Measurement and Simulation of the Longitudinal Impedance of the LHCb VELO

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Abstract
Analysis of beam impedance of any new or redesigned components of the LHC machine is vital in ensuring beam stability and for inclusion of the contribution of individual machine elements in the overall impedance budget. Geometrically complex objects, such as the LHCb VELO presented here of which a broadband contribution is expected, require confirmation via wire measurements of its electromagnetic (EM) simulations. Since the complete object is inaccessible, a mockup of the new VErtex LOcator (VELO) design has been produced and measured electromagnetically, which in turn was validated by EM simulations. This procedure enabled reliable simulations of the entire LHCb VELO object and to verify the required simplifications done to some of the 3D EM models.

Keywords
Longitudinal Impedance, Wire Measurement, VELO, LHCb, CST Simulations, LHC Impedance Model

1 Background

Any element in the CERN accelerator complex that is in proximity to the beam must have its impedance and the potential resultant effects on beam instability considered, along with any potential electromagnetically induced heating. Additionally the object's impedance should be factored into the overall impedance model of the accelerator.

Ideally for impedance analysis, each object is modelled and simulated in electromagnetic (EM) codes, such as CST [3], and then these simulation results are verified via EM measurement. This cross-check with measurements is especially important when dealing with complex structures such as the LHCb VErtex LOcator (VELO), which is structurally difficult to model and simulate. These complex models typically involve making reasonable approximations in geometry and material definitions. The complete VELO CAD model is shown in Fig. 1.

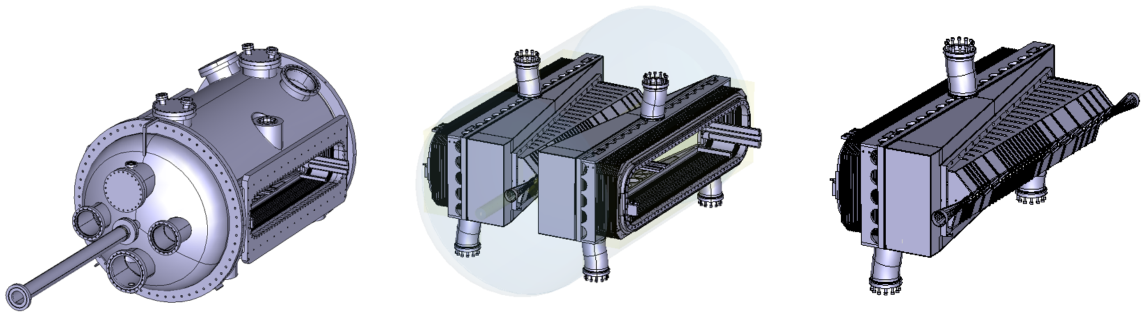

Figure 1: Isometric views of the CAD model of the VELO, showing the complete VELO (left), without the vacuum tank showing the pairs of RF and detector boxes (center) and showing just one pair of RF and detector boxes (right). [1].

The new LHCb VELO design (to be installed during Long Shutdown 2) [2] utilizes many of the major components of the previous design, including the vacuum tank and detector boxes on which the RF (Radio Frequency) boxes sit. The RF boxes contain an array of silicon pixel detector modules that are within a secondary vacuum, separate from the machine vacuum. The reused components remain in the machine and are thus inaccessible for any sort of measurement. The RF boxes have a corrugated structure, it is of major interest to understand how these corrugations, due to their close proximity, interact with the beam. Additionally, the VELO's RF boxes are movable, operating in two functional positions, open and closed. The closed position is when the machine is operating in a stable beam condition, otherwise boxes are in the open position. Due to this geometry switch between open and closed positions, the coupling of the beam to the surrounding space between the structure and vacuum tank changes, thereby modifying the device's impedance.

As a result of these complexities, a mockup of the VELO RF boxes, preserving the relevant corrugated structure, was machined for EM measurements and longitudinal impedance analysis. Just as the actual element, these mockup RF boxes can be placed in either the open or the closed position. Since there is space between the two RF boxes in either position, EM modes are able to radiate into the surroundings, which are an undefined boundary. By having an undefined boundary both measurements and simulations are impossible. To provide a defined boundary for measurements and simulations, the mockup was placed in a cylindrical aluminium tank. This mockup also included copies of the two identical wake field suppressors (WFS) that will be installed on either end of the VELO RF boxes. Both the EM models of the WFS and the RF boxes required extensive simplification to make EM simulations possible, as discussed later in this report.

In summary, the primary components of the VELO mockup consist of the two RF box halves connected to two wake field suppressors on either end of the boxes. These two elements are the most difficult to model of the entire system and require verification via EM measurements. Once these EM models are verified, a complete simulation of the LHCb VELO can be performed.

2 VELO Mockup & EM Model Description

As mentioned, since the actual VELO is unavailable for measurement, a VELO mockup was produced in order confirm via measurement the geometry of the EM model of the VELO structure, in particular the complex geometries of the RF boxes and the wake field suppressors.

2.1 RF Boxes & Tank

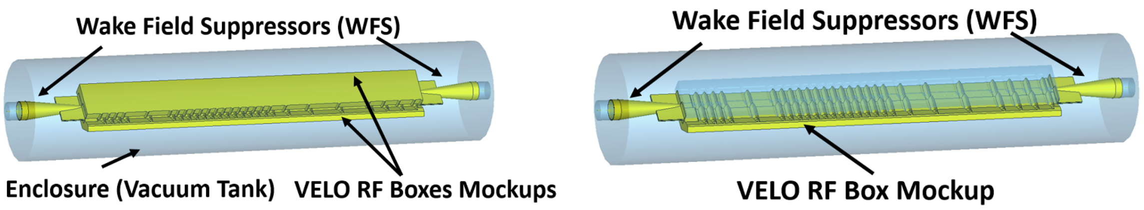

Figure 2: The EM model of the closed VELO mockup, with its major components labeled, on the left. On the right the same model is shown with one of the RF Boxes removed to show the corrugations in detail.

The EM model of the entire mockup, including the WFS's, is shown in Fig. 2, also shown is the model without one of two RF boxes, in order to show the corrugation details. The RF boxes with its corrugated structure are simulation intensive, since the corrugations are rounded, thus requiring very fine meshing. The larger the mesh, the longer the simulation time and thus the corrugations were modelled without rounded edges.

The VELO vacuum tank has a diameter of 950 mm and a length of 1666 mm. For the mock up tank smaller dimensions were chosen, with a diameter of 312 mm and a length of 1496 mm. Note that the VELO vacuum tank is longer and thus contains a straight section of beam pipe connecting one of the wake field suppressors to the exterior of the tank, which is not included in the mockup. The mockup tank includes holders on either end for the WFS to lock into. The VELO RF boxes are supported on two Teflon pieces that allow for the RF boxes to slide into the open and closed position. These Teflon pieces, with their small overall size and low permittivity (ε_r=2.1), have a negligible effect on the EM field distributions.

It was decided to provide the mockup VELO RF boxes with the same length as the true system and to include the same corrugated features. However, these RF boxes are not the same height as the actual ones, since the vertical dimension is geometrically simple and has no effect on EM impedance since they are not seen by the beam directly. The detector boxes are also not included in the mockup, since they are a simple structure and are not close to the beam. Thus including the entire RF box geometries and detector boxes would increase cost, necessitate a larger vacuum tank and unnecessarily increase complexity of the mockup. In the actual VELO, the full-sized RF boxes are resting on the detector boxes which in turn are fully attached to the vacuum tank, seen in Fig. 1. Since the primary goal of these measurements is to understand the effect of the RF boxes and their functional positions on impedance, along with the performance of the WFS's, it was sufficient to include just the corrugations and the configurations of the open and closed VELO positions. A more detailed discussion on the WFS's follows.

2.2 Wake Field Suppressors (WFS) Description

The wake field suppressors function both as a shield and a taper, both acting to reduce the overall impedance of the object. As a shield the WFS prevents the beam from coupling to the surrounding vacuum tank. As a taper, it provides the least possible impedance, since it is a smooth transition. A step causes a impedance contribution.

The wake field suppressors of the mockup are identical to the ones that will go into the machine, including the connection that will attach them to the VELO RF boxes and the beam pipes at either end. The wake field suppressors consists of two sheets of copper foil, which have slits cut into them. The slits allow for mechanical movement due to opening and closing the gap between RF boxes, vacuum pumping and for allowing the WFS to take its final conical shape when installed.

These two sheets are formed into halves of a conical shell when making the transition from the RF boxes to the beam pipes. These conical tubes transition downward from the diameter of the beam pipe to the VELO RF boxes. At the VELO RF boxes there is a split in the two sheets, allowing the VELO to open while still providing some shielding.

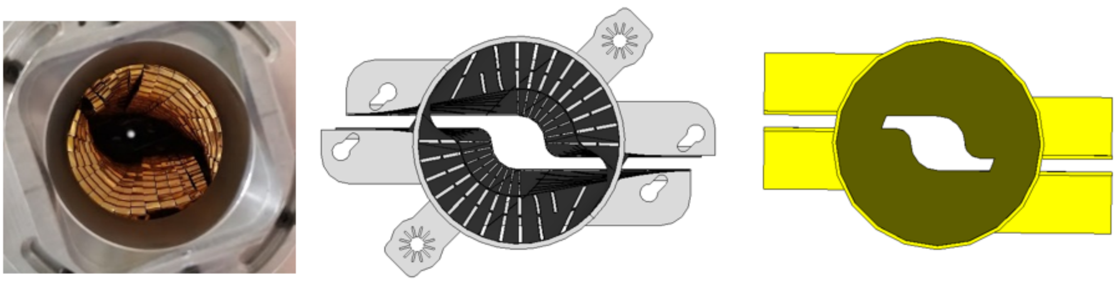

Figure 3: Comparison between the physical WFS (left), the CAD model (center) and the CST EM model (right). Note the somewhat undefined shape of the physical WFS, used both in the mockup and the to be installed VELO. Also the lack of slits on the EM model.

In the CAD and the CST EM model, the WFS is approximated as a rigid conical shape, while in implementation (both in the mockup and actual element) the geometry is somewhat undefined due to the two sheets lack of rigidity. Shown in Fig. 3 is the wake field suppressor's CAD model, the CST model and the actual suppressor in the mockup. The slits in the suppressor, seen in the CAD drawings and the actual element, are not modeled in the CST model, as their size is assumed irrelevant for the shielding functionality. The slit size compared to the wavelengths of interest are too small to have an effect electromagnetically. However, the gap between the two halves, which is enlarged when the VELO is open, has been preserved. For the open position of the WFS, the gaps between the two halves have to be modeled, along with the general shape of the suppressor (seen in Fig. 4).

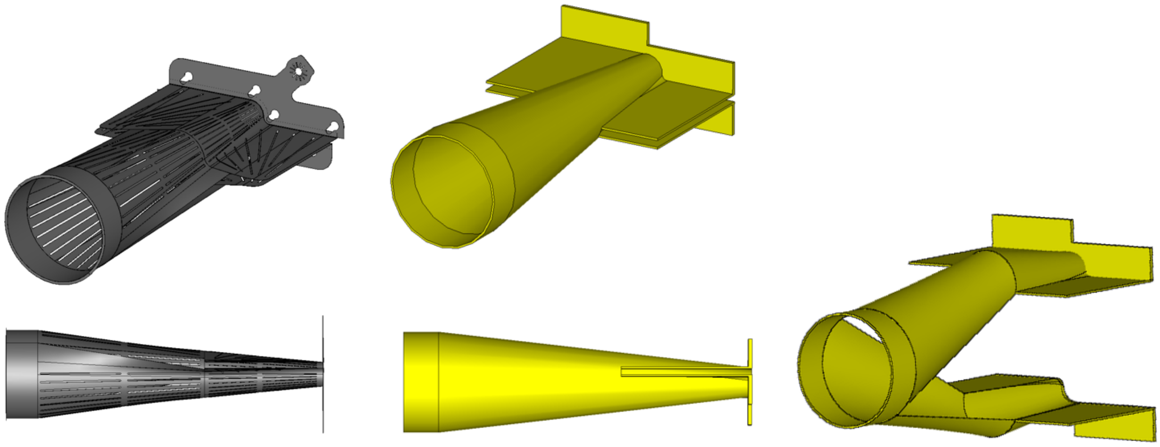

Figure 4: Comparison between the CAD model (left) and the CST EM model(right).

In summary, a number of simplifications have been made in the WFS model; the assumption of a rigid conical shape, the lack of slits and the opening gap between the halves. As with the RF boxes, these model simplifications of a complex structure such as the WFS require verification via EM measurements.

3 Measurement Results and Discussion

3.1 Measurement Setup

As discussed, the VELO mockup provides a well defined setup for characterizing via EM measurement the VELO RF boxes and the wake field suppressors. These are the two elements of the VELO whose complex geometry in EM simulation require experimental verification.

To measure the longitudinal impedance of the VELO mockup, a measurement using a single wire in transmission was performed [4] using a vector network analyzer (VNA) to measure the S-Parameters (scattering parameters). The VELO mockup was measured up to 1 GHz, since at higher frequencies the wire measurement encounters difficulties and seems to lose accuracy. This is due to the wavelength becoming smaller than most of the geometries. Additionally the wire itself will start resonating (quarter wavelength resonance is roughly 800 MHz) DETAILS!

For the wire measurements, it is necessary to match the characteristic impedance of the VELO mockup to the 50 ohm characteristic impedance of the VNA. The characteristic impedance of the mockup was calculated using a simplified model that experiences a TEM propagation mode with the wire acting as the center conductor. Thus, with the central wire as the center conductor and the VELO RF boxes approximated as two parallel plates, the characteristic impedance for a stripline is taken into account, with its characteristic impedance calculated as 275 ohms using CST simulations.

For matching the VNA (50 ohms) to the structure (275 ohms), employing a series resistor was the simplest solution, since a complex matching network would be difficult to implement and its performance would vary over the measurement frequency range. Thus a 225 ohm series matching resistor was added to either end of the wire, contained within the measurement box. For the measurement wire, copper beryllium (CuBe) wire of 0.5 mm diameter is used. The small diameter is to reduce the coupling to

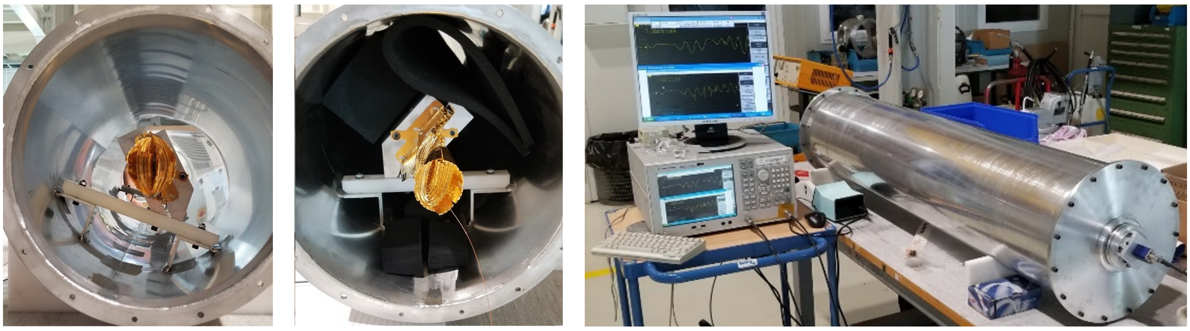

Figure 5: Photos of the VELO mockup (left) and with the absorbing foam inserted (center) and the entire measurement setup (right).

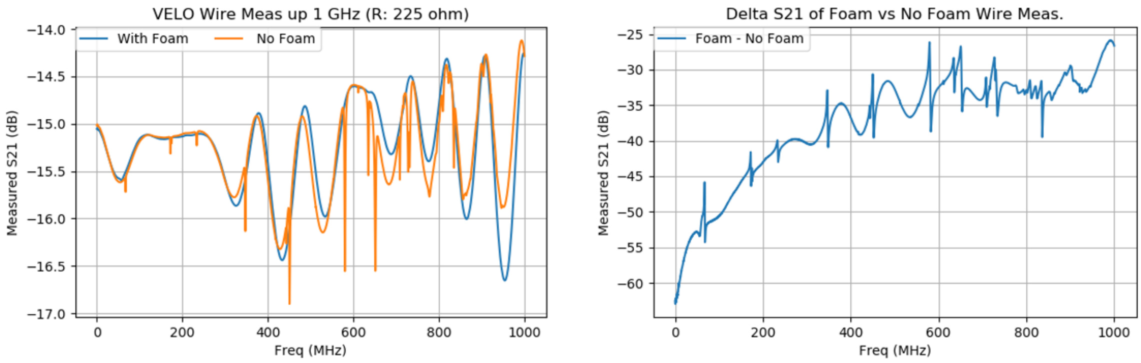

Figure 6: Measured S-Parameters of the VELO mockup, plotting both with and without absorber foam.

the modes as much as possible, to avoid disturbing the EM fields. The benefit of copper beryllium over normal copper is the increased tensile strength, necessary since the wire is pulled taut. A pure copper wire would stretch when used over the same length.

Initial measurements were done with the VELO RF boxes in the closed position, producing a response with a number of resonances. Absorber foam was added to disentangle any potential resonant modes that are due to the tank from any modes from modes of the actual VELO setup. The entire measurement setup, including the mockup with and without foam is shown in Fig. 5. The S-Parameter results of the mockup, both with and without the absorber foam, are shown overlaid in Fig. 6, clearly indicating the resonance peaks disappearing due to the presence of the absorber foam. This allows firstly to identify these resonances as tank modes and secondly indicates that even with the VELO in the closed position there is still coupling from within the RF boxes to the surrounding area within the tank. Since even in the closed position, there is still a gap between the VELO RF boxes.

Measurements of the RF boxes in the open position did not yield usable results. There is simply too much coupling to the surrounding tank to make a useful measurement. Similarly, completely removing the wakefield suppressors resulted in the mockup tank resonating with a variety of modes. Thus in both these cases there is massive coupling to the outer tank and large amounts of resonant modes are seen.

3.2 Impedance post-processing

For both the wire measurements of longitudinal impedance measurements and the simulations of the measurement setup, Python-based post processing was performed to determine the longitudinal impedance using the log formula [4]. To calculate the impedance of the structure it is necessary to use a reference line's S-Parameters to correct the measured S-Parameters, accounting for the structure length and losses due to the matching resistors.

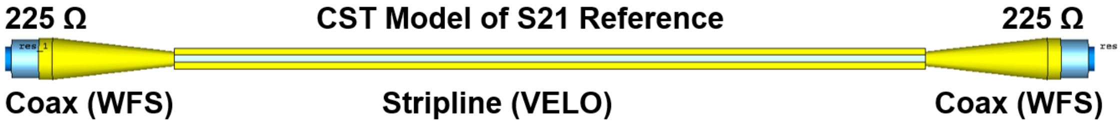

Figure 7: The EM model used in CST to generate the reference data used to calculate the longitudinal impedance in postprocessing.

The reference line's S-Parameters were extracted from CST EM simulations of the coaxial - stripline - coaxial structure, shown in Fig. 7. The strip line section represents the RF boxes of the VELO, with the 1 mm gap corresponding to the closed VELO position. The coaxial structures on either end correspond to the wake field suppressors, following their generally conical shape. The structures start at a larger radius, the beginning of the vacuum tank, where it would be connected to the beam pipe and then tapering down to meet the aperture of the RF boxes. The center conductor for both the stripline and coaxial line approximations is the measurement wire. This reference data is used for the longitudinal impedance calculation using the log formula for all the wire measurement and simulations presented.

3.3 Simulations with Foam Absorber

Note that the objective of simulating the VELO mockup with foam absorber was not to copy exactly the properties, size and positioning of the measured foam. The intention is that any modes present inside the tank are damped away and only the longitudinal impedance of the RF boxes is seen. Thus implementing the foam in simulation can be done in a more general manner. Geometrically the absorber is added to the model as cladding on the vacuum tank, with a outer diameter of 156 mm (same as the tank) and a inner diameter of 100 mm, completely encasing the RF boxes and WFS's of the mockup. The absorber material chosen to approximate the foam of the measurement setup was chosen to have an extremely high magnetic loss tangent (6000 at 1 MHz, 5 at 1 GHz), in order to completely damp any EM modes exposed to it. The experimental setup of the wire with matching resistors was implemented in simulation. Just as with the measured S-Parameters, the simulated S-Parameters are then transformed to longitudinal impedance values using the previously discussed post-processing. Additionally CST wake field simulations were performed of the mockup without the absorber foam.

The simulation results of the mockup without absorber foam show the same generally broadband, with occasional resonances, longitudinal impedance that was observed in measurement. Simulating the wire measurement with foam absorber in the mockup produced the same damping of the resonance peaks as in measurement. Plots of the longitudinal impedance of both of these cases, along with the measurement results, are shown in Fig. 8.

In summary, the generally broadband impedance, with occasional resonances, has been seen in measurement and with two different simulations solvers; S-Parameter simulations of the wire measurement and wake field simulations. More importantly, it was demonstrated, both in measurement and simulation, that these resonant modes are occurring in the vacuum tank around the RF boxes. These resonances are thus irrelevant in regards to the true installation.

Thus the effect of the VELO's RF boxes is confirmed as primarily broadband with the mockup in the closed position, with a slight coupling to the surrounding vacuum tank space. Additionally the EM model of the VELO RF boxes and wake field suppressors is well benchmarked, allowing the same calculation method to be used for simulations of the complete VELO in the true installation geometry (Fig. 9).

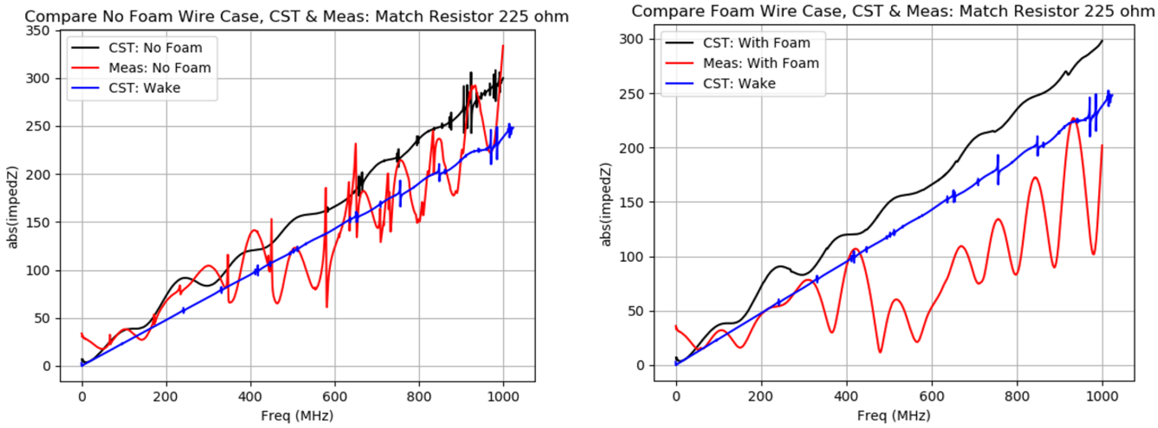

Figure 8: Longitudinal impedance from S-Parameter wire simulations and measurements of the mockup without (left) and with (right) absorbing foam. Note the wake field result plotted is the mockup without the absorber foam for both cases. With the foam present all narrow band resonances disappear

4 Complete LHCb VELO Simulations

With the VELO RF boxes and wake field supressors EM models verified via measurement of the mockup, an EM model of the complete LHCb VELO was created, seen in Fig. 9. The complete VELO was then simulated in the configuration of a wire measurement, in both the open and closed position. These results were then used to calculate the longitudinal impedance, as done with the mockup. The S-Parameters and impedance are shown in Fig. 10.

The results in the closed position is similar behavior, an overall broadband response with a few resonant modes on the broadband profile, to that of the simulated and measured VELO mockup, as to be expected. Once again it is important to note that in the closed position, the beam primarily sees the broadband impedance of the VELO RF boxes and there is little coupling to the surrounding vacuum volume. Once the VELO is opened, the broadband impedance is no longer present and is replaced by a multitude of resonance peaks. These resonant modes are present in the surrounding space within the vacuum tank, since in the open position the gap between the RF boxes and WFS halves is larger, resulting in increased coupling to these modes. These highly resonant modes could couple to the beam spectrum and produce beam-induced heating of the components, which requires a thermal analysis. For the VELO with the SMOG2 device in the open position, the heating analysis is presented in [5]

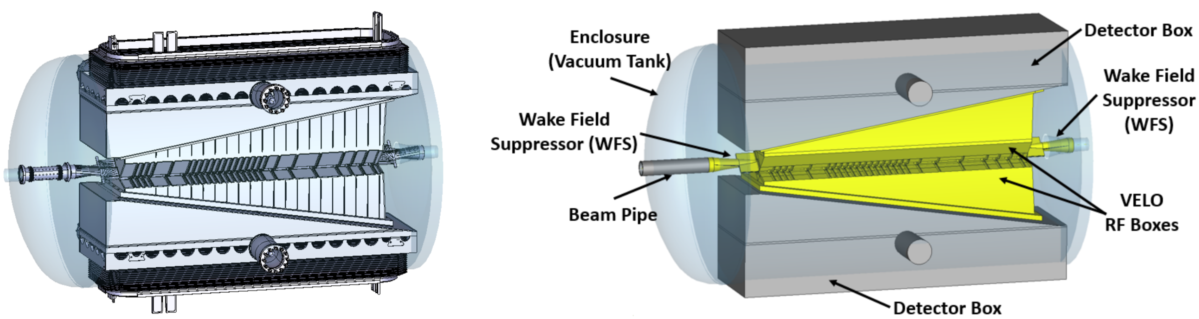

Figure 9: Top views of the CAD model (left) and the simplified CST EM model (right) of the complete LHCb VELO.

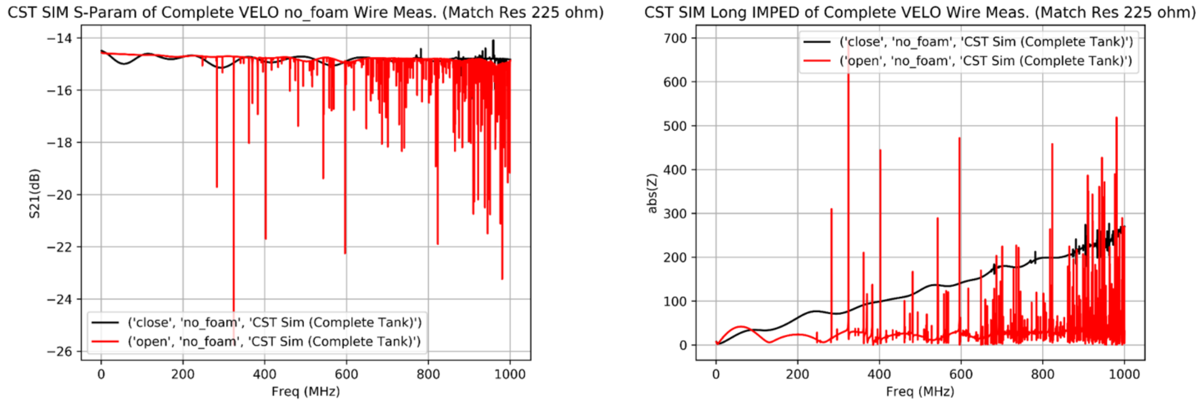

Figure 10: Simulation result of the complete LHCb VELO with the insertion loss of the complete VELO (left) and the resultant longitudinal impedance (right) for the VELO in the open and closed position.

5 Results and Conclusions

It is shown that in the closed position the RF boxes of the VELO represent a broadband impedance. Any resonant modes that were seen in measurement or simulation are occurring in the area surrounding the RF boxes, within the tank. The broadband behavior was observed in both the measurements and simulations by comparing the mockup with and without the damping foam. Since the foam was placed in the tank volume surrounding the RF boxes, only modes with field in that area would be damped.

The EM model of the RF boxes and the WFS was benchmarked, thus allowing for further, more detailed, simulations of the entire LHCb VELO. The simulations of the entire LHCb VELO in the closed position showed that again the impedance is dominated by the broadband impedance of the RF boxes. Once the VELO is in the open position, the behaviour changes, the response is no longer broadband and a number of resonant modes appear instead.

Future analysis includes investigating these modes with the eigenmode solver, which in turn can be used to evaluate the potential beam induced heating and determination of localized heating of the physical elements(see [5]).

Acknowledgements

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