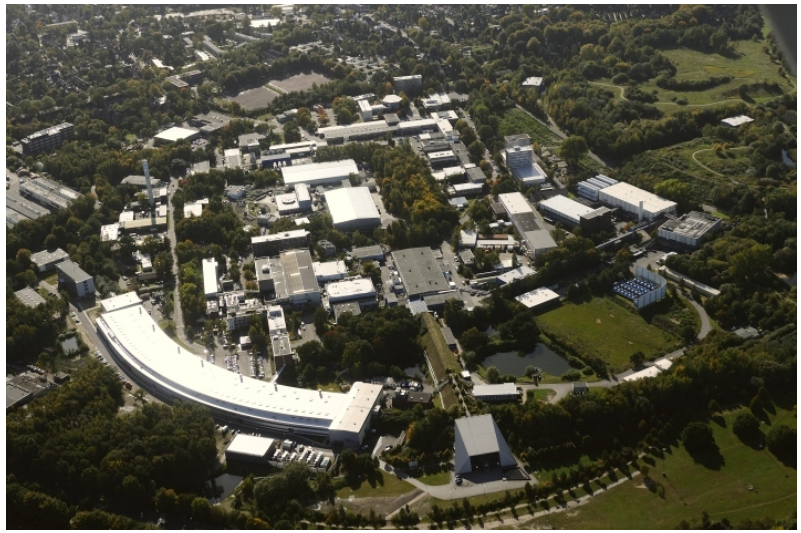
Emittance Growth and Tune Spectra at PETRA III

Presentation at the ECLOUD 2010 workshop



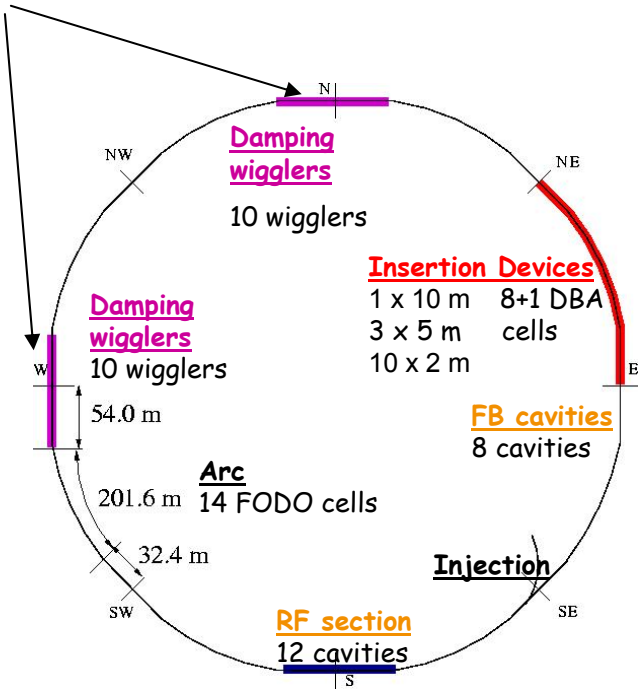
Rainer Wanzenberg

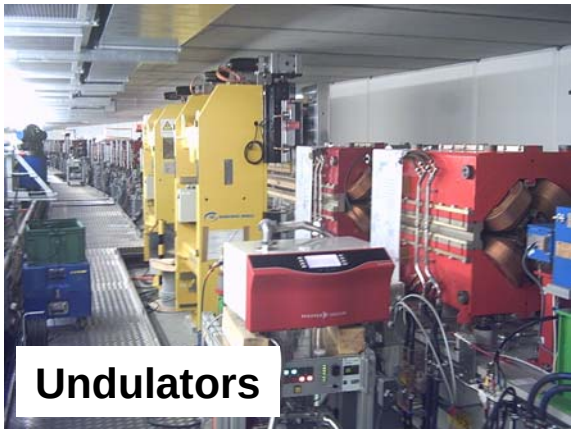
ECLOUD 2010
October 8-12, 2010
Statler Hotel, Cornell University
Ithaca, New York USA

HELMHOLTZ ASSOCIATION

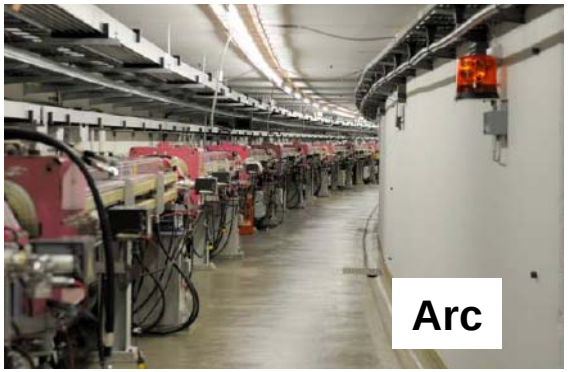
DESY

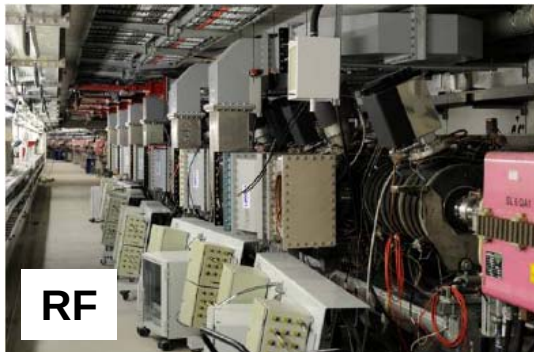
PETRA III - Overview





Parameter	PETRA III
Energy / GeV	6
Circumference /m	2304
Total current / mA	100
Emittance (horz. / vert.) /nm	1 / 0.01





PETRA III - Parameters

Parameter	PETRA III	
Energy / GeV	6	
Circumference /m	2304	
RF Frequency / MHz	500	
RF harmonic number	3840	
RF Voltage / MV	20	
Momentum compaction	$1.22\ 10^{-3}$	
Synchrotron tune	0.049	
Total current / mA	100	
Number of bunches	**960**	**40**
Bunch population / 10^{10}	**0.5**	**12**
Bunch separation / ns	**8**	**192**
Emittance (horz. / vert.) /nm	1 / 0.01	
Bunch length / mm	12	
Damping time H/V/L / ms	16 / 16 / 8	

Harmonic number: h = 3840
Revolution time: 7.68 micro sec

Bunch positions: 960
(8 ns bunch to bunch spacing)

PETRA III is running with positrons !

Damping wigglers

- **Number 20**
- **$L_{wiggler}$ = 4 m**
- **B = 1.5 T**
- **λ = 0.2 m**

} 80 m

ε_x: 4.5 → 1 nm rad

Machine can be operated w/o wigglers

PETRA III – Commissioning / First user runs

2009

- April 10 – May 03, 2009
  - First stored beam (April 13)
  - First light from a undulator (April 30)
  - commissioning BPM electronics
  - First optics checks
- May 20 – June 25, 2009
  - Operation **without wigglers**
  - work on optics, orbit, beam based alignment
- July 6, 2009 - …
  - Operation **with wigglers**
  - with **all** (2 x 10) wigglers from Aug 12

2010

- Feb 18, 2010 - … (with wigglers)
  - Commissioning 3 days / week
  - First user runs (friendly user) 4 days / week
- Aug 2 – Aug 7, 2010
  - Machine studies **without wigglers**
  - Investigation of vertical emittance growth
- Aug 9, 2010 - …
  - Operation **with wigglers**
  - **First regular users (Sep. 2010)**
  - Beam line commissioning

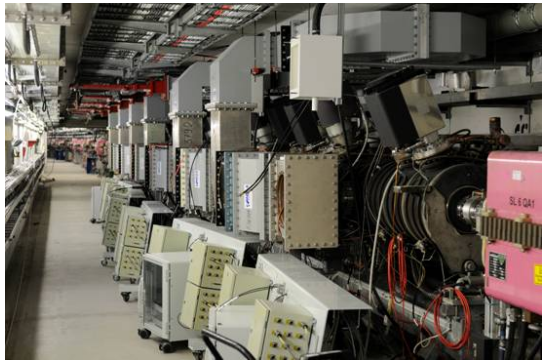
Current Limitations

Coupled bunch instabilities:

PETRA II	Long.	Horiz.	Vert.
I_{thres} (mA)	7	6	6
1/τ (Hz)	35	50	60
Z_{eff}	3.6 MΩ	45 MΩ/m	54 MΩ/m

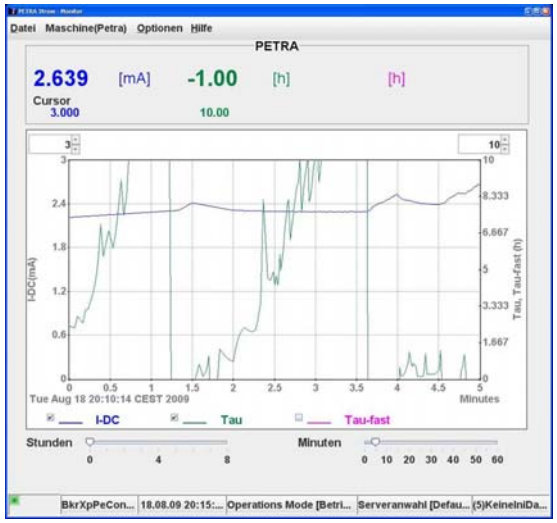
PETRA III: 12 seven cell cavities which large par. shunt impedance

→ powerful broadband (BW≥ 60MHz) feedback neccessary



Single Bunch (TMCI):

Design
2.5 mA



Petra III beam current on Aug 18, 2009

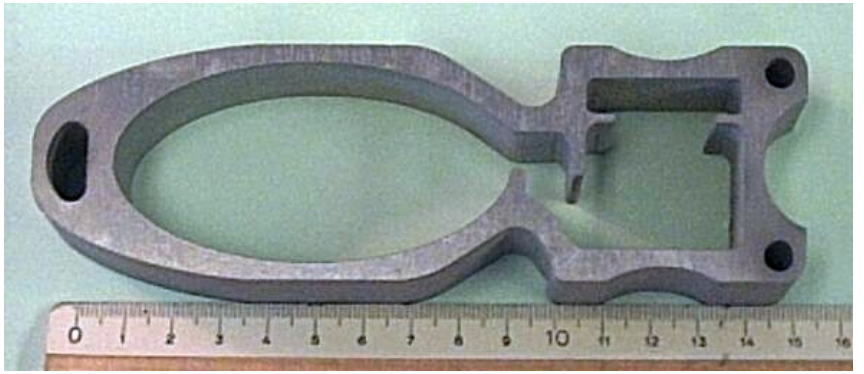
Single bunch intensities of up to 2.9 mA could be stored;
Deliberately limited at this current in ordner not to damage BPM electronics

Measured coherent tune shift vs, current

$$\frac{\Delta f_x}{\Delta I} \approx -0.23 \frac{\text{kHz}}{\text{mA}} \qquad \frac{\Delta f_y}{\Delta I} \approx -1 \frac{\text{kHz}}{\text{mA}}$$

PETRA III Vacuum chamber

Arc: **Al**, 80 mm x 40 mm

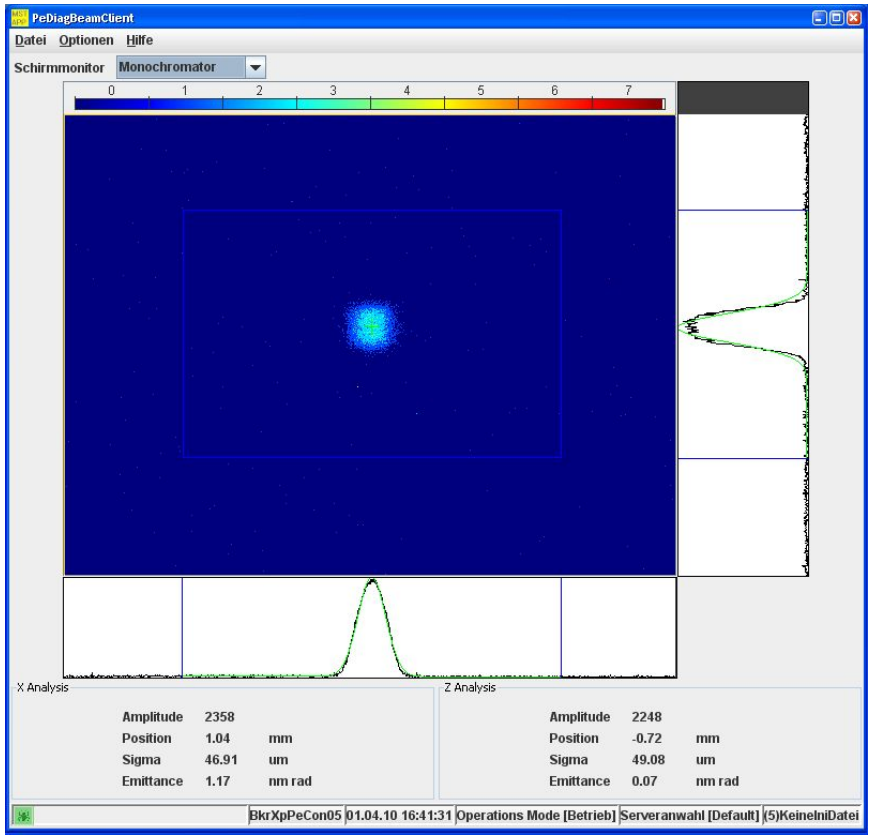


Wiggler: **Al**, 96 mm x 17.9 mm
NEG coated

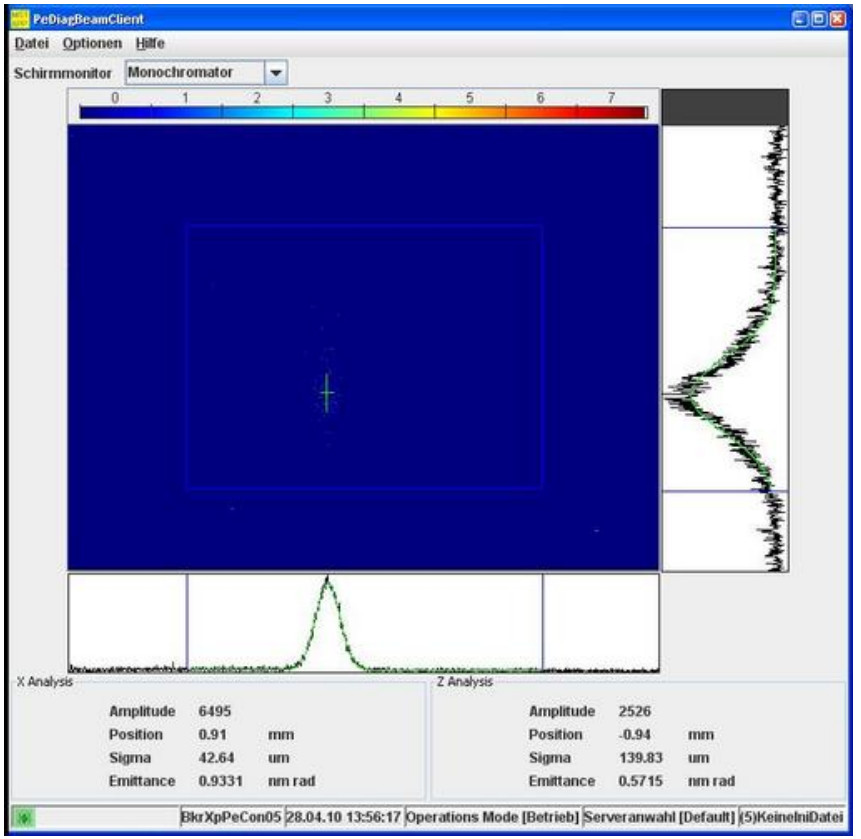
Undulator: **Al**, 57 mm x 7 mm

Vertical emittance blow up

50 mA in 70 bunches



63 mA in 70 bunches

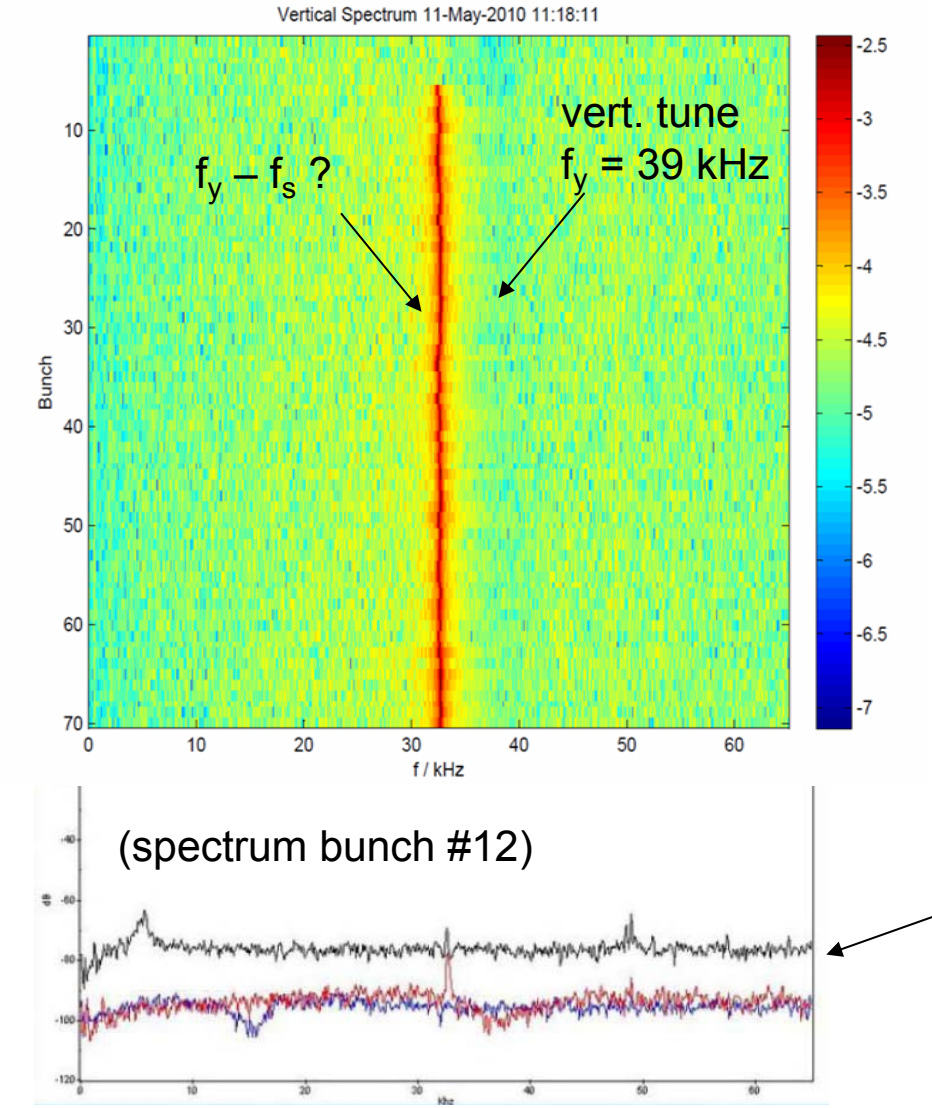


Threshold ~ 50 mA

Synchrotron radiation from a bending magnet is used to image the beam spot onto a high resolution CCD camera system.
(G. Kube et al., Overview of the Diagnostics Systems of Petra III,
Proceedings of EPAC08, Genoa, Italy)

Vertical emittance growth (70 bunches)

Vertical Tune Spectra
70 bunche (Δt_B=96ns), I = 55 mA (May 11, 2010)



Remedy for 70 bunches:
- $\xi \rightarrow +5$
- Increase Gain of vertical feedback by a factor of 4

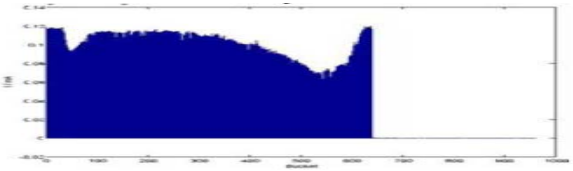
black: longt. spectrum
red: vert. spectrum
blue: horz. spectrum

Signal from the feedback system

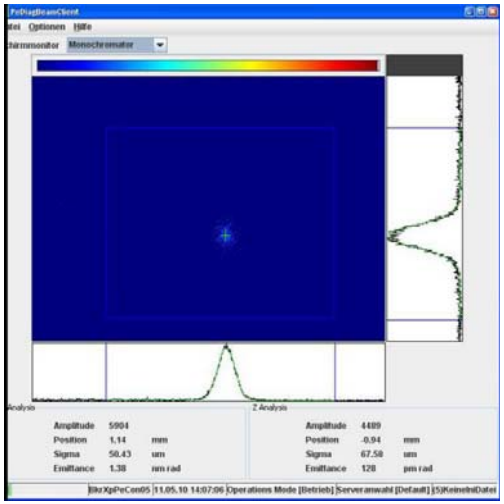
Vertical emittance blow up (640 bunches)

640 bunches, 8 ns bunch spacing + gap
639 x 8 ns = 5112 ns, gap 2568 ns

Bunch current:

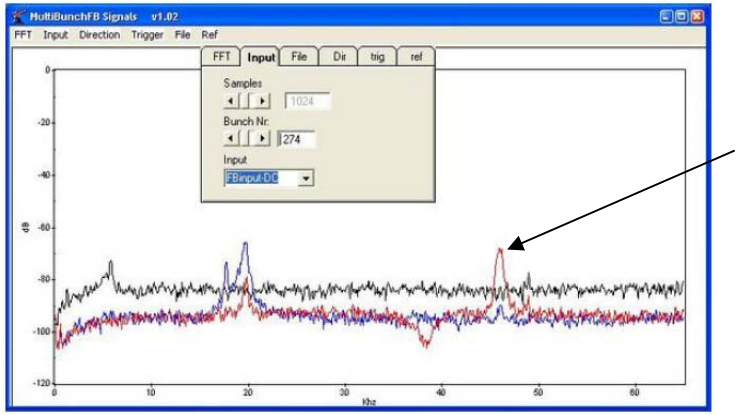


Harmonic number: h = 3840
Revolution time: 7.68 micro sec
Bunch positions: 960 (8 ns bunch spacing)

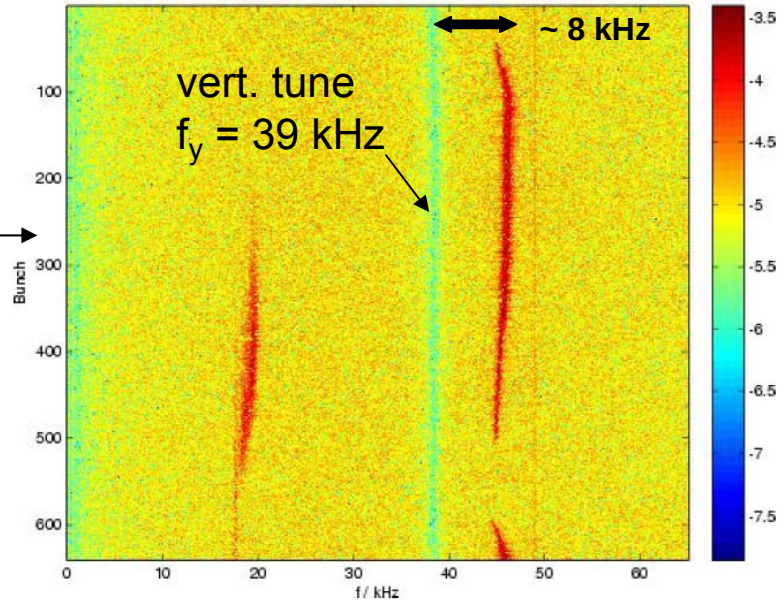


measured emittance on May 11, 2010
Horz. 1.38 nm, total current 65 mA
Vert. 128 pm

Tune spectrum, bunch position #274

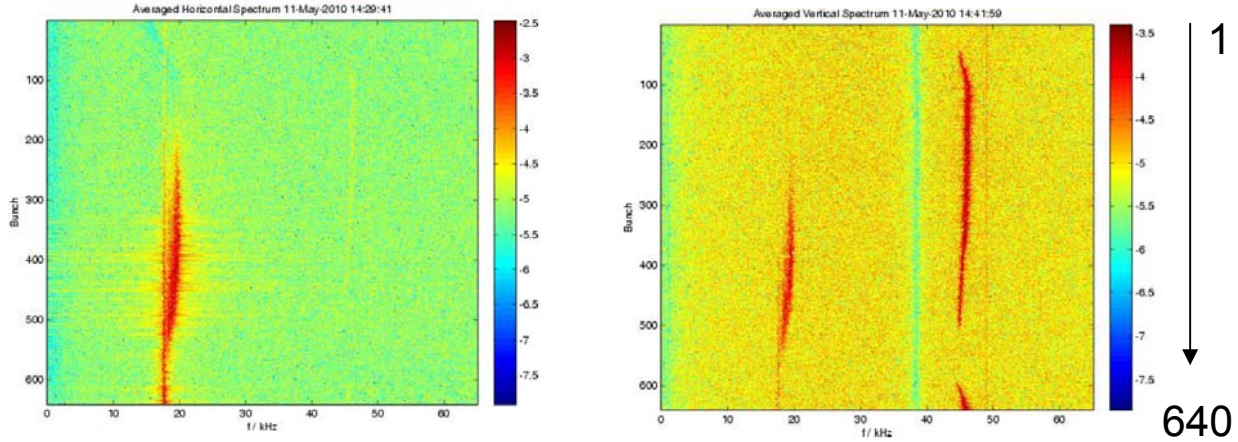


#274



PETRA III und SPS Tune spectra

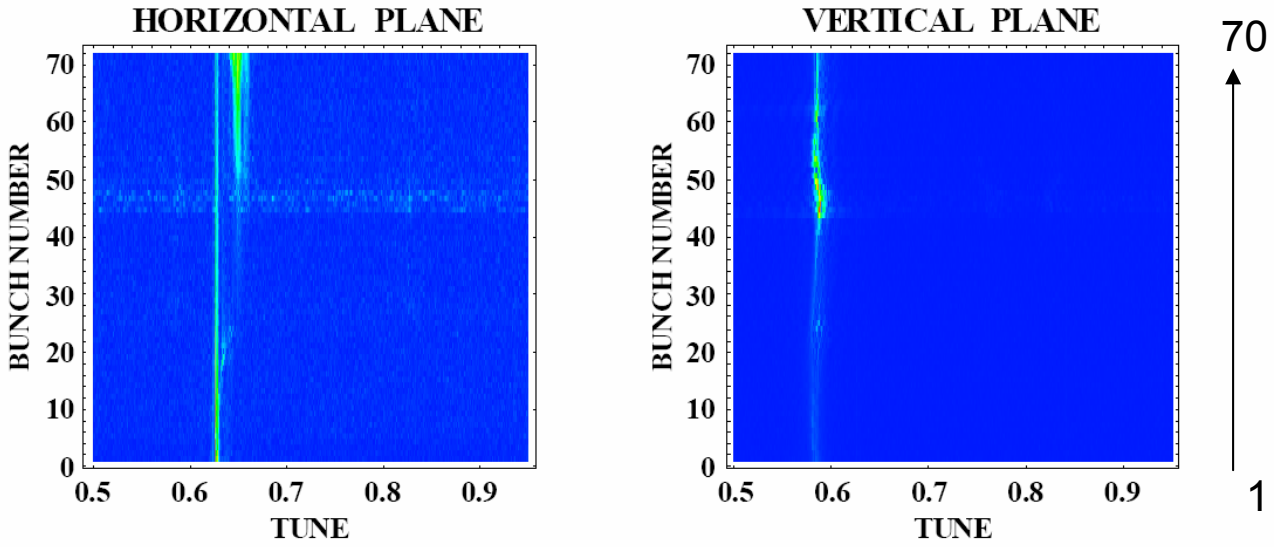
PETRA



PRTRA III
is running e+

e cloud ???

SPS

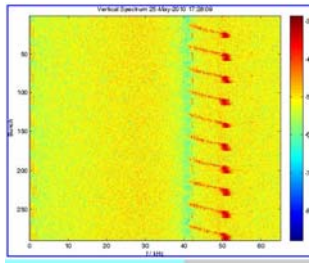


At PETRA III tune spectra have been observed with some characteristics which have been observed at the SPS in connection with electron cloud effects.

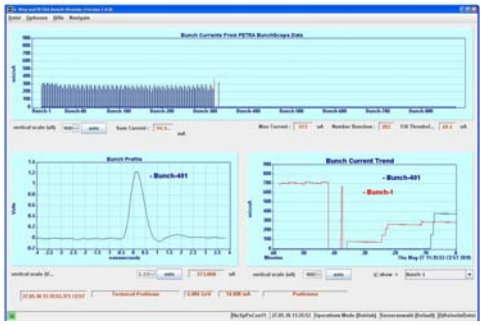
(K. Cornelis, The Electron-Cloud Instability in the SPS
http://conf-ecloud02.web.cern.ch/conf-ecloud02/talks/cornelis.pdf)

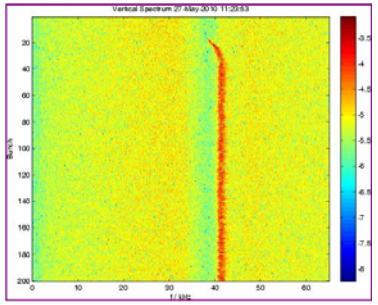
Studies with different filling patterns (May / June 2010)

10 x 29 = 290 bunches

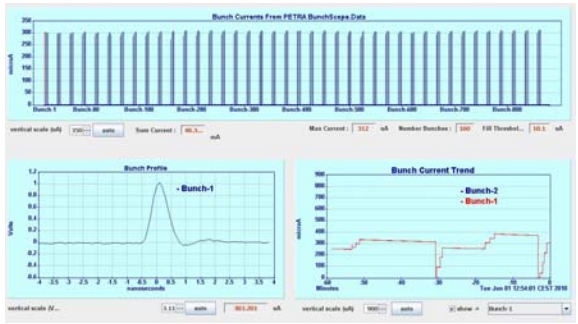


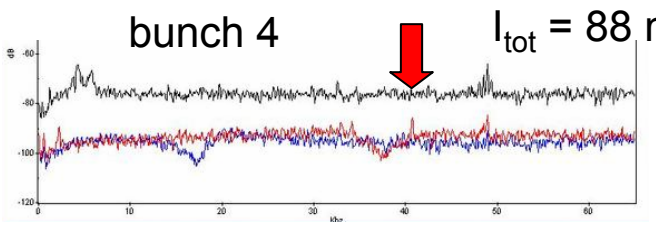
200 bunches + witness bunch





40 x 4 = 160 bunches





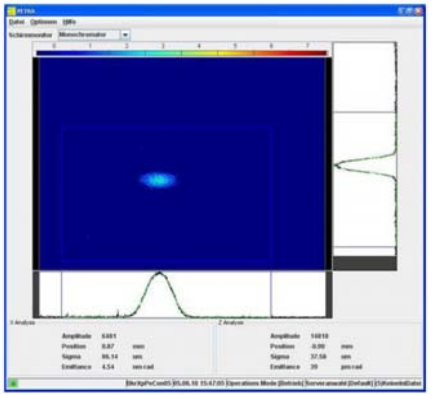
Almost **no emittance blow up** !, bunch-to-bunch spacing 16 ns + gap 144 ns

Studies without wigglers – Aug. 2 – 7, 2010

All wigglers have been moved into the parking position

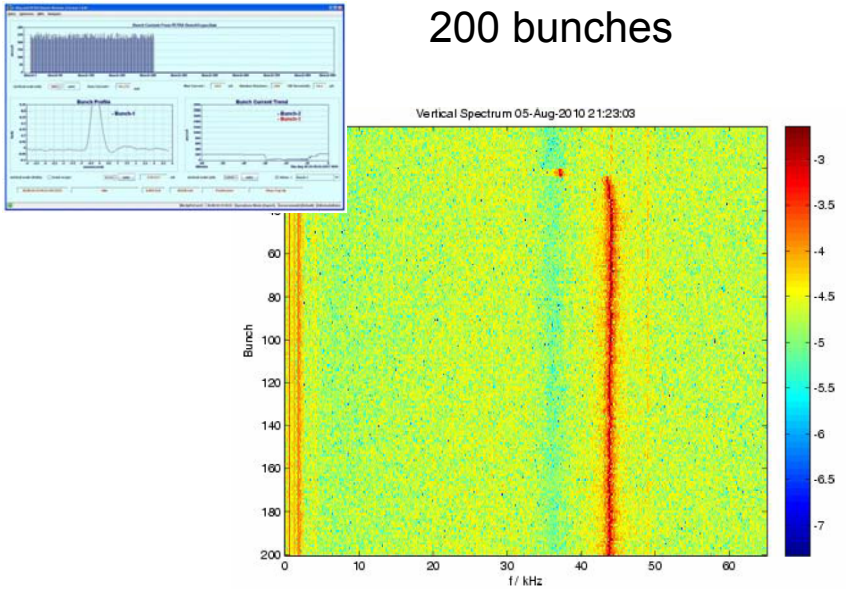
Emittance
~ 4.5 nm rad

(measured vert. emittance 39 pm rad)

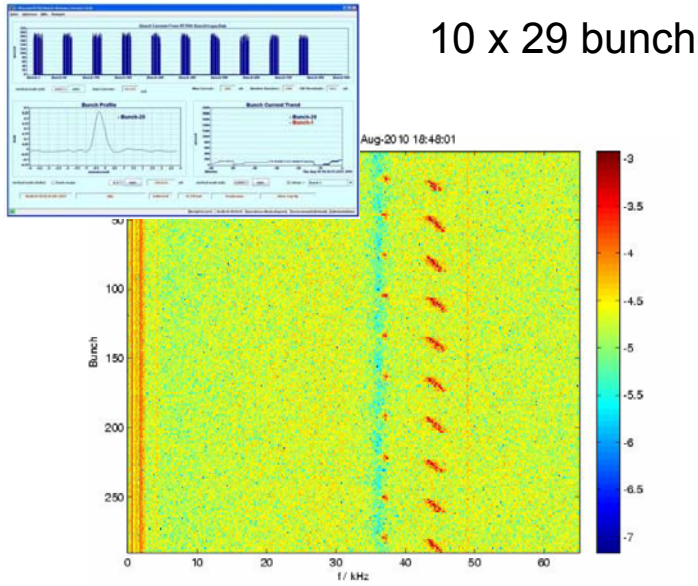


The vertical emittance growth and the sidebands are seen again !

200 bunches

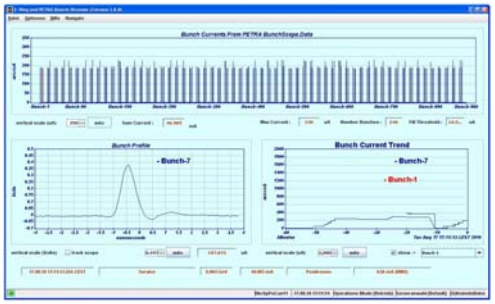


10 x 29 bunches

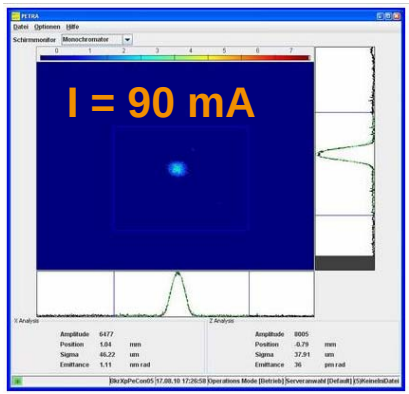


Studies with wigglers – Aug 17 and Sep 15, 2010

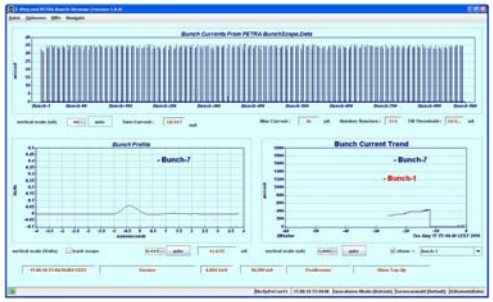
60 x 4 bunches



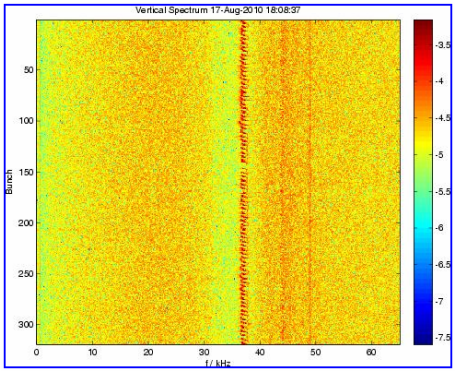
No emittance blow-up

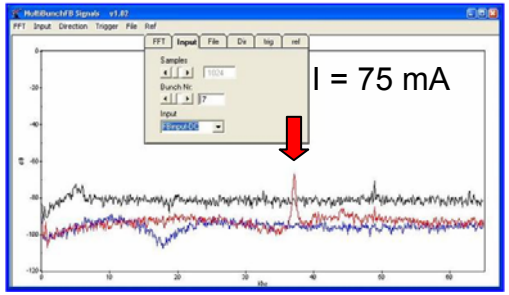


80 x 4 bunches

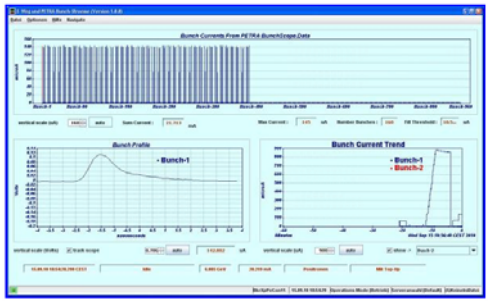


Emittance growth
50 mA … 75 mA
and “upper sidebands”

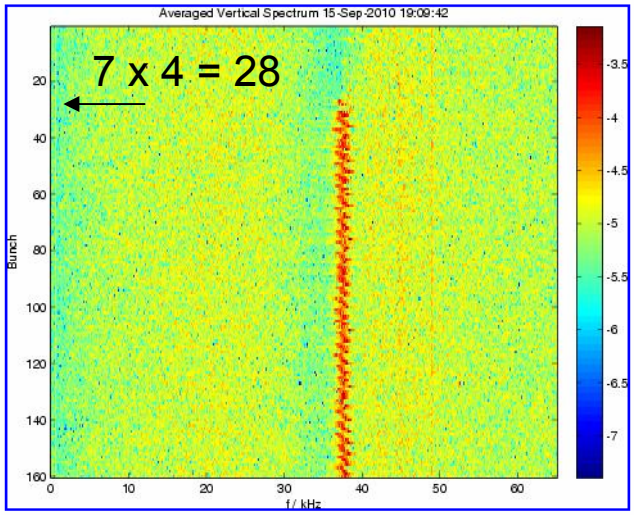




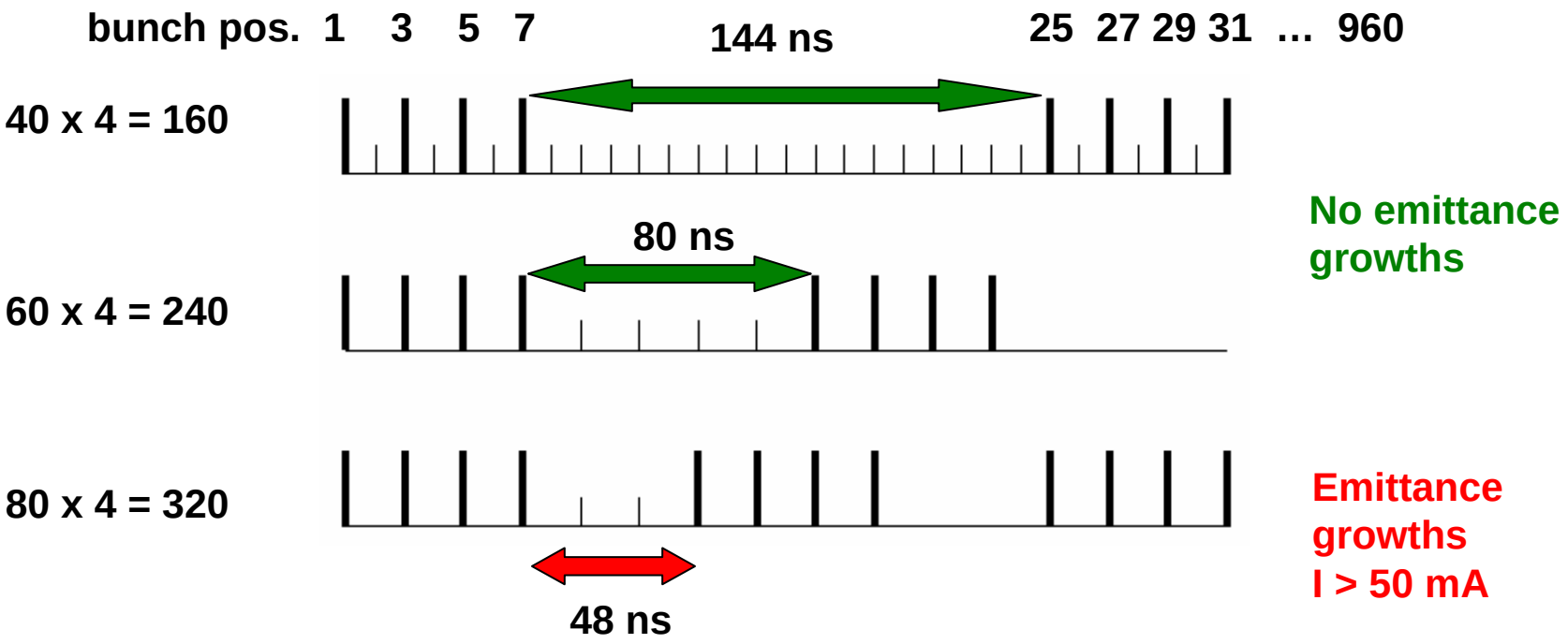
½ 80 x 4 bunches



Emittance growth
and build-up of
“upper sidebands”



Filling pattern N x 4, 16 ns bunch spacing



200 bunches + witness bunch,
upper sidesbands have been observed:

May/June with wigglers, for a witness bunch about 72 ns behind the bunch train
bunch pos #409 (2nd fill) #411 (1st fill) (96 ns behind the bunch train)

Aug 5, (w/o wigglers) 56 ns behind the bunch train (bunch pos #407)
Aug 17 with wigglers 56 ns behind the bunch train (bunch pos #407)

Instability threshold – coasting beam model

Broad band resonator model + coasting beam model *)

$$Z(\omega) = \frac{cR_S}{\omega}\frac{1}{1+iQ\left(\frac{\omega_e}{\omega}-\frac{\omega}{\omega_e}\right)} \qquad (10)$$
$$= K\frac{\lambda_e}{\lambda_+}\frac{L}{\sigma_y(\sigma_x+\sigma_y)}\frac{\omega_e}{\omega}\frac{Z_0}{4\pi}\frac{Q}{1+iQ\left(\frac{\omega_e}{\omega}-\frac{\omega}{\omega_e}\right)},$$

where K is an enhancement factor due to cloud size, pinching etc. [11], and Z_0 is the impedance of vacuum (377Ω). The figure 4 shows $K = 1.5$. In the case of KEKB, the enhancement factor was $K = 2 \sim 4$ for the vertical wake field.

$$U \equiv \frac{\sqrt{3}\lambda_+ r_e\beta\omega_0}{\gamma\omega_e\eta\sigma_\delta}\frac{|Z_\perp(\omega_e)|}{Z_0} = \frac{\sqrt{3}\lambda_+ r_e\beta}{\gamma\nu_s\omega_e\sigma_z/c}\frac{|Z_\perp(\omega_e)|}{Z_0} \quad < 1$$

threshold density:

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{KQ\sqrt{3}r_e\beta L} \qquad K \sim \omega_e\sigma_z/c$$

(L = circumference of the ring) **Q ~ 5 < K**

$$\omega_{e,y} = \sqrt{\frac{\lambda_+ r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

λ_+ = beam line density in the e+ bunch

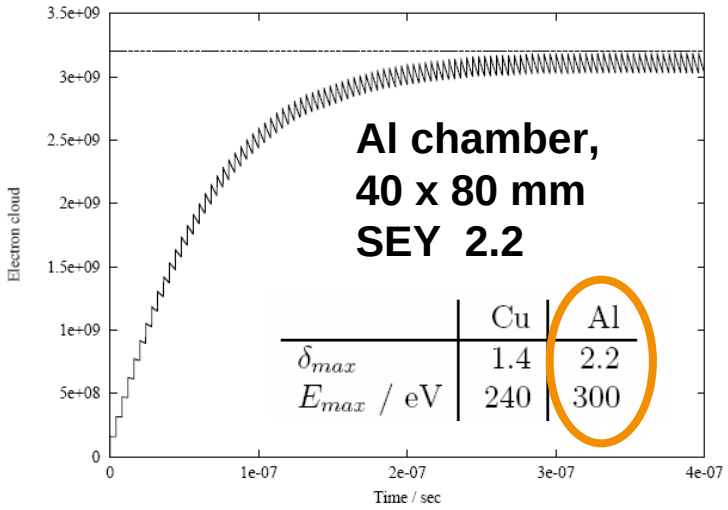
	K = 1	$K \sim \omega_e\sigma_z/c$	**K =**
PETRA III:	8.9 x 10^{12} m^{-3}	**1.4 x 10^{12} m^{-3}**	**6.4**
KEK – B:	0.5 x 10^{12} m^{-3}	0.1 x 10^{12} m^{-3}	**5**

(PETRA III, 960 bunches, 100 mA,
KEK-B, 1200 bunches, 600 mA)

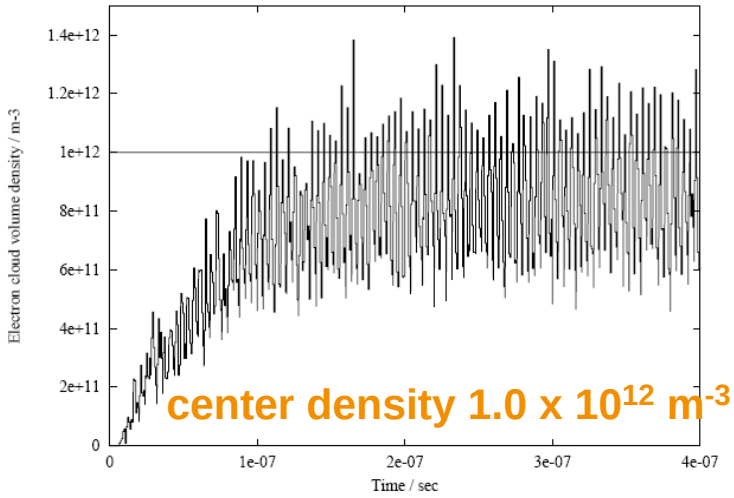
***) K. Ohmi: Electron Cloud Effect in Damping Rings of Linear Colliders**
31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects "ECLOUD'04"

Simulations 2003 (DESY M 03-02, Dec 2003)

Simulation with ECLOUD 2.3: PETRA III, N = 0.5 10^{10}, bunch spacing 4 ns



	Cu	Al
δ_{max}	1.4	2.2
E_{max} / eV	240	300



	PETRA II		PETRA III	
	96 ns	10 ns	A	B
Energy /GeV	7	7	6	6
Bunch Population $N_0/10^{10}$	5.0	4.1	0.5	24.0
Bending radius ρ/m	191.729	191.729	191.729	191.729
dN_γ/dz / m	0.753	0.753	0.645	0.645
Y_{eff}	0.1	0.1	0.1	0.1
dN_{e^-}/dz / m	0.075	0.075	0.065	0.065
$N_0\, dN_{e^-}/dz$ /(10^{10} m)	0.376	0.309	0.032	1.549

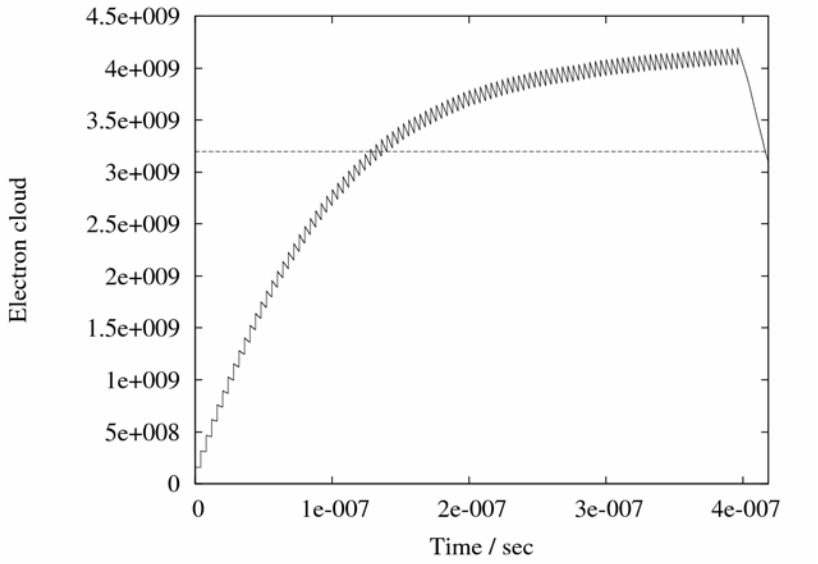
Table 4: Photoelectron emission rates for PETRA II and PETRA III.

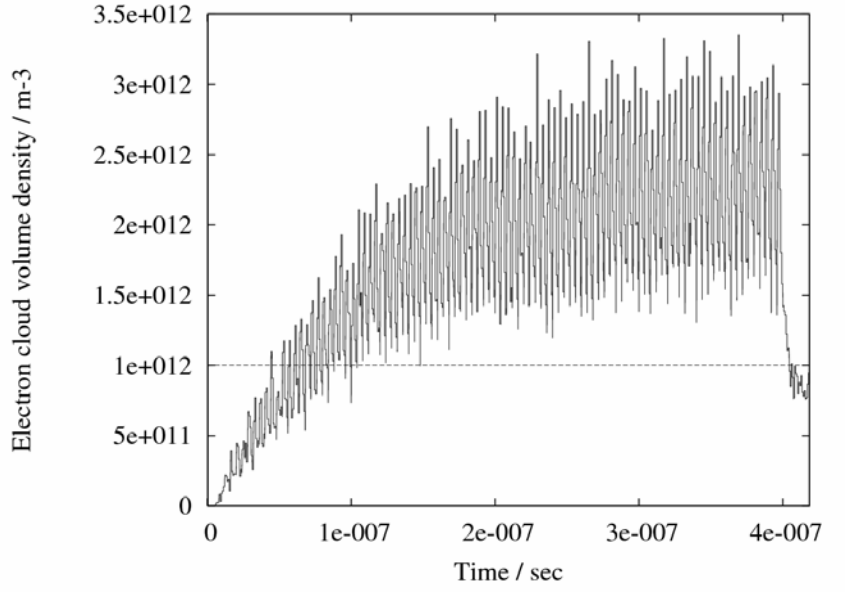
	PETRA II		PETRA III	
	96 ns	10 ns	A	B
chamber area /cm^2	55.8		25.1	
Bunch Population N_0 /10^{10}	5.0	4.1	0.5	24.0
Bunch separation /ns	96	10	4	192
average bunch charge densities: volume $\langle\rho_b\rangle$ / (10^{12} m^{-3})	0.31	2.47	1.66	1.66
Results from the simulations				
Cloud Population /10^{10}/ m	0.46	1.4	0.32	2.2
Average density /(10^{12} m^{-3})	0.83	2.5	1.3	8.7
Center density / (10^{12} m^{-3})	0.7	2.1	1.0	1.5

Table 6: Beam and cloud charge densities for PETRA II and PETRA III.

Simulations 2010 – ECLOUD 4.0

Simulation with ECLOUD 4.0: PETRA III, N = 0.5 10^{10}, bunch spacing 4 ns

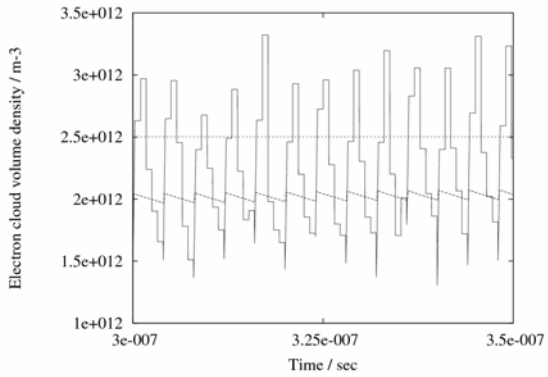




center density ~ 2.5 10^{12} m^{-3}

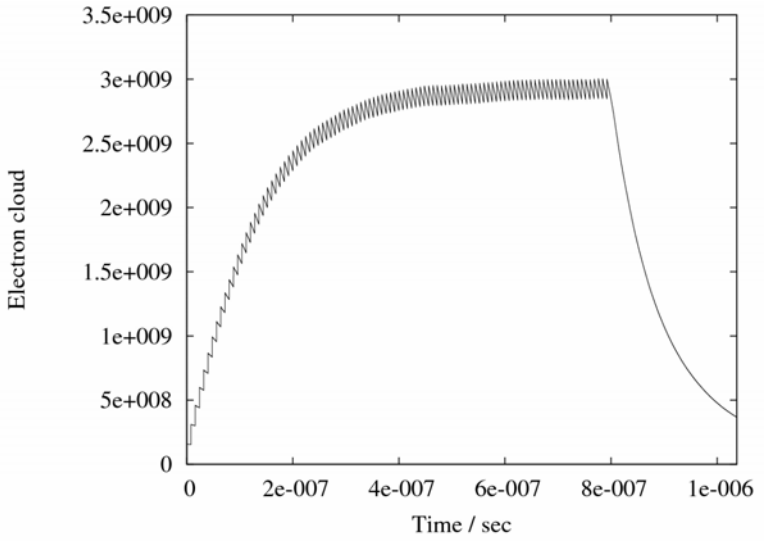
factor 2.5 larger (ECLOUD 2.3)

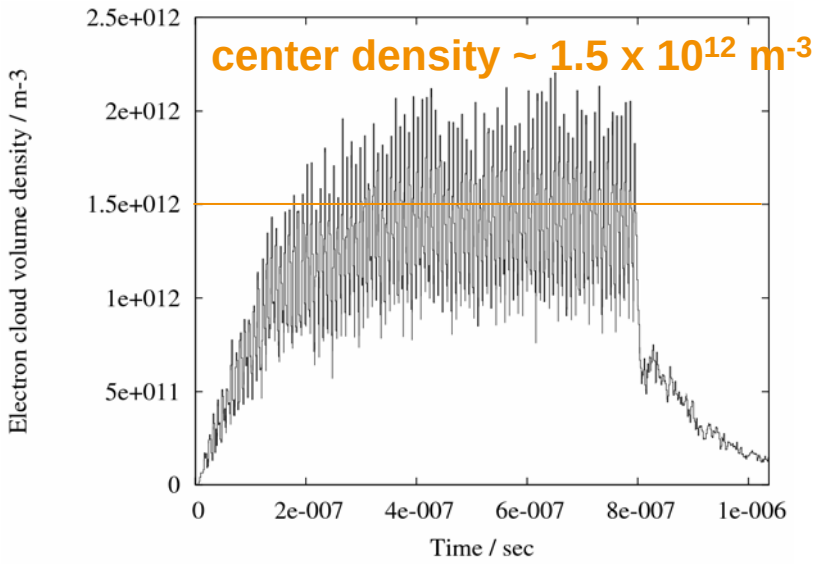
above the threshold from coasting beam model with enhancement factor



Simulations

Simulation with ECLOUD 4.0: PETRA III, N = 0.5 10^{10}, bunch spacing 8 ns
100 mA in 960 bunches or 66 mA in 640 bunches, **SEY = 2.5**





Average beam charge volume density:

$$\langle \rho_b \rangle = \frac{N}{c\ \Delta t\ \ A} \quad = 0.83 \times 10^{12}\ \mathrm{m}^{-3}$$

A = area of the vacuum chamber
= π x 20 mm x 40 mm

Simulated cloud density

$$\langle \rho_c \rangle = 1.8 \langle \rho_b \rangle$$

Neutrality charge density

$$\langle \rho_c \rangle \approx \langle \rho_b \rangle$$

Average charge density and tune shift

	Design	Studies							
# Bunches	960	**640**	10 x 29	200	16 x 10	**40 x 4**	40 x 8	**60 x 4**	80 x 4
Current / mA	100	62	48	54	78	**85**	82	**90**	75
N / 10^{10}	0.5	0.47	0.8	1.3	2.3	**2.5**	1.2	**1.8**	1.1
bunch spacing / ns	8	8	8	16	16	**16 / 144**	8 / 136	**16 / 80**	16 / 48
Average density	From neutrality condition								
Arc / 10^{12} / m^3	**0.83**	**0.77**	**1.3**	**1.1**	**1.9**	**2.1**	**2**	**1.5**	**0.9**
Wigg / 10^{12} / m^3	1.6	1.5	2.6	2.1	3.8	4.1	4	2.9	1.8
	Predicted tune shift								
Vert. tune shift / kHz (arc density)	**0.44**	**0.41**	**0.71**	**0.58**	**1**	**1.1**	**1.1**	**0.8**	**0.5**

Tune shift calculated from the average charge density (neutrality condition):

$$\Delta Q_y = \frac{1}{2}\frac{C}{\gamma} r_e \langle \beta_y \rangle \langle \rho_c \rangle$$

PETRA III
f_0 = 130 kHz

$$\Delta f_y = 0.54 \text{ kHz } 10^{-12} \text{ m}^3 \langle \rho_c \rangle$$

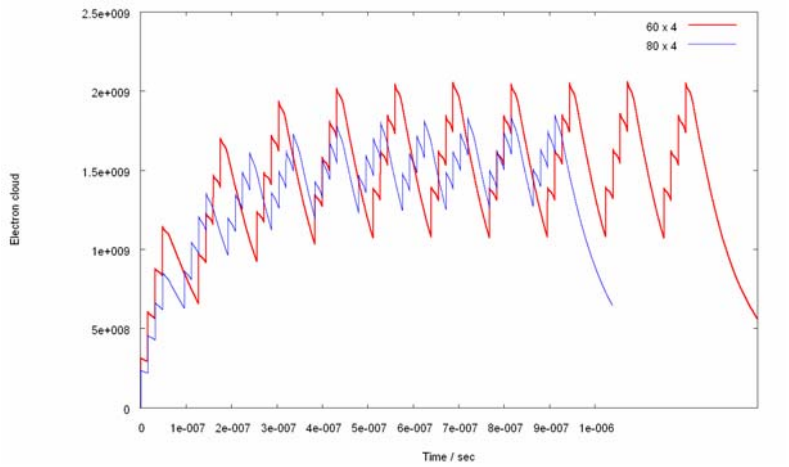
The measurements indicate much larger tune shifts / side bands (about a factor 10) ! ?

0.54 kHz / 130 kHz = 0.004

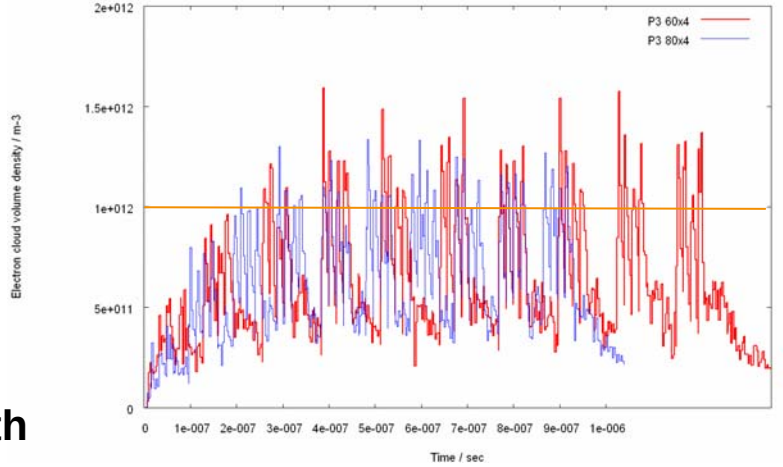
Simulations: 60 x 4 and 80 x 4 bunches

Simulation with ECLOUD 4.0: PETRA III, I = 50 mA
N = 1.0 10^{10} and 0.75 10^{10} ,bunch spacing 16 ns

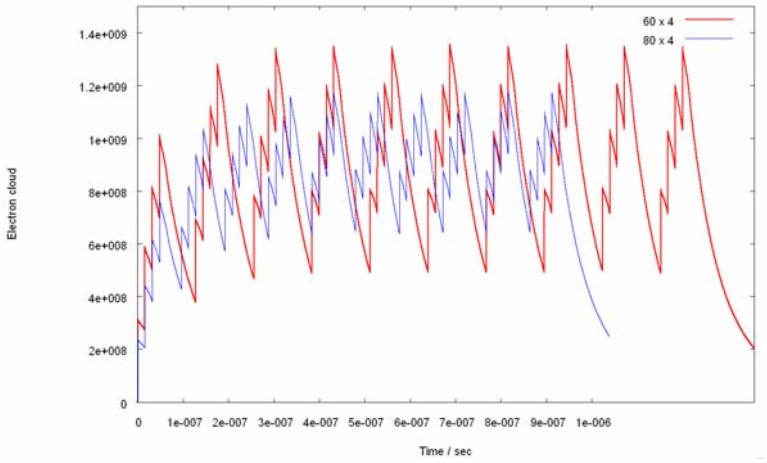
Red 60 x 4 bunches Blue 80 x 4 bunches,



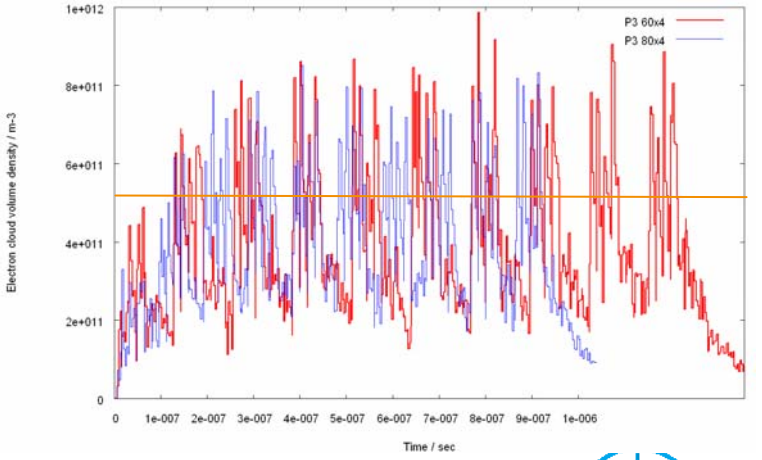
SEY 2.5
center density
~ 1.0 10^{12} m^{-3}



center density is similar in both cases



SEY 2.0
center density
~ 0.5 10^{12} m^{-3}



Summary: Vertical Emittance Growth

- A vert. Emittance growth (factor 2 …4) has been observed at PETRA III for long bunch trains with 8 ns and 16 ns bunch to bunch spacing at a total current of about 50 mA
- There a “upper-sidebands” in the tune spectra with a clear build-up along the bunch train
- The measured tune spectra show some characteristics which have been observed at other storage rings in connection with electron cloud effects.
- The tune shift is much larger than expected from estimates based on the average charge density (neutrality condition)
- For user runs a filling pattern has been found (40 x 4 bunches and 60 x 4 bunches) without a significant emittance growth
- Simulations indicate the same center density for both filling patterns

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