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IMPEDANCE ESTIMATION AND INSTABILITY ANALYSIS FOR KOREA-4GSR STORAGE RING

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Abstract

Korea-4GSR is a future light source in Korea with a circumference of 800 m, an energy of 4 GeV, and a maximum current of 400 mA. Due to the small aperture of the vacuum chamber (12H x 9V octagonal) and the large number of normal-conducting cavities and beam position monitors (BPMs), impedance-induced instabilities are expected to pose challenges at 400 mA operation. In this study, we estimated the storage ring impedance of Korea-4GSR and investigated both single-bunch and multi-bunch instabilities to determine optimal operational conditions, including the analysis of fill patterns

INTRODUCTION

The Korea 4th Generation Storage Ring (4GSR) project began in 2021 and is scheduled for commissioning by 2030. The storage ring will consist of 28 hybrid 7-bend achromats with a total circumference of 800 m. Key machine parameters are summarized in [1]. The baseline configuration includes 9 insertion devices (7 in-vacuum undulators and 2 elliptically polarised undulators) and one bending magnet beamline, operating initially at 200 mA. The storage ring is designed to support up to 24 insertion devices and 28 bending magnet beamlines in future upgrades.

As Korea-4GSR aims for high-current operation, beam instabilities driven by impedance become a major concern. The vacuum chamber has an octagonal cross section (12 mm horizontal × 9 mm vertical) and includes 3 m long IVUs with minimum gaps of 5 mm. A large number of BPMs, vacuum transitions, and RF cavities further contribute to the total impedance. To address this, we modeled the impedance assuming 19 IVUs and 5 EPUs, which represents a realistic scenario for future high-current operation.

In this paper, we calculate the impedance and evaluate the resulting instabilities for 400 mA operation with 24 IDs. As the storage ring model is still under development and additional components may be introduced in the future, the impedance may change. Nevertheless, the instability analysis presented here is based on the current impedance model.

STATUS OF KOREA-4GSR IMPEDANCE MODELING

Resistive wall (RW) impedance and geometric impedances were calculated using ImpedanceWake2D [2] and GdfidL [3]. The Korea-4GSR has a total circumference of 799.30 m, and most of its vacuum chambers are made of aluminum alloy. However, 85.52 m of the chambers, primarily located in the center bends, are made of stainless steel, and 2.52 m are Ti-coated ceramic chambers.

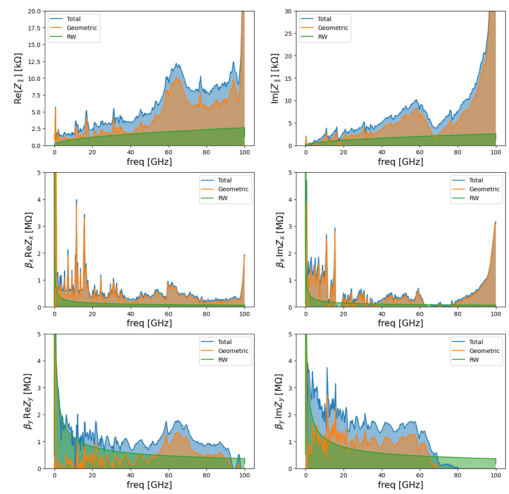

Figure 1: Longitudinal, horizontal, and vertical impedance of Korea-4GSR with 19 IVUs closed.

The effective impedance, as well as the loss and kick factors of each component, are summarized in Table 1, and the corresponding impedance spectra are shown in Fig. 1. We considered 19 IVUs with a minimum gap of 5 mm in the fully closed condition, which represent the dominant impedance sources in Korea-4GSR. The calculated impedances were used to calculated single and coupled bunch instabilities as following.

SINGLE BUNCH INSTABILITIES

Korea-4GSR considers two operation modes: brightness mode and timing mode. Brightness mode corresponds to a 400 mA beam current distributed over approximately 1000 bunches, while timing mode operates with 18 bunches and a total current of 90 mA. In brightness mode, the single-bunch current is approximately 0.4 mA, whereas in timing mode, it reaches 5 mA per bunch. Due to the significantly higher single-bunch charge in timing mode, the potential for single-bunch instabilities must be carefully evaluated to ensure stable operation.

Microwave Instability

Microwave instability (MWI) simulation was performed with PyAT [4]. Two configurations were studied—IVU open

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Table 1: Loss, kick parameters and effective impedances of Korea-4GSR components. Used RMS.bunch length is 3.6 mm and assumed 19 IVU are closed with vertical gap of 5 mm. K_x and K_y are $< \beta_x > \kappa_x$ and $< \beta_y > \kappa_y$, respectively

Components	**Number**	Z/n_{eff} **[mΩ]**	κ_z **[V/pC]**	K_x **[V/pC]**	K_y **[V/pC]**
Resistive wall	1	109.72	16.38	8349.82	48084.69
500 MHz cavity	12	5.14	1.22	73.44	30.59
BPM	176	0.16	29.01×10^{-3}	19.34	19.87
BPM bellows	112	0.22	32.78×10^{-3}	135.23	−6.08
RF components	1	20.54	2.00	1546.41	462.85
LGBM chamber	56	0.22	33.85×10^{-3}	44.71	−104.78
Long. feedback kicker	1	5.37	1.67	711.62	419.58
Combtype gatevalve	80	0.86	14.97×10^{-3}	26.04	7.95
Bellows	168	0.04	3.59×10^{-3}	1.97	16.17
Hor. stripline kicker	1	0.65	0.21	−105.35	58.27
Ver. stripline kicker	1	0.65	0.21	7.47	151.57
DCCT	2	0.14	63.21×10^{-3}	33.68	39.20
Pump	84	0.02	0.56×10^{-3}	6.53	−2.73
Flange joint	700	0.02	0.05×10^{-3}	2.28	6.05
IVU close	19	0.69	1.72×10^{-3}	44.71	−104.78
Total		394.63	48.05	33838.78	52804.6

and closed—without bunch lengthening from higher harmonic cavities (HHCs). The bunch length and energy spread differ between the two cases due to differences in energy loss per turn and main RF voltage (3.08 MV for IVU open, 4.24 MV for IVU closed).

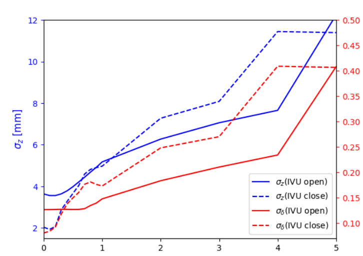

Figure 2: RMS bunch length and energy spread vs. single-bunch current. Only longitudinal impedance is considered.

As shown in Fig. 2, the MWI threshold current is defined as the point where the energy spread exceeds its zero-current value. For the IVU open case, this occurs around 0.6 mA. For the closed case, even at the lowest simulated current of 0.1 mA, the energy spread has already increased by over 1%.

The observed threshold is lower than in other facilities [5, 6], likely due to strong high-frequency contributions from the imaginary part of the longitudinal impedance. The LGBM chambers are the primary suspects, as they show pronounced impedance in the 70–100 GHz range (see Fig. 1), likely caused by photon absorbers and extraction holes near the beam path. Further investigation is underway to clarify the origin of this low threshold.

Transverse Mode Coupling Instability

Microwave instability (MWI) increases the energy spread and bunch length beyond the threshold, but does not immediately cause beam loss. In contrast, transverse mode coupling instability (TMCI) leads to rapid beam size growth and centroid oscillation, potentially resulting in beam loss shortly after the threshold current is exceeded. Here, we report only the vertical threshold current; the horizontal threshold exceeds 5 mA for chromaticity values above 3. The TMCI threshold is defined as the current at which beam size begins to grow significantly.

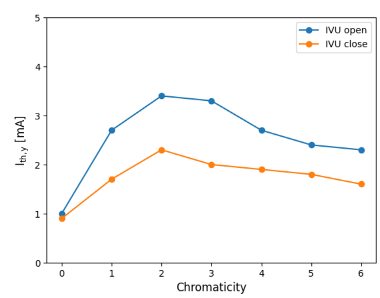

Figure 3: Vertical TMCI threshold current as a function of vertical chromaticity.

Figure 3 presents the vertical TMCI threshold current versus vertical chromaticity. Simulations were conducted up to a chromaticity of 6. For both IVU open and closed configurations, the threshold current peaks at a chromaticity of 2, then decreases with increasing chromaticity. This trend differs from observations at other facilities [5, 6]. Further investigation is ongoing to understand the origin of the reduced threshold at higher chromaticities.

COUPLED BUNCH INSTABILITIES

Coupled-bunch instability (CBI) is a critical issue in brightness mode due to its higher total beam current compared to timing mode. Here, we investigated three sources of

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CBI, assuming a uniform filling pattern with 1332 bunches for simplicity in the calculations.

Resistive Wall Impedance

Resistive wall (RW) impedance is a major source of transverse coupled-bunch instability (CBI) in storage rings. Korea-4GSR is expected to exhibit strong vertical CBI due to its vacuum chamber geometry and insertion device configuration. The chamber has an octagonal cross-section with dimensions of 24 mm (H) × 12 mm (V). In such a flat geometry, quadrupolar impedance cancels horizontal dipolar components while enhancing vertical dipolar impedance. Furthermore, 19 in-vacuum undulators (IVUs) are assumed to operate with a minimum gap of 5 mm.

CBI growth rates were evaluated using PyAT simulations with varying chromaticity. Both horizontal and vertical RW impedances were included, and a rigid bunch model was used. Figure 4 shows the resulting horizontal and vertical growth rates for both IVU open and closed configurations, extracted via singular value decomposition (SVD) [7].

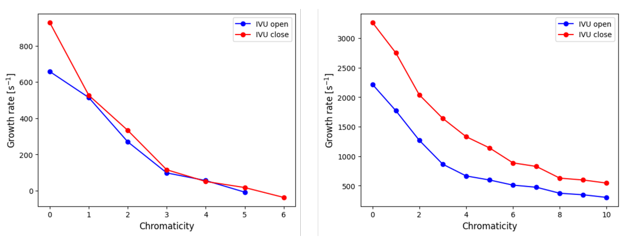

Figure 4: Horizontal (left) and vertical (right) CBI growth rates as a function of chromaticity.

It is well known that increasing chromaticity helps mitigate CBI. In the horizontal plane, the instability is suppressed beyond chromaticity 6. In contrast, vertical instabilities persist even at chromaticity 10. Nonetheless, the growth rates remain within the range controllable by a transverse feedback system.

Robinson Instability with HHC

Korea-4GSR plans to adopt a normal-conducting, HOM-damped active higher harmonic cavity (HHC) for bunch lengthening [8]. However, such HHCs are inherently susceptible to driving Robinson instabilities. In this study, two operating scenarios were considered: 400 mA with 7 HHCs and 200 mA with 5 HHCs. For both cases, the HHC voltage was set to 170 kV.

The cavities' optimal detuning frequency depends on the beam current. The optimal detunings were found to be 299 kHz for 400 mA and 150 kHz for 200 mA, respectively. These values are close to the Korea-4GSR revolution frequency of 375 kHz, which leads to significant coupled-bunch instabilities (CBI), especially in modes 1 and 2. To suppress these instabilities, the cavity coupling factor (β) was increased to 3.

The harmonic cavity simulations were performed using ELEGANT [9]. Only main and harmonic cavity impedances are considered in the simulations. Analytical [10] were compared with simulation-based growth rates, as shown in Table 2. Good agreement is observed when $\beta = 1$, while some discrepancies appear at $\beta = 3$. For 400 mA, increasing β reduces the growth rate, but the required damping strength may exceed the capability of feedback kickers. In contrast, for 200 mA, the dominant mode growth rates are lower than 1100 s^{-1}, which is within a manageable range for longitudinal feedback.

When the HHC detuning frequency is set near zero rather than at the optimum point, CBI can be further mitigated. However, the active HHC has limited detuning capability due to generator power constraints. Moreover, DC Robinson instability can arise when the detuning is too small, except in the 200 mA, $\beta = 3$ configuration. In this stable condition, both mode 1 and 2 are suppressed, and the RMS bunch length and energy spread for the 1332 bunches are 22.41 ± 3.81ps and $0.115 \pm 0.016\%$, respectively.

Table 2: Growth rates from simulation and analytical calculation for each current and β.

Current	Mode	$\beta = 1$ Sim. [s^{-1}]	$\beta = 1$ Ana. [s^{-1}]	$\beta = 3$ Sim. [s^{-1}]	$\beta = 3$ Ana. [s^{-1}]
200 mA	1	1066.8	773.4	893.9	667.2
	2	559.7	72.6	887.2	139.6
400 mA	1	6533.2	6904.3	2497.4	4578.4
	2	3946.8	2606.7	2942.4	2426.0

CONCLUSION

We have been modeling the impedance of our storage ring and investigating both single- and coupled-bunch instabilities. The single-bunch instability threshold currents were found to be lower than expected—0.6 mA or 0.1 mA for microwave instability (MWI), and approximately 2 mA for transverse mode coupling instability (TMCI). These unexpected results require further investigation to fully understand the underlying causes.

For coupled-bunch instability (CBI), increasing chromaticity helps mitigate the effects induced by the resistive wall (RW). Although a chromaticity of 10 does not completely suppress the CBI, the resulting growth rates remain within the range manageable by a transverse feedback system. However, the use of higher harmonic cavities (HHCs) for proper bunch lengthening at 400 mA still requires further study.

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