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The Baby MIND muon spectrometer for the J-PARC T59 (WAGASCI) experiment

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The Baby MIND spectrometer is designed to measure the momentum and charge of muons from neutrino interactions in water and hydrocarbon targets at the J-PARC T59 (WAGASCI) experiment. The WAGASCI experiment will measure the ratio of neutrino charged current interaction cross-sections on water and hydrocarbon aiming at reducing systematic errors in neutrino oscillation analyses at T2K. Construction of the Baby MIND detector within the CERN Neutrino Platform framework was completed in June 2017, where it underwent full commissioning and characterization on a charged particle beam line at the Proton Synchrotron experimental hall.

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1. Introduction

Long baseline neutrino oscillation experiments, amongst others, have confirmed the neutrino sector requires physics beyond the Standard Model. T2K (Tokai-to-Kamioka) discovered electron neutrino appearance in 2013 from a muon neutrino beam with a significance of 7.3σ with a fraction of the approved 7.8×10^{20} protons-on-target (POT) [1], using the Super-Kamiokande water Cherenkov located 295 km from the neutrino production site at the J-PARC. Results excluding zero CP violation at 90% confidence level were announced by T2K in 2016, with data from 20% of the approved POT. With upgrades to the proton beam, reaching 420 kW in 2016, and projected to reach 800 kW in 2019 and 1.3 MW beyond 2020, there is a strong motivation not to be systematics-limited for future runs at T2K and its follow-up project HyperK [2].

The T2K experiment requested an increase in exposure to 20×10^{20} POT, aiming to improve the level of systematic precision to 4%. The J-PARC T59 experiment [3], referred to as "WAGASCI", will address one of the dominant uncertainties, the knowledge of the ratio of neutrino interaction cross-sections in water (far detector) and plastic scintillator (near detector).

WAGASCI proposes to test a new 3-D grid-type detector, to improve on the current understanding of multi-body nuclear effects of neutrino interactions in the 1 GeV energy region, possibly reaching a level of 3% systematic uncertainties. The 3-D modules have higher target fraction (80%), and wider angular acceptance (4π) compared with the ND280 near detectors [4]. They are located on the B2 floor of the ND280 building, where different neutrino spectra are available from different off-axis positions. Measurements with different but fractionally overlapping beam spectra will help resolve contributions from different neutrino energies, important for oscillation analyses given the neutrino beam spectrum at a 2.5° off-axis angle is not monochromatic.

The WAGASCI neutrino modules require additional detectors to determine the momentum of each muon resulting from charged current interactions. This function is fulfilled either side by Muon Range Detectors (side MRDs) and downstream by the Baby MIND detector which is magnetised, providing information on the charge of muons as well as their momenta, Figure 1.

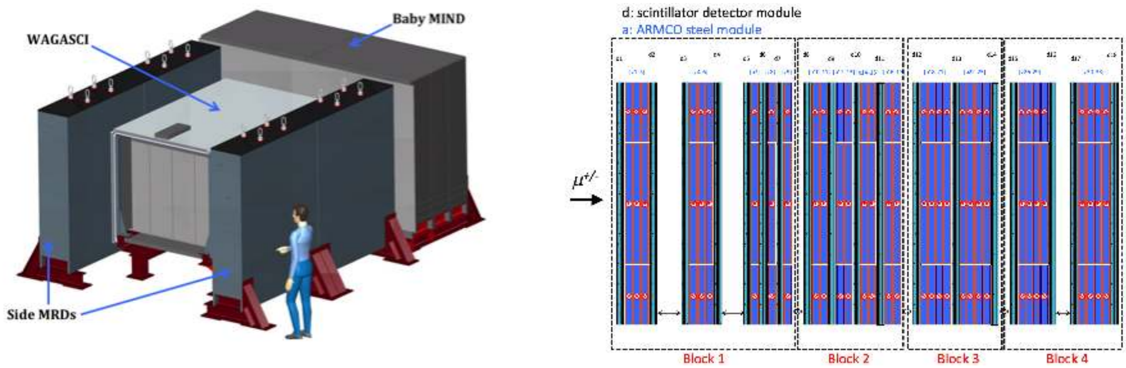

Figure 1: Left) WAGASCI modules: flanked by 2 side muon range detectors (sMRD) and one downstream muon detector (Baby MIND). Right) side view layout of the Baby MIND during beam tests at CERN.

Construction of the Baby MIND was completed in June 2017. It was then tested in June and July 2017 at the Proton Synchrotron experimental hall at CERN with a mixed charged particle beam comprising mostly muons whose momenta were adjustable between 0.5 and 5 GeV/c.

2. Detector description

The Baby MIND collaboration submitted a proposal to the SPSC at CERN, SPSC-P-353 [5], met with approval by the CERN research board as Neutrino Platform project NP05. The detector consists of 33 magnet modules, each $3500 \times 2000 \times 50$ mm^3 (30 mm steel) with a mass of approximately 2 tonnes. Of these magnet modules, 18 are instrumented with plastic scintillator modules. Each scintillator module is constructed from 2 planes of horizontal bars (95 bars in total) and 2 planes of vertical bars (16 bars in total) [6], arranged with an overlap between planes to achieve close to 100% hit efficiency for minimum ionizing muons.

The plastic scintillator counters were made from 220 mm-wide slabs, consisting of extruded polysterene doped with 1.5% paraterphenyl (PTP) and 0.01% POPOP. They were cut to size then covered with a 30-100 μm thick diffuse reflector resulting from etching of the surface with a chemical agent [7, 8]. The horizontal bar size is $2880 \times 31 \times 7.5$ mm^3, with one groove along the length of the bar in which sits a wavelength shifting fiber from Kuraray. The vertical bar size is $1950 \times 210 \times 7.5$ mm^3, with one U-shaped groove along the bar. On each bar, two custom connectors house silicon photomultipliers, MPPC type S12571-025C from Hamamatsu, either side of the horizontal bar, and both connectors at the top for the vertical bar. This geometrical configuration for vertical bars was chosen for ease of connectivity to the electronics, and maintenance operations.

A total of 1744 horizontal bars and 315 vertical bars (including spares) were produced at the Uniplast company (Vladimir, Russia). All bars were measured at INR Moscow with a cosmic ray setup using the same type S12571-025C MPPCs and CAEN DT5742 digitizer [9]. The average light yield (sum from both ends) was measured to be 37.5 photo-electrons (p.e.) per minimum ionizing particle (MIP) and 65 p.e./MIP for vertical and horizontal bars, respectively. After shipment to CERN, all bars were tested once more individually with an LED test setup [10]. 0.1% of bars failed the LED tests and were therefore not used during the assembly of modules.

Support frames for the scintillator modules were machined to high precision by Haba SA. The scintillator bars are held in place using structural ladders that align and maintain the bars, Figure 2. No glue is used in the process, so bars can be exchanged. Each module consists of 2 half-modules, and each half-module consists of one plane of horizontal bars, and one plane of 8 vertical bars. Each half-module is assembled independently, then coupled to its corresponding half-module to form a complete module. Aluminium sheets front and back provide light tightness.

Figure 2: Scintillator modules assembly. Left) top of front half-module showing vertical bars, and the spacers-ladders that hold horizontal bars in place. Middle) rear half-module showing horizontal bars on their ladders. Right) Assembled rear half-module, the front half-module can be seen in the background.

A total of 3996 MPPCs are read out by custom electronics Front End Boards that can process up to 96 channels each, sending charge and timing information of hits in the detector to dedicated data acquisition computers. The magnetisation scheme and electronics, which are two major independent R&D items are discussed separately hereafter.

3. Magnetisation scheme

Project constraints for the design, construction and testing of the Baby MIND came from the need to operate the detector both at CERN and J-PARC on a relatively short timescale. Installation at J-PARC in particular has driven the overall design of the detector. The magnetisation scheme for the Baby MIND developed within the CERN Neutrino Platform framework is a direct result of the requirement to lower segments of detector elements through a narrow shaft down to the lowest floor of the ND280 building pit at J-PARC [11]. The Baby MIND is built from sheets of iron interleaved with scintillator detector modules. The 33 Baby MIND iron magnet modules are all individually magnetised, unlike traditional layouts for magnetised iron neutrino detectors (e.g. MINOS) which tend to be monolithic blocks with a unique pitch between consecutive iron segments and large conductor coils threaded around the whole magnet volume. This allows for far greater flexibility in the setting of the pitch between segments, and in the layouts that these detectors can take.

A prototype was constructed from standard construction steel and completed in March 2016. The first production module was made in September 2016 with ARMCO magnetic steel. Production of the 33 modules proceeded at the rate of one module every 3-4 days, with completion 2 weeks ahead of the scheduled end of February 2017. The assembly zone is shown in Figure 3.

The key design outcome is a highly optimized magnetic field map. A double-slit configuration for coil winding was adopted to increase the area over which the magnetic flux lines are homogeneous in B_x across the central tracking region. Simulations show the magnet field map to be very uniform over this central tracking region covering an area of 2800×2000 mm^2, Figure 3. The B_x component dominates in this region, with negligible B_y and B_z. This was confirmed by measuring the field with 9 pick-up coils wound around the first ARMCO module. Subsequent modules were equipped with one pick-up coil. Test results on the 33 modules show all to achieve the required field of 1.5 T for a current of 140 A, with a total power consumption of 11.5 kW.

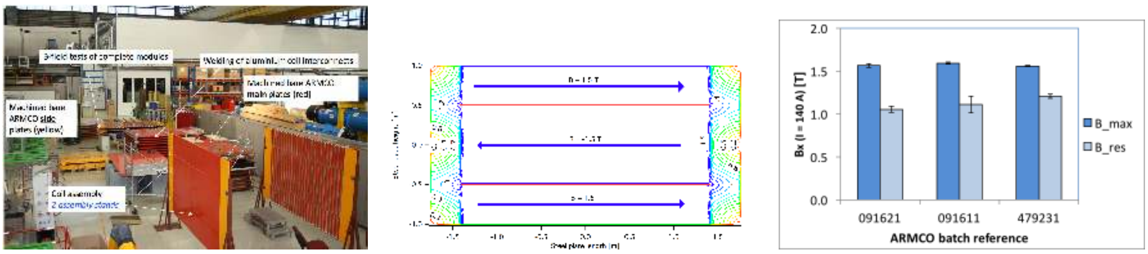

Figure 3: Left) Magnet assembly zone at CERN. Middle) Magnetic field map with a coil along 280 cm of the length of the plate. Right) Measured B field for 33 modules.

4. Electronics

The Baby MIND electronic readout scheme includes several custom-designed boards [12]. The revised version is shown in Figure 4. At the heart of the system is the electronics Front End

Board (FEB), developed by the University of Geneva, Figure 5. The readout system includes two ancillary boards, the Backplane, and the Master Clock Board (MCB) whose development has been managed by INRNE (Bulgarian Academy of Sciences) collaborators.

One critical element in the photosensor readout path is the cable bundle, a 5 m extension coaxial cable RG174U that connects the photosensor to the FEB. Each bundle connects up to 32 photosensors. The purpose is to decouple the FEBs from the scintillator modules, which improves accessibility to FEBs and their long term maintainability. The module end of the bundle hosts some electronics that manages the application of the high voltage to the SiPMs, enabling faulty SiPMs to be switched off at that level. This feature was added after the summer 2016 beam tests, where a short circuit on a single channel would disable a bank of 96 channels.

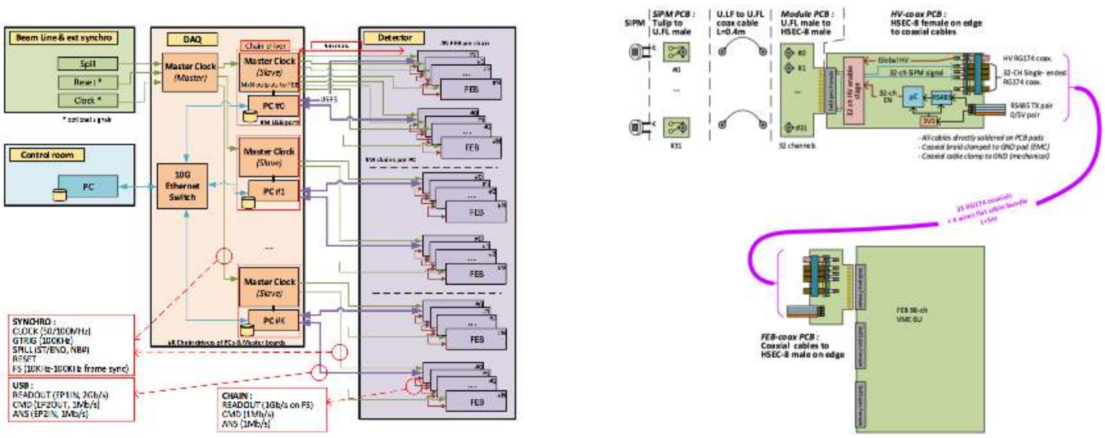

Figure 4: Left) Baby MIND electronics readout scheme. Right) SiPM-to-FEB connectivity.

The FEBv2 hosts 3 CITIROC chips that can each read in signals from 32 SiPMs [13]. Each signal input is processed by a high gain, and a separate low gain, signal path. Both paths comprise independent pre-amplification and "slow" shaping stages with tuneable gain and shaping time constant, respectively. The outputs from the slow shapers can be sampled using one of two modes: a mode with an externally applied delay, and a peak detector mode. A faster shaper can be switched to either HG or LG paths, followed by discriminators with adjustable thresholds providing 32 individual trigger outputs and one OR32 trigger output. An Altera ARIA5 FPGA on the FEBv2 samples these trigger outputs at 400 MHz, recording rising and falling times for the individual triggers and assigning time stamps to these. Time-over-threshold from the difference between falling and rising times gives some measure of signal amplitude, used in addition to charge information and useful if there is more than one hit per bar within the deadtime due to the readout of the multiplexed charge output of $\sim 9\ \mu$s. The ARIA5 also manages the digitization of the sampled CITIROC multiplexed HG and LG outputs via a 12-bit 8-ch ADC.

The FEBv2 is designed to fit into a slot in a minicrate as shown in Figure 5. The front face receives the SiPMs cable bundles, the rear end plugs into the backplane. Up to 6 FEBv2 can be housed in each minicrate. Eight minicrates are distributed either side of the Baby MIND.

The internal 400 MHz clock on the FEBv2 can be synchronised to a common 100 MHz clock. The synchronisation subsystem combines input signals from the beam line into a digital synchronisation signal (SYNC) and produces a common detector clock (CLK) which can eventually be synchronised to an external experiment clock [14]. Both SYNC and CLK signals are distributed to the FEBs. Tests show the FEB-to-FEB CLK(SYNC) delay difference to be 50 ps (70 ps). Signals from the beam line at WAGASCI include two separate timing signals, arriving 100 ms and 30 μs before the neutrino beam at the near detectors [15]. The spill number is available as a 16-bit signal.

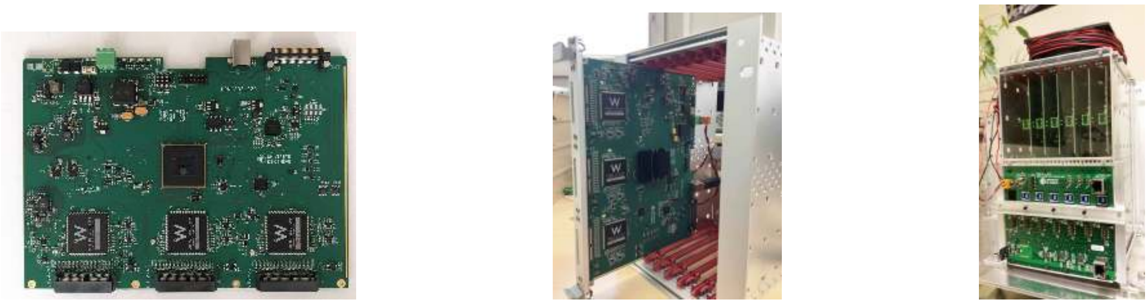

Figure 5: Left) Second version of the electronics readout Front End Board (FEBv2), received at the University of Geneva in March 2017. Middle) FEBv2 in minicrate. Right) rear of minicrate with 6 FEBs connected through a Backplane PCB on the lower half of the minicrate.

Several connection options are possible between the FEBv2 and a DAQ PC. The FEBv2 can be operated as a standalone device, connected directly to a DAQ PC via USB3. This is useful for laboratory measurements on the FEB itself, its maintenance and calibration, and qualification tests on other components such as MPPCs or cable bundles. It is also possible to daisy chain several FEBs via the backplane PCB in experiment data taking mode, with the first FEB in the chain connected directly to the DAQ PC via a USB3 link. In this mode the USB3 bandwidth is shared with the potential 6 FEBs in the chain thanks to a Time Division Multiplexing (TDM) protocol, each FEB having 1/6th of the data throughput. For enhanced measurements or calibration a dedicated option of the chaining is also possible where 1 single FEB in the chain can use the full bandwidth of the single USB3 connection. The DAQ software is platform independent. The data protocol encodes information such as spill number, FEB ID, hit channel number, time and charge, as well as tags to match the TDM data stream to the correct minicrate slot ID.

5. Beam tests

Several beam tests were run on Baby MIND components during summers 2016 and 2017 at the T9 beam line of the Proton Synchrotron experimental hall at CERN. The first campaign in 2016 was focused on FEBv1 tests. Experience gained directed upgrades to the FEB, such as synchronisation scheme improvements, increases to the dynamic range by better matching the output stage of the CITIROC and ADC input stage, new SiPM connectivity with cable bundles. Data also served to test the Simulation and Reconstruction of Muons and Neutrinos (SaRoMaN) package developed by the University of Glasgow [16]. SaRoMaN can process simulated data from GEANT4 [17], simulated neutrino interaction data, and real data from experiment runs. Detector geometry is defined using GDML files [18], which can be used for both simulation and event reconstruction.

In addition to the electronics tests and SaRoMaN benchmarking, an assessment was made of the light yield as a function of hit position for vertical bars, a better understanding being required because of the asymmetry in the light collection due to both MPPCs being located at one end of the bar. A scan of 117 points across the area of three vertical bars was carried out. Results show that hit thresholds must be chosen carefully in order not to reject good events, especially hits at the lower end of the vertical bars. Rather than impose a coincidence of signals from the 2 MPPCs, an approach with a higher threshold on either one or the other MPPC would be preferable. Horizontal bars were tested in an earlier campaign, with hit efficiencies and timing resolution described elsewhere [19].

Between 7th June and 19th July 2017, the Baby MIND was fully commissioned at T9, with all 18 scintillator modules connected via cable bundles to 44 FEBs hosted in 8 minicrates, Figure 6. The charged particle species present in the beam were μ, π, p and e, and their relative content was defined by the beam polarity, its momentum, and the position of absorbers between the target and the experiment zone. Several data runs were taken with momenta ranging from 0.5 GeV/c to 5 GeV/c, changing several parameters of the detector setup such as magnet polarity and electronics settings. Some event displays are shown in Figures 6, 7. These demonstrate the unpacking of the raw data binary files, detector channel assignment and synchronisation of electronics all work, and confirm the magnet is operating as is expected, with beams bending upward or downward in the Y-Z and X-Y projections only, for an incoming horizontal beam.

A muon passing through one module can trigger between 1 and 8 photosensors on that module, though a coincidence is required between vertical and horizontal bars to create a space point. The PS beam spill was around 400 ms, with varying gaps between spills, the minimum being 2.4 s by request. Timing counters on the FEB are organized such that the trigger sampling counter is reset every 10 μs. The definition of coincidence by time for hits on a given module was made on the basis of the time taken for light to travel the whole length of the WLS fiber (4 m at 16 cm/ns = 25 ns) adding some margin. Track selection across all modules is done with hit time selection across a time window corresponding to μ travel time through the length of the detector along the beam direction, 50 ns including margins.

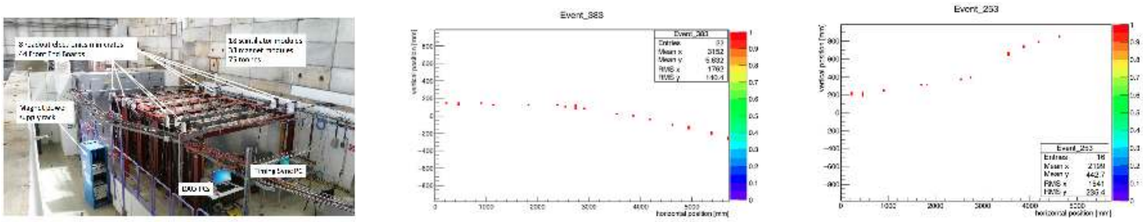

Figure 6: Left) Baby MIND commissioned at the Proton Synchrotron experimental hall at CERN. Middle) +3 GeV/c muon impinging from left on the detector, side view, YZ projection. Right) -3 GeV/c muon impinging from left on the detector, side view YZ projection.

One challenge to be addressed is that of obtaining high charge identification efficiencies for μ^+/μ^- down to 500 MeV/c and below. MIND detectors are ideally suited for experiments such as the Neutrino Factory [20, 21] and nuSTORM [22] where momenta for muons of interest are above 1 GeV/c. They are limited by multiple scattering in the iron, and their use is overlooked for applications requiring good charge ID efficiencies below 1 GeV/c. By optimising the distance between the first magnet modules, rendered possible by the magnet design, simulations show improved charge identification efficiencies down to 400 MeV/c. Preliminary analysis of beam test data shows excel-

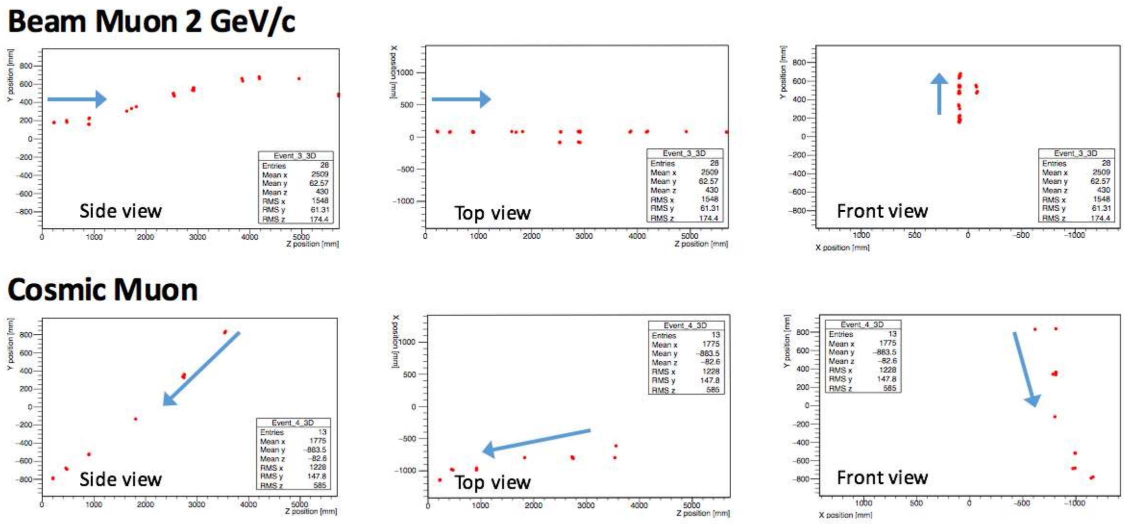

Figure 7: Comparison of a beam muon and cosmic muon in the three different geometrical projections of the detector. The beam impinges on the detector from the left. The arrows indicate the direction of travel of these muons. The direction of the cosmic muon is inferred from timing information.

lent agreement with simulations in the region 0.5 to 5 GeV/c, with charge identification efficiencies above 95% between 1 and 5 GeV/c, dropping to 85% from 1 to 0.5 GeV/c.

6. Conclusions

The Baby MIND spectrometer is designed to measure the momentum and determine the charge of muons resulting from charged current neutrino interactions in the WAGASCI neutrino targets. The novel magnetisation scheme has a highly opimized magnetic field map, and confers modularity and flexibility in the layout of the detector. This approach can be deployed for applications with a wide variety of detector types (water Cherenkov, gas or liquid TPC, scintillator...) and geometries. The design, R&D, construction and qualification phases were completed in June 2017. Extensive measurements were carried out at the CERN PS experimental hall in June and July 2017 with charged particle beams in the range 0.5 to 5 GeV/c, confirming the functionality of all major systems including magnet, scintillators, electronics and DAQ. Results are in agreement with simulations and confirm high muon charge identification efficiencies. The 75 tonne detector was loaded into 4 containers in October for shipment to Japan, due for arrival at J-PARC by mid-December 2017. Installation is planned for Q1 2018, and commissioning for Q2 2018.

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