Analysis week MPP, July 24-28 2023

Alberto Martini

Participating in person (organizers in **bold**): David, Bernardo, **Johannes**, Dagmar, Juan, Anton, **Alberto**, Béla

0.1 Motivation

Define a clear path towards publication. We need to have a solid structure for the group, defining responsibilities and the path that each sub-group should follow.

0.2 To-do list divided into analysis-week sections:

- Power calibration- SA + VNA measurements:
  - Can we avoid subtracting the baseline from the Y-calibration? Is this providing smaller uncertainties associated to the Y-factor? to understand
  - Is the axion resolution smaller than our resolution? Are we safe from this side?
- ADS model:
  - Extract uncertainties on the efficiency coming from the polarization of the field.
  - Need uncertainties for geometry-related quantities.
  - Get disk material uncertainties
  - Mirror reflectivity uncertainties, to be compared with nominal copper value.
  - Change the correlation and see what comes out from the SOL results.
  - Properly take into account the difference in internal distances for the Short and the Open measurements. We already know that the difference is 9mm (30ns)-TO BE ASKED Juan
  - Thermal emission at the mirror needs to be divided by 2 due to the coverage of $4\pi/2$. (to double check if this is really to be done)
  - Understand why the system temperature in 2022 is smaller of 100 deg.
- COMSOL simulation (with ADS comparison):
  - Geometry values are not reliable. There are several different values and we would need to have some central values that everyone have to use.
  - The peaks in the frequency spectrum we have in real data have to be compared with the COMSOL simulation results, like we did for 2022 data (not very urgent but it's a very nice control check).
- Statistical analysis:
  - Start preparing the framework to be used by Madmax, on the line of the Haystac experiment.
  - Check the feasibility of the Bayesian approach for Madmax.
  - Prepare a gitLab repository -> already done!

Contents

1. SA + VNA measurements

Introduction on transmission line theory, when the signal wavelength is not negligible *w.r.t* the electrical one. In such a scenario, voltage and current may vary a lot in amplitude, frequency and phase. Instead, in terms of circuit theory, voltages and currents are not varying and the physical dimensions are small. Therefore, the ideal system is not exactly equivalent to the real one. Let's start from the very beginning: understanding the structure of cables is important. Coaxial cables are layered as the core, dielectric insulator, copper shield, and plastic shielding. Voltage differences can appear between the two conductor lines when a field propagates through. Telegrapher's equation is the base theory used to understand the effects (see Fig. 1.1). We can represent a "simple version" of

$$\frac{d^2V(z)}{dz^2} - \gamma^2 V(z) = 0,$$

$$\frac{d^2I(z)}{dz^2} - \gamma^2 I(z) = 0,$$

- Propagation constant:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

Figure 1.1: Telegrapher's equations and propagation equations.

the system with components: L (Inductance), C (Capacity), R (Resistance) and G (Conductance). Impedance, with the imaginary components, is tricky since transmission is affected as we have reflections and energy losses. The imaginary part represents the losses on the transmission of the signal (see Eq. 1.1).

$$X_0 = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{1.1}$$

We can use "standards", with their own impedance, to terminate the transmission lines, as below:

$$Z_L = \frac{V(0)}{I(0)} = \frac{V_0^+ + V_0^-}{V_0^+ . V_0^-} Z_0 \tag{1.2}$$

We can use standards to calculate the characteristic impedance of the line and a load you may attach to the line. We usually want to calculate the reflection coefficient which describes how much of a mismatch there is (in terms of impedance). See the following equation:

$$Z_L = \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{1.3}$$

In order to better characterise the transmission line, we can perform different measurements: "Short", "Open" and "Load". See Fig. 1.3. The load is measured by connecting the core but not the

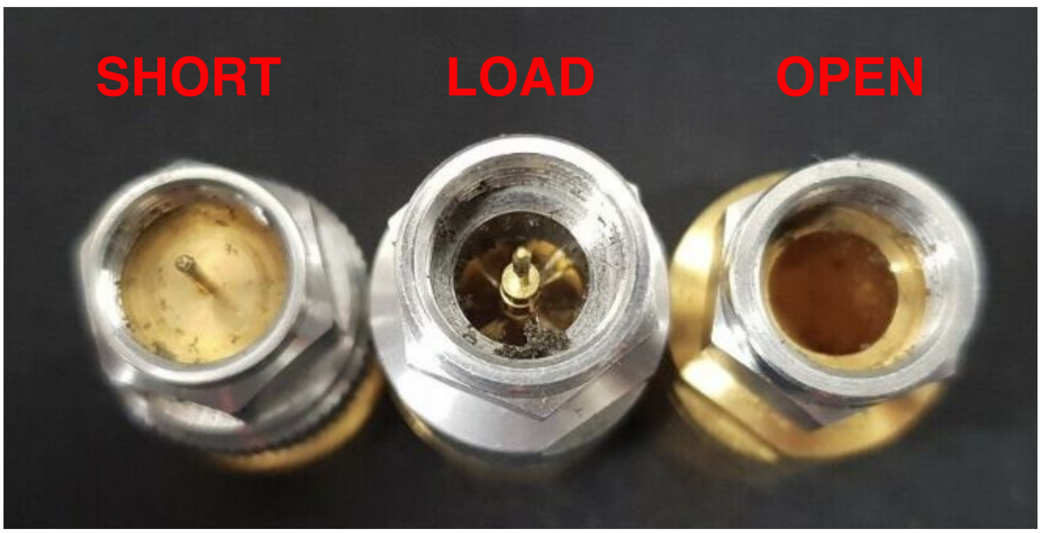

Figure 1.2: Short, Load and Open conditions of a coaxial cable are displayed.

copper. The open does not connect the core part of the cable at all, while the short does not isolate properly the core from the copper (which is therefore directly connected). The plot in Fig. **??** shows that the magnitude of the reflection coefficient is the distance between the point you measure and the center, while the phase is associated with the angle. If one follows the polar lines, we can extract the real and imaginary parts. Fun fact: 85% of the axion filed couples with TE11, while 70% of the axion power goes into TE11.

1.1 Noise

Random motion of electrons into the resistor means thermal voltage fluctuations. The average is 0 while RMS is due to fluctuations. The power coming from the resistor is represented by a black

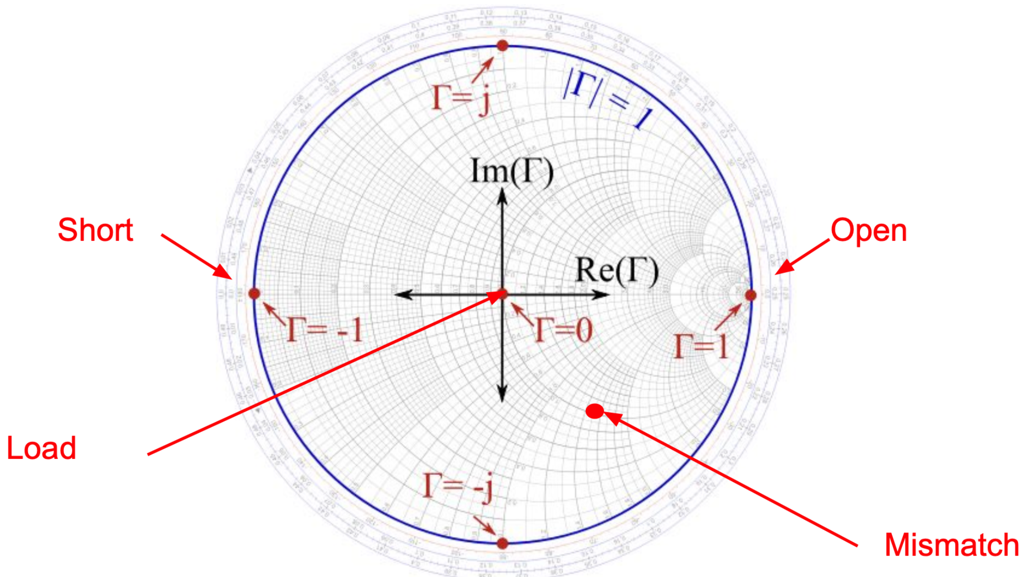

Figure 1.3: Short, Load and Open conditions inside a graph showing real and imaginary parts of the system in polar coordinates.

body radiation, for which:

$$V_n = \sqrt{\frac{4hf\ B\ R}{e^{hf/kT} - 1}}, \tag{1.4}$$

where h is Planck's constant, k is Boltzmann's constant, T is the temperature (in K), B is the bandwidth of the system (in Hz), f is the center frequency of the bandwidth (in Hz), R is resistance (in Ω). Rayleigh-Jeans approximation ($hf << kT$) means that $V_n = \sqrt{4kTBR}$ and we can use it to get the noise of the resistor when a "Noiseless" object is attached to your circuit. You can measure a noise of an object by assuming it to be a resistor with a defined temperature (emitting as a black body), which is a power-equivalent noise. In fact, instead of dealing with the power we convert it into temperature as the noise power is defined as $N_0 = kT_eB$, therefore the equivalent noise temperature is $T_e = \frac{N_0}{kB}$. Usually, LNAs noise temperature corresponds to ∼150 K, so considered negligible, but it amplifies signals of around a factor 1000 as well as the noise. The noise is amplified by a factor 30 db (factor 1000), so the temperature noise goes to ∼300 K*30 db. Therefore, we usually need an attenuator to bring back the noise temperature of the diode to an equivalent temperature of ∼50 K. Of course, this temperature contribution is added on top of the LNA intrinsic noise temperature (if at room temperature it corresponds to a black body radiation at ∼300 K).

1.1.1 Details on amplifiers and their noise

In order to measure the noise, we attach a load to the LNA. Loads provide power in terms of the temperature of the load, plus we have to consider the temperature of LNA. The latter transmits its noise in both directions of the line: towards the receiver for the measurement and towards the load itself. Load and LNA are matched in impedance so we are not considering this as an additional contribution (see Fig. 1.4). In 2022 data-taking we wanted to calibrate (extract the noise) of our

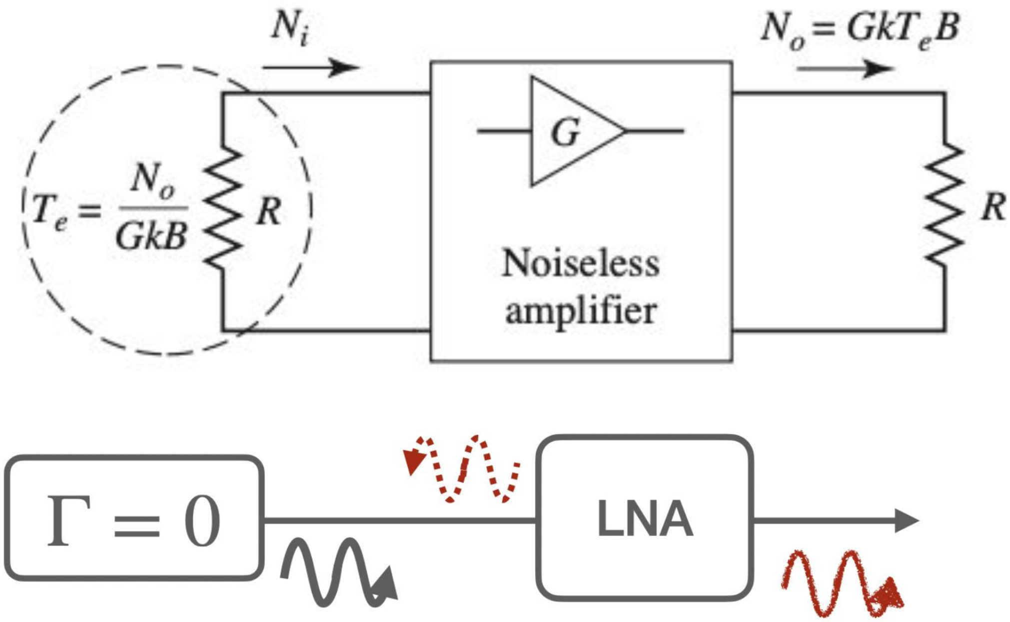

Figure 1.4: LNA noise measurement is done by considering this schema.

system by using the Y-factor method. This is done by measuring the power from 2 sources/loads (in our case diodes) with different temperatures and getting the power ratio as $Y = \frac{N_1}{N_2}$. See Fig. 1.5 for further details. For the 2022 data-taking we used very similar temperatures of the 2 loads, therefore

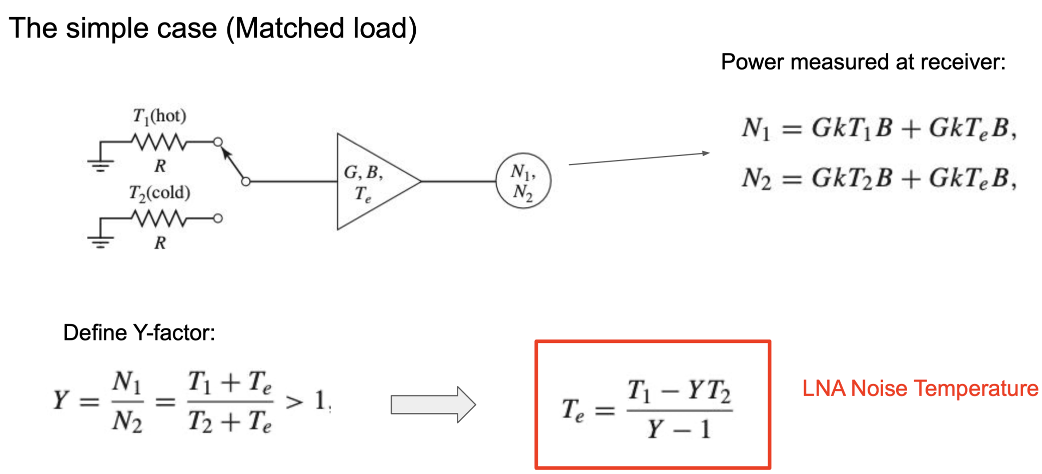

Figure 1.5: Details on the Y factor calibrations.

the Y-factor turned out to be very small and affected by very large statistical fluctuations. In 2023 we can re-produce the measurements with very different temperatures of the loads or introduce an impedance mismatch (needs to be discussed more).
For reference, there are two different ways of characterizing noise power: Equivalent noise Temperature and Excess Noise Ratio (ENR).

1.2 LNA noise model

The Spectrum Analyser (SA) is used to measure Short, Open and Load (SOL) configurations. With the circuit in "Short" you get the voltage, "Open" you got the current and with the "Load" you get a combination of voltage and current which you can use to measure the phase. See Fig. 1.6.

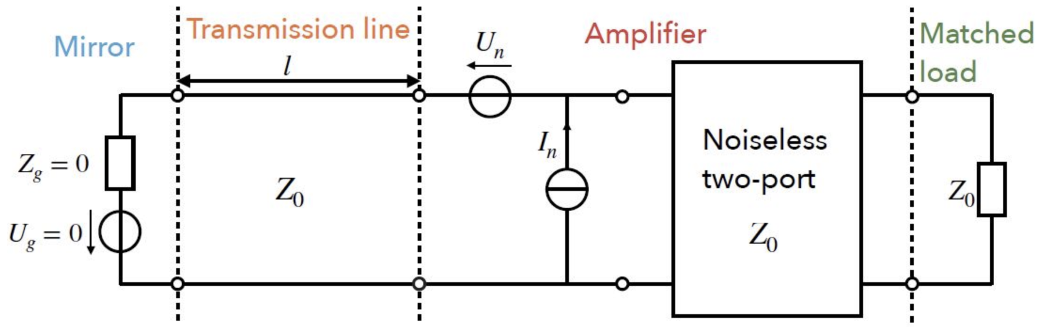

Figure 1.6: Short, Open, Load measurements setup.

With the VNA we can measure the length of the transmission line, the impedance and gain with reflectivity measurements.

1.3 Spectrum Analyser - SA functioning

Plug into the SA an input source; you can adjust the span frequency and the reference level (Attenuator stage), which tells how much attenuation one should apply to the signal in order to avoid saturating the SA. After the input there is a switch provided with a filtering system -> mixing stage, allowing us to jump into an intermediate frequency -> bandwidth filtering stage-> Envelope stage, where we lose the information about the phase of the signal and one can only measure the power -> video bandwidth with a display of the smoothened signals. Details in Fig 1.7. The SA generate a lot

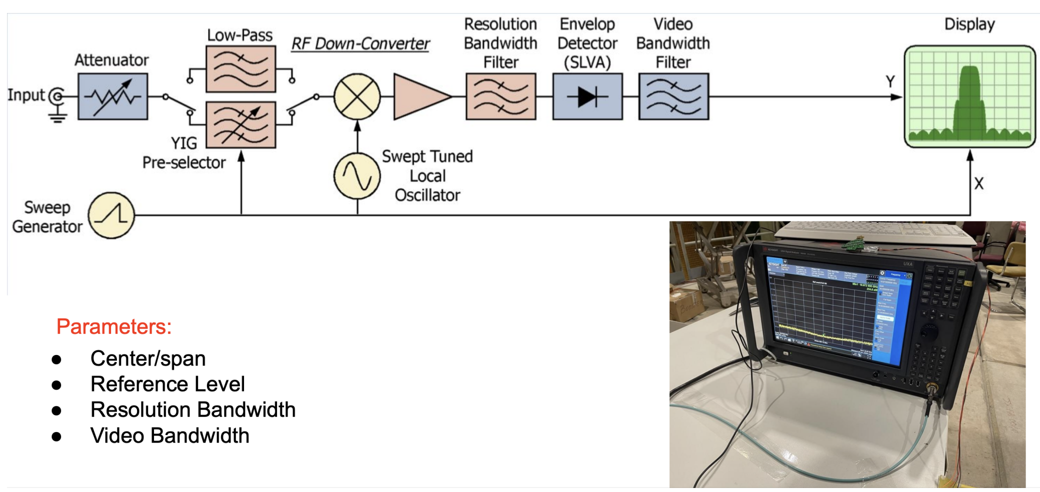

Figure 1.7: Spectrum analyser components details.

of noise, due to the presence of several noise source components.
The baseline measurement (intrinsic noise) is done with the SA being connected only to a load,

which has a much smaller noise. We amplify the signal from our device under test (DUT), so to have a magnified signal and avoid the SA noise being the dominant contribution. Also, we want to convert the power to a temperature quantity. We measure the noise with a diode, switching it to on and off (corresponding to the 2 sources at different temperatures as explained in Sec. 1.1.1) so that we can extract the Y-factor and obtain the temperature of the LNA and the power to noise conversion. In this way, we have a one-to-one conversion between power per bin to Temperature. **Can we avoid subtracting the baseline from the Y-factor calibration? Maybe we can reduce the errors and the uncertainties we introduce might be negligible**.

1.4 Vector Network Analyser - VNA functioning

The VNA computes the reflectivity and transmissivity using a DUT, by letting the signal be transmitted to a load and reflected back into the VNA. Basically measuring s-parameters, reflectivity and Smith chart. Then, we can measure the gain and the length of the transmission line. This is everything we need to know to characterise the system. Examples are shown in Fig. 1.8.

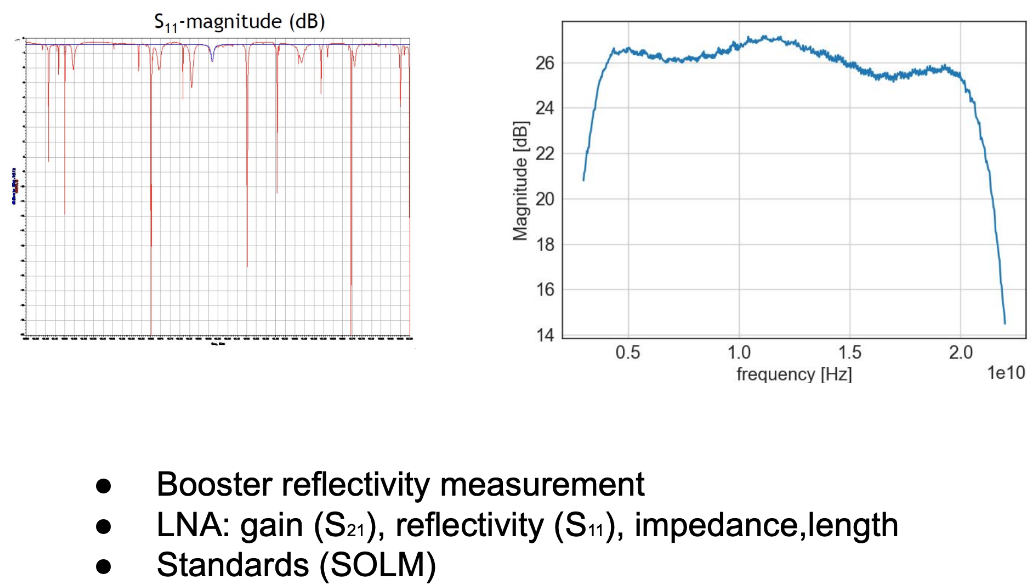

Figure 1.8: Details on the possible measurements done with the VNA.

Then, the measurements done in 2023 are explained and several images about the setup are shown. Note about the Cable connecting the CB100 to the VA: we used 2 cables 3m long. They introduced only a few db of attenuation, therefore it was not a problem. The 7 needed measurements: LNA intrinsic noise, 4 for the SOL+impedence mismatch and 2 measurements for the Y-factor (high and low temperature). The SOL is measured both in a frequency band of 2 GHz (to understand the noise behaviours far from the booster peak) and in a 40 MHz one. See Fig. 1.9. We need to understand the axion resolution and our system, resolution to see if we do not have problems in integrating the whole signal properly.

Define if to put the efficiency η outside the boost factor (in the formula) or in the boost factor so we do not need to add it. And we decided that it will be inside the boost factor. Of course, this will be properly reported and described in the paper.

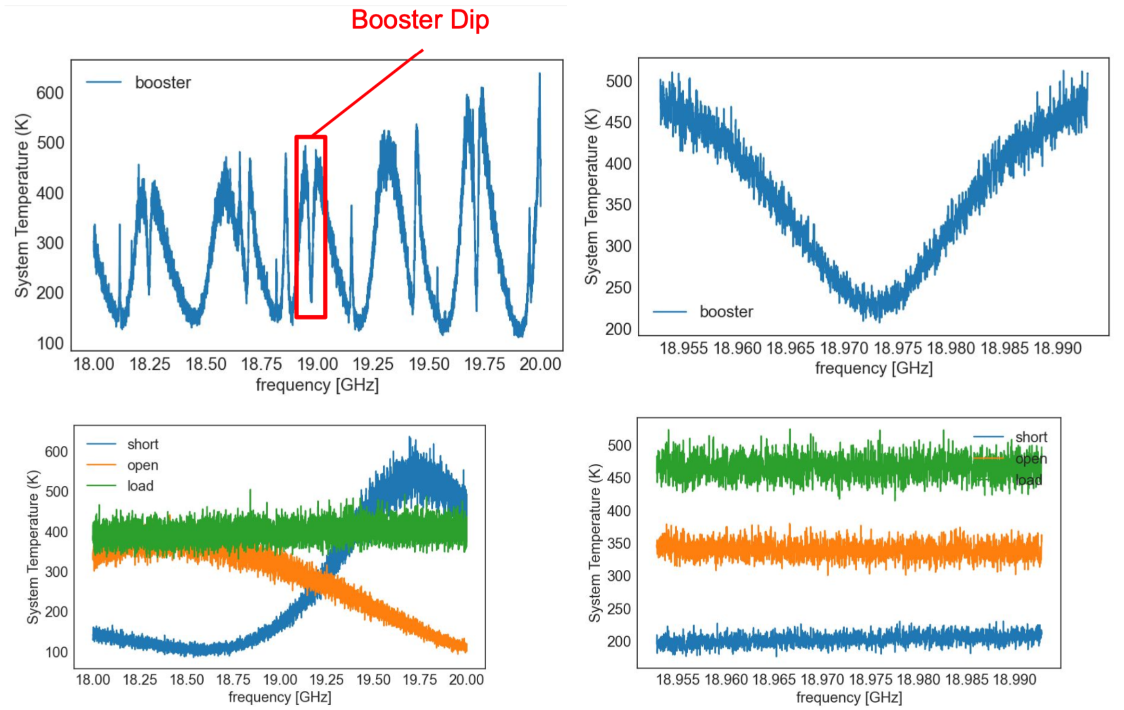

Figure 1.9: Details on the measurements done within a frequency band of 2GHz (left) and 40MHz (right).

1.5 Noise calibration Bonn

The aim is to cross check noise calibration (without magnetc field) and check if the RMS noise fluctuations are decreasing once we integrate in time.

Nobody was able to contribute to this topic, but we agreed that this measurements needs to be properly analysed.

2. ADS model

ADS model provides a 1D simulation of our booster system, in order to extract the boost factor for MadMax.

2.1 Introduction

An uniform electric field that couples perfectly with the axion field is assumed. Maxwell equations are used to solve equations with circular boundaries (CB100 can be seen as a bunch of circular waves). The solutions are infinite (modes) but we can constrain in size and frequency to 80 modes, for CB100, which still implies an over-moded system. Non-propagated modes are not accounted here, and represent the energy losses of the system. We also have to introduce the circular weveguide mode TE11, the one that couple with the axion field and provide the superposition of effects we need (see Fig. 2.1). Of course we also consider the propagation constant, impedance and consequent reflections. Propagation constant defined as $\beta = \sqrt{k^2 - \frac{p'^{\,2}_{nm}}{r}}$, and impedance defined as $Z_{TE} = \frac{kZ_0}{\beta}$. Here, $Z_0 = \sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}} \simeq Z_{\text{free space}}\sqrt{\frac{1}{\varepsilon_r}}$ and $p'^{\,2}_{nm}r$ is the roots of the derivatives of the derivatives of the bessel functions (can be looked up). Then, we use the transfer matrix formalism to understand how the field is propagated through the booster. We assume to operate in single mode, and we can test it by checking the reflectivity. There are different modes that resonates with the booster but none in the frequency range we are interested in (see Fig. 2.2.

The ADS model reproduces the measurement properly so we can be sure that this is the dominant mode. The lower is the peak, the larger is the loss, which depends on the fields coupling. How to determine the boostfactor? In the y-direction the B field should be the most homogeneous possible, then we need the E-field to be polarized in y and coupled to a constant axion field. Depending on how good is the coupling, we have an efficiency factor to take into account. This is extracted by integrating over the transverse-area of the booster: $\eta = \frac{|\int E_{TE11} \cdot \hat{y} dA|^2}{A\int |E_{TE11}|^2 dA} \simeq 0.84$.

We rely on this efficiency to consider our simulation as much real as possible. This makes the ADS 1D simulation to mimic a 3D-like. The uncertainty on such efficiency is important and can be estimated by measurements on rectangular weveguides, where the polarizaion can be extracted. The

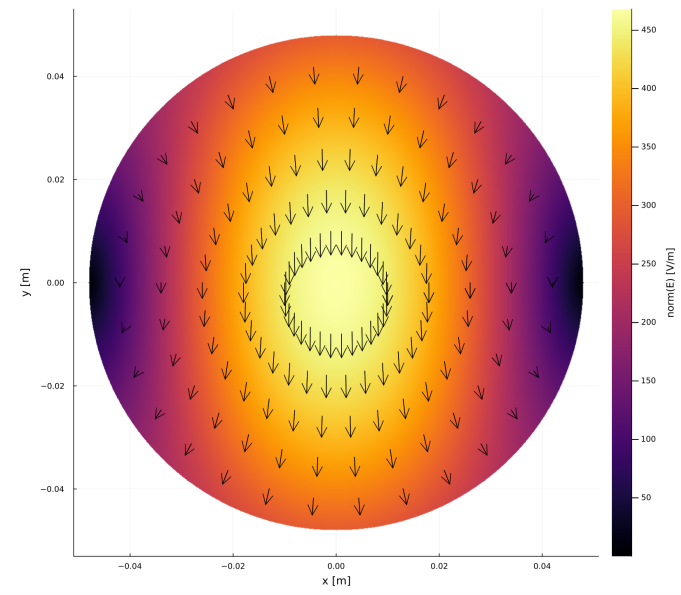

Figure 2.1: Transverse TE11 field inside circular waveguide.

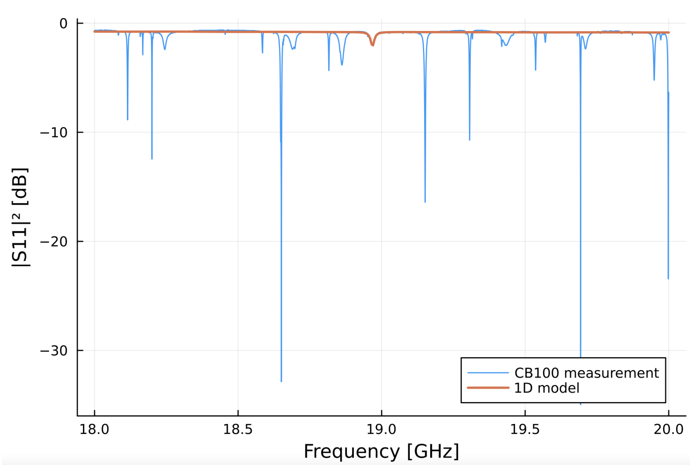

Figure 2.2: Reflectivity of CB100 with 1D ADS model.

guide has a tilted-end and it can produce some non-trivial effects. We should measure it and extract an uncertainty.

2.2 Noise of the booseter

As a general behaviour, a wrongly matched mirror to LNA will generate resonances, producing coherent signals. If we assume the booster to be in the middle between LNA and mirror, we have even more interferences and peaking structures (in terms of deeps) in the frequency spectrum. See Fig. 2.3 for reference. The higher the reflectivity (so badly matched LNA) the larger is the deep. That is why we observe an oscillation when we look at the system temperature VS frequency. The main large oscillation corresonds indeed to the LNA impedance mismatch. See details in Fig. 2.4.

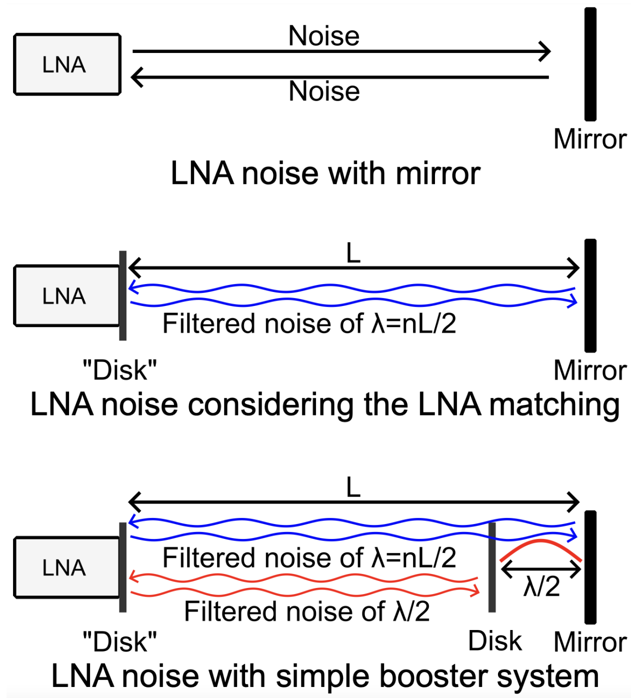

Figure 2.3: LNA noise behaviour considering the LNA badly matched to the mirror.

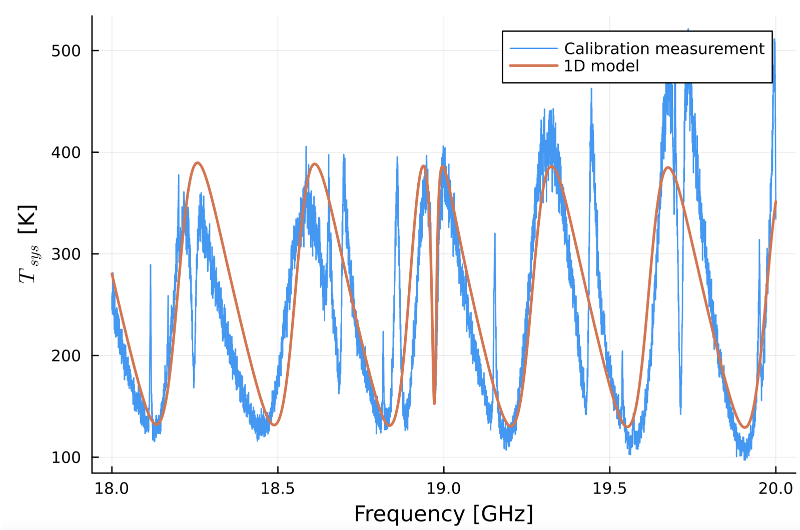

Figure 2.4: Frequency scan done in 2023 data-taking.

2.3 ADS model

A parameter overview is presented, see Fig. 2.5. This is everything we need in order to extract the boost factor andit is a very nice schema to follow towards the publication.

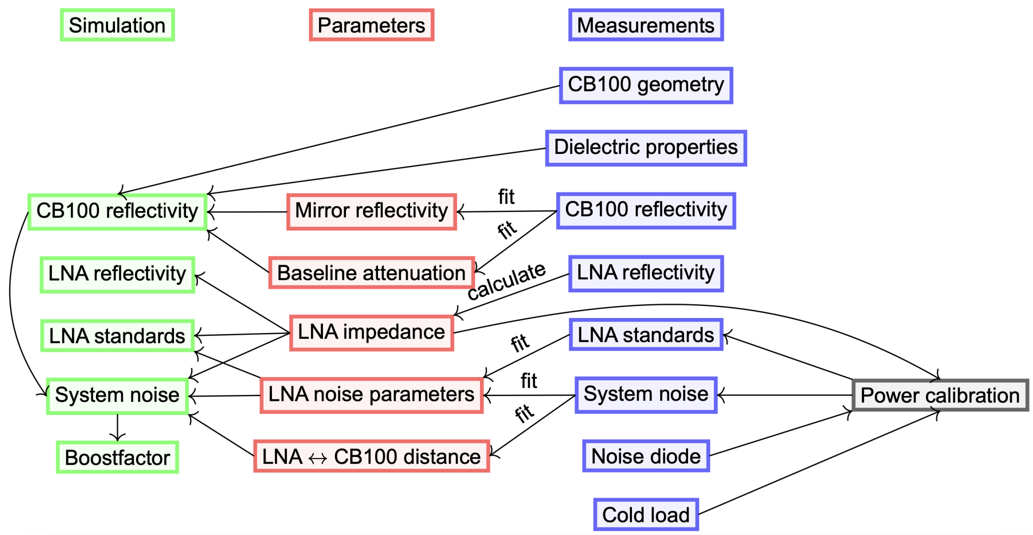

Figure 2.5: Parameters overview.

Geometry

Numbers come from either measurements or fits. There are no associated uncertainties, we need them.

Disk material properties

We have the numbers,but we need to get the uncertainties.

Free parameters

We fit the mirror reflectivity and the baseline attenuation. The former seems to be close to the copper value, but we need uncertainties. The latter is extracted by considering the lost inside the cable, which is simulating the connection line.

2.3.1 LNA

Change the correlation between U and I and see how the system reacts. See Fig. 2.6 as reference. The correlation is assumed 100% (set to 1 in ADS model). We have to change the correlation and

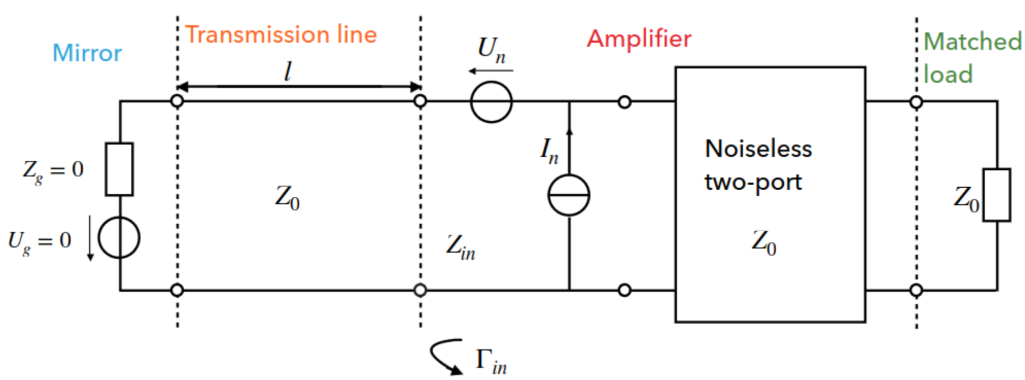

Figure 2.6: LNA noise model.

see what comes out from the SOL measurements. The "old" idea is to extract the internal length from the fit, but there are some mismatches between 2022 and 2023 data. The "new" way is to measure that length and plug it in the ADS model. This already happened during the analysis week! By following the "old" way, the noise parameters extracted after that are not reproducing the measurements properly. We would try to havea better agreement and extract uncertainites. For example the internal length of the short and open could be different. We already know that we have 30 s of difference -> 9 mm (these numbers have to be double checked with Juan). We need to plug this difference in and see what happens. Also, we would like to quantify the effect in the final determination of the boost factor. See Figures 2.7, 2.8 for the plots.

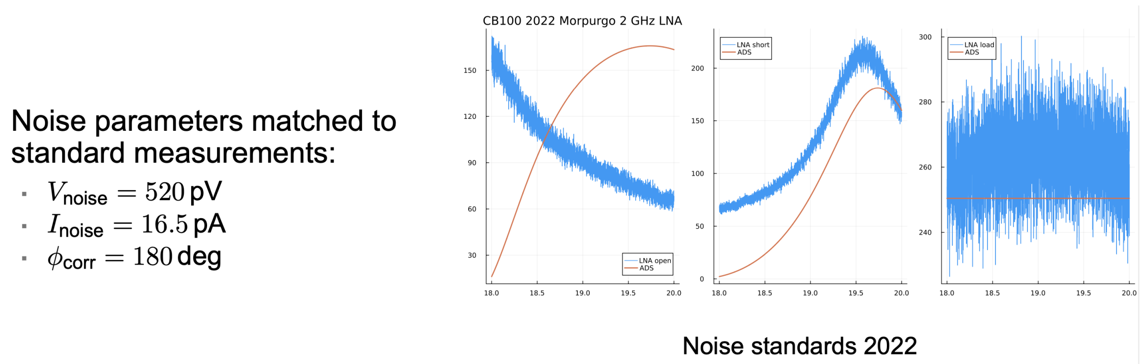

Figure 2.7: Measurements of the standards in 2022.

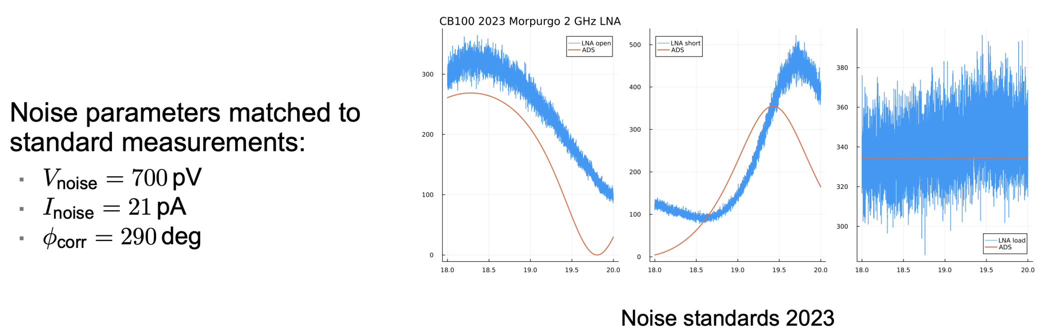

Figure 2.8: Measurements of the standards in 2023.

System noise

If we change the phase correlation between U and I, we influence the result of the fit in the extraction of to the length between LNA and booster. This changes the amplitude of the system temperature and produce positive-peak at the booster frequency. Moreover, by tuning the phase correlation, the model and measurements agree much better. See Figures 2.9, 2.10. This indicates that the length between LNA and booster plays a crucial and central role.

2.3.2 Thermal emission

We consider the booster components as black bodies. We defined the maximum emissivity as 1-absorbtion and that is what we assumed to extract the thermal emission of the mirrors. How much

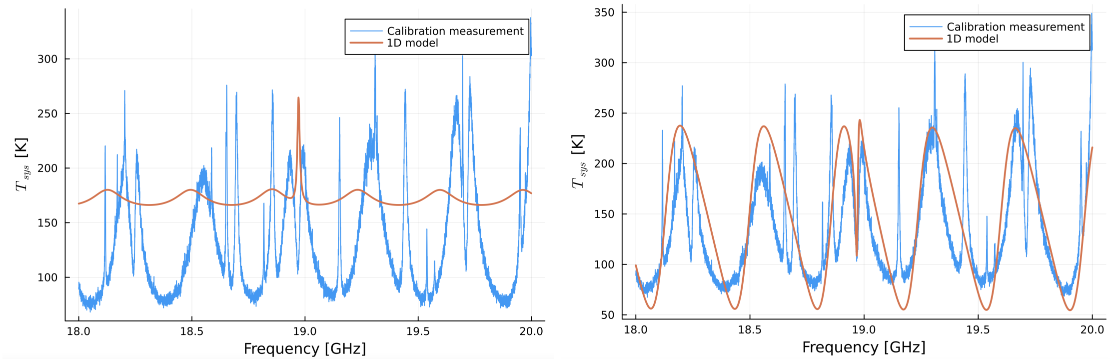

Figure 2.9: Noise system in terms of a frequency scan for 2022 data. Phase correlation is set to 180 on the left and 325 on the right.

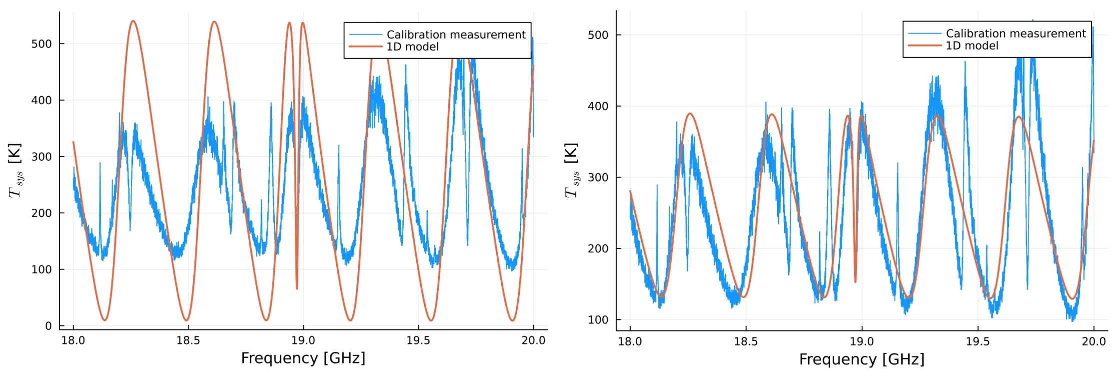

Figure 2.10: Noise system in terms of a frequency scan for 2023 data. Phase correlation is set to 180 on the left and 325 on the right.

is that assumtion true? We concluded that it is :). Moreover, the black body radiation equation is considered as emitted in the whole phase space of 4π but we need the emissivity for one side of the disk,so we need to divide by 2. The number insterted in the ADS model has to be double checked. Steps on the ADS simulation are presented as well as the parameters used!

2.4 Boost factor determination

With all the parameters in place, we can extract the boost factor. Couple of major differences between 2022 and 2023: booster peak position and maximum values. This comparison is done without considering uncertainties, which are now the focus of the presentation. See Fig. 2.11 for reference.

Uncertainties

The connector length uncertainty is the dominant one in the determination of the booster peak maximum. Like a lot! (see also Fig. 2.12, showing that effect). We performed a MC study where we generate 1000 samples of β^2, with parameters being varied within 1 σ (the σs are defined by feeling for the moment). The paramenters are reported in Tab. 2.1, together with corresponding uncertainties. See also Fig. 2.13 as reference. Moreover, we observe that the booster value has a lower threshold at 800. We can always claim, conservatively, that our boost factor is > 800, which

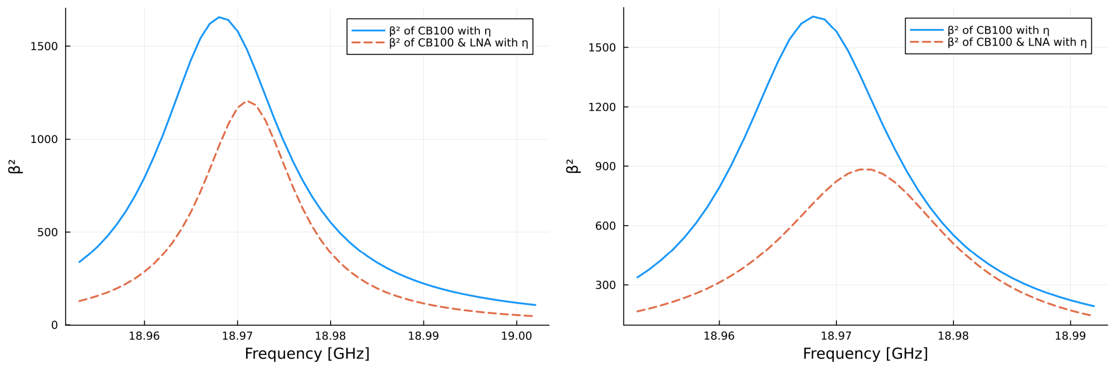

Figure 2.11: Boost factor in terms of frequency for 2022 (left) and 2023 (right) data-taking. Phase correlation is the only parameters that differs between the 2 data-taking periods: it is 325 in 2022 and 333 in 2023.

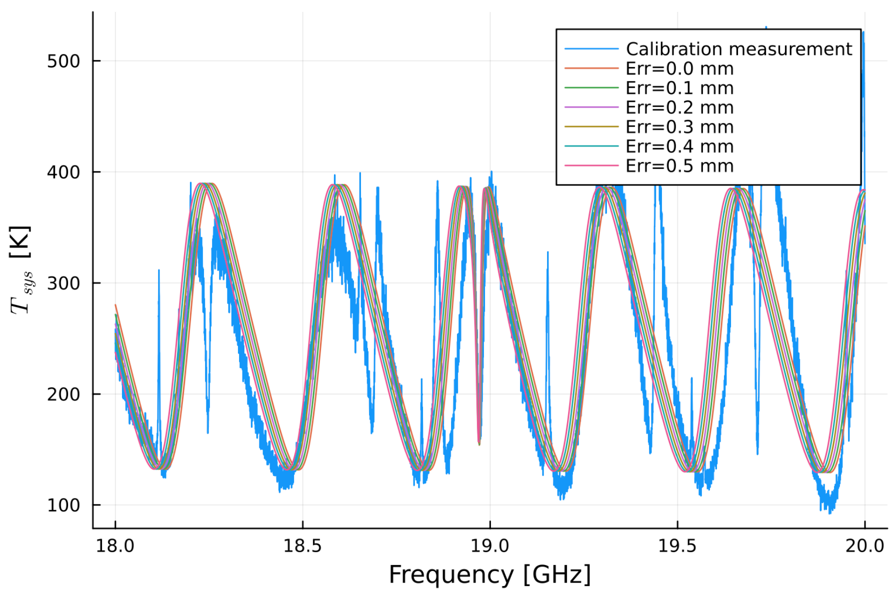

Figure 2.12: Frequency scan dependencies with the connector length.

I_{noise} [pA]	V_{noise} [pV]	ϕ_{corr}	L_{con} [mm]	T [°C]
21±1.05	700±35	333±50	134.7±0.5	20±5

Table 2.1: Uncertainties considered for the parameters given as input to the ADS model.

is good for the limit extraction.

We observe that for the 2022 data-taking the system temperature is smaller by 100 deg *wrt* 2023 which is suspicious (please refer to Figures **??**, 2.10). We do not know exactly how to proceed but it can potentially be an important point to understand.

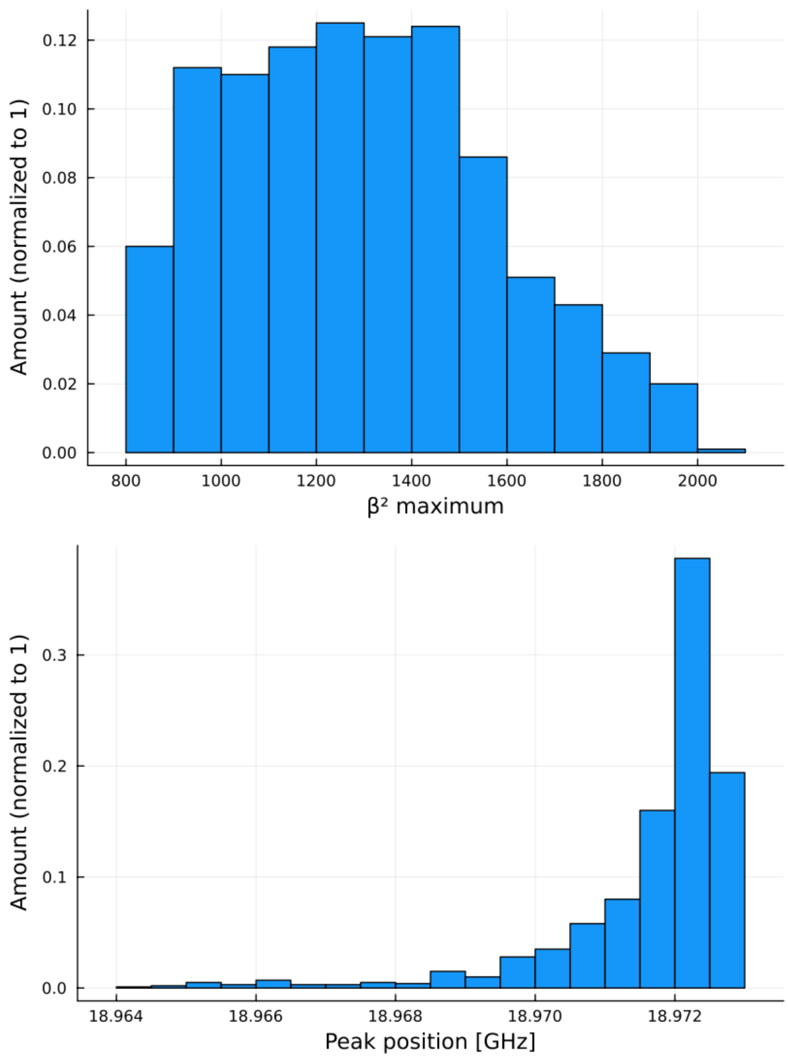

Figure 2.13: Boost factor uncertainty extracted from MC studies.

3. COMSOL

The focus is on CB100 simulation and what has been simulated for the 2023 data taking. In the CB100 system (amplifier, plus waveguide, taper and booster) the simulation acts on the taper + booster parts. Higher order modes are entering in the taper and the booster, and have to be reduced as much as possible to avoid the boost factor to be affected by that. The idea is to make a 1D simulation to check if the system is reacting properly at the discontinuities. We can compare reflectivity measurements with booseted signals, by injecting a signal into the VNA and understand how the axion field would behave (see Fig. 3.1). The VNA signal is reflected by the discontinuity (basically

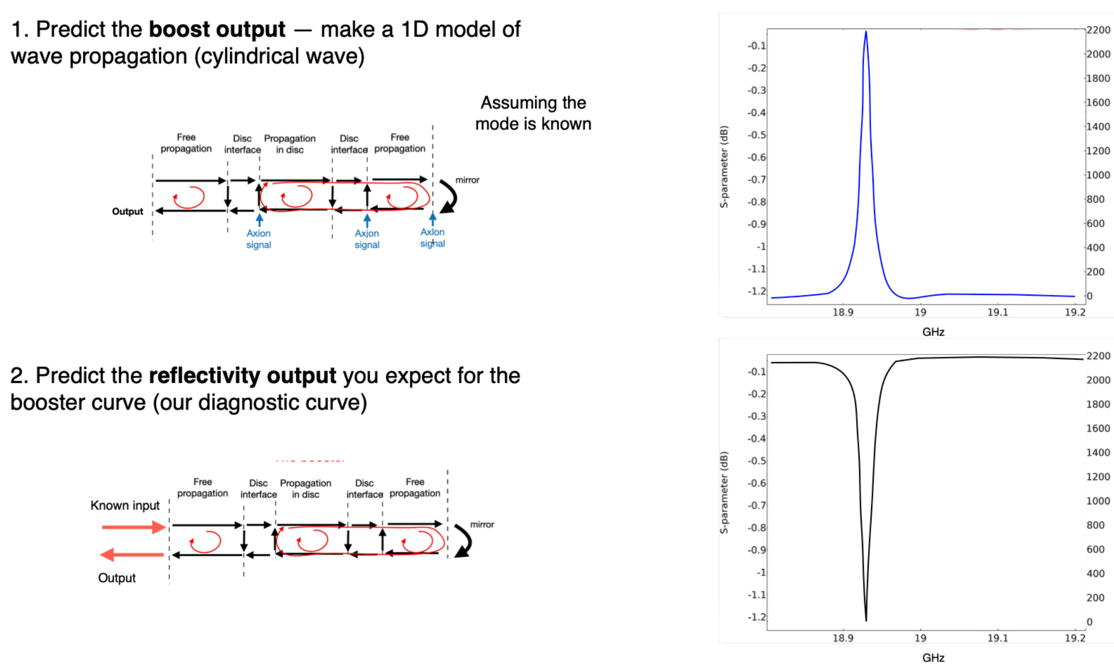

Figure 3.1: COMSOL 1D simulation results.

100%, as showm in point 2 in Fig3.1) until it resonates and it gets stuck inside the booster (working as resonator). This works with the assumption of a single mode propagation.
With COMSOL you can do better, and built a minimalist 3D simulation. First you simulate the single mode TE11 that is not coming with additional modes (from the interaction with discontinuities) because we assume everything being perfect, so no tilted disks and perfect mirror. Nevertheless, the electric field is affected by boundary conditions that produces border effects. The waves are reflected by the mirror and gets stuck mostly in the region between the very last disk and the mirror. This is the indication of a resonant system. One way of checking if the simulation is reliable is to check the booster peak, which is reproduced properly as it agrees with the ADS model results (therefore we assume the COMSOL simulation is ok). See Fig.3.2 for reference. Additional checks: -The axion

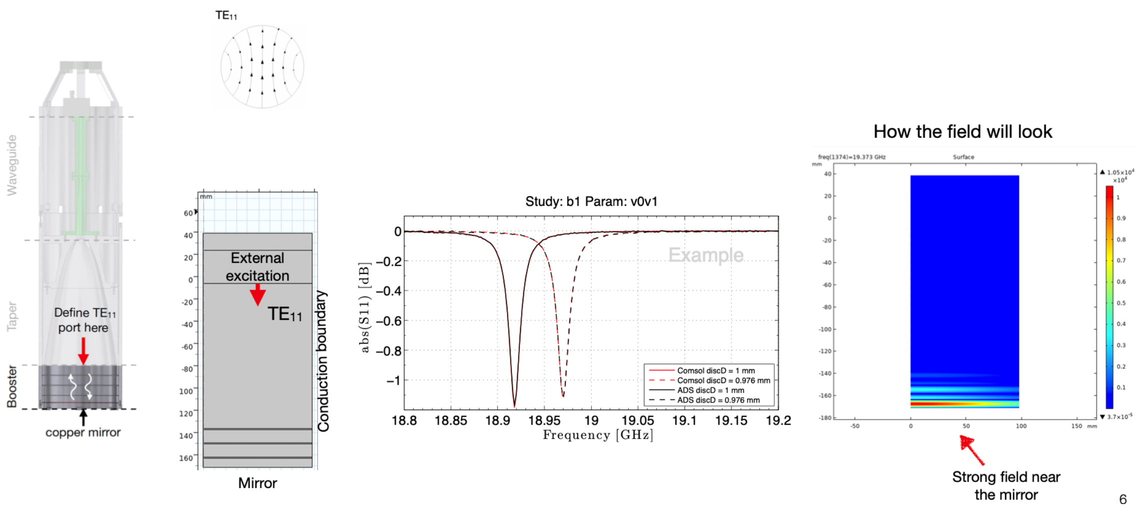

Figure 3.2: COMSOL 3D simulation results. This minimalist 3D simulation is validated with reflectivity and field distribution measurements on 1D models.

induced field has to be compared to TE11, to have an understanding if the simulated field properly represents the axion signal. By taking into account form factor effects, coming from the finite size of the system, the boost factor peak is reduced (see Fig. 3.3).

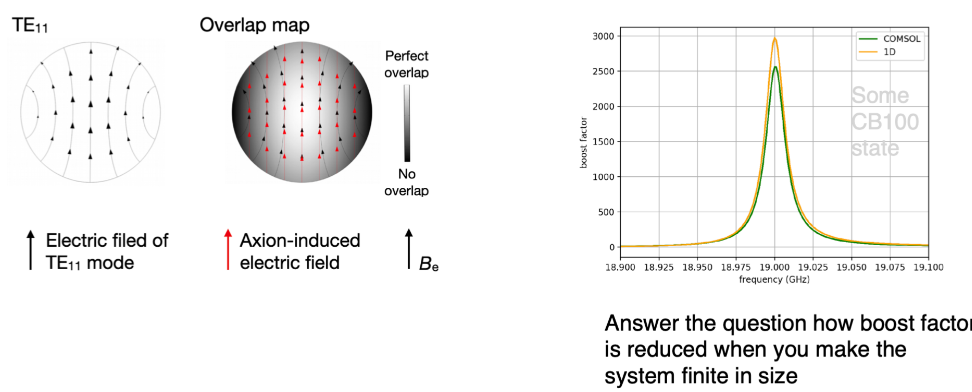

Figure 3.3: COMSOL 3D simulation results. The implement the axion field accounts for form factor effects.

Mirrors are modelled in ADS as a thick rectangular guide, and the behaviour is checked with COMSOL as well to demostrate that the same boost factor is reproduced properly. See Fig. 3.4 as reference.

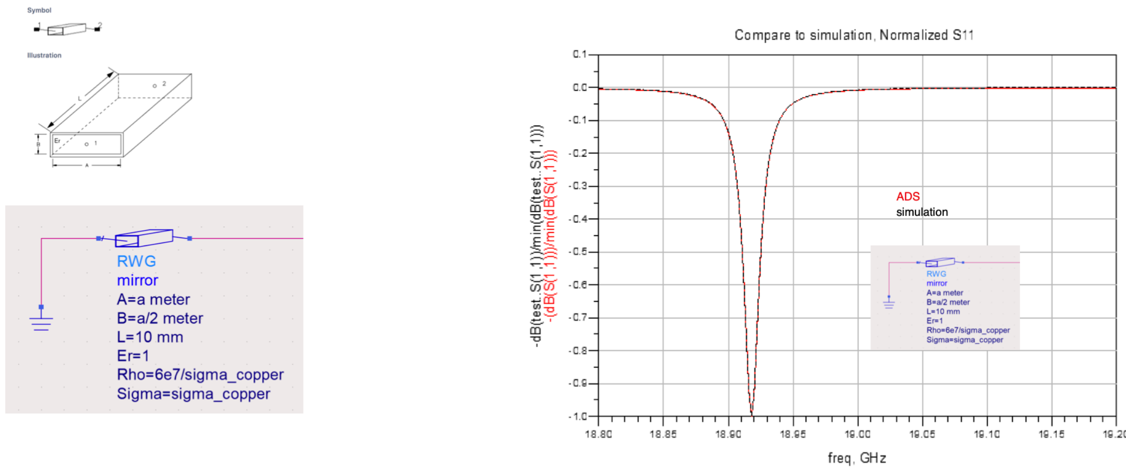

Figure 3.4: COMSOL 3D mirror simulation.

The taper is meant to transfor the field into a smooth one, so to get rid of the higher order modes. By exciting the main mode, the power is distributed to other modes and we can build a matrix that simulate such power transfers. The idea is to get a Generalised Scattering Matrix (GSM) that allows the power to be as much as possible going into the main mode. Note: the system allows the power to be transferred to higher order modes and to be trasnferred back to the main on. The schema in Fig. 3.5 shows how to extract the columns of the matrix by considering different inputs (like SX1, SX2 ..) and checking which other modes are being affected. Basically, waves are injected in one of the inputs and are reflected back to different inputs representing different modes. The ADS model

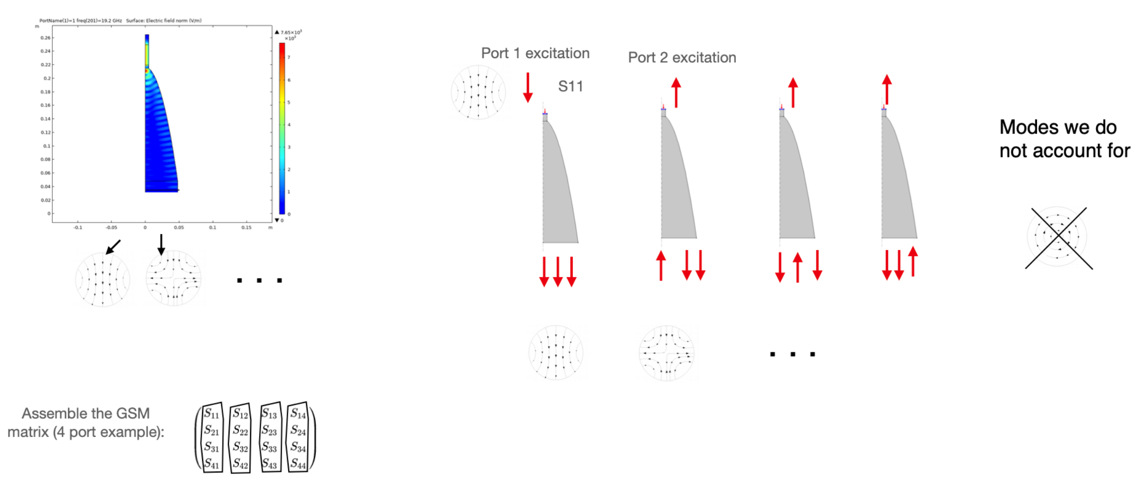

Figure 3.5: COMSOL 3D taper simulation, with excitation of higher order modes.

can reproduce higher order modes and we can compare the result in terms of frequency spectrum with COMSOL. The higher modes peaks are reproduced properly. Note: the presence of the peaks depends a lot on the distance between the mirror and the taper. See Fig. 3.6 for reference. Transverse

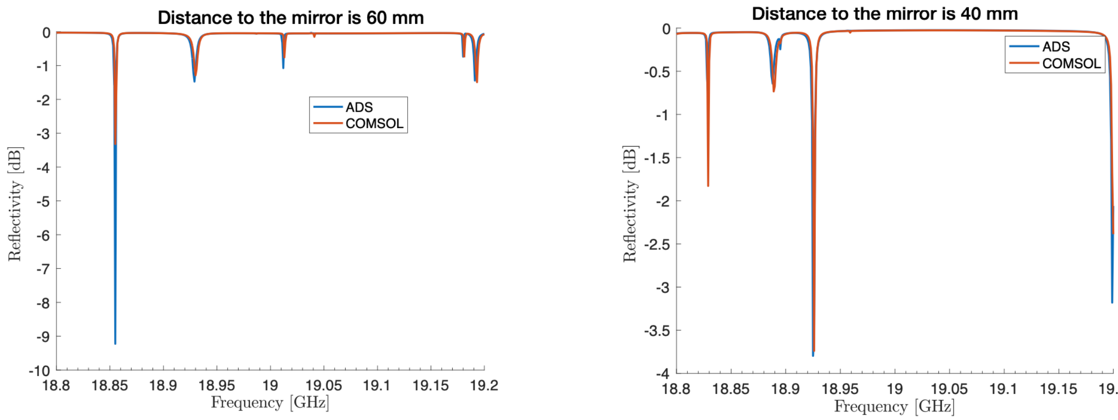

Figure 3.6: COMSOL 3D simulation results. They shows the reproducibility of the behaviour of higher order modes.

modes can also be excited in the booster by condsidering gaps between the discs and the boundaries. Such gaps come from the fact that the rings used to make space between the disks are not 100% matching to the disks dimensions. This effect can not be predicted properly, so COMSOL could provide a feeling about the behaviour of the effects. Results in Figures 3.7, 3.8 show that trasnverse modes are excited a lot by increasing the gaps. This changes the booster peak and width.

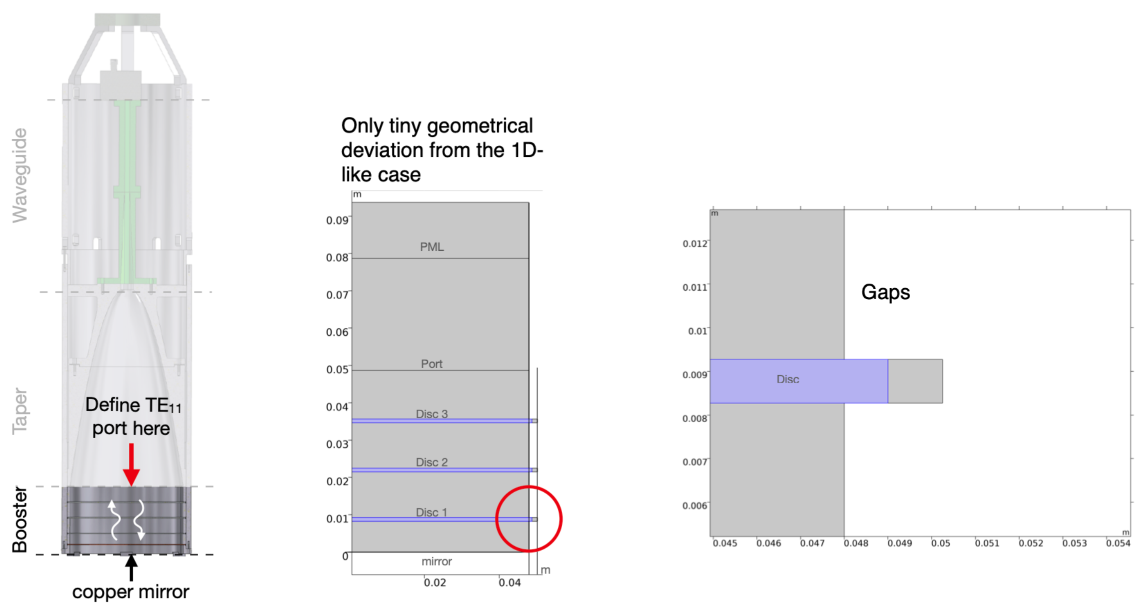

Figure 3.7: Description of the origin of the transverse mode excitation in the booster.

A small guideline of the files used in simulation is given. We are very sensitive to geometry and there are a lot of different sets of dimensions being used. We do not know which one are the "right" ones. Dimensions need to be centralised as official values.

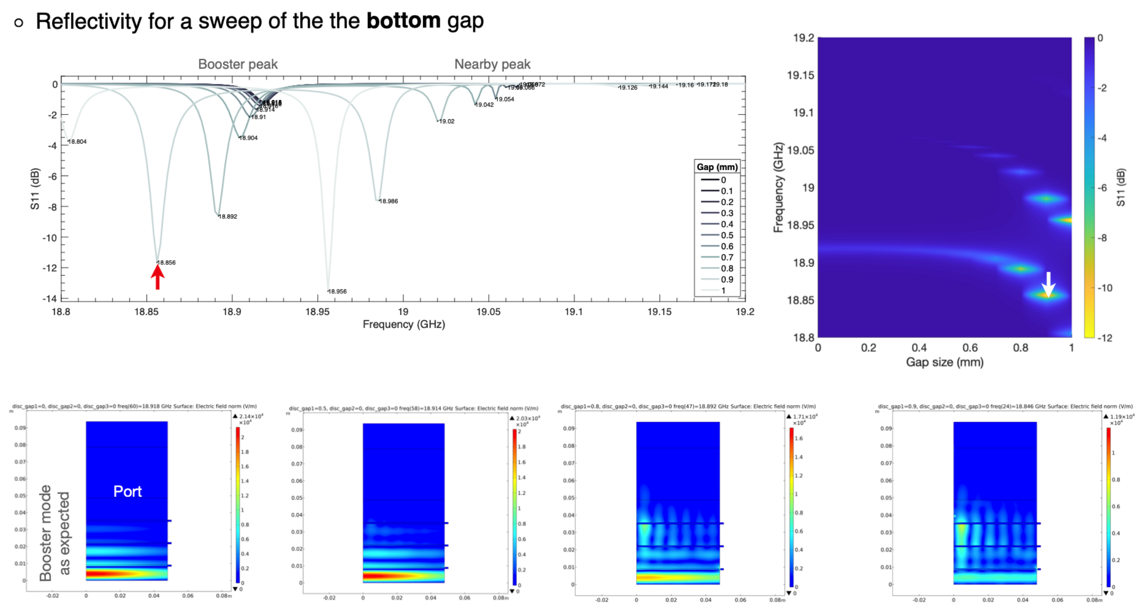

Figure 3.8: COMSOL 3D booster simulation results of the transverse mode excitation in the booster.

From old measurements we have the proof that COMSOL is able to reproduce the peaks from higher modes appearing in data (see Fig. 3.9). We do not have this yet for our current system, and we would need to reproduce it.

Figure 3.9: COMSOL 3D simulation result. It reproduces the peaks in the frequency ranges for 2022 data.

4. Statistical analysis

An introduction on analysis frameworks and what other experiments approach is is presented, followed by what Madmax would need to do to.

4.1 Introduction on Frequentist and Bayesian approaches

Frequentists consider the obtained data behaving as a gaussian function around the correct model. Confidence interval is the quantity the frequentists use to investigate if the data is compatible with a specific model-hypotheses, meaning that "If I repeat the measurement 100 times, I will be right 95 times". This check is done via a test statistics, e.g. by calculating reduced χ^2 and taking degrees of freedom into account. Test statistic needs to have known distributions, so that the reduced χ^2 (reduced means that χ^2 is normalised to the degrees of freedom) is converted to p-value.

On the other hand, Bayesians use priors, which describe the a priori expectation. This could influence a lot the final result, called posterior, in scenarios with weak data. Bayesians consider probability distributions for the parameters (θ) that are used to extract the posterior so: $P(\theta|data) = P(data|\theta) \times P(\theta)/P(data)$. Bayesianists use credible intervals instead, meaning that "95% of the probability density of θ after looking at the data that I have is in this interval". In this case, we compare Bayes Factor for two models/hypothesis M_1 and M_2: $\frac{P(data|M_1)}{P(data|M_2)}$.

4.2 Other experiments approaches

ADMX approach [**?**]: Vertical stacking procedure, weighting by Lorenzian to account for lower signals off cavity resonance. Use of the axion signal shape to apply a frequency-dependent filtering, and enhancing the signal to noise ratio.

Haystac approach [**?**]. Similar to ADMX but explanations much more detailed, much more sensitivity analysis and cross checks (complete list in the slides here).

4.3 Madmax case

What do we need to extract the confidence limit on $|g_{a\gamma}$, frequency dependence? Inputs about uncertainties on the raw power spectrum and boost factor, the magnetic field, disk size, impedance of the amplifier used to extract the Y-factor, and cuts applied on data. The statistical part of the analysis consists of background subtraction via an SG filter and statistical cross-checks using software-based synthetics axion signals.

4.3.1 Statistical analysis details

The statistical analysis is made of the following steps:

- Vertical stacking
- Synthetic Axion
- Background subtraction
- Gaussianity test
- Coverage test (perhaps)
- Limit setting

Vertical stacking

Vertical stacking combines different frequency spectra (at different times), and we could sum the spectra bin by bin. This could introduce problems with a frequency dependence of the booster peak in time. We could therefore correct the offsets and then sum. This comes with systematic uncertainties.

Synthetic axion

Synthetic Axion have equal SNR by definition. We simulate them with specific power, instead of a specific $g_{a\gamma}$, which should be known from calibration. The question is if we can produce a hardware synthetic Axion. Something should exist for 2022 data and was done preliminarily in Munich for 2023. Hardware synthetics are needed to investigate effects introduced by the receiver (transfer function). The signal is smeared to about 1MHz in width, while the booster peak is about 40MHz (in 2023). This would introduce problems for SG filtering if no parametric fit can be found for the background using simulations.

Temperature calibration

Non-linearity means having saturated signals which introduced non-linear behaviours in the receiver chain and/or SA. By comparison between the receiver chain (50 MHz range) and SA (2 GHz range) outputs, the results are very different. We have a measurement of the system temperature from the simulation as well and we need to take one of these results as correct. If we decide to combine the information, it should come with a systematic uncertainty defined from the difference between the different methods. For the 2022 data, we would take the 2 measurements (50 MHz and 2 GHz) and consider the differences as systematic uncertainties, since the simulation is data-dependent (inputs from data).

Background subtraction

Background subtraction can be done with SG filters (very difficult to improve it since it involves more complicated methods), and using Gaussianity tests to demonstrate the effect of different filtering choices (like HAYSTAC did). Another alternative is to properly model the backgrounds in ADS and subtract that in the fit.

Gaussianity test

The Gaussianity test for synthetic axion signal strength is more or less coded up already (using SQUARES statistics). Comparison between the un-modified axion signal to the case with SG filter applied and corrected for our specific case looks good. Gaussianity of the baseline is also checked, where results show that thermal noise is actually Gaussian-like for 2022 data (and a gaussian process with non-zero correlation length for 2023). For details see Fig. 4.1.

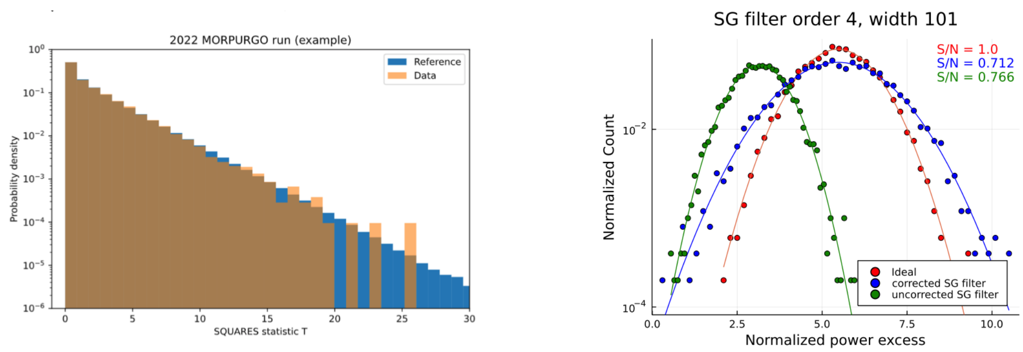

Figure 4.1: Plot showing the gaussianity of the baseline (left) and signal strenght (right).

Limit setting

The limit can be performed in a frequentist approach, where we define a Confidence Limit on the boost factor and proceed bin-by-bin to test the hypothesis of $g_{a\gamma}$=0 and $g_{a\gamma} = x$. $g_{a\gamma} = x$ produces some excess with known mean and standard deviation so that the probability for the data being produced by either one of the models can be compared. We need to find x so that $g_{a\gamma}$=0 is significantly more likely than $g_{a\gamma} = x$ with a p-value of e.g. 0.05 for $g_{a\gamma} = x$. This is a reliable approach if the axion signal is all inside one bin, which is why e.g. HAYSTAC is horizontally merging datapoints weighted by the expected axion line shape. A Bayesian approach could more easily take the full probability distribution of the boost factor from ADS into account as a prior and extract the posterior probability. However a major obstacle for using Bayesian statistics is that proper priors for ALP $g_{a\gamma}$ predictions do not exist in our parameterspace. In such scenario limit setting in a bayesian fashion is a dirty business due to high dependence of the limit on the prior, no matter how conclusive the data is. In the end, we would not follow a Bayesian approach for the paper since it would require non-standard and potentially disputed statistical methods, but the feasibility will be still checked. Most probably a frequentist approach will be the official one.

4.4 Streamline codebase

From Fig. 4.2 we would have a DESY GitLab repository for each block: raw+calibration, boost factor determination, monitoring and peak search. It has already been set up by David, here here by logging in from here. The slides are self-explanatory :)

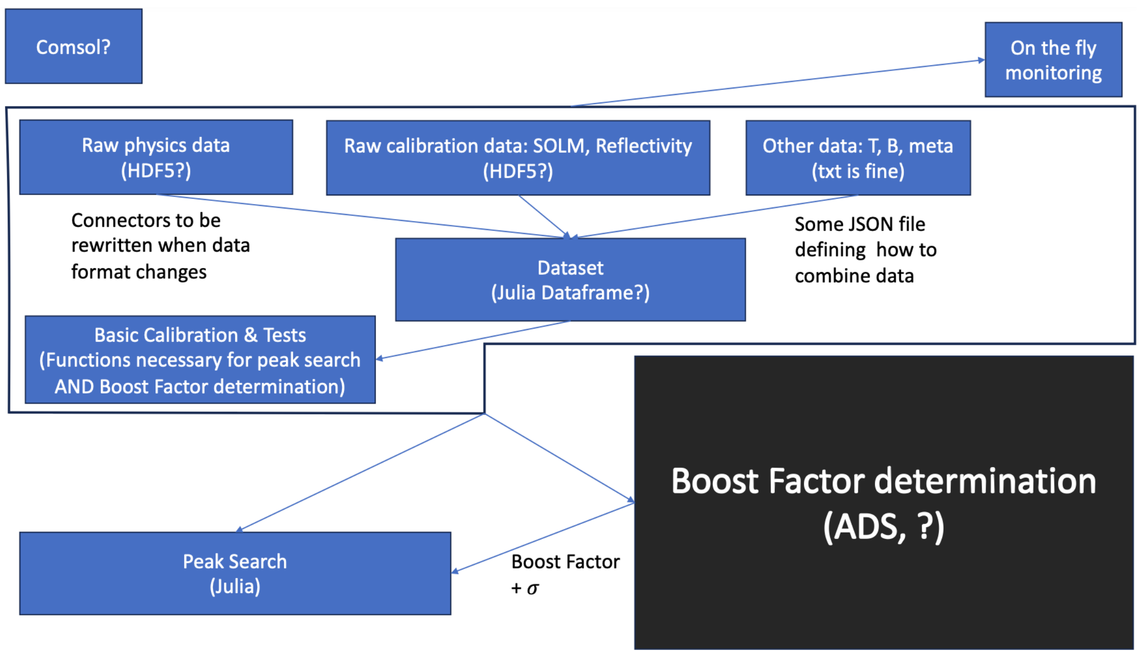

Figure 4.2: Streamline codebase sketch.

5. Organization

Proposal for the main responsibility roles:

- Analysis team coordination: **Alberto**
- Power calibration: **Bernardo** as responsible. David + Anton also contributing
- Boost factor determination: **David** as responsible. Anton + Bernardo also contributing
- Data monitoring: **Dagmar** as responsible. Vijay + Juan also contributing
- Peak search: **Johannes** as responsible. Vijay also contributing

What are the various groups about?

Analysis team coordination: coordinate the whole analysis process to proceed towards pubblication.

Power calibration: take care of the whole calibration process. This provides a lot of inputs to the ADS model for the booster determination.

Boost factor determination: use ADS to extract the boost factor used to get the final limit for MadMax. This serves as input for the Peak finding group.

Data monitoring: replicate the results obtained for 2023 data taking also for the 2022 one. This allows us to be sure that the data we use is in a reasonable shape.

Peak search: extract the final sensitivity with a proper statistical framework.

6. External talks

6.1 CREST+COUSING Analysis overview

Raw data (what come out from hardware-trigger, basically just threshold amplitude) coming out from the DAQ. Then skim a bit the samples and extract key quantities ending with some physics results. They write everything (in terms of digits, not full waveforms) passing the hardware trigger and the main bottleneck is to have a fast system that allows to continuously acquire data. They proceed with a partially blind analysis, looking at the 10% of data, which is then burned but it's important to have a first look at the data and initial checks. They rely on ROOT, usually they call functions from terminal. They also have a GUI that they can use to look at the streams of data so to have a DQM (Data Quality Monitor) system. They ideally want to make the final analysis that rely on a specific bach system (such strategy is not very well followed today) but it's getting stuck due to excessive accesses. They do not want to work on this because they have problems only at the unblinding stage. They have backup disks that can be used by different groups and shared widely (to be sure data is not lost). MPCDF is a nice tool but we can do the analysis on a dedicated batch system. Having CERN recognition is always good to have, so to have access to all the services that they pay for already. They suggest to exploit it but still have some "private" solutions. COUSIN uses Labfolder as an eLog system (instead of writing in a notebook what happened in the lab) but CREST uses eLog. We can check different solutions for us.

For the first analysis step (low-level analysis) they use 2 main packages: one in CC and a new one in Python. The python one is mostly used in the first steps of the analysis to help newcomers understanding the analysis. They uses software as container system so that all dependencies and packages are already installed in such containers, that you can use blindly without any software-related issues. Also, if you upload a code in GitLab, the system automatically creates a (Docker-) container so that it is available to everyone.

High level analysis (I lost it eheh) They have "Cryocluster Discourse" to ask the collaboration for feedback on software-related issues. The questions, and answeres, are stored online.

6.1.1 Workload division

PhD and Postdocs are focused on the main analysis, hardware and simulation. They can then fix issues and/or develop new features. Having two packages (C++ and Python) helps in double check the results. They have some "packages" for newcomers: bootcamp recordings, Indico links with documentation and Discours.

For analysis reproducibility, they stored scripts on GitLab for the final analysis (basically unblinding), so that they can immediately feel how the analysis flow is working and reproduce the final result in 1 week. This allows them to reproduce the results in the future.

6.2 LEGEND data handling

HDF5 files: matrix-like data stored. Each column is a vector of vectors. Metadata: JSON files, used in cascade. So you can overwrite information of specific data taking periods. validity JSON are assigned to make some dataset valid, or outdated or just wrong. To make the files being readable by everyone, goal is to press a button and make the analysis, they use Snakeman (Nextflow not optimal).

Dataflow: raw -> dsp-opt (filtering stage) -> dsp-digital signal process (extract key quantities) -> calib -> events Data stored with a logic behind the name, so to include key info of the dataflow steps.

Snakemake is making new fils from original ones, by passing through configuration files, telling Snakemake how exactly to make the new file.

Hands-on tutorial on how the whole data production system is structured. Mistakes and bugs are tracked in the log given as output."