Institute of High Energy Physics
Chinese Academy of Sciences

CEPC

Progress on MDI design

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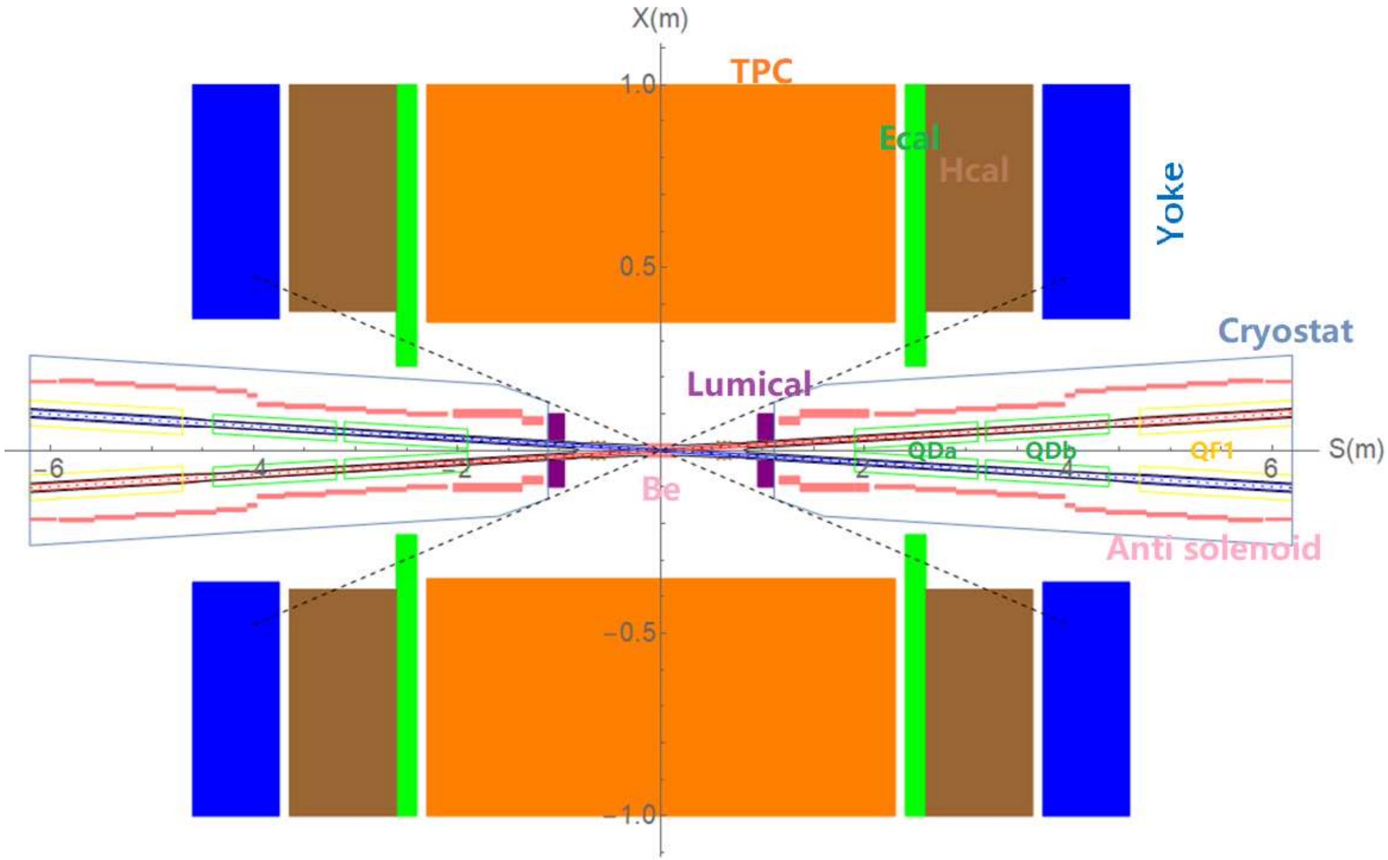
for CEPC MDI group

CEPC IARC meeting
2021-05-11

Outline

- MDI design for High Luminosity Higgs
- CDR → TDR optimization for MDI
- Summary

MDI layout and IR design



- The Machine Detector Interface (MDI) of CEPC double ring scheme is about ±7m long from the IP.
- The CEPC detector superconducting solenoid with 3T magnetic field and the length of 7.6m.
- The accelerator components inside the detector without shielding are within a conical space with an opening angle of cosθ=0.993.
- The e+e- beams collide at the IP with a horizontal angle of 33mrad and the final focusing length is 1.9m.

MDI parameters

	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	8.1°												
QDa/QDb		3.2/2.8T	141/84.7 T/m		1.21m	15.2/17.9mm	62.71/105.28mm	48mm	59mm	724.7/663.1 keV	396.3/263keV	212.2/239.23W	99.9/42.8W
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		7.2T			0.8m			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							1.89/2.04 W	
Beampipe within QF1					1.5m							3.34W	
Beampipe between QD0/QF1					0.3m							26.7W	

QDa/QDb, QF1 physics design parameters

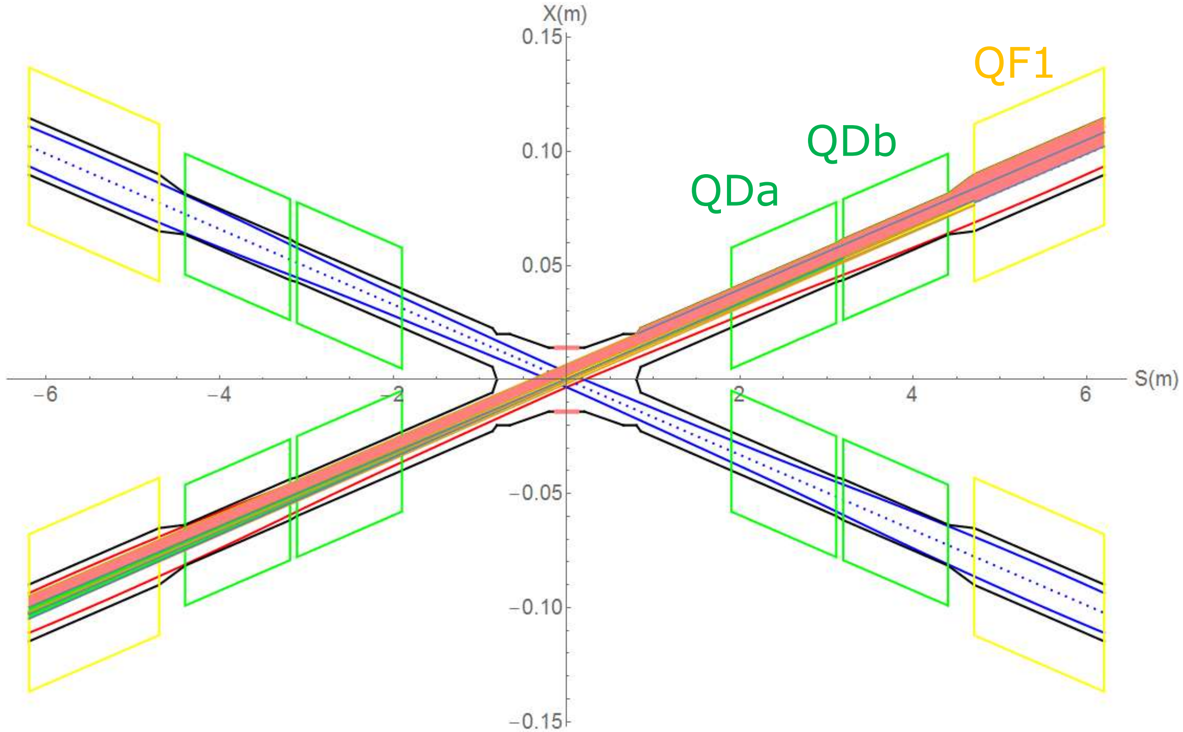
β_y^*=1mm, β_x^*=0.33m

QDa/QDb	Horizontal BSC 2 $(18\sigma_x+3)$	Vertical BSC 2 $(22\sigma_y+3)$	e+e- beam center distance
Entrance	9.15/12.41 mm	12.89/15.22 mm	62.71/105.2 8mm
Middle	10.37/14.84 mm	14.61/14.88 mm	82.84/125.4 1mm
Exit	12.13/17.92 mm	15.21/13.87 mm	102.64/145. 21mm
Good field region	Horizontal 12.13/17.92 mm; Vertical 15.21/15.22 mm		
Effective length	1.21 m		
Distance from IP	1.9/3.19 m		
Gradient	141/84.7 T/m		

QF1	Horizontal BSC 2 $(18\sigma_x+3)$	Vertical BSC 2 $(22\sigma_y+3)$	e+e- beam center distance
Entrance	19.66 mm	13.21 mm	155.11 mm
Middle	23.02 mm	12.00 mm	179.87 mm
Exit	24.14 mm	11.60 mm	204.62 mm
Good field region	Horizontal 24.14 mm; Vertical 13.21 mm		
Effective length	1.5 m		
Distance from IP	4.7 m		
Gradient	94.8 T/m		

SR on IR beam pipe from last bend upstream and Final Doublet

- There is no SR photons hitting the central beam pipe in normal conditions.
- Single layer beam pipe with water cooling, SR heat load is not a problem.

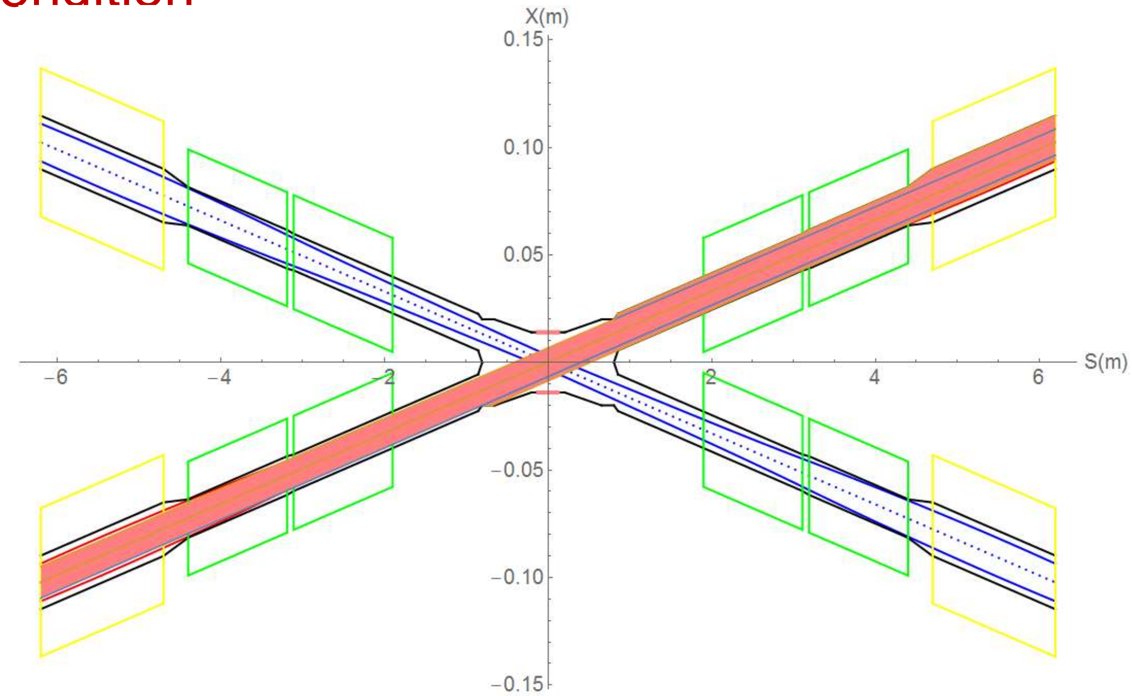


Region	SR heat load	SR average power density
0~805mm	0	0
805mm~855mm	12.5W	69.4W/cm^2
855mm~1.9m(QDa entrance)	1.06W	0.28W/cm^2
QDa	1.19W	0.27W/cm^2
QDa~QDb	3.73W	12.95W/cm^2
QDb	1.31W	0.3W/cm^2
QDb~QF1	26.5W	4.9W/cm^2
QF1	2.39W	0.44W/cm^2

SR from last bending magnet upstream of IP

Abnormal condition

- SR photons hitting the bellows under the extreme beam conditions, temperature rise ~1^{0}C



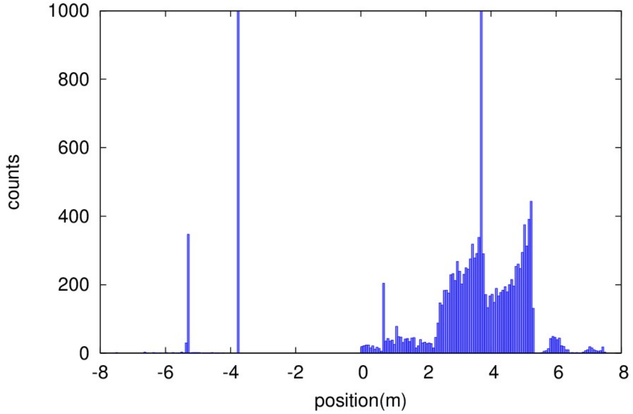
- **Extreme condition, eg, if a magnet power is lost, a large distortion will appear immediately for the whole ring orbit. The beam will be lost when exceeded.**
- **In extreme cases ~ at least 10 times per day. The beam will be stopped within 0.5ms when abnormal. It is not afraid of this 0.5ms for other material beam pipe except beryllium pipe.**
- **The background of the detector should not be considered under abnormal conditions.**
- **It is not necessary to care about whether the beam orbit deviation will affect detector operation, since the high background part will be removed when data analysis is carried out.**

SR will enter into the bellows (no cooling):

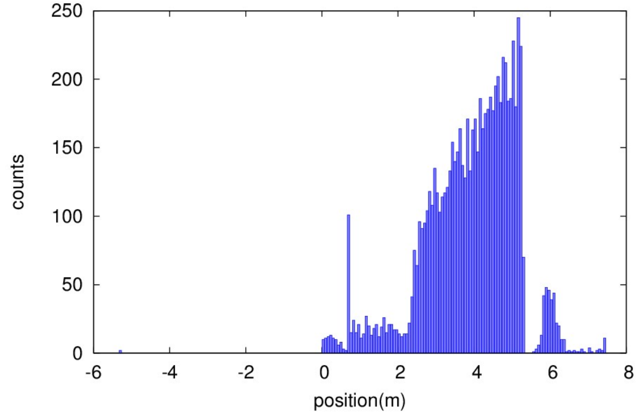
- IP~677mm, no SR heat load.
- -677~-805mm beam pipe, SR power ~14.65W, APD~ 31.8W/cm^2.
- -805~855mm beam pipe, SR power~12.96W, APD~72W/cm^2.
- Temperature rise ~1^{0}C

Beam loss from RBB and BS

Without collimator

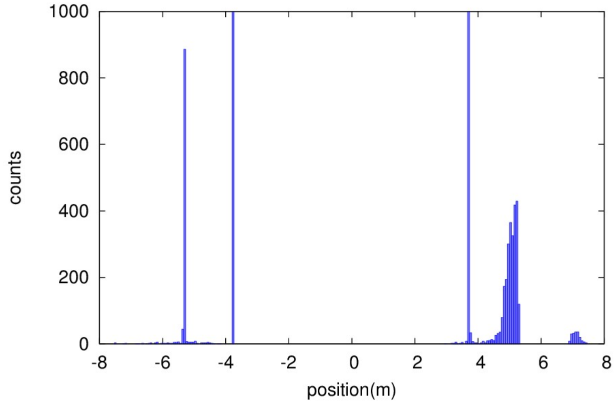


With collimator

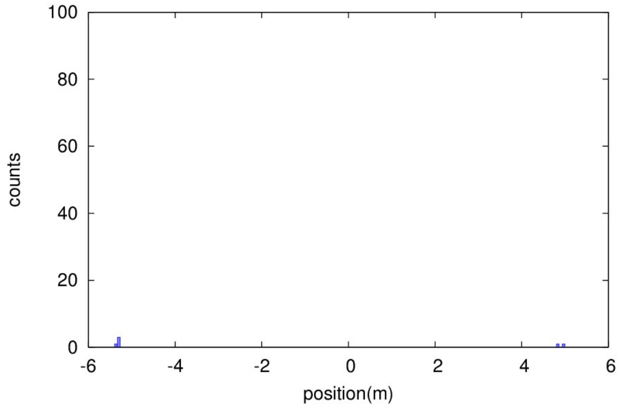


Radiative Bhabha scattering

Without collimator



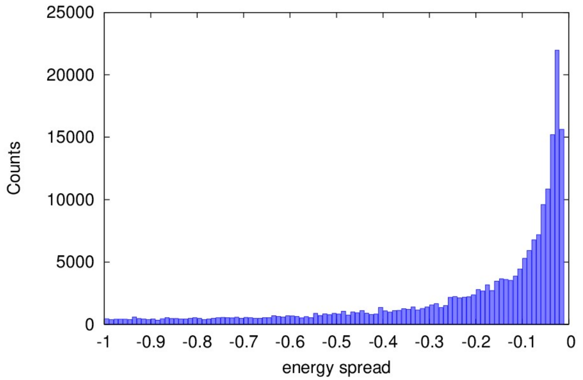
With collimator



Beamstrahlung

Beam loss from Beam-gas bremsstrahlung and Beam thermal photon scattering

events



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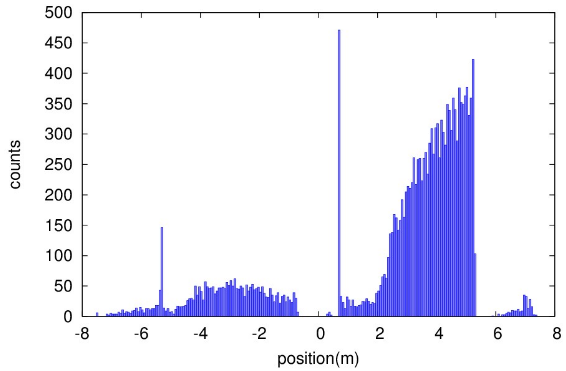
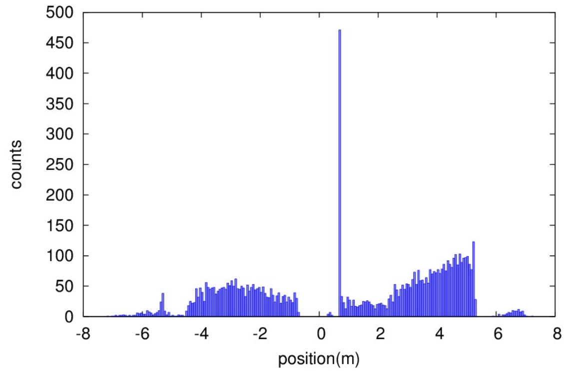
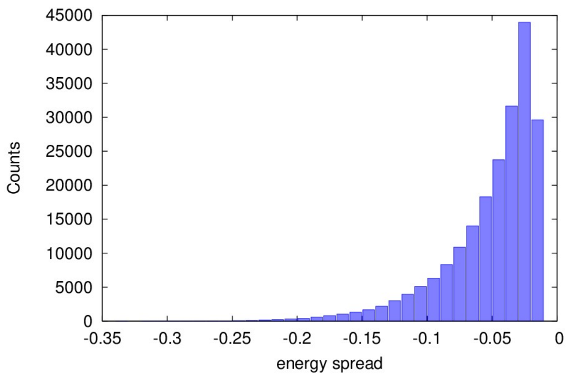


With collimator

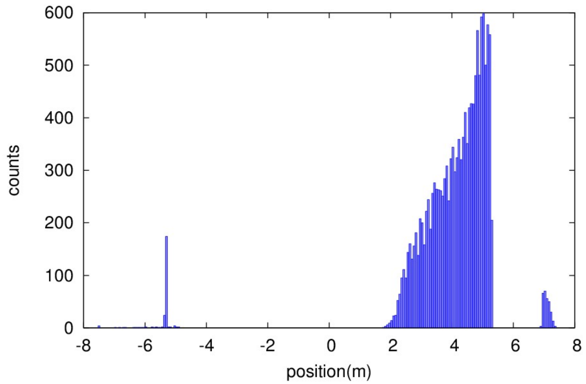


BG

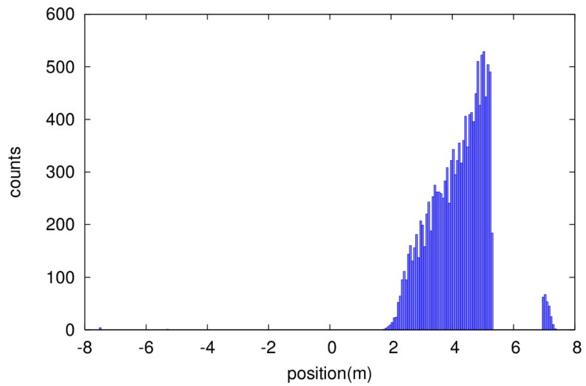
events



Without collimator



With collimator



BTH

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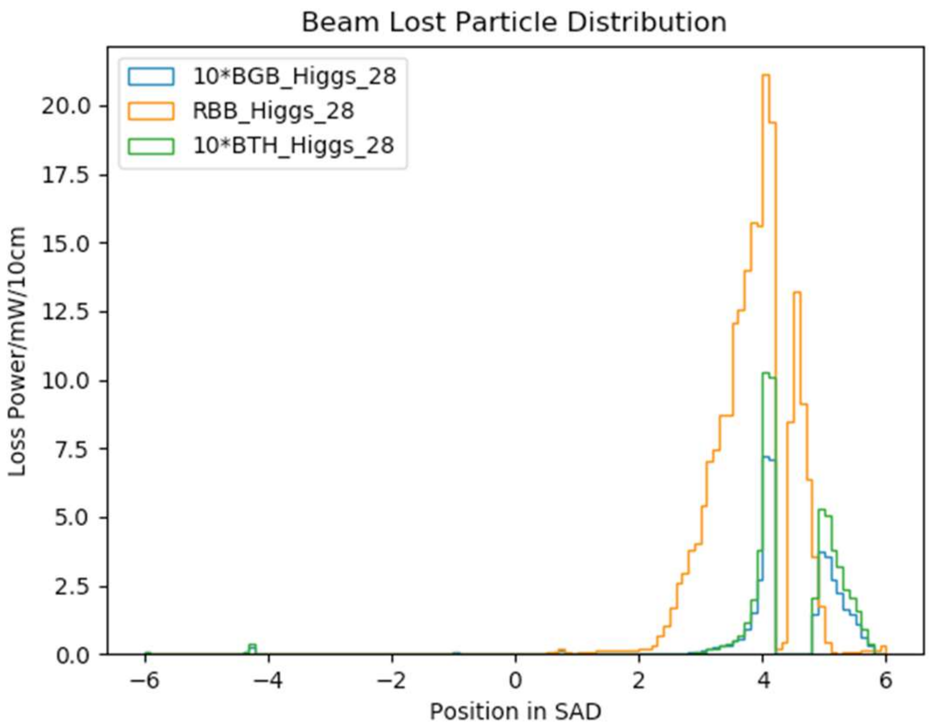
Radiation background

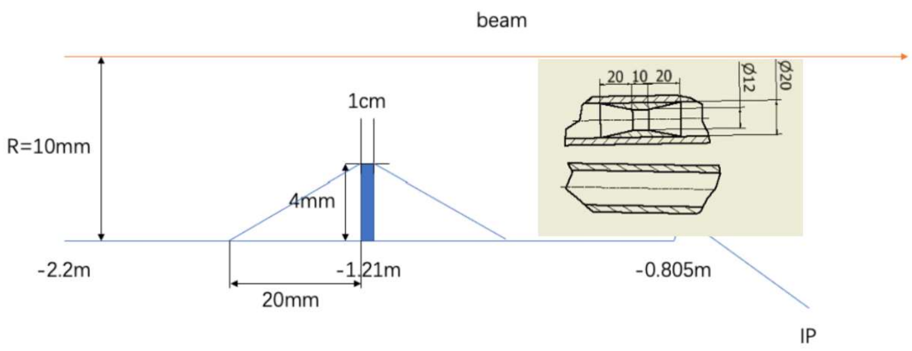
- Including Radiative Bhabha, Beam-Gas, Beam Thermal Photon. Almost No Beamstrahlung.
- Normalized to loss power in mW(one beam).
- Higgs mode in CDR.

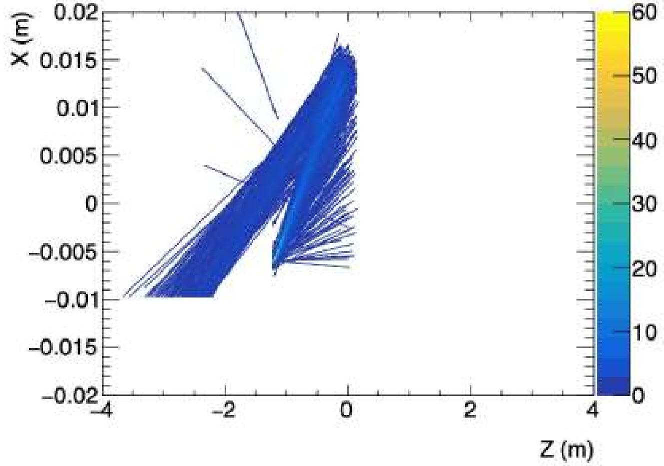


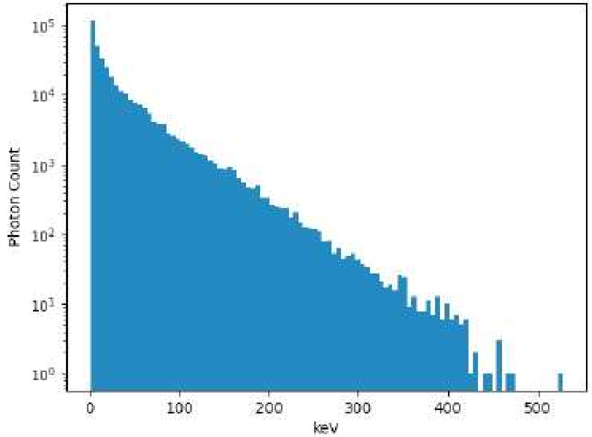
- Higgs Backgrounds on 1st layer of Vertex.
- With a safety factor of 10.

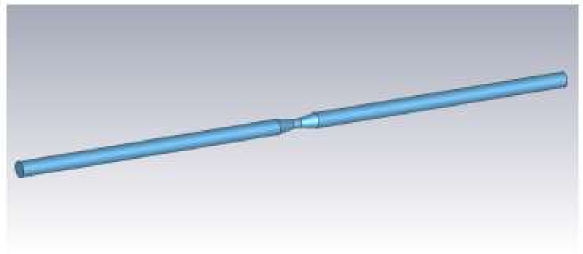
Background type	Hit Density($cm^{-2} \cdot BX^{-1}$)	TID($krad \cdot yr^{-1}$)	1 MeV equivalent neutron fluence ($n_{eq} \cdot cm^{-2} \cdot yr^{-1}$)
Pair production	1.91	526.11	1.05×10^{12}
Synchrotron Radiation	0.026	15.65	
Radiative Bhabha	0.34	592.66	1.44×10^{12}
Beam Gas	0.9607	1235.9	3.37×10^{12}
Beam Thermal Photon	0.02	22.31	6.20×10^{10}
Total	3.2567	2392.63	5.922×10^{12}

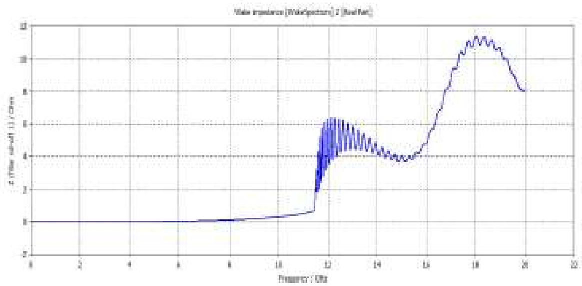
SR mask











- New mask design:
  - Tungsten
  - 4mm height
  - 10mm long
  - Locates at -1.21m
- Original mask at ~-4.2m with 0.6mm heigh
- Lots of photons are secondaries, generate within QD0
- Photons reduced by an order of magnitude
- ~300 photons/BX could hit Be, with a.e. ~100keV
  - ~1.44x10^{-8} W on Be beampipe

Mask length(mm)	Loss factor Trap by mask(V/pc)	Higgs(w)	W(w)	Z(w)	High lumi Z(w)
50	0.1997	0.063	0.238	0.984	2.964

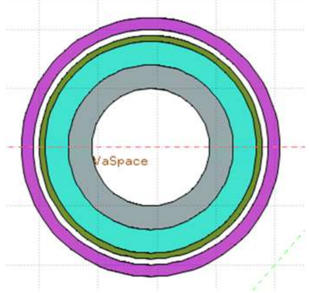
Shielding

- 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 →

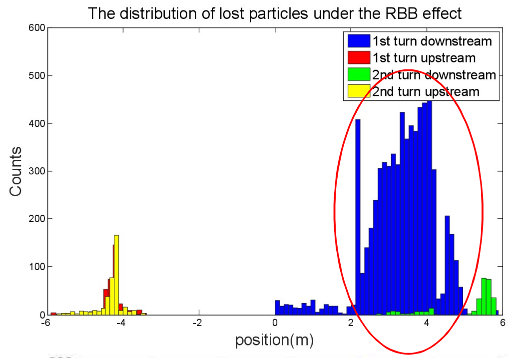
1. Tungsten IR beam pipe,
2. Combined iron and tungsten yoke of SC magnet

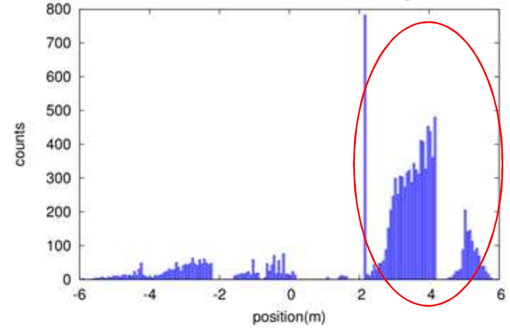
Key Issues on Calculation and Simplification of Beam pipe model

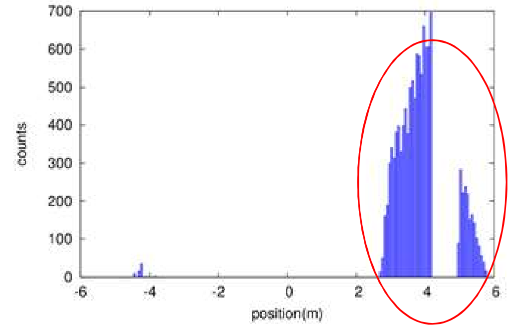


White: Vacuum
Gray: Tungsten Pipe
Light Green: Helium
Heavy Green: Stainless Steel Vassel
Pink: Coil

- Pure tungsten IR beam pipe with 3mm 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





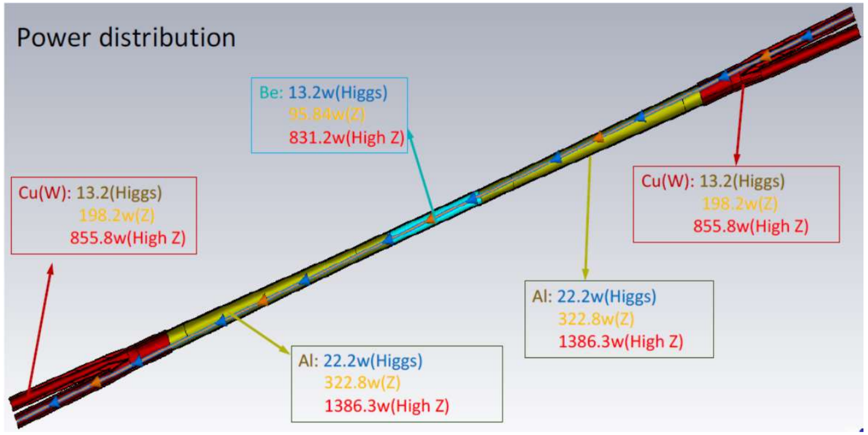


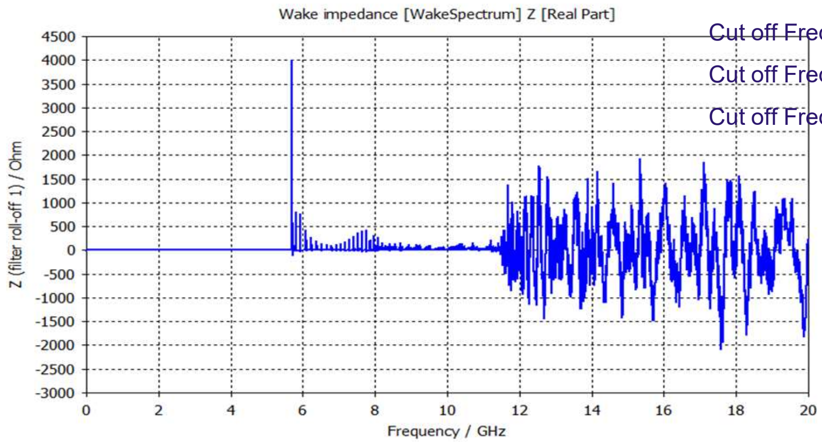
Heat load in IR from beam loss

Region	SR heat load from RBB	SR heat load from BS	SR heat load from BG	SR heat load from BTH
Beryllium pipe	6.7mW	0	0	0
Detector beam pipe	0.024W	0	4.8uW	1.2uW
Accelerator beam pipe before QDa	0.17W	0	4.2uW	1.2uW
QDa~QDb	2.13W	3.8uW	5.9uW	1.8uW
QDb~QF1	0.01W	3.8uW	0.5uW	0.6uW
QF1	0.26mW	0	3.7uW	0.66uW

Heat load in IR from beam loss background is so small, compared to synchrotron radiation and HOM.

HOM power distribution





Cut off Frequency of SCQ Pipe(φ20mm): 11.474GHz

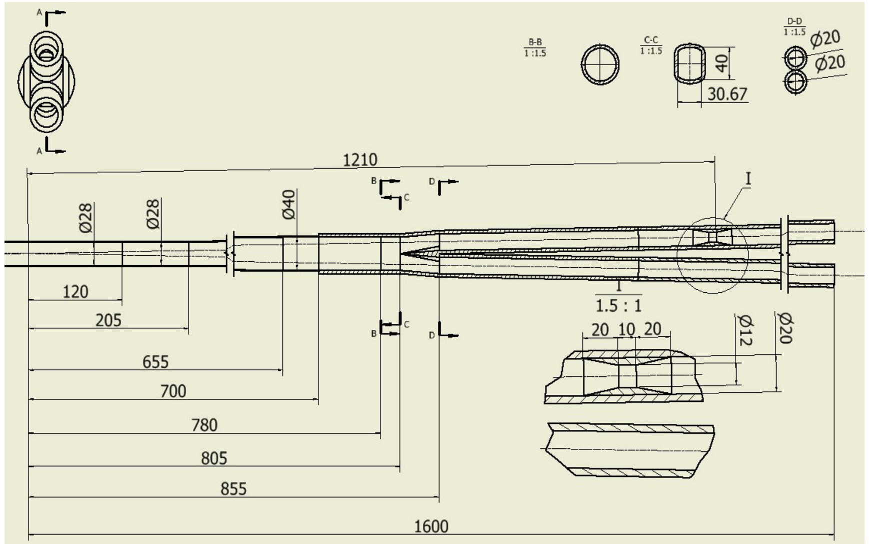
Cut off Frequency of photon masker(φ12mm): 19.123GHz

Cut off Frequency of Be pipe (φ28mm): 8.1957GHz

σ_z=5mm: Two beam in the IR

Loss factor Trap by masker @k_trap: 0.1997v/pc

P_{trap}: H/W/Z/Z(High Lum): 175w/657w/2.71kw/8.17kw

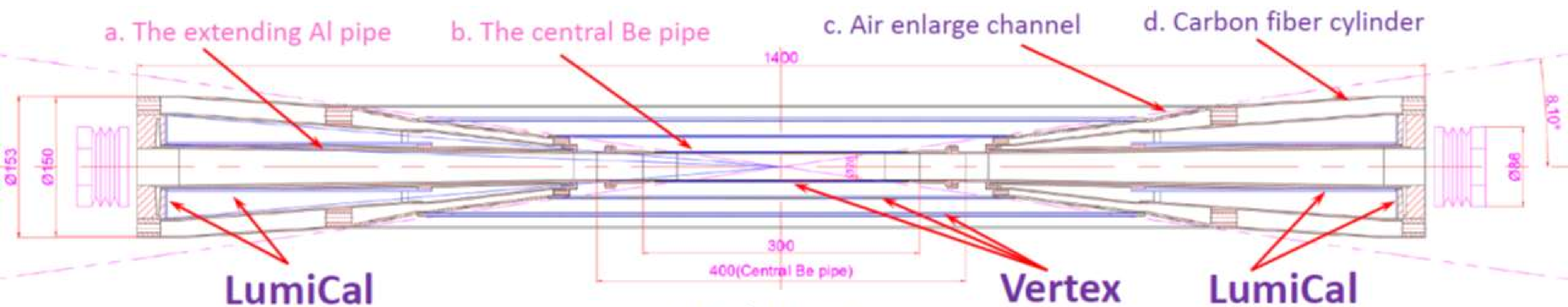


Position	Length(mm)	Higgs(w)	W (w)	Z(w)	High Luminosity Z(w)
Be pipe (w)	120	6.28	23.51	97.12	292.52
Al: Be pipe transition(w)	85	4.45	16.65	68.79	207.20
Al: Transition pipe (w)	495	44.05	164.71	680.25	2048.9
Cu: Y-shape crotch (w)	155	13.79	51.57	213	641.58
Al: Y crtothch to masker	325	19.25	72.01	297.40	895.77
Cu： masker(w)	50	0.063	0.238	0.984	2.964
Al: maser to pipe end	370	0.47	1.76	7.28	21.93
Total	1600	88.353	330.448	1364.824	4110.864

Beam pipe structure

➢ Berryllium (central) and Aluminum(forward) beam pipes

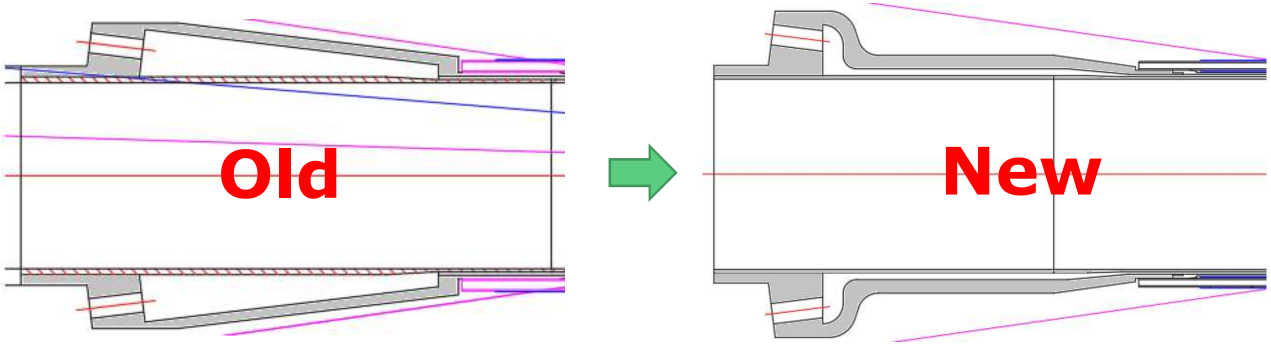
From IP(mm)	Shape	Inner diameter(mm)	Material	Inner surface area(mm^2)	Marker
0-120	Circular	28	Be	10556	
120~205	Circular	28	Al	7477	
205~655	Cone	28~40	Al	48071	Taper: 1.75
655~700	Circular	40	Al	5655	



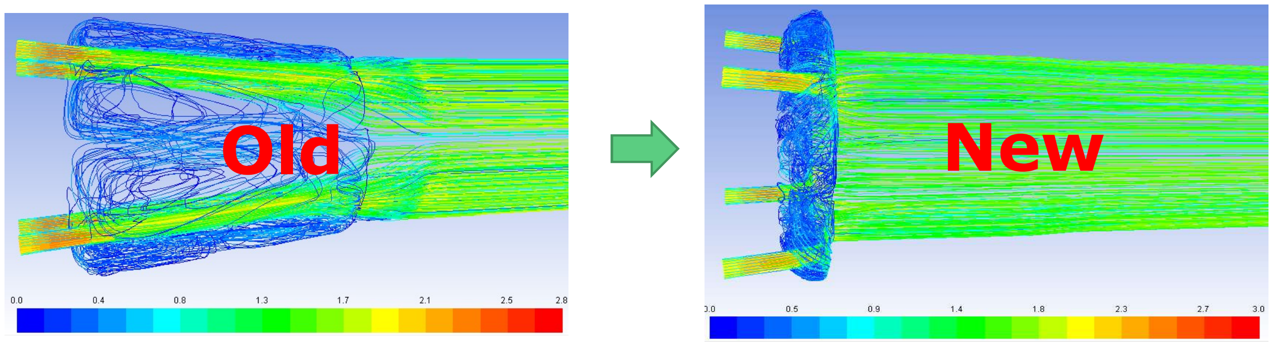
Optimization of central beampipe

Cone structure

Ladder structure



Structural comparison design drawing



Streamline comparison chart

Optimization of
enlarged cooling channel

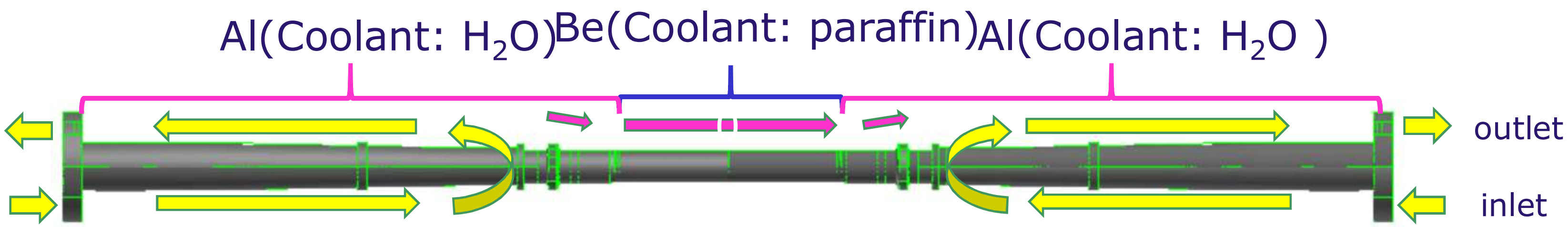
Simulation analysis shows:
Under the ladder structure, the vortex is smaller and fewer, and the flow field is more stable.

Conclusion:
The improved ladder structure will greatly reduce the vibration of the beam pipe caused by unsteady flow

Beam pipe thermal analysis I (CDR Z)

Be pipe parameters:

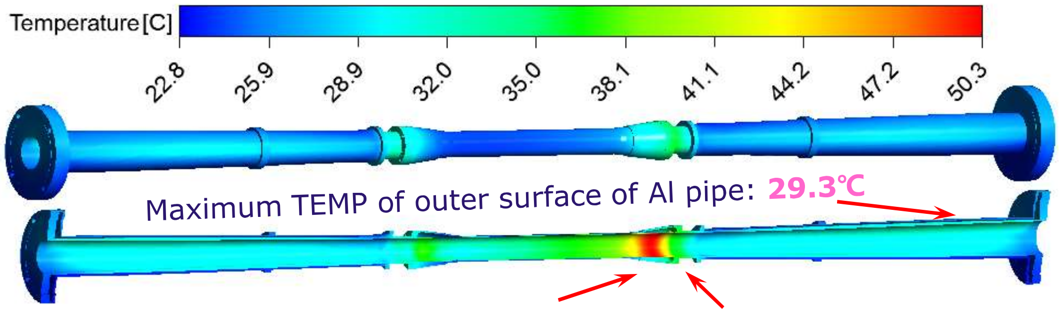
length: 240 mm
Inner Be THK: 0.5 mm
Outer Be THK: 0.35 mm
Gap: o.5 mm



Calculation model:
laminar

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

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



Temperature distribution Cloud

Result:

TEMP rise of Be pipe : 3.2 ℃ (between the inlet and the outlet)
TEMP rise of transition: 13.3 ℃
TEMP rise of Al pipe : 6.3 ℃

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

Conclusion:

Temperature rise and pressure drop are in a safe range.

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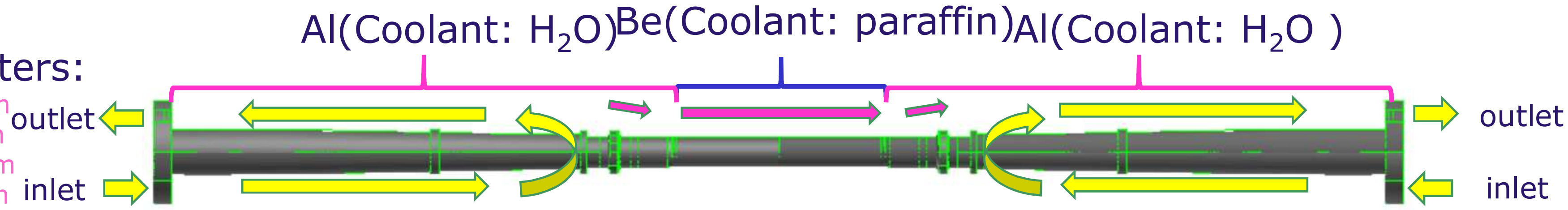
Beam pipe thermal analysis II (High Lumi Z)

Be pipe parameters:

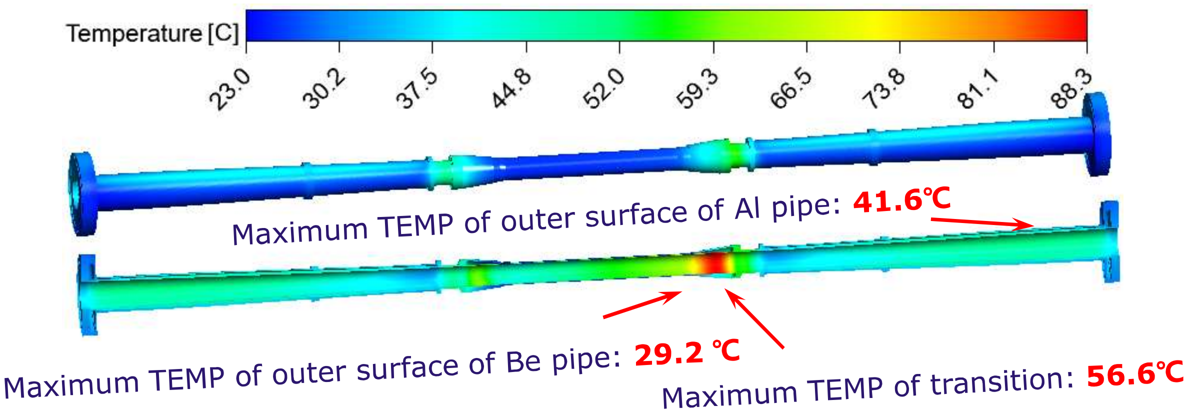
length: 240 mm
Inner Be THK: 0.5 mm
Outer Be THK: 0.35 mm
Gap: o.5 mm



Calculation model:
laminar

Inlet of Be pipe:
TEMP: 23℃
Velocity: 2.0m/s
Coolant: paraffin

Inlet of Al pipe:
TEMP: 23℃
Velocity: 1.5 m/s
Coolant: H_2O



Temperature distribution Cloud

Result:

TEMP rise of Be pipe : 6.2 ℃(between the inlet and the outlet)
TEMP rise of transition: 33.6 ℃
TEMP rise of Al pipe : 18.3 ℃

Pressure drop of Be pipe : 31.9 kPa
Pressure drop of Al pipe : 37.7 kPa

Conclusion:

Although the temperature rise and pressure drop have increased, they are still in the safe range of mechanical properties, and there is a possibility of optimization.

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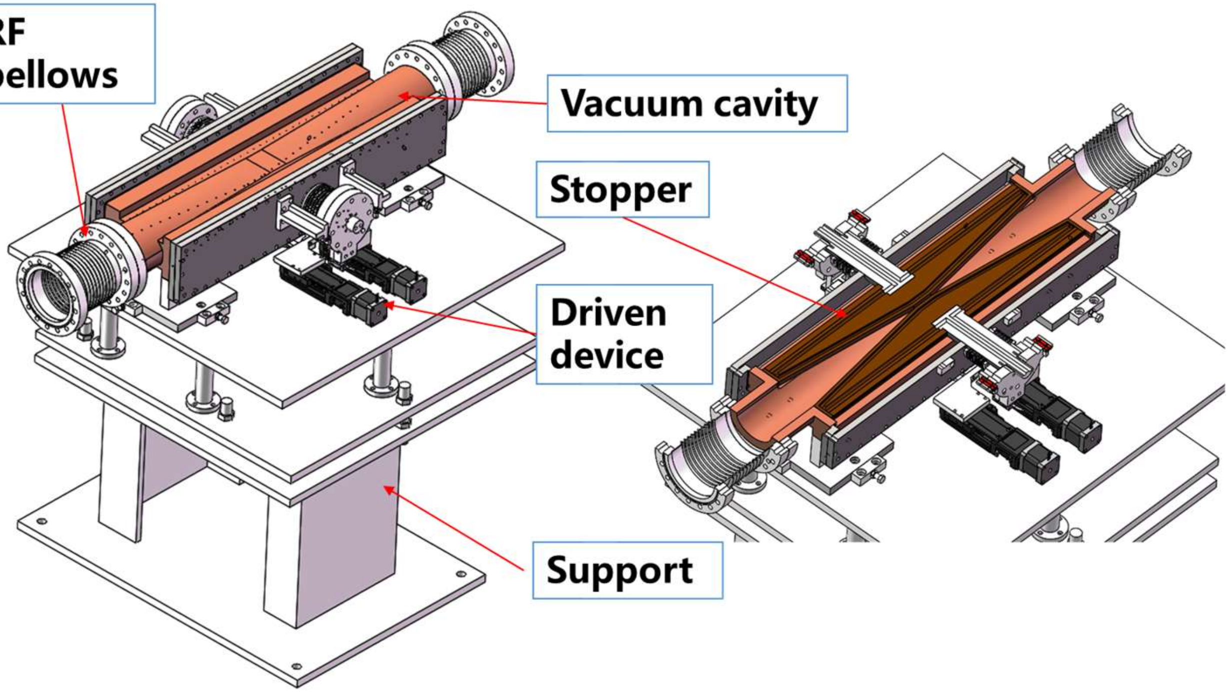
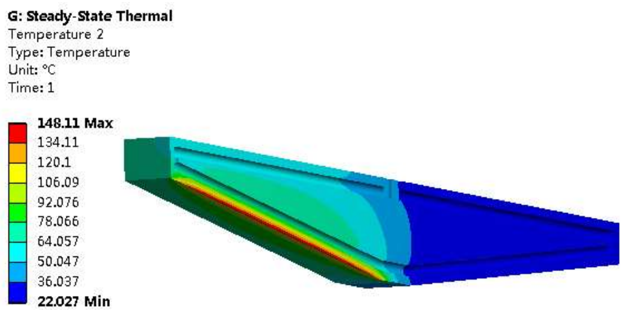
Movable collimators

- Located in straight section between two dipoles, the length is 800 mm.
- SR power: 7700W @120GeV, 30MW

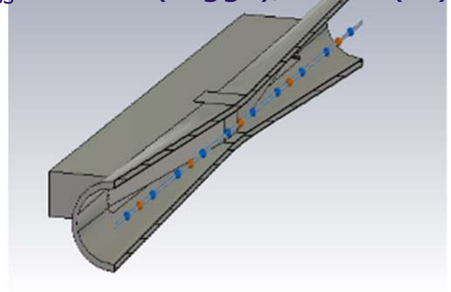


Highest temperature: 148 ℃

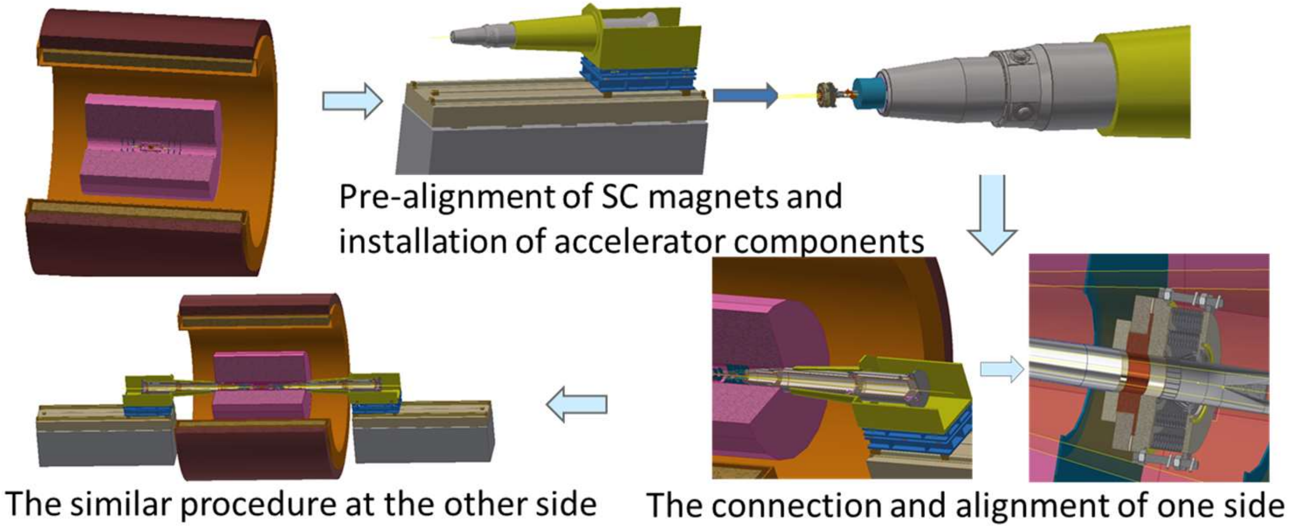


Loss-Factor: 0.045V/pC

P_{loss}: 18.8w(Higgs)/76.1w(W)/265.8w(Z)

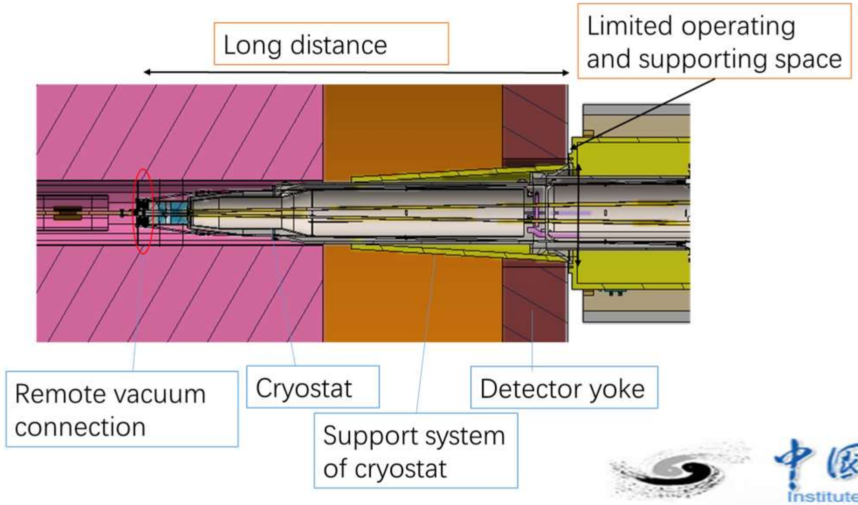


MDI integration and alignment

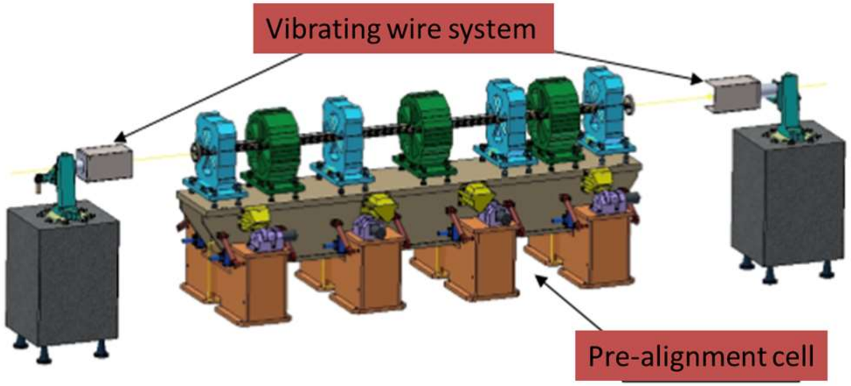


Alignment scenario:

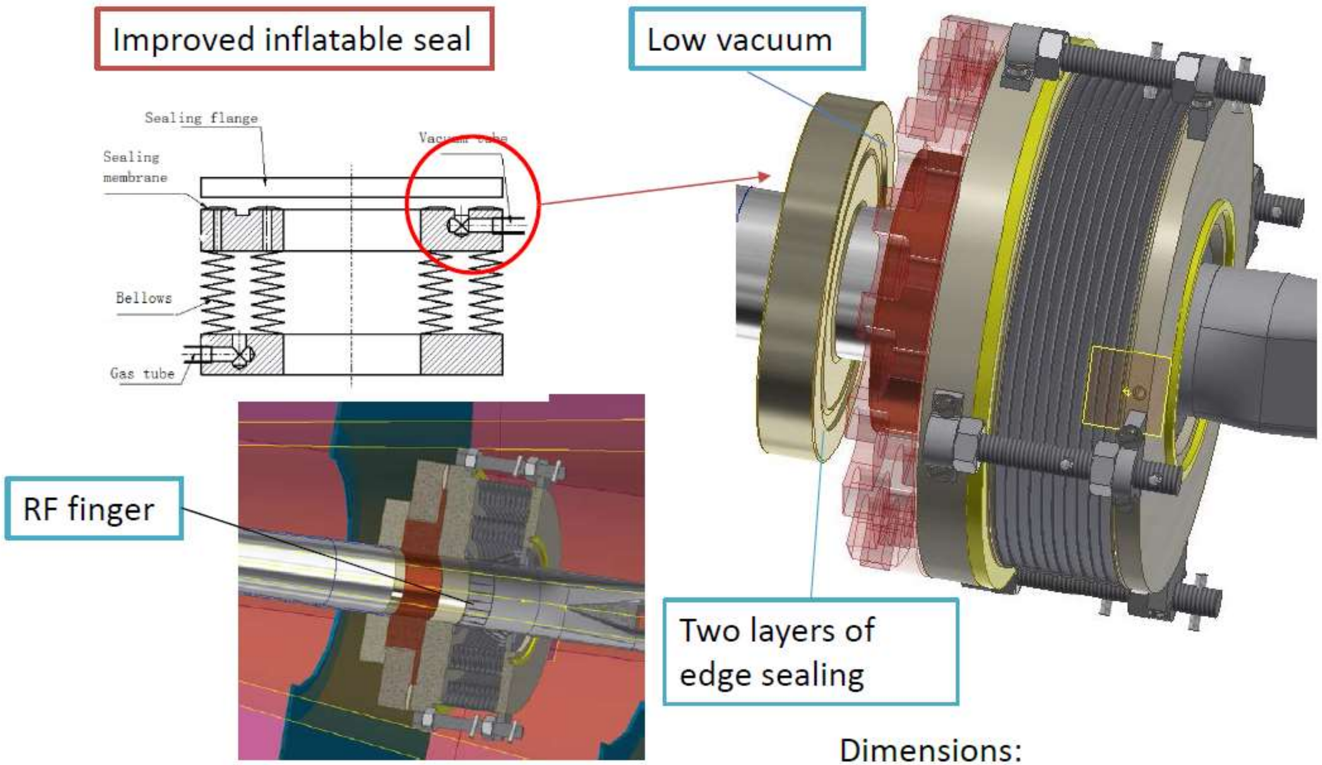
- Pre-align the SC magnets using vibrating wire system to "certain location" to compensate the effect of loads.
- Align the SC magnets in two cryostats using optical system.
- Measure misalignment using SSW and adjust by corrector magnets meet the alignment requirements.



VWS is a candidate pre-alignment method, accuracy of magnet centers: ≤10 μm



Remote vacuum connector



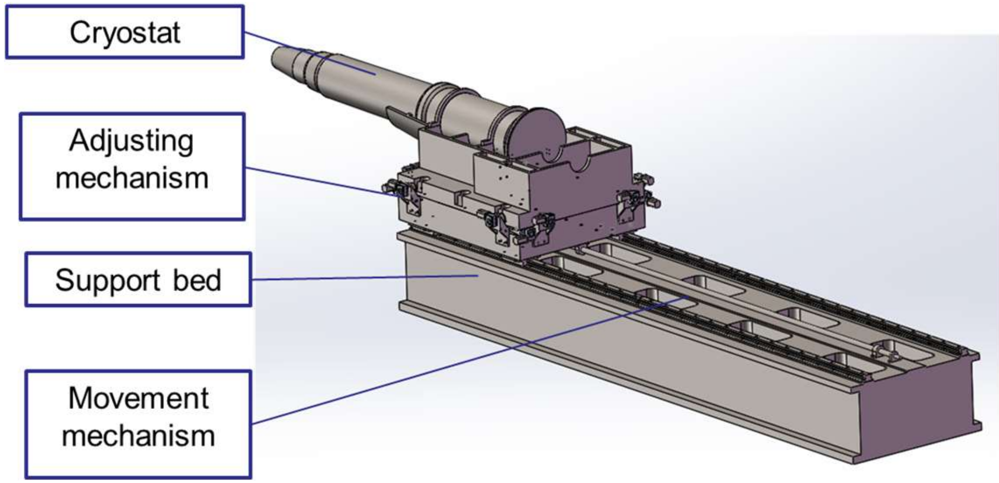
- Replace the sealing membranes by two layers of edge sealing.

Dimensions:

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

- **Difficulties:**
  - Transversal space: All the structure should be within detection angle.
  - Leak rate requirement: Ultra-high vacuum. Leak rate requirement: ≤2.7e-11Pa.m^3/s
  - Longitudinal space: Bellows should absorb deformation when baking. →Add Z-direction support, length has been decreased to 83mm.
  - Minimize thermal loads: The thermal loads mainly includes SR power and HOM power.→ Avoid SR power by layout design, and decrease HOM power by RF finger.
  - Cooling: It is hard to dissipate the heat at RF finger which is thin, low thermal conductivity and far from the coolant.→ FEA

SC magnet supports

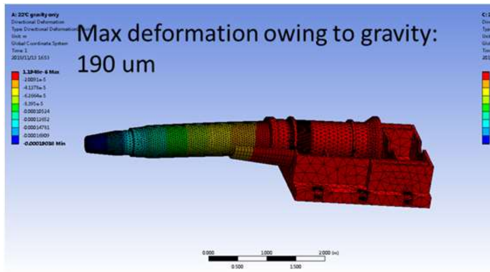


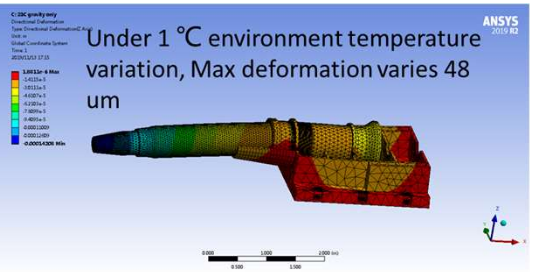
- Cantilever length was 3.6 m, based on the yoke length of 9.2 m.
- The cryostat was 5 meters long with18 mm thick stainless wall. The maximum deformation was 190 um.
- Only the cryostat vacuum vessel weighting 2 tons was considered.

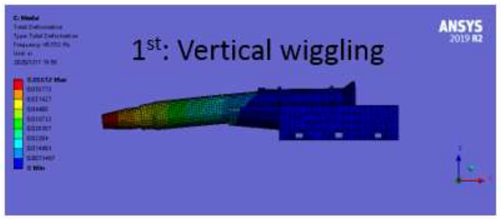
Key points

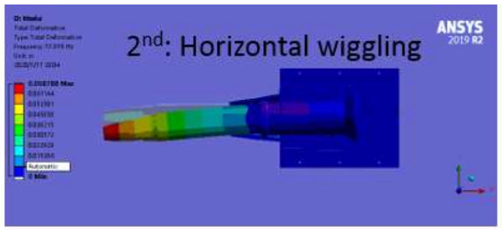
- Stability (static and modal)
- Accuracy
- Easy-operating
- Dimensions

Machine	Constraint	Requirements on ground motion (x/y)
Collider ring	luminosity reduction < 1%	< -/4nm
Booster ring	injection efficiency reduction < 1%	< 150/100nm
Injector linac	total emittance growth < 30%	< 200/250nm









- High stiffness for stability ⟷ (conflict) Flexibility for high accuracy.
- Studies on support stiffness is on-going.
- Motor driven wedges jacks for high stiffness and accuracy.
- Auxiliary support, high damping material/structure are also in consideration

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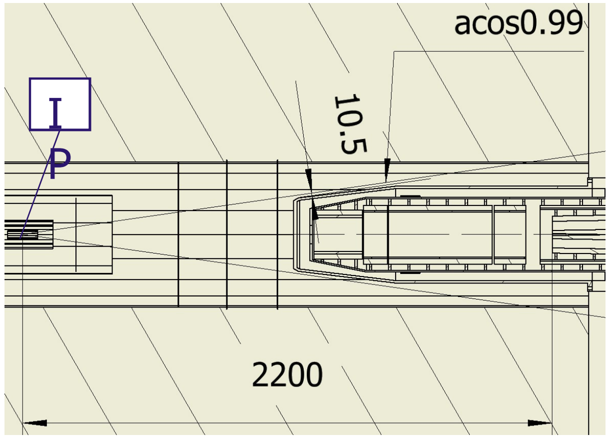
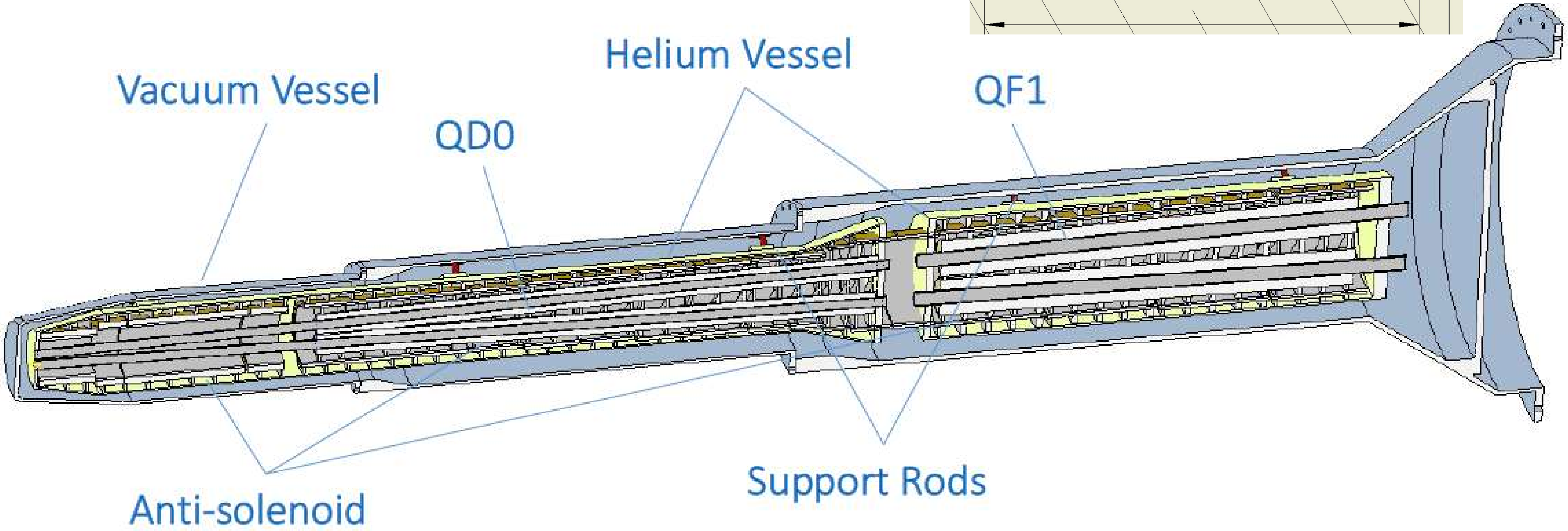
Structure optimization within cryostat

- The model has been upgraded.
- Total length: 5486 mm. Position along Z direction: 1125mm~6611mm.
- Min. distance to acos0.99 angle: 10.5 mm
- The tungsten shielding is not been considered yet.

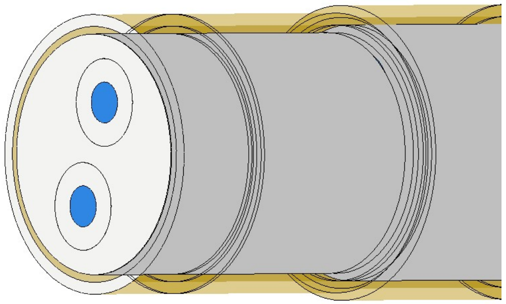




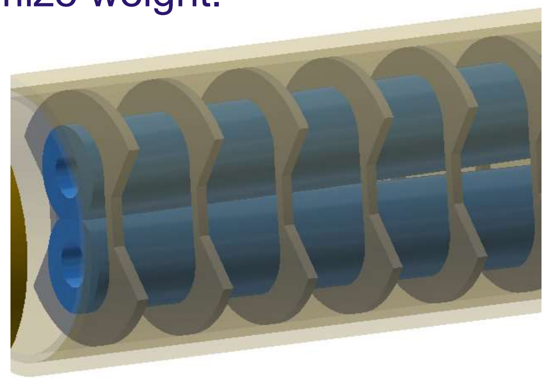
Structure optimization within cryostat

- **Cooling shields are neglected in the analyses.**
- **The magnets are supported to the helium vessels.**
- **Two kinds of magnet supports are considered.**
  - Solid support similar to SKEKB.
  - Skeleton support to minimize weight.

- The position accuracy of SC magnets is 100 um. If the uneven deformation is less than 20 um, it has no big effect on other requirement.
- The solid support of QD0/QF1 has the minimized uneven deformation.
- There should be a skeleton support with less weight and comparable stiffness, saving some space for shielding structure.

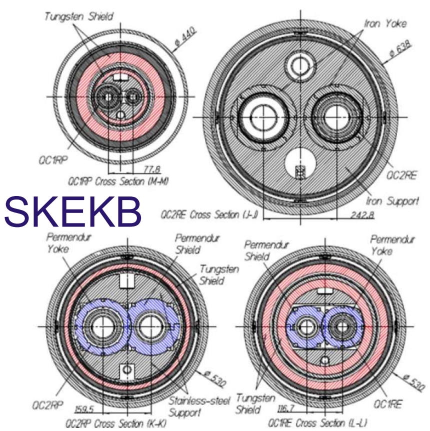


Sketch of solid support



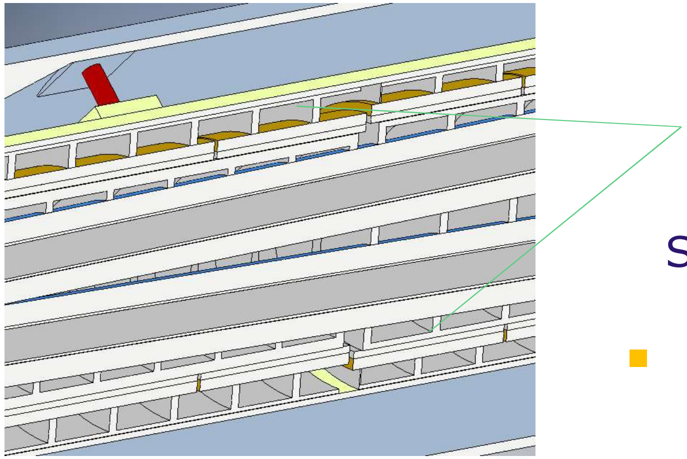
Sketch of skeleton support

Iron support of SKEKB



Static and stability of cryostat

- **Effect of magnet supports**
  - Add outer ring to enhance stiffness
  - Add inner ring to enhance stiffness (equals to enlarge outer diameter of QD0/QF1)



S-o support: skeleton support with outer ring

- Add an outer ring decrease the uneven deformation largely.

Magnet support	uneven deformation in QD0 (um)		uneven deformation in QF1 (um)		Total weight (kg)	Frequency of 1st mode (Hz)
	Vertical	Horizontal	Vertical	Horizontal		
Skeleton	44	5	0.6	0.2	3244	12.7
Solid	7.3	0.6	0.3	0.2	5041	11.3
S-o support	27	1.6	0.7	0.5	3477	13.7

Summary

- Preliminary physics design of MDI in High Luminosity Higgs.
- Single layer beam pipe with water cooling, SR heat load is not a problem.
- Hit density on first layer of vertex detector is low from radiation background.
- New mask is designed and photons hitting Be reduced by an order of magnitude.
- Preliminary design of shielding
- Highest temperature on collimators from SR and HOM is 148 ℃
- HOM heat load updated with revised beam pipe shape.
- Central beampipe with cooling structures optimized; FEA thermal analysis to verify the design.
- MDI alignment system is preliminary considered and designed.
- Sealing of remote vacuum connector is optimized.
- Structure optimization within cryostat and stability is analyzed.

Thanks

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