MADMAX review at DESY, Nov. 11, 2019

Participants

Michael Betz, LBNL, USA (connected remotely)
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Shlomo Caspi, LBNL, USA (connected remotely)
Babette Dobrich, CERN, Switzerland (connected remotely)
Joerg Jaeckel, Heidelberg, Germany
Gijs de Rijk, Technology Department, CERN
Gray Rybka, Univ. of Washington, USA
Horst Schulte-Schrepping, DESY, Germany
Yannis K. Semertzidis, IBS-CAPP/KAIST, South Korea, Chair
Marco Vignati, Sap. Univ. di Roma, Italy (not present, submitted independent review and report)
Udo Wagner, Cryogenics Group, CERN, Switzerland

Talks available at

https://indico.desy.de/indico/event/24270/
Protection key: MADMAX19

Summary of the PRC report:

The committee enthusiastically endorses the physics goals of the MADMAX proposal, claiming ultimate sensitivity for a very large axion frequency range 10-100 GHz in two phases. In some axion models this frequency range includes the axion mass as a dark matter. The detection of axions will open the field of axion astrophysics and provide insight to the formation of galaxies, but also the strong interactions and it will most certainly secure a Nobel Prize for the experiment. We recommend approval of the phase II of the project.

The Magnet is the highest risk for the experiment, but it can be built and operate safely if it is done properly. We endorse the findings of the separate magnet review panel, but we also strongly recommend the appointment of a magnet Czar. Given the cost of the magnet it would be tempting to cut corners, but this can generate delays at the end of the construction. The coils should be dismountable and enough cable should be purchased all at once; enough at least for one extra coil (largest length).

The booster concept is sound, but mitigation plans should be envisaged in case of breakdowns. The whole prototype concept should be tested under realistic conditions inside the cryostat. The detector concepts are adequate and probably will get better with time. The total noise figure should be estimated and tested by controlling the physical temperatures of the various elements to establish which parts are essential and critical in defining the noise temperature of the system. We believe there are untapped opportunities in that direction which could improve the whole sensitivity, especially in the high axion mass spectrum.

MADMAX experiment review by DESY PRC

Monday, November 11, 2019 from **08:00** to **22:00** (Europe/Berlin)
at **DESY Hamburg (SR 1)**

Monday, November 11, 2019

09:00 - 09:30 Executive meeting (committee only) *30'*

09:30 - 09:45 MADMAX design and plan *15'*
Speaker: Dr. Bela Majorovits (MPI für Physik)
Material: **Slides**

09:50 - 10:10 Physics case and booster principle *20'*
Speaker: Javier Redondo (U Zaragoza)
Material: **Slides**

10:20 - 10:35 RF system simulation *15'*
Speaker: Alexander Schmidt (RWTH Aachen)
Material: **Slides**

10:40 - 10:55 Booster proof of principle experiments *15'*
Speaker: Xiaoyue Li (MPI München)
Material: **Slides**

11:00 - 11:20 Coffee break

11:20 - 11:35 Prototype booster and infrastructures *15'*
Speaker: Prof. Erika Garutti (University of Hamburg)
Material: **Slides**

11:40 - 11:55 Detection system *15'*
Speaker: Dr. Olaf Reimann (MPP)
Material: **Slides**

12:00 - 12:15 Magnet design *15'*
Speaker: Walid Abdelmaksoud (CEA Saclay)
Material: **Slides**

12:20 - 12:35 DESY site *15'*
Speaker: Jörn Schaffran (FLA)
Material: **Slides**

12:40 - 12:55 Organisation, resources, finances *15'*
Speaker: Prof. Erika Garutti (University of Hamburg)
Material: **Slides**

13:00 - 14:00 Working lunch (committee only)

14:00 - 15:00 Visit to new labs of Hamburg University *1h0'*

15:00 - 16:00 Closed session of the committee *1h0'*

16:00 - 17:00 Questions to the collaboration *1h0'*

17:00 - 19:00 Drafting of recommendations (committee only) *2h0'*

19:00 - 22:00 Dinner (participation to be clarified)

Physics Motivation

We find the science case for the dark matter axion in the range targeted by MADMAX to be compelling. The axion is a better-motivated candidate for dark matter than most others, and there are several straightforward models of cosmology that lead to axions in the frequency range targeted by MADMAX to be the dominant contribution to dark matter. No other experiment at this time is exploring this range. The team is very enthusiastic and clearly a few people made a considerable effort to reach valuable results in quite a short time. The committee is impressed by the ingenuity of this new method to search for axions as dark matter particles in the frequency range of 10-40 GHz (40-160 μeV) in first phase and 40-100 GHz (160-400 μeV) in second phase. It makes great use of the large energy content of dipole magnets, while probing the large axion mass range. It also fits very well with the current growing number of axion experiments at DESY, and within the experimental and infra-structure capabilities of the lab.

The committee therefore strongly endorses the MADMAX proposal for an experiment at DESY and in particular the phase II of the shown plan. The whole MADMAX mass sensitivity would cover a sizeable fraction of the still allowed and well-motivated region where axions can be the dark matter. Therefore, the MADMAX experiment has significant discovery potential not only for a new particle, but also for discovering a main constituent of dark matter. While risks (axions not existing, not being the dark matter or being outside the mass range reachable by MADMAX) are clearly present, they are outweighed by the potential for a fundamental break-through. Moreover, these risks are common to all searches for new physics. Also, the axion is theoretically particularly well-motivated — the axion explains the absence so far of a measurable electric dipole moment of the neutron - a fact that is hard to explain even by anthropic selection. Despite being well-motivated the targeted mass range is very difficult to reach in other experiments. Therefore, this presents a unique window of opportunity where the MADMAX collaboration is at least several years ahead of potential competitors.

We encourage the collaboration to try to improve sensitivity to reach the DFSZ axion dark matter. As a reminder, axion experiments tend to use 0.45 GeV/cc for their dark matter density and it should be used for direct comparison. The most likely axion dark matter couplings are bounded between the benchmark KSVZ and DFSZ dark matter models. It is extremely unlikely another search for dark matter axions will be performed again soon, so it is important for MADMAX to be as definitive as possible. By reaching the DFSZ axion dark matter model at 100% of the expected dark matter density, MADMAX will have the best chance of detecting plausible axion models. In addition, it would be interesting to also investigate signatures in a wider range of models and signatures as well as detection strategies adapted to them. In addition to the main analyses this would broaden the physics reach, but also would allow in particular PhD students to do their own independent physics analysis.

Possible issues with the use of the Morpurgo magnet at CERN and timeline line conflicts at DESY should be considered and addressed when planning. The project plan should take into account the funding acquisition. A governance for funding acquisition should be formed.

Magnet

The committee is impressed with the speed the collaboration is moving to secure the magnet construction. The recruitment of the teams through the innovation partnership is particularly right on target and, as a consequence, already the team has a good design for the magnet. The magnet plan was already endorsed by the dedicated external review committee, and we also endorse their findings. In addition, we strongly recommend the appointment of a person responsible for the magnet.

1. The committee recommends that the construction of the magnet can only start when the detailed design is finished. All procurement, except for the conductor (which should be ordered right away to save time), can only be launched when the detailed design is finished. Especially still to be looked at are:
    a. connections,
    b. cooling details.
2. The magnet schedule should contain all important decision steps (e.g., conductor quantity to procure).
3. In the construction of the magnet there are not enough control points. The committee recommends to add control points with quality control measurements in between the fabrication steps.
    a. Make cold electrical integrity tests at low temperature.
    b. Warm magnetic measurements.
4. The committee recommends that the magnet be made dismountable such that defective coils can be exchanged.
5. The committee thinks that schedule for the magnet will probably be 6 years after completion of the conceptual design.
6. The conductor quantity to be procured should allow for at least one additional unit of the largest coils.
7. The "Innovation partnership" with industry is a valid approach for such a large and complex magnet, nevertheless, some basic steps, as the completion of detailed design before starting magnet fabrication, should still be followed. The gain here is that the make-ability of the magnet can be introduced early on and that tooling can be put in place in an early stage.

RF and detectors:

We find the baseline HFET-based receiver chain to be well thought out with a completed demonstration. The system uses commercial components and can be directly attached to a prototype system. There is no risk remaining to this.

We applaud bringing a group to the collaboration that can produce and commission quantum-limited amplifiers for the <40 GHz search. TWPA amplifiers can decrease the system noise from 8K to 5K, which increases the speed at which frequencies can be scanned by a factor of 2, making them a worthwhile investment. TWPAs are demonstrated technology, but are not yet commercial. They still require specialists within a collaboration to provide and commission them.

We encourage the collaboration to stay agile while watching for developments in detection technologies above 40 GHz. There are several technologies on the horizon that should allow detection of single photons above 40 GHz that are not yet fully demonstrated. When they have been demonstrated, they should allow for sensitivity beyond the standard quantum limit of linear amplifiers, and would be a significant improvement in MADMAX's sensitivity at higher frequencies.

Booster

One of the most critical aspects, especially in the case of an exclusion result, is the accurate prediction of the detector's "boost factor", as it determines the sensitivity of the experiment. The group has done excellent work of understanding the detector structure and the interaction of axions with photons within. The determination of the boost factor by multiple different simulations looks convincing. The measurement of microwave group velocity has been identified as a link between the simulations to the real setup. This is an extremely valuable tool as it allows to verify simulation results and hence confirm the predicted boost factor. Furthermore, it allows to optimize disk positioning.

The booster concept is well thought out and several studies have been shown. The rail rider system from JPE has been selected as the most promising concept. The committee endorses the proposal for a construction of a prototype and encourages its testing inside a cryostat to test under realistic conditions. The booster and its cryostat detailed design is still missing and should be realized before starting with the manufacturing of the prototype. The cooling of the support structure and the discs has to be worked out, i.e. slider-based cooling of the motors and helium gas conduction cooling for the discs. The piezo motors to move up to 80 disks in the booster have a limited lifetime. Either a redundancy scheme or an easy way to exchange disks and motors is required. A strategy to mitigate failures in the booster and in its prototype, as damage of plates or motors or reflectors for alignment, should be developed. It is not yet clear how the mirrors and plates will be cooled and at which temperature and how this would affect the overall system noise temperature.

Another critical aspect is the detection of excess noise at a power level down to 10^{-22} W due to a potential axion signal. This problem has been addressed by the group and even successfully demonstrated with a proof of principle low noise receiver chain. A good next step would be to develop an accurate model of the system noise floor as a function of gain variation in the electronics and temperature variations in the booster and cryogenic system over a time scale of days.

We encourage the collaboration to look for ways to improve the noise temperature by cooling selected components or the entire booster below 4 K. To fully utilize the benefit of superconducting amplifiers, the thermal component of the system noise should be reduced. Reducing the thermal component to 1K, near the quantum limit, could reduce the system noise from 5K to 2K, a speed improvement of a factor of 6. It may be that this can be achieved not by cooling the entire booster section, which is mostly transparent, but only the antenna region of the experiment, a much less daunting cryogenic task. The thermal transparency of the booster has to be understood to do this however.

We suggest the collaboration compose a detailed operations cadence: What measurements are made each time the dielectrics are reconfigured? What measurements are made periodically during running, even when not moving dielectrics? How are these interleaved with power measurement? This plan is important to guide design of the prototype to optimize the measurements that need to be made, and understand which parameters are important for the science result.

The prototype detector is considered a crucial step to prove several technological challenges for the booster such as, the disk positioning mechanism, the position verification method, the cooling concept and the signal to ratio cryogenic conditions. The experience gained in phase II is considered as essential for the development of the final experiment. The committee therefore fully endorses phase II of the project.

The committee agrees that the cooling power available in the HERA North Hall should be sufficient for the MADMAX experiment for both the magnet cooling to 1.8 K and the detector cooling down to 4.3 K.