CONTROL OF LONGITUDINAL INSTABILITIES IN THE LEB

T.L. Grimm and P.D. Coleman
Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237

Abstract

The potential longitudinal instabilities and their control in the SSC Low Energy Booster are examined. Coasting beam theory shows there is a chance for microwave instabilities at the end of the acceleration period for the maximum design current of 0.5 Adc. The beam is stable to microwave instabilities for the Collider fill current of 0.1 Adc. Single bunch instabilities driven by the RF cavity accelerating mode will be stabilized by beam phase, voltage amplitude, tuner bias and RF feedback loops. The coupled bunch instabilities driven by the cavities' higher order modes and other resonant structures appear to represent the biggest challenge to longitudinal stability. A broadband passive damper on each RF cavity will greatly decrease the chance of any coupled bunch instabilities although other options to aid the damper are investigated. The control of longitudinal instabilities in the LEB appears feasible and should not limit its operation up to the peak design intensities.

I. INTRODUCTION

The SSC Low Energy Booster (LEB) is the first of three booster synchrotrons which supply the proton beam to the Collider. The LEB is a resonant, rapid cycling (10 Hz) machine with 114 bunches spaced 5 m apart[1, 2]. It will boost a maximum beam current of 0.5 Adc, five times Collider fill mode, from 600 MeV to 11 GeV. Six to fourteen quarter-wave ferrite tuned cavities, tuning from 47.5 to 59.8 MHz, will supply a peak ring voltage of 765 kV[3, 4].

The potential longitudinal intabilities and their control are investigated here for the LEB. First, coasting beam instabilities, which are associated with broadband impedances are discussed. Then single bunch instabilities, which are caused by the RF cavity accelerating/fundamental mode, are covered. Finally, coupled bunch instabilities (CBI) which are driven by the RF cavity higher order modes (HOM) and other narrow band impedances, are discussed. A weak instability may stabilize due to nonlinear effects and short interaction times. Thus its only effect would be to increase the longitudinal emittance which would be beneficial because it would simplify matching to the medium energy booster at extraction. If the instability is strong enough to cause beam loss or couples to the transverse direction then it will be necessary to damp the perturbation.

*Operated by the Universities Research Association, Inc. for the U. S. Department of Energy under Contract No. DE-AC02-89ER40486.

II. COASTING BEAM

Coasting-beam theory is used to predict the maximum allowable broadband impedance, Z_L/n. Coasting beam theory is derived for a totally debunched beam, although it has been shown to be applicable for a bunched beam provided the perturbation has many periods within a bunch. For the LEB this implies the perturbation index, n, is much greater than the harmonic number and that the instability would occur at frequencies above ~ 1 GHz (ie. microwave instabilities). Fig. 1 shows the threshold Z_L/n given by the Keil-Schnell criterion during the 50 ms beam acceleration for 0.5 Adc. With the use of shielded bellows, shielded pumping ports and smooth tapers at beam pipe transitions the total Z_L/n of the LEB is predicted to be less than $\sim 1\Omega$. This shows there is a possibility for microwave instabilities in the second half of the acceleration period. The growth rate would be fairly small and a large bucket is available later in the cycle, so the only affect anticipated would be an increased longitudinal emittance.

III. SINGLE BUNCH

There will be many RF control loops available to handle Robinson-type single bunch instabilities in the LEB[5]. These instabilities are driven by the RF cavity accelerating mode. The control loops planned are: beam phase, voltage amplitude, tuner bias, and RF feedback. Since all of the RF buckets are equally filled, beam current feedforward will not improve beam loading transients. If necessary, a peak bunch density loop can also be implemented to control bunch length oscillations. For stable operation with these loops, the gap voltage, V_{gap}, must satisfy[6];

$$V_{gap} > \frac{R_{sh} I_B}{2(1+H)} \tag{1}$$

where $R_{sh} \simeq 100k\Omega$ is the cavity shunt impedance, $I_B = 1$ Aac is the AC beam current, and H is the RF feedback open loop gain. This gives $V_{gap}(kV) > 50/(1+H)$ which means operating voltages above 50 kV do not require any RF feedback. The design RF feedback loop will easily have an $H = 10-20$ which implies operating voltages above 5 kV will be stable. Before a voltage this low is reached multipactoring will have made it necessary to counter-phase the cavities at higher voltages. Thus the RF control loops

0-7803-1203-1/93$03.00 © 1993 IEEE

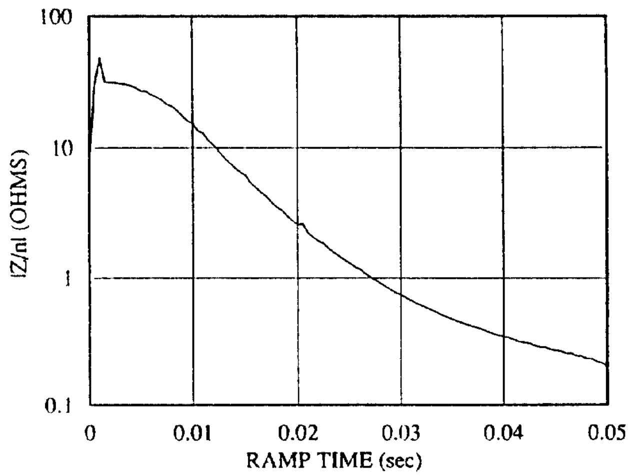

Figure 1. Allowable broadband impedance during LEB cycle.

should not have any trouble controlling the Robinson-type single bunch instabilities.

IV. COUPLED BUNCH

An analysis of CBI in the LEB due to narrowband resonances of the cavity HOMs and other resonant structures (injection and extraction chambers for example) predicts the maximum allowed R_{sh} versus frequency for four e-foldings growth of the instability[7]. Instability due to the cavity's fundamental mode will not be a problem because the cavity bandwidth is much less than the revolution frequency. The total R_{sh} for CBI is about $4k\Omega$ for the $m = 1$ dipole mode at 120 MHz and increases to $28k\Omega$ for the $m = 5$ mode at 1 GHz. HOMs above about 1 GHz should not be a problem for CBIs since the cavity ferrite becomes lossy, the beam current's spectrum will be negligible, and the 8 cm beam pipe is above cutoff to longitudinal modes above 2.9 GHz.

For a given frequency, the total R_{sh} can come from a single beamline component or can be a sum of components such as the cavities. For an undamped cavity the R_{sh} of HOMs will be similar to the fundamental value of $100k\Omega$ which clearly is a problem. Options to correct the cavities' and other structures resonances will be addressed. For now the cavities' R_{sh} will be assumed to be the main contributor to CBIs although the same arguments will apply to other resonant structures.

The options for controlling CBIs can be categorized as either a passive or active system. The passive systems do not require any instability measurement or feedback and the options are: passive dampers, stagger tuning and resonance hiding. The active systems require feedback and possibly measuring the instability, and the options are: active damper, Landau cavity, subharmonic cavity and beam blow-up. If a passive system can eliminate the CBIs then obviously it would be preferable to an active system.

A. *PASSIVE SYSTEMS*

Because there are so many cavity HOMs from 120 MHz up to 1 GHz, which tune with the fundamental mode, a broadband damper will be the primary method of controlling HOMs. A Smythe-type broadband damper with a high-pass filter between the damping cavity and water cooled loads has been designed[8, 9]. The damper is predicted to damp a single cavity's R_{sh} to less than 600Ω from 120 MHz to 500 MHz and maintains R_{sh} to low enough values above 500 MHz that high frequency CBIs should not be unstable. Thus the most dangerous HOMs will be the first two at about 120 and 190 MHz. For six cavities with the cavities' R_{sh} summing, all CBIs would be predicted to be stable. If more cavities are necessary (the lattice has room for 16) then other methods of damping may be necessary for the first two HOMs. If the CBI occurs at a specific frequency, then a narrowband damper such as a coupling loop or capacitive plate could further damp the mode.

Stagger Tuning shifts the HOM resonant frequency in each cavity so they do not overlap thereby decreasing the total R_{sh} at a given frequency, although this would increase the range of resonant frequencies. This could be accomplished by varying the cavity dimensions. The shift would need to be more than the mode's half bandwidth which has been broadened by the damper. For the 120 MHz HOM with the Smythe damper in place the bandwidth is approximately 4 MHz which would require too large of a change in cavity dimension to be useful. Thus stagger tuning would not be practical when the Smythe damper is used.

Another passive method of eliminating CBIs is to remove the resonance by not allowing the HOM frequency to overlap an integer of the revolution frequency. The LEB revolution frequency is about 0.5 MHz which is much less than the damped HOM bandwidth so resonance hiding will not work for the LEB. Also, because the HOMs tune at a different rate than the fundamental they will cross a revolution frequency sometime during the ramp.

B. *ACTIVE SYSTEMS*

An active damper would measure the instability and counteract its growth in some manner. Thus the instability must be at a finite level for an active damper to have any effect. The instability measurement can be done in one of two ways. In the first method the beam oscillations are measured directly using a wall current monitor, while the second method will measure the RF which is driving the instability.

For measurement of the beam oscillations, the bunch-by-bunch phase and peak density variation will be measured using a wall current monitor. This will tell the type and magnitude of the CBIs. The same information could be obtained from a Fourier transform of the beam current. To use these measurements in an active feedback system there will need to be a one turn delay circuit whose delay must shift with the RF frequency. For a narrow bandwidth system (100 kHz) the delay circuit error must be less than

2 μs which should be quite easy, while a wideband system (30 MHz) would require an error less than 8 ns.

A broadband active damper would be needed to damp all possible unstable CBIs. This would require a separate cavity with up to 30 MHz bandwidth, although it could be at high frequency such as 300 MHz and would not need to tune with the RF. If the HOM frequency driving the CBI is known then a narrow band cavity (bandwidth of $2f_s$) or the RF cavity itself could be used at the driving frequency.

For measurement of the RF driving the instability, the overall active damper would be fairly simple. The measured RF would be fed back to the source 180° out of phase. It would be narrowband since the RF comes from HOMs in the cavity. There would be no need for external timing or delay circuits and the measured signal is continuous.

Another way to actively damp the CBIs would be to operate the LEB RF cavity's beam phase and beam amplitude loops from a single bunch instead of the average as is presently envisaged. This would damp the CBIs on that bunch and increase the synchrotron frequency spread between bunches thereby breaking up the coherence of the instability.

A subharmonic cavity operates at a subharmonic of the main RF frequency. This causes a synchrotron frequency shift between bunches which would eliminate the coherence and increase the Landau damping of the CBI[10]. A subharmonic cavity would operate at the RF frequency shifted by a revolution frequency. This small shift relative to the LEB tuning range implies an extra LEB cavity could function as the subharmonic cavity although it would not lead to any acceleration. Since the only additional hardware required (if there is an extra LEB cavity) is the drive frequency and amplitude control system this option will be made available on the LEB. If the instability occurs during a portion of the accelerating ramp where the RF voltage is not maximum then one of the RF cavities in use could be switched to subharmonic operation with the other cavities compensating for it.

A Landau cavity works by applying a harmonic of the RF to the bunches to increase the RF non-linearity seen by the bunches. This increases the synchrotron frequency spread and therefore the Landau damping. The Landau cavity has been shown to work, but requires voltages comparable to the RF and must tune with the RF. Thus the Landau cavity would be as much of an engineering challenge as the present LEB cavity. If a Landau cavity operated over only part of the tuning range its tuning bandwidth could be substantially lower. Due to the complexity and expense of an additional RF system, a Landau cavity will not be designed for the LEB.

Finally, it should be noted that the CBI can be stabilized by purposely increasing the longitudinal emittance or decreasing the bucket size which increases the Landau damping. The increased emittance could be caused by letting an instability grow slowly, driving a microwave instability or intentional noise in the phase loop for example.

V. CONCLUSION

The different types of longitudinal instabilities and their control have been investigated. The beam is stable to microwave instabilities for the Collider fill intensities, but is unstable for peak intensities at the end of the acceleration period. This instability should only increase the longitudinal emittance which is beneficial for matching to the Medium Energy Booster. Robinson-type single bunch instabilities will be controlled by beam phase, voltage amplitude, tuner bias and RF feedback loops. The RF cavity's HOMs will be the principal source of coupled bunch instabilities. Coupled bunch instabilities will be damped primarily with a broadband passive damper on each RF cavity. This will stabilize all modes for Collider fill intensities. For peak intensities the two lowest frequency HOMs will be unstable if there are more than six cavities. This can be controlled with a narrowband passive damper, a subharmonic cavity, cavity beam phase locked to a single bunch or an active damper.

VI. ACKNOWLEDGEMENTS

We would like to thank N.K. Mahale for the use of his simulations of the LEB longitudinal beam dynamics.

VII. REFERENCES

[1] R.C. York, *et al.* The SSC low energy booster: A status report. In *IEEE PAC*, 1991.

[2] U. Wienands. Status of the SSC low energy booster. In *IEEE PAC*, 1993.

[3] C.C. Friedrichs, *et al.* Design of an accelerating cavity for the SSC low energy booster. In *IEEE PAC*, 1991.

[4] P. Coleman, *et al.* Status of the SSC LEB rf cavity. In *IEEE PAC*, 1993.

[5] L. Mestha, *et al.* A digital beam phase loop for low energy booster. In *IEEE PAC*, 1993.

[6] F. Pedersen. A novel rf cavity tuning feedback scheme for heavy beam loading. *IEEE Trans. Nucl. Sci.*, 32:2138–2140, 1985.

[7] R. Baartman. Allowed narrow-band impedance in the SSC LEB. TRIUMPH Design Note TRI-DN-92-K207, 1991.

[8] W.R. Smythe, C.C. Friedrichs, and L.S. Walling. Proton synchrotron rf cavity mode damper tests. In *IEEE PAC*, 1991.

[9] L. Walling, G. Hulsey, T. Grimm, E. Ruiz, and N. Spayd. Investigation of higher-order dampers for the SSC LEB cavity. In *IEEE PAC*, 1993.

[10] C.M. Ankenbrandt, *et al.* Longitudinal motion of the beam in the fermilab booster. *IEEE Trans. Nucl. Sci.*, 24:1449–1451, 1977.