Cold cal update

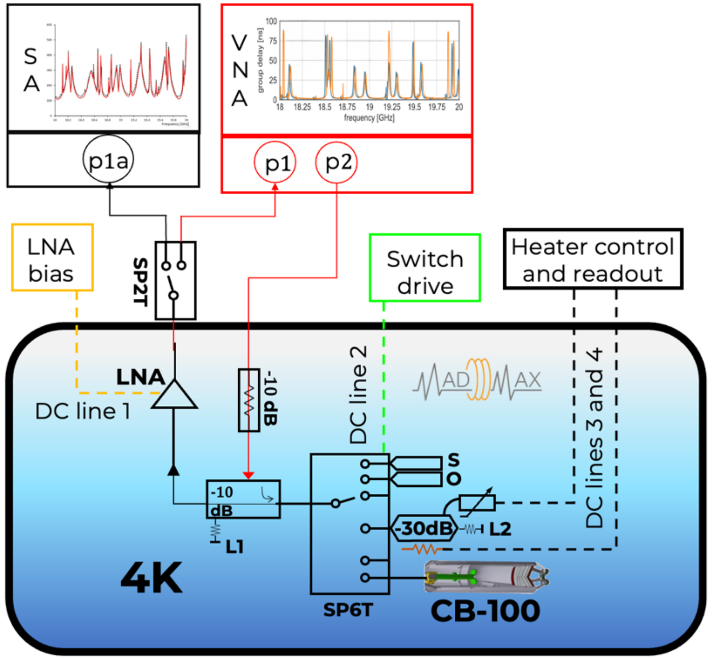
Juan

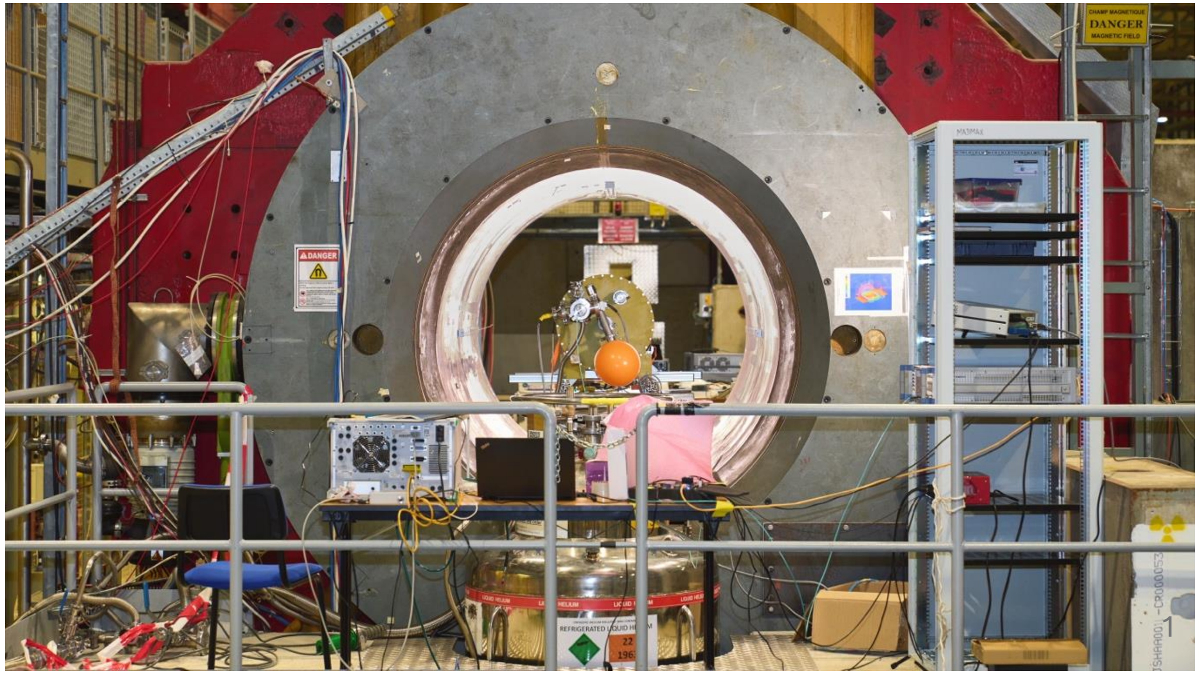
MADMAX summer meeting

03/07/2025

Summary

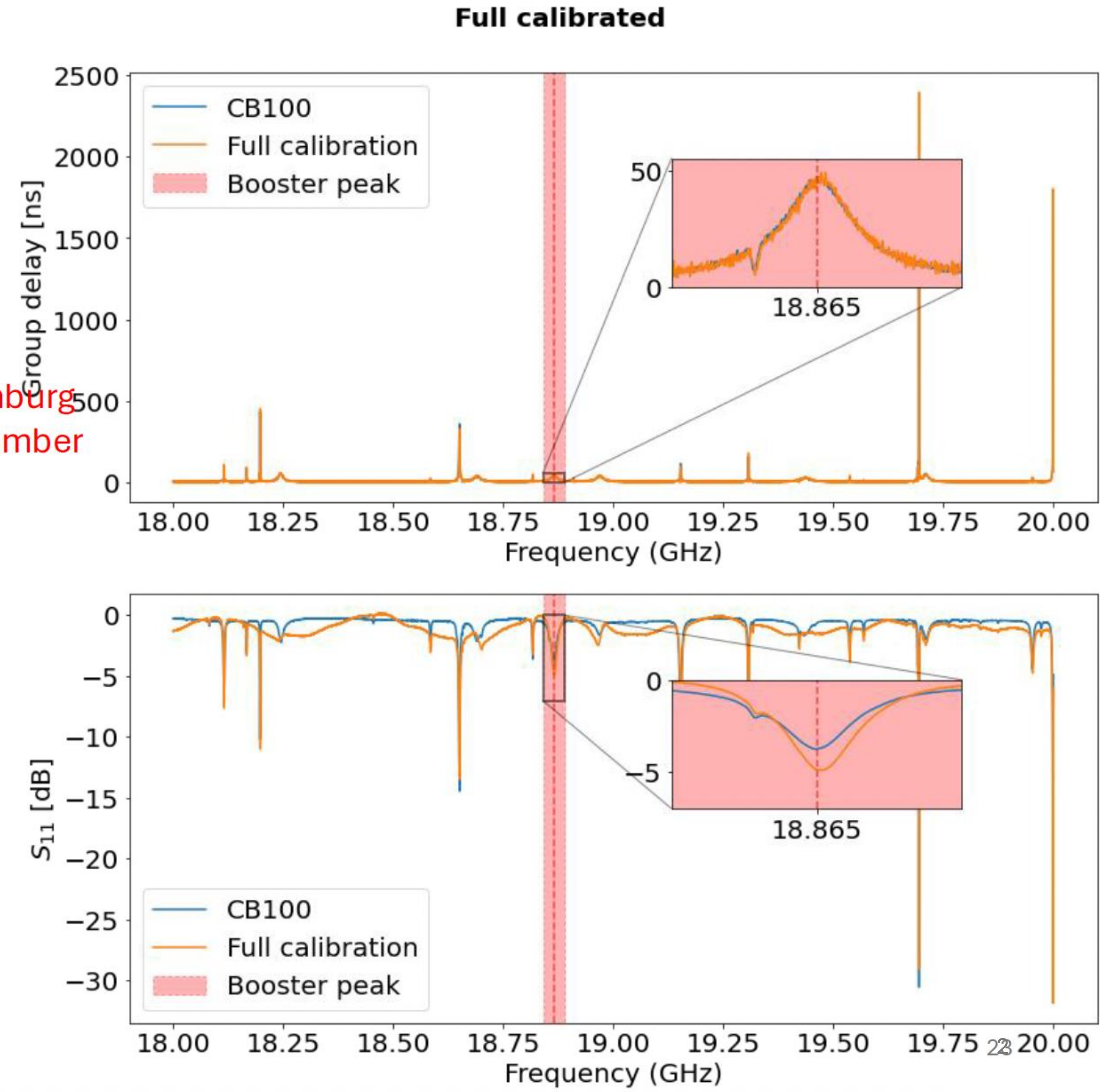
- Goal: analyze the data collected at CERN 2024 to get an ALP limit
- Way: Calibrate the system so a boost factor can be extracted
  - “Calibrate”: Noise calibration (Power → Noise temperature), reflectivity (get S parameters of CB100 at 4K)
  - Proposal: Cold calibration setup to apply a 1-port error correction model





Comparison after using cold calibration setup + one-port error model

Slide taken from Hamburg collab meeting, December 2023



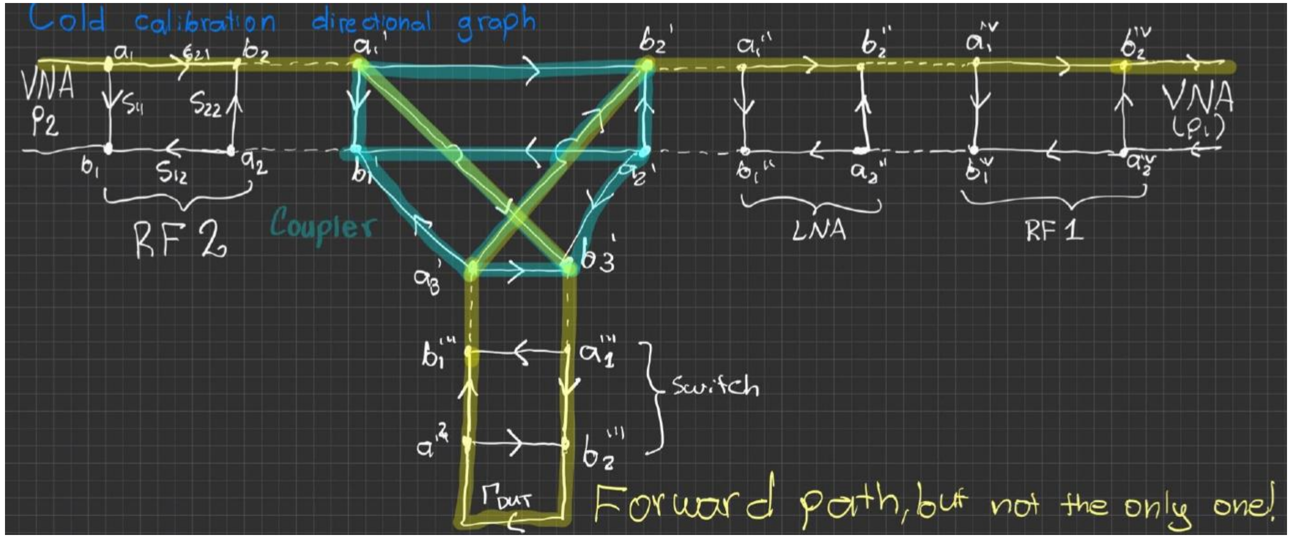
Back then we judged this to be good enough given the ~ 2% uncertainty obtained in group delay.

We agreed that the phase information (contained in group delay) could probably give us enough accuracy to obtain boost factors distributions from it.

Assumptions

- Model works given these three assumptions:
  - The setup can be modeled as a 1-port network → Signal graph theory mathematical check (And now also measurements, see next talk)
  - The standards are independent and very well known → NOT the case (this talk)
  - The VNA measurements can be trusted → NOT the case (next slide)

Aim: given the only partially fulfilled assumptions, how much information can we extract?



“The VNA measurements can be trusted”

We gathered evidence little by little pointing to the possibility that the VNA was malfunctioning:
-Anton not able to to a waveguide calibration
- Alireza seeing fictitious gain right after a calibration was performed
-   Calibration had expired in 2023
-   Cold cal calibration giving problems?

We sent both VNA and autocal kit to be inspected

> *“The module measured out of specification, so I tried to recalibrate it. Unfortunately it seems that the module is defective and needs to be repaired. We can’t do this in the service center in Munich, it would need to go back to the factory for repair and recalibration”* – Anritsu rep.

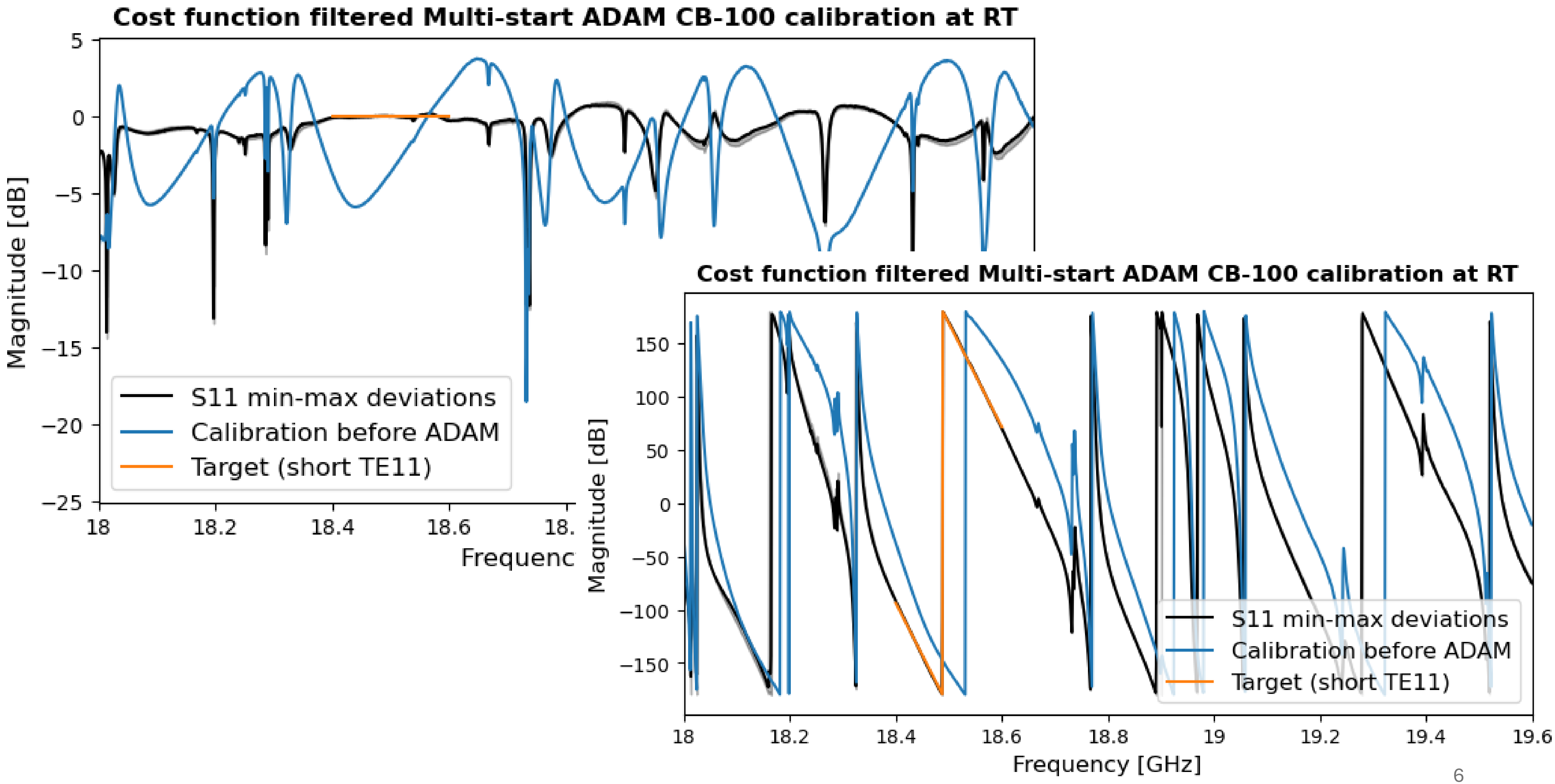
“The VNA measurements can be trusted”

We purchased a new auto-cal kit (b.c. we should in general have 2)

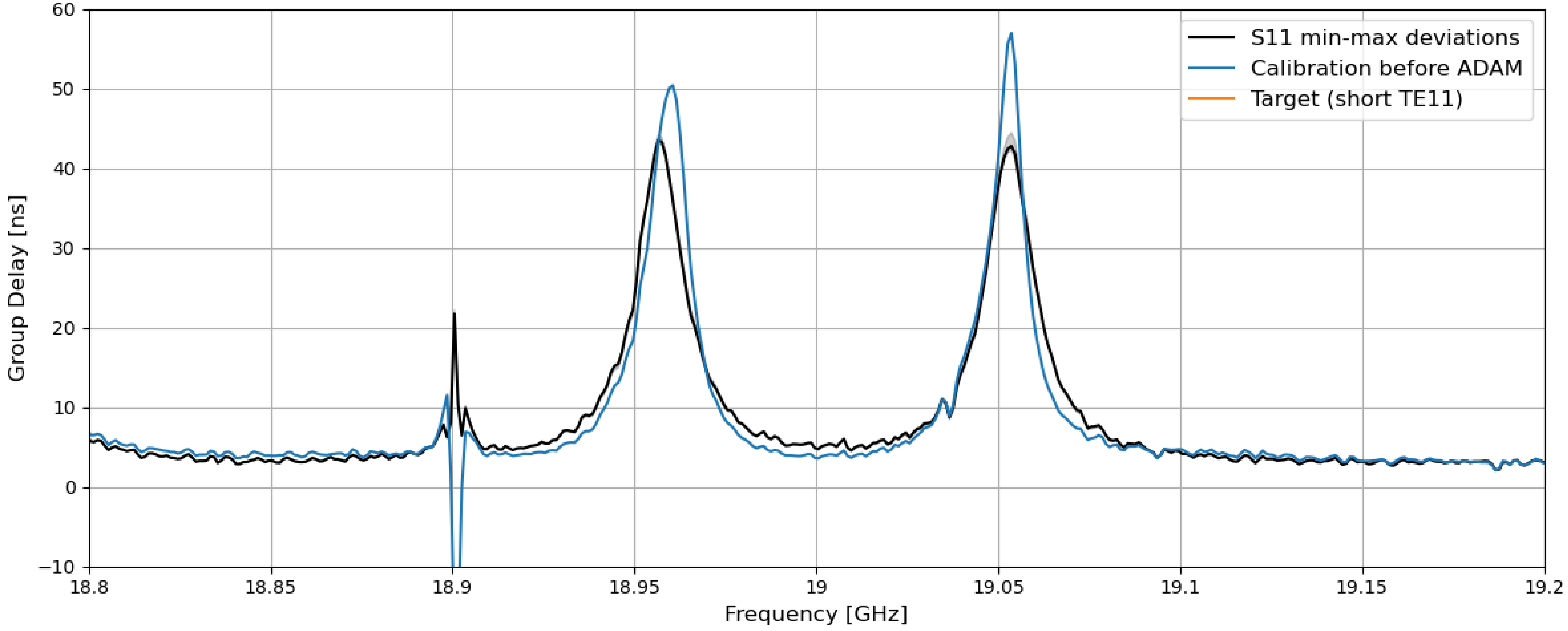
Repair cost is 13kEur. This may be a good opportunity to instead of repairing it, buy a f-f or f-m complementary kit (thus avoiding excessive de-embedding steps of male-male components)

Effects of this new auto-cal kit in cold cal measurement at RT investigated in the next talk!

Cryogenic case



Cryogenic case



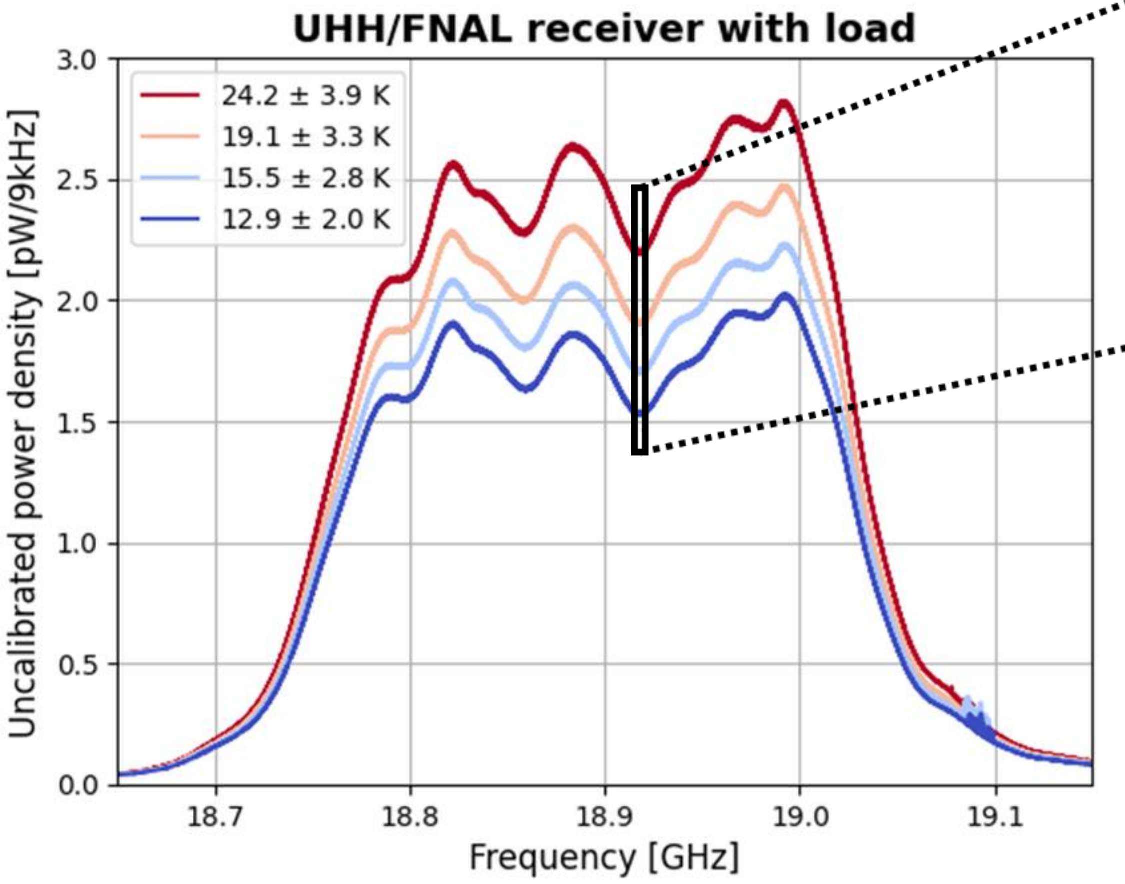
Conclusions and ongoing work

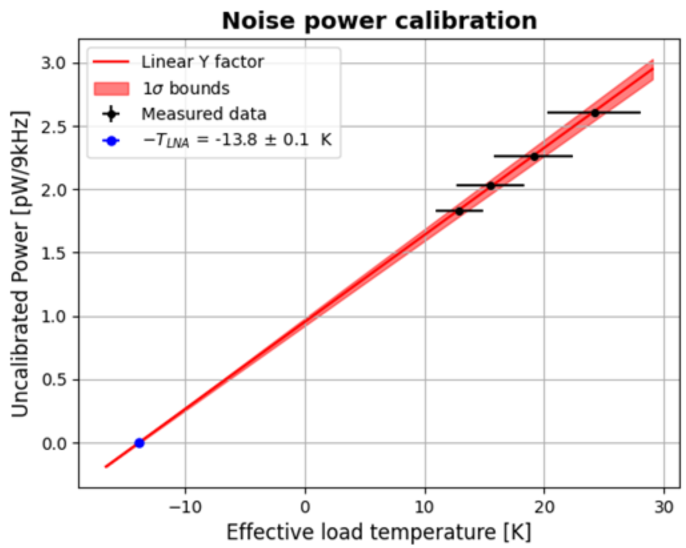
- Effects producing uncalibrated effects studied. Applicability of one-port model, improved measurements (next talk), partial knowledge of standards
- What are the uncertainties related to this approach?
- Can these files now be used to extract a boost factor?

What happens for OB300@CERN?

OB300@CERN

Noise calibration probably only needs to be repeated as for CB100@CERN



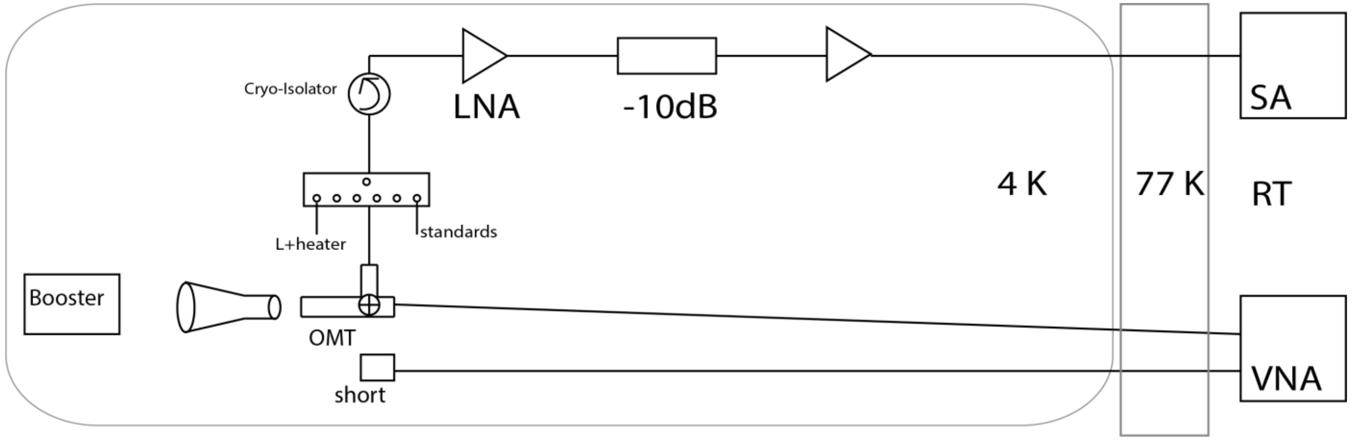


OB300@CERN

Reflectivity calibration should be improved (reducing complexity and uncertainties) by:

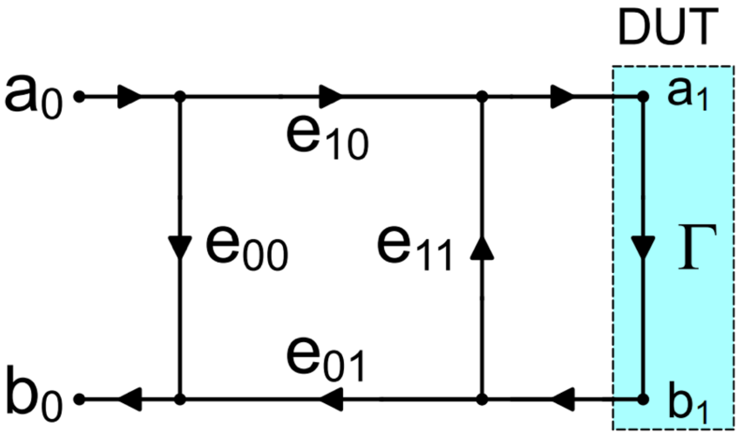
- Making sure the measurements are not ‘contaminated’
  - Save auto-calkit results but also raw results (without calkit itself)
  - Make sure the VNA calibration has not yet expired by the time we take the measurements at CERN
- Know your standards as good as possible or use a calibration scheme that does not require a-priori knowledge of standards
  - Measure S,O,L at 4 K and de-embed them: Fast Lhe dipstick cryostat being prepared should be useful for this. Requires several thermal cycles
  - Use TRL 2-port calibration (I claim this also enables Alireza’s OMT proposal, real-time DAQ, homodyne detection, etc)

OB300@CERN – Simplest setup



Not tested yet

Take the 1-port model



$$\Gamma_{DUT}^{M} = e_{00} + \Gamma \frac{e_{10}e_{01}}{1 - e_{11}\Gamma}$$

Use 1 identical cable connected to a short, get rid of e_{11}, e_{00} by time-gating, assume perfect short reflectivity. Then, instead of 3 unknowns, we only have 1: $e_{10}e_{01} = S_{11}^{\mathrm{M,\,short}}$

OB300@CERN – TRL 2-port calibration

One of KC's collaborators

Two-port microwave calibration at millikelvin temperatures

Leonardo Ranzani,[1,a)] Lafe Spietz,[1] Zoya Popovic,[2] and José Aumentado[1,b)]
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In this work we introduce a system for 2-port microwave calibration at millikelvin temperatures operating at the coldest stage of a dilution refrigerator by use of an adapted thru-reflect-line algorithm. We show that this can be an effective tool for characterizing common 50 Ω microwave components with better than 0.1 dB accuracy at temperatures that are relevant to many current experiments in superconducting quantum information. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4794910]

Done for frequencies below 8 GHz, but other groups have published similar results up to 18 GHz [https://eprintspublications.npl.co.uk/9924/1/eid9924.pdf]

Reason why we did not pursue this in the beginning: Many components, considerably space@4 K needed: 'Keep it as simple as possible'

OB300@CERN – TRL 2-port calibration

Instead of assuming full knowledge of cal standards, one assumes:

$$S_a^T = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Perfect thru: easy: using a female-male kit

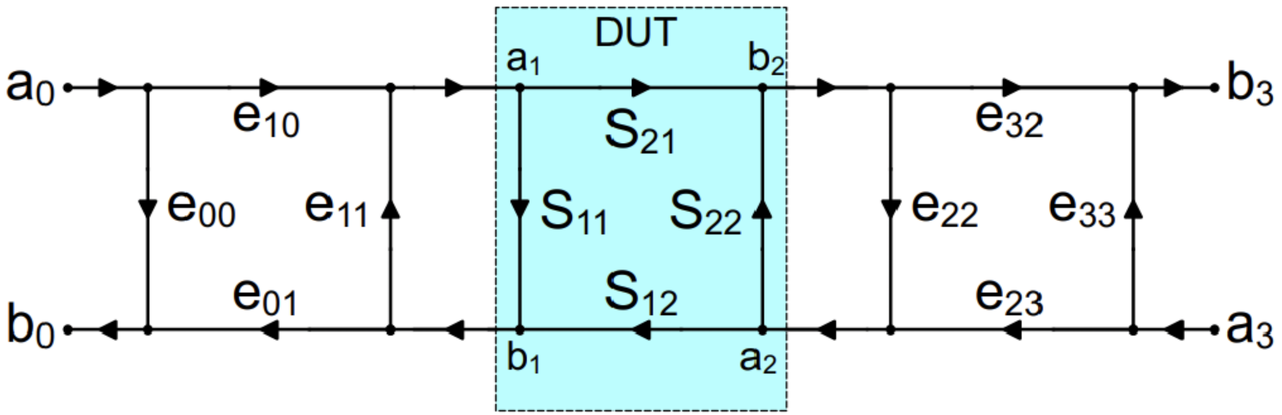
$$S_a^L = \begin{bmatrix} 0 & e^{-\theta} \\ e^{-\theta} & 0 \end{bmatrix}$$

Lossless (and perfectly matched) line. **Not easy!** (e.g., impedance mismatches causing return losses due to the different shrinking ratios of outer and inner conductors)

$$S_a^R = \begin{bmatrix} \Gamma & 0 \\ 0 & \Gamma \end{bmatrix}.$$

Reflective standard: easy. A short should do.

OB300@CERN – TRL 2-port calibration



$\mathbf{e_{00}}$: port-1 directivity
$\mathbf{e_{10}}$: port-1 trans. tracking
$\mathbf{e_{01}}$: port-1 reflect. tracking
$\mathbf{e_{11}}$: port-1 match
$\mathbf{e_{22}}$: port-2 match
$\mathbf{e_{32}}$: port-2 reflect. tracking
$\mathbf{e_{23}}$: port-2 trans. tracking
$\mathbf{e_{23}}$: port-2 directivity

The 2-port error model has 8 unknowns, but TRL standards provide 10 measurements:

- Thru: 2-port measurement (S11,S12,S21,S22)
- Reflect: 1-port measurement (S11), 2 reflects measured in total
- Line: 2-port measurement: (S11,S12,S21,S22)

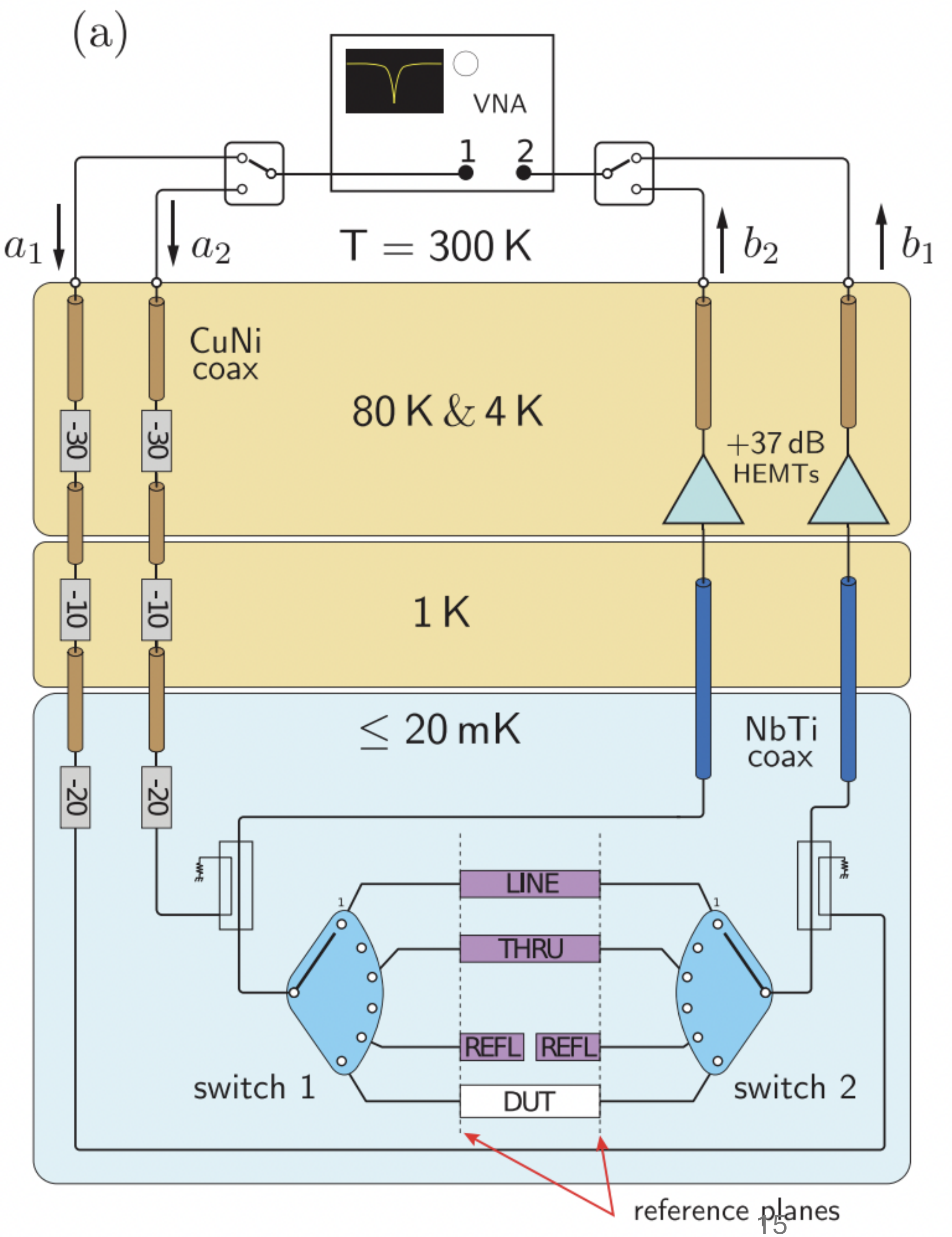
Total = 4+4+2 = 10

But these are not independent....??

TRL 2-port calibration

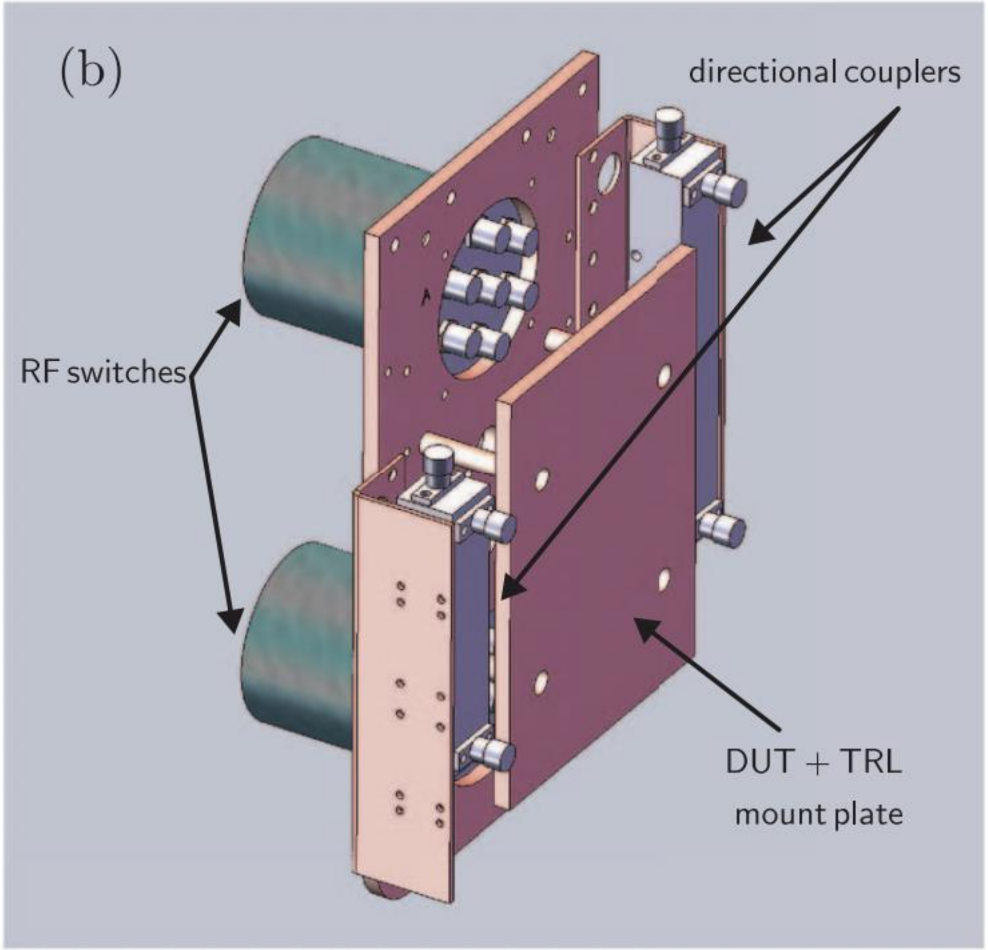
Setup: You can think of this as basically mirroring the CB100 Cold cal setup, roughly twice the components needed

- Either a 4-port VNA or a 2-port VNA with 2 SP2T RT switches (our case). So far: 1 SP2T available, another one purchased
- Cryogenic coax cables. They use semi-rigid superconducting cables. We will use due to less stringent heat load requirements and more strict flexibility needs the already tested in CB100@CERN flexible cryogenic coax cables. All available

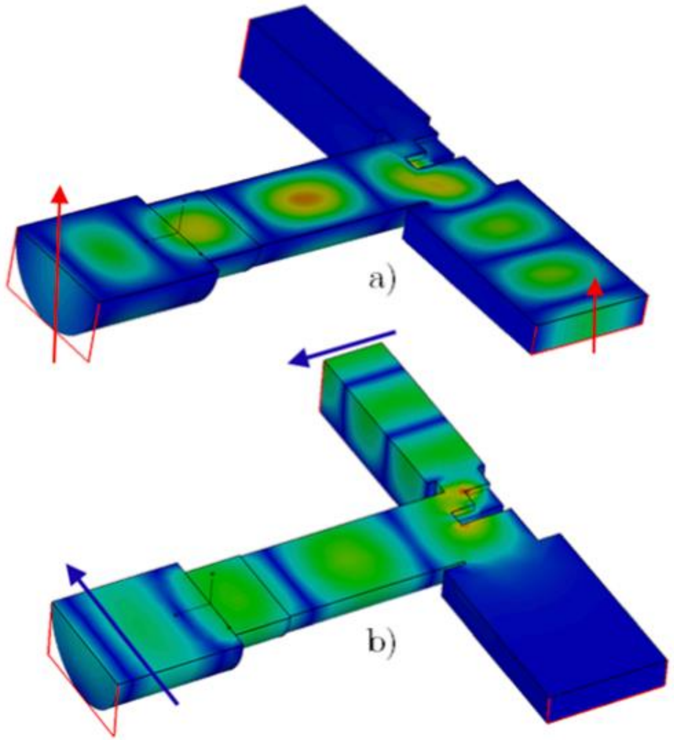


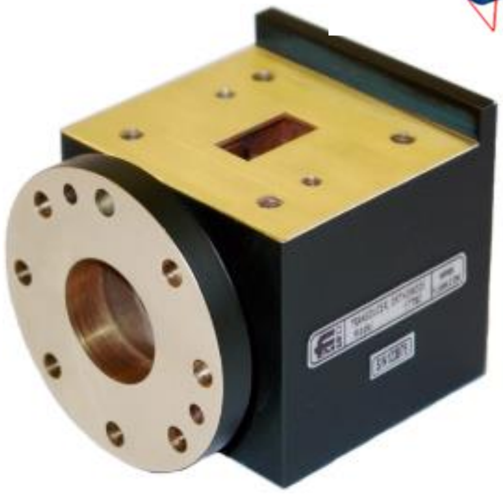
TRL 2-port calibration

- Set of cryogenic attenuators to thermalize inner conductors and reduce RT radiation leaking into the cryostat: I think we have all needed
- 2 SP6T cryogenic switches: We will use 2 Radiall cryo switches operating up to 26 GHz + QPHox controllers. We haven’t made it work yet but we should be close
- 2 cryogenic directional couplers. We have purchased both and they’re at MPP
- TRL calibration standards: We purchased kit from Focus microwave, to be seen if it works at both RT (next talk) and cryo
- 2 cryogenic LNAs. We have several at MPP



What is an orthomode transducer?





An **orthomode transducer** (**OMT**) is a 3-port passive component that is commonly referred to as a *polarisation duplexer*.

It is usually used in radioastronomy and radiometers.

Orthomode transducers serve either to combine or to separate two **orthogonally polarised** microwave signal paths.

An orthomode transducer (OMT) is NOT a power divider!!!

OMT replaces the waveguide (we can see it as a combination of two waveguides)

Slide from Dagmar, HH Collab meeting 02/2025

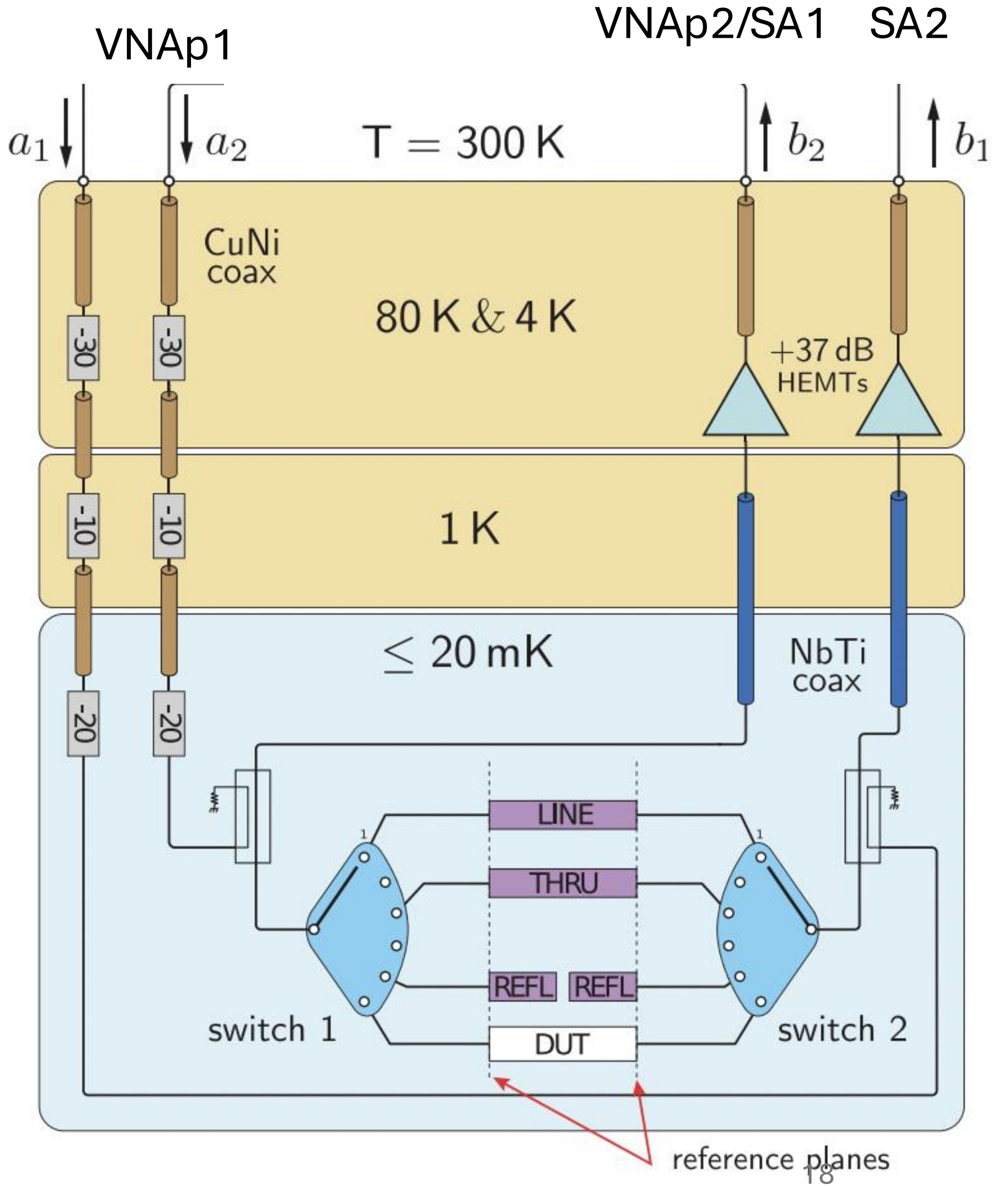
OB300@CERN – TRL

With an OMT, OB300 becomes a 2-port device (like the DUT in the image), even if $|S_{12}| < -50\ \mathrm{dB}$.

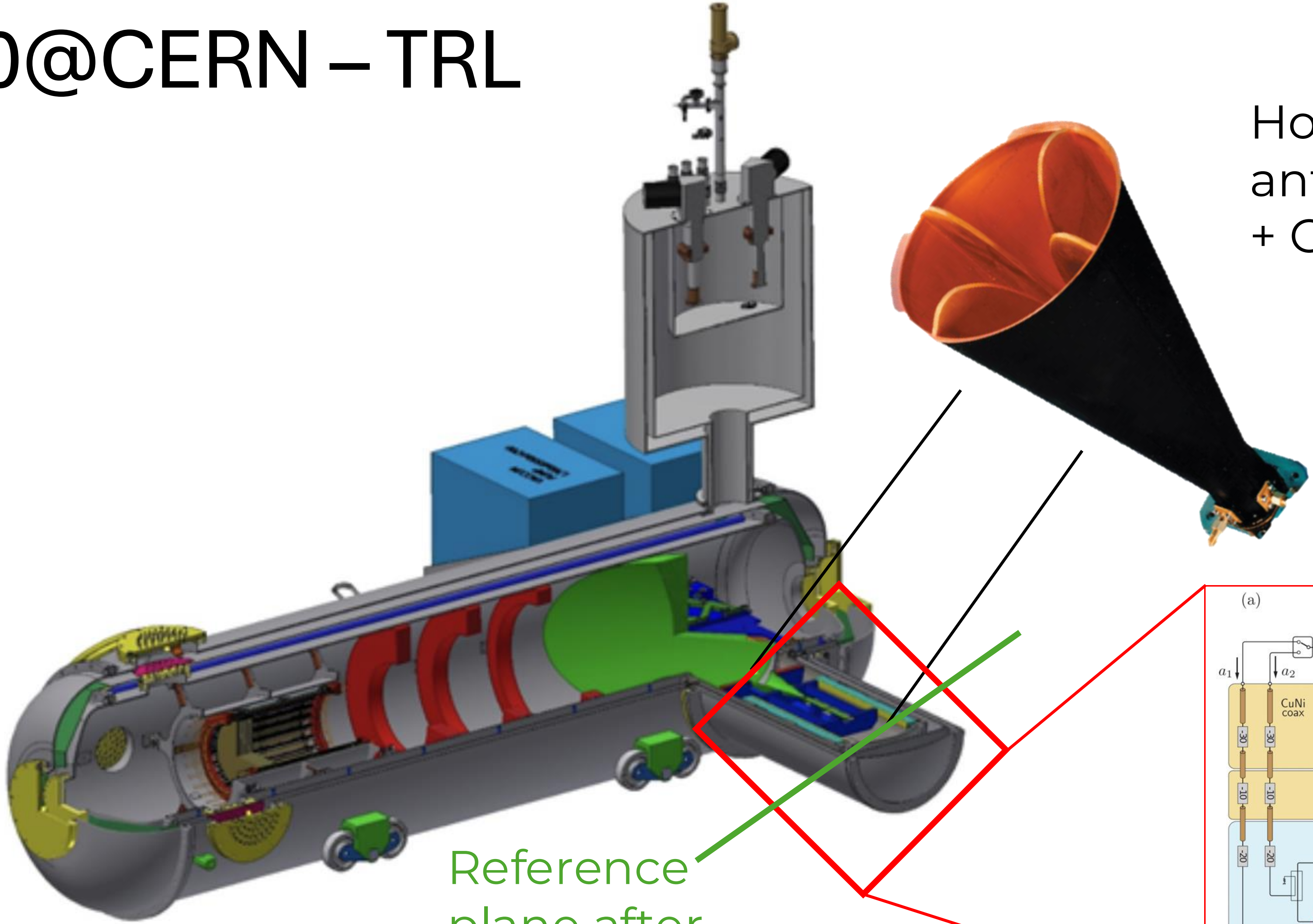
This enables many more possibilities such as:

- Radiometer techniques (homodyne, lock-in, time-domain DAQ)
- RFI, background real-time control with one channel, axion run with the other
- Real-time VNA check-ups
- ?

OMT in its way to MPP, should be measured at RT by Ali&Genia in August

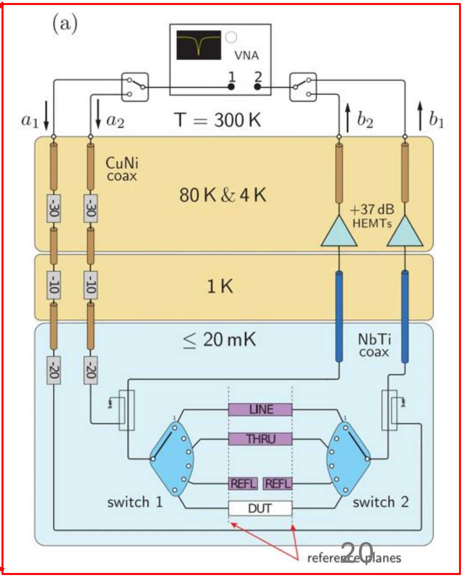


OB300@CERN – TRL



Horn antenna + OMT

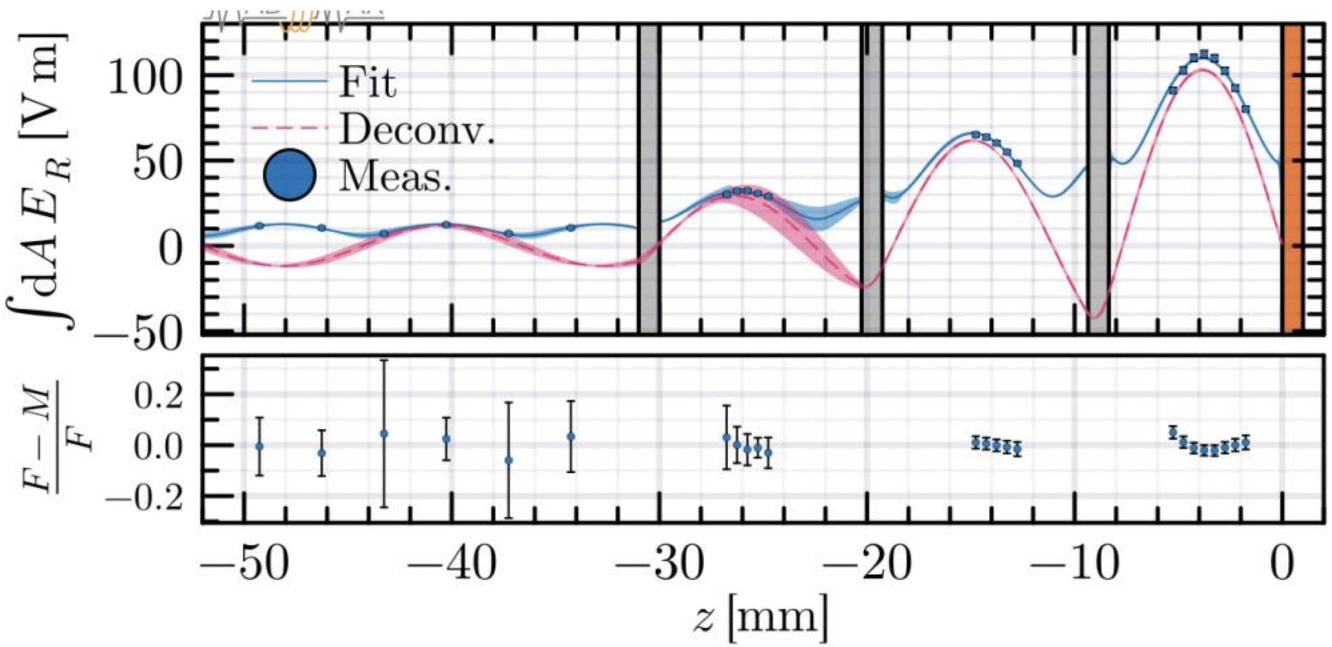
Reference plane after calibration



OB300 boost factor extraction

[https://arxiv.org/pdf/2408.02368]

In an open booster, the boost factor is determined by measuring the reflection-induced electric field excited by the VNA in the booster. This field is measured using the bead-pull method **across the full length**



In short, $\left|S_{11}^{4\,\mathrm{K}}\right|$ at the reference plane is not enough. And AFAIK we won't have a bead-pull method between discs at 4 K... **How will we get the boost factor?**

OB300 boost factor extraction at 4 K?

Perform full reflectivity calibration, bead-pull method & boost factor extraction at RT

Noise calibration at 4 K

Reflectivity calibration moves the reference plane to right before the antenna and gives the S-parameters of the booster with a limited precision: $\pm\, x$ dB, $\pm\, y$ °.

From my naïve perspective, we'll then guess how $\vec{E}$ inside the booster, to get $\beta^2(4\ \mathrm{K})$ with some uncertainty $\delta\vec{E}$.

Which uncertainty dominates $\delta\beta^2(4\ \mathrm{K})$? How much precision should we achieve in $\pm\, x$ dB, $\pm\, y$ °? This is a hard question

Conclusions

Sources causing wiggly spectrum at 4 K determined:

- New auto-cal kit acquired, considering buying a f-m cal-kit do avoid excessive post-processing de-embedding of m-m components. Word of caution to also save raw data!
- New measurements of 1-port setup done at RT by Genia showing great improvement
- Algorithm to exploit mode-devoid booster spectral regions to correct a-priori estimation of standards shows partial success. Not sure about uncertainties

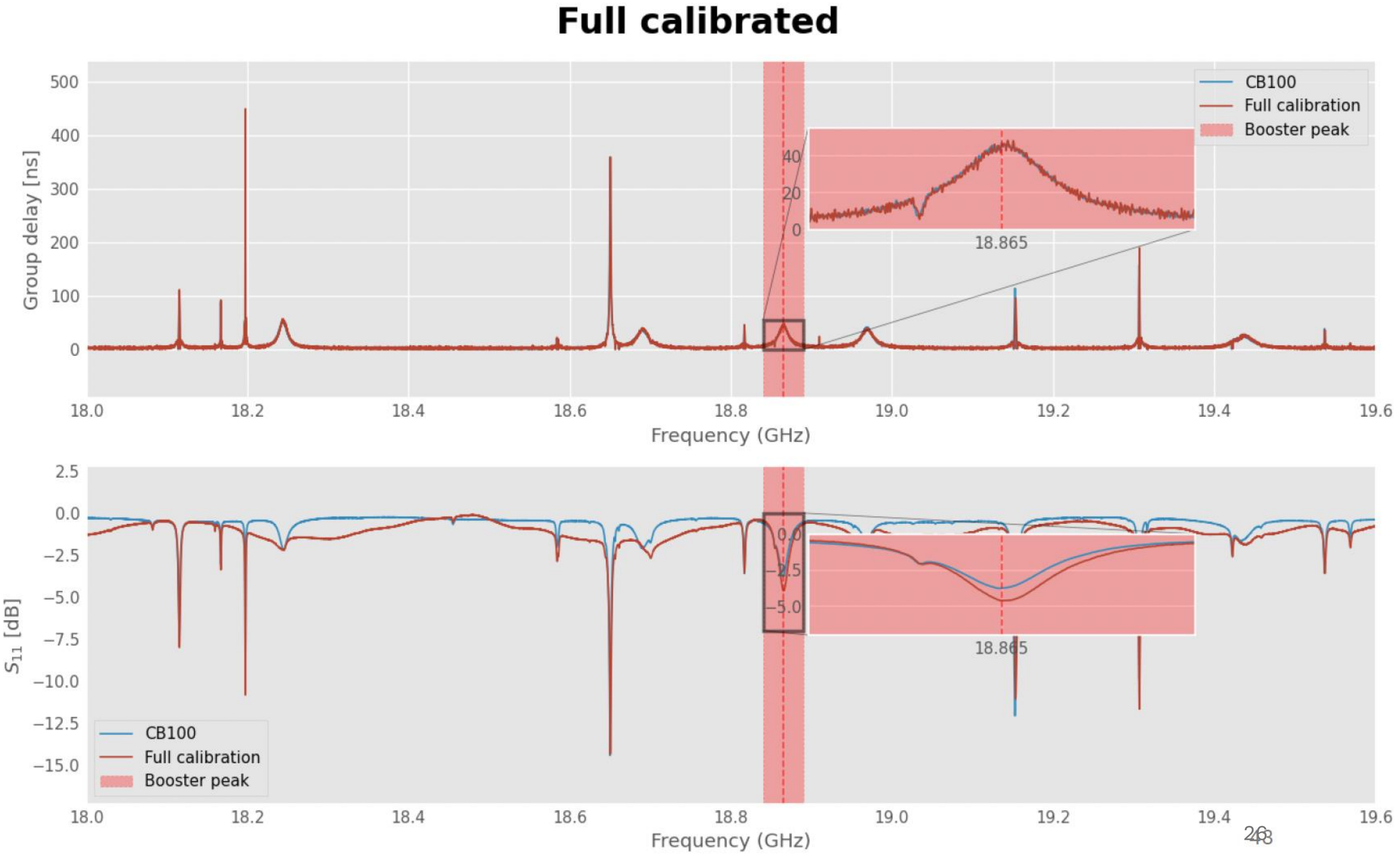
TRL method: in principle can solve the 1-port model issues. Most components already available at MPP. Goal is to test the setup at RT before October 2025.

OMT synergizes very well with OMT and can enable many radiometer techniques

Worth having a discussion on how important these complex calibrations schemes are useful for the boost factor determination of an open booster in cryogenic conditions.

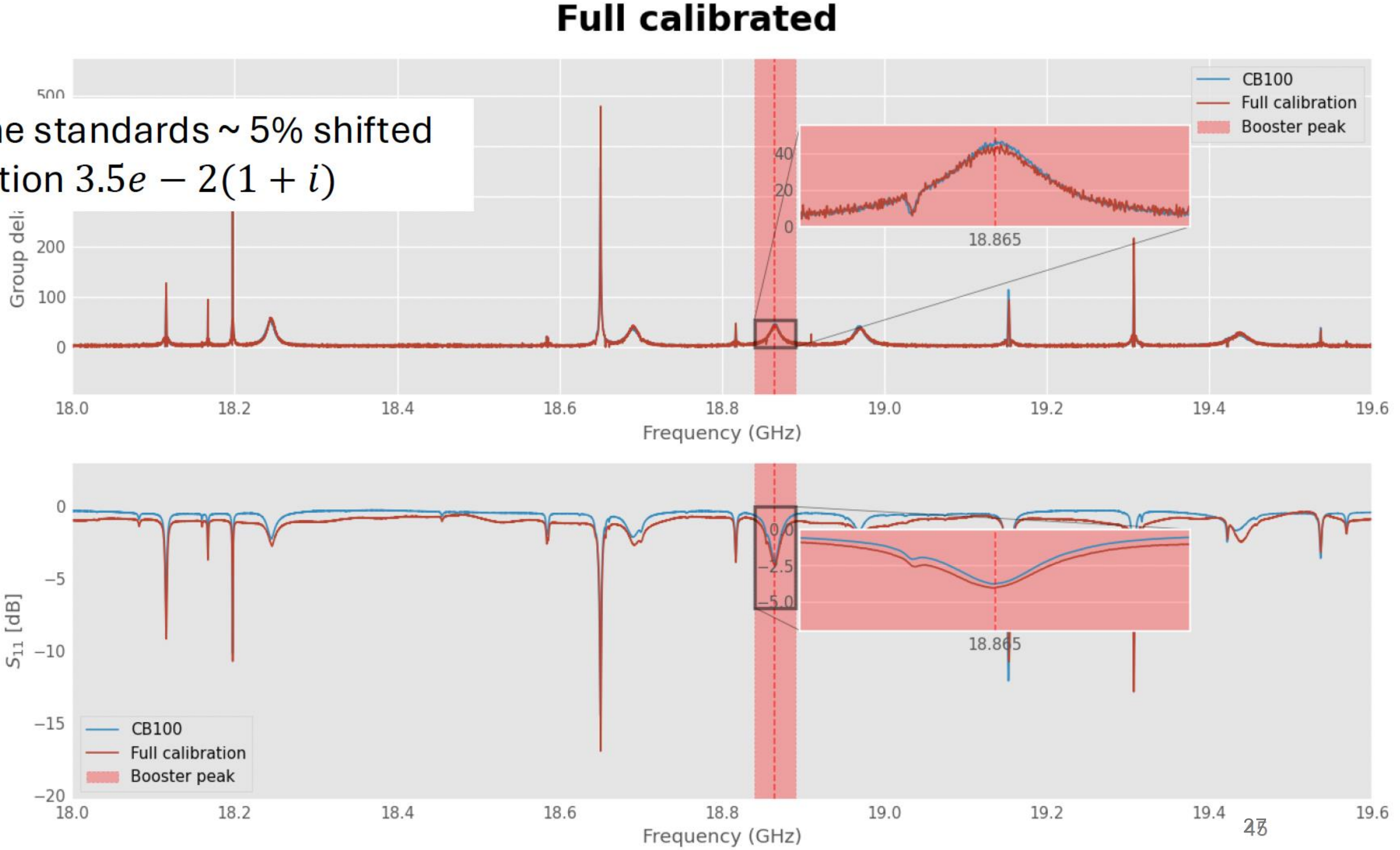
The effect of the lack of knowledge of the standards

Calibration with the standards as I think they are



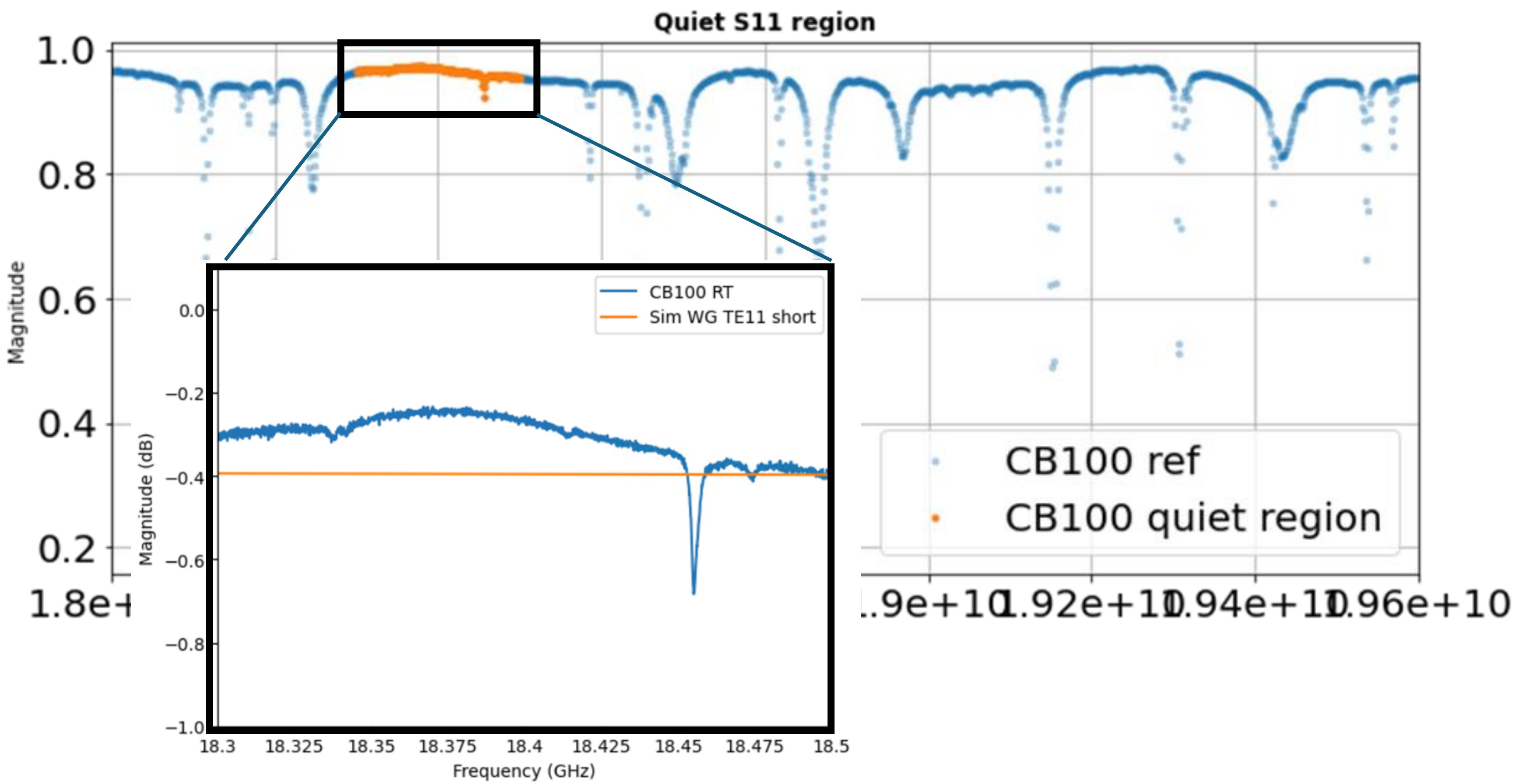
The effect of the lack of knowledge of the standards

Calibration with the standards ~ 5% shifted in a different direction $3.5e-2(1+i)$



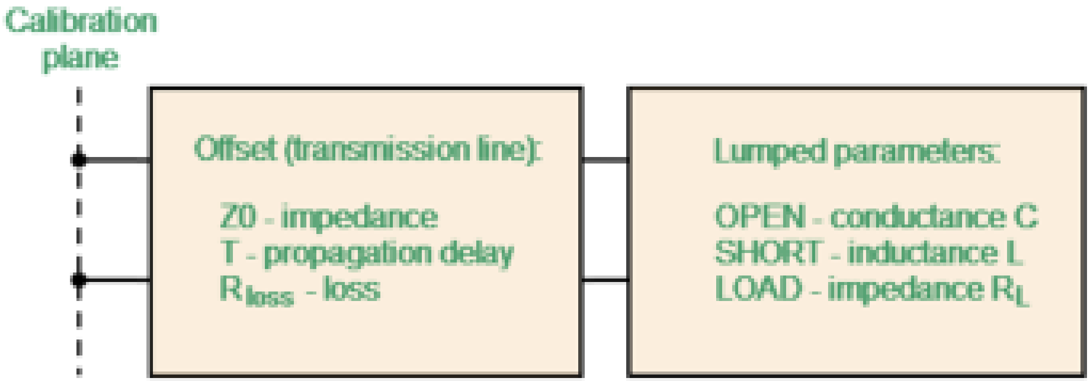
The idea

The booster spectrum is correlated across frequency. The values at frequencies outside the booster region are connected to the values in the booster region



There is a 200MHz region almost devoid of resonances. In a resonance-free frequency, the booster should behave as a delay short

Physical meaning of a nudge



$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh \gamma l}{Z_0 + Z_L \tanh \gamma l}$$

$$Z_L = i\omega L(f)$$

$$S_{11}(f) = \frac{Z_{in}(f) - Z_0}{Z_{in}(f) + Z_0}$$

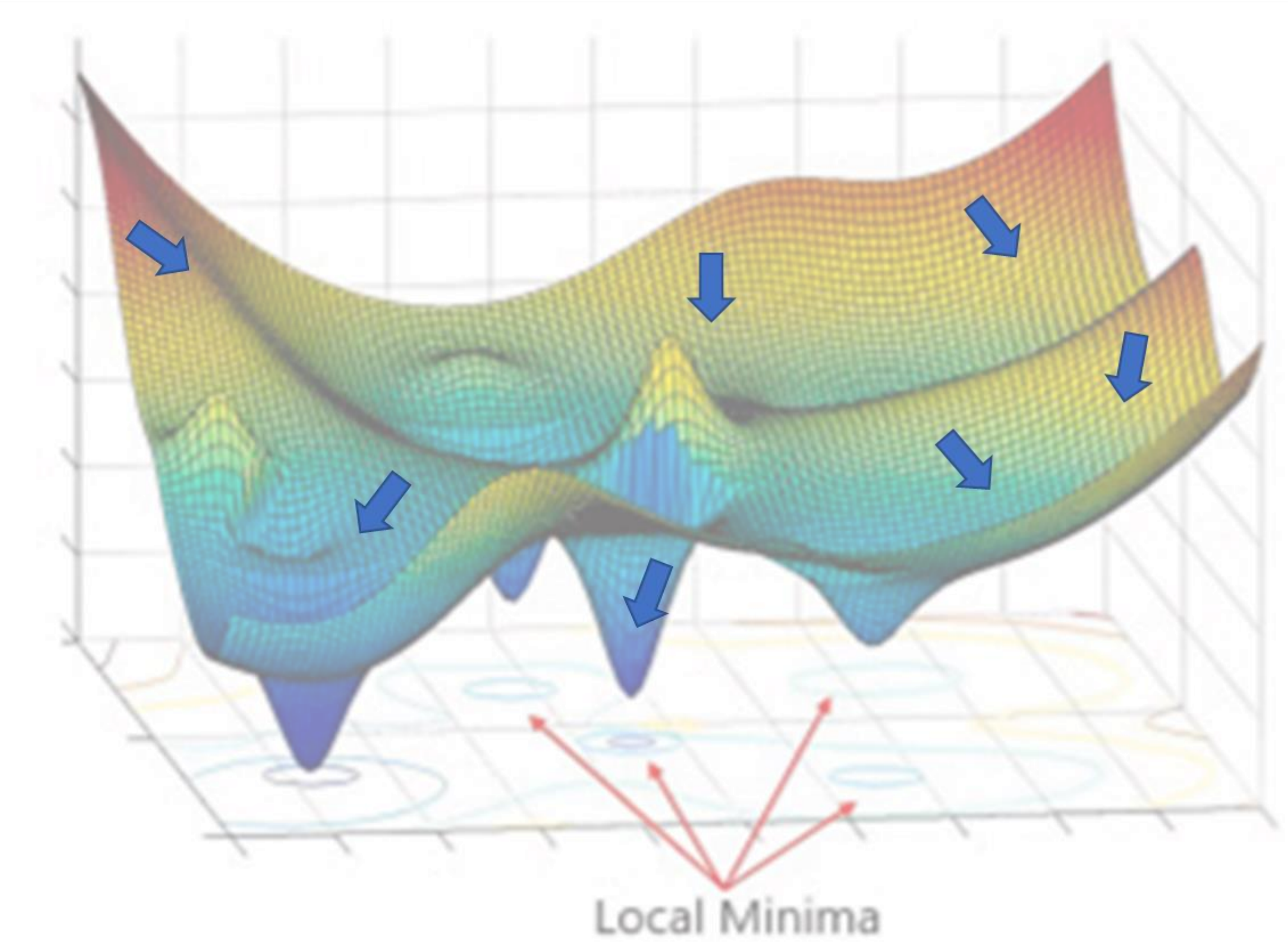
$$\gamma = \alpha + i\beta$$

α: Offset loss [GOhm/s]
β: Offset phase
l: Offset delay [ps]

We can apply a common transmission line to the standards

O,S: + nudging the lumped conductance or inductance
M,L: + nudging the complex s parameters by a small number

The idea: optimization algorithm



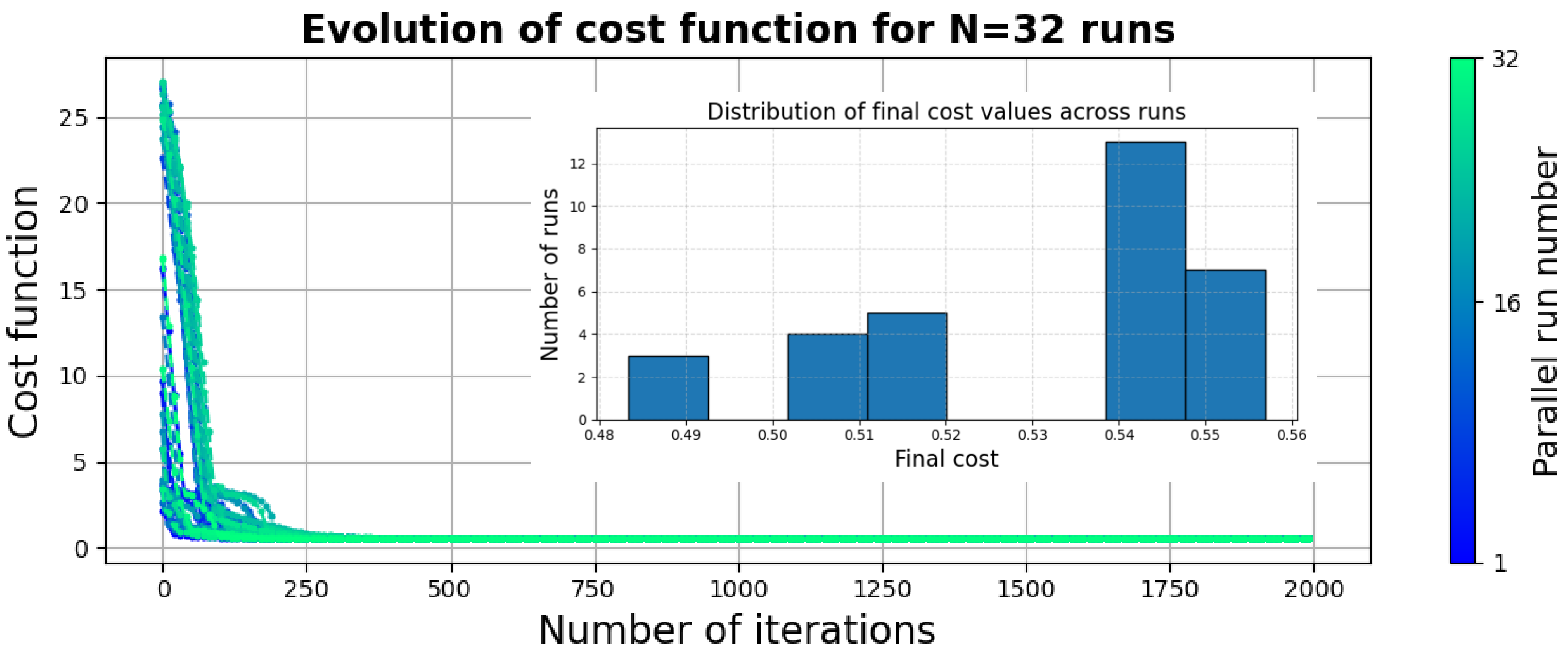
Define a function computing the similarity between a short and the obtained calibration:

$$J = \sqrt{\sum_i S_i^{\mathrm{REF}} - S_i^{\mathrm{CAL}}}$$

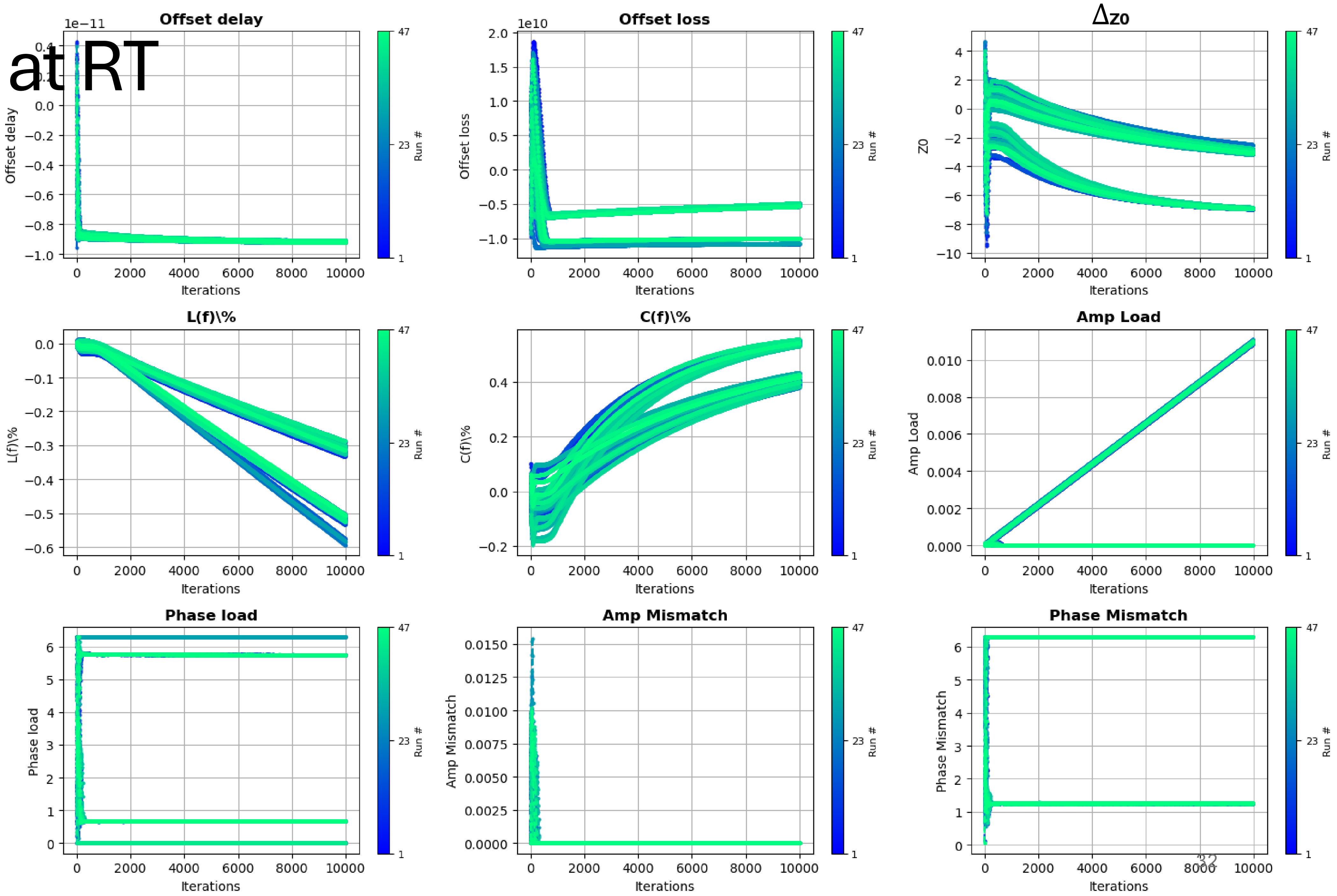
Nudge the calibration standards s-parameters and re-compute J

Perform a multi-start ADAM GD [arxiv.:1412.69800] algorithm to find the optimal nudge

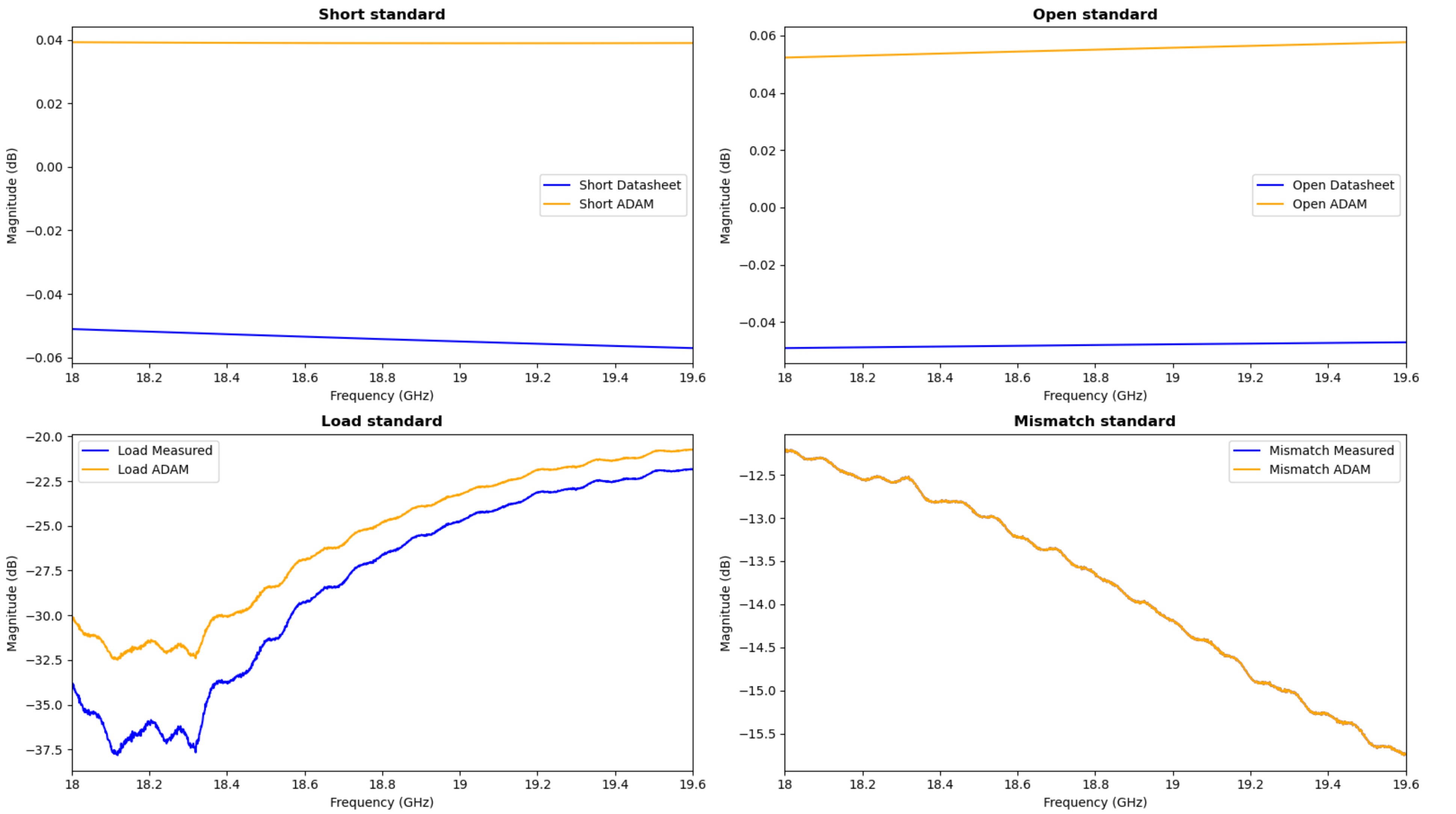
Results at RT



Results at RT



Results at RT

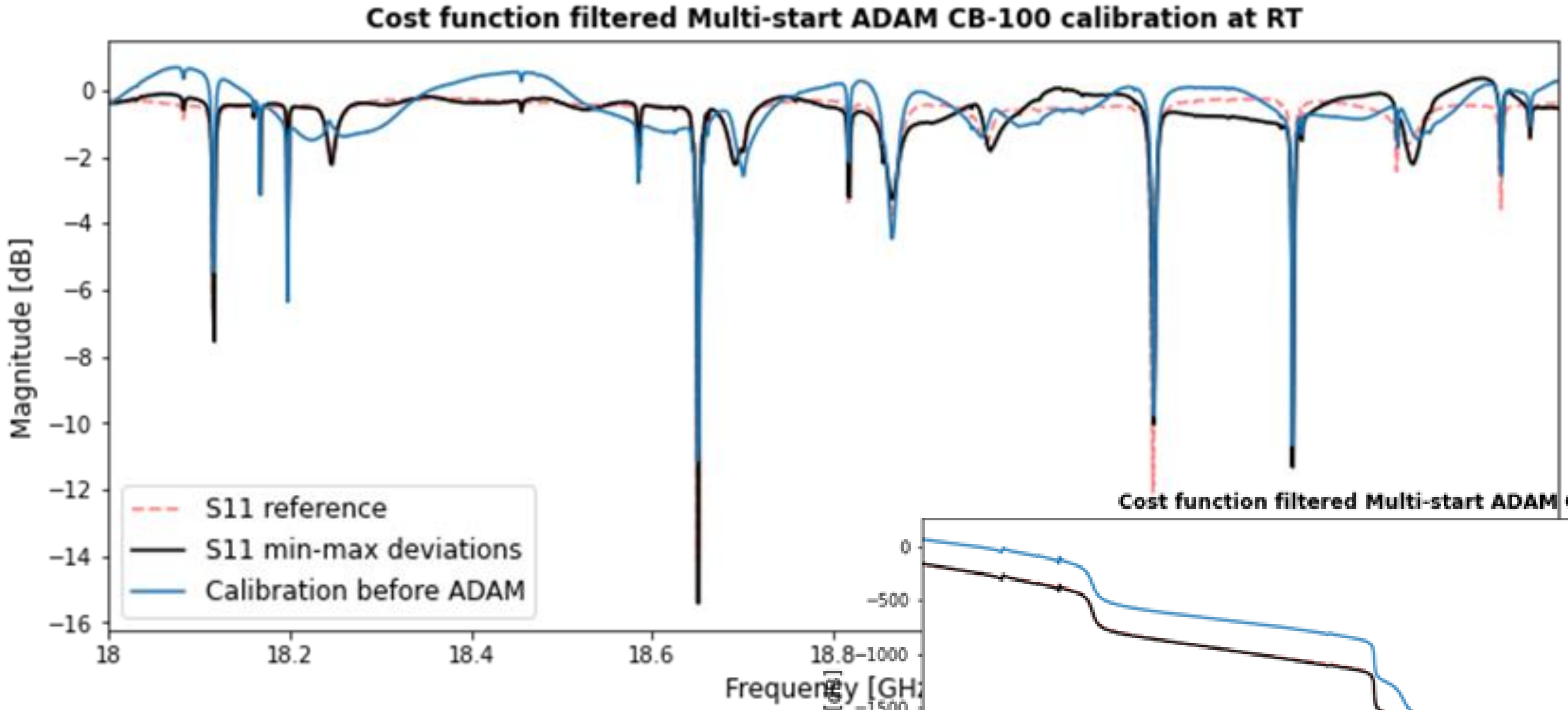


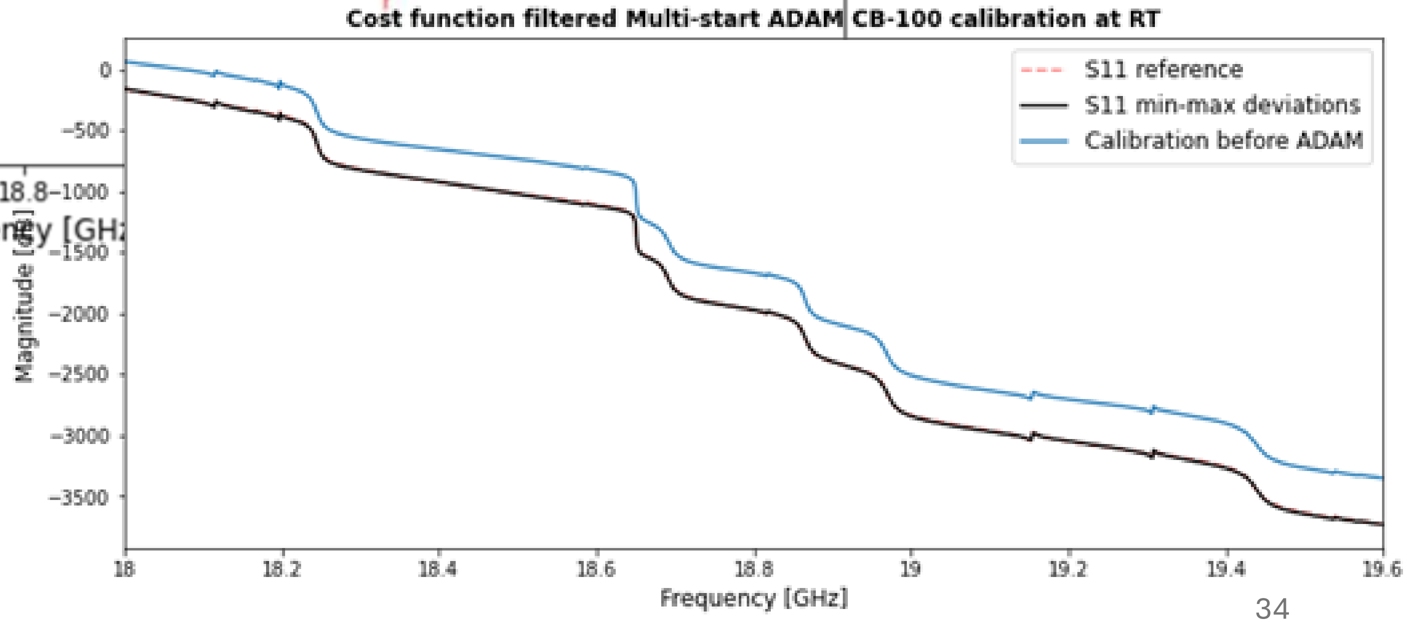
All sensible corrections

Algorithm chose not to nudge the mismatch.

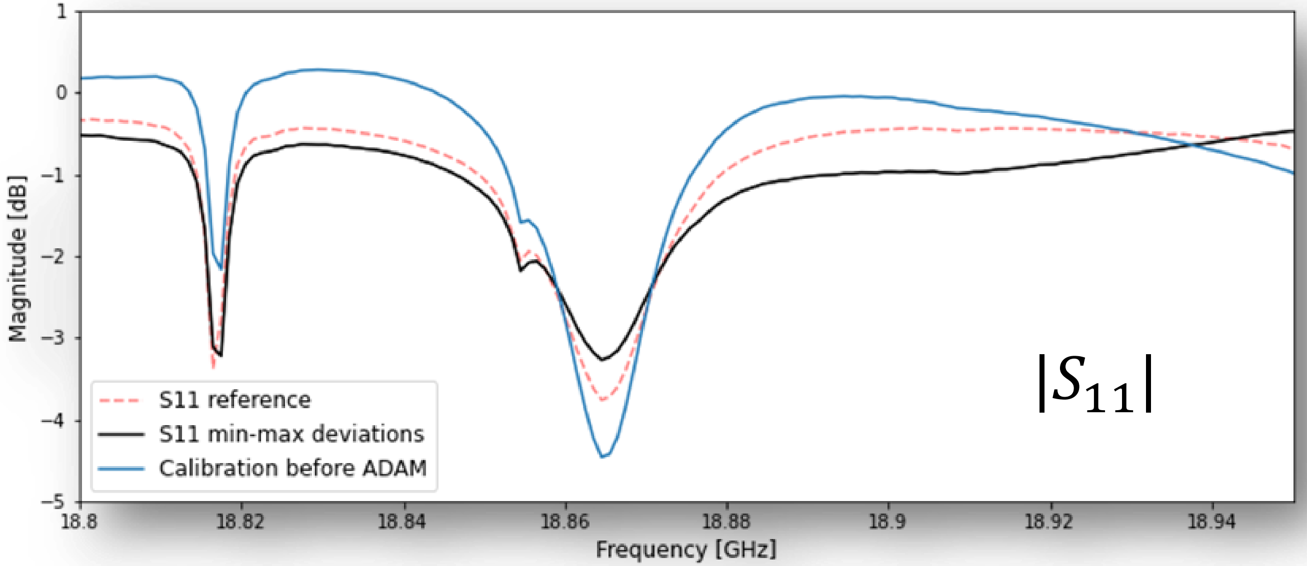
Indeed, the mismatch is the standard that agrees the most between datasheet and measurement

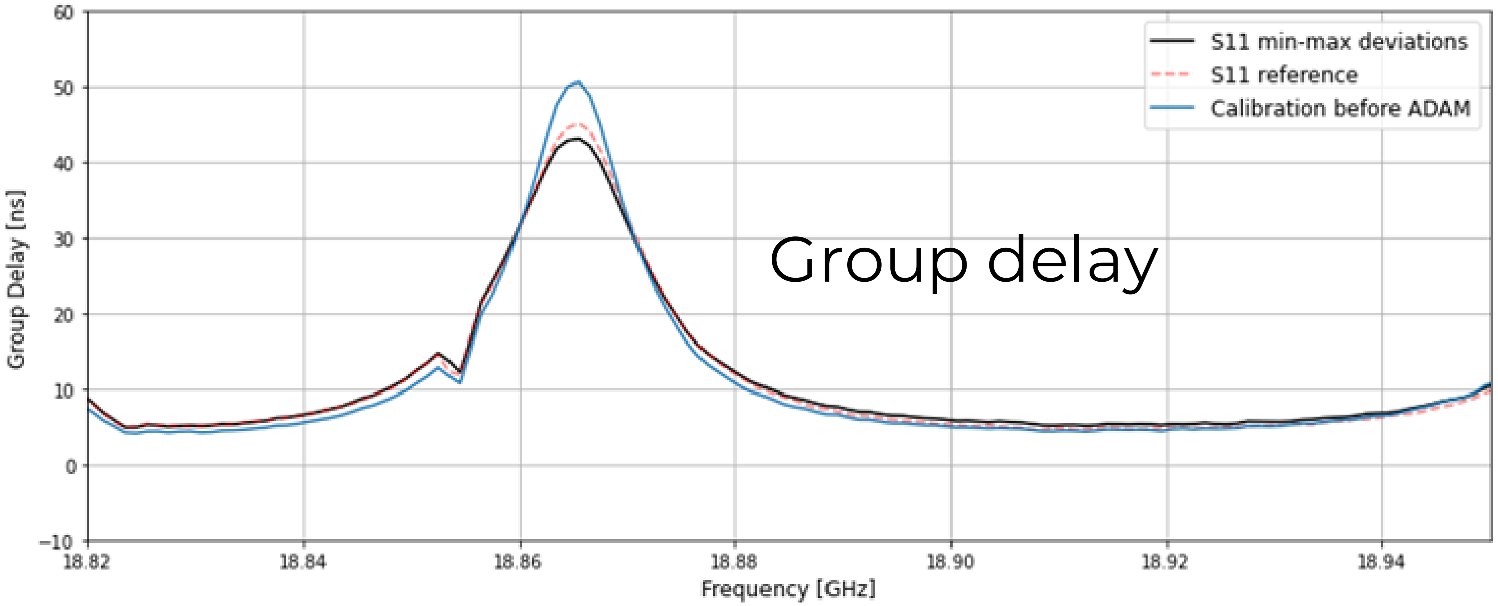
Results at RT





Results at RT





Most of the correction went to the phase disagreement, and therefore also improved group delay

Cryogenic case

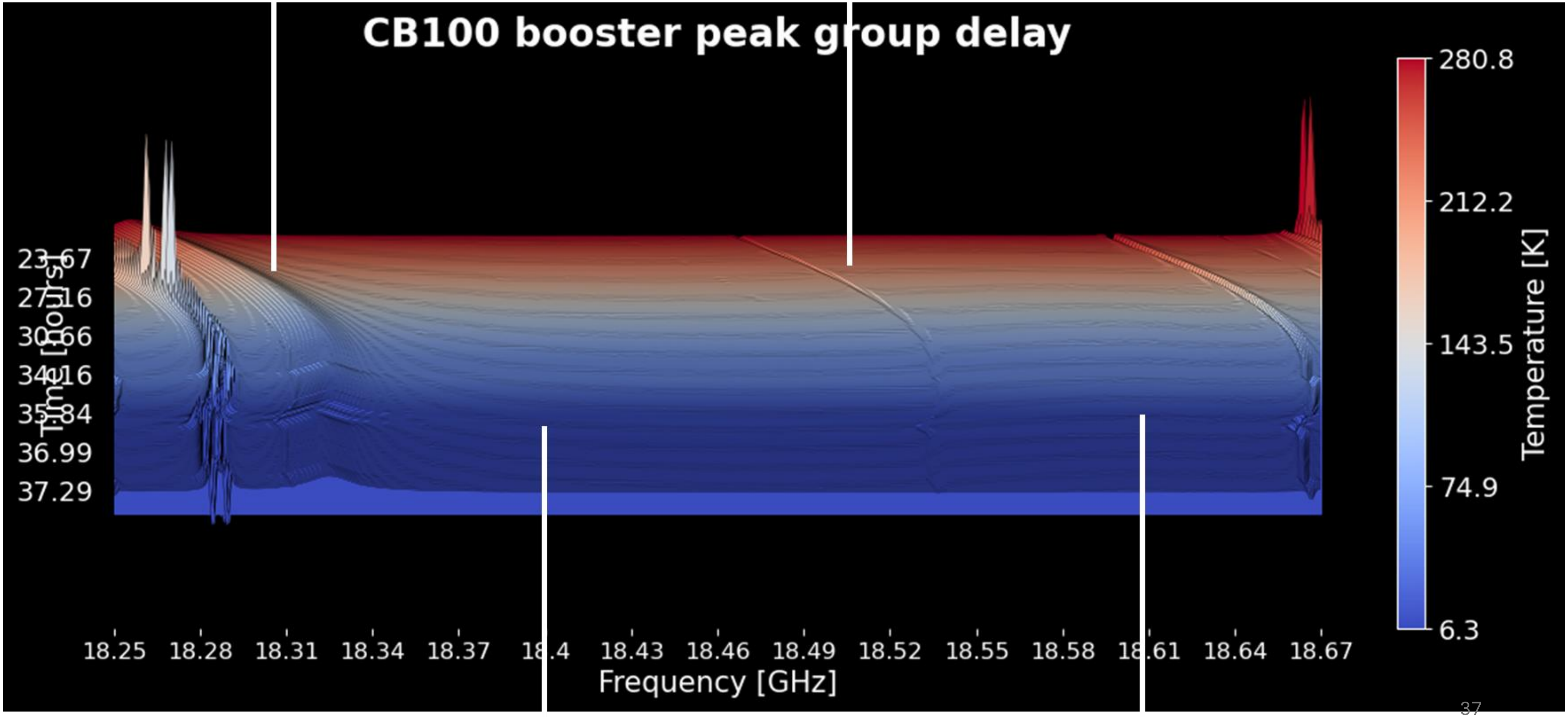
As an objective function, I take the 200MHz modeled short and vary the following parameters:

- Quiet region frequency: from group delay (next slide)
- Length contraction: 0.4% obtained from the integrated thermal expansion coefficient of Aluminium
- Losses: in a waveguide they're dominated by thermal conductivity, which is varied by the residual resistance ratio:

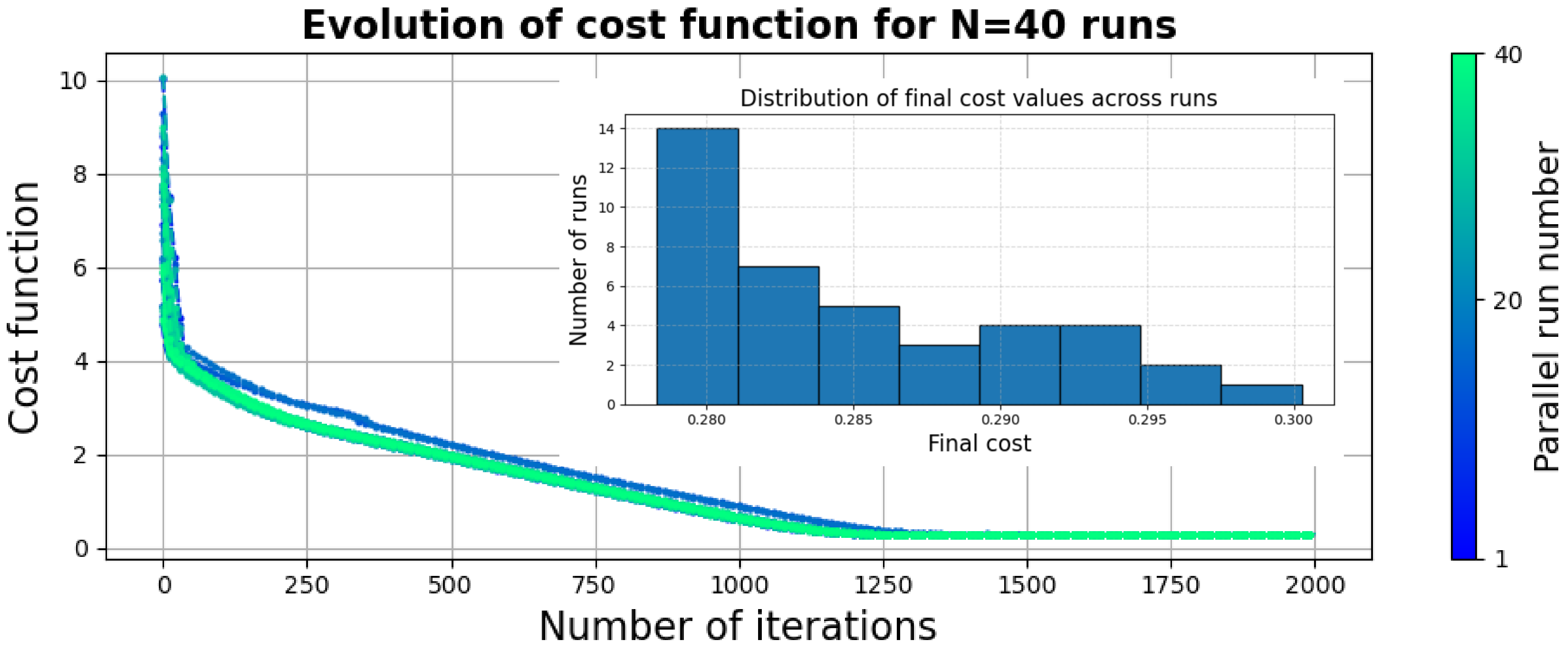
$$RRR = \frac{\rho_{300\ \mathrm{K}}}{\rho_{0\ \mathrm{K}}} \approx \frac{\rho_{300\ \mathrm{K}}}{\rho_{4\ \mathrm{K}}}$$

I assume RRR=10 as a conservative number, the higher, the less lossy. Aluminium depending on purity could have RRR between 10 and 40.000 [https://srd.nist.gov/JPCRD/jpcrd260.pdf]

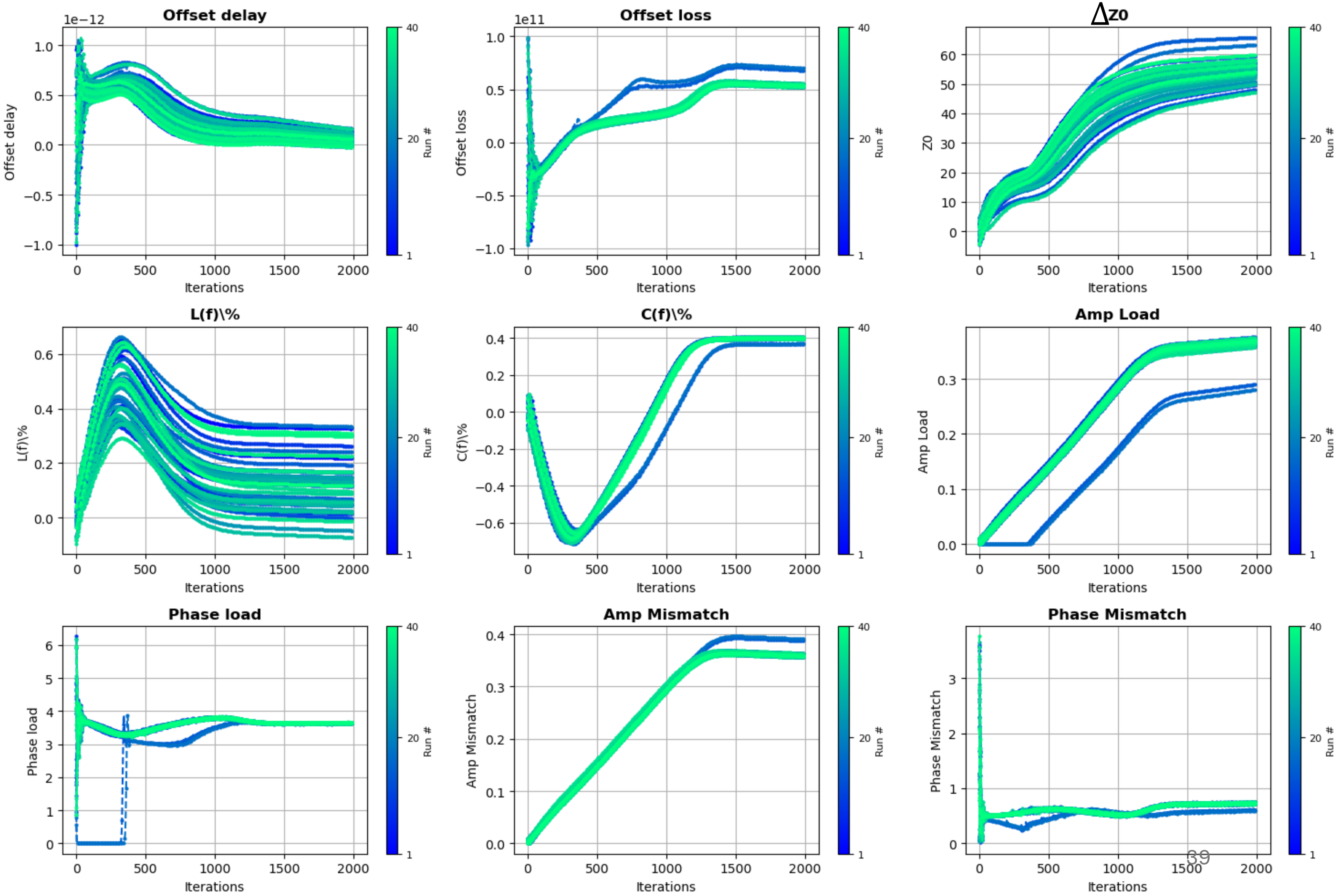
Cryogenic case



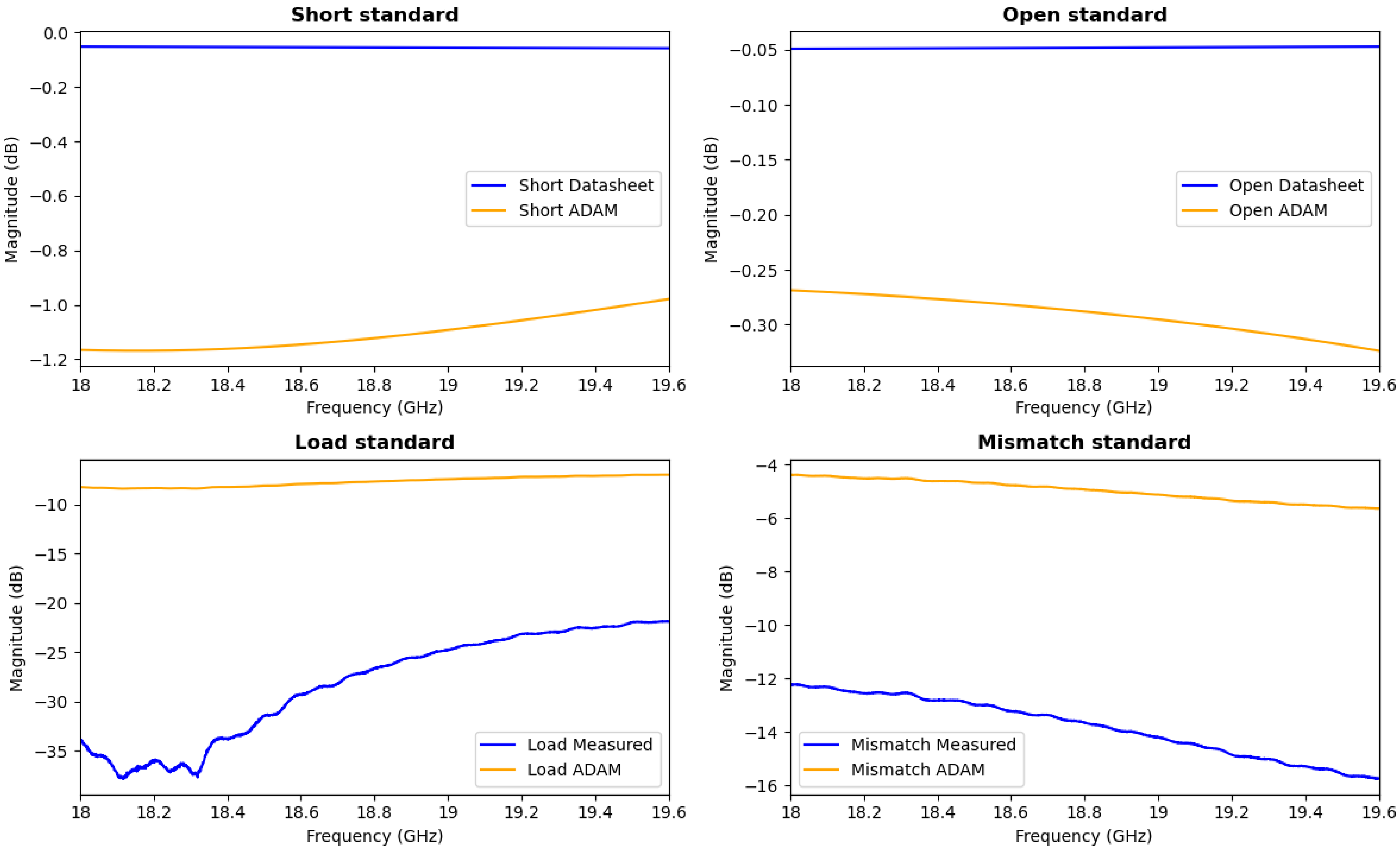
Cryogenic case



Cryogenic case



Cryogenic case



Open standard very similar to RT

Short is measurably less ideal

Load has the highest change (as expected)

Mismatch also found to change considerably