Machine induced background study and simulation optimization at the SuperKEKB accelerator

Antonio Paladino - 2019/11/12
PhD in Accelerator Physics

OUTLINE

- Machine and Detector overview
  - SuperKEKB
  - Belle II and BEAST II
- The SAD tracking simulation
- Collimators studies:
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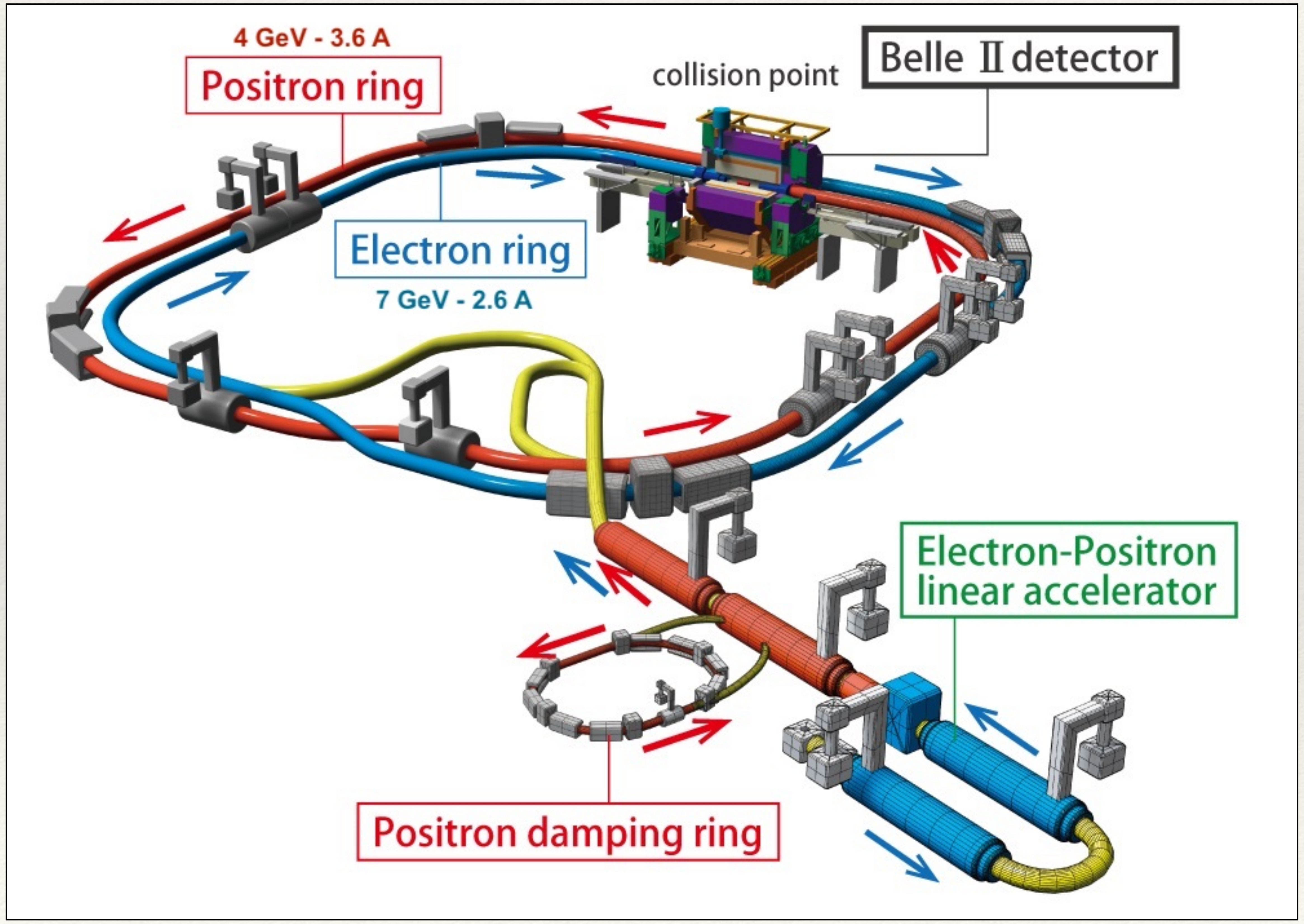
  - Spring 2019 run
  - Study for Fall 2019 run
  - Study for final machine parameters

The SuperKEKB accelerator

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

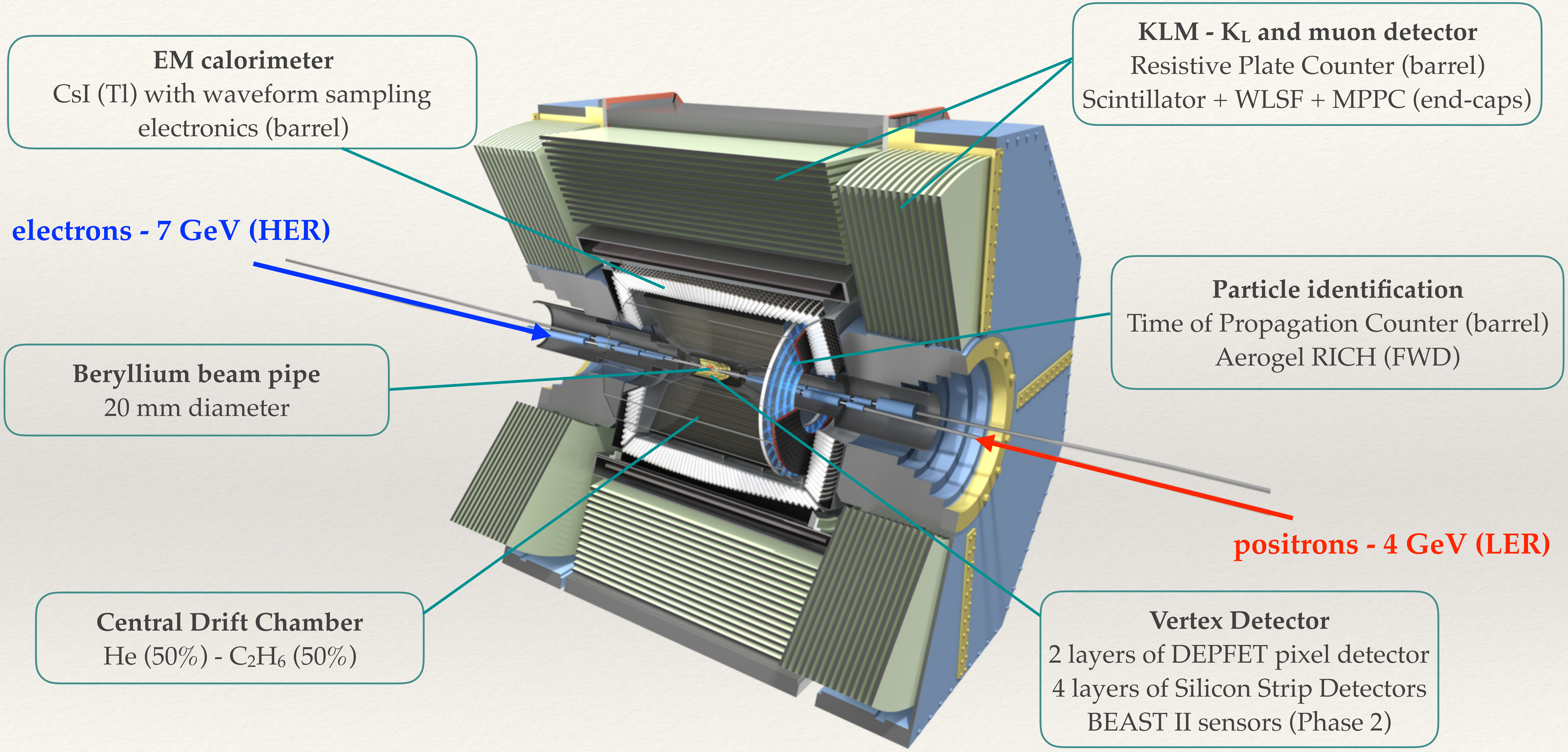
The Belle II experiment targets a total integrated luminosity of about 50 ab^{-1} in ten years of data taking.



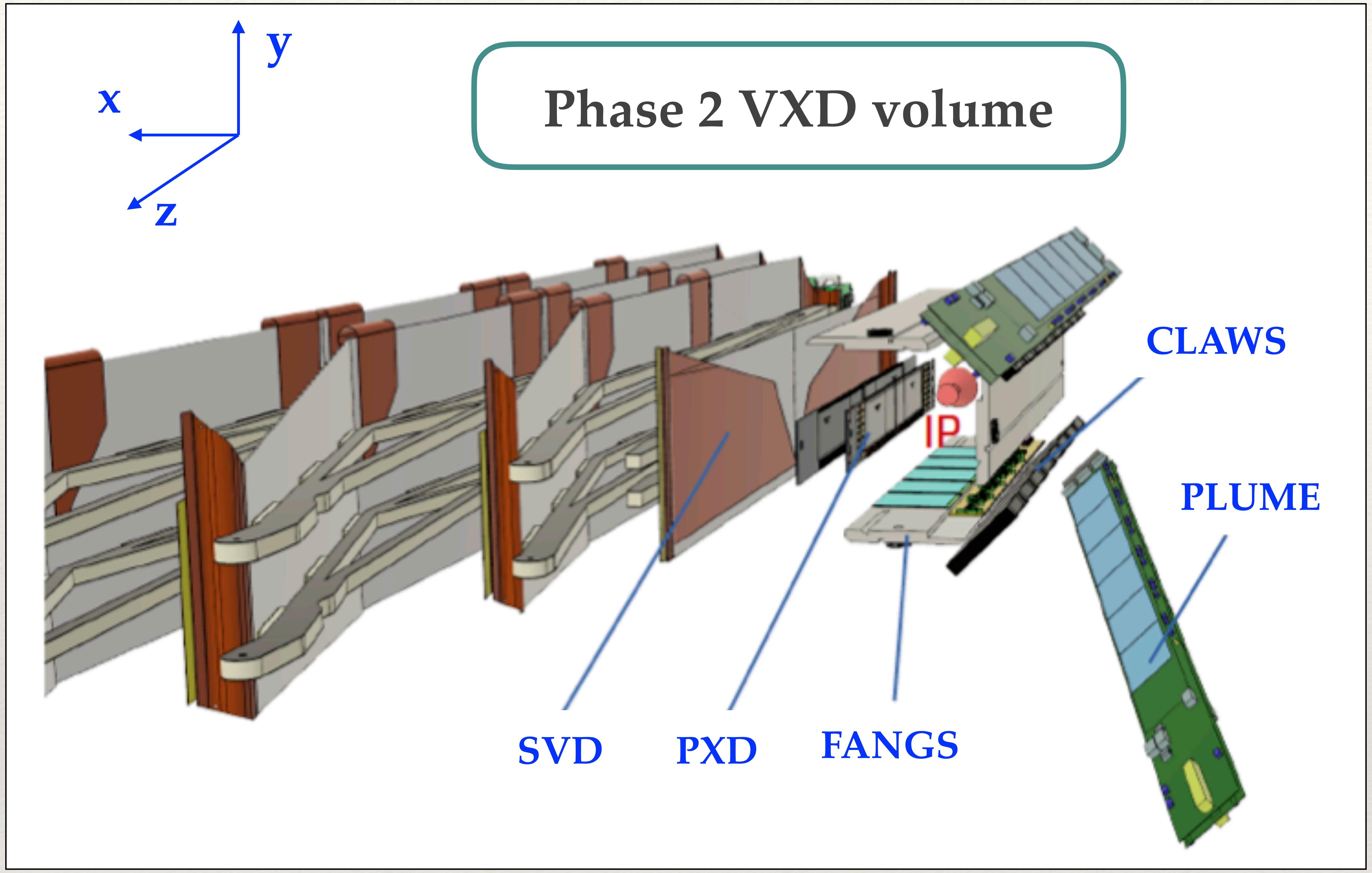
3 commissioning phases:

- Phase 1 - 2016: no Belle II detector, no Final Focus system, no collisions.
- Phase 2 - 2018: Belle II detector in its final position, Final Focus system in place and collisions, VXD volume with BEAST II detectors.
- Early Phase 3 - March-July 2019: full Belle II detector, physics runs, relaxed optics and low currents.
- Phase 3 - Fall 2019-2027: full Belle II detector, physics runs, full peak luminosity to be reached by 2025.

The Belle II detector



BEAST II detectors



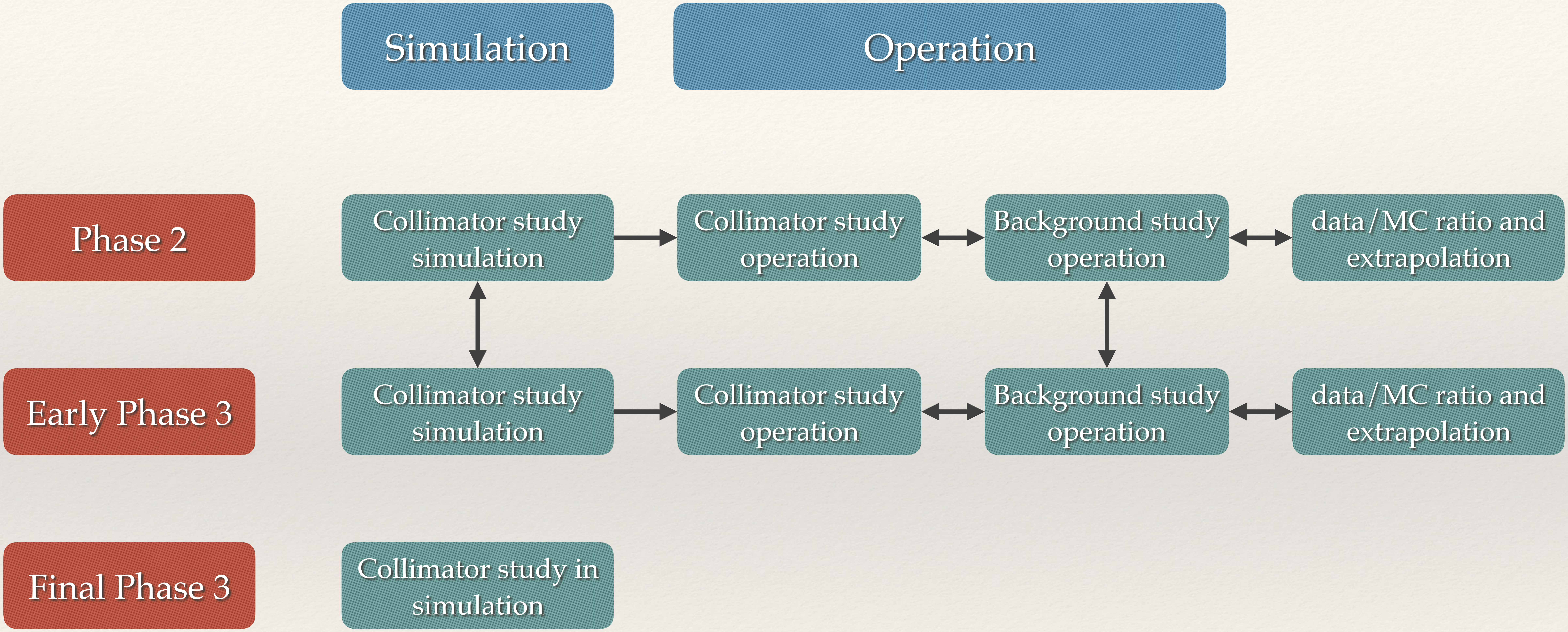
- FANGS - hybrid silicon pixel detectors.
- CLAWS - plastic scintillators with SiPM readout.
- PLUME - double sided CMOS pixel sensors.
- Diamond sensors for ionizing radiation dose monitoring in the IR.
- PIN diodes for ionizing radiation dose monitoring around Superconducting magnets of the Final Focus 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 between two particles of the same bunch, that are lost.	$R_{Tou} \propto \frac{1}{\sigma}\frac{1}{E^3} n_b I^2_{beam}$
Beam-gas scattering: Coulomb elastic scattering or bremsstrahlung with residual gas atoms.	$R_{bg} \propto IP$
Synchrotron Radiation (SR): photon emission from beam particles when subject to acceleration.	$P_{SR} \propto \frac{E^4}{\rho^2}$
Radiative Bhabha: neutron production from emitted photons; off-energy primary particles lost in final focus magnets.	$R_{RB} \propto L$
Two photons process: low momentum electron-positron pairs that can generate multiple hit in the VerteX Detector.	$R_{tp} \propto L$
Injection background: injected bunch performing betatron oscillation around the stored bunch, resulting in particle losses especially in the interaction region.	$R_I \propto R_{inj}$

Steps of the studies



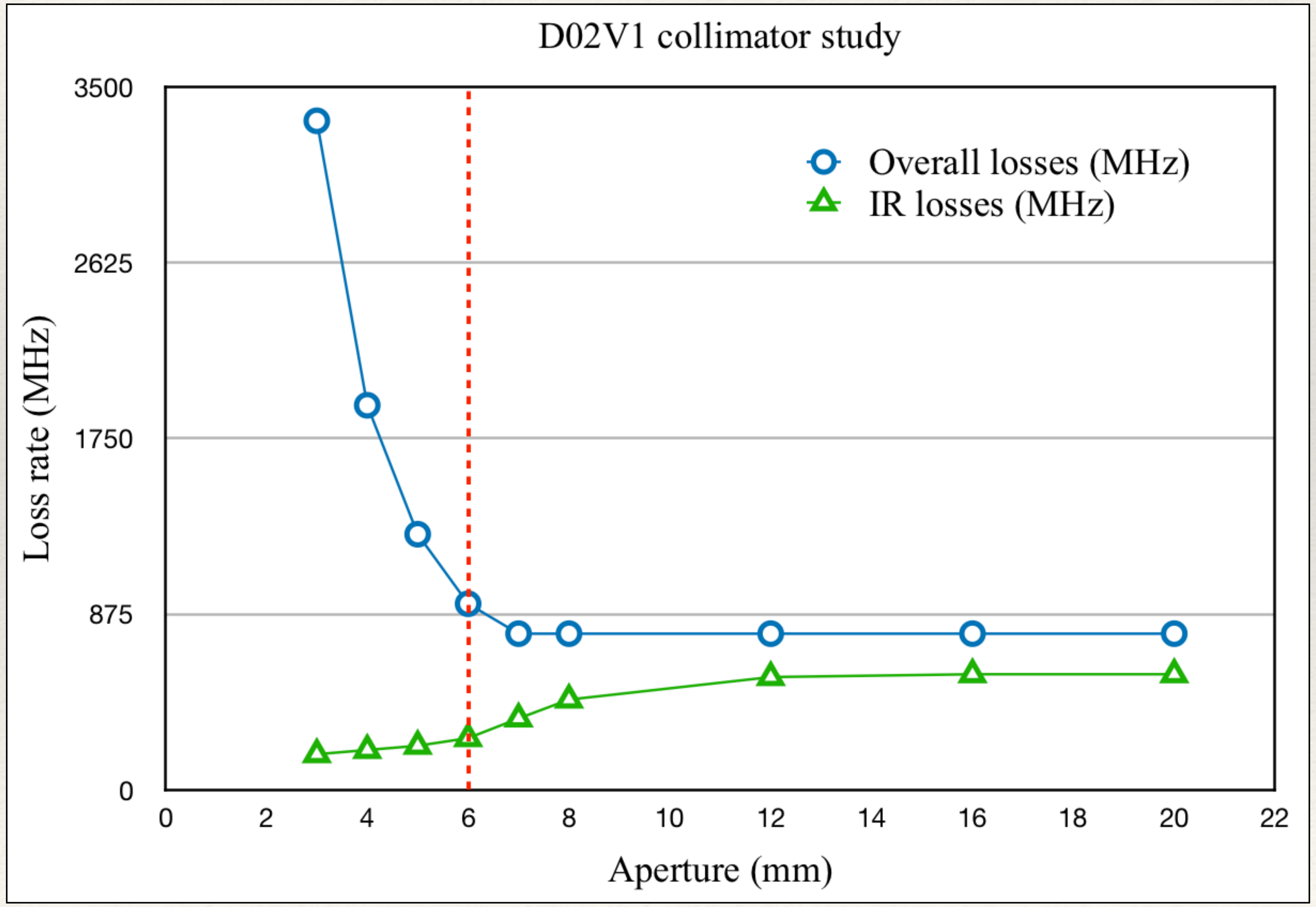
The SAD tracking simulation

- SAD (Strategic Accelerator Design) - integrated code developed at KEK, based on Fortran and C.
- Background simulation: 6D tracking simulation of macro-particles, with RF cavities, synchrotron radiation and intra-beam scattering enabled.
- Each macro-particle has 6 variables: x, y, z, p_x, p_y, δ, where x, y and z are the coordinates in the transverse and longitudinal directions, p_x and p_y are the canonical momenta normalised by the design momentum p_0, δ is the relative total-momentum deviation from the design momentum p_0.
- Three background sources simulated: Touschek, beam-gas Coulomb and beam-gas bremsstrahlung. Differential cross sections implemented in the simulation.
- Lattice divided in slices of 1 m length, except the interaction region, divided in 10 mm slices.
- SAD output used to run GEANT4 simulation, for the interaction of lost particles with the detector and other materials of the interaction region.

Collimators study - 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 collimator aperture: **reduction in IR losses ≥ increase overall losses**.
- Run full simulation with all collimators set at the optimal aperture.

- Two possibilities then:
  - **IR losses < 100 MHz**
    Optimization finished. Collimator setting considered optimal.
  - **IR losses > 100 MHz**
    Use optimised setting as a starting point for a second iteration, to further reduce IR losses, even affecting lifetime.



Constraints in collimators optimization

- Safety limit of 100 GHz on each collimator.
- Transverse Mode Coupling (TMC) instability:
  - A fast head-tail instability may occur when bunch current increases.
  - It depends on the kick factor, which depends on the aperture of an element.
  - Since the bunch current is fixed by machine parameters, the variable to be considered is the collimator aperture.
  - Limits are set to collimators apertures.

$$I_{thr} = \frac{C_1 f_s E/e}{\sum_i \beta_i \kappa_{\perp i}(\sigma_z)}$$

- Expressing collimators apertures in terms of beam size (σ), including dispersion, collimators apertures should satisfy the following condition:

$$(n_\sigma)_{coll} \leq (n_\sigma)_{QCS} \qquad \sigma_x(s) = \sqrt{\beta_x(s) \cdot \varepsilon_x + (\eta_x(s) \cdot \sigma_\delta)^2}$$

- Phase advance wrt narrowest point in the interaction region is also important. If $\Delta\nu = 0.5 \cdot n$ the collimator is more effective to reduce losses.

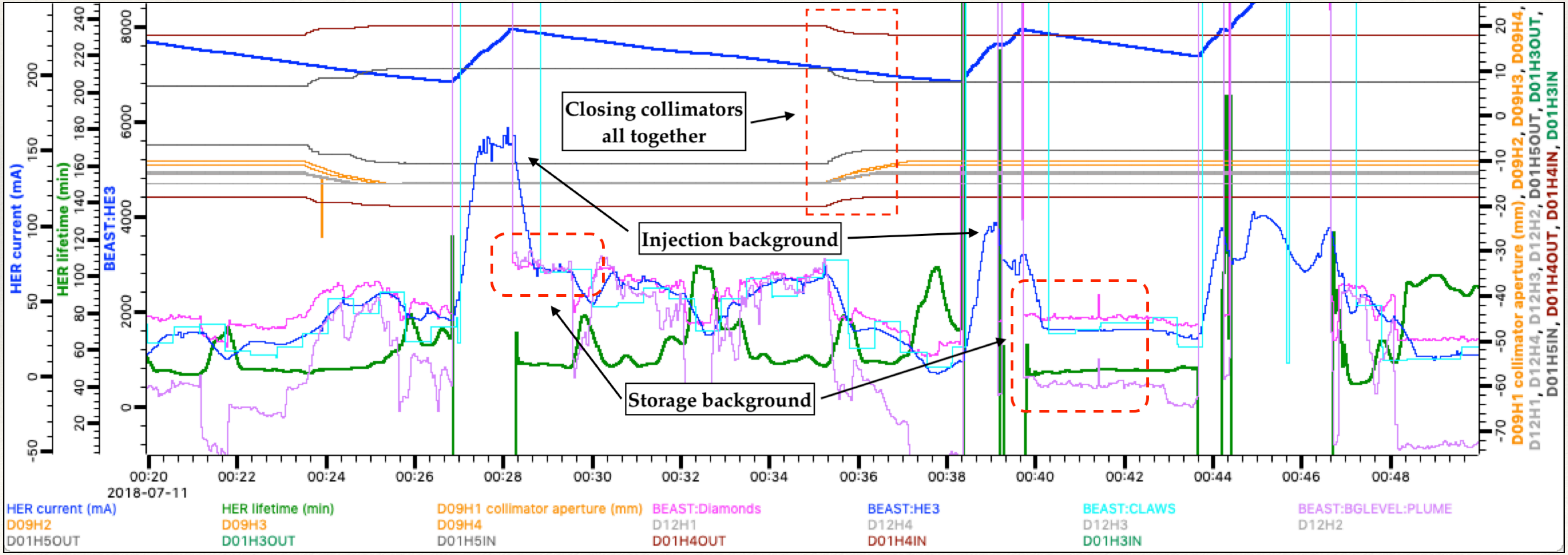
Collimator study - Phase 2 (sim)

- First collimator study done on simulation for Phase 2 optics.
- One iteration needed for HER, two needed for LER.
- With this strategy, collimators are independently optimized.
  - Reduces the time needed for the study and the number of simulation.
  - At these background levels, it's a valid procedure.

	Fully open		1st iteration		2nd iteration	
	LER	HER	LER	HER	LER	HER
IR losses						
Coulomb (MHz)	590	261	79	0.3	48.7	0.3
Brems (MHz)	1	4	1	0.8	0.9	0.8
Touschek (MHz)	50	225	51	4.6	41.1	4.6
Tot (MHz)	641	490	131	5.7	90.7	5.7
Lifetime (s)	41701	8055	927	5641	698	5641

HER collimator study - operation

- A similar strategy was used for collimator studies during operation
- Collimators closed in steps starting from a partially open setting
- At the end, all collimators closed to the optimized setting to see the full background reduction
- **In HER, a background reduction between 30% and 45% was observed.**
- **In LER, a background reduction around 20% was observed.**



Background studies - Phase 2

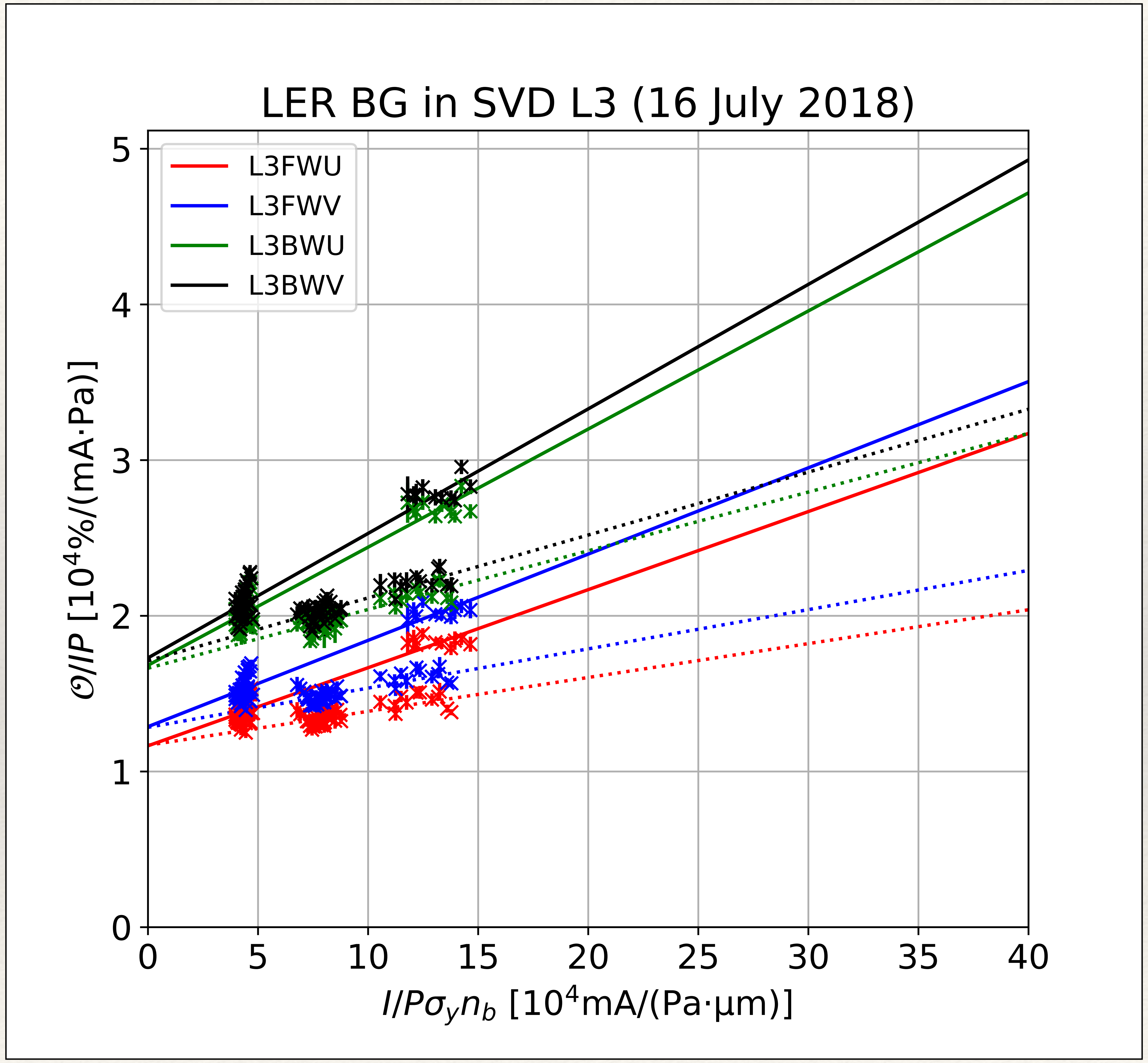
- After collimators optimization, background studies performed to separate beam-gas and Touschek.
- For each detector, the observable can be defined as:

$$Obs. = T\frac{I^2}{\sigma_y n_b} + BIPZ_{eff}^2$$

- The observable can be re-normilized in order to have data laying on a straight line:

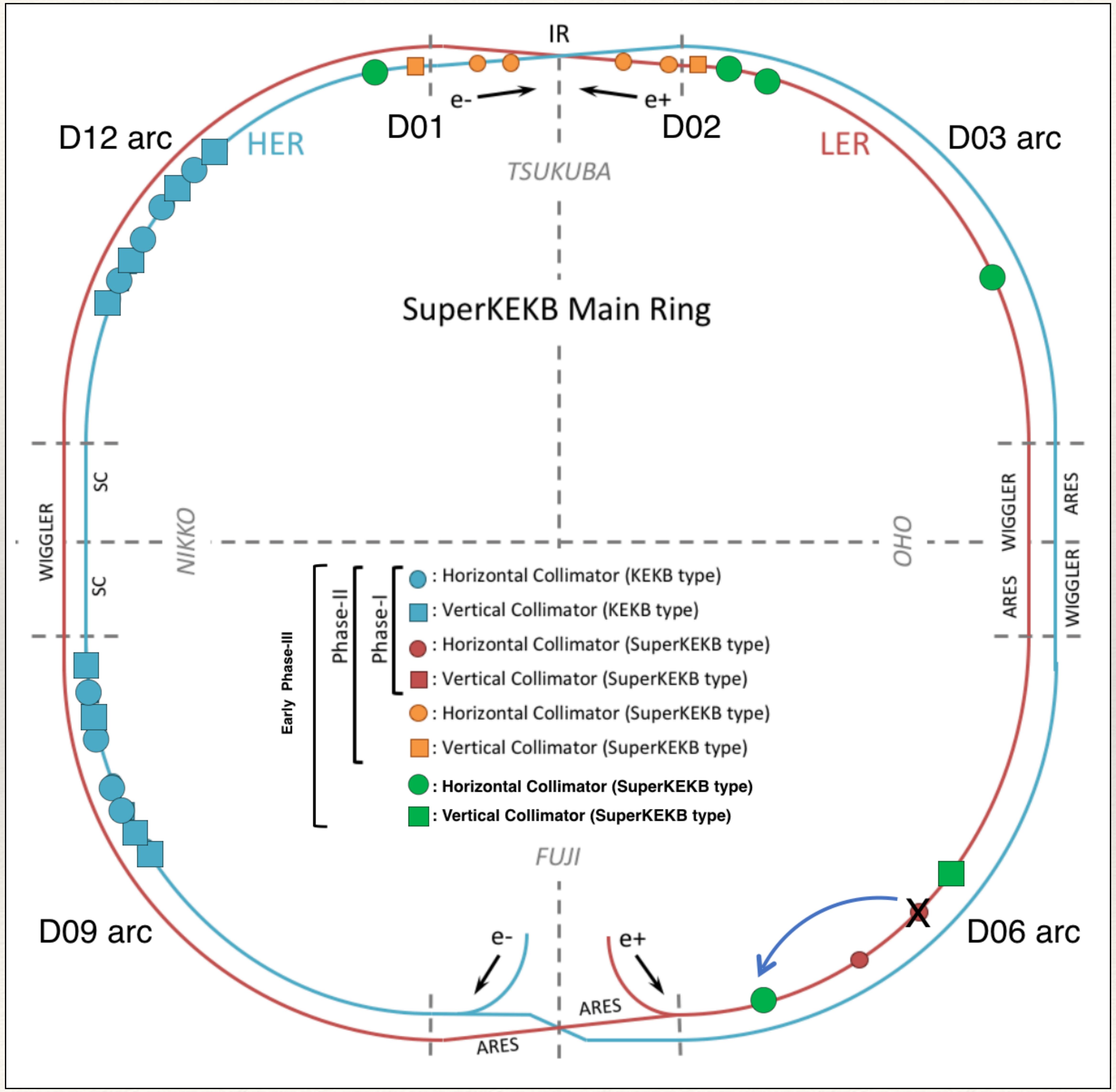
$$\frac{Obs.}{IPZ_{eff}^2} = T\frac{I}{PZ_{eff}^2\sigma_y n_b} + B$$

- B and T are the coefficient for beam-gas and Touschek, and are independent from pressure, beam current, n. of bunches and beam size.
- For SVD, occupancy for layer 3 sensors was the observable. LER beam-gas was the dominant background source, as in all other detectors.



Phase 3 updates

New collimators



Simulation update

- **GEANT4**
- Material of part of the beam pipe changed from tantalum to stainless steel.
- Shields map updated.
- Part of the beam pipe geometry changed to reflect the latest modifications in the design.
- **SAD**
- Implement some offsets of the QCS beam pipe geometry in the SAD output, to allow proper interaction between particles and beam pipe walls.
- Implement in the SAD output the elliptical shape of QCS beam pipe (SAD simulation itself does not support elliptical beam pipe shape).

Collimator study - Early Phase 3 (op.)

- For the Spring 2019 run, similar collimators study was done in simulation.
- Optimization done also during operation, and a simulation was done using the achieved setting.
- Losses in the interaction region for each BG source were compared to the Phase 2 ones.
- From simulation, a reduction of a factor 4-3 was expected for LER-HER.

IR losses	Phase 2 BG study		early Phase 3 optimized		early Phase 3 BG study	
	LER	HER	LER	HER	LER	HER
Coulomb (MHz)	186	1.2	28.6	0.4	44.2	4.3
Brems (MHz)	2.0	2.0	0.9	1.1	0.8	1.2
Touschek (MHz)	160	32.8	49.6	8.9	37.6	10.3
Tot (MHz)	348.0	36.0	79.1	10.4	82.6	15.8
Early Phase 3/Phase 2 ratio			0.23	0.29	0.24	0.44

Background studies - Early Phase 3

- As in Phase 2, a background study was performed after collimators optimization.
- Detectors took data at different beam sizes to extract beam-gas and Touschek BG components, using the same heuristic fit described in slide 14.
- B and T coefficients were used to evaluate SVD occupancies in Phase 2 and early Phase 3 runs.
- Reductions in BG levels observed in early Phase 3 are similar to the expected ones from simulation.
- Absolute BG levels are still not predicted well by simulation.

BG source	Phase 2 occupancy (%)	early Phase 3 occupancy (%)	early Phase 3/Phase 2 ratio
LER beam-gas	0.5	0.14	0.28
LER Touschek	0.09	0.02	0.22
LER tot.	0.59	0.16	**0.27**
HER beam-gas	0.06	0.02	0.33
HER Touschek	0.05	0.02	0.40
HER tot.	0.11	0.04	**0.36**

Next optics studies

- **Additional collimator for Winter 2020 run**
  - An additional vertical collimator will be installed in LER during the short Winter 2020 shutdown
  - It was necessary to decide the position of the new collimator.
  - Simulation provided the best location, confirming what was planned:
    - A collimator in D06V1 position can reduce by a factor 2 beam-gas BG component in LER.

- **Collimator study for final Phase 3 parameters**
  - Extending the study for Winter 2020 run, a priority list of collimators to be installed in the next years could be built, BUT,
  - with final Phase 3 parameters, background levels are much higher. The optimization strategy for collimators may not work anymore. Collimators are not independent one of each other.
  - Losses should be distributed between different collimators.
  - TMC instability sets limits on the minimum aperture of collimators, to be taken into account.

Conclusions

- Simulations performed during Phase 2 gave a reference for the collimators setting during operation.
- BG studies in Phase 2 gave a first estimation of background components.
- A simulation done with the achieved collimators setting allowed to calculate data/MC ratio and to extrapolate background levels to final Phase 3 parameters.

- Simulation was improved and collimators were added before the first Phase 3 run.
- Simulations for the first Phase 3 run predicted a reduction in background levels.
- A similar reduction was obtained comparing data of Phase 2 and the first run of Phase 3.
- Simulation studies were done for optics of Winter 2020 run, to confirm the position where the next collimator will be installed in LER.

- **Possible improvements:**
  - New strategy to be used for final Phase 3 collimators optimization.
  - Check the implementation of BG sources and find possible inconsistencies with the real system.

Thank you

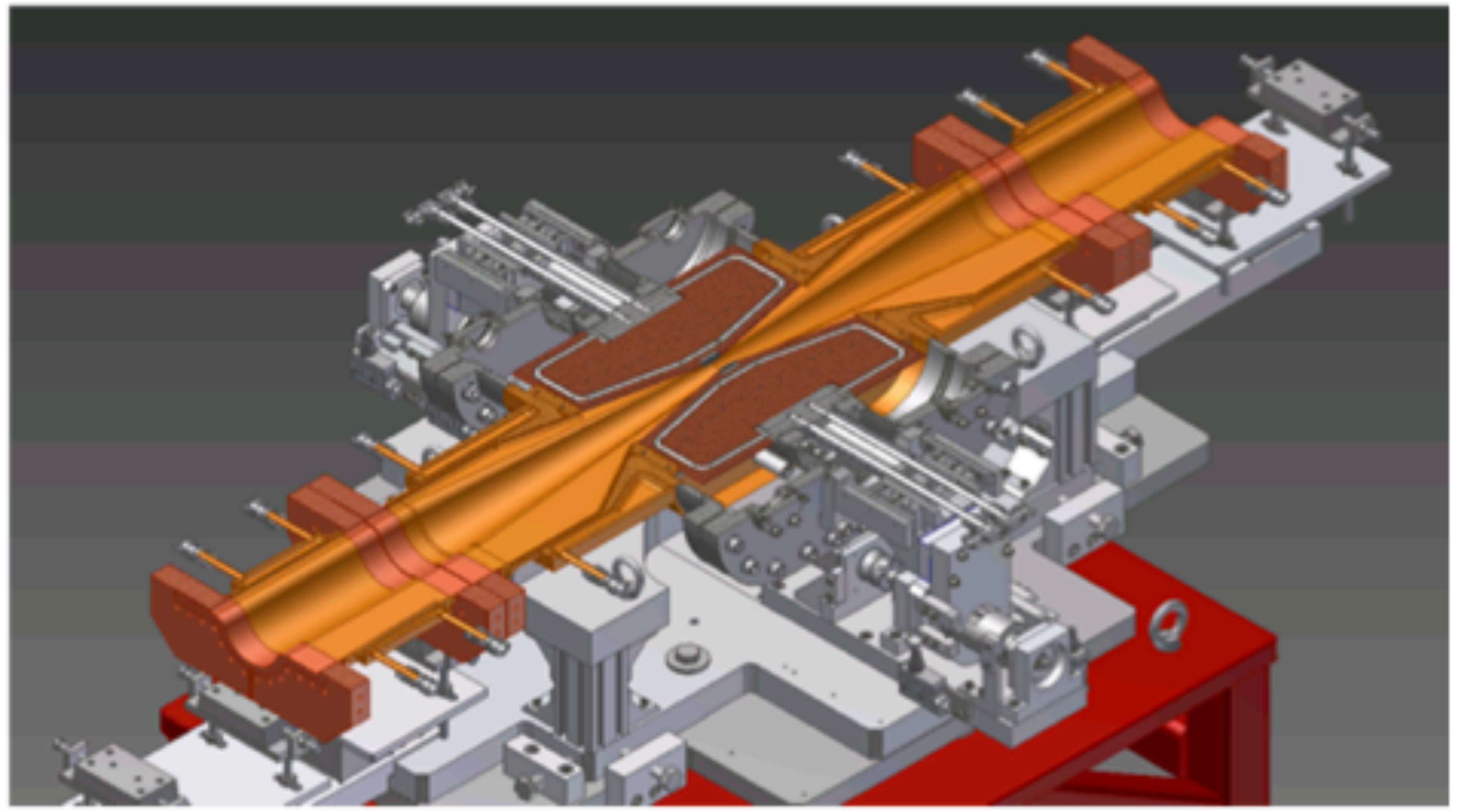
BACKUP

KEKB - SuperKEKB parameters

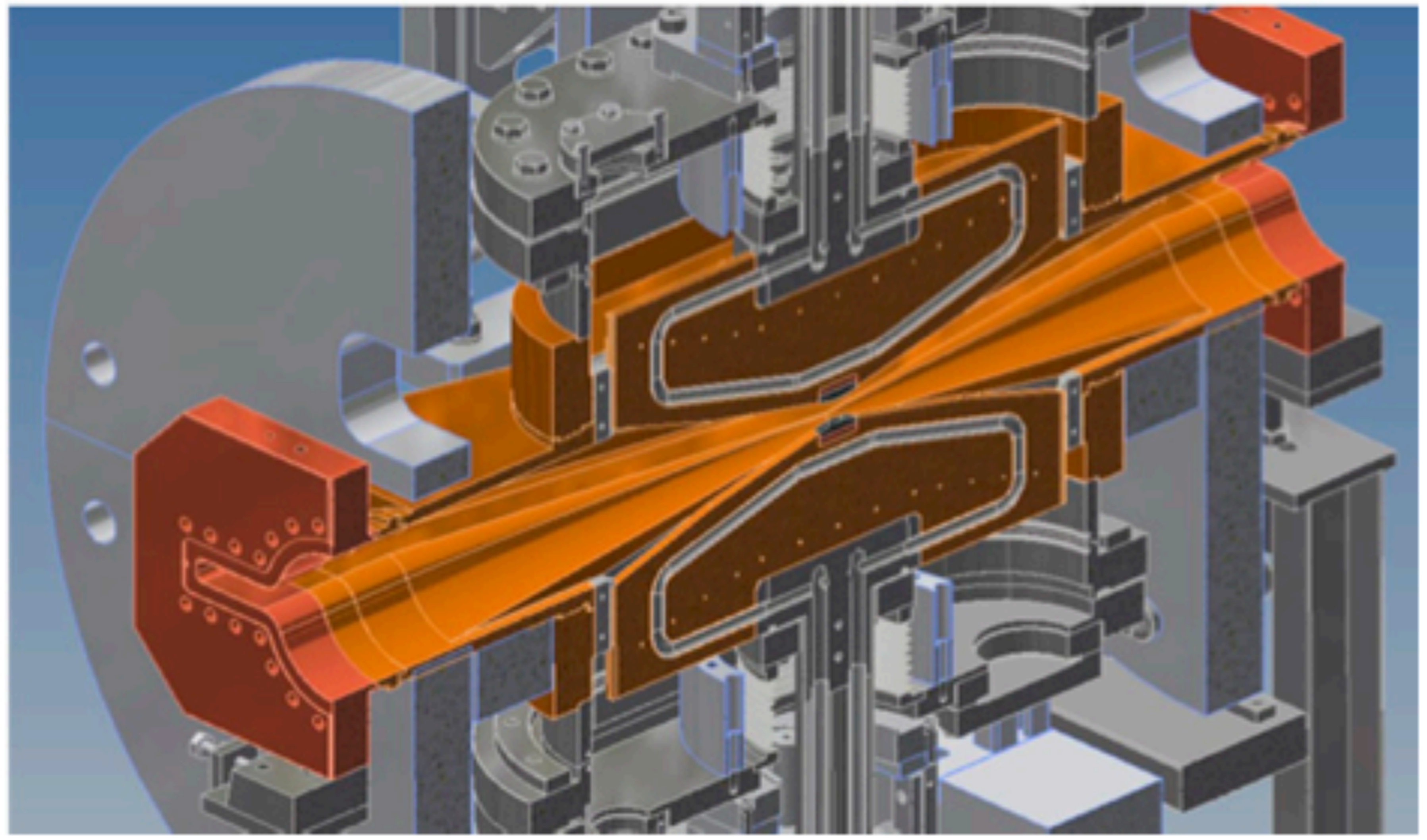
		KEKB		SuperKEKB		
		LER	HER	LER	HER	Units
Beam energy	E	3.5	8.0	4.0	7.007	GeV
Circumference	C	3016.262		3016.315		m
Half crossing angle	θ_x	0 (11*)		41.5		mrad
Piwinski angle	ϕ_{Piw}	0	0	24.6	19.3	
Horiz. emittance	ε_x	18	24	3.2	4.6	nm
Vert. emittance	ε_y	150	150	8.64	12.9	pm
Coupling		0.83	0.62	0.27	0.28	%
Beta function at IP	β^*_x/β^*_y	1200/5.9	1200/5.9	32/0.27	25/0.30	mm
Horiz. beam size	σ_x	147	170	10.1	10.7	μm
Vert. beam size	σ_y	940	940	48	62	nm
Horiz. betatron tune	ν_x	45.506	44.511	44.530	45.530	
Vert. betatron tune	ν_y	43.561	41.585	46.570	43.570	
Momentum compaction	α_p	3.3	3.4	3.20	4.55	10^{-4}
Energy spread	σ_ϵ	7.3	6.7	7.92	6.37	10^{-4}
Beam current	I	1.64	1.19	3.6	2.6	A
Number of bunches	n_b	1584		2500		
Particles/bunch	N	6.47	4.72	9.04	6.53	10^{10}
Energy loss / turn	U_0	1.64	3.48	1.76	2.43	MeV
Long. damping time	τ_z	21.5	23.2	22.8	29.0	msec
RF frequency	f_{RF}	508.9		508.9		MHz
Total cavity voltage	V_c	8.0	13.0	9.4	15.0	MV
Total beam power	P_b	~ 3	~ 4	8.3	7.5	MW
Synchrotron tune	ν_s	-0.0246	-0.0209	-0.0245	-0.0280	
Bunch length	σ_z	~ 7	~ 7	6.0	5.0	mm
Horiz. beam-beam par.	ξ_x	0.127	0.102	0.0028	0.0012	
Vert. beam-beam par.	ξ_y	0.129	0.090	0.088	0.081	
Luminosity	L	2.108×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$
Integrated luminosity	$\int L$	1.041		50		ab^{-1}

Collimators in SuperKEKB

SuperKEKB type



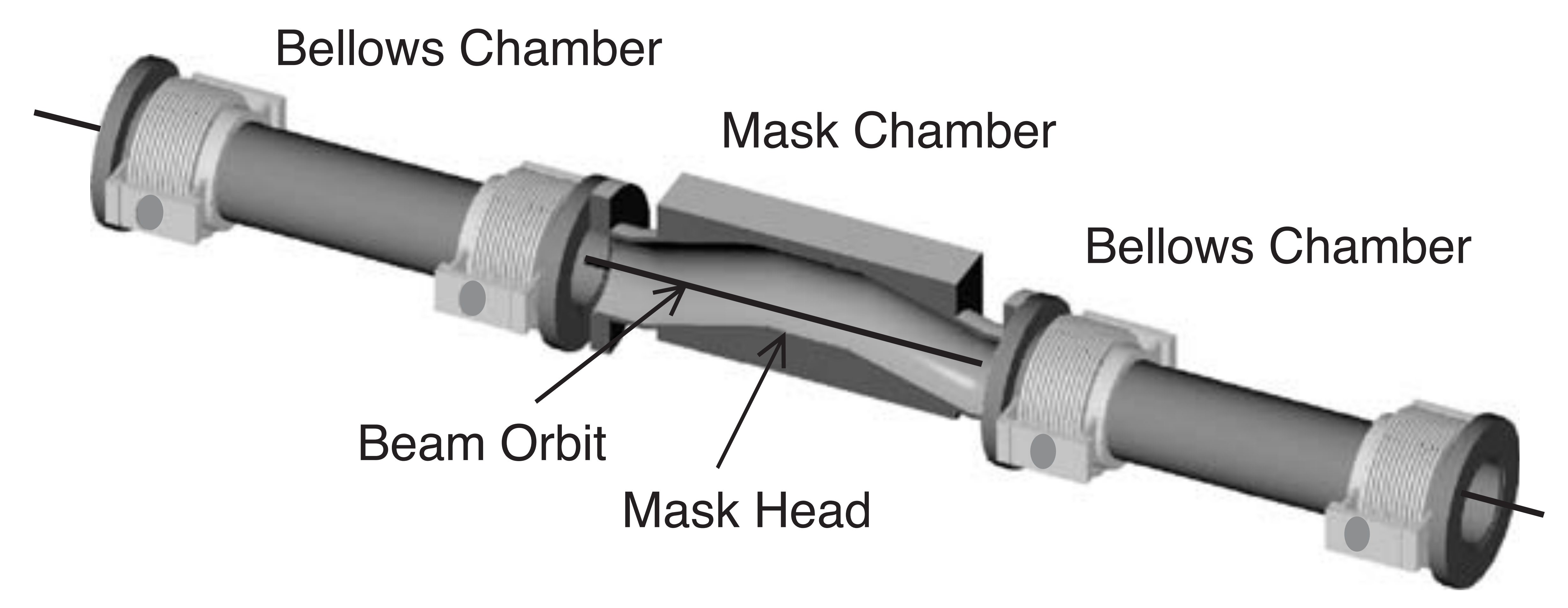
(a) horizontal collimator



(b) vertical collimator

- Touschek, beam-gas and injection backgrounds can be reduced using beam collimators.
- Two types of collimators installed:
  - KEKB type - one movable jaw, installed in HER arc sections
  - SuperKEKB type - installed in IR straight section and in LER

KEKB type



data/MC ratio - Phase 2

- Collimators setting achieved during operation used to run a full SAD/GEANT4 simulation.
- From a comparison between data and simulation, data/MC ratios were evaluated.
- data/MC ratios used to scale the existing Phase 3 simulation and predict background levels for Phase 3.
  - For SVD, extrapolated occupancies over 6% were obtained for Layer 3 sensors, with a limit on tracking performance set to 2%. Clearly too high background foreseen in Phase 3.
- Possible improvements on two sides:
  - Background reduction
  - Simulation

	Phase 3 MC occupancy (%)	Phase 2 "data/MC"	Phase 3 occupancy prediction (%)
HER beam-gas	0.008	600	4.8
HER Touschek	0.0008	1700	1.4
HER tot.			**6.2**
LER beam-gas	0.14	39	5.5
LER Touschek	0.24	4.6	1.1
LER tot.			**6.6**

data/MC ratio - Early Phase 3

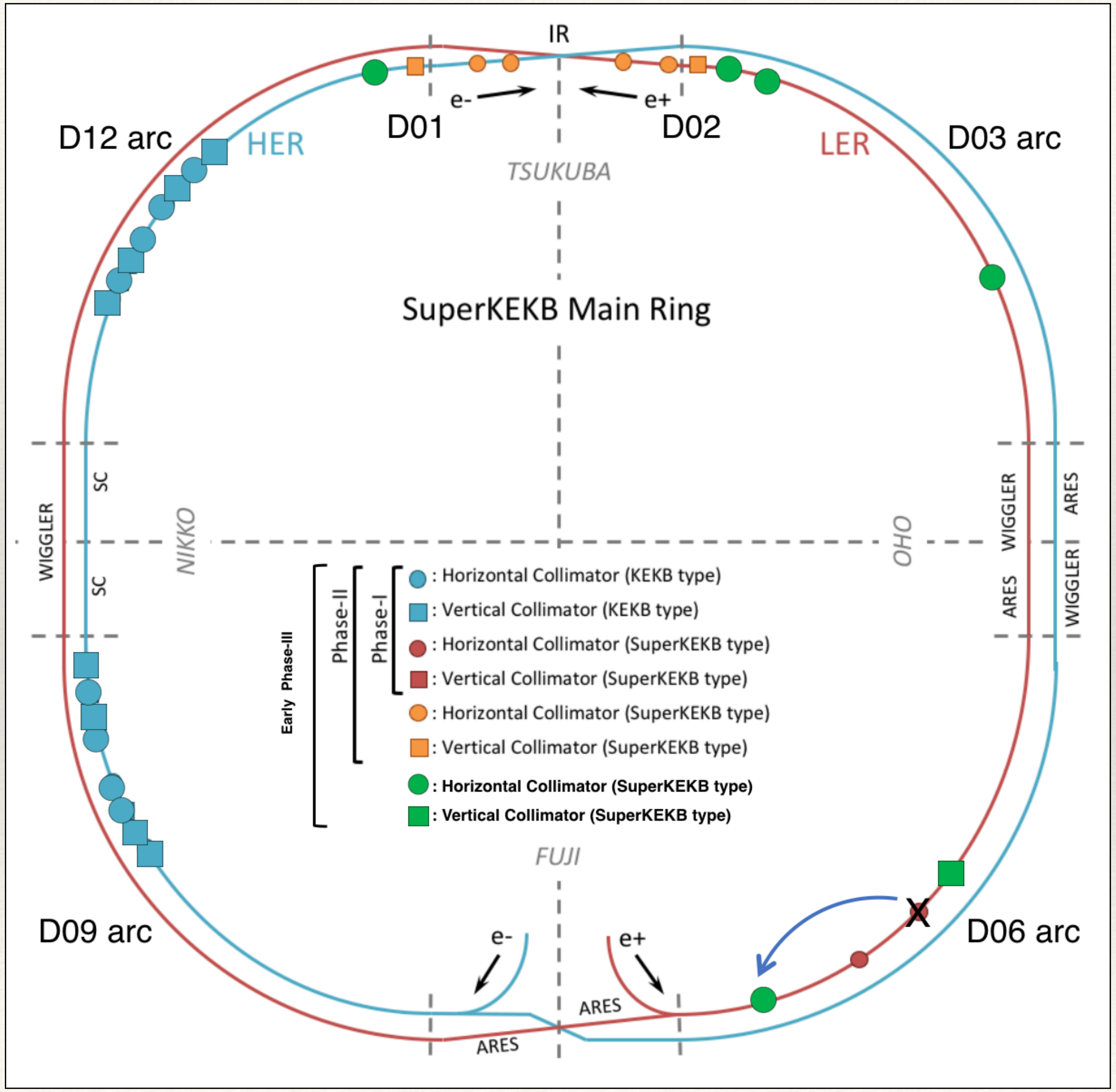
- With early Phase 3 data and simulations, new data/MC ratios were calculated.
- LER ratios are closer to 1, meaning better agreement between data and simulation.
- Better HER beam-gas ratio, but very bad HER Touschek ratio. There must be a big inconsistency between data and simulation, it will be investigated.

- Factors obtained with the simulation updates were used on the old Phase 3 simulation to make a new extrapolation to final Phase 3 parameters. Lower occupancies, but still too high.

Source	Phase 3 MC occupancy (%)	G4_factors	early Phase 3 "data/MC"	Phase 3 occupancy prediction (%)
HER beam-gas	0.0036	11	16	0.63
HER Touschek	0.0003	7.8	1600	4.1
HER tot.	0.0039			**4.7**
LER beam-gas	0.066	4.2	12	3.3
LER Touschek	0.11	3.0	1.1	0.36
LER tot.	0.176			**3.7**

Collimators map

Start of Phase 3 - Spring 2019



Optional collimators to be installed