Transverse Instabilities for High Intensity/ Bunch

Beam Instability Workshop
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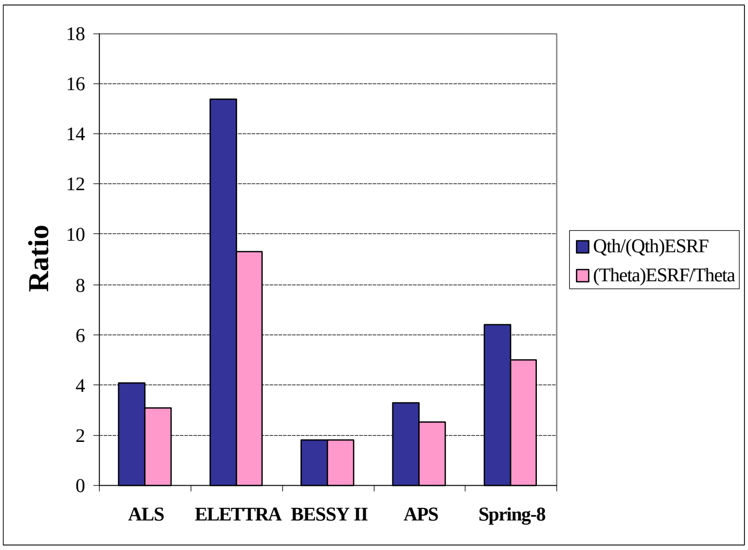
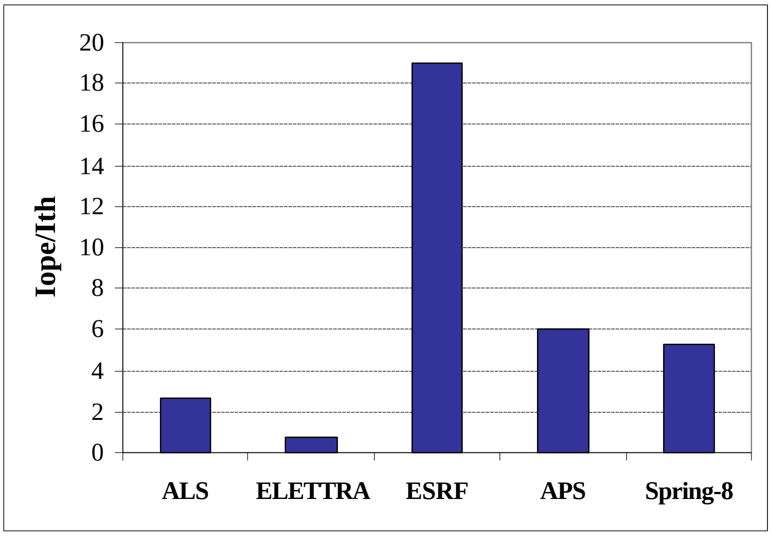
Ryutaro Nagaoka
ESRF

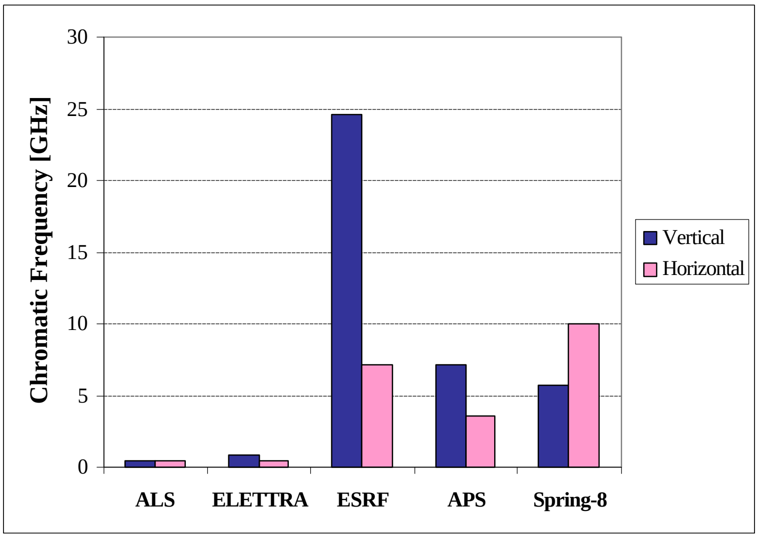
Brief Comparison of Transverse Single Bunch Effects Observed in Different Machines

	ESRF	APS	Spring-8	ELETTRA	ALS	BESSY II	DAFNE
TMCI Ith [mA]	0.8	2	3	40	14	5	>100 mA
TMCI Total charge Qth [nC]	2.25	7.36	14.4	34.6	9.18	4	>32.6
Theta = Qs/Qth [1/nC]	0.0025	0.001	0.0005	0.00027	0.0008	0.0014	<0.00034
Qth/(Qth)ESRF	1	3.27	6.4	15.4	4.1	1.8	>14.5
(Theta)ESRF/Theta	1	2.5	5	9.3	3.1	1.8	>7.35
Iope/Ith	19	6	5.3	0.75	2.64	-	-
GziV	12.9	6	4	0.8	0.5	-	0
GziH	7.6	3	7	0.5	0.5	-	0
fGziV [GHz]	24.6	7.2	5.7	0.6	0.5	-	0
fGziH [GHz]	14.5	3.6	10	0.4	0.5	-	0
f0 [kHz]	355	272	209	1157	1524	1249	3069
Qs	0.0056	0.0074	0.0072	0.0095	0.0073	0.0056	0.011

Data provided with the courtesy of:
K. Harkay (APS)
T. Nakamura (SPring-8)
E. Karantzoulis (ELETTRA)
J. Byrd (ALS)
S. Khan and P. Kuske (BESSY II)
A. Ghigo (DAFNE)

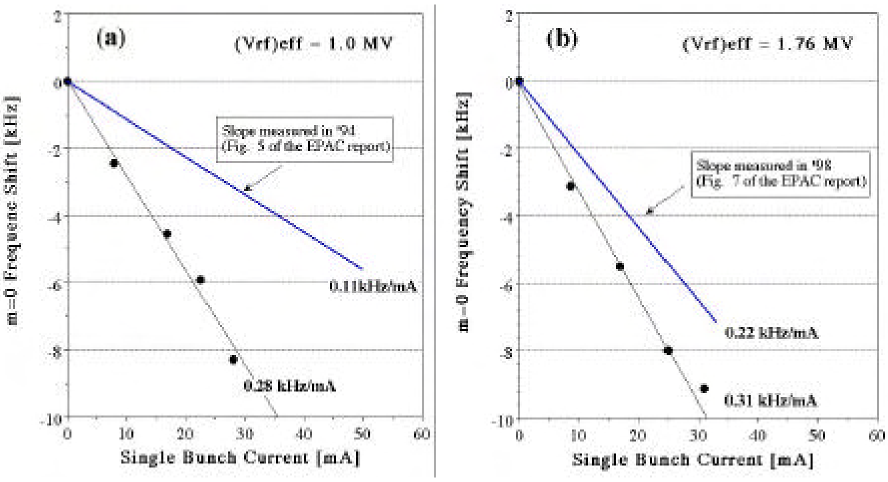






⇒ Although the problem is particularly serious for the ESRF, similar trends are found in other light sources as well.

- Increase of mode detuning with installation of ID low gap chambers in ELETTRA:

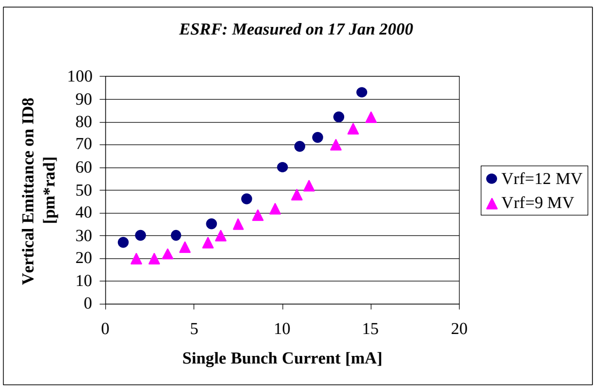


P. Kernel, R. Nagaoka, J.L. Revol, and L. Tosi, ESRF-ELETTRA collabo, July99; E. Karantzoulis et al.,"Observation of Instabilities in the ELETTRA Storage Ring", EPAC94, London, 1994; C.J. Bocchetta et al., "Collective Effects at ELETTRA", EPAC98, Stockholm, 1998.

- A similar observation has been reported from ALS.
(J. Byrd, "Observations of single bunch collective effects in ALS", talk given at Impedance Workshop, Stanford, March 00)

❑ Larger positive x_V increases the threshold current. However, at the ESRF it is observed that;

- Feedback efficiency is significantly reduced.
- Peak betatron tunes are shifted many synchrotron sidebands away (|m| < 10).
- The beam is apparently unstable and blown up.
- x_V too large creates lifetime problems.



Observed vertical emittance blow up with single bunch current (ESRF)

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

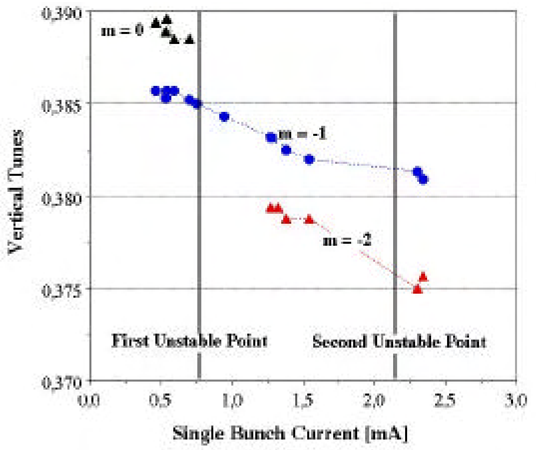
To understand the physics of $\xi > 0$ regime
(i.e. what determines I_{th}) $\equiv$ Main goal of the study

$\Rightarrow$ Both ***experimental*** and ***theoretical*** studies carried out at the ESRF
(G. Besnier, Ph. Kernel**, R. Nagaoka, and J.L. Revol)*

** From University of Rennes, Rennes, France*

*** Thesis student at the ESRF since 1997*

❑ Experimental observations at "small positive chromaticities"



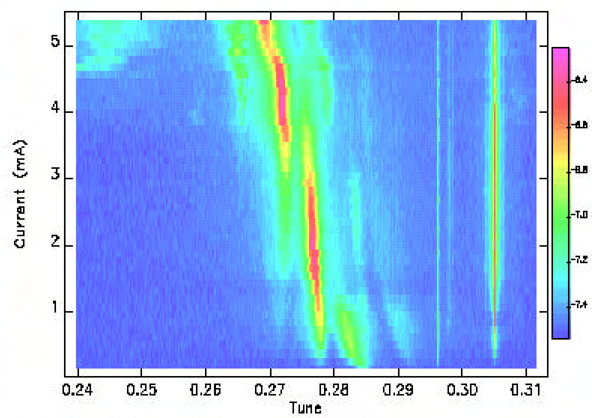


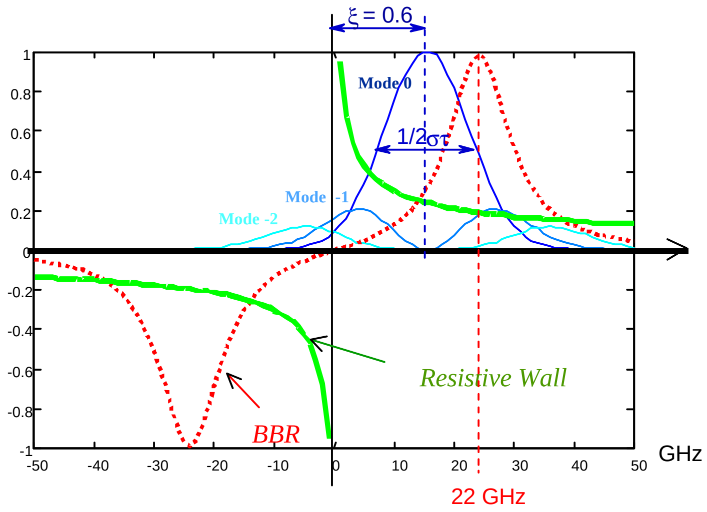
Figure 1: Vertical tune vs. single-bunch current.

Left: "Double thresholds" observed at the ESRF with x ~0.26.
Right: Evolution of peak head-tail frequencies with current in APS (K. Harkay et al, "Impedance and the Single Bunch Limit in the APS Storage Ring", PAC99)

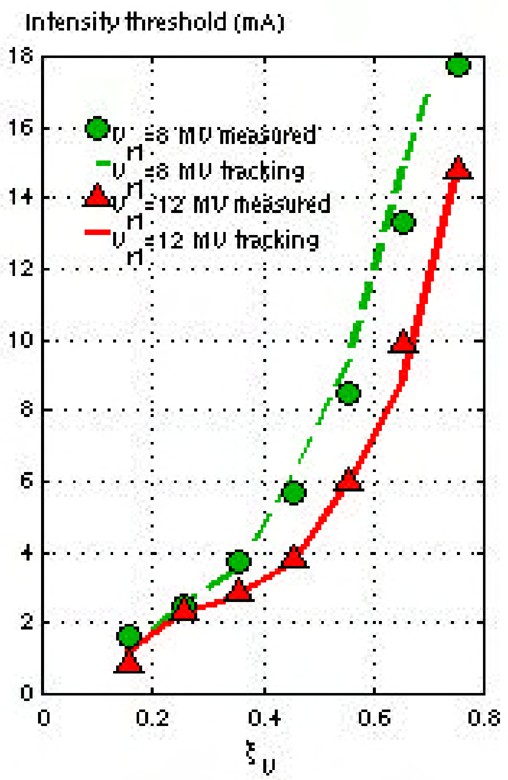
- On top of slight defocusing of each mode, continuous transitions of mode excitations towards higher-orders (m = 0, -1, -2, ...) are seen.

- The observations can be interpreted in terms of the classical theory of Sacherer: A mode that sees more the negative real part of the impedance becomes unstable.

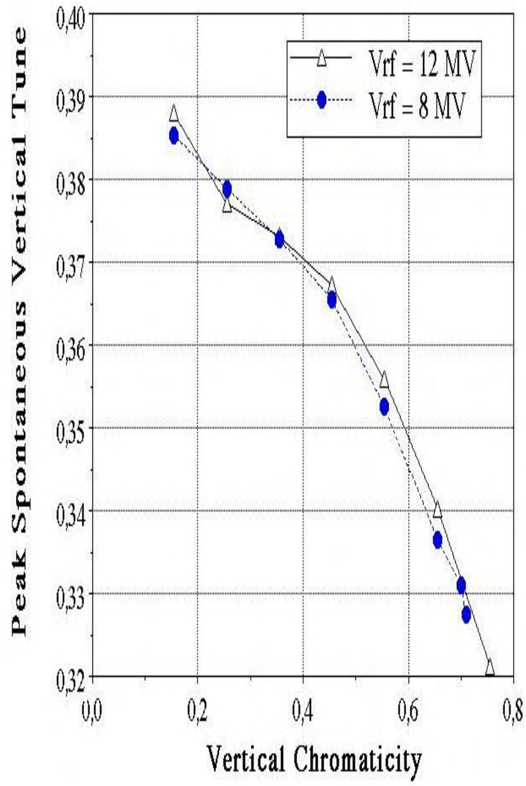
  (F.J. Sacherer, "Transverse Bunched-Beam Instability - Theory", Proc. 9th Int. Conf. on High Energy Accelerators, Stanford 1974, p.347)



❑ Experimental observations of thresholds versus positive chromaticities



Nonlinear rise of threshold current with increasing x > 0.



Large shifts of head-tail frequencies with increasing x > 0.

Theoretical Foundation

Vlasov Equation $\Rightarrow$ Linearlised Vlasov (Sacherer's integral equation)

$$j(w_c - mw_s)\, s_m(l) \;=\; \frac{-eI}{2m_0 cgQ} \sum_p Z_\perp(p) \int_0^\infty J_m[((p+Q)w_0 - w_x)t]$$

$$\times\; J_m[((l+Q)w_0 - w_x)t]\, g_0(t)dt \cdot \sum_{m'} s_{m'}(p) \qquad (1)$$

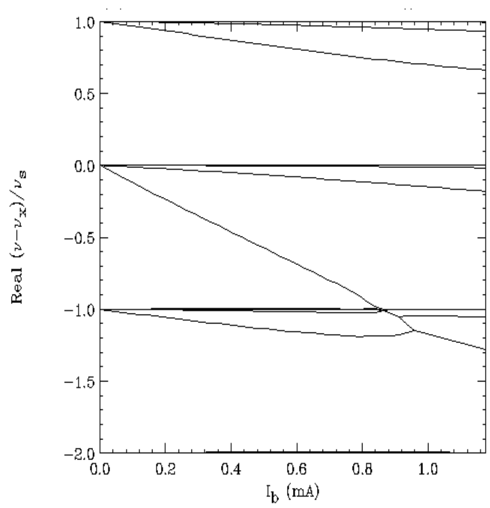
(cf. Eq. 180 of J.L. Laclare, "Bunched-Beam Coherent Instabilities", CERN 87-03)

- Classical head-tail motion if restricted to a single mode.
- Mode-merging if coupling terms are included.

Numerical Methods

1) Frequency Domain Approach :
Eigen solution of modal equations (essentially, solution of Eq. 1).

❑ "MOSES" or "MOSES-like" programs
(Several different versions created at the ESRF)



(cf. Y.H. Chin, "Users's Guide for New MOSES (MOde-coupling Single bunch instabilities in an Electron Storage ring)", CERN/LEP-TH/88-05)

1) Time Domain Approach :

Multi-particle tracking

Basic Transformations:

Transverse:

$$\begin{bmatrix} z_i \\ \dot{z}_i \end{bmatrix}_{new} = \boldsymbol{M}[\, Q_0(1 + x\frac{(e_i)_{new}}{E_0})\,] \bullet \begin{bmatrix} z_i \\ \dot{z}_i \end{bmatrix}_{old} \qquad (2)$$

$$(\dot{z}_i)_{new} = (\dot{z}_i)_{old} + \frac{ceI_b T_0}{EN_p} \int_{-\infty}^{t_i} dt'\, r(t') \cdot D_p(t') \cdot W(t_i - t') \qquad (3)$$

Longitudinal:

$$(e_i)_{new} = (e_i)_{old} + eV_{rf}[(t_i)_{old}] - eU_{rad} - 2(e_i)_{old}\frac{T_0}{T_{rad}} + 2s_{e_0}\sqrt{\frac{T_0}{T_{rad}}}R \qquad (4)$$

$$(t_i)_{new} = (t_i)_{old} + a\frac{T_0}{E_0}(e_i)_{new} \qquad (5)$$

❑ ESRF development (*Ph. Kernel et al.*)
Use of analytical wake functions (BBR + RW), inclusion of amplitude-dependent tune shift, longitudinal wake, full 6-dimension.

❑ SPring-8 development "*SISR*" (*T. Nakamura*)
Use of estimated and calculated impedance (➡ converted to wake functions) for various machine components.

❑ APS development "*ELEGANT*" (*M. Borland*)
Use of analytical wake function (BBR), full 6-dimensional tracking.

❑ "*TRISM-3D*" at CERN *(D. Brandt, G.L. Sabbi, B. Zotter et al.)*
Direct use of wake potentials calculated by wake computation codes (MAFIA, ABCI,...), convolution with "*triangular basis functions*".
Full 6-dimensional tracking with coupling terms included.

ESRF studies (cont'd)

❑ Fitting the observed mode-merging instability with the Broadband Resonator model gives $R_T \cdot b$ ~ 13 MΩ, f_{res} = 22 GHz, Q = 1.

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

❑ Although tracking reproduces rather well the threshold curve with the obtained BBR model, **it requires to assume a much shorter damping time (= 0.2 ms)** than the radiation damping (7 ms), even shorter than the synchrotron period (0.5 ms).

❑ A question arose **if the notion of “*head-tail modes*” is still valid when T_s/t > 1**, if modes as high as $|m|$ ~ 10 can drive such a strong instability, and why the stability lasts until the fast growth develops.

❑ Solution of the most general equation for head-tail motions

(Divide Eq. 1 by $j(w_c - mw_s)$ and sum over m)

$$s\,(l) = \frac{eI}{2m_0 cgQ} \sum_p j\,Z_\perp(p)\cdot s\,(p) \sum_m \frac{1}{w_c - mw_s}$$

$$\times \int_0^\infty J_m[(l+Q)w_0 - w_x)t\,]\cdot J_m[(\,p+Q)w_0 - w_x)t\,]\,g_0(t\,)\,t\,dt \qquad (6)$$

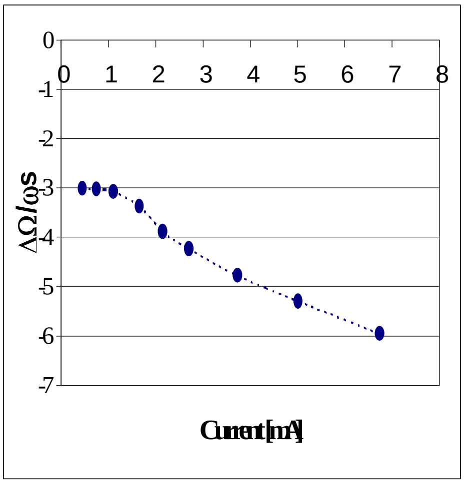
(Eq. 195 of J.L. Laclare, “Bunched Beam Coherent Instabilities”, CERN 87-03)

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

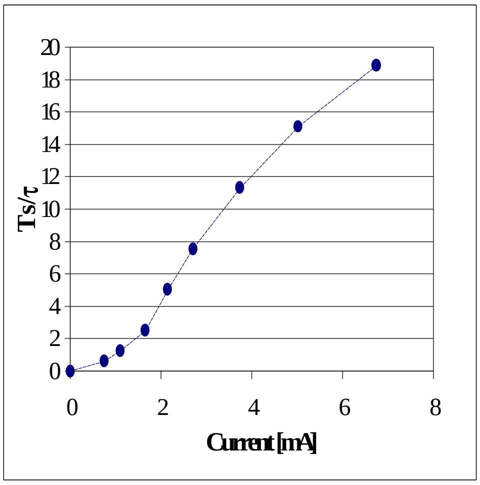
- In case of a Gaussian beam, the summation over m can be carried out analytically.
  i.e. Head-tail modes disappear completely from the equation.

- The complex coherent frequency is numerically searched through the eigenvalue problem.

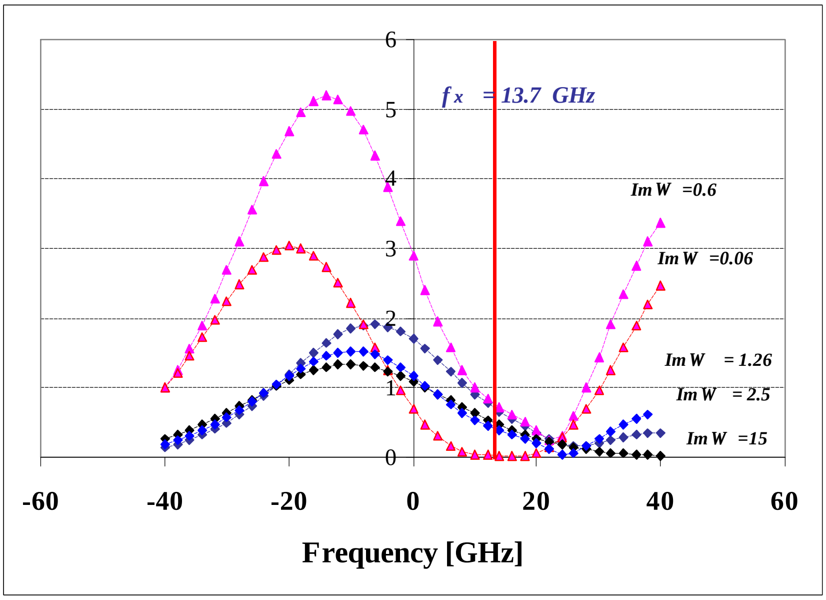
- An example of numerical solution of Eq. 6:
  ESRF parameters
  (R_T = 13 MΩ/m, f_{res} = 22 GHz, Q =1), V_{rf} = 9 MV
  Chromaticity (normalised) = 0.5, and no bunch lengthening



Mode frequency shift



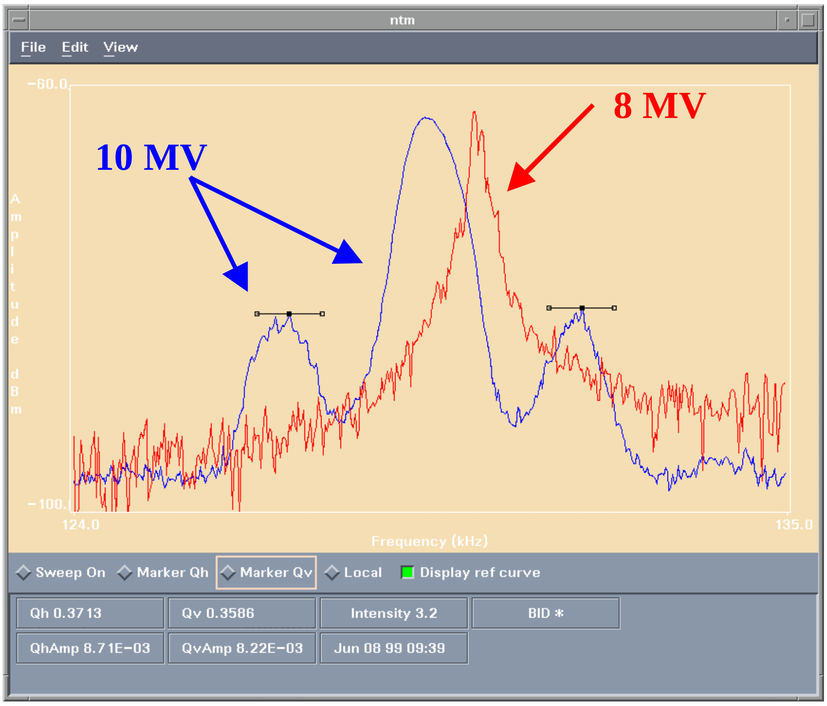
Growth rate



Beam spectra (eigen solutions)

⇒ Observe that at around the same point (~1 mA), the coherent tune, the growth rate as well as the beam spectrum all show ***a transition-like behaviour***.

❑ 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 may be 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 (Eq. 6), they ***approximately derived a dispersion relation similar to that of the coasting beam theory***, describing the fast blow up of the beam:

$$\boxed{1 = \frac{eI_{peak}\,|Z_{\perp}(w_c)|}{4\sqrt{2p}\,nhs_e\,|w_c + w_x|\,m_0gc}}$$

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

It is supposed that the blow-up of the beam is postponed due to existing stabilisation effects such as,
- bunch lengthening (reduced I_{peak})
- synchrotron tune spread Df_s
- betatron tune shift with amplitude

until the beam reaches the fast blow-regime.

The tune spread due to energy $DQ_b = Q_b \cdot x \cdot Dp/p_0$ would then act as an additional stabilisation force, since the growth time is shorter than the synchrotron period.

The fast blow-up would occur when the coherent frequency shift exceeds the width of the tune spread with energy.

⇒ Justification of the derived scenario is underway.

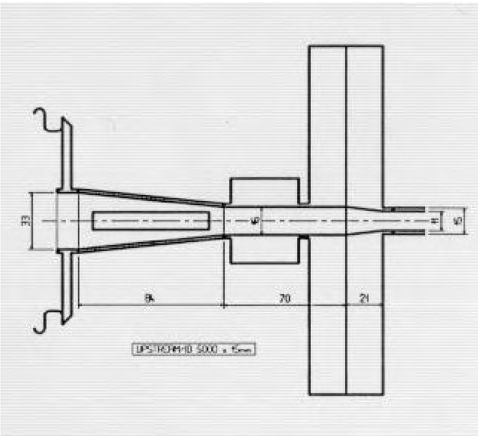
Surrounding Issues

(1) **Impedance (Wake field) Estimates and Calculations**

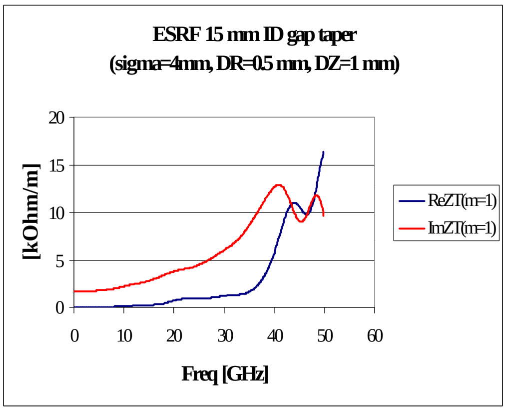
❒ Clarify relative contributions of different machine components (Taper, resistive-wall of low gap chambers, bpm, rf-finger, ...)

- Work made at SPring-8 to evaluate various machine components.
(T. Nakamura, "The Broad-Band Impedance of the Spring-8 Storage Ring", EPAC96)

- Taper calculations made at the ESRF using NOVO, TBCI, ABCI and GdfidL *(T. Guenzel et al.)*.



15 mm ESRF ID taper:



ABCI result: $[\mathrm{ImZT}]_0$ = **1.6 kΩ/m**

❒ Looking into semi-analytical approaches as benchmarks.

- Analytical formulae for tapers
e.g. *R. Warnock's formula (SLAC-PUB-6038, 1993)*

$$Z_L^{(m=0)}(w) = -i \frac{wZ_0 e^2}{4pc} \int_{-g}^{g} dz\, [s'(z)]^2 + \ldots$$

❒ Beam-based transverse impedance modelling.
Many works made in different machines (APS, Spring-8, ESRF, ALS, ELETTRA, …)

❒ Links to beam-based impedance modelling and calculations.

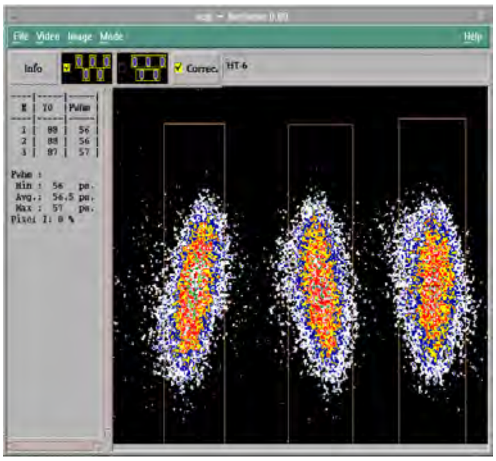
- At APS, the taper impedance deduced from the measured detuning agrees with that estimated using a formula (Bane and Krinsky, PAC93) by ~30%.
  (K.J. Kim, "APS Measurement", Impedance Workshop, Stanford, March 00)

(2) Diagnostics and its development

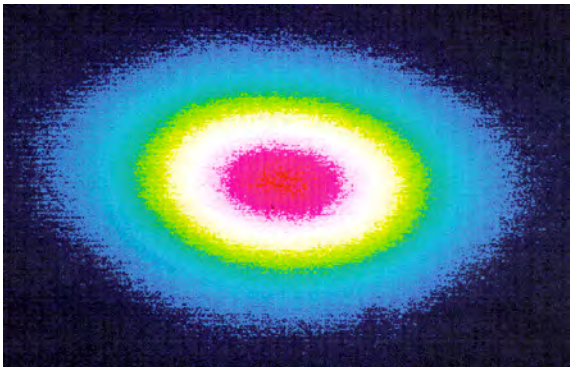
❒ At the ESRF, both the streak camera and the X-ray pinhole cameras are very useful in following the beam stability, especially when the involved frequency range of the phenomena is high (> 10 GHz).

❒ Combination of X-ray pinhole (capable of measuring the vertical emittance down to ~5 pm·rad) and a low coupling operation enables an early detection of the onset of vertical instabilities.

❒ Needs of high-frequency pickups and shakers for high chromaticity operations.



Observed head-tail motions with a streak camera in the vertical mode (ESRF, K. Scheidt et al.)



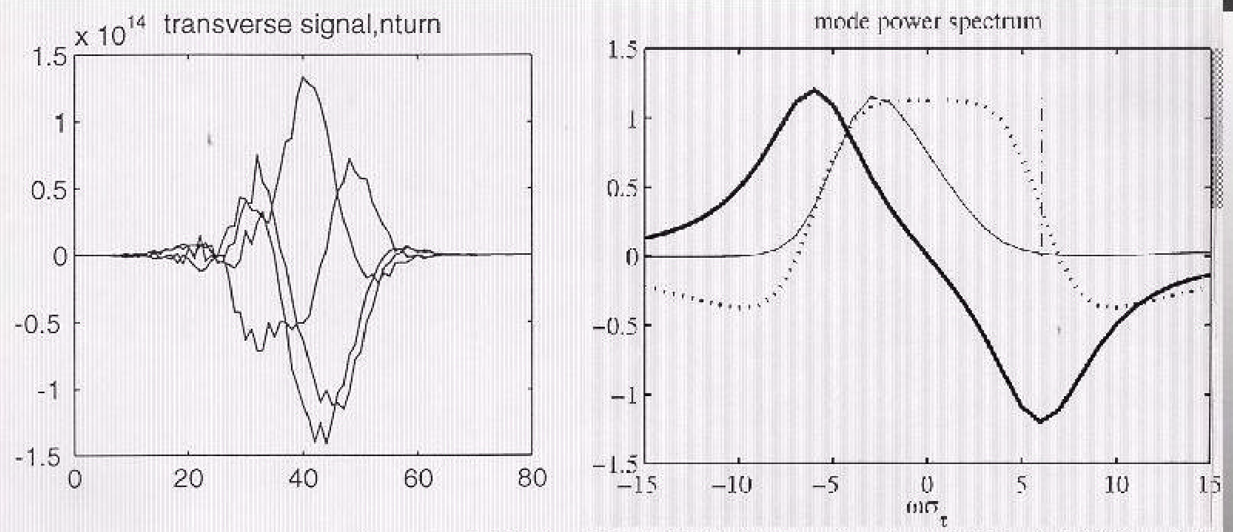
Transverse beam profile measured with a X-ray pinhole camera (ESRF)

(3) Feedback development

❒ An idea recently came up at the ESRF for an extended scheme to apply in the fast beam blow-up regime (E. Plouviez).

Idea for a single bunch feedback improved scheme

E. PLOUVIEZ ESRF



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- Fast rise/damping time => mainly dipolar and quadrupolar motion
- How to detect and manipulate separately dipolar and quadrupolar motion inside a 100ps bunch?

Conclusion

❑ Despite the ESRF case being particularly serious, single bunch transverse instability (TMCI) thresholds appear at a much lower value than the operating current in many light sources.

❑ The principal cause of the instability seems to be closely linked with installation of low gap ID chambers that enhances the mode detuning.

❑ Shift of the chromaticity to a larger positive value or feedback help operate the machine at a higher single bunch current. The ESRF case is far above what the feedback can cope with.

❑ With $\xi > 0$ operation, the single bunch is expected to be intrinsically unstable transversally. Stabilisation effects existing in the machine help postpone the beam blow up.

❑ Studies of the threshold behaviour at a large current with a large chromaticity suggest that the beam be in a fast blow up ("post head-tail") regime, where the head-tail motions no longer play any effect.

❑ Importance of surrounding issues;
- Impedance calculations (taper, bpms, rf-shields, ...)
- Extended feedback schemes
- High frequency/resolution diagnostics

to improve the stability.

Acknowledgement

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