



# Machine-detector interface at SuperKEKB/Belle II

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#### **SuperKEKB**

#### The super **B-factory** at KEK (2018 start)

- Asymmetric-energy 10.57 GeV (c.o.m.)  $e^+ e^-$  collider
- A planned **40-fold** increase in luminosity over KEKB (target: 8x10<sup>35</sup> cm<sup>-2</sup>s<sup>-1</sup> instantaneous, **50ab<sup>-1</sup>** integrated), due to major upgrades:
  - "Nano-beam" scheme (below)
  - Doubled beam currents
  - (large number of upgrades to RF, magnet, vacuum, damping systems)
- First turns Feb. 10, 2016! Exciting times!







Vertical beta function reduction (5.9 $\rightarrow$ 0.3 mm) gives x20

Beam Energies 8.0/3.5→7.0/4.0

#### Belle II

**Central beam pipe:** 2cm diameter, Beryllium with gold coating on inside

**Vertexing:** new 2 layers of pixels, 4 double-sided layers of silicon strips

**Tracking:** 14336-wire drift chamber

**PID:** time-of-flight (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

EM calorimetry: CsI(Tl) crystals

 $K_L$  and  $\mu$ : scintillators (endcap and inner two layers of barrel) and RPCs (remainder of barrel)





### (Some) important beam backgrounds at Belle II

- **Touschek**: intra-bunch Coulomb scattering
  - $\circ$  Squeeze beam  $\rightarrow$  more background



• **Beam-gas**: Coulomb or bremsstrahlung scattering of beam particles with gas in beampipe



• **Synchrotron**: generated by upstream bending magnets



• **Radiative Bhabha** (with collisions):



• **Injection**: particles injected from linac off-orbit

#### SuperKEKB vs. CEPC



#### A very simplistic scaling

| Parameter x [unit]                             | Background (scaling)   | SuperKEKB [LER/HER]  | CEPC/SuperKEKB |
|--|--|----------------------|----------------|
| Current [mA]                                   | Beam-gas ( <b>x</b> )<br>Synchrotron ( <b>x</b> )                            | 3600/2600            | 1/180          |
| Bunch current [mA]                             | Touschek ( <b>x</b> ²)   | 1.4/1.0              | 1/4            |
| Number of filled bunches                       | Touschek ( <b>x</b> )  | 2503                 | 1/50           |
| Luminosity [cm <sup>-2</sup> s <sup>-1</sup> ] | Radiative Bhabha ( <b>x</b> )  | 8 × 10 <sup>35</sup> | 1/40           |
| Beam energy [GeV]                              | Touschek ( <b>x</b> <sup>-3</sup> )<br>Synchrotron ( <b>x</b> <sup>4</sup> ) | 4/7                  | 25             |
| β <sub>y</sub> <sup>*</sup> [μm]               | Touschek ( <b>x</b> <sup>-1</sup> )  | 270-300              | 4              |

#### SuperKEKB vs. CEPC

A very simplistic scaling

- This gives some context to my remaining slides
- Expected CEPC backgrounds compared to SuperKEKB
  - **Touchek**: factor of  $1/4 \times (1/25)^3 \times 1/4 = 10^6$  lower
  - Beam-gas: factor of 180 lower
  - Radiative Bhabha: factor of 40 lower
  - Synchrotron: factor of  $1/180 \times 25^4 = 2000$  higher
  - **Beamstrahlung**: average parameter  $\Upsilon$  is a factor **60** higher
- Of course, **design choices** matter
  - In Belle, S.R. severely damaged original silicon vertex detector
  - ~*No S.R.* in Belle II due to geometry and beam-pipe design
  - $\circ$  The above S.R. estimate does not reflect realistic CEPC geometry and details of magnet system







### Commissioning of SuperKEKB





### Schedule: beam commissioning phases

Phase I (2016)

- Circulate both beams; **no collisions**
- No Belle
- Tune accelerator optics
- Vacuum scrub
- Beam studies

#### Phase II (2018)

- First collisions
- Belle outer detectors
- Develop beam abort
- Achieve nano-beam
- Beam studies



#### Enter the BEAST

What is it?

- A collection of **detector systems** for background measurements in Phases 1+2
- A group of accelerator and detector **collaborators** dedicated to studying beam backgrounds
  - $\circ$  Simulation
  - Detection and characterization
  - Mitigation





#### Enter the BEAST

Primary detectors in BEAST II\* for Phase 1:

| System                         | #   | Unique measurement                        |  |
|--------------------------------|-----|---|--|
| PIN diodes                     | 64  | Neutral vs. charged dose rate             |  |
| Time Projection<br>Chambers    | 4   | Fast neutron flux and tracking            |  |
| Diamonds                       | 4   | Beam abort                                |  |
| He3 tubes                      | 4   | Thermal neutron rate                      |  |
| CsI(Tl) crystals               | 6   | EM energy spectrum, injection backgrounds |  |
| CsI+LYSO crystals              | 6+6 |   |  |
| BGO crystals                   | 8   | EM dose rate                              |  |
| CLAWS plastic<br>scintillators | 8   | Fast injection backgrounds                |  |



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### BEAST operation in phase I

#### Completed

- 24/7 operation for 5 months (top)
- Throughout: beam scrubbing and tuning
- Two weeks of dedicated beam study runs
- Real-time background monitoring and feedback to SuperKEKB group (bottom)
- Dismantled BEAST Phase 1 to make way for Belle II outer detectors and BEAST Phase 2

#### In progress

- Preparing Phase 1 results for publication (next slides)
- Commissioning BEAST Phase 2









### Preliminary BEAST II Phase 1 results



## How well do we understand beam backgrounds?



A heuristic equation

- **Hypothesis**: beam-gas and Touschek explain ~*all* of BEAST observables when not injecting
- **Parametrize** observables as functions of accelerator conditions (I, P, gas composition  $Z_e$ , beam size  $\sigma_v$ )
- Use this to separately measure beam-gas and Touschek, compare to simulation

$$Observable = B \cdot IPZ_e^2 + T \cdot \frac{I^2}{\sigma_y}$$

### Intro: Size-sweep scans

#### **Targeting Touschek**

- Ran beam at 5 different beam sizes and **Observable** at 3 currents (15 runs total)
- Rewrite heuristic so beam-gas is flat:

$$\frac{Dbservable}{IPZ_e^2} = B + T \cdot \frac{I}{PZ_e^2 \sigma_y}$$

- Fit measures sensitivities *B* (offset) and T (slope)
- Example, right
  - Observable from BGOs 0
  - Quality of linear fit validates 0 model



### Results: data/MC comparison

From size sweep scans

- **Data/MC ratios** for beam-gas and Touschek, right (1 is perfect agreement)
  - $\circ \quad {\rm One \ point \ per \ detector \ channel}$
  - **Red**: positron beam
  - Blue: electron beam
- **The conclusion**: simulating beam-gas is *very hard* 
  - Gas conditions are *highly local* and *poorly known*

**Lesson from Phase 1**: accurate simulation requires comprehensive and well-calibrated beam-size, pressure and composition measurements



#### **Results: injection background**

#### Fast BEAST detectors

- Bunches are **hot** after charge has been injected
  - Not simulated
  - Dangerous (particularly for inner detectors)
- Plastic and crystal scintillators have sufficient (~ns) timing to see bunch-by-bunch structure
  - Bunch spacing: 6.3ns
  - Orbit time:  $10\mu$ s
  - Approximate damping time for hot bunch: 1ms

**Lesson from Phase 1:** realtime injection time structure from BEAST shown at SuperKEKB control room was critical for tuning injection.



#### Injection time structure from CsI



#### Results: fast neutrons

A major concern for Belle II

- 2 "micro" TPCs in Phase 1
  - Fast neutrons collide with He nucleus
  - Nucleus recoils and leaves ionization trail
  - Can fit recoil direction in 3D
  - **Goal**: measure rate of fast neutrons, point back to source, compare with simulation
- **Results** (bottom)
  - ( $\phi$ =0 points to beam-pipe)
  - $\circ$  An excess of ~3 with respect to simulation
  - Similar excess for thermal neutron rate from He3 tubes
  - **Understanding the excess is key goal of Phase 2** (8 TPCs)



#### **Results: synchrotron radiation**

#### Using the PIN diode system

- 64 channels in 32 modules mounted directly on beam-pipe. Each module contains:
  - One diode with **Al** foil covering
  - $\circ$  One diode with **Au** foil covering
  - Thermocouple for thermal dark current subtraction

Entries

- SR (x-ray) signature: higher dose in Al-shielded diodes than neighboring Au-shielded diodes
- Plot, right: difference (**Al**-**Au**) in integrated dose for each pair of PIN diodes in Phase 1
  - No significant SR detected





### Additional lessons learned



If we had to do this again

- Beam backgrounds need **organized collaboration** between accelerator and detector experts from the beginning. Work together on:
  - **Simulation** (including tracking code)
  - **Dedicated background detectors** near IP and around ring targeting key background types
  - A **commissioning campaign** with purpose-built detectors at the IP and dedicated beam studies
  - **Mitigation** efforts (shielding, collimation, etc.)
  - A shared **control and monitoring system** (such as EPICS)
- Design and operate accelerator conditions systems (beam size, vacuum pressure and composition) as part of a detector system

#### Status and near future

Phase 1 paper nearing submission

- It's a beast
- Many interesting results not shown today

#### Phase 2

- Many more questions to answer with narrower beams, collisions and final focusing magnets
- Additional beam background detectors in inner Belle II volume (see additional slides)

|  |  |   | Commission<br>BEAST I<br>BEAST I   |
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| Character of Trains, Department of<br>Thermity of Mussin, Department of Physics<br>"Beyone Saw Education, Department of Physics<br>"Beyone Saw Education, Department of Physics<br>"Beyone Saw Education, Department of Physics<br>"Beyone Saw Education Physics<br>The high design luminosity of the SuperKEKB electron-po-<br>backgrounds in the interaction region. As a result, proper<br>success of the Belle I experiment. We report on measure<br>Oldectively taxown as BEAST II, during the so-called physics<br>Bern Backgrounds descreed, compare them with simulation<br>Reywords:<br>Contents<br>1 Introduction<br>2 The REAST II system<br>2.1 The CLAWS Trager<br>2.2 TRA To<br>2.3 CLAWS Trager<br>2.3 CLAWS Trager<br>2.3 CLAWS Installation<br>2.3 CLAWS Installation<br>2.4 CLAWS Installation<br>2.5 Electromagnetic counters and calorimeters .<br>2.4 Charden Laws Calibration<br>2.4 Charden Laws Installation<br>2.4 Store points Part Physica<br>2.5 Electromagnetic counters and calorimeters .<br>2.5 Theorem 2016 Claws Installation<br>2.4 Claws Detector Performance<br>2.4 Claws Installation<br>2.4 Storem Performance<br>2.4 Storem Performance<br>2.5 Electromagnetic counters and calorimeters .<br>2.5 Theorem Performance<br>2.5 Storem Performance<br>3.5 Storem Performance<br>3.5 Storem Performance<br>4.5 St  | Physica, and A<br>icrossed and Arrows<br>icrossed and Arrows<br>by simul<br>ments p<br>see 1 rue<br>n, and d<br>3<br>3<br>3<br>3<br>3<br>3<br>3<br>4<br>4<br>4<br>5<br>5<br>5<br>5<br>5<br>5<br>6  | All fore dama<br>many above dama<br>many above framework<br>and above dama<br>above dama<br>above dama<br>above dama<br>above dama<br>above dama<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above<br>above | with Sout Target (1967; Tabian<br>with Sout Target (1967; Tabian<br>Harrow, K. Neuros EU: WY ACZ. Cando<br>Harrow, K. Neuros, EU: WY ACZ. Cando<br>Harrow, M. 48202, CSA.<br>The Construction of the Construction of the<br>pressing these backgrounds will be critical to the<br>a system of defactured commissioning detectors,<br>a system of defactured commissioning detectors,<br>a system of defactured commissioning detectors,<br>a logical commissioning detectors,<br>Physical detectors, a system of defactured and<br>The Physical detectors of the Construction of the<br>States of the Physical detectors,<br>10 Overview and nucleusing detectors,<br>11 Overview and nucleusing detectors,<br>12 Overview and nucleusing detectors,<br>13 Readout,<br>14 Physical detectors of the Physical detectors,<br>15 Calibration 5<br>16 The Chalterstain 5<br>17 Physical detectors of the Physical description 12<br>14 The Physical description 12<br>15 He table Physical description 13<br>16 Physical description 14<br>10 Detactors of the Physical description 14<br>10 Detactors of t   |





Thank you! (additional slides)





### BEAST II: the commissioning detector

Primary detectors in BEAST II for phase **II**:

| System                                 | Institution  | #                         | Unique measurement             |
|--|--------------|---------------------------|--------------------------------|
| PIN diodes                             | КЕК          | 64                        | Neutral vs. charged dose rate  |
| "Micro" Time<br>Projection<br>Chambers | U. Hawaii    | <del>48</del>             | Fast neutron flux and tracking |
| Diamonds                               | INFN Trieste | <del>4</del> 8            | Ionizing radiation rate        |
| He3 tubes                              | U. Victoria  | 4                         | Thermal neutron rate           |
| CLAWS plastic scintillators            | MPI Munich   | <del>8</del> 2<br>ladders | Fast injection backgrounds     |

...continued





### BEAST II: the commissioning detector

Primary detectors in BEAST II for phase **II**:

| System       | Institution | #            | Unique measurement                                    |
|--------------|-------------|--------------|---|
| Belle II PXD | U. Bonn     | 2<br>ladders | Radiation tolerance for final physics runs            |
| Belle II SVD | KEK         | 4<br>ladders | Radiation tolerance for final physics runs            |
| FANGS        | U. Bonn     | 15           | Silicon pixel sensors<br>(synchrotron x-ray spectrum) |
| PLUME        | Strasbourg  | 2<br>ladders | Silicon pixel sensors<br>(collimator adjustment)      |



### Intro: injection background



From inefficient injection

- Figure right:
  - **Black points**: predicted observable by heuristic
  - **Red points**: actual observable
  - **Blue**: the difference (injection background)

