HER beam Touschek lifetime measurements

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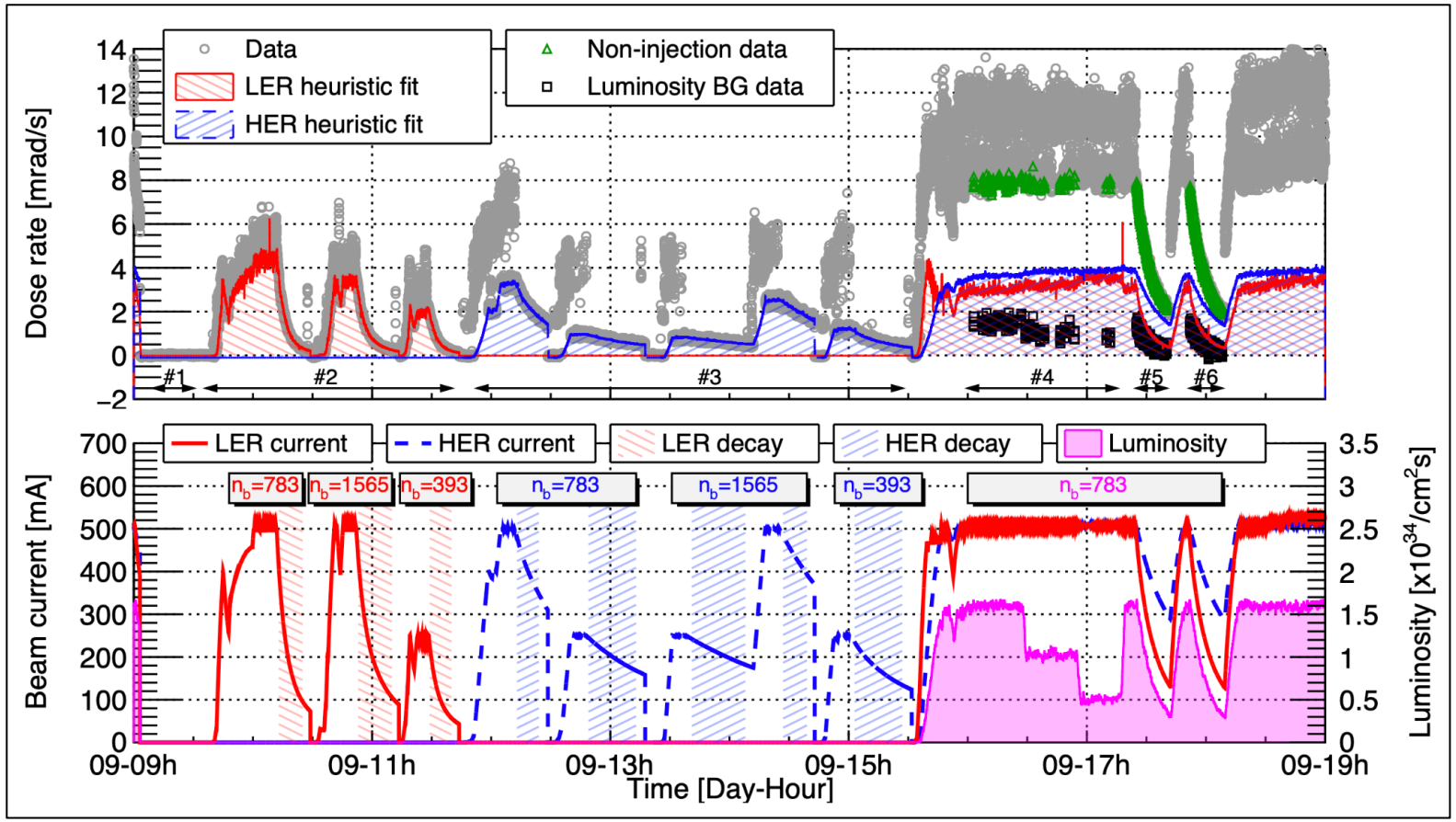
Dedicated beam background measurements in Belle II at SuperKEKB

An example of dedicated beam background measurements in SuperKEKB.
Top: typical measured detector background; bottom: measured machine parameters.



Fit model for beam BG rates in the detector

Beam-gas background
Elastic and inelastic particle scattering off of residual gas molecules

$$O_{\text{beam-gas}} = B \times IP_{\text{eff}}$$

Touschek background
Inelastic scattering of two particles in the same beam bunch

$$O_{\text{Touschek}} = T \times \frac{I^2}{n_b \sigma_x \sigma_y \sigma_z}$$

Luminosity background
Radiative Bhabha and two-photon processes

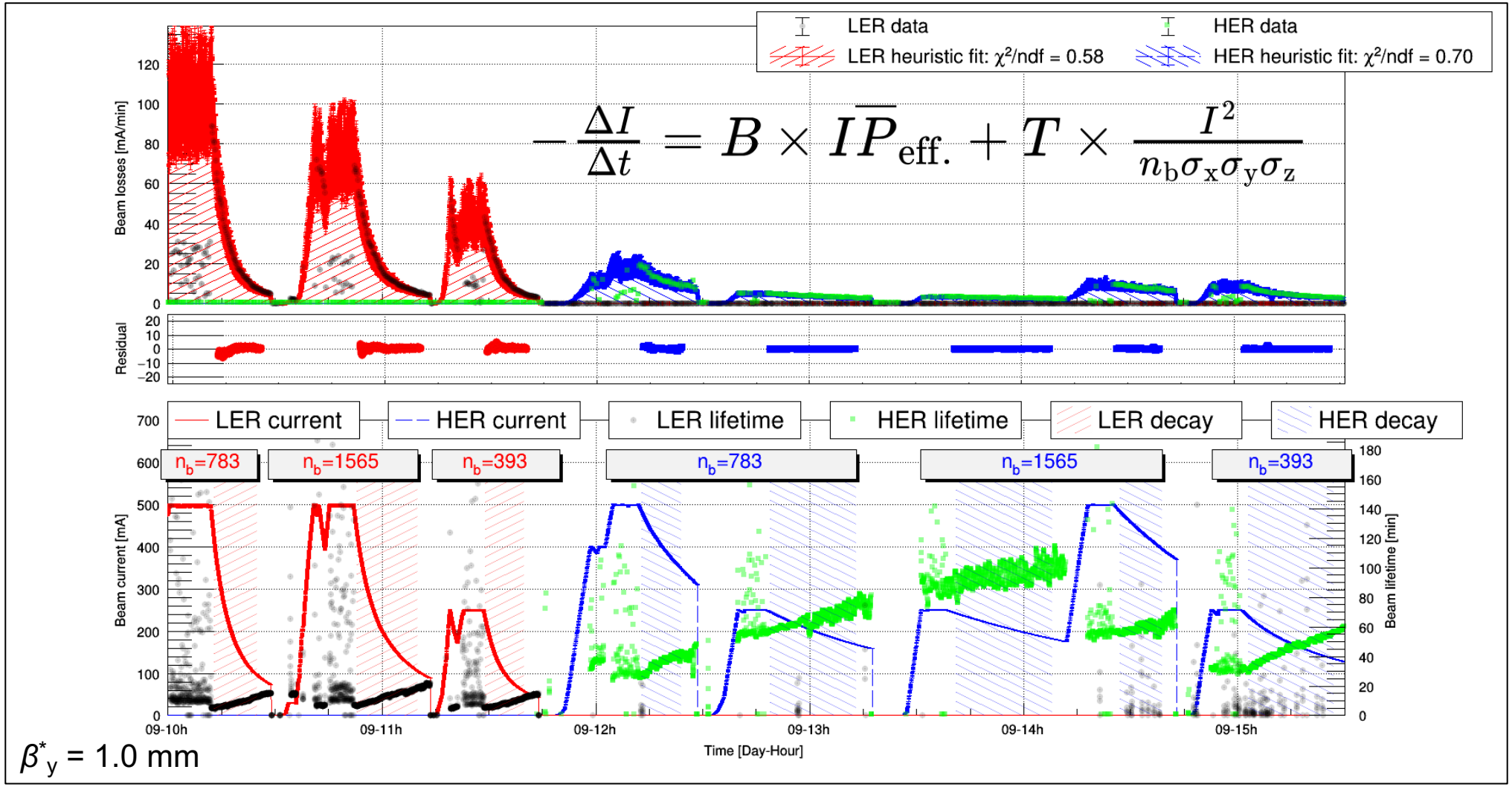
$$O_{\text{lumi}} = L \times \mathcal{L}$$

For more details, see the Phase 3 paper [https://doi.org/10.48550/arXiv.2302.01566]

One could use the same procedure (different number of bunches to separate Touschek from Beam-gas and different beam currents) and SKB data (archived or separately stored monitored beam parameters) for Touschek lifetime measurements.

LER and HER beam loss fit results for May 2020 BG studies

To extract BG sensitivities (B and T) for Beam-gas and Touschek lifetime estimation, one can use beam current change (i.e., losses) data and fit them with the Belle II fit model.



Beam parameters used in the fit

Beam current as a function of beam lifetime

$$I = I_0 \times e^{-\frac{t}{\tau}}$$

lifetime

Heuristic fit formula for beam losses

$$\frac{I}{\tau} = -\frac{\mathrm{d}I}{\mathrm{d}t} = B \times I\bar{P}_{\mathrm{eff.}} + T \times \frac{I^2}{n_{\mathrm{b}}\sigma_{\mathrm{x}}\sigma_{\mathrm{y}}\sigma_{\mathrm{z}}}$$

ring average effective residual gas pressure seen by the beam

# of bunches in the ring

bunch volume

$$\bar{P}_{\mathrm{eff.}} = 3I(\mathrm{d}\bar{P}/\mathrm{d}I)_{\mathrm{CCG}} + \bar{P}_{0,\mathrm{CCG}} = 3\bar{P}_{\mathrm{CCG}} - 2\bar{P}_{0,\mathrm{CCG}}$$

base pressure

average CCG gas pressure over sensing ring sections

Bunch length is the only beam parameter that is not monitored in real-time.

Bunch length
[H.Ikeda, KEK, private communication (2021)]

$$\begin{cases} \sigma_{\mathrm{z}}^{\mathrm{LER}}[\mathrm{mm}] = 5.4466 + 1.7642 \times \dfrac{I^{\mathrm{LER}}[\mathrm{mA}]}{n_{\mathrm{b}}^{\mathrm{LER}}} \\ \sigma_{\mathrm{z}}^{\mathrm{HER}}[\mathrm{mm}] = 6.0211 + 1.3711 \times \dfrac{I^{\mathrm{HER}}[\mathrm{mA}]}{n_{\mathrm{b}}^{\mathrm{HER}}} \end{cases}$$

Vacuum pressure fit parameters should be carefully checked with the SKB Vacuum group to consider all ring sections that contribute to the beam-gas beam losses.

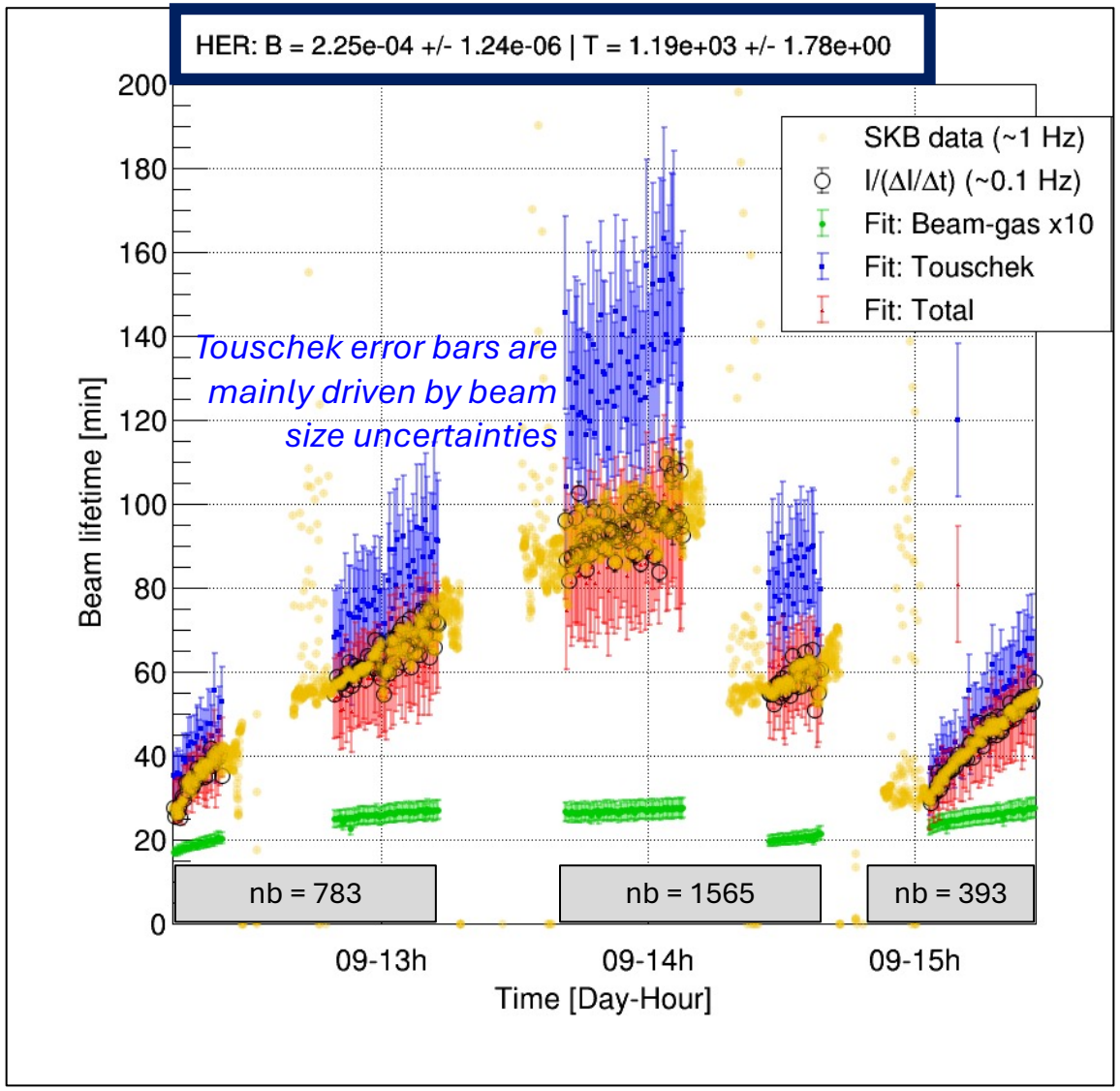
Table 3: Base ($\bar{P}_{0,\mathrm{CCG}}$) and dynamic ($(\mathrm{d}\bar{P}/\mathrm{d}I)_{\mathrm{CCG}}$) fit parameters of the measured CCG gas pressure averaged over sensing ring sections as a function of beam currents.

Date	Sensing ring sections		$\bar{P}_{0,\mathrm{CCG}}$ [nPa]		$(\mathrm{d}\bar{P}/\mathrm{d}I)_{\mathrm{CCG}}$ [nPa/A]	
	LER	HER	LER	HER	LER	HER
May, 2020	D01-D12	D02, D04, D09	14.79 ± 0.22	9.66 ± 0.58	52.08 ± 1.25	11.54 ± 1.44
June, 2020	D01-D12	D02, D04, D09	13.07 ± 0.44	10.13 ± 0.79	36.23 ± 2.00	9.77 ± 2.04
June, 2021	D01-D11	D02, D04, D09, D12	12.68 ± 0.16	10.72 ± 0.04	30.55 ± 0.57	6.24 ± 0.08
December, 2021	D01-D11	D02, D04, D12	7.92 ± 0.95	10.52 ± 0.03	39.76 ± 1.42	5.40 ± 0.04

For more details, see the Phase 3 paper [https://doi.org/10.48550/arXiv.2302.01566]

HER lifetime estimation for May 2020 BG studies

$$-\frac{\Delta I}{\Delta t} = B \times I\overline{P}_{\text{eff.}} + T \times \frac{I^2}{n_b \sigma_x \sigma_y \sigma_z}$$



- All three total lifetime calculations are consistent
  - Archive SKB lifetime calculated online
  - Calculated offline lifetime using beam current changes
  - A sum of Touschek and Beam-gas lifetimes from the fit
- Beam-gas lifetime scaled by 1/10 to fit the figure range
- Touschek lifetime is about 2 times lower than Beam-gas

HER lifetime	Measurements	Simulation	Meas./Sim.
Beam-gas	100.368 ± 78.485 [min]	298.516 ± 3.135 [min]	0.336 ± 0.263
Touschek	37.929 ± 0.057 [min]	59.054 ± 0.114 [min]	0.642 ± 0.002
Uncertainty source	Vacuum pressure, and beam sizes	Monte-Carlo simulation statistics	

Assumptions, uncertainties, and possible improvements

$$-\frac{\Delta I}{\Delta t} = B \times I\overline{P}_{\text{eff.}} + T \times \frac{I^2}{n_{\text{b}}\sigma_{\text{x}}\sigma_{\text{y}}\sigma_{\text{z}}}$$

- Archived EPICS PVs used for the analysis (measured beam parameters):
  - Beam current at beam current monitors: I(LER/HER) = SKB2:BM<L/H>DCCT:CURRENT
    ⇒ DCCT (KEKB [link]) syst. unc. = 10 μA
  - Beam size at X-ray monitors: $\sigma_{x,y}$(LER/HER) = SKB2:BM<L/H>XRM:BEAM:SIGMA<X,Y>
    ⇒ Syst. unc. (x/y) = 10/1 μm (could be overestimated)
    ⇒ Offset Δ(x/y) = 10/7 μm → $\sigma^{\text{corr}} = (\sigma^2 - \Delta\sigma^2)^{½}$ [link]
  - Average vacuum pressure in a given section (D01-12): P_i(LER/HER) = SKB2:VA<L/H>CCG:D<i>_<L/H>ER:PRES:AVG
    ⇒ rel. unc. for individual CCG = 10%
    ⇒ rel. unc. for a section is assumed = 10%/√N, where N is the number of CCGs in the given section
- Most SKB PVs have different timestamps; therefore, a linearly interpolated value between two neighbor points is taken at the given time.
- Possible improvements:
  - Clarify uncertainties for the beam parameters used in the fit.
  - The bunch length (σ_z) could be taken from measurements instead of using fit results.

Potential scenario for HER Touschek lifetime measurements

One polarization at a time: the ring is filled with the beam that has one polarization ← *easier to realize at the machine*	**Multiple trains of bunches with different polarizations: the ring is filled with the beam that has different polarizations depending on the bunch train or bucket number** ← *easier to analyze*
Pros: Relaxed requirements for online beam monitoring. Potentially easier control of machine stability.	**Pros:** Same machine and beam parameters during the measurements for all polarizations.
Cons: Machine and beam parameters (vacuum pressure, stability, and temperature drift of machine equipment) may vary from run to run.	**Cons:** It could be challenging to monitor beam parameters for each train or bucket separately, turn by turn.

Preliminary steps:

1. Belle II HV Off, abort all beams.
2. Prepare e-source and fill patterns (number of bunches) for the measurements.
3. Nb = 393 bunches (the minimum number of bunches used for the dedicated BG studies in the past):
   a) Start beam injection.
   b) Stop injection at 250 mA. Beam decays for 15 min.
   c) Abort the HER beam.
4. Nb = 2346 bunches (the number of bunches used at SuperKEKB in 2024ab). Repeat a)-c).

Human and expertise resources

- The most critical aspect of lifetime measurements is monitoring beam parameters.
  - For the Belle II background study, we can use the data archived in the online KEK archiver, which has a 1-second timestamp and minor time jitter between different EPICS PVs, assuming unknown beam parameters.
  - However, for polarization measurements, this level of precision is inadequate. For instance, you cannot rely solely on the expected bunch length based on outdated measurements; you need real-time data.
- Therefore, it is strongly recommended to discuss with the SuperKEKB monitoring group their current instrumentation and identify any gaps that need to be addressed for accurate measurements.
- One person is sufficient to ensure that the data is collected during measurements.
- The most crucial factors are the machine's stability, data acquisition (DAQ), and synchronization. The machine team will need to assist in ensuring the beam remains stable (i.e., without beam-size blow-ups or pressure rise, no unexpected or uncontrolled orbit drifts).