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COHERENT HIGH-ORDER MODE HEATING IN CESR SLIDING JOINTS FROM MULTI-BUNCHED STORED ELECTRON & POSITRON BEAMS*

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Abstract

Stored beams containing trains of bunches can excite trapped higher-order modes (HOM) in discontinuities such as sliding joints (SLDJTs). Due to the relatively high Q, the trapped fields excited by multiple bunches in a SLDJT can interfere constructively and a coherent enhancement may result at certain SLDJT openings for a given bunch spacing. This resonant HOM loss in the SLDJT causes abnormal heating and can pose an operational problem for CESR at high beam currents or at short bunch lengths. Calculations show resonance behavior at certain SLDJT openings depending on the bunch spacing within each train. Two types of experiments were performed to investigate the SLDJT resonant loss as a function of the SLDJT opening at both 14ns and 28ns bunch spacings. In one type of measurement, the temperatures of 100 SLDJTs with random openings were sampled at each bunch spacing. In another experiment, the temperatures of a selected group of SLDJTs were measured as a function of opening for both bunch spacings. The measurements showed maximum heating at the SLDJT openings consistent with the calculations. The beam current and bunch length dependence of the SLDJT temperatures was also measured. Measures have been taken to set the openings of all CESR SLDJTs sufficiently off resonance so that significant heating does not occur at full design current.

1 INTRODUCTION

Higher-order modes (HOM) can be excited by stored beams containing trains of bunches in discontinuities in the vacuum components, such as in a sliding joint (SLDJT). Modes with frequency lower than the beam pipe waveguide cut-off frequency will be trapped in the discontinuity. Calculations and bench measurements [1] confirmed the existence of the trapped modes in the CESR SLDJT. Though there is no evidence that the trapped modes in the SLDJTs cause beam instability, the heating of the SLDJTs from the HOM power loss is an operational concern with increasing stored beam current in CESR. In usual situations, the heating of SLDJTs is mostly due to synchrotron radiation (SR) power. However, abnormal heating, with temperature significantly higher than expected from SR power, was observed in some SLDJTs. The abnormal heating seemed to occur randomly at various SLDJTs at different beam currents. It was suggested that the observed HOM heating in certain SLDJTs is caused by constructive interference of the trapped fields excited by multiple bunches in a SLDJT ocurring at well-defined bellows gap openings. A program was carried out to investigate the coherent HOM heating in the SLDJTs in CESR to understand the HOM heating and to ensure safe operation of CESR at higher stored beam current with shorter bunch length. This paper reports the finding of the study.

2 CALCULATIONS

As charged particles in a bunch pass by a discontinuity in the vacuum chamber wall of an accelerator, some of the electromagnetic fields traveling with the beam are radiated into the structure to be either dissipated as heat in the walls or reabsorbed by later particles in the bunch or subsequent bunches. In the latter case, if the subsequent bunches are spaced closely such that the fields in the structure have not decayed, the radiated fields from the later bunches will add and in some cases produce resonant buildup. This resonant excitation will occur for trapped (i.e. non propagating) modes in the structure which have frequencies that are harmonically related to the bunch repetition frequency.

A function P(k) is useful to describe the relative population of charges in all the total N_{RF} RF buckets in the ring. P(k) can be defined as $P(k)=q_b(k)/Q_b$ where $q_b(k)$ is the charge in the k-th (k from 0 to N_{RF} - 1) RF bucket and Q_b is the charge in some bunch. If all bunches that are filled have the same charge, Q_b, then P(k) is either 0 or 1 depending whether the bucket is populated or not. The net energy lost by the beam to mode m may then be written generally as an integral of the impedance $Z_m(\omega)$ and the beam's linear charge density spectrum $\lambda(\omega)$,

$$\Delta U_m = \frac{Q_b^2}{\pi}\int_0^{\infty} d\omega\, \mathrm{Re}\{Z_m(\omega)\}\lambda(\omega)\lambda^*(\omega)$$

where the spectrum $\lambda(\omega)$ is a line spectrum at the rotation harmonics of the ring which has an envelope for multiple stored bunches containing an interference pattern within the overall Fourier spectrum of the bunch. Making use of P(k) to describe the bucket population and the fact that the bunch has a gaussian bunch length σ_z, the net power lost P_m to mode m {having an angular frequency ω_m, quality factor Q_m and shunt impedance $(R/Q)_m$ } may be written as

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$$P_m = \frac{Q_b^2 \omega_r^2}{2\pi^2} \sum_{n=0}^{\infty} \left[Q_m \left(\frac{R}{Q} \right)_m \exp\left(-\frac{n^2 {\omega_m}^2 \sigma_z^2}{c^2} \right) \Big/ \left\{ 1 + Q_m^2 \left(\frac{\omega_m}{n\omega_r} - \frac{n\omega_r}{\omega_m} \right) \right\} \right] \times \left| \sum_{k=0}^{N_{RF}-1} P(k) \exp(jnk\omega_r T_{RF}) \right|^2$$

where ω_r is the angular revolution frequency of the ring and T_{RF} is the period of the RF system. The first factor in the sum is the spectral contribution from a single bunch to mode m's high-Q resonance, while the second factor gives the interference factor for all the bunches. The interference factor equals 1 for a single bunch, has a value of the number of bunches N_b for distantly spaced bunches and in general ranges between 0 and N_b^2.

Bench measurements predicted $(R/Q)_m$ of 4.9 ohms, Q≈2000 and a dependence of mode frequency on SLDJT opening of –6.11 MHz/mm with a frequency of 3.574GHz at an opening of 25mm[1]. For 9 trains of 3 bunches (240mA total current) figure 3(d) and (e) give the results of a calculation of P_m for, 14 and 28 ns (71.4 and 35.7 MHz) bunch spacings within the trains with Q values of 200 and 2000, respectively. All four plots show an interference pattern having a gross structure which is periodic at openings that correspond to trapped mode frequencies being multiples of the bunch spacing frequency within a train. The high Q plots show additional interference peaks at frequencies corresponding to multiples of the train frequency. The peaks in these plots occur when the fields from later bunches add in phase with those from earlier bunches or trains. One would expect that the regions of the highest peak power in the high Q plots would be "smoothed" out somewhat due to the fact that high peak dissipation causes SLDJT to move. So the low Q plots of figures 3(d), (e) and figure 2 give an indication of the spacing of regions of opening gaps which are susceptible to resonant heating.

3 MEASUREMENT RESULTS

There are about 100 SLDJTs in the CESR vacuum system, typically between two dipole magnets. The structure of the SLDJT is illustrated in Figure 1.

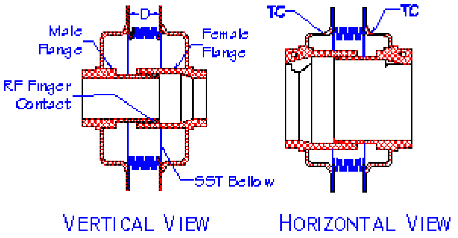

Figure 1. Cross sectional views of a CESR SLDJT.

In a typical configuration, aluminum flanges of the SLDJT are welded to a curved dipole vacuum chamber and a straight quadrupole chamber, with the quadrupole chamber longitudinally constrained. The SLDJT bellows absorb the thermal expansion of the bend chamber with stored. The SLDJT opening, D, (see Figure 1) can be measured *in situ* by a linear potentiometer mounted on the bellows flanges. The SLDJT temperature is monitored by two thermo-couples (TCs) attached to the SLDJT body, as shown in Figure 1. The SLDJT opening varies with the average temperature of the bending chamber. During the studies, control of a SLDJT opening is achieved by controlling cooling water temperature of the associated bending vacuum chamber, via a closed loop cooling water circuit.

3.1. SLDJT HOM heating vs. opening

In one study, temperatures of all SLDJTs were sampled with 240mA stored positron beam (a "9x3" configuration consisting of 9 trains of 3 evenly filled bunches, spaced 14ns apart) at two bunch lengths, namely 13mm and 23mm. The difference in temperature at two bunch lengths, T_{13mm} - T_{23mm} , represents the HOM heating to the SLDJTs at the shorter bunch length. The temperature differences are plotted as a function of the SLDJT openings in Fig. 2. The results agree with the calculation.

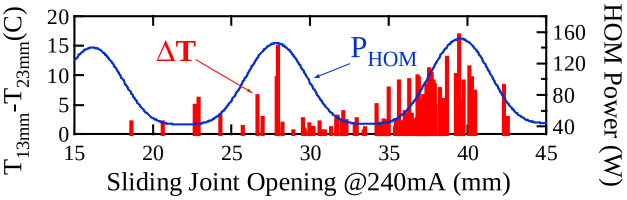

Figure 2. SLDJT temperature difference between short and long bunch length beams vs SLDJT opening for 100 SLDJTs. The calculated difference HOM power (Q=200) for 14ns spaced bunches is also shown.

Detailed measurements of SLDJT heating as a function of opening were taken for a selected group of SLDJTs. The measurements were carried out either during high energy physics (HEP) runs or using dedicated machine study (MS) time. During the HEP measurements, a SLDJT opening was maintained as a constant for 1~2 HEP fills by controlling the bend chamber temperature with the closed water loop. After the SLDJT opening was stepped through a feasible range, the SLDJT temperature is plotted against its opening at a fixed beam current. For MS measurements, total beam current was always maintained as a constant with evenly filled 9x3 bunches. Some typical results are shown in Figure 3. The opening dependence for Q12W SLDJT temperature was measured for both 14ns and 28ns spaced bunches. Q22E SLDJT showed significant HOM heating as its opening was near a resonance at normal HEP condition. Its opening was adjusted during one of the accelerator shutdowns. MS measurements were taken before and after the opening adjustment, with its temperature vs opening shown in Figure 3b. Additional measurements were carried out for more than 10 additional SLDJTs during HEP runs. HOM resonant heating was observed in three of them, with one (Q42E) shown in Fig.3c. These results confirmed the existence of the coherent HOM loss in CESR SLDJTs, and are consistent with the prediction. The coherent HOM loss occurs in a SLDJT at openings of 26.9mm and

38.6mm for the 14ns spaced bunches, and of 26.9mm, 33.0mm and 38.6mm for the 28ns spaced bunches. The measured FWHM of the resonant opening peak is very narrow, ~1.0mm to ~1.5mm.

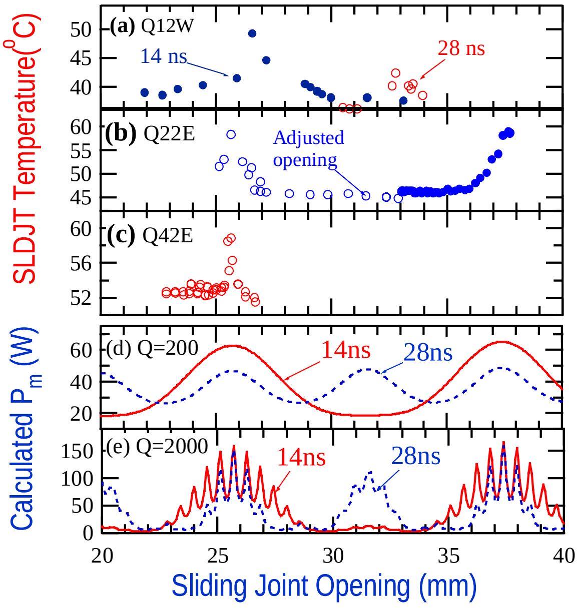

Figure 3. Temperature vs. opening for three SLDJTs. Calculated HOM power (Section 2) as a function SLDJT opening for both 14ns and 28ns bunch spacing are also shown for comparison.

3.2. SLDJT heating vs. Beam Current

For those SLDJTs with their openings near one of the resonances, various measures were taken to shift their openings away from the resonance during accelerator shutdowns. The beam current dependence of the SLDJT heating was measured before and after the opening adjustment for those SLDJTs. One typical result is shown in Figure 4. All the measurements were done with evenly filled, 9x3 bunches with 14ns bunch spacing. A linear beam current dependence of the SLDJT temperature was observed, indicating pure SR heating, when the SLDJT opening was set away from the resonance. It is in clear contrast with the non-linear HOM heating behavior when the SLDJT is near a resonant opening.

3.3. SLDJT heating vs. Beam Bunch Length

SLDJT heating is also measured as a function of bunch length, at a constant total beam current with evenly filled 9x3 bunches of 14ns spacing. The bunch length was varied from 12mm to 23mm by a combination of opening /closing wiggler magnets, by changing RF cavity accelerating voltages and by using two sets of machine optics. The normal CESR HEP optics were used for bunch lengths between 17mm to 23mm. A specially designed high-tune optics were used to change the bunch lengths between 12mm and 16mm. The bunch length was directly measured by a streak-camera. In Figure 5, the behavior of Q22E SLDJT is compared with its opening near and away from the resonant opening. In contrast to a strong dependence on the bunch length when the SLDJT opening was near a resonance, the heating is almost independent of bunch length after its opening was set away from the resonance, indicating dominating SR heating.

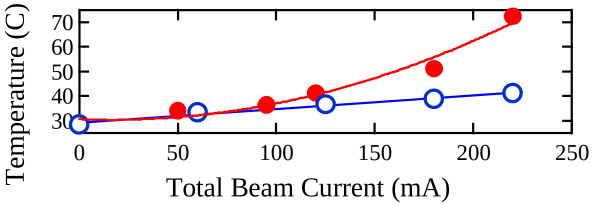

Figure 4. Q22E SLDJT temperature as a function of total beam current, when its opening was near a resonance (solid circles), or away from the resonance (open circles).

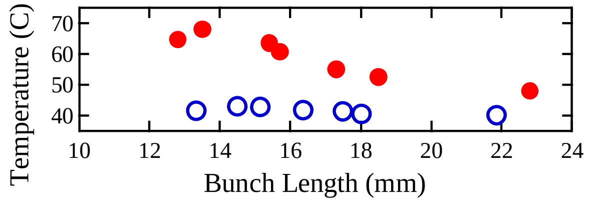

Figure 5. Q22E SLDJT temperature as a function of bunch length, when its opening is near a resonance (full circles), or away from the resonance (open circles).

4 CONCLUSIONS

We have observed coherent HOM heating in CESR SLDJTs, caused by the constructive interference of trapped HOM modes excited by closely spaced bunches. The study has found that the coherent HOM heating occurs in a SLDJT only when its opening falls within narrow and well separated ranges. Values of these resonant openings have been identified by measurements. Measurements of beam current and bunch length dependence of the SLDJT heating indicate that there is no significant HOM loss in the SLDJT when its opening is off the resonance.

During accelerator shutdowns, various measures have been taken to set all CESR SLDJTs well away from the resonant openings. With improved cooling added to the SLDJTs to handle increased SR power at increasing beam current, we expect the safe operation of the SLDJTs with higher stored beam currents at shorter bunch lengths than yet achieved.

5 ACKNOWLEDGEMENT

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6 REFERENCES

[1] E.B.Anderson and J.Rogers,“Trapped Modes in CESR Sliding Joints”, Proc. 1997 Part. Accel. Conf., Vancouver, Canada, IEEE (1998) 369.