Abstract

The accurate analysis of any possible source of beam instability is mandatory for the design of a new particle accelerator, especially for high-current and ultra-low emittance synchrotrons. In the specific case of instabilities driven by the coupling between the charged particle beam and the electromagnetic field excited by the beam itself, the corresponding effect is estimated through the beam coupling impedance. The modeling of this effect is essential to perform a rigorous evaluation of the coupling impedance budget able to account for all devices present in the entire machine. To deal with this problem, this paper focuses on the estimation of the contribution of the joints lying between the different vacuum chamber sections, by performing a comparative numerical analysis that takes into account different aperture gaps between the flanges. The results point out the criticality of many small-impedance contributions that, added together, must be lower than a predefined impedance threshold.

INTRODUCTION

Operating for users since 1994, the existing third-generation Italian synchrotron radiation facility Elettra [1] is going to be replaced by Elettra 2.0 [2, 3], an ultra-low emittance light source able to provide ultra-high brilliant and coherent photon beams. Among several factors that affect the performance of Elettra 2.0, the mutual electromagnetic interaction between the circulating beam and its surrounding environment, evaluated in time domain by the wake field and in frequency domain by the beam coupling impedance [4], has to be carefully investigated in order to maintain the total machine impedance lower than a predefined threshold so as to avoid possible sources of beam instability. This work focuses on estimating the contribution of the joints located between different sections of the vacuum chamber. This problem has also been addressed in other contexts such as CERN-SPS, where RF contacts have been used [5, 6], or PSI-SLS2, where zero gap flanges have been chosen [7]. This paper describes a comparative numerical analysis of the impedance of two types of vacuum flanges, taking into account different gap thicknesses between them. The results highlight how the sum of many impedance contributions, albeit small, can be an issue for potential use in Elettra 2.0.

FLANGE MODELS

Two different types of flanges are considered in this paper. The first one is a Spigot Flange Lip (SFL) type, while the second one is a Spigot Flange Planar (SFP) type.

Mechanical Model

The mechanical drawings of the flanges under evaluation are detailed in Fig. 1. The main difference between SFL and SFP types is the uniformity of the gap that separates the opposite sides of the vacuum joint: in the SFP case this gap is nominally uniform up to the gasket housing.

Electromagnetic Model

A simplified electromagnetic (EM) model has been extracted from the mechanical one to simulate the interaction between the charged particle beam and its surrounding environment by considering the short vacuum pipes, opposite facing flanges and the gasket. To simplify the structure, only the surfaces, volumes and materials interacting with the EM field of the charged particles beam have been taken into account. The correspondence between the mechanical and EM models is summarized in Table 1. The gasket and the flanges are assumed of the same material to further simplify the modeling process.

The basic EM models of the SFP and SFL are shown in Fig. 2. The gap $G$ and the cavity depth $C$ of the parasite cavities formed by the opposite sides of the vacuum joint: in the SFP case this gap is nominally uniform up to the gasket housing.
Table 1: Correspondence between mechanical and electromagnetic model.

<table>
<thead>
<tr>
<th>Mechanic</th>
<th>Electromagnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>inner vacuum volume</td>
<td>inner vacuum volume</td>
</tr>
<tr>
<td>materials wall thickness (*)</td>
<td>background lossy metal</td>
</tr>
<tr>
<td>input and output apertures</td>
<td>open boundaries</td>
</tr>
</tbody>
</table>

*: the minimum thickness of the conductive materials is 1.5 mm, large enough to warranty the full electromagnetic field penetration in the conductors due to the skin effect at the considered frequencies.

**ELECTROMAGNETIC SIMULATIONS**

Two sets of EM simulations have been performed resorting on CST Particle Studio by Dassault Systèmes Simulia [8]. The first set aims to evaluate and compare the longitudinal impedance of the two types of flanges assuming the nominal geometries, while the second set focuses on the evaluation of the effects of the constructive tolerances and parameter variations.

**Flanges Nominal Dimensions**

The nominal dimensions of the flanges are:

- gap: \( G = 0.1 \) mm;
- cavity depth: \( C = 2.4 \) mm;
- total longitudinal length: 20 mm;
- cavity main radius (gasket inner radius): 19.6 mm;
- input and output apertures: the same as the rhomboidal vacuum pipe’s inner dimensions (27 × 17 mm);

The relativistic exciting Gaussian beam has bunch length \( \sigma = 4 \) mm in order to have an impedance estimation up to 25 GHz. The lossy metal considered as background is the AISI 316L stainless steel, with an electric conductivity \( \sigma_{316L} = 1.35 \times 10^6 \) S/m at room temperature.

In order to evaluate the longitudinal impedance of both SFL and SFP, the exciting beam and the wake field integration path are set on the longitudinal \( z \)-axis of the simulated structures, and the wake potentials are calculated by the wakefield solver. In Fig. 3, the SFL (red trace) and SFP (green trace) wake potentials are overlapped.

A first qualitative comparison between the wake potential lengths and initial amplitudes, considered together with the shapes of the parasite cavities (as depicted in Fig. 2), suggests that the SFL cavity has an higher energy storage capability with respect to the SFP one. Performing some numerical analyses, both the broadband and narrowband (resonant) impedance contributions can be estimated, thus enabling a quantitative comparison between the SFL and SFP flanges behaviour in the frequency domain. Each narrowband impedance contribution is characterized by its resonant frequency \( f_r \), its shunt resistance \( R_s \) (i.e. the amplitude of the real part of the complex impedance), and the quality factor \( Q \). These values are summarized in Table 2 for the main longitudinal resonant mode of the investigated flanges.

The longitudinal analysis is then completed by calculating the normalized longitudinal impedances \( Z/n \) [9] (see Fig. 4), where \( n = f/f_{rev} \) is the mode number, with \( f_{rev} \) denoting the revolution frequency of the accelerator. The wake loss factors for SFL and SFP are \( 4.83 \times 10^{-2} \) V/pC and \( 1.31 \times 10^{-2} \) V/pC, respectively. A comparison between the real parts of \( Z/n \) shows that the SFL type is almost 100 times higher than the SFP one, while the ratio of the wake loss factors is about 3.69.

**Table 2: \( R_s \), Q and Re(\( Z/n \)) comparison between the SFL and SFP dominant resonance.**

<table>
<thead>
<tr>
<th>( f_r ) [GHz]</th>
<th>( R_s ) [( \Omega )]</th>
<th>Q</th>
<th>Re(( Z/n )) [( \Omega )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFL</td>
<td>2.9388</td>
<td>1247.7</td>
<td>287</td>
</tr>
<tr>
<td>SFP</td>
<td>4.8793</td>
<td>22.64</td>
<td>56</td>
</tr>
</tbody>
</table>

Figure 2: Electromagnetic model of the two flanges: 3D longitudinal cut views. The SFL type (left) and the SFP type (right).

Figure 3: SFL (red) and SFP (green) wake potential comparison.
Mechanical Tolerances and Parametric Simulations

The previously presented EM analysis on the SFP nominal model has allowed the evaluation of the variations of the longitudinal impedance for different geometric tolerances. Assuming that only one parameter varies at a time, we can now estimate the effects introduced by the unavoidable manufacturing and assembly tolerances. The considered parameter variations and the corresponding effects can be listed and discussed as follows.

- The expansion of the gap G from 0.1 mm to 0.4 mm in steps of 0.1 mm determines the increase of both the main and secondary peak amplitude of the real part of the longitudinal impedance, with a frequency shift toward higher values (see Fig. 5). The wake loss factor increases too (see Table 3).

- The increase of the gasket inner radius from 19.6 mm to 20.0 mm determines the growth of both the main and secondary peak amplitude of the real part of the longitudinal impedance, with a frequency shift toward lower values. The wake loss factor remains constant.

- The increase of the longitudinal length from 10 mm to 70 mm does not provide appreciable modifications on the real and imaginary part of the longitudinal impedance. This is because of the long range nature of the resonant field trapped in the gap, whose frequency (4.8793 GHz) is below the cutoff frequency of the vacuum pipe (7 GHz).

Table 3: Wake Loss Factor Varying the Gap G.

<table>
<thead>
<tr>
<th>G [mm]</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>WLF [10⁻² V/pC]</td>
<td>1.31</td>
<td>2.48</td>
<td>3.63</td>
<td>4.77</td>
</tr>
</tbody>
</table>

Figure 5: Parametric dependence of \( \text{Re}(Z/n) \) on G.

CONCLUSION

The longitudinal normalized impedance and the wake loss factor are useful to provide an effective description of the EM interaction between the charged particle beam and its surroundings. Our simulations show that the normalized longitudinal impedance of the SFP flange type is one hundred times lower than that of the SFL one, thus suggesting the possibility of avoiding the installation of the second flange. Furthermore, thanks to the results of the parametric analysis on the SFP type, we have shown the importance of matching the geometric tolerance limit values for both the gap and the gasket radius. It is worth to mention that the real part of the impedance is also related to the RF heating, which could represent a serious issue, both in terms of cooling and extra RF power that the accelerating cavities have to deliver to the beam. In the next future, the longitudinal impedance, and consequently the RF heating, of the SFP-based vacuum joints could be further reduced acting on the beam-flange coupling by:

- optimizing the cavity geometry (lowering Q);
- shielding the cavity aperture (RF fingers for surface currents).
REFERENCES


