Addendum to MADMAX Proposal: potential tests at CERN during LS3 (2026-28)

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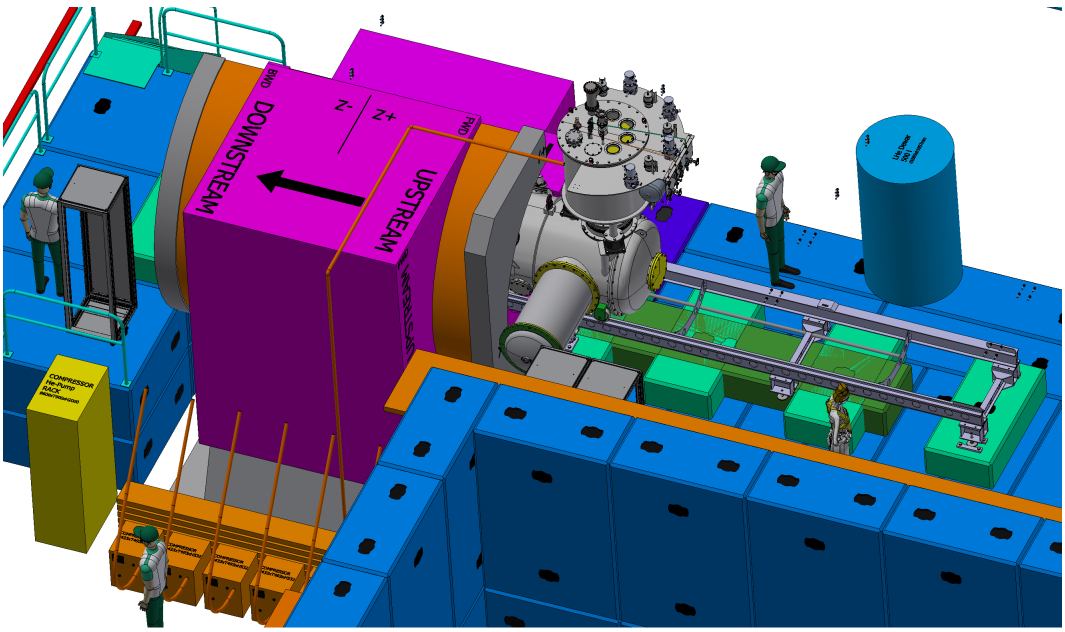

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Abstract

MADMAX has tested various booster prototypes inside the Morpurgo magnet during the beam shutdowns 2021-22, 2022-23 and 2023-24. These tests open the road towards performing measurements with a fully tunable mechanical booster prototype inside a stainless steel cryostat. Booster and cryostat are being built and should be delivered in summer 2024 and commissioned during O(6) months. The current plan is to send them to CERN at the end of 2025. Putting this set-up into the Morpurgo magnet will enable us to validate the dielectric haloscope concept proposed for MADMAX, a crucial step for the final experiment. The idea is to profit from the long shutdown 3 to perform extensive measurements of O(9) months equally shared in 2026, 2027 and 2028: after the concept validation in 2026, the idea is to scan an uncharted region of the axion-like particle (ALP) phase space around the mass $m_a \sim 80$ μeV ($\pm 2\mu$eV) and down to ALP-γ coupling $g_{a\gamma} \sim 10^{-13}$ GeV^{-1}.

Contents

1 Introduction

In the year 2020, the MADMAX collaboration has proposed to use the Morpurgo magnet for validation of the dielectric haloscope concept using prototype boosters and for a first search of Axion-Like Particles (ALPs) in an unexplored part of parameter space [1]. The CERN SPSC has evaluated this proposal and endorsed the plans. The CERN research board decided to offer this opportunity to the MADMAX collaboration during the SPS beam shutdowns from 2022 to 2025 before Long Shutdown 3 (LS3).

In the original proposal [1], the total presence at CERN with the final prototype booster and cryostat was foreseen to be between December to April leaving only few weeks for physics with no contingency. Booster and cryostat are being built and should be delivered by summer 2024, commissioned during O(6) months and ready for shipment to CERN by spring 2025. The current plan is therefore to shift the shipment to end of 2025 and profit from LS3 to operate the final MADMAX prototype inside the Morpurgo magnet during O(9) months equally shared in 2026, 2027 or 2028. In this scenario the expected sensitivity to ALPs is evaluated in this addendum.

2 MADMAX prototype tests at CERN (2022-2024)

MADMAX relies on the principle of a dielectric haloscope [2]. It consists of a set of dielectric discs in front of a mirror - called booster. If exposed to a static B-field, the booster enhances the axion to photon conversion probability, sourcing a very small E-field, that could be detectable with current technology. The amplification of axion to photon conversion probability with respect to a single mirror as function of frequency is called power-boost factor (β^2). To validate this new concept, the MADMAX collaboration follows the strategy of first experimentally verifying the general concept in terms of radio frequency (RF), calibration and mechanical feasibility of a dielectric haloscope inside a dipole magnet using smaller scale proof of principle setups (later called prototypes). Once the necessary new technologies have been verified, they can be implemented into a small-scale prototype of the final set-up, tested in the Morpurgo magnet and deliver competitive ALP limits. The prototypes can then be gradually increased in size and hence sensitivity.

The power-boost factor, i.e. the amplification of the axion to photon conversion with respect to a single dish antenna can be determined by a combination of E-field and reflectivity measurements, thermal noise investigations and simulations. The general principle of quantifying the boost of the axion to photon conversion in a dielectric haloscope was first verified using a so called "closed booster" (CB). This booster has few discs at fixed position which are inserted inside a cylinder with well defined conducting boundary conditions. This allows for a good description of the E-fields inside the system, enabling a reliable understanding of the standing wave patterns (modes) and the propagation of radiation. The power emitted and/or reflected by the booster system is collected by a taper and guided to a receiver system with a HEMT low noise amplifier (LNA) from Low Noise Factory as first stage amplification element. Two closed booster systems, CB100 and CB200 have been build in 2021 and 2023 respectively, similar in functionality but differing in diameter of the discs (100 mm and 200 mm, respectively). A sketch of a closed booster is shown in Figure 1 top.

To finalize the functionality of the experiment, the discs of the dielectric haloscope must be movable. Moreover the discs of the booster need to be operated inside a strong B-field and at cryogenic temperatures (few K). To validate that, a mechanical prototype called open booster 200 (OB200), consisting of one 20 cm diameter sapphire disc moved with three piezo-motors has been developed. The disc is suspended inside the booster mechanical structure using a support ring. Three piezoelectric motors developed for the MADMAX purpose and certified at 5.4 T [3] are moving the disc along ceramic rails. Three commercial interferometer arms are measuring the position of the ring and serve as feedback to the motors. A sketch of the OB200 is proposed in Figure 1 bottom.

To determine the power-boost factor with arbitrary boundary conditions, a dedicated method was developed [4, 5]: a dielectric bead smaller than the respective wavelength is placed in front of the mirror (or in between the discs) and the E-field is determined at the position of the bead by the change of reflectivity with respect to the unperturbed configuration (i.e. without a bead). This provides a direct determination of the E-field at the position of the bead, from which the nominal power-boost factor of the system can be computed. Figure 2 (left) shows the setup that has been built and characterized. It consists of a corrugated horn antenna, connected to a VNA for reflectivity measurements, a focusing mirror and the mirror disc setup with a mechanism that allows to position a bead at any position within the booster (center). Figure 2 shows the measured E-field between the disc and the mirror as well as in front of the disc.

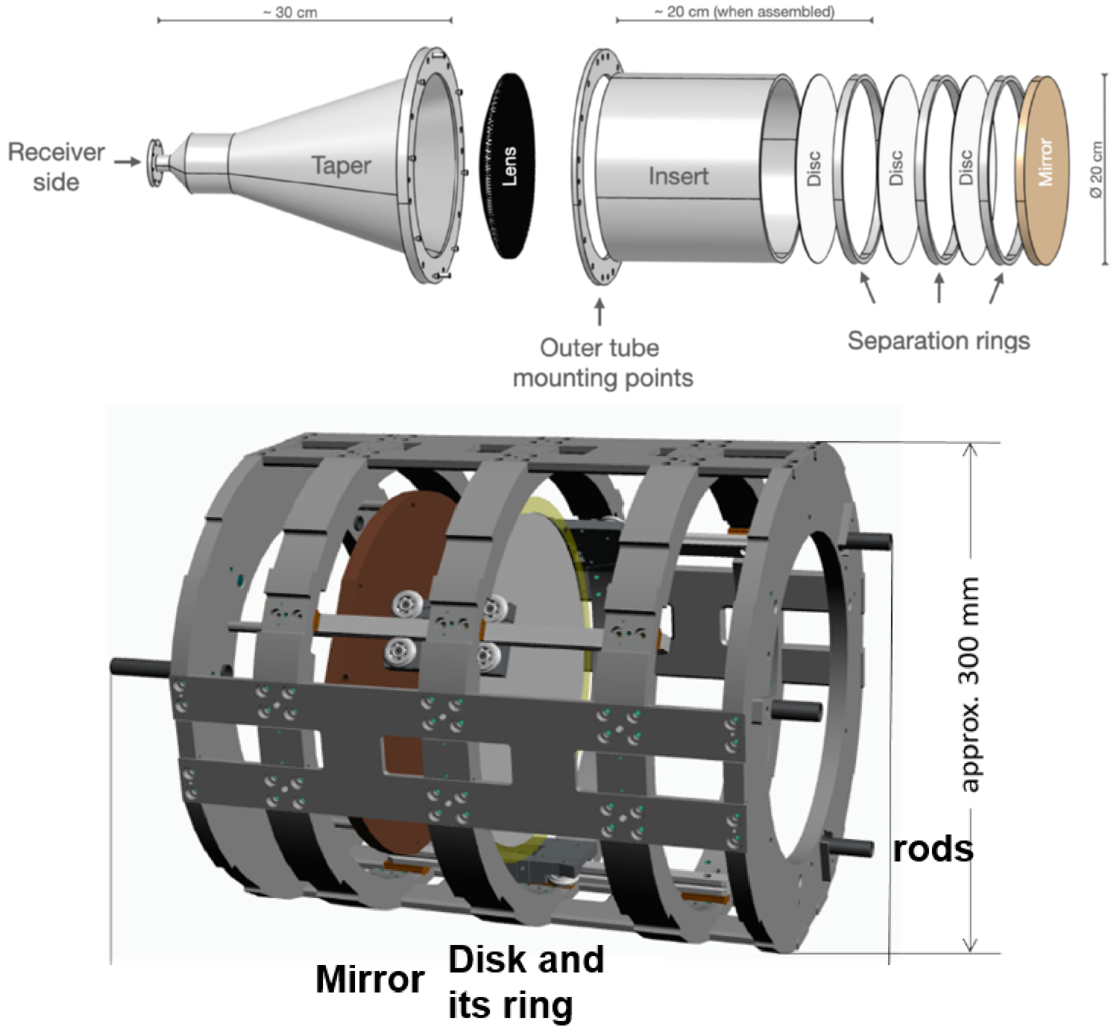

Figure 1: Sketches of closed booster (top) and open booster (bottom).

Table 1 summarizes the OB200, CB100 and CB200 prototype tests that have already been performed in the Morpurgo magnet in 2022-2024, both at room and cryogenic temperature. For the latter an original cryostat design has been developed with the CERN cryolab, consisting of two concentric cylindrical plastic G10 vessel separated by a vacuum layer (Figure 3 top right). Three rounds of tests were carried out in Mar 2022, Mar-Apr 2023 and Feb-Mar 2024 (see Figure 3), establishing:

- the long term (one month) stability of data taking inside the Morpurgo magnet without prohibiting radio frequency interference effects in the north area surrounding;
- the long term (one month) stability of the Morpurgo magnet;
- a first design of the receiver chain including LNA and the DAQ (commercial or

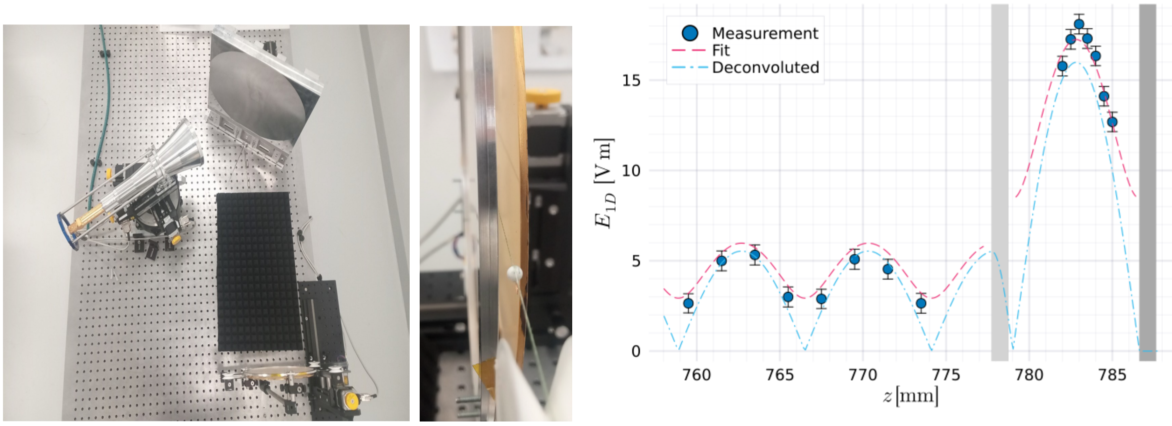

Figure 2: Left and center: Setup for measuring the E-field inside the one disc open booster. Corrugated horn antenna, focusing mirror and one disc plus mirror (behind the black absorber). The center picture shows a close up of the copper mirror and the disc with the bead being positioned between them. Right: E-field at the center of the booster as a function of position along the longitudinal axis normal to the mirror measured using the bead pull method. Shown are the measurement (blue circles), a fit to expected distribution considering finite size of the bead (red dashed) and resulting E-field if finite size of the bead is de-convoluted (light blue dashed dotted). The power-boost factor of the system can be directly calculated from the measured E-field.

home-made devices);

- the complete boost factor calibration procedure at room and cryogenic temperature;
- a robust data monitoring.

The 2024 data taking includes runs at 3 different frequencies 18.5, 18.9 and 19.2 GHz corresponding to an ALP mass of around $m_a \sim 79$ μeV. It lasted 35 days and 410 hours of data are recorded with a B-field above 1 T. Analysis of these data is ongoing. The expected sensitivity is to reach an ALP-photon coupling ($g_{a\gamma}$) of 2-3$\times10^{-11}$ GeV^{-1}, a factor 2 beyond the CAST sensitivity [6].

Type	acronym	ϕ disc [mm]	Nr. of discs	Available	Test at CERN Temp. [K]	Test at CERN Year
Open Booster 200	OB200	200	1	2021	290	2022
Closed Booster 100	CB100	100	3	2021	290	2022, 2023
					10	2024
Closed Booster 200	CB200	200	3	2022	290	2024
			10	*2024*	*290*	*2025*
Open Booster 300	*OB300*	*300*	*3*	*2024*	*10*	*2026*
Prototype Open Booster	*OB300_F*	*300*	*20*	*2026*	*10, 7*	*2027, 2028*

Table 1: MADMAX tests performed (plain) and planned (italic) in the Morpurgo magnet.

Figure 3: Pictures of MADMAX prototypes: OB200 in the Morpurgo magnet (top left) CB100 inside the G10 cryostat (top right) and inside the the Morpurgo magnet (bottom left), CB200 inside the Morpurgo magnet (bottom right).

3 MADMAX plans for LS3 (2025-2028)

Based on this initial success, the next step is to conceive a booster with moveable discs, operating at cryogenic temperature and under magnetic field during a long period, to demonstrate the new dielectric haloscope concept and scan a significant part of the $m_a - g_{a\gamma}$ parameter space. The status of the final prototype booster and cryostat is described in section 3.1, the status of the Morpurgo area in section 3.2, the expected sensitivities are then discussed in section 3.3 and a tentative planning for LS3 exposed in section 3.4.

3.1 Final MADMAX prototype (booster and cryostat)

Combining the expertise gained from OB200 (discs can move under magnetic field at cryogenic temperature) and closed boosters (feasibility of the dielectric booster concept with fixed disc separations) it is possible to move on to a prototype design. This will be used to verify the baseline design of the final MADMAX booster system. This final booster prototype is called Open Booster 300 (OB300) with 300 mm mirror and disc diameter. It will initially be equipped with three sapphire discs, and can eventually be extended with up to 20 discs (see Figure 4 right).

OB300 elements (piezo-motors, disc rings, laser interferometers, ...) are presently being produced and the assembly is expected to be completed by the end of summer 2024. OB300 will be hosted in a stainless steel cryostat, called MADMAX prototype cryostat (MPC, see Figure 4 left) that is being produced by an external company. The expected delivery date to Hamburg is May 2024. The site acceptance test, including a first cool-down of the cryostat, will be performed soon after delivery – the requested infrastructure for electricity, cooling water and helium is already in place in the SHELL laboratory at DESY.

After MPC commissioning, OB300 will be inserted into the cryostat for testing the RF behavior. The system will be first characterized at room temperature. A cold calibration system will be developed based on the CB100 experience using the G10 cryostat which will require O(6) months. With the current schedule for cryostat delivery and OB300 availability the full prototype system can not be sent in time for the 2024-25 beam shutdown period. For this reason, the plan is to send it by the end of 2025 and to perform runs during LS3.

3.2 Status of the Morpurgo area

As presented in the original proposal [1], the Morpurgo experimental area has already been completely refurbished by the CERN team to host MPC. The rails needed to insert the cryostat inside the Morpurgo magnet (see Figure 5 and front page of this report) have already been delivered to CERN and tested for installation successfully in December 2023. A tent isolating from the outside is foreseen to mount the booster and first discussion with CERN has started to implement it in the Morpurgo area.

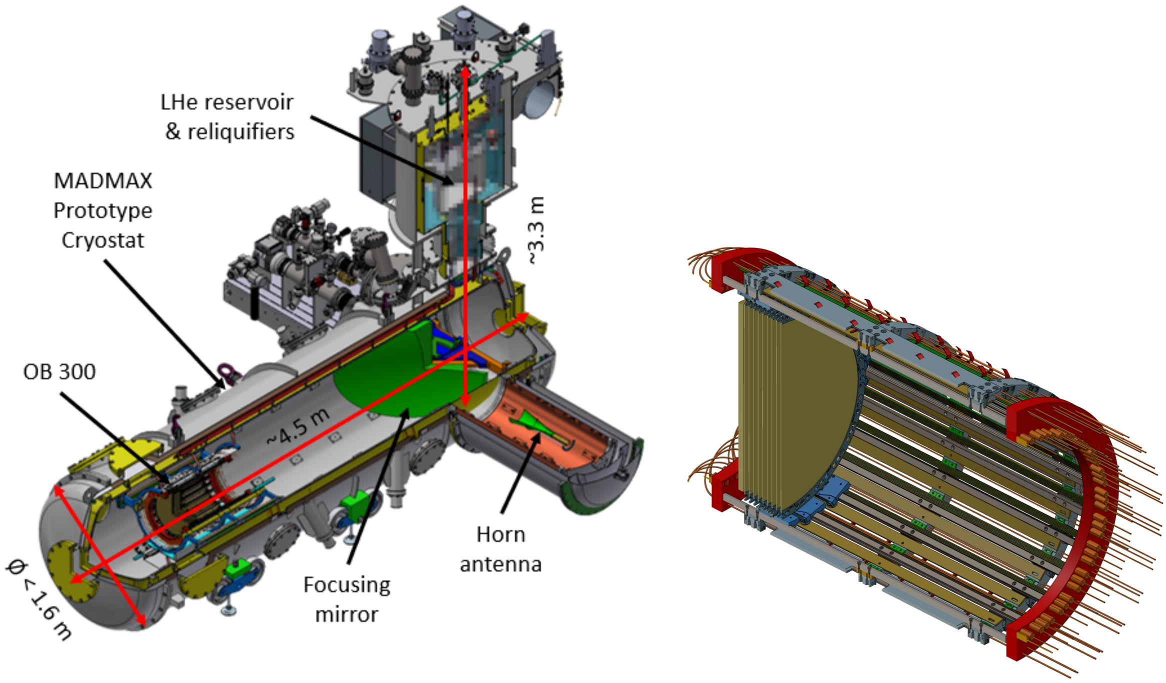

Figure 4: Sketch of the prototype cryostat (left) and of the OB300 booster (right).

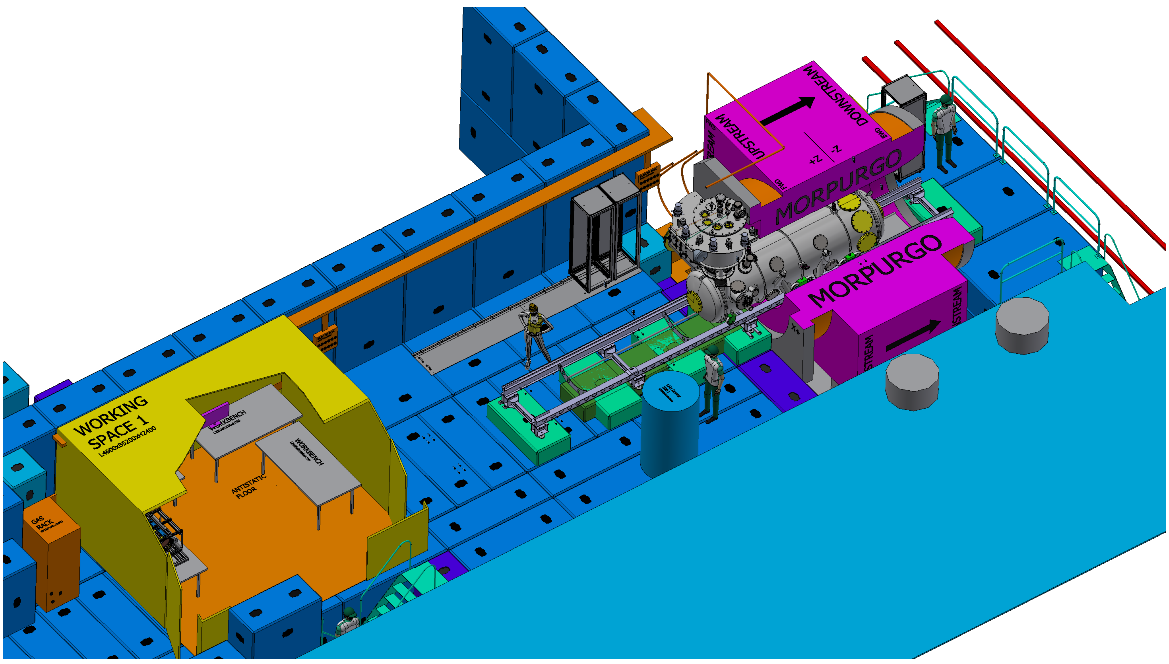

Figure 5: 3D view of the Morpurgo experimental area with the prototype cryostat inside the magnet. The new rail system to insert the cryostat is also visible.

Booster	Cryostat	β^2	T_{sys} [K]	β^2/T_{sys} [K^{-1}]	Sensitivity $\|g_{a\gamma}\|$ [GeV^{-1}]	freq. range [MHz]	Duration [Months]	Year
CB200	–	2000	600	3.3	$\approx 35 \times 10^{-12}$	50	0.1	2024
CB100	G10	1000	20	50	$\approx 20 \times 10^{-12}$	10	0.03	2024
CB200	–	*7000*	*600*	*12*	$\approx 10 \times 10^{-12}$	*10*	*0.2*	*2025*
OB300	*MPC*	*1000*	*10*	*100*	$\approx 5 \times 10^{-12}$	*200 (scan)*	*3*	*2026*
OB300_F	*MPC*	*7000*	*10*	*700*	$\approx 2 \times 10^{-12}$	*1000 (scan)*	*3*	*2027*
		50000	*7*	*7150*	$\approx 0.2 \times 10^{-12}$	*1*	*3*	*2028*

Table 2: Physics reach of various booster setups tested in the Morpurgo magnet. For the 2024 measurements, values from the run with the highest sensitivity are taken. While for the planned measurements, shown in italic, a 1 day measurement is assumed for scanning runs with SNR= 5, a DAQ efficiency of 85% and an ALP mass around 80 μeV. At this ALP mass, the corresponding CAST limit on $|g_{a\gamma}|$ is 66×10^{-12} GeV^{-1} [6]. The scan are performed with 10 MHz frequency step. For the last line, no scan is performed instead a 7 times higher boost factor is obtained w.r.t 2027 by reducing the frequency width to 1 MHz. Also, it is assumed that the cryostat system can be further improved such that the system temperature can be reduced to 7 K.

3.3 Expected ALPs sensitivity

The expected sensitivity for the ALP-photon coupling $|g_{a\gamma}|$ can be expressed as:

$$|g_{a\gamma}| \sim 4 \cdot 10^{-11}\ \mathrm{GeV}^{-1} \times \left(\frac{800}{\beta^2}\right)^{1/2} \left(\frac{T_{sys}}{200\,K}\right)^{1/2} \left(\frac{0.85}{\eta}\right)^{1/2} \left(\frac{10\,\mathrm{days}}{\tau}\right)^{1/4} \left(\frac{1.6\,\mathrm{T}}{B}\right) \left(\frac{72.3\,\mathrm{cm}^2}{A}\right)^{1/2} \left(\frac{0.3\,\mathrm{GeV}}{\rho_a}\right)^{1/2} \left(\frac{SNR}{5}\right)^{1/2} \left(\frac{m_a}{80\,\mu\mathrm{eV}}\right)^{5/4}. \tag{1}$$

To deduce the projected sensitivity some assumptions need to be made: for all three disc booster configurations a B-field (B) of 1.57 T, a signal to noise ratio (SNR) of 5 and a DAQ system efficiency (η) of 85% are assumed. The axion mass (m_a) at which the booster is sensitive is taken to be 80 μeV. The local axion dark matter density (ρ_a) is assumed to be 0.3 GeV/cm^3. The system temperature (T_{sys}) stands for the LNA plus booster noise. Other parameters are the area of the disc (A, e.g. 72.3 cm^2 for 10-cm diameter disc) and the integration time for one booster configuration (τ). Scaling is then possible from these numbers to the different prototypes as shown in Table 2. In 2027, β^2 is scaling linearly with the number of discs (20 discs instead of 3 for OB300). For 2028, optimising the boost factor to a given booster configuration in a very thin frequency range (1 MHz) and running during 3 months should allow us to gain an order of magnitude in sensitivity.

Running during 90 days should allow us to scan around 1 GHz assuming 10 MHz per position and 1 day data taking. This corresponds to an m_a range from 79 to 83 µeV with a $|g_{a\gamma}|$ sensitivity of a few 10^{-12} GeV^{-1}. The expected sensitivity, the width of the frequency range and the year of data taking are listed in Table 2. The former is illustrated

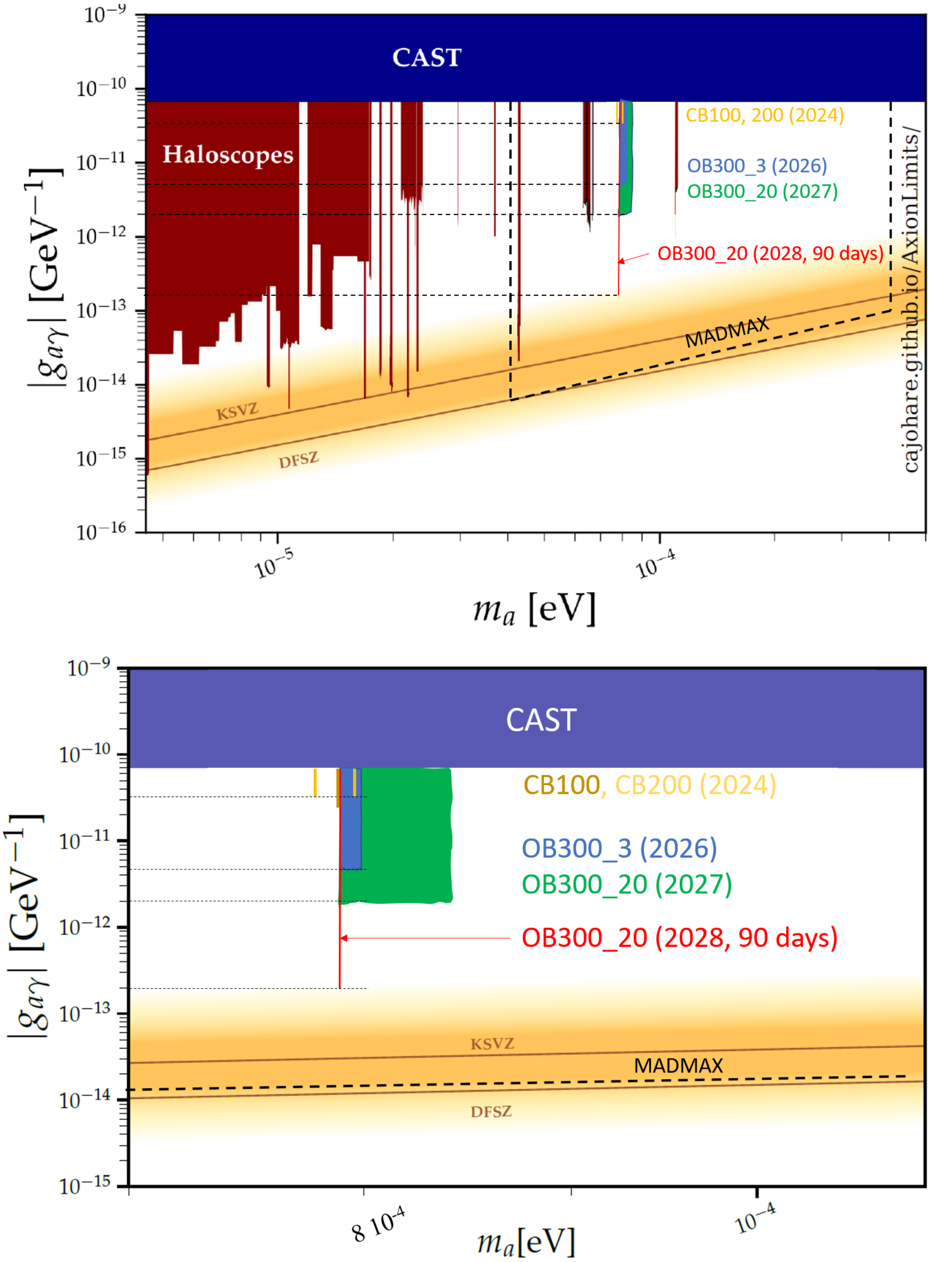

Figure 6: Expected physics reach for the planned 2026, 2027 and 2028 tests in the full plane $|g_{a\gamma}|$-m_a plane compared to the existing searches (top) and in a zoomed-in region around 80 μeV (bottom). The dashed line represents the expected ultimate discovery reach of the final MADMAX design.

Date	Operation	Time (months)
10/2025	Cryostat Shipment from DESY	1
11/2025	Cryostat Installation in Morpurgo area	1
12/2025	OB300 (3 discs) preparation and insertion	0.5
01/2026	Cryostat insertion in Morpurgo and cooling	1
02/2026	Physics run	3
05/2026	Cryostat warm-up	1
06/2026	End of 2026 operation	1
10/2026	OB300 (20 discs) preparation and insertion	2
01/2027	Cryostat insertion in Morpurgo and cooling	1
02/2027	Physics run	3
05/2027	Cryostat warm-up	1
06/2027	End of 2027 operation	1
01/2028	Cryostat insertion and cooling	1
02/2028	Physics run	3
05/2028	Cryostat warm-up	1
06/2028	Cryostat shipment back to DESY	1.5

Table 3: Tentative planning for MADMAX tests during LS3.

in Figure 6. For all future configurations the sensitivity would be enough to improve the limits on dark matter ALPs much beyond the current world best limit from CAST [6] and from astrophysical arguments [7] in the given mass range. The take-home message is nicely illustrated: 2026 allows to validate the dielectric haloscope concept used for the final MADMAX detector, 2027 allows to scan an uncharted region of the ALP phase space around 80 μeV (± 2 μeV) and 2028 allows to go down to few $g_{a\gamma} \sim 2 \times 10^{-13}$ GeV^{-1}, close to the QCD axion theory prediction.

3.4 Tentative run schedule

The MADMAX collaboration asks the SPSC to recommend to the CERN research board the continuation of the successful MADMAX Morpurgo activities during LS3 (2026-2028). A prolonged measurement time as suggested by MADMAX seemed feasible to the YETS responsible.

In the original proposal [1], the total presence at CERN were foreseen to last five months from December to April. Tentative planning of operation shows that cryostat shipment from DESY, installation and cool down should take about 2 months. Warm-up and decommissioning about one month, leaving 2-3 weeks for physics with no contingency. Taking advantage of LS3 with no beam could allow MADMAX to take physics data during longer time (ideally up to 9 months over the 3 years of LS3). This would allow us to probe much larger $g_{a\gamma}$ and mass ranges with conditions very close to the final MADMAX experiment. The physics run could be split into three runs in 2026, 2027 and 2028. The two last runs will be performed with a booster including more discs and/or scanning a different mass range. Assuming no need for storage of the MADMAX cryostat during LS3, the change could take place in the Morpurgo area. A tentative schedule is proposed in Table 3.

4 Conclusions

Thanks to the measurement campaigns at CERN during the beam shutdown periods of 2022, 2023 and 2024, the MADMAX collaboration acquired a solid experience in data taking with the Morpurgo magnet both at room and cryogenic temperature. Ongoing analysis of 2024 data should demonstrate a sensitivity a factor 2 beyond the world best limit.

The next step is to prepare the final prototype to be inserted in the prototype cryostat. Building of both objects is ongoing very smoothly and they should be delivered during the summer 2024. However this prevents the use of the 2024-2025 shutdown slot as O(6) months is needed for a full characterisation. Therefore the next slot will be 2025-2026. Taking advantage of LS3 starting in 2026 we therefore ask for an extension providing O(3) months physics run in 2026, 2027 and 2028 motivated by exploration of the ALP phase space around 80 μeV.

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