Coupled Bunch Instability from JLEIC Crab Cavity Higher Order Modules

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COUPLED BUNCH INSTABILITY FROM JLEIC CRAB CAVITY HIGHER ORDER MODES *

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Abstract

Particle bunches traveling in a ring can excite wakefields inside any radio-frequency (rf) element present. These electromagnetic modes can resonate long enough and interact with subsequent passing bunches. A coherent oscillation between bunches can quickly become an instability and needs to be addressed. The Jefferson Lab Electron-Ion Collider (JLEIC) has a large 50 mrad crossing angle and thus relies on bunch crabbing to achieve high luminosity. Bunch crabbing is done with compact superconducting rf dipole cavities. We study coupled bunch oscillations driven by the higher order modes (HOM) of multi-cell rf dipole (rfd) crab cavities under study for JLEIC, we calculate the instability growth time assuming a symmetric beam frequency spectrum, identify the HOM driving the instability and discuss mitigation measures.

INTRODUCTION

An electron-ion collider (EIC) has been recommended as the next machine to further advance our understanding of QCD. An EIC concept based on the CEBAF 12 GeV machine is being developed at Jefferson Lab [1]. Two of the main requirements on EIC are: high luminosity (10^{34} cm^{-2}s^{-1}) over a broad range of center of mass collision energy and a full acceptance detector. In order to increase the detector acceptance, however, a large beam crossing angle is required, which in turn reduces the collider luminosity. For JLEIC, a crossing angle of 50 mrad means a luminosity reduction of an order of magnitude. The JLEIC high luminosity strategy includes the use of short bunches, high repetition rate and new technologies like cooling of the ion beam and the use of crab cavities. Crab cavities are rf structures optimized to operate in a transverse electric mode. They provide a kick to the passing bunches to produce a tilt in such a way that the bunches collide head-on at the interaction point, effectively canceling the crossing angle and increasing the luminosity.

CRAB CAVITY FOR JLEIC

As part of the R&D towards JLEIC, different compact superconducting crab cavity concepts are being studied. Two different cavitiy designs are presented in this contribution: a 2-cell and 3-cell 952.6 MHz rfd crab cavity with 70 mm beam pipe aperture. Both are modelled in *CST Microwave Studio* and are shown in Fig. 1. Hooks and probes were added to these designs for this study and optimized HOM couplers are currently under study.

Table 1: Crabbing Parameters for JLEIC at High Luminosity Center of Mass Energy

Parameter	Electron	Proton
Energy [GeV]	5	100
Frequency [MHz]	952.6	
Crossing angle [mrad]	50	
β_x^* [m]	0.1	
β_x^{crab} [m]	200	363
Crabbing voltage [MV]	1.52	20.82

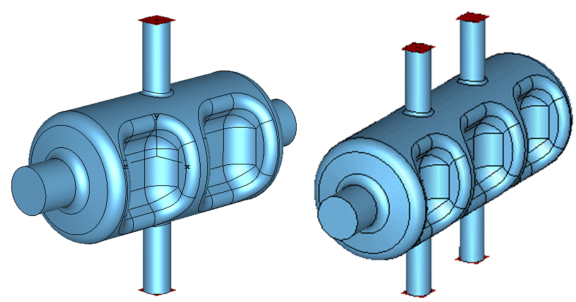

Figure 1: Crab cavity concepts for JLEIC, 2-cell and 3-cell 952.6 MHz cavities with 70 mm aperture.

Multi-cell cavities seem convenient as a small number of them are required to produce the crabbing voltage [2]. In order to produce the required crabbing voltage for the 100 GeV proton beam, 11 2-cell cavities per IP side are needed, vs. 7 3-cell cavities. A total of 22 and 14 cavities in a JLEIC local crabbing scheme [3]. Table 1 presents the general crabbing parameters for JLEIC.

Higher Order Modes

Not only does the cavity produces a field that acts on the beam, but also the beam excites multiple electromagnetic modes, or HOM in the cavity. A JLEIC bunch of 1 cm length can excite HOM up to about 30 GHz. In this contribution we are most interested in trapped modes, i.e. HOM with frequencies below the beam pipe cut-off frequency, as these modes coherently affect subsequent passing bunches, and can drive a coupled bunch instability (CBI).

The shunt impedance R/Q and Q_{ext} of longitudinal HOM are calculated using *CST Microwave Studio*. Figure 2 shows

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the corresponding impedance of longitudinal HOM up to 3 GHz for both cavity designs.

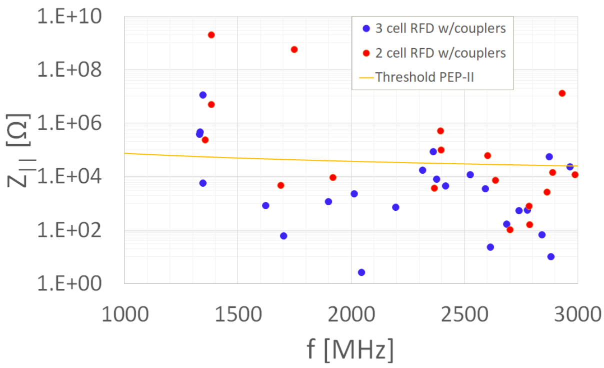

Figure 2: Longitudinal impedance from cavity HOM for 2 (red) and 3-cell (blue) designs. The line shows the threshold impedance assuming the state of the art rf feedback system used in PEP-II.

COUPLED BUNCH INSTABILITY

A bunch traveling through the ring can excite wakefields along different machine elements like the beam pipe, tapers, bellows, rf cavities, etc. However, since rf cavities are designed to be highly-resonant structures, these wakefields may not be completely damped by the time a new bunch comes into the cavity. In this case, bunches become coupled to each other and can start to oscillate coherently. Assuming the beam is formed by M equally spaced bunches, there are μ possible coupled bunch modes (CBM) of oscillation, $0 \leq \mu < M$, and $2\pi\mu/M$ is the phase shift between the oscillation of adjacent bunches.

The Fourier transform of the wakefield is an impedance in frequency space. A simple model of a narrow-band impedance, like a cavity HOM k with ω_k, R_k and Q_k is

$$Z_{||}(\omega) = \sum_k \frac{R_k}{1 + iQ_k\left(\frac{\omega_k}{\omega} - \frac{\omega}{\omega_k}\right)}, \quad (1)$$

the sum runs over all cavity HOM. This impedance couples to the beam frequency spectrum, given by $\omega_{p,\mu} = (pM + \mu)\omega_0 + \omega_s$; p is an integer, ω_0 is the beam revolution frequency and ω_s is the synchrotron frequency.

We are mostly concerned about unstable modes of oscillation that give rise to a CBI. A very detailed study of CBI is presented in [4]. The CBI is characterized by its growth time, and can be calculated through [5]:

$$\tau_{||}^{-1} = C_0 \sum_p \frac{Re\{Z_{||}(\omega_p)\}}{(\omega_p/\omega_0)} \frac{h_a(\omega_p)}{S_a}, \quad (2)$$

$$C_0 = \frac{I_b \omega_0^2 \eta}{6\,(L/2\pi R)^3\, 2\pi\beta^2\,(E/e)\,\omega_s}$$

this is a weighted bunch power spectra sampled at the beam frequencies. For our calculations, we assume $h_a(\omega)$ is the parabolic bunch power spectra and $S_a = \Sigma h_a$, $a = 1$ for dipole mode of oscillation. The ring parameters used are consistent with CBI calculations for JLEIC accelerating rf cavities as presented in [6].

A CBI stability criterion is for the instability growth time to be longer than the damping time: $\tau^i_{growth} > \tau_{damp}$. Various mechanisms can provide some level of damping, e.g. synchrotron radiation or bunch by bunch rf feedback system. In the case of the ion beam, however, synchrotron radiation damping time is very long and an rf feedback system is required. The state of the art feedback system used at PEP-II can handle growth times on the order of milliseconds, which sets a threshold on the HOM impedance, as shown in Fig. 2.

RESULTS

We calculate the longitudinal CBI growth rate for all the possible beam frequencies up to 3 GHz using JLEIC ion ring parameters [6]. A factor of 0.1 is assumed to lower the Q of HOM to simulate a frequency spread due to cavity to cavity differences, as implemented in program *ZAP* [7]. Figure 3 shows the CBI growth rate as a function of the CBM number μ. Negative growth rates represent damped or stable modes of oscillation.

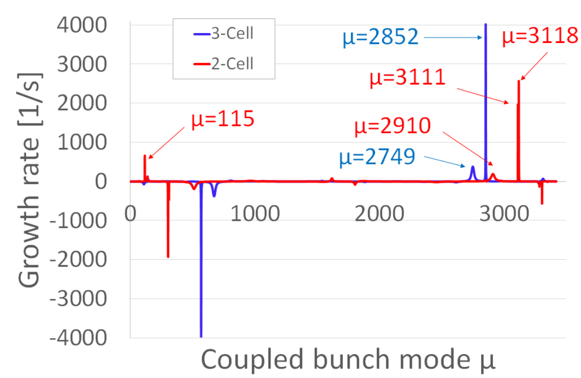

Figure 3: Growth rate vs CBM number corresponding to both cavities. The red (blue) line corresponds to the 2(3)-cell cavity.

For the 2-cell cavity, the CBM with μ=3118 has the fastest CBI growth time of 0.39 ms. Similarly, for the 3-cell cavity, the fastest growth time is 0.25 ms for CBM μ=2852. These modes can not be managed by a PEP-II type rf feedback system, and thus need to be addressed by optimizing the HOM couplers on the cavity. With the knowledge of the growth rate and CBM number, it is possible to identify which HOM drives the instability by evaluating the beam frequency at the corresponding μ and scanning over the integers p to find the closest beam frequency to a cavity HOM. Table 2 shows these beam frequencies and coupling HOM for the two cavity designs.

COMMENTS

We study the coupled bunch oscillations driven by the HOM of 2-cell and 3-cell crab cavity concepts for JLEIC.

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Table 2: Beam Frequencies Matched to a Cavity HOM. Top (bottom) values correspond to the 2(3)-cell cavity.

Mode	μ	p	Beam $f_{\mu,p}$ [MHz]	HOM f [MHz]
1	3118	2	1384.17	1385
2	3111	2	1383.2	1385
3	115	6	2868.27	2866
4	2910	2	1355.26	1357
1	2852	2	1347.2	1349
2	2749	2	1332.89	1334
3	2749	5	2759.02	2743

We calculate the fastest CBI growth time, which is a fraction of a millisecond for both designs. This is faster than the state of the art rf feedback system at a few milliseconds and thus the damping relies on the optimization of the cavity HOM couplers, this is an on-going study. A future analysis of CBI will include a more realistic beam structure than includes gaps, even though the uniform fill generally overestimates the CBI growth time. Also, the HOM impedance can be calculated numerically using *CST Microwave Studio*, for example. This calculation will take into account HOM having different time phases. and enables an accurate calculation of the HOM power that needs to be extracted.

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