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STUDY OF LONGITUDINAL COUPLED BUNCH INSTABILITY FOR SESAME

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I. Introduction

As the particles traverse the ring, they interact with their surrounding electromagnetic fields created by their own charge and current. This field extends for a certain distance behind the particles for a short or long duration of time, and it is called the wake field. As an example when a bunch traverses the RF cavity, it can excite one or more of its higher order modes (HOMs). Depending on the cut-off frequency of beam pipe, the electromagnetic fields of these HOMs could be trapped inside the cavity, however they typically resonate for a long time, and therefore can influence all the bunches in the beam as they go through the cavity. In general, under certain circumstances, the wake field can act back on the beam in such a way that an initial disturbance is amplified and hence instability is generated.

II. Collective phenomena [1]

The key signature for the instability is the current dependence. When the current is low the wake fields are weak, and the beam characteristics are dominated by single particle dynamics. As the beam current is increased, the wake fields become stronger and can influence the beam dynamics, and hence the machine performance, significantly. Some of the instabilities depend smoothly on current, and some others have a well-defined limit. When the current exceeds a threshold value, then the wake field forces overcome the damping mechanisms and therefore an initial disturbance gets amplified. All of these phenomena arise because the beam, as a collection of charges, acts back on itself via the environment in which it travels; for this reason, these are type of phenomena which are called collective phenomena.

III. Instabilities and their effects

In general, there are two types of instability from the point of view of the bunch itself: Single bunch instability (SBI) and multi bunch instability (MBI). SBI is strongly influenced by short-range wake fields arising from small structures in the vacuum chamber such as bellows, discontinuities, vacuum ports, BPMs, etc[1]. MBI are strongly influenced by long-range wake fields. The most important mechanism that gives rise to such wake fields is the excitation of HOMs in resonant structures, mainly the RF cavities, and in a minor importance the finite resistivity of vacuum chamber. In general instability can have two undesired effects on the performance of machine. One is the effect on lifetime and the second is the effect on beam quality. It can reduce the beam lifetime, increase the beam emittance, cause the bunch lengthening, increase the energy spread and in the worst case can bring the beam to loss. In this report the results of investigation of coupled bunch instability (CBI) for the SESAME cavities are given. In the coupled bunch instability, all the bunches act together in such a way as to cause a resonance whose typical time scale is quite short. Without an active feedback system, a CBI can lead to sudden beam losses.

IV. Longitudinal Coupled Bunch Instability [1, 2, 3]

In general the interaction of the beam with the wake fields leads to both an amplitude growth and a frequency shift of the longitudinal beam oscillations. For coupled bunch mode k (k=0, 1,…, M-1), where M is the number of equally spaced bunches, the complex coherent frequency shift (CFS) is given by:

$$\Delta\Omega_{II}^{k} = i\frac{\eta h \omega_0 I_0}{4\pi \nu_s E}[Z_{II}]_{eff.}^{k} \qquad (1)$$

where the effective impedance is the sum of the impedance weighted by the beam spectrum, and is given by:

$$[Z_{II}]_{eff.}^{k} = \sum_{p=-\infty}^{\infty} \frac{\omega_p}{\omega_{rf}} Z_{II}(\omega_p)\, e^{-(\omega_p \sigma_\tau)^2} \qquad (2)$$

where:

$\omega_p \equiv (pM + k + \nu_s)\omega_0$

h, η, ω_0, ν_s harmonic number, phase-slip factor, revolution frequency, synchrotron tune

p integer number.

The real part of CFS gives the shift in the oscillation frequency of the mode, and is driven by the reactive part of impedance. The imaginary part is the growth rate of the oscillation, and is driven by resistive part of the impedance. The motion becomes unstable when the growth rate of the oscillation is larger than the natural damping of the machine.

In the case of a single high-Q resonator tuned near the frequency $pM\omega_0$, a bunch whose length is short compared to the wavelength of the resonator i.e. 60 cm for 500 MHz cavity, has a growth rate given by:

$$\frac{1}{\tau_{II,k}} = \frac{\eta h \omega_0 I_0 R_{eff.II,k}}{4\pi \nu_s E} \qquad (3)$$

where

$$R_{eff.II,k} = \mathrm{Re}[Z_{II}]_{eff.}^{k} \approx (pM + k + \nu_s)\,\mathrm{Re}\, Z_{II}((pM + k + \nu_s)\omega_0)/h - (pM - k - \nu_s)\,\mathrm{Re}\, Z_{II}((pM - k - \nu_s)\omega_0)/h \qquad (4)$$

In a simpler relation the growth rate for longitudinal coupled bunch mode number k, excited by a cavity HOM with shunt impedance R_{II}, is given by:

$$\frac{1}{\tau_{II,k}} = \frac{\eta I_0}{4\pi \nu_s E}\omega_p R_{II}(\omega_p) \qquad (5)$$

We have carried out the calculation for growth time and threshold current of SESAME from the point of view of cavity HOMs. For this purpose the worst case situation has been considered, that means 100% coupling. If we take into account only the natural damping τ_ε given by the emission of synchrotron radiation, the stability condition for a given coupled bunch mode regarding the growth rate of synchrotron oscillation is given by:

$$\frac{1}{\tau_{II,k}} < \frac{1}{\tau_\varepsilon} \qquad (6)$$

In this case, the maximum beam current, which can be stored to meet the stability condition, is given by:

$$I_{b.\max.} = \frac{1}{\tau_\varepsilon}.\frac{4\pi \nu_s E}{\eta h}.\frac{1}{\omega_0 R_{eff.II,k}} \qquad (7)$$

Moreover, in a simpler relation, the threshold bunch current for a stable CBM number k, is then given by:

$$I_{b.\max.} = \frac{1}{\tau_\varepsilon} . \frac{4\pi \, \nu_s E}{\eta} . \frac{1}{\omega_p R_{II,k}(\omega_p)} \qquad (8)$$

The relation between energy and damping time is given by:

$$\tau_\varepsilon(ms) = \frac{C(m)\rho(m)}{13.2 J_\varepsilon E^3 (GeV)} \qquad (9)$$

At low energies the damping time of the ring is large while with the increase in energy the damping time will be reduced. This means, in case of exceeding the instability threshold, the situation at the injection energy is much more dangerous than the high energy case.

V. SESAME characteristics

SESAME is a third generation light source, with serious demand on beam stability along with reliability of operation and beam lifetime [4]. At the present time the plan is to use ELETTRA type RF cavities, whose main parameters are listed in Tab.1.

Table1: Fundamental mode parameters

Frequency	MHz	499,7
Quality factor, Q		39000
Shunt impedance R_s	MΩ	3.4
Max. cavity voltage	kV	630
Max. cavity power	kW	60
Max coupler power	kW	120

Furthermore the cavities also have higher order modes, that reacts with the beam too and lead to the so called multi bunch or coupled bunch instability. The longitudinal CBI analysis, as an important issue for the safe operation and stable beam in the SESAME, has been carried out. Moreover in the Appendix we present longitudinal CBI analysis for the recent developed EU HOM damped cavities as suggested by the Technical Committee Meeting (Nov 2004).

The possible cures for this problem also will be discussed in this report. A typical set of Longitudinal(TM) and Dipolar (TE) HOMs for the ELETTRA type of cavity are given in Tab. 2 and 3.

Table2: Higher Order Longitudinal Modes of ELETTRA type cavities

Longitudinal HOMs			
Mode	f [MHz]	R/Q [Ω]	Q
L0	499.70		
L1	947.16	28.2	42381
L2	1057.96	1.1	36111
L3	1420.24	5.1	25763
L4	1512.24	4.7	26751
L5	1607.17	10.0	19550
L6	1874.88	0.5	16241
L7	1947.06	1.6	27342
L9	2122.36	7.9	30932

Table 3: Higher Order Dipolar Modes of ELETTRA type cavities

Dipolar HOMs			
Modes	f [MHz]	R/Q [Ω]	Q
D1	742.44	4.6	45125
D2	746.02	15.8	25000
D3	1113.12	13.0	37799
D4	1220.34	0.1	64201
D5	1241.79	4.5	7018
D6	1303.82	0.2	46042
D7	1559.50	0.0	33712
D9	1709.90	1.6	17522
D10	1715.25	0.5	43668

In SESAME, the beam is first injected at 800 MeV and then ramped to 2.5 GeV. As we will see in this report, at low energies, the damping time is very low, and as a result the stability threshold for intensity is expected to be very low. The CBI calculations show the necessity of introducing a damping mechanism or feedback system to combat the harmful instabilities.

VI. The result for SESAME Longitudinal CBI

The parameters involved for the calculation of longitudinal CBI for SESAME are given in Tab.4. Growth rate for each single HOM with the nominal current of 400 mA and a fixed synchrotron frequency of 38.35 kHz for different energies from injection energy of 800 MeV to 2.5 GeV is plotted in Fig.1.

As Fig.1 shows, the damping time of SESAME is far greater than the growth time of HOM instability. The worst case instability is predicted for the frequencies of 947.16 MHz and 2122.36 MHz. Instability for the best case is expected to be for 1874.88 MHz.

Table 4: SESAME parameters involved in CBI calculation

Parameter	Value
Operating energy, E (GeV)	2.5
Injection energy (MeV)	800
Momentum compaction	8.55 e-3
Beam current (mA)	400
RF frequency (MHz)	499.654
Harmonic number	215
Synchrotron tune	0.0165
Long .Rad. Damping time (ms)	2.711
Hor. Rad .Damping time (ms)	2.206
Ver. Rad. Damping time (ms)	3.649

Also the threshold current for the longitudinal coupled bunch instability for a range of energy from injection energy of 800 MeV to 2.5 GeV is plotted in Fig.2.

Fig.2 shows the threshold current for different HOMs versus energy from 800 MeV to 2.5 GeV. The best case for instability is for the frequencies of 1947.06 MHz and 2122.36 MHz. The minimum threshold current is for 947.16 MHz with a current of 1.5 mA at injection and 3.5 mA at 2.5 GeV.

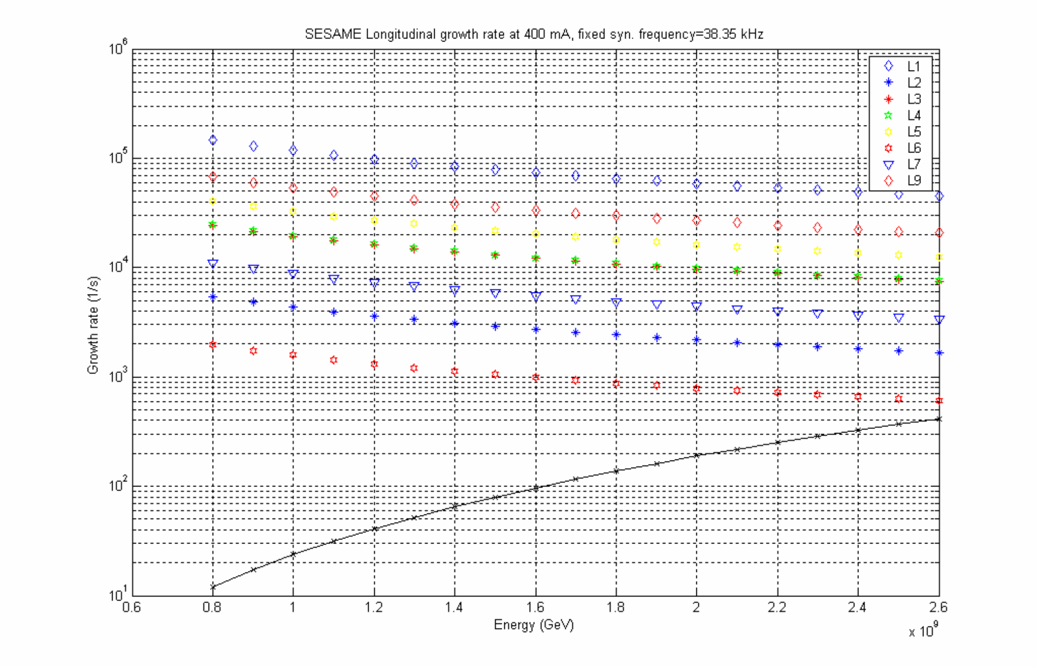

Figure 1: Growth rate (1/s) versus energy for the cavity HOMs

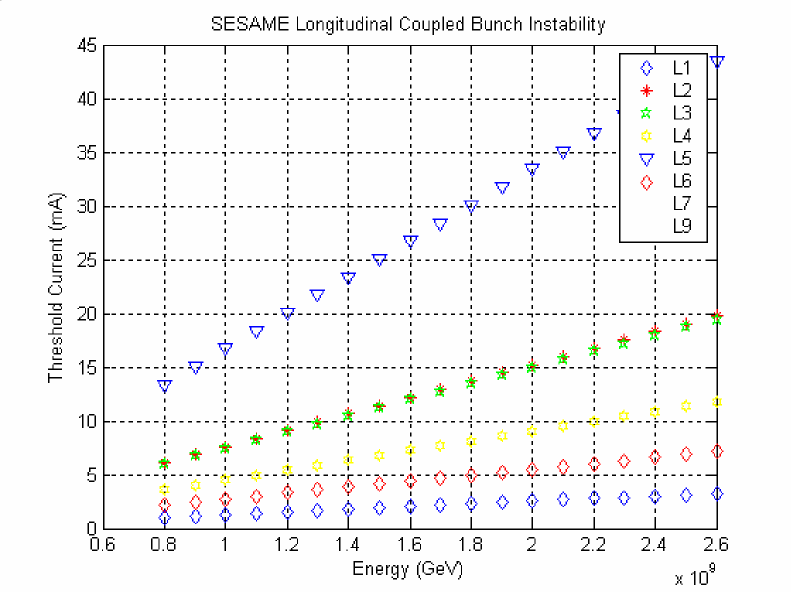

Figure 2: Threshold current due to HOMs versus energy

In case of using a temperature controlled frequency mode shift, to cure the instability, the minimum frequency shift which is needed to stabilize the coupled bunch instability created by the HOM is shown in Fig.3 for each single HOM. Again for the frequency of 2122 MHz we need the maximum frequency shift, to stabilize the LCBI.

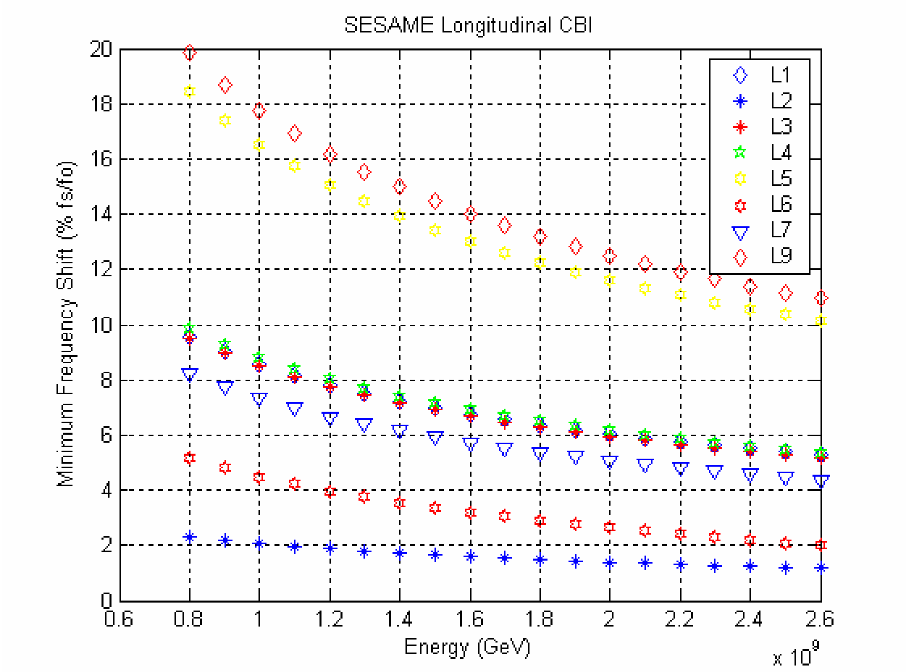

Figure 3: Minimum frequency shift versus energy

To have a better idea of LCBI, TCBI and growing rates for SESAME compared to other light sources, which currently use ELETTRA type cavity, we should have a comparison between them.
From (4) for a given cavity the grow rate is given by:

$$\frac{1}{\tau_{II}} = k_{\tau,II}\omega_p R_{II} \qquad (10)$$

where $k_{\tau,II}$ is the so-called *longitudinal damping factor*.
From (8) we derive the threshold current for a given cavity:

$$I_{b,.\max.} = \frac{k_{i,II}}{\omega_p R_{II}} \qquad (11)$$

where $k_{i,II}$ is the so-called *longitudinal threshold current factor*.
For longitudinal coupled bunch instability, the instability factors for ELETTRA, ANKA, SESAME and SLS normalized to full energy ELETTRA factors are given in Tab. 5. The cavity and RF parameters of SLS and ANKA can be found in [2, 5].

Table 5: LCBI factors for different machines

	$k_{\tau,\text{II}}$	$k_{i,\text{II}}$	$k_{\tau,\text{II}}$, Injection	$k_{i,\text{II}}$, Injection
ELETTRA	1	1	**2**	**0.5**
SESAME	1.6	0.52	**5**	**0.166**
ANKA	2	0.8	**10**	**0.16**
SLS	2.69	1.55	**2.69**	**1.55**

Tab. 5 shows the LCBI conditions for different machines. From the point of view of damping growth, the worst case is for the ANKA at injection energy. From the point of view of threshold current, as well ANKA and SESAME have the worst condition which could make the limitation for these machines for operation at high currents.

VII. Coupled Bunch Instability cures

In general there are some cures for coupled bunch instability, which can be chosen regarding the machine performance and possibility of using them in the machine. The general possible cures for CBI are as follows:

- Reduce or eliminate the strength of HOM in the design of RF cavity
- Using the tuned antenna in the case that there are only few troublesome HOM
- Frequency shift with changes of the cavity temperature or the position of tuning plunge
- Increasing the synchrotron or betatron tune spread
- Active feedback system as the most powerful method

Increasing the synchrotron or betatron tune in the LCBI could be accomplished either by running the RF cavity at lower voltage or by adding a higher harmonic RF cavity. In the case of TCBI, adding octupole magnets to the storage ring lattice or using RF quadrupoles can be used to increase the tune spread. A powerful, easy control and reliable way to cure the CBI is an active feedback system. Such a system is used in DAFNE, BESSYII, and ALS to cure the CBI. Another method that is used for this kind of ELETTRA cavity in ELETTRA/ANKA is using the temperature control to shift the frequency of HOMs.

VIII. References:

[1]. Herman Winick, “Synchrotron radiation sources, a primer” world scientific, 1994, chapter 12.
[2]. M. Svandrlik et al., “Coupled bunch instability calculation for the ANKA storage ring” EPAC98, Stockholm.
[3]. A. Gallo et al., “Advanced of the DAFNE longitudinal kicker geometry to the needs of the BESSY II synchrotron light source”, DAFNE Tech. note: RF-21
[4]. G.Vignola, Attal - SESAME Tech. note **O-1**, Dec.2004
[5]. P. Marchand et al., “RF system for the SLS booster and storage ring” PAC99, US

Appendix I

Longitudinal HOMs measured for EU HOM damped cavity are given in table A.1.

Table.A.1. Higher Order Modes of HOM damped cavity

Longitudinal HOMs	
f [MHz]	R [Ω]
670	2778
701	1960
1520	701
1536	4832
1577	1113
1585	1965
2257	1636
2258	507
2670	3159
3045	635

Growth rate for each single HOM with the nominal current of 400 mA and a fixed synchrotron frequency of 38.35 kHz for different energies from injection energy of 800 MeV to 2.5 GeV is shown in fig.A.1.

Fig.A.2 shows the threshold current for the longitudinal coupled bunch instability for a range of energy from injection energy of 800 MeV to 2.5 GeV.

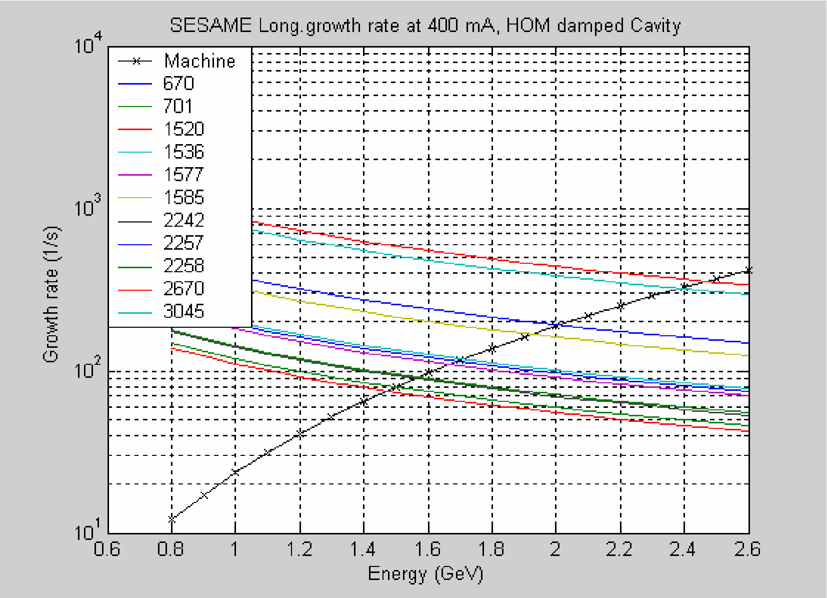

Figure.A.1 Growth rate (1/s) versus energy for the cavity HOMs

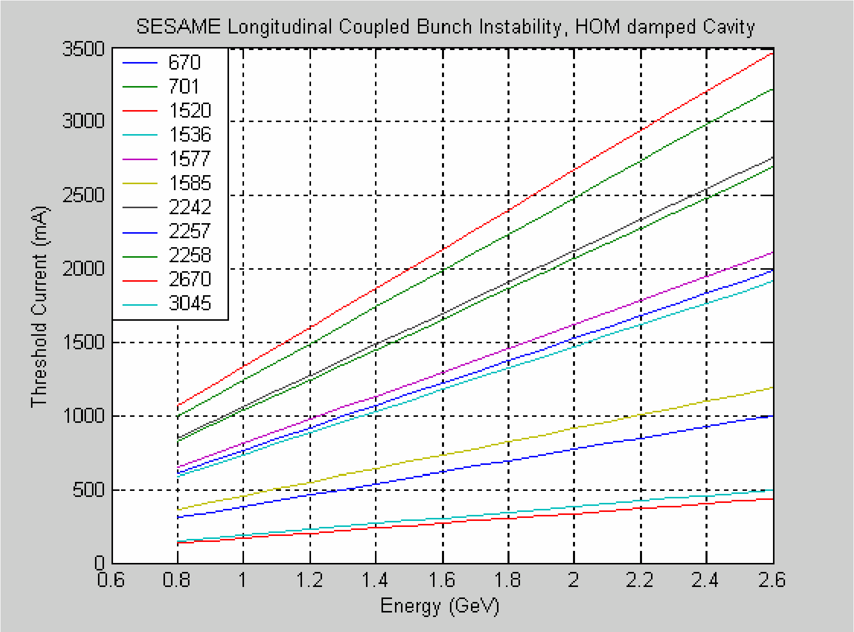

Figure.A.2 Threshold current due to HOMs versus energy

As one can conclude from the comparison between ELETTRA and HOM free cavities, clearly that the EU HOM damped cavity looks very attractive from the instability point of view, but other considerations need to be done, including the economic aspects.