Status report of the CERN light shining through the wall experiment with microwave axions and related aspects

M. Betz (CERN, Geneva)
M. Gasior (CERN, Geneva)
F. Caspers (CERN, Geneva)
M. Thumm (KIT, Karlsruhe)

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Karlsruhe Institute of Technology

Outline

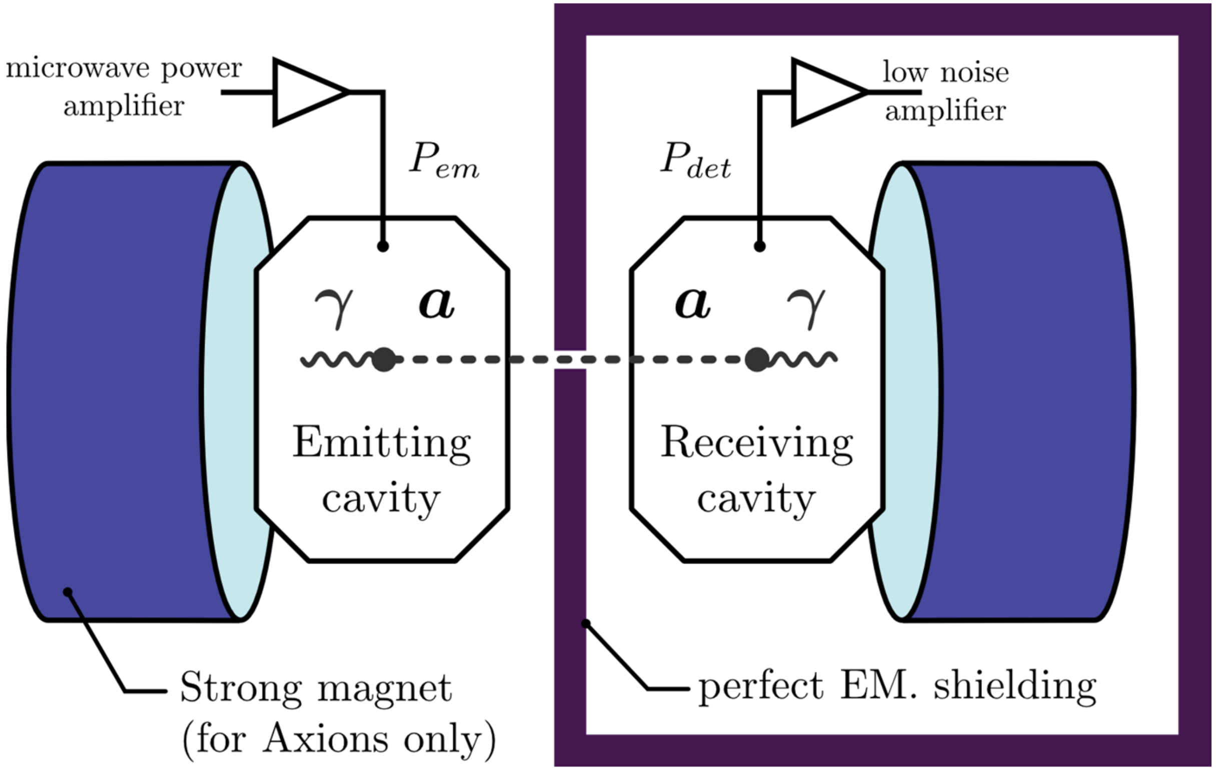
What this talk will be about

- Motivation and Overview of the experiment
- Design of the microwave cavities
- Electromagnetic (EM) shielding
- Shielding diagnostics
- Detecting weak narrowband signals
- Demonstration with commercial instrument
- Chromium oxide - an interesting axion conversion material
- Conclusion and outlook

(Appendix: Dielectric waveguide as a directional “Axion antenna”)

Photon regeneration exp. at CERN

Detecting Axions

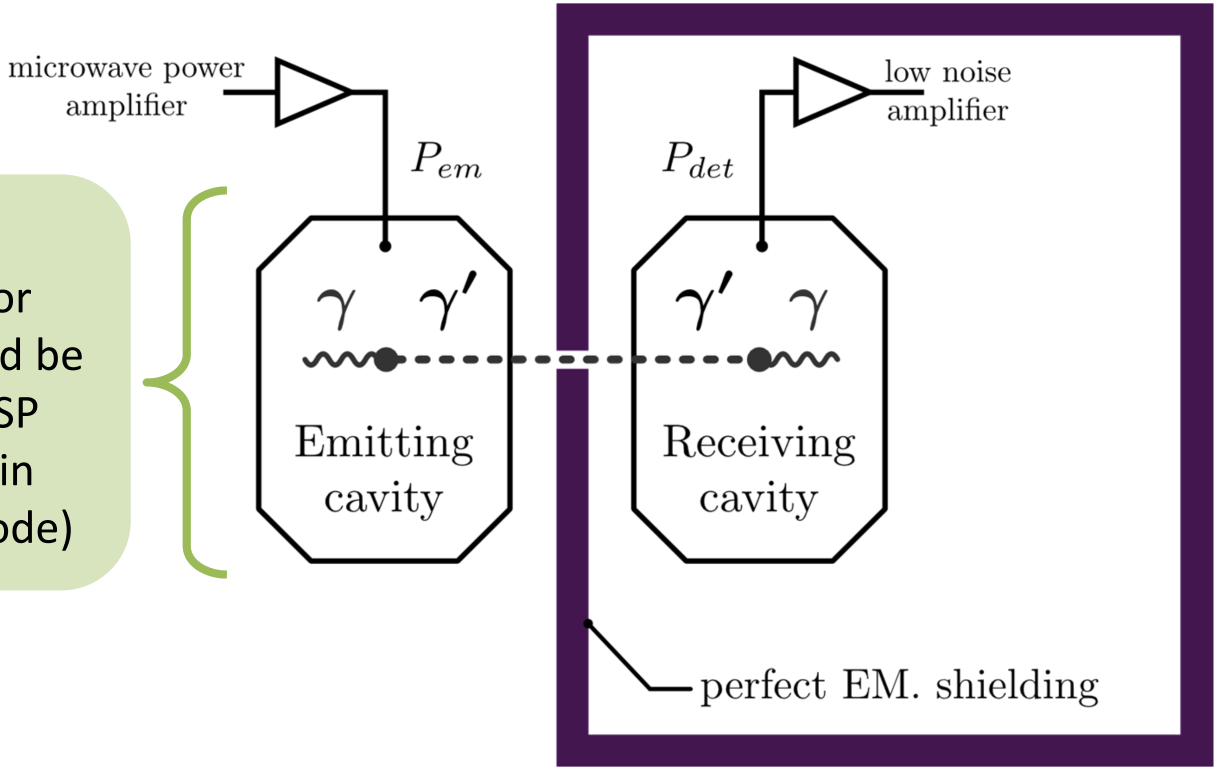


γ	Photon
a	Axion
EM.	Electromagnetic

Photon regeneration exp. at CERN

Detecting Hidden Sector Photons (HSP)

Existing accelerator cavities could be used as HSP emitters (in parasitic mode)

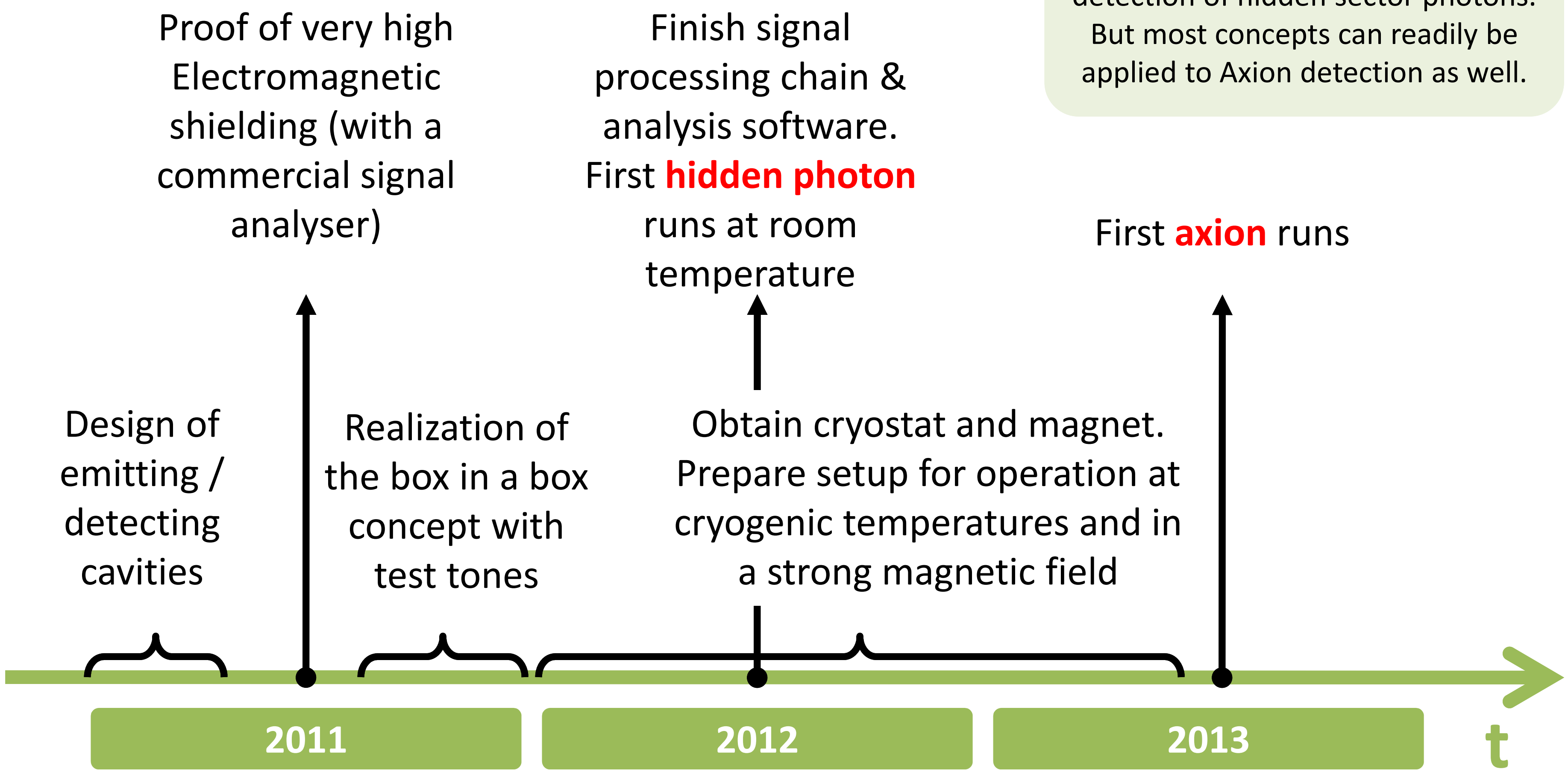


γ	Photon
γ'	Hidden sector photon (**HSP**)
EM.	Electromagnetic

Timeline

What we planned for the next 3 years

This talk mainly deals with the detection of hidden sector photons. But most concepts can readily be applied to Axion detection as well.

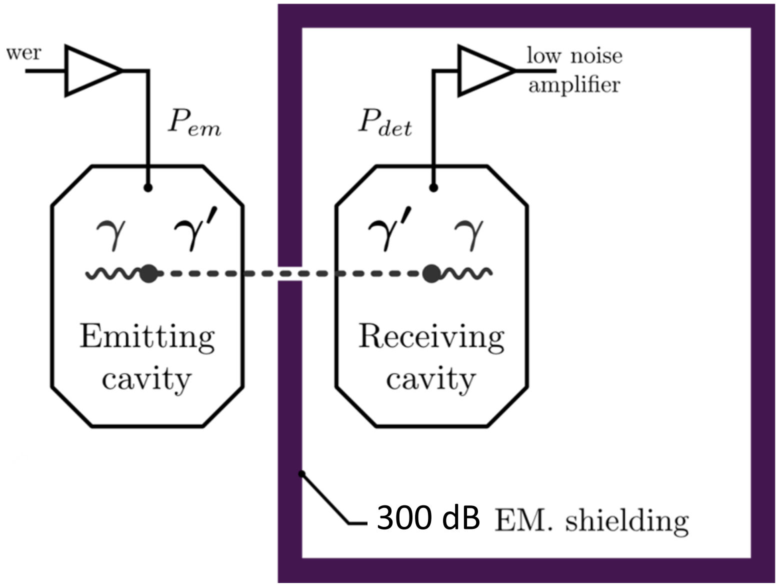


Photon regeneration exp. at CERN

Technical specifications and challenges for hidden photon search

Expected signal power from the receiving cavity

$$\mathscr{P}_{\text{det}} = \chi^4 \frac{m_{\gamma'}^8}{\omega_0^8} |G|^2 QQ' \mathscr{P}_{\text{em}}$$



What we want to achieve (for HSPs):

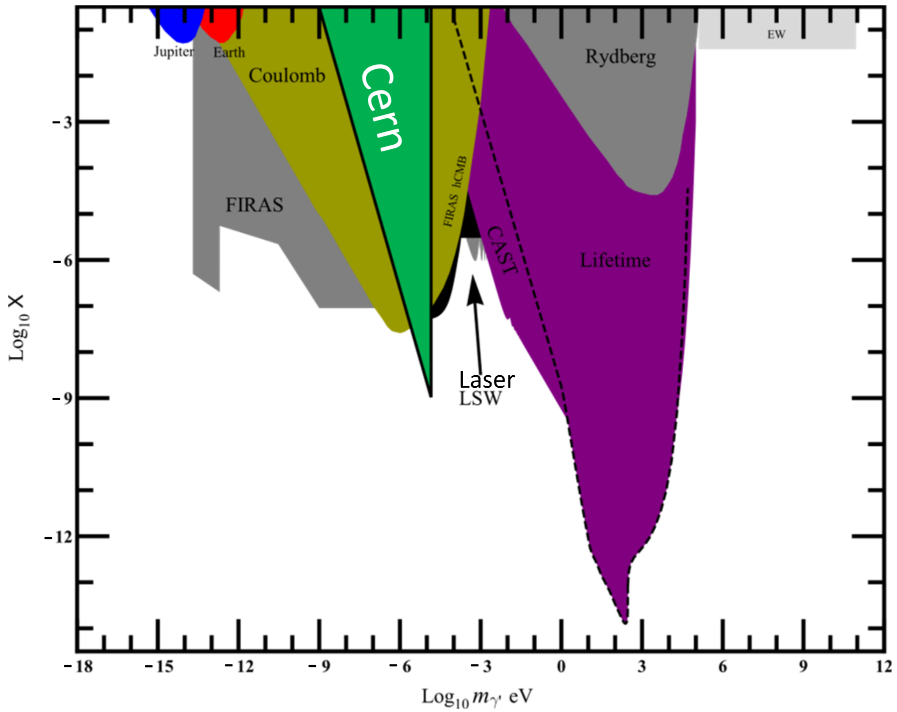
P_{em}	50 W = 47 dBm	Signal power into emitting cavity
P_{det}	10^{-26} W = **-230 dBm**	Signal power from receiving cavity
Q	23 000	Quality factor emitting cavity
Q'	23 000	Quality factor receiving cavity
G	≈ 0.5	HSP. geometry factor
$m_{\gamma'}$	12 µeV ≈ 3 GHz	Hidden photon mass
ω_0	3 GHz	Cavity resonance frequency
X	$1.1 \cdot 10^{-9}$	Coupling factor (exclusion limit)

arXiv:0707.2063v1
F. Caspers, J. Jaeckel, A. Ringwald, A Cavity Experiment to Search for Hidden Sector Photons

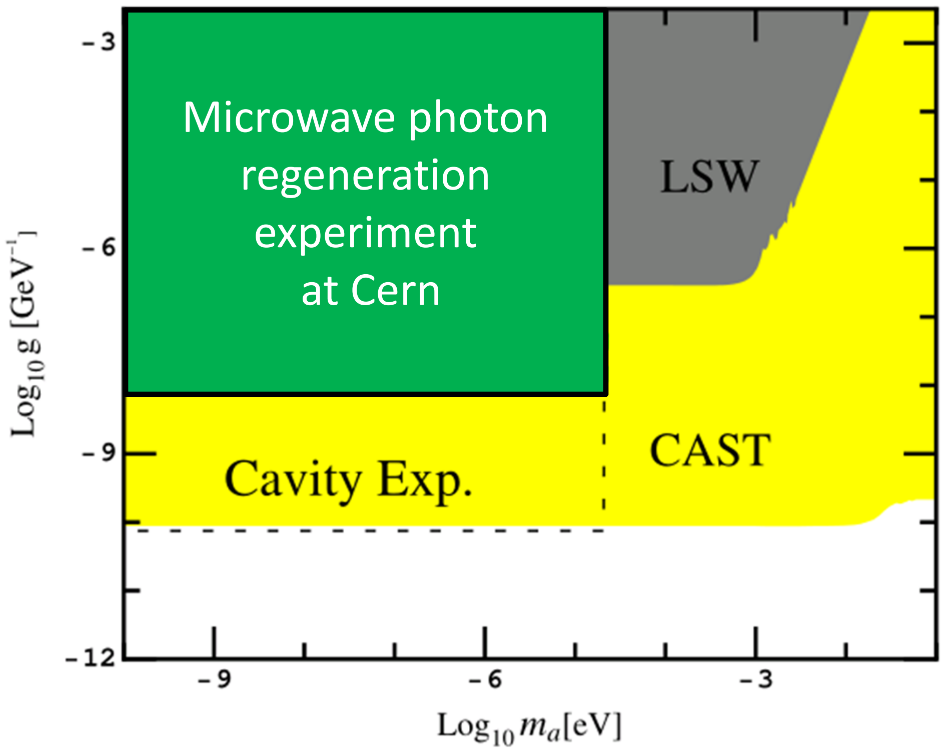
Photon regeneration exp. at CERN

Sensitivity Bounds compared to other experiments

Hidden Sector Photons



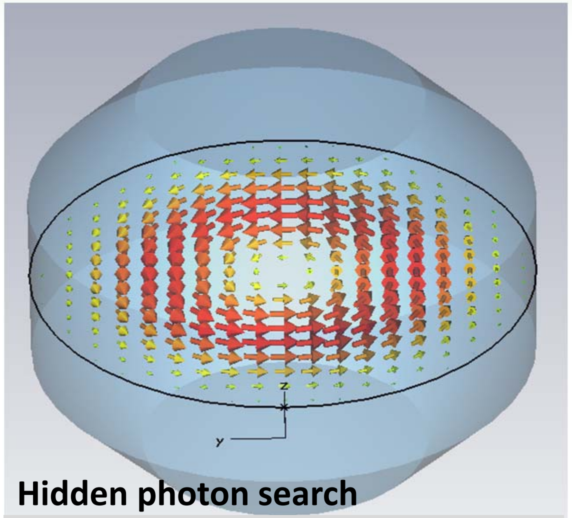
Axions



Exclusion plots with friendly permission from J. Jaeckel
A Cavity Experiment to Search for Hidden Sector Photons, arXiv:0707.2063v1

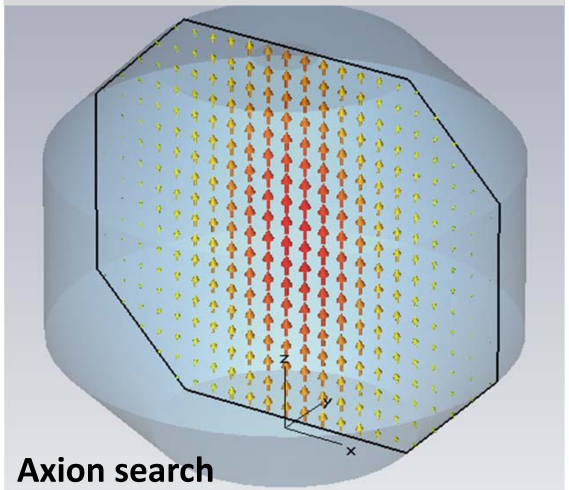
The photon conversion cavities

Choice of cavity mode



Hidden photon search

TE_{011} mode, E–field



Axion search

TM_{010} mode, E–field

1st phase: HSP-search with TE_{011} mode at 2.95 GHz

- high Q-factor
- Favorable hidden photon geometric form factor [1]
- Not suitable for axion search because of cancelation in the axion geometric overlap integral

[1] Rhys G. Povey, John G. Hartnett, and Michael E. Tobar: Microwave cavity light shining through a wall optimization and experiment, Physical Review D 82, 052003 (2010)

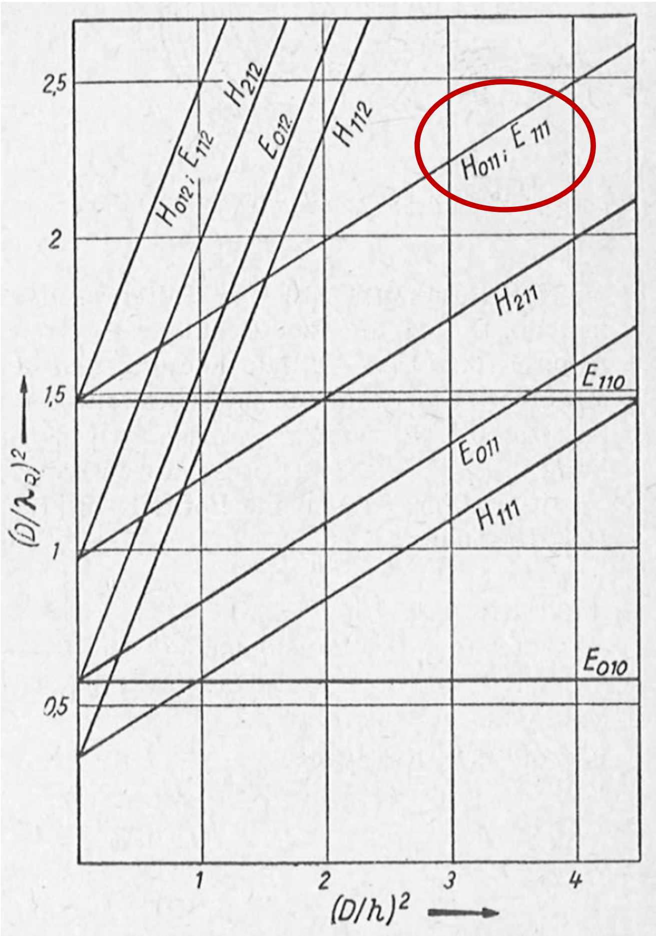
2nd phase: Axion-search with TM_{010} mode at 1.75 GHz

- The RF electric field is parallel to the static magnetic field over a big volume and there is no cancelation in the geometric overlap integral

The photon conversion cavities

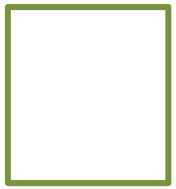
Choice of cavity geometry: Mitigation of mode degeneracy

Mode chart for a cylindrical "Pillbox" cavity



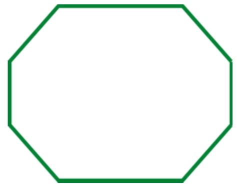
Numerical simulation of a Cylindrical "pillbox" cavity

Mode	f_{res} [GHz]
H_{011}	2.863
$E_{111Sine}$	2.863
$E_{111Cosine}$	2.863
H_{112S}	2.89
H_{112C}	2.89



Numerical simulation of a Cylindrical cavity with beveled edges

Mode	f_{res} [GHz]
E_{111S}	2.62944
E_{111C}	2.62944
H_{011}	2.95545
Similar to E_{112S}	3.02173
Similar to E_{112C}	3.02173

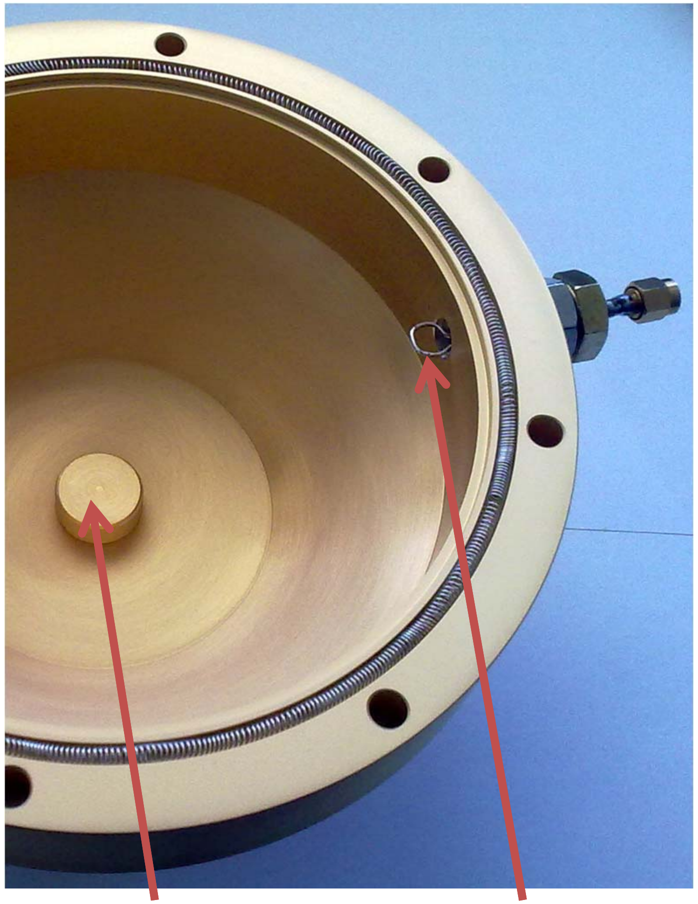


Mode indices: $H_{abc} = TE_{abc}$ $E_{abc} = TM_{abc}$

The photon conversion cavities

Prototypes after machining (left) and coating (right)

Material: Brass (non magnetic)



Fine thread tuning screw Coupler (β=1)

The photon conversion cavities

Resonant frequency and Q-factor measurements

		f_{res} [Hz]	BW_{3dB} (loaded) [Hz]	Q_L
	Cavity 1	2 955 508 499	225 600	13 101
	Cavity 2	2 956 630 999	236 200	12 518
Coated & tuned	**Cavity 1**	2 956 757 751	126 270	**23 416**
Coated & tuned	**Cavity 2**	2 956 757 531	125 180	**23 620**

- Tuning f_{res}
  - Manual, before each experimental run
  - Receiving cavity = fixed reference (not reachable)
- Measuring f_{res}
  - Receiving cavity:
    Output noise power peaks at f_{res}
  - Emitting cavity:
    Reflected power has minimum at f_{res}
    (Also there is a step in phase)

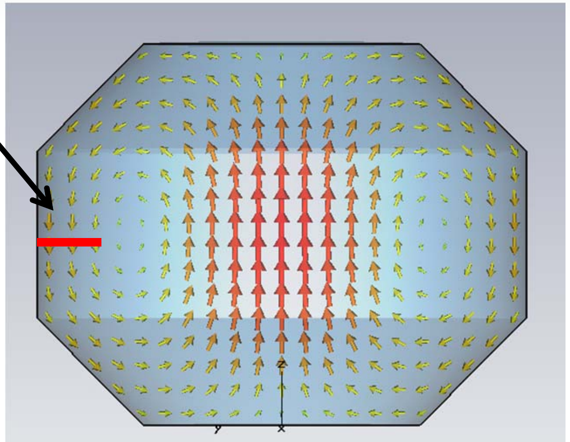
<u>Coating:</u>

- **10 µm silver** for good conductivity
- 0.2 µm gold to prevent oxidation
- skin depth at 3 GHz in silver ≈ 1 µm

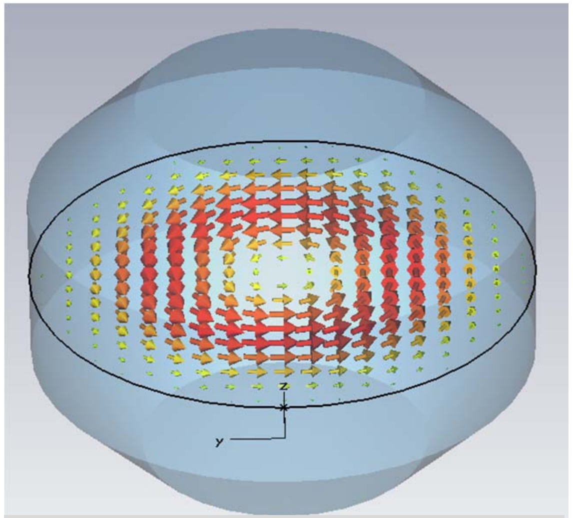
The photon conversion cavities

Numerical simulation of the TE_{011} mode

Possible location of an inductive coupling loop for the TE_{011} mode (The loop extends on the XY-plane)

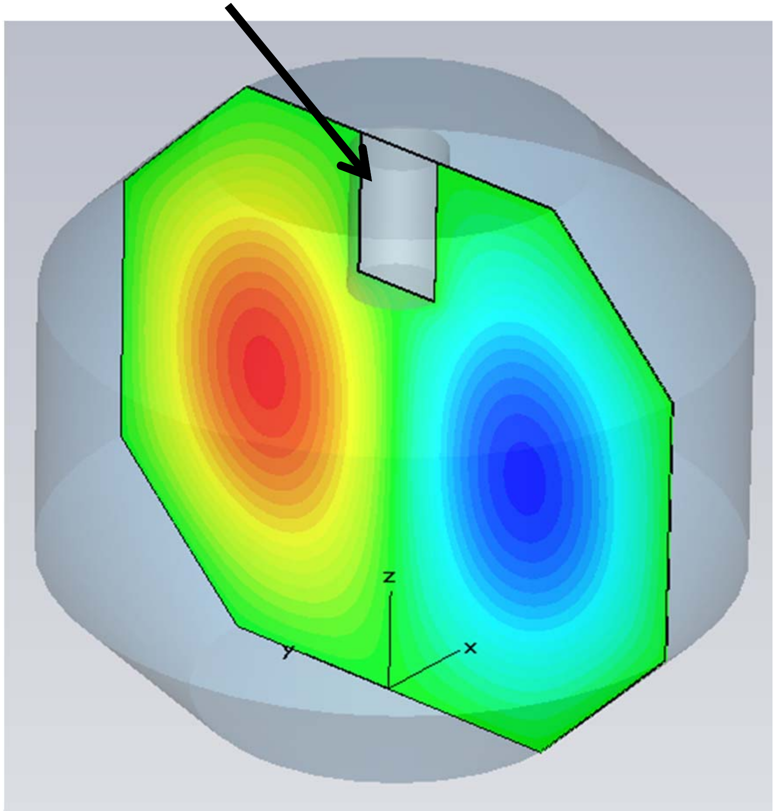


TE_{011} mode, **H–field** on YZ-plane



TE_{011} mode, **E–field** on XY-plane

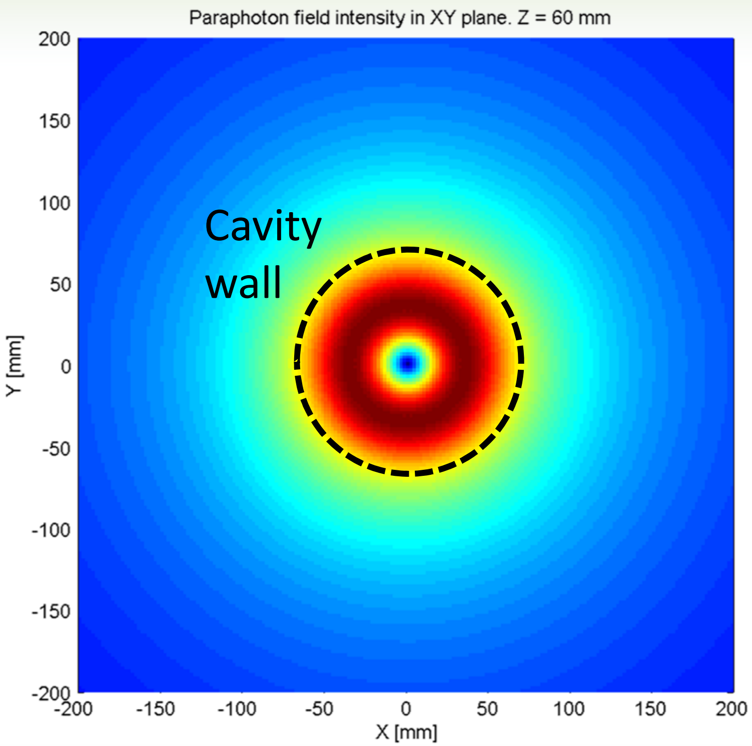
Tuning screw:
(20 mm diameter, fine thread)

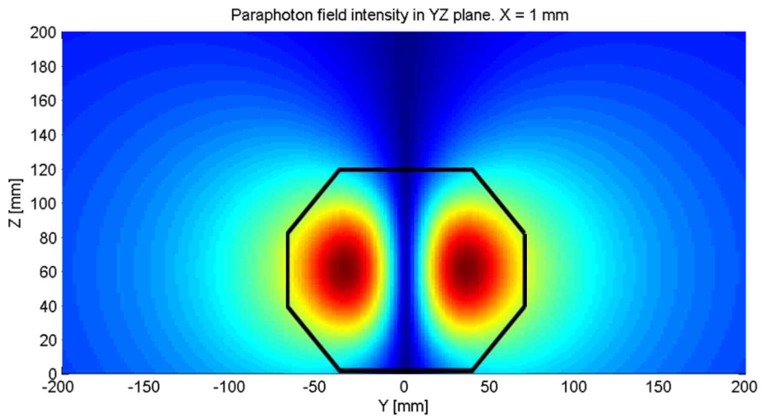


TE_{011} mode, **E–field** in X-direction

The photon conversion cavities

Relative intensity of the hidden photon field





$$B(\mathbf{x},t) = \chi m_{\gamma'}^2 \int_V d^3\mathbf{y}\, \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} a_{\mathrm{em}}(t) A_{\omega_0}(\mathbf{y})$$

Derrived by Joerg Jaeckel and Andreas Ringwald: A Cavity Experiment to Search for Hidden Sector Photons, arxiv:0707.2063v1

- Electric field $A_{\omega 0}(y)$ calculated in Microwave Studio, imported into Matlab
- For every Pixel: 1 evaluation of the integral
- Here: $\mathbf{k_{\gamma'}/\omega = 0.9}$ ≈ very light and relativistic hidden photons
- Hidden photon field ≈ extension of the electric field

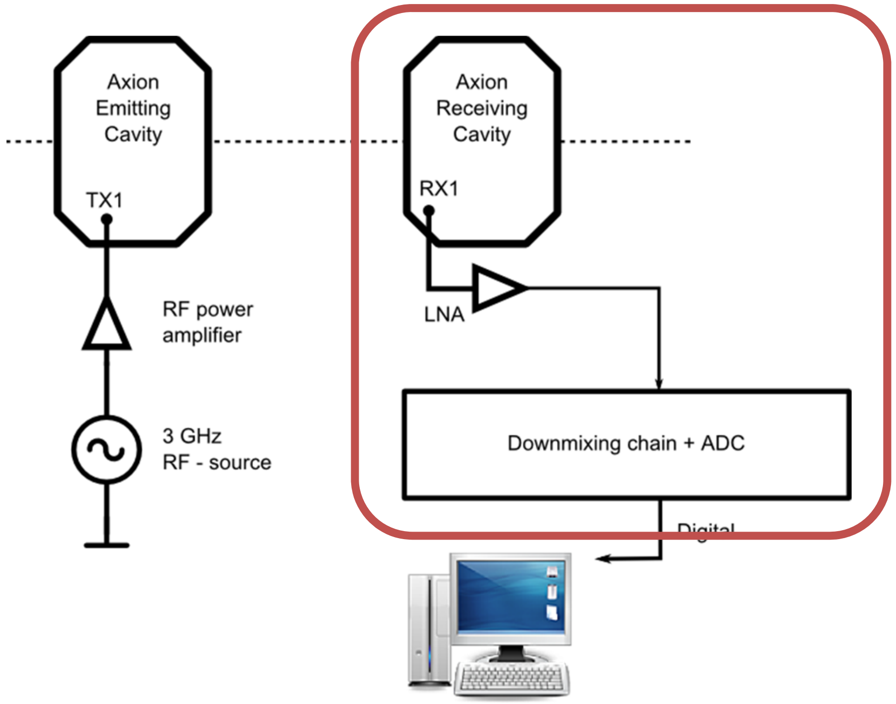
Electromagnetic shielding

General overview, where do we need EM. shielding?

Enviromental
RF noise

Tackled by
EM. shielding

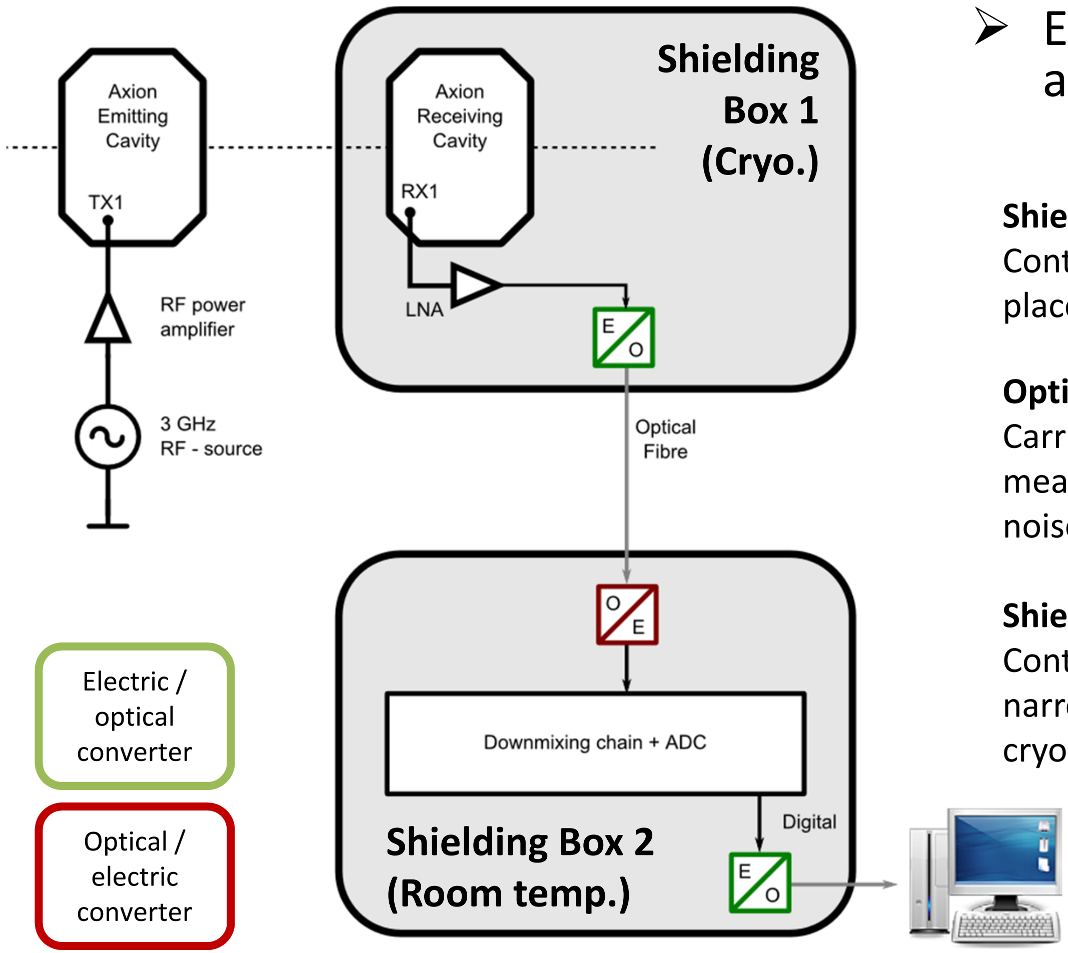
Critical EM. shielding



- Sources of distortion:
  - Enviromental noise
  - Microwave leakage from emitting cavity
  - Thermal noise
- 1 Shielding shell ≈ 100 dB
- This can still be **measured**, thus guaranteed
- Scalable: 3 stacked shielding shells ≈ 300 dB
- The cavity and cryostat walls provide shielding as well

Electromagnetic shielding

Splitting the experiment into two parts



The signal processing electronics can not easily operate at cryogenic temperatures or in strong magnetic fields

- Experiment is split into a cryogenic and room temperature part

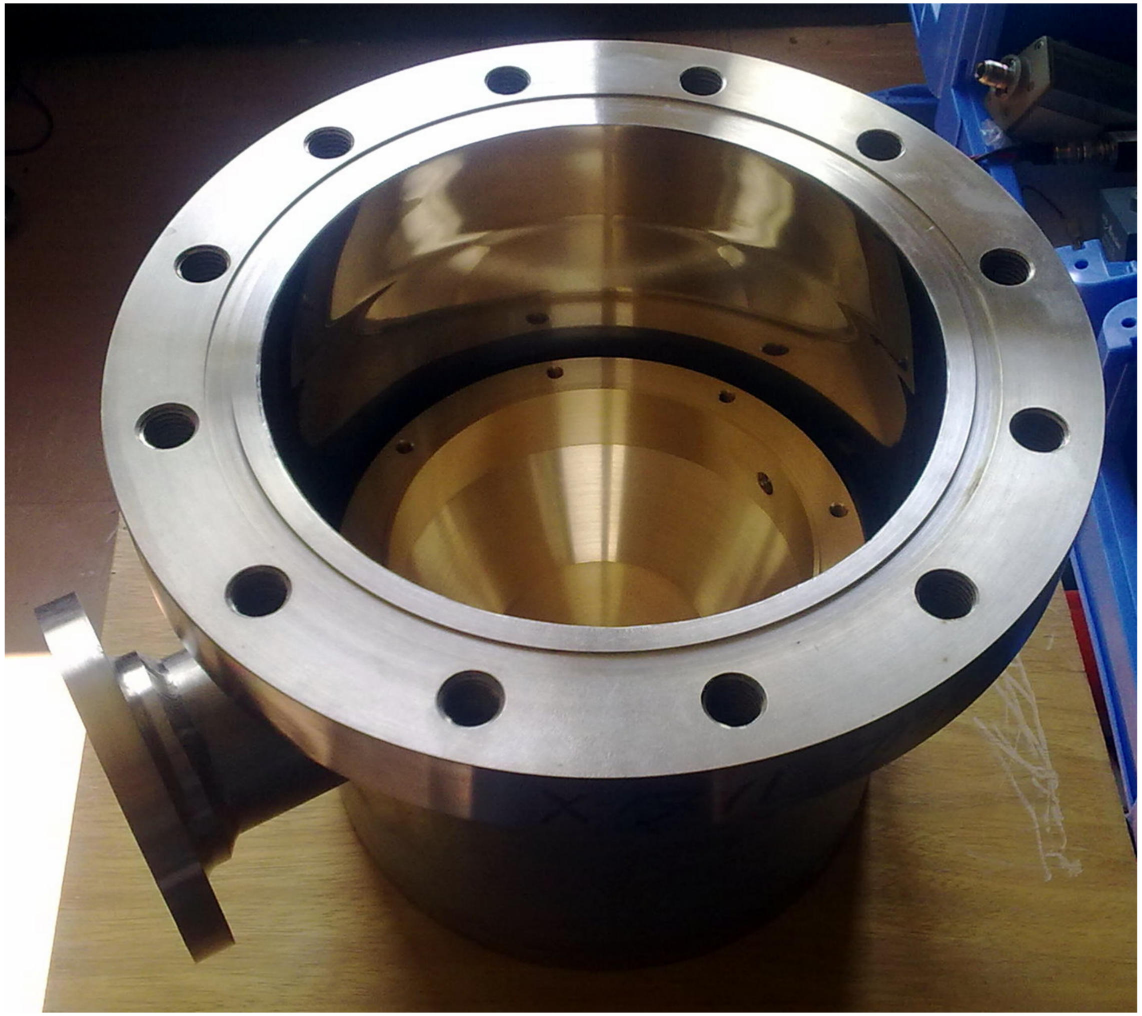
Shielding Box 1
Contains the Axion detection cavity and will later be placed in the cryostat / magnet

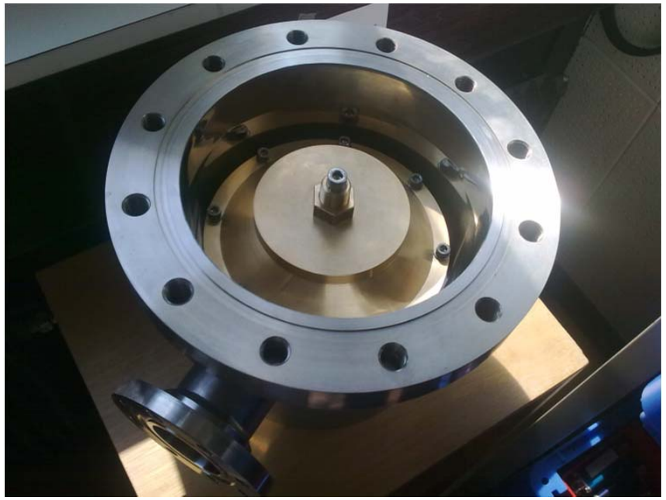
Optical Fibre
Carries the weak signal from Axion conversion to the measurement instruments, unaffected by ambient EM. noise and without comprising the shielding boxes

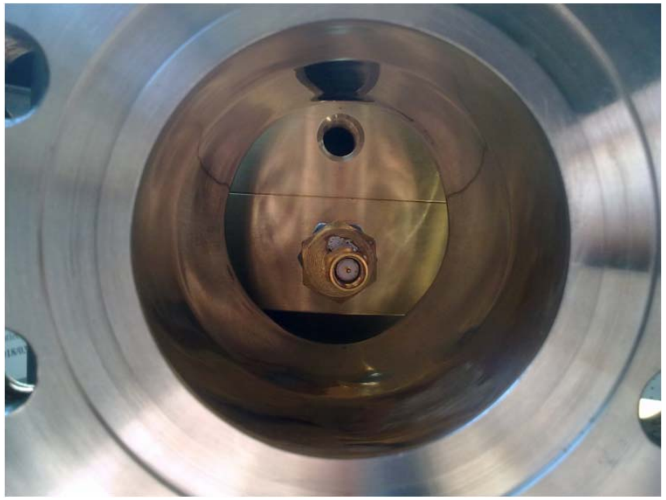
Shielding Box 2
Contains instruments for the detection of weak narrowband microwave signals and will be outside the cryostat / magnet

Electromagnetic shielding

Shielding box 1 prototype, containing the receiving cavity





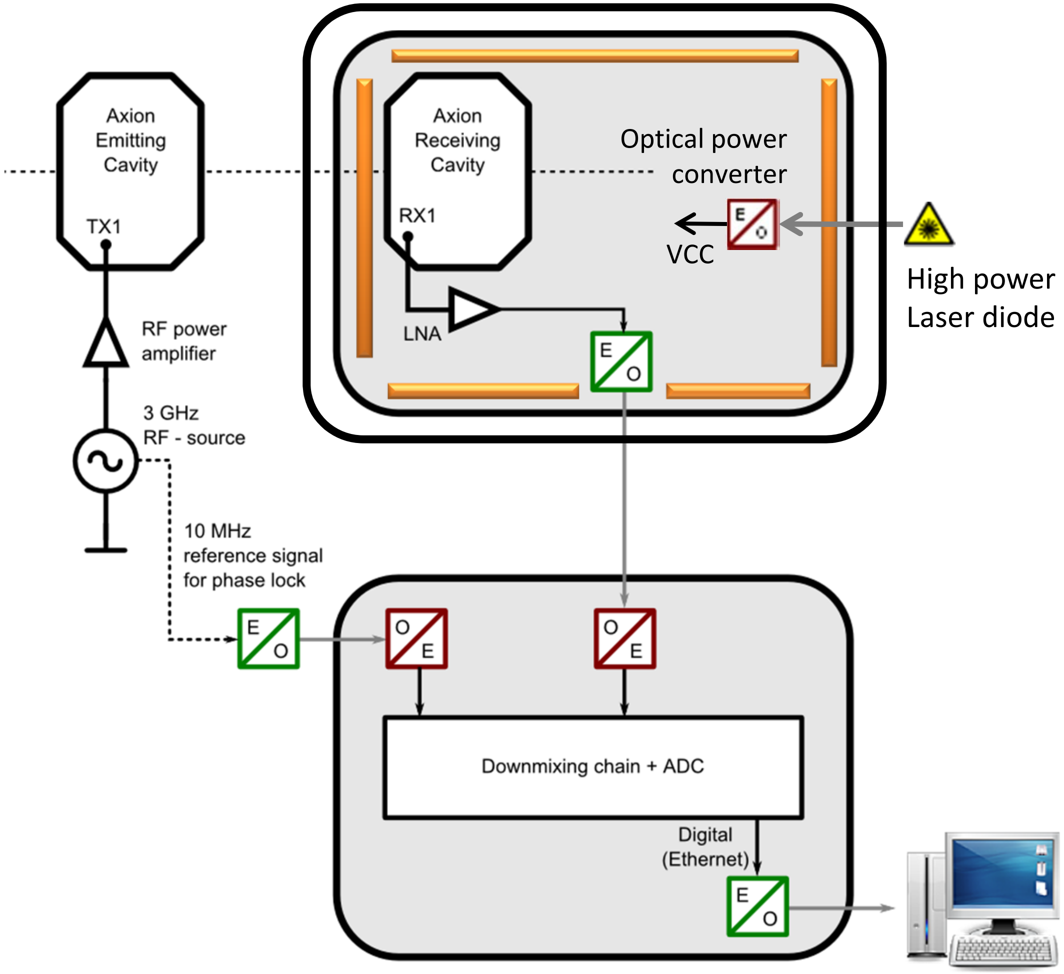


Electromagnetic shielding

Shielding box 2 prototype, containing the instrumentation

Electromagnetic shielding

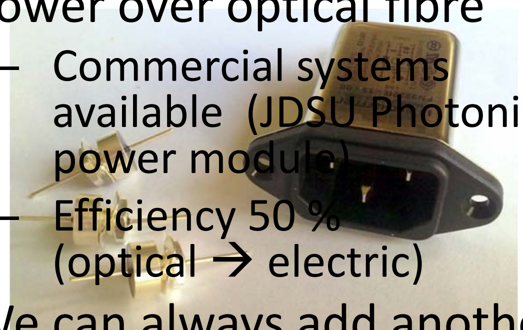
Some practical aspects



- EM absorbing material between shielding layers to dampen unwanted resonances
- Chain of lowpass feedtrough filters for supply voltage

If we still see leakage:

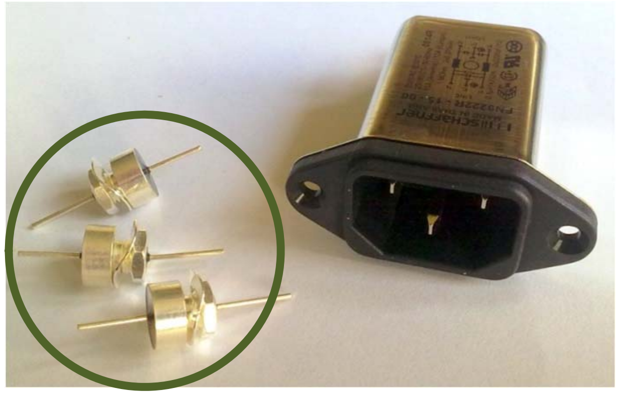
- Power over optical fibre
  - Commercial systems available (JDSU Photonic power module)
  - Efficiency 50 % (optical → electric)
- We can always add another layer of shielding



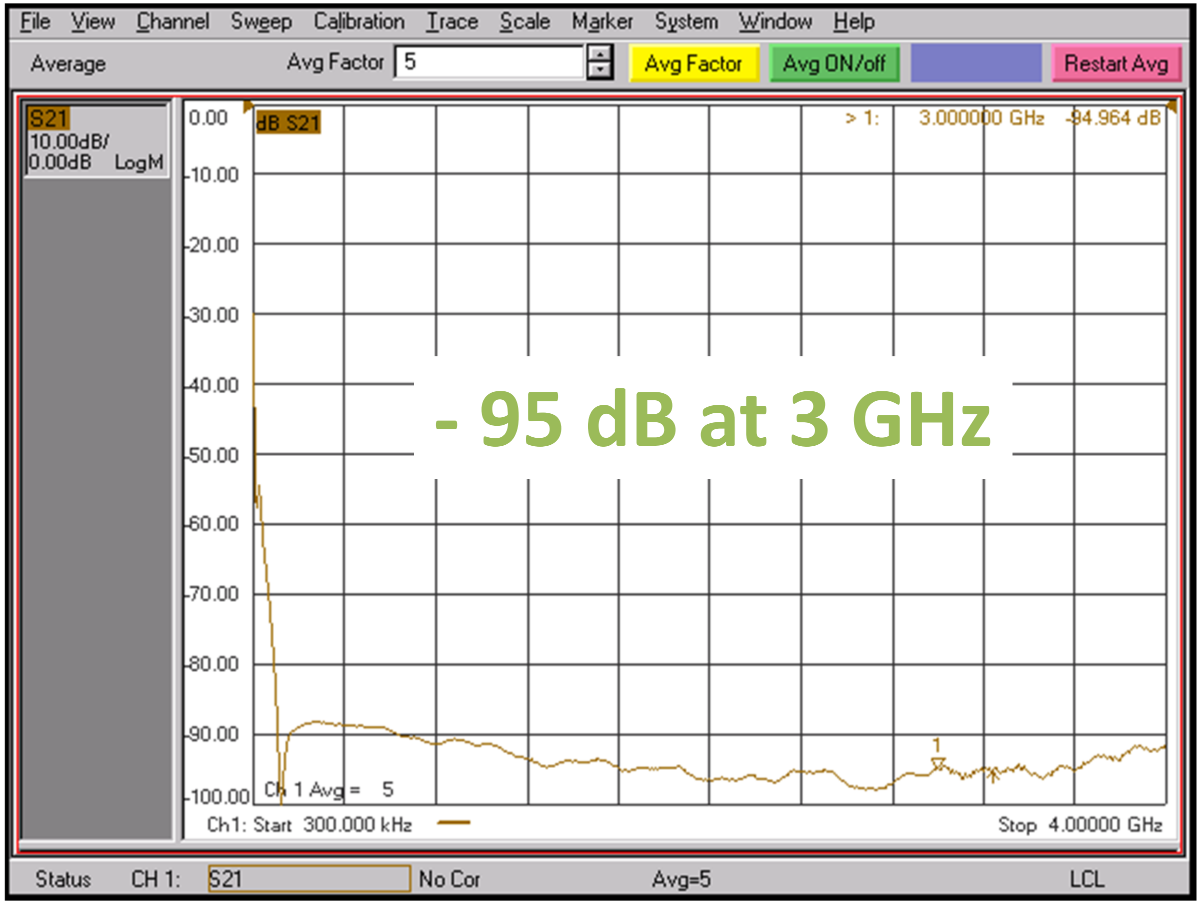
DC – feedtrough filters

For feeding DC power through the shielding while keeping RF out

Syfer SFJNC2000684MX1



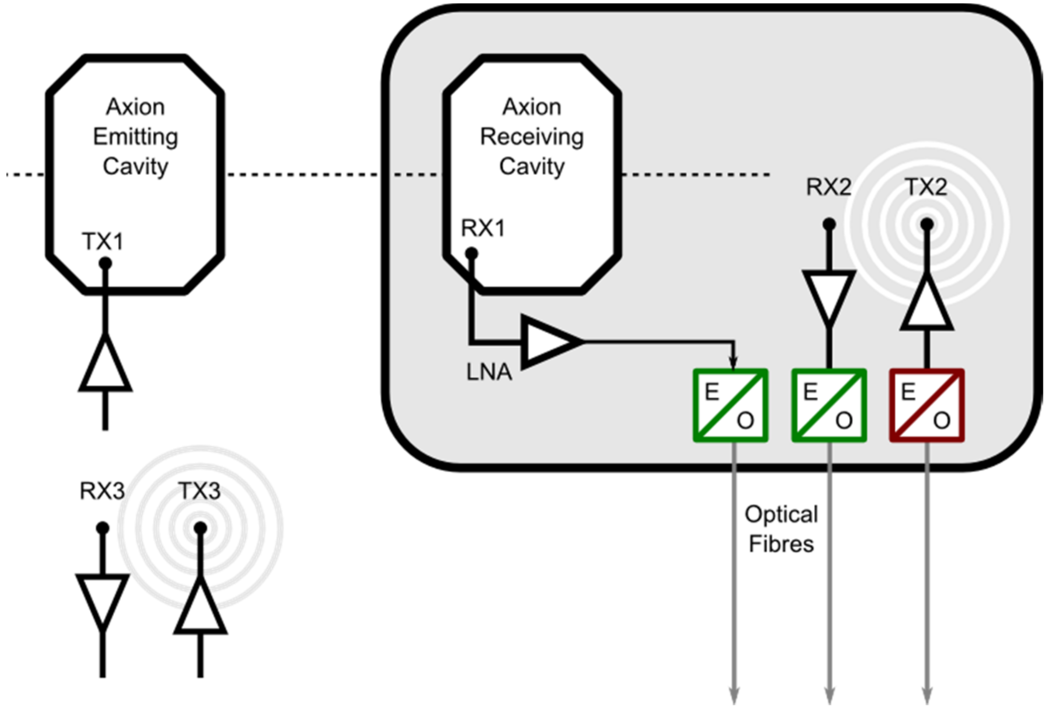
Measurement with a network analyser in transmission



Online diagnostics

Supervising the shielding attenuation with test tones

We need ONLINE diagnostics showing, that the shielding performance is really maintained over the full lifetime of the experiment. **Degradation is possible due to bad and ageing contacts**



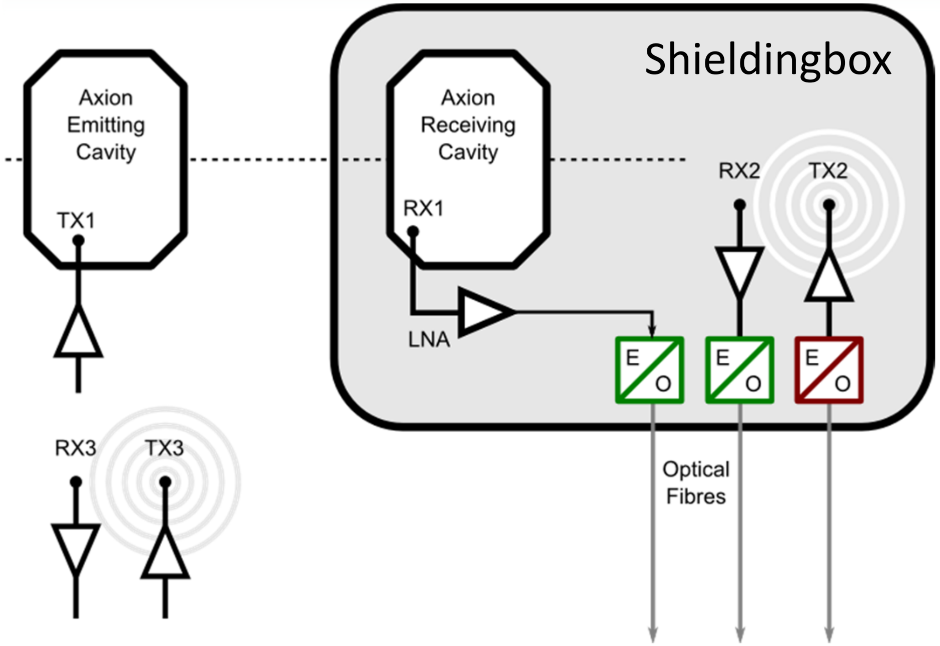
Test tones (TX*n*)

- Low power (µW) probe signals
- Injected in laboratory space and between shielding layers
- Each one has a slightly **different frequency** within the cavity bandwidth
- Monitoring signal power (RX*n*) allows to quantify the attenuation of each shielding layer

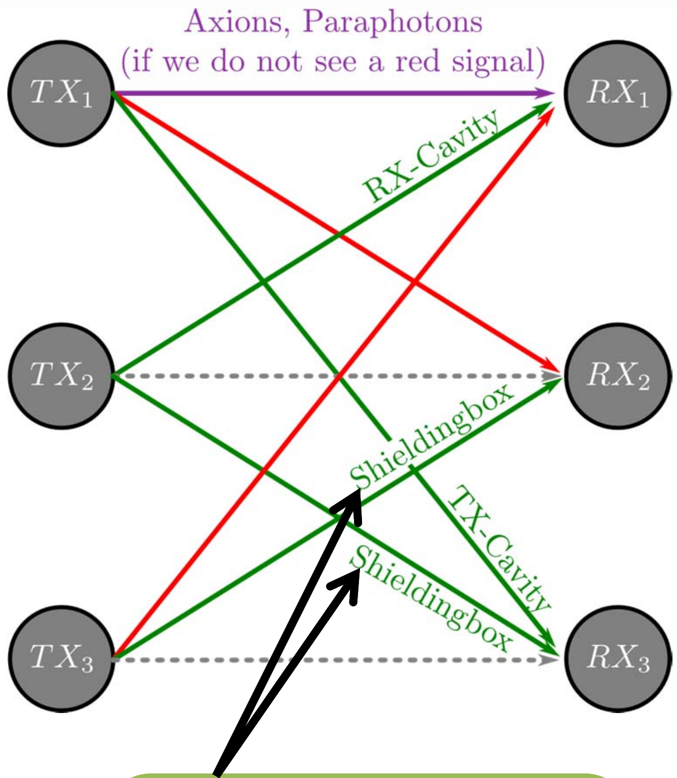
If dynamic range of the receivers is not sufficient, **time multiplexing** is an option.
(Sender and receiver in the same shielding shell are not enabled at the same time)

Online diagnostics

Possible signal-paths



- All possible signal paths are represented as arrows
- **Green signals** pass one shielding layer and can be used to quantify its attenuation
- **Red signals** pass more than one shielding layer. **Observation of a red signal = veto condition on Axion detection**



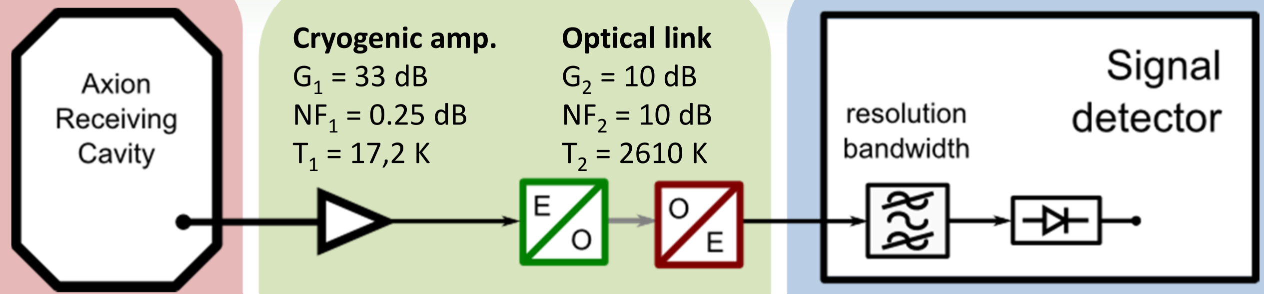
Attenuation of the Shieldingbox is measured twice, giving us redundancy

Detecting weak narrowband signals

Expected signal and noise levels in an example setup

Cryogenic amp.
G_1 = 33 dB
NF_1 = 0.25 dB
T_1 = 17,2 K

Optical link
G_2 = 10 dB
NF_2 = 10 dB
T_2 = 2610 K



Friis formula

P_{signal} = -230 dBm *(from HSPs)*

T_C = 10 K

G_{EQU} = 43 dB

T_{EQU} = 18,5 K

$P'_{signal} = P_{signal}\, G_{EQU}$ = **-187 dBm**

$P'_{noise'} = G_{EQU}\, k\, (T_C + T_{EQU})$
= **-141 dBm/Hz**

resolution bandwidth	Displayed noise floor	min. time trace
1 Hz	-141 dBm	1 sec.
1 mHz	-171 dBm	17 min.
25 µHz	-187 dBm	11 hours

T_n = Noise temp. [K]

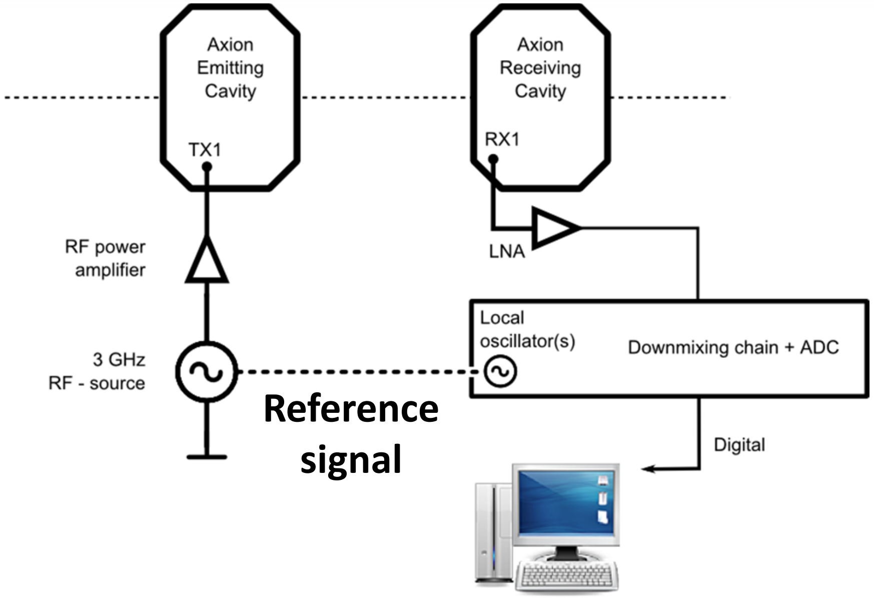
NF_n = Noise figure [dB]

G_n = Gain [dB]

- How to implement this extremly narrowband filter?

Detecting weak narrowband signals

Implementation of the µHz bandwidth filter

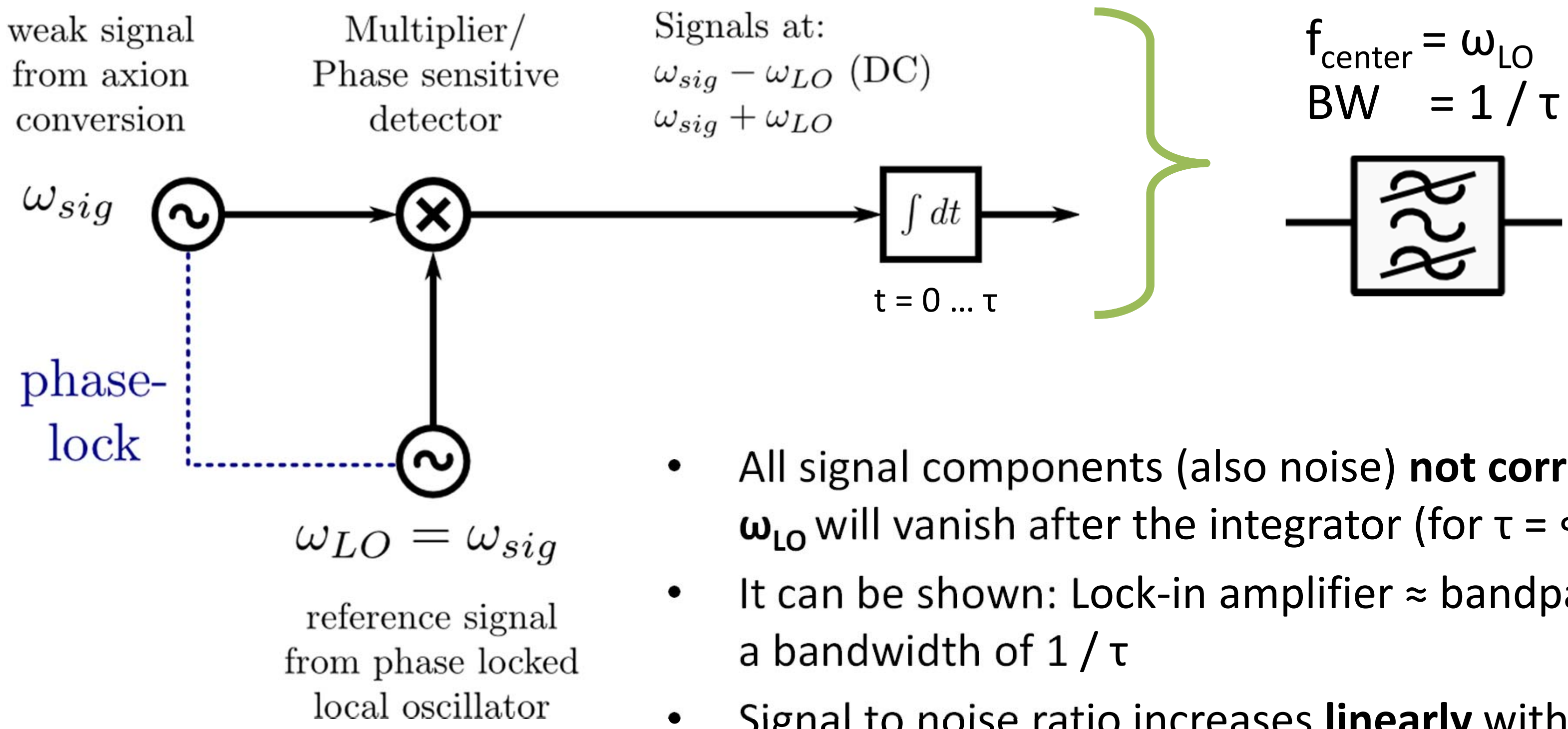


We assume:
Photon → Axion / HSP → Photon conversion does not change the frequency of the original signal

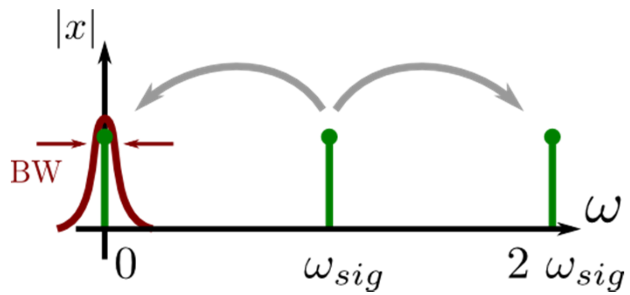
- Luckily we know **exactly** what signal we are looking for
- Exploit the principle of a Lock-in amplifier / correlation receiver / Homodyne detector
- **We test for correlation with a reference signal**
- Filter bandwidths in the µHz range become possible

Detecting weak narrowband signals

Homodyne detection with a lock-in amplifier

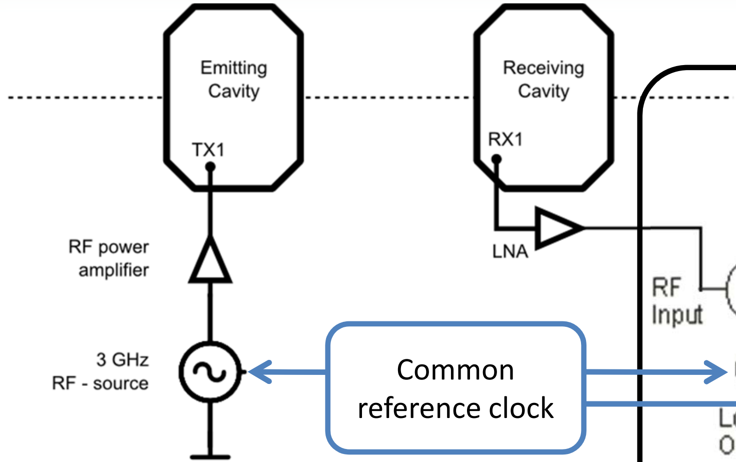


- All signal components (also noise) **not correlated** with $\boldsymbol{\omega_{LO}}$ will vanish after the integrator (for $\tau = \infty$)
- It can be shown: Lock-in amplifier ≈ bandpass filter with a bandwidth of $1 / \tau$
- Signal to noise ratio increases **linearly** with integration time τ ($P_N = k\, T_{SYS}\, BW = k\, T_{SYS} / \tau$)
- Note: Carrying out all signal processing in the **digital** domain is obligatory as analog components are affected by 1/f noise

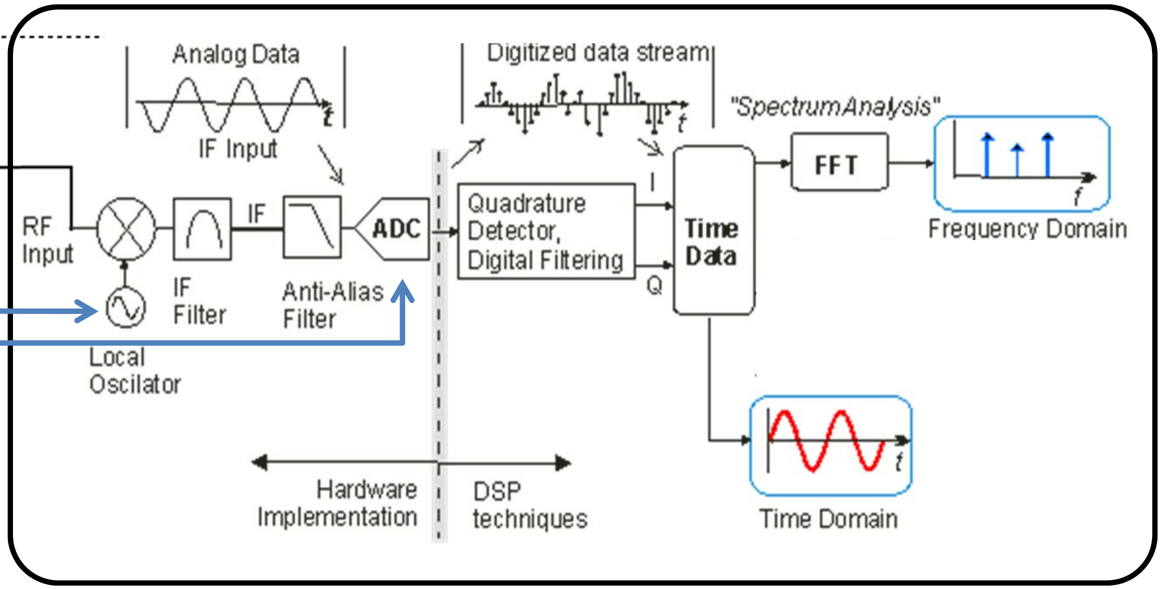


Detecting weak narrowband signals

Homodyne detection with an commercial vector signal analyser



Vector signal analyser (Agilent N9010A EXA)



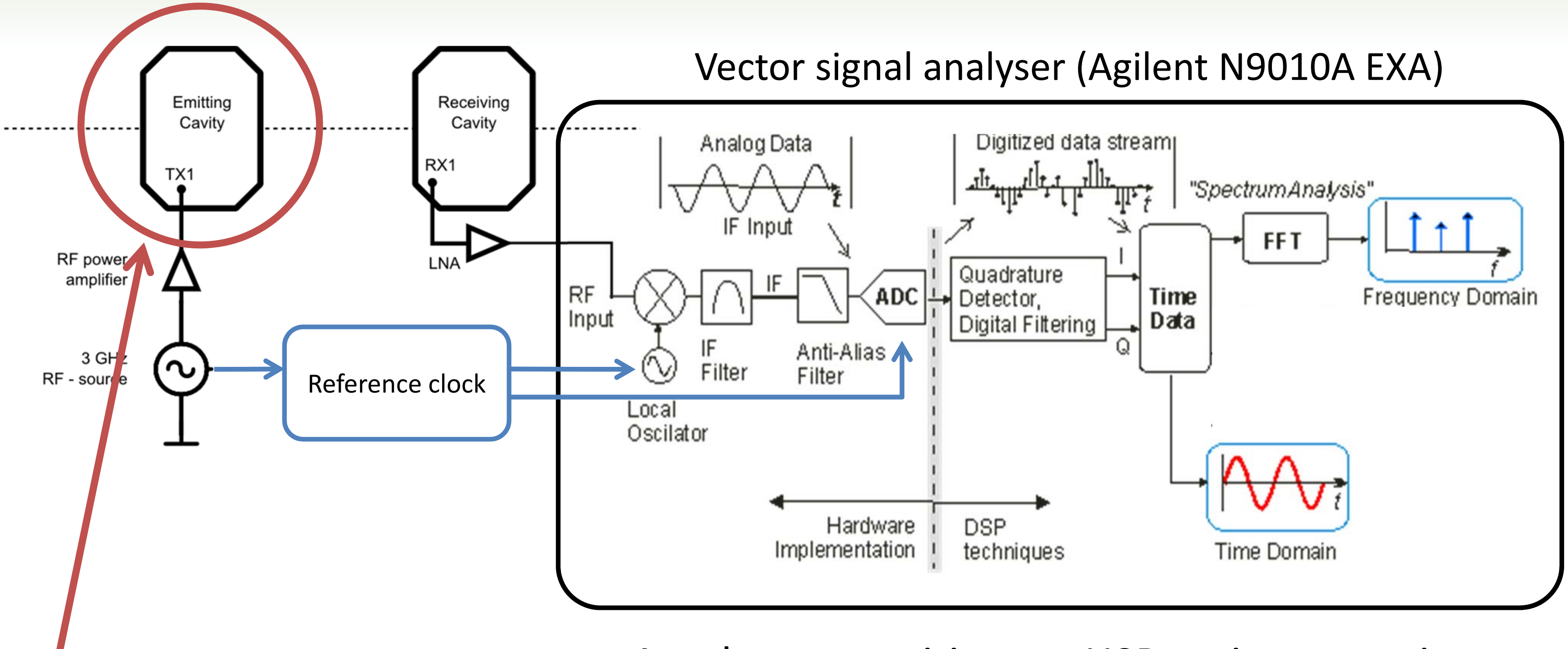
Signal processing chain

1. Analog conversion of the frequency band of interest to an intermediate frequency (**IF**)
2. Analog to digital conversion (**ADC**)
3. Fast Fourier Transformation (**FFT**) ≈ many lock-in measurements in parallel

- Internal phase locked loop circuits in the 3 GHz RF-source and in the vector signal analyser keep everything synchronized to a common reference clock
- Through the synchronization, all the energy of the ω_{SIG} signal should be concentrated in a single bin of the FFT spectrum for arbitrary long time traces τ

Detecting weak narrowband signals

Homodyne detection with an commercial vector signal analyser



This could be an existing microwave cavity from an accelerator

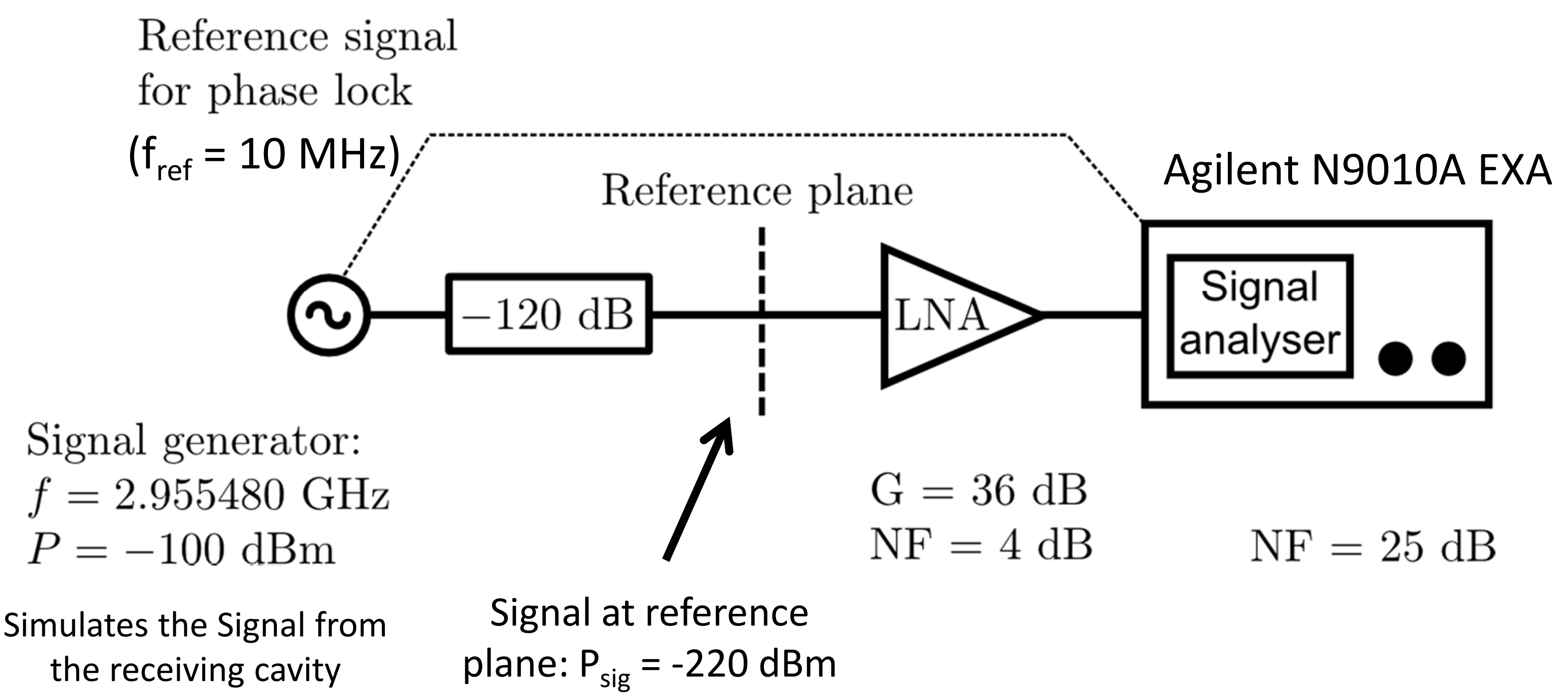
- Accelerator cavities are HSP emitters, we just need to place a detector close to it
- During acceleration, we see a slight change in frequency (~ 1%)
- We can track this, as long as we stay in the resonant bandwidth of the receiving cavity

Suitability of commercial instruments

How stable is the phase-lock for commercial instruments?

How stable is the phase lock for long measurement times?

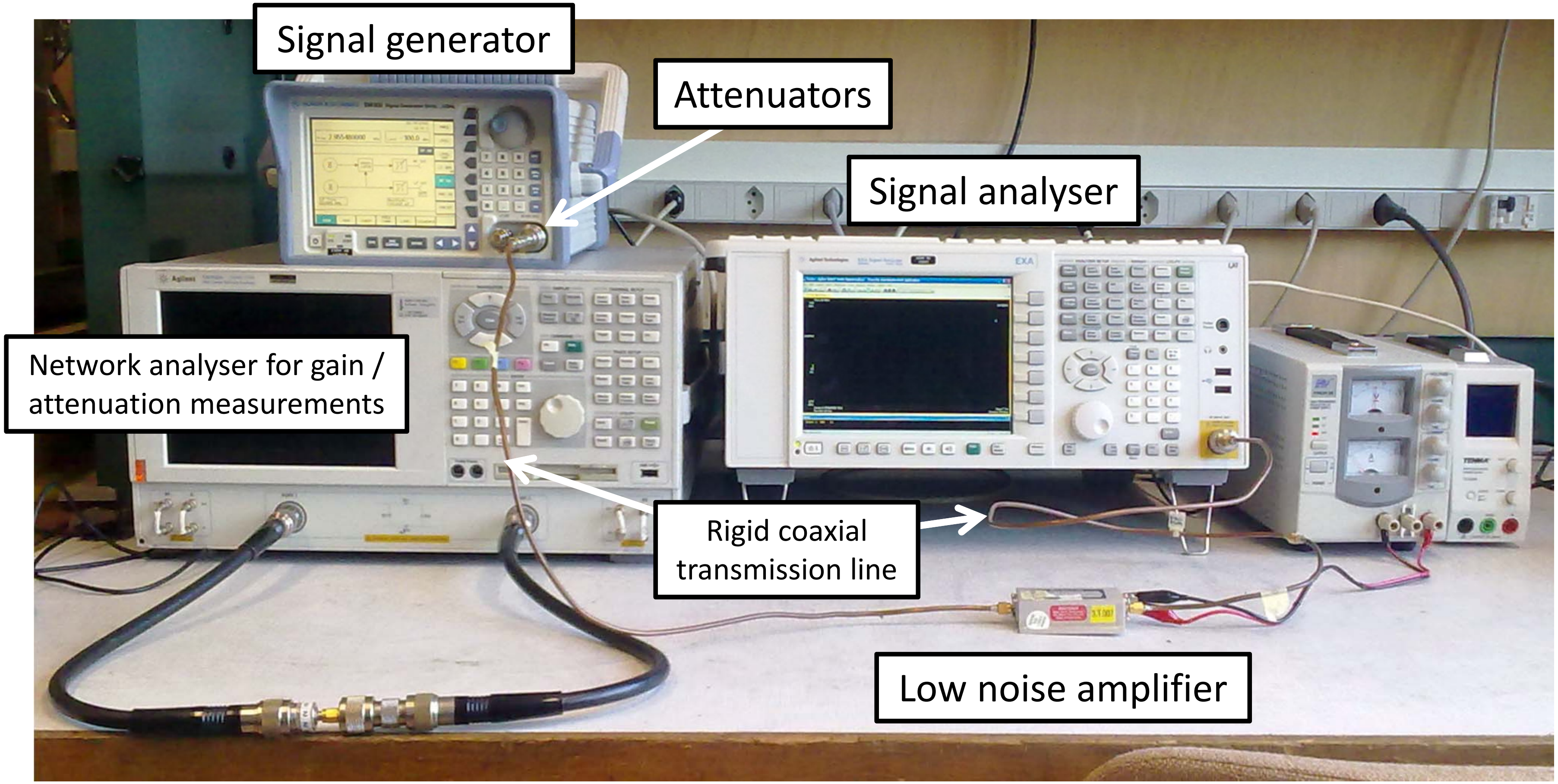
We built an experiment to answer this question and to investigate the feasibility of the narrow band detection approach with a commercial vector spectrum analyser



Also see: Caspers et al. Demonstration of 10^{-22} Watt signal detection methods in the microwave range at ambient temperatures. CERN BE-Note 2009-026 July 09

Suitability of commercial instruments

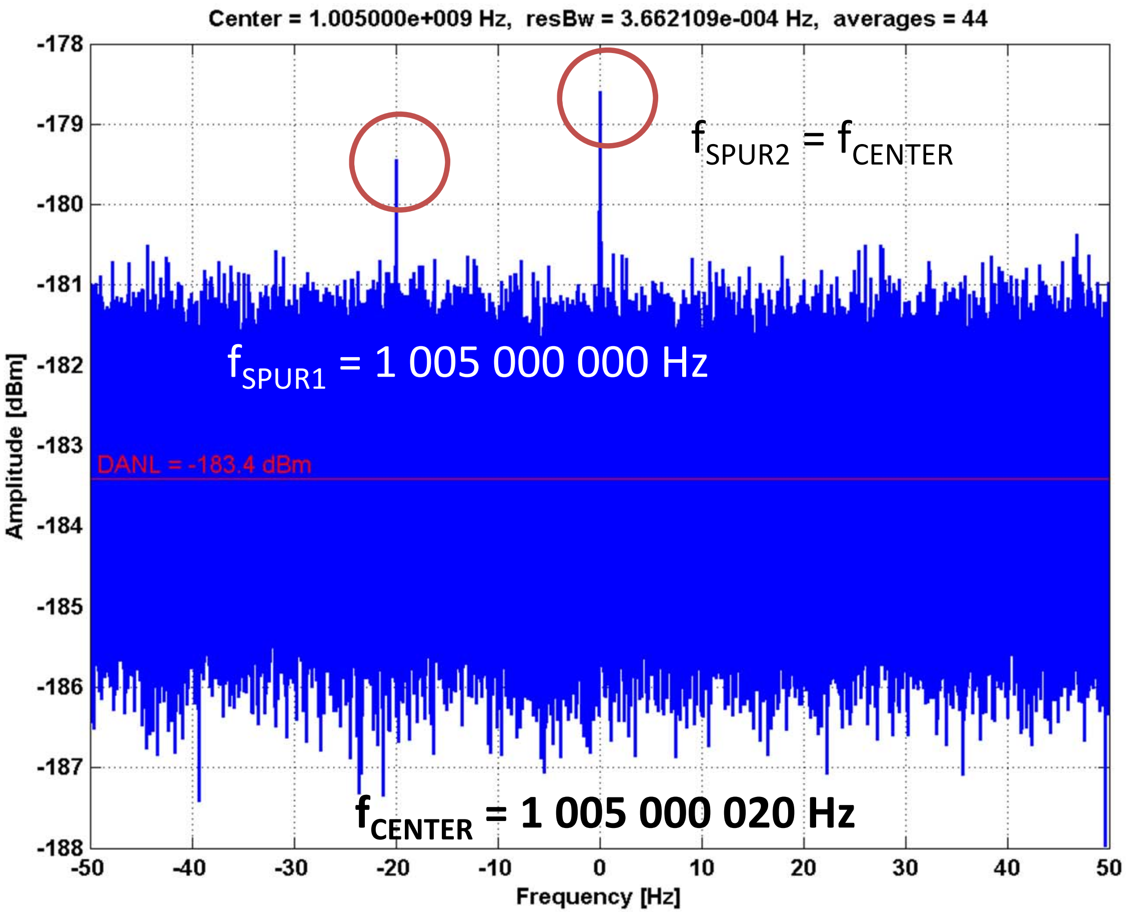
Actual setup in the laboratory



Suitability of commercial instruments

Parasitic internal signals of the analyser

- **Input port terminated, no strong signal sources nearby**
- We should see only thermal noise
- Spurious signals can be observed
  - at the center frequency
  - at even multiples of 5 MHz
- They originate from within the signal processing chain of the instrument
- These frequencies should be avoided in measure-ments with a low noise floor



Suitability of commercial instruments

Analyzing the measurement result

Noise

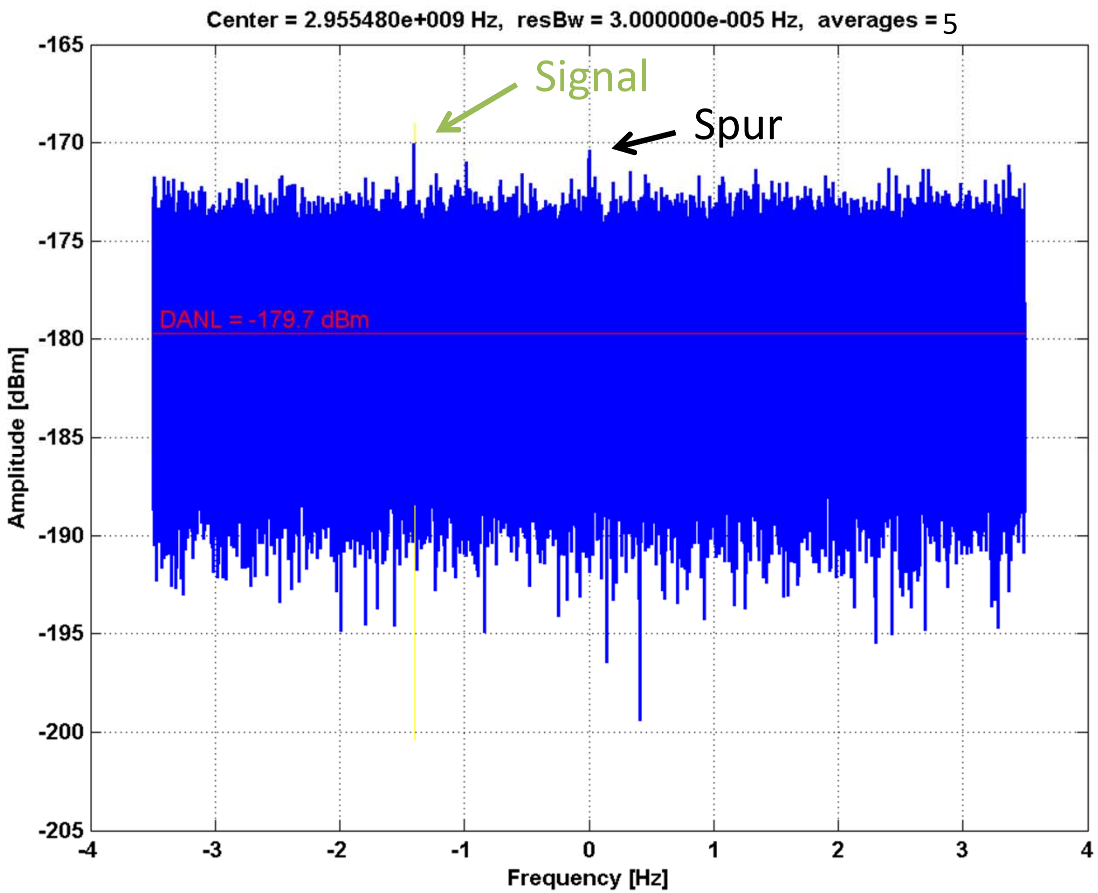
Theoretical prediction:

Thermal noise at
(Δf = 30 μHz):
-219.2 dBm

Amplifier:
Gain = +36 dB
NF = +4 dB

Displayed average noise level (DANL):
-179.2 dBm

Measurement:
Measured DANL:
-179.7 dBm



Signal

Theoretical prediction:

Signal power at source:
-100.0 dBm

Attenuators & cables:
-124.0 dB

Low noise amplifier:
+35.7 dB

Expected signal power:
-188.3 dBm

Measurement:
Measured signal power:
-170.0 dBm

Measurement time: 2 days

We measure the signal 18.3 dB higher than expected
We suffer from leakage!

Suitability of commercial instruments

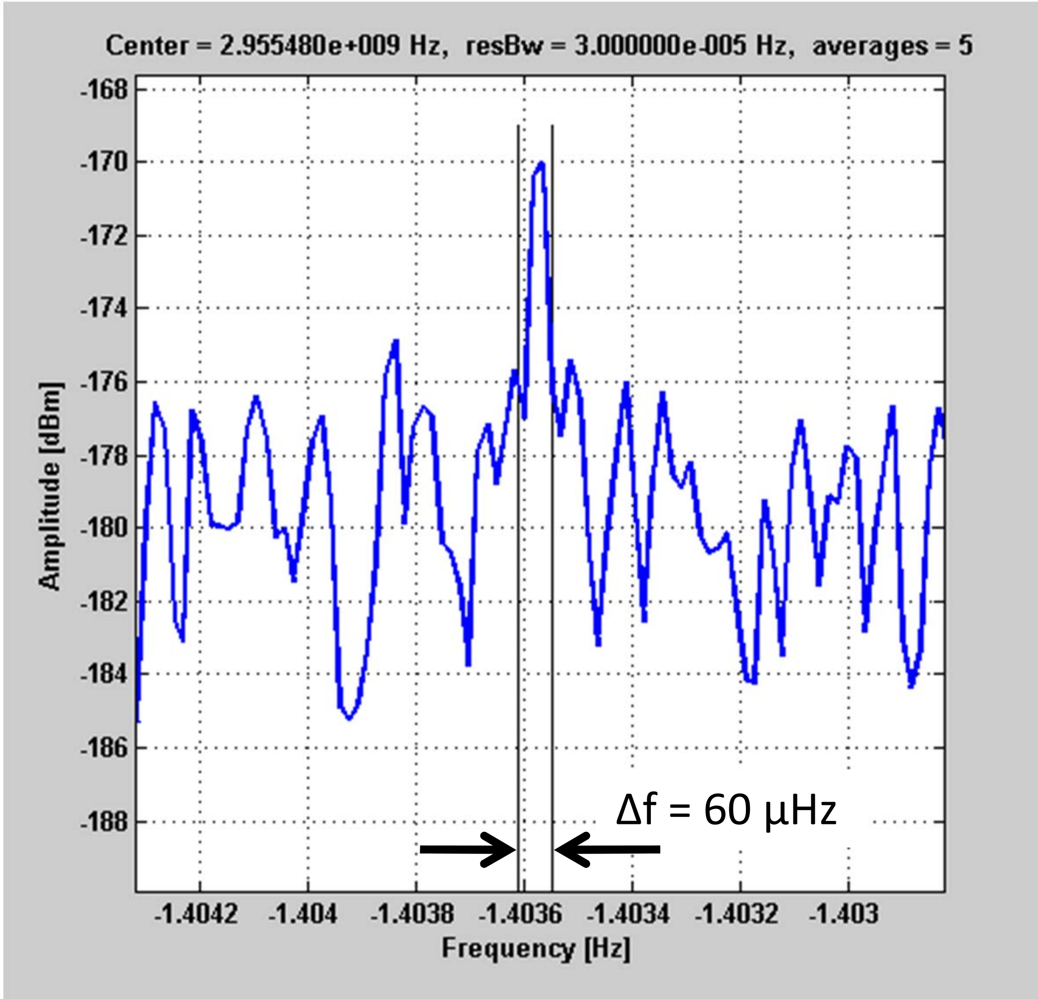
Phase noise and long term stability

- Res. Bw. = 30 µHz
- 5 x averaged
- Measurement time: 2 days
- We still see a sharp peak
- Phase lock between the commercial instruments is satisfactory for long term measurements

Signal spreads out because:
A Hanning window is applied prior to the FFT, trading frequency for amplitude accuracy

Phase noise

temp. drifts? (1 / 30 µHz ≈ 10 h)



Suitability of commercial instruments

What we demand from the signal processing chain

- ✓ Record and process long time traces $\tau \geq 4$ days
- ⚠ Frequency span of the spectrum $f_{max} \geq 20$ kHz
- ⚠ Vertical resolution of ADC $n \geq 24$ bit
- ⚠ Low internal spurious signals
- ⚠ EM. Shielding against environmental signals
- ✓ Phase lock stable, low phase noise
- ⚠ Full control of the signal processing chain

The commercial instrument is useful for initial leakage tests and a good proof of concept

For the actual Axion and HSP search we will design a custom downmixing and signal processing chain

Chromium sesquioxide (Cr_2O_3)

A candidate for an axion conversion material

PHYSICAL REVIEW A **77**, 022106 (2008)

Relativistic nature of a magnetoelectric modulus of Cr_2O_3 crystals: A four-dimensional pseudoscalar and its measurement

Friedrich W. Hehl*
Institute for Theoretical Physics, University of Cologne, 50923 Köln, Germany and Department of Physics and Astronomy, University of Missouri-Columbia, Columbia, Missouri 65211, USA

Yuri N. Obukhov†
Institute for Theoretical Physics, University of Cologne, 50923 Köln, Germany and Department of Theoretical Physics, Moscow State University, 117234 Moscow, Russia

Jean-Pierre Rivera‡ and Hans Schmid§
Department of Inorganic, Analytical and Applied Chemistry, University of Geneva, Sciences II, 30 quai E. Ansermet, CH-1211 Geneva 4, Switzerland

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The magnetoelectric effect of chromium sesquioxide Cr_2O_3 has been determined experimentally as a function of temperature. One measures the electric field-induced magnetization on Cr_2O_3 crystals or the magnetic field-induced polarization. From the magnetoelectric moduli of Cr_2O_3 we extract a four-dimensional relativistic invariant pseudoscalar $\tilde{\alpha}$. It is temperature dependent and of the order of $\sim 10^{-4}/Z_0$, with Z_0 as vacuum impedance. We show that the new pseudoscalar is odd under parity transformation and odd under time inversion. Moreover, $\tilde{\alpha}$ is for Cr_2O_3 what Tellegen's *gyrator* is for two port theory, the *axion* field for axion electrodynamics, and the PEMC (perfect electromagnetic conductor) for electrical engineering.

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Chromium sesquioxide (Cr_2O_3)

A candidate for an axion conversion material

- **α**: Magnetoelectric effect of Cr_2O_3 (Mix of permittivity and permeability)
- Symmetry of α under parity and time is the same as for axions
- Thus one may speculate if Cr_2O_3 increases the conversion probability of axions ← → photons
- Fill part of the cavity volumes with Cr_2O_3
  - **Single crystal**: might be possible to grow in 2 cm diameter rods by a modified Verneuil process [1]
  - **Powder**: readily available as paint colour pigment
  - **Trade off**: sintered / hot pressed powder, largely reduced pore volume compared to powder

[1] Dr. Kinloch & C E Birchenall, J. Crystal Growth, 19,105-8 (1973)

Conclusion

Photon regeneration exp. at CERN

- Electromagnetic interference
  - A critical point for sensitive photon regeneration experiments
  - We proposed: “box in the box” concept, optical fiber signal and power transmission, shielding diagnostic with test tones
  - This way a certain shielding value (i.e., 300 dB) can be **guaranteed**
- Narrowband signal detection
  - A correlation receiver can increase the signal to noise ratio linearly with integration time
  - A commercial signal analyser can be operated as correlation receiver through phase locking
- Chromium oxide
  - Might increase the probability of axion ←→ photon conversion

Outlook

Next steps and questions to be cleared

- Shielding
  - Finish shielding box 1 and 2 with optical signal transmission
  - Realize the shielding supervision with probe signals
- Narrow band detection
  - What limits the resolution BW at the moment?
  - -230 dBm at 3 GHz ≈ 1 Photon every 3 minutes. Do quantum mechanical effects need to be considered?
  - Influence of the analog digital converters vertical resolution and sampling rate on the result (dithering, etc.)?

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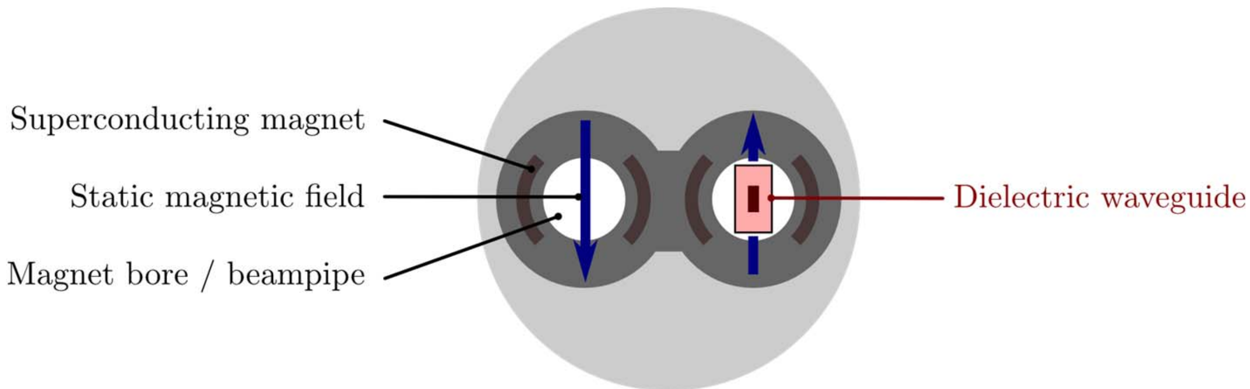
- F. Hehl has contributed the suggestion, to use Chromium sesquioxide as an axion photon converter for microwave experiments.

Appendix:

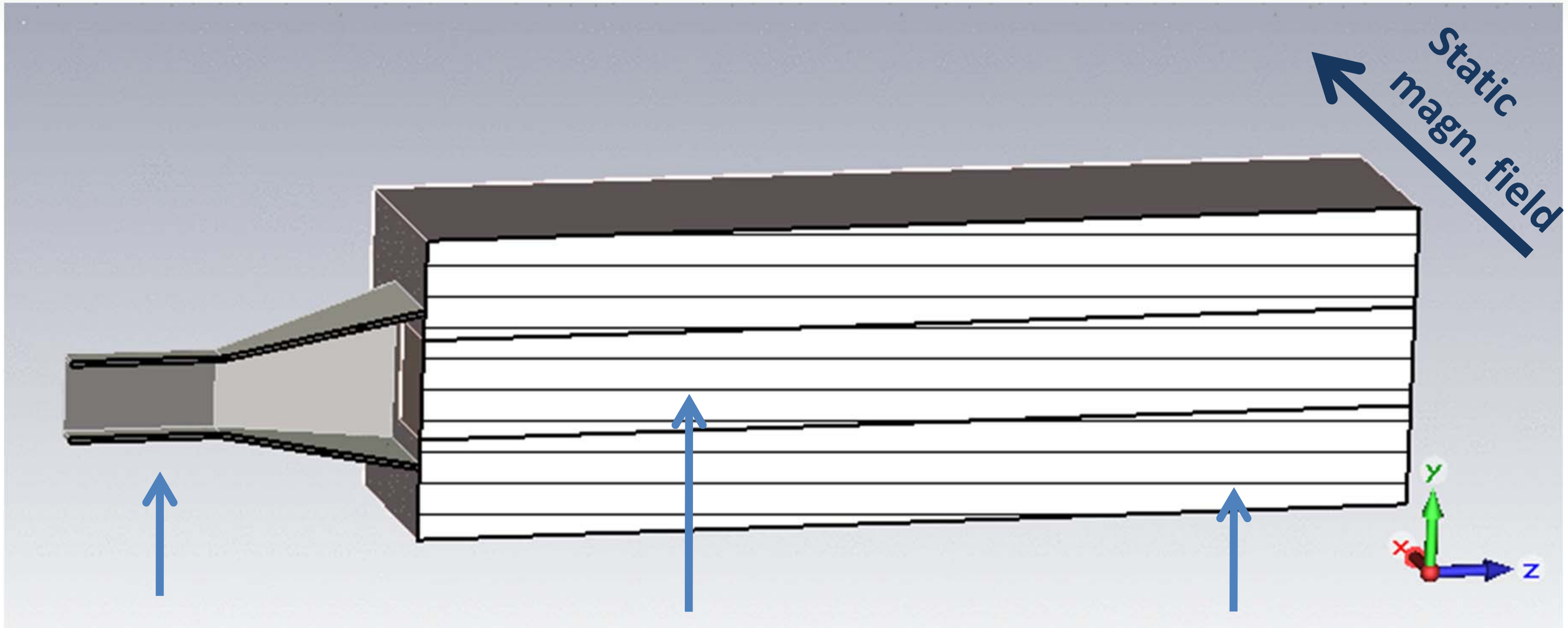
A dielectric waveguide as an "Axion Antenna"

- **Photon regenration at 30 GHz (quasi optical)**
- **Axion antenna**
  - Axion → Microwave photon conversion by the Primakoff effect in one bore of a LHC dipole magnet
  - Dielectric waveguide collects and concentrates converted microwave photons
- **Radiometer**
  - The antenna outputs mostly thermal background noise (T=2K) + a faint additional signal from converted Axions if they exist
  - Radiometer = device to accurately measure small differences in noise power
  - Do we see a difference in noise power with the magnetic field switched on and off?



Dielectric waveguide

Conceptual design of a simple Axion receiving / emitting structure



Metallic waveguide
(to Radiometer)
3.6 mm x 7.1 mm

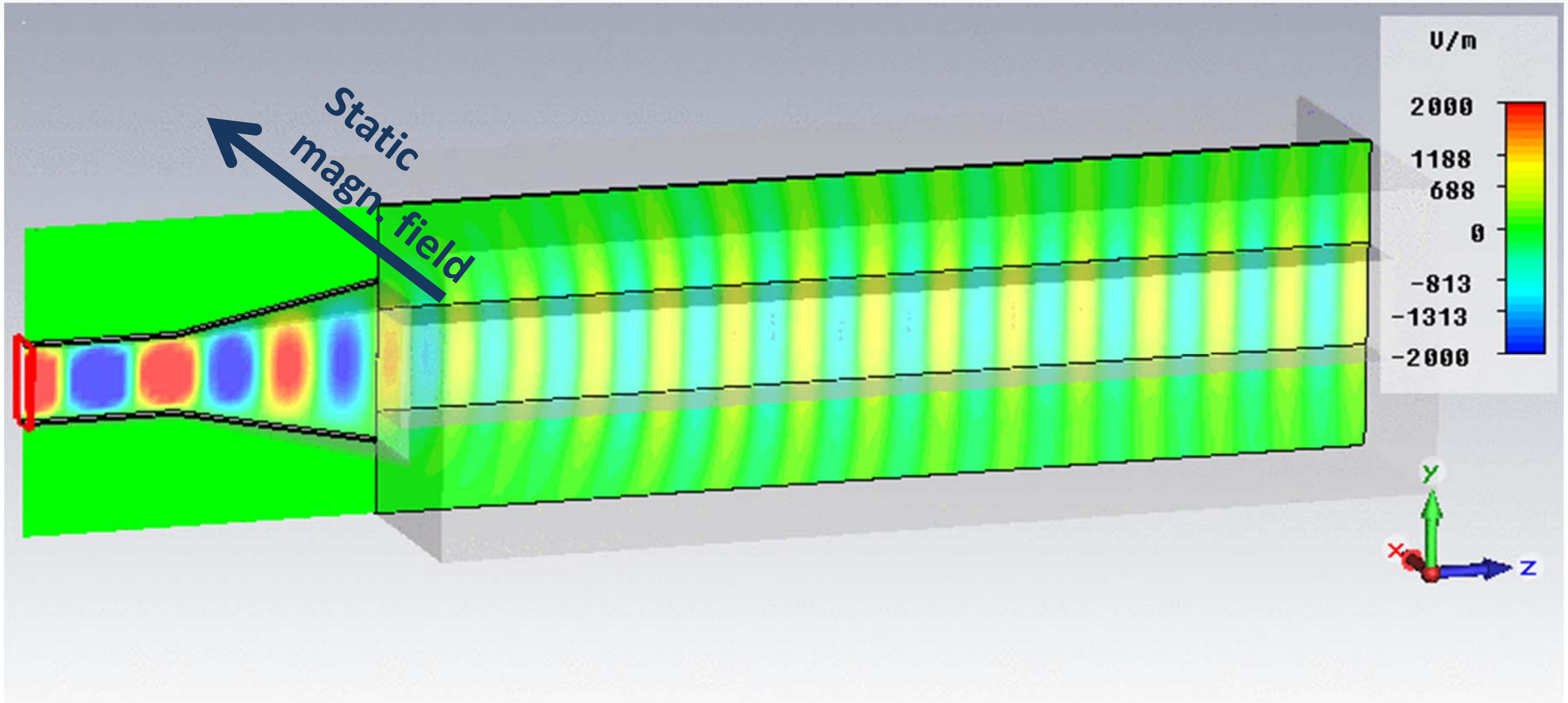
Core
Teflon ε_R = 2.1
15 mm x 10 mm

Cladding
Styrofoam ε_R = 1.08
40 mm x 30 mm

- Low loss transmission at 30 GHz
- Essentially an optical monomode fiber for microwaves
- Operation in travelling wave or standing wave (resonant) mode possible
- Large „active volume“

Dielectric waveguide

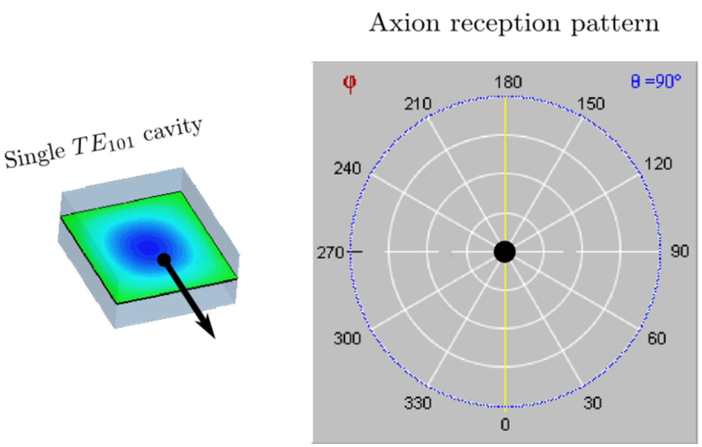
Numerical simulation of the electric field inside the structure

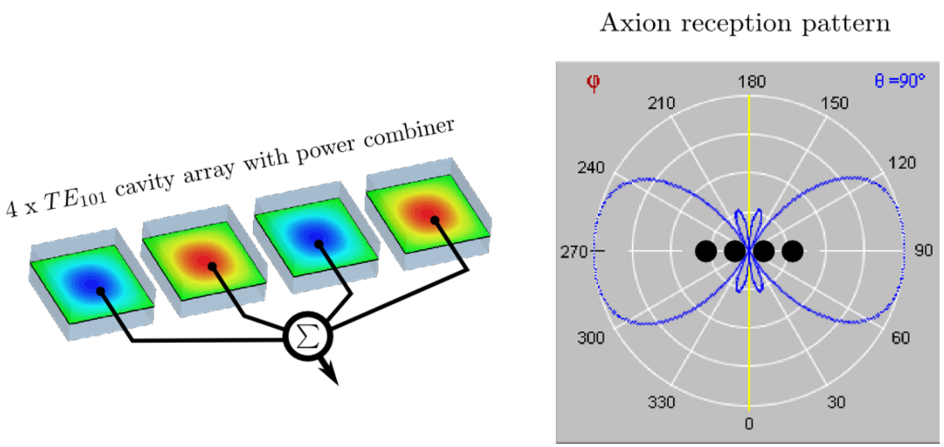


- f = 30 GHz
- Shown is the field component in X – direction, parallel to the static magnetic field of the LHC magnet
- Electric field distribution inside this waveguide resembles laser light shining through a wall experiments like OSQAR, ALPS, etc.

Dielectric waveguide

Why we expect directivity from a waveguide type axion antenna

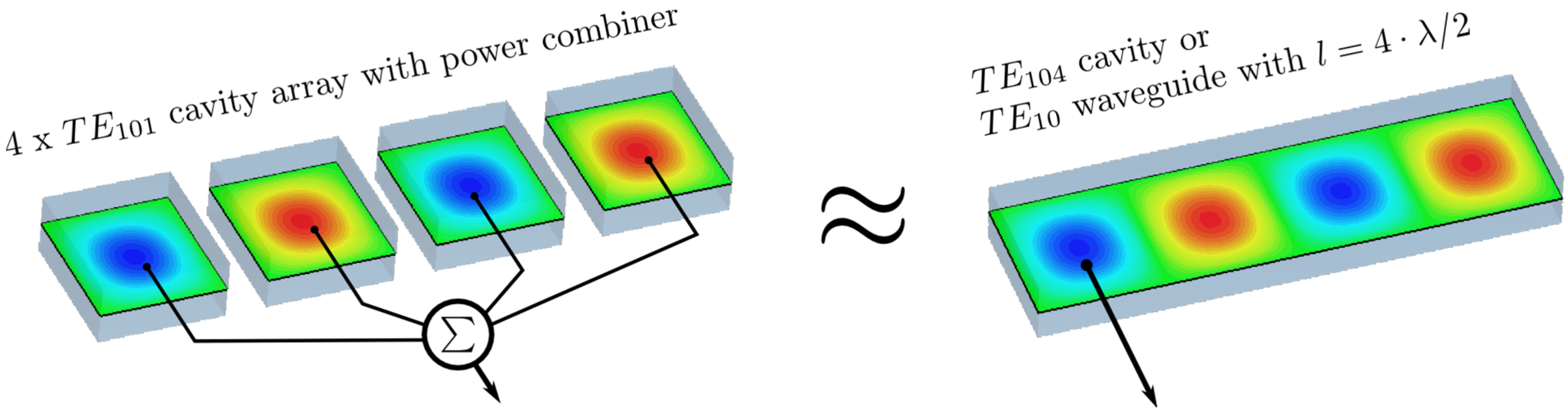




- Looking at microwave experiments for axion detection:
  - A single, fundamental mode cavity shows omnidirectional sensitivity to axion flux → elementary element
  - We can do **beamforming** with an array of multiple elementary elements, combining the output signals with a certain phase relation

Dielectric waveguide

Why we expect directivity from a waveguide type axion antenna

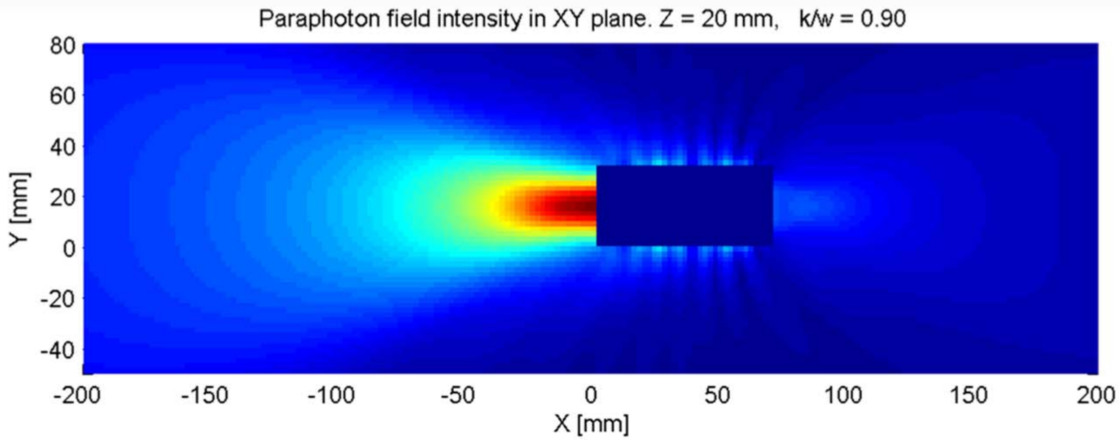


- The electric field in the waveguide resembles an array of multiple elementary elements
- Parameters of the array antenna depend on the waveguide properties
  - Number of elements
  - Spacing between elements
  - Phase shift between elements

Dielectric waveguide

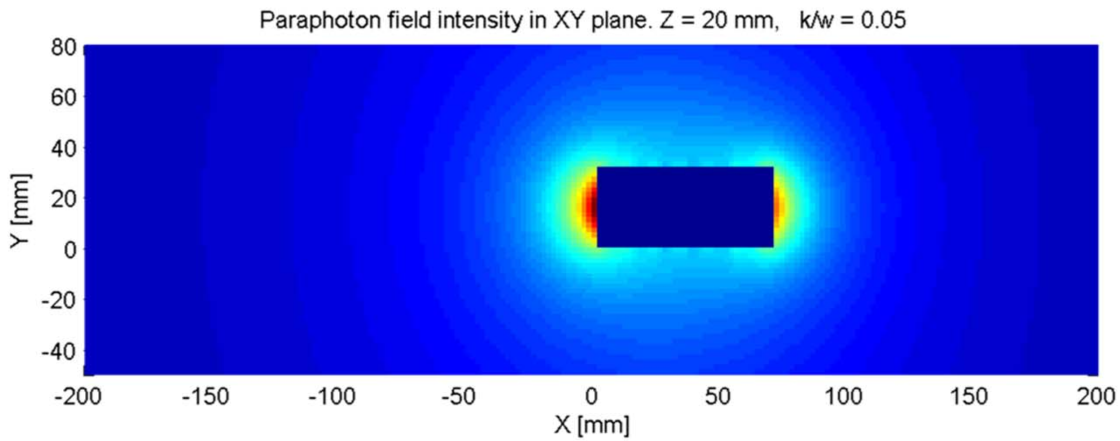
HSP radiation pattern of a dielectric waveguide, travelling wave

Fast hidden photons



We expect very similar patterns for Axions, if a homogenous static magnetic field is used.

Slow hidden photons



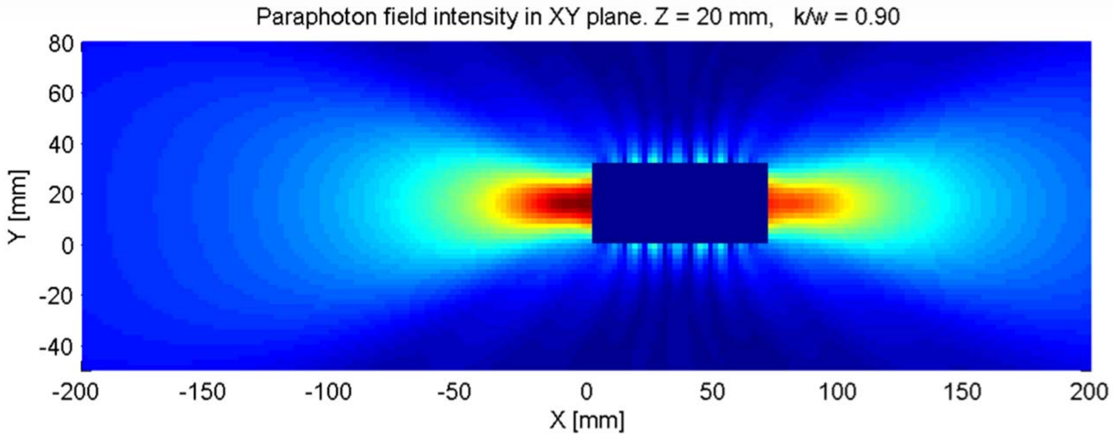
Travelling wave mode at 20 GHz:

Both sides open

Dielectric waveguide

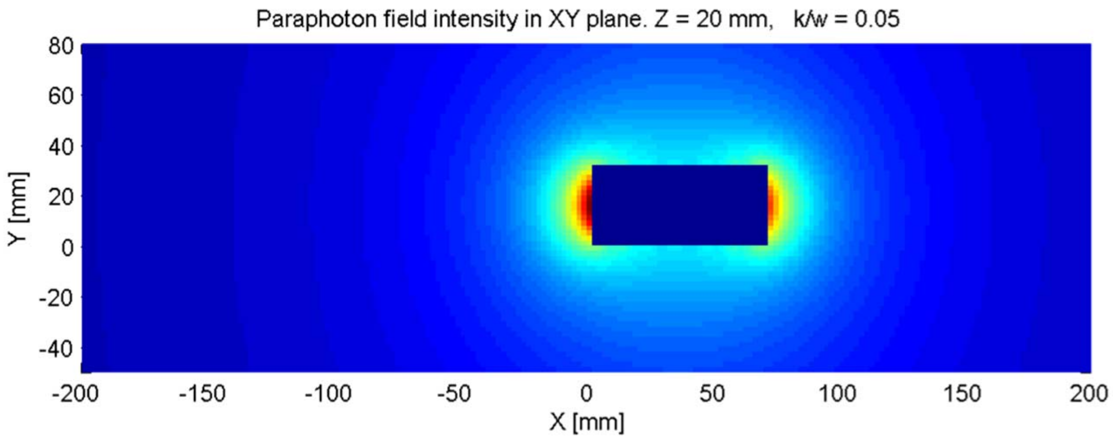
HSP radiation pattern of a dielectric waveguide, standing wave

Fast hidden photons



We expect very similar patterns for Axions, if a homogenous static magnetic field is used.

Slow hidden photons



Standing wave mode at 20 GHz:

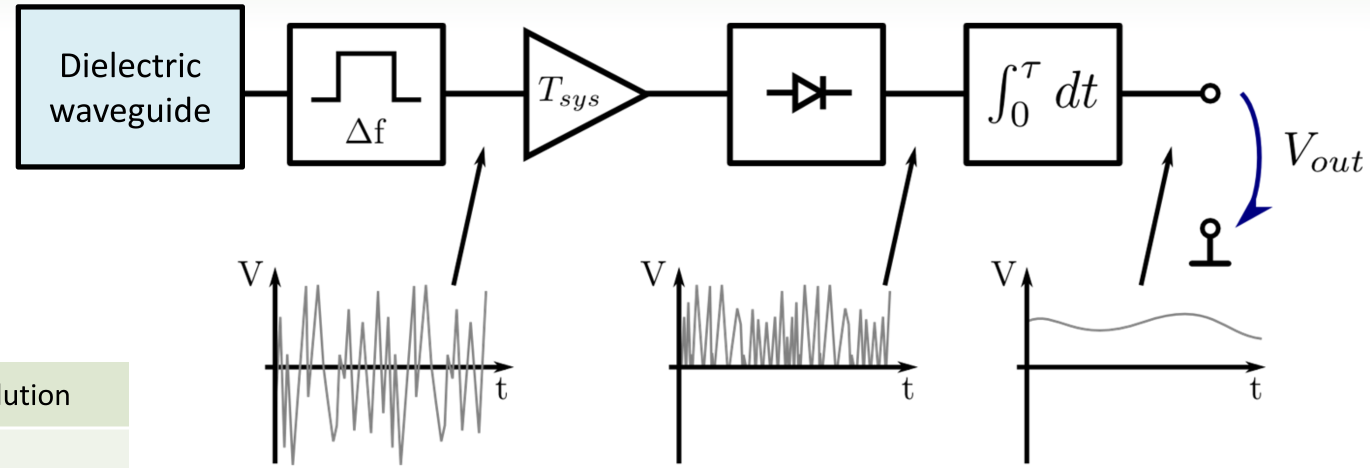
Both sides terminated by a metal plate (electrical short circuit)

Detecting wideband signals

The radiometer

Dicke's radiometer equation:

$$\Delta T = \frac{T_{sys}}{\sqrt{\tau \cdot \Delta f}}$$



ΔT	Noise temperature resolution
Δf	Observation bandwidth
T_{sys}	System noise temperature
τ	Integration time

How to improve on ΔT:

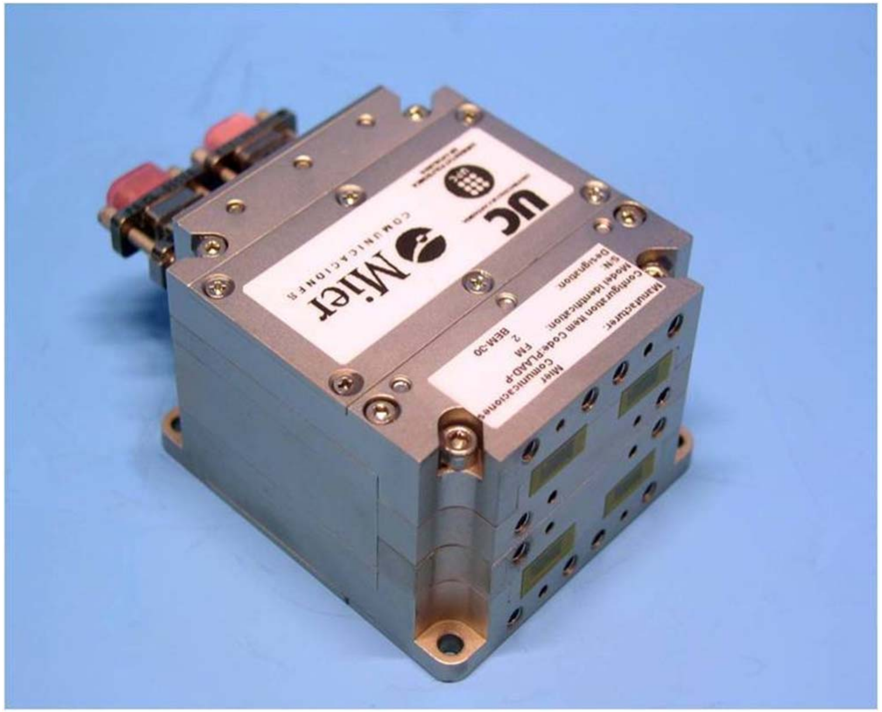
- Reduce the front end noise temperature T_{sys}
- Increase integration time τ
- Increase the observation bandwidth Δf, if applicable

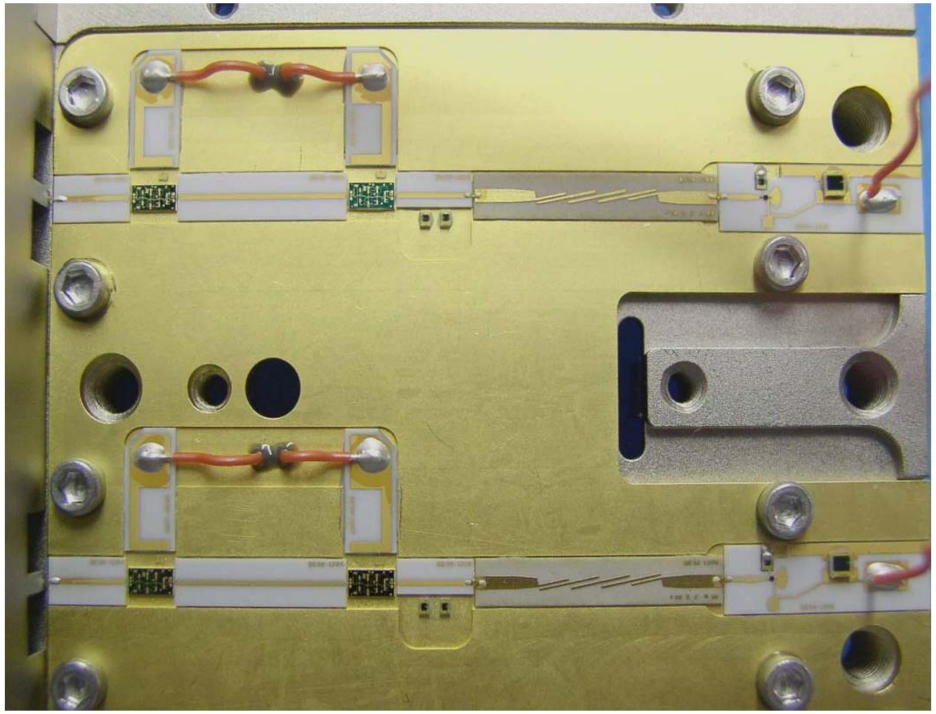
- We quantify the power of the wideband noise signal from the dielectric waveguide in travelling wave mode
- Is there a difference with Axion / HSP source switched on and off?
- A Radiometer is an instrument to measure very small **differences** in noise power

Detecting wideband signals

Microwave Radiometer Receivers; Microwave Background in Space

Pictures show a Radiometer from the **PLANCK** satellite.
It was used to measure the microwave background in space
Center frequency = 30 GHz, Bandwidth = 8 GHz,
Physical temperature = 20 K, **Detector sensitivity = ± 20 µK**





Conclusion

A Dielectric Waveguide as an "Axion Antenna"

- A dielectric waveguide inside a LHC dipole magnet provides a large interaction volume for axion-to-photon conversion, with low transmission loss
- Generally speaking, dielectric waveguides are better suited for this kind of experiment from about 30 GHz onwards (up to the optical range) compared to metallic wave-guiding structures
- To start with the implementation of this novel detection scheme for axion detection, we propose to use a radiometer that operates in range of 30 GHz. This range can be extended in future updates by additional higher frequency instrumentation
- We propose to use very sensitive radiometers in this frequency range which already operate in different satellites, for mapping the microwave background radiation of space
- The proposed wide detection bandwidth requires a significant contribution from the expected thermal noise even if the structure is at 2 K. The converted axion flux would reveal itself as a slight enhancement of this noise level
- Possible interference from man made electromagnetic noise can be excluded or confirmed using suitable test signals to be applied from time to time to the experimental setup