RECENT EXPERIMENTS WITH HIGH ENERGY ELECTRON COOLER IN COSY

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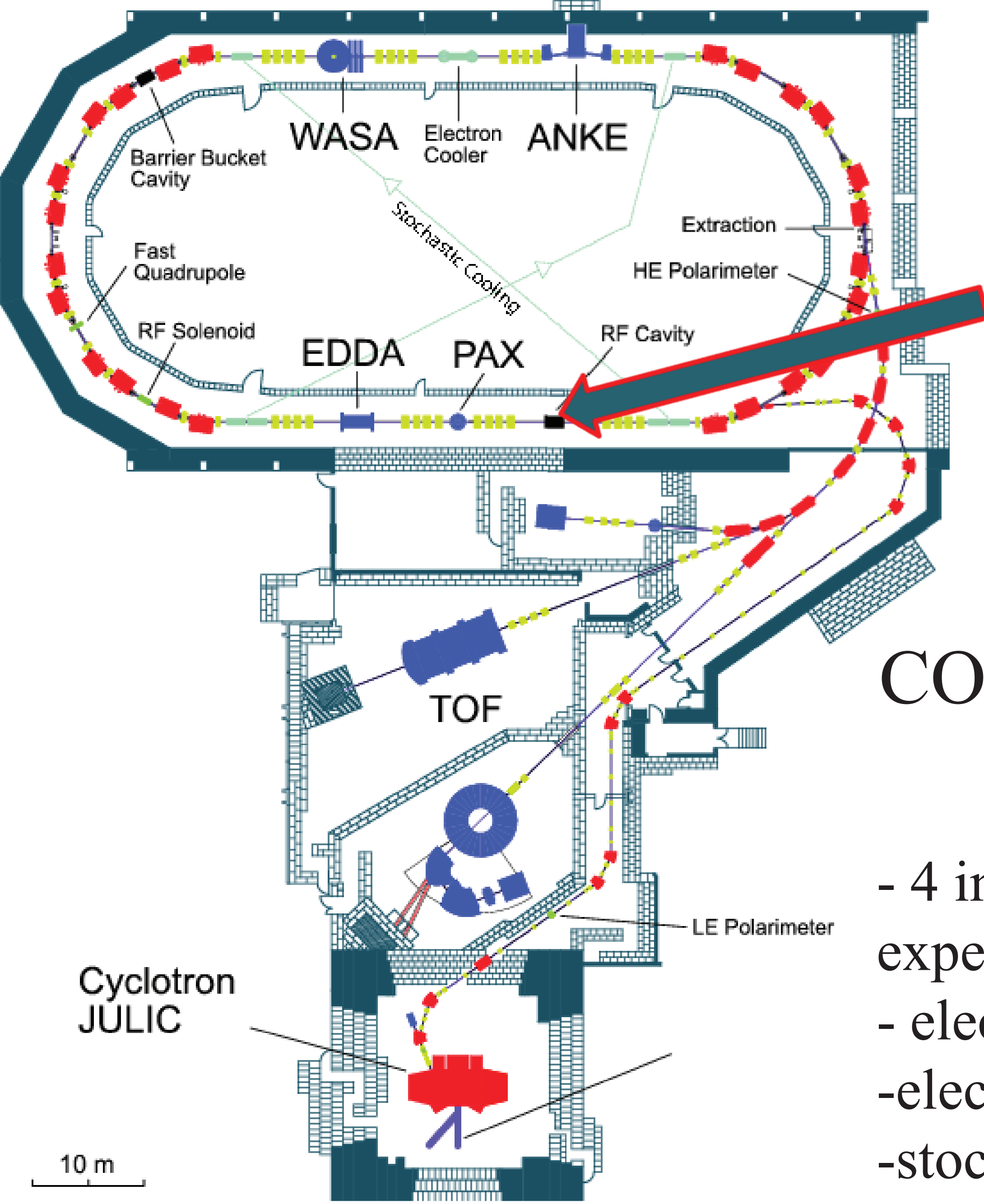
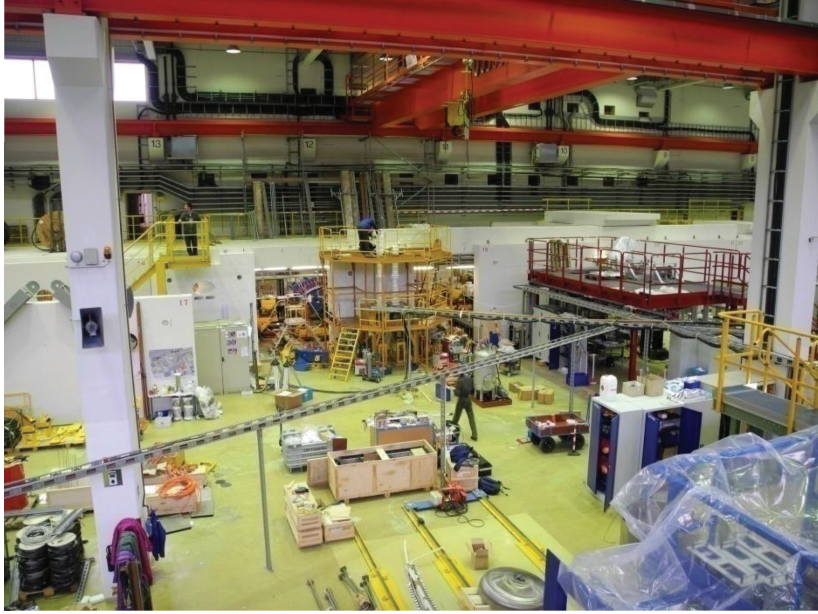
Abstract

The 2 MeV electron cooling system for COSY-Julich started operation in 2013 years. The cooling process was observed in the wide energy range of the electron beam from 100 keV to 1.256 MeV. Vertical, horizontal and longitudinal cooling was obtained at bunched and continuous proton beam. This report deals with electron cooling experiments at COSY with proton beam at energy 1.66 and 2.3 GeV. The proton beam was cooled at different regimes: RF on and off, barrier bucket RF and cluster target on and off.





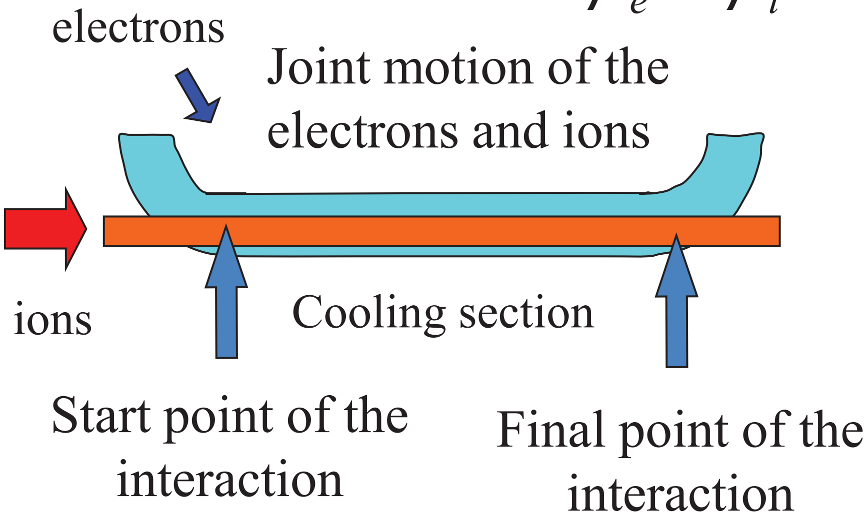
COSY Accelerator Facility

"COoled" SYnchrotron

- 4 internal and 3 external experimental areas
- electron cooling at low momenta
-electron cooling at high momenta
-stochastic cooling at high momenta

P=183.6 m, E=2880 MeV

$$\beta_e = \beta_i$$



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

Parkhomchuk’s empirical formula is much better agreement with computer simulations and experiment measurements.

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

Low energy (< 300 kV) ~ 20 devices in the world

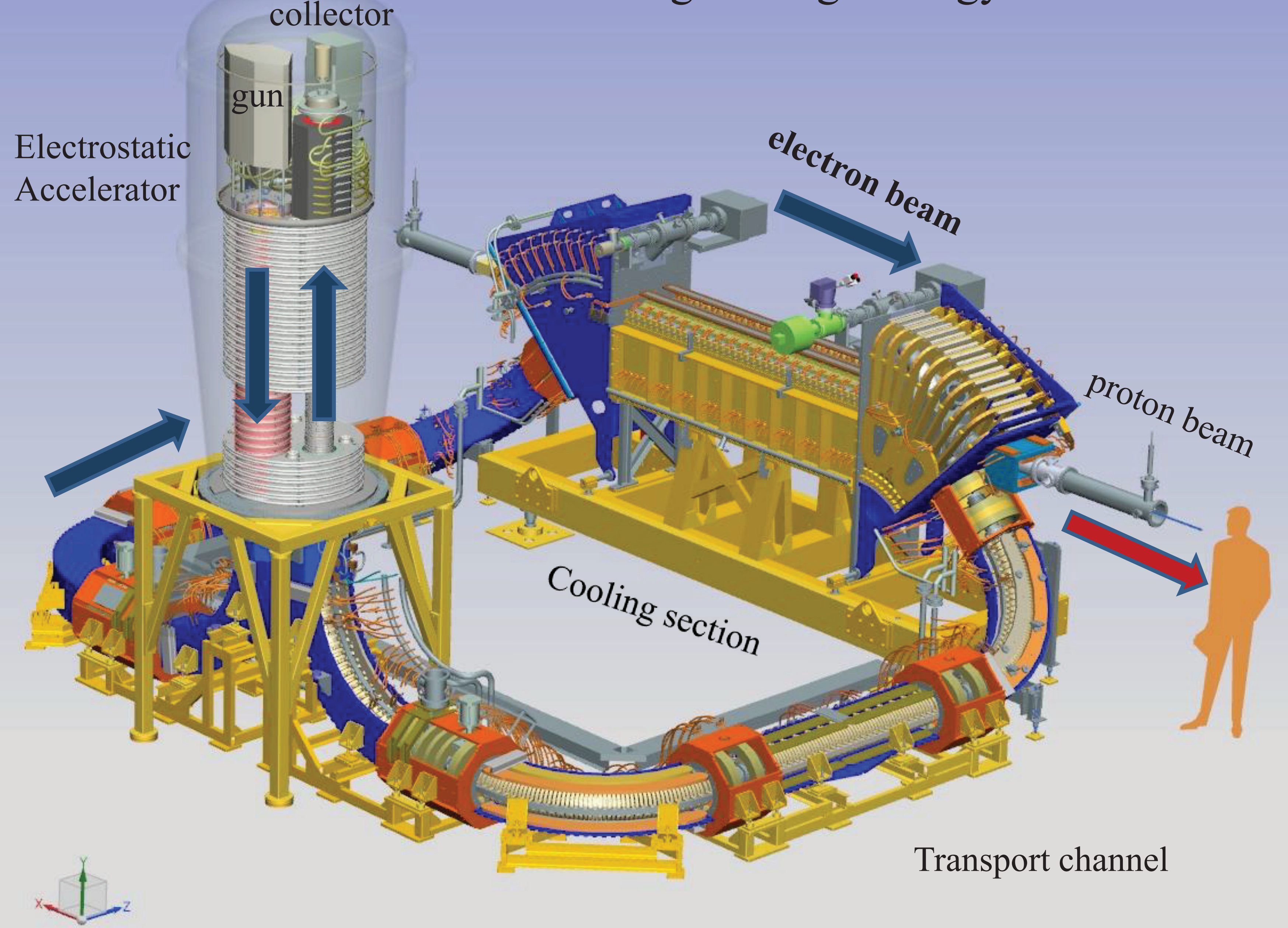
high energy (~ 1 MeV) = 3 devices in the world

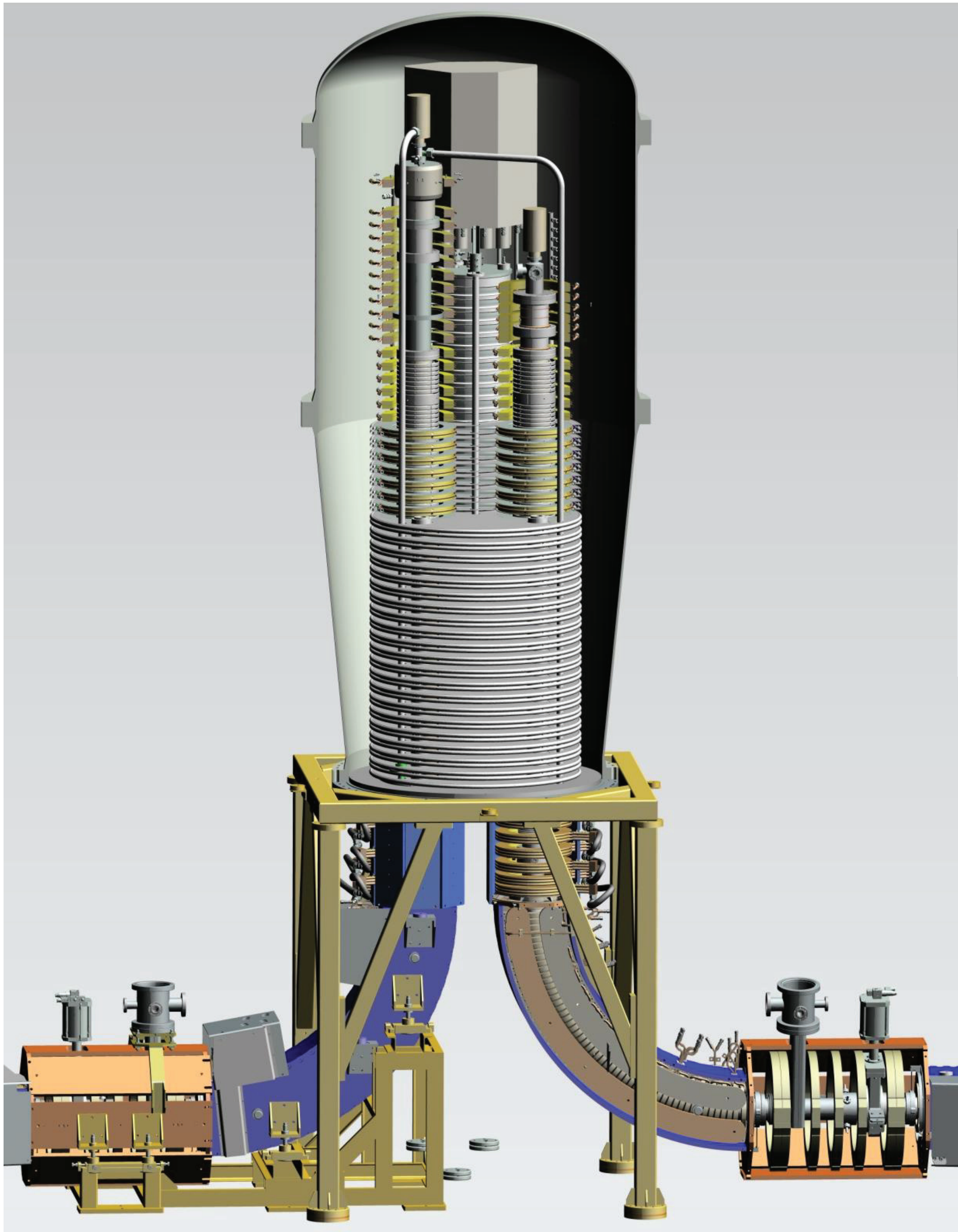
Cooling application

- help of injection: stacking, accumulation … ;
- internal target: residual gas, ionization loss and emittance growth;
- colliding beam: beam-beam effects;
- experiment with precise energy resolution;
- accumulation of the rare isotope production;

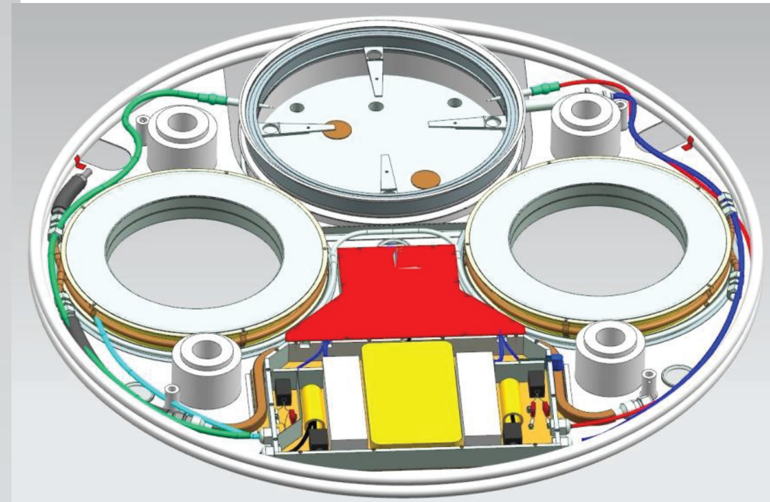
………..

3D design of high energy COSY cooler





3D design of Accelerating Column



Each section contains;

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

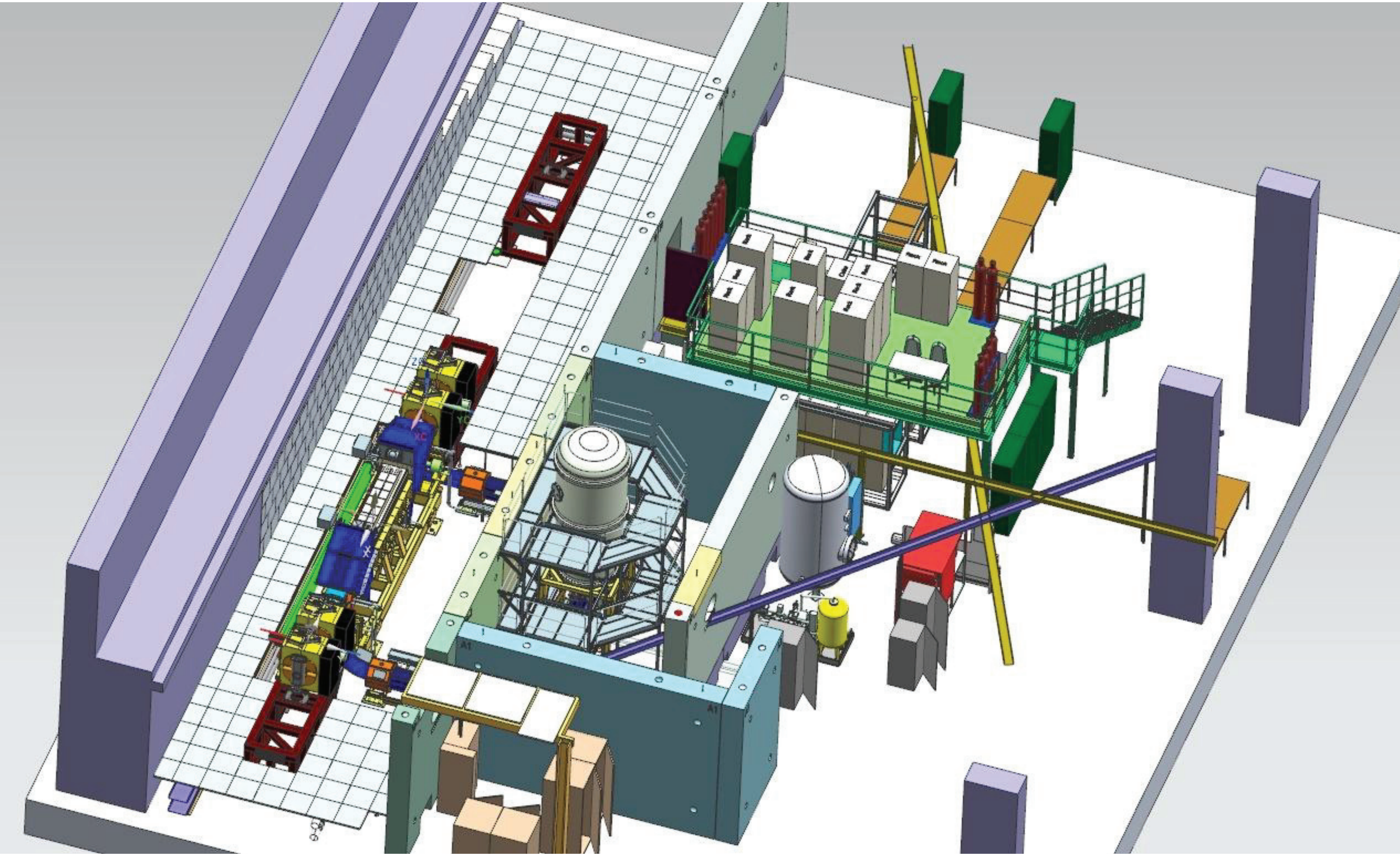
- power supply of the coils of the magnetic field (2.5 A, 500 G);

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

- control electronics;

33 high-voltage section

2MeV electron cooler – integration into COSY



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. Section-module principle of the design of the electrostatic accelerator;

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

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

- in order to have high cooling rate;

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

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

5. Electron Collector with Wien Filter

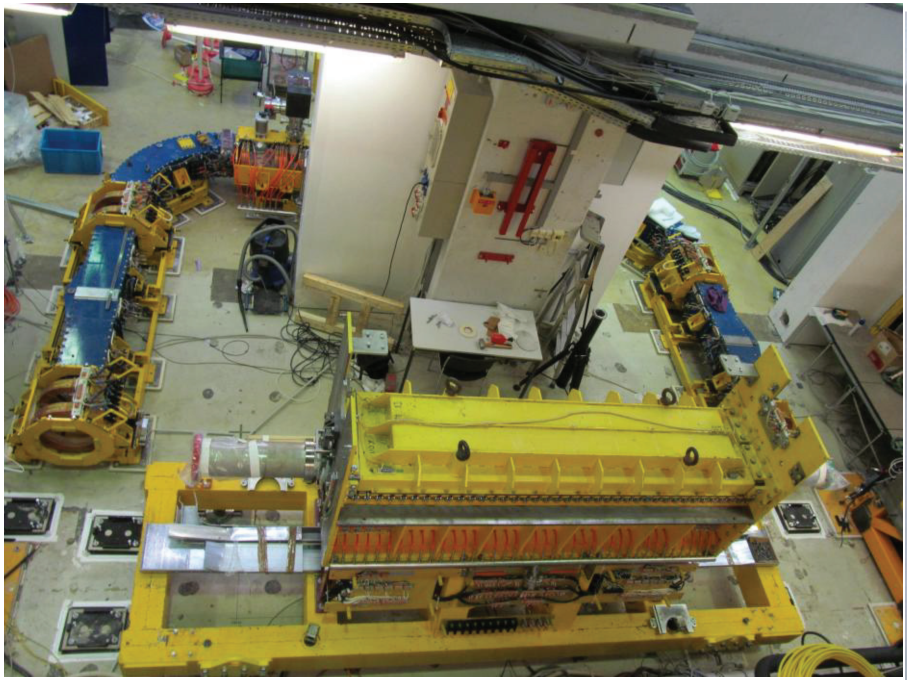
-in order to have small leakage current from the collector

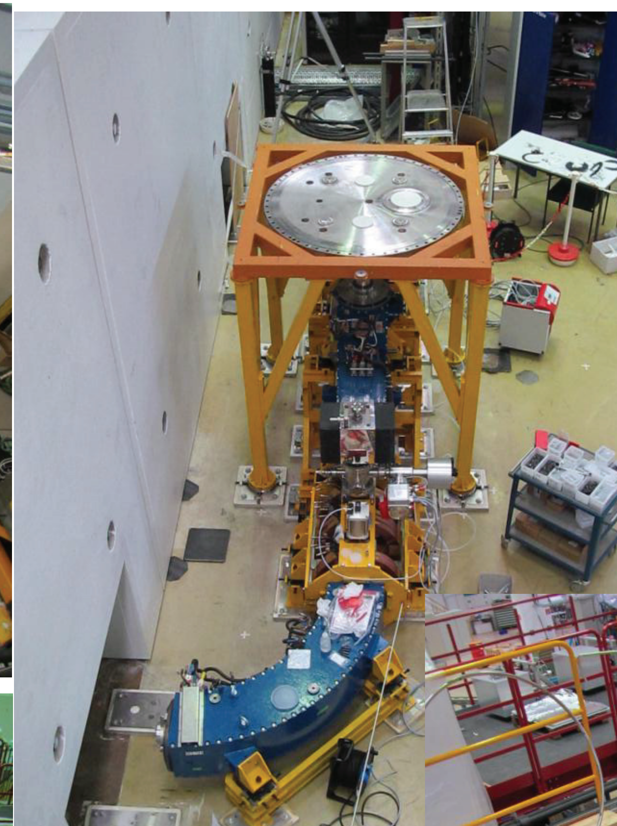
6. “Magnetized” electron motion

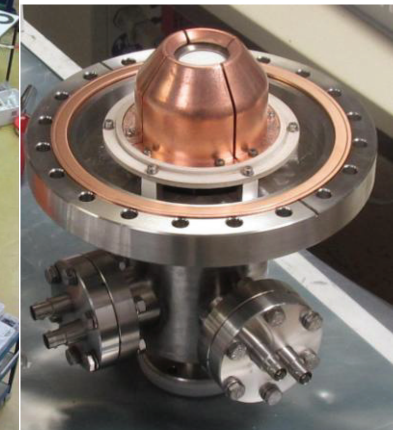
7. “4-sectors” electron gun for diagnostics of the electron beam motion

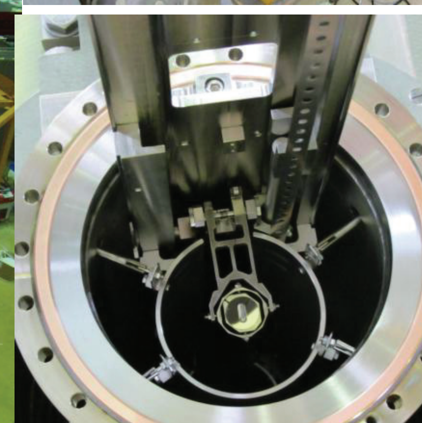
2 MeV Electron Cooler	Parameter
Energy Range	0.025 ... 2 MeV
Maximum Electron Current	1-3 A
Cathode Diameter	30 mm
Cooling section length	2.69 m
Toroid Radius	1.00 m
Magnetic field in the cooling section	0.5 ... 2 kG
Vacuum at Cooler	10^{-9} ... 10^{-10} mbar
Available Overall Length	6.39 m

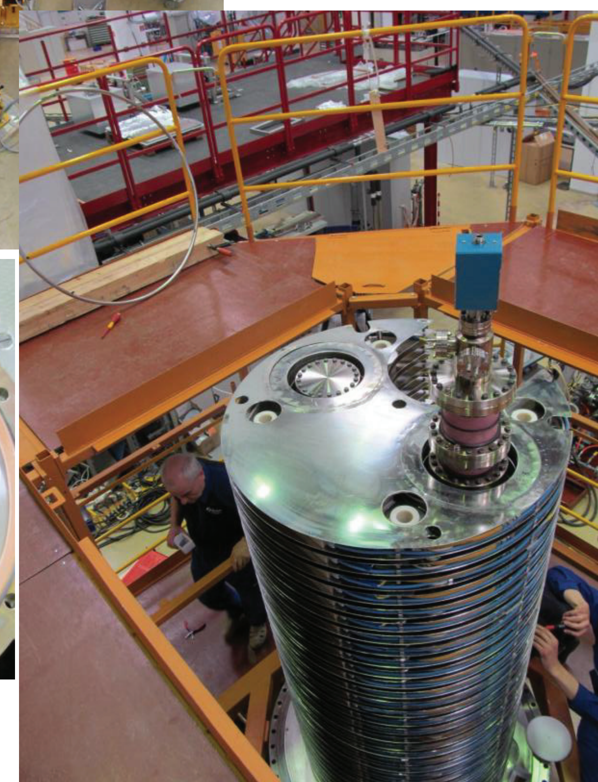
Assembling in COSY











Current status of the 2 MeV e-cooler at COSY

Electron cooling of the proton beam

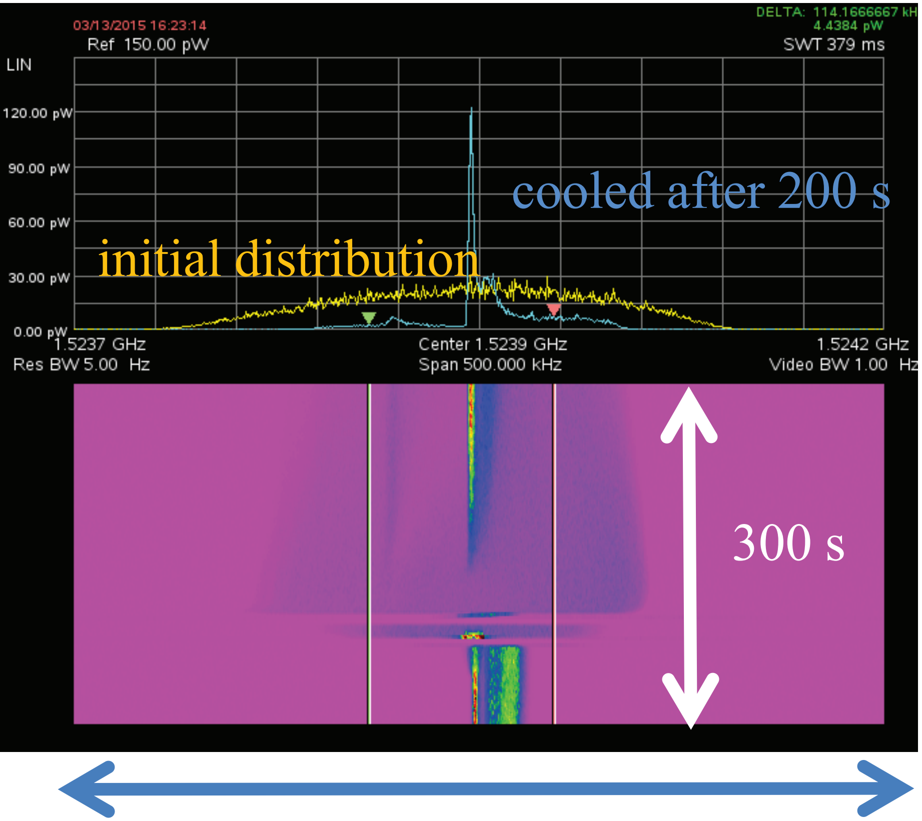
Proton energy, MeV	Electron energy, MeV	Max. electron current, A
200	0.109	0.5
353	0.192	0.5
580	0.316	0.3
1670	0.908	0.9
2300	**1.25**	**0.5**

Maximum electron current and energy so far demonstrated

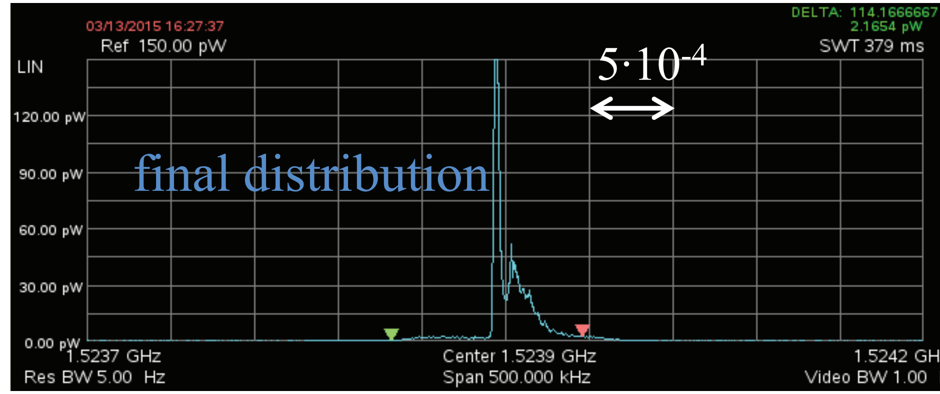
Electron energy, MeV	Electron current, A
0.024	1
1.25	**0.8**
1.5	0.09

The cooler was built by BINP, installed into the COSY ring in 2013

Example of the longitudinal cooling



$\Delta p/p = 5.5\ 10^{-3}$

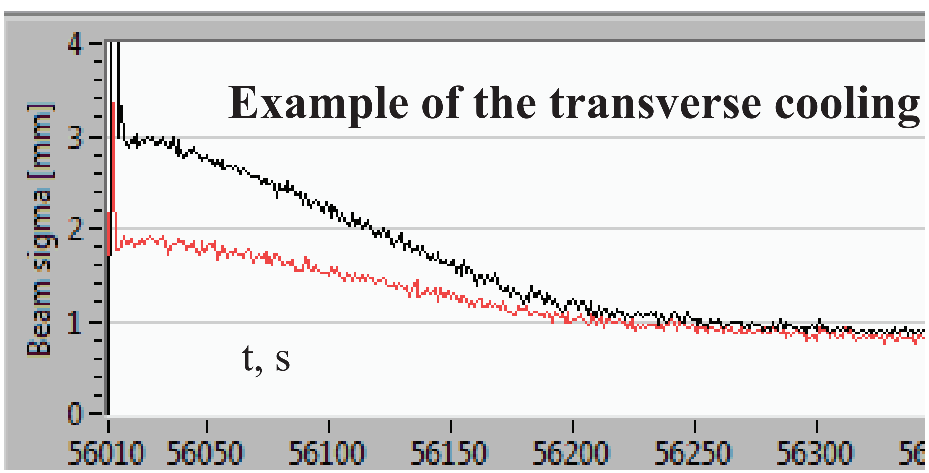


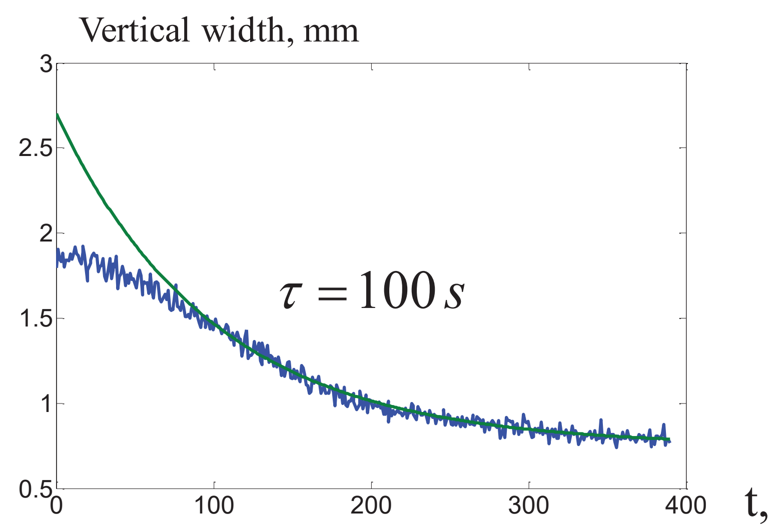
$Np=7\cdot10^{8}$, $Je=400$ mA, $\eta=-0.066$,

Ee=909 kV, $\gamma=2.77$, $\gamma_{tr}=2.25$, $\gamma>\gamma_{tr}$

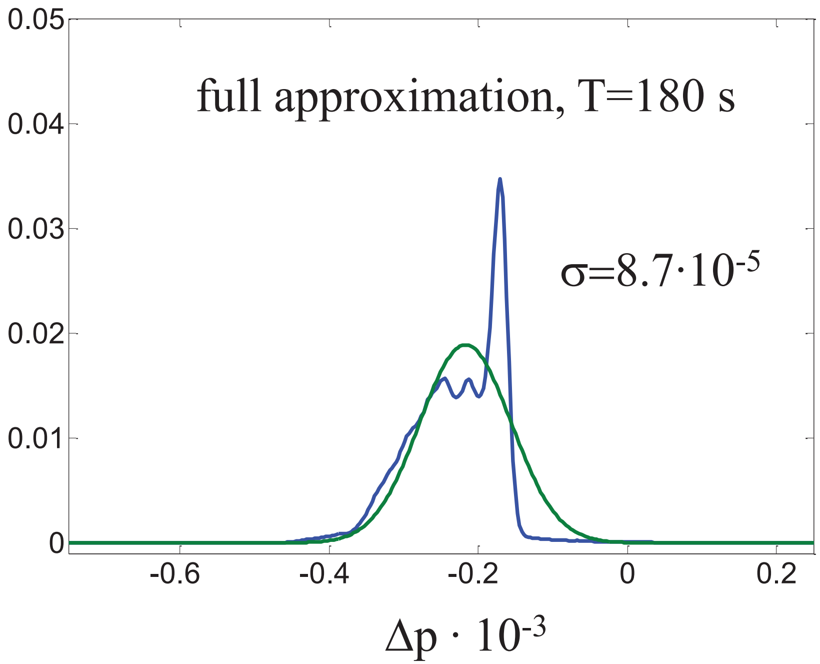
The initial proton momentum spread was widened using white noise beam excitation to $\Delta p/p = \pm 2\cdot10^{-3}$, and it was cooled down during 100 s.

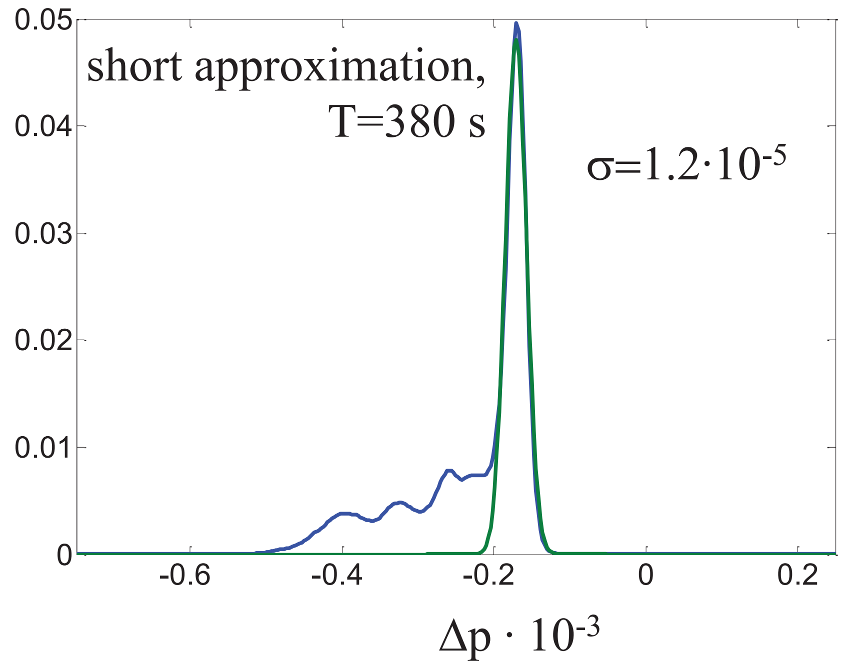
$Np=3\cdot10^{8}$, $Je=800$ mA,





Non-linear fit to gauss distribution function has the different behavior because the definition of the width of the distribution function has some problem.

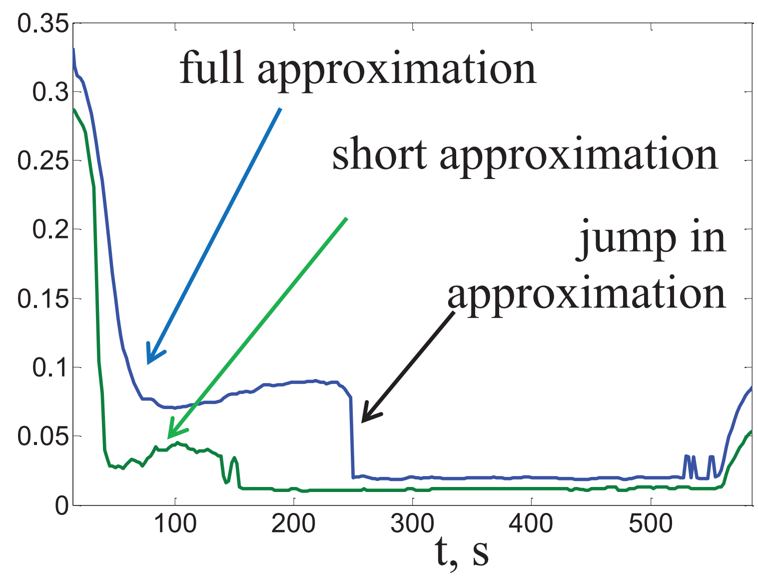




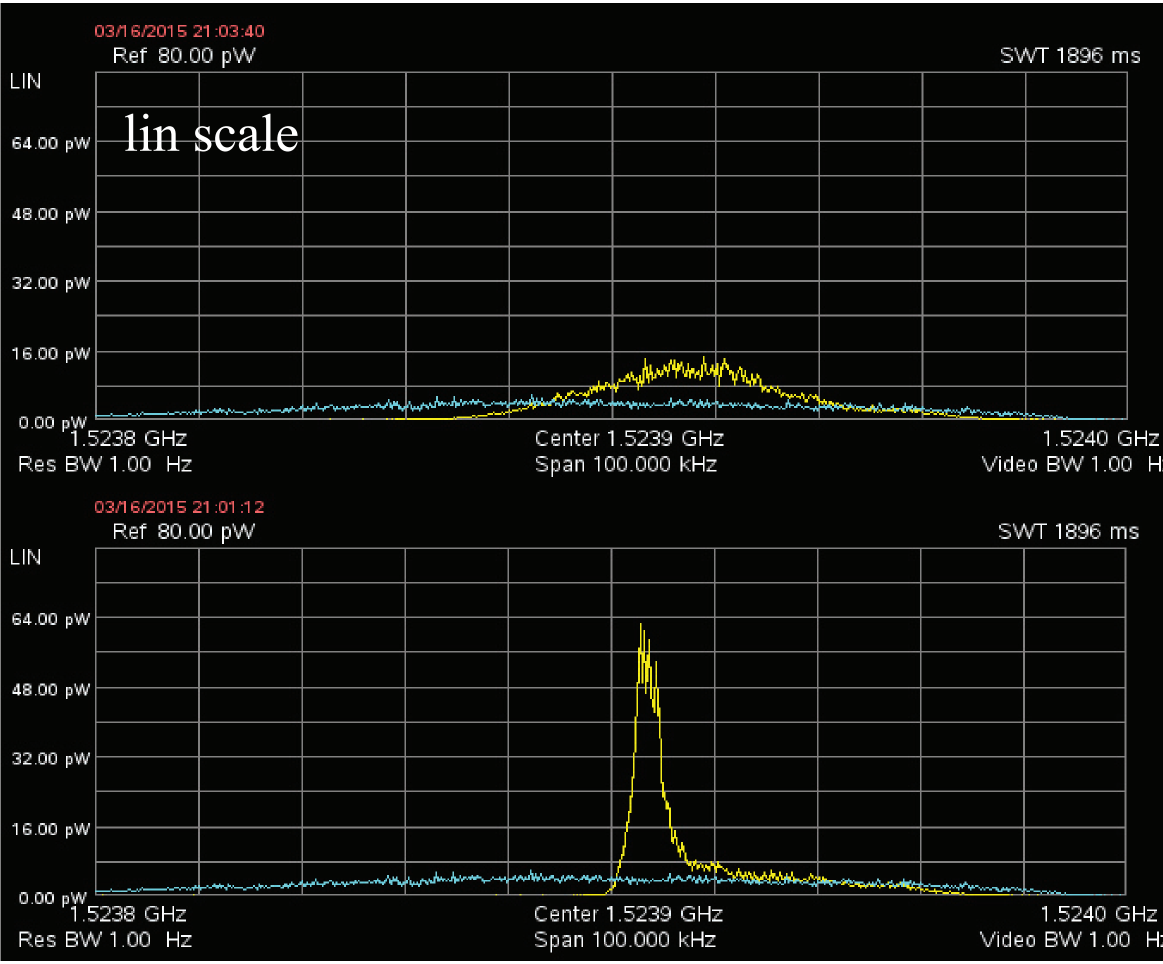
Np=2.7·10[8], Je=520 mA, Ee=909 kV, Experiment time is 21 march 2015 12:26:00 γ_{tr}= 2.259

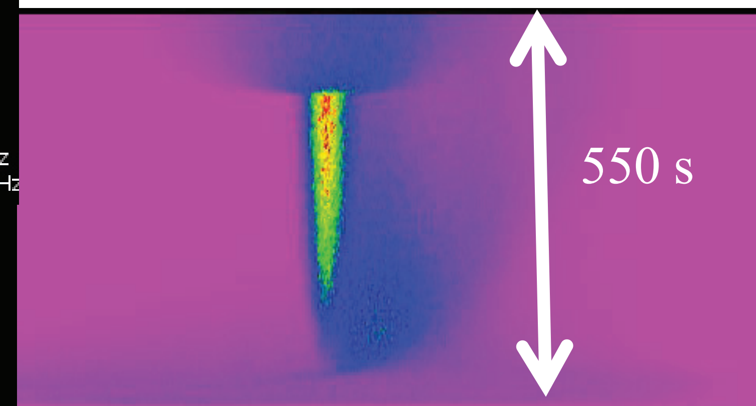
The short approximation takes into account only peak of the distribution function, the full approximation takes into account full shape.

$$w = A \cdot \exp\left(-\left(p - p_0\right)/\sigma^2\right)$$



Electron Cooling of a proton beam and turning off EC



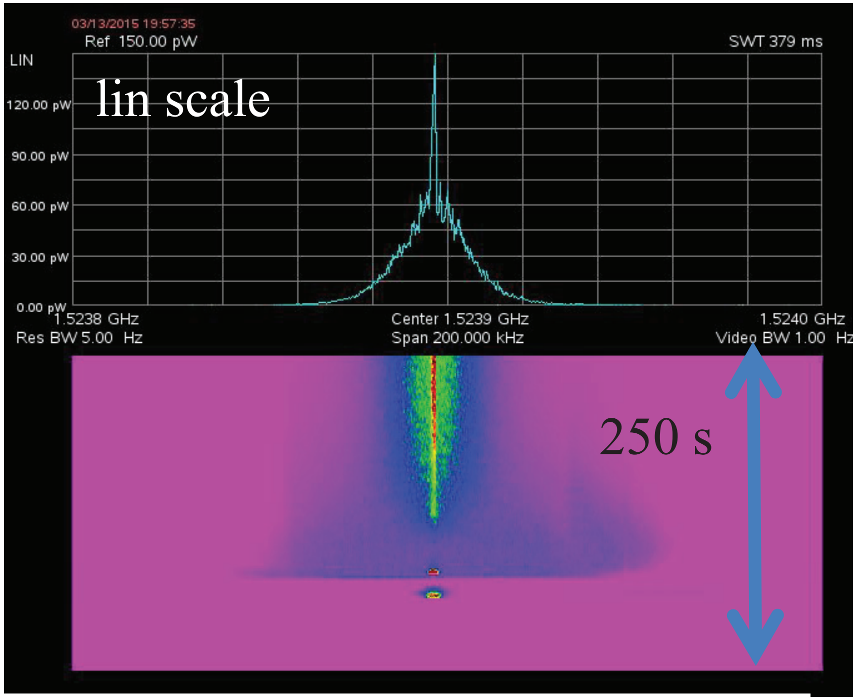


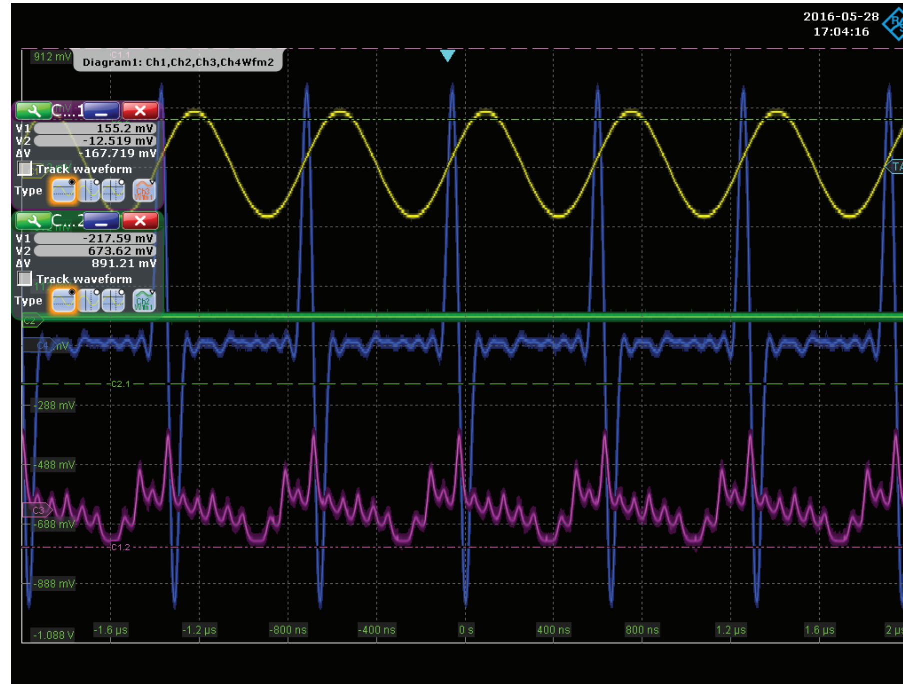
Time span of the color spectrogram 550 s

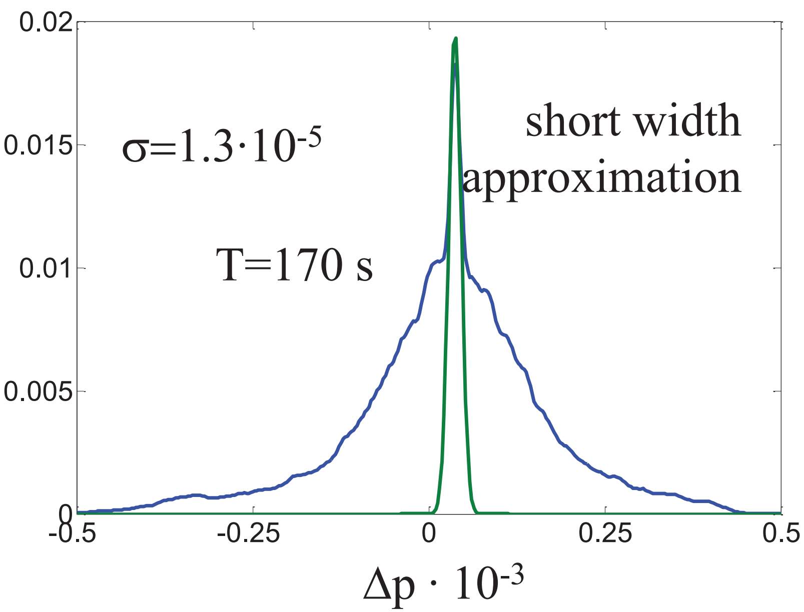
Longitudinal electron cooling process. e-beam turned off leading to fast Δp/p growth. $5 \cdot 10^8$ *protons, 1.66 GeV, electron current 0.8 A*

e-cool can well operate with barrier bucket RF

Barrier bucket signal and Phase probe signal of p-beam





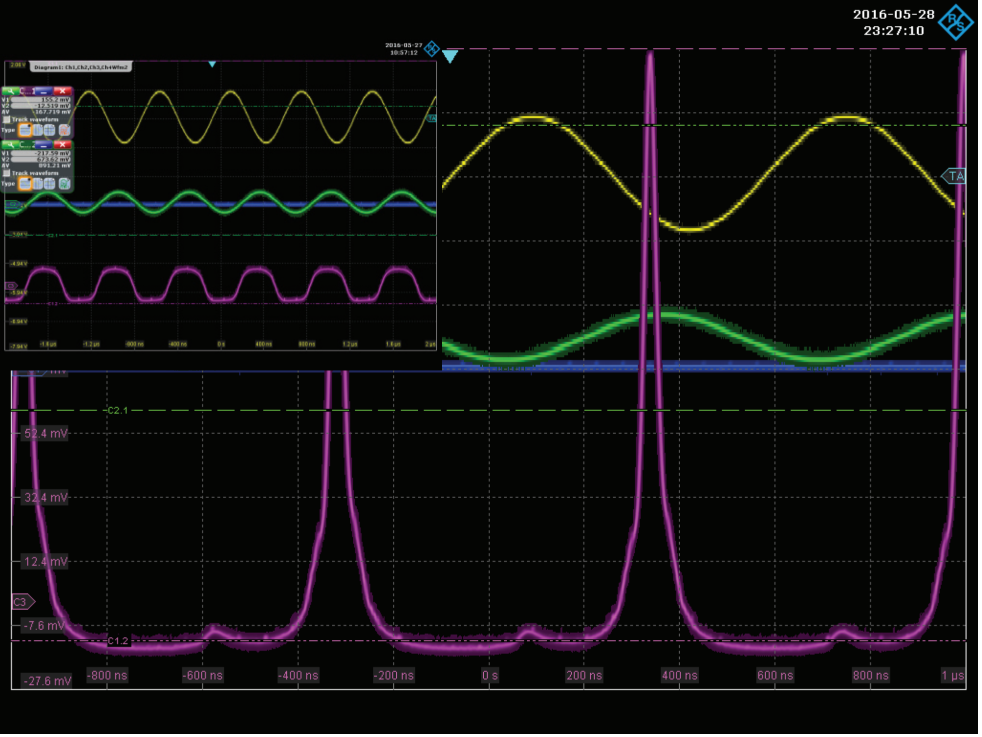


pink is signal from phase probe of p-bar
blue is is signal from barrier bucket RF

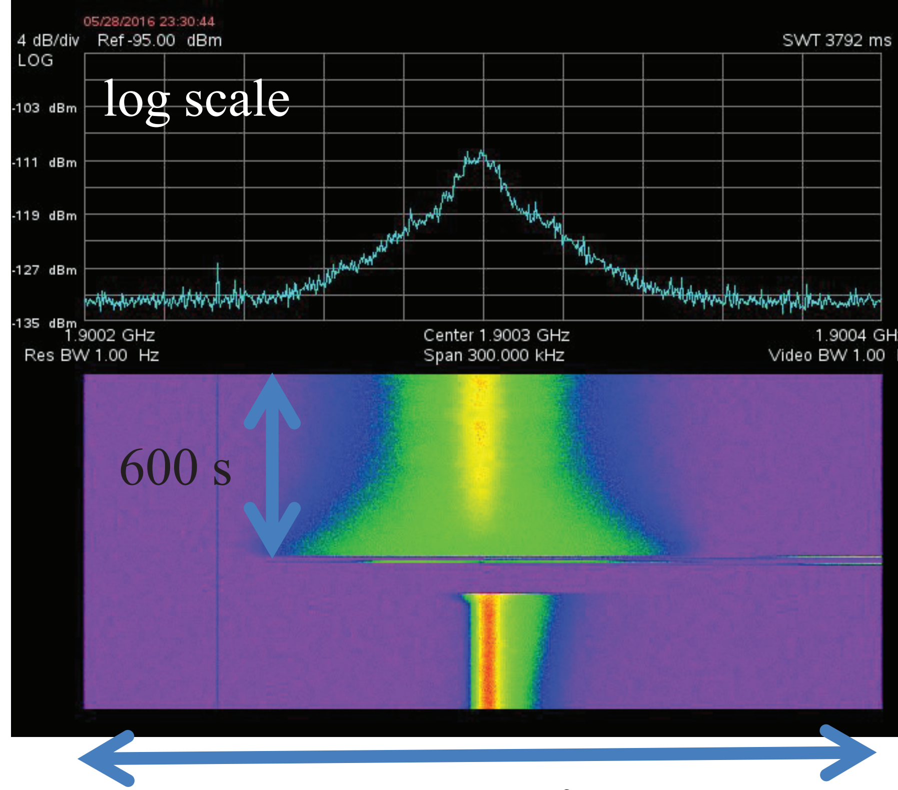
longitudinal cooling at barrier bucket RF voltage

f_{BB}=1.523918 MHz, U_{RF}~200 V

Np=$3\cdot10^8$, Je=550 mA, $\gamma>\gamma_{tr}$ η=—0.066,



RF of 1st harmonic and Phase probe signal of p-beam



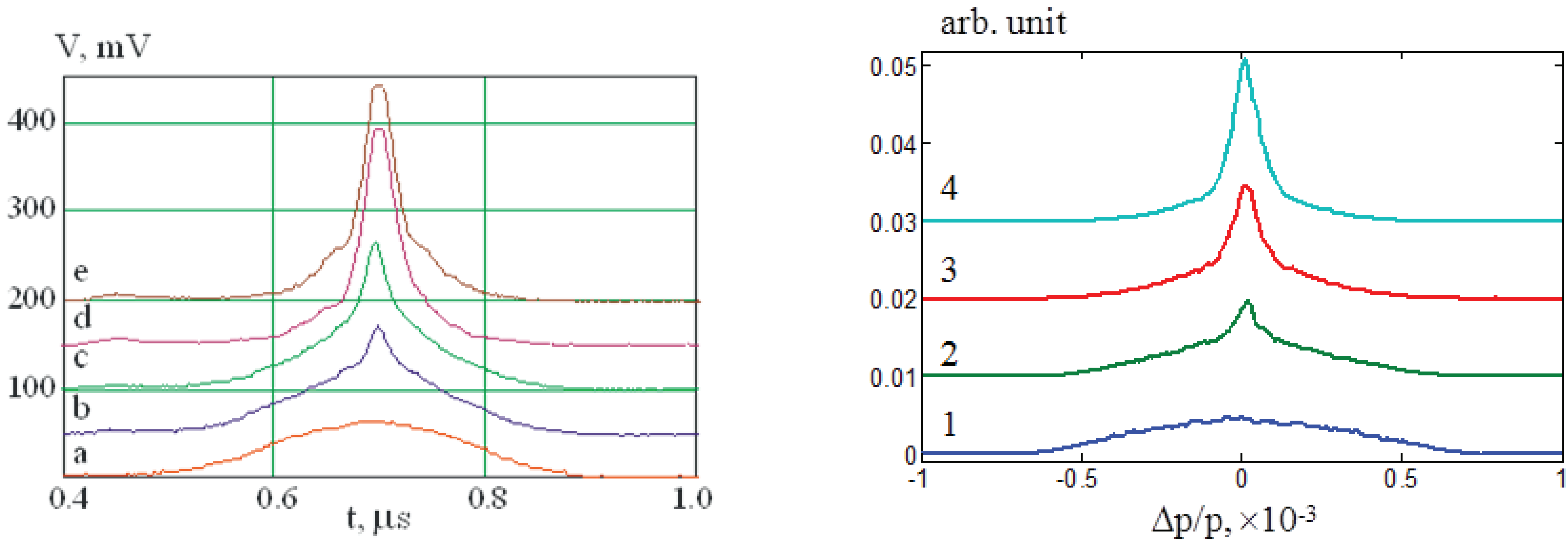
$\Delta p/p = 1.5\ 10^{-3}$

RF on, e-cooling with 570 mA, $Np = 2 \cdot 10^{9}$

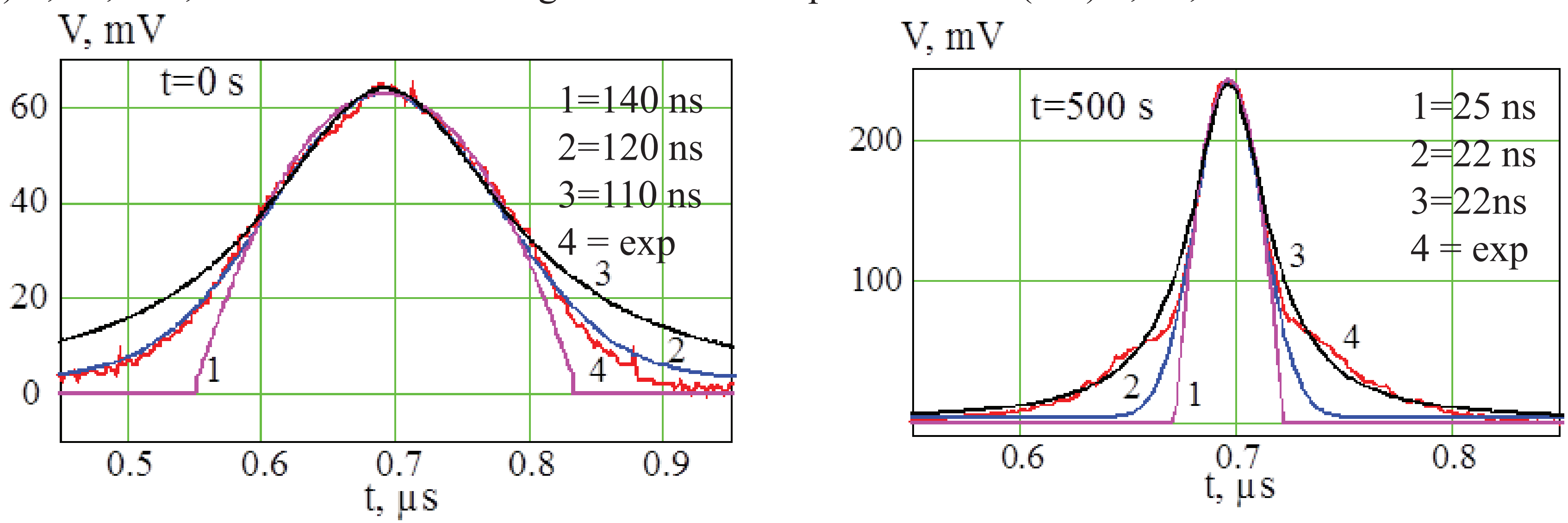
e-cool can well operate with usual RF

One can see that the combine action of the RF and e-cool produces very short beam with high quality. The off-duty factor of the proton beam is 650 ns/30 ns=20. So, the bunched e-cool of the bunched ion may have the gain of the electron current 20 without increasing average current.

The use of bunched e-beam may be some reserve for improvement of DC e-cool. The use of the e-bunch at the same time proton bunch with larger current can increase cooling rate in 20 times ! Certainly the special pulse e-gun and the collector for higher current should be constructed.



Evolution of the longitudinal shape of the proton bunch (left picture) and the evolution of the longitudinal momentum spread of the protons (right picture) during cooling process. The left curves correspond to time (a-e) 0, 60, 100, 330 and 500 s. The right curves correspond to time (1-4) 0, 83, 166 and 250 s.



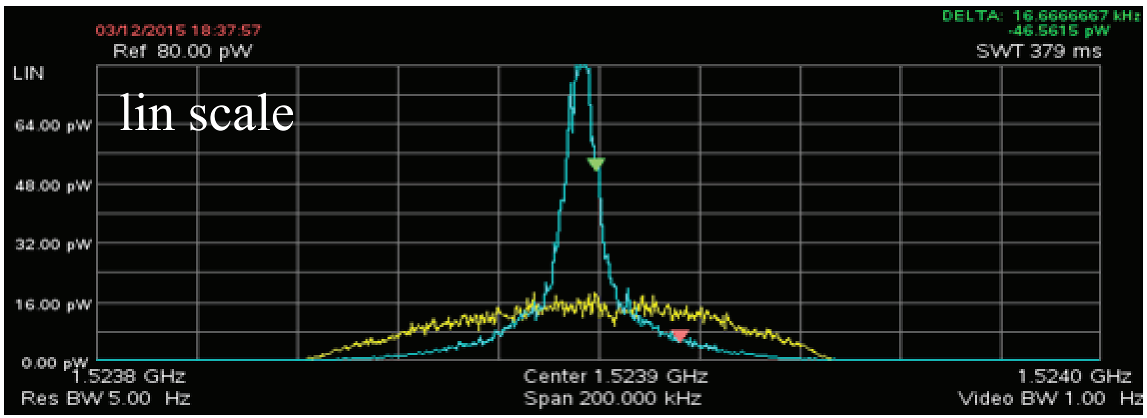
Fitting curves of the shape of the proton bunch for the start (left picture) and the end (right picture) of the cooling process. 1 is parabolic shape, 2 is gauss shape, 3 is Lorentz shape with and 4 is the experimental data.

Main is space charge effect

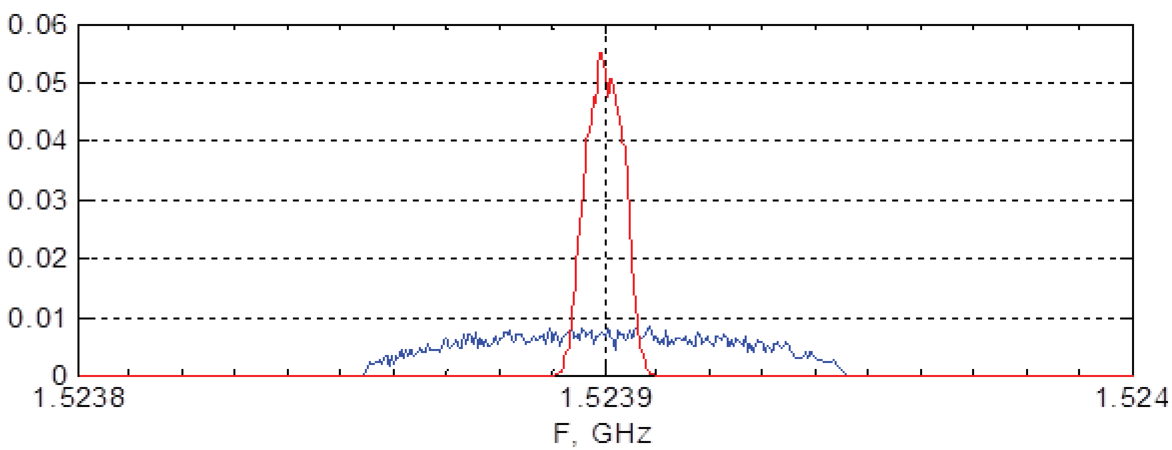
At equilibrium electric field along bunch should compensate RF action and we can estimate bunch length as

$$\sigma_s(J_i) = \left[\frac{3}{2\gamma^2\beta} \Pi^3 \frac{J_{ion}\left(1+2\ln(b/a)\right)}{cU_{RF}} \right]^{1/3}$$

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



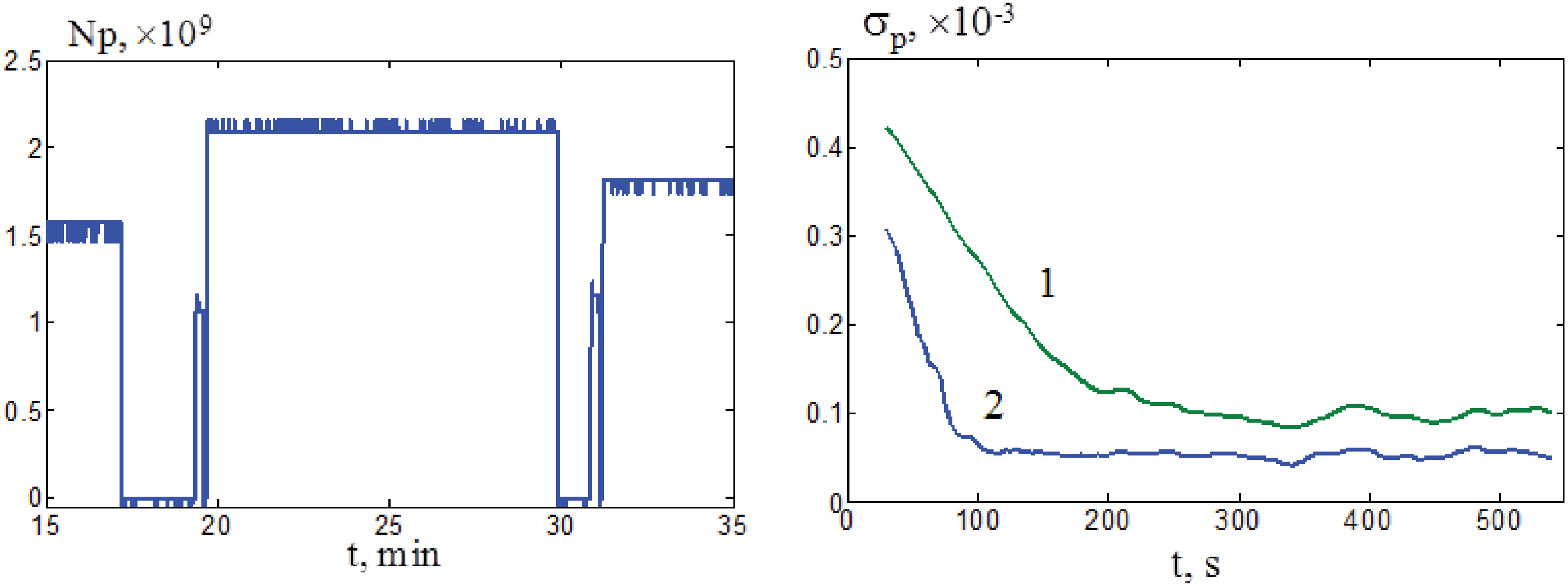
Tail is indication of intrabeam processes or some microbunch instabilities ?



computer simulation doesn't show the tail in the distribution function

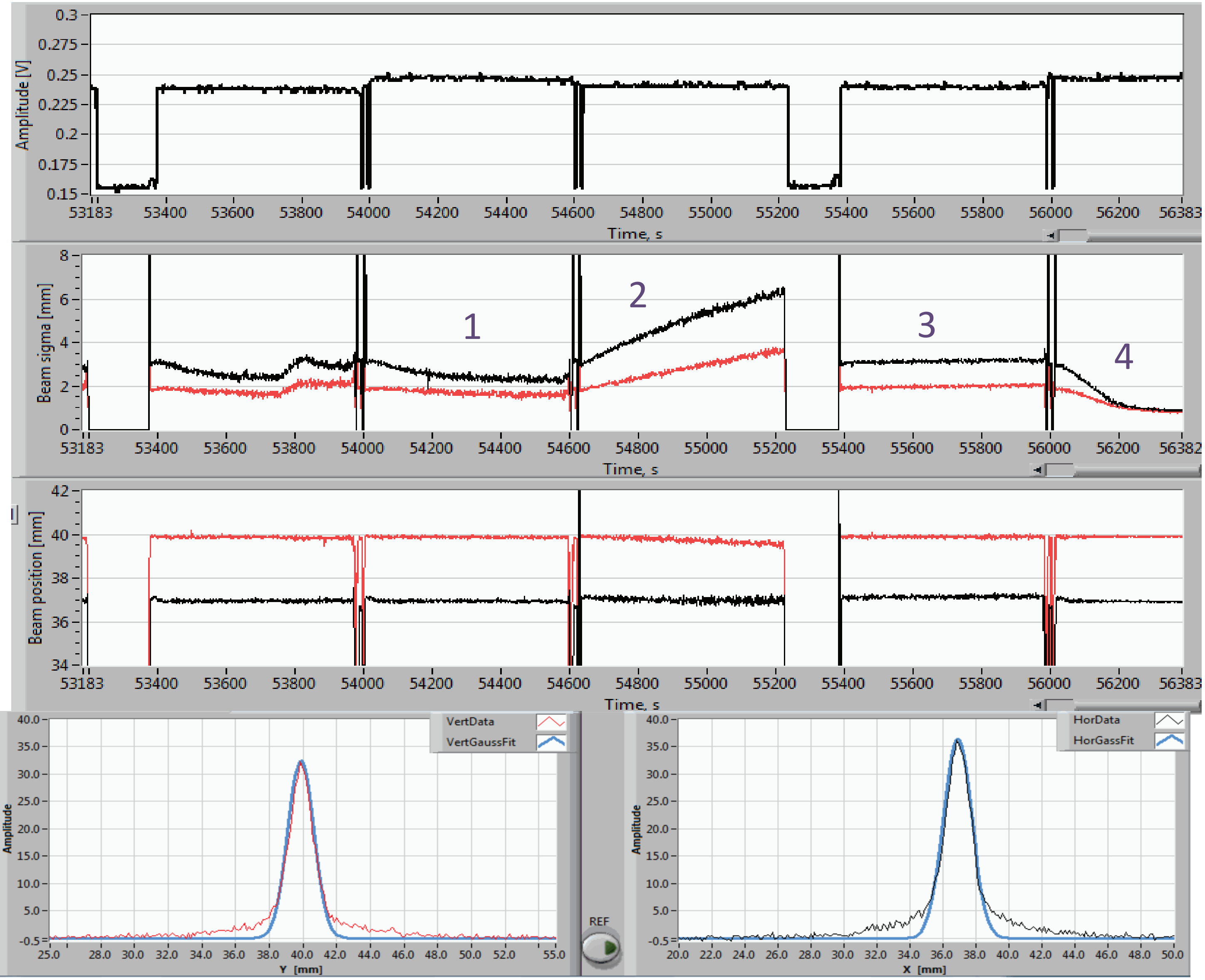
Schottky signal for the non-cooling and cooling states of the proton beam. The top picture is the real experimental signal, the bottom picture is the result of the computer simulation.

The time of the longitudinal cooling doesn't depend from bunched or continuous mode of the proton beam and the typical value for this experiments were about 100-150 s. In time of the cooling process the typical life-time was good enough. The particle losses were not detected during 600 s period.



Signal from beam current transformer (left picture) and decrease of the momentum spread (right picture) during cooling process. The curve 1 describes whole distribution function and curve 2 describes only the central core with Gauss shape.

Transverse e-cooling at 909 kV energy



$3.6 \cdot 10^8$ protons
1.66 GeV

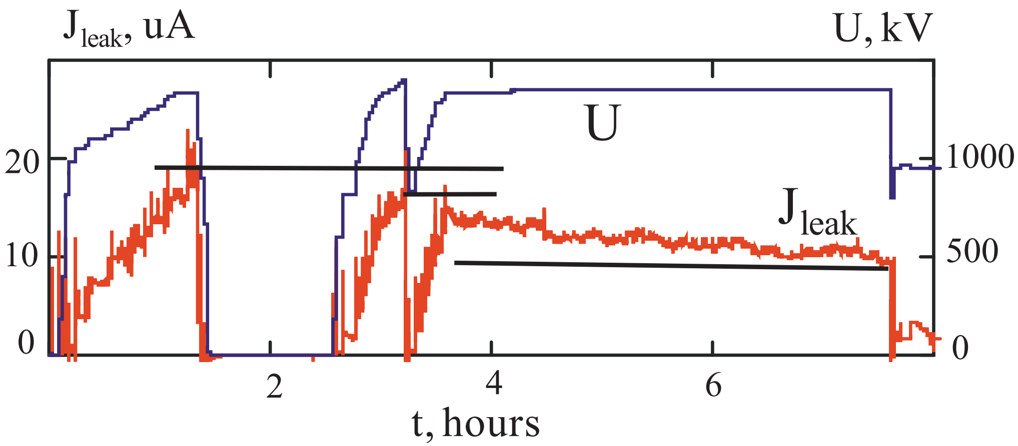
$I_e = 0.8$ A
B_{sol}=1.3 kG

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

$\varepsilon_x = 1.1 \rightarrow 0.1$
ε_y: $=1.3 \rightarrow 0.2$
mm·mrad, normalized beam core within 200s

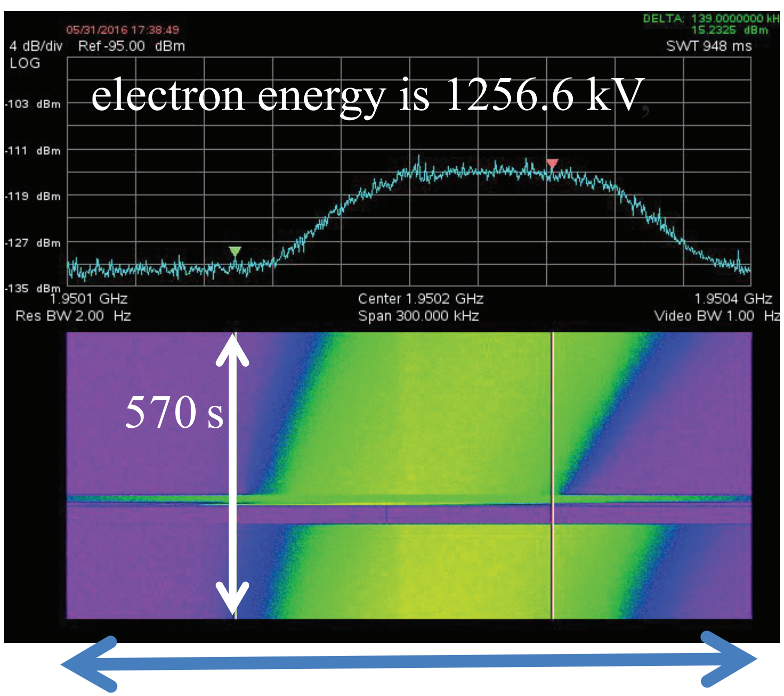
IPM screenshot

Electron cooling with 1256 kV



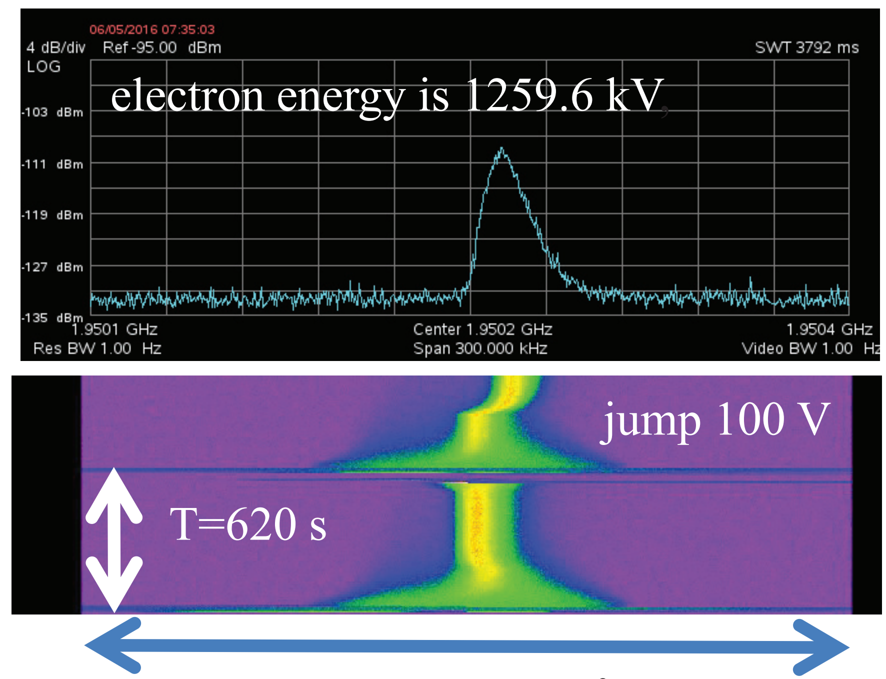
Before the cooling process the training of the high-voltage column was done. During this process leakage current through SF_6 gas decreased from 20 uA to 9 uA.

electron current is 0.5 A



$\Delta p/p = 1.5\ 10^{-3}$

Spectrogram of the cooling process with strong difference between the electron and ion velocities.

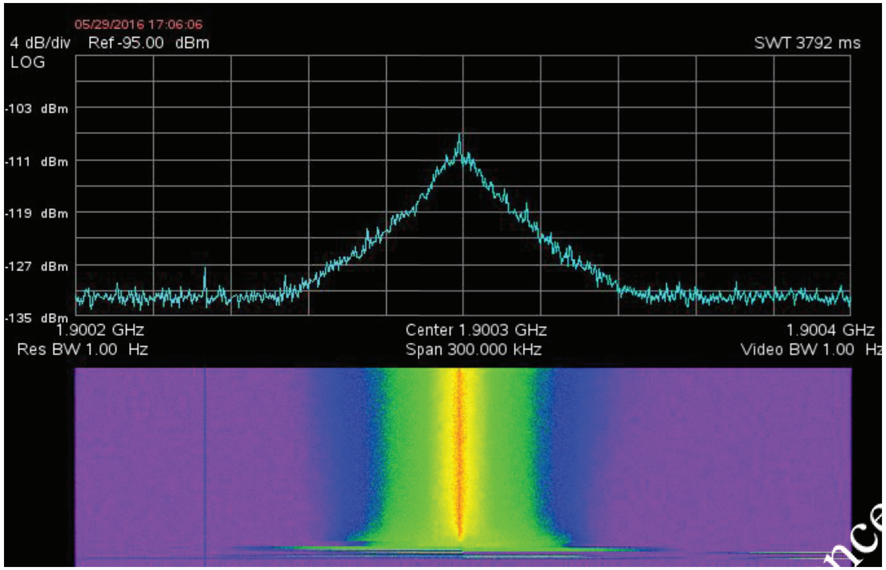


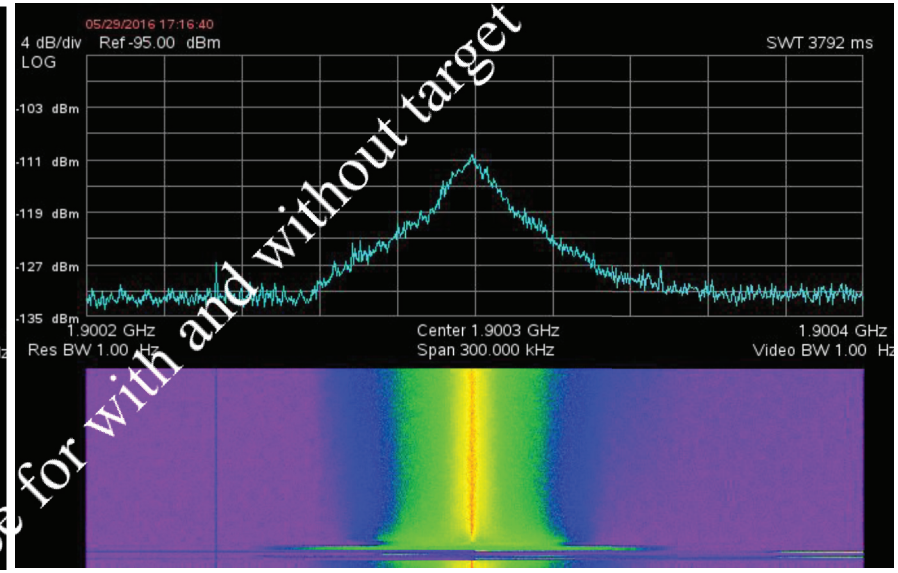
$\Delta p/p = 1.5\ 10^{-3}$

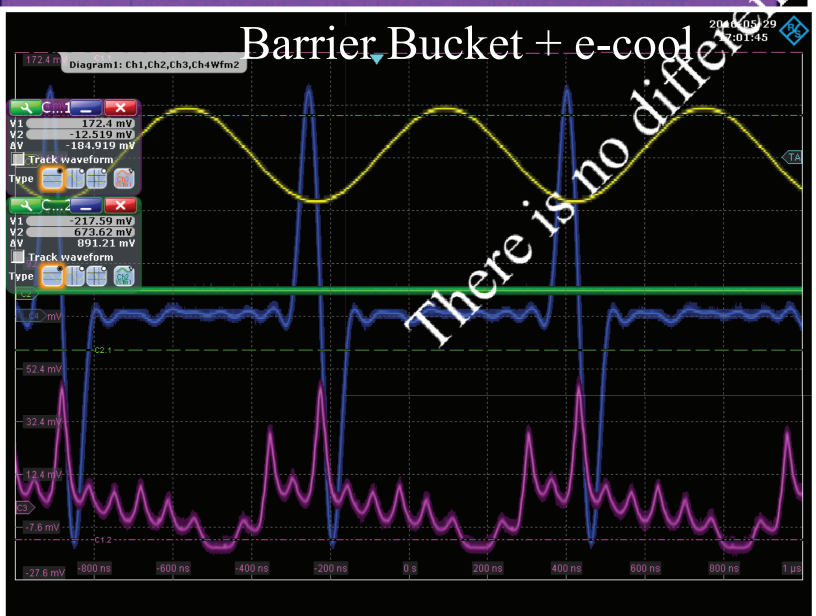
Spectrogram of the cooling process with equal velocities of the electrons and ions.

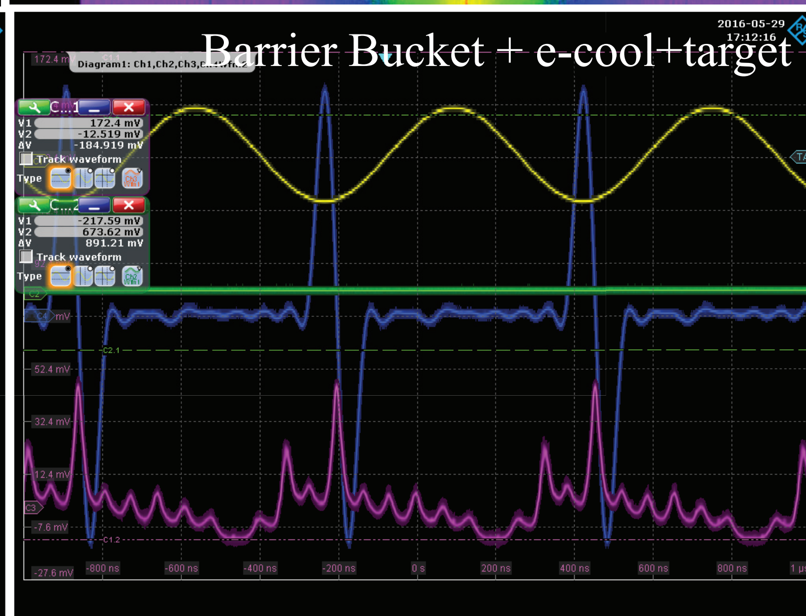
Electron cooling and target 1259.5 kV

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





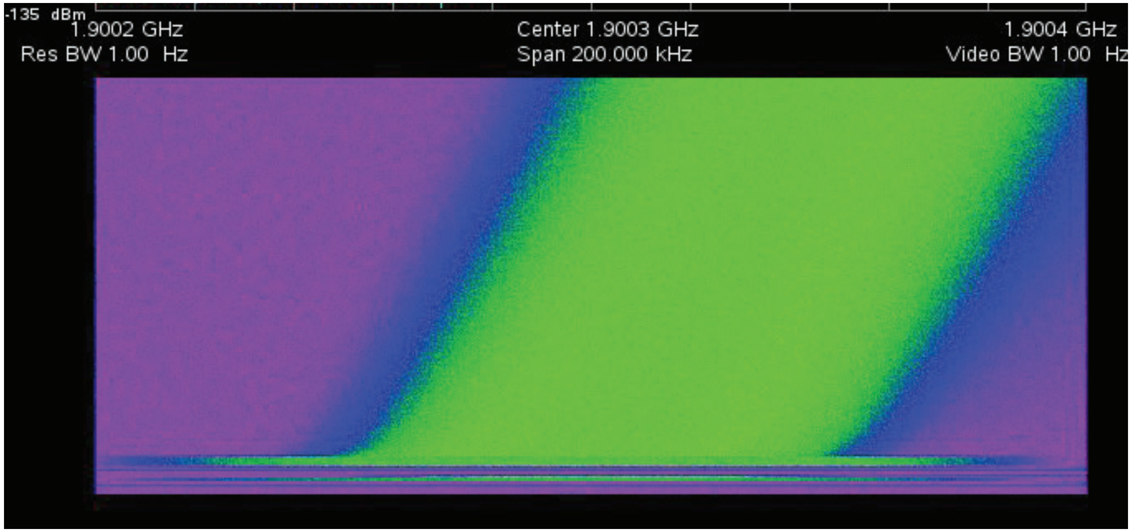




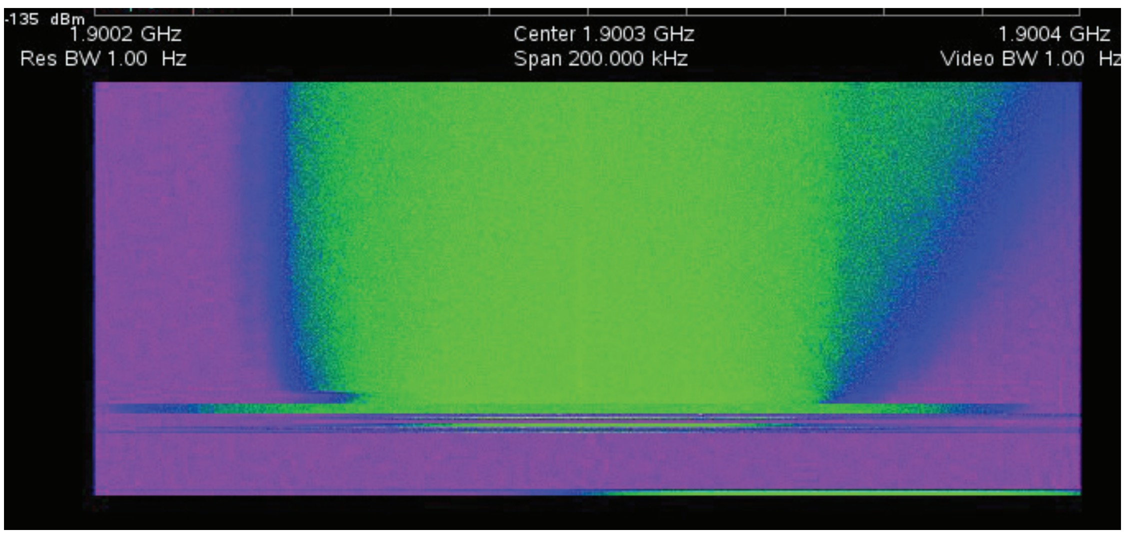
There is no difference for with and without target

Experiments with target without electron cooling

Target has a significant influence on the dynamic of the proton $n_a = 2 \cdot 10^{14}$ cm^{-2}



target



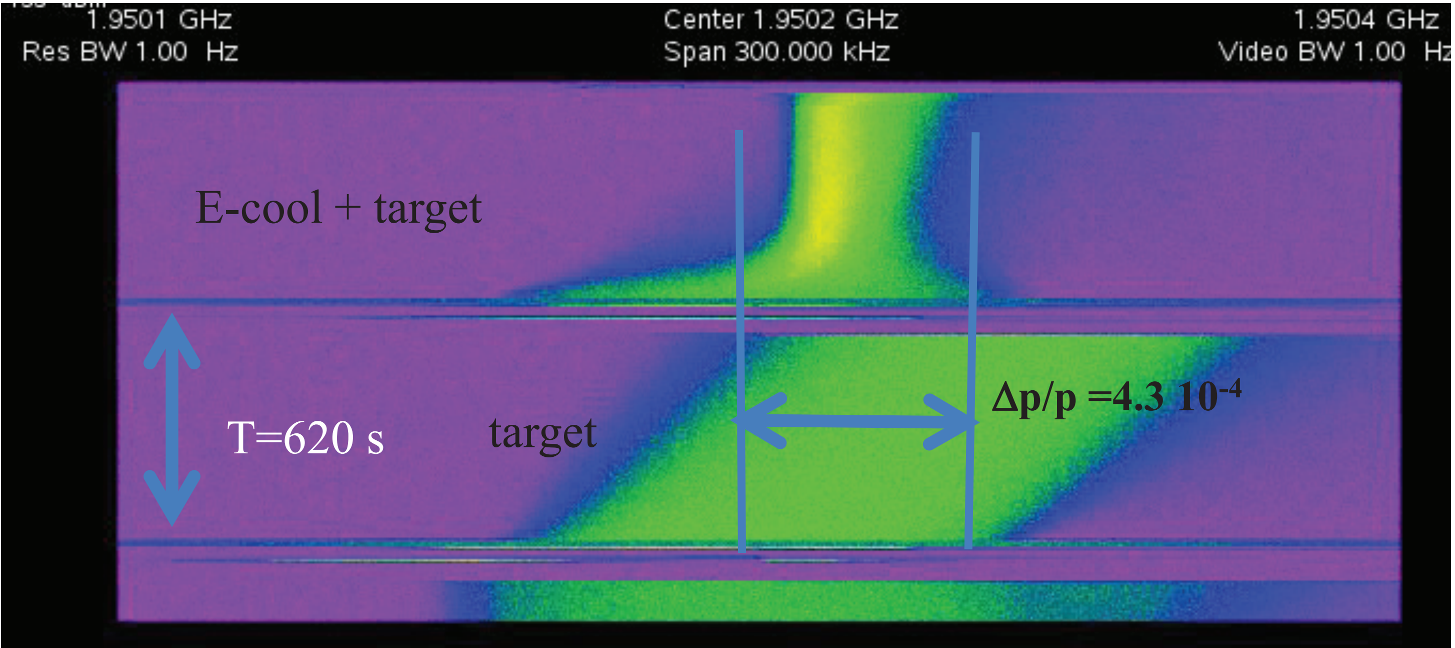
target + barrier bucket

Spectrogram of Schottky noise at target action. The top picture shows ionization loss in cluster target corresponding to hydrogen density $n_a = 2 \cdot 10^{14}$ cm^{-2}. The bottom picture shows the simultaneously action barrier bucket and target. All spectrum duration is about 550 s.

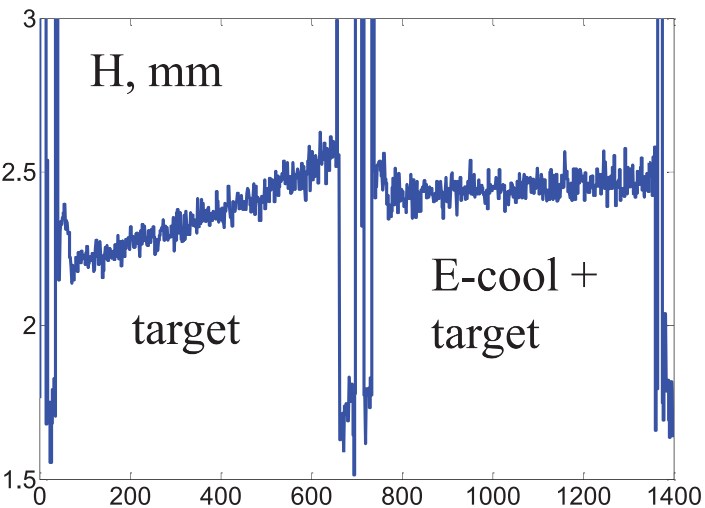
Electron energy 1259.65 kV, Je=500 mA

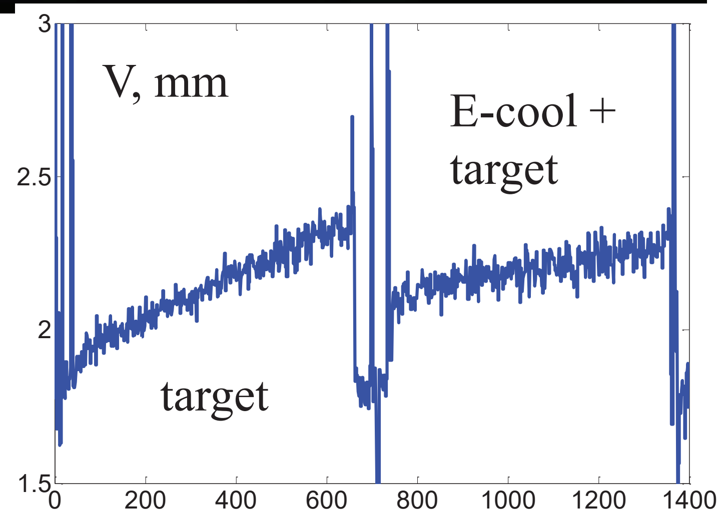
Experiments with e-target

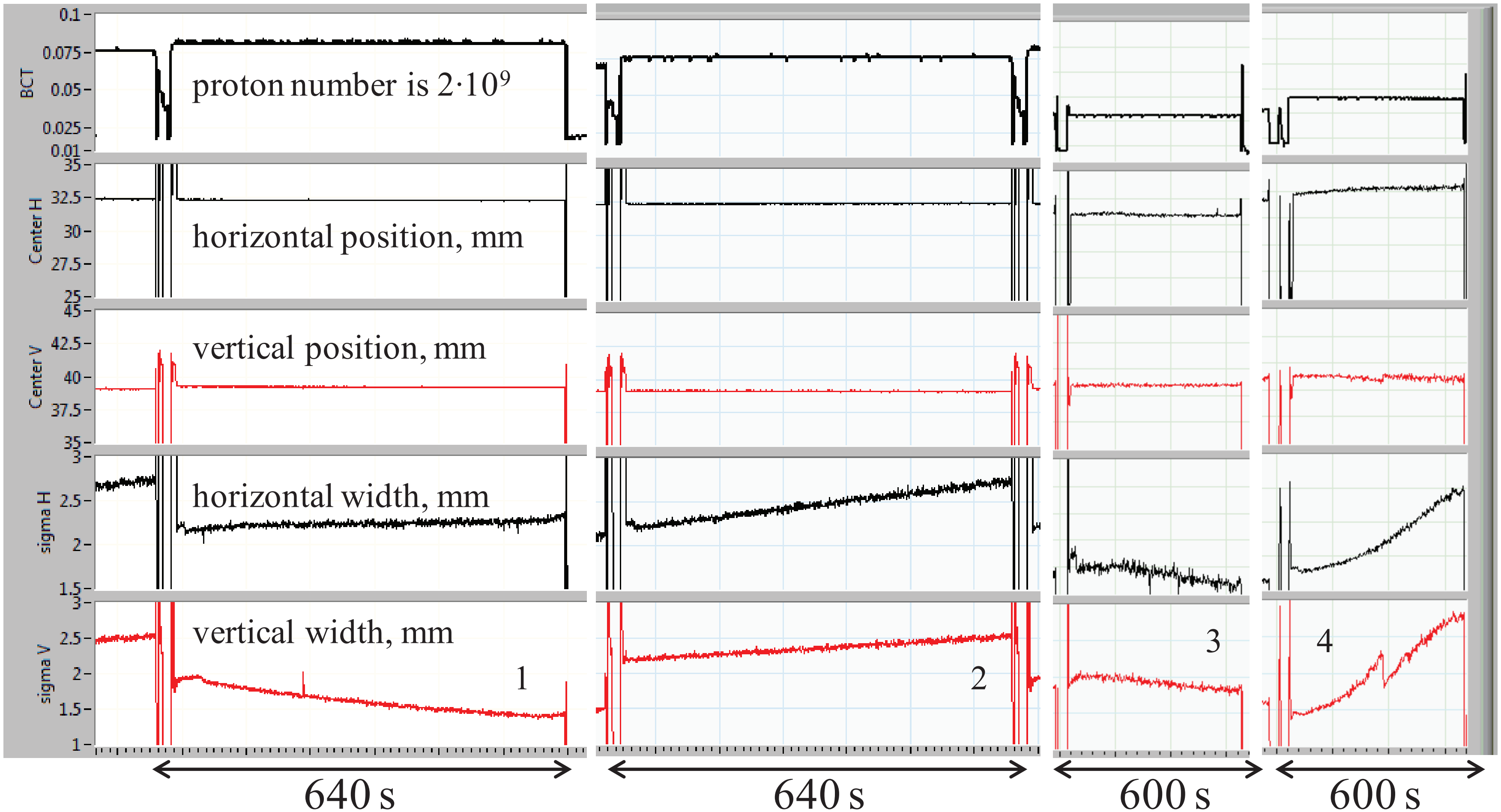
Electron cooling suppressed the longitudinal action of the target with density $n_a = 2 \cdot 10^{14}$ cm^{-2} without help RF.



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

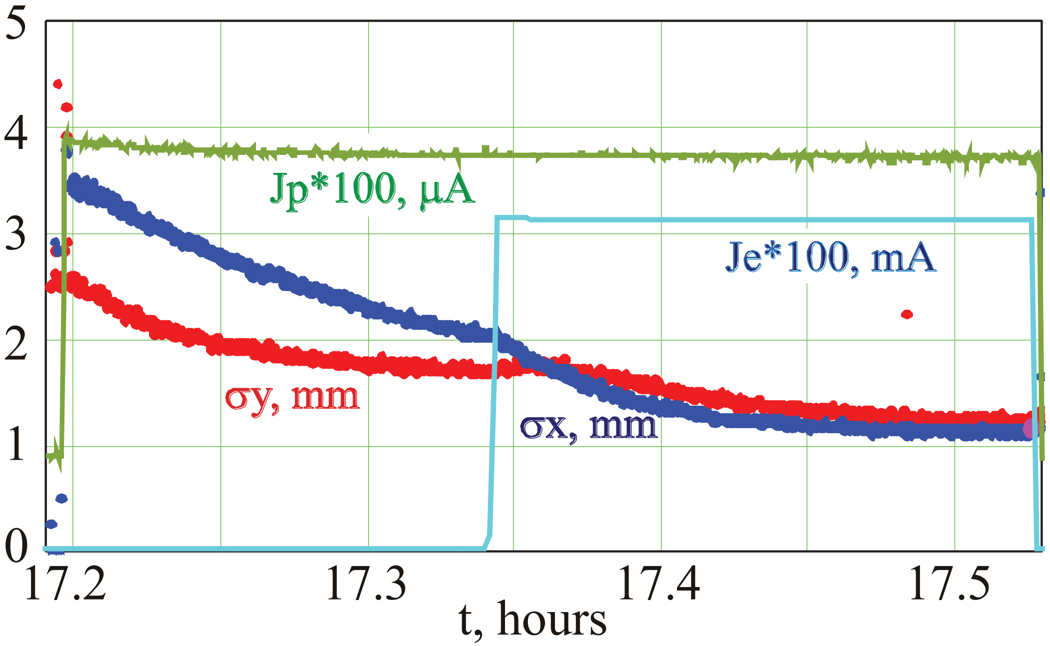




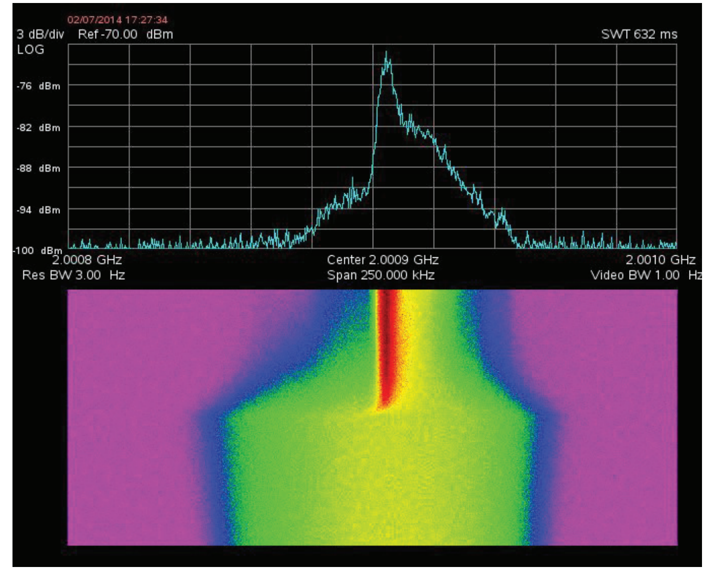


Changing transverse size during cooling experiments. Curve 1 is cooling at energy 909 kV, curve 2 is reference cycle without cooling, curve 3 is cooling at energy 1259 keV, curve 4 is growth of the transverse size at changing working point despite of electron cooling action. Tune was shift at $\Delta Qx/ \Delta Qy = 0.02/-0.01$.

Combine action of stochastic and electron cooling



Only stochastic   Stochastic+e-cooling



initial no longitudinal cool, after e-cooling

Electron energy	908 keV
Proton energy	1.66 Gev
Stochastic cooling	vertical and horizontal
E-cool time	120 s
Stochastic cooling time	400 s
Beta function x/y	4m/3m

Summary

-The key solutions 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) are experimentally verified during operation in COSY.

- Electron cooling may work well together with, target, RF, barrier bucket RF and stochastic cooling

- First experience with energy 1250 kV was obtained.

- The fine tune of the electron beam with diagnostics and correction schemes allowed for faster cooling

$\Delta p/p = 10^{-5}$ in less than 100-200 s

$\varepsilon_x = 1.1 \rightarrow 0.1$, $\varepsilon_y :=1.3 \rightarrow 0.2$ mm·mrad, within 100-200s (beam core)