“Electron cooling device in the project NESR (FAIR)"

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List of the electron cooling devices manufactured from 1988:
LEAR, IUCF, TSR, CELSIUS, TARN-II, ESR, CRYRING, ASTRID, COSY, USA (FNAL),
+ BINP – Germany SIS (1998), China (CSRm, CSRe), Switzerland CERN

The possibility to storage and many-hours traps of the charge ions in the different charge state enables to produce a many interesting experiments in the nucleus and atomic physics.

Physics results obtained with electron cooling

list is not completed

LEAR – all experiments with a slow antiprotons becomes realizable due to use an electron cooling at deacceleration of the antiprotons

ESR (GSI)

- the masses of 280 isotopes was measured with high accuracy

- the masses of 69 isotopes was measured in the first time

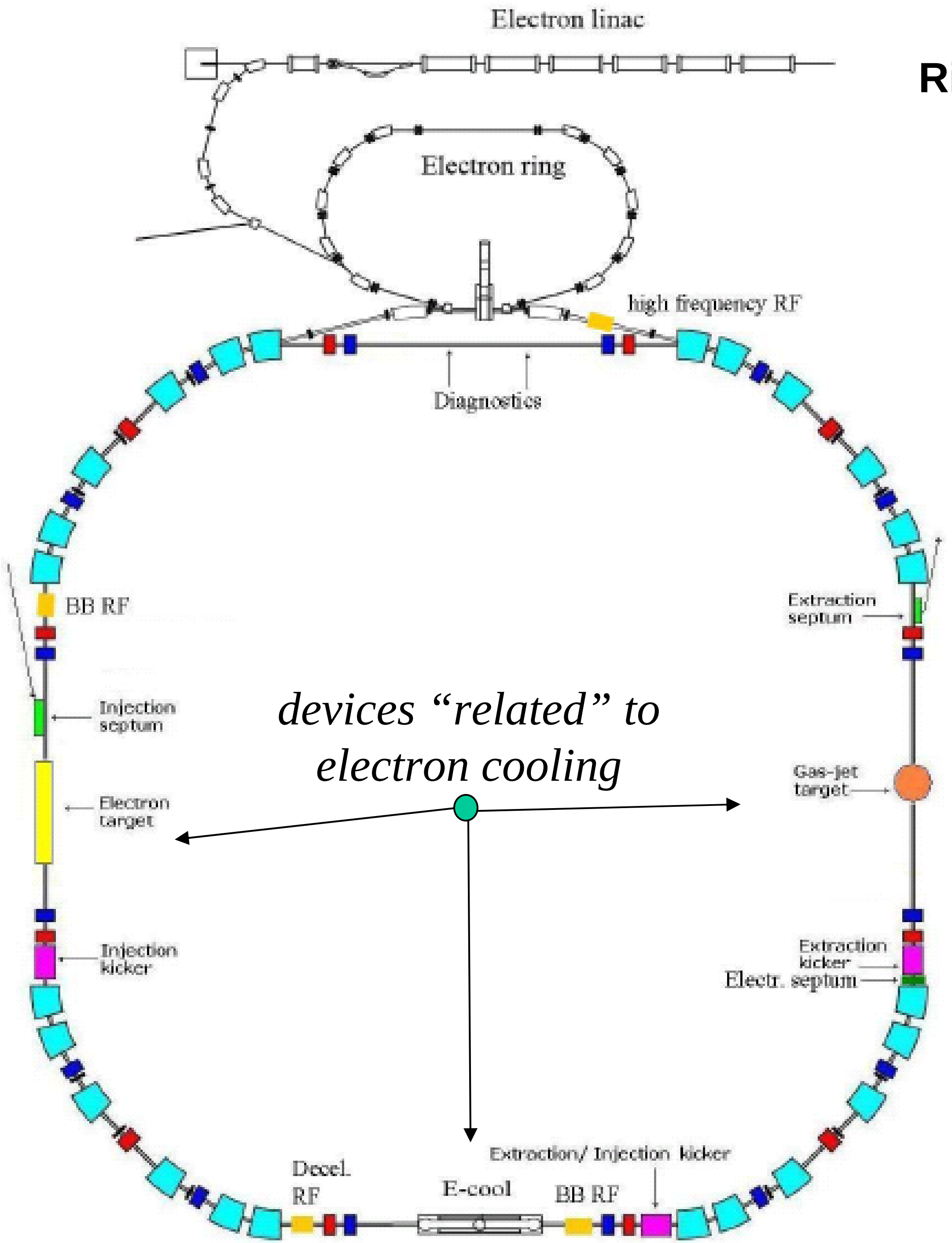
- the life-time of “bare" beta-radioactive nuclei Mn_{52}, Fe_{52} и Fe_{53} was measured

- the precision measurement of the Lamb shift $U_{91}{}^{+}$

-- beta decay of the fully ionized dysprosium element Dy (A=163, Z=66). This element is stable at the standard condition but the ionization opens the additional channels for decay.

Bloomington (USA) – particle physics

TSR (Heidelberg) – the atomic spectroscopy, the recombination, the laser cooling and getting the extremely low effective temperature in the co-moving reference frame a few fraction mK



The New Experimental Storage Ring NESR with its instrumentation for atomic physics experiments

1. Electron cooler
2. Electron target

The NESR will be filled with energetic highly-charged heavy ions and with exotic nuclei. At the gas jet target ion-atom reactions as well as the structure of ionized atoms will be studied; x-ray spectroscopy, zero-degree electron spectroscopy, recoil-ion-momentum spectroscopy, and laser spectroscopy will be available. At the electron target the atomic assisted electron-electron interaction will be studied; here also laser techniques and x-ray spectroscopy will support the experiments.. Moreover, the highly-charged heavy ions can be decelerated in the NESR down to the MeV/u region and extracted toward a fixed target area. There, atomic reactions with highly-charged ions at low velocities will be performed; x-ray spectroscopic and laser techniques will be applied.

Table 1: NESR beam parameters.

	antiprotons	ions
Injection energy [MeV/u]	3000	100–740
Lowest extraction energy [MeV/u]	30	4
Max. number of particles	10^9	10^{10}
$\Delta p/p$ (2σ) at injection	$\leq 1\ 10^{-3}$	$\leq 5\ 10^{-4}$
Transverse emittance $\varepsilon_{H,V}$ (2σ) [mm mrad] at injection	≤ 5	≤ 0.5
$\Delta p/p$ (2σ) after cooling	$\leq 10^{-4}$	$\leq 10^{-4}$
Transverse emittance $\varepsilon_{H,V}$ (2σ) [mm mrad] after cooling	1	0.1–1

Table 2: NESR machine parameters.

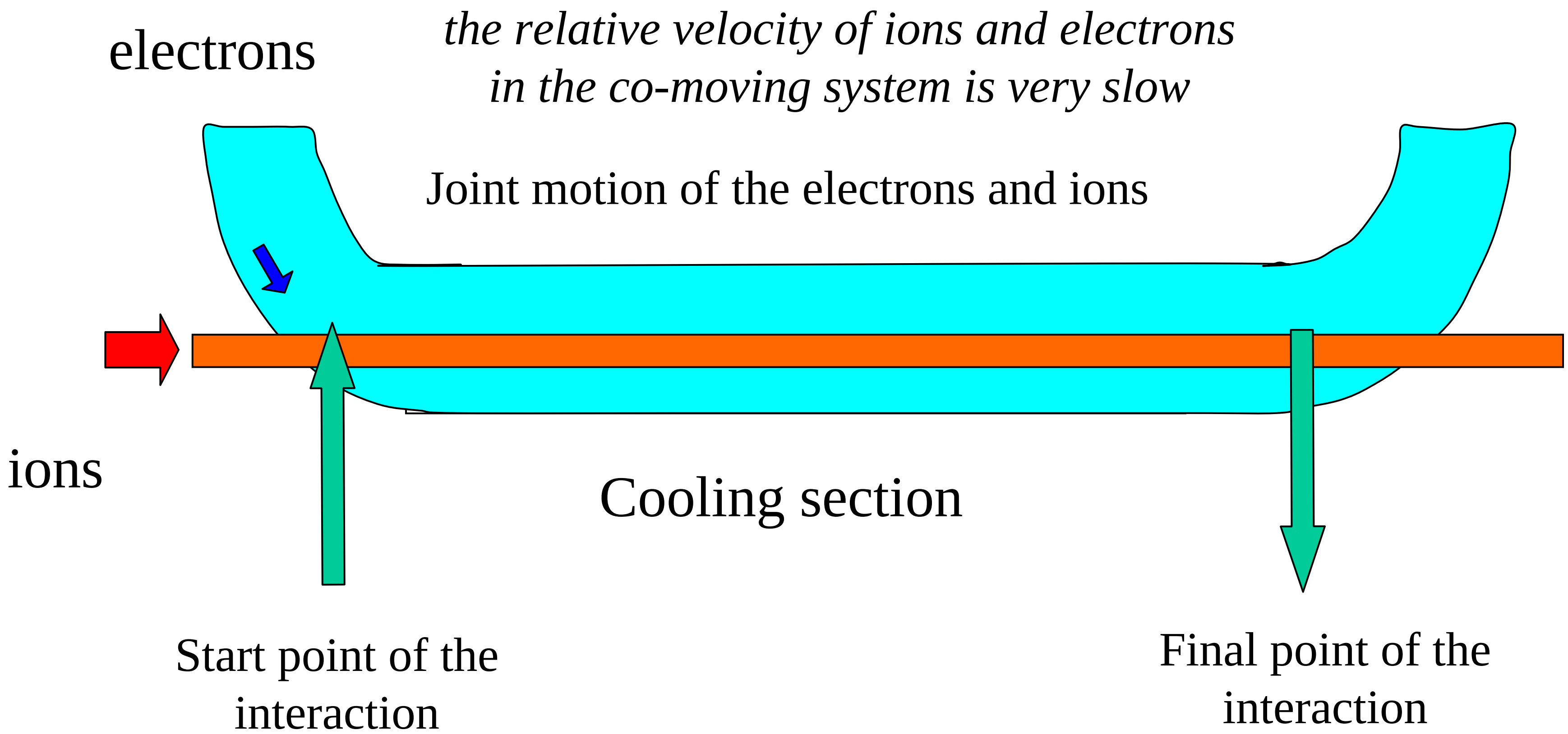
Circumference	222.8 m
Length of straight sections	18 m
Maximum bending power	13 Tm
Minimum bending power after deceleration	0.52 Tm
Max. dipole magnetic field	1.6 T
Max. ramp rate of ring dipole magnets	1 T/s
Maximum A/Z	2.7
Momentum acceptance ($\varepsilon_x = 0$)	$\pm$ 2.5 %
Horizontal acceptance ($\Delta p/p = \pm$ 1.5 %)	150 mm mrad
Vertical acceptance ($\Delta p/p = \pm$ 1.5 %)	40 mm mrad
Horizontal tune Q_x	4.20
Vertical tune Q_y	1.87
Transition energy γ_t	4.59
Maximum dispersion	6.8 m
Beam cooling systems	electron cooling
Vacuum pressure	$\leq 10^{-11}$ mbar

Scheme of the electron cooling

electron cooling - beam preparing

electron target – physics experiment

<u>The energy transfer from the hot ions to the cold electrons</u>



Kinetic equation of the evolution of the distribution function of the ions is complicate enough

$$\frac{dF^i}{dt} = St\left(F^i, F^i\right) + St\left(F^i, F^e\right) + St(F^i, t\arg et)$$

$$\frac{dF^i}{dt} = \frac{\partial F^i}{\partial t} + \frac{\partial F^i}{\partial \vec{q}} \cdot \frac{\partial H}{\partial \vec{p}} - \frac{\partial F^i}{\partial \vec{p}} \cdot \frac{\partial H}{\partial \vec{q}}$$

Hamiltonian dynamics of particles in the electromagnetic fields of the storage ring: betatron oscillation, synchrotron oscillation and so on

$$St\left(F^i, F^e\right)$$

$$St\left(F^i, F^i\right)$$

$$St\left(F^i, t\arg et\right)$$

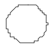
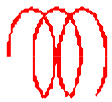
collisional processes

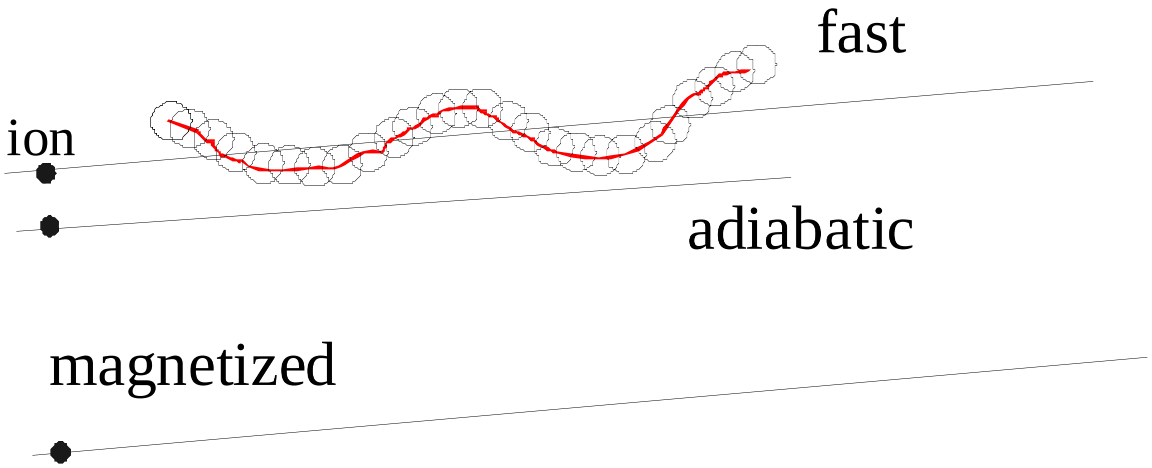
$$St\left(F^i, F^e\right) = \frac{\partial}{\partial p_\alpha}\left(A_\alpha\left(F^e\right)F_a + D_{\alpha\beta}\left(F^e\right)\frac{\partial F^a}{\partial p_\beta} \right)$$

each step demands the physics oversimplify model

most processes lead to non-gaussian distribution function, so direct Monte-Carlo simulation is preferable

Strong magnetized Coulomb interaction – collision types

Larmour motion  moving of force line of the magnetic field 



transverse temperature of the electron gas is not important for cooling

curve of the magnetic force line produces additional "temperature" of electron gas

free Coulomb collision	$\vec{F} = \frac{4\pi n_e e^4 L_C}{m_e} \frac{\vec{v}}{v_{e\perp}^3}$,	$\frac{e^2}{m v_e^2} < \rho < \frac{V}{\omega_H}$
multiply collisions $v \in \left[v_{e\parallel}, \infty\right]$	$\vec{F} = \frac{4\pi n_e e^4 L_C}{m_e} \frac{\vec{v}}{\left(v^2 + v_{e\parallel}^2\right) v_{e\perp}}$,	$\frac{V}{\omega_H} < \rho < \rho_L$
strong magnetization $v \in \left[v_{e\parallel}, \infty\right]$	$\vec{F} = \frac{4\pi n_e e^4 L_C}{m_e} \frac{\vec{v}}{\left(v^2 + v_{e\parallel}^2\right)^{3/2}}$.	$\rho_L < \rho < \frac{V \cdot \tau}{1 + \omega_{pe}\tau}$

Key physical processes for numerical simulation

1. Cooling force

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

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

$V_{\Delta\Theta}^2$ - curve of the magnetic force line

$V_{E\times B}^2$ - drift in the crossed E and B beam

V_e^2 - longitudinal temperature of the electron beam in co-moving reference system

V_s^2 - potential sagging induced by space charge

2. Process in the target

2.1 Ionization energy loss

2.2 Ionization energy spread

2.3 Angle scattering on the nucleus of a target

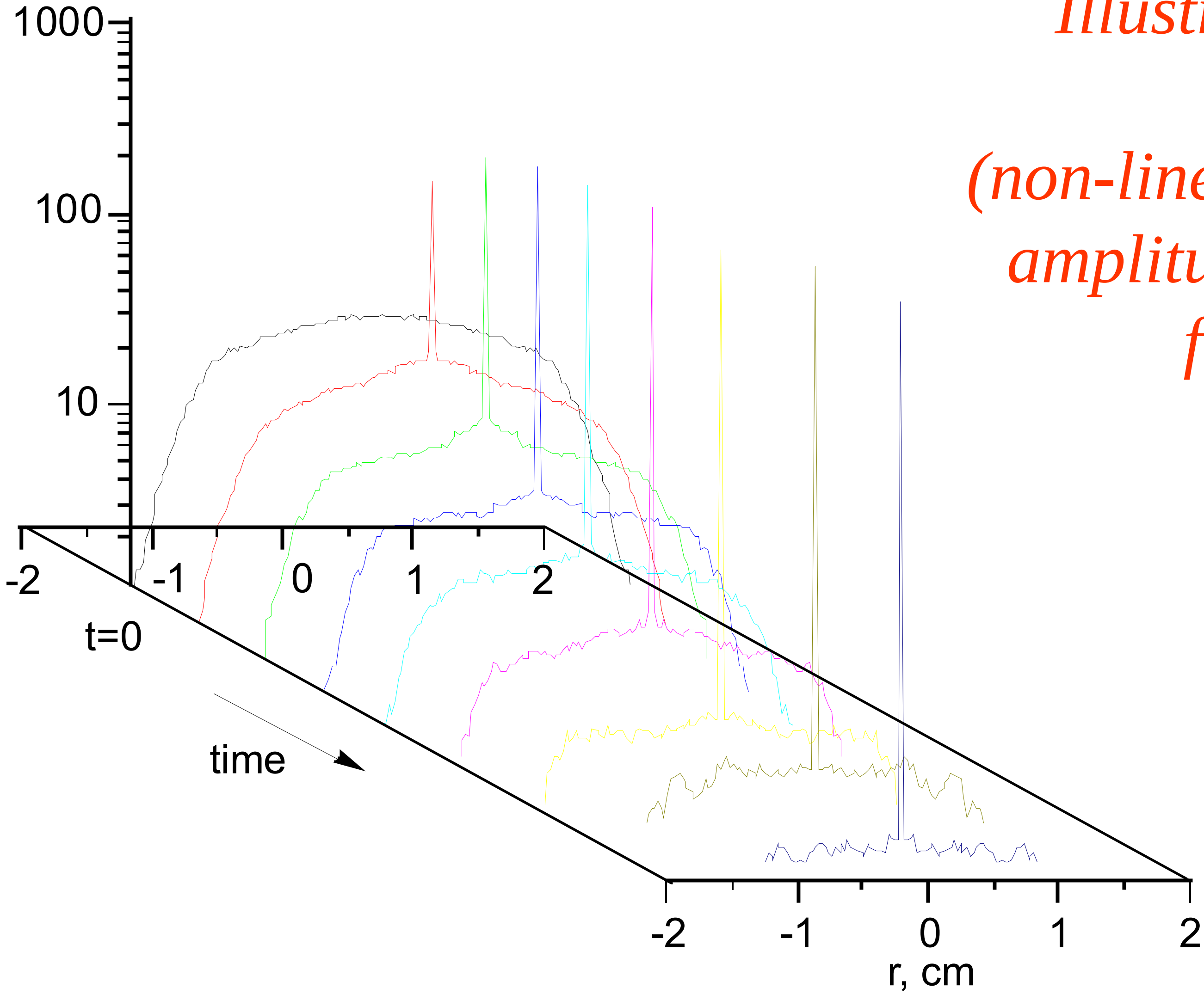
3. Space charge tune shift (Laslett tune shift)

4. Intra – beam scattering processes (the function distribution of the ions in the co-moving reference system is not stationary and in equilibrium)

5. Electron – ion recombination processes (for ion beam only)

Density of proton beam versus beam radius during cooling process

Illustration of the ion beam cooling (non-linear process, low amplitudes are cooling faster than large amplitude)



Example of the beam dynamic calculation with taking into account of target interaction

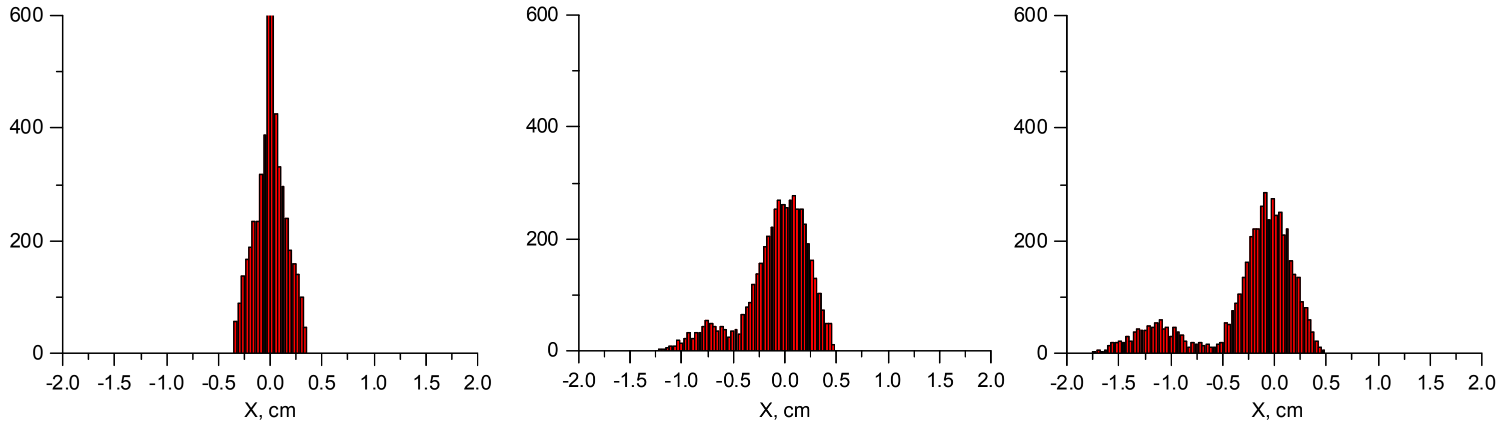


Figure 2.2.3. Picture 1. Changing distribution of the X-position during time.

X postion

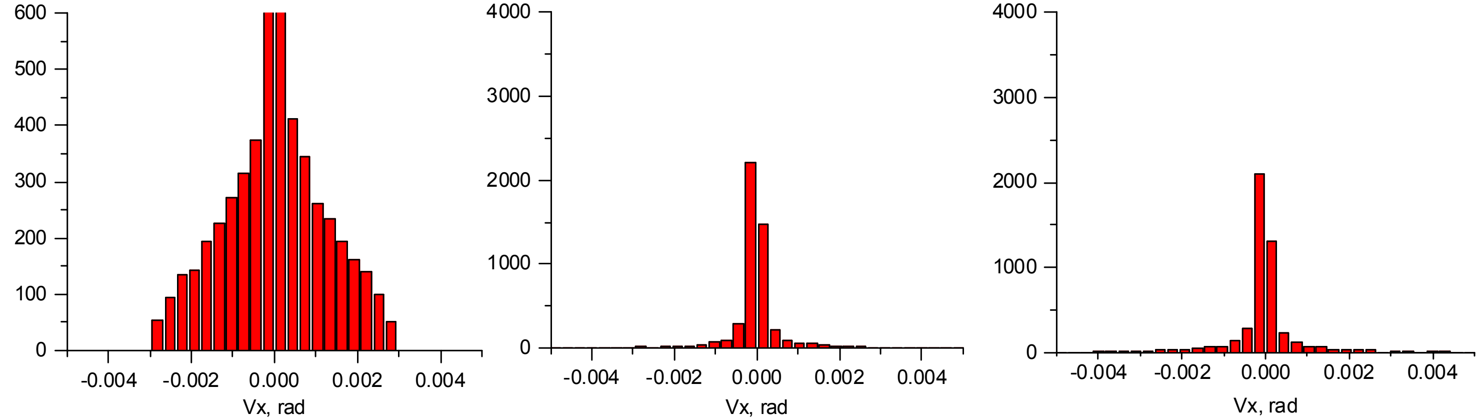


Figure 2.2.3. Picture 2. Changing distribution of the transverse angle during time.

angle

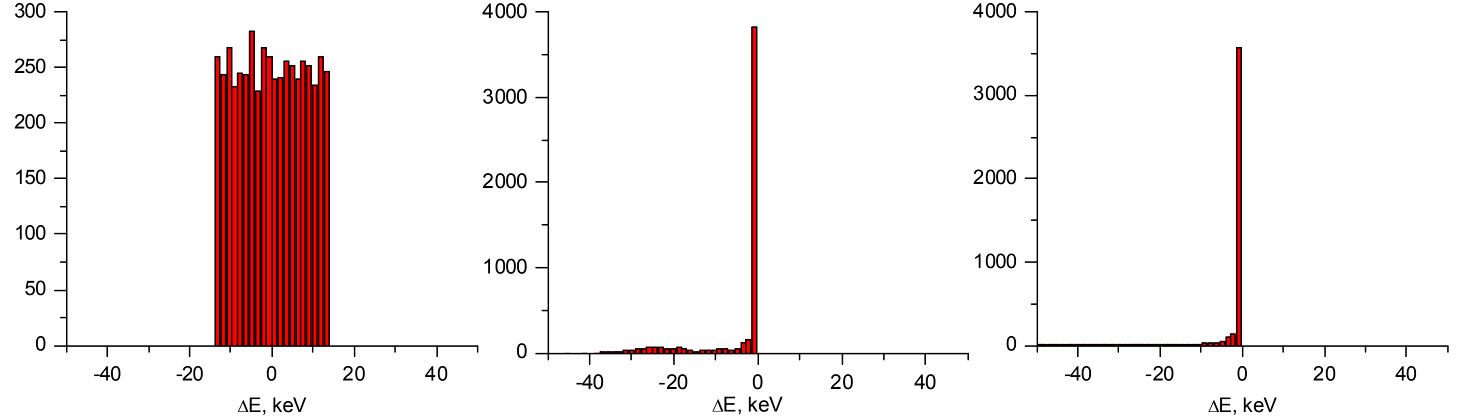
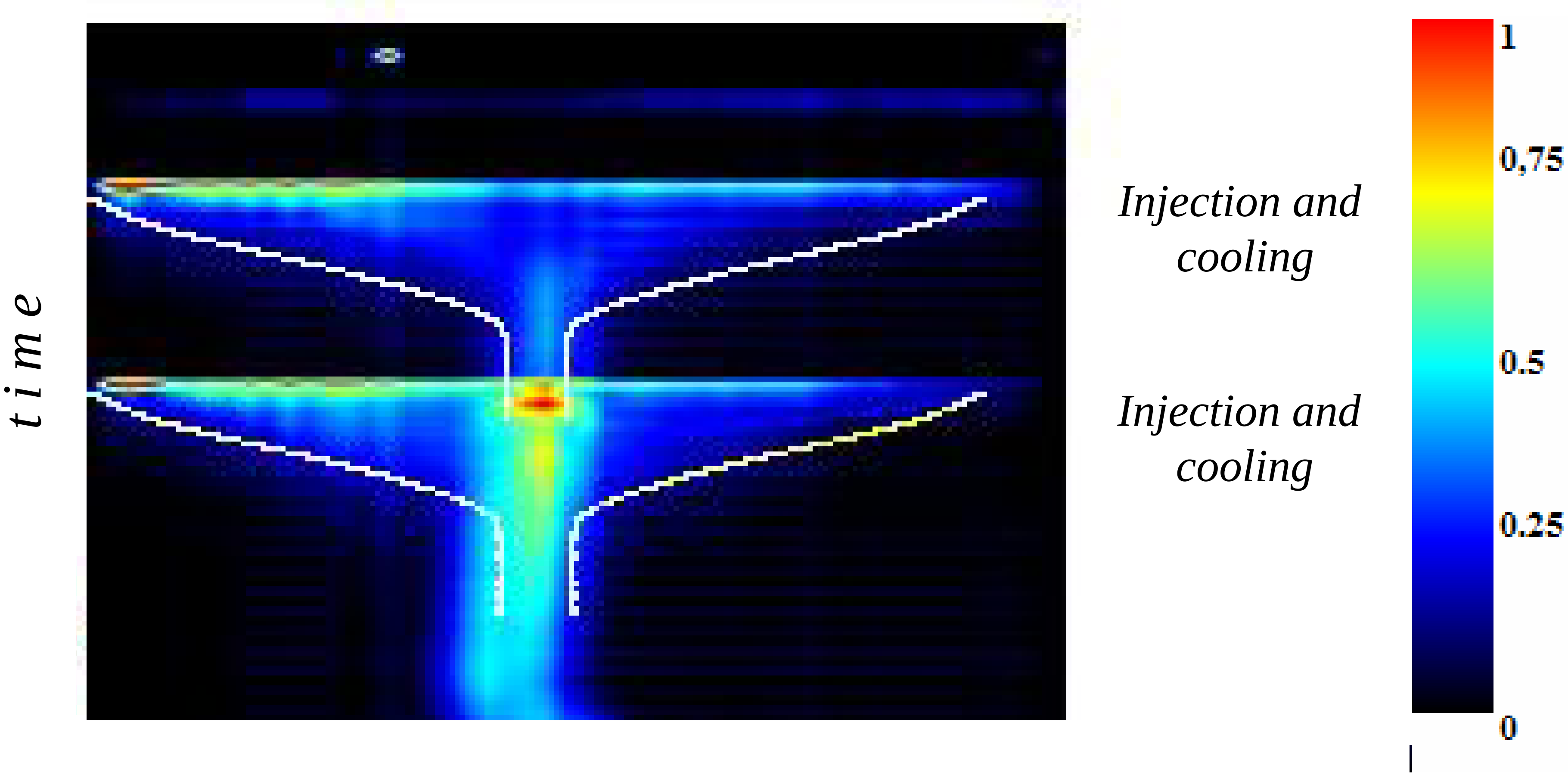


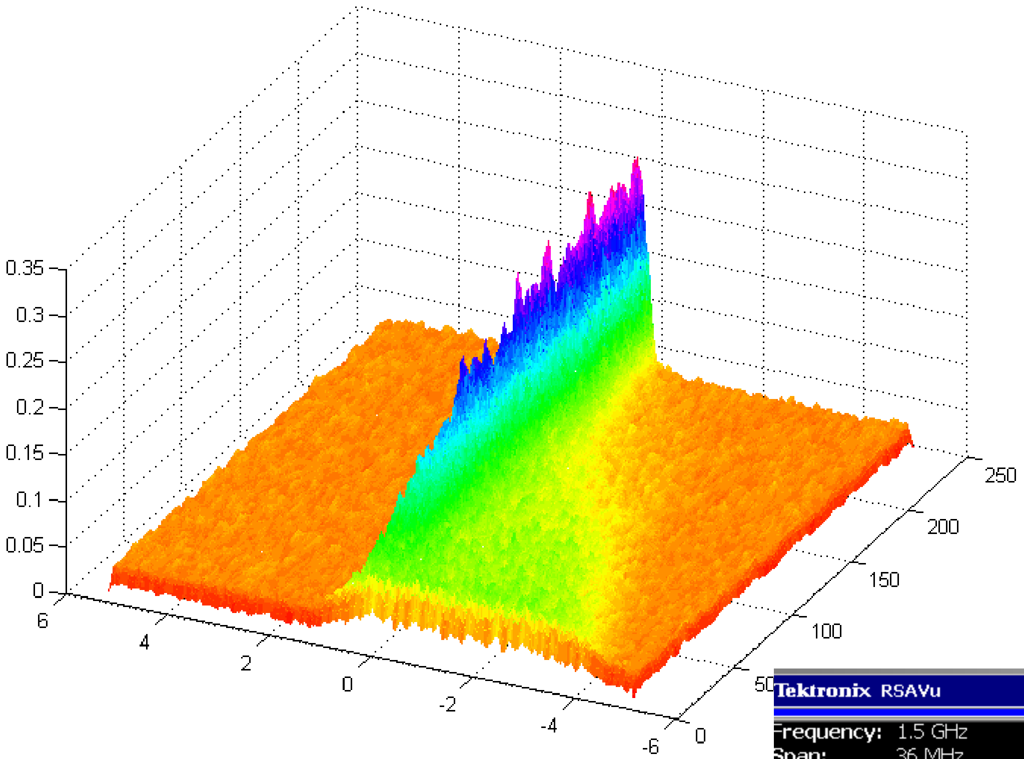
Figure 2.2.3. Picture 3. Changing energy spread of the proton beam during time.

momentum spread

Cooling process in LEIR (LHC)

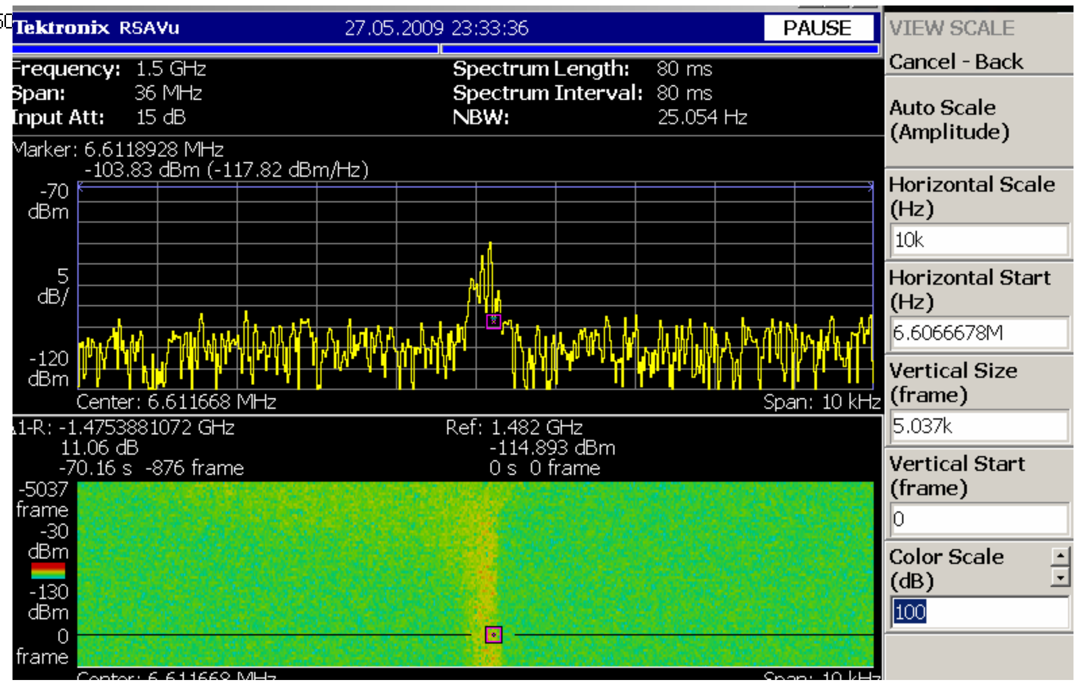
Signal from ion beam profile monitor



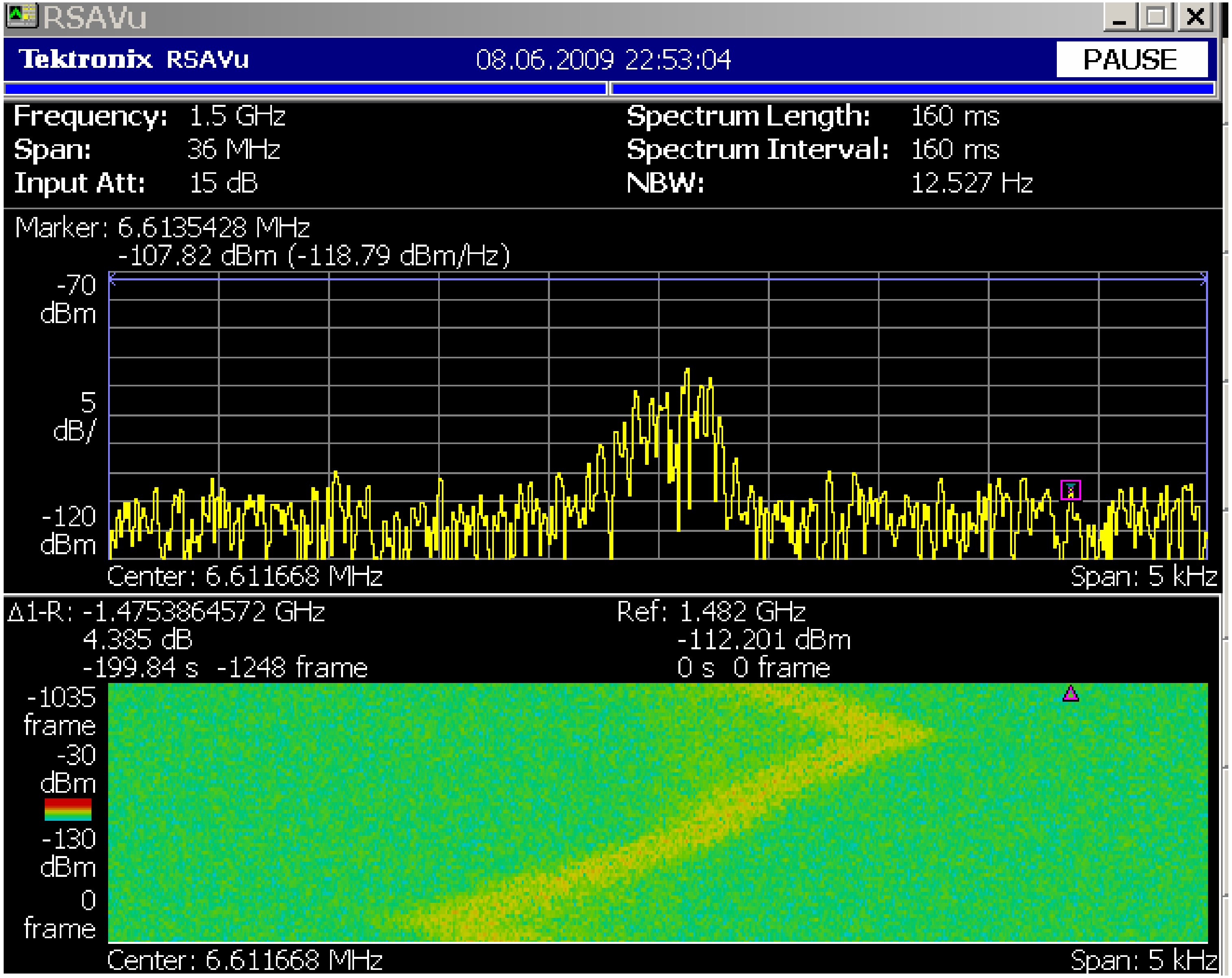


Cooling process in CSRe (IMP, China), Schottky signal

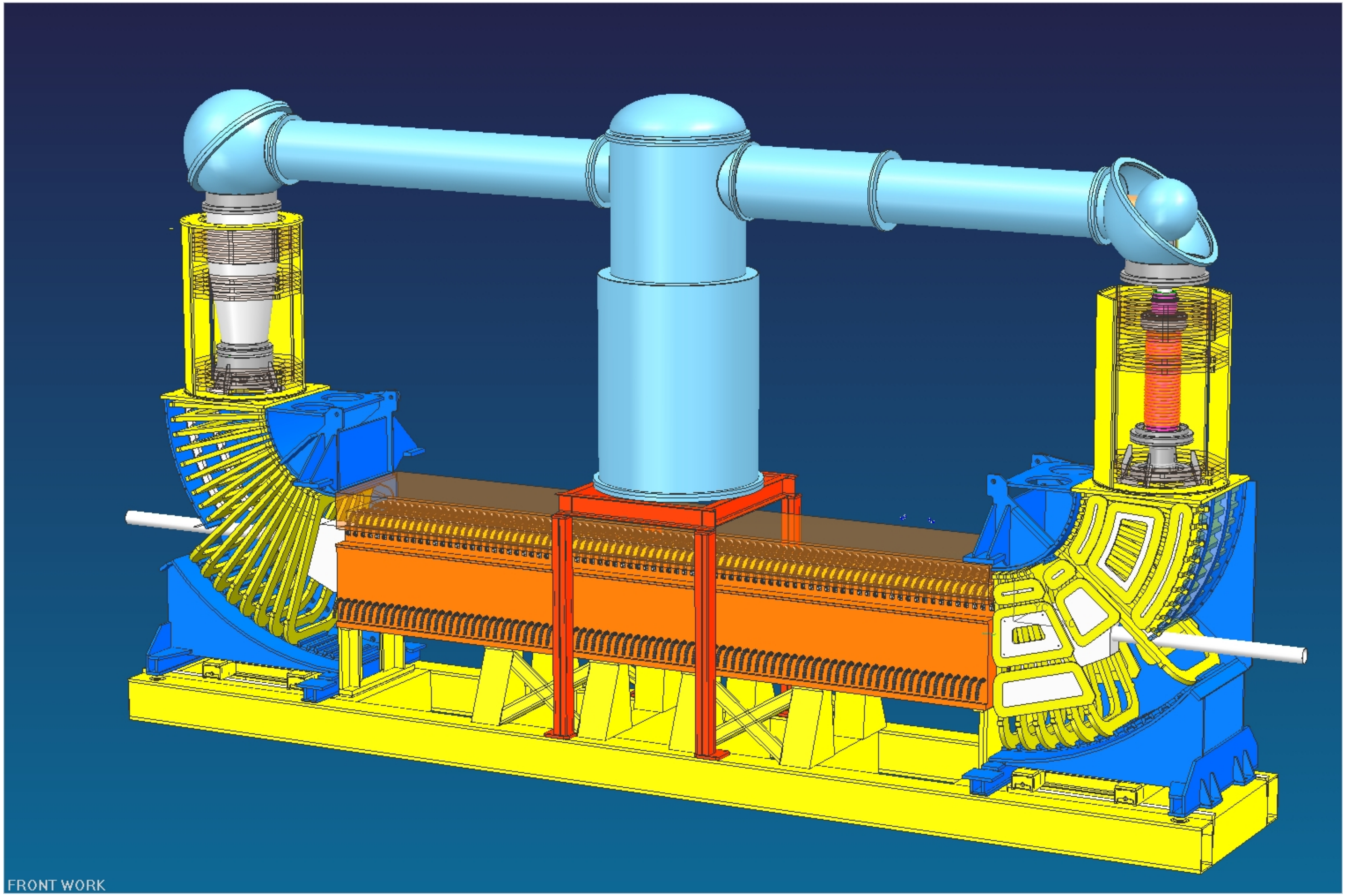
width of the spectrum signal with pick-up electrodes is proportional to the momentum spread of the ion beam



Ion beam is moved along moving electro beam



Coolers produced BINP



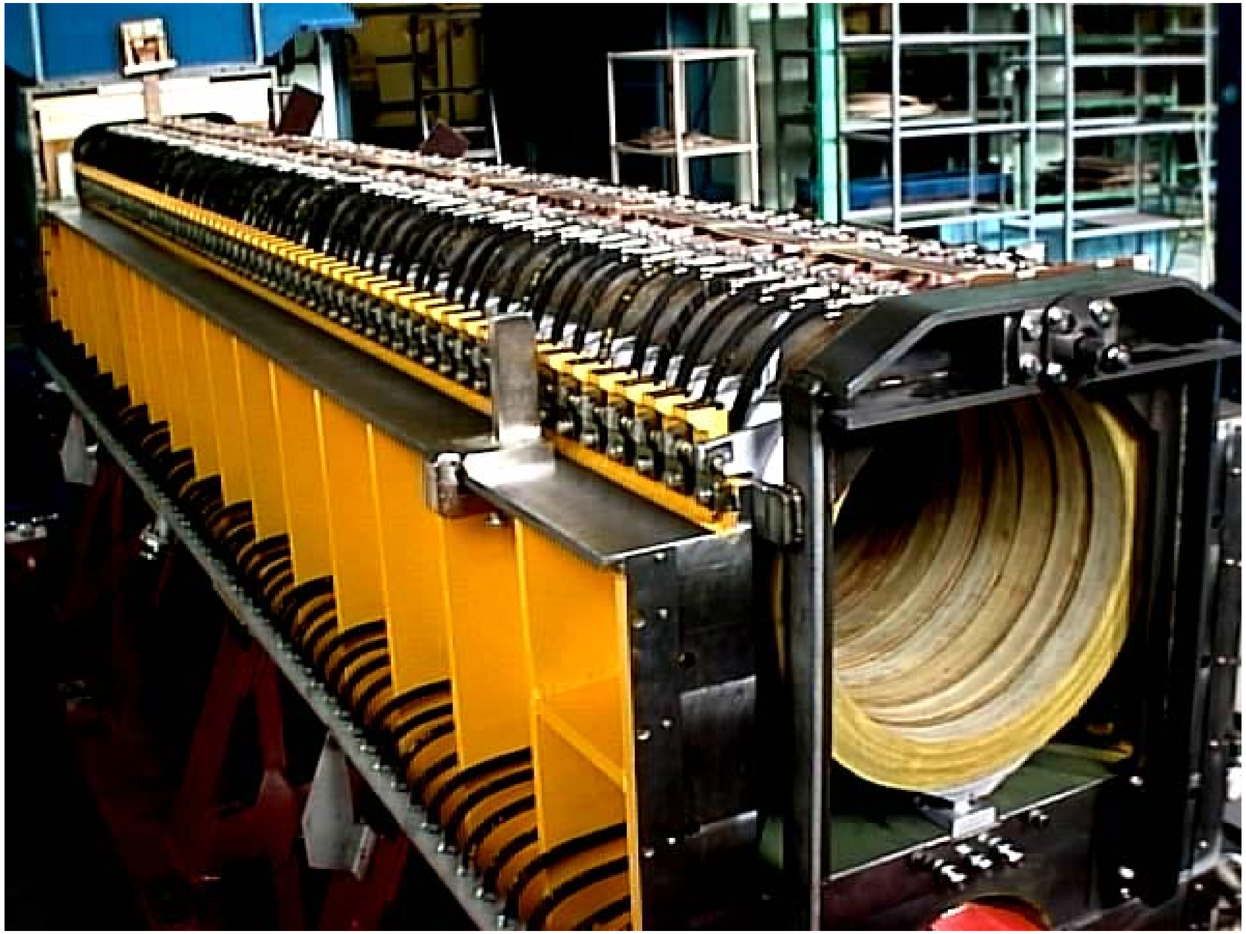
General view of EC500 NESR cooler

Main parameters of the electron cooler for NESR

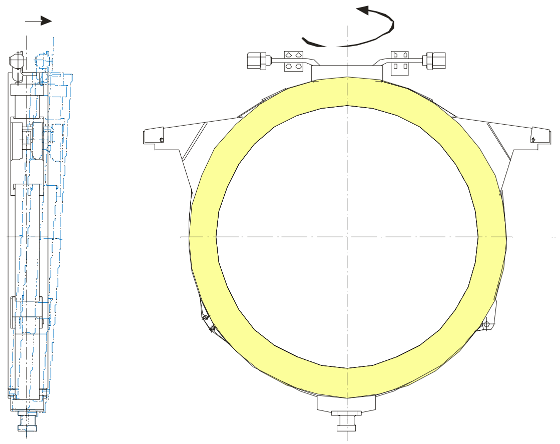
Energy of the reference ion (A/Z≈248/92≈2.7)	740 MeV/u.
Maximum electron energy	450 kV
Electron current	2 A
Diameter of the electron beam in the cooling section	0.5-2 cm
Magnetic field in the cooling section, G	2000
Gun solenoid field, G	4000
Maximum accelerating voltage	500 kV
Ramping of the electron energy (400 kV – 2kV)	less 1 s
Number of dinametron section	25
Voltage per dinametron section	20 kV
SF_6 pressure	1.7
Length of cooler section, cm	500
Residual pressure in the cooling section	10^{-10} – 10^{-11} torr
Fraction of the orbit	0.023

Basic features of coolers produced by BINP

Small variation of the longitudinal magnetic force line is the small effective temperature of the electron gas and the best cooling time



1. Tunable of the coils position for generation precise magnet field at cooling section with straightens about 10^{-5}



Compass like system for measuring of the transverse component of the magnetic field

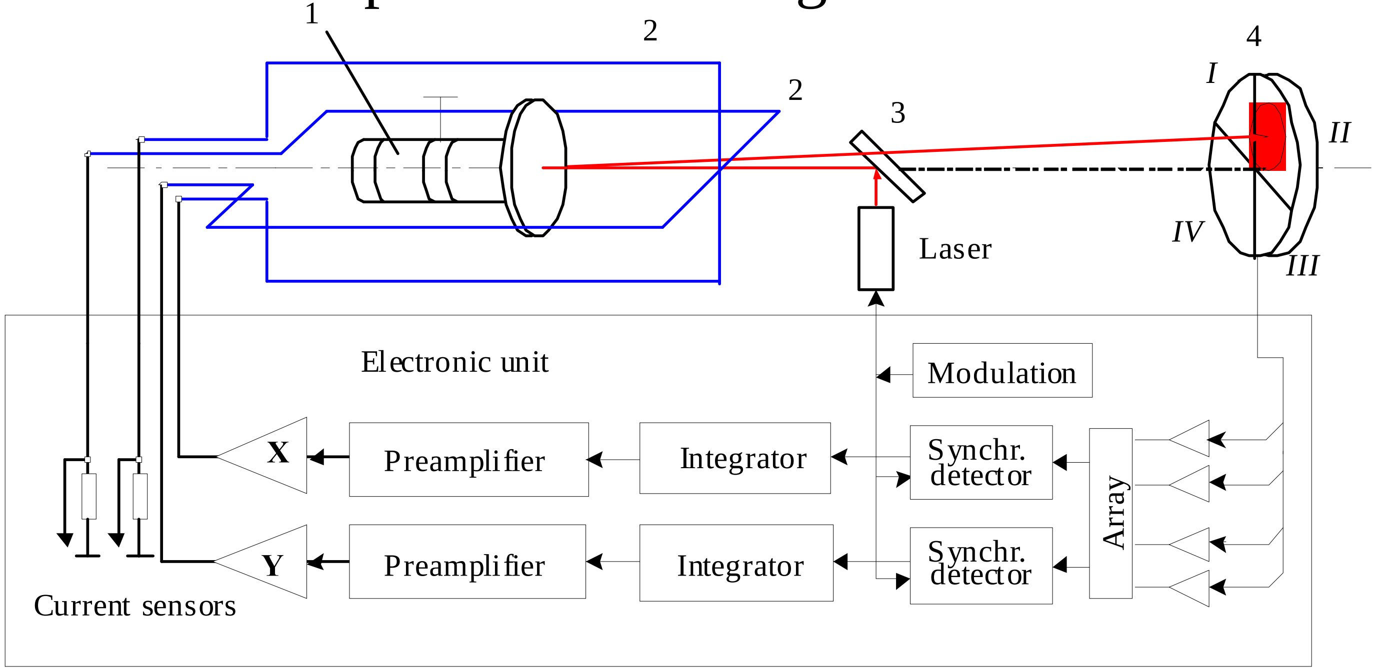
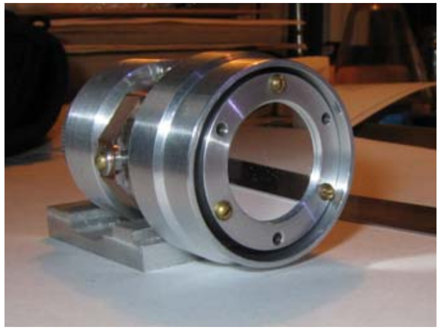
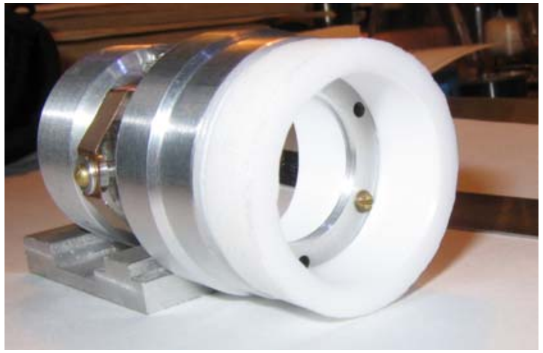
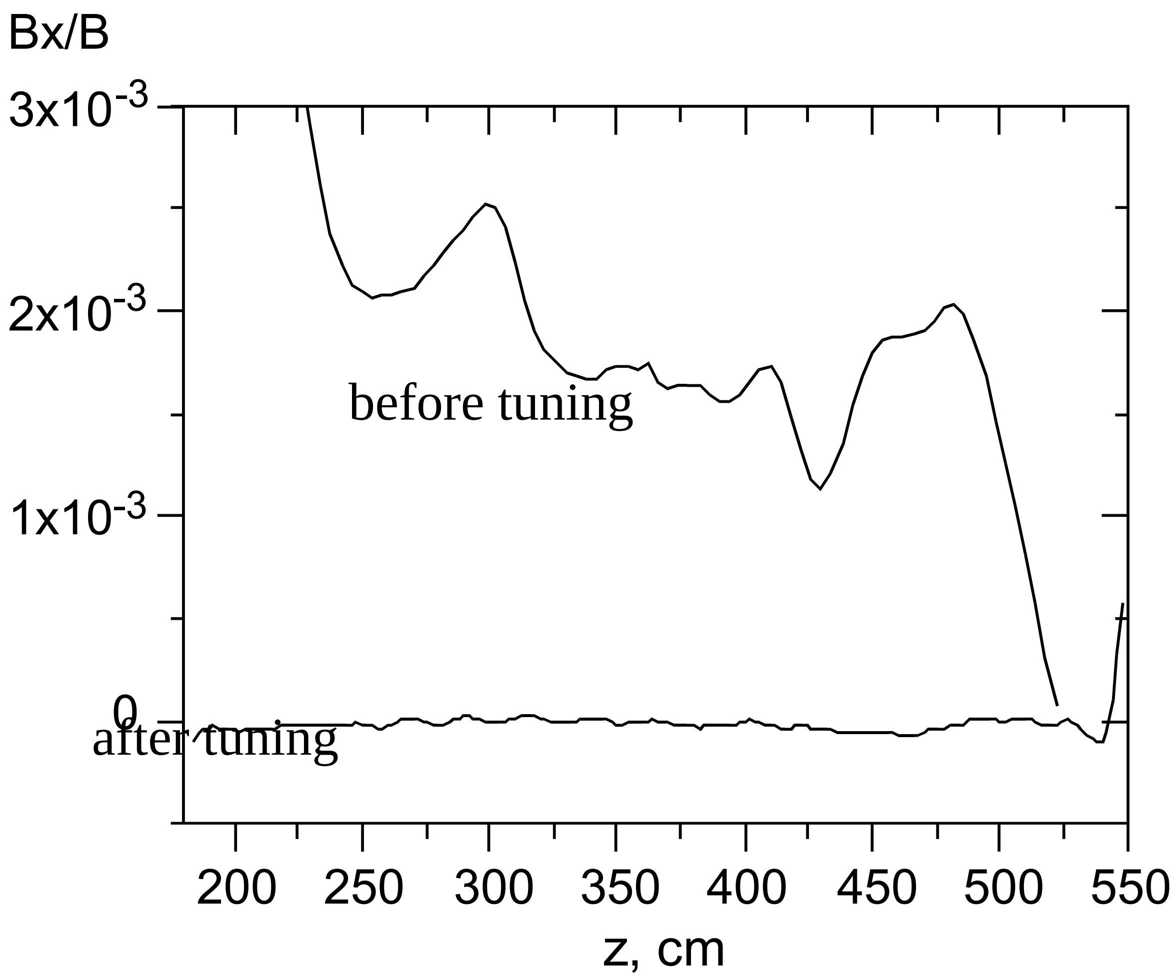


Diagram of the measuring device: *(1)* magnetic sensor, *(2)* conductors of the compensating circuits, *(3)* beam splitter, *(4)* photo-detector, *(*I-IV) photo-detector quadrants, and *(*X, Y) output current amplifiers.



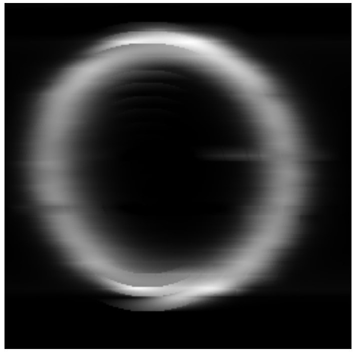


Tuning of the magnetic force line

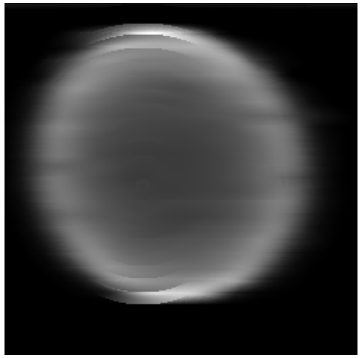


Transverse component of the magnetic field

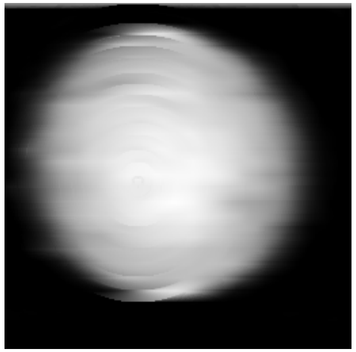
2. Variable beam profile of the electron beam



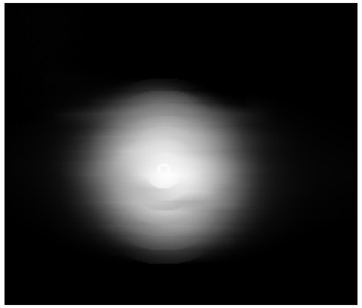
0.6/0.9 kV



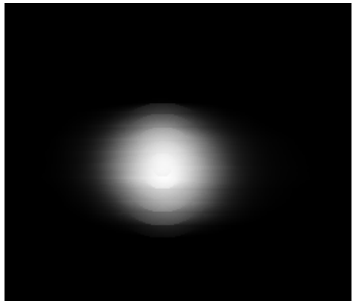
0.2/0.9 kV



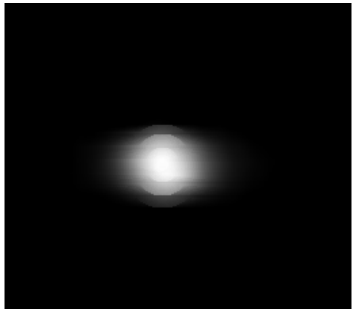
0.05/0.9 kV



–0.2/2.8 kV



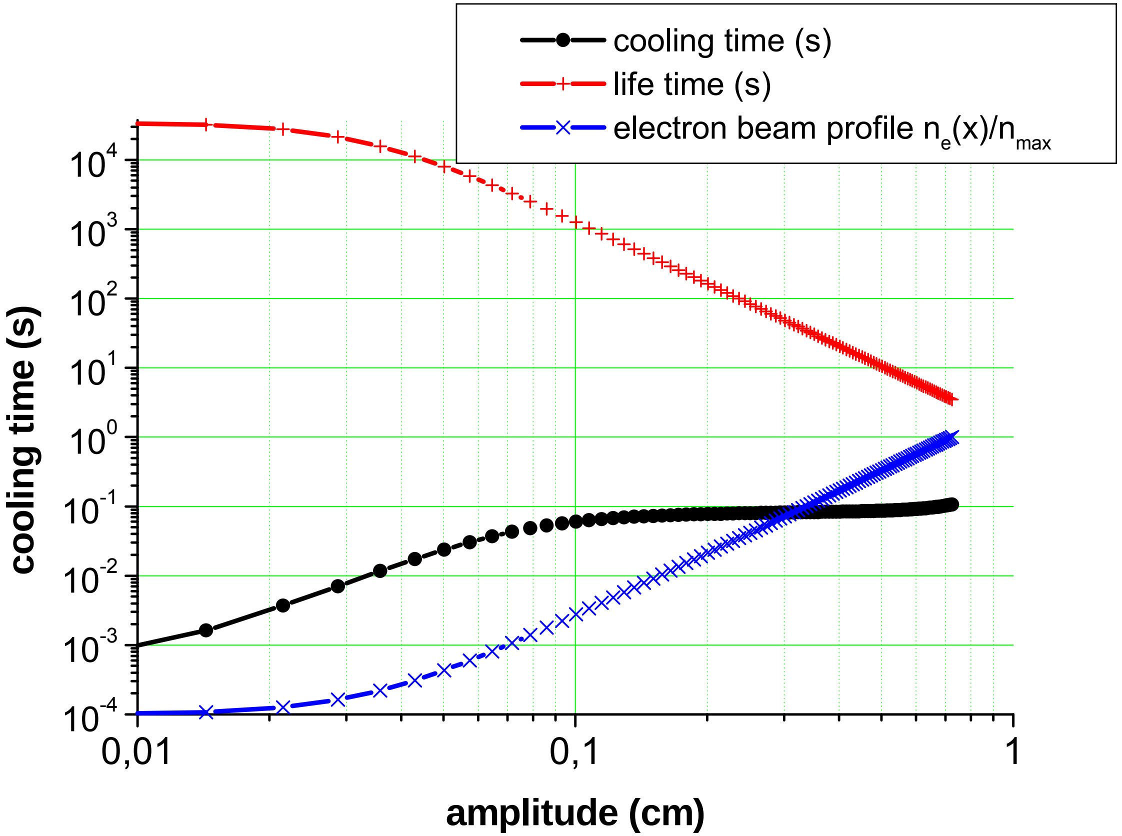
-0.4/2.8 kV



–0.6/2.8 kV

Electron beam distribution for different voltage on the control electrode and the anode.

Cooling with hollow electron beam



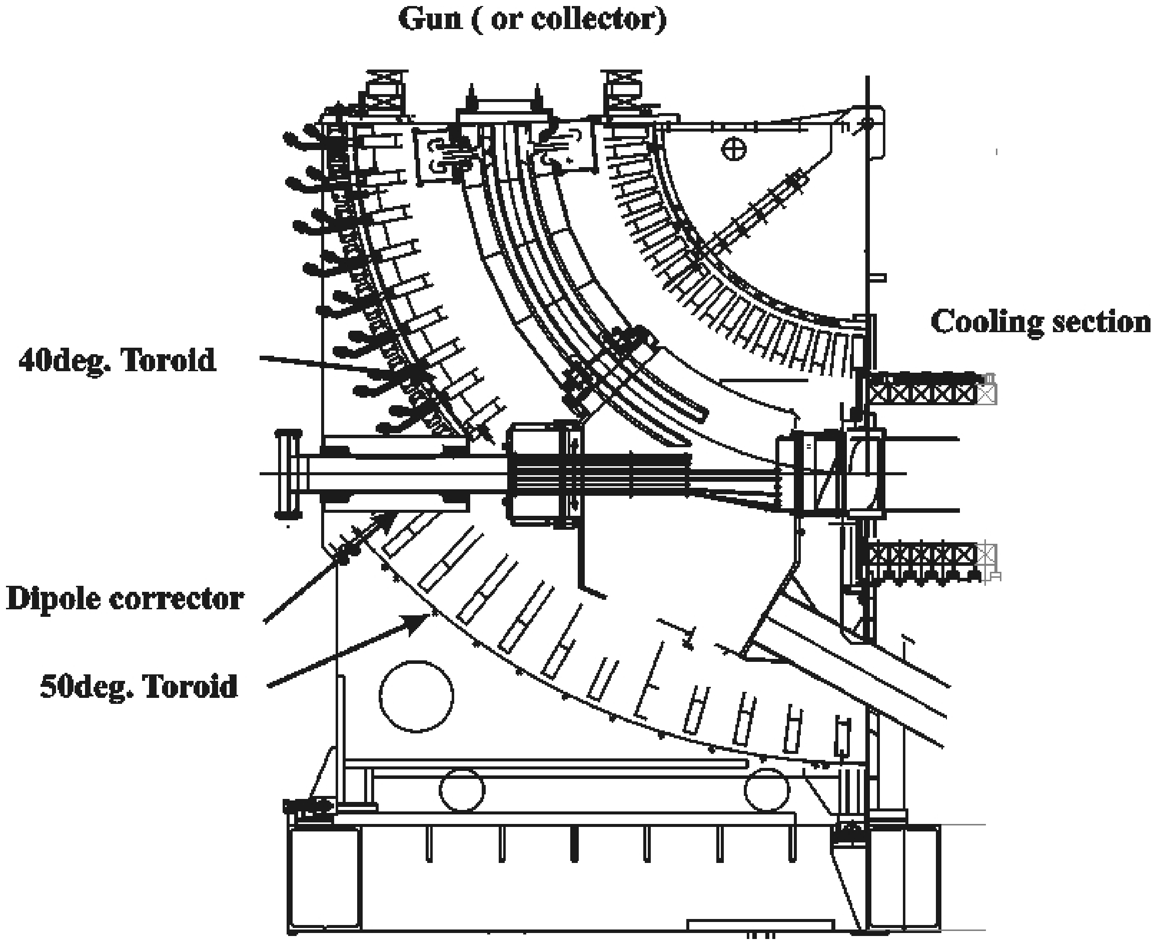
Decreasing electron beam density to center for keep cooling time constant 0.1 sec. Life time by recombination for storage beam with amplitude 1 mm near 1000 sec.

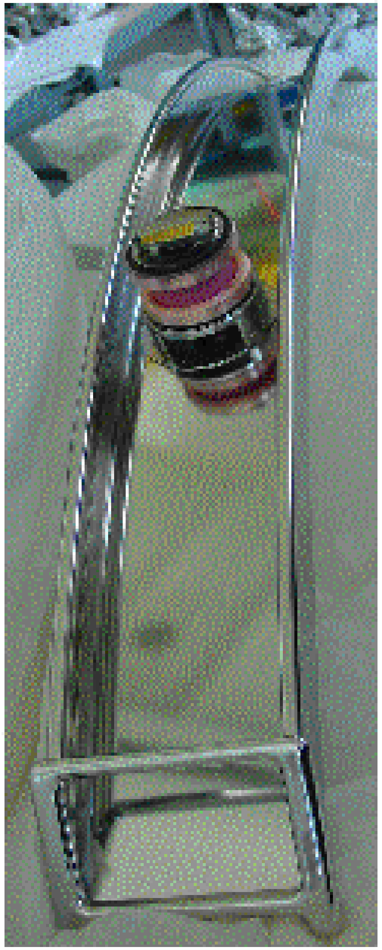
3. Electrostatic bending for compensation drift electrons

$$F = \frac{mV^2}{R} = eE + e\frac{[V \times B]}{c} = const$$

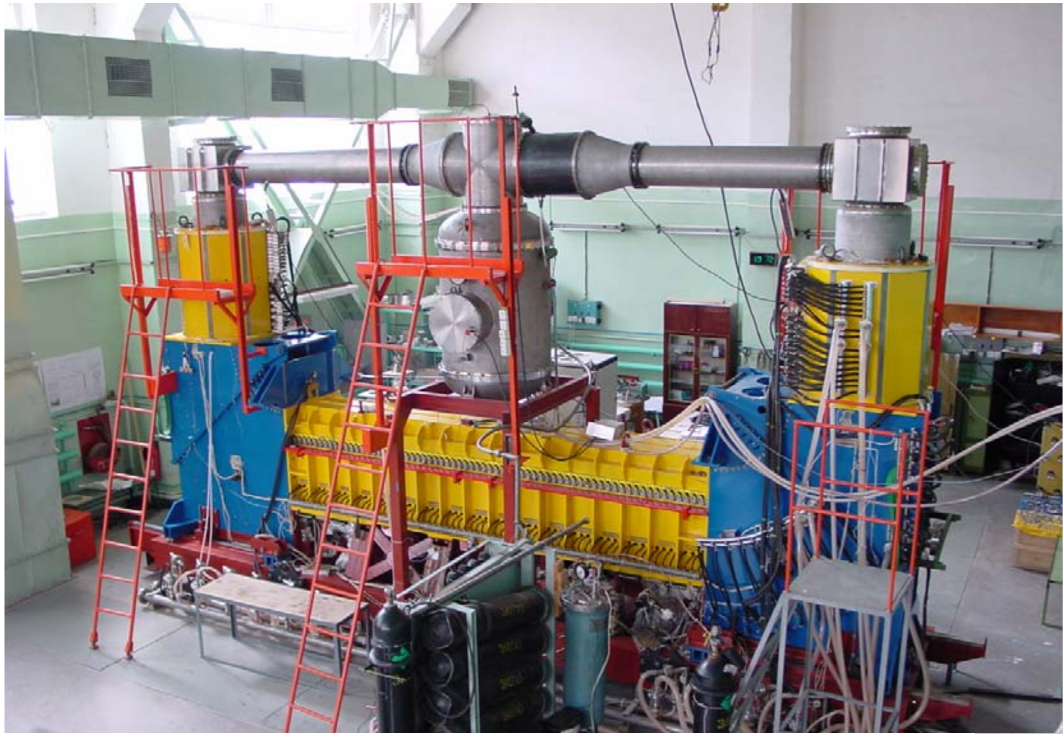
E=0 magnet bending B=pc/eR

B=0 electrostatic bending E=pV/eR





small leakage current means a good vacuum



Lanzhou, China

Novosibirsk

EC – 300 CSRe is prototype of the NESR electron cooler

Cooler NESR: a lot of work is done but much more work is ahead

Thank you for attention