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Sub-GeV particle identification with aerogel Cherenkov threshold detectors and tagged photon beam for the Water Cherenkov Test Experiment

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The Water Cherenkov Test Experiment (WCTE) will be installed in CERN's recently upgraded T9 "Test Beam" Area in Autumn 2024. It has three goals: to prototype photosensor and calibration systems for Hyper-Kamiokande, to develop new calibration and reconstruction methods for water Cherenkov detectors and to measure lepton and hadron scattering on water. The collaboration performed a 3-week-long beam test in July 2023. It uses newly developed aerogel Cherenkov threshold counters (ACTs) to perform an efficient separation of pions from muons in the sub-GeV range, which had not been done before. Additionally, a new compact tagged photon beamline was developed, composed of a Neodymium (N52) Halbach array permanent magnet and a hodoscope array placed downstream of the magnet. The combination of the ACTs and tagged photon beamline provides sub-GeV p, e, pi, mu and gamma test beams. Using this setup, the collaboration was able to estimate the beam flux of CERN's T9 beam.

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1. The Water Cherenkov Test Experiment

The Water Cherenkov Test experiment (WCTE) will be installed in autumn 2024 in CERN's T9 beamline (East Area). The WCTE is composed of a cylindrical Water Cherenkov detector 3.4m in height and 3.8m in diameter and a beam monitoring apparatus. A description of the WCTE is given in [1]. WCTE will help Hyper-Kamiokande [2] reach its targeted precision by developing and testing some of the hardware and calibration techniques that will be used by Hyper-Kamiokande. It will also study the interaction of electrons, muons, pions, protons and photons with momenta between 200 MeV/c and 1.2GeV/c in ultra-pure and Gadoliunium-doped water. The WCTE collaboration performed a three-week long beam test in CERN's T9 beamline in July 2023 testing the particle identification and the tagged photon production set-ups.

2. Sub-GeV particle identification in CERN's T9 beamline

2.1 Charged particle identification set-up

The set-up used to identify charged sub-GeV particles, shown in Figure 1, relies on a pair of trigger scintillators to measure the particle's time of flight. Two hollow plastic scintillators are used to provide beam halo veto.

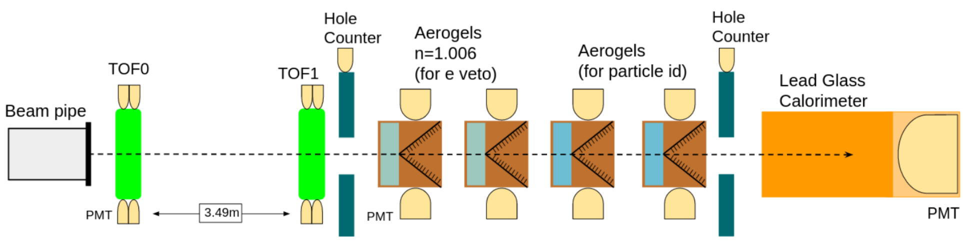

Figure 1: Diagram of the set-up used for the identification and momentum measurement of charged particles during the 2023 beam test.

The WCTE collaboration developed a novel Aerogel Cherenkov Threshold (ACTs) detector, shown in Figure 2 for particle identification. The ACTs are 3D-printed, optically opaque rectangular boxes, each containing one block of custom-made aerogel [3], 10cm by 10cm in height and width, with thickness and refractive index shown in Table 1.

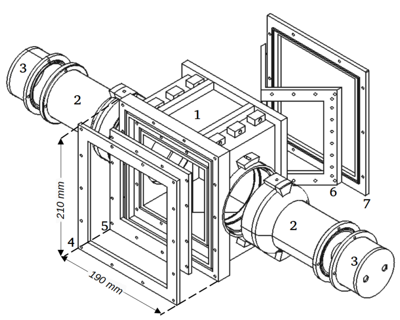

Figure 2: Isometric view of the box design without the aerogel block.

		Threshold momenta (MeV/c)	
n	Thickness (cm)	μ	π
1.006	8+8	962	1 258
1.01	6+6	744	973
1.015	6+6	607	803
1.02	6+6	525	687
1.03	4+6	427	559
1.047	8+8	340	445
1.06	4+6	300	393
1.11	2+2	219	286
1.13	2+2	200	262
1.15	2+2	185	243

Table 1: Characteristics and Cherenkov thresholds for the aerogel blocks. Electrons are above threshold for all momenta considered.

The side of the box facing the beam pipe is lined on the inside with a 3M™ Enhanced Specular Reflector (ESR) film. A triangle mirror made of the same film is located on the opposite side of the aerogel block. These reflect the Cherenkov light produced in the aerogel by particles onto the two flat-face 3.5 inch Hammamatsu R10233 high QE PMT which are mounted on either side of the box. A pair of n=1.006 ACTs is used to flag electrons (only they emit Cherenkov light in these ACTs). Muons are separated from pions by using a second pair of ACTs whose refractive index is adjusted at the pion Cherenkov threshold (e.g. for a 500MeV/c beam, the boxes with n=1.03 are placed in the beamline) such that muons are above and pions below Cherenkov threshold. The risk of knock-on electron background is mitigated by using pairs of ACTs with the same refractive index. A lead glass calorimeter is placed at the end of the beamline, it will be replaced by the water Cherenkov detector in 2024.

2.2 Particle identification method

Heavier particles like protons and deuterons are flagged by their longer time of flight. The time of flight resolution of the WCTE trigger scintillator is 0.35ns. Electrons are separated from muons and pions by applying a 2D cut in the distribution of the downstream ACTs charge (its refractive index is tailored to the beam momentum) against the charge collected in the upstream n = 1.006 ACTs. The pions and muons were separated by applying a cut on the charge collected in the pair of downstream ACTs. Both of these cuts are shown on Figure 3. The position of each cut line was found using a grid search algorithm optimising for particle purity. For a run at 460 MeV/c the WCTE collaboration was able to reach muon/pion separation at the 97.0% (99.6%) purity level in the muon (pion) sample. The ESR film was found to be lightly scintillating with 5 to 10 photon-electron produced per ACT, depending on the momentum and particle type. This film will be exchanged for a non-scintillating Mylar film in 2024. The method used causes the muon selection to contain most of the electron contamination whereas the pion sample is mostly free of it. The T9 beam contains a majority of electrons which is reduced by a factor of about 7 by the online electron veto.

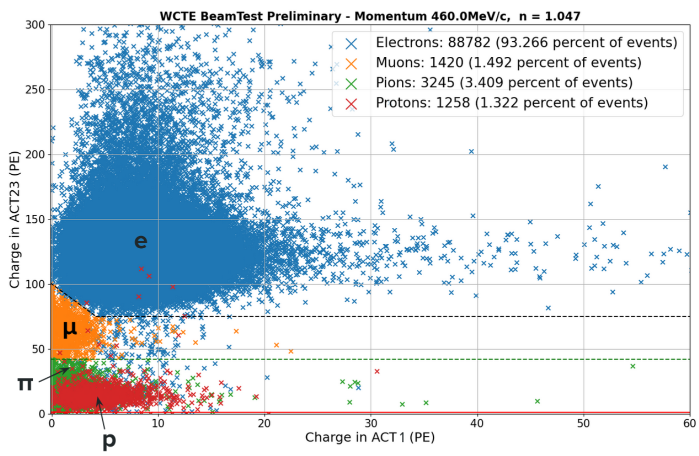

Figure 3: Cut lines used to separate electrons-, muon- and pion-like events. Protons are identified with a time of flight cut.

Once each event is associated with a particle type, this identification is validated using the calorimeter as shown in Figure 4. The purity of the non-electron selection is calculated by assuming that all particles depositing more than the mean charge deposited by electron minus 3 sigma in the calorimeter are electrons. Using this assumption, the muon and pion selection's purity is measured to be 85.7% for an efficiency of 88.6%. The purity of the selection can be significantly improved at the cost of reducing the efficiency which will be done for the 2024 data analysis.

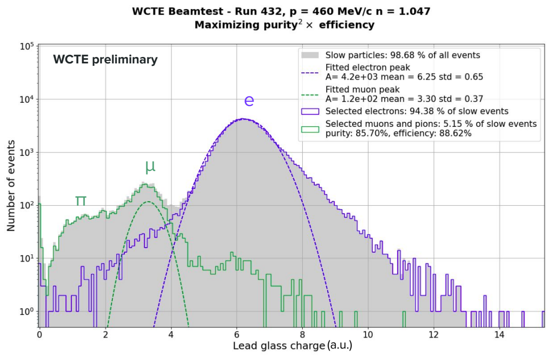

Figure 4: Charge deposited in the calorimeter by particles identified by the ACT cuts as electrons (blue) or as muons or pions (green). A Gaussian distribution is fitted to the electron and muon peaks.

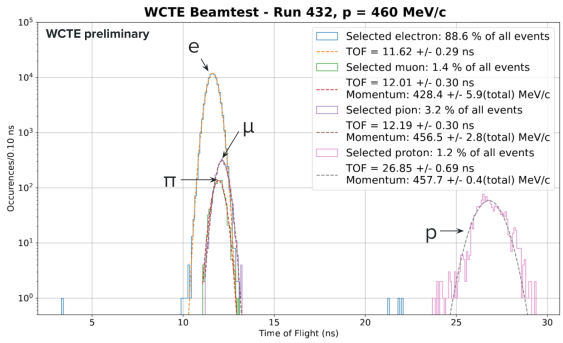

Figure 5: Time of flight distribution of the different particle populations as identified by the ACT cuts described in Section 2.2.

The time of flight of each population is used to measure its momentum which should be similar for all particle types and in line with the beam setting provided by CERN. Figure 5 shows the momentum calculated for each particle type for a run at 460MeV/c showing agreement between the momentum estimated for pions (456.5 ± 2.8 MeV/c) and protons (457.7 ± 0.4 MeV/c). The momentum estimate for the muon is significantly lower due to the important electron contamination and the large uncertainty due to relativistic effects.

2.3 T9 beamline characterisation

With the methods described above, the WCTE collaboration was able to perform the first characterisation of the T9 beam since its refurbishment. This characterisation comprises both the beam composition and momentum at set momenta between 200 MeV/c and 1.2GeV/c with both Aluminium and Berrylium + Tungsten radiator targets. The overwhelming majority of particles were found to be electrons with up to 10^5 particles per spill. The number of pions and protons per spill was found to increase with the beam momentum whilst the number of muons per spill stabilises at about 150 particles/spill after 400 MeV/c. The tungsten radiator is known to boost electron production and it was observed that the relative proportion of electrons in the beam was indeed higher for this target compared to the Aluminium one.

3. Tagged Photon set-up for WCTE

The WCTE collaboration developed a novel compact facility for producing tagged photons of known energy using a low momentum, high intensity beam of electrons. The set-up tested in

July 2023 is shown in Figure 6. It is composed of a pair of trigger scintillators and a single hole counter used in a similar way to what was described in section 2.1. A pair of n=1.006 ACTs is used to ensure that only electrons are triggered on. This beamline includes a compact (16x24x24cm) hollow Halbach permanent magnet made up of 16 Neodymium (N52) permanent magnets arranged in an Halbach array configuration which was originally built for the EMPHATIC experiment [4]. This magnet has a 1.5T peak magnetic field and a 0.23Tm bending power as shown in Figure 7. The last instruments placed on the beam axis are a single ACT with refractive index n=1.15 in which charged particles (except protons) emit Cherenkov light and finally the lead glass calorimeter.

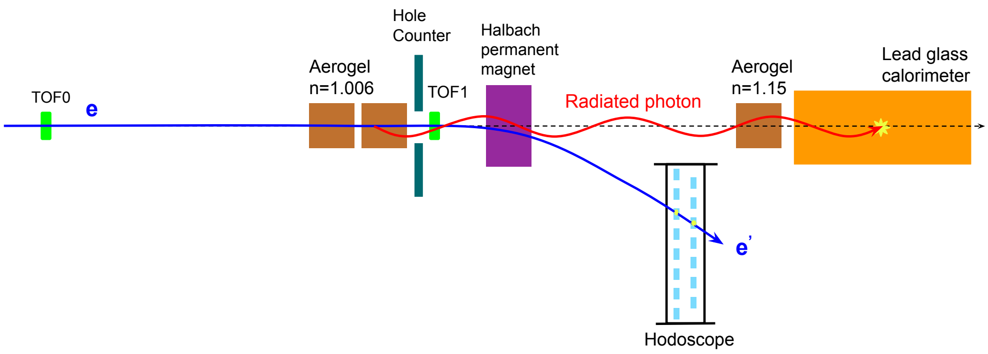

Figure 6: Tagged photon set-up developed by WCTE showing as an example an electron radiating a bremsstrahlung photon in the second ACT box.

Electrons travelling in matter can produce photons in the direction they travel via the bremsstrahlung effect. The total material budget of the beamline prior to the magnet is about 1% of the electron radiation length. Assuming an electron radiates one and only one photon and that photon is emitted along the beam axis, the photon will travel through the n = 1.15 ACT without emitting any light and deposit all of its energy in the calorimeter, thus providing a direct measurement of its energy. All charged particles, including the parent electron, will be bent away from the beam axis by the permanent magnet. If the electron has radiated enough energy, it will be deflected onto a hodoscope which is a set of 15 plastic scintillator bars arranged in an array, located at beam height but offset from the beam axis. Since the deflection depends on the electron's momentum, the position of the hodoscope bar that it hits gives its momentum. The photon's energy is then obtained by subtraction from the known initial electron's momentum. A beam of electron of momenta ranging from 460 MeV/c to 1.2GeV/c was used to produce photons of energy from 100 MeV/c up to 1 GeV/c. The comparison between the photon energy measured using the hodoscope channel and the charge deposited in the calorimeter is shown in Figure 8. There is a linear relationship between these two quantities. About 160 tagged photons were produced per spill across the momentum range considered, a rate that is more than sufficient for performing WCTE's Physics program.

4. Conclusions and outlook

The WCTE will help the Hyper-Kamiokande experiment reach its Physics goals thanks notably to its beamline instrumentation that provides both particle identification and momentum measurement. The beam test performed in July 2023 demonstrated high purity sub-GeV particle

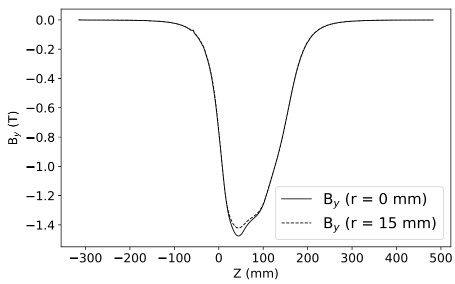

Figure 7: Magnetic field along the axis of the magnet at two different radii.

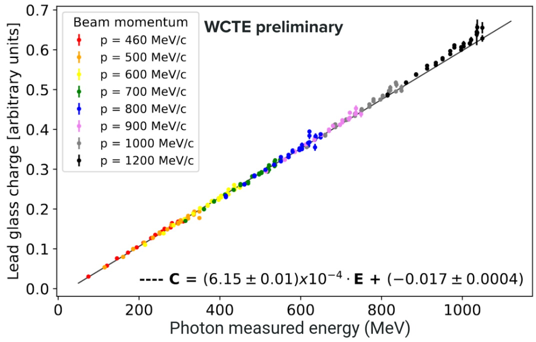

Figure 8: Charge deposited by photons in the calorimeter against their energy as measured by the hodoscope.

identification with the novel ACT detectors achieving a 15% electron contamination in the muon sample with 88.6% efficiency and 0.4% muon contamination in the pion sample at the 93.5% efficiency level for a run at 460 MeV/c. Both the purity and efficiency of the selections are expected to drastically improve following the replacement of the scintillating 3M™ reflecting film by an aluminised Mylar film in 2024. With this technique, the WCTE is capable of producing the first characterisation of the newly refurbished T9 beamline in the sub-GeV range. The collaboration also successfully demonstrated the use of a new compact tagged photon facility based on a 1.5T Halbach array magnet capable of producing hundreds of photons per T9 beam spill in the 100 MeV/c to 1 GeV/c range using a high intensity electron beam of momenta ranging from 460 MeV/c to 1.2 GeV/c. Going forward, the two set-ups will be combined into a single one, on two levels. A muon tagger will be placed behind the water Cherenkov detector and a new time of flight detector will be added to the set-up to improve particle identification and triggering capabilities. The number of ACTs will be increased from 4 to 6.

Acknowledgements

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