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Author
Corlett, J.N.

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J.N. Corlett
Accelerator and Fusion Research Division

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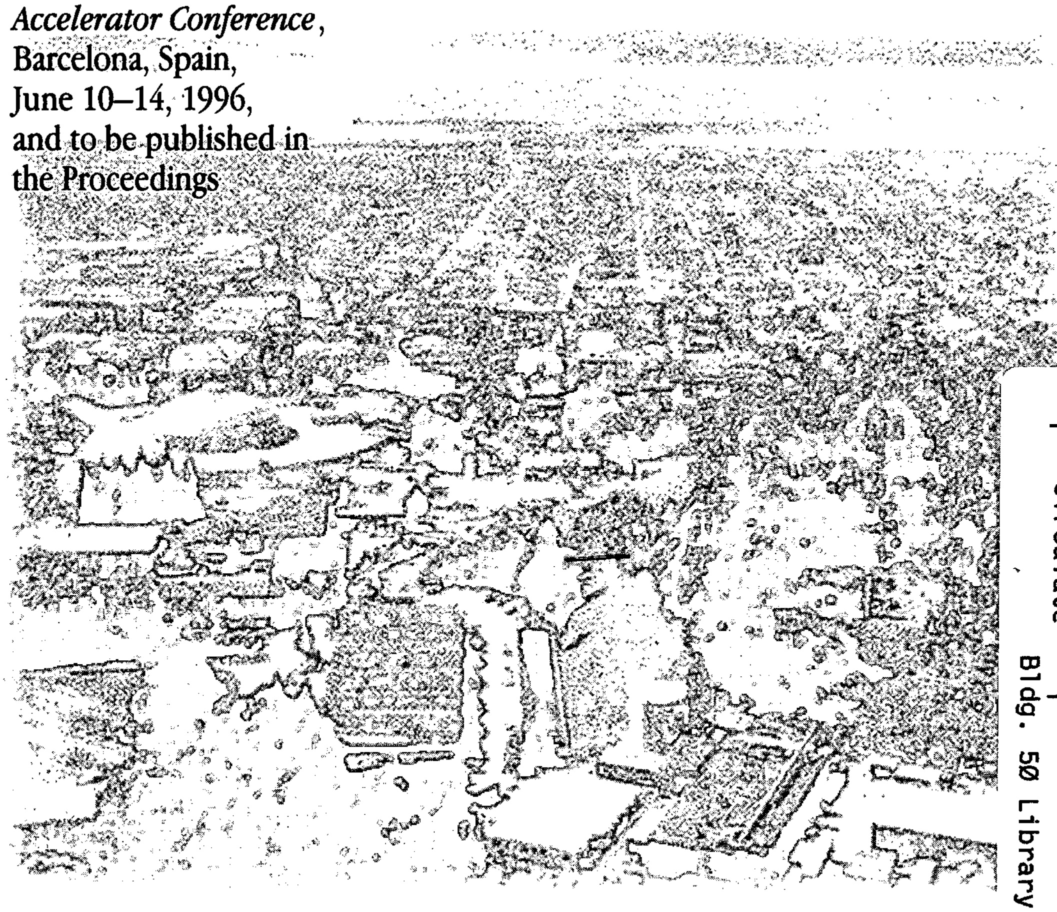

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John N. Corlett,
Glen Lambertson and Charles Kim
Center for Beam Physics
Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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OBSERVATION AND CALCULATION OF TRAPPED MODES NEAR CUT-OFF IN THE ALS BELLOWS-SHIELD

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John Corlett, Glen Lambertson, Charles Kim*,
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract

Observed heating of the RF shields in the bellows of the Advanced Light Source (ALS) storage ring has led to studies of possible causes. One such possibility is resonant impedances near the cut-off frequency of the beam-pipe that arise from small, localized, enlargements of the beampipe cross-section. Calculations of trapped modes in the elliptical-section vacuum chamber, approximated by a rectangular geometry, are described. Measurements of a bellows-shield in the test laboratory are also described, as are temperature measurements of a flexband in the storage ring.

1 BELLOWS ASSEMBLY AND FLEXBAND DESIGN

The bellows asembly contains an RF shield refered to as a "flexband", which is designed to carry the image currents through the bellows assembly with minimal displacement of the current path. The cross-section is elliptical to match that of the ajoining vacuum chambers. A flexband consists of a beryllium copper foil, approximately 75 μm thick, with longitudinal slits that allow the foil to buckle easily when contracted during bakeout and assembly. The flexband is pulled taught by springs during normal operations. Longitudinal motion during normal operations is accomodated by a set of spring fingers at one end of the flexband. Figure 1 shows a cross-sectional view of the flexband in the bellows asembly.

The ring of spring fingers introduces a small 4 mm^2 recess in the chamber wall, forming a small cavity for a trapped mode.

In the original design, the flexband is pre-stressed by rolling to provide a natural outward deflection of the band when longitudinally compressed. This pre-stressing prevents the beryllium copper strips from pulling perfectly straight after assembly, and allows the band to bulge slightly. This creates a previously unforseen shallow bulging cavity of approximately 68 mm length, with a transverse expansion of approximately 0.4 mm at the center of the strips.

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To avoid the bulging of the flexband, a new design without pre-stressing the foil and without chamfered clamping flanges has been built and tested in the laboratory and in the storage ring.

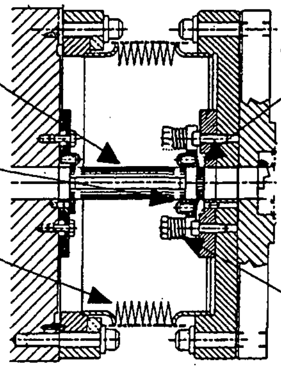

Figure 1. Bellows assembly showing flexband, tensioning springs, and spring fingers

2 ALS OPERATIONS AT HIGH PEAK CURRENT

During commissioning of the coupled-bunch feedback systems for the ALS a few-bunch, high-peak-current fill was used to test the prototype longitudinal feedback system. Under these conditions we experienced the failure of a flexband RF bellows shield [1]. The failure mode resulted in the melting of one of the flexband beryllium copper strips, the end of which then dropped and obstructed the beam aperture. The temperature required to melt the beryllium copper strips is approximately 900°C.

At the time of the flexband failure, the storage ring was filled to 350 mA with seven groups of eight bunches, with coupled-bunch feedback systems operational. The bunches in a group were spaced by 4ns (two RF buckets), with 68 ns between groups, apart from one gap of 52 ns. The rms bunch length with feedback on has been measured using a streak camera, and is 15 ps at this current level. The resulting beam spectrum is shown in figure 2.

With the longitudinal feedback system off we observe significant bunch lengthening as a result of large phase oscillations driven by coupled-bunch instabilities. As bunches move along the RF potential waveform they experience non-linear voltage resulting in a lengthening of the bunch. The beam spectrum is then reduced in frequency extent. Figure 3 shows the beam power spectrum with feedback off in the nominal fill pattern (a train of 320 bunches and a gap of 16 ns). This spectrum is less dense and cuts off at lower frequencies than the previously described fill pattern with feedback on.

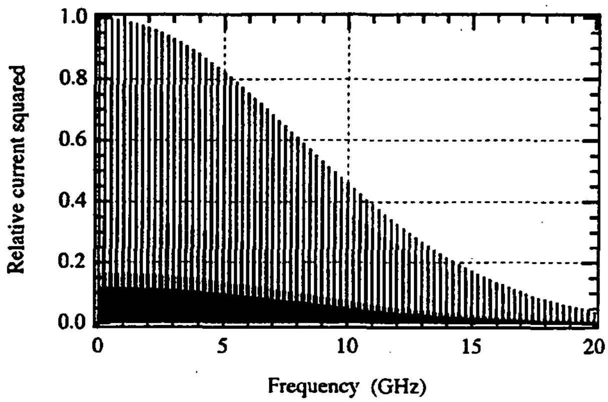

Figure 2. Beam power spectrum 7 groups of 8 bunches, feedback on, bunch length σ = 15 ps.

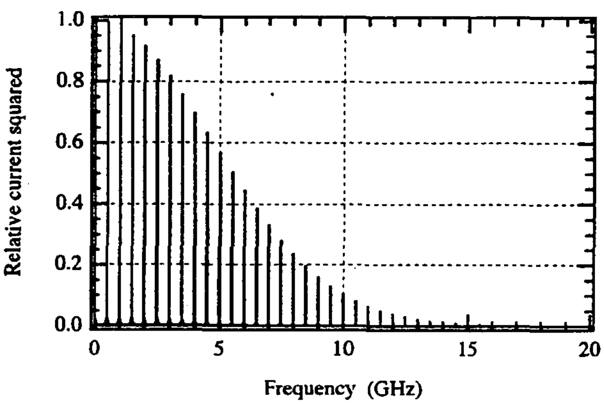

Figure 3. Beam power spectrum 320 bunches, feedback off, bunch length σ = 24 ps

3 RESISTIVE HEATING

The prompt image currents induced in the surface of the vacuum chamber components result in ohmic heating. The surface density of this ohmic power heating in parallel vacuum chamber walls is [2]:

$$P' = 1.2254 \left(q\, f_B \frac{1}{4b} \operatorname{sech} \frac{\pi x}{2b}\right)^2 K \frac{\sqrt{f_B}}{(\omega\sigma)^{\frac{3}{2}}}$$

where q is the charge per bunch, f_B the bunch frequency, 2b the wall spacing, $K\sqrt{f_B}$ the surface resistivity, ω the frequency, and σ the bunch length. We use this expression to approximate the case for the strongly elliptical vacuum chamber in the ALS flexband, where the major/minor axes are 12/1.9 cm respectivey. The image current, and hence the ohmic power, is concentrated in the mid-section strips of the flexband. The central strip, 3 mm wide, is calculated to dissipate 19 mW at the nominal operating current of 400 mA, with feedback on (short bunch).

A 1-dimensional finite element analysis was made to estimate the temperature of a flexband strip with a uniformly distributed heat load, including radiative cooling and constant temperature at the ends of the flexband. For a maximum temperature of 1000°C in a flexband strip, the required power input would be approximately 3 W per strip [3]. The skin depth in the flexband is 2 µm at 5 Ghz, whereas the surface roughness is of the order of 1 µm, therefore we expect the effective surface resistivity and consequently ohmic losses to be increased, perhaps by a factor of a few over the 19 mW.

4 DIAGNOSTIC FLEXBAND

A bellows assembly has been installed in the ALS with diagnostics to allow sampling of the electromagnetic fields between the flexband and the bellows, and by using an infra-red pyrometer, the temperature of the flexband.

Temperature measurements as a function of beam current are shown in figure 4, with different flexband designs and under three different beam conditions. The original design with a slow beam fill to allow the flexband to reach equilibrium temperature at each current level shows large temperature changes at currents above 250 mA. In a fast fill the storage ring current is rapidly increased, the flexband does not reach an equilibrium temperature at each current value measured, and the temperature rises quadratically with the current. Similarly with the new flexband there is a quadratic dependence of temperature on beam current, even when filled slowly.

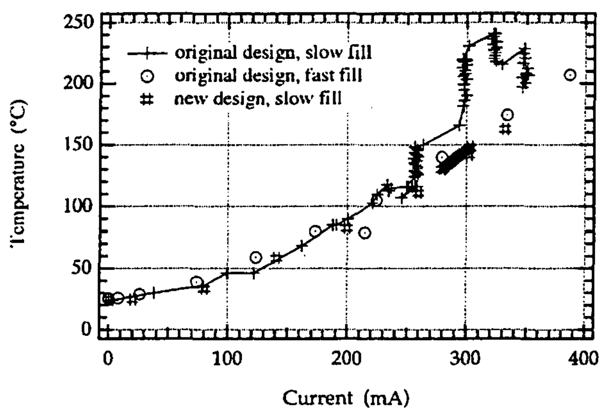

Figure 4. Flexband heating, original (bulging) design and new (straight) design.

The rapid temperature changes in the original design may be a result of the expansion of the flexband causing a resonant mode to move in frequency toward a harmonic of the bunch spacing (nearest strong harmonic is at 16 x RF frequency, or 8 Ghz). The resonant power deposited in the mode then increases with a resultant rapid increase in temperature. For the new design, we see no anomalous temperature changes with a slow beam fill.

The power dissipation per strip to cause melting of the strip is of the order of a few watts. For a TM mode in the flexband, perhaps the central 20 strips carry the majority of current in the mode, and a total power dissipation of approximately 50 W in this mode would be required to melt a central strip.

5 CALCULATION OF CAVITY MODES IN FLEXBAND

The aperture is approximated as a 58 × 19 mm^2 rectangle, which has the same cutoff frequency, 8.3 Ghz, as the elliptical beam pipe. Assuming no bulging of the flexband strips, the 4 mm^2 annular recess at the spring fingers is calculated to cause a high-Q trapped mode at 8.278 Ghz with 160 Ω beam impedance [4].

The slender, tapering bulge at a flexband also introduces a resonator, the resonant frequency of which depends upon the fractional increase $\Delta b/b$ in the 19 mm aperture, as shown in figure 5. The transit-time factor of this field is very small, and there are some uncertainties in it's evaluation, being sensitive to the shapes of the beryllium copper strips. However, the localized recess at the fingers can couple the magnetic field of the bulging flexband resonator to the beam current. This impedance would appear at the lower frequency given in figure 5 and for $\Delta b/b = 0.05$ is calculated to be ≈ 250 Ω.

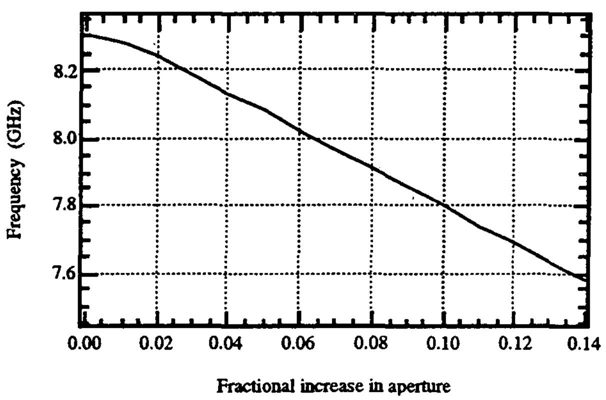

Figure 5. Frequency dependence of mode in flexband versus fractional increase in aperture.

6 MEASUREMENT OF MODES BELOW CUT-OFF

Laboratory measurements of a spare flexband assembly have shown the existence of modes close to but just below the cut-off frequency for TM modes in the vacuum chamber. These modes have been measured with the spring finger assembly alone, and with the flexband assembly included. We excite the modes with a short electric antenna made from a rigid coaxial line, and introduce this antenna carefully into the flexband region. While coupling weakly to modes in the structure we do not significantly perturb them.

The measurements were made on flexband assemblies to which vacuum chambers of the same cross section were fixed at either end. The far ends were closed with metal plates, producing a cavity which could be excited by a probe inserted through an aperture in an end plate.

TM modes formed by travelling waves reflecting at the boundaries at the ends of the vacuum chamber were measured, and from the frequency of the lowest mode we calculate the cut-off frequency of 8.26 Ghz.

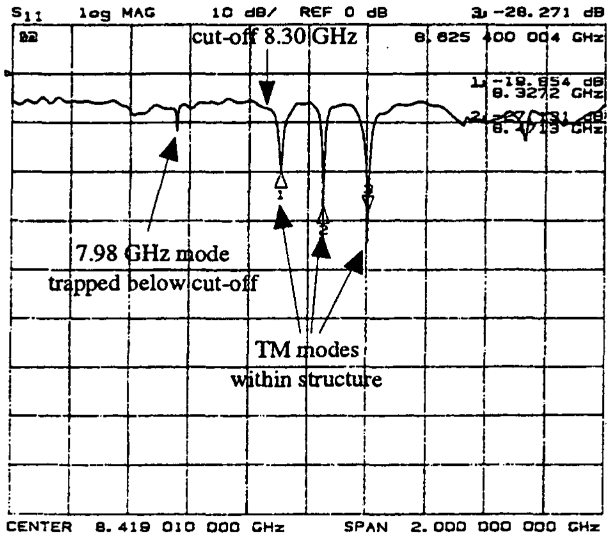

Figure 6. S_{11} measurement showing resonances in apparatus and trapped mode localised in flexband

In addition to the modes formed between the ends of the vacuum chambers, we also observe a mode below the cut-off frequency. By moving the position of the exciting probe we confirm that this mode is localized around the flexband/ spring finger region. The Q value is measured to be 1150, somewhat less than the calculated Q of 5000. Figure 6 shows the resonances as measured using an old-design flexband.

7 CONCLUSIONS

Although thermal time constants and expansion effects complicate the phenomenon, we conclude that the measured and calculated resonance reasonably can explain the observed heating of the flexbands.

The higher than expected "base" temperature of the flexband may be due to resonances observed within the bellows but outside the flexband, and other losses.

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Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road | Berkeley, California 94720

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