# ZS SPS Septa Impedance Measurements and Discussion

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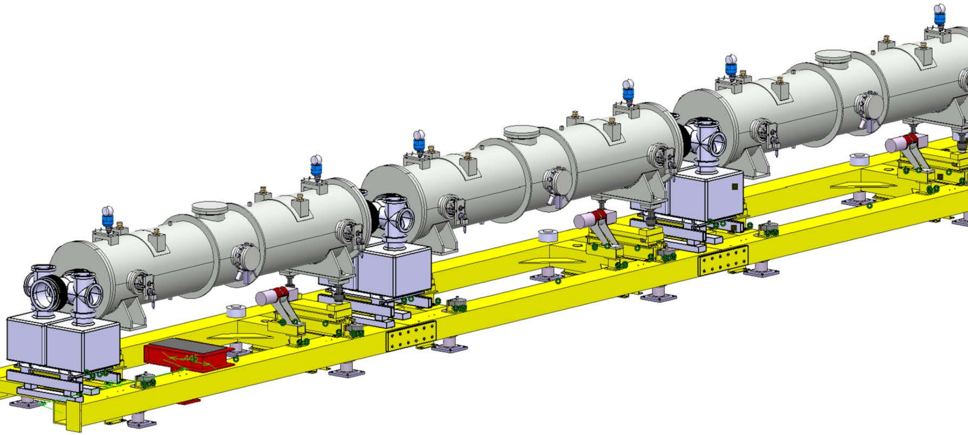
# Contents

# Introduction

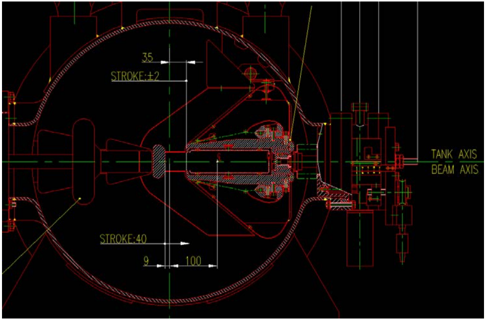
- **AIM:** Evaluate the impedance of the ZS Septa for the SPS. Measurements done using probes and a stetched coaxial wire are used to examine the beam equipment interactions over a broad frequency range and examine the effects of different terminations of the ZS equipment and of different transitions of the device to the surrounding beam pipe

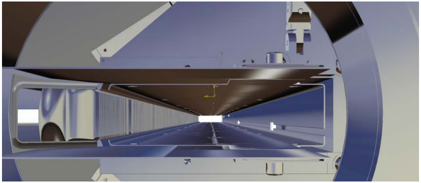
# ZS Layout LSS2

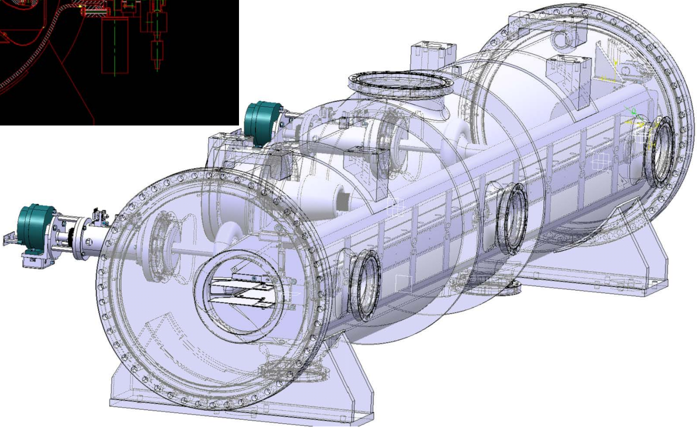
- 5 ZS separated by 6 MP



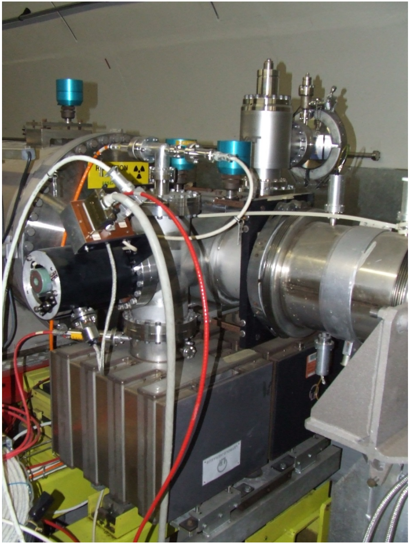
# ZS Geometry



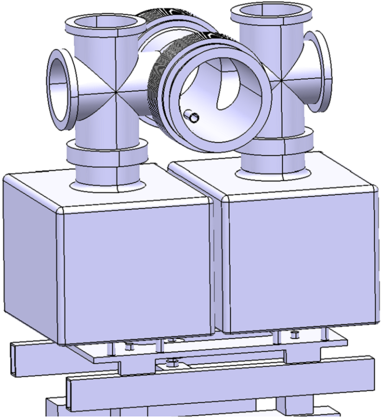





# MP



- MP with or without BI equipment depending position

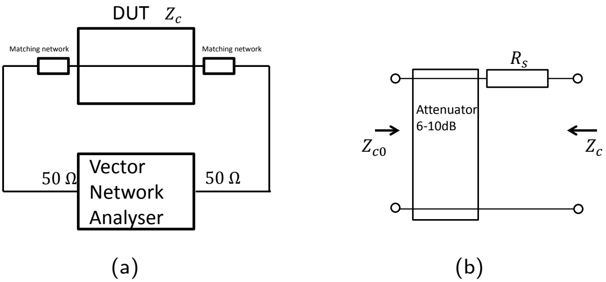


# Notes on the measurements

- The following measurements have been carried out
  - A ZS tank with varying terminations
    - Coaxial wire measurements using a transmission method. Various terminations on the septa system and transitions to the tank.
    - Probe measurements (reflection and transmission) at various depths in order to accurately measure the Q of resonances
  - Pumping module
    - Coaxial wire measurements using a transmission method.
    - Probe measurements (reflection and transmission) at various depths in order to accurately measure the Q of resonances
- The measurements are of a single tank, however in reality the machine setup of multiple tanks and vacuum modules adjacent to one another with a low cutoff frequency between the tanks ($f_c \approx$586MHz for a flange diameter of 30cm):
  - Above the cutoff frequency resonant modes are not confined to one device but can propogate between multiple devices - $f_{res}$, $R_s/Q$, Q are all changed
  - Multi-tank modes can form - additional resonant modes crop up
  - **The measurements presented here should not be considered definitive as representing the impedance of the ZS and pumping modules as seen by the beam**

# Coaxial Wire Measurements

- Typical coaxial wire measurement setup with matching resistors is used




- In this case $Z_c \approx 310\Omega$ so $R_s = 270\Omega$ is used. Some residual mismatch remains thus there are expected to be some oscillations in the measurements

# Probe Measurements

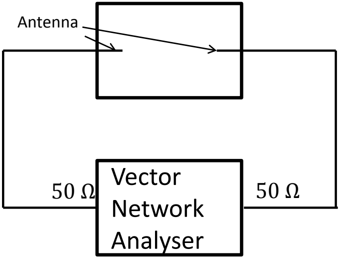



Figure 1: A measurement schema of measurements using antenna. The depth of the antenna is varied in order to excite different resonant modes.

Previous measurements by F. Caspers and co. were done using coaxial wire with matching network (going by the lack of broadband oscillations characteristic of mismatch). Terminations on the device unknown.

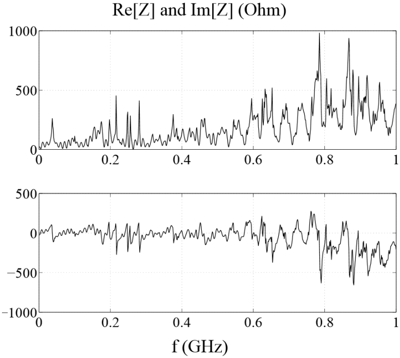



Figure 2: Real and imaginary longitudinal impedances of the ZS measured by the ZS. Courtesy of F. Caspers and E. Chaposhnikova from the proceedings of LHC Workshop, Chamonix, 2001

# Coaxial Wire Measurements

- Notes on labelling:
  - With/without grill - Refers to the presence or lack thereof of a metal grill from the entrance flange towards the septa
  - Anode refers to the termination on the anode circuit of the septa
  - Ion trap refers to the circuit of the ion trap in place in the septa
  - Short means that a circuit connection is shorted at the termination
  - Matched means that the circuit connection is terminated in a matched resistor
  - Open means the circuit connection is terminated by an open circuit
  - Otherwise the connection is connected to it's operational connection

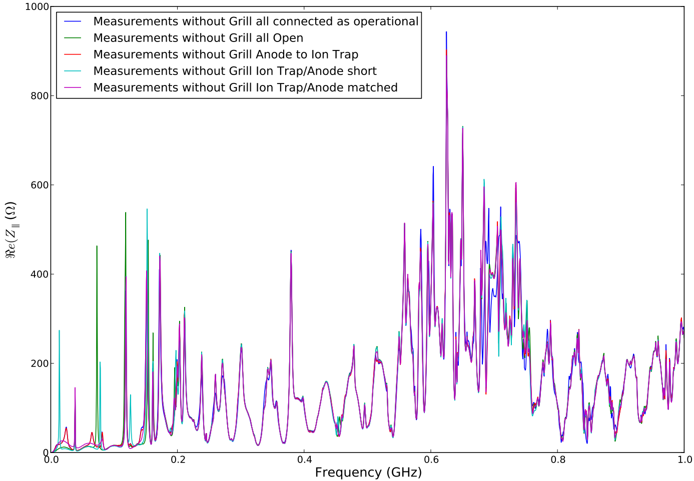



Figure 3: Wire measurements taking different terminations on the external circuits

# Impedance depending on circuit terminations

- There is a clear effect due to the terminations below 200MHz
- The circuits used during operation suppress many resonances seen when the terminations are open or shorted
- Strong resonance left at ≈38MHz ($R_s$=145Ω by wire measurement, likely higher due to de-Qing by coaxial wire)

# Inclusion of a grill in the transition from the beam pipe to the vacuum tank

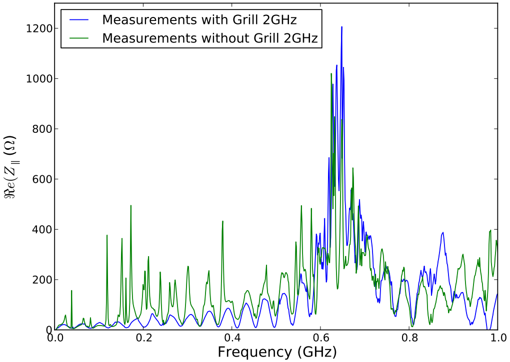



Figure 4: The real component of the longitudinal impedance of the ZS with and without the grill

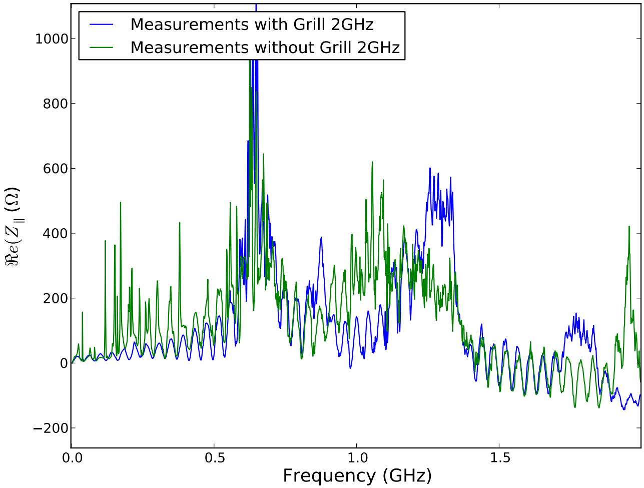



Figure 5: The real component of the longitudinal impedance of the ZS with and without the grill to 2GHz

# Effect of the grill

- All resonances below 500MHz are effectively suppressed
- Increase in the $R_s$ of resonances around 620-660MHz with the presence of the grill
- New series of resonances (broadband?) between 1.2 and 1.35GHz with the presence of the grill

# Simulated Wire Measurements

- We can simulate the wire measurements using CST PS (or HFSS or any other simulation code of your choosing) - allows us to better identify the source of impedance by modifying the model
- Quite time intensive for the ZS - big, large changes in aspect ration
- Many thanks to B. Salvant for the model and some of the simulation results
- In this case a very simplified model is used
- Different frequency ranges are used due to the iterative solver not providing equal resolution to all frequencies within the range (possibility to use frequency step simulations but would be very time consuming).

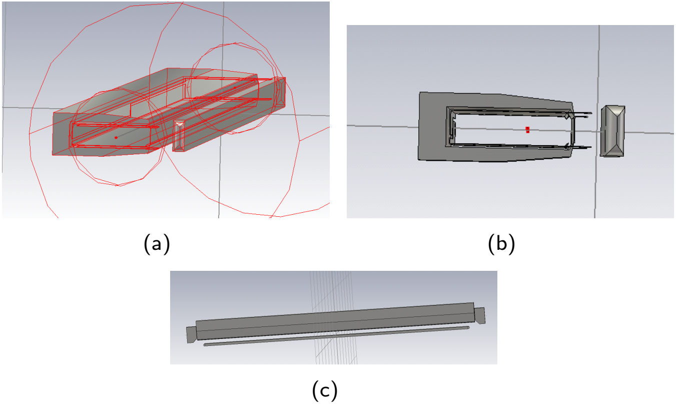



Figure 6: Cross section of the ZS used for simulations.

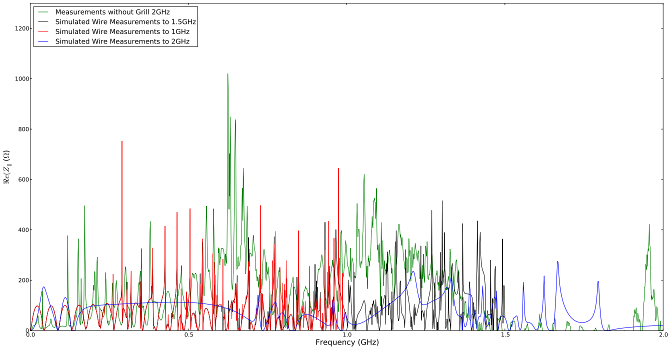



Figure 7: All simulation results of the ZS without the grill in place

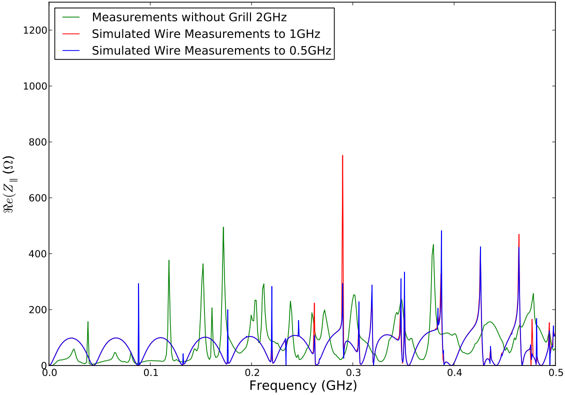



Figure 8: Simulated wire measurements with a range 1MHz-1GHz

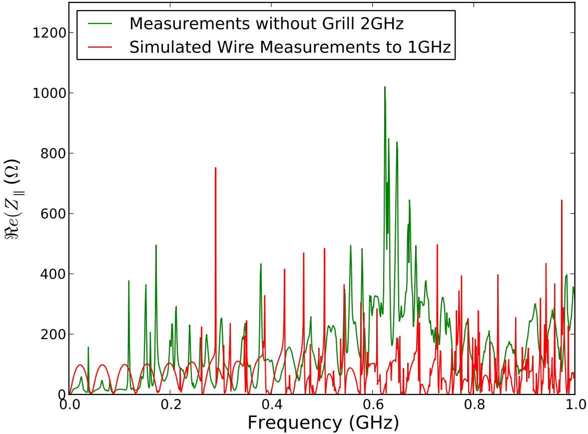



FIGURE 9: Simulated wire measurements with a range 1MHz-1GHz

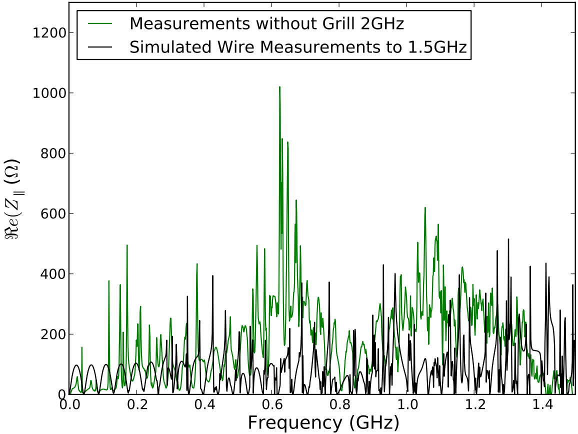



Figure 10: Simulated wire measurements with a range 1MHz-1.5GHz

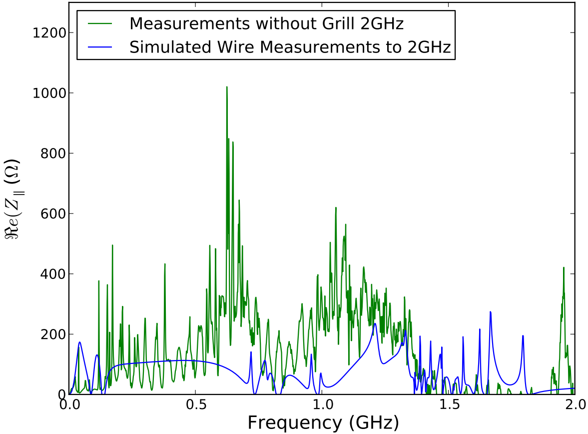



Figure 11: Simulated wire measurements with a range 1MHz-2GHz

# Some comments on simulated measurements

- The type of frequency scan called for determines heavily the results you get for the simulated wire measurements $\rightarrow$ Interpolated simulations give poor results, especially in the case of resonant structure. Fast sweeps or point by point simulations give better results although they are much slower (fast sweeps work well however as they detect the resonances).
- It's clear that the simulated model isn't representing the measured device well - It misses many resonances with the real device.

# Resonances without Grill

Table 1: Resonances below 500MHz for the ZS without the grill

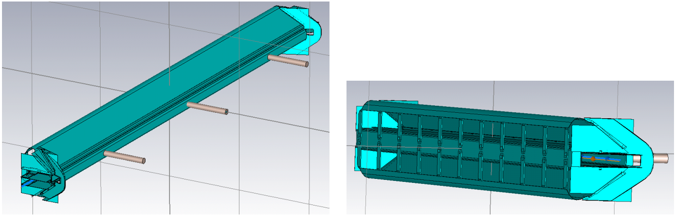
| $f_{res}(MHz)$ | $R_s(\Omega)$ | $Q_{wire}$ | |
|---|---|---|---|
| 23 | 53 | $Q_{wire}$ | |
| 24 | 59 | $Q_{wire}$ | |
| 38 | 156 | $Q_{wire}$ | |
| 65 | 45 | $Q_{wire}$ | |
| 119 | 165 | $Q_{wire}$ | |
| 152 | 364 | $Q_{wire}$ | |
| 162 | 74 | $Q_{wire}$ | |
| 173 | 302 | $Q_{wire}$ | |
| 202 | 159 | $Q_{wire}$ | |
| 203 | 234 | $Q_{wire}$ | |
| 212 | 292 | $Q_{wire}$ | |
| 224 | 78 | $Q_{wire}$ | |
| 239 | 192 | $Q_{wire}$ | |
| 260 | 168 | $Q_{wire}$ | |

Table 2: Resonances below 500MHz for the ZS without the grill

| $f_{res}(MHz)$ | $R_s(\Omega)$ | $Q_{wire}$ |
|---|---|---|
| 273 | 176 | $Q_{wire}$ |
| 300 | 253 | $Q_{wire}$ |
| 318 | 51 | $Q_{wire}$ |
| 347 | 223 | $Q_{wire}$ |
| 359 | 78 | $Q_{wire}$ |
| 379 | 433 | $Q_{wire}$ |
| 401 | 114 | $Q_{wire}$ |
| 434 | 156 | $Q_{wire}$ |
| 465 | 143 | $Q_{wire}$ |
| 477 | 228 | $Q_{wire}$ |
| 493 | 112 | $Q_{wire}$ |

# Wakefield simulations of the ZS with CST

- The model used for wakefield simulations is a more complete version of the model (screen, anode, ion trap etc. all much more completely modelled). Thanks to B. Salvant for simulations and building the model.



(a) (b)

Figure 12: Geometry of the ZS used for wakefield simulations

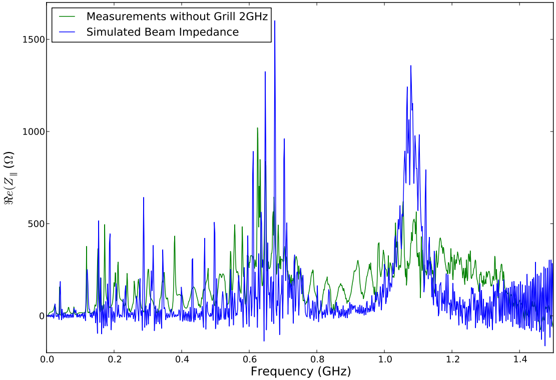



Figure 13: Comparison between beam coupling impedance measured using coaxial wire techniques

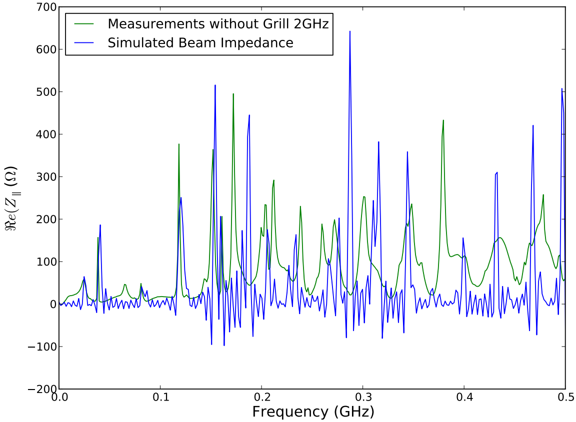



Figure 14: Comparison between beam coupling impedance measured using coaxial wire techniques between 1-500MHz

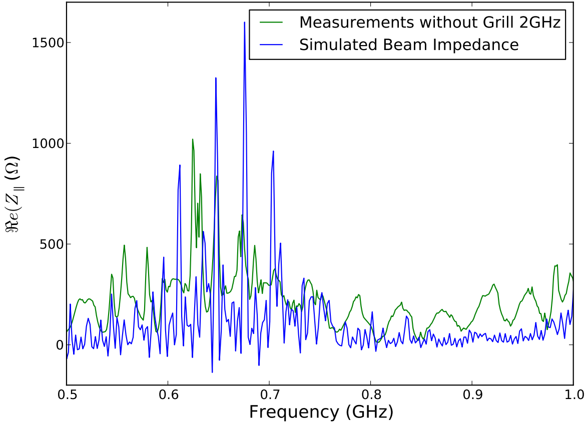



Figure 15: Comparison between beam coupling impedance measured using coaxial wire techniques between 0.5-1GHz

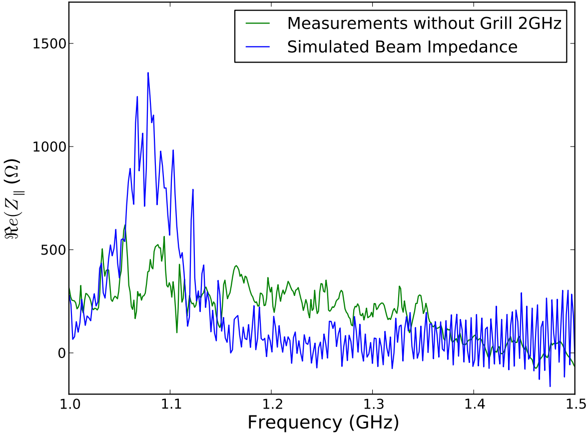



Figure 16: Comparison between beam coupling impedance measured using coaxial wire techniques between 1-1.5GHz

# Some comments on impedance simulations

- The more complex model catches more resonances than the simplified model - almost all resonances below 200MHz, many from 500-800MHz
- Less accurate above 1GHz
- Worth trying coaxial wire simulations of the complete model - likely to be very time consuming but would provide a good basis for comparison
- Big difference in the region 1-1.2GHz

# Probe Measurements

- Probe measurements involve the use of antenna inserted into the device, this allows the excitation of resonant modes provided the probes are at a depth that allows them to interact strongly with the mode (i.e. not at an area of zero field for any given mode)
- We place the probes at various depths in order to excite the most modes - This should be on the path of the beam ideally. We may not excite all modes in the cavity but if the beam doesn't interact with them we don't really care in anycase

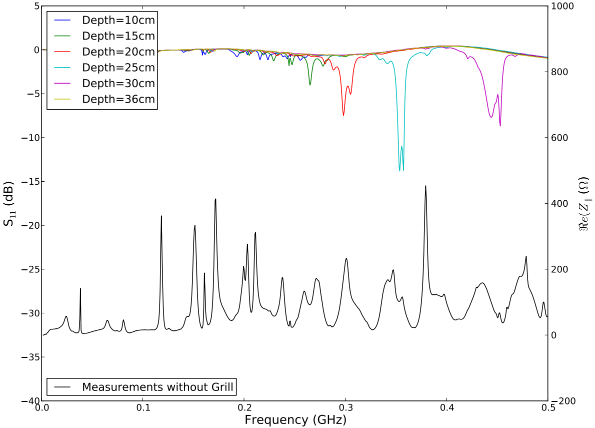



Figure 17: $S_{11}$ with probes at different depths plotted with the beam coupling impedance measured with a coaxial wire, 1-500MHz

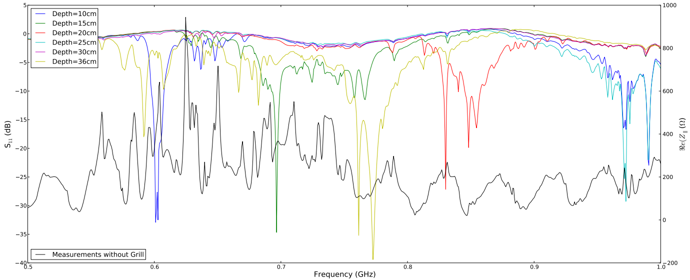



Figure 18: $S_{11}$ with probes at different depths plotted with the beam coupling impedance measured with a coaxial wire, 500MHz-1GHz

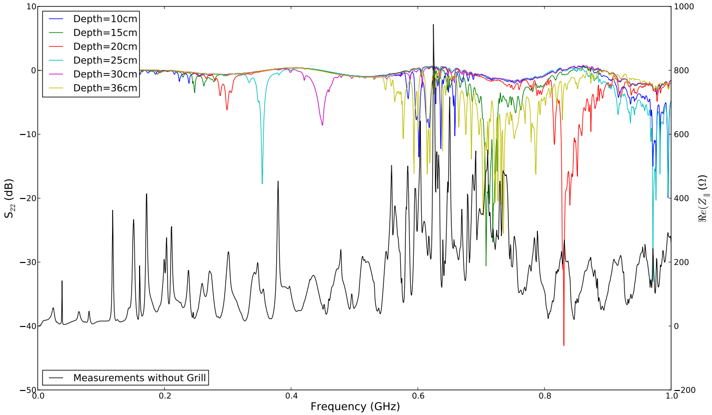



Figure 19: $S_{22}$ with probes at different depths plotted with the beam coupling impedance measured with a coaxial wire, 1MHz-1GHz

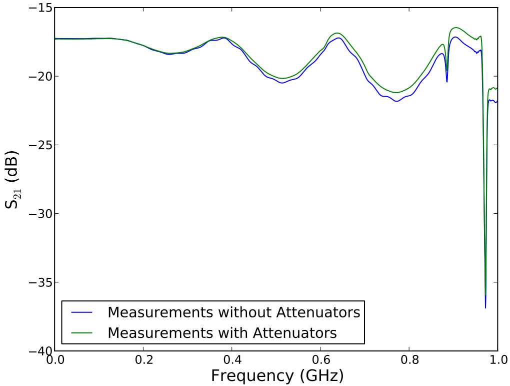



Figure 20: Transmission measurements of the pumping module. Case with attenuators has 20dB added to $S_{21}$ take into account the additional attenuation of the transmitted signal

# Conclusions

- Measurements have shown that the impedance spectrum is very complex within the ZS
  - Strong resonances particularly between 500-700MHz, and 1-1.2GHz
  - Many low frequency resonances that depend on the external circuit
- Simulations with the more complete model give ok agreement with the measurements - modes at low frequencies and high frequencies are not identified
- Unclear if this is due to measurements or lack of resolution/missing components in simulations
- Probe measurements identify many of the resonances seem by the wire measurements - remains to identify the Q factors of the modes and match them to the wire measurements
- **The addition of the grill greatly suppresses resonances below 500MHz in a single module compared to the case without**. However the effect for connected devices is unknown.

# Future Work

- Analysis of the measurements for the imaginary impedance remain to be done
- How to consider the impedance for multiple devices attached together - measurements of this setup would be difficult
- Is it possible to concatenate smaller measurements or simulations? (Mode matching at boundaries for example)

# Methods of the Calculation of Power Loss

- Taking a beam power spectrum (measured or theoretical) and taking the integral of the beam power spectrum with the real component of the longitudinal impedance, multipled by the square of the DC beam current
  - Gives the most realistic estimate, including sidebands around the bunch spacing harmonics due to bunch train structure.
  - For measured spectra you're limited to only one bunch length.
  - It's technically possible to calculate this for any bunch structure provided sufficient computational power is available - Interesting side-effects of bunch train structure can be evaluated.

1. Take measured beam power spectrum and real component of beam coupling impedance (see example below)
2. Calculate the **integral**:

$$P_{loss} = \frac{2}{2\pi} n_{bunch} \left( f_{rev} N_b e \right)^2 \int_{-\infty}^{\infty} d\omega \left| \lambda(\omega) \right|^2 \Re e \left[ (\omega) \right] \qquad (1)$$

3. You have your power loss for the structure

# Methods of the Calculation of Power Loss Contd.

- Taking a bunch power spectrum (often analytical) and summing the product of the bunch power spectrum and the real component of the longitudinal impedance at predicted beam harmonics, multiplied by the square of the DC beam current
  - Useful for predictions of future operational parameters - bunch length can be easily modified for analytical bunch distributions.
  - Does not take into account the effect of bunch train structure (i.e. only equally spaced, equally populated bunches).

1. Choose you bunch spectrum of choice (analytical or measured) and the real component of the longitiudinal impedance of the device (see example below)
2. calculate the **sum**:

$$P_{loss} = 2\left(f_{rev} e n_{bunch} N_b\right)^2 \sum_{n=-\infty}^{\infty} \left|\lambda\left(p n_{bunch}\omega_{rev}\right)\right|^2 \Re e\left[Z_{\parallel}\left(p n_{bunch}\omega_{rev}\right)\right] \tag{2}$$

3. Enjoy/dispair at the resulting answer

# Methods of the Calculation of Power Loss Contd.

- **Strongly resonant impedances only**: Taking a bunch power spectrum and calculating the product of the bunch power spectrum and the shunt impedance of the resonance, multiplied by the square of the DC beam current
    - For a given resonance gives the most conservative (highest) estimate of the power loss.
    - Remember to consider that the resonance may not fall on a beam harmonic. The method is used as a guard against simulation inaccuracy, but a resonance at 10kHz is not a concern for heating for the LHC for example (instabilities are a different story).

1. Choose your bunch power spectrum of choice and the resonance that you which to evaluate, defined by the resonant frequency $f_0$, shunt impedance $R_s$ and quality factor $Q$
2. For the resonance calculate

$$P_{loss,res} = 2\left(f_{rev}\, e n_{bunch} N_b\right)^2 \left|\lambda(2\pi f_0)\right|^2 R_s \tag{3}$$

3. For all resonances calculate

$$P_{loss} = 2\left(f_{rev}\, e n_{bunch} N_b\right)^2 \sum_{n=1}^{\infty} \left|\lambda(2\pi f_0^i)\right|^2 R_s^i \tag{4}$$

4. Let the good/terrible times flow

# Example power loss calculation

- We shall use the MKI11-T13-MC03 as an example
- The beam spectrum will be acquired by simulating a bunch train and taking the FFT of this to acquire the beam power spectrum. The bunch spectrum is analytical. In both cases a $\cos^2$ bunch distribution is assumed. The beam has the following parameters - $N_b$=1.6e11 ppb, $n_{bunch}$=1380, $e = 1.6 \times 10^{-11}$C, $f_{rev}$=11800 kHz. For the bunch train 10 trains of 144 bunches separated by 50ns, each train spaced by 150ns are assumed, but the beam current used is as for 1380 total.
- For the method of beam harmonics on a bunch spectrum 40MHz intervals are used.

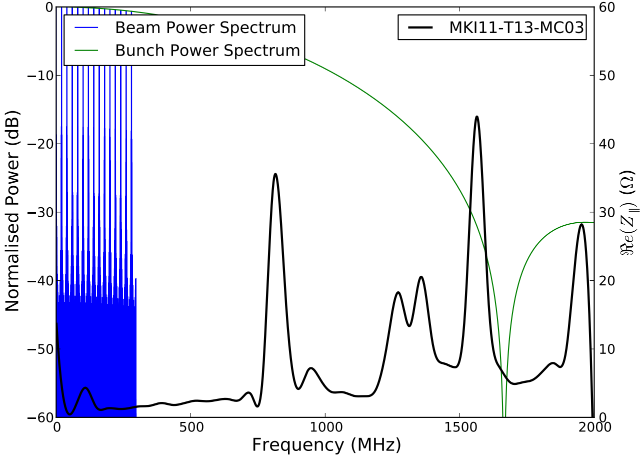



FIGURE 21: The beam and bunch power spectrums overlaid on the real component of the longitudinal impedance of MKI11-T13-MC03

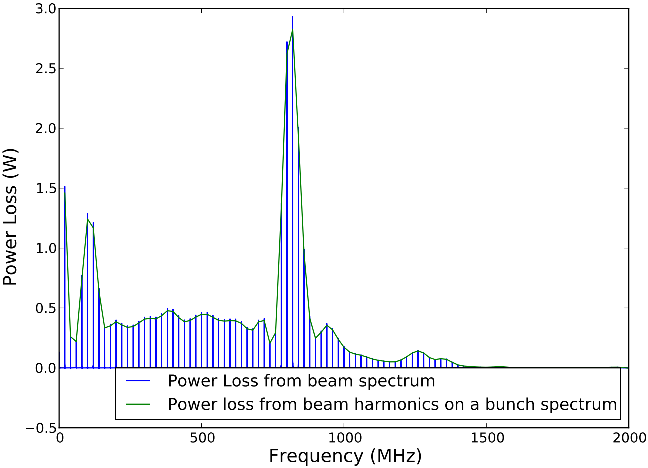



FIGURE 22: The frequency dependent power loss for both the beam and bunch power spectrum methods

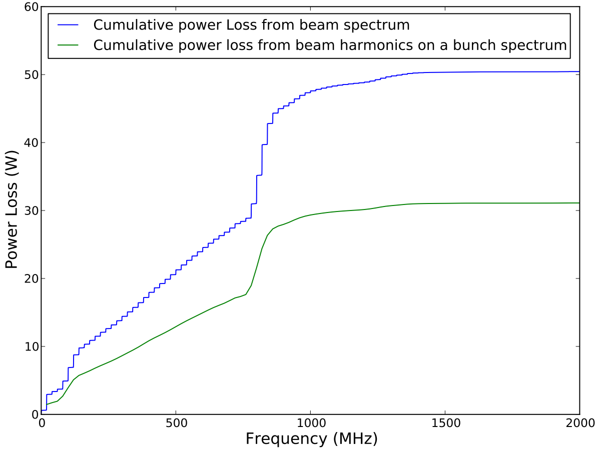



Figure 23: The cumulative frequency-dependent power loss for both the beam and bunch power spectrum methods

Table 3: The power loss expected due to beam-wakefield interactions in the MKIs for the magnets measured so far. All power losses are given in W/m.

| Calculation Method | Power Loss (W) |
|---|---|
| Beam Spectrum | 50 |
| Beam harmonics on bunch spectrum | 34 |
| Resonant method | 5 |