HARMONIC CAVITY SIMULATIONS FOR THE ESRF

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Abstract

The ESRF foresees the installation of a 4th harmonic cavity system to provide bunch lengthening in both multi-bunch filling modes and high bunch current timing modes. Here we will present simulation results of the expected machine performance.

INTRODUCTION

The ESRF-EBS is a 4th generation light source that has been in operation since 2019 with a horizontal equilibrium emittance of $\epsilon_H = 137$ pm [1–3]. The EBS delivers beam in a variety of different filling patterns, splitting the user service mode (USM) between high brilliance filling patterns at a total current of 200 mA (uniform or 7/8+1) or timing modes (4 bunches of 10 mA each, or 16 bunches with 92 mA total). Due to the increased charge density, the lifetime during timing mode operation is significantly reduced. This necessitates an increased vertical emittance, which reduces the transverse coherence. Uniform mode is run with $\epsilon_V = 10$ pm at 25 hours lifetime, 16 bunch mode has $\epsilon_V = 20$ pm for 4.4 hours of lifetime, and 4 bunch mode has $\epsilon_V = 40$ pm for 4.2 hours of lifetime. Table 1 shows the machine parameters for the EBS [4].

Table 1: EBS Machine Parameters

	Units	Value
Energy E_0	GeV	6
Circumference C	m	843.977
Harmonic Number h		992
Revolution Time T_0	μs	2.815
Max. Total Current	mA	200
Max. Single Bunch Current	mA	10
Mom. Compaction Factor α	10^{-5}	8.512
Energy Spread σ_e (@0 mA)	10^{-3}	0.9356
Bunch Length σ_z (@0 mA)	mm	2.921
Sync. Freq f_s (@0 mA)	Hz	1300.58
Energy loss per turn U_0	MeV/turn	2.5325

Harmonic cavity systems are proposed for all 4th generation light sources as a way to alleviate the reduced Touschek lifetime. The harmonic cavities are often operated as either superconducting passive cavities, or normal conducting active cavities [5, 6], although some cases of normal conducting passive cavities can be found [7]. The harmonic system will provide an additional RF voltage which will cancel the first and second derivatives of the main RF voltage at the synchronous phase, flattening the potential and elongating the bunch [8]. However, due to the reduction of the synchrotron tune that follows, beam stability issues are expected (as have been observed and simulated at other facilities) [9]. Dedicated simulations must be performed prior to the installation of a harmonic system in order to prove its feasibility.

These proceedings will first introduce the existing and planned rf installations at the ESRF, before comparing theoretical estimates with beam dynamics simulations for uniform filling mode. Finally, some simulation results in 16-bunch mode will be shown.

ESRF RF SYSTEMS

The ESRF-EBS currently operates with 13 single cell cavities at an RF frequency of 352 MHz. 3 of these cavities are powered by Solid State Amplifiers (SSA) with a maximum forward power of 150 kW, whereas the other 10 cavities are powered by a klystron. Each cavity is designed to deliver 500 kV. It is foreseen that the transmitter will be replaced by a further 10 SSAs, each one providing around 110 kW per cavity.

Table 2: Parameter list for the main and foreseen harmonic systems at the EBS. FP stands for Flat Potential.

	Units	Main	Harmonic
β		2.8	0.5-2.0
$R_{s,u}$ (total)	MΩ	70.6875	6.923
Q_0		37500	35054
N_{cav}		13	3
V_c (total)	MV	6.5	1.48 (FP)

The active harmonic cavity will operate at the 4th harmonic of the RF frequency (1.44 GHz). The cavity design itself is a single cell TM020 with both Higher and Lower Order Mode damping(HOM and LOM). The cavity is still in the design phase, with possible modifications still being possible based on the results of beam dynamics simulations and manufacturing requirements. Figure 1 shows a cutaway model of one cell of the harmonic cavity. Table 2 shows the parameters of the main and harmonic RF systems that are relevant for beam dynamics simulations.

UNIFORM MODE

In order to understand the machine performance in uniform mode, Algorithms for Longitudinal Multibunch Beam Stability (ALBuMS) [10] was used to compute growth rates of different types of instabilities for any different parameter set of main and harmonic cavities. This allowed an easy first probe into the stability region to see which types of instability will be the main limitation for the ESRF case.

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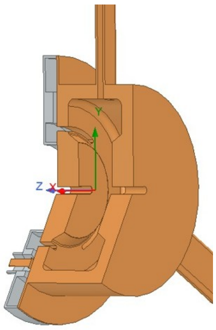

Figure 1: A cutaway of one single cell of the foreseen HC.

Figure 2 shows the results of one such 2D scan, varying the unloaded shunt impedance of the harmonic cavity R_{sh} and the degree of flat potential ξ, which is defined:

$$\xi = \frac{-mV_2 \sin(\phi_2)}{V_1 \sin(\phi_1)}. \qquad (1)$$

where m is the system harmonic, V is the cavity total voltage where the subscript 1 refers to the main cavity and the subscript 2 refers to the harmonic cavity, and ϕ is the synchronous phase.

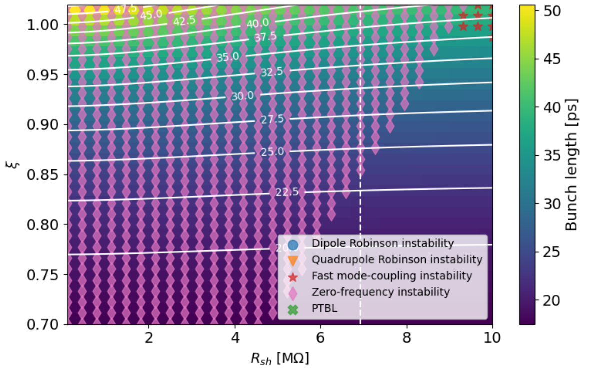

Figure 2: ALBuMS scan of the stability region for an active harmonic cavity in uniform mode at $I_0 = 200\,\text{mA}$ with $\beta_h = 1$. The x-axis is the unloaded harmonic cavity shunt impedance, and the y-axis is the degree of flat potential. The white dashed line represents the nominal HC shunt impedance. The zero-frequency instability is the limiting instability in this configuration.

As can be seen, for $R_{sh} < 9\text{M}\Omega$, the dominant instability that prevents operation close to the flat potential is the zero frequency instability. The zero-frequency instability is introduced and defined in Ref. [9]. Bosch *et al* model the beam motion assuming a rigid dipole oscillation, which oscillates at the Robinson frequency ω_R defined:

$$\omega_R^2 = \frac{\alpha e \omega_1}{E_0 T_0}(F_1 V_1 \sin(\phi_1) + mF_2 V_2 \sin(\phi_2)) \qquad (2)$$

where F is the form factor, and e is the elementary charge.

The coupled bunch mode that is most critical for the ESRF parameter set is the dipole mode, $\mu_0 = 1$. An oscillating beam will interact with the impedance at specific frequencies, and it is shown by Bosch *et al* that the real angular frequency shift is defined:

$$\Omega_R^2 = \frac{\alpha e \omega_1 I_0}{E_0 T_0}(R_{sl,1} F_1^2 \sin(-2\psi_1) + mR_{sl,2} F_2^2 \sin(-2\psi_2)), \qquad (3)$$

where ψ is the detuning of the cavity and ω is the RF generator frequency. The stability criterion is then given by $\omega_R^2 < \Omega_R^2$.

Assuming $I_0 = 200\text{mA}$ and nominal R_{sh}, the threshold predicted in ALBuMS by the Bosch formula is $\xi = 0.85$.

Beam tracking simulations were performed in PyAT [11] with 80,000 particles per bunch in uniform mode on the ESRF computing cluster using MPI. The feedback model is very simple, each turn the beam induced voltage is computed and the new generator correction is calculated and applied with a gain. There are two knobs; Voltage and Phase. In reality these loops are slow, so low gains must be used to ensure a degree of realism. For these simulations, all gains are set to 10^{-4}, which means approximately 100,000 turns are needed to ensure convergence of the generator parameters. For the results presented in these proceedings, more complex feedback systems are not yet considered. The purpose of these simulations is to understand the instability phenomena and push the performance as much as possible without additional hardware. To unlock the full potential of the harmonic cavity, more advanced feedbacks will be needed [5]. The feedbacks are kept on with low gains until the last 10,000 turns where it is switched off. If the equilibrium position or bunch length does not change after this point, then the beam is stable.

Beam tracking simulations were performed under identical machine conditions to validate the Bosch predictions. The results of the tracking simulations can be seen in Fig. 3.

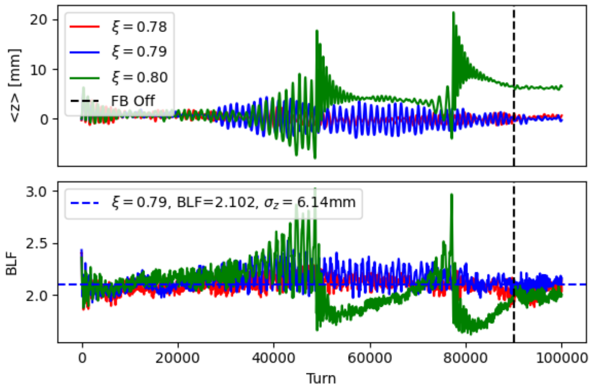

Figure 3: PyAT tracking simulations for $I_0 = 200\text{mA}, V_c = 6.5\text{MV}$.

The tracking simulations shows stability up to $\xi = 0.79$. This is not too far from the Bosch prediction, but certainly not exact. Additional simulations show that, while the thresholds do not match, the qualitative behaviour of the Bosch prediction is in agreement with tracking. For example, if the input parameters are modified in a way where the Bosch theory predicts more stability, then the simulations follow in this direction. This leads to some simple ideas that can be followed to push the stability threshold and obtain more bunch lengthening:

- Increase ω_R. This can be done by keeping the V_1 high.
- Reduce (increase) the shunt impedance of the main (harmonic) cavity
- Modify the detuning of the main (harmonic) cavity to minimize (maximize) the term $\sin(-2\psi)$.

Interestingly, the optimum detuning for uniform mode at 200 mA is $\psi_1 \approx -\pi/4$ and $\psi_2 \approx \pi/4$. This means that the main cavity impedance is maximally destabilizing, whereas the harmonic cavity impedance is maximally stabilizing. The most practical method of pushing this threshold in the ESRF case, is to reduce the number of main cavities from 13 down to 11 while keeping a higher main voltage $V_c = 6.5$MV. This comes at a cost of additional generator power from the main system (but is within or just exceeding the operational limits of the present system). Figure 4 shows the results of tracking simulations performed with $N_{cav,main} = 11$.

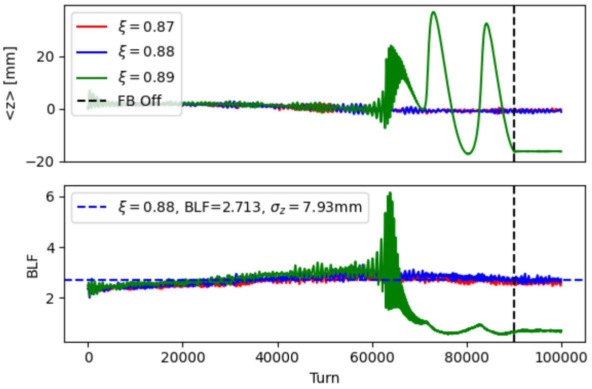

Figure 4: PyAT tracking simulations for the same case as shown in Fig. 3 except for a reduction in the number of main cavities from $N_{cav} = 13$ to $N_{cav} = 11$. The threshold and achievable bunch lengthening have been increased as a result of the reduced main impedance.

Additional gain could also be achieved by applying a detuning offset on the main cavity. These simulations are currently underway and will be reported in the future.

16 BUNCH MODE

When considering single bunches with non-negligible current, it is no longer possible to rely on the analytical approaches. There are additional fields present that are not considered in the theories currently modeled in ALBuMS. For example, the cavity short range wake field will create two additional fields that are the convolutions of the bunch distribution with the resonator from each cavity. These fields distort the overall equilibrium distribution, and when the current becomes too high, the flat potential is no longer achievable. This may help from the point of view of beam stability, as the Robinson frequency will never reach zero, but will certainly limit the maximum bunch length, while requiring numerical approached to find the correct cavity set points. In addition to this, the total machine wake must be included which both lengthens the bunch as well as shifting its equilibrium phase [3]. The phase shift must also be considered in the generator feedback loop to ensure the cavity set points are reached at the arrival time of the bunch.

To satisfy all of these constraints numerically, the phase setpoint of the harmonic cavity was scanned in PyAT in order to find the maximum bunch length for a given value of ξ. The results of this scan can be seen in Fig. 5.

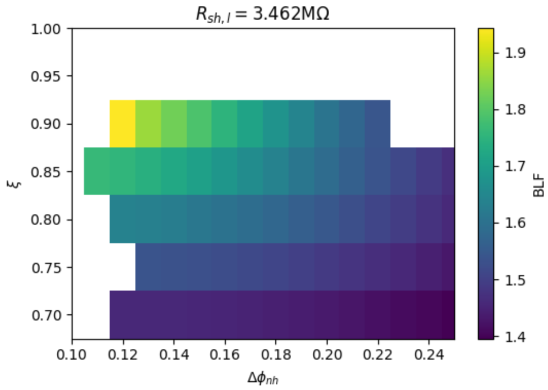

Figure 5: A 2D scan showing the maximum achievable bunch lengthening for 16 bunch operation at 92mA. The bunch length without the harmonic cavity is 7.5mm. The white blocks were simulated but were unstable.

As can be seen, the maximum achievable bunch lengthening factor approximately 2.

CONCLUSIONS

Uniform mode at the ESRF is limited by the zero frequency instability, which prevents operation at close to the flat potential. The threshold of this instability can be increased by taking guidance from the Bosch description of the instability.

In 16 bunch mode, a more numerical approach is needed to obtain the optimum cavity set points. A factor 2 bunch lengthening can be obtained, which will allow operation in 16 bunch mode with a reduced vertical emittance.

The results shown here do not consider advanced feedbacks, which will push performance even further.

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