COLLECTIVE EFFECTS IN THE MAXIV 3 GEV RING

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Abstract

We present calculations of collective instability effects in the 3 GeV electron storage ring of the MAX IV facility currently under construction in Lund, Sweden. The storage ring is designed to deliver ultra-low emittance down to 0.24 nm rad so as to provide high brightness synchrotron radiation from undulators. This is achieved in a comparatively small machine (528 m circumference) through the use of a multi-bend achromat lattice and a compact magnet design with multi-purpose narrow gap magnet blocks. This design features small dispersion leading to low momentum compaction, which, together with the small circular (11 mm radius) chambers, poses a challenge to reach the design current (500 mA in 176 bunches) without exciting instabilities and degrading beam parameters due to the interaction with the machine impedance. Particularly important are multi-bunch resistive wall effects in the NEG coated copper chamber as well single-bunch instabilities driven by the broad-band impedance. A low RF frequency (100 MHz) and harmonic cavities are foreseen to lengthen the bunches and increase instability thresholds.

INTRODUCTION

The MAXIV facility[1,2], currently under construction in Lund, Sweden,will provide a suite of light sources covering a wide photon spectral range and pulse lengths with state-of-the-art performance. The complex includes a 3 GeV storage ring featuring ultra-low emittance (down to 0.2 nmrad) optimized for hard X-rays, a 1.5 GeV storage ring optimized for soft X-rays and UV radiation production and a 3 GeV linear accelerator that fullfills the whole of full-energy injector into both rings as well as delivers beam to a short pulse facility designed to produce spontaneous radiation from undulators with pulse lengths down to 100 fs.

Tables I and II show the main machine parameters relevant for discussing collective effects.

The MAX IV design concept leads to several challenges in reaching stable operation of the machine at high currents. These challenges stem, on the one hand, from a compact magnet design which calls for a small vacuum chamber aperture leading to an increased resistive wall impedance and the excitation of transverse coupled bunch modes. Moreover, the low emittance design leads to a small dispersion function in the archs (few cm maximum), which, coupled with the large bending radius, results in a small momentum compaction factor, and consequently small values for single bunch instability thresholds, particularly for the microwave instability and transverse mode coupling instability.

Table I: Main Parameters of the MAX IV 3 GeV Ring

Energy	3	GeV	E_0
Current	500	mA	I_0
Circumference	528	m	C_0
Harmonic Number	176		h
RF frequency	99.931	MHz	f_{RF}
HC freq./RF freq.	3		n
Mom. Compaction	3.07x10^{-4}		α
Horizontal Tune	42.20		Q_x
Vertical Tune	16.28		Q_y
Beam pipe radius	11	mm	a
Chamber material	Cu		

Table II: MAX IV 3 GeV ring parameters for a bare lattice (no IDs) and a machine loaded with 19 undulators (period length = 18.5 mm. Peak field=1.1 T, length=3.7 m).

Parameter	Bare Lattice	Loaded Lattice		
Energy Loss/Turn	360	856	keV	U_0
RF Voltage (@ 4.5% RF energy acceptance)	1.02	1.63	MV	V_{rf}
Nat.Energy Spread	7.68x10^{-4}	7.82x10^{-4}		σ_E
Nat. RMS Bunch Length	1.20	1.01	cm	σ_{l0}
Horiz. Damp. time	15.8	9.1	ms	τ_x
Vert. Damp. Time	29.30	12.3	ms	τ_y
Synch. Damp. Time	25.6	7.5	ms	τ_L
Synchrotron Tune	1.65x10^{-3}	1.99x10^{-3}		Q_{s0}
Synchronous Phase	159	148	deg	φ_{s0}

In order to face the challenges described above, the MAX IV facility design on the one hand and the 3 GeV ring design on the other incorporate several ingredients that help mitigate these difficulties. First and foremost, the fact that short light pulses will be produced by a LINAC source (the 3 GeV injector LINAC and corresponding Short Pulse Facility) relieves the storage rings from the need to achieve short bunch and single bunch high current operation. This allows us to:

a) choose a relatively low RF frequency for the accelerating cavities, which naturally leads to longer bunches.

b) use harmonic (also called Landau) cavities operating in passive mode in order to further elongate the bunches, reducing the charge density thus alleviating intra-beam scattering, which is not only essential to reach the target equilibrium emittances at high current but also increases the average current thresholds for longitudinal single bunch fast instabilities. In addition, the Landau cavities provide increased tune spread that helps fight instabilities and makes up for the relatively long radiation damping times that result from the large bending radius.

c) require only multi-bunch operation with relatively low current per bunch.

This paper summarizes the first results of a study program aimed at validating these concepts in the case of the MAX IV 3 GeV ring by means of both frequency and time domain calculations.

HARMONIC CAVITIES

Harmonic cavities (HCs) are an essential part of the MAX IV storage rings design concept. They lengthen thebunches, reducing particle density and generate frequency spread that help stabilize the beam through Landau damping. Practical experience[3] has demonstrated the possibility of operating such cavities passively, so that the beam itself provides the excitation of the HC.Nominal lengthening conditions[4] are realized when the first and second derivatives of the total voltage seen by the beam are zero at the synchronous phasewhich leads to an approximately quartic confining potential well and a synchrotron frequency that grows linearly with amplitude.The corresponding RMS bunch length, synchrotron frequency spread and Landau damping time arethen given by [4,5] (cf Tables I and II above for the definition of symbols)

$$\sigma_l = \frac{2\sqrt{\pi}}{\Gamma(1/4)}\left\{\frac{3h\alpha\pi E_0}{2e_0 V_{rf}|\cos\varphi_s|(n^2-1)}\right\}^{1/4}\sqrt{\sigma_E}\,\frac{C_0}{2\pi h}$$

$$\Delta\omega_s = \frac{4\pi^2 2^{1/4}\alpha h\omega_0\sigma_E}{\Gamma(1/4)^3\,\sigma_l}\frac{2\pi h}{C_0}$$

$$\tau_L = \frac{1}{0.6\Delta\omega_s}$$

Tables II and III indicate that the HC can lengthen the bunches by about a factor 5 and reduce the damping time by up to a factor 17 compared to the natural radiation damping time.Since the HC is operated passively [6], nominal lengthening conditions can only be obtained at one beam current for a given choice of HC shunt impedance and HC resonant frequency (or conversely for a given HC tuning angle). Figure 1 shows the shunt impedance and HC tuning angle required to achieve nominal lengthening conditions as a function of energy loss per turn.Since the excitation of the HC cavity for a given beam current also depends on the bunch length itself (through the bunch form factor), the calculation of the bunch equilibrium parameters has to be done self-consistently.

Note that passive operation of the HC implies operation on the Robinson unstable slope of the HC resonance peak, so that the HC detuning has to be chosen so that the growth rate from interaction with the HC fundamental mode is small enough to be counteracted by the Robinson damping the fundamental mode of the main cavities. This requirement leads to larger negative detuning for the HC than required for nominal lengthening conditions and raises the required shunt impedance to achieve lengthening and at the same time stable operation. Figure 2 shows an example of self-consistently determined bunch density distribution for non-nominal lengthening conditions in which about the same lengthening as in the nominal case is obtained with a larger negative detuning.

Table III: Equilibrium Bunch Parameters with HC Operated at Optimum Conditions

Parameter	Bare Lattice	Loaded Lattice		
RMS Bunch Length	5.8	5.4	cm	σ_l
Synch.Freq. Spread	191	209	Hz	Δf_s
Landau DampingTime	1.4	1.3	ms	τ_L
Synchronous Phase	157	144	deg	φ_s

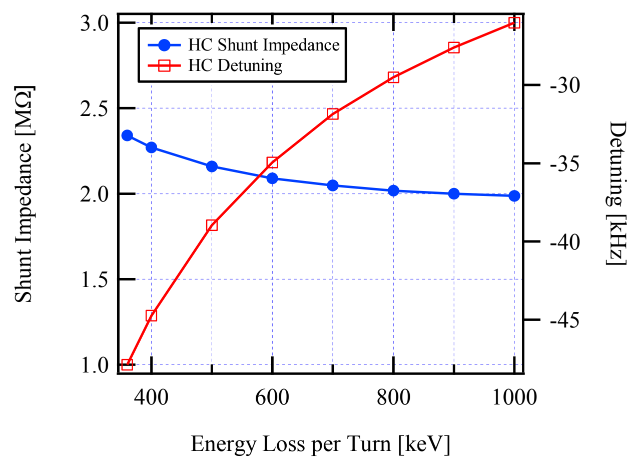

Figure 1: Harmonic cavity shunt impedance ($R_s = V^2/2P$) and detuning fornominal lengthening conditions at nominal beam current. The RF voltage is set for fixed RF momentum aperture (4.5%).

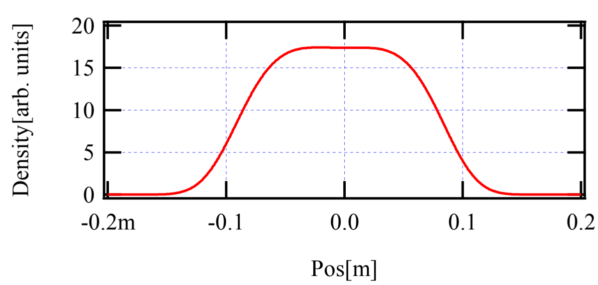

Figure 2: Self-consistently determined bunch density distribution for $R_s = 2.2M\Omega$, HC detuning = -31 kHz (Q=21600). The RMS bunch length is 5.5 cm.

STORAGE RING IMPEDANCE

A detailed impedance budget based on numerical calculations with the code GdfidL[7]has beeninitiated in close collaboration with vacuum chamber designers.Our initial efforts have focused on the resonant behaviour of various vacuum chamber elements, such as bellows, flanges and tapered transitions. Numerically calculated wakefields and shunt impedances were used to estimate the corresponding growth rates of longitudinal coupled bunch modes. In order to properly take into account the modifications to the dynamics due to the HC these estimates are based on the formalism by described in [6]. Figure 3 below shows the estimated maximum allowed shunt impedance for high Q impedances under two conditions: first (black curve) taking into account only radiation damping and second (red curve) taking into account Landau damping, both for a lengthened bunch. The dots indicated calculated values of shunt impedance for various vacuum chamber components.

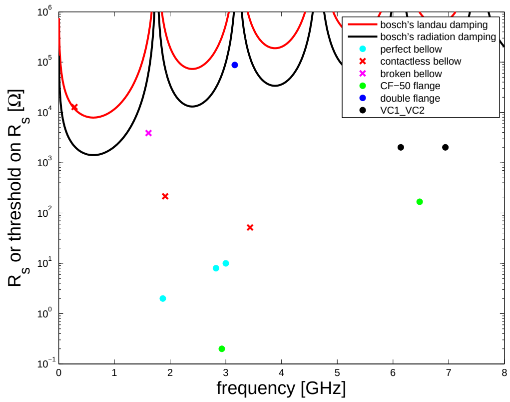

Figure 3: Threshold shunt impedance for resonant modes and shunt impedance from various elements as calculated with GDfidl.

RESISTIVE WALL

Transverse coupled bunch modes driven by the resistive wall impedance are a potential concern given the small pipe radius. Frequency domain calculations with the code rwmbiindicate, however, that the lengthening of the bunches is indeed very effective in stabilizing the beam against resistive wall wake fields. Figure 4 shows the calculated threshold current for synchrotron mode m=0 as a function of chromaticity with and without the HC. The impedance includes the resistive wall as well as a broadband resonator with $R_s = 0.3\,M\Omega/m$ and $f_r = 22\,GHz$.

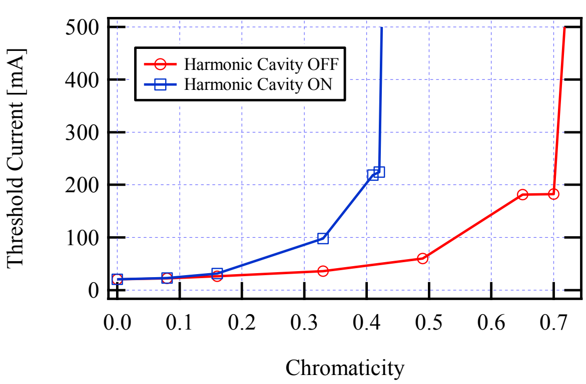

Figure 4: Threshold Current for Resistive Wall Instability (m=0 synchrotron mode).

SINGLE-BUNCH INSTABILITIES

Transverse Mode Coupling

While the use of the harmonic cavities can significantly improve the situation for fast longitudinal instabilities as we have seen above, the same does not happen for the fast transverse single bunch instability or transverse mode coupling. In fact, simulations[8] indicate that the threshold peak current for TMCIdoes not change with the inclusion of HCs for short range (i.e. broad band) wake fields and can even increase but up to a factor 2 for long range (e.g. resistive wall) wakes. Calculations donewith the computer code MOSES [9] assuming a single broad band resonator model with resonant frequency equal to the standard beam pipe cut-off frequency, unit quality factor and transverse shunt impedance of 480kΩ/m indicate a chromaticity around 0.5 is enough to maintain stability up to the nominal beam current (Figure 5).

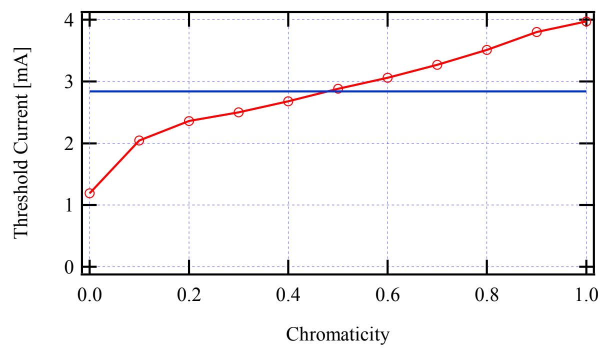

Figure 5: Threshold single bunch current for Transverse Mode Coupling Instability as a function of chromaticity.

CONCLUSIONS

The design of the MAX IV 3 GeV ring implies severe challenges for reaching stable high current operation. The initial calculation shown here confirm that the use of Landau cavities as well as the relatively low current per bunch are effective mechanisms to counteract those difficulties. More detailed studies are needed to fully to validate those concepts.

REFERENCES

[1] M.Eriksson et al, *The MAXIV Synchrotron Light Source*, these proceedings.
[2] M.Johansson et al, *MAX IV 3 GeV Storage Ring Prototype Magnet*, these proceedings.
[3] M.Georgsson et al, *Landau Cavities at MAX II,* NIM A 416, 465 (1998).
[4] A.Hoffman et al, *Beam Dynamics in a Double RF System*, CERN-ISR-TH-RF-80-26.
[5] S.Krinsky and J.M.Wang, *Longitudinal Instabilities of Bunched Beams Subject to a Non-Harmonic RF Potential*, Part.Acc.,Vol 17 , p. 109 (1985)
[6] R.A.Bosh,et al,*Robinson instabilities with a higher harmonic cavity.* PRSTAB Vo. 4, 074401 (2001).
[7] W.Bruns, 3D *EM-Field Solver GdfidL*, http://www.gdfidl.de.
[8] S.Krinsky, *Simulation of Transverse Instabilities in the NSLS-II Storage Ring, BNL-75019-2005-IR*
[9] Y.H.Chin, *Moses User's* Guide, CERN-LEP 88-05, 1988.