

# ELECTRON COOLER OF THE NICA BOOSTER AND ITS APPLICATIONS

S.A. Melnikov, I.N. Meshkov, E.V. Ahmanova, A. A. Baldin, A.V. Butenko,  
I. V. Gorelyshev A.G. Kobets, D. S. Korovkin, O.S. Orlov, K.G. Osipov, A.V.  
Philippov, S.V. Semenov, A.S. Sergeev, A.A. Sidorin, A.O. Sidorin, E.M Syresin.

Joint Institute for Nuclear Research, Dubna, Russia

**2021.11.02**

**The 13th International Workshop COOL'21**

## Introduction

The main tasks of the Booster synchrotron of heavy ions are the accumulation of  $2 \cdot 10^9$  gold ions  $^{197}\text{Au}^{31+}$  or other low-charged heavy ions and their acceleration to the maximum energy (578 MeV/u for  $^{197}\text{Au}^{31+}$ ), which is sufficient for their subsequent stripping to the state of bare nuclei. The application of electron cooling in the Booster at ion energy up to 65 MeV/u makes it possible to significantly reduce the 6D emittance of the ion beam.

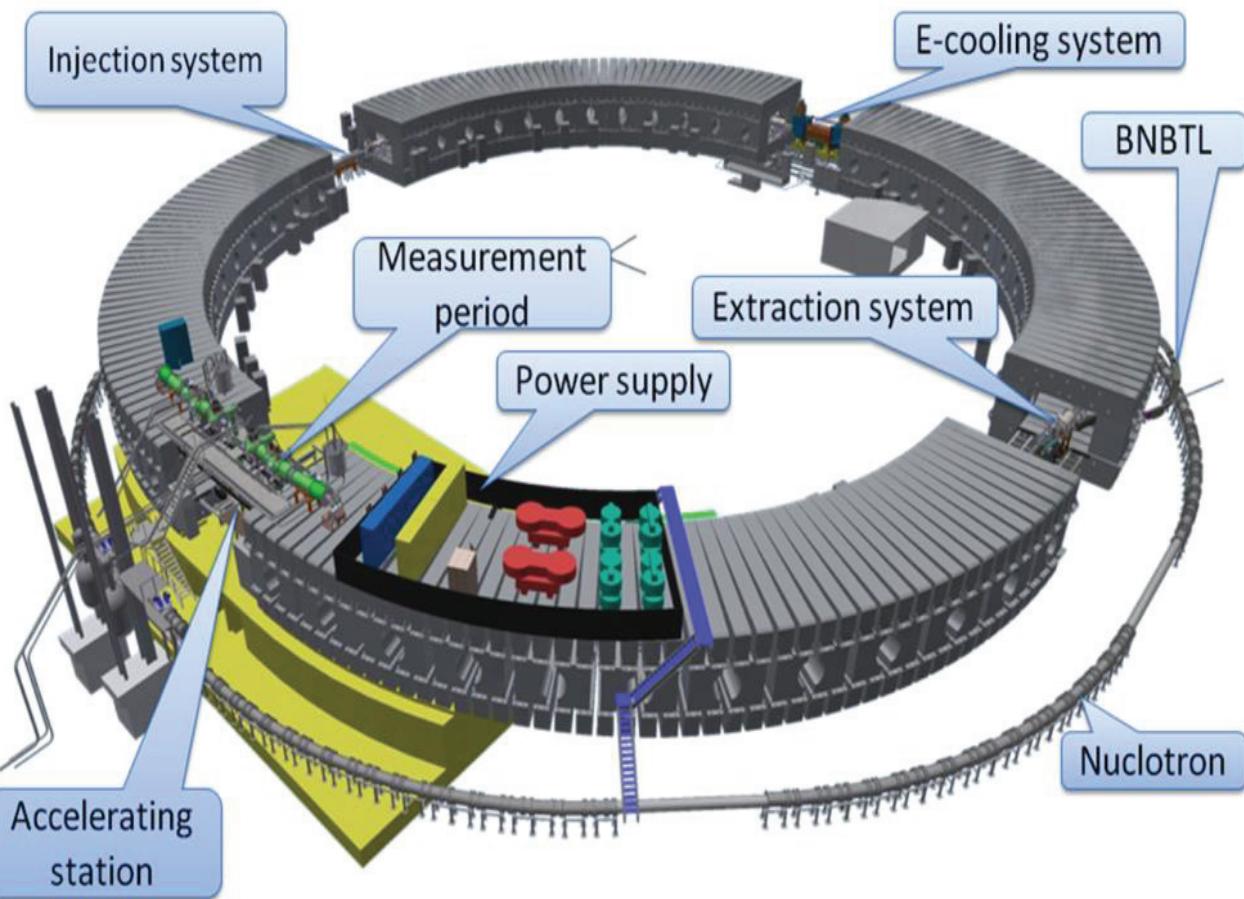
NICA Booster Electron Cooling System (ECS) was developed and manufactured in the Budker Institute of Nuclear Physics.

In this report, all experiments are presented at an injection energy of 3.2 MeV/u.

# NICA Booster Electron Cooling System (ECS)

In the ECS of the NICA Booster, the homogeneity of the magnetic field of this solenoid is made at the level of  $3 \cdot 10^{-5}$  (straightness of the magnetic field line) that provides the design value of the cooling time. The energy of the ECS electrons variates in this range of 1.0 – 50.0 keV

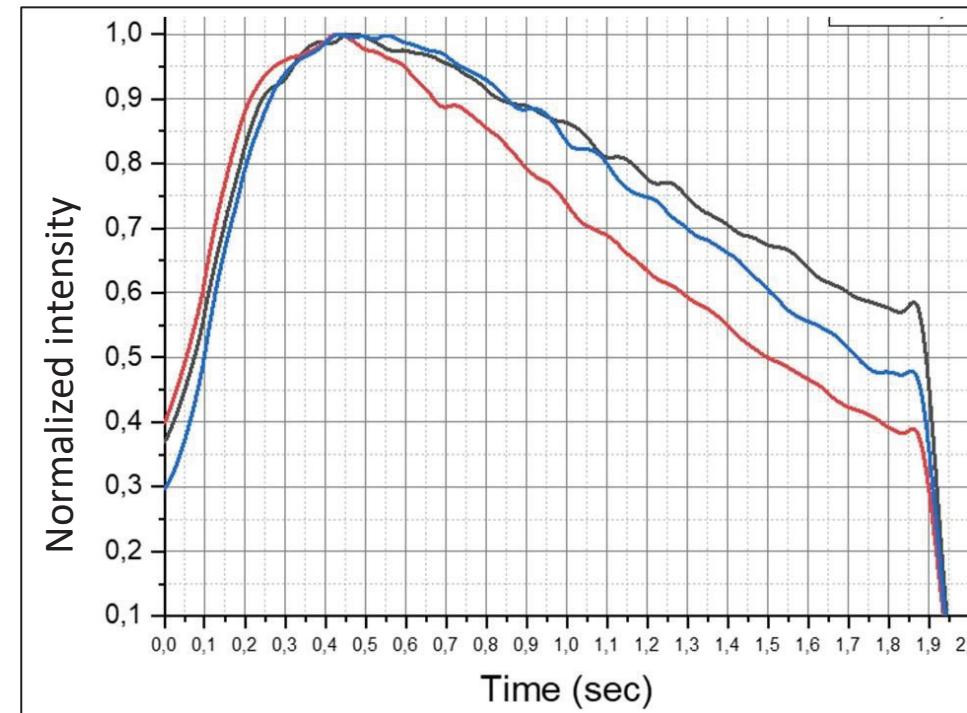
Electron energy E, keV	1.5 – 50
Electron beam current I, A	$\leq 1$
Accuracy of energy adjustment and its stability, $\Delta E/E$	$\leq 1 \cdot 10^{-5}$
Beam current stability, $\Delta I/I$	$\leq 1 \cdot 10^{-4}$
Electron beam loss current, $\delta I/I$	$\leq 3 \cdot 10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, $\Delta B/B$	$\leq 3 \cdot 10^{-5}$ on the length 15 cm
Transverse temperature of electrons in the cooling section (in the particle system), eV	$\leq 0.3$
Correction of the ion orbit at the input and output of ECS	offset, mm $\leq 1,0$ angular deviation, mrad $\leq 1,0$



# First Ion Electron Cooling Experiment

During the first Booster run in December 2020, an experiment was conducted to commission the ECS with a circulating  $\text{He}^{1+}$  helium ion beam at an energy of 3.2 MeV/u (injection energy into the Booster). In this experiment, two diagnostic devices that allowed observing the cooling effect were used: the A. A. Baldin ionization profilometer and a parametric current transformer (PCT) measuring ion beam current.

<b>Ion type</b>	$\text{He}^{1+}$
<b>Ion energy, Mev/u</b>	3.2
<b>Electron energy, keV</b>	1.73 – 1.8
<b>Electron beam current, A</b>	0.1 – 0.2
<b>Electron beam diameter, mm</b>	28

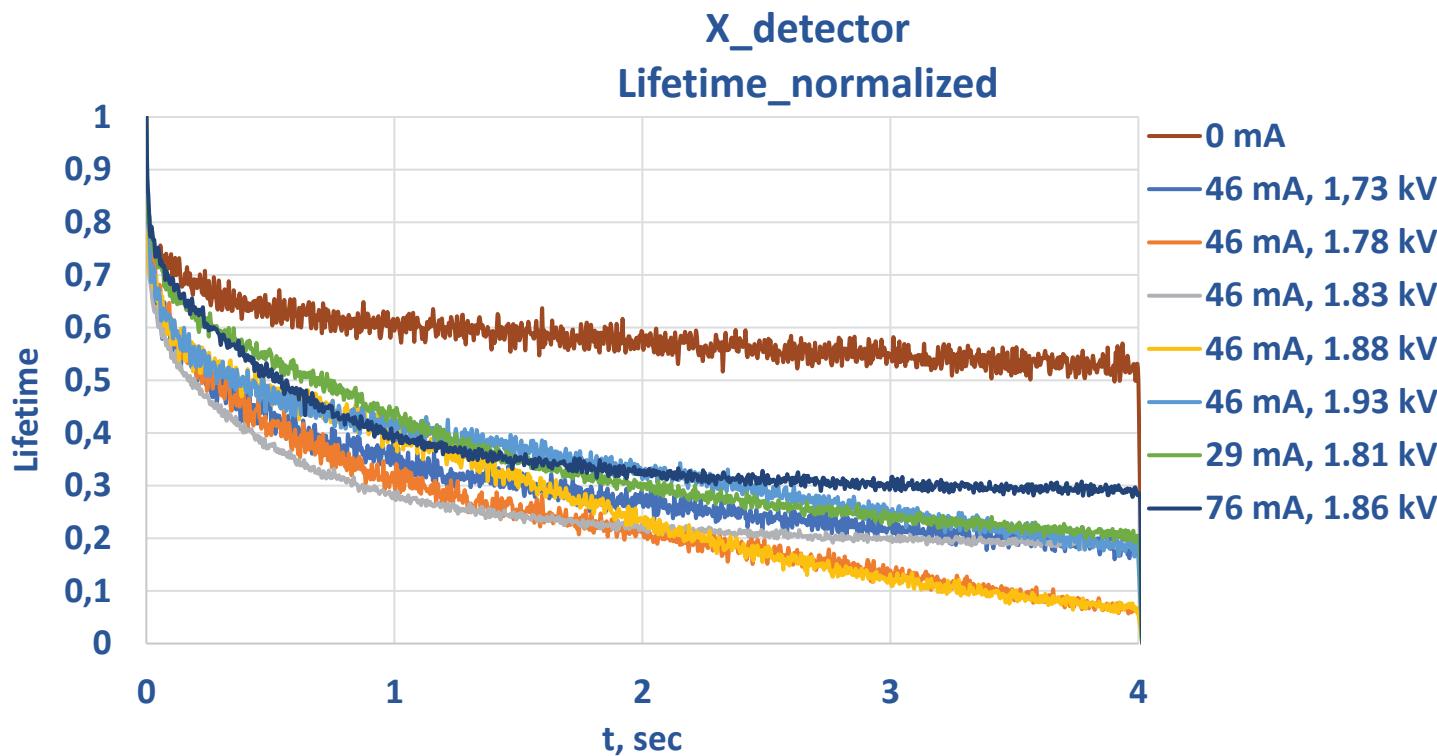


Normalized intensity for different electron energy. Black curve – 1.82 keV, blue curve – 1.72 keV, red curve – 1.76 keV.

As can be seen from figure, the strong decrease in the lifetime of the ion beam occurs at the energy 1.76 keV, which is in good agreement with the theoretical value. The optimal (theoretical) value of the electron energy is equal to  $E_e = \frac{m_e}{m_n} \cdot E_{ion}$ . For  $E_{ion} = 3.2$  MeV it gives  $(E_e)_{opt} = 1.754$  keV, what is different from 1.76 keV by the  $\approx 5.7$  B, or 0.3%.

## Second Ion Electron Cooling Experiment

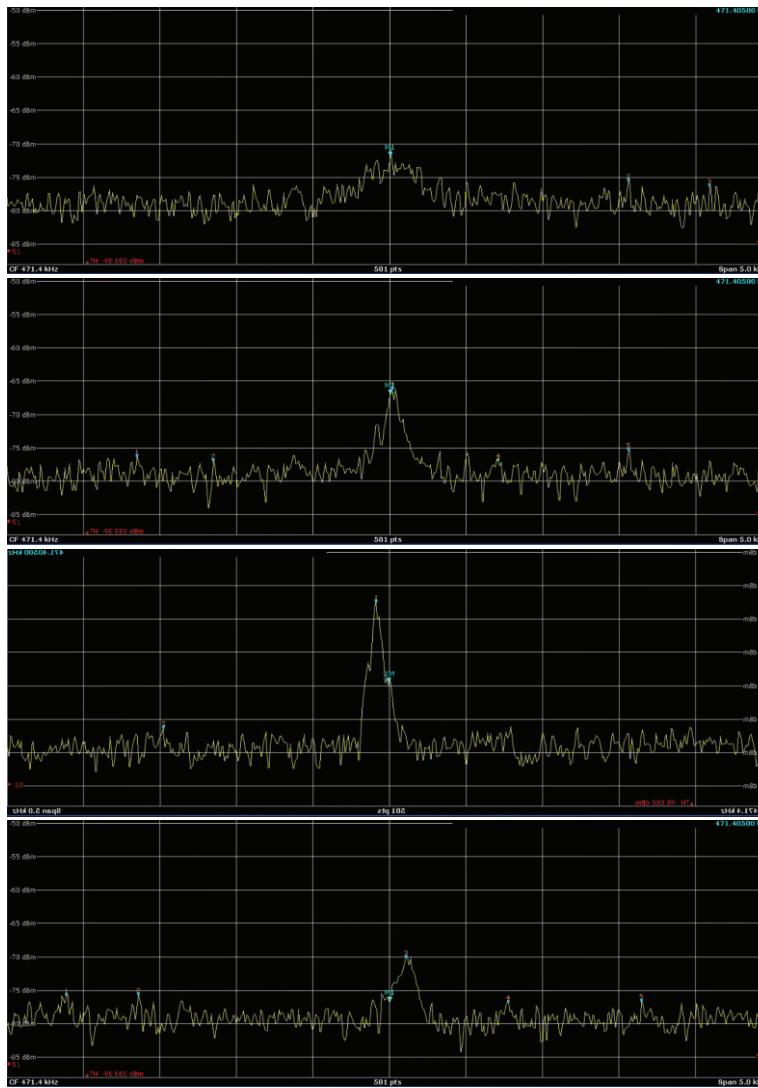
During the second run of the Booster in September 2021, an experiment was conducted for electron cooling of ions  $^{56}\text{Fe}^{14+}$  beam circulating at injection energy of 3.2 MeV/u. A Schottky spectrometer was used as the main detecting device, as well as a profilometer and PTC used during first experiment.



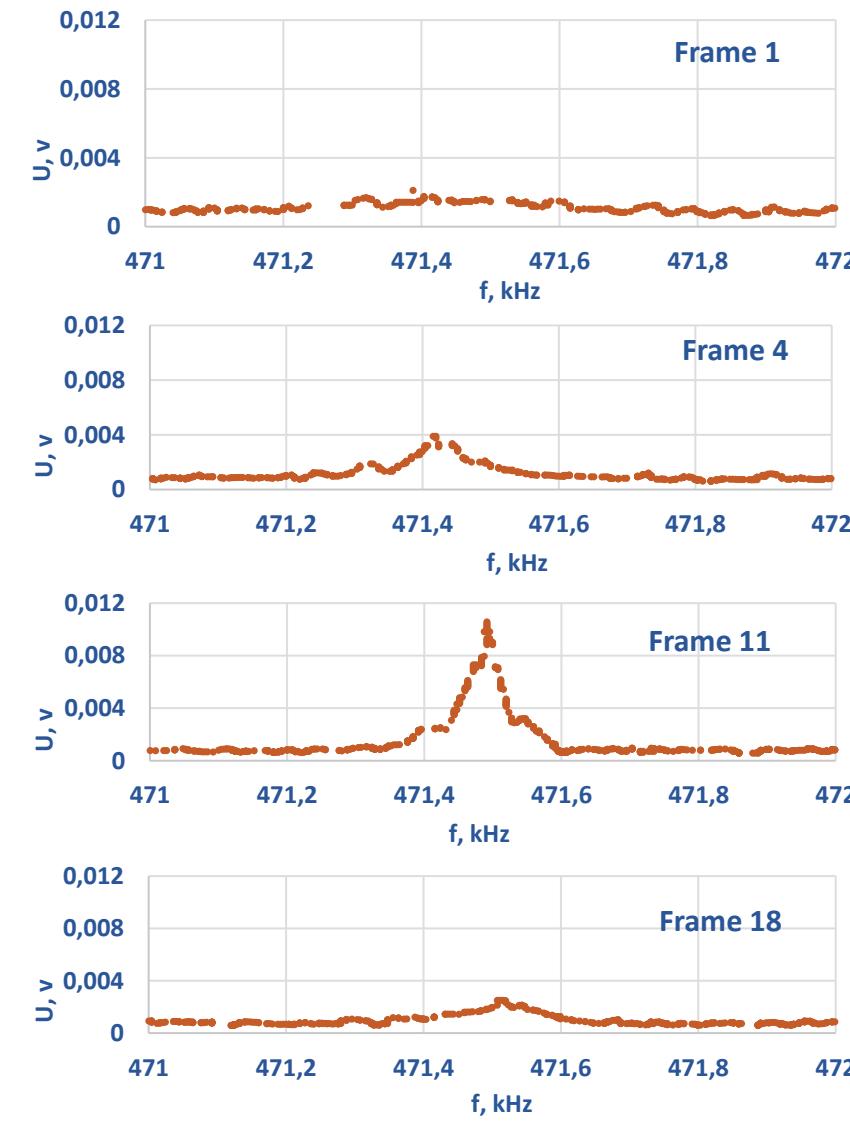
Ion type	$^{56}\text{Fe}^{14+}$
Ion energy, Mev/u	3.2
Electron energy, keV	1.73 – 1.93
Electron beam current, A	0.02 – 0.13
Electron beam diameter, mm	28

# Second Ion Electron Cooling Experiment

## Schottky spectrometer signal (4<sup>th</sup> harmonic of revolution frequency)



digitization and linearization of the signal



t = 0.0 sec

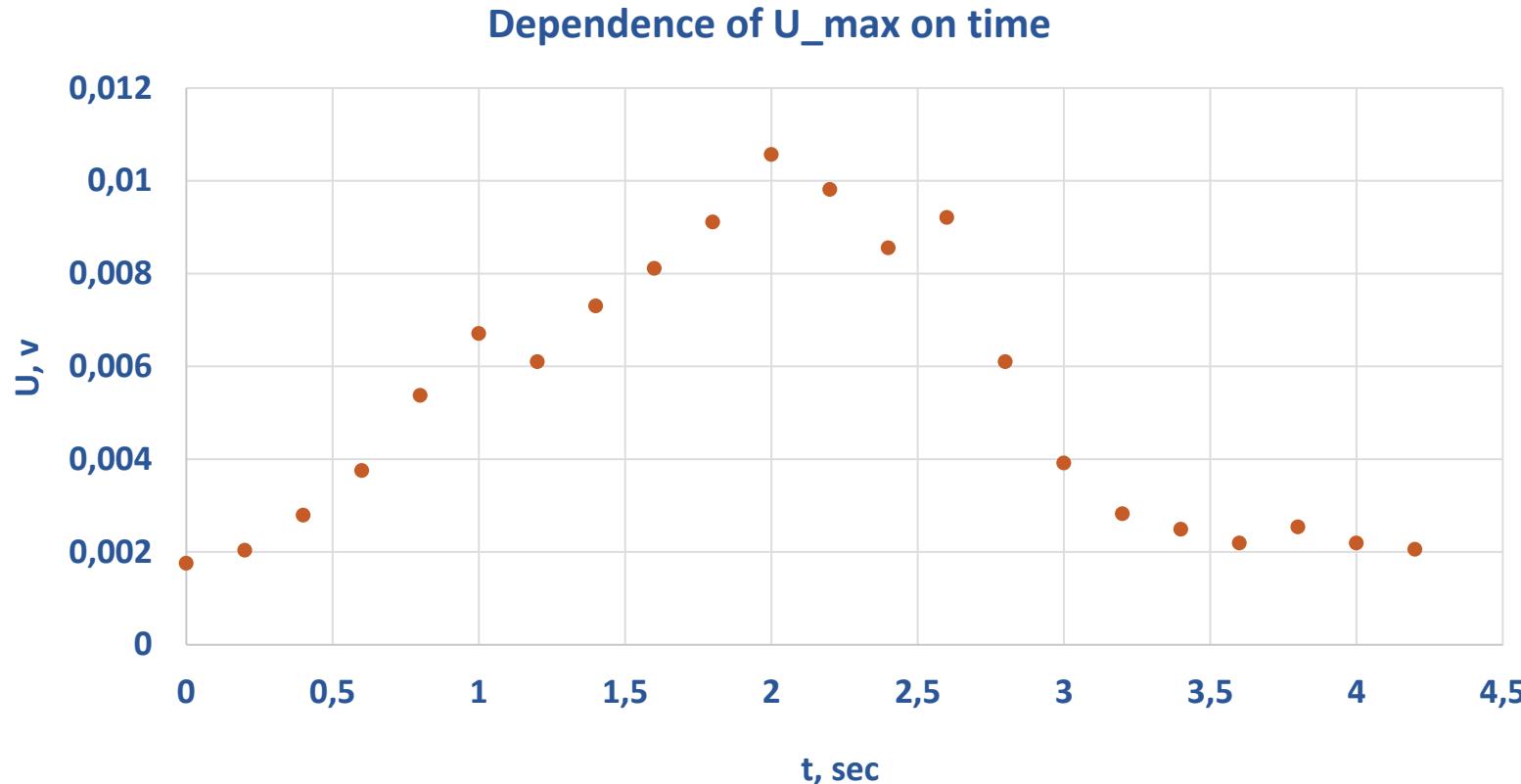
t = 0.6 sec

t = 2.0 sec

t = 3.4 sec

# Second Ion Electron Cooling Experiment

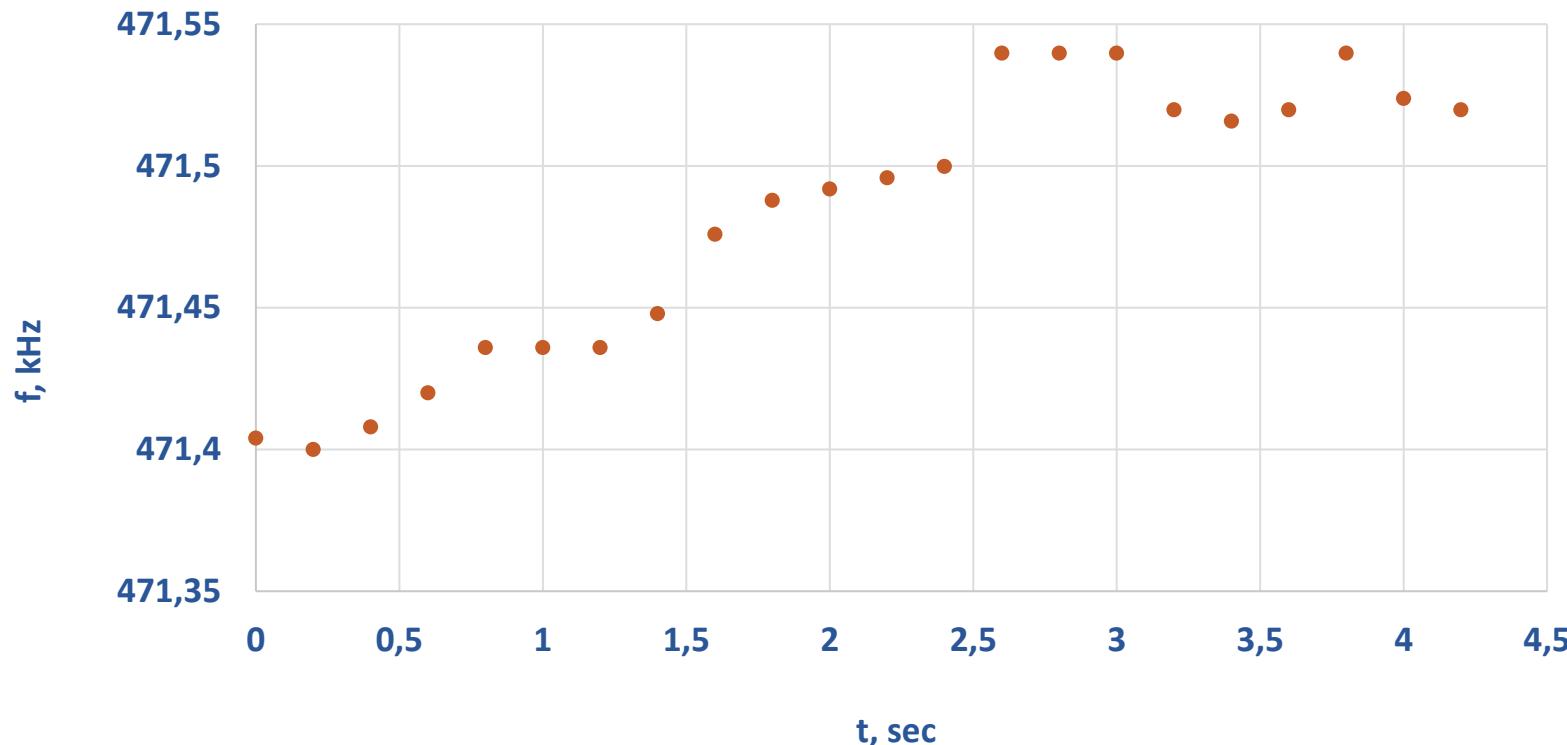
Schottky spectrometer signal (4<sup>th</sup> harmonic of revolution frequency)



# Second Ion Electron Cooling Experiment

## Schottky spectrometer signal (4<sup>th</sup> harmonic of revolution frequency)

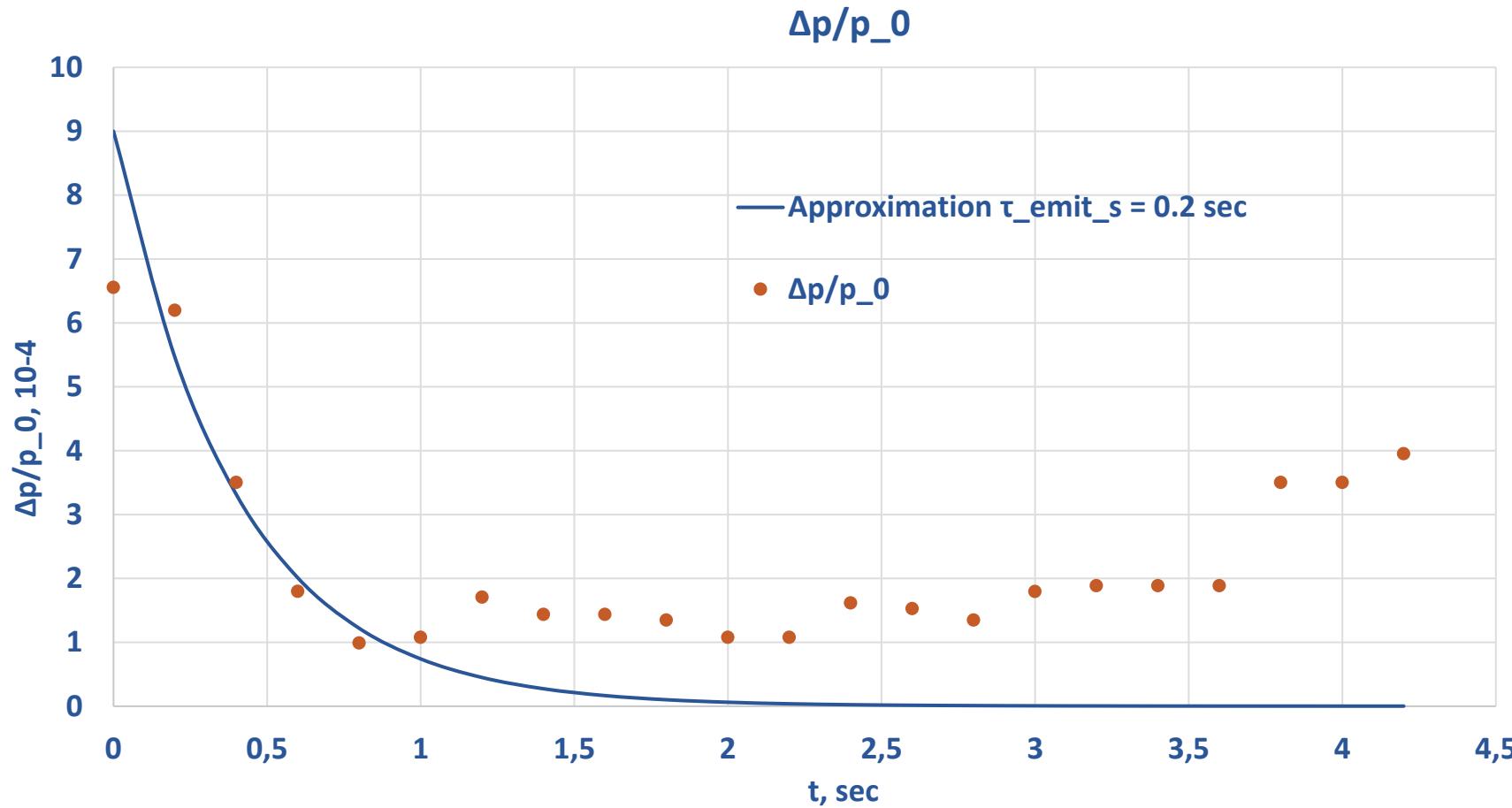
Dependence of the U\_max frequency of the spectrum on time



The frequency of the maximum value of the spectrum was increasing with time, which indicates the compression of the beam orbit (see also slides 10-14)

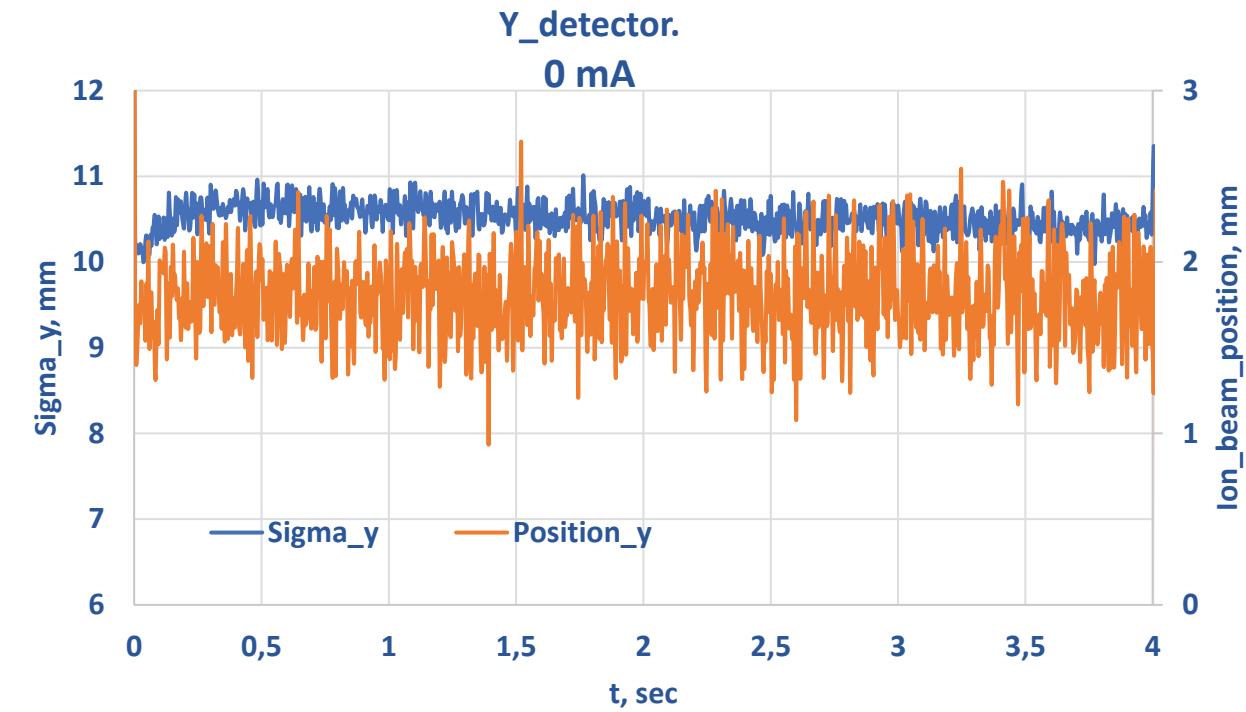
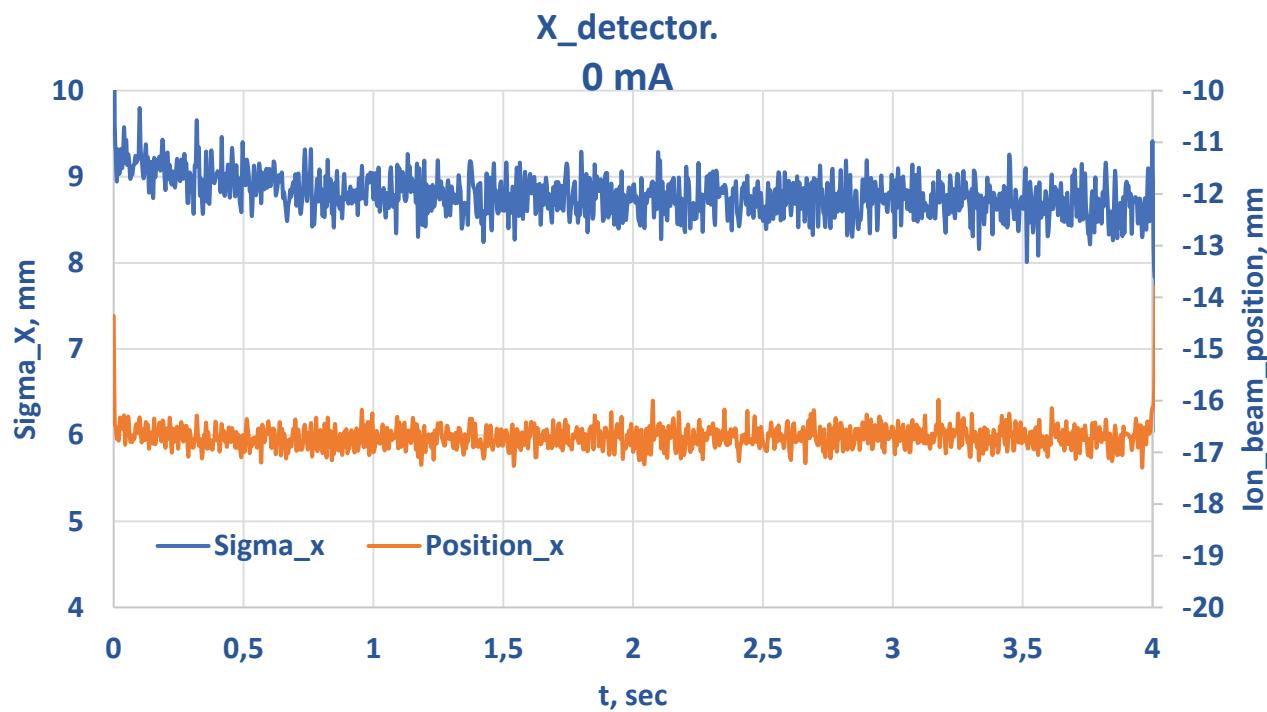
# Second Ion Electron Cooling Experiment

Schottky spectrometer signal (4<sup>th</sup> harmonic of revolution frequency)



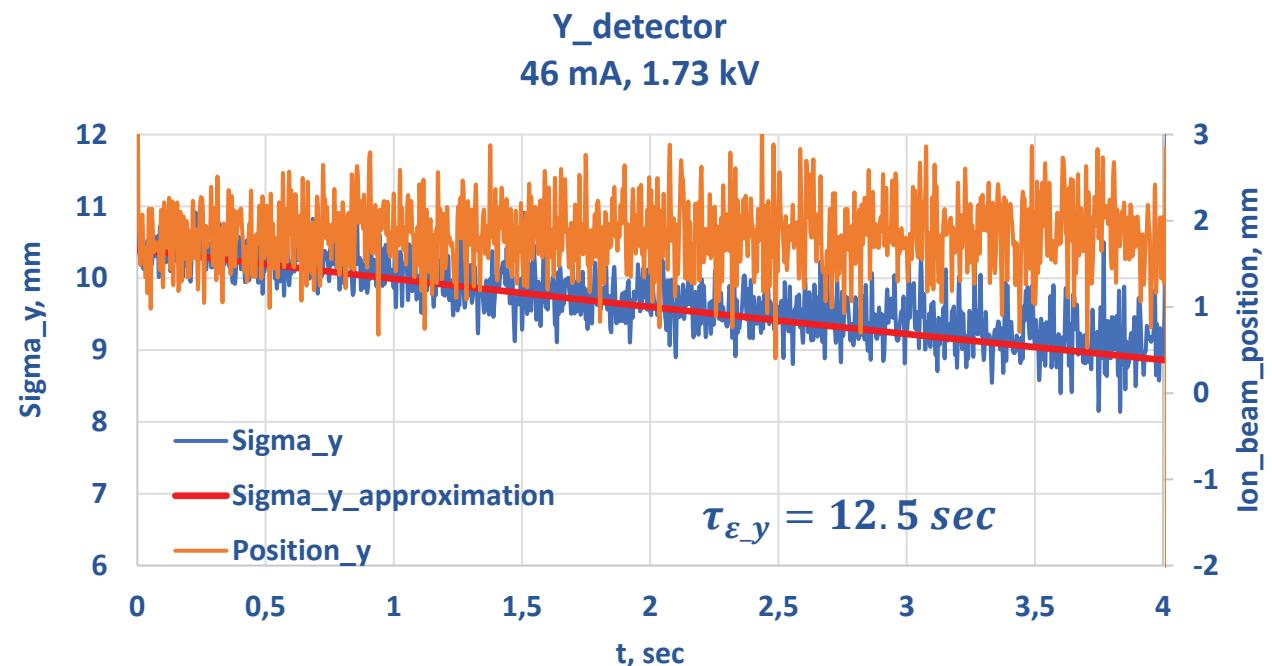
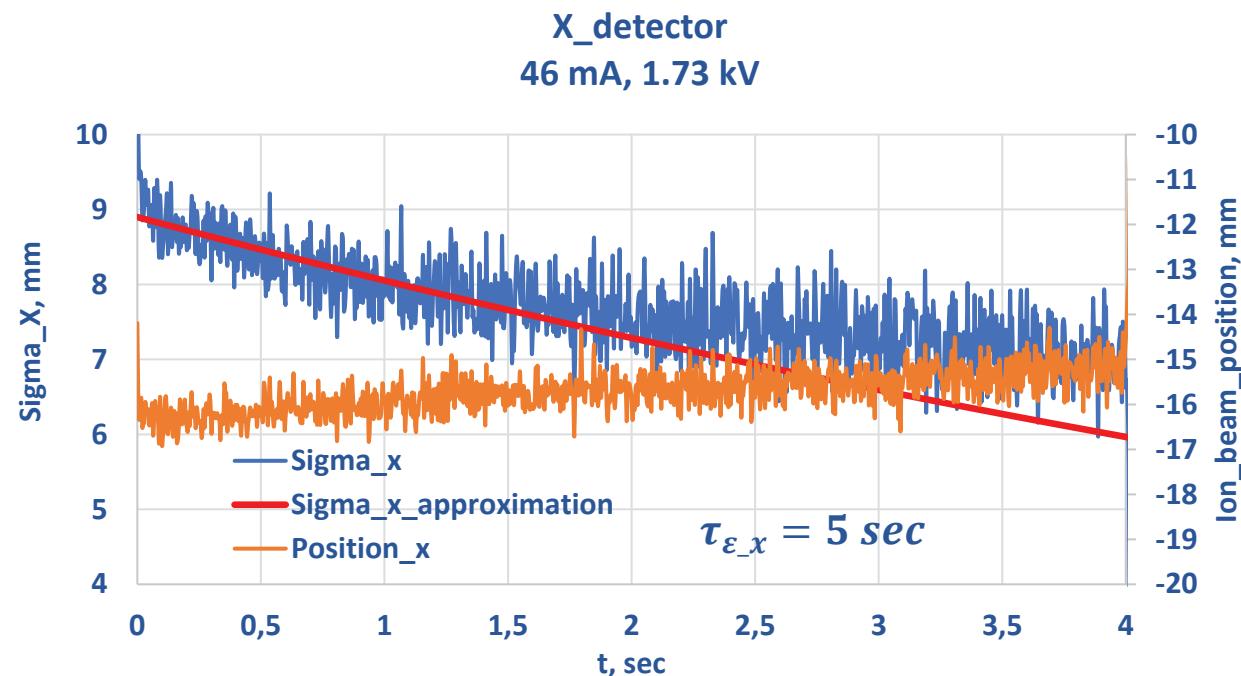
# Second Ion Electron Cooling Experiment

## Ionization profilometer signal

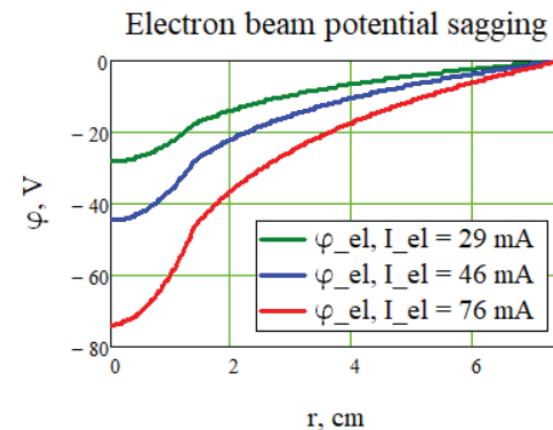


# Second Ion Electron Cooling Experiment

## Ionization profilometer signal

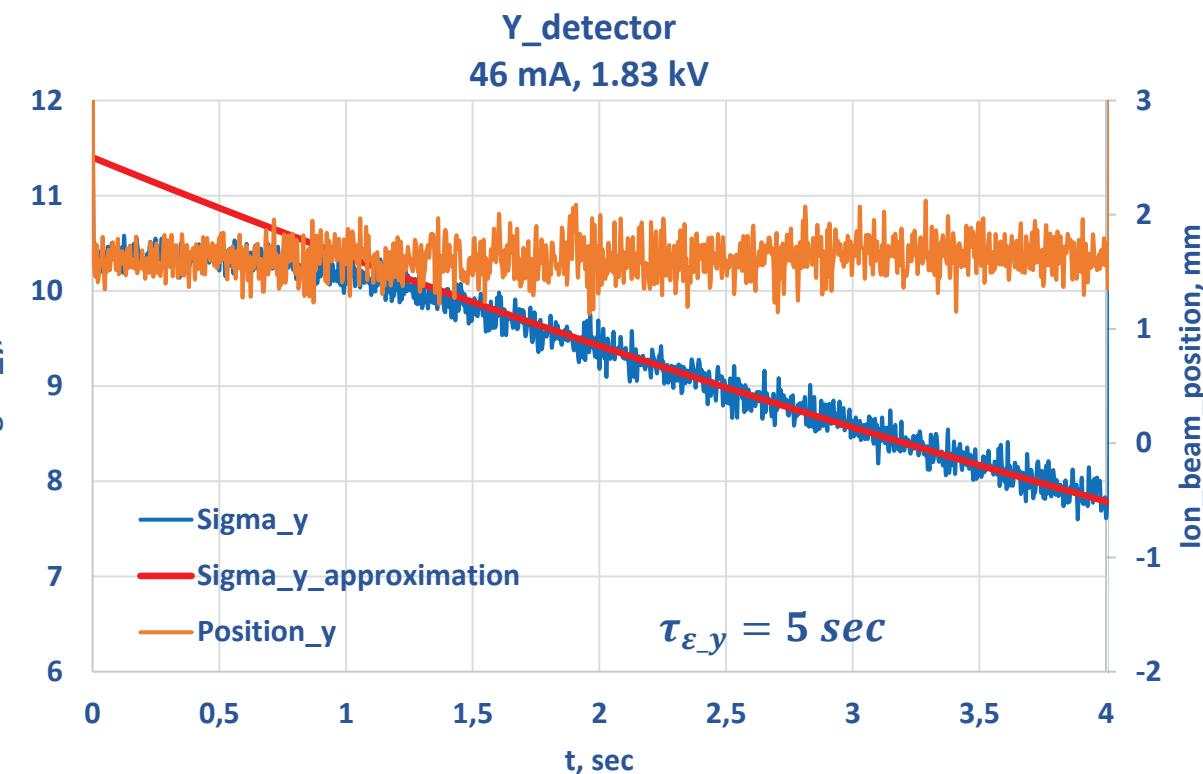
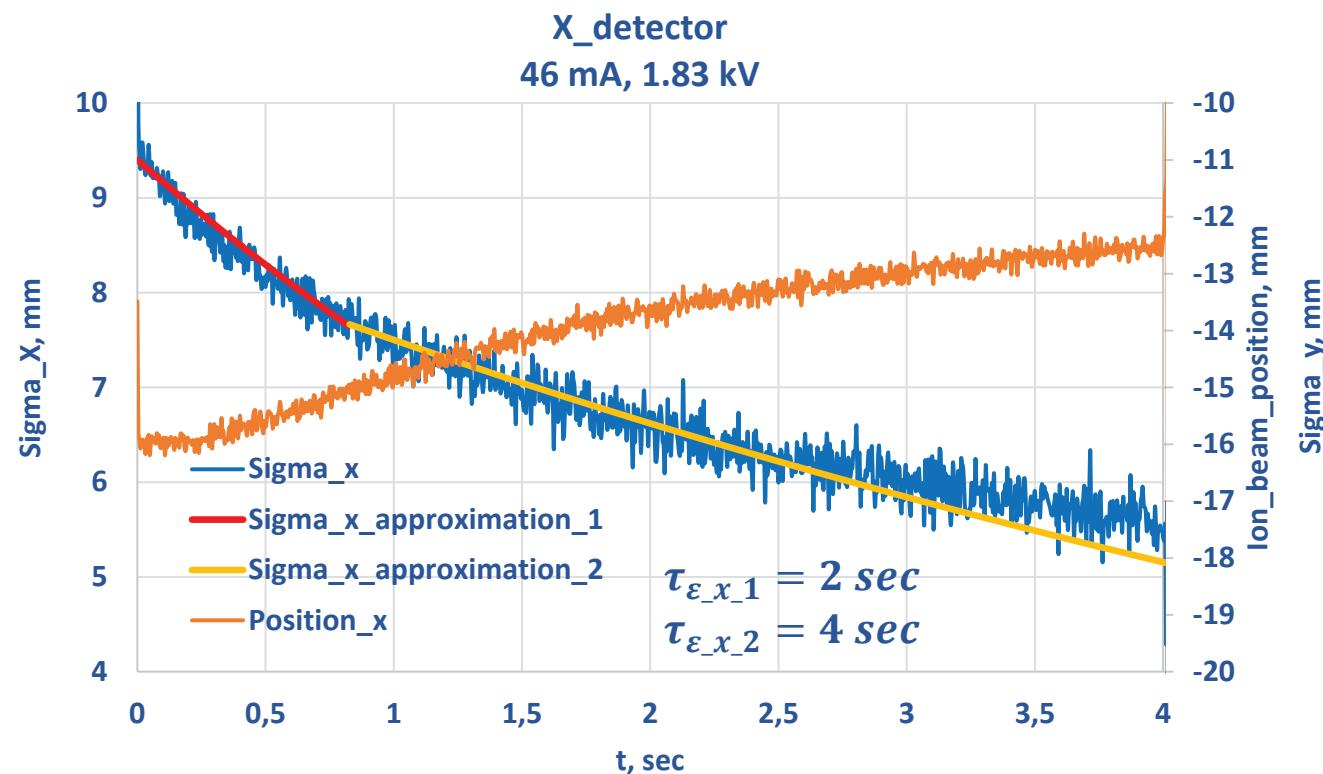


Due to the sagging potential of the electron beam over the radius, the cooling time when tuned to optimal energy turned out to be very long



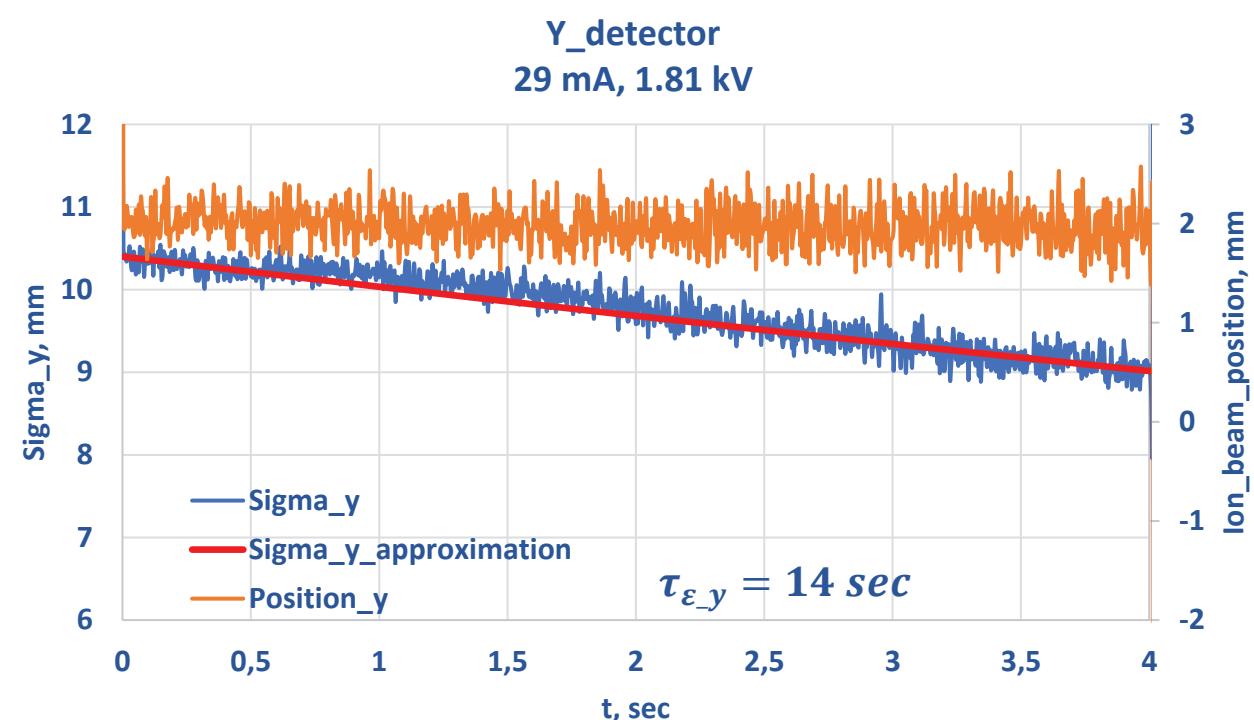
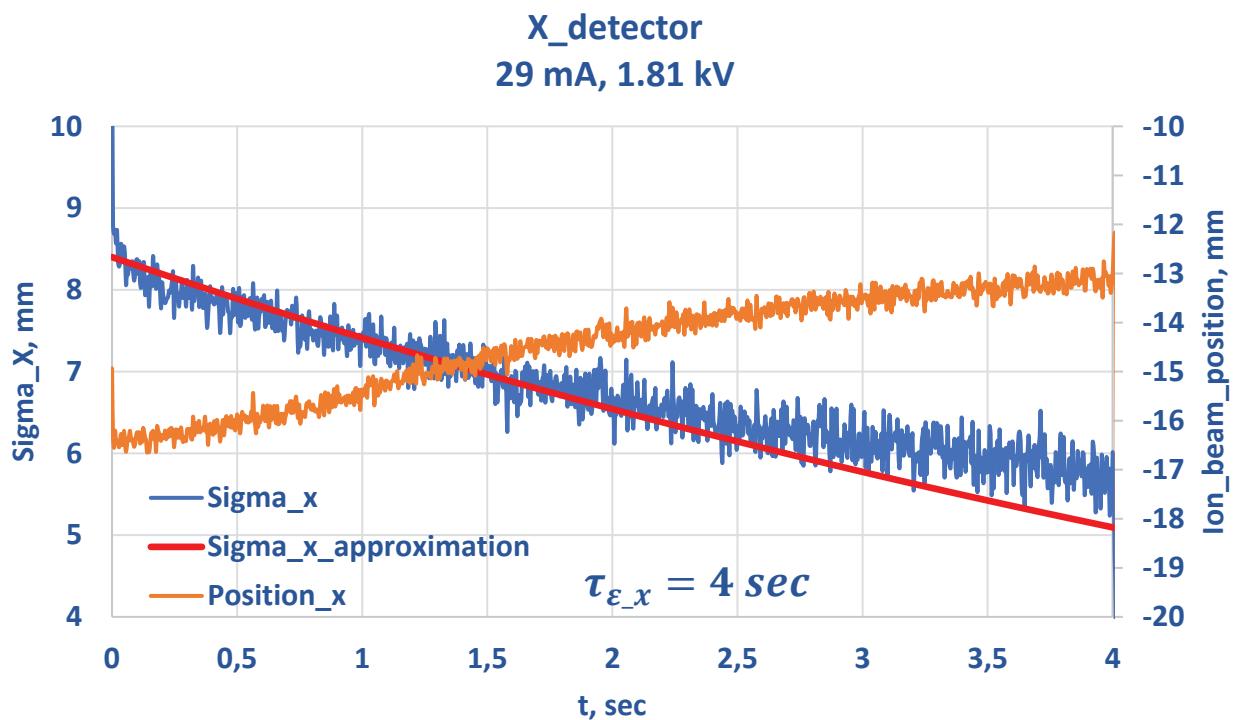
# Second Ion Electron Cooling Experiment

## Ionization profilometer signal



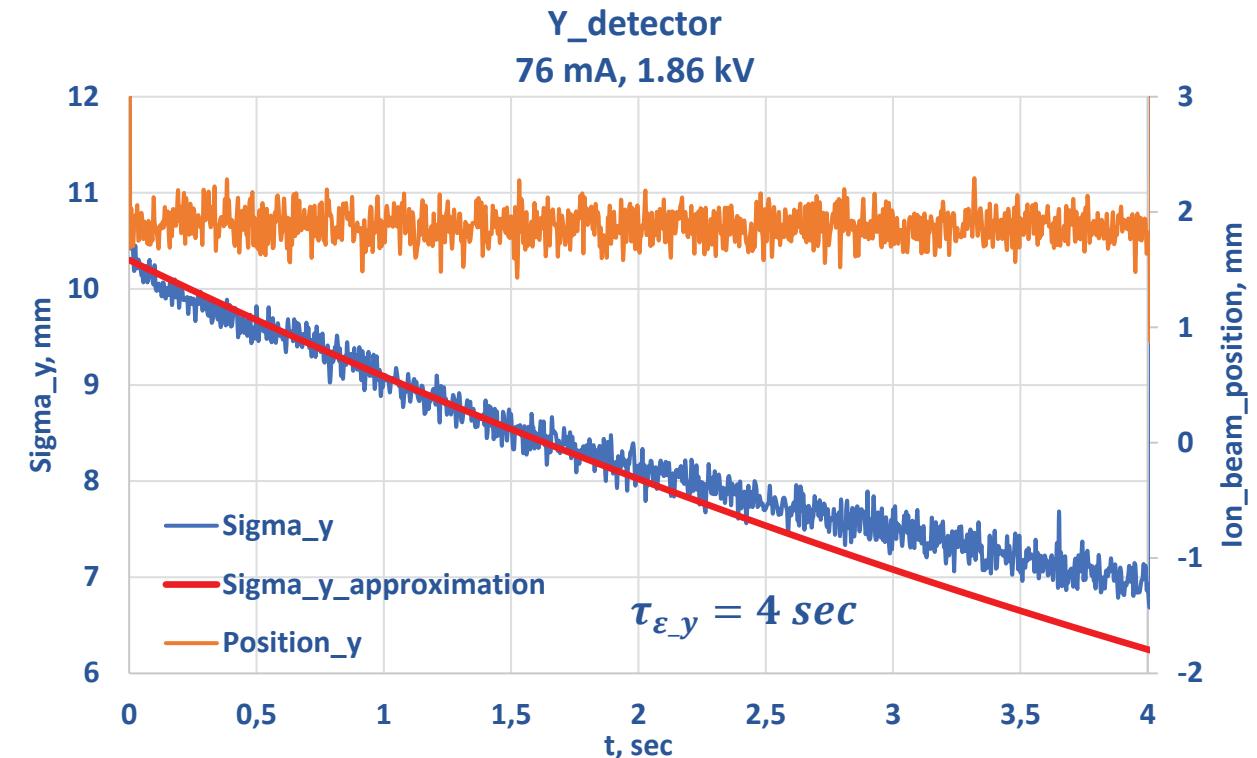
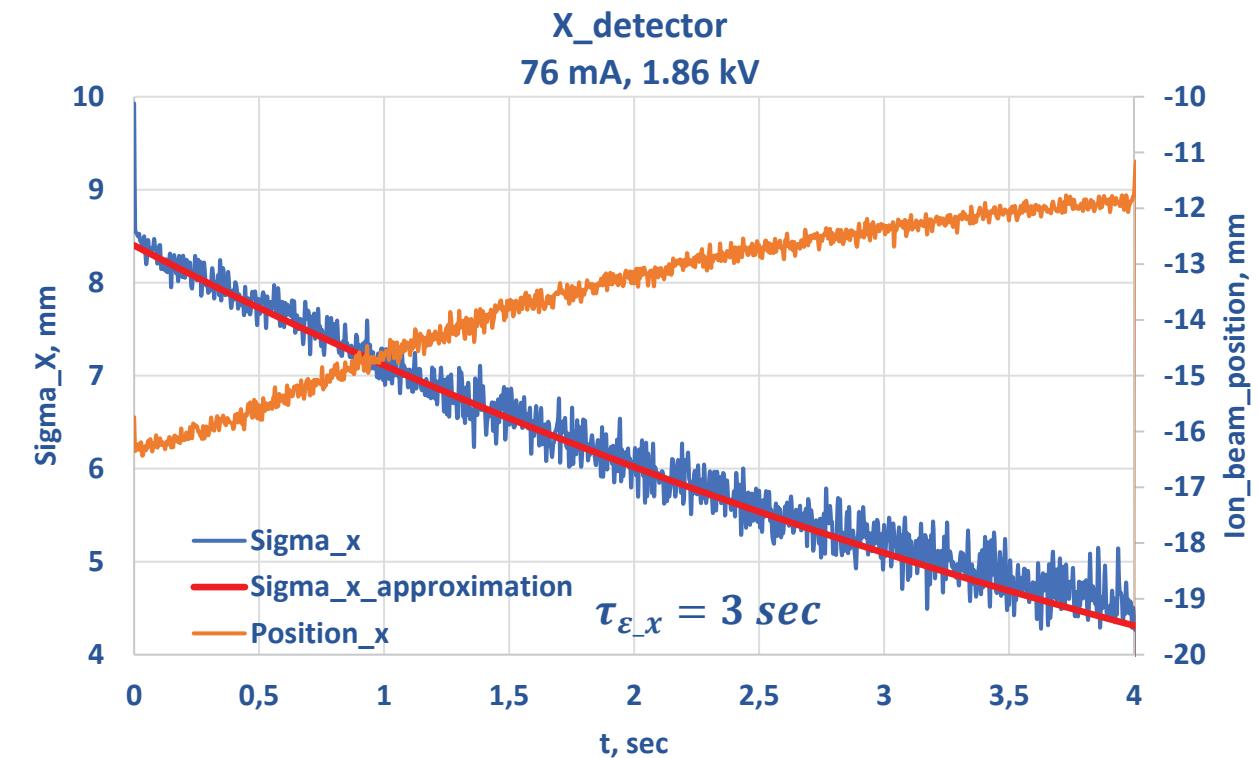
# Second Ion Electron Cooling Experiment

## Ionization profilometer signal



# Second Ion Electron Cooling Experiment

## Ionization profilometer signal



## Development of the Parkhomchuk formula

Due to the strong discrepancy between the theoretical and optimal experimental energy of the electron beam, it was decided to add to the classical V. V. Parkhomchuk formula for the friction force dependence

- sagging of the electron beam potential resulting in increase of the difference of electron and ion velocities. This effect significantly exceeds the effect of flattened distribution
- dependence on the drift velocity in the crossed longitudinal magnetic field and  $v_d(I_{el}, r) = \gamma \cdot c \frac{E_{el}(I_{el}, r) [V/cm]}{300 \cdot B [G]}$

**Total transverse velocity**

$$V_{x,y}(I_{el}, r) = \sqrt{V_{Ion_{x,y}}^2 + \Delta_{el_{x,y}}^2 + \frac{v_d(I_{el}, r)^2}{2} + (\gamma V_0 \vartheta_B)^2}$$

**Total longitudinal velocity**

$$V_s\left(\frac{dp}{p}, I_{el}, r\right) = \sqrt{V_{Ion_s}^2\left(\frac{dp}{p}\right) + \Delta v_{el_s}^2(I_{el}, r)}$$

**Friction force**

$$F_{x,y}\left(\frac{dp}{p}, I_{el}, r\right) = \frac{q_{el} \cdot V_{Ion_{x,y}}}{\left((V_x(I_{el}, r) + \gamma V_0 \vartheta_B)^2 + (V_y(I_{el}, r) + \gamma V_0 \vartheta_B)^2 + V_s\left(\frac{dp}{p}, I_{el}, r\right)^2\right)^{\frac{3}{2}}} \ln\left(1 + \frac{\rho_{max}\left(\frac{dp}{p}, I_{el}, r\right)}{\rho_L + \rho_{min}\left(\frac{dp}{p}, I_{el}, r\right)}\right)$$

**Cooling decrement  
and cooling time**

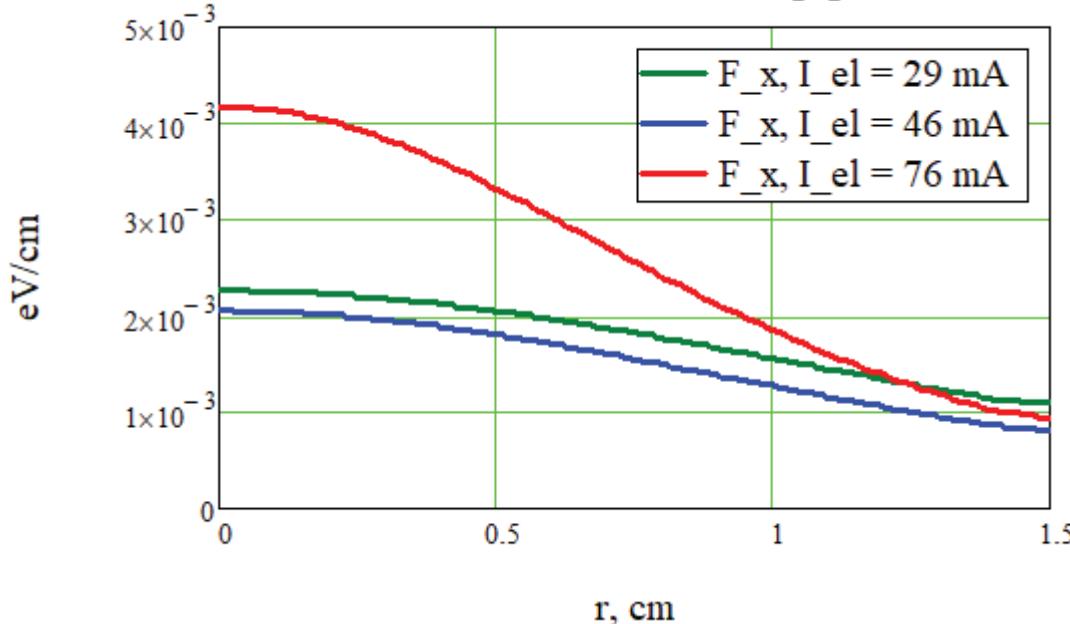
$$D_{x,y}\left(\frac{dp}{p}, I_{el}, r\right) = \frac{F_{x,y}\left(\frac{dp}{p}, I_{el}, r\right) \cdot c^2}{A m V_{Ion_{x,y}}} \Rightarrow \tau_{emit_{x,y}} = \frac{1}{2 \eta} D_{x,y}\left(\frac{dp}{p}, I_{el}, r\right)^{-1}$$

# Development of the Parkhomchuk formula

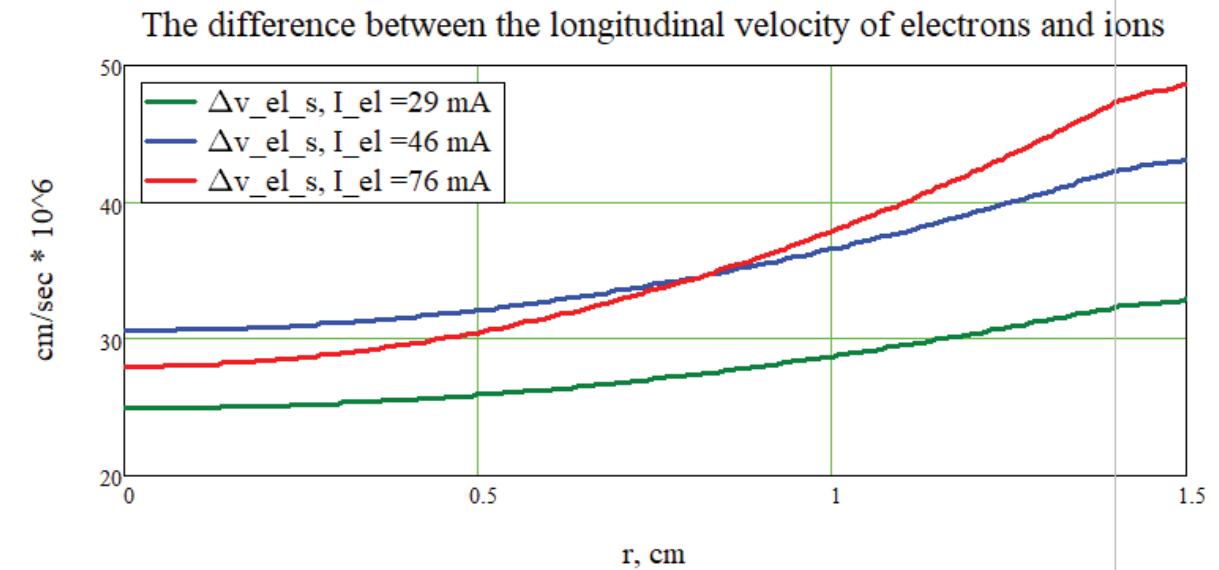
## Calculations

Since the electron beam is magnetized, the collision of an electron with an ion can be considered as an absolutely elastic collision. For these reasons, the transverse temperature of the electrons was chosen to be 0.

Horizontal friction force for  $dp/p = 0.0006$



The difference between the longitudinal velocity of electrons and ions

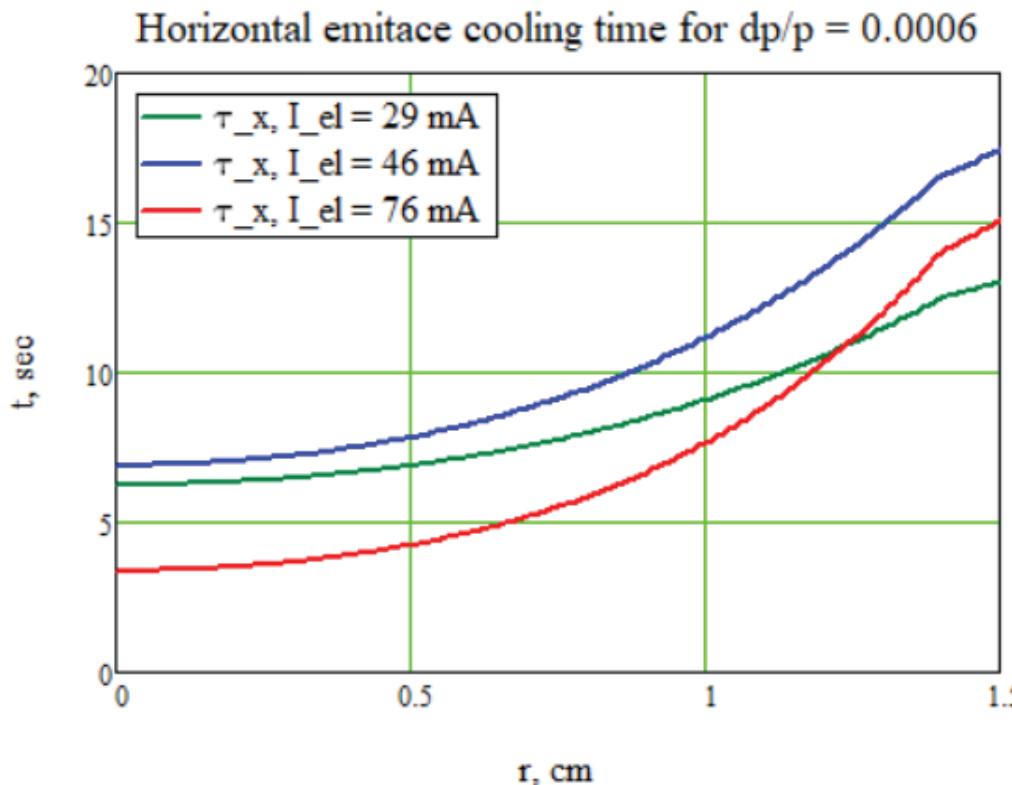


With an increase in the electron current, a competition of micro and macro interactions can be observed:

- increasing in the sagging potential, which leads to an increase in the difference in the longitudinal velocities of ions and electrons, as a result decreasing of the friction force
- increasing in the electron density, which leads to an increase in the friction force

# Development of the Parkhomchuk formula

## Calculations



### Experimental horizontal emittance cooling time

$I$ , mA	$\tau$ , sec
29	4
46	2 – 4
76	3

As the electron current increases, the influence of the space charge increases, and the cooling time increases first (green and blue curves). But with a further increase of the current, the influence of the increase in the friction force begins to prevail over the increase in the longitudinal velocity spread and the cooling time decreases significantly (blue and red curves).

## Conclusions

- electron cooling of heavy ions at injection energy (3.2 MeV/u) it is of practical interest, because it makes it possible to use multi-turn and/or multiple injection;
- the peculiarity of low energy electron cooling is the strong influence of the space charge of the electron beam;
- in this case well known Parkhomchuk formula needs appropriate correction.