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SIMULATION AND ANALYSIS OF WAKE FIELDS AND TRAPPED RF MODES IN INSERTION DEVICE VACUUM CHAMBERS AT THE CANADIAN LIGHT SOURCE

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Abstract

The Canadian Light Source (CLS) synchrotron operates with four in-vacuum insertion devices, three in-vacuum undulators, and one in-vacuum wiggler. Presently, each of the devices occupies half of a straight section. The wiggler is unique in our ring as it is both in-vacuum and shares a straight section with an in-vacuum undulator. We have observed gap dependent beam instabilities in the undulator located in the straight section. To better understand the problem, the cause of the instabilities was investigated using 3D electromagnetic modelling. First, the 'trapped' RF modes (natural resonances) for this undulator chamber, their Q value, and their peak frequencies were analyzed using eigenmode simulation. Secondly, beam excitation of the eigenmodes was simulated with the Wakefield solver. Herein we present the results of this electromagnetic modelling.

INTRODUCTION

The Canadian Light Source (CLS) has 12 straight sections. One of them, the Brockhouse straight consists of an in-vacuum undulator (IVU) and an in-vacuum wiggler (IVW). The CLS operates at a nominal beam energy of 2.9 GeV but has the flexibility to lower the beam energy. During a routine machine studies shift at 1.5 GeV we observed a vertical tune peak at discrete insertion device gap settings indicating an instability. The insertion device gap-width of the instabilities were ~ 70 µm and were separated by a gap-width of ~ 200 µm. The instabilities were not present at 2.9 GeV likely due to the stronger damping. We attribute the beam instabilities to excitation of trapped RF modes similar to observations made at other synchrotrons [1-3]. We have initiated a study to characterize these modes through computational studies. In this paper we focus exclusively on the IVU.

SIMULATION METHODOLOGY

Geometry

The IVU shares a chicaned straight section with the IVW. The overall length of the straight section is 5000 mm. The IVU has a gap separation of 5.2 mm to 29 mm and a magnetic period of 20 mm. The magnet arrays are supported by 1600 mm sub-girders which each connect to out-vacuum girders by 6 pairs of support rods. The system is contained within a UHV chamber with a cylindrical diameter of 300 mm and a length of 1900 mm. Each sub-girder has a Cu-Ni foil sheet for low-loss conduction of the beam image current that terminates inside mounts that also contain flexible tapered RF transitions at the upstream and downstream ends of the chamber. Figure 1 and 2 show a cross-section and side view of the model used for the RF studies.

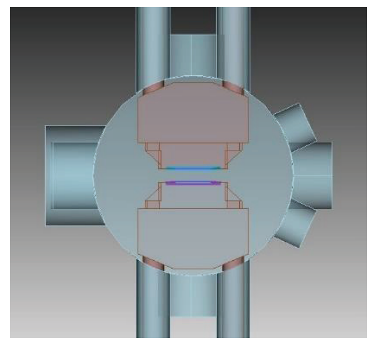

Figure 1: Cut plane view of the IVU model.

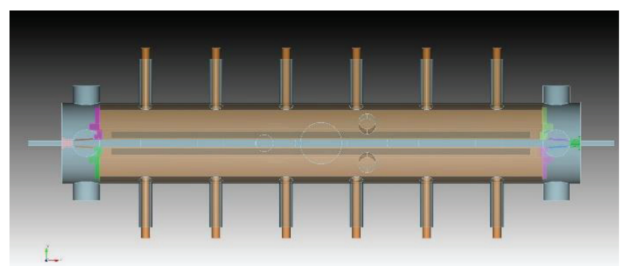

Figure 2: Side view of the IVU chamber and internal structure.

The real IVU structure is internally complex with extended vacuum ports, bolts, chamfered magnet material, heat sinks, etc. A simulation model was constructed by defeaturing/simplifying the internal structure removing the minor yet copious features such as bolts and sliver gaps that are electromagnetically irrelevant. The resulting model consisted of the vacuum chamber, tapers, taper mounts, sub-girders, and support rods. The solid volume of these subcomponents was subtracted from the volume of the vacuum chamber to create a solid vacuum volume for meshing in the simulation codes. This was repeated for IVU gaps 5, 6, 7, 8, 9, 10, 15, 20, and 25 mm.

The vacuum volumes were imported into a simulation code, embedded in a PEC background, meshed, and their

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respective natural eigenmodes and quality factors were calculated. These calculations were repeated using both Gdfidl [4] and CST which produced similar results.

Qualitative Electromagnetic Results

The gap increases the capacitance per unit-length and thereby the TEM-mode characteristic impedance. The resonances of TEM-mode balanced line is only determined by the length of the line and the medium between the conductors. There is a minor gap-dependent effect on the resonances coming from the change in end-fringing fields between the outer ends of the girders and the vacuum chamber walls. The IVU was found to be a TEM-mode structure, similar to a "loaded balanced transmission line"

Here we show a semi-qualitative comparison of the mode field patterns of the IVU with a 5 mm gap, the same model without pumping ports, and the same model without tapers. Figure 3 shows E-field distribution of Mode 2 for the 5 mm model with and without upstream and downstream tapers. When the tapers are present the girders are electrically connected to the chamber walls. As a result, the H-field distribution is perturbed and the field resembles that of a dipole magnet. This effect can be seen in Figures 4 and 5. The mode is also shifted by 36 MHz. The struts also load down the resonant frequencies of the structure.

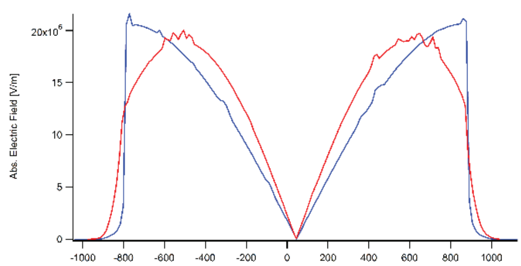

Figure 3: Mode 2 "standing wave" of E-field magnitude for 5 mm IVU gap with tapers (red) and without tapers (blue) along the transverse center line of the IVU. The center zero-crossing indicates clearly a standing wave. At center, the forward and backward waves cancel. At the |E| peaks they add.

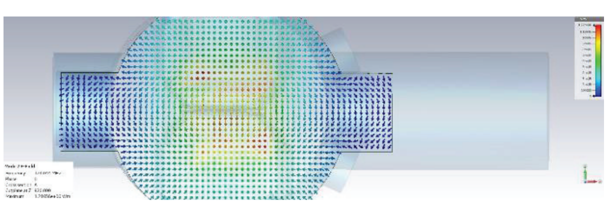

Figure 4: Mode 2 H-field distribution for 5 mm IVU gap without tapers.

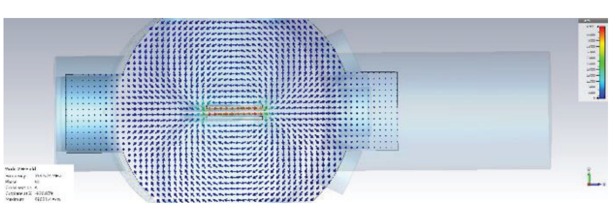

Figure 5: Mode 2 H-field distribution for 5 mm IVU gap with tapers.

The sub-girder struts are a two volume body, an outer cylinder that contains the vacuum and the inner support rod that transmits the mechanical forces. Electromagnetically the combination of the two bodies act as a shorted coaxial line as has been noted by in Dowd *et al.* [3]. Figure 6 shows a surface plot for the relative concentration of the H-field in the vicinity of the struts due to inductive loading. Their location is a possible place to apply ferrite and dampen possible problematic modes.

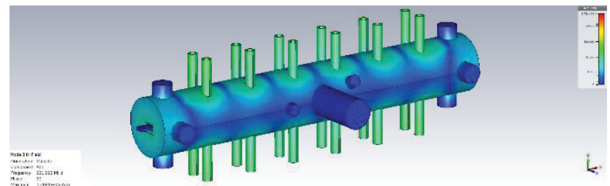

Figure 6: Surface concentration of the H-field for mode 2 of the 5 mm IVU gap model.

The idealized cylindrical pumping ports that line the cylinder have negligible effect on the mode frequencies because the fields are concentrated in the gap and around the girder with the vacuum chamber walls acting as an outer shield. Figure 7 shows a plot of the mode frequencies for the different model geometries.

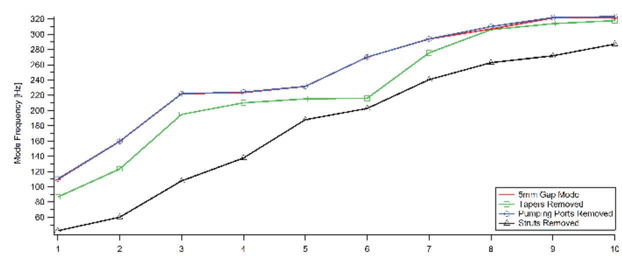

Figure 7: IVU 5 mm gap mode frequencies shifts for the removal of model components.

Quantitative Electromagnetic Results

We calculated the mode frequencies of the IVU as a function of gap. The results are in Fig. 8. We found that the lowest two modes have the behaviour where the frequency gradually increases as the IVU gap is opened. The higher modes had the opposite trend. However, the "higher modes" are those where the fields in the gap are weak and those on the outer girders are strong. This is a so-called "common mode" similar to that of a coaxial cable which has a radial E-field and circular H-field. Bother girders are on the same RF potential in this case. This is again evidence of the TEM-mode nature of the observed modes.

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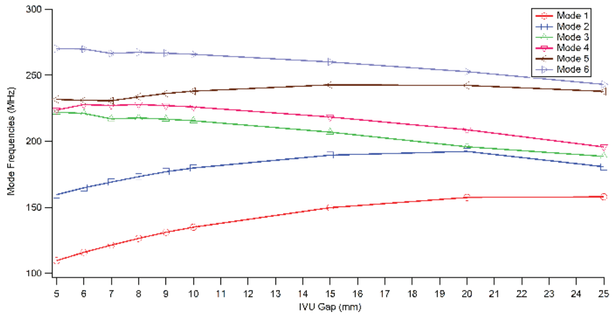

Figure 8: First 6 mode frequencies as a function of IVU gap.

The longitudinal geometric *R over Q* was calculated, for the first 10 cavity modes, as a function of gap from 5-10 mm. The calculation takes into account the transit-time-factor. The resonance plot, shown in Fig. 9, naturally clusters into mode numbers and the frequencies shift with increasing gap size. The strongest peaks occur for 8 and 10 mm gap where they reach 1 Ohm.

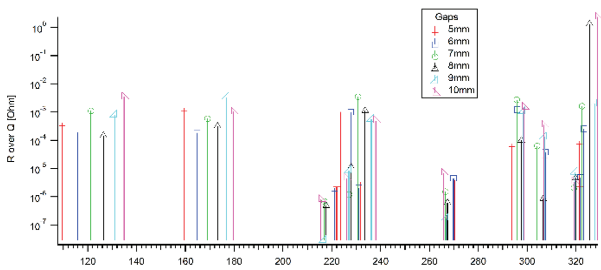

Figure 9: R over Q values as a function of undulator gap

The longitudinal loss factors [5] was calculated as a function of gap using the equation

$$k_z = \int_{-\infty}^{\infty} ds\, W_z(s)\lambda(s) \tag{1}$$

with a Gaussian bunch distribution 10 mm in length. The results are summarized in Fig. 10.

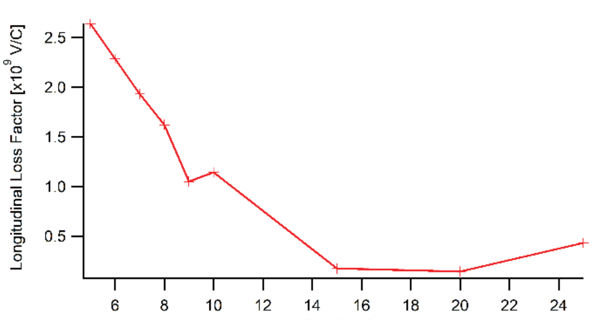

Figure 10: Longitudinal loss factor as a function of undulator gap.

FUTURE WORK

We plan to identify which modes are candidates for the observed beam instabilities by computing the beam coupling impedance as it relates to coupled-bunch instabilities. Observation of the mode growth rate will be made after the upcoming update to the CLS transverse feedback system. Eventually, we would like to explore engineering methods of damping the modes responsible for the beam instabilities.

CONCLUSION

Numerical simulations of the Brockhouse IVU were carried out and natural resonances were identified. The magnet-holding girders and tapers were found to form a balanced TEM-mode transmission line with both ends shorted at most of the critical modes. The Brockhouse IVU is electromagnetically not similar to ridged waveguides, but are instead clearly identifiable as balanced line and as coaxial TEM-mode waveguides. The frequency dependence of the modes on IVU gap was calculated. Geometric *R over Q* and longitudinal loss factors were calculated as a function of gap as well.

ACKNOWLEDGEMENTS

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