Study Status of the Beam Induced Background at CEPC

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On behalf of the CEPC BG Working Group

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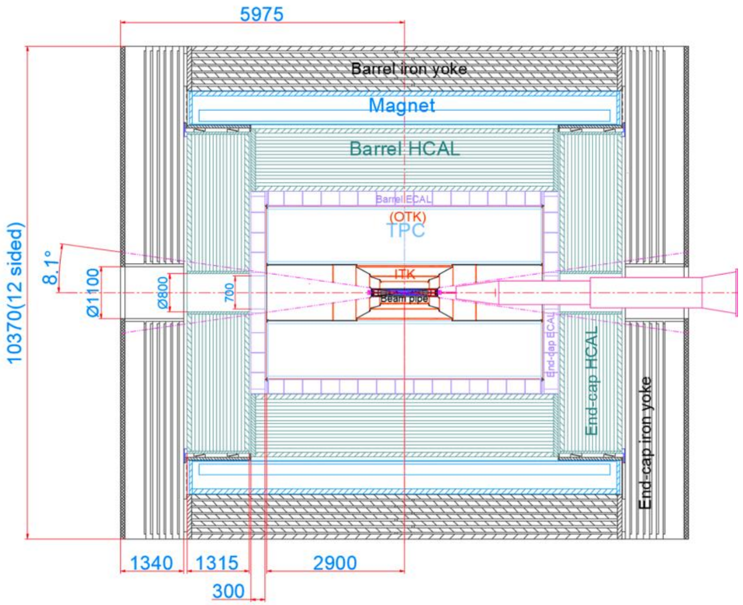
- **Sources and Simulation Steps**
- **SR and Pair Production**
- **Mitigation Methods**
- **Final Results**
- **Experiences at BESIII/BEPCII**
- **Summary and Outlook**

Introduction

- Reasonable Estimation of Beam-induced background levels
  - Based on the 50-MW design of CEPC Accelerator TDR
  - Keep updating with the Ref-TDR detector
- Estimation of the Noise on Detector
- Estimation of the Radiation Environment: contributions from Backgrounds and Signal
- Mitigation Methods



	Higgs	High-Lumi-Z	Low-Lumi-Z
Number of IPs	2		
Solenoid(T)	3		
Circumference (km)	99.955		
Half crossing angle at IP (mrad)	16.5		
Bending radius (km)	10.7		
SR power per beam (MW)	50		12.1
Energy (GeV)	120	45.5	45.5
Energy loss per turn (GeV)	1.8	0.037	0.037
Bunch number	446	13104	3978
Bunch spacing (ns)	277.0	23.1	69.2
[× 23.08 ns]	12	1	3
Train gap [%]	63	9	9
Bunch population (10^{11})	1.3	2.1	1.7
Beam current (mA)	27.8	1345.2	325.0
Beta functions at IP b_x^*/b_y^* (m/mm)	0.3/1	0.2/1.0	0.13/1.0
Emittance e_x/e_y (nm/pm)	0.64/1.3	0.27/5.1	0.27/5.1
Betatron tune n_x/n_y	445/445	317/317	317/317
Beam size at IP s_x/s_y (um/nm)	14/36	6/72	6/72
Bunch length (natural/total) (mm)	2.3/4.1	2.6/9.8	2.5/8.8
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.15	0.04/0.13
Energy acceptance (DA/RF) (%)	1.6/2.2	1.2/1.7	1.0/1.7
Beam-beam parameters x_x/x_y	0.015/0.11	0.0046/0.074	0.0053/0.082
Beam lifetime (Bhabha/beamstrahlung) (min)	40/40	120/280	150/180
Beam lifetime requirement (min)	20	81	68
Luminosity per IP (10^{34} cm^{-2} s^{-1})	8.3	95.2	26

Sources and Simulation Steps/Tools

- Single Beam
  - Touschek Scattering
  - Beam Gas Scattering(Elastic/inelastic)
  - Beam Thermal Photon Scattering
  - Synchrotron Radiation
- Luminosity Related
  - Beamstrahlung
  - Radiative Bhabha Scattering

For Ideal beam with high order magnet error
Other errors like misalignment not included yet

- Injection
- SuperKEKB like sudden beam loss
- Failure Case(injection/extraction/Power Loss…)

Will be considered future except power loss

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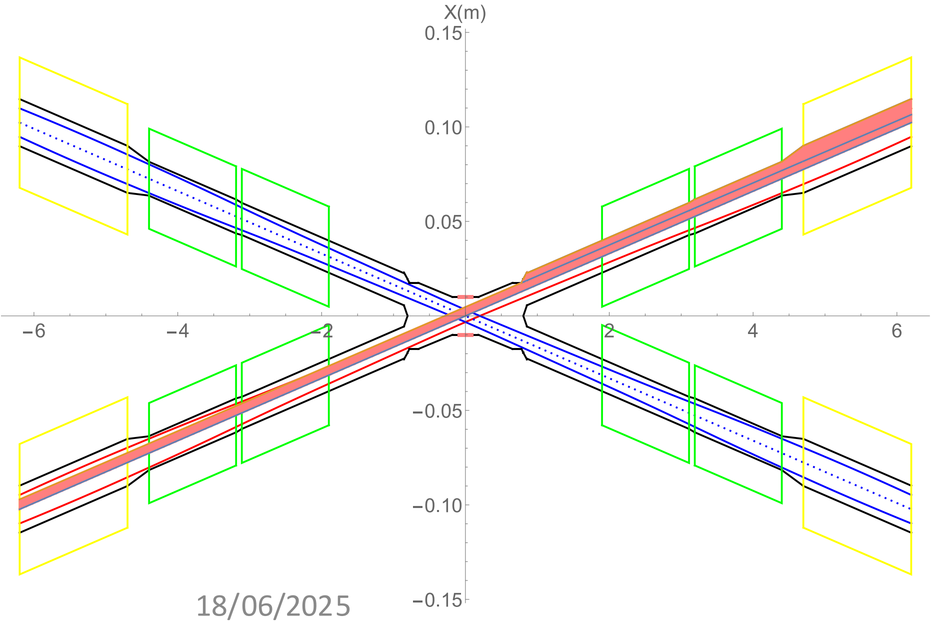
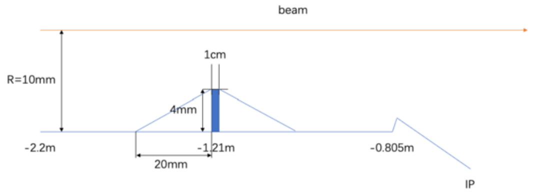
Background	Generation	Tracking	Detector Simu.
Synchrotron Radiation	BDSim/Geant4	BDSim/Geant4	CEPCSW/FLUKA
Beamstrahlung/Pair Production	Guinea-Pig++	SAD	
Beam-Thermal Photon	PyBTH[Ref]		
Beam-Gas Bremsstrahlung	PyBGB[Ref]		
Beam-Gas Coulomb	BGC in SAD		
Radiative Bhabha	BBBREM		
Touschek	PyTSK with SAD		

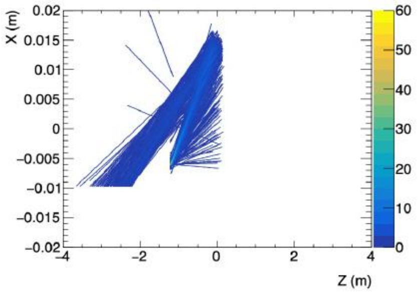
- One Beam Simulated
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(200 turns)
  - Using built-in LOSSMAP
  - SR emitting/RF on
  - Radtaper on
  - No detector solenoid yet

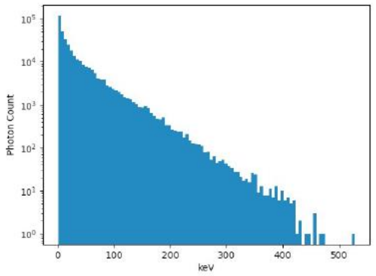
SR BG & Mitigation

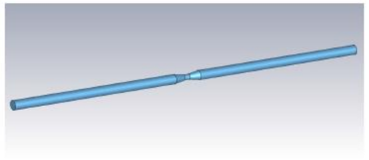
- The central beam pipe was carefully designed to avoid the direct hitting of the SR photons
- The masks are implemented to further mitigate the secondaries, the design is still on going.
  - Several ways has been attempted, including the shrinking of the incoming beam pipe and different position/material/design of the mask.
- The following processes are considered now:
  - Photoelectric, Compton Scattering, Rayleigh Scattering, Pair Creation and X-Ray Reflection(G4 built-in model with version 11.2+)

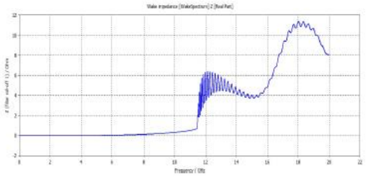












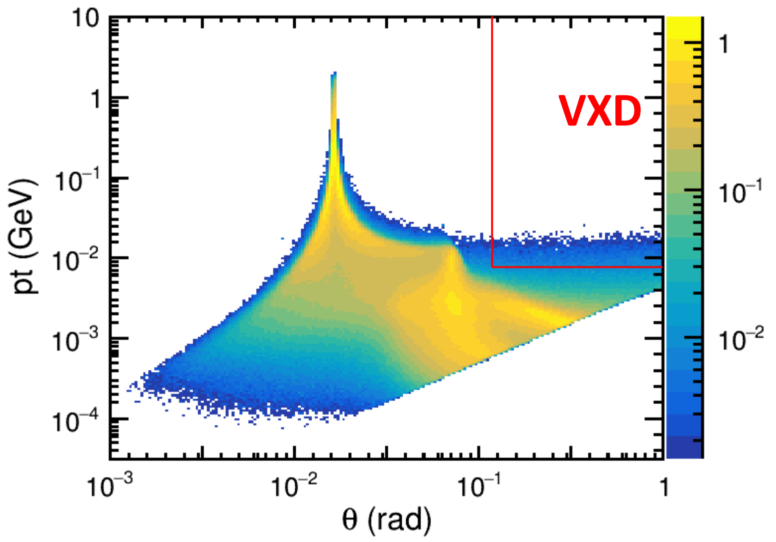
Shielding Methods	SR Backgrounds Level at VXD(MHz/cm^2)
Original	117,191.0
-1.9m mask	91.2
-1.9m mask+5um Au	61.7
-1.9m+-4.3m mask + 5um Au	10
-1.9m+-7.2m mask + 5um Au	<1

Pair Production(Beamstrahlung)

- Luminosity related backgrounds
- One of the dominant backgrounds at the CEPC, may lead to two different impacts:
  - The impacts on detector, caused by the electrons/positrons produced by photons(mainly incoherent)
  - The impacts on accelerator components outside of the IR, caused by the photons directly.
- Hard to mitigate

2022 parameters

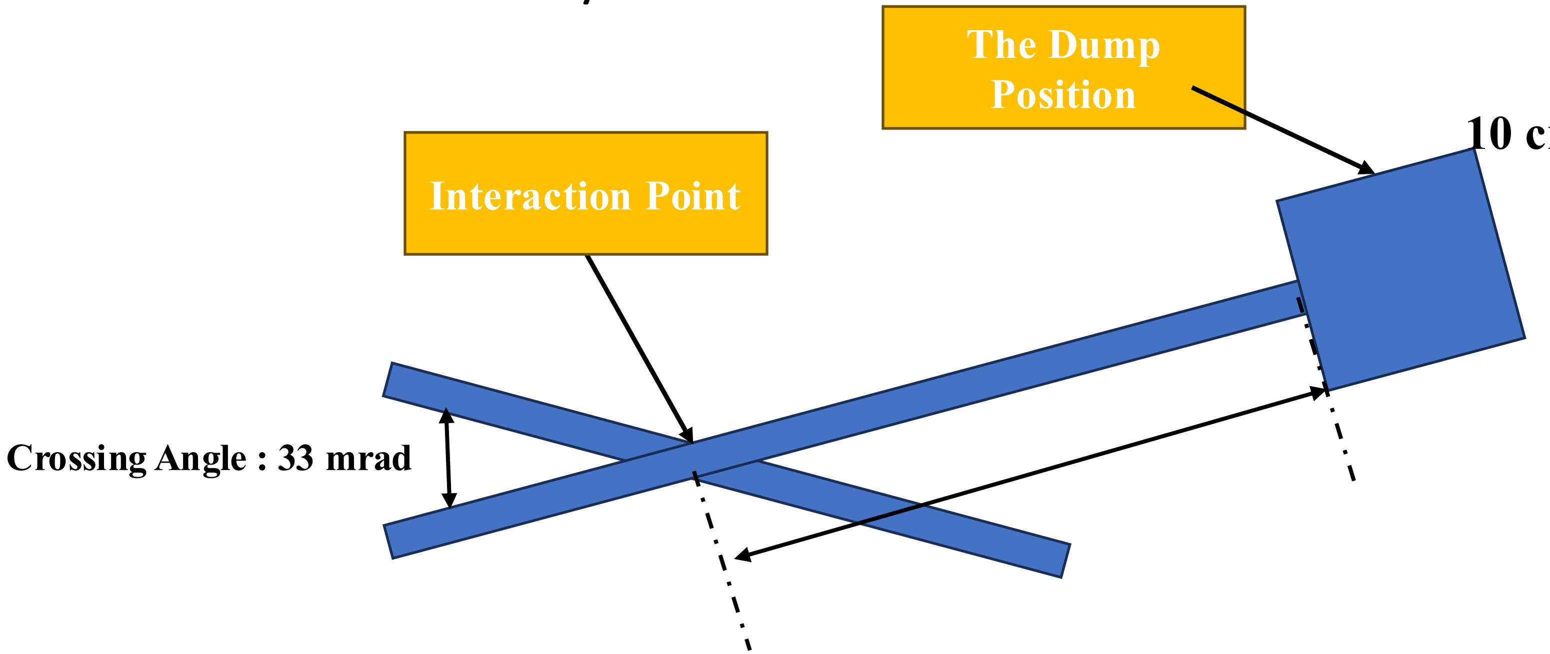
Parameter	Symbol	ILC-500	CLIC-380	CEPC-Z	FCC-Z	CEPC-W	FCC-W	CEPC-Higgs	FCC-Higgs	CEPC-top	FCC-top
Energy	E[GeV]	250	190	45.5	45.5	80	80	120	120	180	182.5
Particles per bunch	N[1e10]	3.7	2	14	24.3	13.5	29.1	13	20.4	20	23.7
Bunch Number				11934	10000	1297	880	268	248	35	40
Bunch Length	sigma_z [mm]	0.3	0.07	8.7	14.5	4.9	8.01	4.1	6.0	2.9	2.75
Collision Beam Size	sigma_x,y [um/nm]	0.474/5.9	0.149/2.9	6/35	8/34	13/42	21/66	14/36	14/36	39/113	39/69
Emittance	epsilon_x,y [nm/pm]	1e4/3.5e4	0.95e3/3e4	0.27/1.4	0.71/1.42	0.87/1.7	2.17/4.34	0.64/1.3	0.64/1.29	1.4/4.7	1.49/2.98
Betafunction	beta_x,y [m/mm]	0.011/0.48	0.0082/0.1	0.13/0.9	0.1/0.8	0.21/1	0.2/1	0.3/1	0.3/1	1.04/2.7	1/1.6
Factor	[1e-4]	612.7	6304.6	2.14	1.7	3.0	2.4	4.8	5.2	5.6	7.10
n_gamma		1.9	4.34	1.0	1.36	0.45	0.59	0.4	0.64	0.22	0.26
Relative loss per particle	%/BX	19.3		0.0041	0.0092	0.0067	0.0072	0.0096	0.0161	0.0062	0.0093

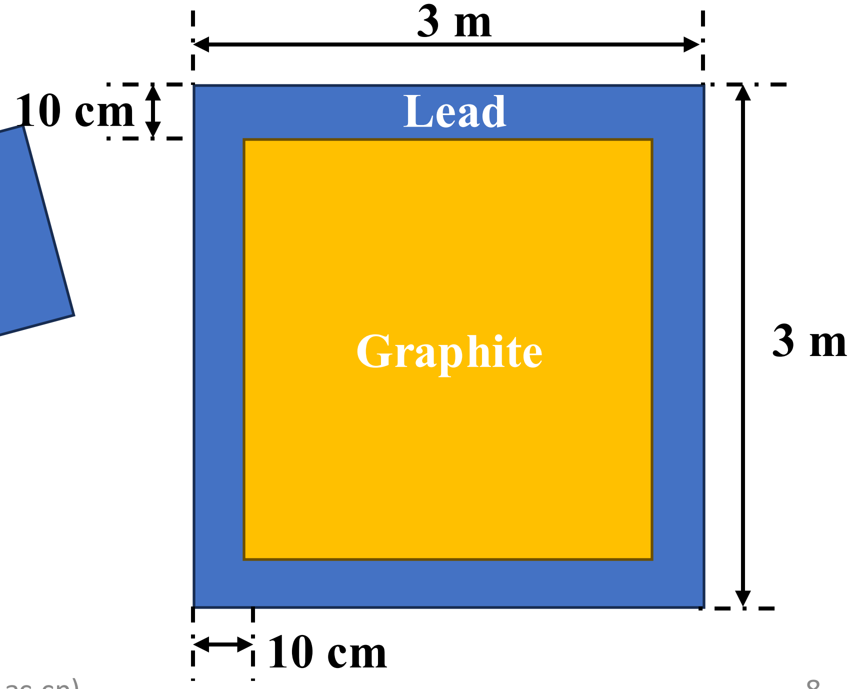


Mode	Higgs	Z(10MW)
Pairs/BX	~2200	~850

Beamstrahlung – Photon Dump

- We have completed the preliminary study on the photon dump and have already developed a reference design for it.
  - The extraction line and the modification of the magnets have not yet been incorporated into the design. The whole system design is on going.
  - The ambient equivalent dose constraint has been met, with a value of less than 5.5 mSv/h.



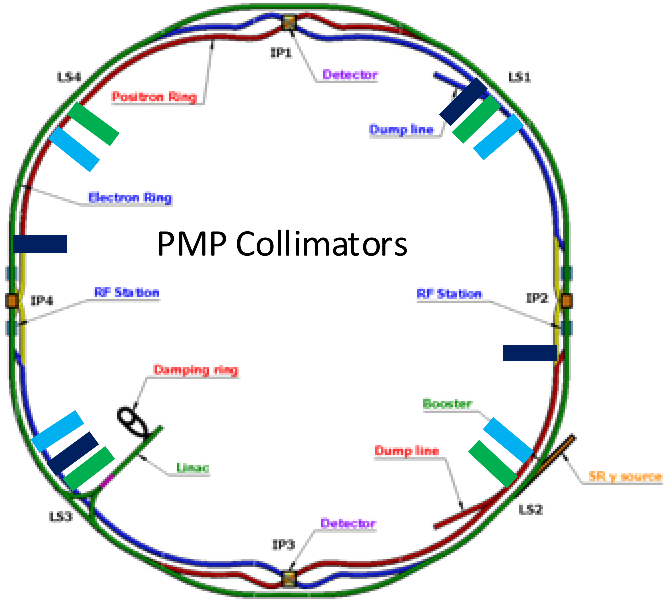


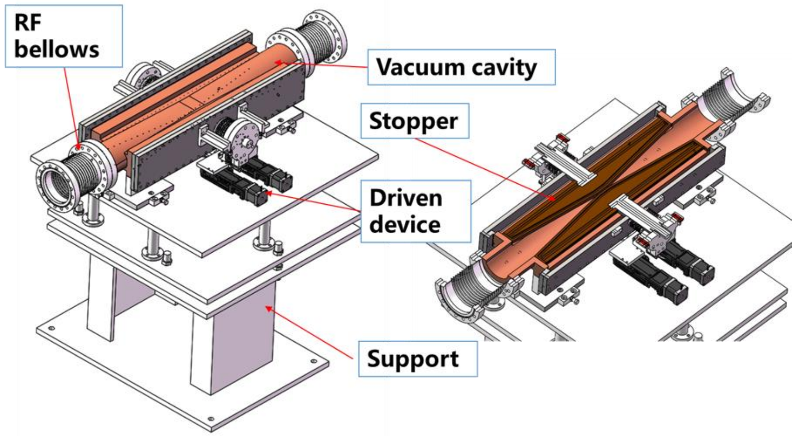
Mitigation of the BG

- The sources of the BIBs has two groups:
  - From IP, luminosity related(pair-production, radiative Bhabha)
  - From anywhere around the ring, less in IP(single beam losses and SR)
- Previously, we have several methods of shielding(or mitigation)
  - Using collimators to block single beam loss outside of the IR
  - Using mask to block SR outside of the Be beam pipe
  - Using heavy metal(like W) somewhere in the IR(like outside the cryomodule)
  - Using paraffine at both ends of the yoke(together with concrete wall maybe) to block the upstream single loss entering the IR

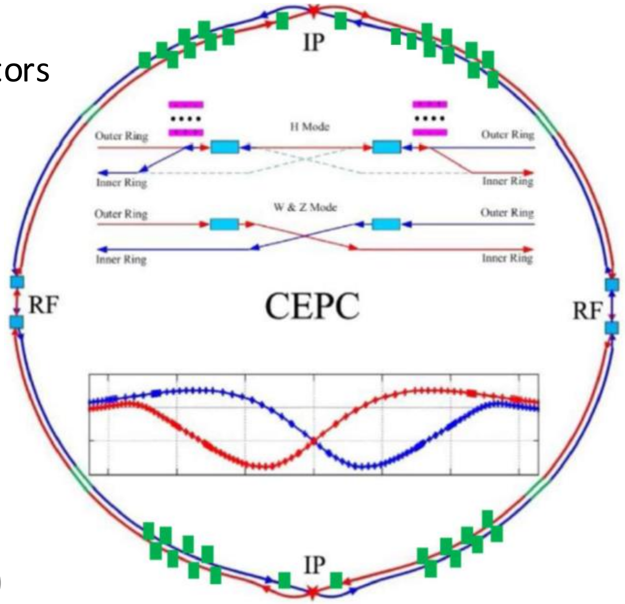
MDI Collimators

- MDI Collimators were implemented to reduce IR loss caused by single beam.
  - 19 sets of collimators(per ring) were implemented for BG mitigation purpose with updated position, and still in optimization.
  - 12 sets of collimators(per ring) were installed for passive machine protection and will also contribute to mitigating beam background.
  - With the implementation of collimators, multi-turn beamstrahlung and radiative Bhabha loss particles have been effectively shielded outside of the MDI region.
  - The MDI collimators are designed with respect to the BSC and impendence requirements





MDI Collimators

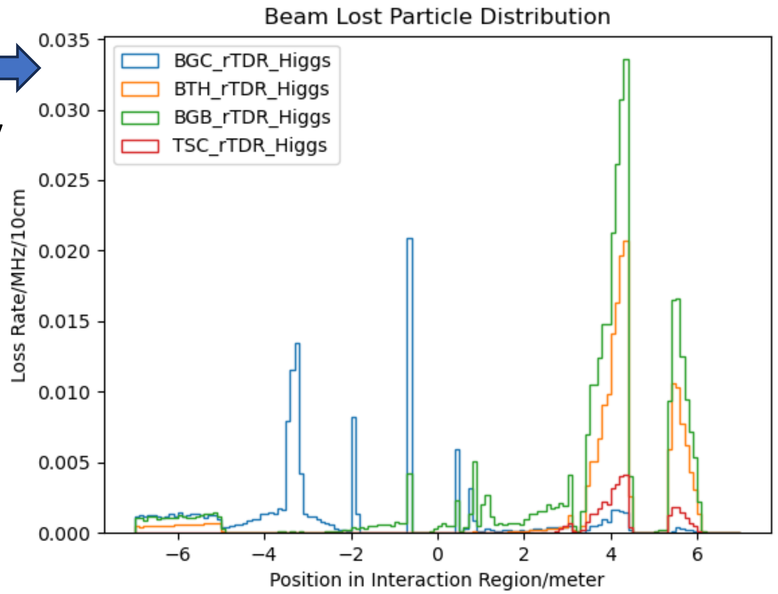


Loss Map at the MDI Region with Collimators

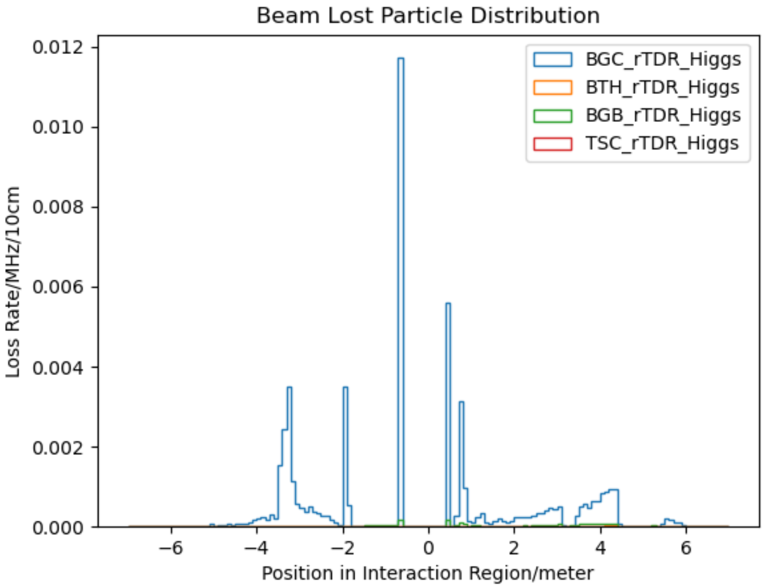
- Single beam only, magnet high order errors implemented
- Loss rate reduced about 2/3 to several order of magnitude at Higgs mode

Acceptable with Collimators

Beam Way



With MDI Collimators



	50MW Higgs, 277ns/BX
Beam Thermal Photon	~0.30MHz/beam in MDI region
Beam Gas Bremsstrahlung	~0.04MHz/beam in MDI region
Beam Gas Coulomb	~0.23MHz/beam in MDI region
Touschek Scattering	~0.06MHz/beam in MDI region

	50MW Higgs, 277ns/BX
Beam Thermal Photon	~0.3 kHz/beam in MDI region
Beam Gas Bremsstrahlung	~4.1 kHz/beam in MDI region
Beam Gas Coulomb	~87.8 kHz/beam in MDI region
Touschek Scattering	~0.3 kHz/beam in MDI region

Loss Rates with Collimators

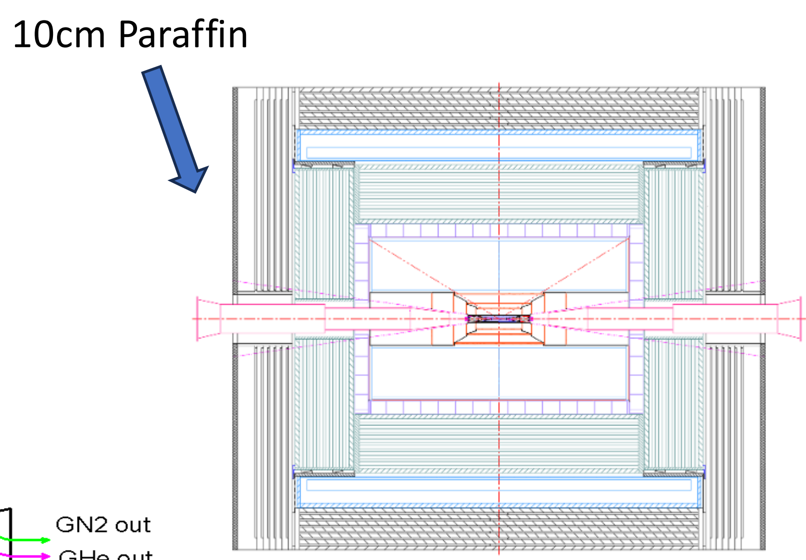
- The table blow shows the loss rate in the MDI region for beam loss backgrounds in 50MW Higgs/Z and 10MW Z mode.
- Comparing with Pair Production, the contributions from beam loss are quite low. Pair Production dominates.

Vacuum Level: 10^{-7} Pa, H_2 Uniform

	50MW Higgs	10MW Z	50MW Z
Beam Thermal Photon	0.3 kHz/beam	24.83 Hz/beam	100 Hz/beam
Beam Gas Brems	4.1 kHz/beam	17.9 kHz/beam	7 MHz/beam
Beam Gas Coulomb	87.8 kHz/beam	20.8 MHz/beam	0.2 GHz/beam
Touschek	0.3 kHz/beam	1.3 kHz/beam	1.6 kHz/beam
Pair Production(Gen. Rate)	1.82 GHz in IR	3.2 GHz in IR	25.5 GHz in IR

Shielding of the Detector

- Shielding has been implemented at both ends of the yoke using the 10 cm of paraffin, and 10mm W outside of the LumiCal-LYSO. The shell of cryo-module also used as shielding. The shielding has reduced ~20%-50% of the BG level.



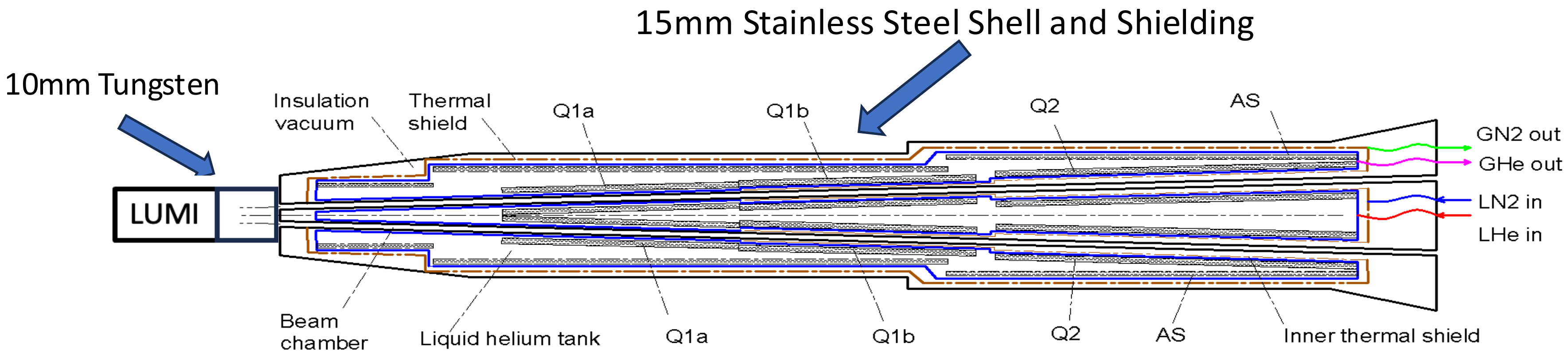


Figure 3.20: The shieding around cryo-module. A 10mm tungsten was used as the outer shell of the LumiCal and IP BPM, and a 15mm stainless steel shell was introduced as the shielding

Shield Effectiveness @ Higgs Mode

- We have obtained a preliminary estimate of the beam-induced background levels in Higgs mode
  - SR included in Vertex
  - ~20%-50% mitigated

Single BG Rates Considered @ Higgs

Vacuum Level: 10^{-7} Pa, H_2

	50MW Higgs, 277 ns/BX
Beam Thermal Photon	~0.3 kHz/beam in IR
Beam Gas Bremsstrahlung	~4.1 kHz/beam in IR
Beam Gas Coulomb	~87.8 kHz/beam in IR
Touschek Scattering	~0.3 kHz/beam in IR
Pair Production(Gen. Rate)	1.82 GHz in IR

March 2025

Sub-Detectors	Ave. Hit Rate		Max. Hit Rate		Max. Occupancy(%)	
	Without Shield	With Shield	Without Shield	With Shield	Without Shield	With Shield
VXD(MHz/cm^2)	2.2	2.2	2.7	2.7	0.003	0.003
ITK-B/E(kHz/cm^2)	0.73/3.5	0.63/2.8	1.9/25	1.0/13	6.3e-3	3.8e-3
TPC(kHz/cm^2)	5.2	3.4	18	11	0.11	0.07
OTK-B/E(kHz/cm^2)	1.2/1.6	0.68/0.93	1.8/4.1	1.1/4.0		3.7e-3/3.7e-2
ECal-B/E(MHz/bar)	0.019/0.079	0.012/0.045	0.90/2.9	0.43/2.9	0.79/3.2	0.54/2.3
HCal-B/E(kHz/cell)	0.18/6.6	0.17/5.3	6.0/326	5.2/221	4.9e-5/0.017	4e-6/0.013
Muon-E(Hz/cm^2)	1.7	1.4	3.7	2.9	0.26	0.20

BG Level at Higgs/Z with mitigation

- We have obtained a preliminary estimate of the beam-induced background levels in Higgs/Low-Lumi-Z/High-Lumi-Z mode with latest CEPCSW
  - The VXD results taken the SR into account. No safety factor

May 2025

Sub-Detectors	Ave. Hit Rate			Max. Hit Rate			Max. Occupancy Per BX(%)		
	Higgs	Low-Lumi-Z	High-Lumi-Z	Higgs	Low-Lumi-Z	High-Lumi-Z	Higgs	Low-Lumi-Z	High-Lumi-Z
VXD(MHz/cm^2)	2.5	10	29	2.8	21	57	2.3e-3	2.1e-3	2.2e-3
ITK-B/E(kHz/cm^2)	0.63/2.4	1.0/4.0	3.1/12	1.3/11.0	3.3/24	10/73	3.2e-3/1.2e-3	6.4e-3/2.5e-3	6.4e-3/2.5e-3
TPC(kHz/cm^2)	3.2	2.9	9.1	13	12	38	0.075	0.071	0.22
OTK-B/E(kHz/cm^2)	0.37/0.94	0.66/1.5	2.0/4.6	0.58/4.1	1.1/6.4	3.3/19	2.1e-3/3.7e-2	4.6e-4/6.0e-3	4.6e-4/6.0e-3
ECal-B/E(MHz/bar)	0.018/0.083	0.013/0.064	0.040/0.20	0.86/3.6	0.33/6.4	0.95/20	0.8/3.5	0.2/0.9	0.2/0.8
HCal-B/E(kHz/gs cell)	0.2/7.0	0.6/5.0	1.9/16	7.0/320	12/170	35/480	4.0e-4/4.0e-2	4.0e-4/3.0e-3	3e-4/3e-3
Muon-E(Hz/cm^2)	3.5	1.2	3.6	10	29	49	0.72	0.08	0.12
LumiCal-Si/LYSO(MHz/cm^2/MHz/bar)	7.0/0.92	7.8/4.7	23/13	1.8e2/1.5	6.5e2/17	1.8e3/44	-/8.2	-/8.2	-/8.2

Radiation Map @ Higgs (Pairs only)

- The radiation map has been simulated @Higgs using FLUKA

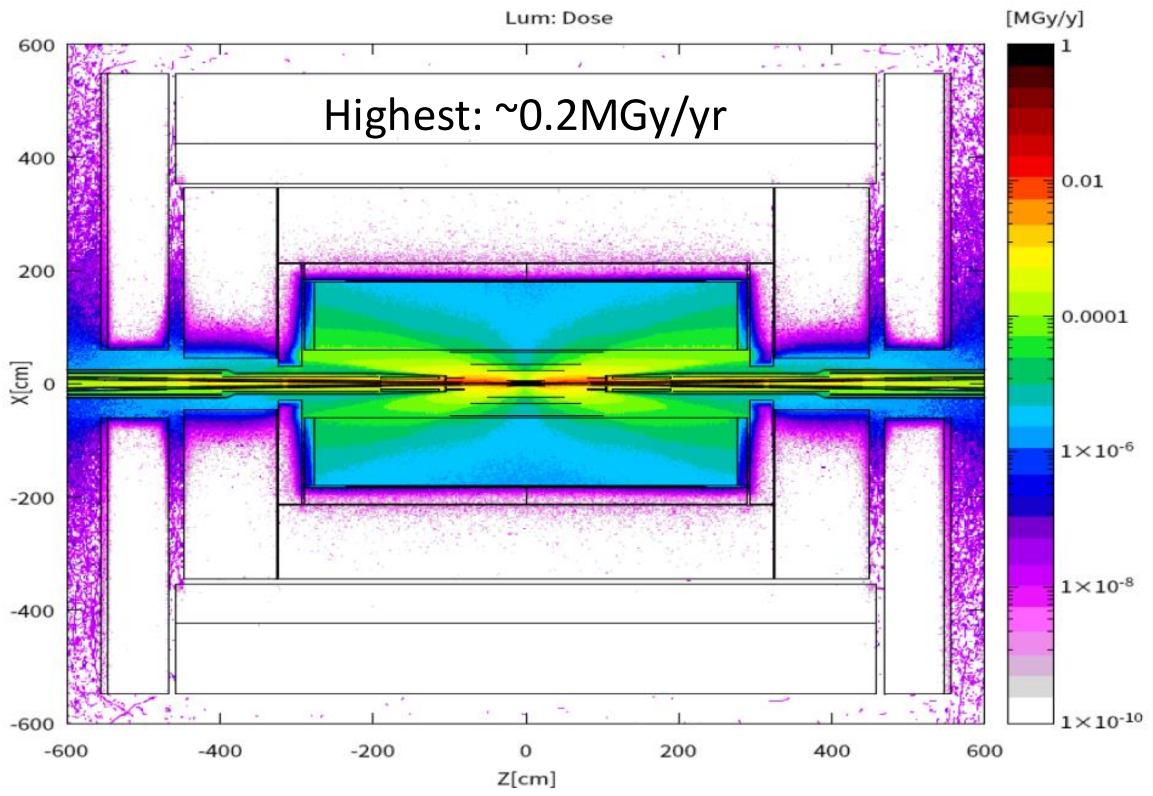


Figure 3.21: The TID distribution caused by Pair Production at the MDI Region, the higest TID is roughly 0.2MGy per year.

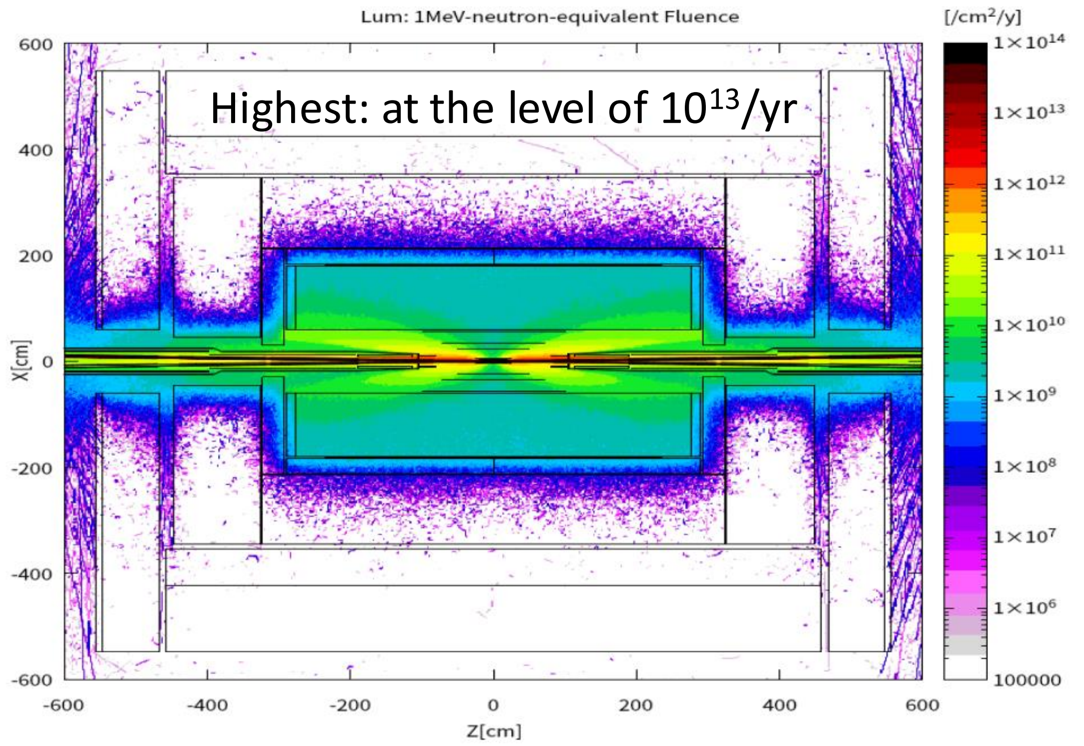


Figure 3.22: The NIEL distribution caused by Pair Production at the MDI Region, the highest number of the 1 MeV silicon equivalent fluence is at the level of 10^{13} per year.

Benchmark – Experiments

- Important to validate the modellings and Monte Carlo Simulation codes for the CEPC beam background simulation with real data where they are applicable.
  - BEPC II/BES III, SuperKEKB/Belle II, LEP I/II…
- Basic Principles – Key Parameters & Distinguish
  - Single beam mode: three dominant contributions from Touschek, beam-gas and electronics noise & cosmic rays.
  - $O_{single} = O_{tous} + O_{gas} + O_{noise+\mu} =$

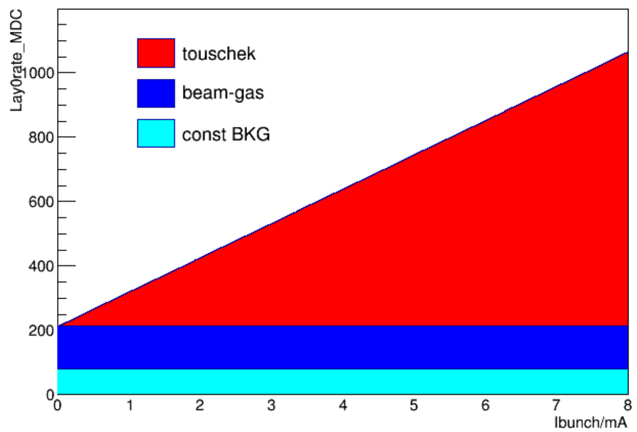
$$S_t \cdot D(\sigma_{x'}) \cdot \frac{I_t \cdot I_b}{\sigma_x \sigma_y \sigma_z} + S_g \cdot I_t \cdot P(I_t) + S_e$$

  - Double beam mode: additional contributions from luminosity related backgrounds, mainly radiative Bhabha scattering
  - $O_{total} = O_{e^+} + O_{e^-} + O_{\mathcal{L}}$(Ideal)

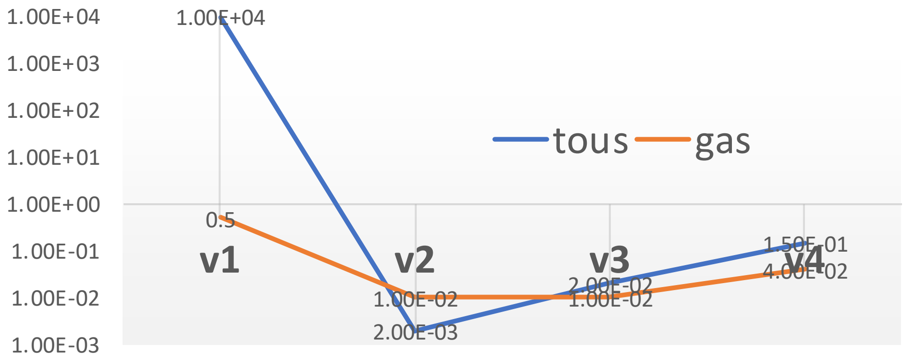
BESIII Benchmark

- BG experiments on BEPCII/BESIII has been done several times.
  - The experiment in 2021 separate the single beam BG sources, the data/MC ratio has been reduced due to the improvement of the IR model and the study of beam–beam.
  - Currently, there remains a gap (5 times in general) between data and MC; further experiments, additional data, and more accurate models are needed. However, the data is lower than the MC, that means the simulation is “conservative”.

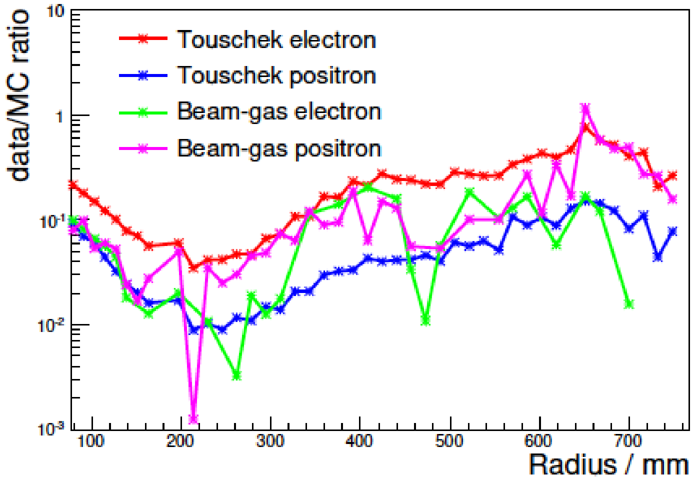
[H. Shi, B. Wang. H. Shi et.al]



BG separation on 1st layer MDC



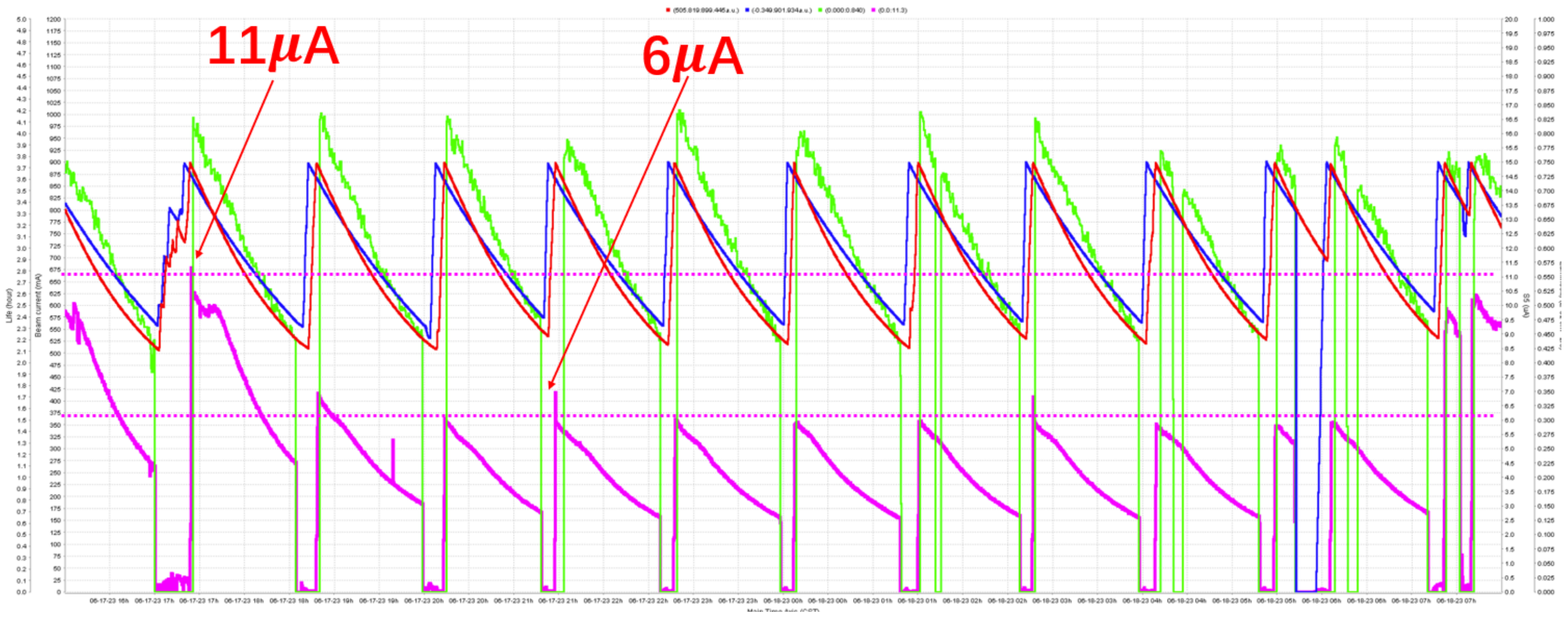
Data/MC radio improvements on 1st layer MDC



Data/MC radio in MDC

BESIII Benchmark

- BG experiments on BEPCII/BESIII has been done several times.
  - The experiment in 2022~2024 was focused on collimators.
  - Backgrounds has been reduced ~40%



Summary & Outlook

- The motivation of the study on beam induced backgrounds has two main concerns:
  - The impact on the detector signal(noise)
  - The radiation caused by the beam induced backgrounds.
- For the MDI region, we've updated the whole design to Ref-TDR Phase, and we are carefully design the layout and key components to make it works better.
  - The material budget of the central Be pipe is ~0.40% X_0 (Gold included)
- A preliminary map for the beam-induced background estimation has been presented including some mitigation methods. The BG level is ~acceptable by detectors and other related systems concerning the 50MW Higgs/Z and 10MW Z mode.
  - The shielding of the detector is still not enough and heavy. We are optimizing the design.
  - Further mitigation strategies and benchmarks can be developed in collaboration with accelerator colleagues as we move towards the Engineering Design Report (EDR) and possibly into the construction phase.
- Currently, only ideal beam was considered. More realistic scenarios need to be studied, including the non ideal beam or error cases.
- Several runs of the beam induced backgrounds experiments at BESIII/BEPCII, we are plan to do more at the latest BEPCII Upgrade project.

Thank You

Backup

Injection Backgrounds @ Higgs

- A preliminary study on the injection backgrounds has been performed:
    - RBB is taken into account in all cases
    - A simplified model of top-up injection beam
    - Tails from imperfectly corrected X-Y coupling after the injection point
    - Some tolerances to imperfect beams from the booster (e.g. too large emittances)
    - non-Gaussian distributions existing/building up in the booster and being injected into the main rings