Beam Backgrounds and Machine-Detector Interface design at the CEPC

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On behalf of the CEPC MDI Working Group

CEPC International workshop EU Edition
2023.07.05@Edinburgh, UK

Outline

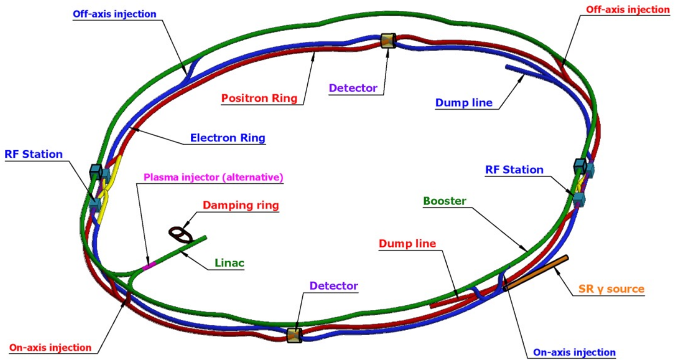
- Introduction
- Design Status
- Beam Backgrounds estimation
- Summary & Outlook

Introduction

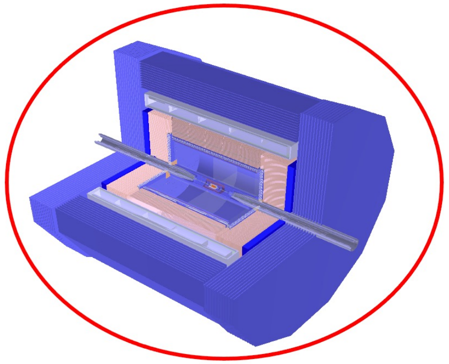
- MDI stands for ”Machine Detector Interface”
  - Interaction Region and other components
  - 2 IPs
  - 33mrad Crossing angle
- Flexible optics design
  - Common Layout in IR for all energies
  - High Luminosity, low background impact, low error
  - Stable and easy to install, replace/repair

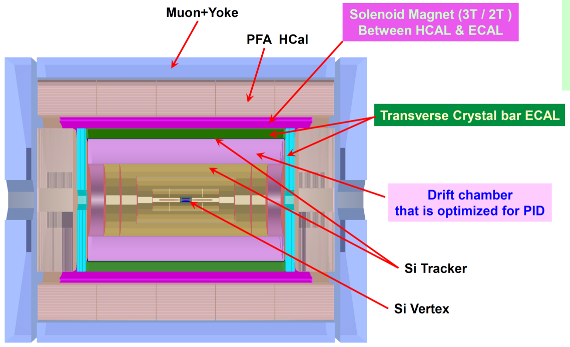
TDR Design

	Higgs	Z	W	$t\bar{t}$
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
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
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
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
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
Betatron tune ν_x/ν_y	445/445	317/317	317/317	445/445
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	**1.0**/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
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	39/40	82/2800	60/700	81/23
Beam lifetime (min)	20	80	55	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**5.0**	**115**	**16**	**0.5**
	67%⇧	259%⇧		



Particle Flow Approach
(ILD-like)





4th Detector concept

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	

Design of the components

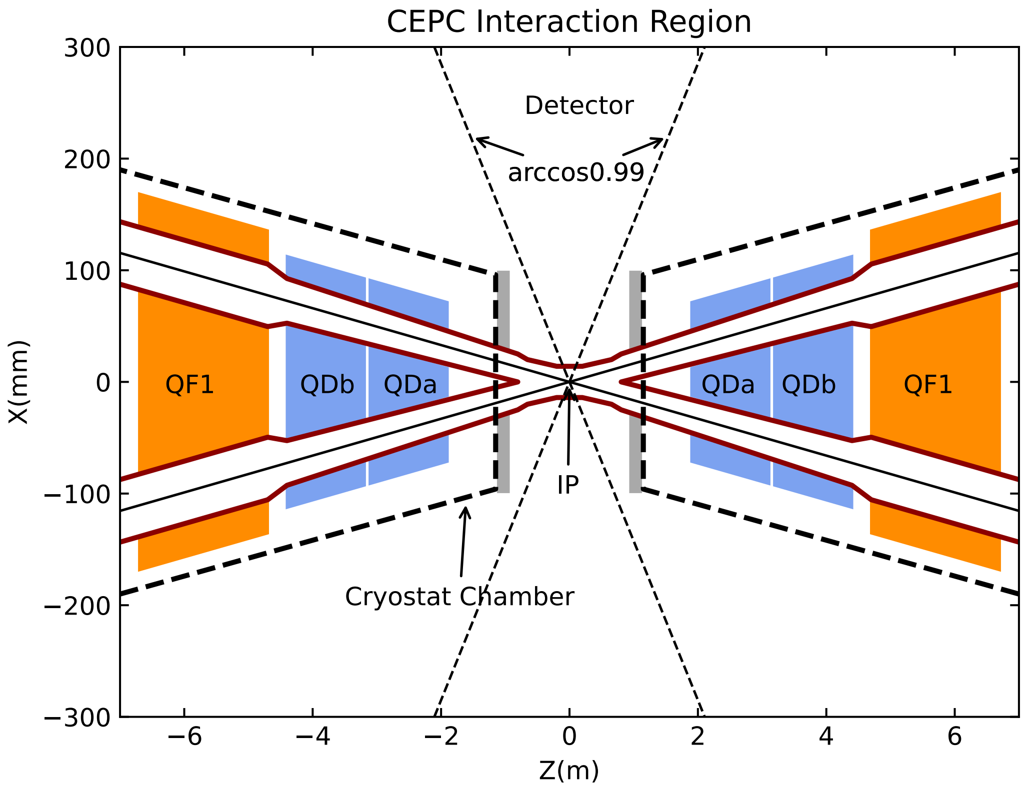
Updated IR

Beam pipe and the interfaces between LumiCal/BPM

SC Magnet Support System/Cryostat Module

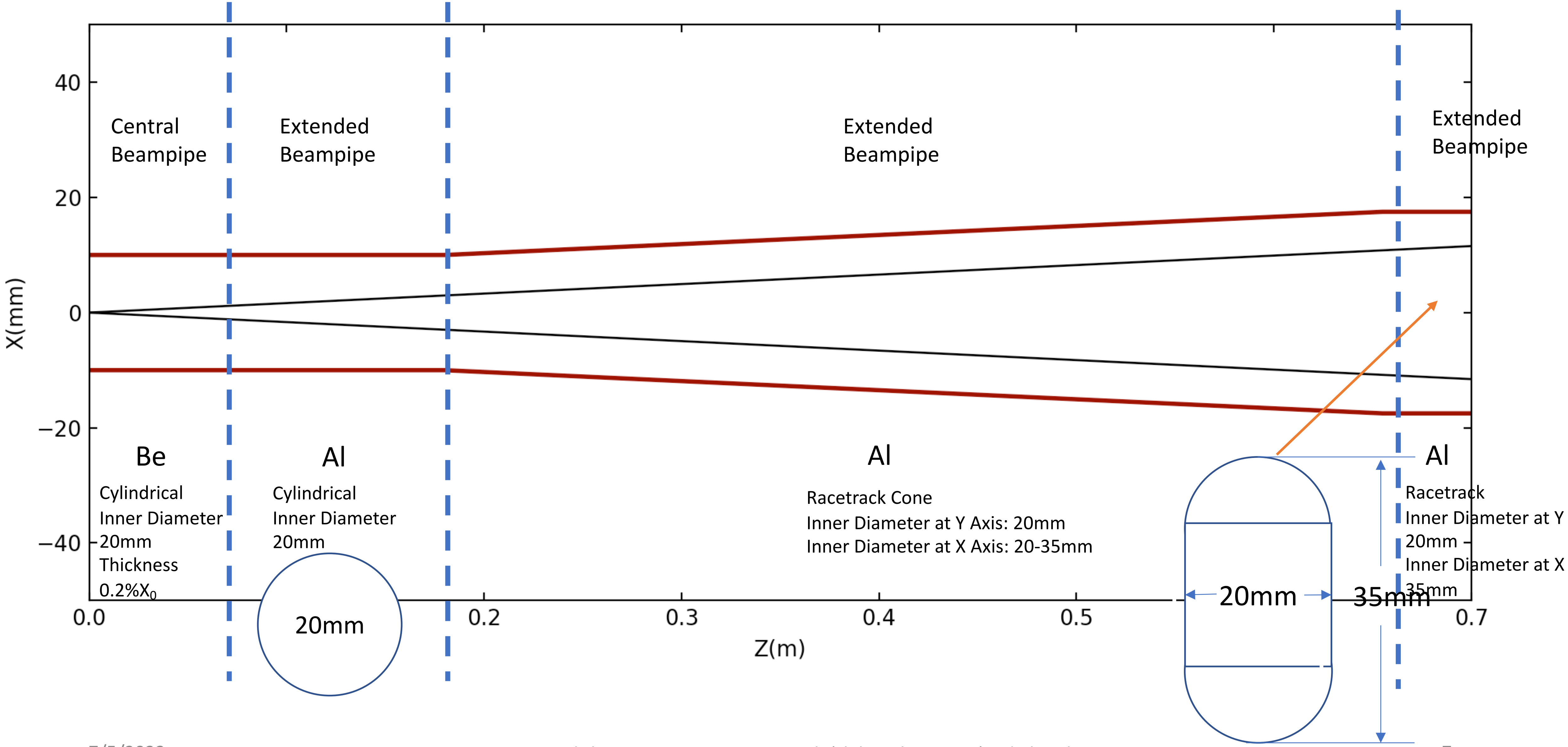
Updated IR

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



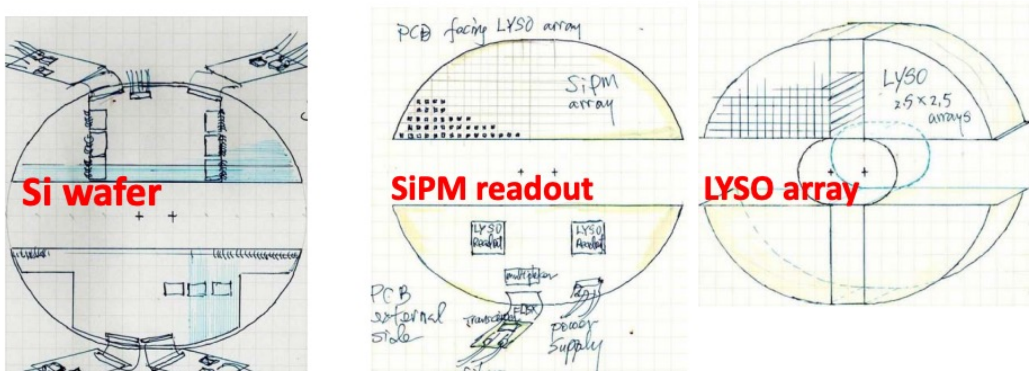
The length of Interaction Region is -7m~7m at TDR Phase

New Beampipe Design – Half Detector pipe



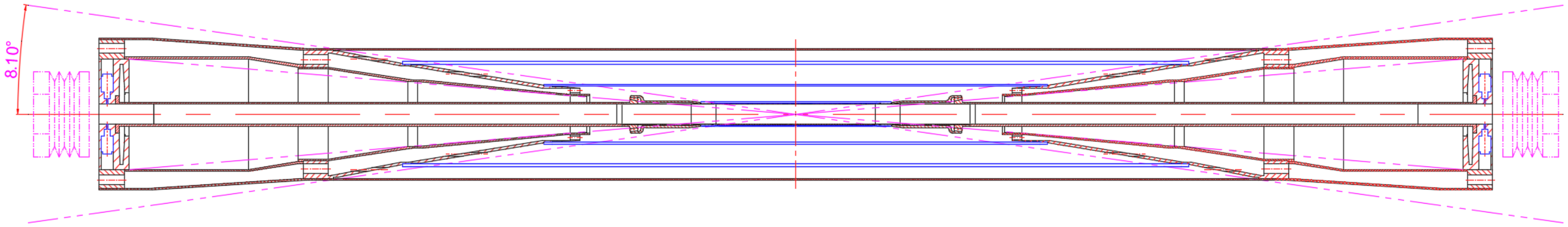
With LumiCal:

- LumiCal consists of several parts, due to the space constrains.
- The material and thickness of the LumiCal would be implemented to the MDI simulation to estimate the impact of the LumiCal



S. Hou

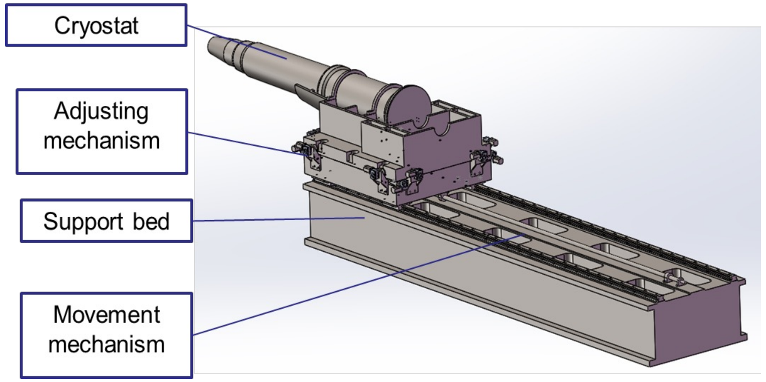
Q. Ji



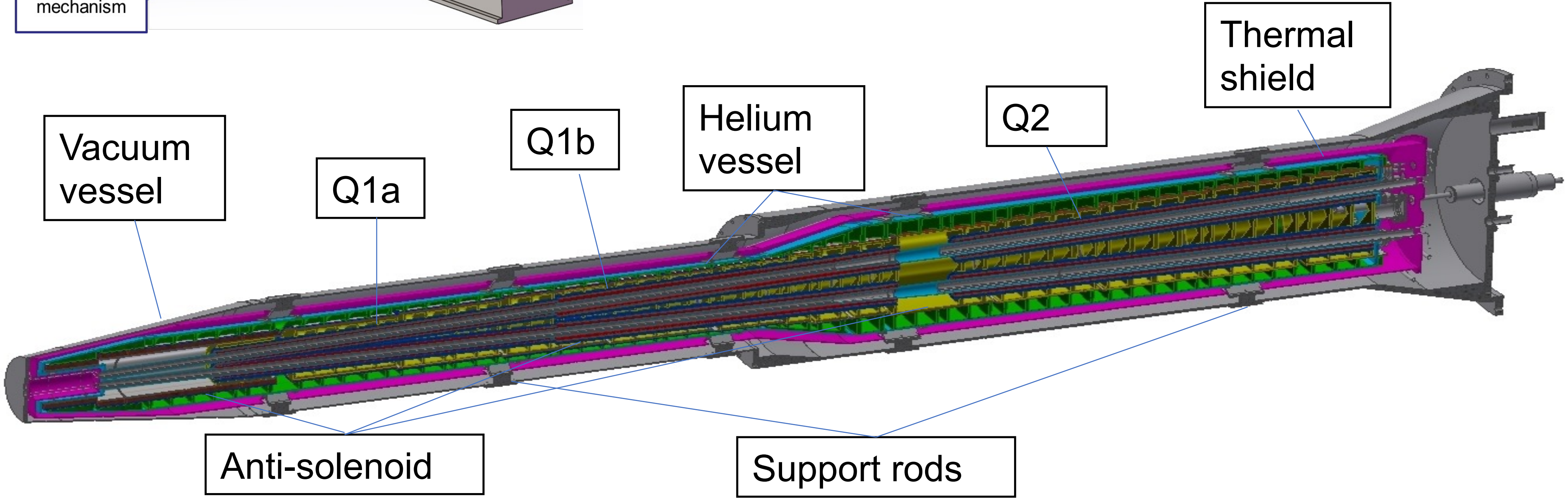
SC Magnet Support System

H. Wang
M. Xu

- After the optimization of the supports in the cryostat, the total weight of the cryostat and the devices inside is 2790 Kg



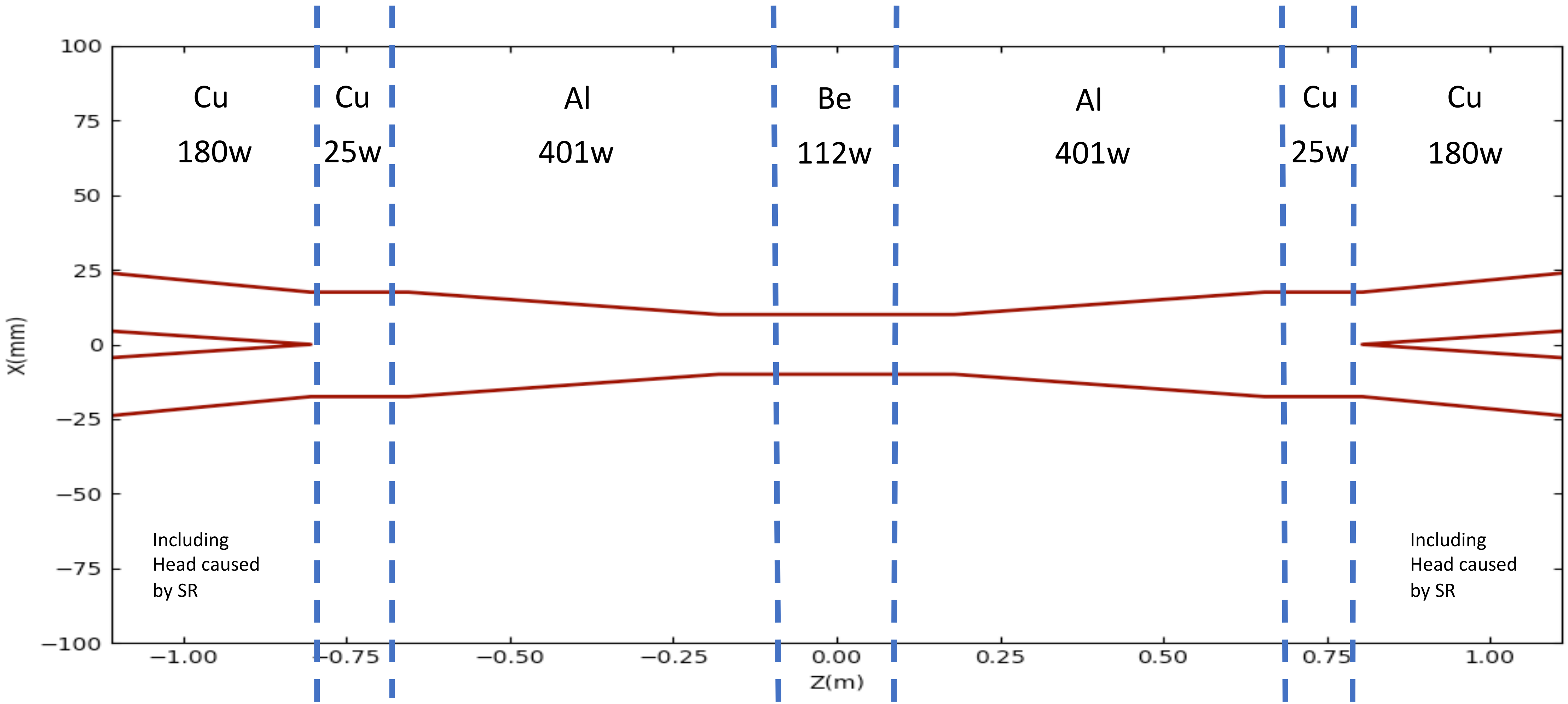
- The cryostat is about 5.6m long. The cantilever length is 5283mm.
- The resolution requirement of the adjusting mechanism < 5 μm.



Safety Check

- Heat Deposition and Analysis
- Beam Backgrounds (Radiation Impacts Estimation)

Heat Deposition

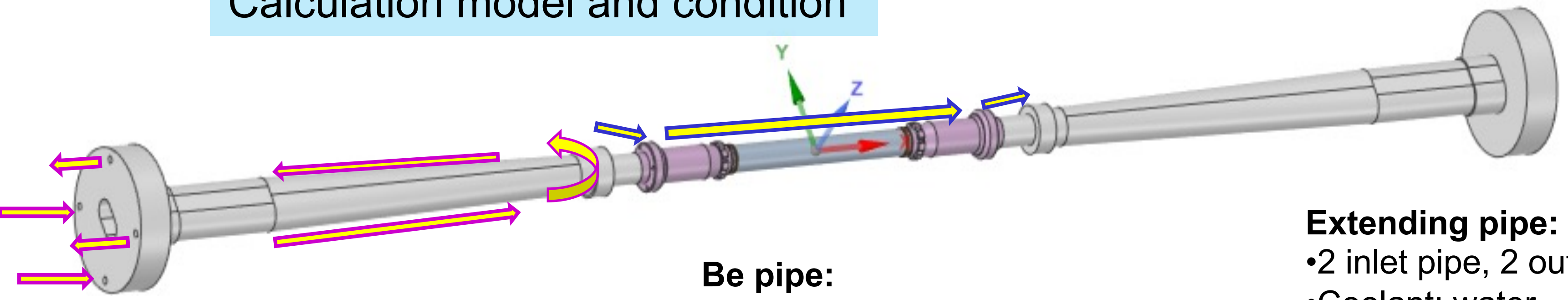


We are considering to change the material beyond bellows to Al due to demands of LumiCal, it wouldn't affect heat deposition to much

Thermal Analysis of the central beam pipe

Calculation model and condition

Q. Ji
Y. Lu



Extending pipe:
- 2 inlet pipe, 2 outlet pipe
- Coolant: water
- Inlet temperature: 20℃
- Inlet velocity: 0.5m/s （1.7L/min）

Be pipe:
- 4 inlet pipe, 4 outlet pipe
- Coolant: water
- Inlet temperature: 20℃
- Inlet velocity: 0.5m/s （0.8L/min）

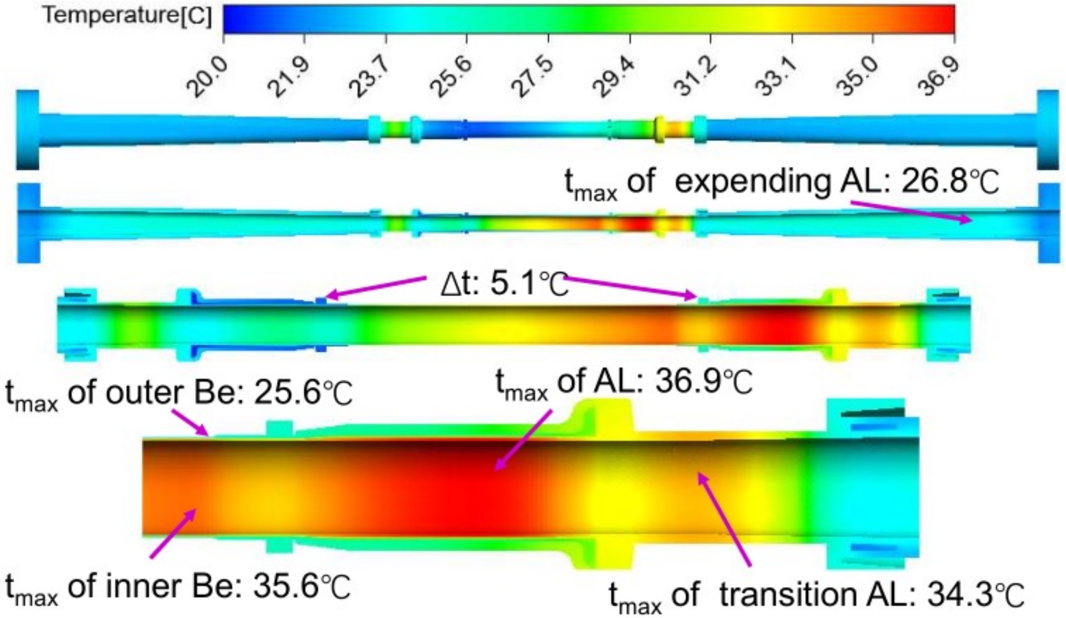
Extending pipe:
- 2 inlet pipe, 2 outlet pipe
- Coolant: water
- Inlet temperature: 20℃
- Inlet velocity: 0.5m/s （1.7L/min）

Heat source distribution

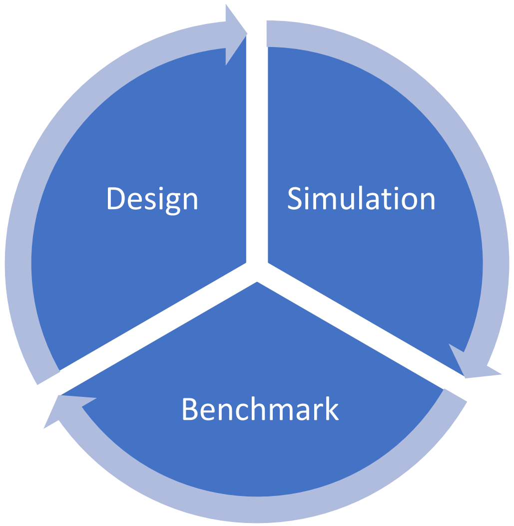
Position	Z(w) & (w/cm2)
Be pipe (w)	55.295 & 1.35
Be pipe transition(w)	29.280 & 0.491
Transition pipe (w)	341.562 & 0.83
Transition (w)	29.28 & 0.701

Calculation results:

- ✓ Temperature difference ~5.1⁰C between two sides of the first layer detector
- ✓ Temperature low, temperature difference small, meet the requirement

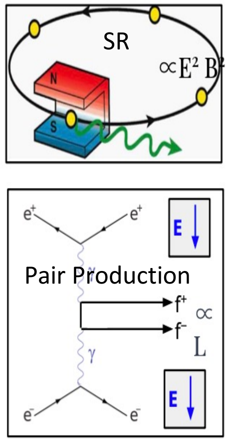


Background Estimation

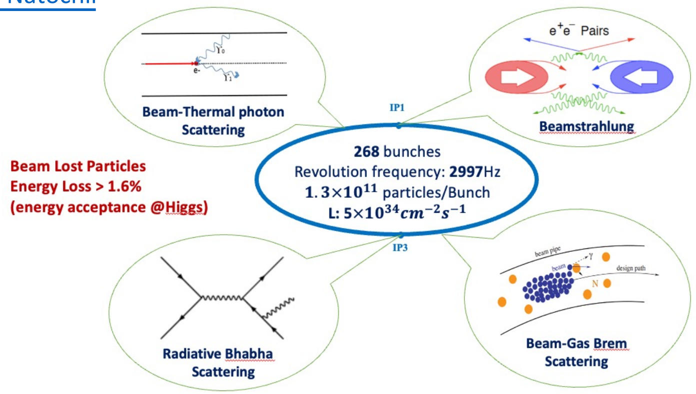


- One Beam
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(50 turns)
  - Using built-in LOSSMAP
  - SR emitting/RF on
  - Radtaper on
  - No detector solenoid yet

A. Natochii

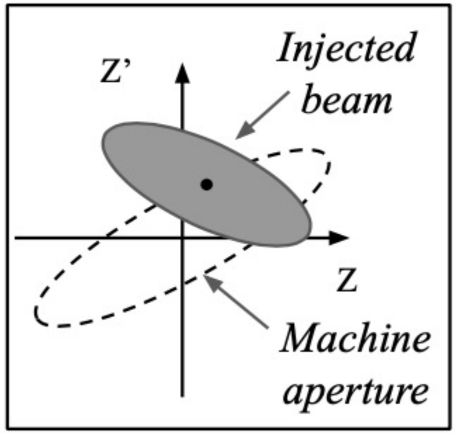


Photon BG



Beam Loss BG

A. Natochii



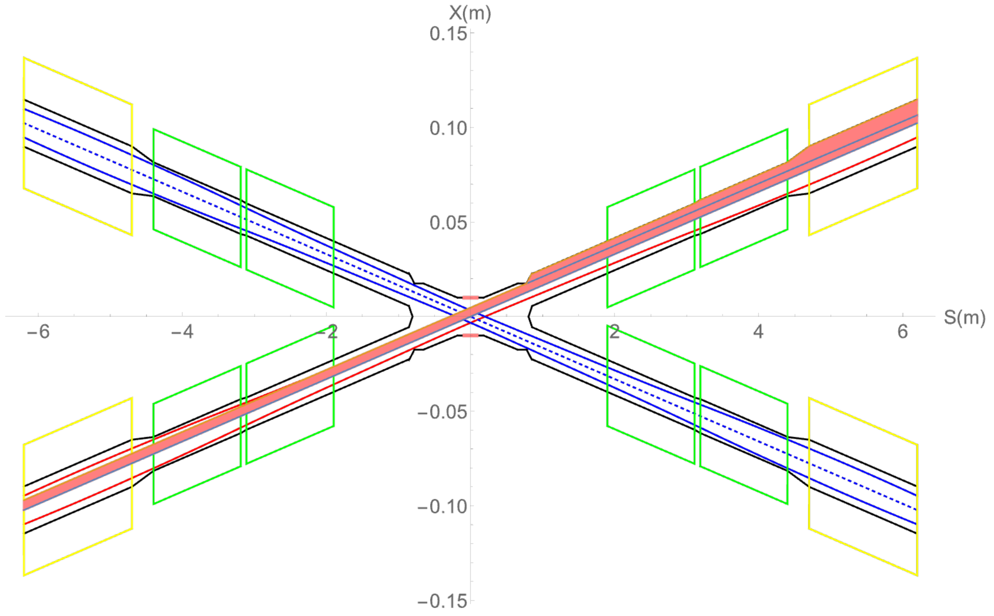
Injection BG

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		

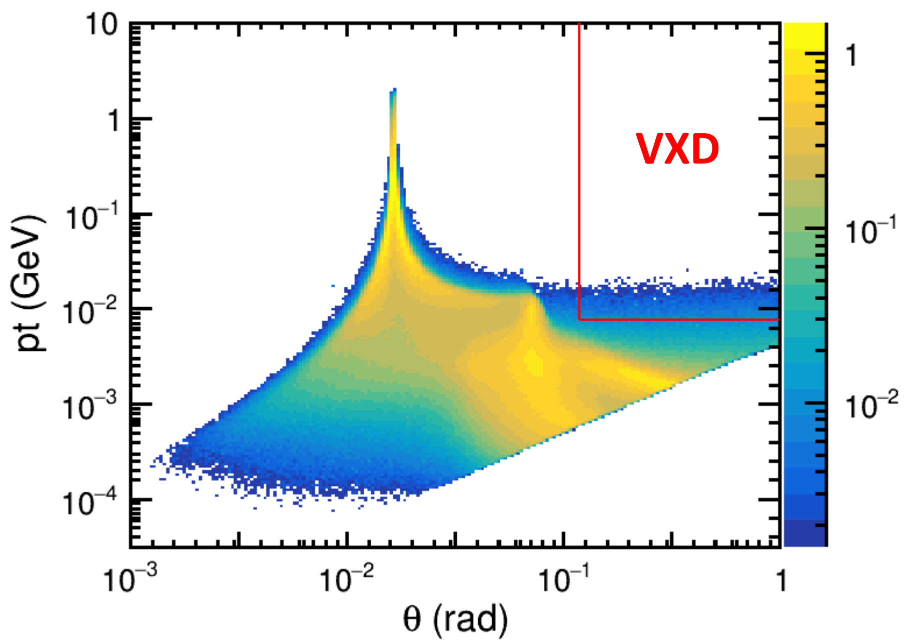
Photon Backgrounds

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

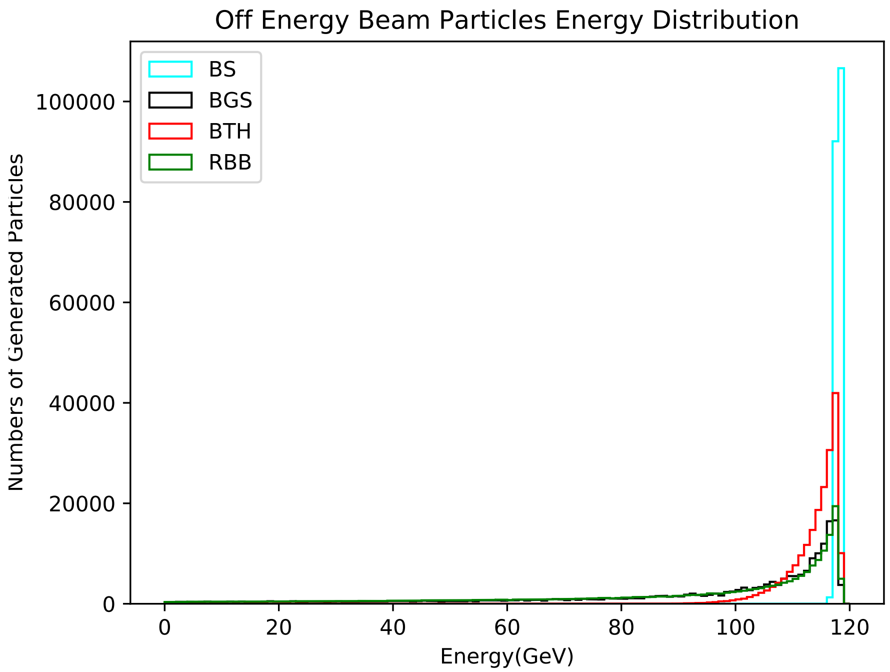


W. Xu



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

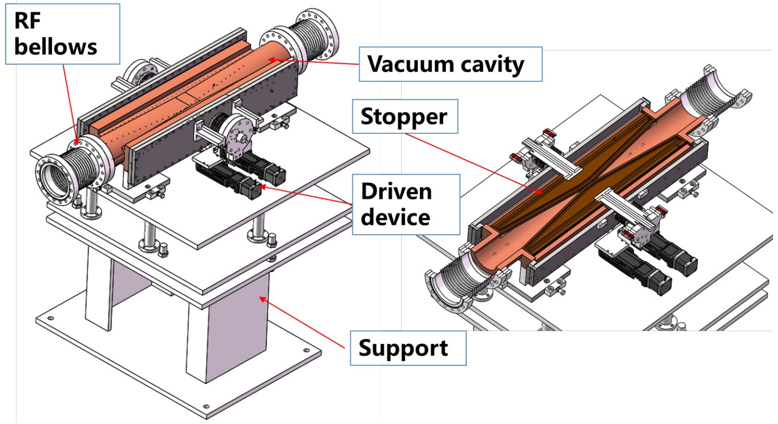
Background	Lifetime	Notes
Beam-Thermal Photon	50.66h	
Beam-Gas Bremsstrahlung	248.90h	Mainly H_2, 1 nTorr
Beam-Gas Coulomb	27.99h	
Radiative Bhabha	40min	

Beam Lifetime @ Higgs

Mitigation of the BG - Collimator

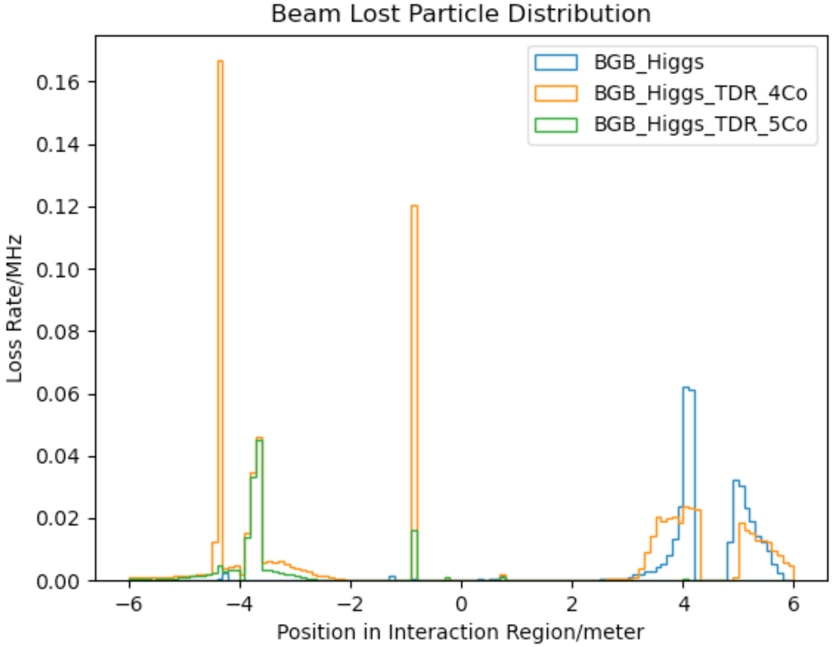
H. Wang, P. Zhang

- 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.



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

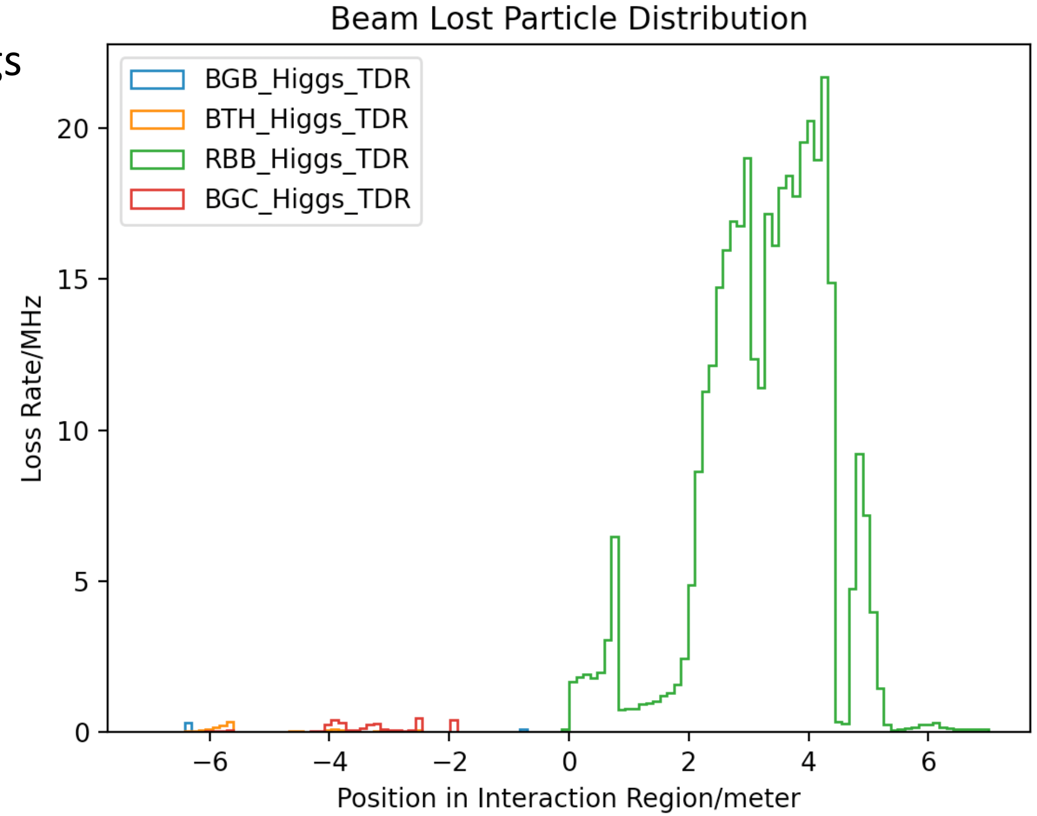


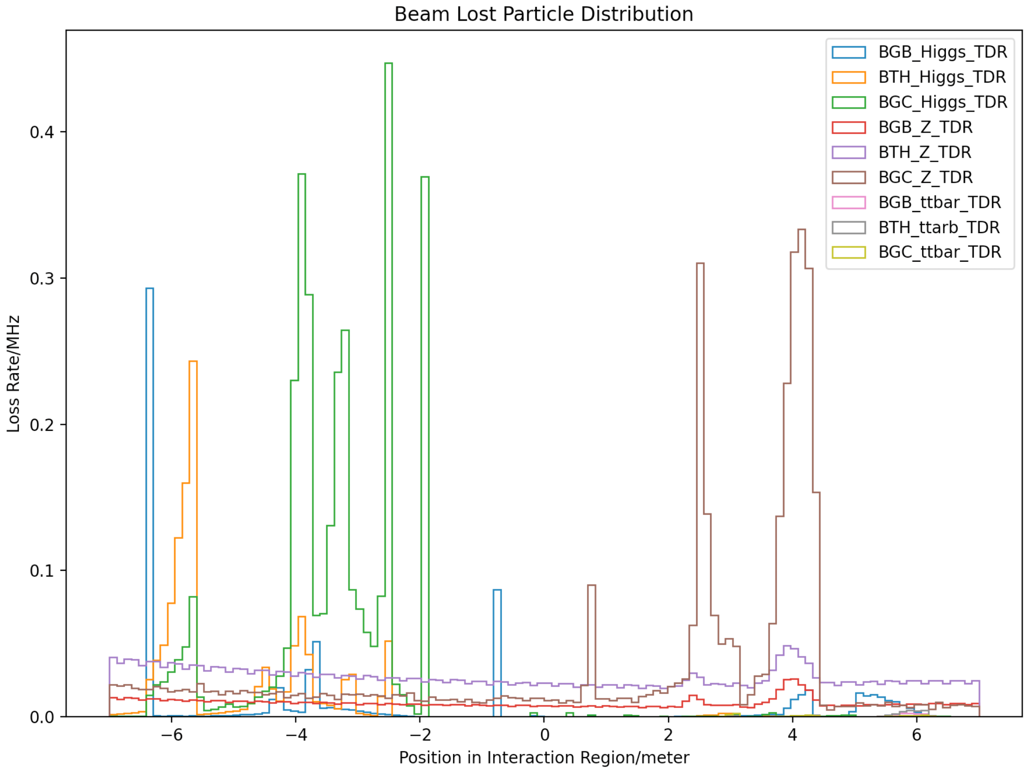
Loss Distribution

- 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

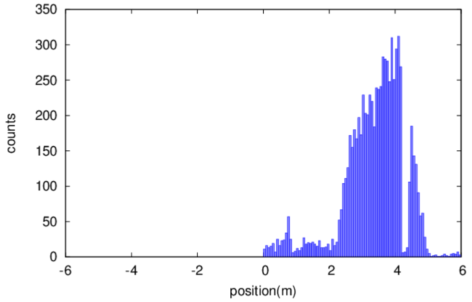
	Hit Density($cm^{-2} \cdot BX^{-1}$)	TID($krad \cdot yr^{-1}$)	NIEL($n_{eq} \times 10^{12} \cdot cm^{-2} \cdot yr^{-1}$)
Vertex	2.3	5360	120.4
TPC	2.59e-2	387.09	42.503
Ecal Barrel	1.16e-3	31.56	8.002
Ecal EndCup	1.36e-3	14.175	6.128
Hcal Barrel	2.78e-5	1.450	0.9326
Hcal EndCup	1.32e-3	26.31	6.351

Injection Backgrounds

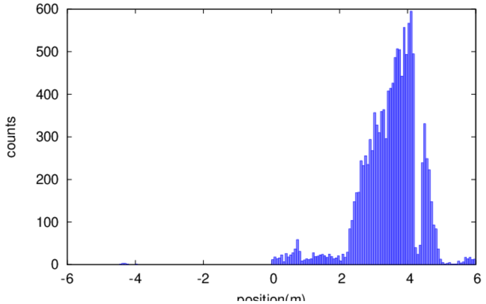
S. Bai

- 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

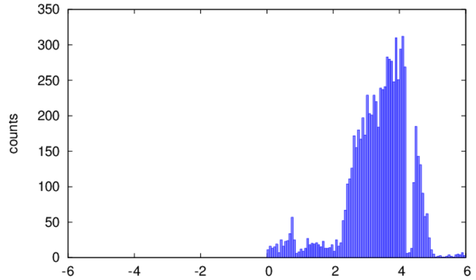
Circular beam



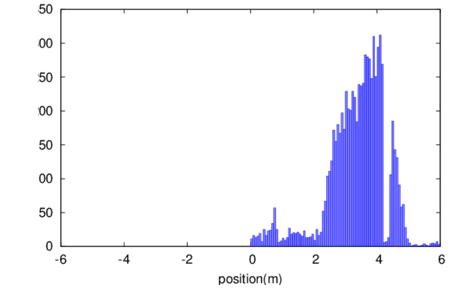
Injection beam



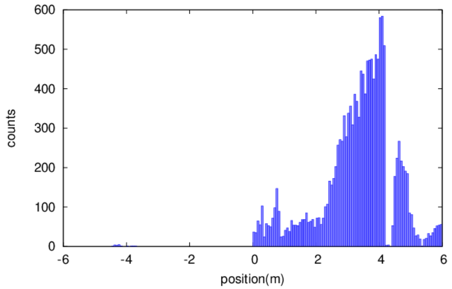
Gaussian beam with 3sigma



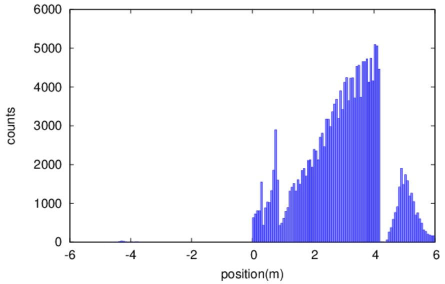
Gaussian beam with 40sigma



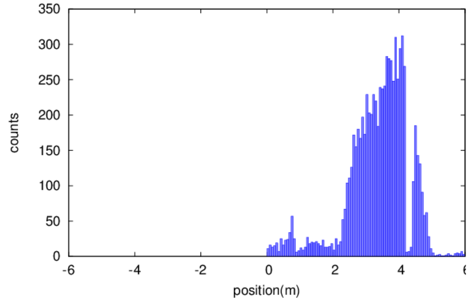
Large emittance ~10times



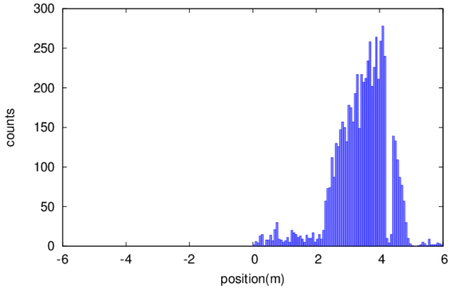
Large emittance ~1000times



Double gaussian beam



Uniform beam



Benchmark – Experiments

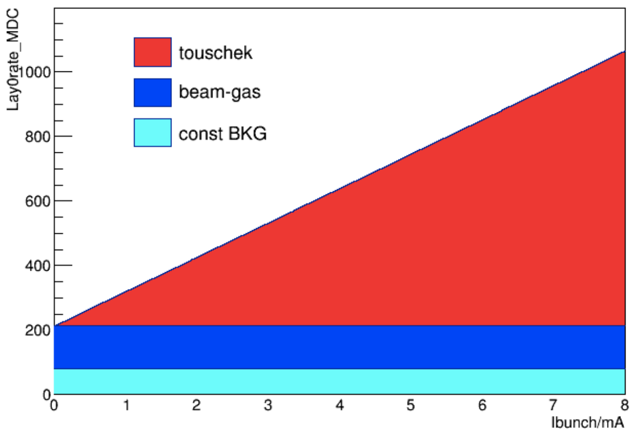
- Important to validate the modellings and Monte Carlo Simulation codes for the CEPC beam background simulation with real data where they are applicable.
  - BEPC II/BES III, SuperKEKB/Belle II, LEP I/II…
- Basic Principles – Key Parameters & Distinguish
  - Single beam mode: three dominant contributions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

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

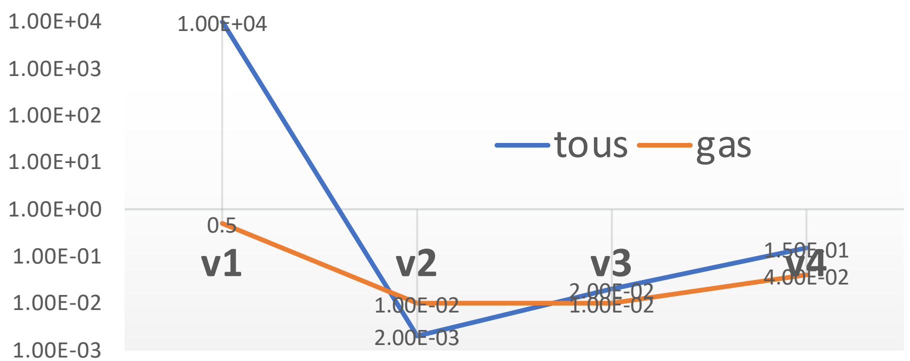
  - Double beam mode: additional contributions from luminosity related backgrounds, mainly radiative Bhabha scattering
  - $O_{total} = O_{e^+} + O_{e^-} + O_{\mathcal{L}}$(Ideal)

Benchmark – Experiments

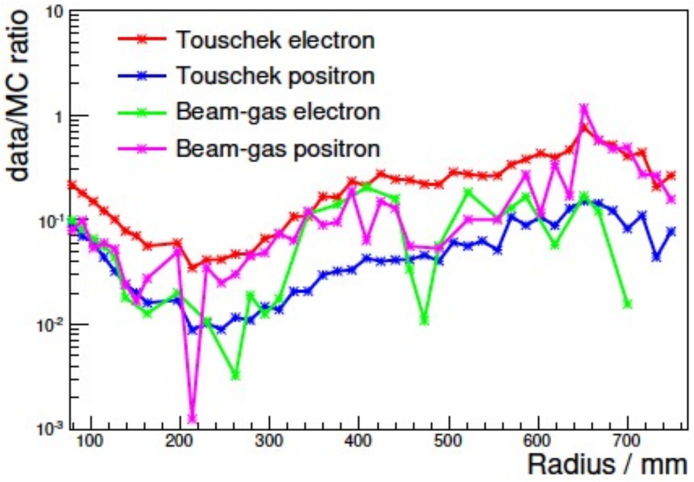
- BG experiments on BEPCII/BESIII has been done 3 times.
  - The experiment in 2021 separate the single beam BG sources, the data/MC ratio has been reduced.



BG separation on 1st layer MDC



Data/MC radio improvements on 1st layer MDC



Data/MC radio in MDC

  - The experiment in 2022/2023 was focused on collimators, we found the collimators work well. Working on data analysis.

Summary & Outlook

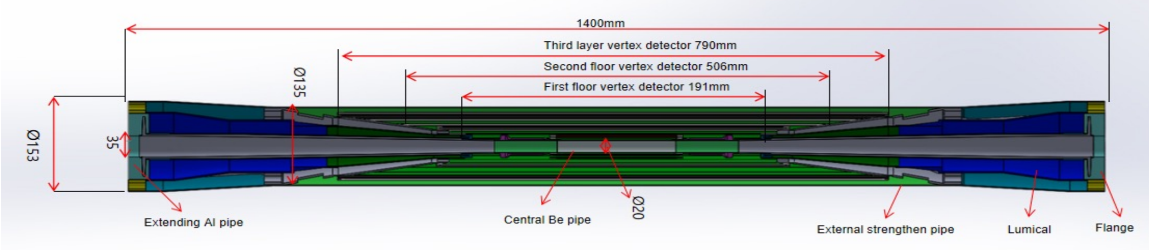
- We are moving our study to TDR phase.
  - Layout & Physics design has been updated.
  - The collimators should work well. The real simulation with tip scattering is updating.
    - Since our collimator team colleagues are updating the collimators settings, we will wait for them.
  - More detailed study is on going, and the full detector simulation on TDR is about to start.
- We will continue developing our own toolkits of beam backgrounds simulation.
  - The interface between different tools & our own tools like generator
  - Tools for visualization and automation
- 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/SuperKEKB.
- The EDR phase of accelerator is about to start.
  - The feasibility of tungsten pipes will be studied..
  - The installation scheme of the whole MDI will be studied.

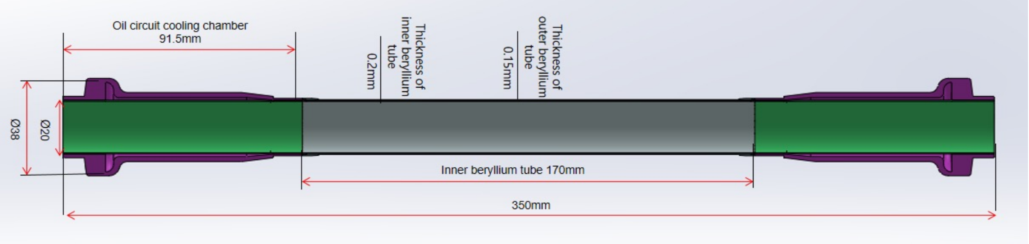
Thank You

Backup

Mechanical Design of the IR Beam pipe

- The center of the beam pipe adopts a double-layer beryllium pipe structure, with an overall length of 350mm.
- The thickness of the inner beryllium pipe is 0.2mm, and the outer beryllium pipe is 0.15mm.
- A 0.5mm cooling gap between the double layer beryllium tubes, which is filled with coolant.
- The coolant enters through the left amplification chamber, passes through the gap between the double layer beryllium pipes, and finally is discharged through the right amplification chamber, taking away the HOM heat from the inner wall through cooling.

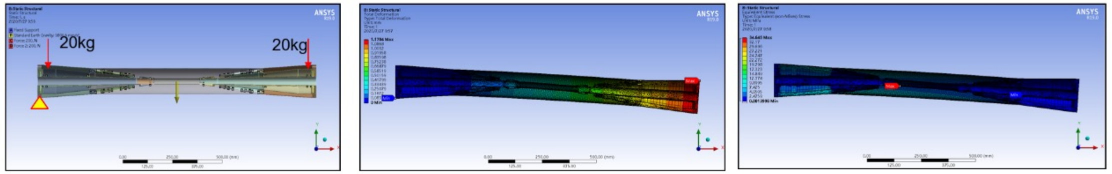




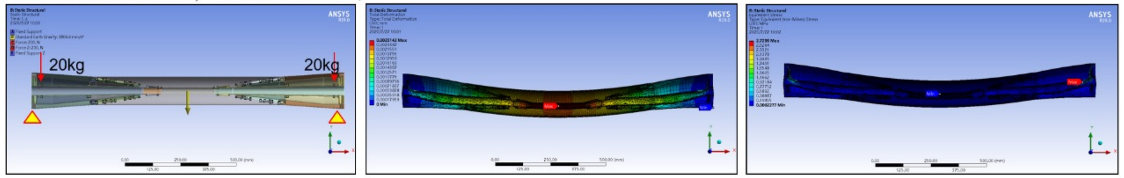
when both ends of the beam pipe are supported, the maximum sink at the center during the simulated installation is 0.0025 mm, and the maximum stress is 2.7 MPa, which meets the requirements and ensures the overall structural safety.

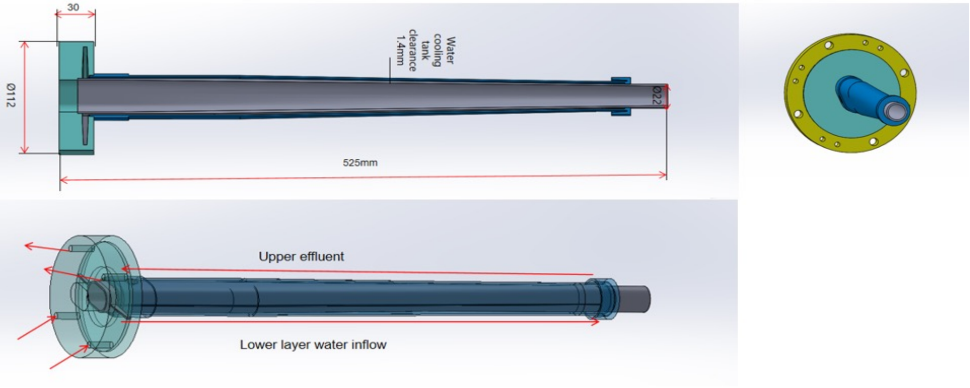
(1) Cantilever installation, One end support, one end cantilever, lumical at each end, 20kg each, results: max deformation 1.2mm, max stress34.6MPa;

In this version, lumical is a thin carbon fiber structure. In order to compare with the previous analysis, 20kg load is still added at the end



(2) Installation in place, support on both ends, lumical on each end, 20kg each, results: max deformation 0.0025mm, max stress 2.7MPa;





Epitaxial aluminum tube structure

Pair Production

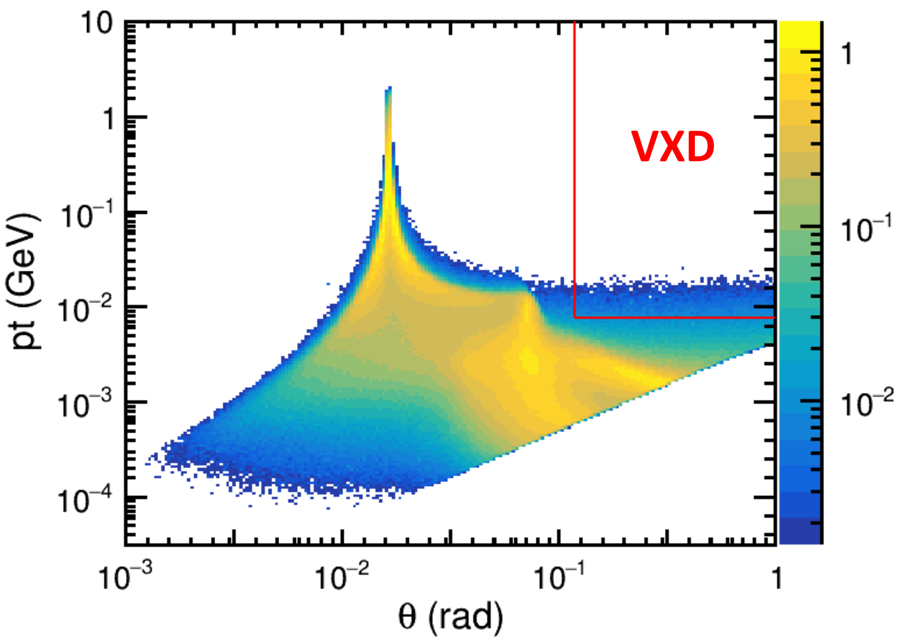
- Pair Production(Beamstrahlung) is one of the dominant background process at the CEPC.

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			

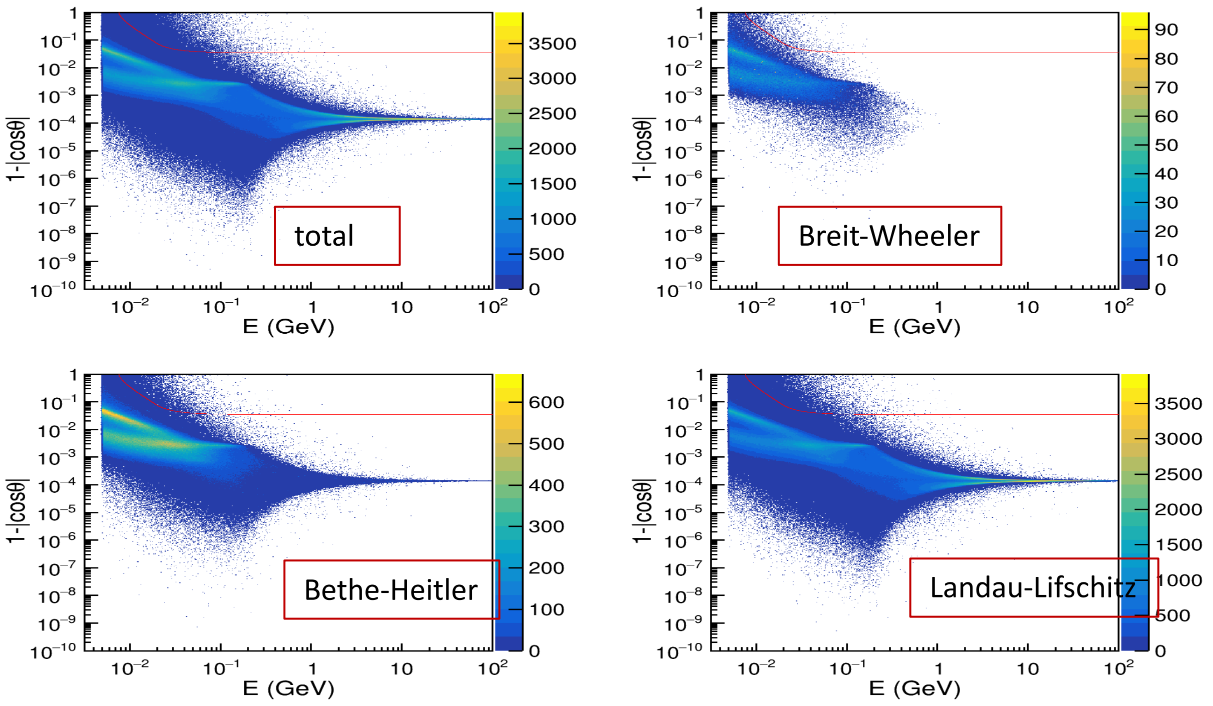
Pair Production

- 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



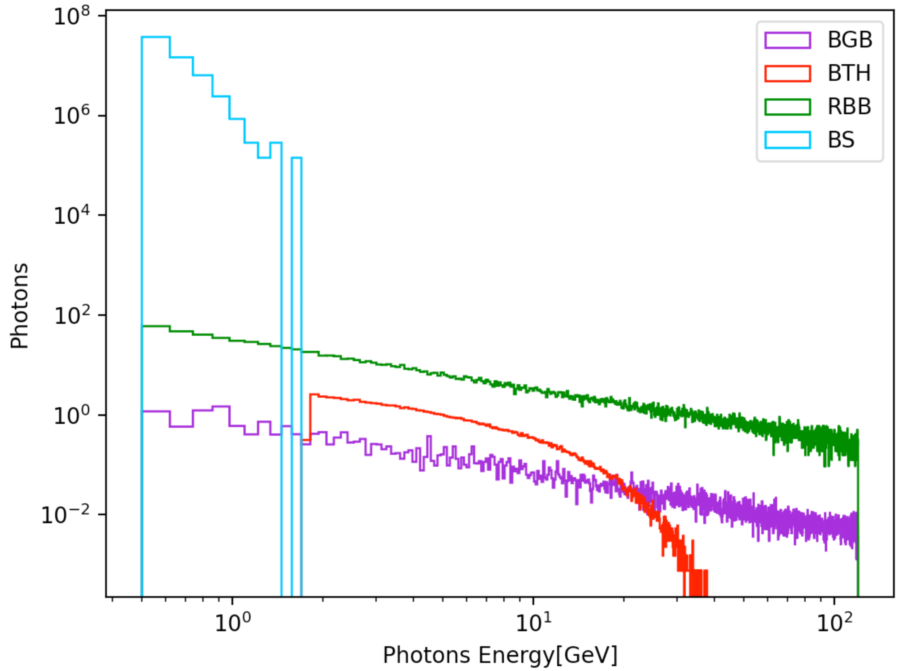
W. Xu

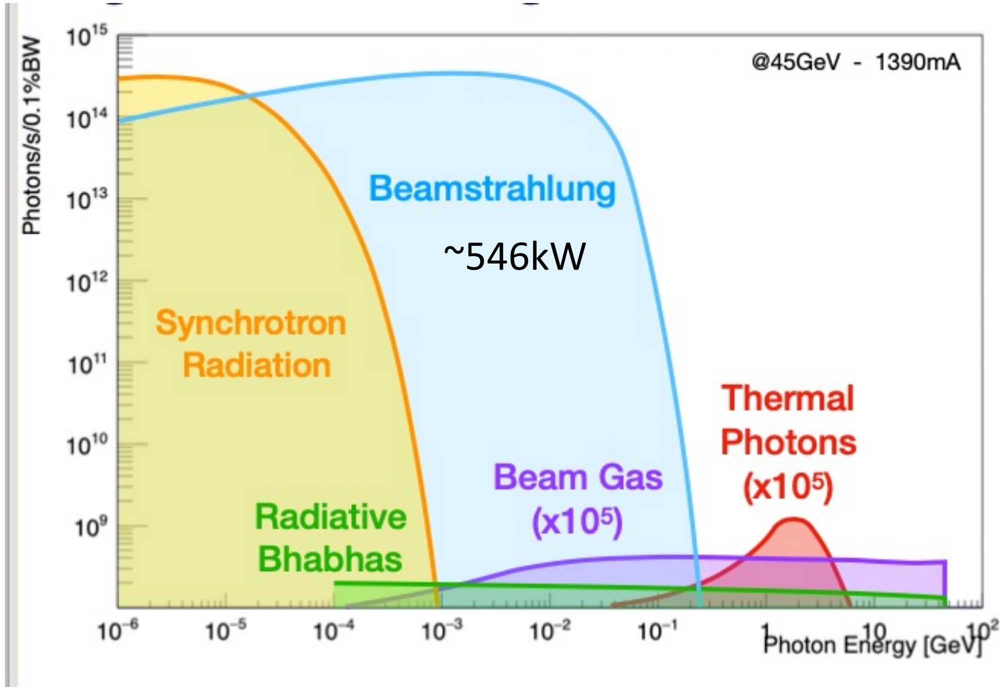


Photon Absorber?

- 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 structure of the first bending magnet downstream of IP will be modified to adopt the new design.

CEPC@Higgs





FCC@Z

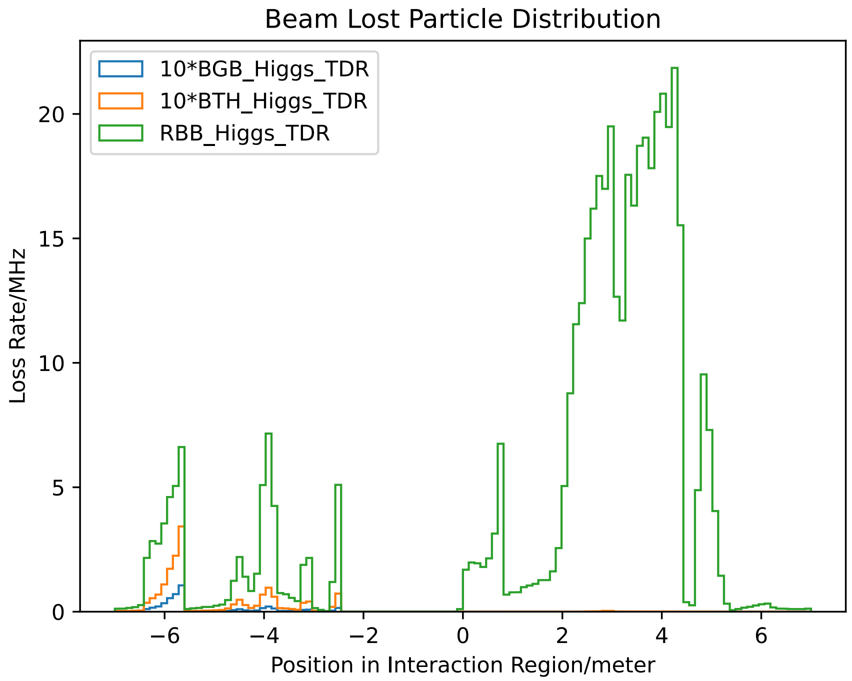
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	**100.0**			
SR power per beam (MW)	**30**			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
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
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
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
Betatron tune ν_x/ν_y	445/445	317/317	317/317	445/445
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	**1.0**/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
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	39/40	82/2800	60/700	81/23
Beam lifetime (min)	20	80	55	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**5.0**	**115**	**16**	**0.5**

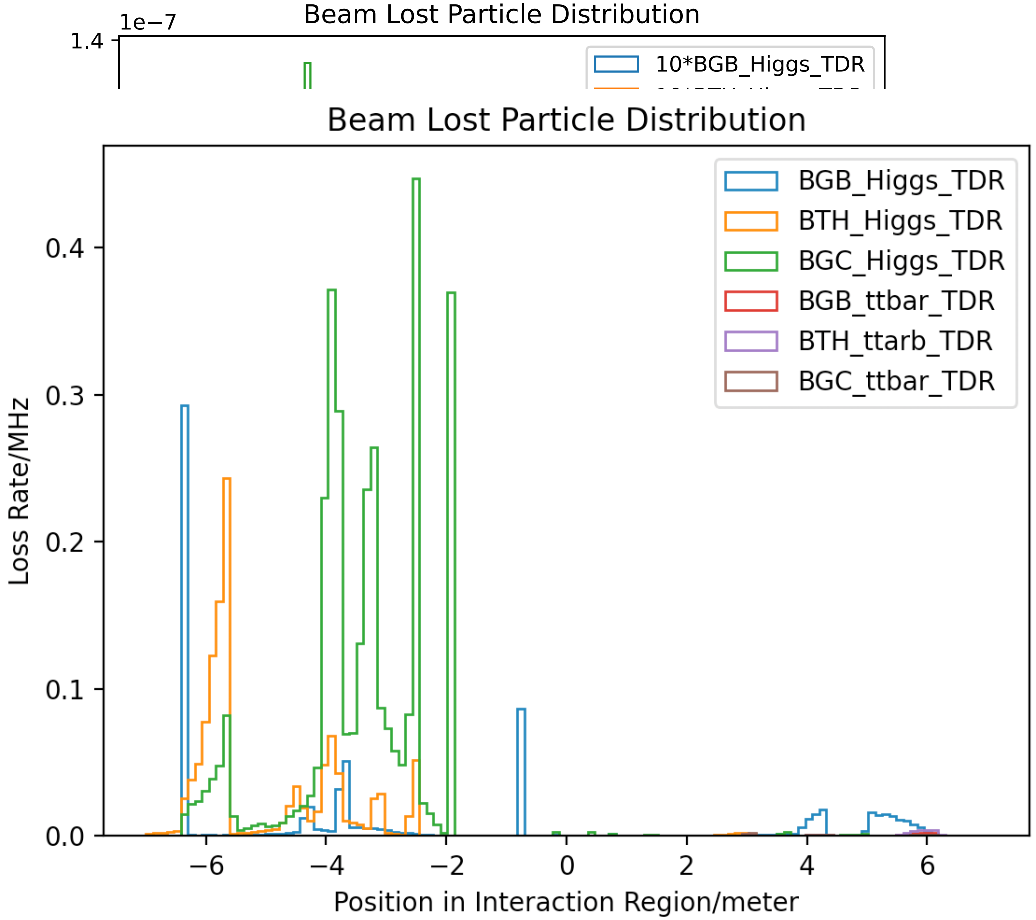
TDR Design

67%⇧ 259%⇧

Beam Loss Particles

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

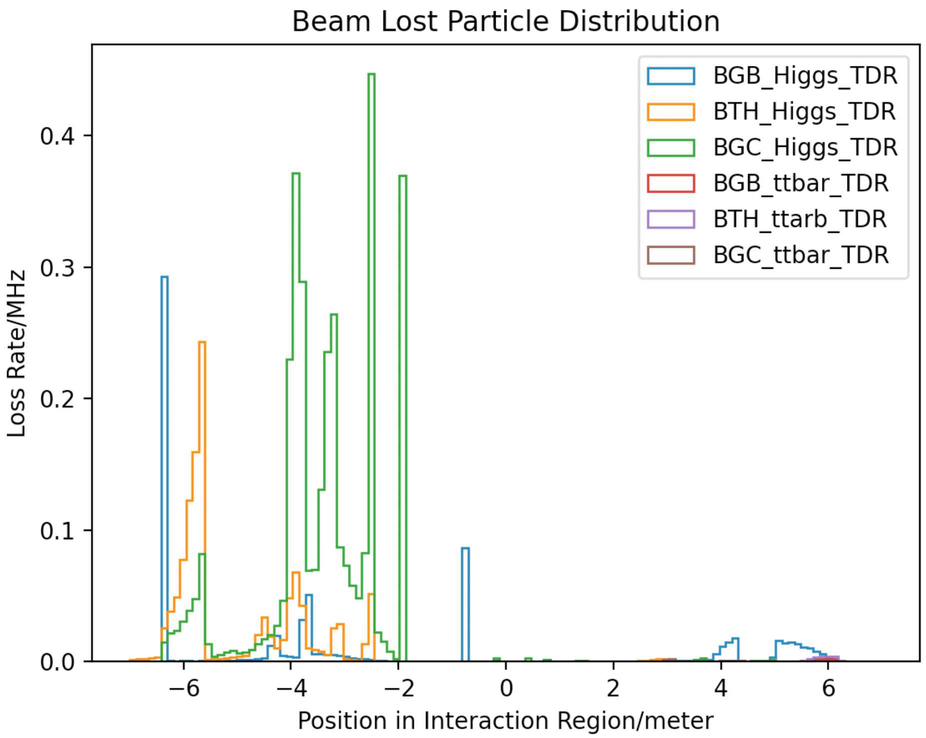




- Upstream Loss Rate is higher than downstream, lo
  - Quads would be one of the hot-spot, shielding might be

Beam Loss Particles

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



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

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.

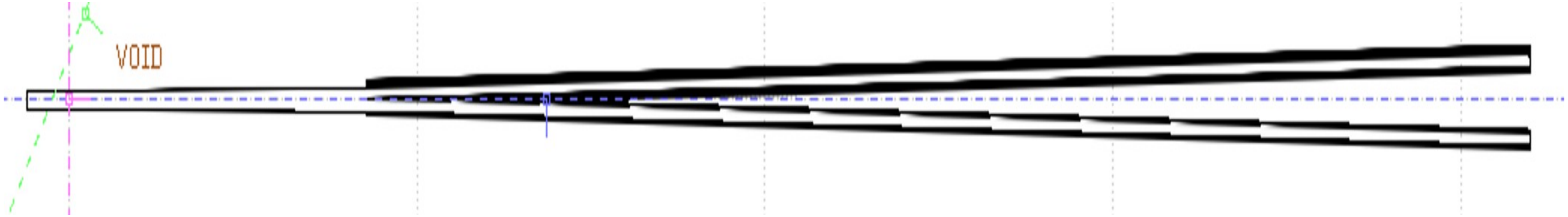
Background	Hit Density($cm^{-2} \cdot BX^{-1}$)			TID($Mrad \cdot yr^{-1}$)			1 MeV equivalent neutron fluence ($n_{eq} \times 10^{12} \cdot cm^{-2} \cdot yr^{-1}$)		
	Higgs	W	Z	Higgs	W	Z	Higgs	W	Z
Pair production	1.8	1.2	0.4	0.50	2.1	5.6	1.0	3.8	10.6
Beam Gas	0.4	0.4	0.2	0.36	1.3	4.1	1.0	3.6	11.1
Total	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

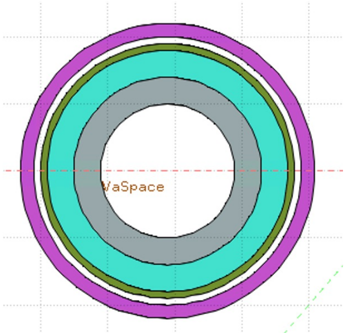
- Take Mask into Account(Higgs):

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

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.

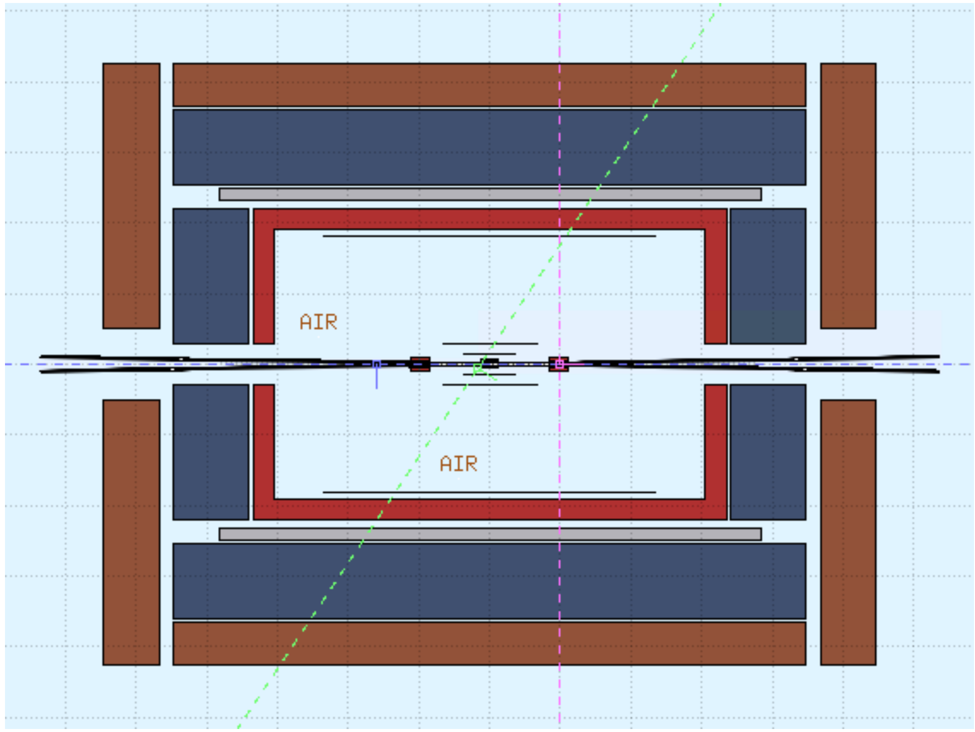




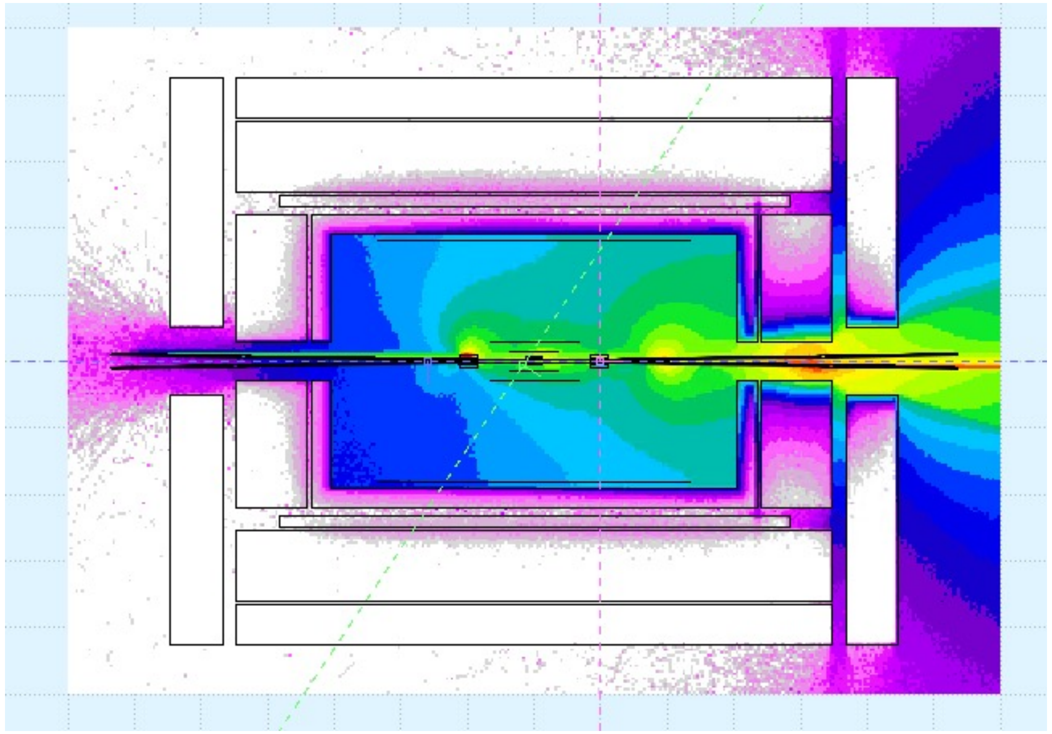
White: Vacuum
Gray: Tungsten Pipe
Light Green: Helium
Heavy Green: Stainless Steel Vessel
Pink: Coil

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)