COSY experience of electron cooling

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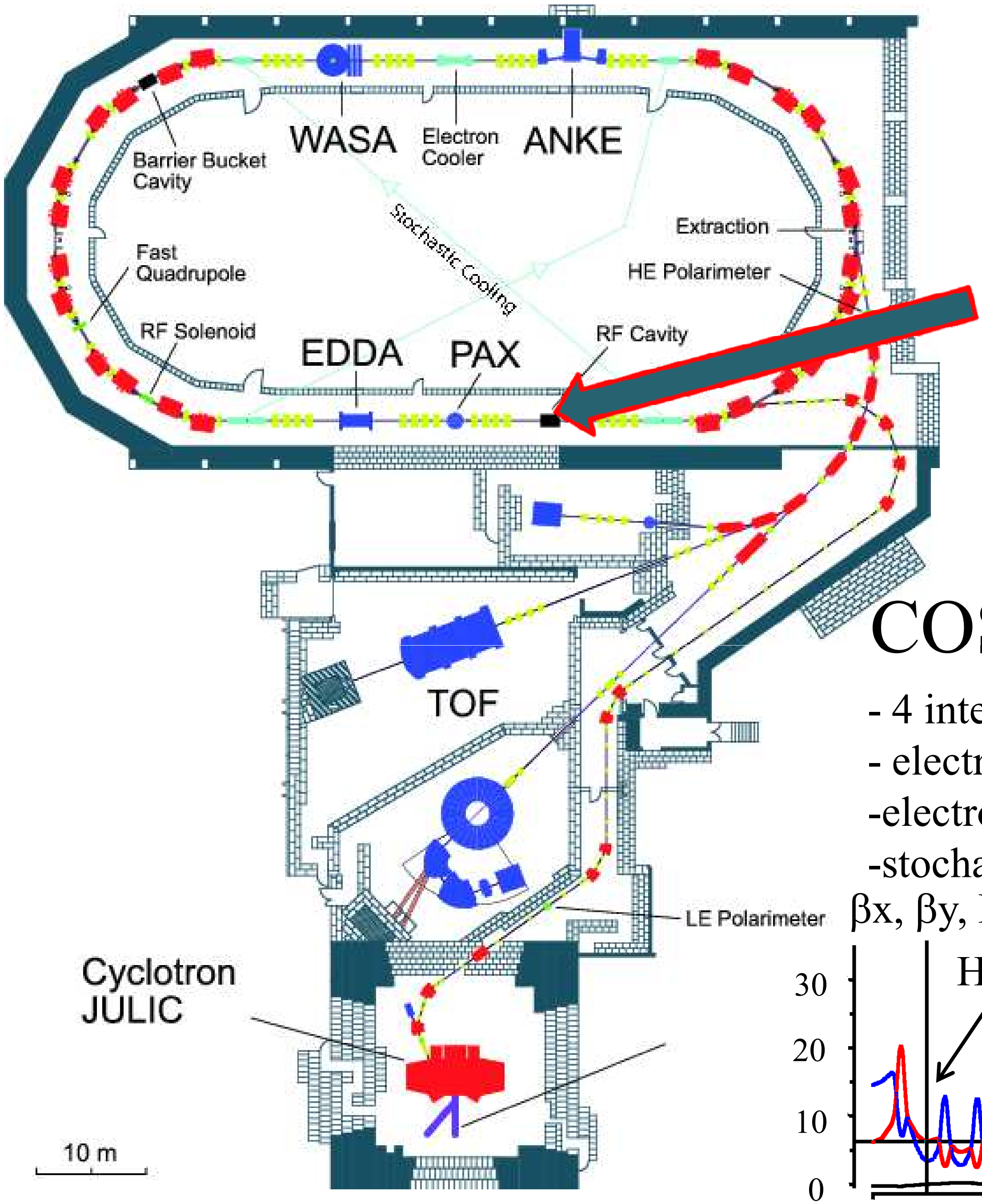
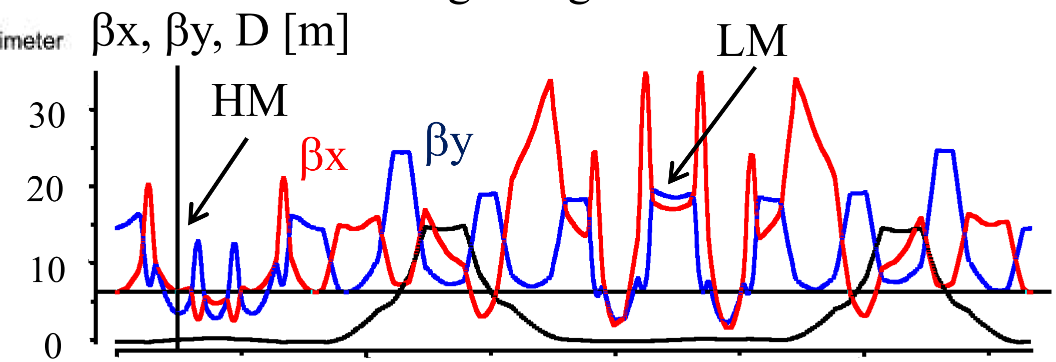
Abstract

The 2 MeV electron cooling system for COSY-Julich has highest energy for the electron cooler with strong longitudinal magnetic field. During operation the cooling process was detailed investigated at different energies of electron beam. The proton beam was cooled at different regimes: RF, barrier bucket RF, cluster target and stochastic cooling. This report deals with the experience of electron cooling at high energy.



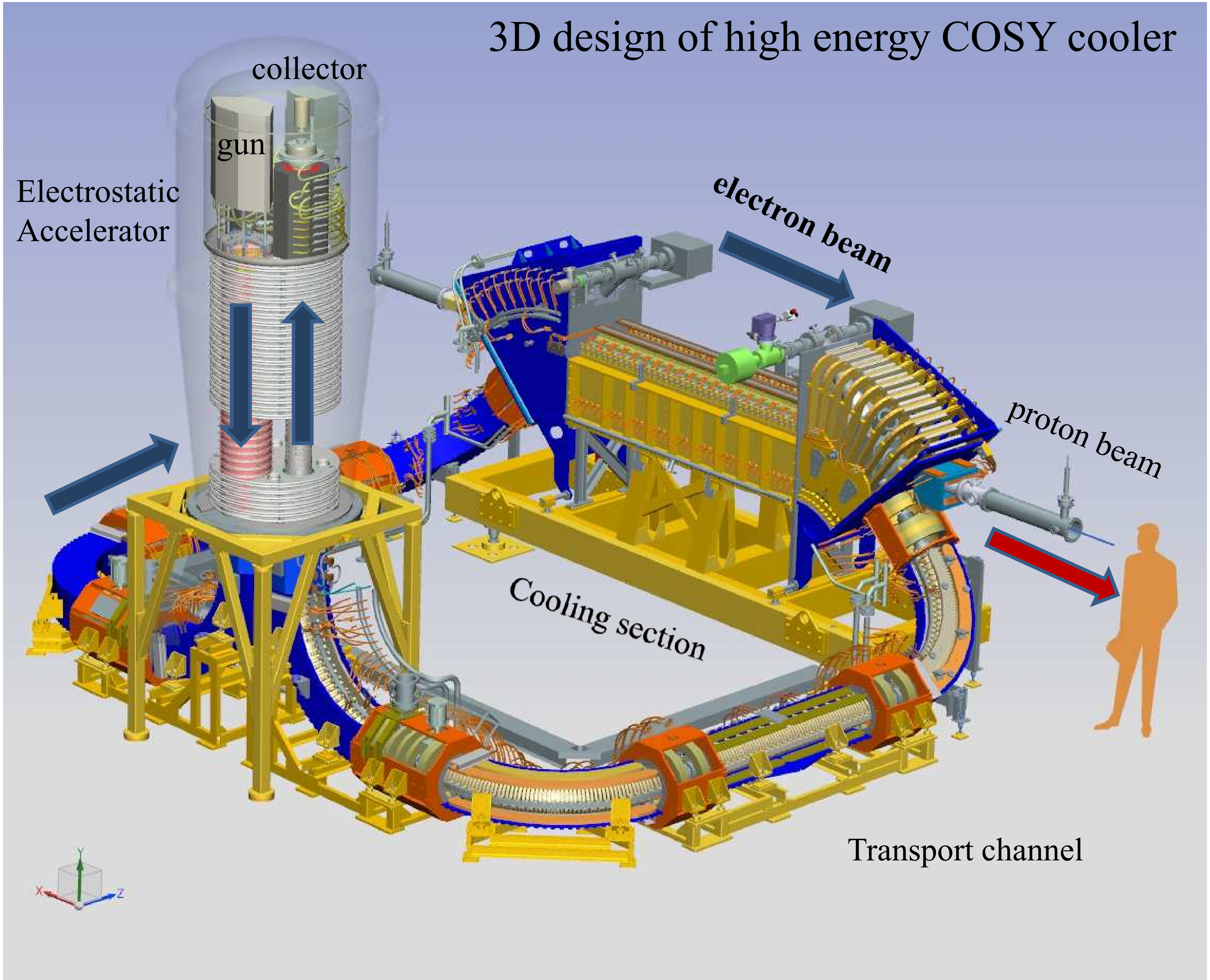
COSY Accelerator Facility

- 4 internal and 3 external experimental areas
- electron cooling at low momenta (LM)
-electron cooling at high momenta (HM)
-stochastic cooling at high momenta



P=183.6 m, E=2880 MeV

βx=6.5 m, βy=3.5 m (High Voltage cooler)


3D design of high energy COSY cooler
collector
gun
Electrostatic
Accelerator
electron beam
proton beam
Cooling section
Transport channel

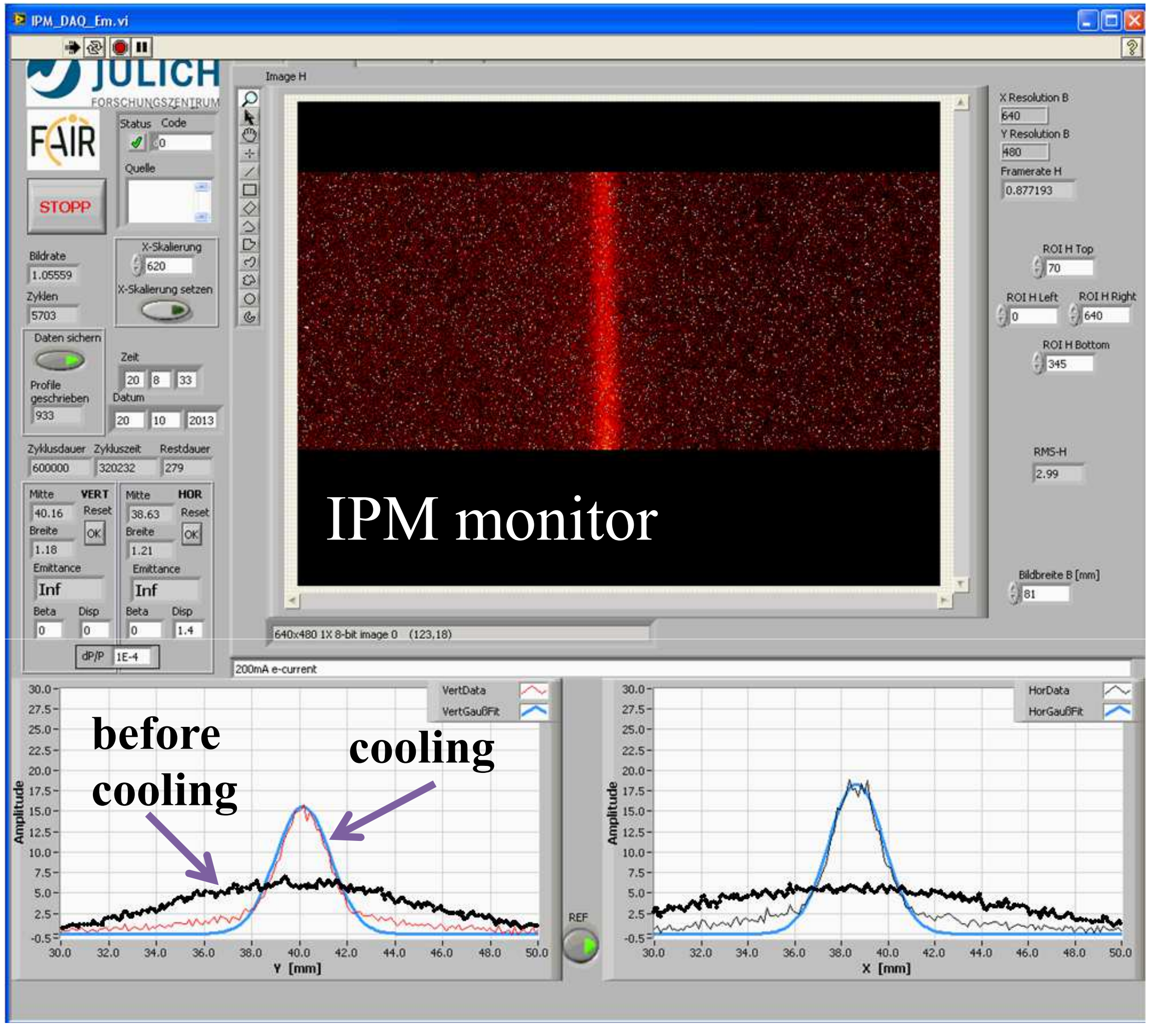
Design parameters of cooler COSY

2 MeV Electron Cooler	Parameter
Energy Range	25 keV ... 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

Electron cooling was investigated at following energies

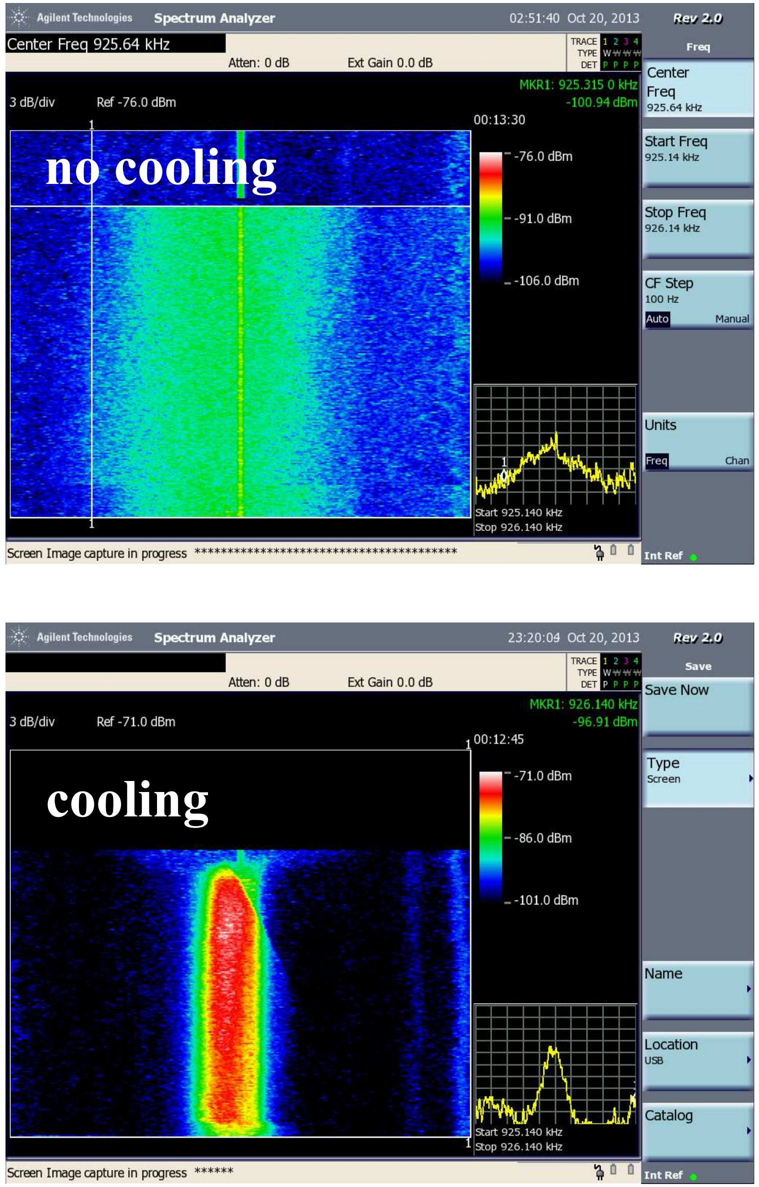
Proton energy, MeV	Electron energy, keV	Max. electron current, A
200	109	0.5
353	192	0.5
580	316	0.3
1670	908	0.9
2300	**1250**	**0.5**

Signal from Ion Profile Monitor



Transverse cooling

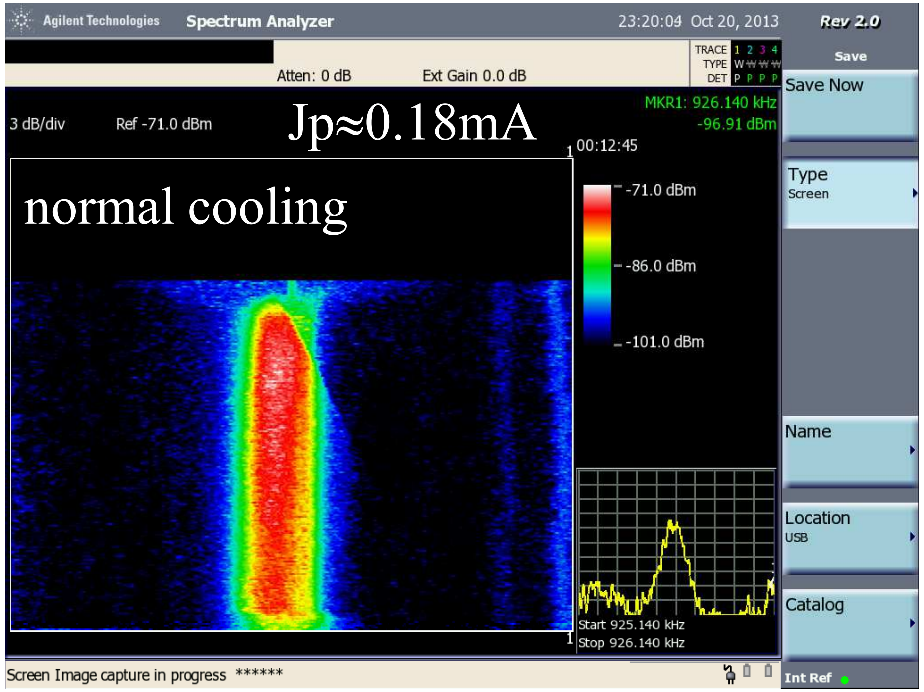
Schottky signal from pick-up

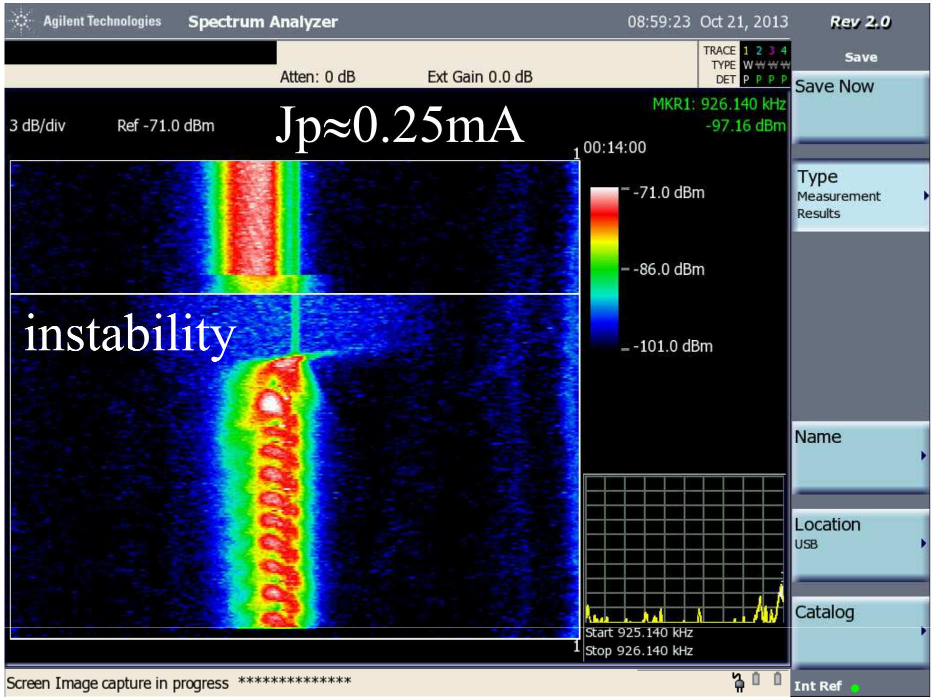


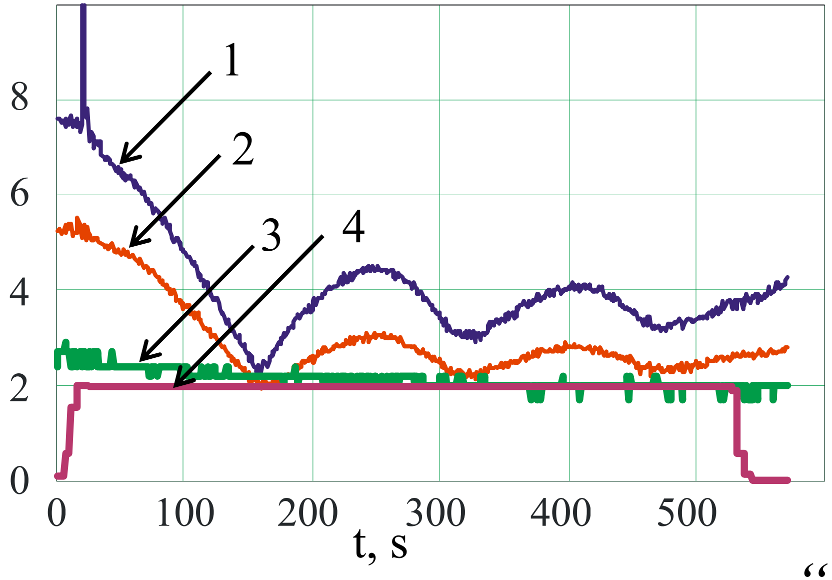
Longitudinal cooling

First cooling experiment - cooling at Ee=109 keV

Large intensity and low momentum spread may induce coherent instability







1 – vertical width (mm)

2 – horizontal width (mm)

3 – proton beam current (0.1 mA)

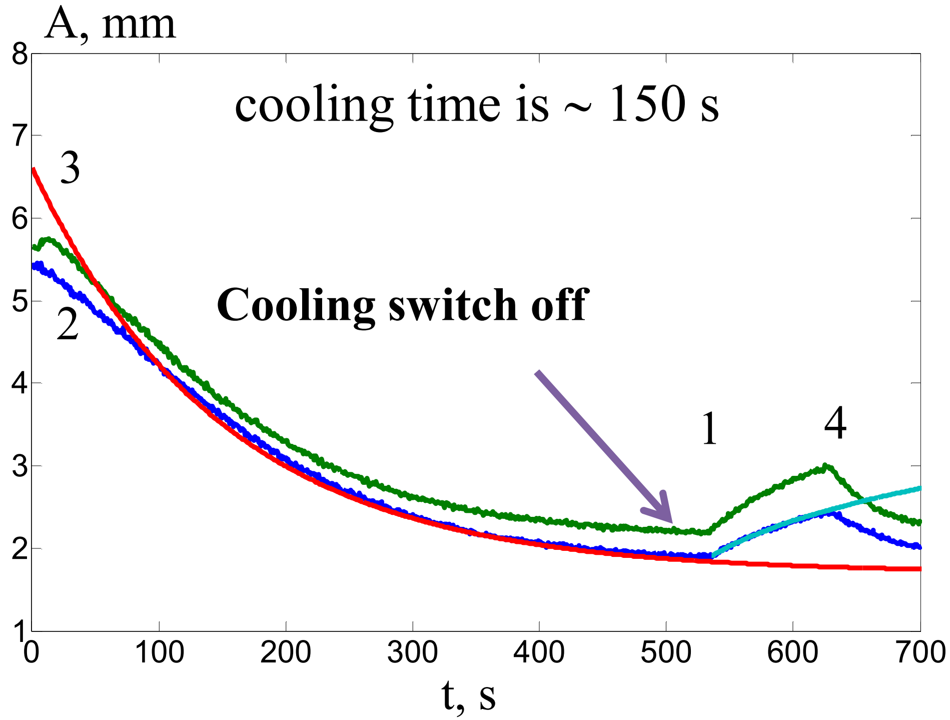
4 – electron current (100 mA)

Ee=109 keV

Increasing of proton intensity switch on the instability. It can be observed in the transverse plane and pickup spectrum both

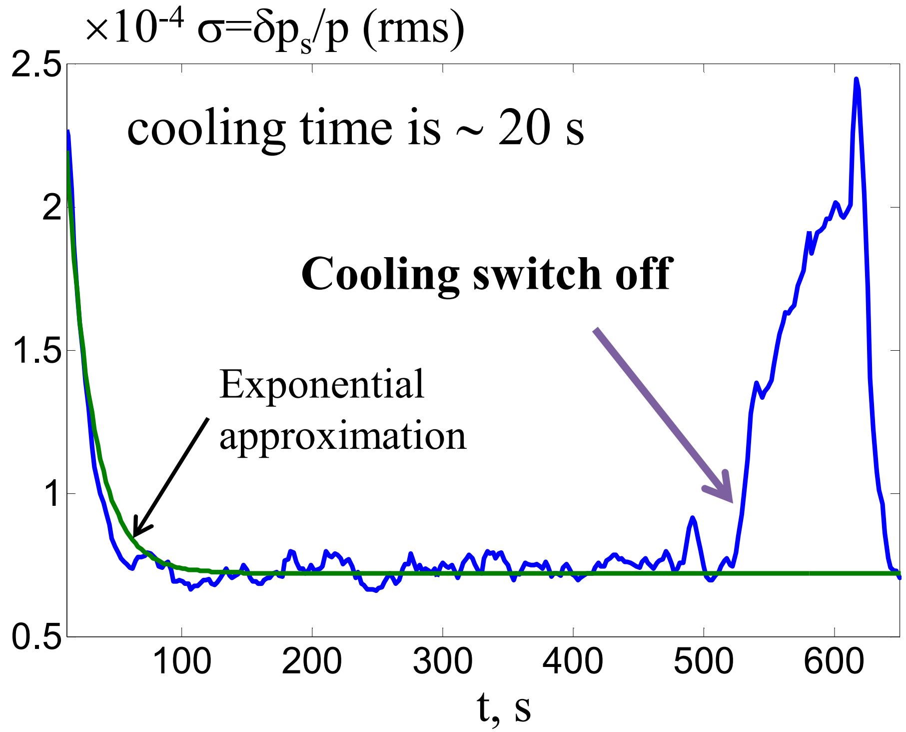
“First problem with coherent instability”

Next step - cooling at Ee=192 keV, electron current 300 mA



Transverse size versus time: 1 and 2 are horizontal and vertical width of proton beam, 3 is exponential estimation of cooling time горизонтальная ширина пучка, 4 – is expansion of proton beam with diffusion coefficient $3\cdot10^{-2}$ мм^2/с.

Transverse cooling

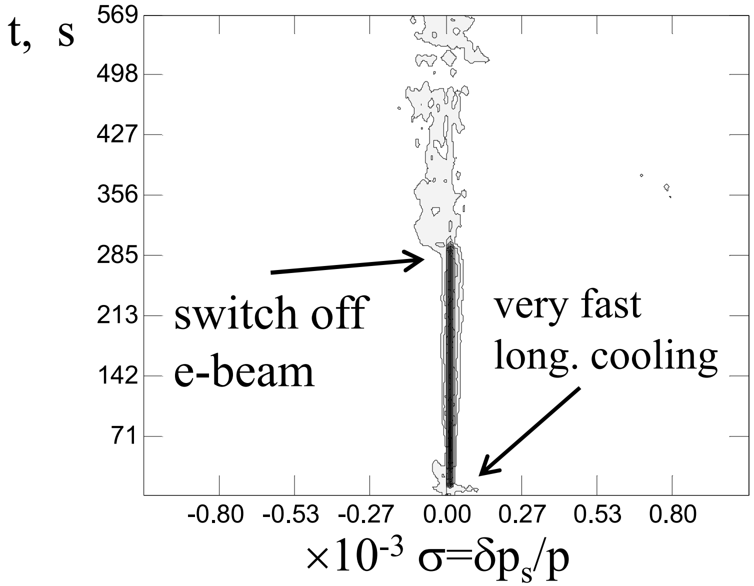


Longitudinal momentum spread (r.m.s) versus time.

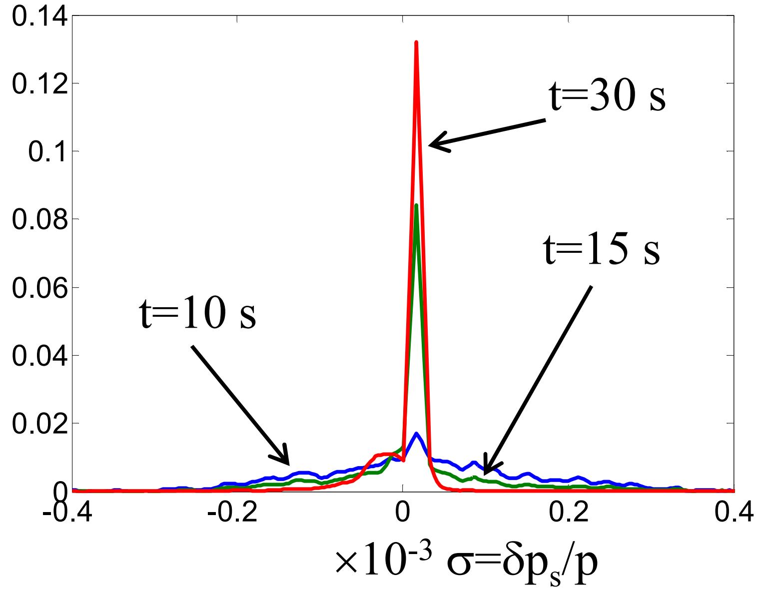
Longitudinal cooling

“First call” – transverse cooling may be worse than longitudinal one

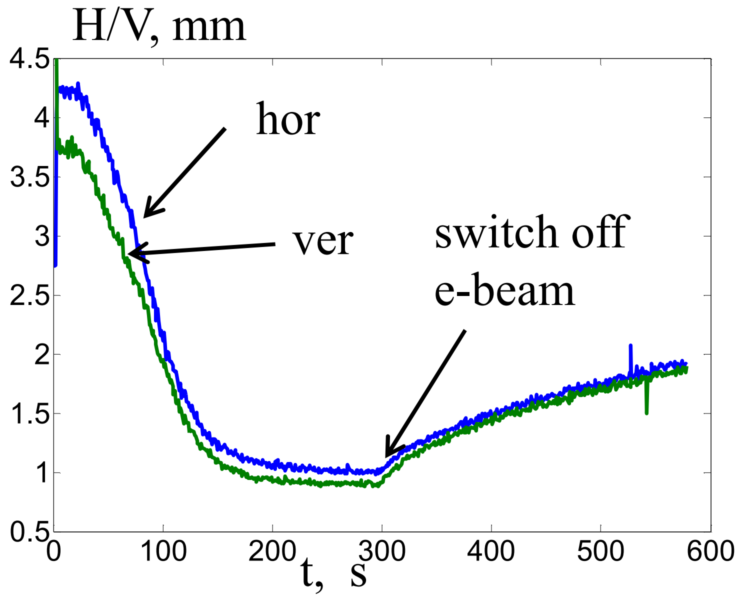
Next step - cooling at 315.85 keV, electron current 300 mA



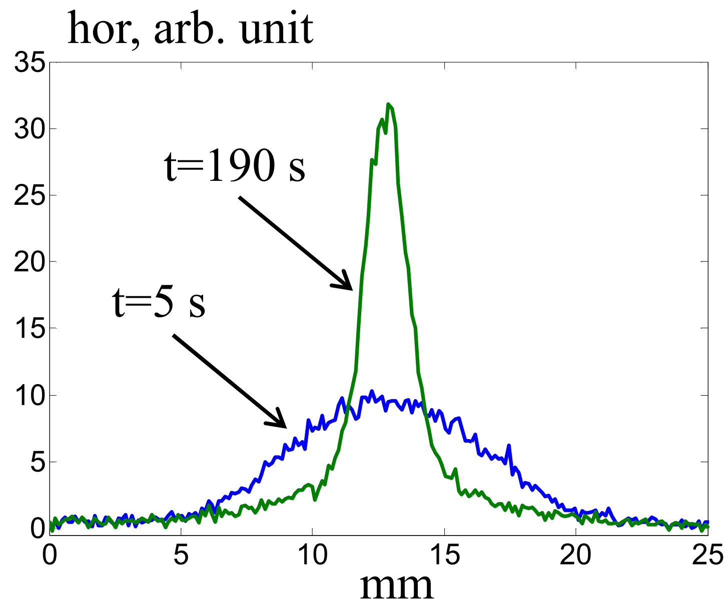
Spectrogram of the longitudinal distribution function versus time. Levels are intensity of Schottky signal



longitudinal distribution function

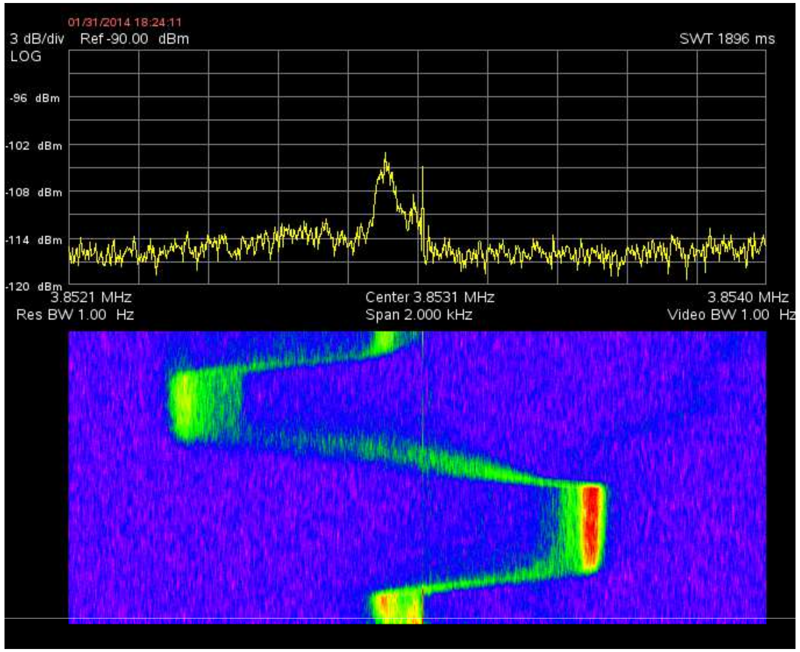


horizontal and vertical width versus time



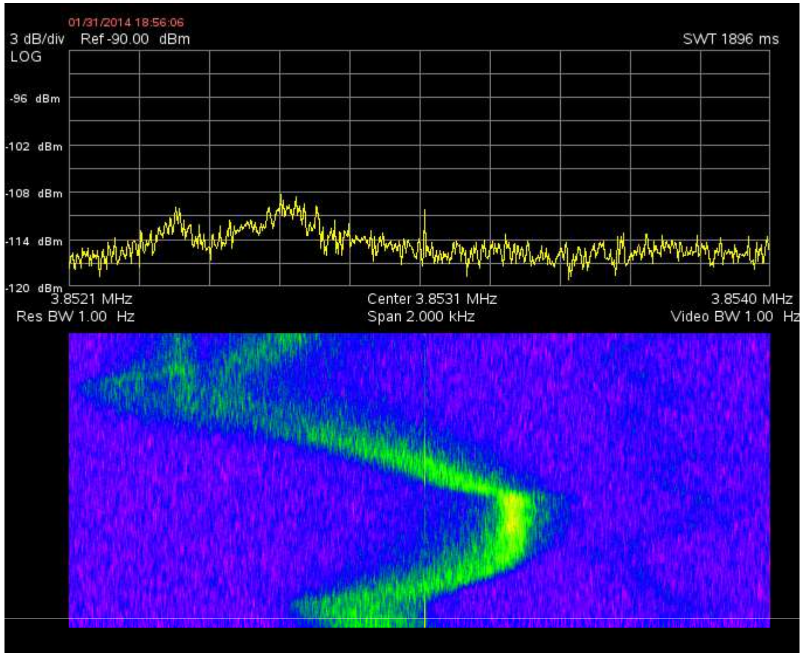
horizontal profile before and after cooling

Larmour rotation can be essential for the cooling process



-300 V 0 +300 V

edip kick=+1/0 A



-300 V 0 +300 V

edip kick=+2/0 A

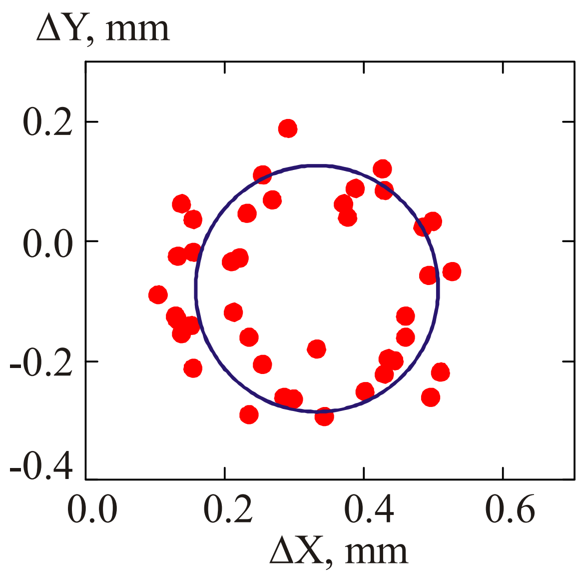
Jump of electron energy for estimation cooling rate

The electron energy is changed according schedule.
315.85 (0 s) → 316.15 (100 s) → 315.55 (300 s) → 315.85 (500 s).
The cycle duration is 600 sec.

$$R_L = 0.2\,mm \qquad B_{cool} = 1275\,G \qquad E_e = 316\,keV \qquad \gamma = 1 + \frac{E_e}{mc^2} = 1.59$$

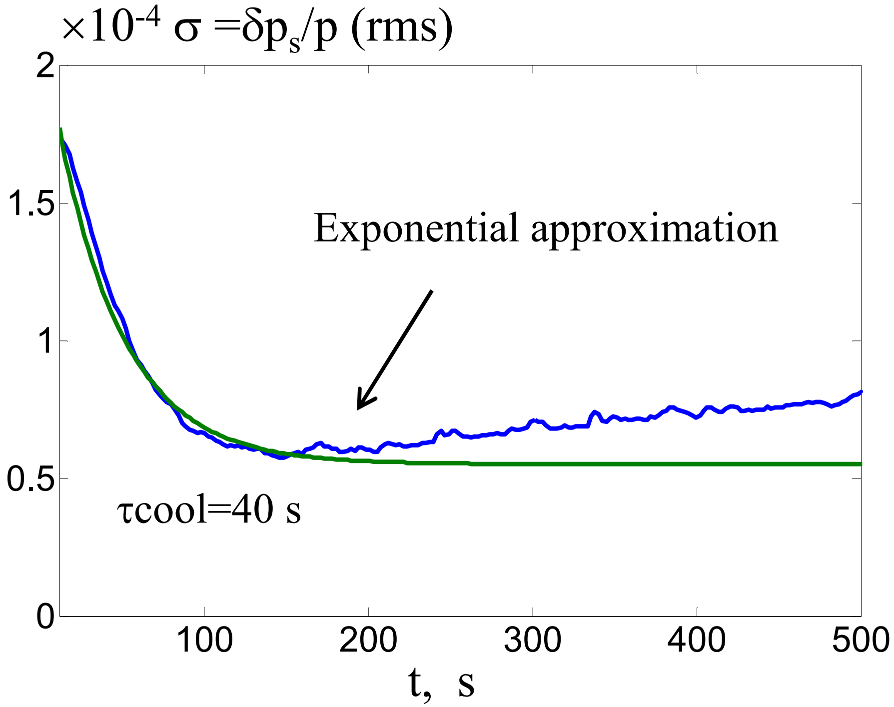
$$\rho = \frac{\gamma\beta m_e c^2}{eB_{cool}} = 1.7\,cm \qquad \rho_{\max} = v_i \tau_{flight} = 0.7 - 2.7\,mm \qquad \frac{\delta p_{e\perp}}{p_0} = \frac{R_L}{\rho} = 0.012$$

Observation cyclotron rotation of the electron beam with BPM at changing of magnetic field (i.e phase shift of motion) in the cooling section.

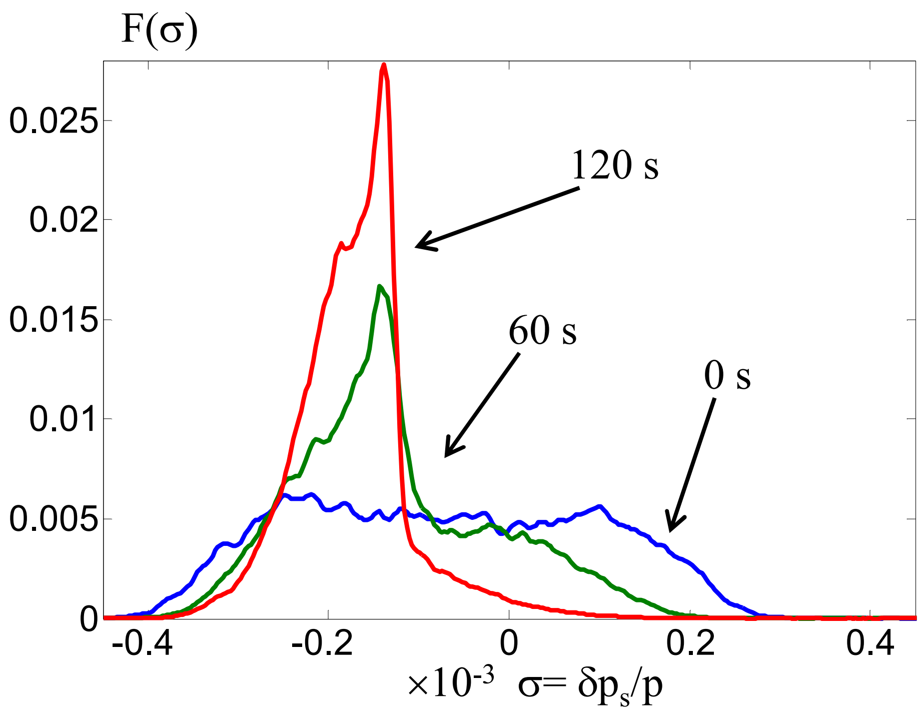


Maximum experience - cooling at 909 keV, electron current up to 900 mA, many good experimental results was obtained

Fast longitudinal cooling



Longitudinal momentum spread (r.m.s) versus time



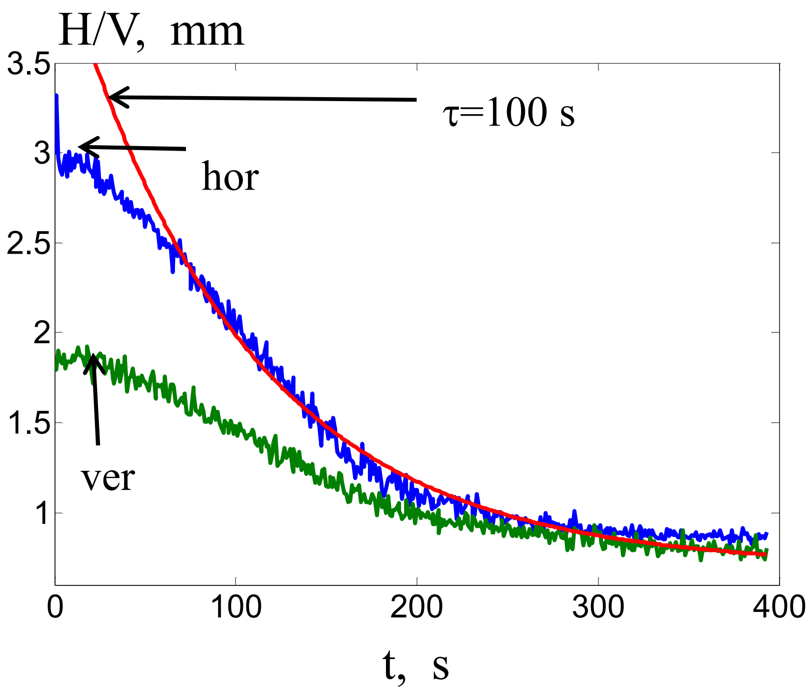
longitudinal distribution function for the different moments of cooling process

Base experiment parameters

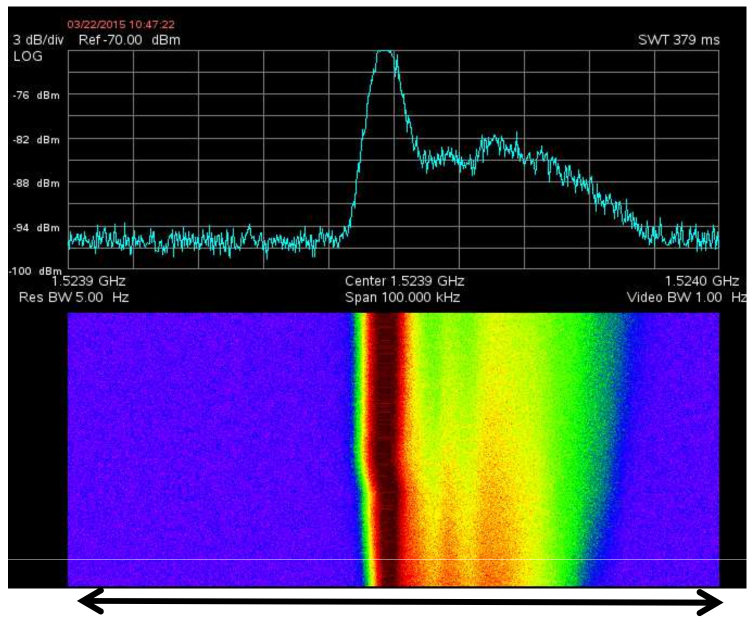
Np=$4\cdot10^8$, Ep=1.67 GeV, γtr=2.26

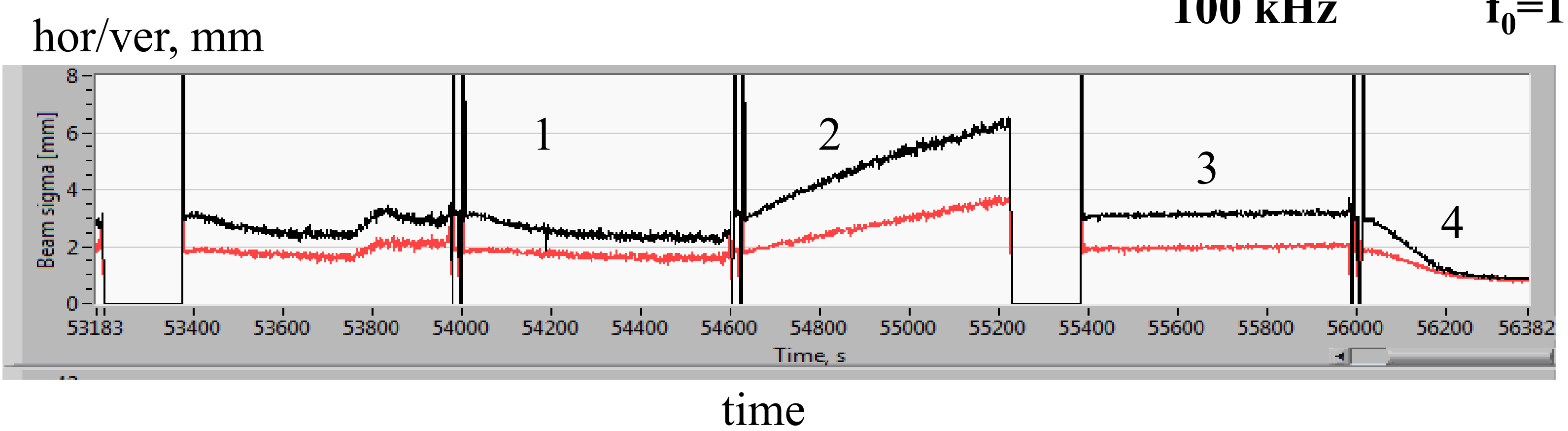
Ee=909.05 keV, Je=520 mA, Uan=5.3 kV, Ugr=0.4 kV, Magnetic field in the cooling section B_{cool}=1380 G

Best transverse cooling at high energy



Schottky signal from pick-up





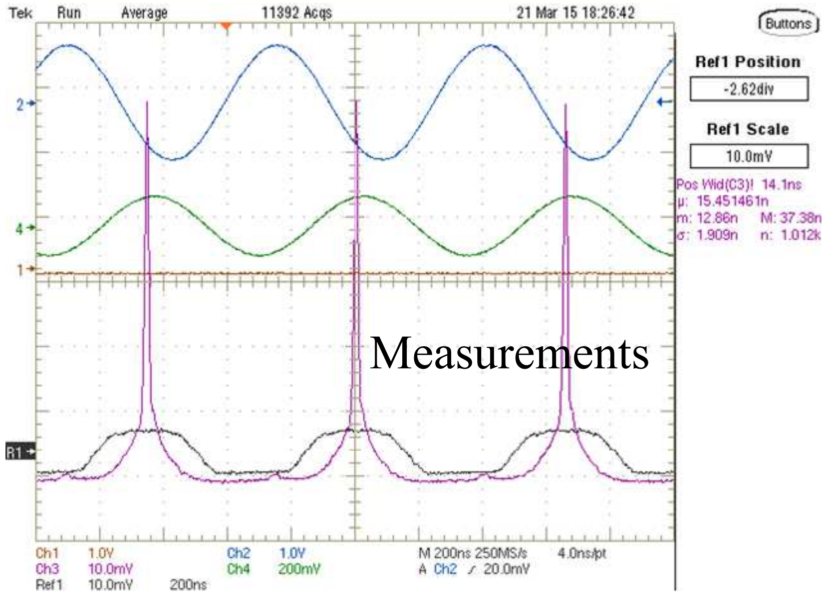
$3.6 \cdot 10^8$ protons, 1.66 GeV I_e = 0.8 A 1.3 kG

1. Noise + EC, 2. Noise only, 3. Reference, 4. EC

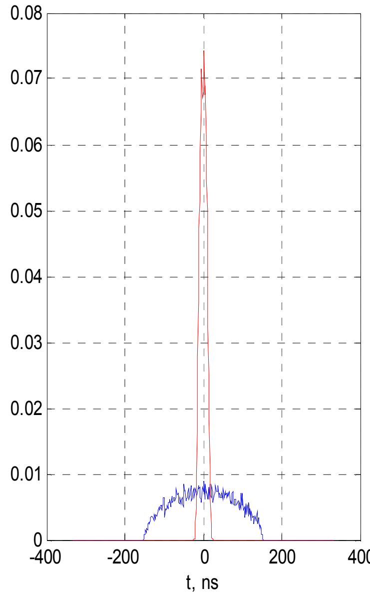
Ee=909 keV

Electron cooling can well operate with usual RF

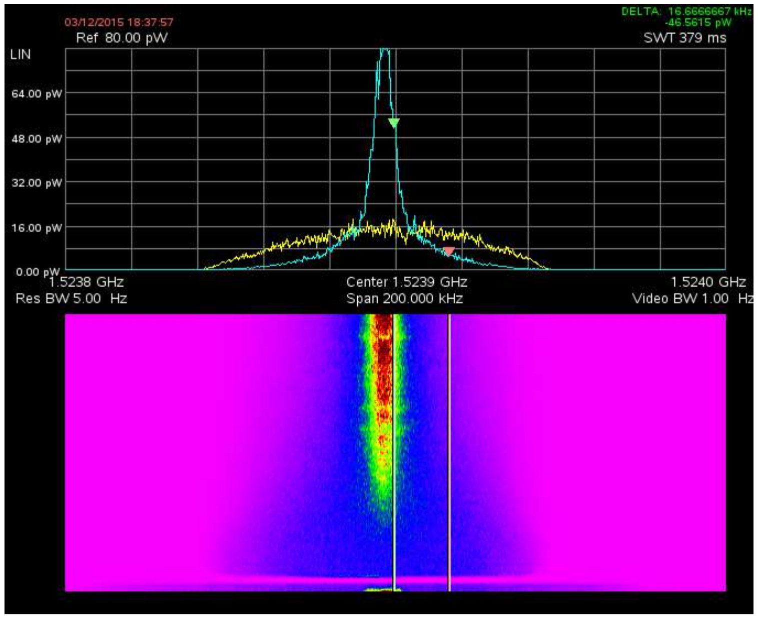
Cooling of bunched proton beam on COSY. Electron energy 908 keV. Electron current 0.5 A.



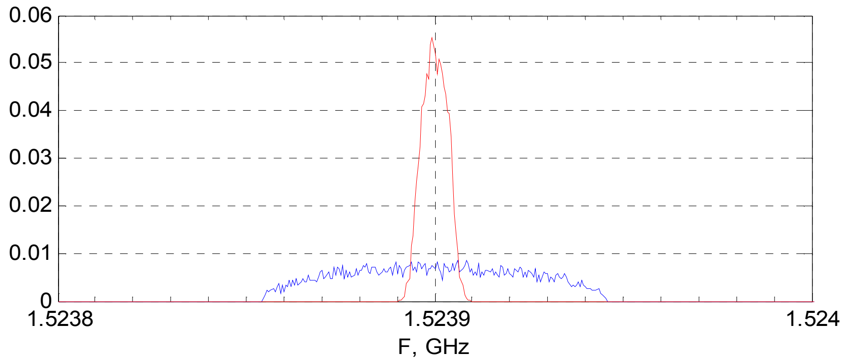
Measurements



Simulations with Parkhomchuk's equation and space charge field

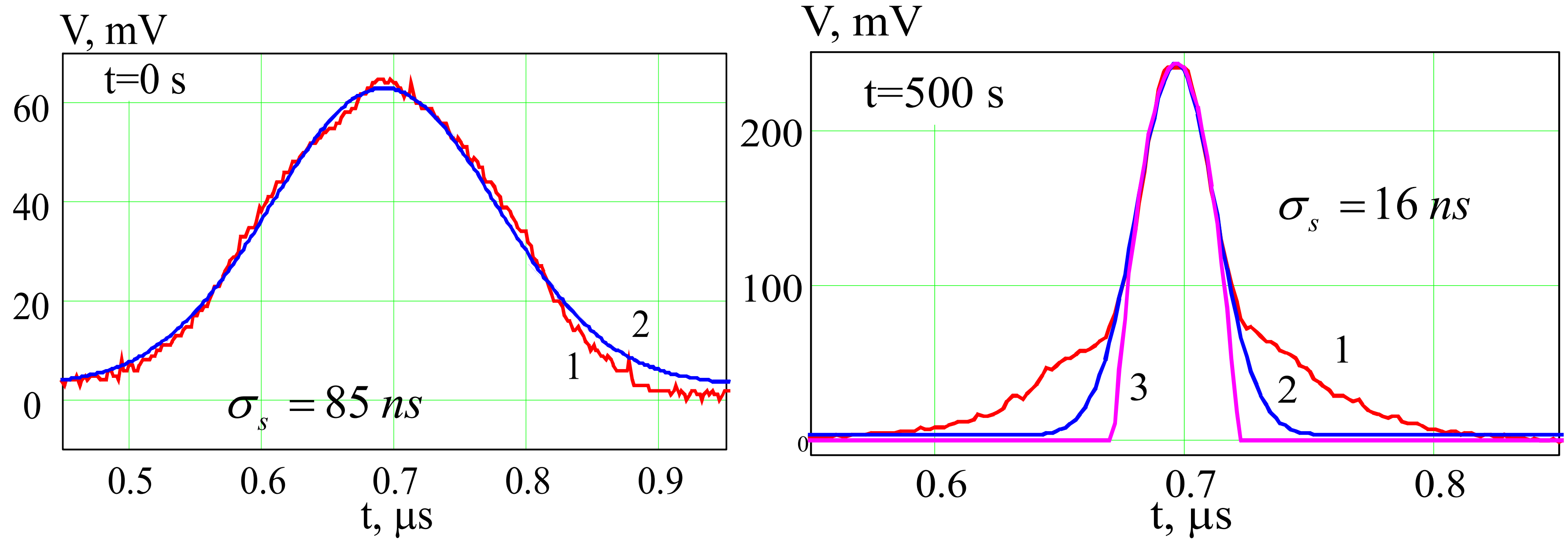


Cooling simulations for COSY



Fitting curves of the shape of the proton bunch for the start (left picture) and the end (right picture) of the cooling process.

RF on, e-cooling with 570 mA, Np=2·10[9], Ee=909 kV



1 is experimental profile, 2 is gauss shape, 3 is parabolic shape

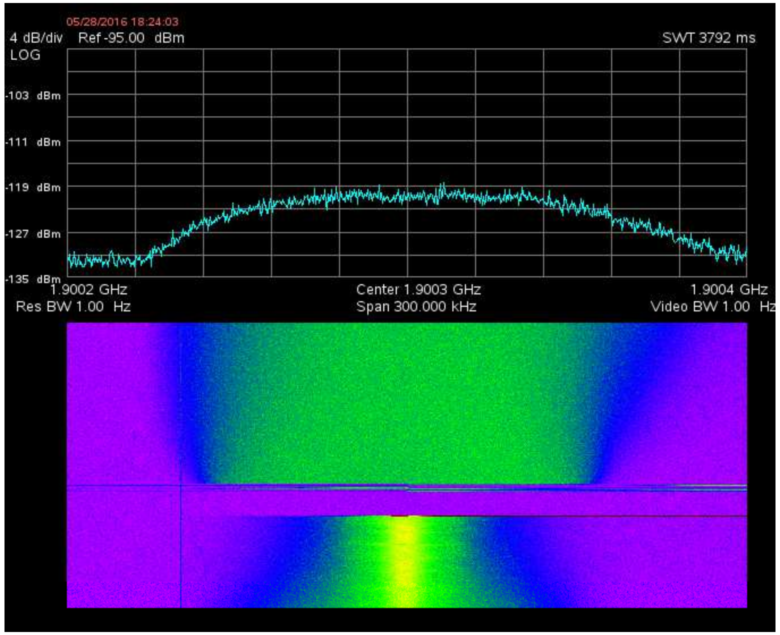
The estimation of the length according equation gives the length 14 ns that is very close to the experimental data. So, the beam core attains equilibrium induced by the space charge force.

$$\sigma_s^3 = \frac{eN_p\left(2\ln\left(\frac{b}{a}\right)+1\right)}{(2\pi)^{3/2}\gamma^2 U_{RF}}\Pi^2$$

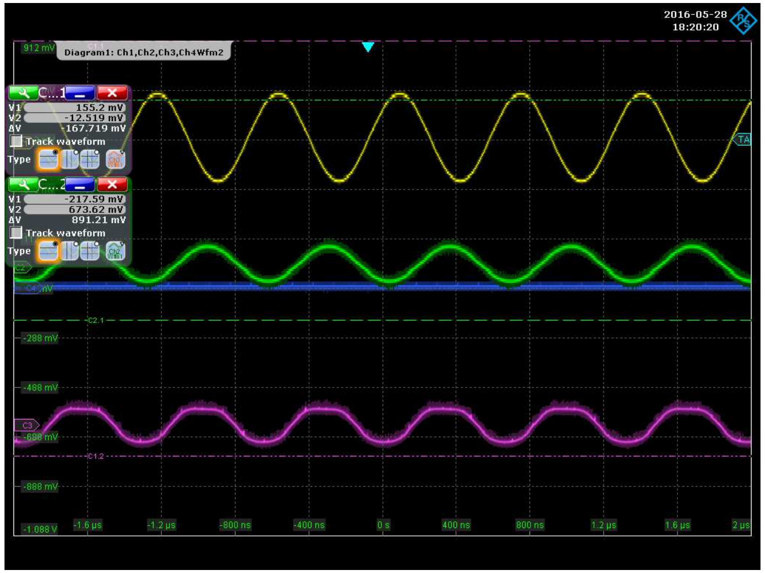
e-cool can help to obtain the space-charge limit

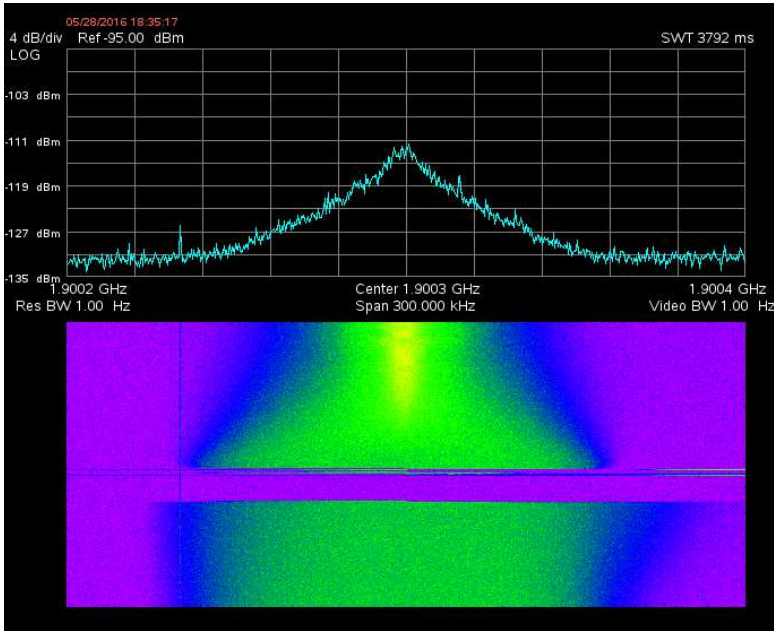
e-cool can well operate with usual RF and target

Ee=909 kV, Np=$2\cdot10^9$, $n_a=2\cdot10^{14}$ cm^{-2}

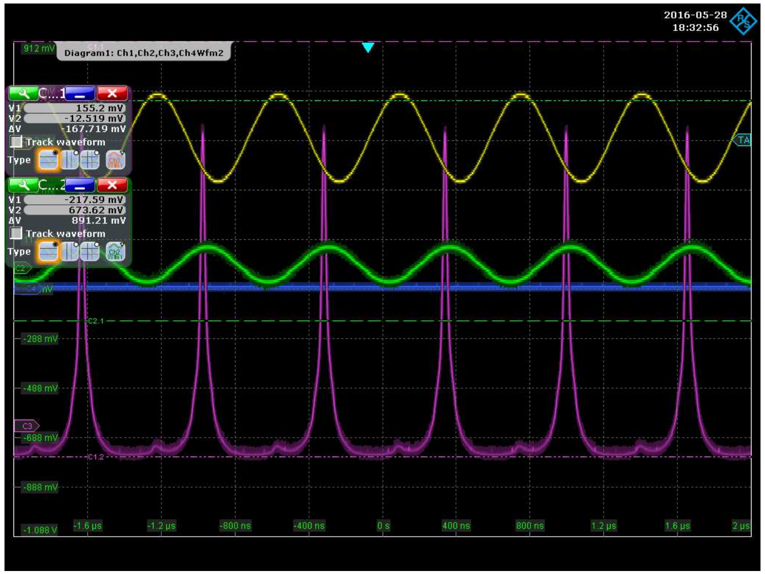


NO COOL

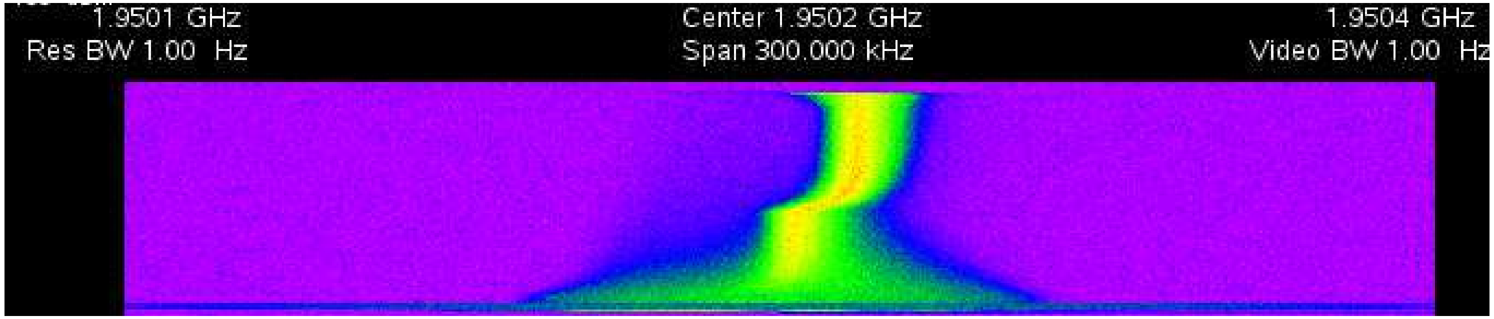




COOL

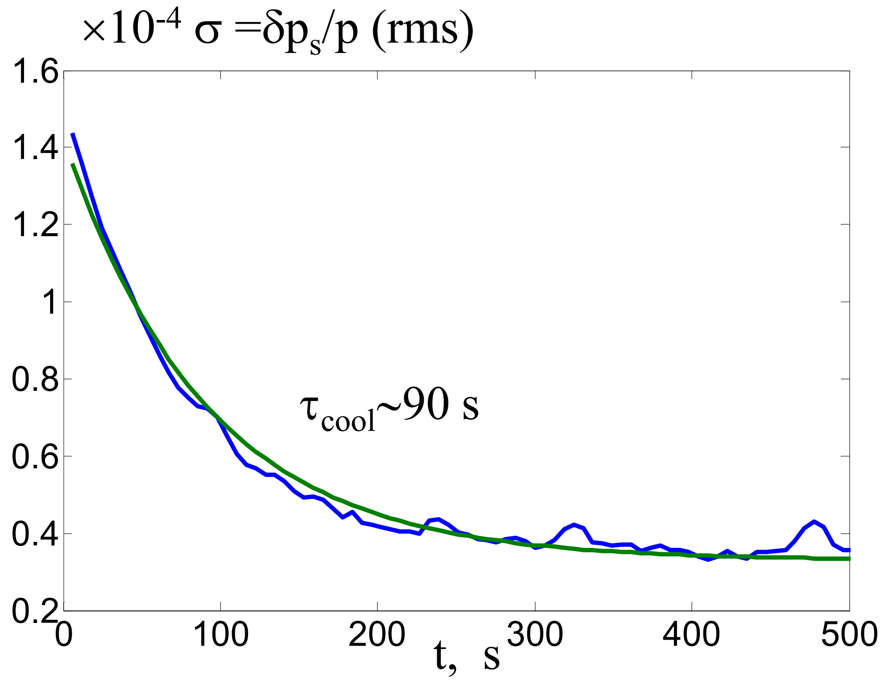


Next step - cooling at 1259 kV

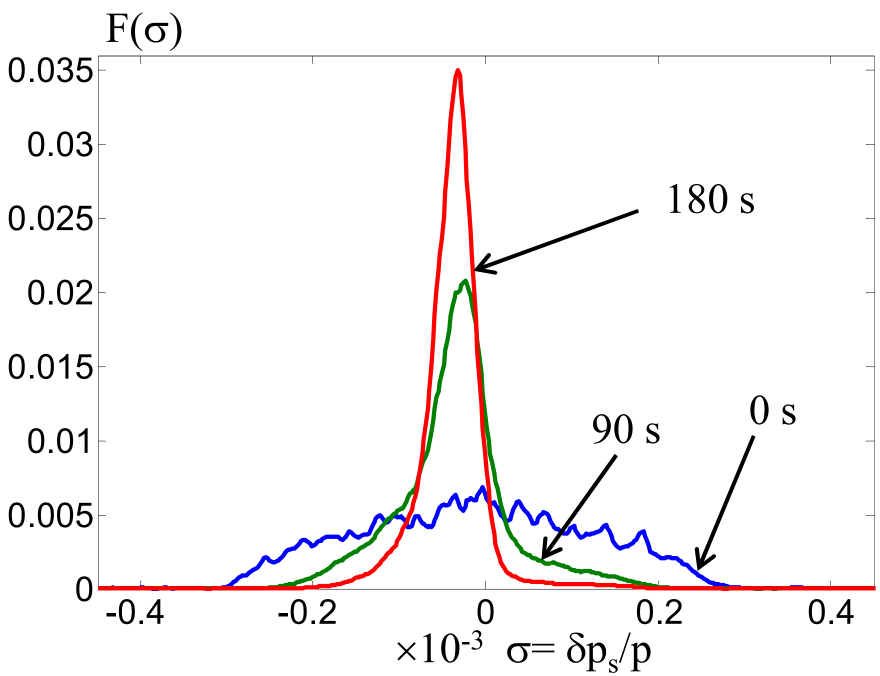


Changing energy of electron beam to 100 V that corresponds to $dp/p=6\cdot10^{-5}$. The equilibrium momentum of proton beam is changed also that can be easily observed with Schottky spectrum analyzer.

Example of the longitudinal cooling at 1259 kV



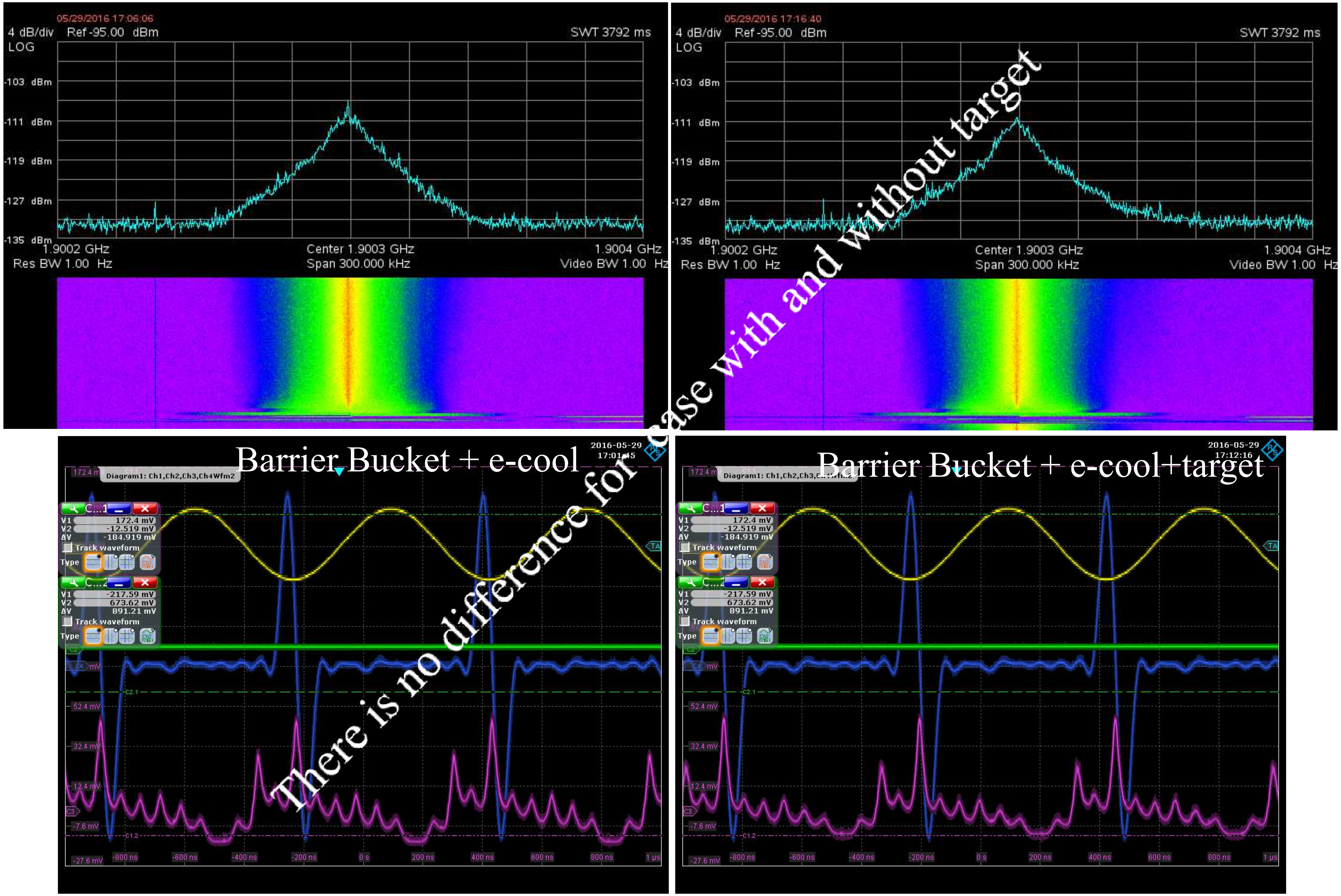
Momentum spread versus time



Evolution of the longitudinal distribution function during cooling process

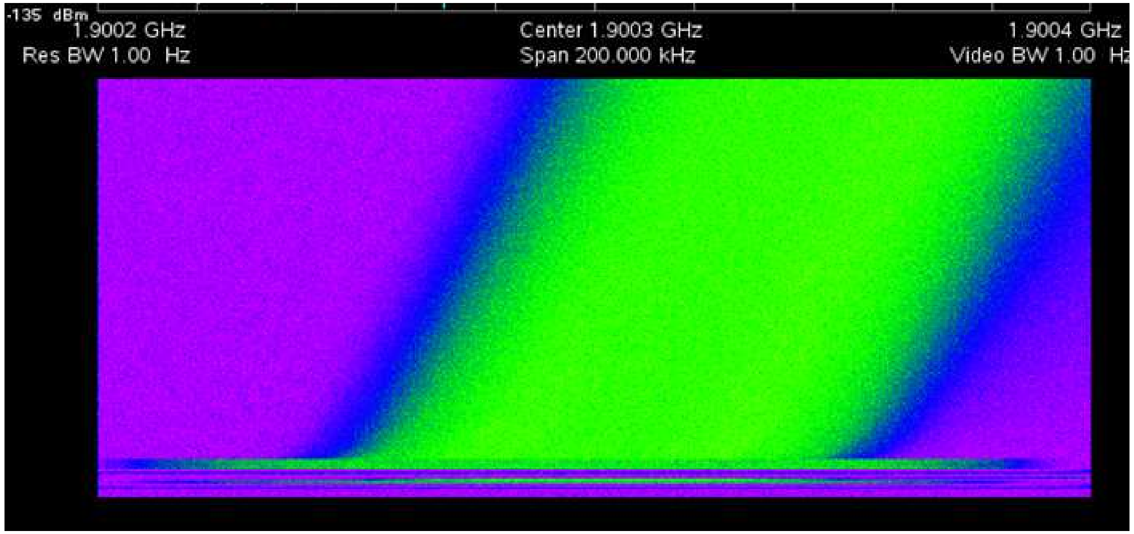
e-cool can well operate with barrier bucket and target

Electron cooling with barrier bucket and target with density Ee=1259.5 kV, $n_a = 2 \cdot 10^{14}$ cm^{-2}

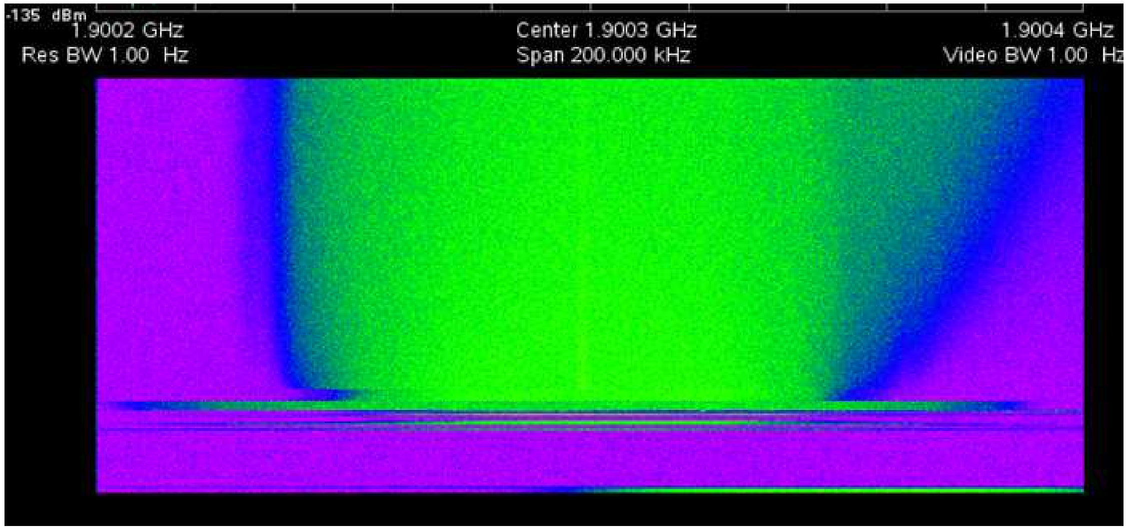


Experiments with target without electron cooling

Target has a significant influence on the dynamic of the proton $n_a = 2\cdot10^{14}$ cm^{-2}



target



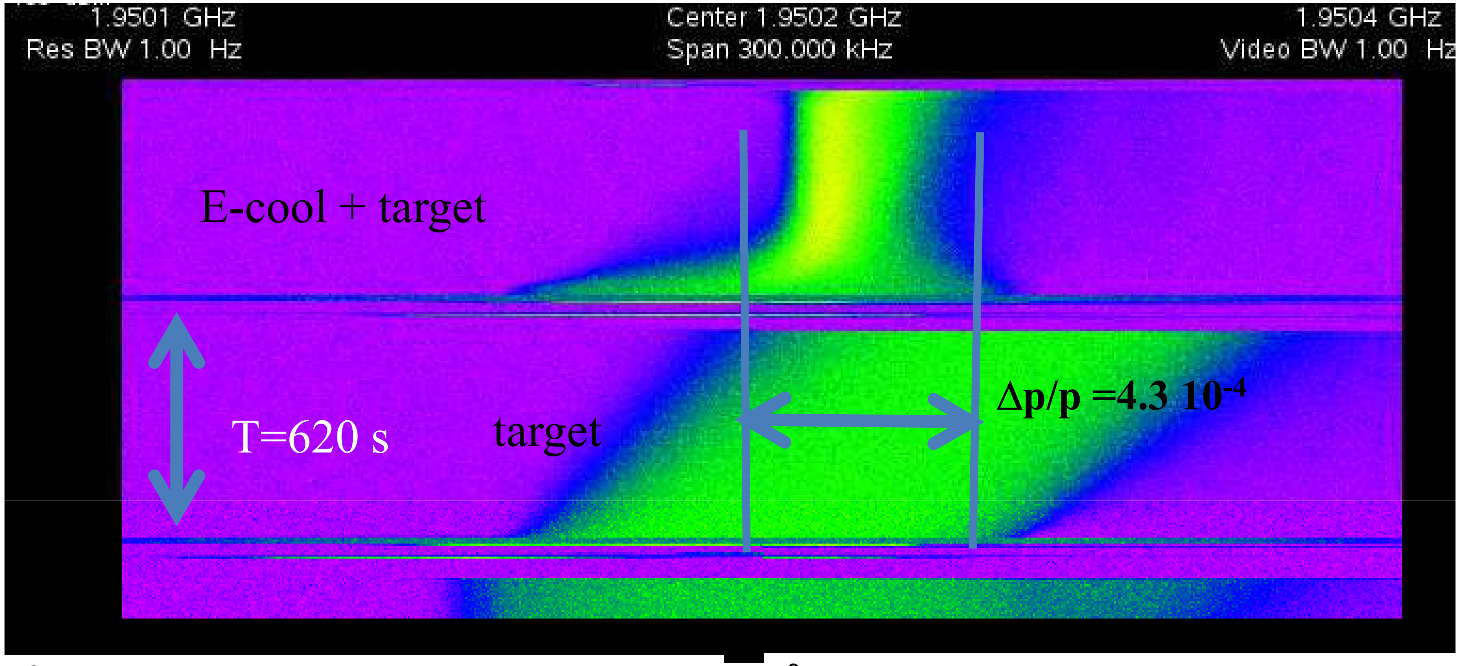
target + barrier bucket

Spectrogram of Schottky noise at target action. The top picture shows ionization loss in cluster target corresponding to hydrogen density $n_a = 2\cdot10^{14}$ cm^{-2}. The bottom picture shows the simultaneously action barrier bucket and target. All spectrum duration is about 550 s.

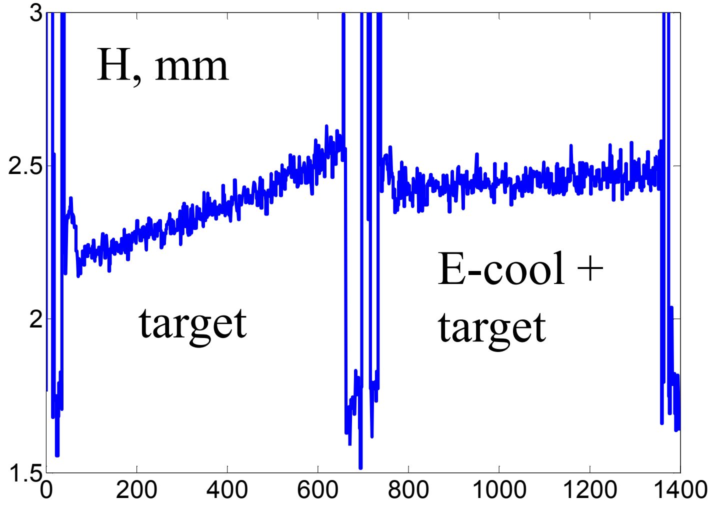
Electron energy 1259.65 kV, Je=500 mA

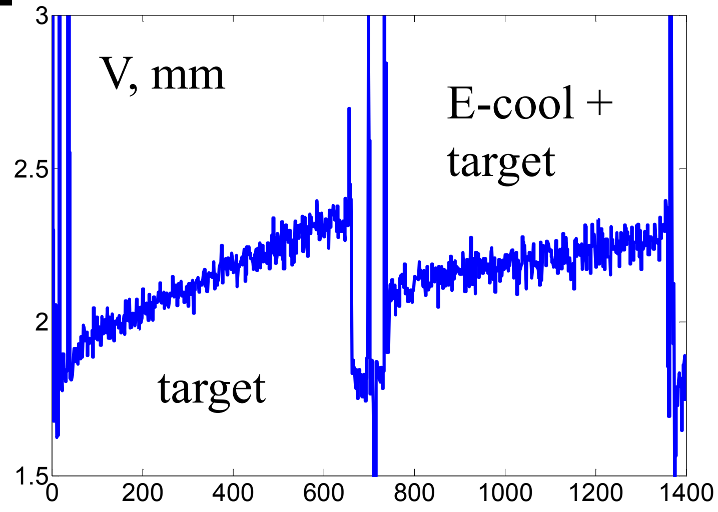
Experiments with e-target

Electron cooling suppressed the longitudinal action of the target with density $n_a = 2 \cdot 10^{14}$ cm^{-2} without help RF.



Electron cooling practically suppressed longitudinal and transverse growth induced by target but the more precise tuning storage ring and e-cooler is necessary.



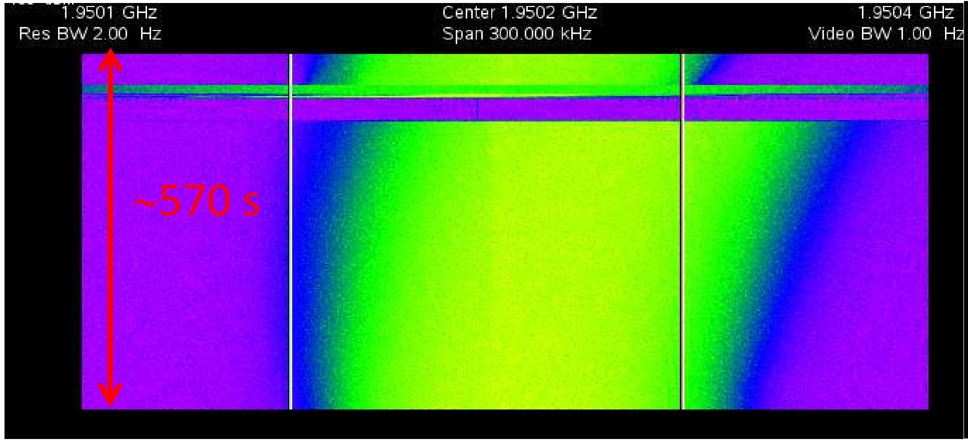


Next part of this report is more about puzzle and features that was observed during operation.

1. Dominance of the longitudinal friction force. The longitudinal cooling is more easy for realization
2. Essential influence of the Larmour oscillation of electron beam to transverse cooling rate at high energy but the longitudinal cooling rate was observed practically the same
3. Changing equilibrium momentum of proton beam at excitation of Larmour oscillation of electron beam
4. Influence of the angle between electron and proton beam on the transverse cooling rather than longitudinal cooling
5. Role of the collective phenomena at electron cooling of the proton beam to the small momentum spread of the proton beam

Milestones of the first cooling at new energy of the electron beam (1.25 MeV)

17:34



Weak shift to new energy Ee=1256 keV

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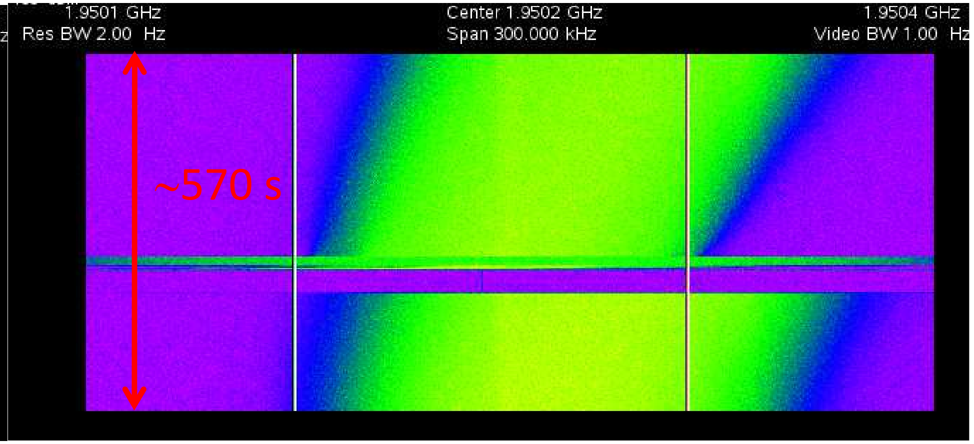
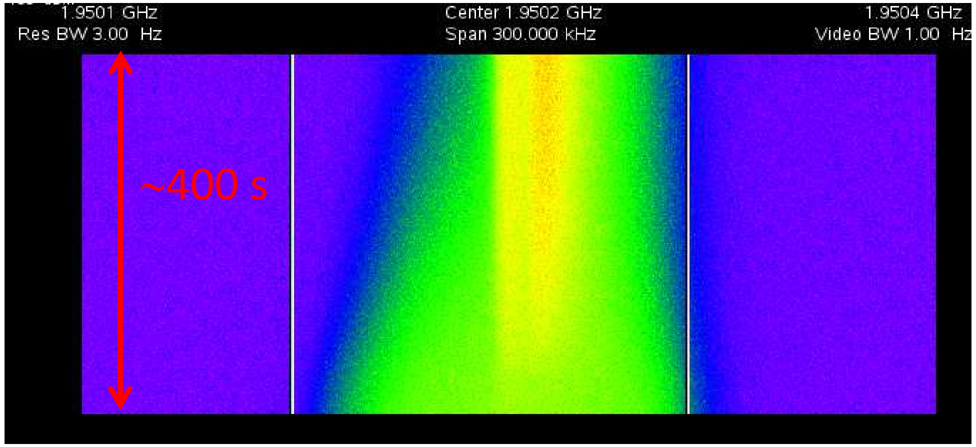


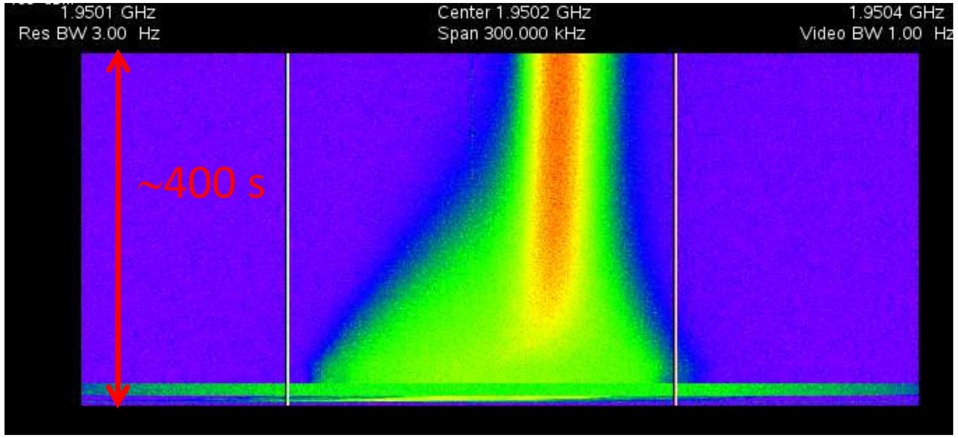
More strong shift to new energy Ee=1256.6 keV

18:47



First cooling at new energy Ee=1259.5 keV

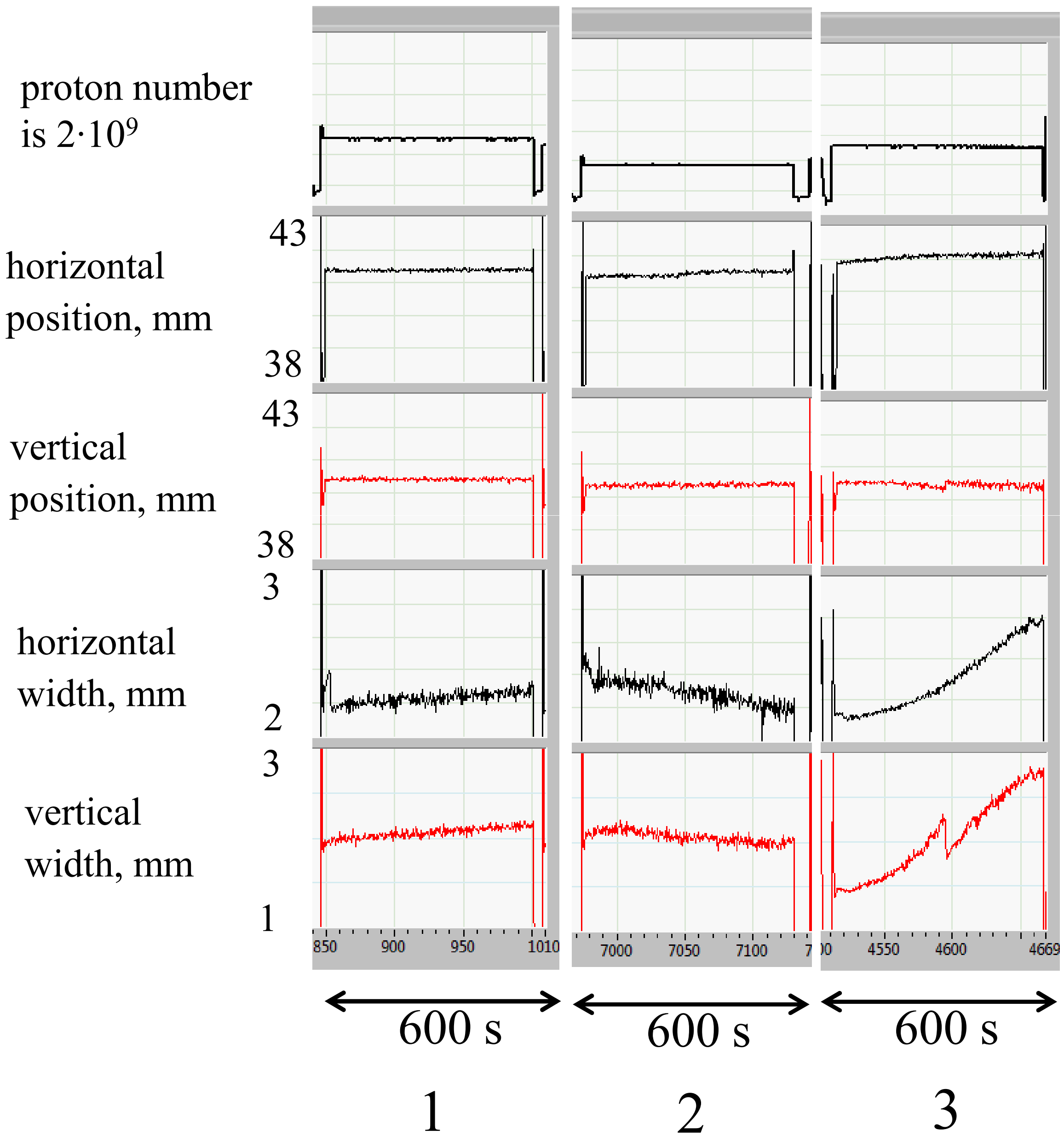
19:07



Good cooling at new energy Ee=1259.55 keV

After ~ 1.5 hours the longitudinal cooling process was obtained at new energy 1259.5 keV (after series experiments at 909 keV energy). The situation with transverse cooling isn't such optimistic.

Transverse e-cooling at 1259 kV energy



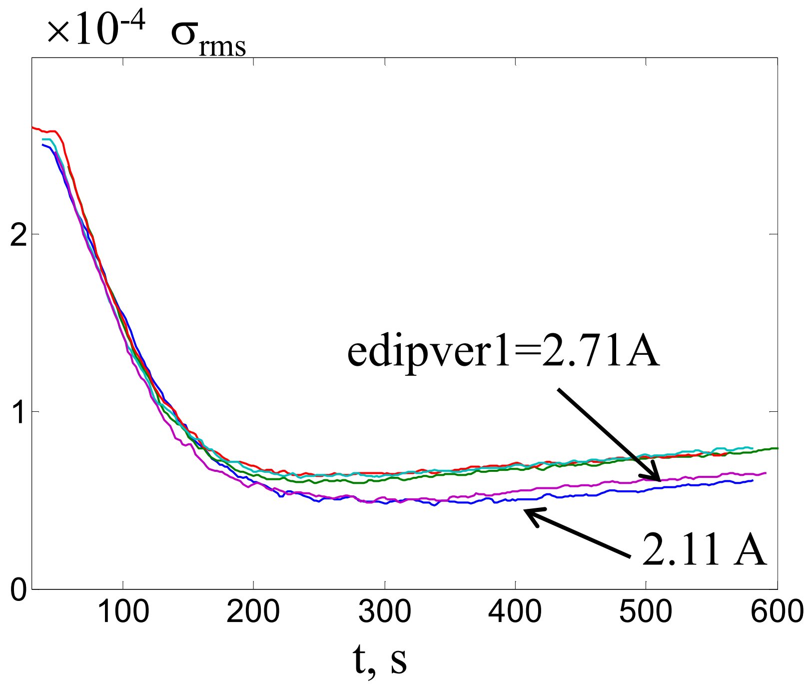
The transverse cooling process was observed after spending much time and efforts.

Maximum attention was given to looking for a working point of storage ring where the electron cooling had maximum effectiveness.

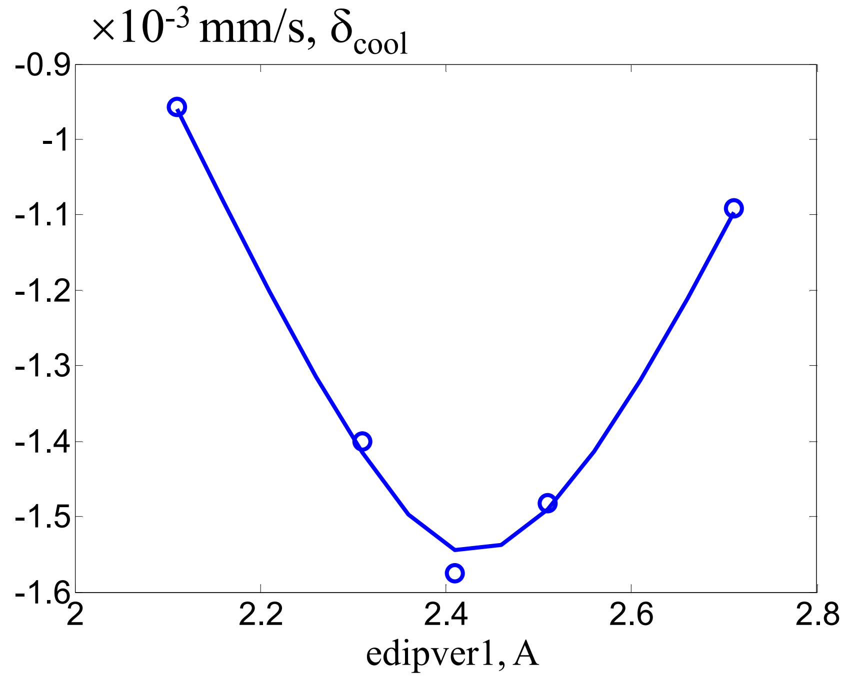
Changing transverse size during cooling experiments. Curve 1 is reference cycle without cooling , curve 2 is cooling at energy 1259 kV, curve 3 is growth of the transverse size at changing working point despite of electron cooling action. Tune was shift at ΔQx/ ΔQy ≈ 0.02/-0.01 (estimation).

Essential influence of the Larmour oscillation to transverse cooling rate but the longitudinal cooling rate was observed the same

momentum spread versus time



horizontal cooling decrement

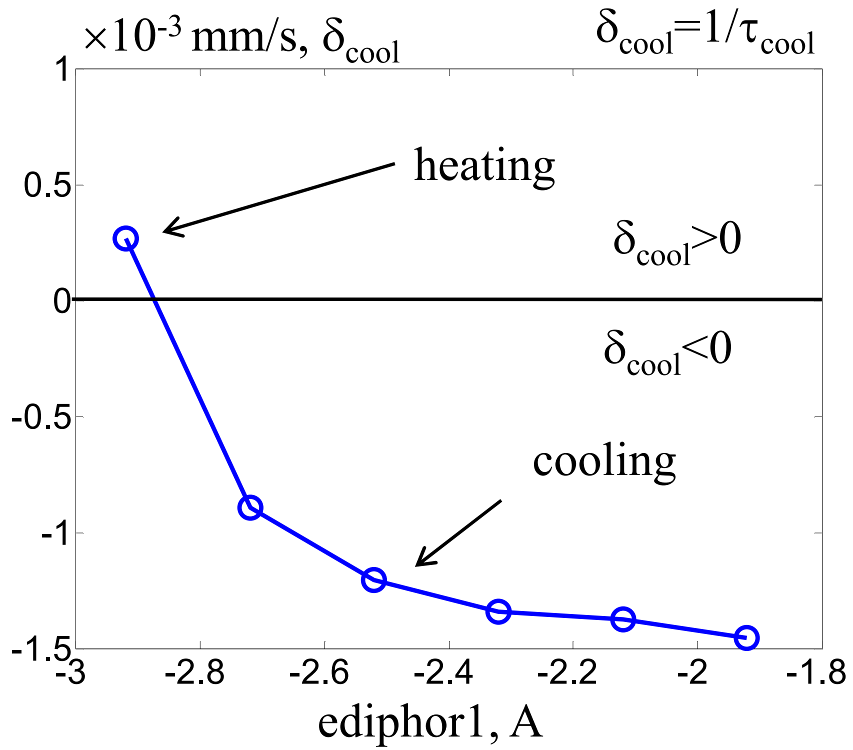


Amplitude of the Larmour oscillation was changed with help of corrector coils with short longitudinal length – edipver 1.

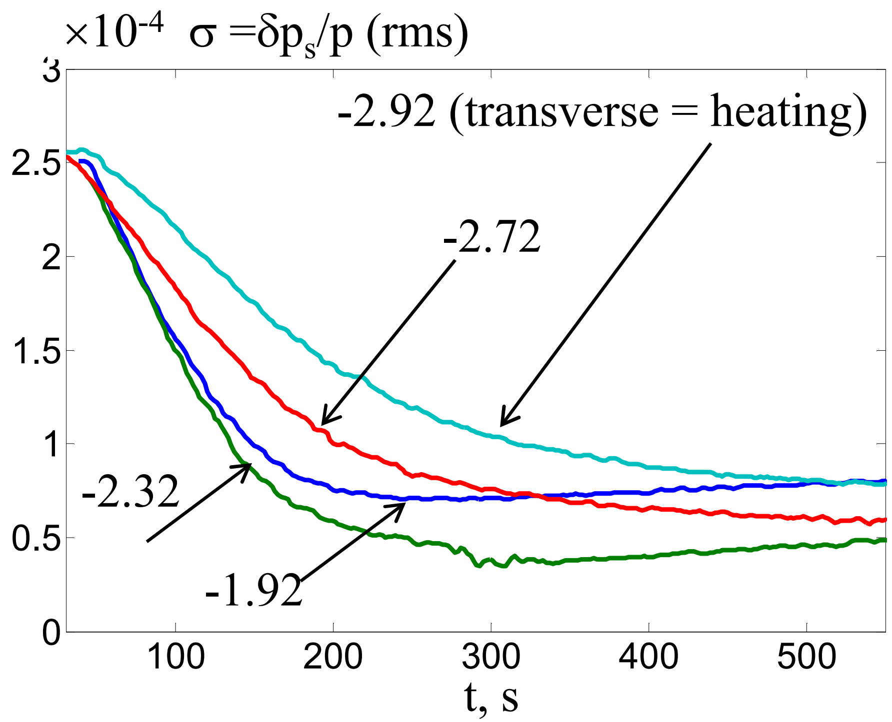
1 A of corrector current may excite Larmour oscillation with radius 0.35 mm

Main parameters of experiment
Electron energy is Ee=907.7 keV
Proton energy is Ep=1.67 GeV
Anode and grid voltages are Uan=3.27, Ugr=0.83 kV,
Electron current is Je=600 mA,
Magnetic field in the electron gun is 230 G, acceleration column is 400 G, collector is 500 G. Longitudinal magnetic field in the cooling section is 1300 G, in the toroid section is 1200 G, bend magnet is 860 G.
Slip-factor of the proton beam is η= -0.035.
The number of proton is Np=$1.6\text{-}1.8\cdot10^9$.

Another example of influence of Larmour oscillation to transverse cooling rate. It is possible to eliminate transverse cooling but the longitudinal decreases not so much



horizontal cooling decrement

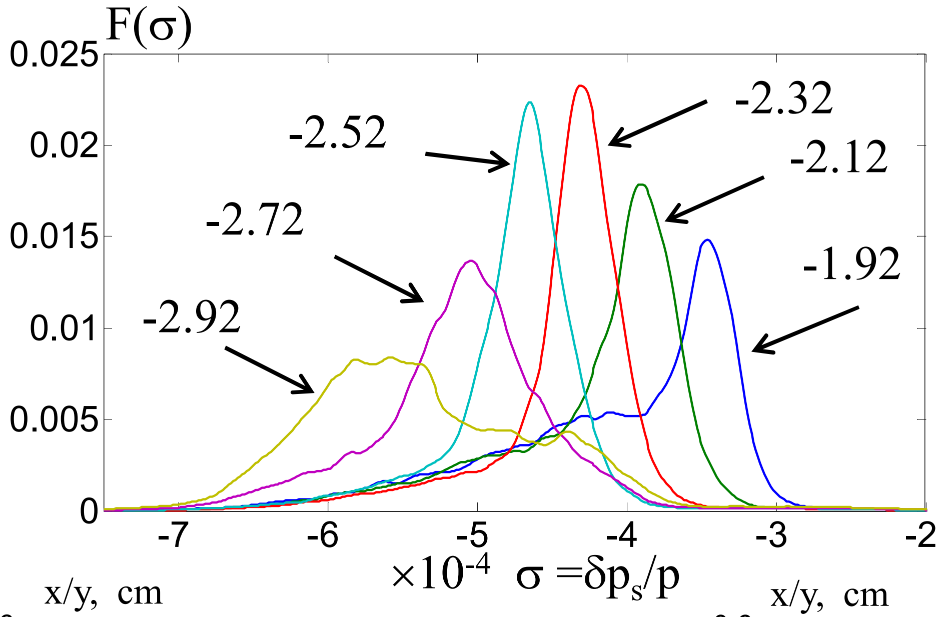


longitudinal momentum spread versus time for different value of current in electron dipole corrector ediphor1

Parameters of the experiments Ee=907.7 kV, Je=595 mA, Uan=3.27, Ugr=0.83 kV

If the Larmour rotation is strong enough it can kill the transverse cooling. The longitudinal cooling time is increased but it present.

It is interesting that the correlation between changing of the dipole corrector and equilibrium momentum of the proton beam. Figure shows the distribution function of the protons in time 500 s for the different value of ediphor1 corrector.



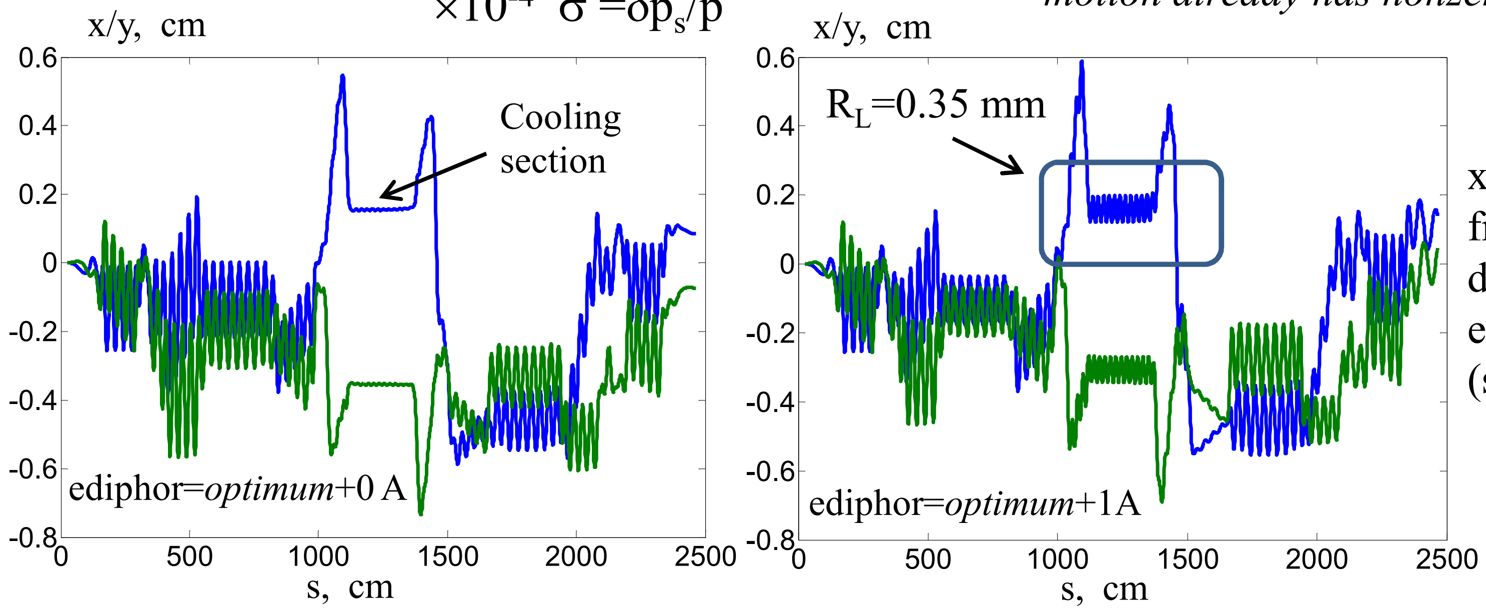
Increase the transverse momentum (Larmour oscillation) leads to *<u>decrease the longitudinal momentum</u>*

$E_e = 909\cdot 10^3\ keV \quad B_{cool} = 1380\,G \quad R_L = 0.35\,mm$

$\gamma = 1 + \frac{E_e}{mc^2} = 2.78 \qquad \rho = \frac{\gamma\beta m_e c^2}{eB_{cool}} = 3.2\ cm$

$\delta\sigma = \frac{\delta p_{II}}{p_0} = \frac{1}{2}\left(\frac{R_L}{\rho}\right)^2 = 6\cdot 10^{-5} \qquad \frac{\delta p_{e\perp}}{p_0} = \frac{R_L}{\rho} = 0.011$

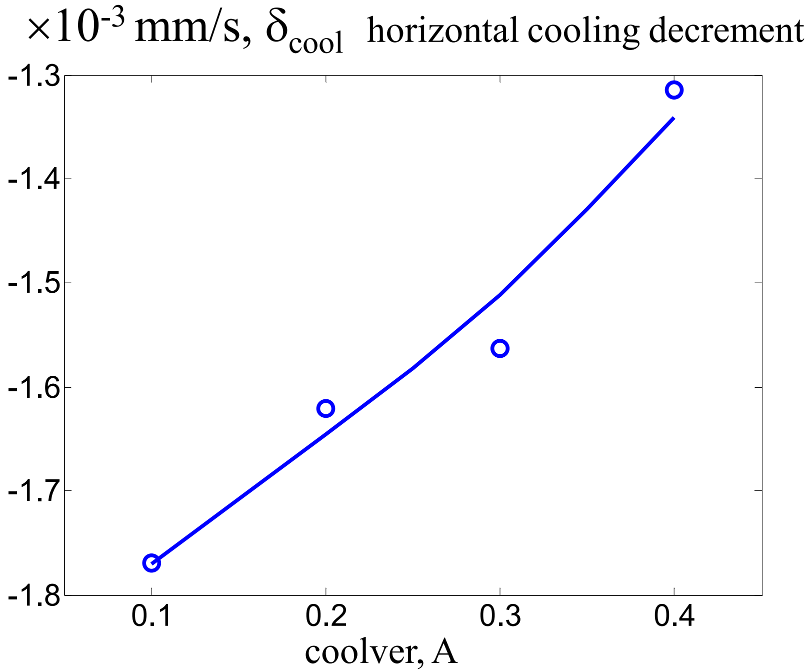
The quality behavior is good. The quantitative difference can be explained that the transverse motion already has nonzero amplitude of Larmour oscillation.



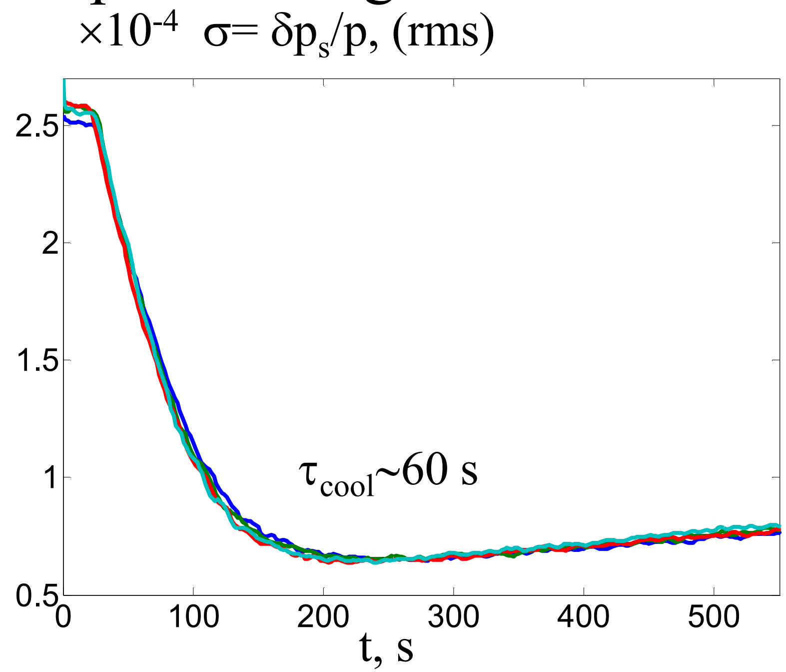
x,y orbit of the electron from accelerating to decelerating tube along electron cooler (simulation)

Demonstration of excitation of Larmour oscillation of electron induced by edip corrector.

Essential influence of the incline of the magnetic force line to transverse cooling rate with compare to longitudinal rate



horizontal cooling decrement



longitudinal momentum spread versus time

Changing angle between electron and proton beam with coolver corrector. This corrector induces the transverse magnetic field along whole cooling section. It leads to incline the magnetic force line and electron beam in the cooling section.

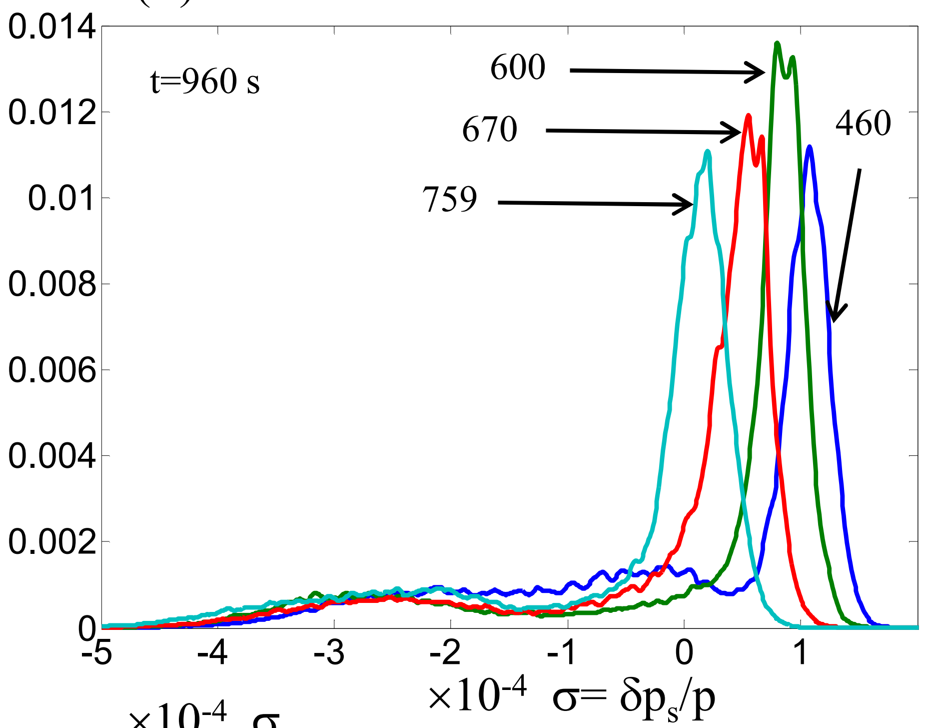
$J_{coolver} = 0.1\,A \rightarrow \delta\theta \approx 4 \cdot 10^{-5}$ $\quad \delta\theta \cdot L_{cool} \approx 0.1\,mm$ $\quad L_{cool} = 2700\,mm$ $\quad B_{cool} = 1380\,G$

Parameters of the experiments Ee=907.7 kV, Je=595 mA, Uan=3.27, Ugr=0.83 kV

So, fine tuning needs for transverse cooling but not for longitudinal cooling .

Role of the value of electron current

Longitudinal electron cooling. The electron current is changed at fixed ratio Ugrid/Uan



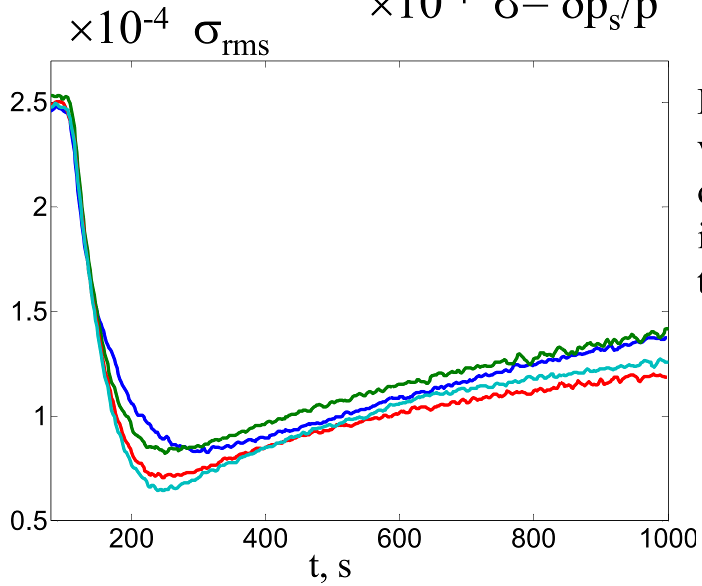
$N_p=4.7\cdot10^8$, Je=600 mA, Ugr=0.83 kV, Uan=3.27 kV, Ee=907.9 kV

The fixed ratio Ugrid/Uan allows to suppose that the regime of the electron gun isn't changed.

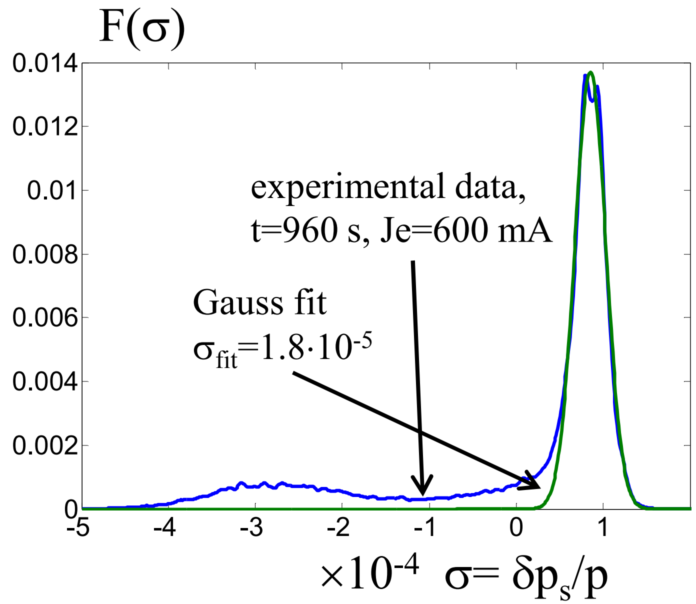
Drift of equilibrium energy is induced by space charge of electron beam.

The longitudinal cooling rate isn't strongly depend from the electron current value.

Example of the fitting of the core of the proton beam. The main part of particle has a small momentum spread.

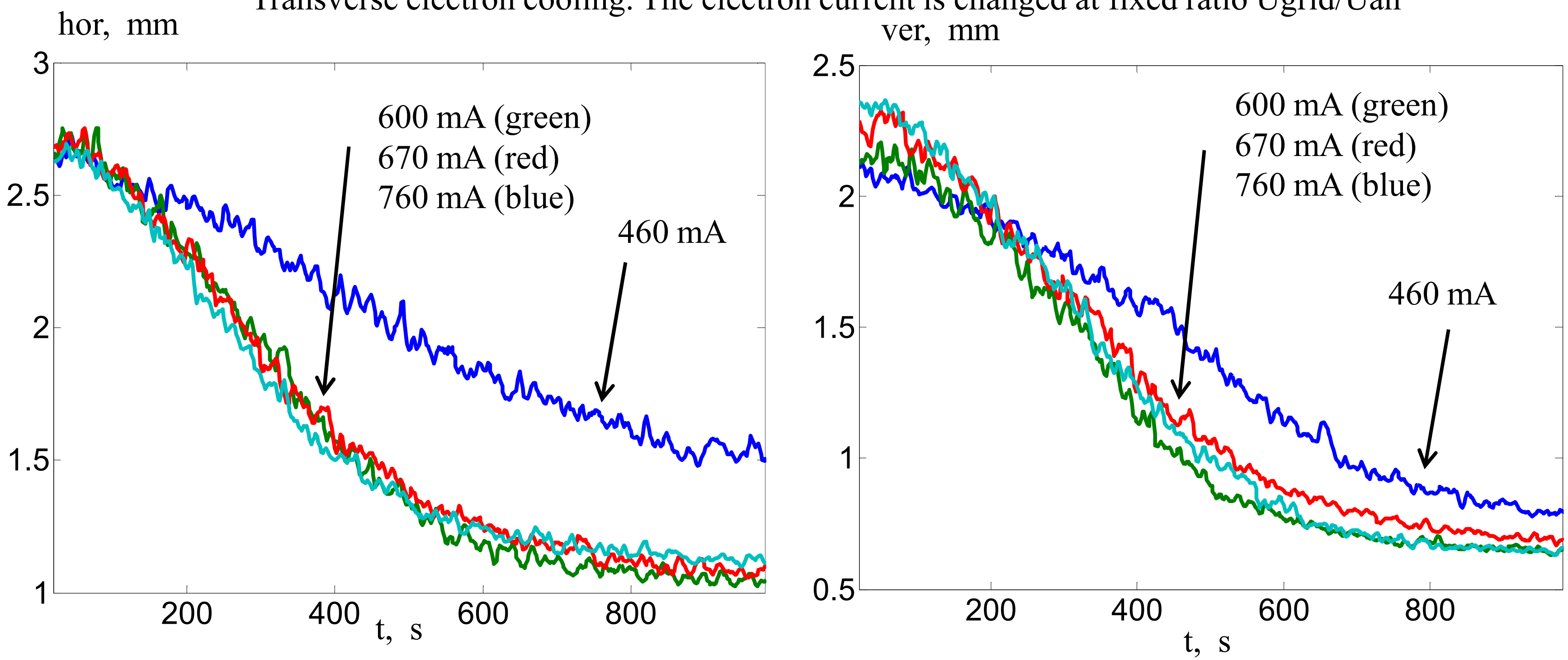


RMS momentum spread versus time. The growth of the momentum spread is induced by the tail un the distribution function.



Role of the value of electron current

Transverse electron cooling. The electron current is changed at fixed ratio Ugrid/Uan

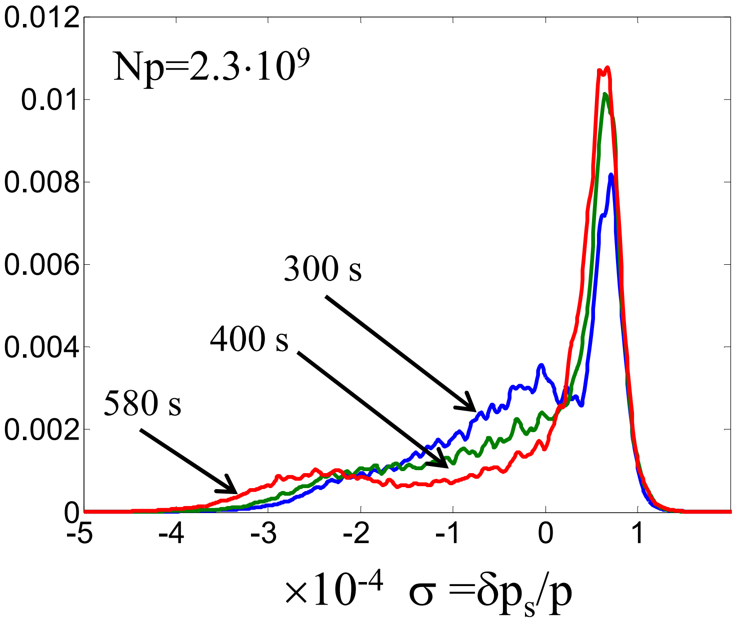


460 mA – Ugrid=0.7 kV Uanode= 2.72 kV Ugrid/Uanode=0.257
600 mA – Ugrid=0.83 kV Uanode= 3.27 kV Ugrid/Uanode=0.254
670 mA – Ugrid=0.9 kV Uanode= 3.54 kV Ugrid/Uanode=0.254
759 mA – Ugrid=0.98 kV Uanode= 3.86 kV Ugrid/Uanode=0.254

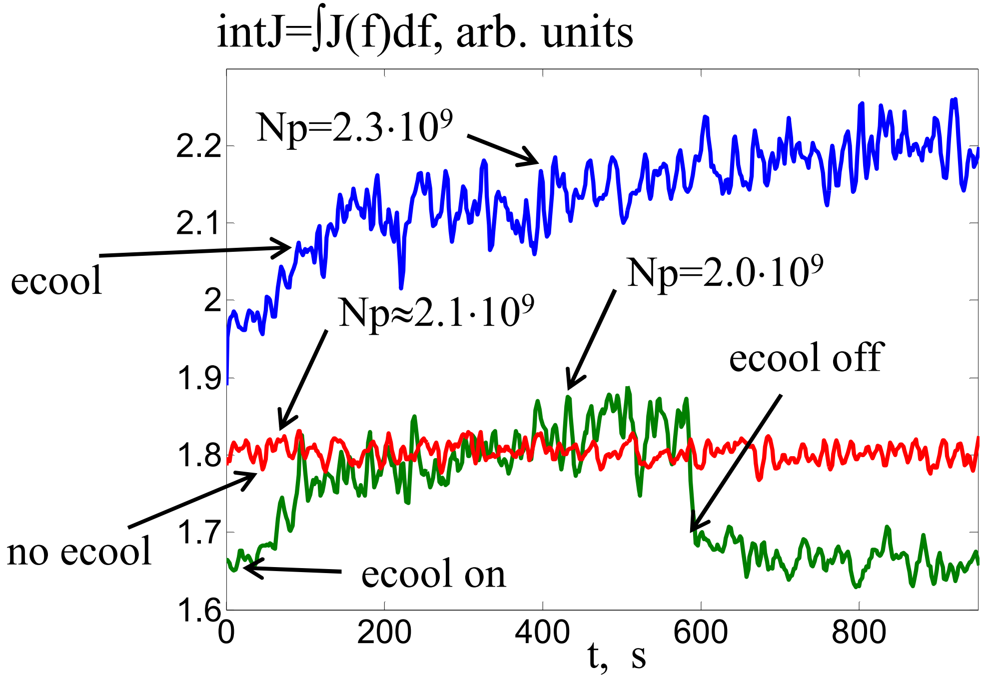
One can see that the transverse cooling suffer from electron current decreasing especially for Je=460 mA

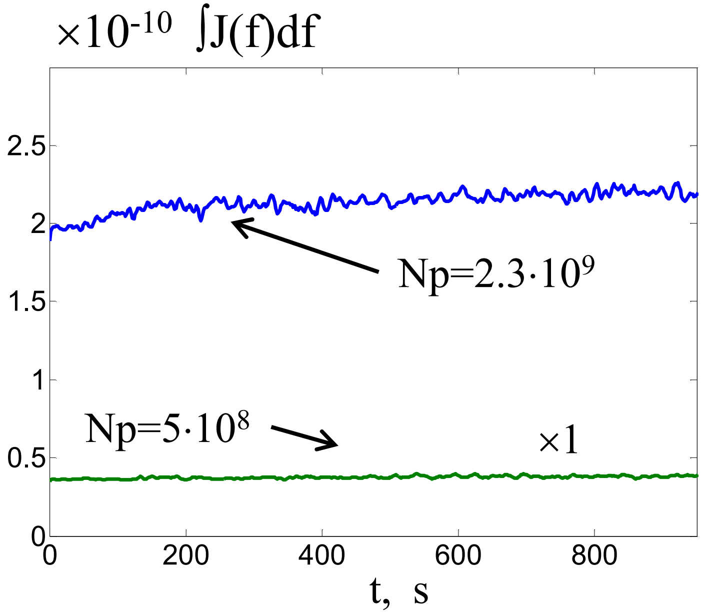
The transverse cooling more depend from the electron current value.

Collective effects (fact or myth) ?



The most experiments shows long tails in the longitudinal distribution function. This tails slowly move during all time of experiment. What is the reason ?

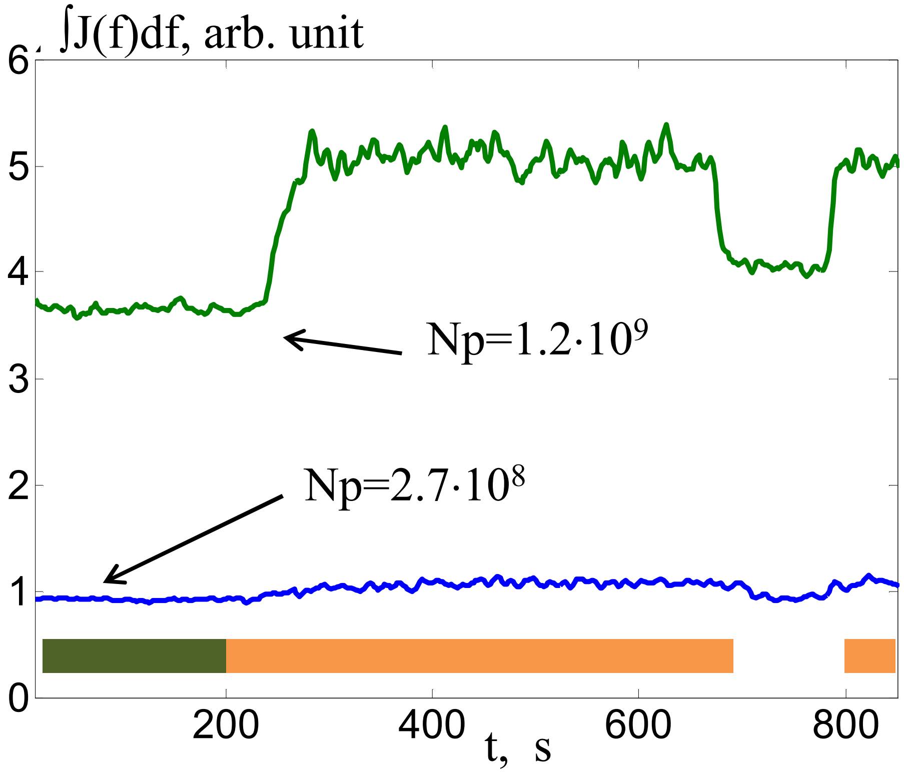


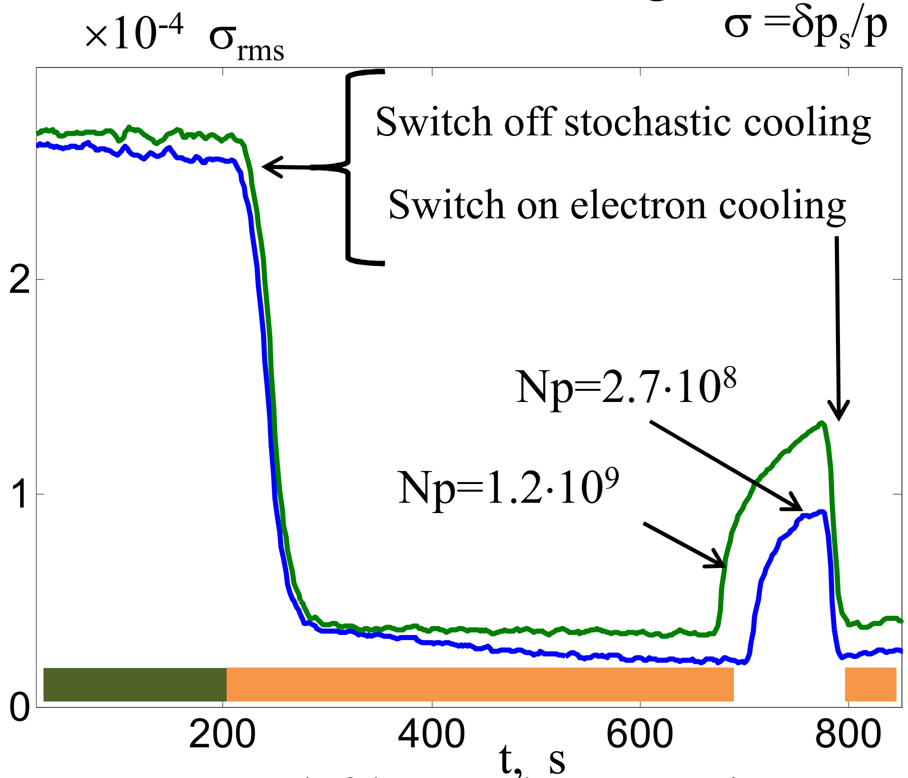


A possible criterion of collective effect is integral of Schottky signal along whole spectrum range. At presence of the collective effect this integral is larger in comparison with the situation when all particle is independent (no collective fluctuation) and the integral of power of Schottky signal is proportional to the particle number.

Je=600 mA, Ugr=0.83 kV, Uan=3.27 kV, Ee=907.9 kV

The changing of integral of Schottky signal at electron cooling is more clear at precooling with transverse stochastic cooling





Momentum spread pf the proton beam versus time

∫J(f)df – integral of power of Schottky signal along whole frequency range. If the particle motion is independent the integral is constant. The collective mode of particle oscillation changes this result.

transverse stochastic cooling

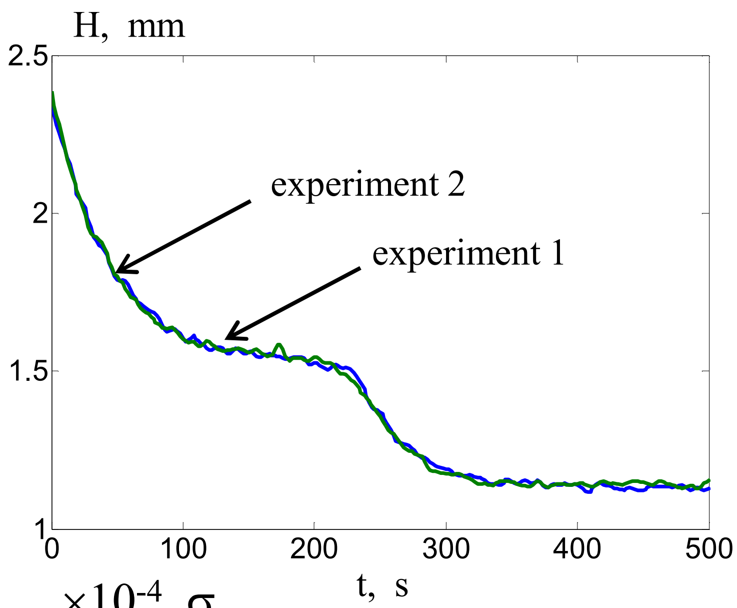
electron cooling

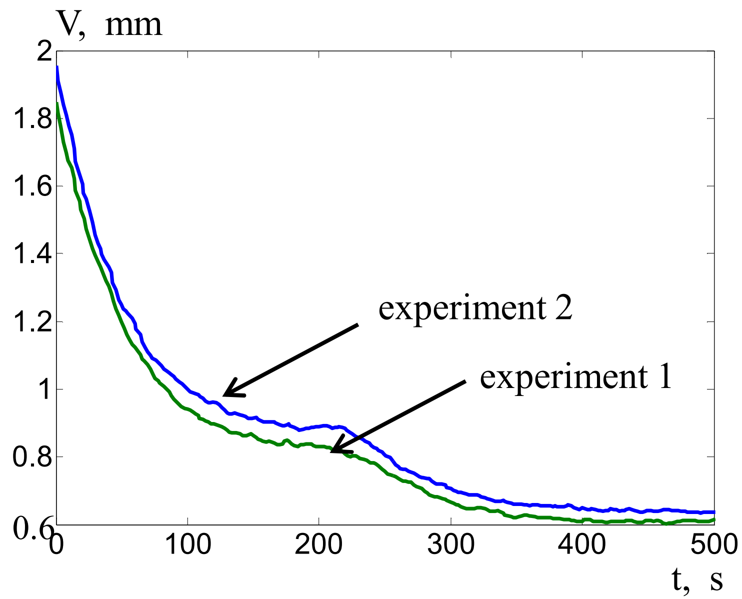
Time schedule
000 s – switch on the transverse stochastic cooling
200 s– switch on the electron cooling with current 600 mA, switch off the transverse stochastic cooling
~ 700 s – switch off the electron cooling (no cooling at all)
800 s – switch on the electron cooling again

Preliminary stochastic cooling increase particle density so the collective effect may be more visualized

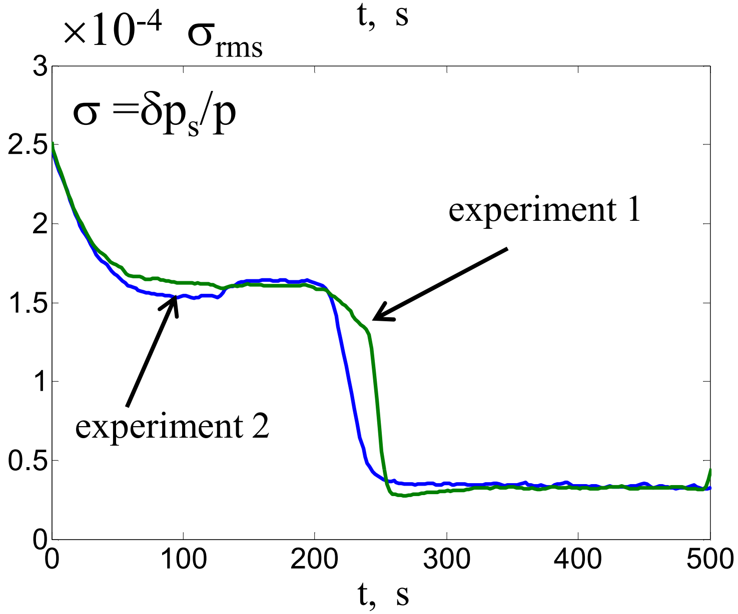
We may observe the normal situation. Decreasing momentum spread leads to decreasing Landau damping. Let pay more attention to impedance problems

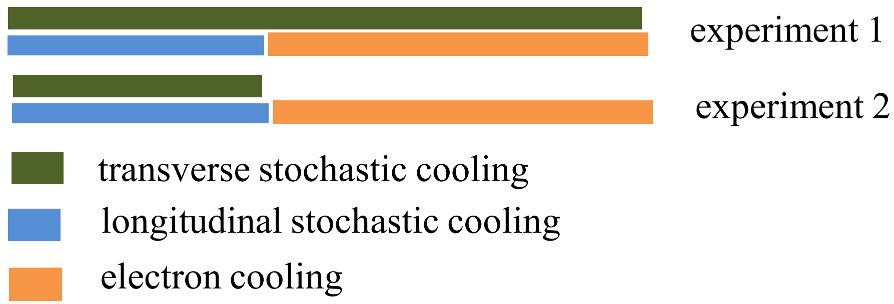
Stochastic precooling strongly improve the ultimate parameters of proton beam





$Np=1.1\cdot10^{9}$.

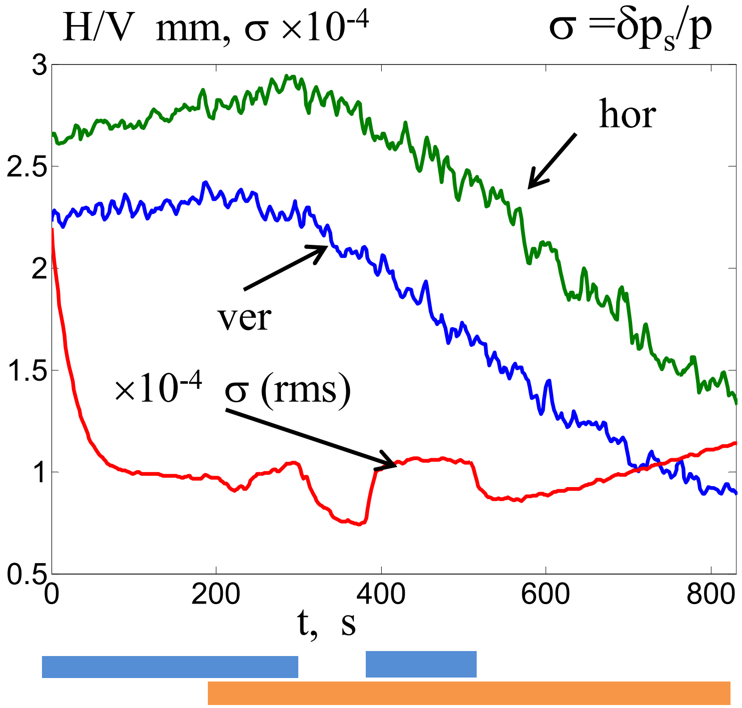




After stochastic precooling procedure the size of the proton beam may be cooled down to minimal value. Also the longitudinal momentum spread may be decreased to very low value. The electron cooling can be operated with transverse stochastic cooling together simultaneously.

Longitudinal stochastic and electron cooling

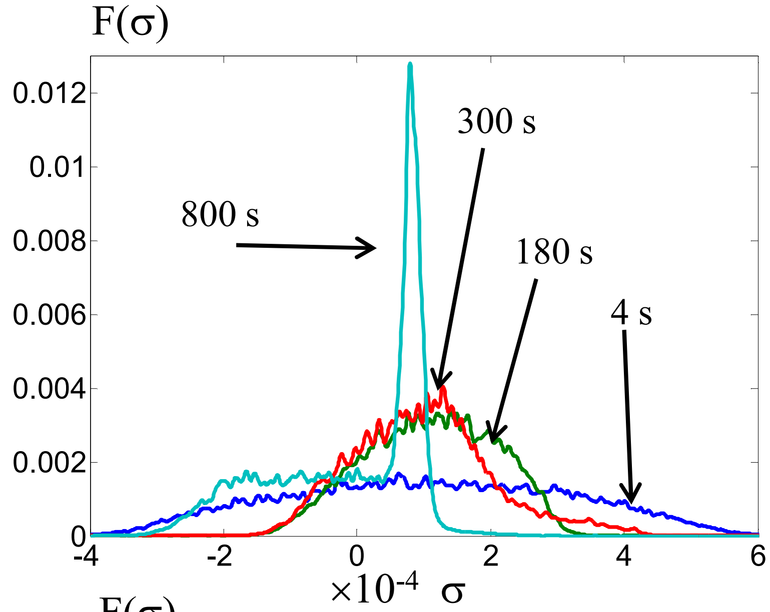
The joint action electron and longitudinal stochastic cooling doesn't change the distribution function (180 and 300 s profiles). The r.m.s. spread after 550 s depends from tail and doesn't show the cooling of bulk protons.



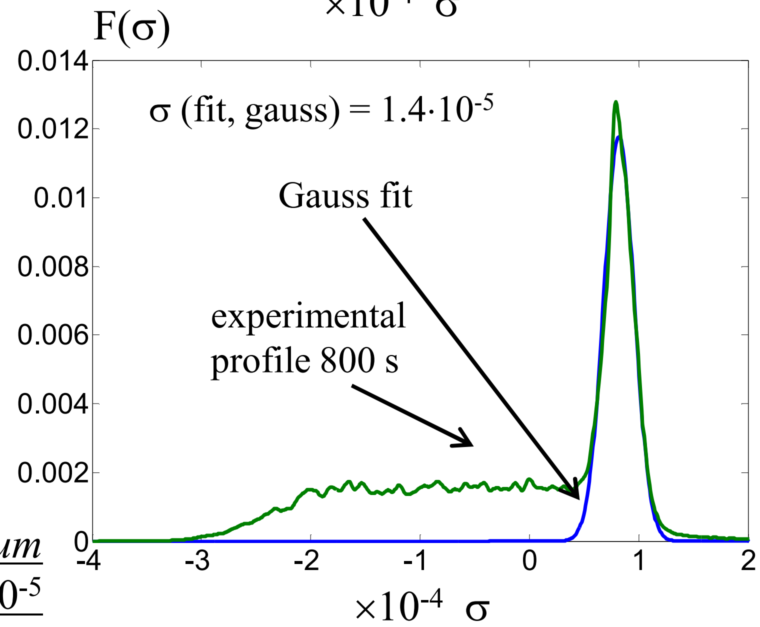
$Np=3.3\cdot10^{8}$,
$Ee=907.9$ kV,
$Je=600$ mA

longitudinal stochastic cooling

electron cooling



000 – turn on longitudinal stochastic cooling
200 – turn on electron cooling with current 600 mA
300 – turn off longitudinal stochastic cooling
380 – turn on longitudinal stochastic cooling
550 – turn off longitudinal stochastic cooling



The electron cooling isn't very effective in joint with longitudinal stochastic cooling. But the cooling power of electron cooling is strongly.

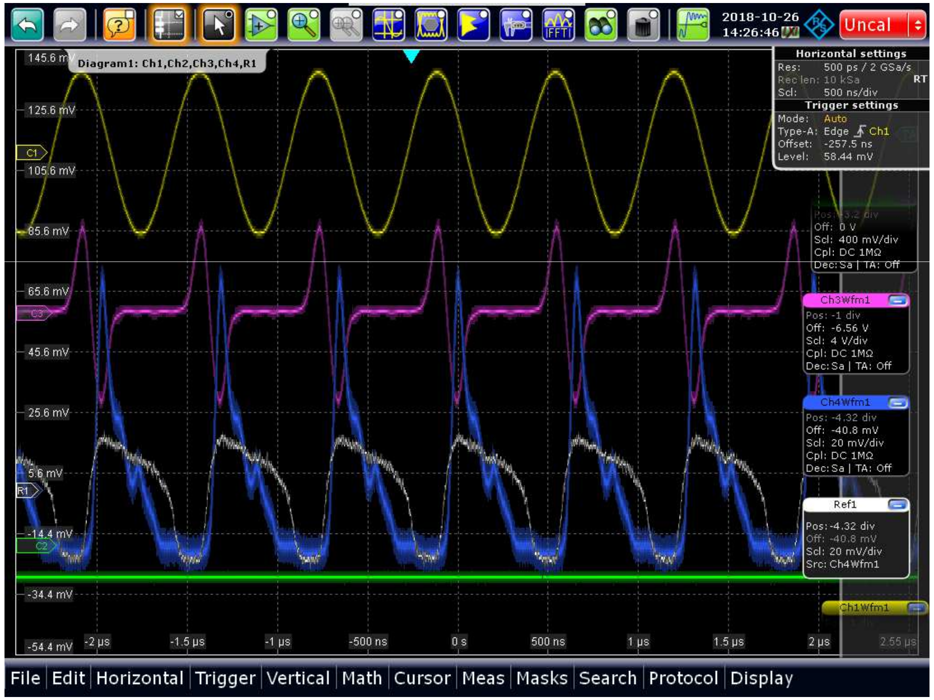
The mail part of proton can be cooled to momentum spread $\sigma = 1.4\cdot10^{-5}$

Stochastic, electron cooling, barrier bucket RF and dense target

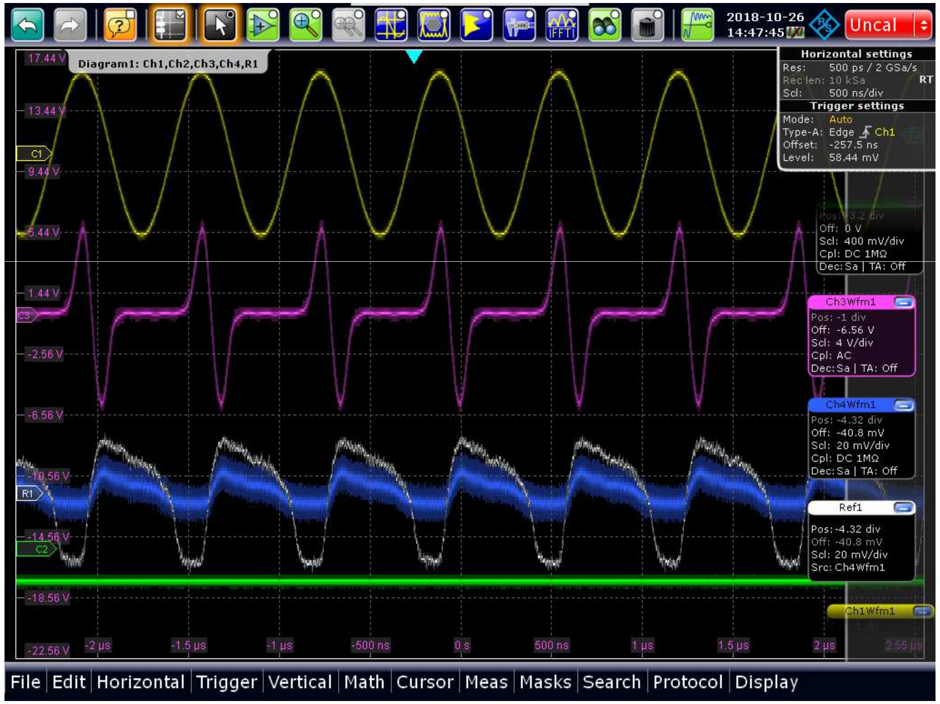
Np=1·10^9, Je=600 mA, Ee=908.085 kV, **na=2.0 · 10^{15} см$^{-2}$**

Screenshot of oscilloscope. The barrier bucket RF signal is magenta, signal from Schottky pick (longitudinal beam shape) up is blue. The time after start of the experiment is about 420-450 s.

Electron and transverse stochastic cooling

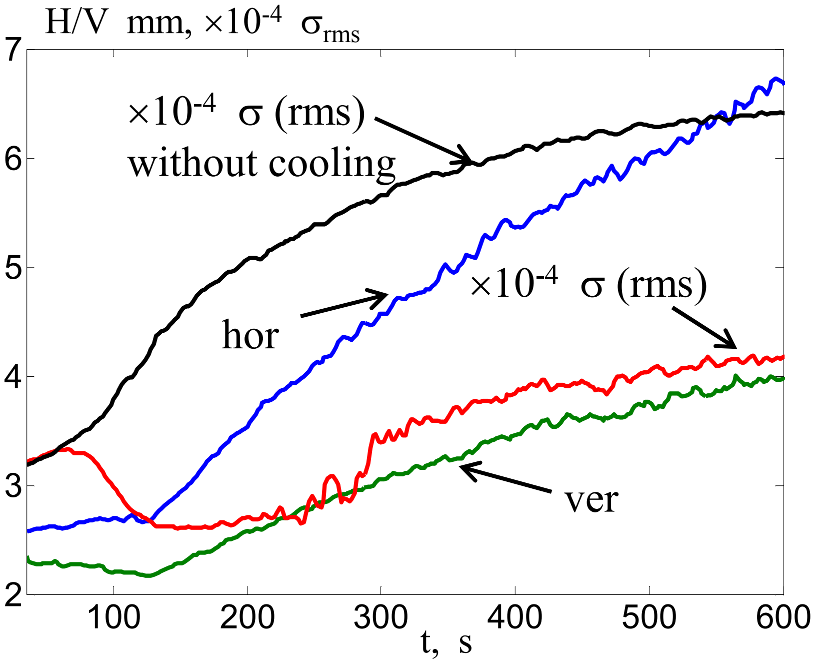


Longitudinal and transverse stochastic cooling

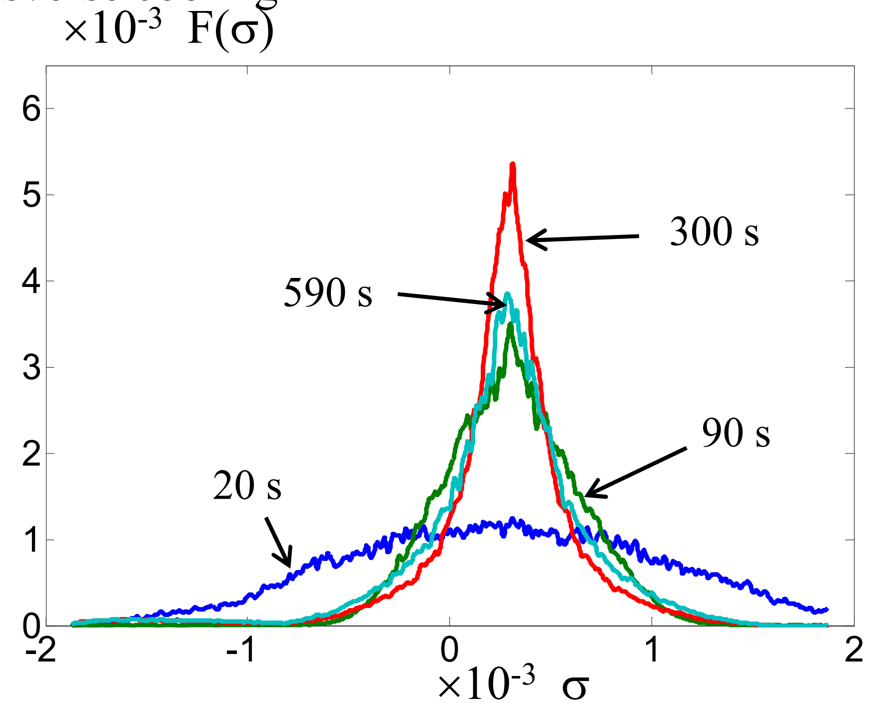


So, the electron cooling helps to keep the longitudinal shape of the proton beam at action of dense target

Unfortunately the single action of the electron cooling at high density target is not enough with point of view of transverse cooling



Horizontal, vertical sizes and momentum spread of the proton versus time



Horizontal, vertical sizes and momentum spread of the proton versus time

Time schedule
000 s – start of barrier bucket RF, p-p 1100 V
030 s – turn on electron cooling with current 600 mA,
100 s – turn on target

Np=$1.7\cdot10^{9}$, Je=600 mA, **na=$2.0 \cdot 10^{15}$ см$^{-2}$**

Only electron cooling

One can see that the electron cooling isn't enough for strong transverse cooling. It leads to decreasing of the longitudinal cooling rate. The start of growth of momentum spread is postponed to 100 s because the it need time for energy lost of particle in order to escape from RF well

<u>BUT the longitudinal cooling is strong despite of the growth of transverse size from 2.7/2.3 to 6.8/4 mm.</u>

Summary

1. COSY experience of use of electron cooling shows that it is enough powerful method in the different region energies
2. The electron cooling may work well together with, target, RF, barrier bucket RF and stochastic cooling
3. The physics of electron cooling may contain an open question and the puzzle with 50 years history may have unopened area.
4. Understanding of physics behavior of the transverse cooling may improve transverse electron cooling to compare today situation.
5. The simple optimization of transverse cooling optimization can be connected with increase of the beta function in the iteration point.