Study status of the CEPC Machine-Detector Interface(MDI) and Interaction Region(IR)

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On behalf of the CEPC MDI Working Group

ICHEP 2022, Accelerator Parallel Session

2022.07.07, Bolgona, Italy(Zoom)

Outline

- Introduction
- Current Study Status
  - Physics Design
    - Layout/Components/Parameters
    - Heat Deposition/Radiation Levels
  - Engineering effort
    - Mechanical Design of components(beampipe, magnets, cryostat, connector…etc)
    - Integration/Installation Scheme
- Summary & Outlook

Introduction

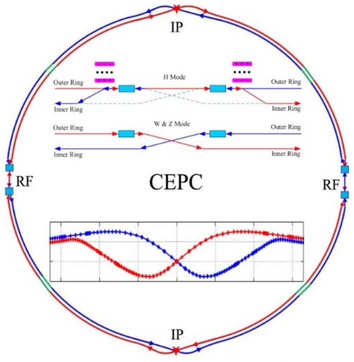
- MDI stands for "Machine Detector Interface"
  - Interaction Region and other components
  - 2 IPs
  - 33mrad Crossing angle
- Flexible optics design
  - Common Layout in IR for all energies
  - High Luminosity, low background impact, low error
  - Stable and easy to install, replace/repair

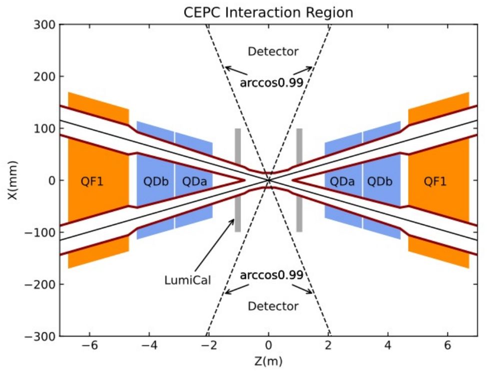
	ttbar	Higgs	W	Z
Number of Ips		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	[illegible]
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	[illegible]	[illegible]
Bunch length (SR/total) [mm]	2.2/2.9	[illegible]	[illegible]	2.5/8.7
Energy spread (SR/total) [%]	[illegible]	[illegible]	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	[illegible]	[illegible]	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	[illegible]	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

2021 Improved Design

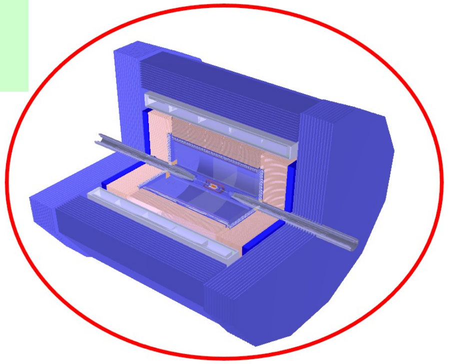
67%⇑

259%⇑

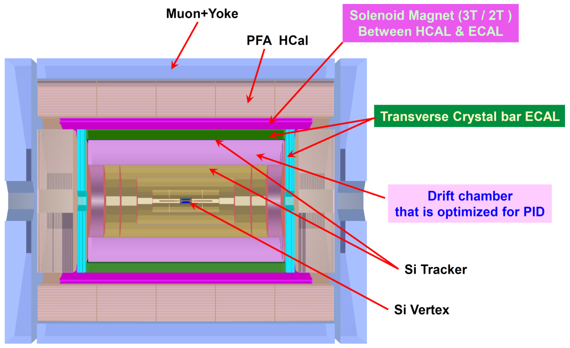




Particle Flow Approach
(ILD-like)



4th Detector concept



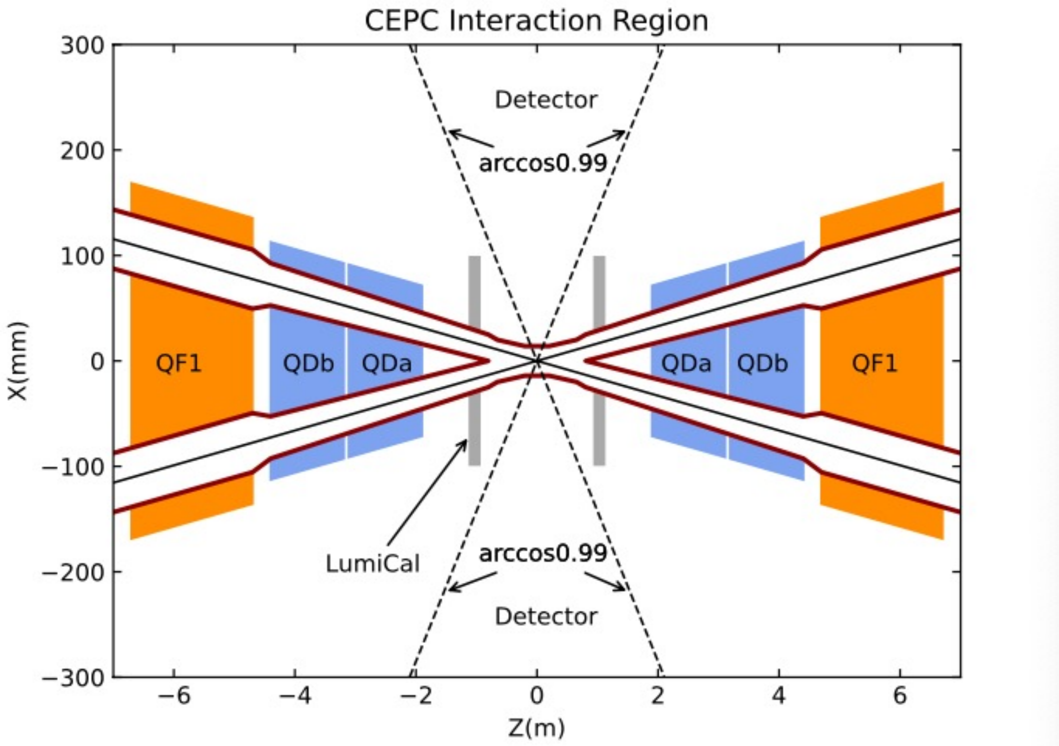
MDI Parameter Table

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	

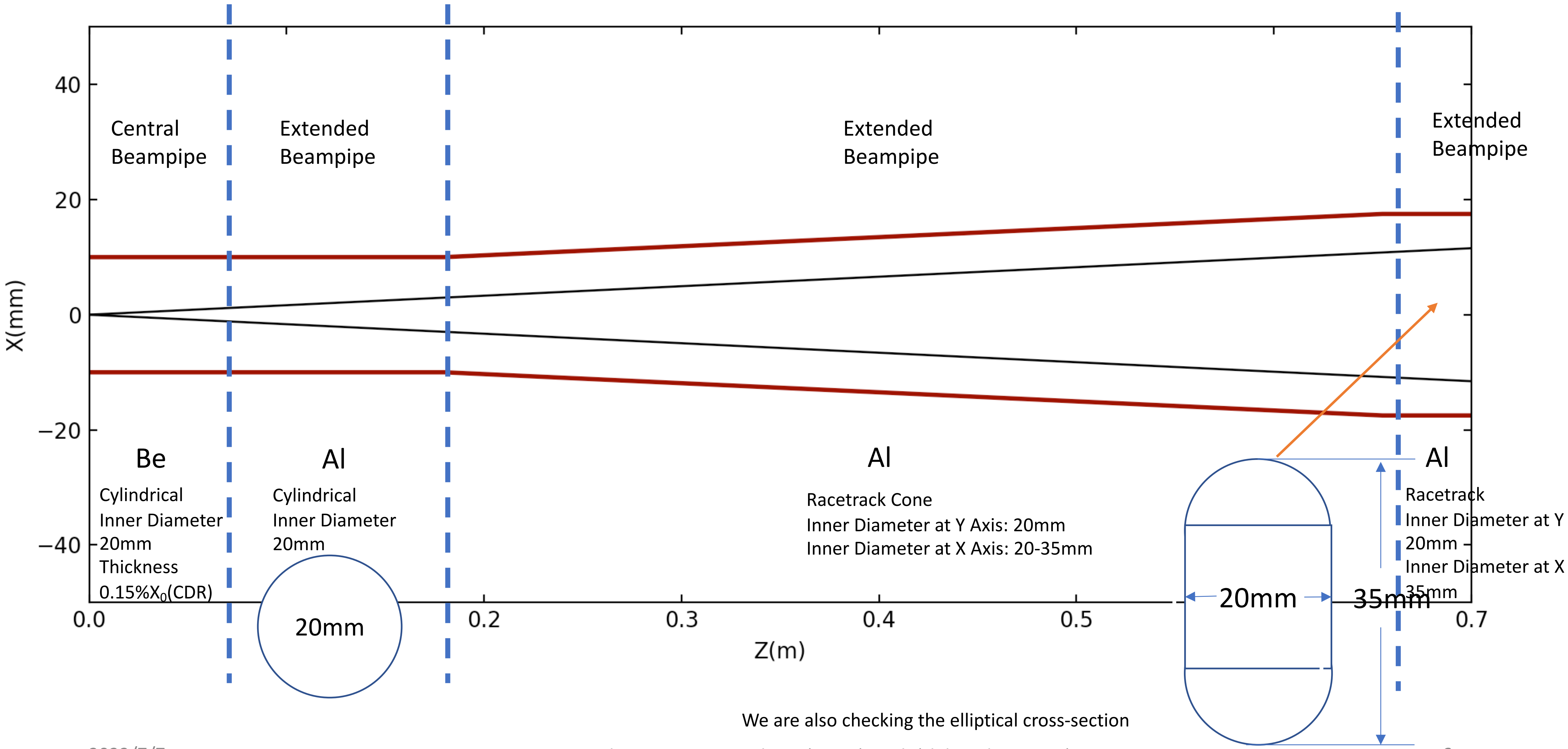
Physical Design

- Interaction Region Layout/Parameters
  - L* = 1.9m / Detector Acceptance = 0.99
- Estimation of the Radiation Level/Heat Deposition



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

New Beampipe Design – Half Detector pipe



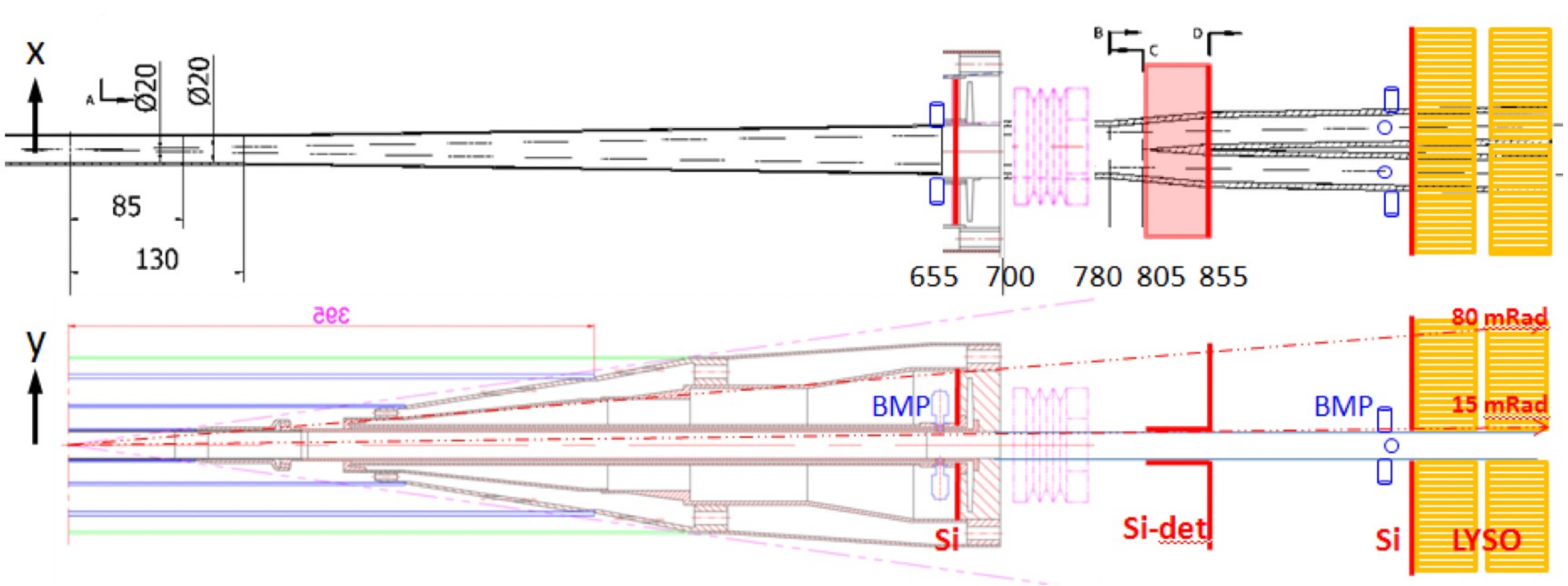
We are also checking the elliptical cross-section

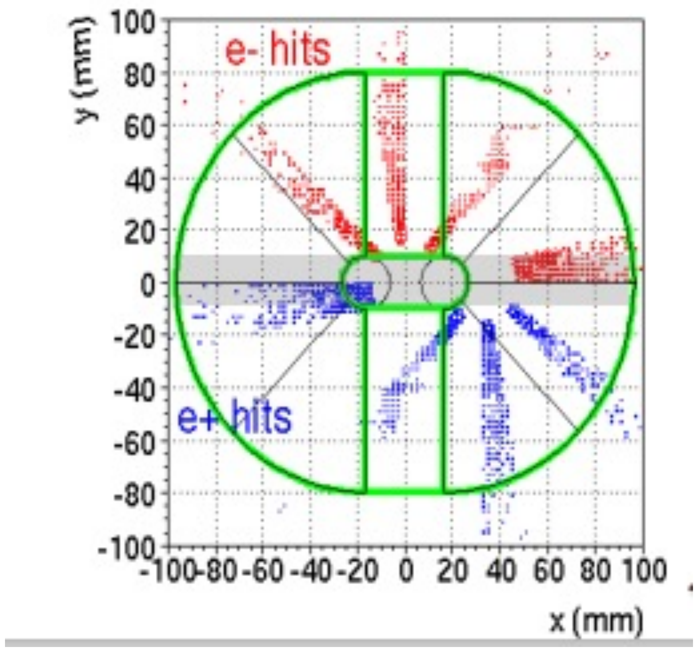
Interfaces between pipe and LumiCal

With LumiCal:

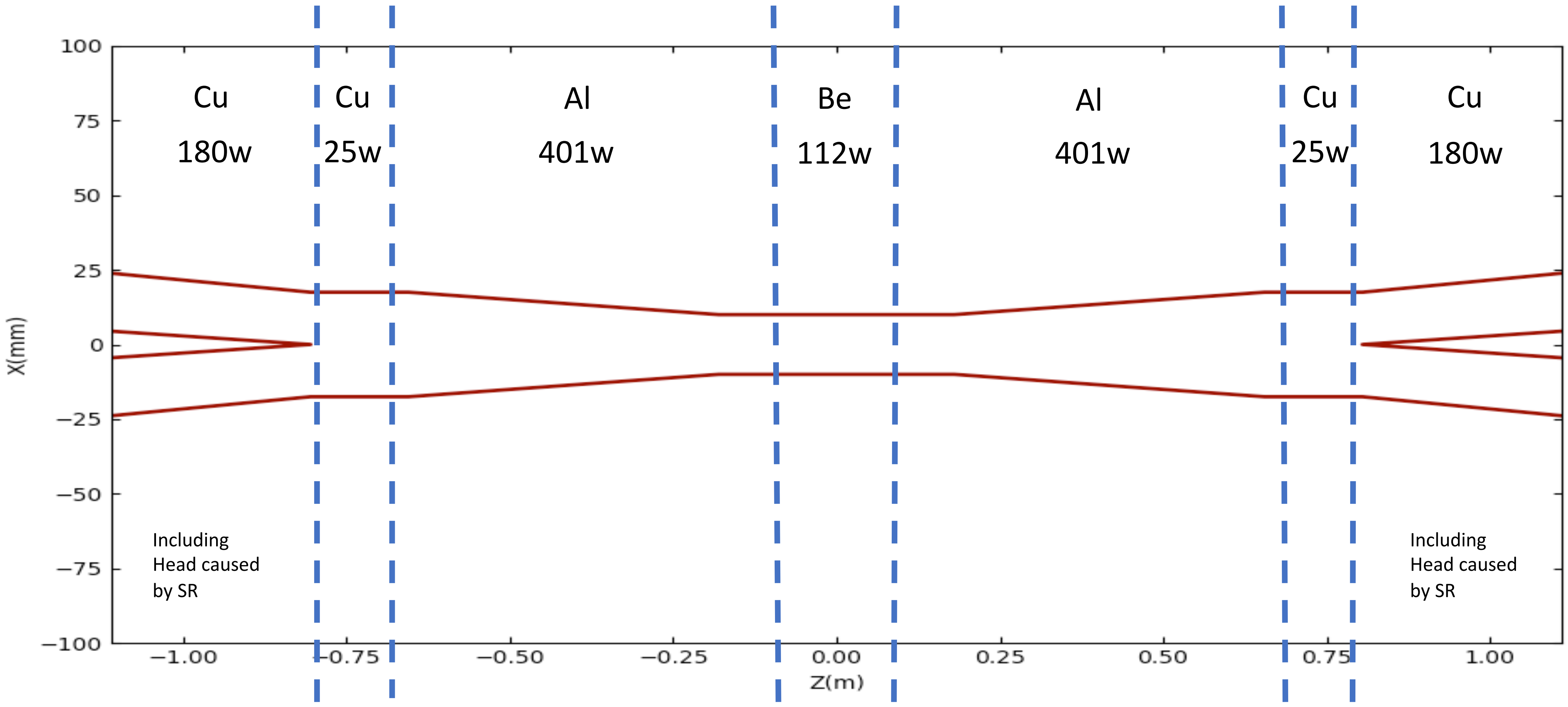
- Will not be putted at detector beampipe region.
  - Therefore, the material of extended beam pipe could be changed.
- The material and thickness(material budget) of the flange&bellow needs to be calculated.

S. Hou





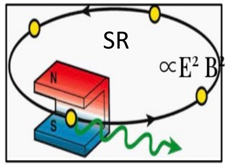
Heat Deposition



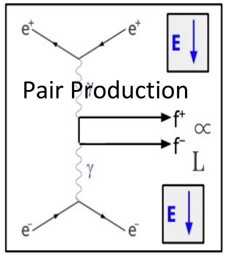
We are considering to change the material beyond bellows to Al due to demands of LumiCal, it wouldn’t affect heat deposition to much

Background Estimation

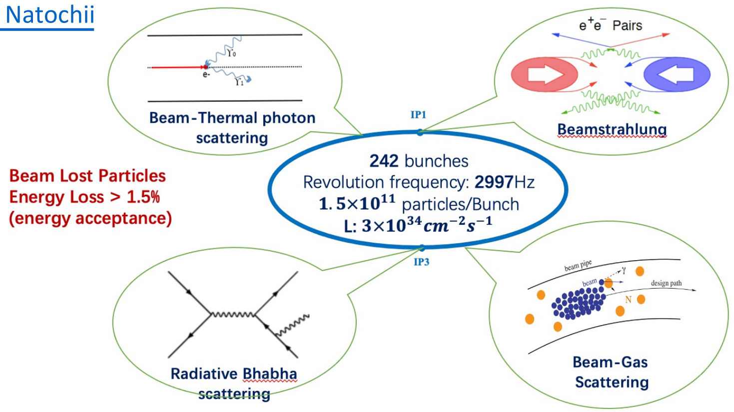
- Simulate each background separately
- Whole-Ring generation for single beam BGs
- Multi-turn tracking(50 turns)
    - Using built-in LOSSMAP with one step ahead output
    - SR emitting/RF on
    - Radtaper on
    - No detector solenoid
- Errors implemented
    - High order error for magnets
    - Beam-beam effect
- 2 IR considered(sum)
- Plan to study the photon bkgs generated during all processes, both single beam and luminosity related.



A. Natochii

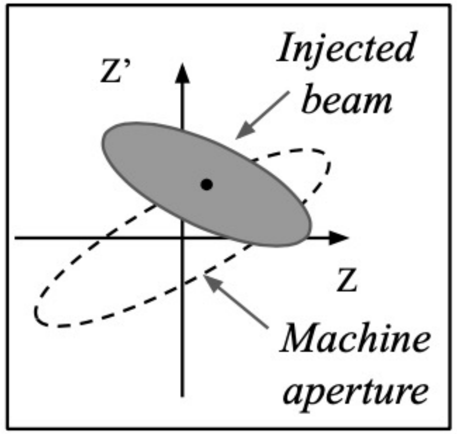


Photon BG



Beam Loss BG

A. Natochii



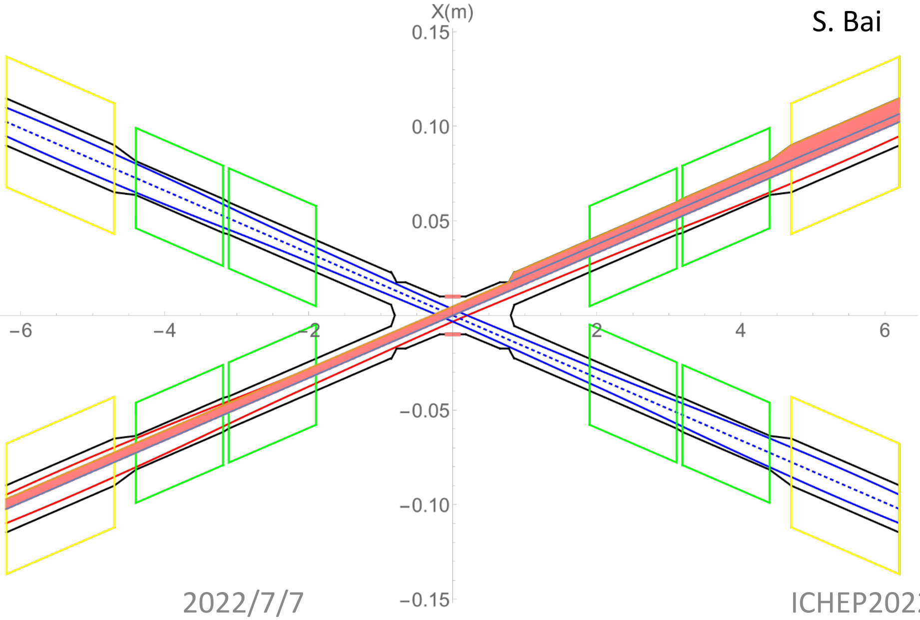
Injection BG

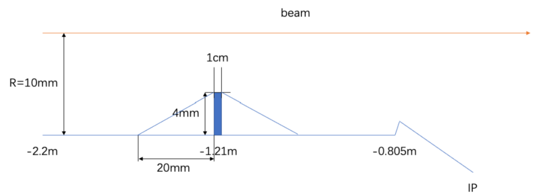
Background	Generation	Tracking	Detector Simu.
Synchrotron Radiation	BDSim	BDSim/Geant4	Mokka/CEPCSW
Beamstrahlung/Pair Production	Guinea-Pig++	SAD	
Beam-Thermal Photon	PyBTH[Ref]		
Beam-Gas Bremsstrahlung	PyBGB[Ref]		
Beam-Gas Coulomb	BGC in SAD		
Radiative Bhabha	BBBREM		

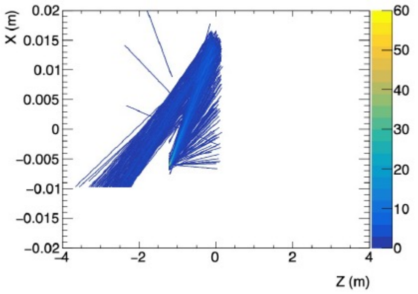
SR BG & Mitigation

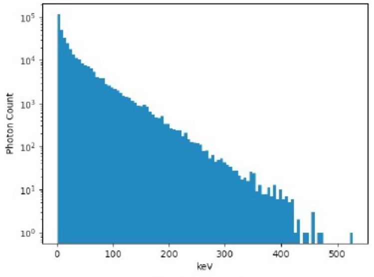
- The SR must be dealt with high priority when designing the circular machine. At CEPC, there would be no SR photons hitting the central beam pipe directly in normal conditions
- However, some secondaries generated within QD would hit the detector beampipe, even the beryllium part. Therefore, the mitigation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

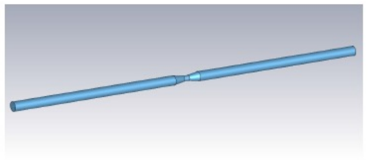
S. Bai

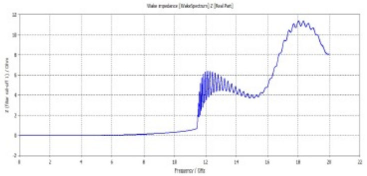










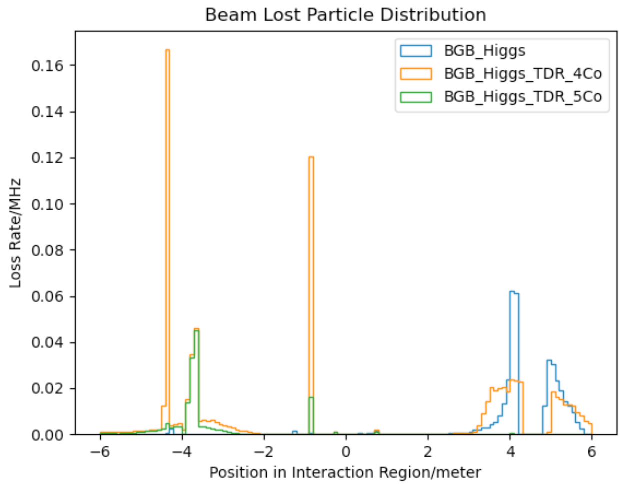


Y. Sun

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-5μmAu	216.0
nomask	39400.0

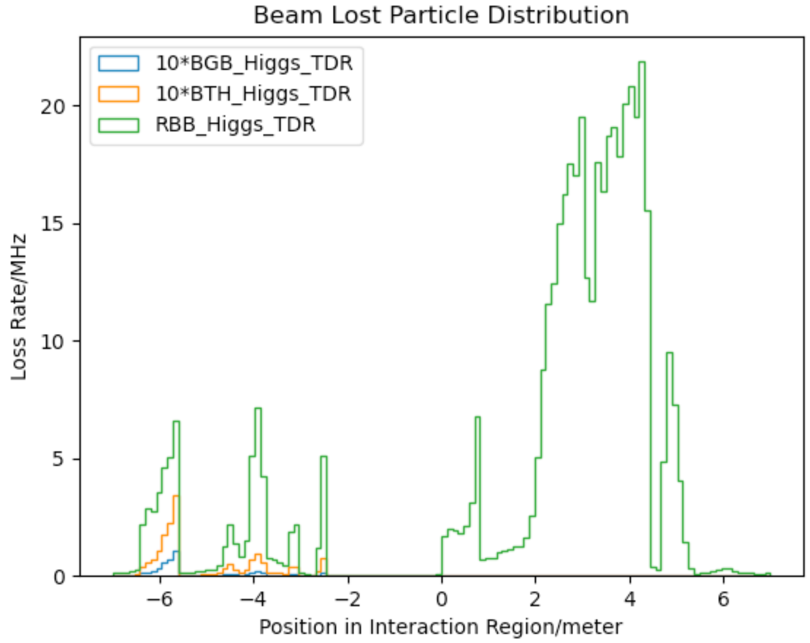
Mitigation of the BG - Collimator

- 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 sets were implemented to mitigate the Beam-Gas background



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



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 plan to have double check on detector simulation(Mokka/CEPCSW/FLUKA)
  - We learn that the background impact on LumiCal must be studied.

Scaling Results on 1st layer of vertex detector

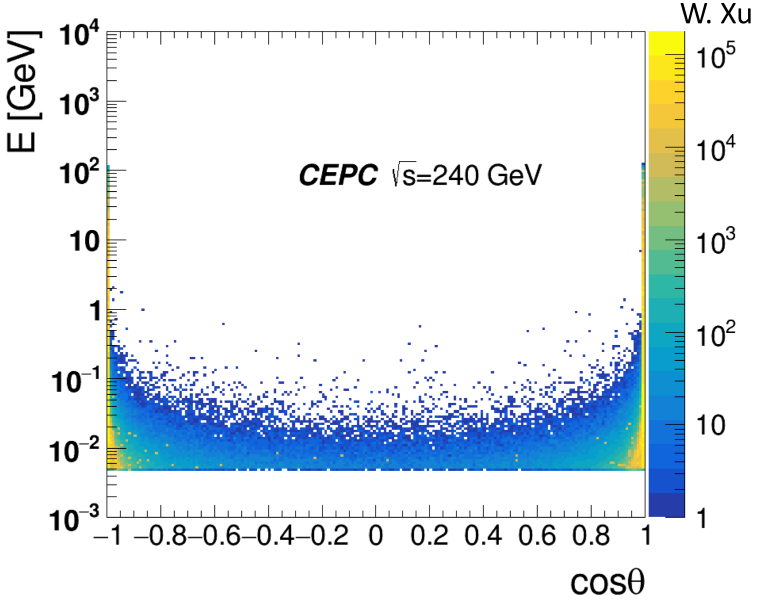
W. Xu

	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

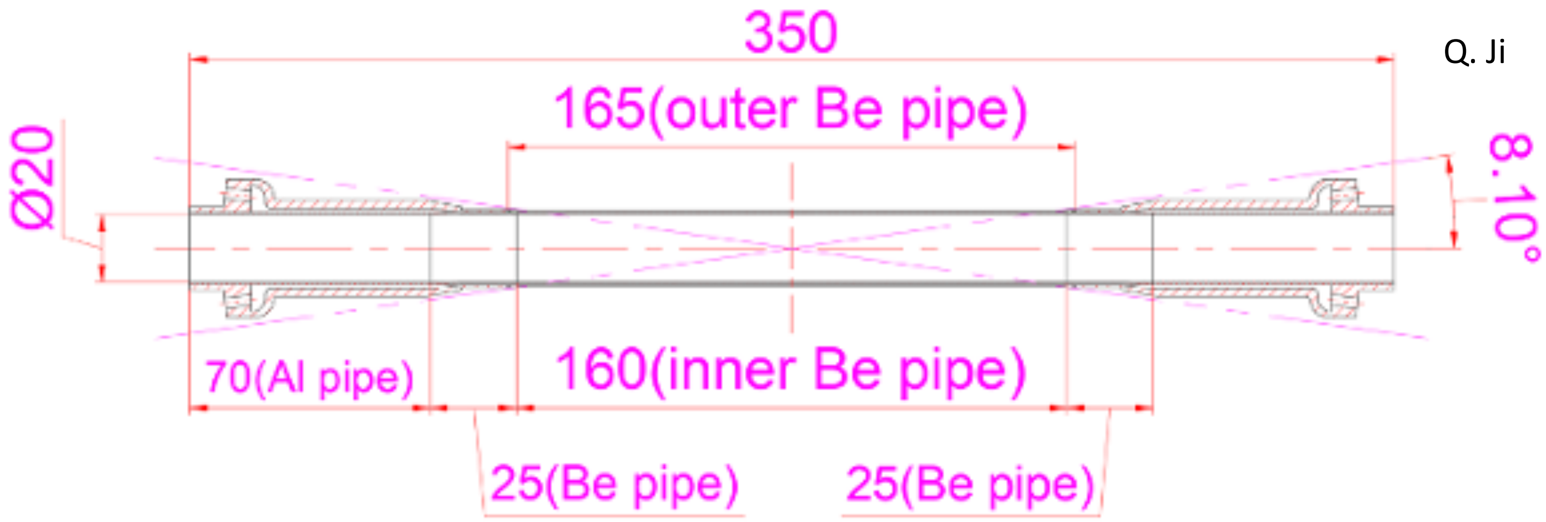
TDR Pair-Production Distribution

W. Xu



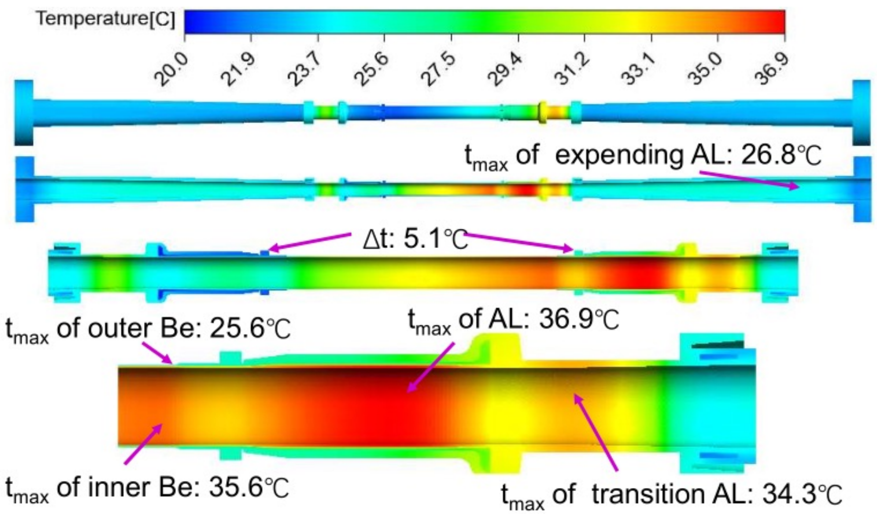
Mechanical Design of the detector beam pipe

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



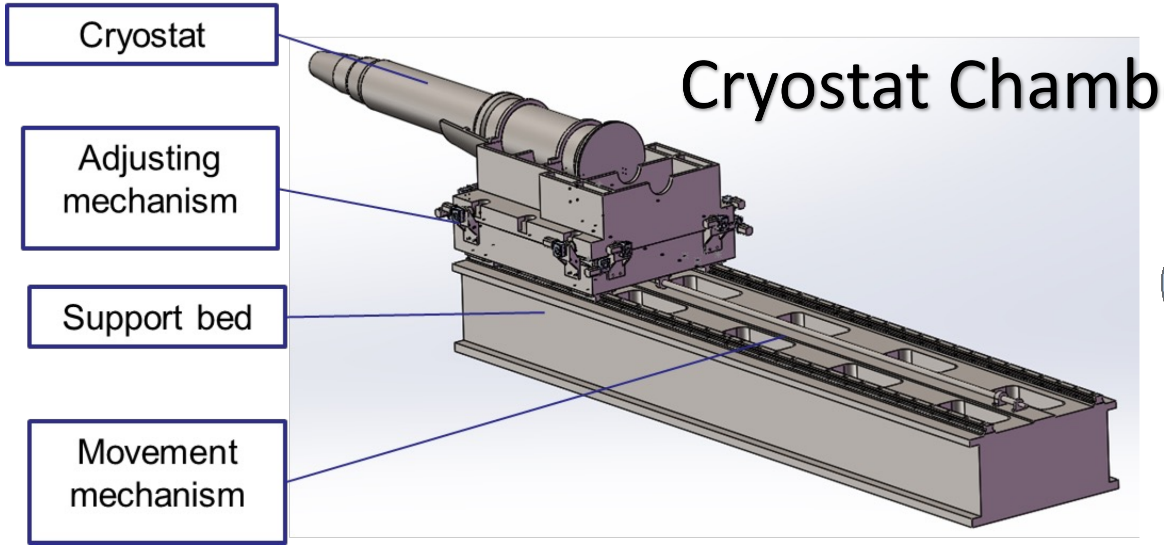
Q. Ji

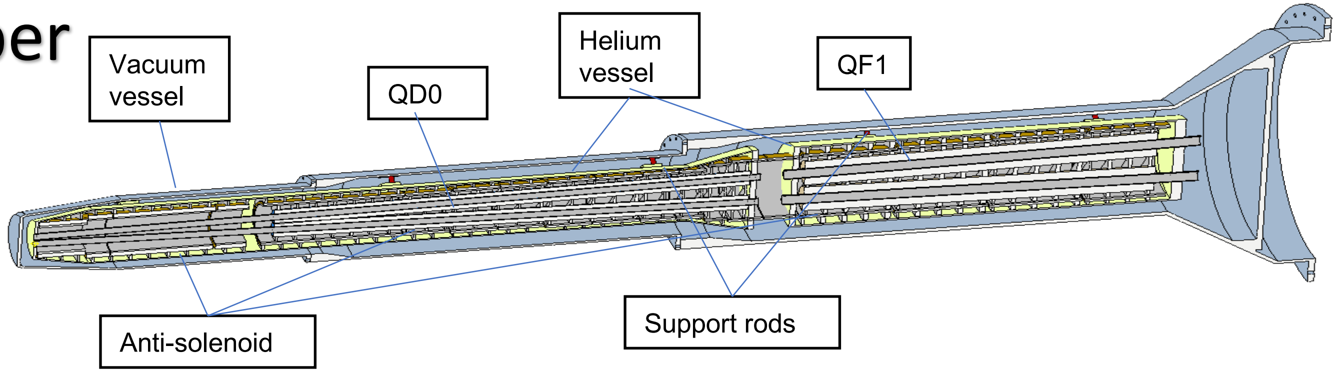
- Coolant might be paraffin or water.
  - If water was chosen, then the corrosion on Be must be studied.
- Preliminary analysis shows that the dynamic temperature/pressure could meet the requirements.



Engineering efforts on several key components

Cryostat Chamber





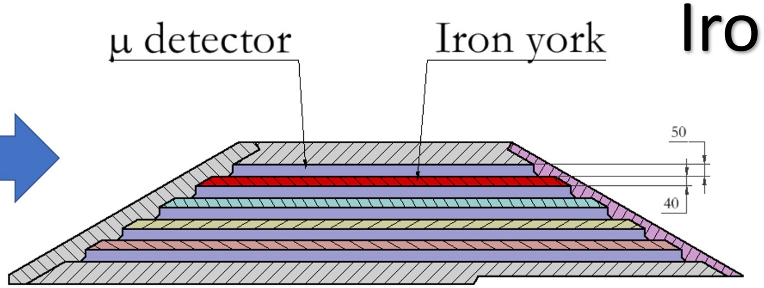
Iron Yoke

The 2021 version：

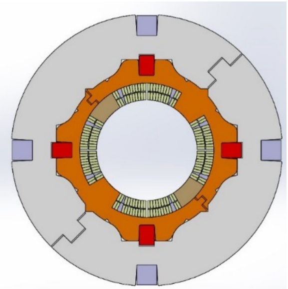
Iron Yoke thinkness：50mm
μ derctor thinkness：40mm

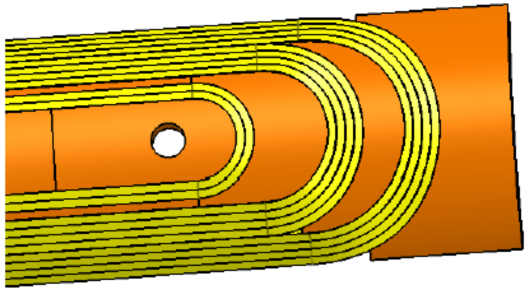
The 2022 version：

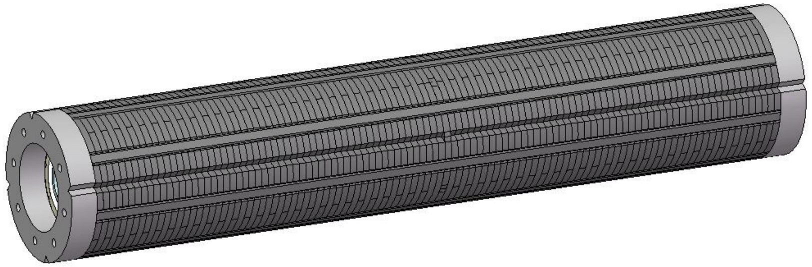
Iron Yoke thinkness：40mm
μ derctor thinkness：50mm



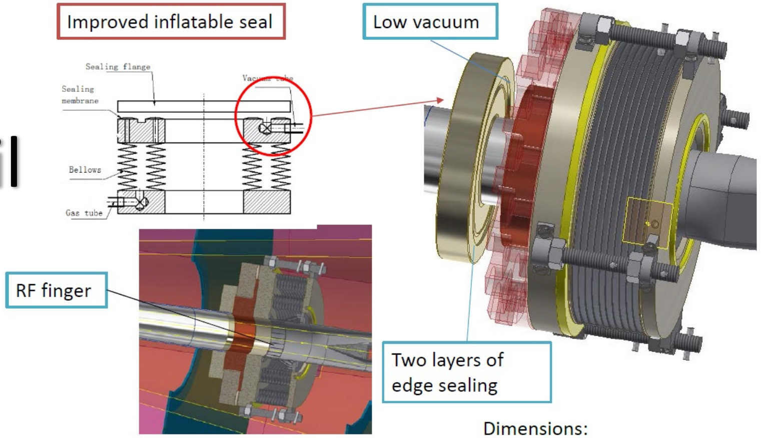
SC Magnets/Coil







RVC

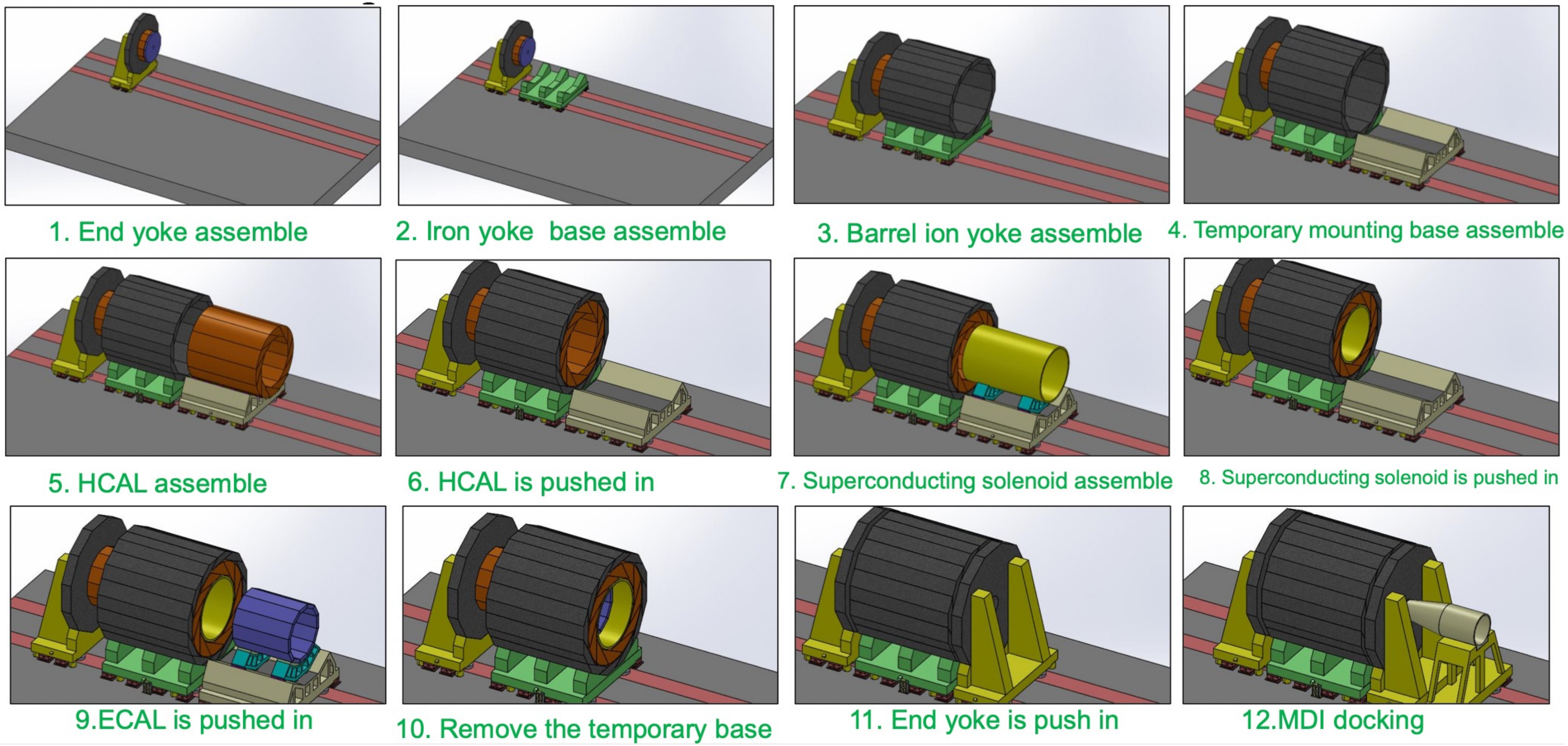


- Replace the sealing membranes by two layers of edge sealing.

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

Preliminary Installation Scheme

- One of the preliminary (conceptual) installation scheme of the CEPC detector.
  - Still facing lots of troubles and challenges.
  - Needs to be optimized further.



Summary & Outlook

- We are moving our design to TDR phase.
  - Layout & Physics design has been updated.
  - The heat deposition calculation was done.
  - The estimation of radiation level caused by BG is under simulation.
  - The mechanical design is updating, including the thermal analysis based on the deposited heat.
- The optimization and validation of current design is always needed.
  - The BESIII backgrounds experiment was done last/this summer. The data has been taken and under analysis.
  - Validate our BG simulation codes using BEPCII and SuperKEKB.

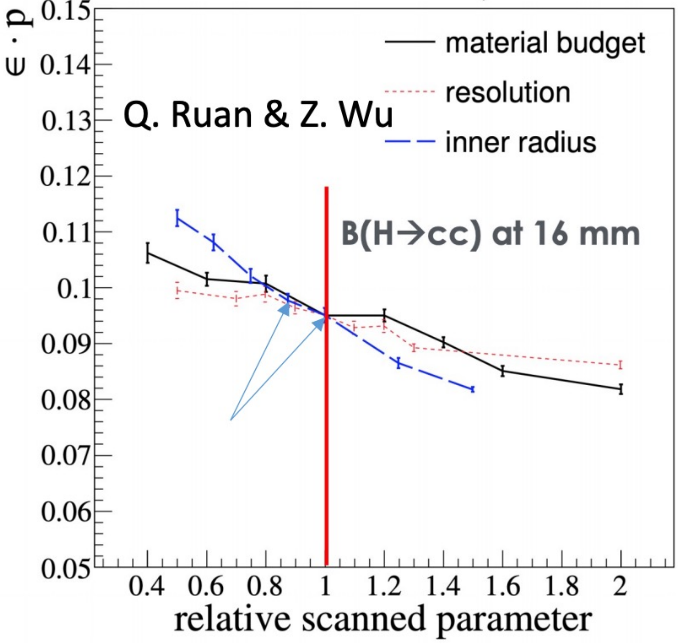
Thank You

Backup

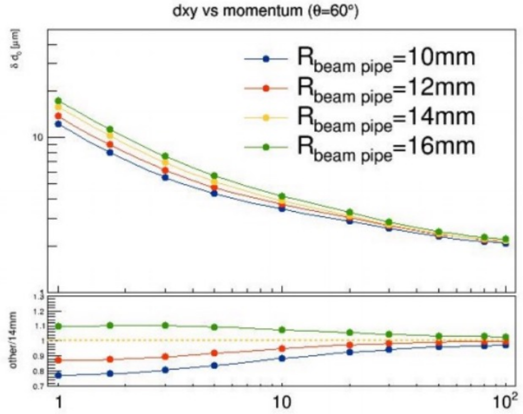
Physics Gains for 20mm Be

- 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

Inputs – Accelerator Parameters

CEPC

2018 CDR Baseline Design

	Higgs	W	Z (3T)	Z (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5 × 2			
Piwinski angle	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^*/β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	2.98	[illegible]	
Bunch length σ_z (mm)	4.4	[illegible]	[illegible]	
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	46.5[illegible]	[illegible]	[illegible]849.5/849.5/425.0	
Natural Chromaticit[illegible]	[illegible]	[illegible]1161	-491/-1161	-513/-1594
Betatr[illegible]	363.10 / 365.22			
S[illegible]	0.065	0.040	0.028	
H[illegible] (2 cell) (k[illegible]	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime† (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

† include beam-beam simulation and real lattice

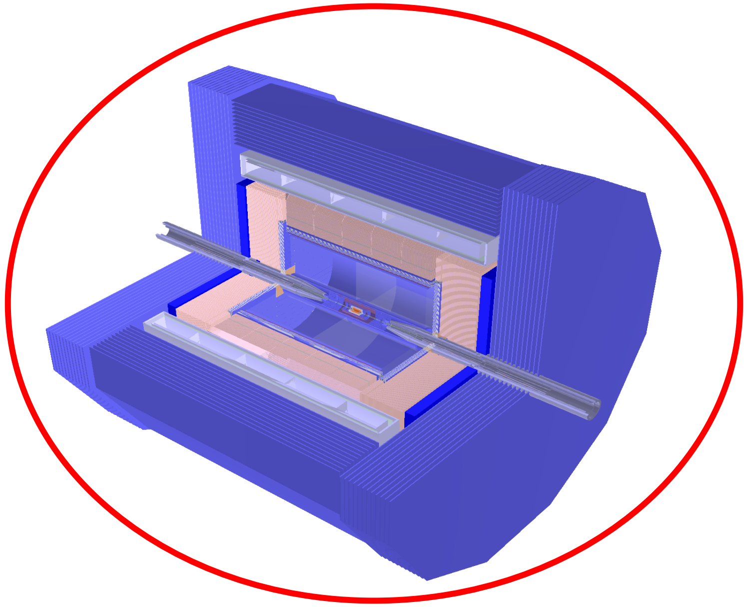
2021 Improved Design

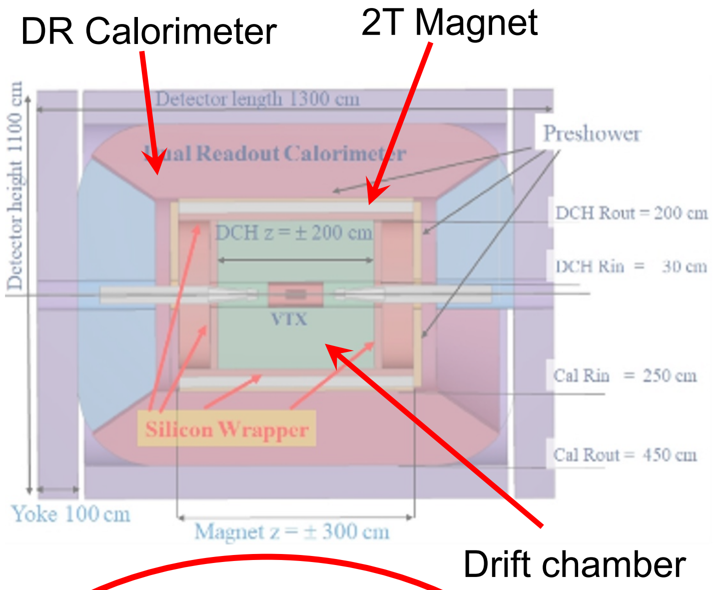
	ttbar	Higgs	W	Z
Number of Ips		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	[illegible]27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	[illegible]	[illegible]/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/[illegible]	[illegible]	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	[illegible]	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3[illegible]	[illegible]/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071[illegible]	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

67%⇑ **259%⇑**

Inputs – Detector Designs

Particle Flow Approach
(ILD-like)

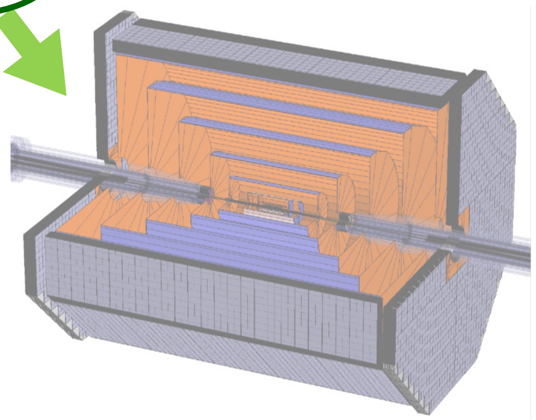


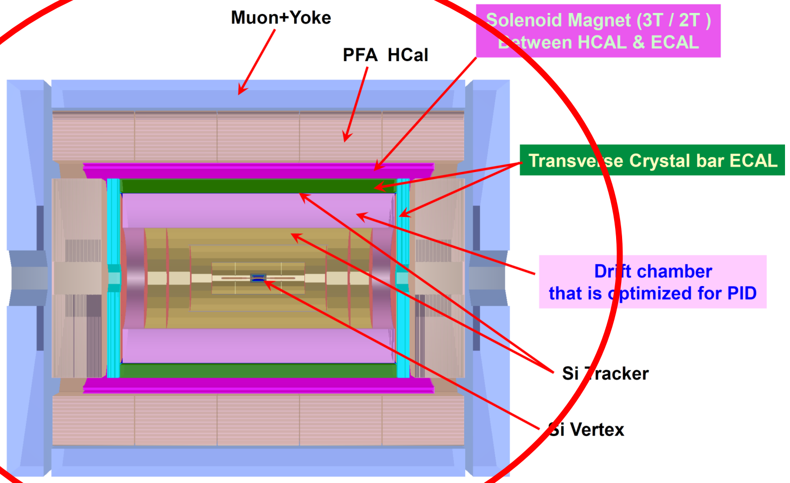


IDEA concept
(also proposed
for FCC-ee)

Si Vertex, Si + TPC, PFA ECal &HCal,

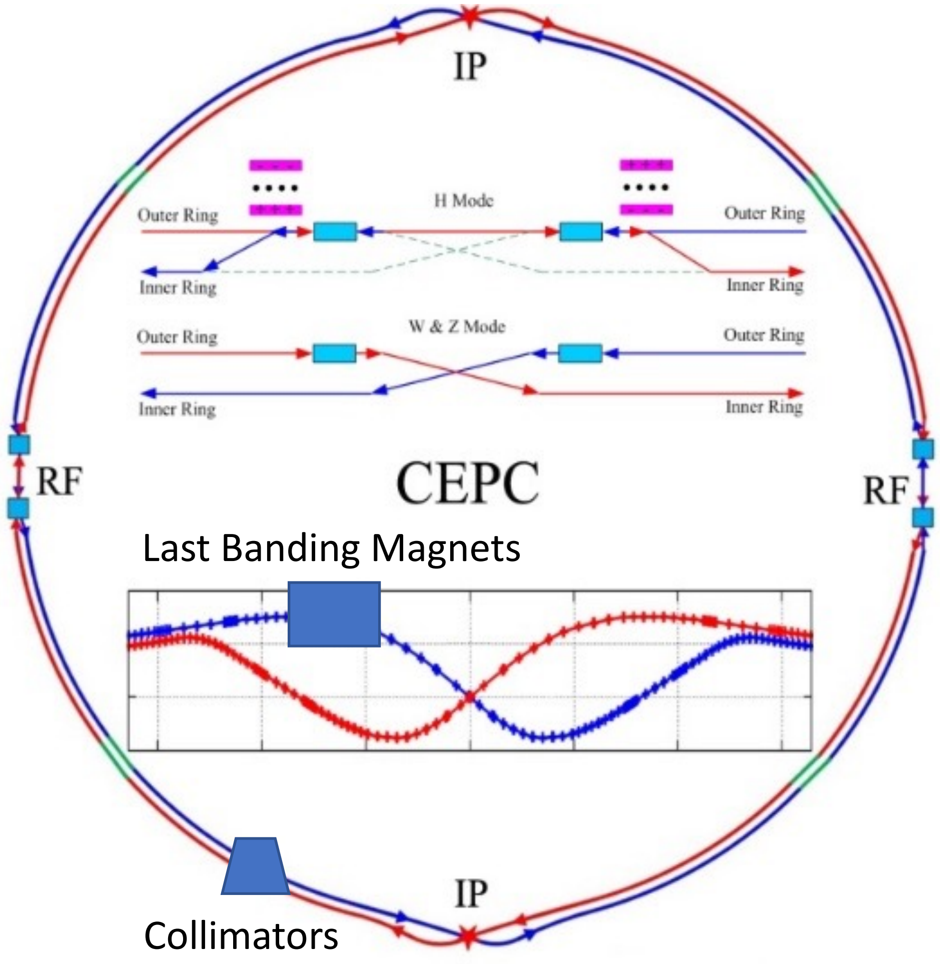
Full Silicon
Tracker
(FST) concept





4th Detector concept

Map of the MDI Study



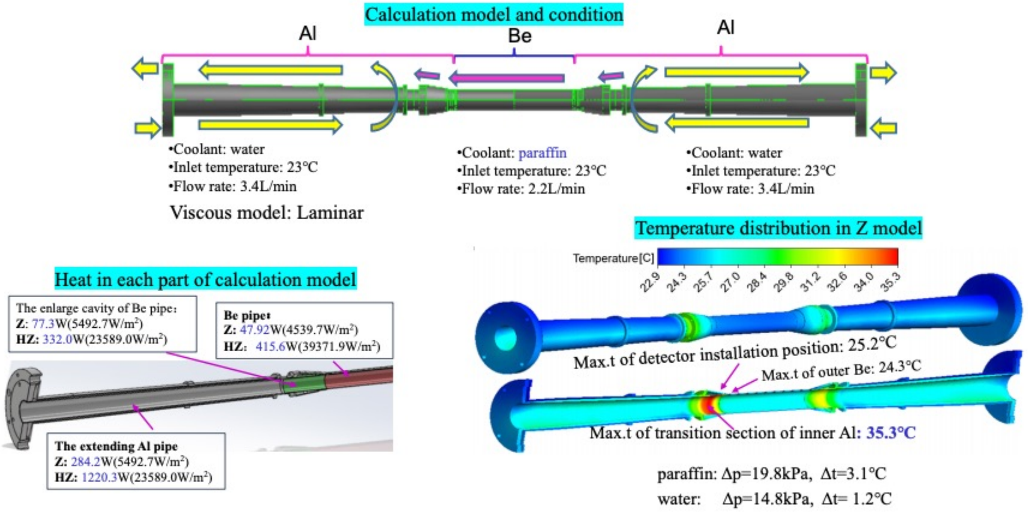
Accelerator

- 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

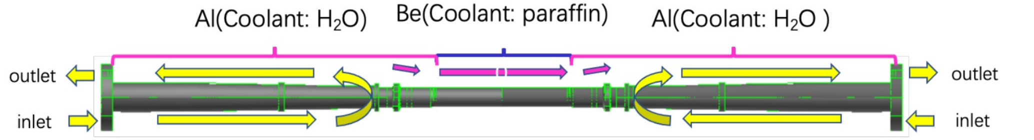
- Central Beam Pipe
- Vertex Detector
- LumiCal
- Silicon Tracker
- TPC
- Hcal
- Ecal
- Solenoid
- Yoke
- Muon Detector
- Hall
- BG Simulation&Shielding
- Software Geometry
- Alignment&Assembly
- Electronics
- Cryogenic
- Radiation Protection
- Booster

Thermal Analysis - CDR



CDR Z parameters

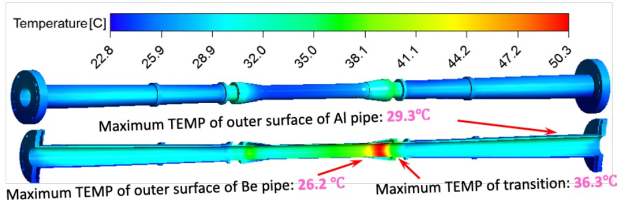
- Pressure drop:
  - Be pipe : 19.8 kPa
  - Al pipe : 19.3 kPa
- TEMP rise:
  - Be pipe : 3.2 ℃ (between the inlet and the outlet)
  - Transition: 13.3 ℃
  - Al pipe : 6.3 ℃
- Temperature rise and pressure drop are in a safe range



Calculation model: laminar

Inlet of Be pipe:
TEMP: 23C°
Velocity: 1.3 m/s
Coolant: paraffin

Inlet of Al pipe:
TEMP: 23C°
Velocity: 1.0 m/s
Coolant: H_2O



Temperature rise:
Be pipe : 3.2 ℃
Transition: 13.3 ℃
Al pipe : 6.3 ℃

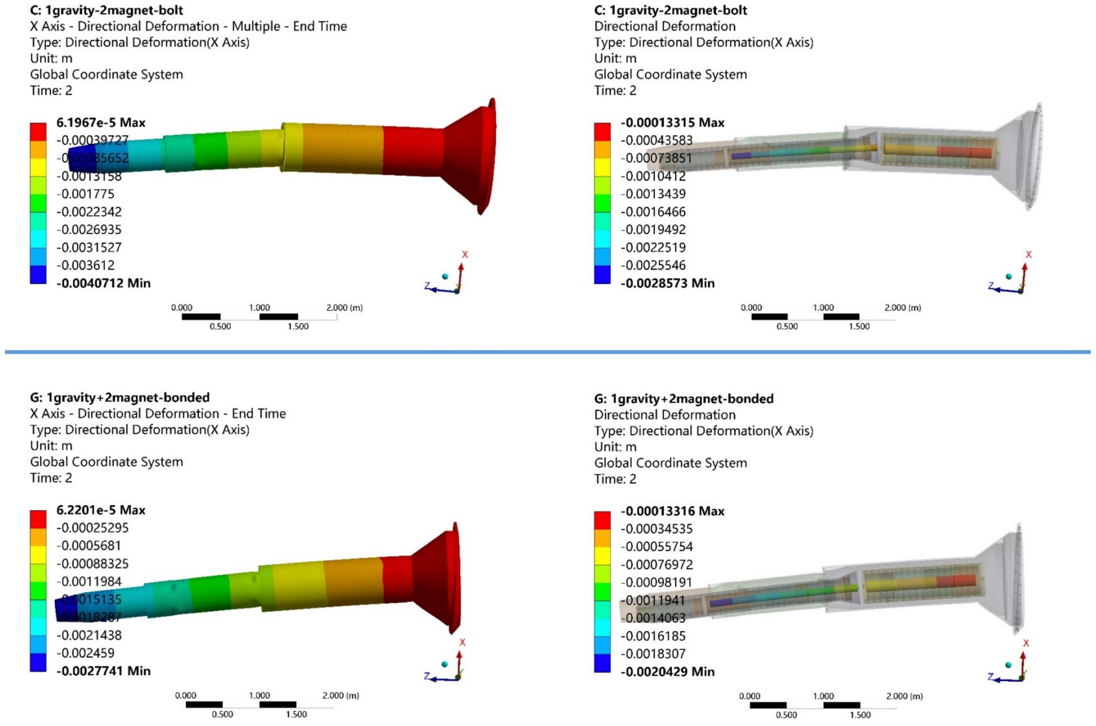
Pressure drop:
Be pipe : 19.8 kPa
Al pipe : 19.3 kPa

Conclusion:
Temperature rise and pressure drop within safe range

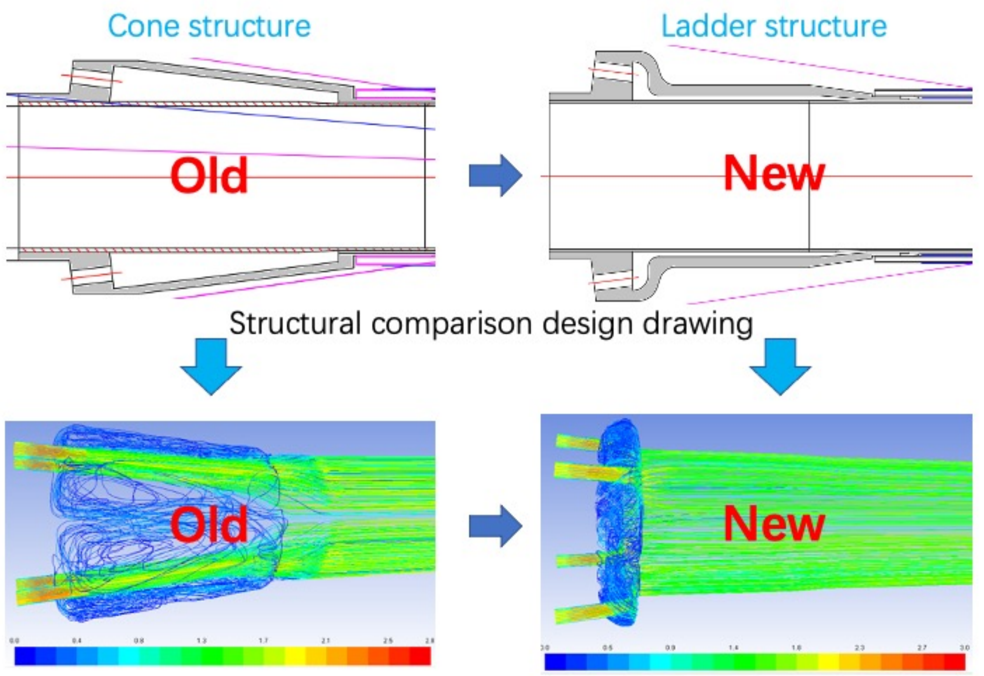
Mechanical Calculation and Optimization-CDR

Refer to [Haijing's Talk]

Deformation Calculation

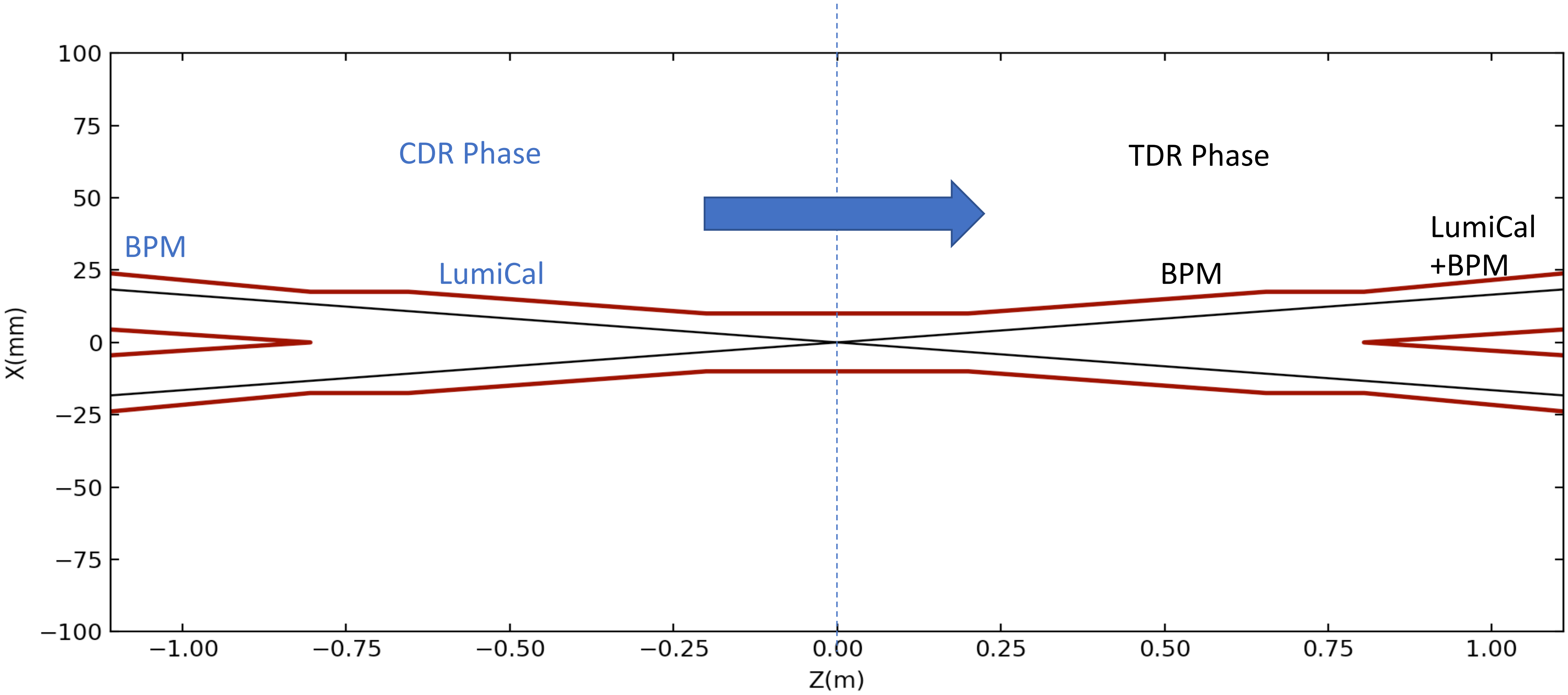


Detailed Beampipe Design



Streamline comparison chart

New Beampipe Design – Cryo to Cryo

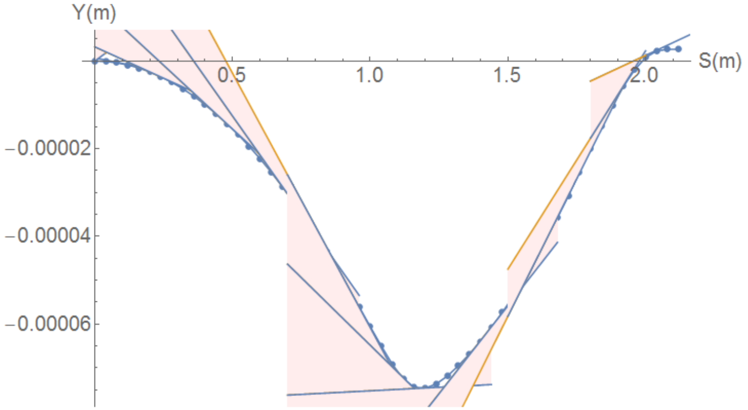


The range between 2 cryostat chambers would be -1.11m~1.11m

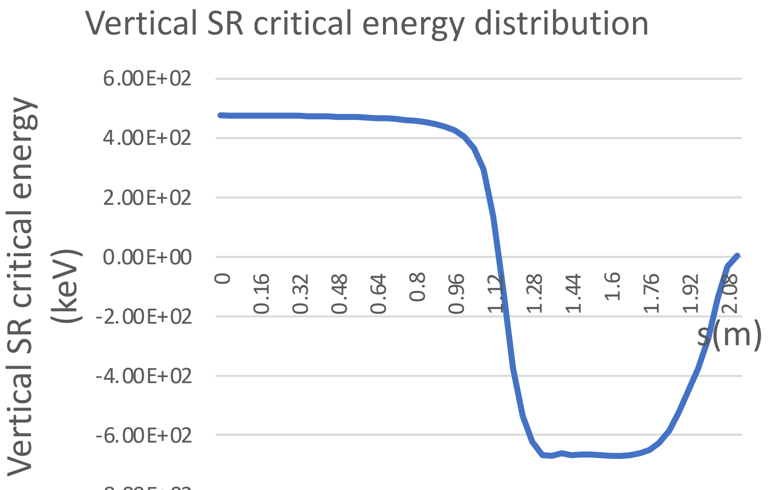
SR from solenoid combined field

S. Bai

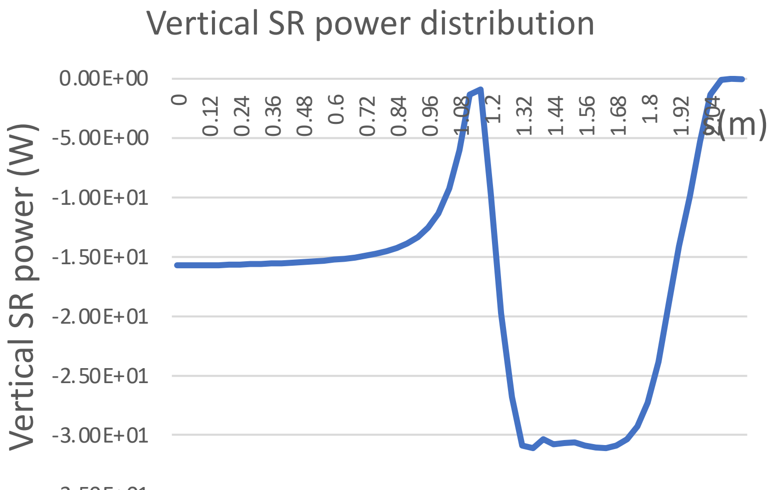
- Horizontal trajectory will couple to the vertical
- Due to the sol+anti-sol field strength quite high, maximum~4.24T, transverse magnetic field component is quite high.
- SR from vertical trajectory in sol+anti-sol combined field should be taken into account.



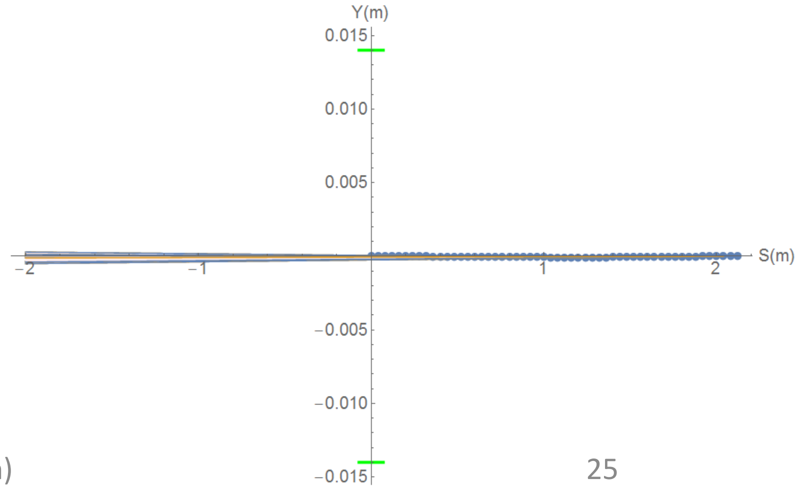
- SR fan is focused in a very narrow angle from -116urad to 131urad
- SR will not hit Berryllium pipe, and no background to detector.
- SR will hit the beam pipe ~213.5m downstream from IP
- Water cooling is needed.



Maximum: 670keV

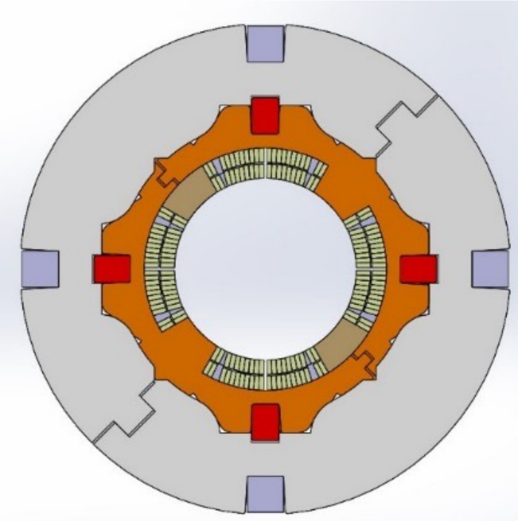


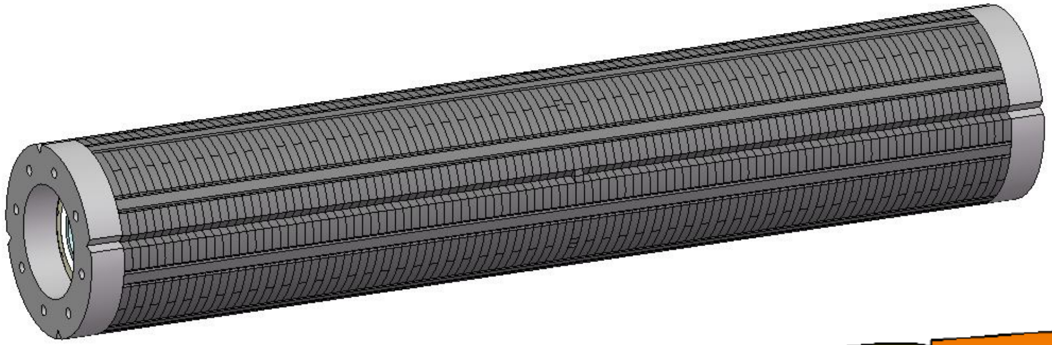
Maximum: 31W

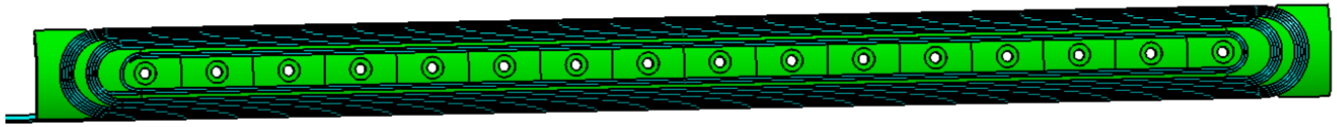


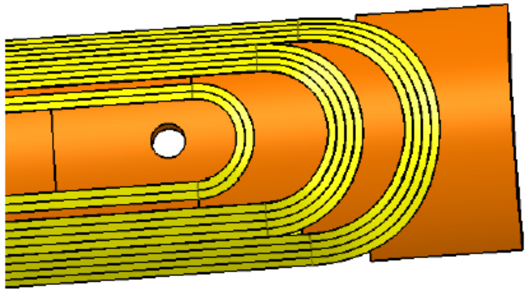
Status of 0.5m single aperture QD0 short model

- High gradient superconducting quadrupole magnet is a key device of CEPC.
- As a first step, research on key technologies of 0.5m single aperture QD0 short model has started (NbTi, 136T/m), in collaboration with HeFei KEYE.
- Including: quadrupole mechanical design, coil winding technology, fabrication of quadrupole coil with small diameter, stress applying and monitoring, quadrupole magnet assembly, field measurement technology, etc.









Manufacture of basic hardware has been completed

Fabrication of Rutherford cable

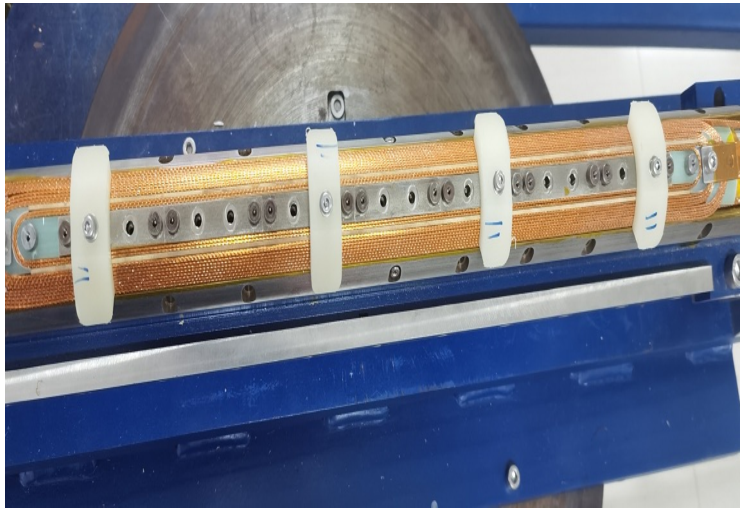
Coil winding machine

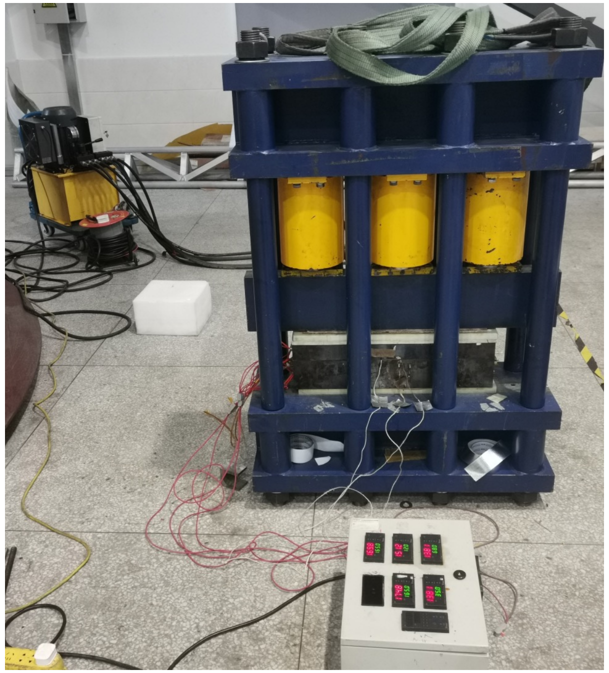
Coil heating and curing system

Coils assembly system

Status of 0.5m single aperture QD0 short model

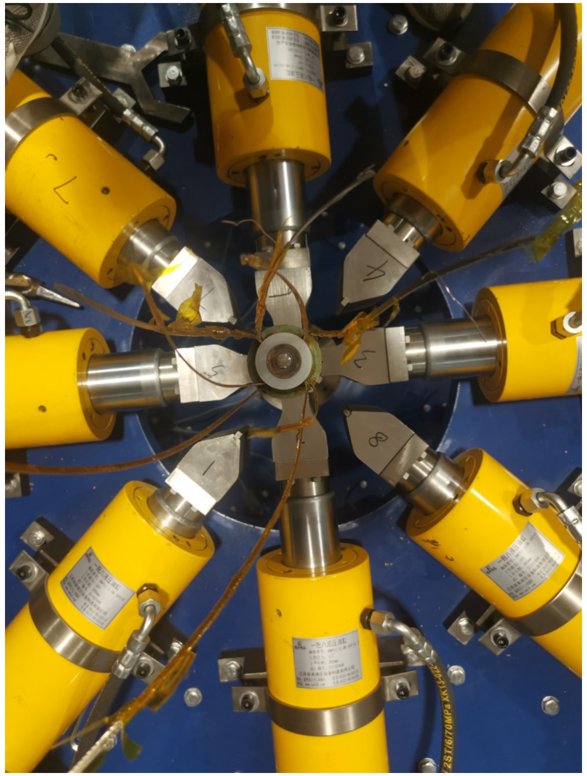
- After a series of exploration and improvement, several SC quadrupole coils have been wound.
- The coils are cured under a certain pressure and temperature.

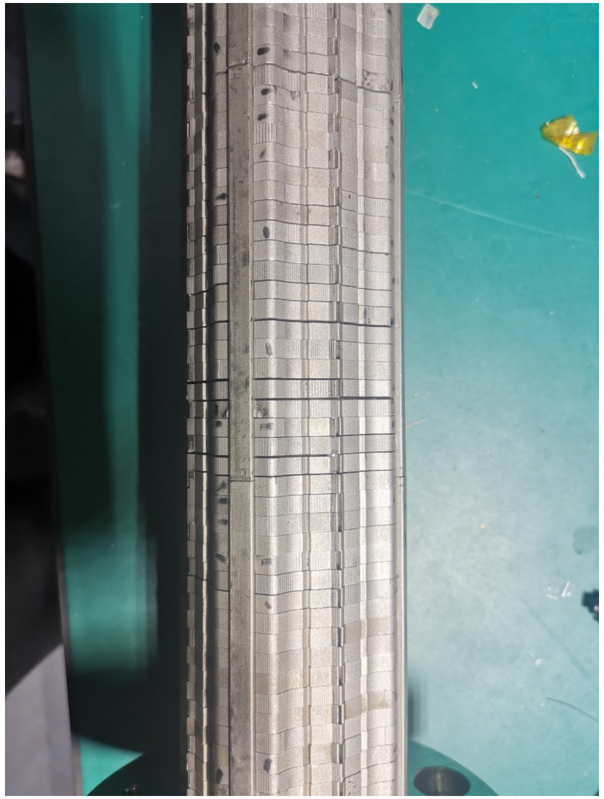


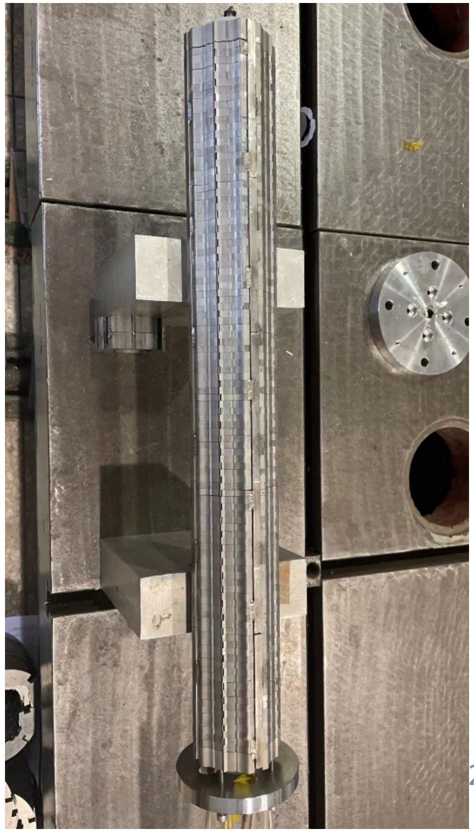


Status of 0.5m single aperture QD0 short model

- Four SC quadrupole coils have been assembled with the stainless collar. Coil resistance and ground insulation tests have been performed.
- Next step, iron yoke will be assembled with the collared-coil.
- Manufacture of 0.5m single aperture QD0 short model will be completed in June.





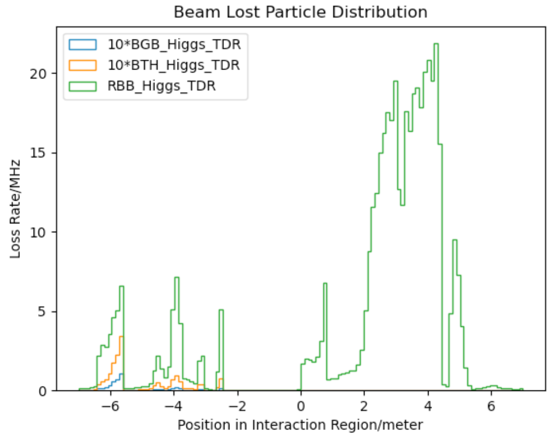


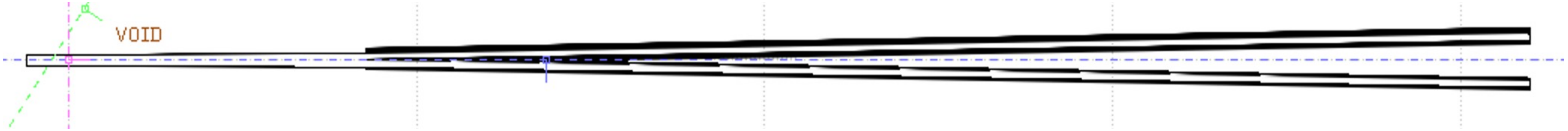
Shielding of the Coils in Magnets

- Beam loss in the downstream IR with a large amount, due to the process of radiative bhabha scattering, beamstrahlung, beam-gas scattering, beam thermal photon scattering.
- Radiation dose may damage the SC magnet coil and the detector.

solution

1. Tungsten IR beam pipe,
2. Combined iron and tungsten yoke of SC magnet





- 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 until now
- Take the loss rate calculated by SAD into account:
  - ~0.00166 Gy/s(0.166rad/s)
  - ~14.35 Gy/day
  - ~36662.49 Gy/lifetime(Higgs plans to run 7 years)
  - Limit is 100000 Gy/lifetime