MADMAX
A Dielectric Haloscope Experiment

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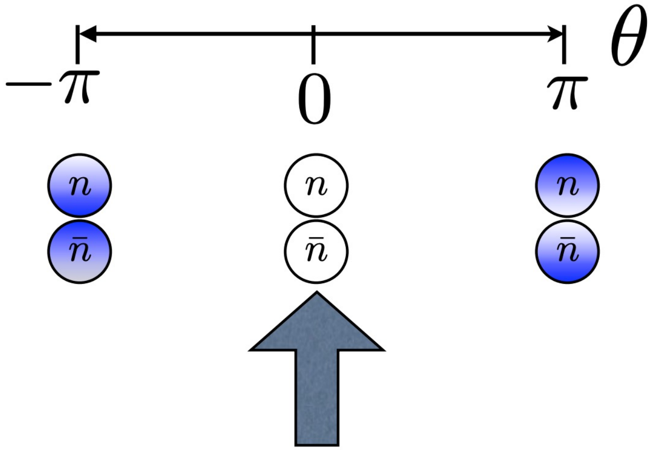
February 22, 2022

- **Motivation**
- **Axion Dark Matter Searches**
- **MADMAX Experiment**
- **Status of R&D**

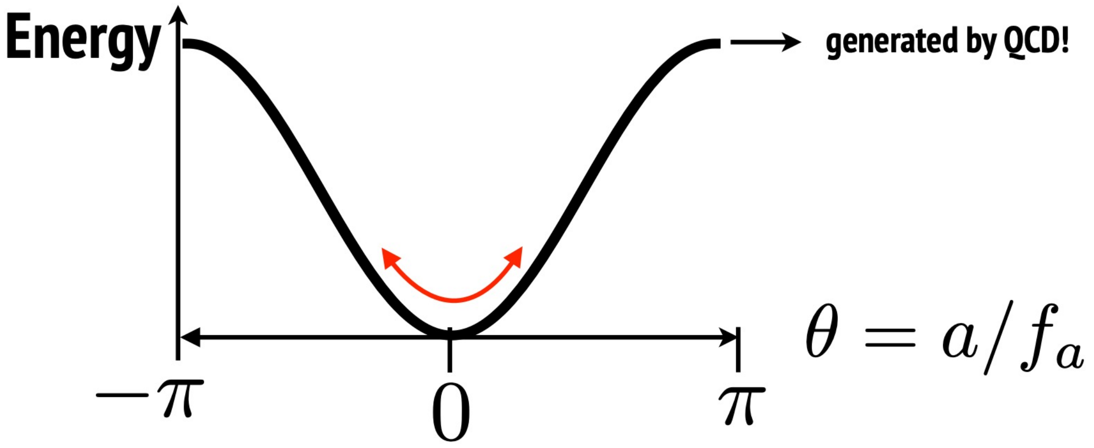
Motivation

- Sources of CP-violation in the Standard Model
  - CP-violation **observed in weak interactions** (neutral Kaon system, 1964)
    - CPV phase measured in the quark-mixing CKM matrix (δ_{13} ~ 1.2 rad)
  - CP-violation **not observed in the strong interactions**
    - CPV θ-term in QCD Lagrangian is allowed and should exist
    - But **$|\theta| < 10^{-10}$** from neutron electron dipole moment measurements
- Lack of observed CP-violation in the strong interactions leads to the **Strong CP Problem**
  - **Why is θ so small?**
  - What if θ is not a fundamental constant?

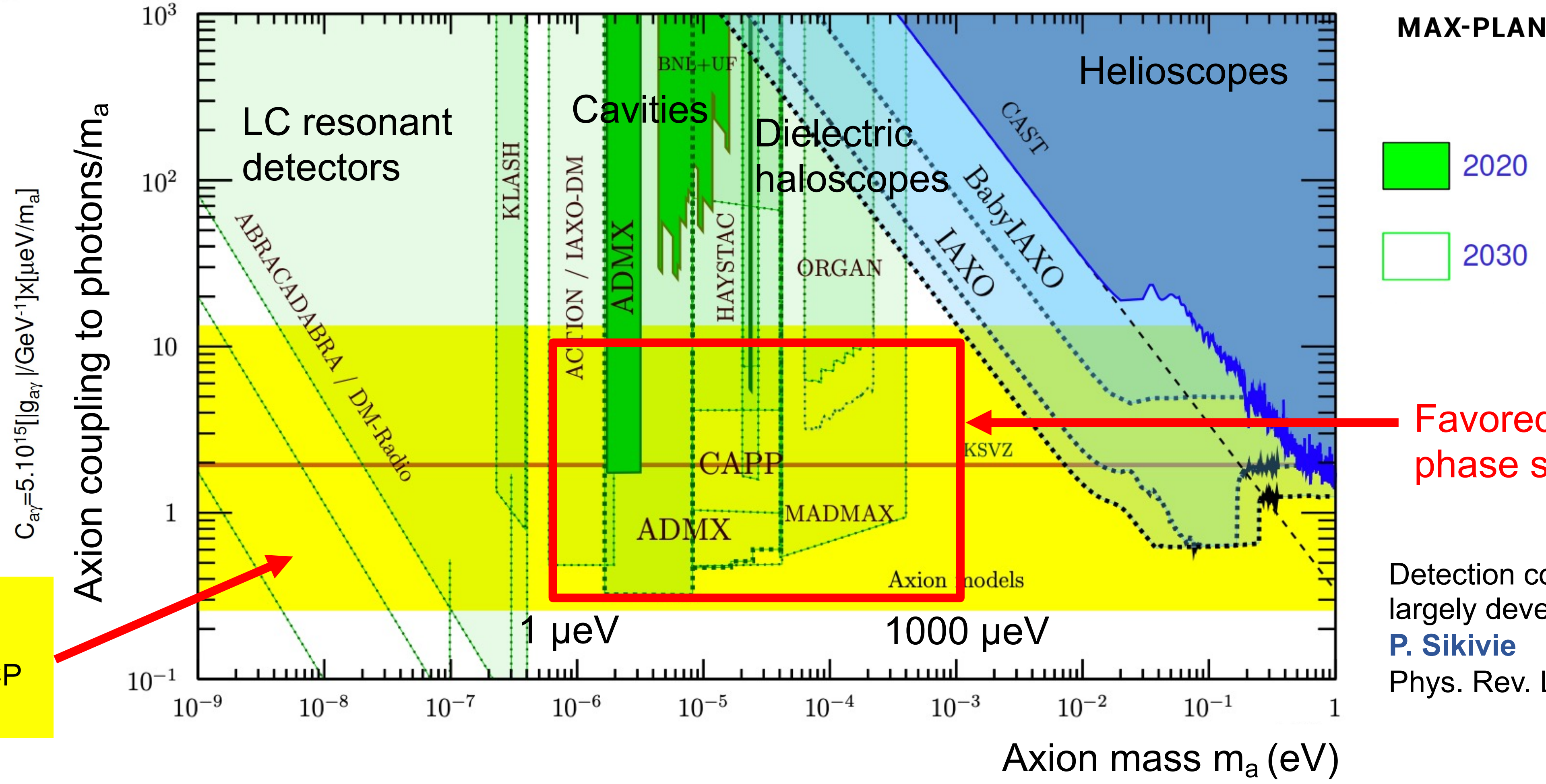


Motivation

- An elegant solution to the Strong CP Problem
  - **Peccei-Quinn Theory** (1977) introduces a new global U(1) symmetry
    - Spontaneously broken symmetry at a high energy scale $f_a >> f_{EW}$
    - **θ becomes a dynamic field** ($\theta = a/f_a$), where **a** is a new light, neutral pseudoscalar boson
  - Leads to oscillations around the minimum, i.e. the **Axion** (Weinberg-Wilczek, 1978)
    - **Very weakly coupled to SM particles**
- Axion is a natural **candidate for Dark Matter**



Axion DM Searches



Yellow band:
QCD axion

- Solving Strong CP problem

Detection concepts largely developed by **P. Sikivie**
Phys. Rev. Lett. **51**, 1415

- Limited region of Axion DM phase space explored by cavity experiments (e.g. ADMX)
- Higher mass region (i.e. 10 – 1000 μeV) still unexplored
- Promising R&D in **dielectric haloscopes** for probing the high mass region (40-400 μeV)

The MADMAX Experiment

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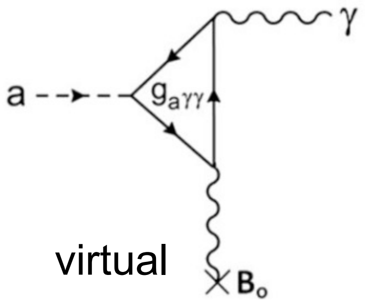
- The **MA**gnetized **D**isk and **M**irror **A**xion *e**X**periment* (a novel Dielectric Haloscope)
- Search for **Axion dark matter** in the mass range **40 μeV – 400 μeV** (10 GHz – 100 GHz)
- Stack of adjustable, parallel **dielectric disks** (~1 m^2) in front of a highly reflective **mirror**
- Disks and mirror (i.e. "Booster") surrounded by a strong (~10 T) static **magnetic field**
- Constructive interference among different sources boost signal to detectable levels (10^{-23} -10^{-22} W)
- Power measured in a **heterodyne receiver** (i.e. frequency mixing and down-conversion)
- Current status: **extensive prototyping phase** in progress
- First tests of scaled-down prototypes in CERN's 1.6 T MORPURGO magnet scheduled for 2022

Primakoff effect
Axion to photon conversion



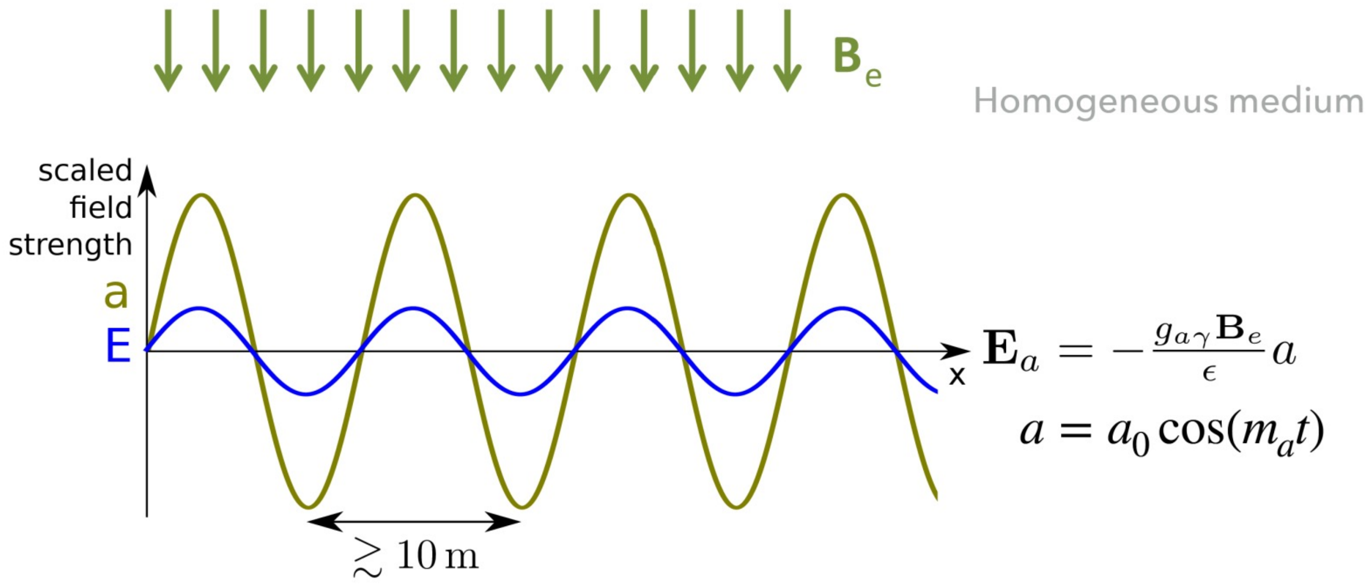
e.g. 100 μeV axion → 25 GHz photon

The MADMAX Collaboration

Collaboration formed October 18, 2017

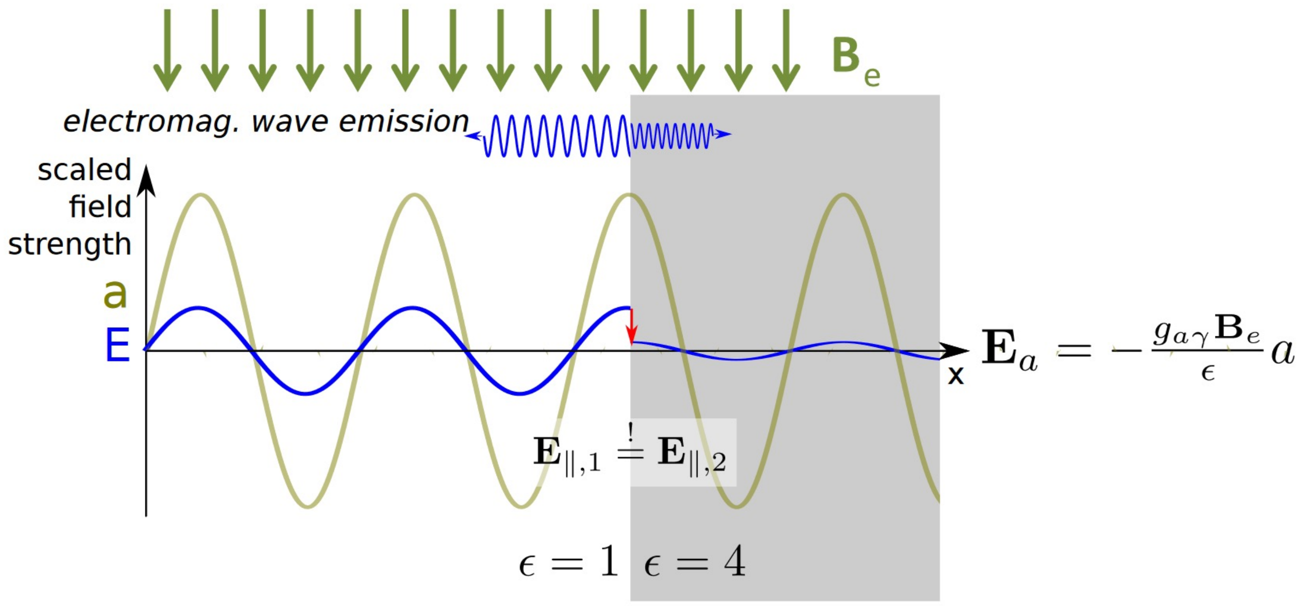
- Centre de Physique des Particules de Marseille (CPPM), France
- DESY Hamburg, Germany
- Néel Institute, Grenoble, France
- MPI für Physik, Munich, Germany
- MPI für Radioastronomie, Bonn, Germany
- RWTH Aachen, Germany
- University of Hamburg, Germany
- University of Tübingen, Germany
- University of Zaragoza, Spain

Dielectric Haloscope Concept



The axion field a(t) sources an oscillating electric field E_a in the presence of an external magnetic field B_e

Dielectric Haloscope Concept



The axion field a(t) sources an oscillating electric field E_a in the presence of an external magnetic field B_e

E_a is different in materials with different ε

$E_{||}$ must be continuous at the surface

Leads to emission of EM waves

Power emitted at a vacuum-to-perfect-conductor interface:

$$P_{sig} = 2.2 \cdot 10^{-27}\mathrm{W}\left(\frac{A}{1\mathrm{m}^2}\right)\left(\frac{B_e}{10\mathrm{T}}\right)^2\left(\frac{g_{a\gamma}}{m_a}\right)^2$$

$$\mathcal{O}\left(\frac{g_{a\gamma}}{m_a}\right) = 1$$

MADMAX Booster Concept

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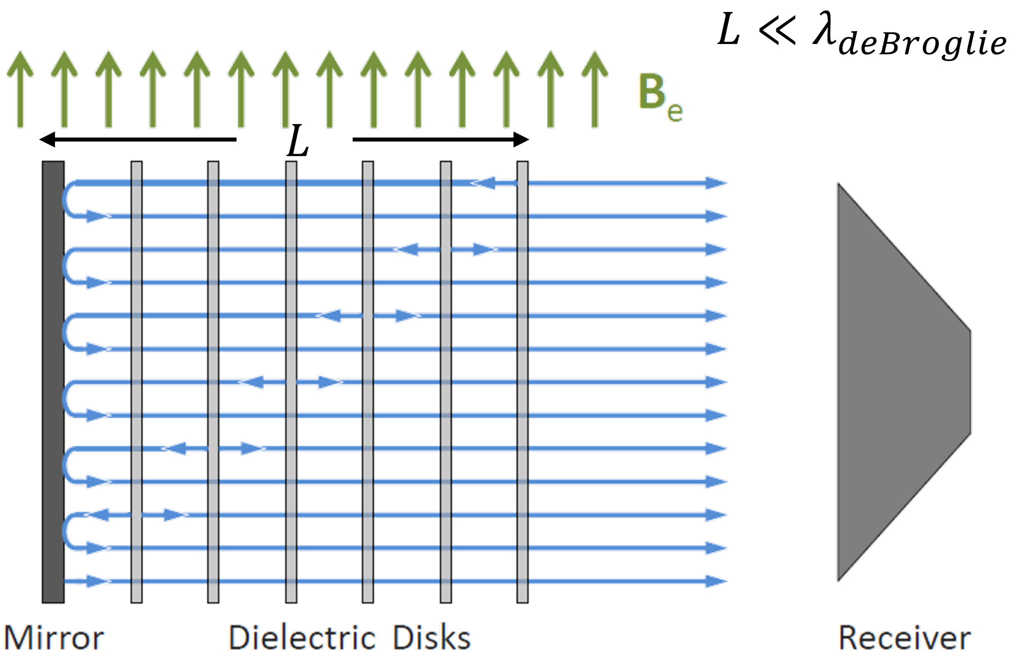

Power enhancement comes from 2 sources:

- **Coherent emission** from multiple interfaces
- **Resonance** effects between interfaces

Power "Boost factor" β^2

$$\beta^2 = \frac{P_{booster}}{P_{mirror\ only}}$$

Output power P of a dielectric haloscope:

$$P_{sig} = 2.2 \cdot 10^{-27} W \left(\frac{A}{1m^2}\right)\left(\frac{B_e}{10T}\right)^2\left(\frac{g_{a\gamma}}{m_a}\right)^2 \beta^2$$

Search for: 40 – 400 µeV CDM axion
Signal: 10 – 100 GHz signal

$\beta^2 > 5 \cdot 10^4$ required to detect QCD axion

The Proposed MADMAX Experiment

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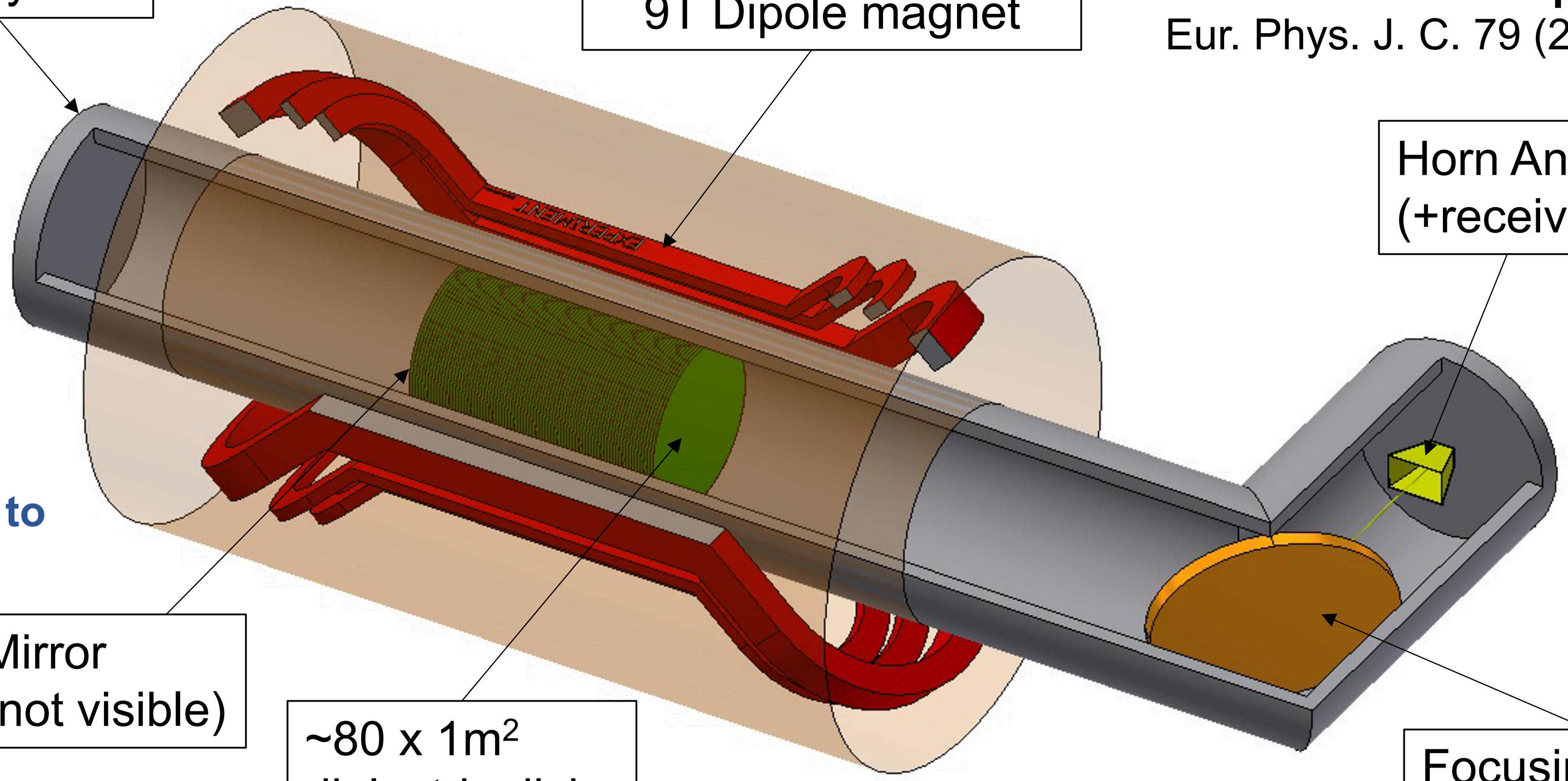
MADMAX White Paper
Eur. Phys. J. C. 79 (2019) 186

Main challenges

- Booster mech.
- Magnet
- Receiver at cold,
  B-field environment

Start with prototypes to validate concepts

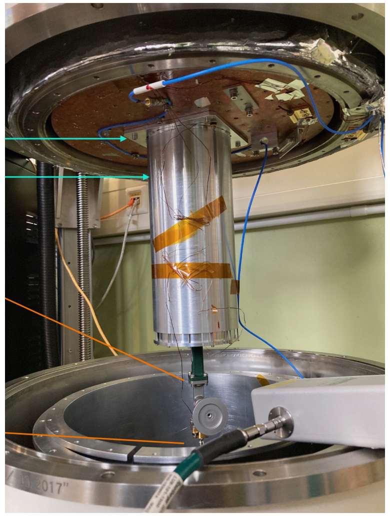


Prototype Boosters

- Test smaller prototypes at room temperature, cold (4K), and in B-field (1.6 T)

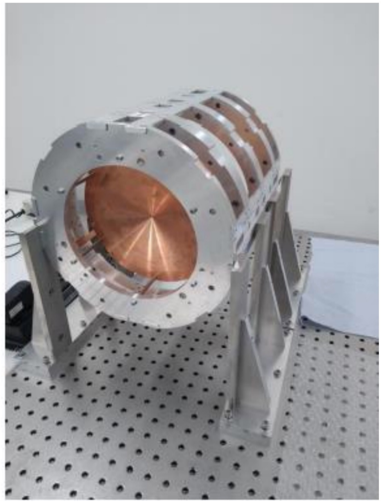
Name	acronym	disc diameter [mm]	Nr. of discs	Availability	Lab of tests (warm, cold, B-field)
Closed booster 100	CB100	100	3	2021	MPI, CERN
Closed booster 200	CB200	200	≥3	2022	
Project 200	P200	200	1	2021	UHH, DESY, CERN
Reduced booster	r-booster	300	≥3	2023	UHH, CERN
Prototype booster	P-booster	300	20	2024	

CB100 @ MPI



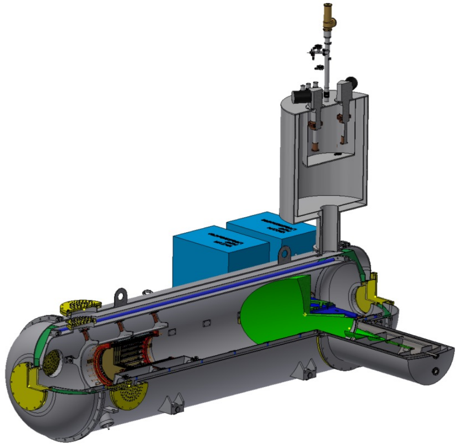
Tested at RT and 4K (2021-2022)

P200 @ UHH



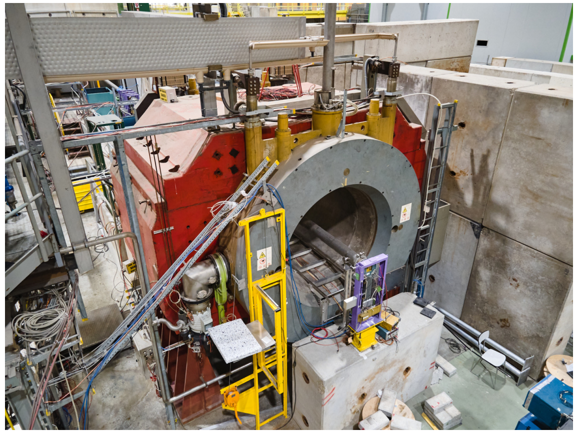
Tests planned in Morpurgo magnet (2022-2023)

r/P-Boosters @ UHH



SHielded Exp. haLL (SHELL) now available

All proto. to be tested in 1.6T MORPURGO magnet @ CERN



Approved by CERN in 2020
Area prepared for MADMAX
Tests begin March 2022.

Closed Booster 100mm (CB100)

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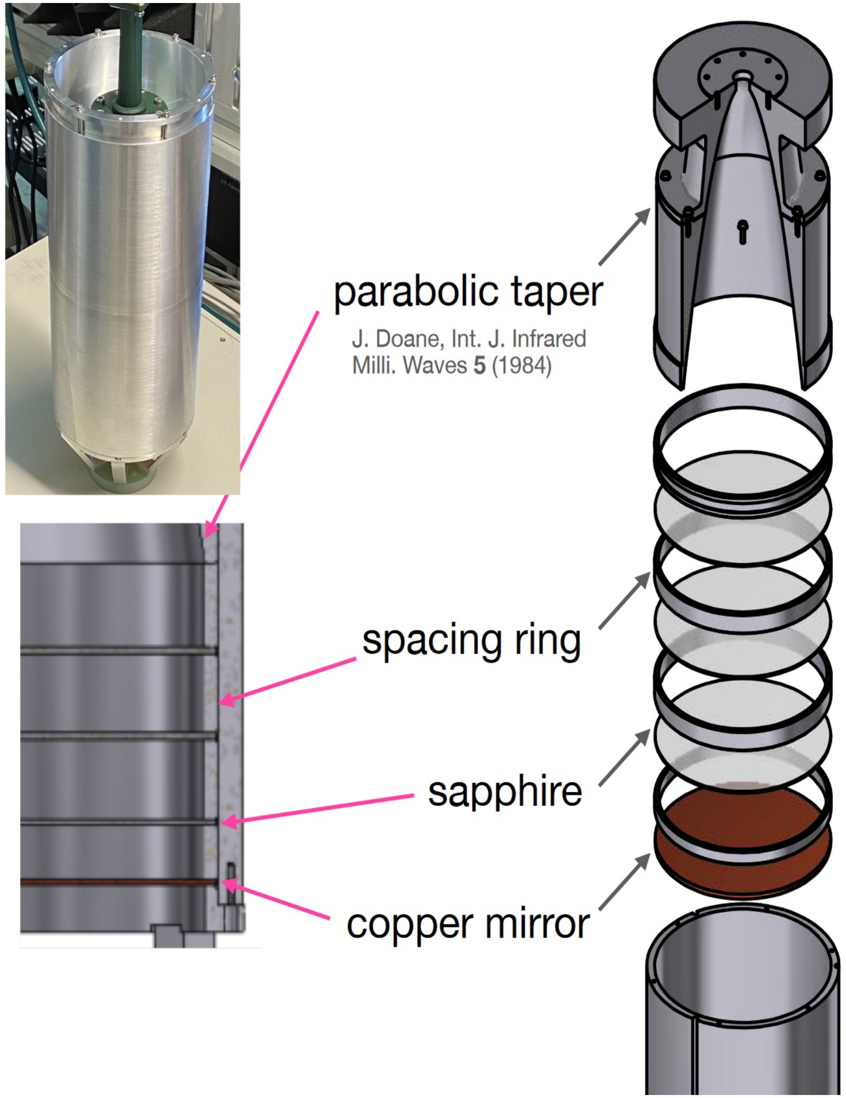
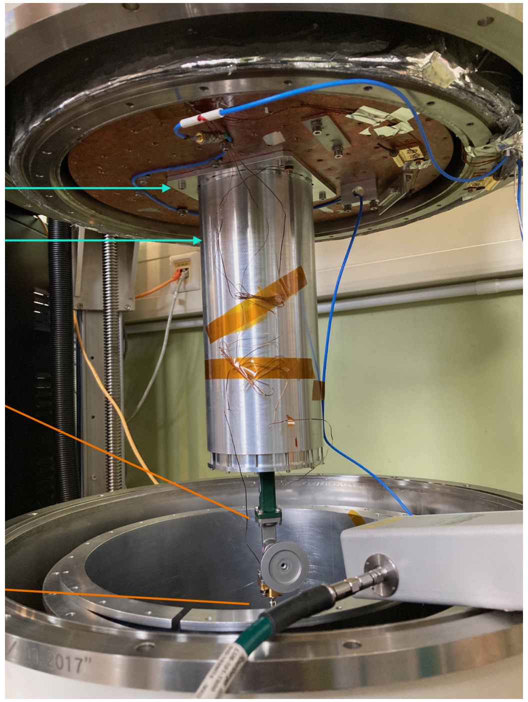
- Closed Booster concept (developed at MPI)
  - Understand RF behavior @ RT, cold (4K), and in 0.5 T (and 1.6 T) magnetic fields
  - Measure reflectivity ($\propto \beta^2$)
  - Cu mirror + 3 sapphire disks Ø=100 mm
  - Fixed disk spacings optimized @ ~19 GHz

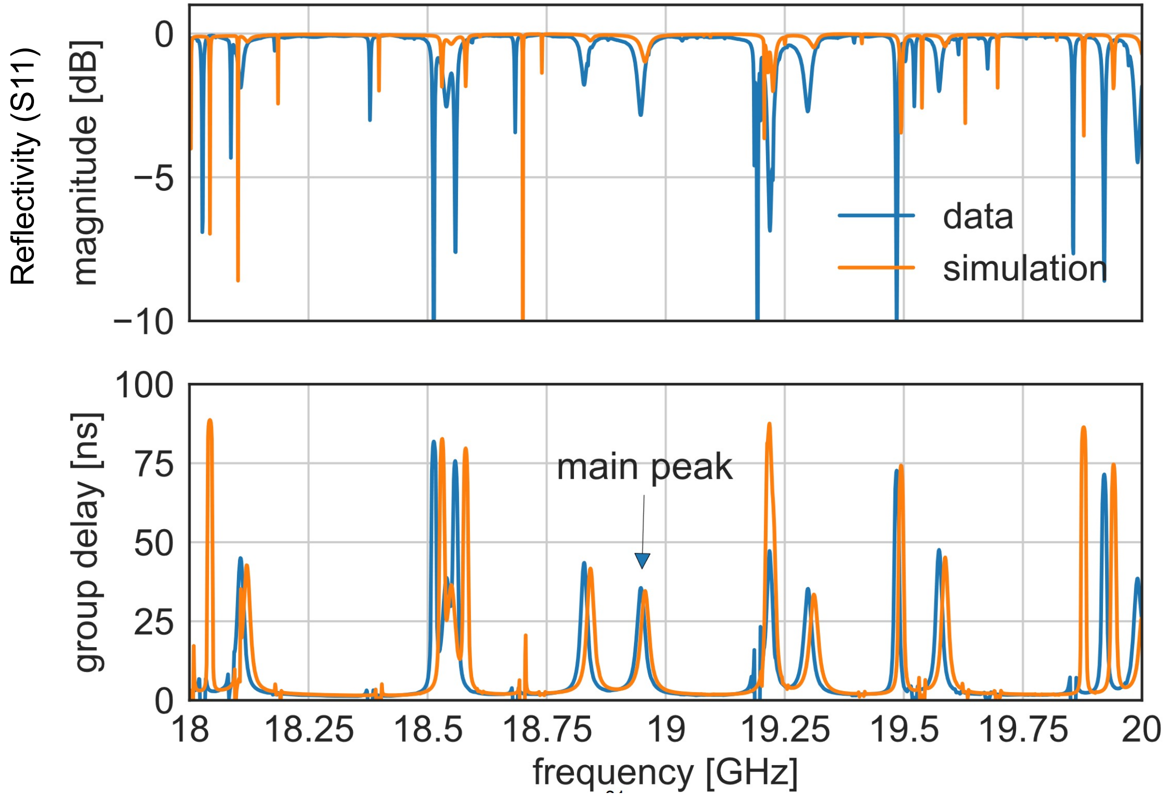


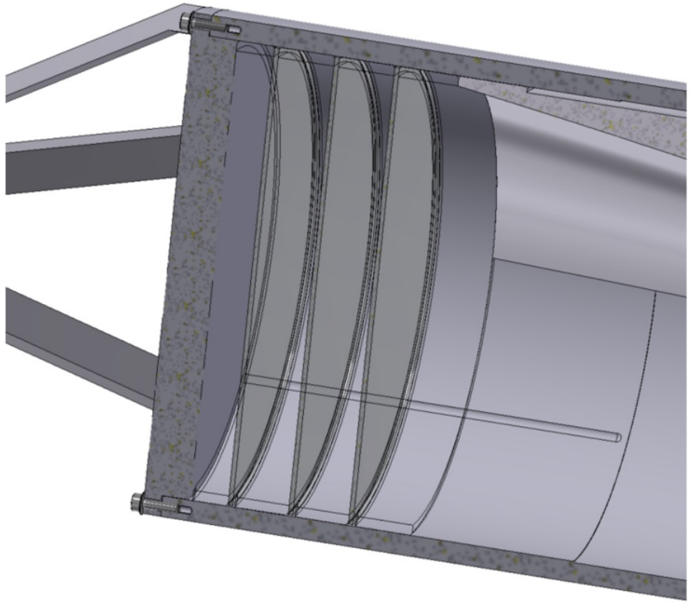
In cryo



Closed Booster 100mm (CB100)

- Results from room temperature measurement:
  - Agreement between simulation and reality is good, given the mechanical uncertainties
  - Boost peak loss is slightly higher because of remaining transverse radiation (current) at sapphire disks rim (solved in newer version of the setup)





Closed Booster 100mm (CB100)

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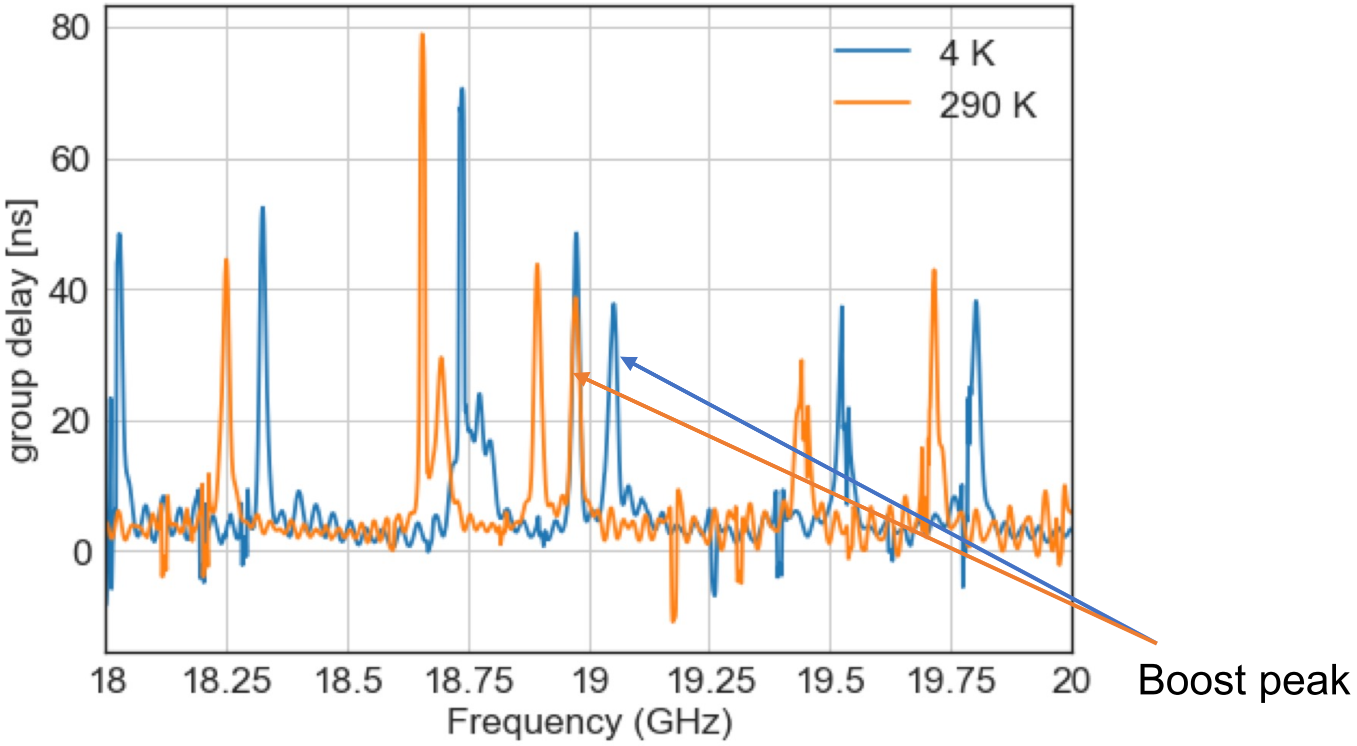
- Results from cryo measurement:
  - Observe Boost peak and mode crossings shift from RT to 4K (as expected)
  - System stable at 4K and good for long term measurement

Group delay:
From RT (290K) to LHeT (4K)



Mechanics Prototype: Project 200

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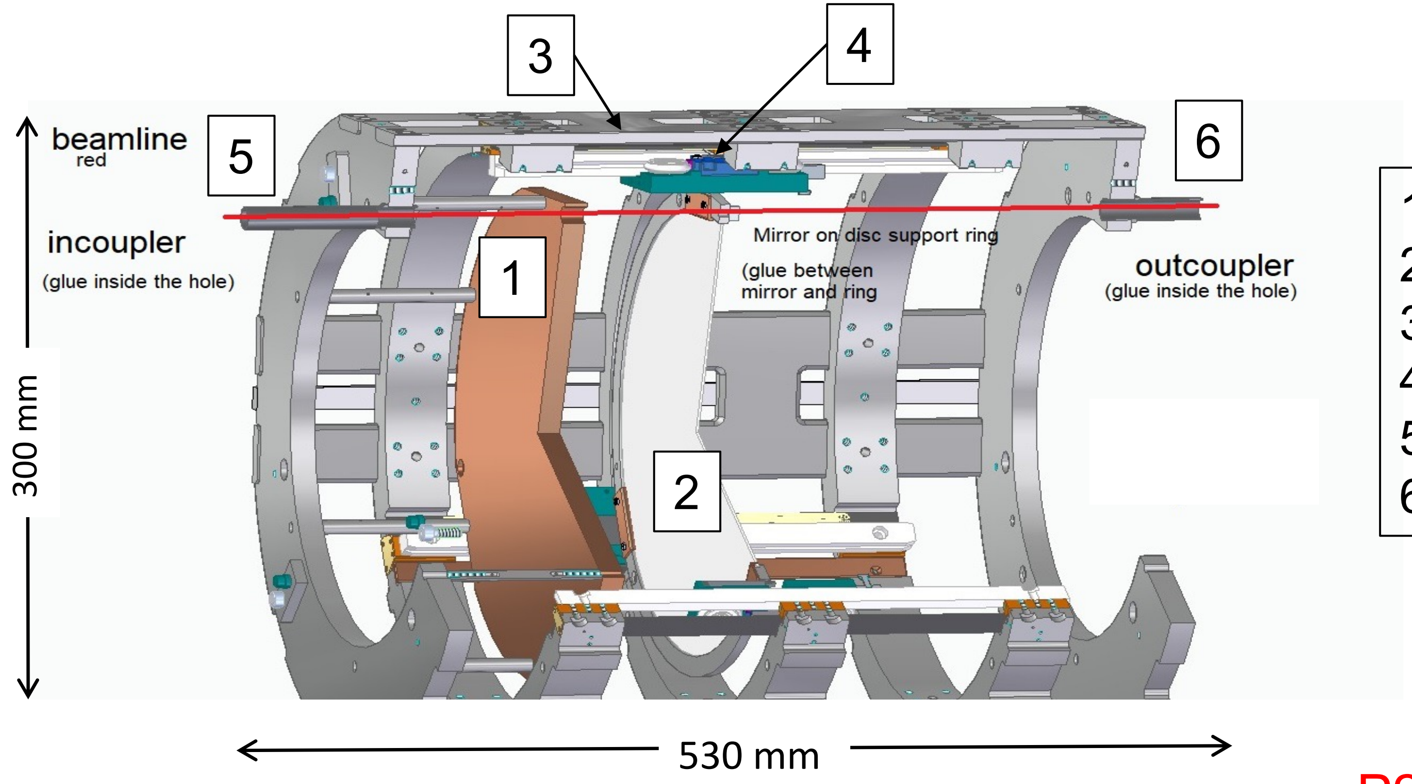


1- Cu mirror (fixed position)
2- Sapphire disk (adjustable positions)
3- P200 support structure
4- (3x) piezo motors
5- interferometer incoupler
6- interferometer outcoupler

Weight < 20 kg

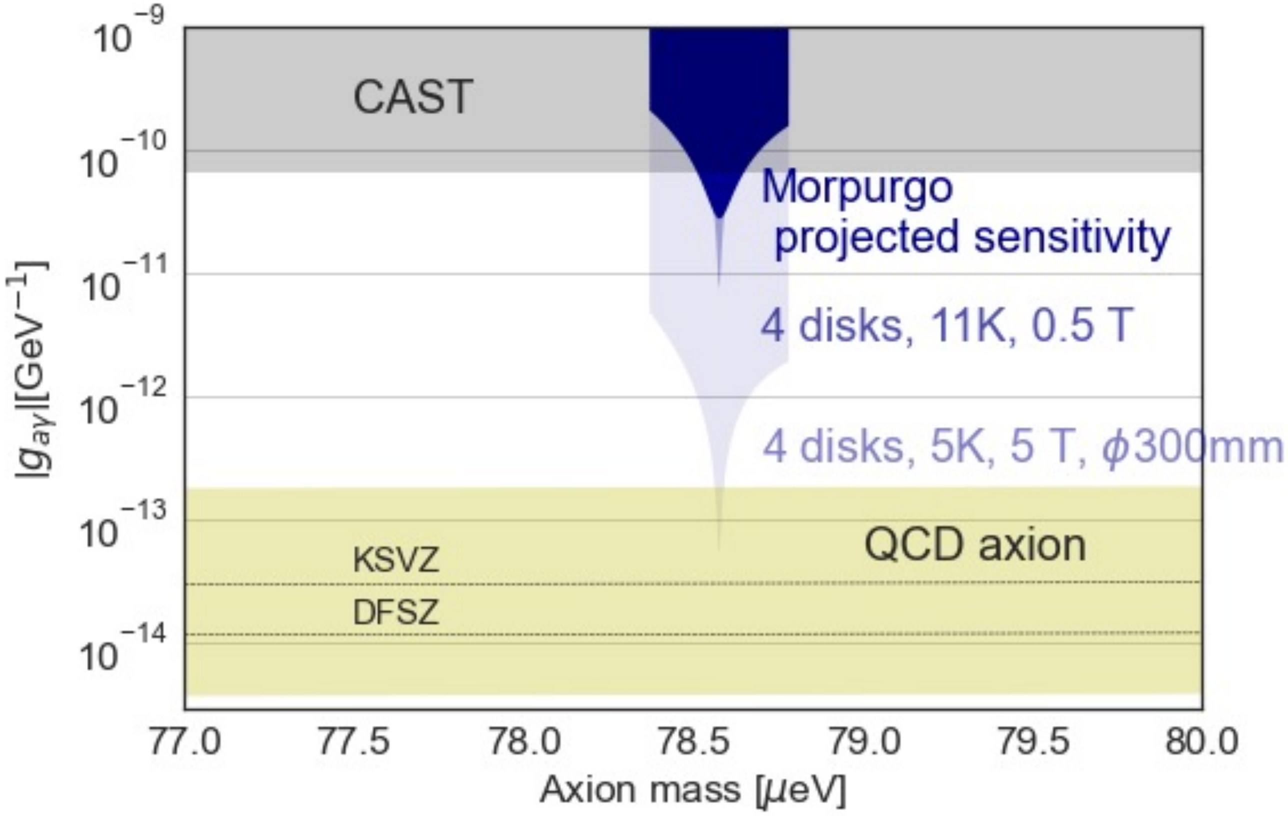
P200 will validates the mechanics for the Prototype Booster

RT Booster Measurements @ 1.6 T

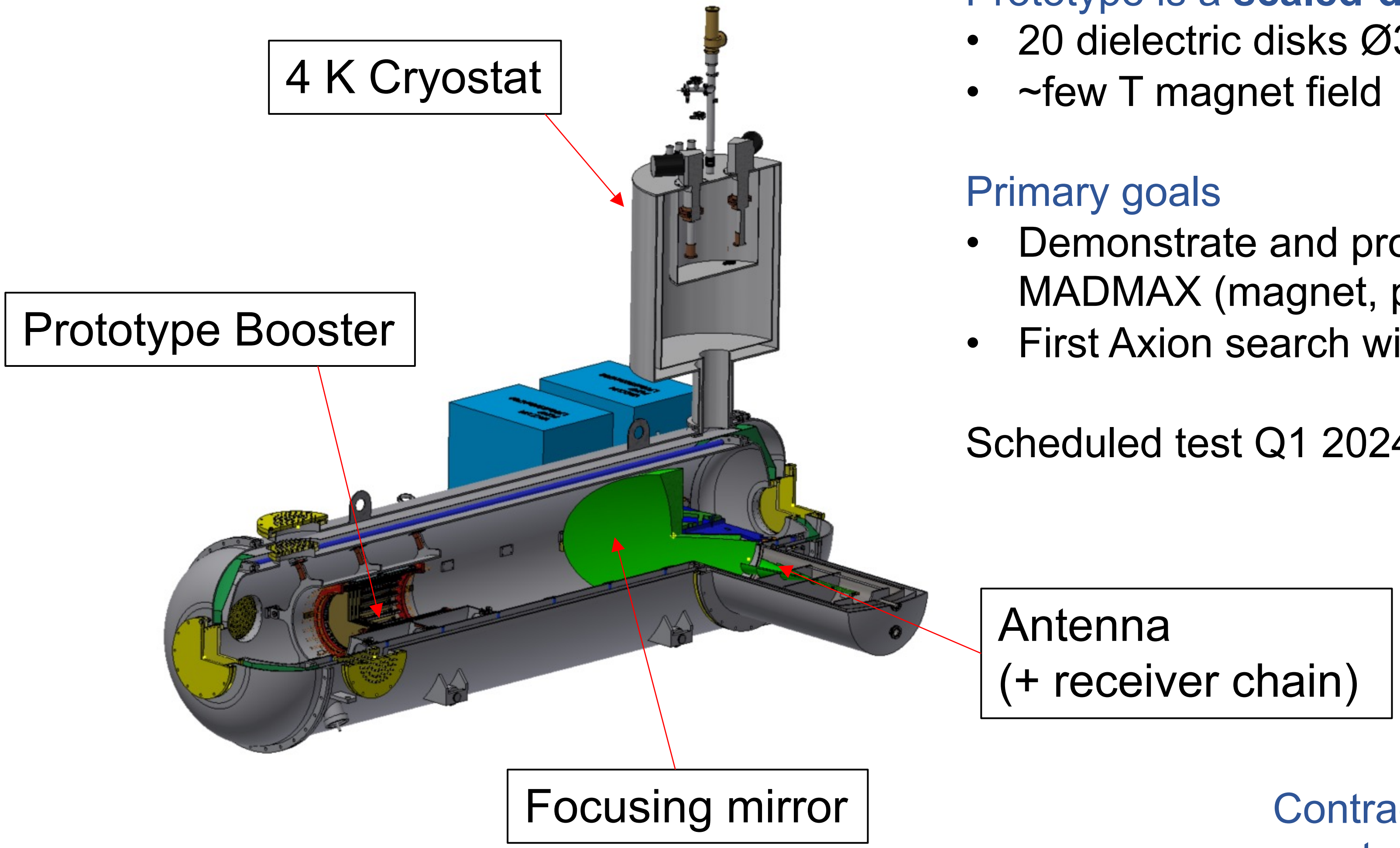
First measurements planned at
CERN‘s MORPURGO Magnet @ 1.6 T

<u>2022</u>
EMC Test → understand RF environment
CB100 (Mar/Apr)
P200 (Apr, without final interferometer)

<u>2023</u>
CB200 → Aim for 1st physics run
P200 → Mechanics tests in a B-field



The MADMAX Prototype



Prototype is a **scaled-down version** of MADMAX
- 20 dielectric disks Ø30 cm
- ~few T magnet field

Primary goals
- Demonstrate and prototype key technologies for MADMAX (magnet, piezo motors, RF system, etc.)
- First Axion search with a dielectric haloscope

Scheduled test Q1 2024 (3 disks), Q1 2025 (20 disks)

Contract signed with Noell for cyrostat construction, to be delivered Q1 2023 @ UHH

Magnet and Motor Prototyping

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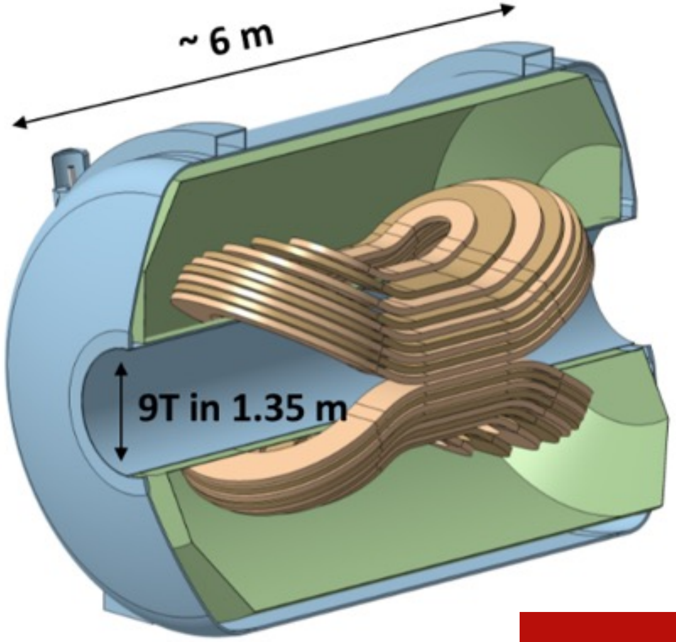
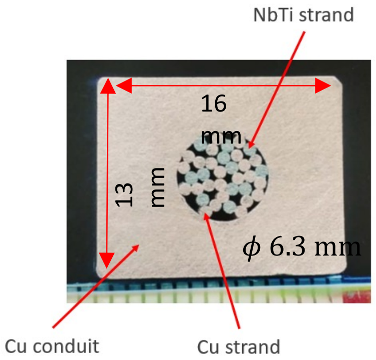
Magnet Design by CEA-Saclay & Bilfinger-Noell

- Dipole Magnet
- B > 9 T, Warm bore 1.35 m, I = 23.5 kA, stored energy ~500MJ
- FOM : 80-100 T^2m^2
- Status: Design and R&D phase in progress



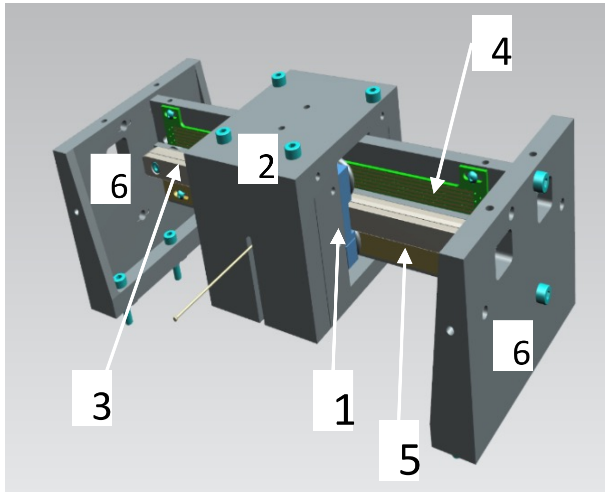
New conductor:
Cable-in-circuit conductor
with Cu profile

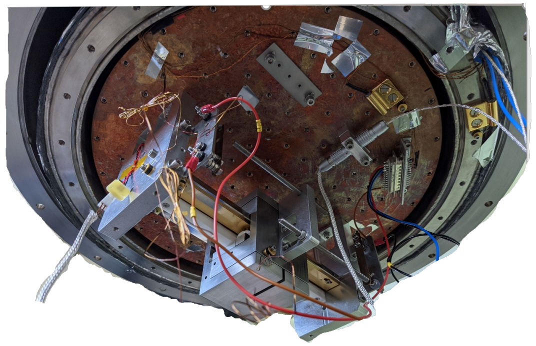


BILFINGER NOELL GMBH

Piezo Motor Design by JPE Innovations

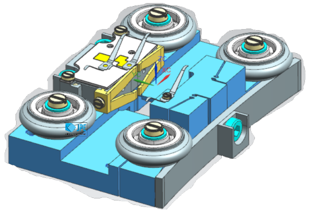
- Operation at cryogenic temperature and in strong B-field
- Reliable design (240 motors to move 80 disks)
- Durability, friction wear, lifetime
- Feasibility verified at 4.2 K and 5.6 T (Jan 2022)
- Status: Design and R&D phase in progress





1 – motor carriage
2 – weight
3 – ceramic rail
4 – PCB
5 – cooling strip
6 – side plates

JPE Driven by innovation

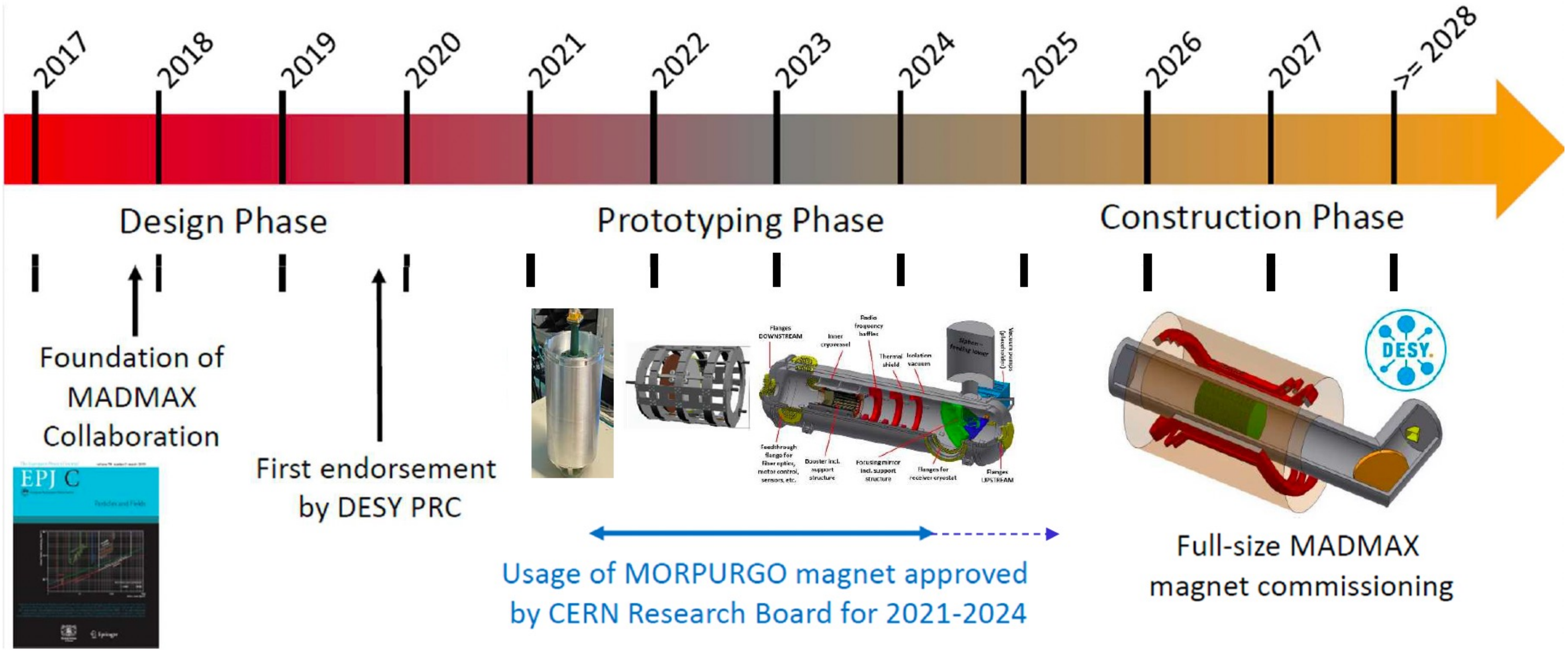


Summary

- MADMAX is a **novel dielectric haloscope** aimed at discovering axion CDM in the range 40-400 µeV.
- **R&D and prototyping is ongoing** in several technologies: e.g. magnets, piezo motors, dielectrics, booster mechanics, low-noise receivers (not everything covered in this talk).
- MADMAX Prototype phase is well under way with several critical tests planned for 2022/5.
- Magnet
  - **New conductor** successfully tested
- Piezoelectric motors
  - **Motors tested successfully at 4.2 K and 5.6 T**
  - Tests in B-Field and P200 planned in Q1 2022
- RF/Booster
  - CB100 **simulations and data agree well** (within mechanical uncertainties)
  - Tests at 4.2 K are stable
- 1.6 T MORPURGO Magnet (CERN)
  - **First RF measurements** planned early 2022
  - Prototype cryostat to be delivered Q1 2023 at UHH. Tests at CERN Q1 2024
- Aim for first ALPs search beyond CAST with closed booster expected in 2023

Backup

MADMAX Timeline



Modified Axion Maxwell Eqns

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a,$$

axion DM modifies maxwell equations:

- new equations:

$$\begin{aligned}
\boldsymbol{\nabla}\cdot\mathbf{E} &= \rho - g_{a\gamma}\mathbf{B}\cdot\boldsymbol{\nabla}a\,,\\
\boldsymbol{\nabla}\times\mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma}\left(\mathbf{B}\,\dot{a} - \mathbf{E}\times\boldsymbol{\nabla}a\right)\\
\boldsymbol{\nabla}\cdot\mathbf{B} &= 0\,,\\
\boldsymbol{\nabla}\times\mathbf{E} + \dot{\mathbf{B}} &= 0\,,\\
\ddot{a} - \boldsymbol{\nabla}^2a + m_a^2a &= g_{a\gamma}\mathbf{E}\cdot\mathbf{B}\,.
\end{aligned}$$

MADMAX Booster Concept

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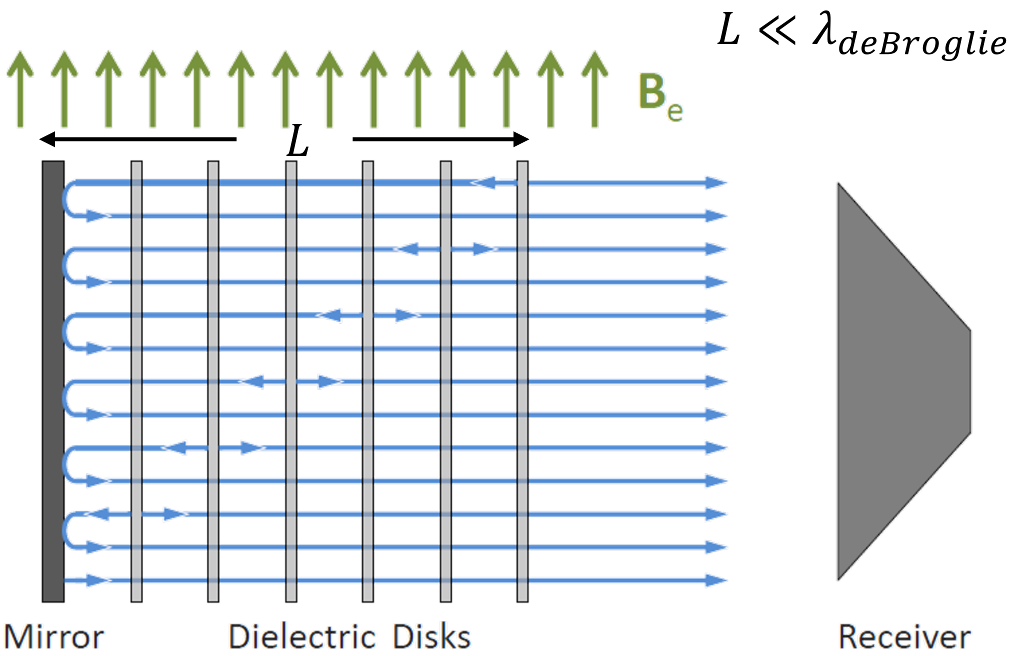
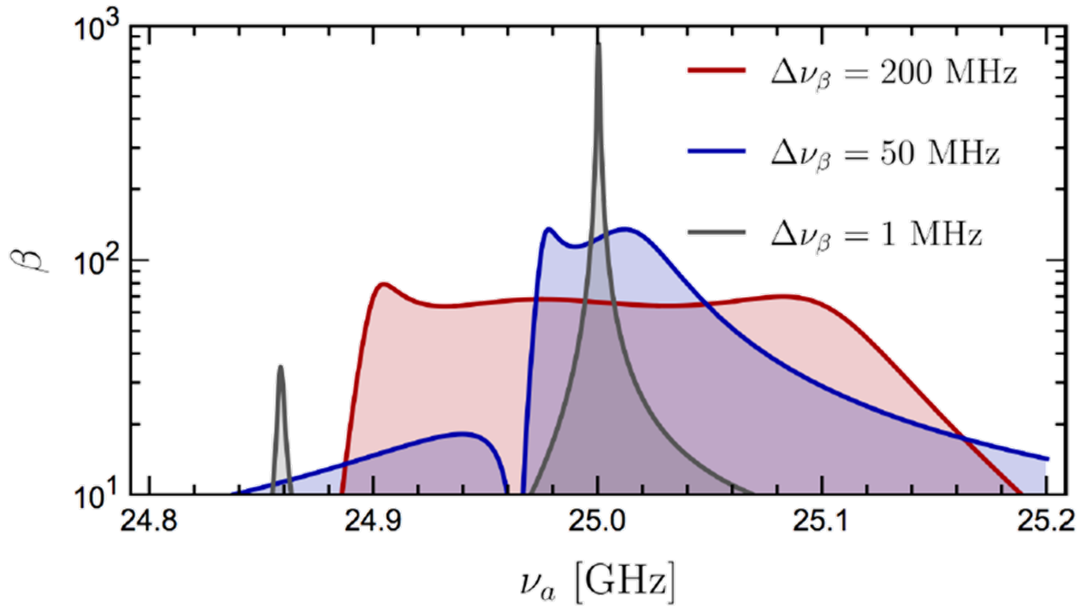


Boost of axion to photon conversion



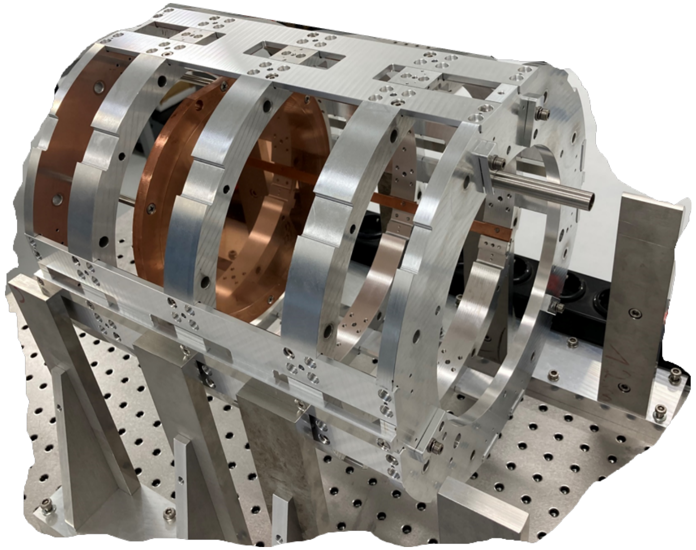
Output power P of a dielectric haloscope:

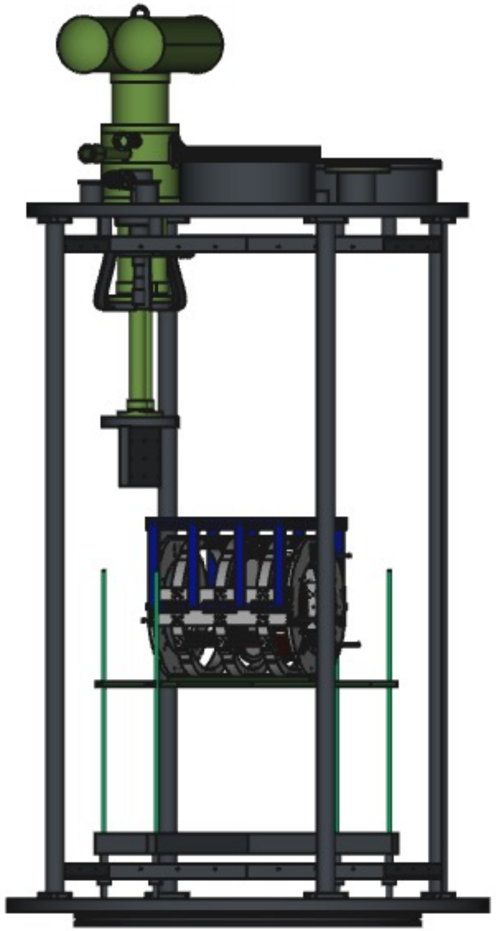
$$P_{sig} = 2.2 \cdot 10^{-27} W \left(\frac{A}{1m^2}\right)\left(\frac{B_e}{10T}\right)^2 \left(\frac{g_{a\gamma}}{m_a}\right)^2 \boldsymbol{\beta^2}$$

- Possibility for narrow-band and broad-band measurements
- Scan axion mass by changing disk positions

Project 200 in LHe @ CERN

Status:
- P200 assembled at UHH
- Tests at RT → Dec'21/Jan'22
- Tests in CERN Cryostat:
  - 1st run → Feb, March 2022
  - 2nd run → Fall 2022





Tests at RT (in Hamburg)
Parameters checked:
- Stepsize
- Positioning accuracy (spec: +/- 10 mm)
- Tilt of the disk
- Reproducibility
- Drift (after 1s, 10 s, 10 min,…)

Tests at 4.2 K (CERN)
Parameters to be checked:
- Repeat RT measurements
- Temperature investigation

Receiver

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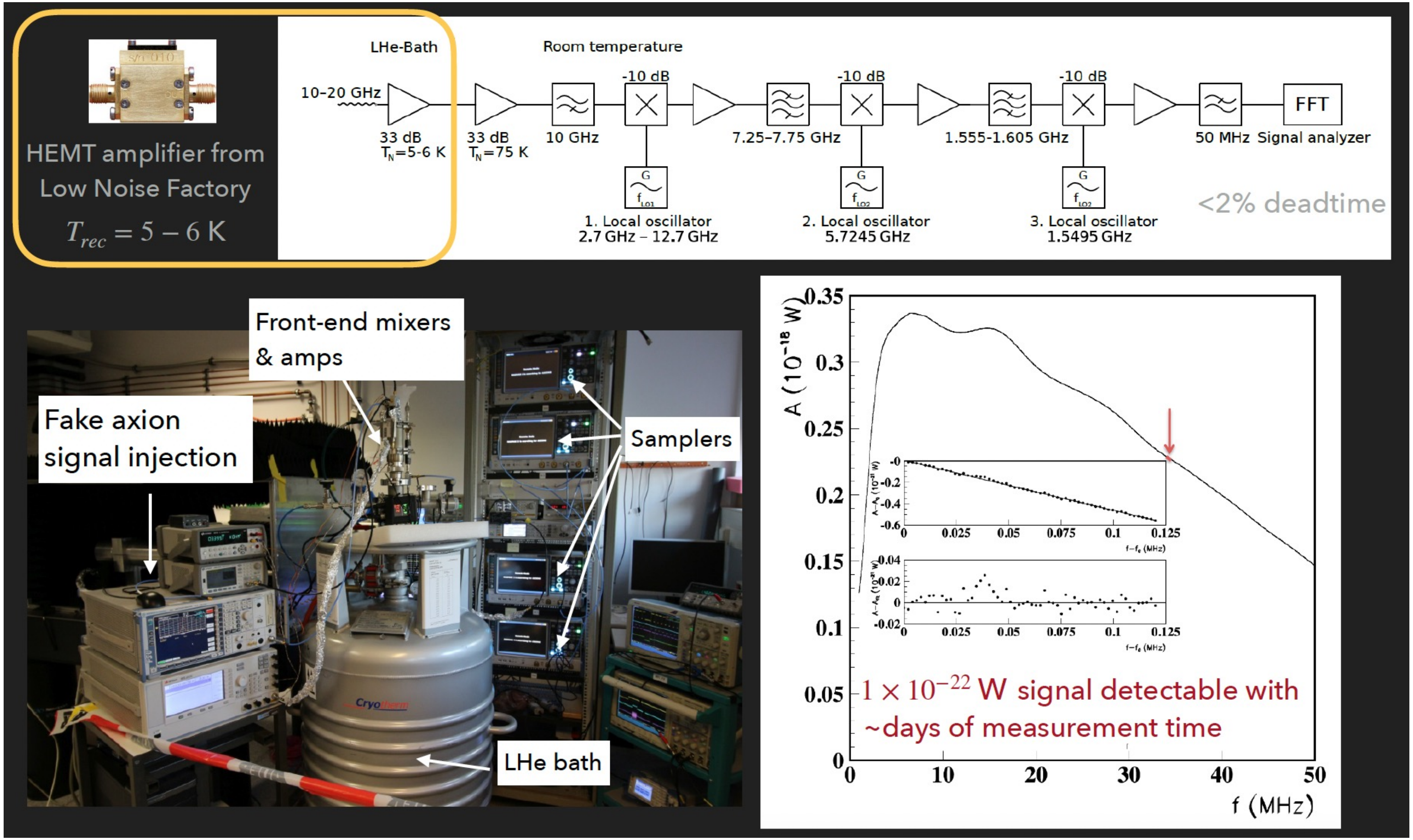

Low-noise Amplifier Developments

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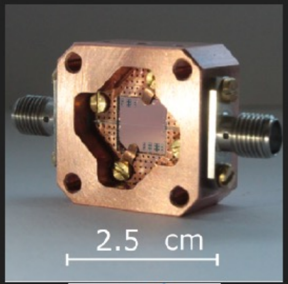
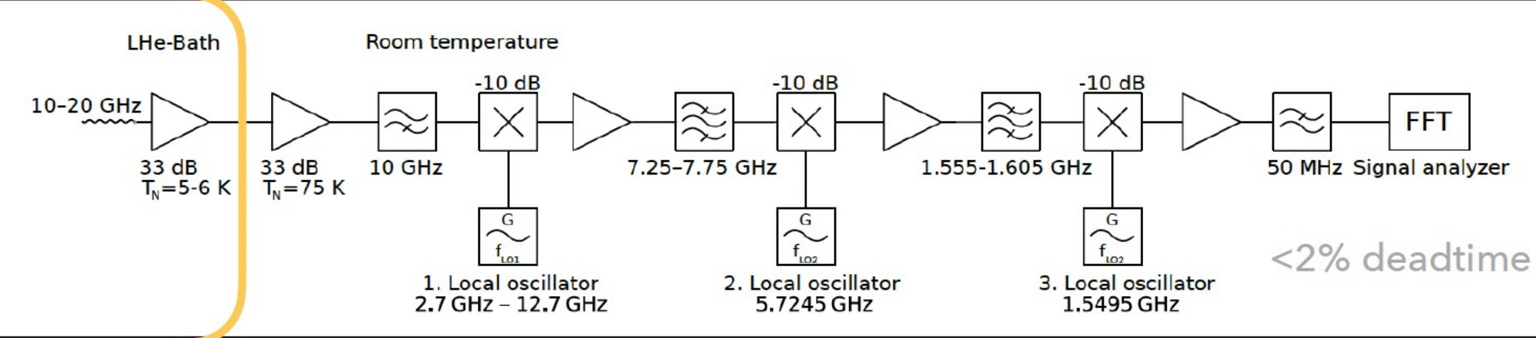
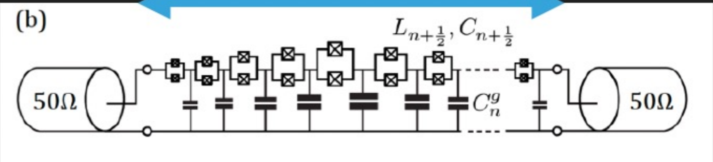
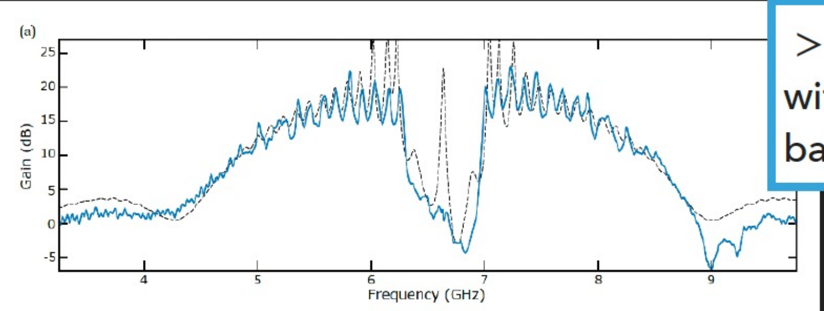




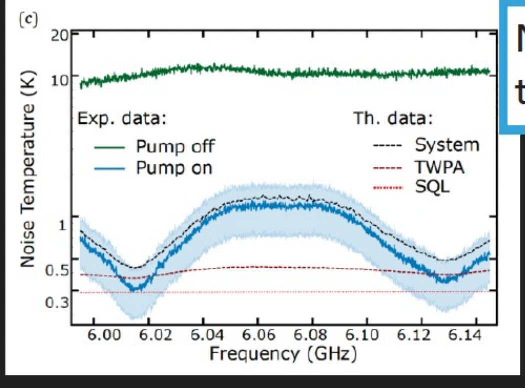
<2% deadtime

~2000 SQUIDS





> 15 dB gain with ~2 GHz bandwidth



Noise temperature close to the quantum limit

- The possibility of using a traveling wave parametric amplifier (TWPA) as the preamplifier is being investigated
  - Potentially halves the system noise temperature

L. Planat, *et. al. arXiv:1907.10158*

The Axion particle

- Regardless of the initial conditions of the universe, the axion field will go to the minimum position. The amplitude will decrease with time, and we can always get a very small value of θ.
- Because the lifetime of the universe if finite, there will always be some oscillations of the axion field. These oscillations have some energy, which will be dark matter in nature.

$\theta(t,\mathbf{x}) = a(t,\mathbf{x})/f_a$
$m_a = 6\text{ meV }(10^9\text{ GeV}/f_a)$

$a(t,\mathbf{x})$ – axion field
f_a – energy scale
$\theta(t,\mathbf{x})$ – an angle $[-\pi, \pi]$
m_a – axion mass

How to detect the Axion

- Lagrangian interaction

$$\mathcal{L} = -C_{a\gamma}\frac{\alpha}{2\pi}\frac{a}{f_a}\vec{B}\cdot\vec{E}$$

- In a static magnetic field, the oscillating axion field generates EM-fields

$$\mathcal{L} = -C_{a\gamma}\frac{\alpha}{2\pi}\theta(t)\vec{B}_{EXT}\cdot\vec{E}$$

- Electric field amplitude independent of mass

$$E_a = C_{a\gamma}\frac{\alpha B_{EXT}}{2\pi}\theta_0\cos(m_a t)$$

Oscillations at frequency

$$\omega \cong m_a$$

CDM Axion Direct Detection

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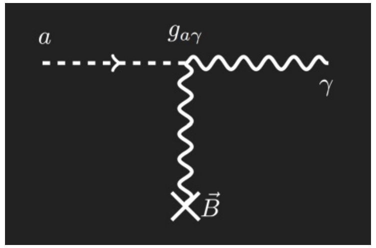
- CDM axions behave like a classical wave, e.g. m_a = 100 μeV
  - Local galactic axion density: $\rho_a = 0.45\, GeV/cm^3$
  - Axion de Broglie wavelength: $\lambda_a = \frac{2\pi}{m_a v_a} \gtrsim 10\, m \ \ (v_a \approx 10^{-3}c)$
  - Axion phase-space occupancy: $\mathcal{N}_a \sim n_a \lambda_a^3 = \frac{\rho_a}{m_a}\lambda_a^3 \sim 10^{22}$



- Axion-photon interaction

$$\mathcal{L}_{a\gamma\gamma} = C_{a\gamma}\frac{\alpha}{2\pi f_a} a F^{\mu\nu}F_{\mu\nu}$$

$$g_{a\gamma} = C_{a\gamma}\frac{\alpha}{2\pi f_a}$$

m_a = 100 μeV
=> 25 GHz microwave photon

Axion parameter space

The Axion:

- A light, neutral pseudoscalar boson
- Small mass and couplings
- Solve the strong CP problem
  - Why does θ≈0?
- Primakoff effect: Axion to photon conversion in a strong B field