MEASUREMENT OF HIGH Q RF CAVITY IMPEDANCE WITH BEAM*

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Abstract

An inexpensive method to measure, with beam, the Rs and Q of narrow-band high order resonances in RF cavities was developed on SPEAR. The two main results of this study are:

- an improved operational stability of SPEAR
- the decision to keep the present cavities for the proposed SPEAR upgrade. SPEAR3 will be run initially at 200 mA, twice the present current.

Just beyond the current threshold, and before step loss, there is a regime in which the beam performs large amplitude, low frequency oscillations. Detailed measurements were performed to characterize the frequency, amplitude, growth and damping time of these relaxation oscillations.

1 INTRODUCTION

SPEAR is a dedicated 2nd generation synchrotron radiation facility. It has two RF stations, each consisting of one klystron and one 5-cell RF cavity. Each cavity has 2 movable tuners, located in the first and fifth cells. Two stations were installed for historical reasons, but only one station is active for 100 mA normal operation. Both cavities are the source of numerous High Order Modes (HOMs), which can cause longitudinal coupled bunch instabilities in normal operation. Since SPEAR has neither HOM dampers, nor a feedback system to damp longitudinal oscillations, nor precise temperature regulation (the water input temperature is only grossly regulated to 2°C), the choice of the working points of both the active and passive cavities is particularly delicate. Detailed measurements of (Rs,Q) of the strongest HOMs and location in temperature-tuner space were needed. The study allowed us to conclude that those RF cavities can be kept for stage 1 of SPEAR3[1] with an appropriate temperature regulation system. Measurements were performed at the injection energy of 2.27 GeV, with the parameters indicated in Table 1.

Table 1: SPEAR Experimental Parameters

E GeV	F_s kHz	L M	f_{rf} MHz	τ_{damp} ms
2.3	28.5	234	358.5	9.3

2 DESCRIPTION OF THE TECHNIQUE

The standard technique for measuring the characteristics of a cavity is to excite it with a low-power signal generator, via an external antenna, and to measure the response on that or on another antenna. The advantages of this method are that it enables the use of arbitrary frequencies, but the disadvantages are that one must carefully measure the transit time factor of each mode, as well as determine the perturbative effect of the exciting antenna. Also, under low power, the cavity is not subject to the thermal and mechanical stresses of a live system, which may perturb the geometry, and hence the HOMs. The beam, however, generates multiples of the revolution harmonic, and the beam responds to the voltage induced at the synchrotron sidebands of these harmonics. Since these are precisely the frequencies of interest, the beam was used to probe the cavities, and beam-induced signals in the cavities were recorded.

The spectral range between 500 MHz and 1.5 GHz was explored. Spans of 20 MHz were recorded at a rate of 1 every 2 s. Details of the procedure have already been reported [2].

The active cavity is under feedback control to maintain the correct phase of the fundamental. Consequently, the 2D tuner space is reduced to a 1D space. As the HOMs are very narrow in the 2D space, it is possible to pass by a dangerous resonance which is just off the path of the regulated tuner motion while searching for those HOMs. Fortunately, the two cavities are virtually identical and one can study the characteristics of the HOM with the cavity under study off and the other cavity powered.

Passive cavity

The tuner positions are varied to find the peak of the resonance. The Q value is determined from the resonance width, obtained by sweeping the RF frequency. To determine the Rs value, the current is increased until the instability starts. The growth rate is then equal to the damping time, τ_{damp}, which is:

$$\frac{1}{\tau_{damp}} = 2\pi\, f_s \frac{p I_o R_s}{2hV_{rf}\, \cos\varphi_s} \qquad \text{Eq. (1)}$$

V_{rf}: RF voltage; h, p: harmonic, HOM number, resp.
Rs: Shunt resistance; f_s: synchrotron frequency

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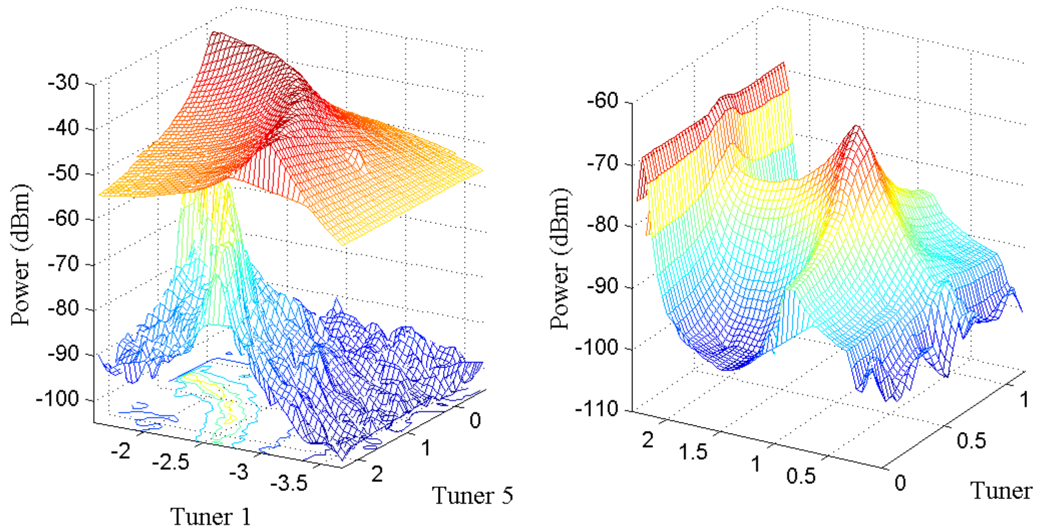

Figure 1: Sweep over tuner space for: fundamental h = 280 and its synchrotron sideband (+fs); h = 750

Active cavity

With no temperature regulation, over the range of possible RF powers, the temperature of the cavity can change by 18°C. The thermal expansion, due to the RF power, moves the HOMs. Their location is then found by varying the RF voltage. Again the Rs value is deduced from the instability current threshold according to Eq. 1. Since sweeping the RF frequency causes the tuners to move in the active cavity, the Q value is found by running beam when the cavity is passive.

In the following table are given some measured HOM characteristics near our working point.

H	750	751	753	924
Rs (kΩ)	84	188	69	58
Q	35000	45000	16000	17500

Table 2: Strongest HOMs near working point

3 EXPERIMENTAL OBSERVATIONS

In general, the HOMs tend to group in clusters, yet there is no pattern common to all. Although some of the HOMs are coupled cell resonances, most are clearly localized in single cells. Of these, some are affected by only one cavity, while others are affected by both cells, but orthogonally. For these HOMs, the interference between the single cell modes can be constructive or destructive. In some cases, there even appears to be some mode splitting of the HOM which is dependent on frequency. The sensitivity of the HOMs to tuner position also varies greatly.

4 TOWARDS NON-LINEAR REGIME

The instability growth time is the quantity of interest for determining the strength of the HOMs. By using the spectrum analyzer as a tuned receiver at the synchrotron sideband and then exciting the resonance, the evolution of the oscillation amplitude is observed as a function of time.

The coupling of the various Fourier modes at the onset of the non-linear regime has been studied. To differentiate between two competing modes, two spectrum analyzers, triggered synchronously, were used. The unstable mode grows exponentially in time while the other Fourier mode remains stable. Once the unstable mode reaches the saturation level, it couples to the other Fourier mode and both become unstable (Figure 2a).

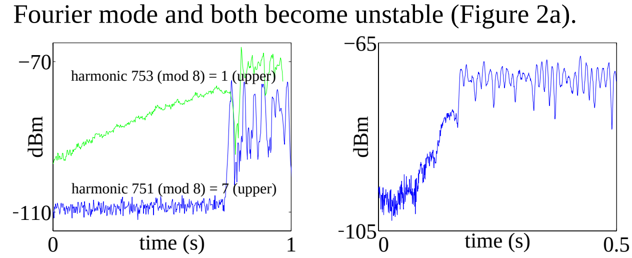

Figure 2: Onset of instability

When the synchrotron sideband reaches "saturation", it undergoes a regular oscillation (Figure 2b). The reproducibility of this behavior for any HOM suggested that the understanding of this oscillation would give insight into the mechanism of the saturation of the longitudinal coupled-bunch instability.

5 RELAXATION OSCILLATIONS

This relaxation oscillation has also been seen in other machines [3][4]. In SPEAR, the period of this oscillation never exceeds 100Hz, compared to the 28.5 kHz synchrotron frequency. The phenomenon is driven by an HOM, so the easiest way to isolate the mechanism for characterization is to measure the beam behavior in the presence of the largest narrow-band resonance of the system, the fundamental (Robinson) mode of the cavity. Tuning on the Robinson mode in the passive cavity insured that this impedance dominated over all others, including the short range wake of the beam.

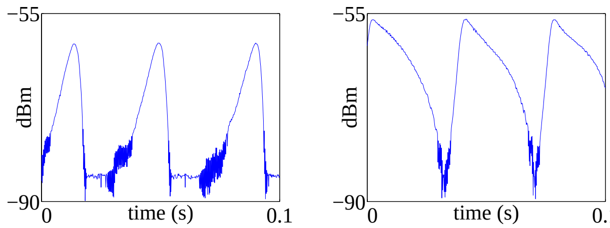

Figure 3: Growth/Damp of upper synchrotron sideband

Growth time, damping time, amplitude and frequency of the low frequency relaxation oscillation were measured as a function of HOM phase and amplitude, current, and energy. Typical analyzer measurements are given in figure 3 and summary plots are given in figure 4. The frequency changes as a function of mode impedance. The growth time, which is always exponential, also depends on the impedance. For a given mode, the power of the oscillation is relatively independent of the impedance once the particle has reached saturation. The damping time shows a strong dependence on the impedance. Unlike the growth time, the damping time is asymmetric with respect to the center of the resonance. On the high frequency side of the resonance, the damping is slower than exponential. The damping time asymmetry leads to a corresponding asymmetry in frequency. During these oscillations, the instantaneous synchrotron frequency decreases by as much as 13%.

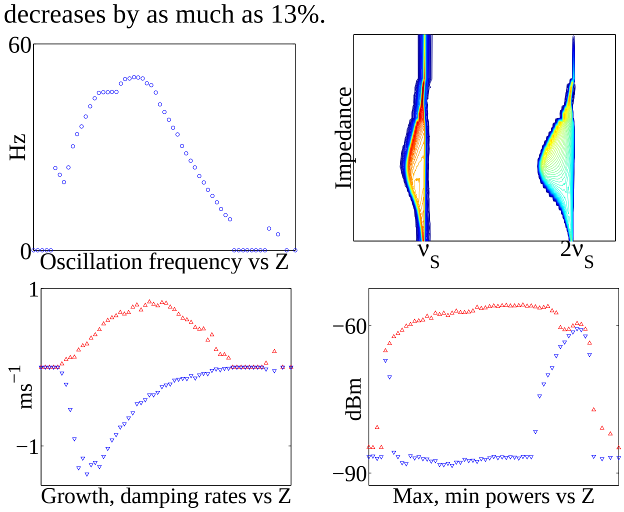

Figure 4: Summary curves of relaxation characteristics

Although the threshold of the oscillation depends on the total current contributing to the instability, the relaxation oscillation loses its regularity and much of its structure for high single bunch currents. Once the tuning of the machine parameters necessary to produce those oscillations was well known, streak camera measurements were made to gain more insight into the instability mechanism (figures 5-6). A detailed discussion of a model is presented elsewhere [5].

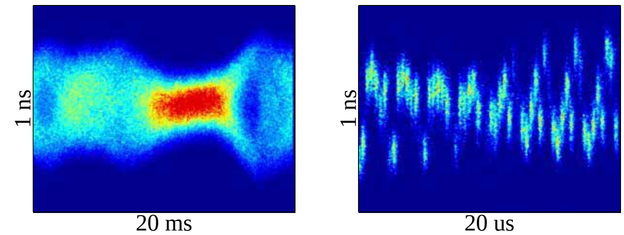

Figure 5: Streak camera images 7 bunches at p = 751

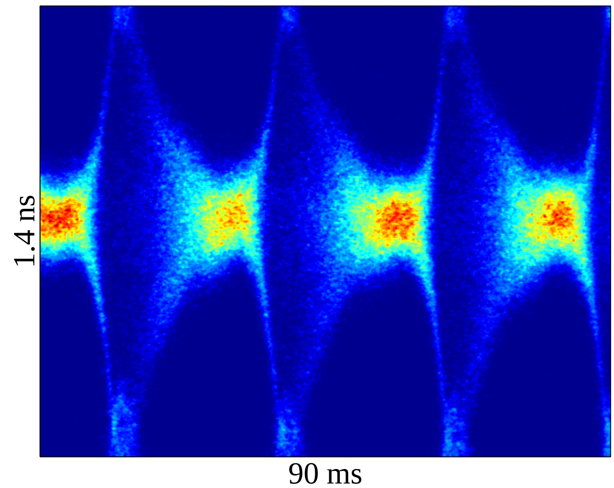

Figure 6: Streak camera images: single bunch p=h=280

CONCLUSIONS

The study has improved the choice of our operating point and has given us the empirical data to determine that the vintage RF cavities can be kept in the proposed upgraded version of SPEAR. We have successfully applied this measurement technique to explore the non-linear longitudinal beam dynamics.

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