BEAM CURRENT LIMITATIONS STUDY FOR CANDLE LIGHT SOURCE

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Abstract

The 350 mA design beam current of CANDLE light source has been evaluated by mean of the beam lifetime limitations due to single and multi-bunch instabilities. The beam current threshold values for single bunch instability are estimated based on the ring broadband impedance calculations. The coupled bunch instability (CBI) is investigated for the original ELETTRA cavity and that adopted for the ANKA.

1 INTRODUCTION

The high flux and brightness of the photon beams in third generation light sources require a large circulating electron current in the storage ring. The circulating electron beam interacts with the surrounding vacuum chamber and excites the wakefields due to chamber walls finite conductivity, surface roughness and the geometrical changes in the chamber geometry. In additional the beam is interacting with the RF cavities excited the longitudinal and transverse HOM's that can resonantly affect the beam. These fields act back on the trailing particles (bunches) resulting to particle longitudinal oscillations, effective transverse emittance growth and consequently the beam current dependent instabilities development. In the frequency domain, induced instabilities are exponentially growing if the imaginary part of the complex frequency shift $\Delta\Omega_n$ of particular beam oscillation mode, induced by wakefields, is negative ($\mathrm{Im}\Delta\Omega_n < 0$). In electron storage rings the synchrotron radiation provides a natural damping to individual particle oscillations (to any collective bunch motion) that defines the instability threshold current I_{th} given by the condition $|\mathrm{Im}[\Delta\Omega_n(I)]| < 1/\tau_r$ where τ_r is the radiation damping time.

2 SINGLE BUNCH INSTABILITY

The most notable single bunch instability, so-called microwave instability, occurs in the longitudinal plane. The excited longitudinal wake fields induce an extra voltage within the bunch increasing the energy spread that results on the bunch lengthening. The threshold current of the microwave instability is given by [1,2]

$$I_{th}^{\parallel} = \frac{\sqrt{2\pi}\,\alpha\sigma_z\left(E/e\right)}{R\left|Z_{\parallel}/n\right|_{bb}}\left(\frac{\sigma_\varepsilon}{E}\right)^2, \qquad (1)$$

where E is the particle synchronous energy, e is the electron charge, $\left|Z_{\parallel}/n\right|_{bb}$ is the normalized longitudinal broadband impedance, n is the harmonic number, α is the momentum compaction factor, σ_z is the bunch length, σ_ε/E is the relative energy spread, R is the average radius of the ring. The current $I_{th}^{\parallel}$ is the average circulating beam current per bunch. Table 1 presents the contributions to broadband longitudinal and transverse impedances caused by chamber finite conductivity, surface roughness, transitions, BPM's and bellows.

Table 1. CANDLE Broadband impedance.

	$(Z/n)_{bb}^{\parallel}\ [m\Omega]$		$Z_{bb}^{\perp}\ [k\Omega/m]$	
	Re	Im	Re	Im
Resist.walls	38	38	0.026	0.027
Roughness	-	63	3.63	-
Transitions	-	11	-	0.465
BPM's	0.065	0.038	0.32	0.19
Bellows	48	190	6.9	5.5
Total	86	302	10.9	6.2

The normalized machine longitudinal broadband impedance for the CANDLE storage ring is equal to $(Z/n)_{bb}^{\parallel} = 0.314\Omega$ and is far below the requirement to the Third Generation machine impedance value of $\left|Z/n\right|_{bb}^{\parallel} \sim 1\Omega$. Corresponding single bunch threshold current value is $I_{th}^{\parallel} = 8.9mA$. Note that CANDLE nominal operation current 350 mA implies the single bunch charge of 0.9 nC that corresponds to circulating current per bunch of $I = 1.24mA$. Fig.1 shows the CANDLE threshold current versus the longitudinal impedance of the storage ring. The single bunch current is below the longitudinal microwave instability threshold current for the low-frequency broadband impedance of the ring below of 2Ω.

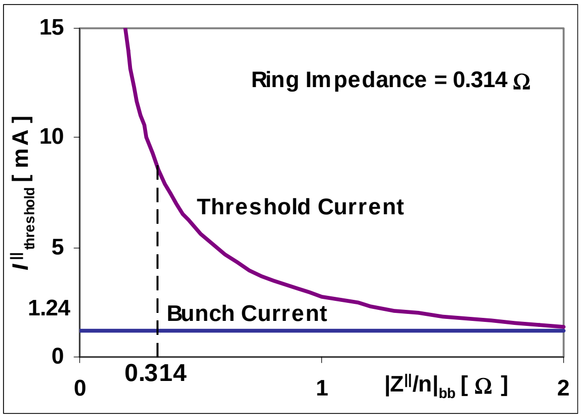

Figure 1. Longitudinal threshold current versus longitudinal broadband impedance.

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The transverse wakefields excited by off-axis bunch in the storage ring cause the transverse fast single bunch instability. The wakefields that excited by the head part of the bunch deflect the tail particles from the center of the chamber thus leading to bunch break-up. The vertical dipole mode is usually dominant in the storage ring as the vertical aperture of the chamber is smaller than horizontal. The transverse emittance of the bunch is enlarged until the head and tail particle interchange the longitudinal positions due to synchrotron oscillations. The threshold current of the transverse single bunch instability is given by [4]

$$I_{th}^{\perp} = \frac{\sqrt{2\pi}\alpha(E/e)}{\overline{\beta}|Z_{\perp}|_{bb}}\left(\frac{\sigma_{\varepsilon}}{E}\right) \qquad (2)$$

with $\overline{\beta}$ the vertical average beta function ($\overline{\beta}$=10.5m). The threshold current for CANDLE storage ring that defines the process stabilization limit for the transverse single bunch instability is then equal to $I_{th}^{\perp} = 113mA$.

The above estimations are conservative: as it follows from the Tab.1, the bellows gives the most essential inclusion in the threshold currents values, whereas the shielded bellows impedance is much smaller.

3 LONGITUDINAL CBI

The narrow band impedance of the storage ring, basically the longitudinal and transverse HOM's excited by beam in the RF cavities, determine the long-range wakefields that are the source of the longitudinal and transverse CBI. The longitudinal wakefields cause the energy oscillations of the successive bunch leading to the longitudinal CBI. In a rigid bunch model, a stored beam consists of M identical bunches uniformly filled in M RF buckets of the ring. The beam has M oscillation modes with phase differences $\Delta\phi = 2\pi n / M$, $(n = 0,1,2...M-1)$ and beam frequency pattern at the single point in the ring contains $pM + n$ harmonics of the revolution frequency ω_0 with p an integer. In addition, each bunch performs synchrotron oscillations with the frequency $\omega_s = Q_s\omega_0$ (Q_s is the synchrotron tune). Thus an observation of the beam at the single point in the ring will detect the signal at the revolution frequency harmonics $(pM + n)\omega_0$ plus the synchrotron frequency ω_s. The spectrum of the beam is then given by $\omega_{np} = \ = (pM + n + Q_s)\omega_0$. If the longitudinal HOM impedance has the resonance at the same frequencies as the beam signal, the longitudinal CBI is developed. The complex frequency shift for the n^{th} beam oscillation mode is given by [2-4]

$$\Delta\Omega_{\parallel}^{n} = iN\frac{\alpha I}{4\pi Q_s(E/e)}\sum_{p=-\infty}^{\infty}\omega_{np}Z_{\parallel}(\omega_{np})e^{-(\omega_{np}\sigma_{\tau})^2} \qquad (3)$$

with I the average circulating current, α the momentum compaction factor, E/e beam energy (eV), σ_{τ} the bunch length (sec) and N the number of cavities. The imaginary part of the complex frequency shift can give rise to an instability if $\mathrm{Im}[\Delta\Omega_{\parallel}] < 0$, with the growth rate $\alpha_G = -\mathrm{Im}[\Delta\Omega_{\parallel}]$. The growing is inconvertible if the growing rate exceeds the damping rate of the synchrotron oscillations.

The longitudinal CBI for the CANDLE storage ring has been studied for two options of the RF cavities: the original ELETTRA cavity [5] and that adopted for the ANKA [6]. Fig.2 presents the longitudinal coupled bunch instabilities growing rate versus the relative mode index n for the 282 beam oscillation modes. The two longitudinal modes of ANKA cavity, L4 and L5, drive the instability at the relative oscillation modes of 9 and 76 respectively with the growth rate exceeding the damping rate of synchrotron oscillation. In addition, two modes, L2 and L9, are critical that with low frequency change can excite the longitudinal CBI at the beam oscillation modes 41 and 92.

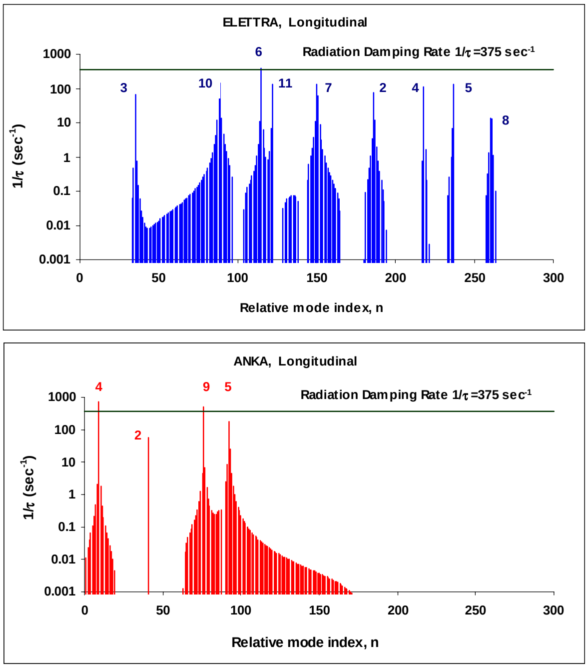

Fig.2 Longitudinal CBI growing rate in CANDLE for ELETTRA and ANKA type cavities

There are nine local maximums on distribution curve for ELETTRA cavity. The growing rates of instabilities are mostly below the synchrotron radiation damping $\alpha_s = 375\sec^{-1}$, except of L6 longitudinal mode that excites the instability at relative oscillation mode of n=115. Although the growing rates of these instabilities are below the synchrotron oscillations damping rate, they have very narrow stable frequency band. For example, the increasing of resonant frequency of ELETTRA cavity longitudinal mode L11 on $160MHz$ leads to increasing of growing rate of relative mode $n = 122$ from $\alpha_G = 136\sec^{-1}$ to $\alpha_G = 770\sec^{-1}$. Another example: the decreasing of L8 mode resonant frequency on 520 MHz, changes the $n = 260$ oscillation mode instability growing rate from $\alpha_G = 13.7\,\mathrm{sec}^{-1}$ to $2225\,\mathrm{sec}^{-1}$.

4 TRANSVERSE CBI

The long-range transverse wake fields (transverse HOM) produced by the off-axis beam in the cavities are the source of the transverse coupled bunch instabilities. The rigid bunches experience only the dipole transverse oscillations and the mode spectrum lines of the signal in the horizontal (x) and vertical (y) planes are similar to longitudinal one: $\omega_p^{x,y} = (pM + n + Q_{x,y})\omega_0$ with $Q_{x,y}$ the betatron tunes. The complex frequency shift is given by cavity transverse impedance $Z_\perp(\omega)$ as

$$\Delta\Omega^n_{x,y} = -iN\bar{\beta}_{x,y}\frac{\omega_o I}{4\pi(E/e)}\sum_{p=-\infty}^{\infty} Z_\perp(\omega_p)e^{-(\omega_p\sigma_\tau)^2} \qquad (5)$$

with $\bar{\beta}_{x,y}$ the average transverse beta-functions and

$$Z_\perp(\omega) = \sum_{k=1}^{K}(\omega_\Gamma^k/\omega)\cdot R_\perp^k \Big/ \left[1 + iQ_k\left(\omega_\Gamma^k/\omega - \omega/\omega_\Gamma^k\right)\right], \qquad (6)$$

where $R_\perp^k$ is the cavity transverse shunt impedance. The transverse oscillations are unstable if the imaginary part of the complex frequency shift is negative. The parameters of the transverse HOM of the ELETTRA and ANKA cavities were taken from [5] and [6], respectively. The growing rates of transverse CBI for horizontal and vertical transverse beam oscillation modes in CANDLE with ELETTRA and ANKA type cavities are presented in Fig. 3 and Fig. 4.

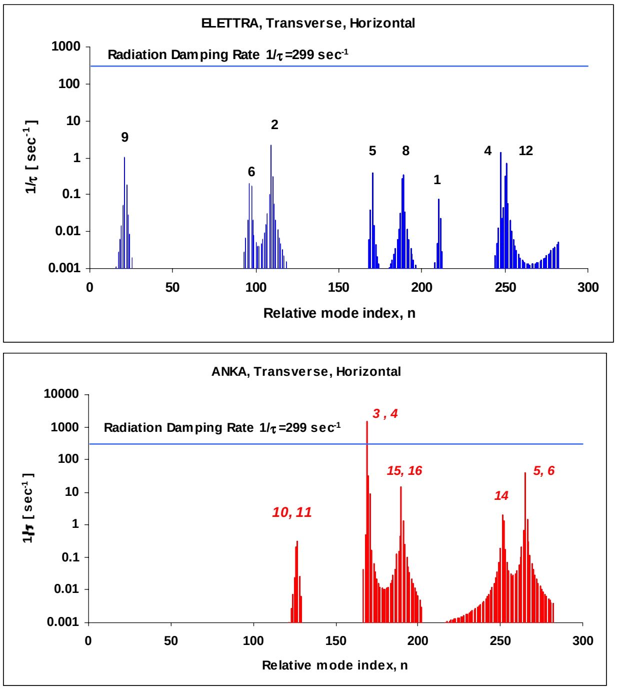

Fig.3 The transverse CBI growing rate for ELETTRA and ANKA cavities. Horizontal plane.

As it follows from the Figures, the modes that excite the CBI in the horizontal plane produce unstable transverse oscillations in vertical plane as well. The ELETTRA and ANKA cavities have 9 and 5 critical transverse HOM respectively, that causes unstable coupled bunch oscillations.

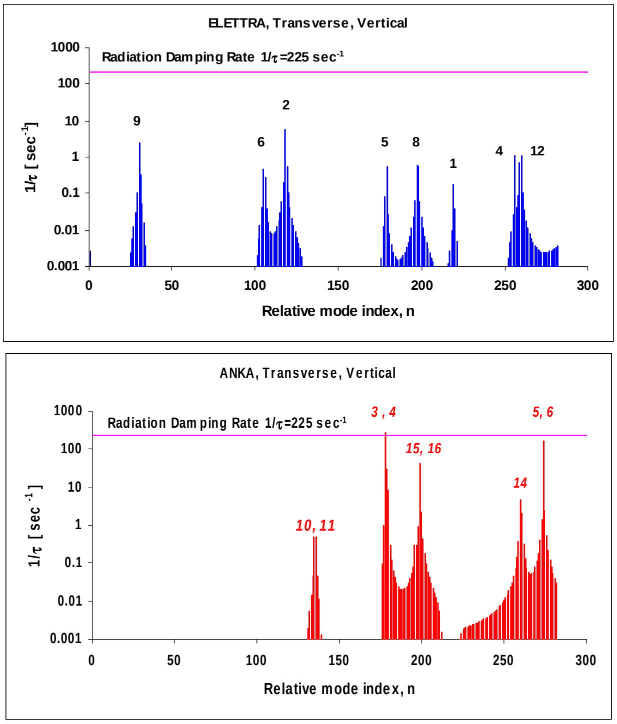

Fig.4. The transverse CBI growing rate for ELETTRA and ANKA cavities. Vertical plane.

SUMMARY

An existing technology of RF cavities manufacturing leads to individual distinction for each of preparing cavity. The cavities for the CANDLE storage ring will be carefully certified to determine HOM's parameters. Developed in the paper methodology will allow to calculate the expected instabilities in the ring and to develop the instabilities cure procedure.

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