Beam lifetime estimation at SuperKEKB

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Motivation: Transverse polarization measurements at SuperKEKB

Use Touschek lifetime to measure beam polarization

The Chiral Belle Conceptual Design Report: Upgrading SuperKEKB with a Polarized Electron Beam

Belle II Collaboration

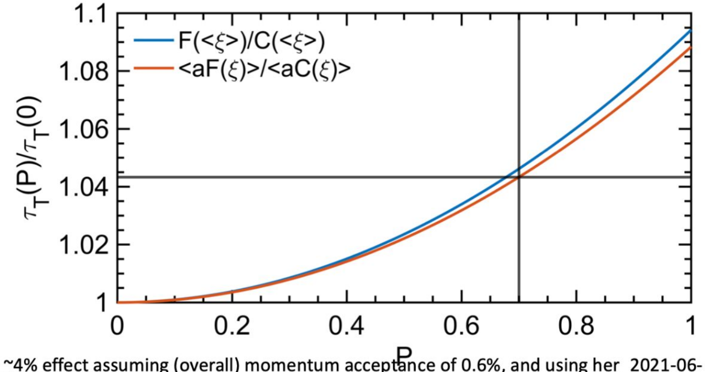
Executive Summary

Upgrading the SuperKEKB electron-positron collider with polarized electron beams opens a new program of precision physics at a center-of-mass energy of 10.58 GeV, the mass of the $\Upsilon(4S)$ meson. This white paper describes the physics potential of this 'Chiral Belle' program. It includes projections for precision measurements of $\sin^2\theta_W$ that can be obtained from independent left-right asymmetry measurements of e^+e^- transitions to pairs of electrons, muons, taus, charm and b-quarks. The $\sin^2\theta_W$ precision obtainable at SuperKEKB will match that of the LEP/SLC world average but at the centre-of-mass energy of 10.58 GeV. Measurements of the couplings for muons, charm, and b-quarks will be substantially improved and the existing 3σ discrepancy between the SLC A_{LR} and LEP A^b_{FB} measurements will be addressed. Precision measurements of neutral current universality will be more than an order of magnitude more precise than currently available. As the energy scale is well away from the Z^0-pole, the precision measurements will have sensitivity to the presence of a parity-violating dark sector gauge boson, $Z_{\rm dark}$. The program also enables the measurement of the anomalous magnetic moment $g-2$ form factor of the τ to be made at an unprecedented level of precision. A precision of 10^{-5} level is accessible with 40 ab^{-1} and with more data it would start to approach the 10^{-6} level. This technique would provide the most precise information from the third generation about potential new physics explanations of the muon $g-2$ 4σ anomaly. Additional τ and QCD physics programs enabled or enhanced with having polarized electron beams are also discussed in this White Paper.

In order to implement e^- beam polarization in the SuperKEKB high energy ring (HER), three hardware upgrades are required: 1) introduction of a low-emittance polarized source that supplies SuperKEKB with transversely polarized electrons that provide separate data sets with opposite polarization states; 2) a system of spin rotator magnets that rotate the spin of the electrons in the beam to be longitudinal before the interaction point (IP) where the Belle II detector is located, and then back to transversely polarized after the IP; and 3) a Compton polarimeter that provides online measurements of the beam polarization at a location between the first spin rotator and the IP. A precision measurement of the polarization is also made at the IP by analysing the spin-dependent decay kinematics of τ leptons produced in a $e^+e^- \to \tau^+\tau^-$ data set. This White Paper will review the current status of the R&D associated with the three hardware projects and describes the τ polarimetry analysis of 0.4ab^{-1} of e^+e^- data collected at the $\Upsilon(4S)$ with the *BABAR* experiment that shows the high precision that can achieved. This paper includes a summary of the path forward in R&D and next steps required to implement this upgrade and access its exciting discovery potential.

For SuperKEKB

From
Farah MAWAS
Aurélien MARTENS
Slides at Feb
Chiral Belle meeting



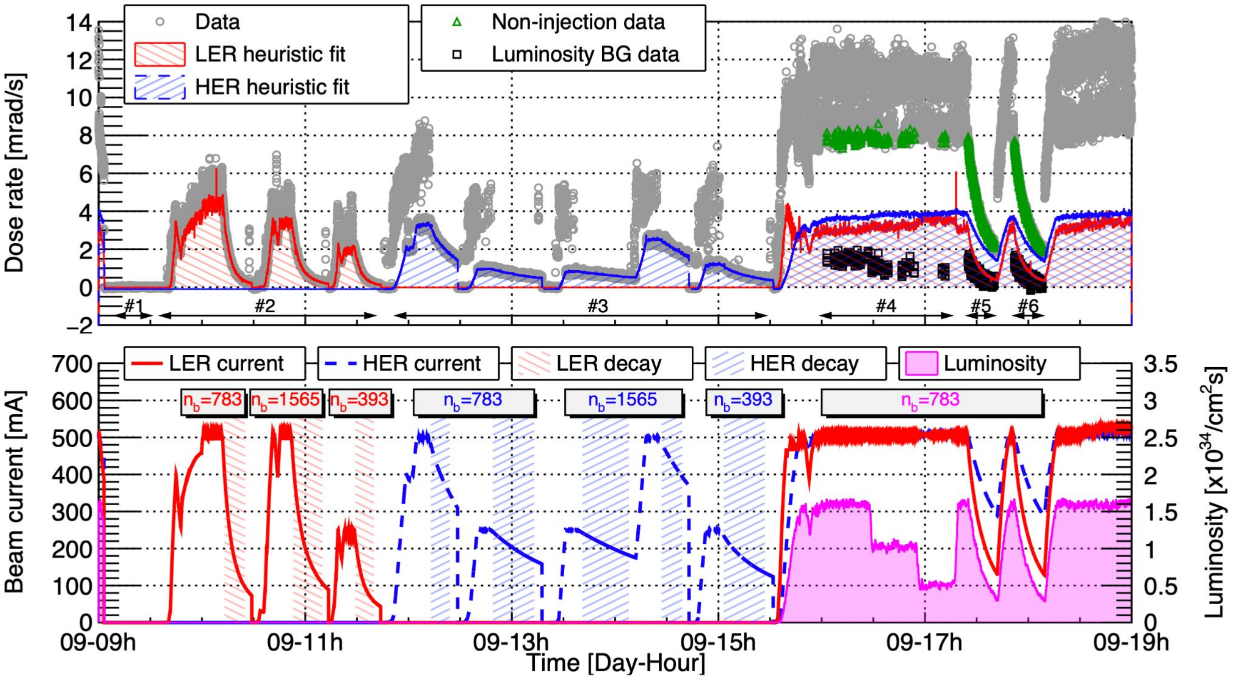
- It is ~4% effect assuming (overall) momentum acceptance of 0.6%, and using her_2021-06-09_231636.388_MeasOpt
- This is likely observable in SuperKEKB
- May need to inject both polarized and unpolarized beams in the ring and measure bunch/bunch intensity with time to minimize systematics (feasbile according to Demin)
- Maybe F/C factor could be calibrated by comparing measurements with various momentum acceptances ? (linked to RF voltage ?)

10/02/2023 IJCLab Update about Compton polarimeter 7

Background measurements

We could use the same data for Touschek lifetime measurements

A dedicated beam-induced background measurement is performed to measure each background component separately, usually twice a year



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

Beam-gas background

Elastic and inelastic particle scattering off of residual gas molecules

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

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]

Heuristic fit formula

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

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

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

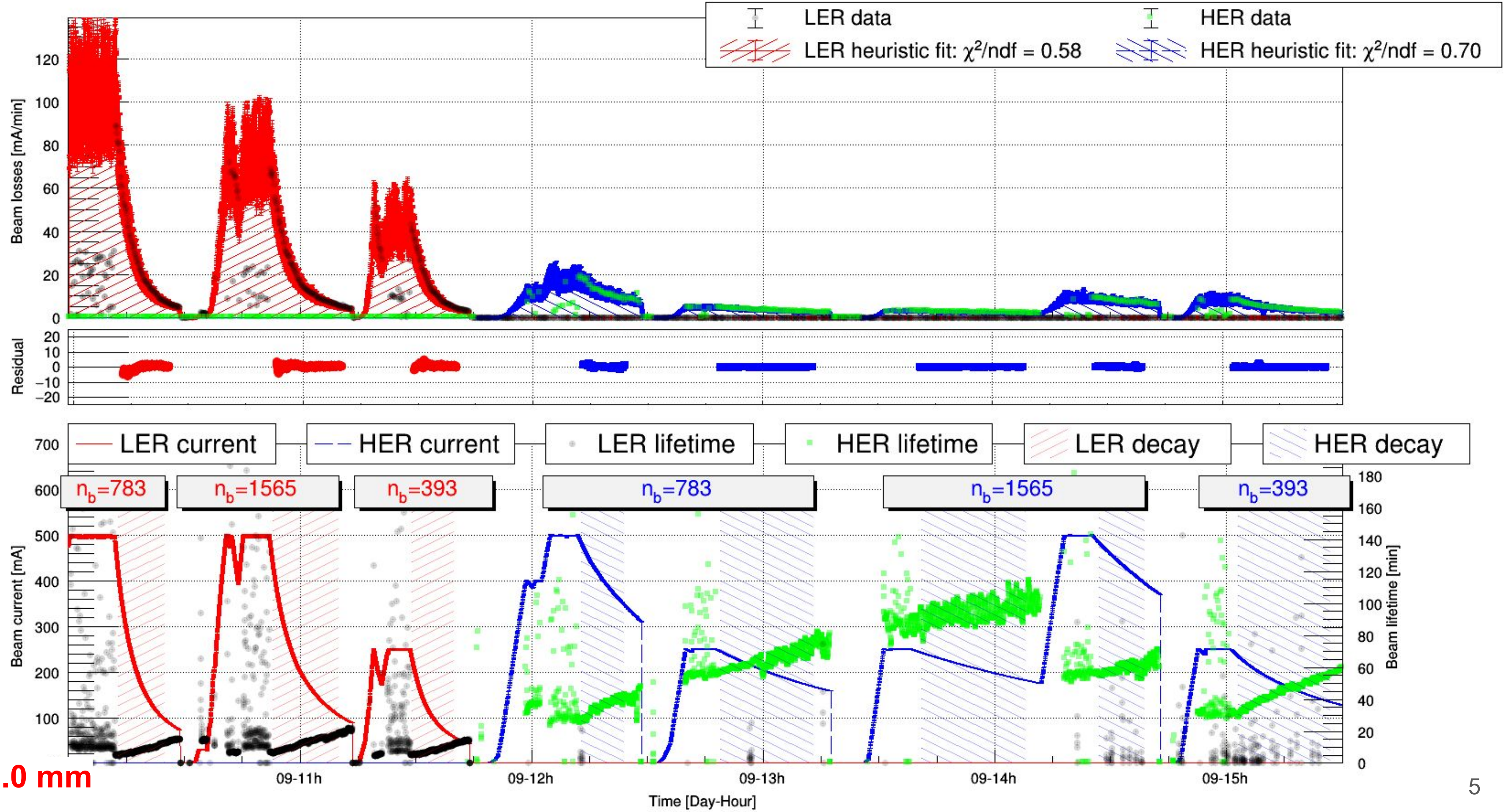
Table 3: Base ($\bar{P}_{0,\mathrm{CCG}}$) and dynamic ($(\mathrm{d}\bar{P}/\mathrm{d}I)_{\mathrm{CCG}}$) fit parameters of the measured CCG gas pressure averaged over sensing ring sections as a function of beam currents.

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

Calculated every 10 sec.

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

Fit results for May 2020

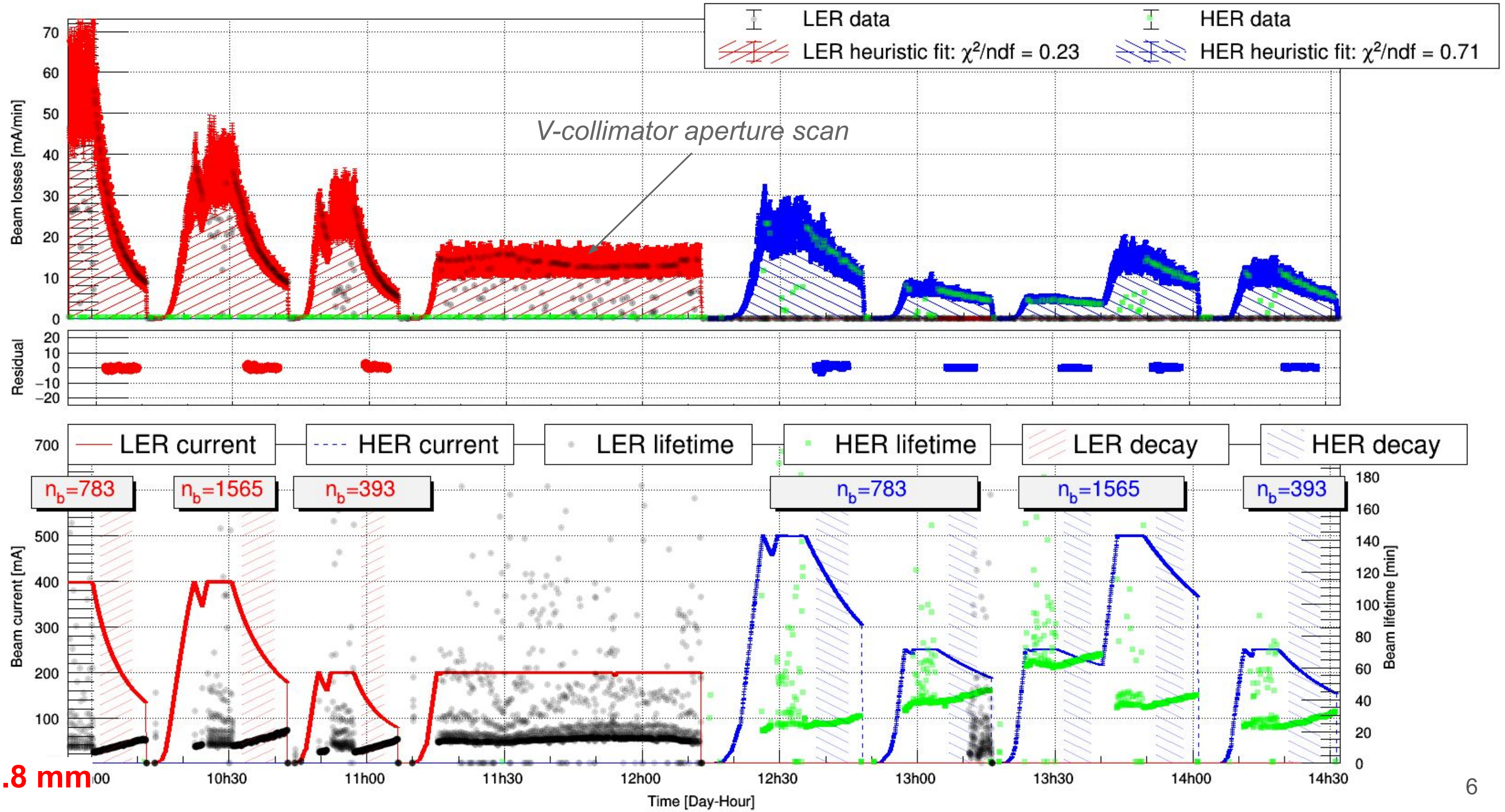


β^*_y = 1.0 mm

Calculated every 10 sec.

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

Fit results for June 2020

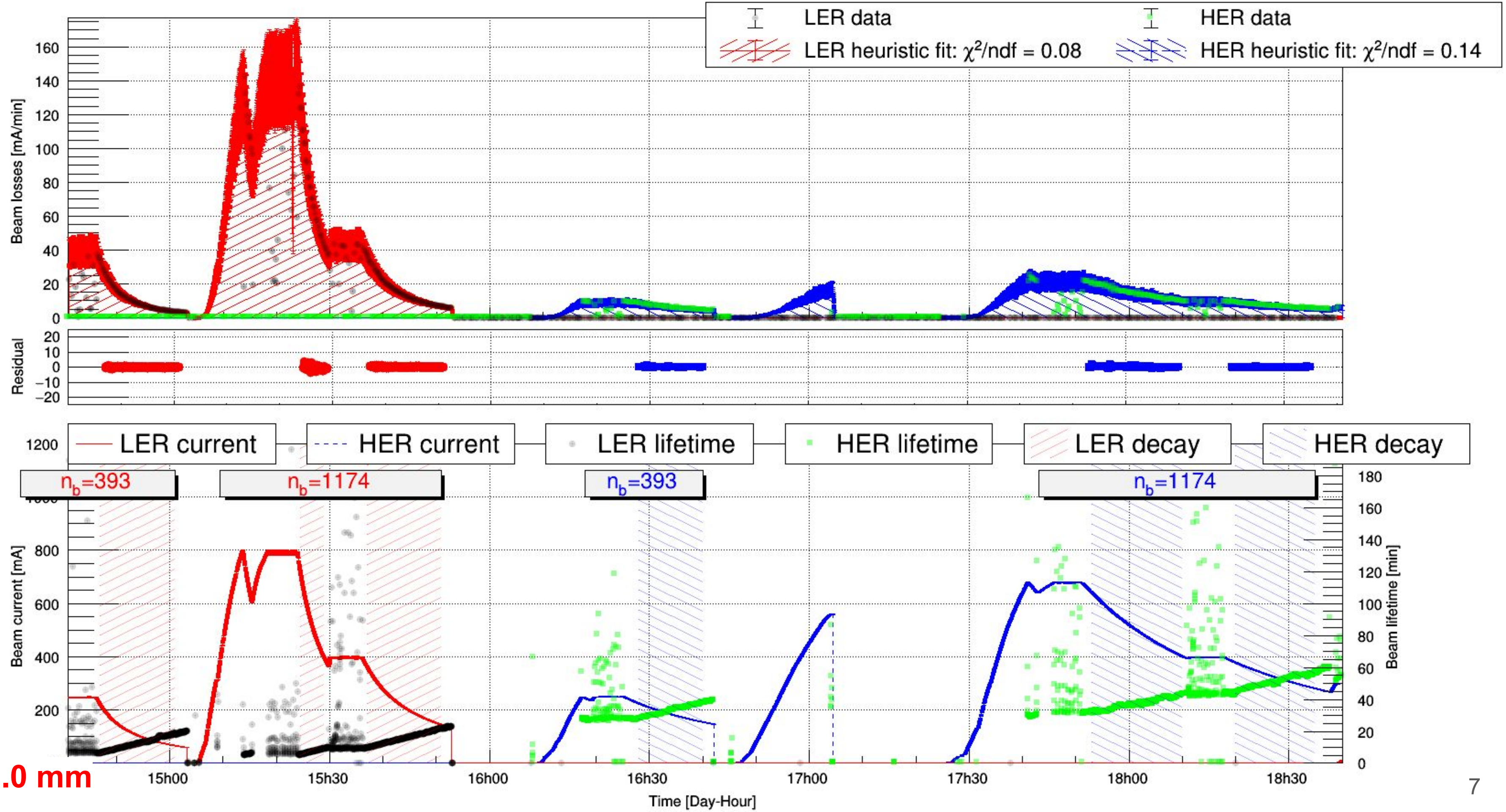


β^*_y = 0.8 mm

Calculated every 10 sec.

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

Fit results for June 2021

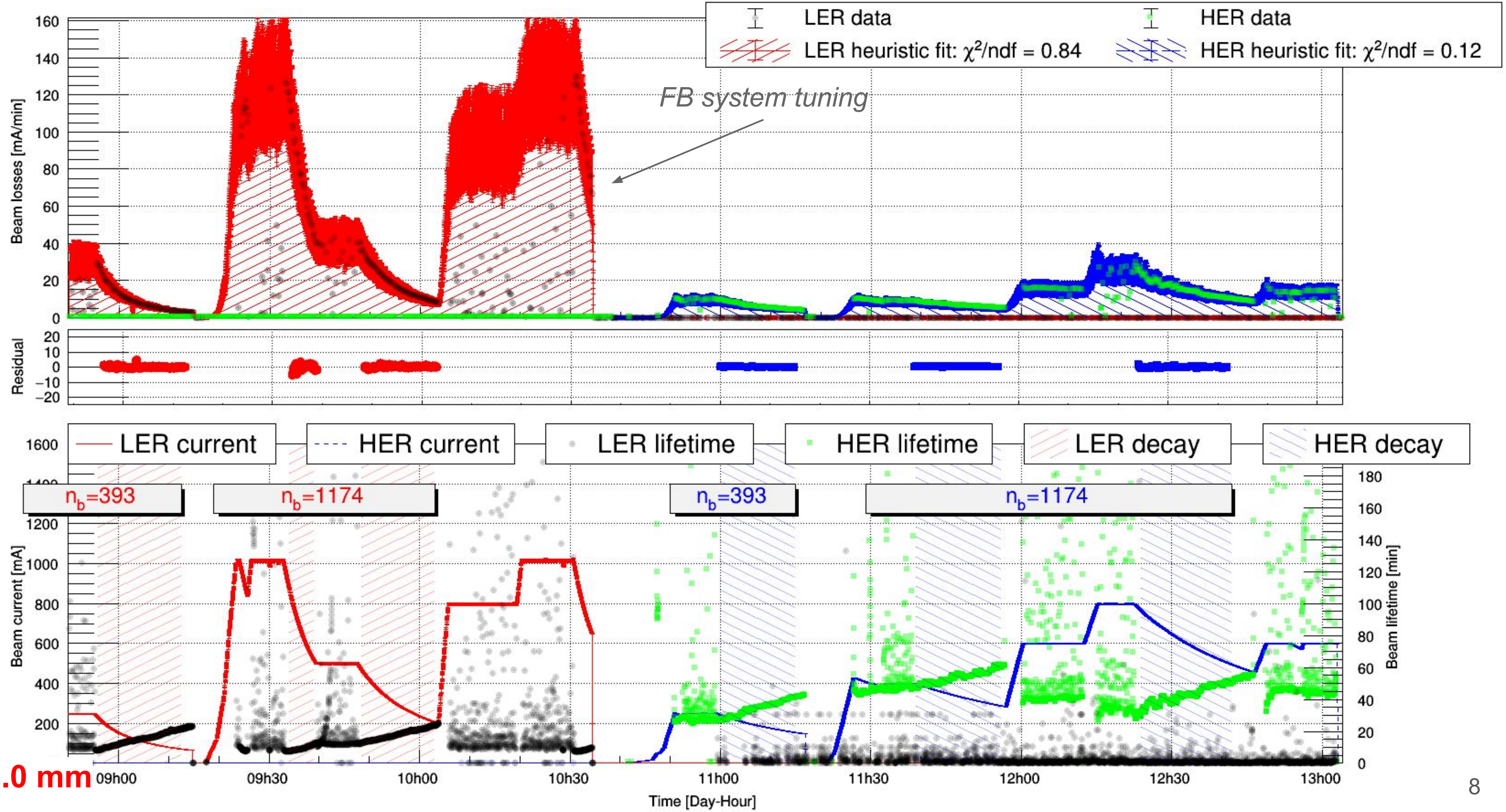


β^*_y = 1.0 mm

Calculated every 10 sec.

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

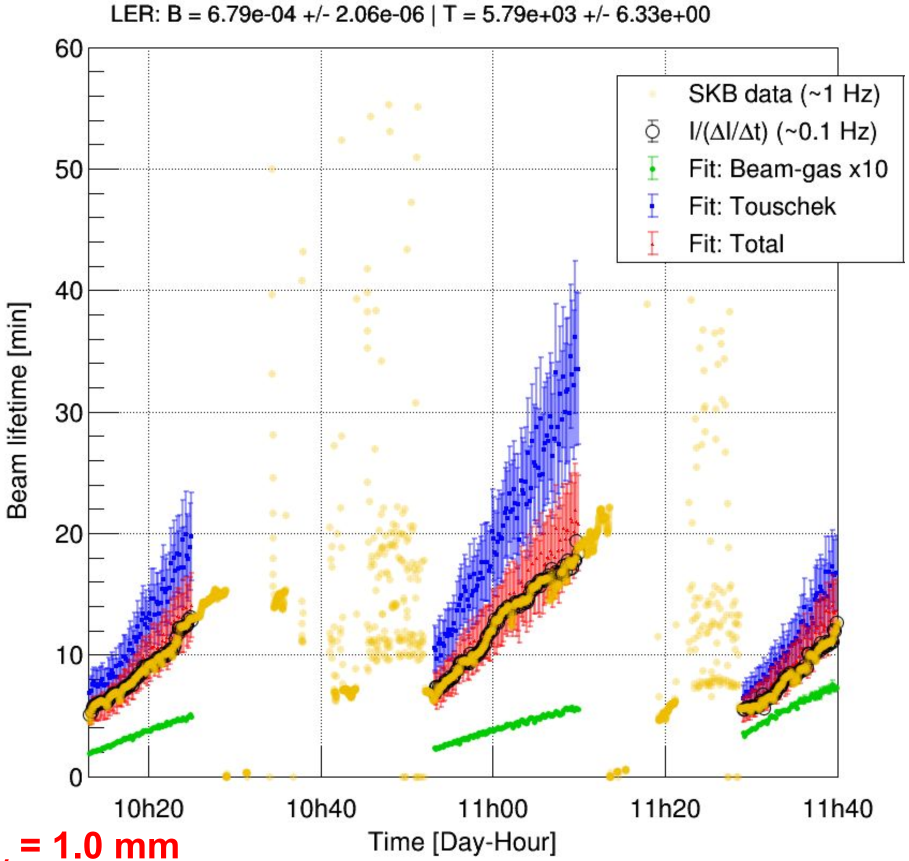
Fit results for Dec. 2021

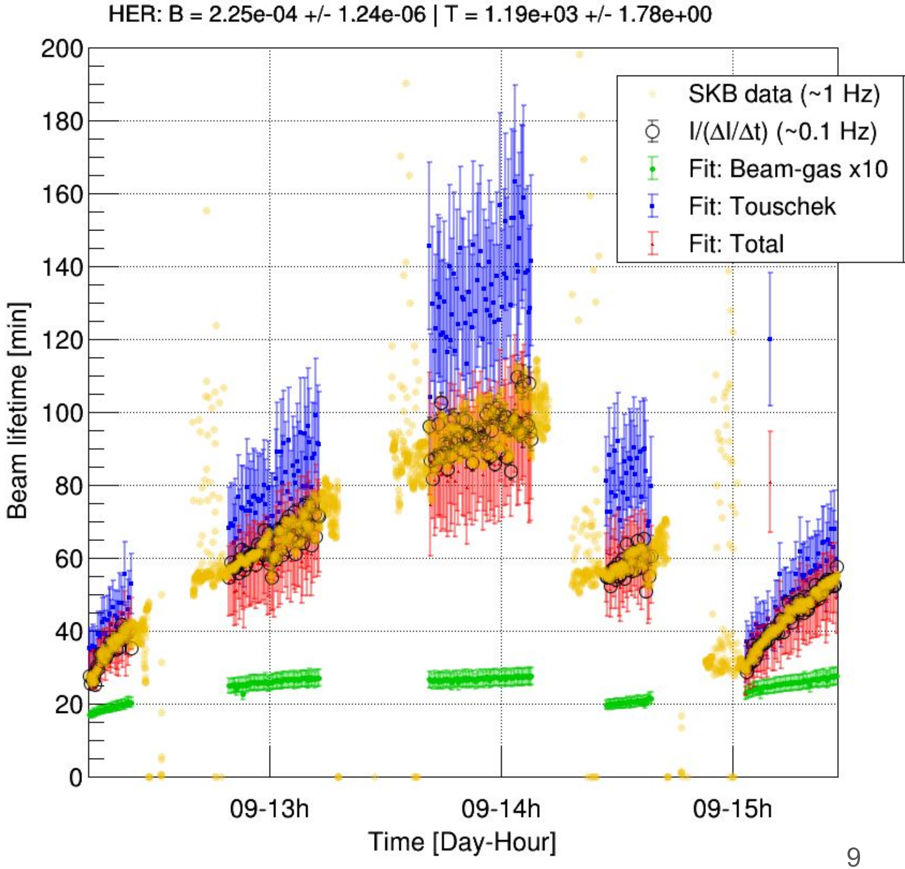


β^*_y = 1.0 mm

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

Beam lifetime estimation for May 2020

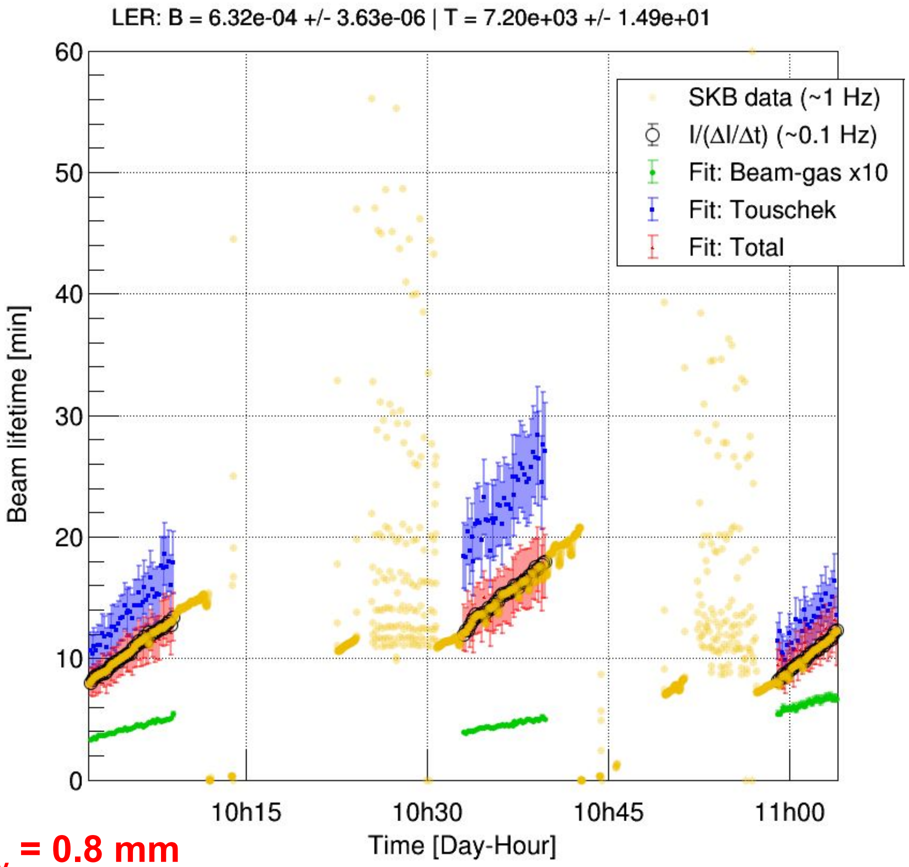


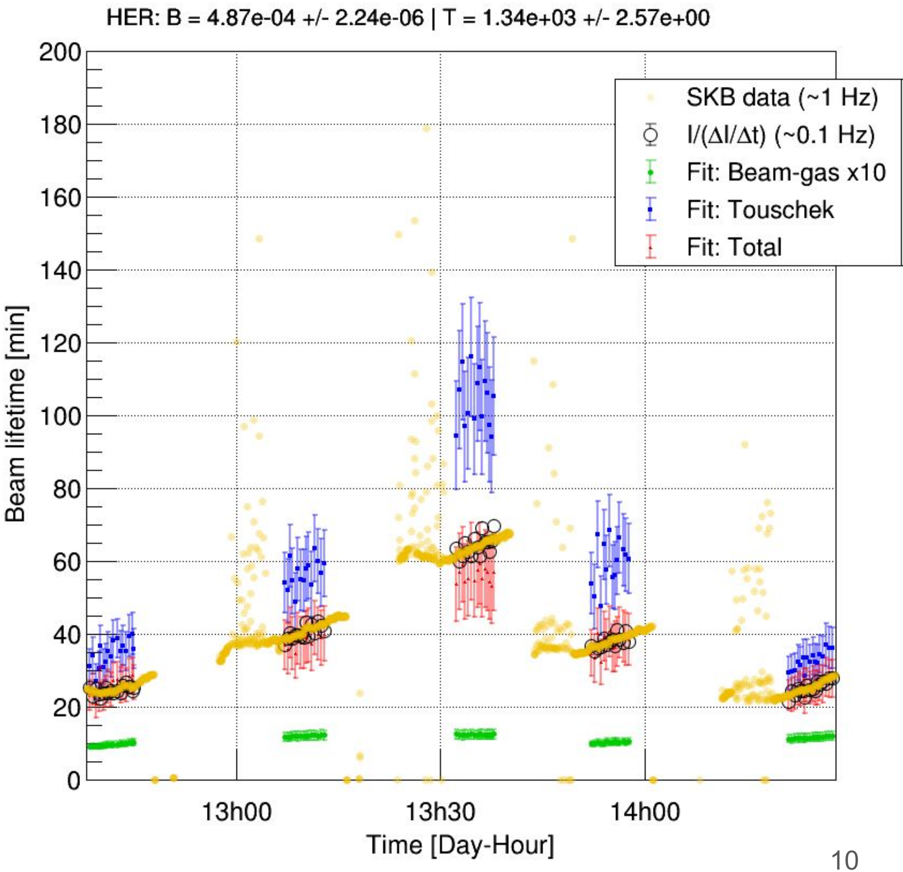


β^*_y = 1.0 mm

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

Beam lifetime estimation for June 2020



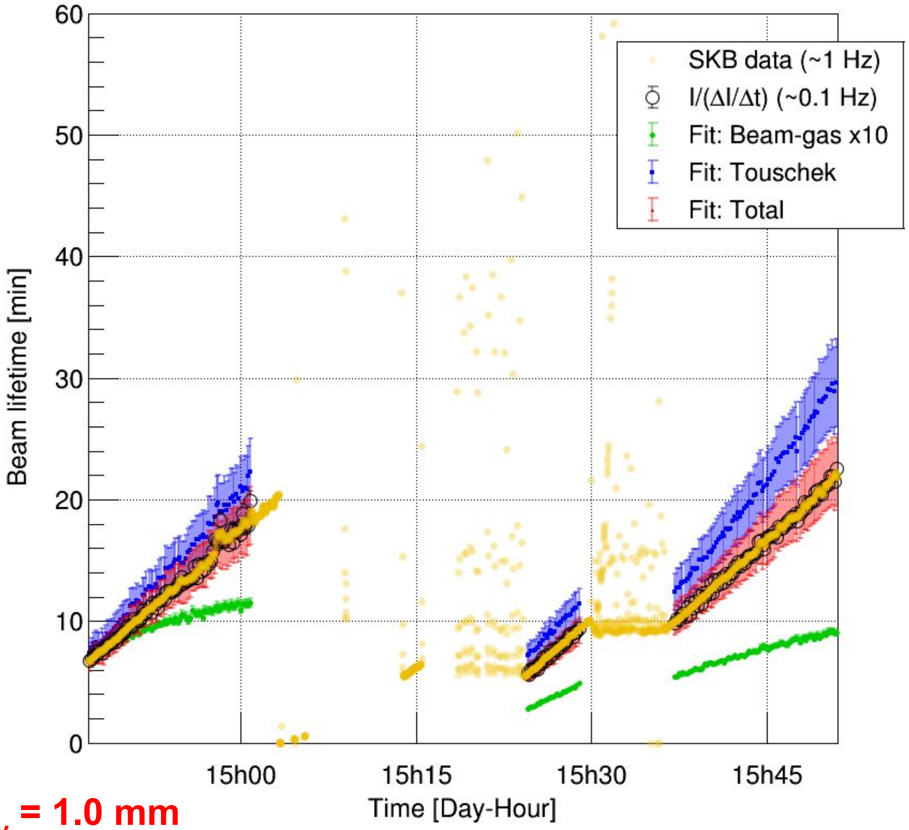


β^*_y = 0.8 mm

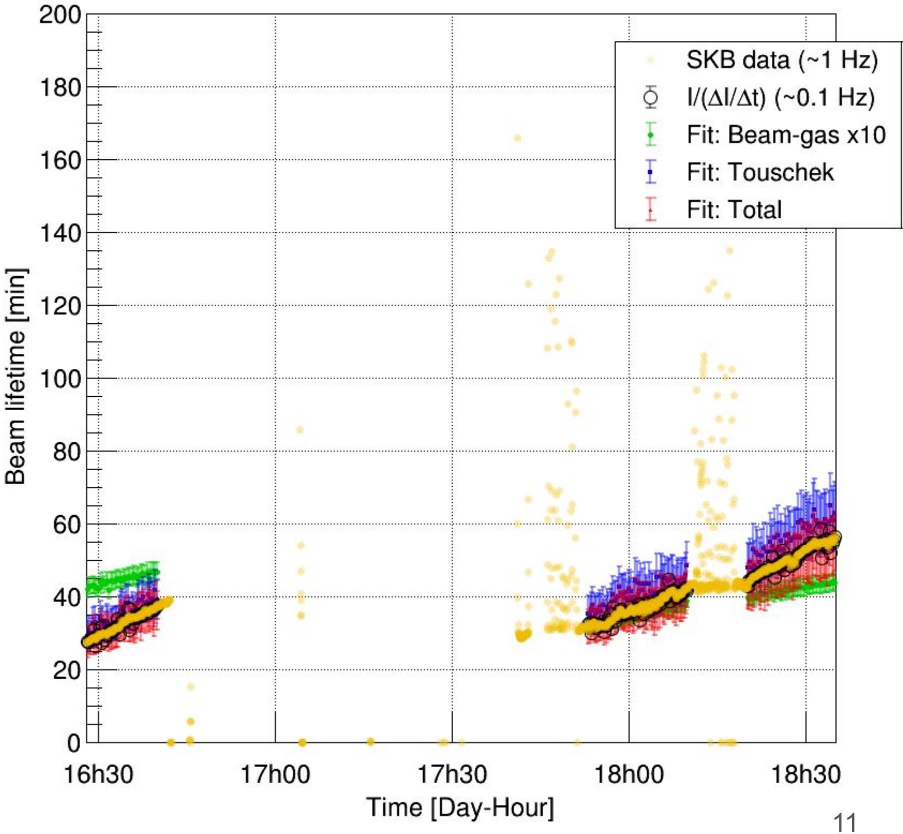
$$-\frac{\Delta I}{\Delta t} = B \times I\overline{P}_{\mathrm{eff.}} + T \times \frac{I^2}{n_{\mathrm{b}}\sigma_{\mathrm{x}}\sigma_{\mathrm{y}}\sigma_{\mathrm{z}}}$$

Beam lifetime estimation for June 2021

LER: B = 4.12e-04 +/- 2.43e-06 | T = 9.67e+03 +/- 1.36e+01



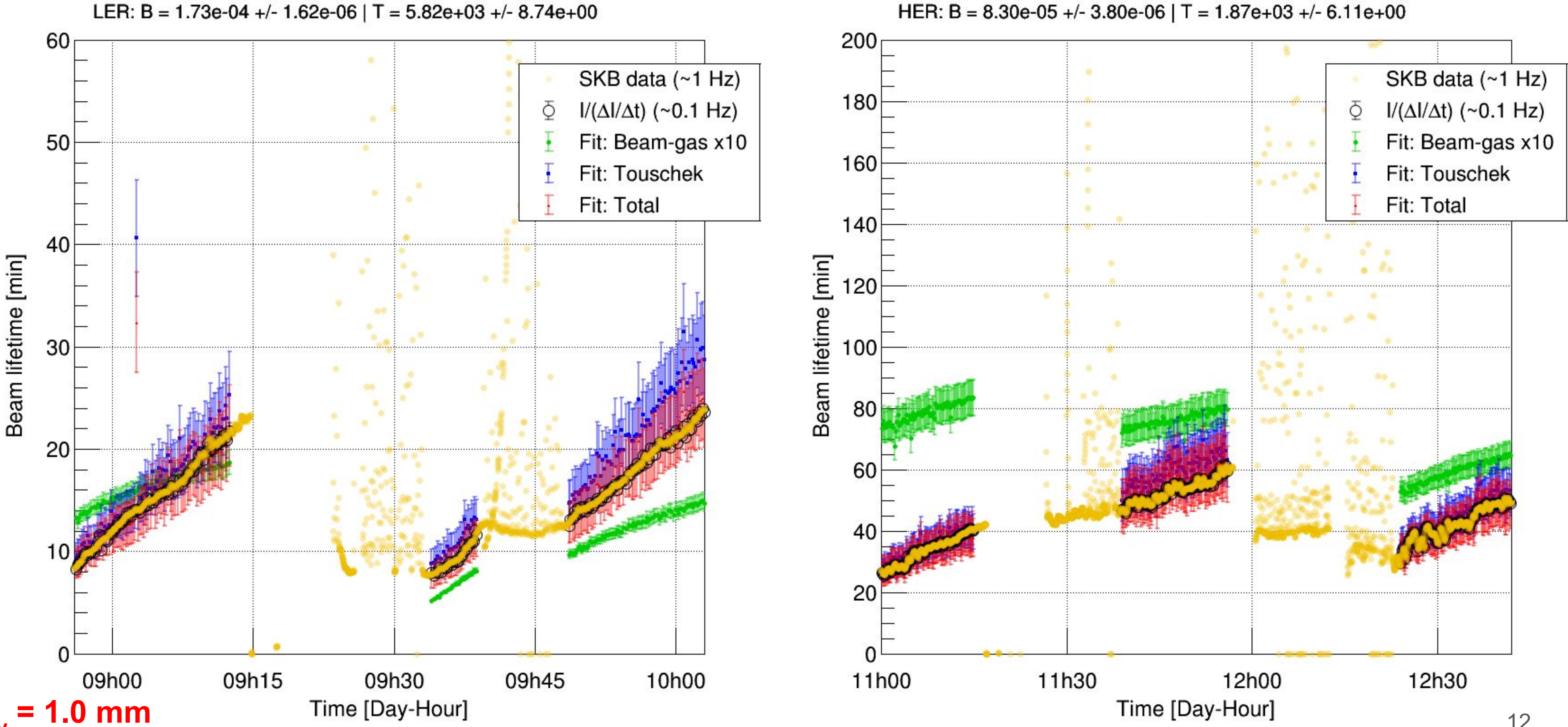
HER: B = 1.43e-04 +/- 4.45e-06 | T = 1.62e+03 +/- 5.81e+00



β^*_y = 1.0 mm

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

Beam lifetime estimation for December 2021



β^*_y = 1.0 mm

Experimental data fit (EXP) VS SAD simulation (SIM)

EXP uncertainty source: fit parameters (B, T) & vacuum pressure (P_0, dP/dI)
SIM uncertainty source: statistics

May 2020

Beam-gas LER:	EXP = 7.277 +/- 6.745 [min]	SIM = 25.471 +/- 0.243 [min]	EXP/SIM = 0.286 +/- 0.265
Touschek LER:	EXP = 5.173 +/- 0.006 [min]	SIM = 6.749 +/- 0.008 [min]	EXP/SIM = 0.766 +/- 0.001
Beam-gas HER:	EXP = 100.368 +/- 78.485 [min]	SIM = 298.516 +/- 3.135 [min]	EXP/SIM = 0.336 +/- 0.263
Touschek HER:	EXP = 37.929 +/- 0.057 [min]	SIM = 59.054 +/- 0.114 [min]	EXP/SIM = 0.642 +/- 0.002

June 2020

Beam-gas LER:	EXP = 11.023 +/- 10.019 [min]	SIM = 32.592 +/- 0.273 [min]	EXP/SIM = 0.338 +/- 0.307
Touschek LER:	EXP = 8.722 +/- 0.018 [min]	SIM = 13.985 +/- 0.023 [min]	EXP/SIM = 0.624 +/- 0.002
Beam-gas HER:	EXP = 52.044 +/- 38.692 [min]	SIM = 334.795 +/- 3.292 [min]	EXP/SIM = 0.155 +/- 0.116
Touschek HER:	EXP = 33.656 +/- 0.064 [min]	SIM = 45.126 +/- 0.275 [min]	EXP/SIM = 0.746 +/- 0.005

June 2021

Beam-gas LER:	EXP = 19.764 +/- 17.721 [min]	SIM = 60.807 +/- 0.443 [min]	EXP/SIM = 0.325 +/- 0.291
Touschek LER:	EXP = 6.390 +/- 0.009 [min]	SIM = 15.716 +/- 0.018 [min]	EXP/SIM = 0.407 +/- 0.001
Beam-gas HER:	EXP = 238.081 +/- 151.571 [min]	SIM = 660.056 +/- 5.382 [min]	EXP/SIM = 0.361 +/- 0.230
Touschek HER:	EXP = 27.929 +/- 0.100 [min]	SIM = 46.505 +/- 0.138 [min]	EXP/SIM = 0.601 +/- 0.003

December 2021

Beam-gas LER:	EXP = 38.354 +/- 36.346 [min]	SIM = 34.968 +/- 0.291 [min]	EXP/SIM = 1.097 +/- 1.039
Touschek LER:	EXP = 10.614 +/- 0.016 [min]	SIM = 15.659 +/- 0.017 [min]	EXP/SIM = 0.678 +/- 0.001
Beam-gas HER:	EXP = 450.678 +/- 274.018 [min]	SIM = 760.409 +/- 4.992 [min]	EXP/SIM = 0.593 +/- 0.360
Touschek HER:	EXP = 24.107 +/- 0.079 [min]	SIM = 46.554 +/- 0.136 [min]	EXP/SIM = 0.518 +/- 0.002

Assumptions, uncertainties, and improvements

Heuristic fit formula:

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

- 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 → $\sigma^{corr} = (\sigma^2 - \Delta\sigma^2)^{1/2}$ [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 timestamp, 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