Experimental observation of longitudinal electron cooling of dc and bunched proton beam at 2425 MeV/c at COSY

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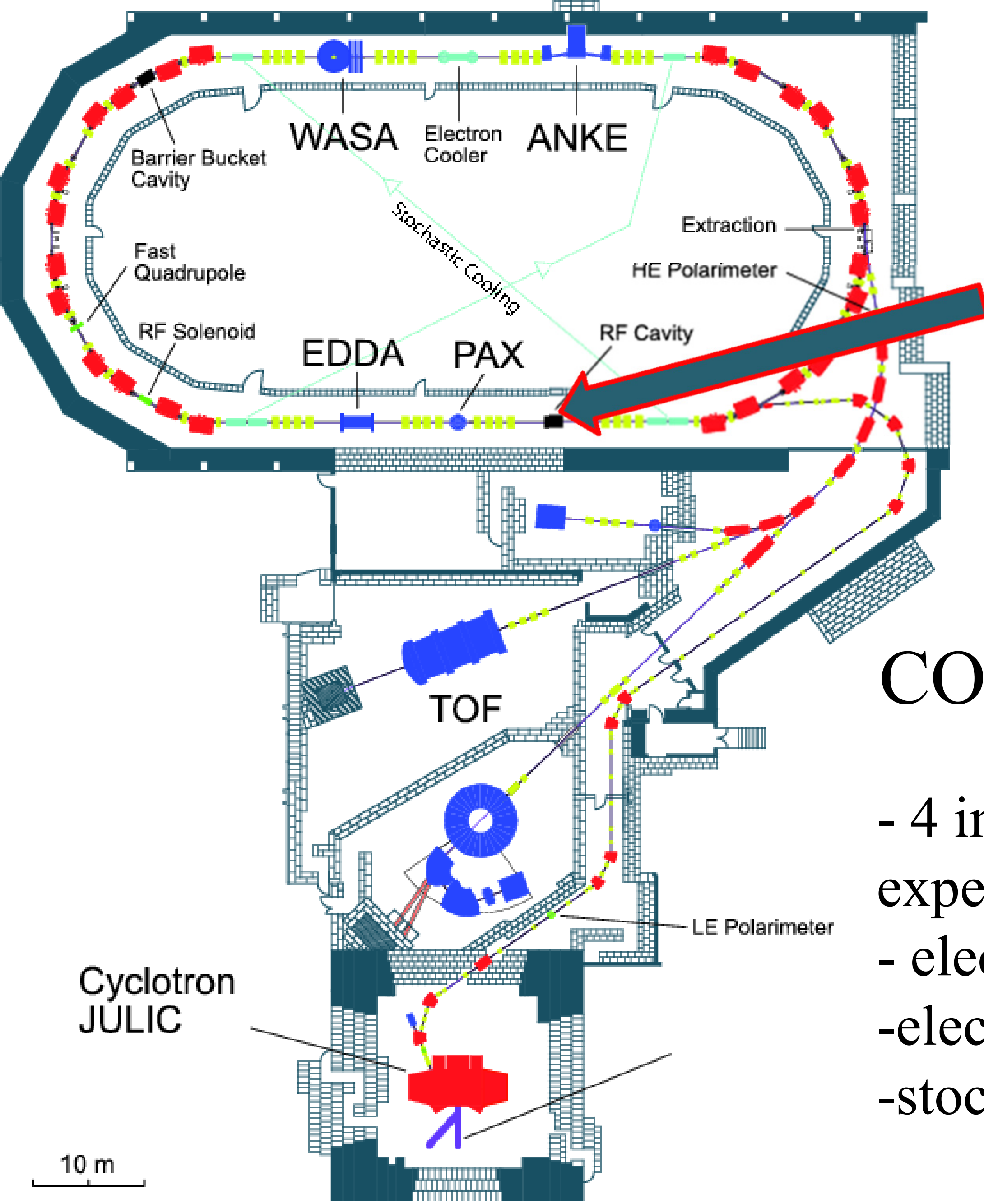
Abstract

The 2 MeV electron cooling system for COSY-Julich started operation in 2013 years. The cooling process was observed in the wide range energy of the electron beam from 100 keV to 908 keV. Vertical, horizontal and longitudinal cooling was tested at bunched and continuous beams. The cooler was operated with electron current up to 0.9 A. This report deals with the description of the experimental observation of longitudinal electron cooling of DC and bunched proton beam at 2425 MeV/c at COSY.

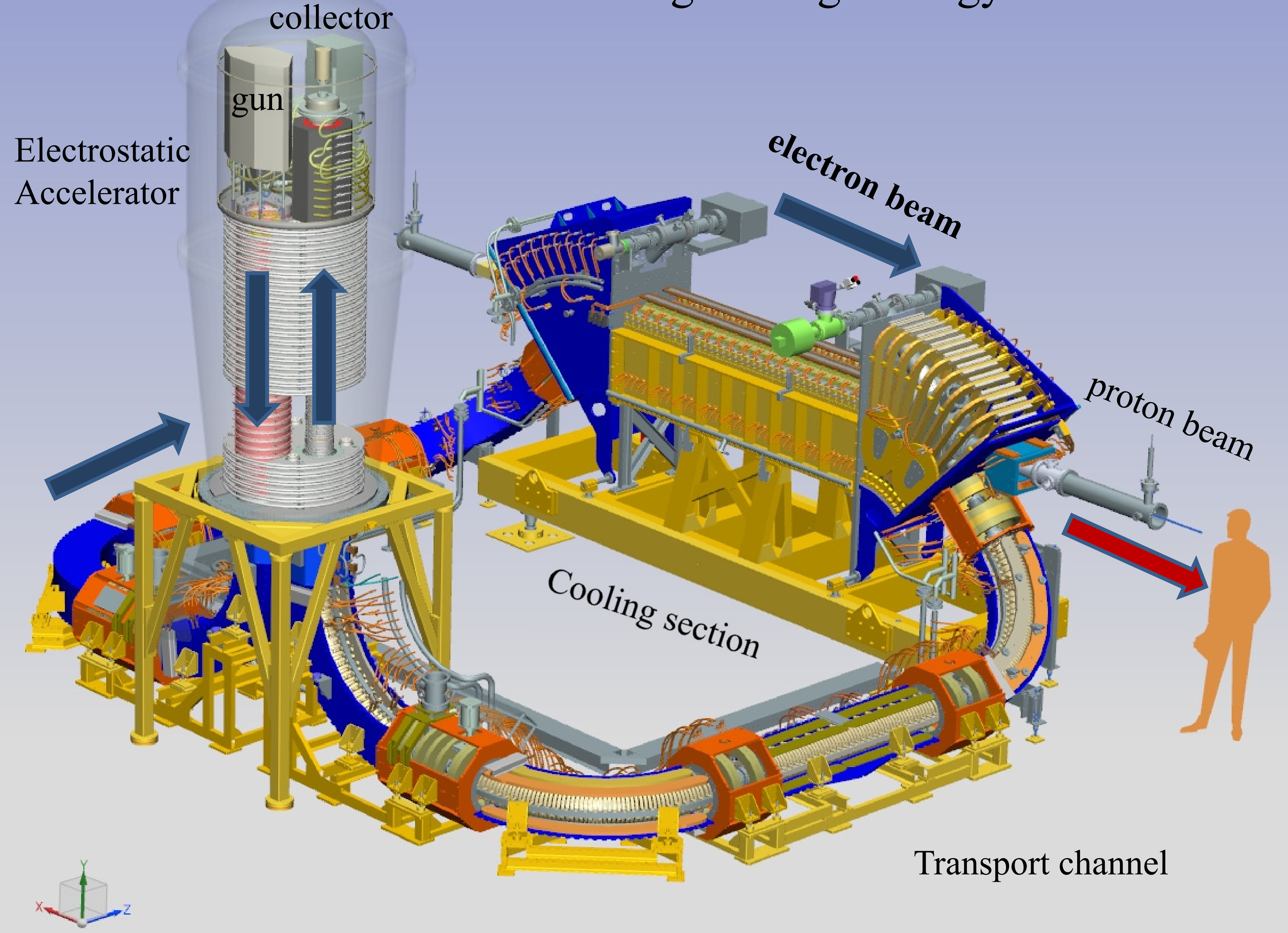


COSY Accelerator Facility

- 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

3D design of high energy COSY cooler



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

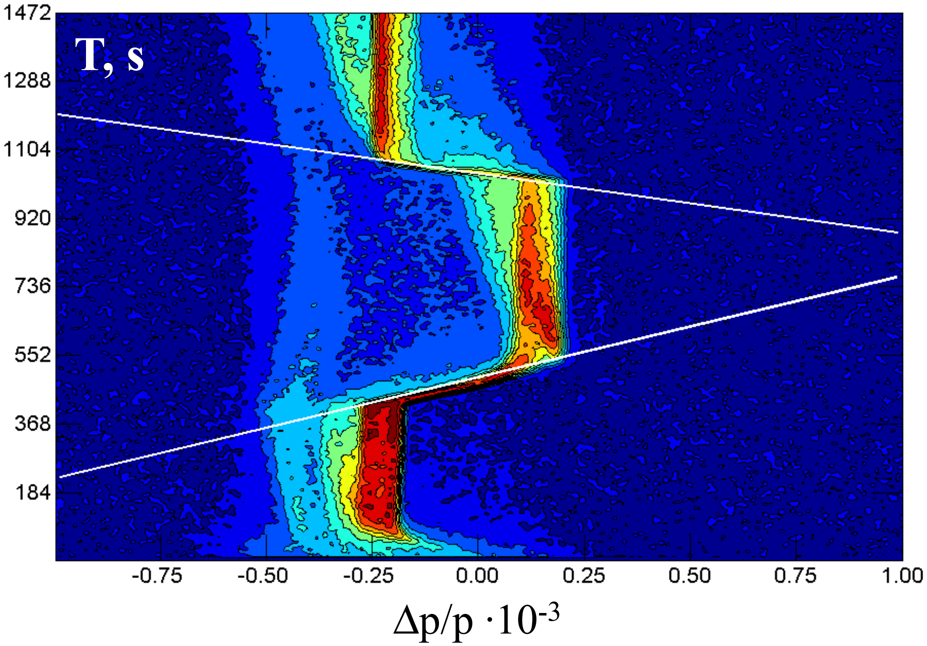
-in order to have small leakage current from the collector

6. “Magnetized” electron motion

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

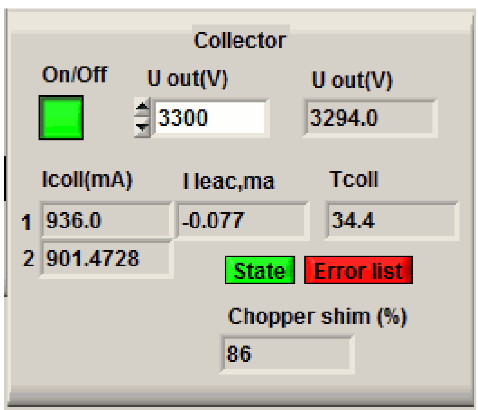
2 MeV Electron Cooler	Parameter
Energy Range	0.025 ... 2 MeV
Maximum Electron Current	1-3 A
Cathode Diameter	30 mm
Cooling section length	2.69 m
Toroid Radius	1.00 m
Magnetic field in the cooling section	0.5 ... 2 kG
Vacuum at Cooler	10^{-9} ... 10^{-10} mbar
Available Overall Length	6.39 m

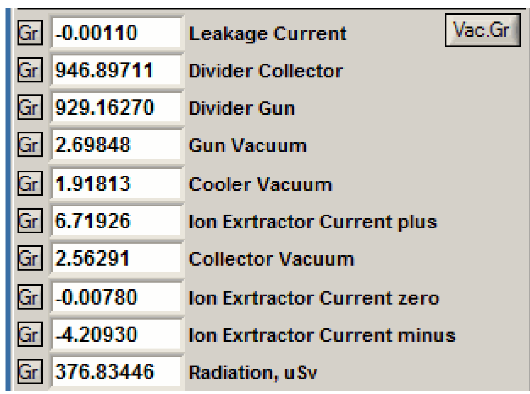
Now in operation in COSY FZJ



$Np=1.5 \cdot 10^8$, Ee=909.5-910-909.5 kV,

Je=400 mA **$\lambda=\delta p/\delta t=3\text{-}7\ 10^{-6}\ s^{-1}$**

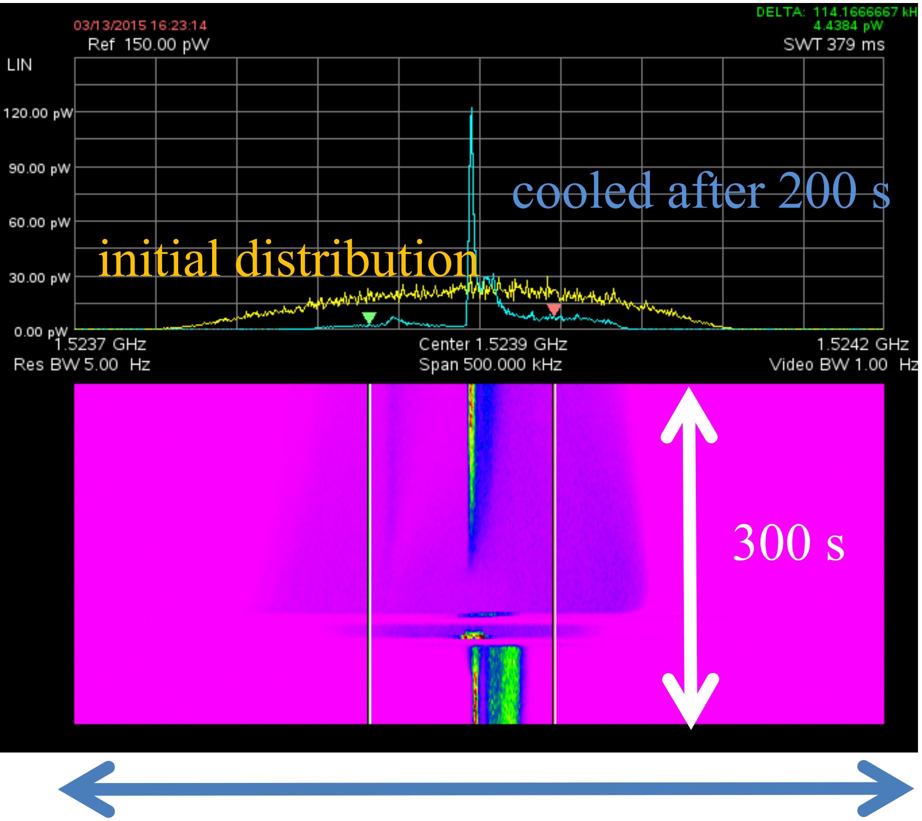




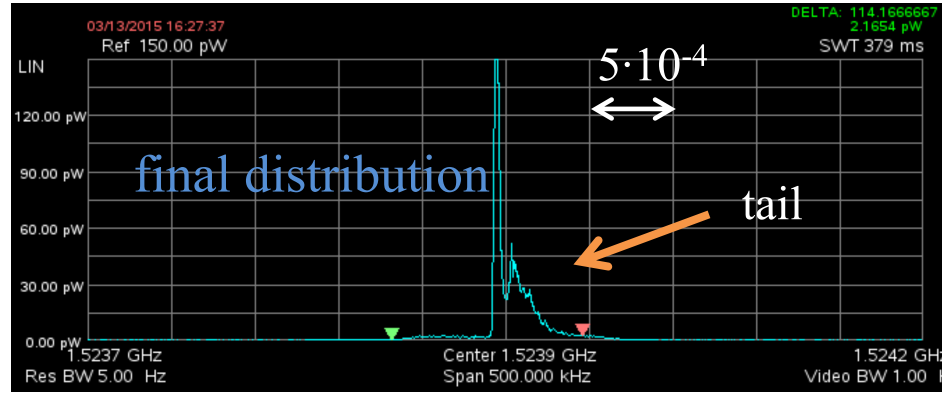
Collector current is up to 900 mA at voltage 0.900 MeV and leakage current less 1 mkA

Now using 0.9 A e-current is positive for cooling process

Example of the longitudinal cooling

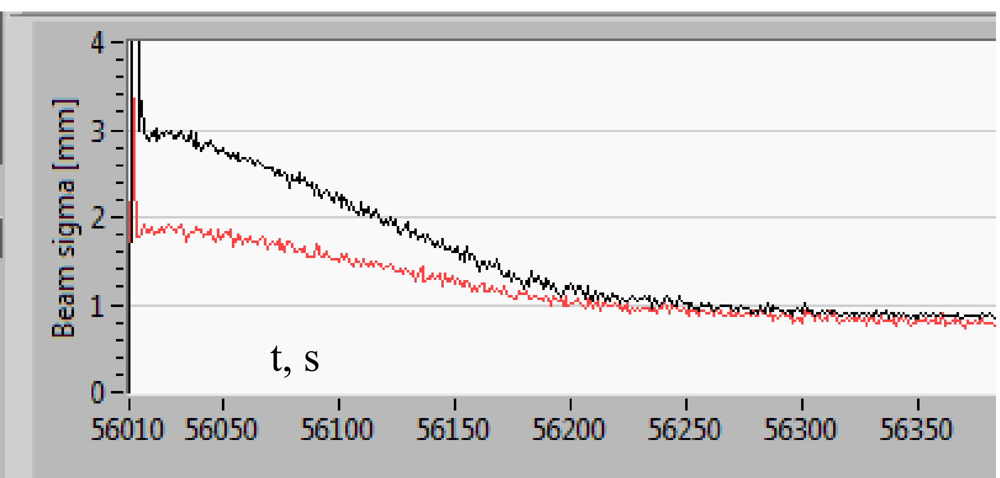


$\Delta p/p = 5.5\ 10^{-3}$



$N_p = 7\cdot10^8$, $J_e = 400$ mA, $\eta = -0.066$,
$E_e = 909$ kV, $\gamma = 2.77$, $\gamma_{tr} = 2.25$, $\gamma > \gamma_{tr}$

Cooling process is fast enough. 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 but a tail formation was observed.



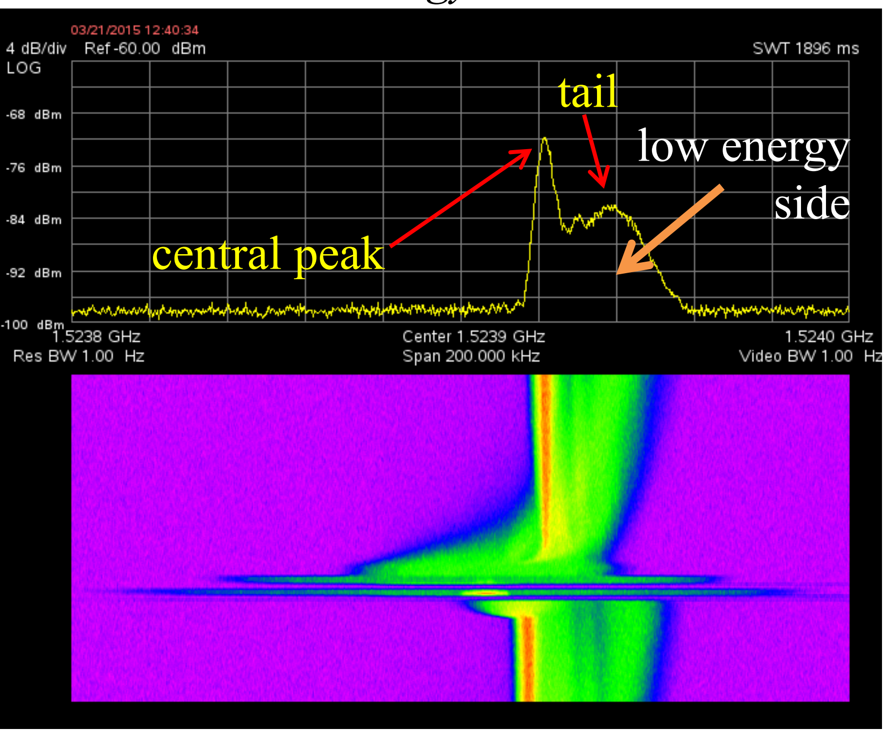
Example of the transverse cooling

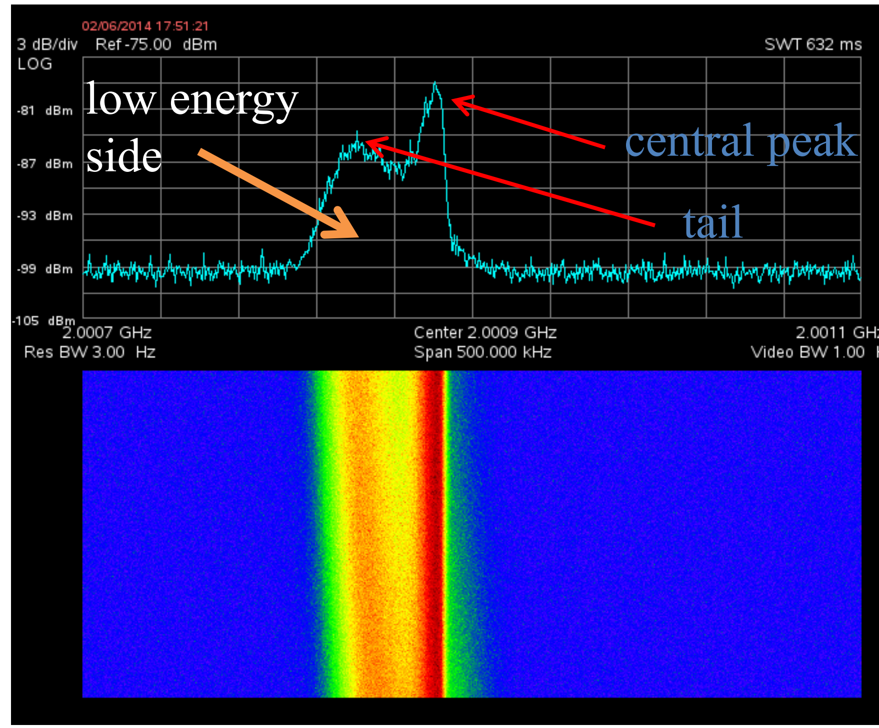
$N_p = 3\cdot10^8$, $J_e = 800$ mA,

The Schottky spectrum shows that the distribution function of the proton beam consists from the central high peak and the tail directed to the low energy area. This tail was observed in the most experiments with cooling of the proton beam so this problem was investigated in more detail. Results of our investigations are described below.

The tail has vector to the side of low energy

above transition energy *below transition energy*





Je=800 mA, γ_{tr}=2.25, $\gamma>\gamma_{tr}$, Np=$2.8\cdot10^8$

η=−0.066

Je=310 mA, γ_{tr}=4.2, $\gamma<\gamma_{tr}$, Np=$5.5\cdot10^8$

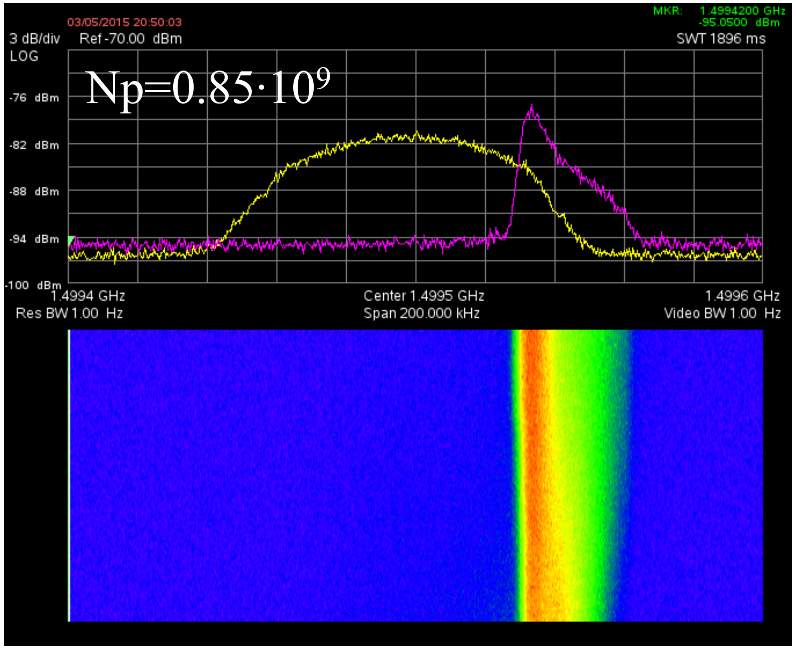
η=+0.073

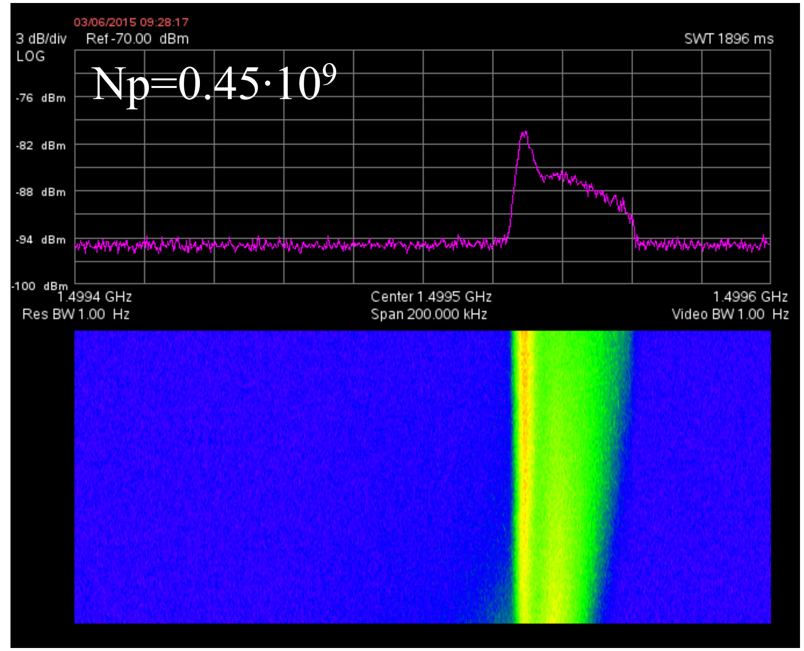
$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2} = \frac{p}{dp}\frac{df}{f}$$ slip-factor

Tail formation doesn't depends from the choice of the working point: below or above of the gamma transition Ee=908 kV

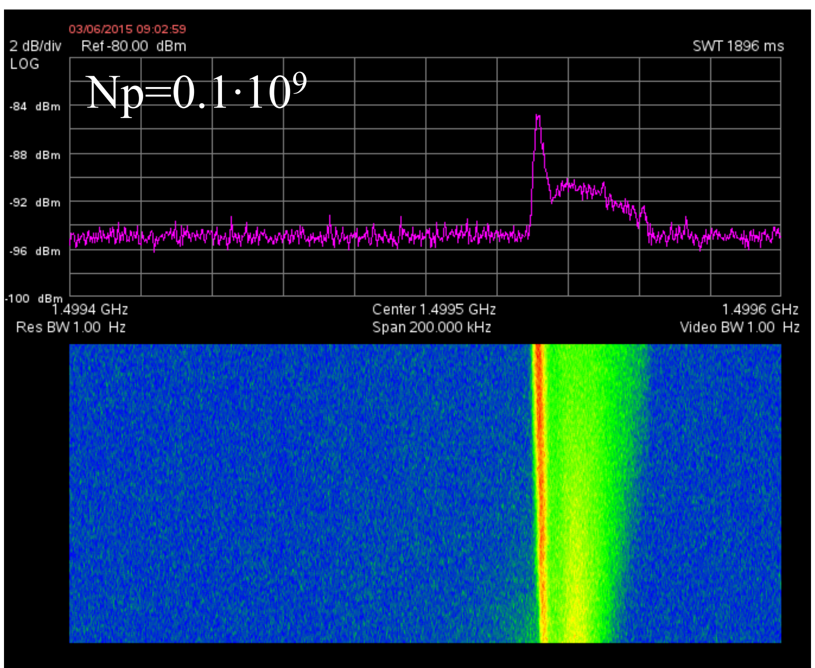
Logarithmic scale

Review of Experimental Observation





Time = 600 s



Je=300 mA, η=-0.066,
Ee=909 kV, γ=2.77, γ_{tr}=2.25, $\gamma>\gamma_{tr}$,
600 s after cooling start

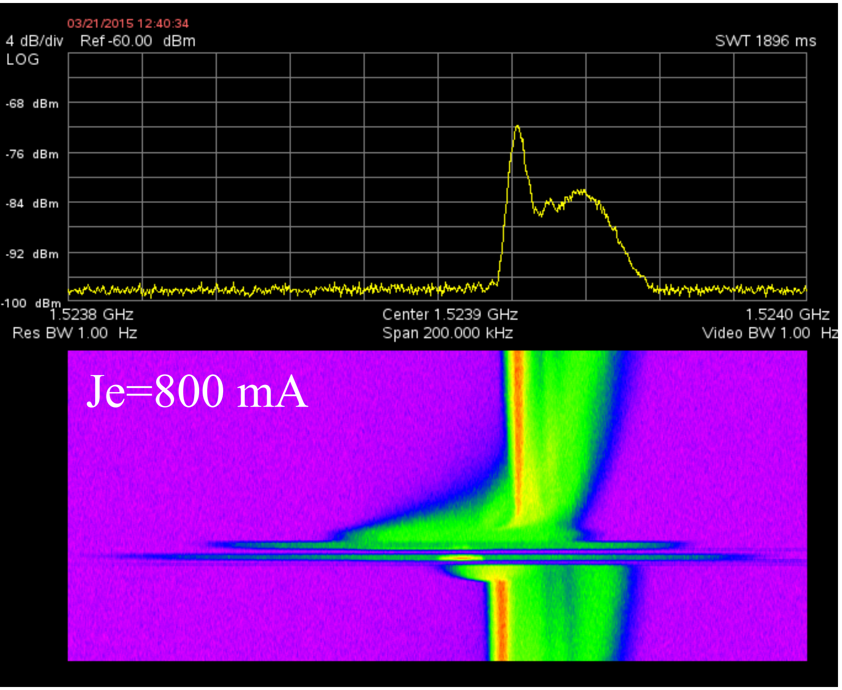
Shape of the distribution function depends from number of the proton !

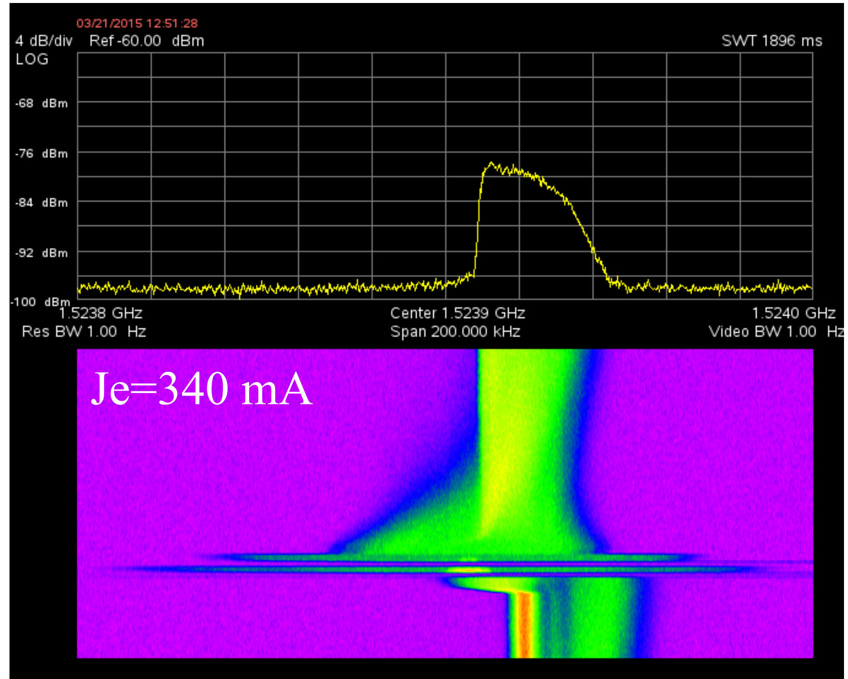
The decrease of the proton number leads to more pointed shape of the distribution function

Logarithmic scale

Review of Experimental Observation

$Np=2.8\cdot10^{8}$





Time = 600 s

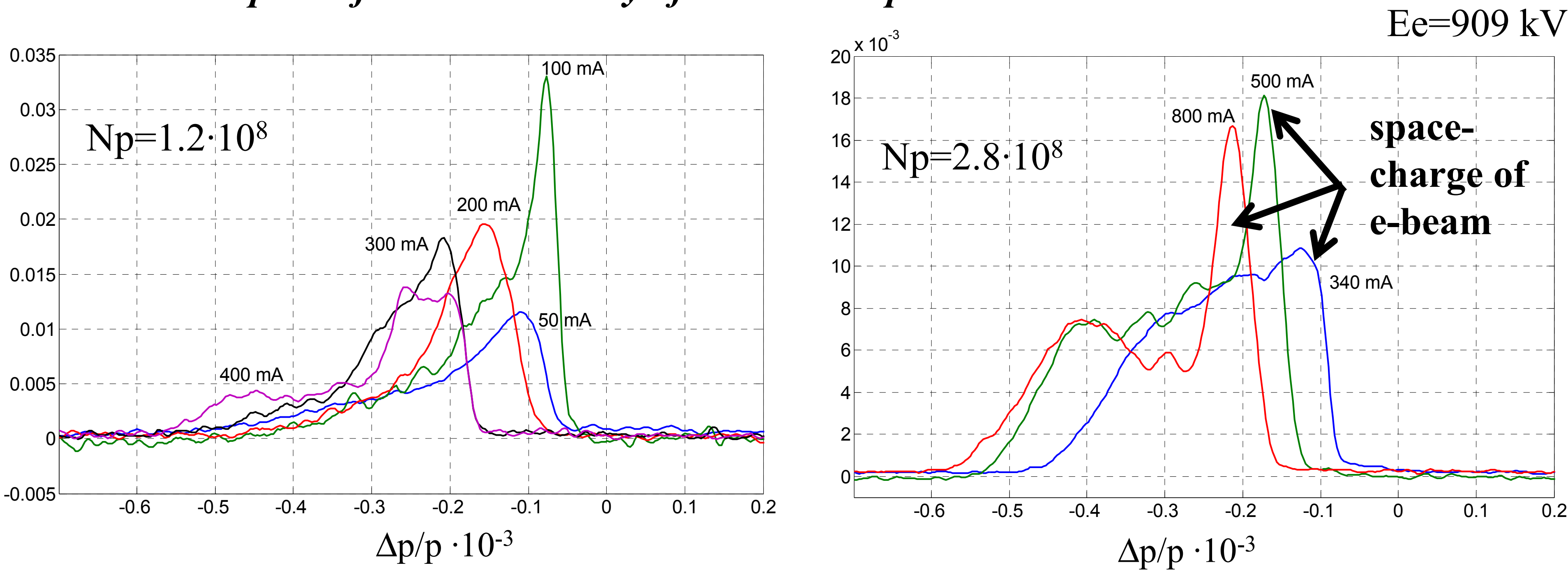
$\Delta p/p = 2.2\ 10^{-3}$

Schottky spectrum of the proton at cooling with electron current 800 mA (left) and 340 mA (right) at energy 909 kV.

Shape of the distribution function depends from the electron current too !

The increase of the electron current leads to more pointed shape of the distribution function

Process depends from the intensity of both beam: proton and electron



Distribution function at the different electron currents and proton number. The time is fixed as 370 s after the injection. The distribution function is normalized to unity (scale is linear). There are transverse cooling also during all experiments.

1. Shift of the peak center induced by the space charge at Je=500 mA, b=5 cm, a=0.3 cm

$$\frac{\Delta p}{p} = \frac{eJ}{\gamma\beta^3 c}\frac{1}{m_e c^2}\left(2\ln\left(\frac{b}{a}\right)+1\right) = 8.5\cdot 10^{-5} \approx 1\cdot 10^{-4}$$

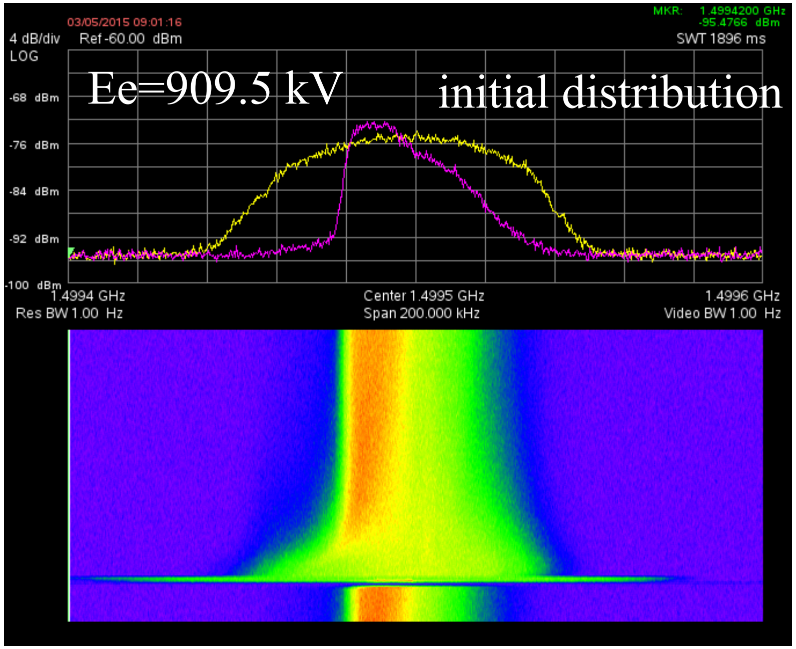
2. Changing equilibrium energy inside the electron beam induced by the potential sagging

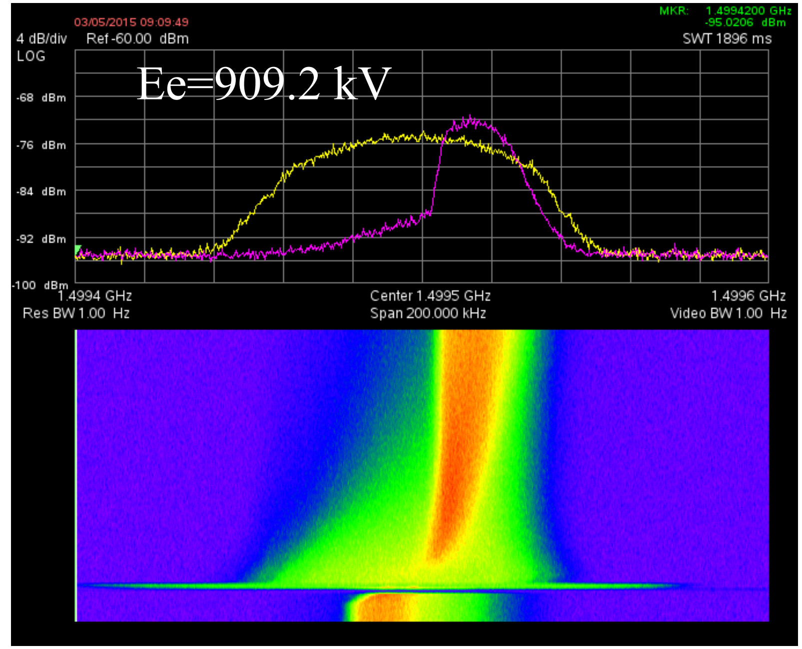
$$\frac{\delta p}{p} = \frac{eJ}{\gamma\beta^3 c}\frac{1}{m_e c^2} = 1.3\cdot 10^{-5}$$

One can see the shift of the peak center induced by the space charge. But more there is a tail directed to the low energy. The shift can be described by the space charge, **but the tail itself can't be described with simple theory.**

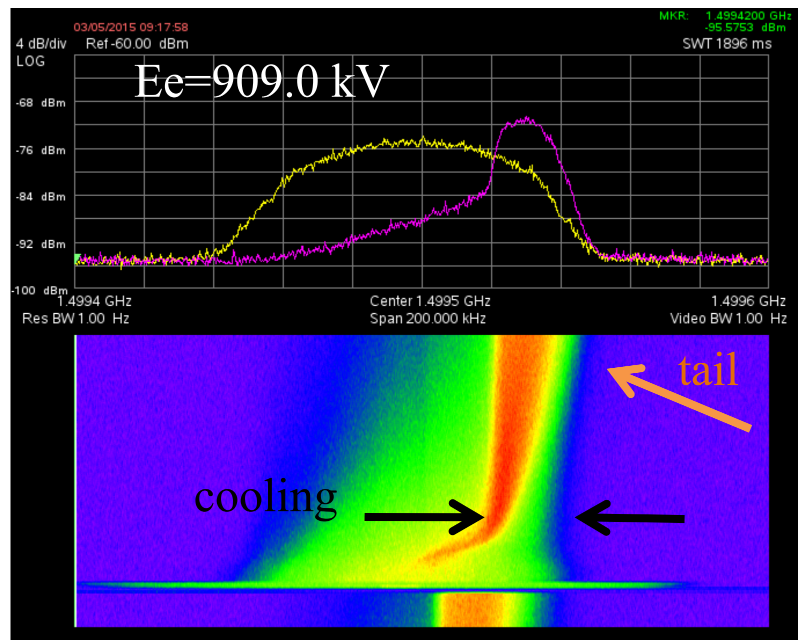
Cooling to the different equilibrium energies

Review of Experimental Observation





Time = 500 s



Np=1·10[9], Je=300 mA, η=-0.066, γ_{tr}=2.25, $\gamma>\gamma_{tr}$

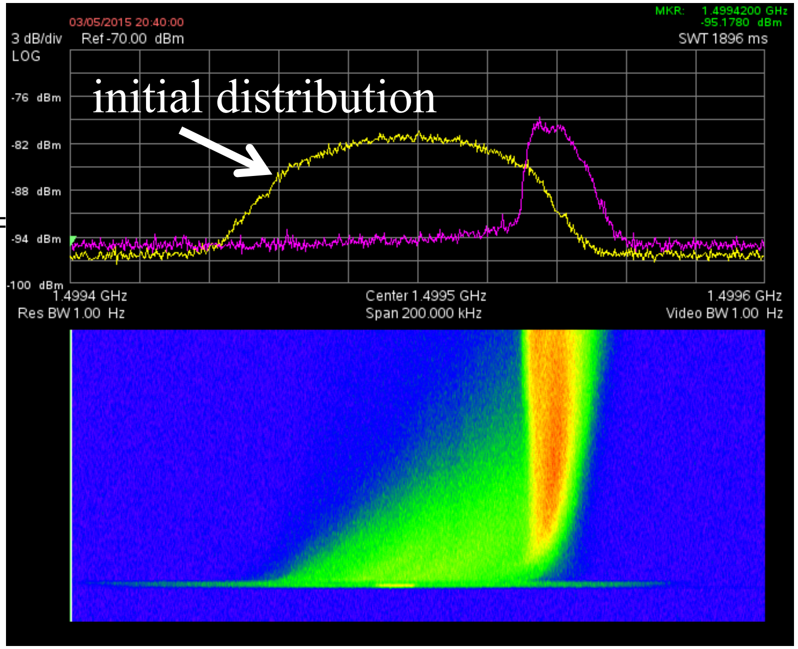
The behaviour of the longitudinal cooling doesn't depend from the energy of the electron beam. The protons are cooled to the equilibrium energy but the tail is formed to the side of the low energy. The more particle absorbed in the main peak of the distribution function, the more tail is formed.

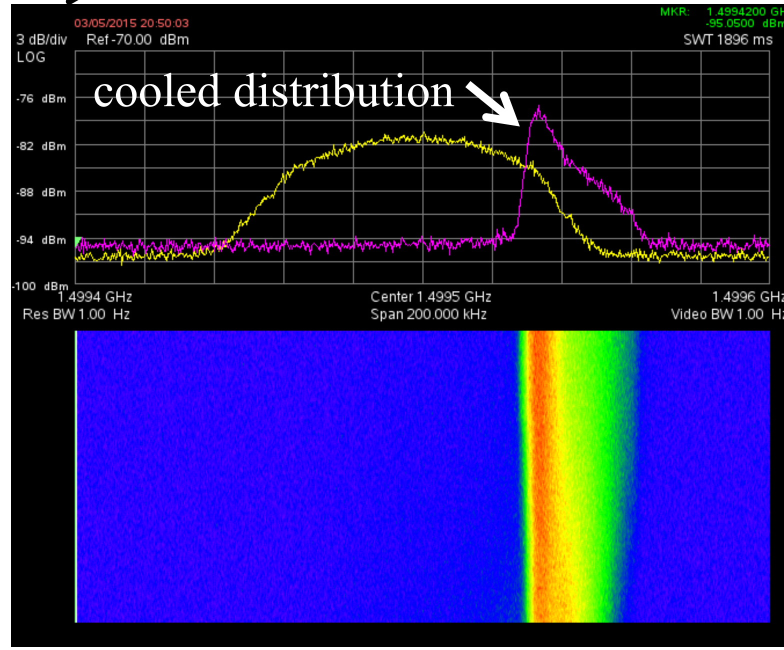
Review of Experimental Observation

Long cycle

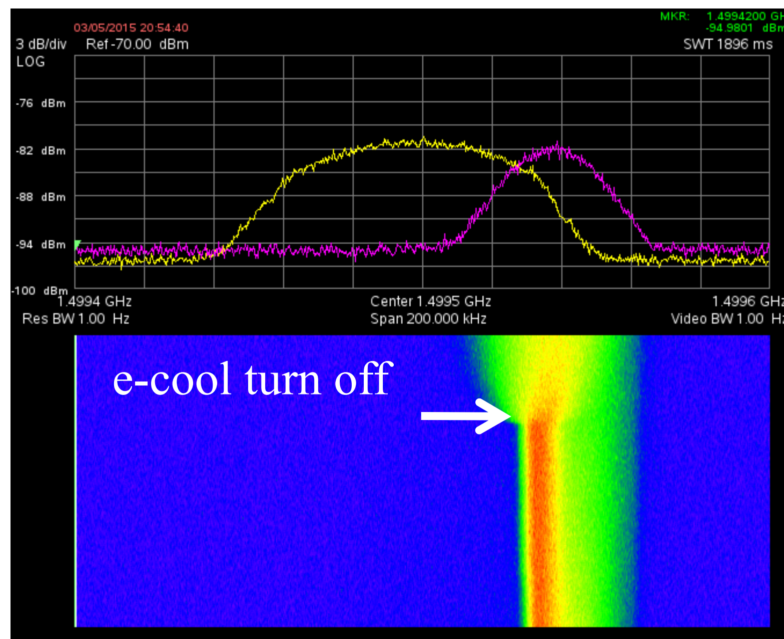
600 s

Time = 500 s





300 s



$N_p=0.85\cdot10^9$, $J_e=300$ mA, $\eta=-0.066$,
$E_e=909$ kV, $\gamma=2.77$, $\gamma_{tr}=2.25$, $\gamma>\gamma_{tr}$

After long time the main peak and tail is formed even the e-cool energy has large shift relative to energy of the proton beam.

After switching off e-cool the distribution function becomes symmetrical and more wide. So, the electron cooling forms asymmetrical shape of the distribution function.

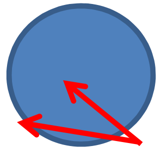
Logarithmic scale

Possible reason for the tail formation in the distribution function of the proton

1. Changing equilibrium energy inside the electron beam induced by the potential sagging

$$\frac{\delta p}{p} = \frac{eJ_e}{\gamma\beta^3 c}\frac{1}{m_e c^2} = 1.3\cdot 10^{-5}$$

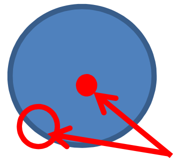
at J_e=500 mA



2. Because of the optic mismatching the electrons may have the different Larmour radius on the different distance from beam axis. It leads to changing longitudinal momentum for the different radiuses inside electron beam

$$\frac{\Delta p_{\parallel}}{p} = \frac{1}{2}\left(\frac{eB}{\gamma\beta mc^2}\right)^2 R_L^2 = 1.2\cdot 10^{-5}$$

at R_L=100 um, B=1500 G



3. The role of the vacuum can be estimated as :
Moreover the direct experiment with the degradation of the vacuum condition in COSY to a few times doesn't show the visible effect in the picture of the cooling process.

$$\frac{\delta p}{p} f_0 = \frac{4\pi n_a r_e^2 c}{\gamma\beta^3}\frac{m_e}{m_p} L_C = 2\cdot 10^{-8} c^{-1}$$

at $p=5\cdot 10^{-9}$mbar

New idea about tail formation welcome!

Coherent instability hypothesis

The behavior of the cooled and no cooled proton beam may be significantly different . The electron cooling can reveal the problems that were hidden by high momentum spread of the proton beam. As it is known the “Landau damping” suppressed many natural coherent instability like negative mass instability or instability at interaction with resonance mode. Decreasing the momentum spread of the proton beam to the range 10^{-4} suppressed the Landau damping. So, the interaction with surrounding electrodes the quality of such beams can be limited by coherent instabilities. Further we evaluate the behavior of the distribution function due to instability of coherent oscillations. The direct simulation of the set of the particle was taken as model.

Description of Model

Algorithm:

1. Initial particle set ($\Delta p_m/p$, ϕ_m) has gauss distribution f in momentum space and uniform as phase function (in longitudinal direction). During process with space-charge phenomena the beam becomes modulating along orbit that can be described azimuthally harmonics

2.

$$\rho_q = \sum_{n=1}^{N} f_n(\Delta p/p) \cdot \exp\left(i \frac{2\pi (q-1)(n-1)}{N_c} \right) \qquad 1 \le q \le N_c$$

$$f_n = histogram(\phi_m, N_c = 64)$$

$$\sum_n f_n = 1$$

3. The action of space-charge is calculated with impedance model.

4. Equation of motion is calculated for each particle in set ($\Delta p_m/p$, ϕ_m). The total number of particle about 300 000.

Description of Model

"Collective" electrical field of the particle calculate as phenomenological "impedance" model

$$U_q = -I_0 Z_q \rho_q \qquad I_0 = eNf_0$$

U_q – amplitude of "q" – harmonic of RF – voltage induced by the coherent effects

Z_q – impedance of "q" – harmonic

ρ_q – ratio of particle that "q" – harmonic contains.

I_0 – the total current of the proton beam

f_0 – revolution frequency

N – number of particle

$$Z_q = R \cdot \frac{1 + iQ_{res}\left(\frac{q_{res}}{q} - \frac{q}{q_{res}}\right)}{1 + Q_{res}^2\left(\frac{q_{res}}{q} - \frac{q}{q_{res}}\right)^2} \qquad R = \left|Z_0\right| \cdot q_{res} \cdot Q_{res}$$

simple resonator type impedance model; at $q \to 0$ the Z_q converges to impedance of smooth vacuum type; at high q the impedance $Z_q \to 0$ without assistance

Equation of proton dynamics is divided for different steps

$$\delta\varphi_{n+1/2} = \delta\varphi_n + \pi \cdot N \cdot \eta \cdot \delta p_n$$ – semi-step of longitudinal moving

$$\delta p_{n+1/2} = \delta p_n + N \frac{eU_n\left[\delta\varphi_{n+1/2}\right]}{\gamma\beta^2 m_p c^2}$$ – step of the influence of the collective field

$$\delta p_{n+1} = \delta p_0 + \left(\delta p_{n+1/2} - \delta p_0\right) \cdot \exp\left[-N \frac{A_{cool}}{\left(\left(\delta p_{n+1/2} - \delta p_0\right)^2 + \gamma^2\theta_{eff}^2\right)^{3/2}}\right]$$ – cooling step

$$\delta\varphi_{n+1} = \delta\varphi_{n+1/2} + \pi \cdot N \cdot \eta \cdot \delta p_{n+1}$$ – semi-step of longitudinal moving again

$$A_{cool} = \frac{4 r_e r_p L_{cool}}{\gamma^2 \beta^2 c \pi a_e^2} L_N \left(\frac{J_e}{e}\right)$$ – constant of electron cooling

J_e – electron current; θ_{eff} – effective angle of distortion of magnetic force line;

a_e – electron beam radius; L_N – Coulomb logarithm; δp_0 – momentum of electron beam;

L_{cool} – length of the cooling section; N – number of proton turns in one macro-step;

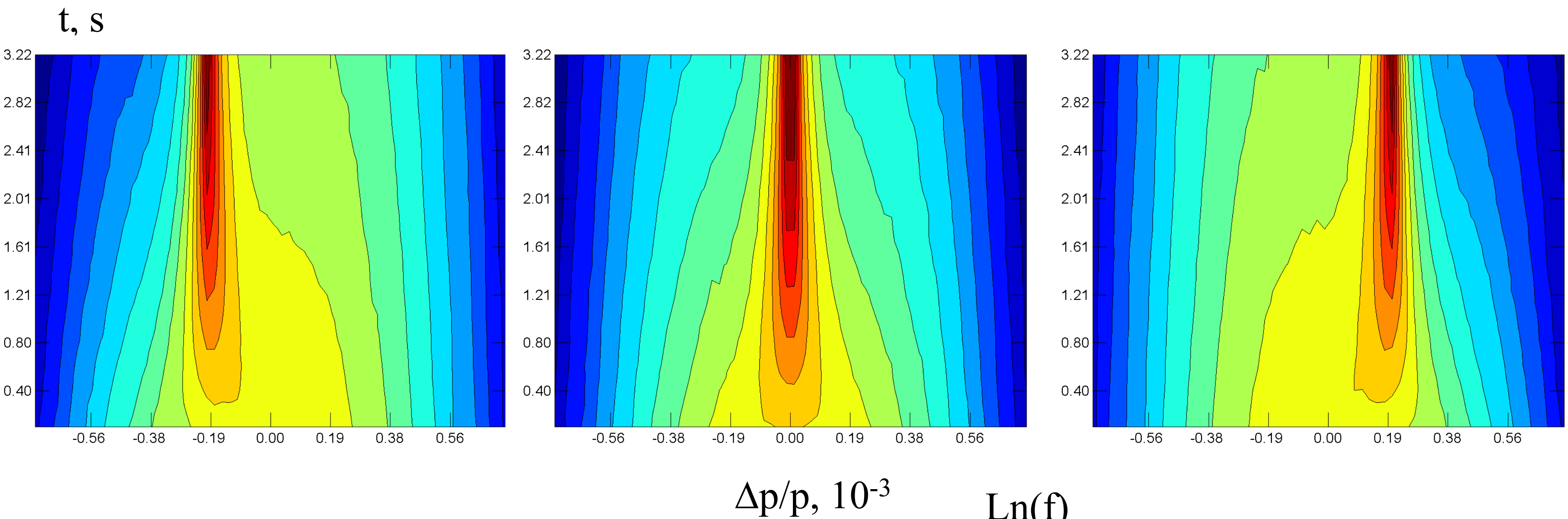
$$\eta = \left(p/\omega_s\right)\left(d\omega/dp\right) = \left(1/\gamma^2 - 1/\gamma_{tr}^2\right)$$ – dispersion of revolution frequency;

Remark about simulation

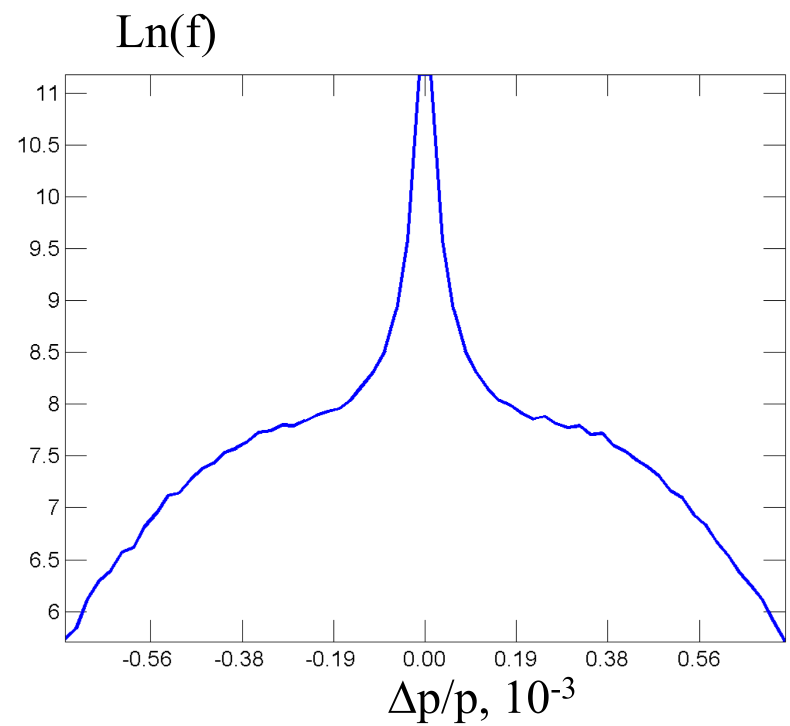
During each macro-step the coherent field was calculated with Fourier transformation of the density distribution of the particle. The distribution density along azimuthally angle was estimated with 64 space cells. As result the momentum and azimuthally position of the macro-particle was calculated taken into account e-cool force and impedance inducing field. This model may be expanded to the estimation of the external RF field (sin-like or barrier-bucket types).

The complexity of the algorithm makes simulations of longer time intervals difficult. Because the instability rate was artificially increased in order to analyze the qualitative factors. The process of the initial cooling also is eliminated from simulation. The result of simulation of another computer code is used as initial parameters of the particles.

Precooling process

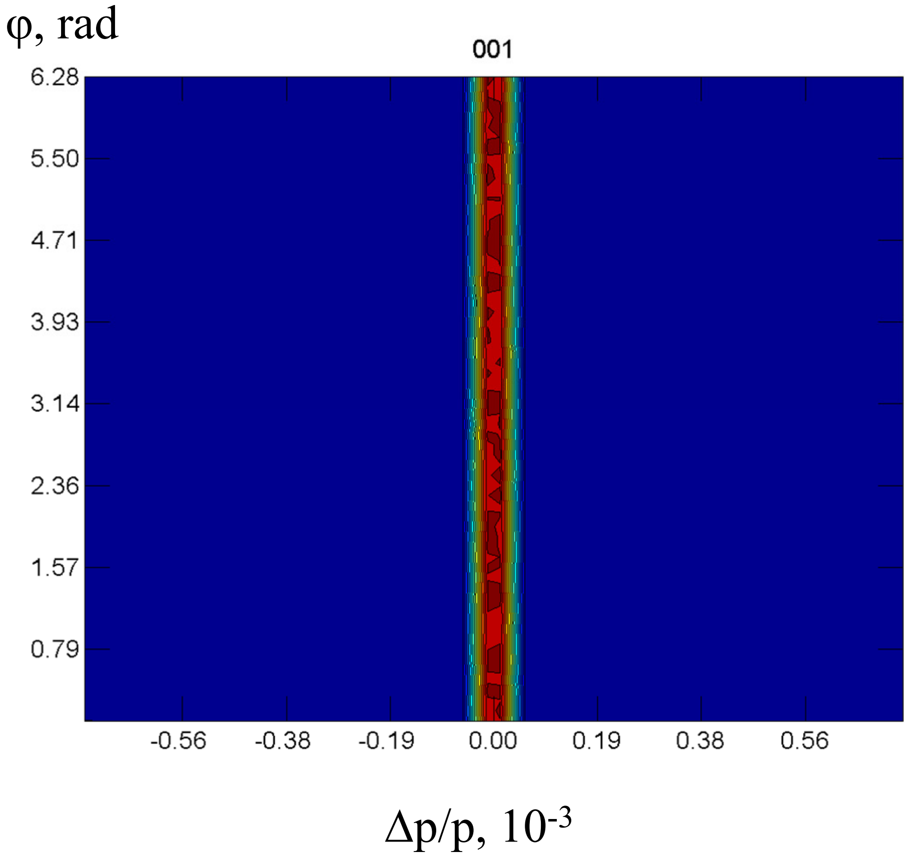


for optimization of the calculation procedure:
the first the precooling procedure was done without collective effects;
The second the collective effects is started instantly

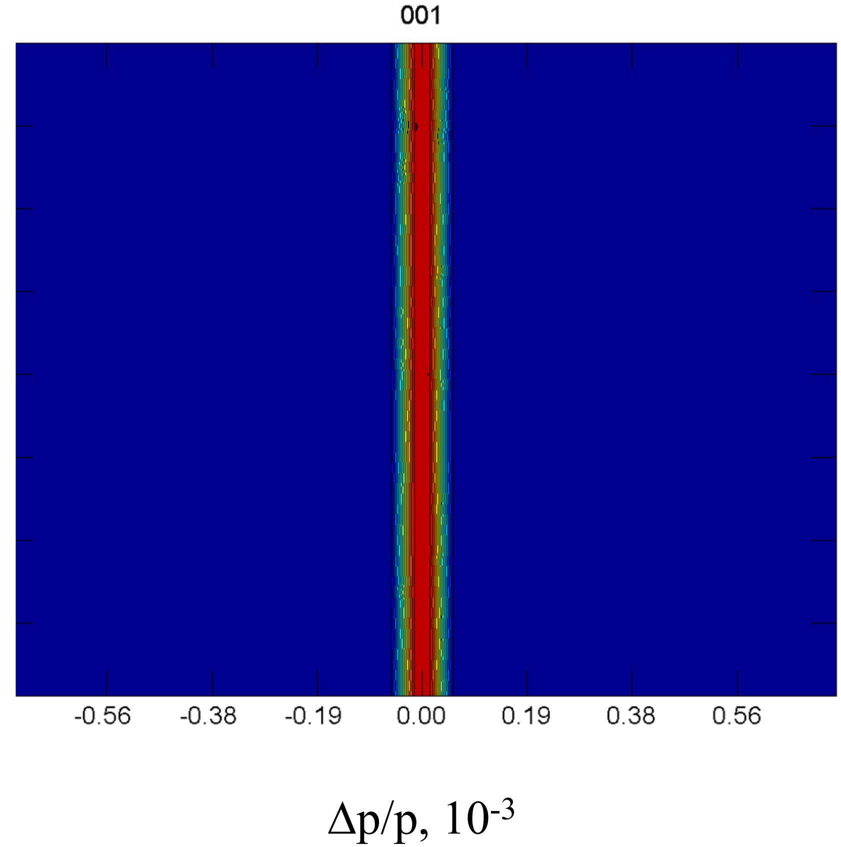


Distribution of particle (f) in the end of pre-cooling process

Coherent instability hypothesis



$$Q_{res} = 10, \quad q_{res} = 7, \quad \eta = -0.05$$



$$Q_{res} = 10, \quad q_{res} = 7, \quad \eta = -0.2$$

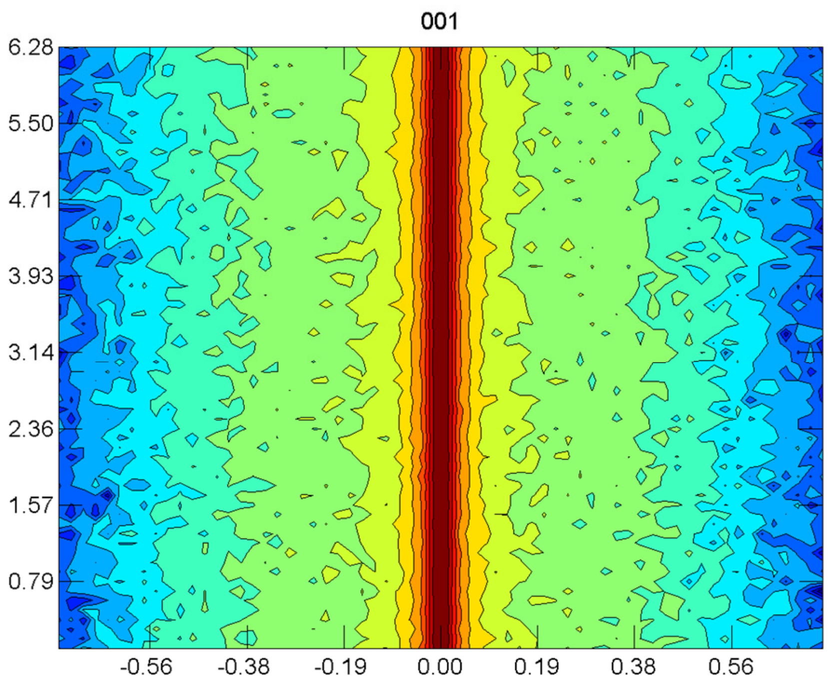
Histogram of number particle in space phase–momentum for different value of quality factor Q_{res} and resonance harmonic q_{res}, contour lines is specified by *Ln* values of particle in cells

the increase of the slip-factor improves the situation because of Landau damping

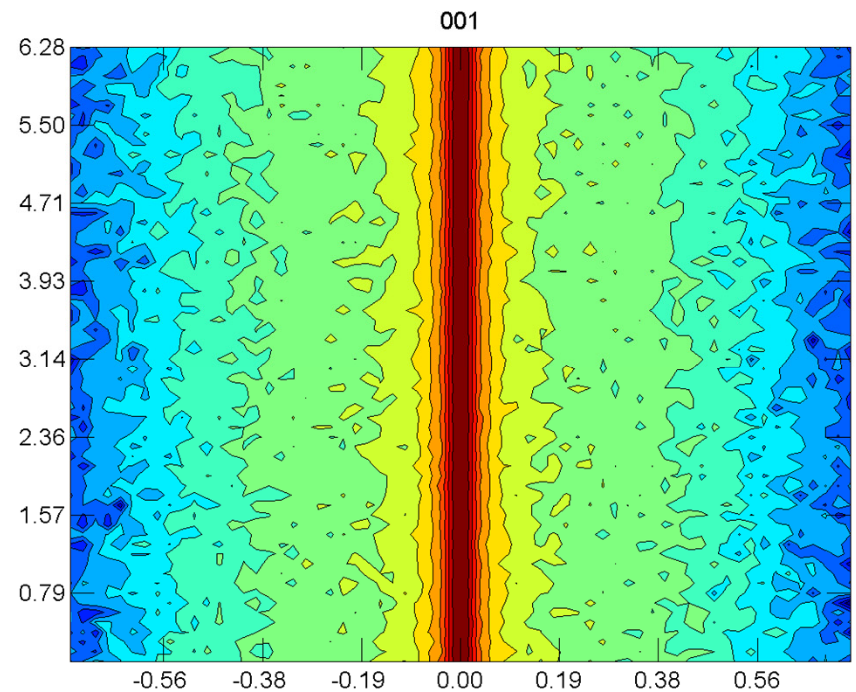
Demonstration of the coherent instability without e-cooling

Interaction with impedance of resonator mode, high mode

φ, rad



Δp/p, 10^{-3} $Q_{res} = 27, \quad q_{res} = 19$



Δp/p, 10^{-3} $Q_{res} = 17, \quad q_{res} = 19$

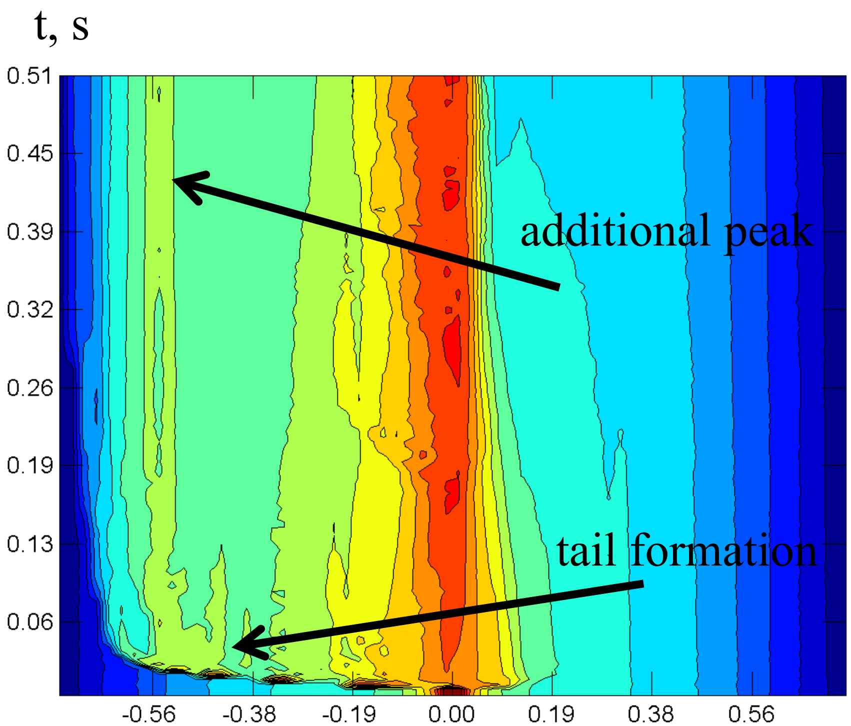
Histogram of number particle in space phase—momentum for different value of quality factor Q_{res} and resonance harmonic q_{res}, contour lines is specified values of particle in cells Ln(f)

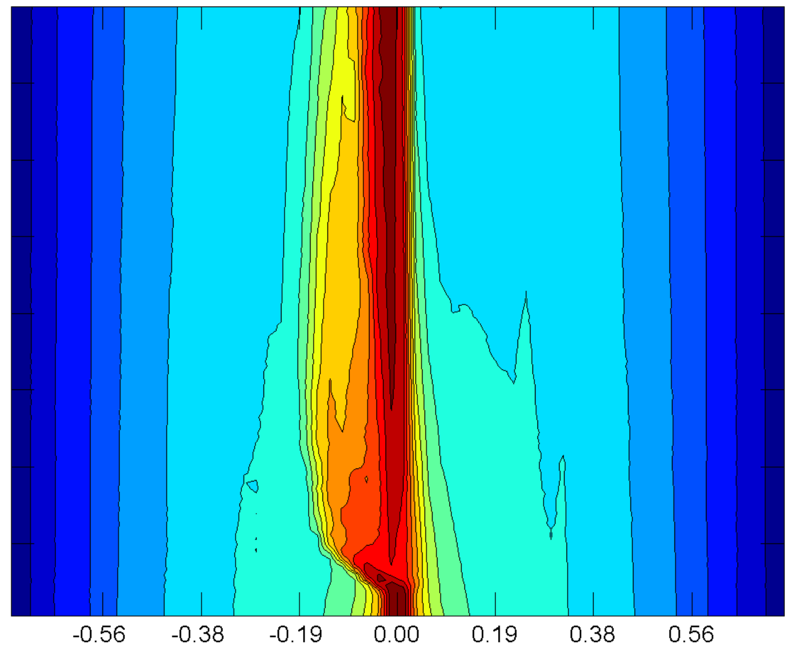
$Np=1.2\cdot10^{10}$, Π=180 m, a=0.5 cm, b=5 cm, η=-0.05,
Je=0.5 A, E_e=908 keV, a_e=0.5 cm, L_{nc}=5.0, L_{cool}=250 cm, $\theta_{eff}=3\cdot10^{-5}$
N=20, Q=2 – harmonic multiplier, $N_{particle}$=300 000, $N_{macro\text{-}step}$=100 000,
phase-space mesh Nc= 64 cell

duration 0.86 s

Demonstration of the coherent instability with e-cooling

Coherent instability hypothesis





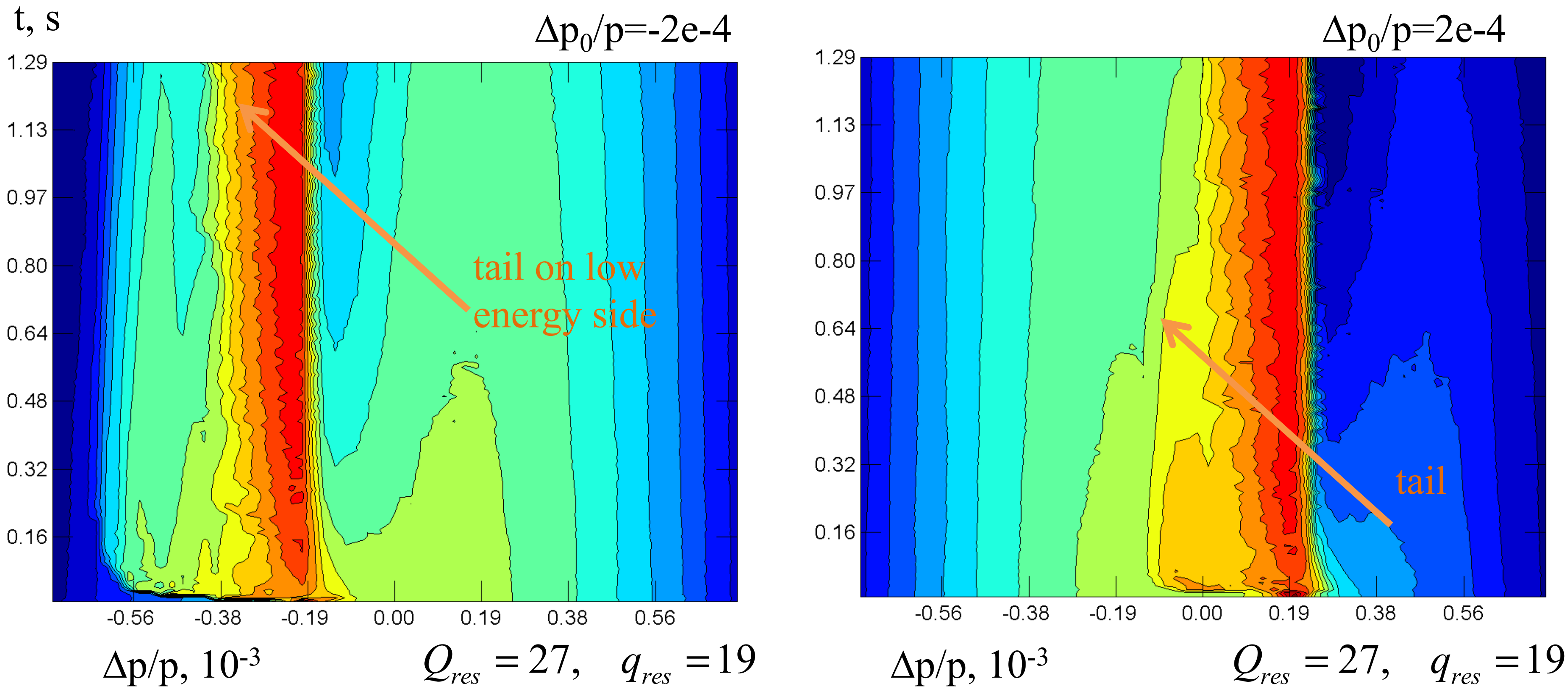
Δp/p, 10^{-3} $Q_{res} = 27, \quad q_{res} = 19, \quad \eta = -0.05$ $Q_{res} = 2, \quad q_{res} = 19, \quad \eta = -0.05$

Ln Spectrogram of the momentum spread versus time

The initial cooled beam acquires very fast the tail of the particle. After that the tail is stable and is located from low energy side. The particle having positive momentum shift continues cooling to the equilibrium energy. The distribution function may have an additional peak located on some distance from the equilibrium energy about. **This behavior is similar to the experimental facts shown before.**

Certainly the interaction with resonator's mode with low quality factor doesn't lead to the essential asymmetrical shape of the distribution function.

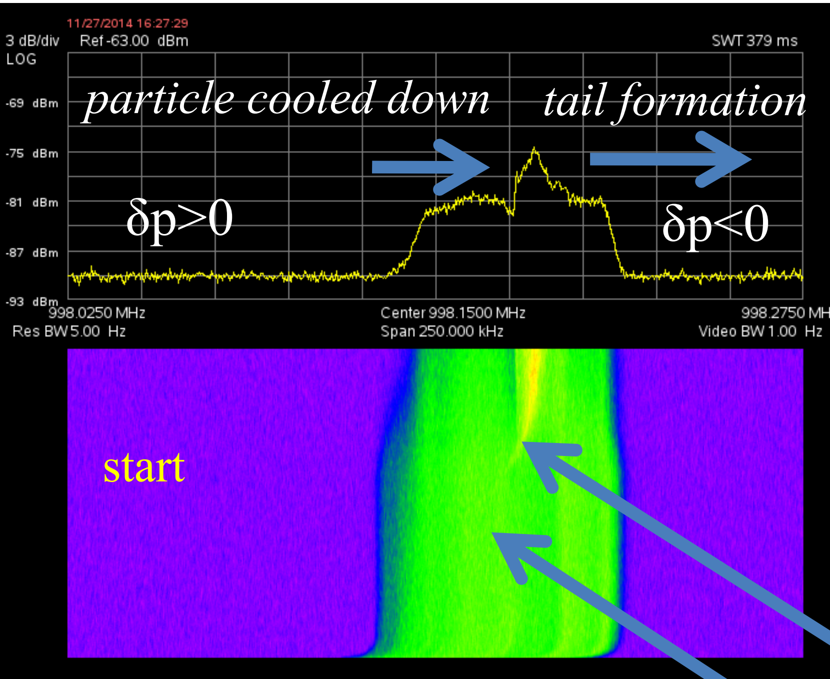
Coherent instability hypothesis



Ln Spectrogram of the momentum spread versus time

Evolution of the distribution function can depend from the initial condition. The left picture corresponds to the precooling state with $\Delta p_0/p$=2e-4, the right picture is $\Delta p_0/p$=2e-4.

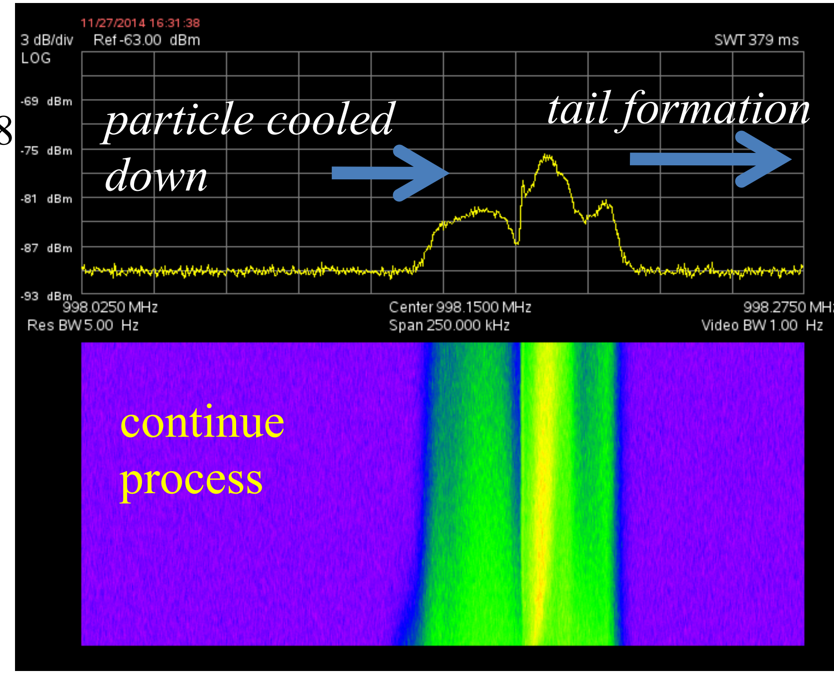
Experimental data from COSY, Ee=908 kV, Je=400 mA, Np=$1.5 \cdot 10^9$



experiment

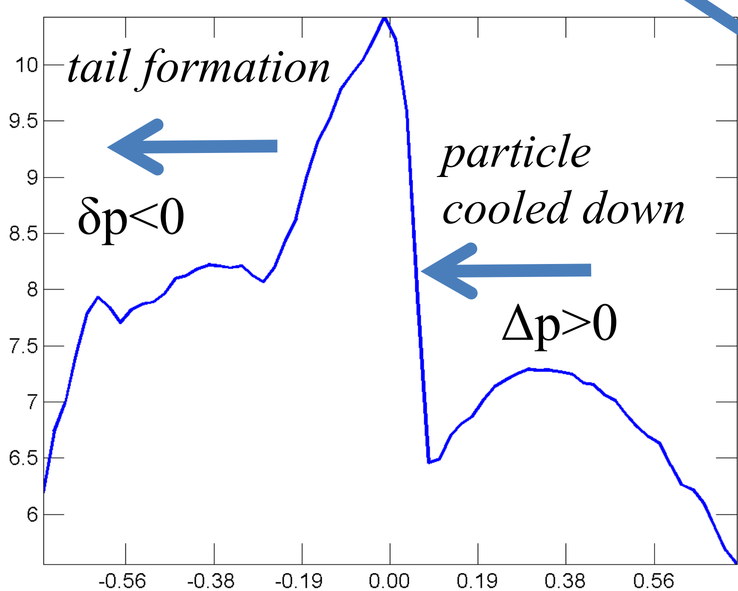
$\gamma > \gamma_{tr}$ $\eta = -0.048$

because of **$\gamma > \gamma_{tr}$ the experiment and simulation pictures are reflected**

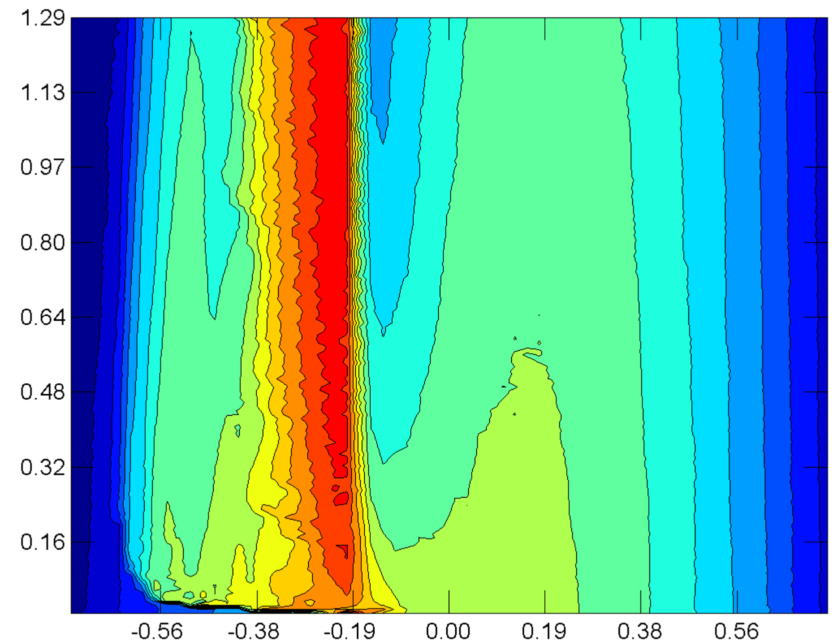


cool start

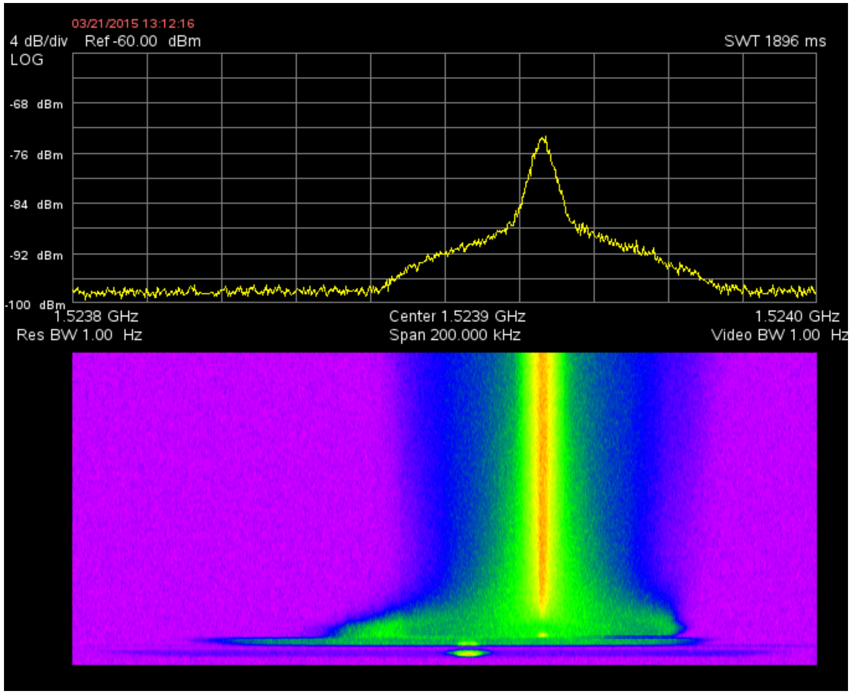
no cool

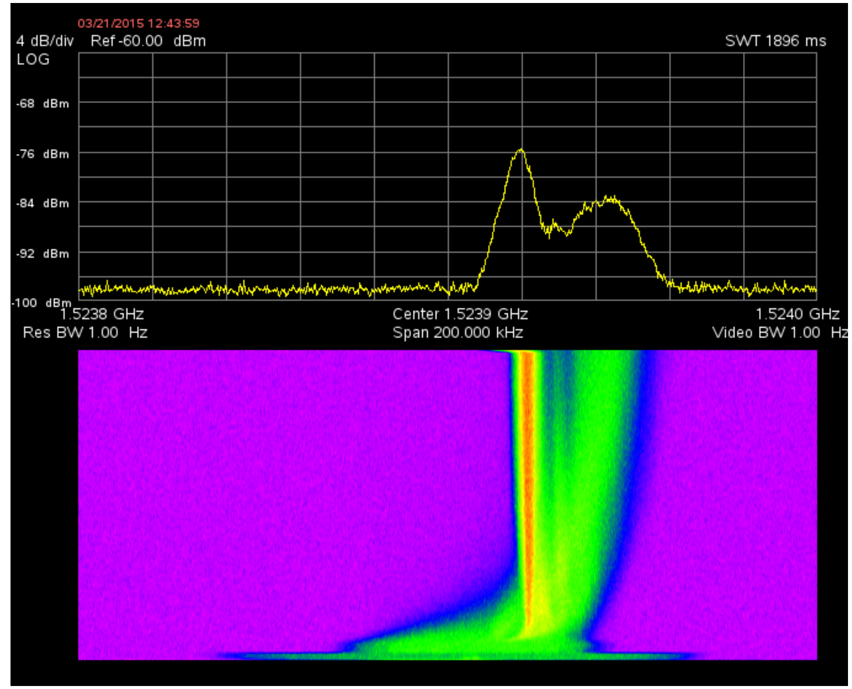


simulation



RF potential well makes the distribution is symmetrical

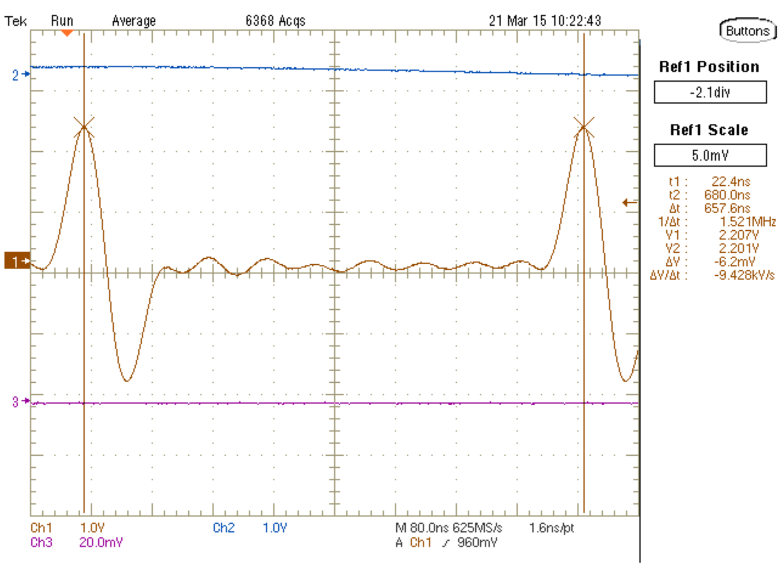




250 s

e-cool + barrier bucket RF

e-cool only



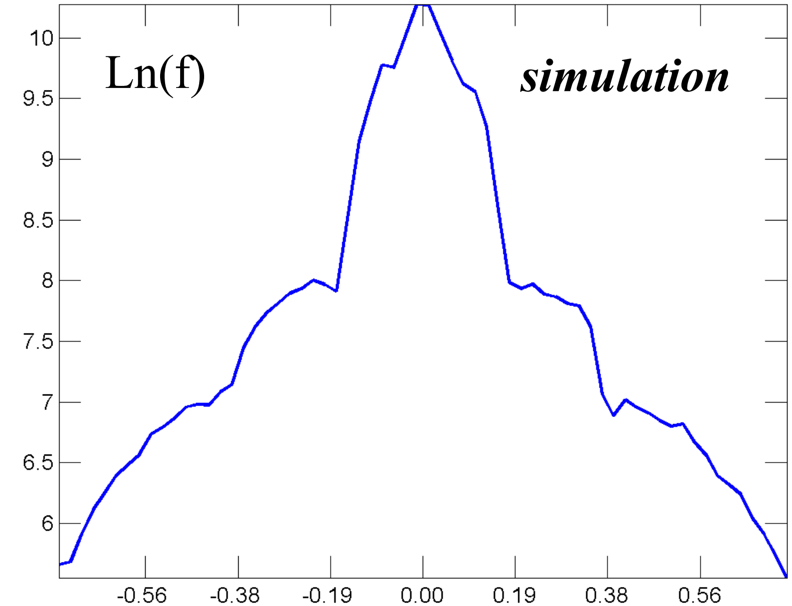
longitudinal cooling at barrier bucket RF voltage

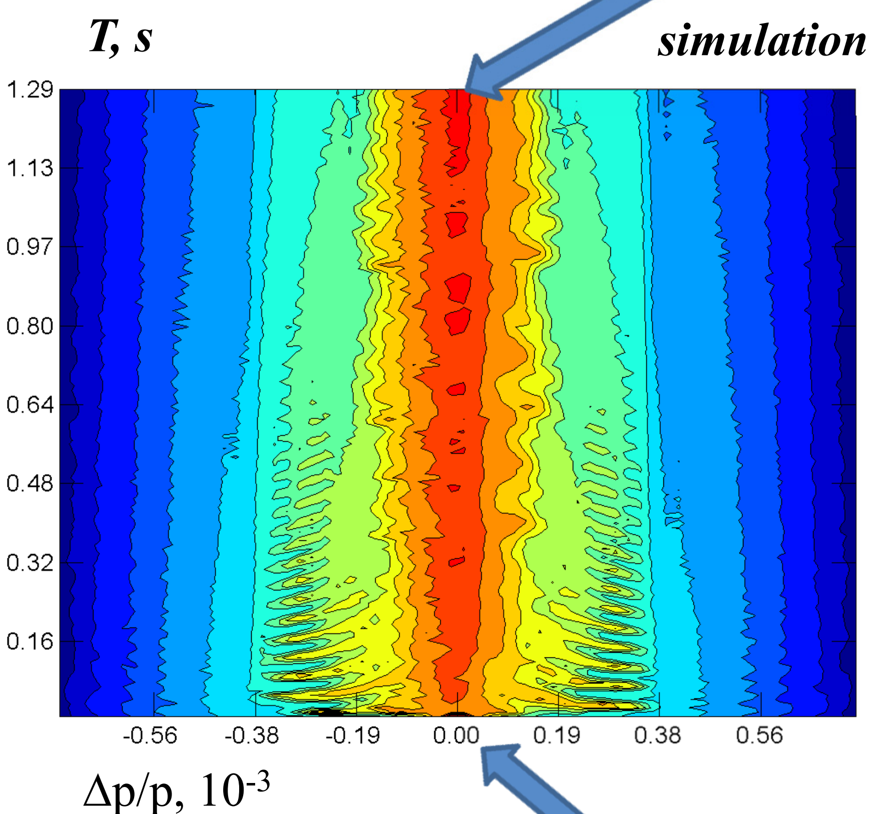
f_{BB}=1.523918 MHz, U_{RF}=240 V

$N_p=3\cdot10^8$, Je=810 mA, $\gamma>\gamma_{tr}$ $\eta=-0.066$,

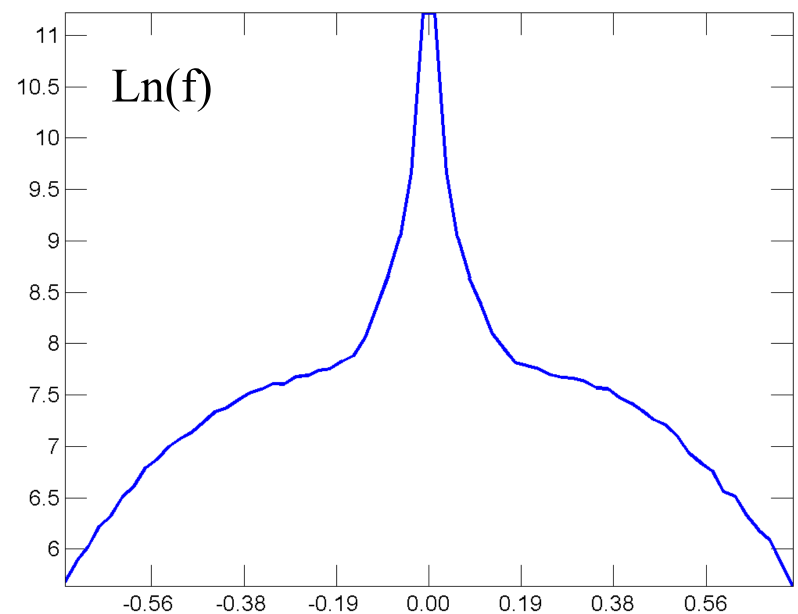
The barrier bucket RF action can be described in the following way. The loss energy particle acquires energy from RF voltage. So, a mixing process in the phase space occurs here. Thus the distribution function becomes symmetrically shape

The final shape of the distribution function. The action of the instability was blurred by the barrier bucket potential.

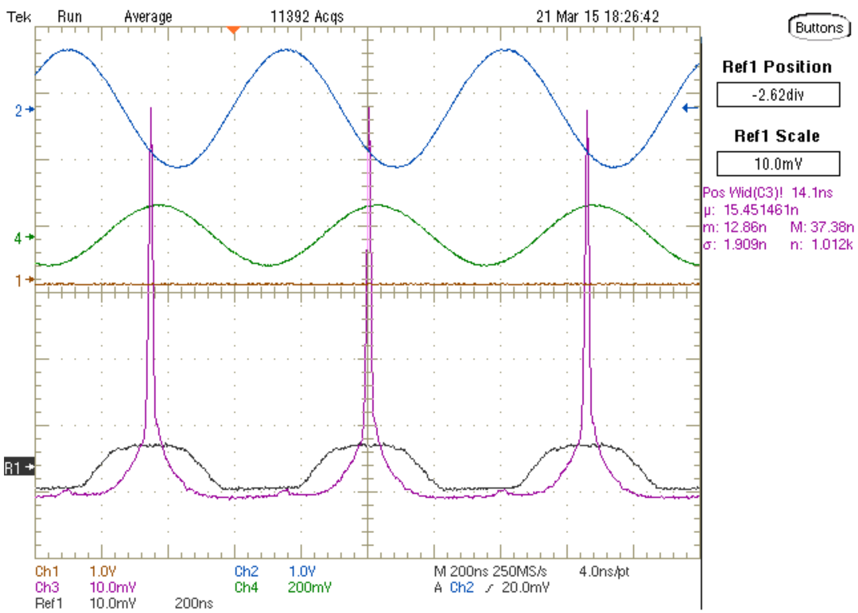




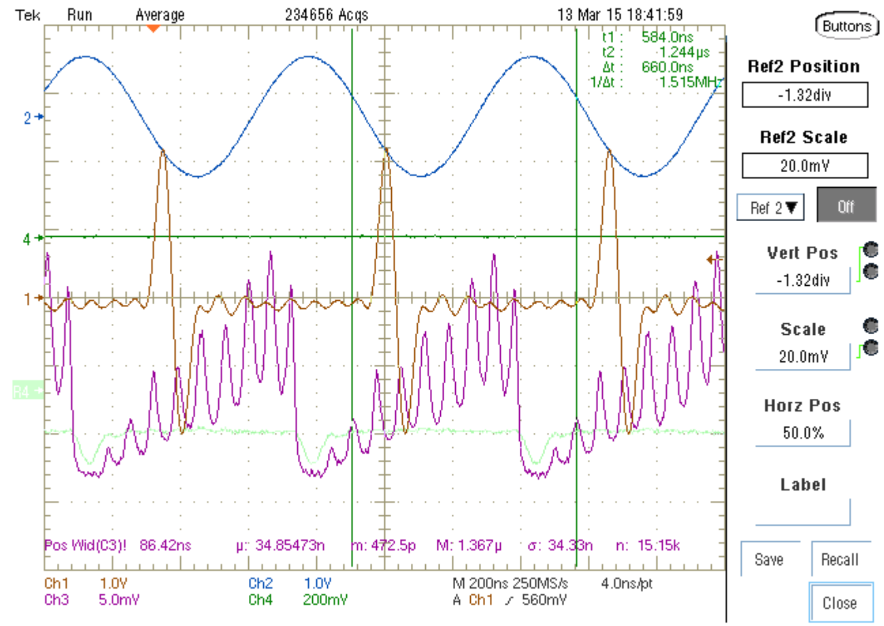
Simulation of barrier bucket. In spite of the instability action the shape is symmetrical.



Precool state. The distribution function was initially cooled after that the space charge was turned on.



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



Barrier bucket signal and Phase probe signal of p-beam

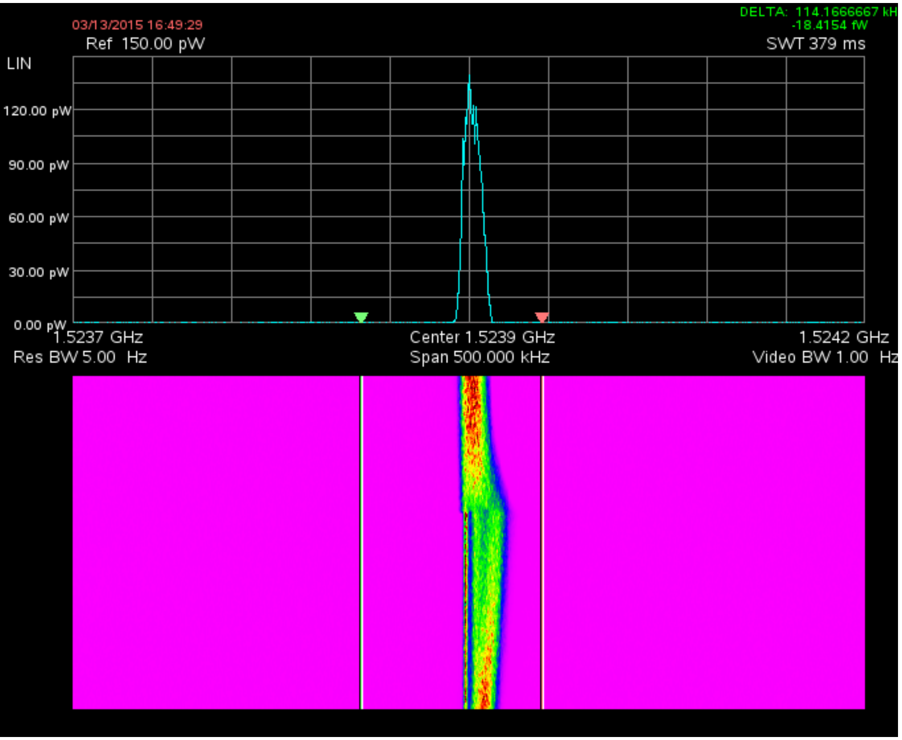
One can see that the combine action of the RF and e-cool produces very short beam with high quality. The off-duty factor of the proton beam is 650 ns/30 ns=20. So, the bunched e-cool of the bunched ion may have the gain of the electron current 20 without increasing average current.

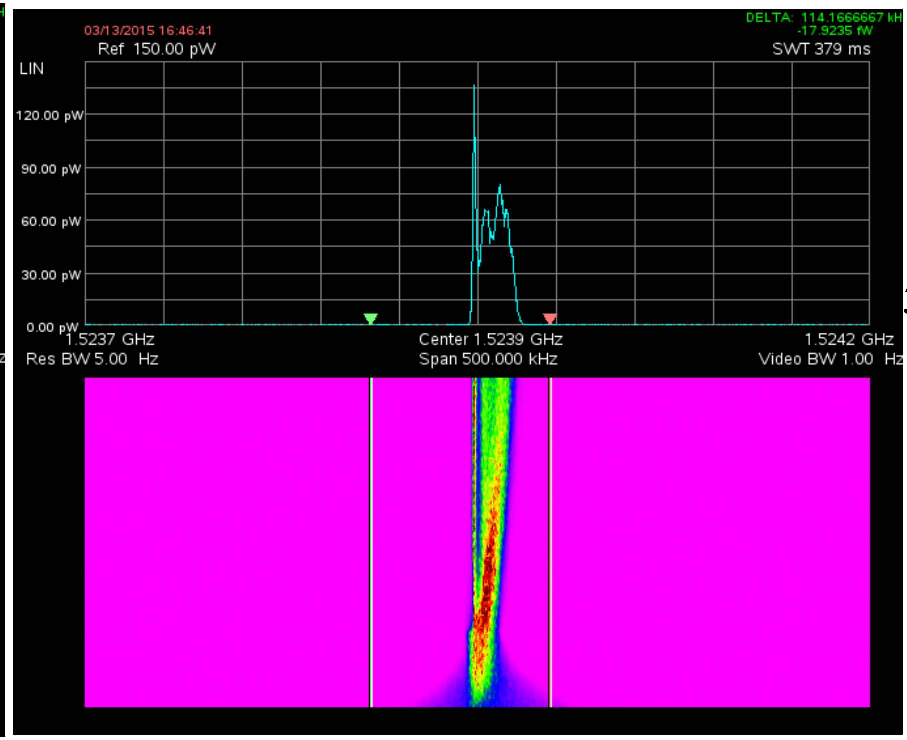
So, the use of the e-bunch beam with larger current and victory under negative collective effects can increase cooling rate in 20 times !

Stochastic cooling makes the distribution is symmetrical also

COSY, Ee=908 kV

Linear scale





500 s

e-cool + stochastic cooling, symmetrical shape of the distribution function

e-cool only, very narrow central peak with a tail of the distribution function

J_e=400 mA, $N_p=7\cdot 10^8$ $\gamma>\gamma_{tr}$ $\eta=-0.066$

The stochastic cooling may be considered as broadband feedback system, so this system can suppress the fluctuation of the space charge.

Summary

The electron cooling can reveal the problems that were hidden by high momentum spread of the proton beam. The collective effects can describe some features of behavior of the distribution function during cooling process in COSY. Certainly, the simulation gives only the general description of the cooling process in the presence of the collective instability. Improvement of the situation with coherent instability may be obtained by paying additional attention to impedance budget or use of working point with larger slip-factor.

New idea about tail formation is welcome!