US Belle II Project
Conceptual Design Report

Principal Investigators:

D. M. Asner[†], J. E. Fast, R. T. Kouzes, G. Tatishvili, L. S. Wood
Pacific Northwest National Laboratory, Richland, Washington 99352

A. J. Schwartz, K. Kinoshita
University of Cincinnati, Cincinnati, Ohio 45221-0011

T. E. Browder, K. Nishimura, S. Vahsen, G. Varner
University of Hawaii, Honolulu, Hawaii 96822

A. Vossen
Indiana University, Bloomington, Indiana 47408

T. Pedlar
Luther College, Decorah, Iowa 52101

V. Savinov
University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA

R. Godang
University of South Alabama, Mobile, Alabama 36688

L. Piilonen
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0435

G. Bonvicini, D. Cinabro
Wayne State University, Detroit, Michigan 48202

March 9, 2012

[†] Contact:david.asner@pnnl.gov

Contents

I BEAST simulation 3

1 Simulation strategy 3

1.1 Backgrounds background 3

1.2 micro-BEAST-TPCs 3

2 Design optimization 9

2.1 micro-BEAST-TPCs 9

2.1.1 Locations 9

2.1.2 Gas optimization 9

2.1.3 Pixel chip positions 9

2.1.4 Rates 9

3 Detection efficiency 12

3.1 micro-BEAST-TPCs 12

3.1.1 Neutron 12

3.1.2 EM particles 12

3.1.3 Beam backgrounds 12

Part I

BEAST simulation

In this section, Monte Carlo simulations studies are described. These studies were performed in order to design and optimize the BEAST detectors and in particular the micro-BEAST-TPCs. The micro-BEAST-TPCs should be able to distinguish the beam background types by measuring the angular distributions of the nuclear recoils procured when neutrons scatter elastically off the nuclei of the gas-target.

These section is divided into three parts: the **simulation strategy** is introduced, the **design optimization** and the **detection efficienciy** of beams background-dependent of various type of particles are presented.

1 Simulation strategy

1.1 Backgrounds background

There are three types of background: Radiative Bhabha (RBB), Coulomb and Touschek due to either the beams collision or individual electron and positron beams. These backgrounds are producing mostly electromagnetic particles and neutrons.

1.2 micro-BEAST-TPCs

A three steps simulation strategy is adopted to enhance the recoil number due to the neutrons.

- first step: basf2 simulation of the different background contributions
    - profiles the particles: types, origins, energy and angular distrivutions, passing through the TPCs
- second step: particles profiles served as an event generator for a GEANT (standalone) simulation
- third step: Fast Monte Carlo for
    - electron drift parameterization (using v_{drift}, D_l and D_t)
    - GEMs or avalanche-charge parameterization
    - digitization into pixel hit

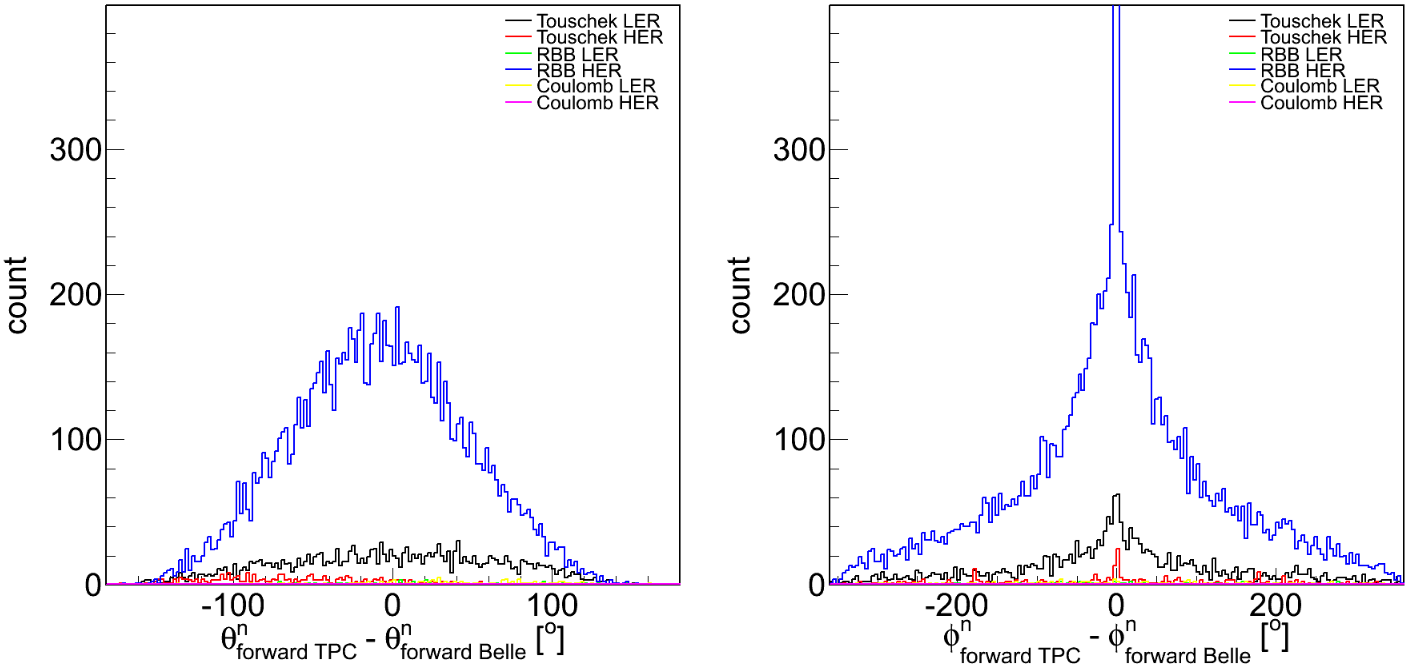


Figure 1: Left: difference between TPC and Belle polar angles. Right: difference between TPC and Belle azimuthal angles

Neutron backward shell TPC angle distributions in the dock space

Neutron direction is determined:

- not by the neutron momentum direction at the production vertex
- by the direction determined from the difference between the production and decay vertexes
- TPC z-axis is rotated by 180^o compared to Belle z-axis
- differences due to neutron multiple scatterings

The BEAST Monte Carlo simulation toolkit is currently being assembled within basf2 framewrok and will mostly rely on already available standalone simulation programs developped by each groups involved in the BEAST detectors. The flow chart in Figure 1 shows the simulation steps of micro-BEAST-TPC, which will perform the following tasks:

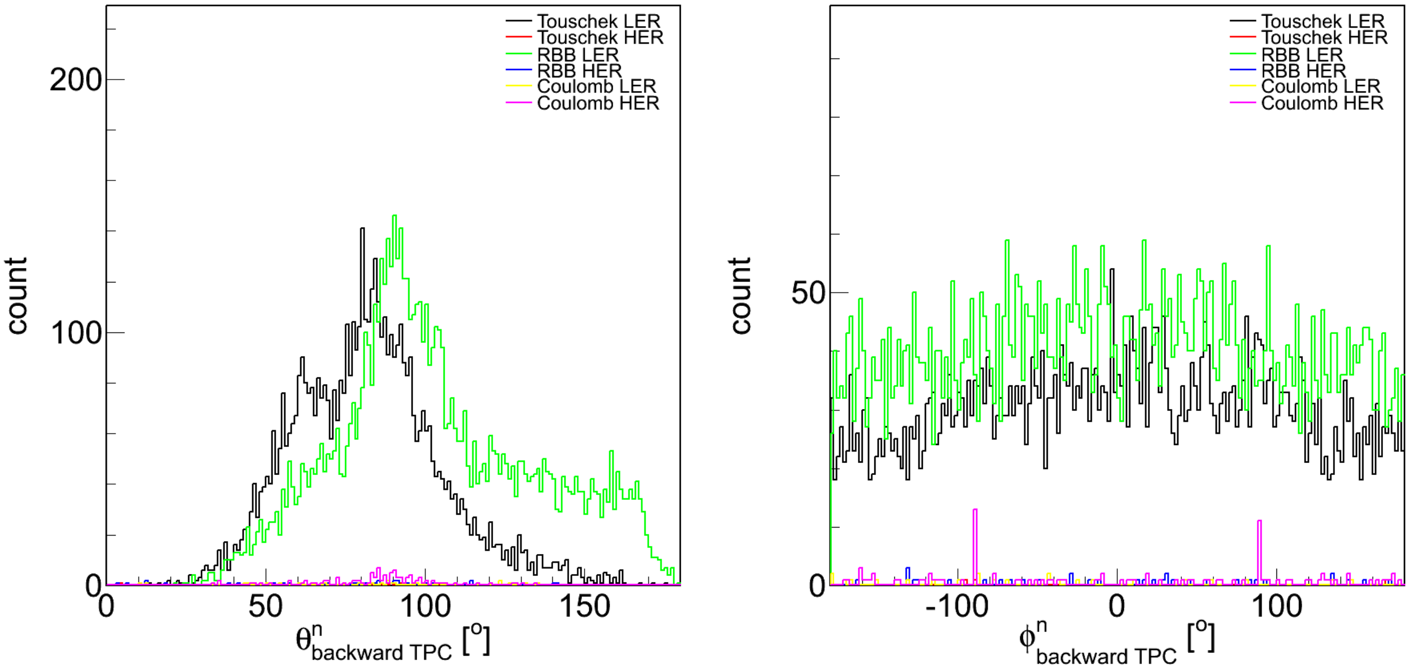


Figure 2: Left: backward shell TPC polar angles. Right: backward shell TPC azimuthal angles.

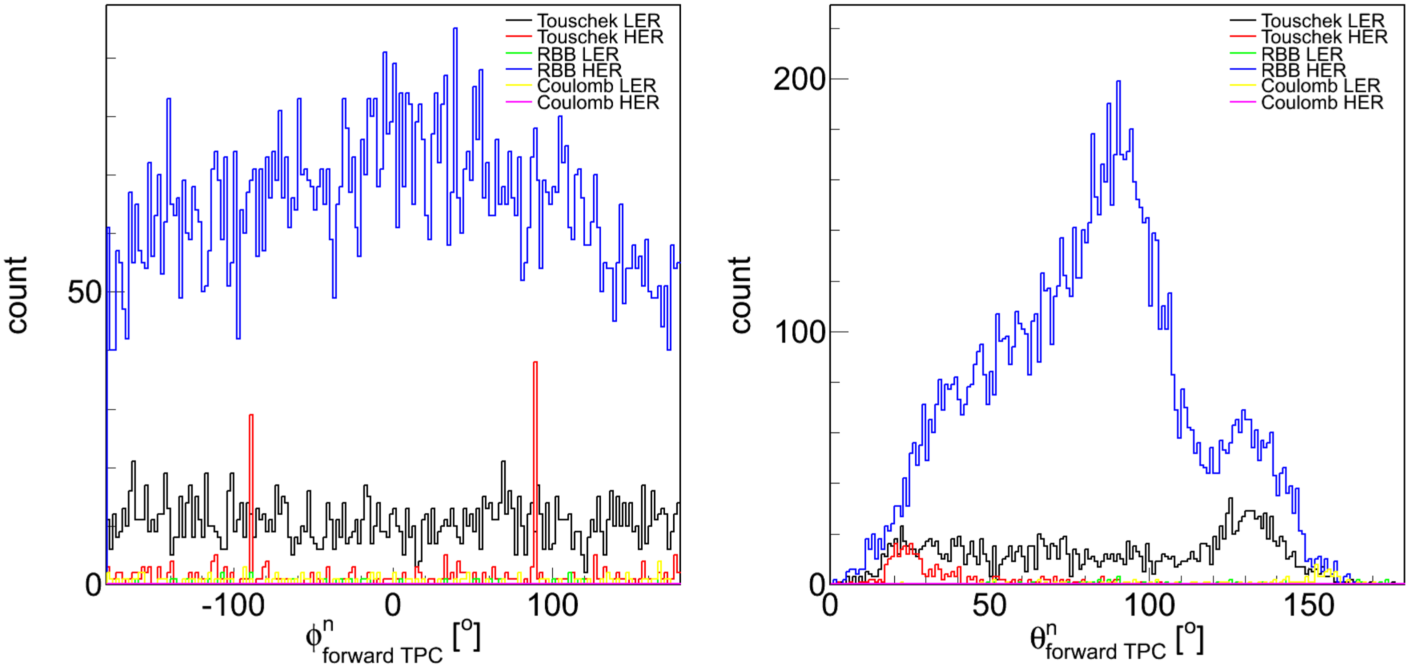


Figure 3: Left: forward shell TPC polar angles. Right: forward shell TPC azimuthal angles.

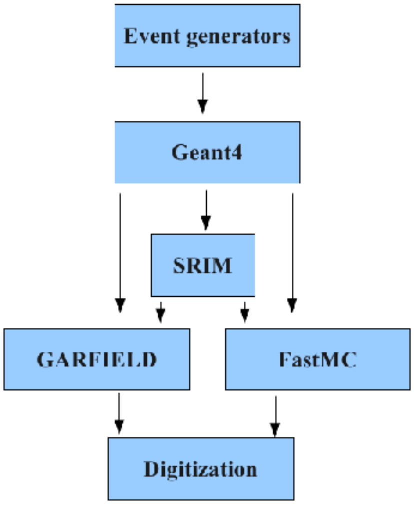


Figure 4: Flow chart showing the simulation steps expected for photons, WIMPs, nucleons, nuclei, leptons and mesons.

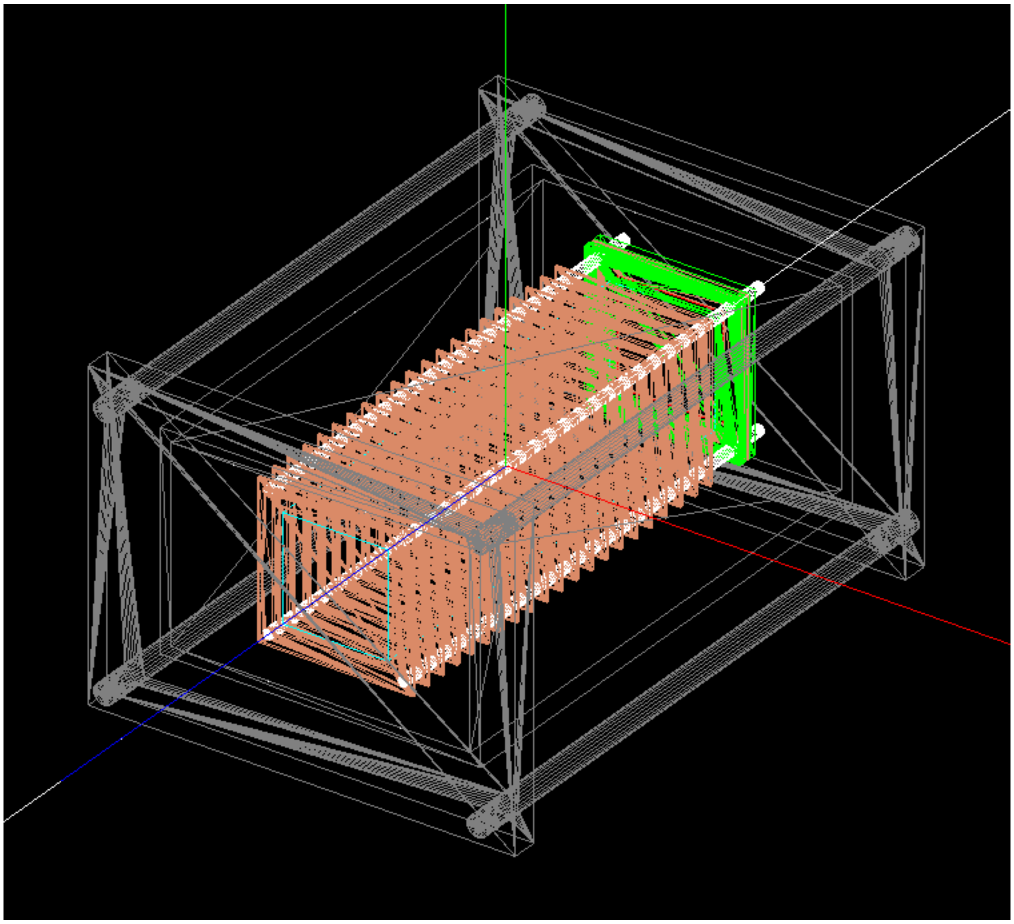


Figure 5: G4 drawing of a single micro-BEAST-TPC.

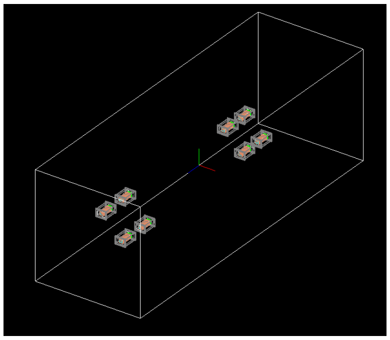
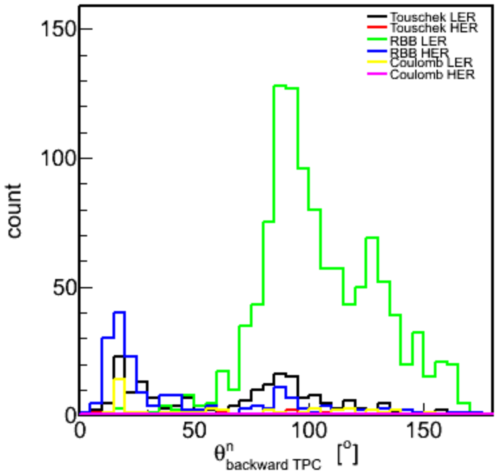
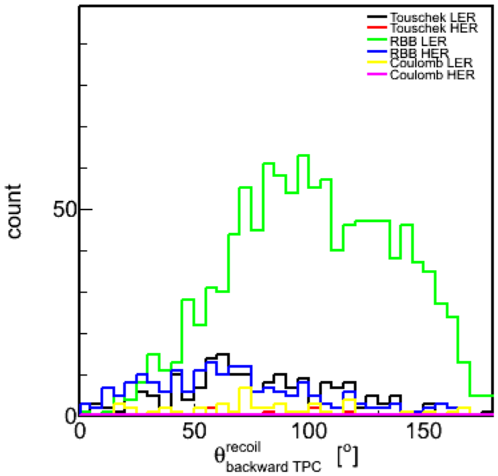


Figure 6: G4 drawing of eight micro-BEAST-TPCs located at the dock space.

- An event generator will simulate the signal and background sources. E.g., for the WIMP case: the predicted WIMP velocity distribution for the signal and cosmic-ray-induced radiation and radiation emitted by detector material for the background.
- An accurate geometry and materials description.
- The interaction between the incoming particle and the target gas or/and detector materials will be modeled using either the GEANT4 [[?]] physic classes, SRIM [[?]], or GARFIELD [[?]], depending the particle type, which may lead to the creation of ionization along the trajectory of the incoming particle or/and along the recoil product of the incoming particle scattering off gas-nuclei. SRIM[[?]] and GARFIELD[[?]] can model theses processes fairly well.
- Then the electrons [[?]] (or negative ions [[?]]) drift under the influence of the electric field. Negative ions can be formed in the case the electrons from the ionization can attach themselves to the gas-molecule to form negative ions). GARFIELD or a fast Monte Carlo simulation using the gas properties calculated by MAGBOLTZ [[?]] can simulate the drift of ionization (electrons, or negative ions in the case of negative ion drift), towards the GEMs with a constant velocity in a homogeneous electric field. The GEMs which then amplify the signal. In an area of high field near the GEMs, the electrons detach from the negative ion. Therefore a normal avalanche occurs both in the case of electrons and negative ions. We plan to model the GEMs with a parameterized simulation.


Touschek LER
Touschek HER
RBB LER
RBB HER
Coulomb LER
Coulomb HER
count
150
100
50
0
0
50
100
150
$\theta^{n}_{\text{backward TPC}}$ [°]


Touschek LER
Touschek HER
RBB LER
RBB HER
Coulomb LER
Coulomb HER
count
50
0
0
50
100
150
$\theta^{\text{recoil}}_{\text{backward TPC}}$ [°]

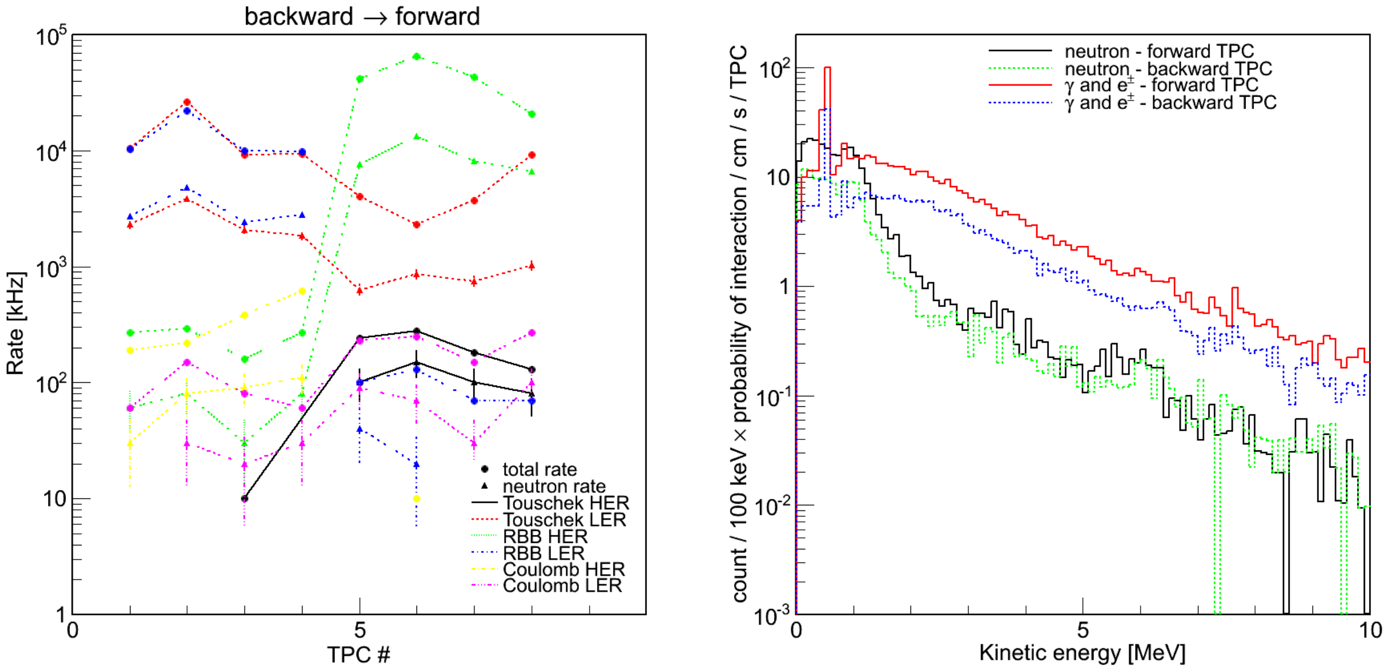


Figure 7: Left: expected rate at TPC location. Right: expected rate of interacting particles in a single TPC

- The digitization software then simulates how the resulting avalanche-charge is detected by the electronic readout, in our case pixel electronics [[?]] .

2 Design optimization

2.1 micro-BEAST-TPCs

2.1.1 Locations

2.1.2 Gas optimization

2.1.3 Pixel chip positions

2.1.4 Rates

5

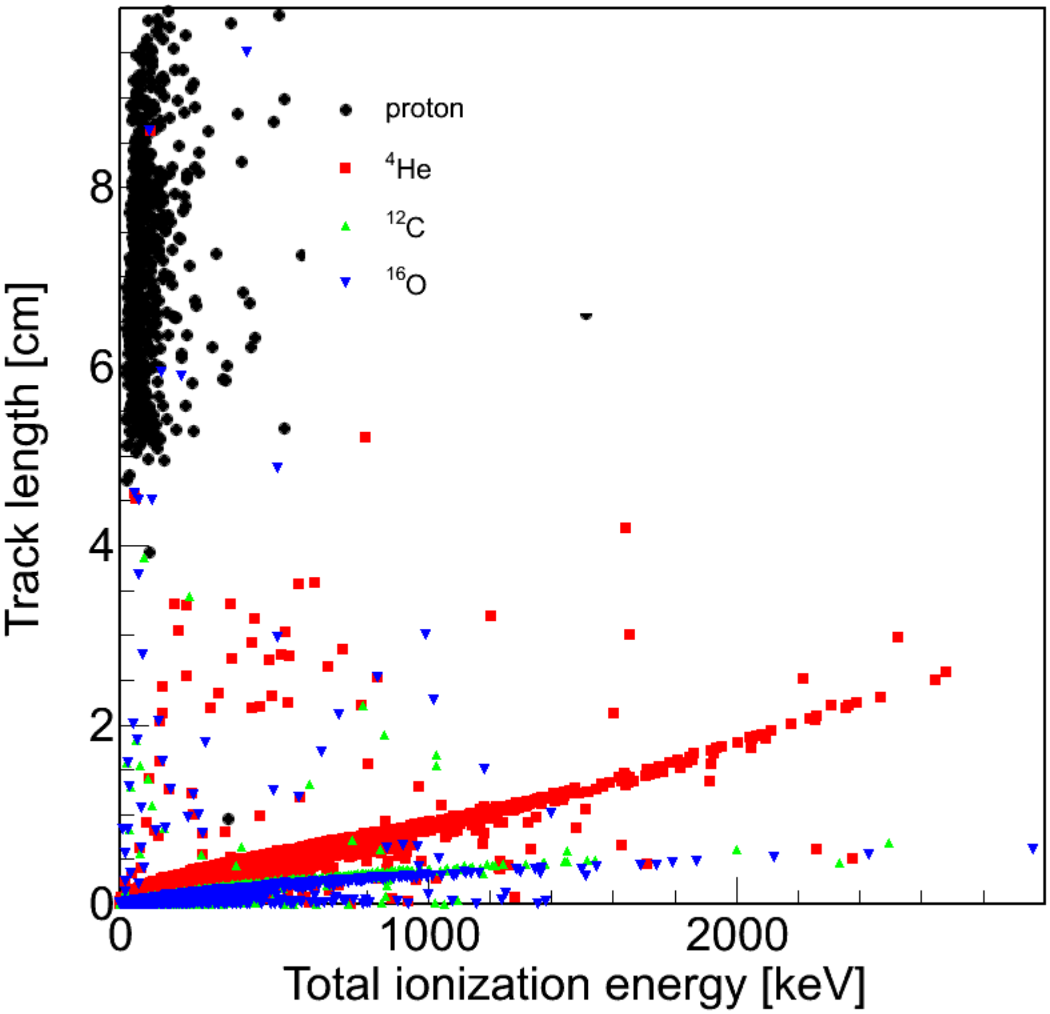


Figure 8: Track length as function of total ionization energy.

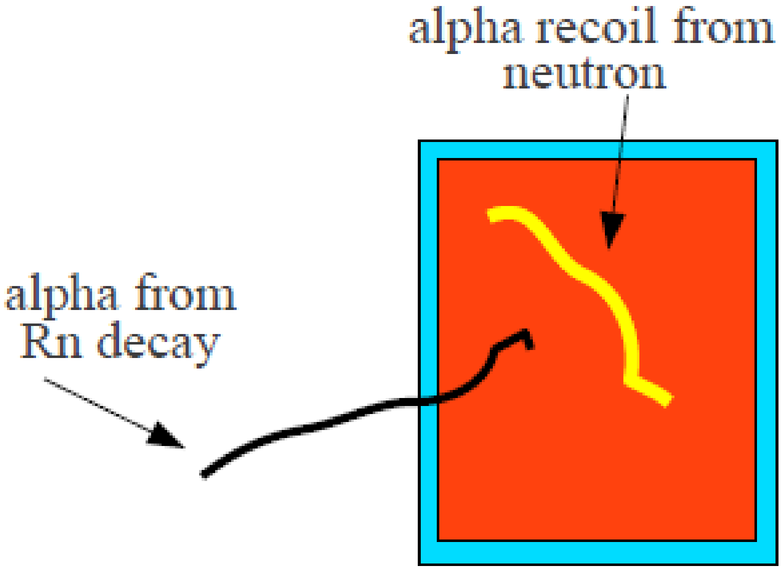


Figure 9: Edge cut drawing.

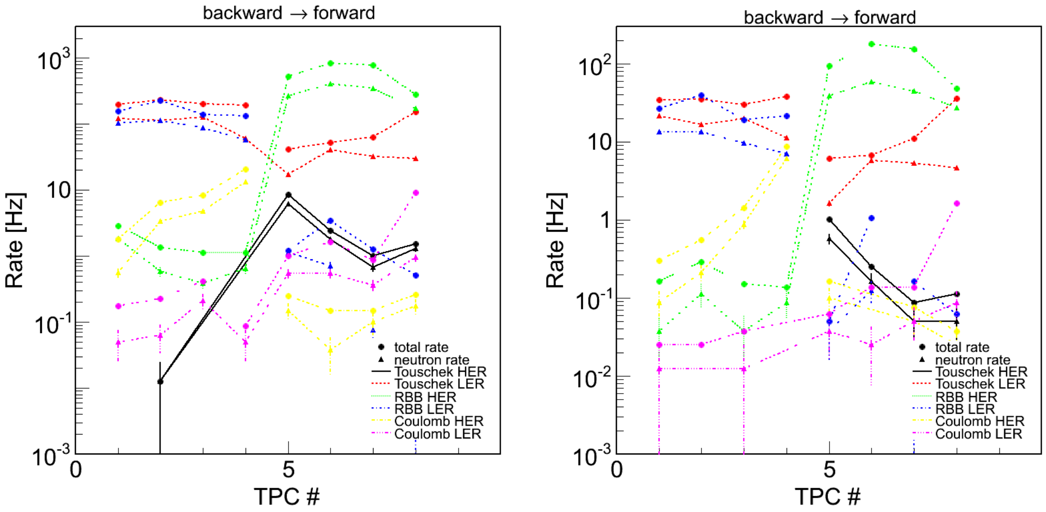


Figure 10: Left: Interactiom rate in TPC. Right: rate with directionality and edge cut to remove alphas contamination.

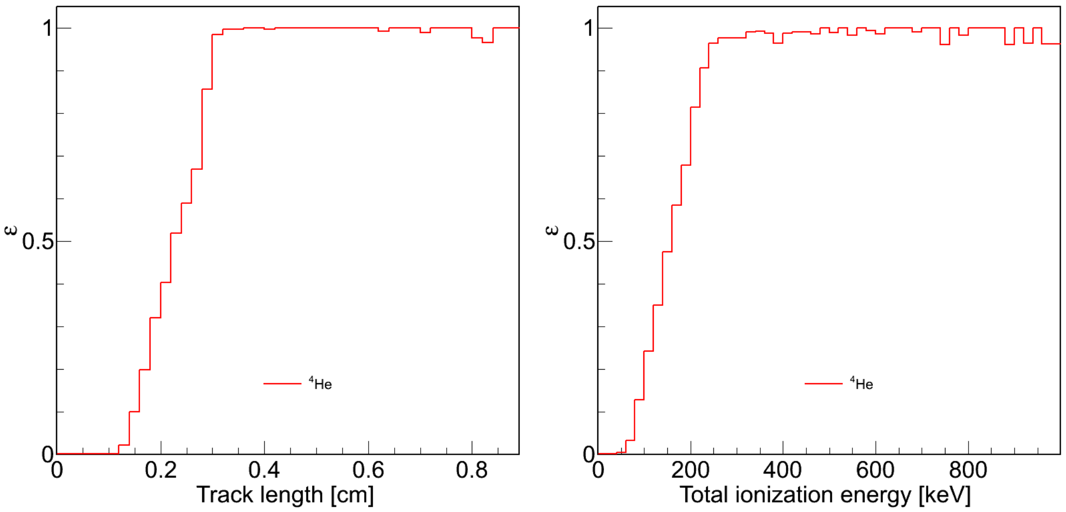


Figure 11: Left: efficiency vs. track length. Right: efficiency vs. total ionization energy.

3 Detection efficiency

3.1 micro-BEAST-TPCs

3.1.1 Neutron

3.1.2 EM particles

3.1.3 Beam backgrounds

- FE-I3
  - chip size 0.84 cm x 0.76 cm
  - pixel size 50 μm x 400 μm
  - 18 column x 160 row
  - 400 ns time range with 16 graduation
  - 100k e^- charge range with 128 graduation
- FE-I4
  - chip size 2 cm x 1.68 cm
  - pixel size 50 μm x 250 μm
  - 80 column x 336 row
  - 1600 ns time range with 64 graduation

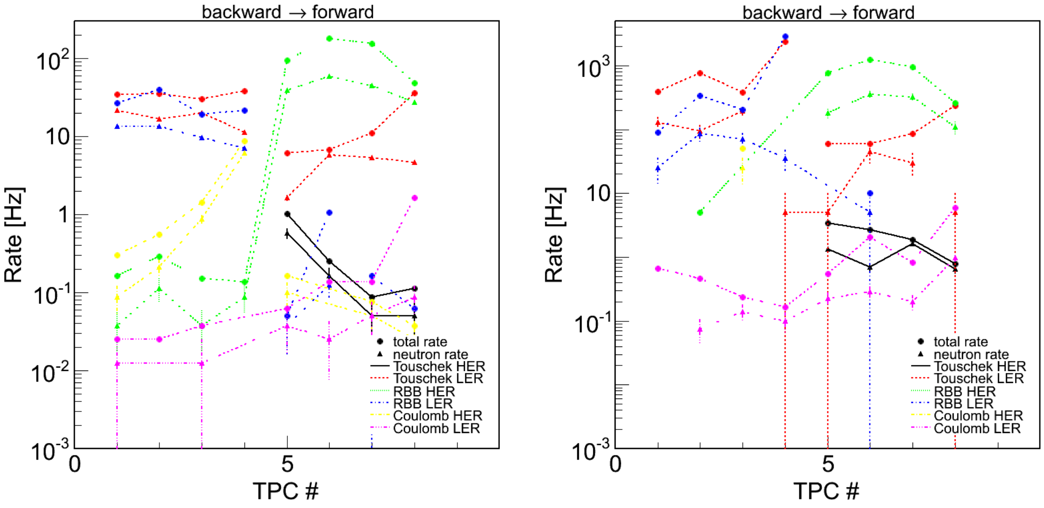
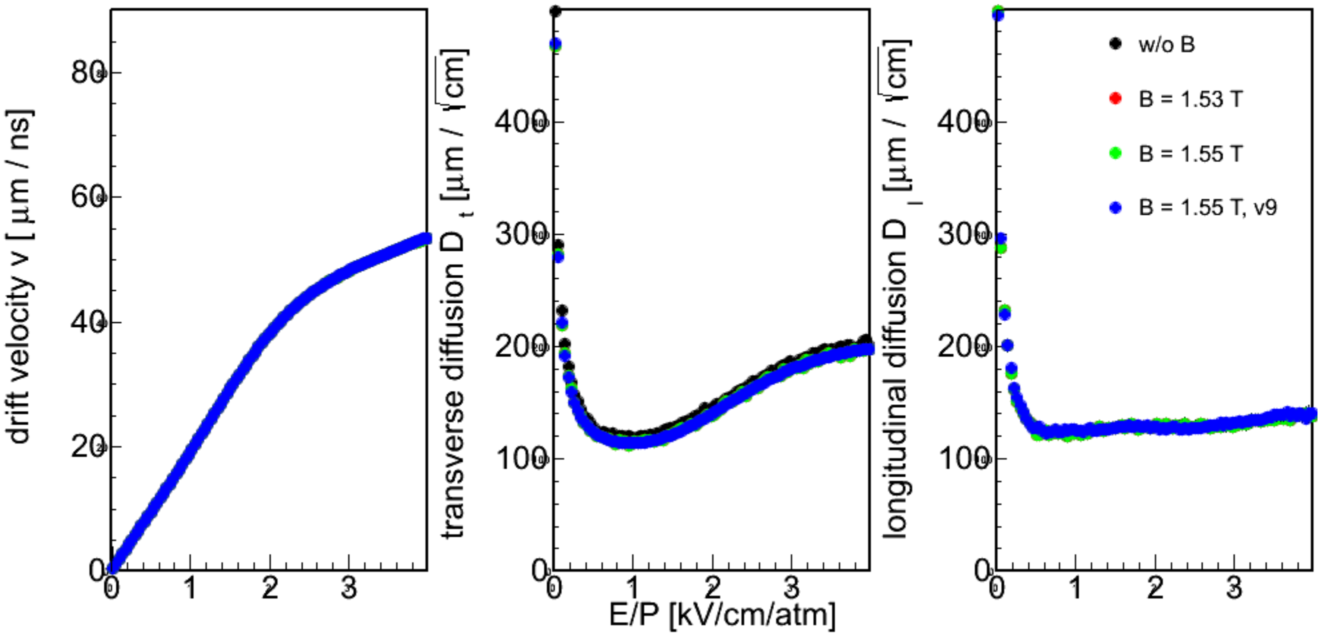


Figure 12: Rate with directionality and edge cut. Left: $He : CO_2 : 70 : 30$ at 1 atm. Right: C_4H_{10} at 1 atm.

  - 100k e^- charge range with 16 graduation

- drift velocity high enough to clear chamber volume rapidly
- but not too high to have a good 3D hit resolution
- maximum of v_{drift}(E/P) for the lowest σ_l at low drift field to keep drift voltage reasonably low and cage field simple
- attachment coefficient low
- gas gain o(100)
- need to keep eye on diffusion coefficients and gas gain
- simulate gas / gas mixture with
  - iC_4H_{10} (flammable and explosive)
  - $Ar:CO_2$
  - $He:CO_2$
  - $He:CF_4$
  - $He:CH_4$ (flammable, but not explosive)



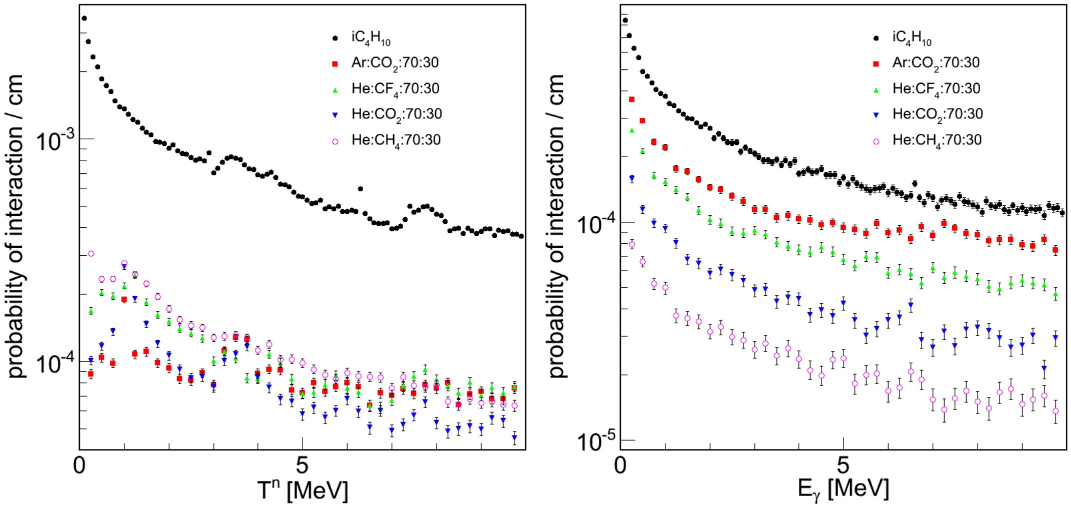


Figure 13: Interaction probability per centimeter as function of kinetic energy for various gas and gas mixtures. Left: neutron. Right: photons.

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.

	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).*

Figure **??** 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 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 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.

References

[1] T. Kim, M. Freytsis, J. Button-Shafer, J. Kadyk, S. E. Vahsen and W. A. Wenzel, "Readout Of TPC Tracking Chambers With GEMs And Pixel Chip", Nucl. Instrum. Meth. **A589** (2008), 173-184

[2] R. Cizeron, A. Durand, T.L. Geld, V. Lepeltier, B. Meadows, Michael T. Ronan, S. Sen, A. Valassi, G. Wormser, "A Mini - TPC for SLAC B factory commissioning", Nucl. Instrum. Meth. **A419** (1998), 525-531

[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)