Electron Cooling of Intensive Ion Beam

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Contents

1. Introduction: 3 rings – similar features

Peculiarities of electron cooler rings:

- Large value of the beam emittance (100 π·mm·mrad)
- Large momentum spread (1%)
- High intensity

CELSIUS (U

Inj

at 400 MeV

COS ertical acceptance 24 π·mm·mrad

Injection energy 45 MeV, H^-, stripping injection

Intensity 8 mA: 10^{11} protons (coasting beam)

HIMAC (Chiba, Japan): Vertical acceptance 24 π·mm·mrad (also!)

Injection energy 6 MeV/u, Ar^{18+}

Intensity $1.5 \cdot 10^9$ ions (coasting beam)

All three rings are subjected to "the electron heating"!

2. «Electron heating» at CELSIUS

electron cooling and «electron heating» at CELSIUS», Workshop on Beam Cooling, Montreux, 1993

In presence of the electron beam the ion beam lifetime is much shorter:

50 - 100 s without electron beam,

0.5 - 1 s at electron current of 100 mA.

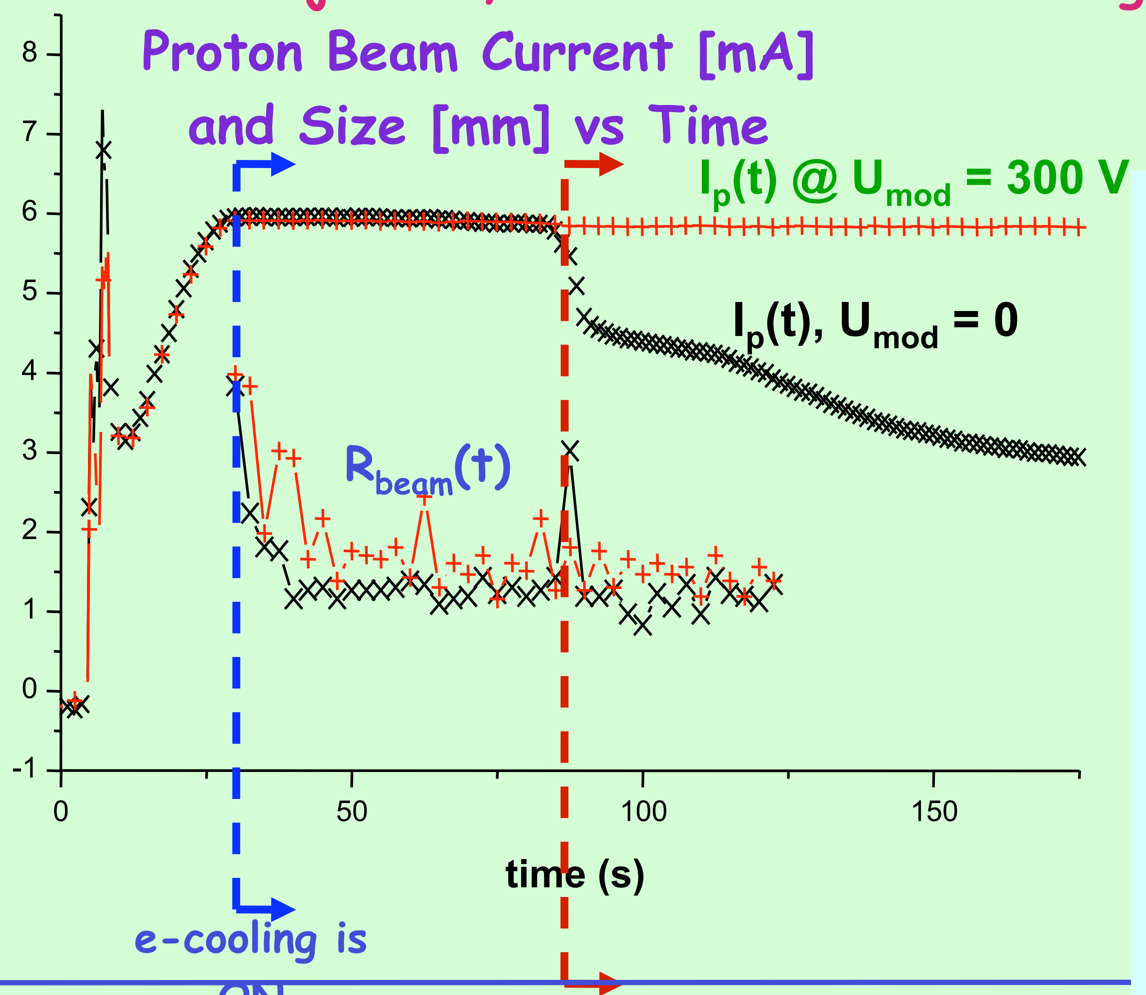
Heating at CELSIUS

D.Reistad, V.Parkhomchuk et al. (1999)

Injection, Acceleration and Cooling of Proton Beam

E_p = 400 MeV

I = 600 mA



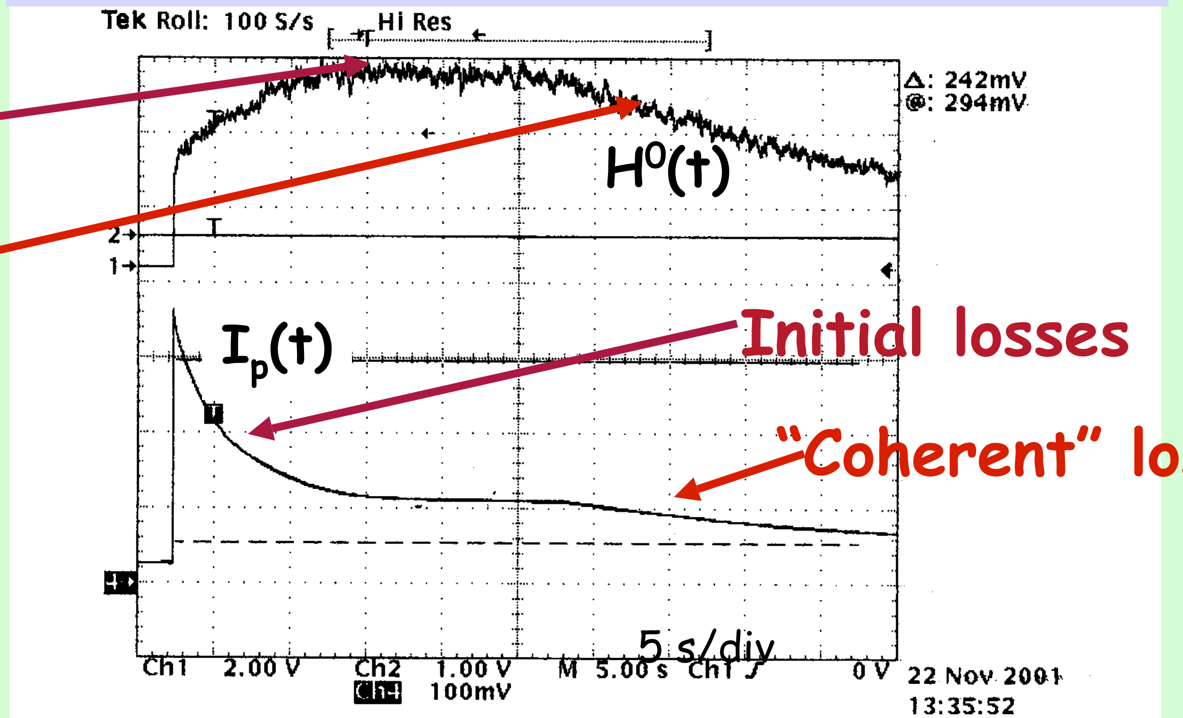
When electron cooling is ON (at t ≈ 30 s) proton beam shrinks in Δt ~10 s

but in 20 s later transverse beam oscillations occur and proton beam begins to

Electron energy modulation helps to keep beam intensity constant.

3. Injection in COSY – "the initial and coherent losses" (2001)

Typical graphs of injection in COSY



Beam shrinks and decays

E_p = 45 MeV

$N_p \sim 10^{10}$

I_e = 250 mA

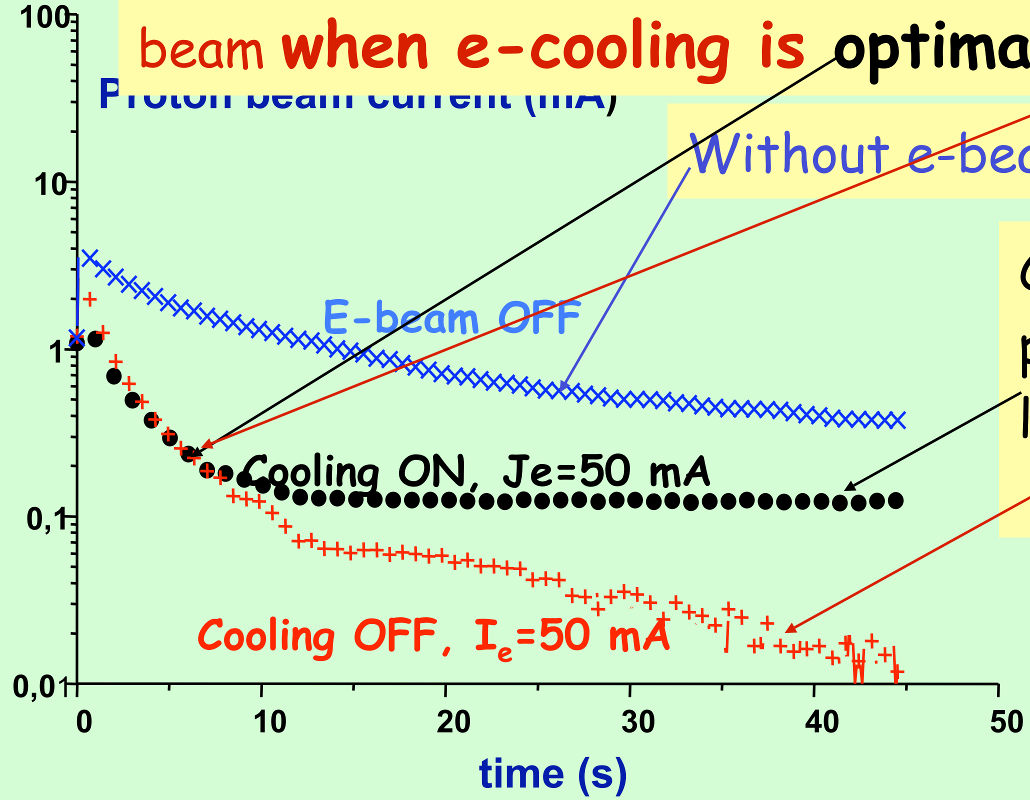
The dependence on time

(a) neutrals generation rate and
(b) proton beam intensity ($1.275 \cdot 10^{10}$ protons/div).

4. Initial (Incoherent) Losses

Experiments with detuned electron energy at CELSIUS (1998)

High losses at high intensity p-beam occur in presence of electron beam **when e-cooling is optimal or detuned**

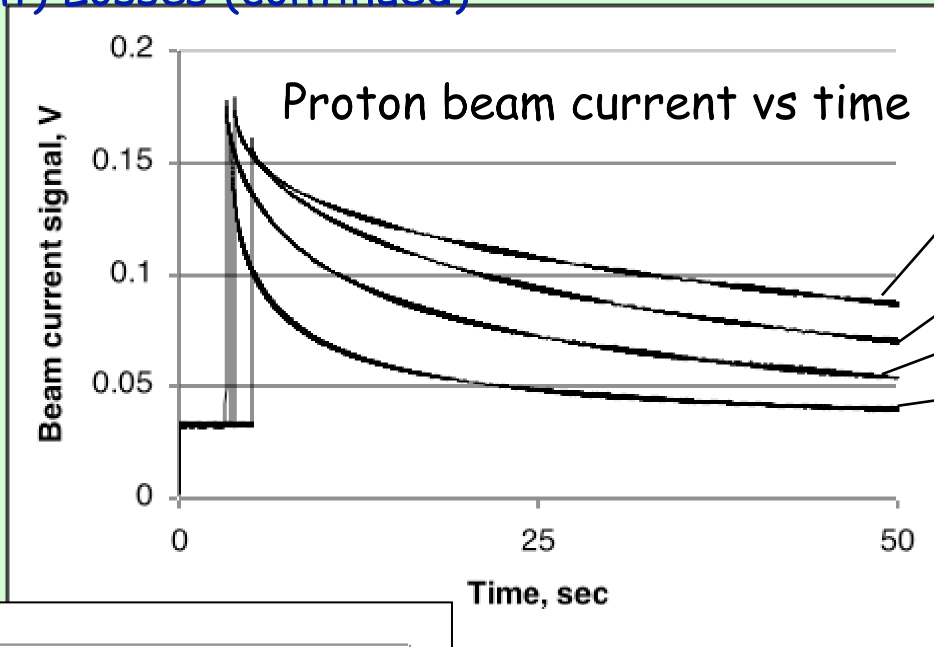


Without e-beam life time of p-beam is long

Cooling at low intensity p-beam provides a long lifetime comparatively to one without cooling

4. Initial (Incoherent) Losses (continued)

COSY, detuned electron energy

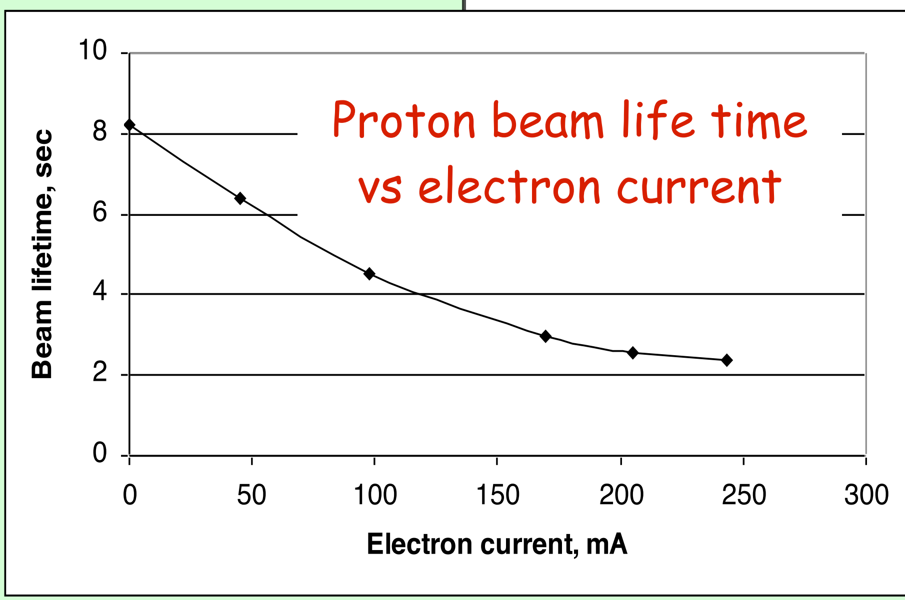


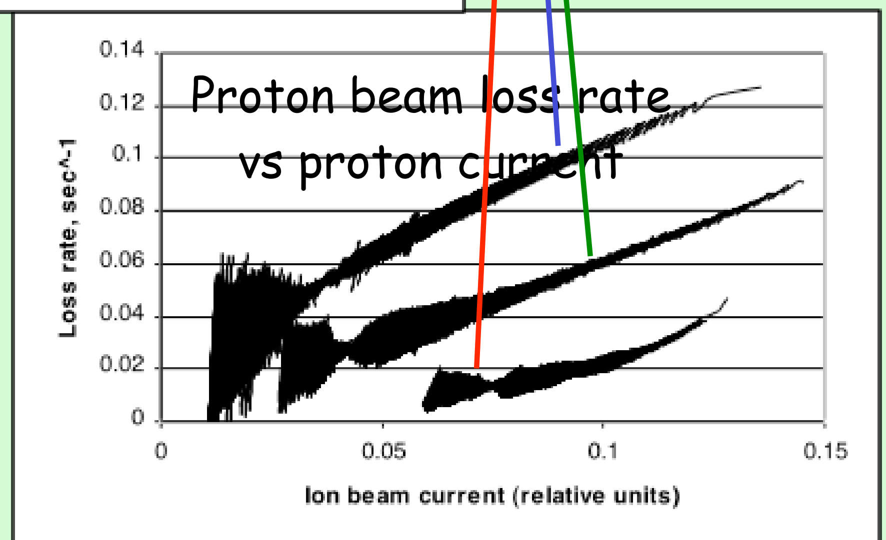
I_e = 0 (losses !)

I_e = 45 mA

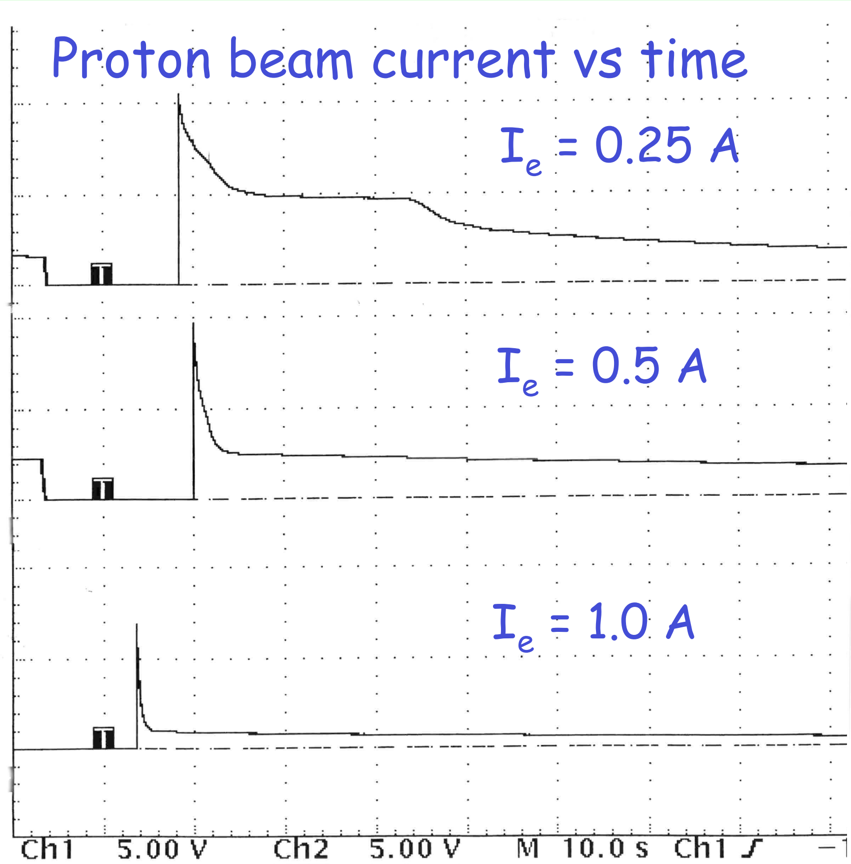
I_e = 98 mA

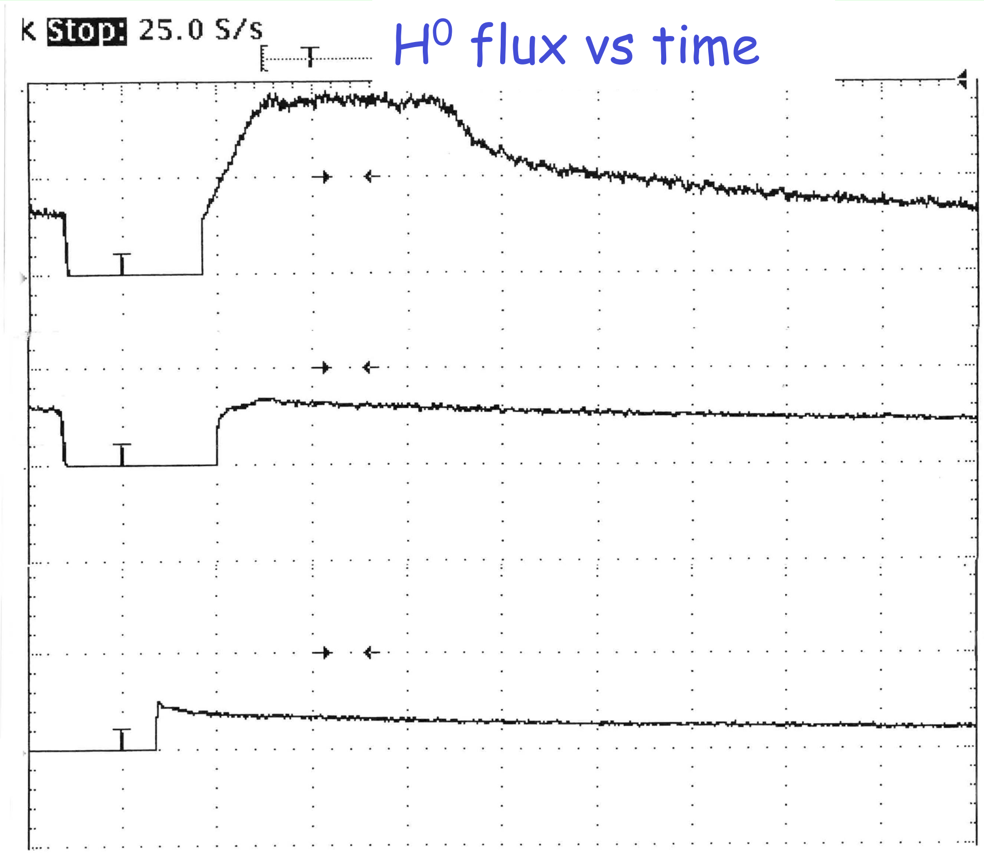
I_e = 243 mA





COSY, August 2005: e-cooling at different e-beam current





Effect of nonlinear field of the electron beam?

CELSIUS:

Ion beam size before cooling (at 400 MeV) ~ 25 x 20 mm^2 (?)

Electron beam diameter 20 mm

COSY:

Injected ion beam cross-section 40 x 75 mm^2

Electron beam diameter 25.4 mm

HIMAC (no "initial losses"!):

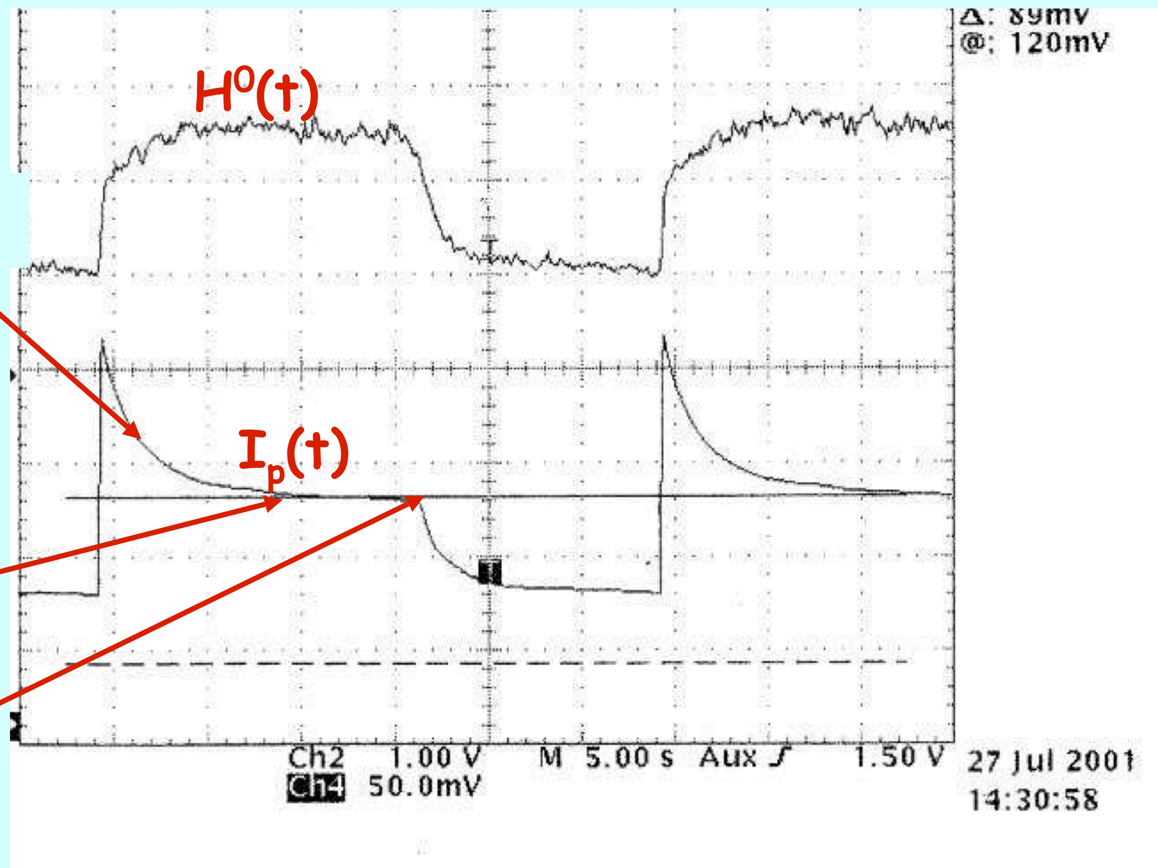
Injected ion beam cross-section 13 x 50 mm^2

Electron beam diameter 64 mm

Two-beam instability: V.Parkhomchuk, D.Pestrikov, "Coherent instabilities at electron cooling", Workshop on Beam Cooling, Montreux, 1993.

5.Coherent instability at COSY & HIMAC

5.1. Single injection in COSY



Initial losses

Coherent oscillation start

Oscillations "jump"

(see next slide)

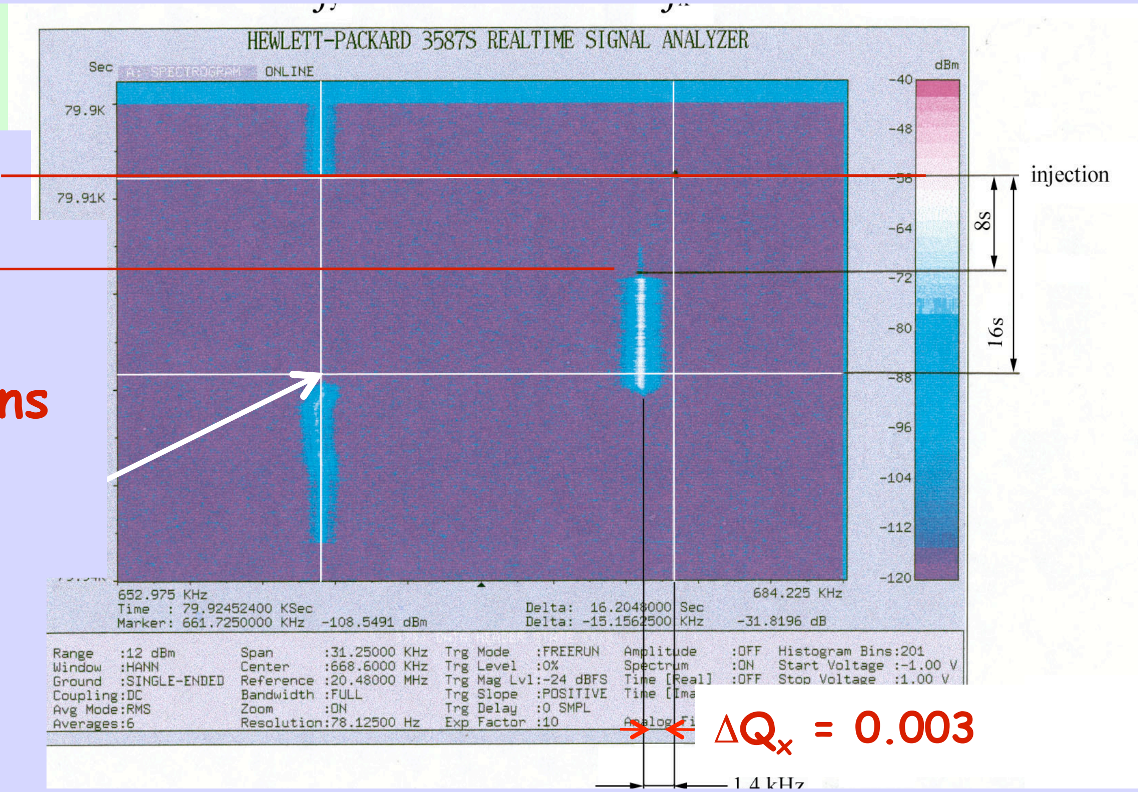
Coherent instability development in COSY

t= 0 injection

t= 8 s

hor. oscillations and bunching start

to vertical oscillations



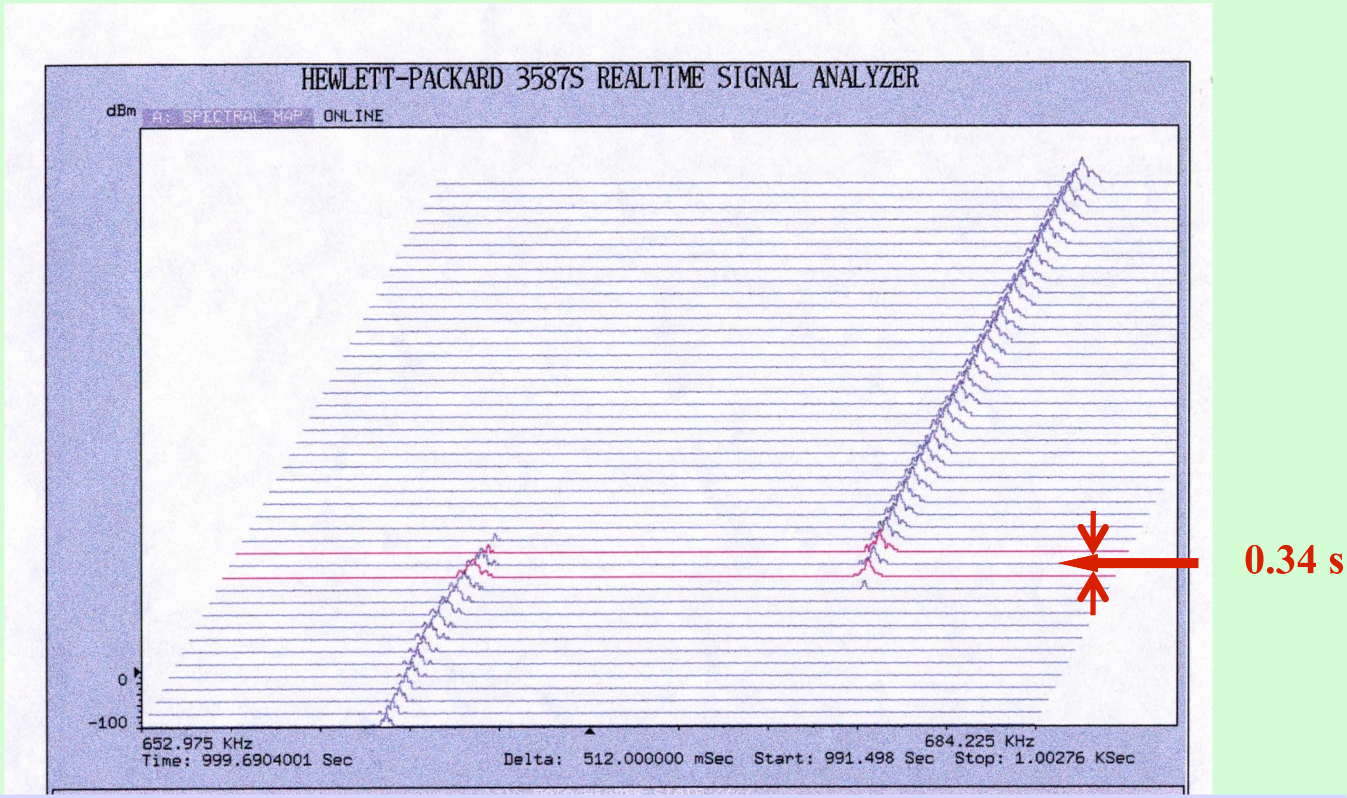
Q_x = 3.62

Q_y = 3.66

ΔQ_x = 0.003

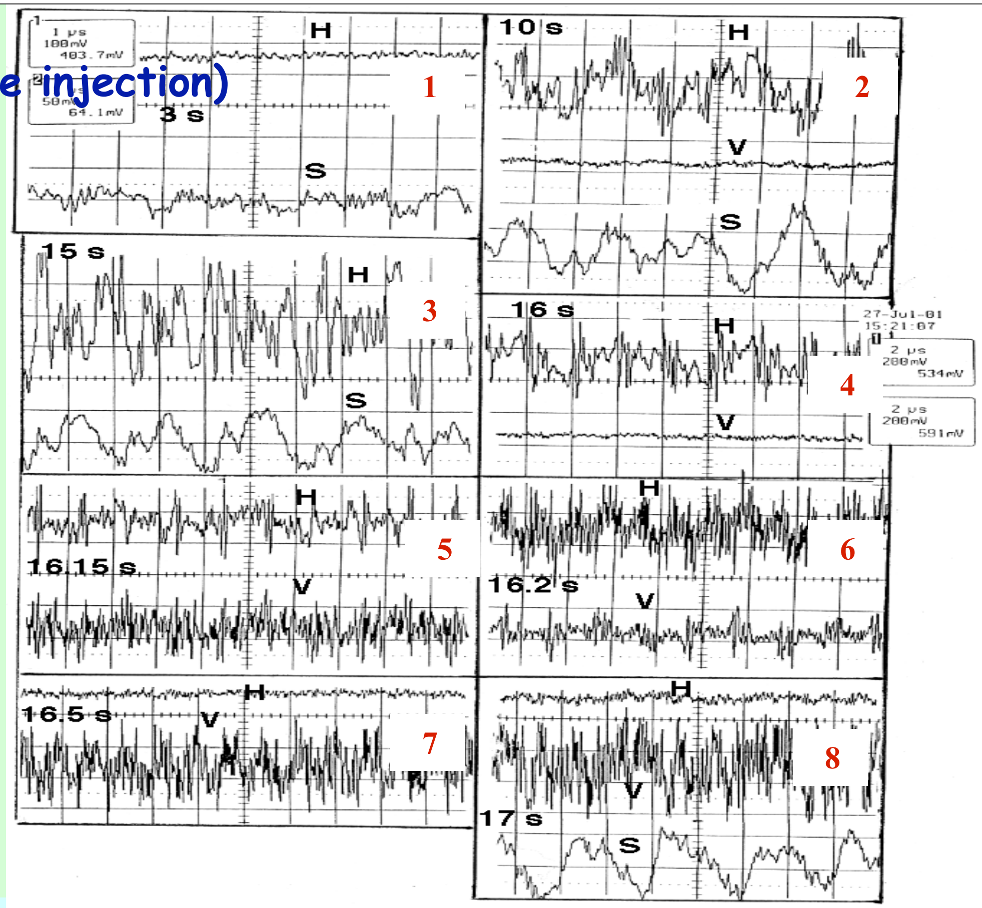
The Schottky noise spectrum in the betatron frequency range in transition area (near "the jump").

Coherent instability development in COSY



The Schottky noise spectrum in the betatron frequency range in transition area (near "the jump"). The detailed scan: the lines differ in time by 0.17 s

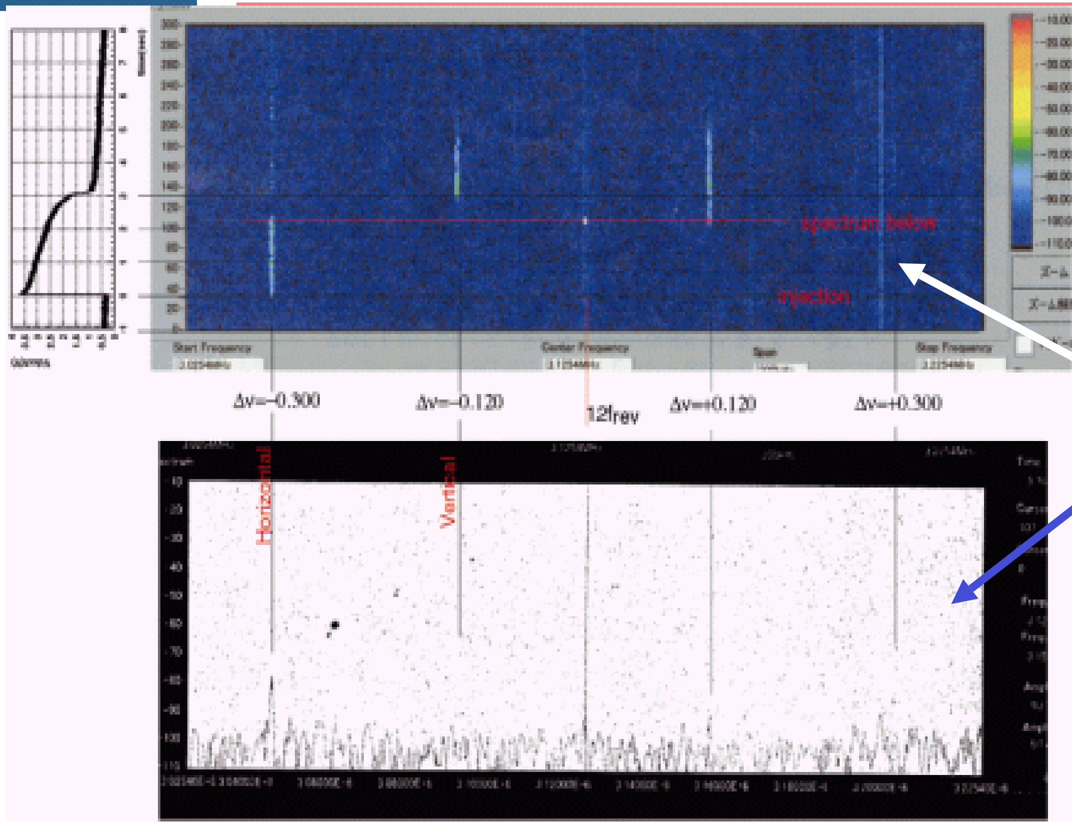
Coherent instability development in COSY



Beam Position Monitor analog signals clearly demonstrating the collective oscillations of the p-beam: the signals from differential horizontal (H) and vertical (V) PU's and sum (S) PU.

Note: longitudinal oscillations (sum signal) appear together with horizontal one and present later on.

Transverse Coherent Oscillation



$Q_x = 3.67$, $Q_y = 2.88$

Intensity: $5 \cdot 10^8$ppp

The same phenomenon in HIMAC!

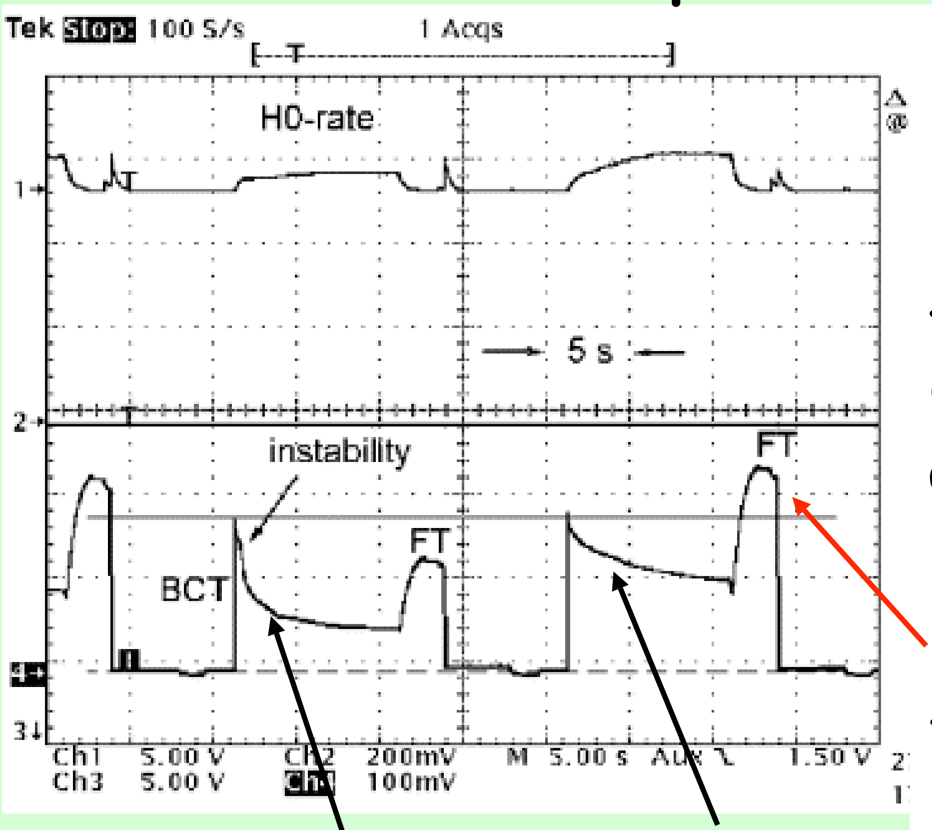
(April 2003)

The horizontal coherent oscillation has been observed since just after injection, and intensity has been gradually decreased. The intensity is rapidly decreased, immediately when the oscillation mode changes to the vertical direction from the horizontal one.

Increasing the vertical tune by 0.001 (Qy=2.881), the oscillation is disappeared.

5.Coherent instability: single injection and acceleration

COSY: Setupole correction

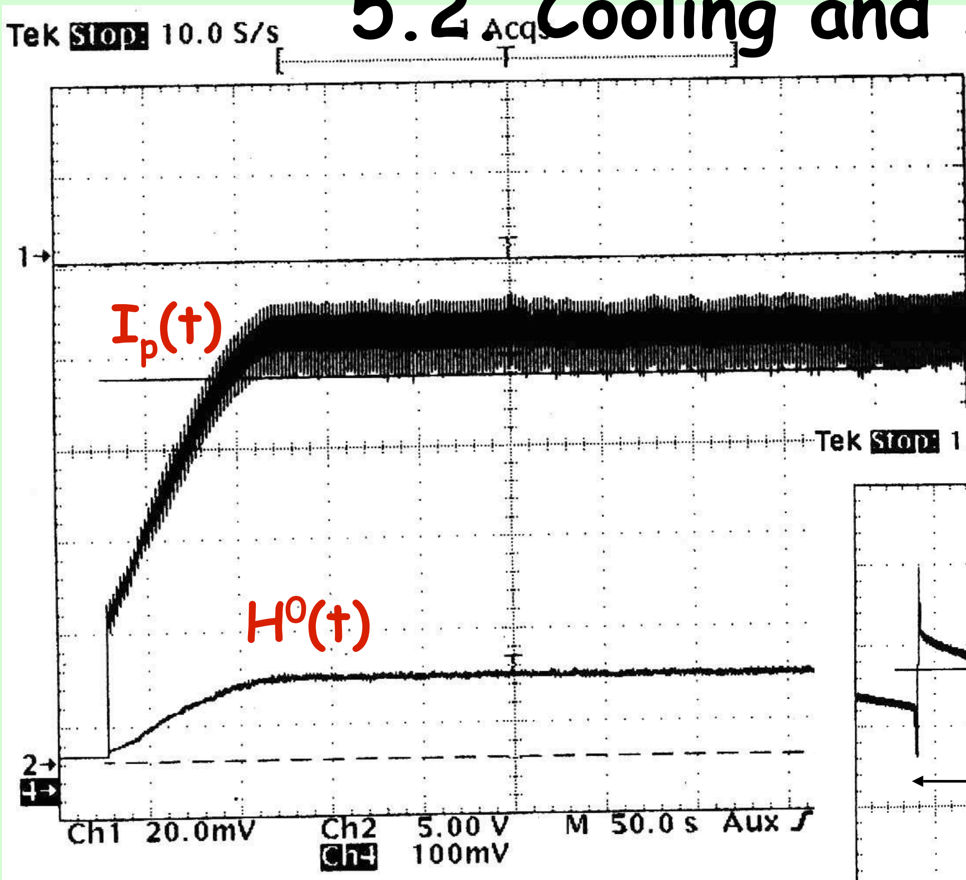


"Standard" setting of sextupoles

Optimised setting of sextupoles

As result of sextupole correction accelerated beam increased in two times

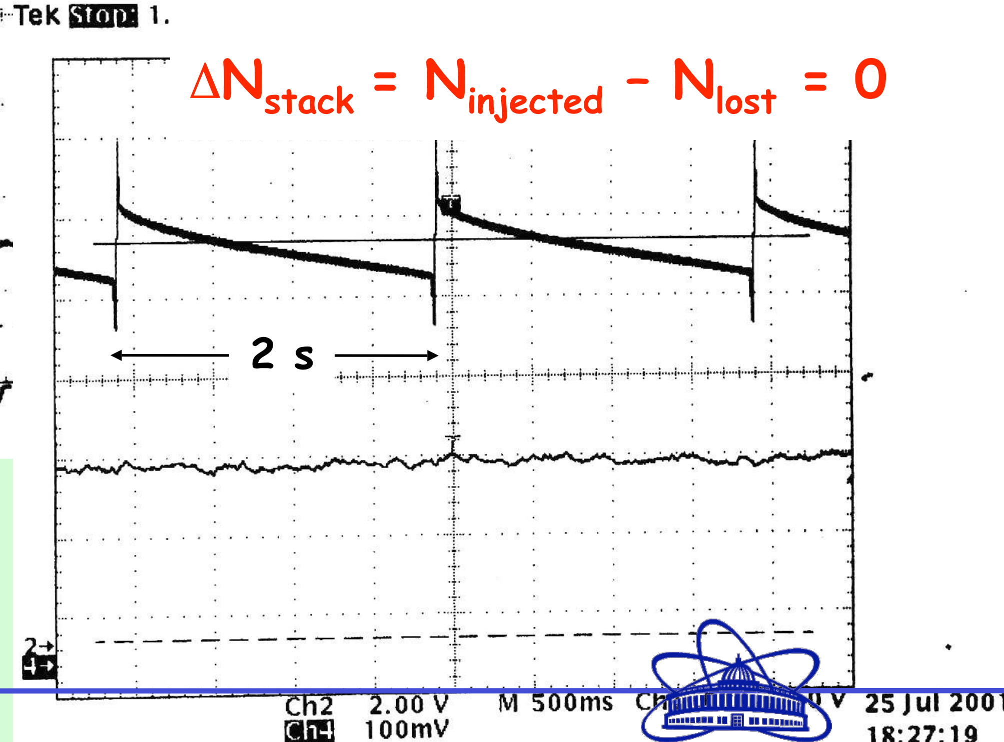
5.2. Cooling and stacking at COSY



Limitation of the stack intensity!

Intensity balance per injection cycle:

$$\Delta N_{stack} = N_{injected} - N_{lost} = 0$$



5.3.Three Ways to The Transverse Coherent Instability Suppression

- Feedback systems:

LEAR: (CERN) bandwidth 500 MHz - $8{\cdot}10^{10}$ protons

COSY: bandwidth 70 MHz - 10^{11} stored protons

- Variation of electron beam energy,

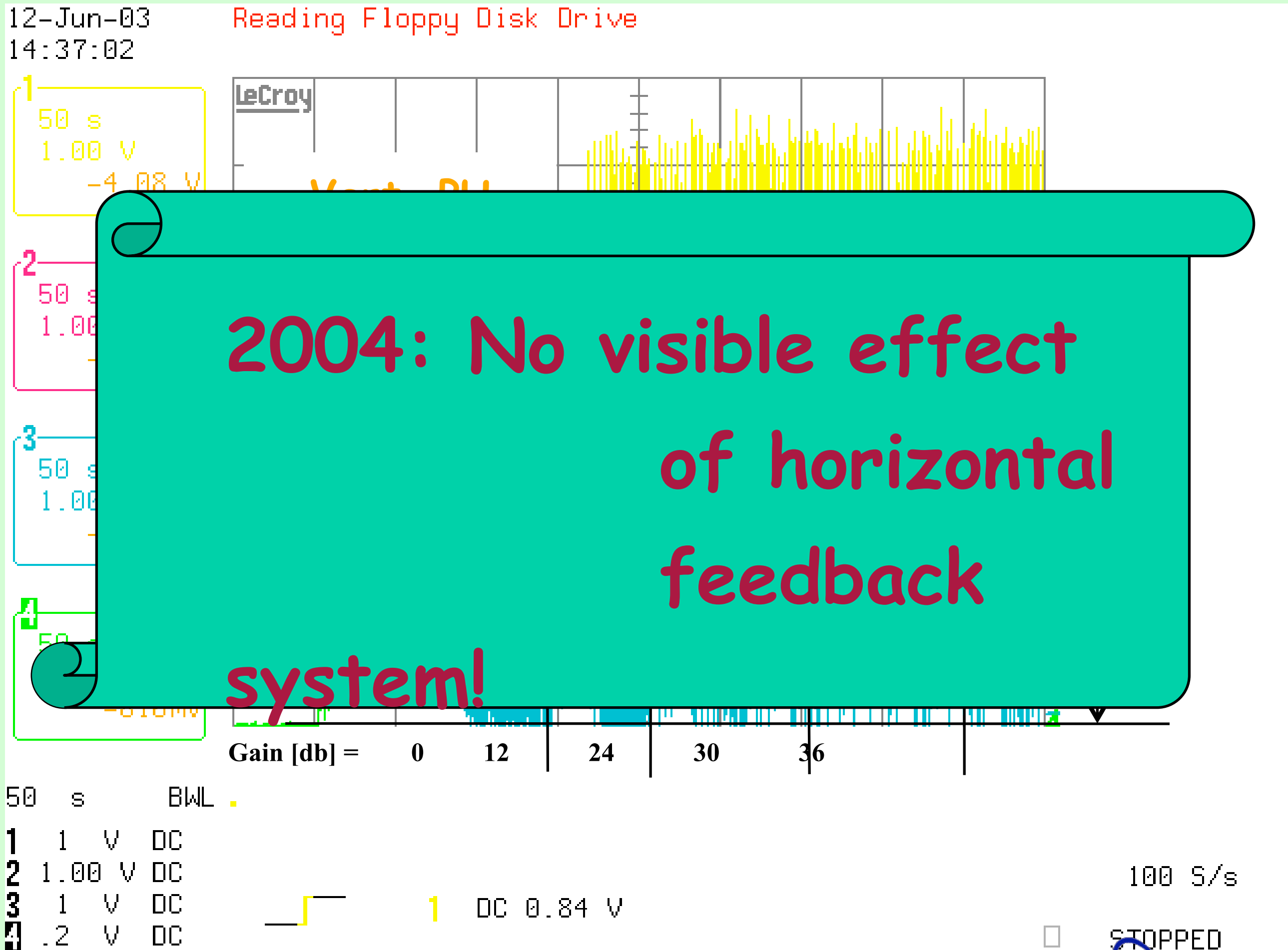
CELSIUS: 50 V amplitude at E_e= 115 keV

- "Hollow beam"

V.Parkhomchuk and colleagues, Budker INP

Vertical Feedback system in COSY (2003)

Feedback gain optimization

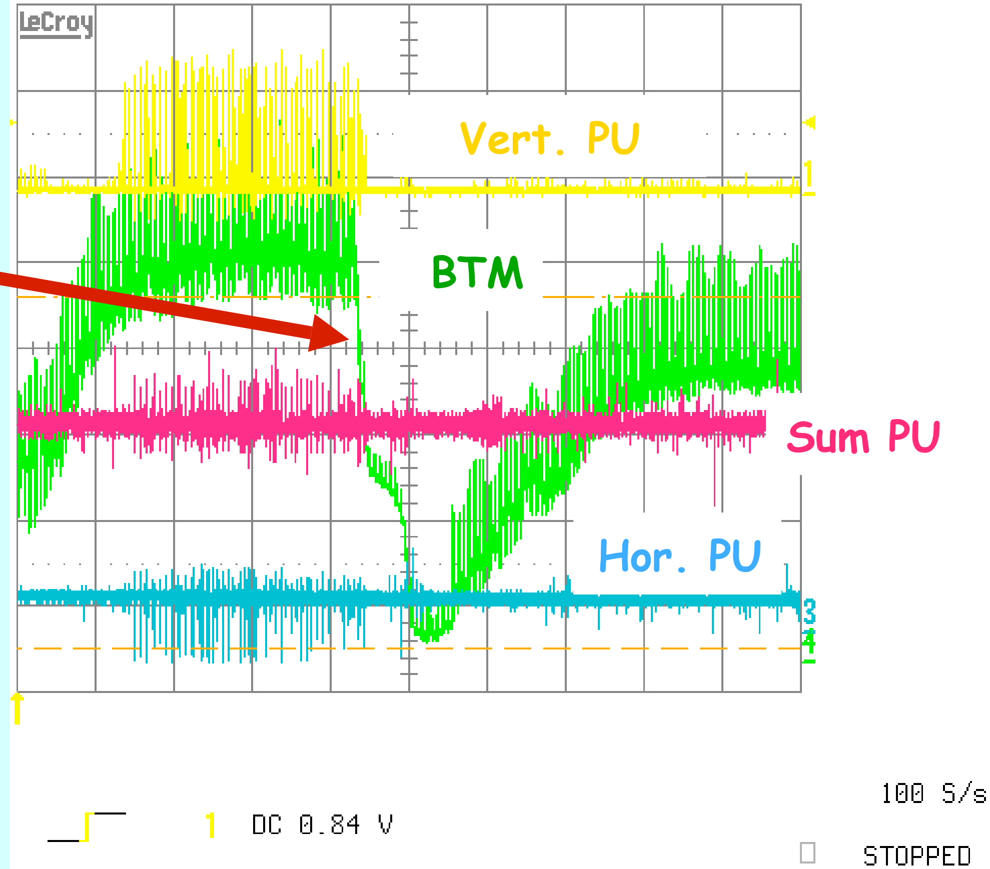


2004: No visible effect of horizontal feedback system!

5.Coherent instability: instability suppression

em in COSY: Sextupole

Coherent instability developes when **the sesxtupoles** mxg were **switched OFF** at t = 215 s. (Feedback is ON)



5.4. IBS (?) and longitudinal modulation

Influence of transverse heating

Atn = attenuation

$(V_{noise})_{rms}$ = 6 V/**Atn**, Δf = 0.1 – 2 MHz, I_e = 250 mA

Schottky noise: 18th harmonics, f = 5.8 MHz

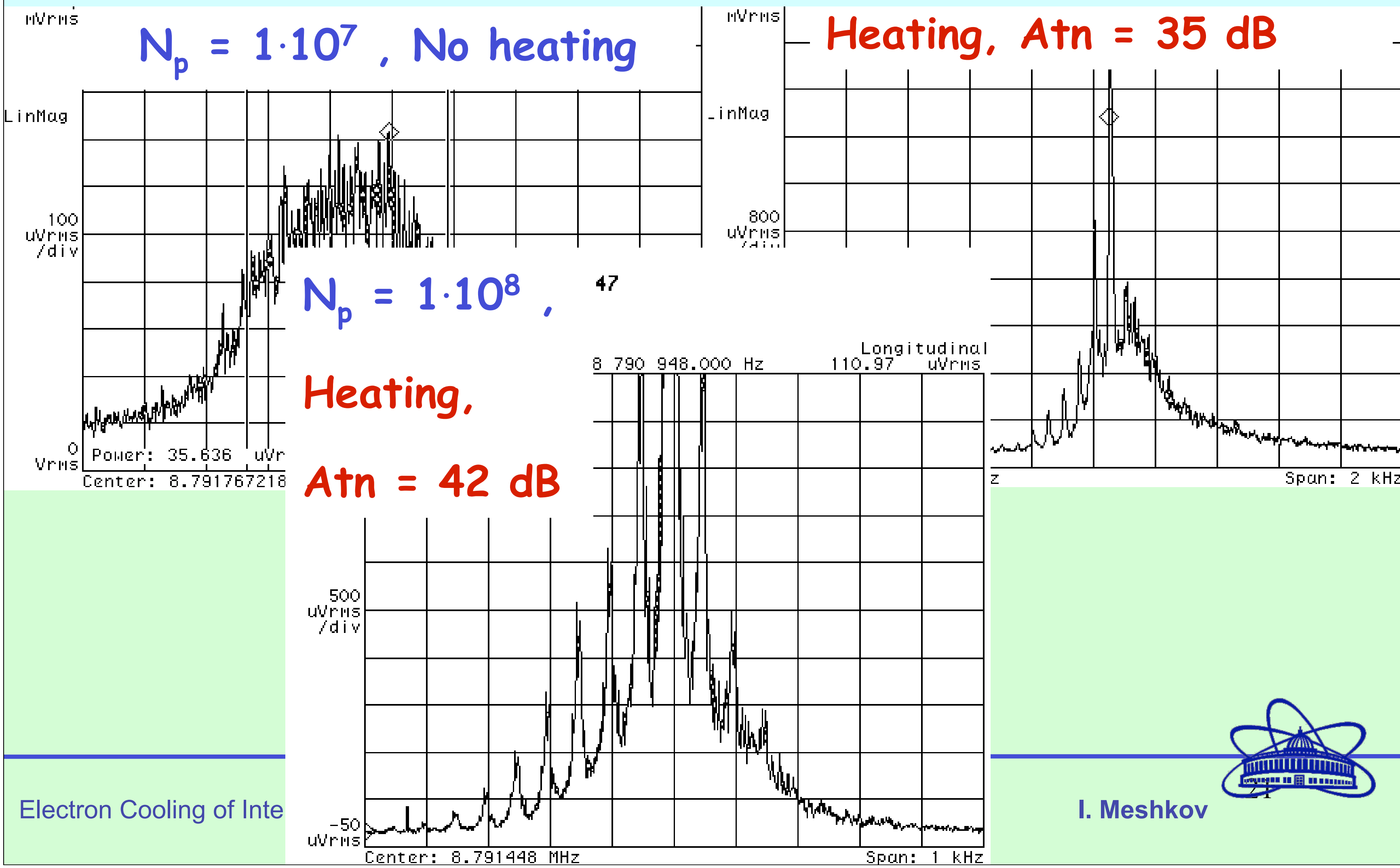
$N_p = 1 \cdot 10^7$, No heating

Heating, Atn = 35 dB

$N_p = 1 \cdot 10^8$,

Heating,

Atn = 42 dB



6. Ion Cloud in An Electron Cooling System

- Theoretical "forecast":

N.S.Dikansky, V.V.Parkhomchuk, D.V.Pestrikov, Instability of Bunched Proton Beam interacting with ion "footprint", Rus. Jorn. Of Tech. Physics, v.46 (1976) 2551.

P. Zenkevich, A. Dolinskii and I. Hofmann, Dipole instability of a circulating beam due to the ion cloud in an electron cooling system, NIM A 532 (October 2004).

- First experimental discovery:

E.Syresin, K.Noda, T.Uesugi, [I.Meshkov], S.Shibuya, Ion lifetime at cooling stacking injection in HIMAC, HIMAC-087, May 2004, EPAC'04, Lucerne, 2004.

“Natural” neutralization

Potential at the electron beam axis:

$$U_e(r=0) = \frac{I_e}{\beta c}\left(1 + 2\ln\frac{b}{a}\right)$$

a,b – electron beam and vacuum chamber radi

Neutralization level
due to variation of the vacuum chamber radius:

$$\eta_{neutr} \equiv \frac{(n_i)_{ionization}}{n_e} = \frac{2\ln\frac{b_2}{b_1}}{1 + 2\ln\frac{b_2}{a}}, \quad b_2 > b_1 .$$

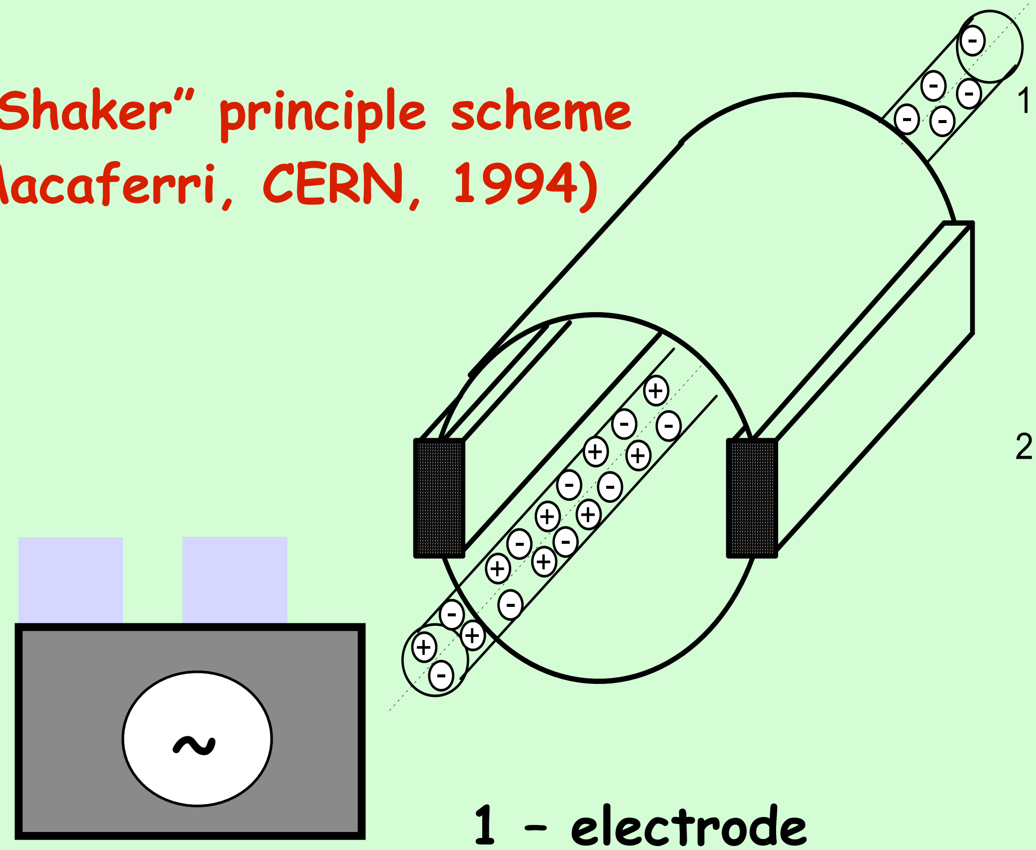
Electron energy in partially neutralised electron beam:

$$E_e = eU_{cathode} - (1 - \eta_{neutr})\frac{I_e}{\beta c}\left(1 + 2\ln\frac{b}{a}\right).$$

Control of the neutralization level with "The Shaker"

"The Shaker" principle scheme
(R.Macaferri, CERN, 1994)

The residual gas ions oscillate in the solenoid magnetic field and electric field of the electron beam.



1 – electrode

2 – conducting glass

Control of the neutralization level with the shaker:

The ion oscillation frequency is equal to

$$\omega = \sqrt{\omega_i^2\left(1-\eta_{neutr}\right)+\omega_B^2/4} \pm \omega_B/2$$

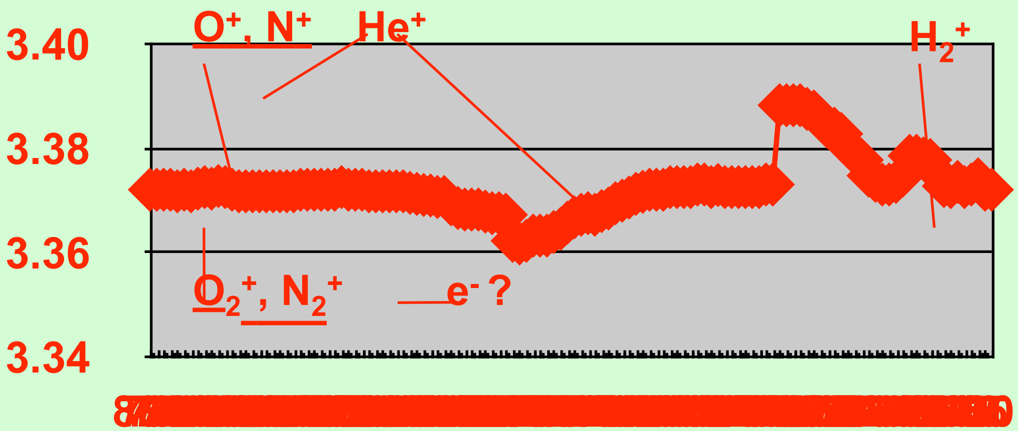
$$\omega_B = \frac{ZeB}{Am_p} \qquad \omega_i^2 = \frac{Ze^2 n_e}{2Am_p}$$

The ions can be "shaken out" if

$$f_{shaker} = \omega / 2\pi \ .$$

6. Ion cloud…

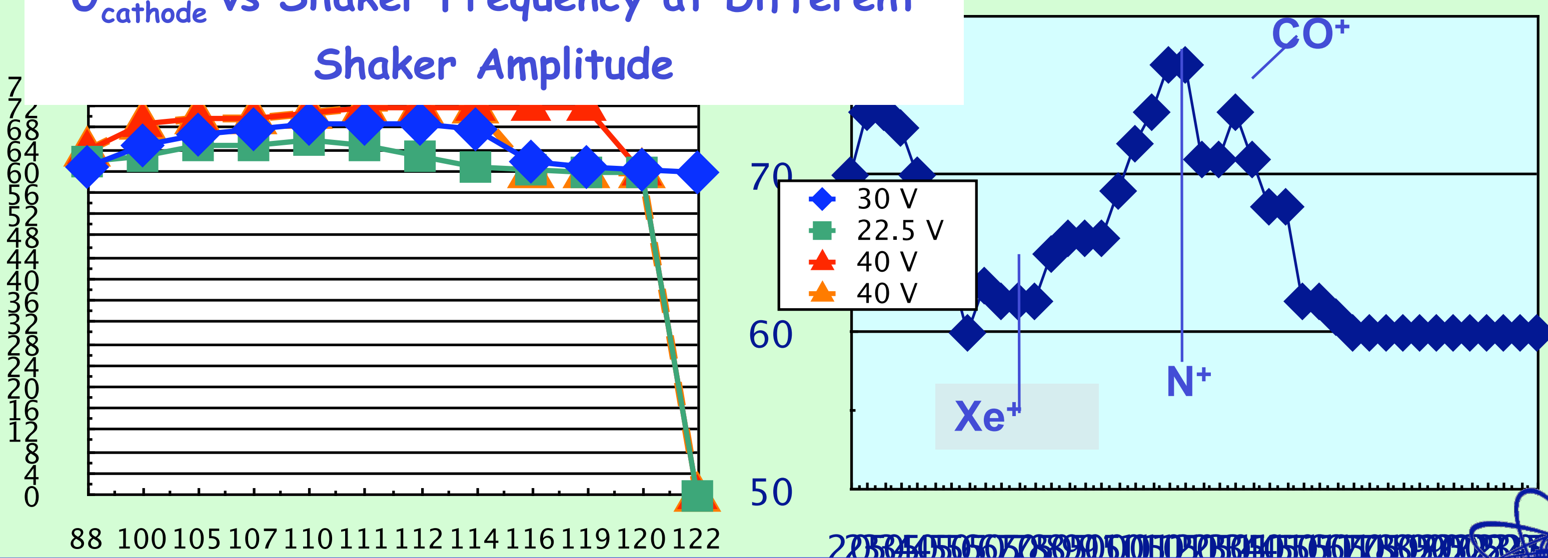
April 2004



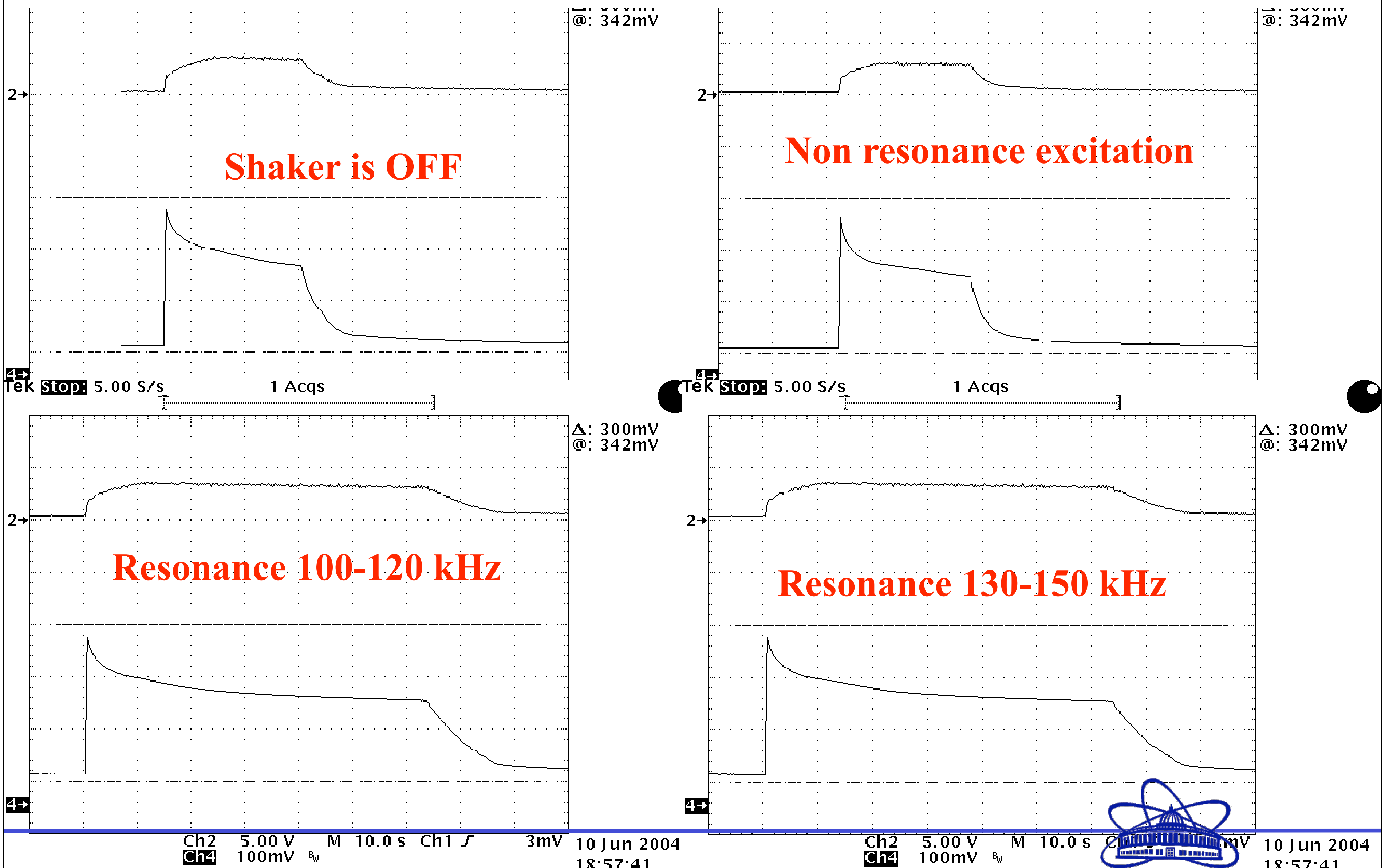
A/Z of residual gas ions stored in electron beam

June 2004

$U_{cathode}$ vs Shaker Frequency at Different Shaker Amplitude



COSY: Shaker Effect on Proton Beam Life Time at Single Injection



Conclusion

1. Electron cooling permits to form ion beams at high phase space density, however the problems of the ion beam stability specific for electron cooler rings appear.
2. First problem relates to interaction of an ion circulating in the ring with nonlinear field of cooling electron beam.
3. Second problem is related to development of two beam instability in cooled ion beam.
4. Third problem: the threshold of this instability decreases when "secondary" ions of residual gas are stored in the cooling electron beam
5. The threshold of this instability can be increased when feedback system and control of "the natural neutralization" (with a shaker, for instance) are applied.

Thank you for your attention!

Der Erste May 2002 Demonstration

in COSY Control Room