Direct search for dark matter axion with MADMAX

Fabrice Hubaut, Pascal Pralavorio

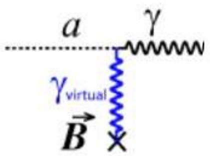
CPPM/IN2P3 – Aix-Marseille Université
(Marseille, FRANCE)

1- Scientific context
2- MADMAX principles and set-up
3- Prototyping *(magnet, receiver, booster)*
4- French contributions
5- Timeline

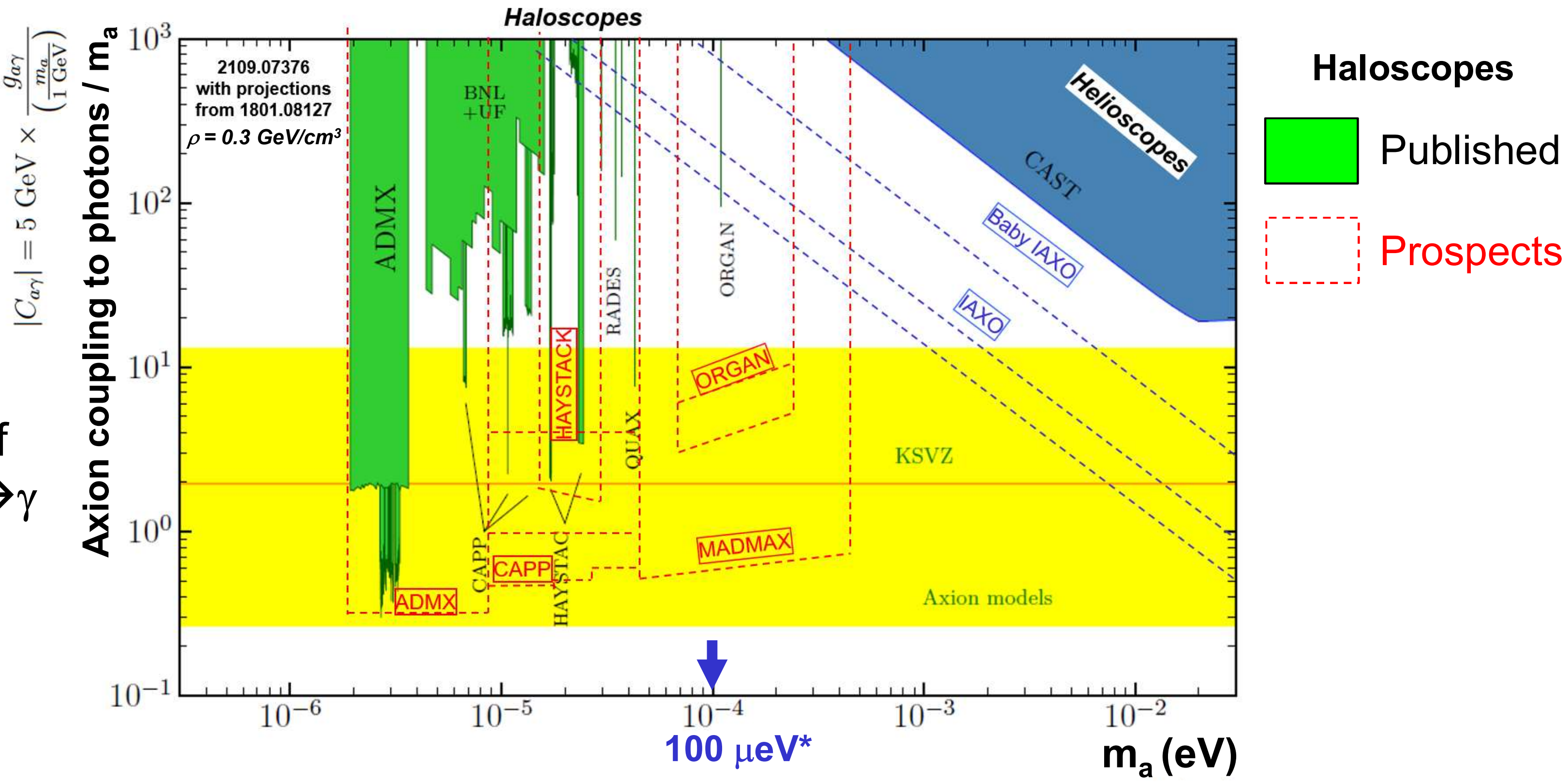
Axions++ Workshop – 26 September 2023

Scientific context (1/2)

- **Haloscopes** *(using a-γ coupling)* **main way to search for Dark Matter axion**



Primakoff effect $a\gamma^* \rightarrow \gamma$



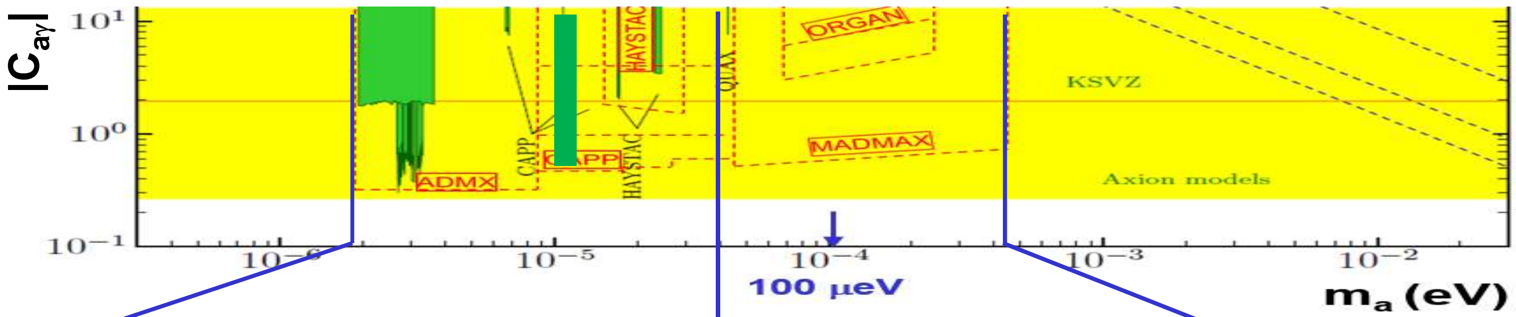
MADMAX can probe the favored post-inflationary m_a = O(100) μeV* range

**Nat. Com.* 13 (2022) 1, 1049 : 40 < m_a [μeV] <180

Scientific context (2/2)

❑ Haloscope experimental challenges

- Convert axions into photons *[E field of O(10^{-12}. $\frac{B}{10\,T}$) V/m]* ➔ **high B_{field}** *[B >> 1T]*
- Boost E_{field} *[up to detectable P~10^{-22} W]* ➔ **resonant** set-up
- Scan over range of axion mass ➔ **tunable** set-up *[precision mecanics]*



2 μeV [0.5 GHz]

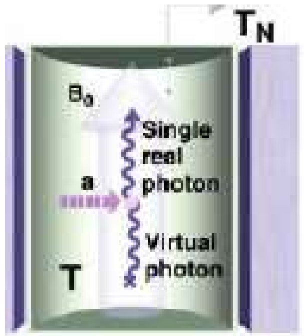
40 μeV [10 GHz]

400 μeV [100 GHz]

[$\nu_a=\nu_\gamma$]
→ Microwave regime

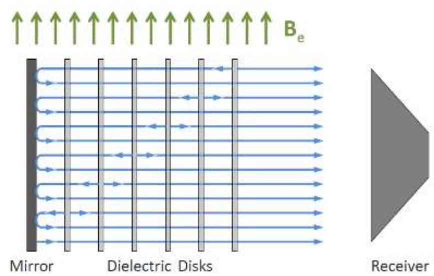
Cavities

[baseline concept **1983**]
PRL51 (1983) 1415



Multi-cavities, Very High B

Cavity size too small + high noise



MADMAX

e.g. Dielectric haloscopes

[novel concept **2013**]
PRD88 (2013) 115002

MADMAX (1/2)

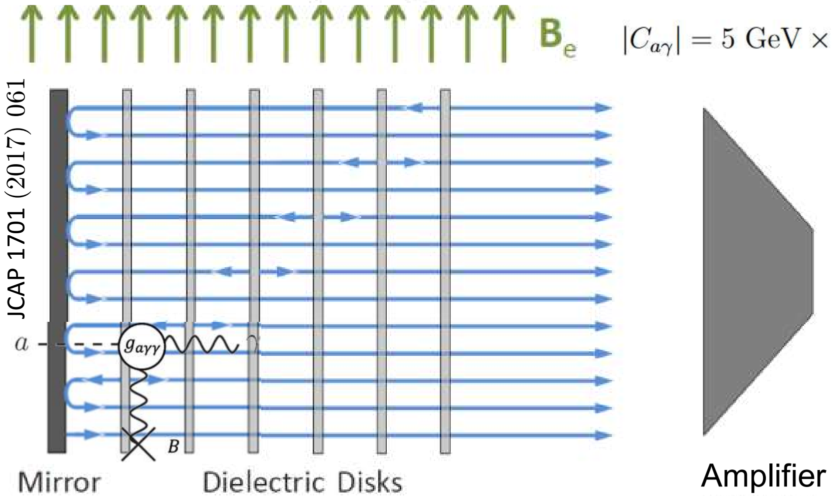
White Paper [EPJC 79 (2019) 186, 1901.07401]

❑ Principles

- **Constructive interference** of coherent photon emission at dielectric layers surface (~leaky resonators cavities): boost (β^2) wrt mirror only [β^2 α ε, δ, N]

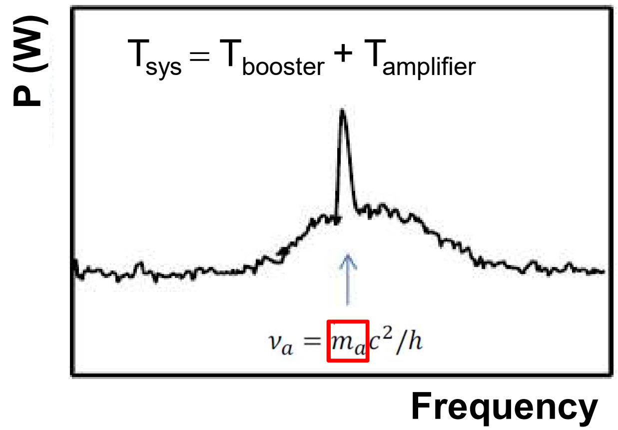
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

$$|C_{a\gamma}| = 5\ \mathrm{GeV} \times \frac{g_{a\gamma}}{\left(\frac{m_a}{1\ \mathrm{GeV}}\right)}$$



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

Thermal Noise



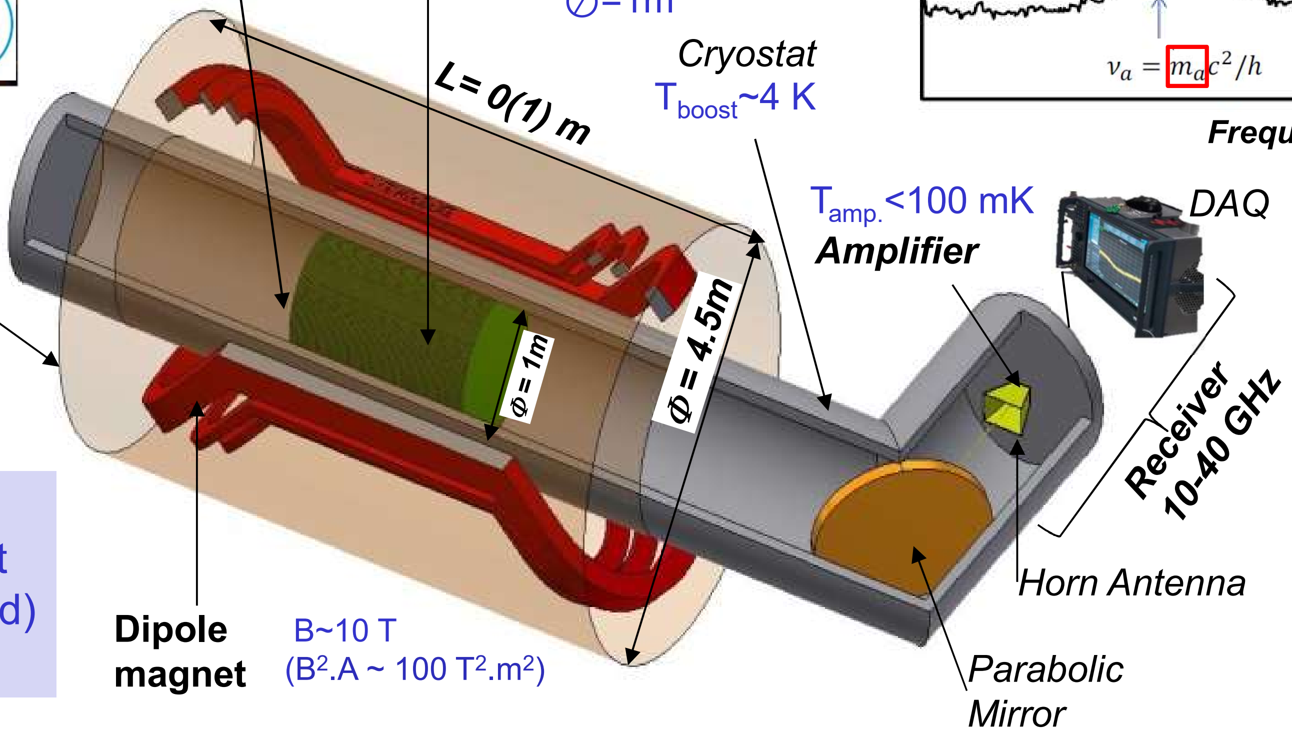
- **Axion mass scan** : by moving discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

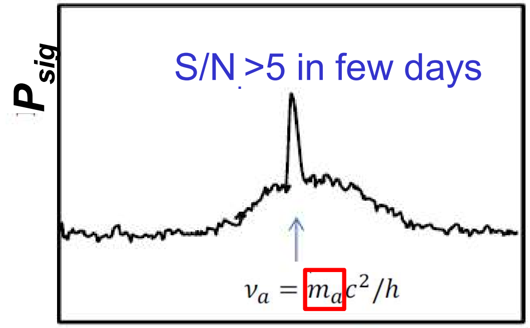
MADMAX exploits a new exp. approach to cover an uncharted phase space

MADMAX (2/2)

~ 50 people, French (2), German (6), Spanish (1) and US (1) institutes

Experiment location: HERA in former H1 iron yoke





3 main challenges :

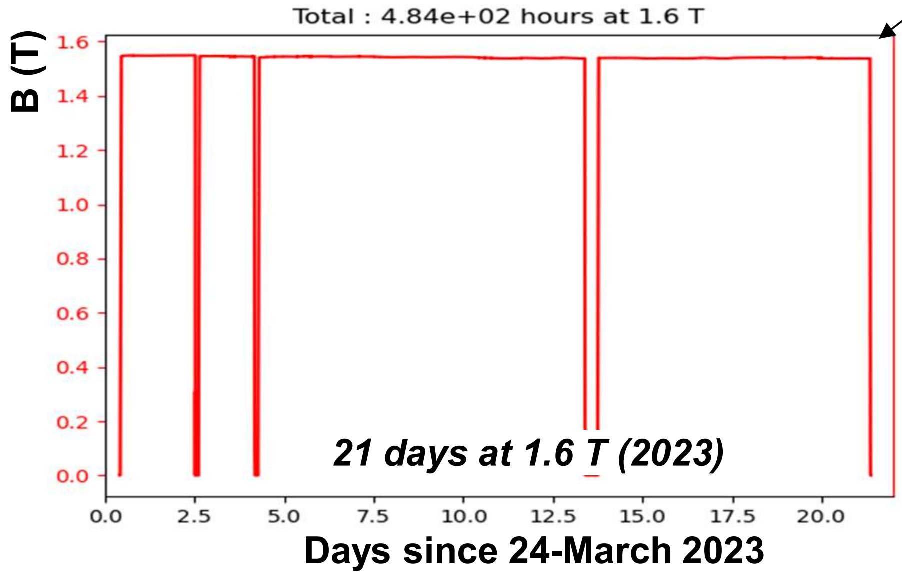
- High field dipole magnet
- Receiver (10's GHz, cold)
- Booster (cold, B field)

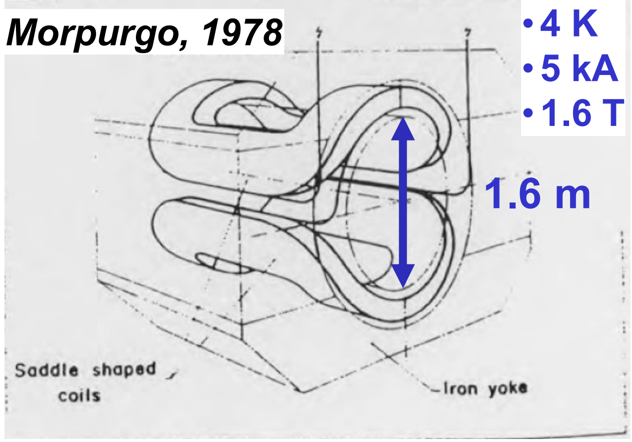
Start with prototyping phase to validate concept: cutting-edge R&D

Magnet for prototype

❑ **CERN borrows us the world largest warm bore dipole magnet**

- **Jun 1978 :** Installation in the North Area at CERN
- **Sep 2020** : CERN RB approves usage by MadMax (YETS)
- **Mar 2021** : full refurbishing around magnet area
- **Mar 2022 : i**nstallation of new power converters
- **Apr 2022** : magnet recommissioning
- **Mar-Apr 2023:** MADMAX full user of the magnet



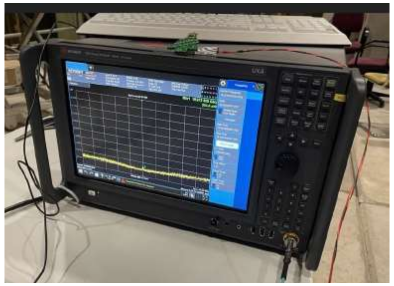


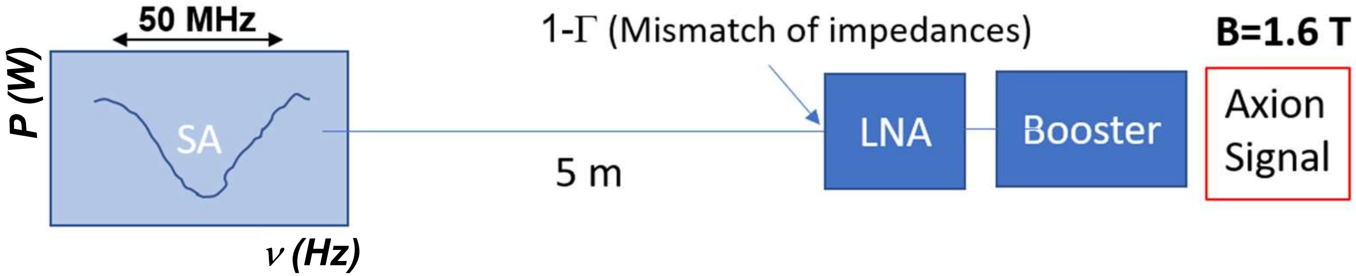
Receiver system for prototype

❑ Composed of

- **Low Noise Amplifier (LNA) ...**
  - ✓ "Classic" HEMT

- **… connected to custom-made receiver**
  - ✓ Three mixing stages to down sample from 20 GHz to 50 MHz
  - ✓ Fast Fourier Transform in 4 samplers → 1% dead time
  - ✓ Tested at CERN in 2022 but difficult to move + some saturation & time instability
- **… connected to commercial spectrum analyzer (SA)**
  - ✓ Tested at CERN in 2023 : stable, no saturation but higher dead time*





- **… P (W) calibrated with a noise diode (50 K) → System temperature (T_{sys} in K)**

* Improve dead time next year by adding data streaming

Develop the booster concept

❑ Address the two main challenges

- Move the disks at μm level precision at cold and under high B-field
- Understand RF behavior → Calibrate boost factor

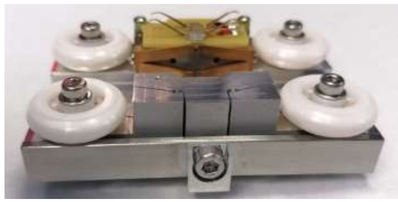
Name	Goal	Type	Made of	Avail.	Test	Room Temp. **Cold (10 K)**
P200	Piezo-motor + mechanics	Open Booster	1 moveable disk ϕ = 200 mm	2021	**2022**	
CB100	RF studies + First physics	Closed booster	3 fixed disks ϕ = 100mm	2021	2022, 23, **24**	
CB200	RF studies + First physics	Closed Booster	4 fixed disks ϕ = 200 mm	2022	24	
OB300	Scan ALP around 100 μeV	Open Booster	3-20 moveable disks ϕ = 300 mm	2024		**25, 26?**

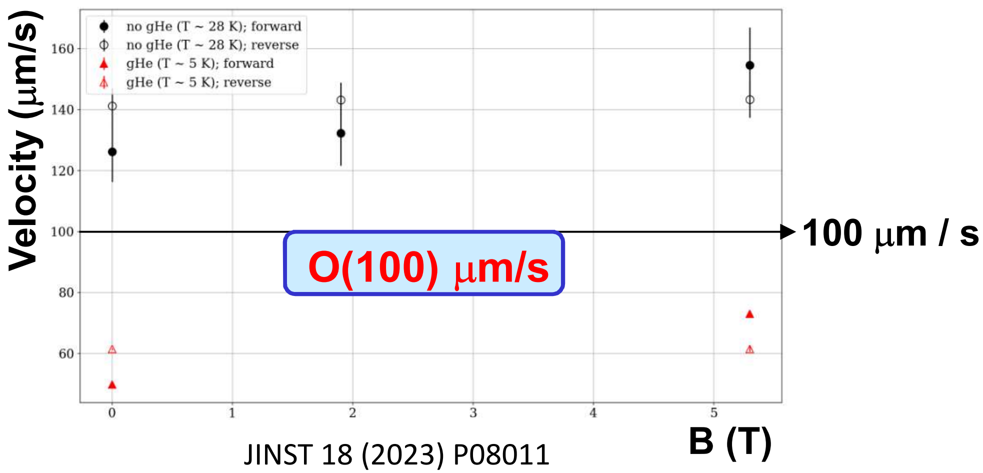
Gradually building the 'final' booster design

Disk drive (1/2)

Name	Goal	Concept	Made of	Avail.	DESY magnet test
P200	Piezo-motor + mechanics	Open Booster	1 **moveable** disk ϕ = 200 mm	2021	2022

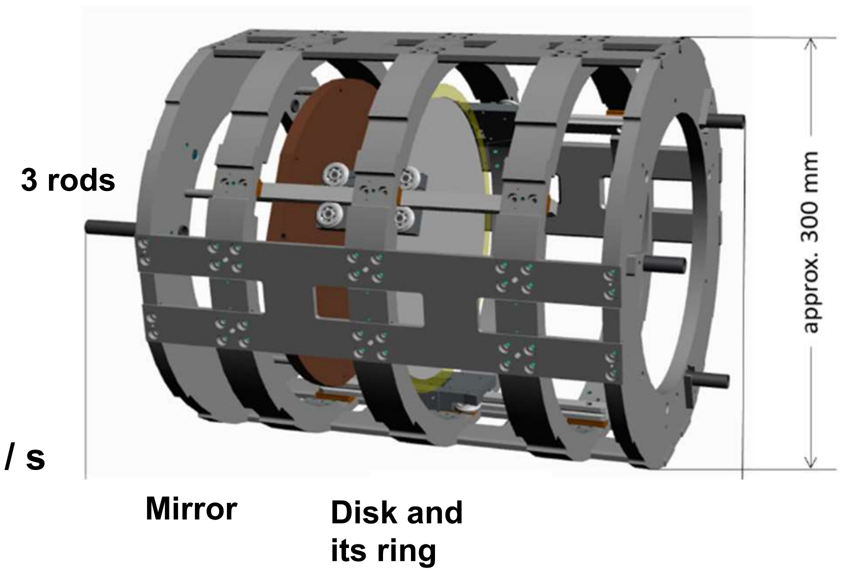
Successful test of JPE piezo motor at 5 K and 5.3 T *(ALP magnet in DESY)*





JINST 18 (2023) P08011

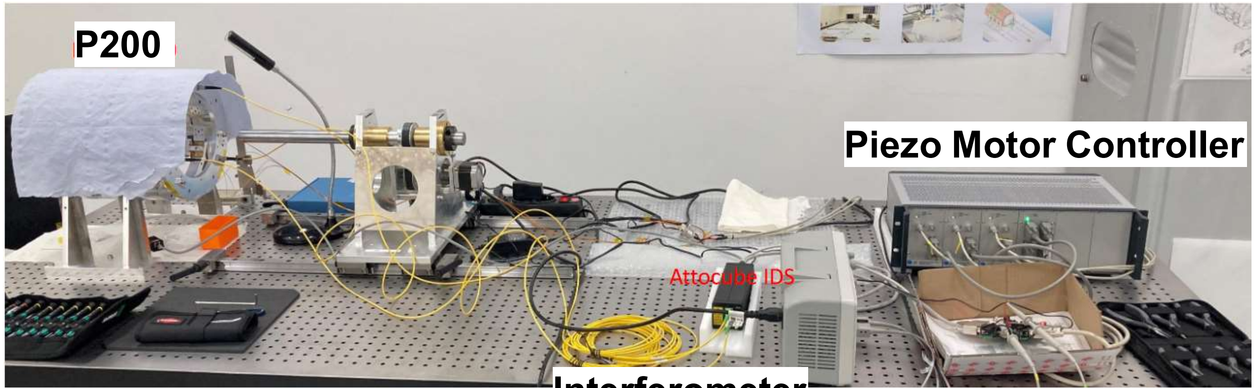
Build full mechanical structure of Open Booster and insert 1 mirror + 1 disk *(3 piezo motors)*



Disk drive (2/2)

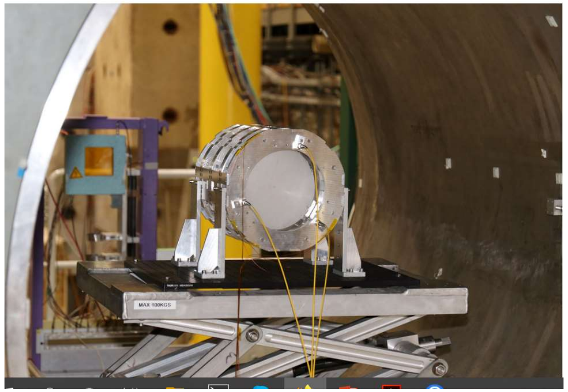
Name	Goal	Concept	Made of	Avail.	Morpurgo test
P200	Piezo-motor + mechanics	Open Booster	1 **moveable** disk ϕ = 200 mm	2021	2022

Tested in the lab, in a CERN cryostat (4K) …

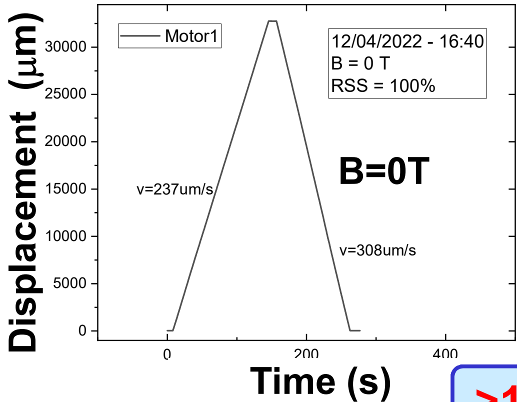


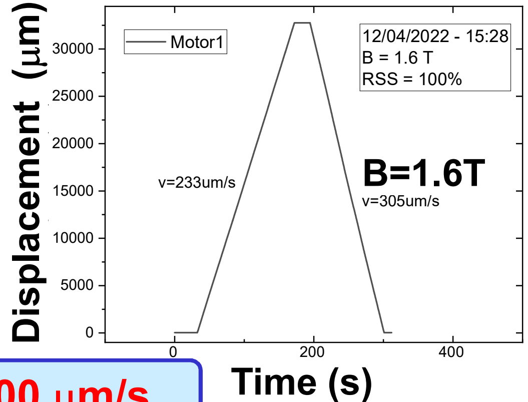
Interferometer

… and under 1.6 T



Validate piezo motors + booster mechanics

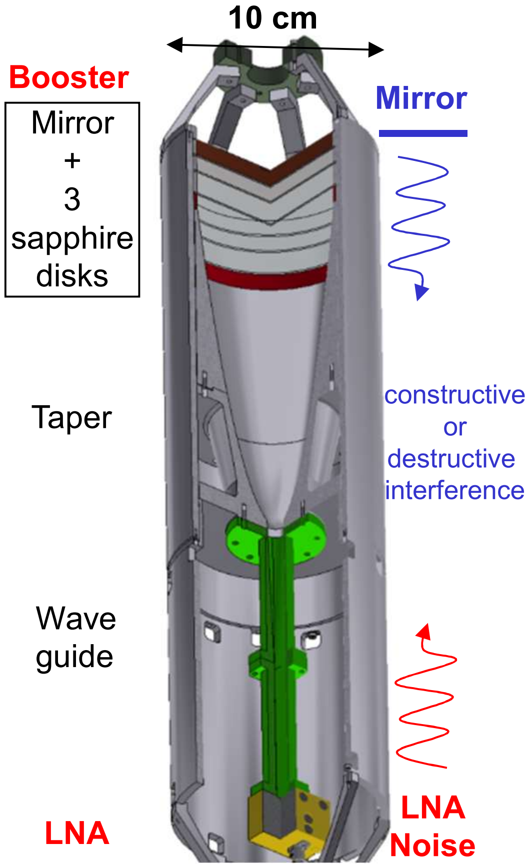




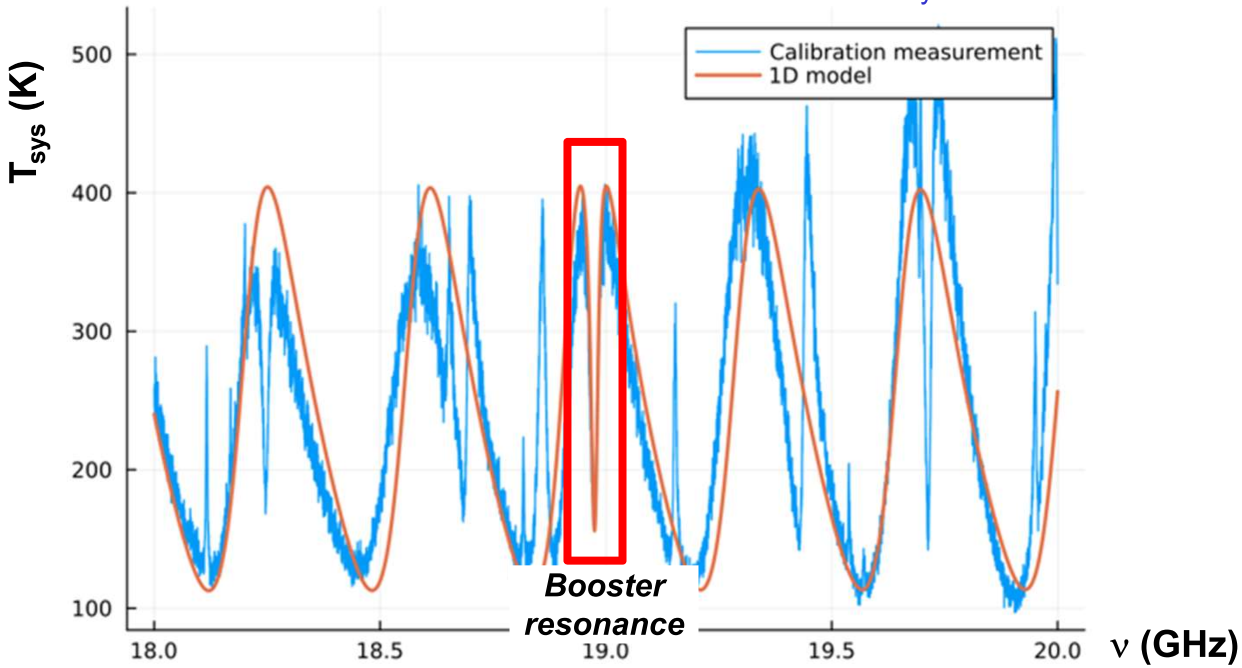
>100 μm/s

RF (1/3)

Name	Goal	Concept	Made of	Avail.
CB100	RF studies	Closed booster	3 **fixed** disks ϕ = 100mm	2021



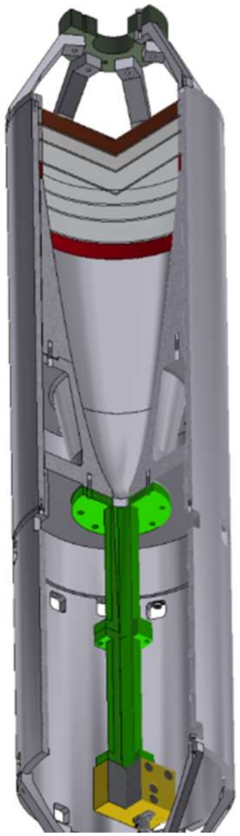
Simulate **LNA** (ADS) and **Booster+taper** system (COMSOL)
→ compare with measured system temperature (T_{sys}) in 18-20 GHz

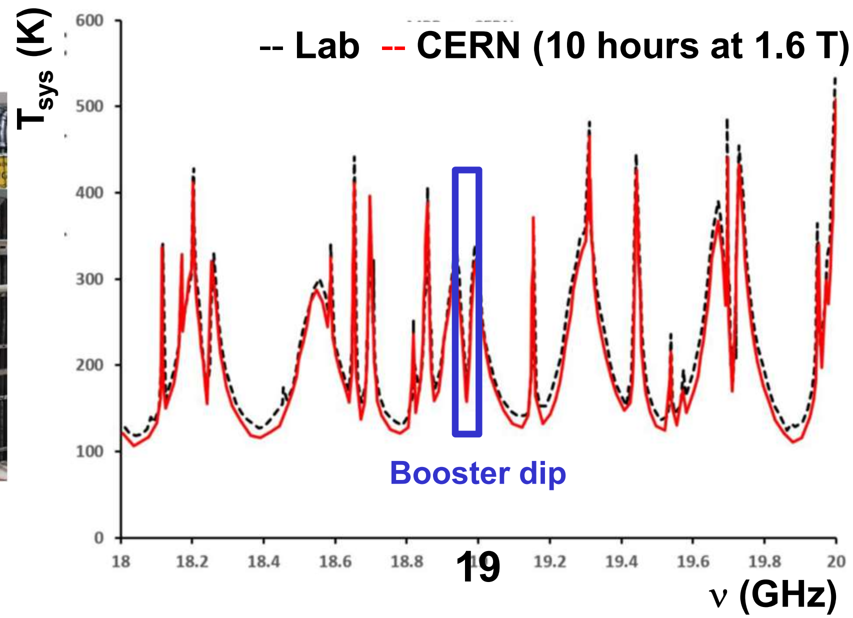


Model the RF behavior *(esp. at the booster resonance)*

RF (2/3)

Name	Goal	Concept	Made of	Avail.	Morpurgo test
CB100	RF studies	Closed booster	3 **fixed** disks ϕ = 100mm	2021	2022

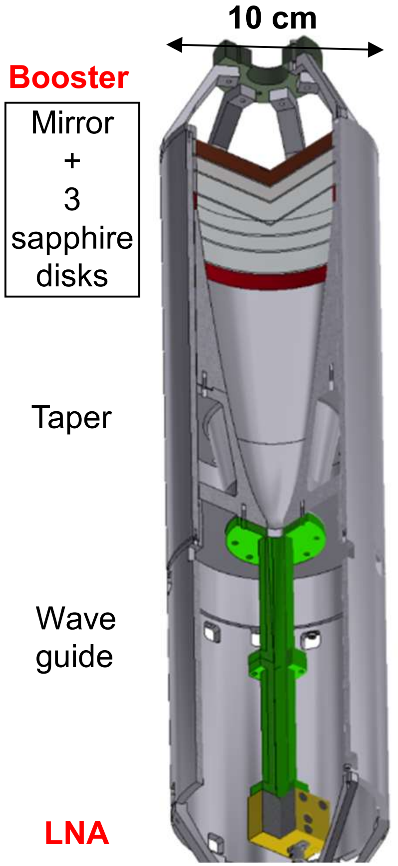




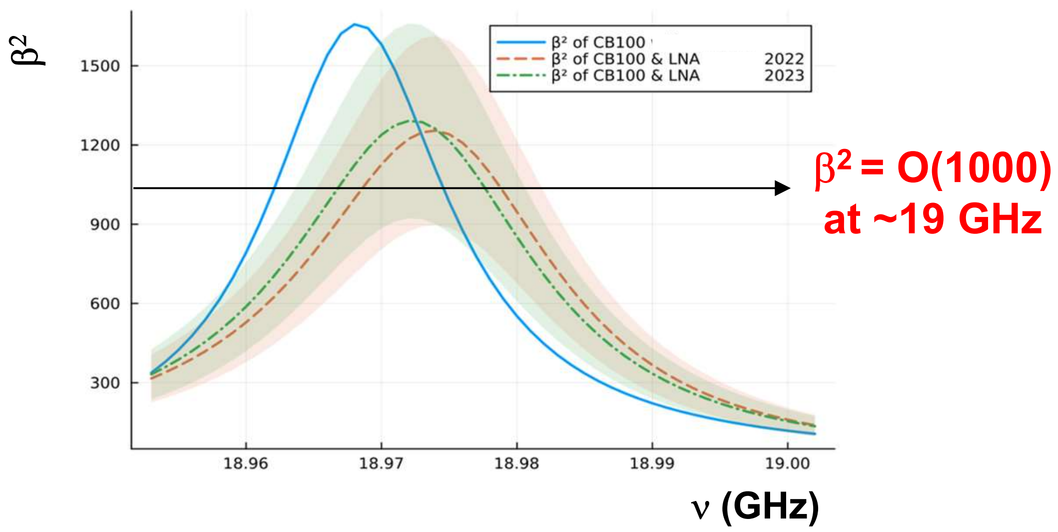
No impact from the CERN environment

RF (3/3)

Name	Goal	Concept	Made of	Avail.
CB100	RF studies	Closed booster	3 **fixed** disks ϕ = 100mm	2021



Simulate **LNA** (ADS) and **Booster+taper** system (COMSOL)
→ Extract the boost factor shape

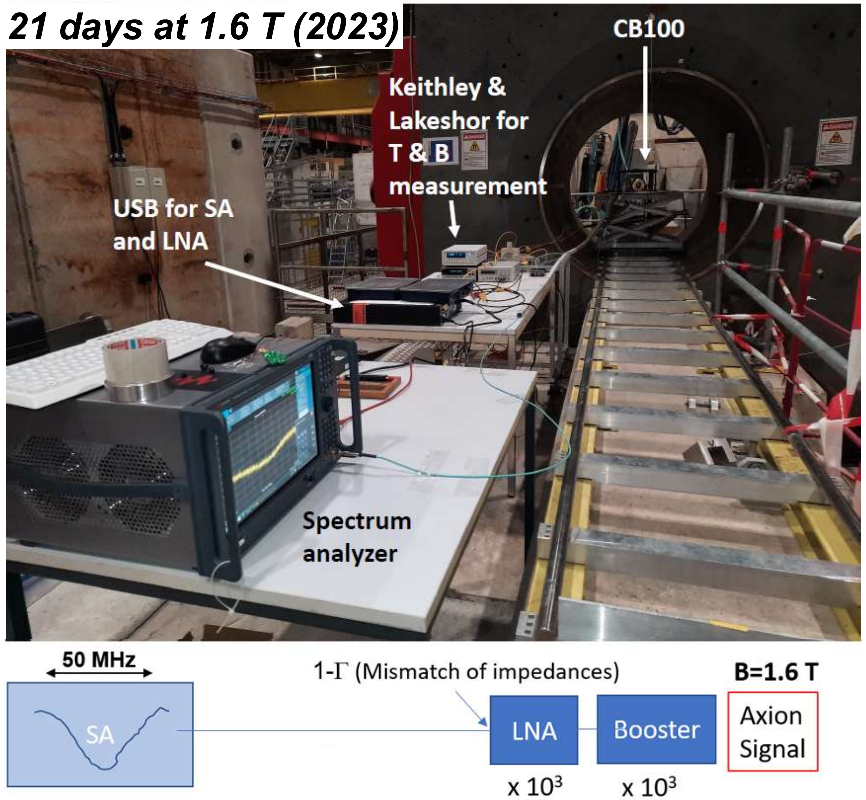


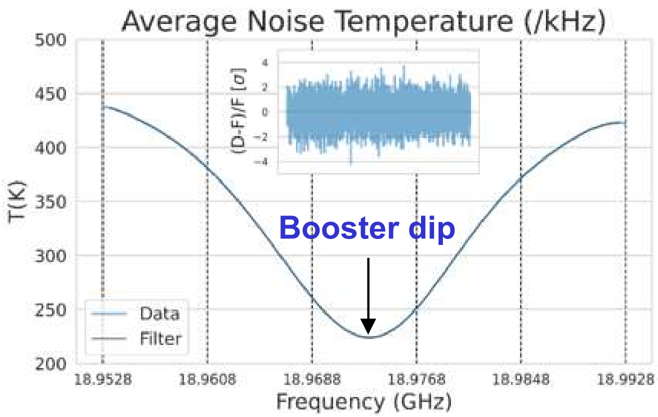
Model the boost factor shape with systematic uncertainties

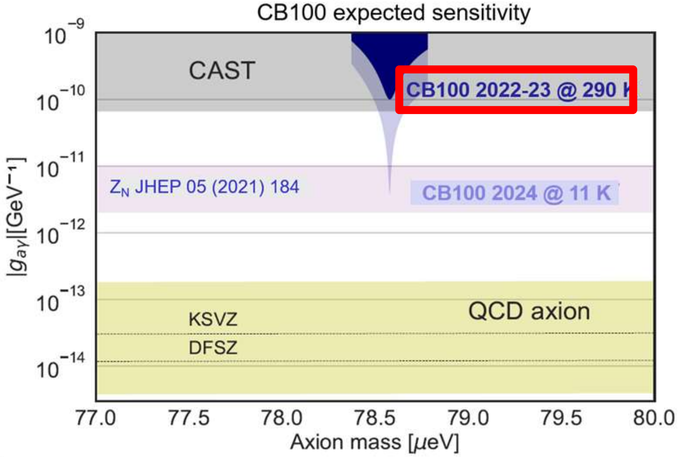
ALP Physics (1/3)

Name	Goal	Concept	Made of	Avail.	Morpurgo test
CB100	First physics	Closed booster	3 **fixed** disks ϕ = 100mm	2021	2022, 2023

21 days at 1.6 T (2023)





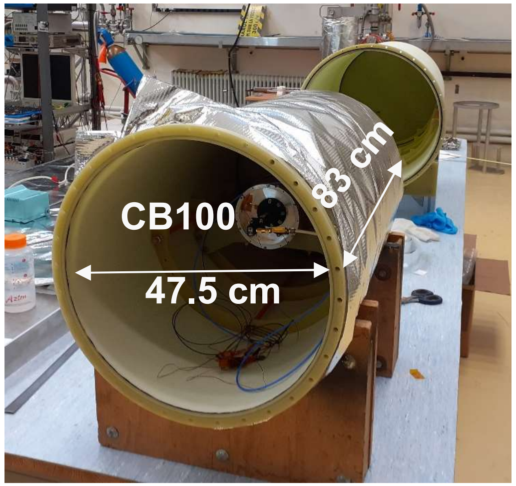


Very stable with time over 21 days → First physics in prep.

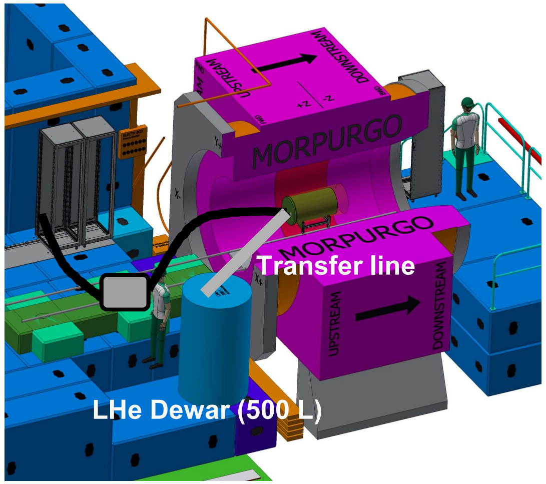
ALP Physics (2/3)

Name	Goal	Concept	Made of	Avail.	Morpurgo test
CB100	RF studies + First physics	Closed booster	3 **fixed** disks ϕ = 100mm	2021	**2024**

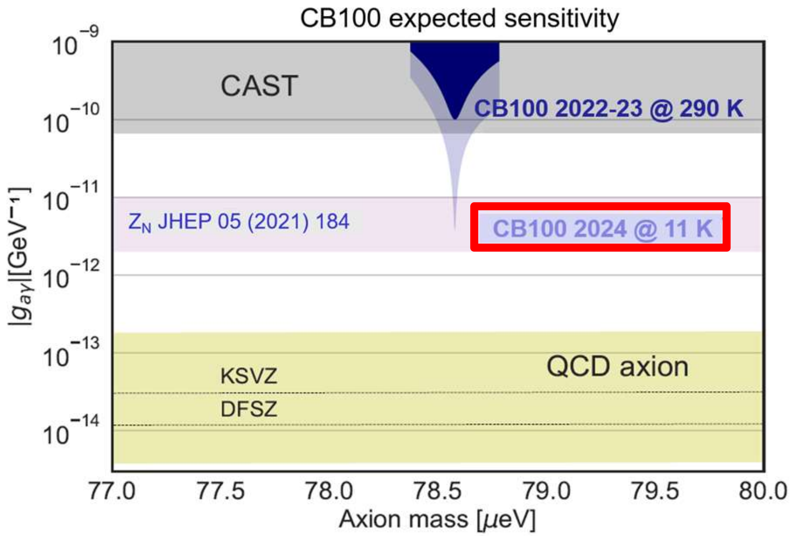
Develop a 'cheap' cryostat with CERN cryolab to cool the booster + LNA → Validated the principle in 2023



Vacuum between Inner and Outer vessel



He flow from dewar to cryo
→ **cooling in ½ day**
→ **Stable <10K during >10 hours**

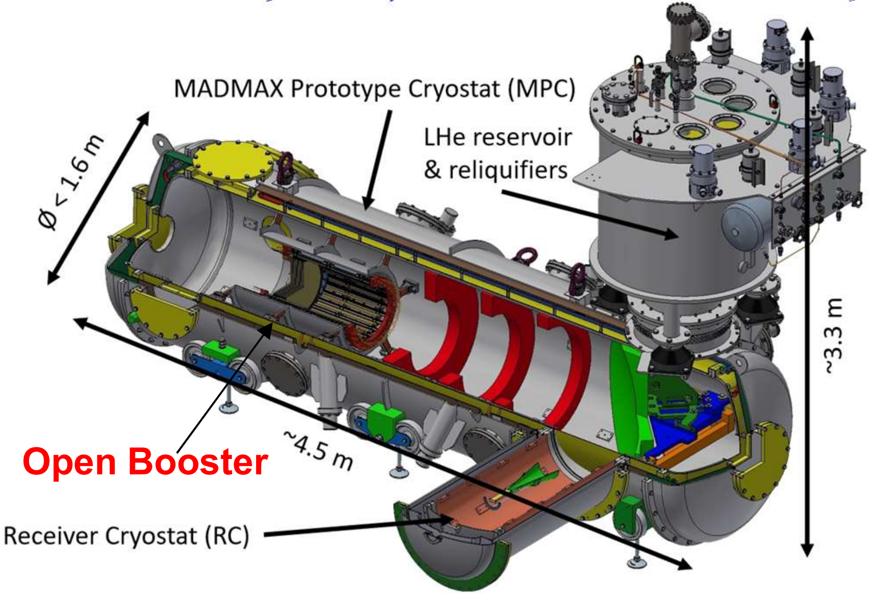


First short cold run in 2024

ALP Physics (3/3)

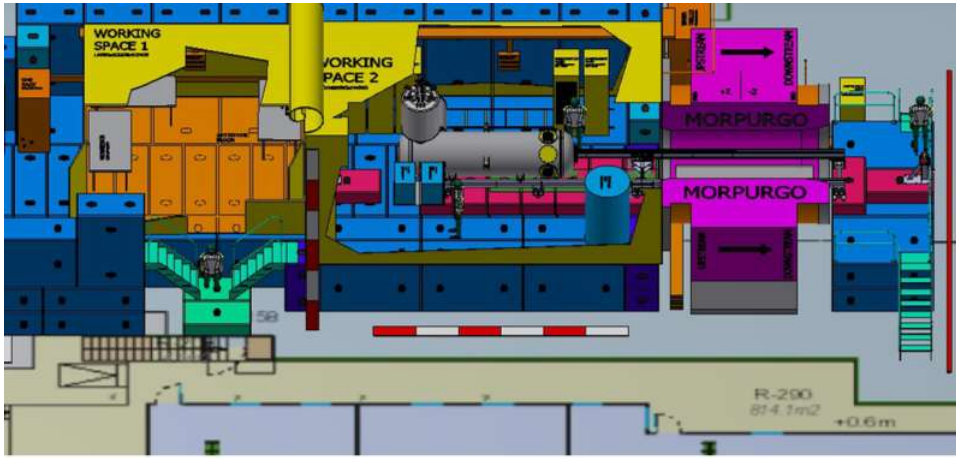
Name	Goal	Concept	Made of	Avail.	Morpurgo test
OB300	Scan ALP around 100 μeV	Open Booster	3-20 **moveable** disks ϕ = 300 mm	2024	**2025, 26?**

Open Booster inserted in a Stainless Steel cryostat *(to be delivered in Mar 2024)*



Open Booster built with P200 and CB100 experience

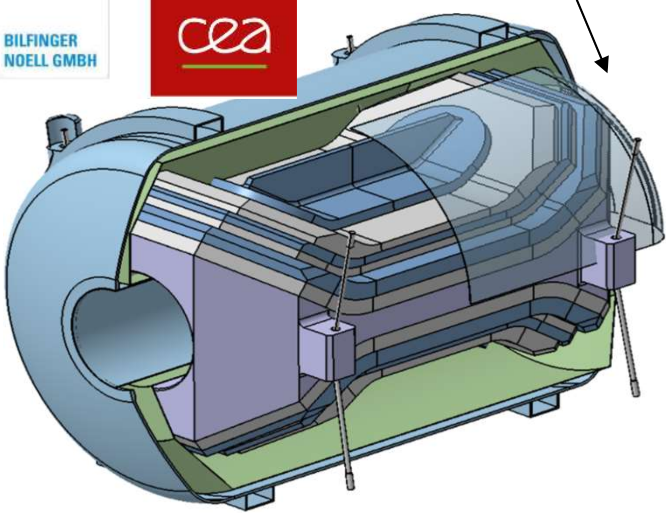
Morpurgo CERN area refurbished to host the SS cryostat

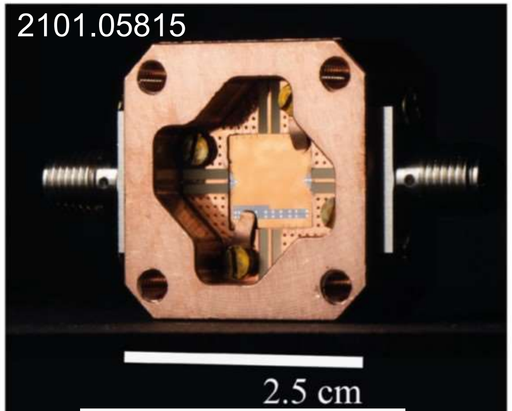


Long cold run + mass scan in 2025 (26?)

MADMAX & France

- **Two French institutes joined MADMAX in 2020**
  - **CPPM :** precision mechanics, CERN tests coordination, simulation / data analysis
  - **Institut Néel :** final ultra-low noise amplifier
  - \+ **CEA-IRFU** : work on final magnet design





Upgraded LNA : TWPA

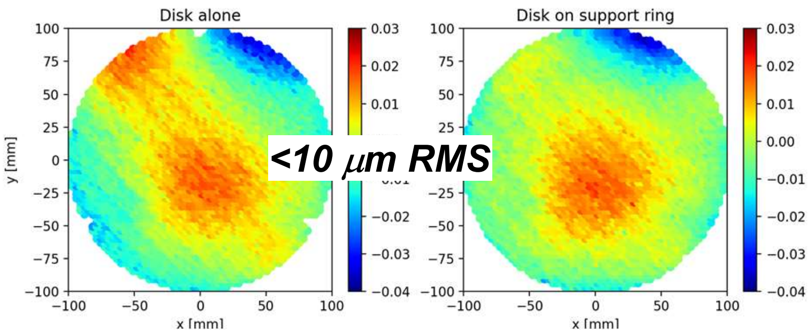
\+ **CNRS IRL** ``*DMLab*” **(with Helmholtz Inst.) :** MADMAX is a central project

MADMAX looking for new (French) institutes to join !

MADMAX & CPPM

❑ Precision mechanics (μm)

- Precision 3D measurements of disk
- Fabrication of disc support rings



- **Next** : Design of the mechanical support of the OB300 booster

❑ Coordination of proto tests at CERN

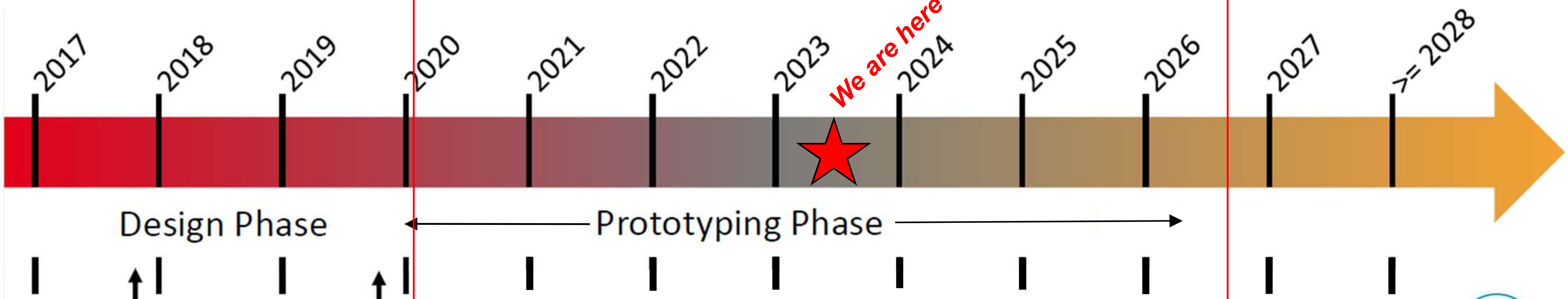
- Initiate the choice of the magnet
- Prepare infrastructure around the magnet

- Coordinate the tests during beam shutdown periods (1 month / year)

❑ Simulation / data analysis

- PhD student started Oct. 2022 on P200 and CB100 data analysis + simulation of OB300

MADMAX timescale

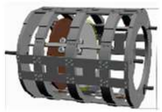


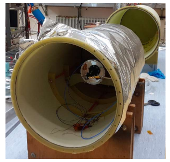
Design Phase

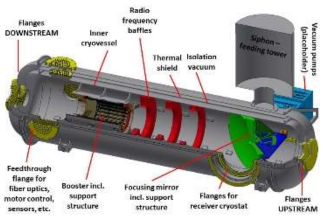
Prototyping Phase

Foundation of MADMAX Collaboration

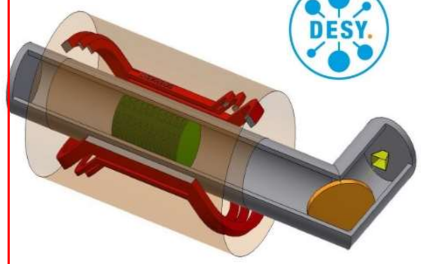
First endorsement by DESY PRC







Usage of **MORPURGO magnet (1.6T)** approved by **CERN** Research Board during beam shutdown



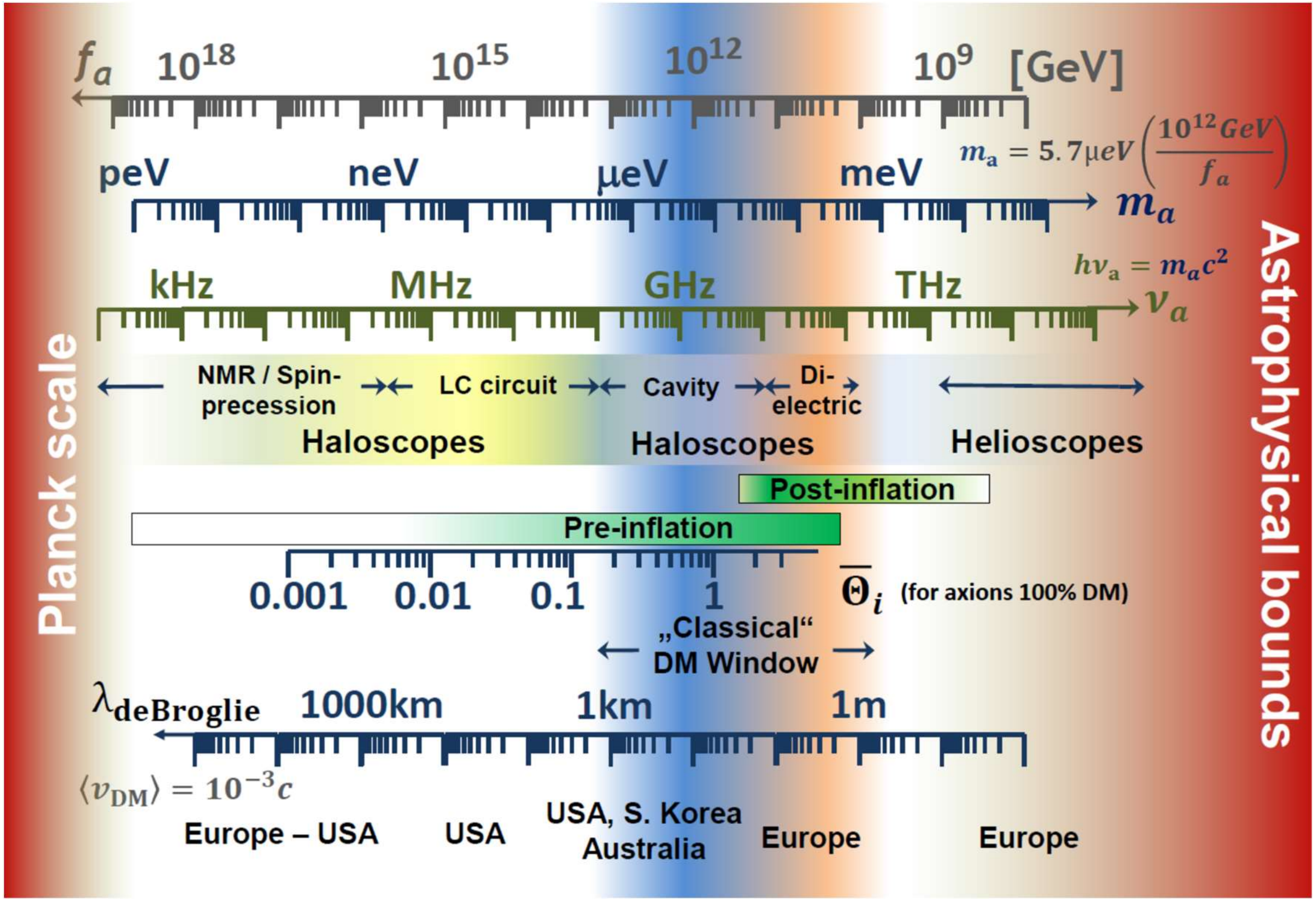
Full-size MADMAX magnet commissioning

1000- 10000 | 10 – **220** | **1.6** | **0.01**-0.1

$$g_{a\gamma} \propto \left(\frac{50000}{\beta^2}\right)^{1/2} \times \left(\frac{T_{sys}}{4\ \mathrm{K}}\right)^{1/2} \times \left(\frac{10\ \mathrm{T}}{B_e}\right) \times \left(\frac{1\ \mathrm{m}^2}{A}\right)^{1/2} \times \left(\frac{4\ \mathrm{days}}{t}\right)^{1/4} \times \left(\frac{\mathrm{SNR}}{5}\right)^{1/2}$$

BACKUP

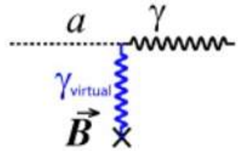
Axion scales



Axion/ALP searches

- ❑ **Coupling to photon (most) promising way to detect axion**

Primakoff effect $a\gamma^* \rightarrow \gamma$



Haloscopes

Relic DM axions

High axion flux

Model dependent

QCD axion DM

[1-1000 μeV]
[0.25-250 GHz]

e.g. MADMAX

Helioscopes

Solar axions

Medium axion flux

Mildly model dependent

QCD axion / ALP

[higher masses up to keV]

e.g. (Baby)IAXO

Lab experiments

Lab produced
→ fully controlled setup

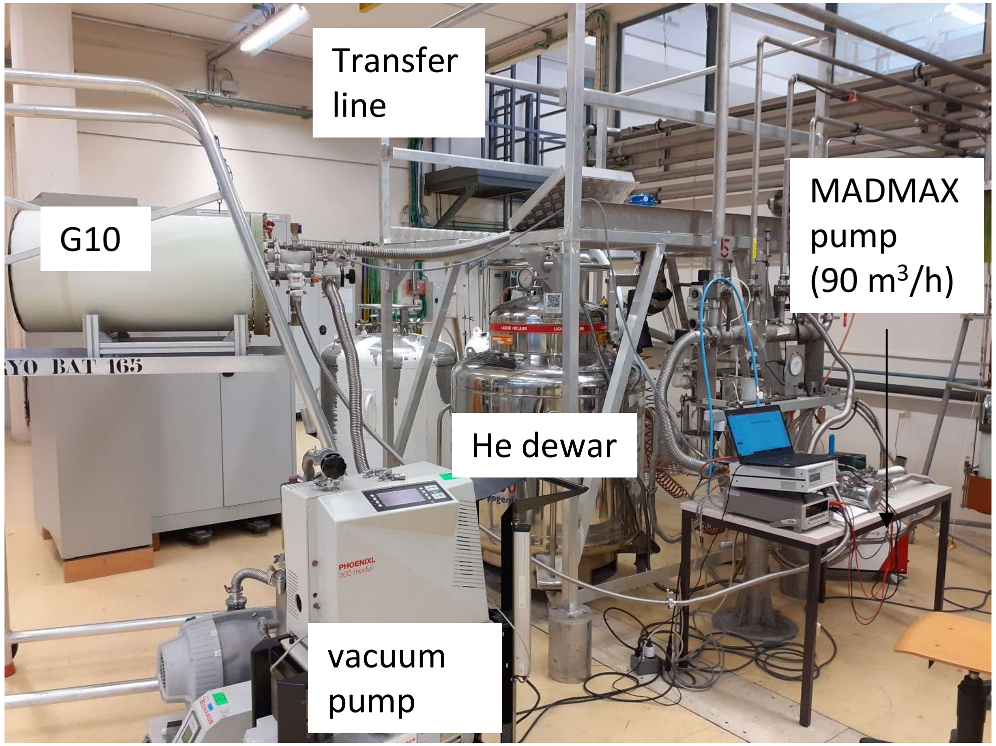
Low axion flux

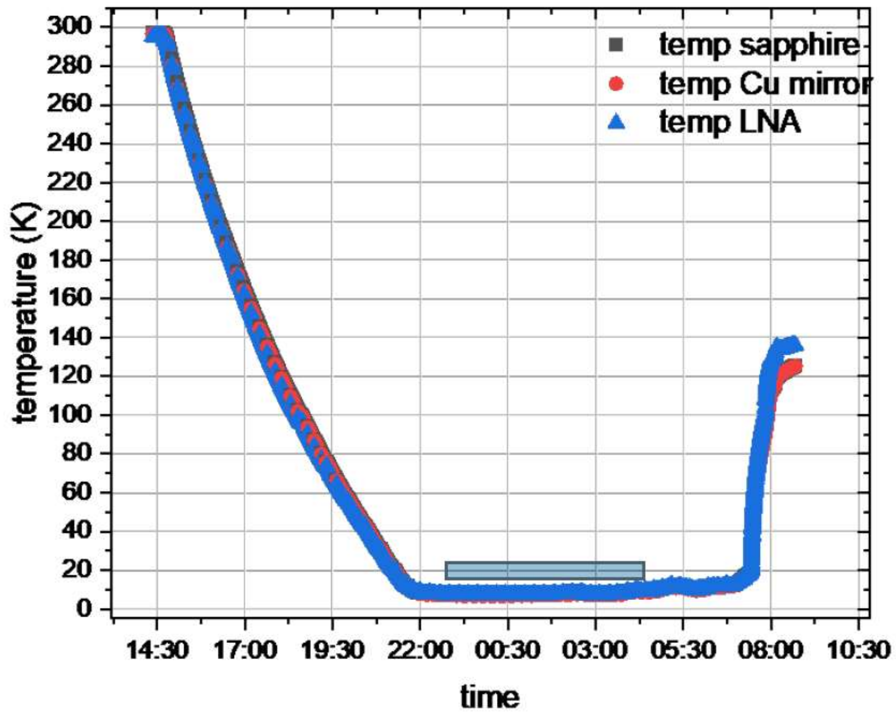
Model independent

ALP

e.g. ALPS II

G10 cryostat

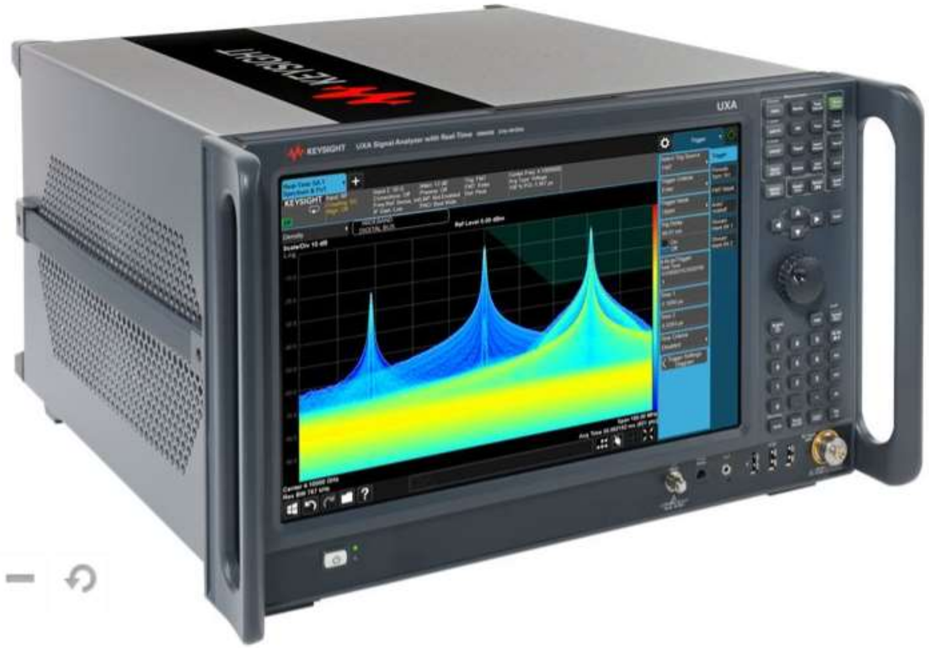




Spectrum Analyzer

2023 → Keysigth : N9040B

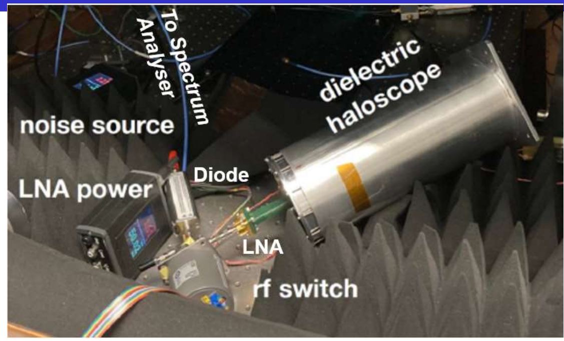
2024 → Rhode&Schwarz FSW26 with streaming option



CB calibration

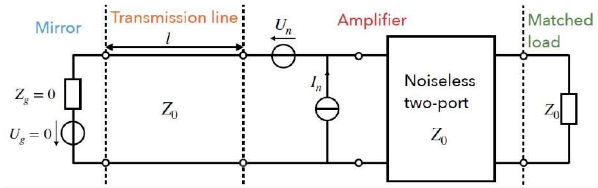
1- Power (W/kHz) to Thermal Noise Temp. (K) :

- Use a well calibrated diode with a 30 dB Attenuator
- T Diode On = Room Temperature + 50K = 345 K
- T Diode Off = Room Temperature = 295 K
- With P (Diode On), P (Diode Off), estimate reflections
- From P (LNA + Booster), P (Diode On), P (Diode Off) deduce **T (LNA + Booster)**



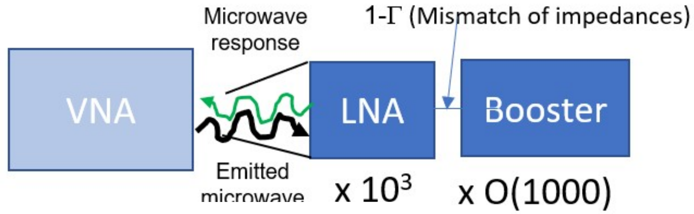
2- ADS model (I_n, U_n) for LNA Noise

- Short / Open / Load with RF switch gives access to circuit parameters



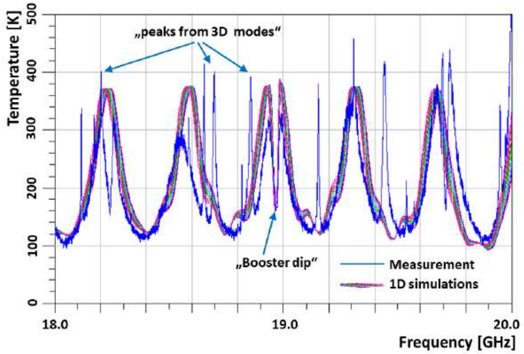
3- Reflectivity measurements with a VNA

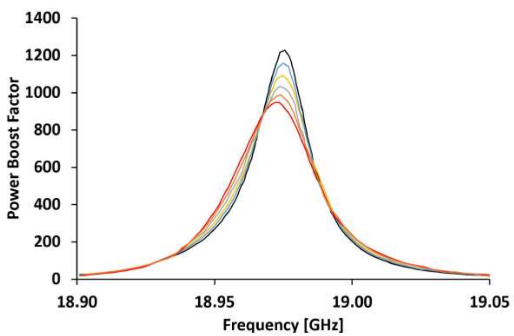
- Should match the 3D COMSOL simulation of the booster + taper



4- Merge ADS and COMSOL simu → Tsys (K)

- Should match the measured Tsys
- Wavy because of coherent and destructive interference (different propagation length) when injecting the LNA noise in the booster



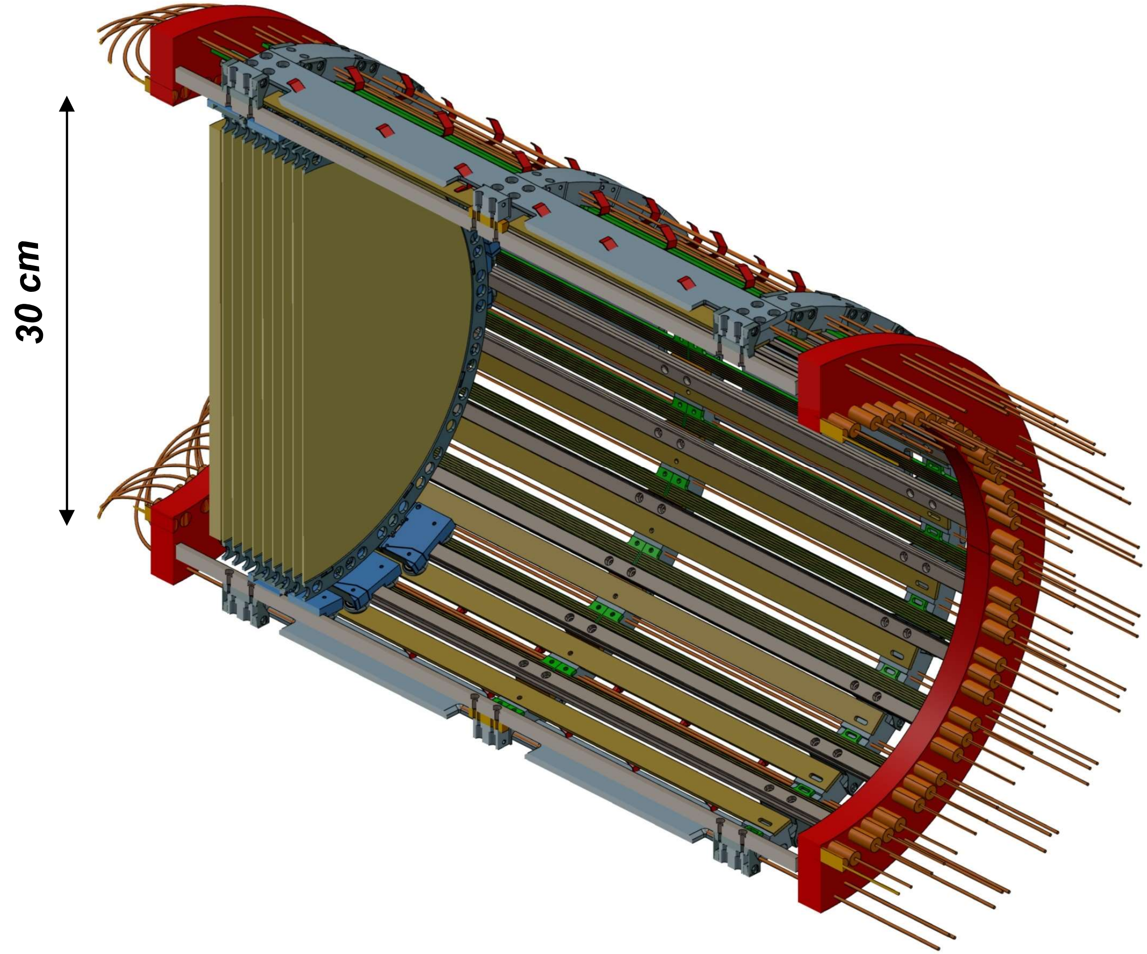


5- Deduce the Booster factor from the model

- Including uncertainties

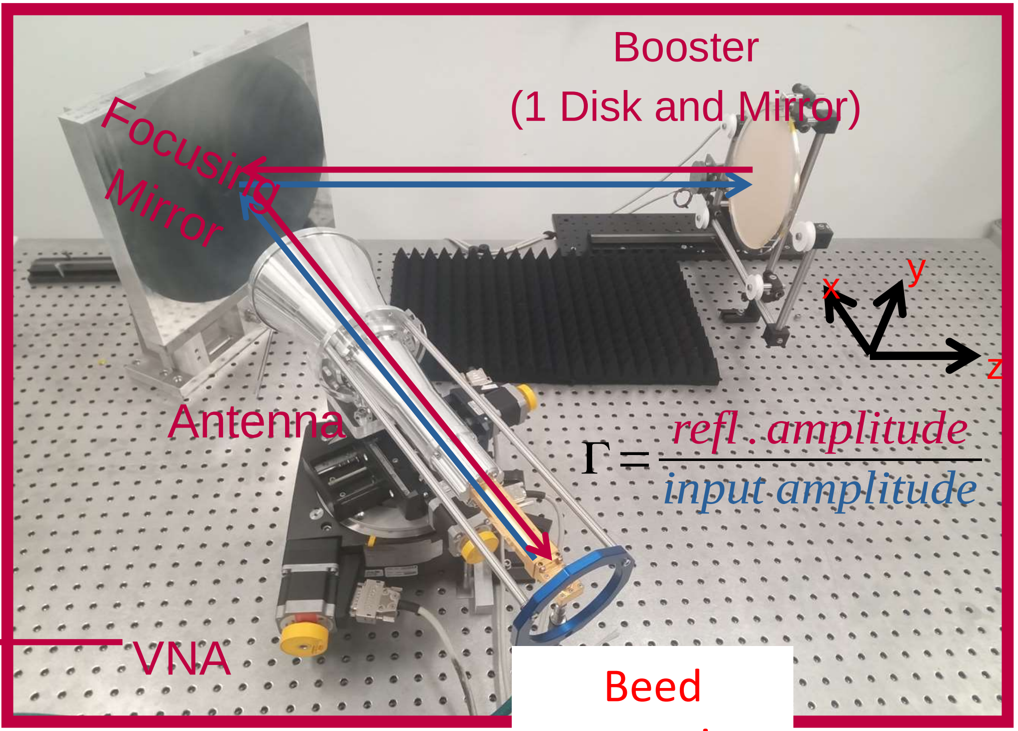
Procedure is being finalized

OB300

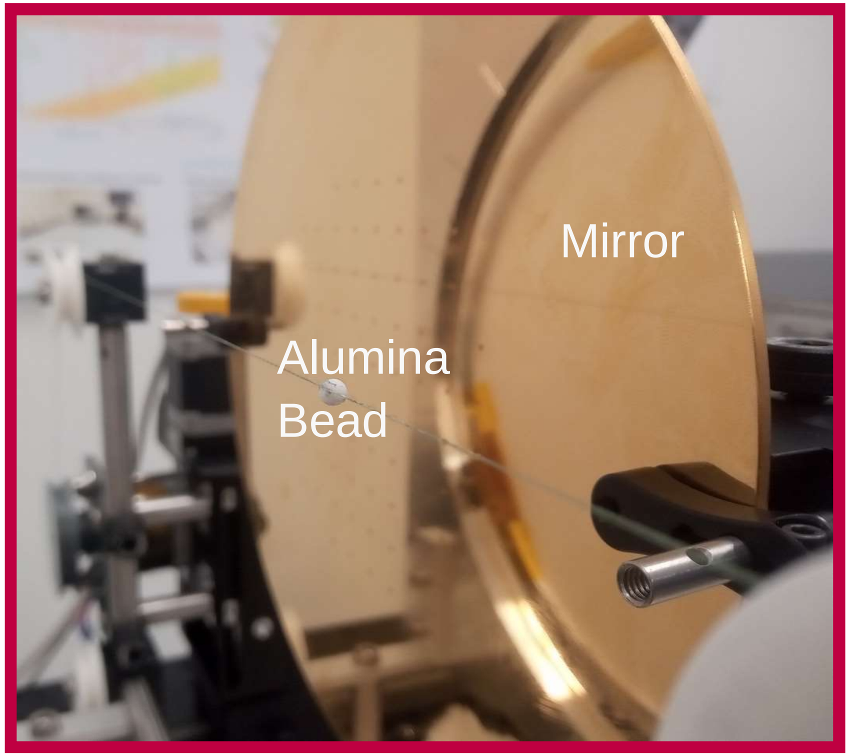


OB calibration (1/2)

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



VNA



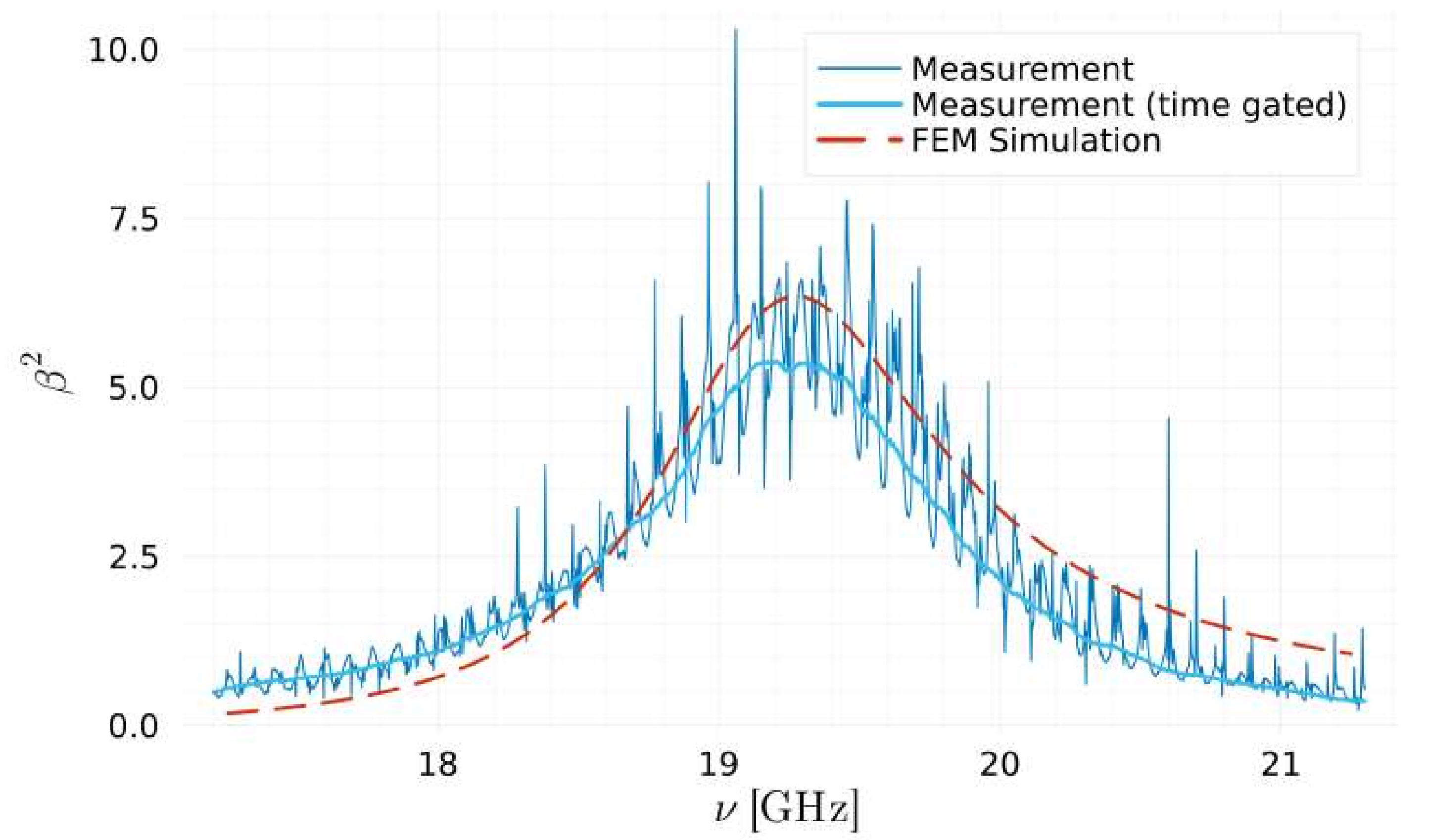
Beed properties

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

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

OB calibration (2/2)

Test with a single disk (low boost factor)



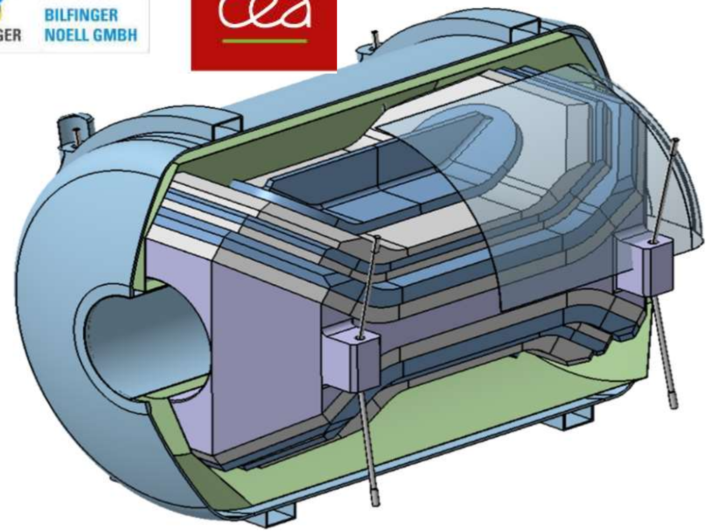
Procedure is being finalized

Towards final magnet / receiver

❑ Progresses on final magnet

- Design completed: 2x9 skateboard coils with novel copper CICC conductor

[NbTi with Cu jacket @ 1.8K]



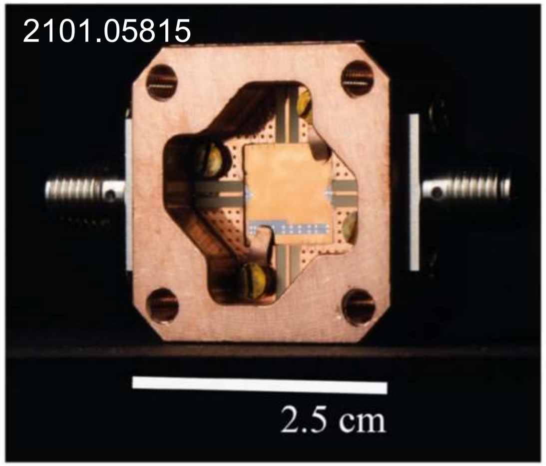
- Recently demonstrated that coils will be safe in terms of quench protection
- **Next** : Design, manufacture and test a small MADMAX coil (6T)

❑ Progresses on final receiver

- Very low noise pre-amplifier *[P_{sig}~T_{sys}]*

HEMT (G=33 dB, 4K added noise) below 40 GHz

- Josephson Junction being developed to further minimize noise *(quantum limit)*



TWPA prototype with G>20 dB and 1K added noise at 10 GHz

- **Next**: >40 GHz techno. to be developed