Obstacle Detection in the LHC Beampipe and Other Possible Beam Diagnostics Applications

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Motivation

In certain accelerators strange objects were found…
How to locate them without using the beam???

Is Waveguide Time Domain Reflectometry (TDR) new?

- Waveguide mode TDR has been used for more than 20 years to locate undesired deformations on long waveguides in telecommunication towers (from the ground to the antenna)
- Also it was used at ESRF to locate discontinuities (record of a profile) in their vacuum chamber during assembly

  [ref:CERN-PS 92-30 AR; Wireless impedance measurements and fault location on ESRF vacuum chamber assemblies]

Synthetic pulse TDR

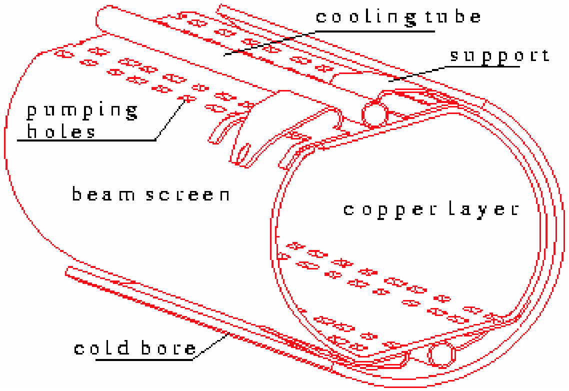
All measurements are done in the frequency domain, conversion to time domain by FFT

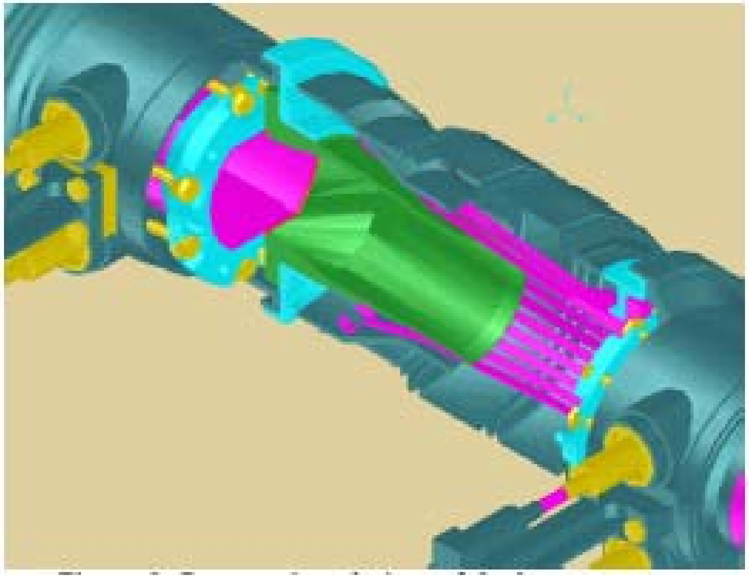
Avantages:

- A state-of-the-art vector network analyzer (VNA) can be used
- All parameters can be well controlled => good reproducibility and wide range of settings
- Waveguide calibration and dispersion compensation is possible
- High dynamic range due to frequency domain measurement

Waveguide modes on the beam-pipe

- Axial slots cut azimuthal wall currents => TE modes radiate and are thus attenuated
- Interconnects with axial conducting strips trap TE modes to some extend
- Wall currents of the TM modes are rather similar to the image current distribution of the beam itself
- Thus TM modes are almost not affected by the slots, as they have axial wall currents only





➔ TM modes have to be used

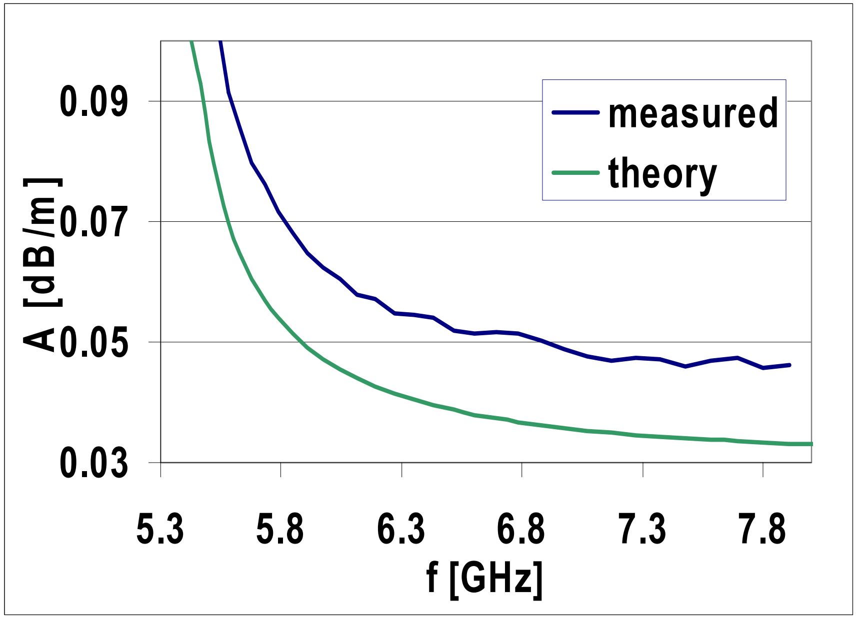
Challenges of synthetic pulse band-pass mode TDR on the beam-pipe

- Attenuation: limits the range of the reflectometer => high dynamic range of the VNA is indispensable (more than 100 dB!)
- Waveguide dispersion => step-by-step “focusing” to short sections required
- A Higher Order Waveguide mode has to be used => Mode Mixing
- Multiple reflections by interconnects: Can we look through 50 or more interconnects?

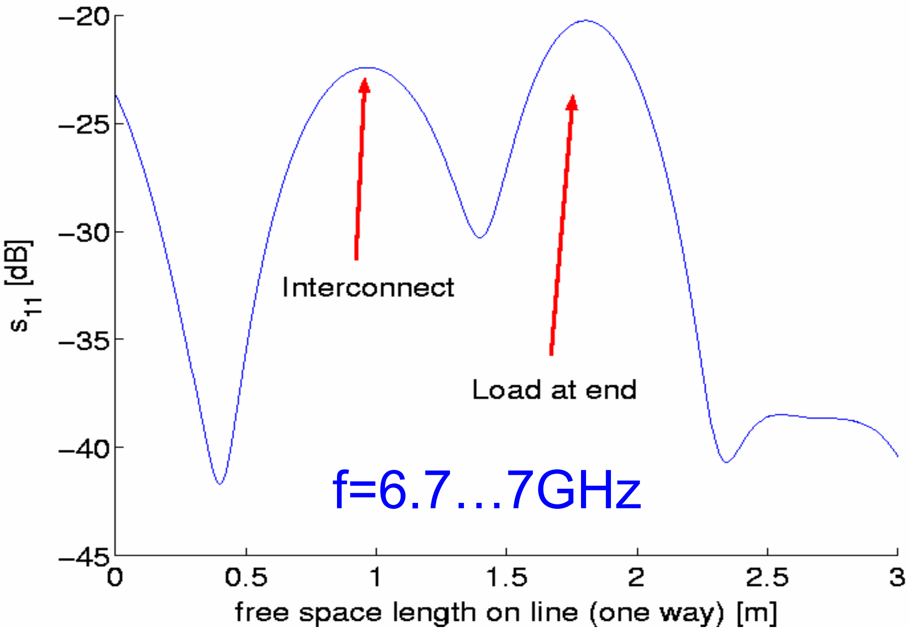
Attenuation

Two main components:

Power dissipated in the beam-pipe: 0.05dB/m at room temperature



Power reflected by the interconnects: at least 0.02dB per interconnect but may be higher (preliminary measurement, mode conversion not accouned for so far)



Estimation of range

- The dynamic range of the current VNA of about 120dB for S_{11}
- The total attenuation (including interconnects) is expected to be smaller than 0.07dB/m
- The smallest obstacle to be found (M3 nut size) should give a reflection of -40dB

⇒ attenuation budget (room temperature) = 80dB,

one-way: 40dB

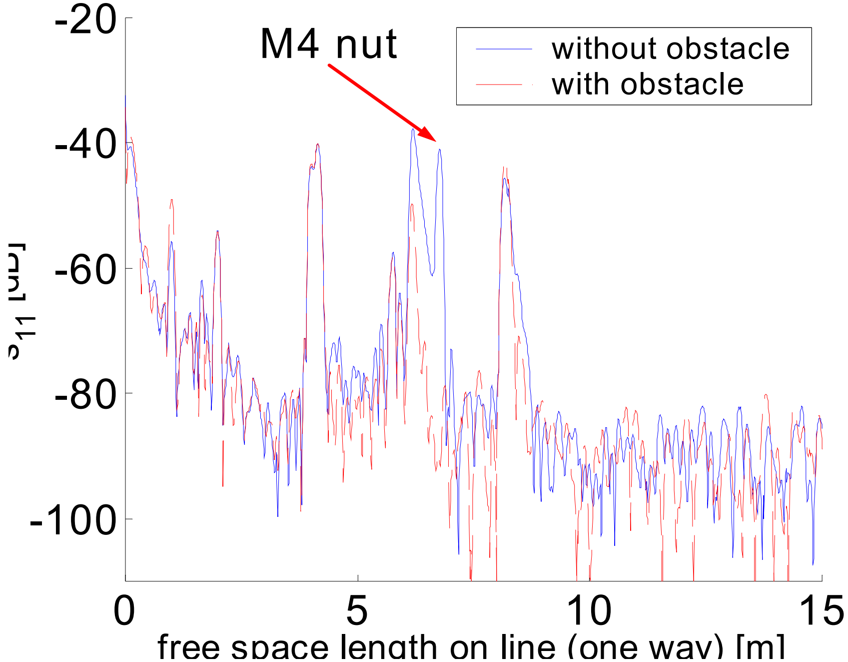
⇒ range = 600m

At low temperature (20K) the attenuation should decrease by a factor 2 to 3, allowing to cover 1 arc (~2km) in transmission mode or half an arc in reflection mode

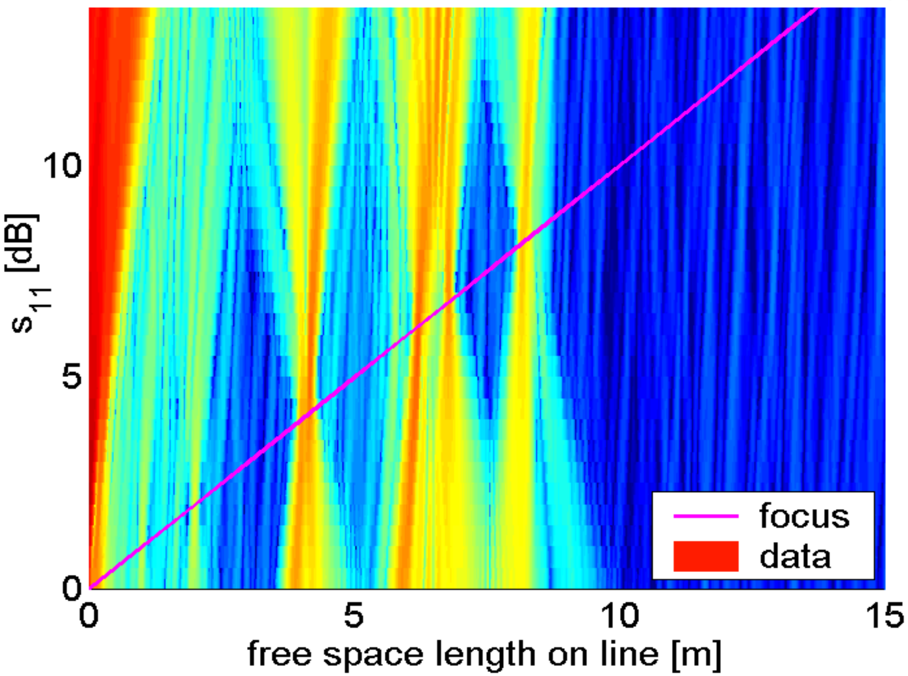
Dispersion compensation

- Step-by-step focusing
- Colored surface representation of data helps identify reflections

Measured and refined data from a 8m line with an artificial obstacle:



Red to blue: high to low amplitude of S_{11}



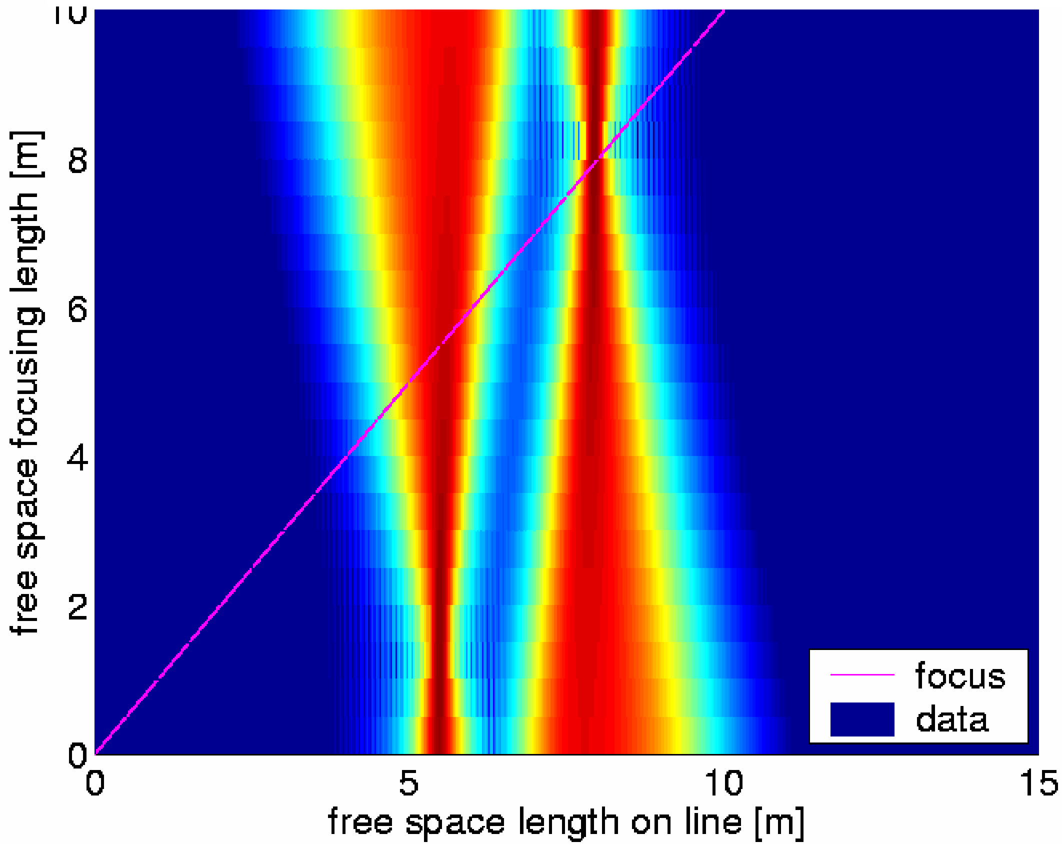
Mode Mixing

- Focusing works well just for one mode ➔ the other modes are suppressed considerably

Simulation of the TE_{c11} and the TM_{01} mode from one reflection on the beam-pipe

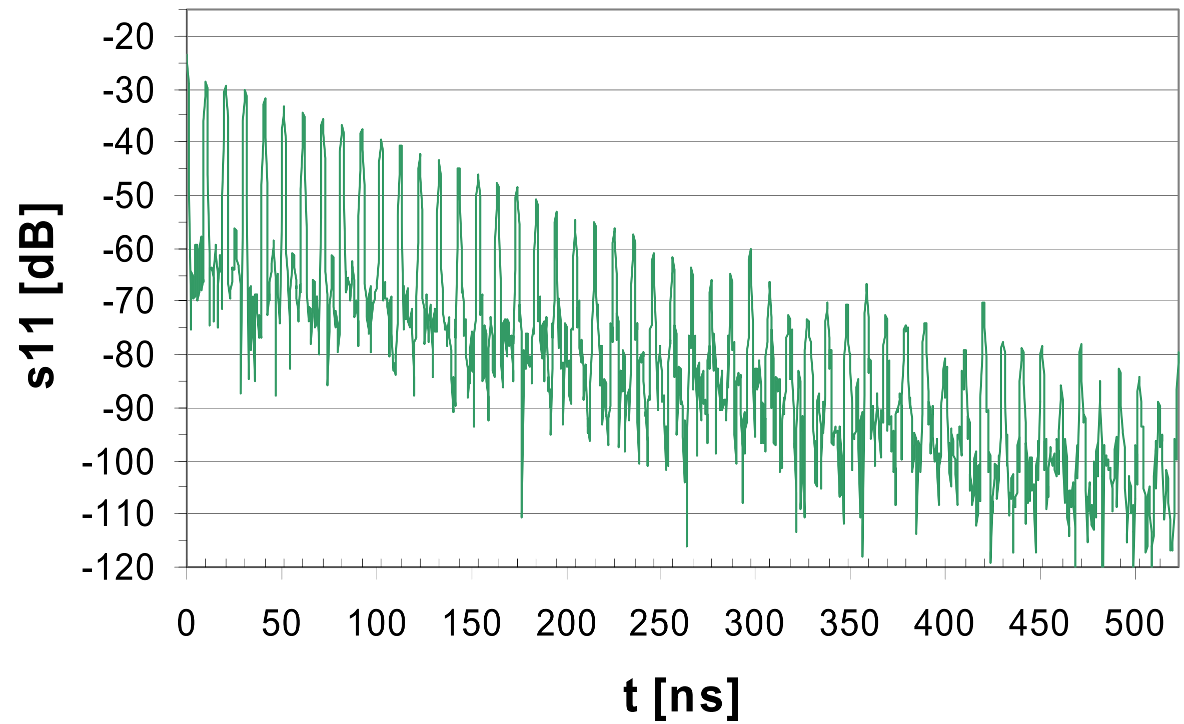
The “bad” mode is focused too early!

Red to blue: high to low amplitude of S_{11}



Multiple Reflections

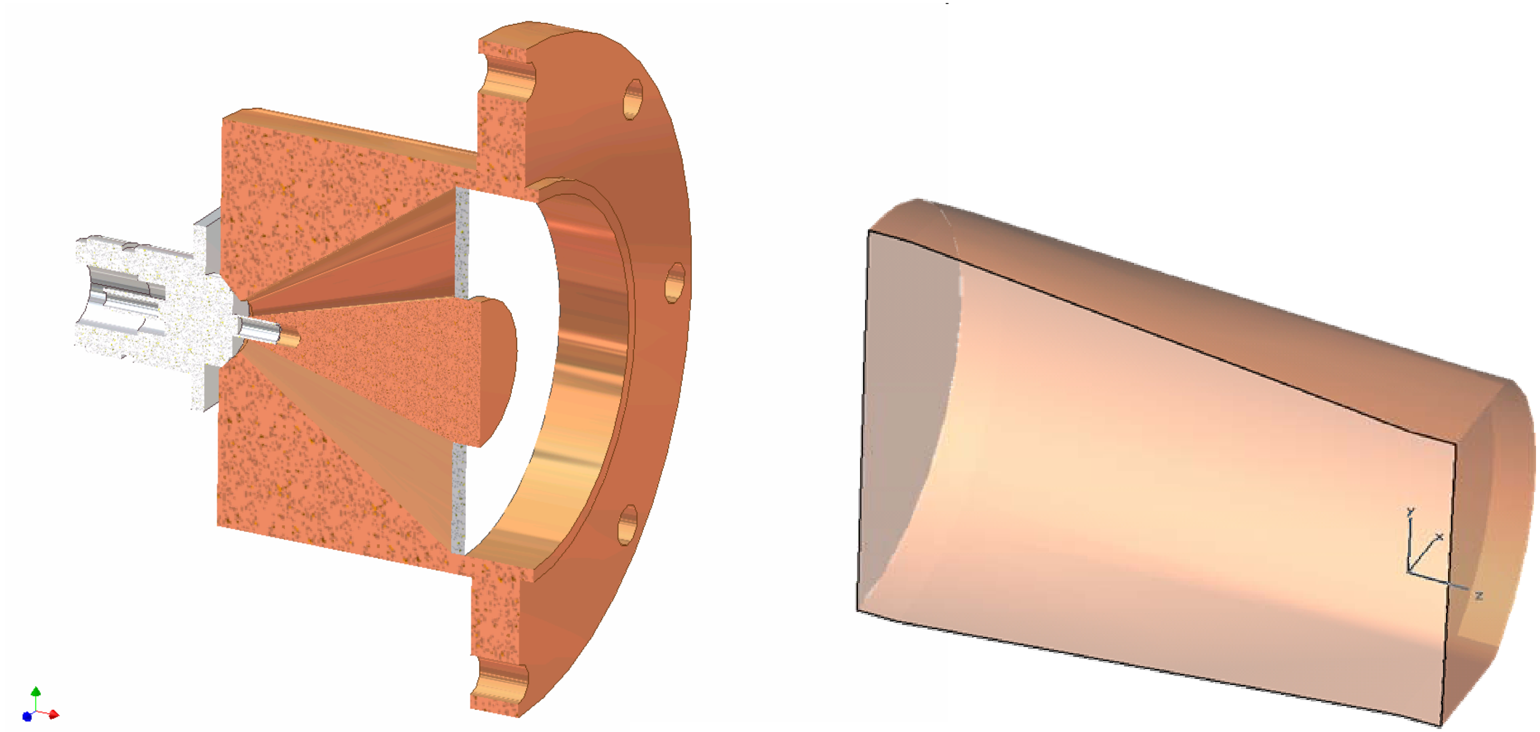
- Model measurement with 50 BNC cables
- BNC connectors between two cables simulate effect of interconnects between 2 cryomagnets (similar S_{11})



Microwave mode coupling structure for measurements during LHC assembly

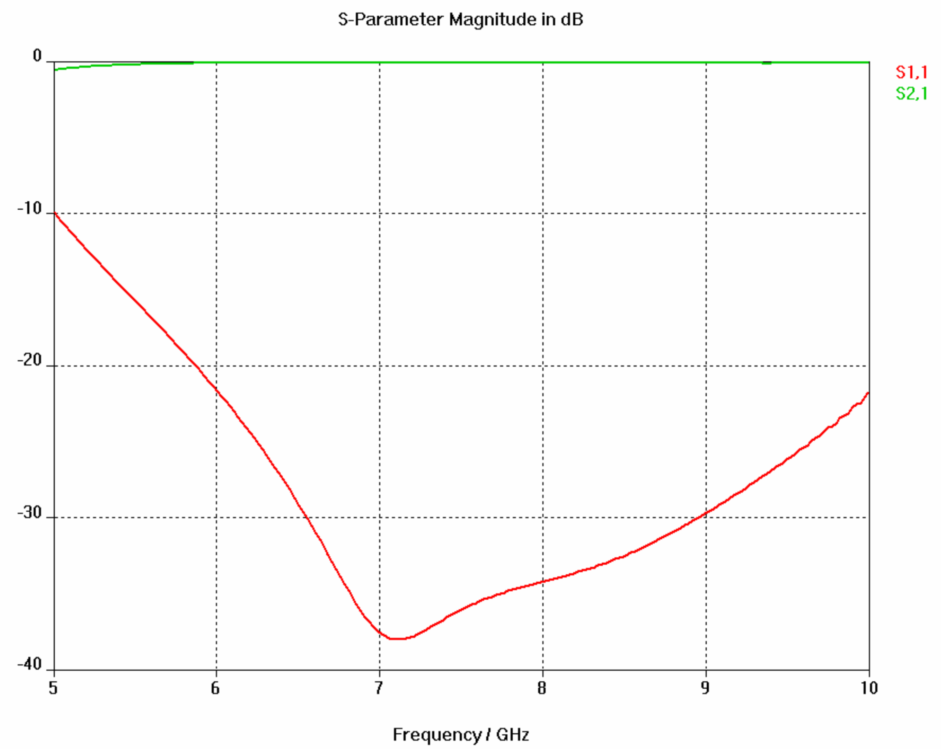
- During assembly sections of 200m length are accessible for reflectometer measurements
- Both E_{01} and H_{10} modes shall be used
- Objectives: homogeneity of beampipe, contact fingers, forgotten tools, bolts, etc.
- Only about 16cm are available between the adjacent magnets for mounting the microwave coupler
- Measurement at ambiant temperature in air
- Prototypes are under construction…

Design for E_{01} mode launcher used during assembly



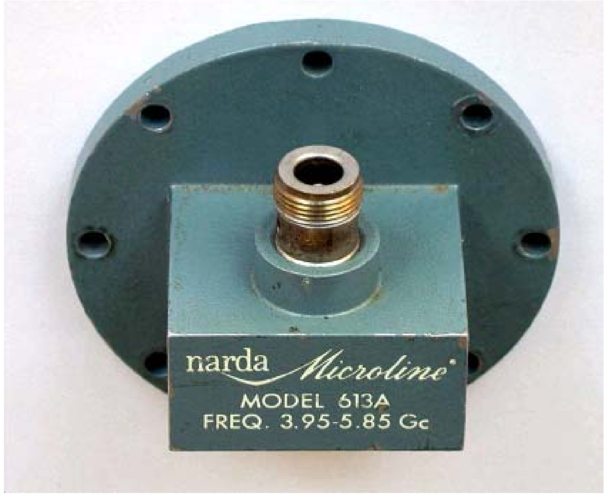
- Conversion from TEM mode on 50 Ω coax into E_{01} on circular waveguide, inspired by conical transmission line as used for low reflection diameter changes
- Transition to E_{01} on beam-pipe

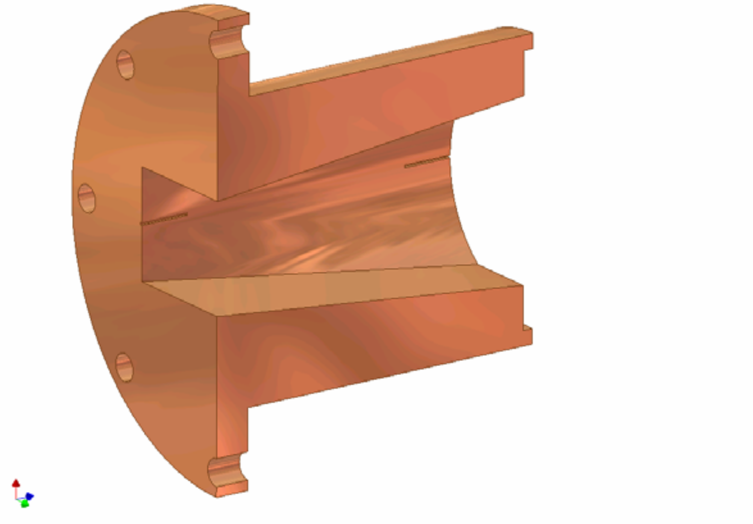
Simulated S-parameters



- Very good match over entire measurement frequency range (6 to 9 GHz)
- E_{01} cutoff in beamscreen @5.3GHz, 9GHz maximum frequency of currently available network analyser Agilent E8358A

Design for H_{10} mode launcher used during assembly

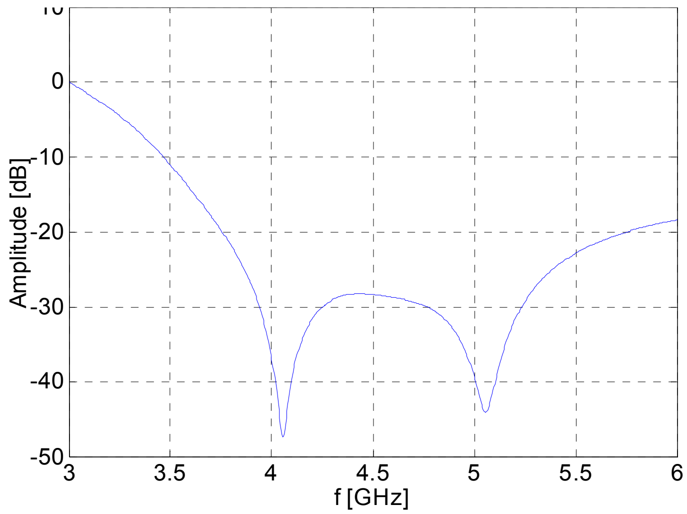




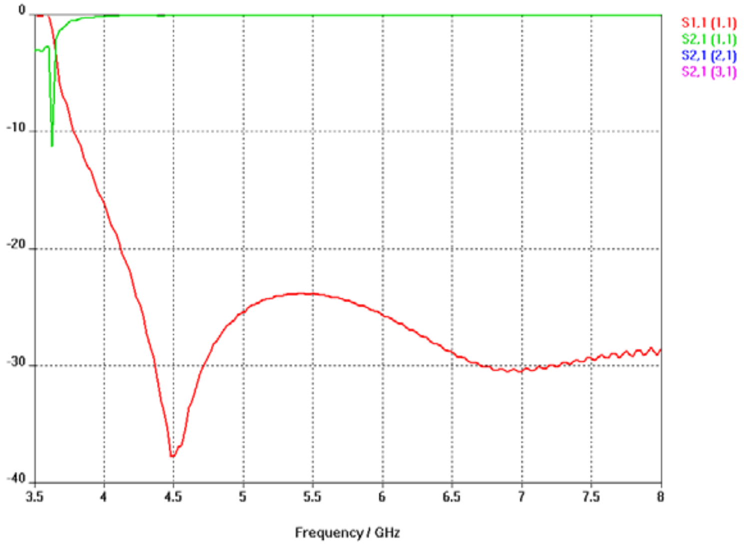
- Commercial coax to C-band waveguide (nomial frequency range: 3.95 to 5.85GHz) junction to excite rectangular H_{10} mode
- Transition to H_{c11} in beam-pipe (with the index c for cosine defining the polarization of the electric field for the H11 mode being vertical)

Simulated S-parameters

S11 of C-band coax to rectangular waveguide transition



Simulated reflection of rectangular waveguide to LHC liner transition

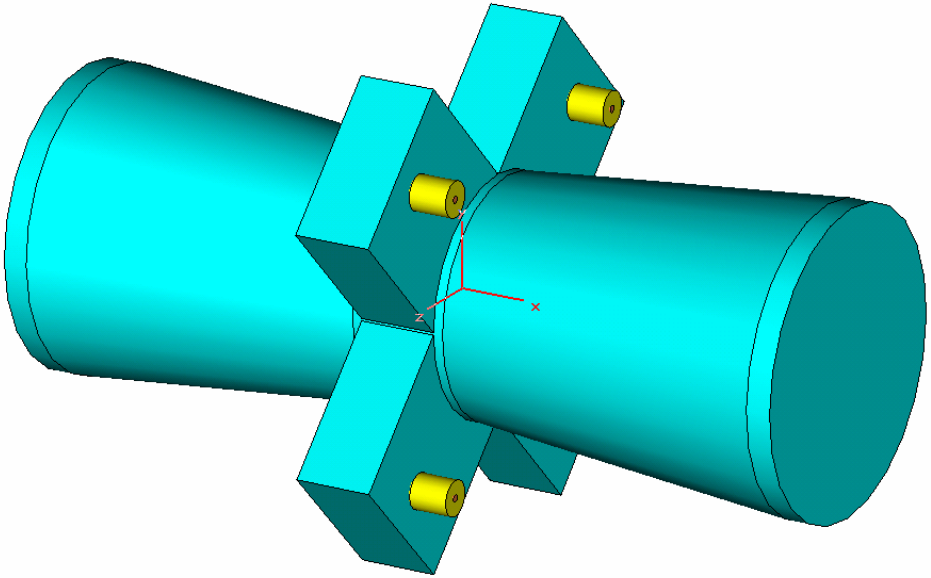


- Measurement frequency range for H_{c11} mode: 4 to 6 GHz, could be extended up to 7.5 GHz
- H_{c11} cutoff on LHC beamscreen: 3.6 GHz, upper frequency limit determined by mode conversion
- Reasonable match up to 6GHz

Microwave mode coupling structure for in situ measurements

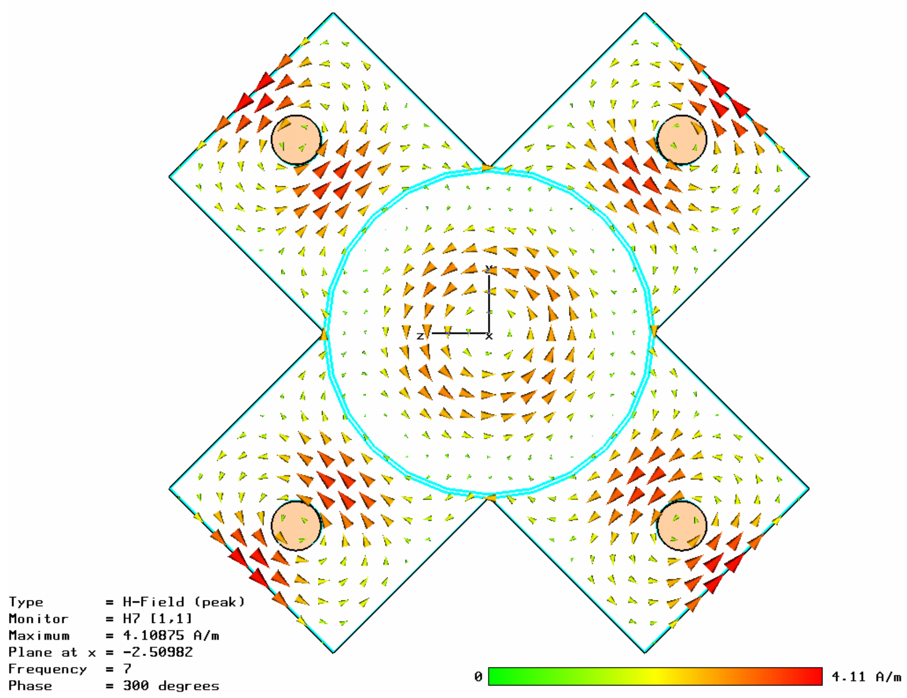
- In situ operation of the reflectometer in the LHC would be interesting
- Standard LHC buttons do not work well above 0.5GHz due to their high capacity to ground
- We would therefore need some sort of coupling structure suitable for waveguide mode excitation between 4 and 8 GHz (at the end of one arc, 32 in total)
- These structures should preferably be usable for mode-selective excitation
- They have to be close to a shutter in order to permit wave propagation in one direction only with reasonable bandwidth
- Severe space, shape and material constraints

Proposed structures (1/1)



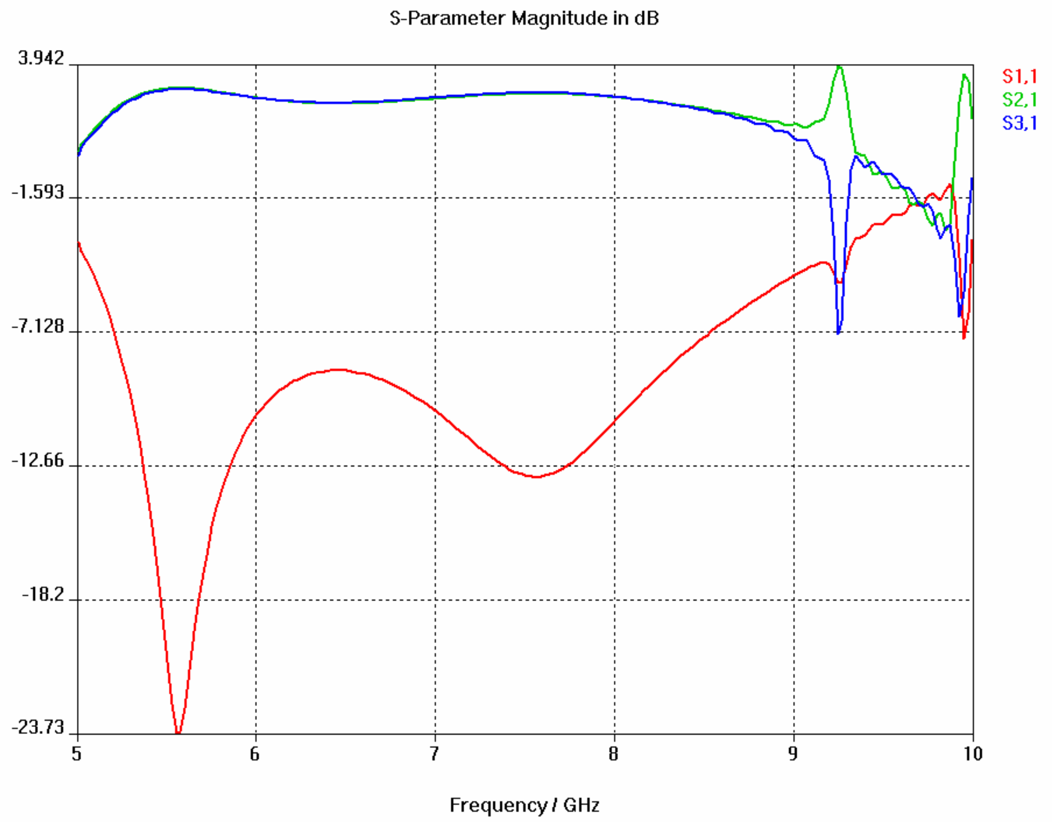
- Simulation using Microwave Studio
- Four rectangular waveguides of H_{10} type
- Reduction of beampipe diameter necessary
- Rather proper E_{01} mode excitation in beampipe, reasonably good match
- Cannot be used for excitation of H_{11} mode in beampipe

Proposed structures (1/2)



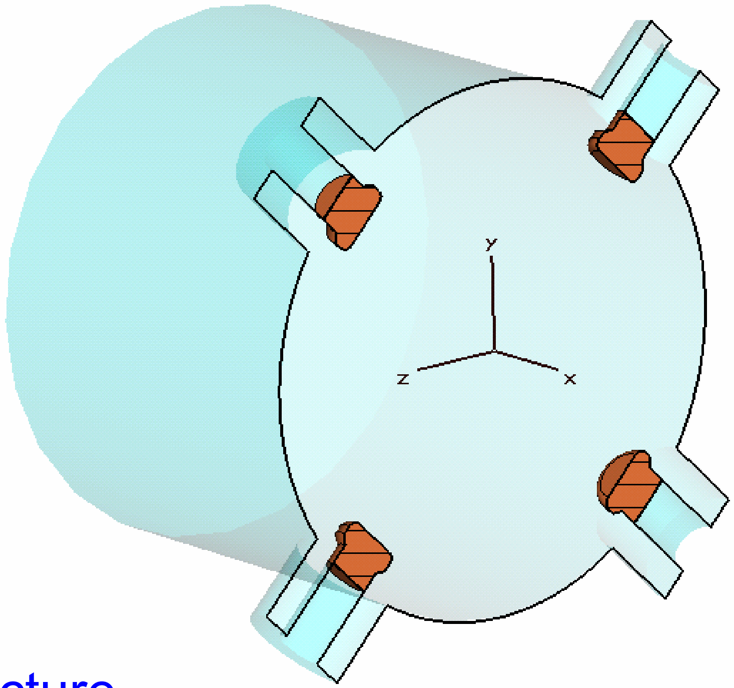
- Field pattern at 7GHz (H field)

Proposed structures (1/3)



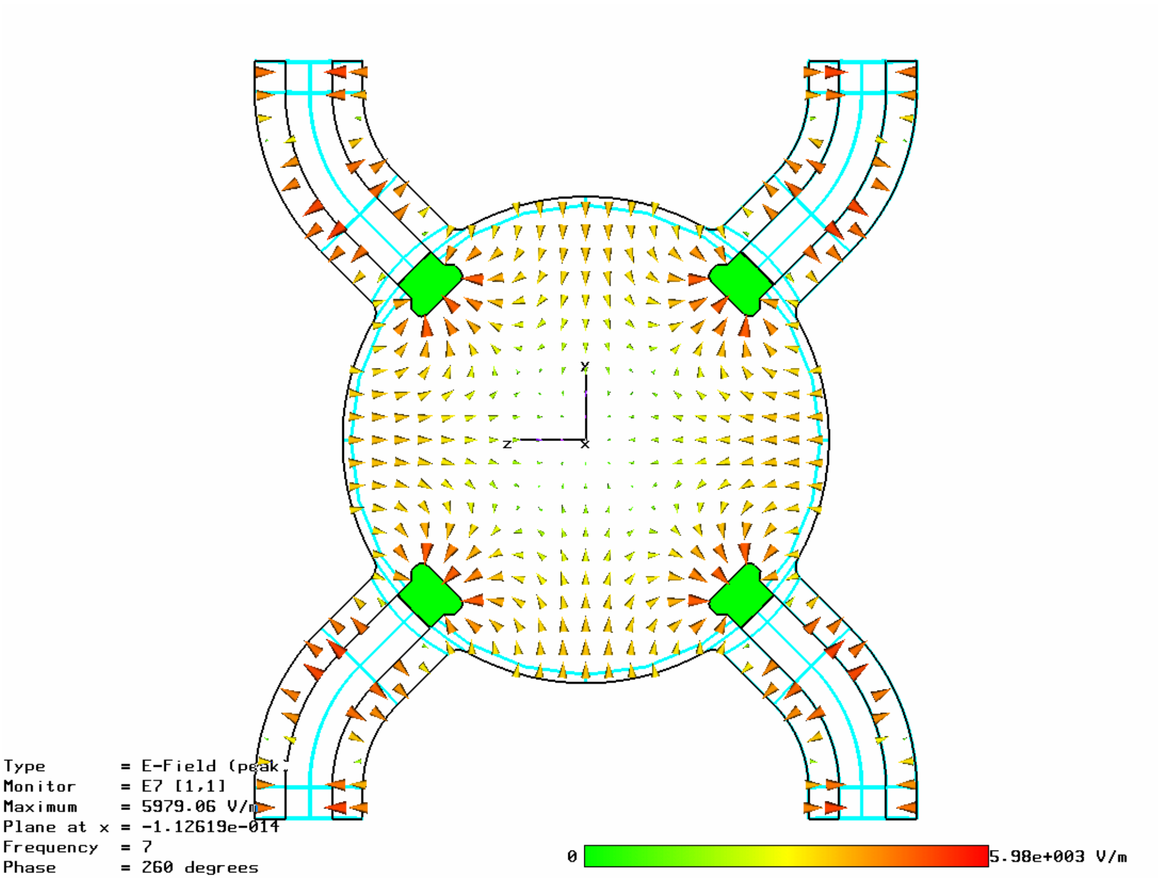
- S parameters with vacuum valve open

Proposed structures (2/1)



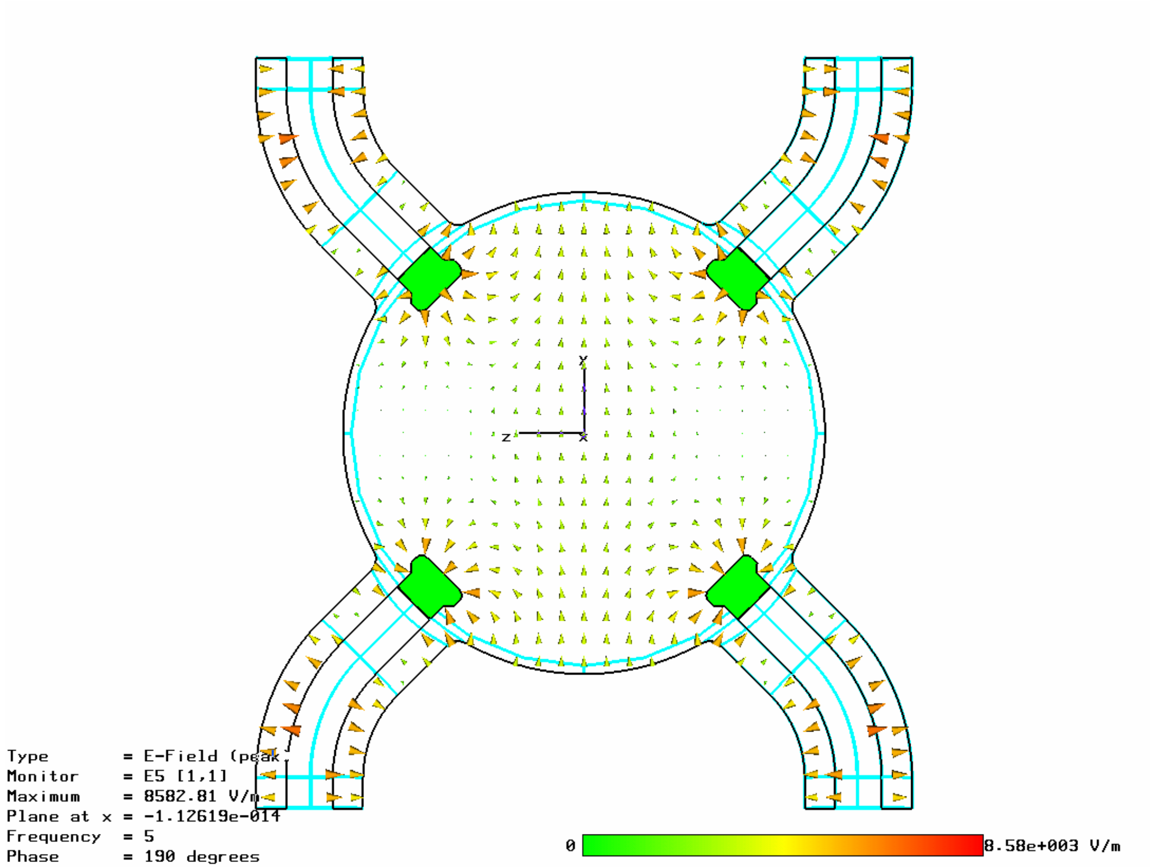
- 4 button structure
- Less complicated design than structure with waveguides
- More versatile, can be used for both E and H modes
- Much poorer E_{01} performance

Proposed structures (2/2)



- In phase excitation of all 4 buttons => E_{01} mode

Proposed structures (2/3)

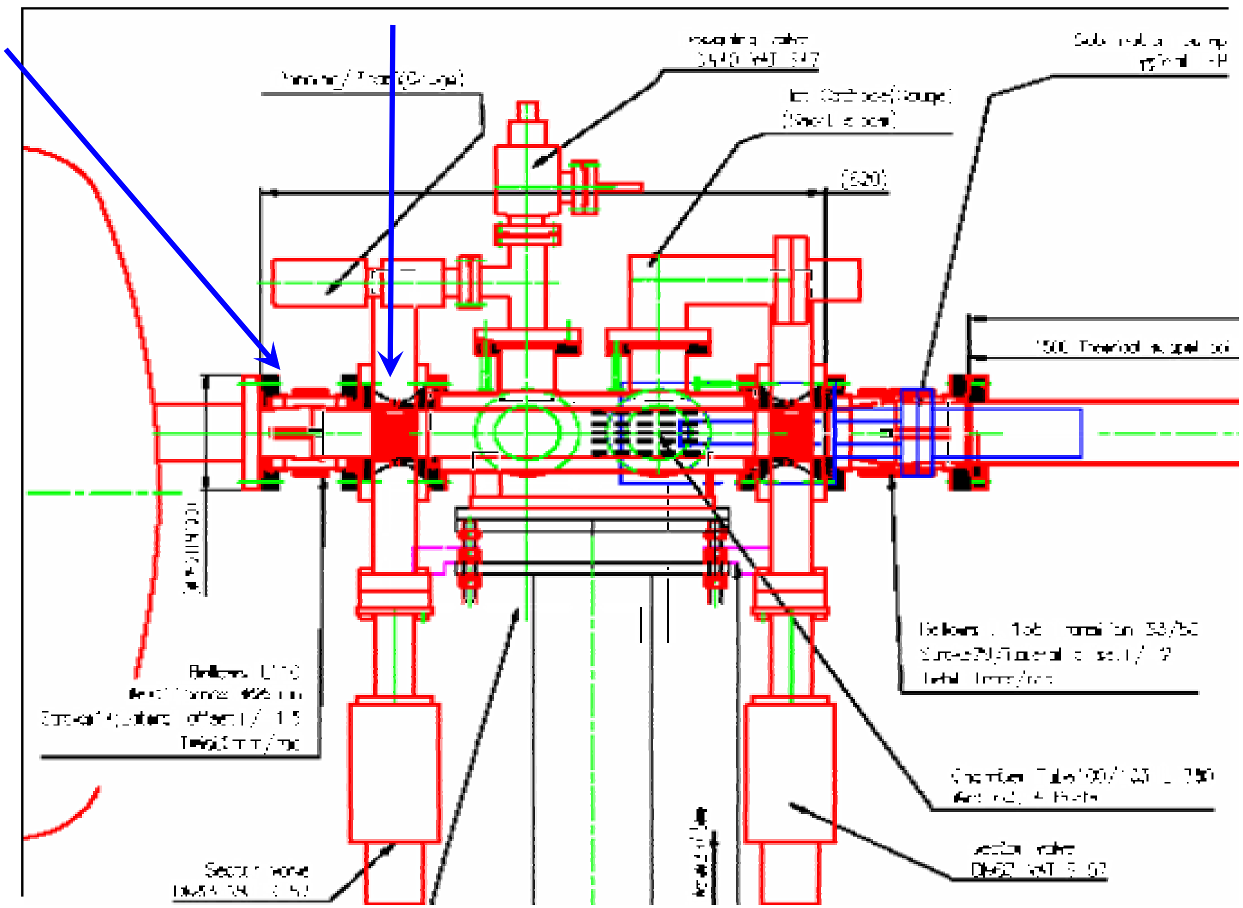


- Upper and lower buttons excited in opposite phase => H_{11} mode

Coupler Installation

Envisaged Location of Coupler

Vacuum valve



Potential Applications for Beam Diagnostics

- Schottky diagnostics
  - TEM-like response, longitudinal and transverse plane (2-8 GHz or beyond)
  - Waveguide mode response (from 5.5GHz for TM and from 3.6GHz for TE modes) [wakefield]
    - Caution: it may be difficult to separate TEM-like and wakefield reponse on the same button (recent CTF-experience!)
- Other potential applications
  - Coherent synchrotron radiation (waveguide mode excitation) from the beam?
  - Measurement of electron cloud density via S_{21} (?!?)
  - Electron cloud shaker?

Conclusion

- A detection of various kinds of obstacles in the beam-pipe appears to be feasible.
- During assembly, at room temperature, it should be possible to cover about 600m
- The range should increase to 1000m and beyond for low temperature operation, if current estimations turn out to be correct.
- Two different kinds of mode launchers have been designed:
  - During assembly, measurements will be done using both E01 and Hc11 modes
  - 3D EM Simulation using Microwave Studio show rather promising results in terms of match and undesired mode rejection
  - Various coupler structures for in situ operation habe been considered. The 4 mushroom shaped buttons appear to be a good compromise for the required waveguide mode excitation