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BEAM IMPEDANCE EVALUATION FOR CERN PS GATE VALVES BY SIMULATION AND BENCHMARK MEASUREMENT

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Abstract

The CERN High Luminosity LHC project calls for a doubling of beam intensity which requires a clear identification of possible longitudinal instability sources in the injector chain. This requirement yields the need to further improve the longitudinal impedance model for the Proton Synchrotron (PS). In this impedance model it is necessary to include not only obvious impedance sources, such as RF cavities and kickers but also seemingly innocuous elements like certain vacuum components.

Individually these vacuum elements would give only a small impedance contribution, however, due to the large number of these elements in the machine, their resultant combined impedances impact the overall impedance budget. This paper presents the electromagnetic simulation analysis of the PS sector gate valves along with EM measurements confirming the simulation model. These measurements are especially crucial in this case since no complete mechanical model or drawings are available and assumptions had to be made regarding its interior mechanical structure.

INTRODUCTION

Currently, the PS longitudinal model is in the early stages of development and as a result significant impedance elements such as the cavities and kickers were given priority. The focus has since been expanded to the contribution of the smaller, passive elements, such as vacuum components. One such vacuum element is the ultra-high vacuum (UHV) gate valves.

Within the PS ring there are a total of one hundred straight sections with a gate valve placed within every tenth section, to provide vacuum sectorization. The beam sees ten total valves. Figure 1 shows straight section 10 of the PS with the gate valve circled in red.

The valve is a stainless steel body with a bore size of 145 mm and a bore length of 100 mm. When the valve is open, the gate mechanism rests in the section of the rectangular housing (180 x 414 x 21mm) completely away from the bore. A standard PS-beam pipe, with no transitions, is connected to either side of the bore.

Since there is an abrupt cross-sectional change from beam pipe to the valve geometry and back to beam pipe, a resonator is formed. The mode field patterns and resonance frequencies are dependent on the geometry and any of the internal structures of the valve. Thus an accurate simulation model that includes the complete, internal structure is essential.

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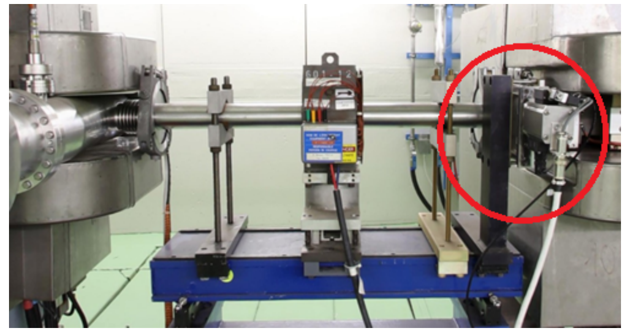

Figure 1: UHV Valve (circled in red) within straight section 10 of the PS.

SIMULATION MODELS

For the gate valves, the manufacturer provides a CAD model [1] which can be used as a starting point for electromagnetic (EM) calculations. The CAD model only represents the dimensions of the bore and housing structure, without the proprietary geometry of the gate mechanism (Fig. 2a). A simplified impedance model, based on this CAD model, was created for the calculation of the transverse impedance [2] of the valve (Fig. 2b).

The exclusion of the gate mechanism from the simulation model drastically changes the EM-performance and thus entirely different, and misleading, impedance contributions are calculated. It was therefore necessary to build a more complete model, that includes the gate mechanism, using educated assumptions and verify it via EM-measurements.

Figure 2c shows the complete valve geometry that includes the valve's gate mechanisms. The gate mechanism consists of the actual gate which is mounted on rollers, with the top of this roller-gate assembly attached to an armature. The armature connects to the far side (away from the bore) of the housing structure. The open position of the gate was deduced from physical inspection of spare valves available at CERN. Note that the overall internal volume of the valve has now greatly decreased, especially at the portions furthest away from the beam pipe section.

ELECTROMAGNETIC SIMULATIONS

The EM simulations were performed using Eigenmode and Wakefield solvers in CST [3]. The Wakefield simulation results for both the simplified model and the complete model with gate mechanism are shown in Fig. 3.

The simplified valve model has two significant modes at 1394 MHz and 1601 MHz, with shunt impedance (R_{sh}) values of 41 kΩ and 40 kΩ, respectively. These modes were

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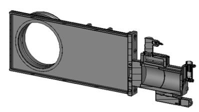
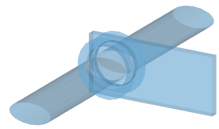
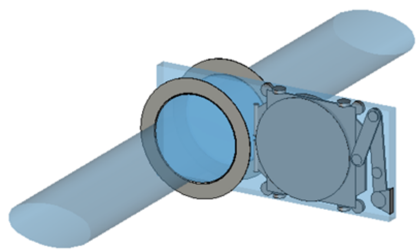


(a) CAD model from the supplier.



(b) Simplified model.



(c) Complete model with the gate mechanism.

Figure 2: Comparison of UHV valve geometries.

identified as the TM_{030} and TM_{040} using the electric field monitors within the program.

At lower frequency is the fundamental TM_{010} mode at 856 MHz and the TM_{020} mode at 1092 MHz, both contributing with much lower R_{sh} values.

The complete valve model, with the added internal geometry has the fundamental TM_{010} mode at 1504 MHz and with a larger longitudinal impedance contribution, 36.2 kΩ. Also the other, higher-order modes (TM_{020}, TM_{030} etc.) are no longer present in the frequency range analyzed.

The electric fields of the TM_{010} mode for both the simplified and complete geometry are shown in Fig. 4. Since for the complete geometry, the remaining empty volume is nearly symmetric along the center of the beam pipe, the TM_{010} mode's longitudinal electric field maxima is seen by the beam. This large field maxima at the beam results in a larger R_{sh} for the complete geometry model than for the simplified model.

The same complete valve model was also benchmarked using the Eigenmode solver (shown in Fig. 5). By comparing the resonance frequencies and R_{sh} of the TM_{010} mode in both solvers the model is further verified.

Slight differences in the simulation results are accounted for by differences in the solvers. The Eigenmode solver employs a tetrahedral solver compared to hexahedral of the Wakefield solver. Additionally for the Eigenmode solver there is a closed boundary at the end of the beam pipes, compared to the Wakefield solver's open boundary conditions, which is more representative of the device within the machine. These Eigenmode boundary condition reflects the EM measurement setup employed.

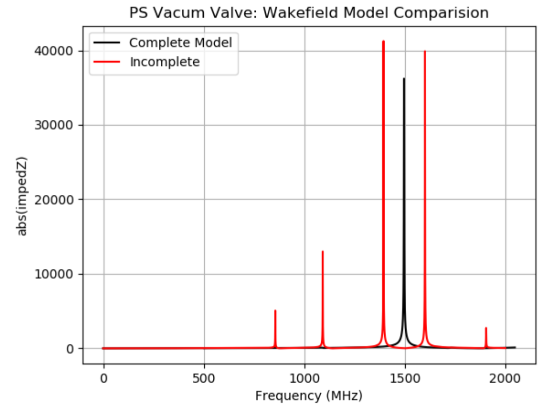


Figure 3: Simulated longitudinal beam impedance of the simplified valve model versus the complete valve model.

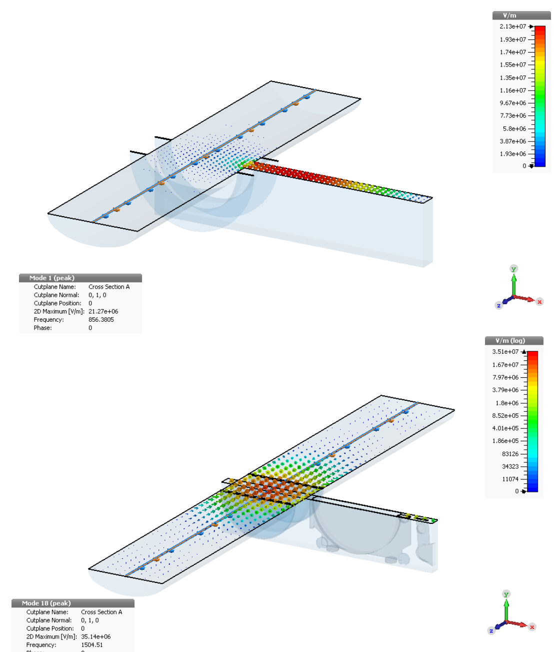


Figure 4: Comparing TM_{010} mode electric field patterns.

ELECTROMAGNETIC MEASUREMENTS

The verification of this new geometry was done via EM-measurements using a vector network analyzer and capacitively coupling coaxial RF-probes. The valve itself had PS beam pipes connected to either side of it with the open ends closed with a flange cover. These flange covers had on-beam-axis openings to insert the RF-probes. The RF-probes couple to on-axis resonances which are then measured via transmission. In all cases, it has been assured that only a weak coupling of the probes to the valve's resonance of less than approximately 100 mdB occurred. This weak coupling is to avoid a falsification of the measurement trace due to overcoupling to the mode, resulting in a lower Q value measured. The measurement results are compared to simulations of the new geometry (Table 1 and Table 2).

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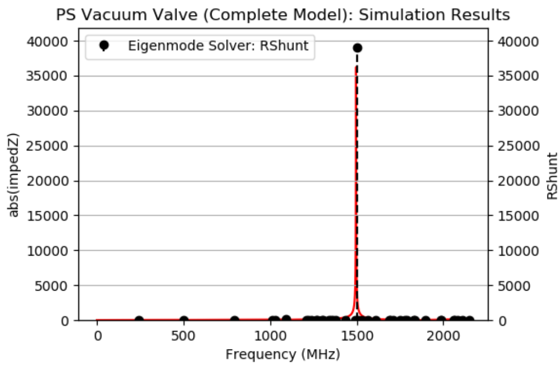

Figure 5: Longitudinal beam impedance from the Wakefield solver (red) overlaid with the shunt impedance values from the Eigenmode solver (stem graph).

Note that direct measurement of resonance modes in the valve without using the beam pipes is not possible since the coupling between the probes and the modes would be too strong. Additionally this measurement setup would not reflect the actual boundary conditions seen by the valves within the PS, since a large portion of the valve's resonating mode is evanescing into the beam pipe.

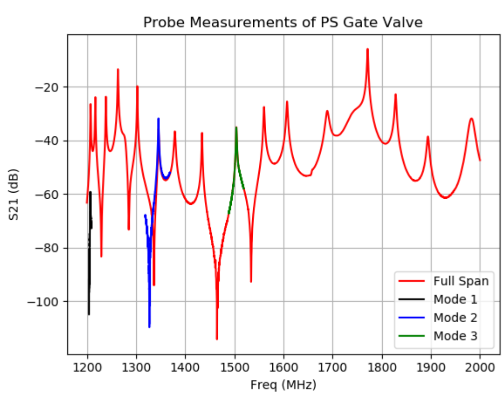

Figure 6: Measurement traces taken with a VNA using coaxial RF-probes.

Figure 6 shows the measurement traces taken. There are a total of four measurement traces plotted: the broadband measurement trace (red) with three re-measured, smaller frequency window traces for the most significant resonances at frequencies (f_{res}) of approximately 1207 MHz, 1346 MHz, and 1504 MHz that could be excited with the centered probe positions. These modes are reproduced in the Eigenmode solver as the TE_{115}, TE_{116} and TM_{010} modes, showing agreement between simulation and measurement (Tab. 1). For the resonance frequencies the agreement is excellent, within a few MHz. The measured Q-values are within good agreement for the TE_{115} and TM_{010} modes. Though the TE_{116}'s measured Q is much smaller than simulated, likely due to overcoupling during measurement. It should be mentioned that the selected measurement set-up restricts the positioning of the measurement probes onto the beam axis.

The TM_{010} mode's values from measurement, Eigenmode and Wakefield simulation are shown in Table 2. The f_{res} from measurements and the Eigenmode solution are identical (1504 MHz) with the Wakefield solver's frequency 8 MHz lower. All three Q-values are all within very good agreement. These results give confidence in the new simulation model of the gate valve as well as the simulated impedance values.

Table 1: Comparison of Measured Mode to Eigenmode

Mode		**Measured**	**Eigenmode**
TE_{111}	f_{res}	1207 MHz	1209 MHz
	Q	2352	2806
TE_{116}	f_{res}	1345 MHz	1348 MHz
	Q	1442	3241
TM_{010}	f_{res}	1504 MHz	1504 MHz
	Q	1184	1295

Table 2: Comparison of Measured TM_{010} Mode to Eigenmode and Wakefield

TM_{010} Mode	f_{res}	**Q**	R_{sh}	**R/Q**
Measured	1504 MHz	1184	-	-
Eigenmode	1504 MHz	1295	39.0k	30.18
Wakefield	1496 MHz	1207	36.2k	30.00

CONCLUSION

A more mechanically complete simulation model of PS gate valve was created via reasonable assumptions of the unknown internal mechanisms of the valve. This simulation model was then verified via EM measurement of the valve itself. As expected, adding the internal geometry significantly changes the resonances within the structure, both the frequency and position of the fields, and thus the impedance contribution. The longitudinal impedance model of the PS has been updated with the impedance contribution of these ten valves.

REFERENCES

[1] VAT Group AG, Switzerland, http://www.vatvalve.com

[2] S. Persichelli *et al.*, "The transverse beam coupling impedance of the CERN Proton Synchrotron", *Phys. Rev. Accel. Beams*, vol. 19 no. 4, p.041001, April 2016

[3] CST AG, Darmstadt, Germany, http://www.cst.com

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