# Study Status of Beam Backgrounds at the CEPC

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On behalf of the CEPC MDI Working Group

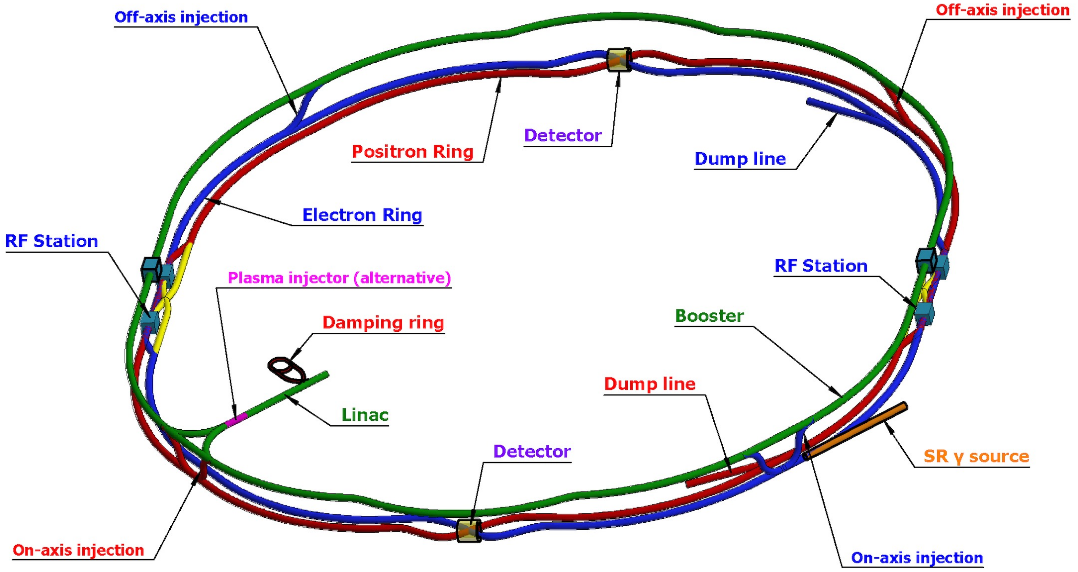
IAS Program on High Energy Physics(HEP 2023)
2023.02.14@Hong Kong

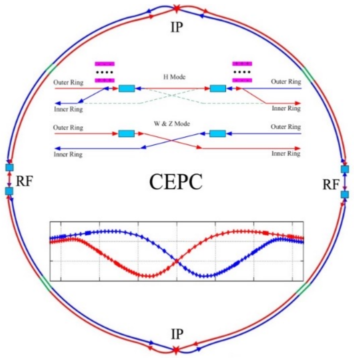
# Outline

- Introduction
- The Design and Results on CDR Phase
- The Design and Preliminary Results on TDR Phase
- Summary & Outlook

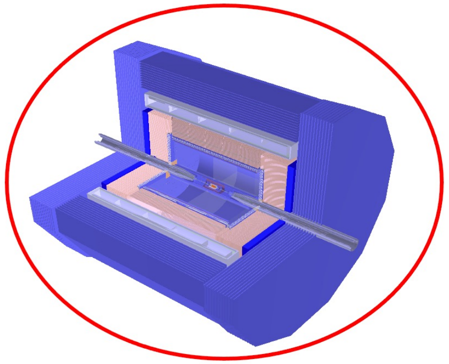
# Introduction

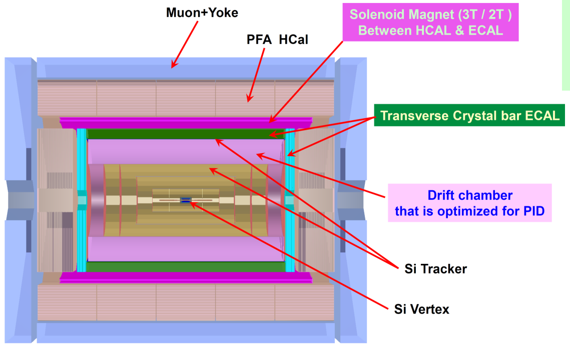
- MDI stands for "Machine Detector Interface"
  - Interaction Region and other components
  - 2 IPs
  - 33mrad Crossing angle
- Flexible optics design
  - Common Layout in IR for all energies
  - High Luminosity, low background impact, low error
  - Stable and easy to install, replace/repair



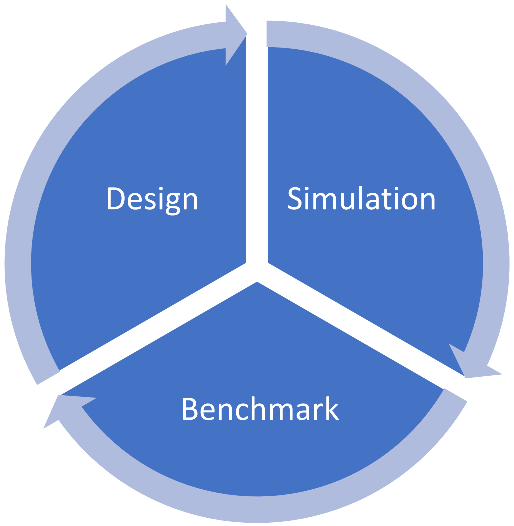

**Particle Flow Approach**
( ILD-like )



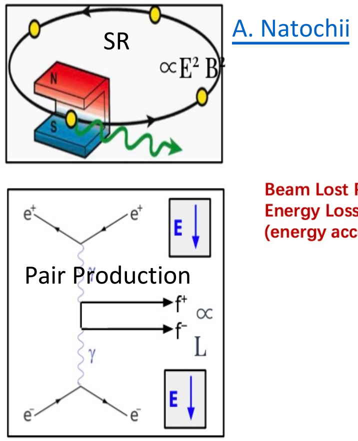



**4th Detector concept**

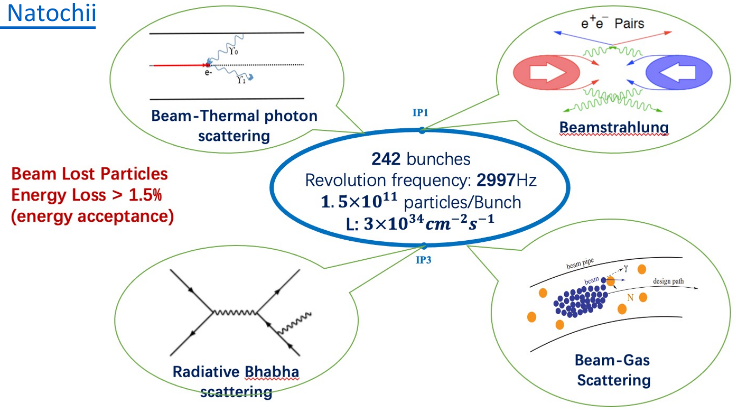
# Background Estimation



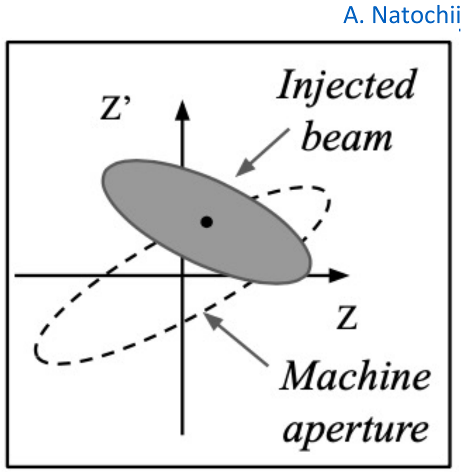

- One Beam
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(50 turns)
  - Using built-in LOSSMAP
  - SR emitting/RF on
  - Radtaper on
  - No detector solenoid yet




Photon BG




Beam Loss BG




Injection BG

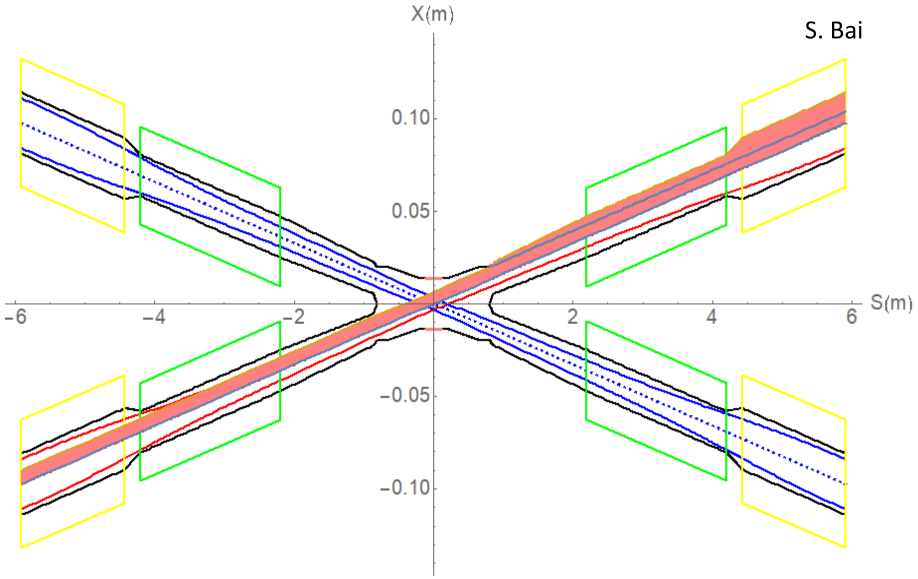
| Background | Generation | Tracking | Detector Simu. |
|---|---|---|---|
| Synchrotron Radiation | BDSim | BDSim/Geant4 | Mokka/CEPCSW |
| Beamstrahlung/Pair Production | Guinea-Pig++ | SAD | |
| Beam-Thermal Photon | PyBTH[Ref] | | |
| Beam-Gas Bremsstrahlung | PyBGB[Ref] | | |
| Beam-Gas Coulomb |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

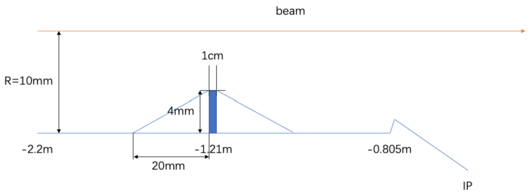
# CDR

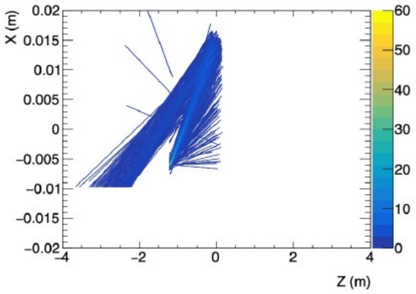
# SR BG & Mitigation

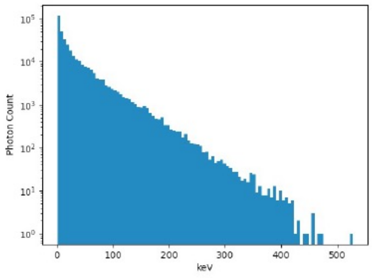
- The SR must be dealt with high priority when designing the circular machine. At the CEPC, there would be no SR photons hitting the central beam pipe directly in normal conditions
- However, some secondaries generated within QD would hit the detector beampipe, even the beryllium part. Therefore, the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

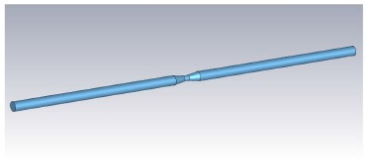
S. Bai

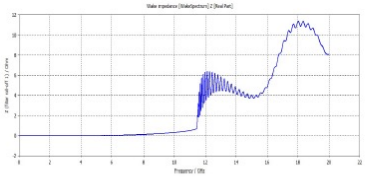


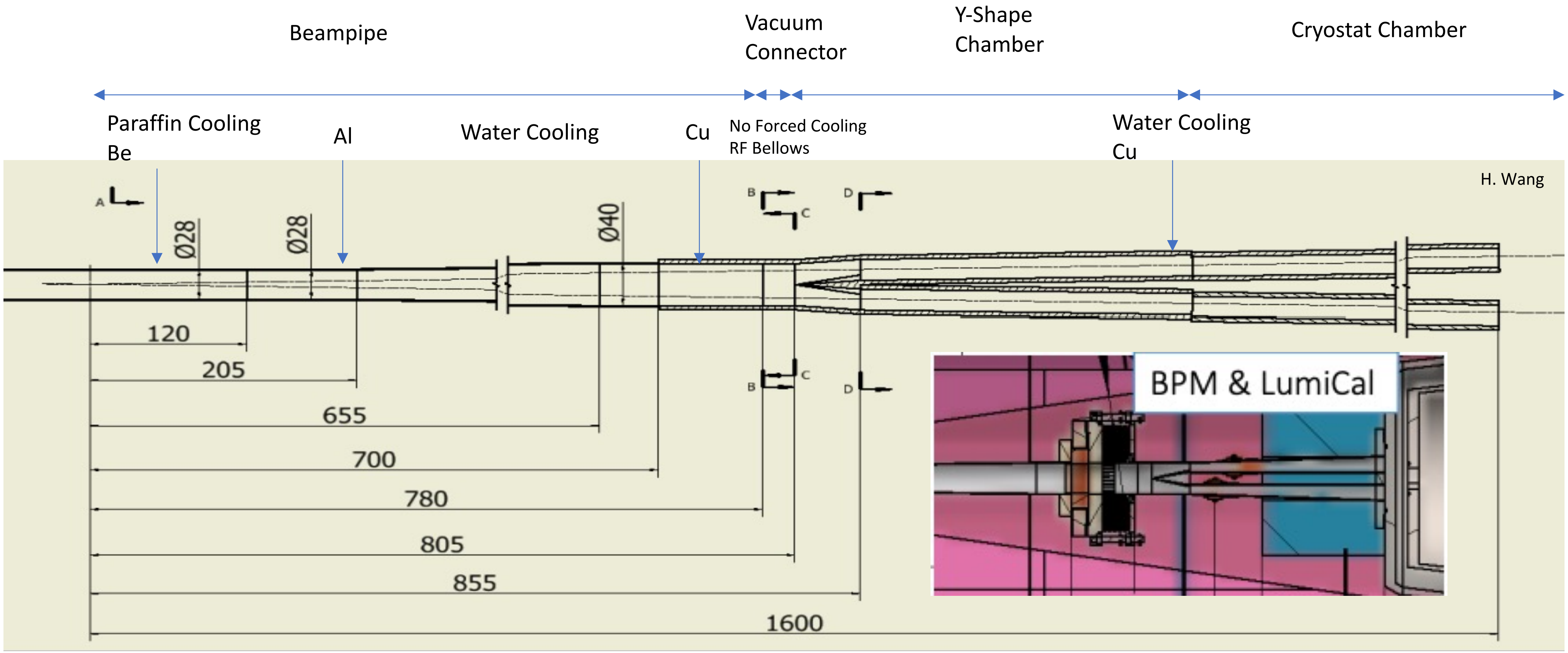





Y. Sun

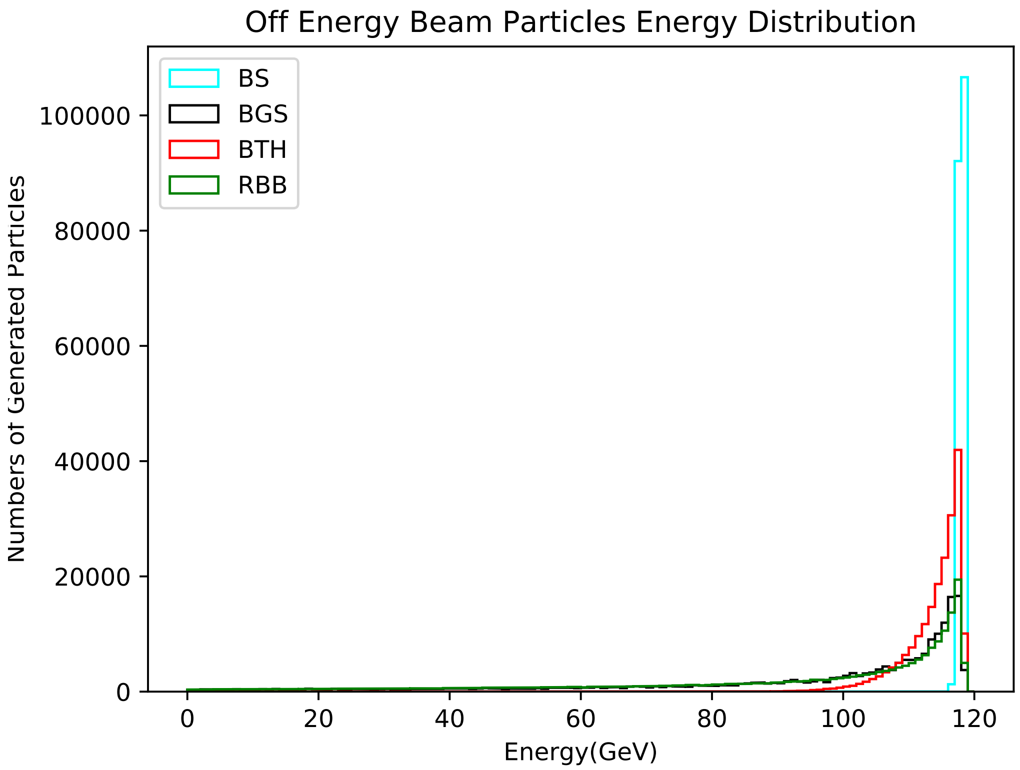
| Methods | photon number of hitting on Be(N) |
|---|---|
| 1.21-mask-Cu | 1736.0 |
| 1.21-mask-W | 1698.0 |
| 2.2-mask-Cu | 1147.0 |
| cons-no mask-Cu | 257364.0 |
| cons-no mask-W | 148030.0 |
| 1.21-mask-Cu-5$\mu$mAu | 216.0 |
| nomask | 39400.0 |

# Revised Beampipe Design

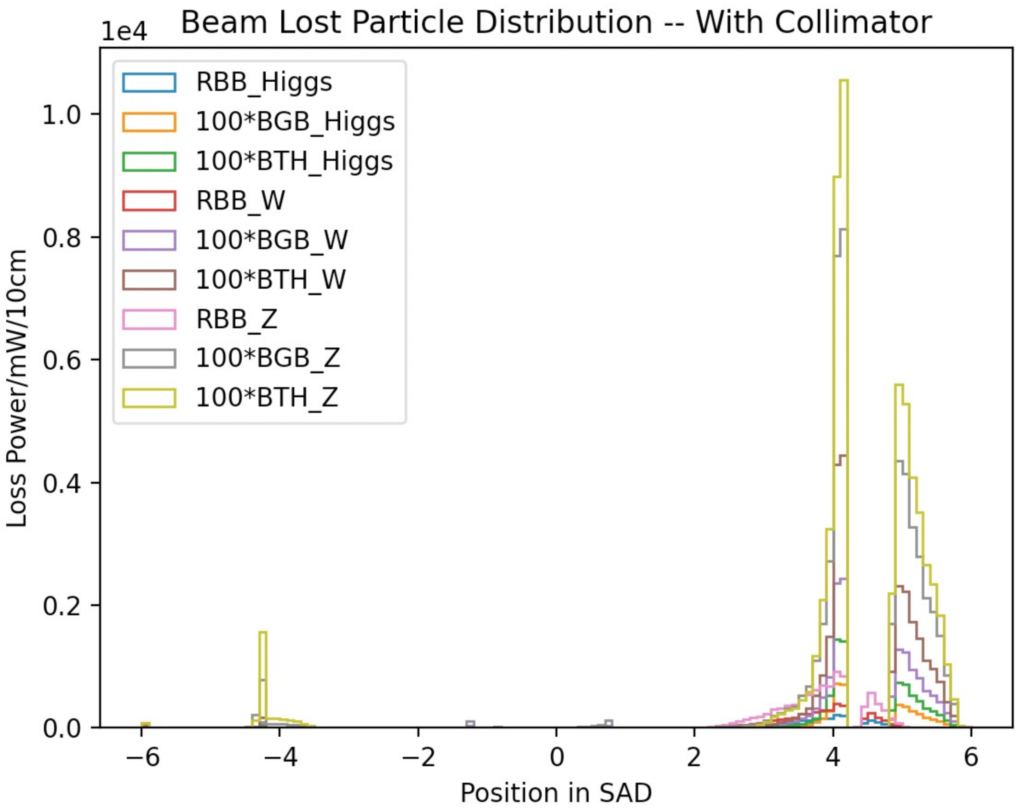


# Lost distribution

- The loss power due to beam loss background is low.
  - < 1w / 10cm
- The loss in quads must be taken special care of.




Energy Spectra




Loss Power

# Detector Impact

- 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

# 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 $\beta_x^*/\beta_y^*$ (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 $\sigma_x/\sigma_y$ (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 $\xi_x/\xi_y$ | 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 |

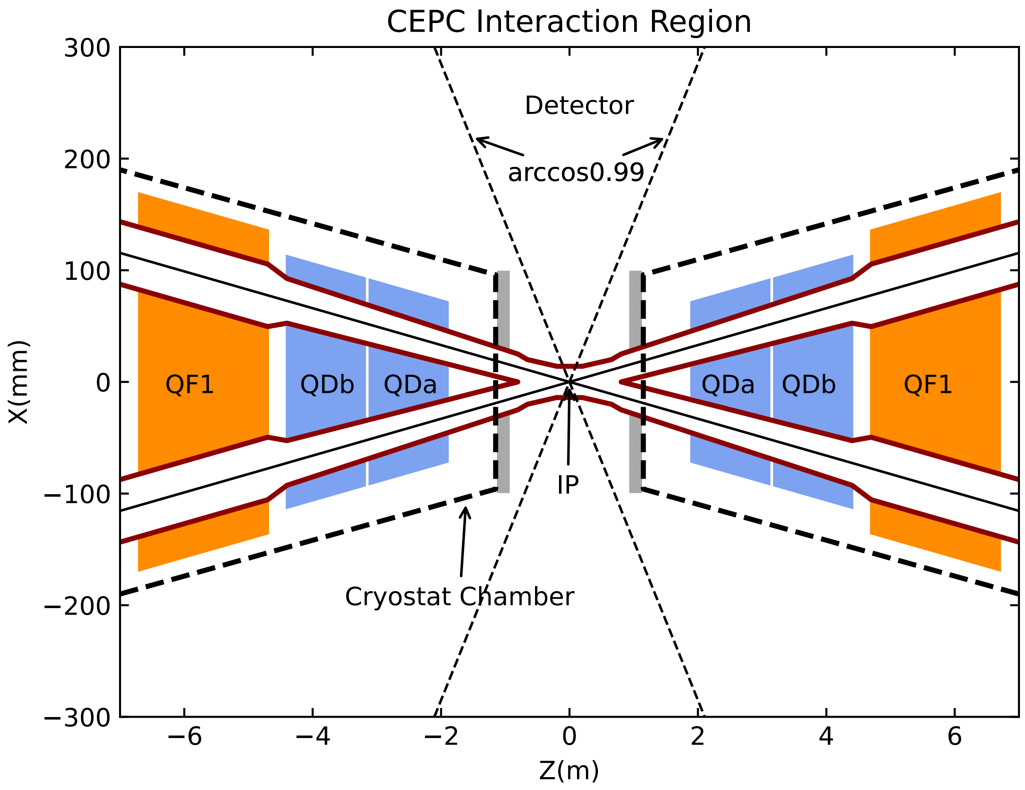
# MDI Parameter Table

S. Bai

| | range | Peak filed in coil | Central filed gradient | Bending angle | length | Beam stay clear region | Minimal distance between two aperture | Inner diameter | Outer diameter | Critical energy (Horizontal) | Critical energy (Vertical) | SR power (Horizontal) | SR power (Vertical) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L* | 0~1.9m | | | | 1.9m | | | | | | | | |
| Crossing angle | 33mrad | | | | | | | | | | | | |
| MDI length | ±7m | | | | | | | | | | | | |
| Detector requirement of accelerator components in opening angle | 8.11˚ | | | | | | | | | | | | |
| QDa/QDb | | 3.2/2.8 T | 141/84.7T/m | | 1.21m | 15.2/17.9mm | 62.71/105.28 mm | 48mm | 59mm | 724.7/663.1keV | 396.3/263keV | 212.2/239.23 W | 99.9/42.8 W |
| QF1 | | 3.3T | 94.8T/m | | 1.5m | 24.14mm | 155.11mm | 56mm | 69mm | 675.2keV | 499.4keV | 472.9W | 135.1W |
| Lumical | 0.95~1.11m | | | | 0.16m | | | 57mm | 200mm | | | | |
| Anti-solenoid before QD0 | | 8.2T | | | 1.1m | | | 120mm | 390mm | | | | |
| Anti-solenoid QD0 | | 3T | | | 2.5m | | | 120mm | 390mm | | | | |
| Anti-solenoid QF1 | | 3T | | | 1.5m | | | 120mm | 390mm | | | | |
| Beryllium pipe | | | | | ±120mm | | | 28mm | | | | | |
| Last B upstream | 64.97~153.5m | | | 0.77mrad | 88.5m | | | | | 33.3keV | | | |
| First B downstream | 44.4~102m | | | 1.17mrad | 57.6m | | | | | 77.9keV | | | |
| Beampipe within QDa/QDb | | | | | 1.21m | | | | | | | 1.19/1.31W | |
| Beampipe within QF1 | | | | | 1.5m | | | | | | | 2.39W | |
| Beampipe between QD0/QF1 | | | | | 0.3m | | | | | | | 26.5W | |

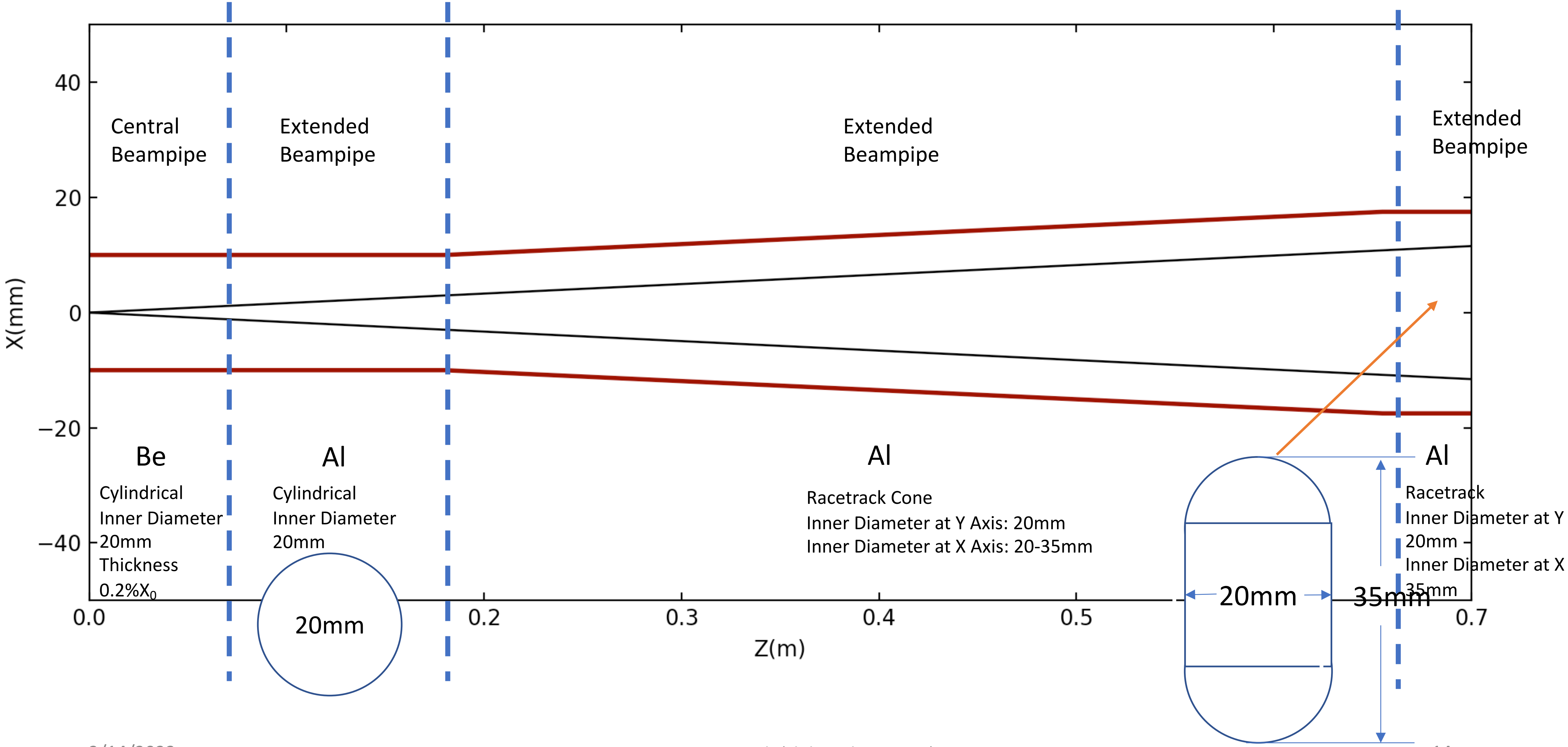
# Updated IR

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




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

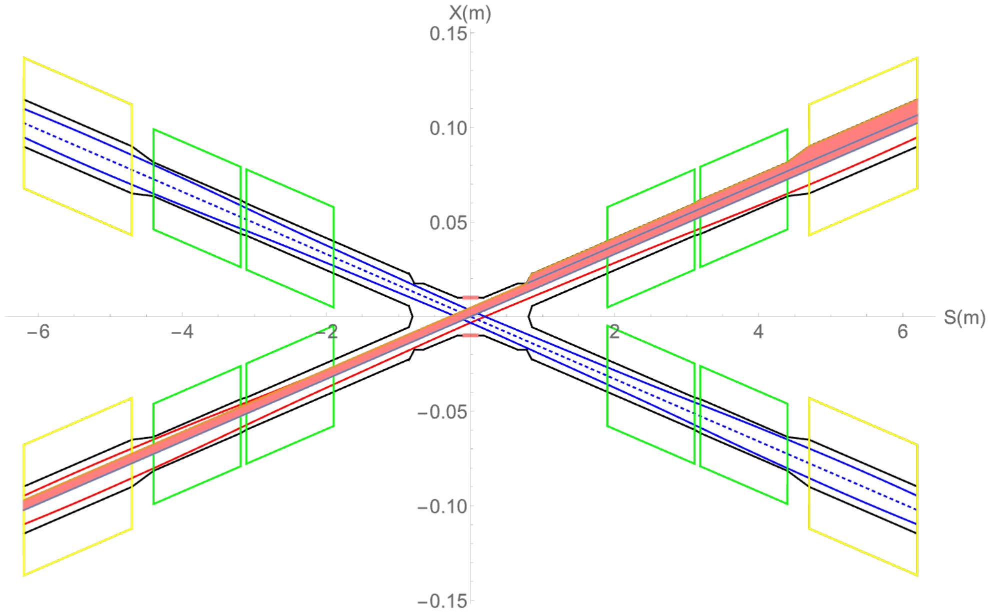
# New Beampipe Design – Half Detector pipe



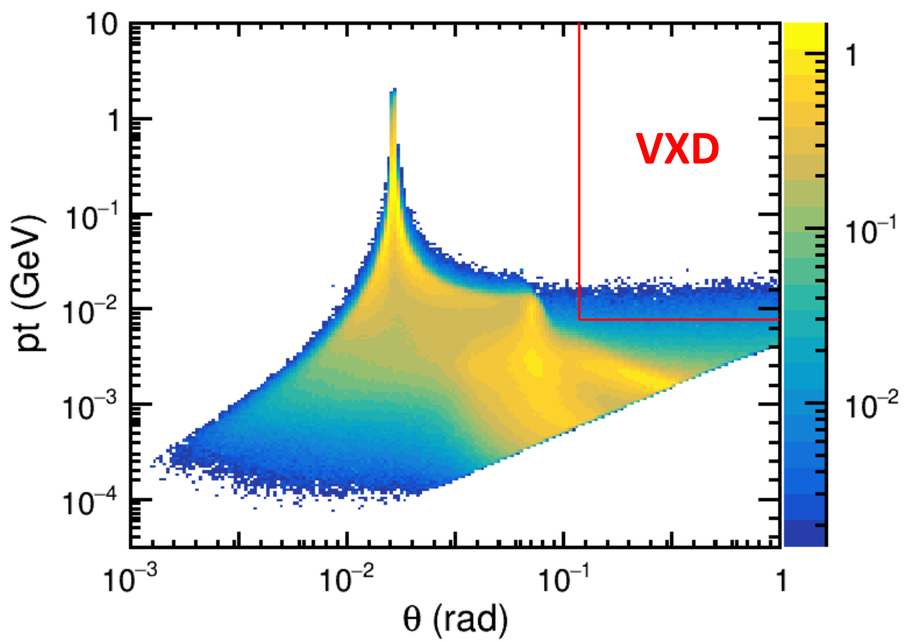
# Photon Backgrounds

- Synchrotron Radiation:
  - The study based on TDR is ongoing.
  - Currently, the masks adopted to TDR designs works.
- 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.

S. Bai



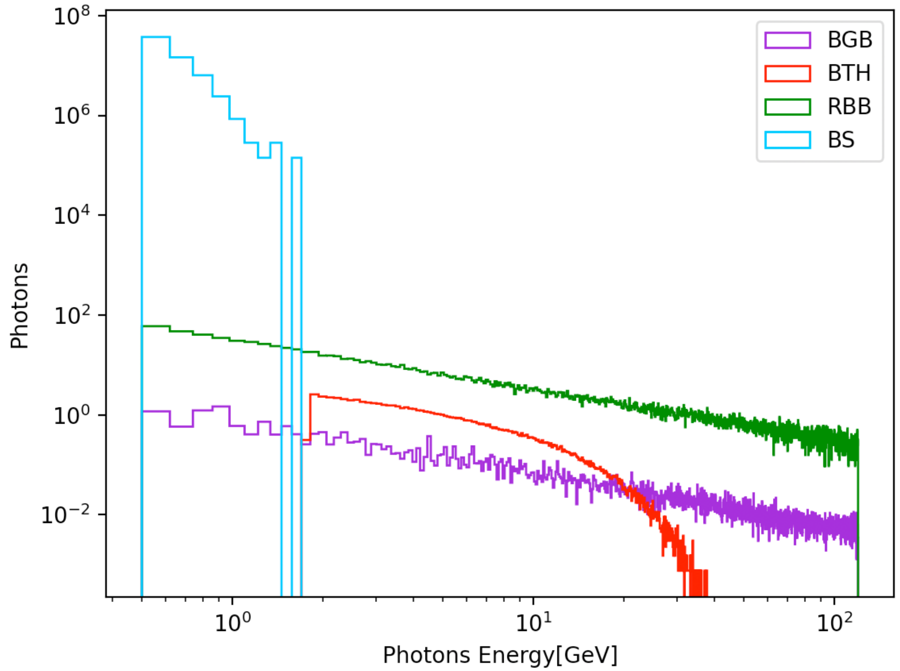

W. Xu

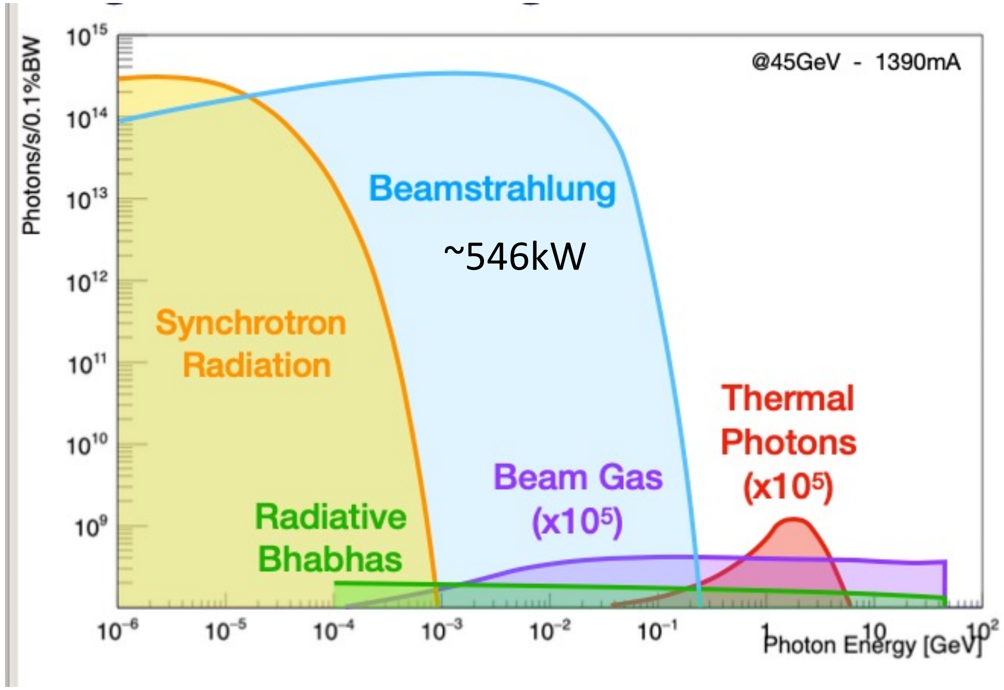


# Photon Absorber?

- 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
  - The photons are very hard, contains multi-MeV or even few-GeV photons.
- The study on this issue has been started.

CEPC@Higgs



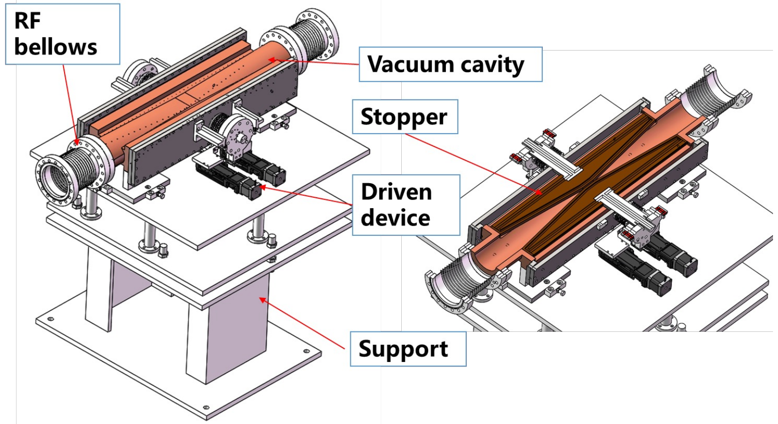




FCC@Z

# Mitigation of the BG - Collimator

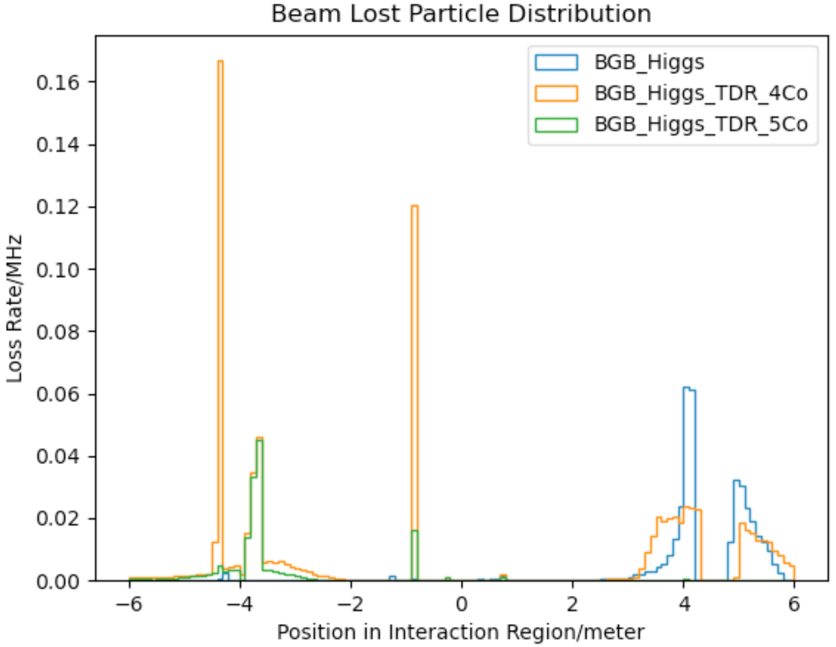
H. Wang, P. Zhang

- Requirements:
  - Beam stay clear region: 18 $\sigma_x$+3mm, 22 $\sigma_y$+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.




S. Bai

| name | Position | Distance to IP/m | Beta function/m | Horizontal Dispersion /m | Phase | BSC/2/m | Range of half width allowed/m |
|---|---|---|---|---|---|---|---|
| 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 |

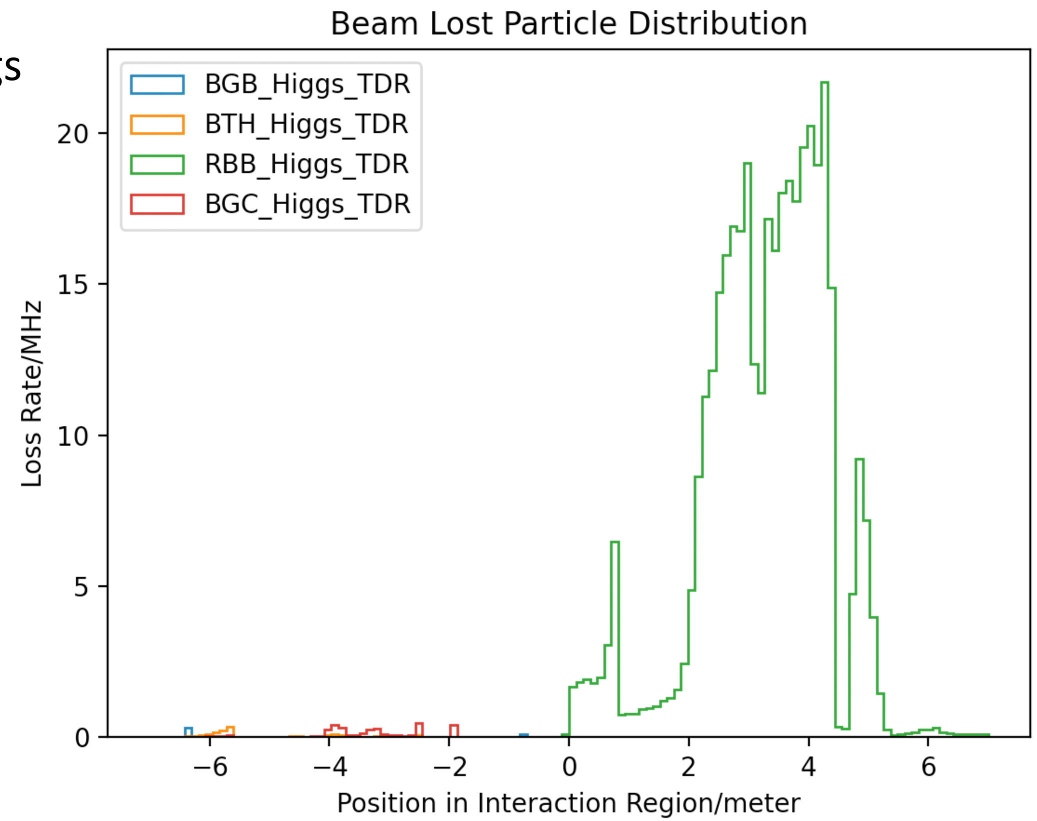


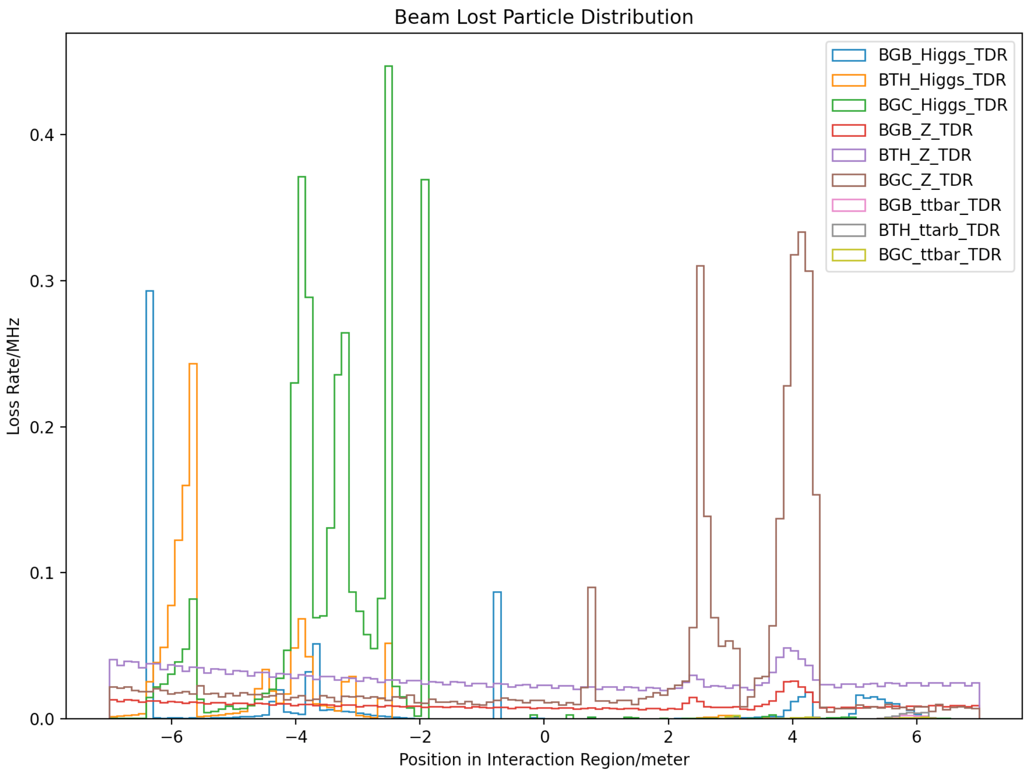
# Loss Distribution

- Errors implemented
  - High order error for magnets
  - Beam-beam effect
- 2 IR considered(sum)

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

@Higgs




@Higgs
+ttbar
+Z

# 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 |

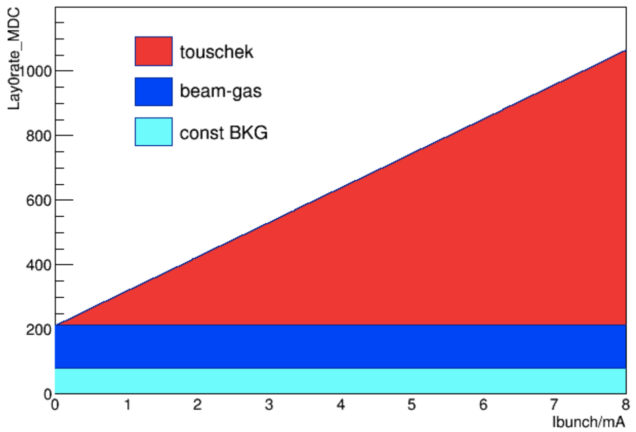
| | Hit Density($cm^{-2}\cdot BX^{-1}$) | TID($krad\cdot yr^{-1}$) | NIEL($n_{eq}\times 10^{12}\cdot cm^{-2}\cdot yr^{-1}$) |
|---|---|---|---|
| Vertex | 2.3 | 5360 | 120.4 |
| TPC | 2.59e-2 | 387.09 | 42.503 |
| Ecal Barrel | 1.16e-3 | 31.56 | 8.002 |
| Ecal EndCup | 1.36e-3 | 14.175 | 6.128 |
| Hcal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

# Benchmark – Experiments

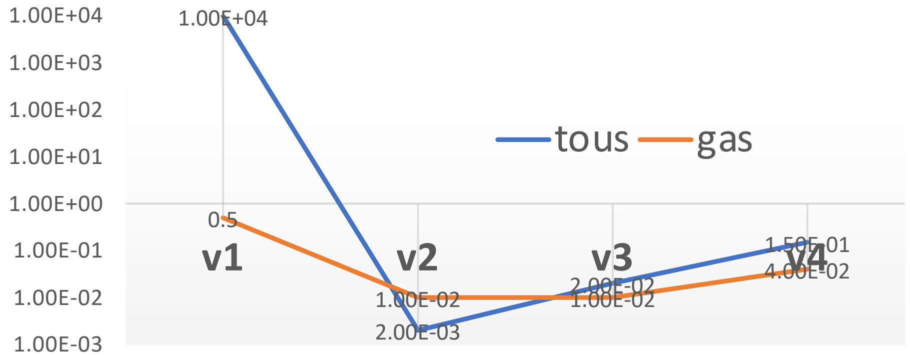
- Important to validate the modellings and Monte Carlo Simulation codes for the CEPC beam background simulation with real data where they are applicable.
  - BEPC II/BES III, SuperKEKB/Belle II, LEP I/II…
- Basic Principles – Key Parameters & Distinguish
  - Single beam mode: three dominant contributions 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)

# Benchmark – Experiments

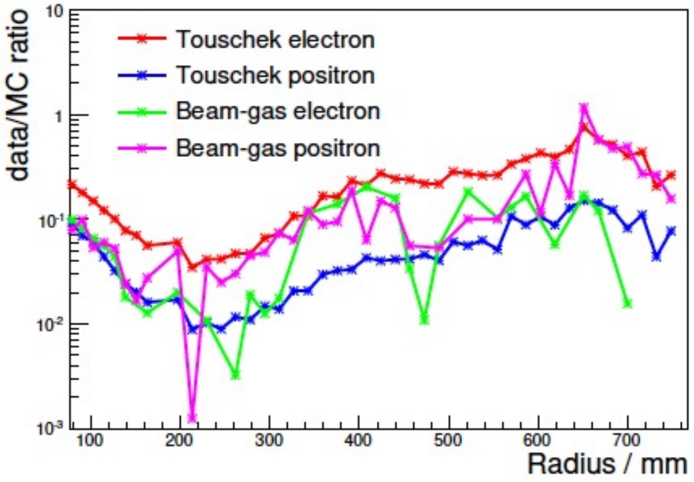
- BG experiments on BEPCII/BESIII has been done twice.
  - The experiment in 2021 separate the single beam BG sources, the data/MC ratio has been reduced.




BG separation on 1st layer MDC




Data/MC radio improvements on 1st layer MDC




Data/MC radio in MDC

  - The experiment in 2022 was focused on collimators, and more data/experiments are needed.

# Summary & Outlook

- We are moving our study to TDR phase.
  - Layout & Physics design has been updated.
  - We are trying to finish the aperture modal and the collimator settings.
  - The tracking methods has been updated. New tools/toolkits are underdevelopment.
  - More detailed study is on going, and the full detector simulation on TDR is about to start.
- The optimization and validation of current design is always needed.
  - The BESIII backgrounds experiment was done last/this summer. We plan to do more in the following years, containing the study on Collimators.
  - Validate our BG simulation codes using BEPCII and SuperKEKB.
- List & Study on different beam loss scenarios.
- Collaboration are welcomed.

Thank You

# Backup

# Pair Production

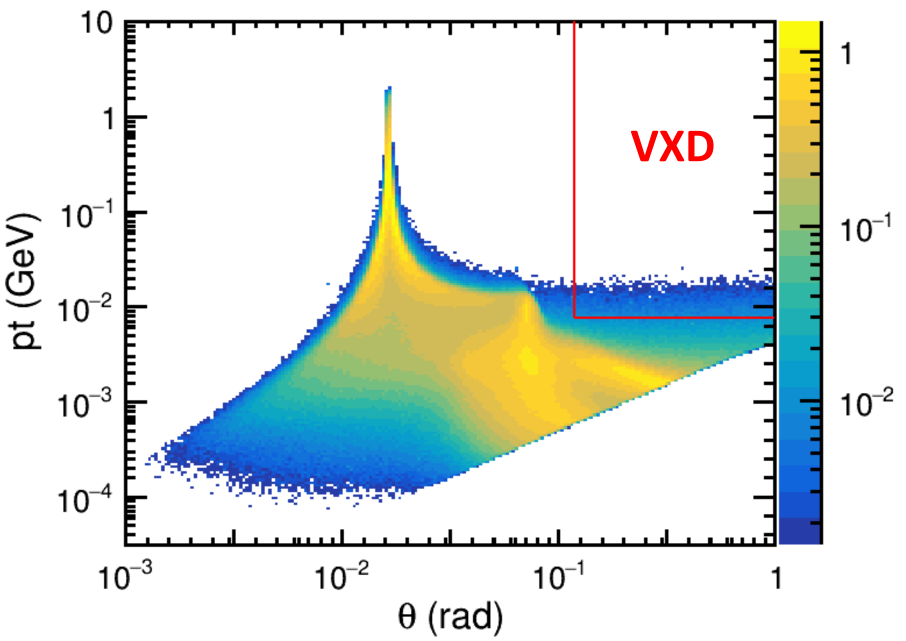
- Pair Production(Beamstrahlung) is one of the dominant background process at the CEPC.

| 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 | | | |

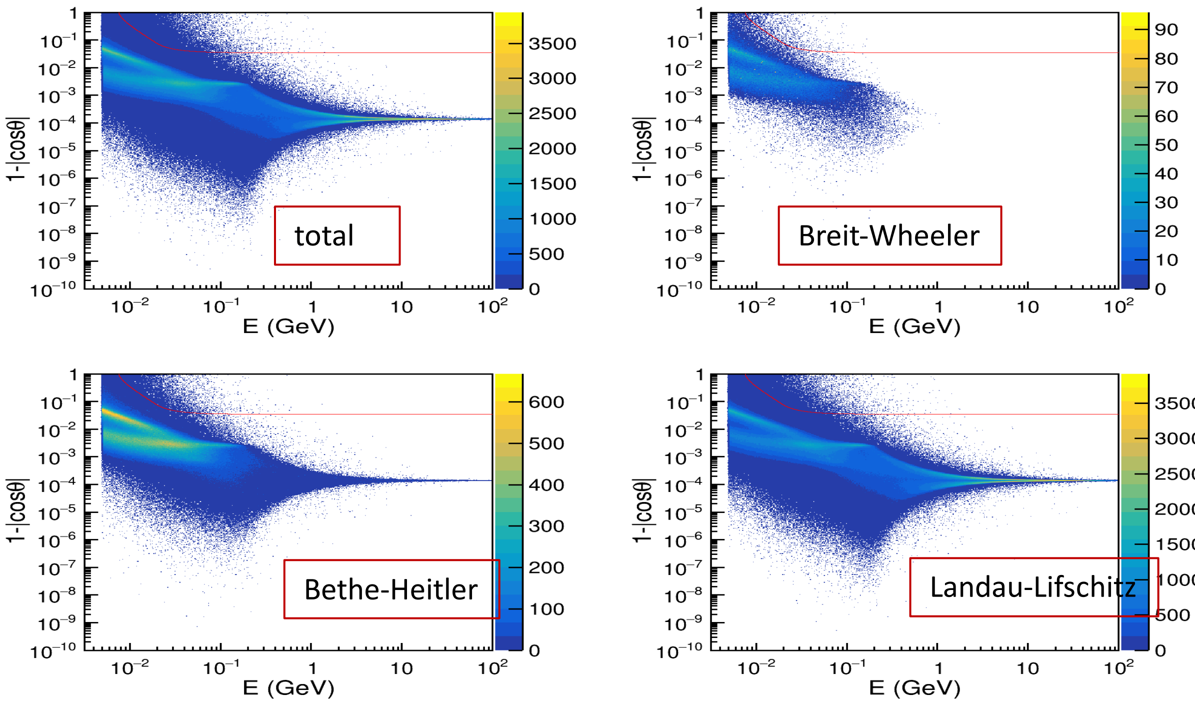
# Pair Production

- 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.

W. Xu

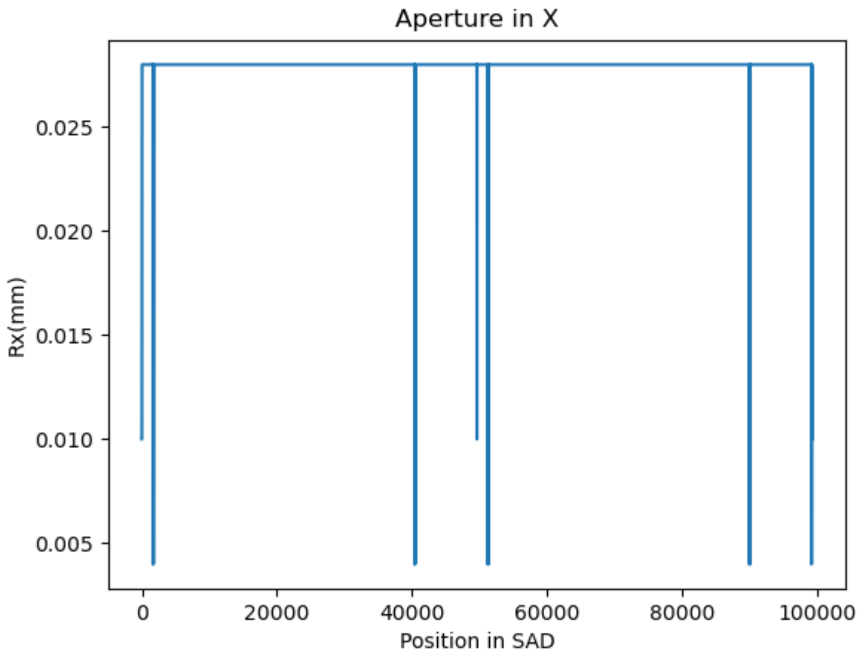


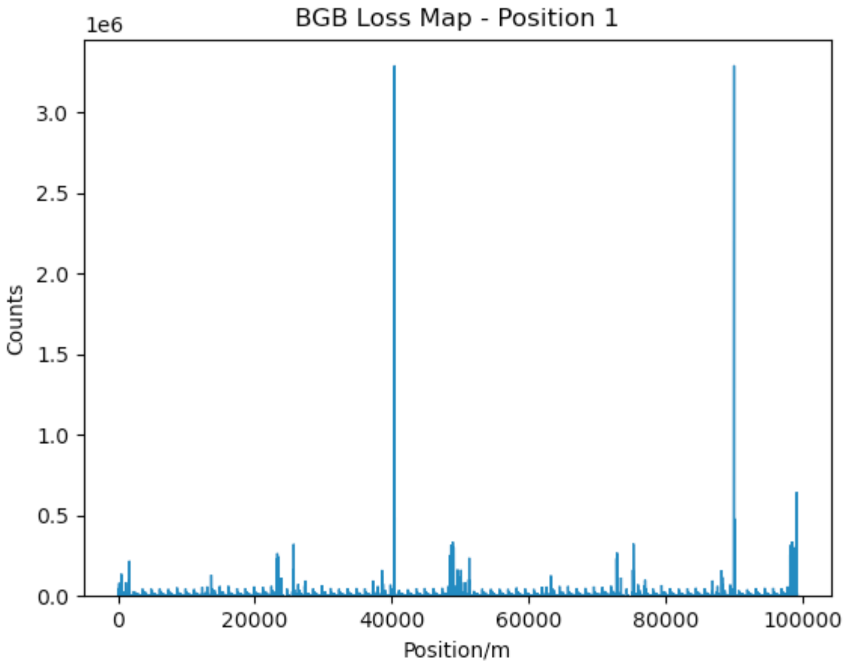

W. Xu



# 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.

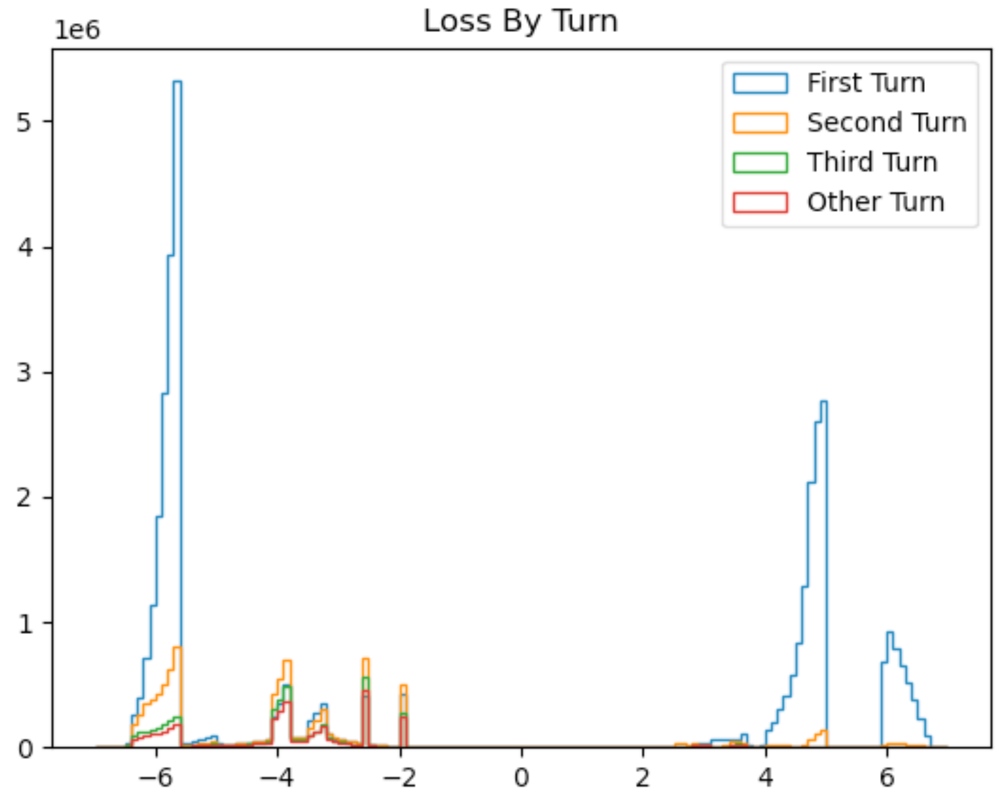


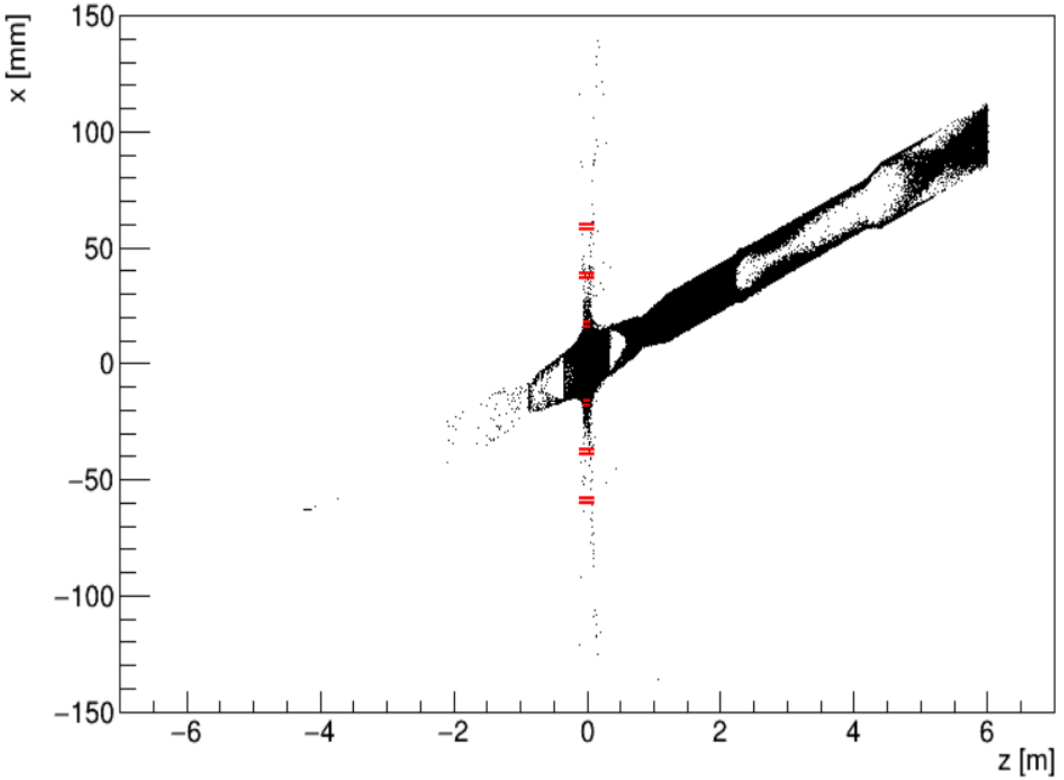
# Loss Distribution – With Collimators

- The loss in first turn dominants.

BGB

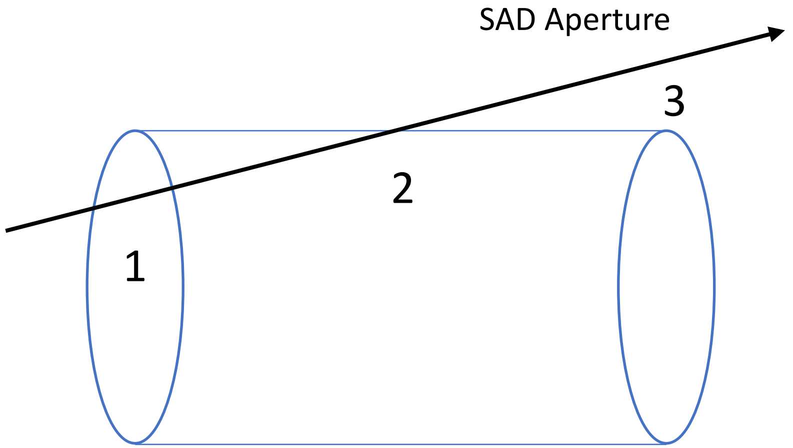


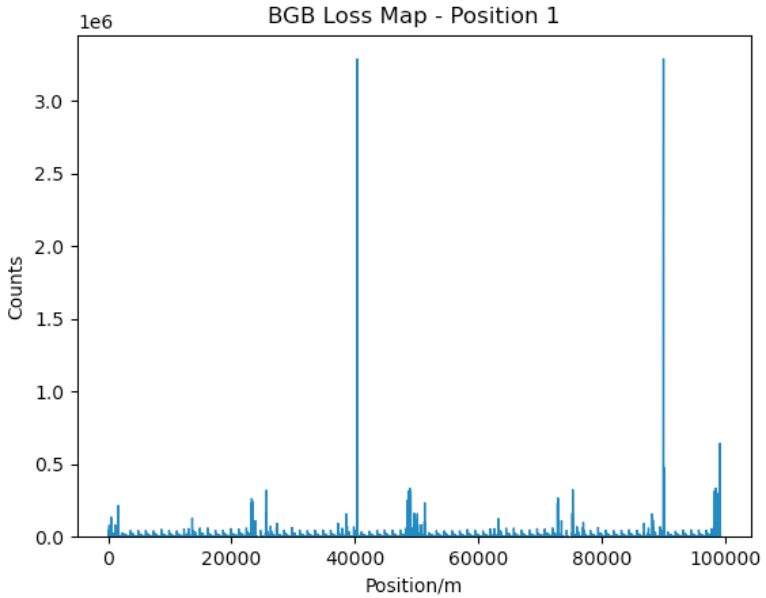

RBB

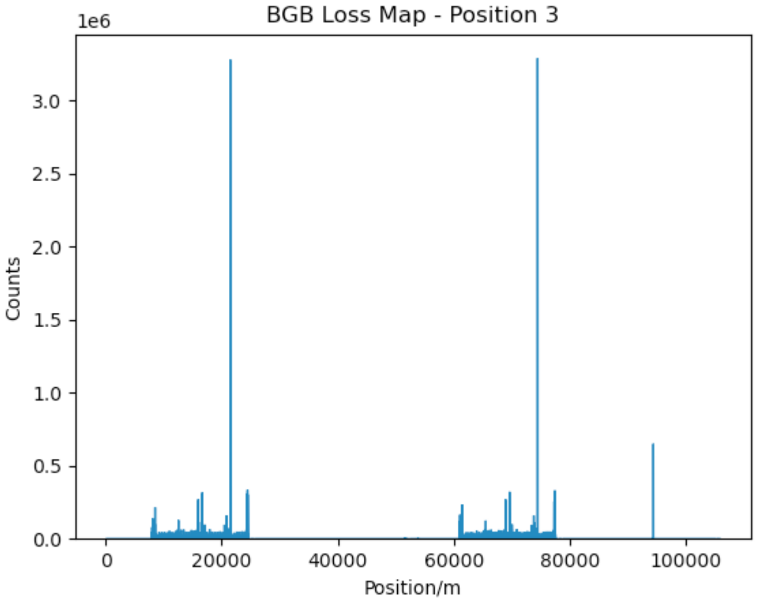


# Particle Position Optimization

- 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.

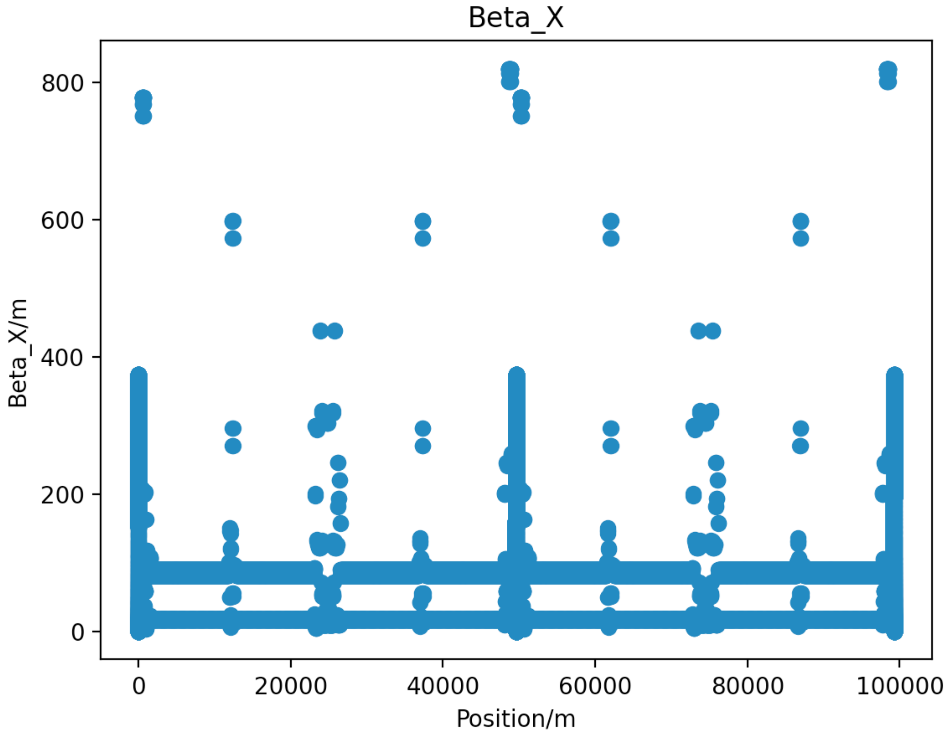


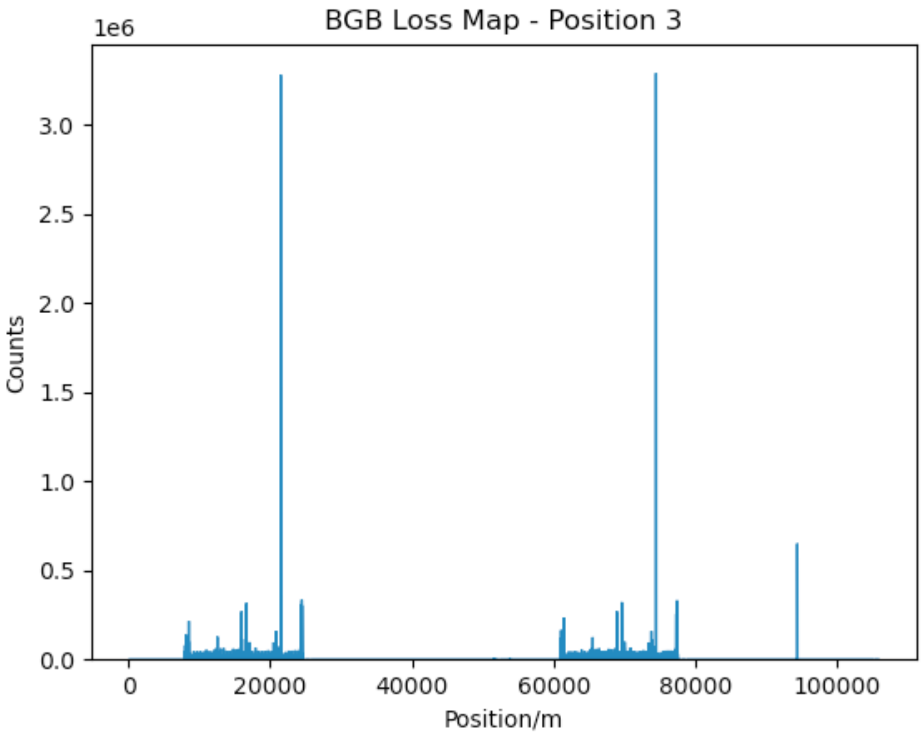



# Where these peaks come from?

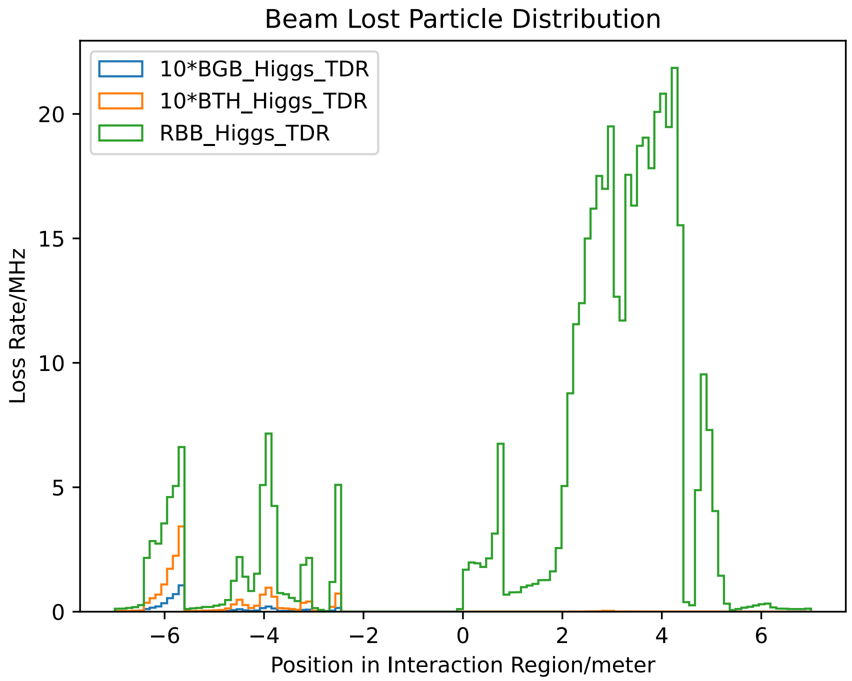
- The diameter of the beampipe in all regions except the IR and collimator is 56mm, with the length of the components itself.
- The drift chambers and dipoles in the IR and 200m before the IR are sliced to 10cm, with aperture set properly.
  - Since the beam-gas coulomb scattering has not been well studied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

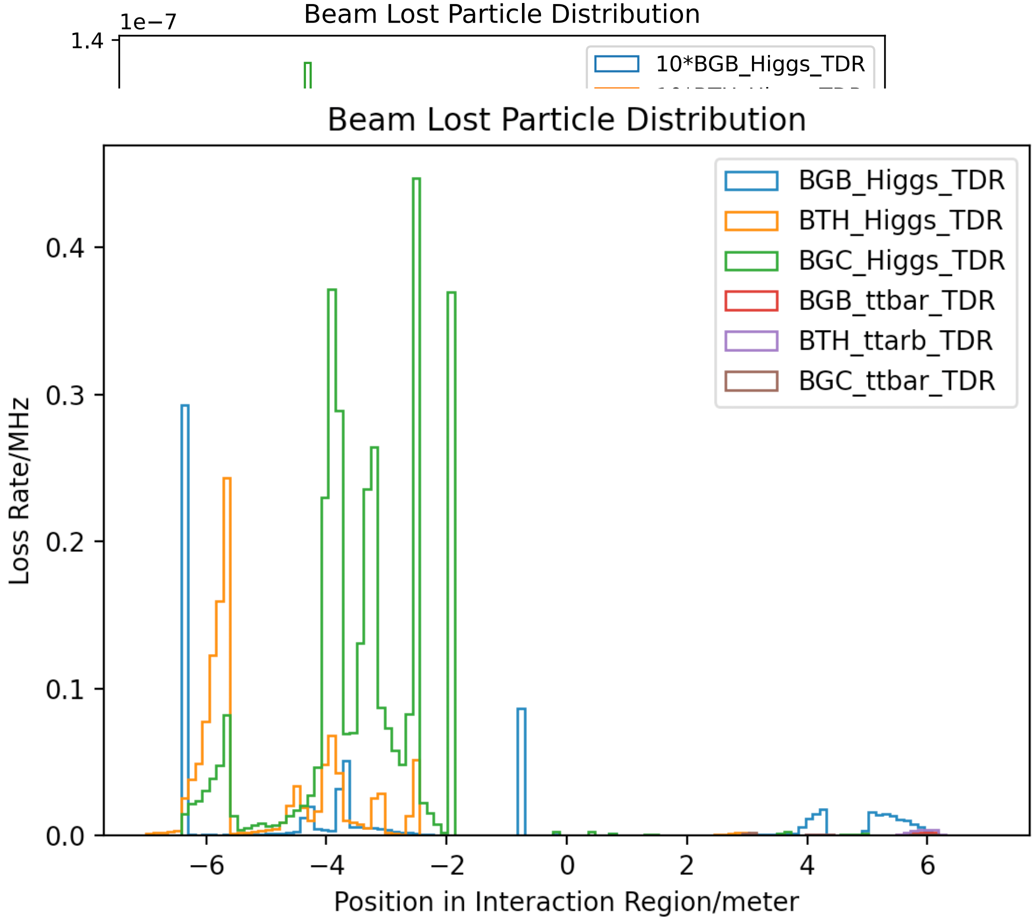


# Beam Loss Particles

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




- Upstream Loss Rate is higher than downstream, lo
  - Quads would be one of the hot-spot, shielding might be

# Beam Loss Particles

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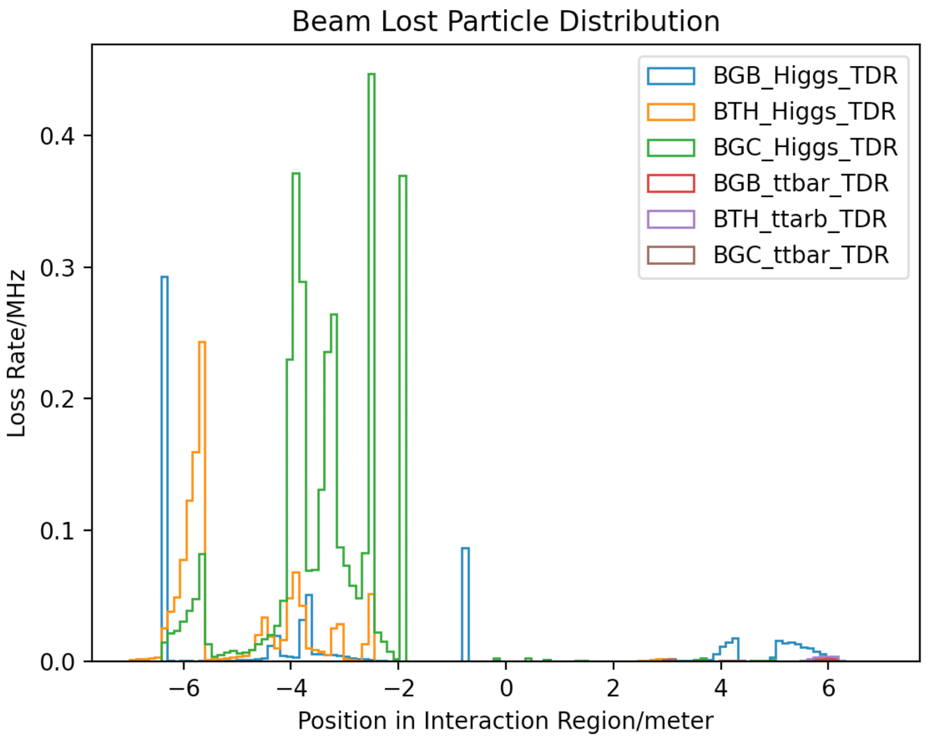
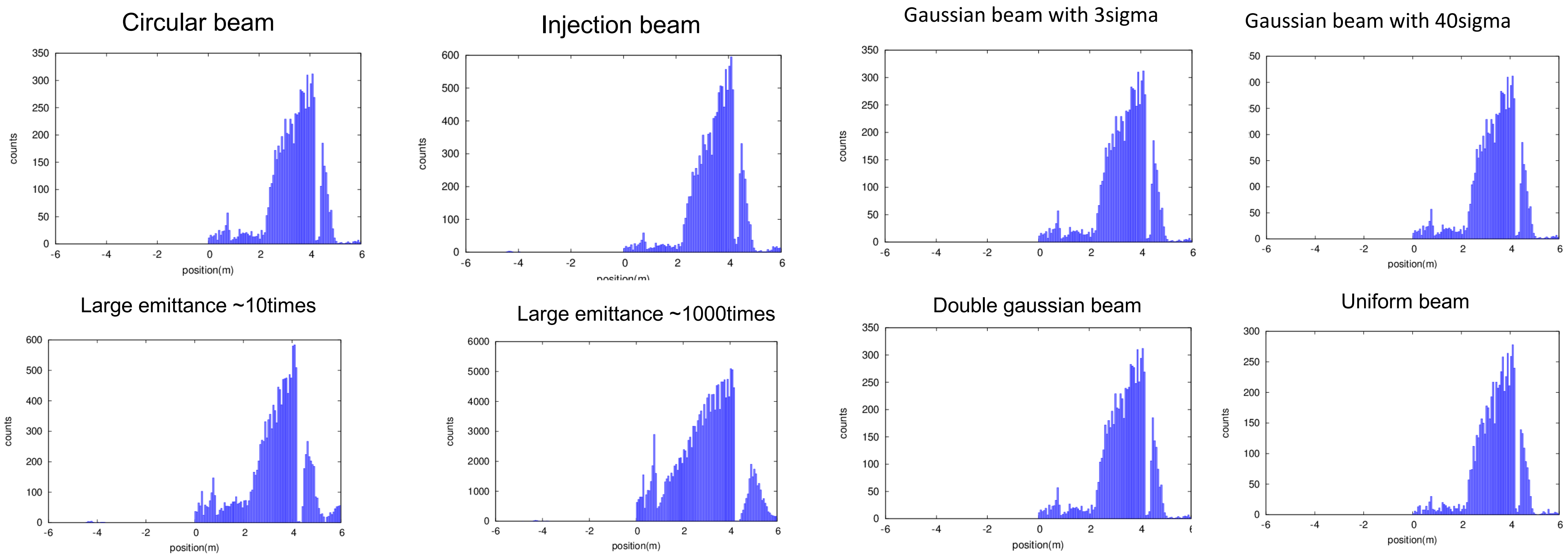



- Upstream Loss Rate is higher than downstream, loss power isn't
  - Quads would be one of the hot-spot, shielding might be needed.

# Injection Backgrounds

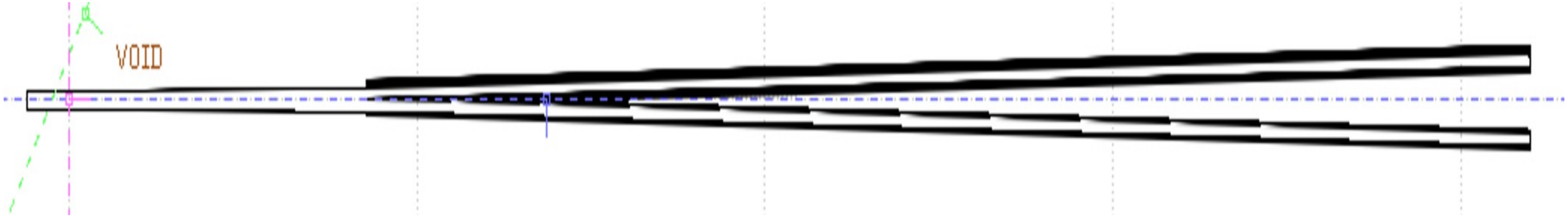
S. Bai

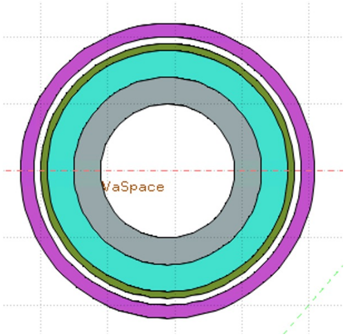
- A preliminary study on the injection backgrounds has been performed:
  - RBB is taken into account in all cases
  - A simplified model of top-up injection beam
  - Tails from imperfectly corrected X-Y coupling after the injection point
  - Some tolerances to imperfect beams from the booster (e.g. too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



# 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.

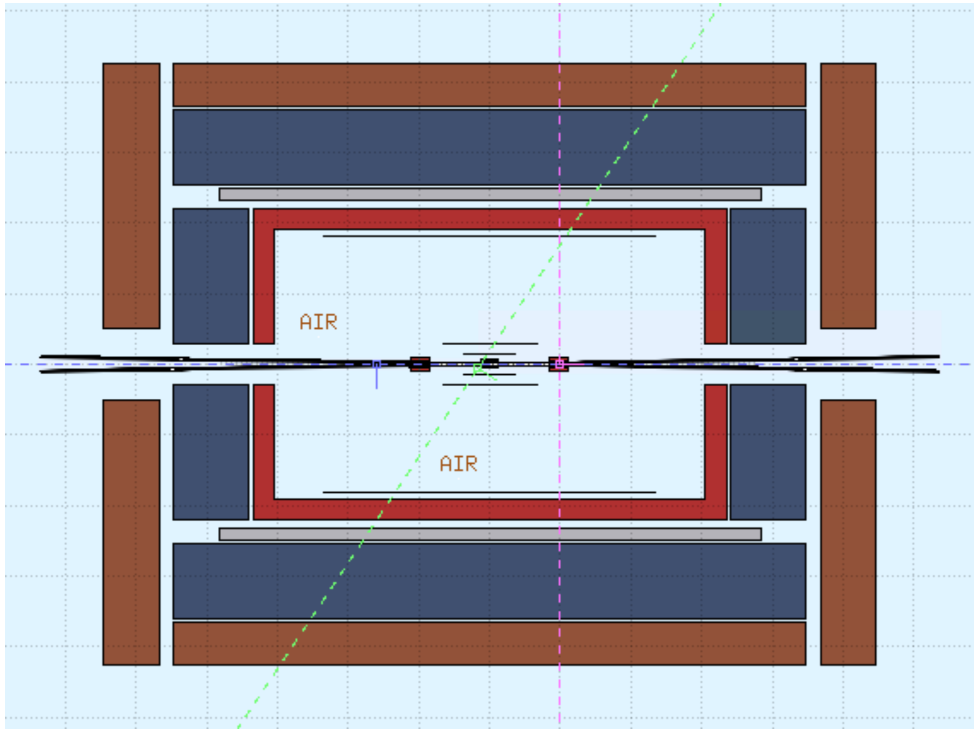


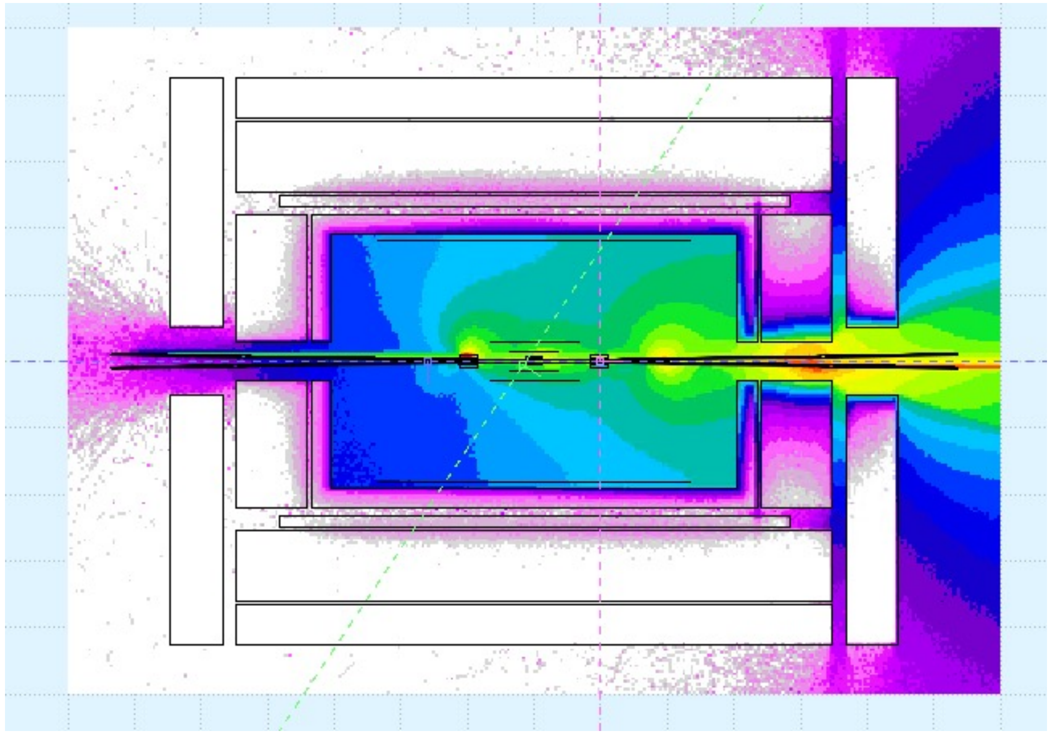
White: Vacuum
Gray: Tungsten Pipe
Light Green: Helium
Heavy Green: Stainless Steel Vassel
Pink: Coil

# Detector 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)