

An Overview of the COMET Experiment and Its Recent Progress*

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Abstract

Forbidden in the Standard Model, Charged Lepton Flavour Violation is a strong probe for New Physics. The COMET Experiment will measure one of these processes: that of COherent Muon to Electron Transitions, where a muon converts to an electron in the presence of a nucleus without the emission of any neutrinos. COMET aims to improve the current limit on this process by four orders of magnitude. Being built in two phases at J-PARC, Tokai, Japan, COMET will first take data in 2018, where it should achieve a factor 100 improvement on present limits. This report gives an overview of μ - e conversion and the COMET experiment as well as a summary of the recent progress in construction and design.

INTRODUCTION

Lepton flavour conservation has been a key ingredient in our description of the world of particle physics since the first experiments showed a muon to decay to an electron only if accompanied by the emission of two other massless (or so they thought) fermions. Tests of the validity of this conservation have continued, through searches for neutrinoless muon decay to an electron accompanied by either a photon, an electron-positron pair, or in the presence of an atomic nucleus.

The COMET experiment will search for the last of these processes, in COherent Muon to Electron Transitions, where the nucleus is additionally left unchanged. COMET is being built at the Japanese Proton Accelerator Research Centre (J-PARC), in Tokai, Japan and will first take data in 2018, during Phase-I. Phase-II shall follow at the beginning of the next decade, and aims to improve the sensitivity to the μ - e conversion process by four orders of magnitude compared to the present limit. The following sections gives an overview of muon-to-electron conversion, an outline of the COMET experiment as a whole, and a summary of the recent progress in its construction and design.

THE MUON-TO-ELECTRON CONVERSION PROCESS

Muon-to-electron conversion occurs as the neutrinoless decay of a muon in the presence of an atomic nucleus. Since no neutrinos are emitted, and if the nucleus is left unchanged, the process is essentially a two-body interaction such that the energy of the out-going electron has a fixed value, E_e , given by the equation:

$$E_e = M_\mu - E_{\text{Binding}} - E_{\text{Recoil}} \quad (1)$$

where M_μ is the mass of the muon, E_{Binding} is the binding energy of the original muon-nucleus system, and E_{Recoil} is the recoil energy of the nucleus. The last two terms are small compared to the muon mass, so that the μ - e conversion signal occurs close to 105 MeV and is well separated from electrons of Standard Model muon decay (with neutrino emission), which for a free muon can only achieve energies up to half the muon mass.

Further background suppression can be achieved using timing information of the process, which is fixed to the lifetime of the muonic atom. In aluminium, the target of choice for COMET, the lifetime of the muon is about 864 ns, whilst the signal energy is $E_e = 104.97$ MeV.

To remove uncertainties in the initial muon wavefunction, the conversion rate is typically normalised to the rate of muon nuclear capture. The current limit on μ - e conversion comes

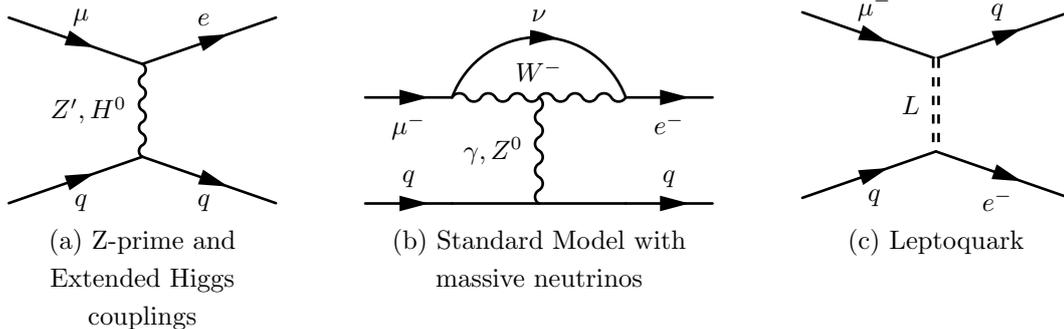


FIG. 1: Example Feynman diagrams that give rise to μ - e conversion. The dipole term with a SM neutrino in (b), whilst allowed in the SM with neutrino oscillations, is heavily GIM suppressed.

from the SINDRUM-II experiment [2], which used a gold target and set a 90% confidence limit on the Conversion Rate (C.R.) at 7×10^{-13} . COMET will be built in a staged approach hoping to improve this limit (but using an aluminium target) by about two orders of magnitude at each stage. The Single-Event-Sensitivity (SES) is the figure of merit for a μ - e conversion experiment's ability to observe the signal process. It is equivalent to the minimum value of the conversion rate where the experiment can still expect to see one signal event during the run. For COMET Phase-I, our SES is 3×10^{-15} , which should improve to 3×10^{-17} for Phase-II.

In principle, neutrino oscillations alone produce this sort of charged lepton flavour violation through penguin diagrams like that shown in Fig. 1b. However, if this were the only mechanism, the process would be highly GIM suppressed by the tiny mass squared difference of the neutrinos to conversion rates of order $\mathcal{O}(10^{-54})$. As a corollary, if New Physics is to be seen it must be well beyond both the Standard Model and even neutrino oscillations. There is no dearth however of models that give measurable conversion rates, including leptoquarks, Z -primes, extended Higgs couplings, supersymmetry, and of course heavy neutrinos [11] as shown in Fig. 1.

THE COMET EXPERIMENT

The COMET beamline and detectors are built to provide an intense, low energy muon beam, whilst minimizing all backgrounds. Key backgrounds include: intrinsic ones which occur when negative muons stop in a target, processes related to impurities in the beam, detector effects such as particle misidentification and pile-up, and cosmic backgrounds.

Using a delayed-time detector window, shown schematically in Fig. 2a with a pulsed proton beam removes most of the beam related backgrounds. Proton bunches of 100 ns produce a beam flash of about 200 ns (Fig. 2b) at the stopping target and by filling every second bucket in the J-PARC Main Ring (MR), a bunch separation of $1.17 \mu\text{s}$ can be achieved. Since the muon lifetime in aluminium is 864 ns, a high suppression of beam related backgrounds can be achieved, provided the extinction factor, which quantifies the number of protons in between bunches, can be kept low. Extinction factors of around 10^{-9} were originally thought necessary, but in late 2014 extinction levels of around 10^{-12} were measured at J-PARC [10].

The intrinsic backgrounds for COMET are any process involving a negative muon stopping in the target and resulting in an electron close to 105 MeV. This includes radiative

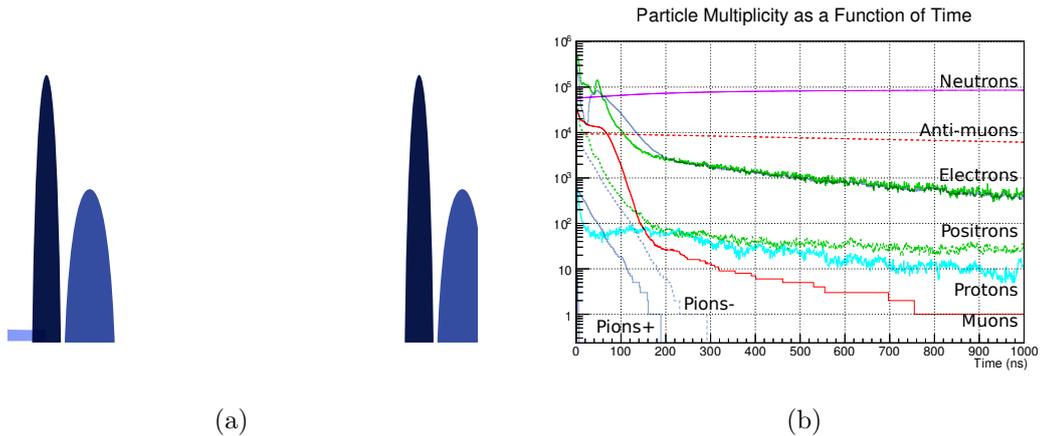


FIG. 2: Timing structures in COMET. (a) Schematic of the bunch structure and time-gated detector window used to reduce prompt beam-related backgrounds. (b) Simulated particle fluxes, integrated over the entire experiment and produced by protons at $t = 0$. The y-axis is in arbitrary units, but normalised to give the correct relative flux for each particle type.

muon capture followed by pair-production from the photon (either internally or externally) and the Standard Model decay of the bound muon. Of the two, the bound muon decay is expected to dominate. Whilst electrons from free muon decay cannot be produced above half the muon mass (in the muon rest frame), a high-energy tail arises from the nuclear recoil, and whilst it falls steeply above 55 MeV, it remains significant compared to the limit on the conversion rate. Since only the energy can be used to distinguish such electrons from μ - e conversion electrons COMET requires a high precision particle detector and a minimal material budget for the stopping target. Reducing the stopping target length, however, must be offset by the decrease in the muon stopping rate, which favours a thicker target, and makes a low energy muon beam desirable. Furthermore, muons above 77 MeV/c are undesirable since they can produce electrons with signal-like energies.

To achieve a low energy, high intensity muon beam with few impurities COMET uses two novel approaches: capturing backwards emitted pions and muons from the production target using superconducting solenoid fields, and a combination of bent solenoids, vertical dipole fields and collimators along the muon beam transport. Both of these remove the high-energy components of the beam whilst maintaining a high muon intensity, and the long decay length of the bent transport solenoids additionally improves beam purity since most pions will decay.

COMET Phase-II

Fig. 3b shows a schematic of the configuration for Phase-II. From this it can be seen that the muon transport beamline captures pions coming backwards from the production with respect to the proton beam, which itself enters from the top-left corner of the image. In Phase-II, this secondary beam is then transported around 180° of bent solenoid (with a small straight section in the middle for possible collimators and field matching). The beam is then directed on to the stopping target which is made of 200 μm thick aluminium disks, and followed by a beam blocker that should absorb any beam that does not stop in the target. Electrons produced in the target are then collected by a graded magnetic field, and transported around a second section of bent solenoid with a much larger aperture. The

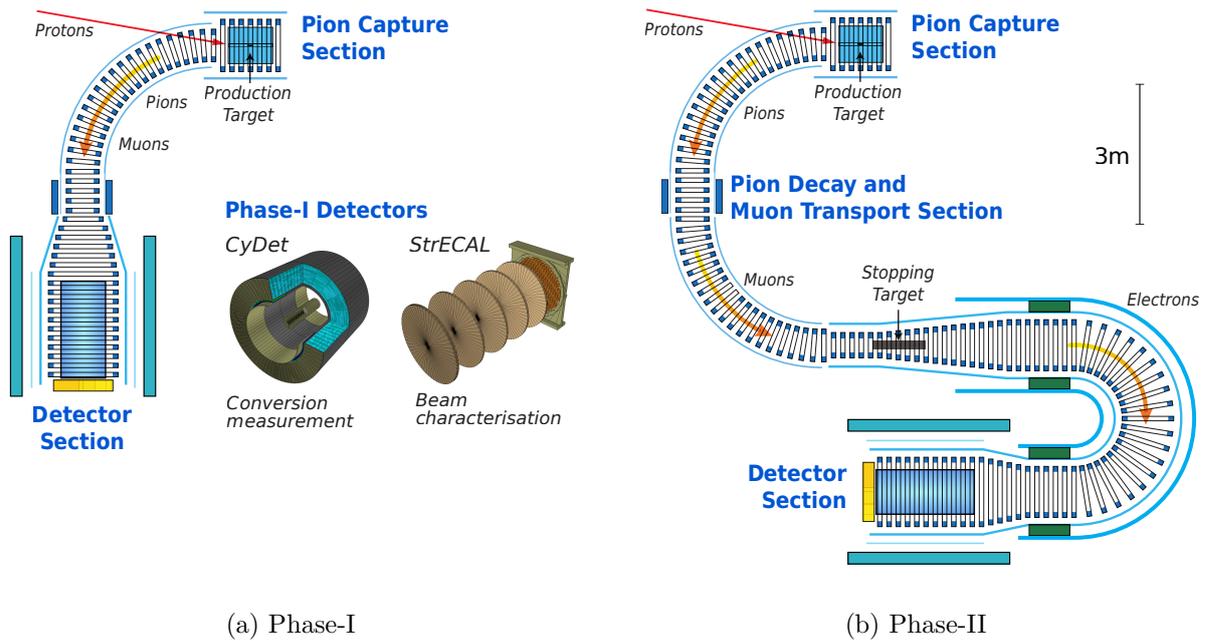


FIG. 3: The COMET experiment in the two different phases. (a) The Phase-I beamline configuration, which is identical to Phase-II up to the first 90° of the bent muon transport solenoid and excluding the production target. (b) The Phase-II beamline then moves the detector solenoid back, extends the muon transport beamline, and adds an extra bent solenoid between the stopping target and detector.

dipole field along this region is tuned to remove low energy electrons from decay-in-orbit and other charged particles coming from the stopping target. Additionally, having no line-of-sight between the target and the detector helps reduce backgrounds from neutral particles such as photons from radiative muon capture. Finally, the electrons enter the detector system formed by a series of straw tracker planes and a crystal electromagnetic calorimeter (ECAL).

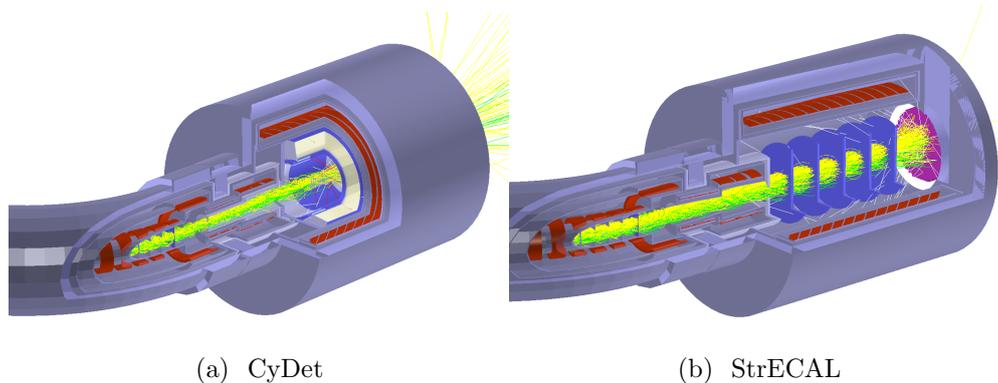


FIG. 4: Simulated event displays for the two different Phase-I detectors. Track colour shows the particle ID: electrons (yellow), muons (green), photons (white), protons (red).

COMET Phase-I

Given the number of new techniques being employed for COMET Phase-II there are many uncertainties associated with the expected production yields, beamline dynamics and consequently the final background rates. It was therefore decided to take a staged approach, such that COMET Phase-I will build the production target and first 90° of muon transport beamline. Phase-I will operate two different configurations, either to perform beam characterisation or to make a μ - e conversion measurement, aiming for a hundred-fold improvement on the limits set by the SINDRUM-II experiment. Fig. 3a illustrates the beamline that will be used for Phase-I, showing how the first 90° for Phase-II will be built at this stage. To be able to both study the beam properties and measure $\mu^- + N \rightarrow e^- + N$ at Phase-I, two different detector systems will be used as shown in Fig. 4.

CONSTRUCTION AND ON-GOING RESEARCH AND DEVELOPMENT

Facility Construction

Fig. 5 shows two images of the construction of the COMET facility. The COMET building joins on to the existing Hadron Hall at J-PARC and contains the experiment area on the lowest level, a staging and craning area on the first and second floor, and offices and control rooms on the top floor. In January 2015, the fifteenth COMET collaboration meeting was held in J-PARC and KEK where the collaboration were able to view the nearly finished building. By March 2015, the first beamline components were being installed, starting with the first 90° of bent muon transport solenoid that will be used for Phase-I.

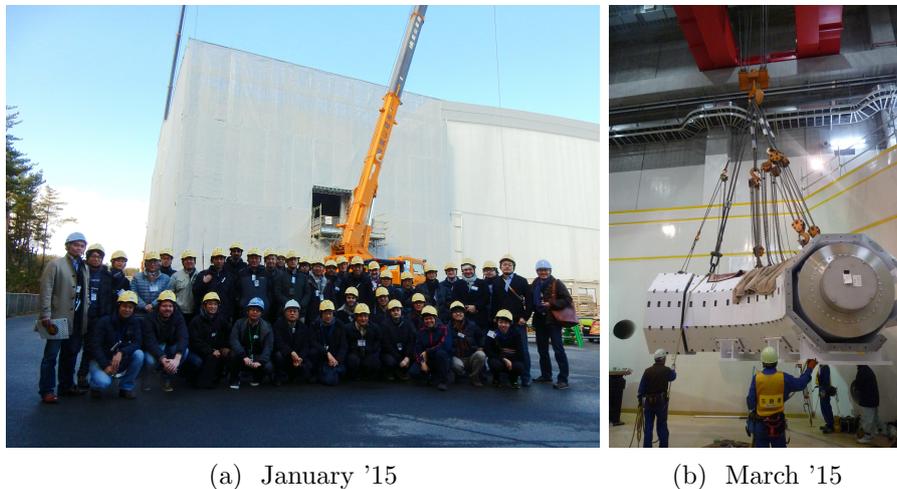


FIG. 5: Construction of the COMET building and beamline. (Fig. 5a) The COMET collaboration in front of the nearly finished COMET Experiment Building at the 15th collaboration meeting in January 2015. (Fig. 5b) Installation of the first 90° of the bent muon transport solenoid in March 2015.



FIG. 6: Preparation of various components of the CyDet detector. The outer and inner walls have been purchased (left) and wire stringing has begun (right).

The CyDet: a Cylindrical Detector for the Phase-I Physics Measurement

In order to achieve the desired two orders of magnitude improvement over SINDRUM-II at Phase-I, the detector needs to be blind to most of the beam flash, and the large number of low-energy electrons produced by bound muon decay in the target. The detector known as the CyDet (Cylindrical Detector) will be tasked with this measurement. It combines a Cylindrical Drift Chamber (CDC) with two rings of Cherenkov Hodoscope and Scintillation counters which provide a trigger and t_0 for each event.

Contained in a co-axial solenoidal field, the inner radius of the CDC is tuned such that the detector is blind to most of the beam flash, which will enter and remain in the region close to the solenoidal axis given its relatively low momentum. The same is true for the bulk of the bound muon decay spectrum, the majority of which has momentum less than 60 MeV. Given the stopping target diameter and the 1 T field magnitude in the detector, the inner wall of the CDC is set to 60 cm which means electrons with less than 60 MeV coming from the target are unable to reach the detector. Fig. 4a shows an event display from a simulation of the CyDet with the beam flash from a single proton bunch passing through it.

Construction of the CDC is well under way with about 40% of all wires already strung. In total 150 days are expected to be needed to complete wire stringing, which should finish in November when tensioning checks can be performed before transportation to the COMET facility. In the meantime, tests using prototype versions have been on-going using both cosmic rays and electron beams at Tohoku University in Japan. Additionally, significant work is under way to study the use of a purely track-based trigger, which could allow the triggering hodoscopes to be removed and higher beam rates supported.

The StrECAL: a Straw Tube Tracker and Crystal ECAL Detector

The StrECAL, consisting of several Straw Tube Tracker stations (five in Phase-I, but possibly more for Phase-II) followed by an ECAL is able to measure both momentum and energy of particles over the full cross section of the beam as is shown in Fig. 4b. As such, in Phase-I it will predominantly be used to profile the beam and understand the impurity

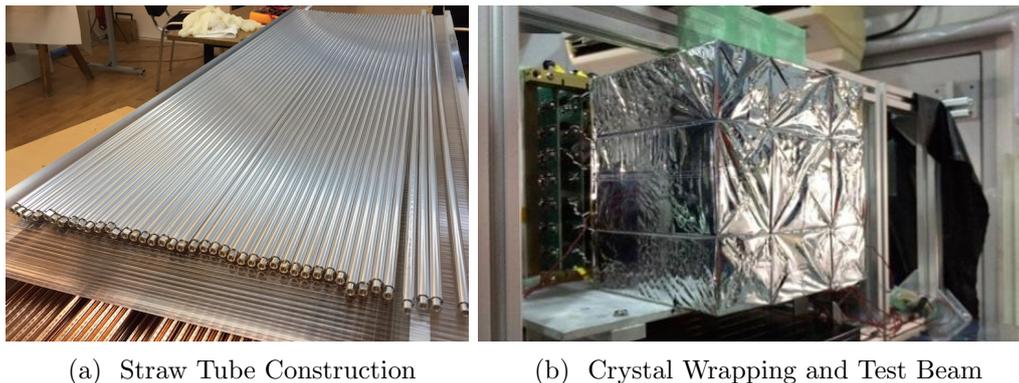


FIG. 7: Preparation of various components of the StrECAL detector. (a) Production of 2500 aluminised-Mylar has been completed and a prototype detector has been prepared for beam and cosmic tests. (b) Crystals for the ECAL wrapped and mounted for characterisation and resolution studies in an electron beam.

rate, momentum distributions, transport beam optics, and additionally the production target distributions. Furthermore, by building, testing and running the StrECAL in Phase-I, significant understanding of the detector can be progressed in anticipation of Phase-II.

For the Straw Tube Tracker, straw production for Phase-I was recently completed, with 2500 tubes being made in total. The straws use the single-seam welding procedure developed for NA62 [4] which is able to reduce the straw thickness whilst maintaining mechanical strength.

In parallel, work on the ECAL is well under way. The decision to use LYSO (Lutetium Yttrium Sulphate) was taken in February 2015 and procurement has already begun with 200 crystals expected to have been purchased by the end of the fiscal year. Despite its increased cost, LYSO was chosen over GSO due to its increased light yield and response time which lead to an improved energy resolution and greater robustness against pile-up. These properties have been tested and confirmed in dedicated beam tests at PSI, Zurich and at Tohoku University in Japan. Each crystal is $2 \times 2 \times 12$ cm which is about 10 radiation lengths for an electron at 105 MeV and in total, by Phase-II, about 2272 crystals will be used. Avalanche photodiodes (APDs) will be mounted to each crystal which will then be wrapped in Teflon tape and grouped into modules of 2×2 crystals to be wrapped in aluminised Mylar.

Simulation, Offline Software and Expected Backgrounds

Simulating the COMET experiment is no easy task, given that some 10^{19} Protons are expected to be stopped in the production target at Phase-I whilst to achieve the desired sensitivity fewer than one background events should occur. This means the simulation needs to be both highly efficient and highly detailed, with accurate modelling of the geometry and material properties, magnetic fields, and underlying physics processes.

However, the current modelling of hadronic processes is such that there is large disagreement between different models for the pion and muon yield in the backwards direction at the production target from protons with 8 GeV kinetic energy. To improve the situation, data from the HARP experiment [3] and some input from the MuSiC [12] experiment has been used, in addition to running with multiple different hadronic production models, including

Geant4 (QGSP_BERT_HP) [9], MARS [8], Fluka [1] and PHITS [5].

In addition, there are limitations in the description of the physics of bound muons. For muon nuclear capture, whilst the branching fraction is known to be about 61% for a stopped negative muon in aluminium [7] the rates for subsequent charged or neutral particle emission are not well known. The AlCap experiment [6] will measure daughter particles and the results from this experiment are feeding back in to the COMET simulation. At the same time, default Geant4 does not accurately reflect the most recent theoretical calculation of the electron spectrum for bound muon decay, instead using only a rather crude parametrisation to adapt the distribution from free muon decay spectrum. Custom physics modelling is therefore being included to address these issues.

The simulation chain begins with the production target, where any of the codes listed above can be used, then moves on to the beam and detector simulations which is based on Geant4. Energy deposits produced at this stage can then either be fed directly into a detector and electronics response package, or via a resampling package that allows a smaller set of proton events to be robustly resampled and smeared in time. The COMET Software includes all these aspects (and more) and recently reached its first stable release in April this year. Since then, two large scale productions have taken place.

DEVELOPMENTS SINCE NUFACT 2015

Since the NuFact conference in August, significant progress has been made on several fronts. For the CDC, wire stringing was completed in November, and wire tensioning measurements are well under way.

Several beam test programs have been carried out including a test at PSI to look at novel particle identification (PID) methods using the ECAL, and separate Straw Tracker and CDC prototype tests at Tohoku University, Sendai, Japan.

On the simulation side, custom muon physics has been completely implemented, including the bound muon decay spectrum and preliminary results from the AlCap experiment. Additionally, there have been significant improvements to the geometry and field calculations, which are shown in Fig. 8.

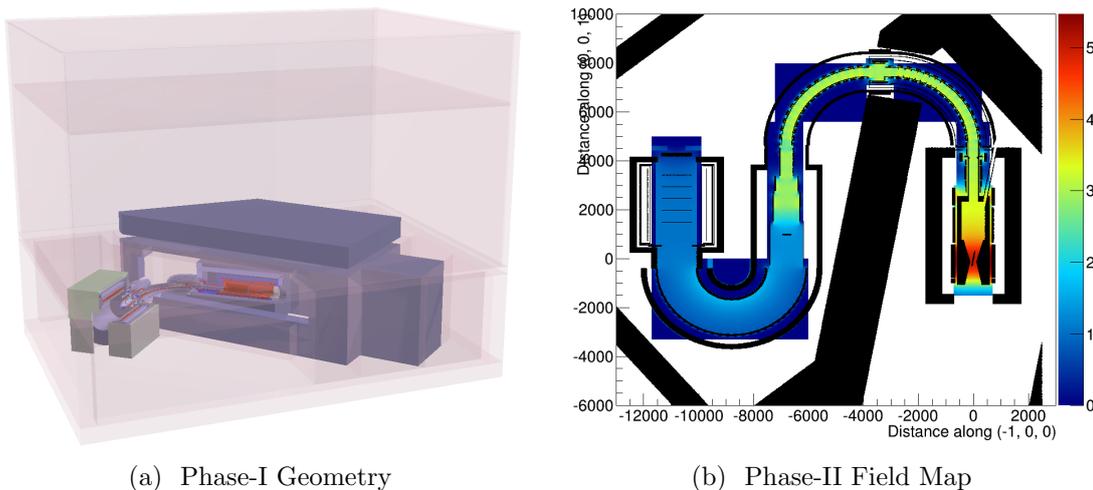


FIG. 8: (a) The current representation of the geometry for Phase-I. (b) The magnetic field magnitude for Phase-II (colour, units are Tesla) with a slice through the geometry overlaid (black).

SUMMARY

The process of muon to electron conversion is a highly sensitive probe for new physics beyond the Standard Model. The COMET experiment will make the first measurement of this process since the SINDRUM-II experiment in 2006. Using several new techniques including a pulsed proton beam, backwards capture of pions and muons from the production target, and bent solenoids combined with tuned dipole fields and collimators allow for Phase-II's four-orders-of-magnitude improvement to the signal sensitivity compared with SINDRUM-II. Given the uncertainties associated with such novel approaches, COMET will first run Phase-I with a reduced transport beamline and two dedicated detectors, with data taking beginning in 2018, and an expected sensitivity of 3×10^{-15} . Progress is well under way, in particular, for the building and facility construction, delivery of the first beamline sections, detector development, and offline software.

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