Beam-induced backgrounds at SuperKEKB

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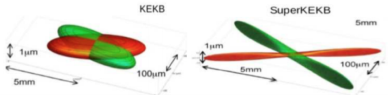
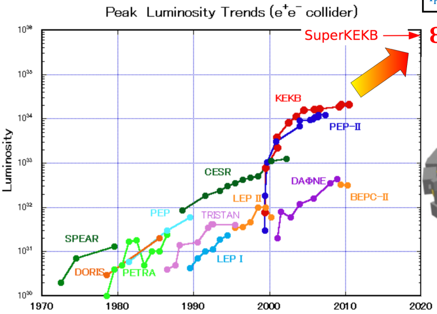
Overview

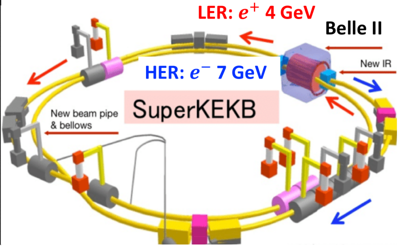
- Upgrade to KEKB asymmetric $e^- e^+$ collider
- Projected 40 fold increase over KEKB's world record luminosity



KEKB	SuperKEKB
$I_{\text{LER}} = 1.64\text{A}, \sigma^*_{y,LER} = 0.94\mu m$	$I_{\text{LER}} = 3.6\text{A}, \sigma^*_{y,LER} = .048\mu m$
$I_{\text{HER}} = 1.19\text{A}, \sigma^*_{y,HER} = 0.94\mu m$	$I_{\text{HER}} = 2.6\text{A}, \sigma^*_{y,HER} = .062\mu m$



$8\times10^{35}\text{cm}^{-2}\text{s}^{-1}$



High luminosity comes at the cost of elevated beam backgrounds.

Why do we care about beam backgrounds?

Beam Backgrounds

Undesirable background particles generated by the SuperKEKB accelerator.

- Negative effects of beam backgrounds
  - Performance degradation in Belle II detectors
  - Increased hit occupancies
  - Increased analysis backgrounds
  - Can damage Belle detectors

Belle II detector	Quantity	Expected value	Upper limit value	Safety factor	Dominant process(es)
PXD	occupancy	1.1%	3%	3	two-photon, synchrotron radiation
CDC	wire hit rate	400 kHz	200 Hz	0.5	radiative Bhabha, two-photon
CDC	electr. neutron flux	2.5	1	0.3	radiative Bhabha, Touschek
CDC	electr. dose rate	250 Gy/yr	100	0.3	radiative Bhabha, two-photon
TOP	PMT hit rate	5–8 MHz	1 MHz	0.2	radiative Bhabha, two-photon
TOP	PCB neutron flux	0.35	0.5	3	radiative Bhabha, Touschek
ARICH	HAPD neutron flux	0.3	1.0	3	radiative Bhabha
ECL	crystal dose rate	6 Gy/yr in BWD	10 Gy/yr	2	radiative Bhabha, two-photon

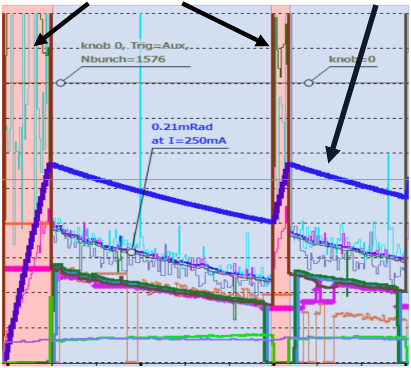
An important early goal is to validate and improve this BG simulation. This will improve phase 3 predictions, and will tell us if extra background remediation measures are needed.

Some essential accelerator terminology

- **Injection:** Charge is injected into the main ring to increase the beam current
  - Increases background rates
  - In general, Belle II detector HV is turned off
- **Storage:** When stable beams are circulating. No additional charge is injected
  - Generally safe for Belle II data taking
  - Lower background levels than injection
- **Continuous injection** (not shown in picture): Continuous rapid short injections to keep the current constant
  - If backgrounds are low enough to support Belle data taking, this mode is ideal for producing high luminosities

Traces indicate relative background levels

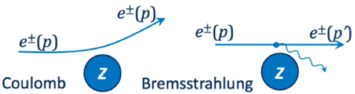
Thick blue trace is beam current



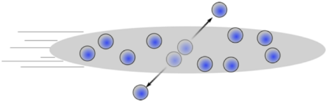
- Injection
- Storage

Beam background sources

Single Beam Backgrounds

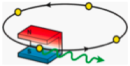


- **Beam-gas:** Bremsstrahlung and Coulomb scattering of beam particles with gas atoms in the beam pipe



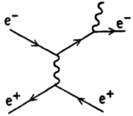
- **Touschek Effect:** Coulomb scattering between particles within a beam bunch

- **Synchrotron Radiation:** Produced by bending magnets



Luminosity Dependent Backgrounds

- **Radiative Bhabha:** Produced from collisions



- **Two γ processes:** Electron-positron pairs produced from low momentum $ee \to eeee$ processes

Injection Background

- Arise when charge is injected into a circulating beam bunch. This injection perturbs the bunch causing a brief spike in background rate
- **Difficult to simulate!**
- Essential to reduce before continuous injection

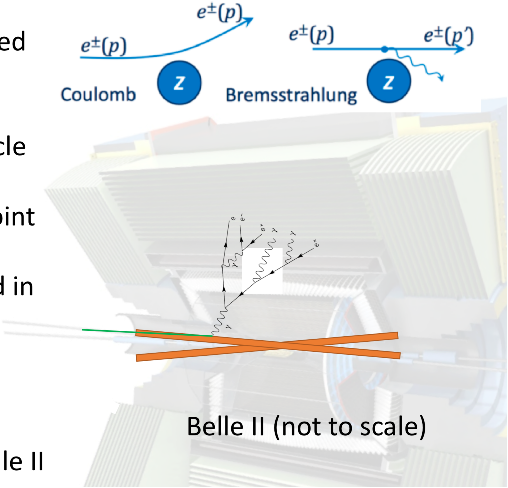
Single beam background example: beam-gas

Step 1: beam particle deflected from nominal orbit

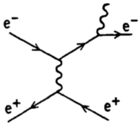
Step 2: deflected beam particle eventually hits beam pipe wall, near interaction point

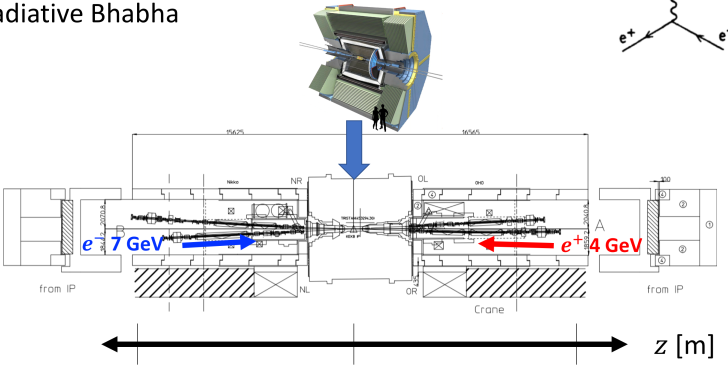
Step 3: secondaries produced in EM shower, including neutrons via giant dipole resonance

Step 4: secondaries reach Belle II

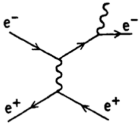


Step 1: Electrons and positrons interact via radiative Bhabha

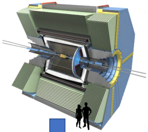


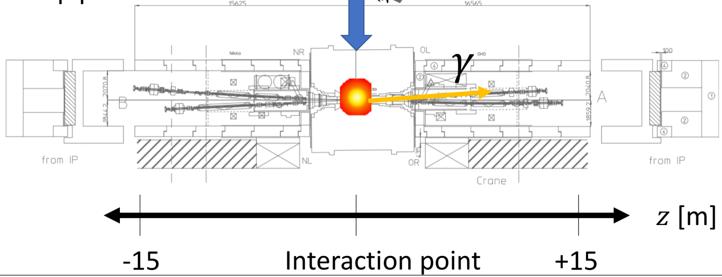


Step 1: Electrons and positrons interact via radiative Bhabha



Step 2: Photon produced travels *straight* through beam pipe

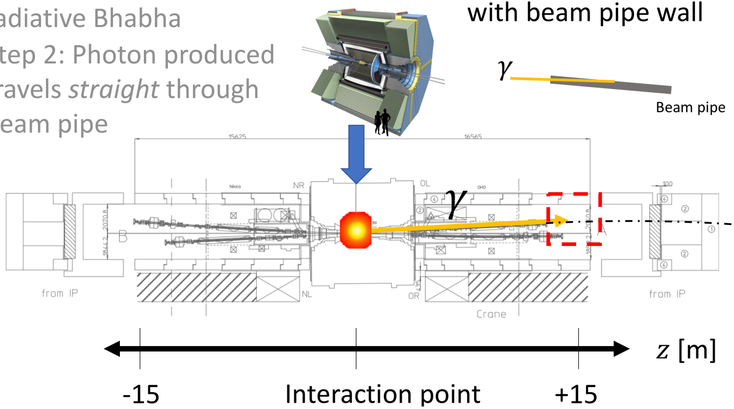




Step 1: Electrons and positrons interact via radiative Bhabha

Step 2: Photon produced travels *straight* through beam pipe

Step 3: As beam pipe bends, γ eventually collides with beam pipe wall



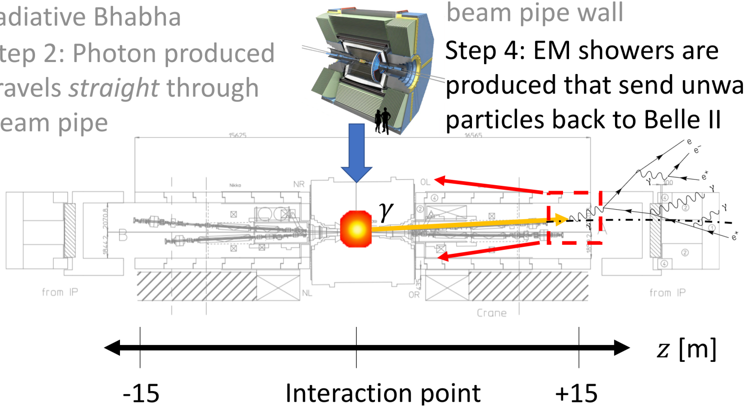
Collision background example: Radiative Bhabha

Step 1: Electrons and positrons interact via radiative Bhabha

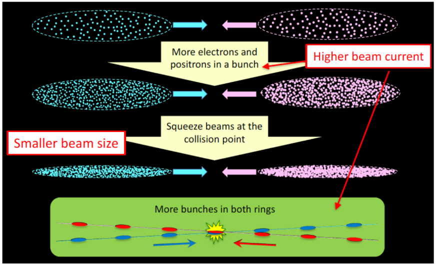
Step 2: Photon produced travels *straight* through beam pipe

Step 3: As beam pipe bends, γ collides with beam pipe wall

Step 4: EM showers are produced that send unwanted particles back to Belle II



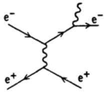
Increasing Luminosity ⟷ Elevated Backgrounds



Higher beam currents lead to increased beam-gas and Touschek scattering rates

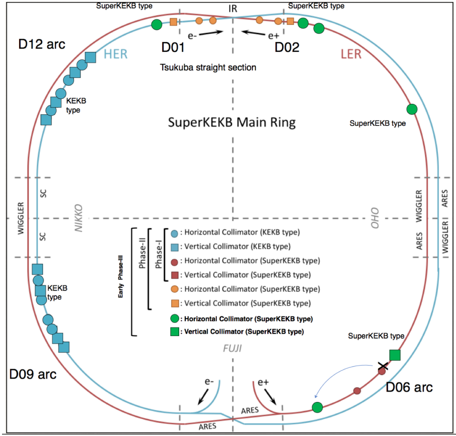
Smaller beam sizes lead to increased intra-bunch scattering (Touschek)

Increasing luminosity leads to increased rates of radiative Bhabha and two photon processes



Careful beam optics tuning and collimation are essential for background mitigation.

Beam optics tuning and collimation help to mitigate backgrounds!

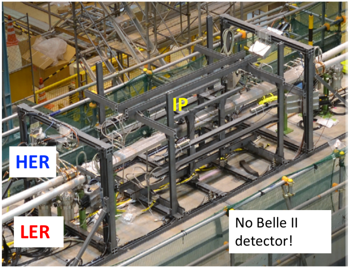


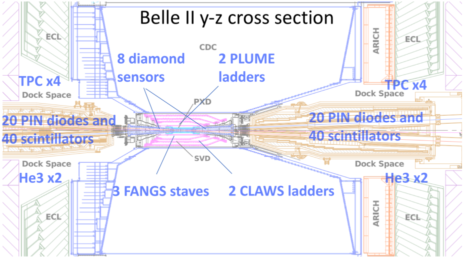
- Horizontal collimators on both inner and outer sides of the rings are effective for reducing Touschek backgrounds
  - KEKB only had horizontal collimators on inner side
- SuperKEKB Coulomb beam-gas levels are expected to be 100 that of KEKB
  - Vertical collimators are essential for reducing this background
- **Collimators must be optimized when beam optics are changed!**

Beam Commissioning and BEAST

Beam commissioning has been divided up into three phases.

Phase 1 (Feb 2016-June 2016) **Phase 2 (Feb 2018-July 2018)** **Phase 3 (March 2019-???)**



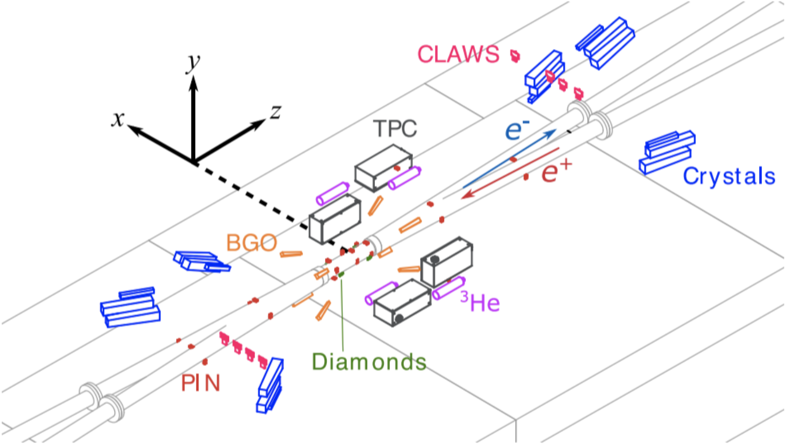


P1 Goals: First measurements of single beam backgrounds, search for SR, vacuum scrubbing

P2 Goals: Measure single beam and collision backgrounds and assess if background levels are safe for VXD operation

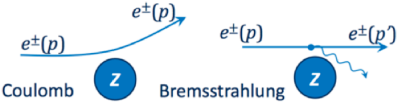
P3 Goals: Background remediation, collimator optimization, reach design luminosity!

Phases 1 and 2 had a dedicated suite of BEAST background detectors. A few remnants of BEAST remain in phase 3, but are (mostly) no longer contained within Belle


y
x
z
TPC
CLAWS
e-
e+
Crystals
BGO
3He
Diamonds
PIN

Phase 1 Results

Measuring background contributions: Beam-gas and Touschek

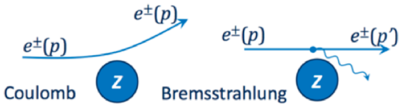


Beam-gas: Bremsstrahlung and Coulomb scattering of beam particles with gas atoms in the beam pipe

Question

Which *beam* quantities would you suspect beam-gas background rates to depend on?

Measuring background contributions: Beam-gas and Touschek



Beam-gas: Bremsstrahlung and Coulomb scattering of beam particles with gas atoms in the beam pipe

Question

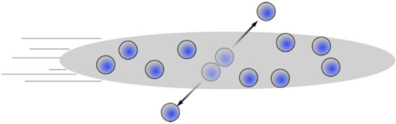
Which *beam* quantities would you suspect beam-gas background rates to depend on?

Single Event Level Contribution	Contribution around ring
Coulomb scattering, for instance $\propto q^2 Z_{eff}^2$	Depends on beam current and beam pressure $\propto IP$

Answer:

$$\text{Rate}_{bg} = B \cdot IPZ_{eff}^2.$$

Measuring background contributions: Beam-gas and Touschek



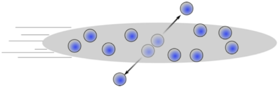
Question

Which *beam* quantities would you suspect Touschek background rates to depend on?

Touschek is a bit more complicated overall [1].

[1] See here for details

Measuring background contributions: Beam-gas and Touschek



Question

Which *beam* quantities would you suspect Touschek background rates to depend on?

Single Event Level Contribution	Contribution around ring
Scattering of particles within a bunch $\propto \frac{I_{bunch}}{\sigma_x \sigma_y \sigma_z}$	Depends on number of bunches and current within bunch $\propto N_b I_{bunch}$

Answer:

$$\text{Rate}_T = T \cdot \frac{N_b I_{\text{bunch}}^2}{\sigma_y} = T \cdot \frac{I^2}{\sigma_y N_b}.$$

Measuring background contributions: Beam-gas and Touschek

$$\text{Rate} = \text{Rate}_{\text{bg}} + \text{Rate}_{\text{T}}$$

- During single beam background studies the assumption is that contributions to background rates are exclusively due to beam-gas and Touschek effects

Combined Heuristic

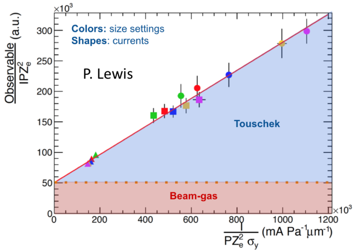
$$\text{Rate} = B \cdot IPZ_{eff}^{2} + T \cdot \frac{I^2}{\sigma_y N_b},$$

where B and T, respectively, are beam-gas and Touschek *sensitivity* parameters. B and T can be measured in both experiment and simulation!

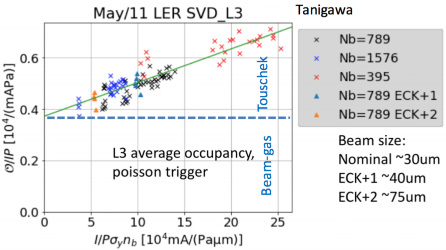
Divide Rates by IPZ^2_{eff} and plot the scaled rates vs $\frac{I}{P\sigma_y N_b Z^2_{eff}}$

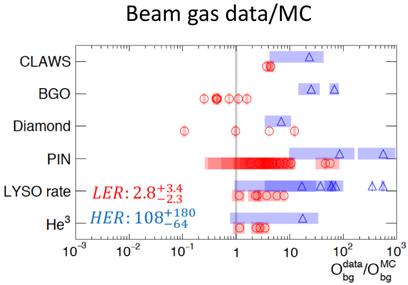
$$\frac{\text{Rate}}{IPZ^2_{eff}} = B + T \cdot \frac{I}{P\sigma_y N_b Z^2_{eff}}$$

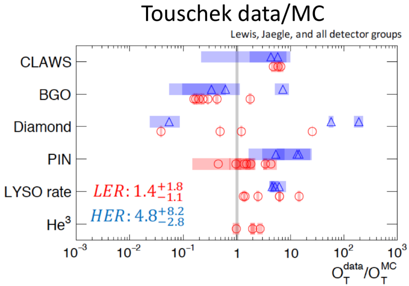
Phase 1 study varying beam size



Phase 3 study varying number of bunches and beam size





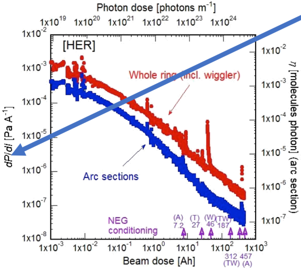


Observed rates exceeded predictions from simulation. HER beam-gas rates two orders of magnitude above prediction. Thermal neutrons are slightly elevated.

Phase 1 Results: Vacuum Scrubbing

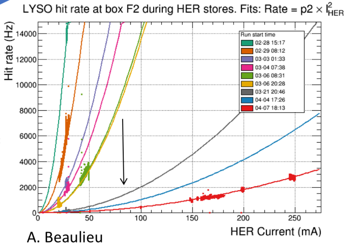
$$Rate_{BG} \propto IZ_e^2 P = IZ_e^2 \left(P_0 + I \cdot \frac{dP}{dI}\right)$$

HER integrated beam dose > 500 A-h



Phase 1

BEAST background in the HER vs time



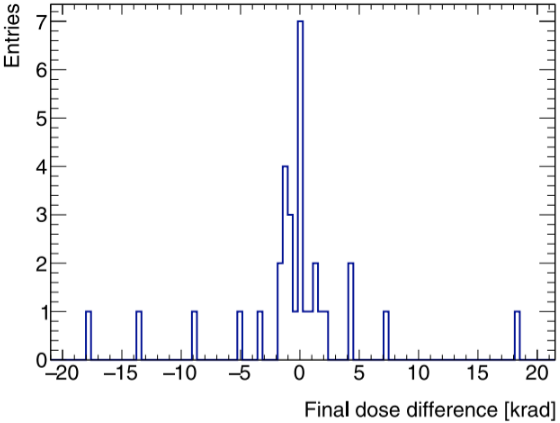
A. Beaulieu

Y. Suetsugu et al (SuperKEKB vacuum group)
N.B. This is a log-log scale plot

BEAST data shows the HER backgrounds decreasing as vacuum scrubbing proceeds.

Vacuum scrubbing reduces the dynamic pressure in the ring, causing a reduction in beam-gas backgrounds. HER is "better scrubbed" than LER (more on this when we talk about phase 3).

Phase 1 Results: Synchrotron



Differences between aluminum-shielded and gold-shielded PIN diode pairs used to set an upper limit on SR

Phase 1 Takeaways

Background Component	Simulation Method
Touschek	SAD (accelerator tracking code) generates and tracks scattered particles. If lost near IP: passed to GEANT4.
Beam-gas Coulomb	
Beam-gas Bremsstrahlung	
Radiative Bhabha	BBBrem/BHWide → GEANT4
QED 2-photon	Aafh → GEANT4
Synchrotron Radiation	SR generation in GEANT4
Injection BG	Injection particles provided by accelerator group→ SAD →GEANT4
Beam dust	-
Neutrons	All of above

Touschek slightly elevated. **100 fold excess of HER beam-gas in data.** Simulation suggests beam-gas won't dominate later on

Not measured in phase 1

Detailed measurements performed. These backgrounds don't look problematic…see paper!

Belle II detector	Quantity	Expected value	Upper limit value	Safety factor	Dominant process(es)
PXD	occupancy	1.1%	3%	3	two-photon, synchrotron radiation
CDC	wire hit rate	400 kHz	200 Hz	0.5	radiative Bhabha, two-photon
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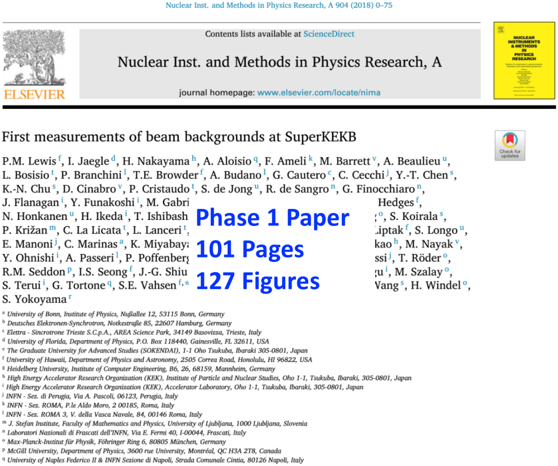
ECL	crystal dose rate	6 Gy/yr in BWD	10 Gy/yr	2	radiative Bhabha, two-photon

Conclusion

Single beam bkgs safe when extrapolated to full luminosity operation with full set of perfect collimators ⟶ safe to install Belle II



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First measurements of beam backgrounds at SuperKEKB

P.M. Lewis [f], I. Jaegle [d], H. Nakayama [h], A. Aloisio [q], F. Ameli [k], M. Barrett [v], A. Beaulieu [u], L. Bosisio [t], P. Branchini [l], T.E. Browder [f], A. Budano [l], G. Cautero [c], C. Cecchi [j], Y.-T. Chen [s], K.-N. Chu [s], D. Cinabro [v], P. Cristaudo [t], S. de Jong [u], R. de Sangro [n], G. Finocchiaro [n], J. Flanagan [i], Y. Funakoshi [i], M. Gabri … Hedges [f], N. Honkanen [u], H. Ikeda [i], T. Ishibash … [o], S. Koirala [s], P. Križan [m], C. La Licata [t], L. Lanceri [t], … iptak [f], S. Longo [u], E. Manoni [j], C. Marinas [a], K. Miyabaya… kao [h], M. Nayak [v], Y. Ohnishi [i], A. Passeri [l], P. Poffenberg… ssi [j], T. Röder [o], R.M. Seddon [p], I.S. Seong [f], J.-G. Shiu … u [i], M. Szalay [o], S. Terui [i], G. Tortone [q], S.E. Vahsen [f,*] … Vang [s], H. Windel [o], S. Yokoyama [r]

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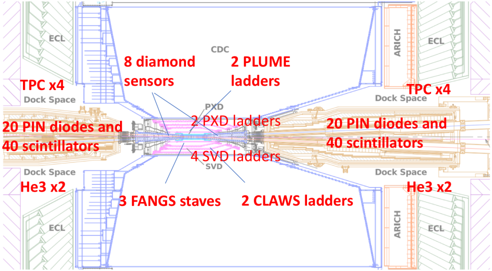
Lots of additional results found here!

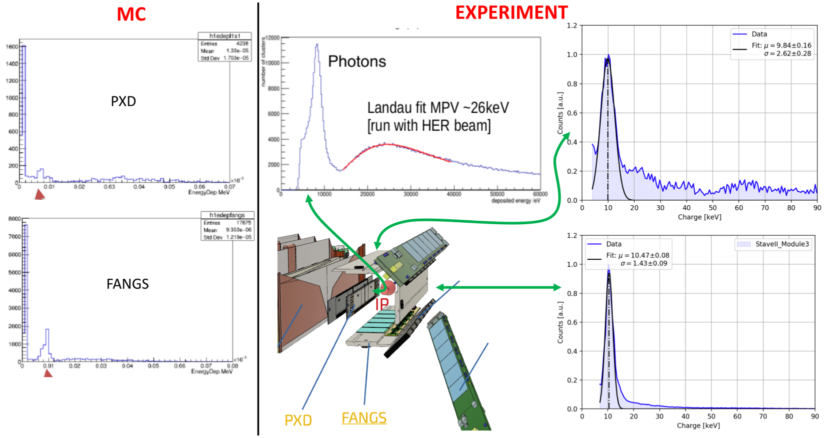
BEAST Phase 2 System



Rest of Belle II detector operational as well!

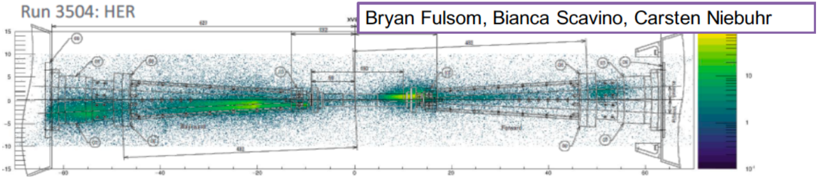
Detector	Unique Measurement
FANGS	Synchrotron spectrum
CLAWS	Injection Background
PLUME	Tracklets with pointing
Diamonds	Beam abort and ionizing dose
He3	Thermal neutrons
TPCs	Fast neutrons
PIN	Radiation dose around QCS -> Collimator adjustment
QCSS	X-ray and total loss distribution -> Collimator adjustment

Phase 2 first observation of SR



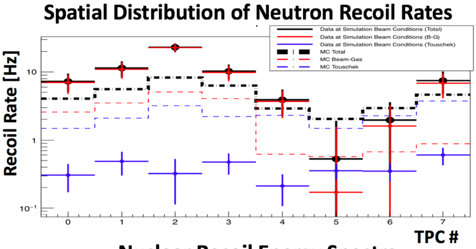
SR observed in PXD, FANGS, and Diamonds. This was *post*-dicted by simulation after removing a Geant4 low energy cut. Extrapolated to phase 3 conditions and deemed safe, however still more work is needed

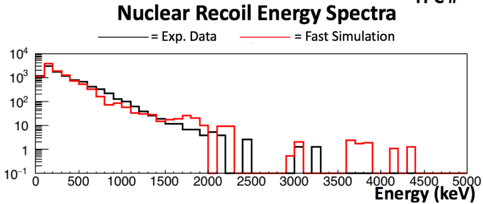
Phase 2 scraping backgrounds

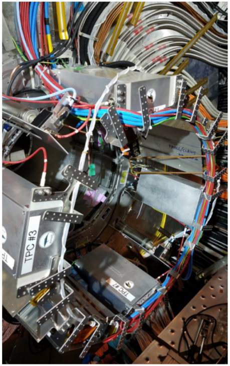


Large scraping backgrounds observed in HER. Optimizing collimators and beam orbit adjustments help reduce these (more in phase3 slides)

Phase 2 other results: Neutrons





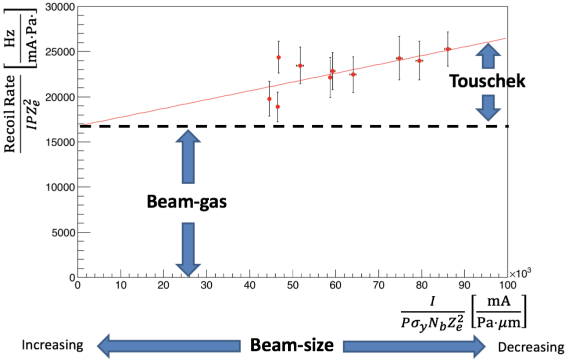


Neutrons critical for several Belle II detectors (see table, p. 27). Spatial distribution and energy spectra in good agreement with simulation.

Phase 2 Principal Studies

1. HER study June 11th, 2018
2. LER study June 12th, 2018
3. HER study July 16th, 2018
4. LER study July 16th, 2018

$$\frac{\text{Recoil Rate}}{IPZ_e^2} = B + T \cdot \frac{I}{PN_b Z_e^2 \sigma_y}$$

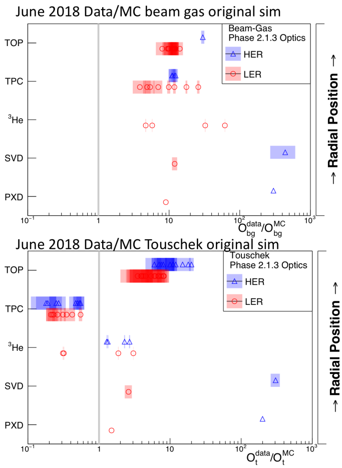


Simulation Improvements

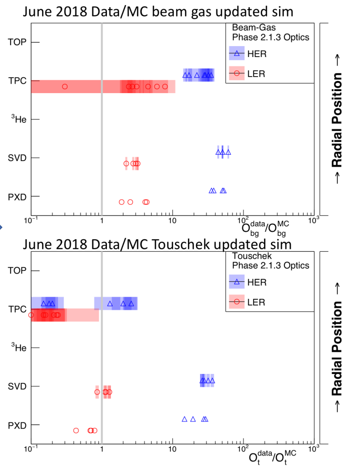
1. Improved Geant4 beam-pipe geometry inside QCS (a few improvements listed below)
   - Change beam pipe material from Tantalum to SUS316L
   - Modify beam pipe geometry to fit to the latest CAD drawing
   - Implement elliptical inner radius around QC1
2. **Include beam-gas bremsstrahlung in all samples**

Phase 1 and 2 background measurements provide feedback on simulation accuracy. Improved data/mc agreement is required for trustworthy extrapolations to design luminosity (see bottom of p.4)

Phase 2 summary results after simulation improvements



Credit: Zac Liptak



Simulation reliability improved with these changes. Possible HER simulation problem.

Status at the end of Phase 2

*Generally speaking, we want to **measure, fully understand, and mitigate** the following beam background components to safe levels*

Background Component	Simulation Method
Touschek Beam-gas Coulomb Beam-gas Bremsstrahlung	SAD (accelerator tracking code) generates and tracks scattered particles. If lost near IP: passed to GEANT4.
Radiative Bhabha	BBBrem/BHWide → GEANT4
QED 2-photon	Aafh → GEANT4
Synchrotron Radiation	SR generation in GEANT4
Injection BG	Injection particles provided by accelerator group→ SAD →GEANT4
Beam dust	-
Neutrons	All of above

Touschek, Beam-gas Coulomb, Beam-gas Bremsstrahlung: Measured in Phases 1,2.
Too high for early Phase 3
Large data/mc discrepancy
Mitigate with collimators based on simulation

Radiative Bhabha, QED 2-photon: Expected to dominate in Phase 3
Marginal observation in Phase 2
Lowest simulation uncertainty.

Synchrotron Radiation: measured in Phase 2. ~OK

Injection BG, Beam dust, Neutrons: measured in Phases 1,2
LER injection BG is ~ OK
mitigation is purely experimental
(injection tuning) not simulation based

Phase 2 Takeaways

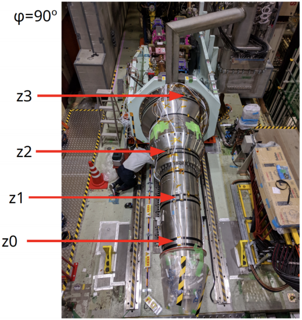
1. Based on simulation corrected by data/MC, beam backgrounds must be reduced by a factor of 2 in short term and 10 in long term
2. Simulation reliability improved between phase 2 and phase 3
3. Simulation predicted that new phase 3 collimators will provide a factor of 5 reduction in single beam backgrounds

Belle II detector	Quantity	Expected value	Upper limit value	Safety factor	Dominant process(es)
PXD	occupancy	1.1%	3%	3	two-photon, synchrotron radiation
CDC	wire hit rate	400 kHz	200 Hz	0.5	radiative Bhabha, two-photon
CDC	electr. neutron flux	2.5	1	0.3	radiative Bhabha, Touschek
CDC	electr. dose rate	250 Gy/yr	100	0.3	radiative Bhabha, two-photon
TOP	PMT hit rate	5–8 MHz	1 MHz	0.2	radiative Bhabha, two-photon
TOP	PCB neutron flux	0.35	0.5	3	radiative Bhabha, Touschek
ARICH	HAPD neutron flux	0.3	1.0	3	radiative Bhabha
ECL	crystal dose rate	6 Gy/yr in BWD	10 Gy/yr	2	radiative Bhabha, two-photon

Enter Phase 3: Beam background remediation

BEAST Detectors in Phase 3

- Most of "BEAST" retired
- A few dedicated BG detectors remain
  - Diamonds
  - CLAWS++ on QCS
  - PINs on QCS
  - He-3 in tunnel
  - TPCs in tunnel
- BEAST online DAQ for BG monitoring via EPICS will keep running

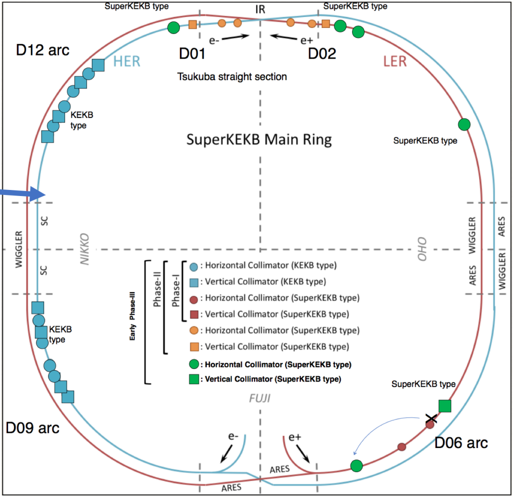


BEAST detectors are now primarily used to monitor conditions outside of the IR. Diamonds system now includes sensors around the beam pipe and throughout the QCS regions.

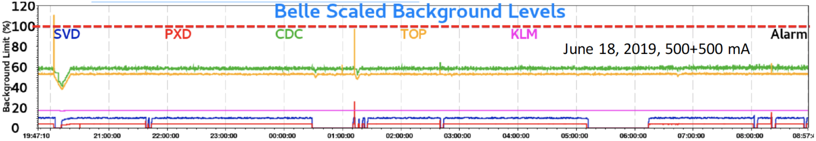
Rough background timeline

1. March-April 3rd:
   $\beta_y^* = \text{detuned} \rightarrow 8\text{mm} \rightarrow 6\text{mm} \rightarrow 4\text{mm} \rightarrow 3\text{mm}$ (stopped by fire accident)
2. April 25th-26th: Recover back to 3mm optics
3. May 9th and May 10th: Aggressive collimator studies (LER and HER, respectively)
   - reduced LER storage background by 20% and HER storage bkg by 50%
4. May 11th: LER Background Study
5. May 12th: HER Background Study
6. May 14th: LER Background Study with narrower collimators
7. June 9th: LER beam size study

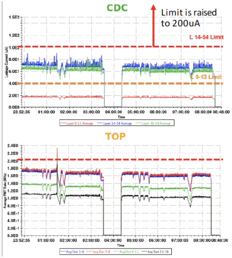
4 new LER collimators



New: Online Rate Monitoring (BCG)

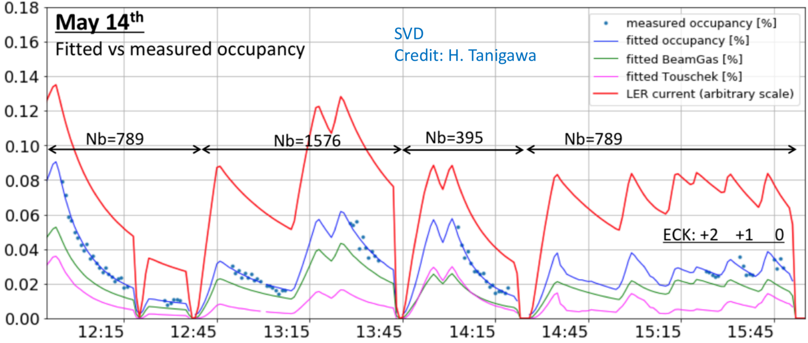


- Total (storage + injection) bkg compared against 100% "alarm limits"
- Clear how much headroom we have to raise beam currents
- Detect when bkg conditions (e.g., injection backgrounds) deteriorate → take immediate action
- Most detectors: safety factors order 5-10. Exceeding 100% implies soft performance degradation, but not physical danger
- CDC and TOP <= 2, currently limiting beam currents
- CDC: >100% can occur during injection spikes, causing HV trips, significant downtime
- TOP: >100% leads to unacceptable deterioration of PMT photocathode and efficiency loss before 2020



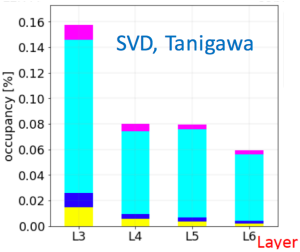
CDC and TOP were limiting max beam currents and hence, luminosity, in early phase 3.

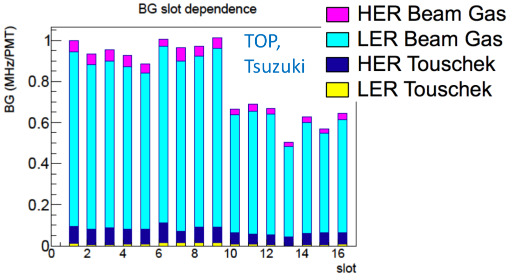
Global picture (3)



Combined Heuristic fits data well for SVD, TOP, and diamonds.

Global picture (4)





LER Beam-gas is dominant storage background in all detectors.

Global picture (5)

- Why is LER beam gas bkg so high?
- Because dynamic pressure is high in all of LER, especially in D02
- Possible options for reducing LER beam-gas
  - Modify IP beam steering
  - Add collimators
  - Modify optics to match existing collimators better
  - Reduce dynamic pressure
- Recommendation: pursue all four
- Dynamic pressure reduction via
  - Vacuum scrubbing with detuned beams, Belle II off
  - Beam pipe heating
  - Additional / improved pump

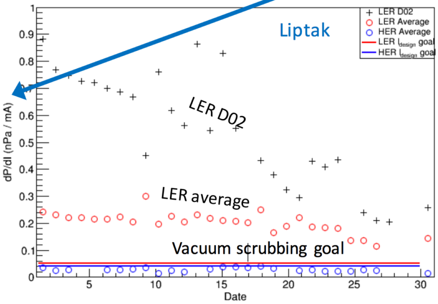
Note: may also improve Z_{eff}

Slide Credit: S. Vahsen

Touschek Beam-gas

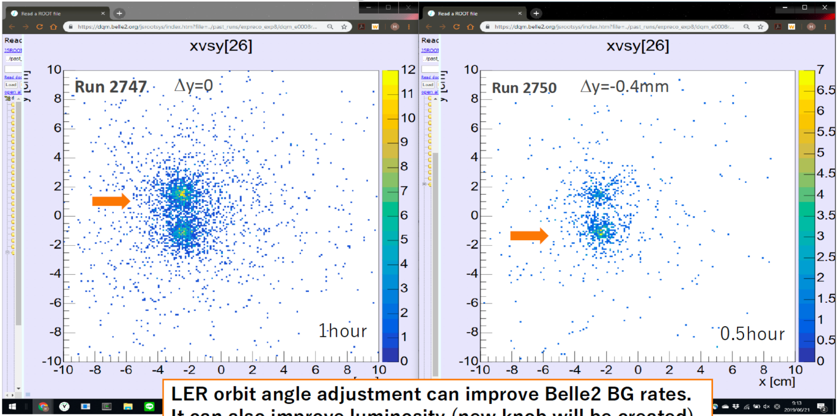
$$Rate = T \times \frac{I^2}{\sigma_y n_b} + \mathrm{B} \times \mathrm{IP}$$

$$Rate = T \times \frac{I^2}{\sigma_y n_b} + \mathrm{B}' Z_{eff}^2 \times \mathrm{I}(P_0 + \mathrm{I}\, dP/dI)$$



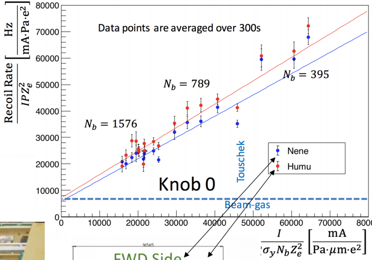
x-y view around z=+60cm before/after moving LER orbit downward

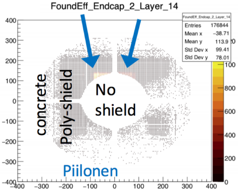
Slide Credit: Nakayama-san

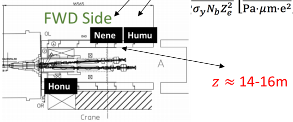


LER orbit angle adjustment can improve Belle2 BG rates.
It can also improve luminosity (new knob will be created).

- FWD KLM endcap sees severe neutron backgrounds in outermost layers
- May require additional shielding...







- Meanwhile TPCs (neutron detectors) observe large LER Touschek background

Extrapolating the Touschek rates seen in the TPCs provides an upper limit of $\mathcal{O}(10^{11})$ neutrons/year/cm^2 (above threshold of 65 keV) toward the FWD KLM endcap.

Data vs. MC

- bkg simulation perfect ⇔ data/mc = 1
- Typically, data/mc >1. We use data/mc as correction factor for simulation, for instance to estimate backgrounds at design luminosity
- Three groups have results
  - Diamonds: observe data/MC ~ 1
  - SVD/TOP: shown to right

From beam lifetime

Tanigawa, Tsuzuki

Data/MC in SVD,TOP

	total loss	SVD L3	(SVD L4-6)	TOP
LER beam-gas	**1.9-4.1**	**12-13**	(5.4-6.9)	**1.5**
LER Touschek	**1.3-1.8**	**1.0-1.1**	(0.87-1.1)	**0.16**
HER beam-gas	**10**	**16**	(19-27)	**7.7**
HER Touschek	**3**	**1600**	(760-900)	**510**

- Total loss rate data/MC <=10. SAD simulation *reasonably* accurate.
- LER Touschek: good.
- HER Touschek: suspect simulation problem (MC rate is toooo small).
- Beam gas: data/mc high even for total loss rate. Note that dynamic pressure is already accounted for in these ratios and does not include measured Z_{eff}. Need to investigate beam-gas normalization. Gas injection study?

Loss rates indicate that HER SAD simulation is fine, yet SVD and TOP both see large HER excesses in data indicating a potential problem in Geant4 HER simulation.

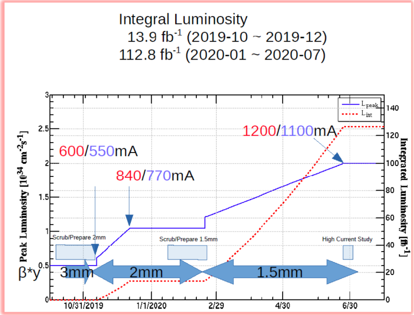
recently updated at 33rd B2GM

Credit: Nakayama-san

ASSUMPTIONS

(risky ⟷ realistic)

- Integral Efficiency (~65%)
  - Integration Time Efficiency ~90%
    - 8H maintenance & 4H startup / 2weeks
    - 12H linac study / week
  - SuperKEKB Availability 85%
  - Belle2 Availability 85%
    - Availability @ 2019-06-02 is 89.6%.
- Luminosity Performance
  - Baseline: 0.5 x 10^{34} @ 600/550mA(n_b=1576, β*y=3mm)
  - No beam-beam parameter improvement
  - β*y staging: 2mm @ 2019-11 → 1.5mm @ 2020-02
  - Improvement by squeezing β*y: 1/√β*y → 1/β*y during operation period
    - Assuming detector background independence with β*y.
  - Beam current limit improvement: x√2 @ 2019-12-12 → x2 @ 2020-06-24
    - Assuming factor 2 improvement of CDC current limit until next summer.
    - Assuming no current limit for protecting detector.
- Machine Study
  - ***No future beam development time is counted.***



In this slide, we assume
2019 winter: 0.84/0.77A, beta_y*=2.0mm, L=1.0*10^34
2020 summer: 1.20/1.10A, beta_y*=1.5mm, L=2.0*10^34

Extrapolations through summer 2020

This extrapolation based on the scaling the latest BG measurement using machine parameters.
Another approach is being prepared, to scale the BG simulation with future optics, using latest Data/MC ratio.

In this slide, we assume
2019 winter: 0.84/0.77A, beta_y*=2.0mm, L=1.0*10^34
2020 summer: 1.20/1.10A, beta_y*=1.5mm, L=2.0*10^34

LER Touschek	2019 winter	2020 summer
Beam current (I^2)	x2(0.84A)	x4(1.2A)
Collimator reduction factor	x1	x1
Total	**x2**	**x4**

LER Beam-gas	2019 winter	2020 summer
Beam current(I^2)	x2(0.84A)	x4(1.2A)
1/beta_y*	x1.5	x2
Vacuum scrubbing (dP/dI) *	x2/3	x1/2
Collimator reduction factor **	x1	x1
Total	**x2**	**x4**

* My personal guess
** "x1" might be optimistic. Vertical collimation at squeezed optics will be more difficult

- HER Touschek, HER Beam-gas are assumed to be much smaller than LER also in 2020.
- Lumi-BG is not yet measured in Phase3. We expect x2(x4) lumi-BG in 2019(2020) than now, which we assume to be smaller than LER BG.
- Based on these assumptions, LER beam-gas will be still a dominant background source in 2020

⚠ Simply increasing beam currents will lead to intolerable BG, even with vacuum scrubbing

➡
- **New LER collimator(s)**
- **Optics adjustments**
- **Intensive vacuum scrubbing**

Concluding remarks

- Beam backgrounds are a critical issue at Belle II
- The Belle II beam background group has performed extensive measurements of single-beam backgrounds, which are the most uncertain
- Currently, LER beam-gas backgrounds in CDC and TOP limit the maximum beam currents, and hence the luminosity

Background remediation is ongoing work that requires careful coordination between accelerator and detector experts to ensure the safety and longevity of Belle II detectors

Useful Resources

Selected Papers

1. BEAST Phase 1 Paper: 101 page tome containing thorough descriptions and analyses of phase 1 backgrounds.
2. Shameless plug for the TPC development paper

For online background monitoring and online analysis

1. Git repository with CSS OPI files that you can clone. (Requires DESY account and KEK VPN. There's a bit of a learning curve.)
2. List of PVs currently being archived.

For offline background analysis

1. Most recent background Monte Carlo campaigns
2. Phase3 summary data prepared by Zac Liptak
3. Alternative phase 3 summary data prepared by Luka can be found at `/home/belle/luka/public/background` on KEKCC

Backup

Summary

- Status
  - Horizontal collimators are added after Phase2, and they suppress Touschek bkg
  - LER beam gas bkg now dominates (>= 70% of total background)
  - CDC and TOP limit max beam currents
  - Injection bkg bursts are a persistent problem, causing CDC HV trips
  - QCS and (we think) beam-dust related background bursts endanger detectors
- Recommendations
  - LER beam gas reduction: beam steering study, optics modification, new vertical collimators, intense LER vacuum scrubbing
  - Improve HER simulation for improved long-term bkg prognosis
  - Check beam-gas normalization with gas injection study
  - Improve injection further, especially for HER
  - Improved / faster / redundant abort system (See Ikeda-san's talk later)

Minor/Major troubles

Minor

Trouble	Impact on operation	Frequency
High injection loss on collimators or bellows diamonds	Injection stops for a minute	few per hour
Recoverable CDC HV trip	Injection stops for few minute	1~2 per shift
Beam aborts due to large injection loss on collimators	Takes ~20min to accumulate the beam again	1~2 per day
Irrecoverable CDC HV trip	Injection stops for ~30 minutes	several times during phase3
QCS quenches	Takes few hours to resume QCS operation	several times during phase3
Severe QCS quenches	Damage on collimators or Belle2 sensors	several times during phase3

Major

Beta Squeezing

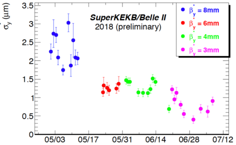
Slide Credit: Morita-san

Phase	βx* [mm]		By* [mm]		State	L_{peak} cm^{-2}s^{-1}	I_{LER}/I_{HER}, nb [mA]	Start
	LER	HER	LER	HER				
2.0	384	400	48.6	81	Detuned for Beam Capture			
2.1.0	200		8		Collision	9.3 x 10^{32}	250/220, 600	04/16
2.1.1	200		6		Collision	13.7 x 10^{32}	340/285, 789	05/22
2.1.2	200		4		Collision	13.6 x 10^{32}	340/285, 789	05/28
2.1.3	200		4	3	Collision	13.2 x 10^{32}	240/285, 789	06/08
2.1.4	200		3		Collision	10.5 x 10^{32}	320/265, 789	06/11
2.1.5	100		4		Collision	10.9 x 10^{32}	340/285, 789	06/12
2.1.6	200	100	4		Collision	19.0 x 10^{32}	340/285, 789	06/13
2.1.7	200	100	3		Collision	26.6 x 10^{32}	340/285, 789	06/20
2.2.0	200		2		Optics Correction			06/07
2.3.0	100		2		Not achieved			

Important machine parameter β_y^*!

$$\sigma_y^* = \sqrt{\epsilon_y \beta_y^*}$$

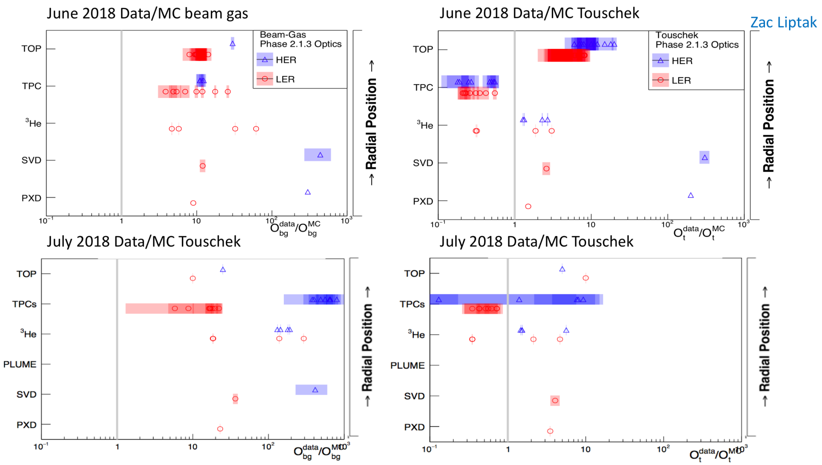
Vertical beam size!



β_y^* = 2mm in most recent runs and background levels were too high for Belle data taking! Ultimately, the goal is to push β_y^* to 0.27mm in LER and 0.30mm in HER so we've got a long way to go!

Phase 2 initial summary results

Zac Liptak



Overall, LER background rates dominate, but HER data rates $\mathcal{O}(1000)$ times higher than predicted?!

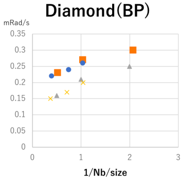
LER single-beam study on May 11th & 14th

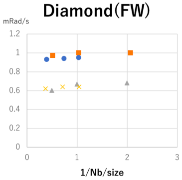
Touschek vs. Beam-gas

$$\text{Obs} = BIPZ_e^2 + T\frac{I^2}{\sigma_y N_b}$$

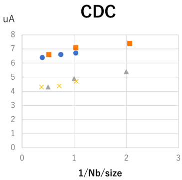
LER
I=150mA

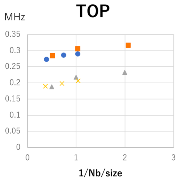
Nbunch scan (May 11)
Size scan (May 11)
Nbunch scan (May 14, narrow collimators)
Size scan (May 14, narrow collimators)

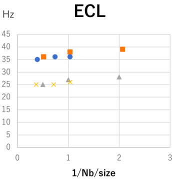




Preliminary
Credit: H. Nakayama







Slopes are almost flat
→ LER Beam gas
>> LER Touschek

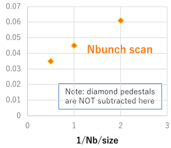
HER single-beam study on May 12th

Touschek vs. Beam-gas

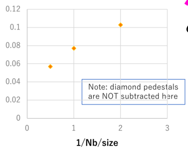
$$\text{Obs} = BIPZ_e^2 + T\frac{I^2}{\sigma_y N_b}$$

HER
I=145mA

Diamond(BP)

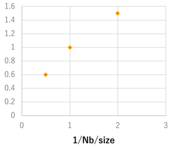


Diamond(BW)

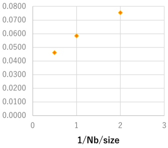


Preliminary
Credit: H. Nakayama

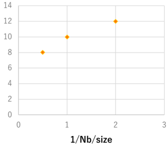
CDC



TOP



ECL



HER BG is much smaller than LER BG
(HER Touschek and Beam-gas are comparable)

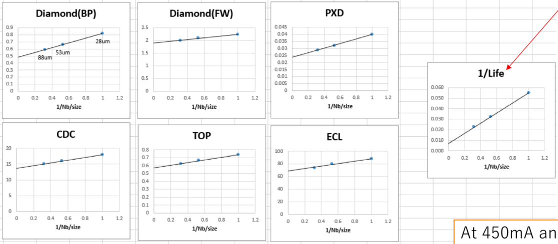
LER single-beam study on June 9th

Belle2 rates vs. beam size

$$\text{Obs} = BIPZ_e^2 + T\frac{I^2}{\sigma_y N_b}$$

$$\text{Loss Rate} \propto \frac{1}{\tau}$$

LER single-beam study on June 9th, I=450mA



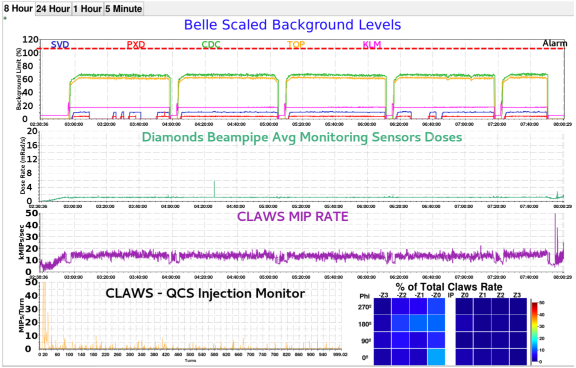
LER, 450mA	Dia_BP	Dia_FW	PXD	CDC	TOP	ECL	1/life
slope	0.34	0.34	0.02	4.37	0.17	19.93	0.047874
Beam-gas(intercept)	0.48	1.90	0.02	13.64	0.57	68.40	0.007279
Touschek@100um	0.10	0.10	0.00	1.27	0.05	5.78	0.013883
T/(T+B)	17%	5%	17%	9%	8%	8%	66%

Preliminary

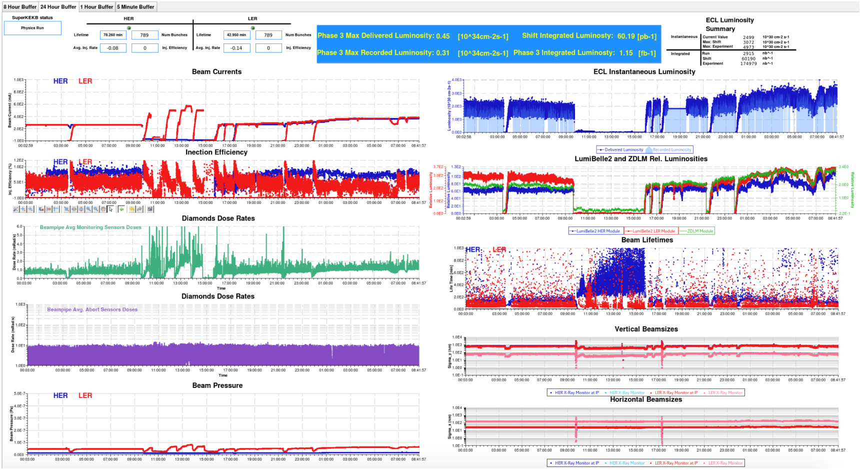
Credit: H. Nakayama

At 450mA and 100um (nominal beam size during collision), LER Touschek is <10% in outer detectors and QCS_FW diamonds, ~20% in PXD and BP diamonds

- Set of CSS displays that display live 1-second summary accelerator and detector data
- Displays EPICs process variables which are archived and can be accessed for real time "online" analysis
- Can be accessed on your local machine (links for instructions in the *Useful Resources* slide)

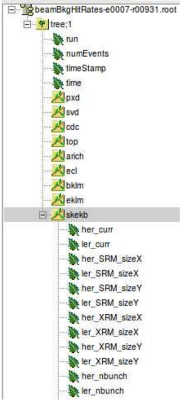


Live Online Monitoring

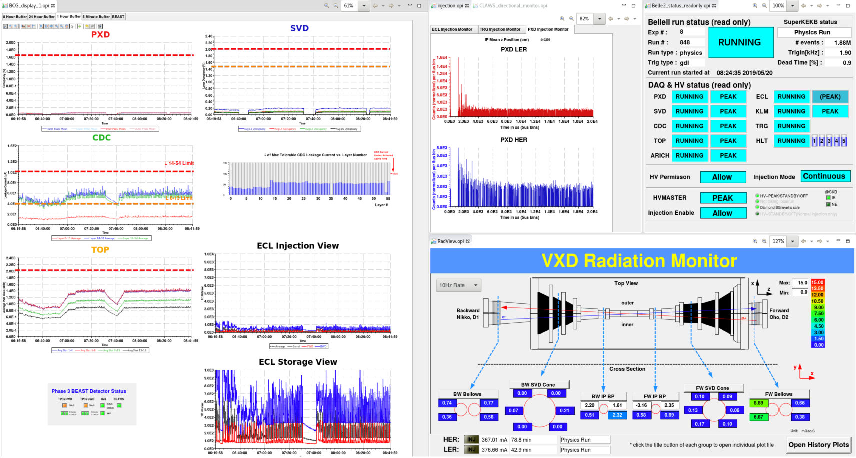


Offline global data

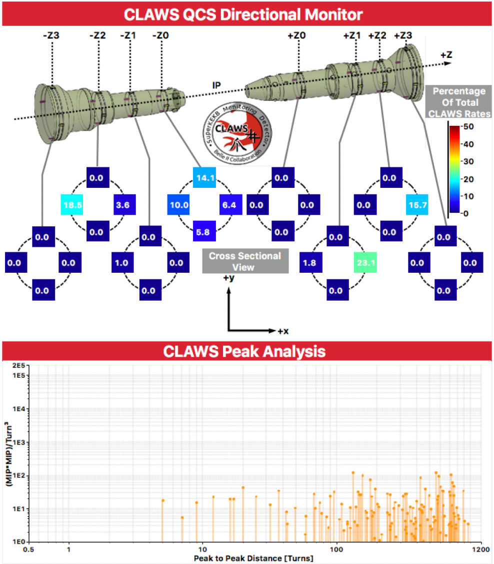
- Basf2 module now exists for producing Belle II detector summary ntuples (thanks to M. Staric and J. Bennett)
  - Modules and classes found: `background/modules /BeamBkgHitRateMonitor/`
  - Steering file: `background/tools/beamBkgHitRates.py`
- Belle II summary data is then merged with SuperKEKB data into a “global” ntuple that can be readily used for analysis



Live Online Monitoring

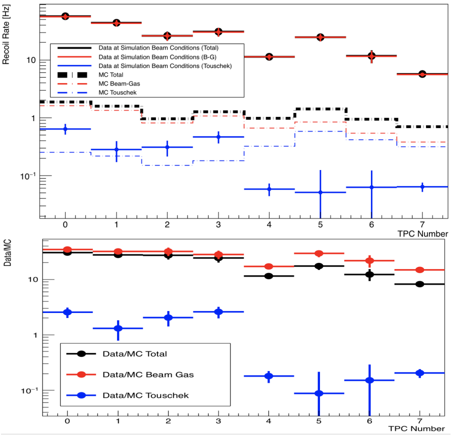


Live Online Monitoring

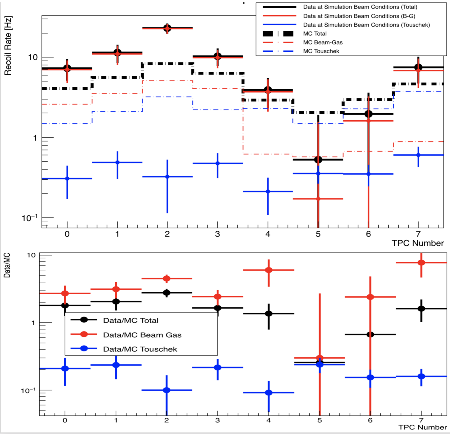


Recoil Rate Results June 2018 Studies

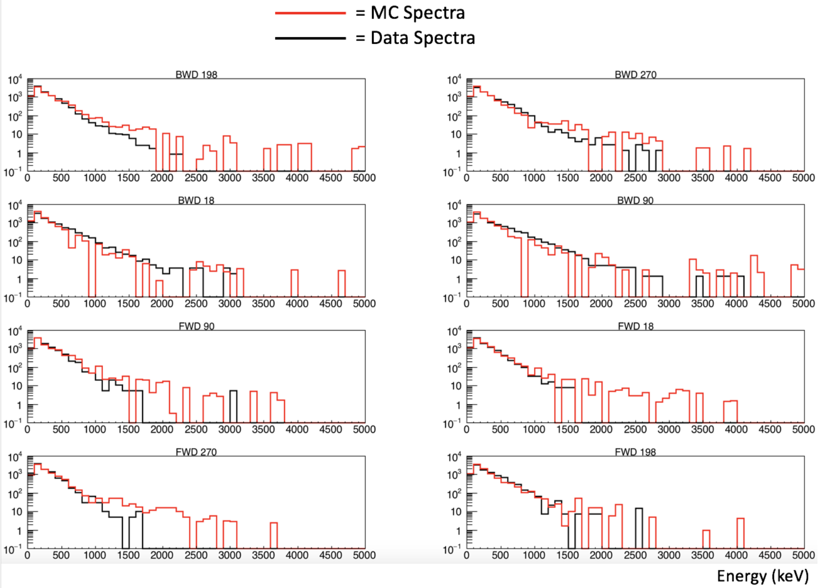
HER



LER



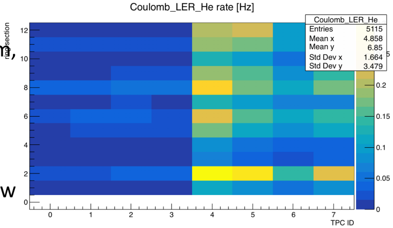
Electron Ring Recoil Spectra June 2018 Studies



Pressure Reweighting Motivation

- We've been naively using the average pressure around the ring for background analyses
- Since pressure around the ring is not uniform, it would be better to use something that's more representative of exp. conditions
- **Litmus test:**

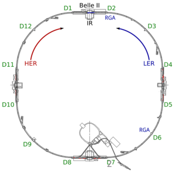
1. Use MC that gives rate contributions for each of the 12 ring sections → won't follow the combined heuristic using average pressure
2. Use these rates to come up with a weighted pressure (one for each TPC in LER and one for each TPC in HER)
3. Show that using this weighted pressure "reconstructs" the combined heuristic



$$\widehat{P(t)} = \sum_{i=1}^{12} w_i P_i(t)\,;$$

where $w_i \equiv \frac{n_i}{\sum n_i}$

Reweighted Pressure



- To test this new reweighted pressure with the combined Heuristic, we come up with ”pseudo”-rates, $R(t)$, where beam gas is scaled to pressure conditions in data:

$$R(t) \equiv \sum_{i=0}^{12} n_{i,BG}^{MC} \left(\frac{P_i^{data}(t)}{P^{MC}} \right) + \sum_{i=0}^{12} n_{i,T}^{MC}$$

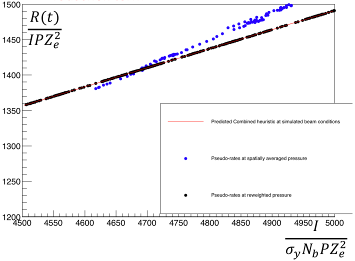
Pseudo-rates

Beam-gas term

Touschek term

Note: $P_i^{data}(t)$ is the spatially averaged CCG pressure reading in region D-i; $i \in [1,12]$

Compare $\frac{R(t)}{I_{MC}PZ_e^2} = B + T \cdot \frac{I_{MC}}{PZ_e^2 \sigma_y N_b}$ for $P(t) = \overline{P(t)}$ and $\widehat{P(t)} = \sum_{i=1}^{12} w_i P_i\,(t)$



Pressure Reweighting Remarks

- Pressure reweighting using $\widehat{P(t)} = \sum_{i=1}^{12} w_i P_i\,(t)$, where the P_i's are the average CCG pressure reading for the ith ring section in data yields only marginal differences in predicted B and T
- Using the average CCG pressure reading in each ring section is a step better than using the average CCG pressure reading over the entire ring, but it still may be overly simplified
- **We have not included any dynamic pressure corrections**
  - From p. 49 of phase 1 paper: $P_{beam} = 3 \cdot P_{CCG} - 2 \cdot P_{base}$
  - In phase 1 LER, $P_{CCG} \gg P_{base}$ so we're overestimating B by nearly a factor of 3!
  - **We must include dynamic pressure corrections as they are more representative of experimental conditions and may also improve agreement in data/MC**