A novel dielectric haloscope

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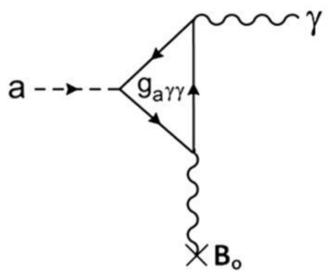
On behalf of the MADMAX collaboration

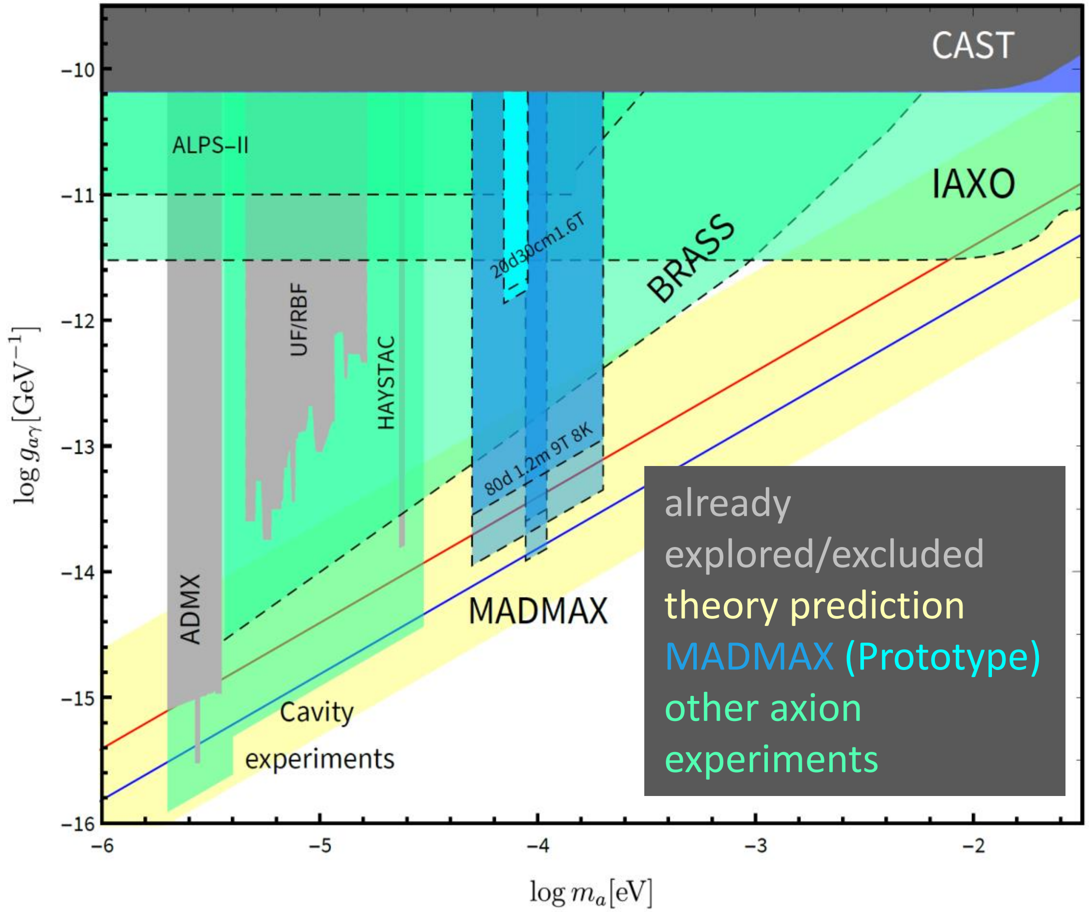
Recent Progress in Axion Theory and Experiment
Sept 5th 2022

MADMAX
Looking for the Axion

- Axion is a hypothetical particle conceived to explain the strong CP problem.
- Axions → very low mass, very weak interaction with all SM particles. Excellent candidate for cold dark matter.
- Primakoff effect: axions couple to photons in the presence of a strong magnetic field.

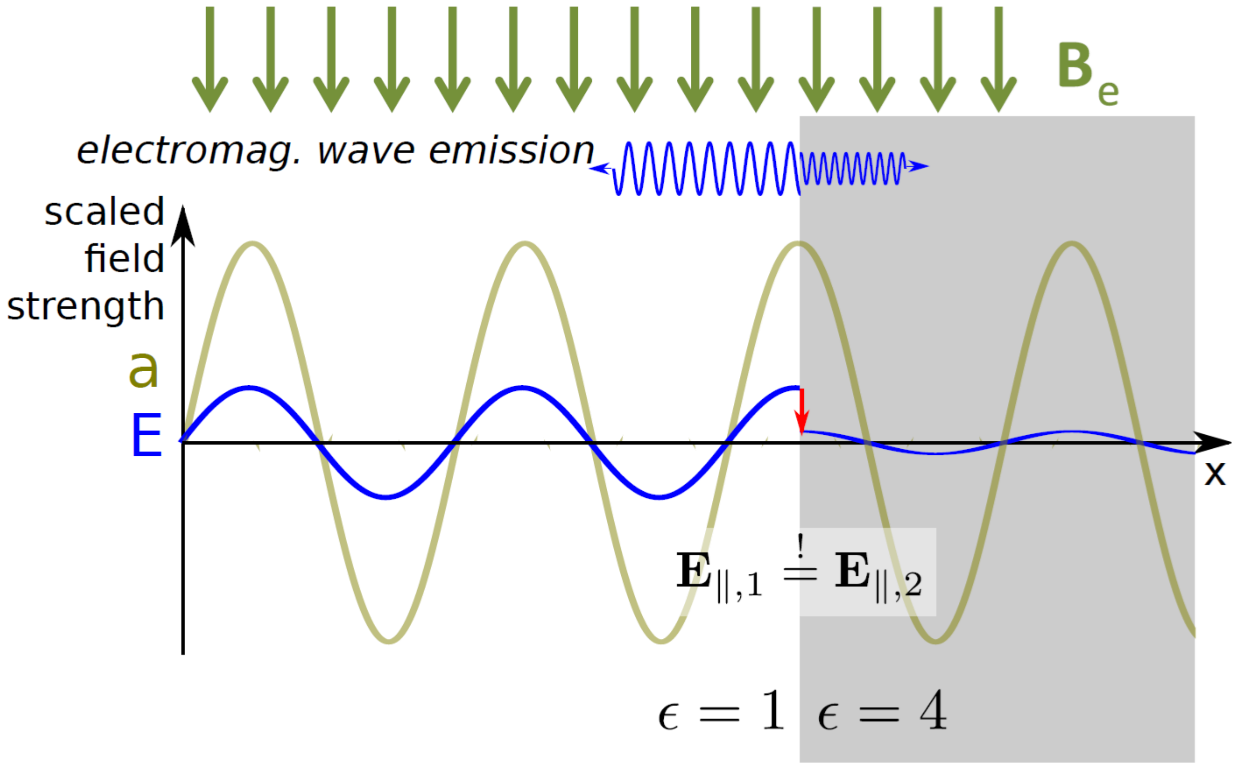


- The MADMAX experiment → search for axion dark matter in the range from 40 μeV to 400 μeV.



[arXiv:2003.10894]

MADMAX: A dielectric haloscope



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

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

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

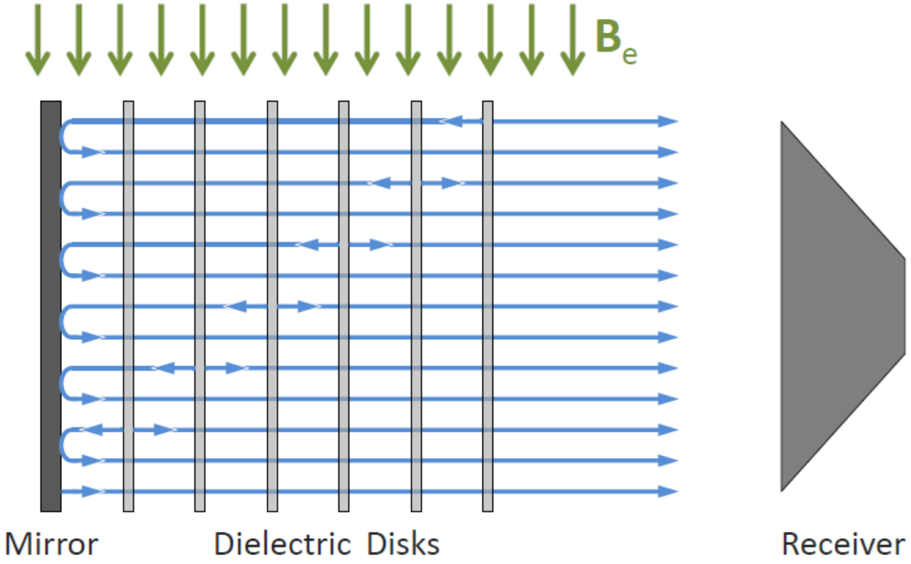
At the surface, $E_{\|}$ must be continuous
→ Emission of electromagnetic waves

Output power P from a single mirror per unit area A is:

$$\left(\frac{\boldsymbol{P}}{\boldsymbol{A}}\right)_{\boldsymbol{mirror}} \sim \mathbf{2 \cdot 10^{-27}} \frac{\mathbf{W}}{\mathbf{m^2}} \left(\frac{\boldsymbol{B_{||}}}{\mathbf{10}\ \boldsymbol{T}}\right)^{\mathbf{2}} \left(\boldsymbol{g_{a\gamma\gamma}/m_a}\right)^{\mathbf{2}}$$

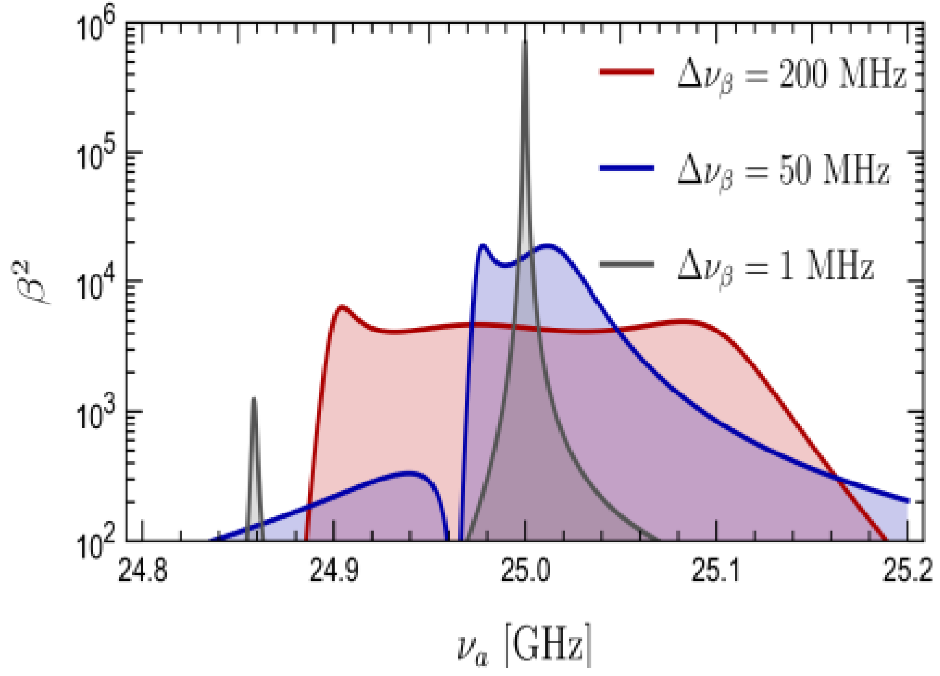
MADMAX: A dielectric haloscope

Constructive interference of coherent photon emission at several interfaces



MADMAX PRL118 (2017) 091801

Boost of axion to photon conversion



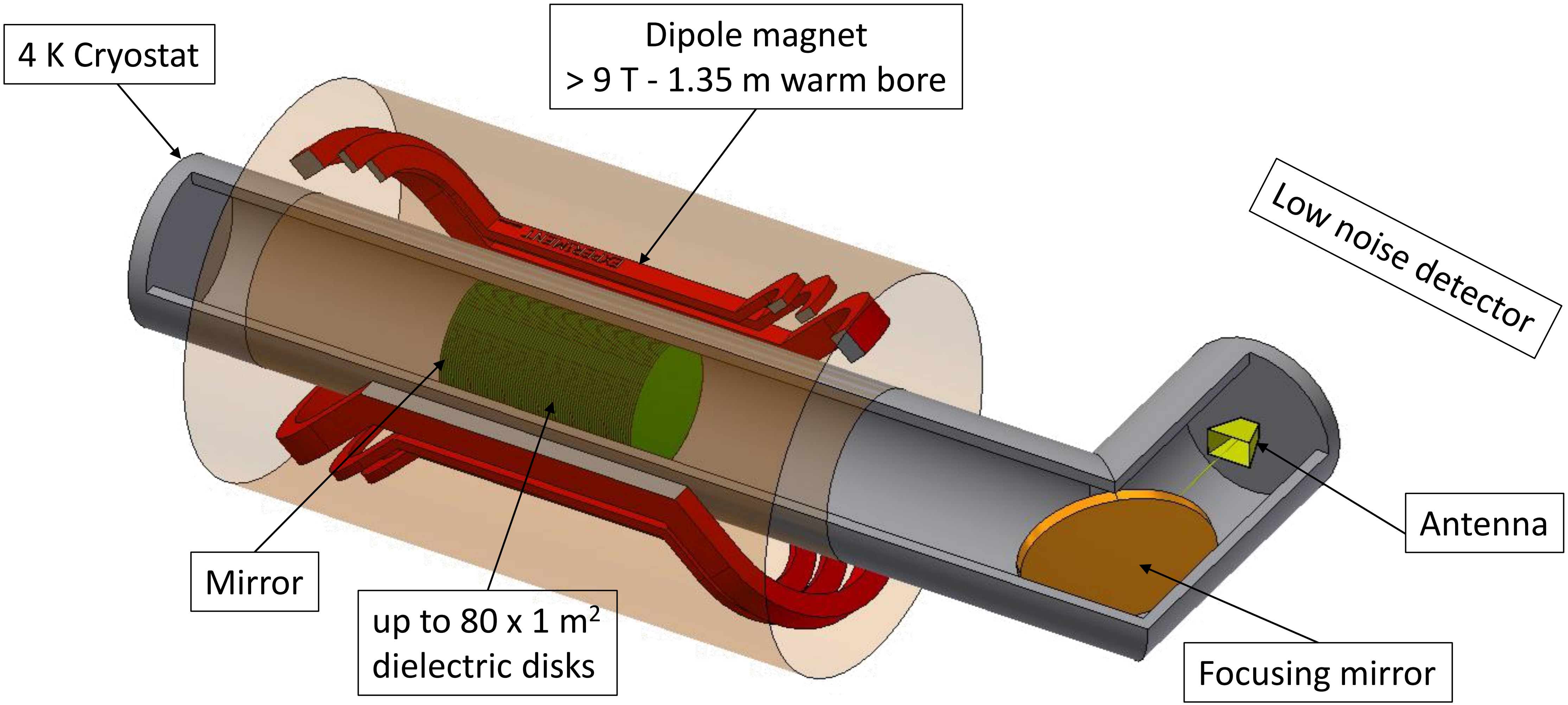
Output power P of the dielectric haloscope per unit area A is:

$$\left(\frac{P}{A}\right)_{booster} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{||}}{10\ T}\right)^2 \left(g_{a\gamma\gamma}/m_a\right)^2 \beta^2$$

The power boost factor

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

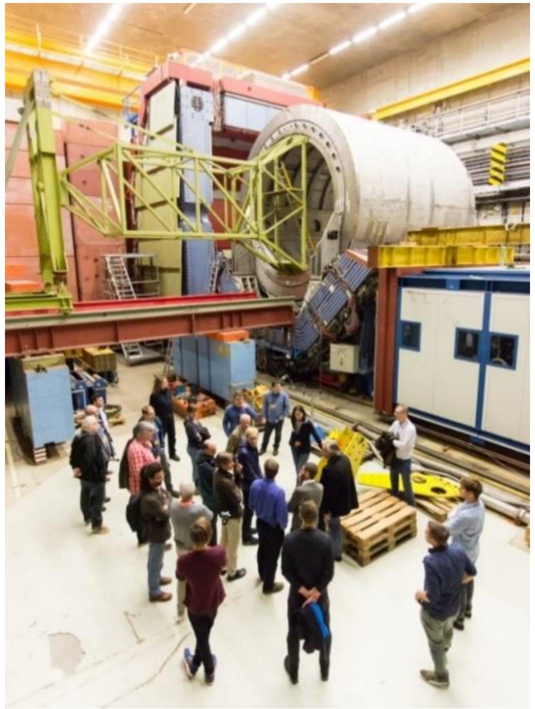
MADMAX: the final setup



MADMAX collaboration

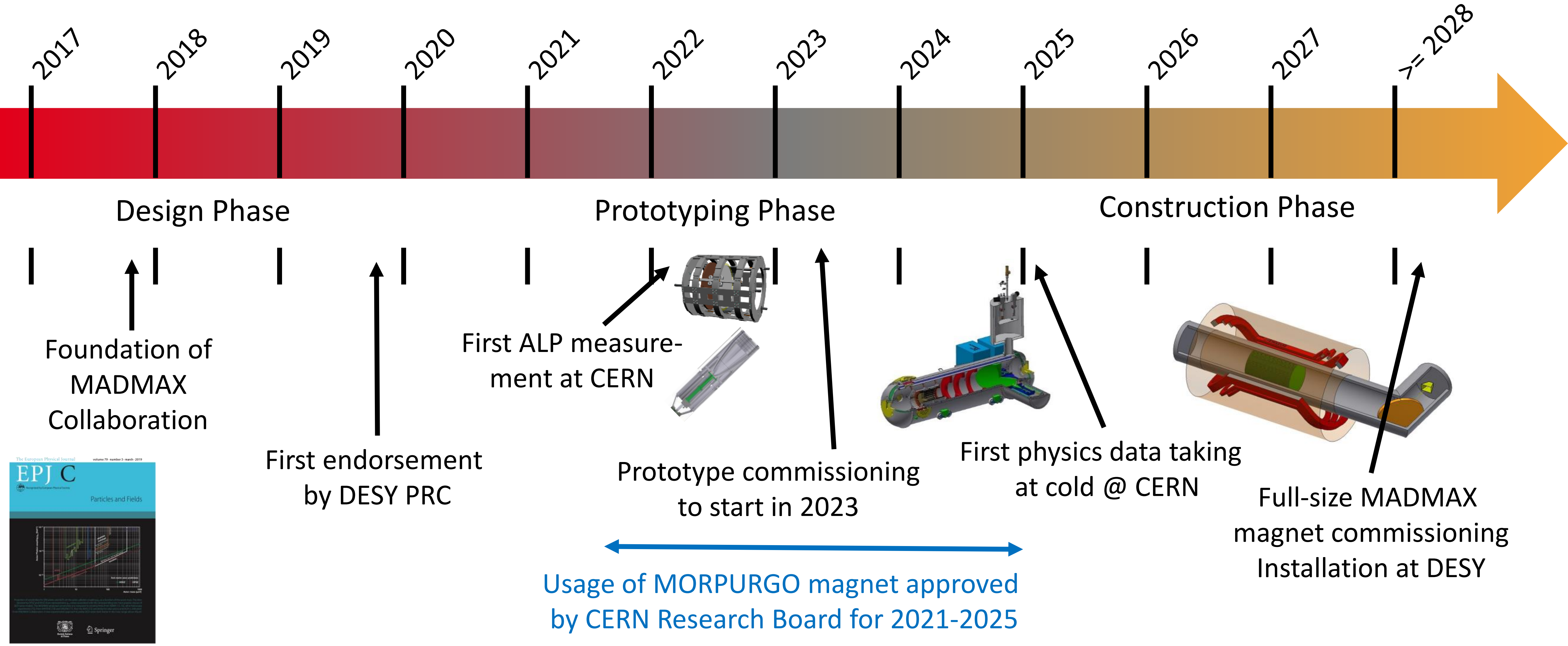
MAgnetized Disk and Mirror Axion eXperiment

Collaboration formed on 18th Oct. 2017



RWTH AACHEN UNIVERSITY · Max-Planck-Institut für Radioastronomie · NÉEL institut · DESY. · Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG · CPPM · MAX-PLANCK-INSTITUT FÜR PHYSIK · EBERHARD KARLS UNIVERSITÄT TÜBINGEN · Universidad Zaragoza

Timescale

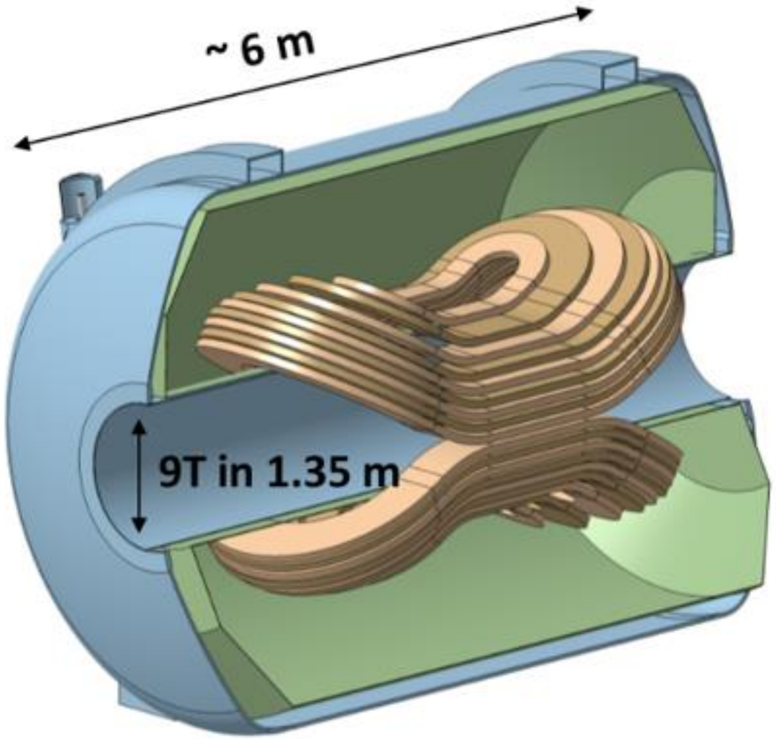

2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
>= 2028
Design Phase
Prototyping Phase
Construction Phase
Foundation of MADMAX Collaboration
First endorsement by DESY PRC
First ALP measure-ment at CERN
Prototype commissioning to start in 2023
First physics data taking at cold @ CERN
Full-size MADMAX magnet commissioning Installation at DESY
Usage of MORPURGO magnet approved by CERN Research Board for 2021-2025
EPJ C
Particles and Fields
Springer

MADMAX magnet

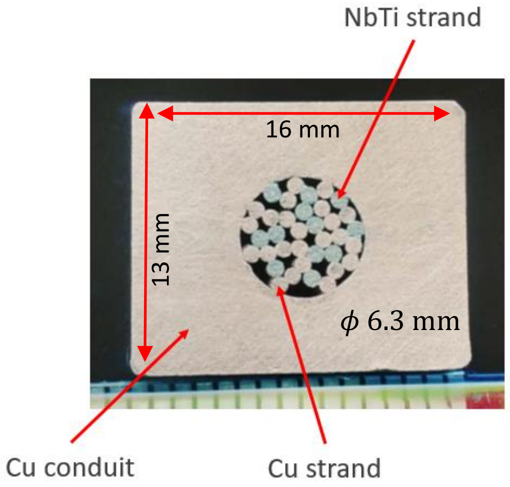
MADMAX Magnet

Magnet Design (work in progress) by CEA-Saclay & Bilfinger-Noell

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



New conductor:
CICC with Cu profile



R&D Risk mitigation→
Quench propagation velocity tests with new conductor using a dedicated solenoid magnet:
MAdmax **C**oil for **Q**uench **U**nderstanding (**MACQU**)

MADMAX Magnet

Magnet Design (work in progress) by CEA-Saclay & Bilfinger-Noell

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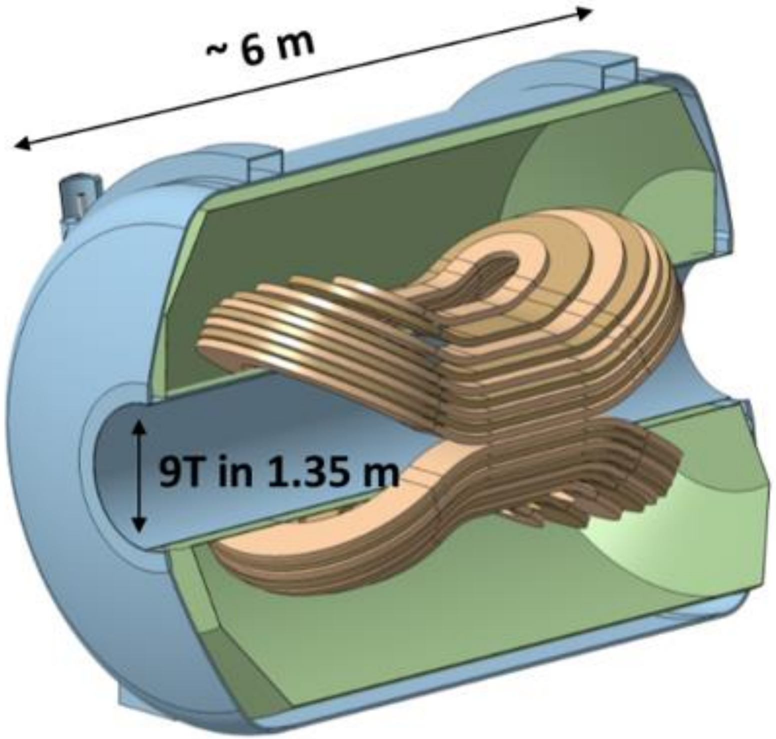

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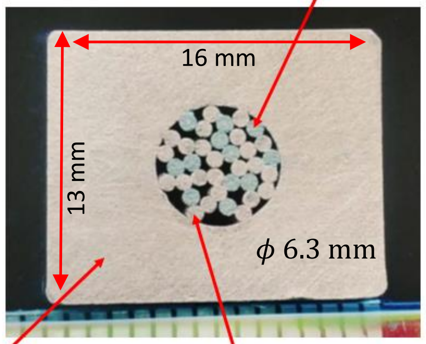
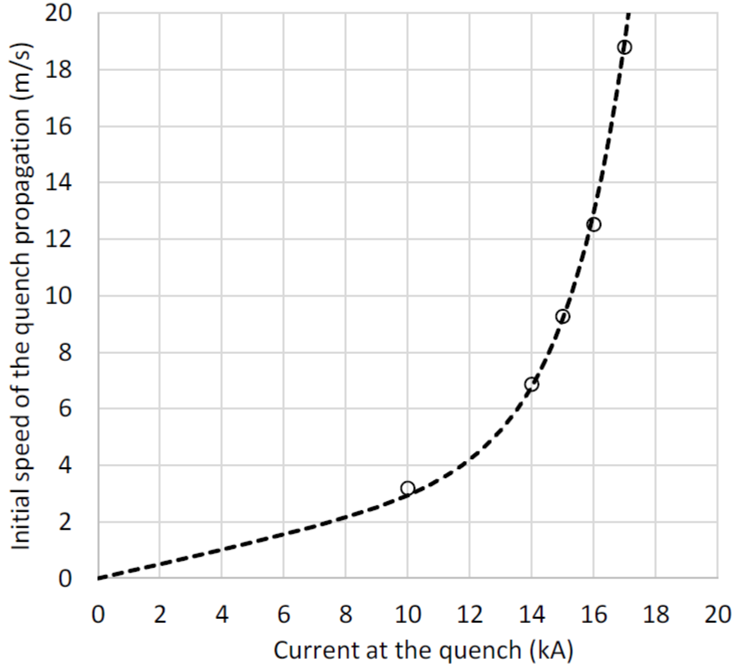


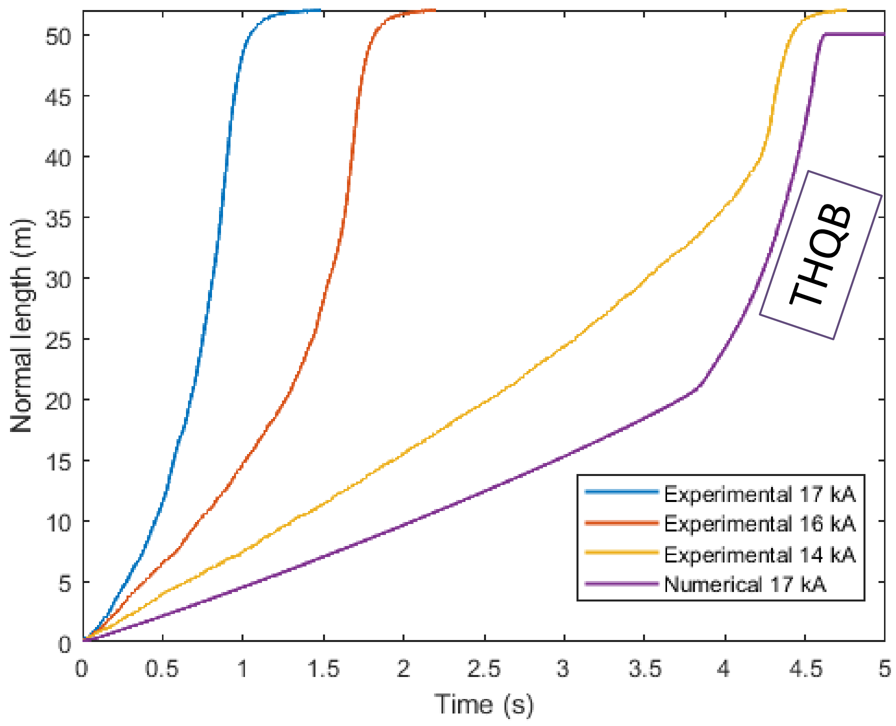
Quench propagation velocity tests with new conductor at CEA-Saclay, France

MACQU magnet

MADMAX Magnet

MACQU: Quench propagation velocity tests



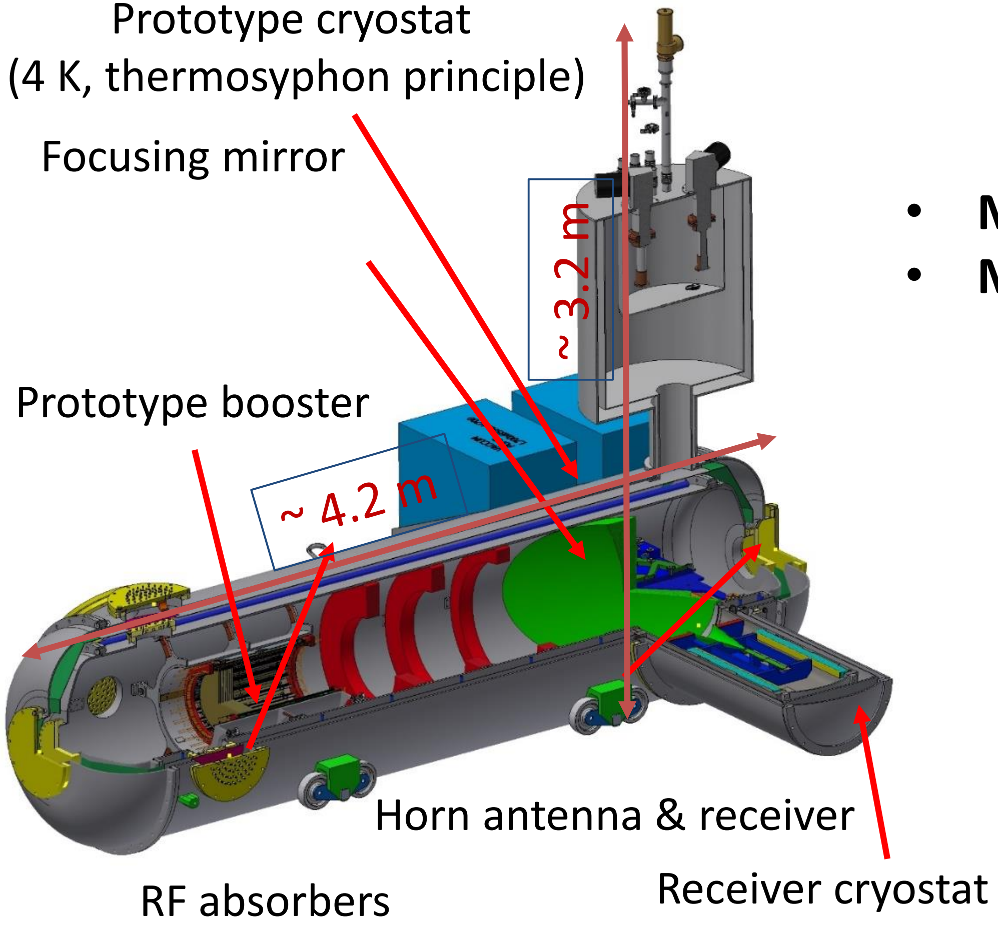


Quench propagation speed ~10 m/s ; detection < 1 s (within specifications - very successful results!)

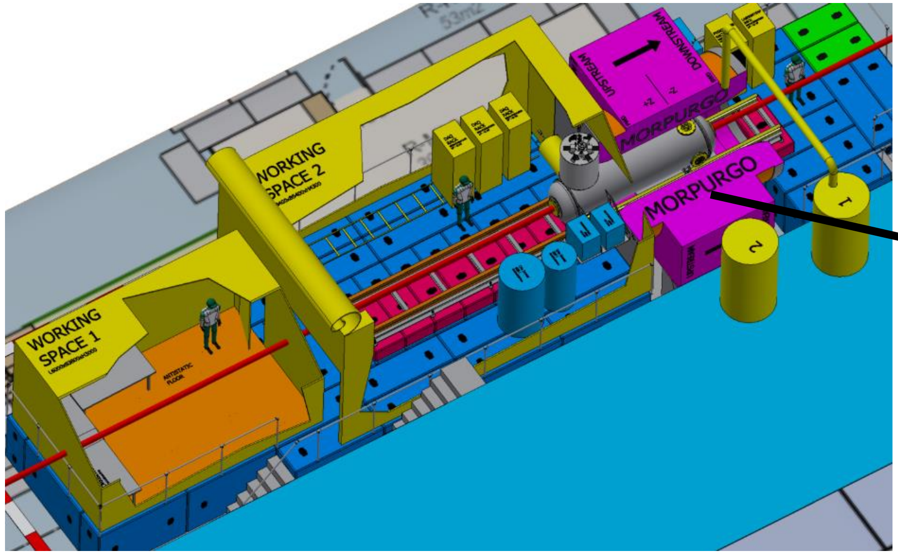
After normal quench initiation → second quench propagation acceleration → **Thermal Hydraulic Quenchback** phenomenon: pre-warming of the conductor by friction forces due to He flow

MADMAX prototyping phase

The MADMAX Prototype

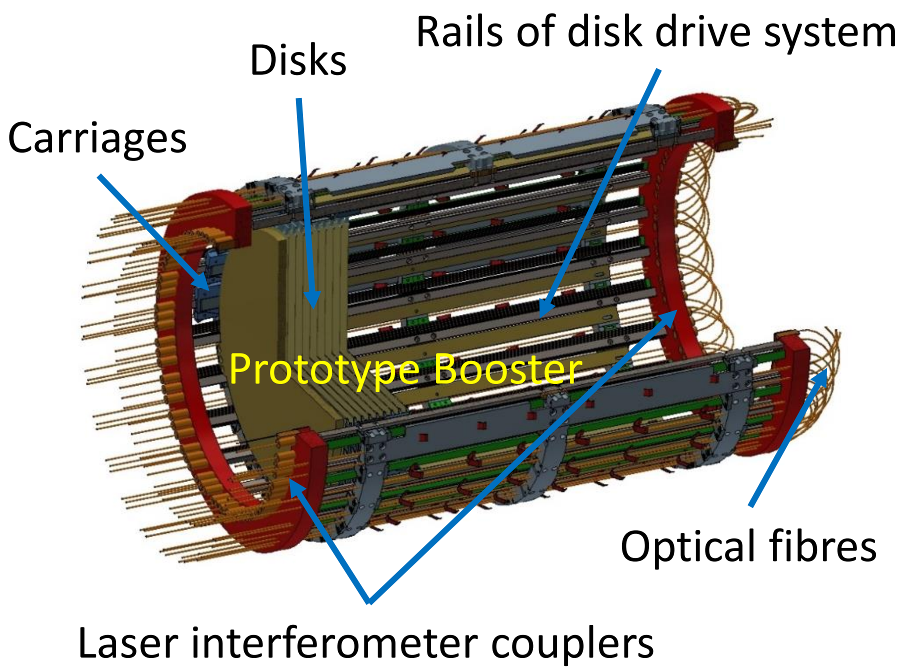


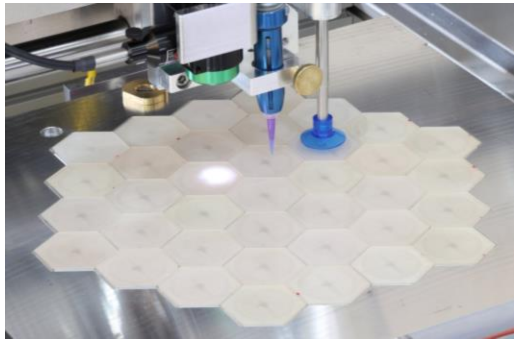
- Down-scaled version of MADMAX:
  - Reduced number of disks
  - 1/16 disk area
  - 1/5 magnetic field
- **Main goal #1**: Demonstrating and prototyping key technologies
- **Main goal #2**: Competitive ALP search with a dielectric haloscope

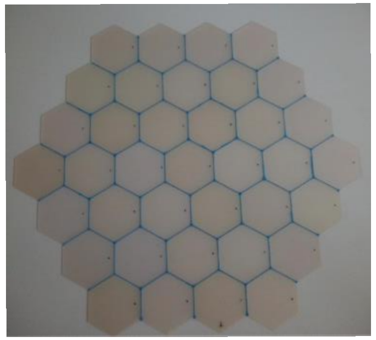


MORPURGO @ CERN

The booster







- Booster is the heart of MADMAX : a mirror and several adjustable dielectric discs

- Operating conditions:
  - Cryogenic temperatures: 4 K
  - High magnetic field: up to ~10 T
  - Vacuum or cold (He) exchange gas

- Disk weight: 600 g for Ø300 mm

➢ **Piezo-driven actuator system with feedback from laser interferometer with absolute precision**

- Candidate disk materials:
  - **$LaAlO_3$ ($\varepsilon \approx 24$, $\tan\delta \approx$ a few 10^{-5})**
  - Sapphire ($\varepsilon \approx 9$, $\tan\delta \approx 10^{-5}$)
- $LaAlO_3$ available as 3″ wafers at maximum

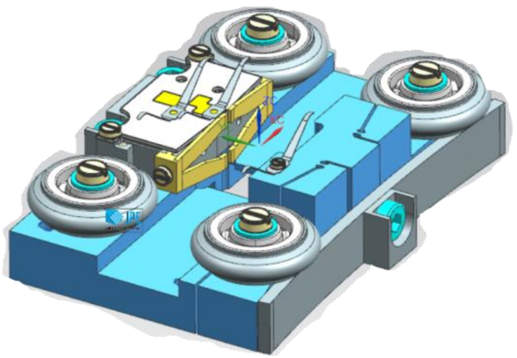
➢ **Tiling necessary → Semi-automatic gluing machine**

Piezoelectric motors

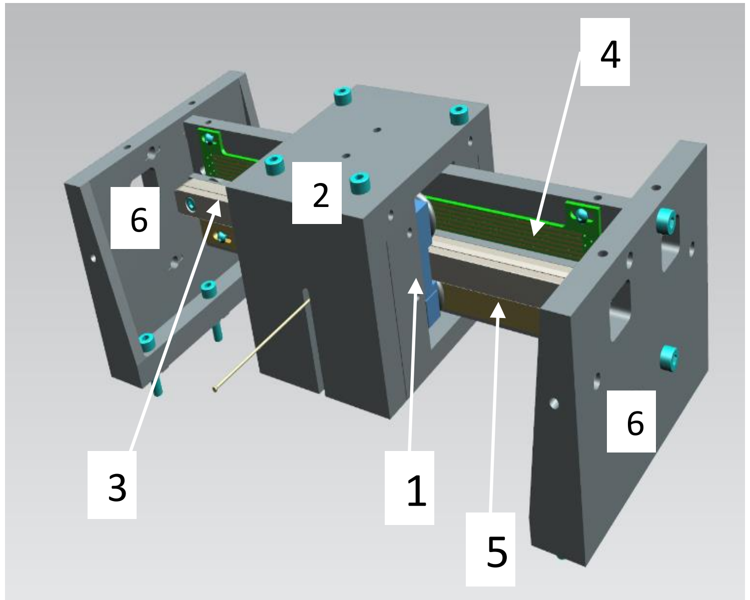
Piezo motors

Challenges:

- Operation at cryogenic temperatures and in B-field
- 240 motors to move and to position 80 disks
- Long travel range, lifetime
- Weight of the discs



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



Why Piezo Motors?

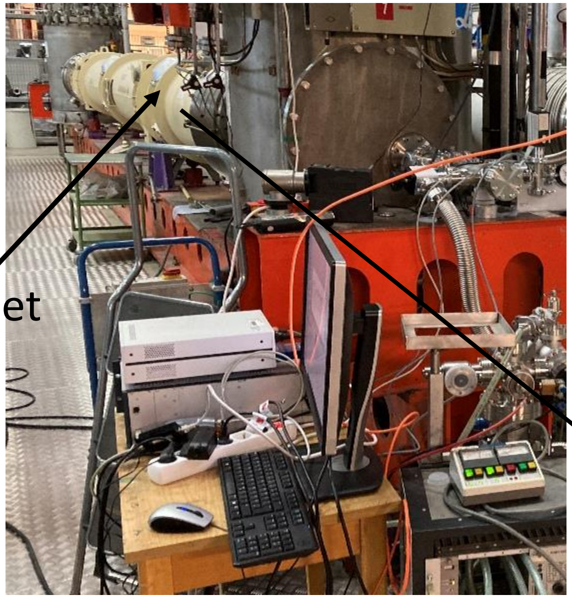
- Very precise (positioning accuracy ±10 μm)
- Self-locking
- Vacuum compatible
- Compact

Supplied by JPE Driven by Innovation : https://www.jpe-innovations.com/

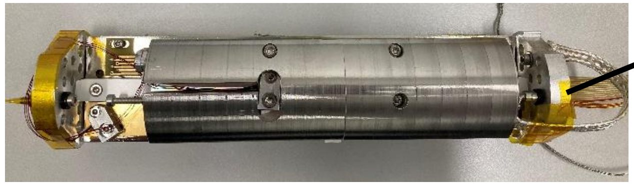
Piezo motor tests

First tests → no laser interferometer
Use end switches → measure time
→calculate motor speed

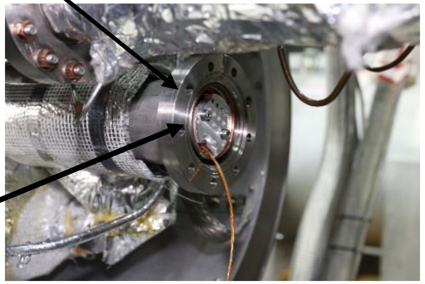
magnet



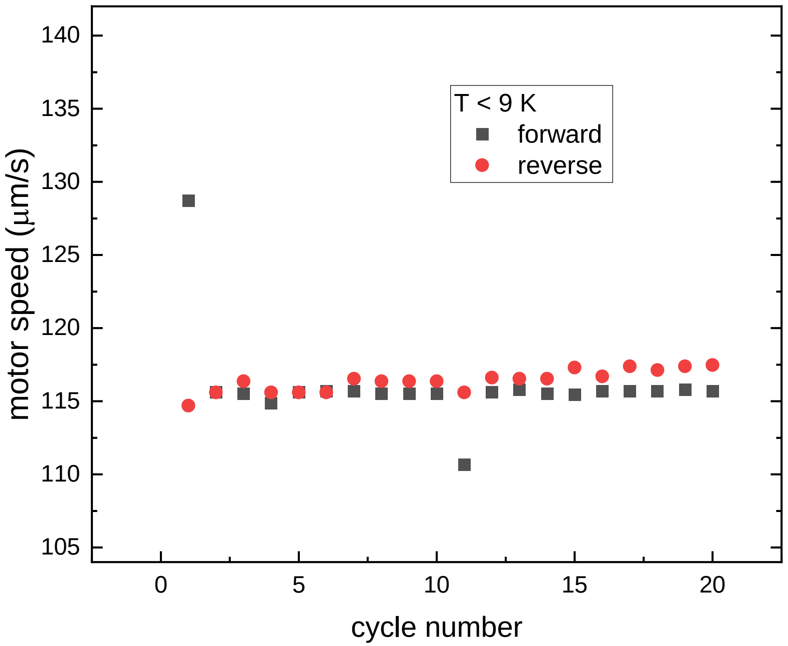
ALPS II test magnet



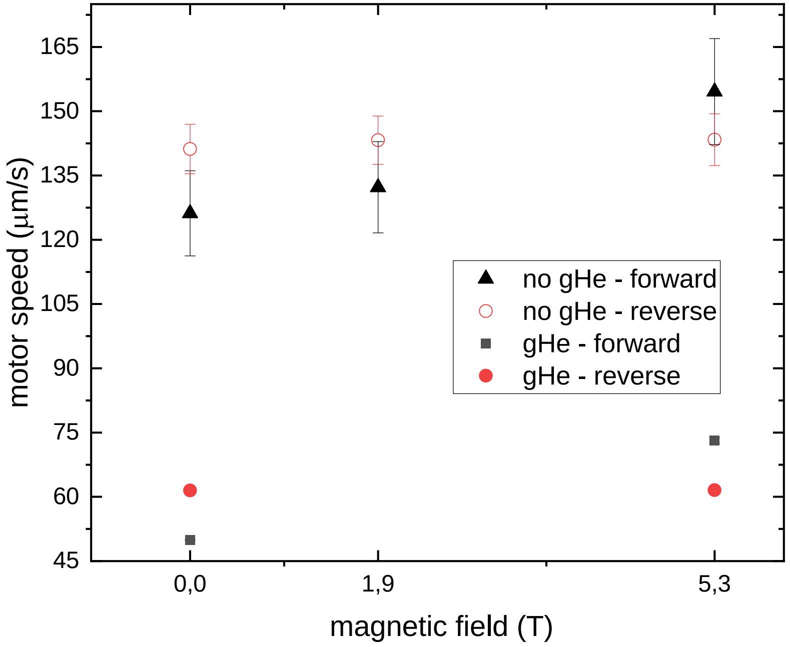
Piezo motor setup



Tests at 4 K – no B-field



Tests in the magnet

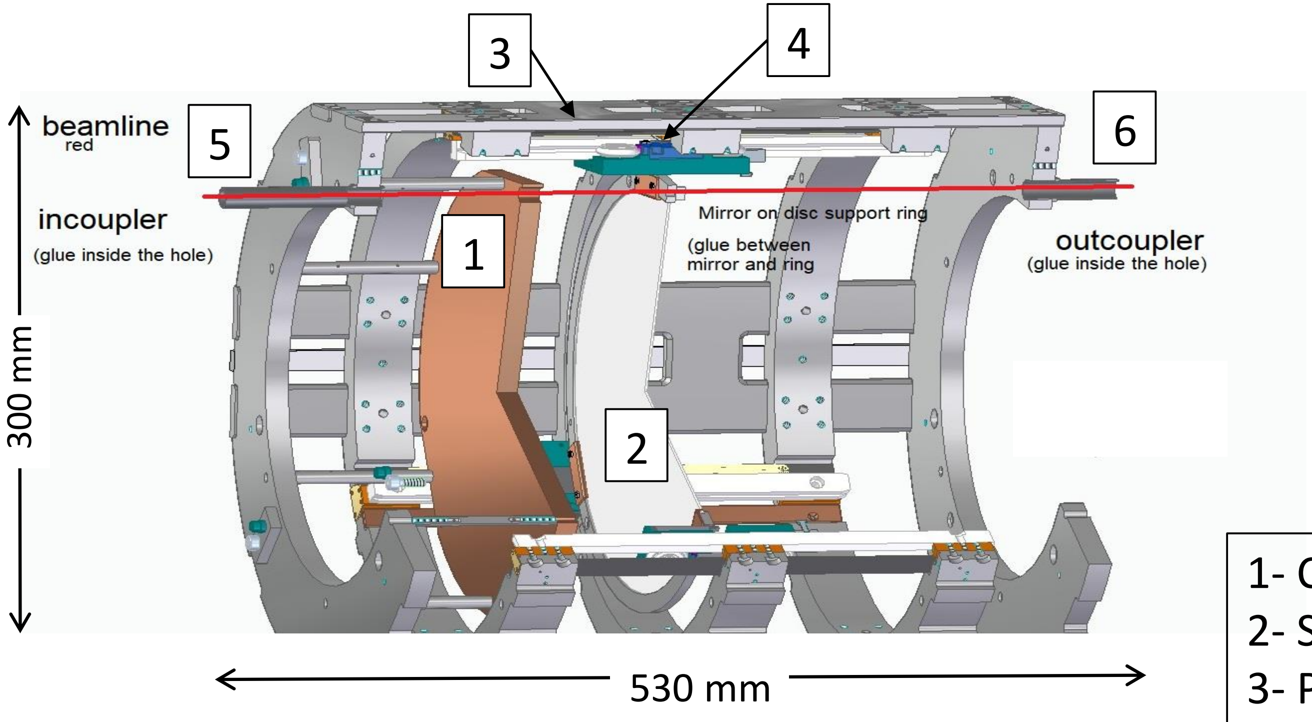


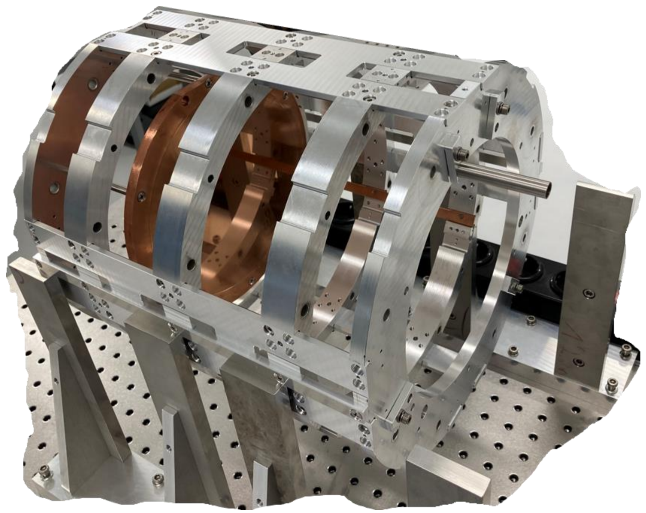
- Small hysteresis forward/reverse direction
- Tests in vacuum (no field) within specs v > 100 µm/s
- Tests at 1.9 T and 5.3 T in vacuum (28 K)
- Use of gHe to improve cooling of setup (to 5 K)

Mechanics Prototype: P200

Mechanics Prototype: Project 200

Goals: verifiy feasibility of 3 **piezo motors** moving one disk along a 200 mm rail at **cryogenic** temperatures in a vacuum volume. Study the **temperature** distribution along the hardware. First tests with laser interferometer.

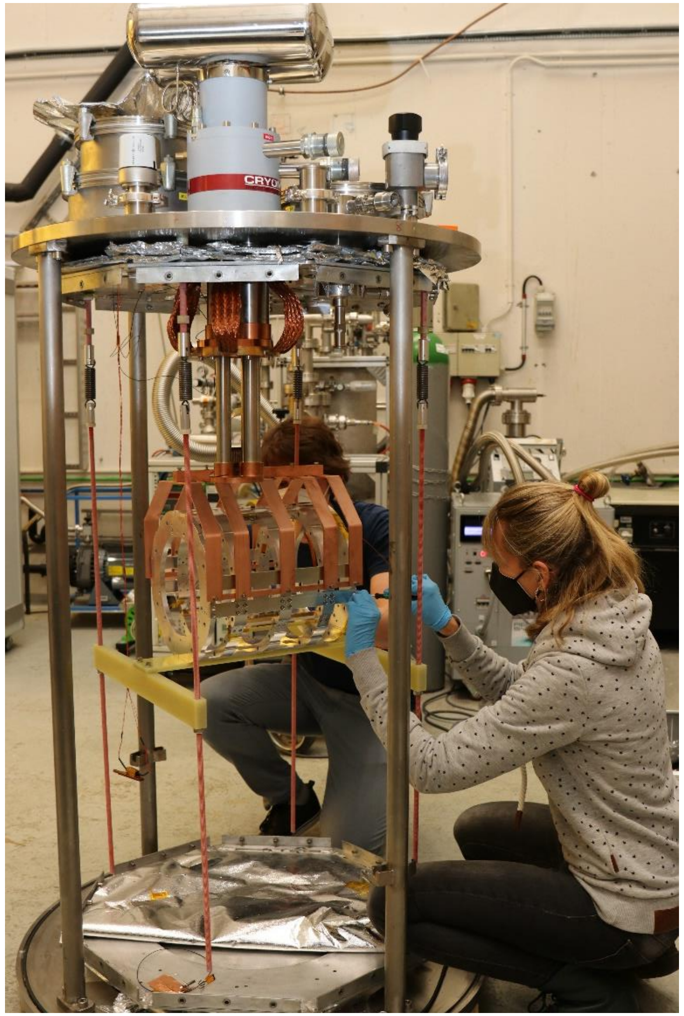




1- Cu mirror (fix position)
2- Sapphire disk (adjustable position)
3- P200 backbone structure
4- (3x)piezo motors
5- interferometer incoupler
6- interferometer outcoupler

Project 200 at CERN

P200 mounted inside cryostat

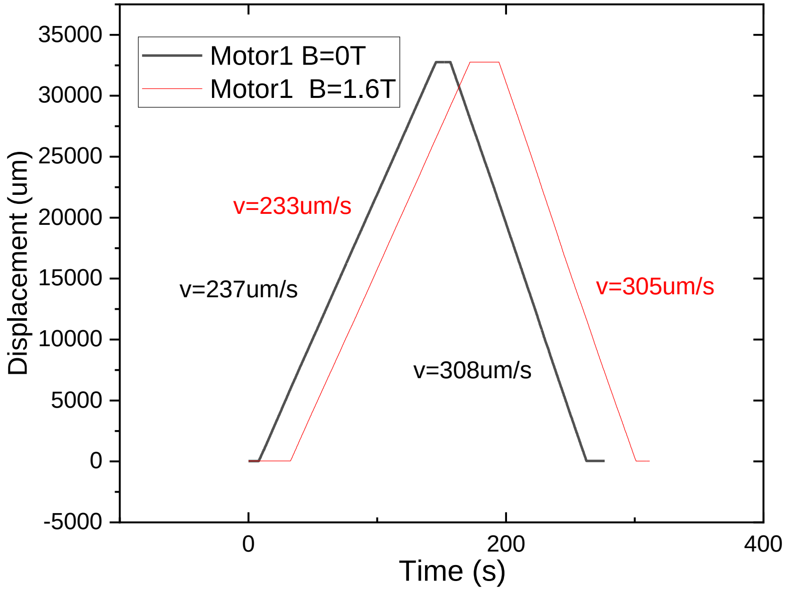


Experimental run at CERN in Spring 2022

- Cryo tests in the Cryolab
- B field test using Morpurgo magnet (1.6 T)

Successful stories:

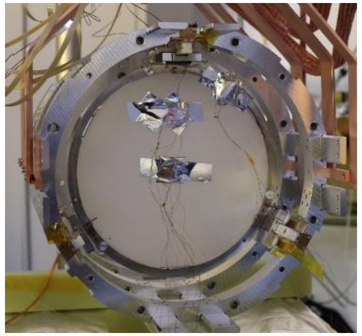
- 3 motors moved at cryo T and in B field
- Synchronised movement of the motors to move a disc
- Laser interferometer (Attocube) tested



No difference in disc velocity with/without B field

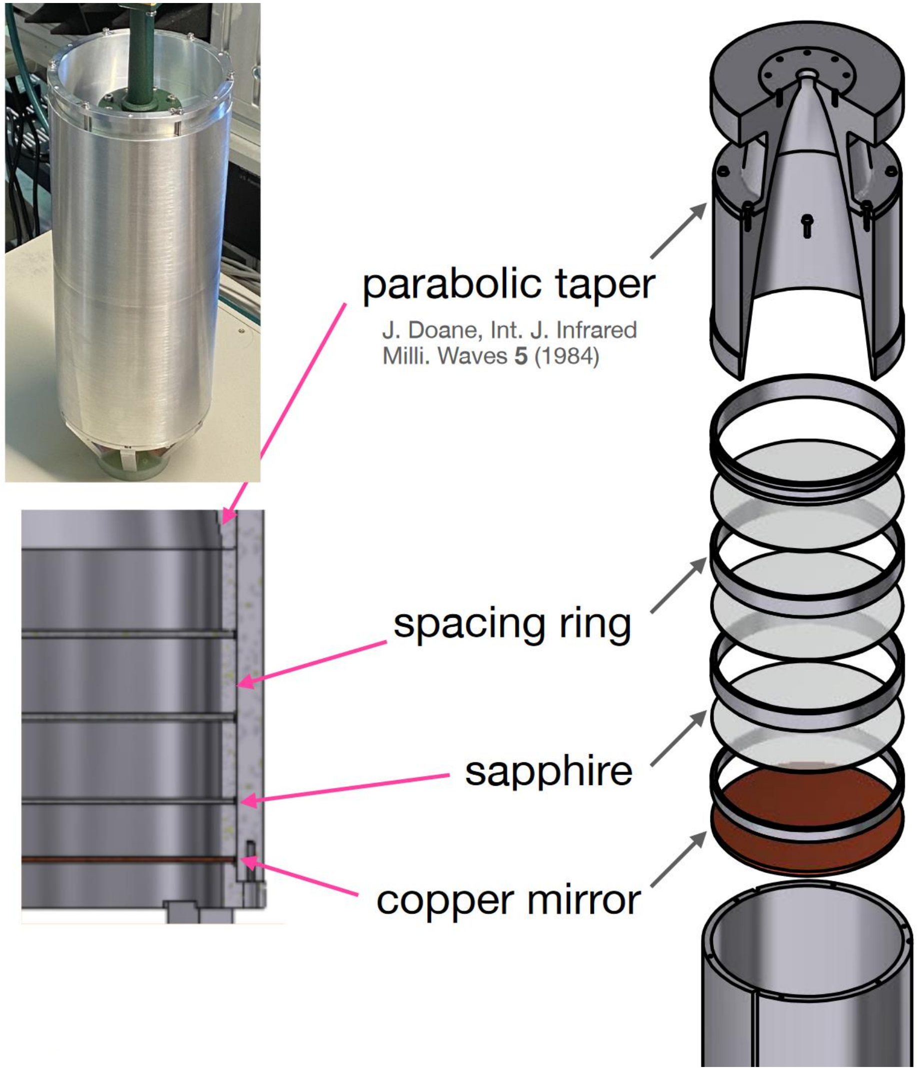
P200 in Morpurgo magnet

Sapphire disc inside P200



Physics Prototype: CB100

Closed Booster (CB100)



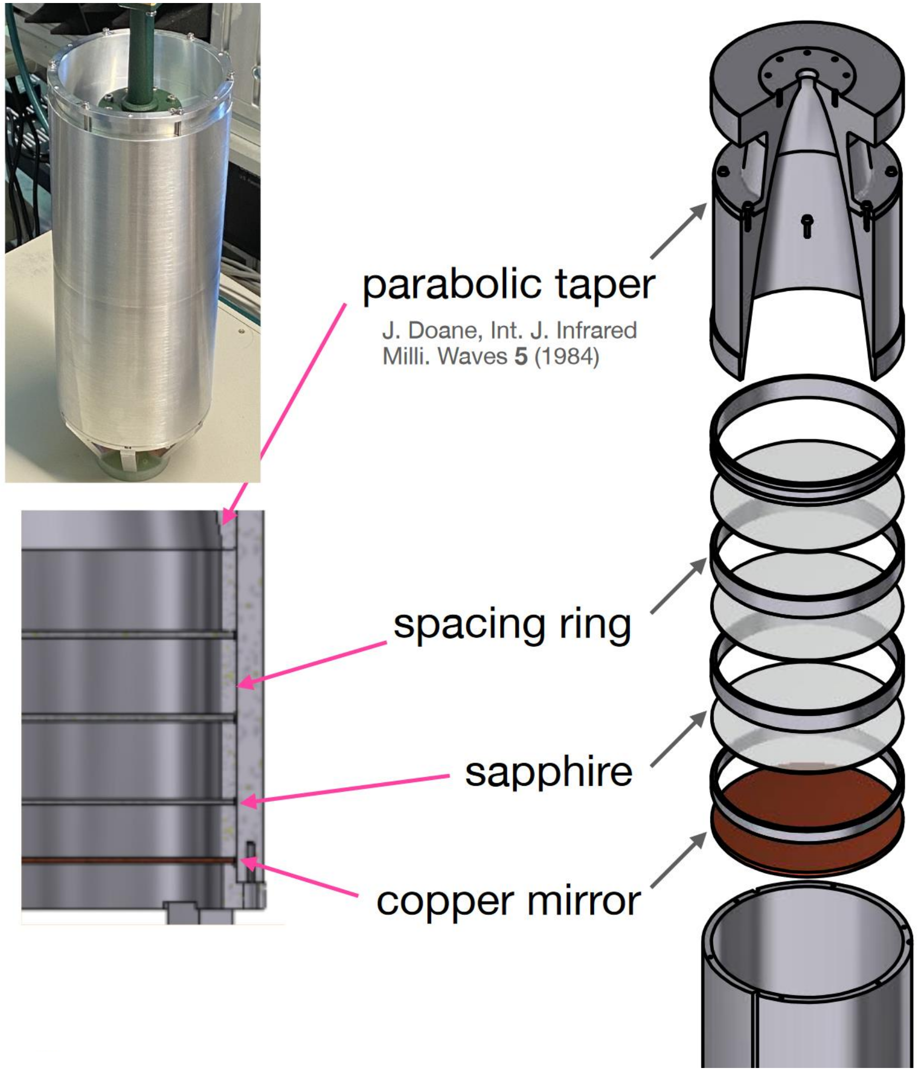
Properties:

- 100mm inner diameter
- 3 sapphire disks in resonant configuration (Boost β^2~2000)
- Receiver coupling via taper
- Designed for magnetic field and 4 K operation

Goals:

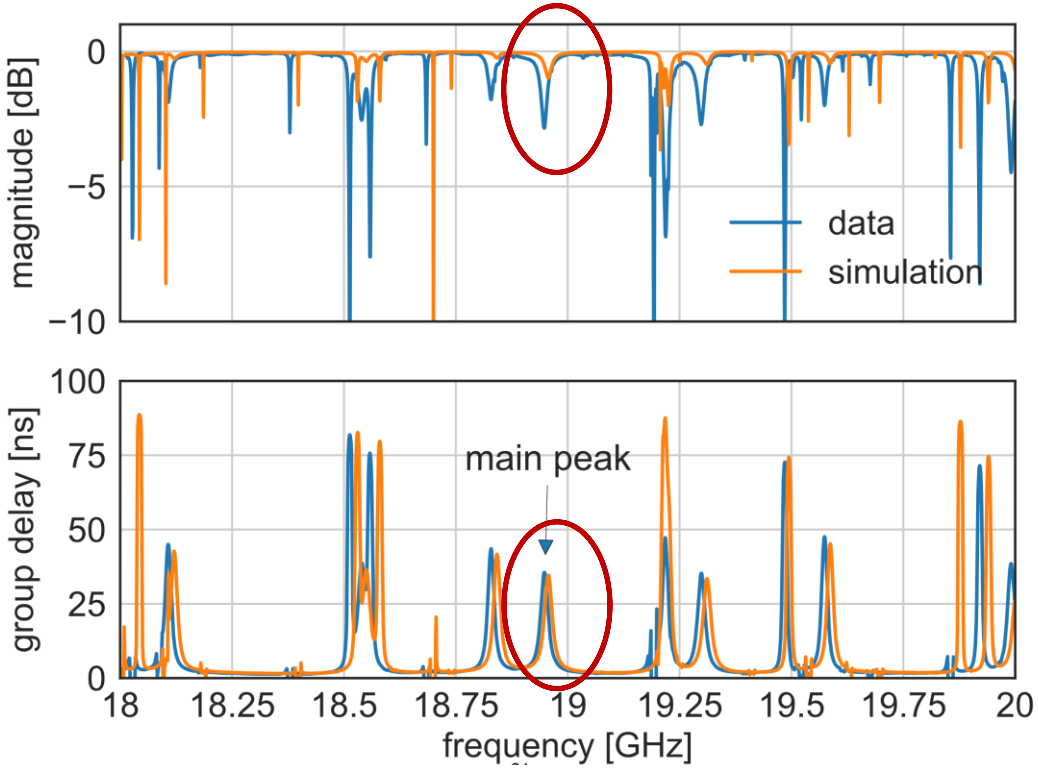
- Verification of concept
- Closed system to reduce radiation losses (conducting boundary) → understand other loss mechanisms
- First ALPs measurement at 4 K and in a B-field

Closed Booster (CB100)



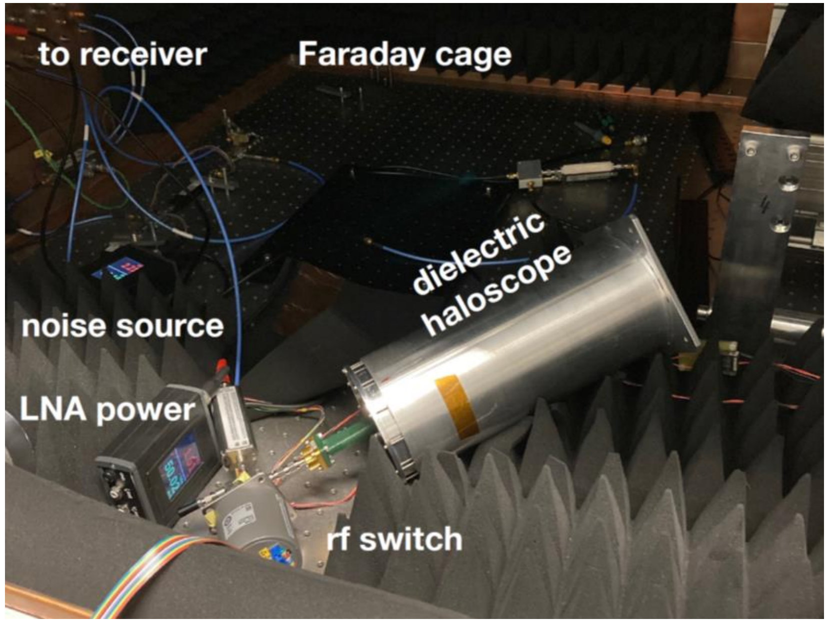
Results from room temperature measurement:

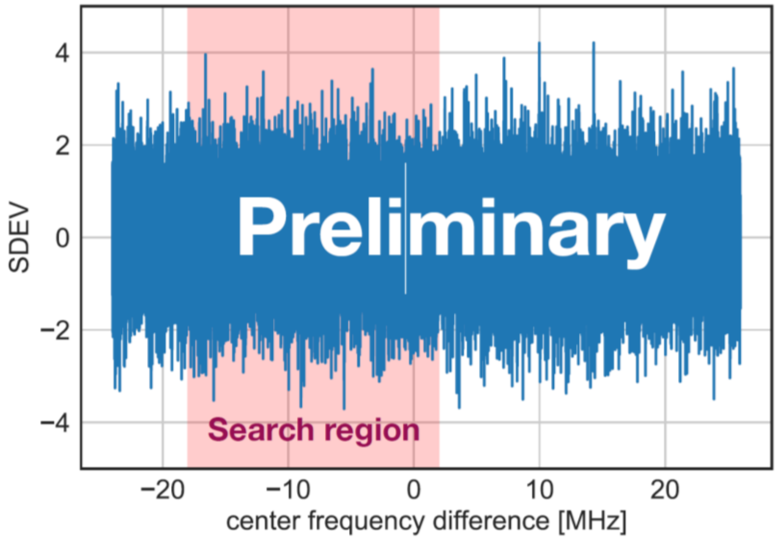
- Measurements agree with simulation (considering the mechanical uncertainties)
- Boost peak loss is slightly higher because of remaining transverse radiation (current) at sapphire disks rim

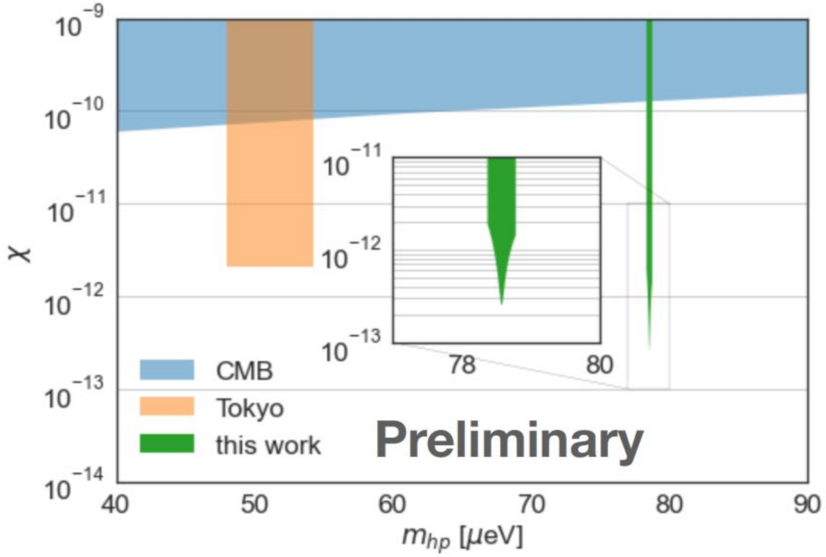


Hidden photon search

- Hidden Photon search performed at room temperature
- Hidden Photon to microwave conversion without B-field
- 32 days of data taking
- Noise temperature of ~200 K
- No excess observed in the data

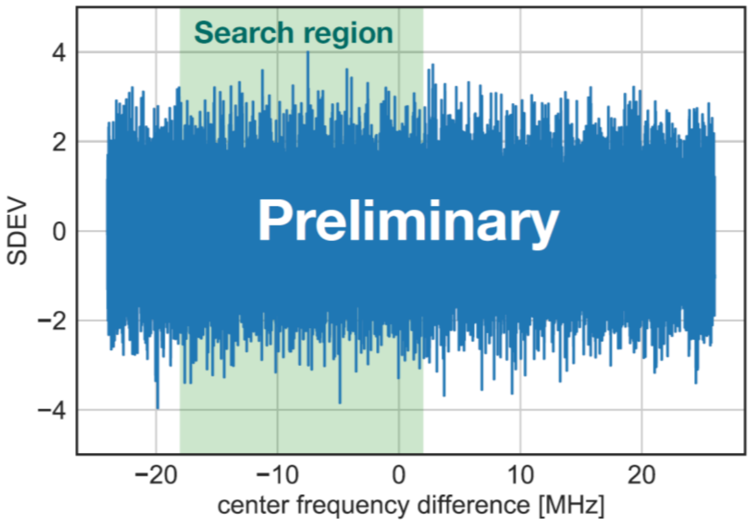


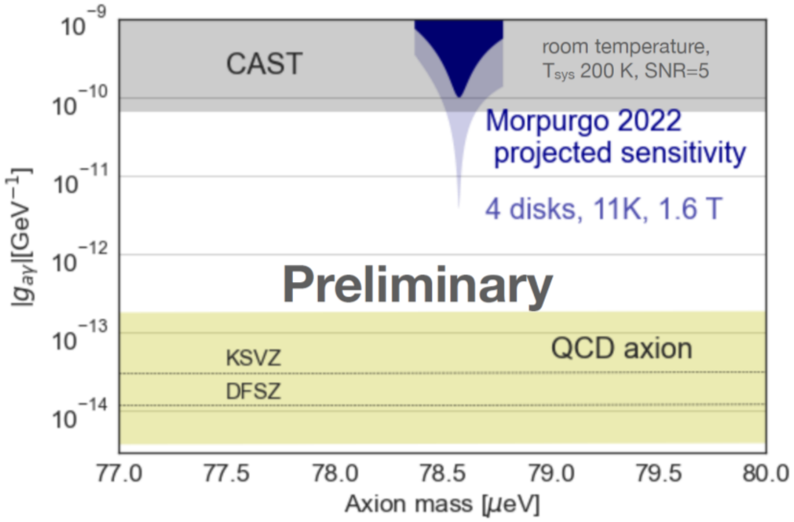


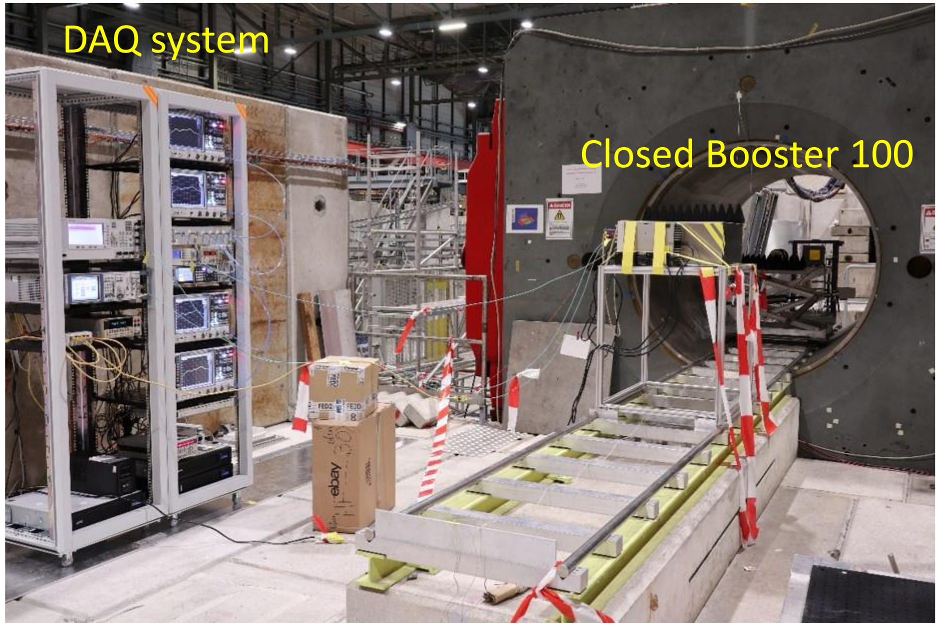


Axion Like Particle Search with CB100

- 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
- Possibilities for an upgrade allowing to cool the setup to < 10 K in Morpurgo currently under investigation







MADMAX

MAgnetized Disk and Mirror Axion eXperiment

Summary and Outlook:

- Magnet
  - New conductor succesfully tested
  - Quench propagation velocity within specs
  - Next: further R&D conductor
  - Design of a magnet demonstrator
- Mechanics feasibility
  - Motors successfully tested at 4.2 K , in a 5.3 T field and in a He gas environment
  - Sapphire disc moved at cryo T and in B-field
- Closed Booster
  - CB100: Simulation and data agree
  - First ALPS search at CERN
  - Next: Simple cryostat for CB100 @ Morpurgo
- Outlook:
  - CB200 being tested (200 mm discs)
  - Prototype (open) booster in design

Thank you for your attention!