US Belle II Project
Conceptual Design Report

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1.1 SuperKEKB Commissioning Detector

1.1.1 US Role in a Background Commissioning Detector

The US Belle II groups have a lead role in the design, construction, and operation of the SuperKEKB commissioning detector (also affectionately known as BEAST II in the Belle II collaboration), which will characterize beam-induced backgrounds near the interaction point (IP), starting in Fall 2014. The commissioning detector is needed to prevent radiation damage to the Belle II detector, to provide feedback to the accelerator during commissioning, and to improve our simulation of beam induced backgrounds, which will be more important in Belle II than Belle due to the increased luminosity. The proposed work on the commissioning detector would be a natural continuation of our role during KEKB beam commissioning in 1997 and 1998, and allow the US groups to take a leadership role during a critical phase of the experiment, while requiring only modest investment in equipment and manpower. This is made possible by leveraging the historical involvement and technical expertise on radiation monitoring, gas/pixel tracking detectors, mechanical structures, and DAQ electronics in the US groups.

1.1.2 Commissioning Detector Motivation

Recently the Belle II collaboration decided on a baseline scenario for completing the Belle II detector and commissioning the SuperKEKB accelerator: A partially instrumented version of the Belle II detector will be rolled into the SuperKEKB beam line in the fall of 2014. The Belle II superconducting solenoid will be present and operational, allowing the accelerator group to operate the beams under realistic magnetic field conditions, so that the final-focus optics can be commissioned. During the initial stages of accelerator commissioning high radiation levels are expected, especially during vacuum scrubbing. The barrel calorimeter (ECL), superconducting solenoid, and barrel and endcap K_L/muon detectors will be in place and operational, but to prevent radiation damage, the innermost Belle II detectors (pixels, silicon strips, drift chamber, and iTOP) will not be installed. Instead, these inner subdetectors will be replaced by the SuperKEKB commissioning detector.

Experience with KEKB, as well as PEP-II [2], has shown that during beam commissioning and vacuum scrubbing, it is critical to measure the particle and x-ray backgrounds near the interaction point in detail. Such measurements are needed to provide real-time measurements of luminosity and background levels to the accelerator group, to ensure a sufficiently low radiation level before the final detector is installed, and to tune the simulation of beam-related backgrounds that affect physics measurements in the Belle II detector. Due to higher beam currents and luminosity, beam-related backgrounds will be larger in Belle II than experienced in Belle. Due to the innovative nano-beam scheme employed by SuperKEKB, the relative contribution of different background components (e.g., beam-gas interactions, Touschek scattering, and synchrotron radiation) will also differ from that in KEKB. There are large uncertainties in the levels predicted by simulation, so that direct, *in situ* measurements of these backgrounds are needed.

The Hawaii group led the KEKB commissioning detector effort in 1997 and 1998. The group provided the mechanical structure, drift tubes, and DAQ electronics for the BEAST (Beam Exorcism for a STable experiment) commissioning detector, shown in Fig. 1, and led installation and operation of this detector at KEK. BEAST detected the first KEKB beam in December 1998, the first Bhabhas, provided important feedback during the subsequent accelerator commissioning, and provided data needed for tuning the simulation of beam-induced backgrounds in the Belle detector.

Detailed x-ray and neutron measurements were lacking in BEAST, but are clearly needed here: an unexpected synchrotron radiation component, due to a steering magnet that had not been simulated, burned a hole into the first Belle beampipe. During the initial KEKB operation there was also larger radiation damage to the first Belle silicon strip detector than expected, requiring early replacement of that detector system. Neutrons from beam backgrounds produced unexpectedly large backgrounds in the Belle KLM detector endcaps, increasing their dead time and decreasing their efficiency. Scaling to Belle II conditions, it was concluded that the resulting KLM performance losses would become unacceptable, which is why some of the KLM glass RPCs will be replaced with a with a scintillator-based design. This illustrates the significance of neutron backgrounds, and the importance of understanding their production. Neutrons also were an important unexpected background in the BaBar DIRC detector, and they are difficult to measure precisely.

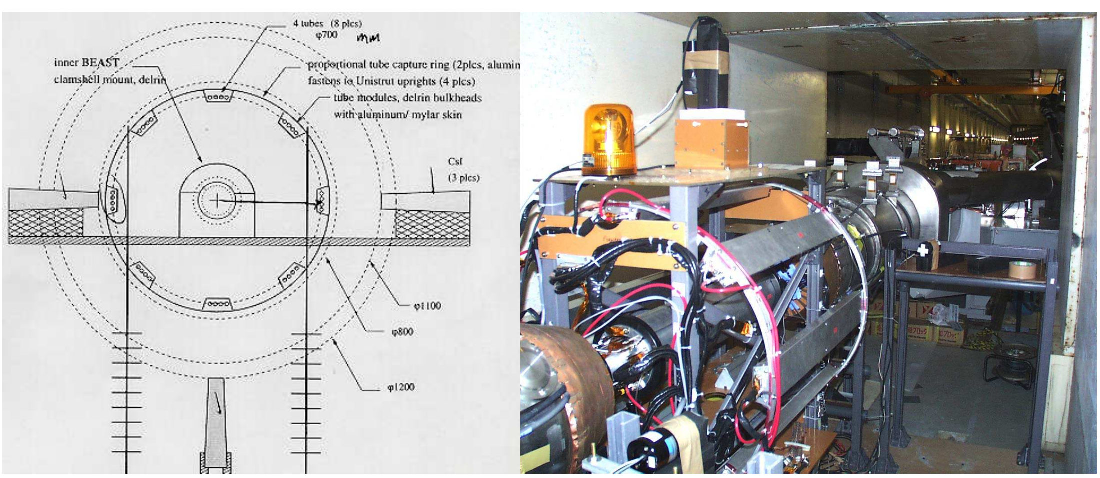

Figure 1: *Technical drawing (left) and photo (right) of the original KEKB beam commissioning detector, BEAST.*

1.1.3 Accelerator Group Goals / Motivation

Recently a consensus was formed on the commissioning scenario of SuperKEKB between the Belle II group and the SuperKEKB accelerator group. In this scenario, the commissioning will be performed in three steps.

In the first step (Phase 1) from January 2015 to May 2015, the machine commissioning will be done without the final focus quadrupole magnets (QCS's) and the Belle II detector. The main goals in this period is to complete the basic machine commissioning including the commissioning of each accelerator component and to perform enough vacuum scrubbing before the Belle II detector is rolled in. Although no beam-collision will be done in this phase, some preliminary machine studies on more essential beam dynamics issues for a high luminosity will also be done such as low-emittance tuning. It is expected that the stored beam currents will reach $0.5 \sim 1$A in this phase. For increasing the beam currents, tuning of the beam feedback system for suppressing the beam instability will be important. The Belle II group requests that the vacuum scrubbing with $0.5 \sim 1$A for at least one month in total should be done. During Phase 1, the commissioning of the damping ring for the positron beam will also be done.

In the second step (Phase 2) from January 2016 to April 2016, the accelerator commissioning will be done with QCS's and Belle II. Although the vertex detector will not be installed in this phase, the machine condition will be the same as that in the final stage from the viewpoint of the accelerator tuning and the full luminosity tuning will be done. The target luminosity at the end of this phase is $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Machine tuning in this phase includes optics tuning, beam collision tuning with the nano-beam scheme and tuning and the study on the detector beam background. As for optics tuning, the continuous orbit correction during the beam operation, tuning of squeezing the beta functions at the IP (low-beta tuning) and tuning on the low vertical emittance (low-emittance tuning) are important. Among them, low-beta tuning is essentially important in SuperKEKB and the achievable luminosity depends largely on the minimum value of the vertical beta functions at the IP. Squeezing the beta functions at the IP is not easy task and maybe we will need several years to attain or approach to the design values of the IP beta functions. As for beam collision tuning, the orbit feedback system to maintain the optimum beam collision and the beam tuning for suppressing the beam-blowup due to the beam-beam effects are important. In SuperKEKB, we will need a much faster orbit feedback, since the luminosity is much more sensitive to the motion of QCS's than the case of KEKB. As for the detector beam background, a realistic detector beam background will be studied before installation of the vertex detector. In SuperKEKB, there are three major sources of the detector beam background, *i.e.* the Touschek effect, the beam-gas Coulomb scattering and the radiative Bhabha process. The beam backgrounds from the Touschek effect and the beam-gas Coulomb are very sensitive to the IP beta functions. Since we will not reach the design values of the IP beta functions in this phase, we will need some extrapolation to estimate the ultimate beam background with the design machine parameters based on the study in this phase. The beam background from the radiative Bhabha process is not very sensitive to the IP beta functions and so the extrapolation to the design luminosity seems relatively straightforward. An example of the machine parameters corresponding to the target luminosity of $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is $\sim$ 1A in the beam currents, $\sim$ 2.4mm in the vertical beta function, which is 8 times larger than the design, and $\sim$ 0.025 in the vertical beam-beam parameter. The scenario mentioned above for Phase 2 is called the baseline scenario. In addition, we keep another scenario as a backup option where the commissioning in Phase 2 will be done with QCS's and without the Belle II detector in the case of some unexpected problems such as a delay in the Belle II construction.

In the third step (Phase 3) starting from October 2016, the full beam commissioning with the full Belle II detector will be done. At a some point in this phase, the physics experiment will start after some detector tuning, if needed.

1.1.4 Commissioning Detector Description and US Contributions

The US Belle II groups will perform simulation work needed to optimize the commissioning detector design (such as placement of subdetectors and optimization of the shielding required to protect the Belle II calorimeter from radiation damage during vacuum scrubbing) and design and build the following commissioning detector components: the mechanical support structure for mounting subdetectors, a PIN-diode array for monitoring radiation dose from charged particles and x-rays, and micro Time Projection Chambers for detailed monitoring of neutrons.

KEK will have responsibility for the calorimeter shielding, including its detailed mechanical design. A range of (non-US) collaborating institutes will install other detector prototypes and subsystems on the commissioning detector, such as silicon strip and pixel detectors, a drift chamber prototype, and a BGO crystal-based luminosity monitor.

1.1.5 Commissioning Detector Design and Simulation

Figure 2 shows the SuperKEKB commissioning detector conceptual design. The instantaneous and integrated radiation dose throughout the inner detector volume will be monitored with an array of 64 PIN diodes, labeled "Diode Array" and "Diode Ring" in the figure. Neutrons will be monitored with an array of eight micro Time Projection Chambers (micro-TPCs). Eight sets of BGO calorimeter crystals will be used for luminosity monitoring. In addition, two prototype pixel detector (PXD) ladders, two silicon vertex detector (SVD) modules, and a $10 \times 10 \times 30$ cm central drift chamber (CDC) prototype will be installed at their nominal Belle II positions. Since (in contrast to the Belle commissioning scenario) the outer Belle II sub-detectors will be present, EM and neutron shields (high-Z material and borated polyethylene, respectively) may be required to protect the barrel calorimeter from radiation damage during vacuum scrubbing. The different monitors will be mounted on a common mechanical structure, which is expected to be similar to that of BEAST used in Belle, shown in Fig. 1, but must now fit within the ECL calorimeter radius. Due to the proximity of accelerator magnets, non-magnetic materials such as fiberglass-based "Unistrut" support beams and brass connectors are required throughout.

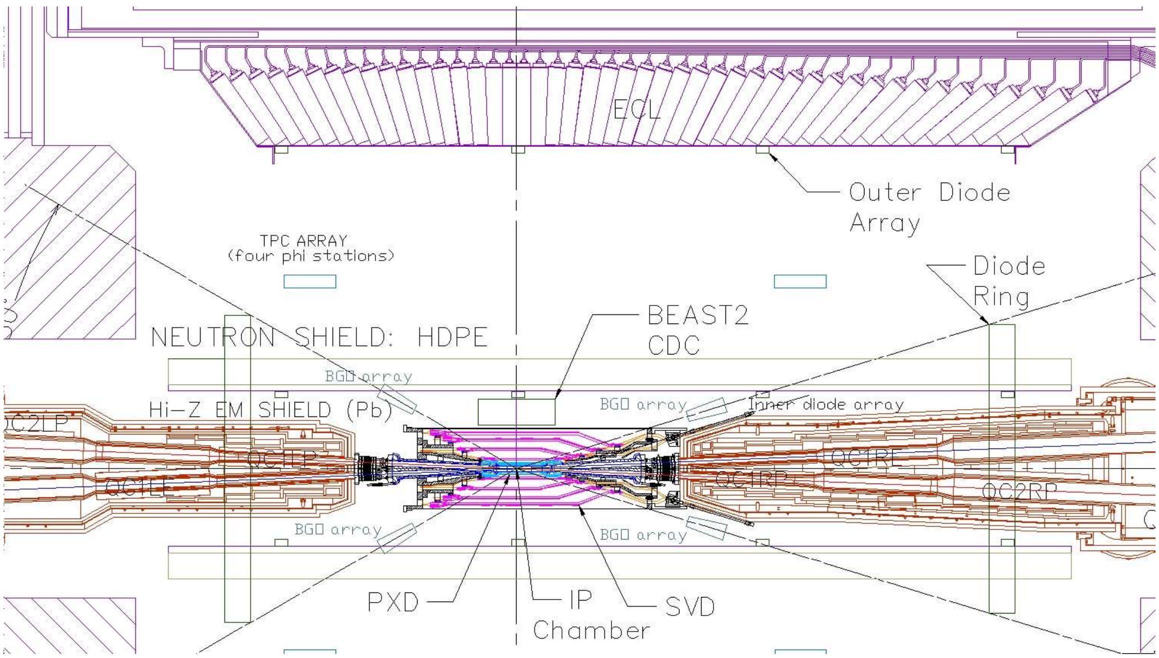

Figure 2: *Conceptual design of commissioning detector. Depending on measured radiation levels, the shield may be removed during later stages of commissioning.*

Members of the Hawaii group, led by Professor Vahsen, will perform simulations of the beam backgrounds expected during the commissioning period. They will work closely with KEK and the other groups involved to iterate the design of the commissioning detector, including the placement of subsystems, the mechanical support structure that positions these subsystems, and the shielding to protect the Belle II calorimeter. In order to produce the current conceptual design on very short notice, the Hawaii group started out by analyzing the existing beam background Monte Carlo simulation (an effort lead by Dr. Nakayama at KEK), which assumes the final SuperKEKB design parameters for the beams, and the final Belle II detector geometry. First results from this analysis (discussed below), combined with simple scaling arguments and conservative assumptions, provided good initial design guidance, but also have large uncertainties. The group will proceed to implement a dedicated GEANT geometry based on the commissioning detector conceptual design, and run a revised background simulation that assumes commissioning beam conditions. This should provide a more firm estimate of the background rates expected during commissioning and will allow us to refine the conceptual design into a technical proposal. Future simulations should include beam-gas bremsstrahlung, which is not included in the most recent background simulations, but may be important during commissioning.

Figure 3 shows the radiation dose deposited in the electromagnetic calorimeter (ECL) by two beam background processes during 10^7 seconds (one snowmass year - an upper limit on the commissioning period) of accelerator operation at SuperKEKB design luminosity. Table 1 shows the corresponding radiation dose for all simulated background processes, averaged

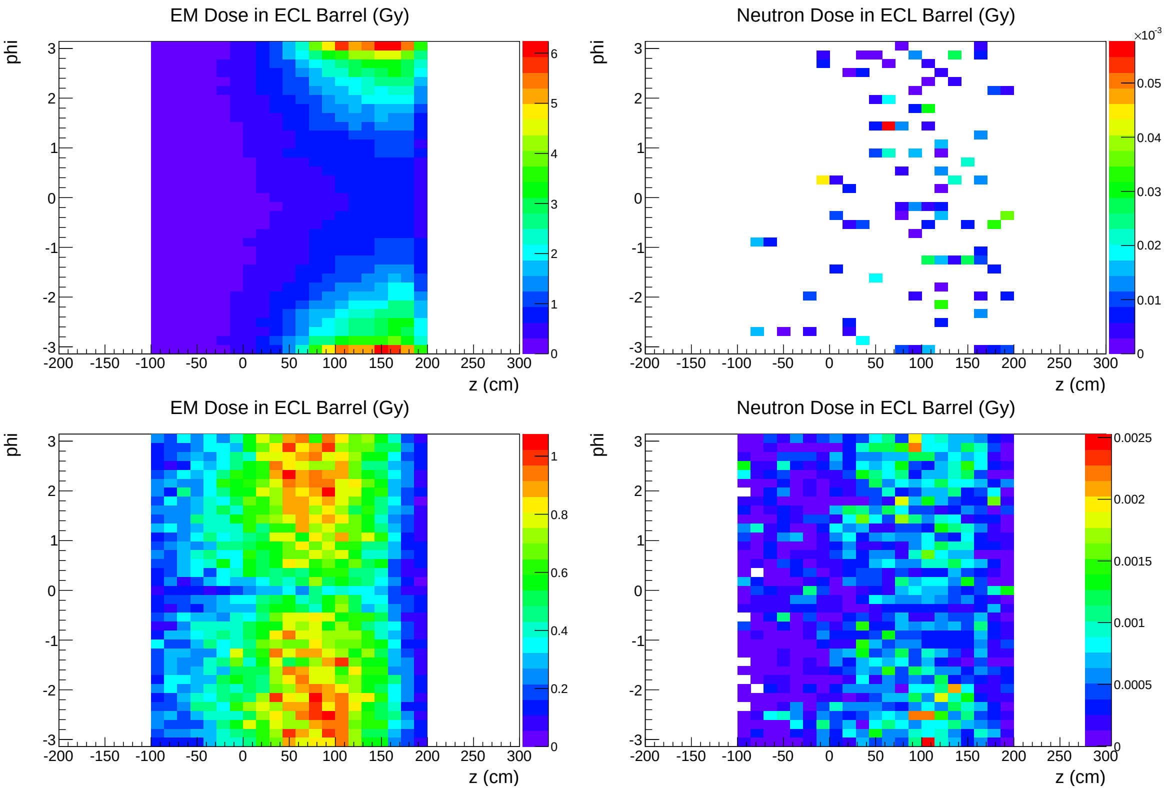

Figure 3: *Expected radiation dose in the electromagnetic calorimeter barrel from per snow-mass year (10^7 seconds) of running at SuperKEKB design luminosity, extrapolated from simulating 20 μs of accelerator operation. Upper plots show radiative Bhabha events originating from the high energy electron ring (HER), while the lower plots show beam-gas Coulomb events originating from the low energy positron ring (LER).*

over the whole calorimeter barrel. For reference, a dose of order 10 Gray (=1 krad) can start to degrade calorimeter performance.

At design luminosity and design beam conditions, radiative Bhabha events contribute the largest dose. More than 99% of the total ECL dose is due to electromagnetic (EM) radiation (x-rays, electrons, and positrons), with the remainder being deposited mainly by neutrons, protons, and pions. Since neutrons require a different shielding strategy than the other particles, and because of the Belle detector's vulnerability to neutrons, we usually separate out the neutron component when quoting simulation results. Both EM particles and neutrons that end up in the ECL originate primarily from the QCS magnet regions, where the beams are strongly focused. These conclusions hold for all simulated backgrounds types, and they are expected to hold for commissioning conditions. During commissioning, however, there will be much lower luminosity, less focused beams, smaller beam currents, and a much worse vacuum. As a result it is expected that the radiation dose will be completely dominated by beam-gas events. There is no trivial way to scale the dose calculated during design conditions to commissioning conditions. The vacuum can easily be three orders

	Total Dose (Gy)	EM Dose (Gy)	Neutron Dose (Gy)
Coulomb (beam-gas) HER	0.002	0.002	0.0000
Coulomb (beam-gas) LER	0.306	0.296	0.0003
Radiative Bhabha HER	0.574	0.573	0.0000
Radiative Bhabha LER	0.131	0.131	0.0002
Touschek HER	0.005	0.005	0.0000
Touschek LER	0.440	0.438	0.0003
Total	1.458	1.445	0.0008

Table 1: *Expected average dose in the electromagnetic calorimeter from beam backgrounds, per snowmass year (10^7 seconds) of running at SuperKEKB design luminosity, at a vacuum pressure of 10^{-9} Torr (simulation).*

of magnitude worse, leading to three orders of magnitude higher dose for the same beam conditions. In that (hypothetical, since the beam conditions will differ) case the total dose from beam-gas Coulomb events would be of order 30 Gray for an average ECL crystal per month of running with 30% duty cycle. Since the calorimeter dose is not uniform, the hottest crystals would receive a dose that is up to three times larger. This could endanger the calorimeter. To illustrate that the radiation levels can be severe during commissioning; the highest radiation dose rate seen during KEKB/Belle commissioning was 0.25 mGy *per second*, i.e. much higher than the beam-gas dose rate predicted for SuperKEKB design luminosity and 10^{-9} Torr vacuum pressure.

In conclusion, at present there is some guidance from simulation regarding the composition and origin points of beam-induced backgrounds, but the normalization is very uncertain. Shielding of the calorimeter against EM particles from beam-gas events may be required during the commissioning period. The conceptual design includes high-Z (lead) shielding that extends well past the QCS hot spots around $z = \pm 1$ m. The drawing shows the thickness of the lead shield as 2.6 cm, or 4.6 radiation lengths, which would reduce the EM dose by a minimum of 2 orders of magnitude. Fast neutrons are not strongly affected by the EM shield, and the stopping of charged particles in the EM shield is likely to result in additional neutron dose in the calorimeter. Hence the conceptual design also includes 10 cm of borated polyethylene to moderate and capture neutrons. This would reduce the dose from neutrons by approximately one order of magnitude, so that it remains small compared to the dose from EM radiation. The thickness of both shields will be adjusted as we refine our simulations. It is possible that only the EM shield will be needed, so that the conceptual design, which includes both EM and neutron shielding, is conservative.

1.1.6 Commissioning Detector Dose Monitor

To monitor doses on the ECL we plan on an array of silicon PIN diodes. Ionizing radiation effectively causes an increase in the dark current from such diodes. This current can be passively amplified and its integral is proportional to the ionizing radiation dose. Such a system was used at CLEO and CESR to monitor and as a beam tuning aid to minimize beam induced radiation. At CLEO half of the diodes were behind a thin layer of high-Z shielding, a layer of gold paint, and half were unshielded. X-rays from synchrotron radiation are considerably reduced on the shielded diodes while particle radiation from beam-gas scattering and radiative Bhabha events is not. Thus the difference between a shielded and unshielded diode pair gives a direct measure of the synchrotron radiation component of the dose. At CLEO and CESR this made it easy to map the location and extent of synchrotron radiation and backscattering fans caused by the beams passing through the final focusing elements and x-rays scattering off of shielding elements.

Based on simulations of beam induced backgrounds on Belle II we expect the highest doses on the ECL to be experienced by the inner rings of crystals on the two endcaps. During commissioning the endcaps will not be in place, and we plan to simply construct aluminum hoops of the proper radius that would be supported off of beam line elements to hold diodes in the location eventually to be occupied by the two endcap inner rings of crystals. Each hoop would have slots to insert 8 diode pairs arrayed uniformly in ϕ. Each pair would have one diode shielded behind a thin layer of high-Z material and the other not. Thus we would get a low resolution view of any sharp x-ray features incident on the beam pipe at the longitudinal position of the ECL endcaps. Such features get broadened as they scatter out of the beam pipe, thus making a higher resolution view not useful. We expect, based on the simulations of the backgrounds, that those diodes in the plane of the rings would see x-ray features while those out of the plane would not.

In addition to these 32 endcap diodes we would locate 32 more in a barrel configuration, to monitor doses that other crystals in the endcaps and barrel would receive. The barrel diodes would be arranged in pairs, inside and outside the shielding, at four z-positions, and at every 90° in ϕ. The barrel diodes would all be shielded, as any x-rays would be absorbed by inner detectors. The location of all diodes is shown on the Figure 2. The diodes in the barrel would simply be "velcroed" to either the shielding or the inside of the ECL.

The diode signals would be brought to remote analog amplifiers on shielded co-axial cables. Keeping the amplifiers remote allows us to adjust the gain as the dose regime changes during the scrubbing and beam tuning processes. We would emulate the CLEO and CESR experience in having a low and high gain output, useful for monitoring and tuning during injection versus normal running, giving the system robustness and flexibility. We still have to work out how and where the system's output is digitized. Ideally, we would take advantage of existing KEK infrastructure. Since we envision these radiation monitors to be useful in beam tuning, they should be digitized and made available in real-time to the KEKB control room.

The sensors, cables, and mounting hardware will be constructed at Wayne State using the groups in-house technical support. A PNNL electrical engineer will design remote amplifiers. Members of the Wayne State group, led by Professor Cinabro, will oversee the construction, installation, and commissioning of this sub-system, and analyze the resulting data.

1.1.7 Commissioning Detector: PXD group plans

Given the proximity of the Belle II DEPFET pixel detector (PXD) to the beams, it is especially vulnerable to beam backgrounds. The commissioning efforts of the PXD group are led by Dr. Marinas of Bonn University. The PXD group favors a two-stage commissioning scenario, where the silicon detectors (PXD and SVD) will be installed after beam pipe vacuum scrubbing and machine tuning, in order to prevent or limit radiation damage to the delicate silicon detectors. The PXD group has extensive plans for measurements during the commissioning period, which can only be briefly summarize here:

- Temperature and humidity sensors: The proper environmental conditions inside the silicon detectors' chamber are vital to ensure the safe operation of the sensors. During the commissioning detector operation, the chamber will be instrumented with several temperature and humidity sensors, complemented with Bragg fibers for a double cross check. These small devices will be attached directly onto the beam pipe, the PXD cooling blocks, and on the inner and outer surfaces of the thermal enclosure.

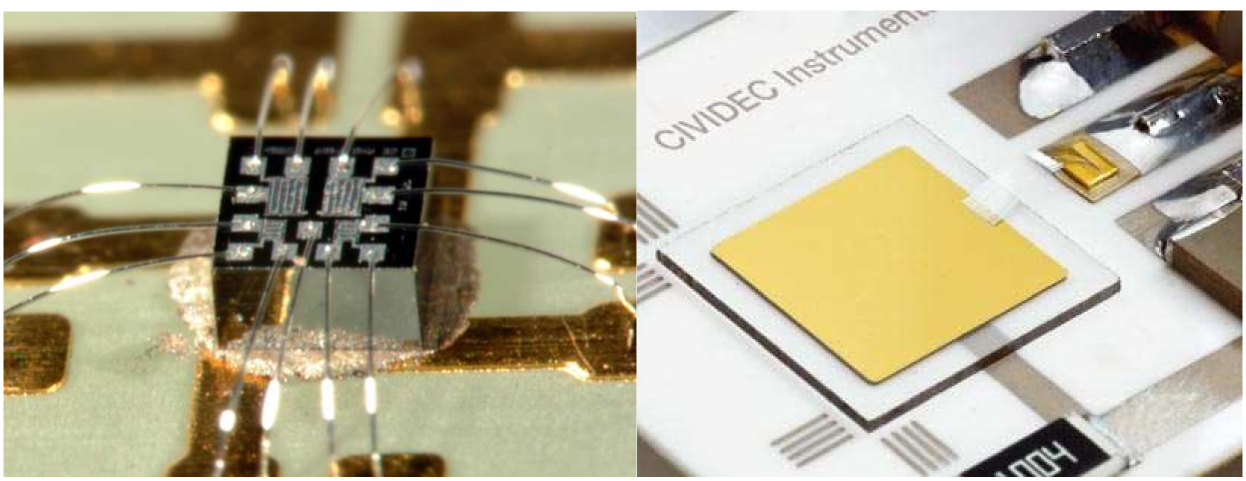

Figure 4: *Left: radFET glued onto a PCB. The wire bonds provide perspective on the detector size. Right: Single channel CVD diamond. The radiation hardness of the diamond detectors makes them very useful for measurements in harsh environments.*

- Accumulated doses and instantaneous rates: To complement the PIN diodes from the US institutes, the PXD group will install radFETs and single channel diamond detectors, shown in Figure 4. The diamond detectors can be used both for direct measurements and for calibration of the other detectors. Although the final placement of these devices is not decided yet, the radFETs have to be positioned close to the interaction point to measure the doses that the innermost PXD-layer will receive. This can be achieved due to the small size of the device combined with thin readout wires. The radFETs, depending on the oxide thickness and operation parameters, could withstand up to a few Mrad without degradation.

The single channel diamonds are bigger devices (of order cm^2) and should stay away of the interaction point due to the lack of space. These devices are operated very close to the interaction point in the LHC experiments, so radiation damage is not an issue at the expected BEAST II doses. A 6-mm thick cable is needed to bias and read the detector.

Diamond sensors will also be used as fast detectors in a beam loss abort system. The proposed layout comprises 4 stations in the forward and 4 in the backward regions, close to the beam masks, in the horizontal and vertical directions.

The PXD group will provide manpower for the design, installation, data taking and analysis of the detectors discussed. In addition, the PXD group can do the electron irradiation of the PIN diodes to be provided by the US groups using the ELSA Linac 1 accelerator (Bonn, Germany), with 17 MeV electrons.

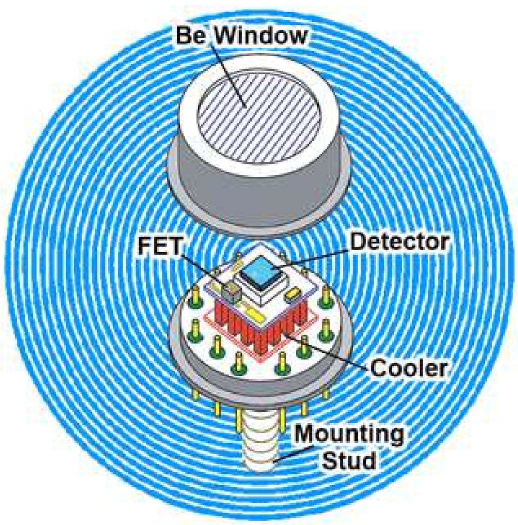

Figure 5: *Left: The photon energy spectrum has to be determined with high accuracy. One of the proposals is the use of silicon drift detectors. Right: Half DEPFET ladder after being cut from the wafer. One full ladder will be obtained by gluing two half pieces as the one shown here.*

- Near field antenna: The PXD group expects also major noise contributions considering the fact that the innermost layer of the pixel detector will be just 2 mm away of the surface of the beam pipe. To explore the noise contribution on the PXD sensors, a near field antenna, designed especially for this purpose, will be installed instead of one

DEPFET ladder. In addition, this device can help the SuperKEKB machine group in the commissioning of the accelerator.

- Photon energy spectrum: The photon energy spectrum has to be measured with high resolution (down to a few keV) in order to estimate the synchrotron radiation in the detector, and to study the radiation damage to DEPFET sensors in this range. The final device has not been decided on yet, but a small silicon drift detector seems suitable for this purpose. The detector has to be as close as possible to the final DEPFET sensor location, in order to measure the real photon spectrum the PXD will see. The PXD group will contribute with manpower for the installation, data taking and data analysis.

- Once the radiation levels have been determined to be sufficiently low, two DEPFET ladders will be installed in their nominal Belle II positions, to exercise the assembly and operation procedures of the final PXD. The ladders have to be operated under final conditions, and the full services that will later be used for the real PXD have to be ready and operational. These services include data transmission, DAQ, power supplies, the CO_2 cooling plant, the cooling and support structures around the beam pipe, capillaries for air cooling and the thermal enclosure for the SVD and PXD. The PXD group will install the detector, and operate and analyze the data.

1.1.8 Commissioning Detector Luminosity Monitoring Device

Introduction

Members of the National Taiwan University High Energy Physics Group (NTUHEP), including YuTan Chen, GuanBo Lin, and FaHui Lin, led by Professor Minzu Wang and Dr. Jing-Ge Shiu, contribute the luminosity monitoring device. FaHui Lin and Yutan Chen will install the device in the summer of 2014, while someone else will operate it after that.

The luminosity monitor will provide: (1) luminosity information using coincidence signals from the back-to-back feature of candidate Bhabha events, and (2) background intensity with accumulated charges as a function of time.

Detecting System

This monitor consists of 8 sets of BGO (Bismuth Germanate) scintillation crystals fixed around the interaction point. A full ring version of this device has been used at Belle for the luminosity monitoring of KEK-B, and has been proved to be radiation hard (up to an accumulated dosage of 100 Mrad). The scintillation lights of each BGO crystal will be imaged through an array of optical fibers onto photomultiplier tubes in the readout system.

There are different commissioning scenarios for sub-detector installations in BEAST2. In T0 and T1 scenarios, the BGO luminosity monitor is not installed. In T2 scenario (no SVD nor PXD installed), the BGO luminosity monitor is installed inside the VXD volume, right near the interaction point. These 8 BGO crystals are mounted on 2 aluminum rings (i.e. 4 crystals on one ring), which are fixed to the inner tube in VXD volume. The 4 forward crystals are located at the line with an angle of 11.5° by the symmetric axis, while other 4 backward crystals are located with an angle of 20° by the symmetric axis. (Figure 1 and Figure 2).

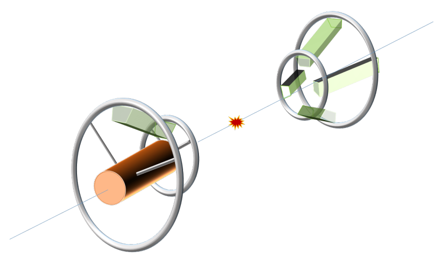

Figure 6: 3-D conceptual drawing crystals (green) mounted on the aluminum rings (metallic) near the interaction point inside the VXD volume. The brown cylinder shows the inner tube inside VXD volume where the rings can be fixed to with screws and support timbers.

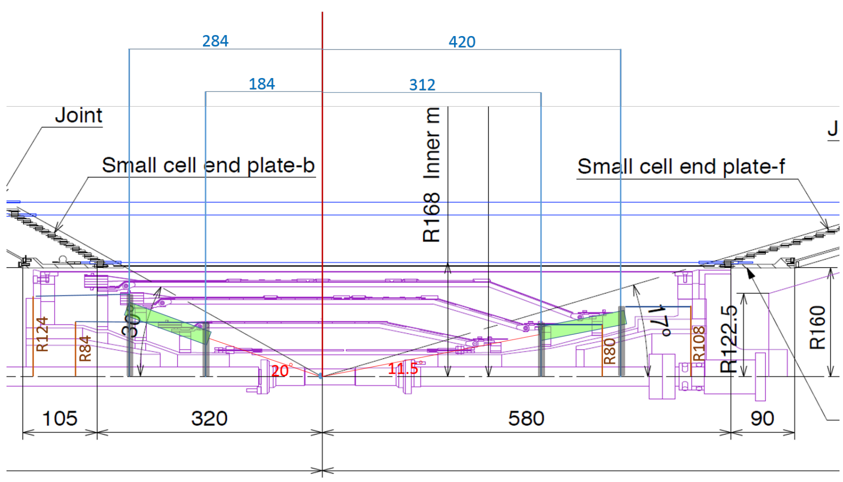

Figure 7: Sub-detector installation blueprint (partial), focusing on the VXD, showing locations of crystals (green) and aluminum rings (gray).

Readout System

We use one MAPMT (multi-anode photomultiplier tube) to receive scintillation light from the crystals. The MAPMT needs $900V$ high voltage and we hope that KEK can provide the HV power supply. There are 8 channels for 8 BGO crystals respectively. Between the crystals and PMTs, there are 8 optical fibers, one for each crystal. The fiber array should

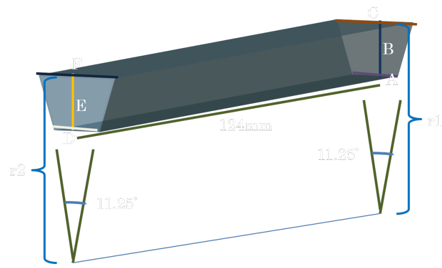

Figure 8: The dimension of a single BGO crystal.

type	A	B	C	D	E	F	r1	r2
B5 (mm)	22.938	12.280	25.356	30.828	19.616	34.692	130.48	177.87

be about 25 m long. The fibers are put into a soft black hose (also about 25 m long) with about 1 cm in diameter. The required length is to connect the crystal in VXD volume to the MAPMT at the readout system zone. The space needed in the readout system zone should be about 1 m^3 .

The output signals from the MAPMT are charges. After the front-end circuit, the signals become logic signals and digitized charge information. The signal frequency should be kept under 104 Hz with proper threshold settings. The characteristic time or decay time for BGO scintillation is about 300 ns.
The 8 logic signals will go through a logic circuit (implemented with FPGA, as shown in Figure 4) to obtain the coincident signals via the back-to-back feature of Bhabha event. After subtracting the signals from random coincidence, the signal rate gives the luminosity information.

Figure 9: The Xilinx vertex V4 FPGA board

The first version of the readout circuit will be produced in summer 2013, and the final version will be produced in the end of 2013.

Simulation
The simulation task, using GEANT4, is underway in order to get the conversion factor

Figure 10: Back-to-back signal Bhabha candidate event Logic: (B1 and F3) or (B2 and F4) or (B3 and F1) or (B4 and F2)

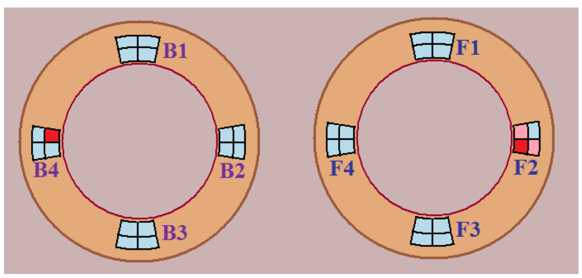

Figure 11: Not Back-to-back signal background event Logic: (B1 and F1) or (B1 and F2) or (B1 and F4) or . . . or (B4 and F4)

between the rate of triggered events and the instant luminosity. At this stage, the particle-gun generator is used. We impose an energy cutoff at 0.5 GeV to get rid of background events, which is reasonable from simulation results. This energy cutoff corresponds to the threshold of input signals. From calculation of Bhabha scattering, the luminosity required for one particle detected per second is estimated to be about 10^{30} cm^{-2} s^{-1}. The BBBREM generator is planned to be applied to simulate the radiation Bhabha events (which may differ from Bhabha events by about 10%).

System Test

There is a plan to check the device response before its installation at KEK. The expected time should be around the spring of 2014. We will use a radiation testing facility (about 10^4 Curie Co-60 source) in northern Taiwan to get the conversion factor between the accumulated charge and the received radiation dose. It will be important to have some ideas about the effect of radiation damage or annealing behavior of this monitor in the same test.

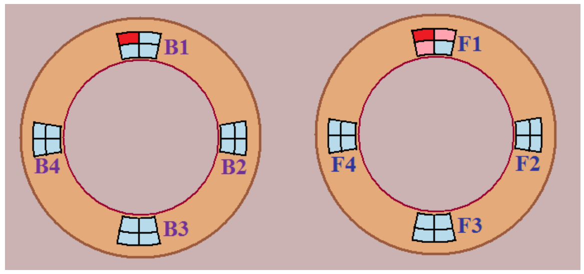

Figure 12: Geometry of BGO Luminosity Monitor, made up of 8 BGO crystals, plotted with GEANT4 in BASF2

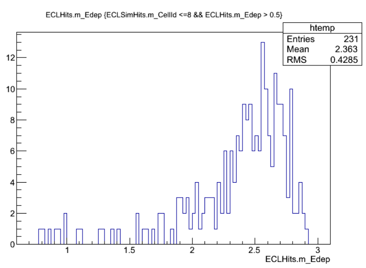

Figure 13: Simulation of 1000 events (e^+, e^-, γ) with energy 4 GeV at $\theta = 10.5°$ to $12.5°$, and full range of ϕ.

1.1.9 Commissioning Detector micro-TPCs

In order to monitor and study neutrons, we will install eight gas-filled micro-TPC detectors. Fast neutrons produce heavily ionizing nuclear recoil via elastic scattering in the gas volume. We will measure the ionization trails produced by these recoils in 3D, by employing a high-resolution TPC charge readout, based on gas electron multipliers (GEMs) and pixel electronics [1]. This makes it possible to tag fast (MeV-scale) neutrons, and to measure both their energy and direction, which is not possible with other types of detectors. The neutron measurements will allow us to identify the neutron production points, which can be used to validate and tune the neutron component in the beam background simulation. At high gain settings, such gas TPCs can also be used to reconstruct minimum ionizing particle (MIP) tracks, and (with thin vessel walls and appropriate positioning) to obtain x-ray spectra in the keV range, which would be sensitive to synchrotron light (SR) backgrounds. In that case, energy deposits from MIPs, x-rays, and neutron recoils can be distinguished via the specific ionization (dE/dx) and ionization pattern measured. Since we already plan to use diodes for measuring x-rays, and expect to install a drift chamber prototype for tracks, we will optimize the TPCs for neutrons, but at the same time it will be good to have some redundancy in our commissioning setup, where the unexpected typically does occur. The micro-TPCs will be radiation hard (up to at least 50-100 Mrad), and capable of high data rates, as they will employ pixel chips developed for the ATLAS experiment at the LHC.

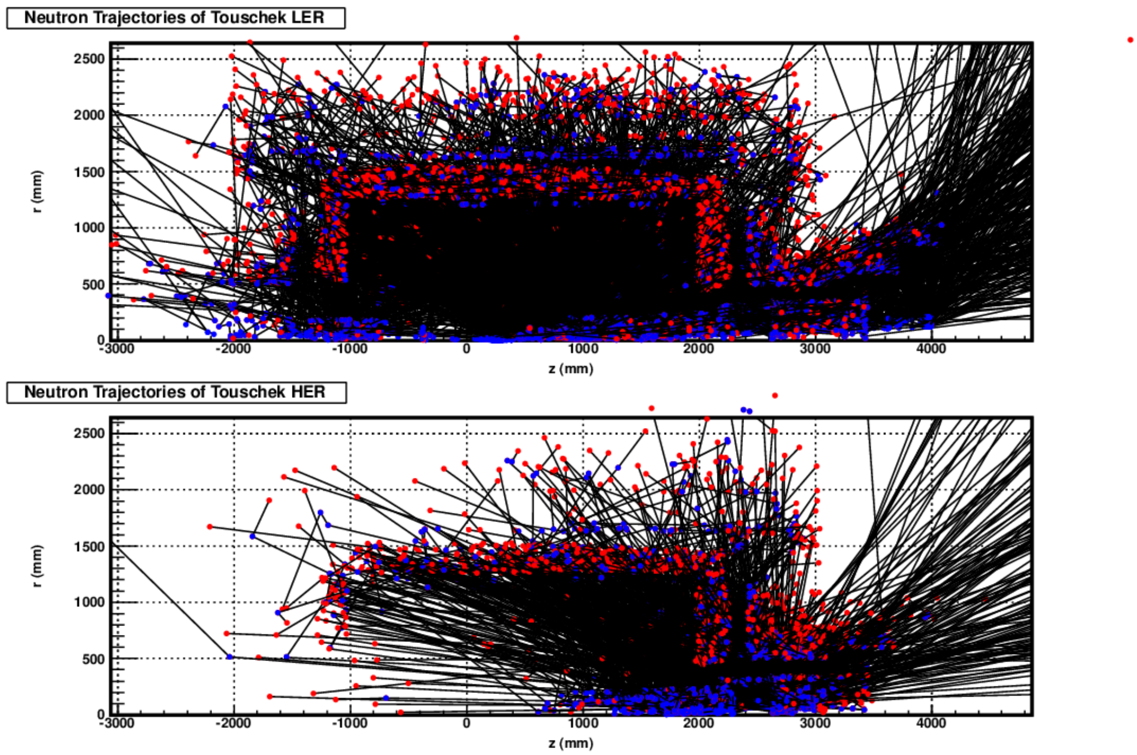

Figure 14: *GEANT production points (blue), GEANT decay points (red), and trajectories (black) of neutrons that deposit energy in the calorimeter, for Touschek backgrounds originating from the low energy ring (upper) and high energy ring (lower).*

Figure 14 shows the trajectories of neutrons that deposit energy in the calorimeter, for two types of beam background. The majority of neutrons are generated near the QCS magnets, but the detailed distributions differ by background type. To monitor these neutrons in detail, we will position the micro-TPCs between both the forward and backward QCS magnets and the ECL calorimeter, i.e. at a radius of 70 cm from the beamline, positioned at z=1 m and z=-1 m along the beams. There will be four TPCs at each z position, mounted 90 degrees apart in azimuthal angle, so that we can measure the ϕ-distribution of the neutrons, which is not flat (see e.g. Fig. 3, and similar plots in the KLM system chapter). Each TPC will have an active volume of 5 cm $\times$ 5 cm $\times$ 20 cm. The longest dimension is the direction of the TPC drift field, which will be parallel to the Belle II solenoid magnetic field, to minimize diffusion of drift charge. 13 cm^2 of the 5 $\times$ 5 cm readout plane would be instrumented with pixels, the rest of the area will be used for gain calibration of the TPCs. The radial positioning of the TPCs will depend on the amount of neutron shielding to be used in the commissioning detector, and may vary between the different stages of commissioning. If

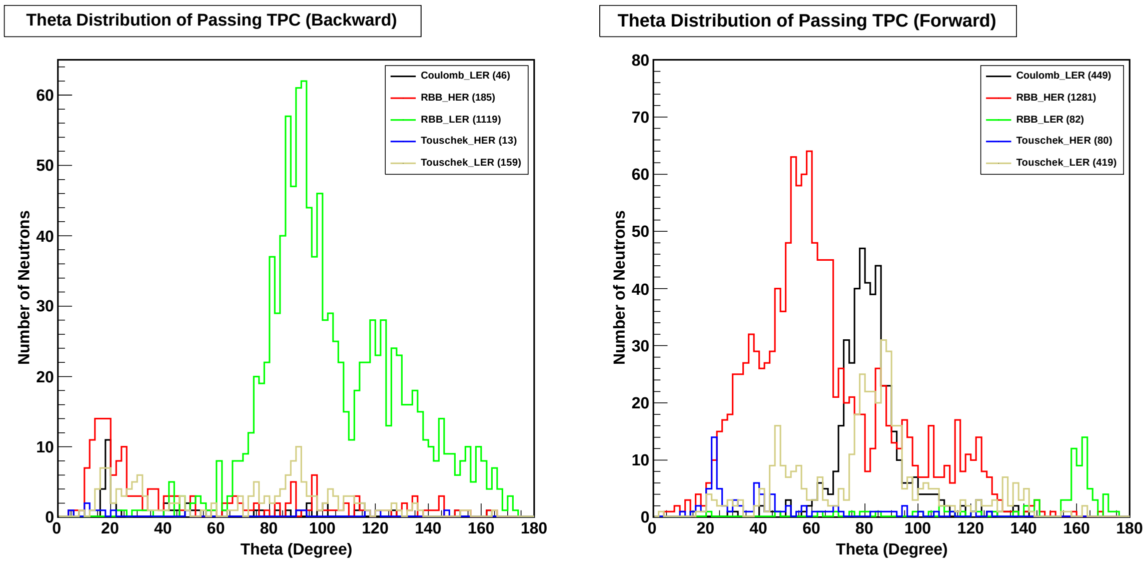

Figure 15: *Polar angle of neutrons that pass through the backward (left) and forward (right) array of micro-TPCs. The angle plotted is the polar angle of the incoming neutron direction, as seen by each micro-TPC.*

no neutron shielding is used, all TPCs can stay at r=70 cm for the entire commissioning period, so that they are mechanically independent from the shielding and other monitors. If we decide to install as much as 10 cm of polyethylene during vacuum scrubbing, this would greatly reduce the neutron rate, and wash out the directional information at r=70 cm. In that scenario we would mount half of the forward and backward TPCs between the high-Z and polyethylene during this period, with the center of the TPC at r=35 cm. That would allow us to simultaneously study the (unshielded) production of neutrons, while monitoring the (shielded) rate of neutrons incident onto the ECL.

Figure 15 shows the polar angle distributions of only those neutrons which traverse the TPCs at the nominal position of r=70 cm, for each beam background process. The difference in the angular distributions, combined with the different dependence of each background process on accelerator parameters (beam current, luminosity, beam size, and vacuum pressure), should allow us to distinguish and measure the neutron production from each process during beam commissioning. The rates of neutrons traversing the TPCs are given in table 2, and are very large at design luminosity - of order 100 kHz to MHz. The fraction of neutrons that scatter elastically and lead to a reconstructable recoils in the TPCs, however, is low, of order 0.1%. As a result the expected signal rate in each TPC is of order a kHz at design luminosity. As discussed above, all backgrounds except those from beam-gas are expected to be much lower during commissioning, while those from beam-gas could be much higher. The pixelated TPC image plane will be read out at 40 or 80 MHz, which is fast enough to separate individual recoils even at the highest possible neutron rates, of order GHz, due to the low probability of elastic scattering. In that scenario we would run in a pre-scale mode,

	Rate in backward TPCs (MHz)	Rate in forward TPCs (MHz)
Coulomb HER	0.00	0.00
Coulomb LER	0.05	0.09
Radiative Bhabha HER	0.45	3.55
Radiative Bhabha LER	3.45	0.35
Touschek HER	0.05	0.15
Touschek LER	0.55	1.15

Table 2: *Predicted rate of neutrons traversing the backward and forward micro-TPC arrays, at design luminosity.*

where we only read out and save a fraction of the events.

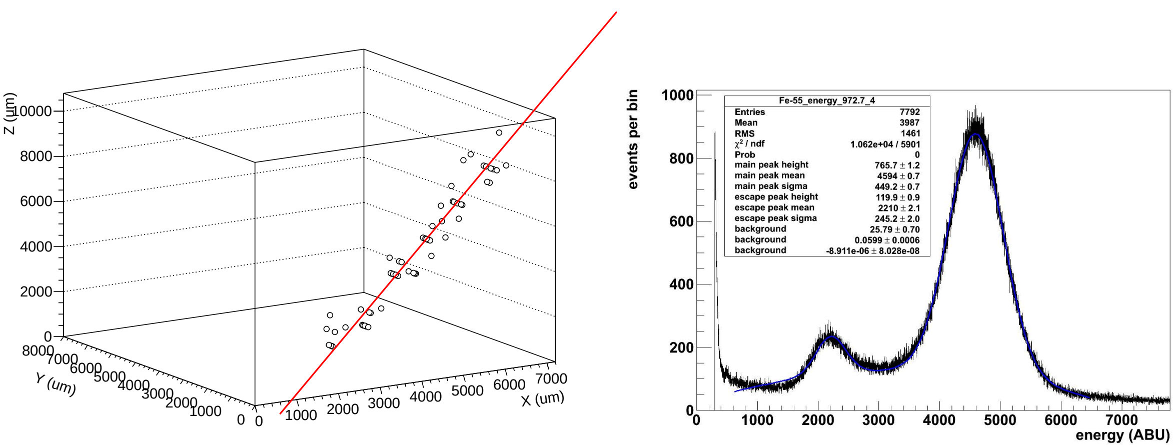

Figure 16: *Example of cosmic ray track (left) and FE-55 x-ray spectrum (right) recorded with micro-TPC prototype at the University of Hawaii.*

The micro-TPCs with GEMs and pixels are innovative, but low risk, as readily available components will be employed: standard GEMs available from CERN, the ATLAS FE-I4 pixel chip (available from LBNL), and DAQ electronics available from SLAC. The combined operation of GEMs and ATLAS pixels was previously demonstrated with a 1 cm^3 prototype at LBNL, by a team including Hawaii faculty member Vahsen. The LBNL prototype measured charged tracks with excellent (< 100 μm) point resolution, and obtained FE-55 x-ray spectra with good (about 20% FWHM) energy resolution [1]. The Hawaii group recently constructed a similar micro-TPC prototype, which is currently being commissioned. First results from Hawaii, shown in Fig. 16, also indicate excellent detector performance, and the group is currently demonstrating neutron detection. Neutrons can be detected in gas TPCs by reconstructing the nuclear recoils resulting from elastic scattering of the neutrons with the nuclei in the target gas. Figure 17 shows a simulation of 1-MeV hydrogen nuclei recoil-

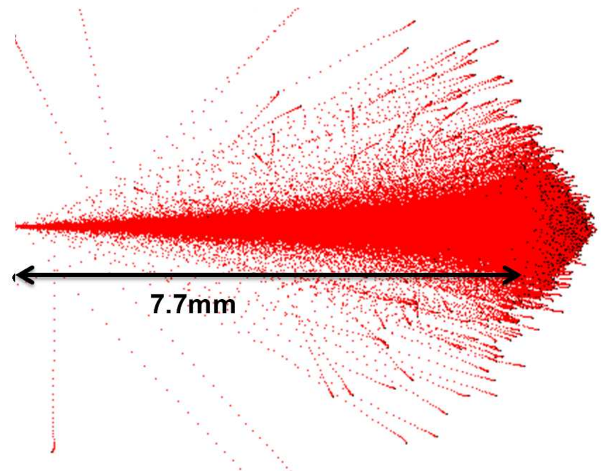

Figure 17: *Simulation of ionization deposited by 1-MeV Hydrogen nuclei in* C_4H_{10} *gas at 1 atmosphere.* 10^5 *recoils with identical start position and velocity have been superimposed for visibility.*

ing in atmospheric-pressure isobutane gas. The ionization trails from such neutron-induced recoils are of similar length as the cosmic track shown in Fig. 16, but the expected amount of ionization is of order hundred times greater for nuclear recoils, and hence much easier to detect. For the commissioning detector, we expect to use a helium-based gas mixture.

As the University of Hawaii group is already developing TPCs for fast neutron detection [4][5], relatively modest resources are needed to adapt them to the commissioning detector. Before production of the final micro-TPCs for the Belle II commissioning detector can begin, they will perform a final round of prototype optimizations and demonstrations. The group will design a new gas vessel, and slightly modify the layout of the readout electronics so that they are compatible with the micro-TPC geometry. The final prototype demonstration will include detailed neutron source measurements, as neutron detection (through the tracking of nuclear recoils from elastic neutron/gas-nucleus scattering) has not been explicitly demonstrated with the specific TPC readout technology used, though it has been demonstrated with very similar TPCs [3]. A collimated neutron source for these tests has already been constructed, and first neutron measurements are ongoing. The final demonstration should use the new ATLAS-FE-I4 pixel chip. Previous measurements at LBNL and Hawaii used the older ATLAS-FE-I3 pixel chip, but FE-I4 has an active area of 3.36 cm^2, almost three times that of FE-I3. This has the advantage that only four readout chips will be needed to instrument the 12 cm^2 readout plane of each micro-TPC.

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[3] K. Miuchi et al., “Performance of a micro-TPC for a time-resolved neutron PSD”, Nucl. Instrum. Meth. **A517** (2003), 219-225

[4] J. Yamaoka, H. Feng, M. Garcia-Sciveres, I. Jaegle, J. Kadyk, Y. Nguyen, M. Rosen, S. Ross, T. Thorpe, S. Vahsen, “Application of Time Projection Chambers with GEMs and Pixels to WIMP Searches and Fast Neutron Detection”, TIPP2011, submitted to Elsevier Physics Procedia (2011)

[5] S. E. Vahsen, H. Feng, M. Garcia-Sciveres, I. Jaegle, J. Kadyk, Y. Nguyen, M. Rosen, S. Ross, T. Thorpe, J. Yamaoka,“The Directional Dark Matter Detector”, arXiv:1110.3401v1 (2011)

A Appendix: SuperKEKB Commissioning Detector

This appendix contains supplementary information relevant to the commissioning detector, such as a more detailed discussion of the US contribution, a description of contributions from non-US institutions, and results from preliminary simulation studies, which guided the conceptual design of the commissioning detector.

A.1 Commissioning Detector: Beam Background Dose Estimates

	Total Dose (rad)	EM Dose (rad)	Neutron Dose (rad)
CoulombHER	0	0	0
CoulombLER	0.027	0.026	0.0010
RBBHER	0.384	0.375	0.0081
RBBLER	0.076	0.070	0.0024
TouschekHER	0.044	0.043	0.0007
TouschekLER	0.121	0.118	0.0029
Total	0.649	0.633	0.0151

Table 3: *Expected dose in the electromagnetic calorimeter from beam backgrounds, per month of running at SuperKEKB design luminosity, at a vacuum pressure of* $10^{-}9$ *Torr (simulation). In the 20* μs *simulated there was no ECL dose from beam-gas Coulomb events originating in the HER.*

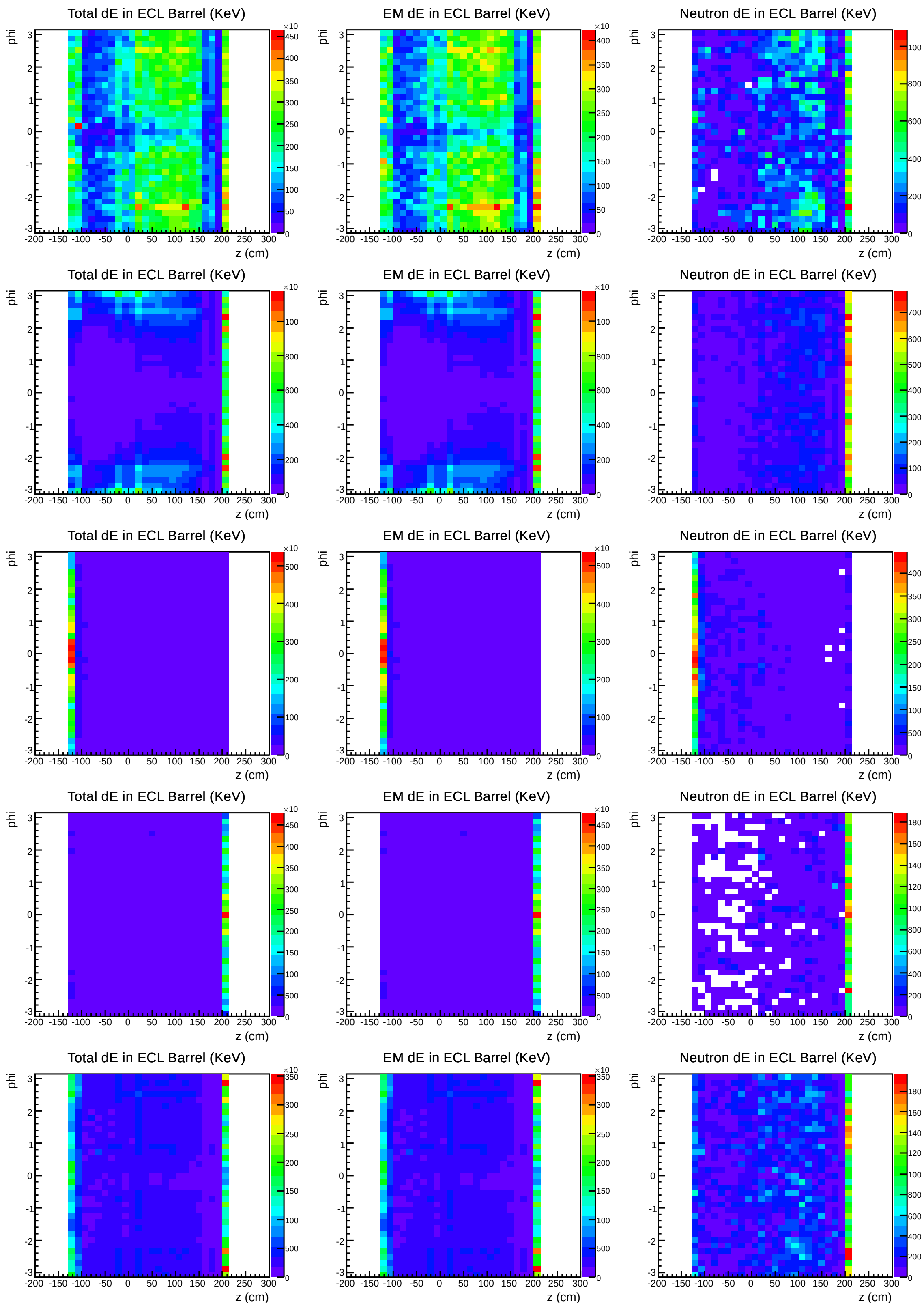

Figure 18: *Distribution of energy deposited in the electromagnetic calorimeter (ECL) from Radiative Bhabha Events, Beam-Gas Coulomb Events, and Touschek Scattering in 20 μs at SuperKEKB design luminosity (simulation). Backgrounds originating from the positron low-energy ring (LER) and electron high-energy ring (HER) were simulated and are hence*

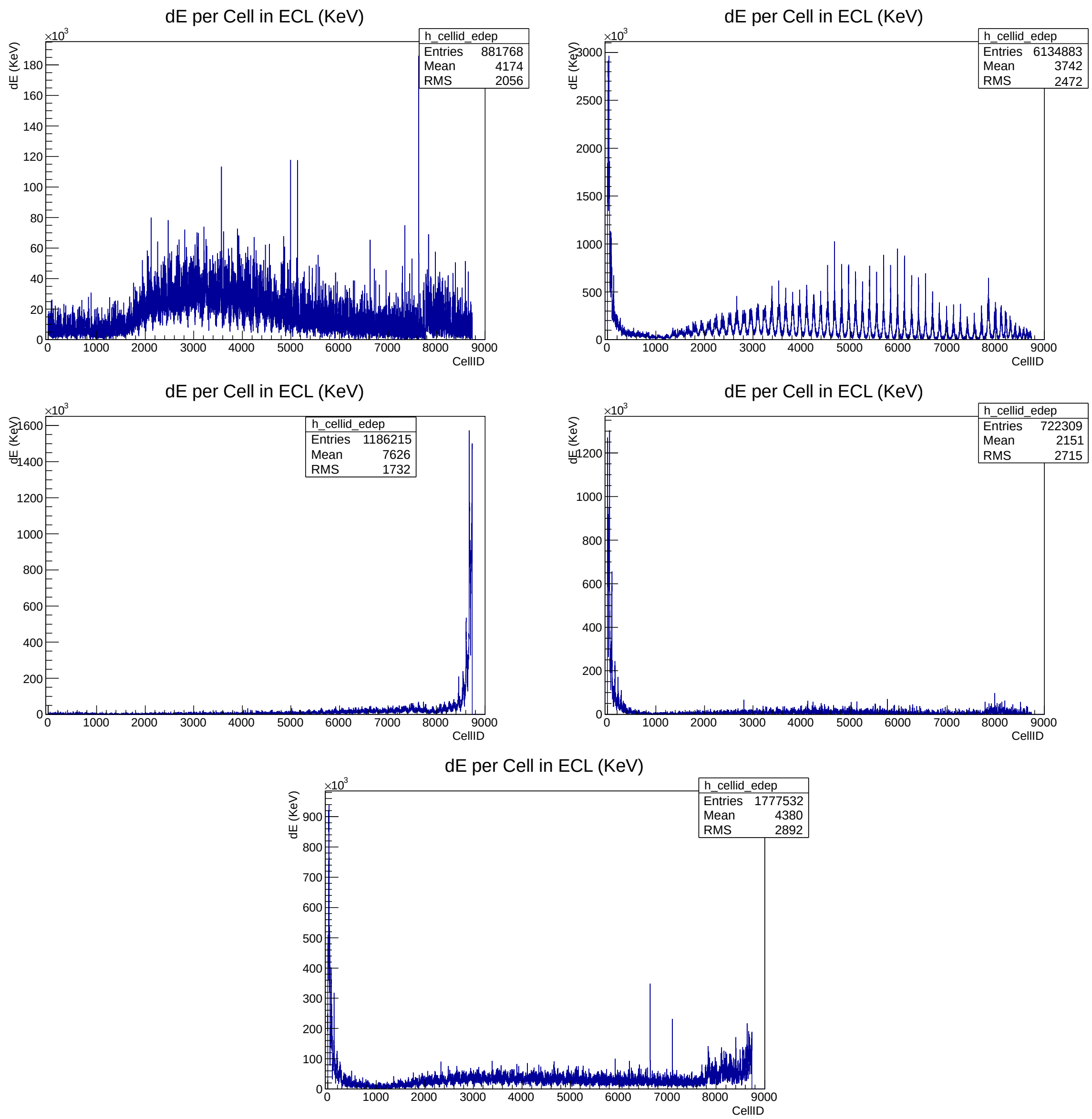

Figure 19: *Energy deposited versus electromagnetic calorimeter (ECL) crystal ID number, for Radiative Bhabha Events, Beam-Gas Coulomb Events, and Touschek Scattering, in 20 μs at SuperKEKB design luminosity (simulation). Backgrounds originating from the positron low-energy ring (LER) and electron high-energy ring (HER) were simulated and are hence plotted separately. In the 20 μ simulated there was no ECL dose from Beam-Gas Coulomb Events originating in the HER.*

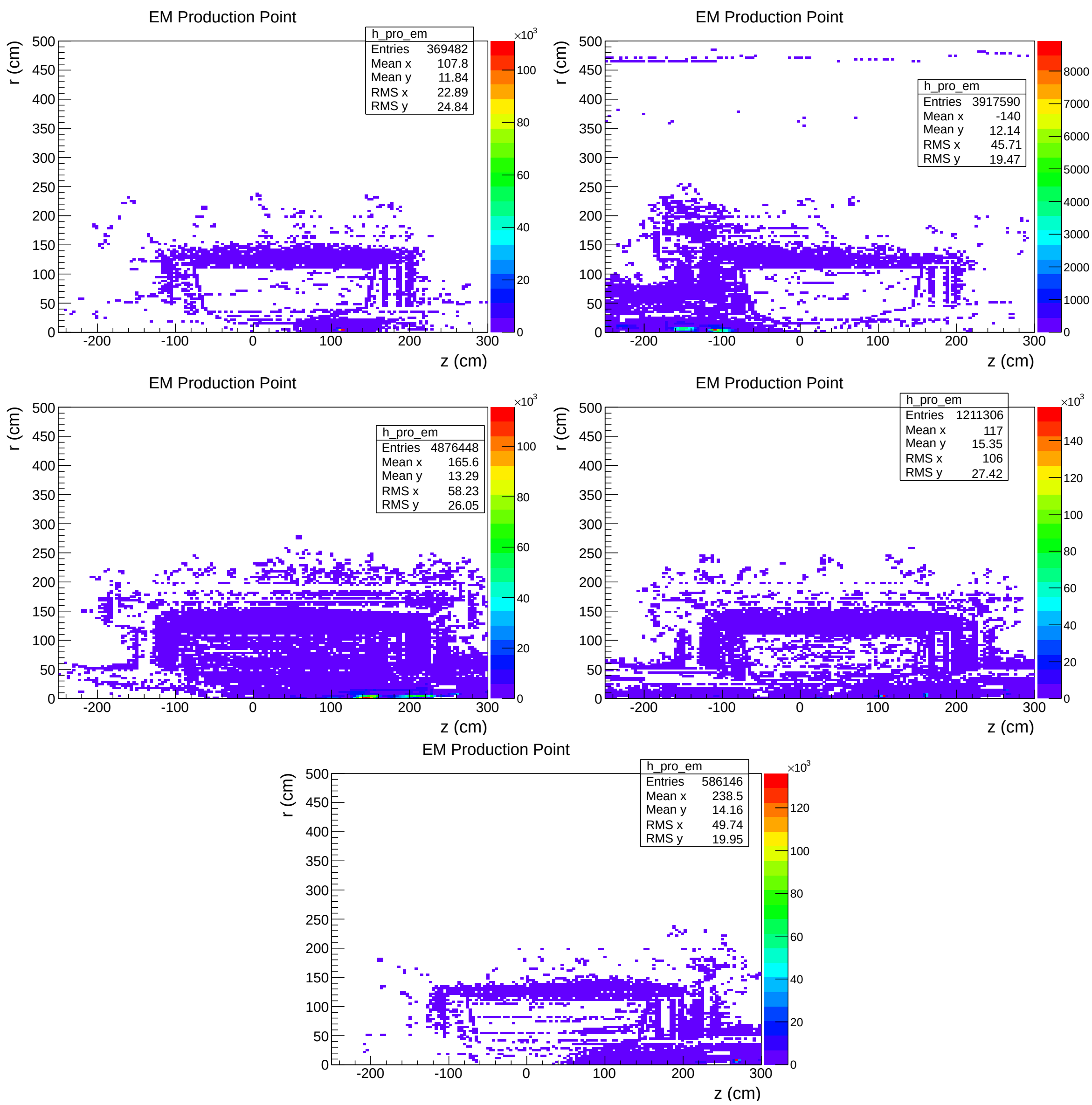

Figure 20: *Production point of EM radition for Radiative Bhabha Events, Beam-Gas Coulomb Events, and Touschek Scattering, in 1 μs at SuperKEKB design luminosity (simulation). Backgrounds originating from the positron low-energy ring (LER) and electron high-energy ring (HER) were simulated and are hence plotted separately. In the 1 μ simulated there was no ECL dose from Beam-Gas Coulomb Events originating in the HER.*

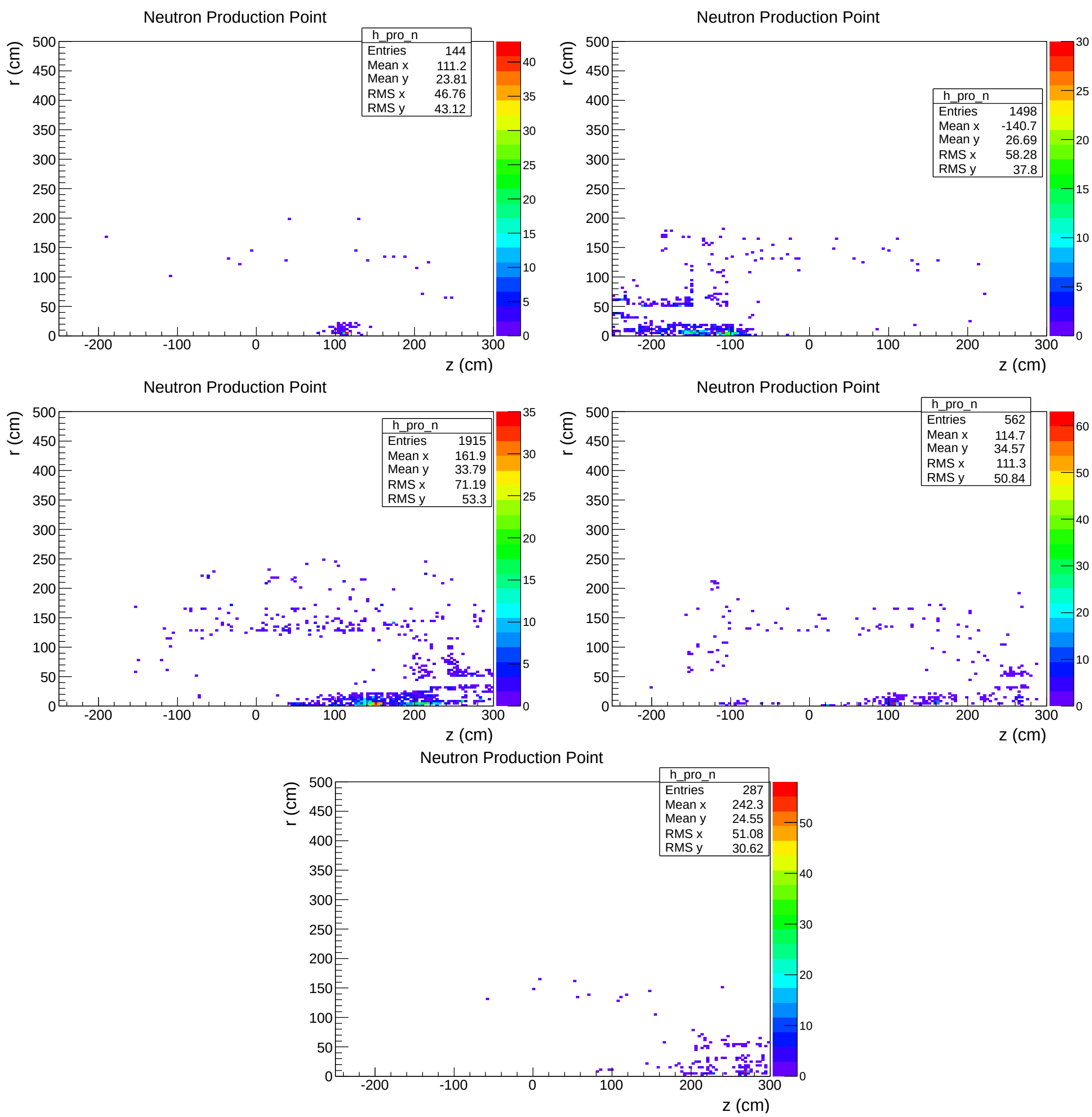

Figure 21: *Production point of neutrons for Radiative Bhabha Events, Beam-Gas Coulomb Events, and Touschek Scattering, in 1 μs at SuperKEKB design luminosity (simulation). Backgrounds originating from the positron low-energy ring (LER) and electron high-energy ring (HER) were simulated and are hence plotted separately. In the 1 μ simulated there was no ECL dose from Beam-Gas Coulomb Events originating in the HER.*

A.2 Commissioning Detector: Neutron Simulations

	Rate in backward TPCs (MHz)	Rate in forward TPCs (MHz)
Touschek LER	0.8	0.35
Touschek HER	0.3	0.01
Coulomb LER	0.75	0.15
Radiative Bhabha LER	0.25	2.35
Radiative Bhabha HER	2.7	0.3

Table 4: *Predicted rate of neutrons traversing the backward and forward micro-TPC arrays, at design luminosity.*

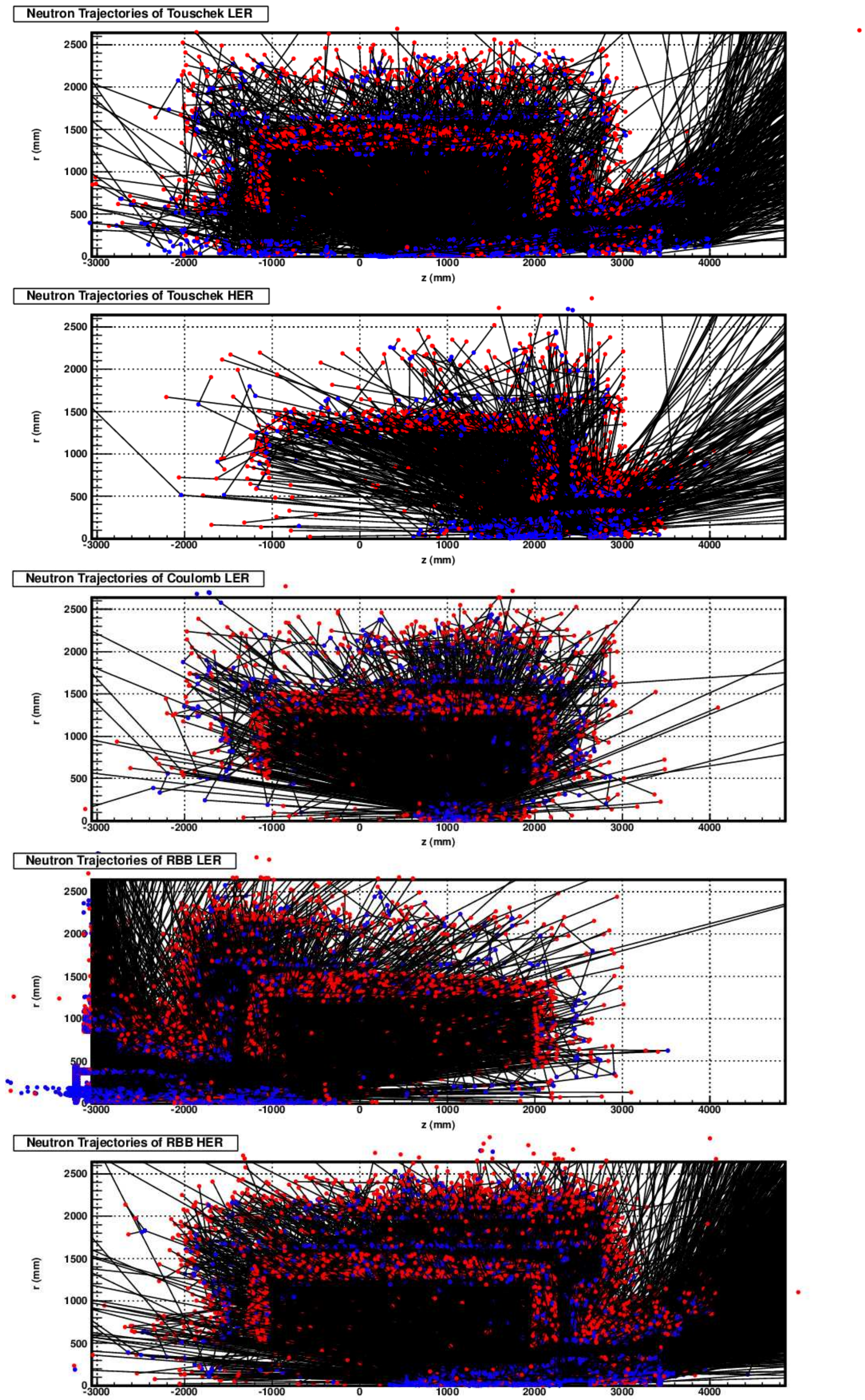

Figure 22: *GEANT production points (blue), GEANT decay points (red), and trajectories (black) of neutrons that deposit energy in the Calorimeter.*

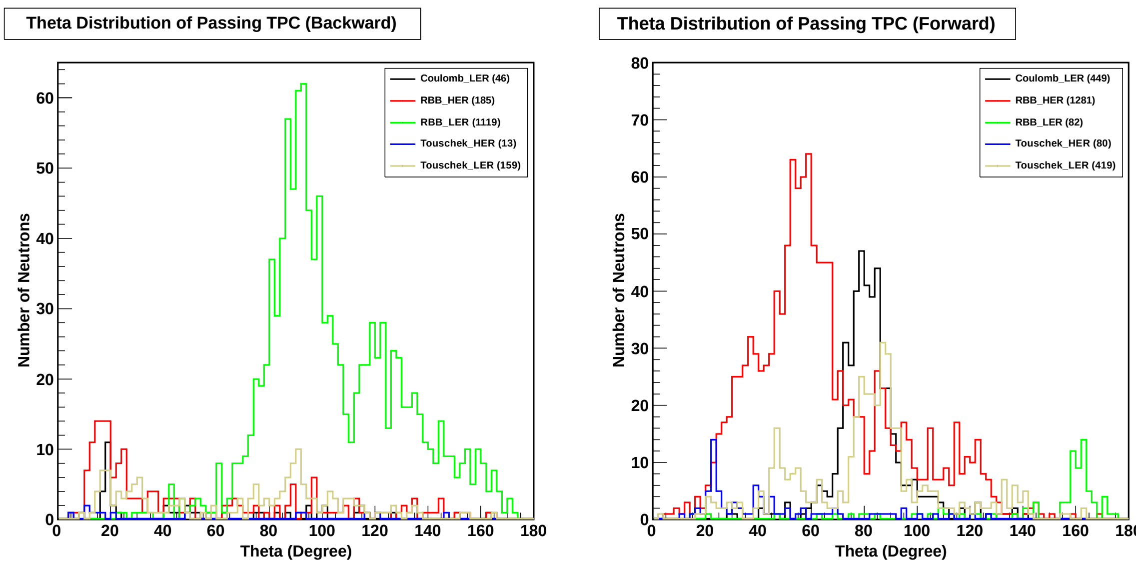

Figure 23: *Polar angle of neutrons that pass through the backward (left) and forward (right) array of microTPCs. The angle plotted is the polar angle of the incoming neutron neutron direction, as seen by each microTPC.*

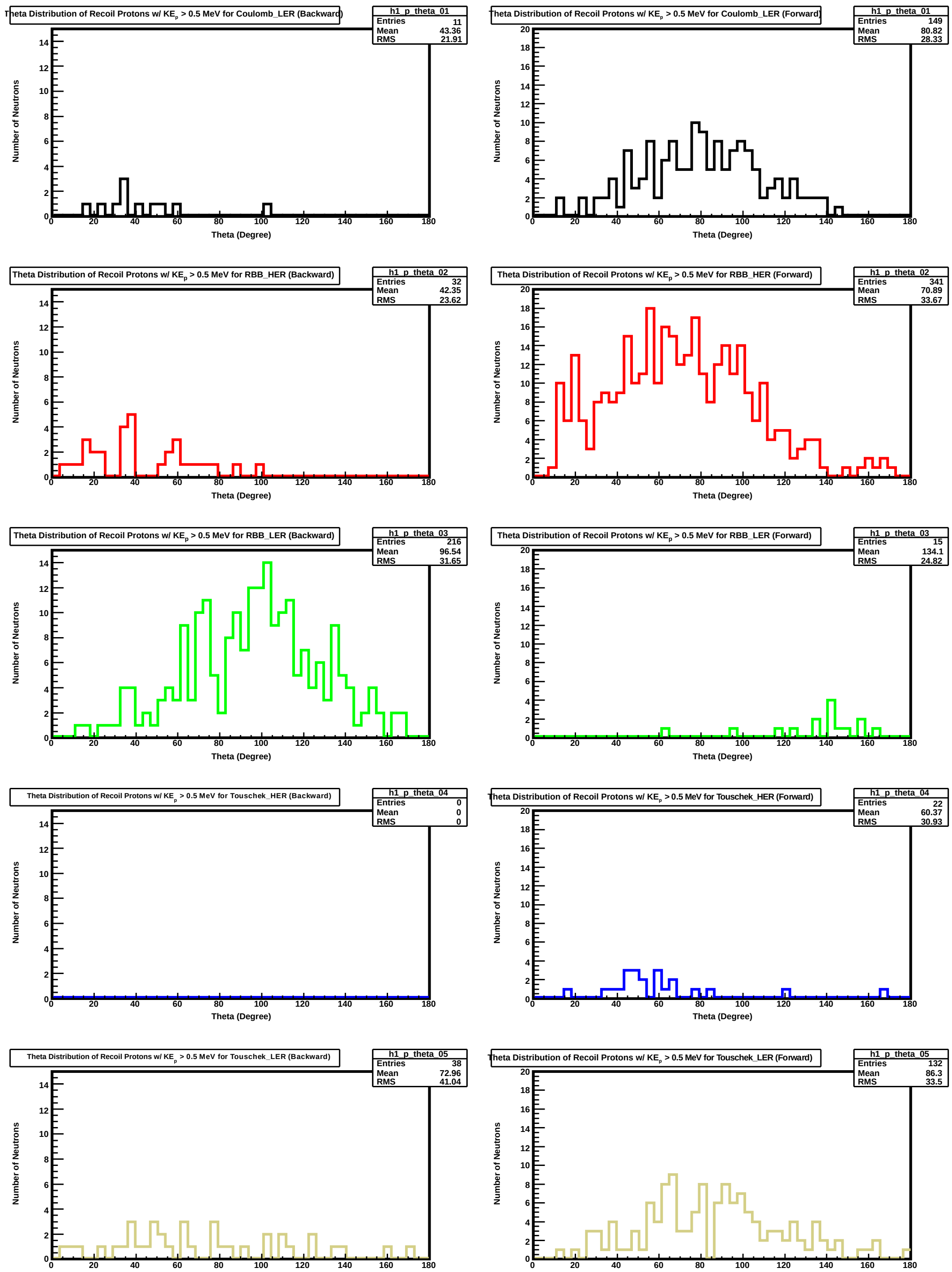

Figure 24: *Polar angle of proton recoils with* $E > 500$ *keV, from elastic neutron scattering in the backward (left) and forward (right) array of microTPCs. This is what we would expect to observe in the detector with a Hydrogen-based target gas.*

gas mixture	Ar:CO2 (70:30)	He:CF4 (70:30)	He:CO2 (70:30)	iso-C4H10 (100)	He:CH4 (70:30)
field strength simulated (V/cm)	1.0	1.0	1.0	2.0	1.0
drift velocity (μm/ns)	8.9	85	8.7	46.4	71.3
transverse diffusion ($\mu m/\sqrt{(cm)}$)	86.3	57	86.2	107	218.8
longitudinal diffusion ($\mu m/\sqrt{(cm)}$)	86.3	76	87.3	86	141.5

Table 5: Key parameters of candidate TPC gas mixtures.

A.3 Commissioning Detector: Micro-TPC Simulations

Candidate target gases for the micro-TPCs are: $\mathrm{He:CF_4}$, $\mathrm{He:CO_2}$ and iso-$\mathrm{C_4H_{10}}$, and $\mathrm{He:CH_4}$. Helium and Hydrogen-based target gases are best for neutron detection, and the light target atoms maximize energy transfer during elastic scattering. An addition, we typically use $\mathrm{Ar:CO_2}$ for prototype studies and calibration. This section summarizes they key performance parameters of these candidate gases, which were used to arrive at the micro-TPC specification in the commissioning detector CDR.

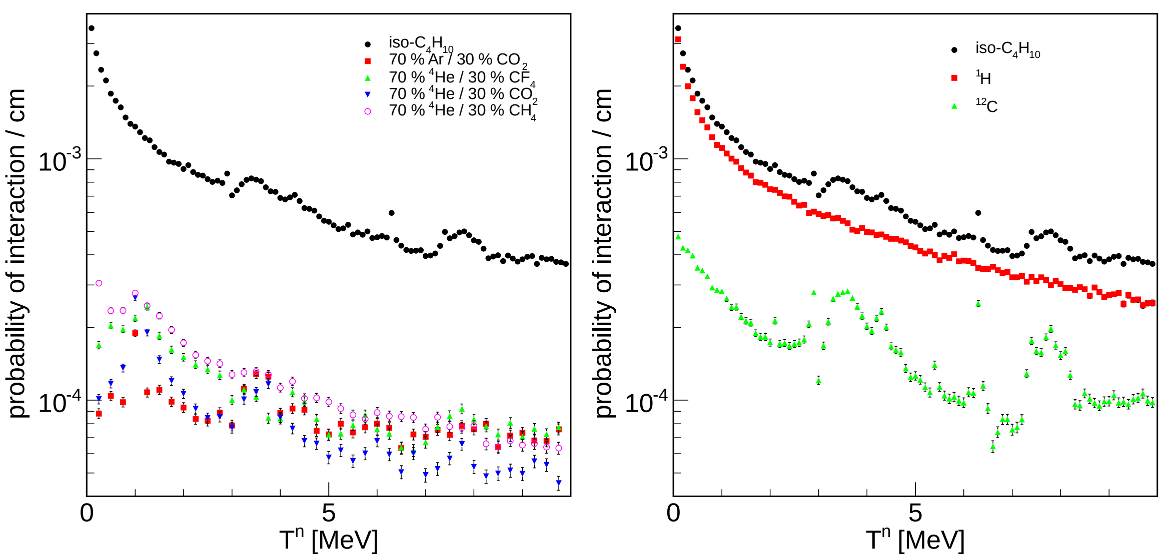

Figure 25: *Probability of neutron scattering per cm of target gas, at atmospheric pressure and room temperature. Below 2-MeV, the scattering is almost exclusively elastic. The effiency of iso-C4H10 is an order of magnitude higher than that of other candidate gases, simply because there are 10 hydrogen atoms per molecule. Hydrogen is also better than Helium for maximizing energy exchange during scattering, and in that the scattering probability for the target nucleus (Hydrogen) is significantly higher than that of other nuclei in the gas. The drawback of working with hydrogen-based gas mixtures is safety - they tend to be flammable.*

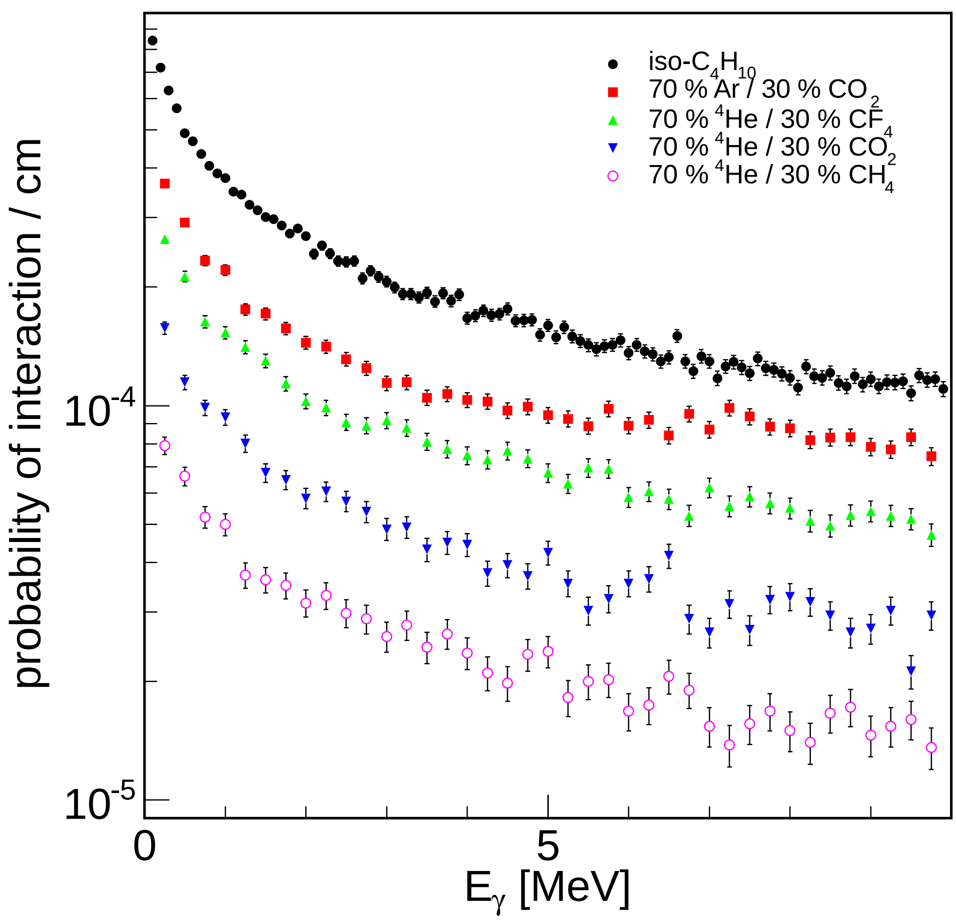

Figure 26: *Probability of gamma-ray scattering per cm of target gas, at atmospheric pressure and room temperature.*