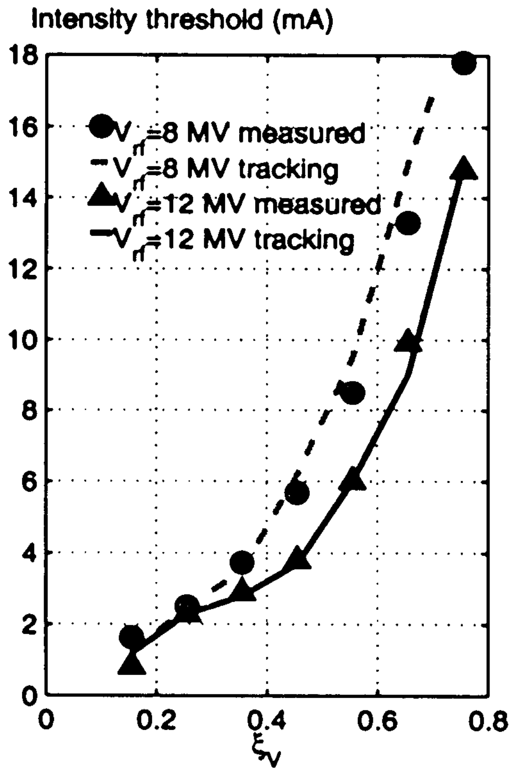
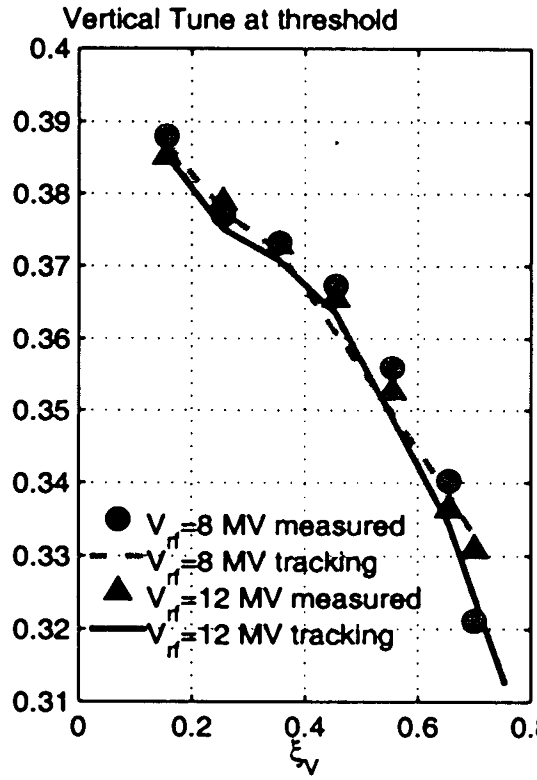
Observation and Analysis of Transverse Single Bunch Threshold Behaviour at Positive Chromaticities

(G. Besnier, Ph. Kernel, R. Nagaoka, and J.L. Revol)



Nonlinear rise of threshold current with increasing $\xi > 0$.



Large shifts of head-tail frequencies with increasing $\xi > 0$.

- Pushing ξ_V towards larger positive values increases the threshold current (how 15 mA is achieved for User Operations).
- However, feedback efficiency is significantly reduced.
- Peak betatron tunes are shifted many synchrotron sidebands away ($|m| < 10$).
- The beam is apparently unstable and blown up.
- ξ_V too large creates lifetime problems.

To understand the physics of $\xi > 0$ regime
(i.e. what determines I_{th}) ≡ Main goal of the study

⇒ Both *experimental* and *theoretical* studies carried out
(Numerical studies with tracking and mode-matrix calculations).

- ❑ Tracking computation reproduces correctly the threshold curve with the obtained BBR model, provided that a damping time (= 0.2 ms) much shorter than the radiation damping (7 ms), even shorter than the synchrotron period (0.5 ms) is assumed.

- ❑ Our initial picture was a successive interaction of higher-order head-tail modes with the peak negative resistivity (around –22 GHz).

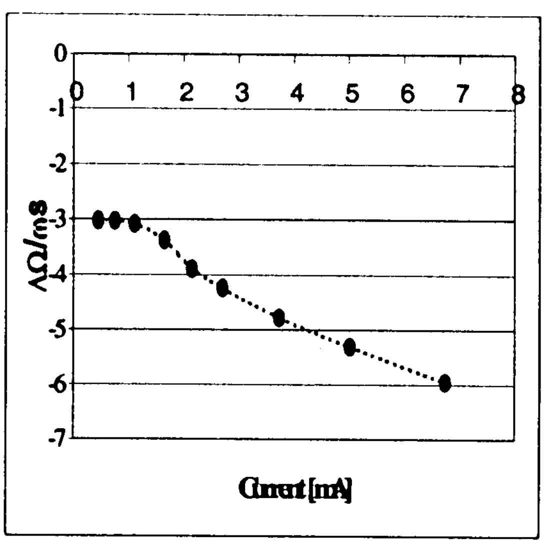
- ❑ However, a question arose **if the notion of "*head-tail modes*"** is still **valid when $T_S/\tau > 1$,** if head-tail modes as high as $|m| \sim 10$ can drive such a strong instability, and also why such a fast growth can develop.

- ❑ Solution of the most general equation for head-tail motions
(Eq. 195 of "Bunched Beam Coherent Instabilities" by J.L. Laclare)

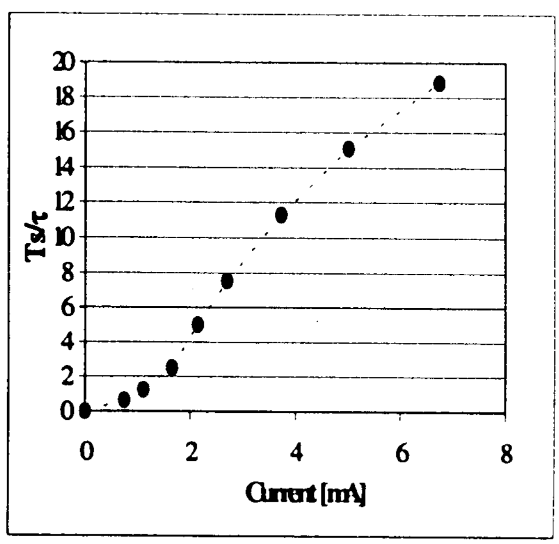
$$\sigma(l) = \frac{el}{2m_0 c\gamma Q}\sum_p jZ_\perp(p)\cdot\sigma(p)$$

$$\times\sum_m \frac{1}{\omega_c - m\omega_s}\int_0^\infty J_m[(l+Q)\omega_0 - \omega_\xi)\tau]\cdot J_m[(p+Q)\omega_0-\omega_\xi)\tau]\, g_0(\tau)\,\tau d\tau$$

In which, a beam harmonic is
coupled to all other beam harmonics (...bunched beam nature)
and composed of all possible head-tail modes.

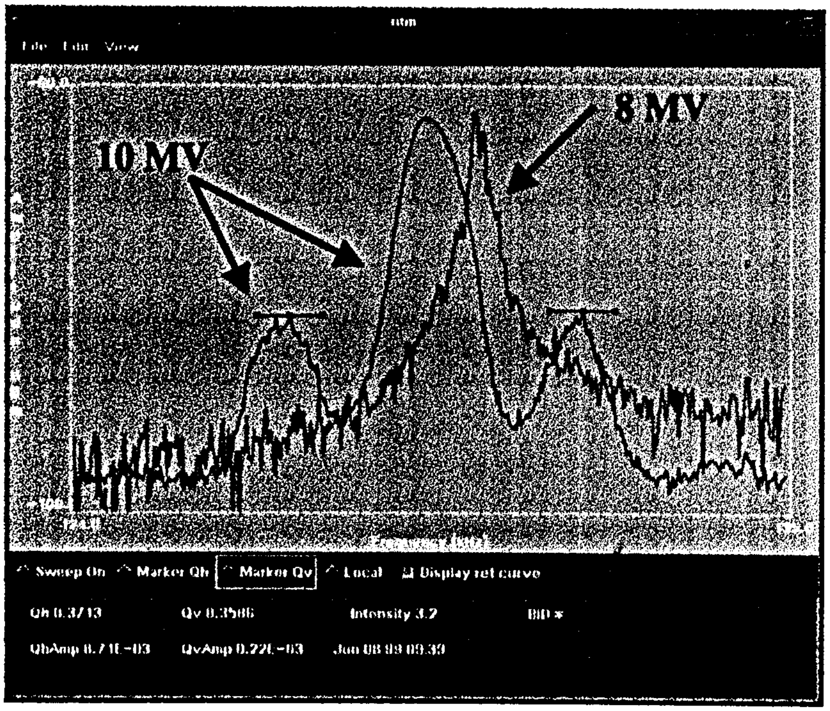


Mode frequency shift



Growth rate

❑ Some experimental evidence:



Observation of spontaneous head-tail frequencies as a function of the RF voltage V_{rf}.

⇒ Appearance of neighbouring mode frequencies as the instability is enhanced with an increase of V_{rf} (8 → 10 MV).

⇓

❑ Both experimental and numerical results suggest that the current threshold in $\xi > 0$ ***nonlinearly*** approaches a regime where the growth time is comparable to or shorter than the synchrotron period.

→ A mode-merging like instability initially develops among neighbouring modes.

→ All head-tail modes finally contribute to a highly excited bunch state.

→ ***The concept of head-tail motions is lost.***

This regime is tentatively named as a "***post head-tail regime***".
(This idea was firstly proposed by G. Besnier within the group)

- In the literature one finds a study with a similar motivation being already made by R.D. Ruth and J.M. Wang.

  (R.D. Ruth and J.M. Wang, "Vertical Fast Blow-up in a Single Bunch", IEEE Transactions on Nuclear Science, NS-28, No. 3, June 1982)

  From the previous most general coupled-equation, they approximately derived a dispersion relation similar to that of the coasting beam theory, describing the fast blow up of the beam:

$$1 = \frac{eI_{peak}\,|Z_{\perp}(\omega_c)|}{4\sqrt{2\pi}\,\nu\eta\sigma_{\varepsilon}\,|\omega_c + \omega_{\xi}|\,m_0\gamma c}$$

- An independent derivation of a similar constraint has recently been carried out by G. Besnier, including attempts to introduce a stability criteria.

  ⇒ Justification of the results are underway.

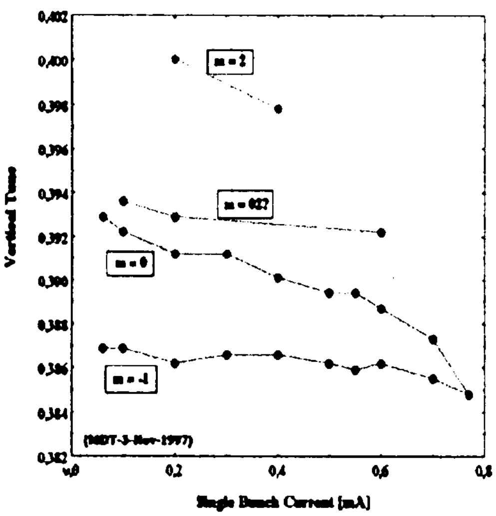
Some Beam-Based
Broadband Impedance Characterisation at the ESRF

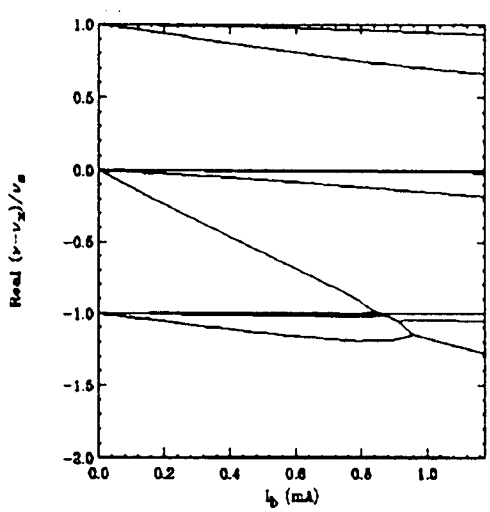
❑ Longitudinal broadband impedance fitted with the BBR model with the bunch lengthening data *(Cecile Limborg et al. 1996)*:

$$f_{res} = 30\ \text{GHz},\ R_S = 42\ \text{k}\Omega,\ Q = 1$$

(cf. Corresponds to $|Z_L/n|_0 = 0.5\ \Omega$,
while a fit with the pure inductive model gives 1.5 Ω)

❑ Vertical broadband impedance fitted with the BBR model with the mode-merging instability
(G. Besnier, Ph. Kernel, R. Nagaoka and J.L. Revol, 1997):





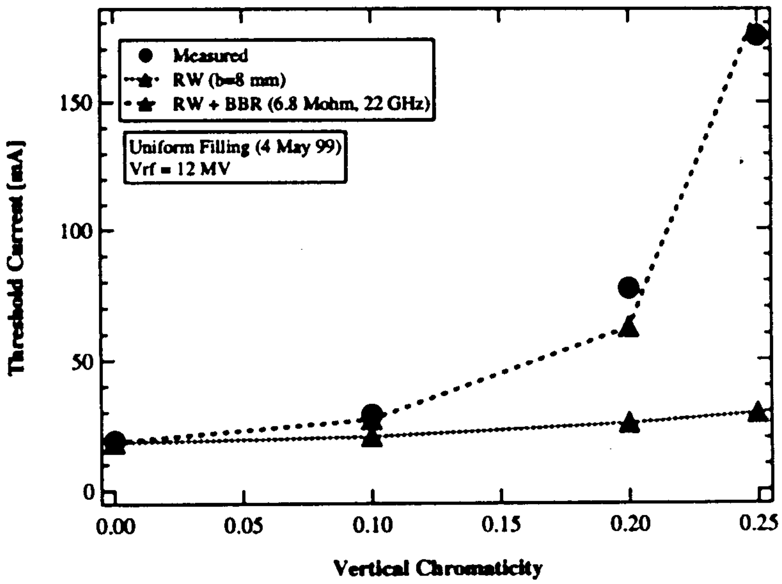
$$f_{res} = 22\ \text{GHz},\ R_T\beta = 13\ \text{M}\Omega,\ Q = 1$$

By requiring $[Z_L(\omega)]_{BBR}$ and $[Z_T(\omega)]_{BBR}$ to satisfy

$$[Z_T(\omega)]_{BBR} = \frac{2c}{d^2}\cdot\frac{[Z_L(\omega)]_{BBR}}{\omega} \quad \text{at zero frequency,}$$

$$d = [\frac{2c}{R_T}\cdot\frac{R_S}{\omega_{res}}]^{1/2} = 5{,}3\,mm \text{ is found (in a reasonable range).}$$

- From the vertical resistive-wall instability threshold in the uniform filling, decomposition of resistive-wall and BBR is attempted *(R. Nagaoka, J.L. Revol, J. Jacob and T. Guenzel)*:



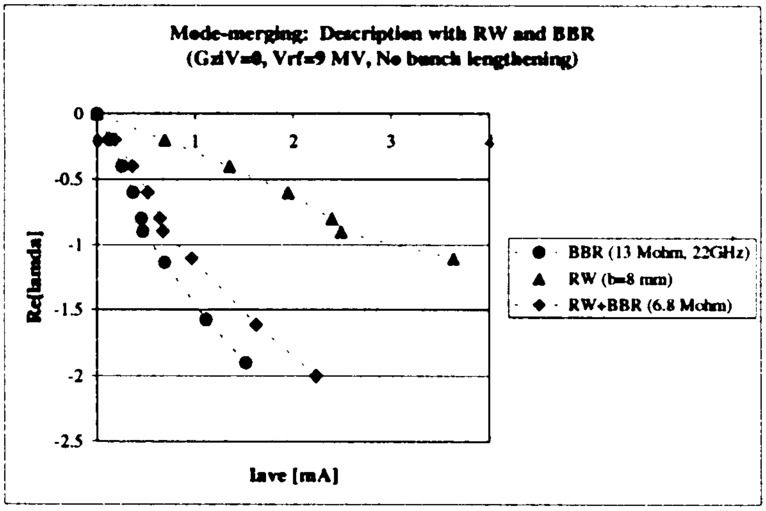
The threshold at zero chromaticity is not sensitive to BBR.
⇒ b = **8 mm** is deduced.

This is in good agreement with b_{eff} = **7.3 mm**, obtained from evaluation of resistive-wall components from the low-gap ID vessels

However, with the resistive-wall impedance alone, there is a large underestimation of the measured threshold curve.
⇒ Suggests a siginificant stabilisation due to BB-impedance.

BBR was introduced, keeping its f_{res} fixed to 22 GHz as found from the mode-merging instability and fitting R_T with Q=1.
⇒ **$R_T \cdot \beta$ = 6.8 MΩ** is deduced.
⇒ The reduced shunt impedance R_T is in favour of other single bunch observations.

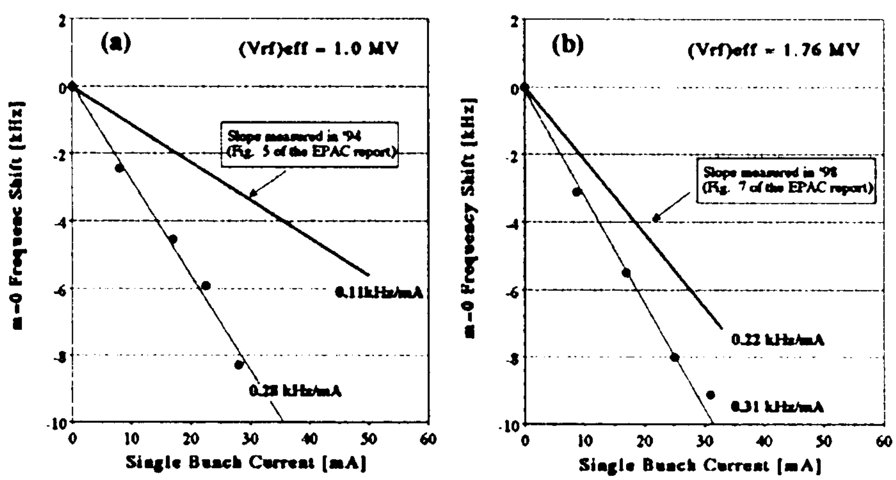
❑ The obtained combination of BBR+RW from the multibunch threshold is applied to mode-merging calculation:



⇒ A rather good reproduction resulted. It suggests a non-negligible contribution of the RW impedance to the single bunch detuning.

R_T/Q ~ 2 MΩ/m (β_{ID} ~ 3.3 m) is nearly *three orders of magnitude* larger than the zero frequency inductance evaluated for an ID low-gap taper.
⇒ Does this mean that ID tapers are not the major contributors?

Evolution of mode 0 detuning with installation of ID low gap vessels in *Elettra* seems to contradict with this hypothesis.



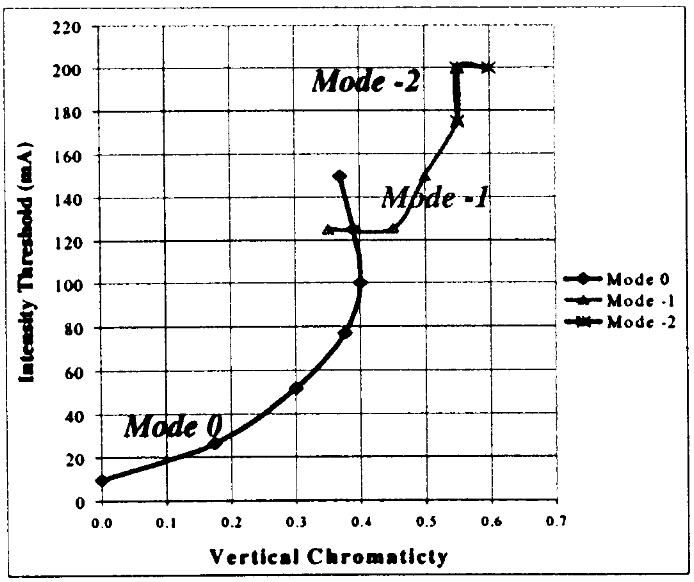
(P. Kernel, R. Nagaoka, J.L. Revol, and L. Tosi, ESRF-ELETTRA collabo, July99)

⇒ Could it mean that BBR model with Q=1 is not appropriate?

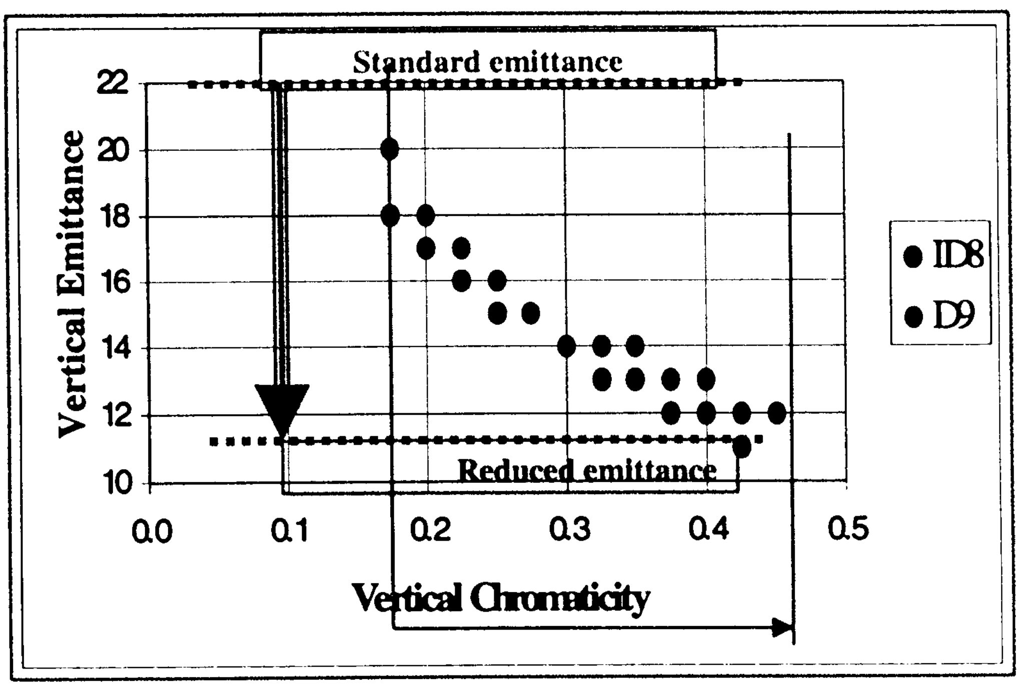
Observation of Resistive-Wall Effects at the ESRF

(J.L. Revol, R. Nagaoka, J. Jacob and E. Plouviez)

- Multibunch operation at the ESRF is affected by the resistive-wall instabilities. Chromaticities must be shifted to positive to suppress the instability. Threshold current with $\xi_V=0$ is only ~10 mA in the uniform filling.

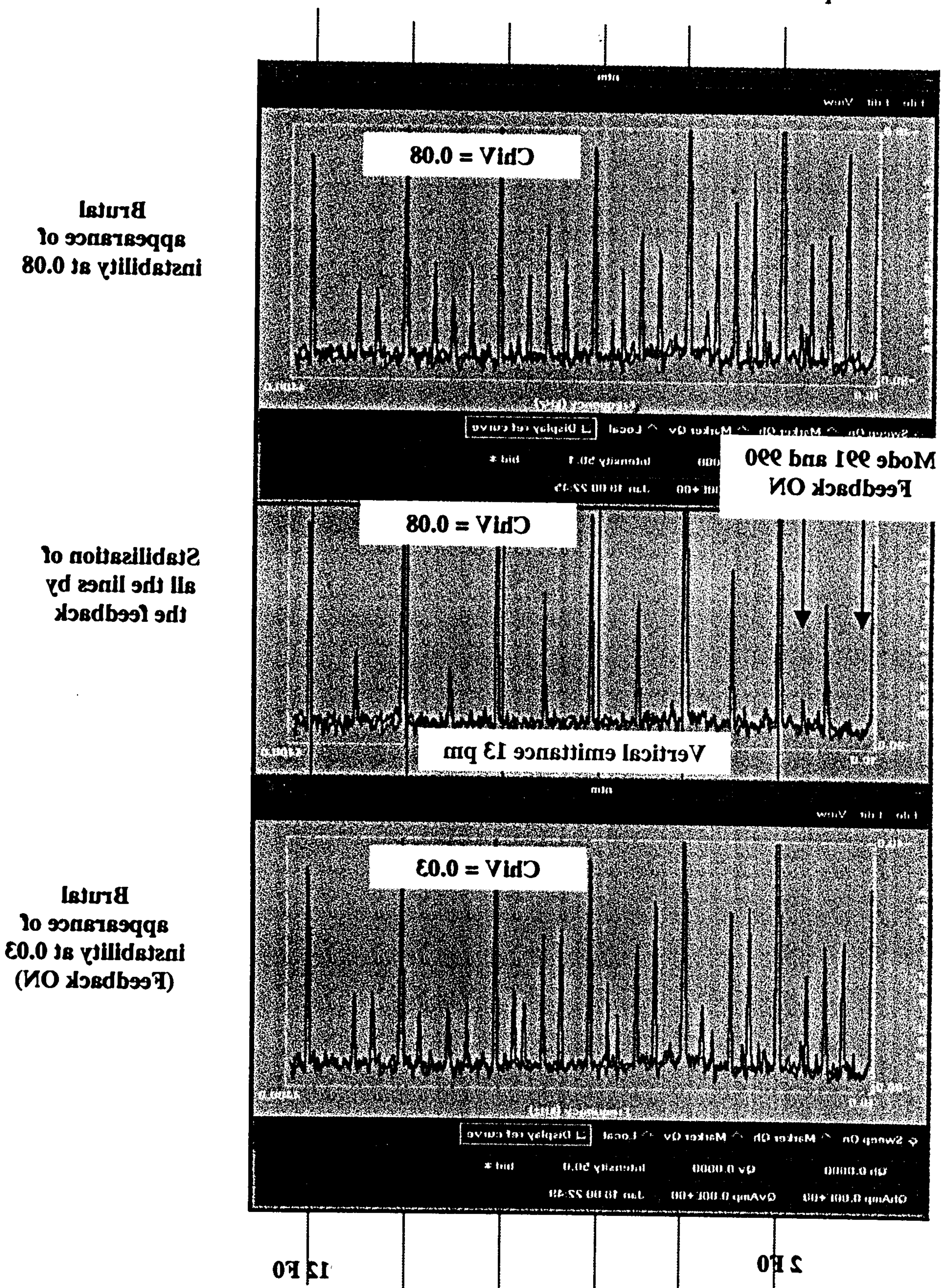


Measured threshold current versus ξ_V in the uniform filling



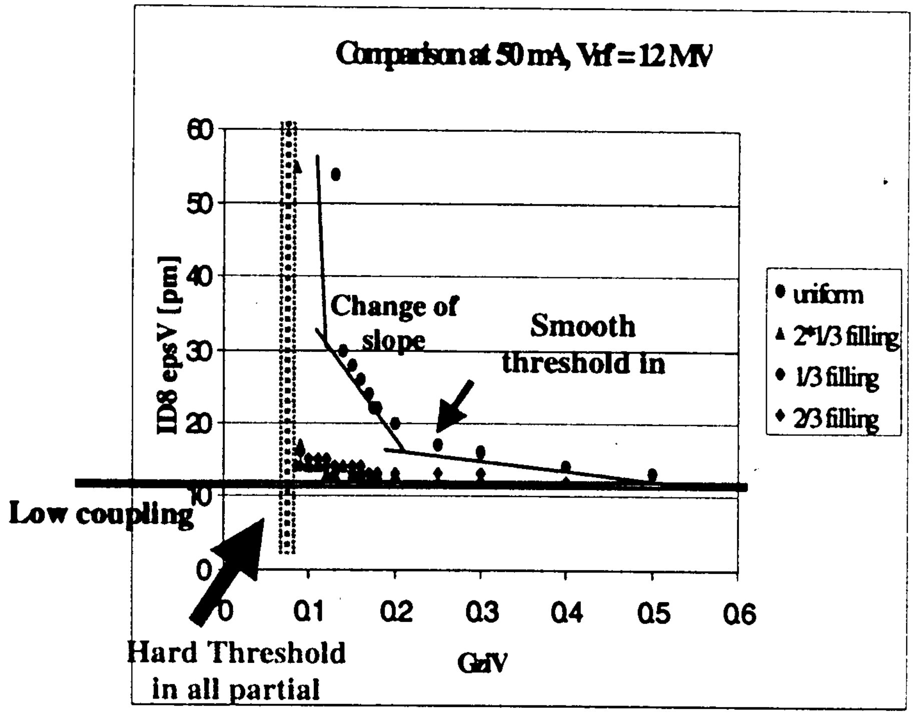
Influence of the instability on the vertical emittance in the uniform filling.

☐ Impact of Transverse Feedback

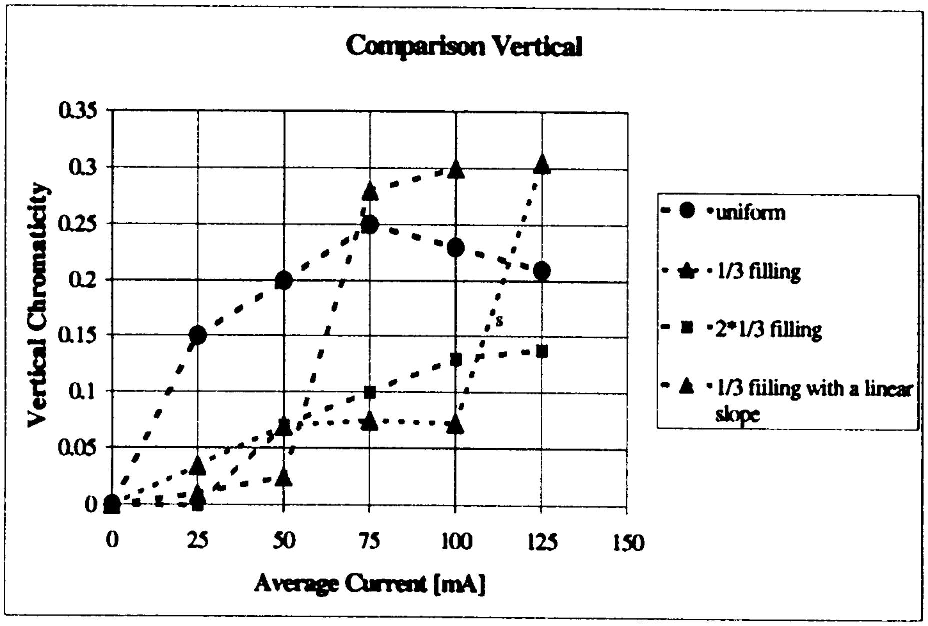


Mode by mode prototype transverse feedback in 2*1/3 filling

❑ Experiments performed showed **a distinct stabilising effect to exist in other filling modes** (1/3, 2*1/3, 2/3 filling etc.).



Vertical emittance versus chromaticity for a fixed current.

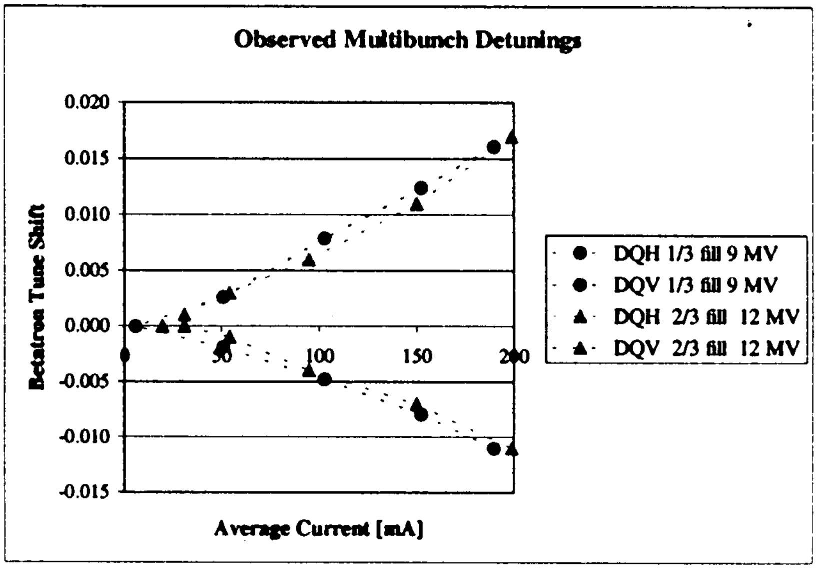


Vertical emittance versus chromaticity for a fixed current.

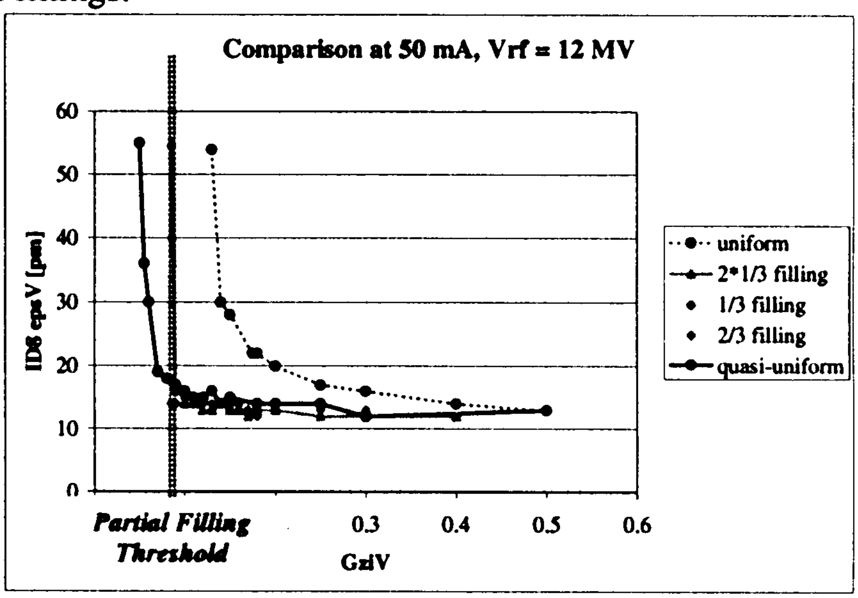
⇒ It appears that "beam gaps" help to give significant stabilisation (i.e. multibunch nature). However, a single bunch effect seems to become important at higher currents.

❑ Large incoherent betatron tune shifts observed since long are suspected to come from an asymmetry of resistive wall chamber cross sections.

(cf. "Coupling Impedance of Beam Pipes of General Cross Section", R. Gluckstern and J. van Zeijts, CERN SL/AP 92-25,
"Resistive Wall Impedance of Beam Pipes of General Cross Section", K. Yokoya, Part. Accel. 41, 1993, p.221)



❑ It was also observed that a beam filling without any gap and with current modulation (i.e. "*modulated uniform*") gives more stability than partial fillings.



⇒ An idea arose if the observed ***stabilisation is due to an intra-beam tune spread*** arising from the current dependent tune shift.

⇒ Quantification of this effect is on the way *(R. Nagaoka et al).*