Machine induced background study and simulation optimization during the commissioning run of the SuperKEKB accelerator

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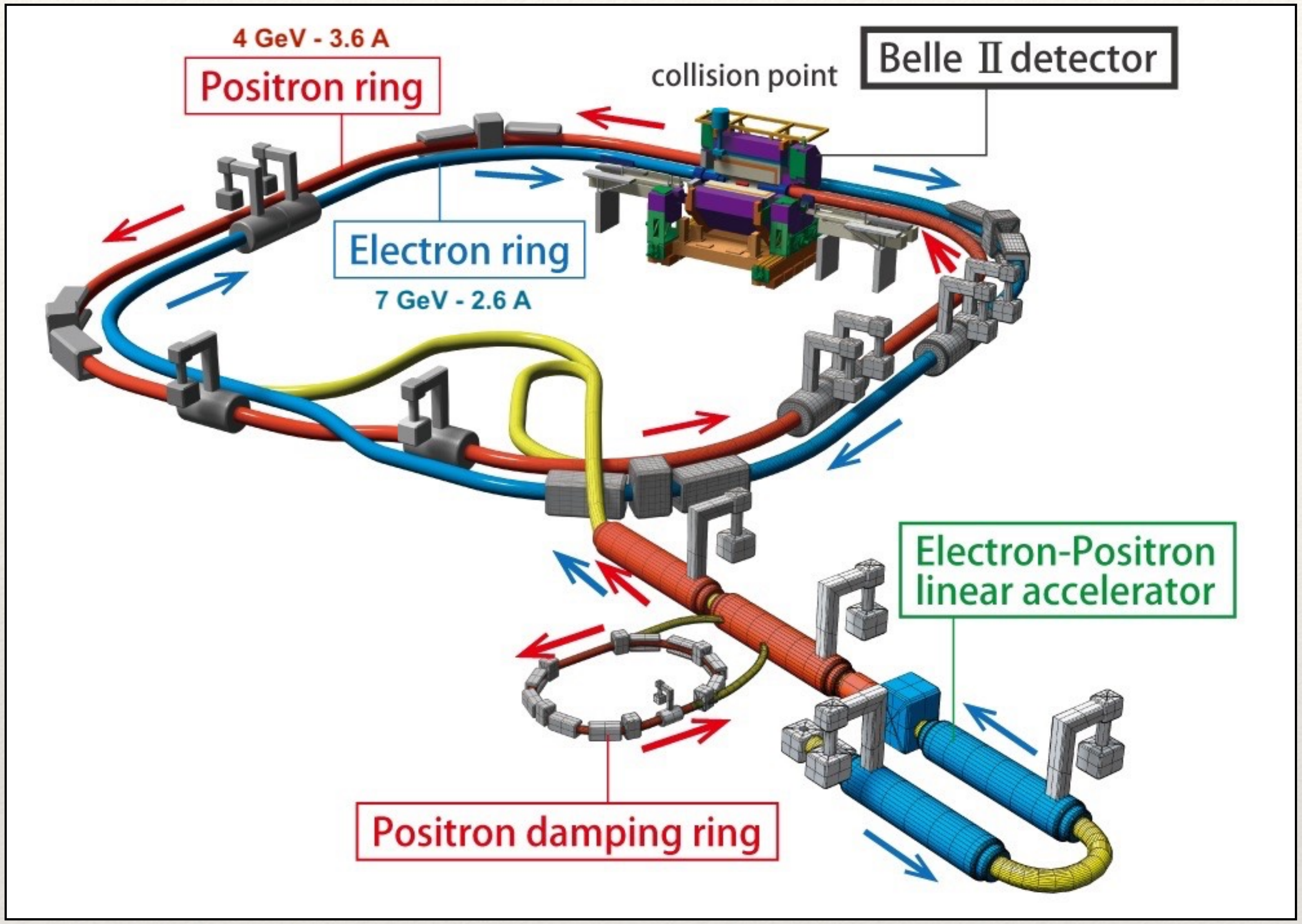
OUTLINE

- Machine and Detector overview
  - SuperKEKB
  - Belle II and BEAST II
- Collimators
  - Phase 2 setup
  - Simulation study
  - Phase 2 operation study

SuperKEKB



The SuperKEKB accelerator is located in Tsukuba, Japan.

It is an asymmetric electron-positron collider that aims to reach the unprecedented instantaneous luminosity of 8×10^{35} cm^{-2} s^{-1}.

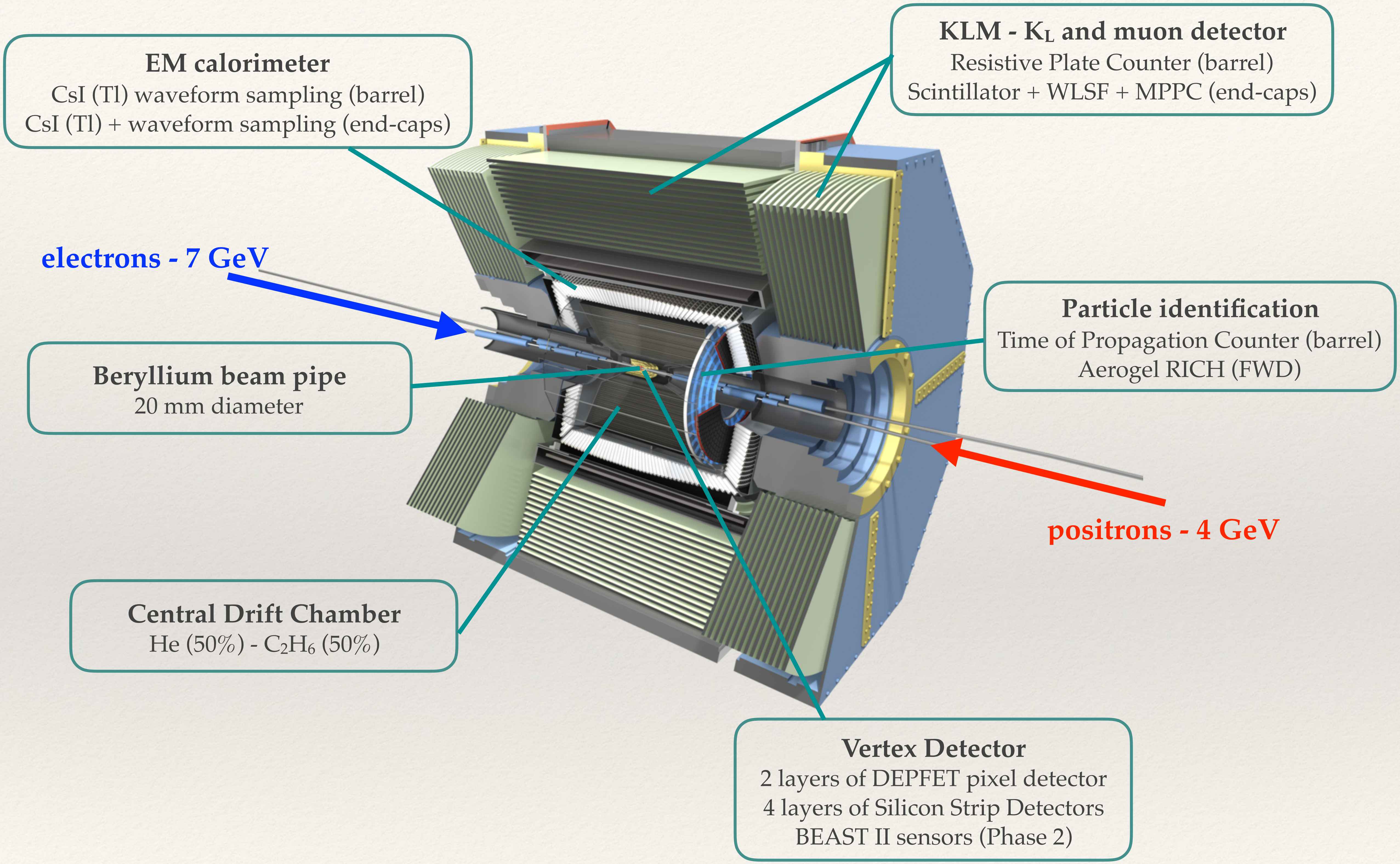
The Belle II experiment targets a total integrated luminosity of about 50 ab^{-1} in ten years of data taking.

- $E_{CM} = 10.58$ GeV, $\Upsilon(4S)$

3 commissioning phases:

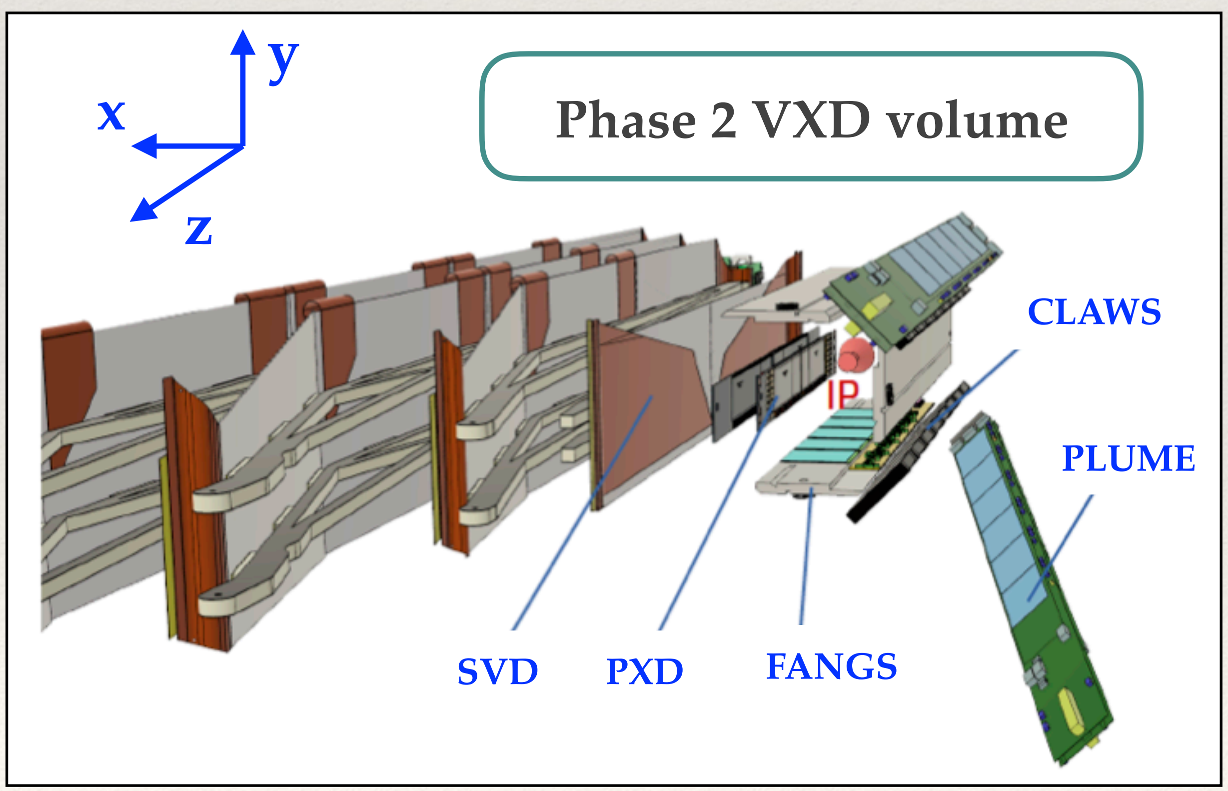
- Phase 1: no Belle II detector, no Final Focus system, no collisions.
- Phase 2: Belle II detector in its final position, Final Focus system in place and collisions, VXD volume with BEAST II detectors.
- Phase 3: full Belle II detector, physics runs.

The Belle II detector



BEAST II detectors

- FANGS - hybrid silicon pixel detectors.
- CLAWS - plastic scintillators with SiPM readout.
- PLUME - double sided CMOS pixel sensors.
- Diamond sensors for ionizing radiation dose monitoring in the IR.
- PIN diodes for ionizing radiation dose monitoring around Superconducting magnets of the Final Focus system (QCS).
- ^{3}He detectors for thermal neutron flux measurements.
- TPC detectors for fast neutron flux and direction measurements.



Goal for Phase 2: separate each background component, in order to validate the simulation and reliably extrapolate background levels to Phase 3.

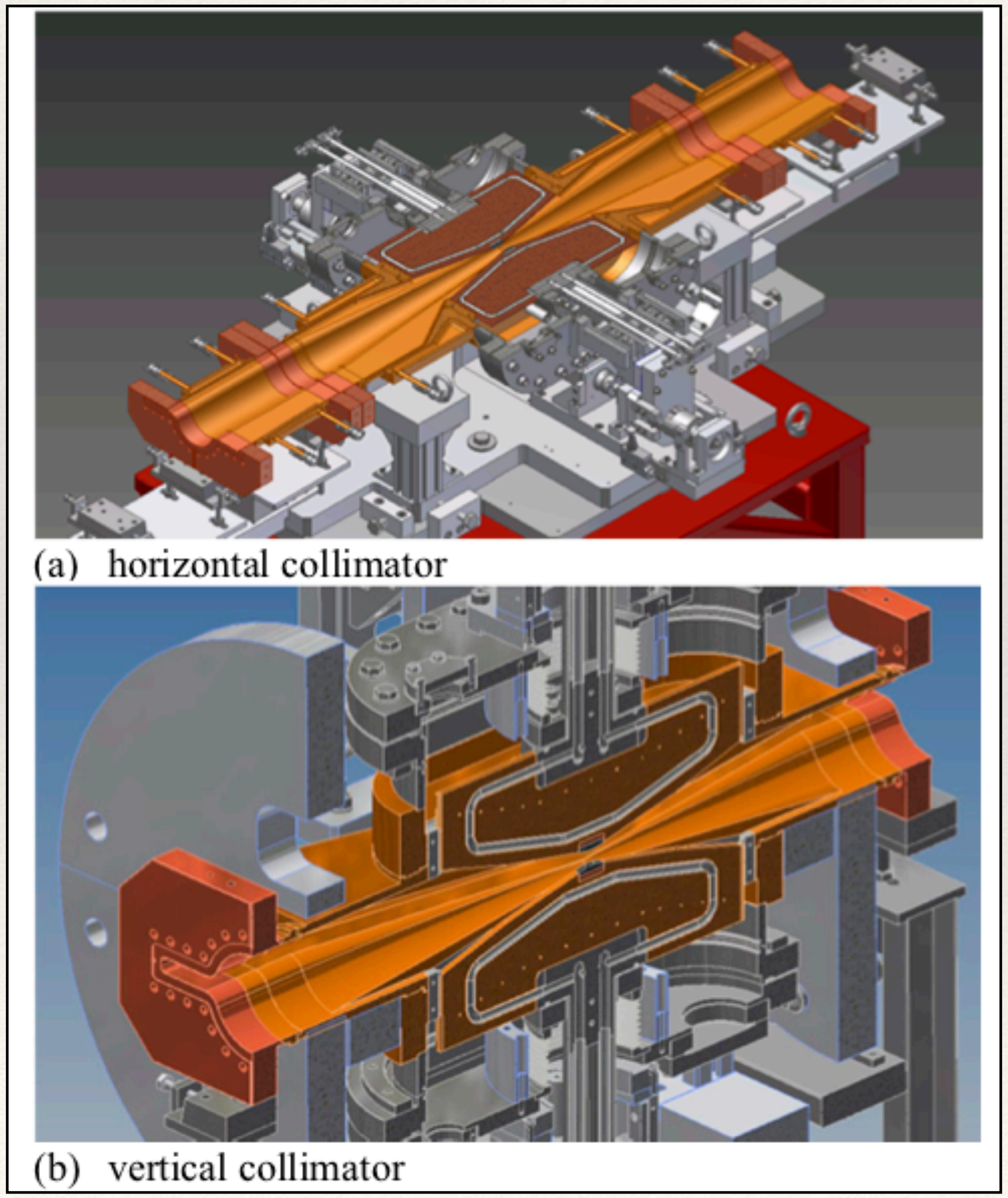
Background sources

Touschek scattering: single Coulomb scattering event. Phase 1: measured, consistent with simulation.	$R_{Tou} \propto \frac{1}{\sigma} E^3 n_b I^2_{beam}$
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 (SR): 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)	

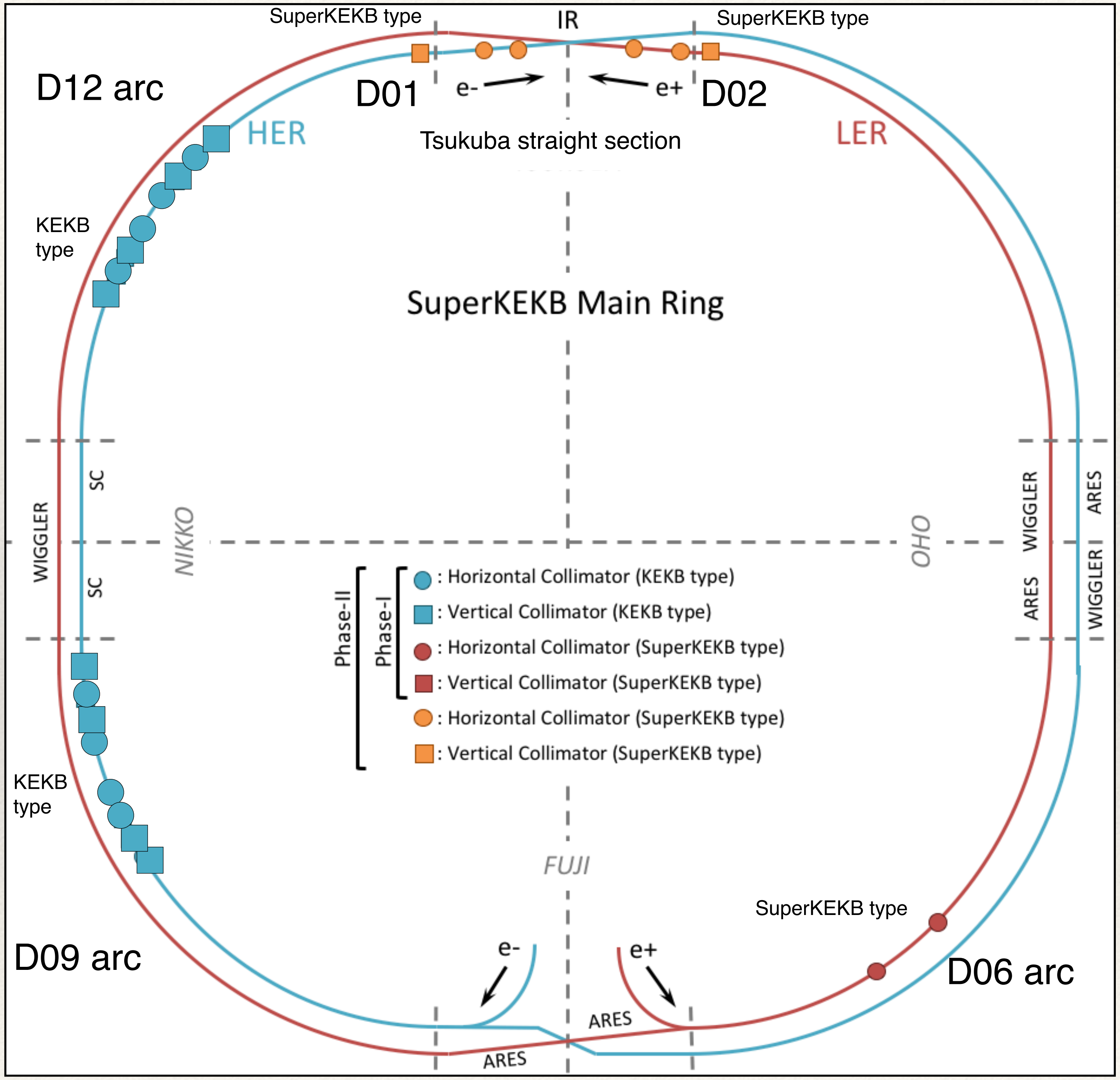
Collimators in Phase 2

IR Touschek, beam-gas and injection backgrounds can be sensibly reduced with collimators.

- KEKB type: only one movable jaw
- SuperKEKB type: two independent movable jaws, lower impedance.


(a) horizontal collimator

(b) vertical collimator

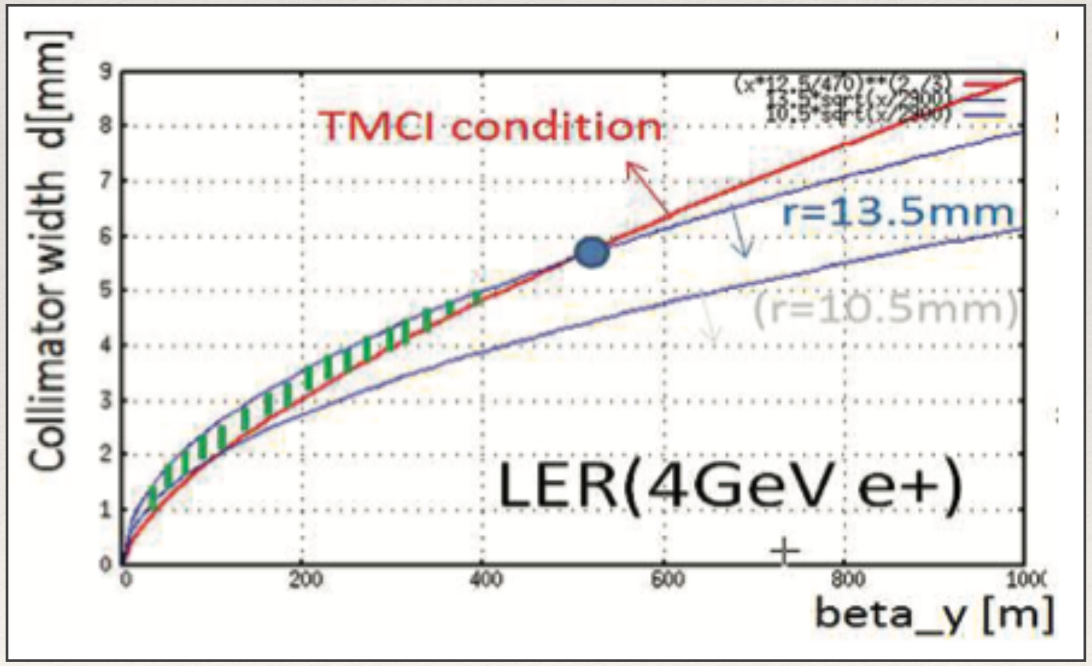


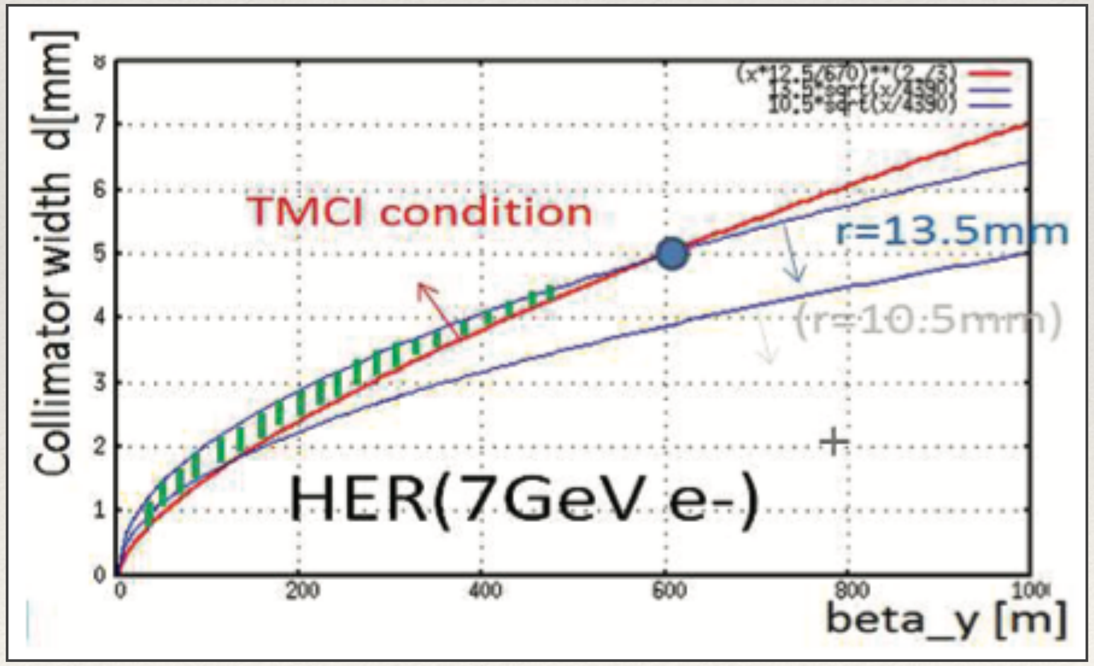
Collimators positioning

- Horizontal collimators are positioned where β_x is large. Collimator physical aperture defined by: $d/\sqrt{\varepsilon\beta_{coll}} \leq r_{IR}/\sqrt{\varepsilon\beta_{IR}}$
  Fixing the right side of the equation, the maximum aperture is given by: $d_{max} \propto \beta^{1/2}$

- For vertical collimators, position is determined also by Transverse Mode Coupling (TMC) instability condition, that is derived from bunch current threshold condition:

$$I_{thresh} = \frac{C_1 f_s E/e}{\Sigma \beta_y k_y \sigma_z} \longrightarrow d_{min} \propto \beta^{2/3} \qquad k = 0.215 A Z_0 c \sqrt{\frac{\theta_{slope}}{\sigma_z d^3}}$$





See: H. Nakayama et al., "Small-Beta Collimation at SuperKEKB to Stop Beam-Gas Scattered Particles and to Avoid Transverse Mode Coupling Instability," Conf. Proc. C **1205201**, 1104 (2012).

Collimator study with simulation

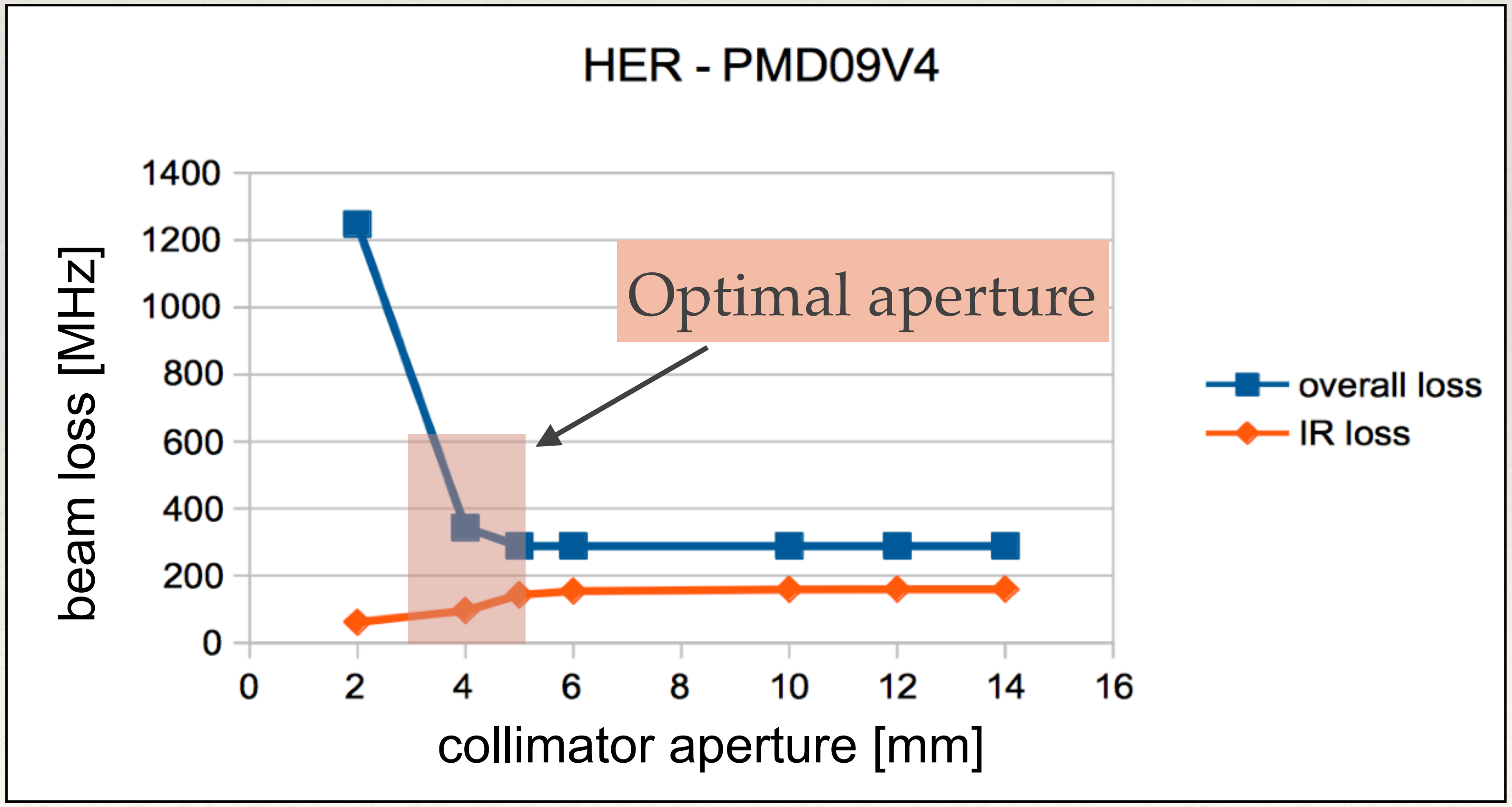
- Simulation performed with Strategic Accelerator Design (SAD) code.
- Simulation with single beams, tracking a full bunch of particles.
- Results are scaled to the actual number of bunches of each optics.
- One background source at a time: Touschek, beam gas Coulomb scattering and bremsstrahlung.
- All data are collected together to find the overall losses in the ring and the losses in the interaction region (IR).
  - Overall losses used to estimate beam lifetime
  - IR losses used to estimate beam background

GOAL: reduce IR losses to a few tens of MHz keeping lifetime as long as possible. For Phase 3, losses on each collimator should be less than 100 GHz.

Collimator study with simulation - strategy

- Starting point: all collimators fully open.
- Close one collimator at a time, in steps, and observe the changes in background level and beam lifetime.
- Find the optimal collimators aperture: reduction in IR losses keeping beam lifetime (almost) unchanged.
- Run another simulation using optimized collimator apertures and observe the overall effect.
- Use the optimized configuration as a starting point for a second iteration of the same procedure.

Results of simulation for one of the vertical collimators, for different apertures.



Collimator study with simulation - results

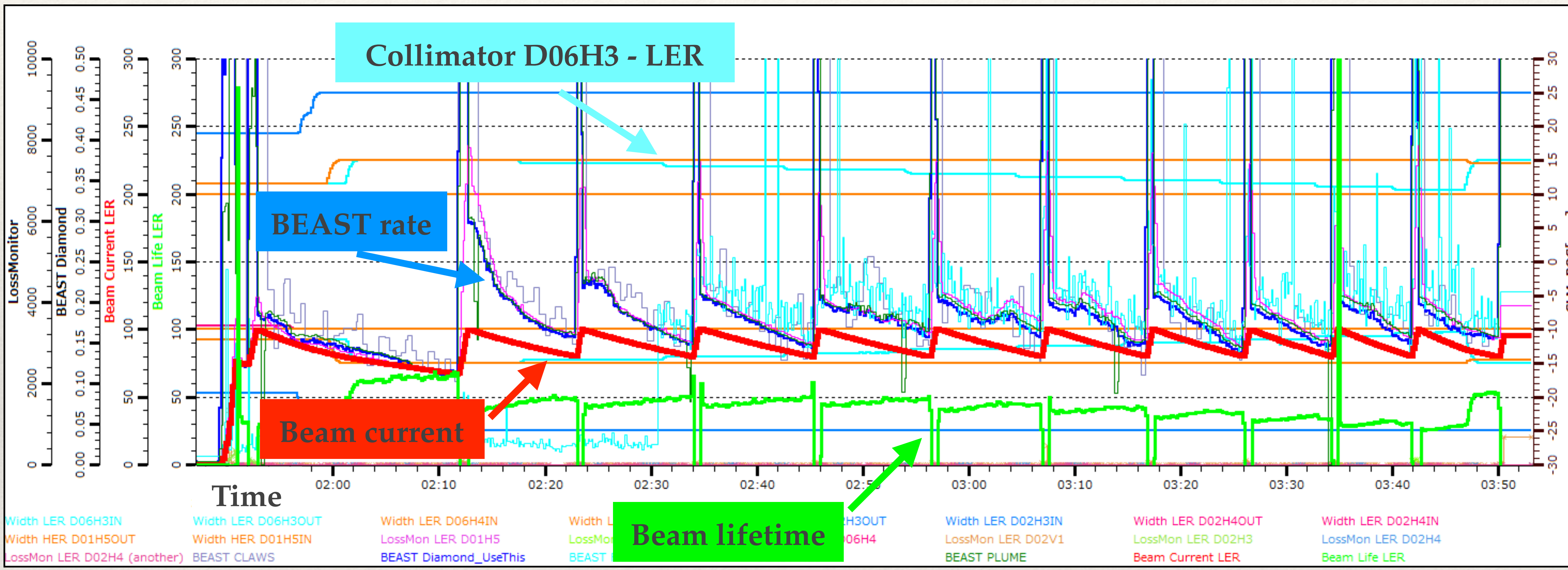
- Collimator study performed for nominal parameters of Phase 2.
- Repeated for Phase 2.1.7 - the one adopted for real collimators study and for most of the other background studies.

	LER		HER	
Collimators	beam lifetime [min]	IR losses [MHz]	beam lifetime [min]	IR losses [MHz]
Fully open	16.4	1406	74.0	841
Optimized	10.2	90	69.0	6
Parameter				
I_{beam} [mA]	302		251	
n. of bunches	789		789	
tot n. of particles	18.8×10^{12}		15.7×10^{12}	
β_x^* [mm]	200		100	
β_y^* [mm]	3		3	

- The output of the simulation gives position and momentum of particles lost in the IR. This is used as an input for the GEANT4 simulation, where the geometry of the Belle II detector is implemented and the effect of particles lost in the IR can be evaluated.

Collimator study during Phase 2

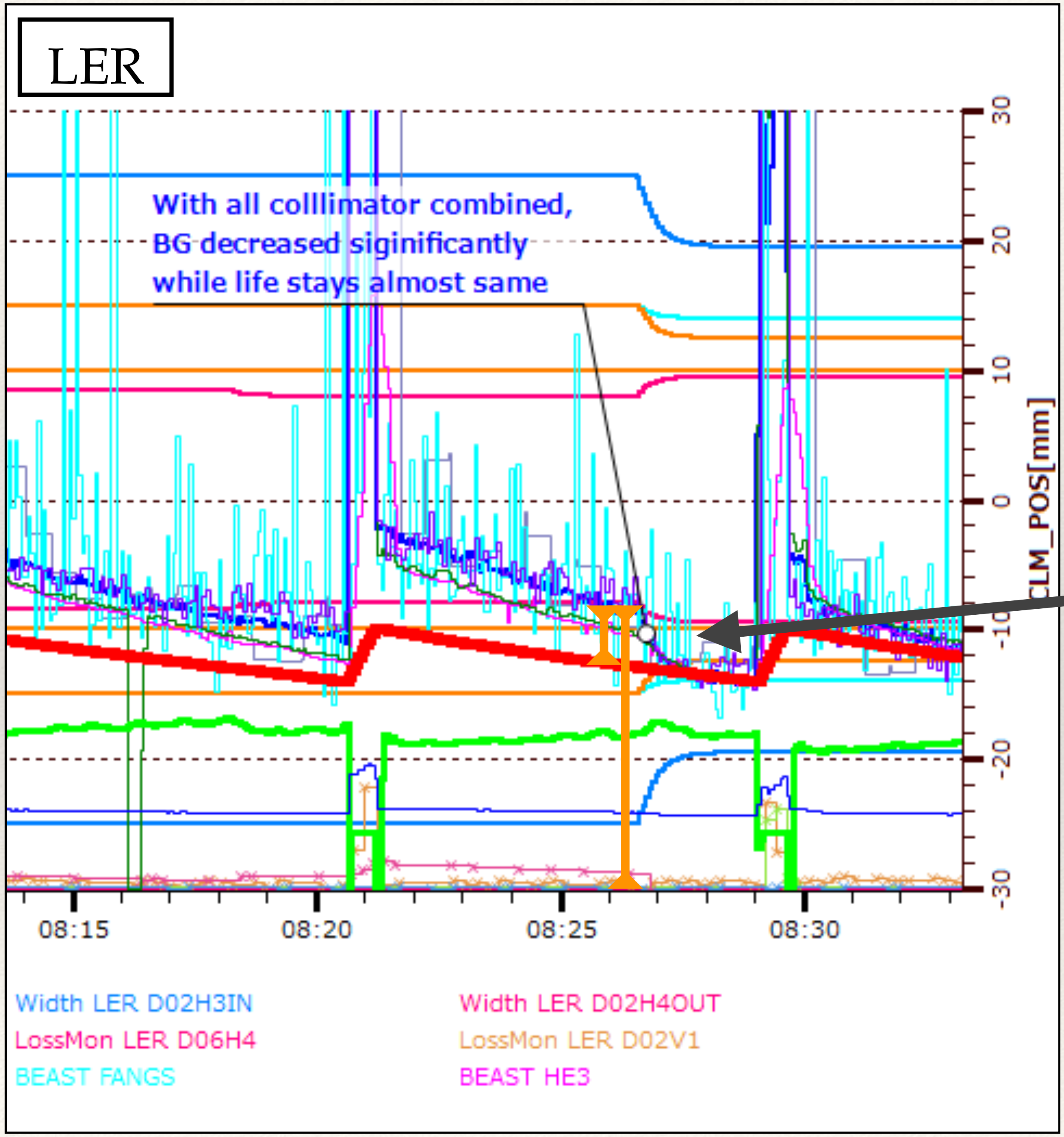
- Strategy similar to the study based on simulation: from an "open" collimators configuration, gradually close each collimator individually to find the best compromise between background level and beam lifetime.



- Collimators closed in step of 0.5 mm.
- Study performed only on horizontal collimators, no time available for studies on vertical collimators.

BG reduction after collimator study

- After closing collimators individually, all collimators were closed at the same time to their optimised aperture —> reduction in IR background clearly visible.



At the end of a collimator study, all collimators were opened as in the initial configuration, and then closed all together to their optimised aperture. A reduction in the background level is observed. No significant change in beam lifetime.

Around 20% reduction in background level

Comparison between simulation and data

- Comparison between data and simulation has been done by BEAST and Belle II sub-detectors, and for HER there is a big discrepancy in background levels O(100-1000).
- To understand where this comes from, I run the simulation with two different collimator settings: before and after the collimator studies done in Phase 2.

	LER		HER	
Collimators	beam lifetime [min]	IR losses [MHz]	beam lifetime [min]	IR losses [MHz]
Open (oper.)	13.5	158	67	14
Optimized (oper.)	10.1	150	53	5.4
Fully open (sim)	16.4	1406	74.0	841
Optimized (sim)	10.2	90	69.0	6

- For LER, the simulated background reduction is about 5%, while during operation the reduction was about 20%.
- The difference between the two optimized configuration for LER comes from beam-gas component: no optimization done on vertical collimators during operation.
- For HER, simulated background reduction of almost a factor 3, while during operation it was almost a factor 2.

Next steps

- Understand where the discrepancy between data and simulation of 2-3 orders of magnitude comes from, and if needed modify the simulation to reproduce experimental data.

- Simulation for beginning of Phase 3, with optics similar to the end of Phase 2 and additional collimators for LER that will be installed soon.
- Simulation for nominal parameters of Phase 3, adding even more collimators on LER to improve background reduction. To be used to decide where to install additional collimators in the next years.

- Collimators studies foreseen at the beginning of Phase 3, together with other background studies.
- Collimators studies to be done constantly during Phase 3, especially when changes in optics are done.

Thank you!

Backup slides

Machine parameters - SuperKEKB

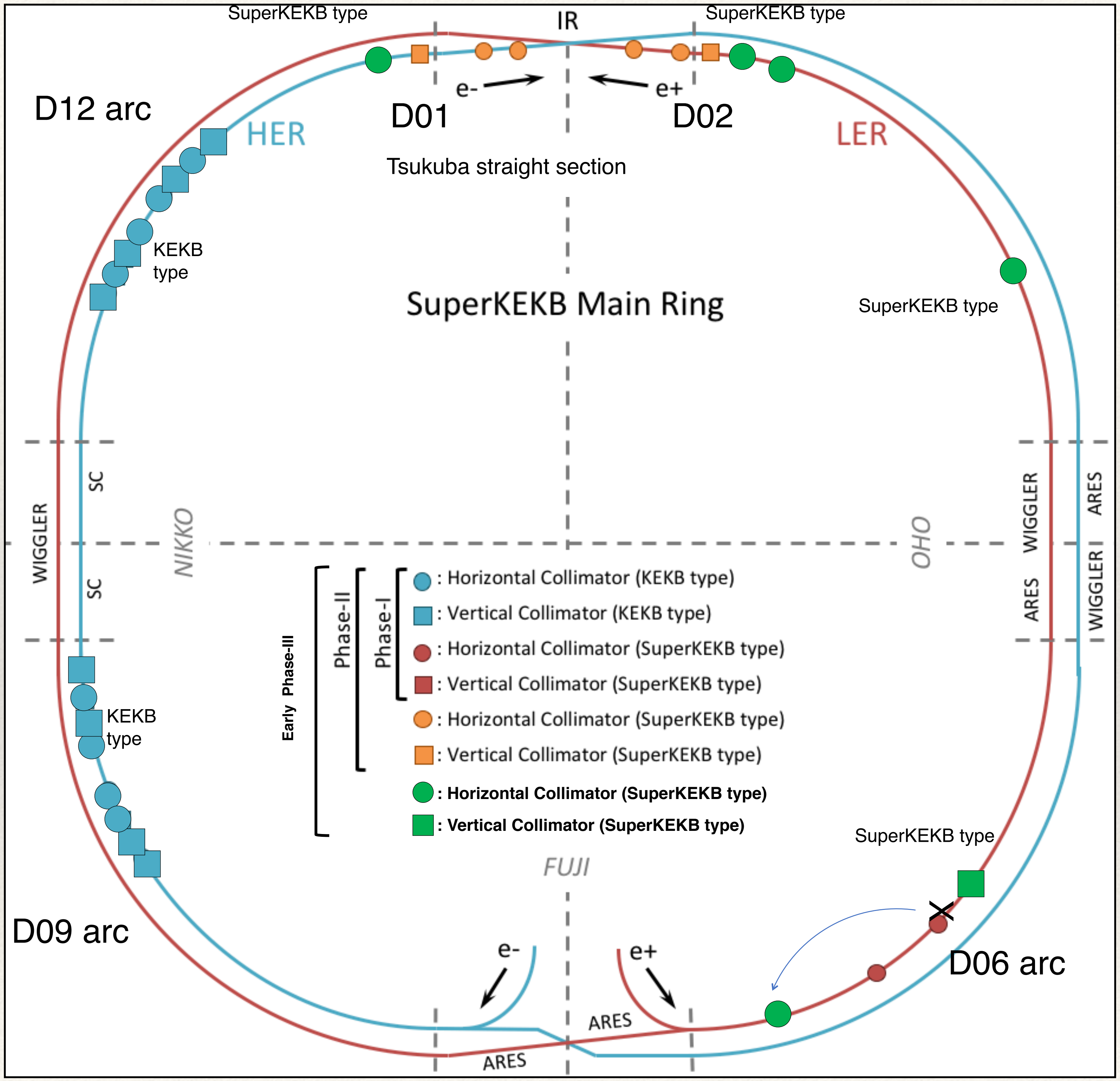
2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	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 parameters - KEKB/SuperKEKB

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}		$cm^{-2}s^{-1}$

Collimators location - early Phase 3



Collimators in Phase 2 operation

- To adjust collimators, the physical aperture of Final Focus magnets (QC1 and QC2) in terms of number of σ_x has to be considered:
  - Collimators with larger $N\sigma_x$ than QC1/QC2 can be closed without loosing lifetime.
  - Closing collimators at same (or more) $N\sigma_x$ as QC1/QC2 helps avoiding QCS quenches

HER	SetPos [mm]	beta_x [m]	nu_x	Nsigma
D09H1	-10.00	39.7	15.98	**23.4**
D09H2	-11.00	39.7	15.49	**25.7**
D09H3	-13.00	39.7	14.83	**30.4**
D09H4	-13.00	39.7	14.34	**30.4**
D12H1	-12.50	39.7	8.73	**29.2**
D12H2	-12.50	39.7	8.24	**29.2**
D12H3	-13.00	39.7	7.58	**30.4**
D12H4	-15.00	39.7	7.09	**35.1**
D01H4OUT	18.00	27.6	0.51	**50.5**
D01H4IN	-18.00	27.6	0.51	**50.5**
D01H5OUT	9.50	19.3	0.29	**31.9**
D01H5IN	-9.50	19.3	0.29	**31.9**
QC2 (-2.9m)	35.0	249.6	0.24	**32.7**

Cannot be reduced more because of too much losses during injection

LER	SetPos [mm]	beta_x [m]	nu_x	Nsigma
D06H3OUT	14.00	24.2	26.22	**62.0**
D06H3IN	-14.00	24.2	26.22	**62.0**
D06H4OUT	12.50	24.2	26.70	**55.4**
D06H4IN	-12.50	24.2	26.70	**55.4**
D02H3OUT	19.50	120.6	43.54	**38.7**
D02H3IN	-19.50	120.6	43.54	**38.7**
D02H4OUT	9.50	10.5	44.23	**64.1**
D02H4IN	-9.50	10.5	44.23	**64.1**
QC1 (1.18m)	10.5	12.9	44.34	**63.8**

β_x large during Phase 2, even with collimator fully open $N\sigma_x$ is smaller than QC1