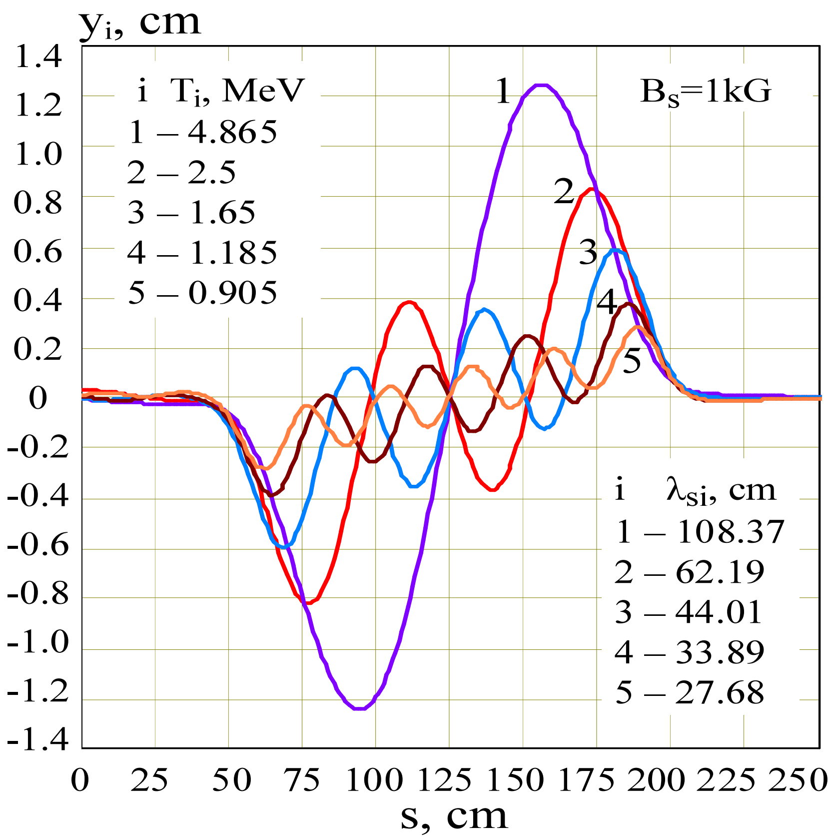
Total 1258

Type of coil types for longitudinal magnetic field is about 20

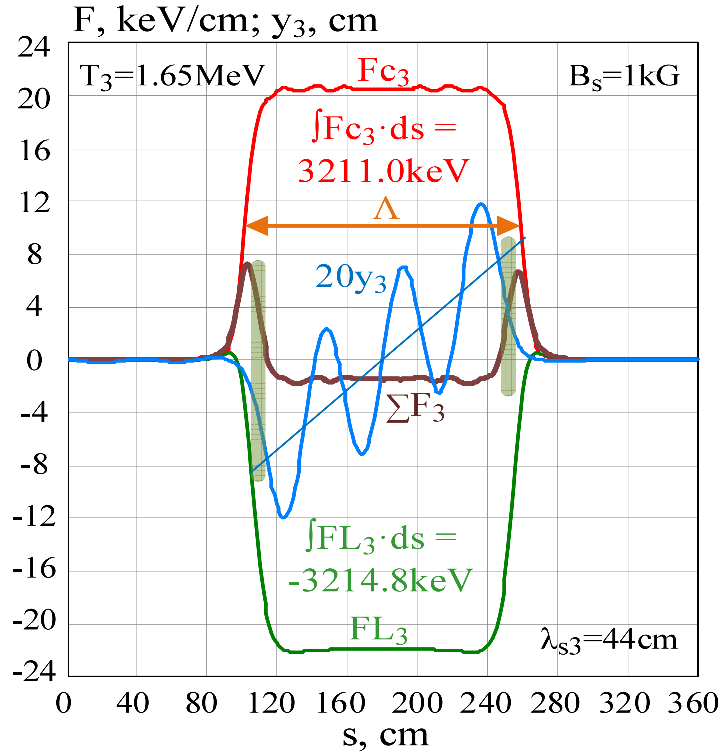




The resonant principle of magnetized optics



Electron motion in electron cooling system NICA. Radius of bend magnet is R=1m.The longitudinal field is Bs=1kG. The electron has pass of the bend in resonant way. The calculations are performed by MAGEL code. At resonant energy, electrons entering to bend without transverse energy leave it without “heating”. Some of these energies are equal to 4.865, 2.5, 1.65, 1.185 and 0.905 MeV. Electrons oscillate relative to force line when passing a bend.



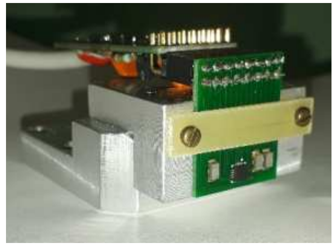
Profiles of the centrifugal force Fc3(s), the Lorentz force FL3(s) and ∑F3(s) = Fc3(s)+FL3(s) along the axial force line (s).

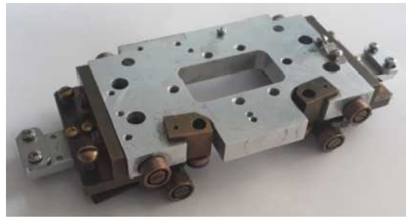
Magnetic measurements – Bend elements

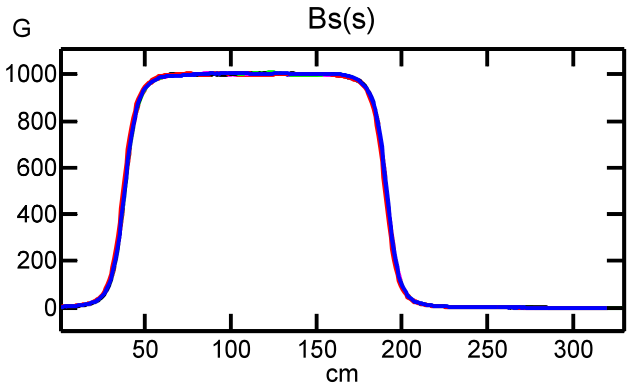
Horizontal bend

Vertical bends

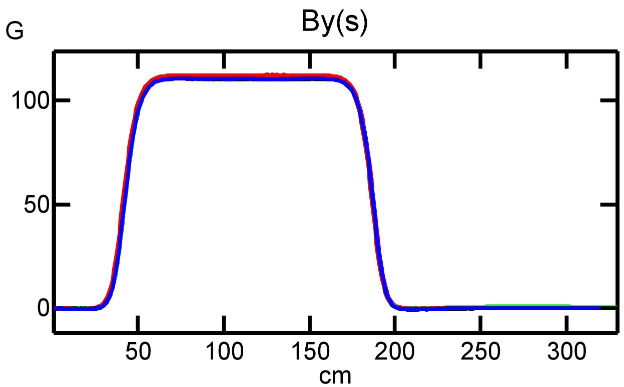
Carriage for Hall probe



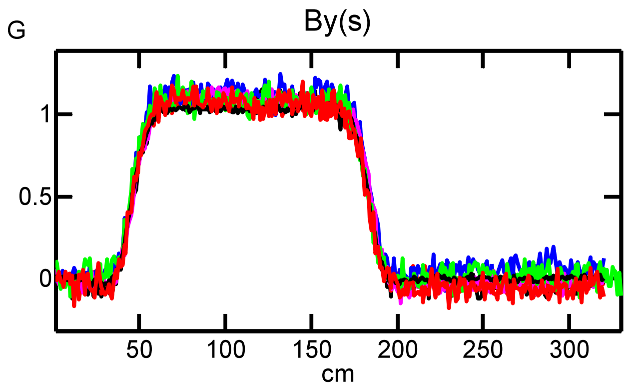




Longitudinal field = 195A



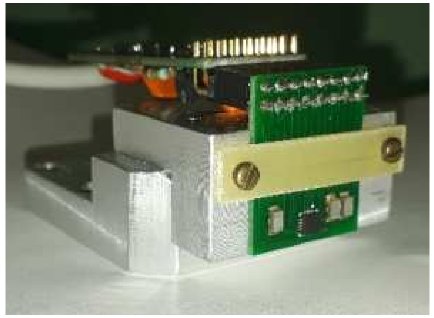
Bending field = 270 A

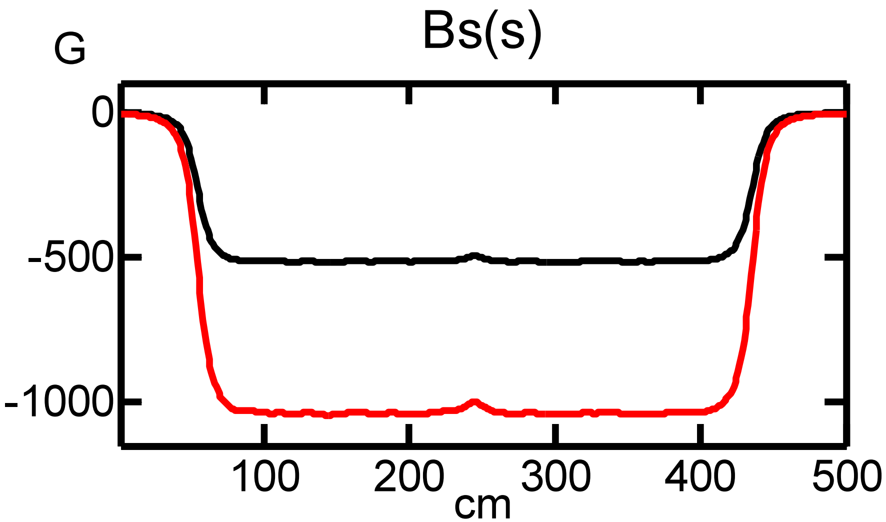


Bending corrector field, pair C1-C2 (3 A), working value up to 20 A

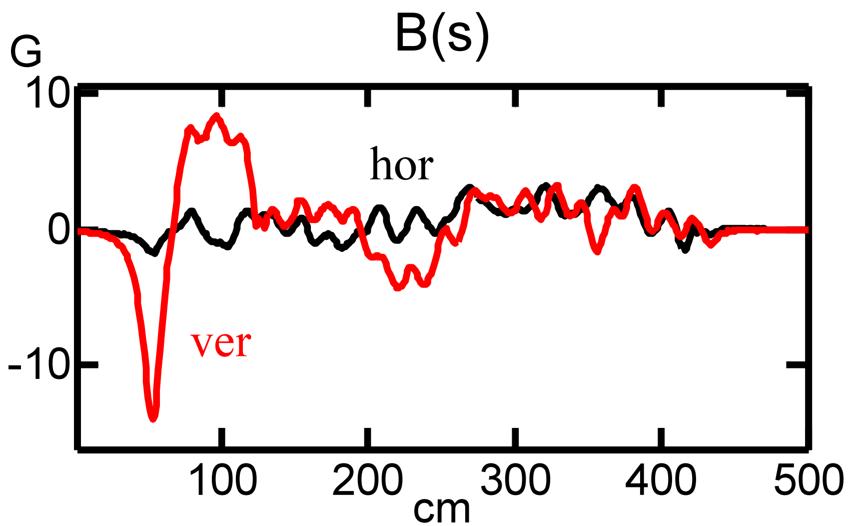
Magnetic measurements – Straight Elements

Carriage for Hall probe



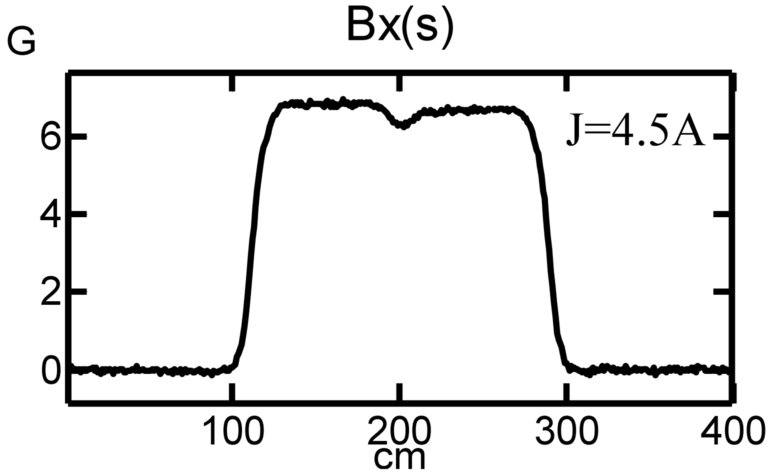


Longitudinal magnetic field



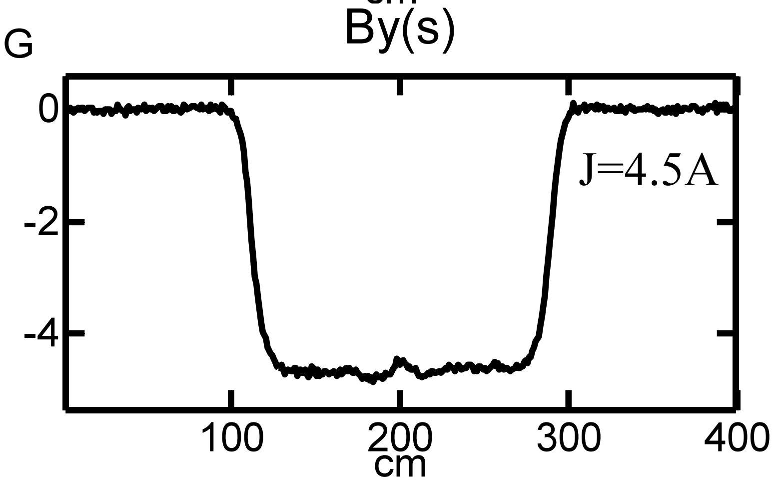
Transverse magnetic field at Bs=1 kG

Magnetic measurements – Corrector System of cooling section

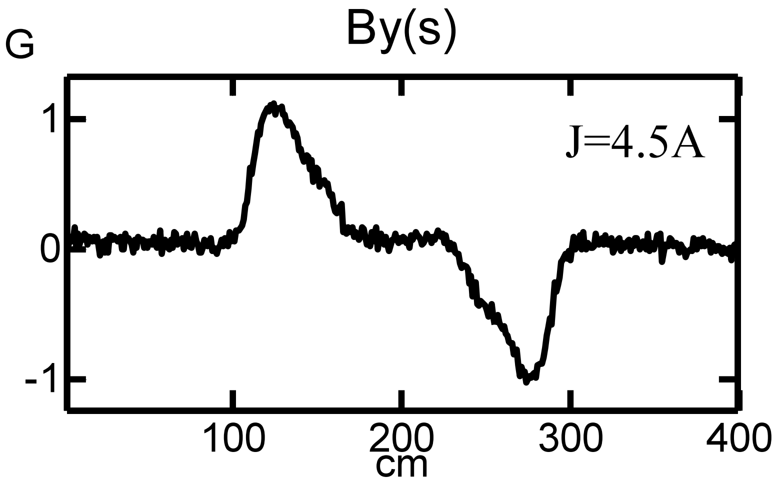


Horizontal corrector

regulate position of electron beam

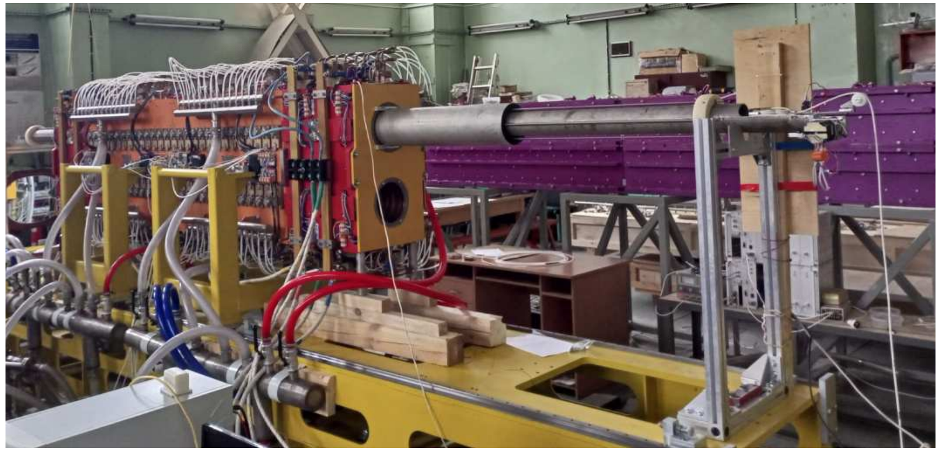


Vertical corrector

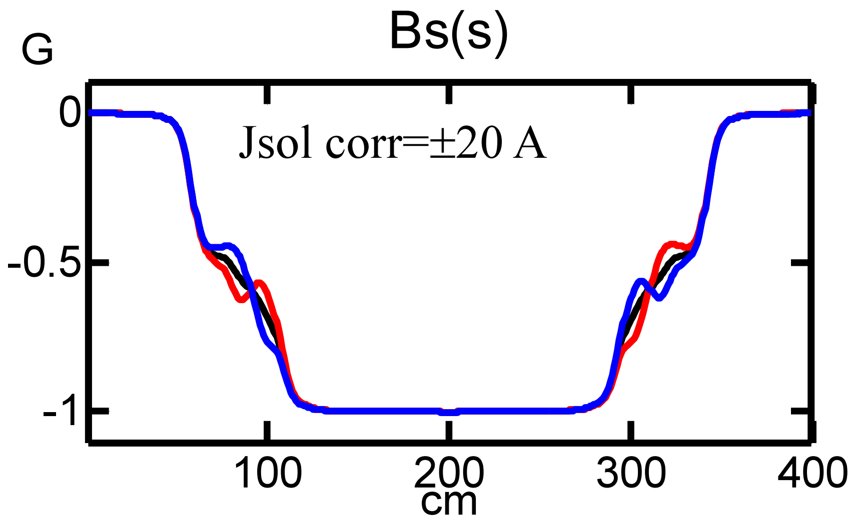


Linear field corrector

regulate edge field in cooling section



Hall system of magnetic field measurement



Longitudinal field corrector for proper input of electron beam in cooling section

Why magnetic field quality is important in cooling section ?

Decreasing of the distortion of the force line of the magnetic field increases the maximal value of the friction force. This effect is essential for small difference of ion momentum from equilibrium value.

$$\Delta\vec{p} = \vec{F}\cdot\tau = -\frac{4e^4 n_e \vec{V}\tau}{m_e\left(\sqrt{V^2+V_{eff}^2}\right)^3}\ln\left(1+\frac{\rho_{max}}{\rho_L+\rho_{min}}\right)$$

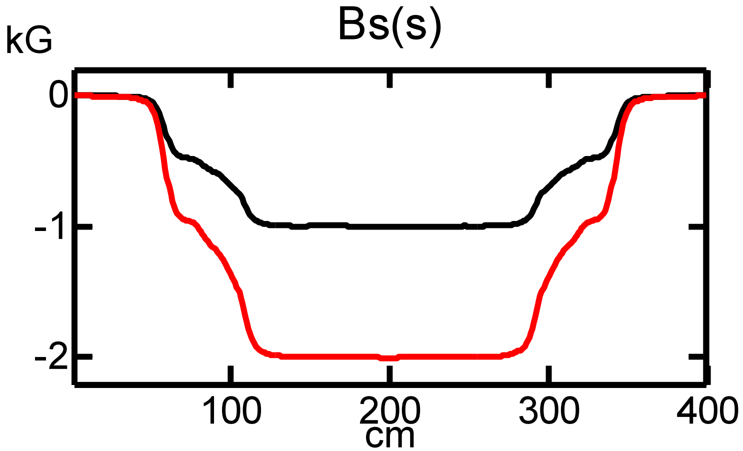
$$V_{eff}^2 = V_{\Delta\Theta}^2 + V_{E\times B}^2 + V_e^2$$ *effective temperature*

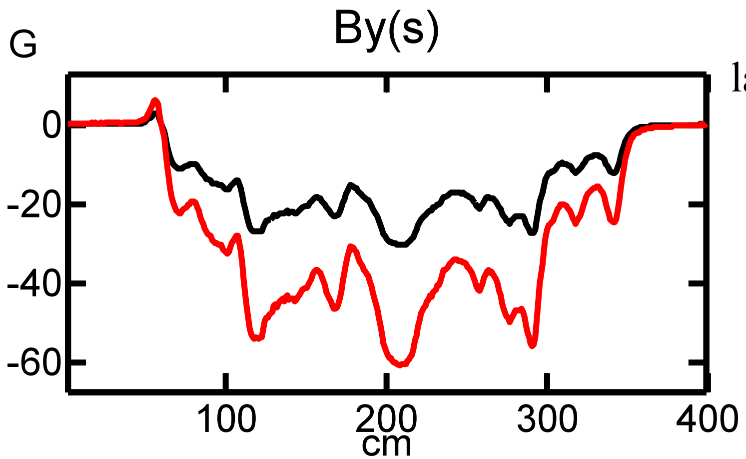
$$V_{\Delta\Theta} = \gamma\beta c\sqrt{\left\langle \Delta B^2/B_s^2 \right\rangle}$$ $\left\langle \Delta B^2/B_s^2 \right\rangle$ *ripple of the magnetic field*

$\gamma_E\beta_E/\gamma_{30}\beta_{30}$	E, кэВ
1.9	100
8.0	1000
13.8	2000

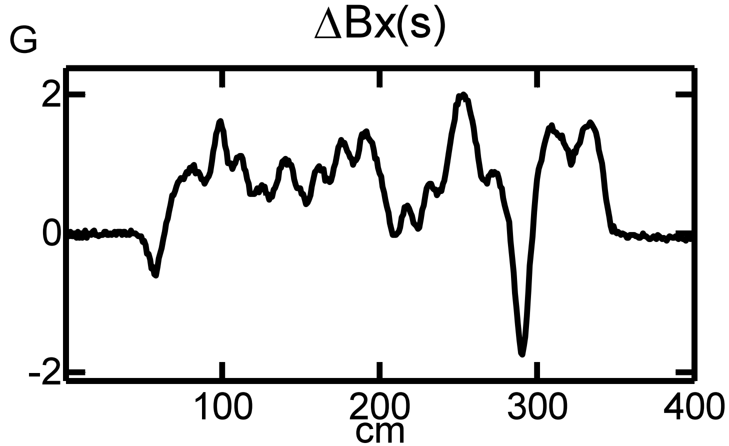
Cooling section – standard BINP decision with pancake coils

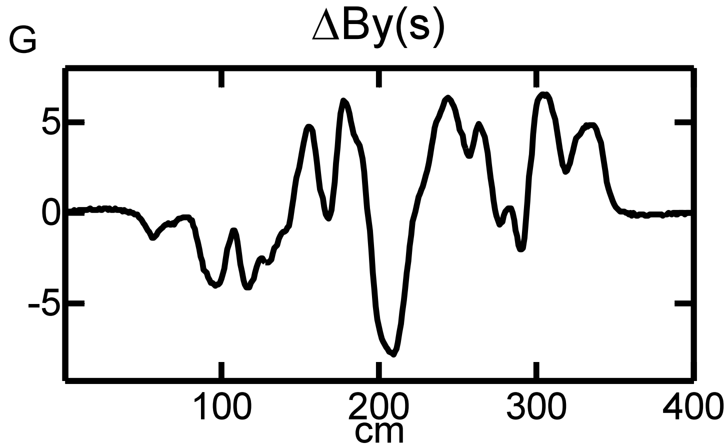
Cooling Section – Hall Measurement

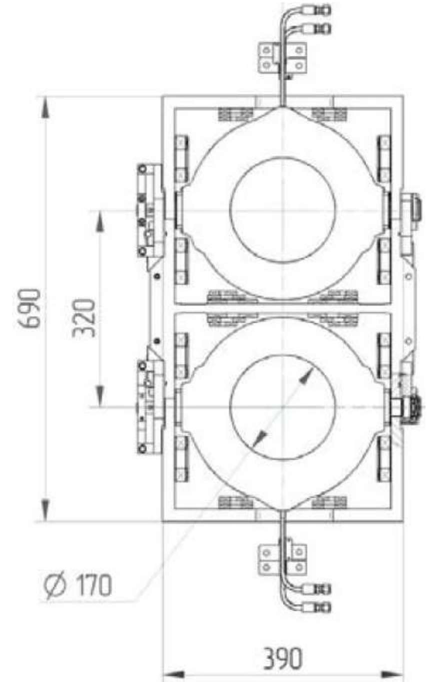




large difference between tune in horizontal and vertical direction





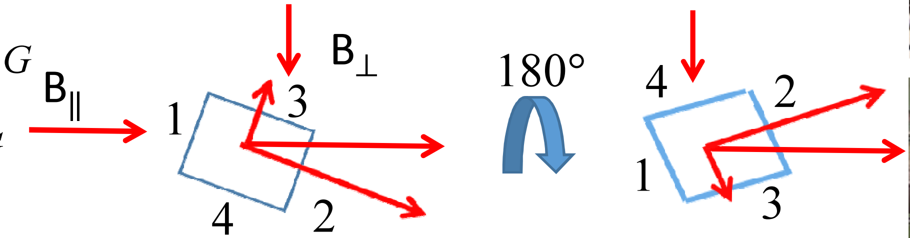


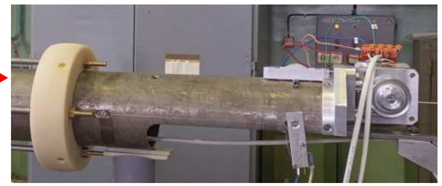
Hall measurement has problem to distinguish between incline magnetic field and incline of the hall probe. Rotation of the measurement system slightly helps to solve this problem

$$\sqrt{\langle dB_x^2 \rangle} = \sqrt{\sum \Delta B_x^2 / (Np-1)} \approx 0.5\, G$$

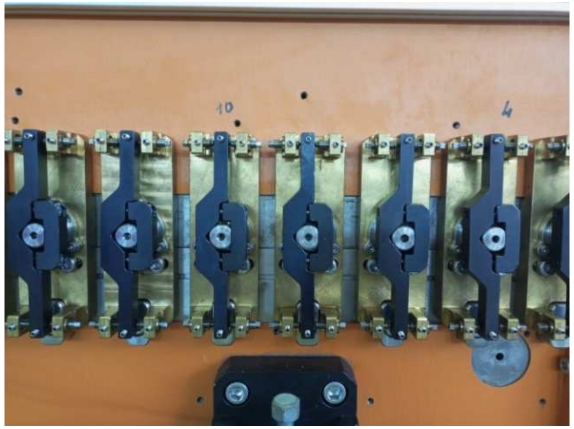
$$\sqrt{\langle dB_y^2 \rangle} = \sqrt{\sum \Delta B_y^2 / (Np-1)} \approx 4\, G$$

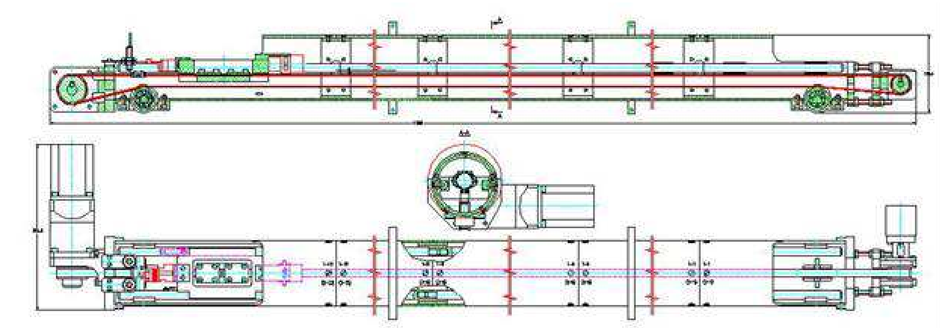
dS=135-265 cm, Bs=1000 G

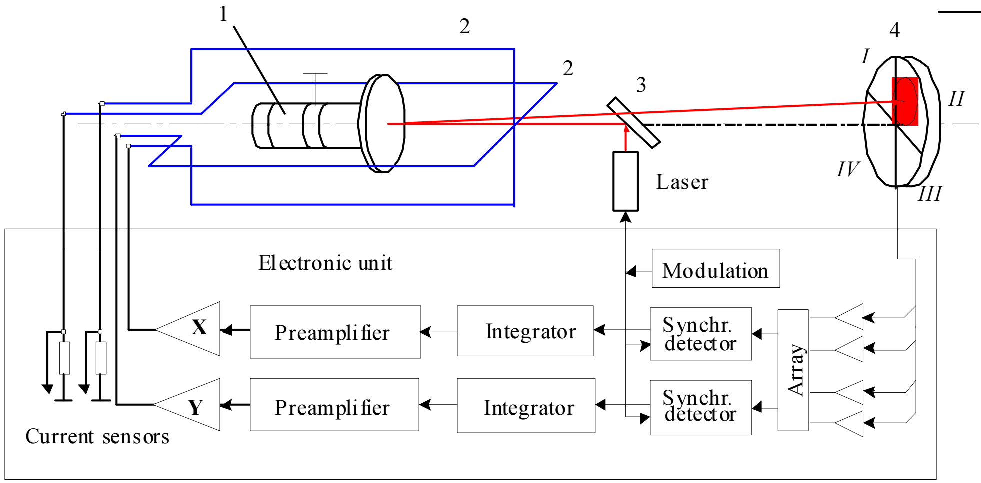


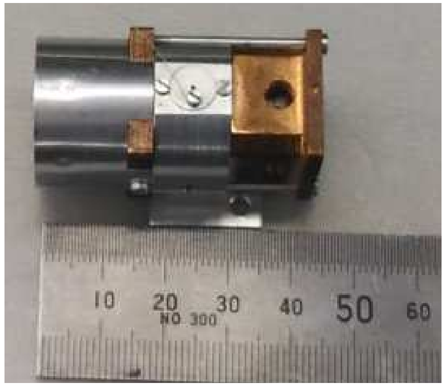


Compass Magnetic Measurements – Cooling Section



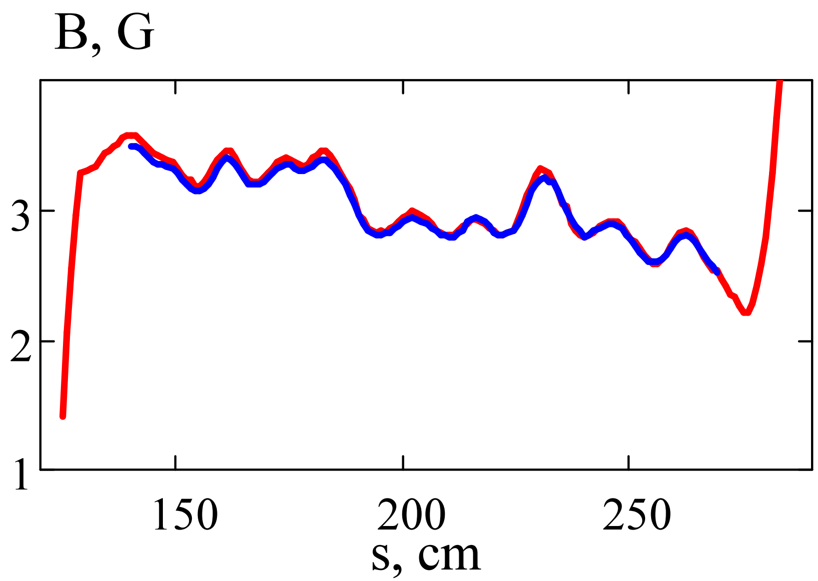






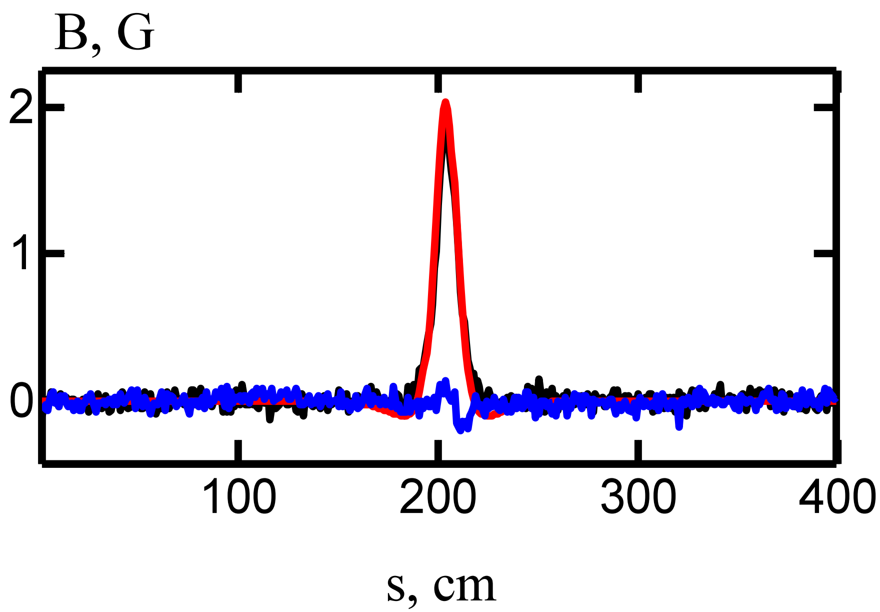
Compass Magnetic Measurements – Cooling Section

Use of cooling section correctors expand the area of compass measurement



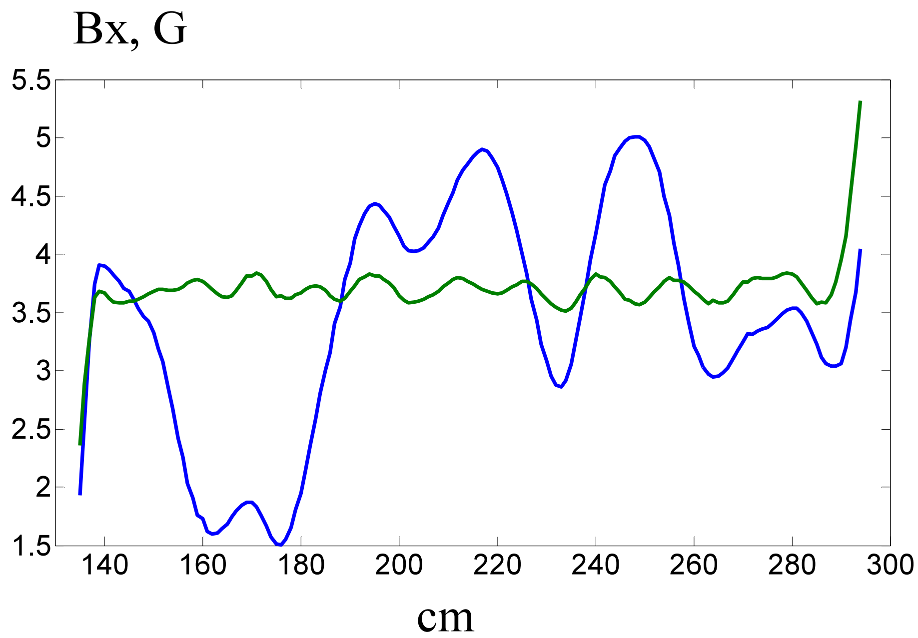
Blue is pure compass measurement
Red is combination of compass and cooling section correctors

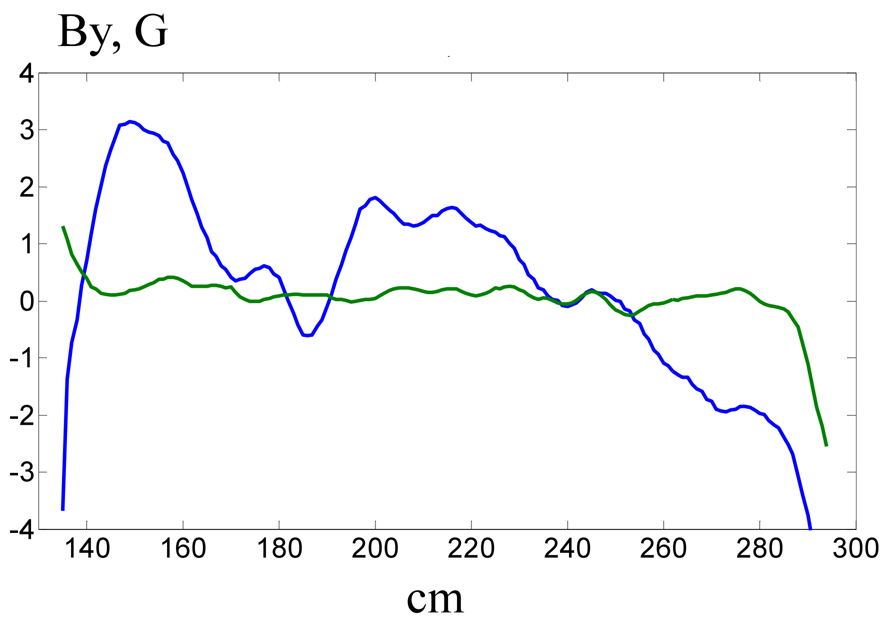
Response profile from incline of one coil



To tilt coil, the “edges” of the adjusting unit was moved 5 turns (~2.5 mm) on top and bottom of unit in one direction

After preliminary tuning of magnetic force line with Hall system and modification of adjusting unit the quality of magnetic force line was improved by 10 times





$$\langle dB_x \rangle = \sqrt{\sum \Delta B_x^2 / (Np-1)} \approx 1.1\,G$$

$$\langle dB_y \rangle = \sqrt{\sum \Delta B_y^2 / (Np-1)} \approx 1.3\,G$$

dS=144-274 cm, Bs=1000 G

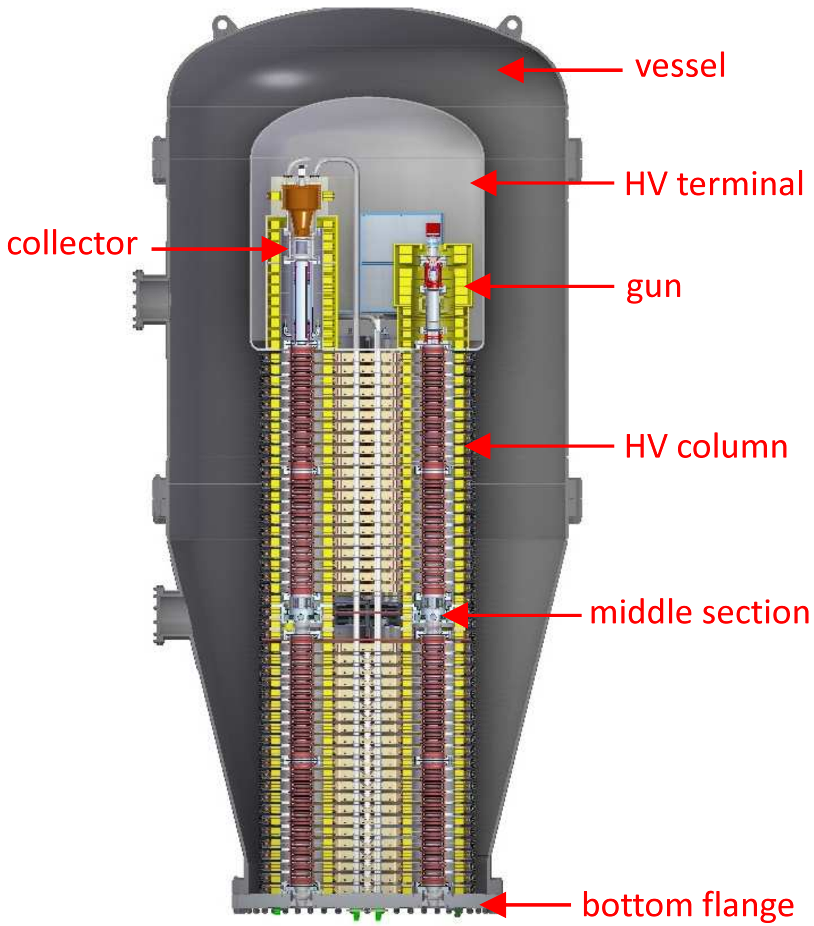
$$\langle dB_x \rangle = \sqrt{\sum \Delta B_x^2 / (Np-1)} \approx 0.08\,G$$

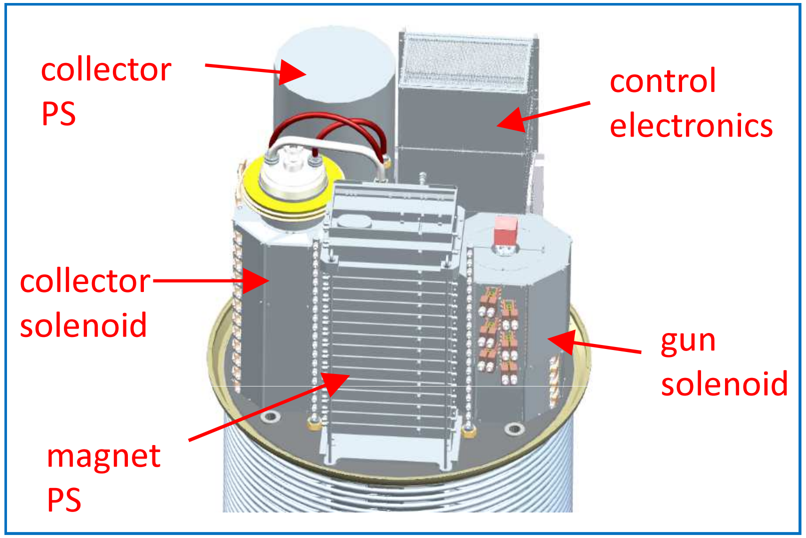
$$\langle dB_y \rangle = \sqrt{\sum \Delta B_y^2 / (Np-1)} \approx 0.13\,G$$

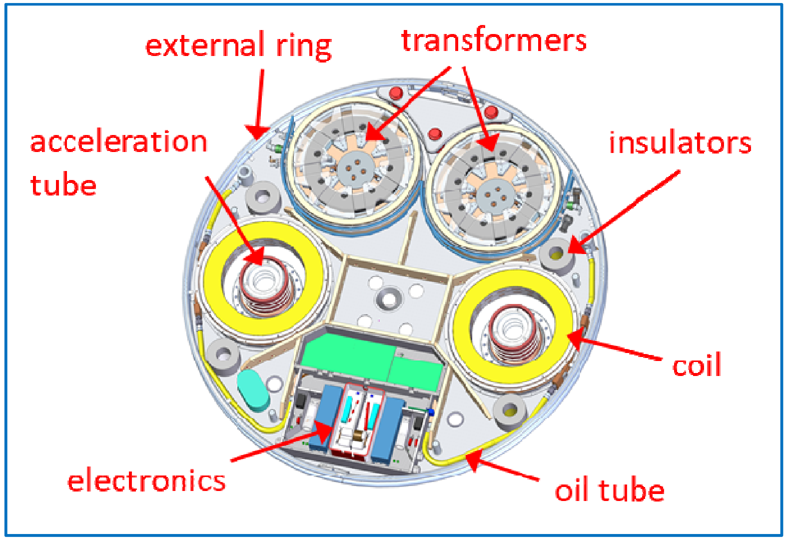
dS=144-274 cm, Bs=1000 G

High voltage system

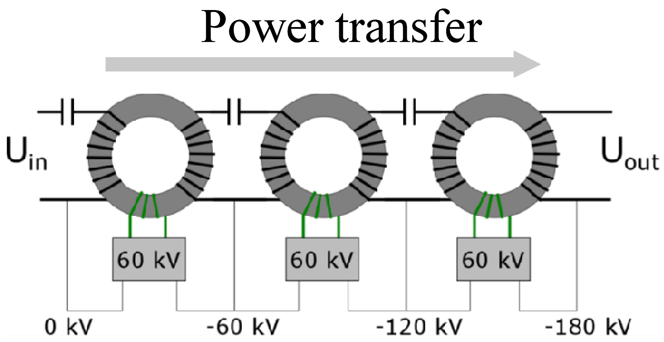
Purpose of the high voltage system is production of electron beam in electron gun and acceleration for working energy in electrostatic tube. After interaction with ion beam electrons move to high voltage again where they are decelerated in another electrostatic tube and dumped in electron collector.

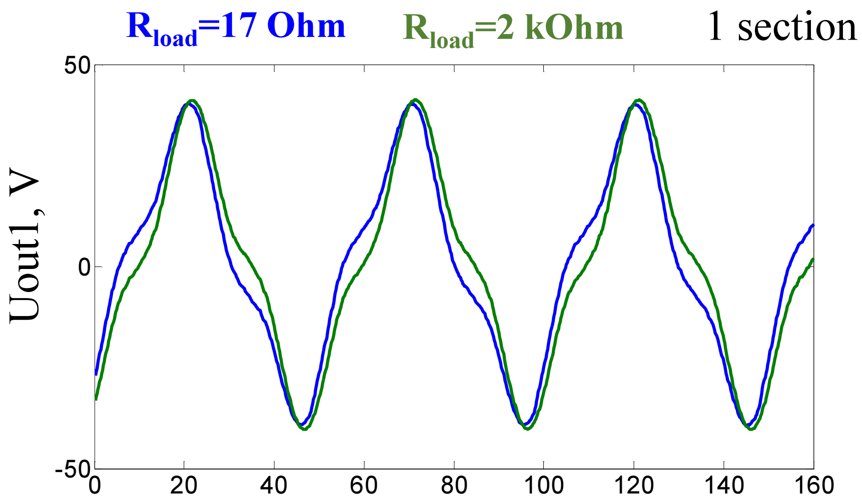


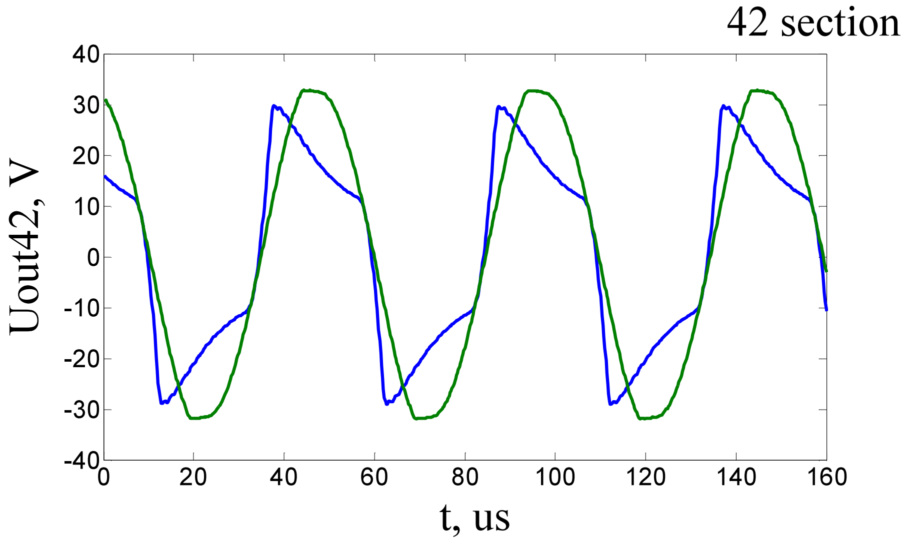




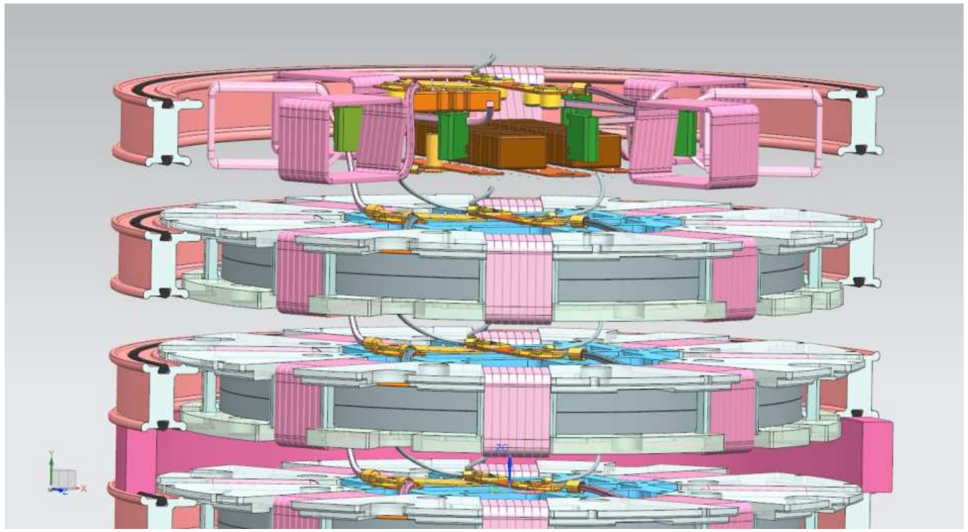
Cascade transformers



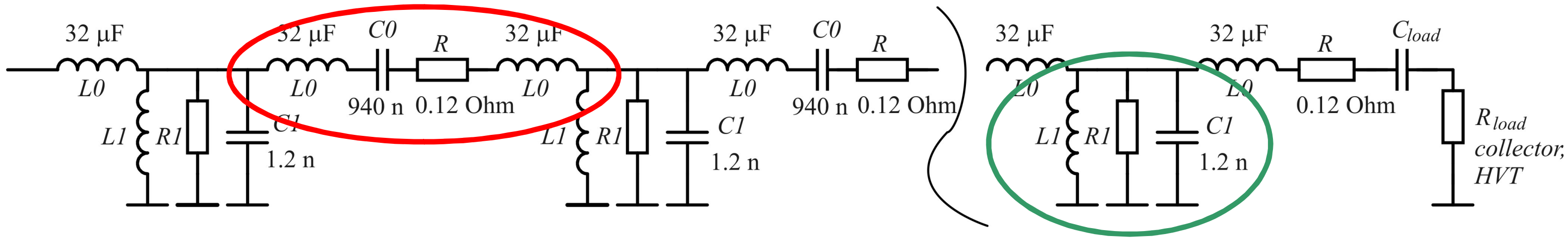




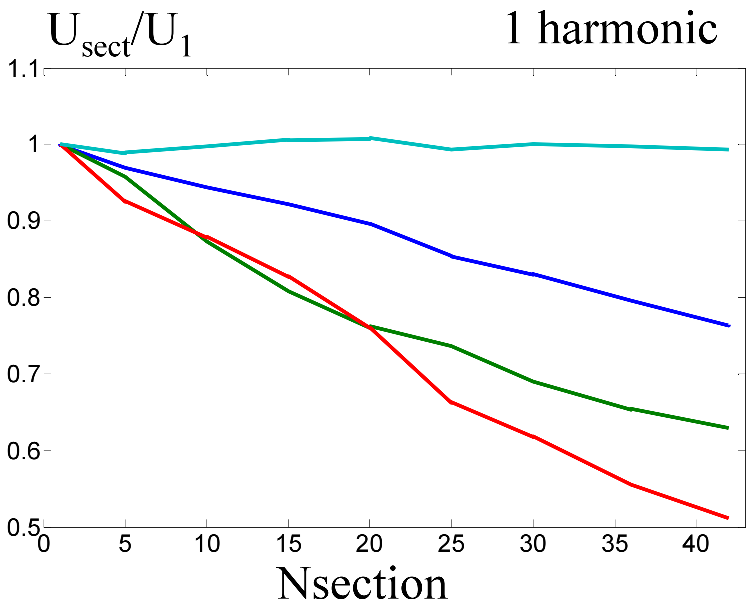
All 8 transformers were built and tested.

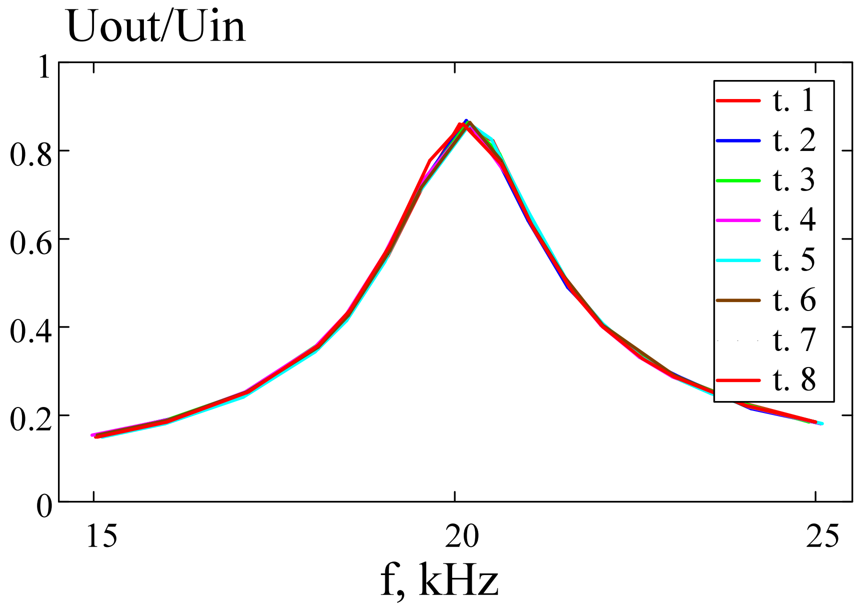


Construction of cascade transformer

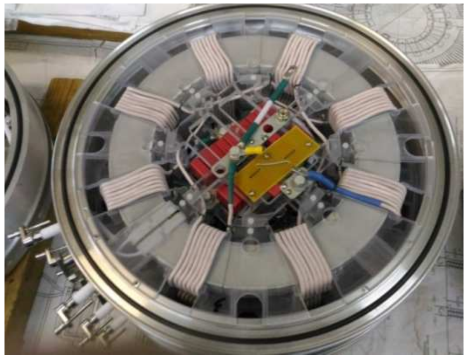


physics principle of operation of cascade transformer is combination of series and parallel resonances induced by the leakage inductance and compensative capacitances

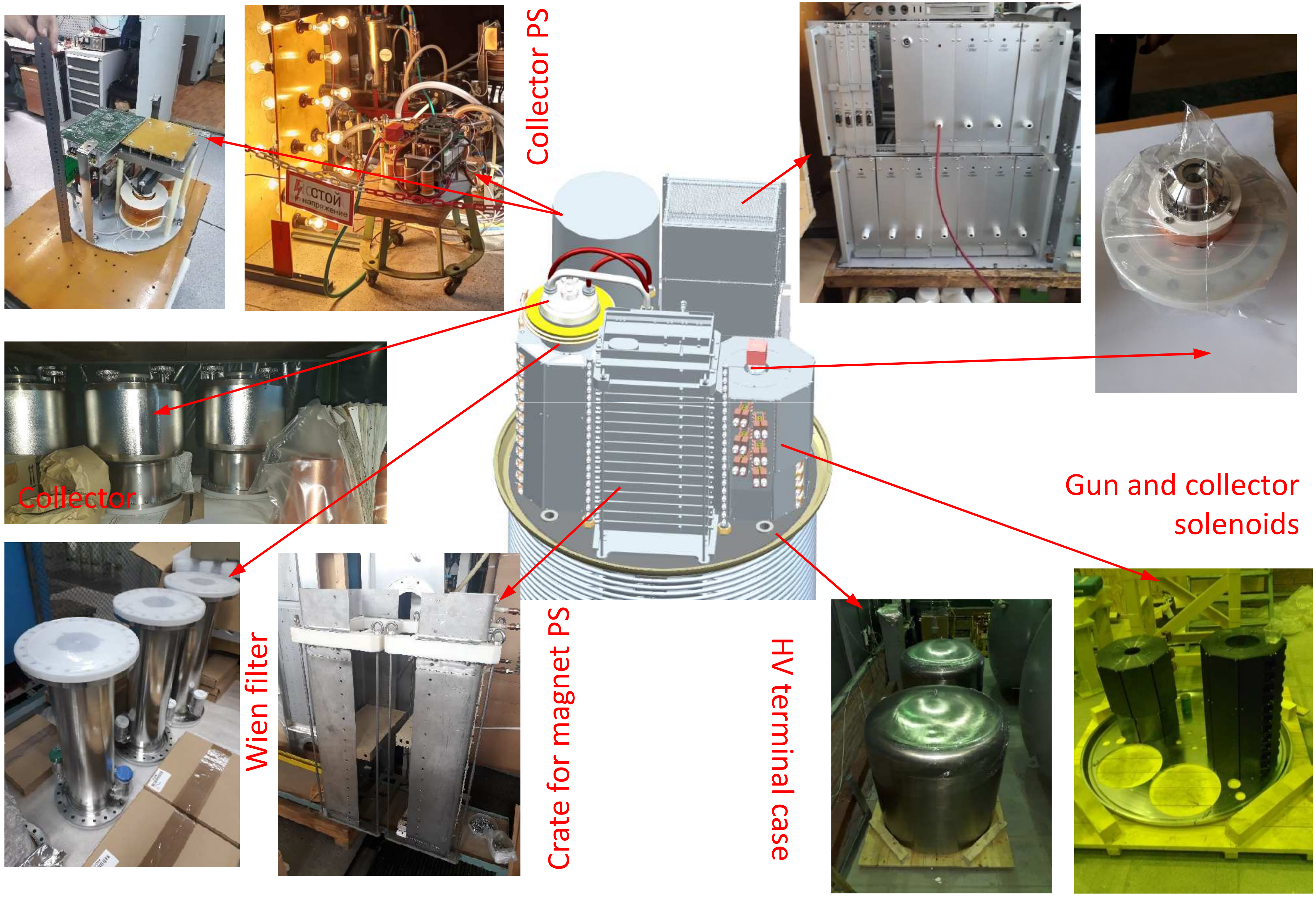




1=blue, f0=20.1 kHz, R_{load}=17 Ohm
2=green, f0=20.4 kHz, R_{load}=17 Ohm
3=red, f0=19.7 kHz, R_{load}=17 Ohm
4=light blue, f0=20.1 kHz, R_{load}=2000 Ohm

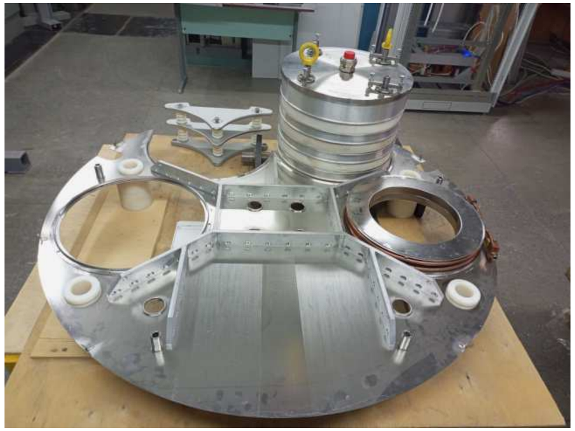


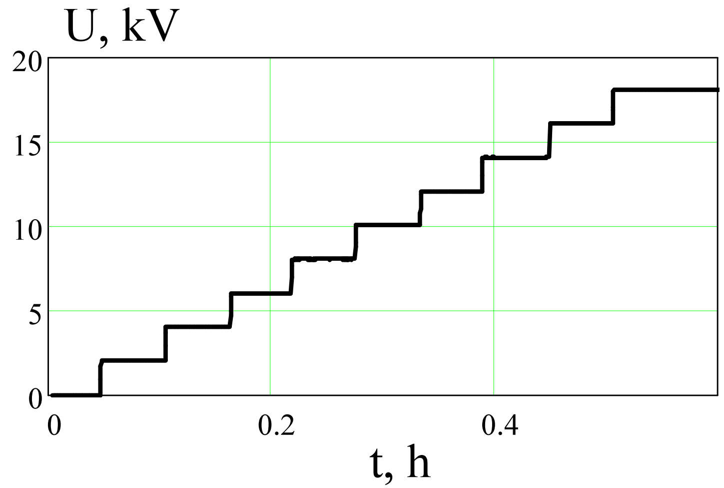
High voltage terminal

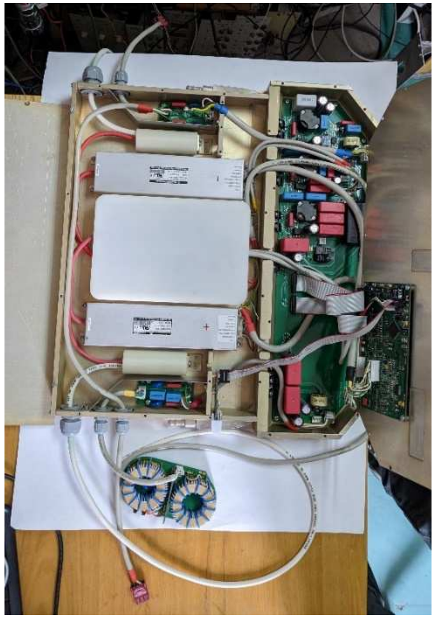


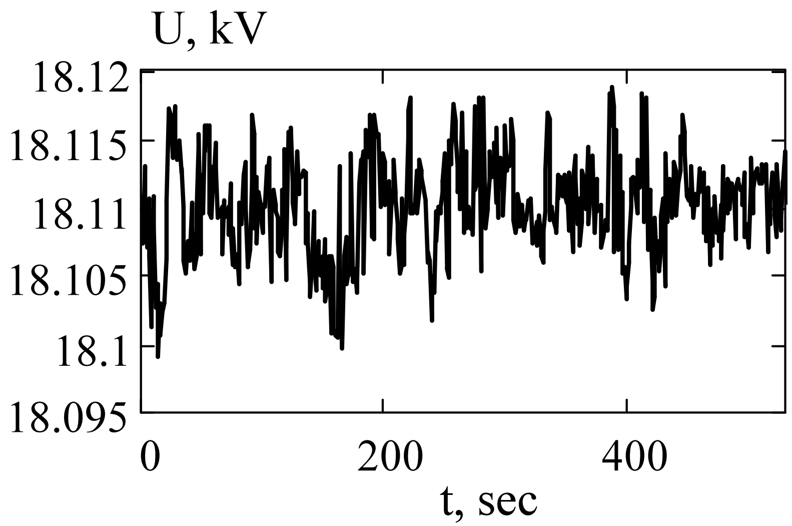
Electronics of the high voltage column

One section contains 2 HV power sources (+- 30 kV) and power source for magnetic coils.
Connection with control computer is provided by ZigBee.



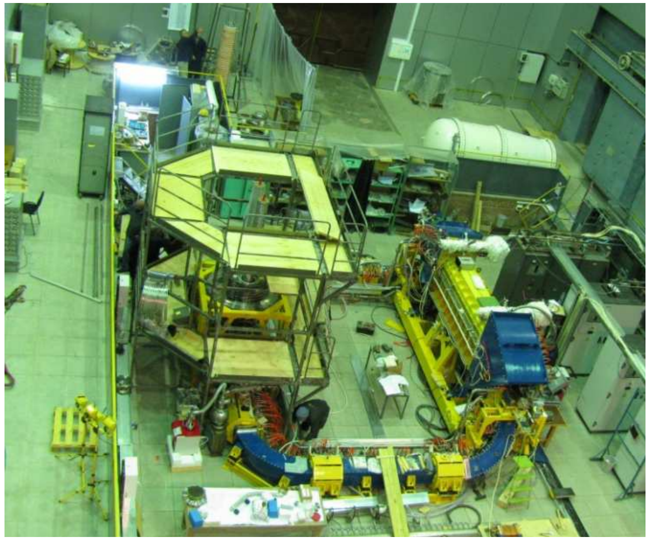


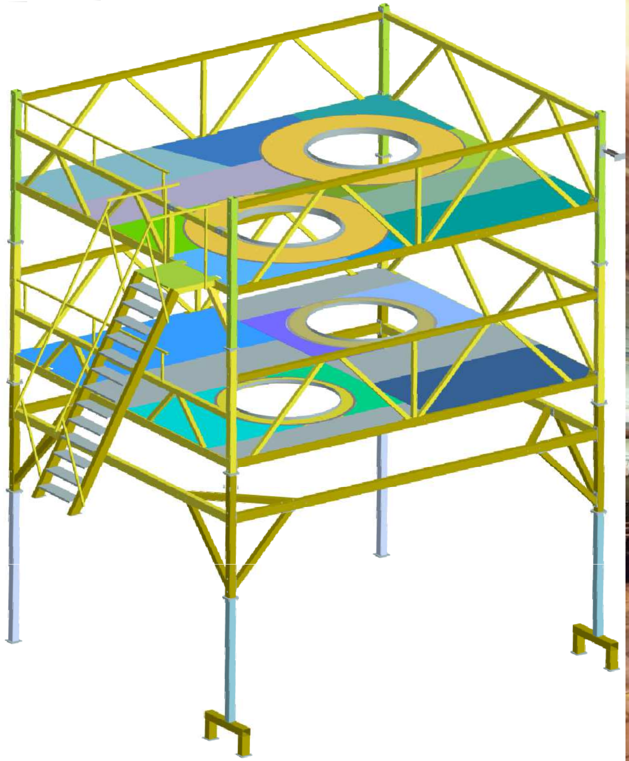


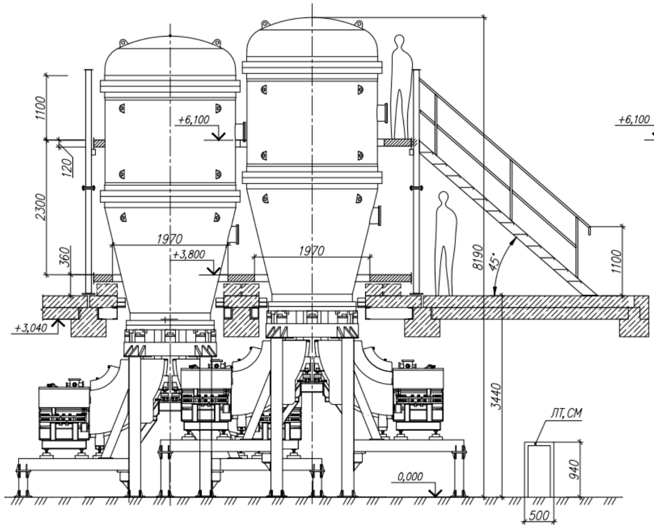


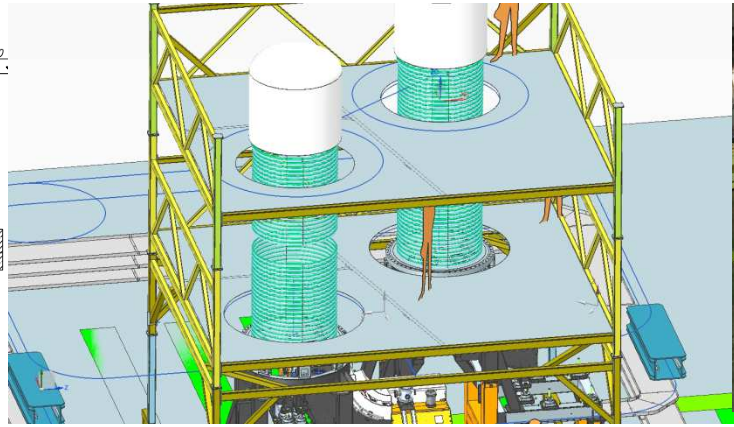
Service platform for HV system

COSY cooler platform





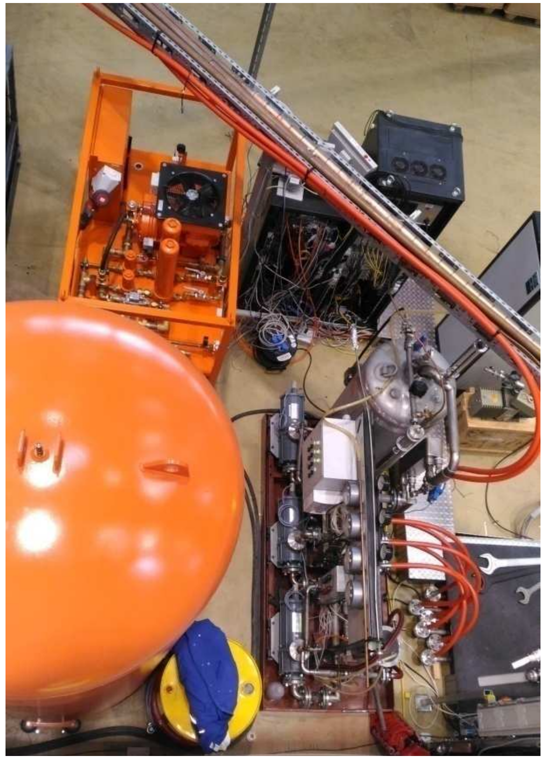




SF_6 system for NICA e-cooler

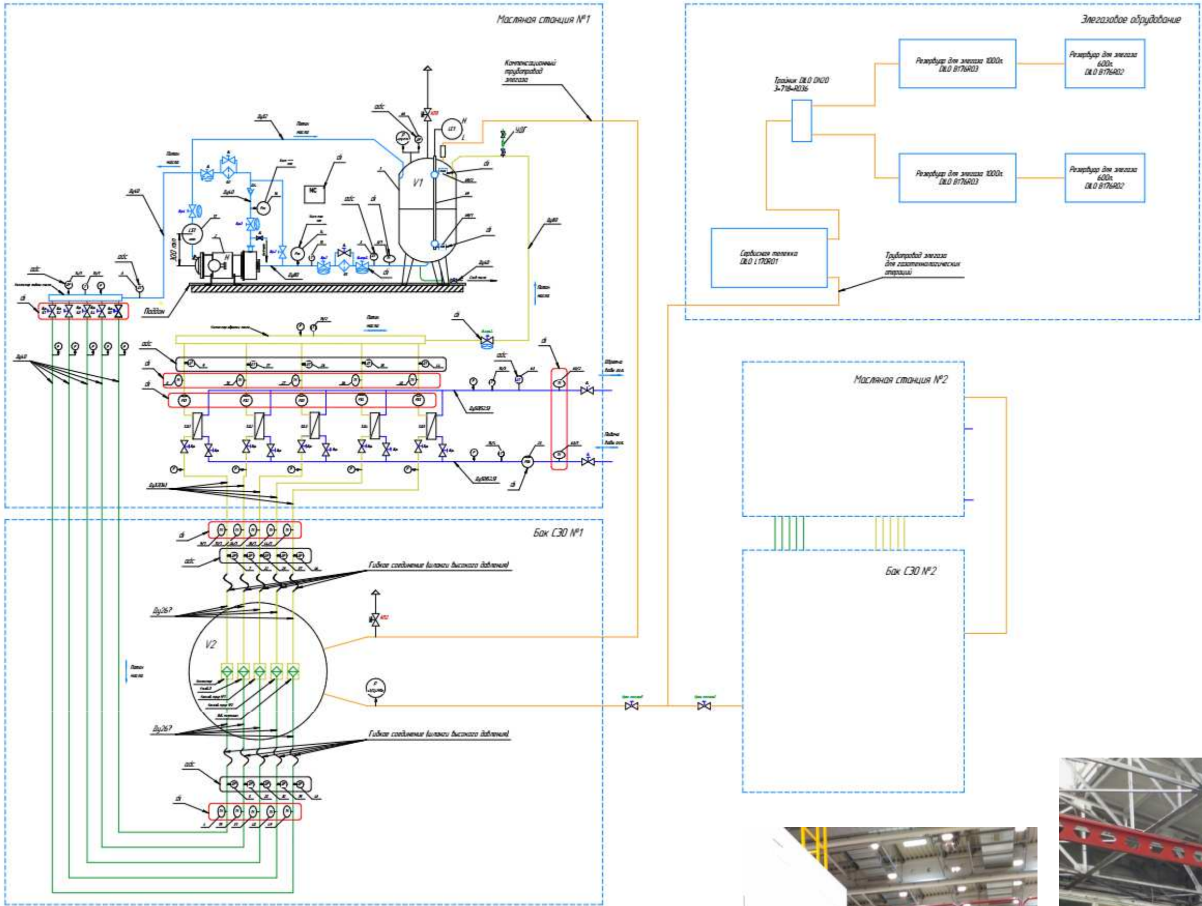
DILO L170R01

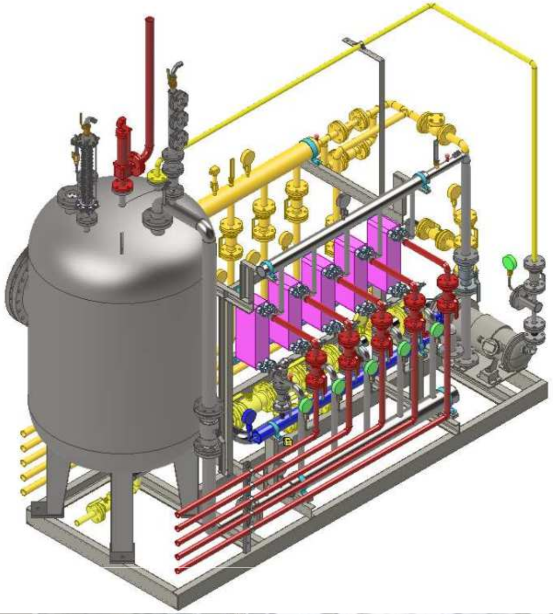
COSY example

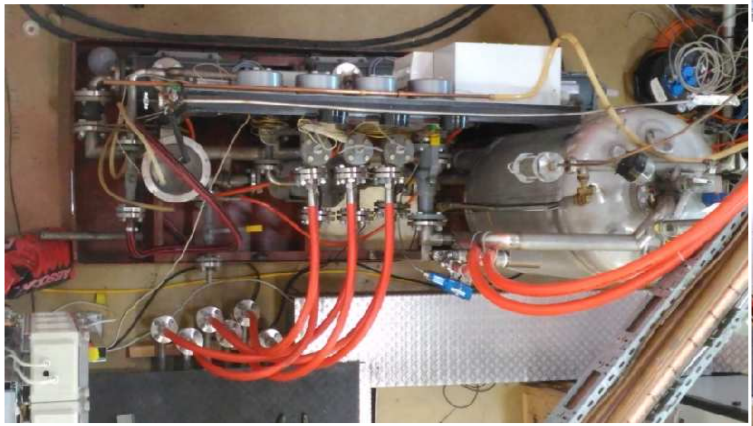


SF_6 system in JINR

Oil cooling system







Oil System for COSY e-cooler

Oil system for NICA e-cooler

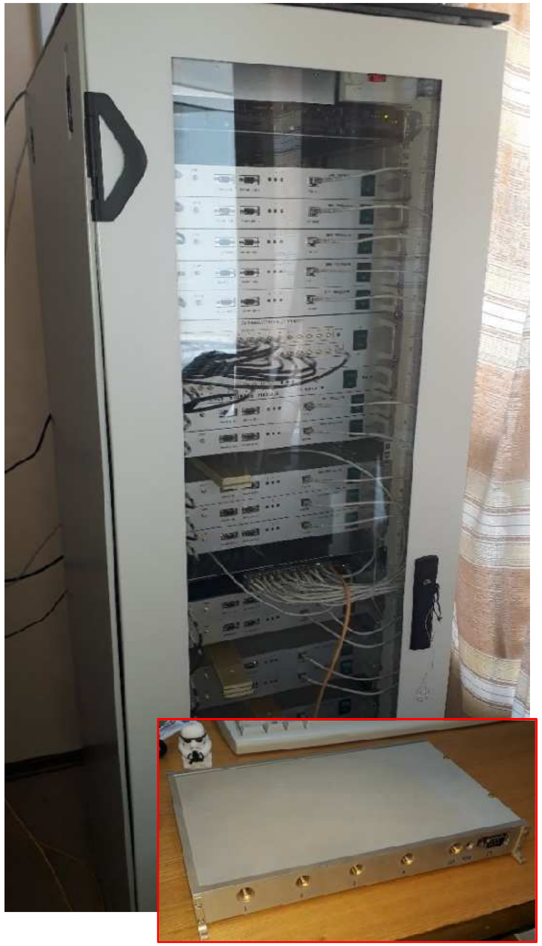
Power sources production

IST power sources are produced and partly tested. Most of them are packed and ready for sending to JINR

Cascade transformer power sources are produced and are in the process of testing

Corrector power sources: MPS-20 sources are produced. MPS-6 sources are produced and are in the process of testing . Racks for PS are being prepared for assembling.

Control electronics and BPM

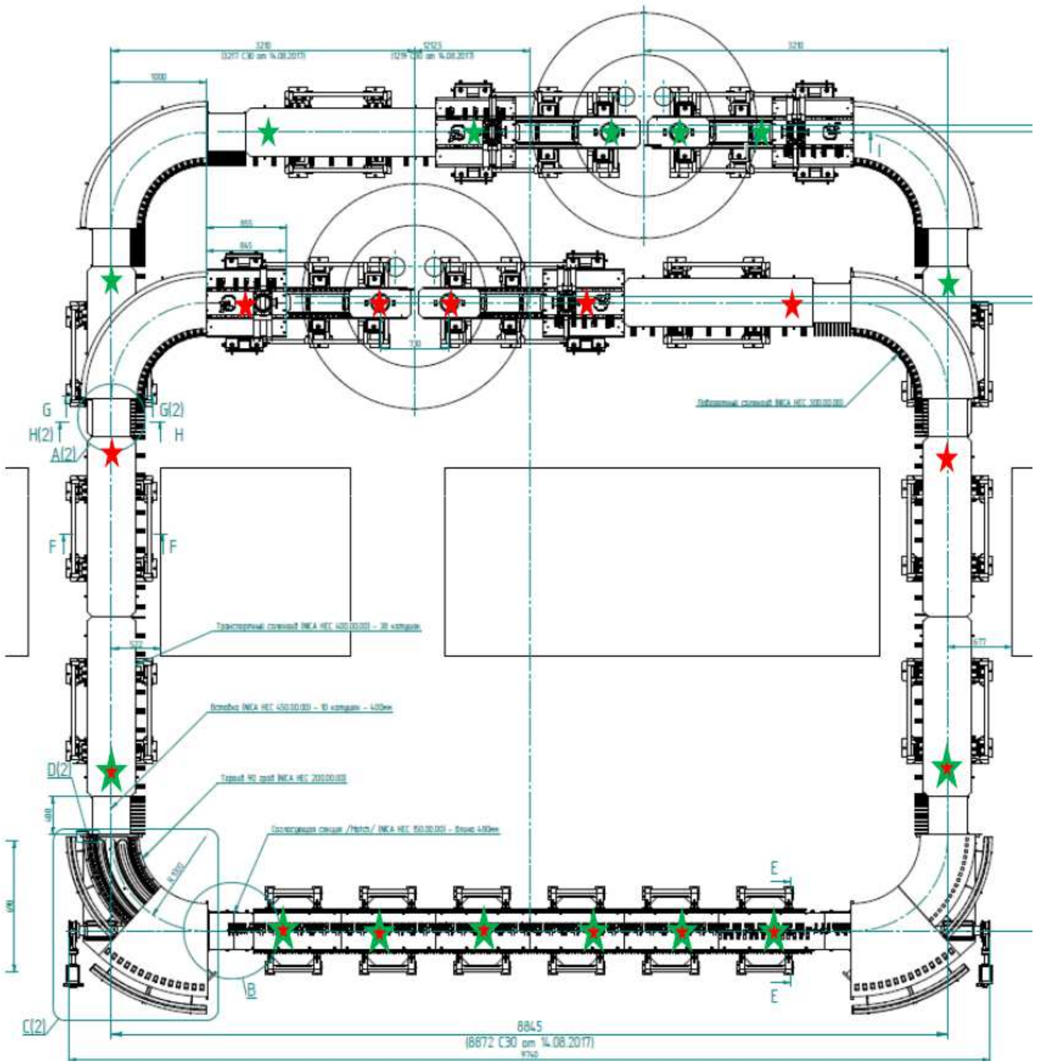


BPM electronics

Interlock system

CAN-Ethernet gateway

BPMs position



Спасибо за внимание

Thank you for your attention