Study Status of Beam Backgrounds at the CEPC

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On behalf of the CEPC MDI Working Group

The 2022 CEPC MDI Workshop

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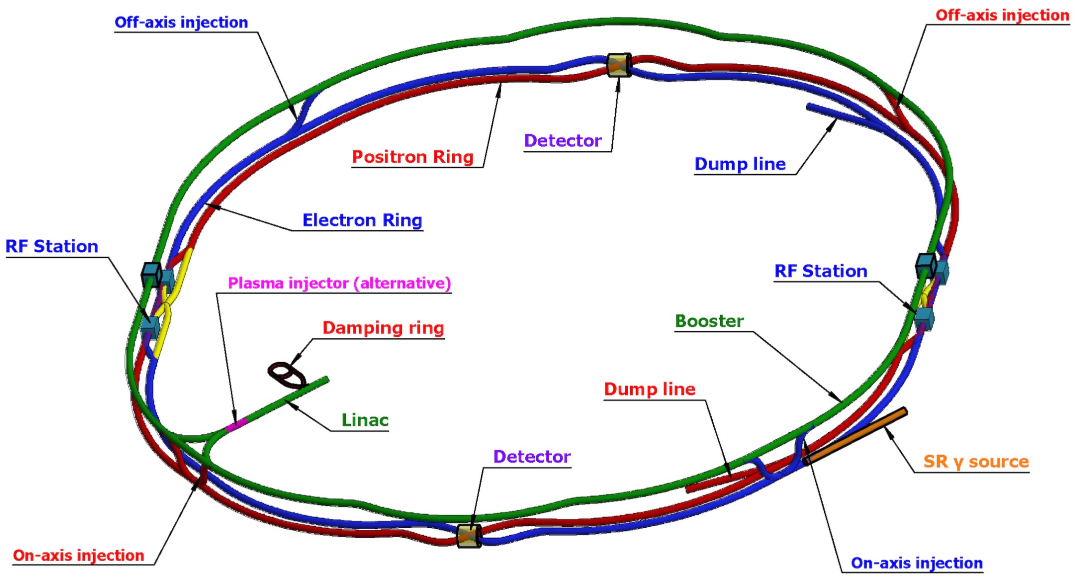
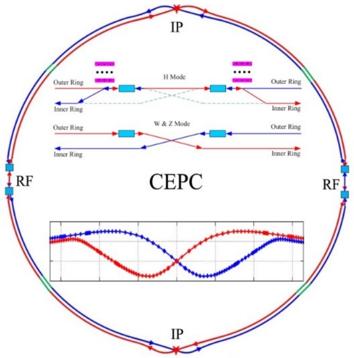
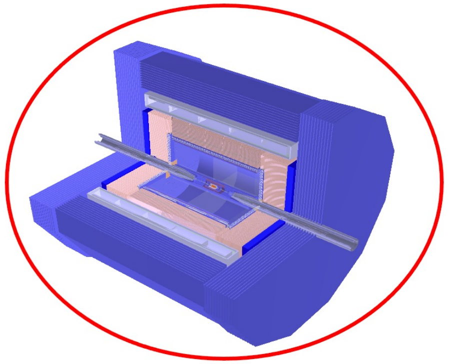
Introduction

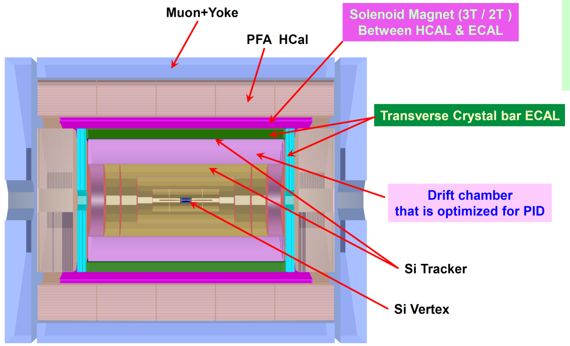
- MDI stands for ”Machine Detector Interface”
  - Interaction Region and other components
  - 2 IPs
  - 33mrad Crossing angle
- Flexible optics design
  - Common Layout in IR for all energies
  - High Luminosity, low background impact, low error
  - Stable and easy to install, replace/repair





Particle Flow Approach (ILD-like)





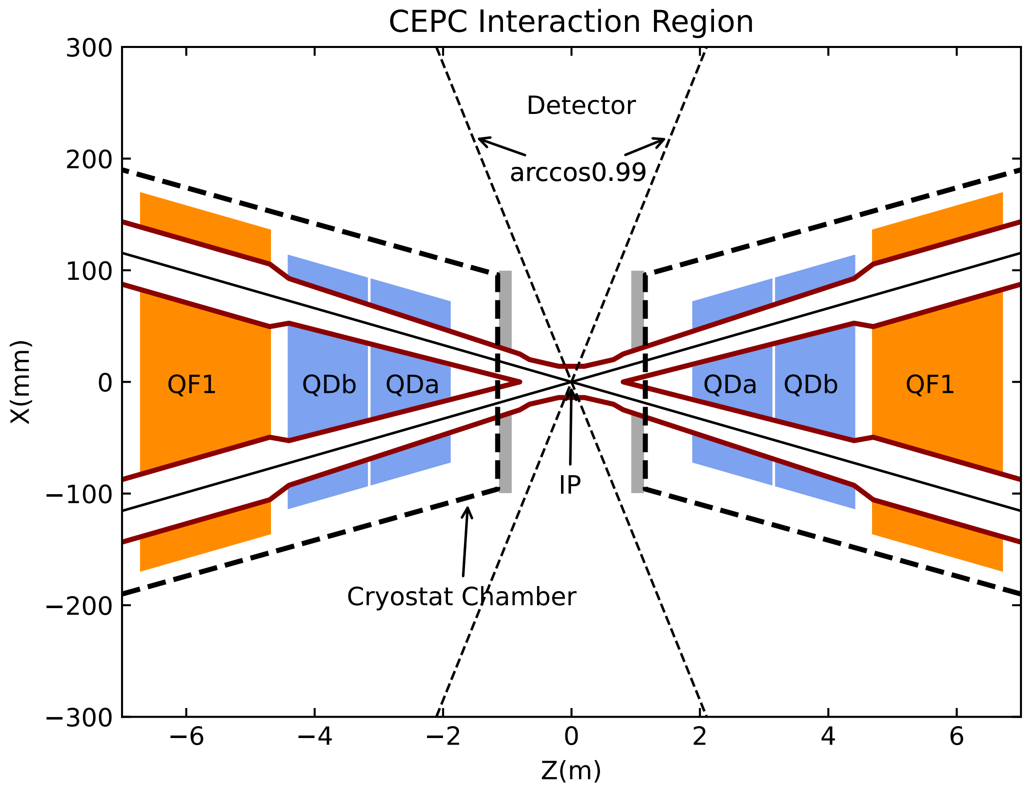
4th Detector concept

Parameters on TDR Phase(30MW)

	Higgs	Z	W	ttbar
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Bunch number	268	11934	1297	35
Bunch spacing (ns)	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Beam current (mA)	16.7	803.5	84.1	3.3
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.3/1.7	1.2/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
Beam lifetime (bhabha/beamstrahlung) (min)	39/40	80/18000	60/700	81/23
Beam lifetime (min)	20	80	55	18
Hour glass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34}/cm^2/s)	5.0	115	16	0.5

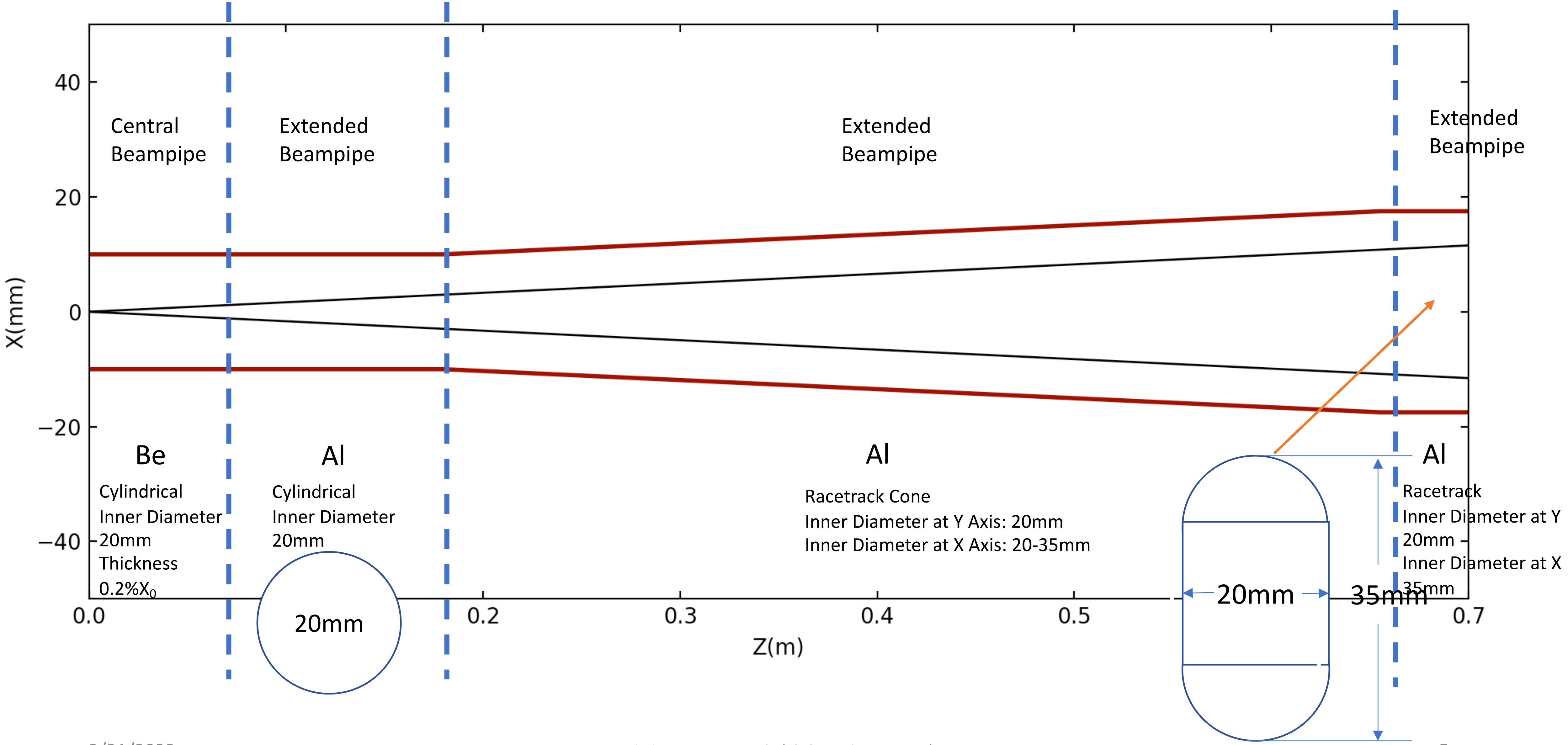
Updated IR

- Interaction Region Layout/Parameters
  - L* = 1.9m / Detector Acceptance = 0.99

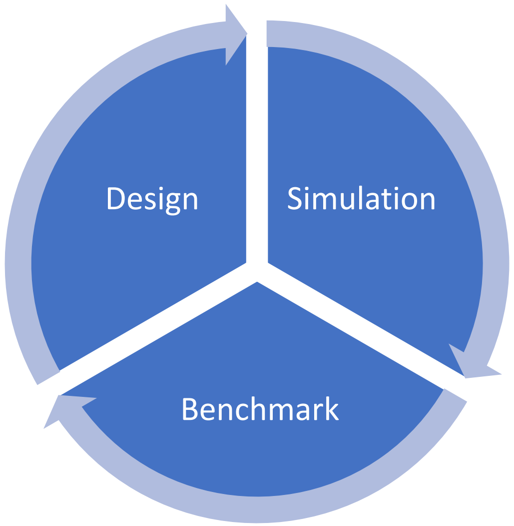


The length of Interaction Region is -7m~7m at TDR Phase

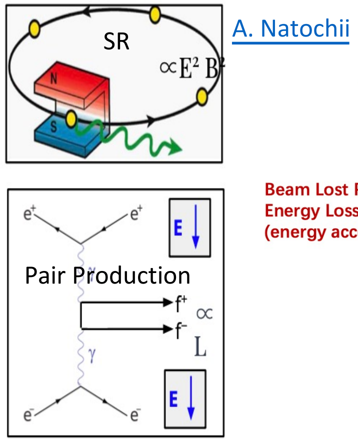
New Beampipe Design – Half Detector pipe



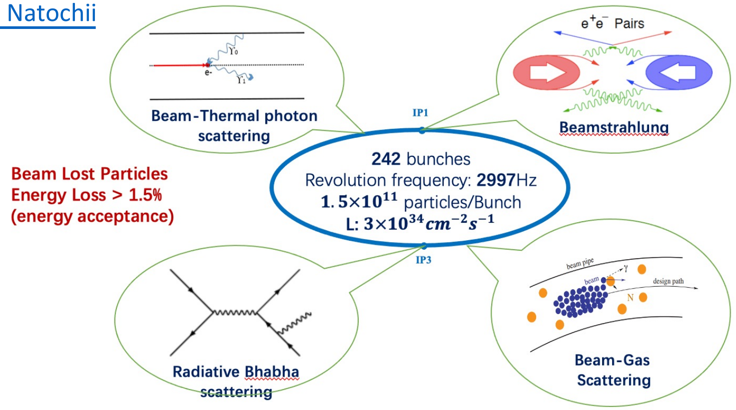
Background Estimation



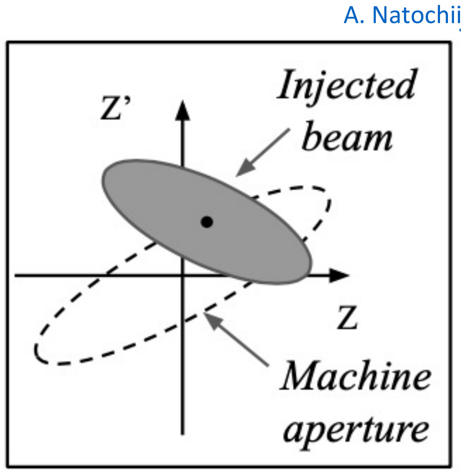
- One Beam
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(50 turns)
  - Using built-in LOSSMAP
  - SR emitting/RF on
  - Radtaper on
  - No detector solenoid yet



Photon BG



Beam Loss BG

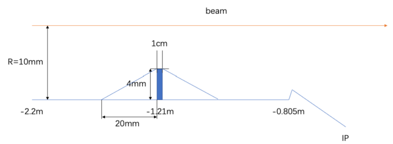


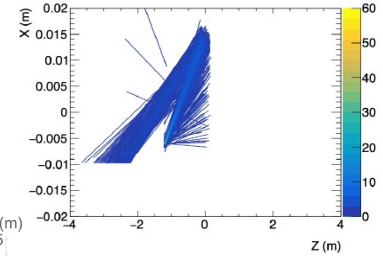
Injection BG

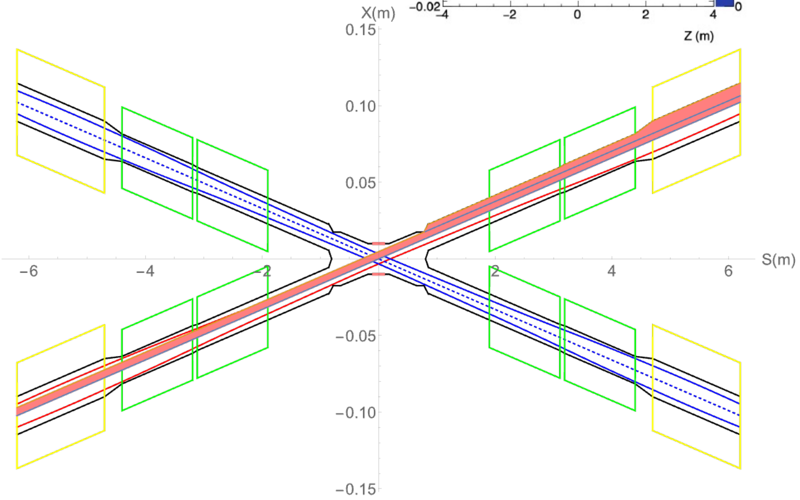
Background	Generation	Tracking	Detector Simu.
Synchrotron Radiation	BDSim	BDSim/Geant4	Mokka/CEPCSW
Beamstrahlung/Pair Production	Guinea-Pig++	SAD	
Beam-Thermal Photon	PyBTH[Ref]		
Beam-Gas Bremsstrahlung	PyBGB[Ref]		
Beam-Gas Coulomb	BGC in SAD		
Radiative Bhabha	BBBREM		

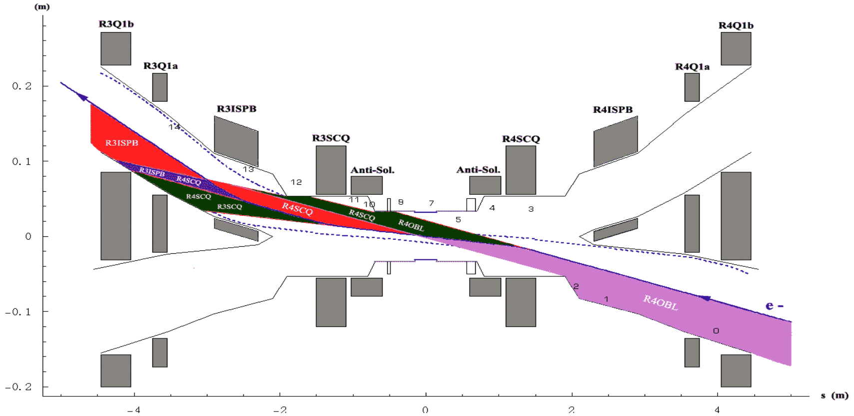
SR BG & Mitigation

- The SR must be dealt with high priority when designing the circular machine. At the CEPC, there would be no SR photons hitting the central beam pipe directly in normal conditions
- However, some secondaries generated within QD would hit the detector beampipe, even the beryllium part. Therefore, the mitigation methods must be studied. We compared several methods based on CDR.









Beam orbit and SR fans @ BEPCII

Y. Sun

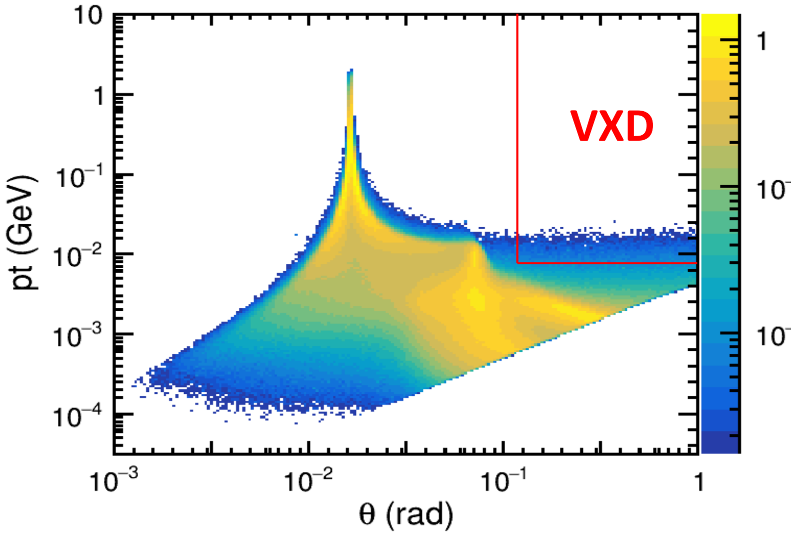
Methods	photon number of hitting on Be(N)
1.21-mask-Cu	1736.0
1.21-mask-W	1698.0
2.2-mask-Cu	1147.0
cons-no mask-Cu	257364.0
cons-no mask-W	148030.0
1.21-mask-Cu-5μmAu	216.0
nomask	39400.0

Pair Production/Other Photons

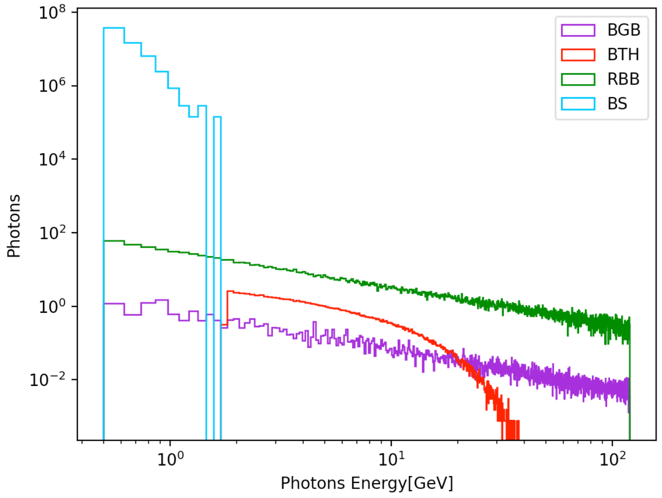
For more information about this, please refer to Wei’s talk later

- Pair Production(Beamstrahlung) may lead to two different impacts:
  - The impacts on detector, caused by the electrons/positrons produced by photons
  - The impacts on accelerator components outside of the IR, caused by the photons directly.
- The huge deposited power due to the photons(mainly from BS, plus others) might be harmful to the machine, found by FCC.
  - At higgs mode, roughly 93.1 kW@30MW(150kW@50MW)
  - At Z mode, <E>~2.2MeV, ~450kW@30MW(720kW@50MW) in ~11m(22-33m in the first bending magnet).
  - The photons are very hard, contains multi-MeV or even few-GeV photons.

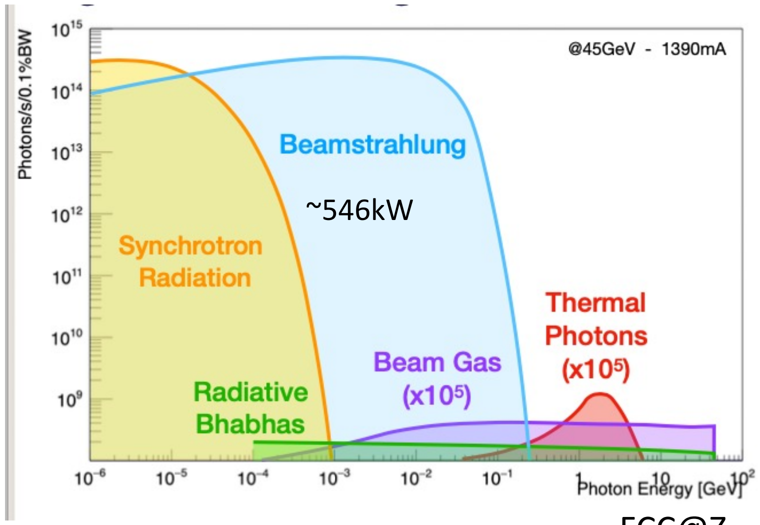
Photon Dump?



W. Xu



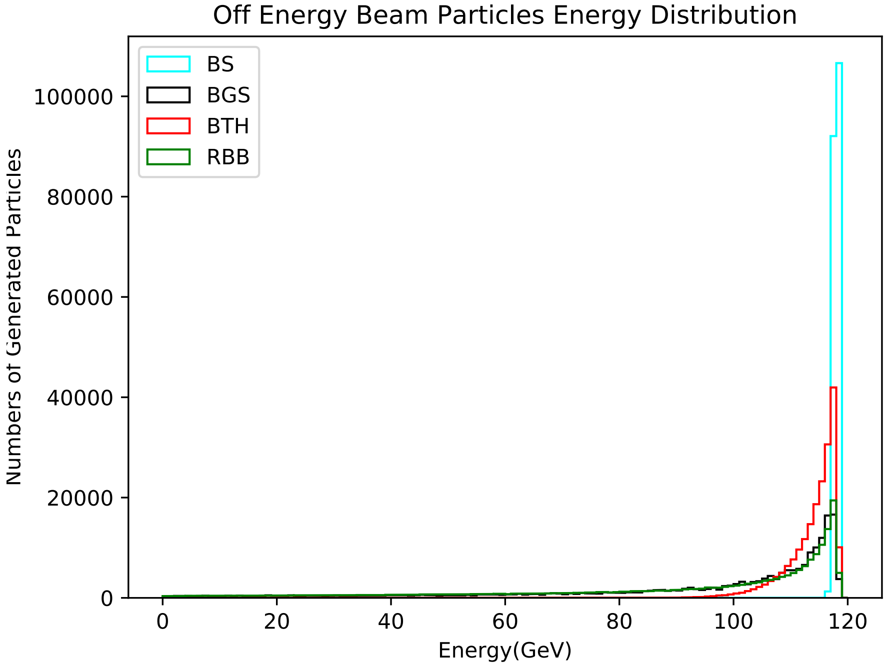
CEPC@Higgs



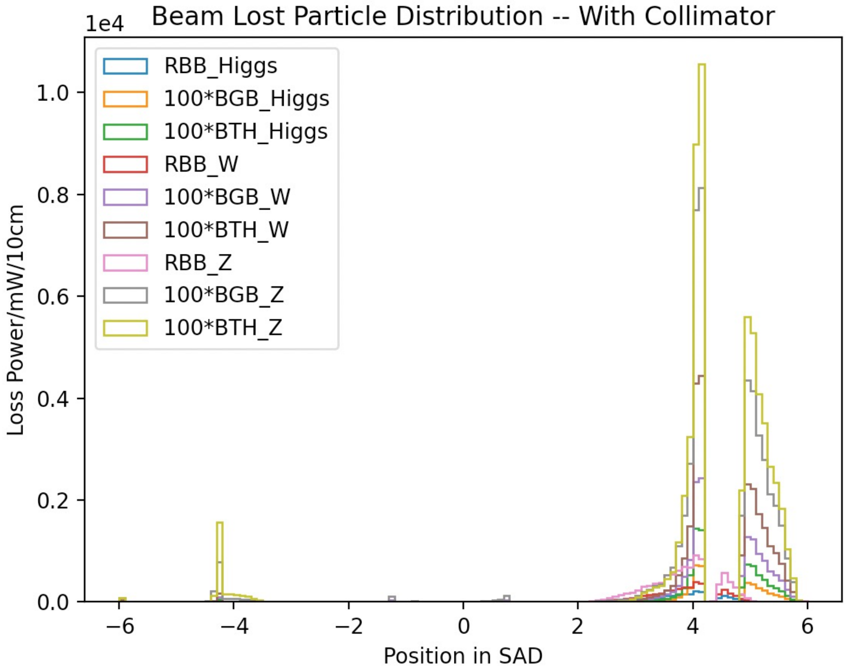
FCC@Z

Beam Loss Particle

- Back to CDR Phase, some fundamental work has been done, like the analysis of the energy spectra of beam loss particles, the effectiveness of the collimators(loss map turn by turn)…



Energy Spectra

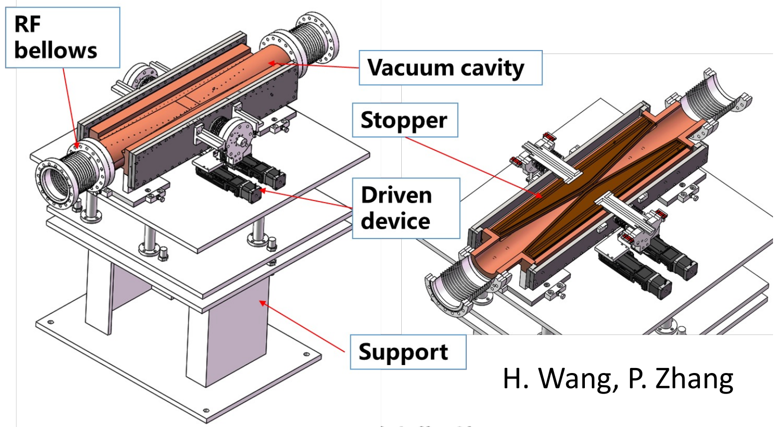


Loss Power

Mitigation of the BG - Collimator

For more information about this topic, please refer to Sha's and Haijing's talk yesterday, and Xiaohao's talk tomorrow

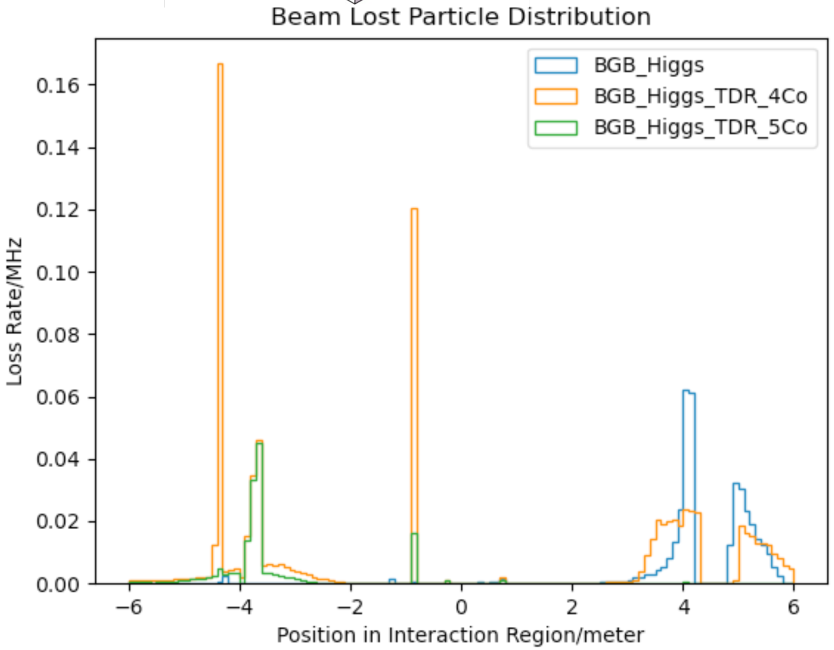
- Requirements:
  - Beam stay clear region: 18 σ_x+3mm, 22 σ_y+3mm
  - Impedance requirement: slope angle of collimator < 0.1
- 4 sets of collimators were implemented per IP per Ring(16 in total)
  - 2 sets are horizontal(4mm radius), 2 sets are vertical(3mm radius).
- One more upstream horizontal collimator were implemented to mitigate the Beam-Gas background
- More Collimators for Machine Protection is ongoing, they should also be benefit for BG mitigation.
- Collimators are set the be ideal ones now.



H. Wang, P. Zhang

S. Bai

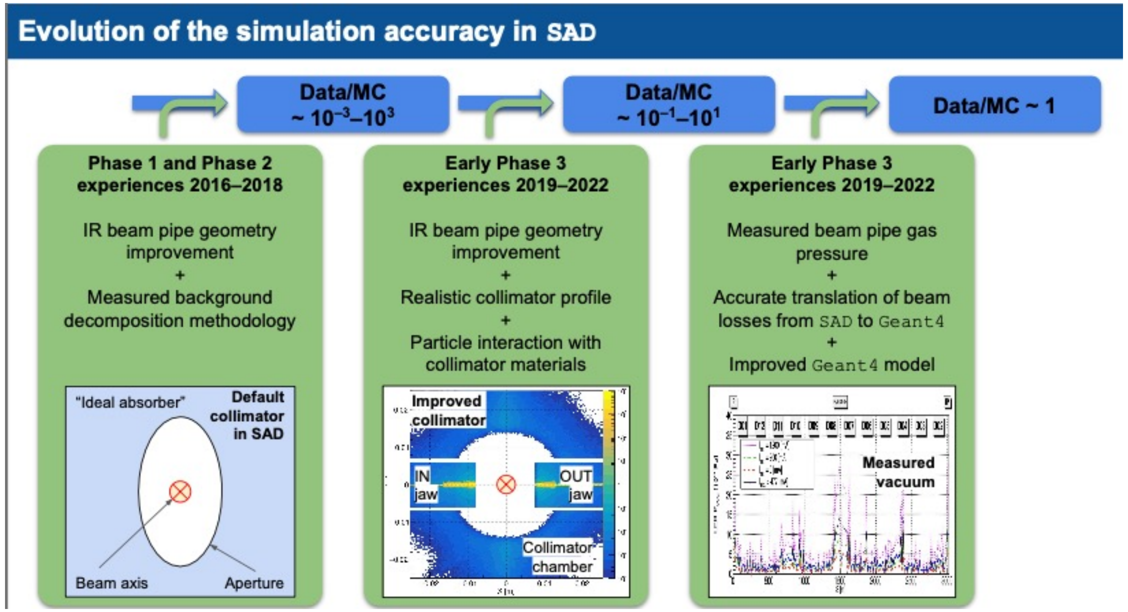
name	Position	Distance to IP/m	Beta function/m	Horizontal Dispersion/m	Phase	BSC/2/m	Range of half width allowed/mm
APTX1	D1I.785	44611	20.7	0.12	164.00	0.006	1~6
APTX2	D1I.788	44680	20.7	0.12	164.25	0.006	1~6
APTY1	D1I.791	44745	105.37	0.12	165.18	0.0036	0.156~3.6
APTY2	D1I.794	44817	113.83	0.12	165.43	0.0036	0.156~3.6
APTX3	D1O.5	1729.66	20.7	0.06	6.85	0.00182	1~6
APTX4	D1O.8	1798.24	20.7	0.12	7.10	0.00182	1~6
APTY3	D1O.10	1832.52	20.7	0.25	7.22	0.00182	0.069~3.3
APTY4	D1O.14	1901.1	20.7	0.25	7.47	0.00182	0.069~3.3
APTX5	DMBV01IRU0	56.3	196.59	0	362.86	0.01178	2.9~11.78



Future works on Collimators

- Currently, Collimators are set to be ideal ones.
  - At real case, of course they won't
  - Therefore, the interaction code should be implemented, and the tracking of secondaries should be needed at some cases.
  - SuperKEKB improve the ratio of Data/MC using this methods.
- Actually, the geometry is mismatch in SAD/Detector Simulation tools like Mokka. Improving are necessary.

A. Natochii



Detailed work on design of collimators

- Preliminary work has been done using FLUKA back to CDR Phase(Early 2020)
  - Methods/Steps
    - SAD Tracking
      - Add one more collimator in SAD Lattice.(-31m from IP)
      - Let SAD output the loss particles at the collimator.
    - FLUKA Simulation
      - Build Collimator Model in FLUKA.
      - Output the electrons come out from the collimator.
      - Add a detector(0.1cm thick vacuum ring, outer radius is the radius of pipe at out of the IR, inner radius is the radius of pipe at -0.2m) at -6m.
      - For now, we mainly concern electrons/photons/neutrons.
    - SAD Tracking
      - Track the electrons implemented from FLUKA
    - Full Detector Simulation if needed(Mokka)
  - Results
    - Almost no electrons/neutrons could enter the IR. However, another stage of collimators could also be considered.
    - Direction of photons are very close to the beam(cosZ > 0.9999), almost no impacts on the IR.

Loss Distribution

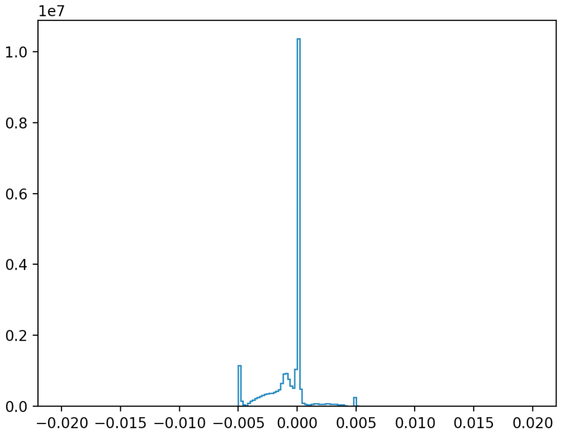
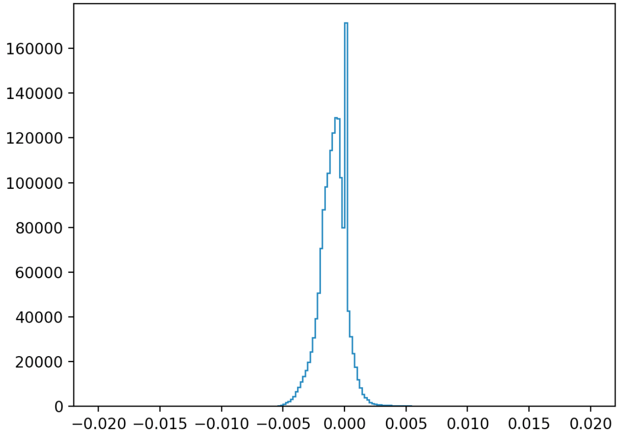
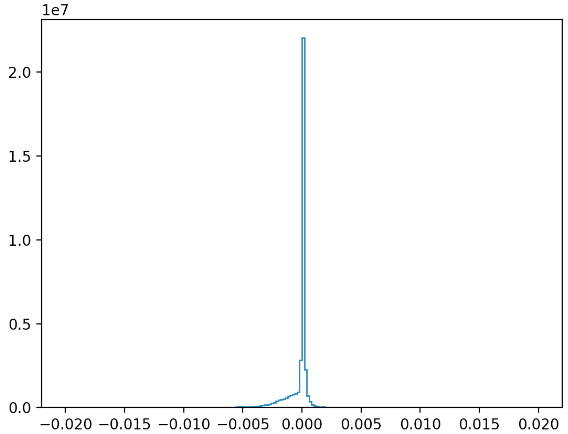
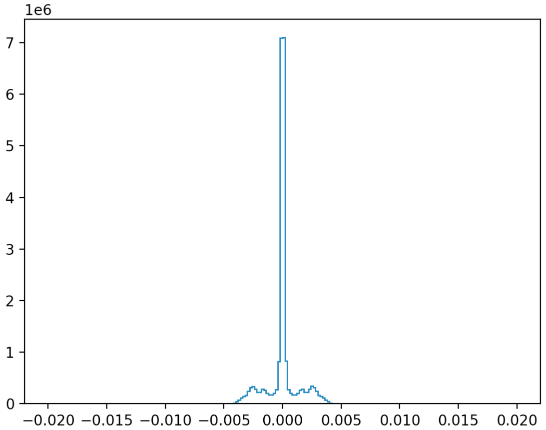
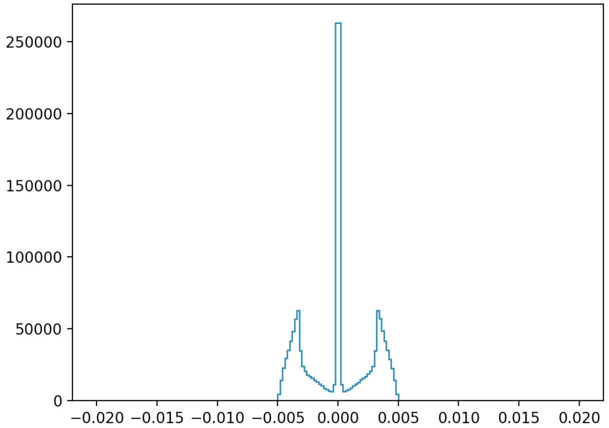
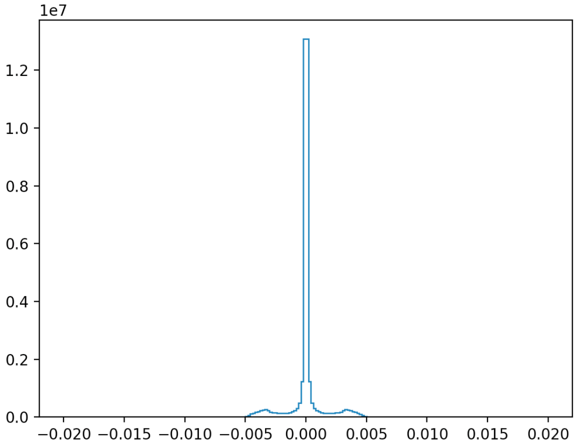
- Average Theta_Z and Energy of Loss Particles:

average theta/rad	BGB	BTH	BGC
Higgs	0.00307725042012	0.00308127699092	0.00294731619585
Z-pole	0.0024459553963060237	0.002540682266912946	0.003186191377046982
ttbar	0.0038236837001350238	0.0030871275506335243	0.0034985540360784233

Average Energy/GeV	BGB	BTH	BGC
Higgs	101.53252654768343	107.51971444616053	120.05252903226118
Z-pole	44.69673706787736	44.67623558196711	45.49308030629436
ttbar	171.9848469814191	175.43680765714643	

High Energy and Very Close to Beam

Loss Distribution

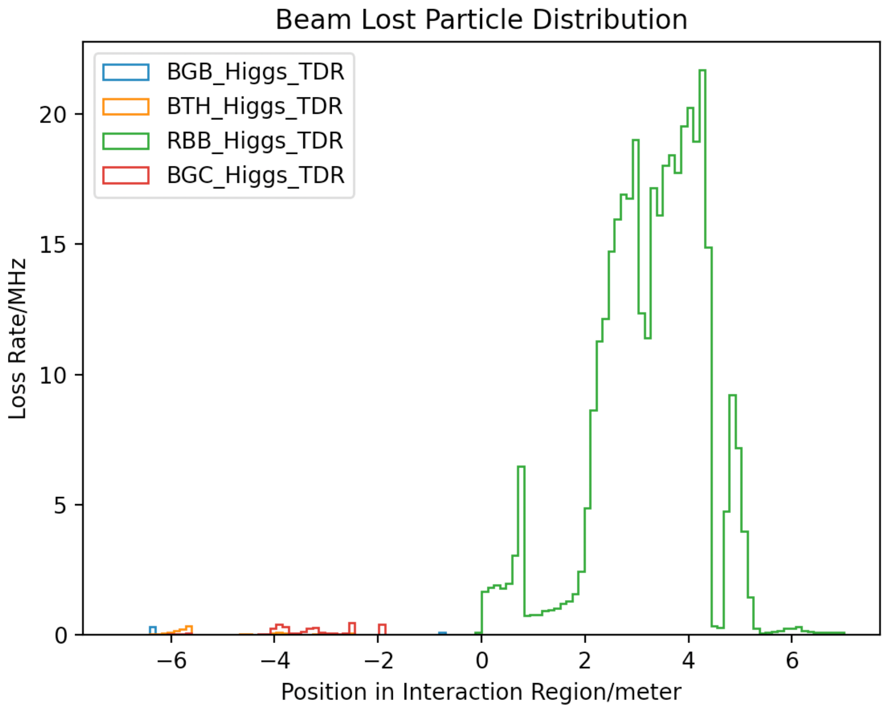
	BGB	BGC	BTH
Theta_X			
Theta_Y			

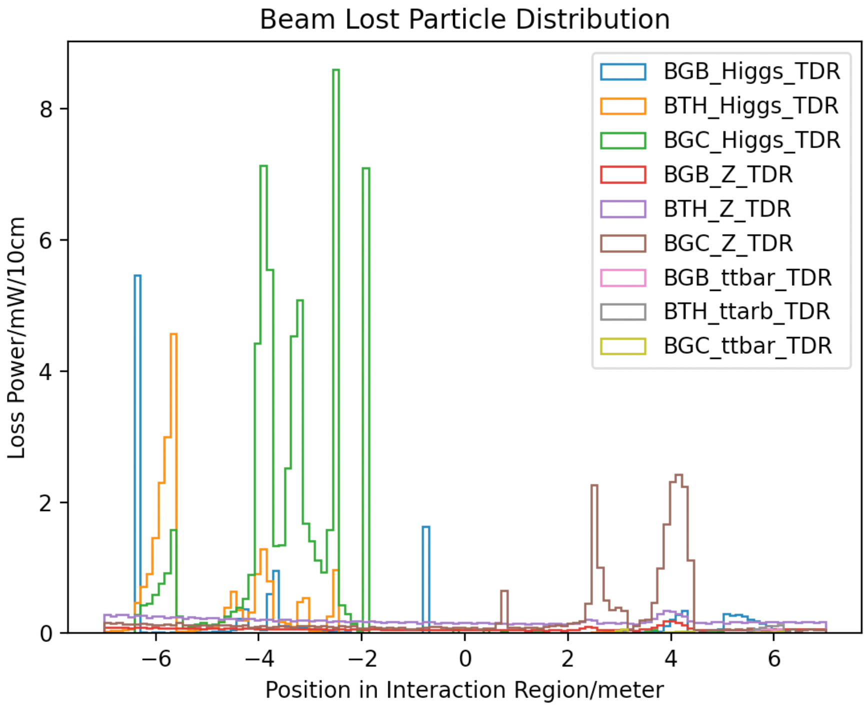
Loss Rate/Loss Power

- Errors implemented
  - High order error for magnets
  - Beam-beam effect
- 2 IR considered(sum)
- Loss Rate is in the level of MHz/10cm; Loss Power is in the level of mW/10cm
- Current Collimators could not mitigate BGC effectively. We need more.

$$Loss\ Rate = \frac{Loss\ Number}{Loss\ Time} = \frac{Bunch\ number * Particles\ per\ Bunch * (1 - e^{-1})}{Beam\ Lifetime}$$

@Higgs

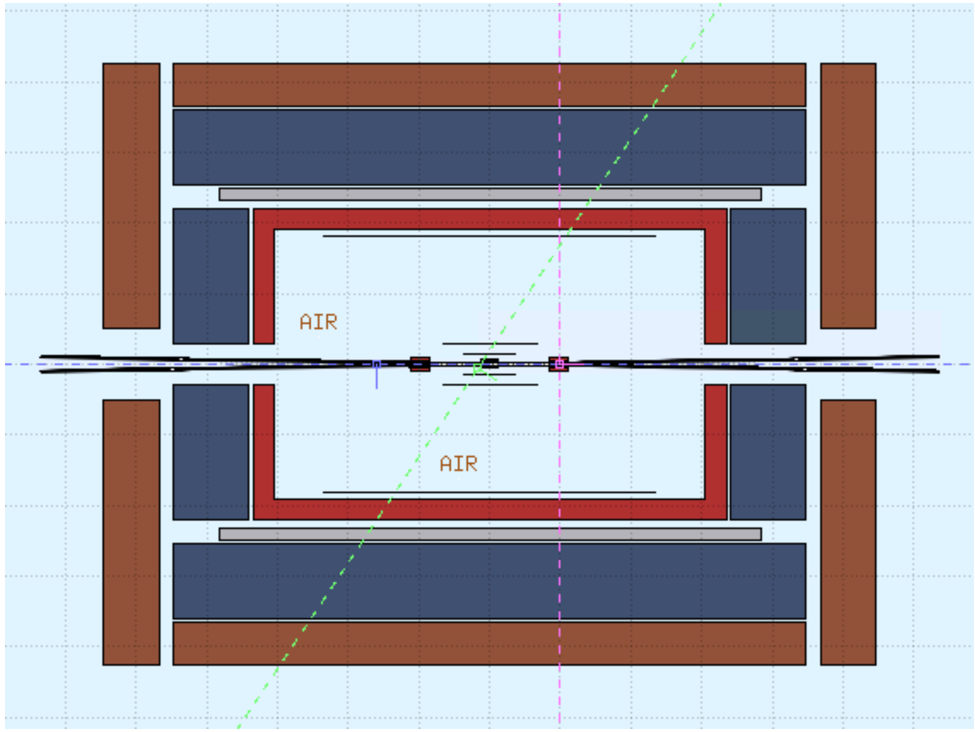




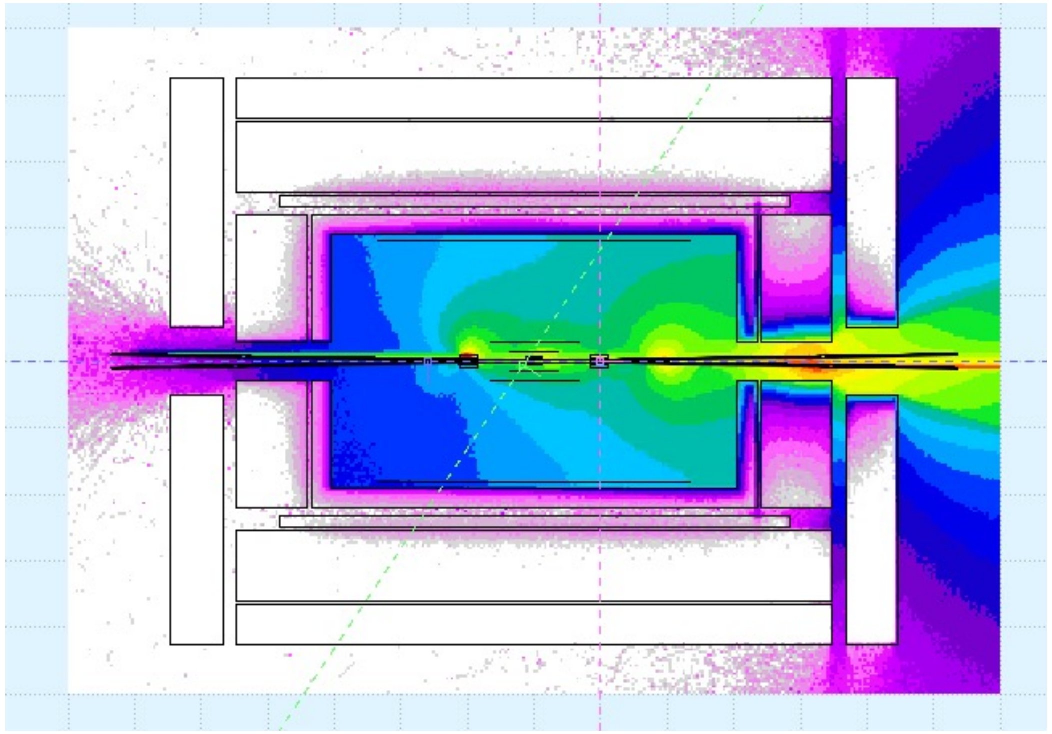
@Higgs
+ttbar
+Z

Detector Simulation -- FLUKA

- The initial version of detector simulation has been performed using FLUKA.
  - The Endcup/Lumical must be taken care of.
  - We plan to improve the accuracy of the model and make comparison.



Sample Model



TID(Sample)

Contributions from Beam Background

Preliminary

- Let's take TPC as an example
  - Hit Density is $6.37\times10^{-3}\boldsymbol{cm^{-2}}\cdot\boldsymbol{BX^{-1}}$ @ Z-pole
    - This number was simulated from CDR Paras.
    - Among them, ~67% was contributed by Pair Production
  - TPC Ranges from 30cm~180cm in R, ~450cm in Z(length)
  - Therefore, the inner most part of TPC has an area of 60*450*pi(Barrel), ~$8.48\times10^{4}\ cm^{2}$
  - Bunch Spacing is 23 ns, BX Rate is ~ 10^{8} Hz(Similar to Physics Estimation by Manqi, the physics hit rate is ~$10^{9}\ Hz$)
  - The Hit Rate in TPC(inner most) by Beam Backgrounds is ~$5.4\times10^{10}\ Hz$(over-estimated)
  - Roughly, the Hit Rate caused by Beam Background is ~54 times more than Physics Hits(~66% caused by Pair Production, ~36 times)
  - Considering that the beam parameters in TDR is higher than CDR, the number should also higher than 36. Scaling from the parameters, it is ~60 times higher(pp only).
    - Using this scaling methods, the FCCee number should also be 36.
  - The vertex and endcup detectors would also suffer from such rates.
  - How to mitigate?

Ways to improve/Future Work

- Tracking Methods
  - Implement the weight
  - Lots of samples, or try to perform the energy/position scan?
- Update the toolkit
  - The MDIToolkit developed by Qinglei needs to be updated.
- Detector Simulation
  - CEPCSW integration. Thanks to Guangyi for Dose calculation codes(under developing).
  - Geometry?
  - Estimate the impacts from Loss Distribution?
- Validating the Software
  - Using Experiments/Literature
- Optimize the Interaction Region
- Real/Error scenarios.
- Mixing with Physics Signals.
- Radiation Detectors like BEASTII at SuperKEKB.

Summary & Outlook

- SR could be dealt with masks and optimized beam pipe.
- Pair Productions is important, more that half detector hits come from it. It is hard to suppress. At the same time, the photons are also important. They won't impact detectors to much, but the deposited power are huge. The new design like a photon dump might be needed to deal with it.
  - Physics Potential?
- The multi-turn beam loss particles could be absorbed by the collimators to prevent the IR. The beam-gas and beam thermal photons lost immediately after the scattering are hard to suppress. Other detector hits comes from these three. More collimators are needed to absorb the coulomb scattering.
- The shielding of the hotspot in the IR would be needed.
- Still a lot of work needs to be done.

Thank You

Backup

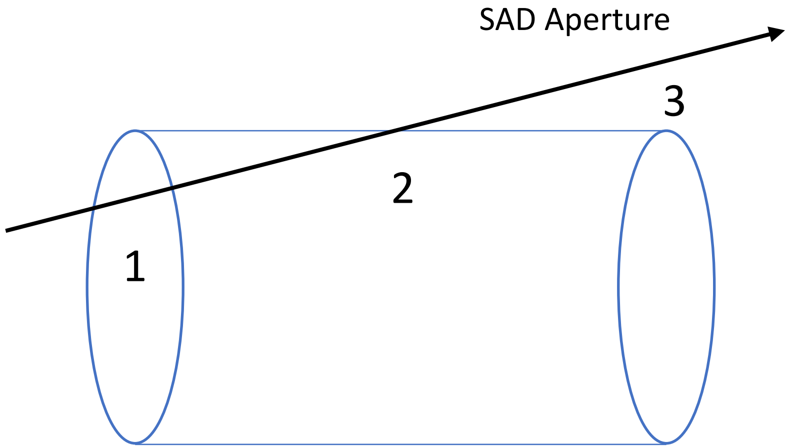
Pair Production

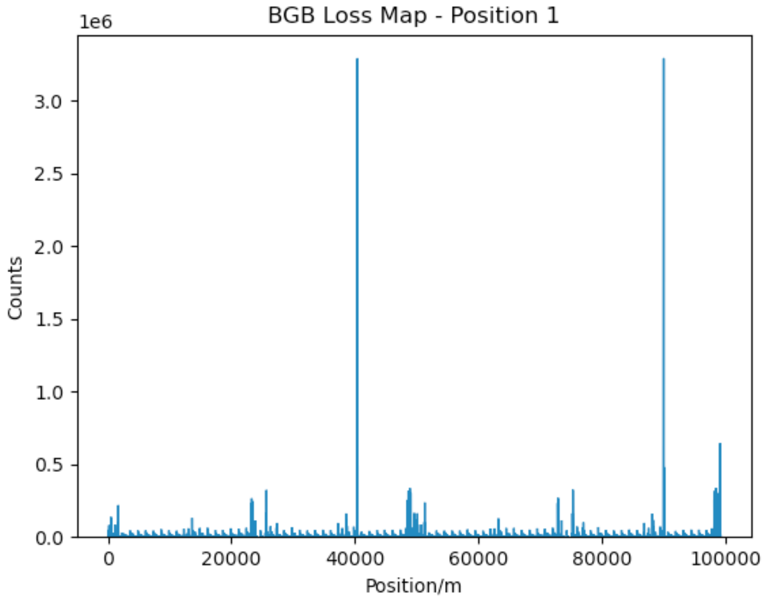
- Pair Production(Beamstrahlung) is one of the dominant background process at the CEPC.

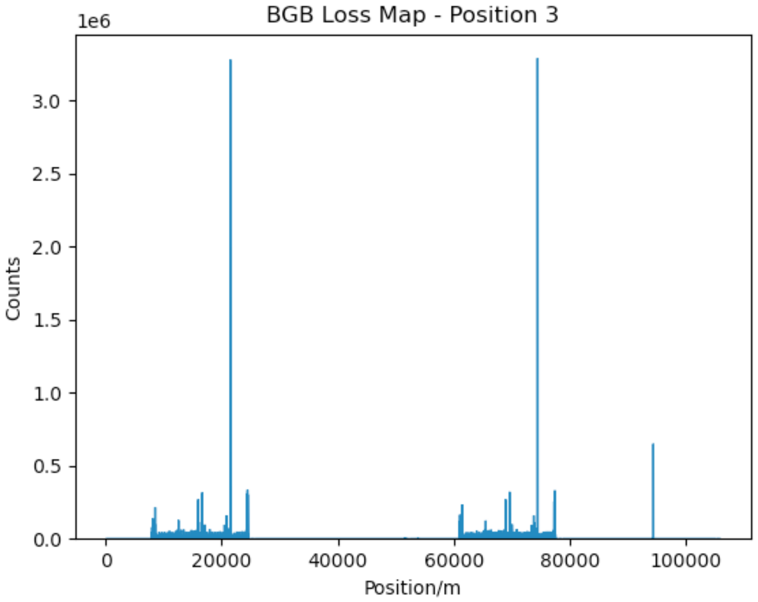
Parameter	Symbol	ILC-500	CLIC-380	CEPC-Z	FCC-Z	CEPC-W	FCC-W	CEPC-Higgs	FCC-Higgs	CEPC-top	FCC-top
Energy	E[GeV]	250	190	45.5	45.5	80	80	120	120	180	182.5
Particles per bunch	N[1e10]	3.7	2	14	24.3	13.5	29.1	13	20.4	20	23.7
Bunch Number				11934	10000	1297	880	268	248	35	40
Bunch Length	sigma_z [mm]	0.3	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
Power Deposited by photon	P [W]										
SR Relative loss	%/turn							1.3			

Particle Position Optimization

- We learnt than the position outputted by SAD might not be true.
  - In our previous study, we used the position "1" as the loss position
  - To do so, we have to perform the simulation twice.
  - However, SAD is a monte carlo simulation program. When the twice simulation performed, the position "1" might be changed.
  - Therefore, the position "3" should be used with changing the position of X/Y.

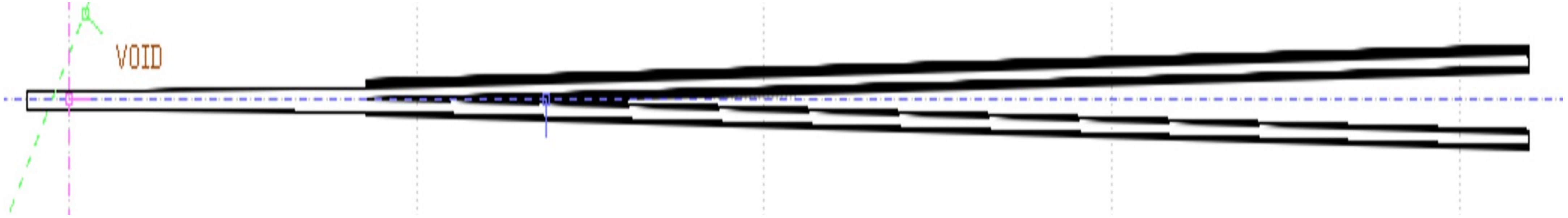


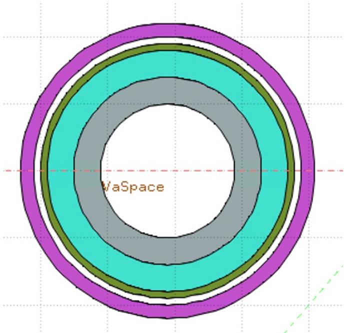




Beam Pipe Simulation -- FLUKA

- The initial version of shielding of the quads has been performed using FLUKA.
- Pure tungsten IR beam pipe with 4mm thickness without cooling taken into account, simulate the Absorbed Dose on Coil (Region)
- Only Beam-Gas beam loss is taken into account , calculated based on loss distribution from SAD:
  - ~0.00166 Gy/s(0.166rad/s)
  - Safe for Higgs. Other sources on going.





White: Vacuum
Gray: Tungsten Pipe
Light Green: Helium
Heavy Green: Stainless Steel Vassel
Pink: Coil

Detector Impact - CDR

- SR Hit Number on Be beam pipe per bunch crossing.

	Higgs	W	Z
Hit Number	**~320**	**~28**	**<1**

- Preliminary results on 1st layer of vertex. Safety factor of 10 applied.

Background	Hit Density($cm^{-2} \cdot BX^{-1}$)			TID($Mrad \cdot yr^{-1}$)			1 MeV equivalent neutron fluence ($n_{eq} \times 10^{12} \cdot cm^{-2} \cdot yr^{-1}$)		
	Higgs	W	Z	Higgs	W	Z	Higgs	W	Z
Pair production	1.8	1.2	0.4	0.50	2.1	5.6	1.0	3.8	10.6
Beam Gas	0.4	0.4	0.2	0.36	1.3	4.1	1.0	3.6	11.1
Total	2.17	1.6	0.6	0.86	3.4	9.7	2.0	7.4	21.7
Total_oCDR	2.4	2.3	0.25	0.93	2.9	3.4	2.1	5.5	6.2

- Take Mask into Account(Higgs):

Background	Hit Density($cm^{-2} \cdot BX^{-1}$)	TID($Mrad \cdot yr^{-1}$)	1 MeV equivalent neutron fluence ($n_{eq} \times 10^{12} \cdot cm^{-2} \cdot yr^{-1}$)
Beam Gas	0.4	0.39	1.0

TDR Estimation – with safety factor of 10

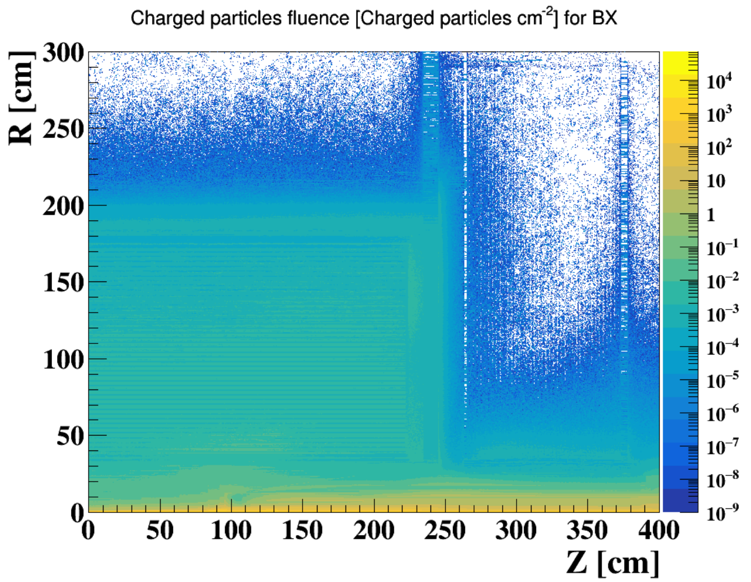
- For fast estimation, we try to perform some scaling based on CDR results according to Luminosity.
- The full-detector TDR simulation has been started.
  - We are updating the tools.
- We plan to have double check on detector simulation(Mokka/CEPCSW/FLUKA)

Scaling Results on 1st layer of vertex detector

W. Xu

	CDR	TDR(30MW)	TDR(50MW, Upgradable)
Higgs (3T)	2.93	5.00	8.00
Z (2T)	32.1	115.0	184.0

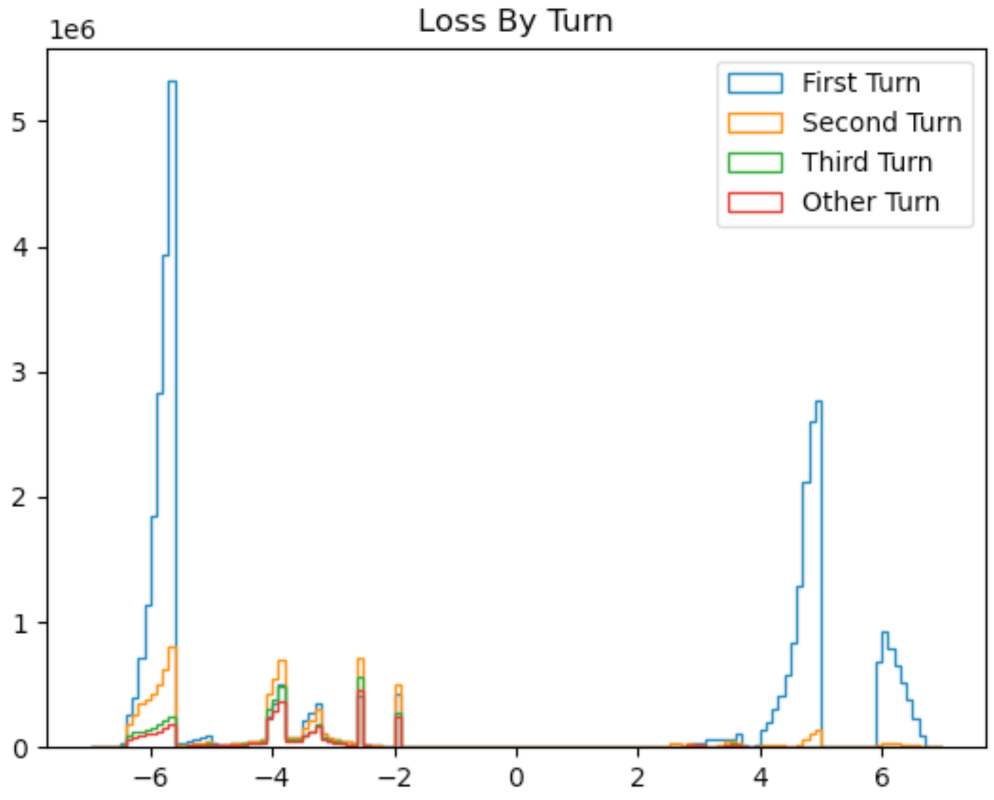
	Hit Density($cm^{-2} \cdot BX^{-1}$)	TID($krad \cdot yr^{-1}$)	NIEL($n_{eq} \times 10^{12} \cdot cm^{-2} \cdot yr^{-1}$)
Vertex	2.3	5360	120.4
TPC	2.59e-2	387.09	42.503
Ecal Barrel	1.16e-3	31.56	8.002
Ecal EndCup	1.36e-3	14.175	6.128
Hcal Barrel	2.78e-5	1.450	0.9326
Hcal EndCup	1.32e-3	26.31	6.351



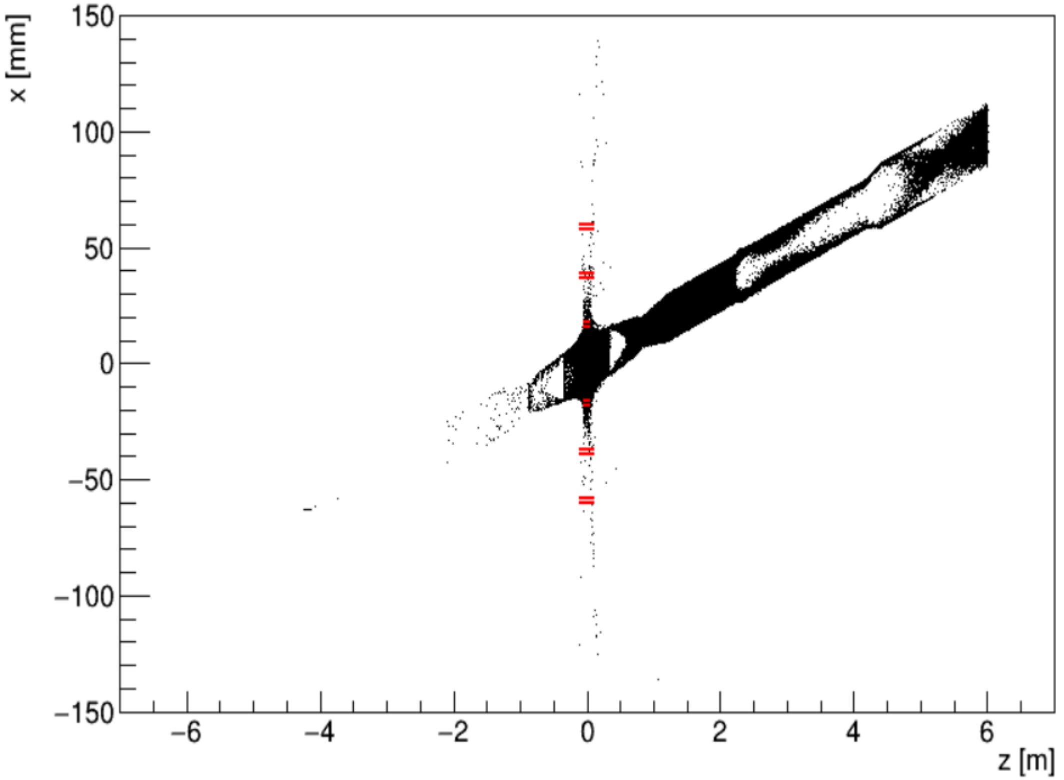
Loss Distribution – With Collimators

- The loss in first turn dominants.

BGB

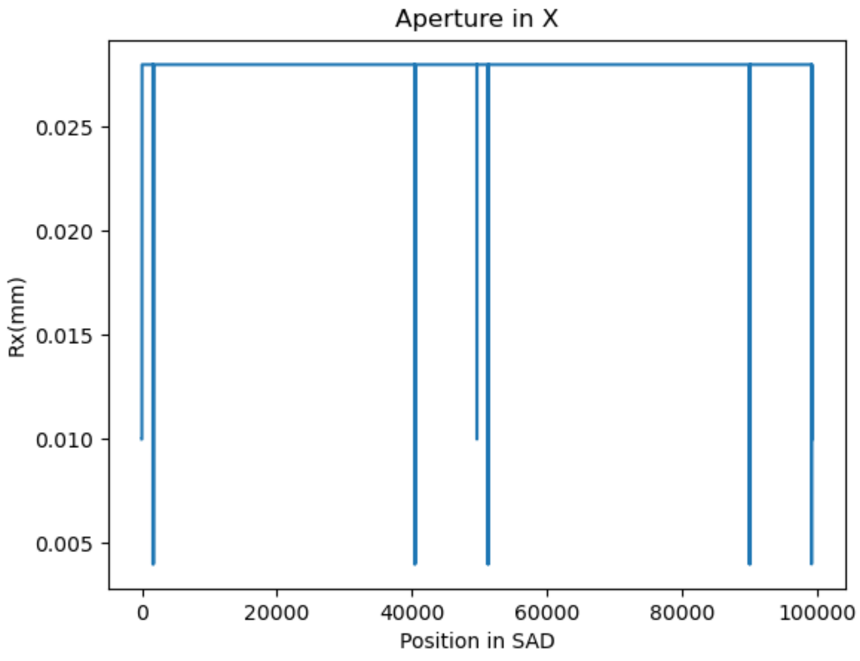


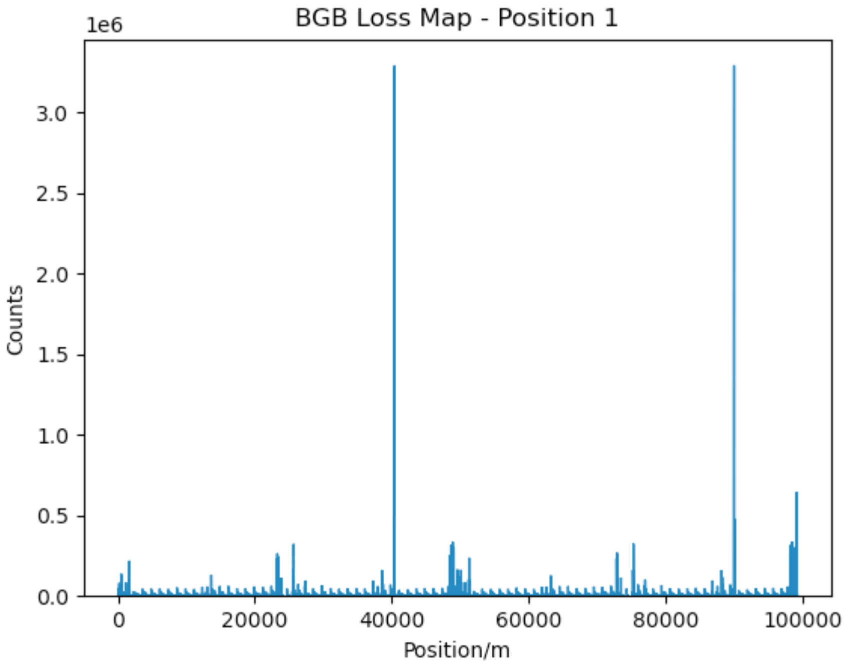
RBB



Aperture Model – With Collimator

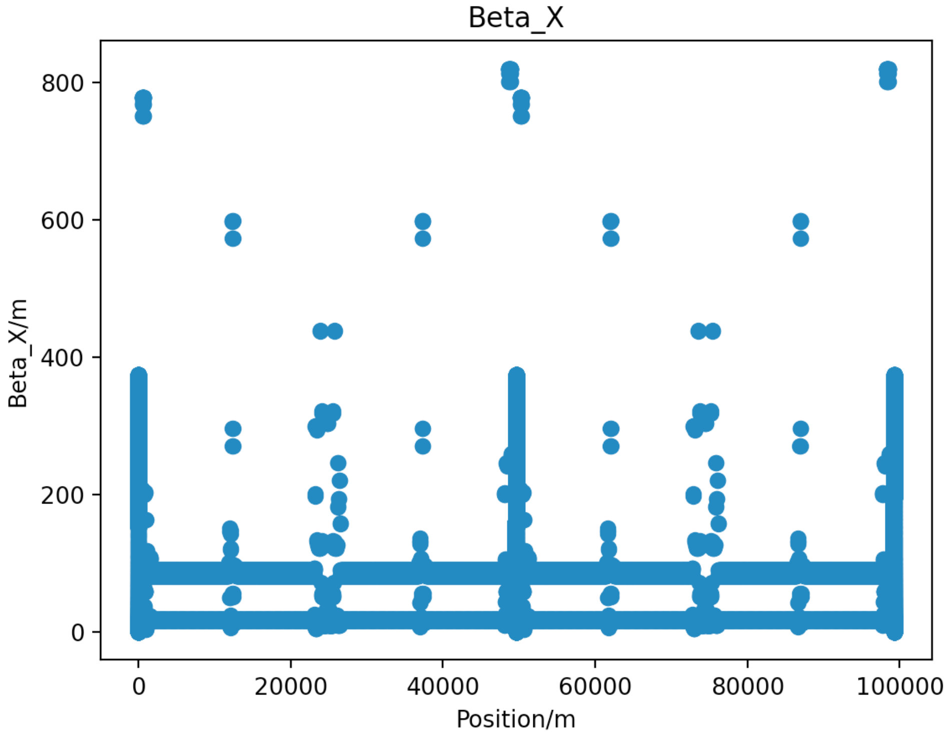
- The diameter of the beampipe in all regions except the IR and collimator is 56mm, with the length of the components itself.
- The drift chambers and dipoles in the IR and 200m before the IR are sliced into 10cm, with aperture set properly.
  - Since the beam-gas coulomb scattering has not been well studied yet, only X apertures is presented.

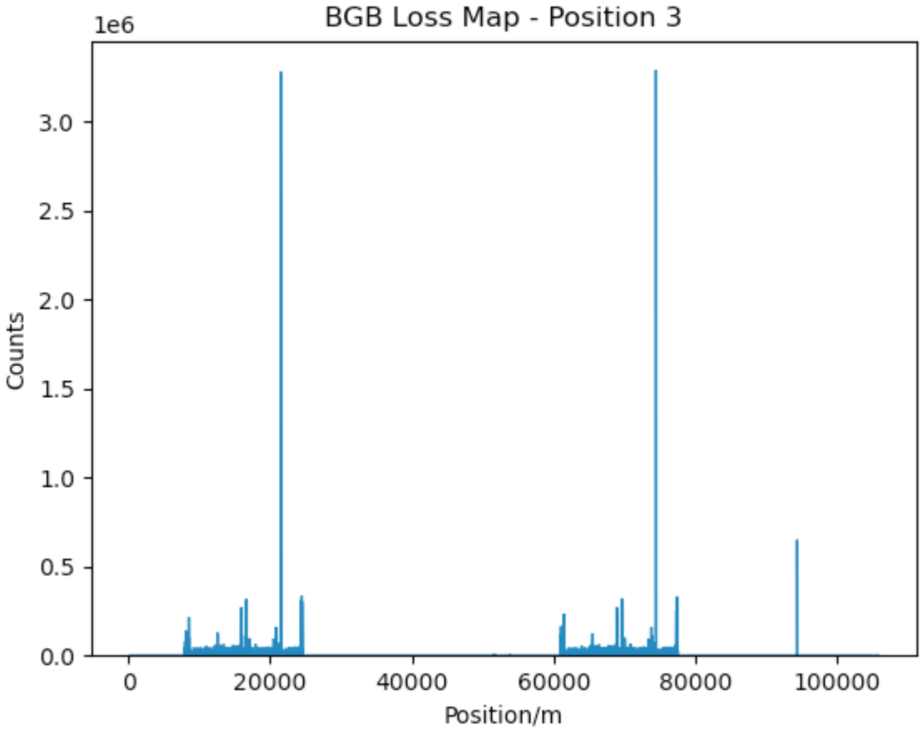




Where these peaks come from?

- The diameter of the beampipe in all regions except the IR and collimator is 56mm, with the length of the components itself.
- The drift chambers and dipoles in the IR and 200m before the IR are sliced to 10cm, with aperture set properly.
  - Since the beam-gas coulomb scattering has not been well studied yet, only X apertures is presented.



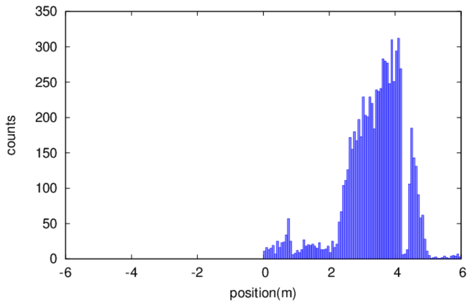


Injection Backgrounds

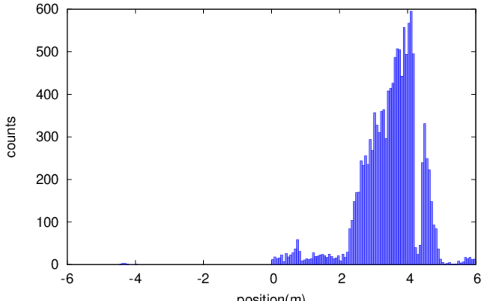
S. Bai

- 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

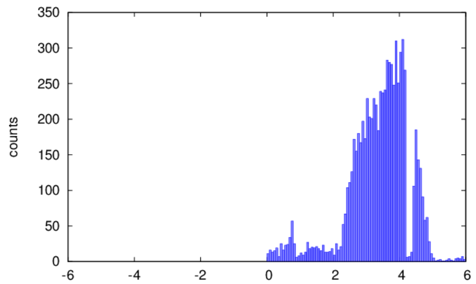
Circular beam



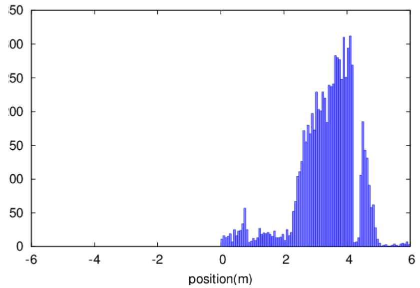
Injection beam



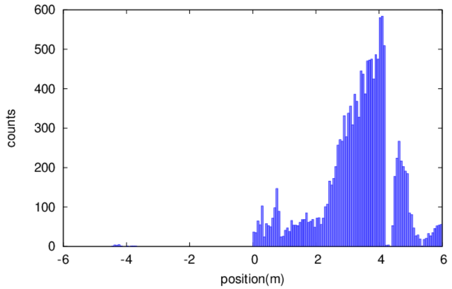
Gaussian beam with 3sigma



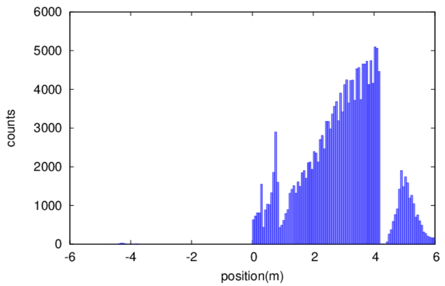
Gaussian beam with 40sigma



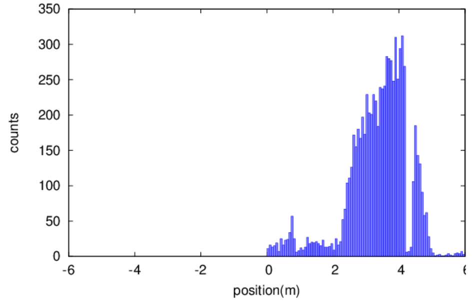
Large emittance ~10times



Large emittance ~1000times



Double gaussian beam



Uniform beam