CLUSTER OF EXCELLENCE
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MADMAX

Towards a Dielectric Axion Haloscope

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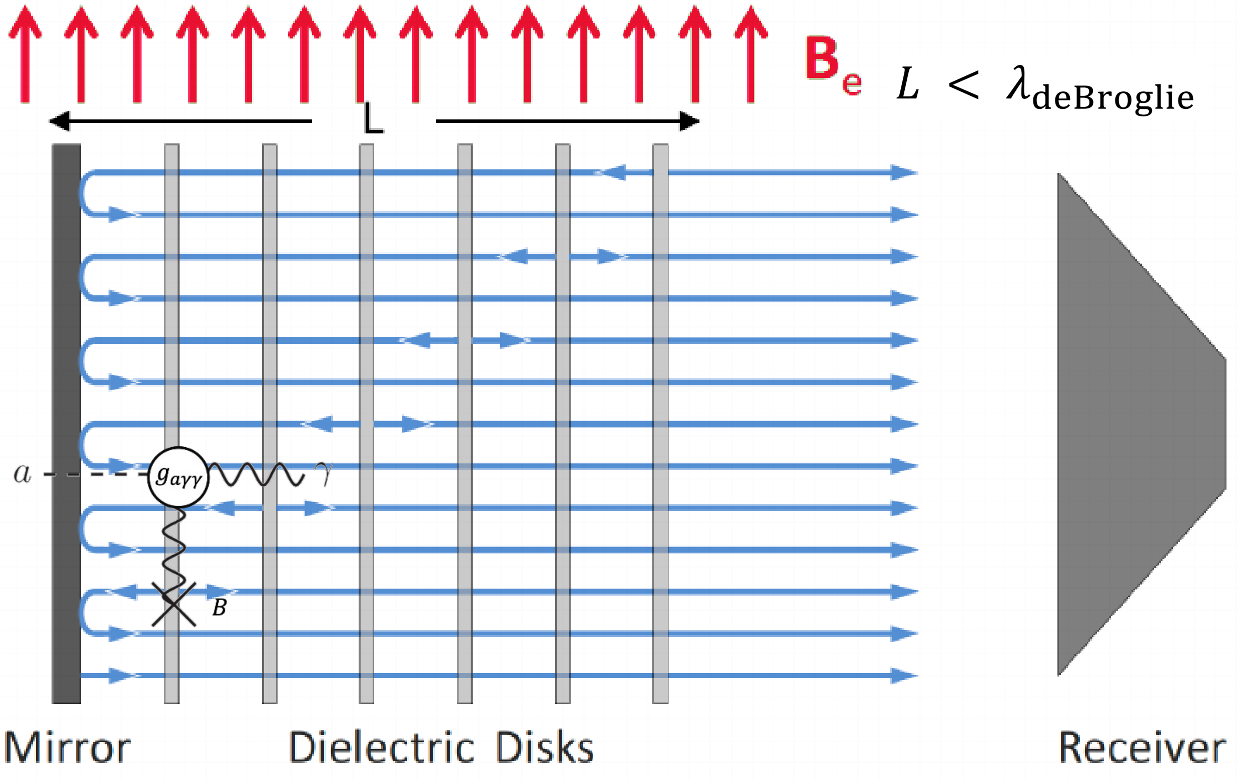
Universität Hamburg

On behalf of the MADMAX Collaboration

Open Dielectric Haloscope

MADMAX:

- Tunable in frequency coverage:
  ~10-100 GHz
- Boost emitted power through:
  - coherent emission from multiple interfaces
  - constructive interference effects
- Coupling to $g_{a\gamma\gamma}$ scales with:
  - external field, $\propto B$
  - conversion surface, $\propto A^{0.5}$



$$g_{a\gamma} = 2.04(3) \times 10^{-14}\ \mathrm{GeV}^{-1} \sqrt{\frac{\mathrm{SNR}}{5}}\ \frac{400}{\sqrt{\beta^2}} \sqrt{\frac{1\mathrm{m}^2}{A}} \sqrt{\frac{T_{sys}}{8\mathrm{K}}}\ \frac{10\ \mathrm{T}}{B_e} \sqrt{\frac{0.8}{\eta}} \left(\frac{1.3\ \mathrm{days}}{\Delta t}\right)^{1/4} \sqrt{\frac{300\ \mathrm{MeV}^2}{\rho_0}} \left(\frac{m_a}{100\ \mu\mathrm{eV}}\right)^{5/4}$$

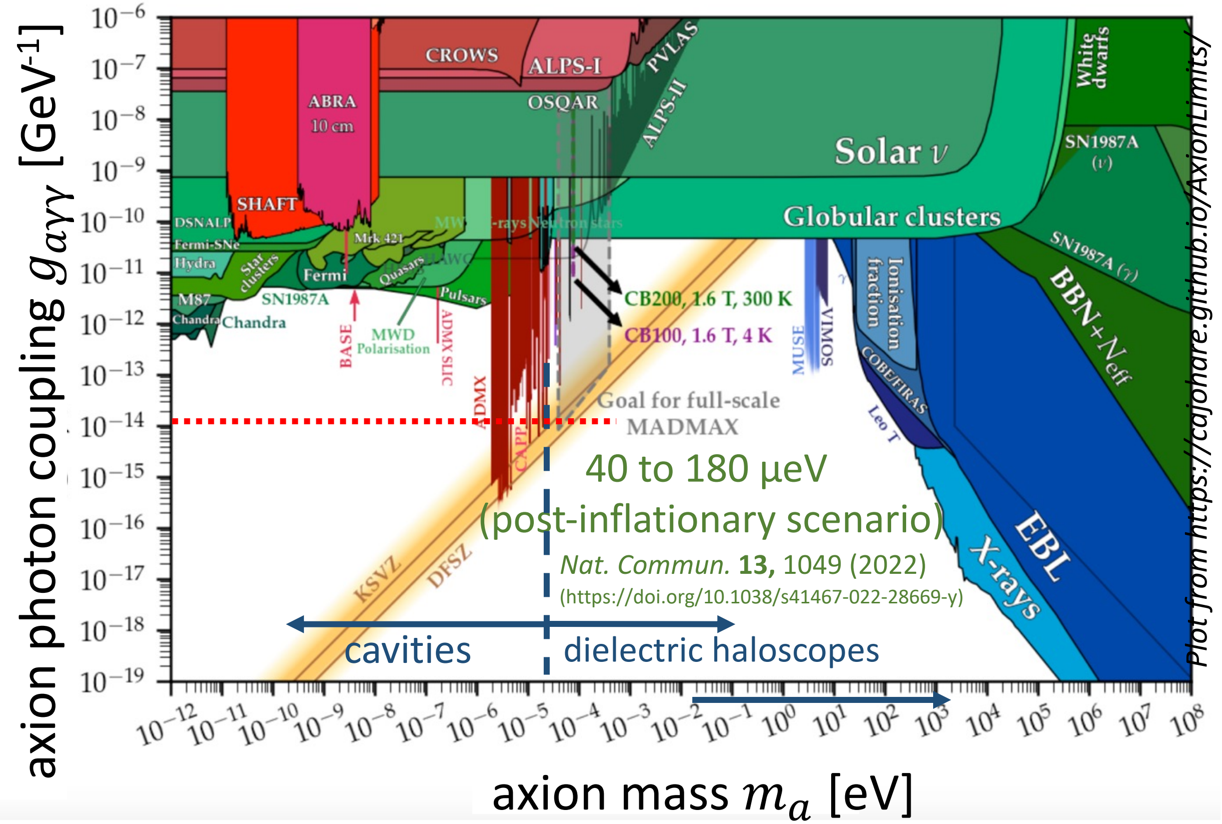
Open Dielectric Haloscope

MADMAX:

- Tunable in frequency coverage:
  ~10-100 GHz
- Corresponding to axion mass:
  40-400 μeV

- Coupling to $g_{a\gamma\gamma}$ scales with:
  - external field, $\propto B$
  - conversion surface, $\propto A^{0.5}$

Power boost factor: $\beta^2 = \frac{P_{\text{total}}}{P_{\text{mirror}}}$



$$g_{a\gamma} = 2.04(3)\times 10^{-14}\ \text{GeV}^{-1}\sqrt{\frac{\text{SNR}}{5}}\ \frac{400}{\sqrt{\beta^2}}\sqrt{\frac{1\text{m}^2}{A}}\sqrt{\frac{T_{\text{sys}}}{8\text{K}}}\ \frac{10\ \text{T}}{B_e}\sqrt{\frac{0.8}{\eta}}\left(\frac{1.3\ \text{days}}{\Delta t}\right)^{1/4}\sqrt{\frac{300\ \text{MeV}^2}{\rho_0}}\left(\frac{m_a}{100\ \mu\text{eV}}\right)^{5/4}$$

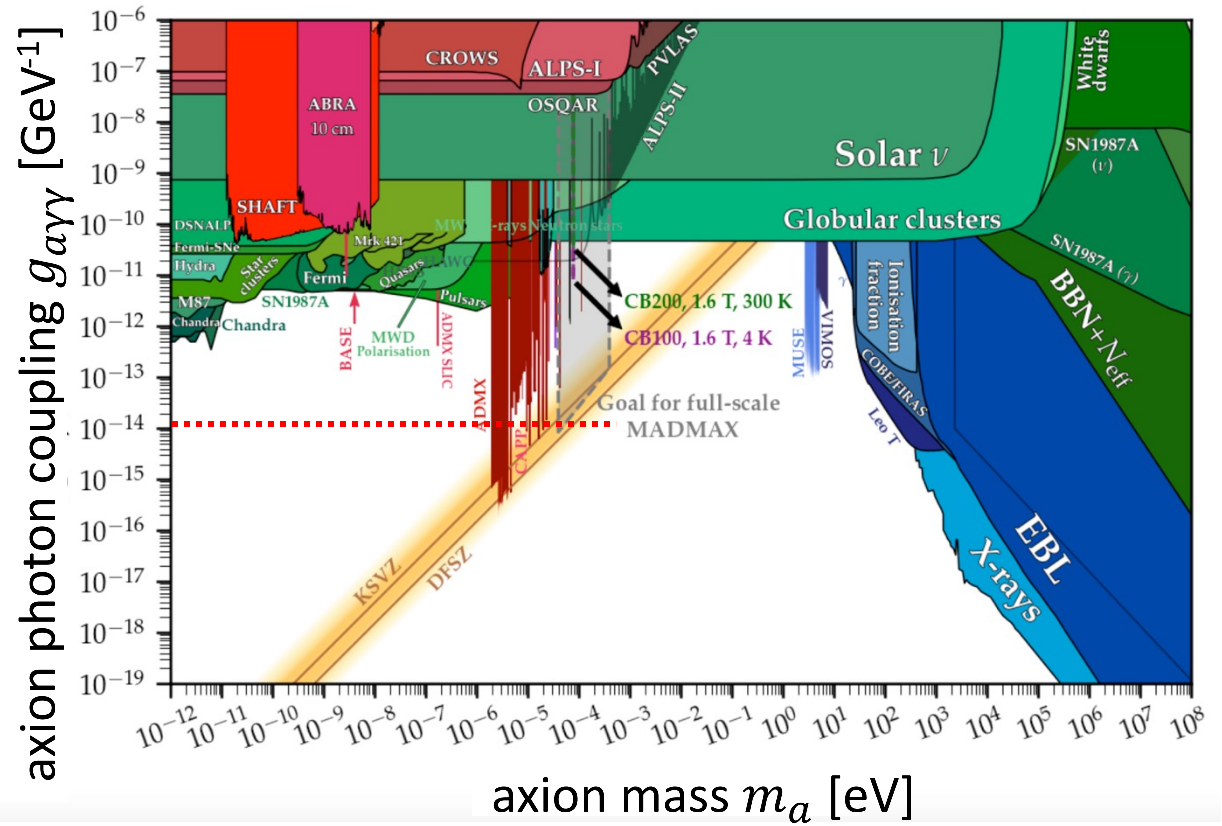
Open Dielectric Haloscope

MADMAX
baseline design

$$N_{\text{disc}} = 80$$
$$A_{\text{disc}} = 1.2\ \text{m}^2$$
$$B_{\parallel} = 9\ \text{T}$$
$$T_{\text{sys}} = 8\ \text{K}$$

Feasibility studies
on prototype systems

- N_{disc}, A_{disc} → Disk tiling, flatness alignment, …
- $B_{\parallel}$ → Checked with MACQU
- T_{sys} → Require prototype tests in a cryostat



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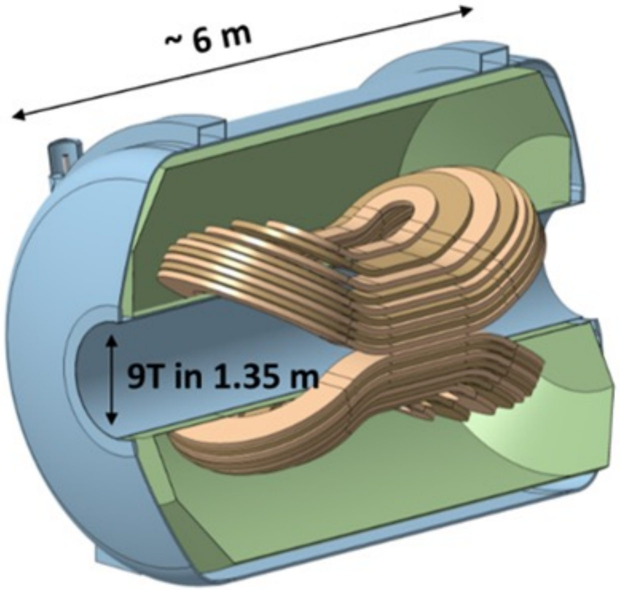
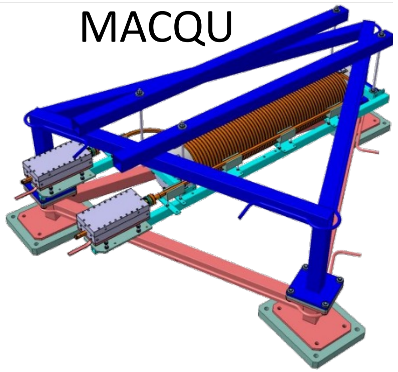
MADMAX Magnet Update



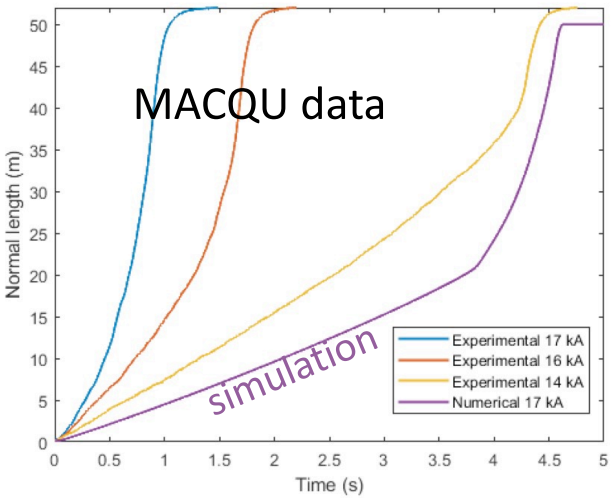
Development in innovation partnership

BILFINGER
BILFINGER NOELL GMBH
cea
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

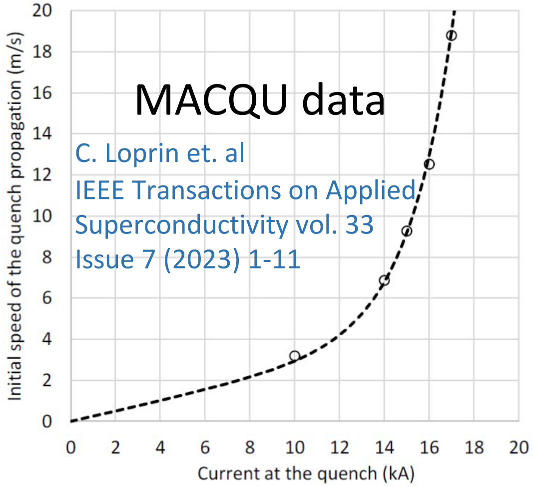
- Dipole Magnet most critical item for full-size MADMAX
- Design for 9 T large bore conceptually very well advanced
- **Novel conductor: cable in copper conduit**
  ➔ **production is feasible**
- Quench propagation velocity was measured in dedicated setup: **MA**dmax **C**oil for **Q**uench **U**nderstanding
  ➔ Main project risk mitigated: **Quench propagation according to requirements for safe operation**

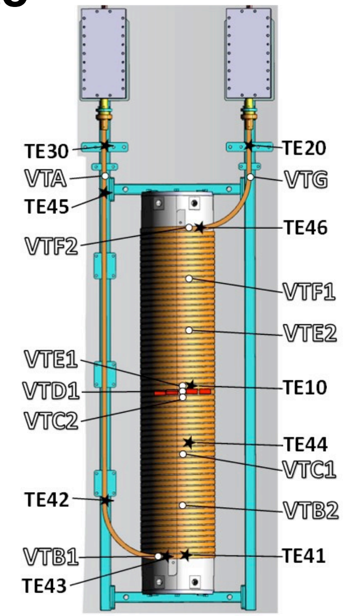


Quench propagation

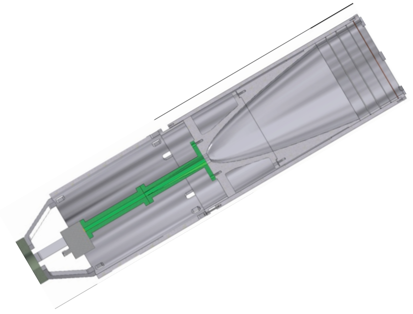


Quench velocity





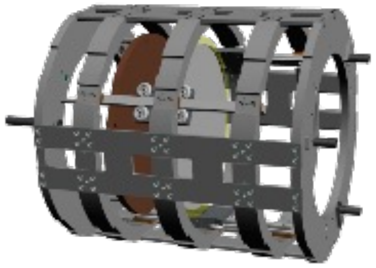
Staged Prototype Program



Closed Boosters (CB):

∅ = 100 mm (**CB100**), 3 Al_2O_3 disks

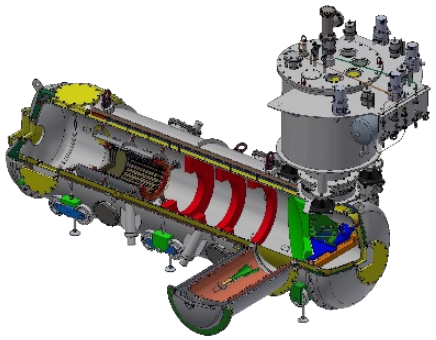
∅ = 200 mm (**CB200**), 3 Al_2O_3 disks



Open Boosters (OB):

∅ = 200 mm (**OB200**), 2 Al_2O_3 disks

∅ = 300 mm (**OB300**), 3 disks (Al_2O_3 & $LaAlO_3$)



Large bore (∅ = 760 mm) cryostat allows operation of all prototypes

Fits into the 1600 mm warm bore of MORPURGO magnet at CERN

Aim:

First ALP run at ~19 GHz with system "easy to simulate"

Increase ALP sensitivity & understand scaling issues

➔ Understanding readout chain and RF behaviour

Technical test of components (motors, interferometer, ..)

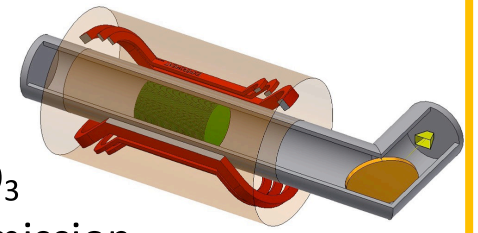
Proof-of-concept for MADMAX

➔ Establish boost factor calibration in an OB

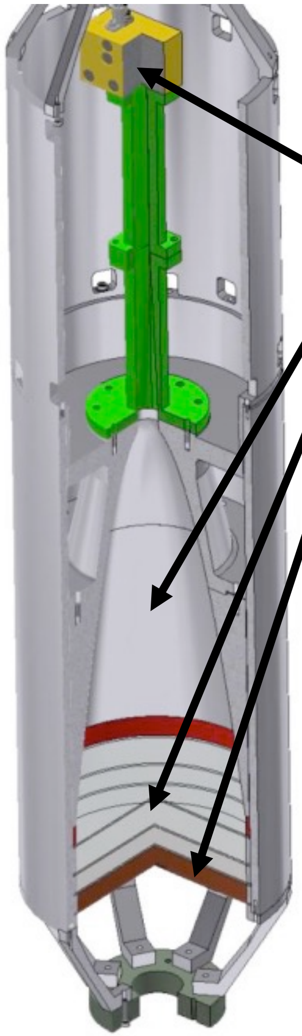
GOAL

MADMAX

- Many disks with large ∅ ➔ **tiled** $LaAlO_3$
- Boost dish antenna emission

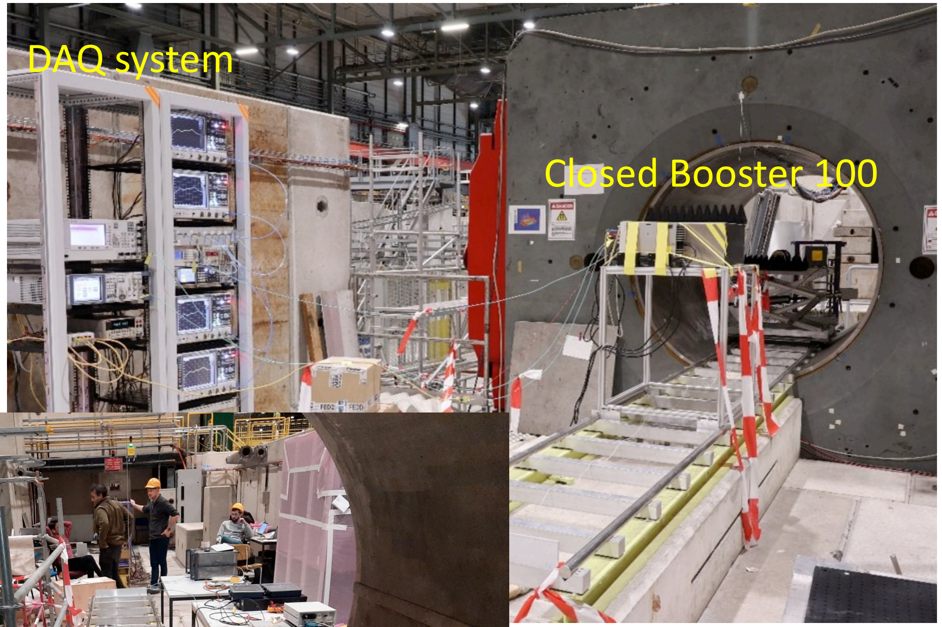


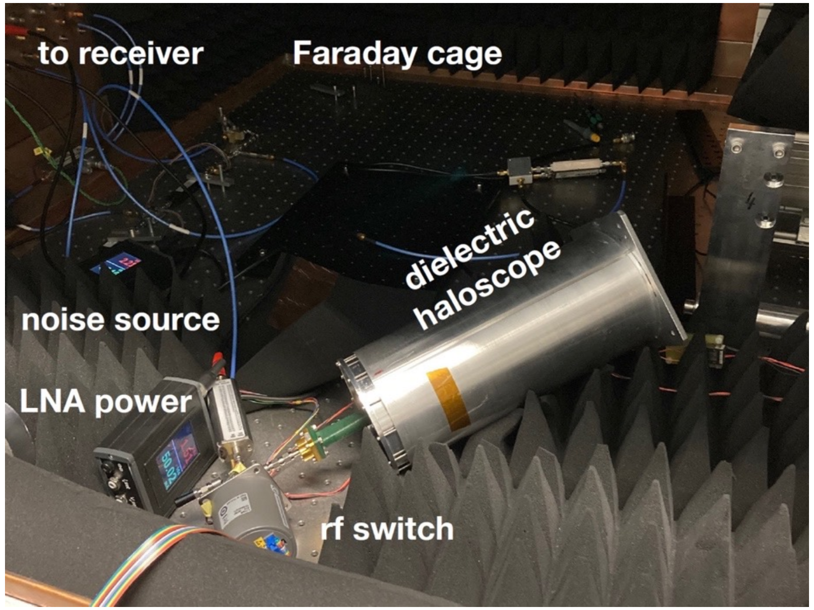
CB100: First ALP Search

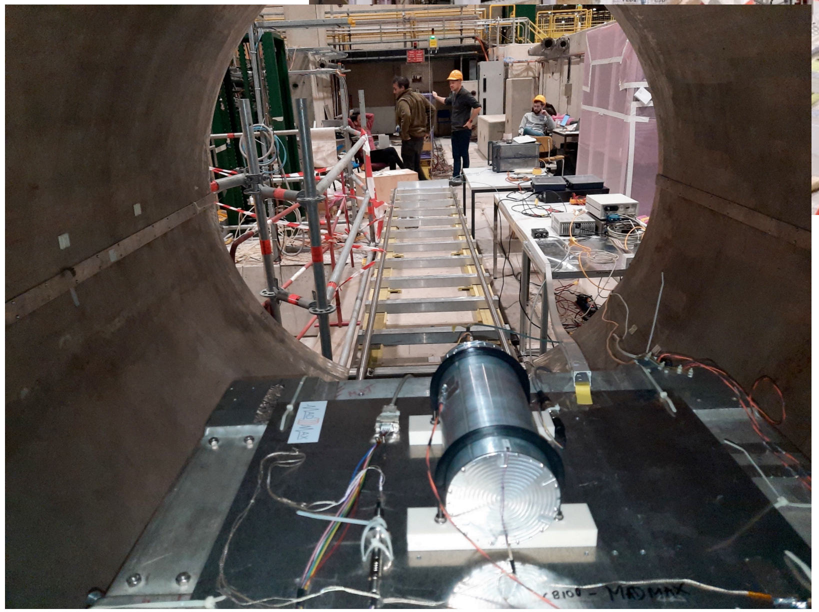


Simple closed system to understand RF behaviour

- Receiver
- Parabolic taper
- 3x Ø100 mm disks (fixed distances)
- Copper mirror



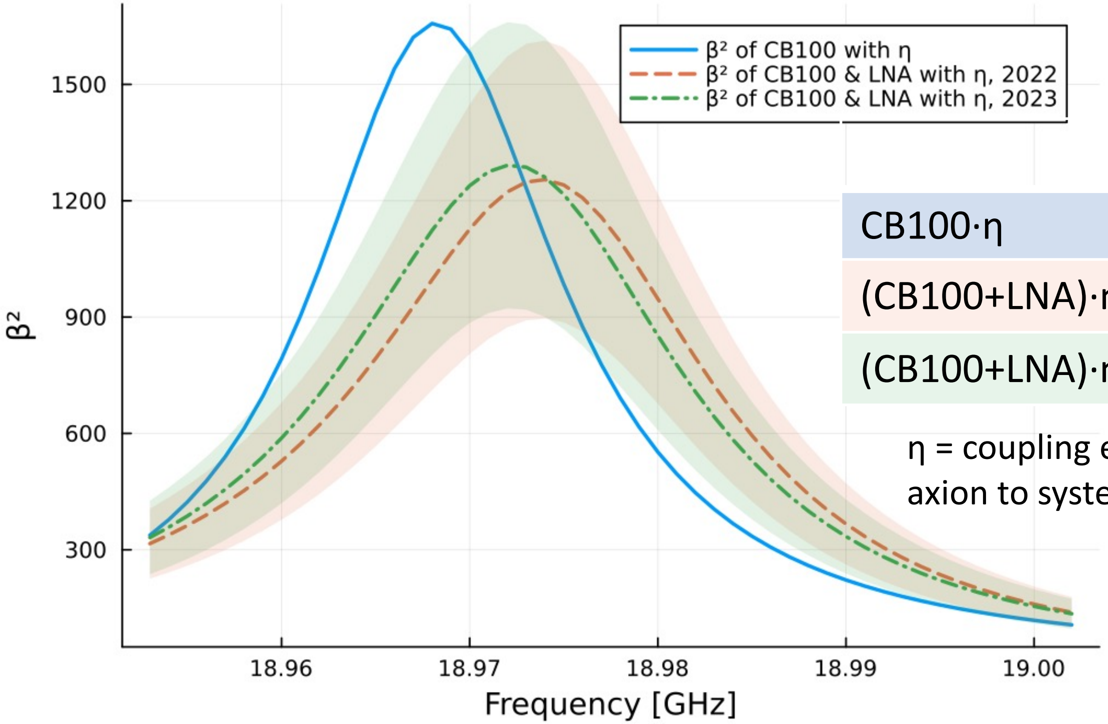




Tested in MORPURGO @ CERN in 2022 and 2023

CB100: First ALP Search

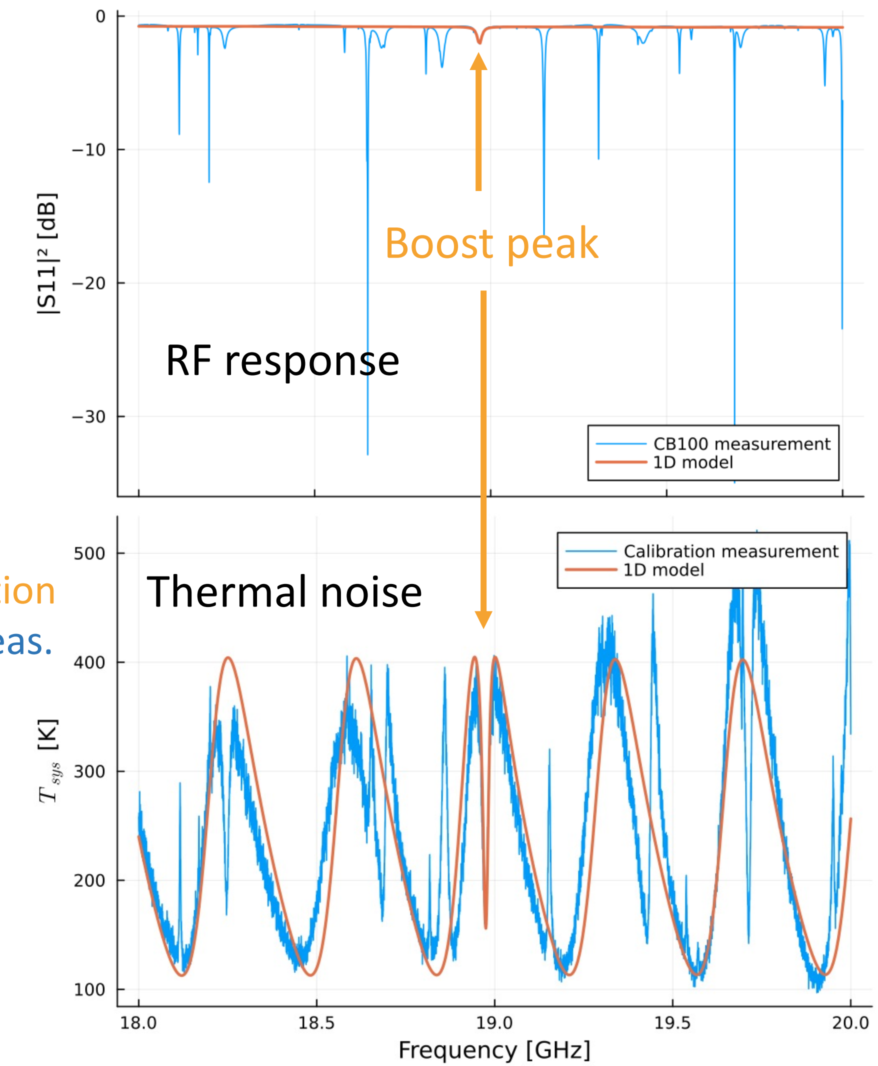
Boost factor extracted from model tuned to data ➔



	Q
CB100·η	1185
(CB100+LNA)·η	862
(CB100+LNA)·η	903

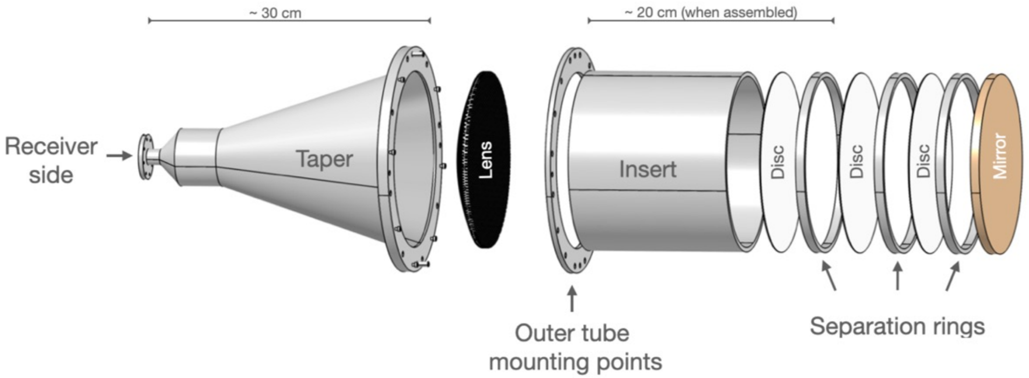
η = coupling efficiency of axion to system

ADS simulation
2GHz SA meas.



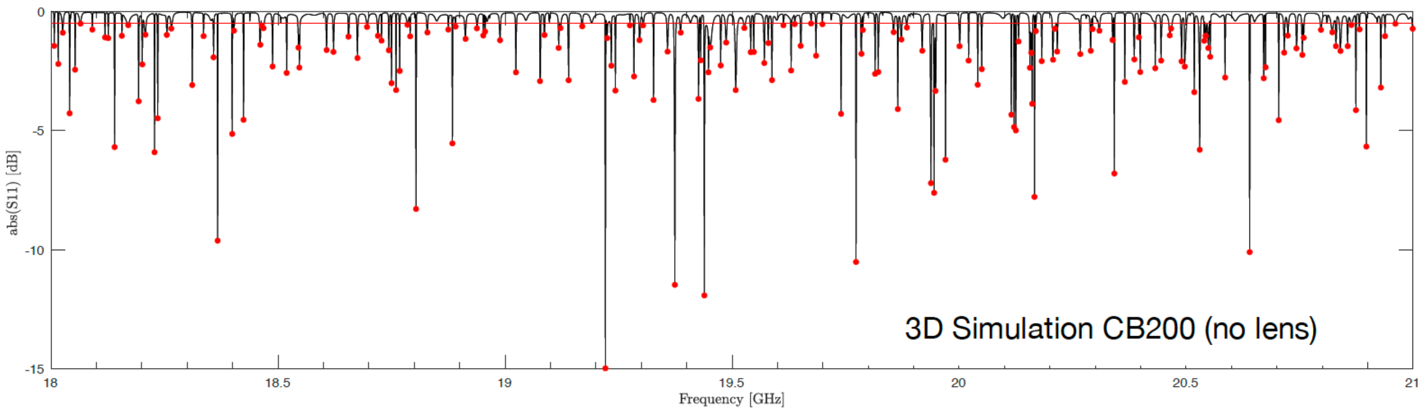
Consistent Boost factor in 2022 and 2023
Different LNA matching impedance: 25 Ohm (2022), 30 Ohm (2023)
➔ Data analysis ongoing

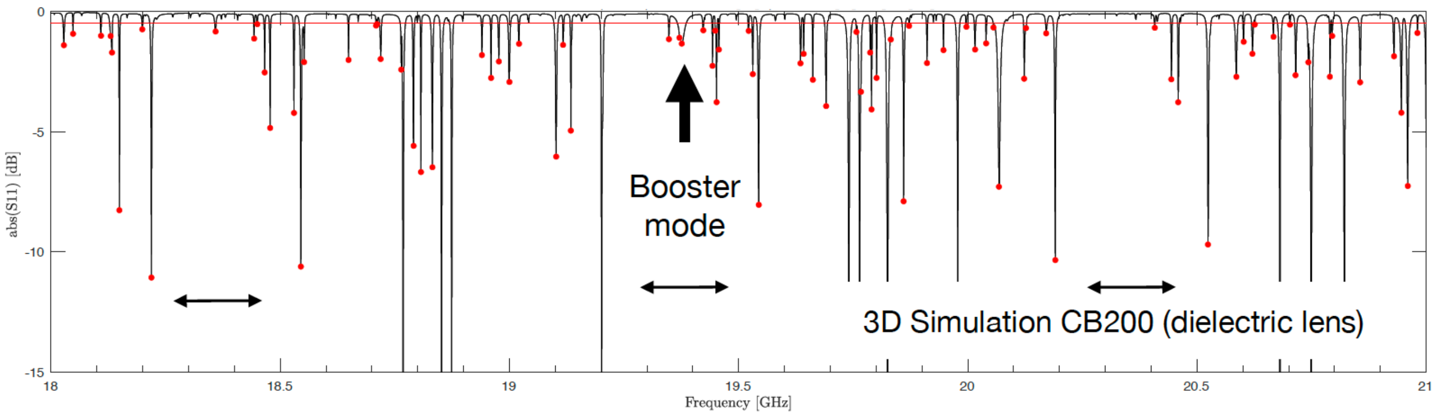
CB200: Understanding Scaling



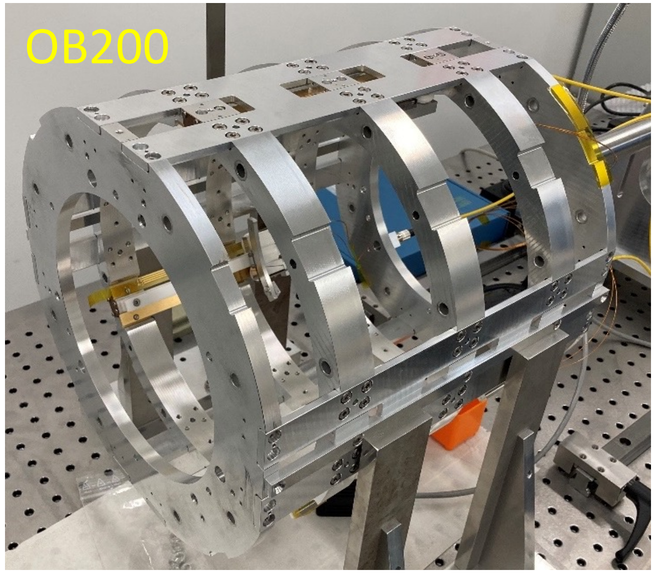
- Coupling to $g_{a\gamma\gamma}$ scales with:
  - conversion surface, $\propto A^{0.5}$

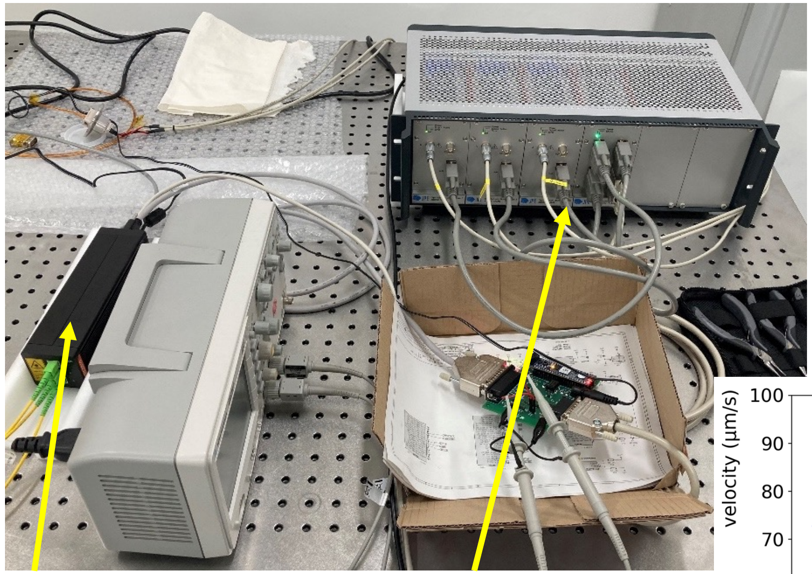
Larger dimensions increase the number of allowed modes
➔ Learn to deal with overmoded systems relevant for OB
➔Using a dielectric lens (Rexolite) decreases coupling of unwanted modes and allows for "quiet" regions in the spectrum





OB200: Technical Feasibility



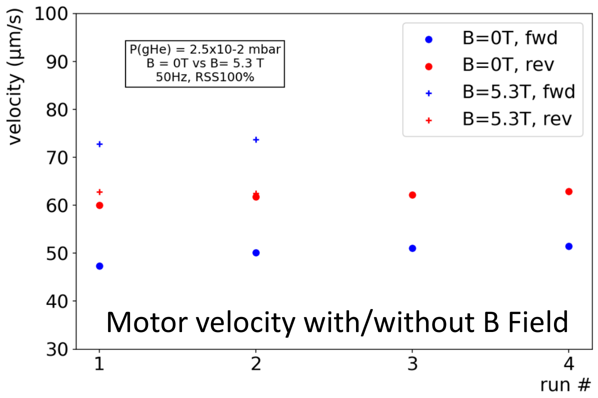


Laser interferometer   Piezo controllers

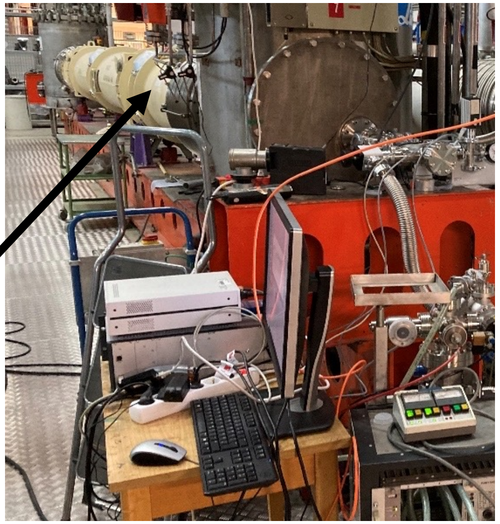
Successful piezo motor tests in cryogenics & inside ALPS II magnet

→ **Motor works in 5.3 T field and at 5 K**

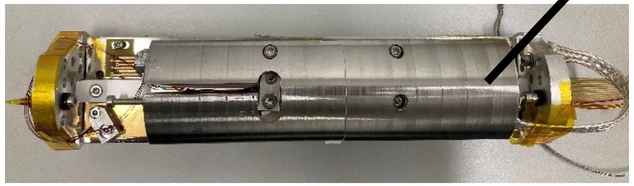
arxiv:2305.12808



ALPS II magnet test stand



Single motor test rig



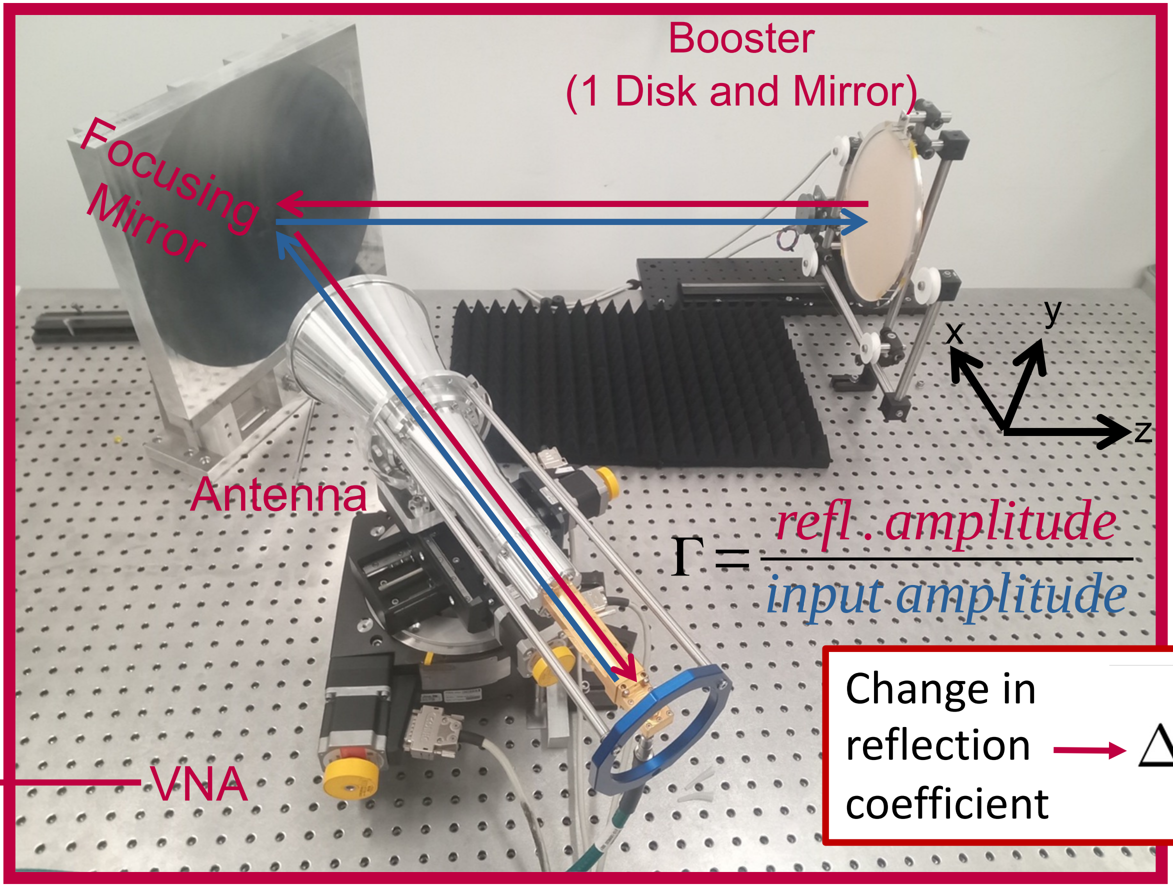
Mechanical demonstrator with:

- One 200 mm sapphire disk in titanium ring + mirror
- Three JPE piezo motors on self-built carriages
- Piezo controller system for driving a disk with three motors
- attocube WITTENSTEIN Group interferometer for displacement measurement

➔ **Successfully tested at CERN cryolab and at MORPURGO**

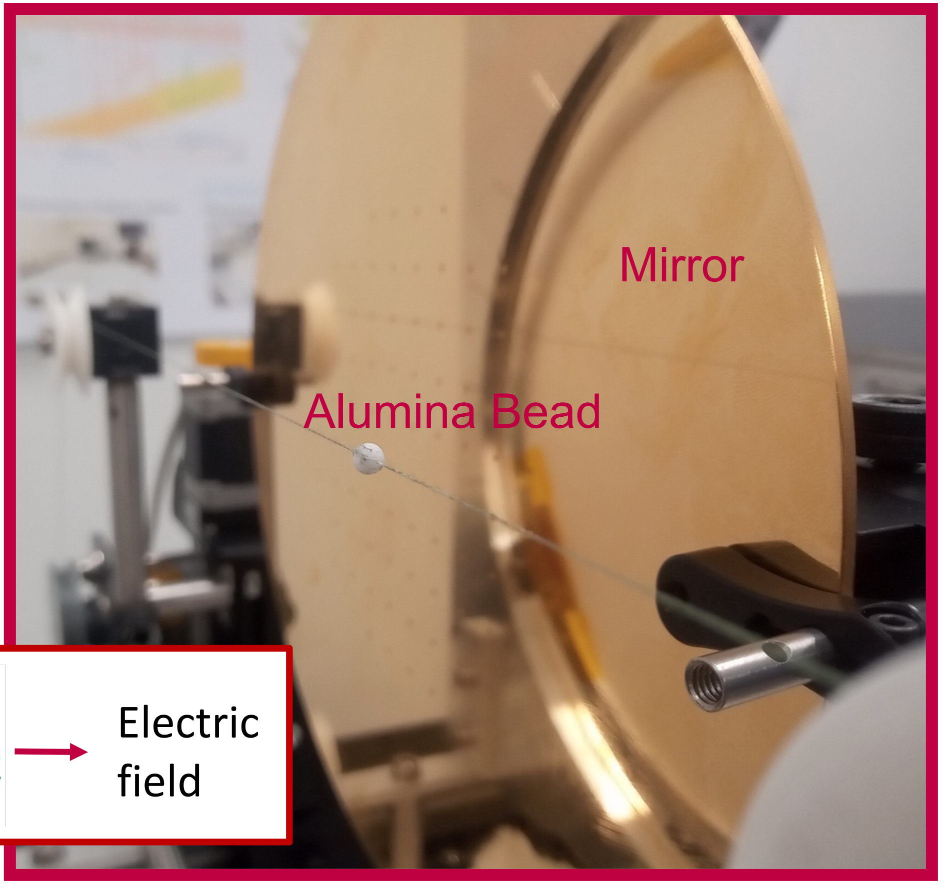
Open Booster Calibration

Boost factor determined using Bead Pull Method (non-resonant perturbation theory) + reciprocity theorem

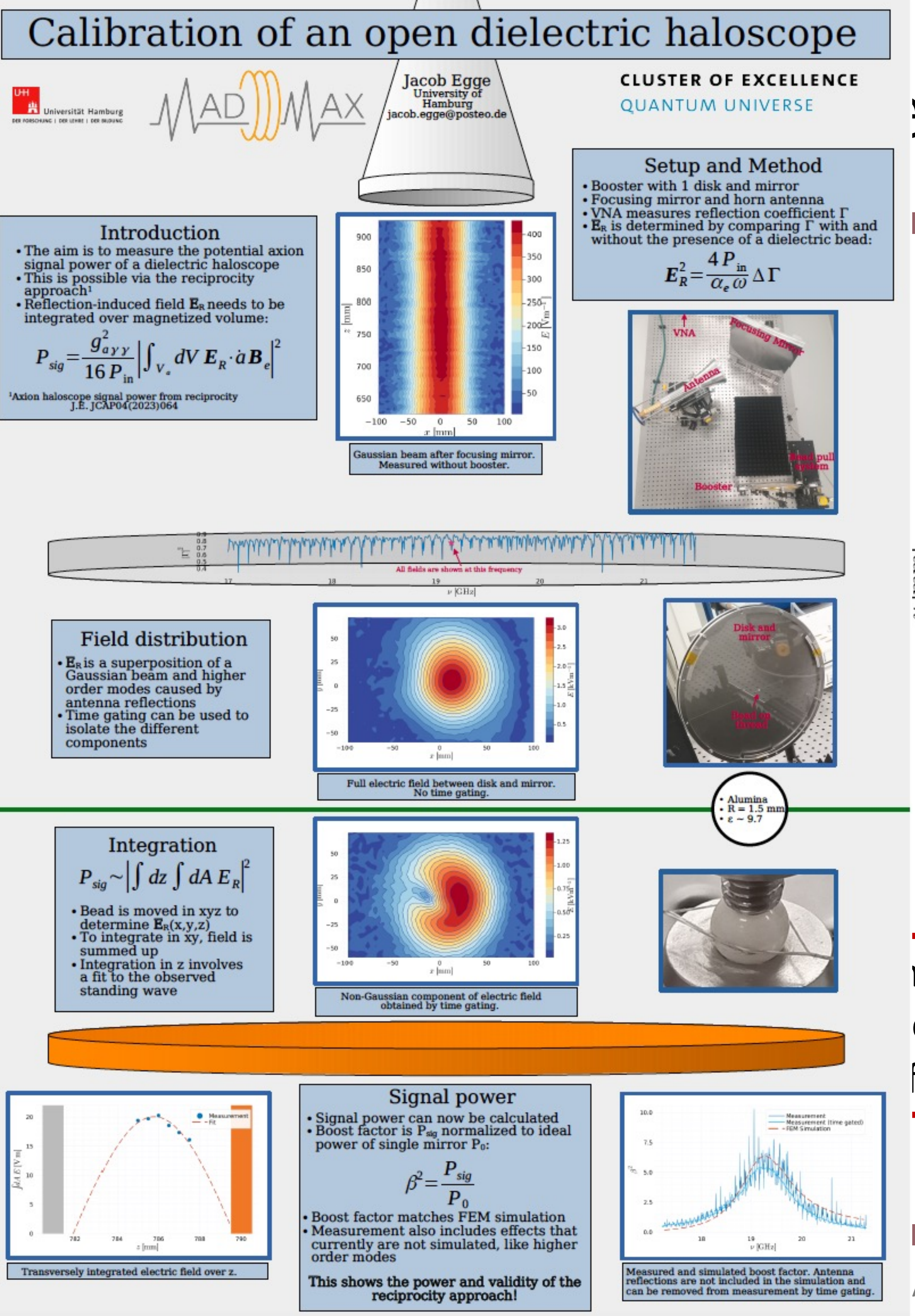


Beed properties

Change in reflection coefficient → $$\Delta\Gamma = \frac{\alpha_e \omega}{4P_{\text{in}}} \boldsymbol{E}_R^2$$ → Electric field



See poster by Jacob Egge



Calibration of an open dielectric haloscope

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Introduction

- The aim is to measure the potential axion signal power of a dielectric haloscope
- This is possible via the reciprocity approach[1]
- Reflection-induced field E_R needs to be integrated over magnetized volume:

$$P_{sig} = \frac{g^2_{a\gamma\gamma}}{16 P_{in}} \left| \int_{V_a} dV \, E_R \cdot \hat{a} B_e \right|^2$$

[1]Axion haloscope signal power from reciprocity J.E. JCAP04(2023)064

Setup and Method

- Booster with 1 disk and mirror
- Focusing mirror and horn antenna
- VNA measures reflection coefficient Γ
- E_R is determined by comparing Γ with and without the presence of a dielectric bead:

$$E_R^2 = \frac{4 P_{in}}{\alpha_e \omega} \Delta\Gamma$$

Gaussian beam after focusing mirror. Measured without booster.

Field distribution

- E_R is a superposition of a Gaussian beam and higher order modes caused by antenna reflections
- Time gating can be used to isolate the different components

Full electric field between disk and mirror. No time gating.

Integration

$$P_{sig} \sim \left| \int dz \int dA \, E_R \right|^2$$

- Bead is moved in xyz to determine $E_R(x,y,z)$
- To integrate in xy, field is summed up
- Integration in z involves a fit to the observed standing wave

Non-Gaussian component of electric field obtained by time gating.

Signal power

- Signal power can now be calculated
- Boost factor is P_{sig} normalized to ideal power of single mirror P_0:

$$\beta^2 = \frac{P_{sig}}{P_0}$$

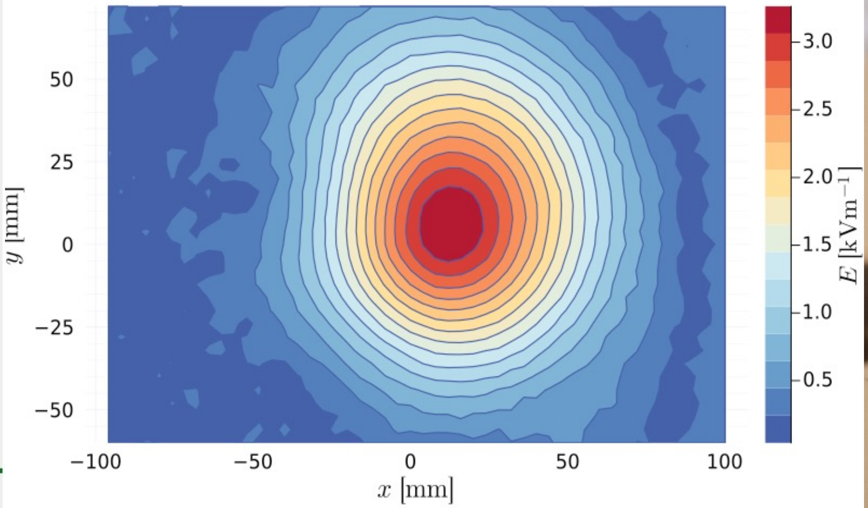
- Boost factor matches FEM simulation
- Measurement also includes effects that currently are not simulated, like higher order modes

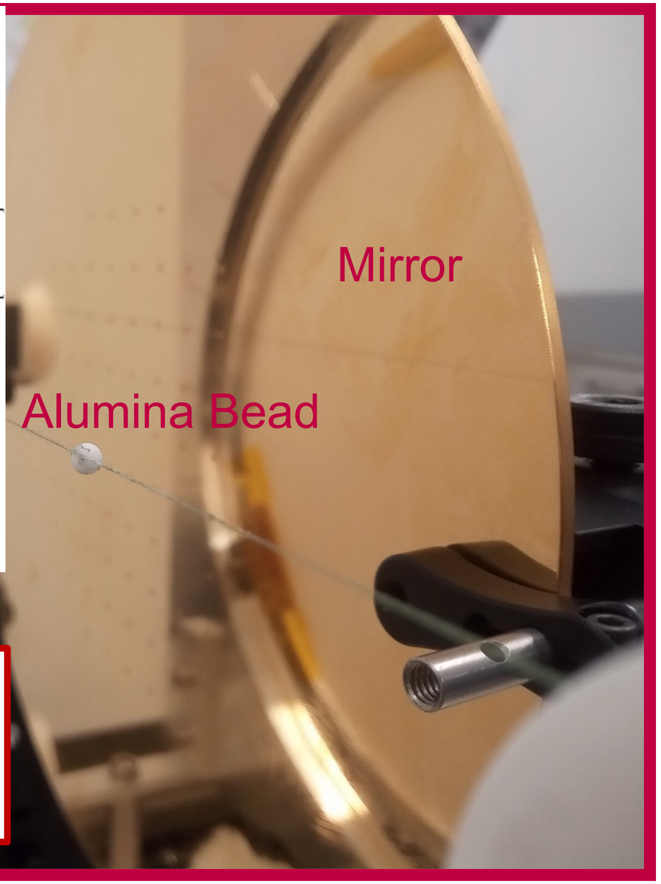
This shows the power and validity of the reciprocity approach!

Transversely integrated electric field over z.

Measured and simulated boost factor. Antenna reflections are not included in the simulation and can be removed from measurement by time gating.

en Booster Calibration



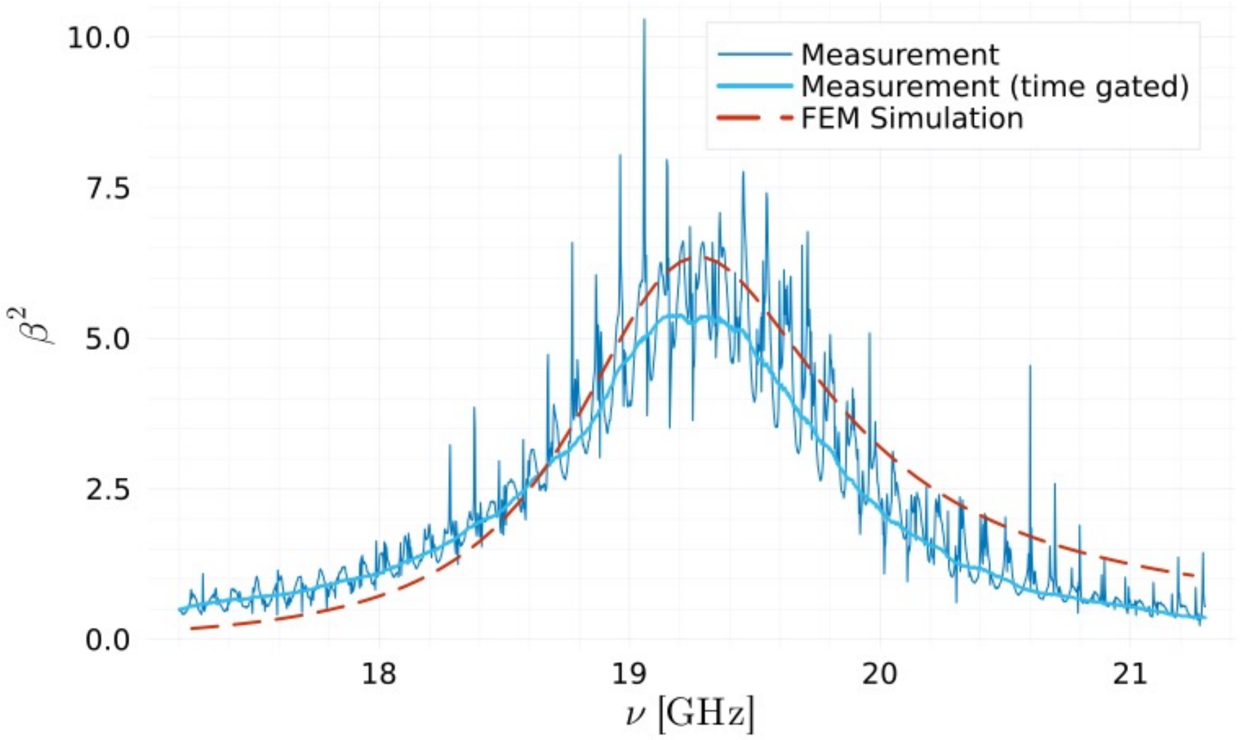


nge in
ction → $\Delta\Gamma = \dfrac{\alpha_e \omega}{4 P_{in}} E_R^2$ → Electric field
ficient

See poster by Jacob Egge

Signal Power

$$\beta^2 = \frac{P_{\text{sig}}}{P_0} \qquad P_{\text{sig}} = \frac{g_{a\gamma}^2}{16 P_{\text{in}}} \left| \int_{V_a} \mathrm{d}V \, \boldsymbol{E}_R \cdot \dot{a} \boldsymbol{B}_e \right|^2$$



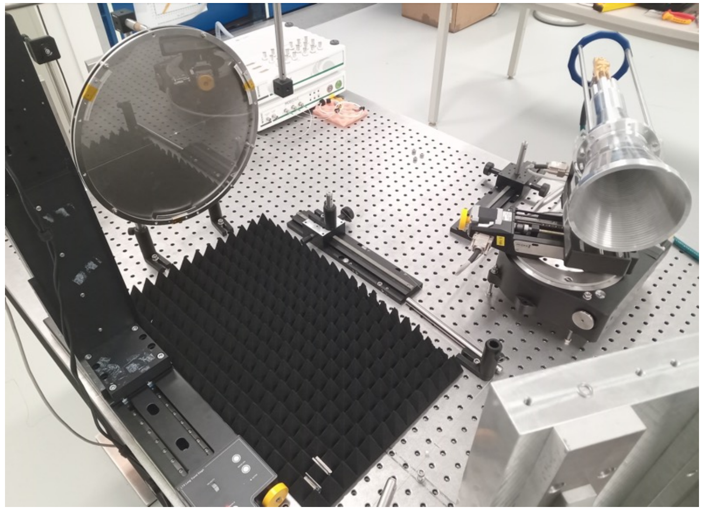
Single disk "low" boost factor

- Measure max. E-field between disk and mirror
- Calculate signal power
- Includes effects currently not simulated:
  - Antenna coupling
  - Transverse field perturbations

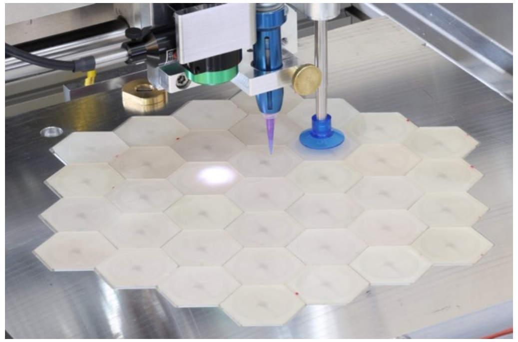
See poster by Jacob Egge

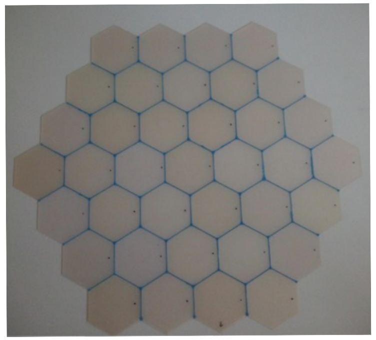
OB300: work in progress

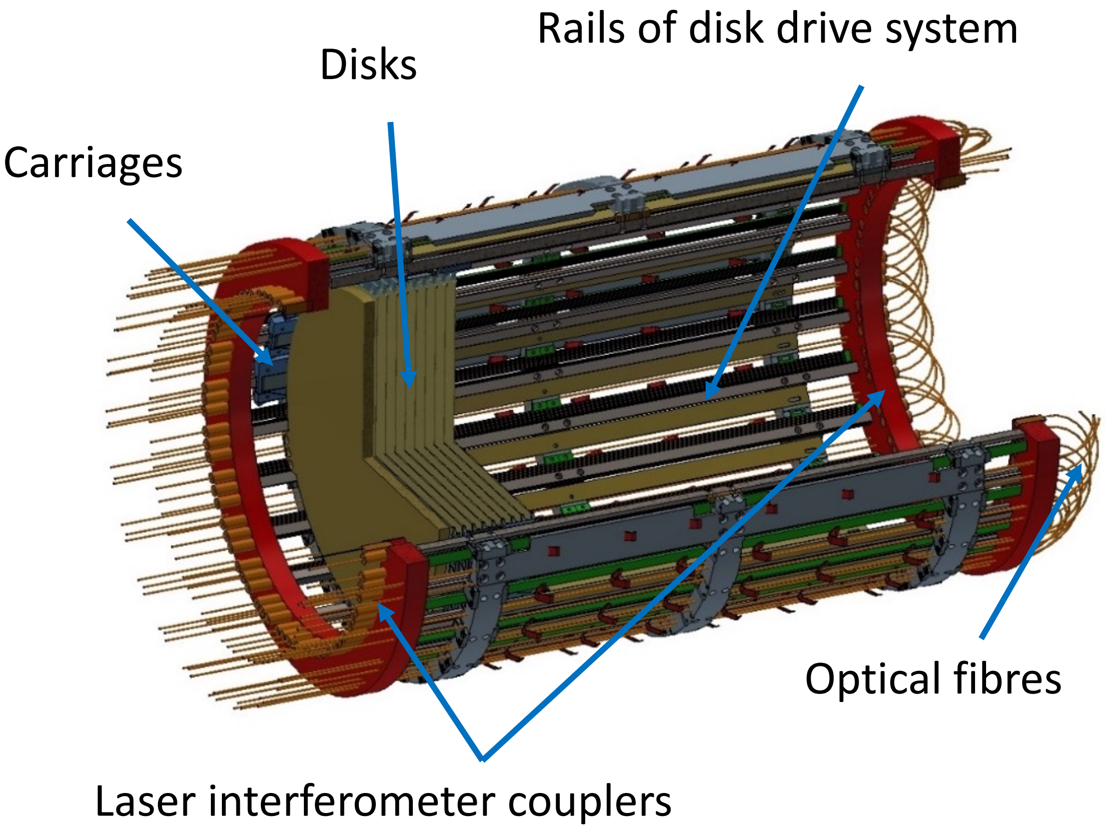
- Calibration of boost factor with 3 x ∅ = 300 mm disks



- Tiling of ∅ = 300 mm $LaAlO_3$ disks

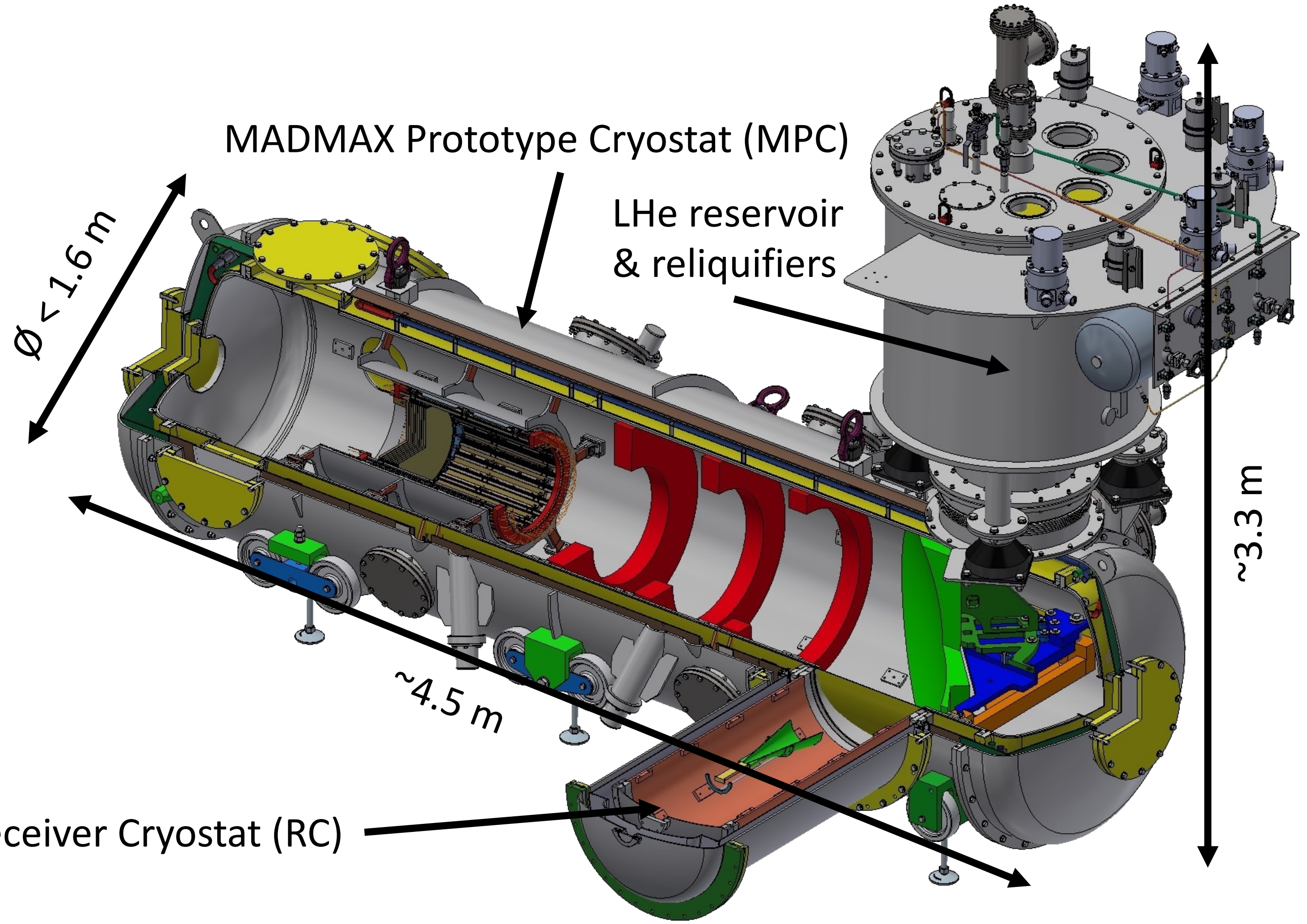






- Building mechanical structure for OB300

MADMAX Prototype



- Manufactured by Bilfinger Noell GmbH
- Two vacuum vessels:
  - inner (4 K) cooled via LHe circulating through double-wall
  - outer (isolation vacuum)
- Closed-loop system with 4 cryocoolers for reliquification of LHe
  ➔ during operation: 50 l LHe

- Delivery expected begining of 2024
- Commissioning with OB300 in Hamburg mid 2024

MADMAX Staged Program

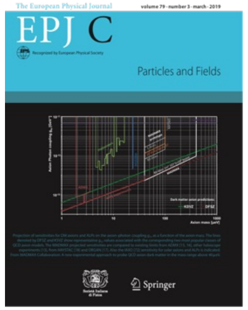
2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | >= 2028

Design Phase

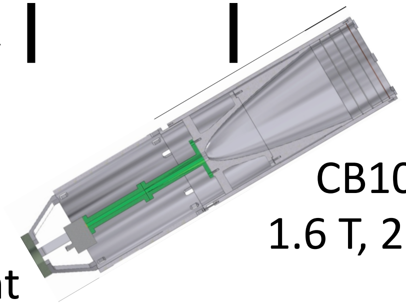
Prototyping Phase

Construction Phase

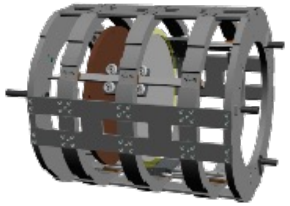
Foundation of MADMAX Collaboration



DESY PRC endorsement



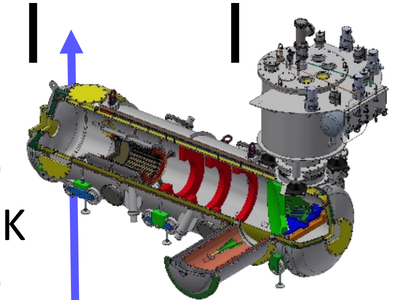
CB100
1.6 T, 295 K



OB300
295 K

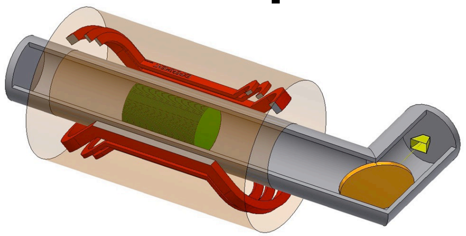
CB100
1.6 T, 4 K
CB200
1.6 T, 295 K

OB300
4 K



OB300
1.6T, 4 K

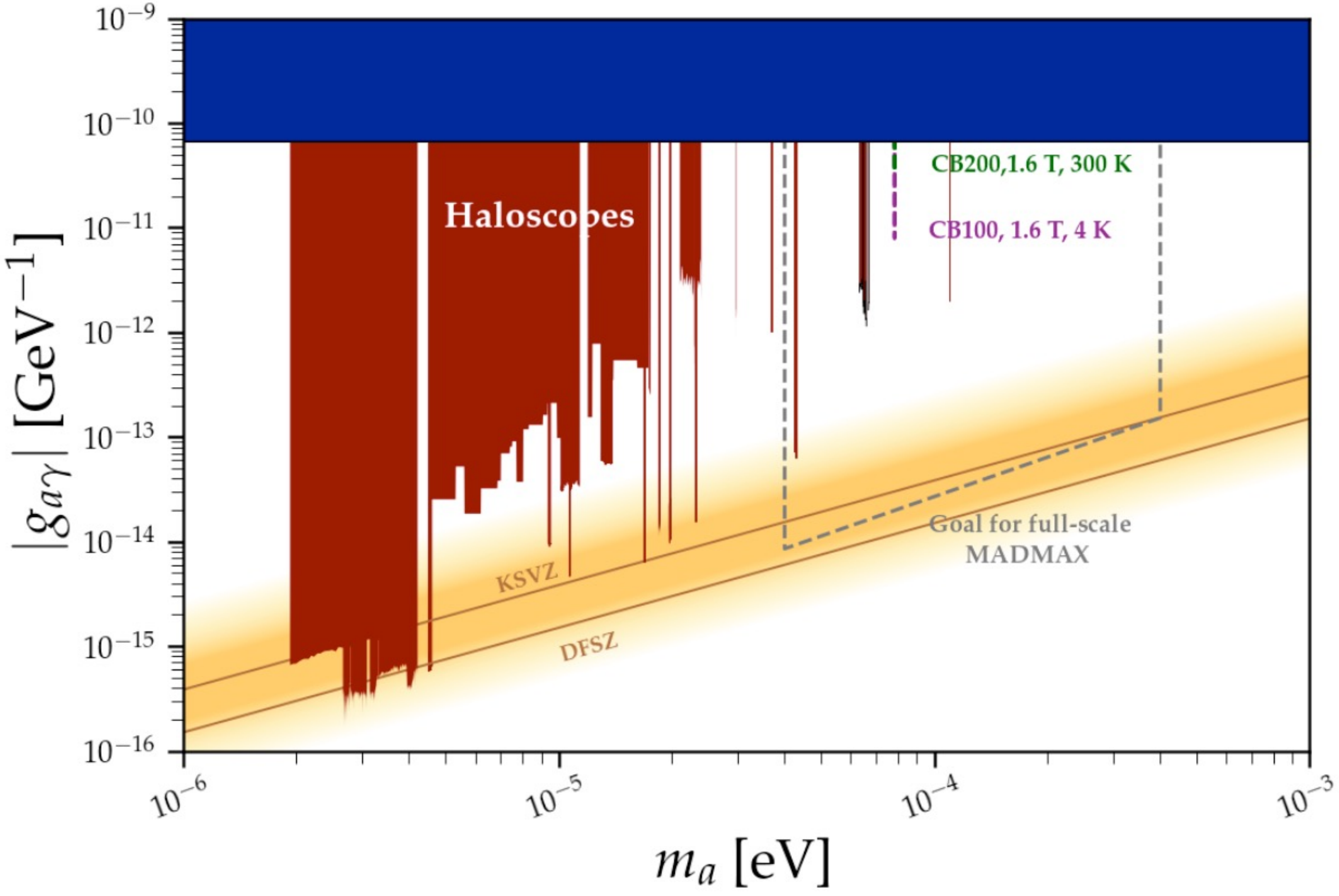
Usage of MORPURGO magnet approved by CERN Research Board for 2021-2025



Full-size MADMAX commissioning

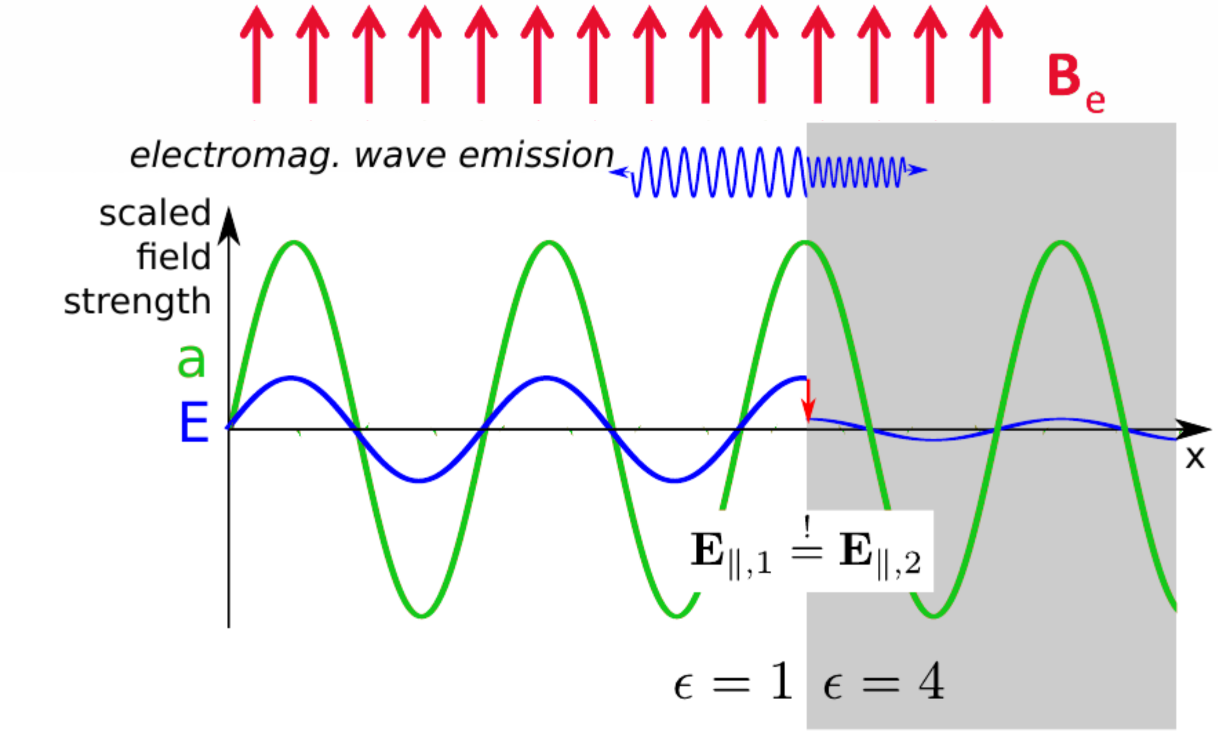
BACKUP

Coverage



Haloscopes
CB200,1.6 T, 300 K
CB100, 1.6 T, 4 K
Goal for full-scale MADMAX
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

Dielectric Haloscope



In an external magnetic field $\boldsymbol{B_e}$ the axion field $a(t)$ sources an oscillating electric field $\boldsymbol{E_a}$

$$\boldsymbol{E_a} \cdot \boldsymbol{\epsilon} \sim 10^{-12}\ \mathrm{V/m} \text{ for } B_e = 10\ \mathrm{T}$$

$\boldsymbol{E_a}$ is different in materials with different ε

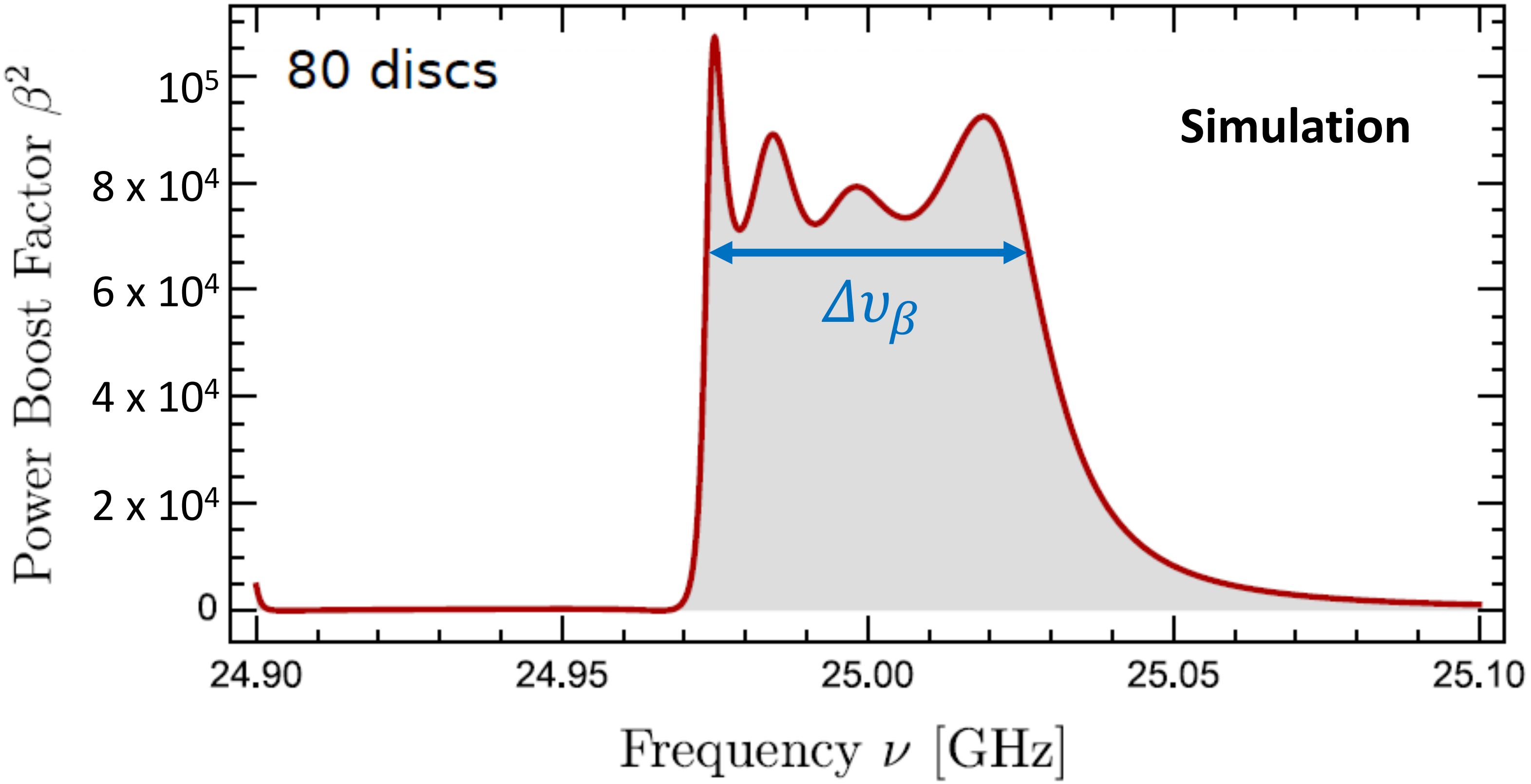
At the surface, $E_{\|}$ must be continuous
→ Emission of electromagnetic waves

Power emitted from a single surface: $P/A = 2.2 \cdot 10^{-27}\, \frac{\mathrm{W}}{\mathrm{m}^2} C_{a\gamma} \left(\frac{B}{10\ \mathrm{T}}\right)^2$

$\mathcal{O}(C_{a\gamma}) = 1$

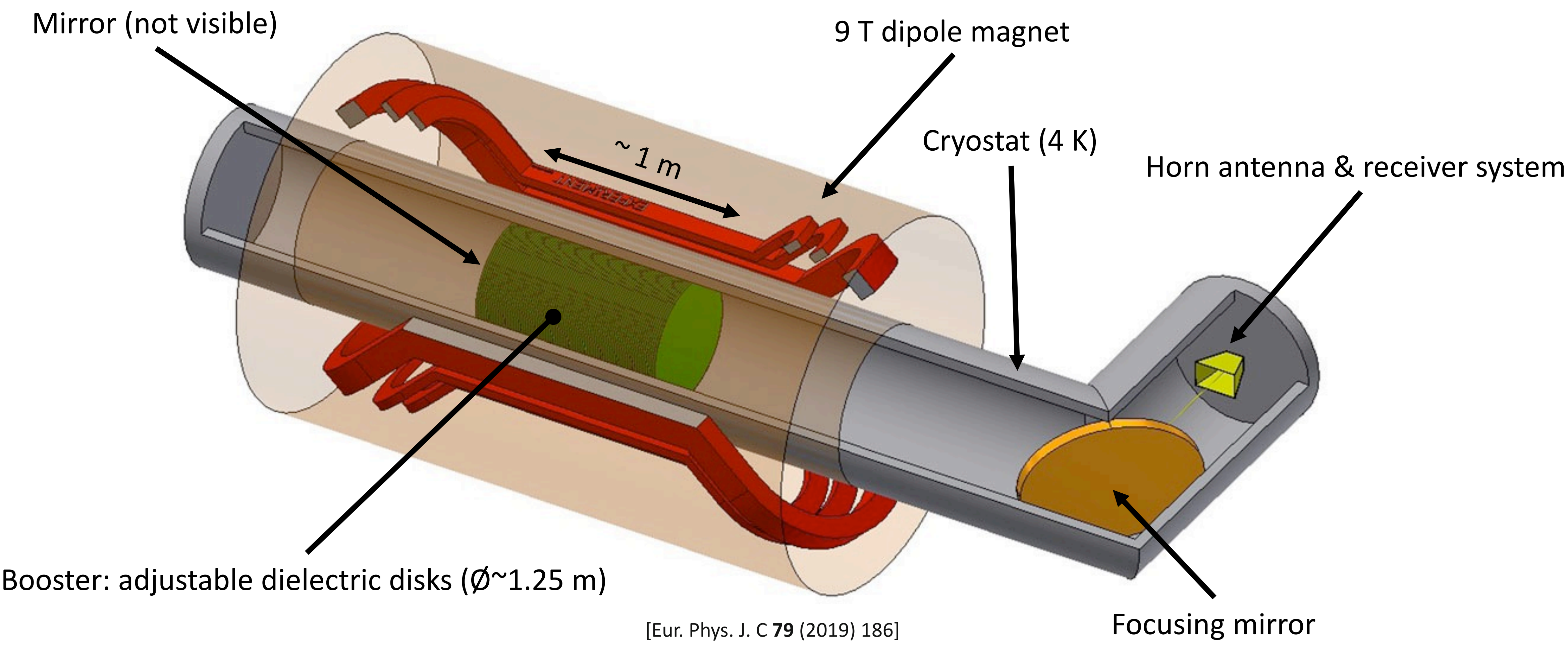
Dielectric Haloscope

- In perfect world (1D simulation): $|\beta^2| > 10^4$ achievable with 80 disks and $\varepsilon = 24$
- Non-uniform disk spacing of $\sim \lambda/_2$ can achieve broadband response
- Tuning of sensitive frequency range by adjusting disk spacing
- Area law: $\beta^2 \Delta \upsilon_\beta$ ~ const.



The MADMAX Experiment

MAgnetized **D**isk and **M**irror **A**xion e**X**periment



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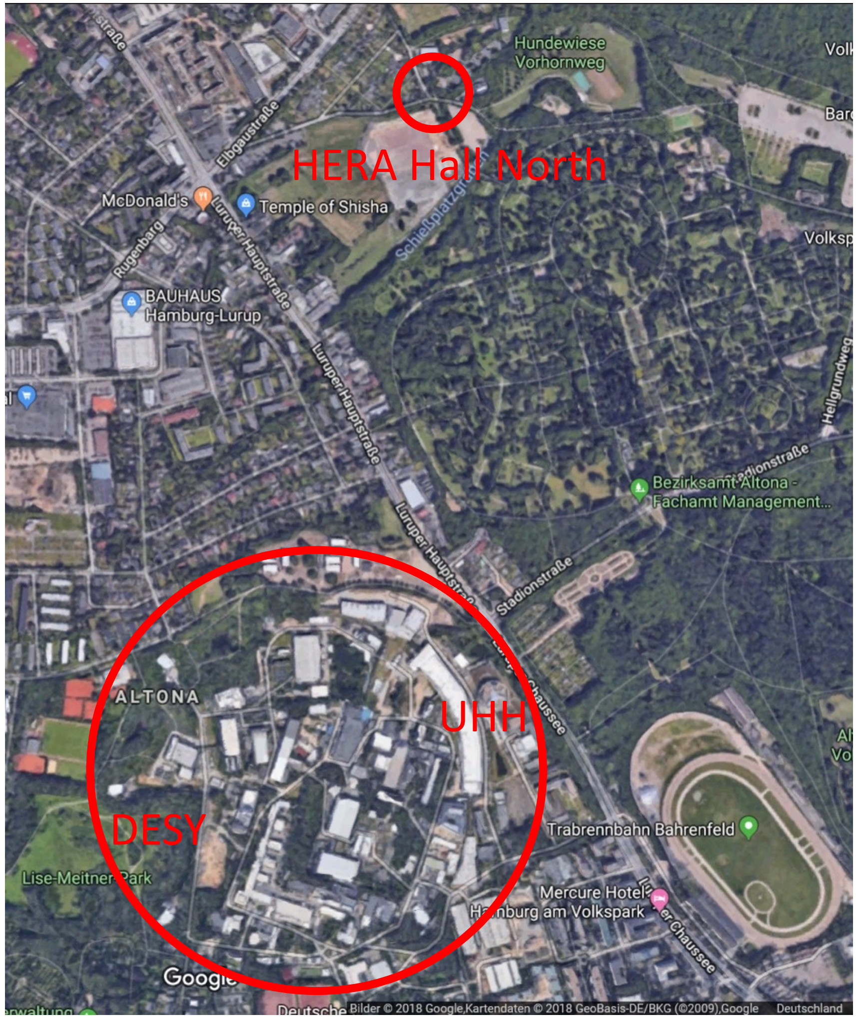
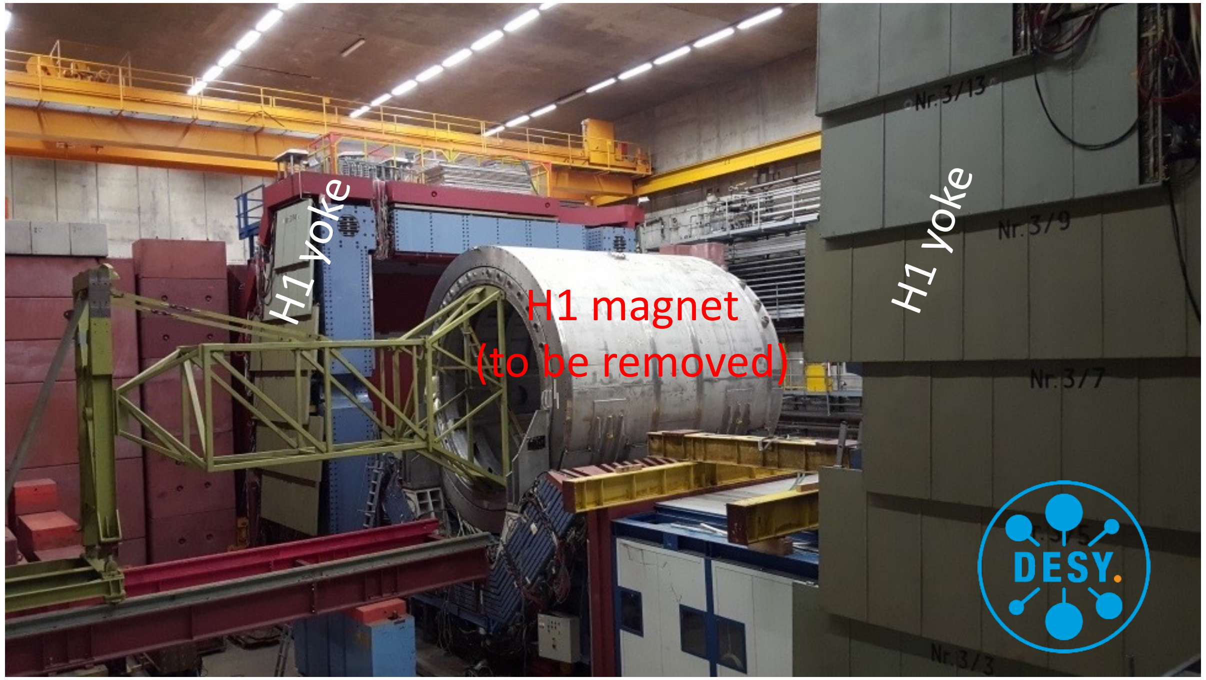
Designated Experimental Site

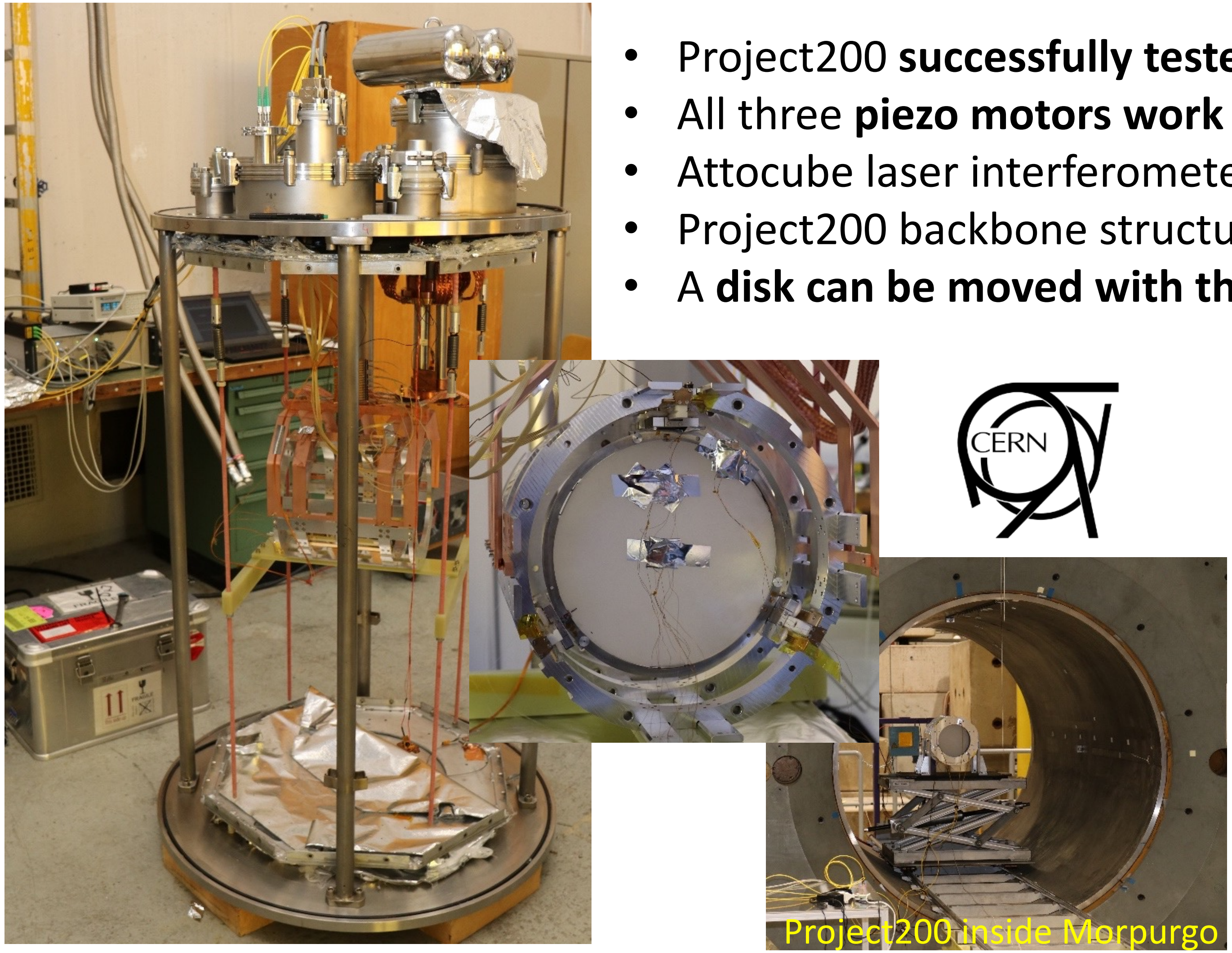


- MADMAX to be operated at HERA Hall North
- Make use of DESY infrastructure
  → Cryoplatform to be operational in 2025
- Benefit: re-use H1 yoke as magnetic shielding



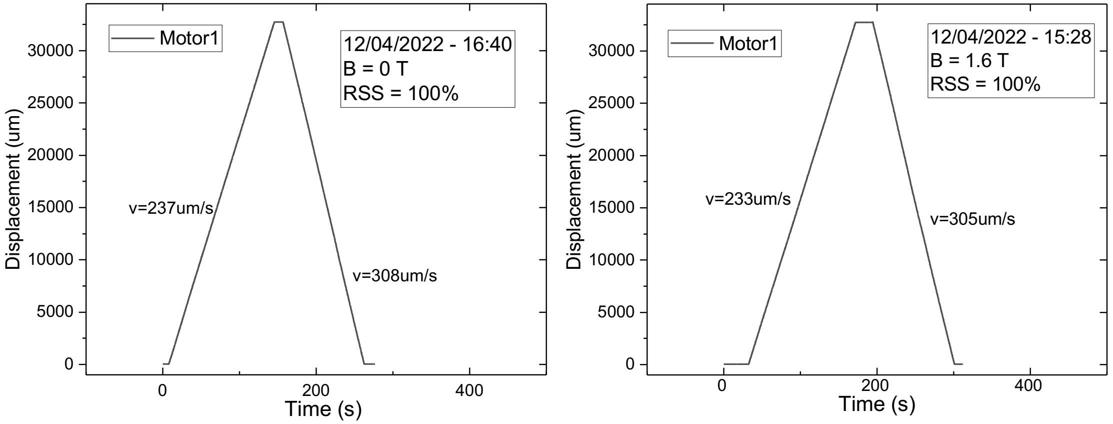
Testing the Disk Drive

- Project200 **successfully tested at CERN Cryolab and in CERN's Morpurgo magnet**
- All three **piezo motors work at cryogenic temperatures and in 1.6 T field** (at RT)
- Attocube laser interferometer works at cryogenic temperatures
- Project200 backbone structure **keeps optics alignment during cool-down**
- A **disk can be moved with three motors** using the laser interferometer feedback



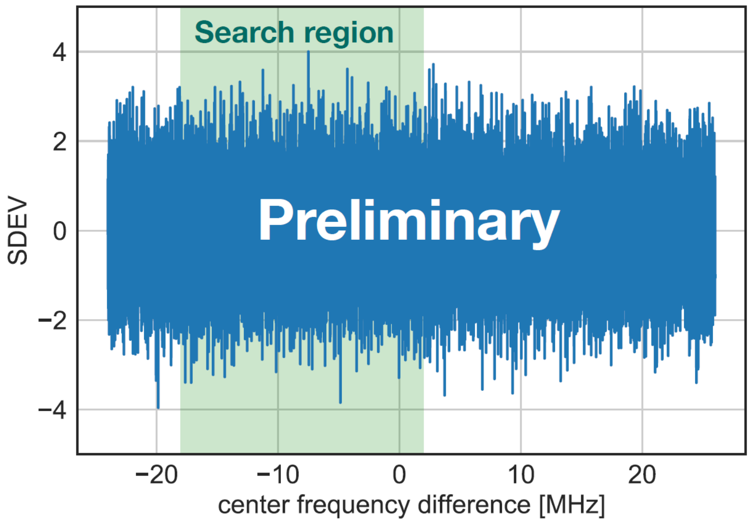
CERN

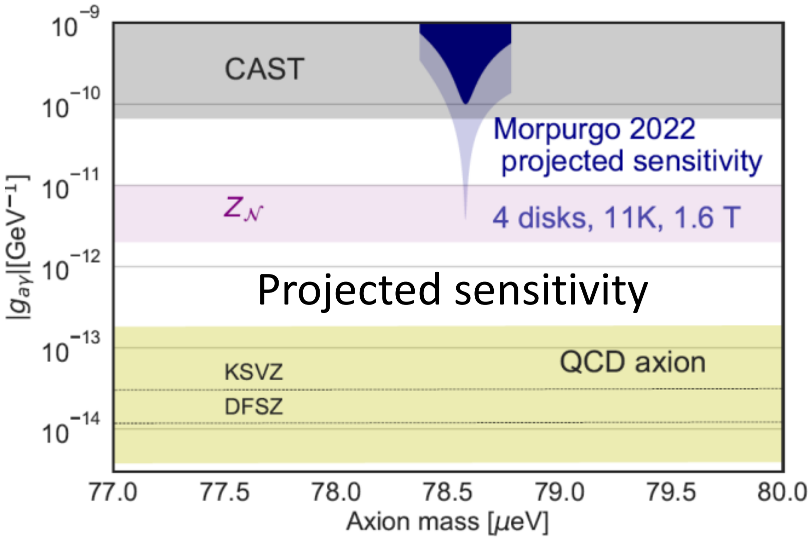
No difference in disk velocity with/without B field

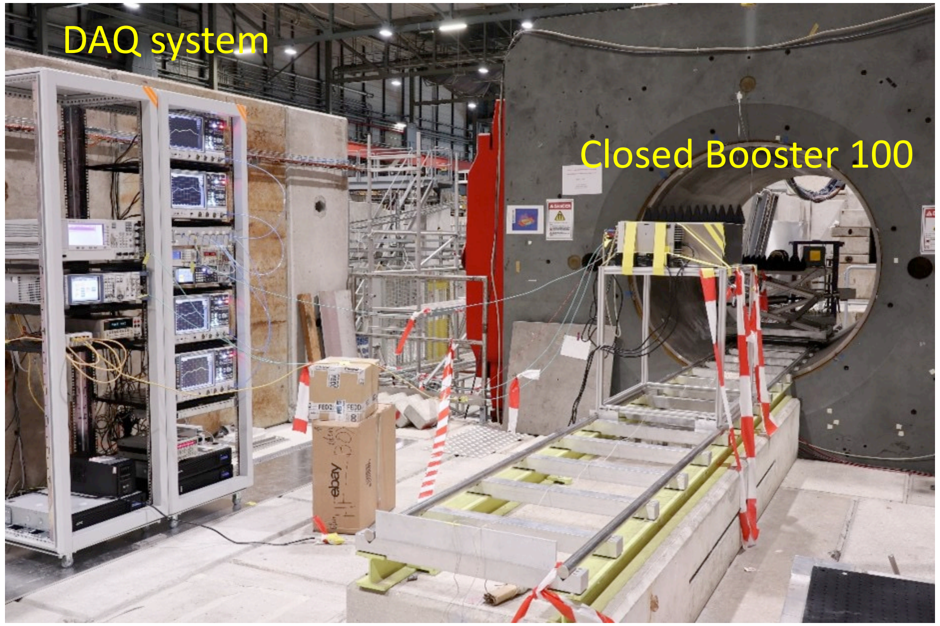


Axion Like Particle Search

- Opportunity to perform ALP search in CERN's Morpurgo magnet (1.6 T) was used in Mar/Apr 2022
- In total 10 h at 1.6 T with ~ 200 K noise temperature
- Sensitivity not dominated by RFI in CERN North Hall
- Possibilities for an upgrade allowing to cool the setup to < 10 K in Morpurgo currently in preparation

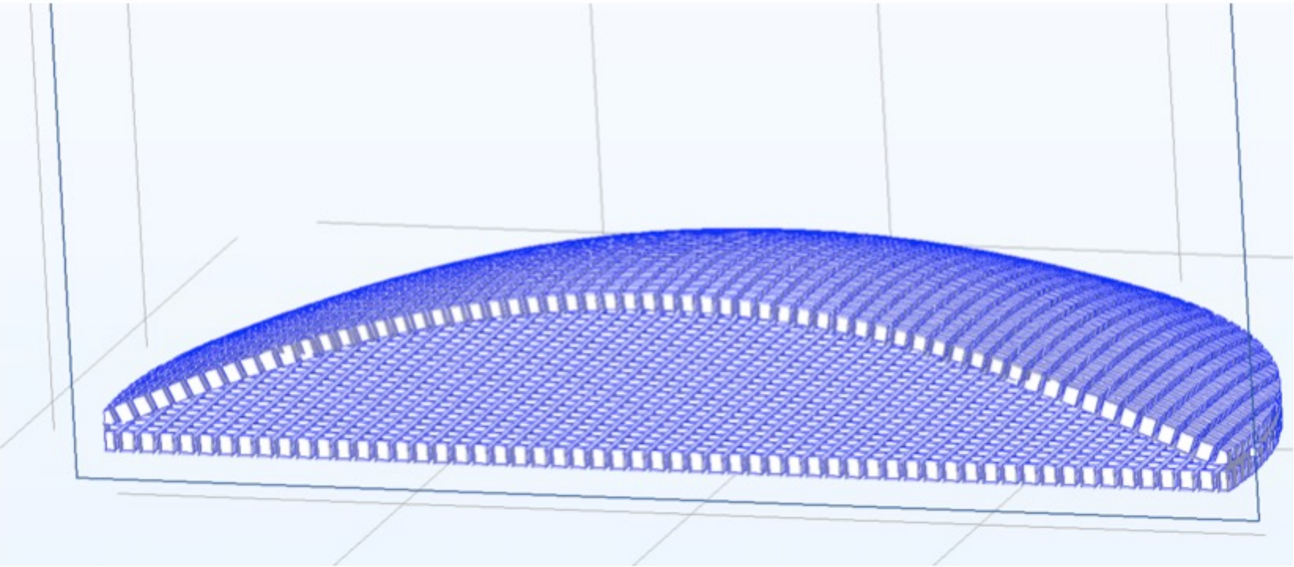


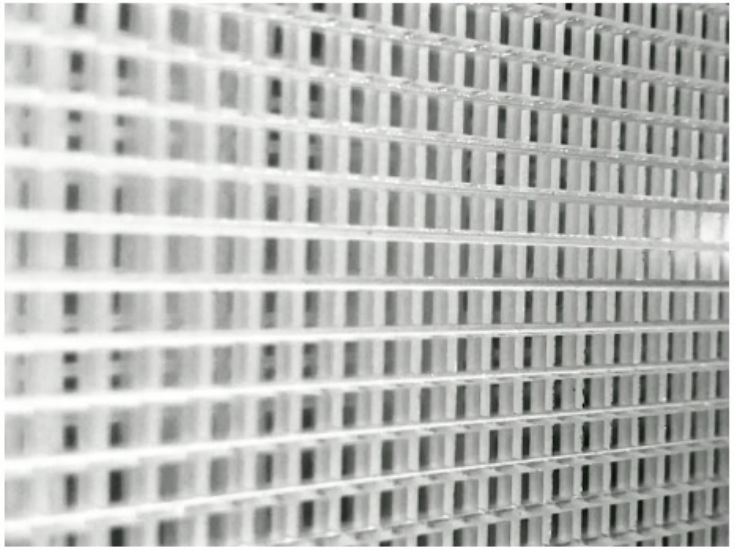




Dielectric Lens

Rexolite: dielectric constant = **2.53** and low loss
3d-printed and designed to mitigate reflection for our range of interest of ~18 to 20 GHz.

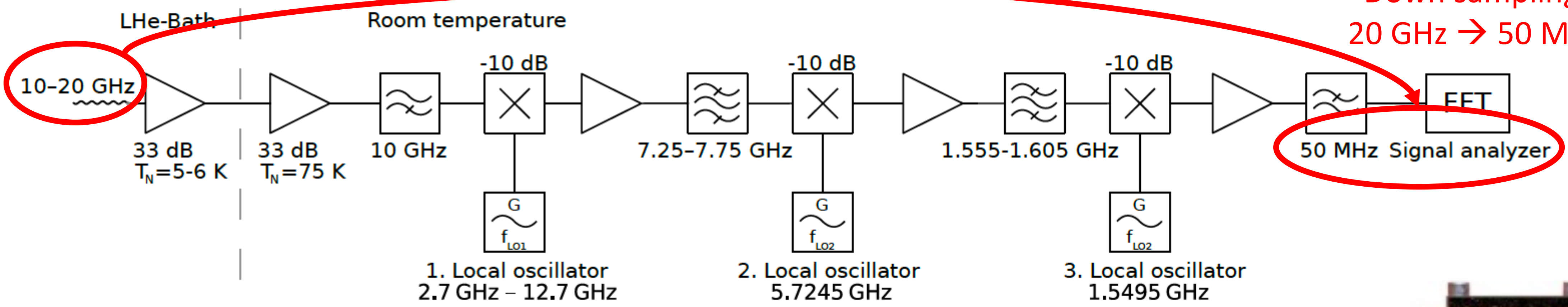


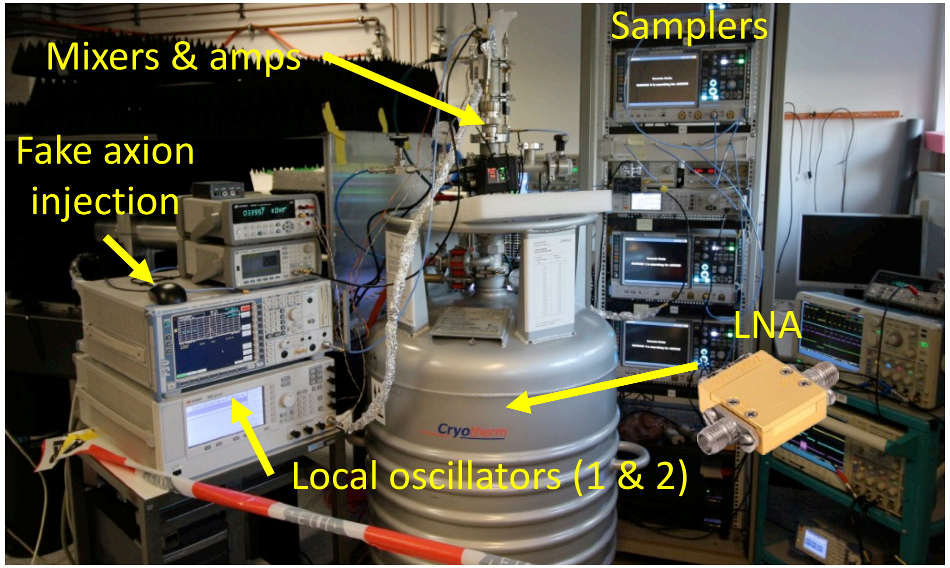


Contact: Anton Ivanov <ivanovan@mpp.mpg.de>

Receiver Chain

Down sampling:
20 GHz → 50 MHz



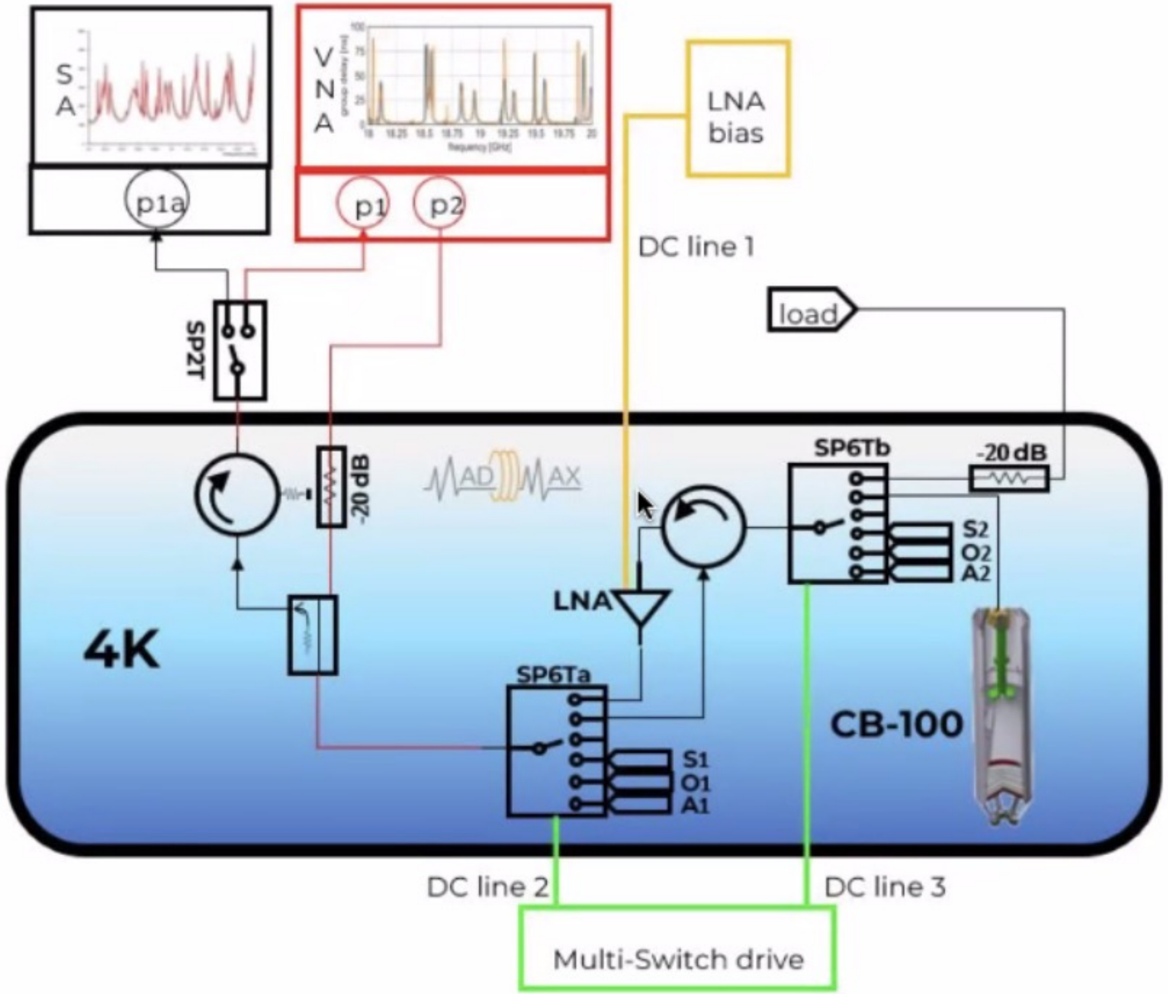


- Receiver chain with low-noise amplifier and three mixing stages
- Amplifiers for high frequencies developed: TWPAs for < 30 GHz

Test setup at MPP with 4 samplers and fake axion injection:
Detection of 1.2 x 10^{-22} W signal within few days

Low-noise cryogenic amplifier (noise temperature 5 to 6 K)

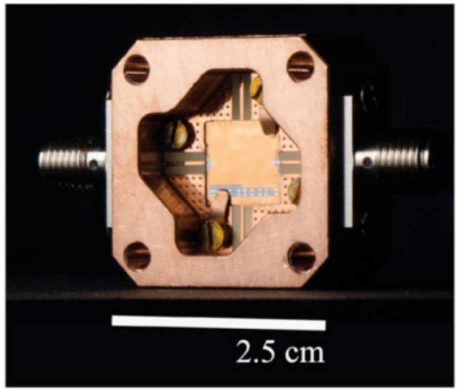
Cold Calibration Idea

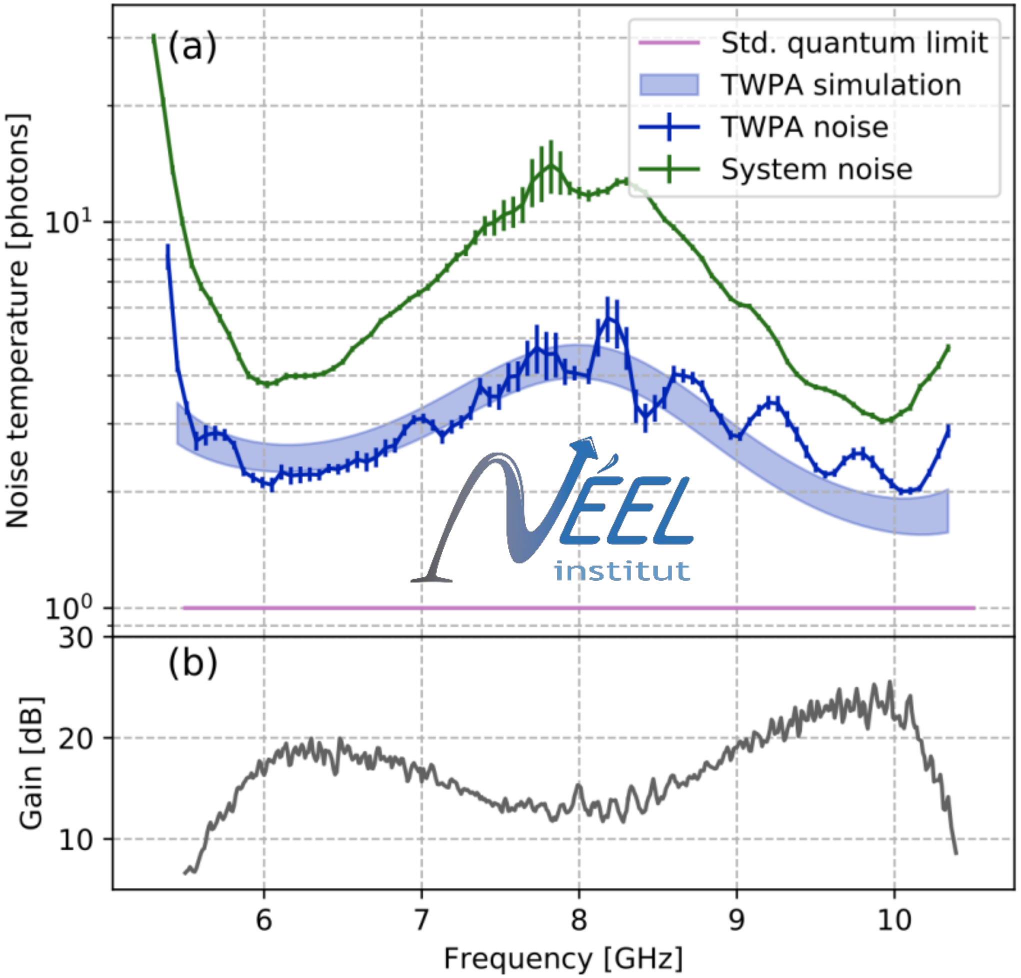


Simulation still missing

Quantum-limited Amplifier

- Traveling wave parametric amplifier (TWPA)
- **First 10 GHz TWPA** produced (PRX 10, 021021)
- Added noise: 1 K above quantum limit
  (20 dB gain @ 10 GHz)
- Future development to 30 GHz





[Reversed Kerr TWPA arXiv:2101.05815]

MADMAX Collaboration Meeting
September 2022 @ Hamburg