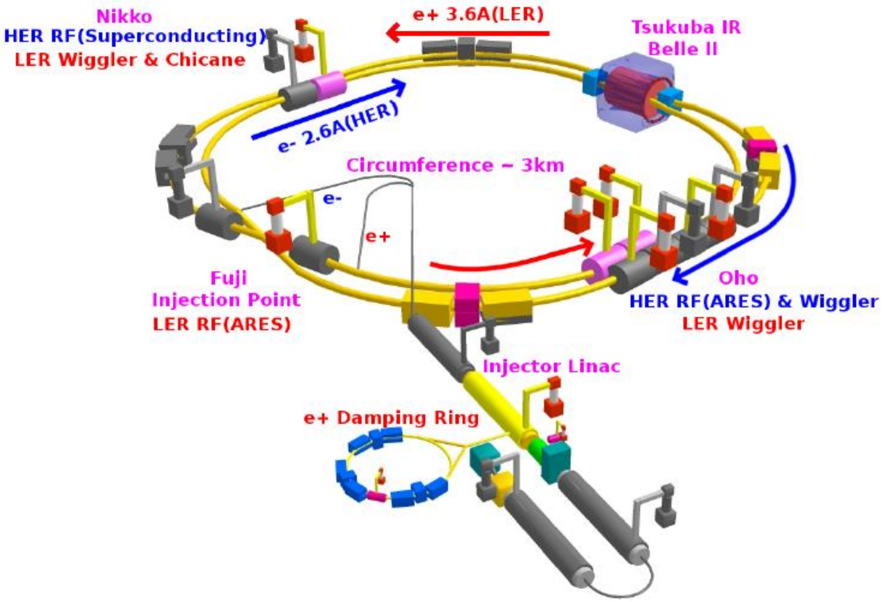
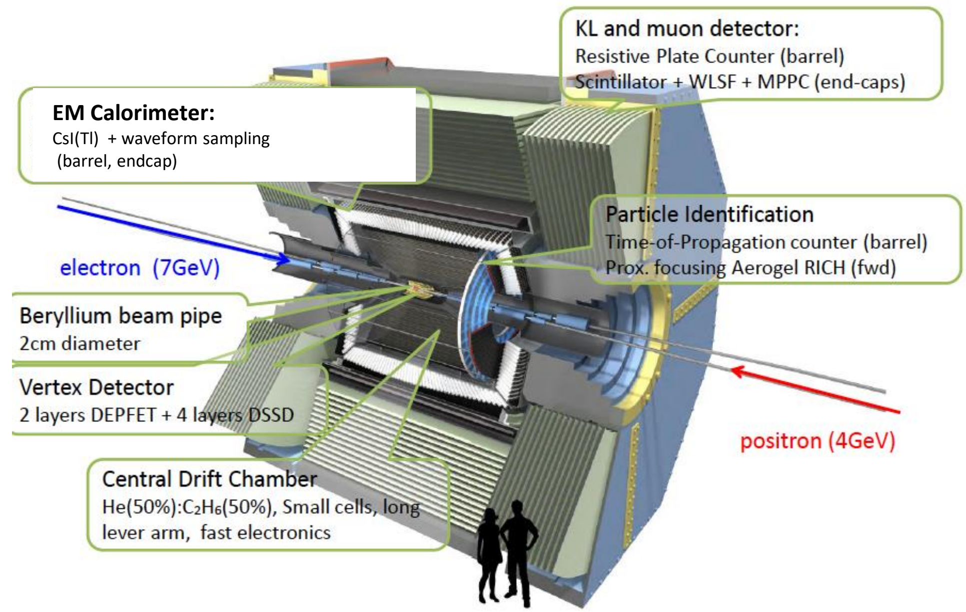
7GeV(e-), 4GeV(e-)





Belle II beam background simulations and measurements

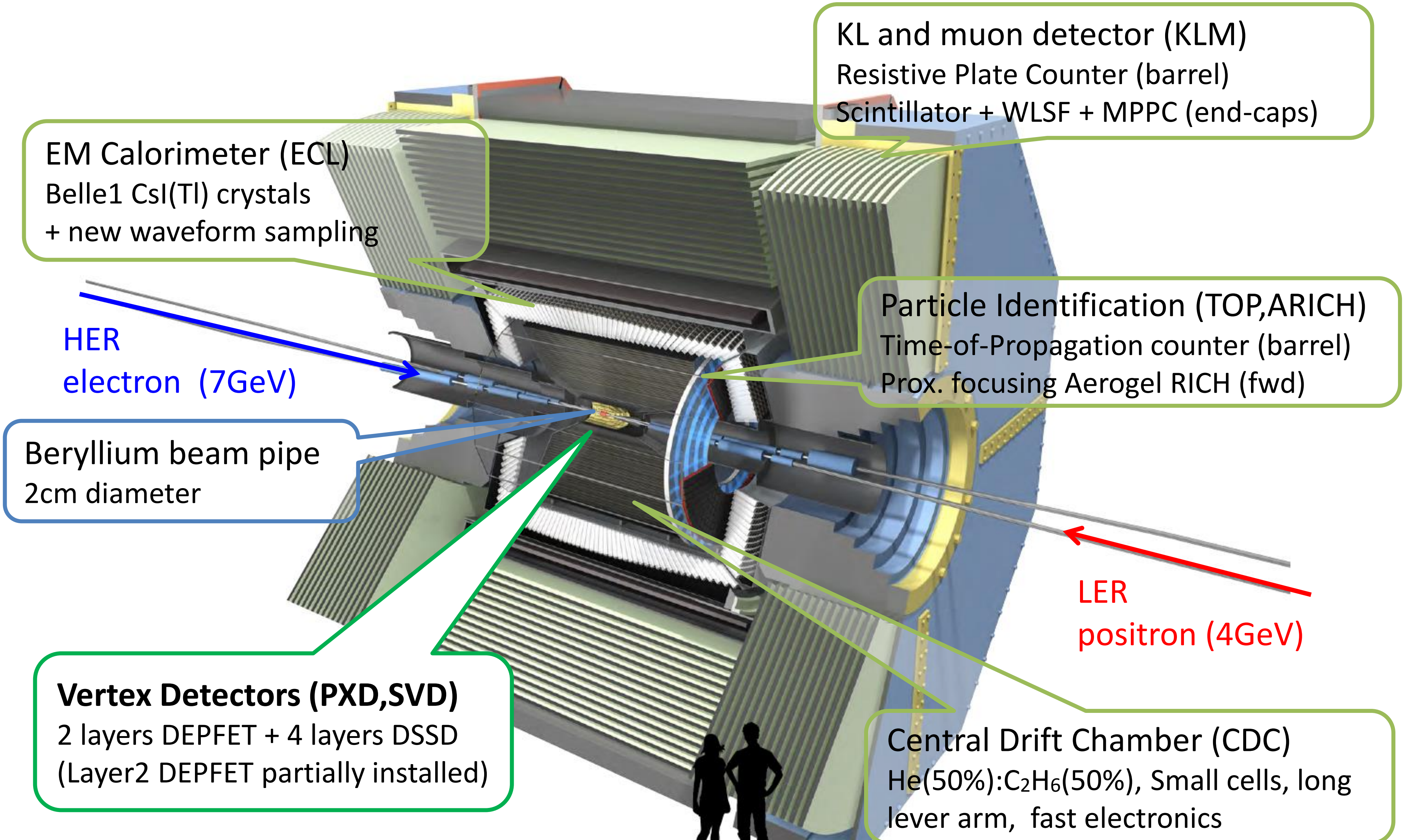
Hiroyuki Nakayama (KEK), on behalf of
SuperKEKB/Belle II collaboration

Nov. 19th, 2019
CEPC workshop at IHEP

Today's Contents

- **Beam background sources at SuperKEKB/Belle II**
  - Touschek scattering/Beam-gas scattering
    - Countermeasures: collimators and shield structures
  - Synchrotron radiation
  - Luminosity-dependent BG (radiative Bhabha, 2-photon process)
  - Background simulation tools
  - Simulated BG rates at full luminosity
- **Background measurement at SuperKEKB**
  - Single-beam BG studies to measure Touschek and Beam-gas separately
  - Data/MC ratio measured by BG studies, extrapolation for future
  - Latest "big picture" of Belle II background
- **Summary**

Belle II Detector



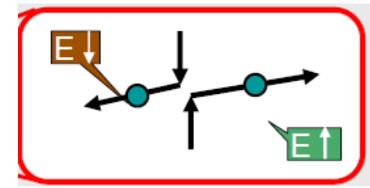
Beam background

- Beam-induced background at SuperKEKB accelerator can be dangerous for Belle II detector
- Beam BG determines survival time of Belle II sensor components and might lead to severe instantaneous damage
- Also increases sensor occupancy and irreducible analysis BG

SuperKEKB Beam BG sources

- *Single-beam BG:* Touschek, Beam-gas Coulomb/Brems, Synchrotron radiation, injection BG
- *Luminosity BG:* Radiative Bhabha, two-photon BG, etc..

1.Touschek scattering

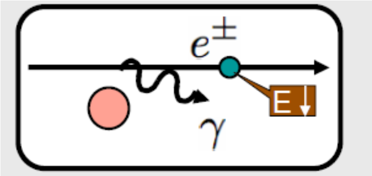


- Intra-bunch scattering : Rate∝(beam size)$^{-1}$,(E_{beam})$^{-3}$
- Touschek lifetime: should be >600sec (required by injector ability)

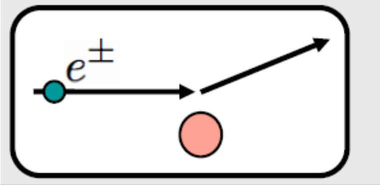
  → ring total beam loss: ~375GHz (LER), ~270GHz(HER)
- Horizontal collimators to reduce loss inside Belle II (|s|<4m)
  - collimators added at 0~200m upstream IP are very effective
- Collimator width optimization
  - Initial values: $d_x = Max[d_{x\beta}, d_{x\eta}], \quad d_{x\beta} = n_x\sqrt{\varepsilon_x\beta_x},\ d_{x\eta} = \eta_x(n_z\sigma_\delta)$
  - Further optimization to balance IR loss and beam lifetime
  - Smaller loss rate on the last collimators (~20m upstream IP) is preferred
- After careful optimization of collimators, simulated beam loss in the detector can be mitigated to few hundred Hz level
  - 3 orders of magnitude smaller than the loss without any collimators

2.Beam-gas scattering

Brems



Coulomb



- Scattering by remaining gas, Rate ∝IxP
- Due to smaller beam pipe aperture and larger maximum βy, beam-gas Coulomb scattering could be more dangerous than in KEKB

$$\frac{1}{\tau_R} = cn_G\langle\sigma_R\rangle = cn_G \frac{4\pi\sum Z^2 r_e{}^2}{\gamma^2}\left\langle\frac{1}{\theta_c{}^2}\right\rangle$$

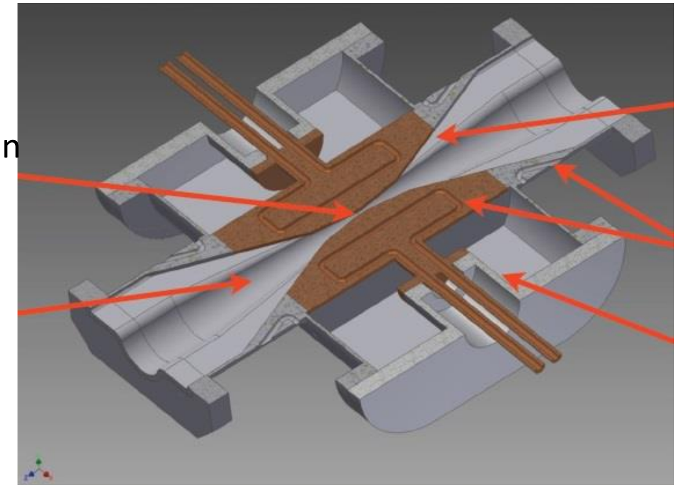
	KEKB LER	SuperKEKB LER
QC1 beam pipe radius: r_{QC1}	35mm	***13.5mm***
Max. vertical beta (in QC1): $\beta_{y,QC1}$	600m	2900m
Averaged vertical beta: $<\beta_y>$	23m	50m
Min. scattering angle: θ_c	0.3mrad	0.036mrad
Beam-gas Coulomb lifetime	>10 hours	35 min

How to cope with beam BG?

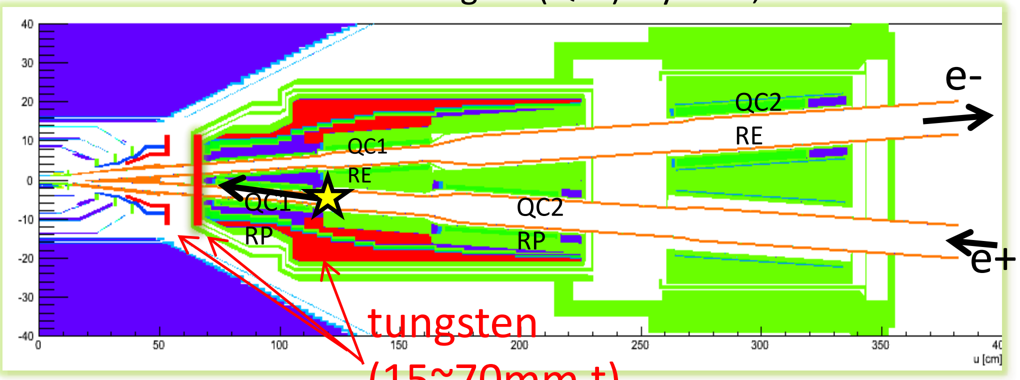
- Movable collimators
  – Arc collimators and horizontal collimators near IP
  – Very narrow (d~2mm) vertical collimators

- Shielding structures
  – Thick tungsten structures inside Final Focus cryostat and vertex detector volume
  – Stops showers from beam loss "hot spot", at ~1m upstream from IP
  – Polyethylene shield to reduce neutrons

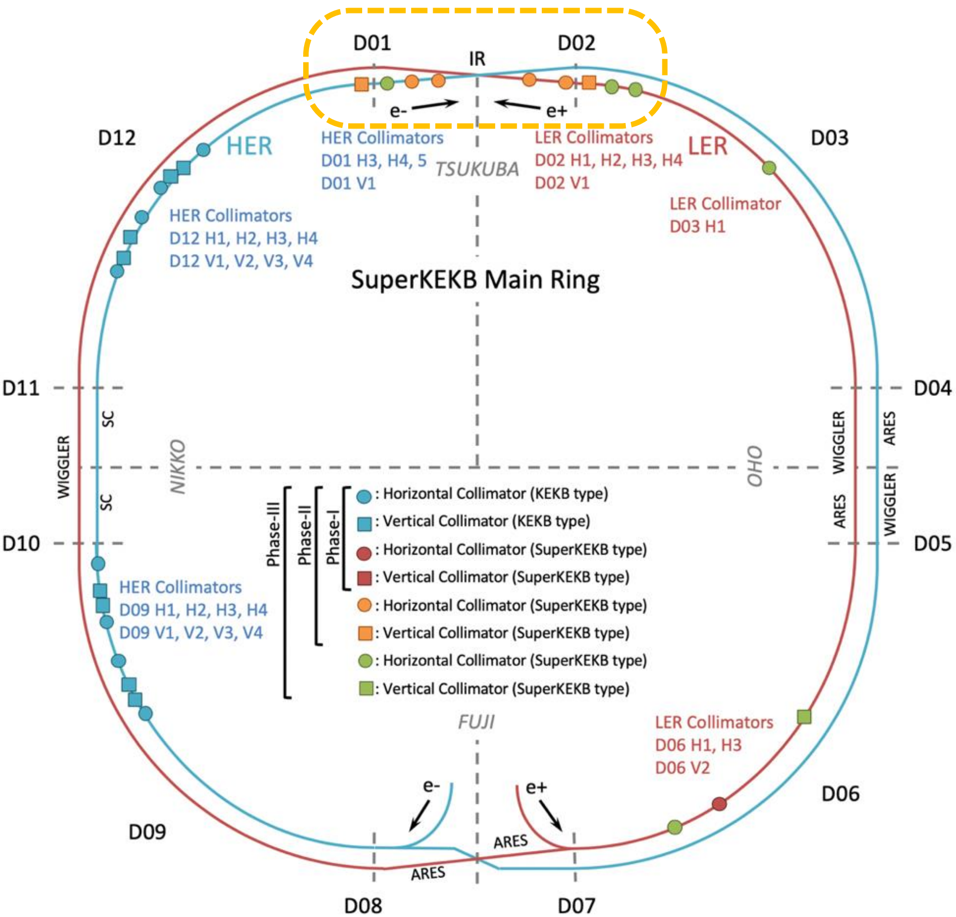
SuperKEKB horizontal collimator



Final focus magnet (QCS) cryostat, R-side



SuperKEKB Collimators



As of 2019 autumn,

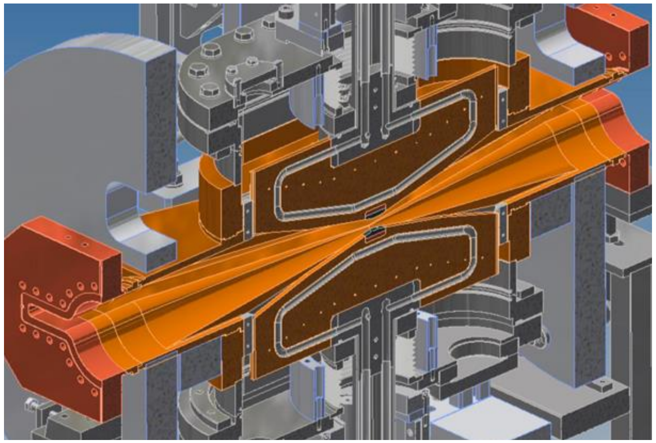
29 movable collimators installed

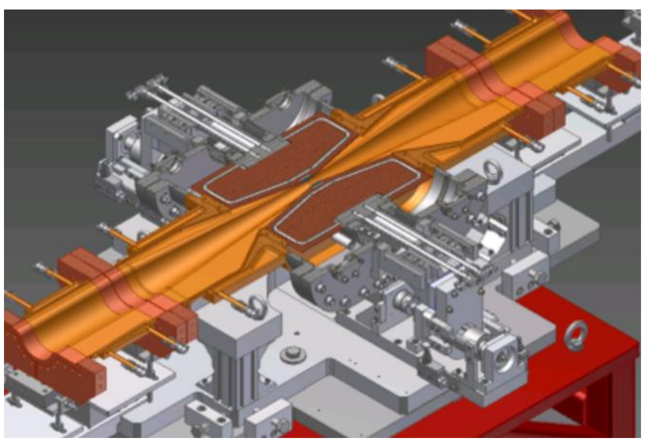
LER(9):
- 7 horizontal, 2 vertical "SuperKEKB type" collimators
  - horizontal: D06H1, D06H3, D03H1
    D02H1, D02H2, D02H3, D02H4
  - vertical: D06V2, D02V1

HER(20):
- 3 horizontal, 1 vertical "SuperKEKB type" collimators
  - horizontal: D01H3, D01H4, D1H5
  - vertical: D02V1
- 8 horizontal, 8 vertical "KEKB type" collimators
  - horizontal: D12{H1,H2,H3,H4},D09{H1,H2,H3,H4}
  - vertical: D12{V1, V2, V3, V4},D09{V1,V2,V3,V4}

A new vertical collimator will be added to LER D06V1 during this winter shutdown

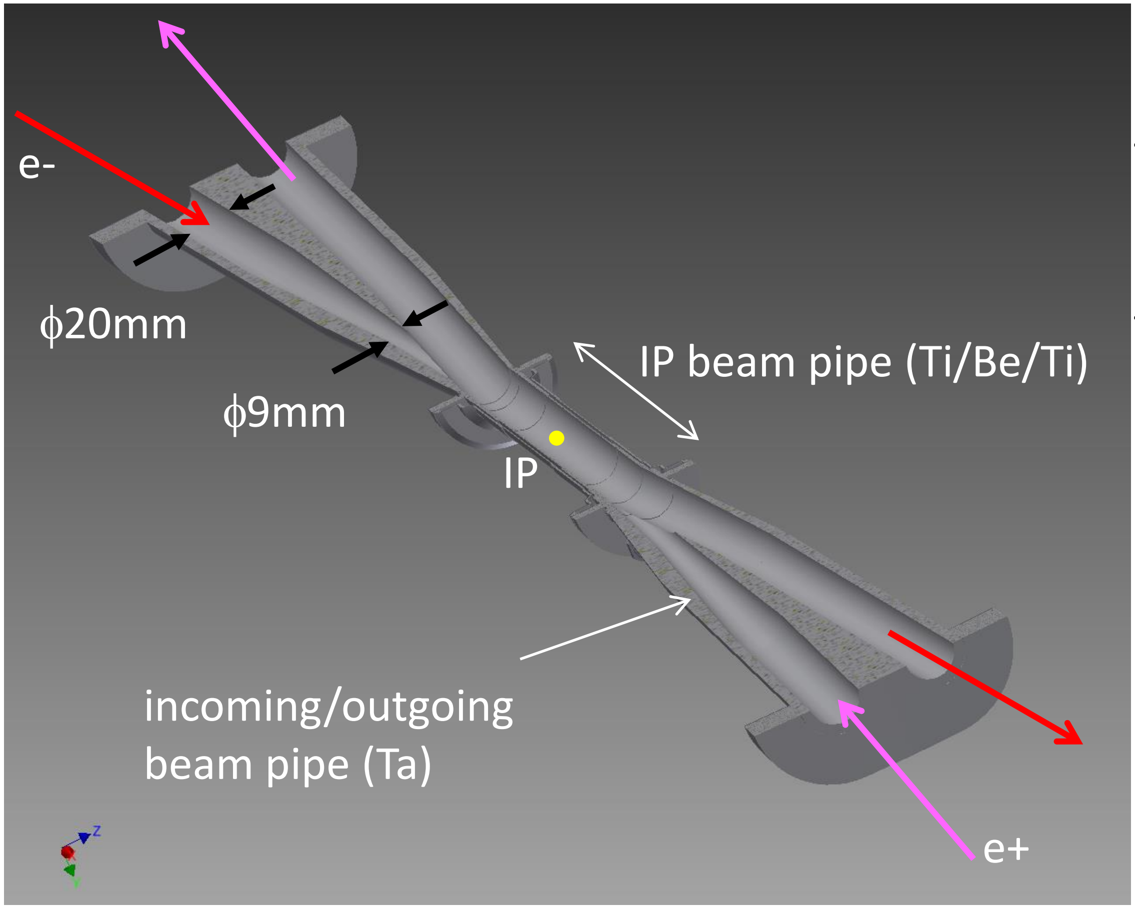
Vertical Collimators





- To reduce IR loss of beam-gas Coulomb BG, very narrow (~2mm half width) vertical collimator at βy=~100m is required
- TMC instability is an issue, low-impedance design of collimator head is important
- Precise control (Δd~50um) of collimator head is required, since IR loss is quite sensitive to the collimator width
- Head should withstand ~100GHz loss (tungsten is used)
- Secondary shower (tip-scattering) effect should be carefully examined

3. Synchrotron radiation



Inner surface of Be pipe is coated with Au layer (10um)

Kanazawa's talk on Wednesday morning

- ϕ20mm→ϕ9mm collimation on incoming beam pipes (no collimation on outgoing pipes, HOM can escape from outgoing beam pipe)

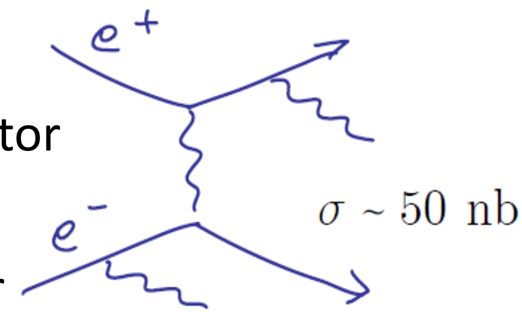
- Most of SR photons are stopped by the collimation on incoming pipe.
- Direct hits on IP beam pipe is negligible

- To hide IP beam pipe from reflected SR, "ridge" structure on inner surface of collimation part.

4. Luminosity-dependent background

Radiative Bhabha scattering

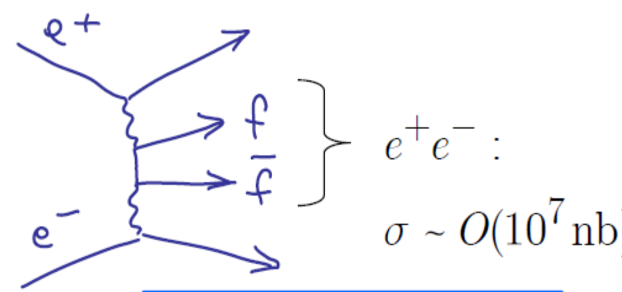
- Rate ∝ Luminosity (KEKBx40)
- Spent e+/e- with large ΔE could be lost inside detector (see next page)
- Emitted γ hit downstream magnet outside detector and generate neutrons via giant-dipole resonance



Bhabha scattering

2-photon process

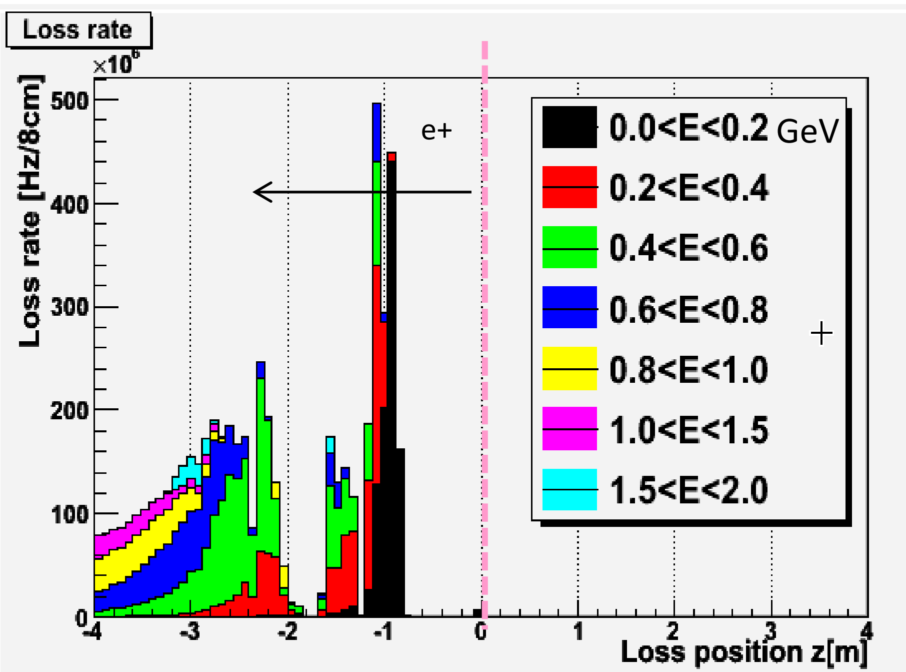
- Rate ∝ Luminosity (KEKBx40)
- e+ e- → e+ e- e+ e-
- Emitted e+e- pair curls by solenoid and might hit inner detectors multiple times



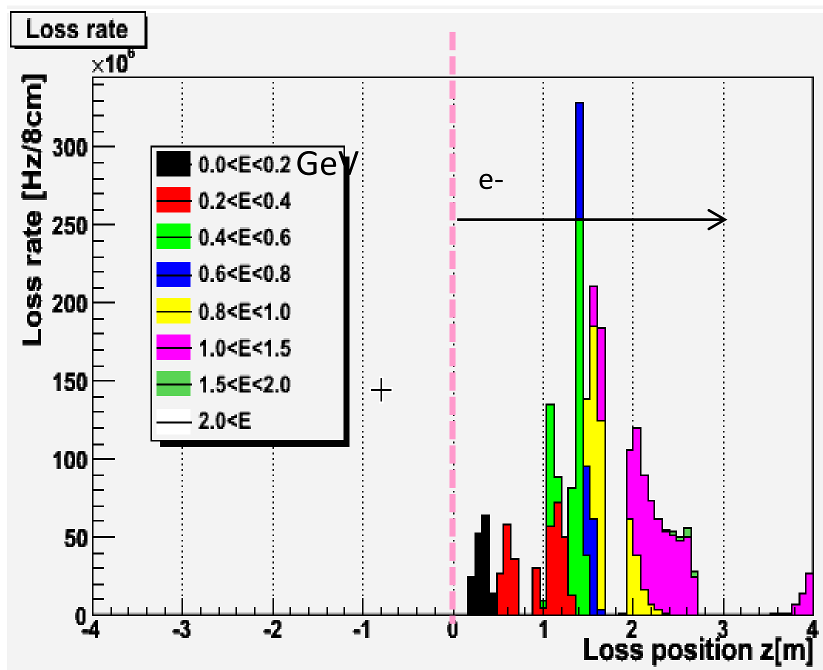
2-photon-processes

Spent e+/e- loss position after RBB scattering

LER(orig. 4GeV)



HER(orig. 7GeV)



If ΔE is large and e+/e- energy becomes less than 2GeV, they can be lost inside the detector (<4m from IP), due to kick by the 1.5T detector solenoid with large crossing angle(41.5mrad)

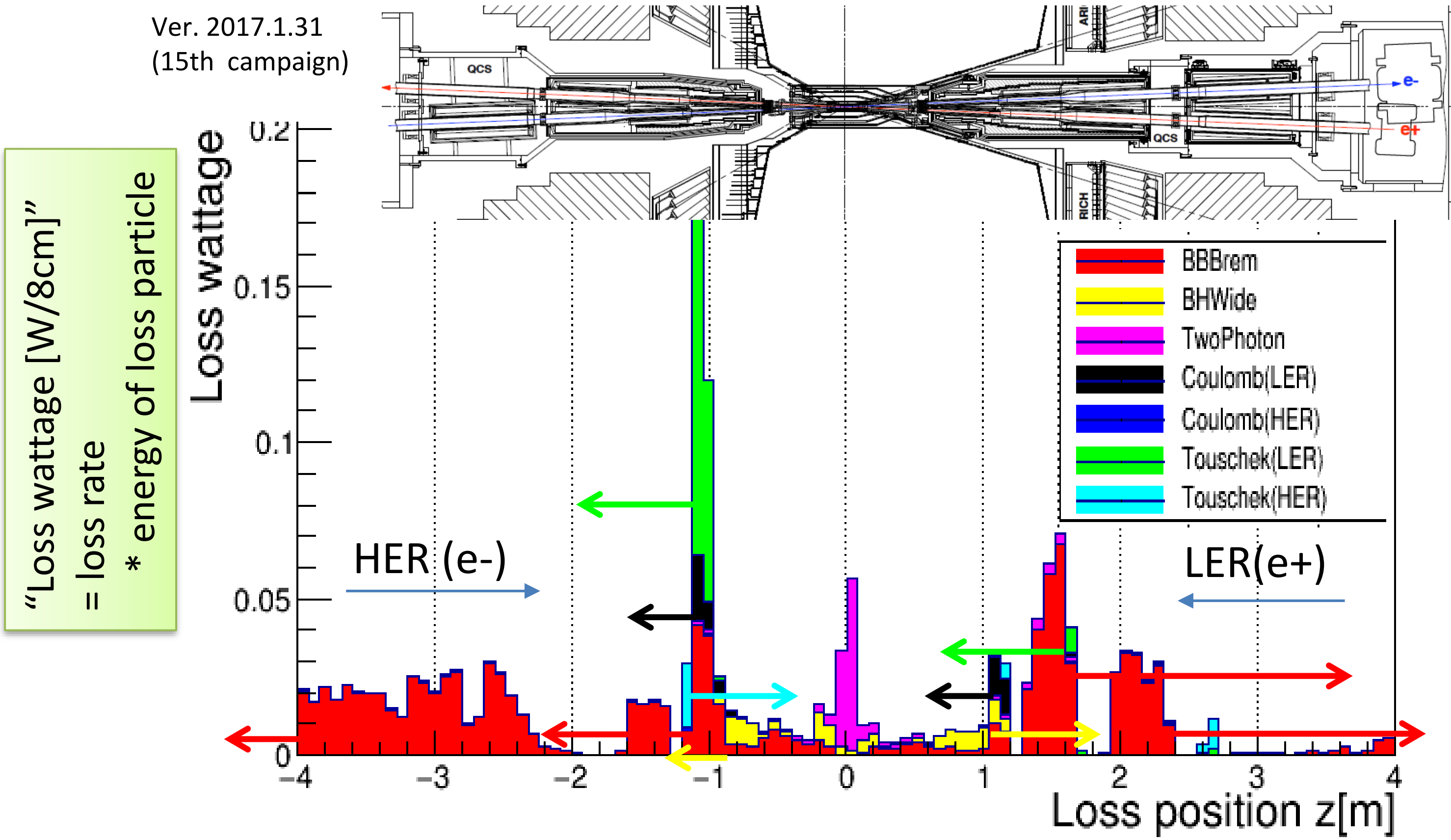
Background simulation tools

- Use SAD for multi-turn tracking in the entire rings
- Use GEANT4 for single-turn tracking within detector and full simulation

BG type	BG generator	Tracking (till hitting beam pipe)	Detector full simulation
Touschek/Beam-gas	Theoretical formulae [1]	SAD [2] (up to ~1000 turns)	GEANT4
Radiative Bhabha	BBBREM/BHWIDE	GEANT4 (multi-turn loss is small)	GEANT4
2-photon	AAFH	GEANT4 (multi-turn loss is small)	GEANT4
Synchrotron radiation	Physics model in GEANT4 (SynRad)	GEANT4	GEANT4

[1] Y. Ohnishi et al., PTEP **2013**, 03A011 (2013).
[2] SAD is a “Home-brew” tracking code by KEKB group, http://acc-physics.kek.jp/SAD/

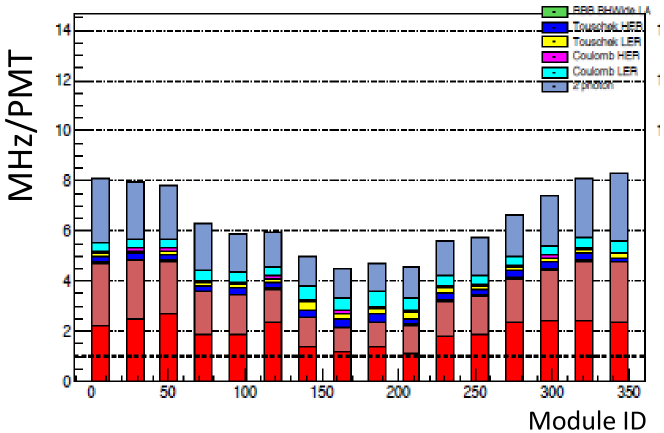
Simulated BG loss distribution (design optics)



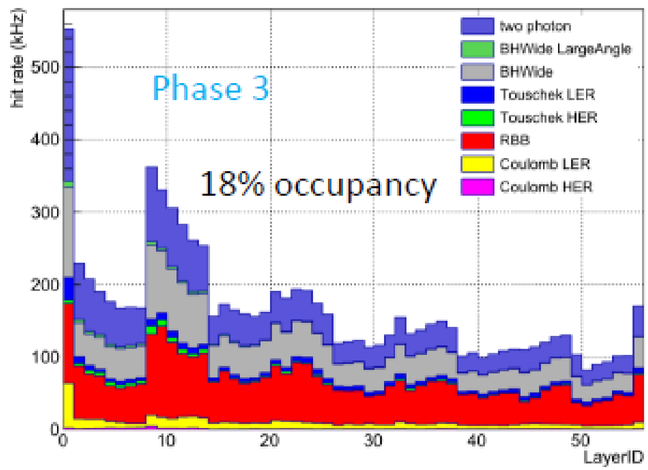
	LER (4GeV e+)	HER (7GeV e-)
Lumi-dependent BG	BBBrem: **1.08 W** (0.06 W in |z|<65cm) BHWide: 0.11 W (0.04 W), 2photon: 0.14 W(0.11W)	
Touschek	0.27 W (0.42GHz)	0.04 W (0.03GHz)
Coulomb	0.06 W (0. 10Hz)	0.00 W (0.002GHz)

Simulated Sub-Detector BG rates

TOP PMT rate



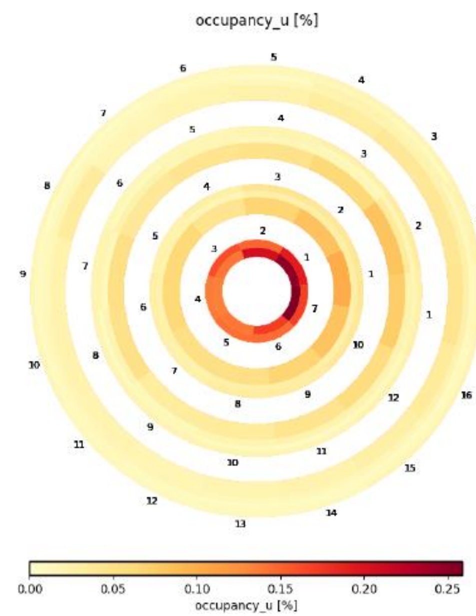
CDC wire rate



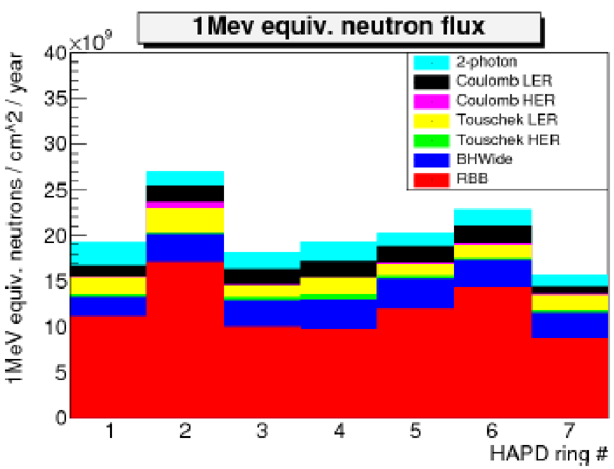
PXD occupancy

Layer #1
0.84 % occupancy
from 2-photon

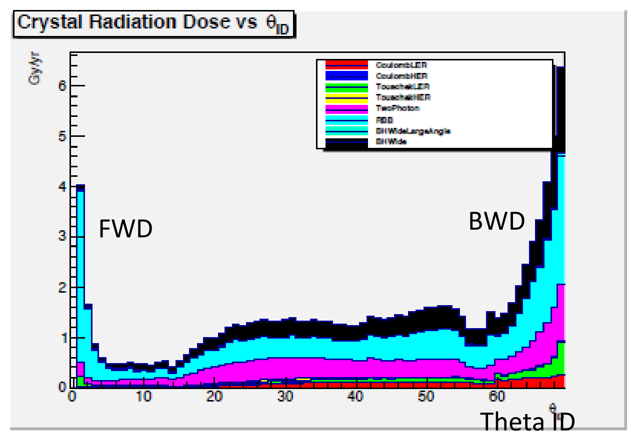
SVD occupancy



ARICH neutrons



ECL crystal dose



Simulation shows that sub-detectors will survive ~10 years at full luminosity (except TOP PMTs, which will be replaced in few years)

Simulated Sub-Detector BG rates

listing SF<5 only

SF=Safety Factor

	16/17th campaign result	limit	SF
PXD occupancy	2photon:0.8% , SR:~0.2% (10th)	< 3%	3
SVD occupancy	2 photon:0.6%, others:0.7%	<2~3%	2
CDC wire hit rate	350kHz at layer#8	<200kHz	0.6 (*1)
CDC Elec.Borad n-flux* (averg.)	3.2	<1	0.3 (*2)
CDC Elec.Board dose	270 Gy/yr	<100 Gy/yr	0.3 (*3)
TOP PMT rate	5-8 MHz/PMT	<1 MHz/PMT (*3)	0.3
TOP PCB n-flux*	0.35	<0.5	3
ARICH HAPD n-flux*	0.3	<1	3
ECL crystal dose	6 Gy/yr in BWD	<10 Gy/yr	2
ECL diode n-flux*	?	<1	4
ECL pile-up noise	?	0.8 at Belle-I	?

KLMs studies are not included

(*1) effect on tracking performance is under study
(*2) more frequent SEUs and firmware reload
(*3) possible to replace electronics
(*4) ~40% of TOP PMTs have this lifetime. Other PMTs have longer lifetime

*neutron flux in unit of 10^{11} neutrons/cm2/yr, NIEL-damage weighted

BG simulation summary

- Collimators are installed to mitigate Touschek/Beam-gas BG
- Radiative Bhabha spent e+/e- are dominant BG source at full design luminosity

- Simulated BG rates on subdetectors at full luminosity seems acceptable, but safety margins are small
  - Exception: 1/3 of TOP PMTs need replacement after few years of operation

→ <u>Simulated BG rates should be verified by machine studies</u>

Beam background measurement during SuperKEKB 2019 runs

~ hot from the oven ~

3-phase SuperKEKB commissioning

Phase1 (2016 Feb-June)

DONE

- No final focus, no Belle II
- Vacuum baking, beam tuning

“First Measurements of Beam Backgrounds at SuperKEKB” Nucl.Instrum.Meth. A914 (2019) 69-144

Phase2 (2018 Mar-July)

DONE

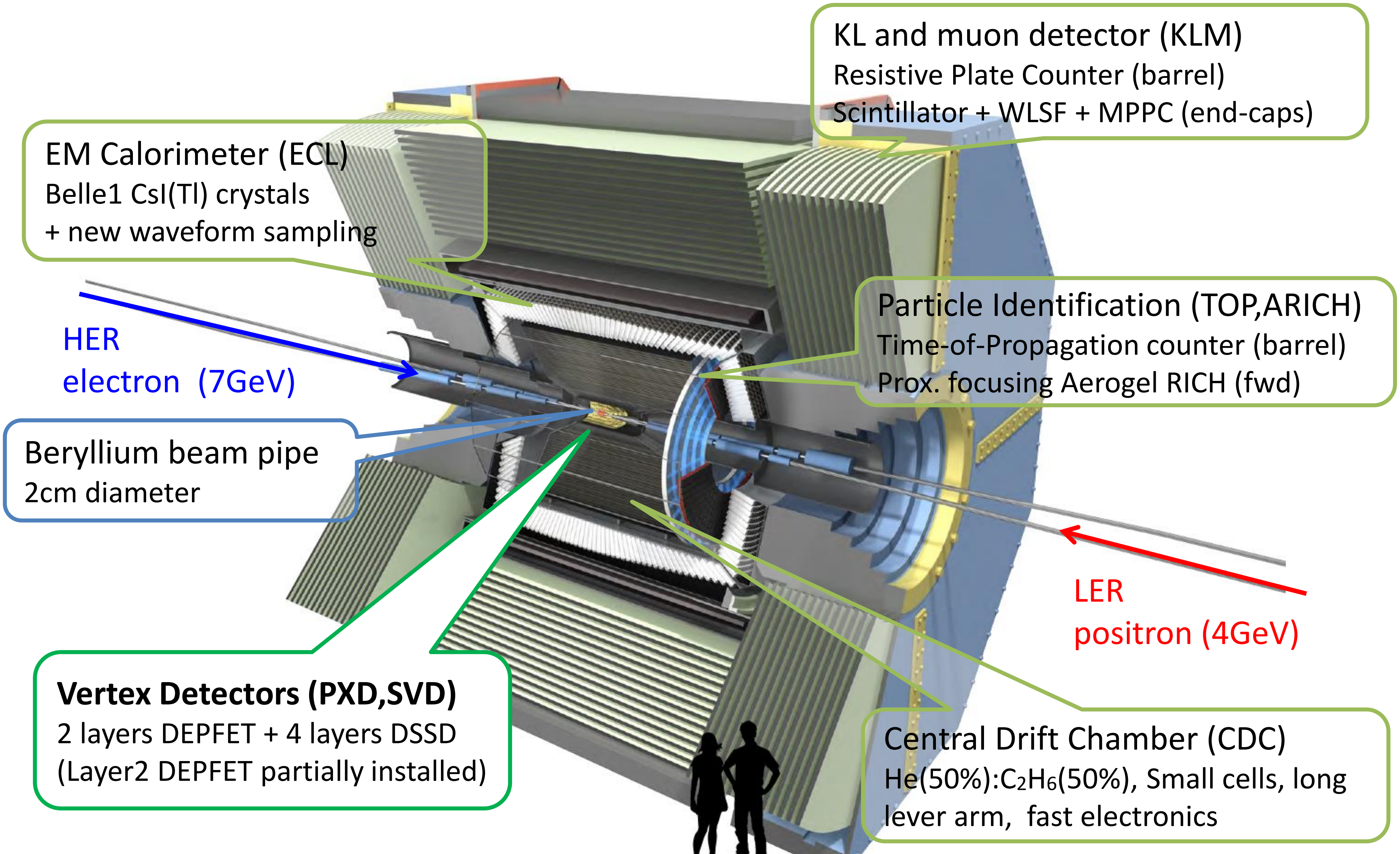
- Final focus and Belle II installed (partial inner detector)
- Collision tuning + early physics samples

Paper in preparation

Phase3 (2019 Mar-Jun, Oct-Dec, 2020 …)

- All Belle II sensors installed -- “in full swing”
- Aim for higher luminosity with further focused beams

Belle II Detector



Single-beam BG study

for measuring Touschek and Beam-gas component separetely

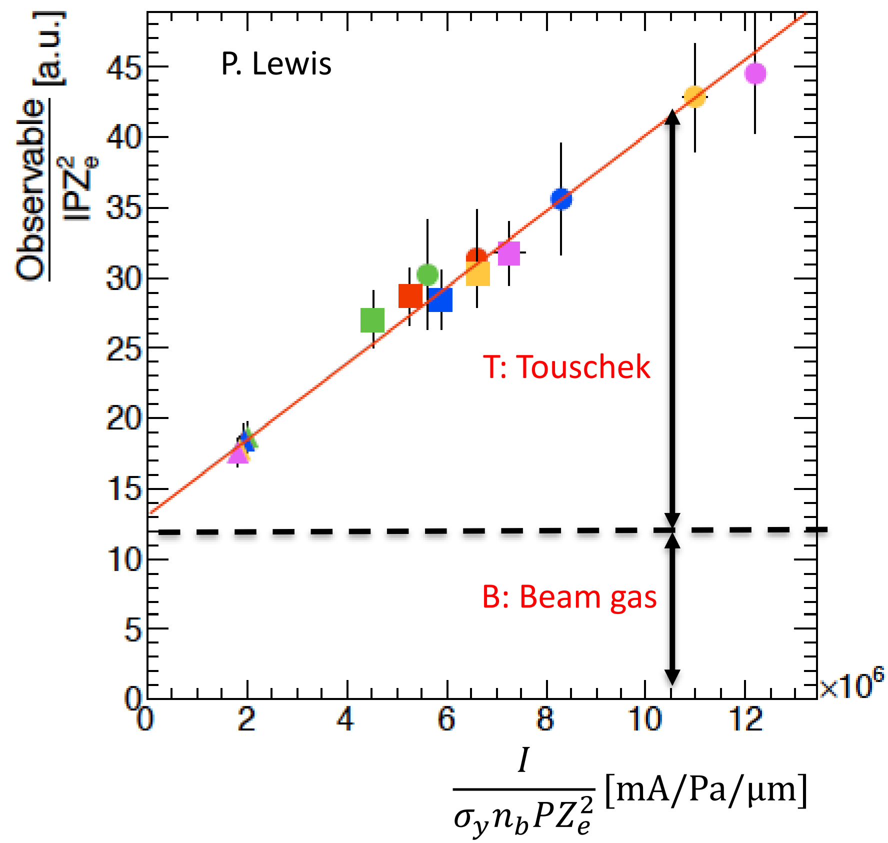
$$Rate = T\frac{I^2}{\sigma_y n_b} + BZ_e^2 IP \longrightarrow Rate/Z_e^2 IP = T\frac{I}{\sigma_y n_b P Z_e^2} + B$$

Linear function

T, B: Touschek/Beam-gas coefficient
σ_y: vertical beam size, n_b: number of bunches
P: pressure, I: beam current
Z_e: effective atomic number of residual gas

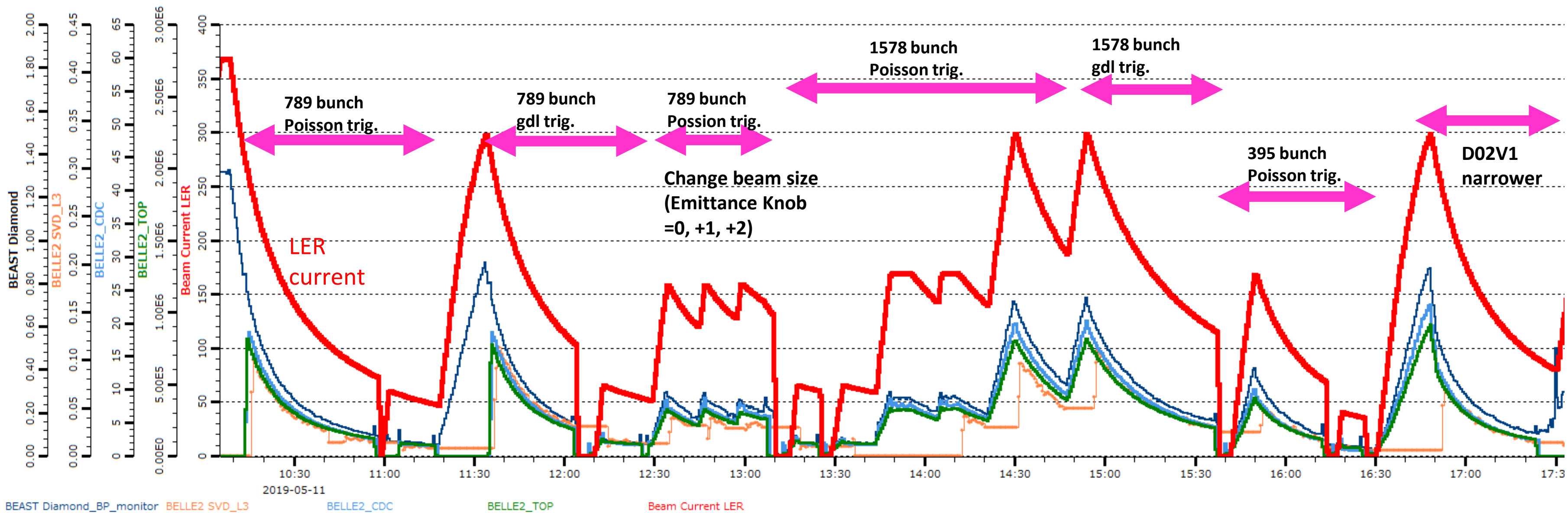
Strategy:

- **Assume Touschek + Beam-gas and no other BG component**
- **Vary beam sizes and number of bunches (which should affect Touschek component only)**
- **Fit for T and B coefficients and compare them against estimation by MC**
- **Use measured data/MC ratio for scaling BG simulation at future optics**



A snapshot from a single-beam BG study

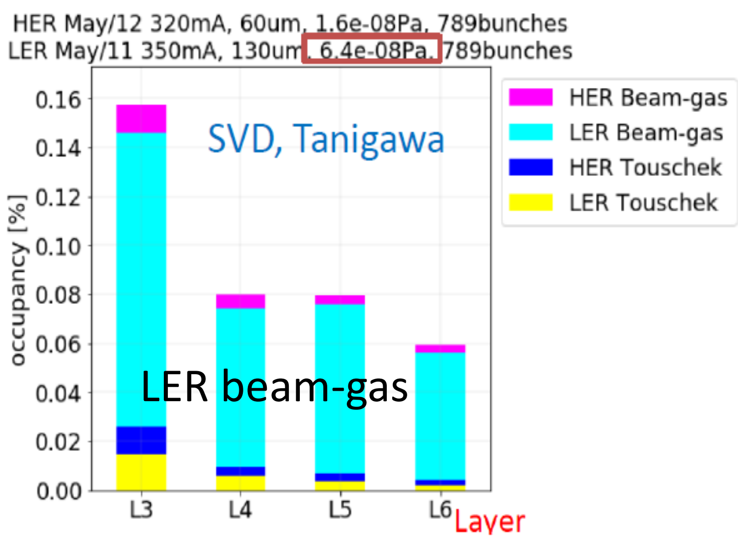
Example: LER single-beam study on May 11th

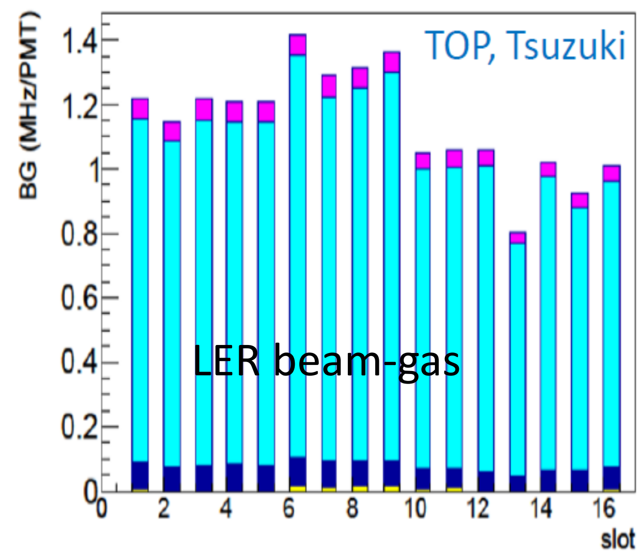


- Number of bunches =789/1578/395. Vertical beam size: 3 different sizes.
- As we increase beam size or number of bunches, Belle II BG rates at the same beam current becomes smaller (due to decrease in Touschek BG)
- <u>Observed dependency are consistent with the “Touschek+ Beam-gas” model (no significant indication of other BG sources)</u>

Beam background composition during typical physics runs

May background studies, HER 320mA, LER 350mA, 789 bunches





- In these plots, BG rates measured by single-beam studies are scaled to the physics run parameters (larger beam sizes due to collision)
- Exact composition depends on collimator settings and detectors, but..
  - LER storage BG >> HER storage BG, ratio > =4
  - LER Beam-gas dominates (~70% of total BG)
- Scaled Touschek + Beam-gas is consistent with total BG during physics runs
  → lumi-BG is still negligible, as expected at this luminosity

Data/MC ratio, scaling to design optics

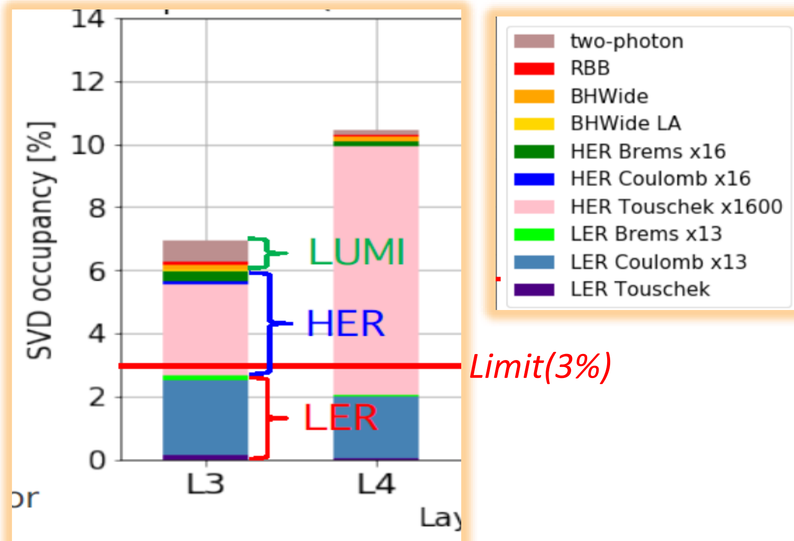
Data/MC ratio in 2019 May studies

SVD L3 Occupancy (Recent condition)

		data	MC	data/MC
LER Beam-gas	11th	0.26 %	0.020 %	**13**
	14th	0.14 %	0.012 %	**12**
LER Touschek	11th	0.03 %	0.029 %	**1.0**
	14th	0.02 %	0.022 %	**1.1**
HER Beam-gas		0.03 %	0.0016 %	**16**
HER Touschek		0.02 %	1.6e-5 %	**1600**

SVD, Tanigawa

Simulated BG rate at the final optics, scaled by latest data/MC ratio



SVD, Tanigawa

Data/MC ratio for inner detectors are

- O(1) for LER Touschek, O(10) for Beam-gas
- Huge for HER Touschek due to very small MC estimate

Data/MC ratio for outer detectors: in preparation

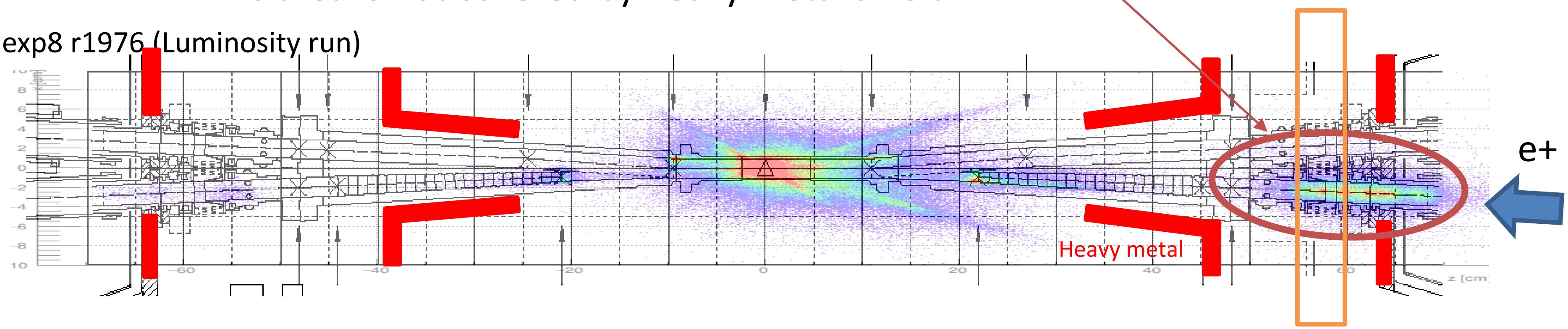
Scaled SVD rates at the final optics will exceed the limit(3% occupancy), with large uncertainty in HER Touschek

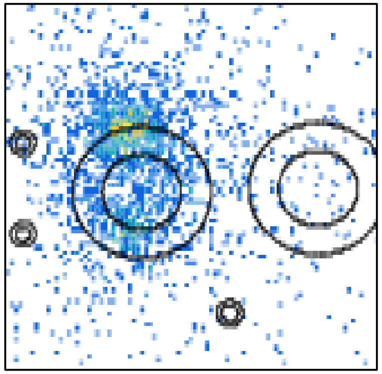
We need further BG mitigation (and understanding of HER Touschek)

Where BG showers come from?

- Construct vertices from e+ tracks and e- tracks to find BG shower source points
- "hot spot" around LER upstream bellows pipes (z=+60cm)
  - This area is not covered by heavy metal shield

exp8 r1976 (Luminosity run)





<u>Possible mechanism</u>

- Large beam loss at z=+110cm, inside final focus magnet
- BG showers develop along the beam line, leak from LER upstream bellows and reach Belle II drift chamber

- By changing vertical orbit inside the final focus magnet, we observed change in hot spot distribution and <u>decrease in BG rate</u>

Beam Background "big picture"
(as of mid. June 2019)

- Achieved machine parameters
  - beta_y*=3mm, 1576bunch, 650+650mA, L~0.5*10^34

SuperKEKB design parameter
beta_y*=0.27/0.30mm, 2500bunch, 3600+2600mA, L~80*10^34

- Our bottle-neck is CDC (and TOP)
  - CDC HV trips (storage BG + injection BG spikes) lead to frequent DAQ down time
  - TOP PMT photocathode lifetime issue
- Dominant source: LER beam-gas BG
  - Touschek BG is small enough, thanks to new horizontal collimators installed after Phase2
- Keep good injection condition is very important
  - To avoid CDC HV trips & loss monitor aborts at collimators (and allow us to close the collimators even narrower to reduce BG further)
- Severe "beam-dust" events damaged collimator head/QCS/Belle II
  - Beam core hit the collimator head and melted it!
  - Tip-scattering effect increased after this accident
  - We had to replace the head after 2019 spring run

Summary of BG measurement

- BG studies in 2019 spring run showed:
  - Beam BG is currently dominated by LER beam-gas
  - Data/MC ratio is O(10) for beam-gas, O(1) for LER Touschek

    → further BG mitigation is needed!
  - Luminosity BG is still small, as expected
  - We found adjusting beam orbit can reduce BG rates

2019 autumn run is ongoing!!!
- beta_y*: 2mm→1.5mm→1.2mm
- Vacuum scrubbing progress contributes to BG reduction
- Aggressive collimator settings (d=2mm→ 1.7mm) can reduce BG by factor of 1.5~2
- Injection BG gets more stable

Overall summary

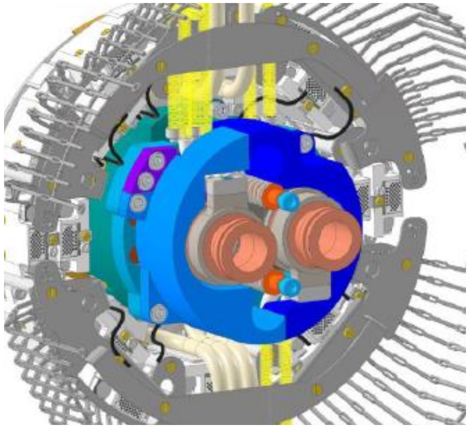
- Beam background at SuperKEKB can be dangerous and many countermeasures have been applied
- BG simulation predicts the impact on Belle II detectors
- BG measurements provides scaling factors between data and MC, which should be used for future extrapolation
- We still need further background mitigation

backup

Possible BG mitigation plans

Adding more shields

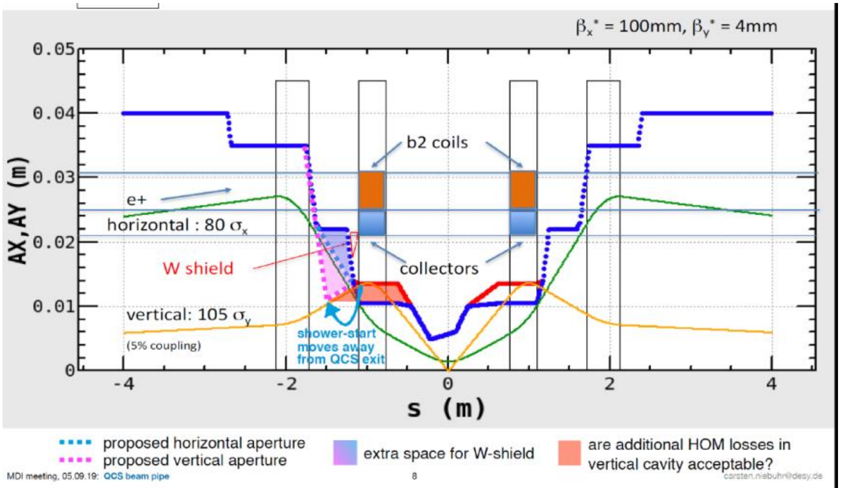
Katsuro Nakamura



- Additional shield around QCSR bellows
- Although quite challenging to find space, serious consideration ongoing
- Aiming for install together with VXD2021
- Activity lead by VXD mech group

•Or, make bellows itself by Ta.

Carsten



Beam loss inside QC1 can be moved upstream by squeezing upstream beam pipe?
Can we put more shielding?
Mechanical/simulation study ongoing.

Adding new collimators

- 2 LER vertical collimators already installed(D06V2, D02V1)

beta_y*=2mm

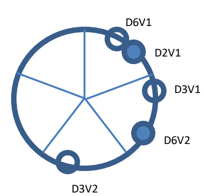
Phase2.1.7	beta_y	nu_y	Δnu	d[mm]
PMD06V1	61.43	28.90	+0.04	5.4
PMD06V2	**19.24**	**30.54**	+0.18	3.0
PMD03V1	16.96	41.47	+0.12	2.8
PMD03V2	16.96	42.63	+0.28	2.8
PMD02V1	**20.81**	**44.91**	**+0.06**	3.1
QC1RP995	**391.1**	**46.35**	+0	13.5

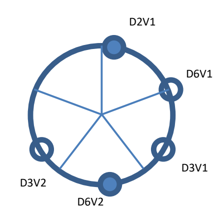
…

beta_y*=0.27mm (full-lumi)

Phase3	beta_y	nu_y	Δnu	d[mm]
PMD06V1	61.43	28.92	+0.10	2.0
PMD06V2	**19.24**	**30.56**	+0.24	1.1
PMD03V1	16.96	41.49	+0.17	1.1
PMD03V2	16.96	42.66	+0.34	1.1
PMD02V1	**111.75**	**44.83**	**+0.01**	2.7
QC1RP995	**2794.00**	**46.32**	+0	13.5

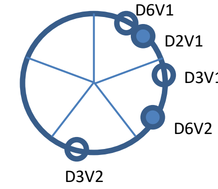
Δnu_y
(mod 0.5)





Additional LER V collimator for 2020

(2.0mm or smaller optics)



- D06V1
  - Pro: Good phase, can effectively reduce IR loss and reduce burden on D02V1
  - Pro: Large beta_y (easier handling)
  - Con: far from IP (no impact on particles scattered in D06-D03)
- D03V1
  - Pro: near IP
  - Con: unmatched phase, but might have some impact on particles scattered in D06-D03
- D03V2
  - Pro: completely unmatched phase, might be effective to protect IR from crazy beam
  - Pro': near IP, but it does not help because of ↓
  - Con: completely unmatched phase, expect no impact on particles scattered in D06-D03

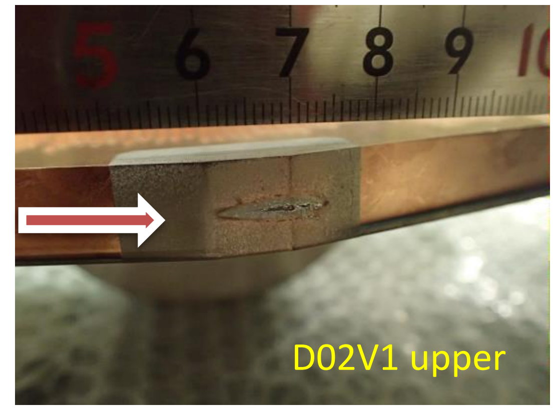
could save D02V1 from severe dust events

Vacuum bump study on June 13th suggests beam-gas scattering at D01, D12-D07 can also contribute to IR loss

We decided to install **D06V1** in winter shutdown.
For the next opportunity, I propose to install **D03V1**.

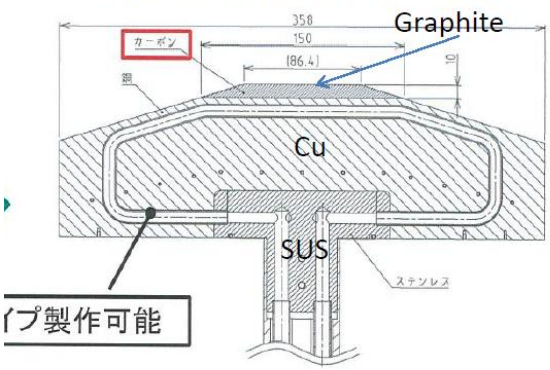
Low-Z collimator head option

- D02V1 collimator head was severely damaged by beam loss due to “beam-dust” event.
- D02V1 will be protected by adding D06V1, but then D06V1 could be damaged
- If D06 collimator head can be made with low-z material, loss is not localized and it could survive “beam-dust” event



S. Terui

Graphite head (not final design)

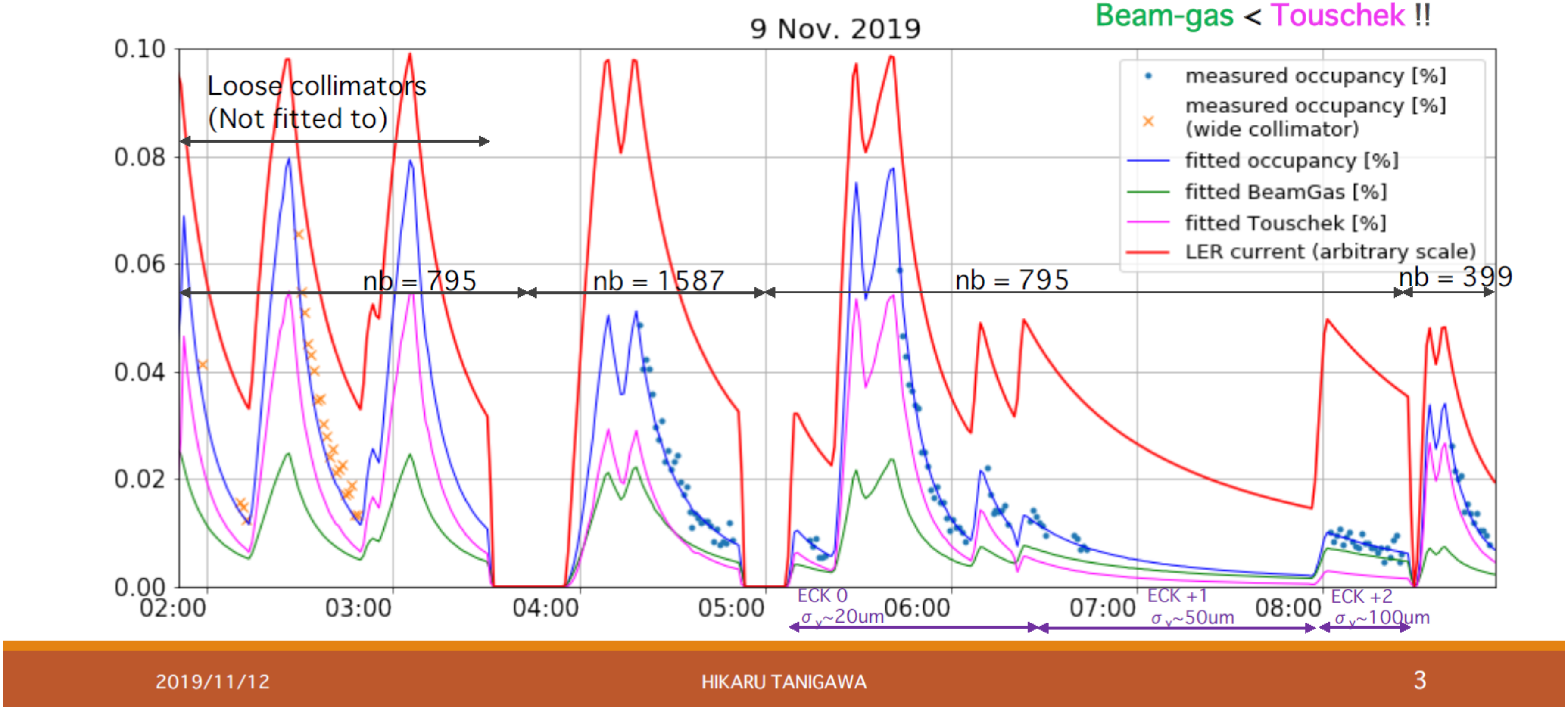


- Material choice: Ta? Graphite? Ti ?
- Simulation shows particles losing >2% energy at low-Z collimator will be lost downstream and will not reach IR
- Aiming for install in 2020 fall/winter
- Activity mainly lead by SKB vacuum group

BG study plots from 2019 autumn run

LER (Nov 9th): Fit result

Good fit quality.
Beam-gas < Touschek !!

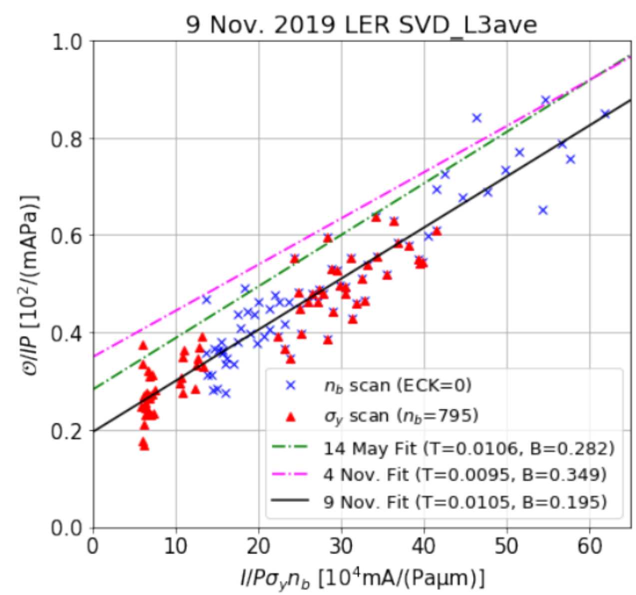


LER: Compared to May

No comparison with June (only done with physics trig)

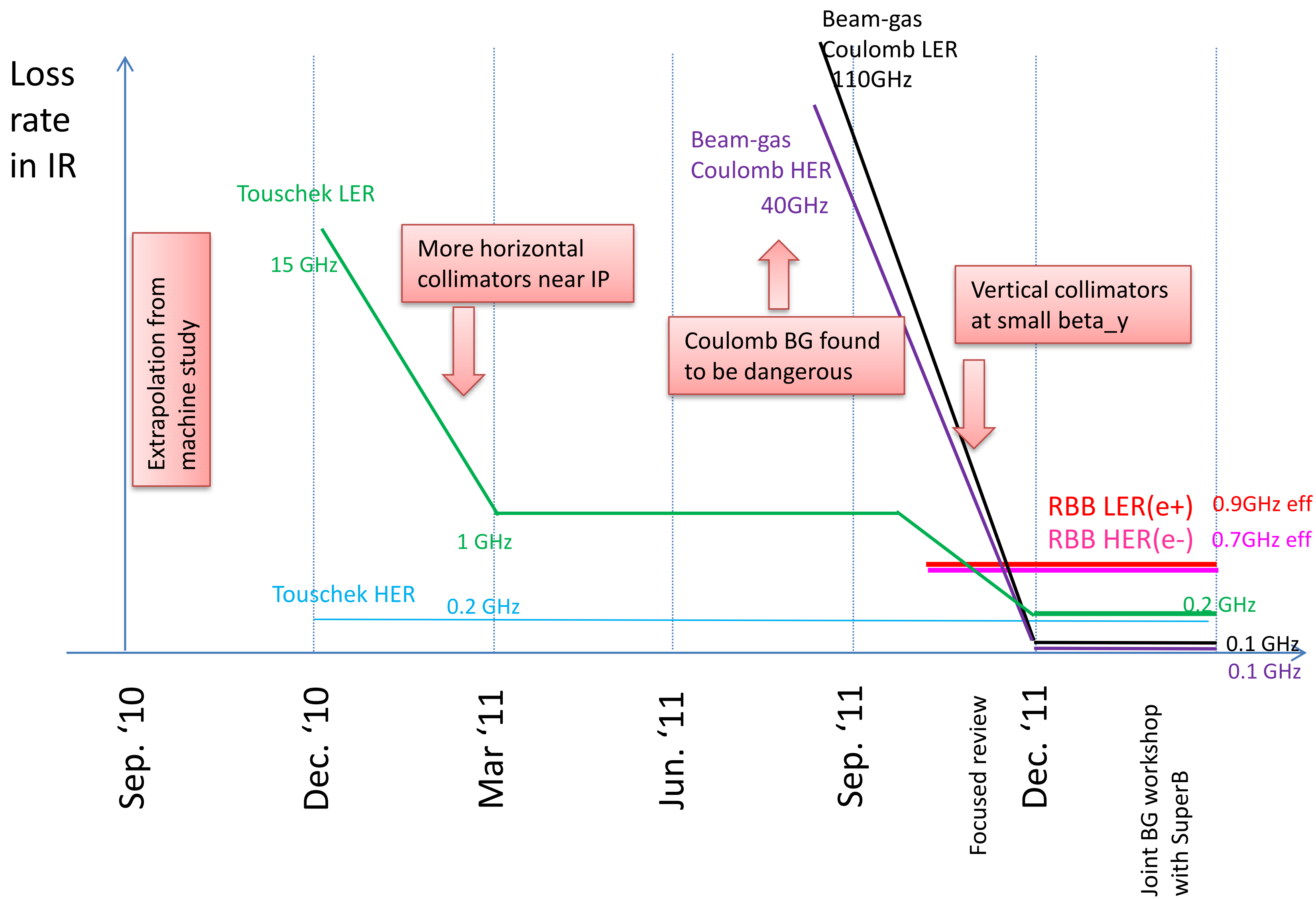
May 14th (200/3 mm) -> Nov 11th (80/2mm, tight collimator)

- Beam-gas (offset): 70%
  - partly due to relatively lower D02 pressure than May? (backup)
- Touschek (slope): no change



SuperKEKB beam backgrounds

Background reduction history



Where we should put the vertical collimators?

Collimator aperture should be narrower than QC1 aperture.

$$d/\sqrt{\varepsilon\beta} < r_{QC1}/\sqrt{\varepsilon\beta_{QC1}} \Rightarrow d_{max} \propto \beta^{1/2}$$

TMC instability should be avoided.

Transverse Mode Coupling instability

Assuming following two formulae:

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i k_{\perp i}(\sigma_z)} > 1.44 \text{ mA/bunch (LER)}$$

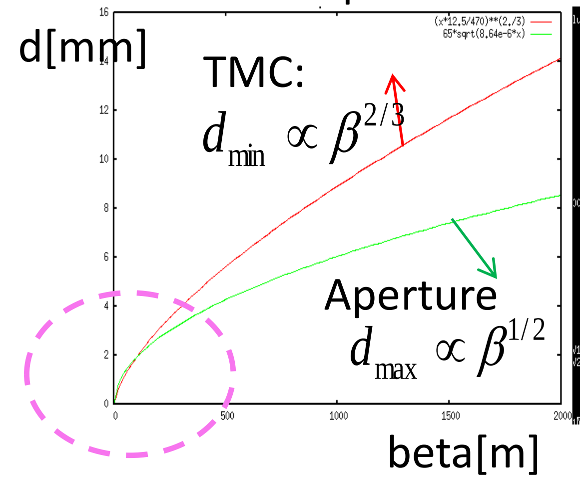
taken from "Handbook of accelerator physics and engineering, p.121"

Kick factor $$k_{\perp} = 0.215 A Z_0 c \sqrt{\frac{\theta}{\sigma_z d^3}}$$

(in case of rectangular collimator window)

$$\Rightarrow d_{min} \propto \beta^{2/3}$$

Collimator position



We should put collimator where beta_y is rather SMALL!

For more details, please check out following paper:
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)

IR loss is quite sensitive to vertical collimator width

ler1604, V1=LLB3R downstream

V1 width[mm]	IR loss [GHz]	Total loss[GHz]	Coulomb life[sec]
2.40	**0.04**	153.9	1469.8
2.50	**0.05**	141.8	1594.8
2.60	**0.09**	131.0	1724.9
2.70	**0.24**	121.4	1860.2
2.80	**1.65**	111.4	2000.5
2.90	**11.48**	100.8	2014.3
3.00	**21.98**	90.3	2014.3

Based on element-by-element simulation, taking into account the causality and the phase difference, up to 100 turns (Nakayama)

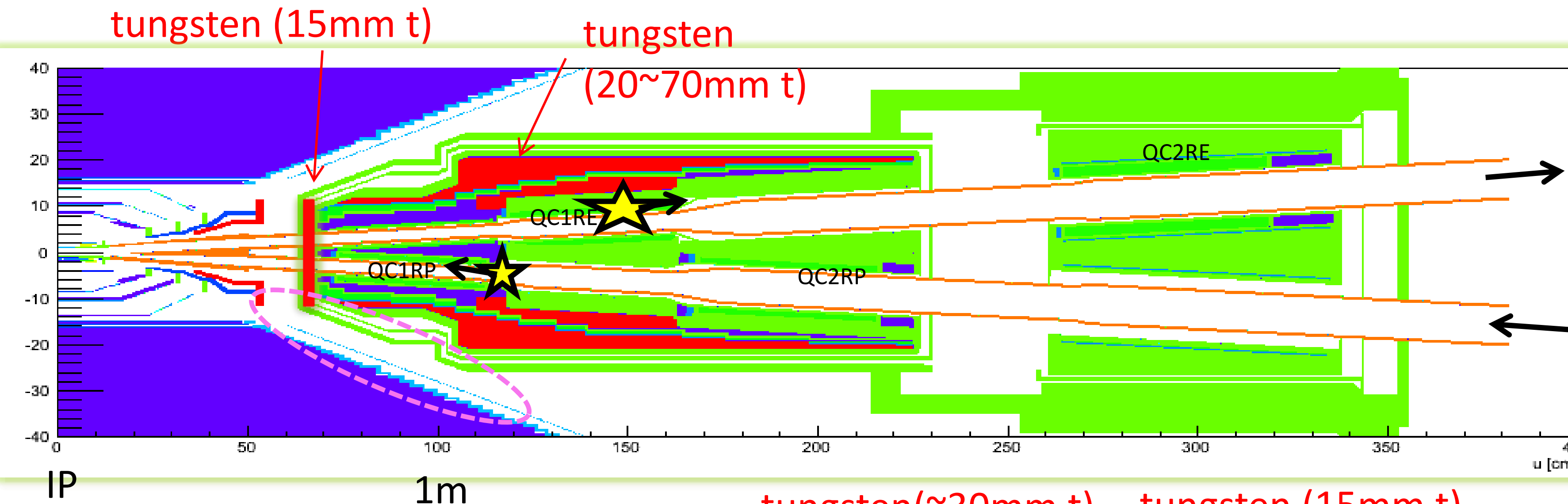
her5365,V1=LTLB2 downstream

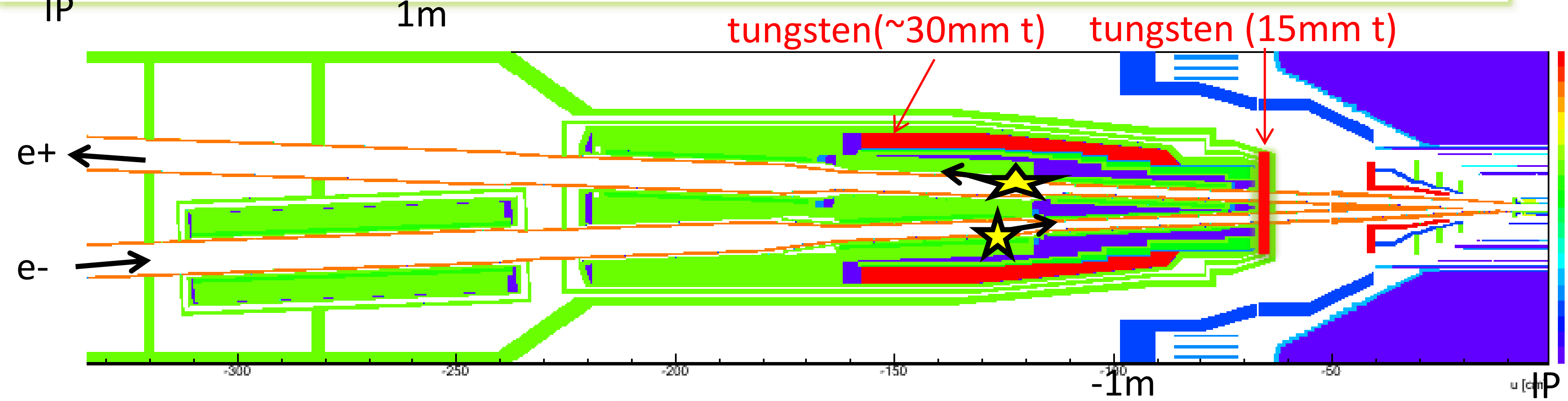
V1 width[mm]	IR loss [GHz]	Total loss[GHz]	Coulomb life[sec]
2.10	**0.0007**	49.6	3294.0
2.20	**0.001**	45.2	3615.2
2.30	**0.357**	41.0	3951.3
2.40	**7.99**	33.0	3985.9
2.50	**13.1**	27.9	3985.9

Just a few hundreds micron wider setting of vertical collimator width can lead to significant increase on IR loss. Quite dangerous!

Typical orbit deviation at V1 : +-0.12mm (by iBump V-angle: +-0.5mrad@IP)

Tungsten shields inside Final Focus cryostat

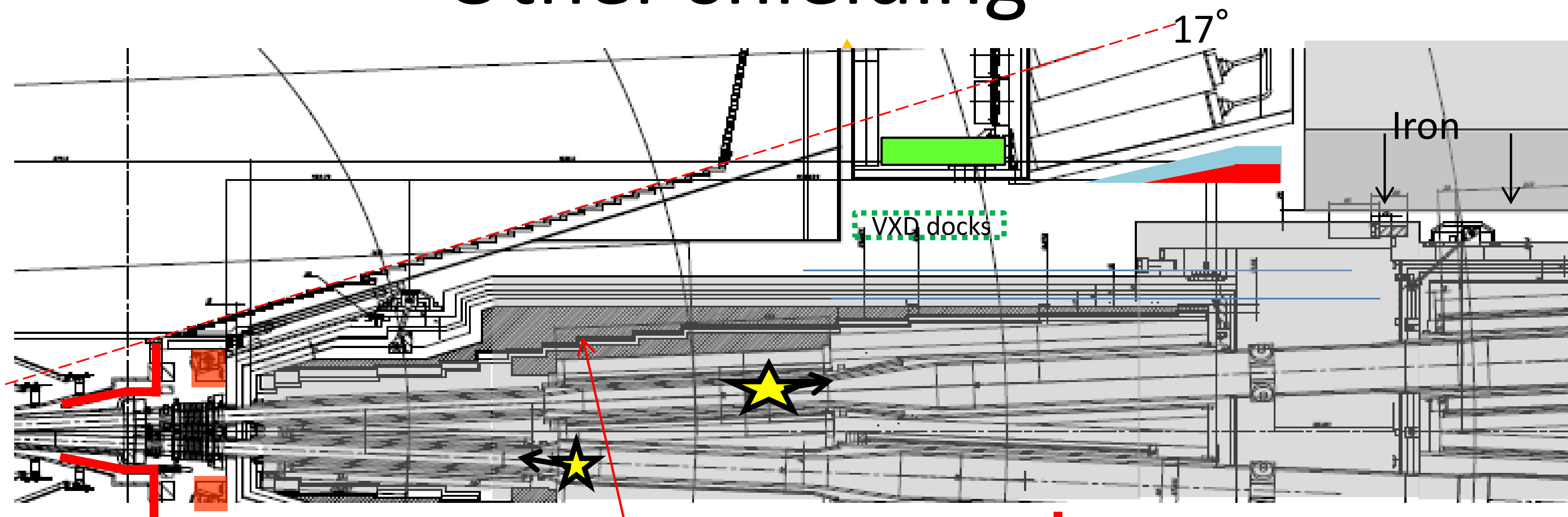




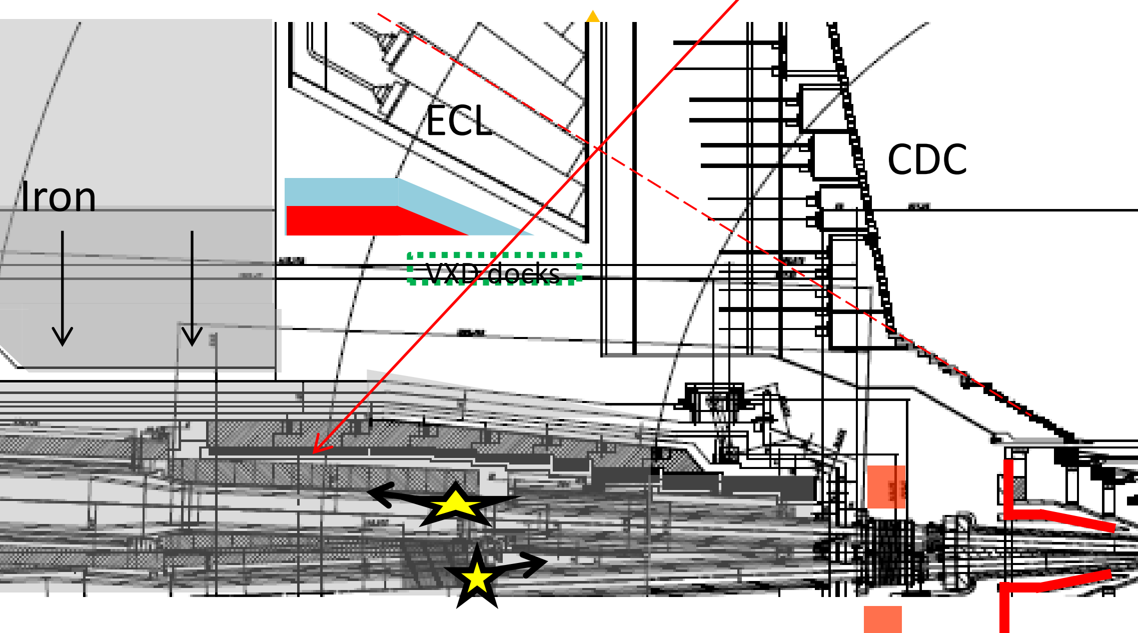
Major beam loss position by Touschek or Beam-gas

Thick tungsten shields can significantly stop background showers originated from |s|>65cm.

Other shielding



Thick tungsten layers inside cryostat



Heavy metal shields to protect VXD from showers generated in cryostat

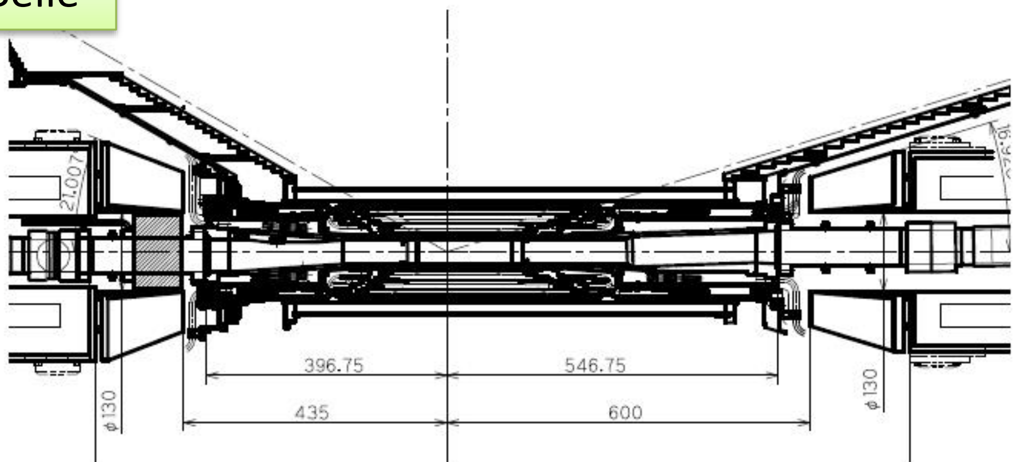
Neutron shield to protect HAPDs in ARICH (Boron-doped Polyethylene)

ECL shield, for included for (Lead + Polyethylene)

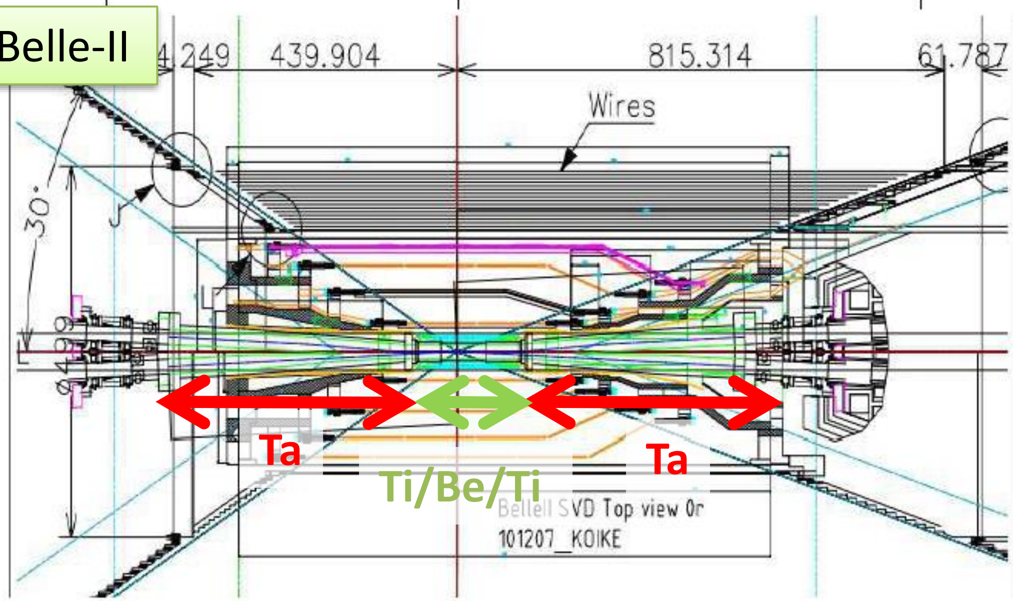
Remote Vacuum Connection structure in front of QCS reduces showers from RBB loss at |s|~60cm (6cm-thick SUS)

Interaction region

Belle



Belle-II

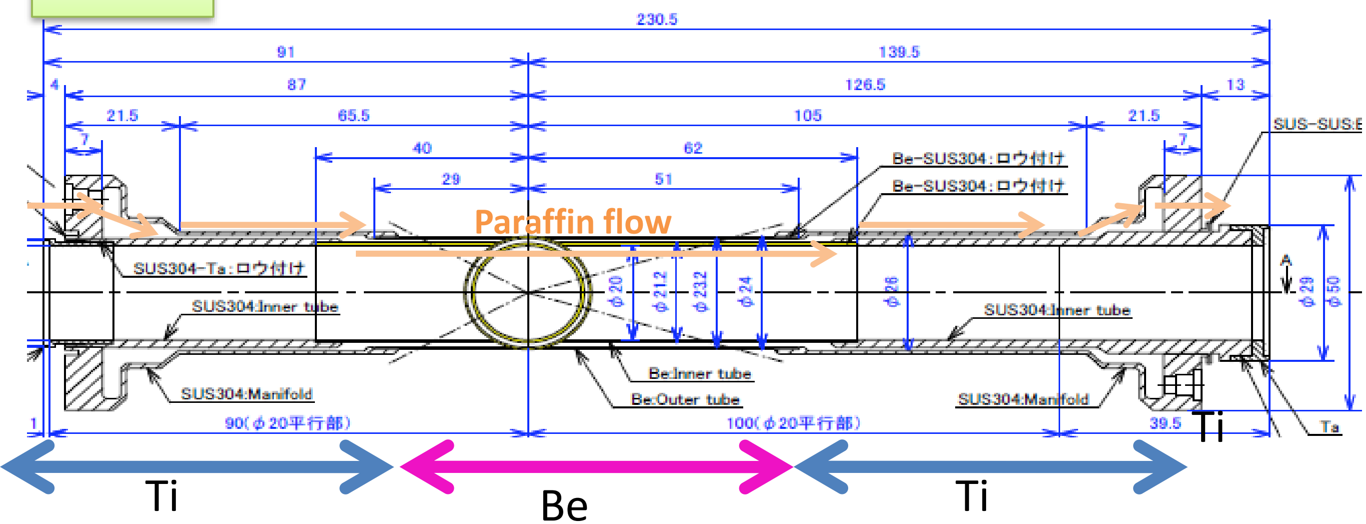


<Belle-II>

- Smaller IP beam pipe radius (r=15mm⇒10mm)
- Wider beam crossing angle (22mrad⇒83mrad)
- Crotch part: Ta pipe
- Pipe crotch starts from closer to IP, complicated structure
- New detector: PXD (more cables should go out)

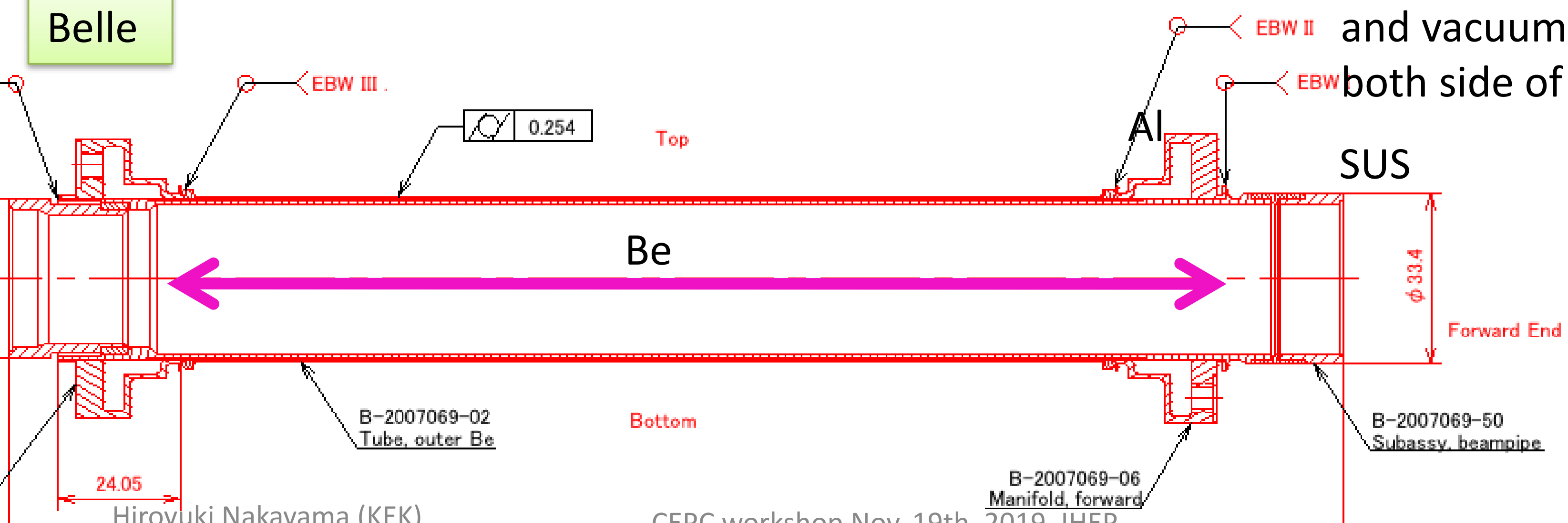
IP beam pipe

Belle-II

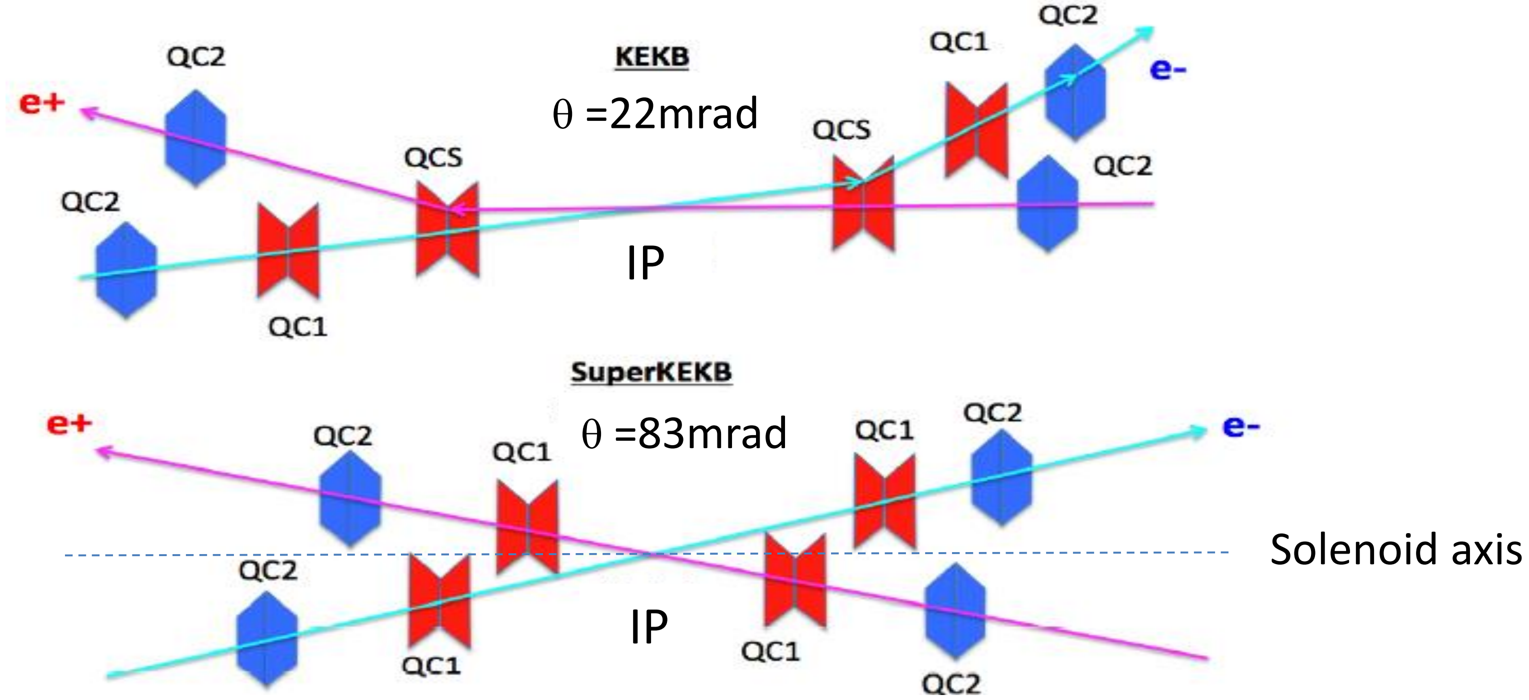


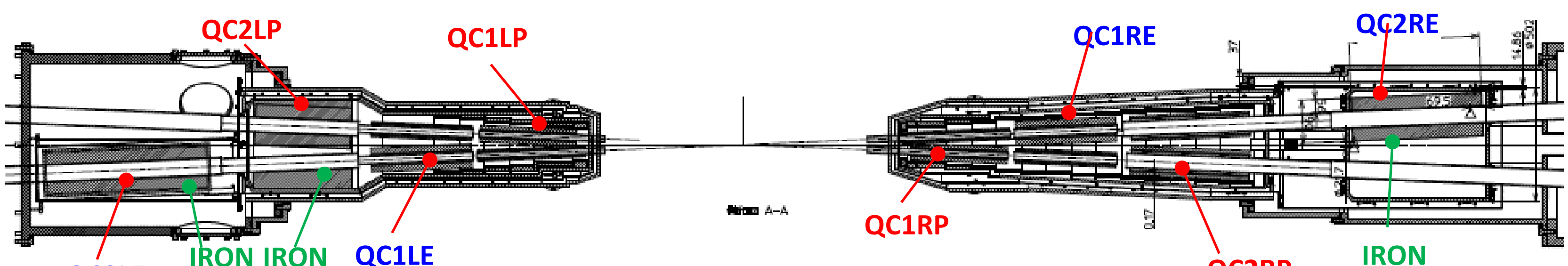
- Light material (Be) inside detector acceptance
- Paraffin ($C_{10}H_{22}$)flow to remove heat from mirror current (~80W)
- Gold plating (~10um) on inner wall to stop SR
- Much simpler Be shape (also much cheaper) since we allow Paraffin and vacuum to attach both side of welding

Belle



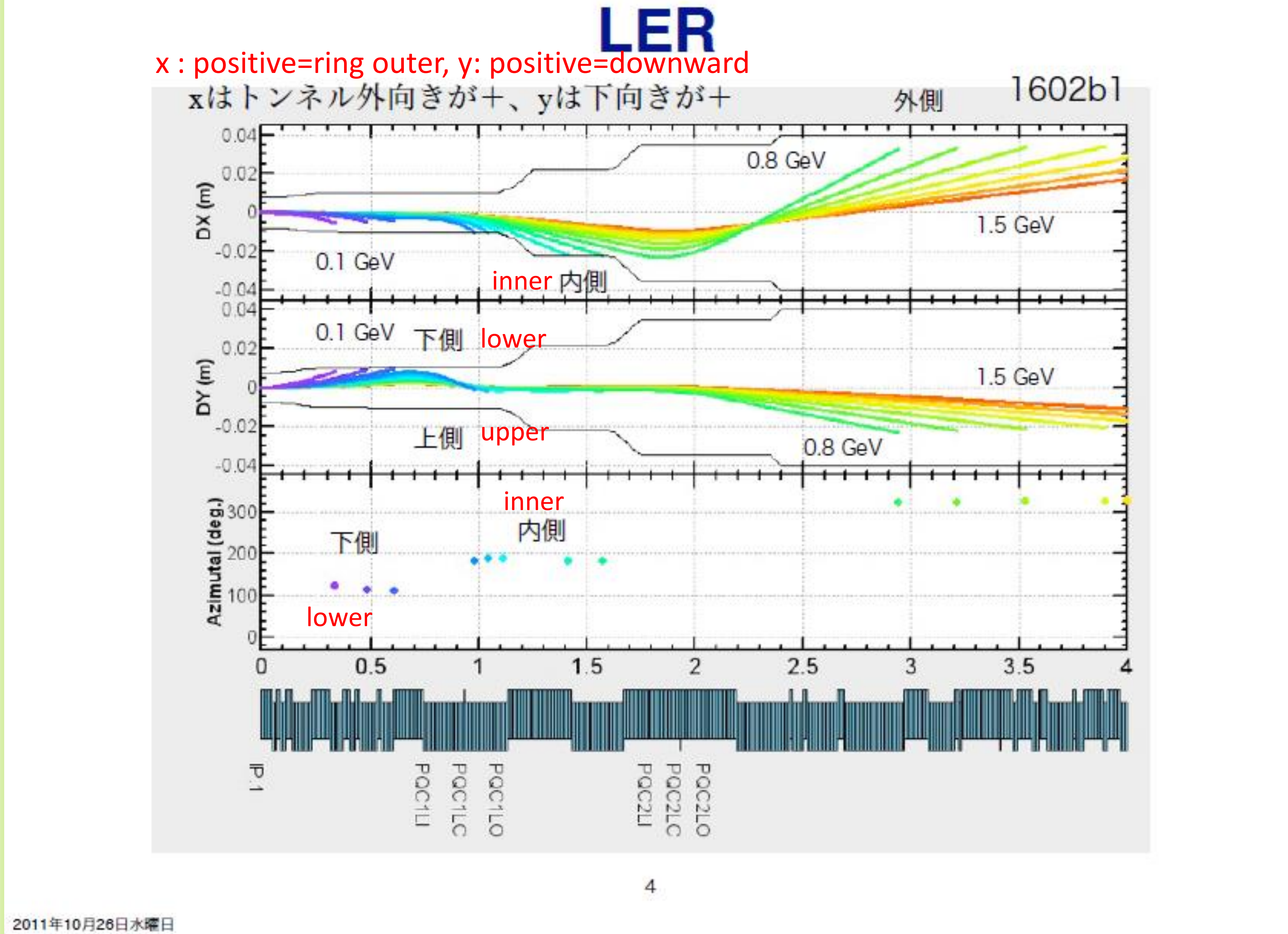
Final focusing magnets





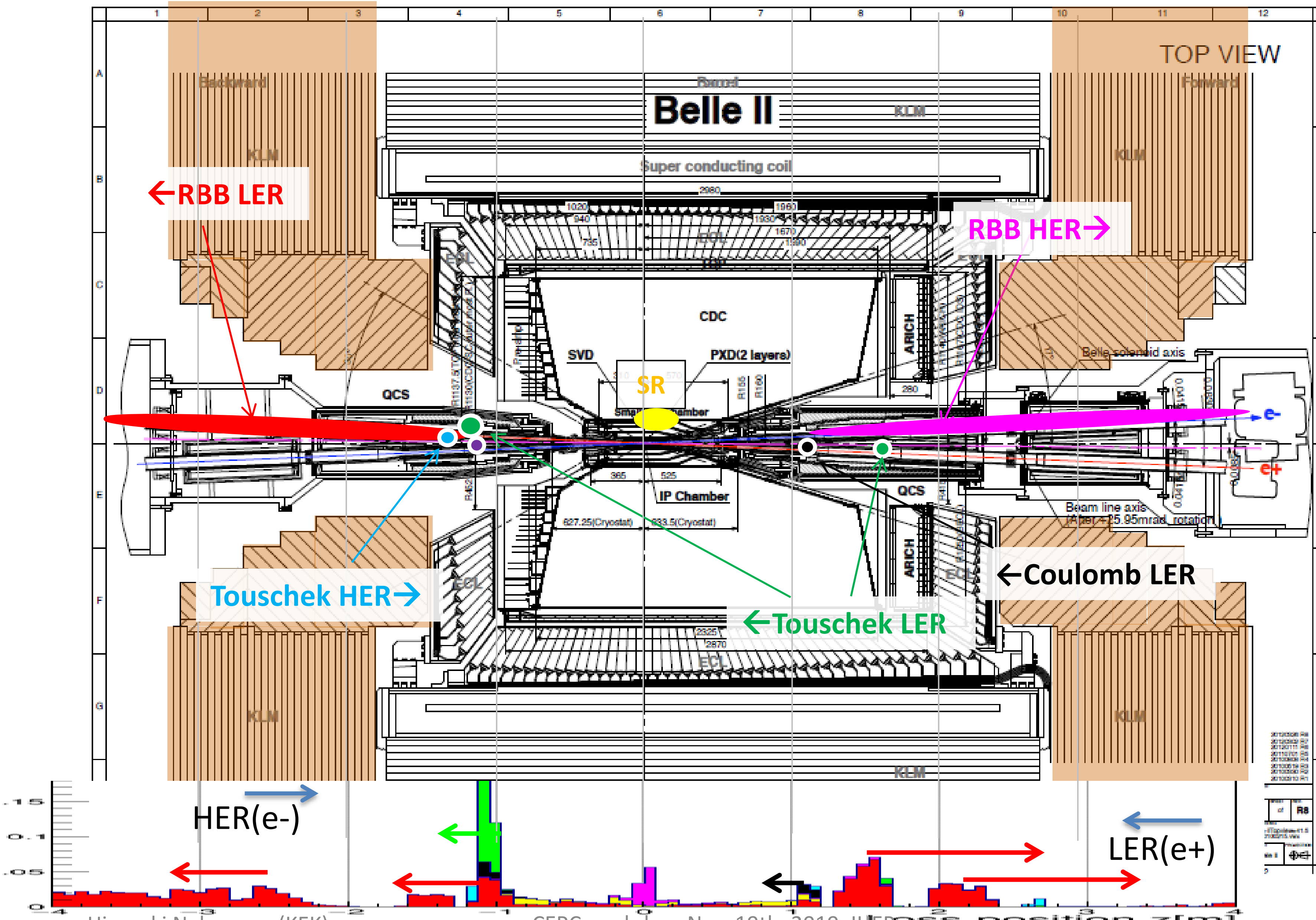
- Larger crossing angle θ
- Final Q for each ring→ more flexible optics design
- No bend near IP→ less emittance, less background from spent particles

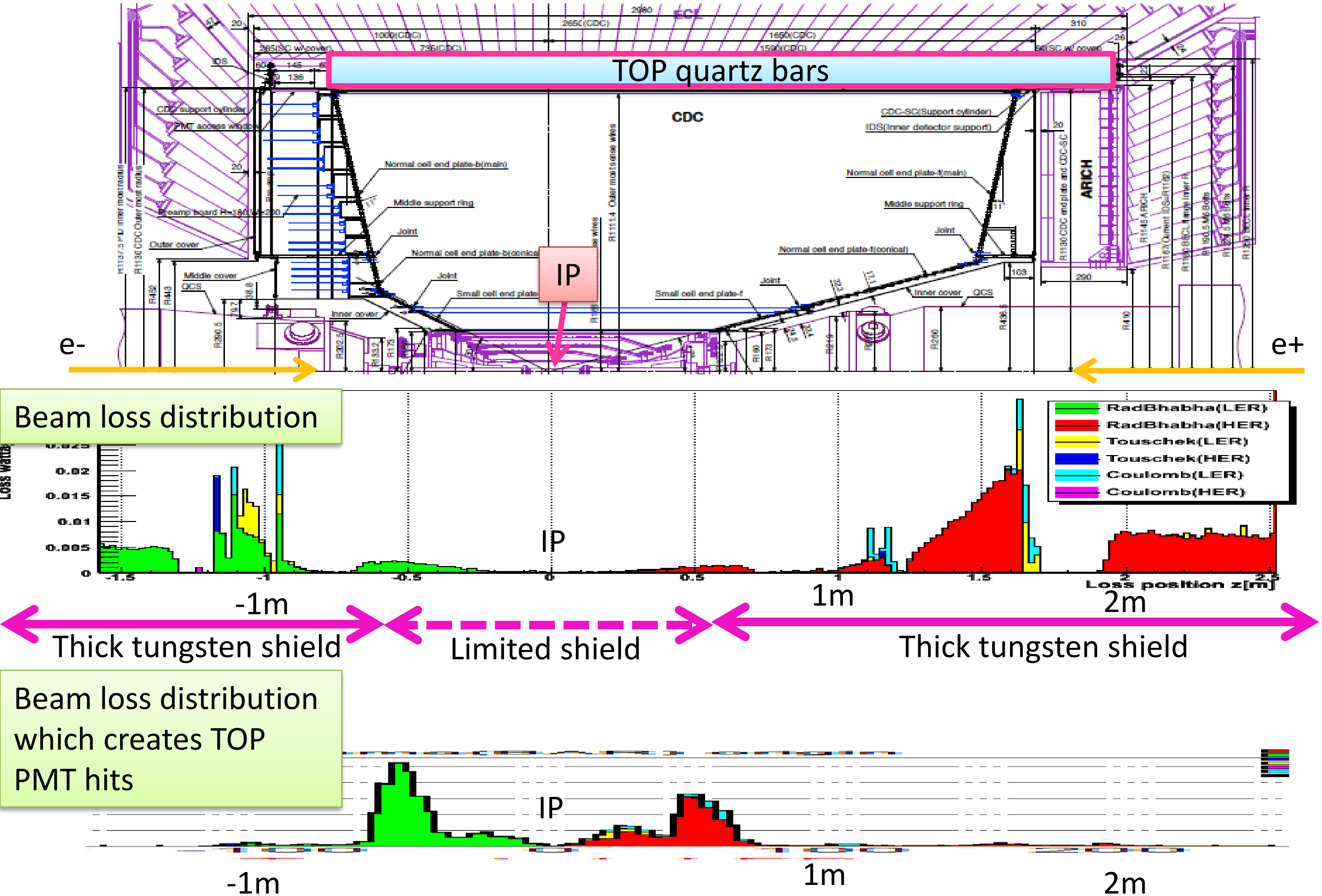
Beam orbit after RBB scattering



Background Global picture

Ver. 2017.1.31





TOP quartz bars
CDC
ARICH
ECL
IP
e-
e+
Beam loss distribution
RadBhabha(LER)
RadBhabha(HER)
Touschek(LER)
Touschek(HER)
Coulomb(LER)
Coulomb(HER)
Loss position z[m]
-1m
1m
2m
Thick tungsten shield
Limited shield
Thick tungsten shield
Beam loss distribution which creates TOP PMT hits
IP
-1m
1m
2m