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Active lower order mode damping for the four rod LHC crab cavity

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ABSTRACT

The high luminosity upgrade planned for the LHC requires crab cavities to rotate bunches into alignment at the interaction points. They compensate for a crossing angle near 500 μrad. It is anticipated that four crab cavities in succession will be utilized to achieve this rotation on either side of each IP in a local crossing scheme. A crab cavity operates in a dipole mode but always has an accelerating mode that may be above or below the frequency of the operating mode. Crab cavities are given couplers to ensure that unwanted acceleration modes are strongly damped however employing standard practice these unwanted modes will always have some level of excitation. Where this excitation has a random phase it might promote bunch growth and limit beam lifetime. This paper sets out a method for active control of the phase and amplitude of the unwanted lowest accelerating mode in the crab cavities. The paper investigates the level of suppression that can be achieved as a function cavity quality factor and proximity to resonance.

1. Introduction

This paper demonstrates by analysis and modeling the feasibility of applying active damping to the lowest unwanted acceleration mode in crab cavities as would be appropriate for the LHC luminosity upgrade. This paper sets out the configuration and timing enabling a Low Level RF (LLRF) control system to actively damp the unwanted mode.

A novel aspect of this paper is the implementation of a cyclic or multi-valued set point. An unwanted mode must be controlled by RF near its center frequency by manipulation of the I and Q components. Excitation is at the bunch repetition frequency and a designer aims for this to have no harmonic relationship to the unwanted modes. The paper shows how a cyclic or multi-valued set point minimizes control action.

The planned LHC luminosity upgrade [1] will utilize compact crab cavities [2] to adjust the orientation of the proton bunches at certain interaction points (IP) so as to increase luminosity to a defined level that can be maintained throughout the bunch lifetime [3]. Maximum luminosity is achieved when bunches are in perfect alignment. Depending on the luminosity leveling scheme utilized, perfect alignment might not be utilized until the bunch population has been depleted after many hours of operation. For the proposed optics, luminosity would be reduced by a factor of about four when there is no bunch alignment using a crab cavity. The precise reduction factor depends on the level of focusing achieved. The proposal for the luminosity upgrade is to have control of the crabbing angles at interaction points 1 (ATLAS) and 5 (CMS).

A crab cavity is a deflection cavity operated with a 90° phase shift [4] so that a particle at the front of a bunch gets a transverse momentum kick equal and opposite to a particle at the back of a bunch while a particle at the bunch center receives no transverse momentum kick. The overall effect is the application of an apparent rotation to the bunch. In this paper a transverse change in momentum for a bunch or a particle as it passes through a cavity will be referred to as a kick. A kick is the integral of the force with respect to time per unit charge. As protons at the LHC travel close to the speed of light, the kick divided by the velocity of light is a voltage and henceforth all kicks will be expressed as a voltage.

The simplest scheme for controlling crabbing angles is a global scheme as was applied at KEKB [5]. In such a scheme only one crab cavity is required per ring. Once the bunch has a crabbing angle it rotates one way and then the other way with respect to its nominal path as it passes through successive quadrupoles. For a given transverse voltage in the crab cavity the maximum angle of rotation is limited by the focusing properties of the lattice. The lattice is arranged so that bunches have the ideal crabbing angle at the interaction points. For the LHC luminosity upgrade, studies have indicated that having the bunch oscillating about its axis along the entire circumference is unacceptable; for this reason the current proposal is to use a local crabbing scheme [6].

For a local scheme, crab cavities would be located before and after each of the two IPs so that the crab rotation can be removed. Both sets of crab cavities are positioned in a location of relatively high beta so as to minimize the voltage that must be applied in order to get the

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appropriate rotation at the IP and to cancel the rotation after the IP.

The highest bunch repetition rate at the LHC is 40.08 MHz for 25 ns operation and 20.04 MHz for 50 ns operation, the crab cavity needs to operate at a multiple harmonic of these frequencies. Crab cavities are currently being designed to operate at 400.8 MHz which is the same frequency as the accelerating RF and is sufficiently low for non linearities of the crab kick along the length of the 80 mm long bunches to be acceptable with respect to machine performance [6].

A crab cavity invariably uses a dipole mode to provide the transverse momentum kick. All RF cavities which admit dipole modes must also admit longitudinal modes. A designer aims for a high R/Q value of the operating dipole mode and low R/Q values for other modes. The R/Q value for each mode is $1/(2\omega C)$, which is half the capacitive impedance and it determines the level of interaction of that mode with bunches passing through the cavity. Here the shunt impedance is taken as the acceleration voltage squared divided by the dissipated power, V^2/P. Crabbing and deflecting cavities designed to operate in a dipole mode will always have one accelerating mode with an R/Q value comparable with the dipole mode's R/Q. Typically this mode has a frequency which is below that of the dipole mode as would be the case for the compact four rod crab cavity [7]. Design optimization of the four rod cavity reduced the R/Q of the low frequency accelerating mode to less than 1/7 of the R/Q of the operating dipole mode. An innovative design for the LHC crab cavity also exists where the acceleration mode frequency is somewhat higher than the operating mode [8]. For this and similar cavities the R/Q of the accelerating mode is between 1/2 and one 1/3 of the R/Q of the operating mode and hence more damping is required.

Section 2 of this paper looks at the level of bunch by bunch excitation that would exist in the Lowest Order Mode (LOM) of the four rod crab cavity when strongly damped with an external Q-factor, Q_e of 100 and for the anticipated LHC bunch structure. This would often be referred to as the sum wake.

Section 3 proposes active damping with a feed forward controller as a method to further reduce longitudinal dispersion of bunches. Feed forward has been demonstrated experimentally on accelerating cavities as a means of compensating beam loading [9], although this paper outlines how such a scheme could be used for compensating excitation of unwanted longitudinal modes in deflecting cavities. Active damping has been investigated previously for mixed higher order modes in a superconducting cavity [10]. The paper claimed some level of success however the damping was not sufficient over a range of modes to warrant implementation at CEBAF. The expected level of damping achievable for the four rod LHC crab cavity is much higher by virtue of the fact that the active damping control system can be optimized to eliminate excitation in a single mode. Damping the acceleration mode of the crab cavity to a Q_e of 100 without compromising the operating mode is technically challenging. It is hoped that the application of active damping will allow the level of passive damping to be reduced.

Section 4 simulates the effectiveness of active damping at eliminating variations in longitudinal acceleration after gaps in the LHC bunch structure. Results presented in this section are again for the case when the acceleration mode is strongly damped with a Q_e of 100. This is the required level of damping in the absence of active damping.

Section 5 firstly considers active damping with the same control parameters used in Section 4 for the case when Q_e is increased to 300. As the quality factor is increased it becomes increasingly unlikely that the acceleration mode could be driven to become resonant. Covering a worst case scenario, this section shows that satisfactory active damping of the accelerating mode can be achieved even when it has moved to become resonant with the bunch repetition frequency.

Section 6 considers active damping performance with moderate detuning and significant measurement errors. After the consideration of measurement errors it is apparent that even a relatively poor estimate for the feed forward term still gives greatly improved damping performance with respect to the case without control.

Calculations and numerical simulations reported in this paper have been obtained by integration of the envelope equations [11] and the model is described in the appendix. The envelope equations are also used to model the output circuit of the power amplifier. This assumes the amplifier has an output cavity or tank circuit as would be the case for all high power, high efficiency amplifiers. Input parameters for the model include measurement errors, latency in the control system, microphonics and bunch charge fluctuations. The feed forward control scheme that has been proposed eliminates issues with latency (time delays). Solutions of the envelope equations with no measurement delays give the required feed forward drive power.

2. Mode excitation with no damping

A cavity mode voltage $V(t)$ can be referenced to its center angular frequency ω in terms of its in phase and quadrature components as

$$V(t) = \Re[(A_r + jA_i)e^{-j\omega t}]. \tag{1}$$

Increments for the in phase and quadrature parts of the phasor induced by a bunch of charge q passing through the cavity with RF phase α are given by

$$\delta A_r = \frac{q\omega}{2}\left(\frac{R}{Q}\right)\cos\alpha \tag{2}$$

and

$$\delta A_i = \frac{q\omega}{2}\left(\frac{R}{Q}\right)\sin\alpha. \tag{3}$$

When the unwanted accelerating mode frequency of a crab cavity is close to a multiple of the bunch repetition frequency then the phase α varies slowly in time and large voltages accumulate in the cavity.

Excitation within a bandwidth is referred to as resonant and the voltage moves in phase with the excitation. For modes with high loaded Q-factors, Q_L, and when a multiple of the bunch repetition frequency is not within several bandwidths of the cavity's natural frequency then the final voltage settles between quadrature and anti-phase to the kick being provided by the bunches. Fig. 1 shows the cavity voltage phase before and after the passage of a bunch when not excited near to resonance; this is the case of most interest as one designs cavities to

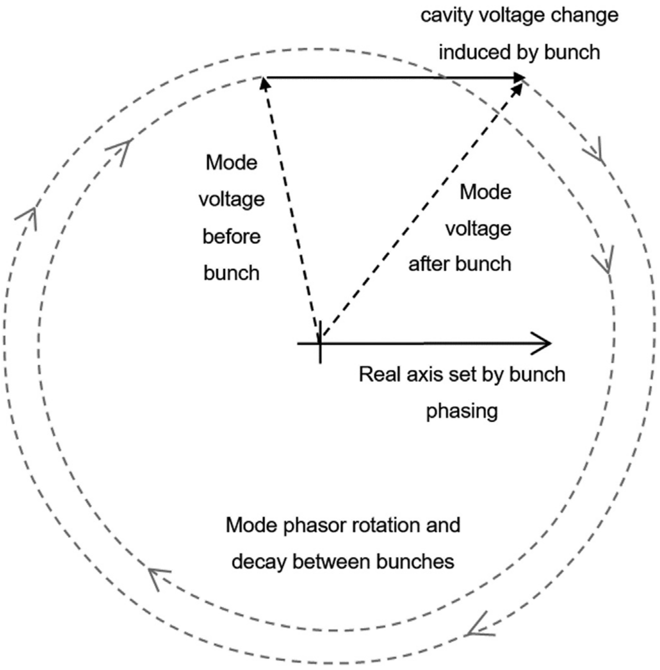

Fig. 1. Off resonant excitation of a mode.