COUPLER STRUCTURES FOR THE LHC BEAM PIPE WAVEGUIDE MODE REFLECTOMETER

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Abstract

The LHC reflectometer will be used to detect and localise obstacles and other kinds of discontinuities in the LHC beam screen. An important part of this device is the RF coupler element, which provides the interface between the beam screen and the measurement equipment. Two different scenarios of operation are considered. The first option consists in carrying out measurements during assembly by directly branching a coupler to the end of the beam screen. The second one is a permanent installation to be used in situ requiring a different kind of coupler to keep the aperture free. The goal is to achieve a reasonably well matched spurious mode-free excitation over a 25% bandwidth for the TM_{01} and the TE_{c11} mode[1], respectively. The fulfillment of the required features is severely complicated by space and material restrictions arising mainly from vacuum and installation constraints.

INTRODUCTION

For the LHC reflectometer *two modes of operation* are envisaged:

- The *assembly* version: During construction of the LHC, fast inspections of each dipole magnet (15 m) as well as checks of longer sections such as two cells (214 m) or more are foreseen. The measurements have to be performed at ambient temperature and in air. Two types of special coupling structures will be mounted directly onto the open end of the beam screen in place of a plug-in module.
- The *in situ* version: After completion of the LHC, measurements will be done over the length of half an arc, corresponding to about 1250 m. Thus, looking from both sides, an entire arc can be covered. The measurements can be performed after cool-down to increase the spatial range, since the attenuation is expected to decrease considerably for operation at 20 K. This option requires the permanent installation of 32 dedicated couplers since standard LHC button pick-ups do not meet the performance requirements.

Special coupling structures for both versions were designed and simulated using the CST Microwave Studio package.

[1] The index c stands for the cosine (horizontal) polarisation of the TE_{11} mode

Waveguide modes on the beam screen

In recent studies [1, 2] the attenuation as well as the cut-off frequencies of the first waveguide modes on the LHC beam screen have been determined. For reflectometer operation the first TE mode (TE_{c11}) and the first TM mode (TM_{01}) will be used. These modes are suitable since they show low attenuation (about 0.07 dB/m) and are rather easy to excite. Furthermore they do not couple much to other modes in a sufficiently wide frequency range.
The lower frequency limit is given by the cut-off frequency f_c of the respective mode. As a rule of thumb, a waveguide should not be operated below $1.1 f_c$ to $1.2 f_c$ to avoid intolerably high dispersion and attenuation. This leads to lower frequency limits of about $f_{min,TE} = 4.0$ GHz for the TE_{c11} mode and $f_{min,TM} = 6.0$ GHz for the TM_{01} mode, respectively.
The upper frequency bound is determined by the cut-off frequencies of the higher order modes that are spuriously excited. As will be seen later on, the obtainable frequency ranges are between 4 and 6 to 7.5 GHz for the TE mode and between 6 and 8 to 10.5 GHz for the TM mode, depending on the performance of the mode launcher. A spatial resolution[2] approaching 8 cm is achieved for reflectometer operation with 3 GHz bandwidth.

THE ASSEMBLY VERSION

The mode launchers of the assembly version will be mounted directly on the beam screen during the construction of LHC. Since the beam screen is only accessible between the dipoles, the coupling elements have to be designed to fit in the gap where the installation of the plug-in modules (interconnects) is foreseen. There are no other special requirements, apart from surface cleanness.

TM mode launcher

In a waveguide with circular cross-section, the field pattern of the TM_{01} mode is perfectly rotationally symmetric and similar to that of the TEM mode. This inspired the use of a rotationally symmetric transition from a coaxial line to a circular waveguide. A coaxial cone transition as described in [3] was used to increase the diameter of the coaxial feed line. In order to excite the TM_{01} mode in the waveguide, the inner conductor must end at a certain location. A low reflection excitation was achieved by minimising S_{11} as a function of the length of the inner conductor

[2] 6 dB pulse width using a Bessel FFT window with $\beta = 11$

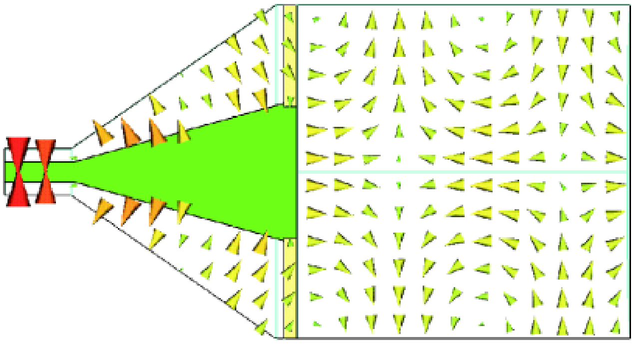


Figure 1: The field pattern of the TM mode at 7.5 GHz. On the left side is the coaxial port, on the right the circular waveguide. The green material as well as the material surrounding the structure was defined as a perfect conductor, while yellow represents the dielectric disc.

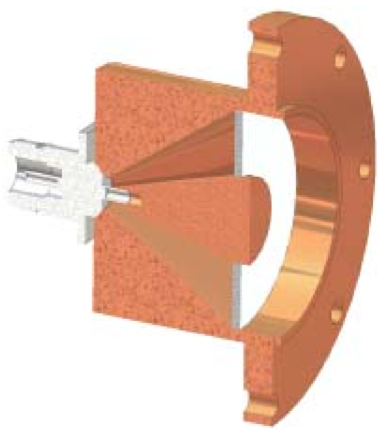
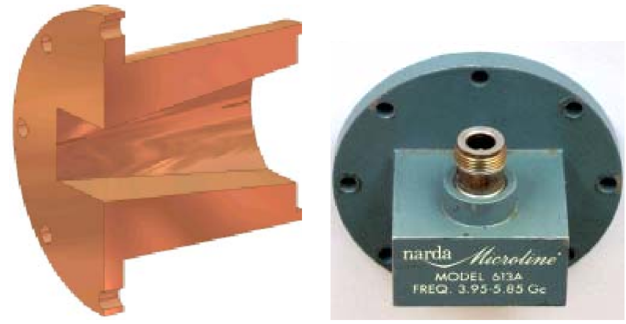


Figure 2: Mechanical drawing of the TM mode coupler. The measurement equipment is connected on the type N connector to the left, while on the right side a customized transition to the beam screen cross-section can be mounted.

stub as well as the opening angle of the cone transition. This kind of geometry was used a for high power application in [4]. In Fig. 1 the simulated field pattern in shown. An additional dielectric disc was inserted to hold the inner conductor in place.

For an ideal rotational symmetry the first higher order mode that can be excited is the $\mathrm{TM}_{\mathbf{02}}$ mode with a cut-off frequency of 10.9 GHz. Therefore potentially the usable bandwidth is very large, ranging from 6 to about 10.5 GHz. After the excitation of the TM_{01} mode in a circular waveguide, a transition to the beam screen cross-section is needed. This part proved less critical in terms of reflection than in terms of mode conversion. In fact, for reasonably short transitions with lengths between 50 to 100 mm, the excitation of the TE_{c21} mode, which is similar to the TE_{11} in a rectangular waveguide, is of the order of -20 dB. It turned out that the impact of mode conversion does not depend much on the length of the transition.
For the entire coupling module the simulations gave rather



(a) C-band waveguide adapter, specified frequency range: 3.95 to 5.85 GHz

(b) Customized transition from the rectangular to the beam screen cross-section

Figure 3: The two parts of the TE mode coupler

promising results, predicting an average S_{11} of roughly -28 dB. In practice, however, an S_{11} of -20 dB was found, which is still very satisfying. The discrepancy appears to be due to mechanical tolerances in the region where the coaxial line starts to widen. Since the cross-section is small at this location, tiny mechanical misalignments can have a considerable impact on the overall reflection coefficient.

TE mode launcher

A very common way to excite the fundamental TE_{10} mode in rectangular waveguide is to let the inner conductor of a coaxial line extend into the waveguide from the longer side. This would be possible for the beam screen, too. However, this kind of mode launcher excites the TM_{01} mode as well. Therefore, in order to maximize the usable bandwidth, a two-step approach was used. First, the TE_{10} mode was excited in a customary C-band coax to rectangular waveguide adapter. This component is flatter than the beam screen and can thus be used without spurious modes up to roughly 7.5 GHz. Then the wave is guided into the beam screen by a customized transition (Fig. 3).
As for the TM mode coupler this transition is not very critical in terms of S_{11}, but it is susceptible to mode conversion. The overall performance of the TE mode coupler depends thus on the quality of the commercial rectangular mode launcher as well as on the customised transition. For operation between 4.0 and 7.0 GHz an S_{11} as low as -22 dB was measured on a prototype.

THE IN SITU VERSION

The in situ version of the reflectometer will be used for measurements of the LHC cold arcs. For this purpose, coupling structures will be installed at the extremities of each arc in the warm section. After cool-down the copper resistivity should be small enough to allow operation in reflection mode over at least half an arc's length. In addition to obstacle detection, other interesting applications can be thought of, in particular

- Transmission measurements over one arc after cool-down. This allows evalutation of the effective sur-

face impedance variation of the beam screen in the microwave range as a function of the temperature and the magnetic field (magnetoresistive effect).
- Electron cloud diagnostics
- Use of the buttons as clearing electrodes for charged particles by application of a high voltage DC bias (several kV).

In order to provide the necessary "directivity" the couplers are to be installed adjacent to the sector valves at the end of the arc. When carrying out reflectometer measurements the sector valve has to be closed. Vacuum and beam dynamics requirements pose severe space and material constraints. For this reason a very compact design is desirable. The most critical parameter turned out to be the free beam pipe aperture, which must be larger than 55 mm if no special mechanical alignment is used [5].

Modes on the circular beam pipe

At the location envisaged for coupler installation the beam pipe is circular with a diameter of 63 mm, compared to a radial beam screen aperture of 44.2 mm in the cold arcs. Obviously, in a given frequency range many more modes will propagate in the large beam pipe than in the beam screen where we want to perform the actual measurements. For reflectometer operation the TM_{01} mode will be preferred on account of its low radiation losses through the slots.

Coupler geometries

In order to achieve a spurious mode-free excitation, a geometry with four-fold symmetry has been chosen. For such a structure the first strongly excited higher order mode is the TE_{41} with a cut-off frequency of 8.05 GHz. Thus, a 2 GHz wide frequency range from 6 to 8 GHz is available for TM mode operation.

After having tried many different geometries in the numerical simulation, the structure with four mushroom shaped buttons has been adopted (Fig. 4). The structure is tilted by 45° with respect to the horizontal plane in order to meet space restrictions and to enhance the TE mode coupling performance. It represents a compromise between mechanical complexity and RF performance. In addition it can be used for TE modes, too, which makes it interesting for several fringe applications. If all four buttons are fed in phase, the TM mode is excited. On the other hand, a phase opposition of the top button pair and the bottom button pair gives the TE mode with vertically polarised E field (TE_{c11} in the beam screen).

This geometry was optimised for TM mode excitation taking into account a minimum free beam pipe aperture of 55 mm. As expected the S_{11} found is much higher than for the assembly couplers. The final version showed an insertion loss due to reflection of about 3 dB for the TM mode and about 6 dB for the TE mode.

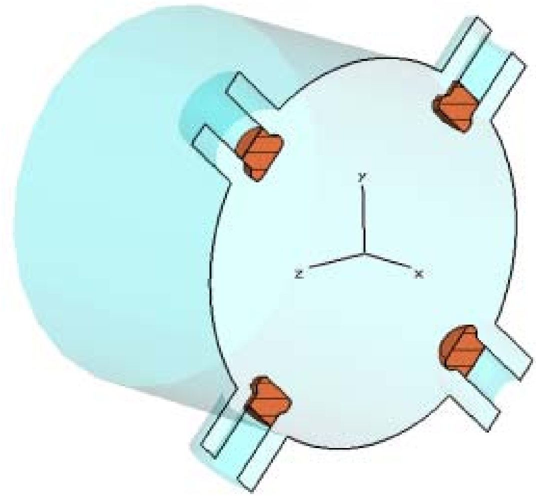


Figure 4: Geometry of the in situ coupler with the beam going along the x axis.

CONCLUSION

Coupling structures for the assembly version and for the in situ version of the LHC reflectometer have been designed and simulated. At the present time, prototypes of the assembly version couplers have been manufactured and tested, yielding very satisfying results. Concerning the in situ couplers, the design turned out to be rather delicate due to various constraints, in particular the required minimum free beam pipe aperture. However, a promising geometry has been found, namely the structure with four mushroom shaped buttons.

ACKNOWLEDGEMENTS

We would like to thank Paul Cruikshank, Noël Hilleret, Bernard Jeanneret and Raymond Monnin for important contributions, as well as Flemming Pedersen, Trevor Linnecar and the AB-RF group for support.

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