“HIGH ENERGY ELECTRON COOLING"

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HB2012, 17-22 September 2012, Beijing, China

Motivation

- **Higher Luminosity at COSY with cooled beams**

Limits of the COSY stochastic cooling system
→ Luminosity $\leq 10^{31}$ cm^{-2} s^{-1}

Requests for future COSY experiments
→ Luminosity $\geq 10^{32}$ cm^{-2} s^{-1}

Combination of electron and stochastic cooling at the same high beam energy

- FZJ IKP responsible for the High Energy Storage Ring **HESR** in the FAIR project

- **Challenge: Development of the high energy electron cooler for HESR/FAIR (4.5 MeV - 8 MeV)**

Modes of Operation with PANDA

JÜLICH FORSCHUNGSZENTRUM

Experiment Mode	High Resolution Mode	High Luminosity Mode
Target	Hydrogen Pellet target with $4*10^{15}$ cm^{-2}	
rms-emittance	1 mm mrad	
Momentum range	1.5 – 8.9 GeV/c	1.5 – 15.0 GeV/c
Intensity	$1*10^{10}$	$1*10^{11}$
Luminosity	$2*10^{31}$ cm^{-2} s^{-1}	$2*10^{32}$ cm^{-2} s^{-1}
rms-momentum resolution	$5*10^{-5}$	$1*10^{-4}$

Main feature of cooler COSY

1. Classical design with longitudinal magnetic field;

-very wide range of the operation, the preferable smallest energy is 25 keV, it is injection energy;

2. The section-module principle of the design of the electrostatic accelerator ;

-each section contains the high-voltage module and coils of the magnetic field;

3. Cascade transformer for power supply of the magnetic coils;

- smooth longitudinal magnetic field along accelerated tube demands power to many coils;

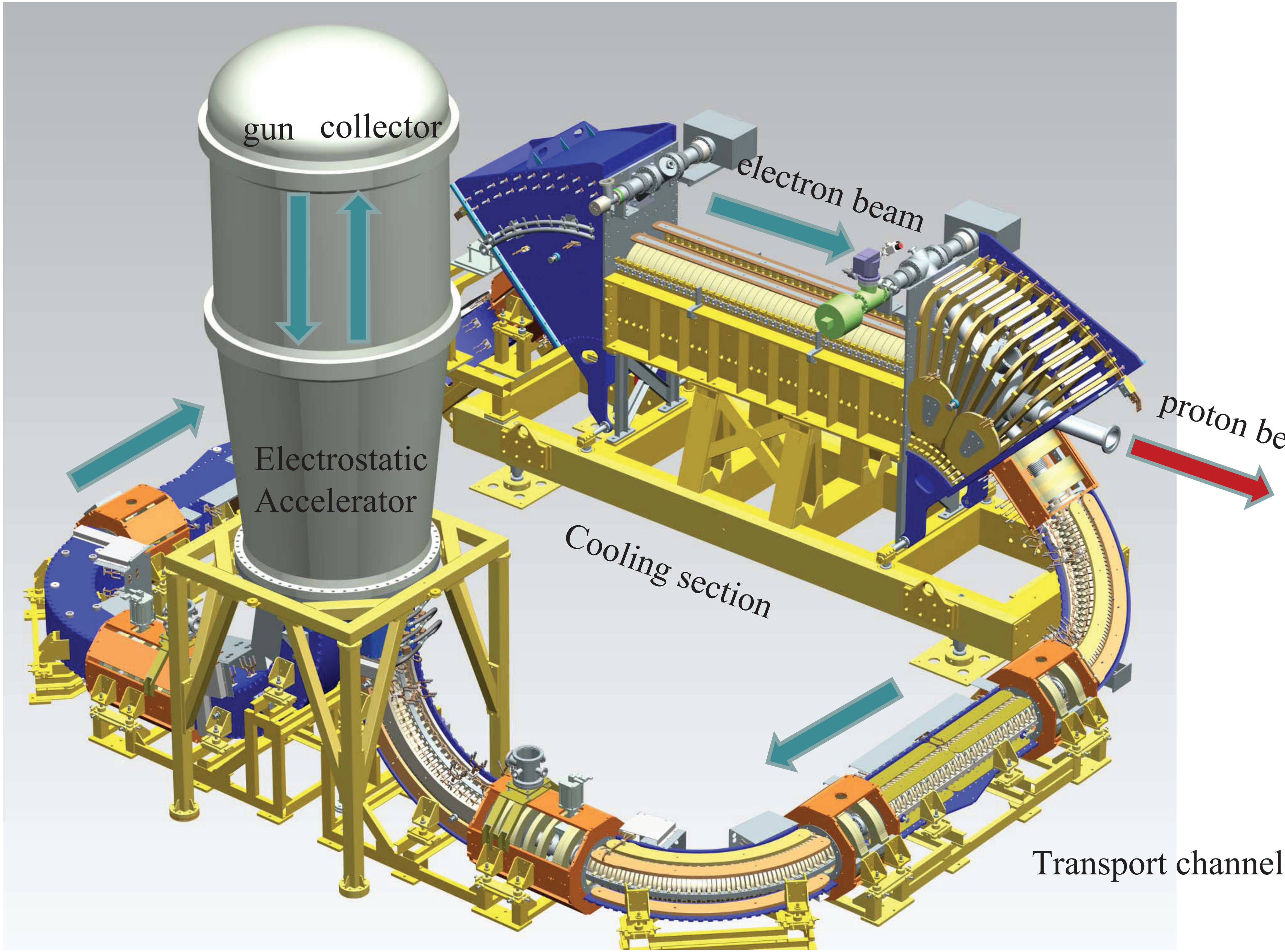
4. Possibility for on-line control of the quality of the magnetic field.

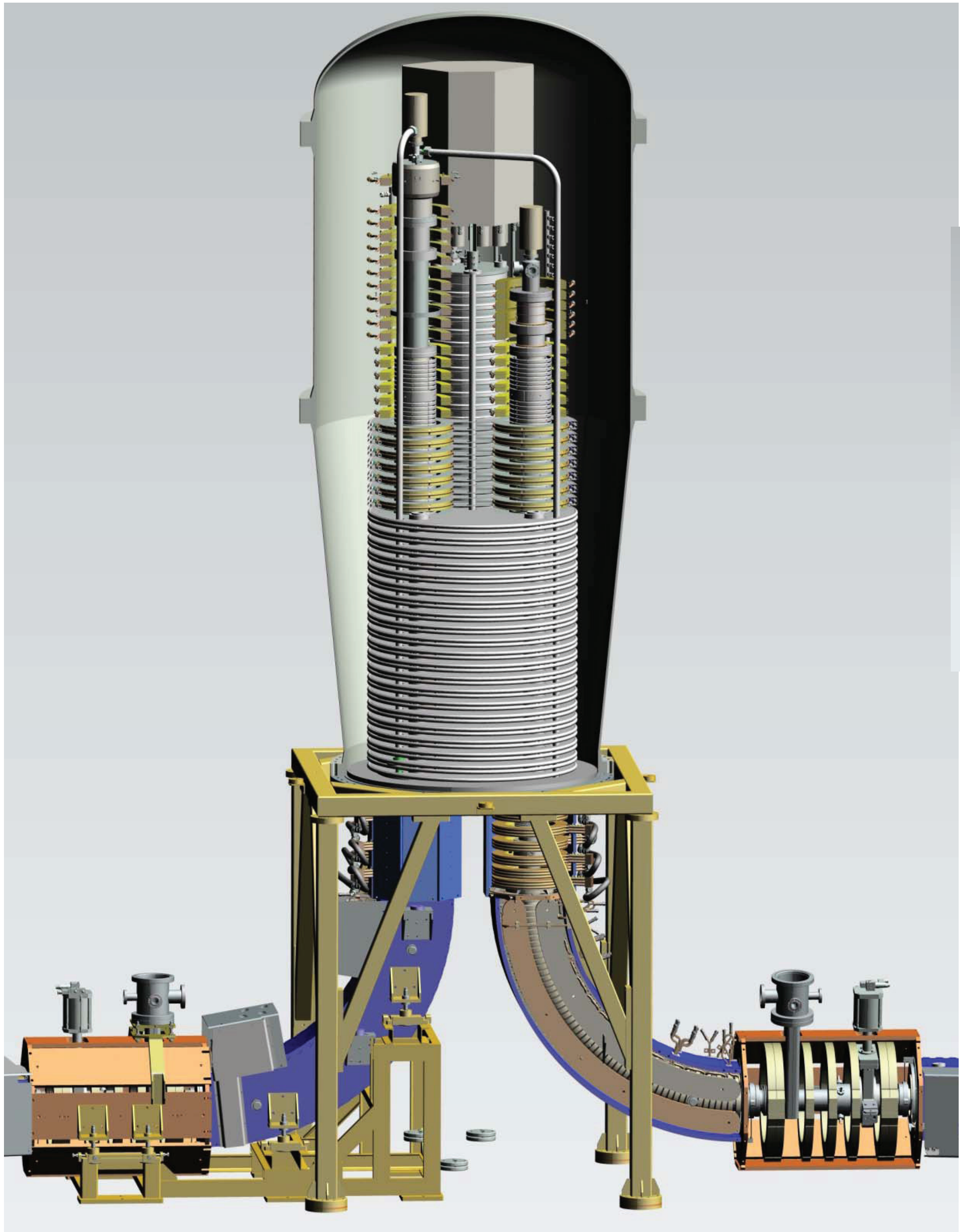
5. Electron Collector with Wien Filter

- in order to have small leakage current from the collector

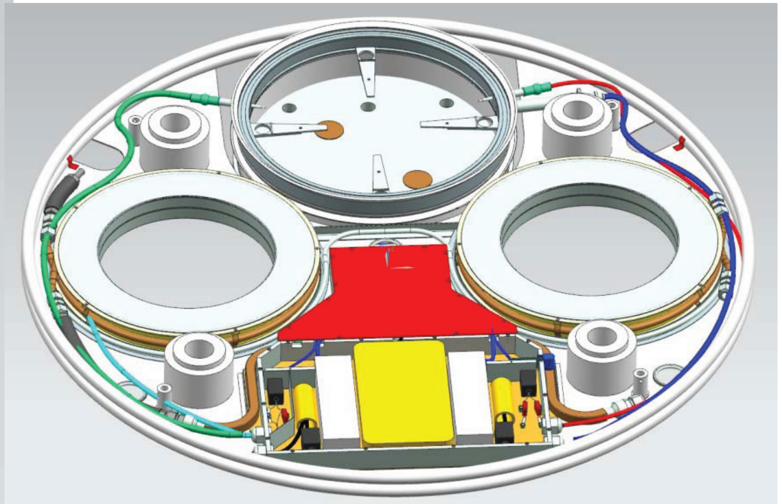
2 MeV Electron Cooler	Parameter
Energy Range	0.025 ... 2 MeV
Maximum Electron Current	1-3 A
Cathode Diameter	30 mm
Cooling section length	2.69 m
Toroid Radius	1.00 m
Magnetic field in the cooling section	0.5 ... 2 kG
Vacuum at Cooler	10^{-9} ... 10^{-10} mbar
Available Overall Length	6.39 m

3D design of COSY Cooler





3D design of Accelerating Column



Each section contains;

- high-voltage power supply +/- 30 kV;

- power supply of the coils of the magnetic field (2.5 A, 500 G);

- section of the cascade transformer for powering of all electronic components;

33 high-voltage section

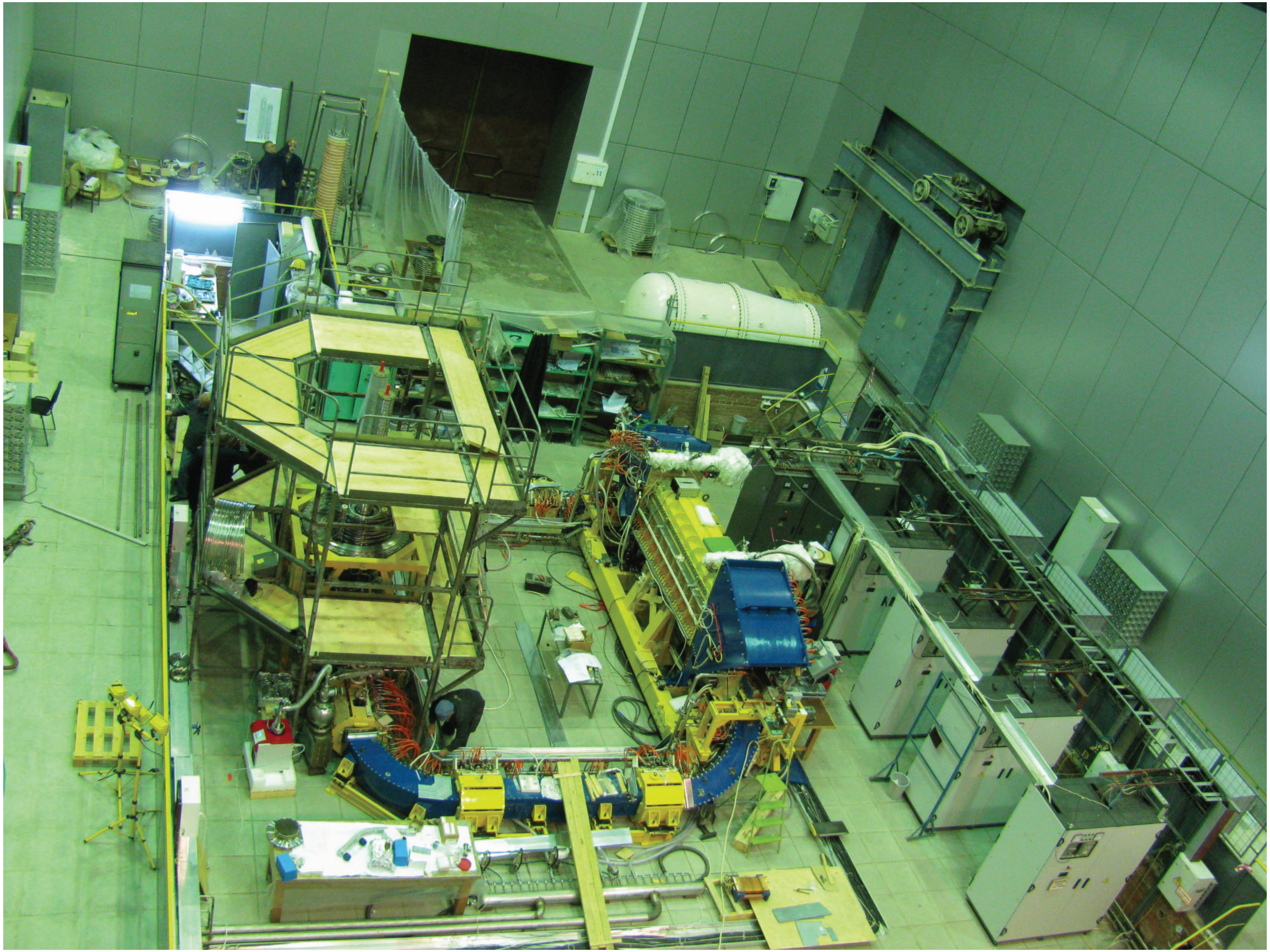


Photo of COSY Cooler during commissioning

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 the ion momentum from equilibrium value. So, this effect may is keyword parameter for the experiment with intrinsic target.

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

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

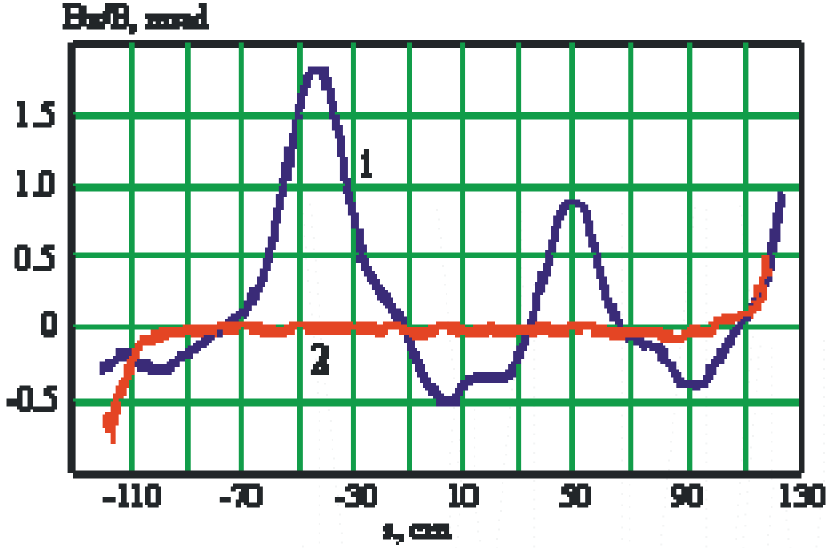
$$V_{\Delta\Theta} = \gamma\beta c\sqrt{\left\langle \Delta B^2\right\rangle} \quad \left\langle \Delta B^2\right\rangle -$$ *ripple of the magnetic field*

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

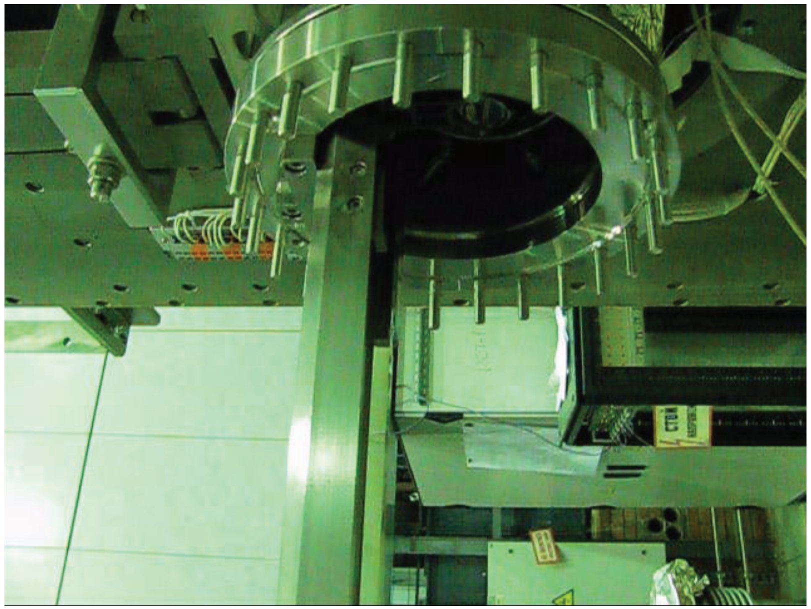
Cooling section – standard BINP decision with pan-cake coils

Possibility for on-line control of the quality of the magnetic field

According Parkhomchuk's equation the cooling force strongly depends from the quality of the magnetic field in the cooling section

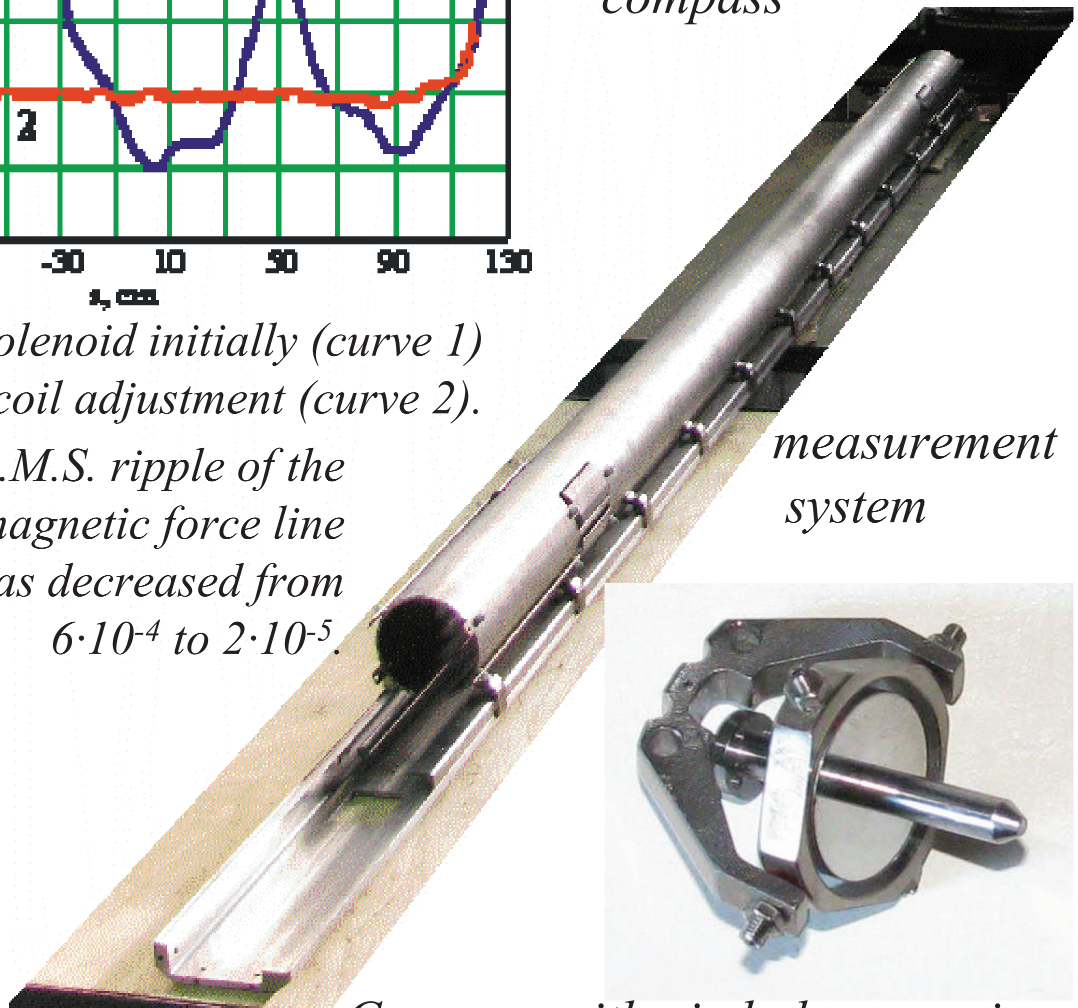


Horizontal magnetic field in the cooling solenoid initially (curve 1) and after few iteration of coil adjustment (curve 2).



R.M.S. ripple of the magnetic force line was decreased from $6\cdot10^{-4}$ to $2\cdot10^{-5}$.

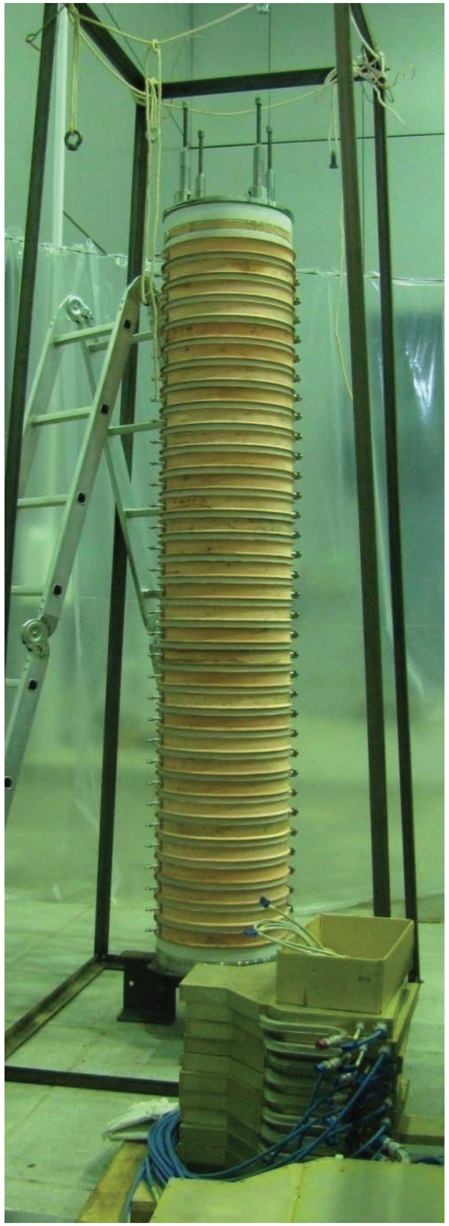
Guide rail of compass



measurement system

Compass with gimbal suspension

Power for Acceleration Column



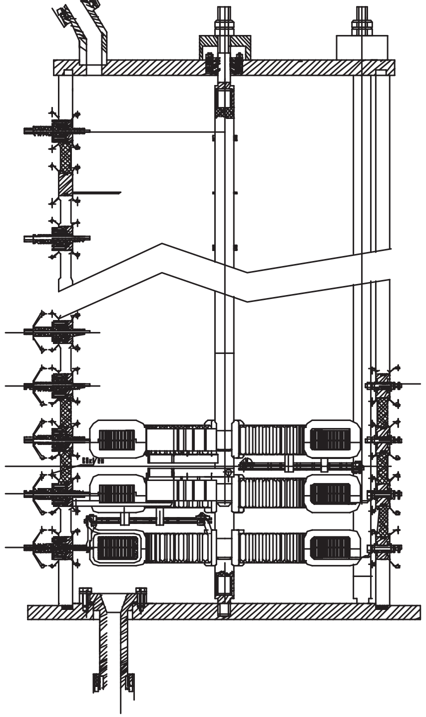
-transformers connected to series;

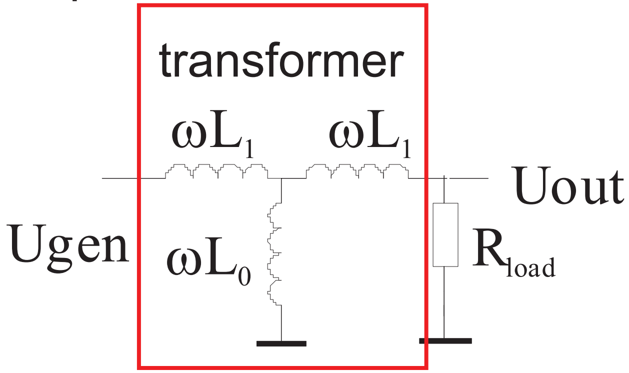
-tube is alternation of the ceramic and metal rings (sections);

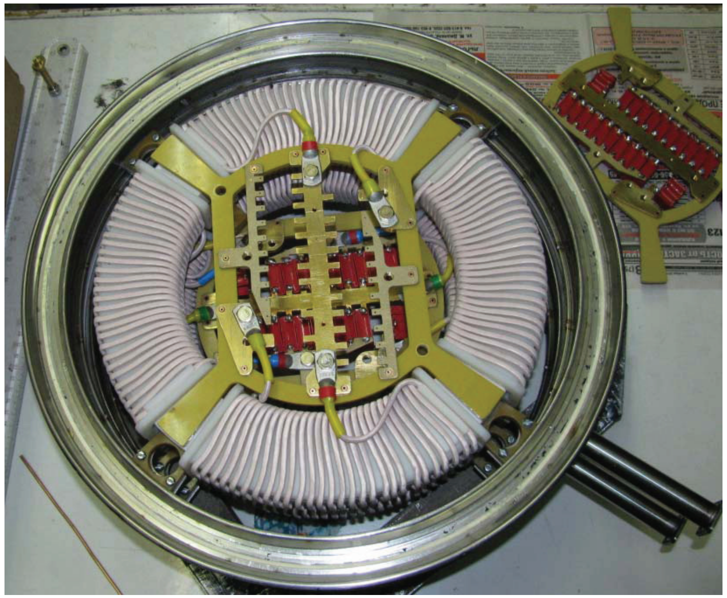
- tube is filled by oil;

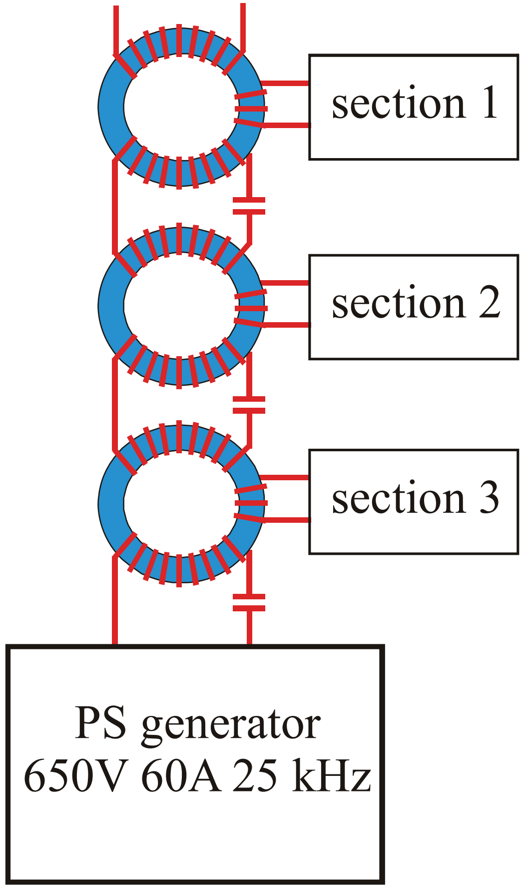
- section has special spark-gaps;

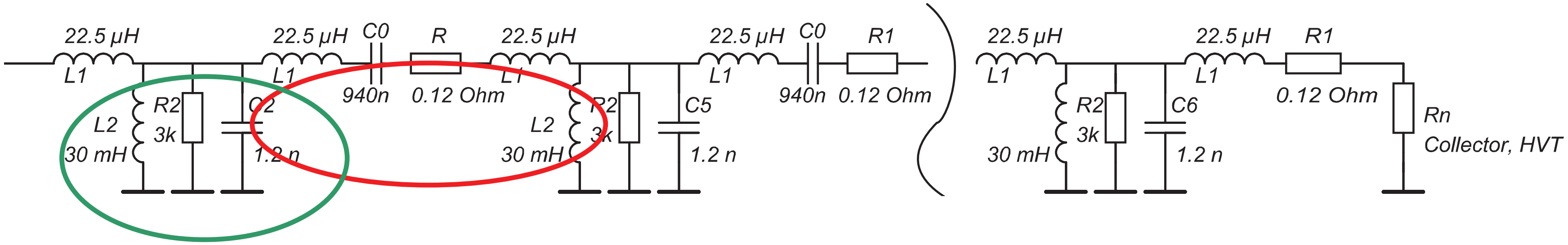
"Accelerating tube is composed with transformers"









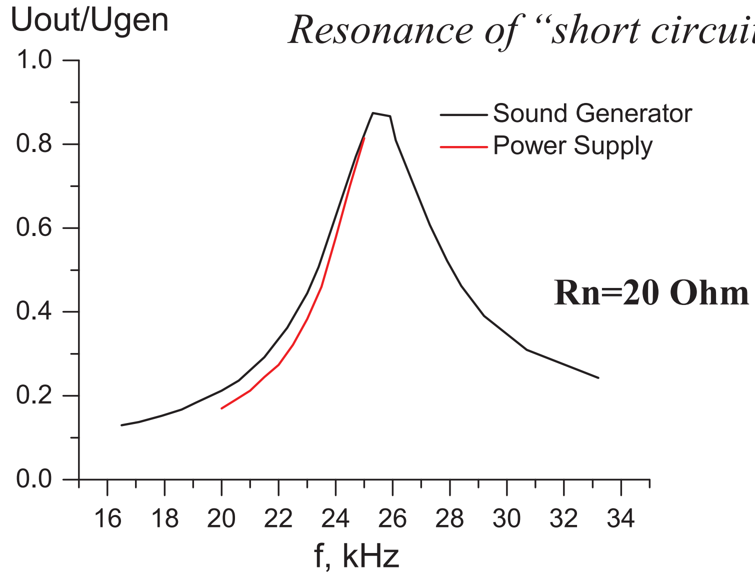


principle of operation of cascade transformer is combination of series and parallel resonances induced by the leakage inductance and compensative capacitances

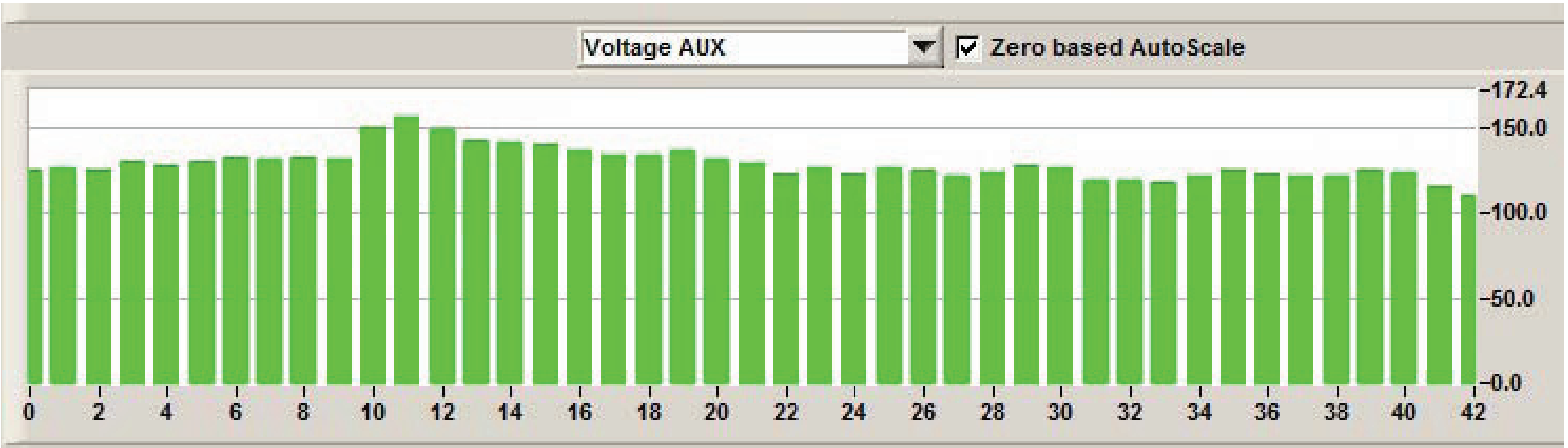
- transfer constant on load resistor 20 Ohm is 0.9, the r.m.s. voltage 700 V corresponds to 25 kW of power

Series resonance curve

Resonance of "short circuit"



Distribution Power Along Accelerated Column



Wien Filter –
try to catch electrons that run away from collector

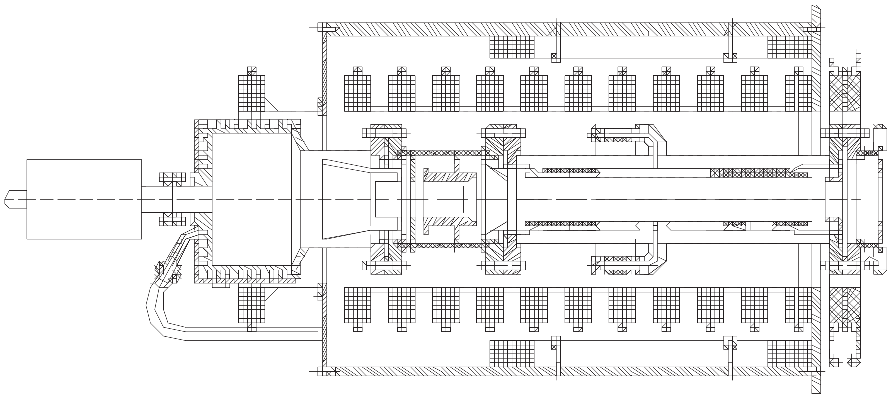
Area with crossed electrical and magnetic fields compensated each other

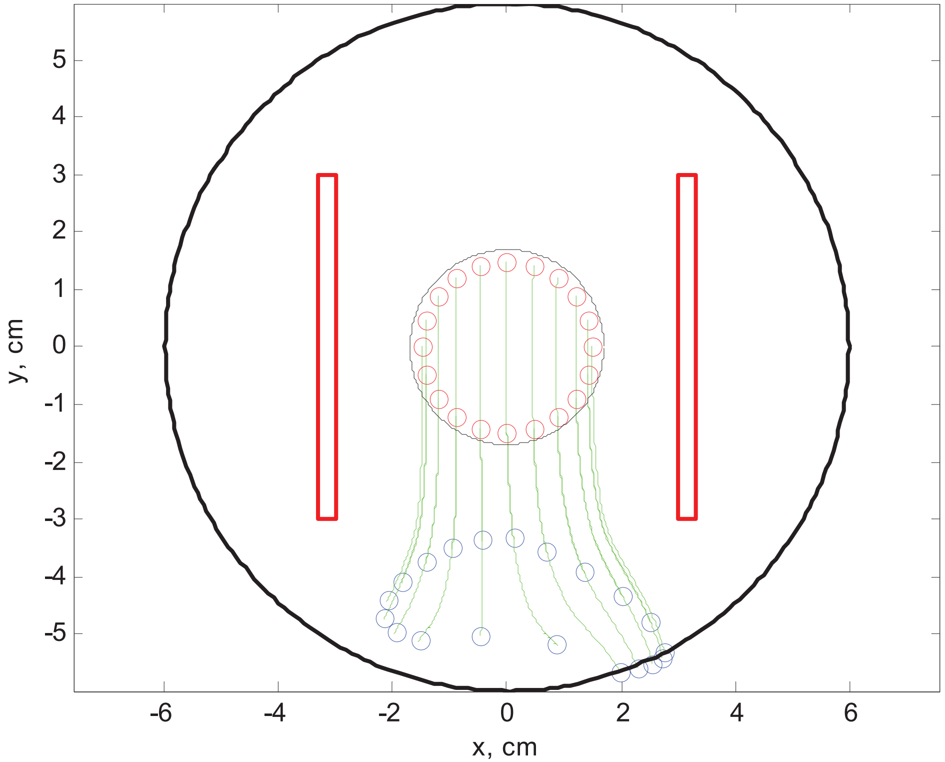
$$\vec{F}_{\perp} = e\vec{E} - \frac{e}{c}\left[\vec{v}\times\vec{B}\right] = 0$$

primary beam

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

secondary beam





Motion of primary beam is red circle and motion of reflected beam is blue circle

The experimental recuperation coefficient is 10^{-5} - 10^{-6}

Operational aspects, section structure, accelerating column

Electrostatic accelerator

High voltage terminal

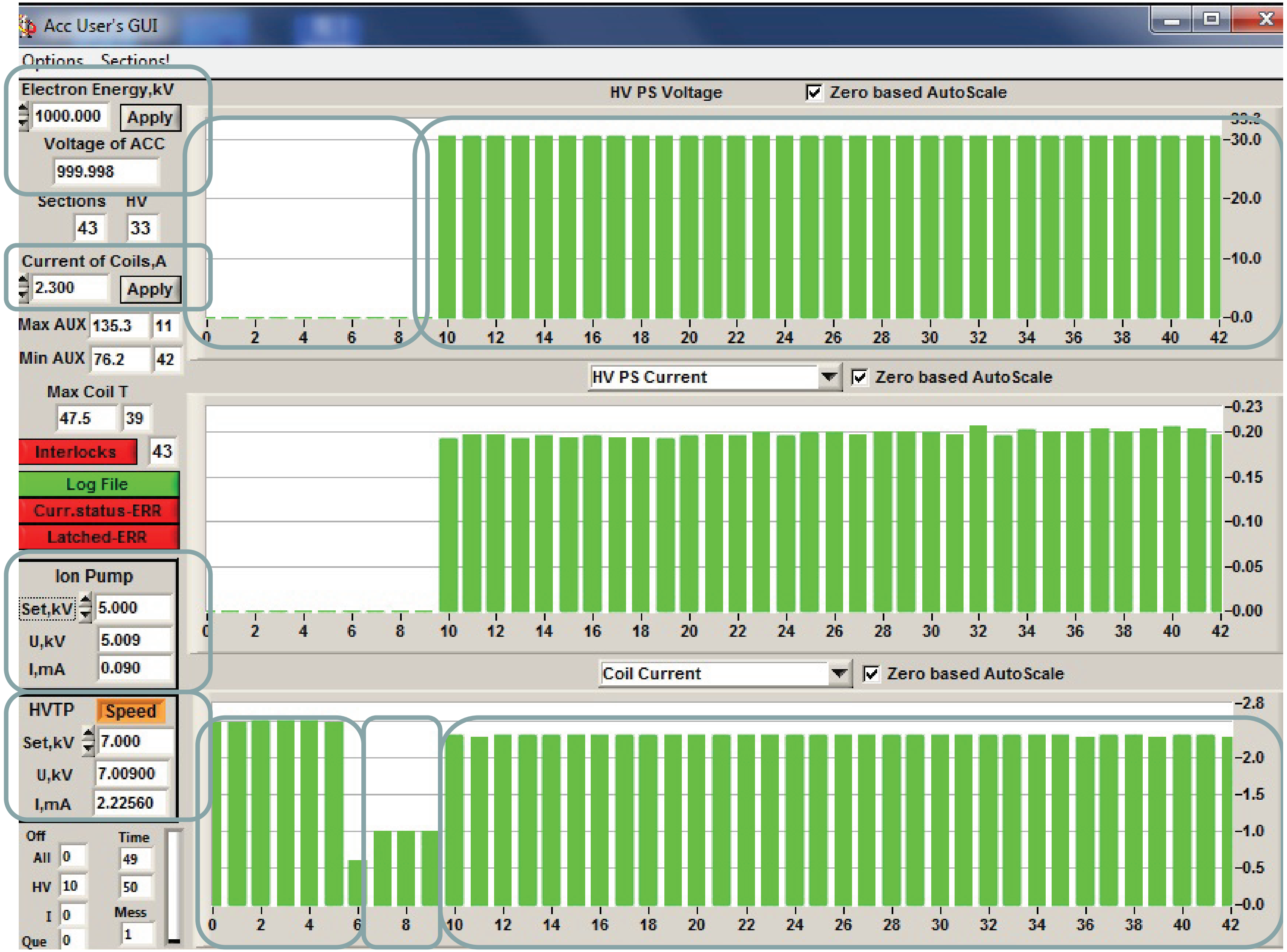
Distribution of high voltage along accelerator column

Installed and measured energy is 1 MeV

Current in the coils of accelerator column

Ion pump in high-voltage terminal

Potential of the high-voltage terminal with reference to accelerator tube

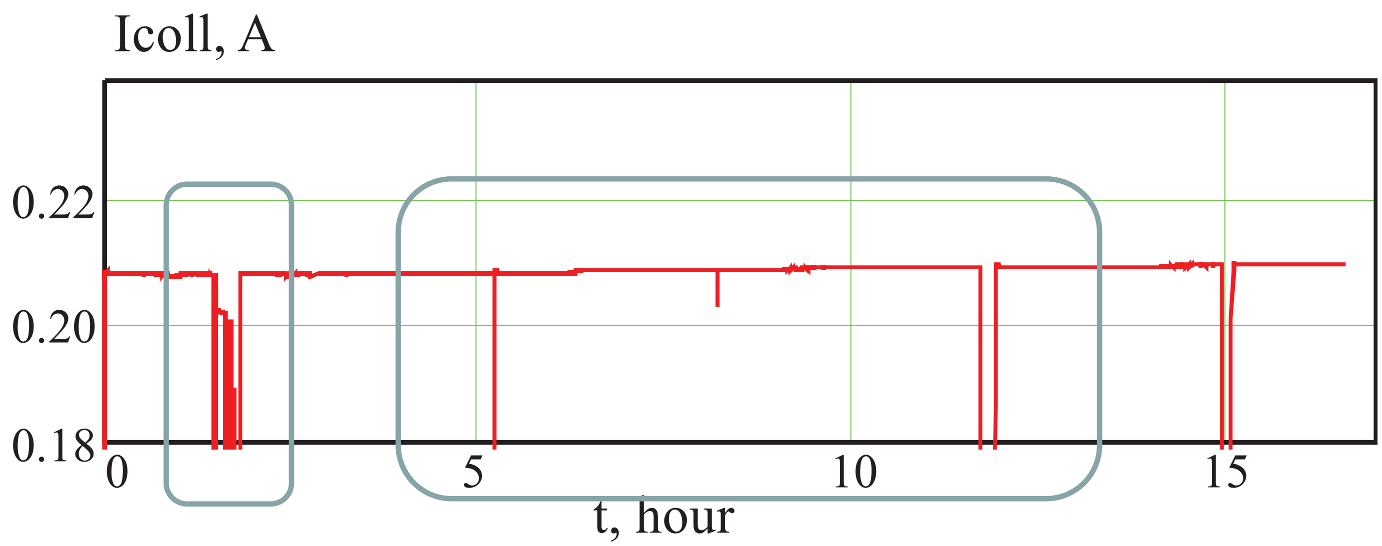


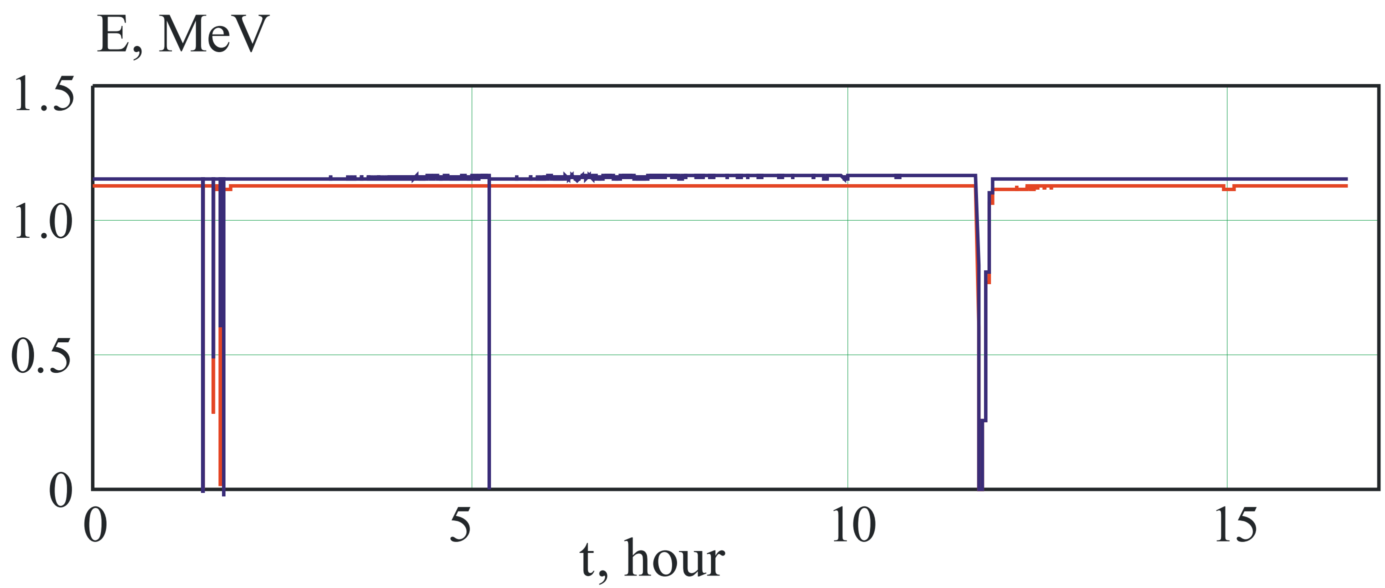
Collector

Gun

Distribution of the magnetic field in the accelerator column

Operational aspects. Example of the long training regime, the electron current was about 200 mA. The electron energy was about 1 MeV. The total time of the training procedure is 6 day and night.

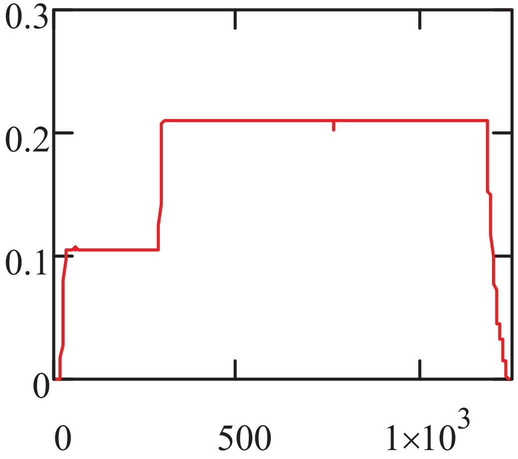




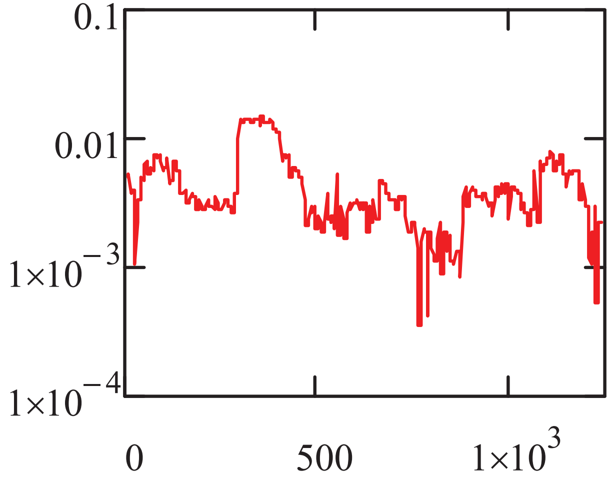
Sometimes the recuperation breakdown occurs often and sometimes rarely. The nature of the breakdown is not made clear yet. It seems that this behavior can be improved by a training procedure. The possible reason of the breakdown are small dust particle, charge of the accelerator tube isolator …or ???

Operational aspects. Example of the short training regime, the electron current was about 200 mA. The electron energy 1 MeV

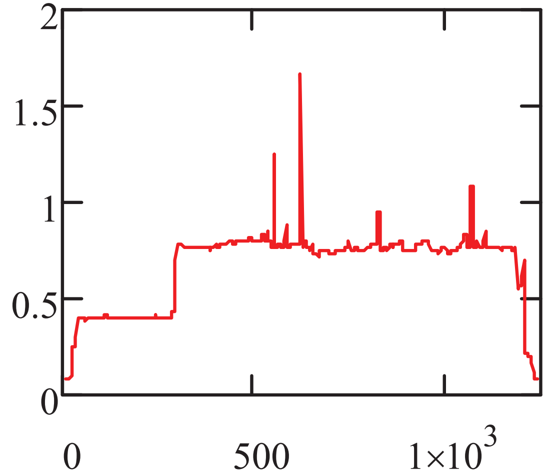
Je, A



Jleak, mA

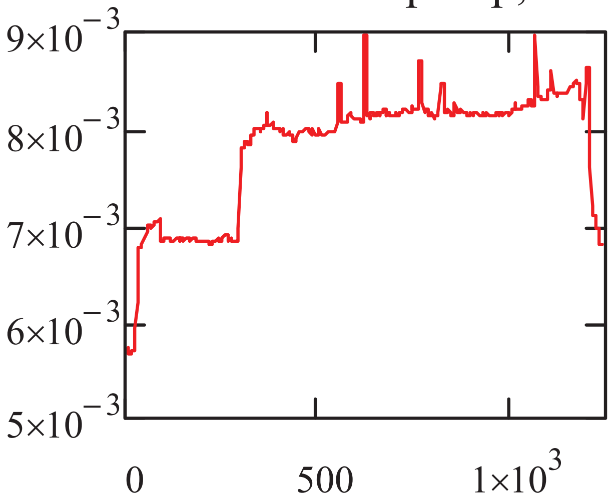


J_{HVTP}, mA



t, sec

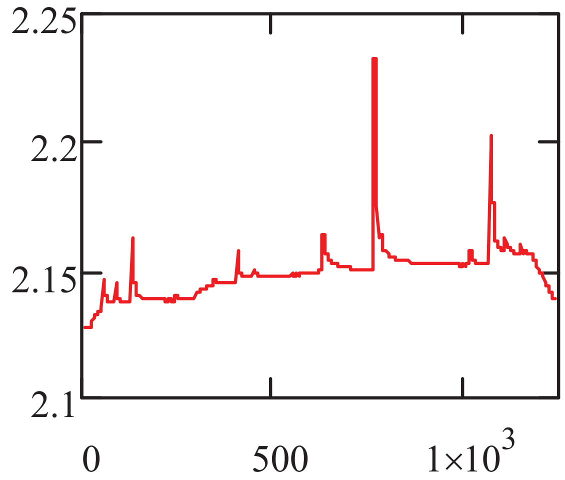
Collector ion pump, mA



t, sec

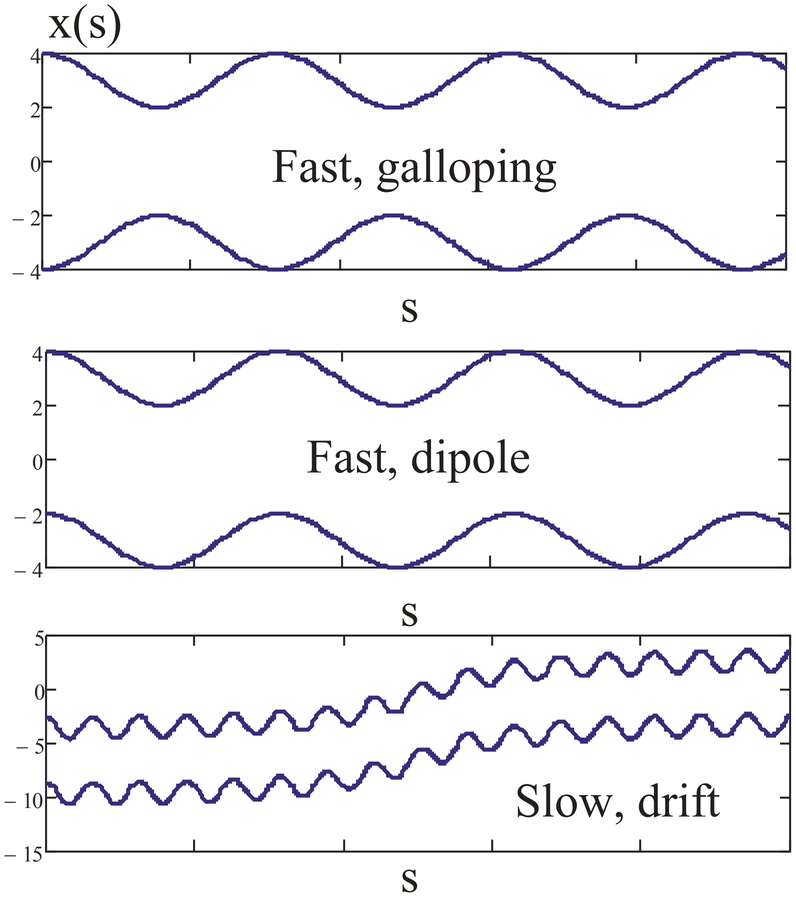
The regime with 200 mA current is stable enough. In time of the operation the vacuum fluctuation is observed. The typical vacuum value is a few 10^{-8} mbar. The evolution of the leakage current and peak of the HVTP current is observed also.

Gun vacuum, 10^{-8} mbar

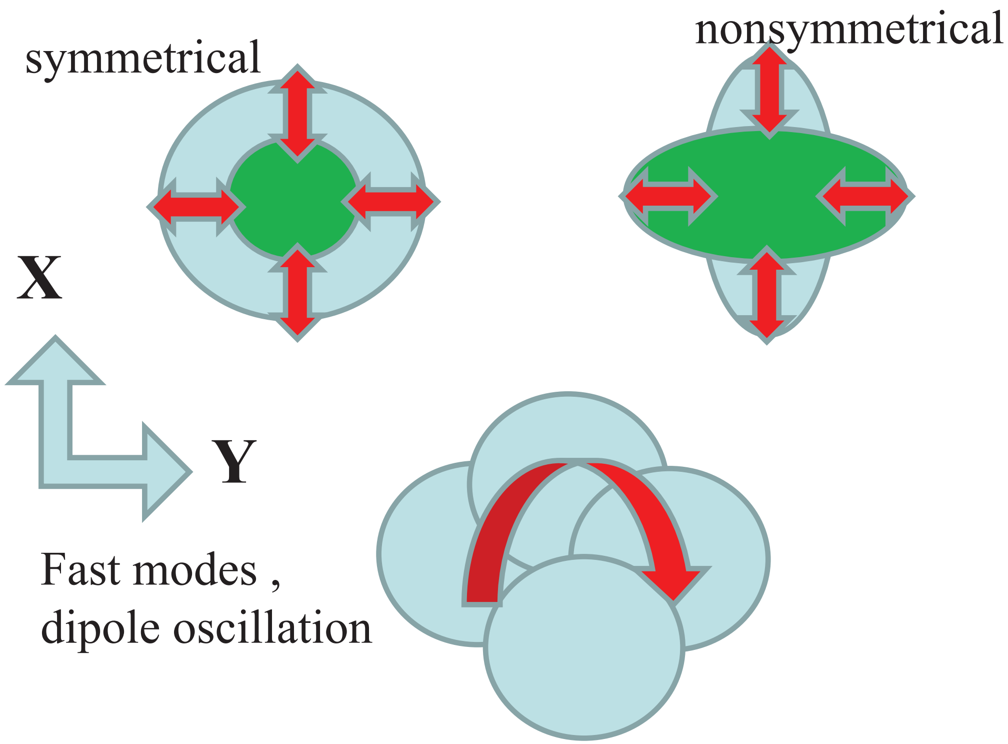


t, sec

The particle motion at a presence of a large magnetic field can be described as combination of the fast larmour oscillation and slow drift motion. In spite of the fact that, the adiabatic criteria isn't satisfied the drift description of particle motion is correct. The reason is smallness of the transverse component of the magnetic field in comparison with the longitudinal component.



Fast modes, galloping of the shape of the electron beam



Modification of the beam shape and position

Canonical coordinates can be chosen as (X,Y) and (X',Y') instead of the usual (X,X') and (Y,Y') . At such choice the dynamic of each pair is slightly coupled.

Diagnostics of the shape of the electron beam

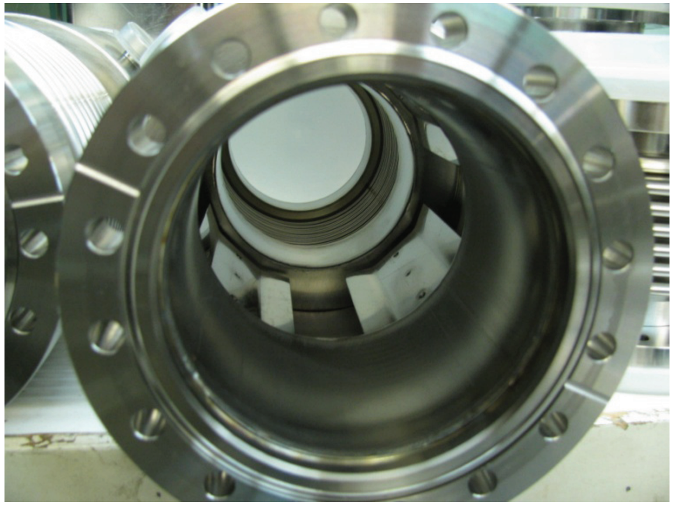
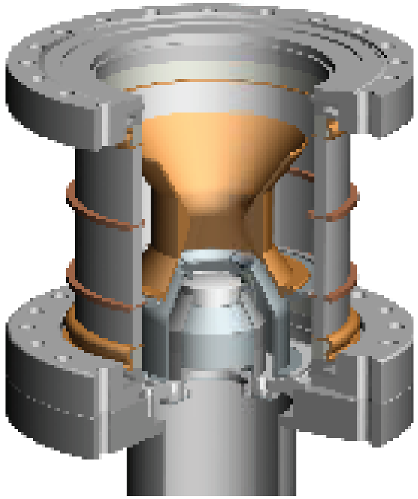
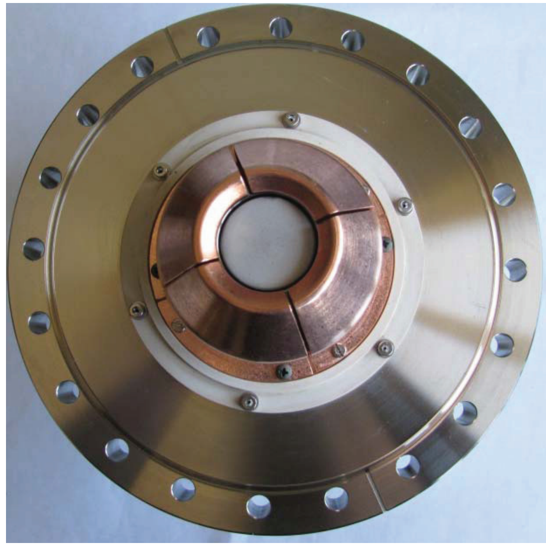
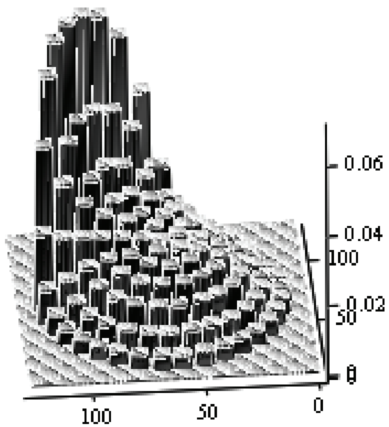


Photo Pick-Up System





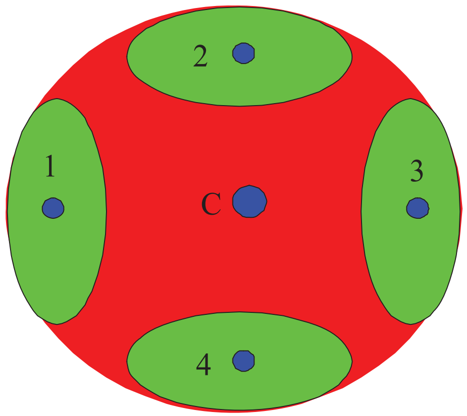
4 sector electron gun



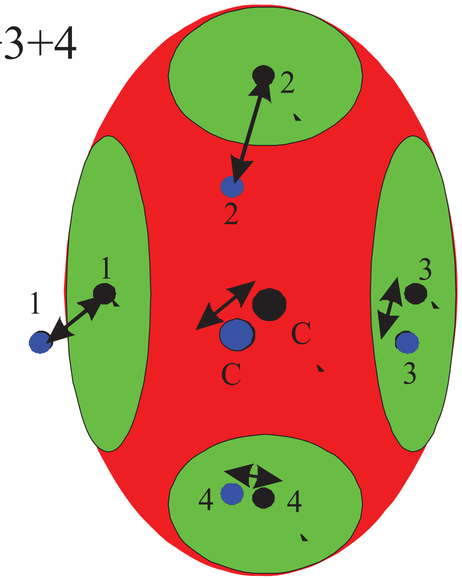
Voltage is applied to one sector

Center=1+2+3+4

Pick-Up 1



Pick-Up 2



The combination of the constant and modulation voltage is applied to the electrodes

Lengthy coils in longitudinal direction the control the position of the center of Larmour rotation; Short coils control the amplitude of the Larmour oscillations

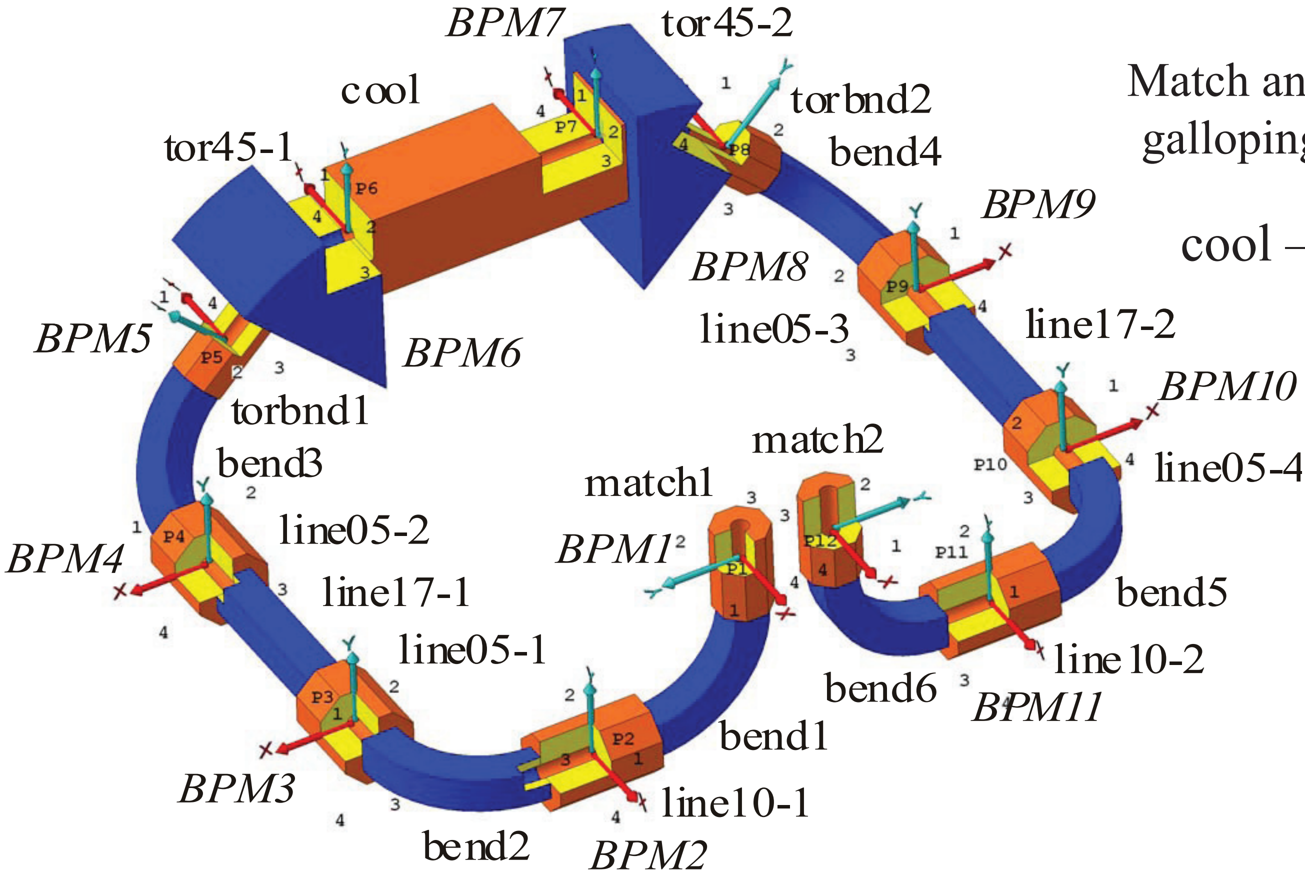
Optic features of COSY cooler

line17hor, line17ver, all bends– correctors of the beam shift

line10– correctors of the beam kick

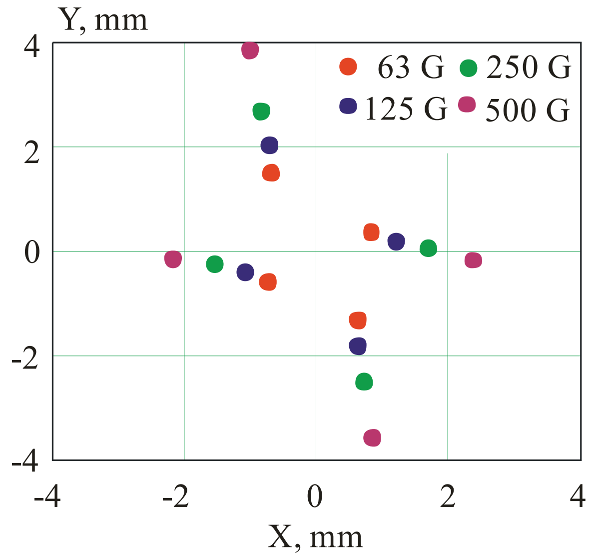
Match and torbnd– correctors of the galloping of beam shape correction

cool – convergence of ion and electron beams



Location of BPMs and magnetic elements of COSY coolers

The simple verification of the diagnostic tools at electron energy 30 keV

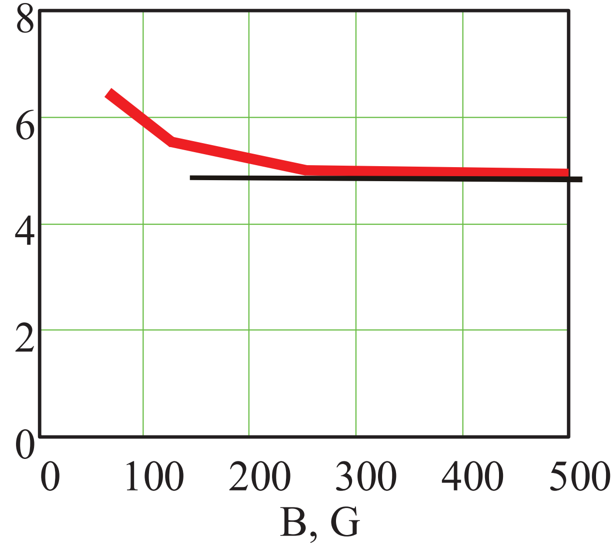


At small value of the magnetic field the size of the electron beam is determined not only by the magnetic field but the anode value also

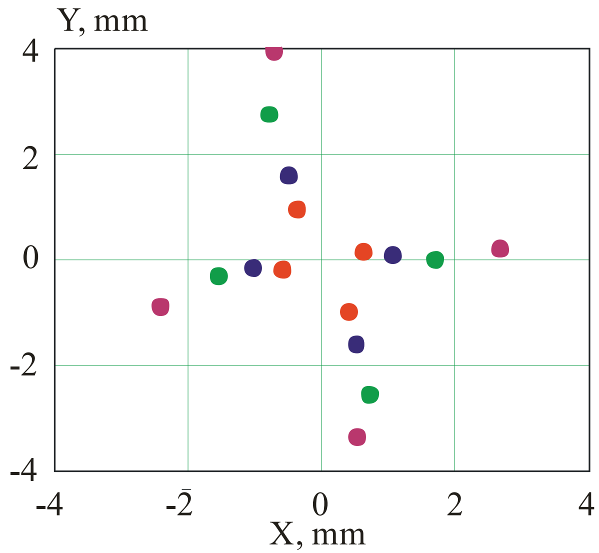
$$r_{BPM}^2 / B_{gun} = const$$

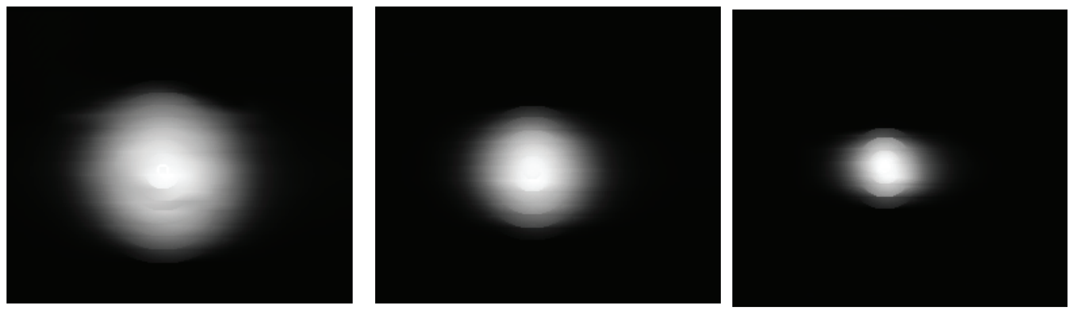
Conservation of the magnetic flux

$$B_{gun} r_{gun}^2 = B_{BPM} r_{BPM}^2$$



Change shape of the electron beam by the potential of the control electrode



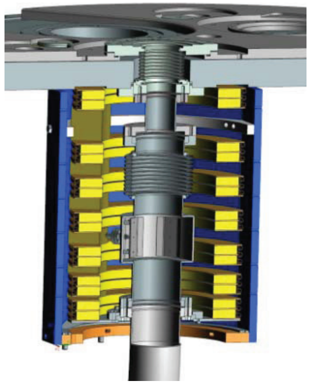


Ugr/Uan= –0.2/1.4 kV -0.4/1.4 kV –0.6/1.4 kV

Pictures was done with wire probe

Action of magnetic elements

Diagnostics of optic elements

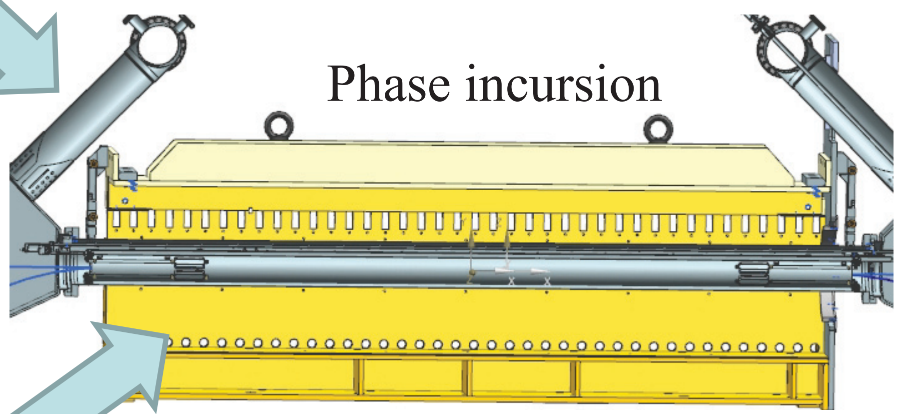


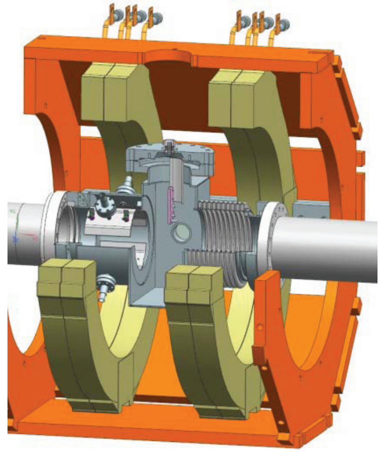
Registration Beam Motion

Line05, BPM

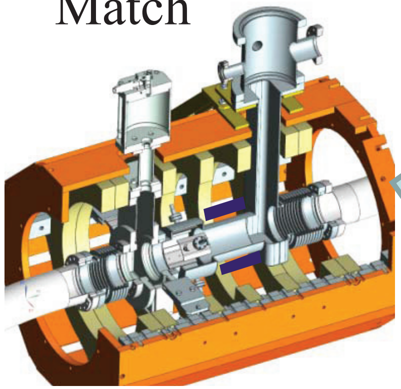
Cool

Phase incursion





Match

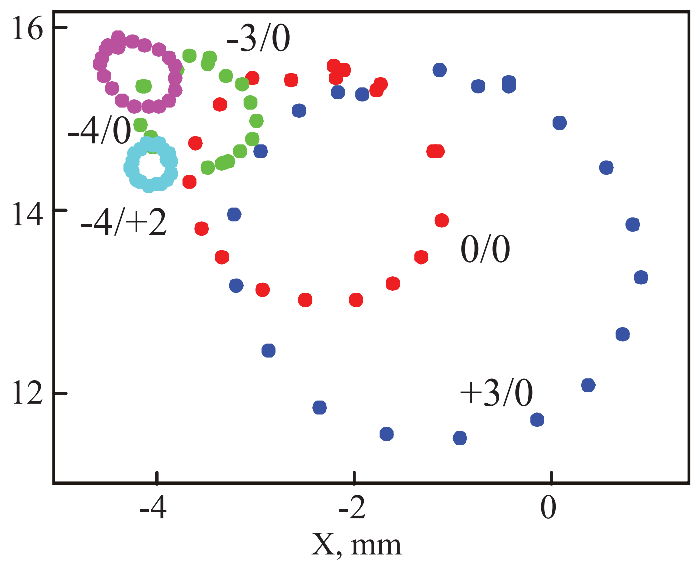


Short Electron Dipole Corrector

XXX, any element

Compensation of Dipole Motion

1 MeV

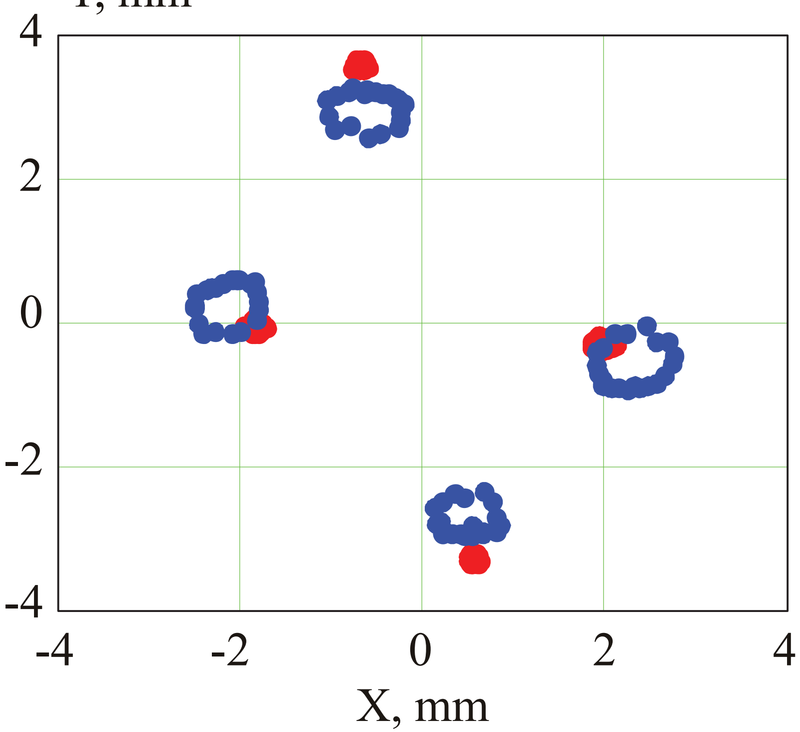


Effect of the short dipole corrector is combination of the shift of the center of electron beam with excitation of Larmour rotation

Optic features of COSY cooler

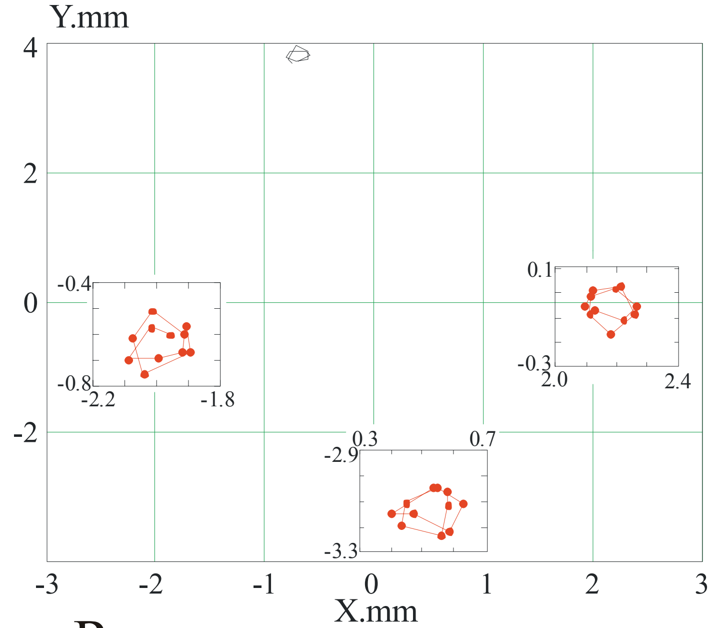
Oscillation of the beam shape (galloping)

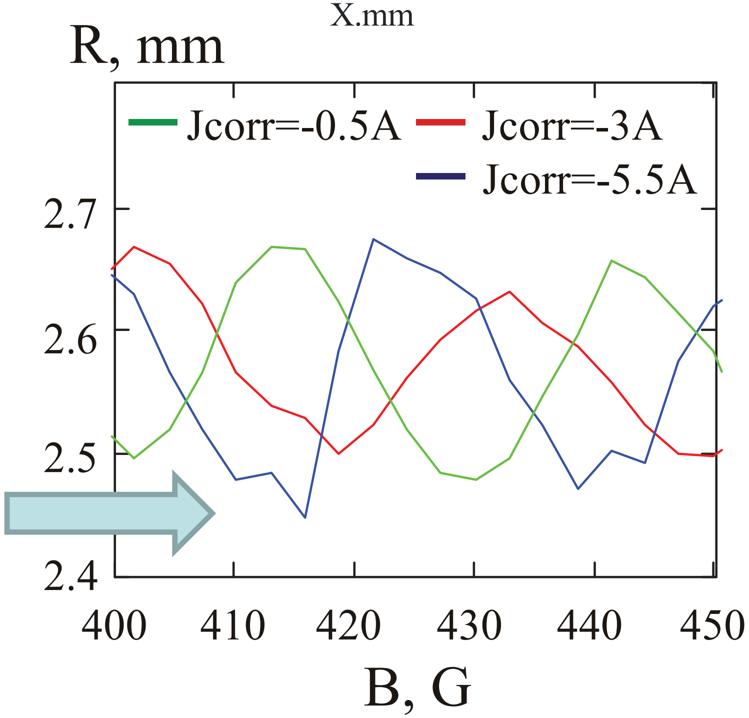
Kick is produced by quadrupole corrector



Electron energy E=150 keV

Kick is produced by axial-symmetric corrector located in the matching section

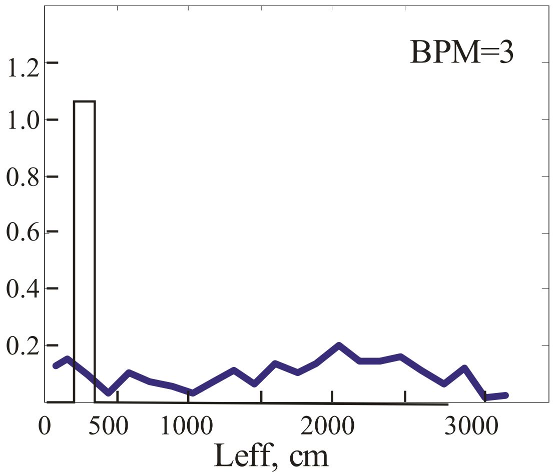


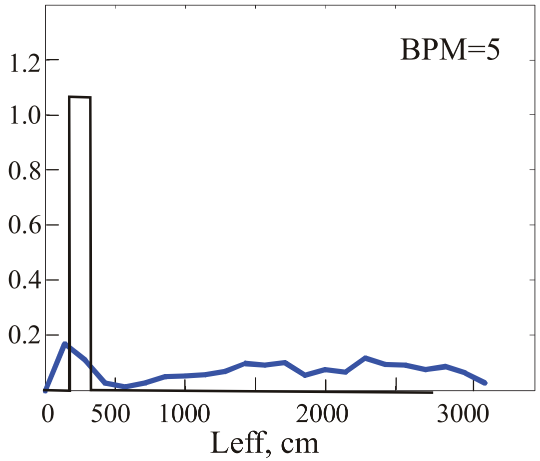


Fourier transform can strongly improve the sensitivity of the methods

Optic features of COSY cooler

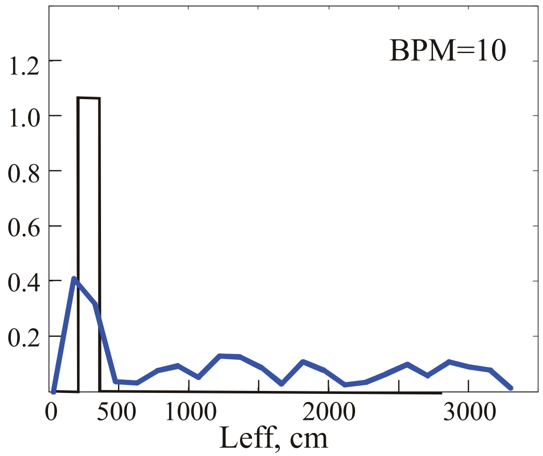
Registration of the oscillation of beam shape (galloping). Rectangular peak corresponds to the radial oscillation with amplitude 0.1mm .
BPM-3 and 5 before phase rotation elements, BPM-10 and 11 after

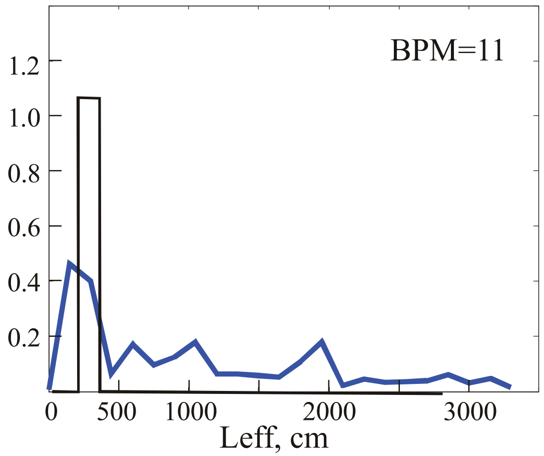




Energy = 500 keV
Jcoll ≈ 500 mkA (DC)
Jmod ≈ 5mkA (AC)

Fourier transform from the radius beam as function of the magnetic field in the cooling section. The longitudinal magnetic field is recalculated to the length of Larmour spiral.

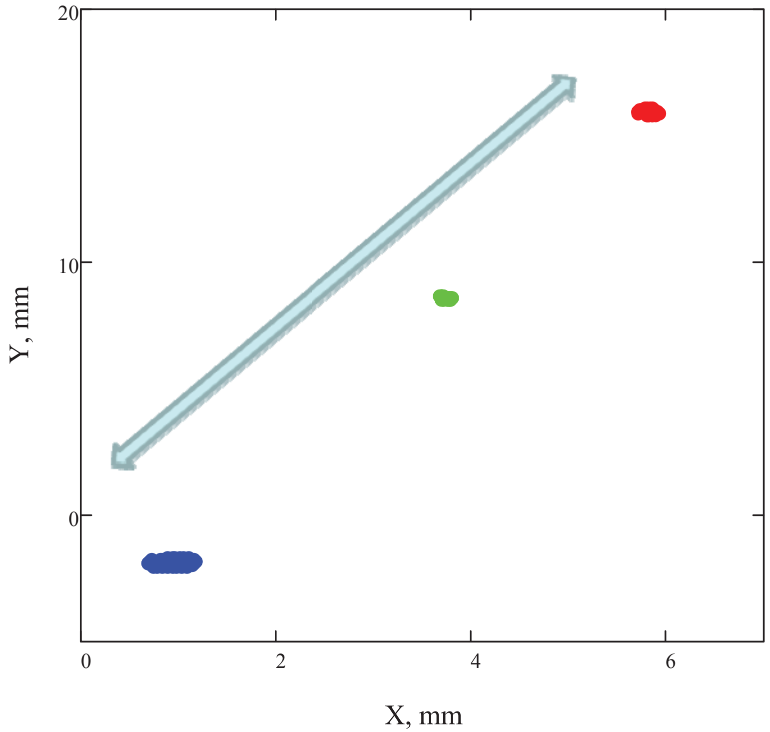




Optic features of COSY cooler

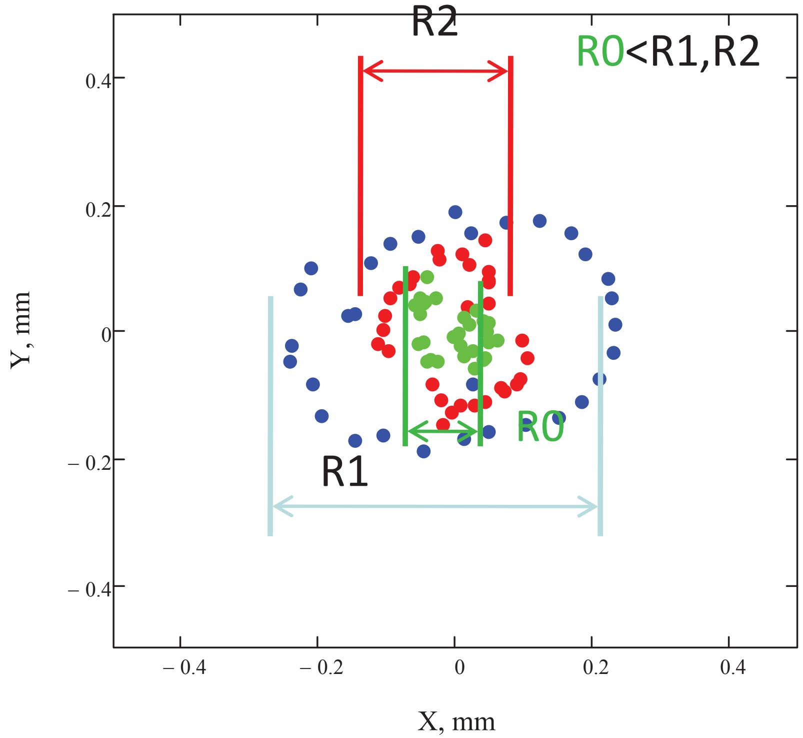
Dispersion functions of the electron beam motion

First dispersion is the shift of the center of the electron beam



The different values of the bending magnet fields; red curve is 14.2 G , blue curve is 15.5 G and green curve 14.7 G.

Second dispersion is the change radius of the larmour oscillation. The reason is the resonance or non-resonance between kicks of the electron at input and output of the bend magnets. This effect is observed at 150 keV energy yet.

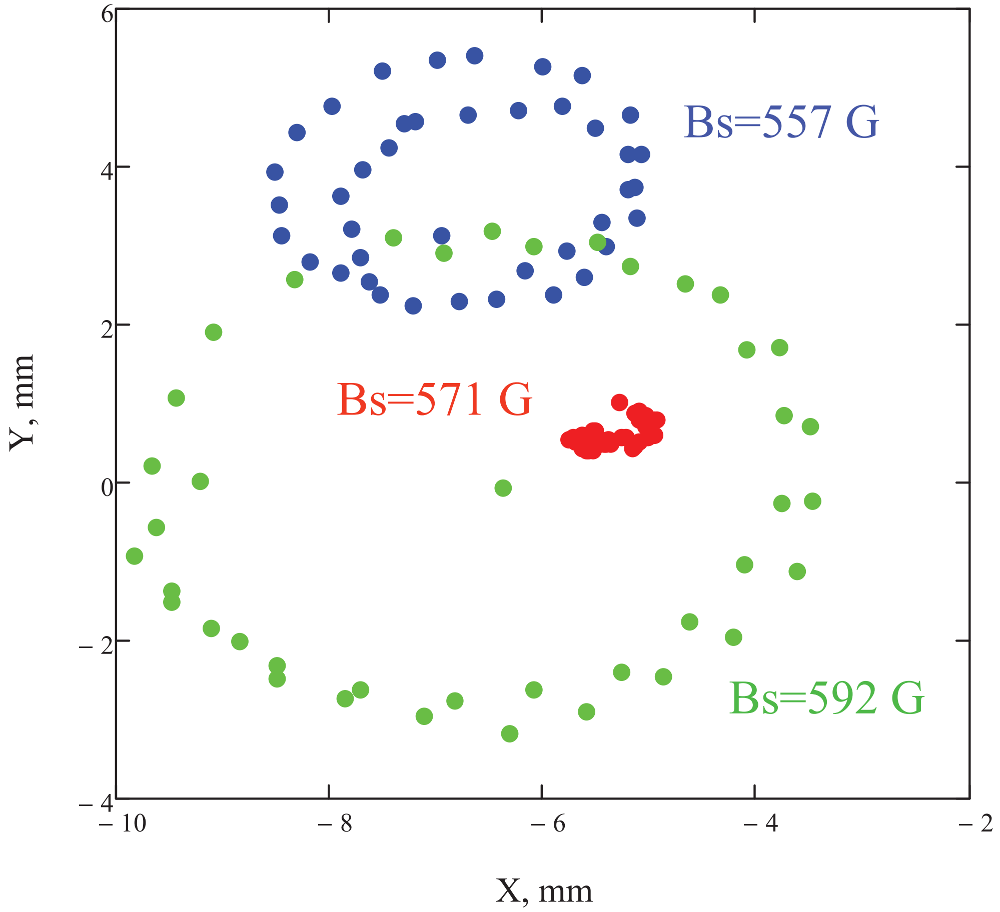


BPM=10, the curves is measured with scanning magnetic field in the cooling section

Optic features of COSY cooler

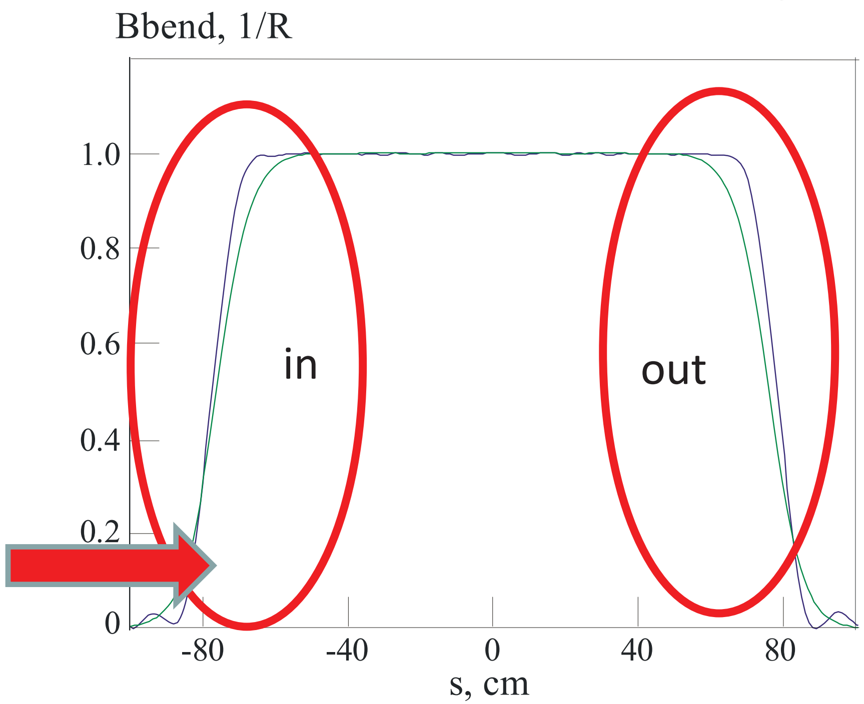
The effect of the resonance transition of the bend magnets is more essential at 0.5 MeV energy.

The bend field is fixed the longitudinal field is changing



BPM is 10 after cooling section
The scanning of the magnetic field in the cooling section from 680 G to 792 G. The curves are measured at the different values of the longitudinal magnetic field in the bend magnets.

Curve of the bend field and curvature of the magnetic force line along bend magnets



The curvature of the magnetic force line is different from the bend field so the transverse field is excited in "in" and "out" points. The minimal value is obtained when the "in" compensates "out".

Summary

- The key problems of the electron cooler 2 MeV (modular approach of the accelerator column, the cascade transformer, the compass base probe located in the vacuum chamber, the design of the electron gun with 4-sectors control electrode) is experimentally verified during commissioning in Novosibirsk.
- The strong surprises aren’t observed and the cooler are ready to assembly and commissioning in COSY.
- The strong longitudinal field is useful for the electron beam transportation.