Direct detection of Axion dark matter with MADMAX

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DMLab 3rd annual meeting 2023
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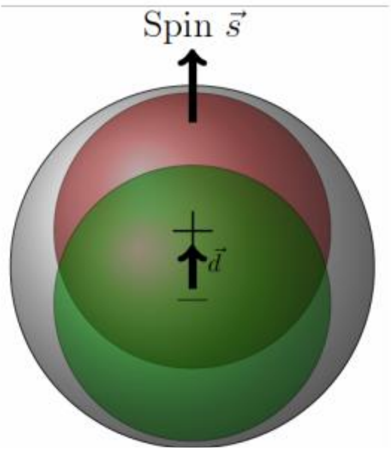
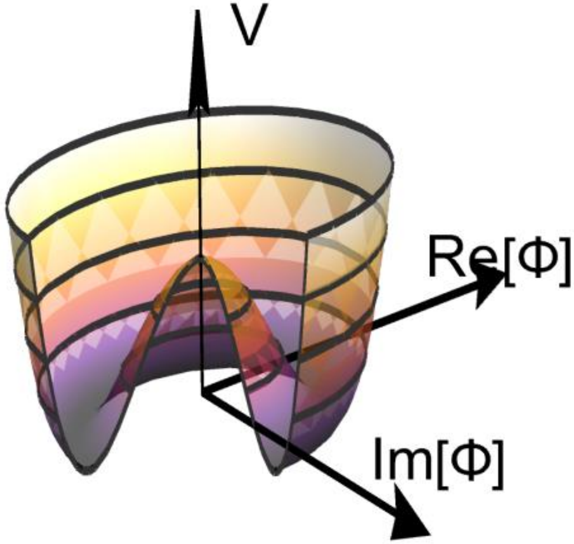
Strong CP Problem

- CP violation in strong sector
  - QCD Lagrangian has a CP violating term that is controlled by θ parameter ($-\pi < \theta < \pi$)
  - This term leads to a neutron electric dipole moment

$$d_n = (2.4 \pm 1.0)\,\theta \times 10^{-3}\,\mathrm{e\,fm}$$

  - Current experiments give upper bound of $|d_n| < 1.8 \times 10^{-13}\,\mathrm{e\,fm}$ leading to $|\theta| < 0.8 \times 10^{-10}$
- Strong CP problem = fine tuning problem: Why is a free parameter θ so small?
- Solution: Peccei – Quinn mechanism provides a dynamic reason for the small value of θ by introducing a new U(1) symmetry that is spontaneously broken at a high energy scale f_a ; generating a new-light neutral pseudo scalar boson that is called **'Axion'**





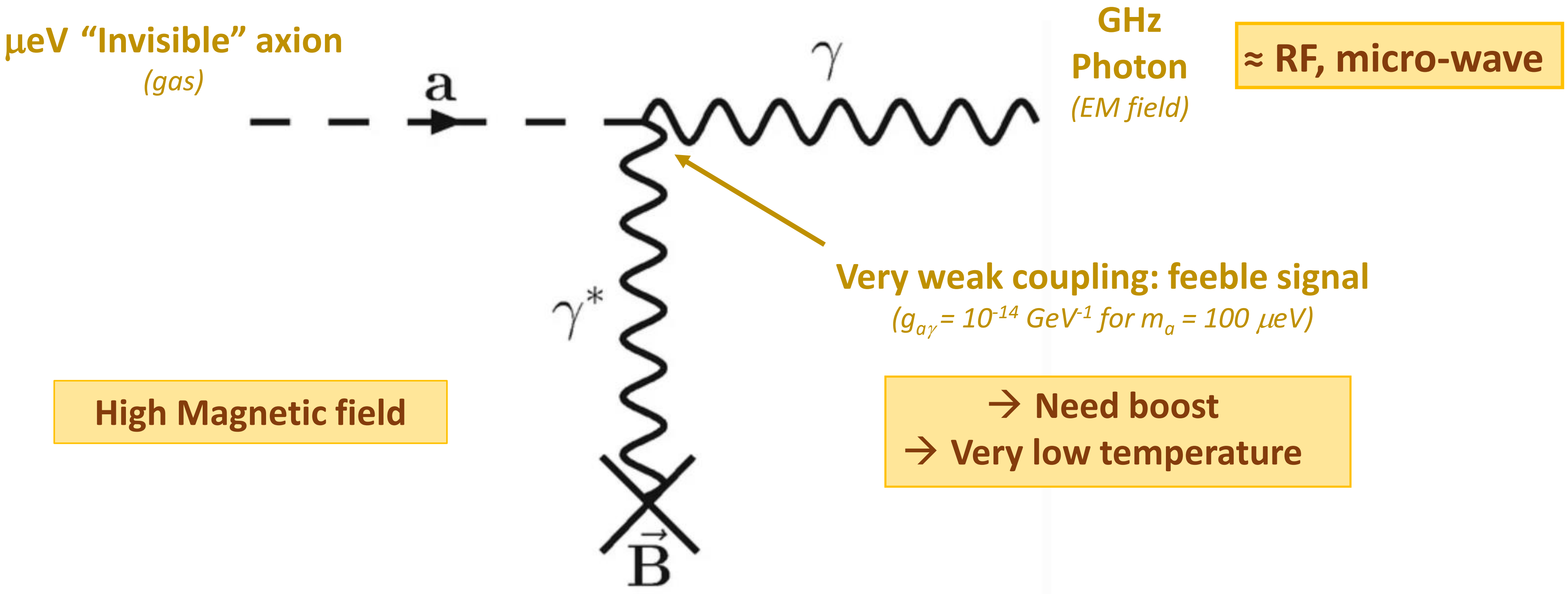
Axion properties

- All properties of axions controlled by just one parameter: f_a
  - Models with $f_a \sim f_{EW}$ excluded a long time ago, new models (KSVZ and DFSZ) have f_a ($O(10^{10})$ GeV) >> f_{EW}
  - Tiny mass [$\mathbf{m_a} \approx m_p f_p / \mathbf{f_a}$ << eV],
  - Very weakly interacting [suppressed by $f_{\mathbf{a}}$]
  - $\tau_{axion} > t_{Universe}$
- Axion like particles (ALPS) = $m_a \times f_a$ not constant

QCD Axion = DM candidate motivated by particle physics since 40 years

How to see the axion ?

- Convert it to a photon in magnetic field (inverse primakoff effect)
    - Several experimental constraints



Axion search very rich in experimental challenges

Axion/ALP direct searches

Lab experiments	Helioscopes	**Haloscopes**
Lab produced fully controlled setup	Solar axions	Relic DM axions
Low axion flux	Medium axion flux	High axion flux
Model independent	Mildly model dependent	Model dependent
ALP	QCD axion / ALP	QCD axion DM [1-1000 μeV]
e.g. ALPS II	**e.g. (Baby)IAXO**	**e.g. MADMAX**

Axion mass range

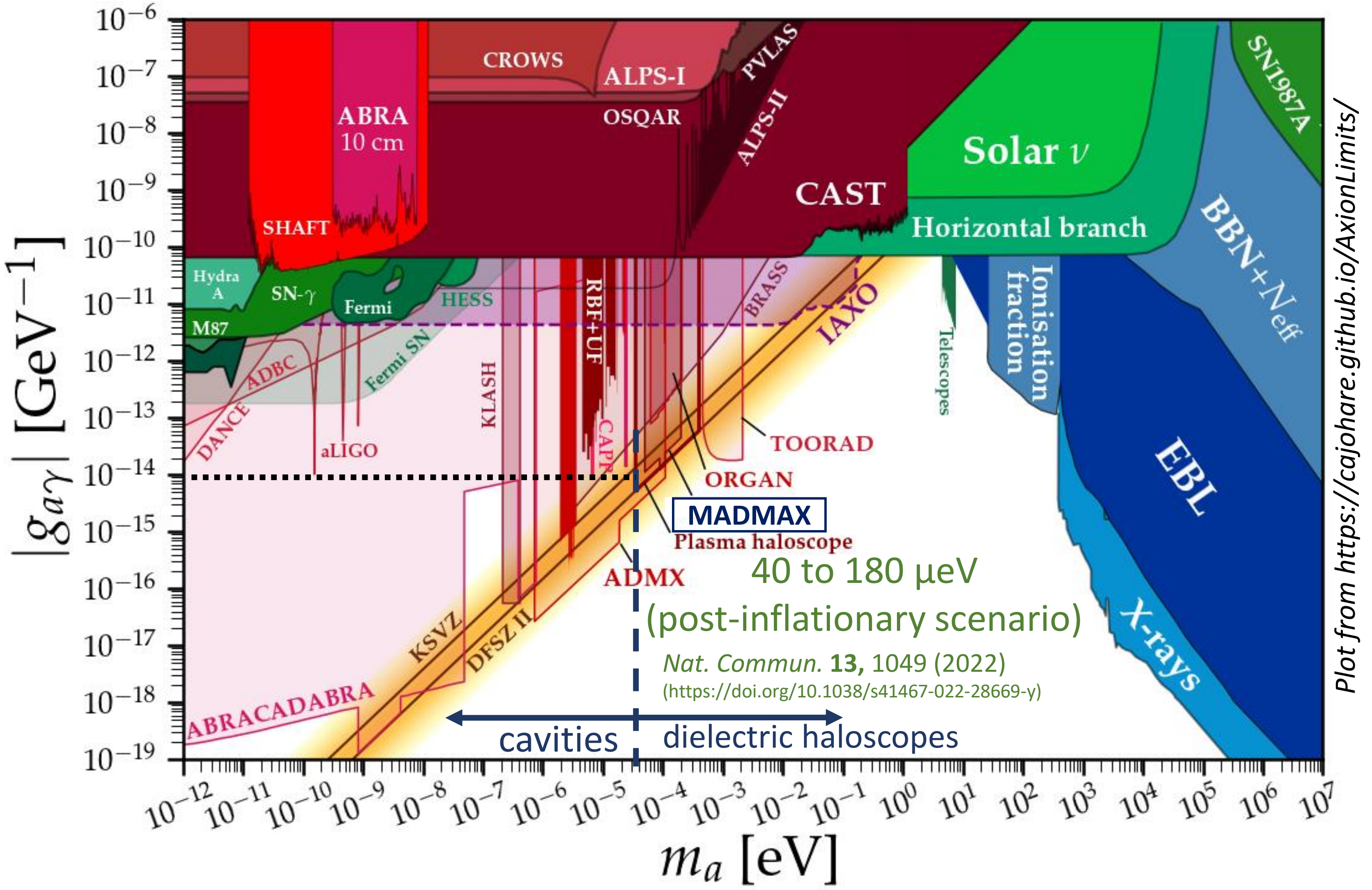
MADMAX goals:

- Probe the QCD axion mass:

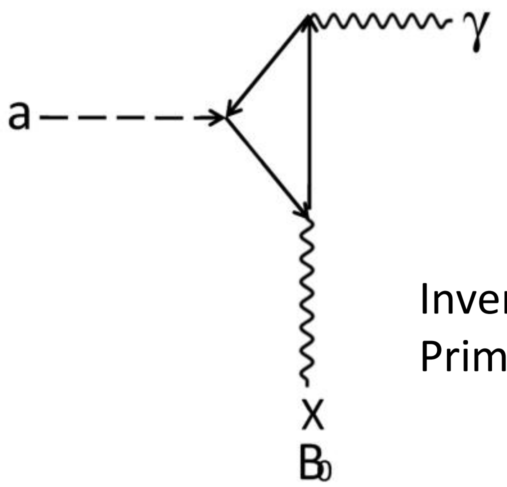
  40-180 μeV
- Tunable in frequency coverage:

  10-45 GHz

- Traditional cavity experiments have many limitations to operate above 40 μeV, therefore new technologies are required to probe this range



Dielectric haloscope: principles



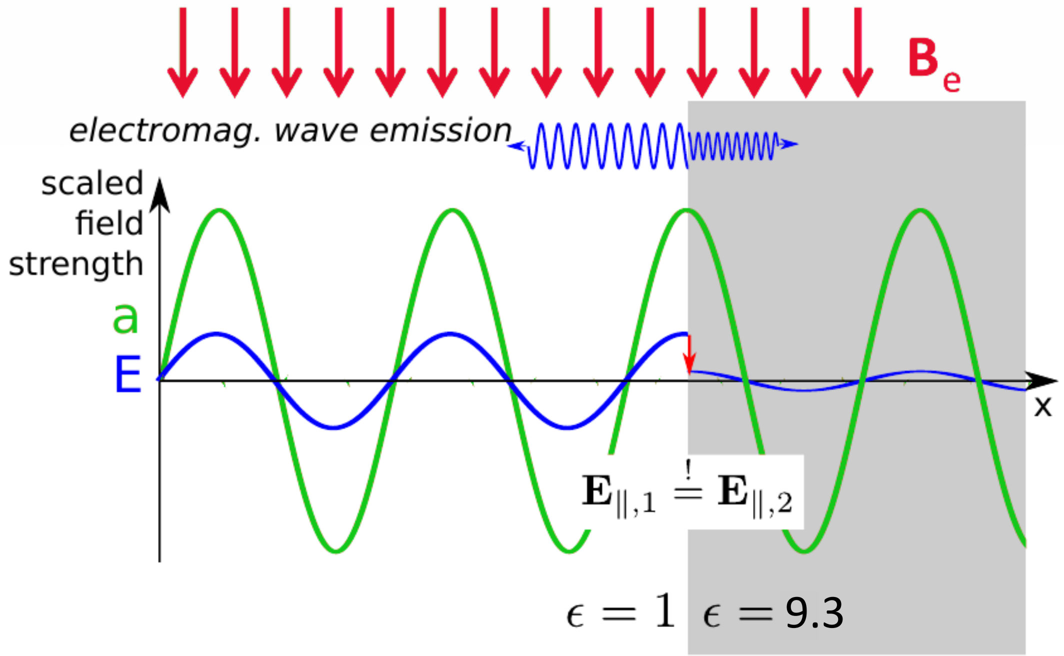
Inverse Primakoff effect

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, $E_\parallel$ must be continuous
→ **Emission of electromagnetic waves**



Dielectric haloscope: principles

- **Constructive interference** (and resonance) of coherent photon emission at dielectric layers surface (leaky resonators cavities)

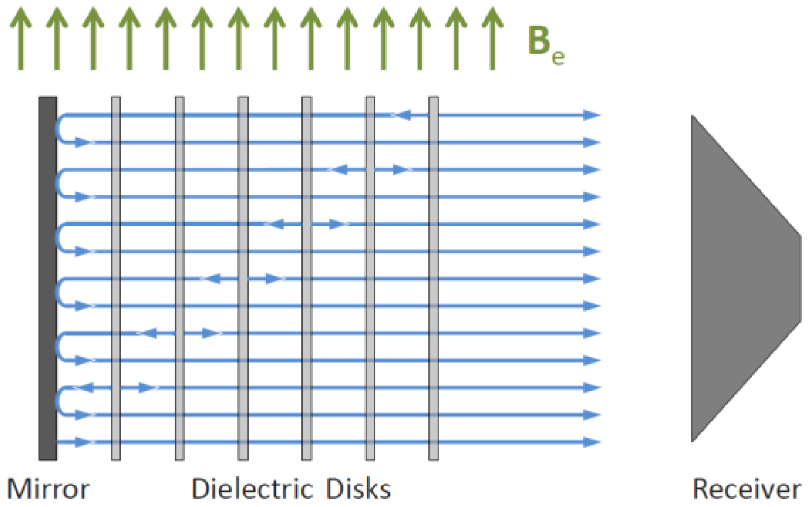
$C_{a\gamma} = 5\ \text{GeV}\ |g_{a\gamma}|\ /\ (m_a\ /\ 1\ \text{GeV})$

$$P_{sig} = 10^{-22}\ \text{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \text{T}}\right)^2 \times \left(\frac{A}{1\ \text{m}^2}\right) \times C_{a\gamma}^2$$

$$P_{sig} = 10^{-22}\text{W} \times \left(\frac{SNR}{5}\right) \times \left(\frac{T_{sys}}{4\ \text{K}}\right) \times \left(\frac{4\ \text{days}}{t}\right)^{1/2}$$

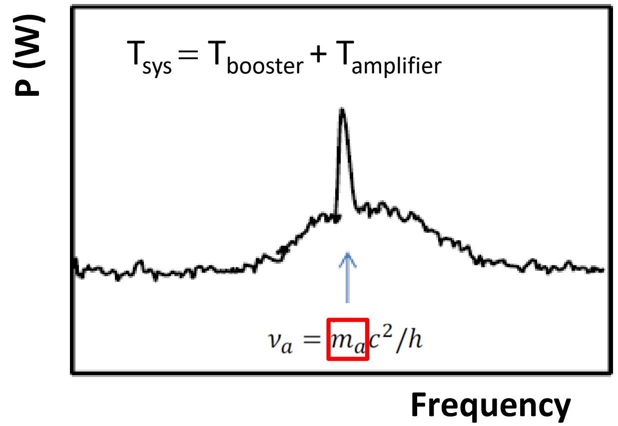
Power boost factor:

$$\beta^2 = \frac{P_{\text{total}}}{P_{\text{mirror}}}$$



Booster

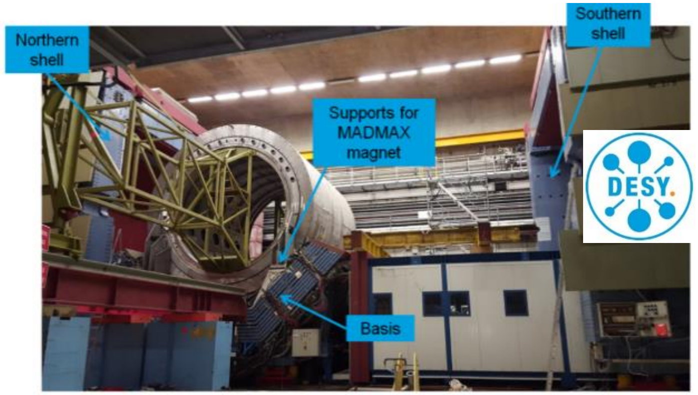
Thermal Noise



- **Axion mass scan** : by positioning discs with µm precision at 4K under 10 T *(50 MHz step)*

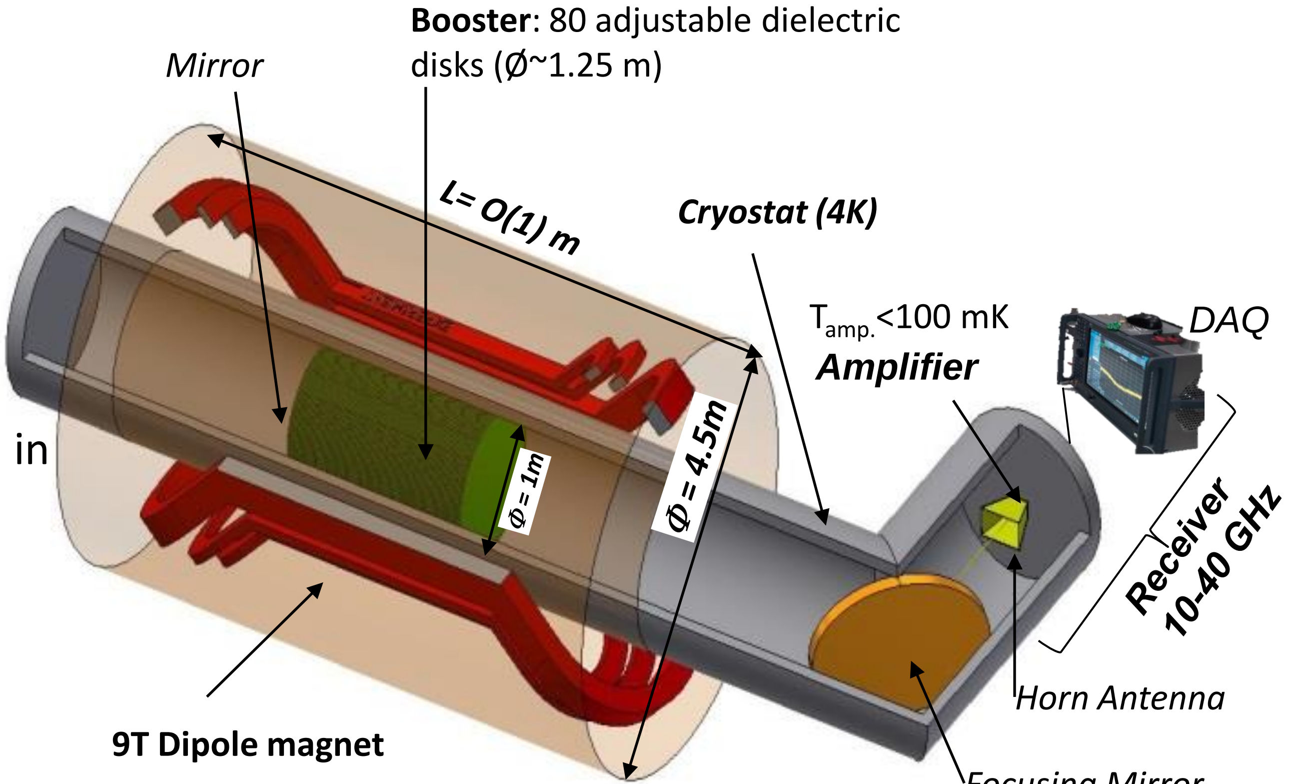
The MADMAX collaboration

- Formed in 2017. 10 institutes: French (2), German (6), Spanish (1) and US (1) → ~50 people



Experiment location: HERA H1 iron yoke in DESY, Hamburg

To be constructed in 2028

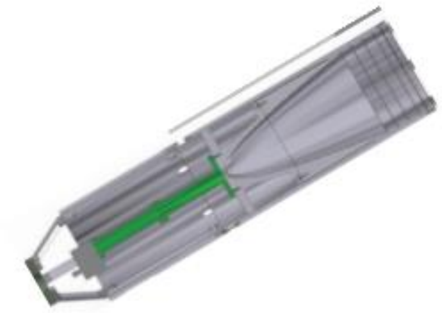


[Eur. Phys. J. C **79** (2019) 186]

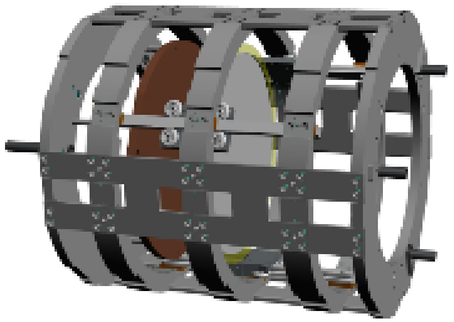
Experimental Challenges :
- High B-field
- Low Temp. (4 K)
- O(10) GHz regime
- µm precision for mechanics

MADMAX prototypes

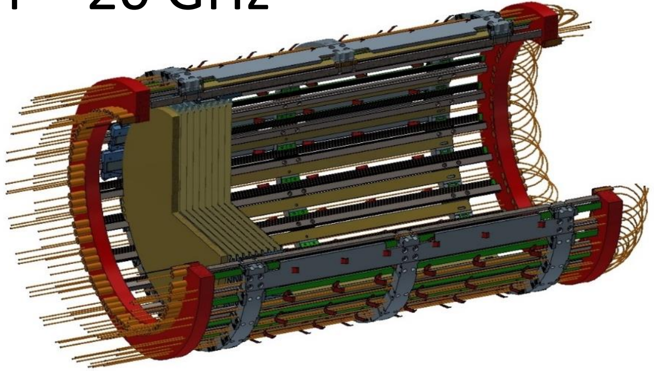
- Validate the new concept of dielectric haloscope using several prototypes
  - Construct the prototypes using sapphire (ε = 9.36) dielectric disks
  - Test the prototypes at CERN using 1.6 T Morpurgo dipole magnet during beam shutdown period
- Prototypes to probe the region:: m_a ~ 80 μeV, f ~ 20 GHz



CB100



P200



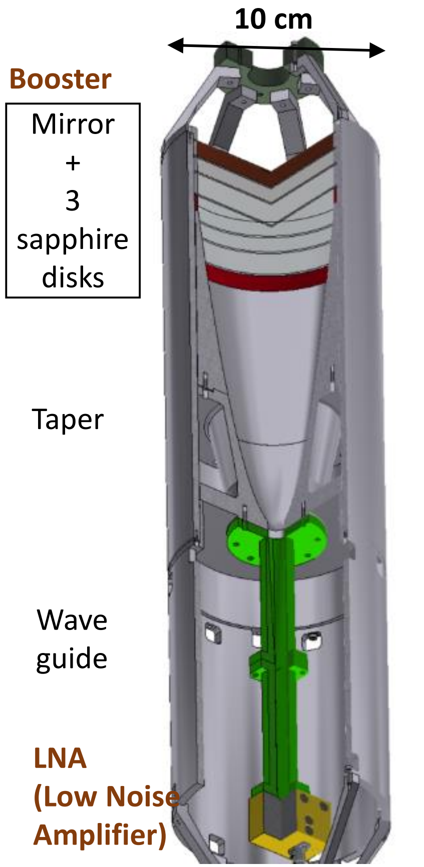
OB300 (upcoming)

Name	Setup	Goal	Available
CB100	3 fixed disks, ϕ = 100mm	RF studies + First physics	2021
P200	1 moveable disk, ϕ = 200 mm	Piezo-motor + mechanics	2021
OB300	3 moveable disks, ϕ = 300 mm	Scan ALPs	2024

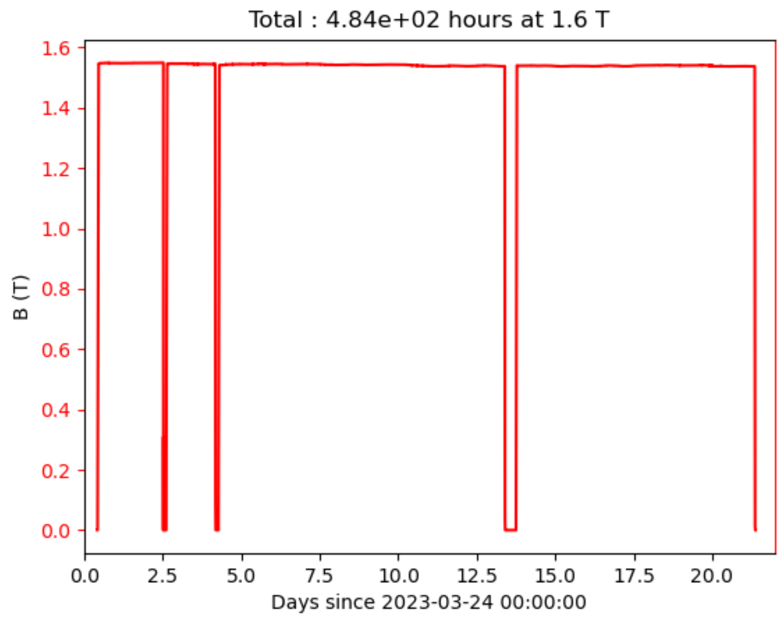
I participated to CB100 data taking, P200 data analysis and OB300 simulations

CB100: First ALP search

- Goal: To understand the RF response of the system and perform an ALP search

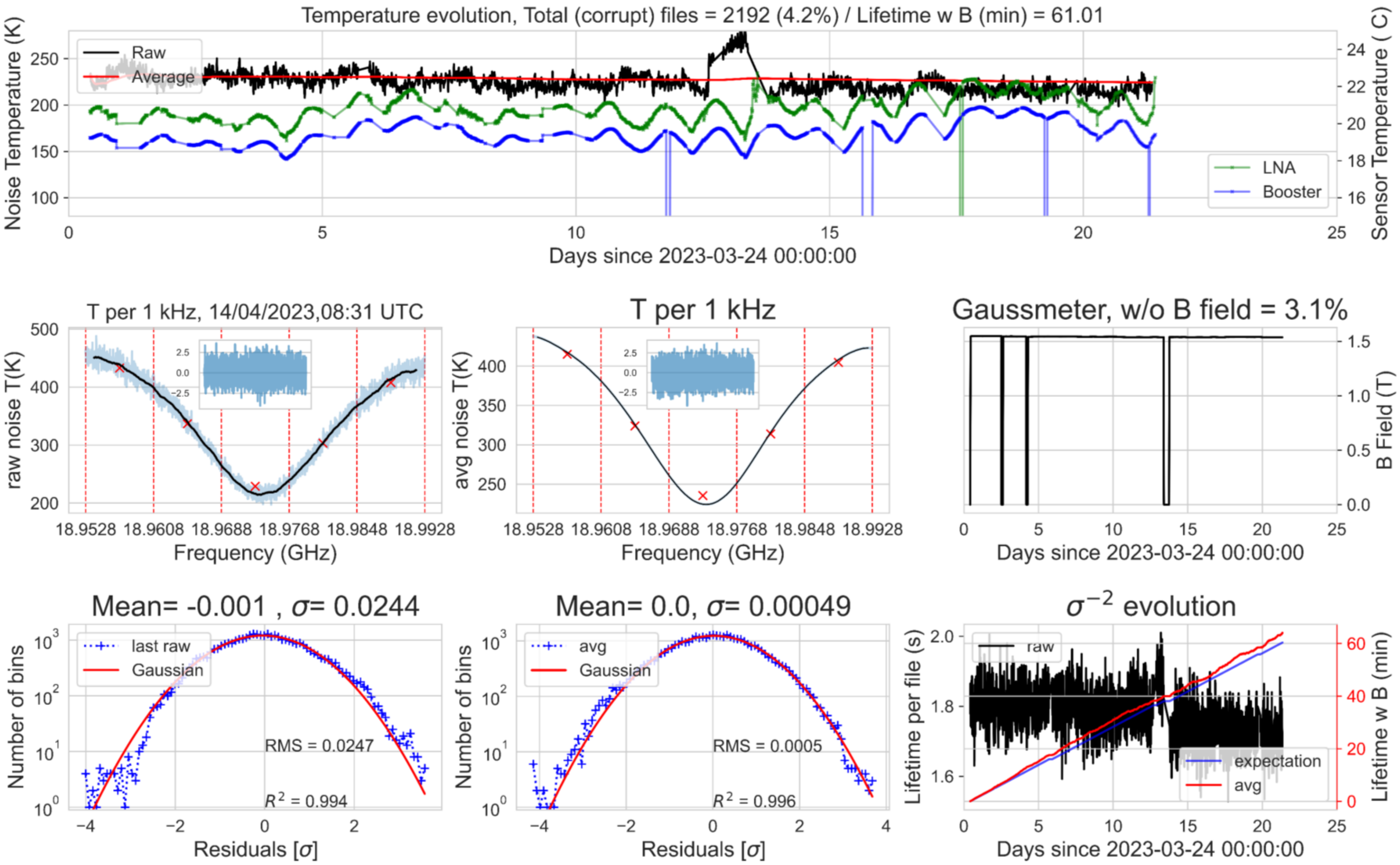


CB100 booster prototype



Magnetic field availability was very stable - 95% during 21 days of data taking in 2023 (10 hours in 2022)

CB100: Stable Data monitoring 2023



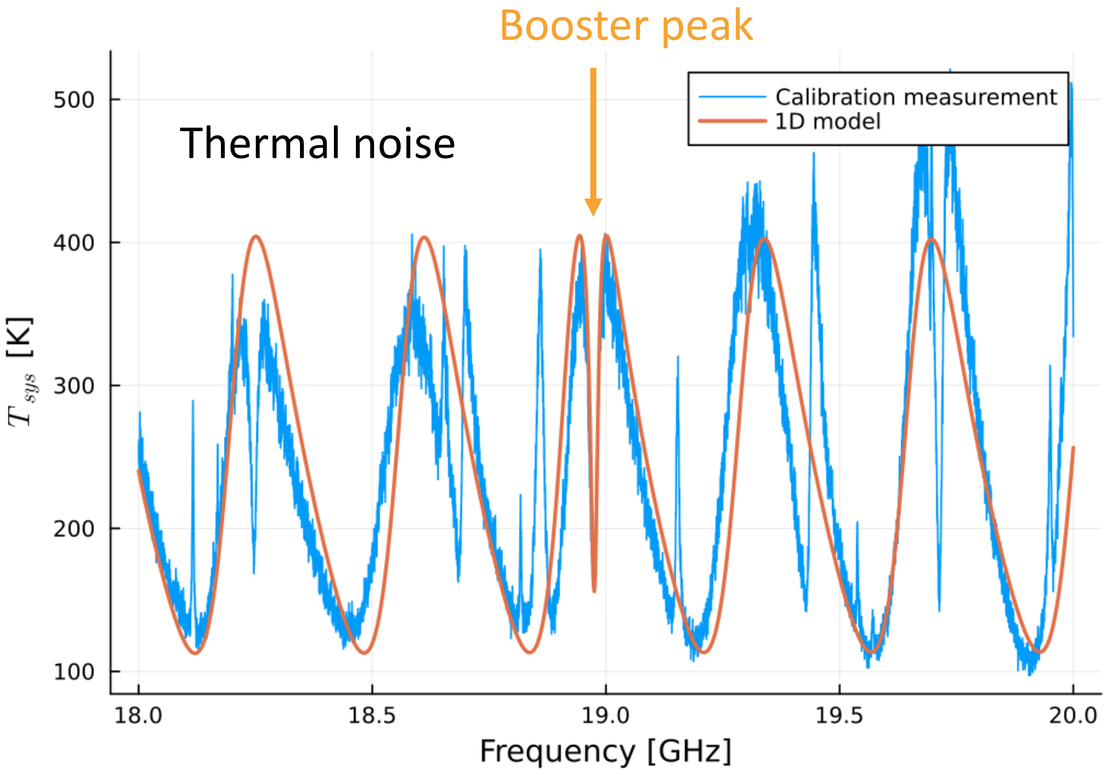
Dicke equation :

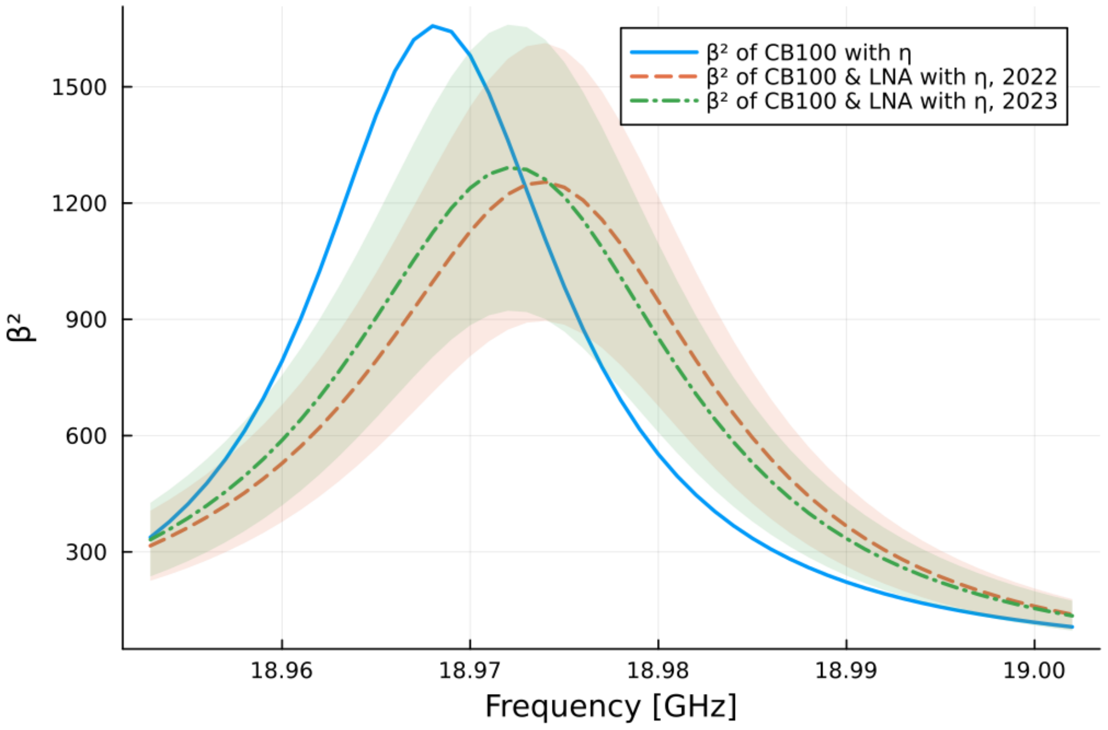
$$\tau = \frac{1}{B\sigma^2}$$

B = bandwidth (1kHz)

CB100: Understanding the booster RF behaviour

- Simulate the LNA response (ADS) to reproduce the noise temperature data
- Simulate booster+taper system (COMSOL) and calibrate boost factor shape including systematics **β^2 = O(1000) at ~19 GHz**

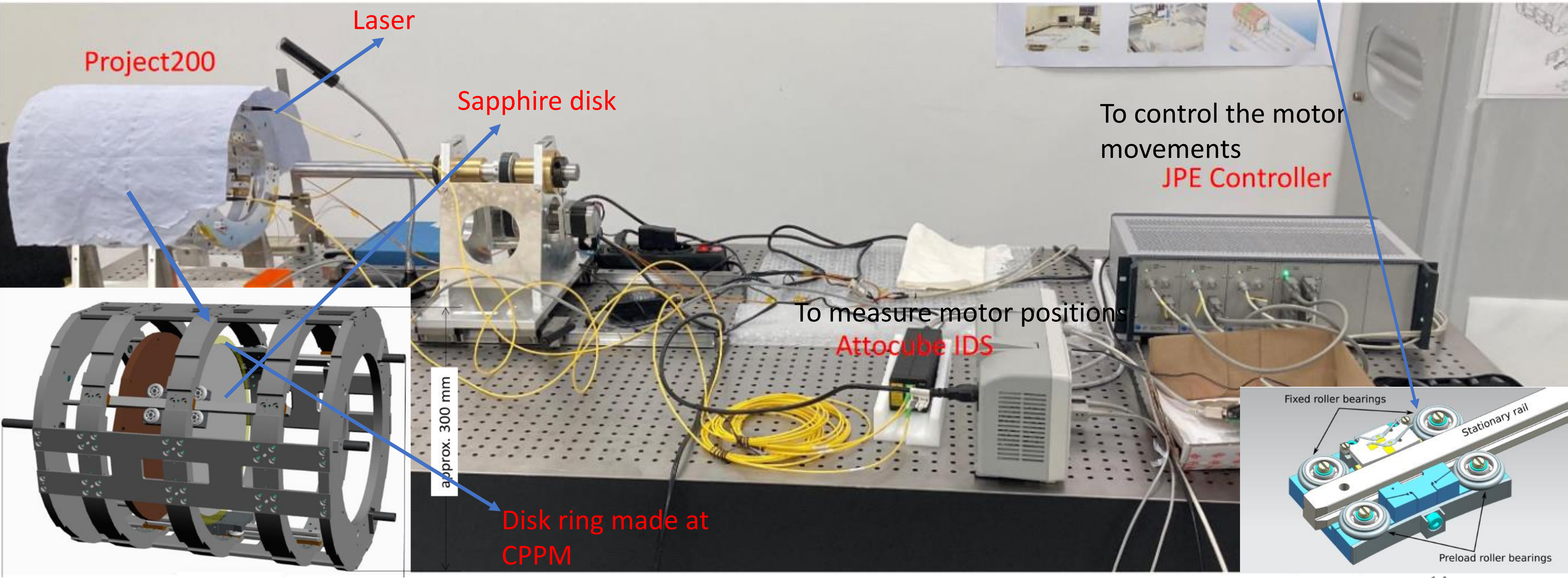




Paper in preparation (to be completed end of the year)

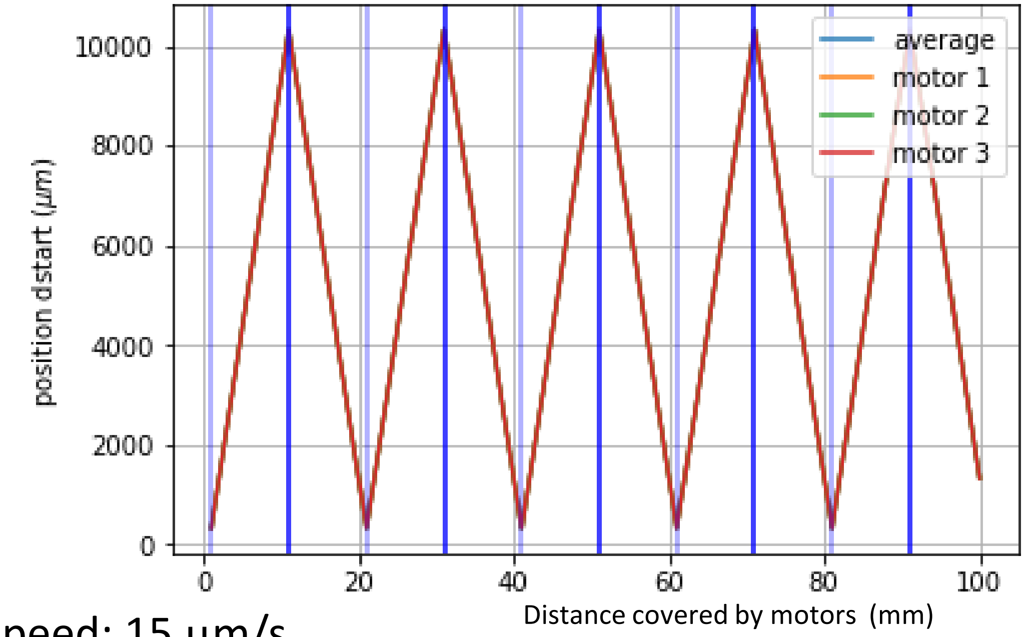
P200: Disk positioning system

- Precise control of 200 mm diameter sapphire disk position with three piezo motors
  - Position error Δd = target position (controller) – measured position (interferometer)

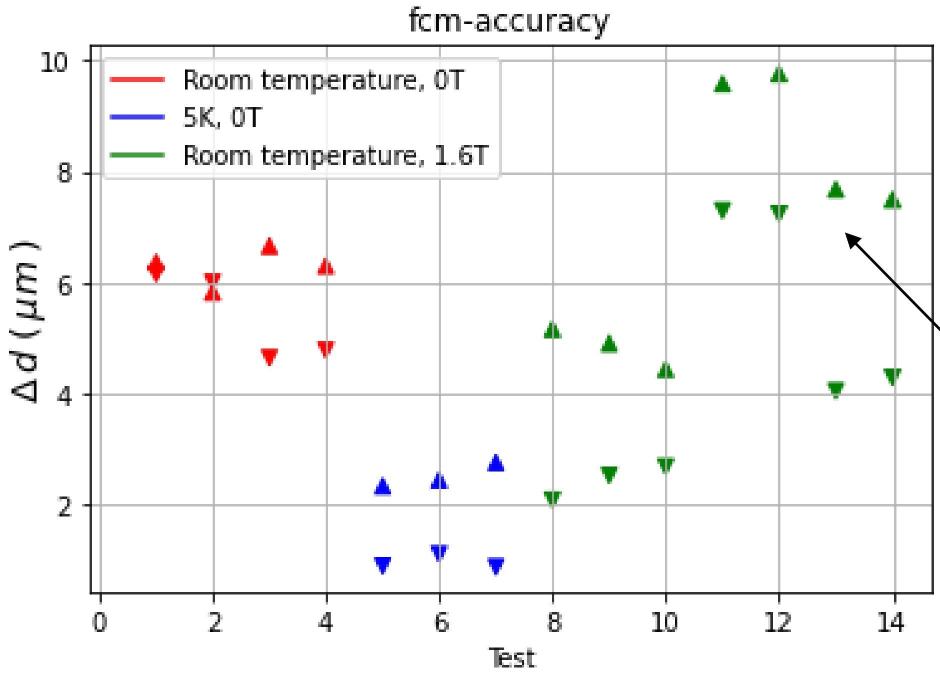


P200: Test results

- Motors tested in 2022 at room temperature (DESY), at cryogenic temperatures (CERN), and in magnetic field (CERN MORPURGO)
  - Motors/mechanics work at cold temperature (5K) and high magnetic field (1.6 T)
  - The accuracy of piezo motor positioning better than 10 μm



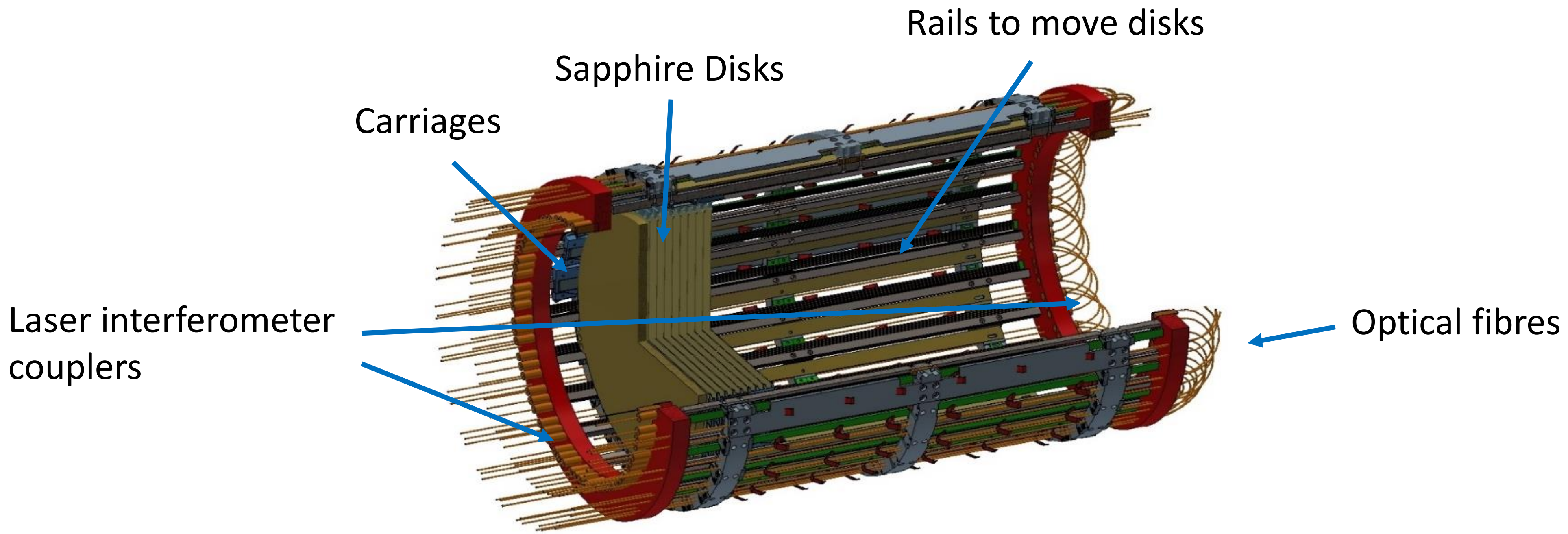
Avg speed: 15 μm/s



The triangles show the measured position error during forward and backward motion

Paper in preparation

OB300 booster



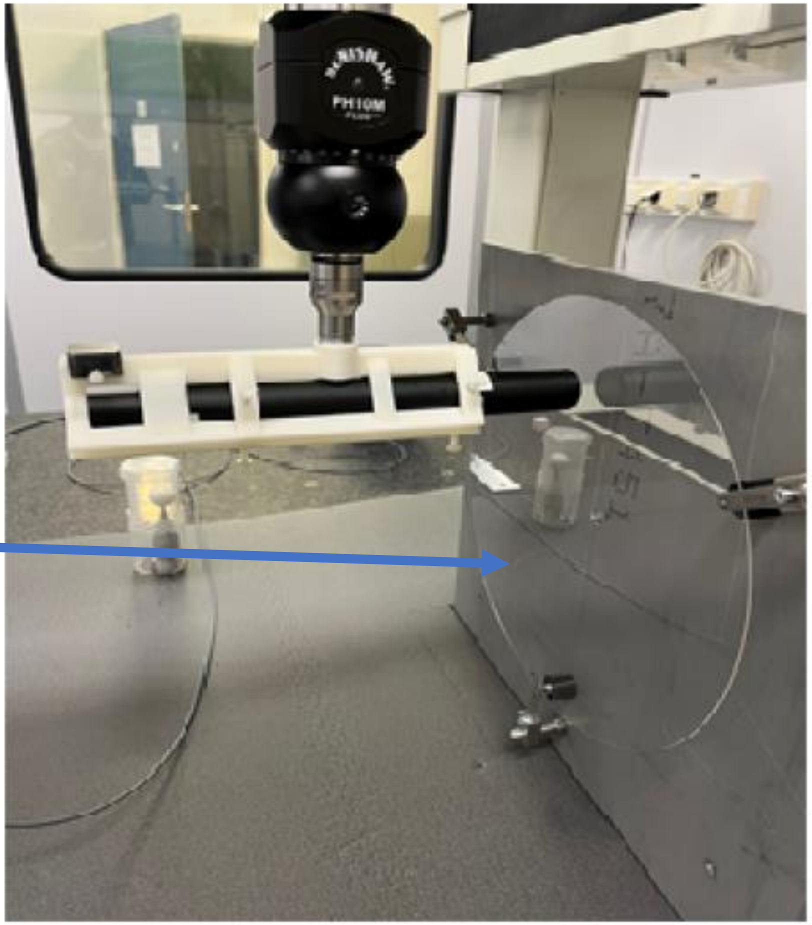
To be assembled in Hamburg
December 2023

Goals of the study:

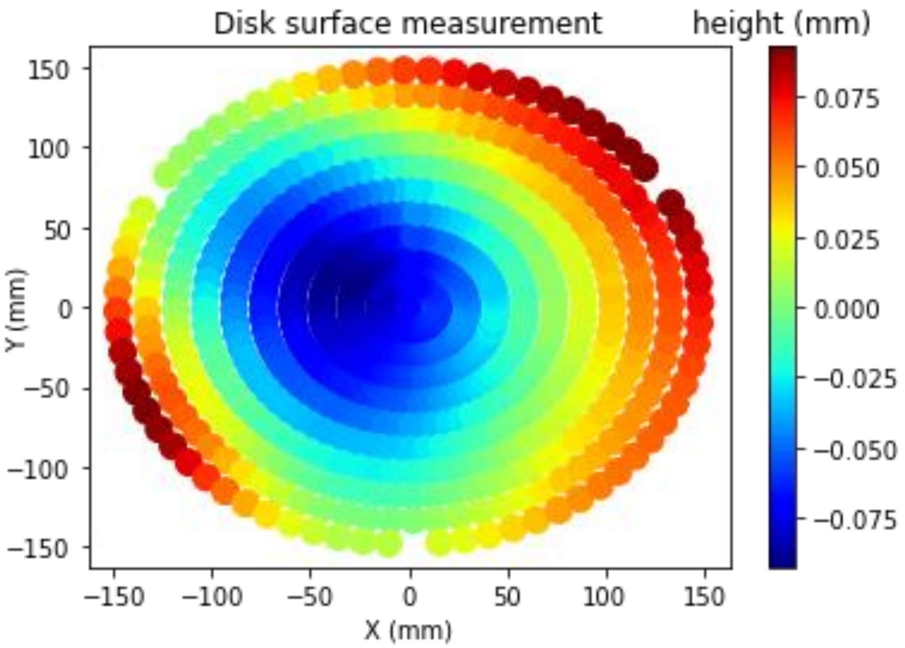
1) Measure the disk planarity,
2) Perform simulations of disk position and ordering to optimize boost factor,
3) Predict electric field and compare it with measurements.

OB300: Disk planarity measurements at CPPM

300 mm
sapphire
disk

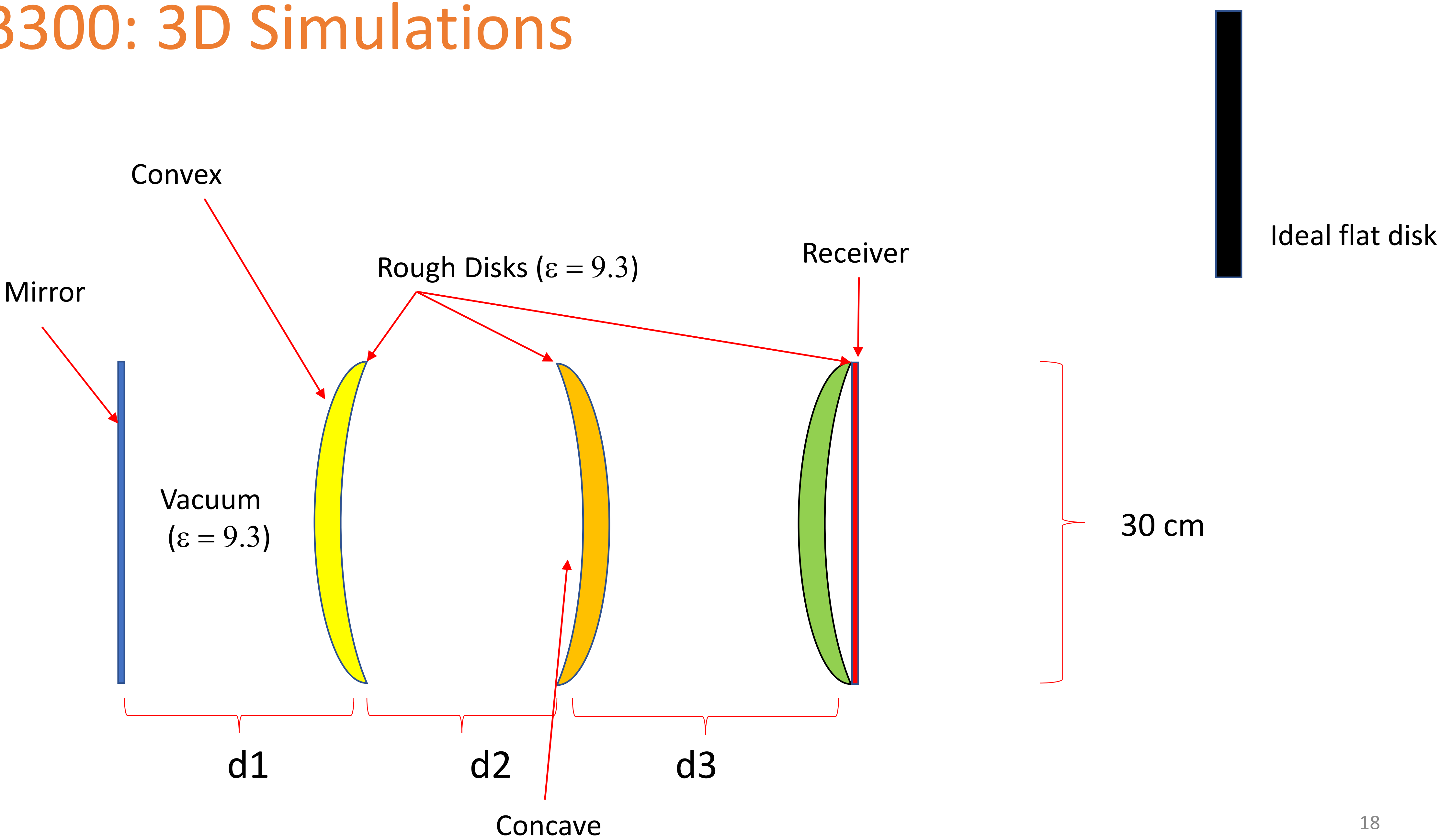


Planarity of 4 sapphire disks of 1 mm thickness measured with O(1) μm precision



- ~ 500 points of measurement
- **52 μm RMS**
- Bowl shape coming from the manufacturing process

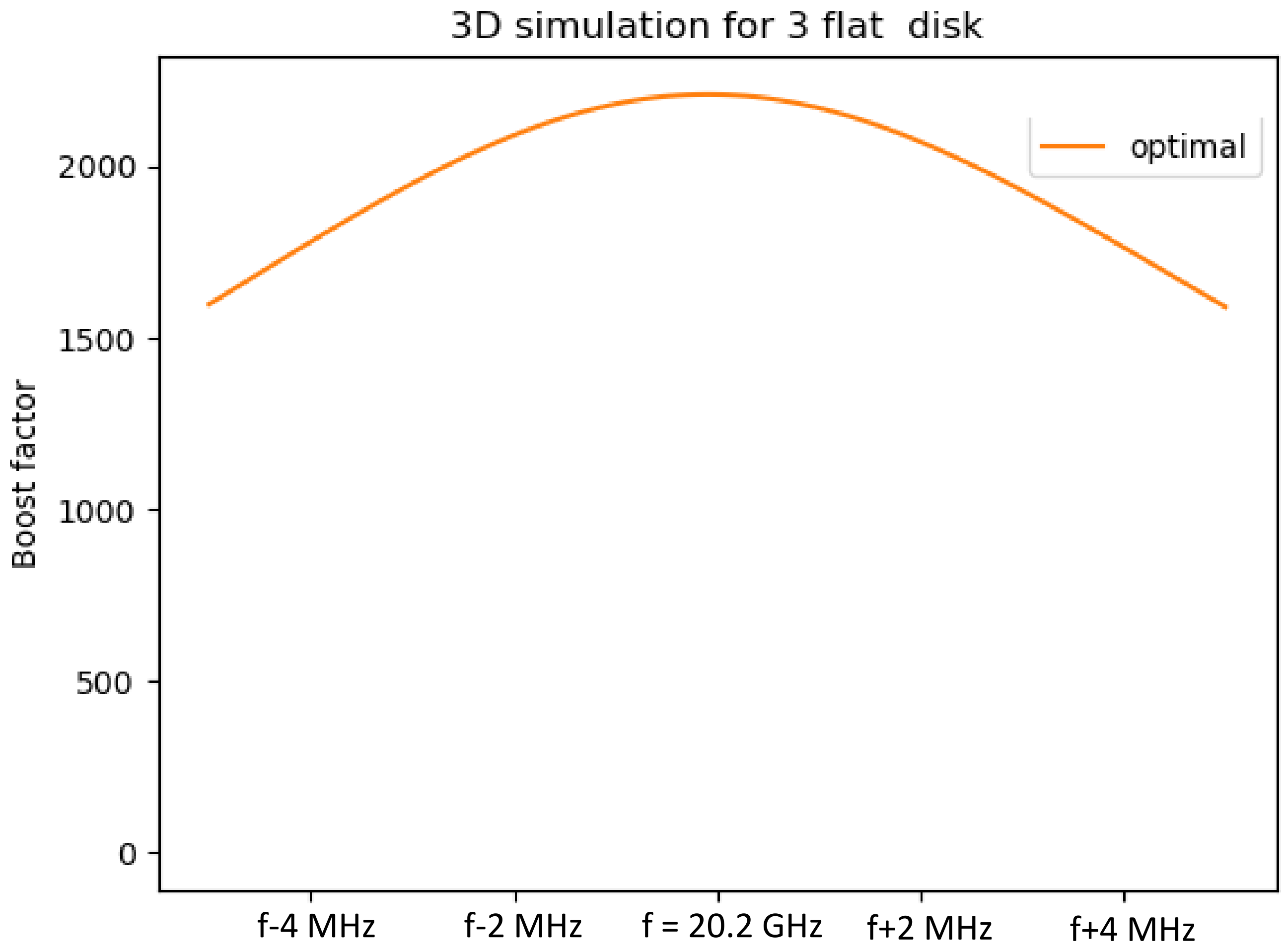
OB300: 3D Simulations



OB300: 3D simulations

- Simulation based on the theoretical paper: arXiv:1906.02677
  - Calculate β^2 by recursive Fourier propagation of EM fields
  - Use an optimizer to maximize the boost factor by varying the distances
  - First result obtained using ideal flat disks to serve as a benchmark
  - β^2 is similar to CB100, but $P \propto \beta^2 * A$

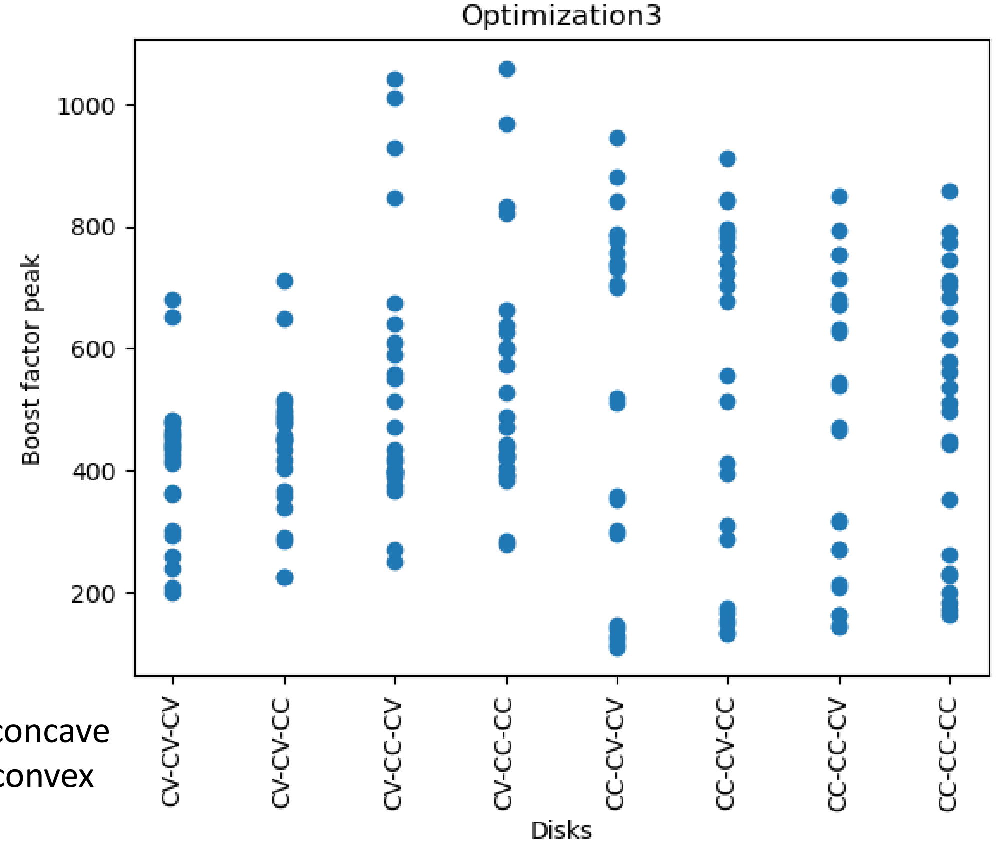
Power boost factor: $\beta^2 = \frac{P_{\text{total}}}{P_{\text{mirror}}}$



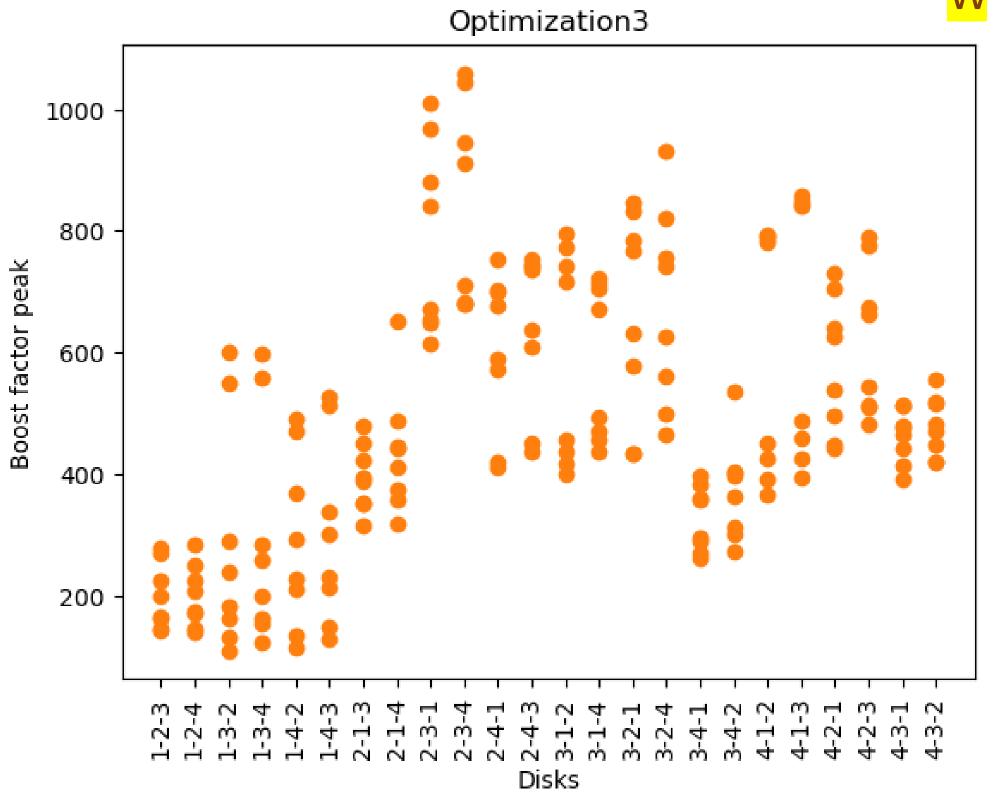
OB300: Boost factor optimization

- Among 192 configurations, some orientation and ordering are preferred
  - Best β^2 is 1000 compared to 2000 for flat disks

Work in progress



CC = concave
CV = convex



OB300 assembly in 2024, compare the simulation with data

Conclusion

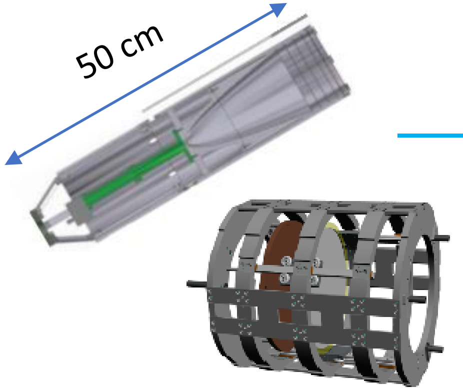
- Axions can solve the strong CP problem and the dark matter problem
- MADMAX dielectric haloscope to probe the axion mass range around 100 μeV that is favoured by post-inflationary scenarios
- MADMAX currently in the prototyping phase to validate the dielectric haloscope concept
  - CB100 two data taking completed in March 2022 and March 2023 at CERN (paper in preparation)
  - P200 disk positioning system shown to work at 5K temperature and 1.6 T magnetic field
  - OB300 final prototype to be assembled in the coming weeks
- I participated to CB100 data taking, P200 data analysis and OB300 simulations

Future plan

Name	setup	Goals
P200	1 moveable disk ϕ = 200 mm	Analysis ongoing, a paper in making
CB100	3 fixed disks ϕ = 100mm	Experimental run at cold and in magnetic field at CERN 2024
CB200	4 fixed disks ϕ = 200 mm	Experimental run in magnetic field at CERN 2024
OB300	3 moveable disks ϕ = 300 mm	Assembly and Calibration Dec 2023, experimental run at cold in 2025/2026

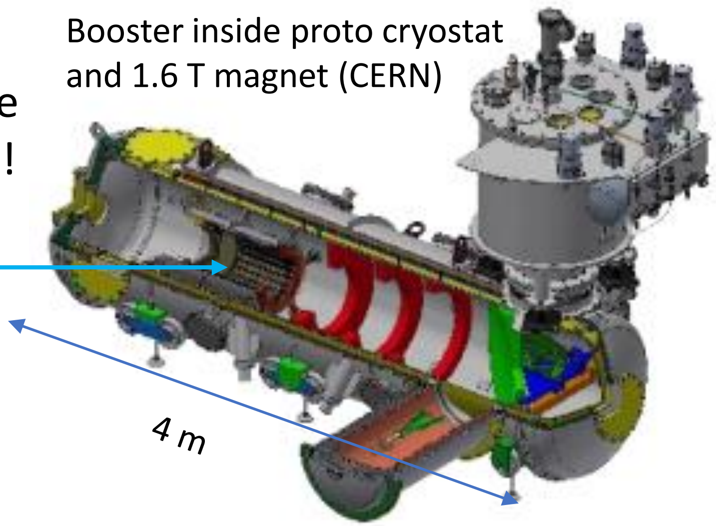
2021 — 2025 — 2028

Proto boosters
CB 100, P200

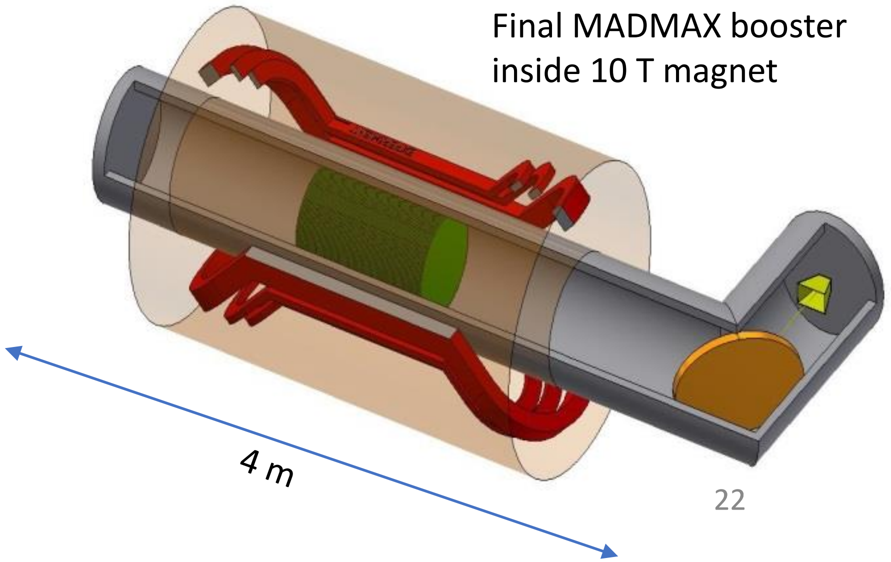


We are here!!!

Booster inside proto cryostat and 1.6 T magnet (CERN)



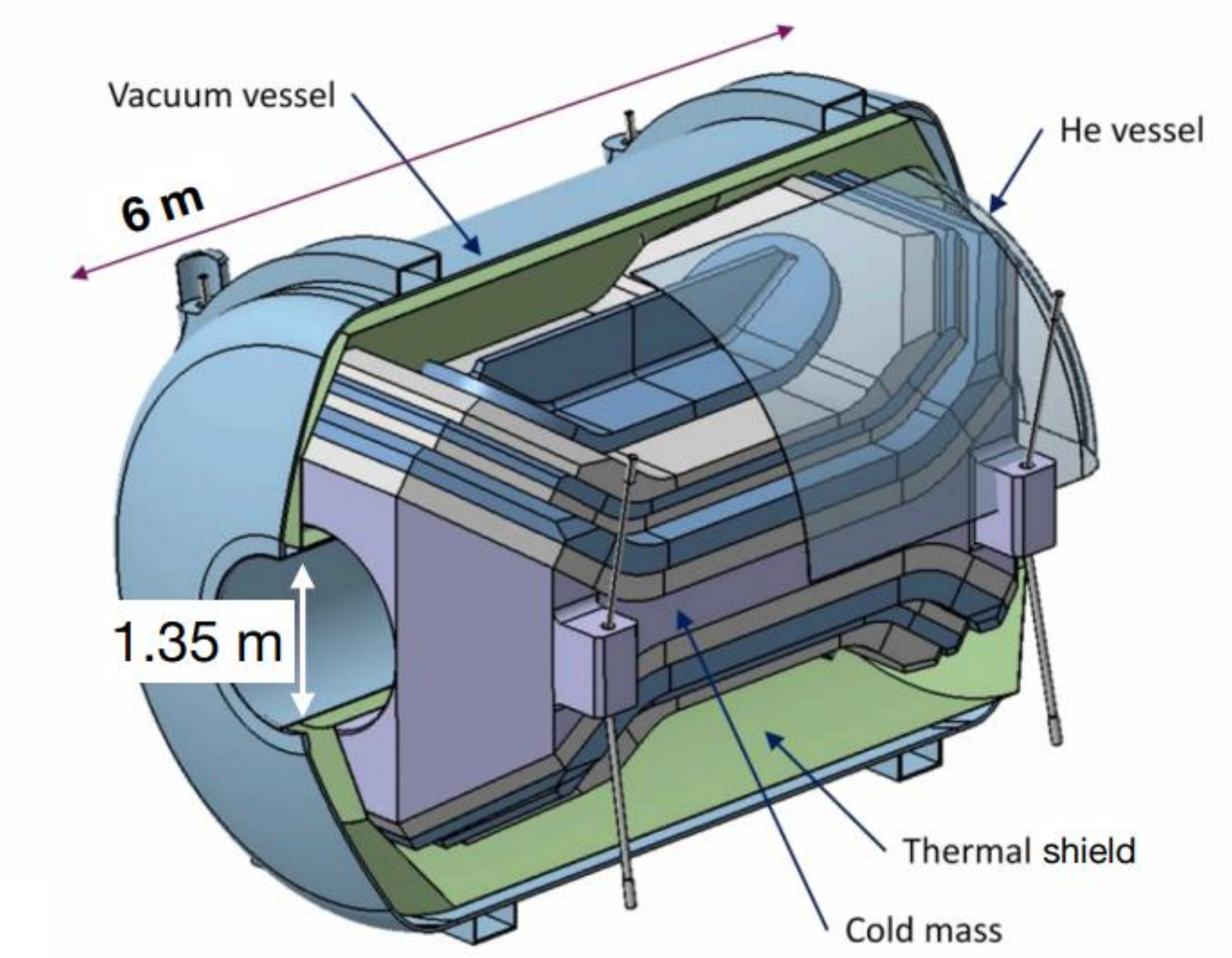
Final MADMAX booster inside 10 T magnet

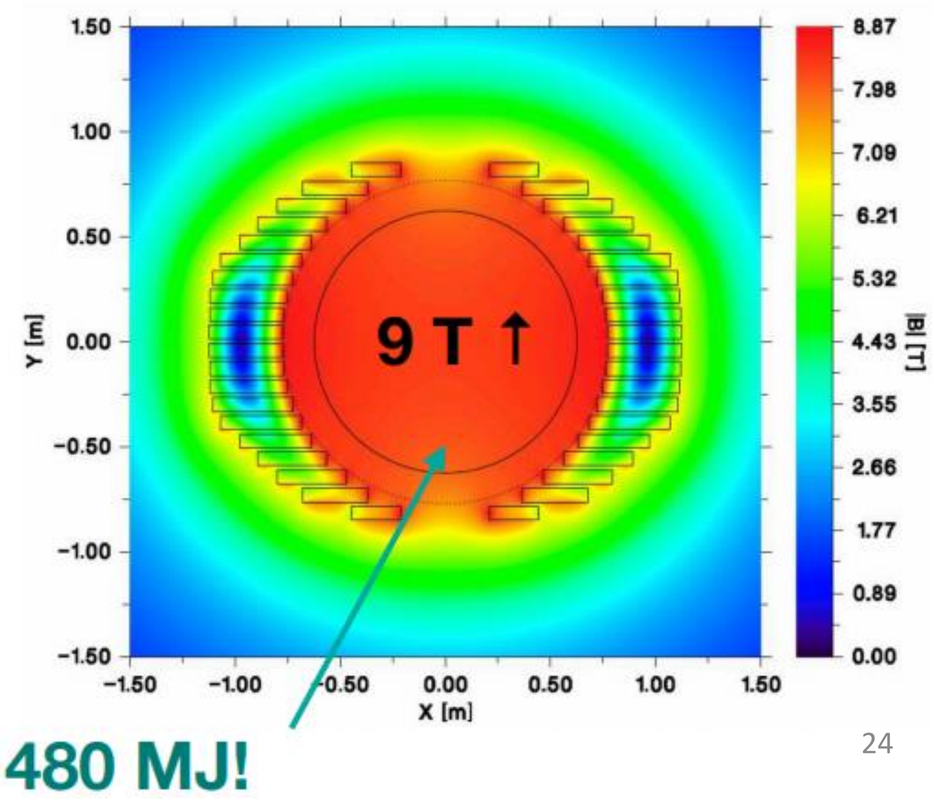


Thank you

Magnet

- European Innovation partners: CEA Saclay and Bilfinger Noell
- FoM: B^2A = **100 T^2m^2**



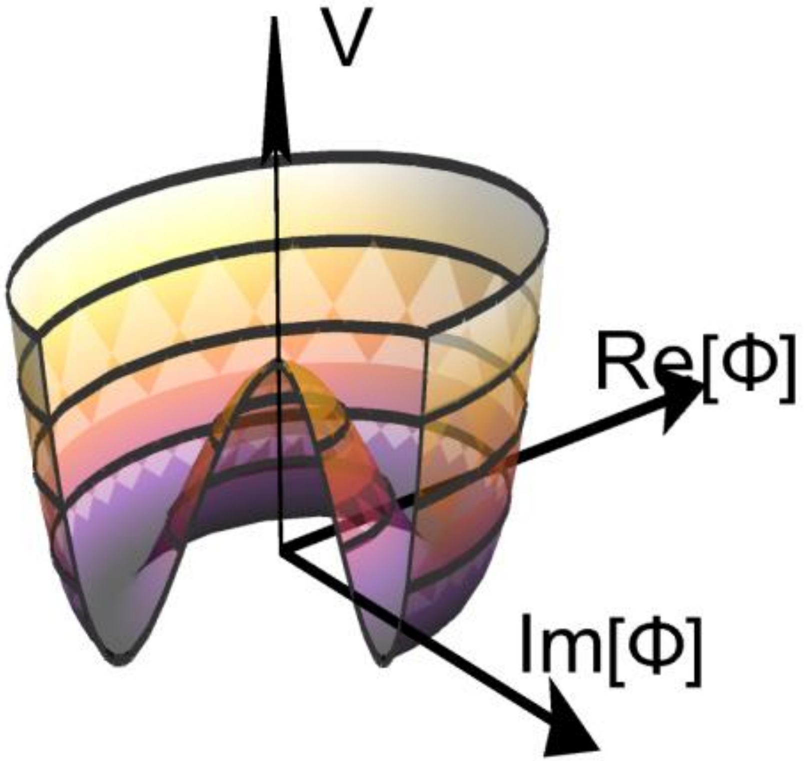


PQ mechanism

New field: $\Phi = R(t, \mathbf{x}) \exp[i\theta(t, \mathbf{x})]$

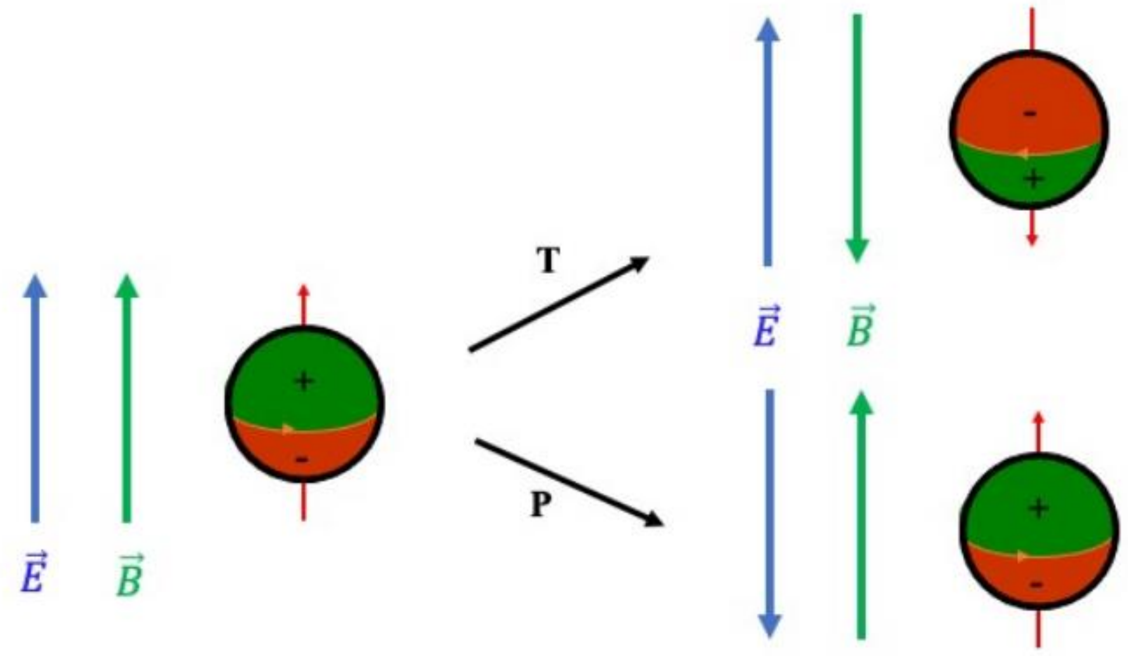
The potential favors θ = 0, thus solving the strong CP problem

Original PQ mechanism already disproved, two modified PQ mechanisms (KSVZ and DFSZ) are the object of interest for current experiments



Arxiv: 2308.16003

Neutron Electric dipole moment (nEDM)



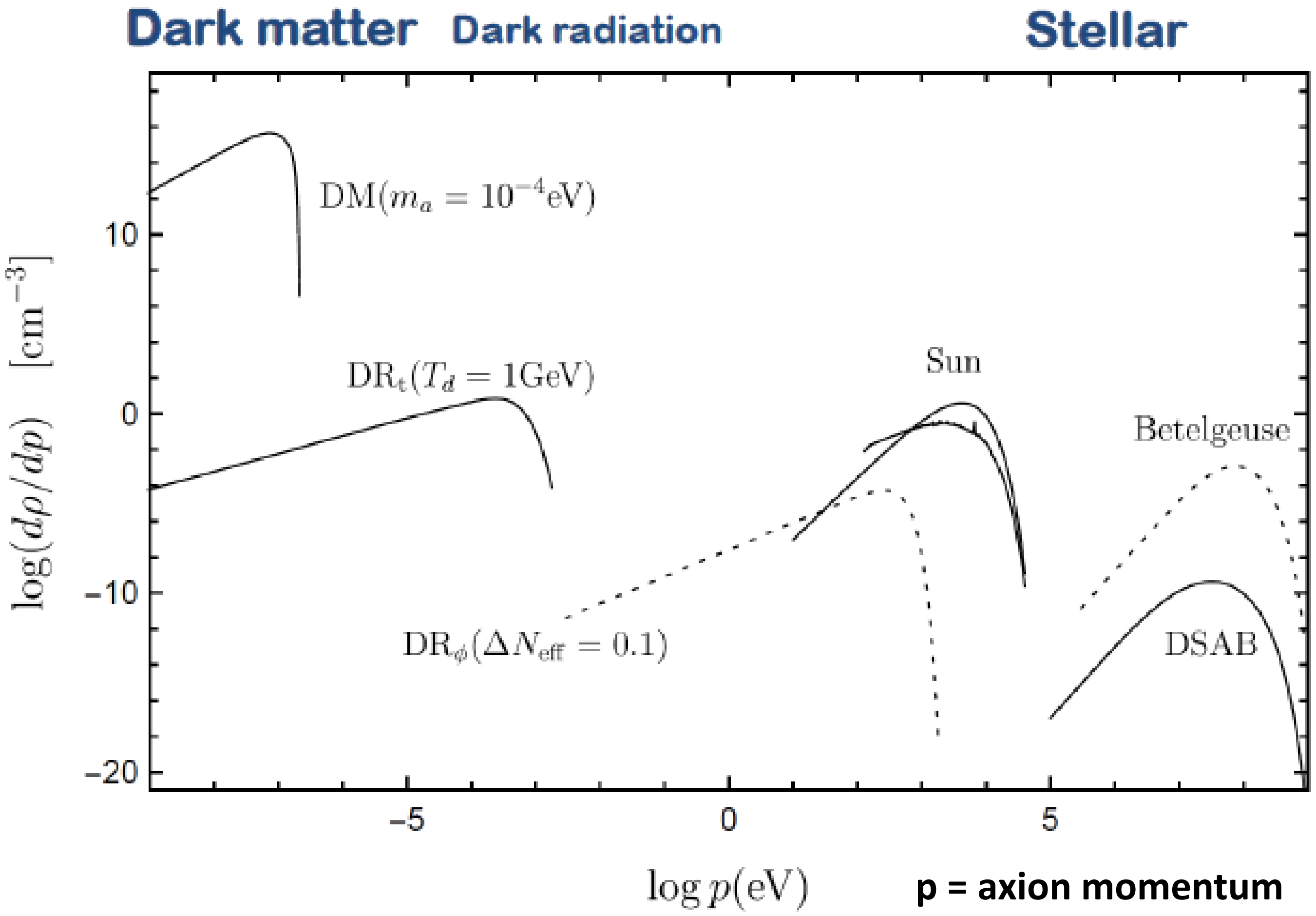
H = −**d** · **E**

d = d**σ** is the electric dipole moment, E is electric field

d is odd under CP, while E is even

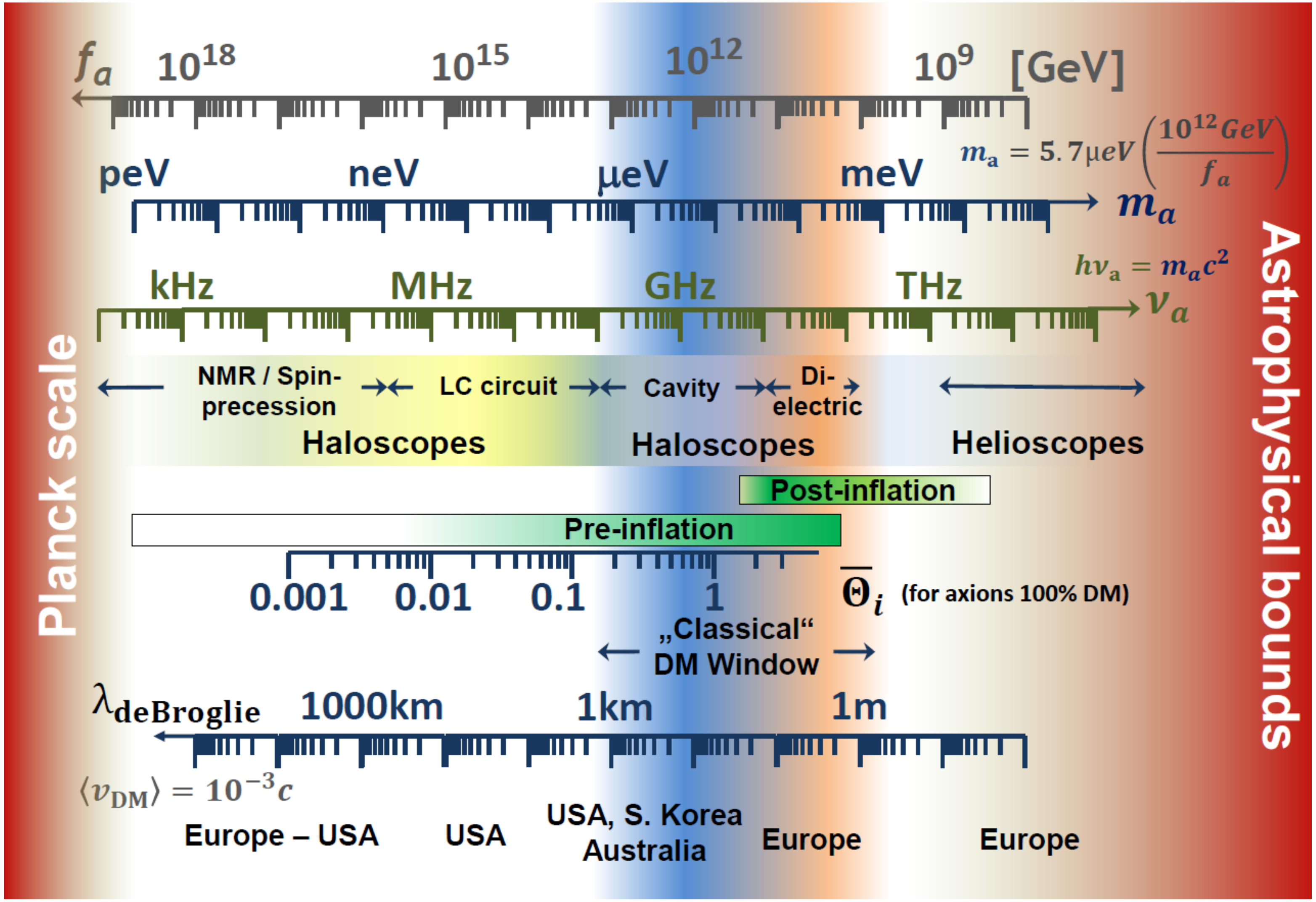
The combined term leads to CP violation

Sources of axions

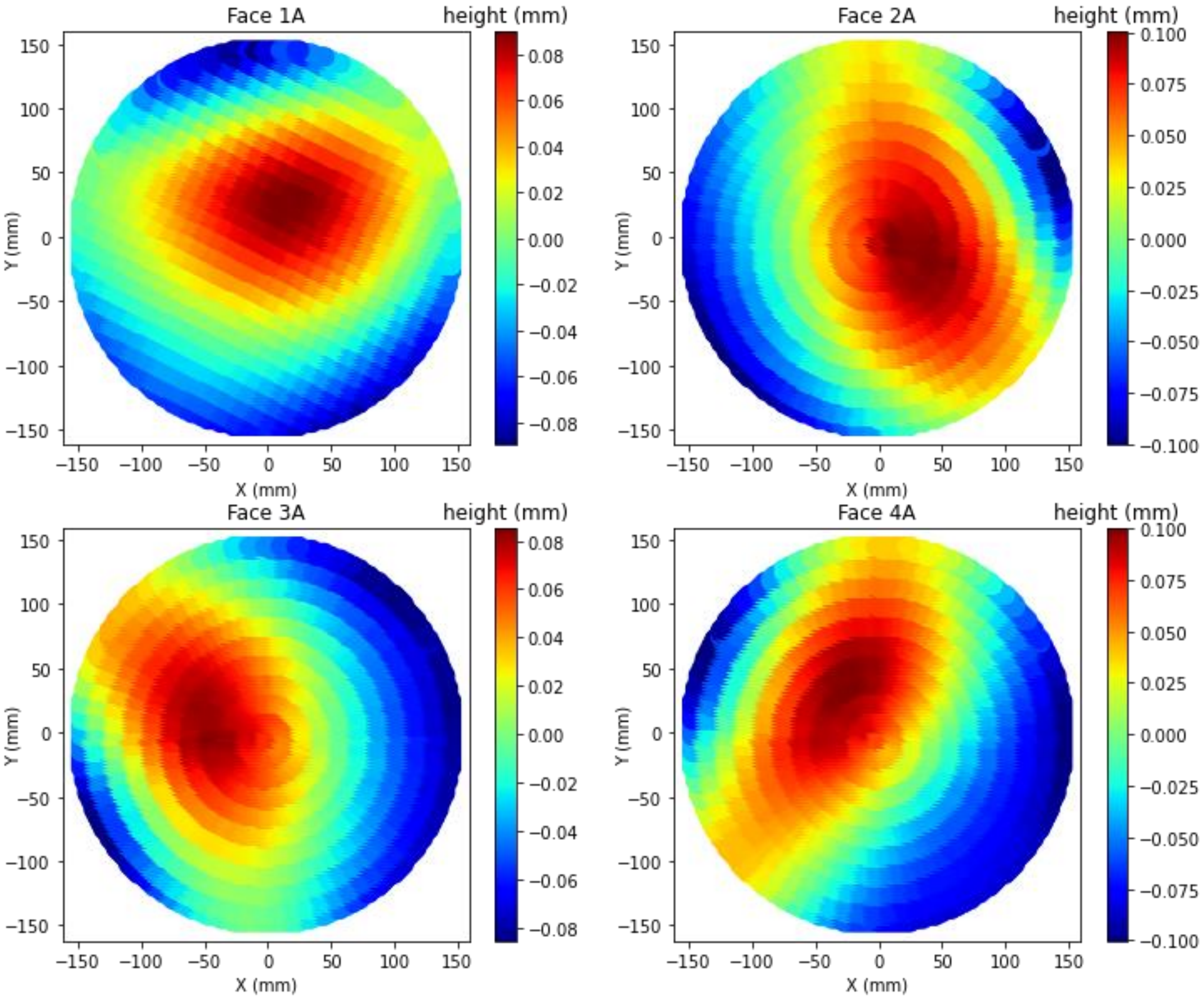


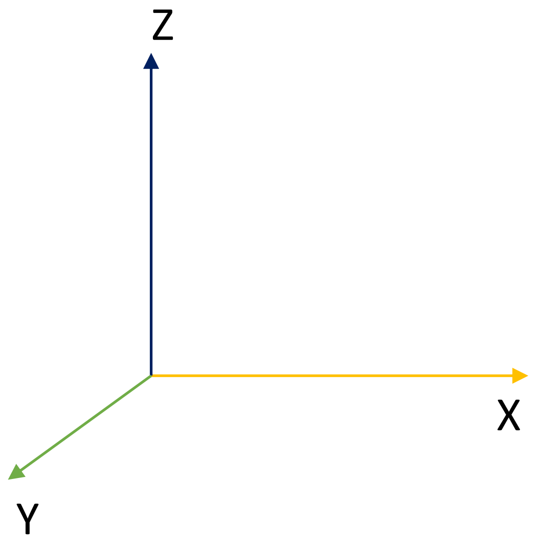
p = axion momentum

Axion scales



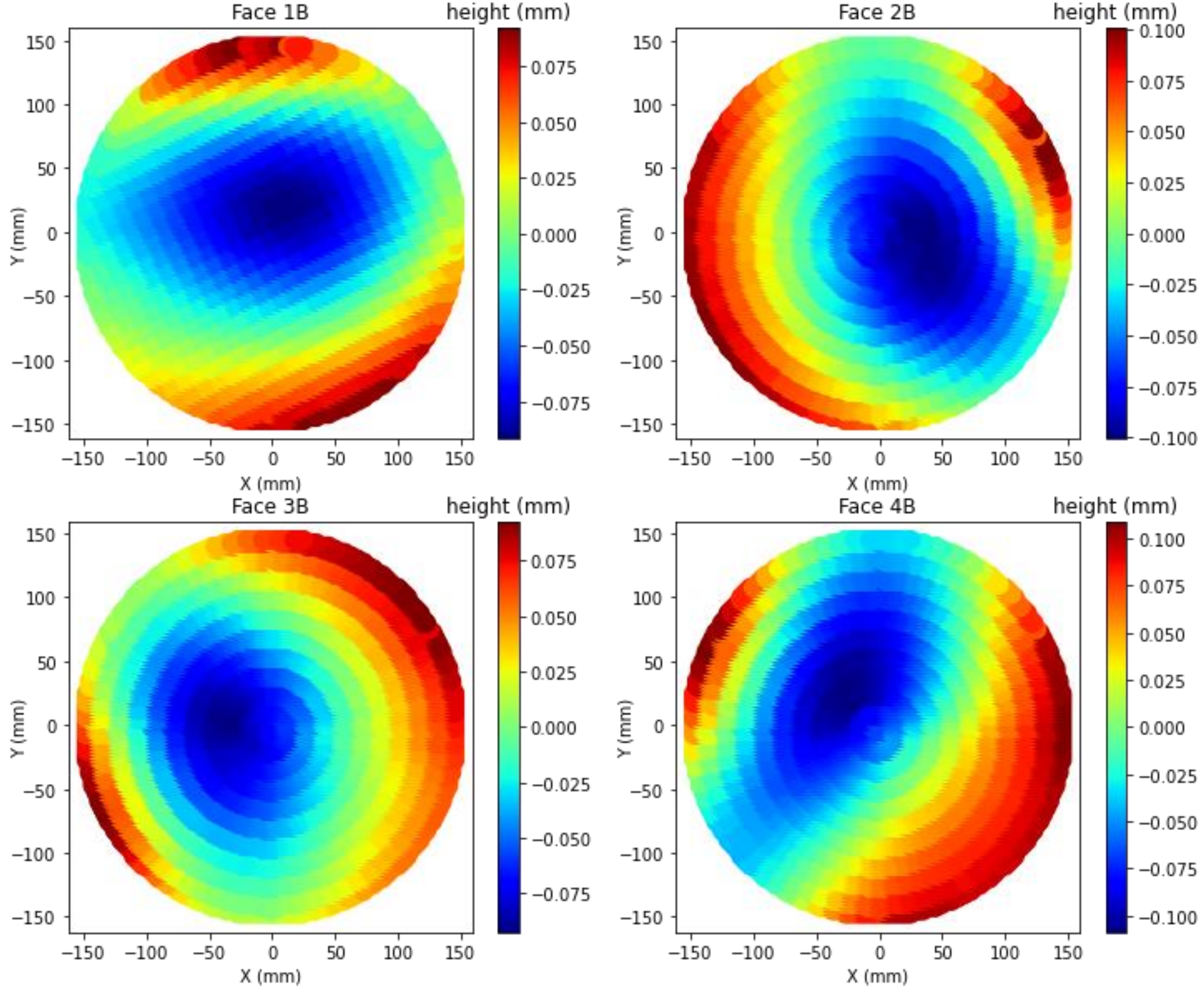
Disk interpolated measurements

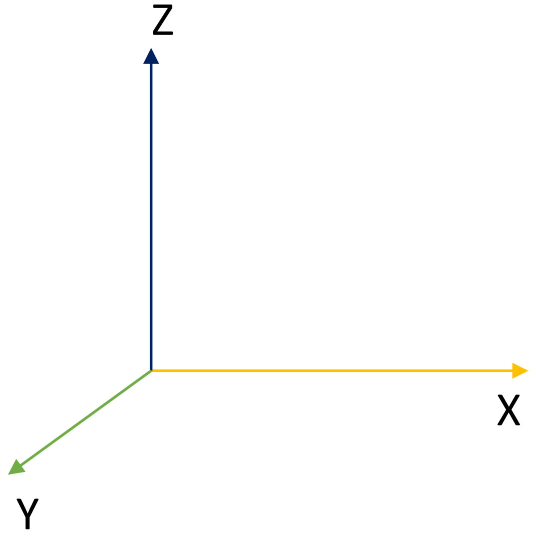




All the disk faces similar to each other

Disk interpolated measurements





Déformation 3D grossit x500

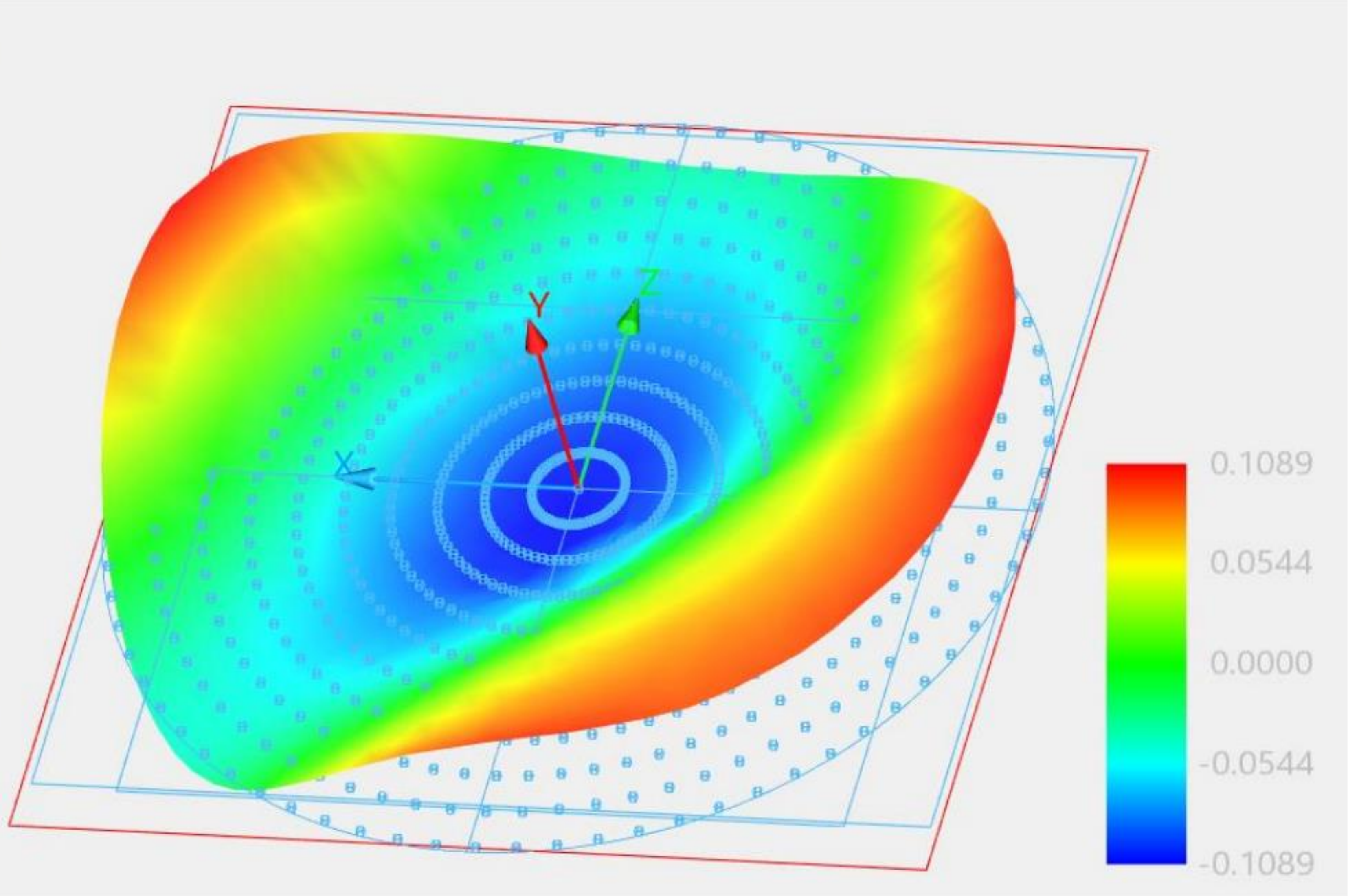
ID	PLN_3
Type	Plan, Tchebychev, Construction ı
Description	Plan Total Face A

Géométrie Détails Points

Date / Heure	21.03.2023	16:14:54
Points	718	
Ecart-type	0.0605	
Point / Min.	-0.1089	64
Point / Max.	0.1089	140
Etendue	0.2178	
Longueur	295.9551	
Largeur	295.6166	
Epaisseur matériau		

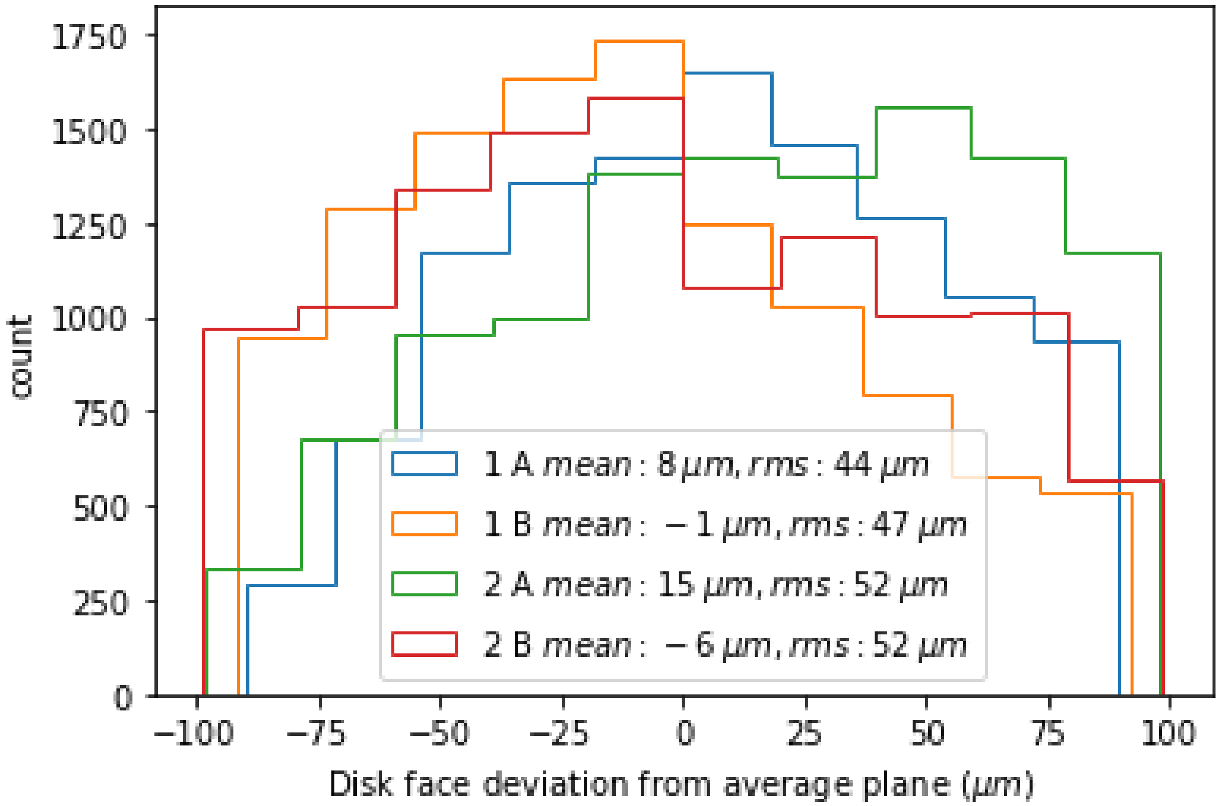
Tolérances et déviations

	Tol sup	Tol inf	Ecart	Graphiqu
x			0.0000	
y			0.0000	
z			0.0000	
R			0.2178	



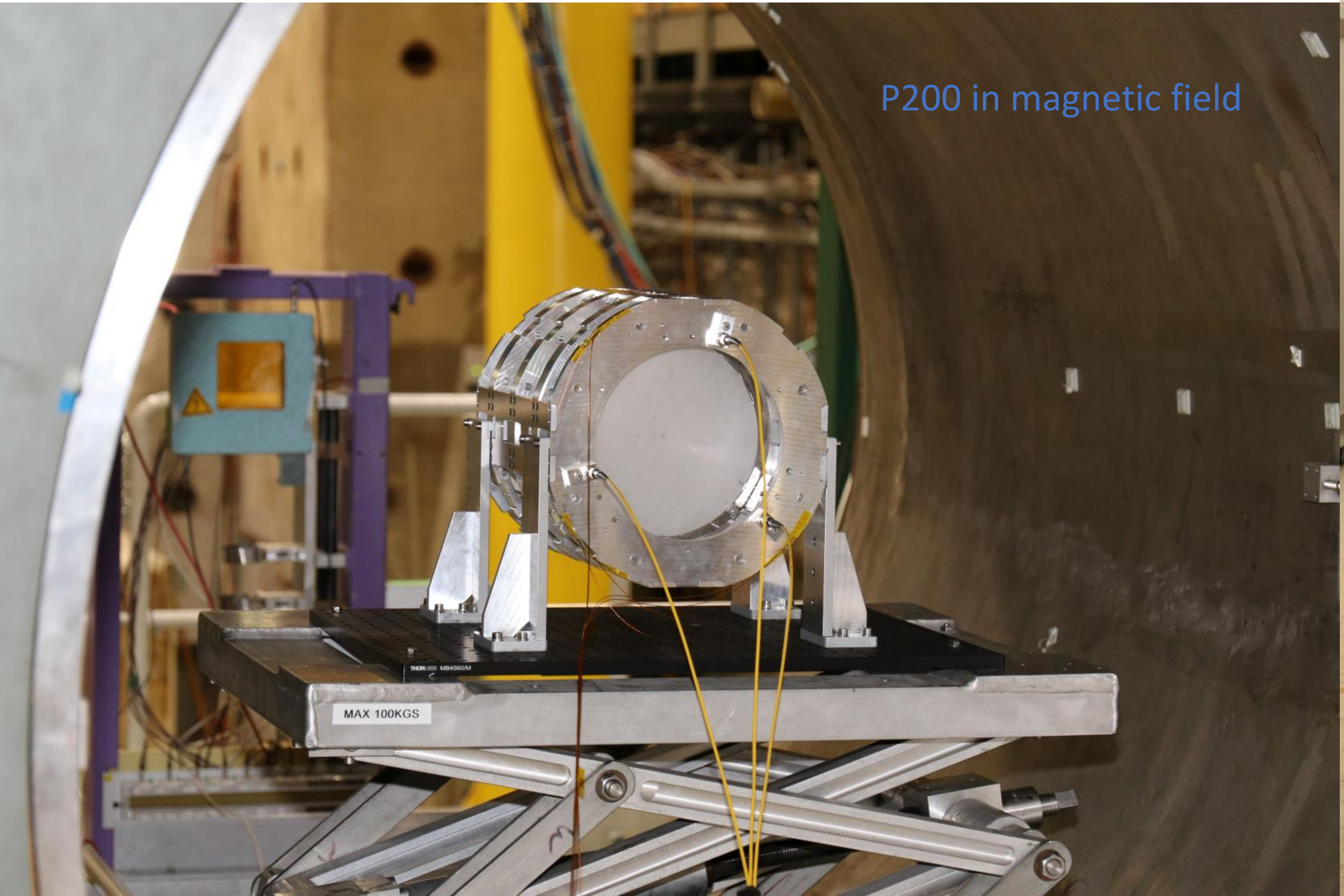
Disk 4 face A shape visualized by multiplying the surface height by 500

Using disk measurement interpolation 2.5 mm * 2.5 mm

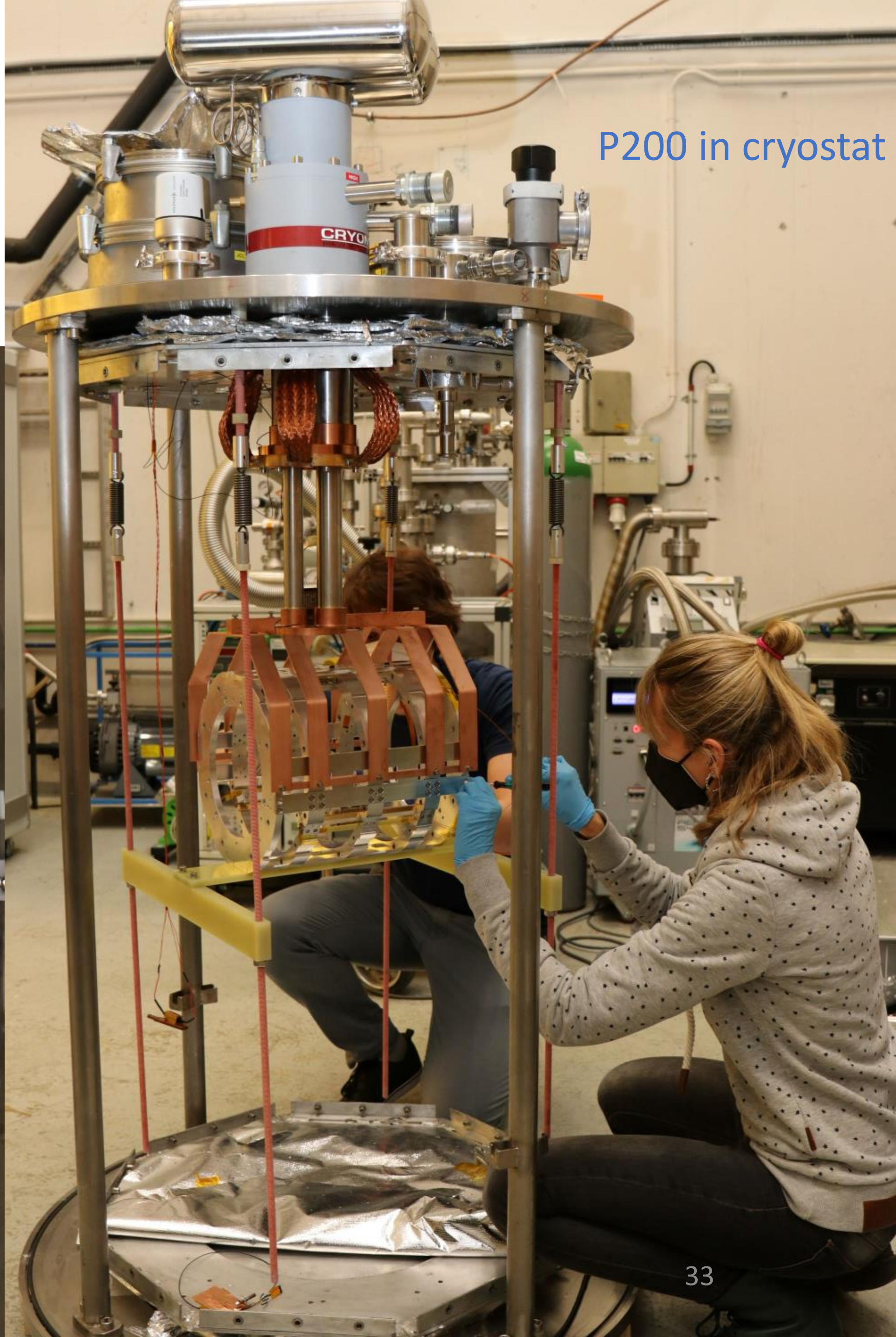


Disk 1 faces has less deviations in the surface measurement (lower rms values) than disk 2

P200 tests



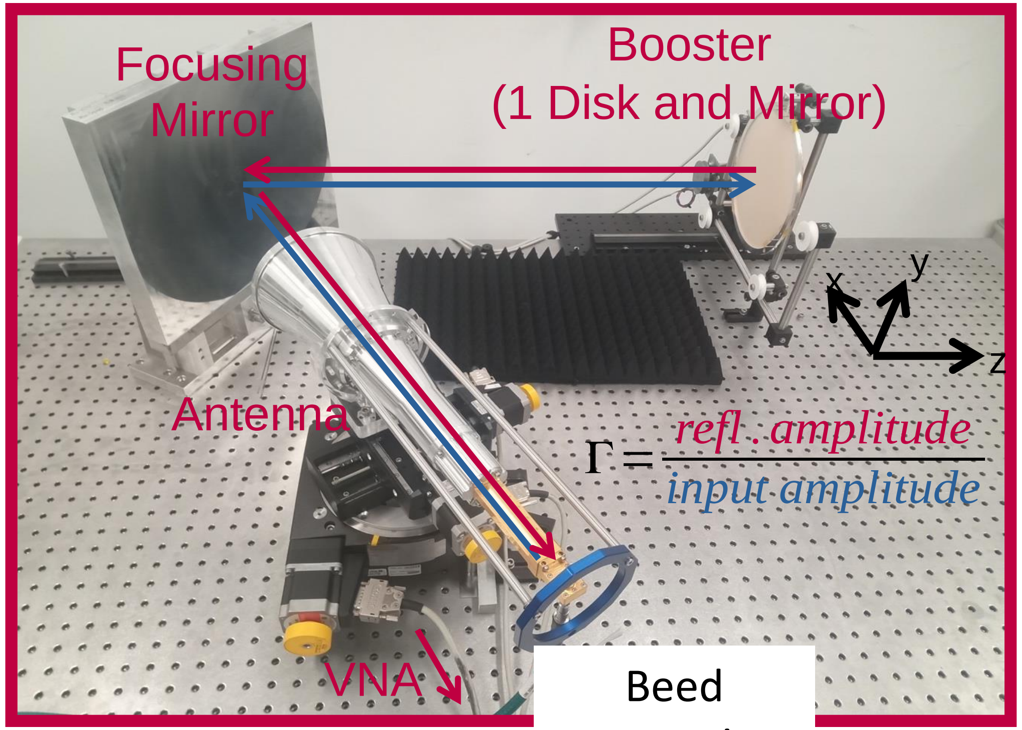
P200 in magnetic field

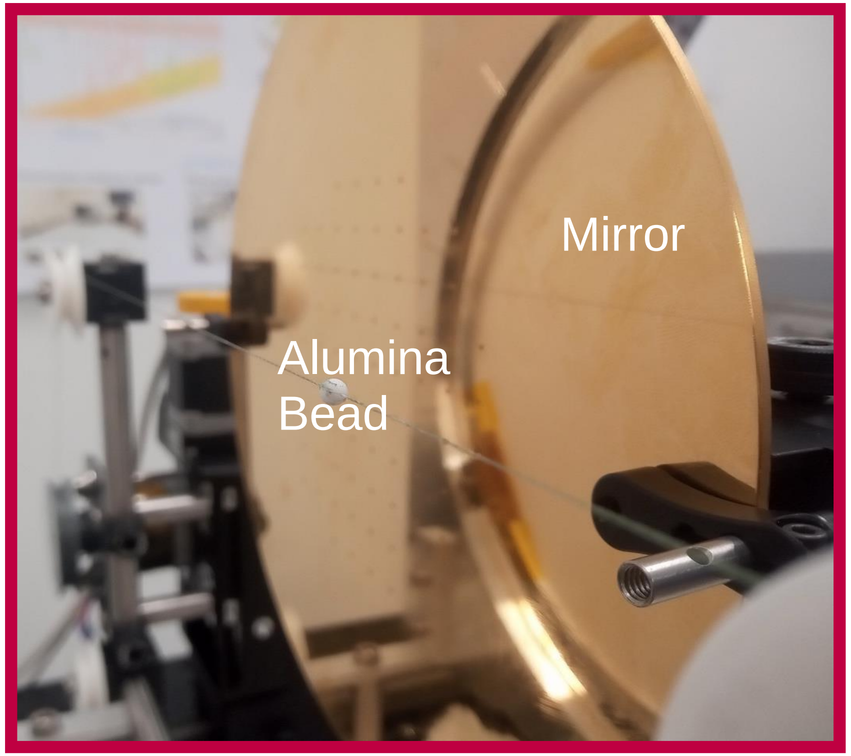


P200 in cryostat

OB calibration (1/2)

Boost factor determined using Bead Pull Method (non-resonant perturbation theory)
+ Lorentz reciprocity theorem   J. Egge, [JCAP 04 (2023) 064]





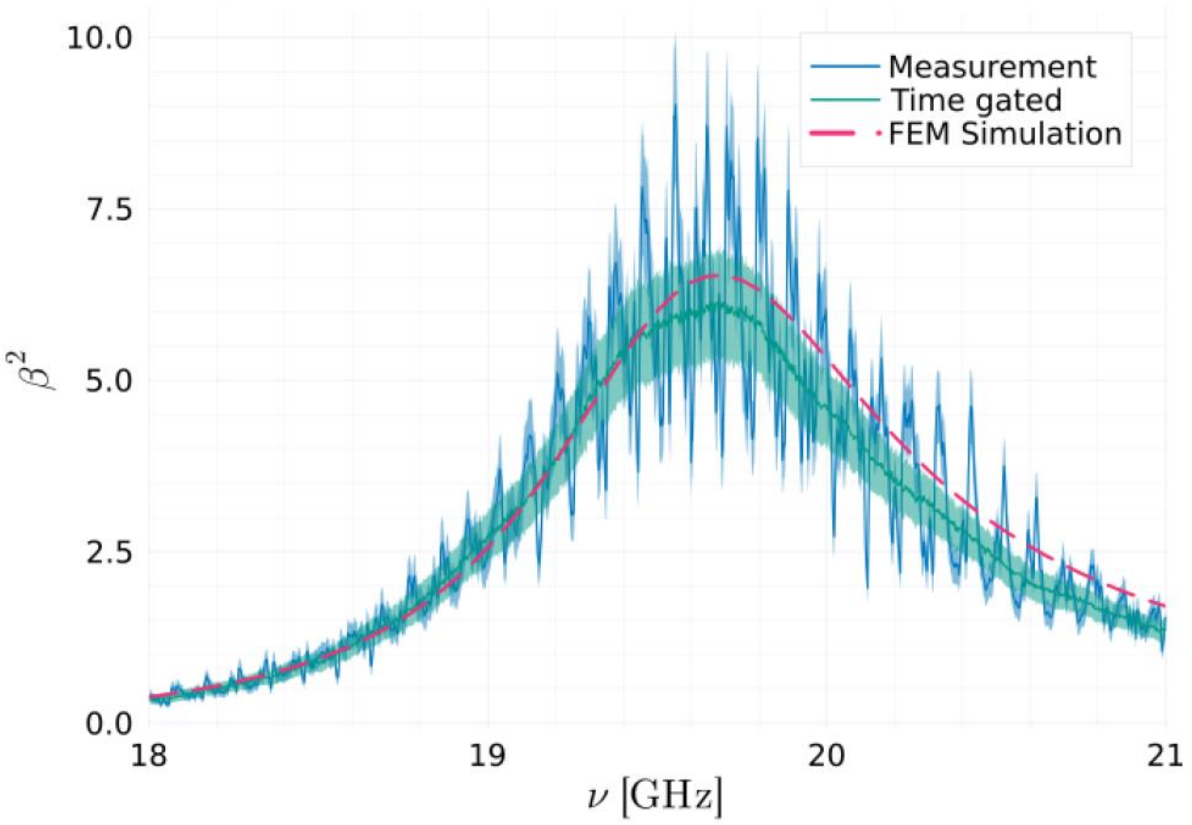
Beed properties

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

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

OB calibration (2/2)

Test with a single disk + mirror (low boost factor)



Measure boost factor (+ systematics)

[paper in preparation]