APPLICATION PROGRAM FOR RW IMPEDANCE CALCULATION FOR TPS RINGS

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Abstract

A Python application program has been developed for resistive-wall (RW) impedance and coupled-bunch instability calculation in the Taiwan Photon Source (TPS) booster ring (BR) and storage ring (SR). The main purpose is to evaluate whether the RW impedance associated with present and future chamber configurations, especially the accumulation of narrow-gap insertion-device (ID) chambers planned for TPS, can become an operational concern. The code combines analytical thick-wall RW formulas with segmented chamber modelling so that each section can be assigned its own length, cross section, aperture, conductivity, and magnetic permeability. For the SR, ID segments can be imported automatically from a workbook to estimate the total RW impedance from all planned IDs and to scan mitigation options such as bunch lengthening with the passive superconducting harmonic cavity, chamber replacement, or material changes. For the BR, the same framework evaluates injection-energy RW behaviour in mixed elliptical and circular chambers. The program reports segment and total transverse RW impedances, dominant coupled-bunch modes, coherent tune shift, growth rate, and growth time through a graphical user interface (GUI) and headless export mode. It also provides a practical computational basis for future TPS upgrade (TPS-II) chamber and ID studies.

INTRODUCTION

Resistive-wall (RW) wake fields arise from the finite conductivity of the vacuum chamber and can drive transverse coupled-bunch instabilities [1]. For the TPS booster ring (BR) [2], this issue is particularly important at 150 MeV injection energy, where synchrotron-radiation damping is weak and narrow stainless-steel chambers can excite fast coherent motion. For the TPS storage ring (SR) [2], the concern is different but equally relevant: standard arc and straight chambers coexist with many insertion-device (ID) vacuum chambers, some with small gaps, so the effective RW impedance depends strongly on the installed machine configuration, bunch length, and fill pattern.

A unified application program is therefore useful for connecting chamber geometry and material choice to instability metrics that can be used in engineering design and operation studies. The present Python program was developed as a general-purpose TPS analysis tool. It sup-ports BR and SR ring presets, segmented chamber descriptions, template-based material selection, and work-book-driven ID configuration for the SR. The practical objective for TPS operation is to import the currently planned future IDs, accumulate their RW contribution together with the stand- ard SR chambers, and determine whether the resulting coupled-bunch growth times remain acceptable or require mitigation. The same software can then be reused to test cures in a controlled way, including bunch lengthening with the harmonic cavity, replacing selected chambers, increasing aperture, or changing conductivity assumptions.

The workflow is intentionally close to how TPS studies are carried out. Users first define ring parameters, then build the segmented chamber model, either manually or by importing ID metadata. The code next evaluates segment-wise RW impedance, sums the total machine impedance, samples the impedance at coupled-bunch spectral lines, and computes coherent tune shift and growth rate. Because the same data structure can be applied to both the present TPS rings and future upgrade scenarios, the program also serves as a screening platform for TPS-II [3], where new arc chambers, long straight sections, and future IDs should be checked early for possible RW-driven instability risks.

GUI AND PYTHON CODE STRUCTURE

The software is organized around ring presets, segment templates, imported ID metadata, and a shared analysis engine. At start-up, the program loads BR and SR default machine parameters, then constructs notebook pages for the visible chamber segments. In SR mode, a workbook loader reads the selected configuration sheet and rebuilds the ID pages dynamically. Each page stores editable fields for cross section, dimensions, length, conductivity, and permeability, while the numerical backend converts these values to a unified segment list before computation. This arrangement allows the user to switch from booster studies to storage-ring future-ID studies without rewriting the underlying algorithm.

The GUI shown in Fig. 1 is split into two functional regions. The left panel contains ring selection, workbook controls, machine parameters, and chamber-segment pages; a vertical splitter and a scrollable input frame keep large SR configurations accessible on a single monitor. The right panel displays segment-wise impedance curves, the full growth-rate distribution, and a zoom around the selected reference mode. A recalculation prompt prevents accidental use of stale results when parameters are changed, while the same backend also supports command-line export in nogui mode. In practice, the code structure follows a clear narrative: parse ring and segment inputs, instantiate material and geometry models, evaluate frequency-dependent RW impedance, assemble the total machine impedance, scan modal growth rates, and finally render plots and export numerical summaries.

This narrative structure was chosen so that the application remains readable for machine-physics users. Instead of

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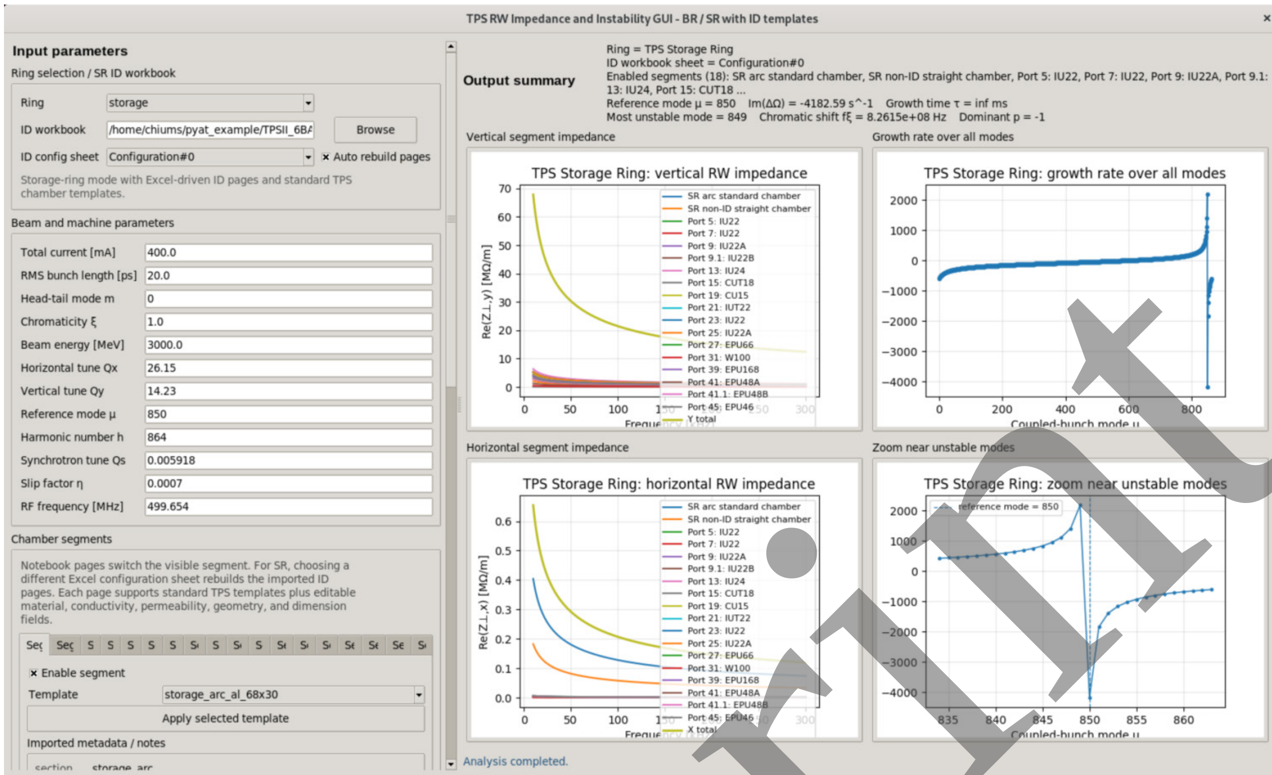

Figure 1: Storage-ring GUI of the Python application. The same framework is extended to the storage ring through workbook-driven ID pages and ring-specific preset.

burying the analysis inside a monolithic script, the implementation separates ring presets, workbook import, segment templates, impedance evaluation, and plotting/export functions. As a result, the same program can be extended from the present TPS BR and SR to TPS-II candidate chambers by replacing the imported segment list and ring parameter block, while preserving the same RW formulas and instability workflow.

RW IMPEDANCE MODEL AND INSTABILITY ALGORITHM

For a chamber segment of length Li, conductivity σ_i, relative permeability μ_{ri}, and effective half aperture b_i, the application adopts the low-frequency thick-wall RW model. In this regime the image currents penetrate the wall by a skin depth that decreases as $|\omega|^{-1/2}$, so the RW impedance is largest at the lowest sampled frequencies, where coupled-bunch modes are most sensitive.

$$\delta(\omega) = \sqrt{\frac{2}{\mu_0 \mu_r \sigma |\omega|}} \tag{1}$$

The transverse RW impedance of segment i is written separately for the horizontal and vertical planes through geometry factors $G_{x,i}$ and $G_{y,i}$ [4]. In one-dimensional notation, G_i denotes the corresponding plane-dependent factor.

$$\frac{Z_{\perp i}(\omega)}{L_i} = \frac{Z_0 \delta_i(\omega)}{2\pi b_i^3} G_{x,y,i}(sgn(\omega) - i) \tag{2}$$

where $G_{x,y,i}$ is a geometry factor for round, elliptical, or custom cross sections. The total machine impedance is obtained by the length-weighted sum over all enabled segments, which is essential for TPS because the BR contains both elliptical and circular chambers, whereas the SR combines standard arc and straight chambers with imported ID segments.

$$Z_{\perp,tot}(\omega) = \sum_i Z_{\perp,i}(\omega) \tag{3}$$

For M equally spaced bunches, the code samples the total impedance at coupled-bunch sidebands. With the rigid-bunch approximation, the coherent frequency shift for mode μ is obtained from the sampled transverse impedance [5].

$$\Delta\Omega = \Omega_m - \omega_\beta - m\omega_s \approx \frac{-i}{4\pi^{3/2}} \frac{\Gamma(m+\frac{1}{2})}{m!(2m-1)!!} \times \frac{n_B I_B e c}{Q_\beta E} \sum_{p=-\infty}^{\infty} Z_1^{\perp}(\omega_p) h_m(\omega_p - \omega_\xi) \tag{4}$$

The coherent tune shift is $\Delta\nu = \mathrm{Re}(\Delta\Omega)/\omega_0$, while the growth rate is given by the imaginary part of $\Delta\Omega(\omega)$. Positive $\mathrm{Im}(\Delta\Omega)$ corresponds to an unstable mode in the convention used here.

$$\tau^{-1} = \mathrm{Im}(\Delta\Omega), \quad \tau = 1 / \mathrm{Im}(\Delta\Omega)\,. \tag{5}$$

For the RW case, the strongest contribution comes from the lowest sampled frequencies, so the most dangerous modes occur near $\mu \sim= M - \nu_\beta$. The strong $1/b^3$ scaling makes the program useful for sensitivity studies of chamber radius, ID gap, material conductivity, and bunch-lengthening scenarios. Algorithmically, the code selects the BR or SR preset, builds the enabled segments, computes the segment and total impedances on a frequency grid, scans all coupled-bunch modes, and reports the dominant mode, coherent tune shift, growth rate, and growth time.

Algorithmically, the program proceeds as follows: (1) select the BR or SR preset; (2) create default standard segments or import SR ID segments from a workbook; (3) assign material, conductivity, permeability, cross section, and dimensions; (4) compute segment impedances on a frequency grid; (5) build the total horizontal and vertical impedances; (6) scan all coupled-bunch modes and identify the dominant unstable mode; and (7) export plots. In SR applications, this sequence makes it straightforward to compare a no-ID reference, a present-configuration model, and a future all-planned-ID model using the same numerical engine. The program is therefore not limited to reporting a single growth time, but is intended to reveal which chamber family or installed ID dominates the RW budget and whether mitigation should focus on geometry, material choice.

For the SR, the code can also be used in a mitigation-oriented mode motivated by recent TPS studies. In that mode, the same chamber model is combined with different rms bunch lengths or fill assumptions to examine how the passive superconducting harmonic cavity changes the bunch spectral power density, shifts the effective impedance weighting, and relaxes the fastest growth rate. This capability is important because the all-ID case can increase the vertical RW impedance substantially, so the decision on whether RW is a concerned issue depends not only on chamber layout but also on longitudinal operating conditions.

RESULTS

For the BR [6-7], the segmented model reproduces the expected coupled-bunch behaviour at 150 MeV. Using the realistic mixture of elliptical and circular booster chambers reported in internal TPS studies, the program identifies the dominant vertical mode near $\mu = 818$ and gives a growth time of about 24 ms at I = 0.5 mA, $\sigma_t = 41$ ps, and $\xi_y = 1$; the corresponding horizontal dominant mode is slower, about 73 ms [8]. These results are consistent with the physical expectation that the smaller vertical aperture of the elliptical booster chambers dominates the RW budget, while the circular sections partially relax the fastest growth rate compared with an all-elliptical estimate.

For the SR, the application combines standard arc and non-ID chambers with workbook-imported ID segments. Representative calculations based on the future all-ID case show that the strongest mode occurs around $\mu \sim= 849$ at 3 GeV and 500 mA. Compared with the no-ID reference, inclusion of all planned IDs increases the total vertical RW impedance by roughly a factor of 4.5 and can reduce the fastest growth time from about 2.8 ms to below 1 ms in a short-bunch case [9]. This is precisely the type of question for which the program was developed: whether the cumulative RW impedance of all planned IDs remains tolerable, and if not, which mitigation lever is the most effective.

The same framework is also useful for mitigation studies. Internal TPS SR scans show that bunch lengthening with the passive harmonic cavity relaxes the instability substantially: when the effective rms bunch length is increased beyond about 40 ps, the fastest vertical RW growth time becomes much longer and can even turn into net damping for the uniform-fill reference case. The application therefore allows a direct comparison between geometric cures, such as enlarging aperture or replacing a chamber family, and operational cures, such as harmonic-cavity bunch lengthening or feedback requirements.

Taken together, the BR and SR examples indicate that the program is suitable not only for low-energy booster scans and high-current storage-ring configuration studies, but also for forward-looking upgrade work. Because the same segmented engine can ingest modified ring parameters and future chamber lists, it can be applied to TPS-II candidate scenarios to screen whether new straights, arcs, or ID chambers would aggravate RW-driven coupled-bunch motion before detailed hardware design is finalized.

Table 1 summarizes the main TPS parameters used in the BR and SR presets. In practical use, the BR preset serves as a fast screening tool for injection-energy studies, while the SR preset evaluates how installed or planned IDs, chamber replacements, and conductivity assumptions alter instability margins. Comparisons between BR, SR, and TPS-II-style studies remain internally consistent because the same program preserves the same segmented data model, RW formulas, and modal scan procedure.

Table 1: TPS Parameters

Parameter	BR	SR
Energy	150 MeV	3 GeV
Circum.	496.8 m	518.4 m
h	828	864
ν_s	0.02606	0.005918
Chamber	35 x 20 + round	68 x 30 + IDs

SUMMARY

A compact Python application has been developed for RW impedance and instability calculation in the TPS booster and storage rings. It links segmented chamber descriptions directly to total RW impedance, dominant mode number, coherent tune shift, growth rate, and growth time, and was motivated by the practical need to screen present and future ID configurations.

The BR and SR cases show that the tool reproduces realistic instability scales, identifies the dominant chamber contributors, and compares cures including aperture or material changes. The same segmented workflow can also be reused for TPS-II chamber and ID screening studies.

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