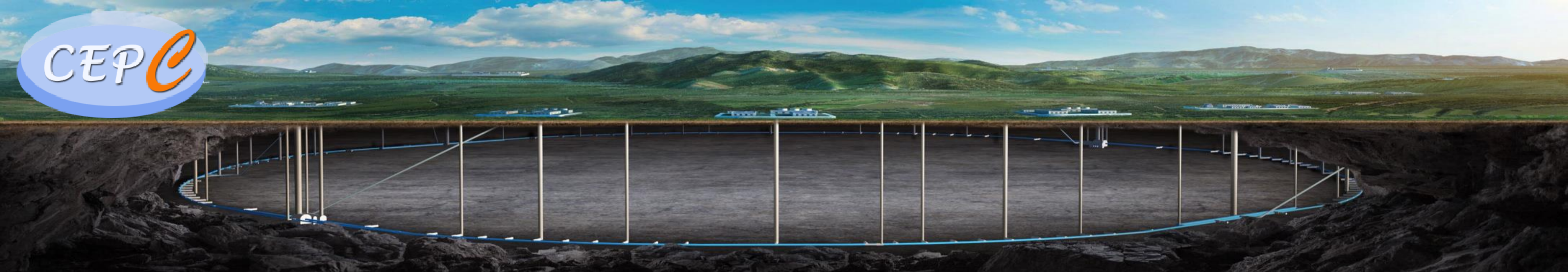

CEPC MDI and Beam Measurement

Haoyu SHI
(On behalf of the CEPC MDI Working Group)

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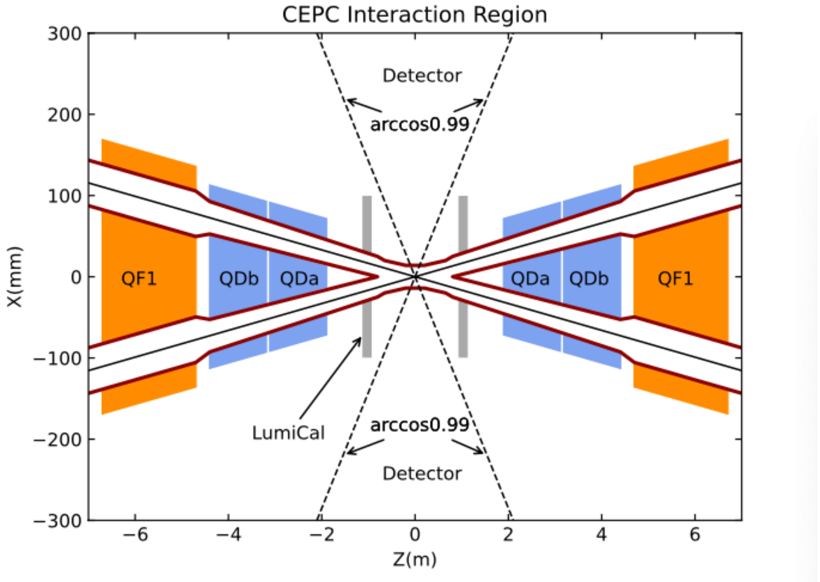
Institute of High Energy Physics
Chinese Academy of Sciences

Content

- Introduction
- Requirements
- Technology survey and our choices
- Technical challenges
- Detailed design including electronics, cooling and mechanics
- Beam Induced Background Estimation
- Research team and working plan
- Summary

Introduction

- This talk relates to the Ref-TDR Chapter 3: MDI and Beam Measurement.
- There will be several topics in this chapter and talk, mainly including
  – The Layout of the IR Region
  – Key components like central beam pipe
  – Beam induced background estimation
  – LumiCal



Requirement

- Tight Space of MDI components(cone angle of ~ 300mrad including the acc. components)
- Low material budget and stable beampipe
  - Low material budget(<0.15%X_0)
  - Temperature and stress acceptable
- High precision measurement of the luminosity
  - 10^{-4} precision @ Z-pole
- Reasonable Estimation of Beam induced background level
  - Understanding of Beam induced Backgrounds
  - Mitigation methods
  - Based on the 50-MW design of CEPC Accelerator TDR

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	50			
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	29.52	5.98	1.23
Bunch number	446	13104	2162	58
Bunch spacing (ns)	355 (53% gap)	23 (10% gap)	154	2714 (53% gap)
Bunch population (10^{11})	1.3	2.14	1.35	2.0
Beam current (mA)	27.8	1340.9	140.2	5.5
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	2.7/10.6	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.15	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.0/1.5	1.05/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.0045/0.13	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.1	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.032	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	40/40	90/930	60/195	81/23
Beam lifetime requirement (min)	20	81	25	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	8.3	192	26.7	0.8

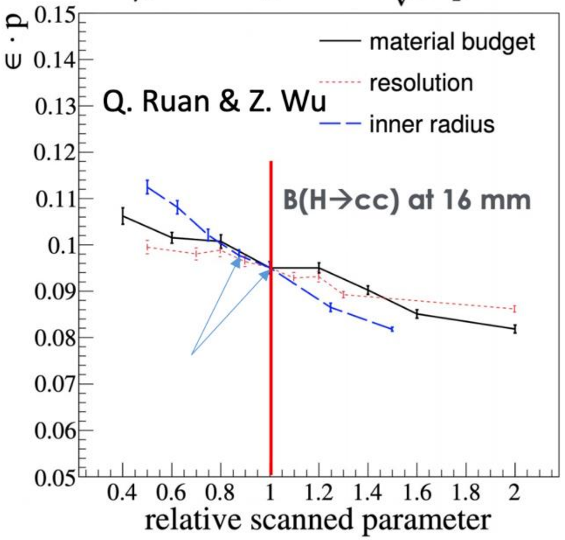
Technology survey and our choices

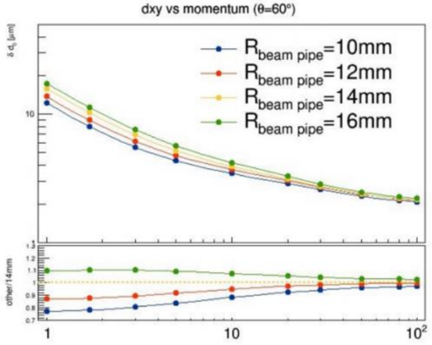
- Beam pipe
  - Be as material
  - 2-layer, ultra-thin design
  - Shrinking of the inner diameter from 28mm in CDR to 20mm in TDR to have a better performance of the detectors, ~15% increase comparing to 28mm in CDR

- First estimates made with fast simulation and scaling

$$\frac{\delta_\mu}{\mu} \propto \frac{\sqrt{S+B}}{S} \propto \frac{1}{\sqrt{\epsilon \cdot p}}$$

$$\sigma_{d_0}^2 = \sigma_{geom}^2 + \sigma_{MS}^2 = \left(\frac{\sigma_1 r_2}{r_2-r_1}\right)^2 + \left(\frac{\sigma_2 r_1}{r_2-r_1}\right)^2 + \sum_{j=1}^{n_{scatt}} (R_j \Delta\Theta_j)^2$$





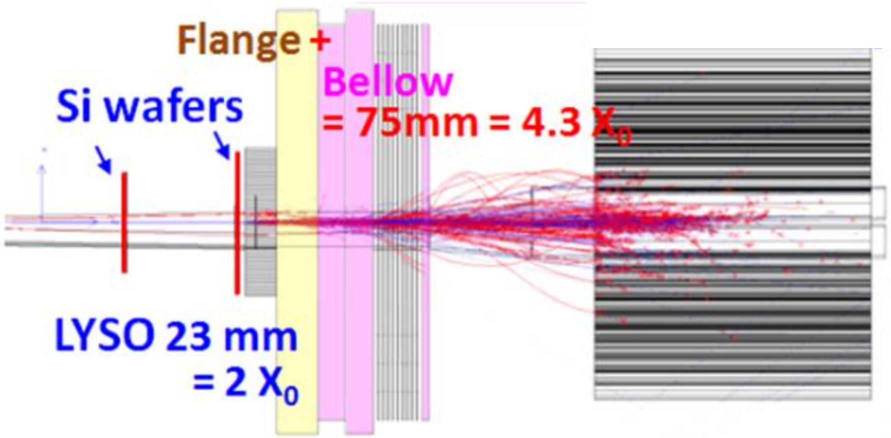
H. Zeng

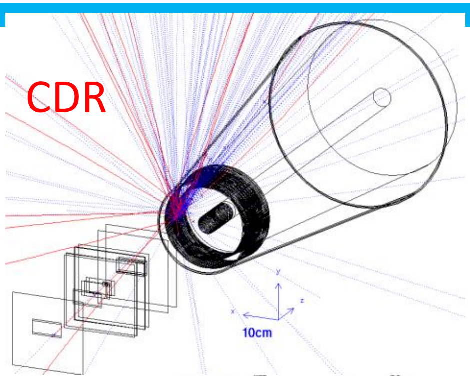
- Implement the geometry in simulation and run a full analysis to estimate the physics gains

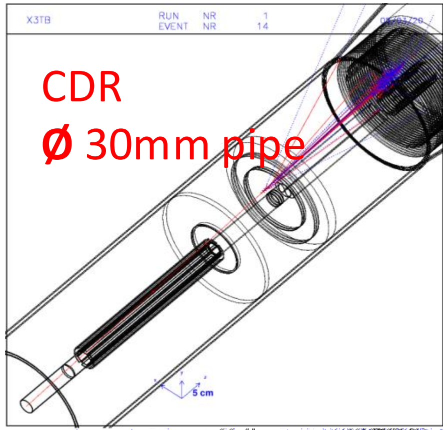
G. Li

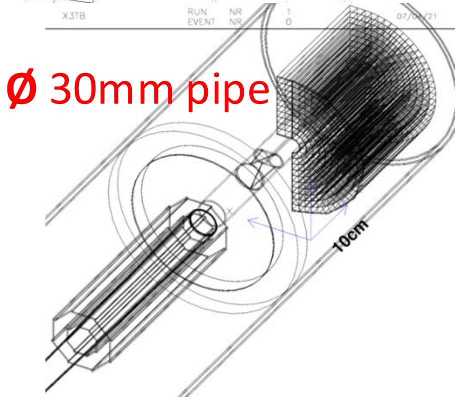
Technology survey and our choices

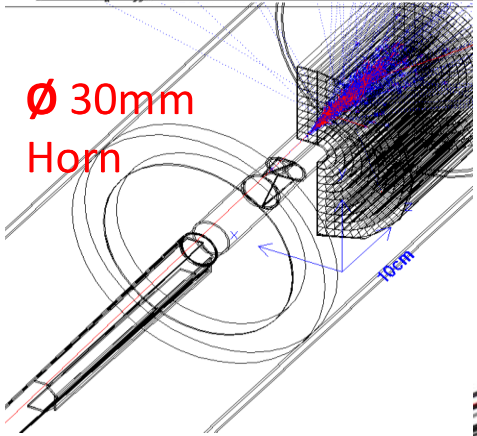
- Luminosity Calorimeter
  - Updated together with the revolution of beam pipe/MDI
  - Si wafer + Crystal
  - Be window
  - Moon Cake like design

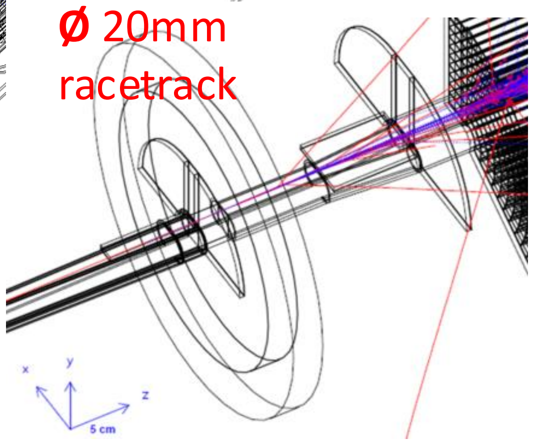








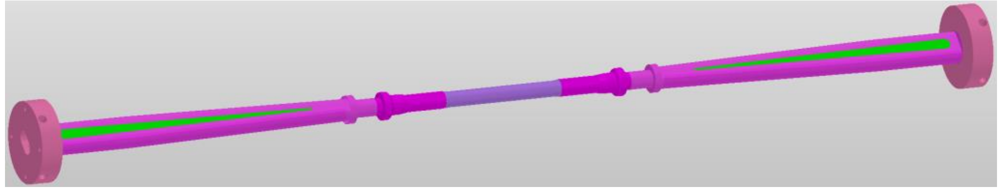




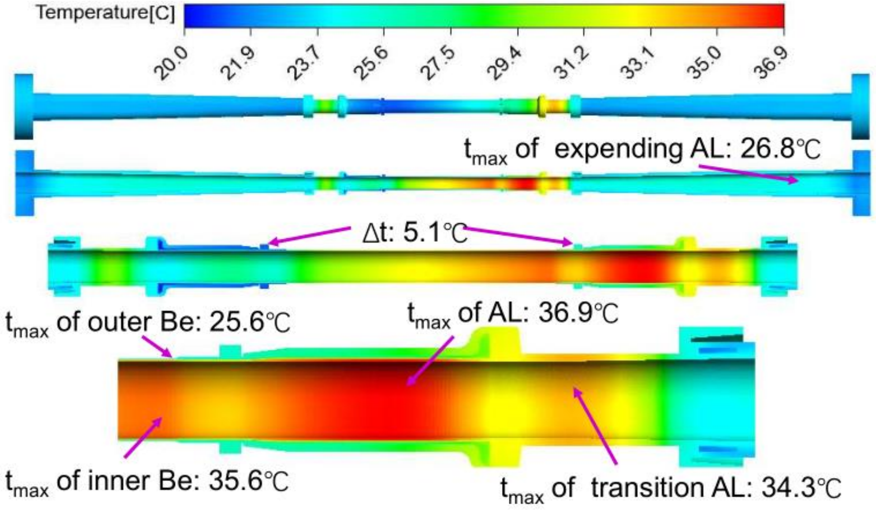
Main Technical Challenges

- For whole region layout:
  - Cryo-Modules, cables, LumiCal and other components in tight space(cone angle of ~300 mrad including the acc. components)
- For Key components:
  - Beampipe: Thickness < 0.15% X_0
  - LumiCal: 10^{-4} precision @ Z-pole; Radiation Safety for itself and others
- For Beam Induced Background Estimation:
  - The Tools and Methods to have a reasonable estimation.
  - The Mitigation methods to let the BG level could be acceptable by all sub-detectors

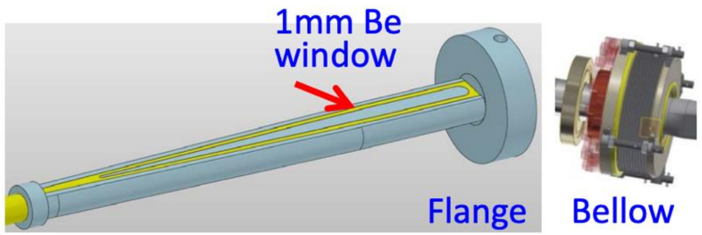
Detailed design including electronics, cooling and mechanics

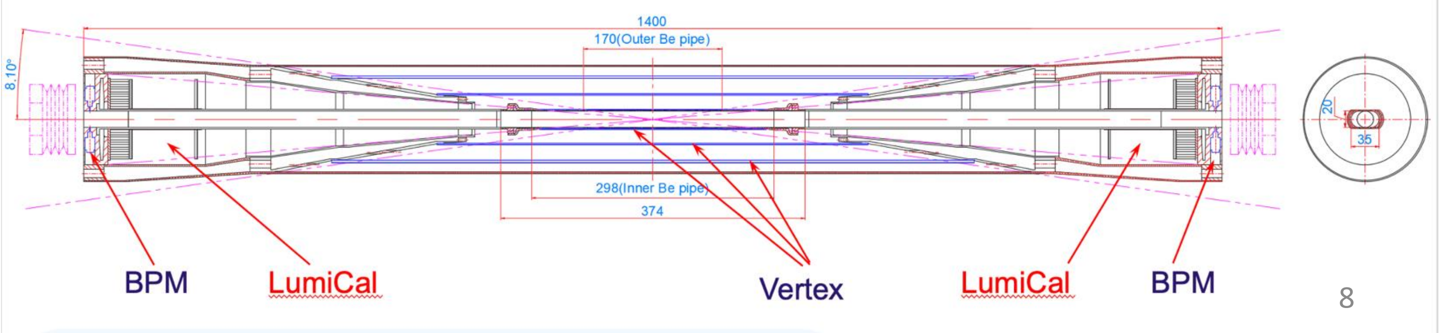


- Beam pipe



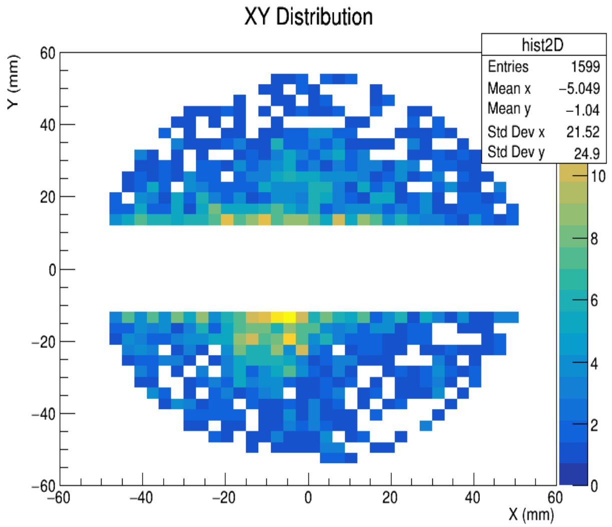
  - Inner Diameter 20mm
  - Inner Layer with thickness of 0.20mm
  - Gap for coolant with thickness of 0.35mm
    - Water chosen as coolant instead of paraffin
  - Outer Layer with thickness of 0.15mm
  - Possible Gold coating with thickness of 10um
  - Low material budget window for LumiCal, together with high-Z material for shielding

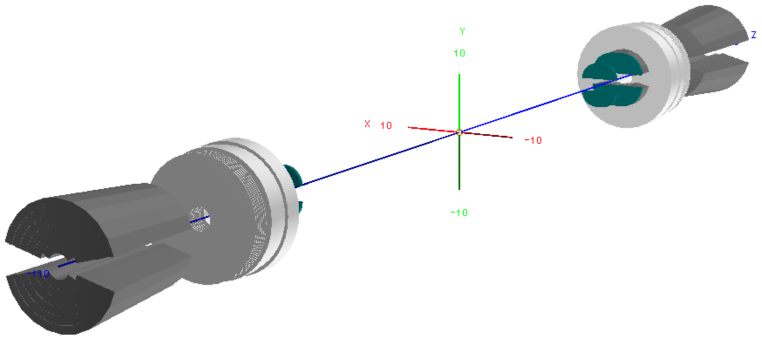


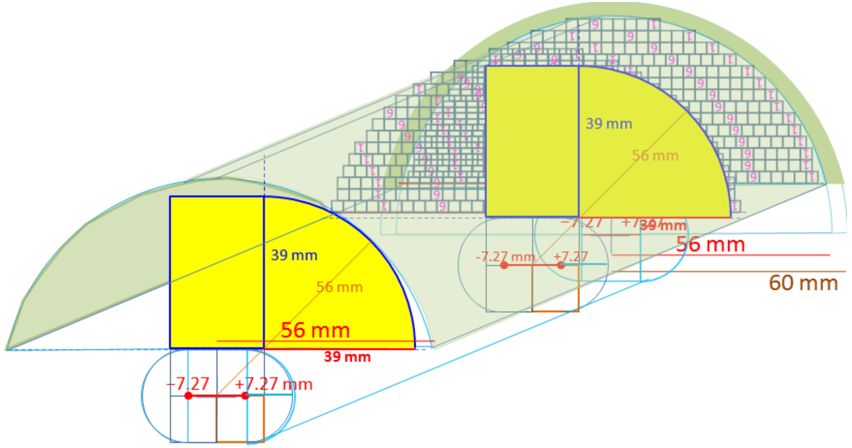


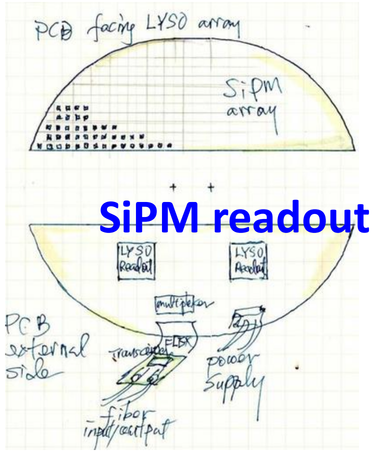
Detailed design including electronics, cooling and mechanics

- LumiCal
  - 2 parts, first Si wafer + LYSO, second LYSO only
    - First Silicon Wafer locates at 560mm, than 640mm
    - First LYSO has a length of 23mm(starts from 647mm)
    - Second LYSO has a length of 100mm(starts from 950mm)
  - Half Moon-cake like design
    - Height ~ 39mm, radius ~ 56 mm



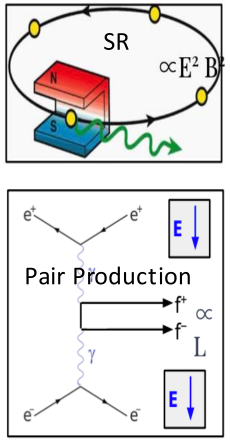






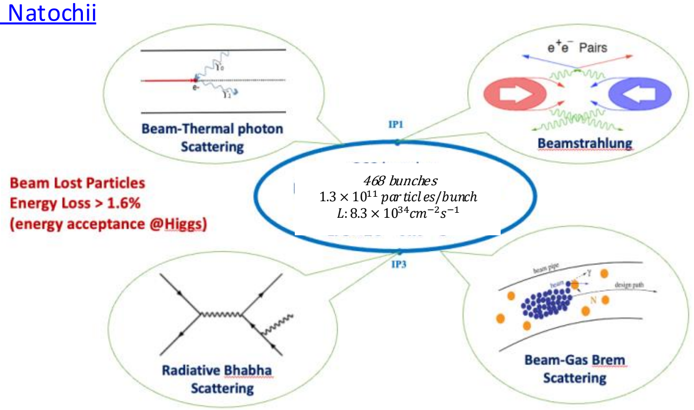
Estimation of Beam Induced Backgrounds

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



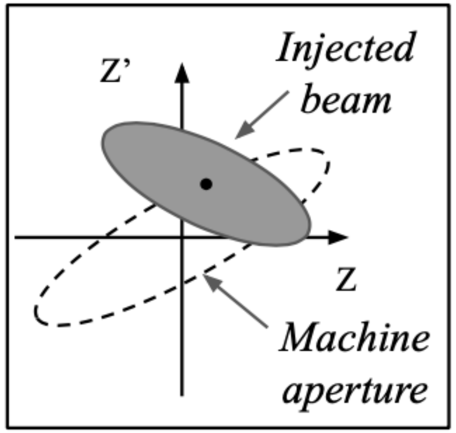
Photon BG

A. Natochii



Beam Loss BG

A. Natochii



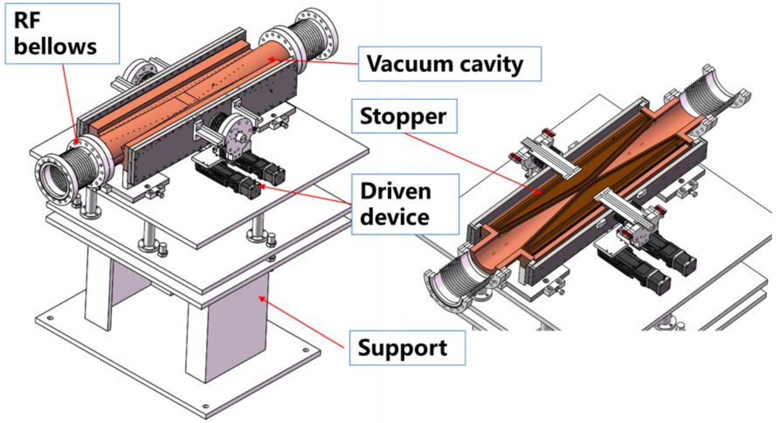
Injection BG

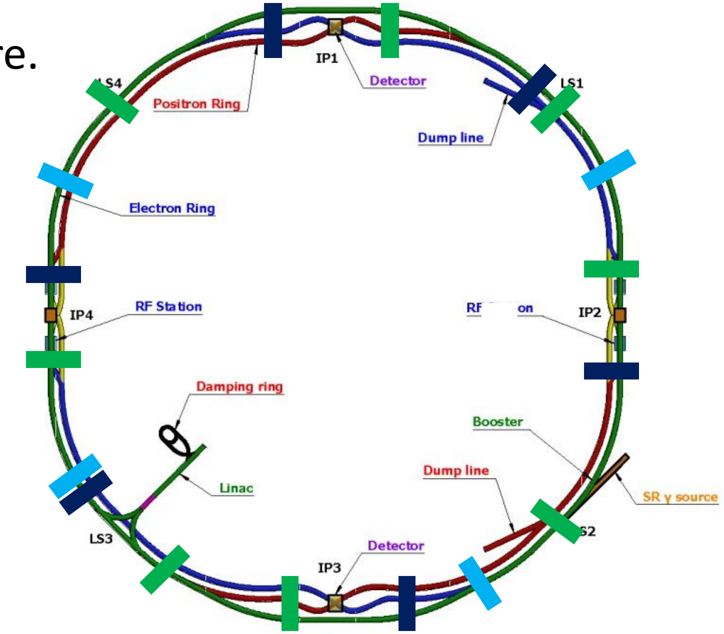
Background	Generation	Tracking	Detector Simu.
Synchrotron Radiation	BDSim	BDSim/Geant4	
Beamstrahlung/Pair Production	Guinea-Pig++		
Beam-Thermal Photon	PyBTH[Ref]		
Beam-Gas Bremsstrahlung	PyBGB[Ref]	SAD	CEPCSW/FLUKA
Beam-Gas Coulomb	BGC in SAD		
Radiative Bhabha	BBBREM		
Touschek	TSC in SAD		

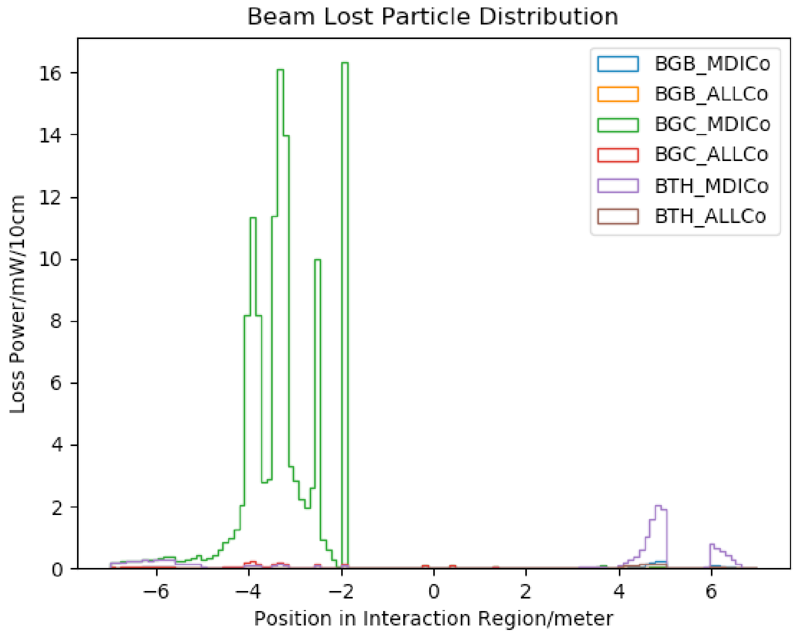
- One Beam Simulated
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(200 turns)
  - Using built-in LOSSMAP
  - SR emitting/RF on
  - Radtaper on
  - No detector solenoid yet

Mitigation Methods for Single Beam

- 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
- A preliminary version of Collimator designed for Machine protection is finished. ~20 sets of collimators with 3mm radius are set alongside the ring.
- Needs to add more.





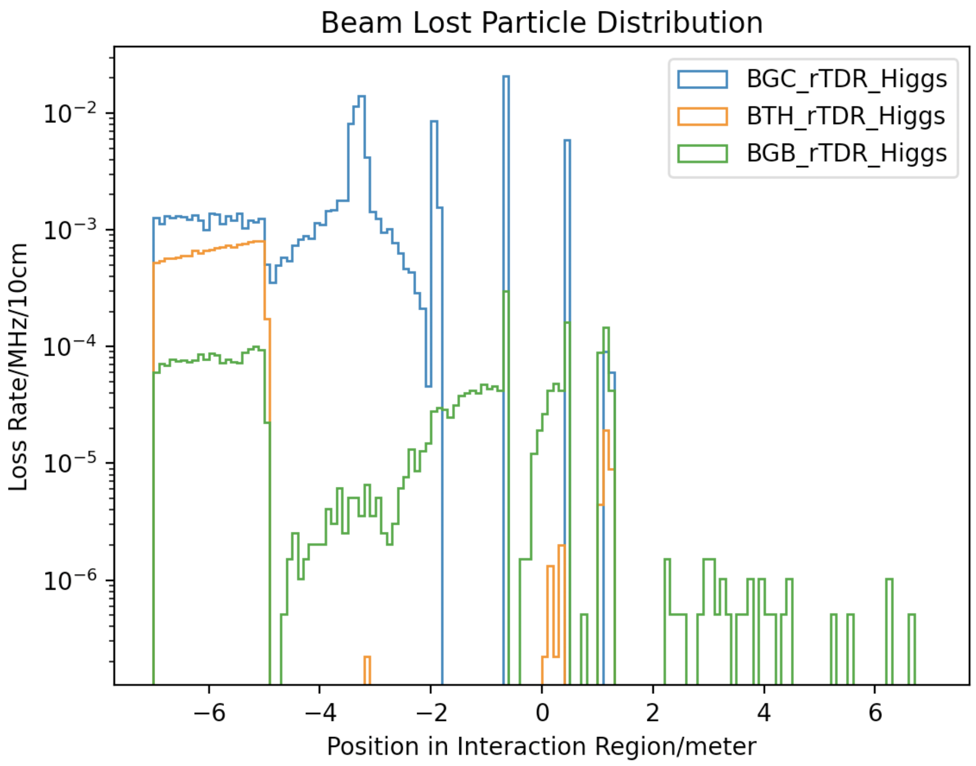


Loss Map of Single Beam @ IR

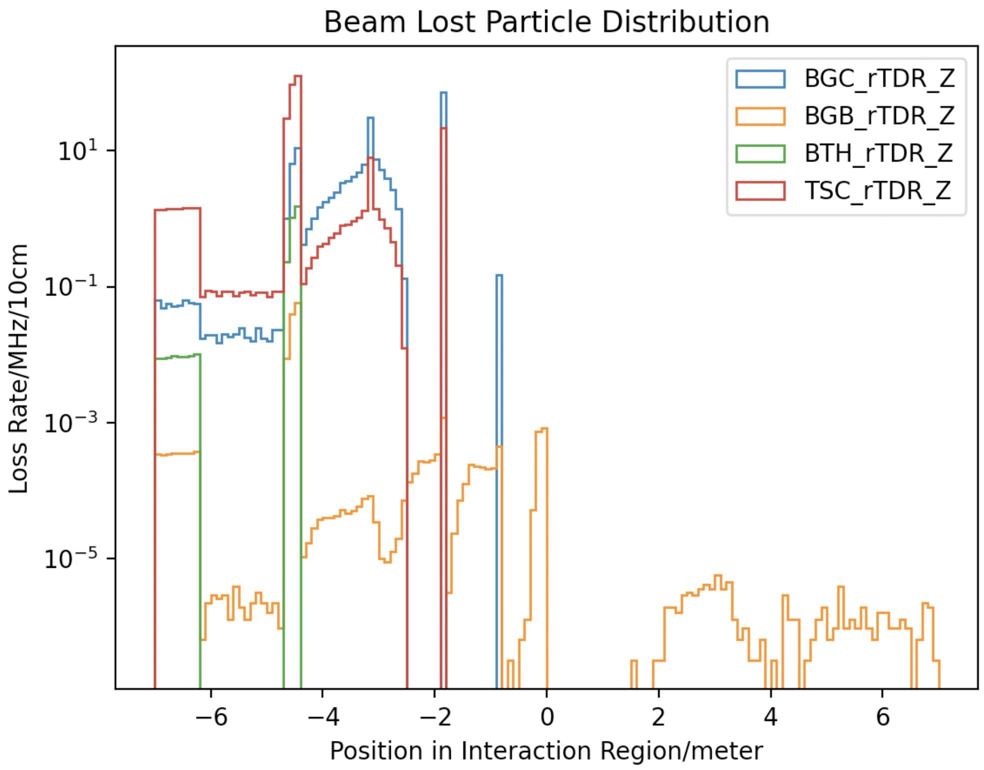
- Errors implemented
  - High order error for magnets
  - Beam-beam effect
- IR Magnet Field(Detector Solenoid/Anti-solenoid) updating
- Higgs acceptable, Z is under optimization(Considering that SuperKEKB's standards of 100MHz IR loss rate)

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

@Higgs



@Z-pole

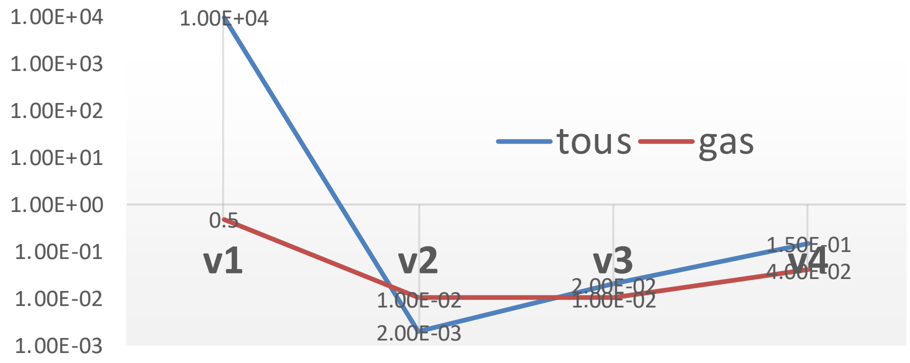


Estimation of Impacts in the MDI

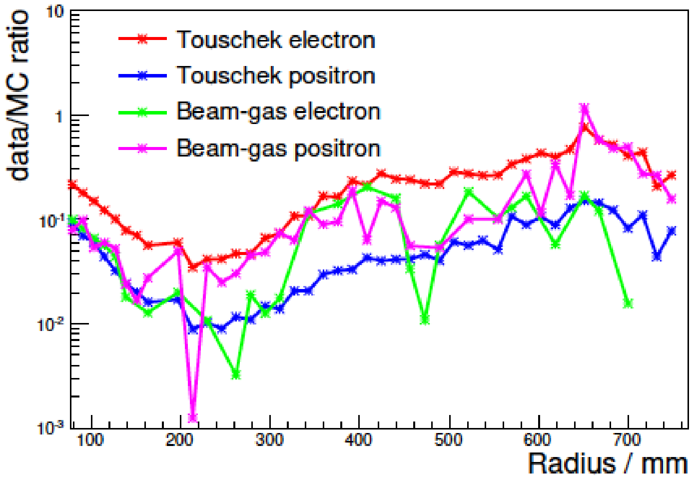
- Noise on Detector(Backgrounds)
  - Occupancy
  - Estimate using the same tool with Physics simulation, Analysis by Detector
- Radiation Environment(Backgrounds + Signal)
  - Radiation Damage of the Material(Detector, Accelerator, Electronics, etc…)
    - Estimate using the same tool with physics simulation including the dose calculation/FLUKA
  - Radiation Harm of the human beings and environment
    - Estimate using the same tool with physics simulation including the dose calculation/FLUKA

Benchmark and Validation

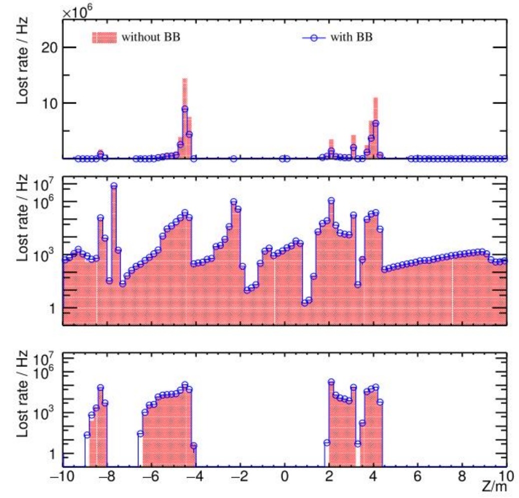
- BG experiments on BEPCII/BESIII has been done several times.
  - We separated the single beam BG sources using SuperKEKB method, the data/MC ratio has been reduced 2 order of magnitude due to update of the IR model.
  - Study on beam-beam reduced another ~15% of simulation.



Data/MC radio improvements on 1st layer MDC



Data/MC radio in MDC



Simulation w.i./w.o. Beambeam

Working plan

	2024.12	2025.6	Beyond Ref-TDR
Key Components like Be beam pipe			Study on Au-Coating Study on Al-Be Welding and Anti-corrosion on Be
LumiCal	Design optimization based on Simulation	Mechanical Design including cable and cooling	Module assembly and Beam Test if possible
BG Estimation	Whole Map Estimation on 4 modes, including preliminary thoughts on Mitigation Methods to try to make the hit level acceptable	Whole Map Estimation and Mitigation on 4 modes, including the thoughts on injection backgrounds	Benchmark experiments on BESIII or SuperKEKB

Research Team

- The working group consists of many people from different institutions/universities, including
  - IHEP: ~ 20 staff(including colleagues from acc. side), most of them have participated in BEPCII/HEPS/etc., and ~ 7 students
  - IPAS: Suen Hou, participated in LEP, Editor of MDI Chap of CDR
  - NJU: 1 staff, ~10 students, participated in ATLAS
  - JLU: 1 staff, 1 students , participated in BESIII/Belle II
  - VINCA(Serbia): 5 staff, Ivanka Bozovic was the editor of MDI Chap of CDR

Contents of the TDR Document

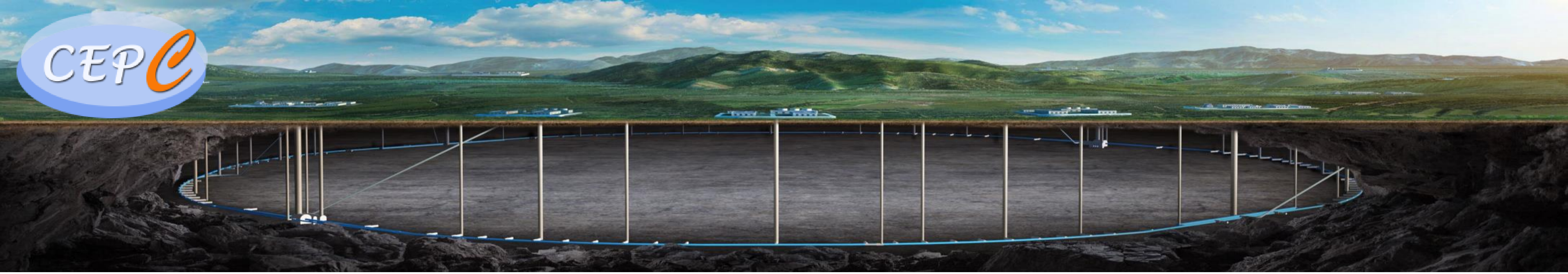
3、 Machine Detector Interface and Beam Measurement (Haoyu/Suen/Sha)

- 3.1. Introduction & Requirements(Haoyu)
- 3.2. IR Layout(Haoyu/Sha/Quan/Haijing)
- 3.3. Key design/parameters(beampipe, final focusing, etc..)
  - i. Central Beampipe(Quan, Haoyu)
  - ii. Final Focusing System, Anti-solenoid(Yingshun)
  - iii. Cryo-Module(Xiangzhen, Xiaochen)
- 3.4. Detector/IR Backgrounds(Haoyu)
  - iv. Introduction
  - v. Shielding Design/mitigation methods
  - vi. Estimation
    - 1) General Noise Level/Dose Level
    - 2) Impacts on Sub-Detectors:
      - a) Interaction Region/LumiCal(Haoyu/Renjie/Yilun)
      - b) Vertex(Hancen)
      - c) Silicon Tracker(Zhan/Dian)
      - d) TPC(Xin/Jinxian)
      - e) ECal/HCal(Weizheng/Fangyi)
  - vii. Benchmark: Experiments on BESIII(Bin)
- 3.5. Beam Measurement System(Suen/Lei/Weiming/Haoyu)
  - viii. LumiCal(Suen/Lei/Weiming)
  - ix. Radiation Monitoring System Proposal(Haoyu/Guangyi/Zhongjian)
- 3.6. Summary & Outlook
- 3.7. Ref. List

Summary

- The tasks of the MDI and Beam Measurement are very critical and challenge, including:
  - The design of layout in a very tight space(cone angle of ~300 mrad including the acc. components)
  - The design of key components like beam pipe and quad-magnets.
  - The Luminosity Measurement System
  - The Estimation of Beam-induced backgrounds and mitigation methods.

- For the design of key components, the technical design has been finished last year(published Acc. TDR volume), more engineering effort are needed like manufacture, welding and gold coating for the Be beam pipe, and will be proceeded in future.
- For the Beam Measurement system, mainly the LumiCal, the design of the first version has been finished, the simulation and optimization will be finished by the end of this year.
- For the beam induced background estimation, there will be a whole map later this year. Further mitigation and benchmark could be continued together with accelerator colleagues towards the EDR and maybe construction phase.



Thank you for your attention!

中国科学院高能物理研究所
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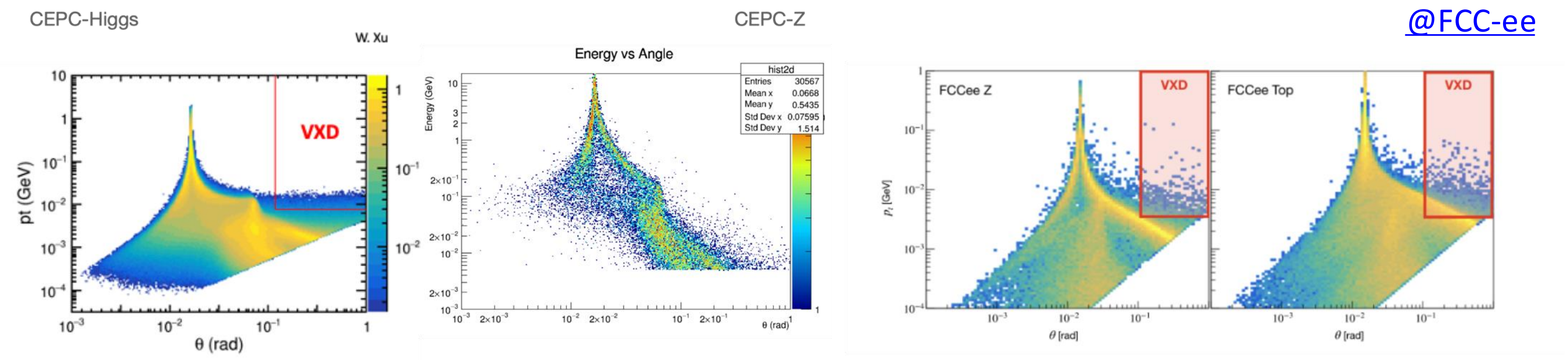
Backup

BG Simulation Status

		Higgs	Z	W	ttbar
Vertex	Noise	Simulated, acceptable	Optimizing	Before Dec 2024	Before Dec 2024
	Radiation	Simulated	Optimizing	Before Dec 2024	Before Dec 2024
Silicon Tracker	Noise	Simulated, acceptable	Optimizing	Before Dec 2024	Before Dec 2024
	Radiation	Simulated	Optimizing	Before Dec 2024	Before Dec 2024
TPC	Noise	Simulated, acceptable	Simulated, acceptable	Before Dec 2024	Before Dec 2024
	Radiation	Simulated	Optimizing	Before Dec 2024	Before Dec 2024
ECal	Noise	Simulated, acceptable	Optimizing	Before Dec 2024	Before Dec 2024
	Radiation	Simulated	Optimizing	Before Dec 2024	Before Dec 2024
HCal	Noise	Simulated, acceptable	Optimizing	Before Dec 2024	Before Dec 2024
	Radiation	Simulated	Optimizing	Before Dec 2024	Before Dec 2024

Benchmark and Validation – Step by Step

- If possible, step by step. If not, using Experimental Data.
  - For Pair-Production, we could have some generation level cross check with FCC-ee's simulation Results



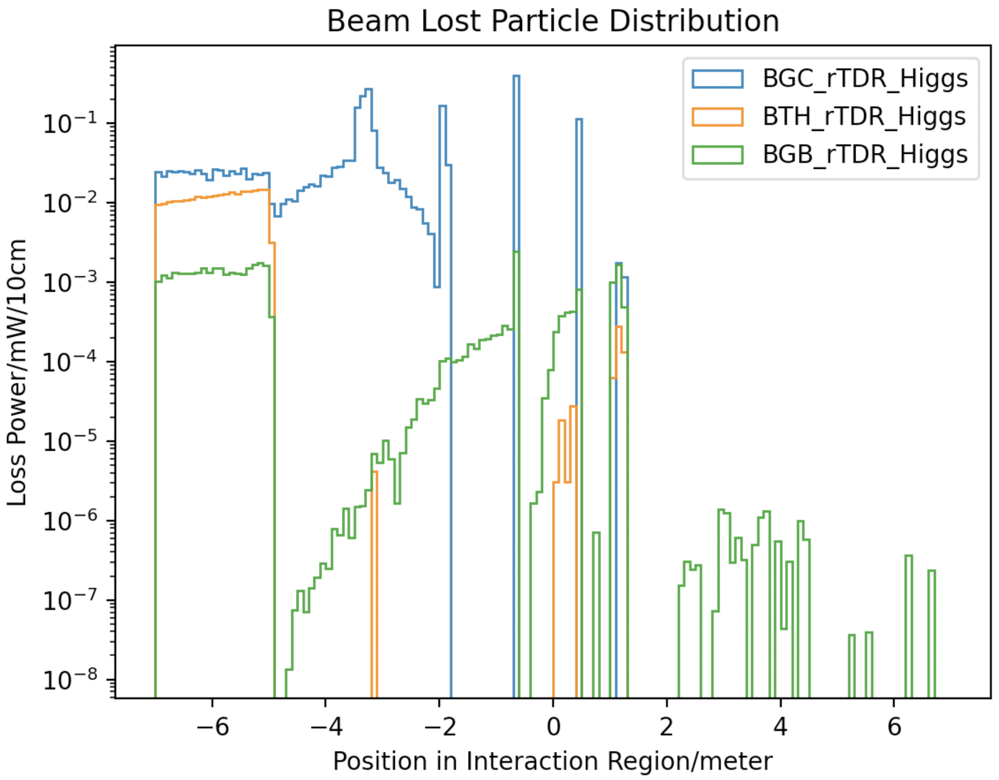
  - For Single Beam BG, we have the same generation formula with SuperKEKB

Loss Power of Single Beam @ IR

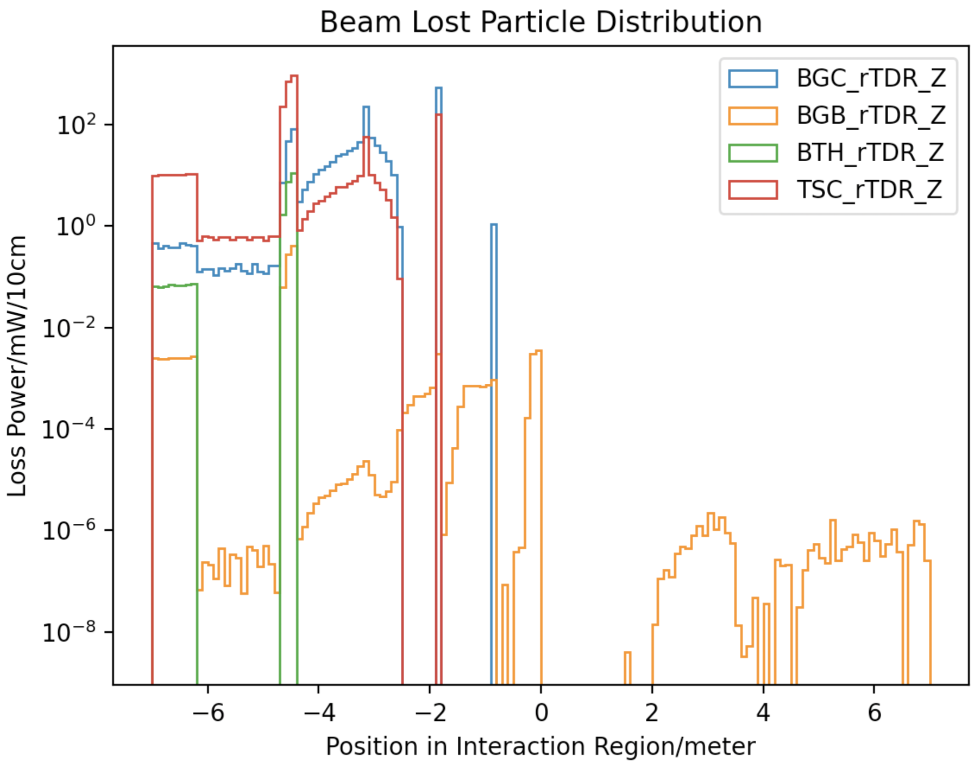
- Errors implemented
  - High order error for magnets
  - Beam-beam effect
- No Solenoid Currently

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

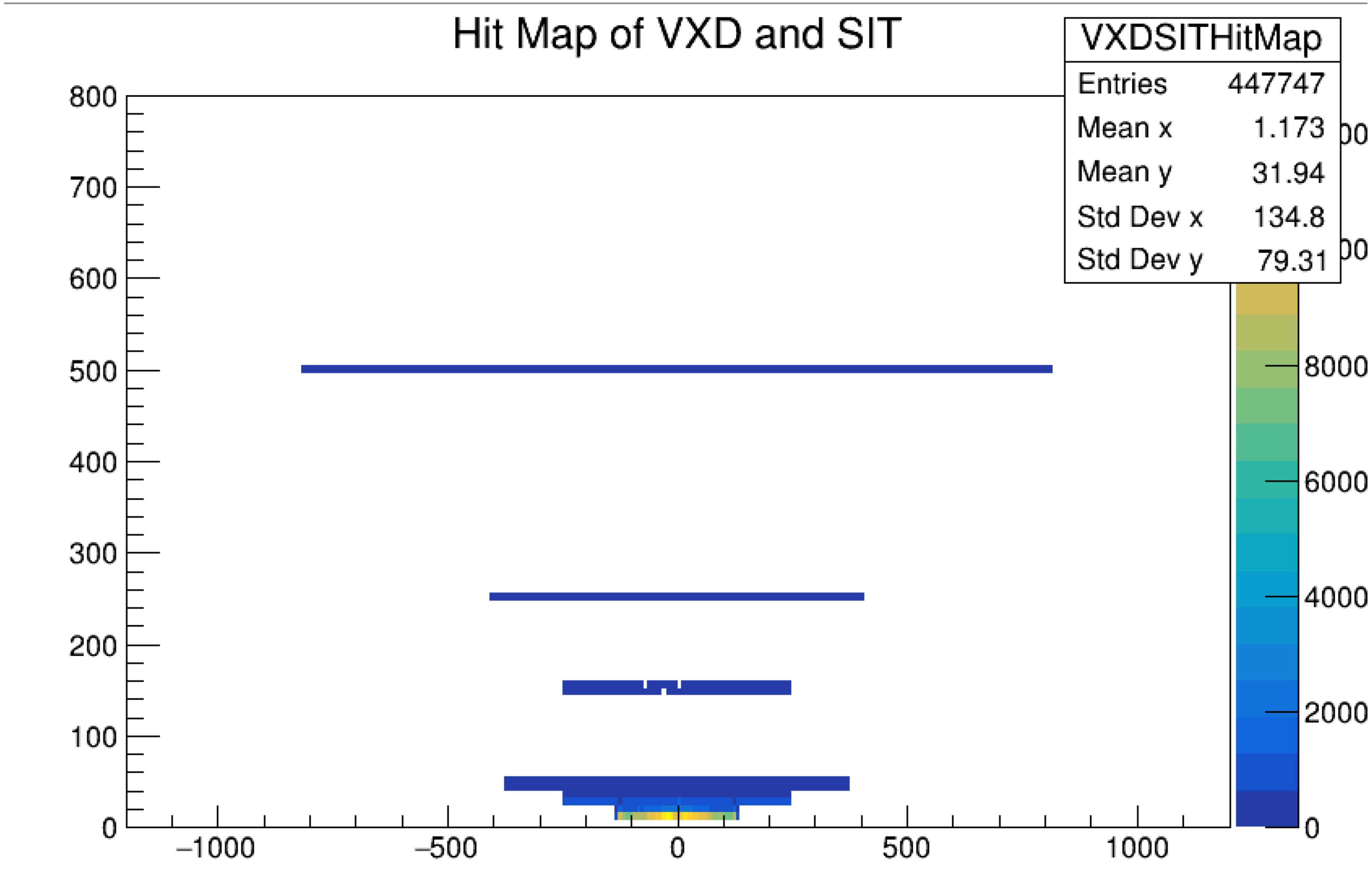
@Higgs



@Z-pole

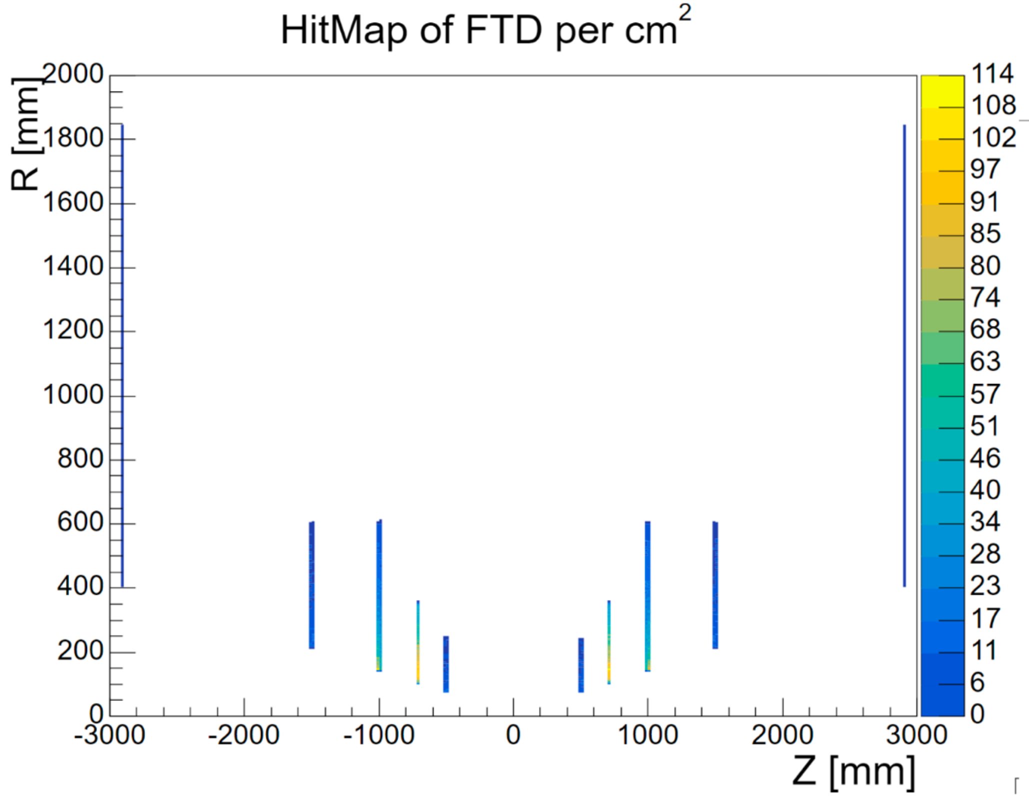


Hit Map of Detectors

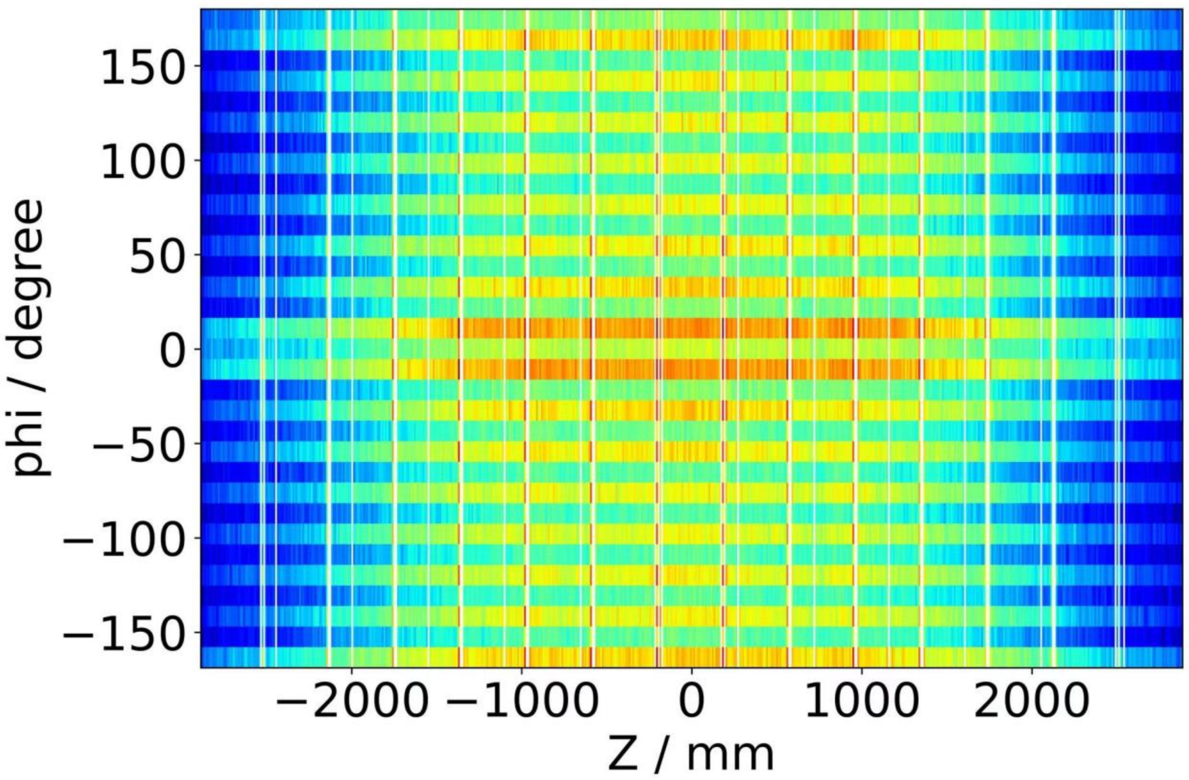


Hit Map of Detectors

@ST Endcup
By Zhan

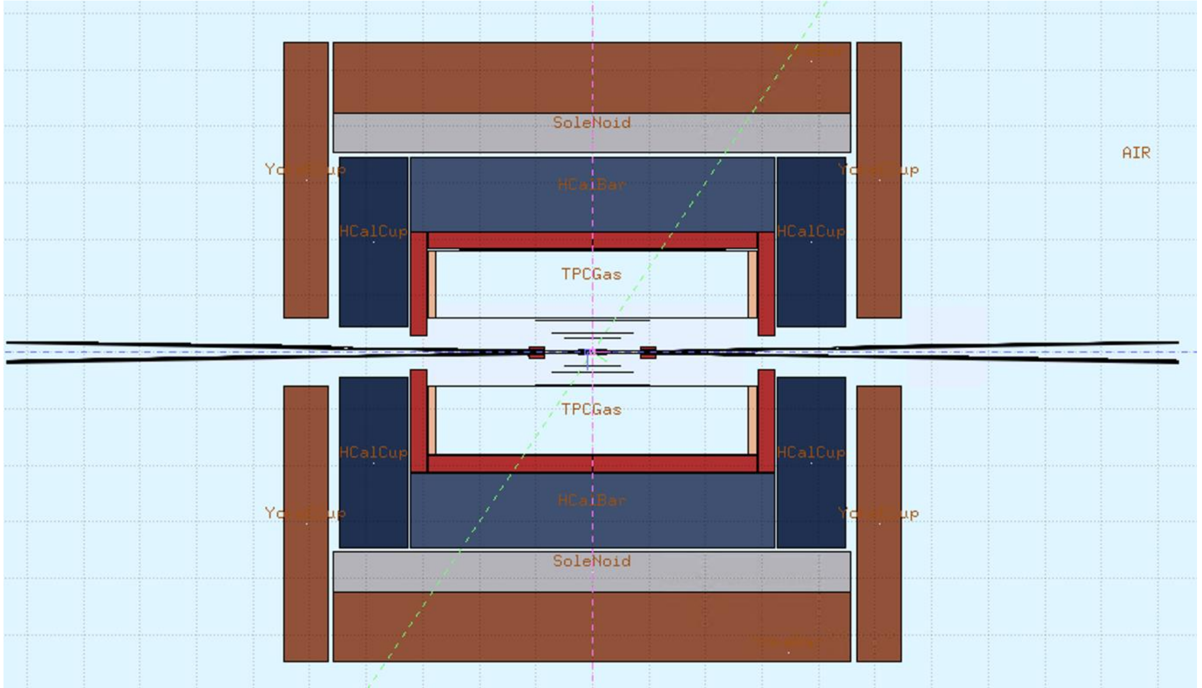


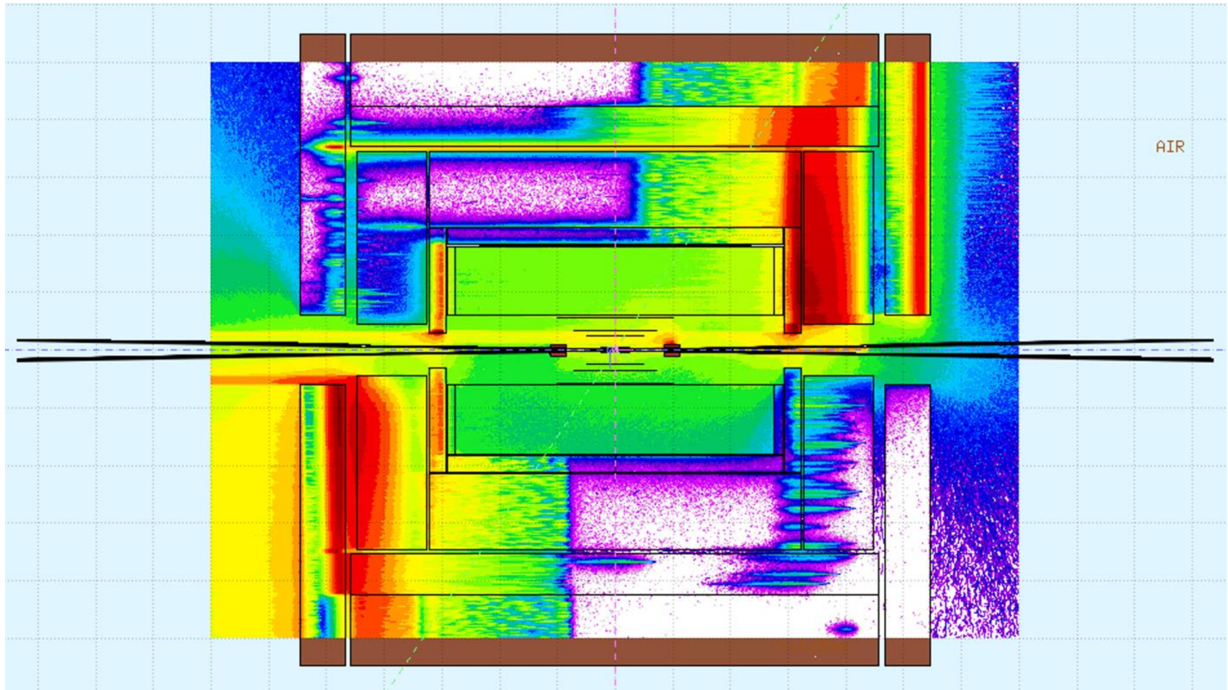
@Ecal Barrel
By Weizheng



FLUKA Results

- Using FLUKA to simulate radiation level, including the Charged particle fluence, absorbed dose, NIEL(1MeV Si equivalent) and Dose-EQ
  - Higgs results needs to be updated





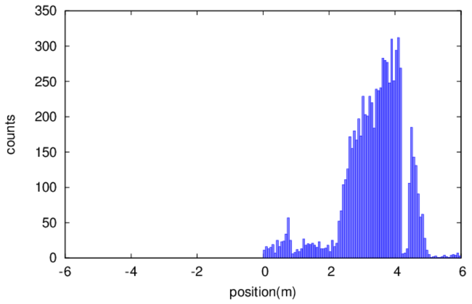
Injection Backgrounds @ Higgs

- A preliminary study on the injection backgrounds has been performed:

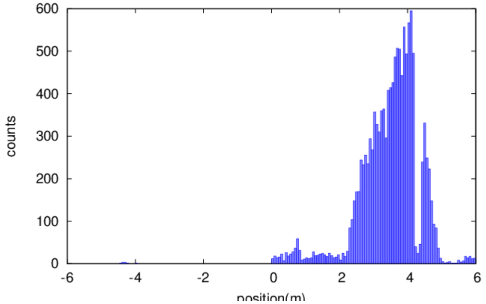
S. Bai

  – 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

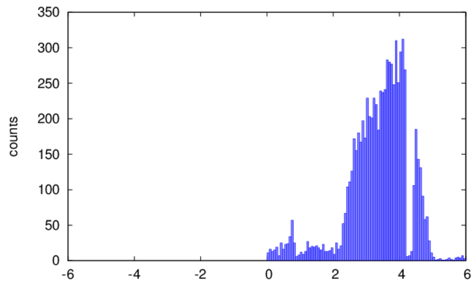
Circular beam



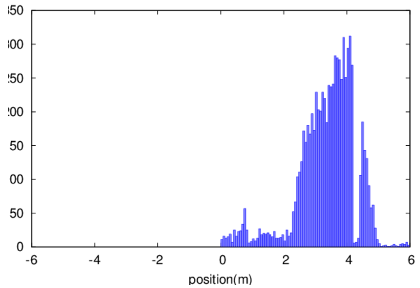
Injection beam



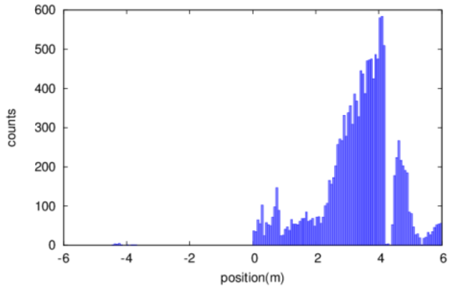
Gaussian beam with 3sigma



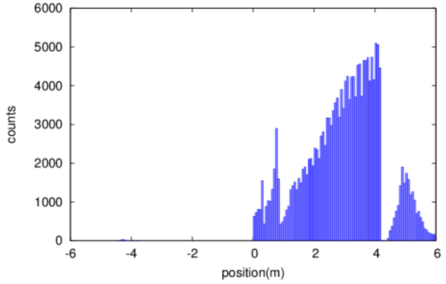
Gaussian beam with 40sigma



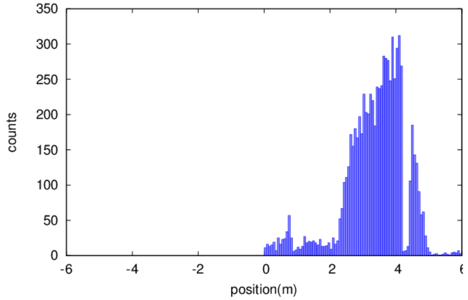
Large emittance ~10times



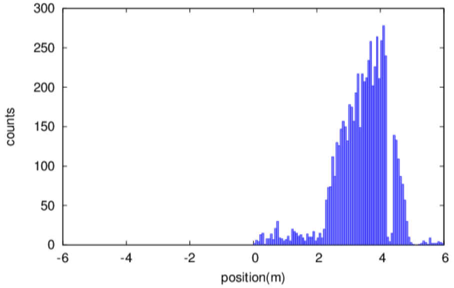
Large emittance ~1000times



Double gaussian beam



Uniform beam



Key aspects of the MDI design(Both Acc. And Det.)

- Beam induced backgrouds
  - The MDI region is now improved as more realistic, and software model developed. Narrow the difference with future experiments.
  - Backgrounds, collimators, IR beam losses, SR, IR radiation level & fluences
  - Beamstrahlung dumps with radiation levels.
- Heat loads in IR region
  - HOM heating, SR, Beam loss backgrounds, Beam pipe thermal analysis
- IR magnet system & Cryostats
  - FF Quads & Correctors
  - Solenoid compensation & anti-solenoid design update
  - Cryomodule design update, thermal and mechanical analysis of the structure, optimization of heat and mass transfer of the helium, design of current leads. PI&D scheme determination, assembly process design and alignment considerations.
- IR Mechanical model, including vertex and lumical integration, and assembly concept
  - Cooling for vertex and vacuum chambers
  - Remote Vacuum connection, IR BPMs
  - Integrate in the design an alignment system
  - Overall integration and installation for all components in the MDI. Specific installation procedure.

MDI Work Map

Accelerator

IP Feedback
BG Simulation
Lumi Monitor
HOM absorber
Vacuum Chamber
SR Masks
QDa/QDb/QF1
Anti-Solenoid
Cryostats
BPMs
Instability&Impendance
Cooling
Shielding
Assembly&Supporting
Alignment
Connecting System
Vacuum pumps
Last Bending Magnet
Collimators
Control

Detector

Central Beam Pipe
Vertex Detector
LumiCal
Silicon Tracker
TPC
Hcal
Ecal
Solenoid
Yoke
Muon Detector
Hall
BG Simulation&Shielding
Software Geometry
Alignment&Assembly
Electronics
Cryogenic
Radiation Protection
Booster