High voltage cooler

M. Bryzgunov, A. Bubley, A. Goncharov, V. Panasyuk, V. Parkhomchuk, V. Reva D. Skorobogatov
(BINP SB RAS, Novosibirsk) Russia
J. Dietrich, TU Dortmund and Helmholtz Institute Mainz, Germany,
V. Kamerdzhiev (FZJ, Jülich) Germany

RUPAC-12
24-28 September
TUXCH01
Saint-Petersburge

What is beam cooling?

- Cooling is reduction of the phase space occupied by the beam (without the reduction of beam intensity).
- Equivalently, cooling is reduction of the random motion of beam particles.
  - Cooling process violates Liouville's theorem

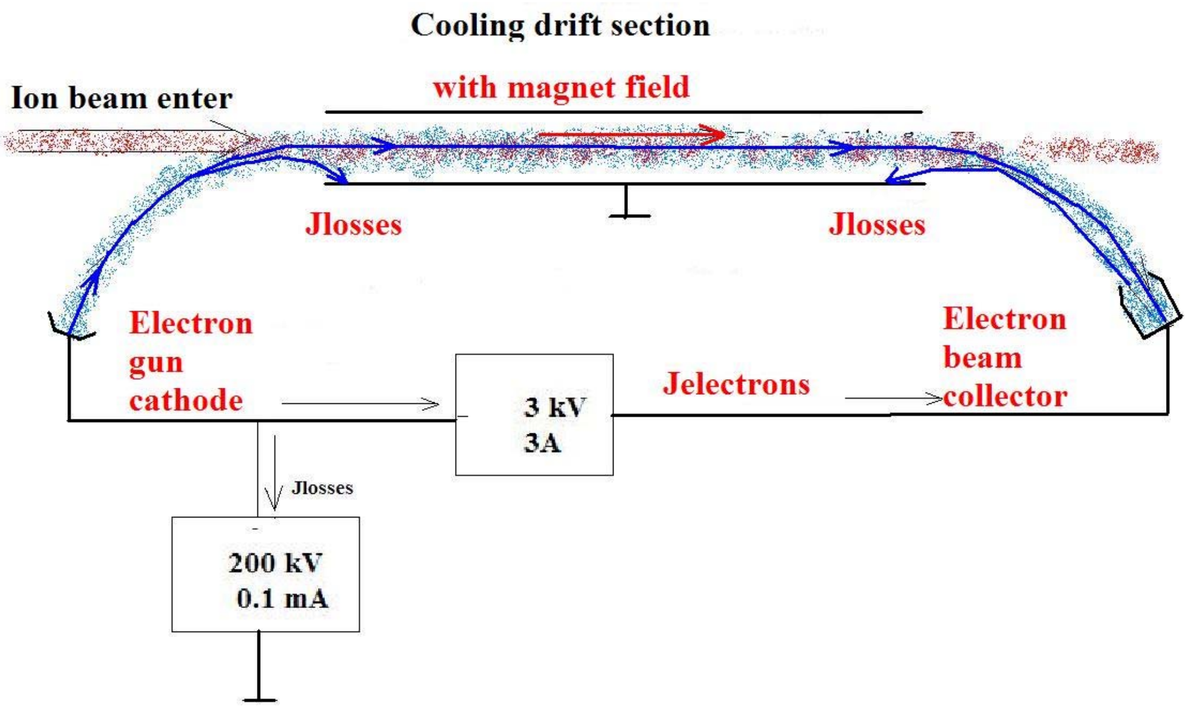
Need for cooling

- Injection help: stacking, accumulation, phase-space manipulation etc.
- Rare isotope and antiparticle production: accumulation of many pulses of antiparticles
- Internal fixed target: emittance growth from target scattering
- Colliding beams: beam-beam effects, residual gas scattering, intra-beam scattering, rf noise
- Precise Energy Resolution: narrow states, threshold production

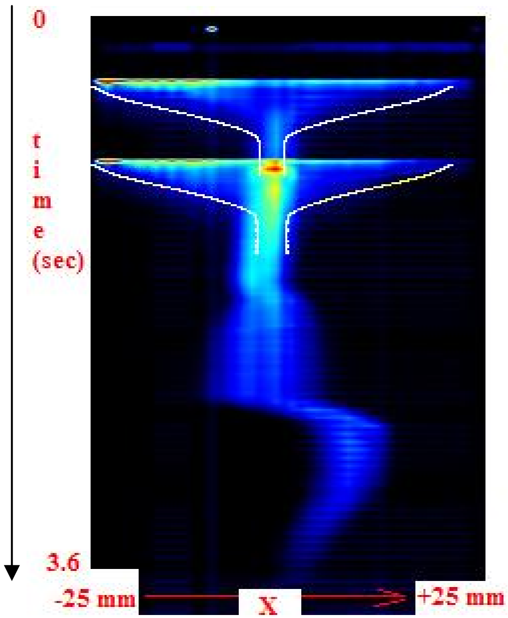
How does electron cooling work?

The velocity of the electrons is made equal to the average velocity of the ions.

The ions undergo Coulomb scattering in the electron “gas” and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



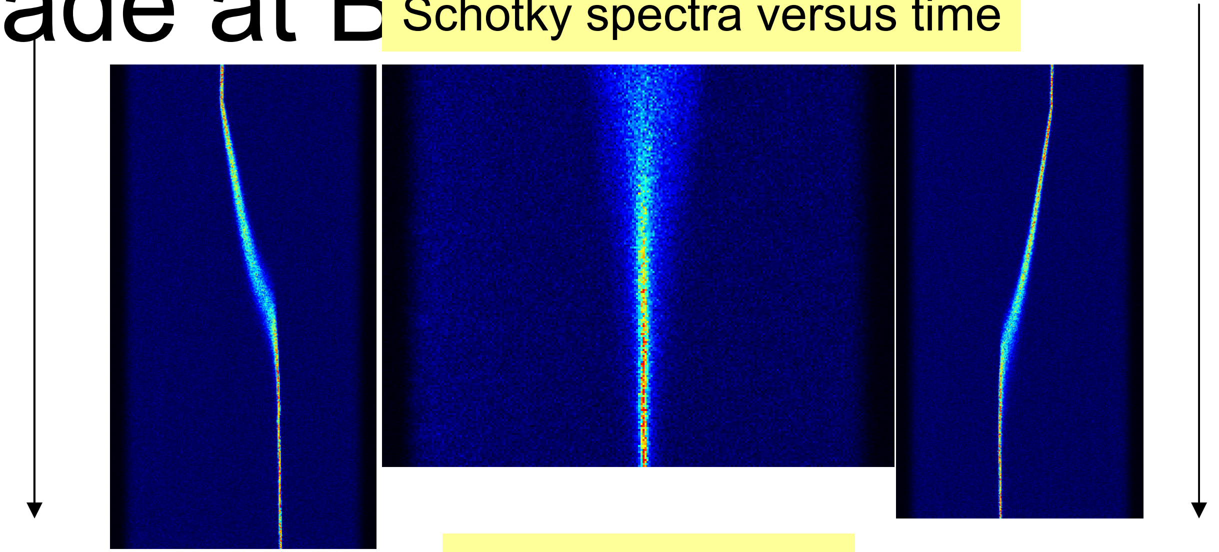
Examples of operation previous coolers made at BINP



Beam profile monitor versus time cooling <0.2 s

LEIR CERN for LHC Pb*Pb
5 MeV/n- Pb
ions beam 2 injection with
Cooling bunching and then
acceleration

Schotky spectra versus time



Jump electron beam energy up

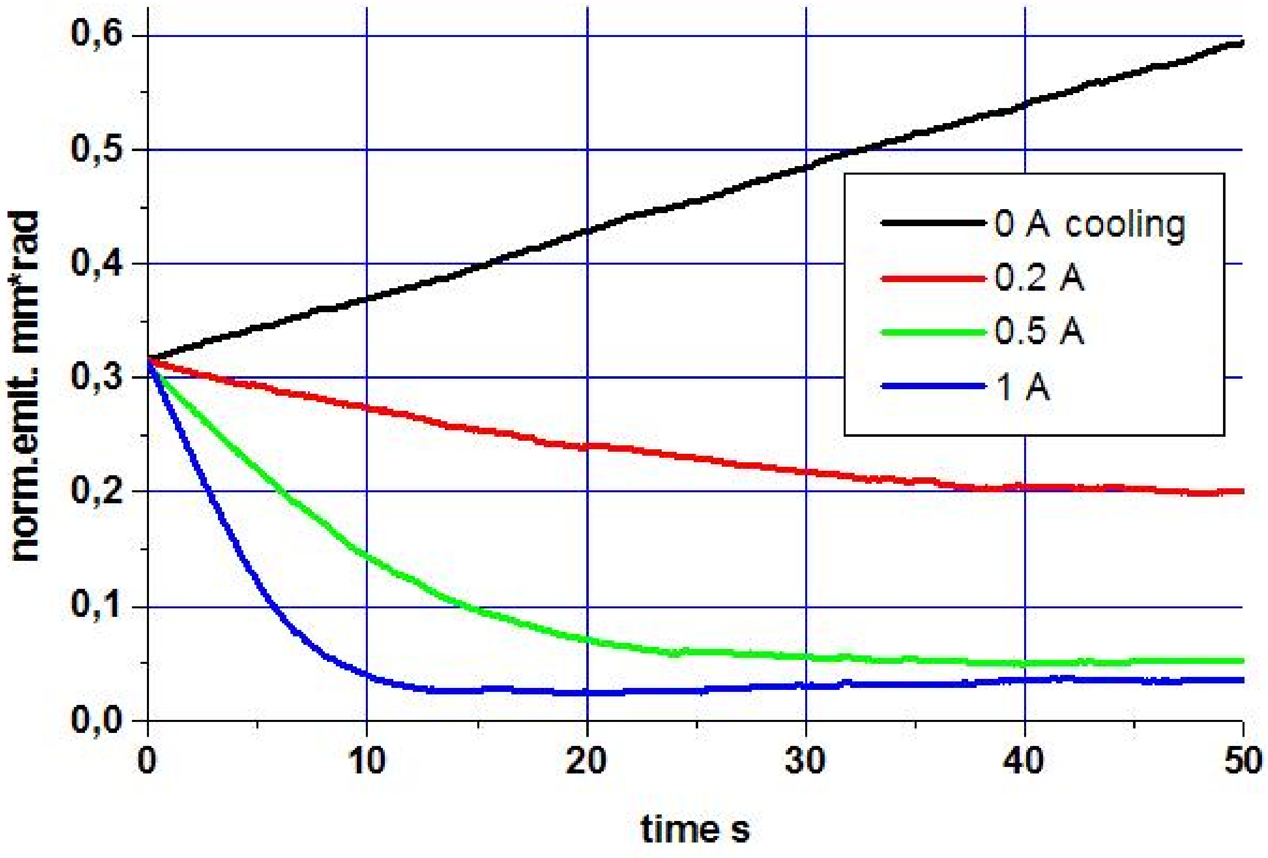
Cooling ion beam After acceleration

Jump electron Beam energy down

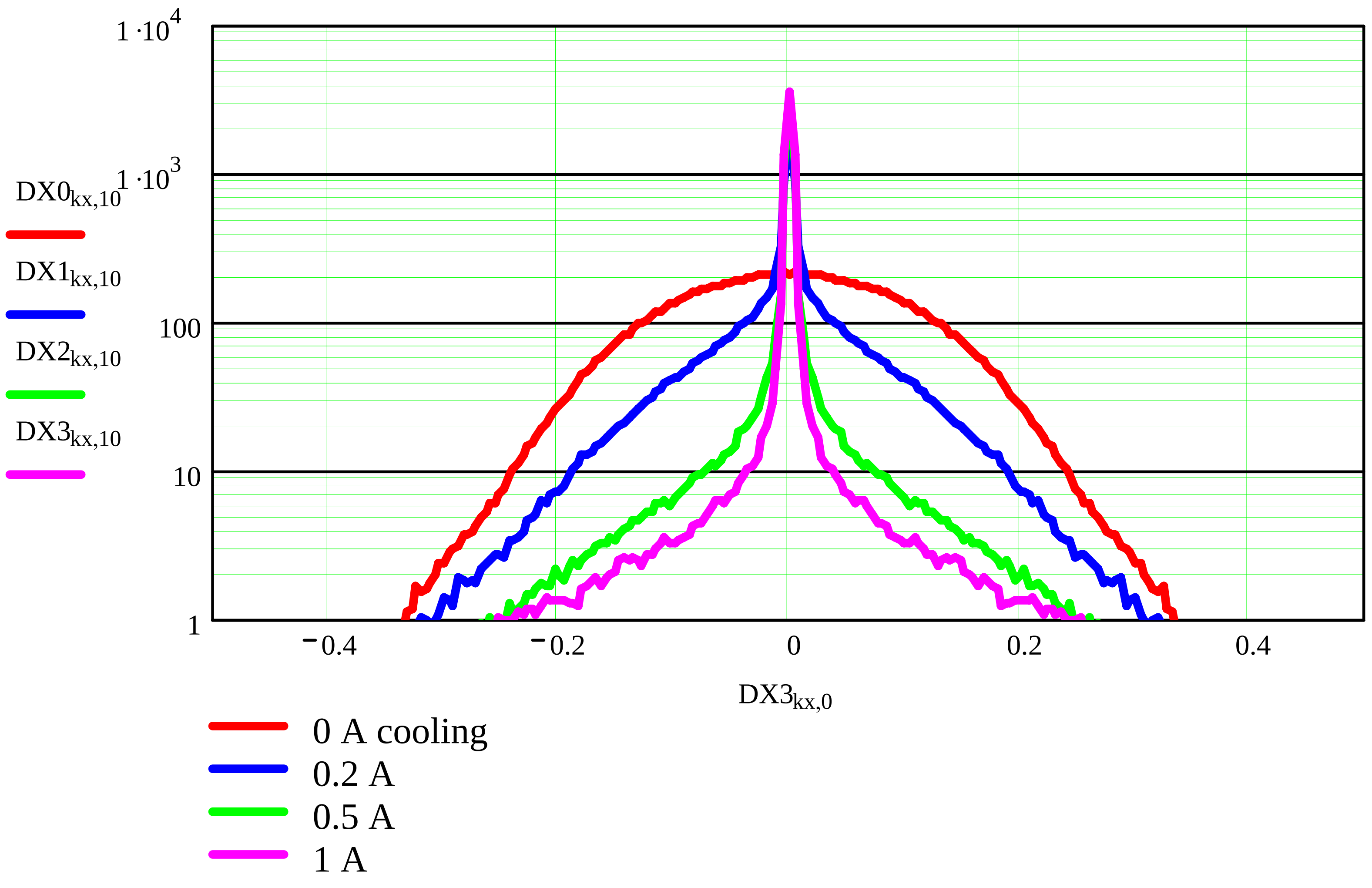
IMP CSRe Landjou China
The momentum spread cooling 400 MeV/u C^{+6}
The electron current 0.75 A.
The cooling time 20 sec at good agreement with calculation from data of cooling force.
Initial momentum spread 2E-4 final 2E-5.

Calculation parameters of COSY proton beam under action electron cooler.

Calculation was made for 1 MeV electron beam energy, a electron beam diameter 10 mm and magnet field 2 kG at cooler section.



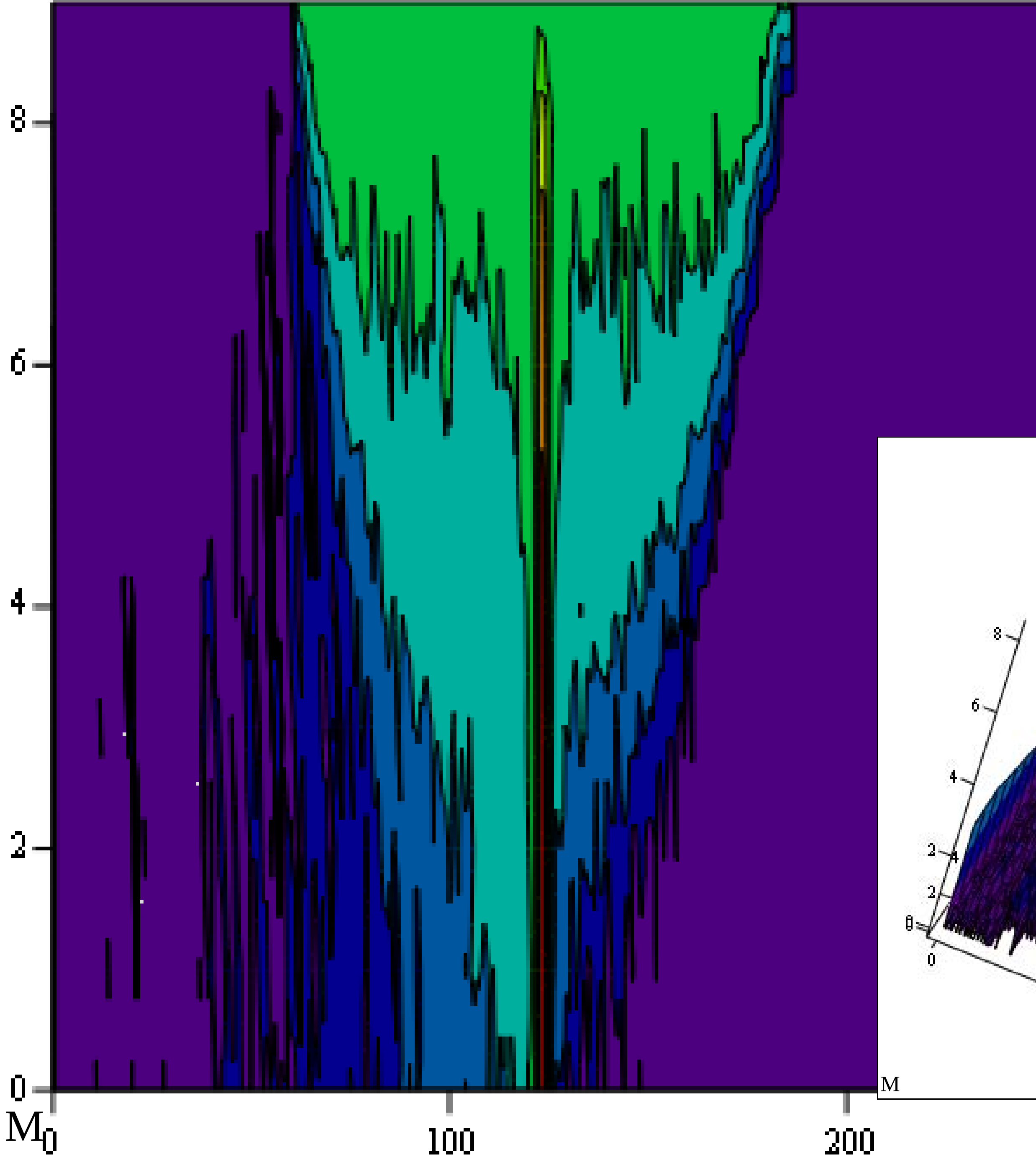
Calculation profile of proton beam under cooling
different electron current after 50 s cooling

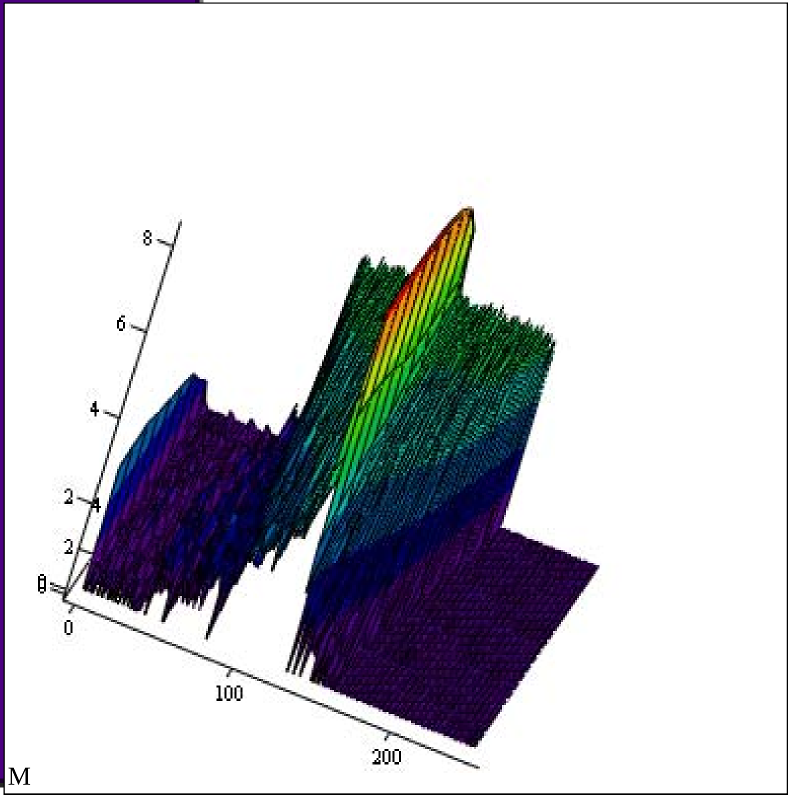


Cooling electron current 0.5 A

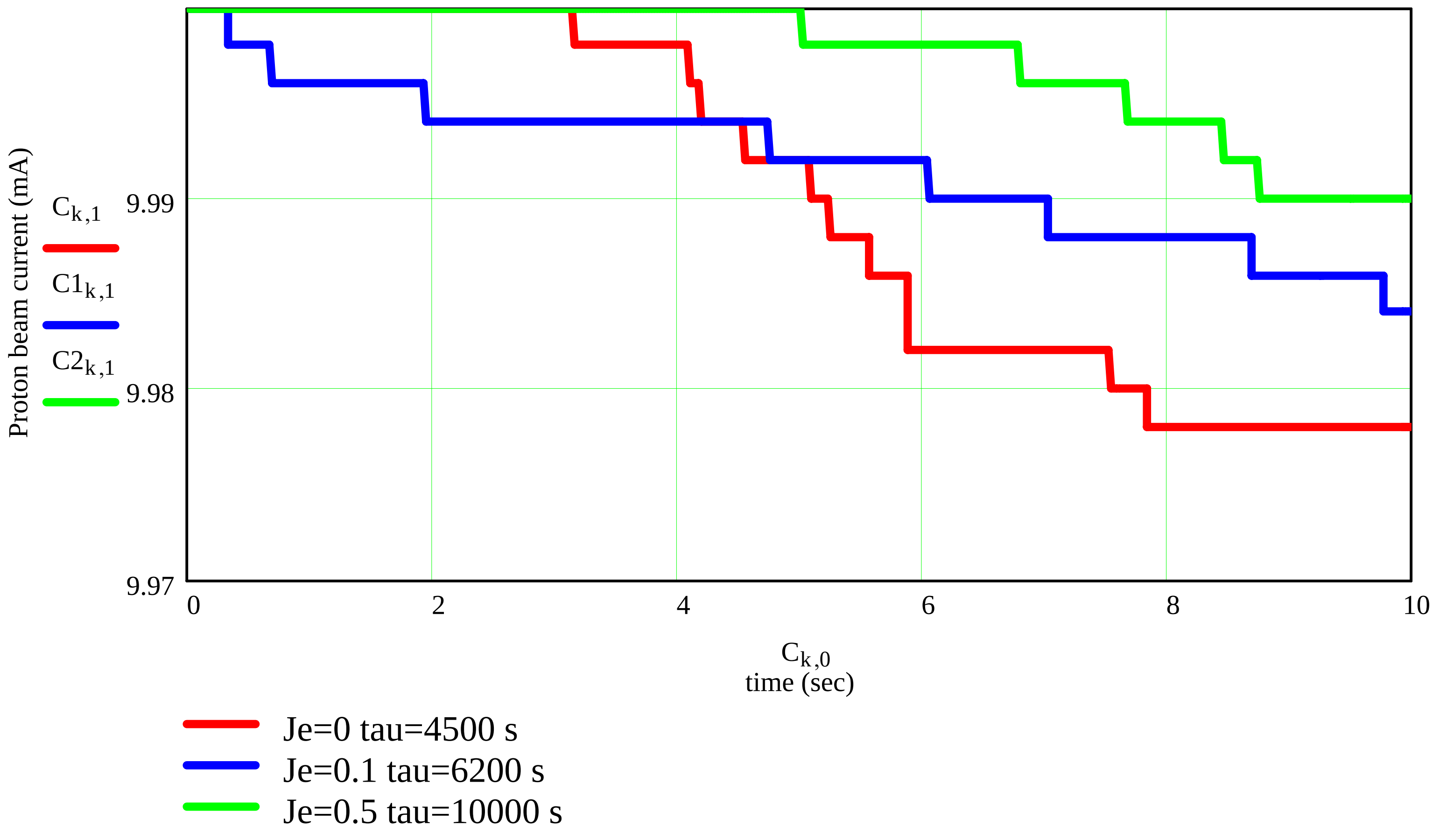
Time 50 s

The initial momentum spread dp/p=+-5E-4



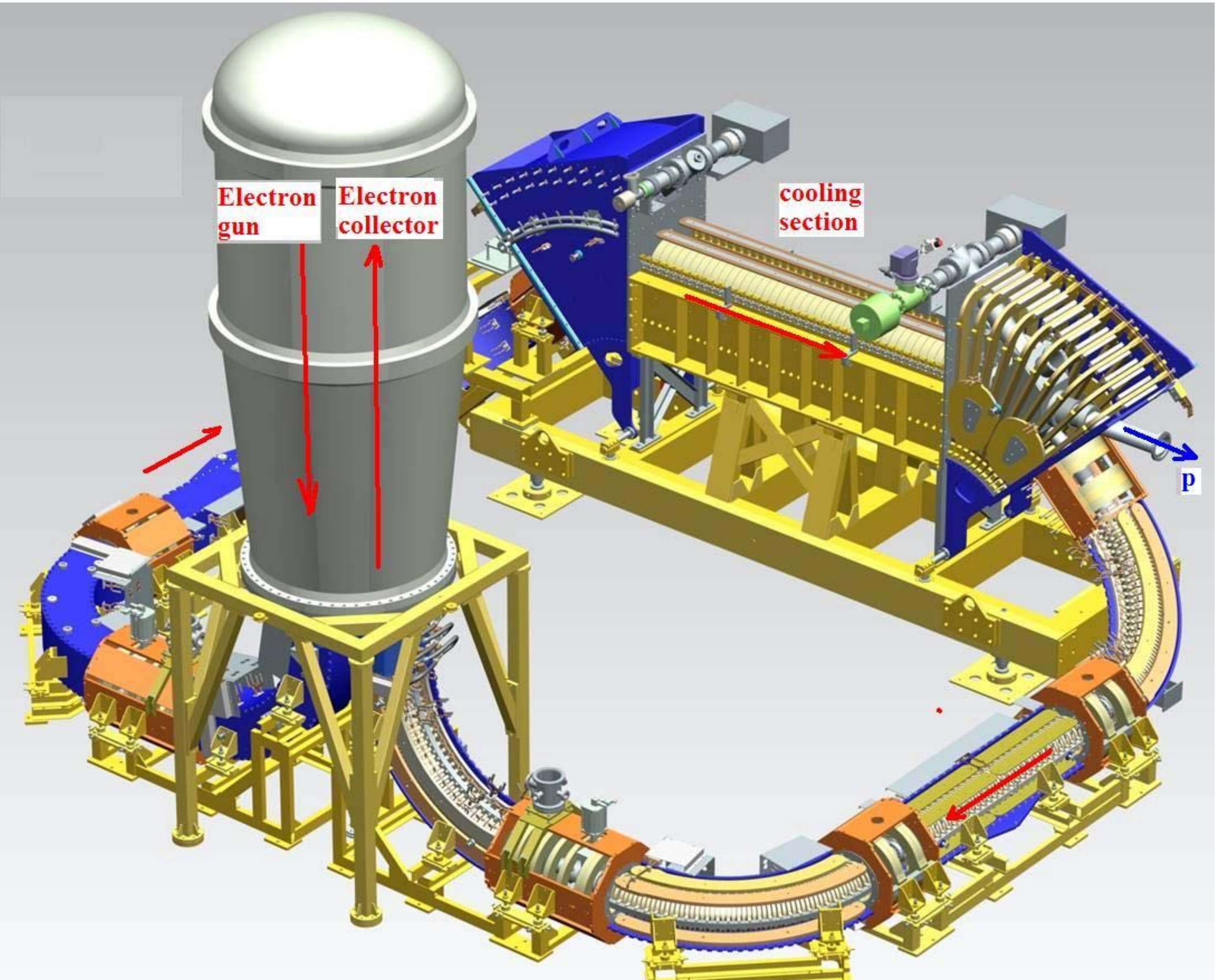


Proton beam life time

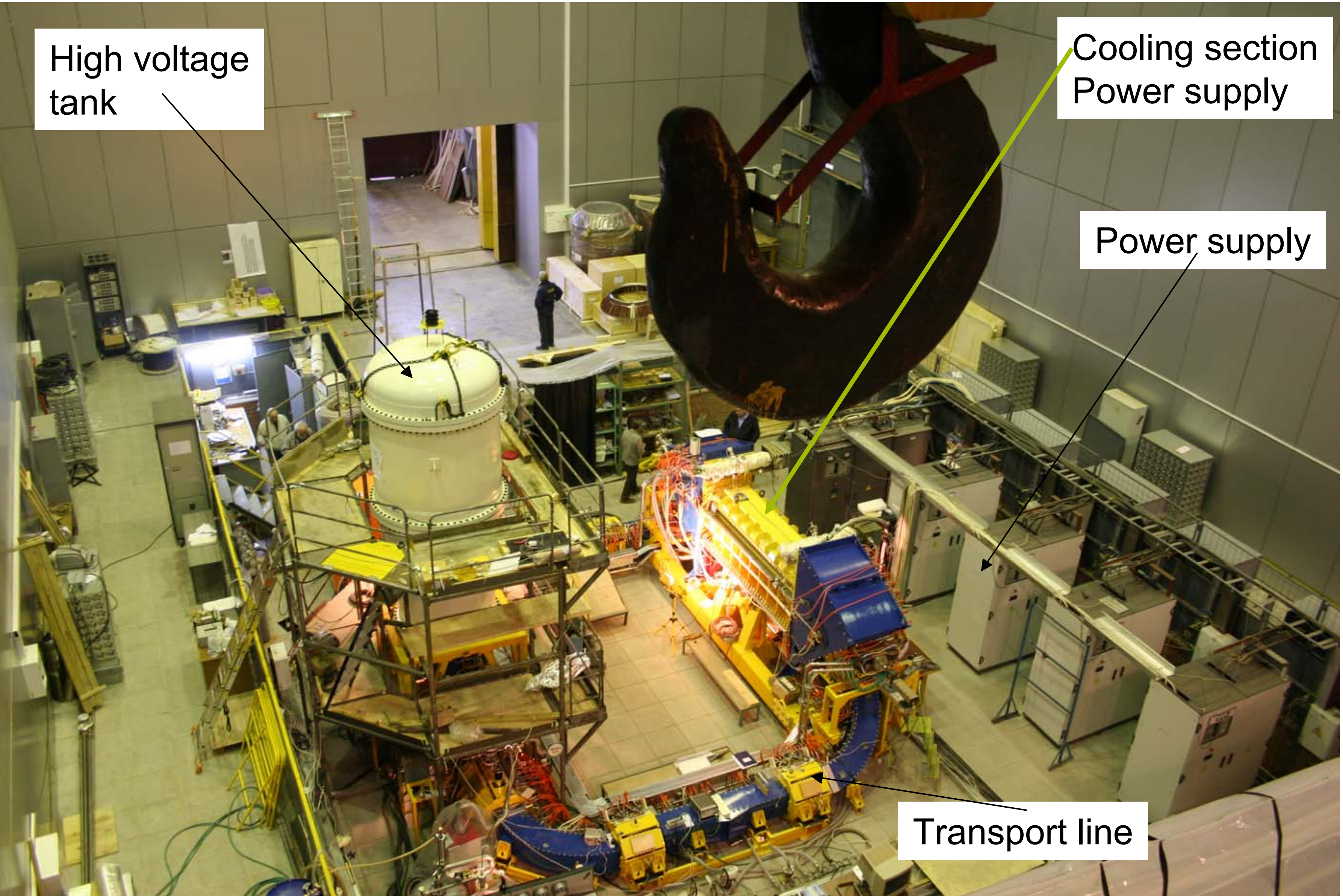


Design of 2 MeV cooler for COSY (Julich)

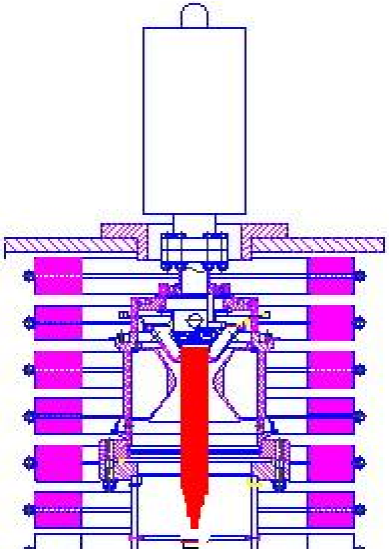
High voltage tank, transport lines for electron beam, toroid for joint proton and electron beams, cooling section and toroid for separation proton and electron beams.



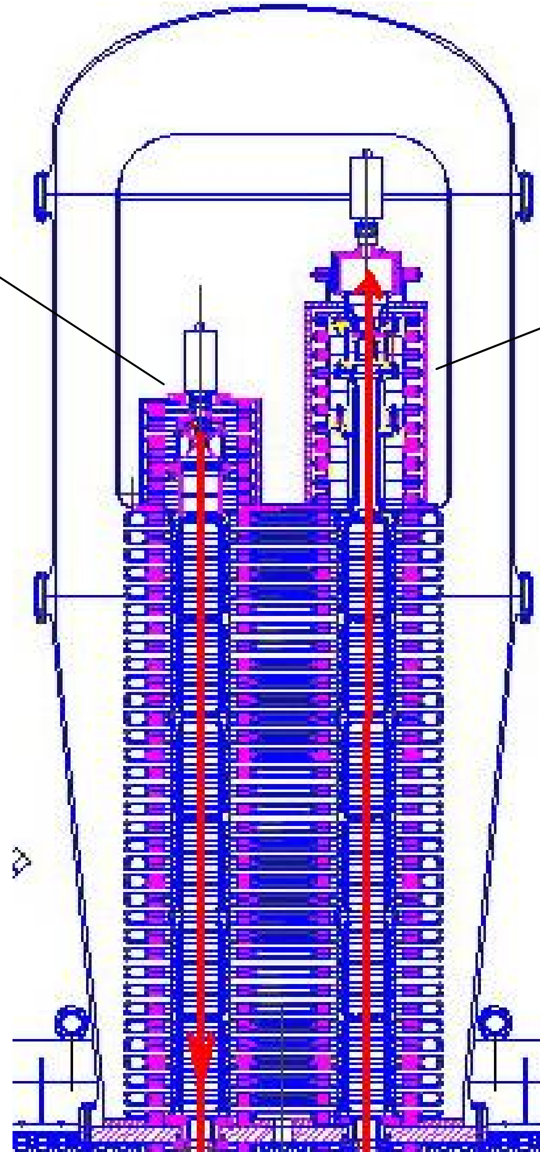
Cooler in BINP (19.03.2012)- view from cabin of lifting crane



High voltage tank

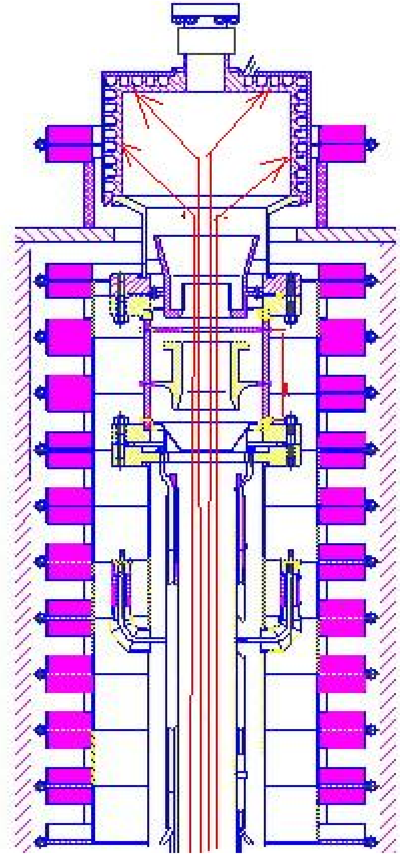


Electron gun with 4 sectors for modulator



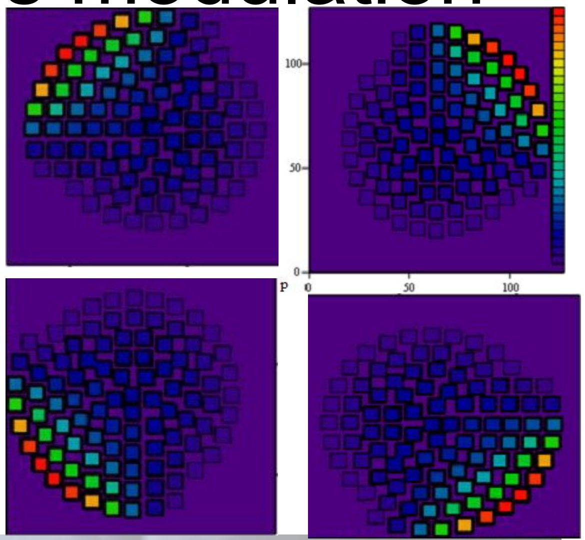
33 sections
At serios 33*(+30 kV-30kV)=
2000 kV

Fill SF6 gas 5 bar for electrical isolation

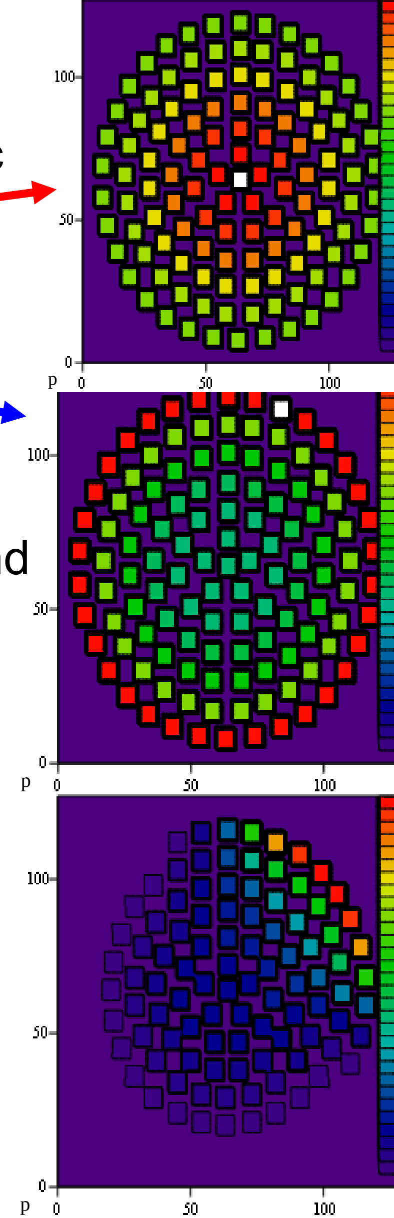


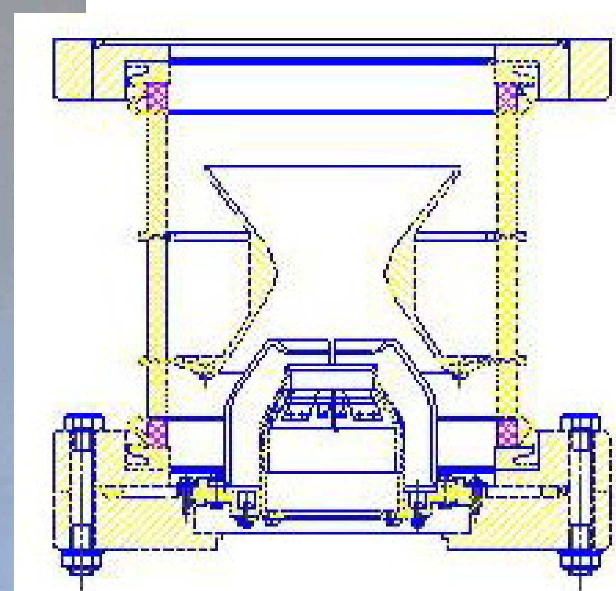
Electron beam collector with Wein filter for suppression reflected electrons

Electron gun
4 sectors modulation



Electron beam parabolic shape with maximum at center, "hollow" with minimum at center, AC modulation single sector for measuring quadruple oscillation and rotation beam on different pickups along cooler



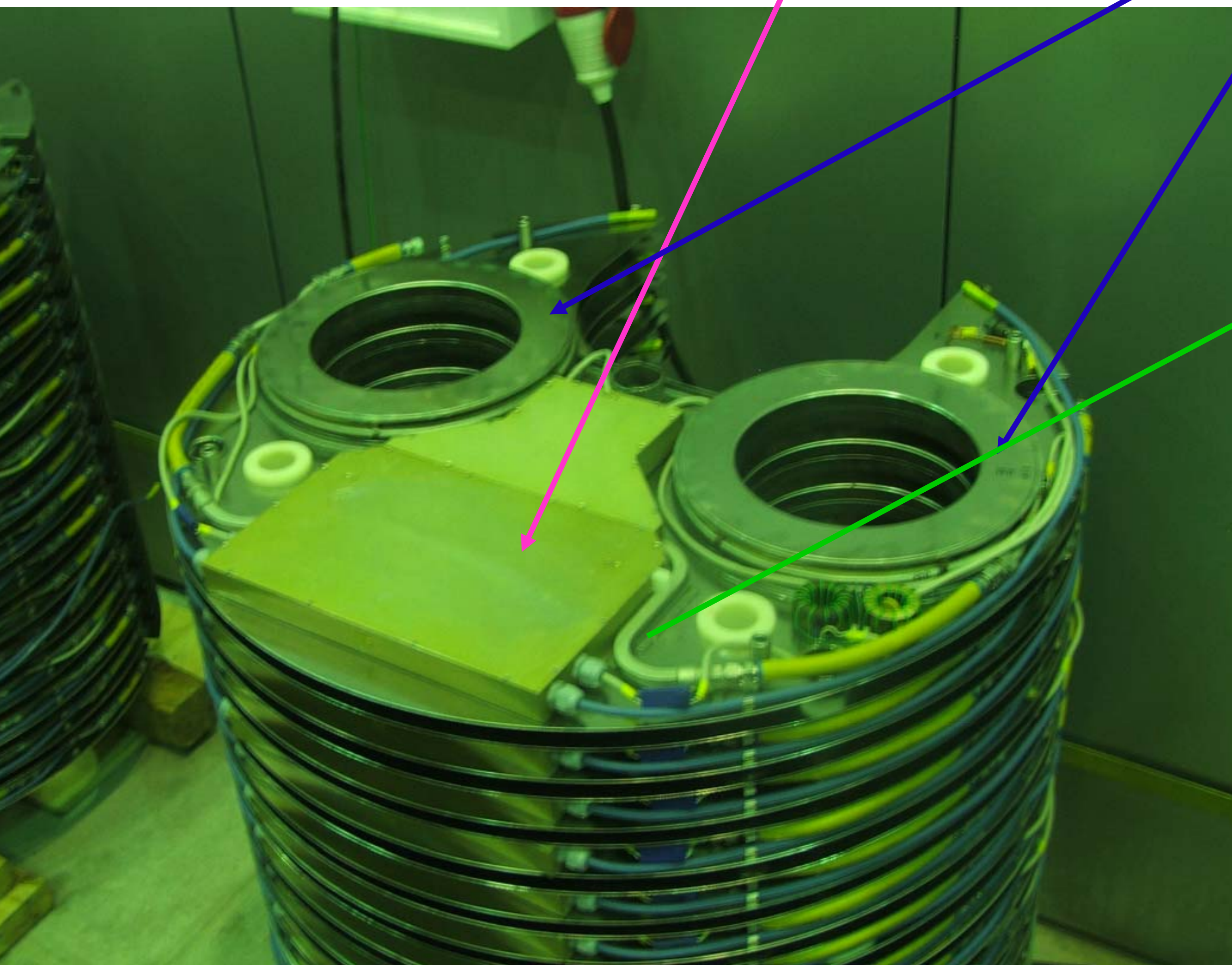


Power for high voltage tank

1. Solenoid coils around acceleration and de-acceleration tubes at each section from 33
2. high voltage PS +30 kV and -30 kV at section
3. Control and communication boxes at sections
4. High voltage PS for electron gun and collector
5. Control and communication boxes at high voltage terminal

Sections

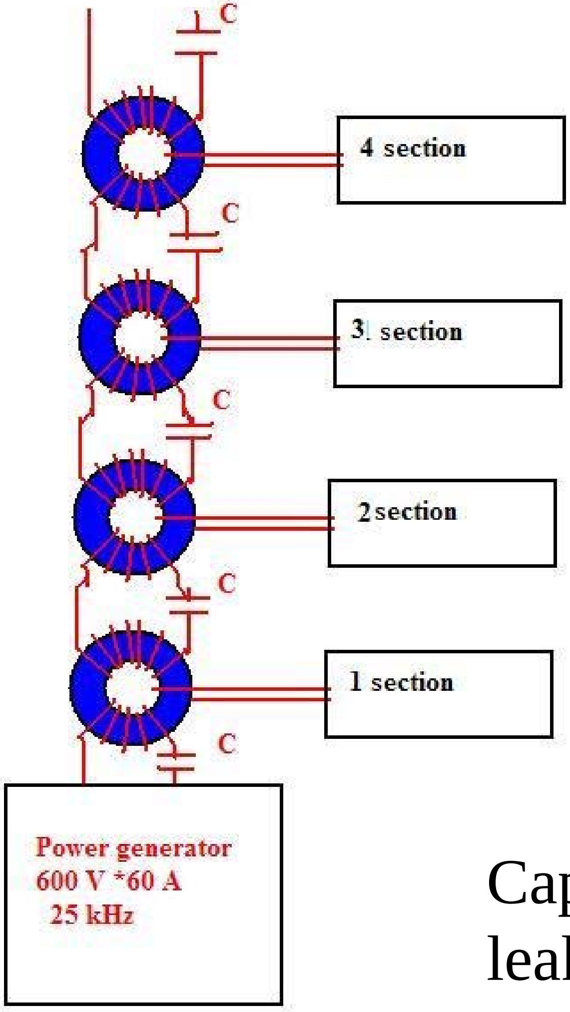
Electronic with high voltage PS, solenoid coils

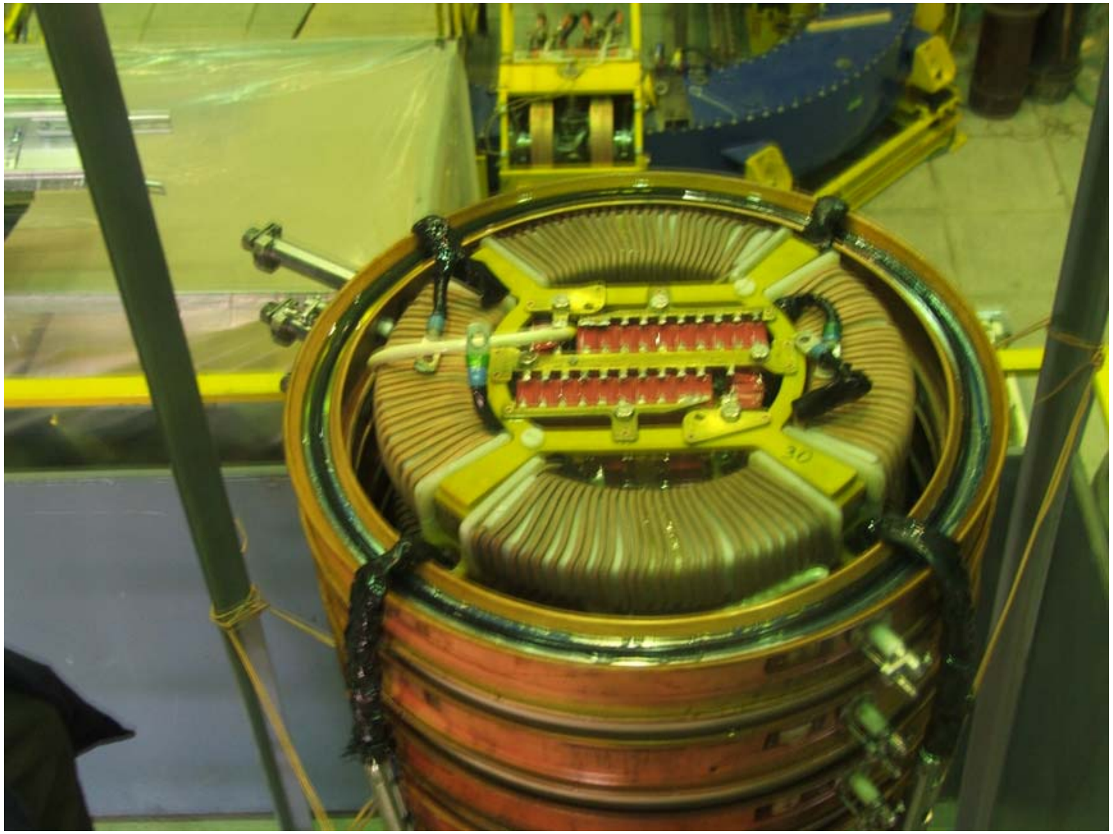


Oil cooling tube

For more details see poster Skorobogatov D.

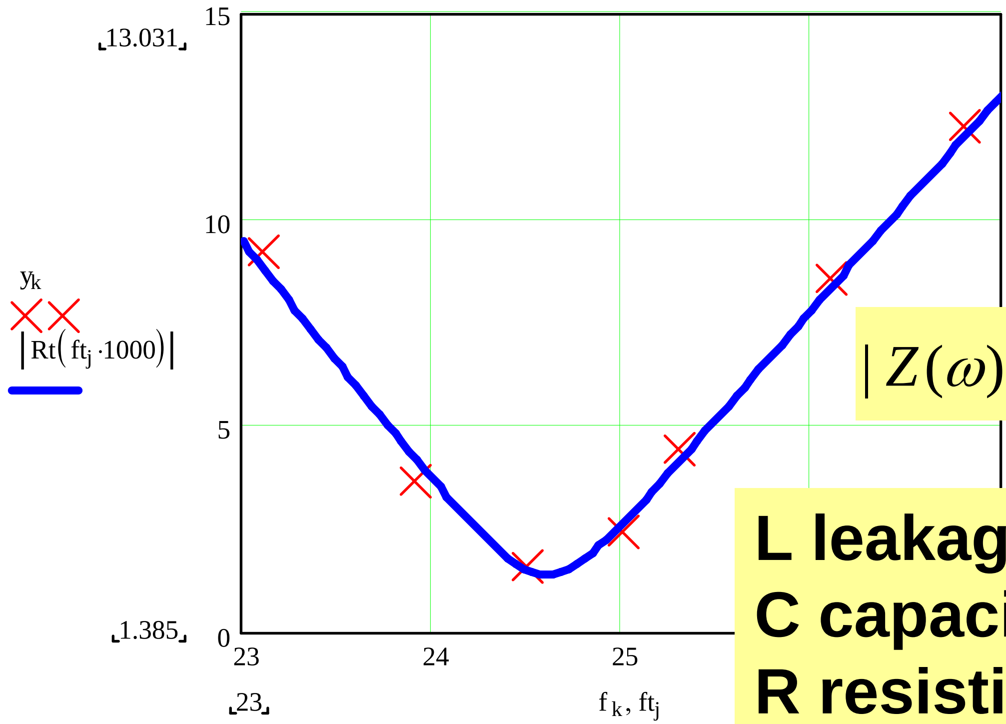
Cascade of serial transformers with amorphous Fe core for powering sections



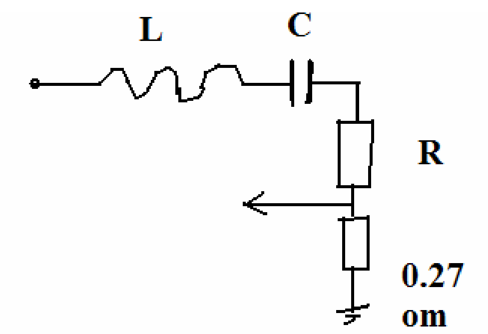


Capacitors used for compensation leakage inductance

Characteristic of shorted cascade transformer



U/J versus frequency kHz



$$|Z(\omega)| = \sqrt{(R + R_{sh})^2 + (\omega L - 1/(\omega C)^2)}$$

L leakage inductance
C capacitor for compensation
R resistive losses at transformer
Minimum resistor 2 ohm correspond 30 kWt at high voltage terminal for 700 V amplitude in ground side for resistive loading.

Electronics of section

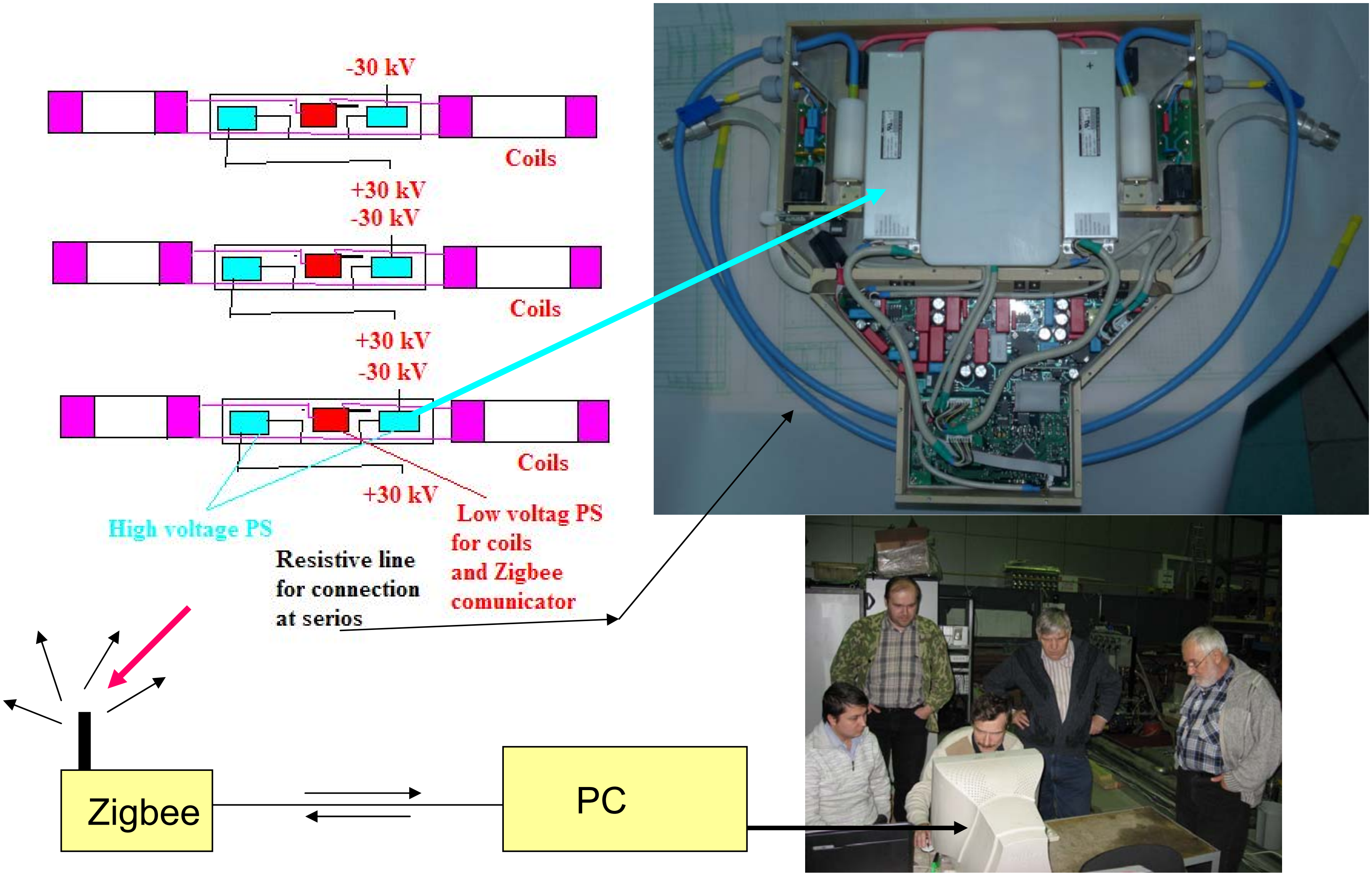
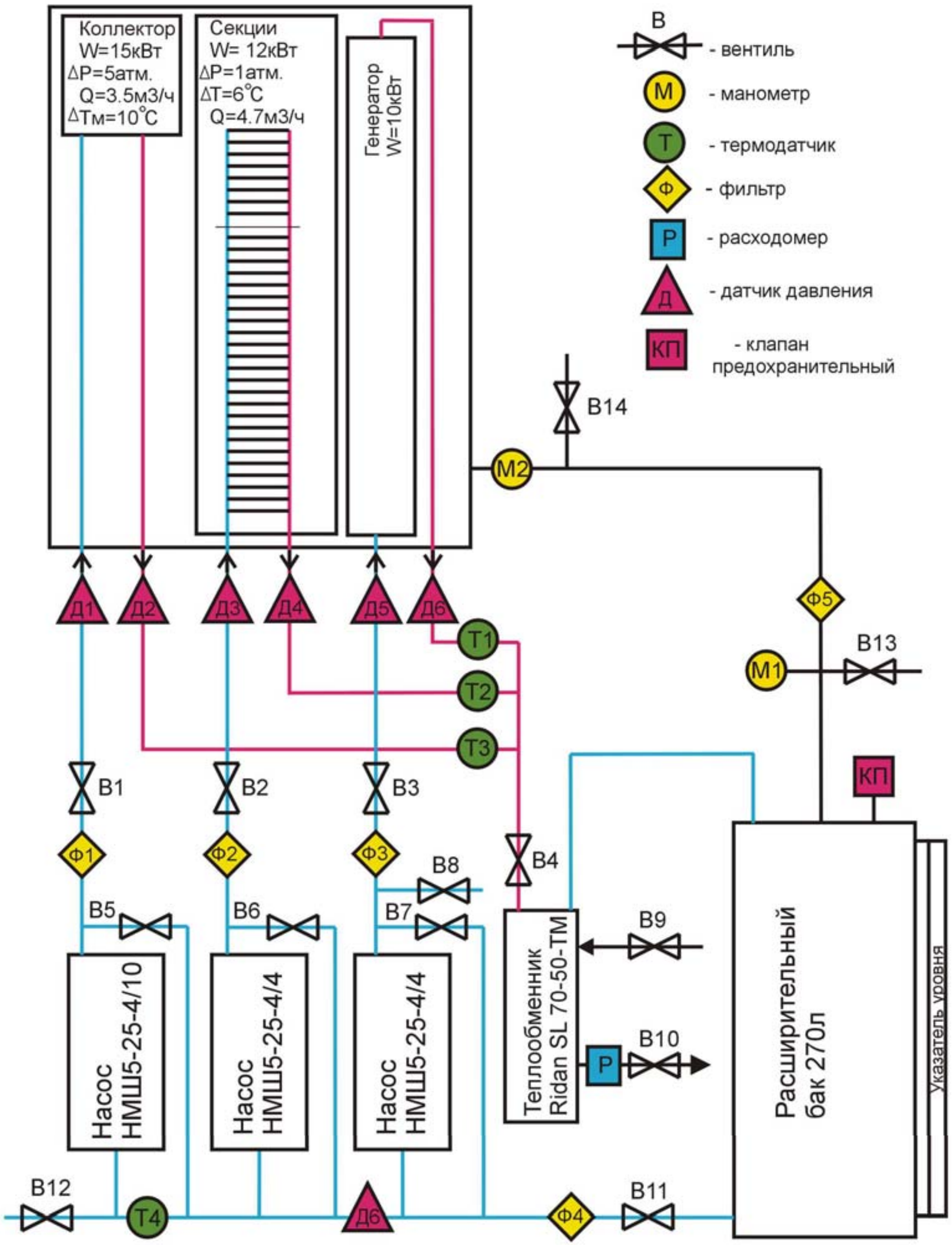


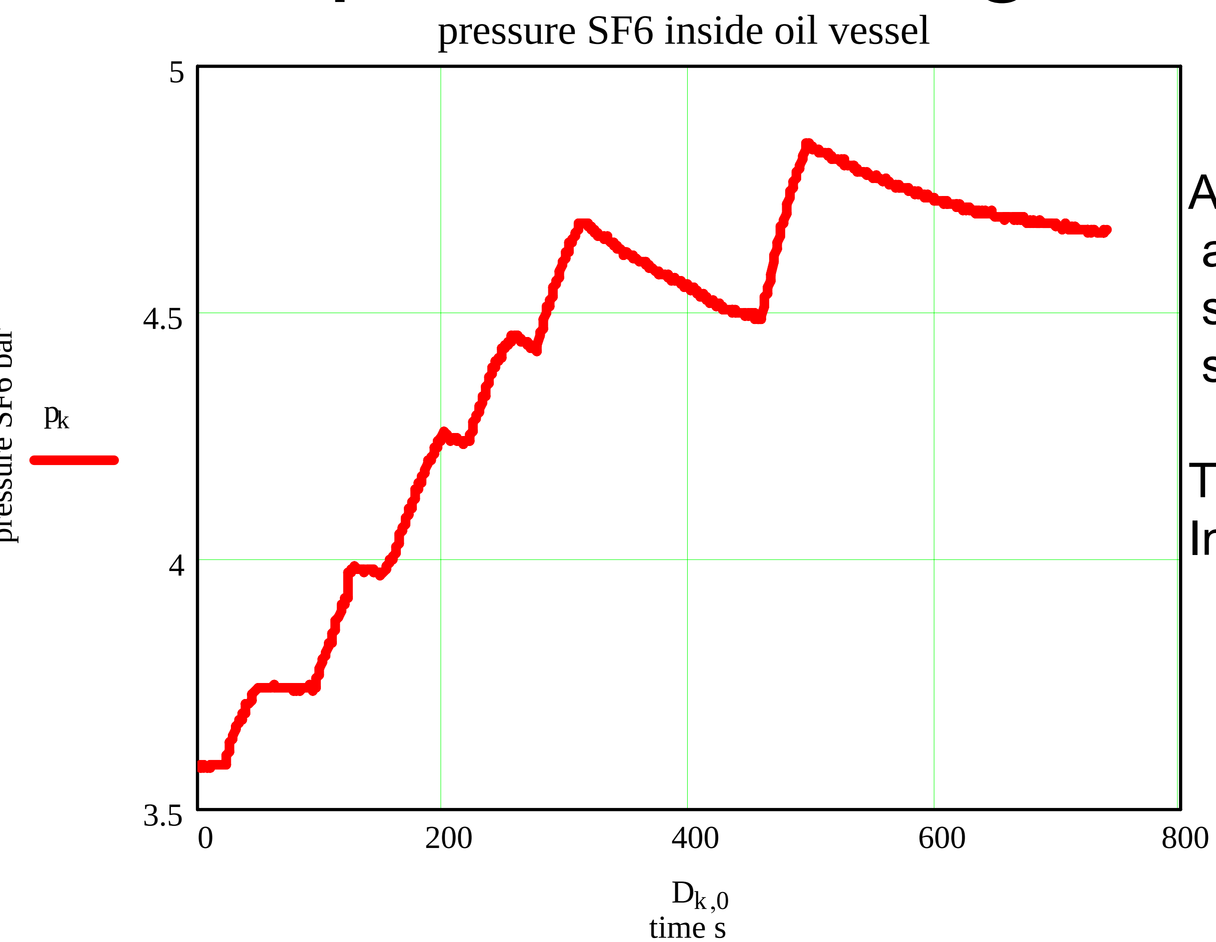
Схема системы масляного охлаждения



Oil cooling inside high voltage tank

1. Collector of electrons and electronics at high voltage terminal
2. solenoids and electronics at 33 sections along colon
3. Cascade transformer

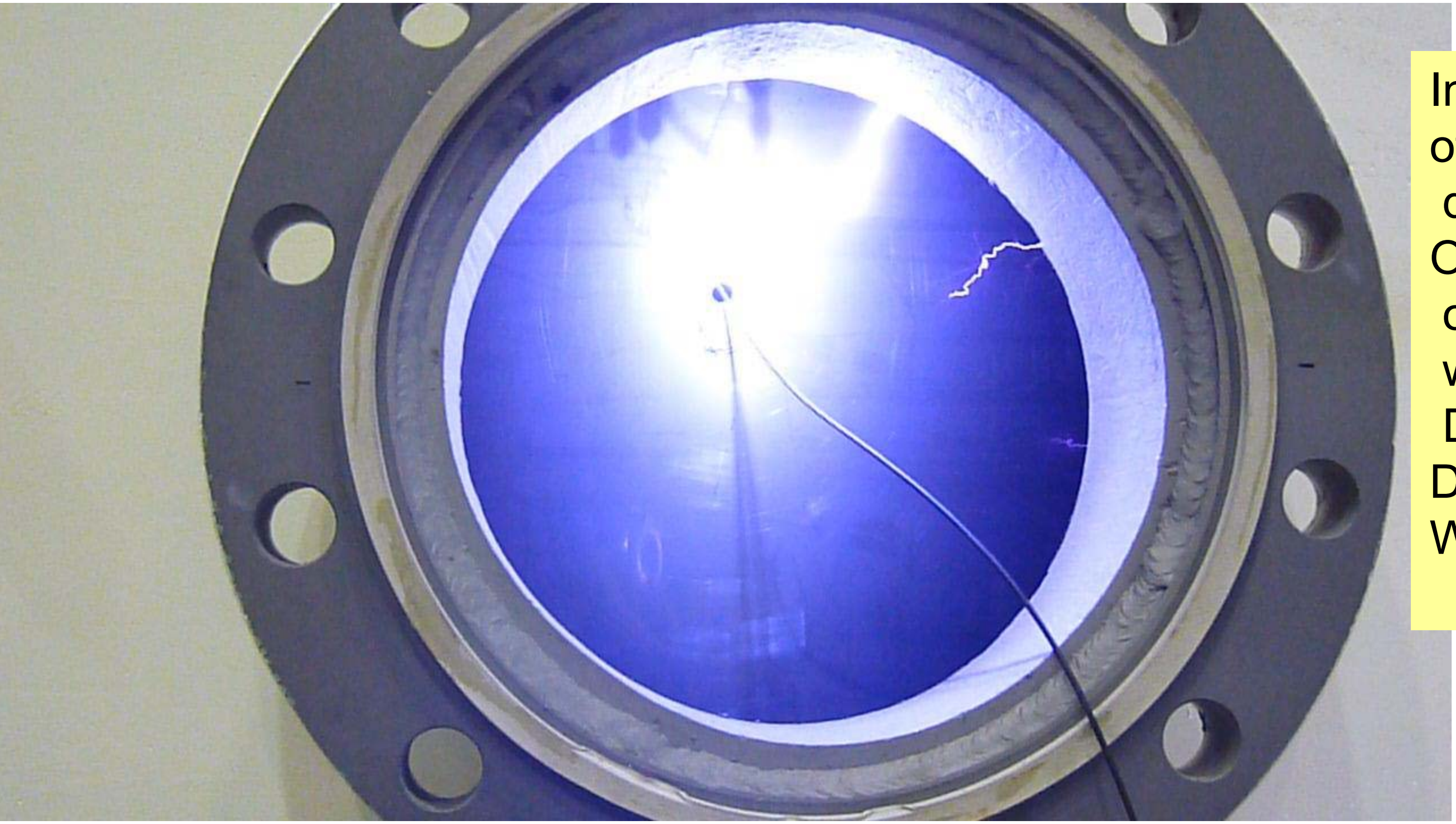
Dilution SF6 at transformer oil (43%) improve breaking-down voltage



After add pressure of SF6 at oil we can see about 50% slow decreasing pressure by solution SF6 at oil

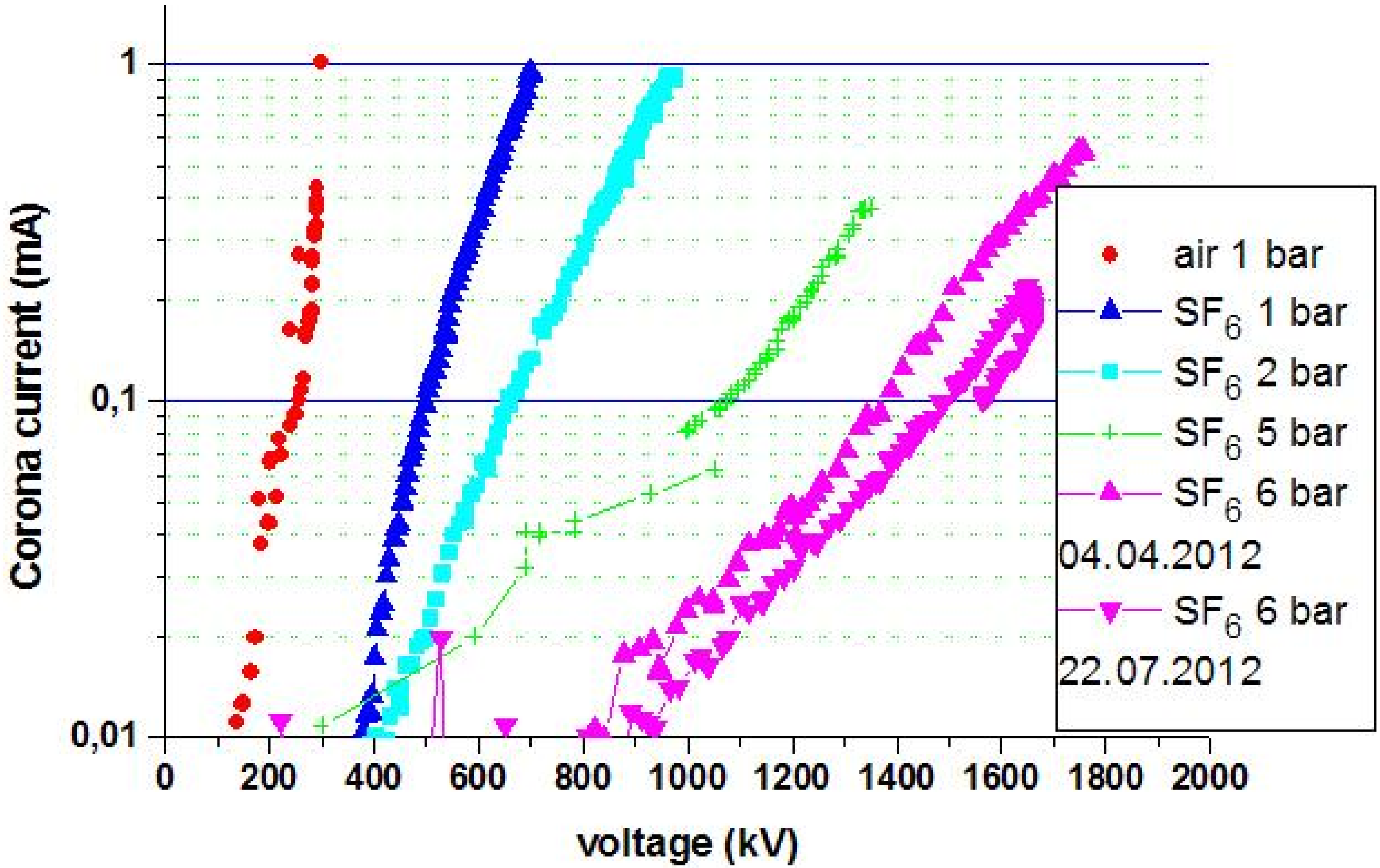
The oil breakdown voltage Increased 2-3 times!

300 kV sparking at air for test electronics with open flange for inspection position of sparking

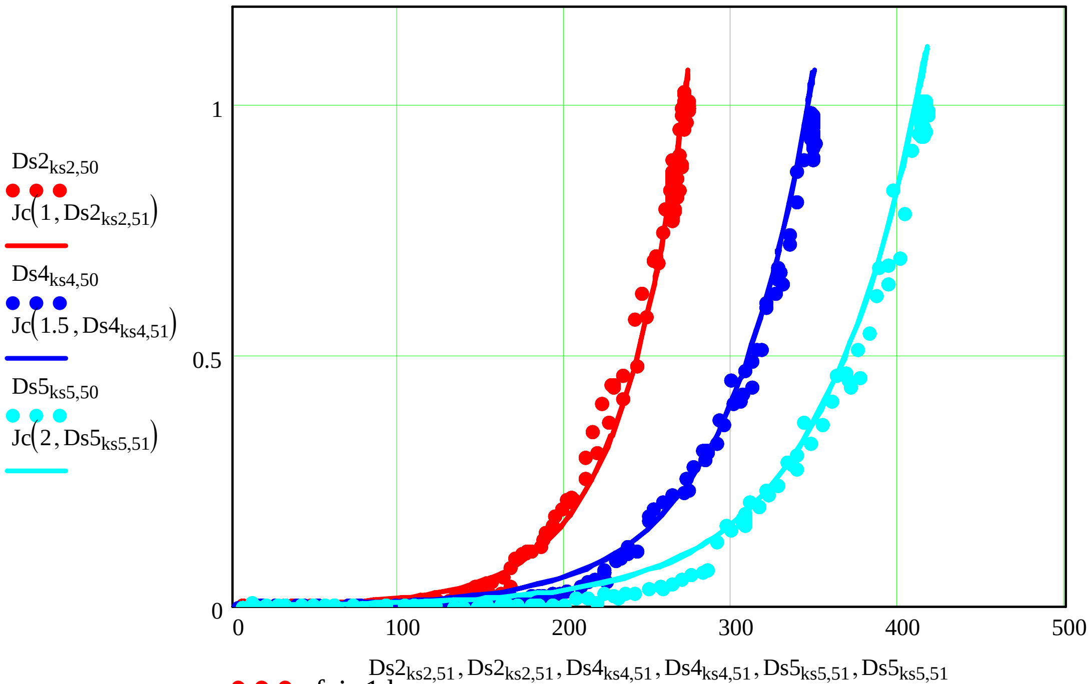


Initially results
of sparking was
damage electronic.
One of element
of electronic device
was founded weak
Detail see at poster
D. Skorobogatov
WEPP032

Experiments with high voltage for different SF6 pressure



Experiments with different gases and pressure



$$Jc(p,U) = e^{\frac{U - U1 * p^{0.6}}{U2 * p^{0.6}}}$$

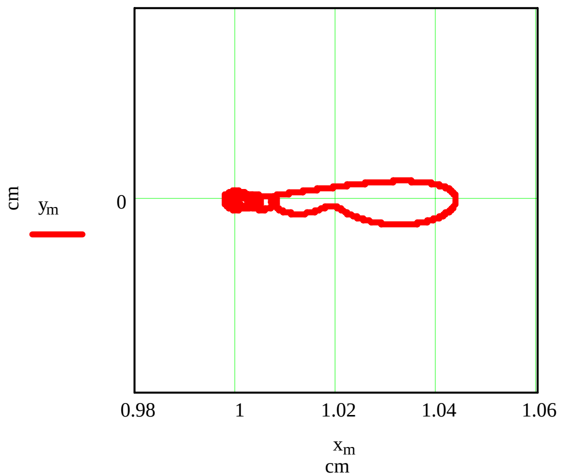
U1 voltage for corona current 1 mA

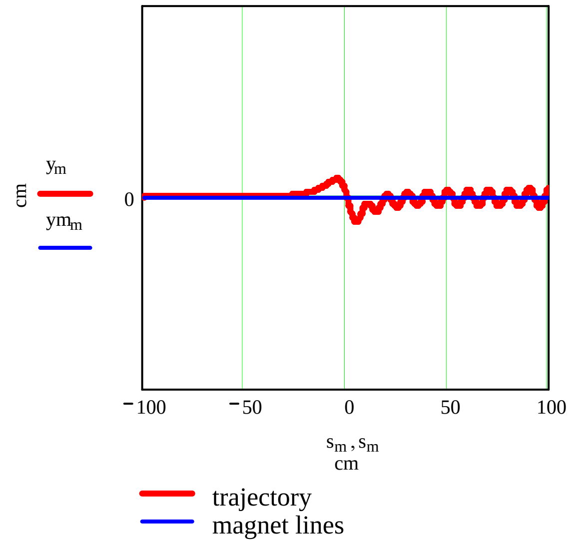
U2 voltage of rate increasing corona current

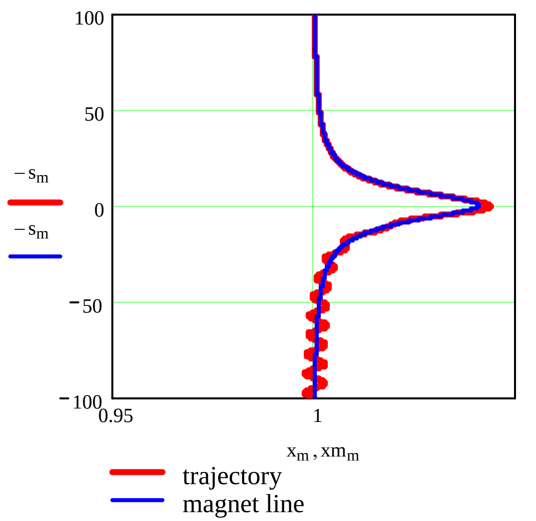
	U1(kV)	U2(kV)
Air	270	40
CO_2	343	40
CO_2 +0.3%CCl_4	405	60
SF_6	670	80

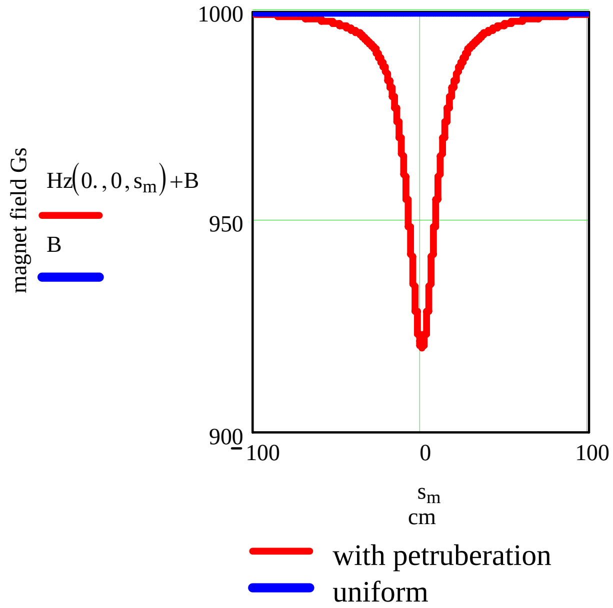
For 100 mkA corona current on 2 MV
pSF=6=9 bar
But more smooth surface inside high voltage tank
Can change this number

Low energy motion at longitudinal field with 10% modulation 1 cm off center 0.2 MeV electron energy



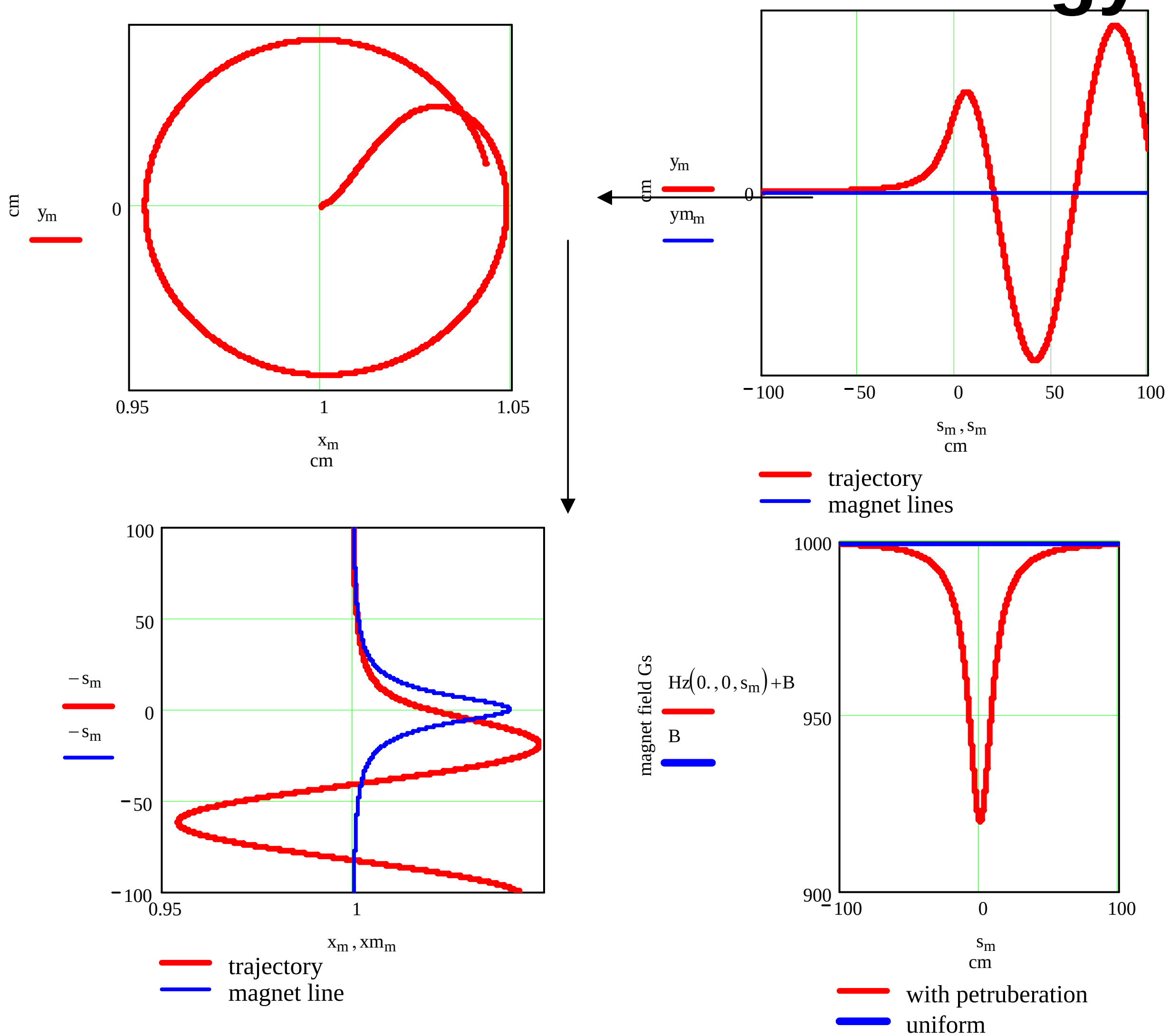






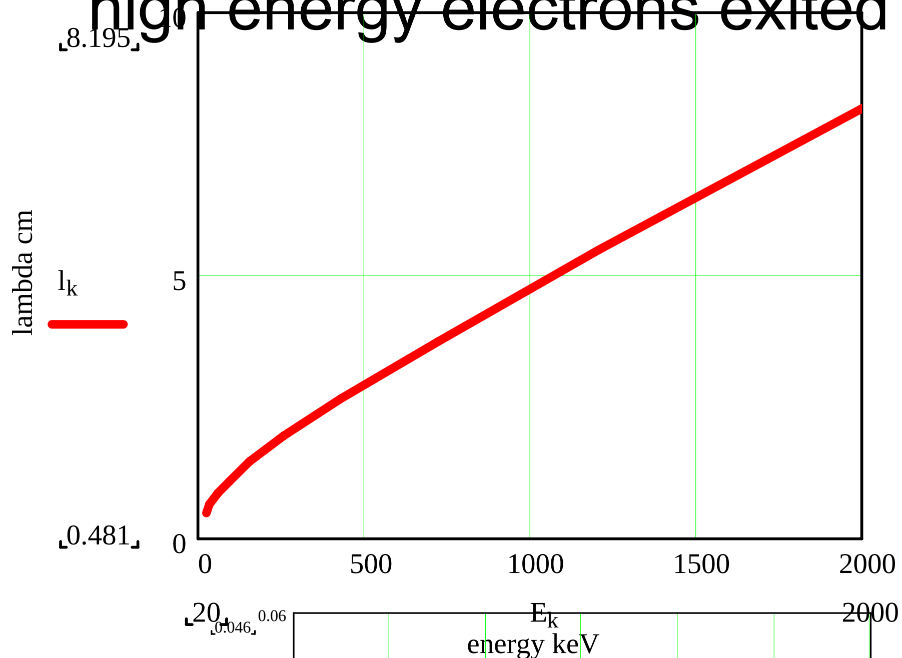
Electron follow along magnet line with excitation Larmor oscillations relatively low amplitude

High voltage motion at longitudinal field with 10% modulation 1 cm off center1 MeV electron energy



Electron ecxited amplitude Larmor oscillation equel of amplitude of geometry bump magnet lines

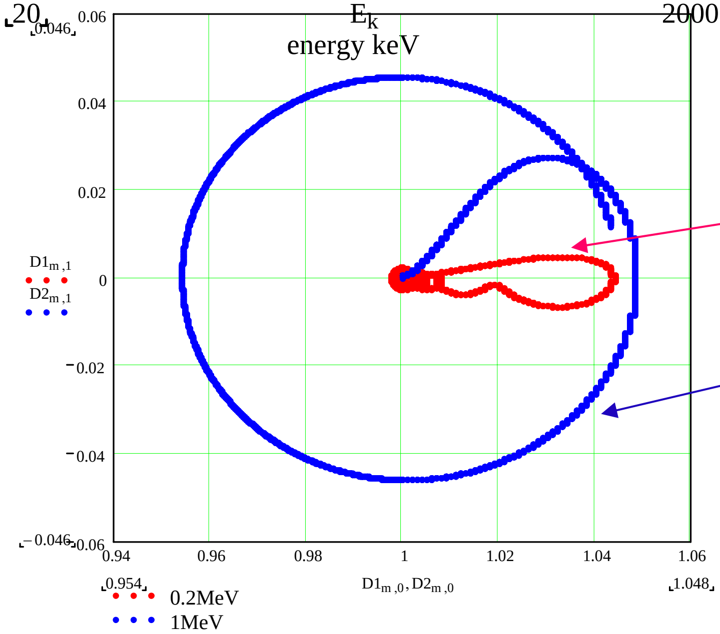
Low energy electrons pass magnet fields modulation adiabatically but high energy electrons exited high amplitude Larmor rotation



$$\Delta = \frac{pc}{eB}$$

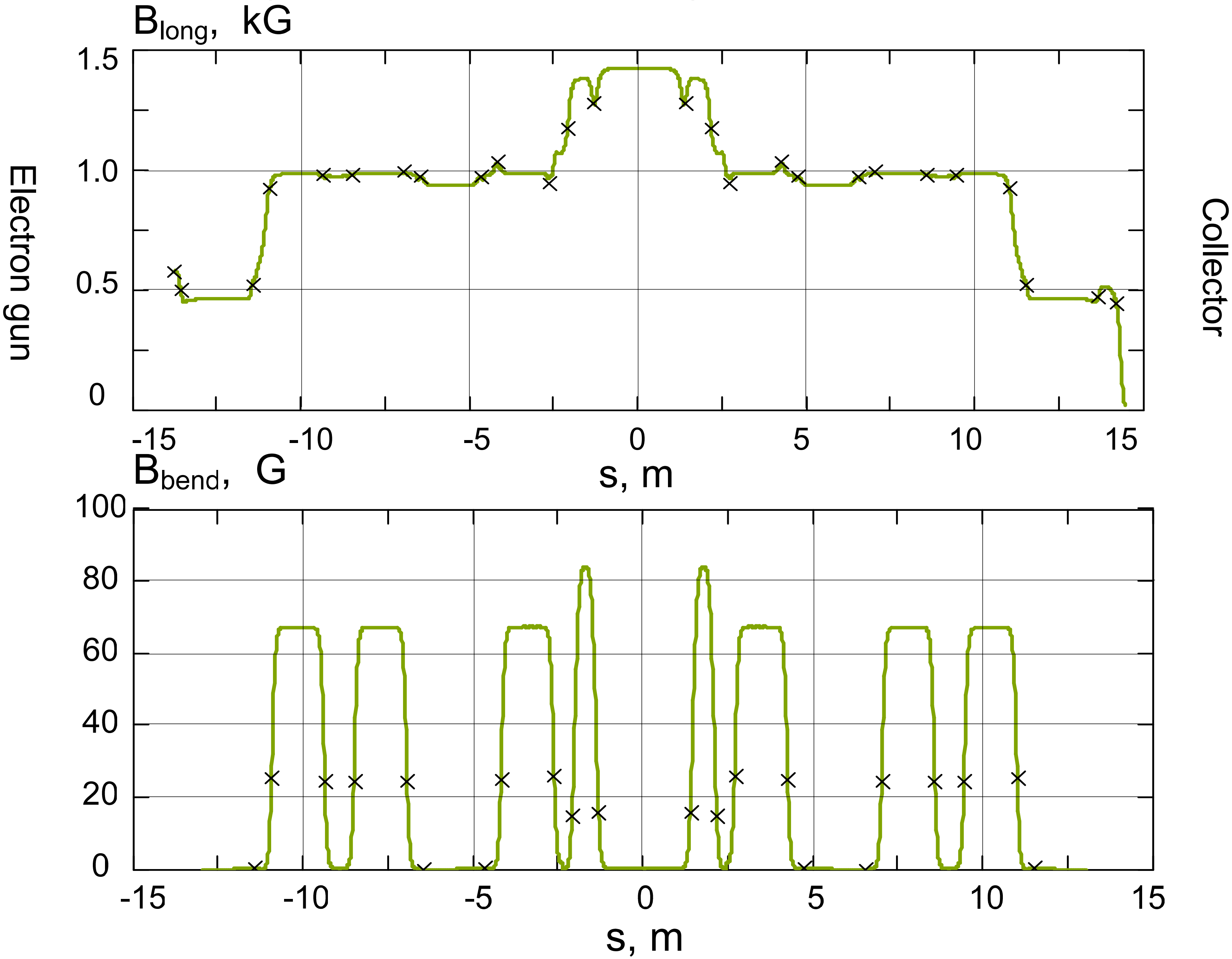
$$\rho(s) = \rho_0 e^{is/\Delta}$$

Longitudinal spiral length
P- electrons momentum
B- longitudinal magnet field

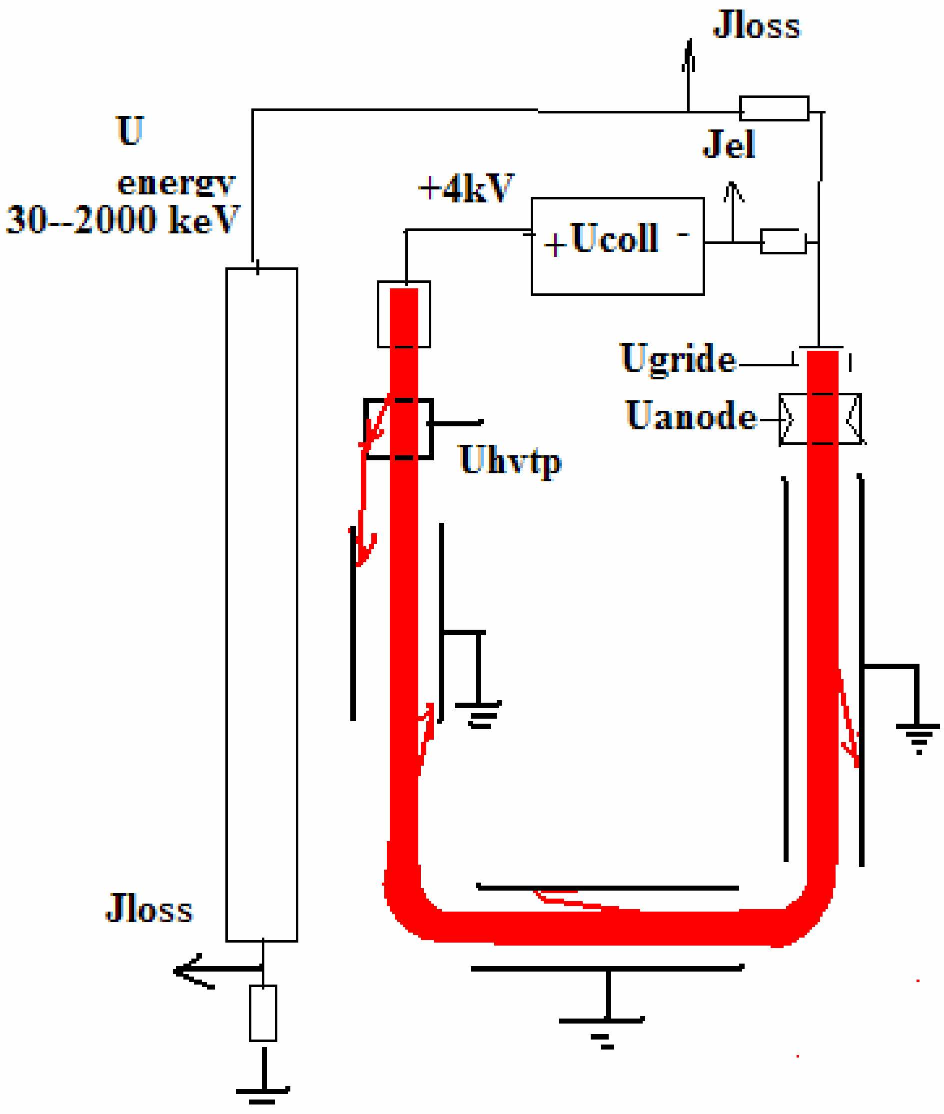


0.2MeV electron just follow magnet line (red line)
but 1 MeV electron exited 0.45 mm amplitude (blue line)
after passing 10% modulation magnet field

Magnet fields along electron beam



Simplified cooler circuit



1. Ugride and Uanode control electron beam current and profile
2. Electron current measured at shunt from collector PS to high voltage "ground"
3. Losses current measured at high Voltage terminal and ground as current At HV PS
4. Uhvtp voltage of Wein filter for suppression back scattered electrons. Current at HVTP Is current reflected from collector. There is first step of recuperation.

All system is work in normal mode

Electrostatic accelerator

High voltage terminal

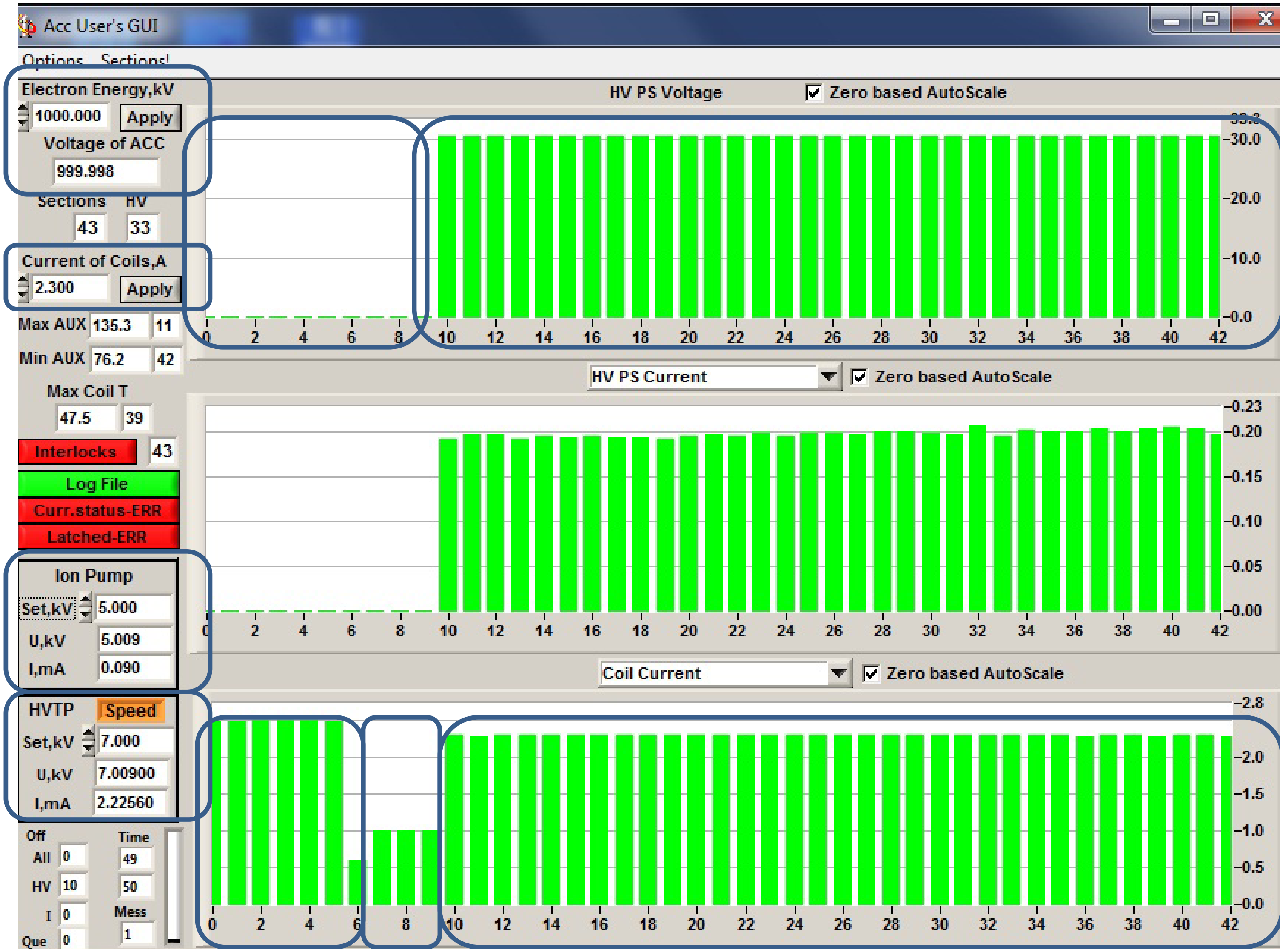
Distribution of high voltage along accelerator column

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

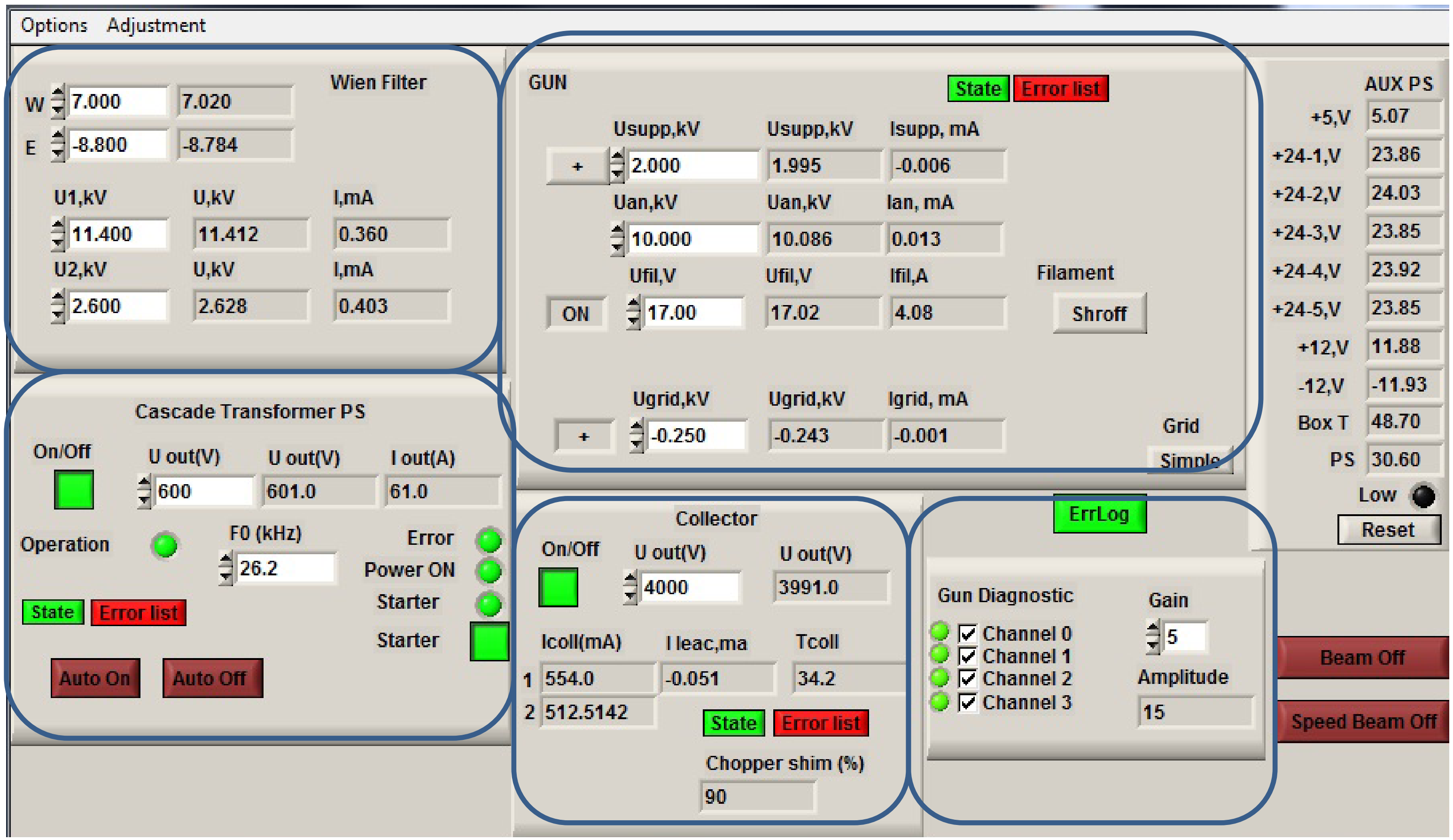
Distribution of the magnetic field in the accelerator column

All system is work in normal mode

High Voltage Terminal

Wien-filter subsystem

Gun collector electrode subsystem



Cascade transformer PS for powered accelerator column: supply voltage, base frequency

Collector subsystem: switch, collector voltage, indicator of the collector current, collector temperature, chopper shim

Control of the modulation system of the gun for BPM : switches for gun electrodes, amplification signal to applied to electrodes

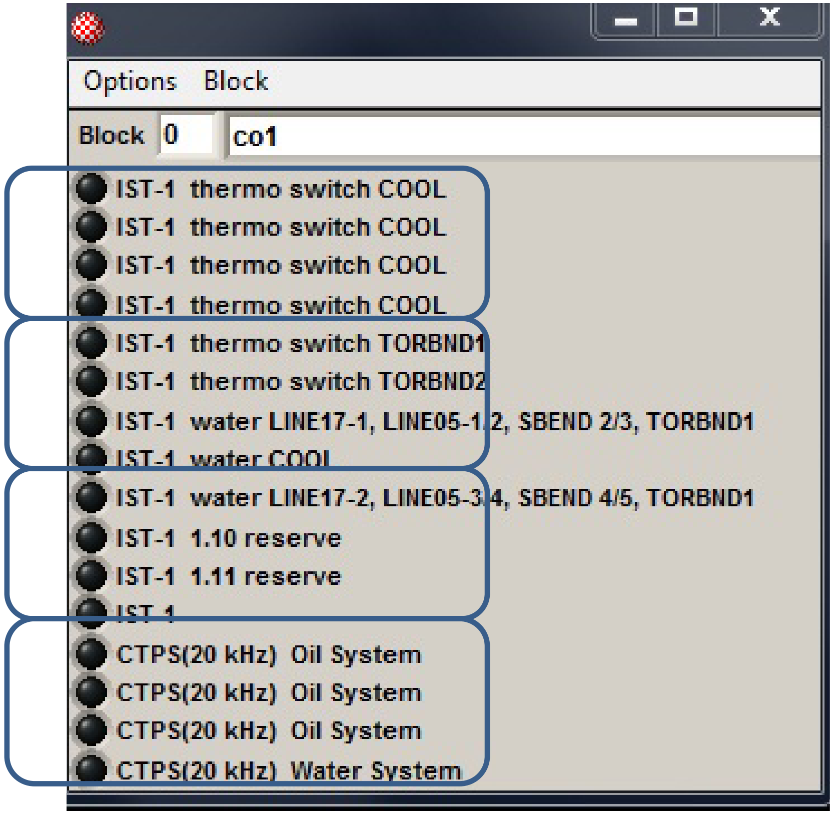
All system is work in normal mode

Interlock system:

All interlock signal is collected to group with 4 elements, all elements is combined with logical OR and controlled one output. A system can be switched on when the system collects all quadruple of interlock signals.

System IST-1 : power supply of the cooling section

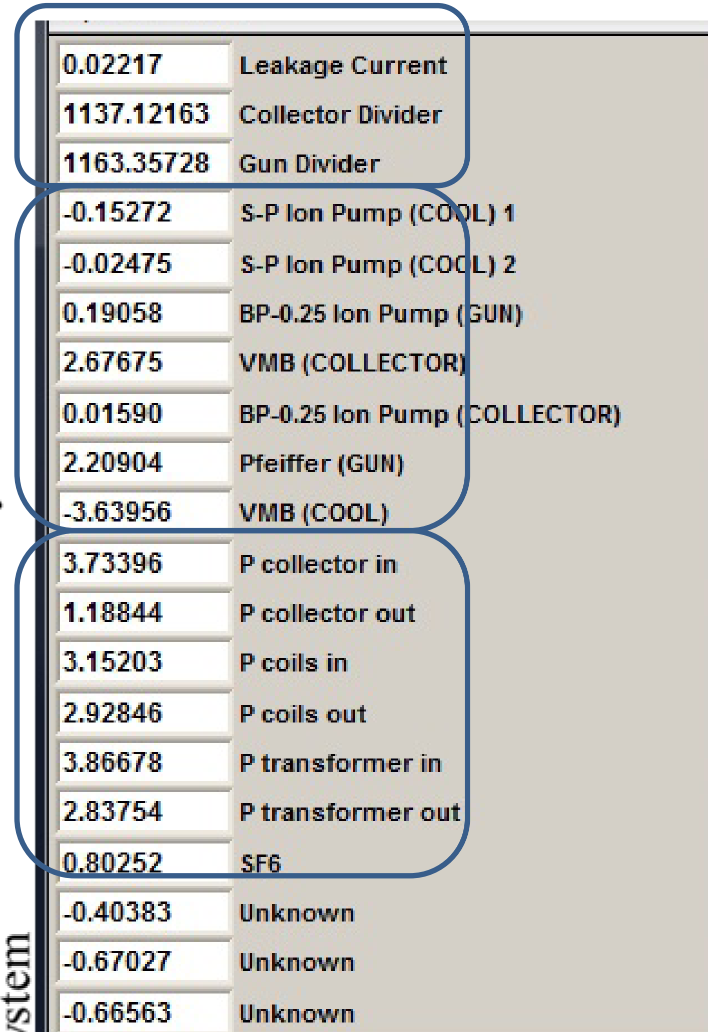
Cascade Transformer Power Supply



Technician divider

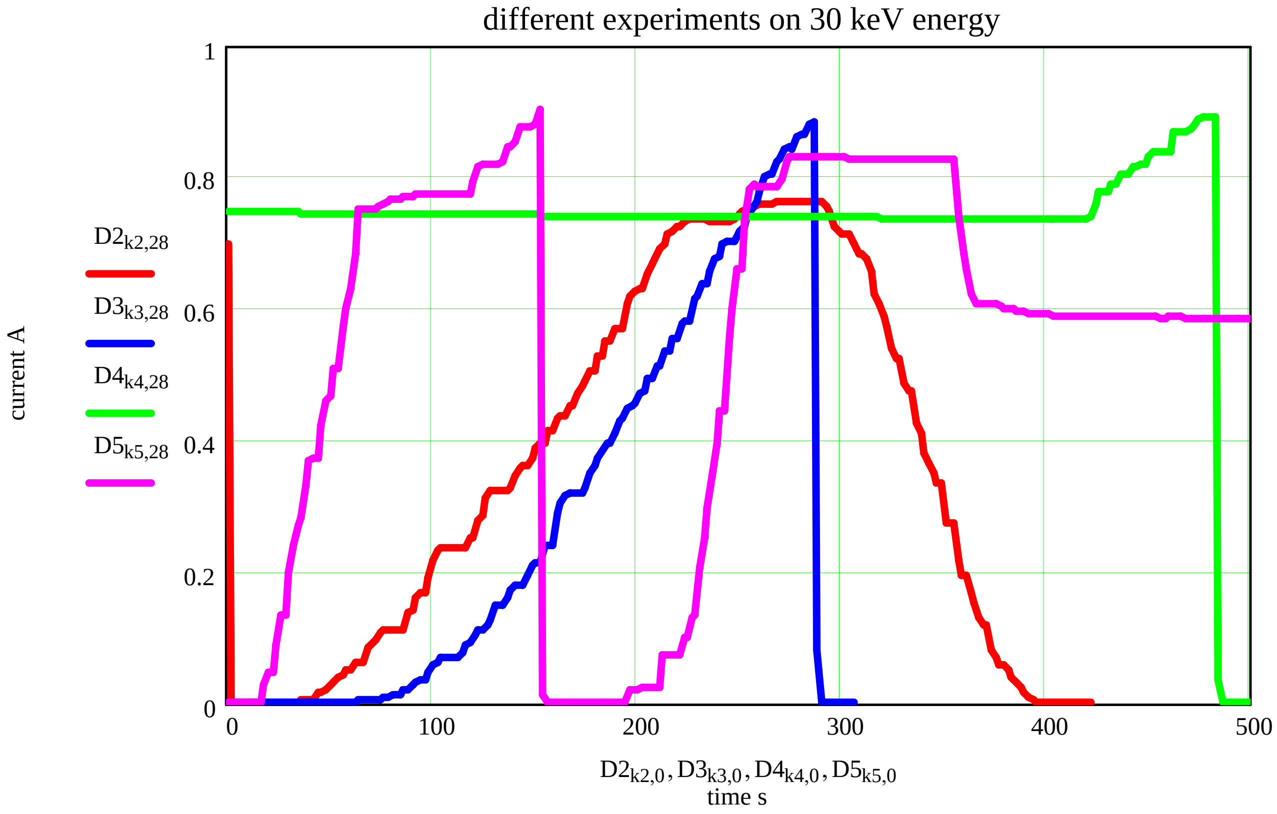
Vacuum System

Pressures in oil system

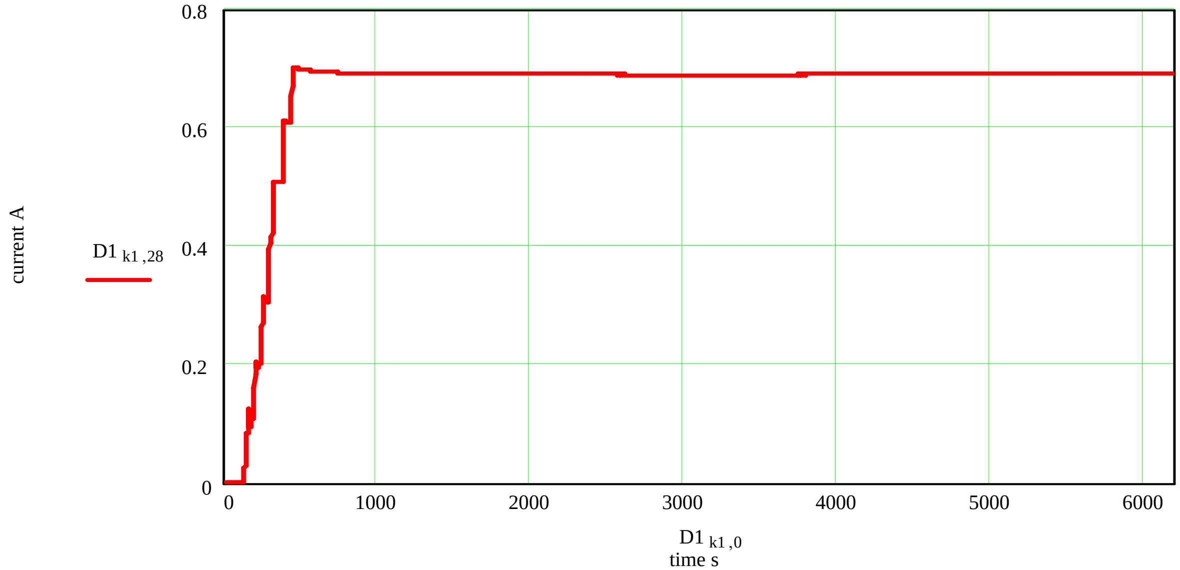


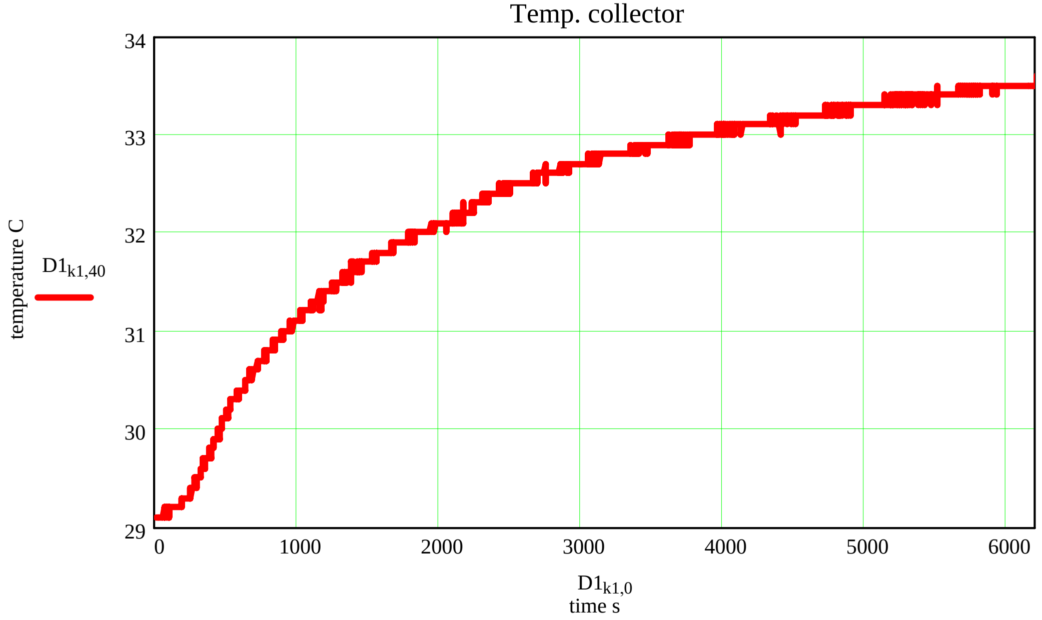
associated measurements

30 kV operation, current 0.8-0.9 A



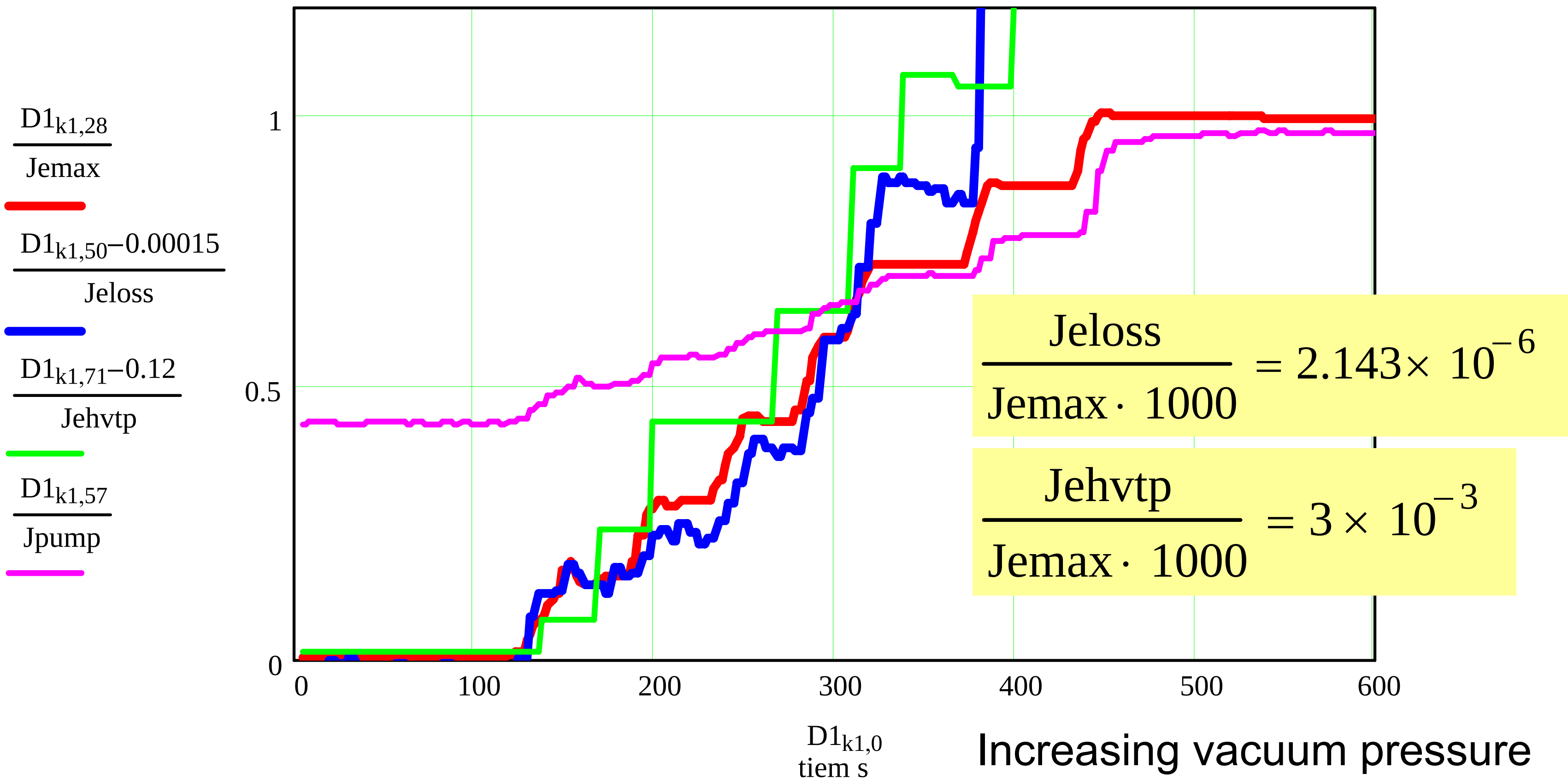
2 hour 30 kV *0.7 A operation





Temperature of collector
29→33 C

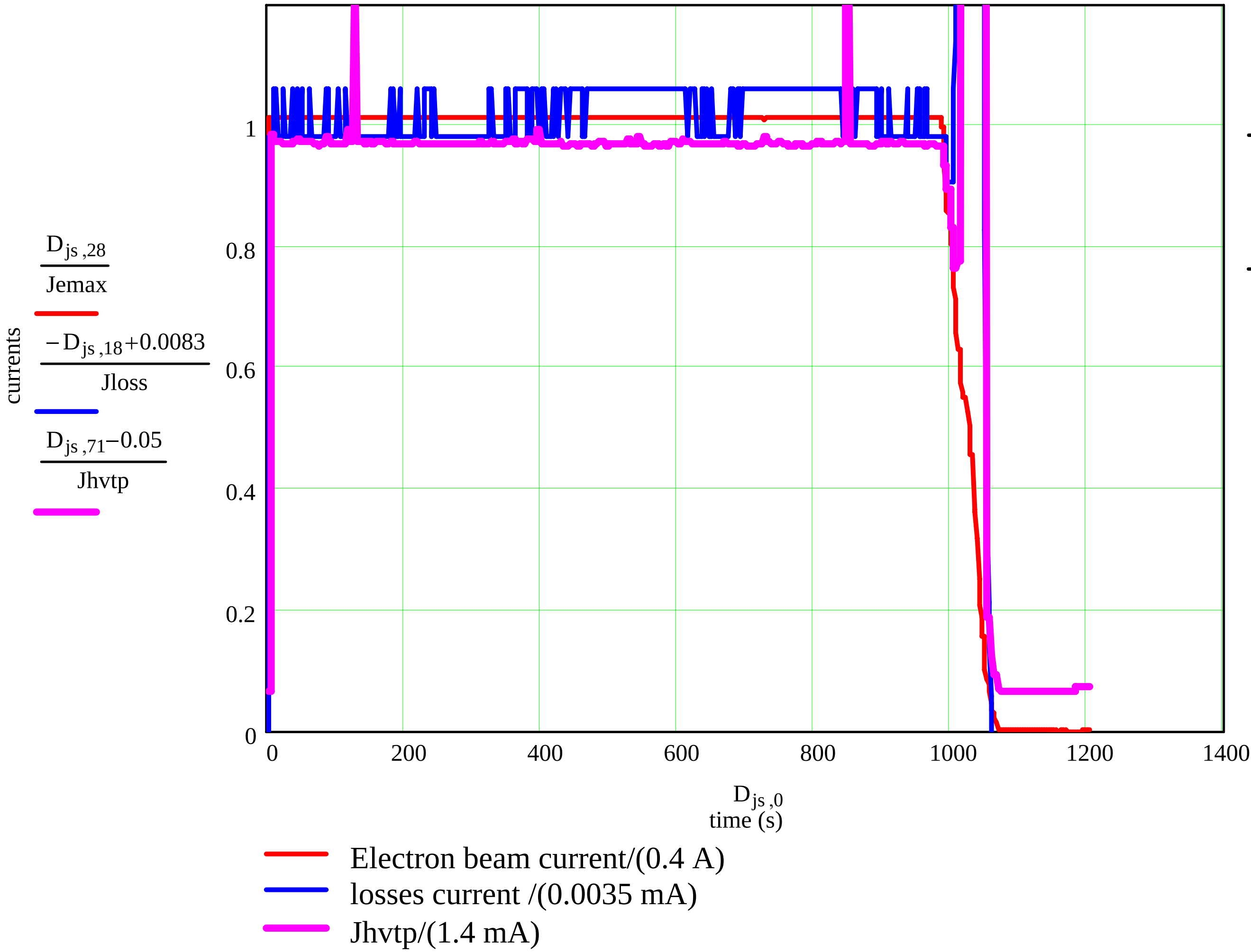
Recuperation on 30 kV



Je/(0.7 A)
Jloss/1.5 mkA
Jhvtp/(2.1 mA)
Ion pump current/15 mkA

Increasing vacuum pressure by degassing vacuum chamber of electron beam bombarding is main limitation in current!

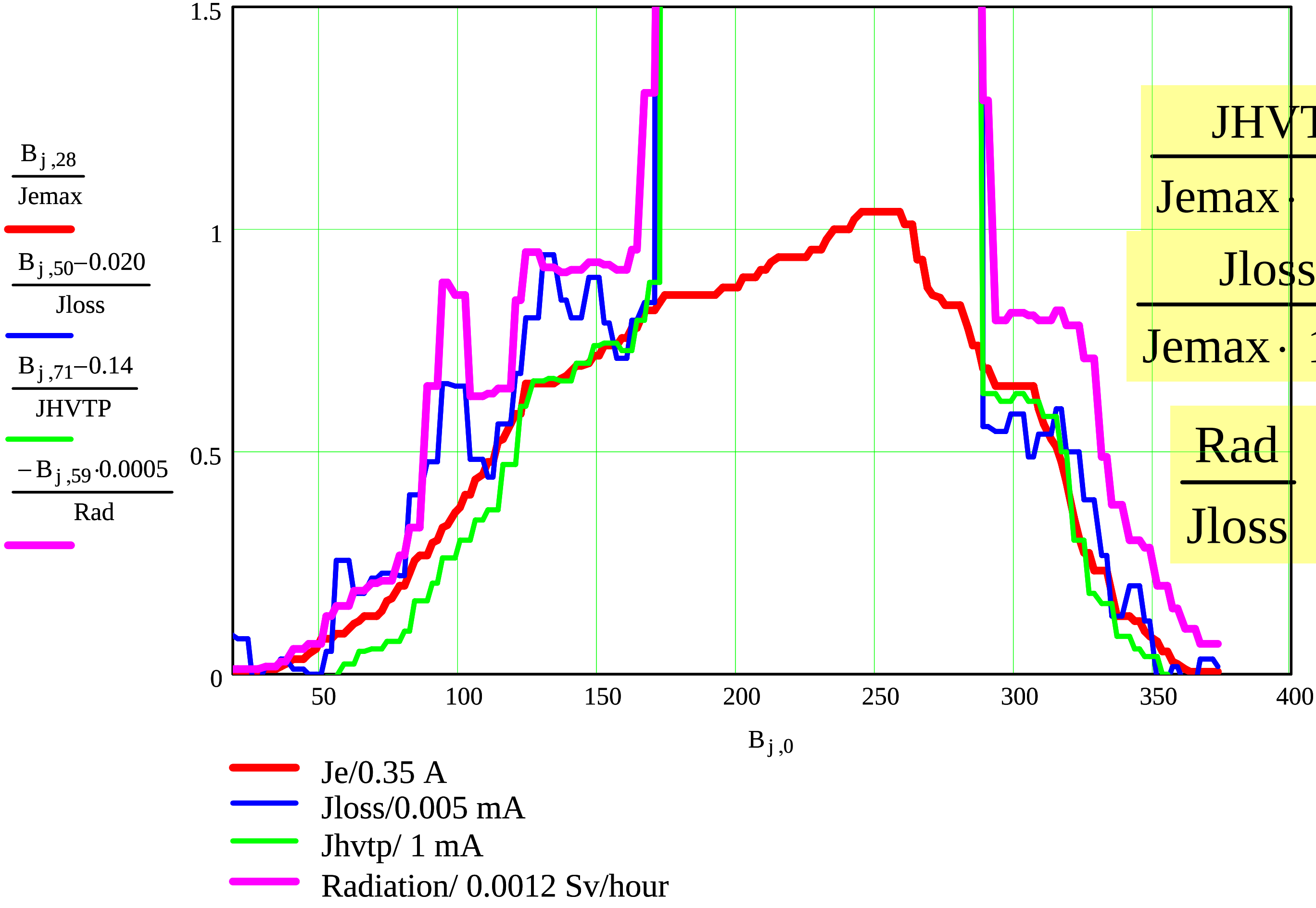
150 keV



$$\frac{Jloss}{Jemax \cdot 1000} = 8.75\times 10^{-6}$$

$$\frac{B_{40,71} - B_{2,71}}{Jhvtp \cdot 1000} = 9.075\times 10^{-4}$$

1000 keV

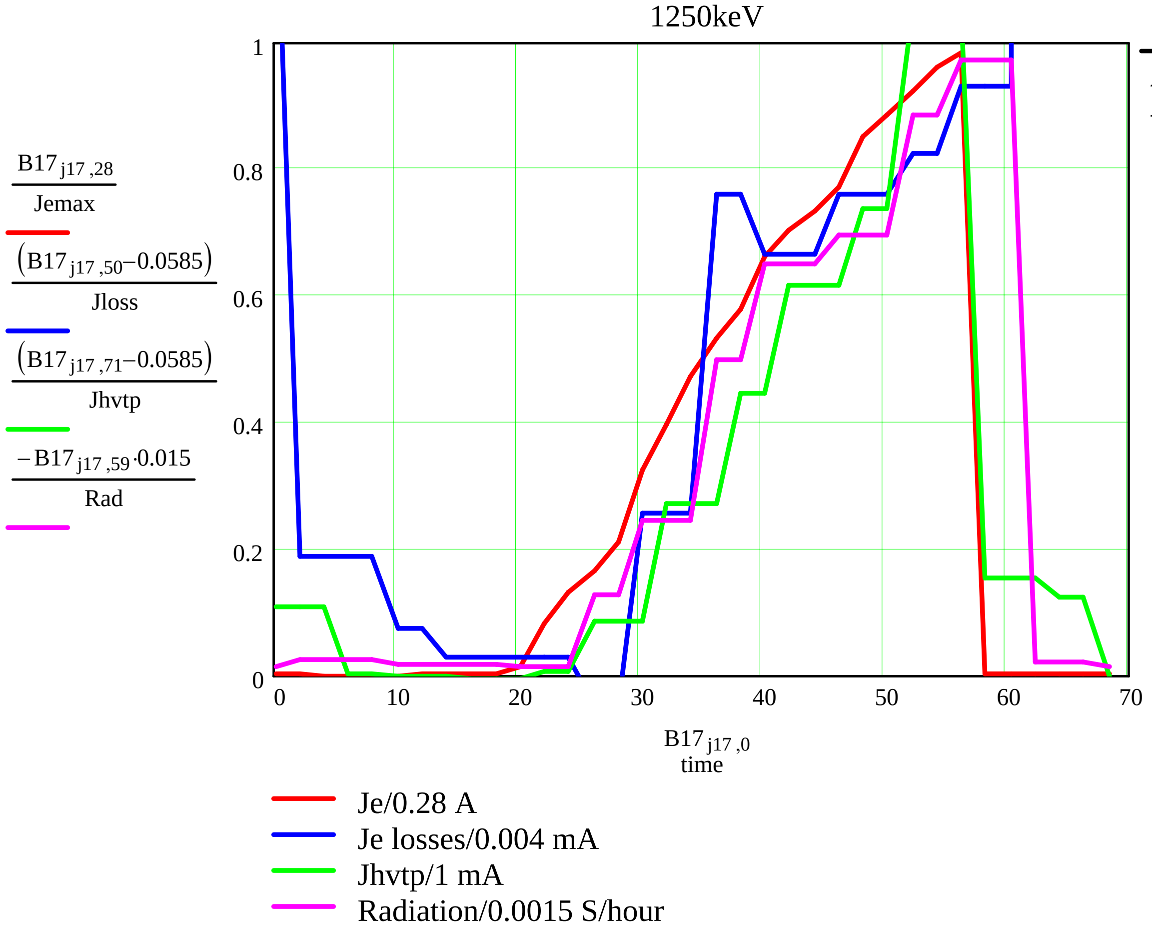


$$\frac{JHVTP}{Jemax \cdot 1000} = 2.857 \times 10^{-3}$$

$$\frac{Jloss}{Jemax \cdot 1000} = 1.429 \times 10^{-5}$$

$$\frac{Rad}{Jloss} = 0.24$$ Sv/h/mA

1250 kV

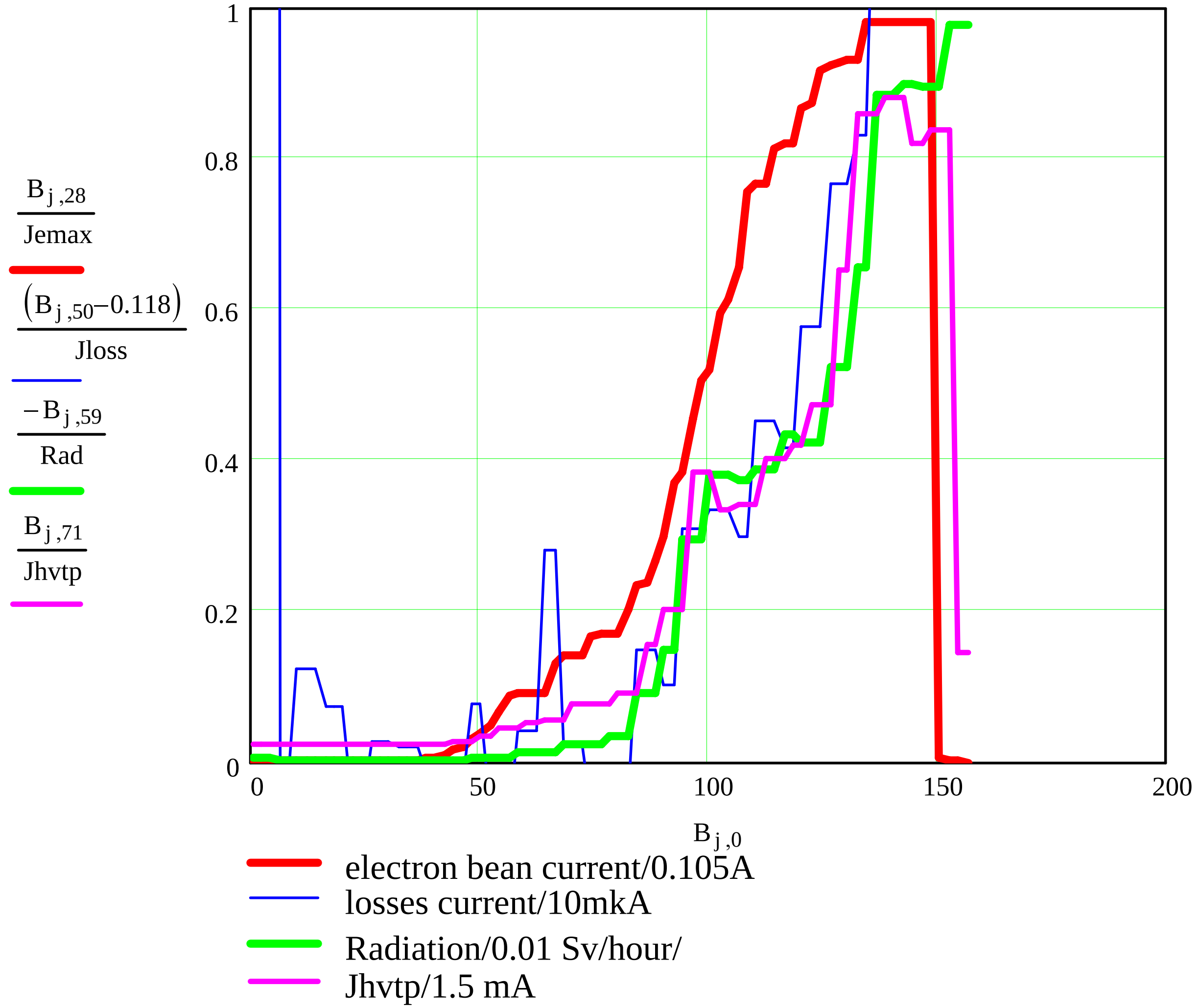


$$\frac{Jloss}{1000 \cdot Jemax} = 1.429\times 10^{-5}$$

$$\frac{Jhvtp}{1000 \cdot Jemax} = 3.571\times 10^{-3}$$

$$\frac{Rad}{Jloss} = 0.375$$

1500 kV



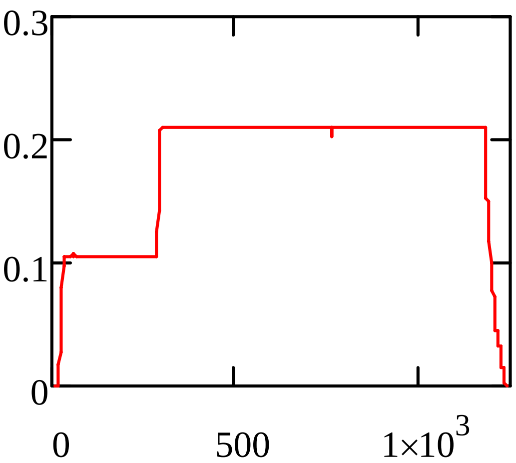
$$\frac{Jloss}{1000 \cdot Jemax} = 9.524 \times 10^{-5}$$

$$\frac{Jhvtp}{Jemax \cdot 1000} = 0.014$$

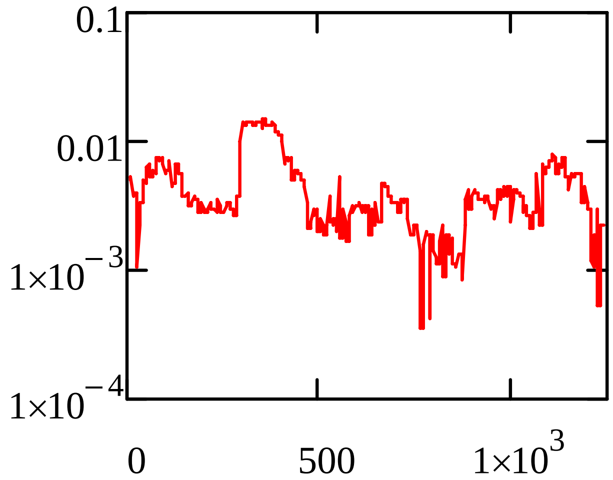
Rad/Jloss=0.75 Sv/hour/1mA

Example of the long training regime - 20 min, the electron current was increased and decreased in nominal regime. The electron energy 1 MeV

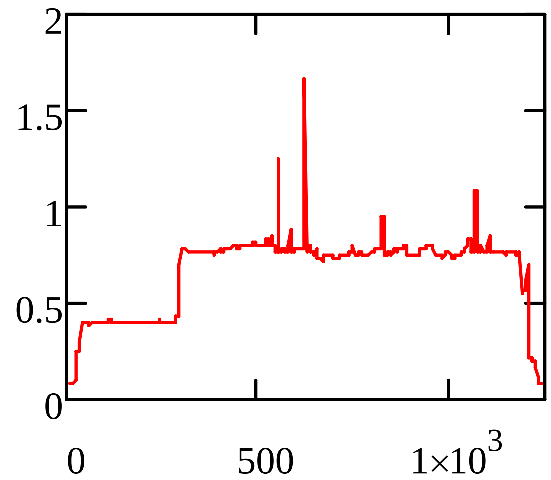
Je, mA



Jleak, mA

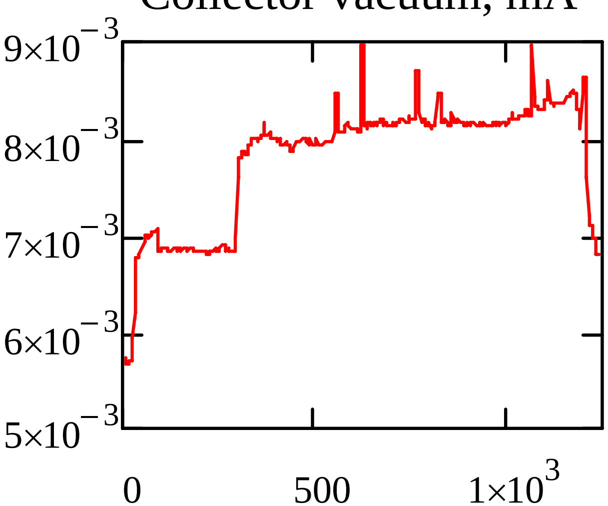


J_{HVTP}, mA



t, sec

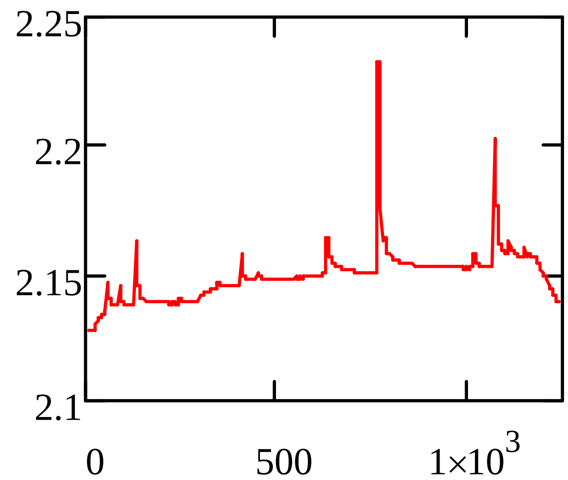
Collector vacuum, mA



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.

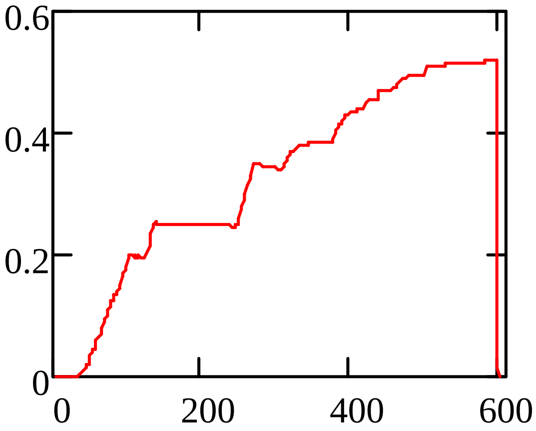
Gun vacuum, 10^{-8} mbar



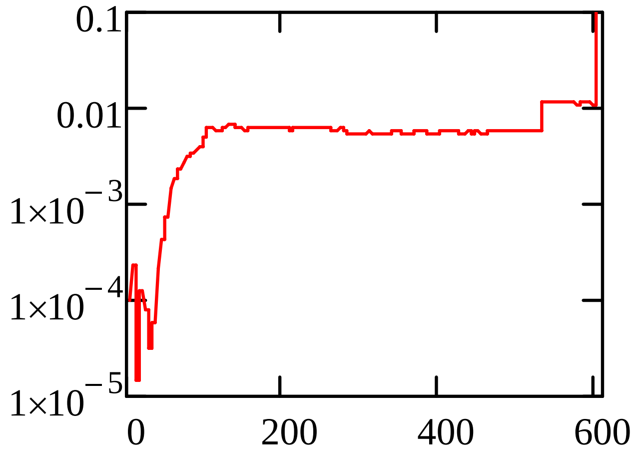
t, sec

Example of the regime with a recuperation breakdown. The electron energy 1 MeV. The essential prior events isn't observed.

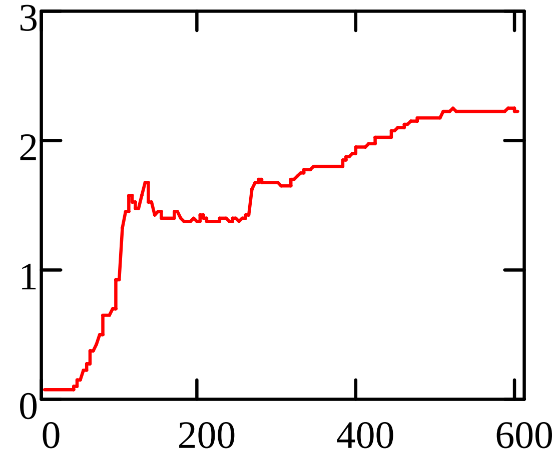
Je, mA



Jleak, mA

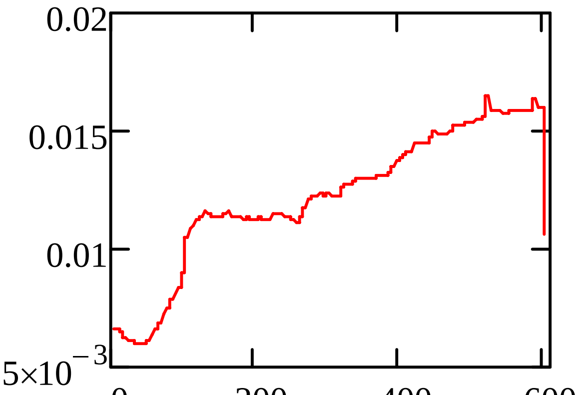


J_{HVTP}, mA



t, sec

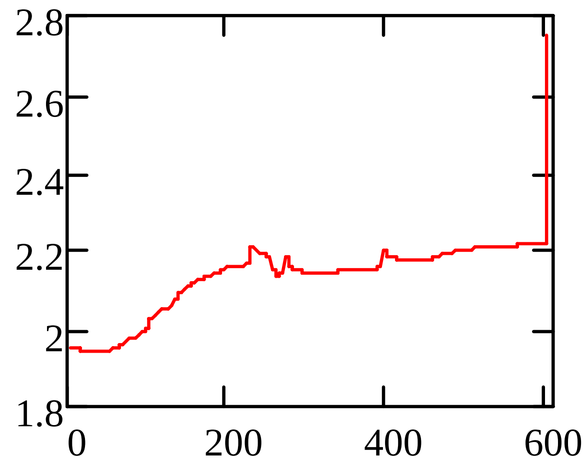
Collector vacuum, mA



t, sec

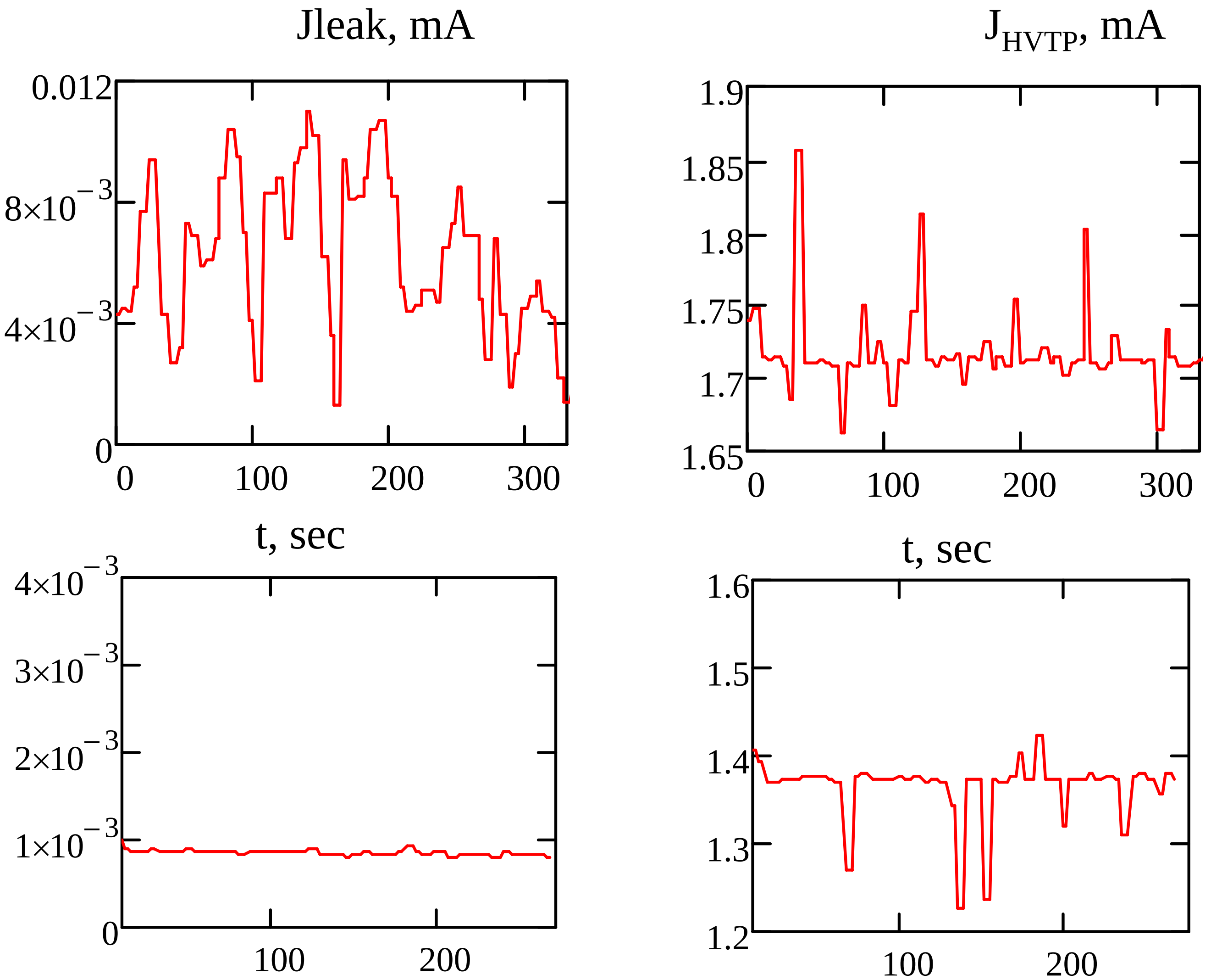
The current 500 mA was obtained.

Gun vacuum, 10^{-8} mbar



t, sec

Training of new orbit at 30 keV energy

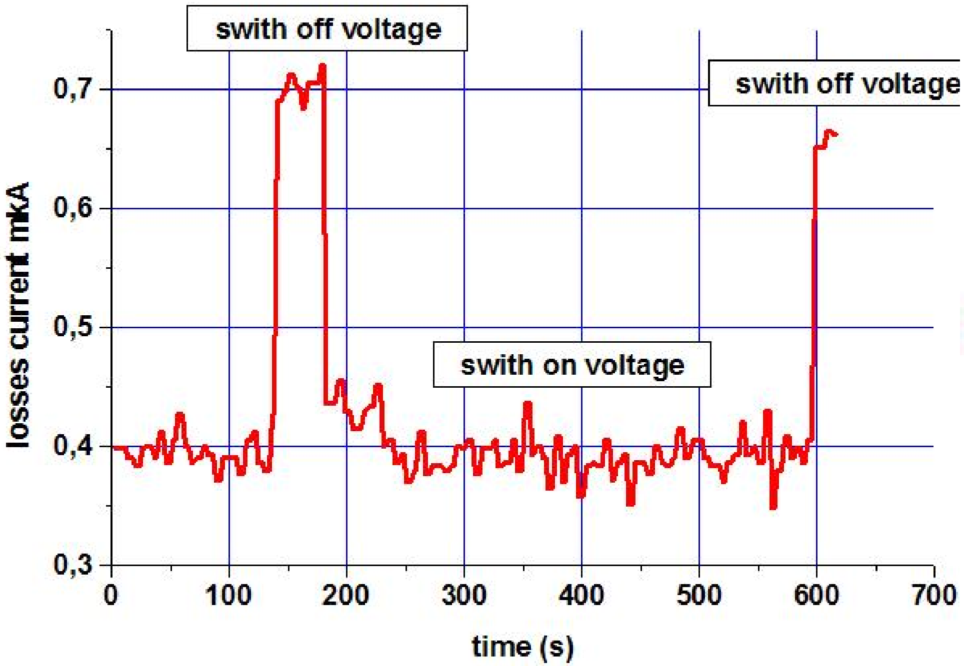


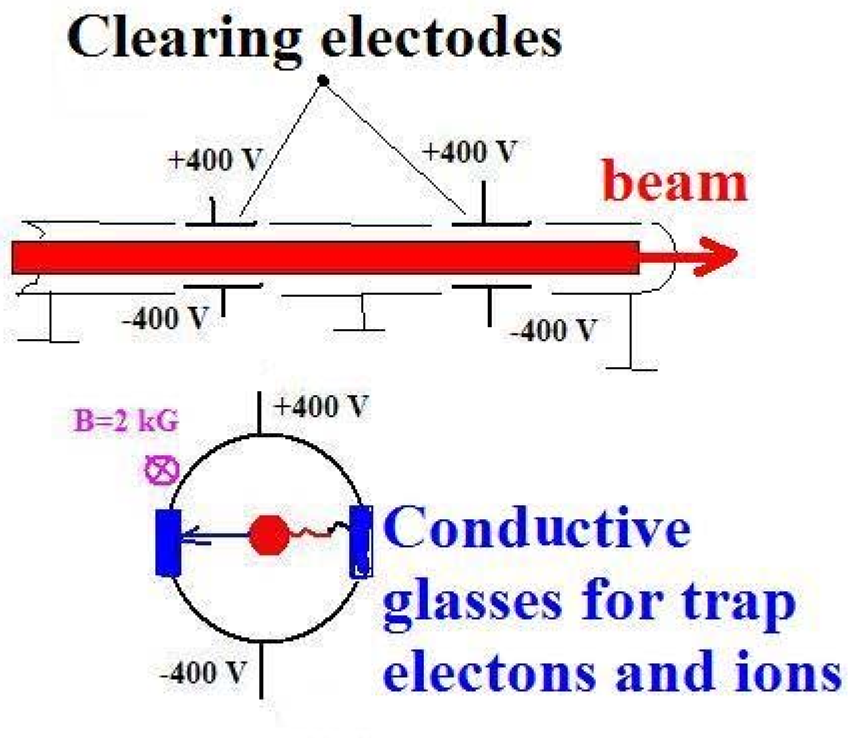
Je=370 mA

Je=270 mA

Below some current value the behavior of the electron current is dramatically change. There is no any fluctuation of the leakage current. The reason is some dynamic of the secondary ions.

Clearing electrodes





Increasing losses current from 0.4 mkA to 0.7 mkA when the clearing voltage switch off

Beam U=30 keV Je=0.1 A

For ionization cross section 1E-17 cm^2 vacuum average along beam 7E-9 mbar   gives 0.3 mkA ionization current

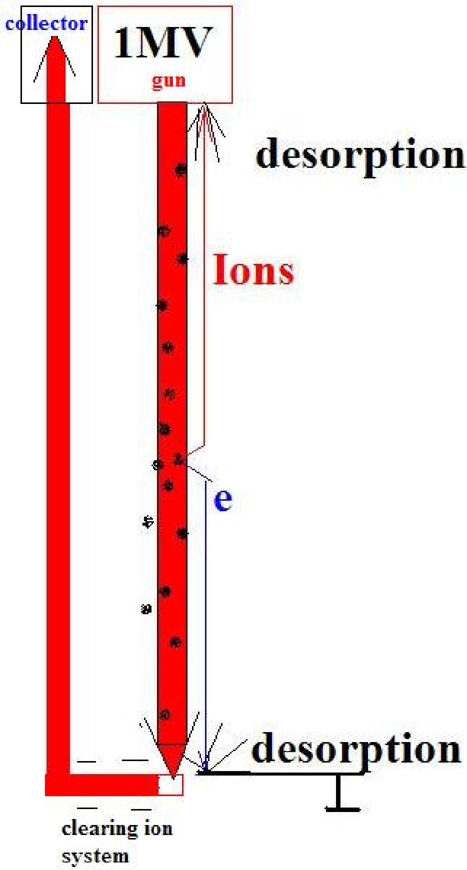
Vacuum instability-
by desorption under action of secondary ions and electrons

Collector efficiency + ions current from ionizing gas

$$J_{loss} = (\alpha + a * p) * J_e$$

$$p = p_0 + b * J_{loss} \quad J_{loss} = \frac{(\alpha + p_0 \times a) \times J_e}{1 - a \times b \times Je}$$

$$a \times b = \frac{\sigma_i * dl * \eta}{q * dVpump / dt}$$



$\sigma i := 10^{-16}$ Cross section ionization of residual gas cm^2

$dl := 1500$ Length of electron beam cm

$\eta := 0.1$ Desorption atoms/ion 100-0.01

$dVdt := 20000$ Pumping rate cm^3/s

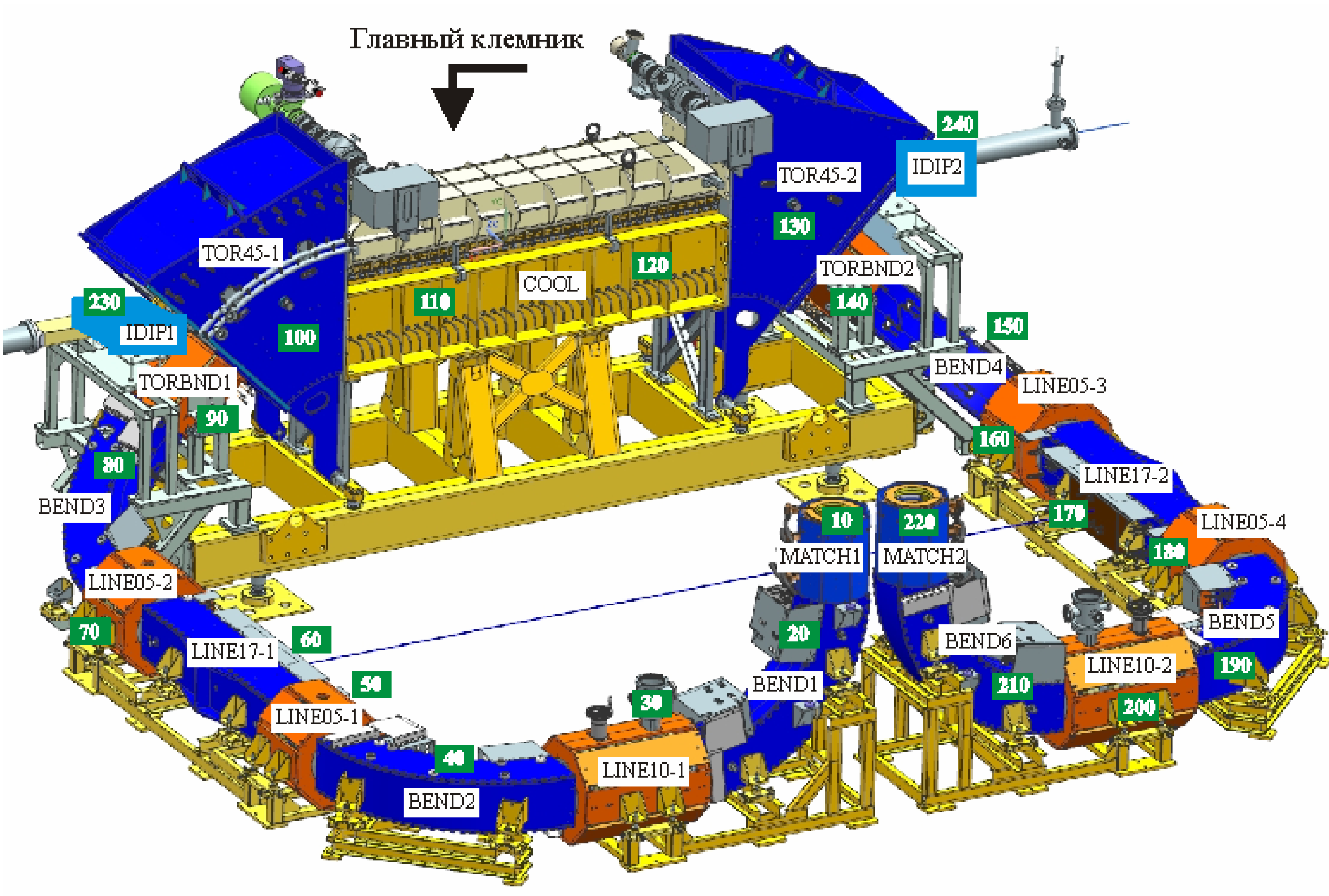
$q := 1.6 \cdot 10^{-19}$ Electron charge coolon

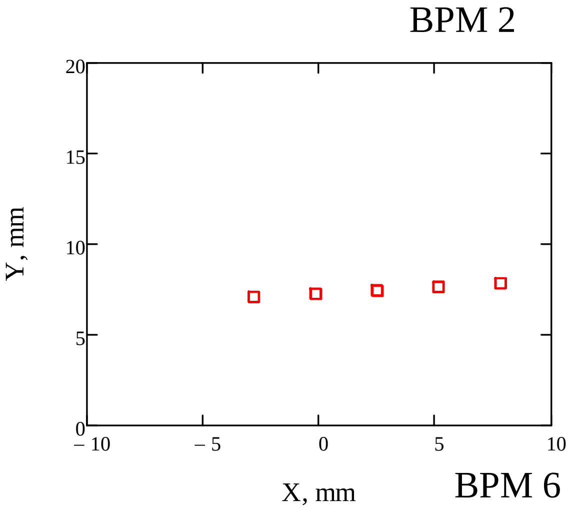
$$d := \frac{\sigma i \cdot \eta \cdot dl}{q \cdot dVdt} \qquad d = 4.688$$

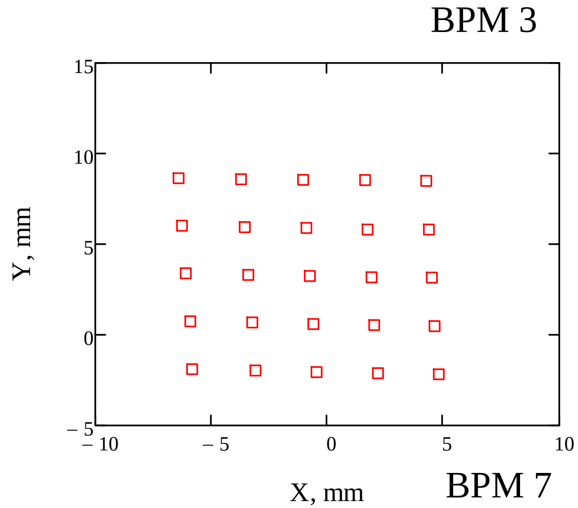
Jemax=0.2A

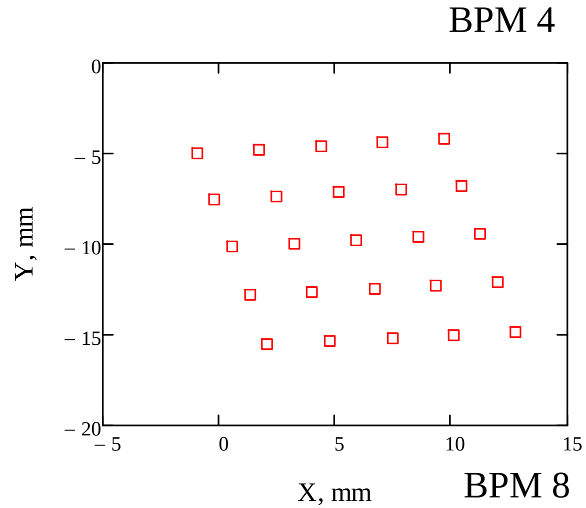
Training by electron beam decrease η there is the only way!

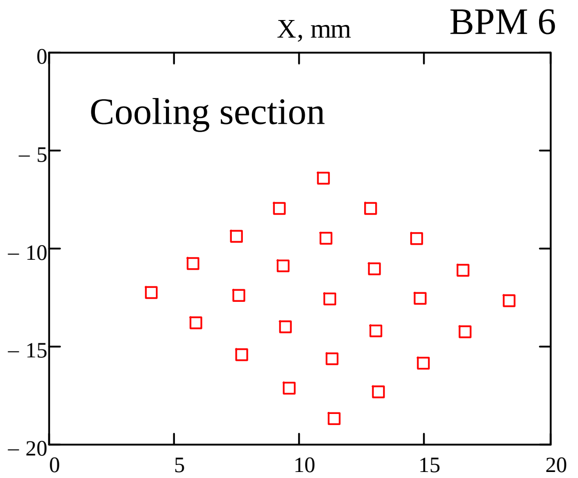
Magnetic elements of the COSY electron cooler

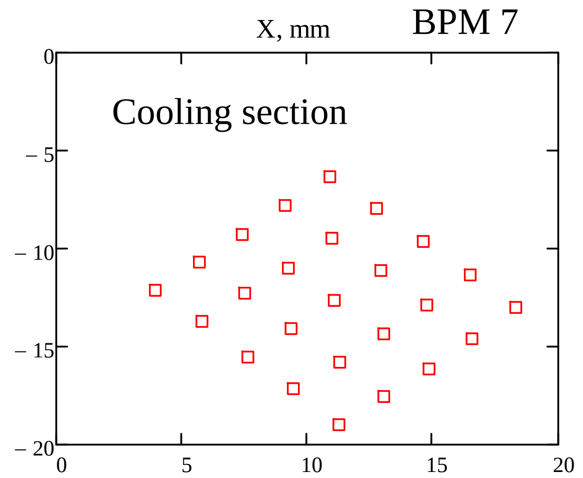


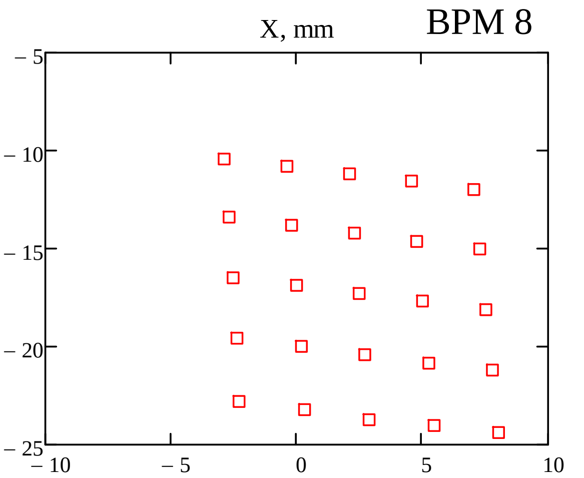


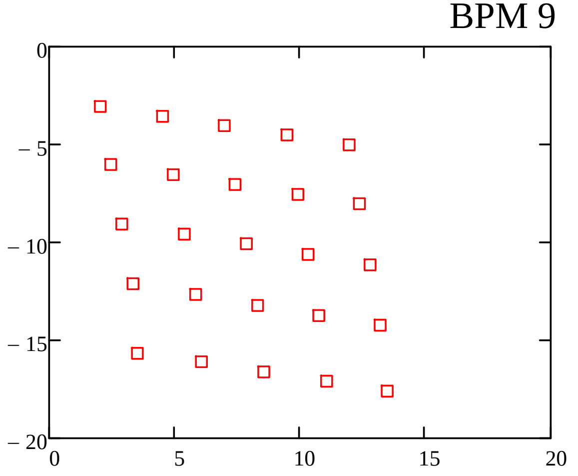


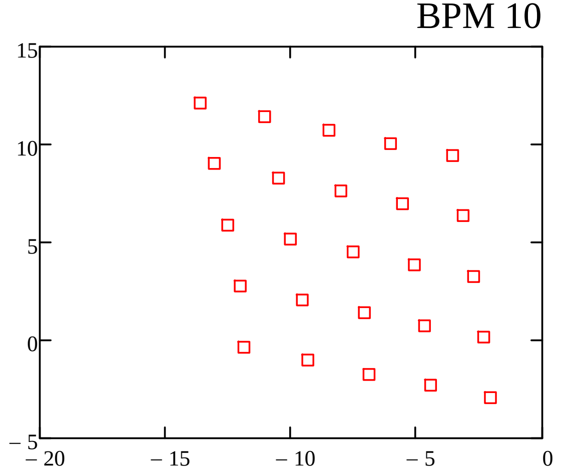










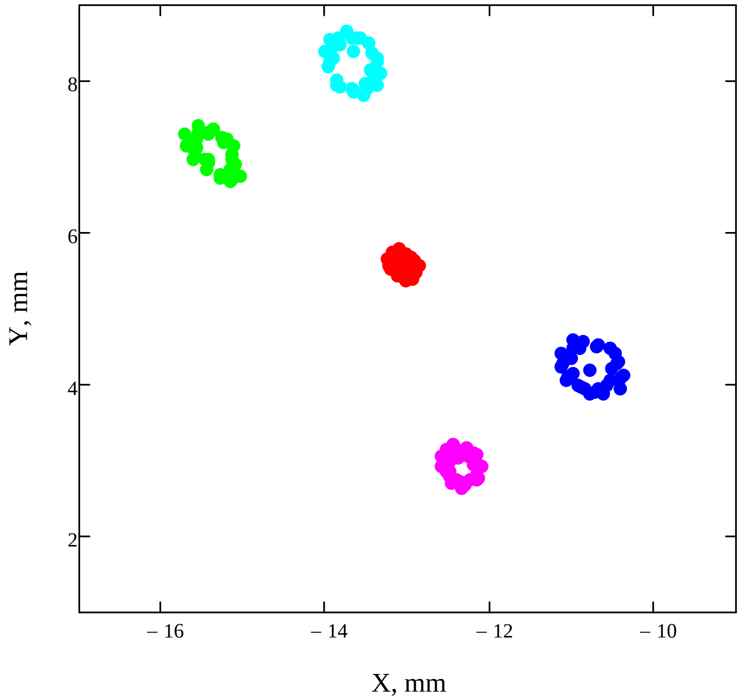


Demonstration of the BPM working.

Scanning bend1 and bend2 magnets

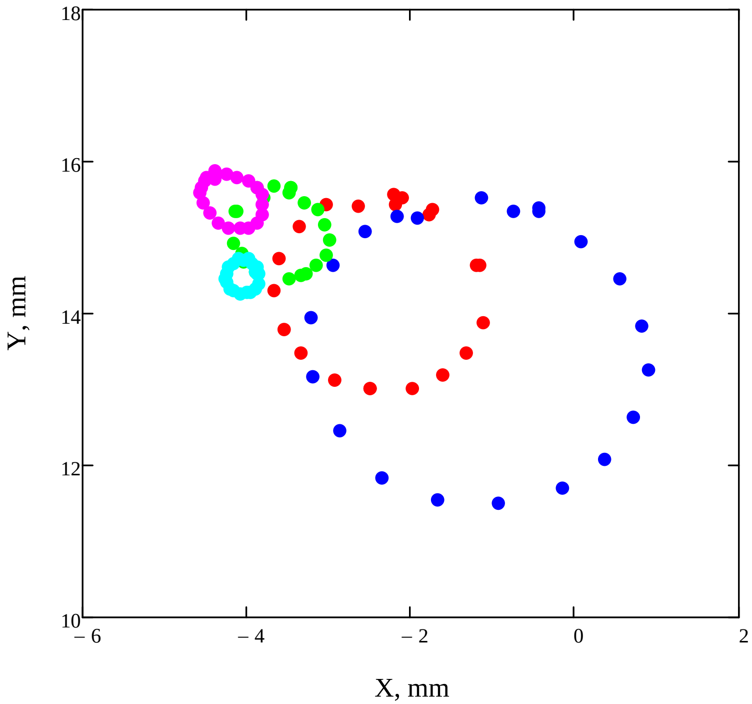
Control of the dipole component of electron motion

Energy 150 keV, pick-up 10,
Scanning of the magnetic field in the cooling section130-145 A (about 2.5 larmour oscillations)



Electron Dipole Correctors is +/- 3A

Energy 1000 keV, pick-up 10,
Scanning of the magnetic field in the cooling section 250-270 A (about 1 larmour oscillations)



ediphor= 0.0 A, edipver=0.0 A
ediphor= 3.0 A, edipver=0.0 A
ediphor= -3.0 A, edipver=0.0 A
ediphor= -4.0 A, edipver=0.0 A
ediphor= -4.5 A, edipver=2.0 A

Conclusion:
Results of commissioning cooler looks very permissible for next step at developing of the high voltage cooler.
Initial push for start this project for COSY was

"COOL05 from report **Jürgen Dietrich Forschungszentrum Jülich GmbH**
Step towards HESR Cooler
Technologically (0.3 MV > 2 MV > 8 MV)
Physically (model verification)

Interplay of electron and stochastic cooling"

Now we will have hard and interesting job for realization proton beam cooling at COSY. This step will demonstrate potential of magnetized cooling on high energy.

Thanks all BINP colleges