Electron Cooling of Proton Beam in COSY and S-LSR

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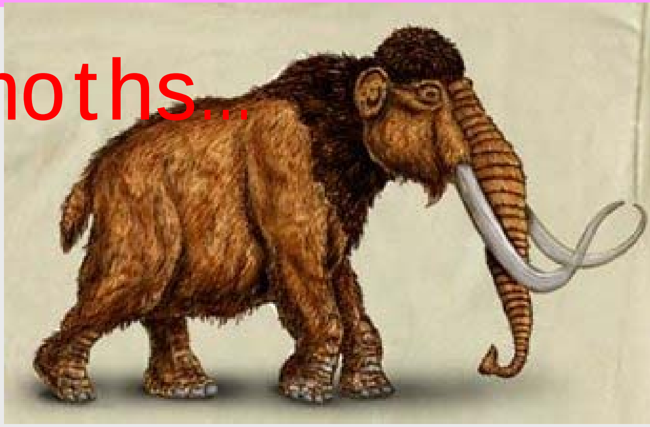
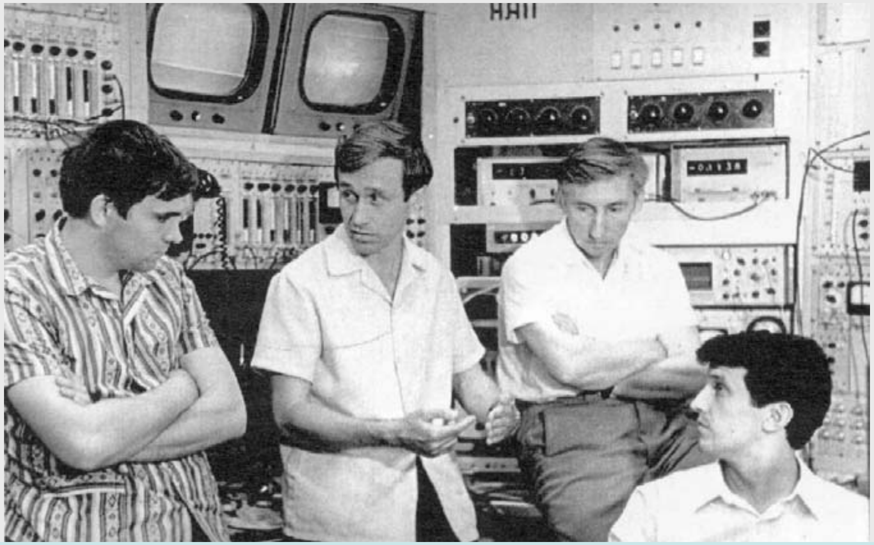
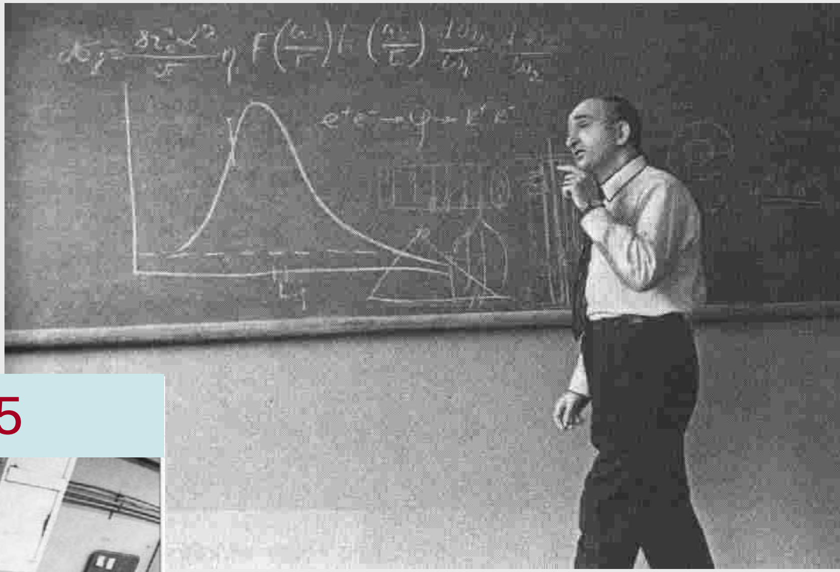
I. Preface

Siberia is The Fatherland of mammoths…

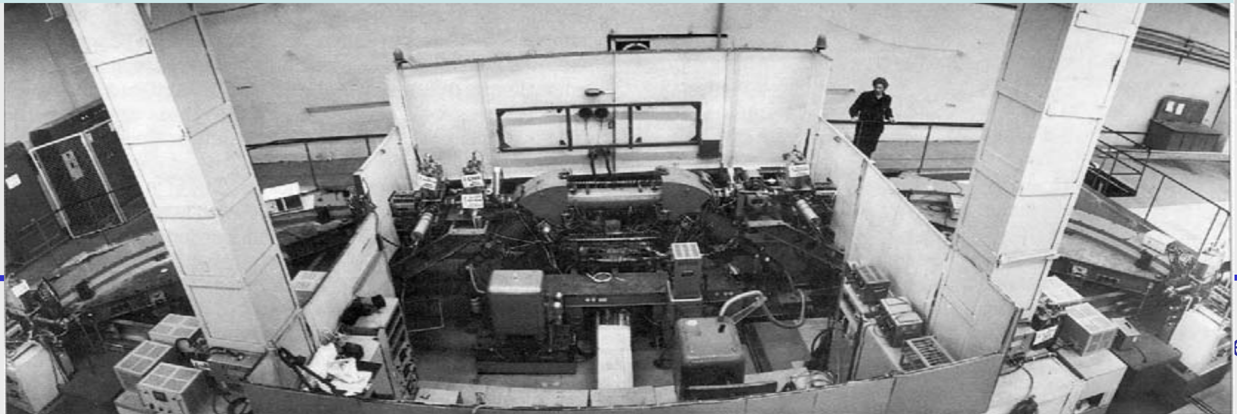


…and electron cooling!





1974 – EPOC (эпоха) of NAP-M - 1985



2. Introduction: COSY – Injection

Experimental Studies of Proton Injection and Storage at Electron Cooling

2000: FZJ – JINR – Budker INP

2001 – 2006 - … : FZJ – JINR

2. Introduction: COSY – Injection and Electron Cooling (Contnd)

Typical graphs of injection in COSY

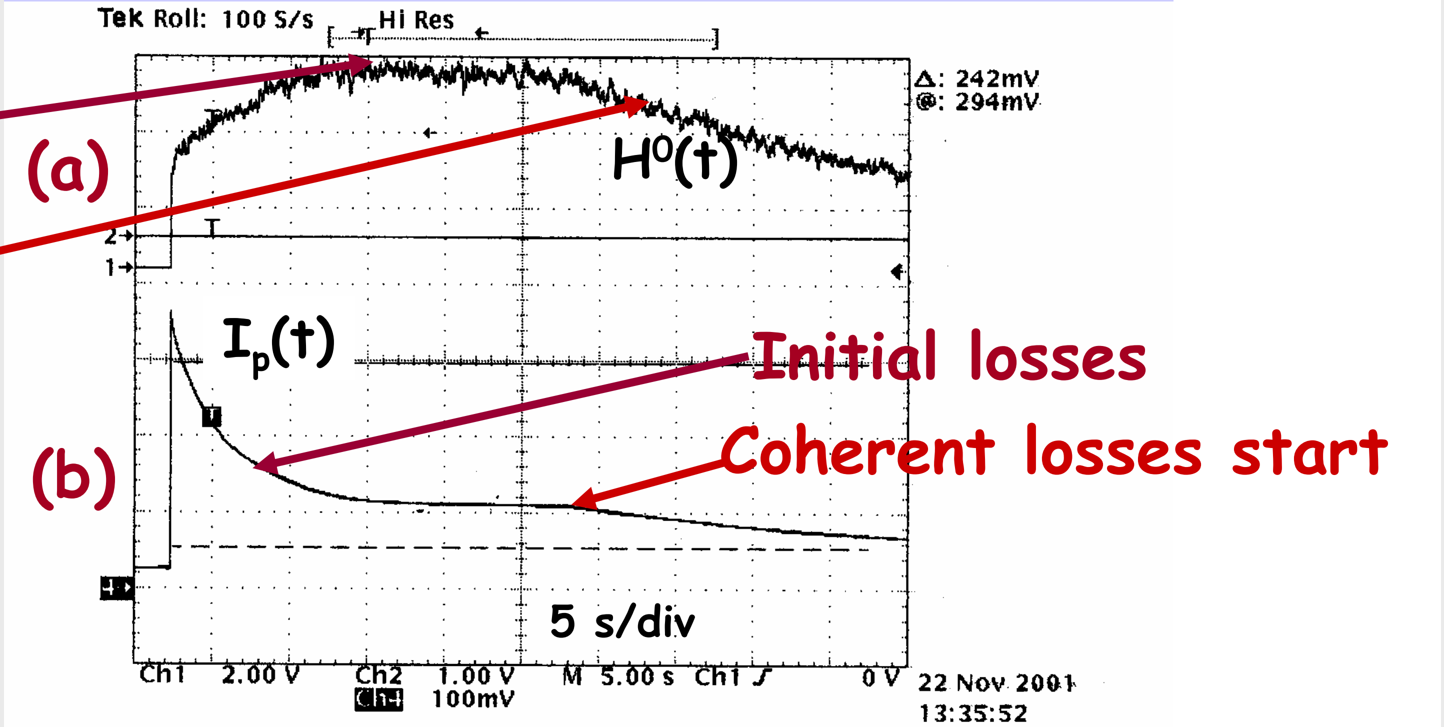
Beam shrinks

and decays

E_p = 45 MeV

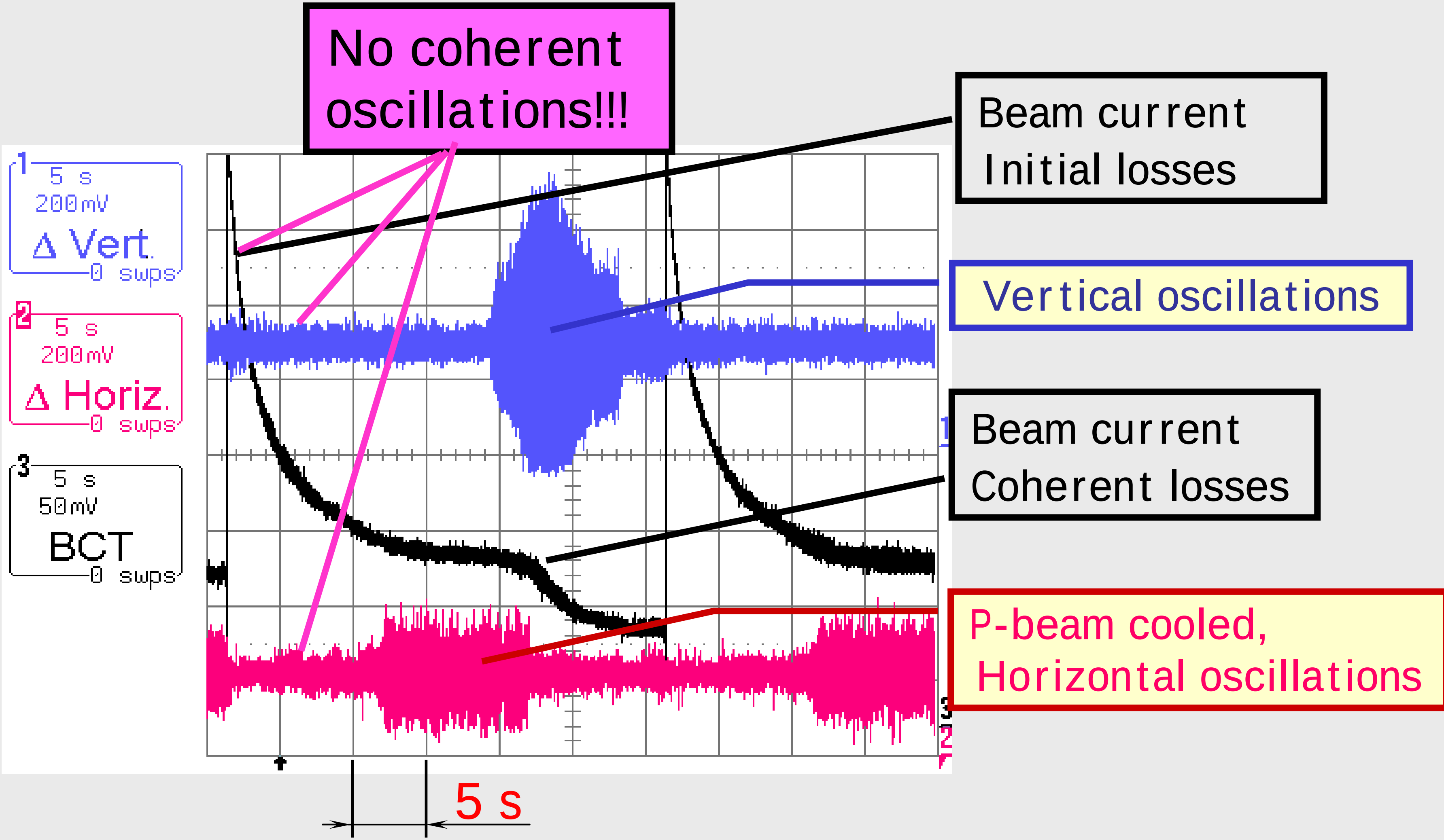
N_p ~ 10^{10}

I_e = 250 mA



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

2. Introduction: COSY – Injection and Electron Cooling (Contnd)



3. «Electron heating» at CELSIUS

First report: D.Reistad et al., «Measurements of electron cooling and «electron heating» at CELSIUS», Workshop on Beam Cooling, Montreux, 1993

Following studies: D.Reistad, V.Parkhomchuk et al.,

The effect: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.

3. «Electron heating» (continuation)

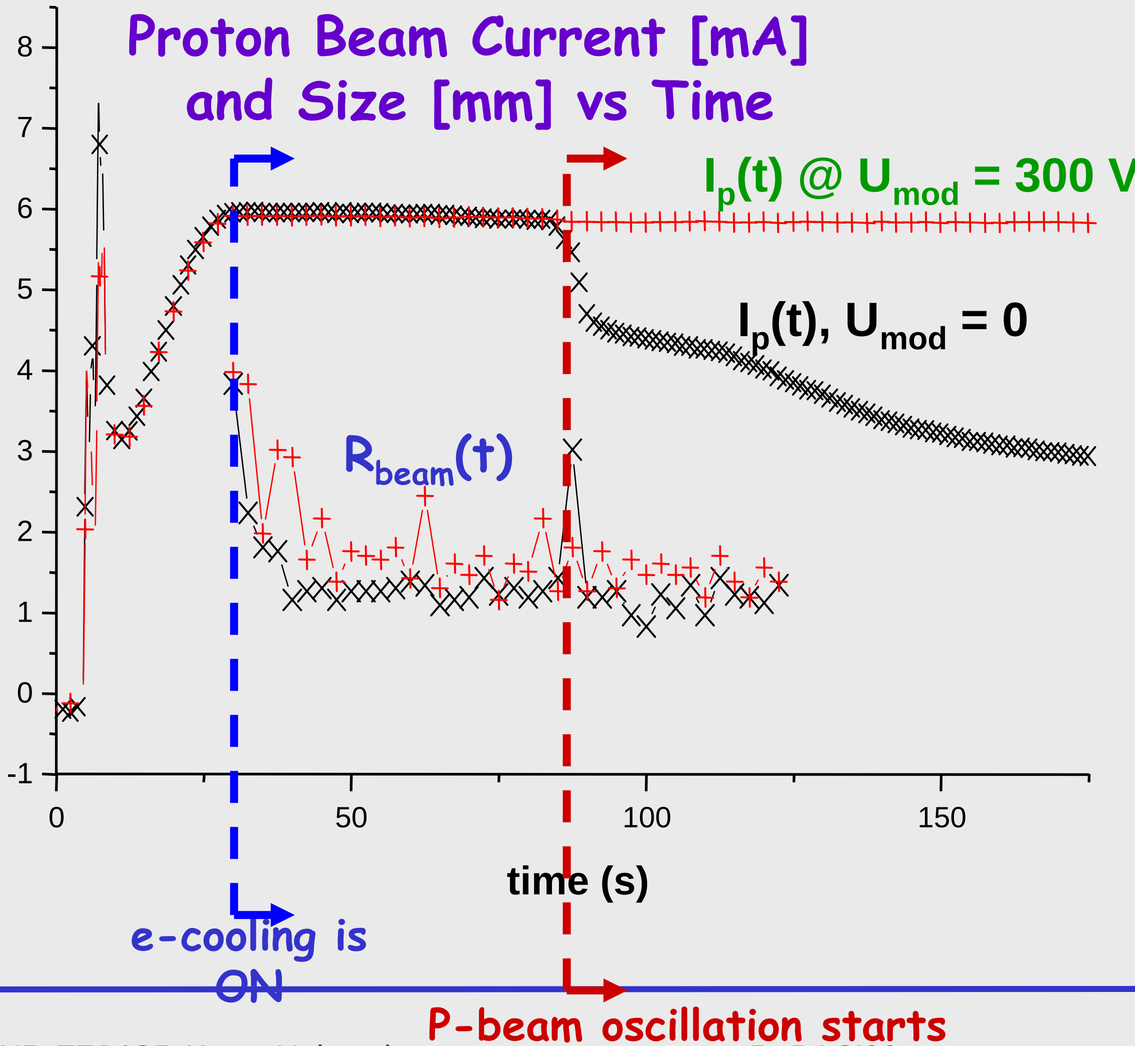
Heating at CELSIUS

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

Injection, Acceleration and Cooling of Proton Beam

E_p = 400 MeV

I_e = 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 loose intensity.

Electron energy modulation helps to keep beam intensity constant.

4. Initial (Incoherent) Losses

Experiments with detuned electron energy

at CELSIUS (1998)

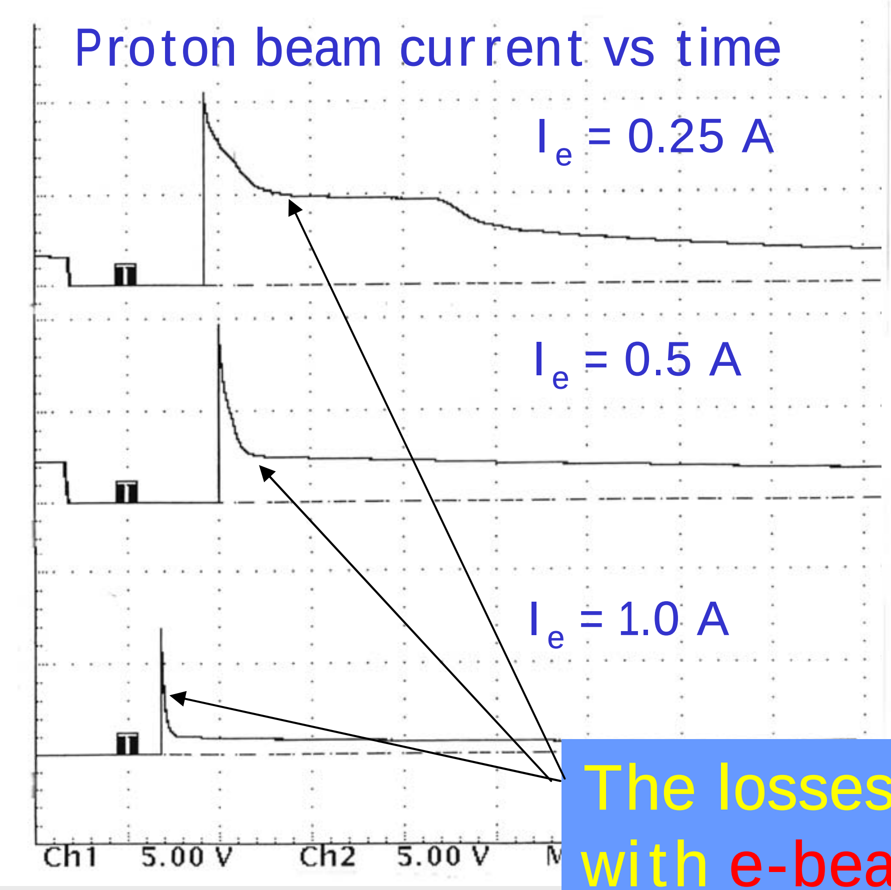
and

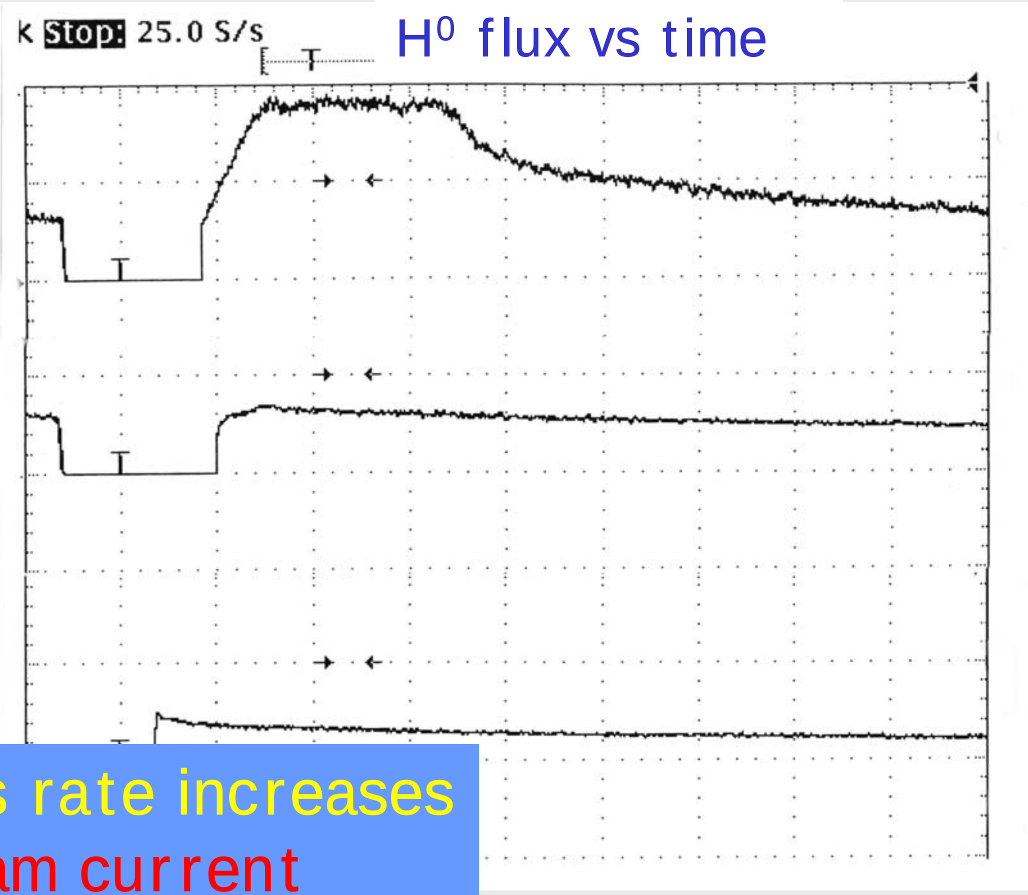
at COSY (2000)

have shown the incoherent losses appear

even when electron cooling does not work.

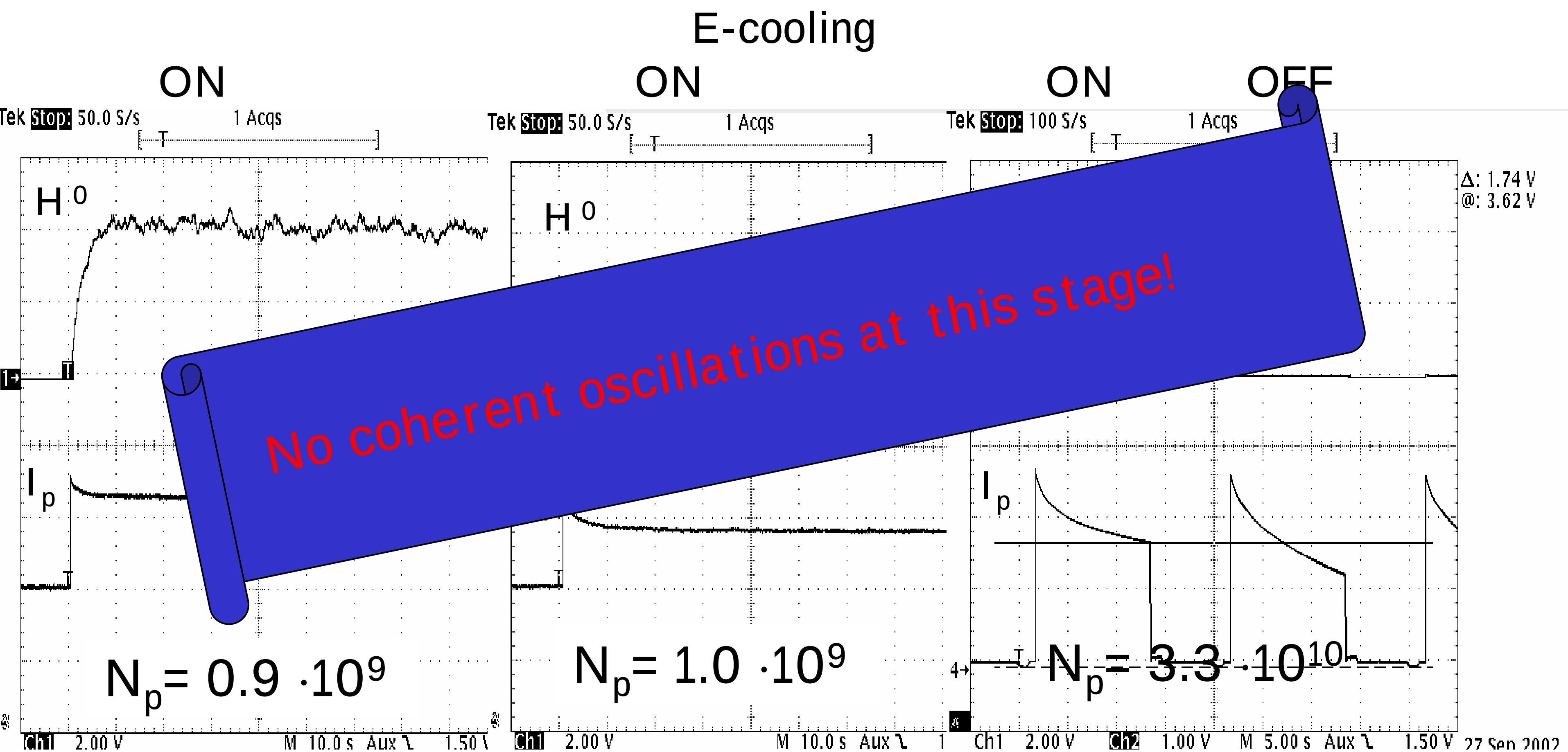
COSY, August 2005: e-cooling at different e-beam current





The losses rate increases with e-beam current

4. Initial (Incoherent) Losses (Ccntnd)



$(\varepsilon_p)_1$ $(\varepsilon_p)_2 \sim 3\cdot(\varepsilon_p)_1$ $(\varepsilon_p)_3 \sim (\varepsilon_p)_2$

The losses rate increases with proton beam emittance and proton number

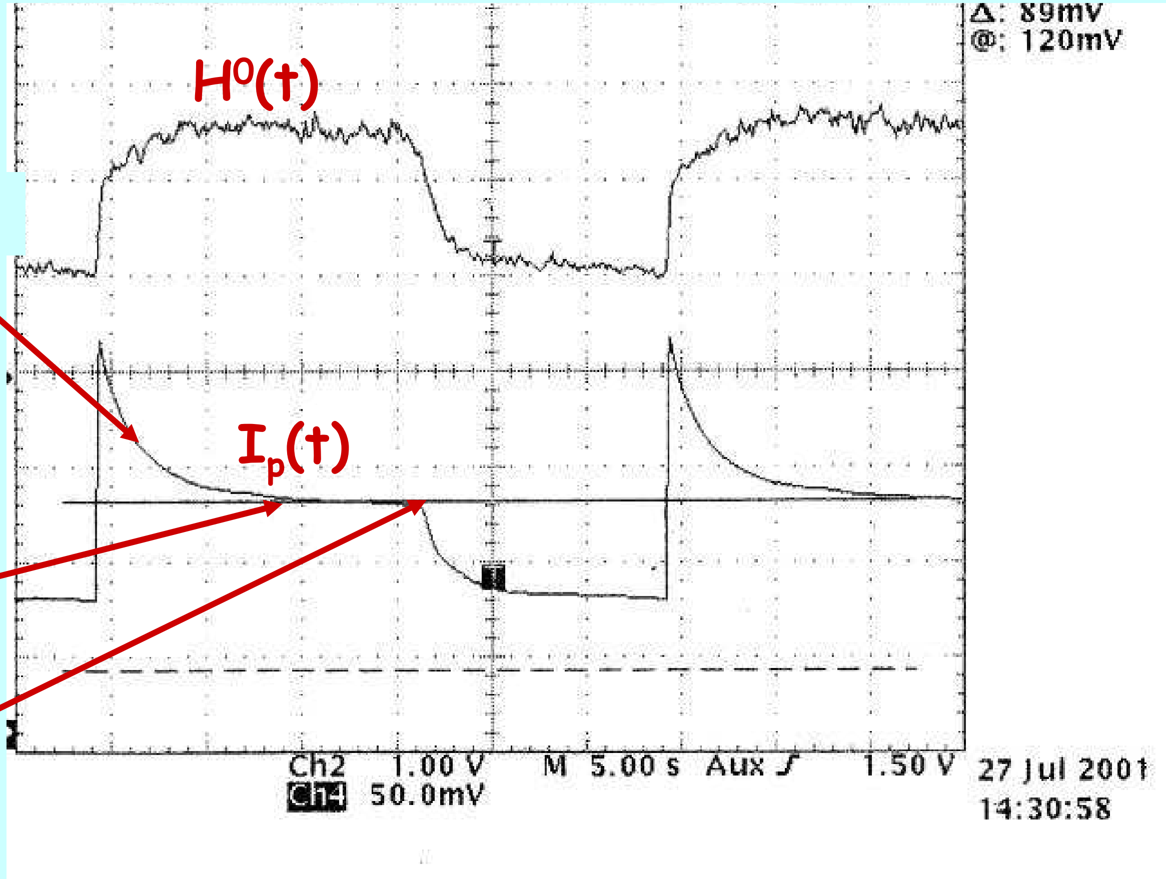
5.Coherent instability

5.1. Single (rare) injection

Initial losses

Coherent oscillation start (no losses!)

Oscillations "jump" (see next slide)

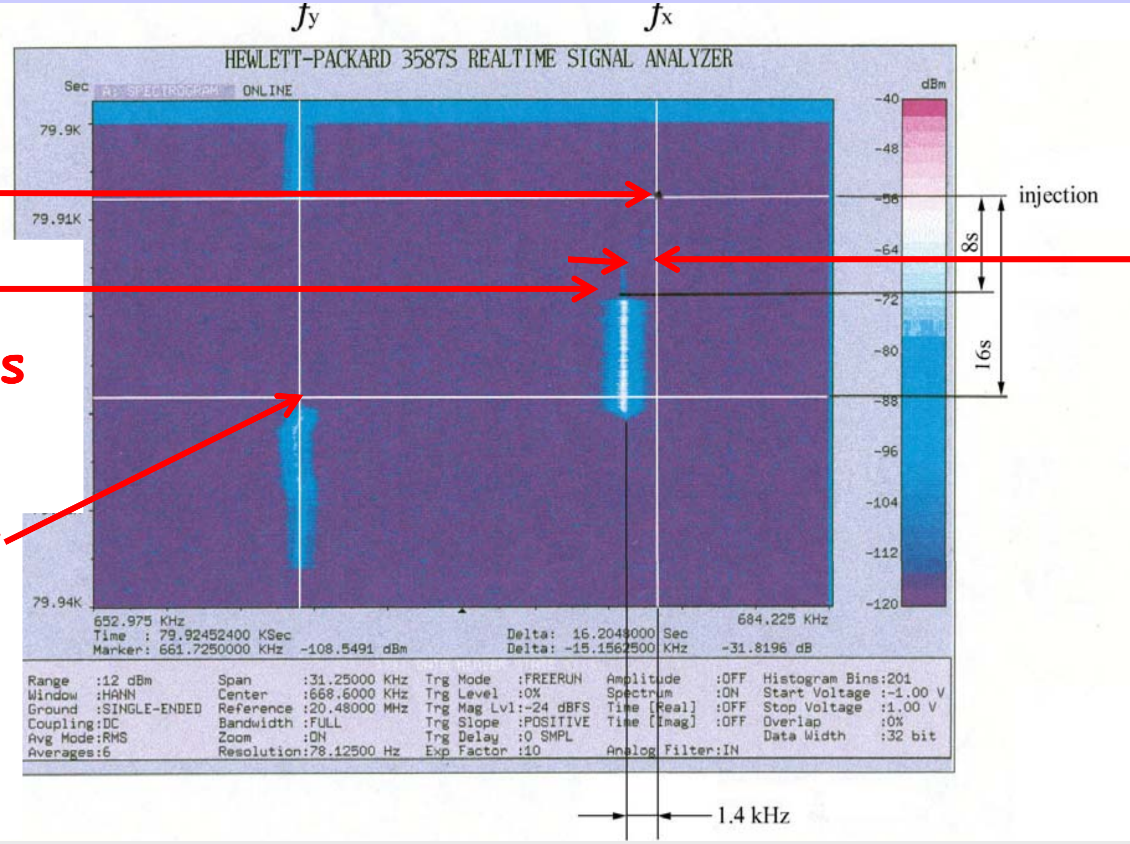


Coherent instability development in COSY

t= 0
injection

t= 8 s
hor. oscillations and bunching start

t= 16 s “jump” to vertical oscillations



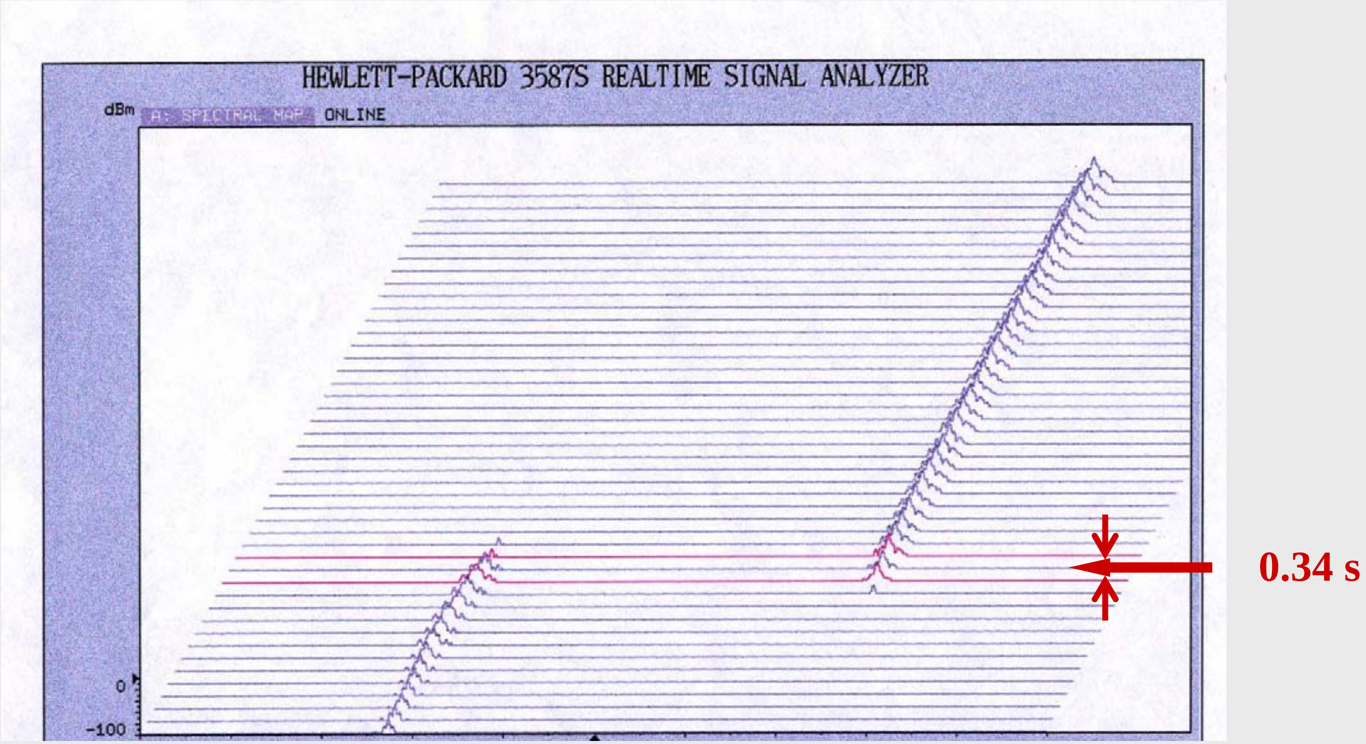
ΔQ_x = 0.003

Q_x = 3.62

Q_y = 3.66

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

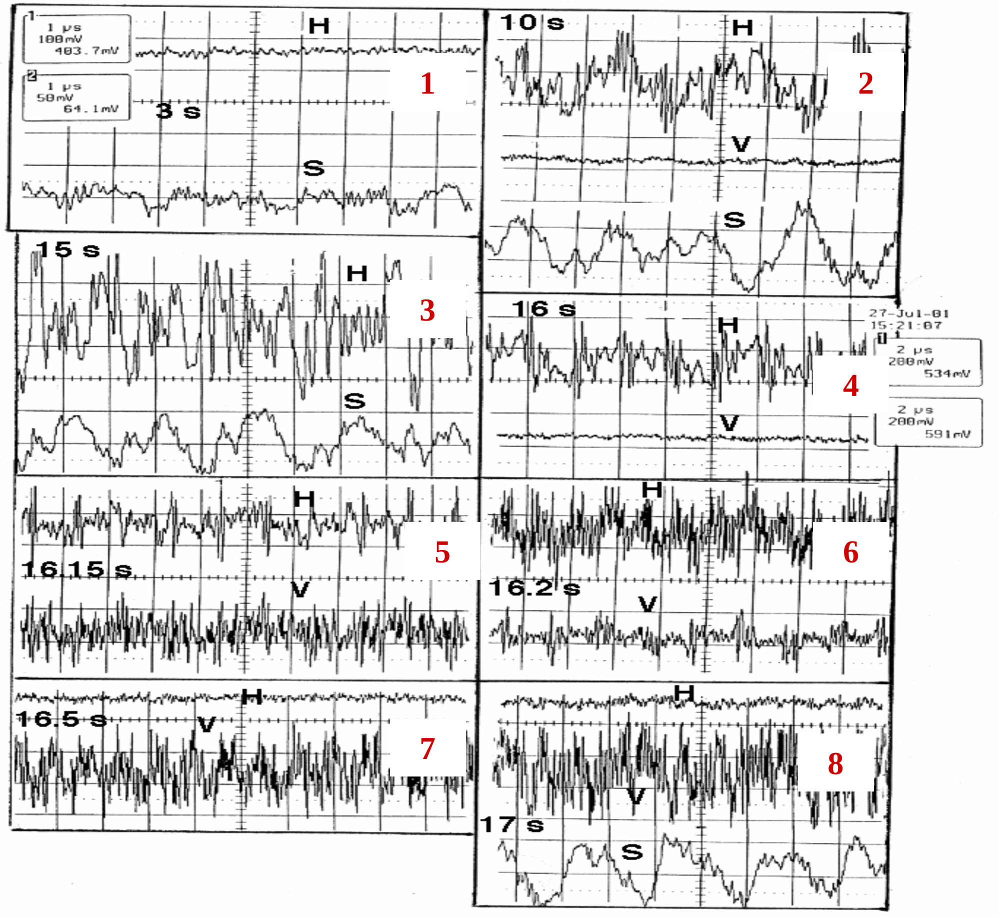
Coherent instability development in COSY



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.

5. Coherent instability: single injection

Coherent instability development in COSY

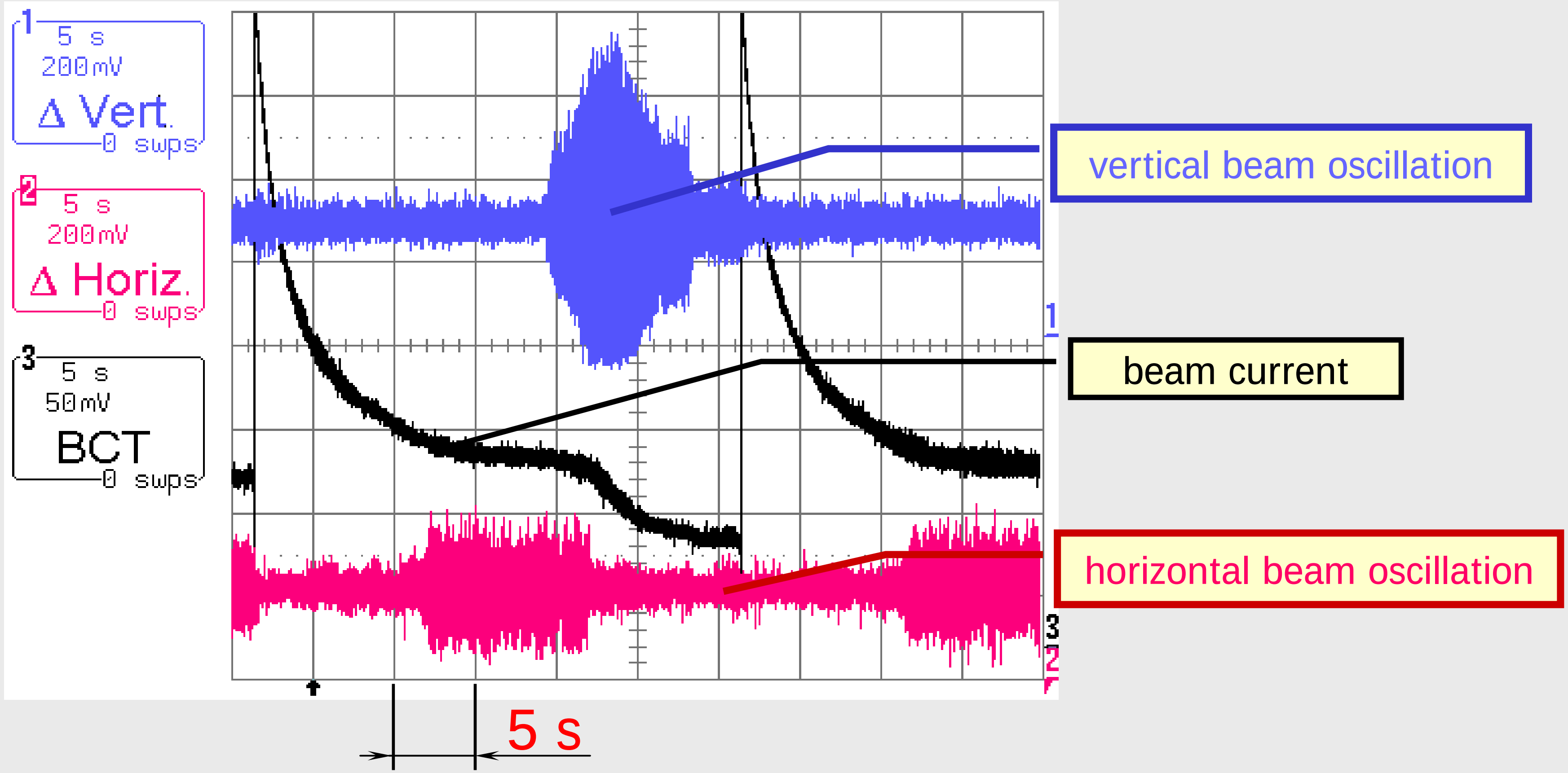


Beam Position Monitor analog signals clearly demonstrating the collective oscillations of the p-beam: the signals from differential horizontal (H) and vertical (V) PU's and sum (S) PU.

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

5.Coherent instability: single (rare) injection

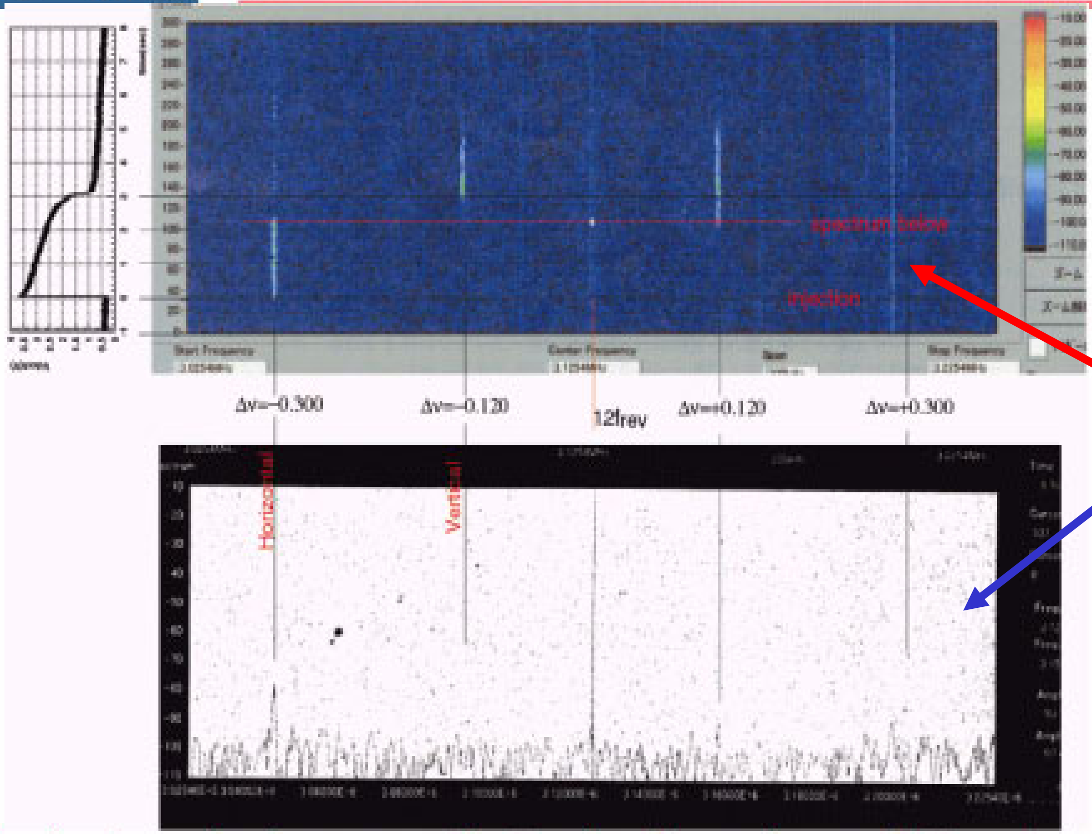
Coherent instability development in COSY



NIRS HIMAC

5.Coherent instability: single (rare) injection

Transverse Coherent Oscillation



Ar^{18+}, 6 MeV/u

$Q_x = 3.67$, $Q_y = 2.88$

Intensity: $5 \cdot 10^8$ppp

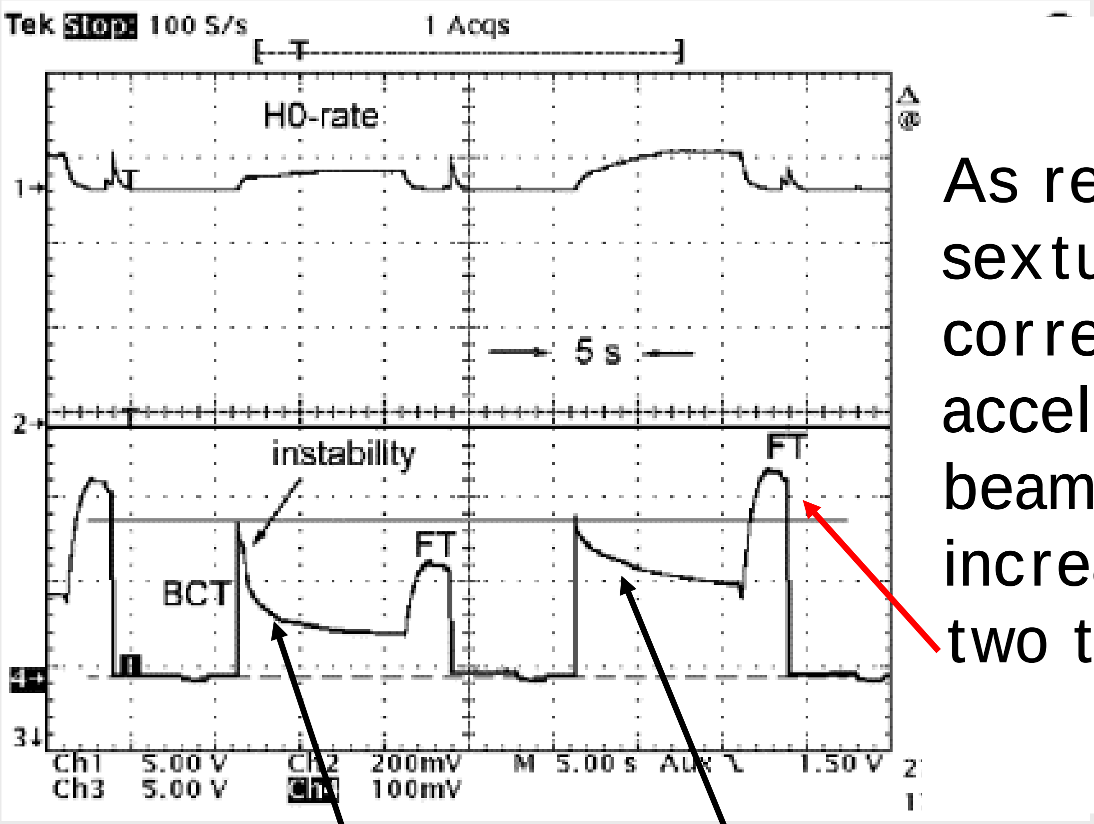
The same phenomenon in HIMAC!

(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.

COSY: Sextupole correction



As result of sextupole correction accelerated beam increased in two times

“Standard” setting of sextupoles

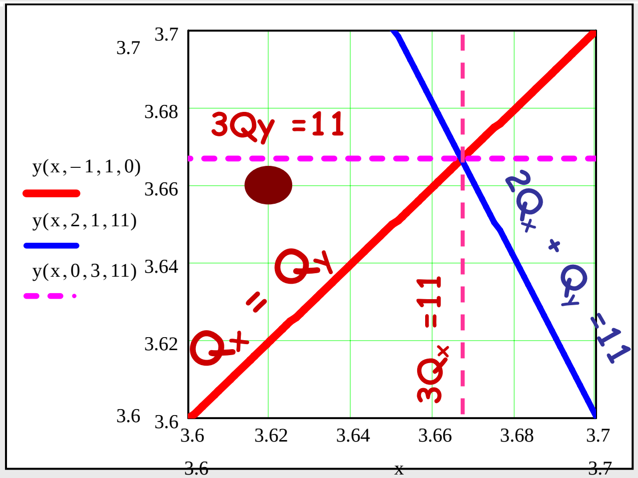
Optimised setting of sextupoles

5.Coherent instability: single injection

What is a nature of "the jump"?

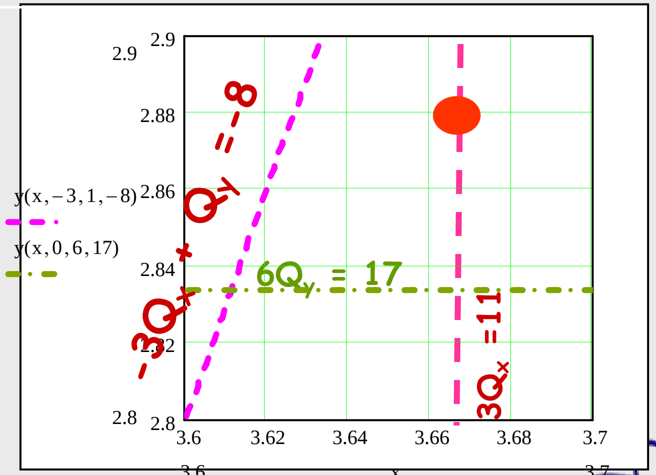
COSY: **Qx = 3.62**

Qy = 3.66



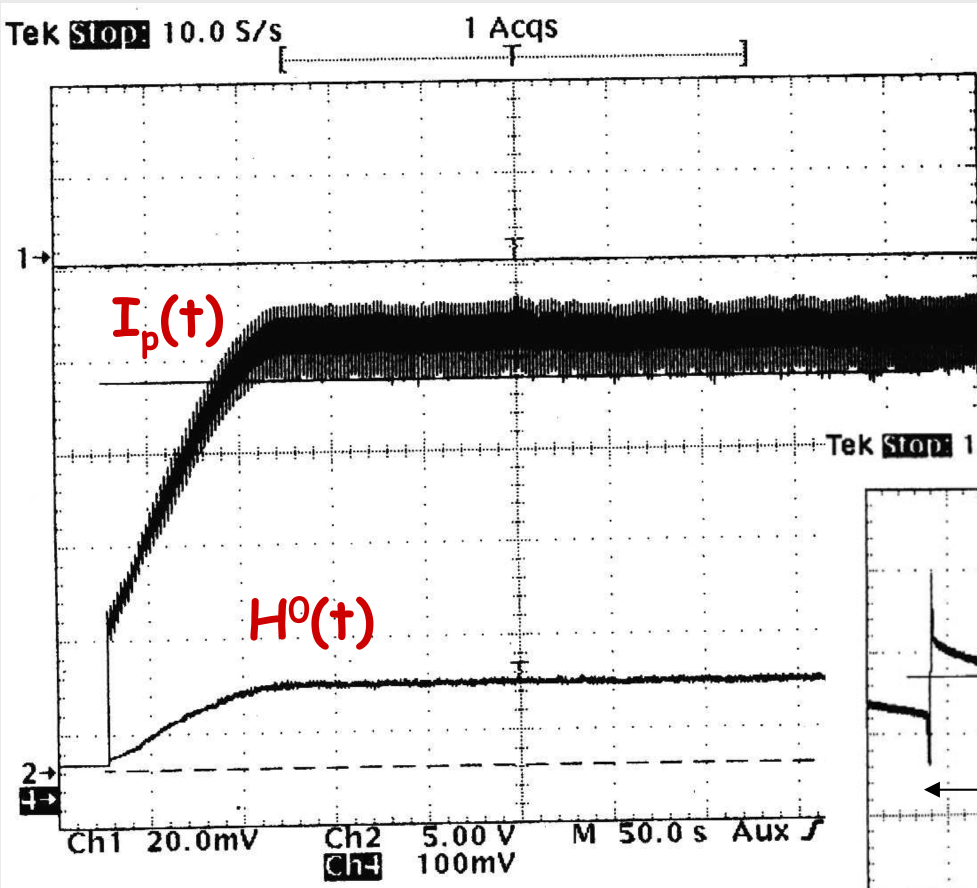
HIMAC: **Q_x = 3.67**

Q_y = 2.88



Coupling?

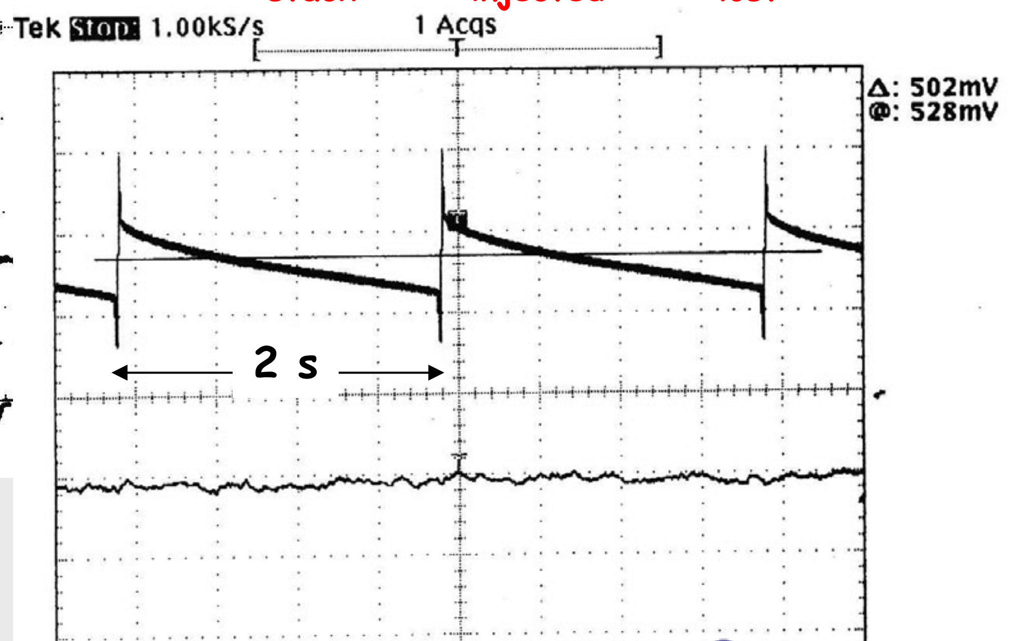
5.2. Cooling and stacking at COSY



Limitation of the stack intensity!

Intensity balance per injection cycle:

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



5.3.Three Ways to The 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, most effective - square-wave modulation

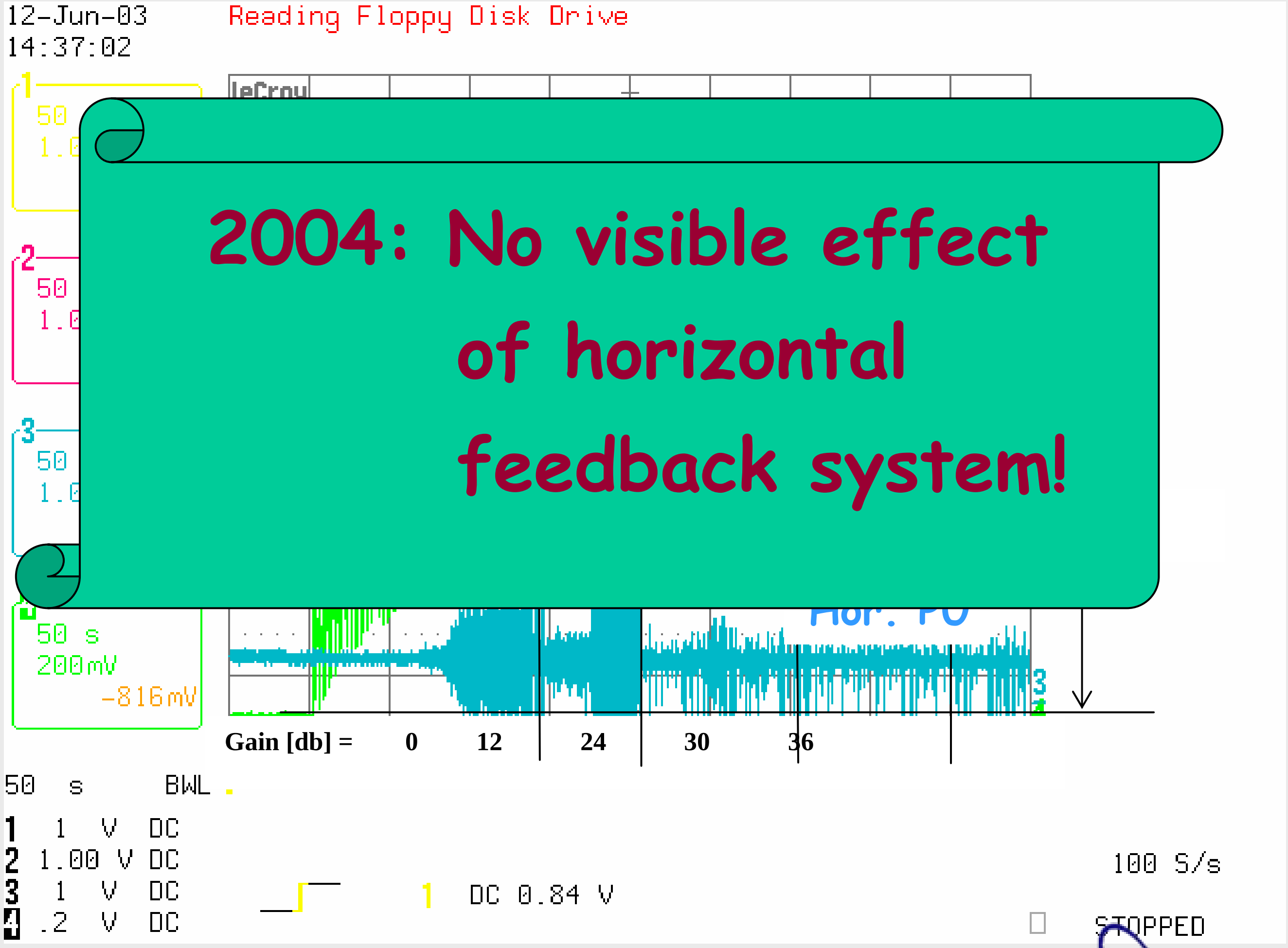
CELSIUS: 50 V amplitude at E_e= 115 keV

- "Hollow beam"

V.Parkhomchuk and colleagues, Budker INP

Vertical Feedback system in COSY (2003)

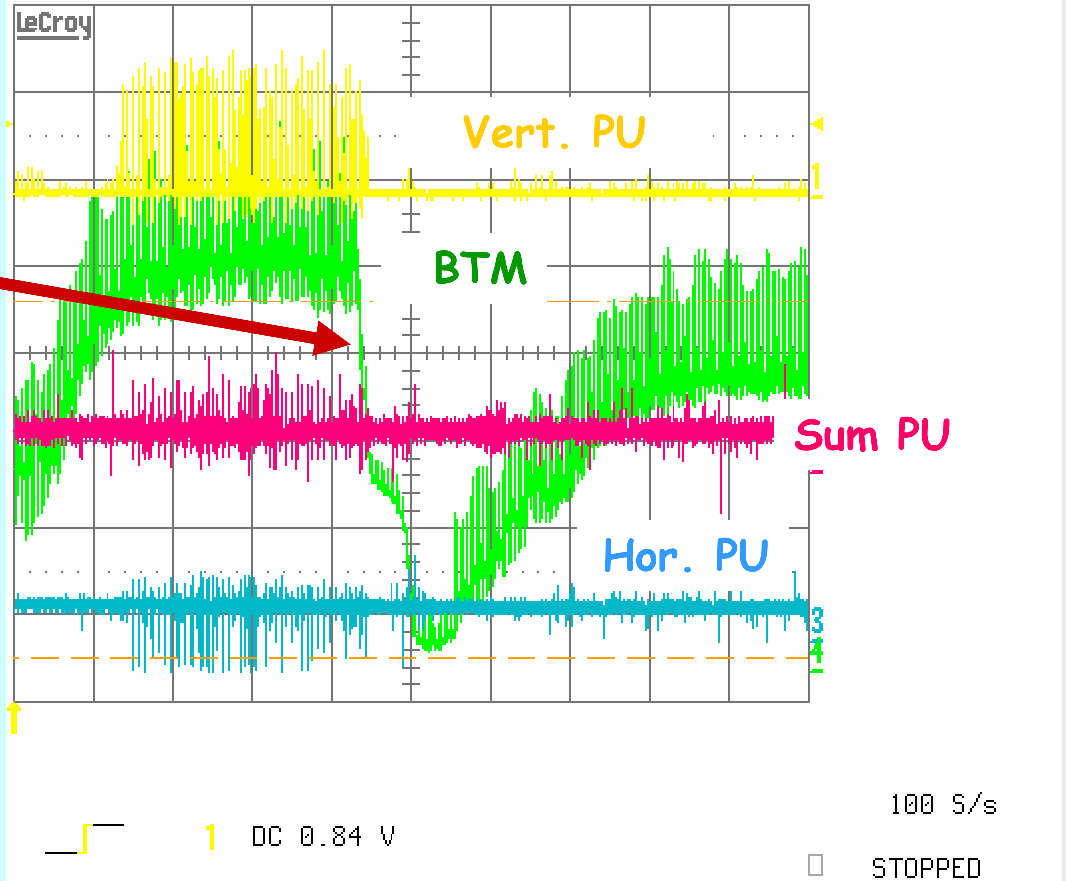
Feedback gain optimization



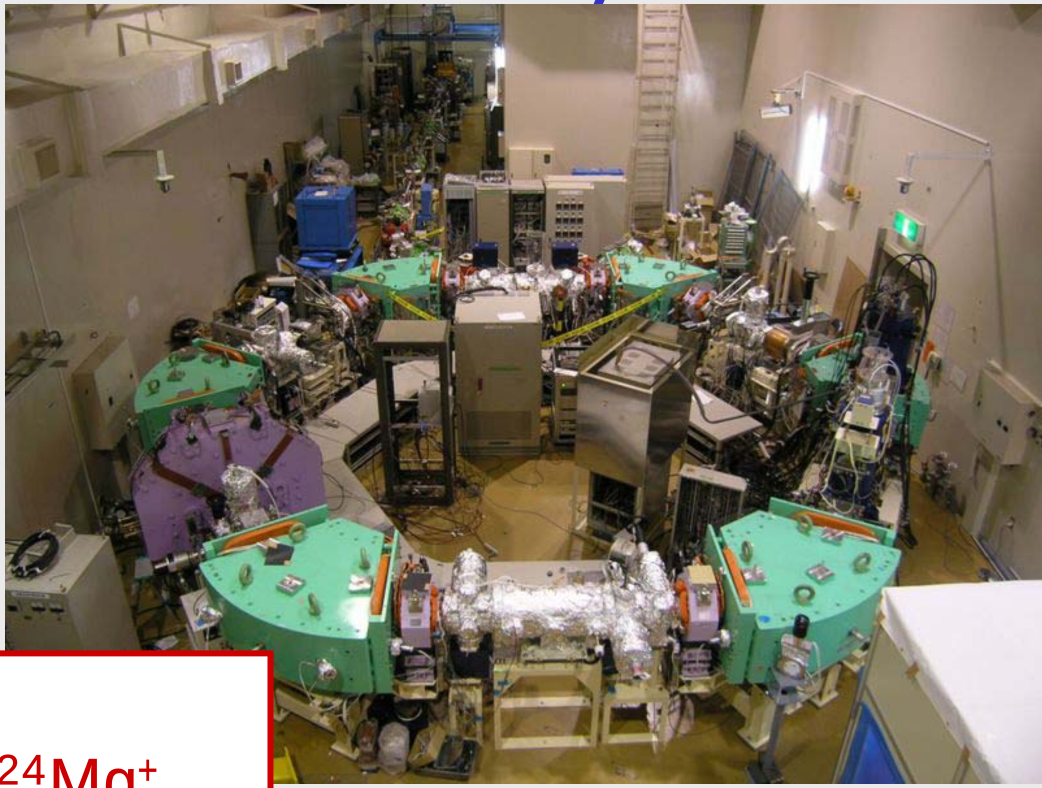
2004: No visible effect of horizontal feedback system!

Vertical Feedback system in COSY: Sextupole Effect

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



Feedback Damping of Coherent Instability at S-LSR



S-LSR Parameters

Particles	p	C^{6+}	$^{24}Mg^{+}$
Energy, MeV/amu	7	2	0.035
Circumference, m	22.557		
Straight section length, m	2.66		

Cooling methods:

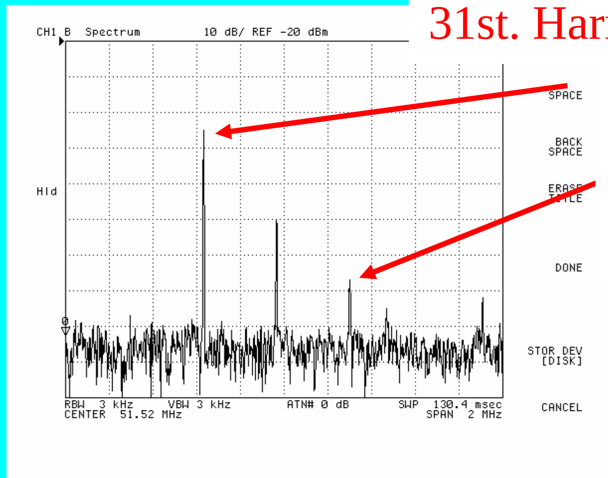
Electron and Laser cooling

Cooling section length, m ~ 0.7

5.Coherent instability: instability suppression

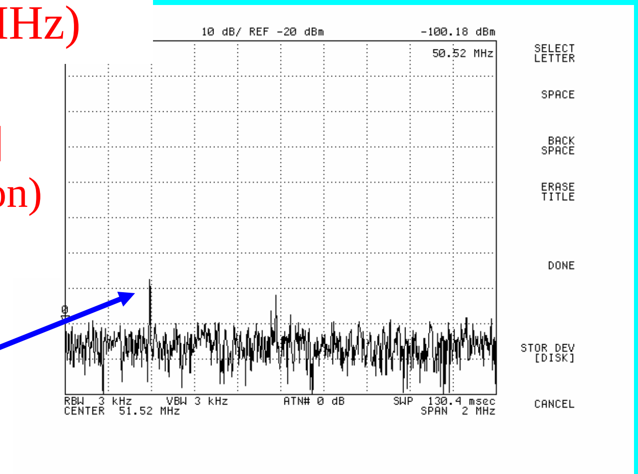
Feedback Damping of Coherent Instability at S-LSR

31st. Harmonics(f_{31} = 51.15 MHz)



Vertical sidebands
-45[dBm] & -86[dBm]
(-50 [dBm] Termination)

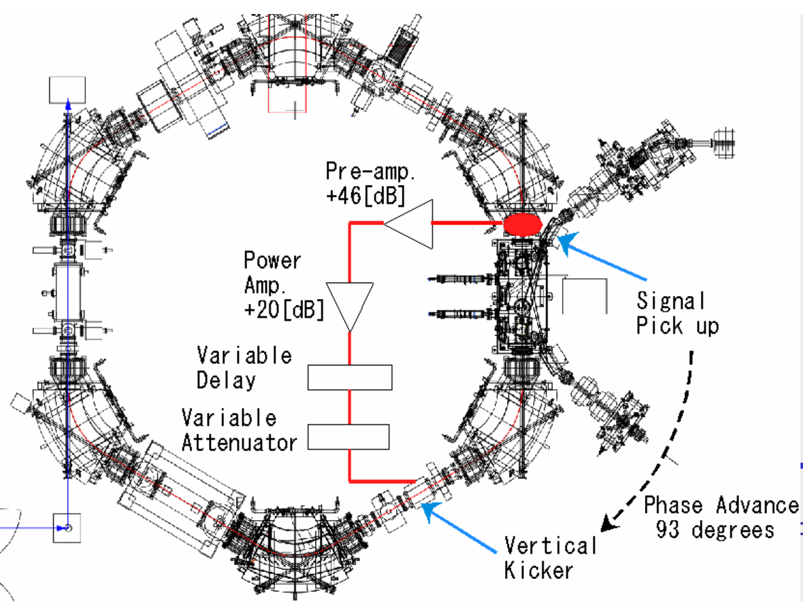
Horizontal Sideband
-88 [dBm]
(50[Ω] Termination)

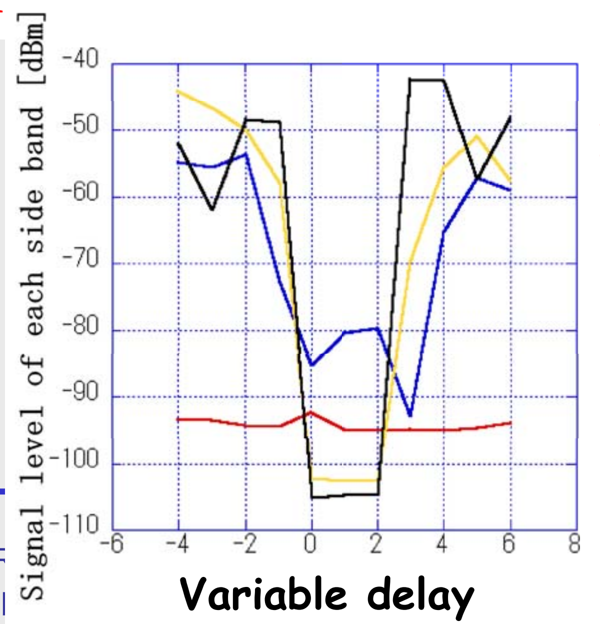


Feedback Off

Feedback On

Feedback Damping System at S-LSR





Precise timing adjustment with the precision of a few nanoseconds is needed.

Measured vertical betatron sidebands

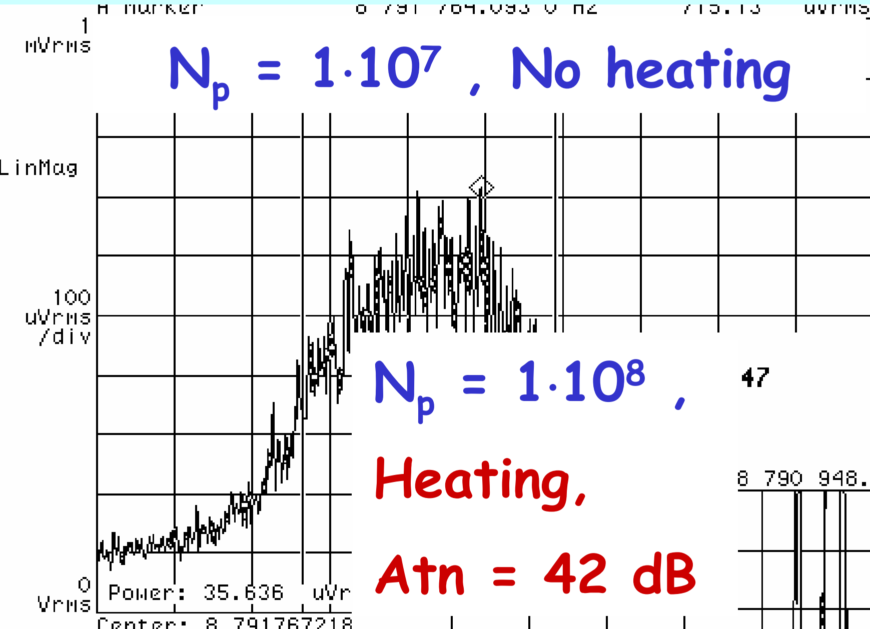
1.235[MHz]:Red
23.8[MHz]:Blue
51.15[MHz]:Orange
96.2[MHz]:Black

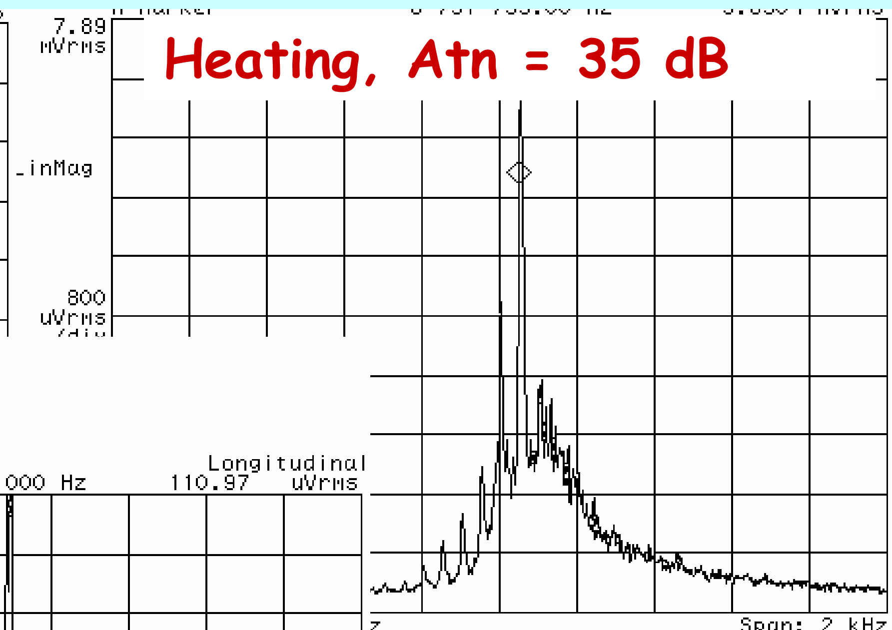
5.4. IBS (?) and longitudinal modulation

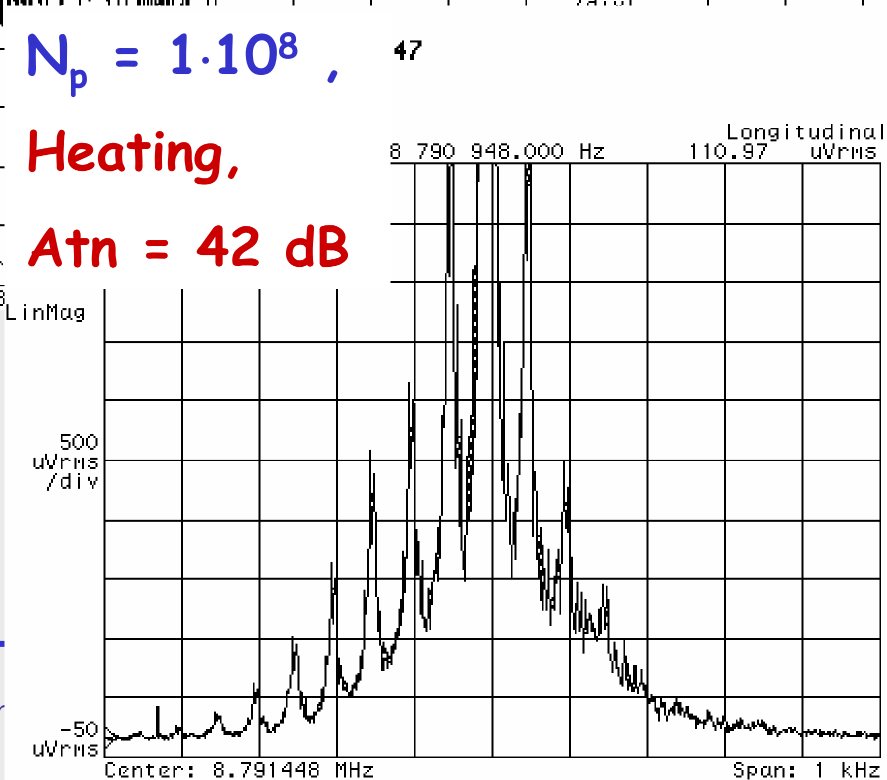
Influence of transverse heating Atn = attenuation

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

Signal of Schottky noise: 18^{th} harmonics, f = 5.8 MHz







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, Proc. EPAC’04, Lucerne, 2004.

"Natural" neutralization

Potential at the electron beam axis:

a,b – electron beam and vacuum chamber radi[i]

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

Neutralization level
due to variation of the vacuum chamber radius:

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

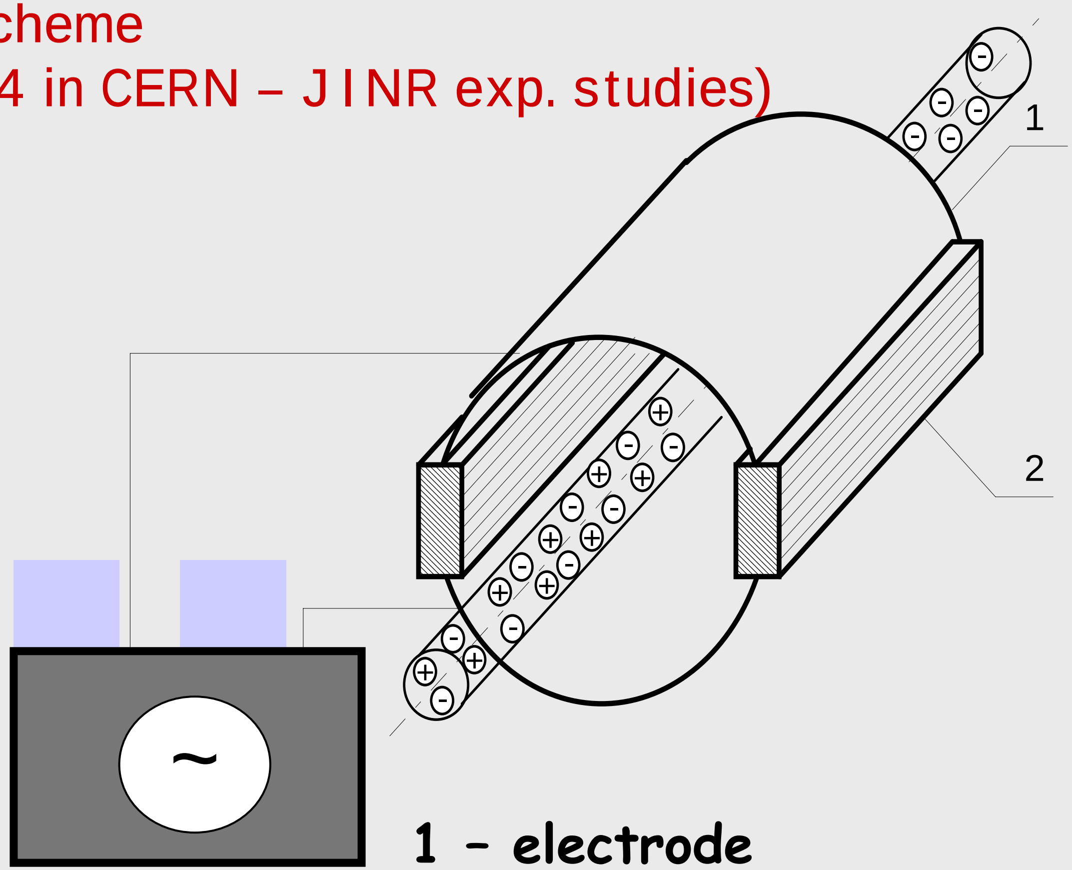
Electron energy in partially neutralised electron beam:

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

Control of the neutralization level with "The Shaker"

"The Shaker" principle scheme
(R.Macaferri, CERN, 1994 in CERN – JINR exp. studies)

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



1 – electrode

2 – conducting glass ("Parkhomchuk's trap")

Control of the neutralization level with the shaker:

The ion oscillation frequency is equal to

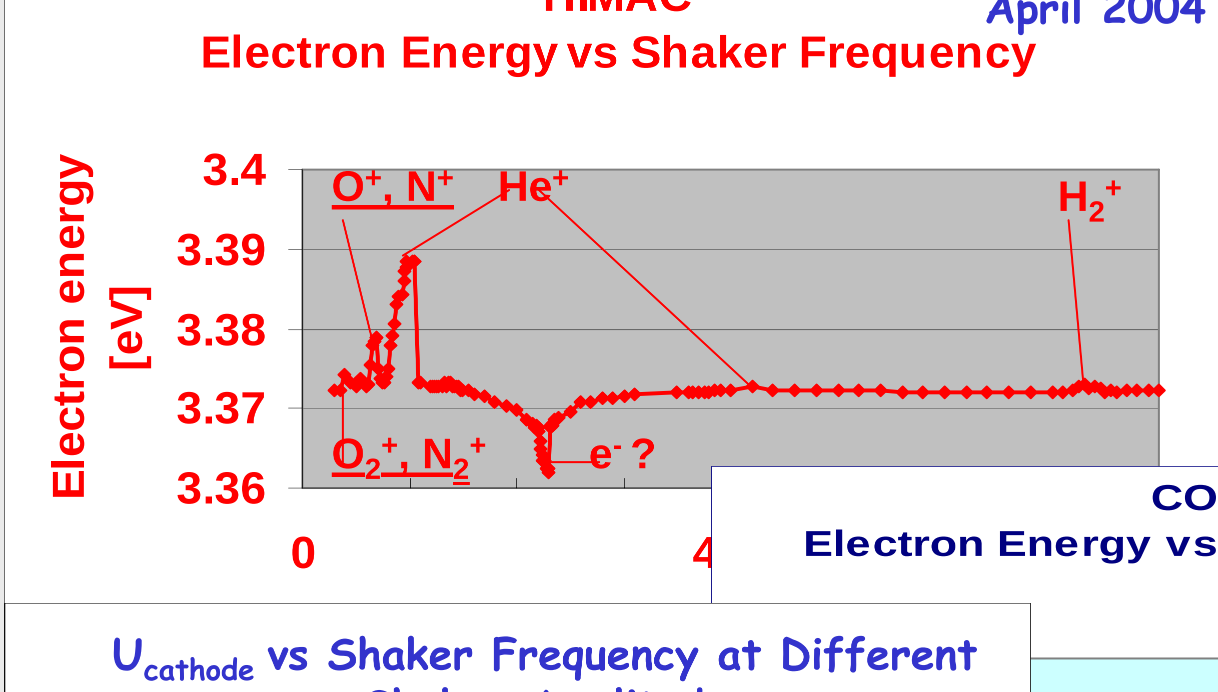
$$\omega = \sqrt{\omega_i^2\left(1-\eta_{neutr}\right)+\omega_B^2/4} \pm \omega_B/2$$

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

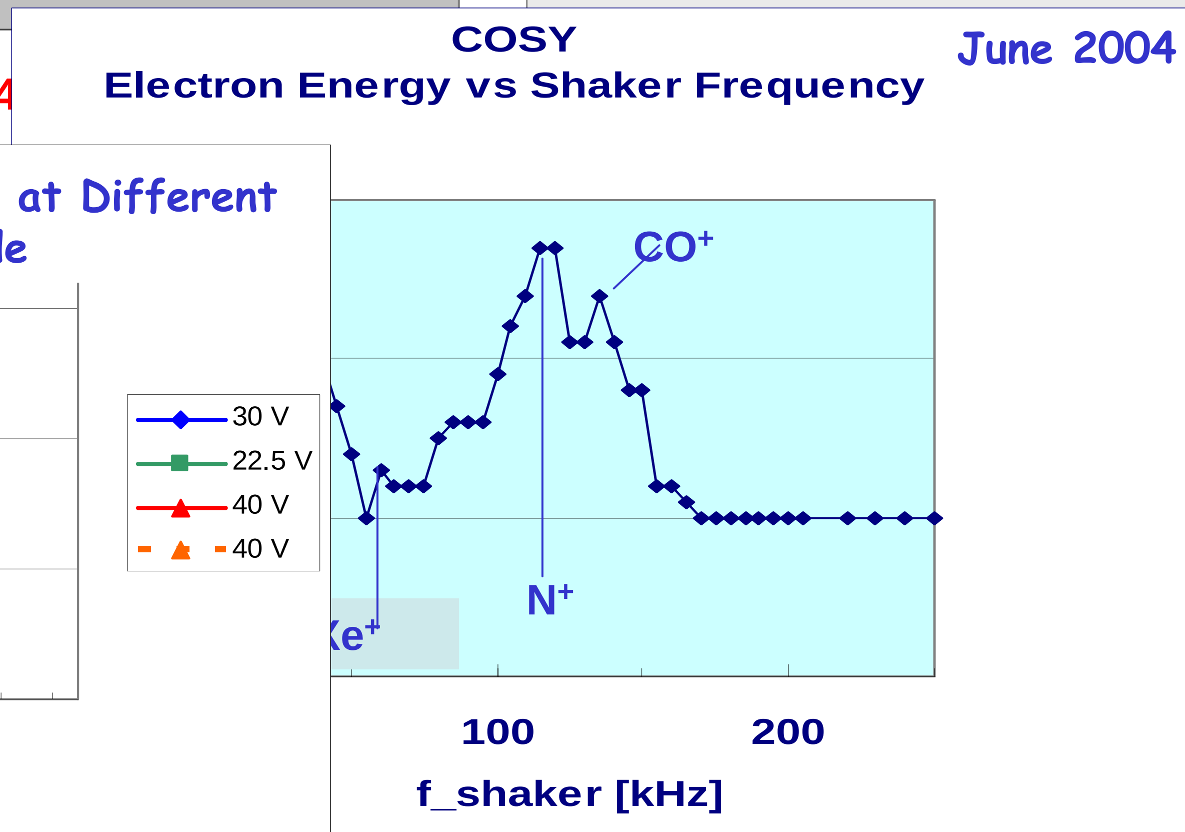
The ions can be "shaken out" if

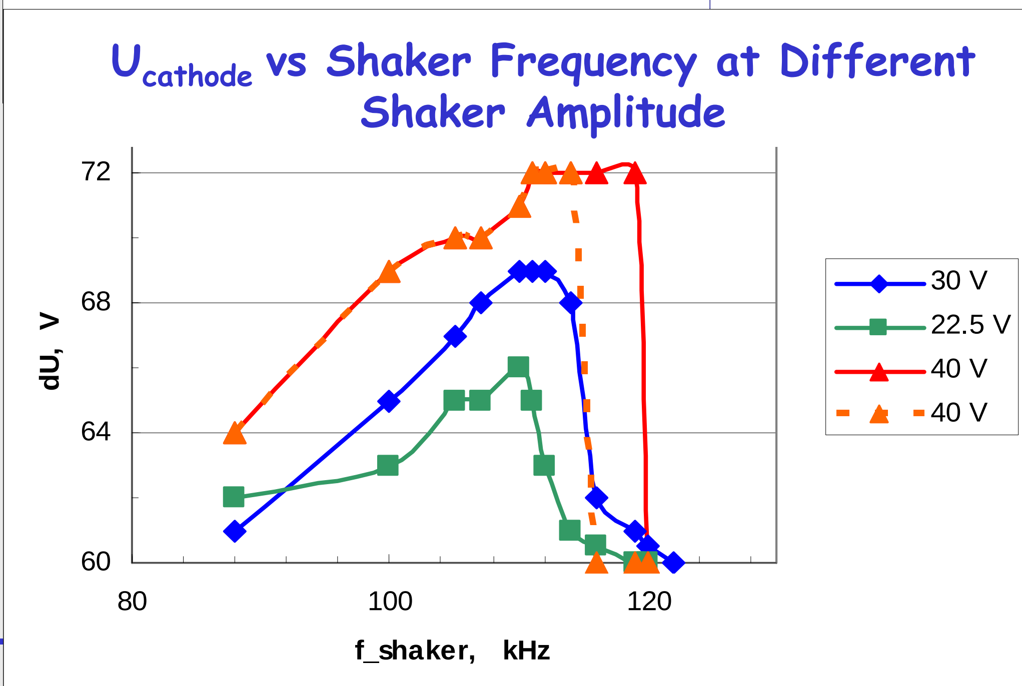
$$f_{shaker} = \omega / 2\pi \; .$$

6. Ion cloud…



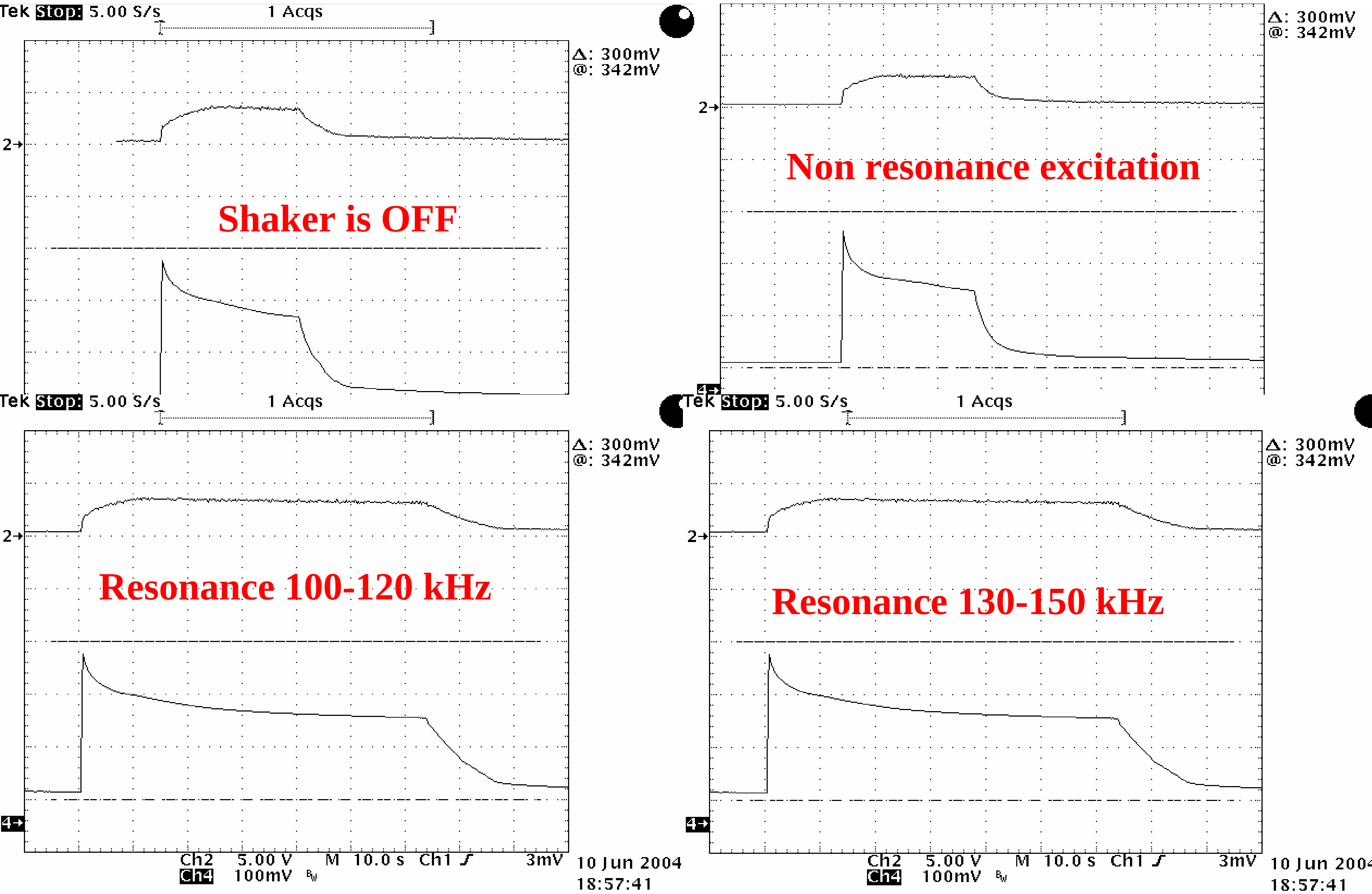
A/Z of residual gas ions stored in electron beam





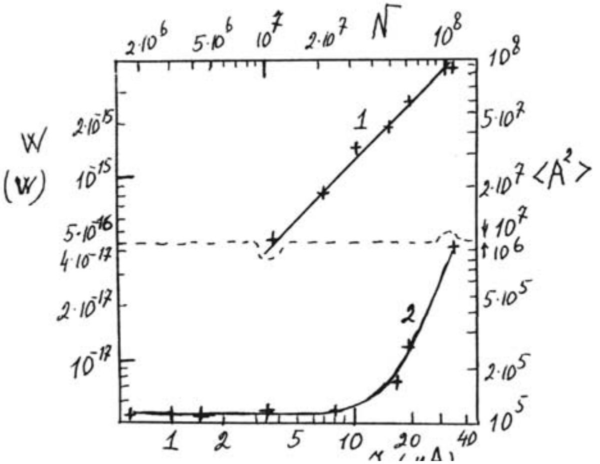
6. Ion cloud…

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



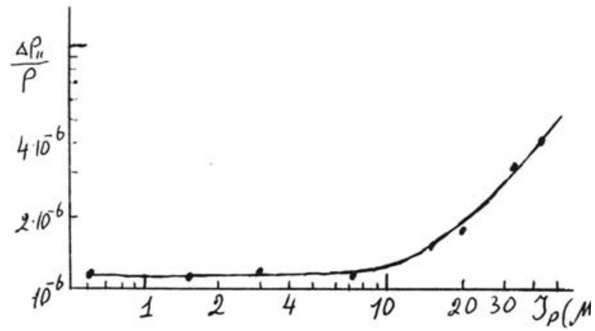
7. Proton beam ordering: NAP-M ⇒ COS

V.Parkhomchuk et al., NAP-M (1979)

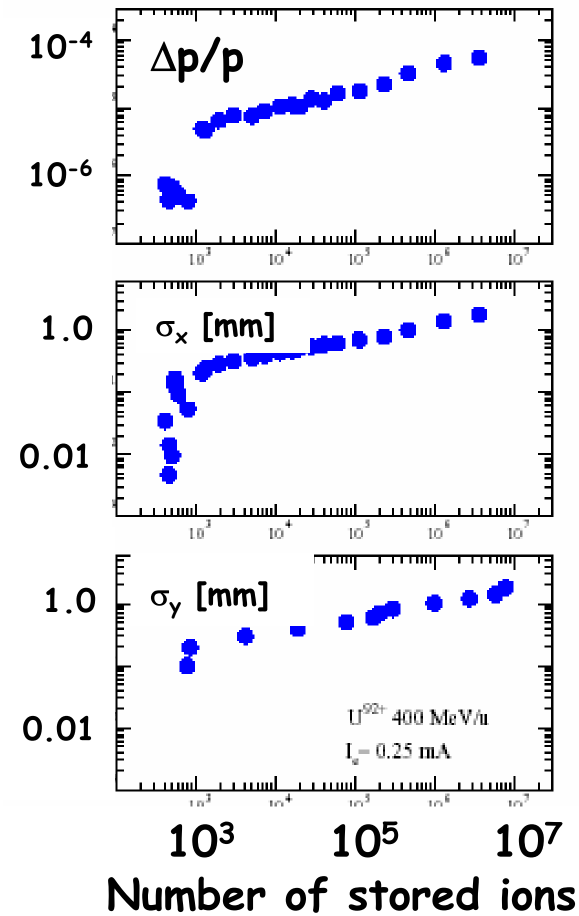


Schottky noise power of uncooled (1) and cooled (2) proton beam at 68 MeV

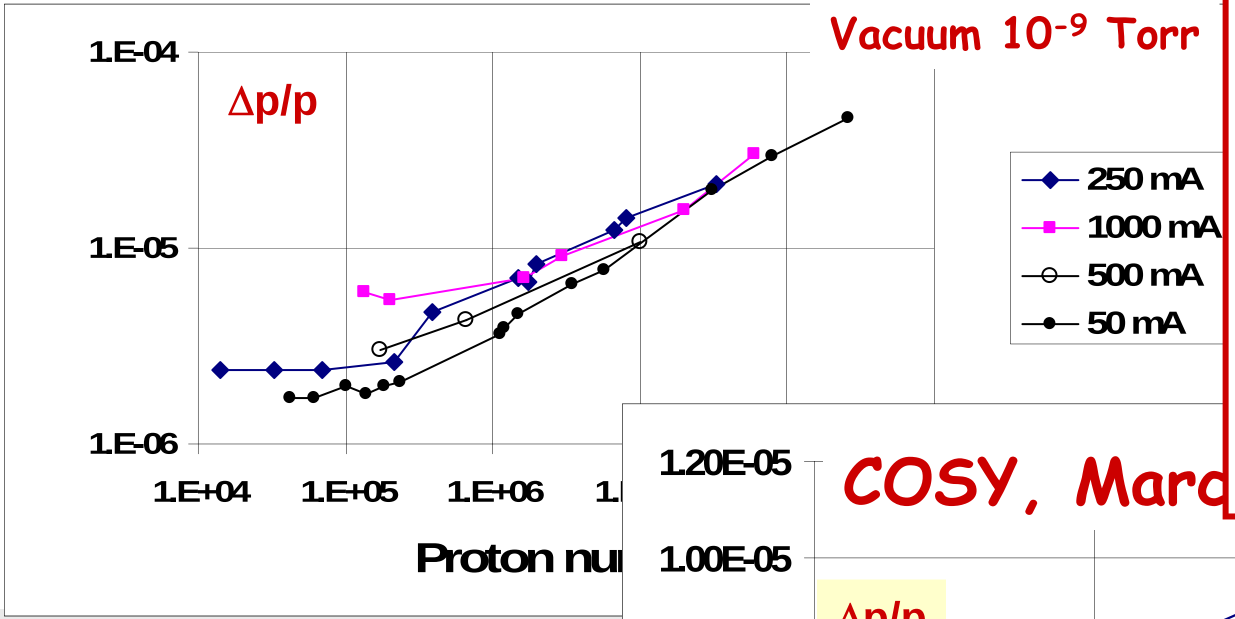
Δp/p vs p-beam curren

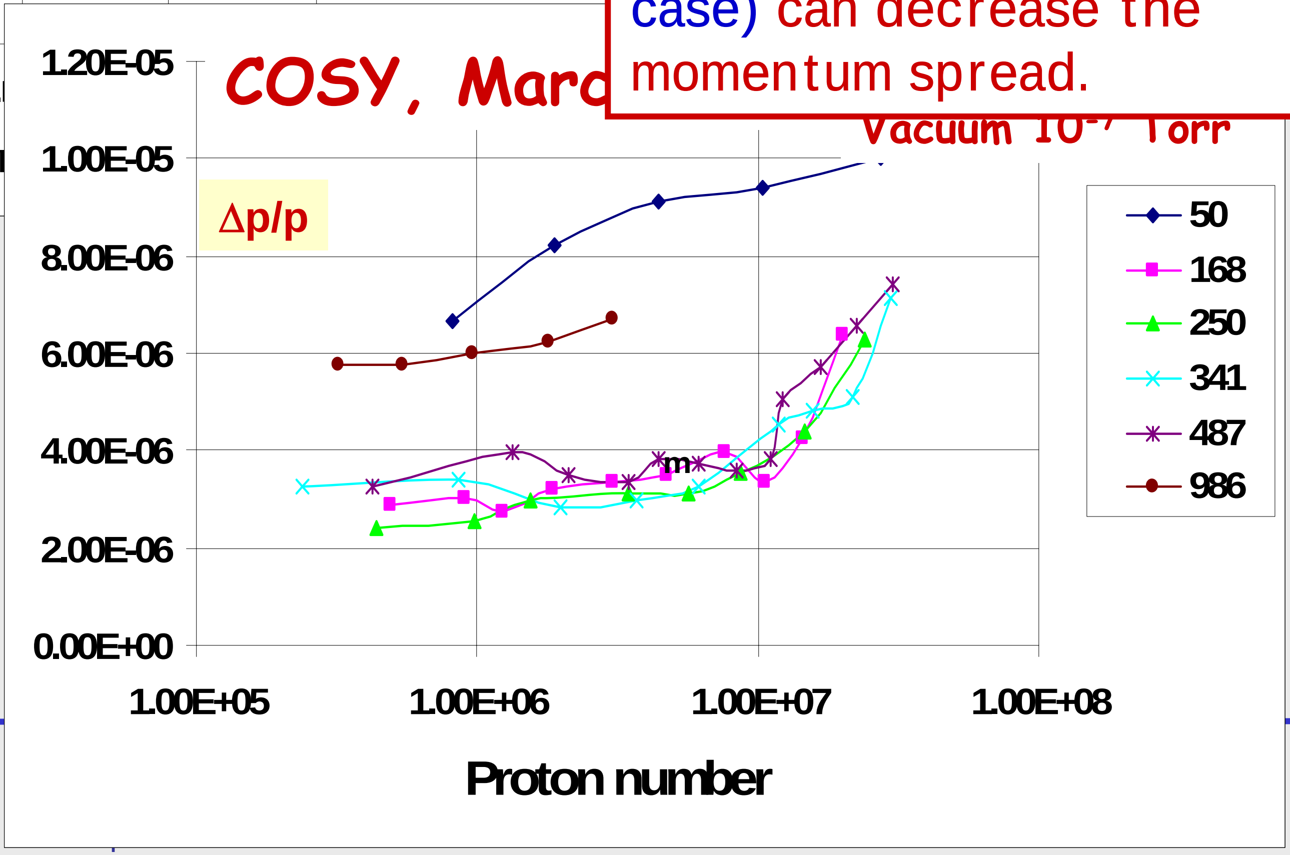


"Phase transition" of U^{92+} beam at 400 MeV/u in ESR, M.Steck et al. (2004)



COSY, August 2005





Note:

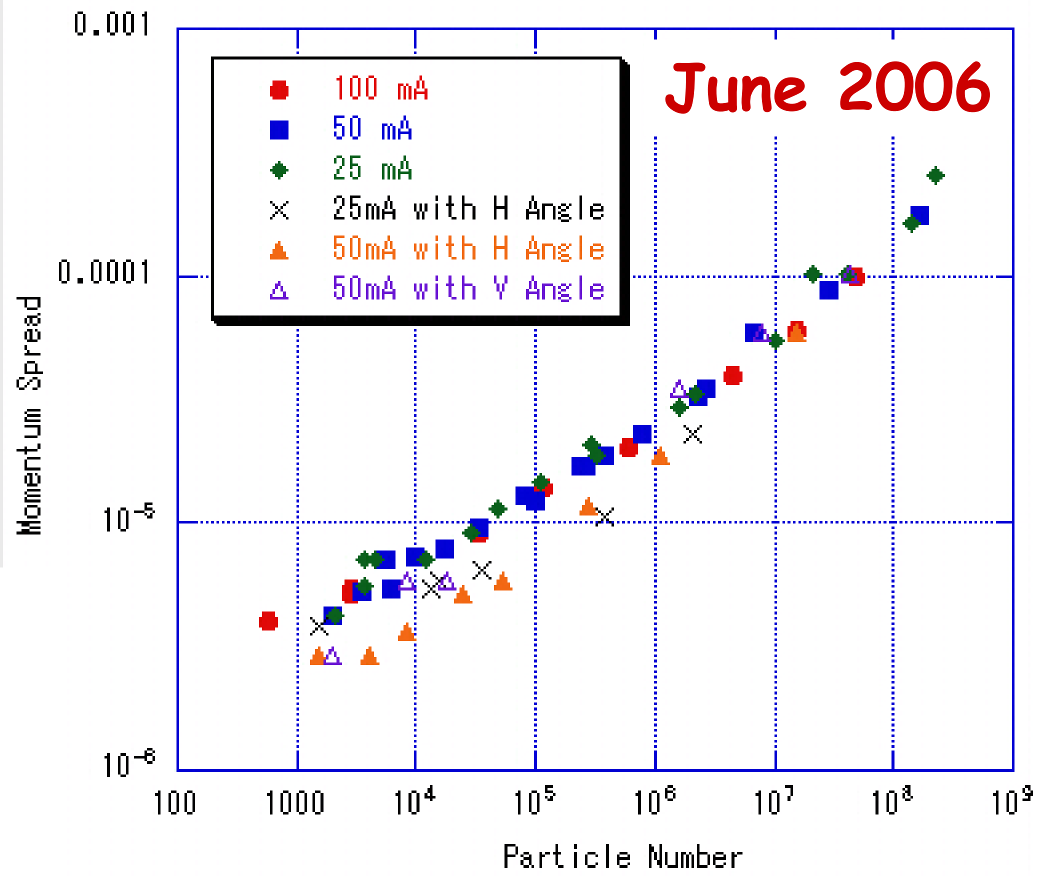
at poor vacuum for 10^7 protons $\Delta p/p = 4\cdot10^{-6}$,
at good vacuum for 10^7 protons $\Delta p/p = 10^{-5}$

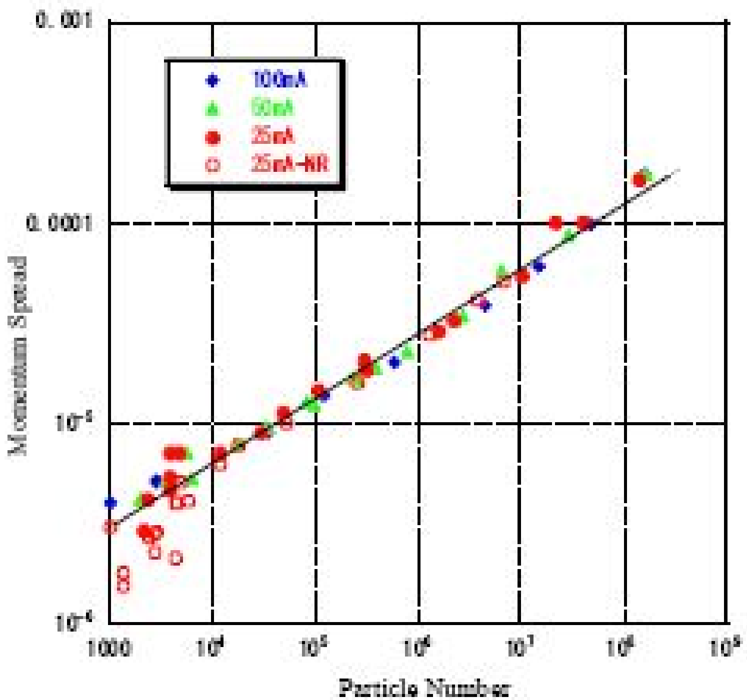
⇓

Additional transverse heating (rest gas in our case) can decrease the momentum spread.

7. Proton beam ordering: NAP-M ⇒ COSY ⇒ S-LSR (Contnd)

S-LSR





Beam ordering criteria

"Common" criterion: $\Gamma = \frac{U}{T} = \frac{Z^2 e^2}{aT} > 1$

1st criterion: $\Gamma_1 = \frac{Z^2 e^2}{a_{\parallel}\sqrt{T_{\parallel} T_{\perp}}} < 1$

(the necessary condition)

2st criterion: $\Gamma_2 = \frac{Z^2 e^2}{T_{\parallel} \sigma_{\perp}} > \pi$

(the sufficient condition)

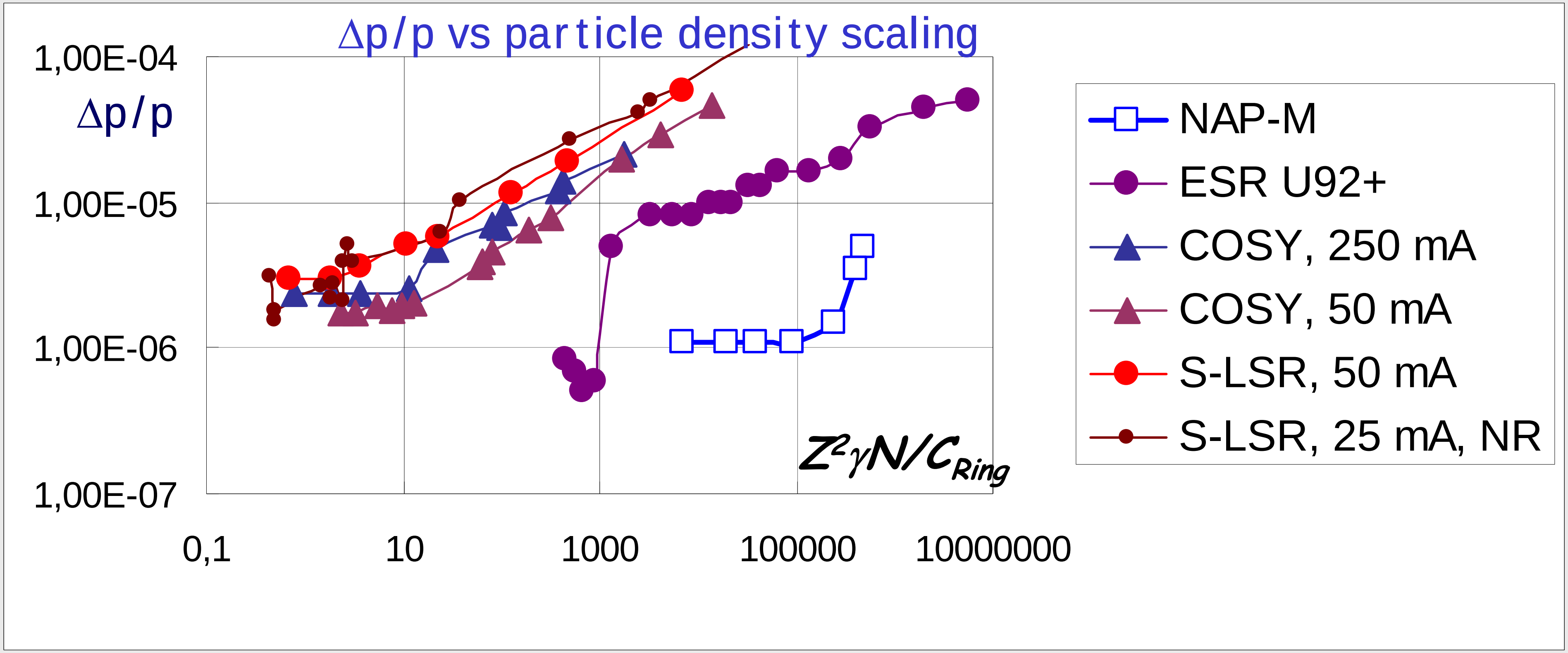
T.Katayama,
I.Meshkov,
D.Möhl,
A.Sidorin,
A.Smirnov
(2003)

Do note:

$\Gamma_2 \propto \frac{1}{T_{\parallel}\sqrt{T_{\perp}}}$

Conclusion: to reach an ordering state one needs to have a cold ion beam of a low intensity (large $a_{||}$)

Comparison of Beam ordering Experiments



Conclusion: “The Density Factor” reached in COSY and S-LSR experiments is much smaller than in the NAP-M and ESR experiments, but… …the proton temperature and Γ-factors ?

Stability of Magnetic field, electron energy and electron current?

Comparison of The Ordering Criteria

Ring	NAP-M	ESR	COSY	S-LSR
Circumference, m		108,4	183.5	22.56
Ions	p	$^{238}U^{92+}$	p	p
E, MeV/u	65	400	45	7
$\Delta p/p$	$1\cdot10^{-6}$	$0.7\cdot10^{-6}$	$1\cdot10^{-6}$	$1\cdot10^{-6}$
a_x, mm	**0.1**	0.01	**0.5 (?)**	**?(0.5)**
N	$2\cdot10^{7}$	1000	1000	1000
Γ_1 (<1)	**0.28**	**0.0015**	**0.001**	**0.001**
Γ_2 (> 1)	**0.012**	**4.3**	**0.5**	**2.9**

Conclusion According "Ordered Beam"

No sudden reduction of momentum spread ⇒
up to now no ordered beam at COSY ans S-LSR.

Results are very similar to NAP-M experiments.

Additional transverse heating during cooling process can decrease the momentum spread.

Conclusion: to reach an ordering state one needs to have a cold ion beam of a low intensity (large $a_{||}$)

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.

authors and

Thank you for your attention!

Der Erste May 2002 Demonstr

in COSY Control Room