Study status of Beam Backgrounds and MDI Design at the CEPC

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On behalf of the CEPC MDI Working Group

CEPC Workshop 2024, MDI Session

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Outline

- Introduction
- Current Study Status
  - Layout and Key Components
  - Beam induced Backgrounds
- Summary & Outlook

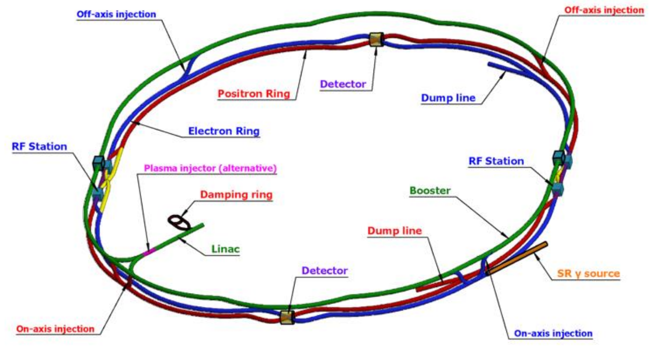
Introduction

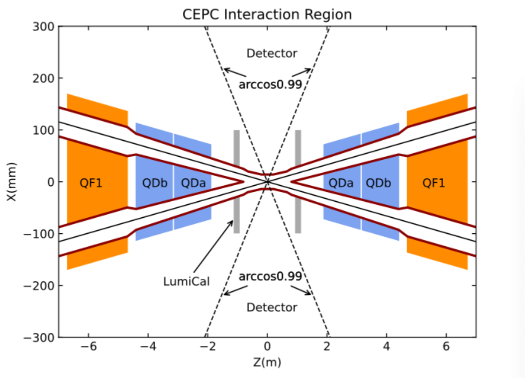
- MDI stands for ”Machine Detector Interface”
  - Interaction Region and other components
  - 2 IPs
  - 33mrad Crossing angle
- Flexible optics design
  - Common Layout in IR for all energies
  - High Luminosity, low background impact, low error
  - Stable and easy to install, replace/repair

TDR Design

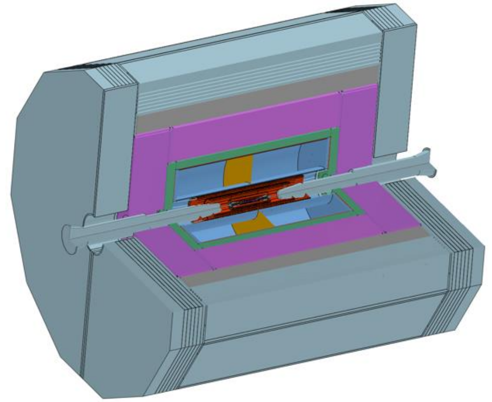
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	**100.0**			
SR power per beam (MW)	**30**			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	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**

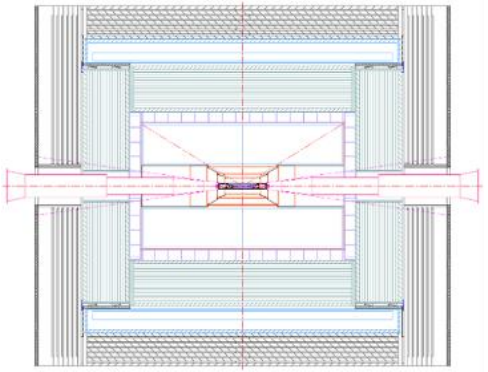
67%⇧ 259%⇧





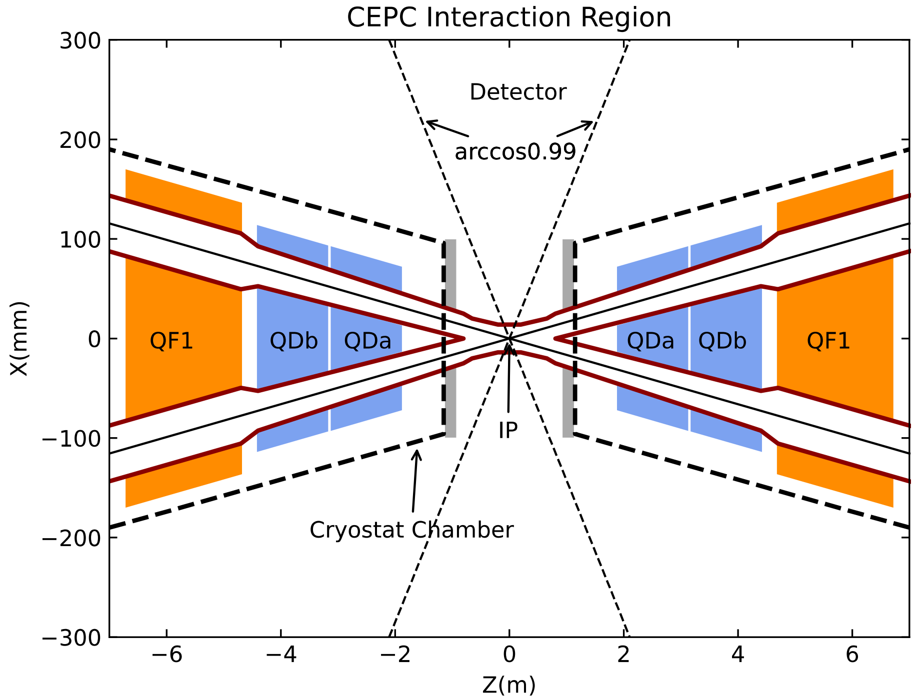
Ref-TDR

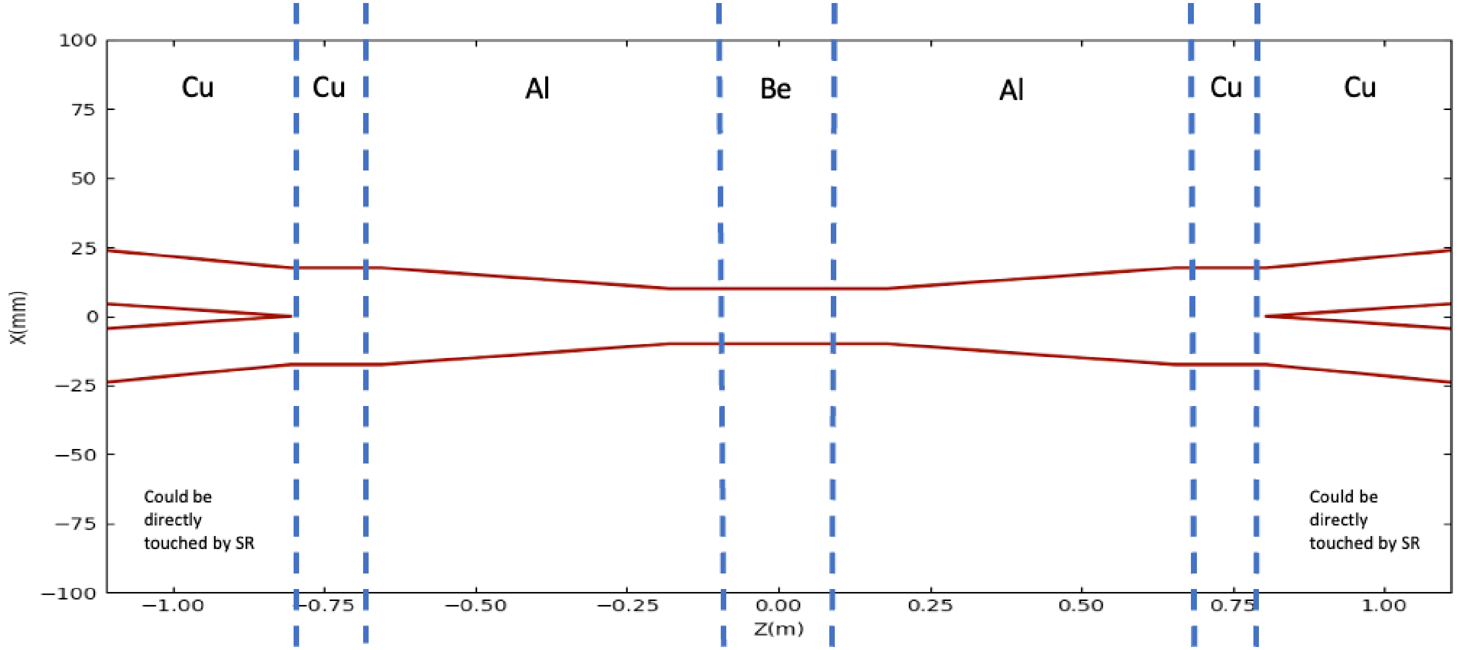




Updated IR for CEPC

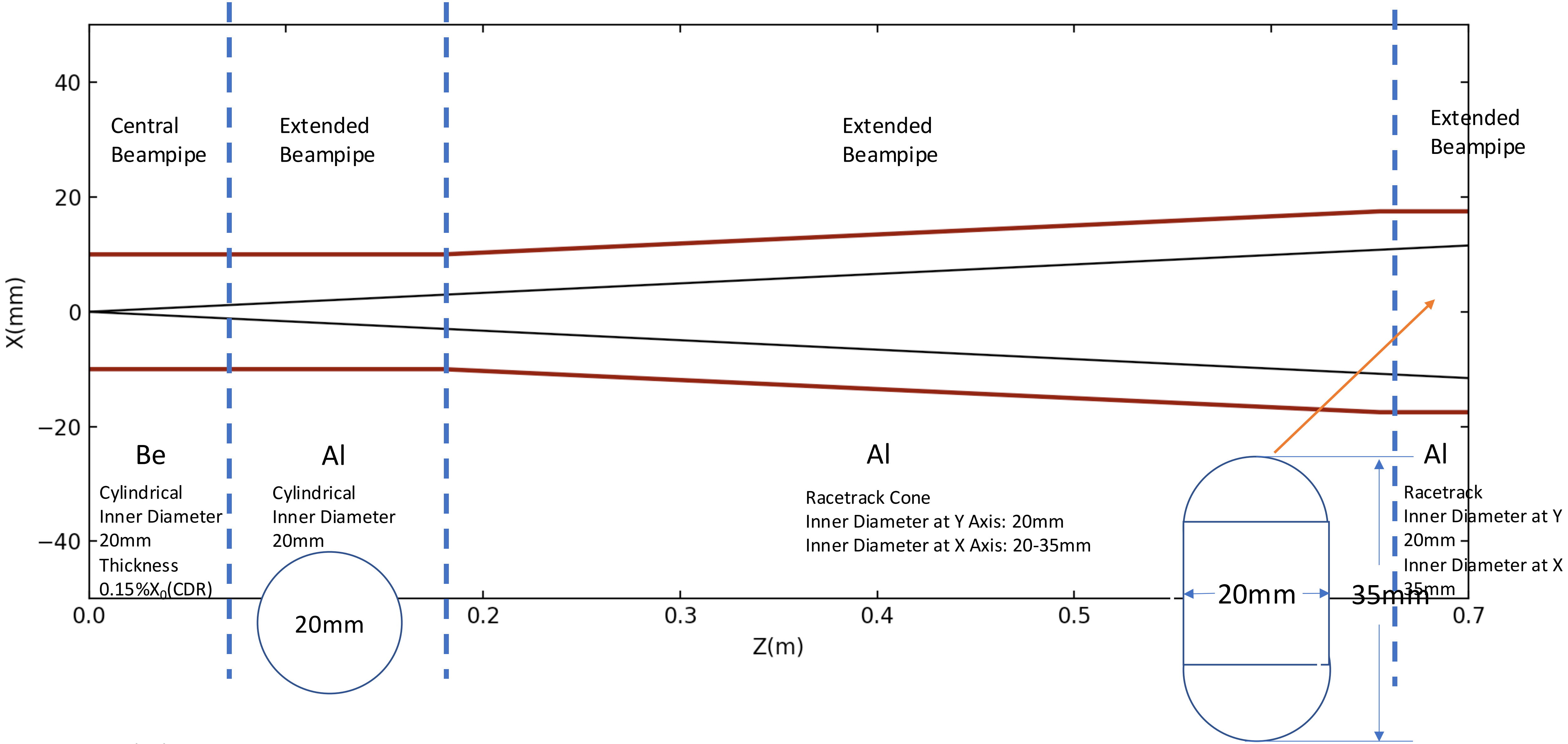
- Interaction Region Layout/Parameters
  - L* = 1.9m / Detector Acceptance = 0.99





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

New Beampipe Design – Half Detector pipe

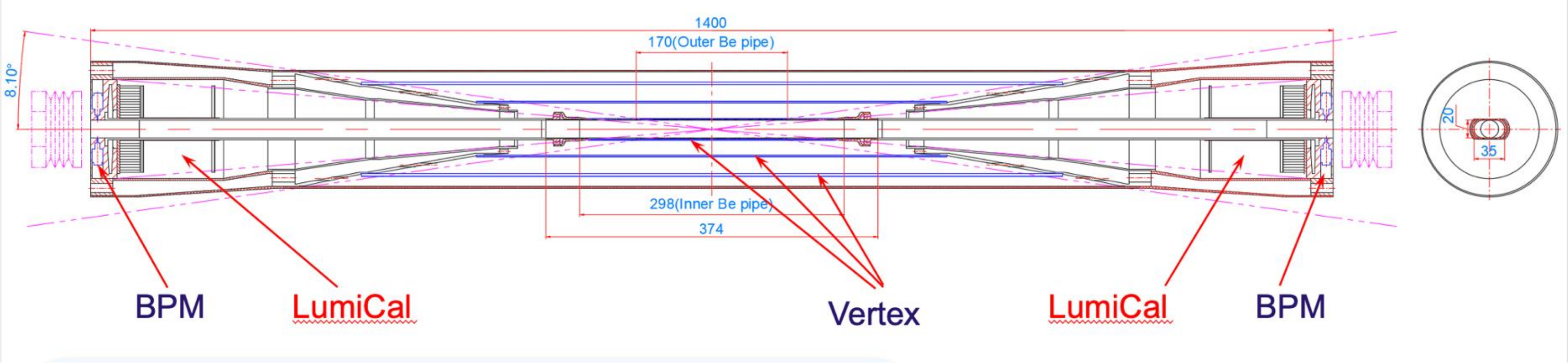


Mechanical Design of the detector beam pipe

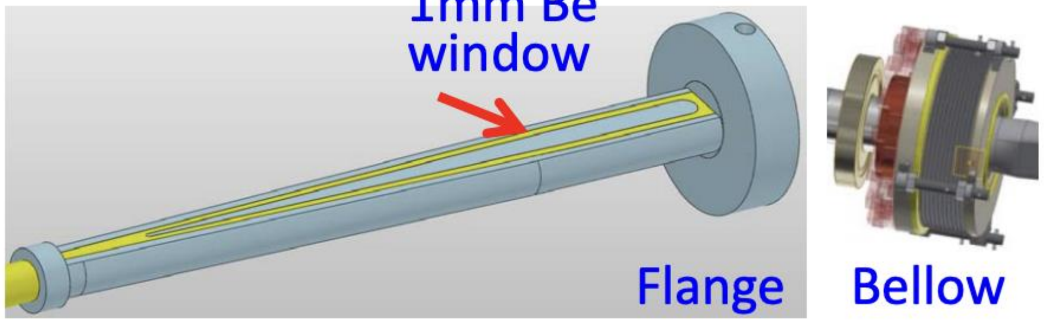
L. He's talk at this workshop

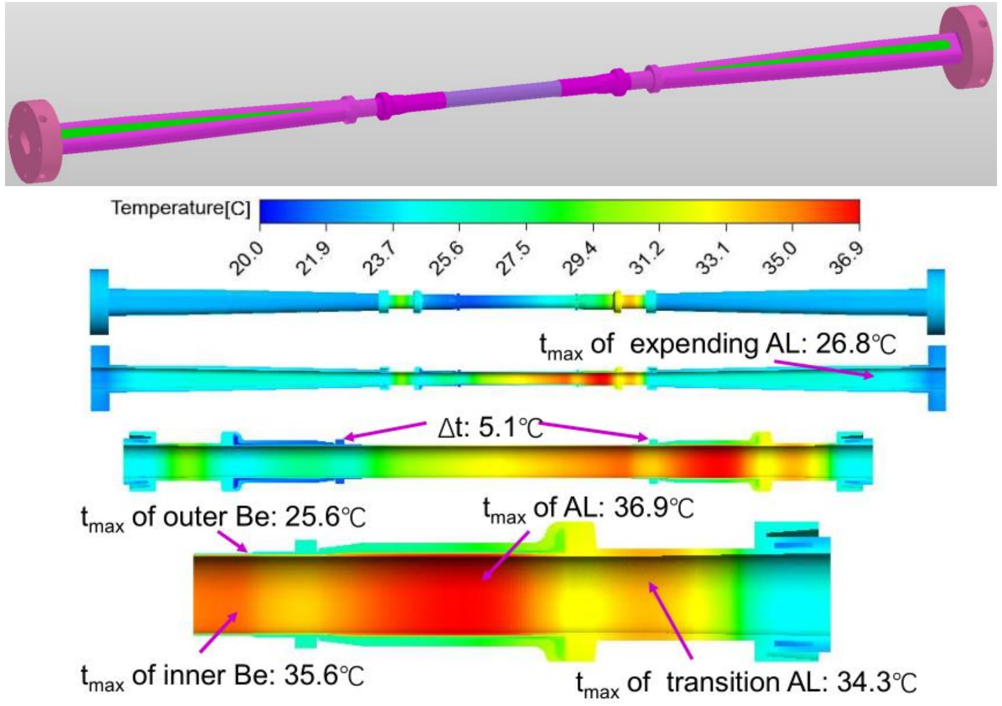
Q. Ji, L. He

Outer Be Layer: 0.15mm
Gap: 0.35mm, Coolant
Inner Be Layer: 0.2mm
Thickness: ~0.2%X_0



Q. Ji, H. Wang



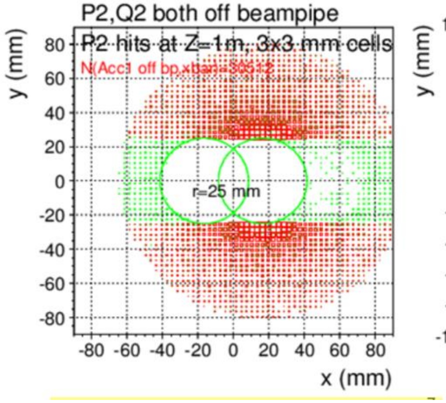


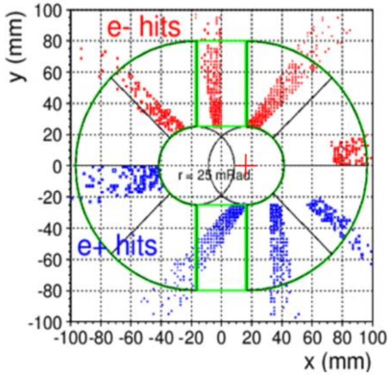
- Water or Paraffin could be used as the coolant
- Preliminary analysis shows that the dynamic temperature/pressure could meet the requirements.

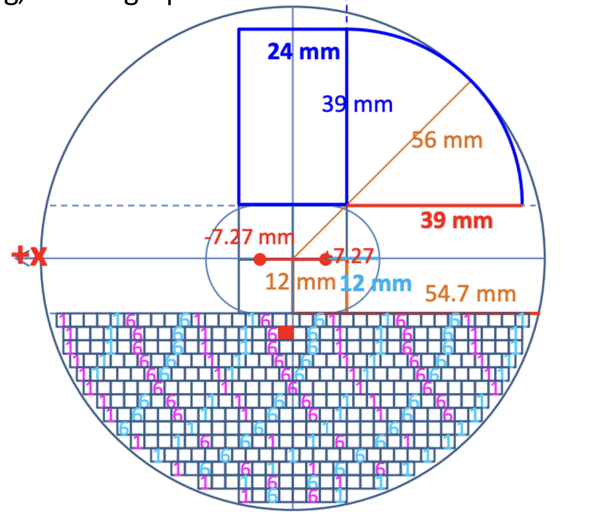
Design of the LumiCal

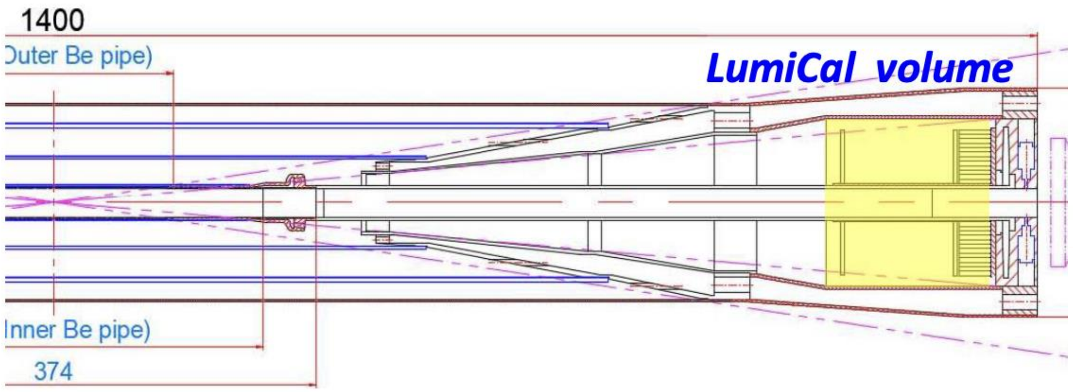
S. Hou and X. Sun's talk at this workshop [S. Hou]
J. Gong, J. Zhang's poster

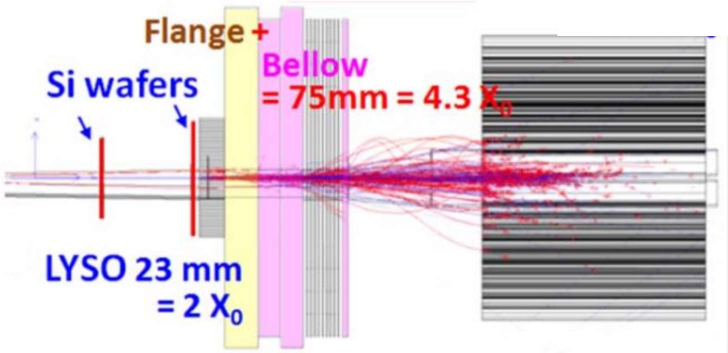
- LumiCal has been updated:
  - Two parts, one before Flange, and one after
  - LumiCal before flange:
    - 560~700mm,
    - Two Si-wafers, $2X_0$ LYSO
  - LumiCal after bellow:
    - 790~950mm
    - $14X_0$ LYSO

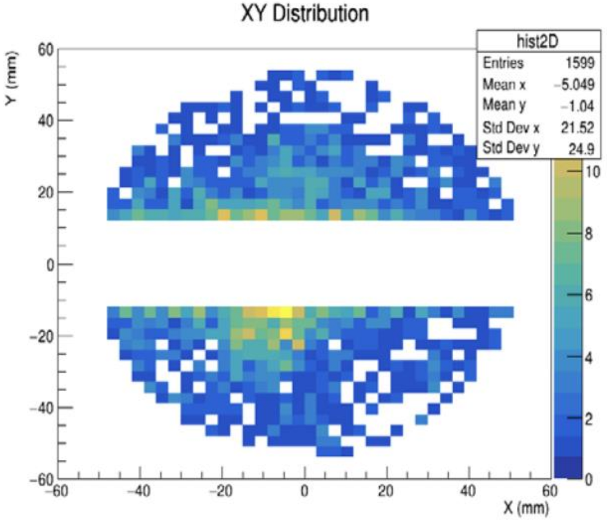






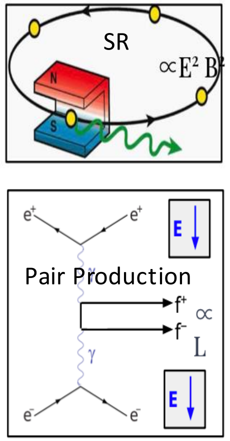






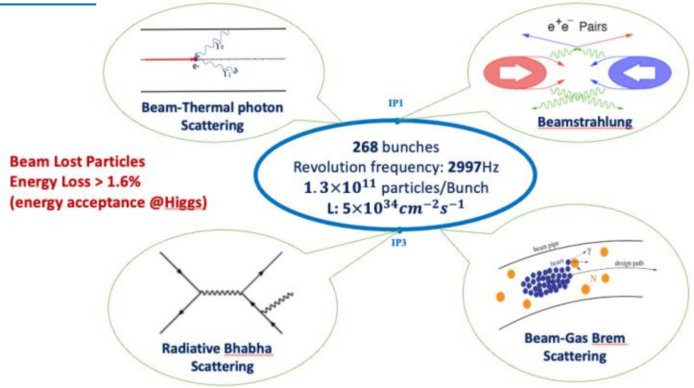
Background Estimation

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



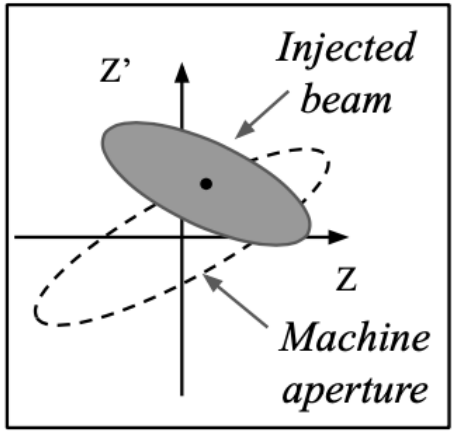
Photon BG

A. Natochii



Beam Loss BG

A. Natochii



Injection BG

Background	Generation	Tracking	Detector Simu.
Synchrotron Radiation	BDSim/Geant4	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		

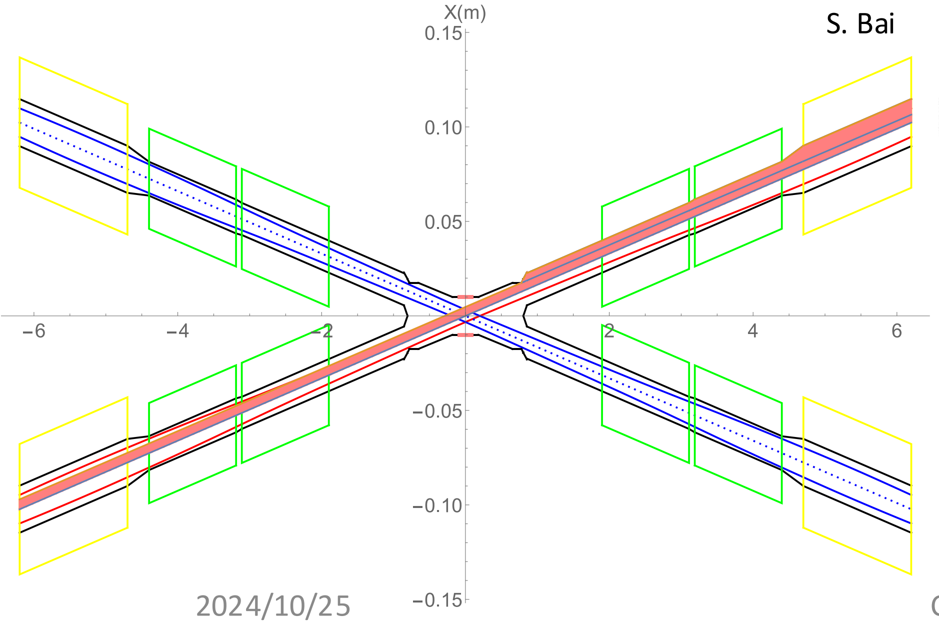
- One Beam Simulated
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(200 turns)
  - Using built-in LOSSMAP
  - SR emitting/RF on
  - Radtaper on
  - No detector solenoid yet

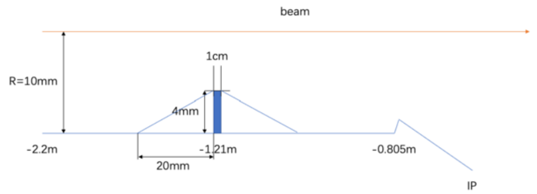
SR BG & Mitigation

Y. Tang’s poster(No.46) this workshop

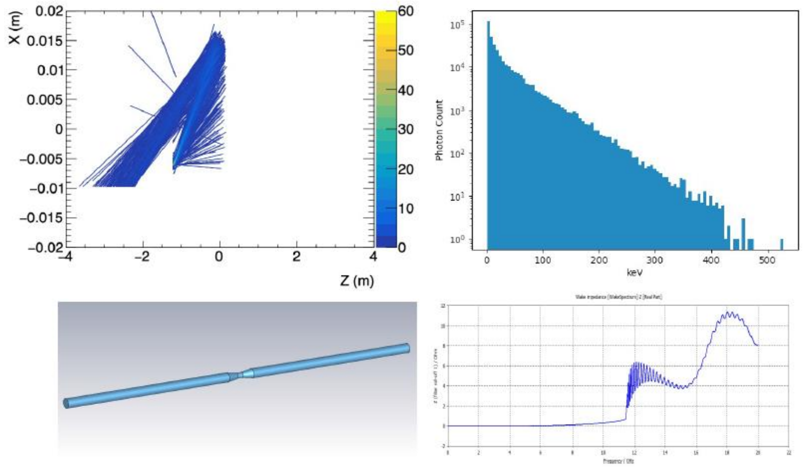
- The central beam pipe was carefully designed to avoid the direct hitting of the SR photons
- The masks are implemented to further mitigate the secondaries
  - Several ways has been attempted, including the shrinking of the incoming beam pipe and different position/material/design of the mask.

S. Bai





Y. Liu



Y. Sun

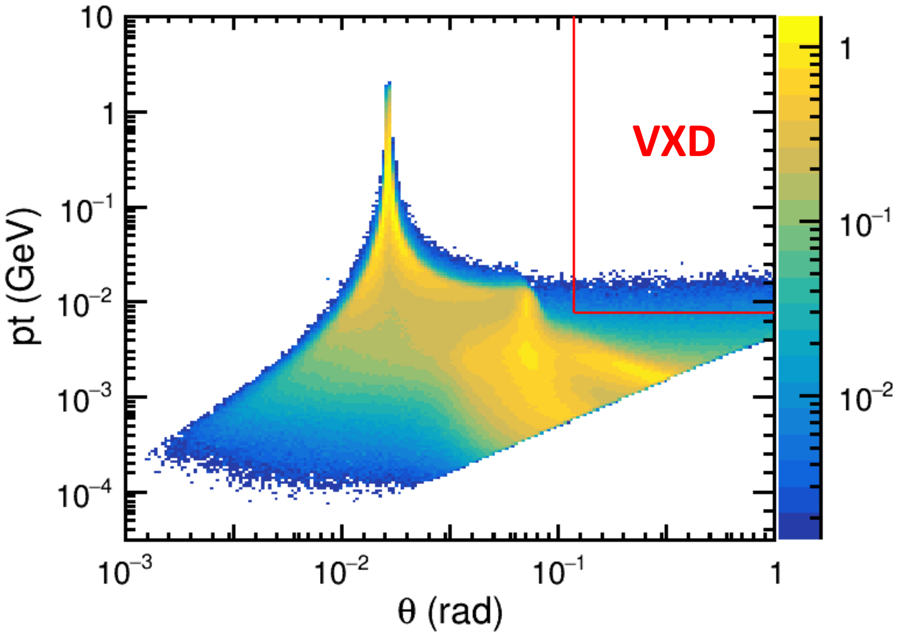
Methods	photon number of hitting on Be(N)
1.21-mask-Cu	1736.0
1.21-mask-W	1698.0
2.2-mask-Cu	1147.0
cons-no mask-Cu	257364.0
cons-no mask-W	148030.0
1.21-mask-Cu-5μmAu	216.0
nomask	39400.0

Pair Production(Beamstrahlung)

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

W. Xu

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

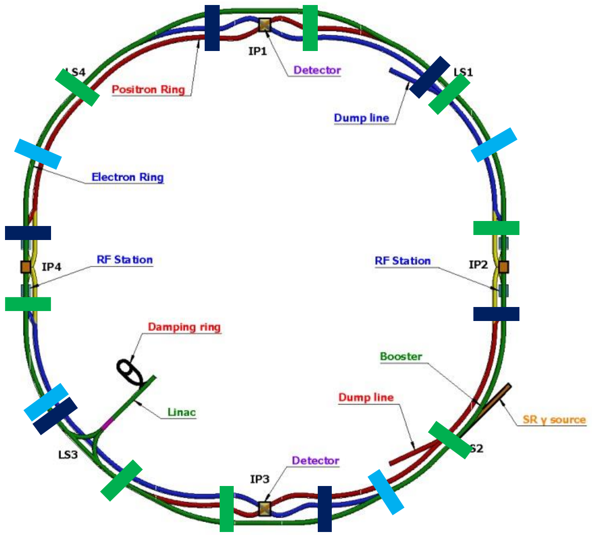


Mitigation of the BG

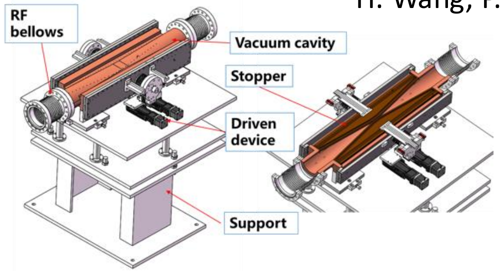
- Collimator design Requirements:
  - Beam stay clear region: 18 σ_x+3mm, 22 σ_y+3mm
  - Impedance requirement: slope angle of collimator < 0.1
- Collimators were implemented to reduce IR loss caused by single beam.
  - 16 sets of collimators were implemented for MDI purpose
  - ~20 sets of collimators were installed for passive machine protection and will also contribute to mitigating beam background.
- With the implementation of collimators, multi-turn beamstrahlung and radiative Bhabha loss particles have been effectively shielded outside the interaction region.
- Shielding has been implemented at both ends of the yoke using the 10 cm of paraffin.

X. Cui's talk at this workshop

S. Bai, Y. Wang, X. Cui

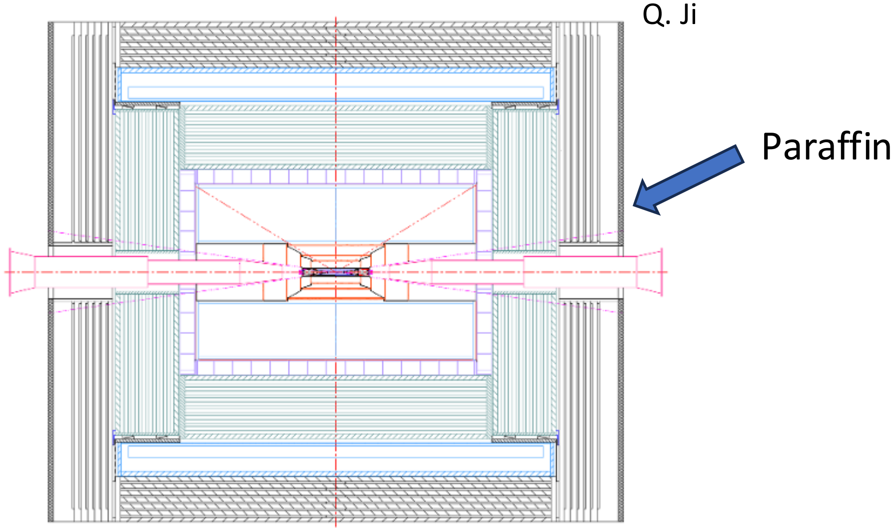


H. Wang, P. Zhang



- for H betatron collimator
- for momentum collimator
- for vertical collimator

Q. Ji



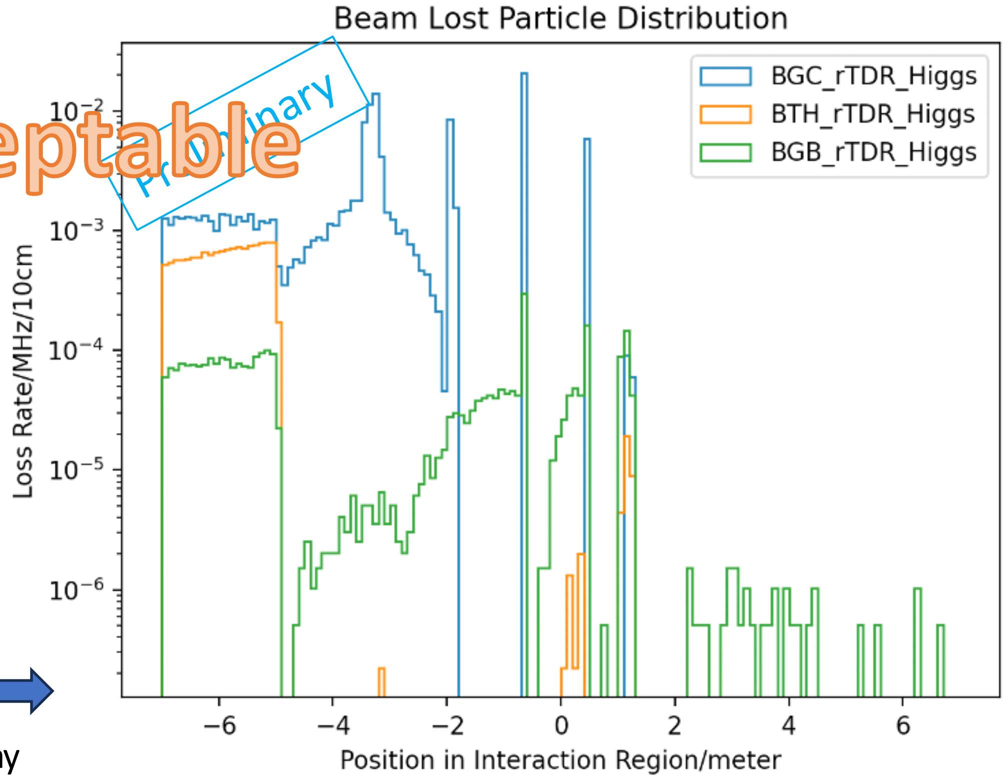
Loss Distribution

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

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

~ 5x, especially upstream

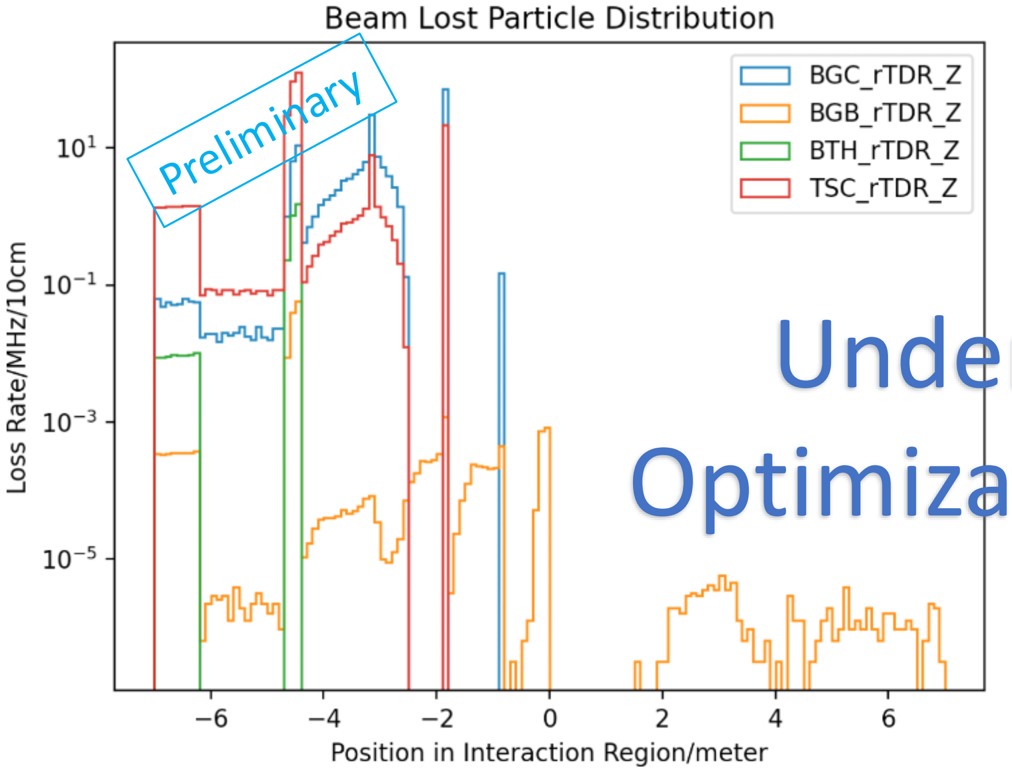
@Higgs



Acceptable

Beam Way

@Z-pole



Under Optimization

Estimation on Impacts in the IR

- Noise on Detector(Backgrounds)
  - Occupancy
  - Estimating using the same tool with Physics simulation
- Radiation Environment(Backgrounds + Signal)
  - Radiation Damage of the Material(Detector, Accelerator, Electronics, etc…)
    - Estimating using the same tool with physics simulation including the dose calculation
    - Or FLUKA
  - Radiation Harm of the human beings and environment
    - Estimating using the same tool with physics simulation including the dose calculation
    - Or FLUKA
- The detector simulation on Ref-TDR is ongoing.

Estimation on the impacts in the IR

- We have obtained a preliminary estimate of the beam-induced background levels in Higgs mode
  - Assume an operational time of 7000hr/yr

BIB Rates Considered @ Higgs

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

	50MW Higgs, 346ns/BX
Pair Production	~1.82GHz in IR
Beam Thermal Photon	~0.36MHz/beam in IR
Beam Gas Bremsstrahlung	~0.04MHz/beam in IR
Beam Gas Coulomb	~0.24MHz/beam in IR

H. Lu and J. Zhang's talk later

Acceptable

Sub-Detectors	Ave. Hit Rate(MHz/cm2)	Max. Hit Rate(MHz/cm^2)	Max. Occupancy(%)	Ave. TID(Gy/yr)
Vertex	0.49	0.61	0.022	~21000
ITK	0.0021	0.25	0.025(Strip)	128
TPC	0.092	0.20	0.0028	23.4(Supporting)
OTK – Endcap	0.0002	0.0006	0.35(Strip)	6.95
ECal – Endcap	0.011/bar	0.3/bar	0.0008	0.322
HCal – Endcap	0.002/GS	0.05/GS	0.0005	0.044
Muon – Endcap	0.00000001/cell	0.00002/cell	0.006	0.21
LumiCal – Crystal	3.37	7.82	9.1	2610

Benchmark – Experiments

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

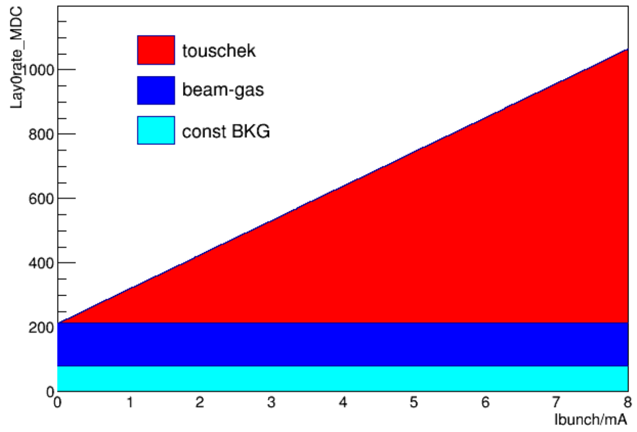
$$S_t \cdot D(\sigma_{x'}) \cdot \frac{I_t \cdot I_b}{\sigma_x \sigma_y \sigma_z} + S_g \cdot I_t \cdot P(I_t) + S_e$$

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

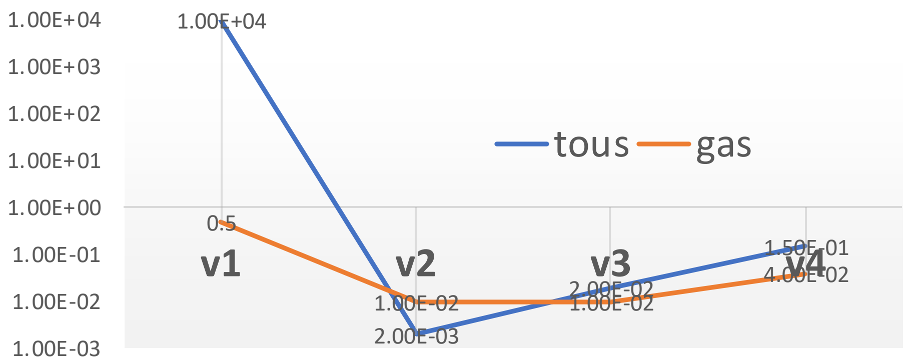
BESIII Benchmark

- BG experiments on BEPCII/BESIII has been done several times.
  - The experiment in 2021 separate the single beam BG sources, the data/MC ratio has been reduced due to the improvement of the IR model and the study of beam–beam.

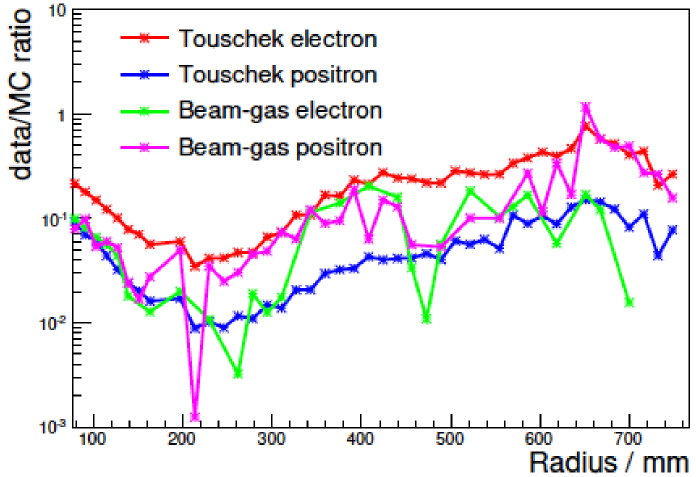
H. Shi, B. Wang. H. Shi et.al



BG separation on 1st layer MDC



Data/MC radio improvements on 1st layer MDC

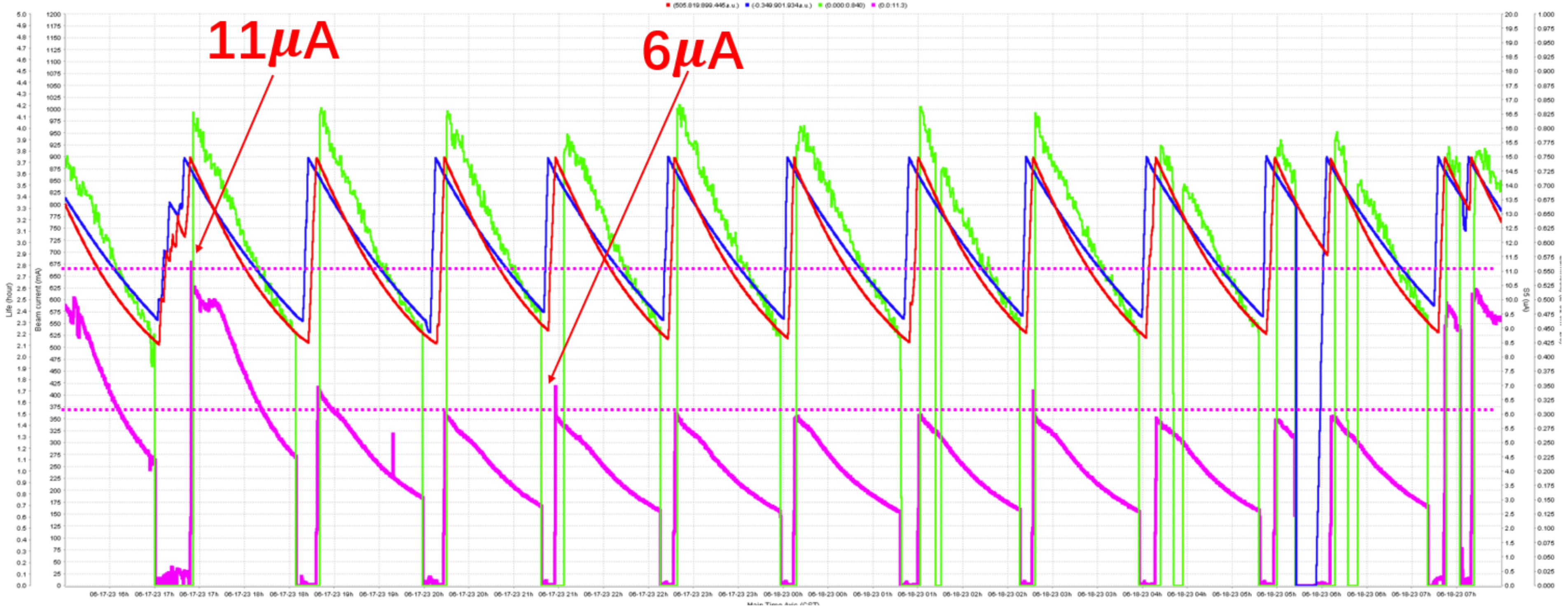


Data/MC radio in MDC

BESIII Benchmark

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

B. Wang



Summary & Outlook

- The study on Beam induced background is very important, including for a machine at the design phase. As well as the Design of MDI and IR Region.
- The importance of the beam induced backgrounds contains two main aspects:
  - The impact on the detector signal(noise)
  - The radiation caused by the beam induced backgrounds, the harm caused by the radiation.
- For the MDI region, we are updating the whole design to Ref-TDR Phase, and we are carefully design the layout and key components to make it works better.
- For the future high energy machine like CEPC,
  - We have updated the simulation to adopting TDR phase. The work on Higgs mode is almost done and acceptable, the work on Z mode is on going, the work on the other two mode will be done soon.
  - The mitigation helps a lot. However, we are sure to need more.
  - The benchmark of the simulation and the data from experiments are always needed.
  - Any kind of help/contribution/cooperation is appreciated.

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Thank You

Backup

MDI Parameter Table

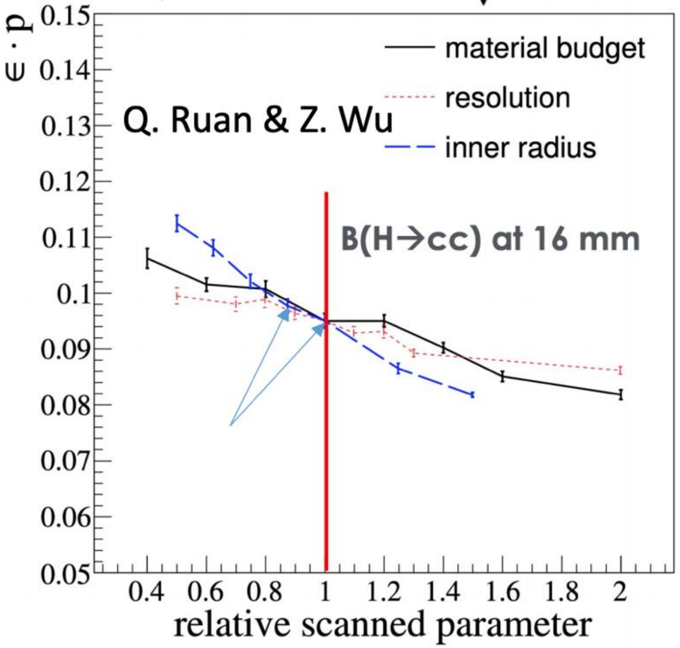
S. Bai

	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		3.2/2.8T	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	0.56~0.7/0.9~1.1m				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	

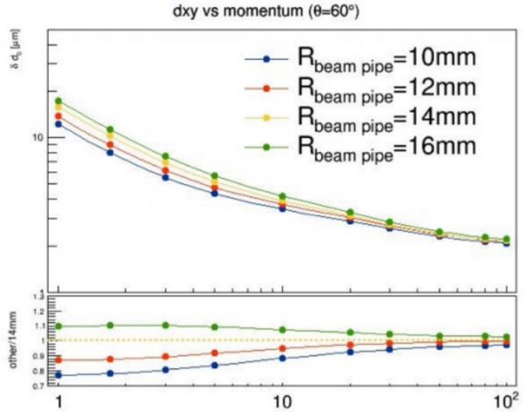
Physics Gains for 20mm Be

- First estimates made with fast simulation and scaling

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



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

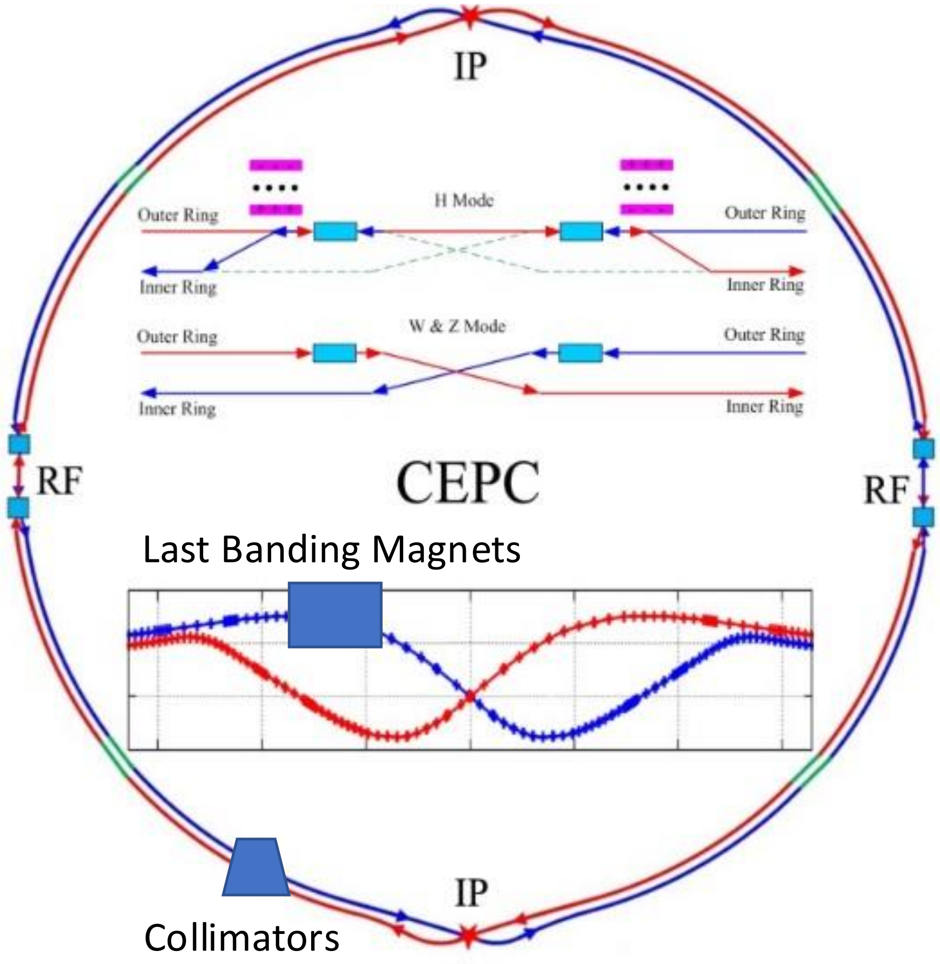


H. Zeng

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

G. Li

Map of the MDI Study



Accelerator

- IP Feedback
- BG Simulation
- LumiCal
- Vacuum Chamber
- SR Masks
- QD0/QF1
- Anti-Solenoid
- Cryostats
- BPMs
- Instability&Impendance
- Cooling
- Shielding
- Assembly&Supporting
- Alignment
- Connecting System
- Vacuum pumps
- Last Bending Magnet
- Collimators
- Control

Detector

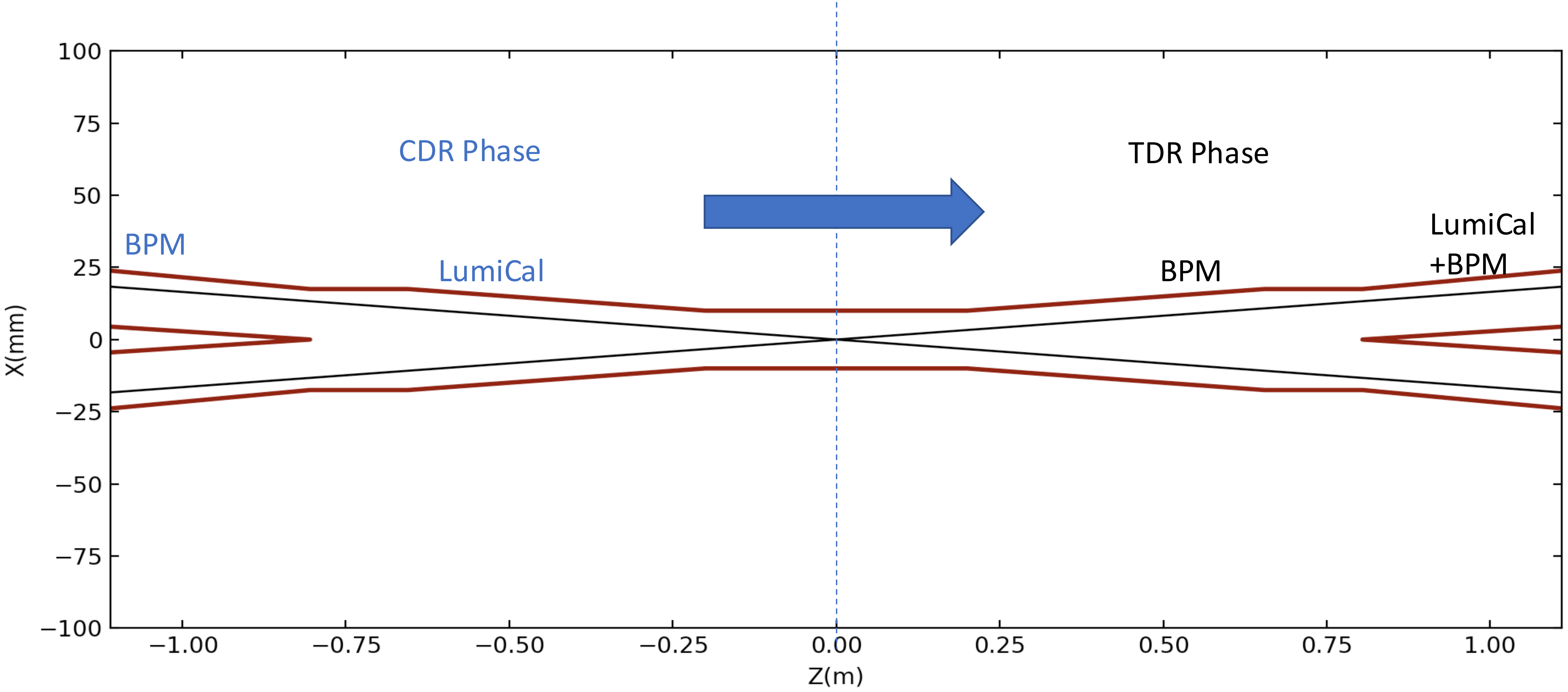
- Central Beam Pipe
- Vertex Detector
- LumiCal
- Silicon Tracker
- TPC
- Hcal
- Ecal
- Solenoid
- Yoke
- Muon Detector
- Hall
- BG Simulation&Shielding
- Software Geometry
- Alignment&Assembly
- Electronics
- Cryogenic
- Radiation Protection
- Booster

Beamlife time @ 50MW

D. Wang

	tt	Higgs	W	Z
***Bhabha Lifetime* (min)**	80	40	60	85
***Quantum Lifetime (lattice+BB+BS)* (min)**	78	40	45	100
***Touschek Lifetime* (hour)**	1404	119	30	6
***Vacuum Lifetime* (hour)**	24	14	8	5
Beam-gas scattering (hour)	122	16	9	5.2
Beam-gas bremstrahlung (hour)	60	207	222	552
Beam-gas electron scattering (hour)	165099	340963	167888	215395
Beam-gas electron bremstrahlung (hour)	62	221	247	565
***Quantum Lifetime* (hour)**	10^{14}	10^{12}	10^{9}	10^{15}

New Beampipe Design – Cryo to Cryo

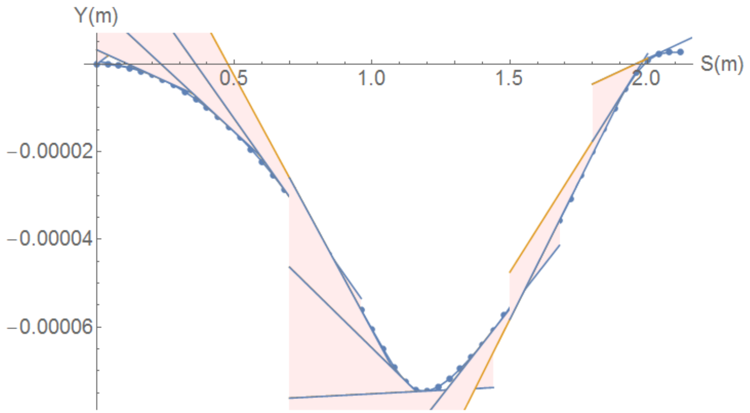


The range between 2 cryostat chambers would be -1.11m~1.11m

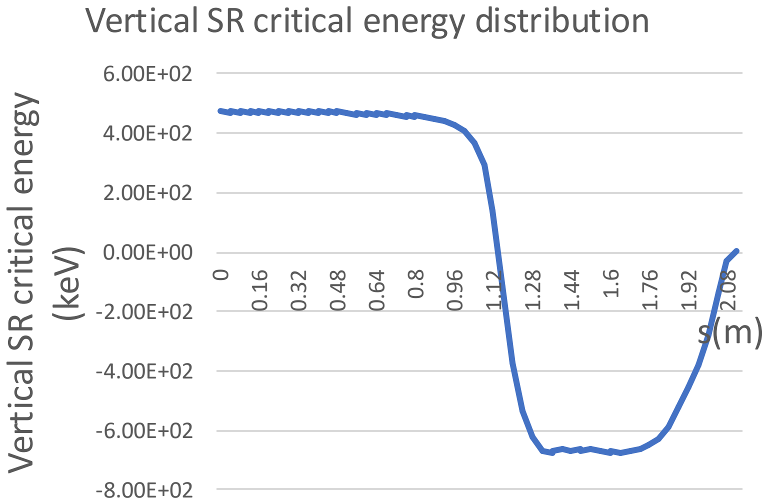
SR from solenoid combined field

S. Bai

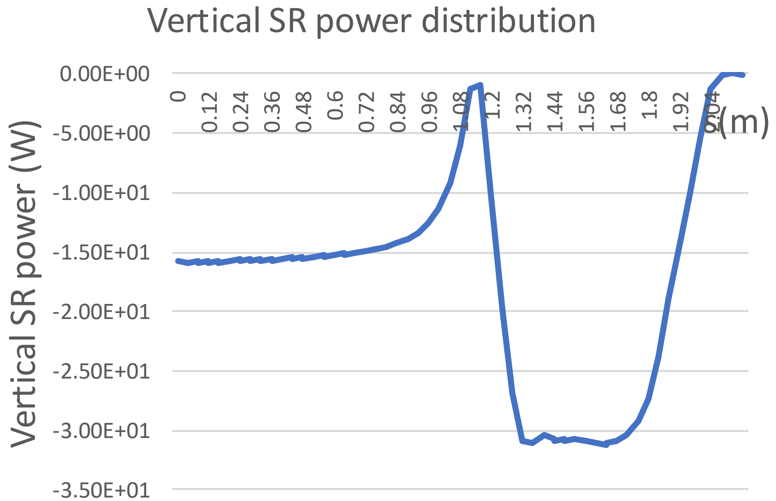
- Horizontal trajectory will couple to the vertical
- Due to the sol+anti-sol field strength quite high, maximum~4.24T, transverse magnetic field component is quite high.
- SR from vertical trajectory in sol+anti-sol combined field should be taken into account.



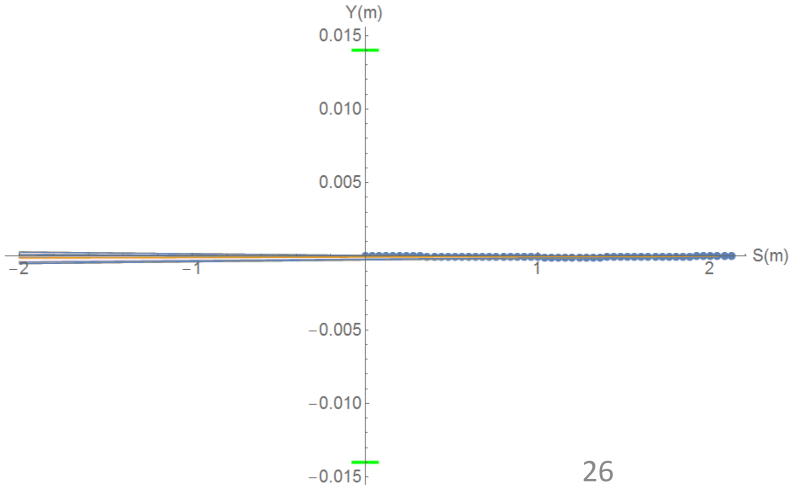
- SR fan is focused in a very narrow angle from -116urad to 131urad
- SR will not hit Berryllium pipe, and no background to detector.
- SR will hit the beam pipe ~213.5m downstream from IP
- Water cooling is needed.



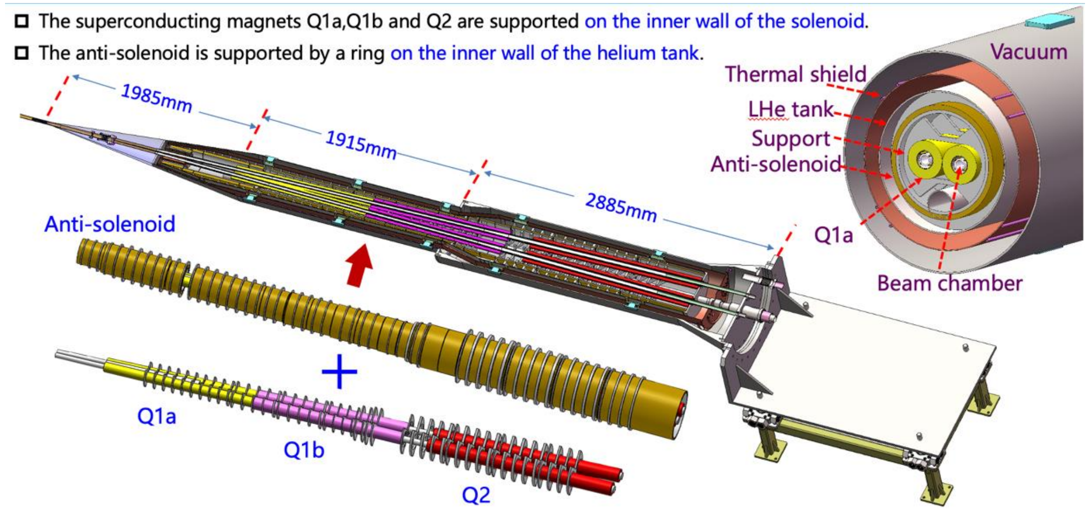
Maximum: 670keV



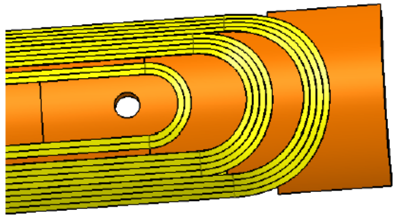
Maximum: 31W



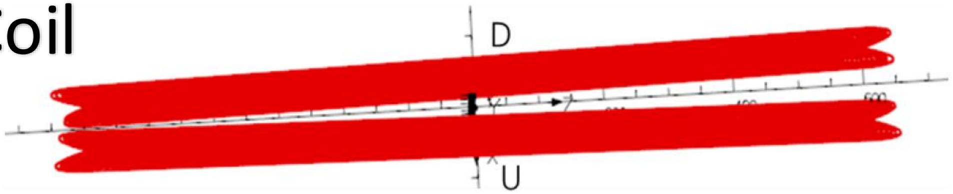
Engineering efforts on several key components



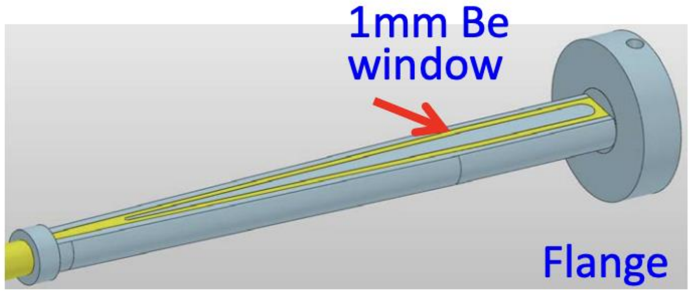
Cryostat Chamber



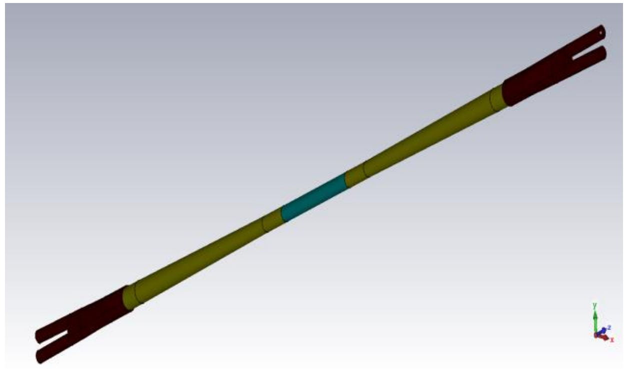
SC Magnets/Coil

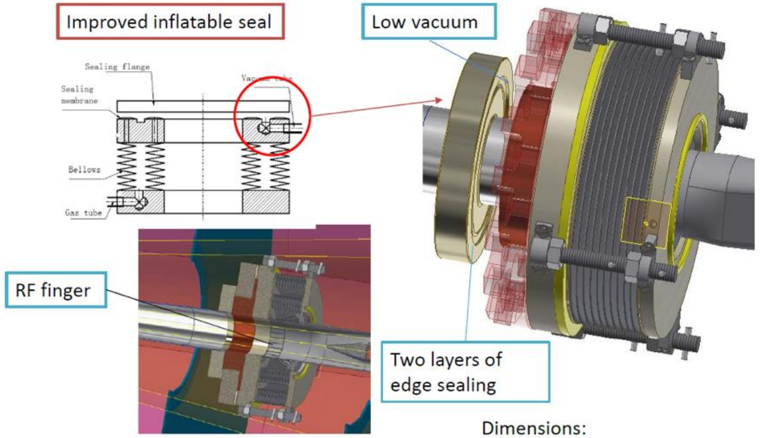


RVC



Lumi Window





- Replace the sealing membranes by two layers of edge sealing.

Dimensions:
- Transversal: Max. φ174mm
- Longitudinal: ~83mm

Tungsten alloy vacuum chamber