Background during phase 3 and projections to full luminosity and beyond

Belle II VXD open workshop, 8-11 July 2019

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Belle II

SuperKEKB Commissioning Detector BEAST II 獣 Belle II Collaboration

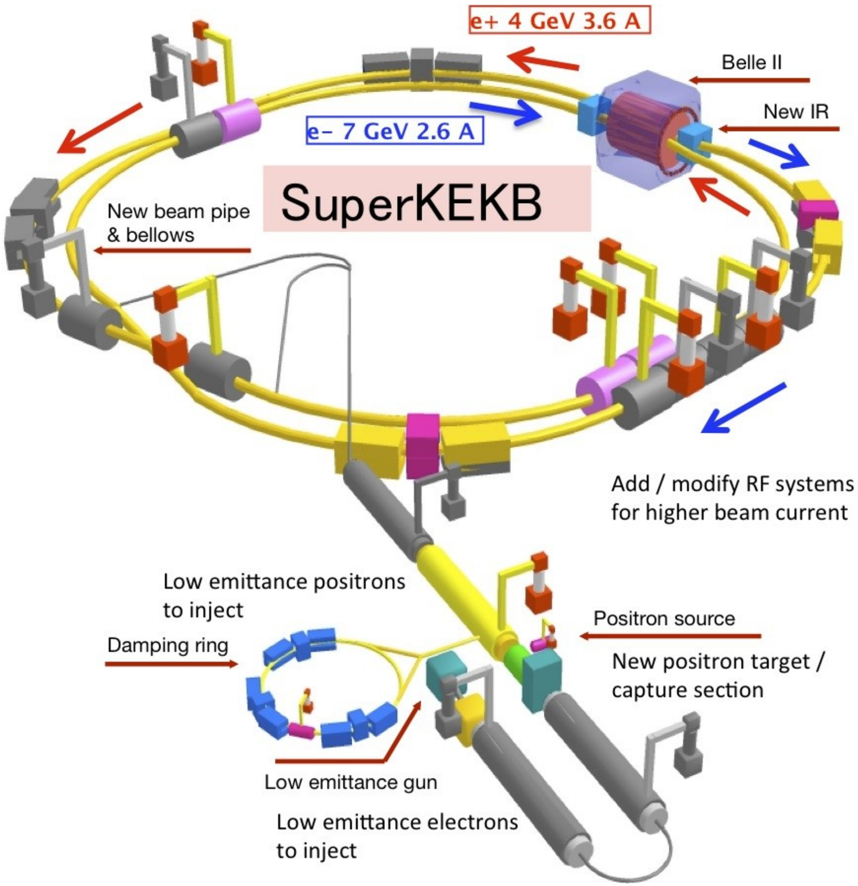
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Outline

- This talk concentrates on the sources of background, the tools to control it and the extrapolation to full phase 3 luminosity (and beyond).
- The PXD and SVD talks (on top of the running experience) concentrate on the limits of the detectors as the background increases.

- Results shown here draw upon plenary presentations from S. Vahsen and H. Nakayama shown at last Belle II collaboration meeting.

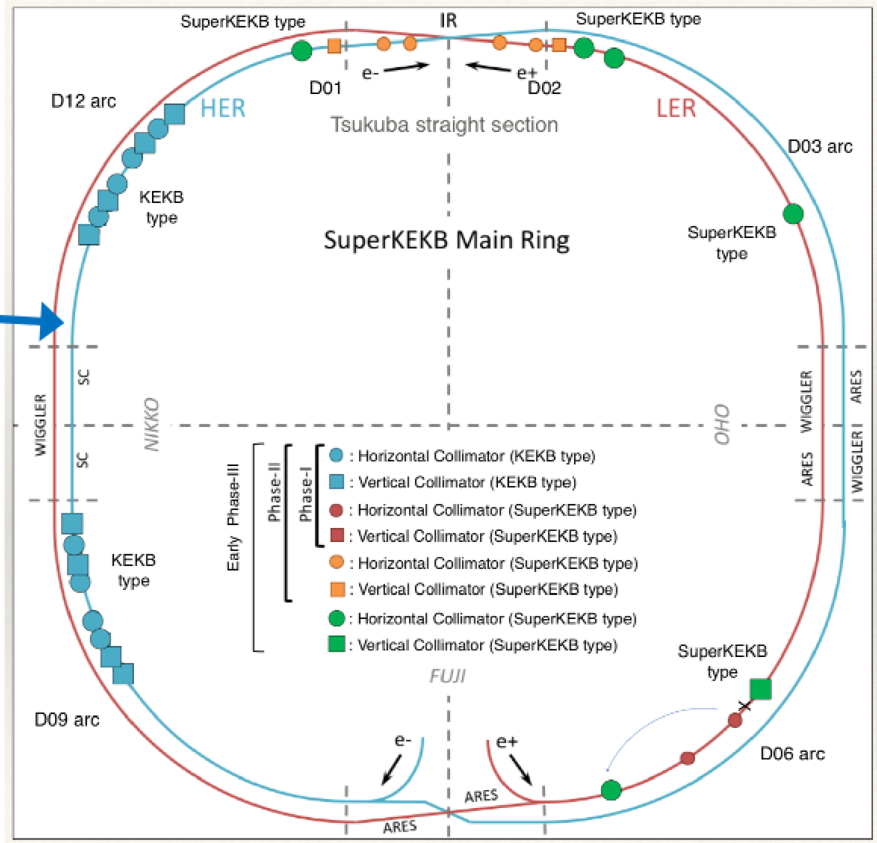
SuperKEKB @ Tsukuba, Japan



- New Super Flavor factory in Tsukuba, Japan
- Asymmetric e+e- collider @ E_{cm} = 10.58GeV
- Design Peak luminosity $L = 8 \times 10^{35}$ cm^{-2} s^{-1}
- Commissioning in multiple phases
- Phase 1: Feb. - June 2016
- Phase 2: Feb. - July 2018
- Early Phase 3: March – June 2019
- Full Phase 3: reach design lumi (202X)

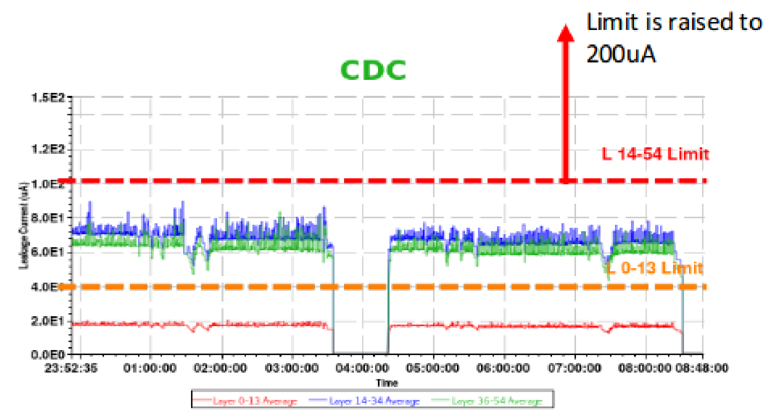
Beam backgrounds: developments

- Improved BG monitoring
  - Online: Belle II rates
  - Online: Vertex distributions
  - Offline: Automated summary files
- Four new LER collimators
- Established continuous injection in both rings
- BG mitigation & study May 9-14 (Nakayama et al.)
- Beam currents increased up to 600-700 mA



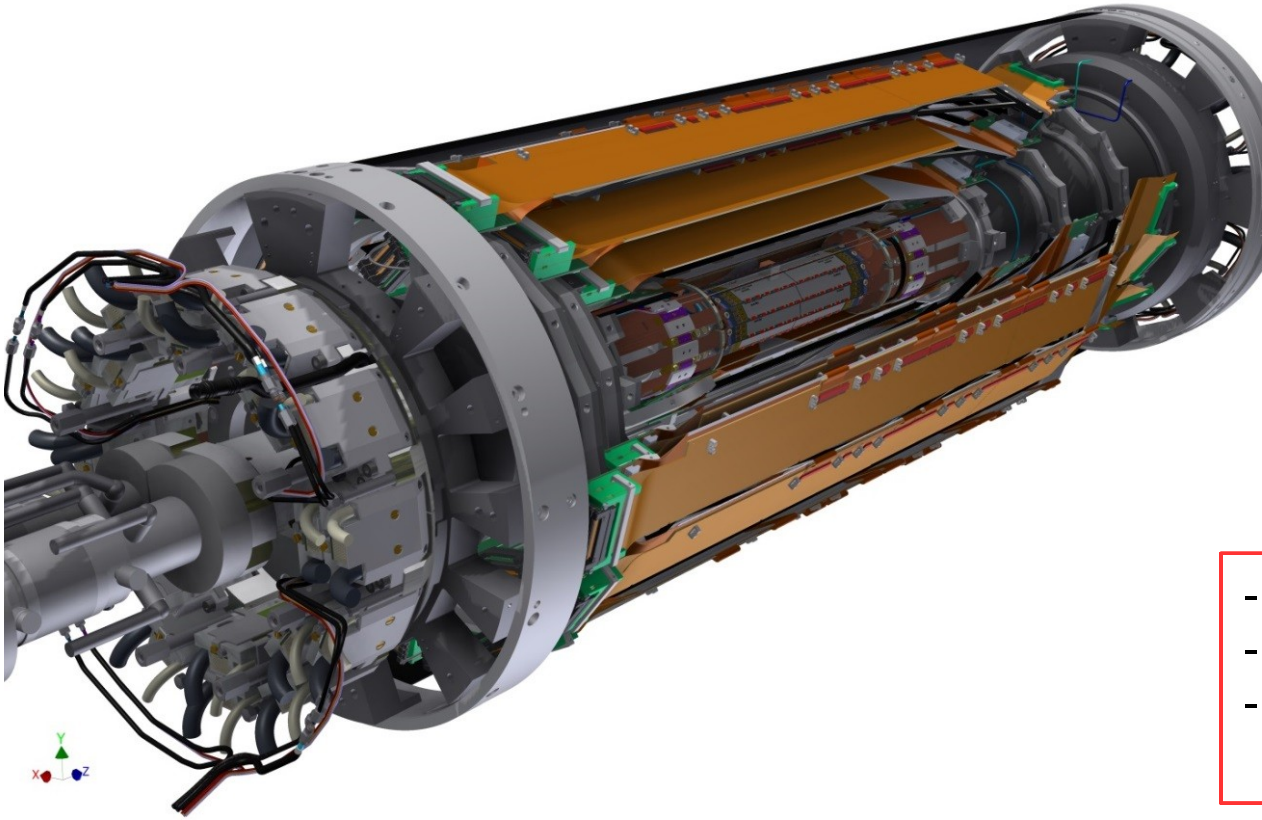
Beam background "big picture" (as of mid June)

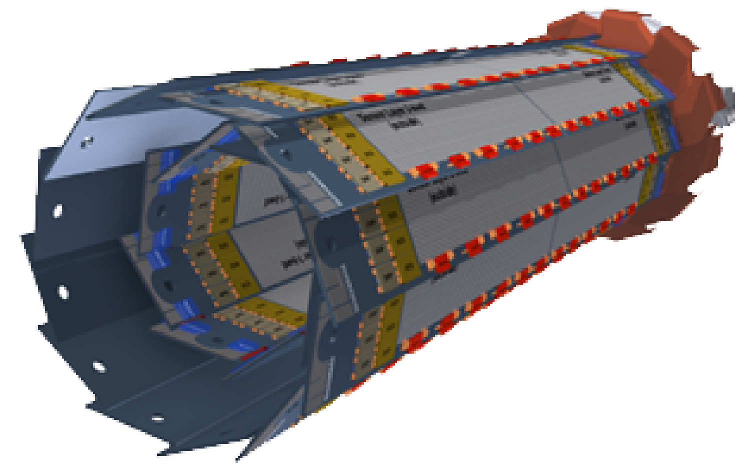
- Machine parameters
  - beta_y*=3mm, 1576bunch, 650+650mA, L~0.5*10^{34}
- Our bottle-neck is CDC (and TOP)
  - CDC HV trips with large BG (storage + injection)
  - TOP PMT photocathode lifetime get shorter
- Dominant source: LER beam-gas BG
  - Touschek BG is small enough, thanks to newly-installed horizontal collimators after phase2
- <u>Keep good injection condition</u> is very important
  - To avoid CDC HV trip
  - To avoid loss monitor aborts at collimators (and allow us to close the collimators even narrower)



After moving to beta_y*=2mm, Belle2 was turned ON only at ~300mA.
When L~1.2*10^{34} is achieved with 800mA, BG was x3 higher to turn on Belle2.
Note that we didn't have enough time for collimator optimization with 2mm optics

The Belle II vertex detector





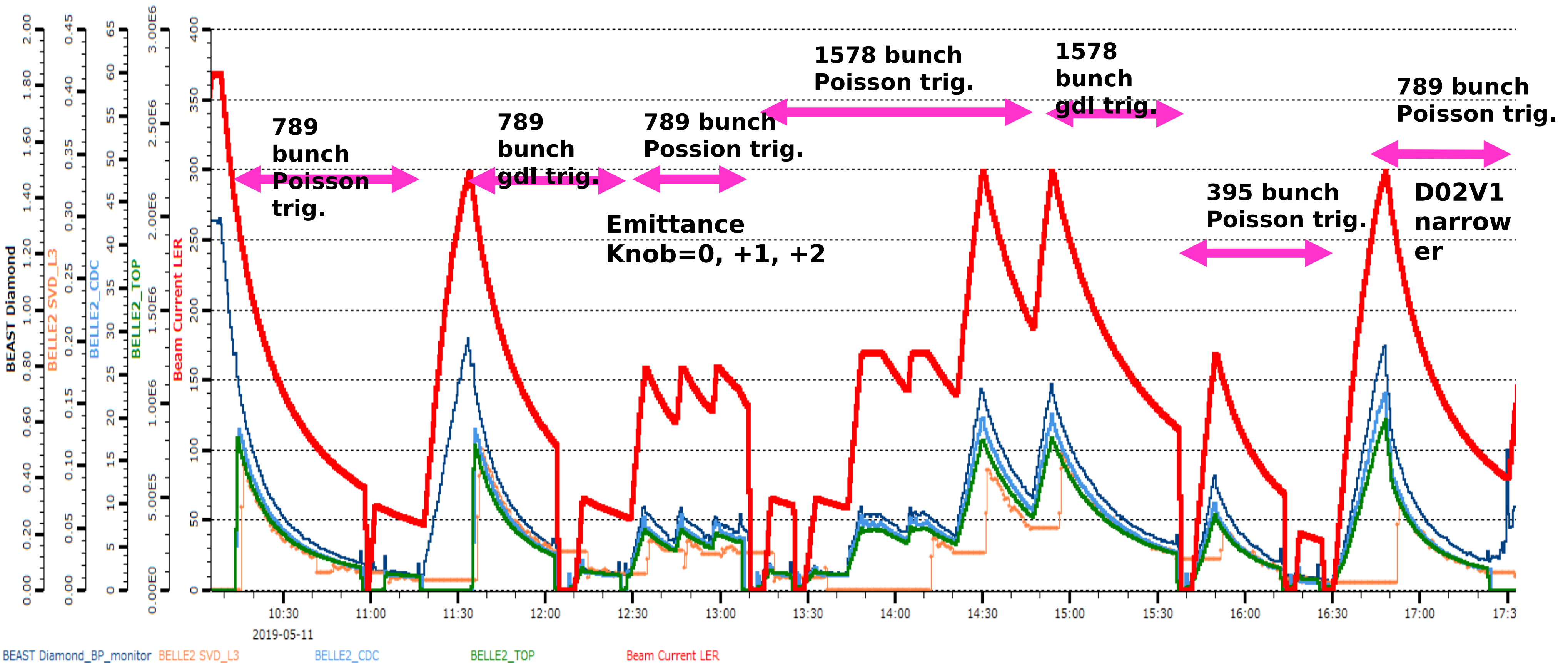
- 3% hit occupancy limit on sensor
- Trigger rate of up to 30kHz
- Sensor and ASICSs rad. hard for 20Mrad in ten year operations

- Sensors and chips are rad. hard for 10Mrad in 10 years of operation
- Optimal tracking performance for SVD for occupancy <2-3%.

Background sources

Touschek scattering: single Coulomb scattering event. Phase 1: measured, consistent with simulation.	$R_{Tou} \propto \frac{1}{\sigma} E^3 n_b I_{beam}^2$
Beam-gas scattering: Coulomb scattering with residual gas atoms and bremsstrahlung. Phase 1: measured, more than predicted in simulation but	$R_{bg} \propto IP$
Synchrotron radiation: photon emission from beam particles. Phase 1: not measured.	$R_{sr} \propto E^2 B^2$
Radiative Bhabha: neutron production from emitted photons; particle loss because of too much ΔE wrt nominal energy. Phase 1: not measured.	$R_{RB} \propto L$
Two photons process: low momentum e^+e^- pairs hitting VXD. Phase 1: not measured.	$R_{tp} \propto L$
Injection background: injected bunch is perturbed, resulting in particle losses. Phase 1: measured (time structure and energy of radiation produced)	

LER single-beam study on May 11th



- Study hit occupancy in PXD/SVD from stored positron beam only

- Random triggered, varying fill pattern, varying vertical beam size

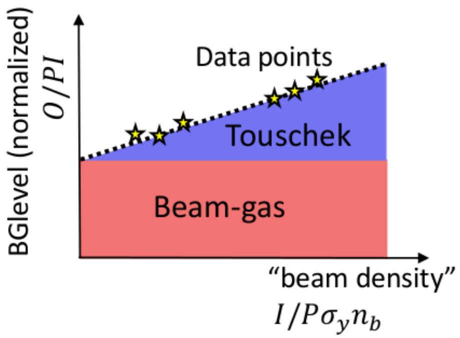
Fitting single beam storage background

Heuristic model for Touschek and Beam-gas:

$$Occupancy = B \cdot PI + T \cdot \frac{I^2}{\sigma_y n_b}$$

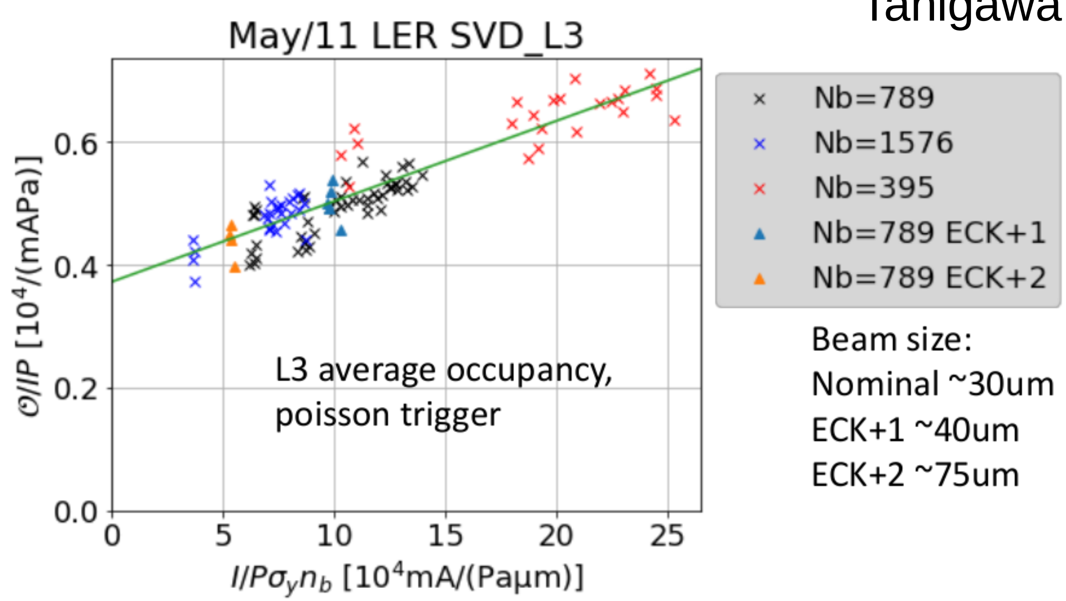
$$\frac{O}{PI} = B + T \cdot \frac{I}{P \sigma_y n_b}$$

I: current
P: pressure
σy: vertical beam size
Nb: Number of bunches around the ring



SVD layer 3

Tanigawa



Beam size:
Nominal ~30um
ECK+1 ~40um
ECK+2 ~75um

- Fill pattern and beam size scan give consistent results
- The behavior is well understood as Touschek and Beam gas backgrounds

Fitting single beam storage background

Heuristic model for Touschek and Beam-gas:

$$Occupancy = B \cdot PI + T \cdot \frac{I^2}{\sigma_y n_b}$$

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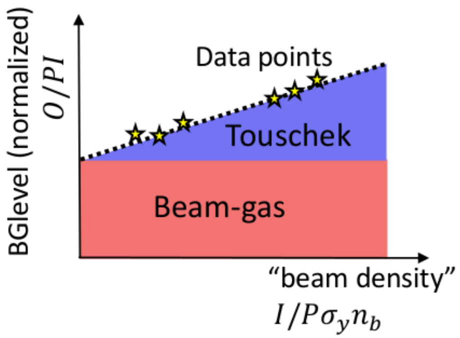
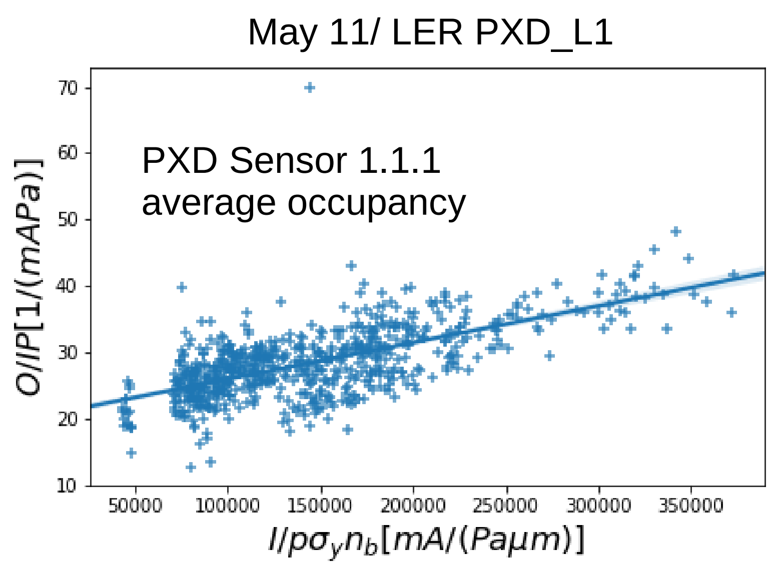


PXD layer 1

Slavomira



- Heuristic fits work also for PXD with noise filtered occupany (noisy pixels masked).

- LER beam gas background dominates for PXD&SVD (Largest background component currently)

- For PXD, beam gas background largest on +X side and smallest (/2) on -X side. Also true for SVD L3.

Mitigation of LER storage backgrounds

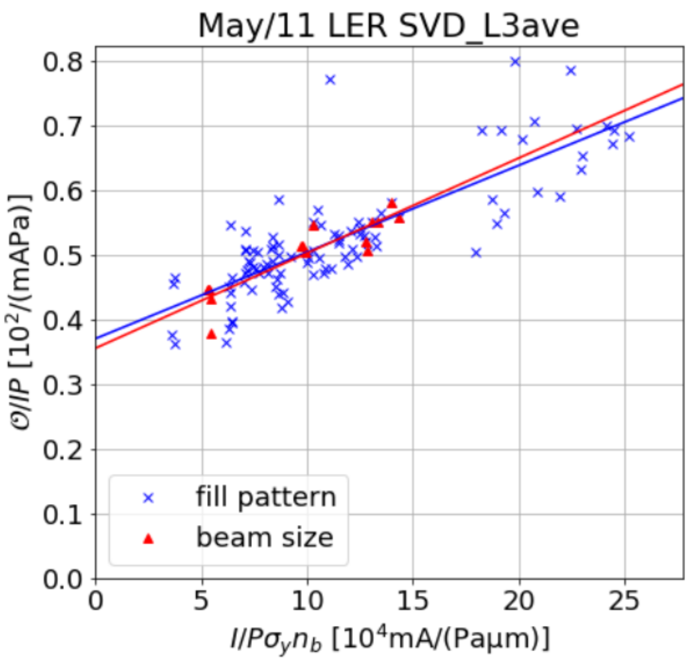
Optimization of vertical collimators in LER ring can reduce background from beam gas.

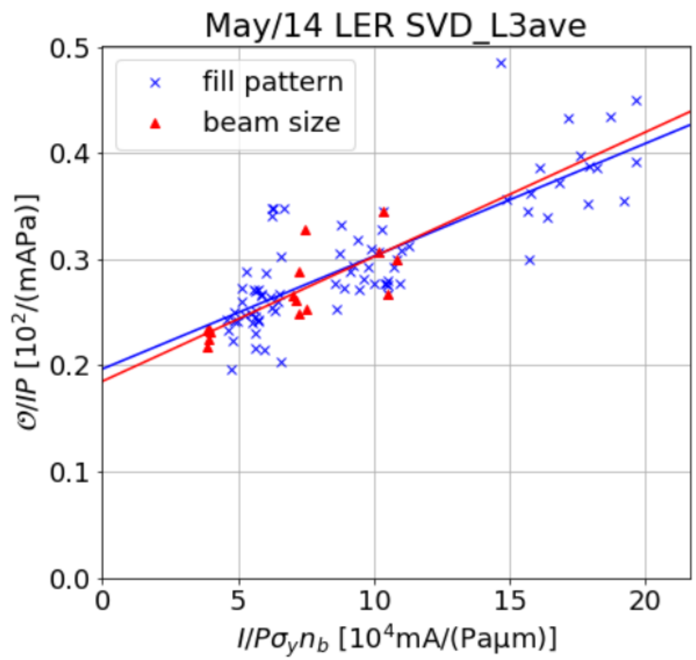
Beam gas sensitivity is 50% reduced for SVD after optimization on May 14th.
Touschek sensitivity remains unchanged (very small).

More mitigation of LER beam gas backgrounds possible in future by installation of additional vertical collimators.

'Recent' conditions (May 19)

	LER	HER	
βy*	3	3	mm
I	0.6	0.6	A
Nb	1576	1576	
P0	1.9	1.1	e-8Pa
dP/dI	9.54	1.34	e-11Pa/mA
σy	100	50	um





L3 Occupancy on the recent condition

May 11th

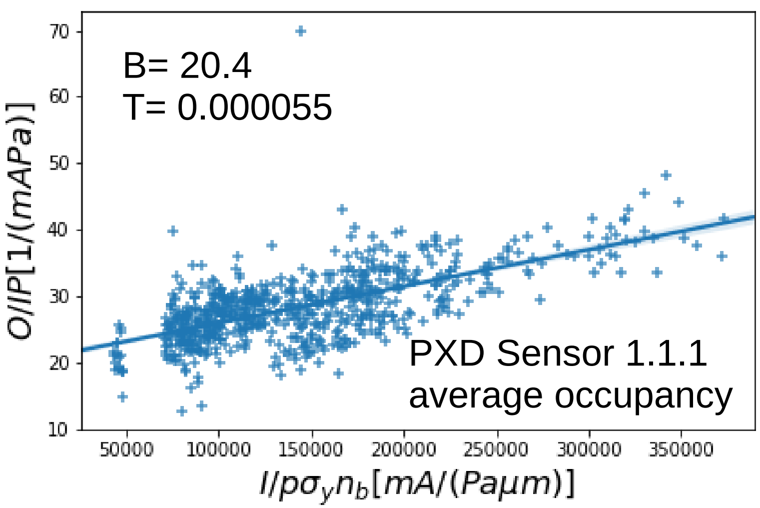
	Beamgas	Touschek
fp	0.258%	0.0306%
bs	0.248%	0.0336%
Δ	0.04	0.10

May 14th

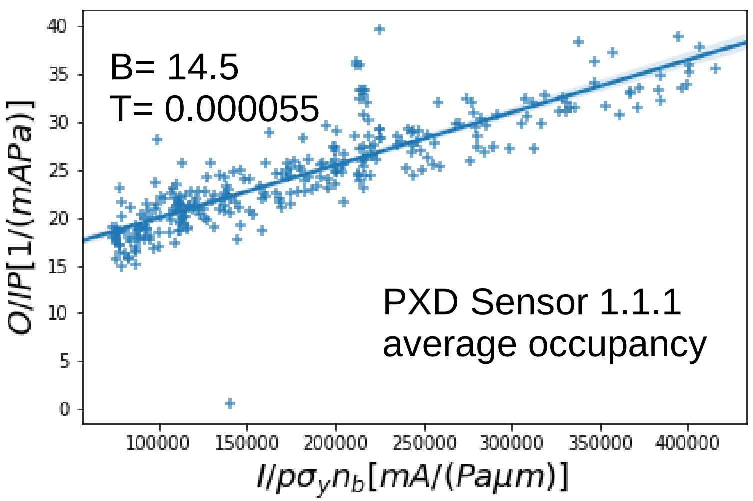
	Beamgas	Touschek
fp	0.137%	0.0243%
bs	0.129%	0.0268%
Δ	0.06	0.10

LER storage backgrounds PXD May 11th and 14th

May 11/ LER PXD_L1



May 14/ LER PXD_L1



For PXD L1, the beam gas sensitivity is reduced by ~25% with new collimator settings.

data / MC summary in VXD

Compare data/MC ratio for Beam gas and Touschek sensitivity
Perfect data/MC agreement means ratio 1

	Total loss (ring)	PXD L1	PXD L2	SVD L3	SVD L4-6
LER Beam-gas (May 14)	1.9-4.1	~8	~7	12-13	5.4-6.9
LER Touschek (May 14)	1.3-1.8	~0.5	~0.3	1.0-1.1	0.9-1.1
HER Beam-gas (May 12)	10	~8	~3	16	19-27
HER Touschek (May 12)	3	~810	~310	1600	760-900

- Simulation of total loss of particles in the whole ring seems OK
- Mostly, ratios for total loss rate and for Bkg in VXD behave similar
- Large tension for HER Touschek in SVD&PXD (much too low in MC)

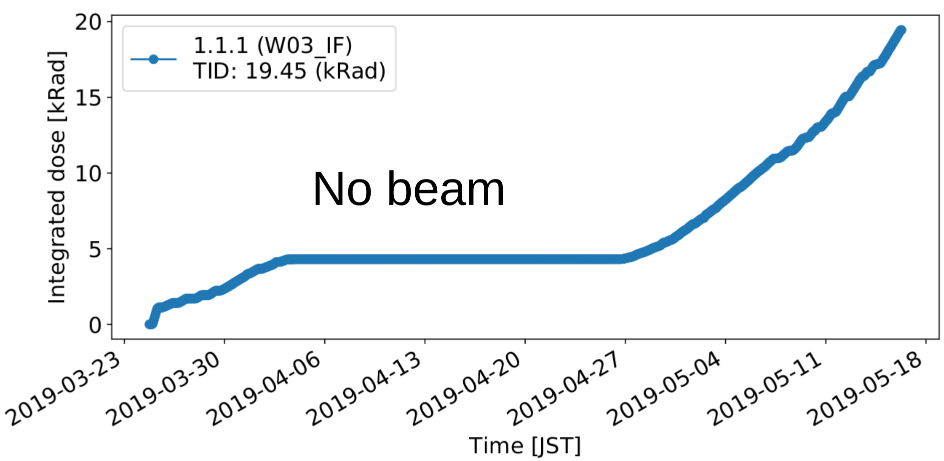
PXD TID in spring run (up to mid May)

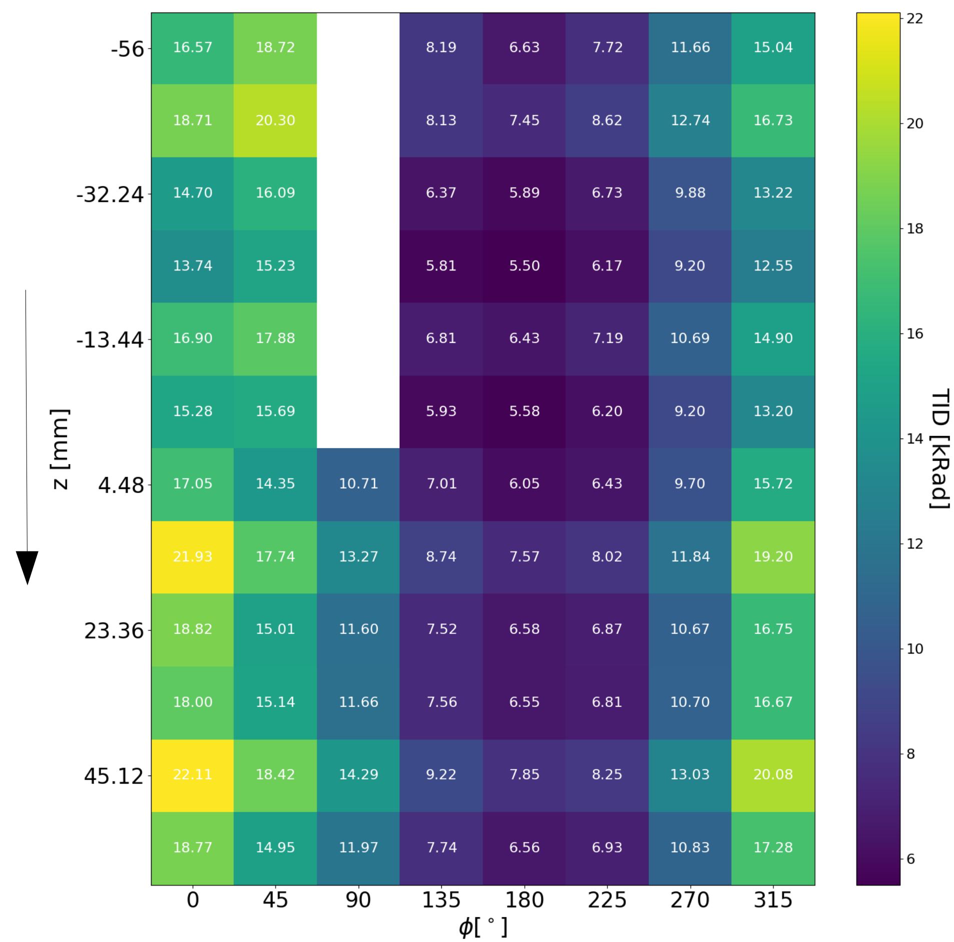
H. Schreeck

PXD sensitive to energy deposits >5keV

Construct total ionizing dose from measured PXD hits for layer 1.

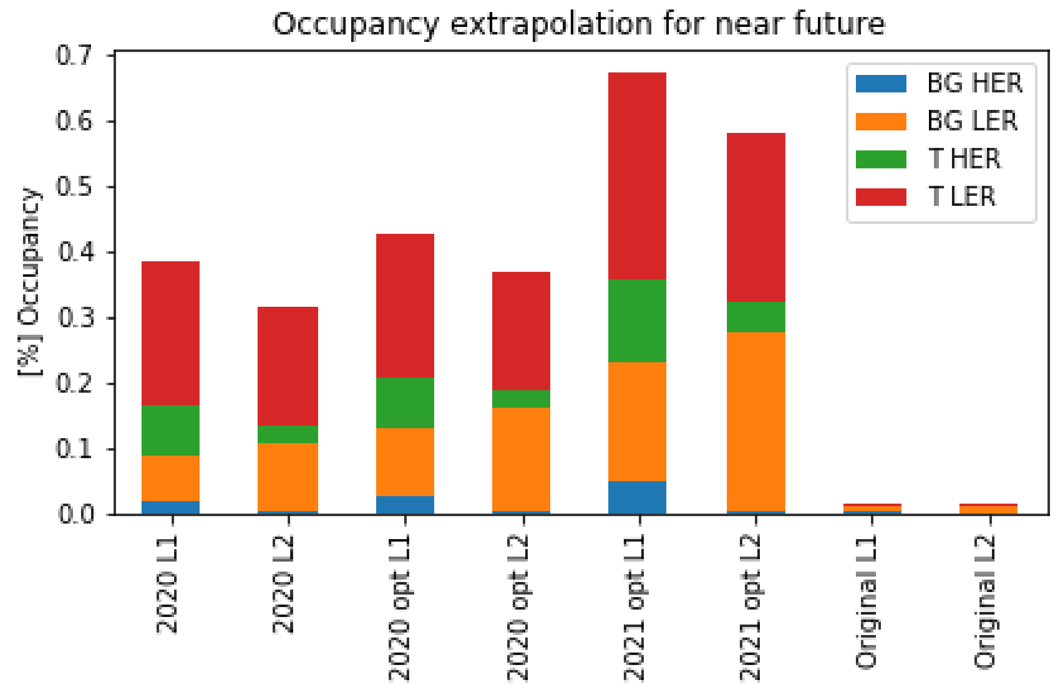
Very preliminary





PXD background: Near future

- Use heuristic fit results for recent single beam studies on May 12 (HER) and May 14 (LER)
- Scaling relations
  - Touschek: $\sim I^2 / n_b$
  - Coulomb scattering: $\sim I\ P / \beta^*_y$
- Background dominated by LER beam gas but still tolerable for 2020/2021 extrapolation

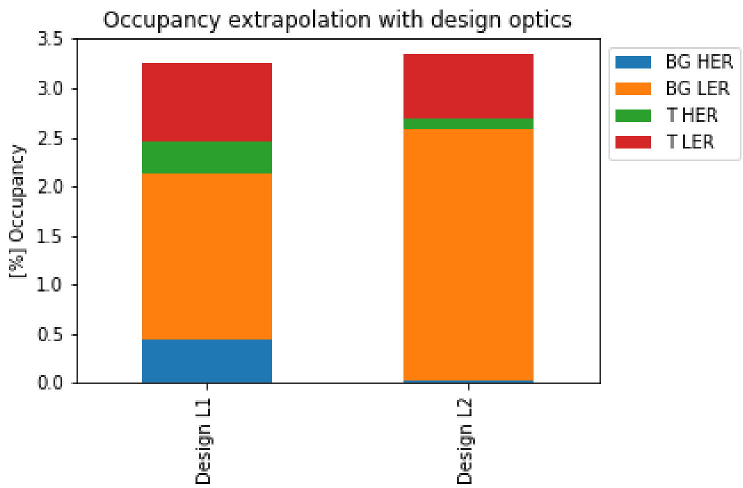


name	new β^*_y [mm]	I HER [mA]	I LER [mA]	σ_y[µm]	n_b
Original	3.0	171	141	38	1576
2020	3.0	1000	1500	38	1576
2020 opt	2.0	1000	1500	38	1576
2021 opt	1.4	1300	1800	38	1576

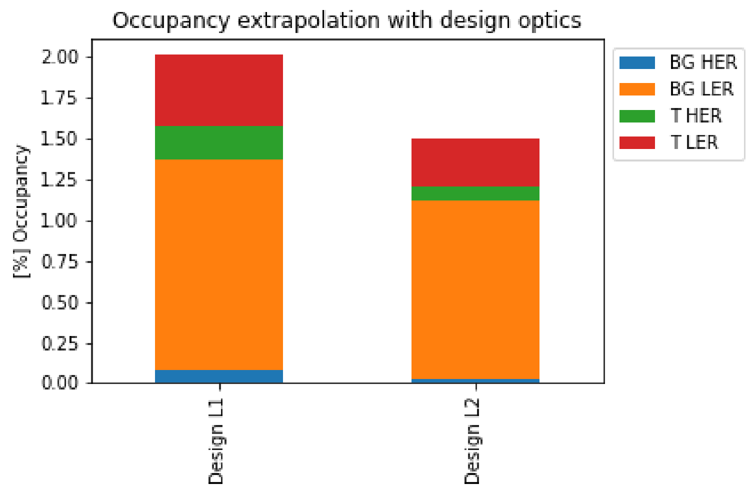
PXD background: Design optics

name	new β_y^* [mm]	I HER [mA]	I LER [mA]	σ_y[µm]	n_b
design	0.3	2600	3600	38	2500

Worst case (+X Sensors)



Average all sensors



- Single beam storage backgrounds alone could hit PXD occupancy limits
- Luminosity related backgrounds not measured only MC (1.2% for L1)
- Large uncertainties in this extrapolation (β^*_y)

SVD background: Near future

Extrapolate May data (12th, 14th) by beam parameters (I,P,βy*), assuming

- Beam-gas ∝ I * P / βy*
- Touschek ∝ I^2
- improvement of LER dP/dI (tentative)

=> estimate occupancy on the most sensitive sensor (Layer 3, +X BW, V side)

- max tolerable currents at current optics ?
- smaller βy* in two years
  - 2020: βy* 2.0mm
  - 2021: βy* 1.4mm
  - not the same as the latest plan presented this morning!

SVD Occupancy (Layer 3 +X BW sensor)

Preliminary	current optics	“2020”	“2021”
βy*	3.0 mm	2.0 mm	1.4 mm
I_LER, I_HER	2.0/1.5 A	1.4/1.0 A	1.8/1.3 A
dP/dI	1/3	1/2	1/3
total occupancy* (limit: 2-3%)	**2.1 %**	**1.55 %**	**2.64 %**

* breakdown in backup.

- We still have room for higher currents (2.0/1.5A) at this optics.
- With smaller βy*, BG level reaches limit in 2021 due to larger Beam-gas BG.

SVD background: Design optics

Extrapolate May data (12th, 14th) by beam parameters

- Beam-gas ∝ I * P / βy^*
- Touschek ∝ I^2 / Nb
- 1/3 improvement of LER dP/dI (tentative)

=> SVD L3 occupancy ~20% >> limit 2-3%

SVD Occupancy (Layer 3 average)

Preliminary	2019 May	design optics	factor
LER Beam-gas	0.14 %	16.8 %	6_I x $6/3_P$ x $10_{\beta y}$
LER Touschek	0.02 %	0.6 %	6^2_I x 0.6_{Nb}
HER Beam-gas	0.03 %	3.9 %	4_I x 4_P x $10_{\beta y}$
HER Touschek	0.02 %	0.3 %	4^2_I x 0.6_{Nb}
total	**0.21 %**	**22 % >> 2%**	

parameters for scaling
βy*: 3mm -> 0.27, 0.3 mm
I: 0.6A -> 3.6, 2.6 A
Nb: 1576 -> 2500

Reliability of the scaling should be discussed.

- Scaling by βy* gives a huge factor x10.
- No effect of βy* on Touschek?

Lumi BG not included.

- ~ 1% in the old MC. Never been measured.

Extrapolation beyond phase 3

- Upgrade to $L_{new}=40\times10^{35}cm^{-2}s^{-1}$ (x5 above full phase 3 luminosity)
- Luminosity dependent backgrounds expected to increase by x5.
  - MC estimate for occupancy on PXD L1 is ~1.2%
  - MC estimate for occupancy on SVD L2 is ~1%
  - Not yet measured from data (work in progress)
- Scaling of single beam storage backgrounds
  - Optimistic: will be same as full phase 3
  - no simulation of upgraded beam optics
  - unclear how machine parameters will change
- Ignorance absored into safety factor (x5).

Summary

- Many developments at SuperKEKB accelerator to increase lumi & keep save bg levels
  - Collimators (installation/optimization), reduce , vacuum conditions
  - Makes extrapolation uncertain
- So far, only storage backgrounds are accurately measured and compared to simulation
  - Dedicated single beam storage studies
  - Scaling with machine parameters seems valid
  - data/MC ratios improved but could be better(→HER Touschek too small in MC)
- For PXD, background extrapolation seems OK in near future but hits occupancy limit for design optics.
  - Special case for PXD: Injection backgrounds and gated mode (see PXD talk)
- For SVD, backgrounds levels close to limit for near future (2021) and exceed limits for design optics
  - w/o effective background mitigation, occupancy may be too high for efficient tracking
- Little to say about extrapolation beyond design optics. But very probably that current VXD detectors cannot cope with it.

backup

LER dynamic pressure

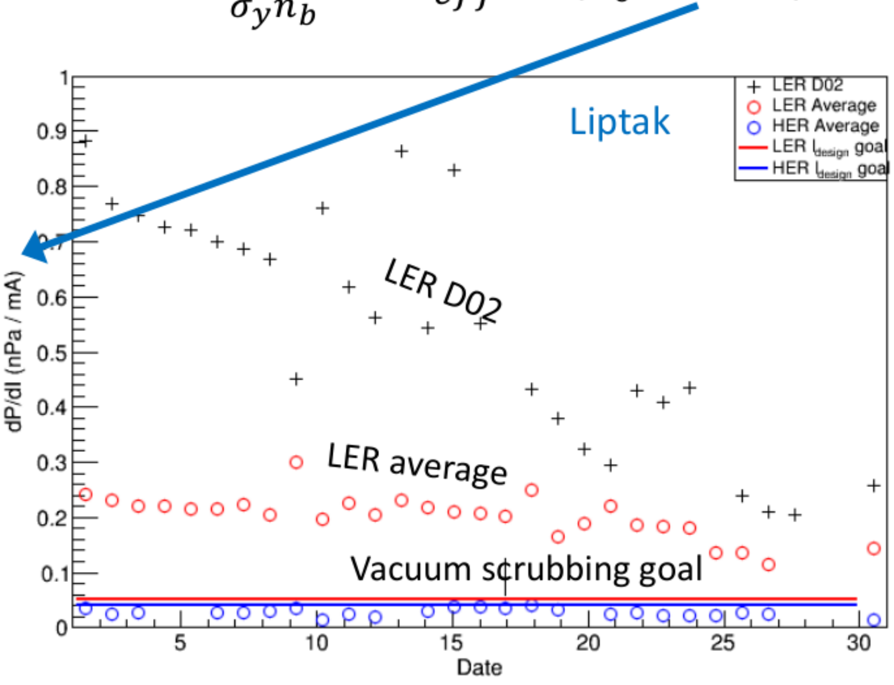
- Why is LER beam gas bkg so high?
- Because dynamic pressure is high in all of LER, especially in D02
- Possible options for reducing LER beam-gas
  - Modify IP beam steering
  - Add collimators
  - Modify optics to match existing collimators better
  - Reduce dynamic pressure
- Recommendation: pursue 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}

Touschek   Beam-gas

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

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



SVD background: Near future Break up

Extrapolate May data (12th, 14th) by beam parameters (I,P,βy*), assuming

- Beam-gas ∝ I * P / βy*
- Touschek ∝ I^2
- improvement of LER dP/dI (tentative)

=> estimate occupancy on the most sensitive sensor (Layer 3, +X BW, V side)

- max tolerable currents at current optics ?
- smaller βy* in two years

SVD Occupancy (Layer 3 +X BW sensor)

Preliminary	current optics	"2020"	"2021"
βy*	3.0 mm	2.0 mm	1.4 mm
I_LER, I_HER	2.0/1.5 A	1.4/1.0 A	1.8/1.3 A
dP/dI	1/3	1/2	1/3
total occupancy* (limit: 2-3%)	**2.1 %**	**1.55 %**	**2.64 %**
LER Beam-gas	0.81 %	0.89 %	1.43 %
LER Touschek	0.66 %	0.32 %	0.53 %
HER Beam-gas*	0.28 %*	0.20 %	0.45 %
HER Touschek*	0.31 %*	0.14 %	0.23 %

* Lumi BG is still negligible, according to MC.
** since sensor-by-sensor estimation is difficult for HER, assume that the hottest sensor has 2x average occupancy.

- We have room for higher currents (2.0/1.5A) at this optics.
- With smaller βy*, BG level reaches limit in 2021 due to larger Beam-gas BG.

SVD background: Design optics (2)

Try another method using old final-Phase3 MC (16th campaign, before G4 geometry update)

oldPhase3MC x $(\text{newMC/oldMC})_{\text{Phase2JuneJuly}}$ x $(\text{data/newMC})_{\text{2019May}}$

- new/old : before/after geometry update

SVD L3 Occupancy [%]

Preliminary	old Phase3 MC	g4update	data/MC	product	estimate (1)
LER Beam-gas	0.066 %	4.2	13	**3.6 %**	16.8 %
LER Touschek	0.11 %	3.0	1	**0.33 %**	0.6 %
HER Beam-gas	0.0036 %	11	16	**0.63 %**	3.9 %
HER Touschek	0.00033 %	7.8	1600	**4.1 %**	0.3 %
total	0.18 %			**8.7 %**	22 %

- Huge scaling factor for HER Touschek makes it a dominant BG source.
- Not consistent with the first estimate.

We need new MC to make the best estimate.

High Level Status

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

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, 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

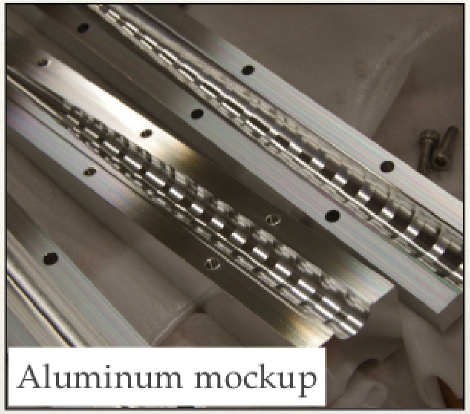
Radiative Bhabha, QED 2-photon:
Expected to dominate in Phase 3
Marginal observation in Phase 2
Lowest simulation uncertainty.

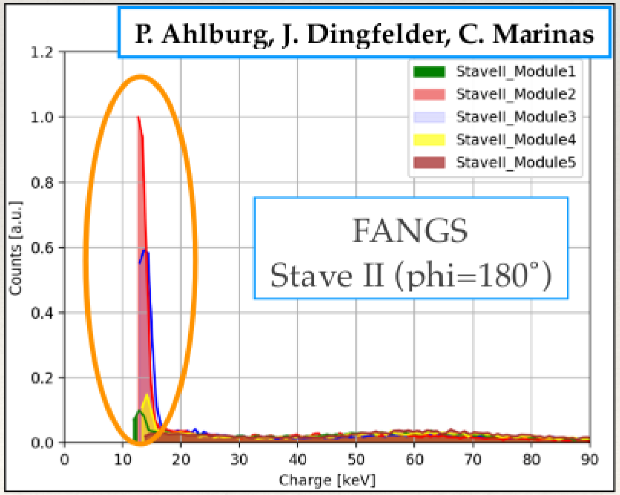
Synchrotron Radiation:
measured in Phase 2. ~OK

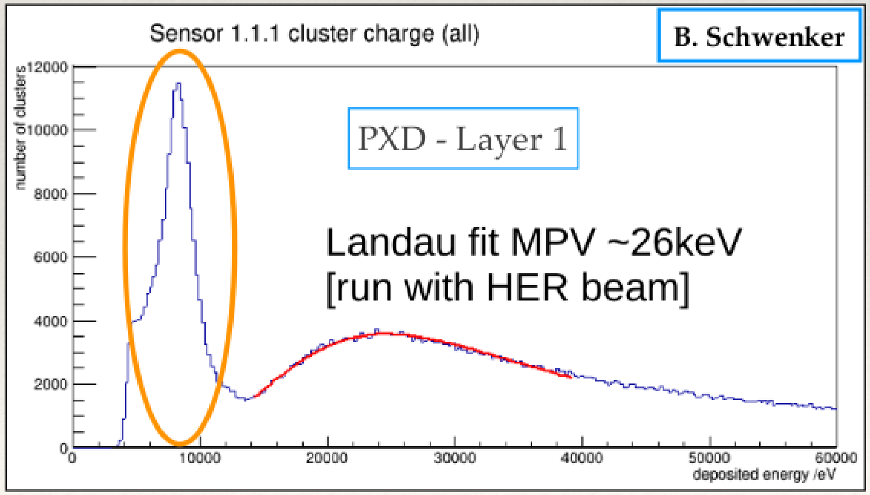
Injection BG, Beam dust, Neutrons:
measured in Phases 1,2
LER injection BG is ~ OK
mitigation is purely experimental
(injection tuning) not simulation based

Synchrotron radiation

- $R_{sr} \propto E^2 B^2$ —> bigger contribution expected from HER.
- Energy of SR photon expected to be from a few keV to tens of keV.
- Inner surface of beryllium pipe coated with Au layer to absorb SR photons.
- Ridge structures of incoming pipes to avoid hits from forward reflected SR photons to IR beam pipe.
- Direct hits stopped by tapered shape of incoming beam pipes.
- PXD (+X) and FANGS (-X) observed SR peaks for both beams, around 8-10 keV.
- Z distributions for HER and LER are the same —> same mechanism of SR generation.

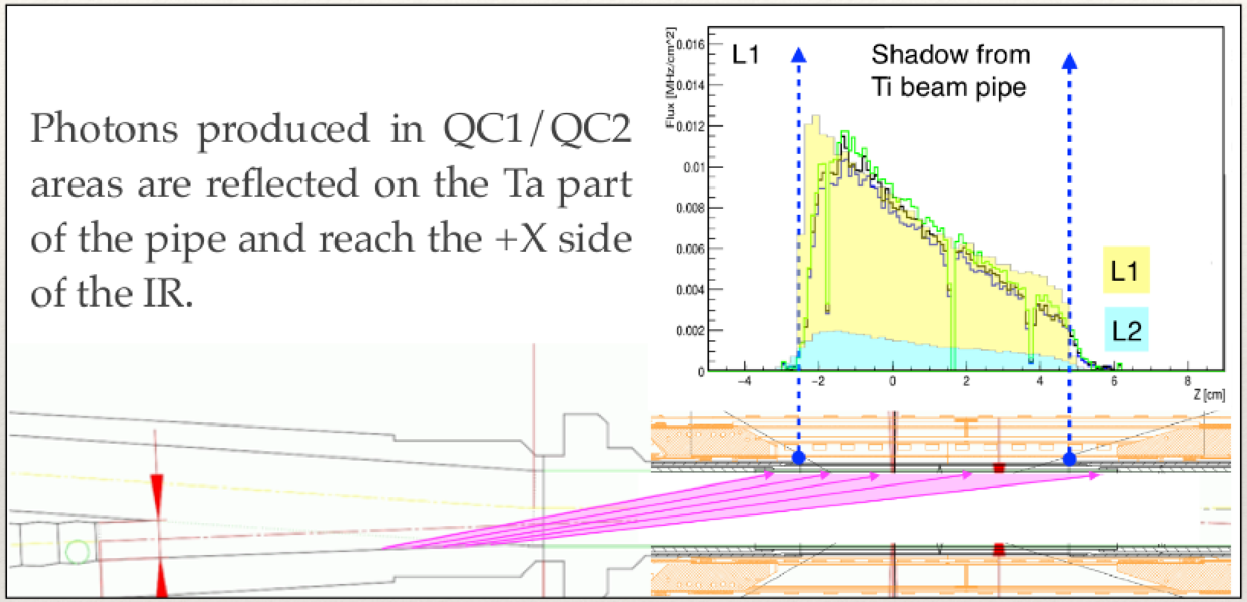






Synchrotron radiation

- It's unlikely to have direct hits from SR. The most probable mechanism is reflection of photons generated in QC1/QC2 sections.

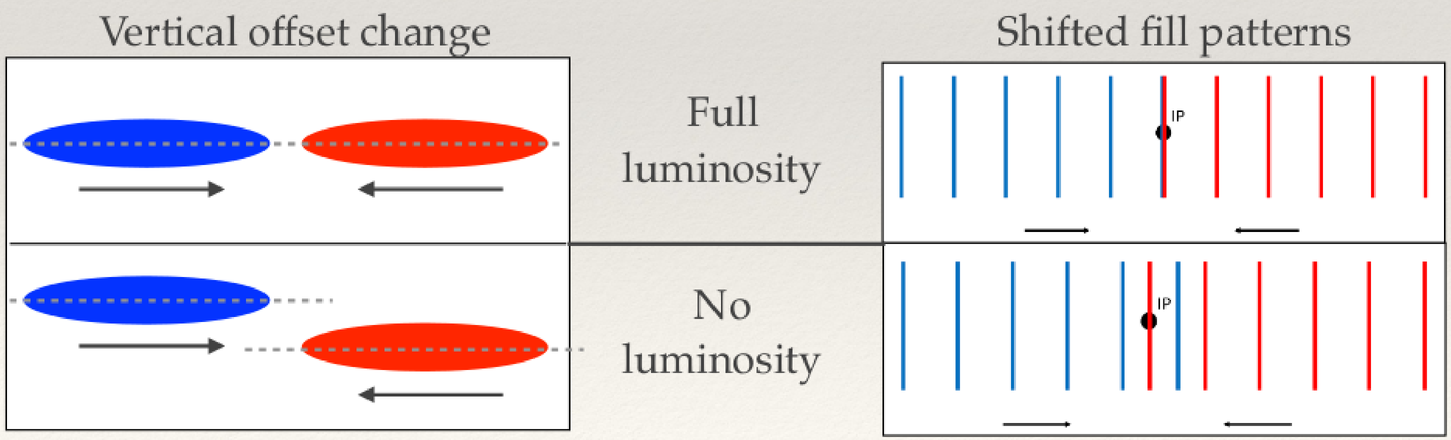


- Au layer in Phase 2: 6.6 μm
  Au layer in Phase 3: 10.0 μm
- The most recent simulations for SR can reproduce qualitatively the data, with still a few differences in the rate ratio between layer 1 and layer 2.

Luminosity background

1. After losing energy through photon emission, particles could be over-bent by QCS magnets, hit beam pipe walls and produce EM showers.
   - In SuperKEKB separate QC magnets are used for incoming and outgoing beams, but still this remains the actual dominant component of background.
2. Photons from Radiative Bhabha interact with iron in the magnets and produce neutrons.
   - Additional shielding to stop neutrons from hitting outermost sub-detectors.
3. In the two-photons process *e e —> e e e e* low momentum e^+e^- pairs can hit tracking detectors and affect their performance.

- These contributions depend on luminosity and should go to zero with no luminosity.
- Studies of luminosity background done in two ways:

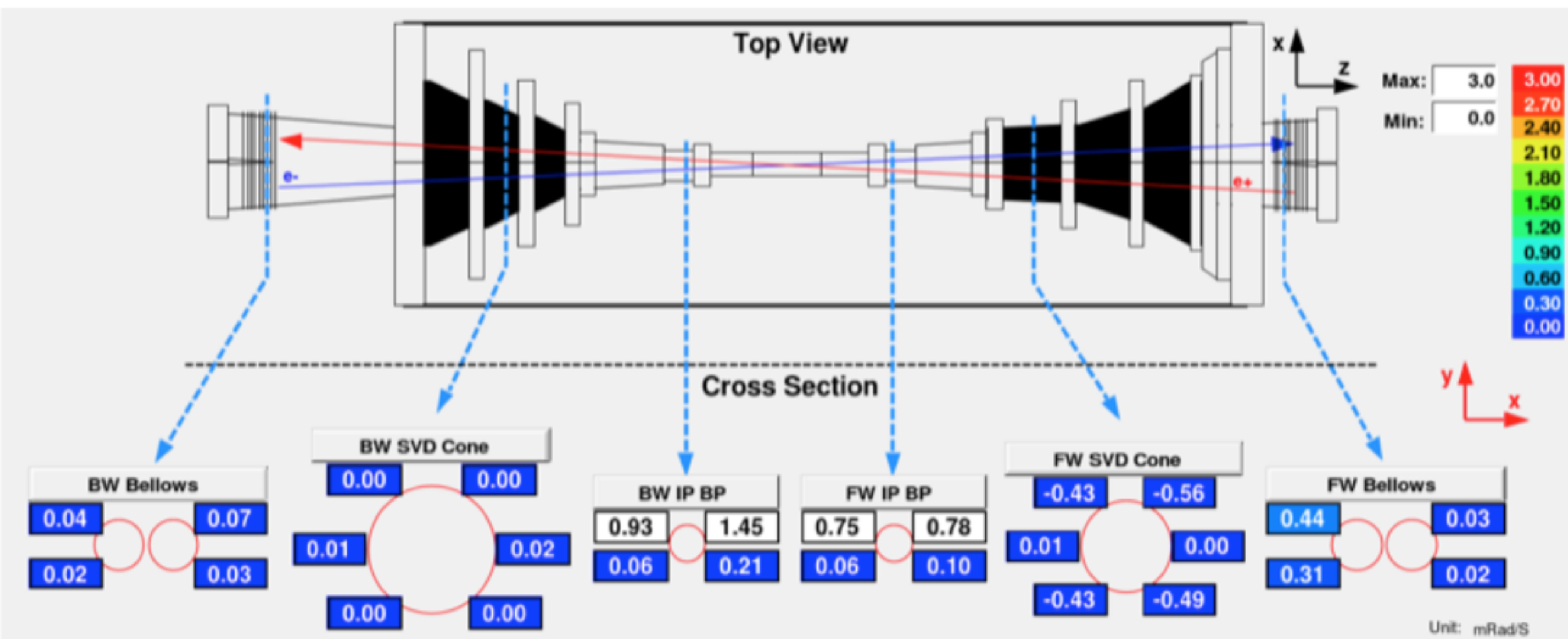


Diamond system in phase 3

28 sCVD diamond sensors installed

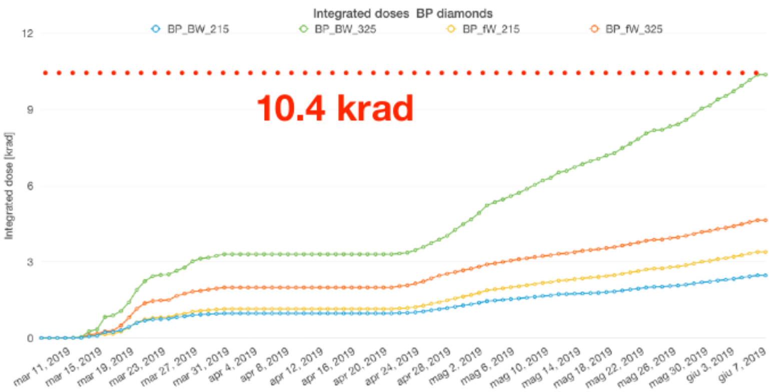
- 4(FWD) + 4(BWD) = 8 on the beam pipe, same locations as in Phase 2
- 6(FWD) + 6(BWD) = 12 on the SVD support cones,
- 4(FWD) + 4(BWD) = 8 on the QCS, Nov 2018

24 read-out at present

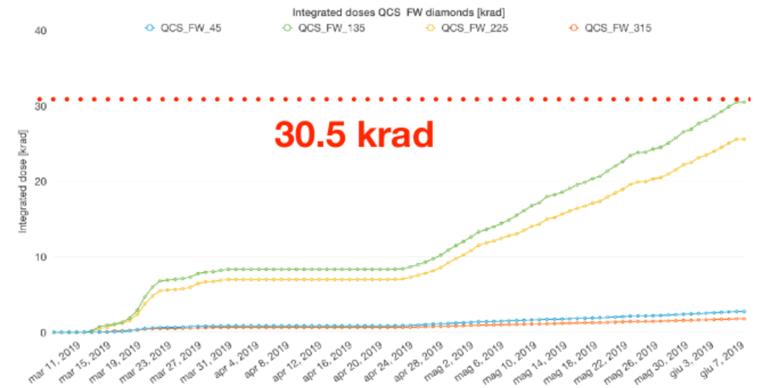


Integrated dose

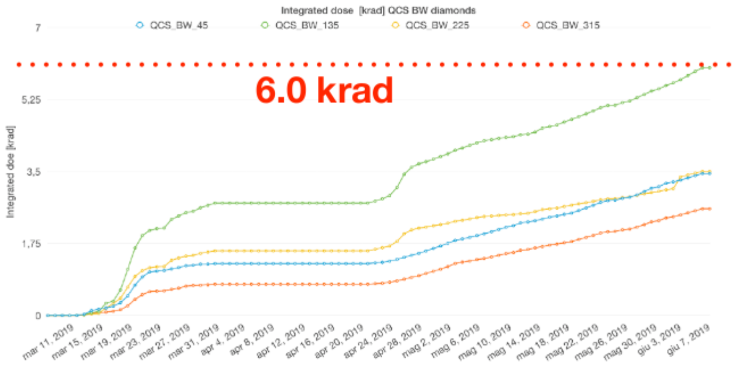
BP diamonds



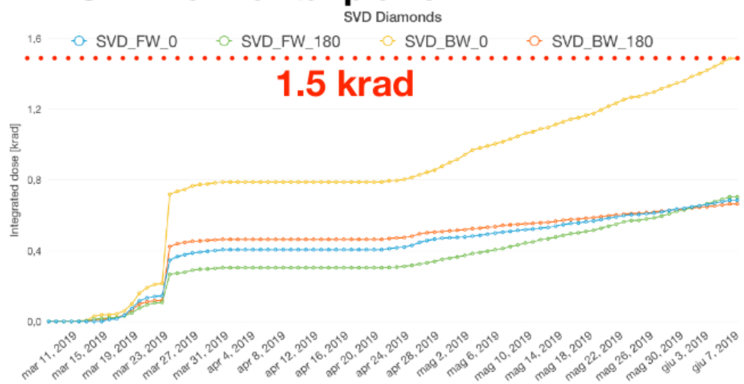
QCS FWD



QCS BWD



SVD horizontal plane



Effect of new LER collimators

- Simulation: IR loss rates in MHz Paladino

	Phase 2	Phase 3 LER: 5/14 HER: 5/12	Change
LER beam-gas Coulomb Brehms	188 186 2	45 44 1	75% ↓
LER Touschek	160	37.6	75% ↓
HER beam-gas Coulomb Brehms	3.4 1.2 2.2	5.5 4.3 1.2	60% ↑ *
HER Touschek	32.8	10.3	70% ↓

- Measurement: SVD occupancy in % Tanigawa

Compared BG rates on the sensors at approximately same position

- Phase 2: L3 sensors in +X direction (phi=0)
- Phase 3: L3.1 sensors (phi = – 18 deg)

	Phase 2 *	Phase 3 **	
LER beam-gas	0.10	0.14	40%↑
LER Touschek	0.04	0.02	50%↓
HER beam-gas	0.06	0.02	70%↓
HER Touschek	0.05	0.02	70%↓

- Compared to Phase 2, Touschek reduced by factor 2-3 with new horizontal collimators.
- LER vertical collimators also reduce the Coulomb beam gas component effectively

*) collimators on 5/14 not yet at target position. MC statistics low.

BG extrapolation toward 2020 summer

In this slide, we assume Morita-san's latest roadmap
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**

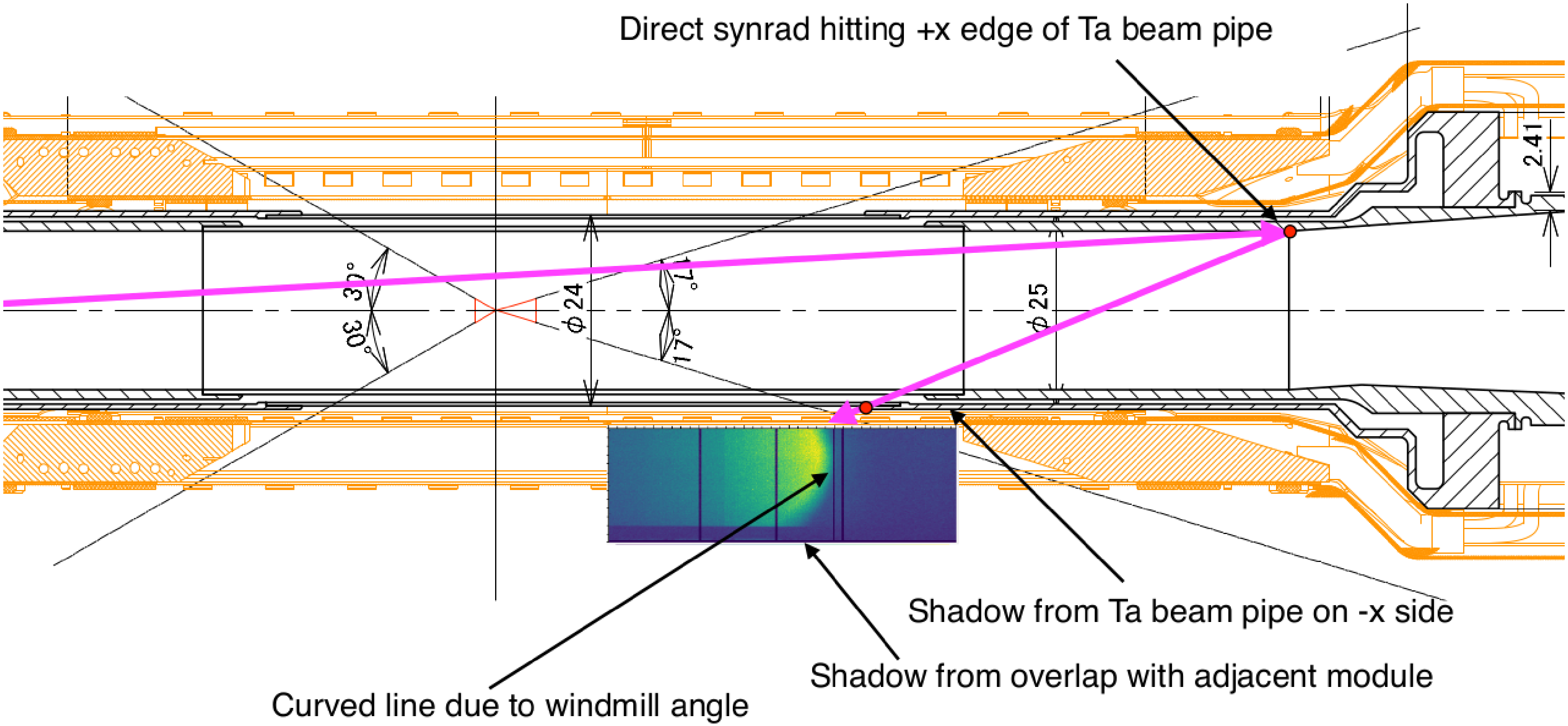
LER Beam-gas	2019 winter	2020 summer
Beam current(I^2)	x2(0.84A)	x4(1.2A)
1/beta_y*	x1.5	x2
Vacuum scrubbing (dP/dI)	x2/3	x1/2
Collimator reduction factor	x1*	x1*
Total	**x2**	**x4**

- HER Touschek, HER Beam-gas are assumed to be much smaller than LER 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 effective vacuum scrubbing

→ **- New LER collimator(s)**
- Optics adjustments

Synchrotron Radiation Bacgground on June 23



Machine parameters - SuperKEKB

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

Machine Design Parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Half crossing angle	ϕ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam param.	ξ_y	0.129	0.090	0.088	0.081	
Bunch Length	σ_z	6.0	6.0	6.0	5.0	mm
Horizontal Beam Size	σ_x^*	150	150	10	11	μm
Vertical Beam Size	σ_y^*	0.94		48	62	nm
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$