CEPC 束流管物理设计

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2022 年度 CEPC 束流管及铍相关应用研讨会

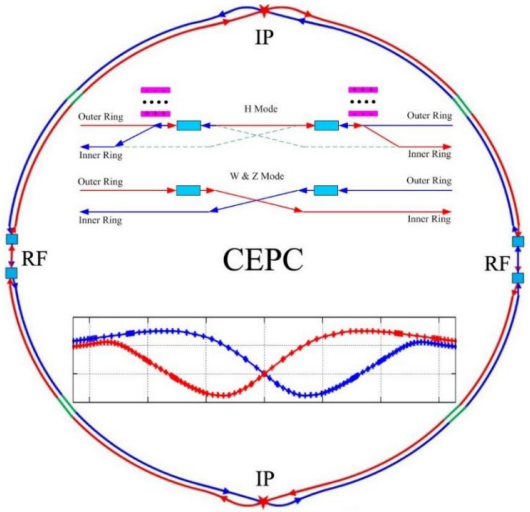
2022.5.6，北京

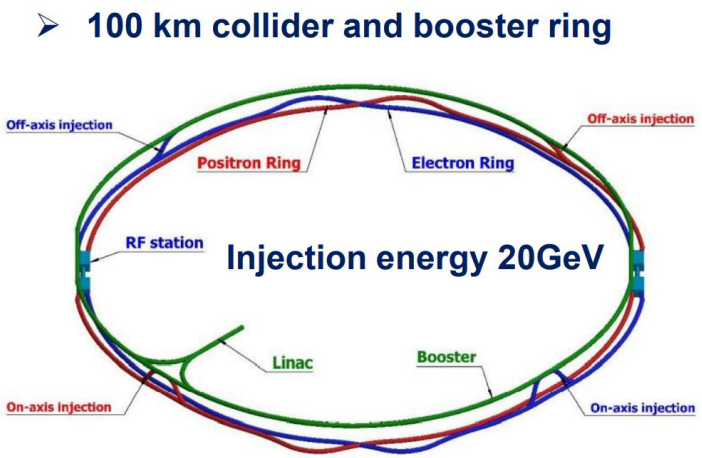
报告主要内容

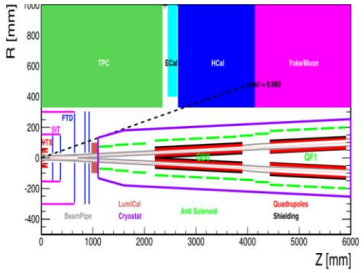
- CPEC 及 MDI 介绍
- 束流管设计要求
- 当前束流管物理设计
- 总结与展望

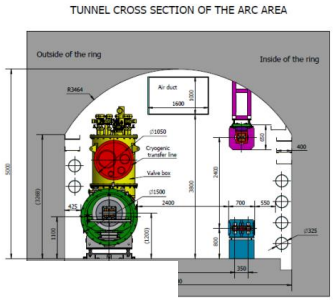
CEPC 介绍

- 环形正负电子对撞机（Circular Electron Positron Collider, CEPC）
  - 作为 Higgs / Z / W 工厂
  - ~ 4M Higgs boson / 4T Z boson / 100M W boson
  - 约 100 公里长，由直线加速器/增强器/储存环组成
  - 计划运行约 10 年，未来可升级成为 SppC
  - 2018 年发布概念设计报告（CDR），正准备和撰写技术设计报告（TDR）









For More Information about CEPC, please refer to Haijun's talk here

Introduction – Accelerator Parameters

	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		
Bunch length σ_z (mm)	4.4			
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	[illegible]	[illegible]	[illegible]	
Natural Chromaticity	[illegible]	[illegible]	-491/-1161	-513/-1594
Betatron [illegible]	363.10 / 365.22			
S[illegible]	0.065	0.040	0.028	
H[illegible] (2 cell) (kw[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

2018 CDR Baseline Design

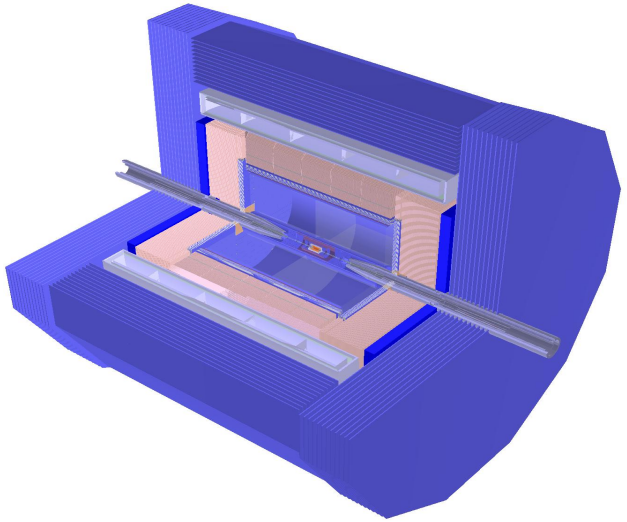
	ttbar	Higgs	W	Z
Number of Ips	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
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	[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

2021 Improved Design

67%⇑ **259%⇑**

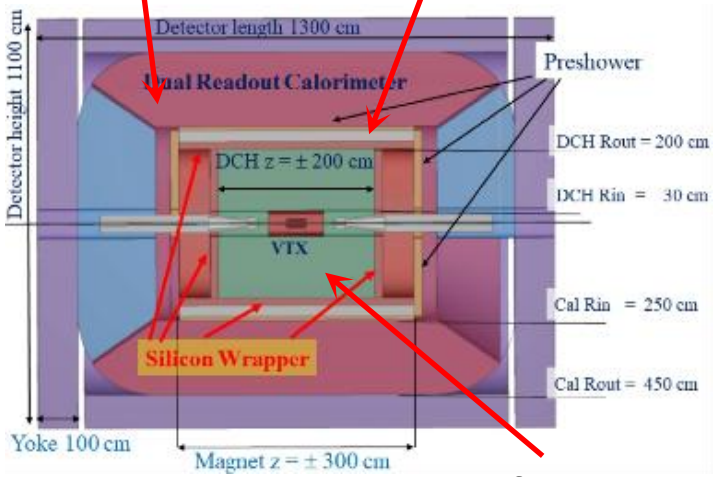
Introduction – Detector Designs

Particle Flow Approach
(ILD-like)



DR Calorimeter

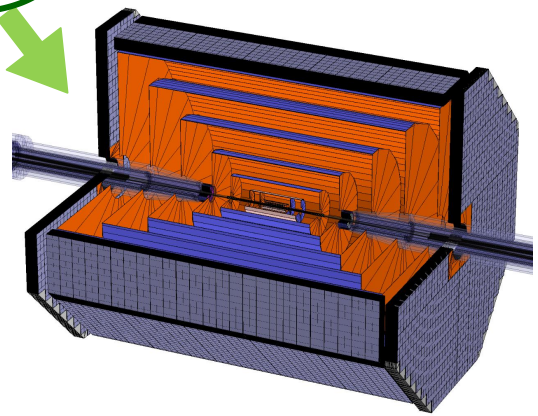
2T Magnet



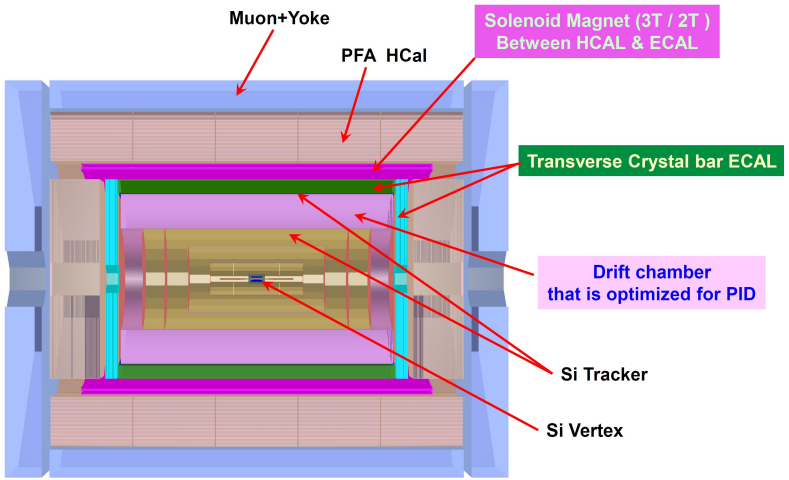
Drift chamber

IDEA concept
(also proposed for FCC-ee)

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



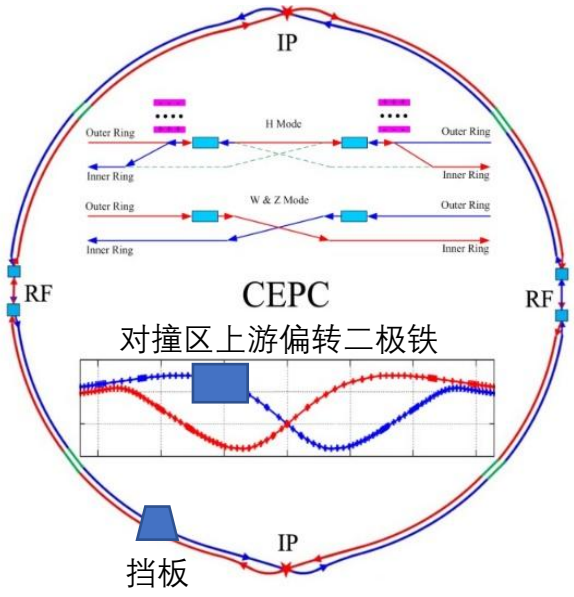
Full Silicon Tracker (FST) concept

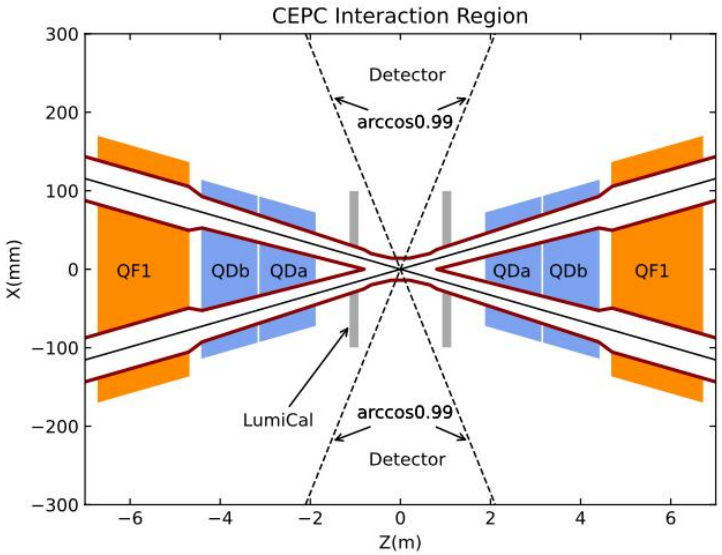


4th Detector concept

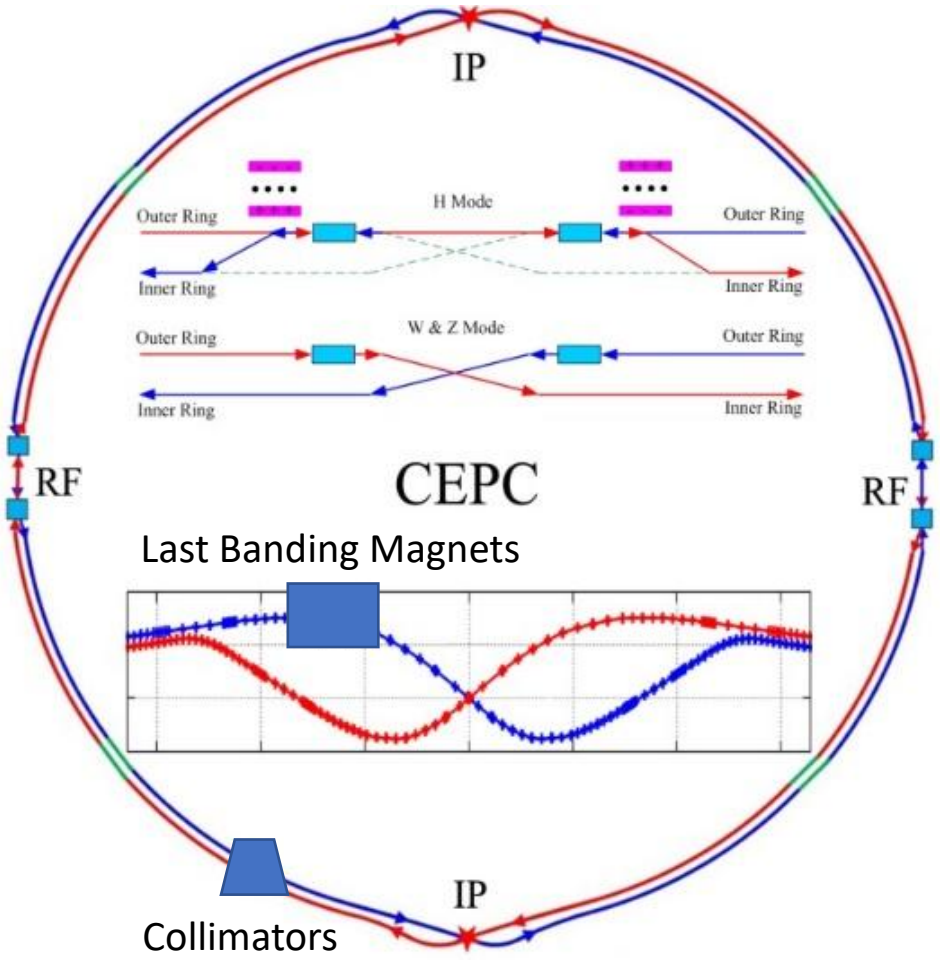
CEPC MDI 介绍

- MDI 代表加速器-探测器接口区域(Machine Detector Interface)
  - 对撞区及外部相关部件
  - 两个对撞点——两个对撞区
  - 33mrad 交叉角
- “可扩展”的对撞区设计
  - 适用于所有能量的统一设计
  - TDR 的对撞区范围是 14m（CDR 是 12m）
- 设计目标
  - 高亮度，低本底，高容错率（物理）
  - 易安装/易拆卸/可维护（机械/工程）





MDI 涉及到的子系统

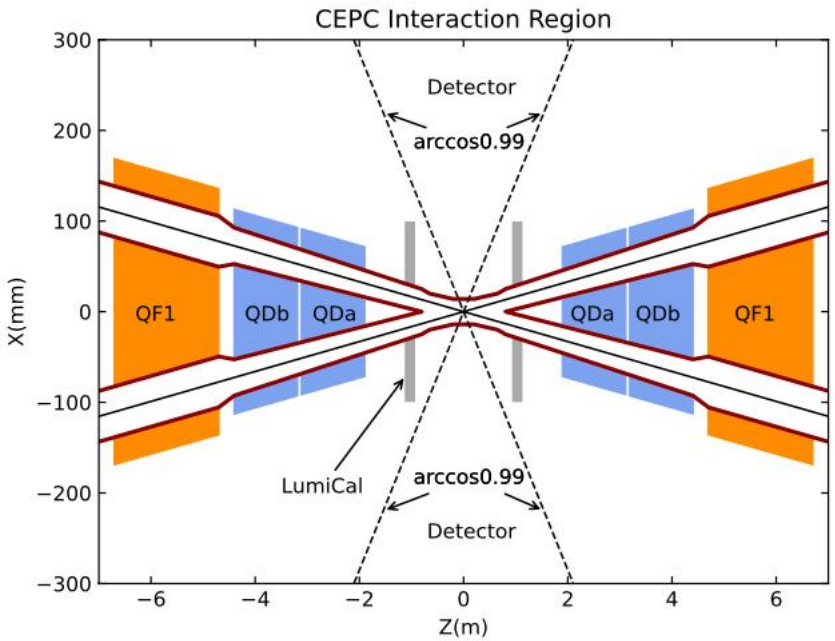


Accelerator
IP Feedback
BG Simulation
LumiCal
Vacuum Chamber
SR Masks
QD0/QF1
Anti-Solenoid
Cryostats
BPMs
Instability&Impendance
Cooling
Shielding
Assembly&Supporting
Alignment
Connecting System
Vacuum pumps
Last Bending Magnet
Collimators
Control

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

对撞区设计是关键

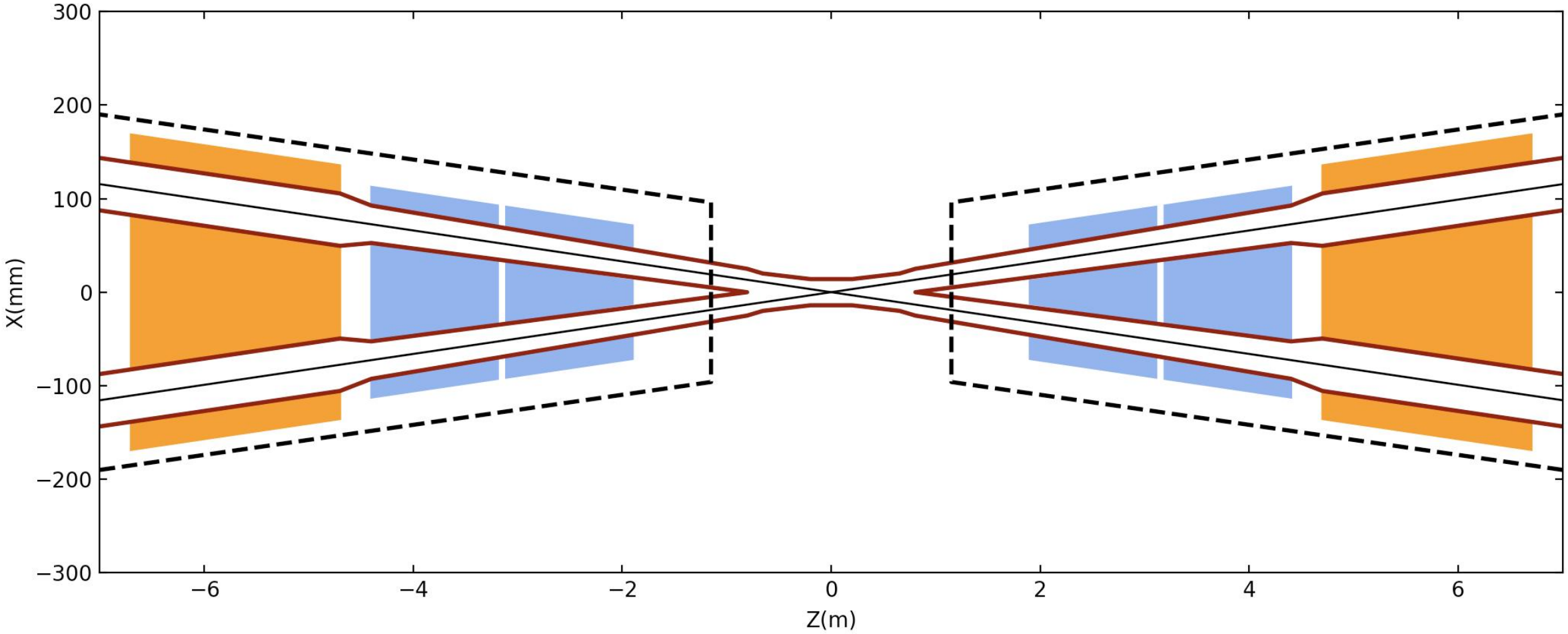
- 探测角的划分（Acos 0.993 ---> Acos 0.99）
  - 探测角以内是信号存在区域（Detector Acceptance）
- 探测角以外的要求和设计难度
  - 部件众多（亮度探测器、束流位置测量仪器等等）
  - 支撑结构众多（加速器、探测器部件的线缆、支撑）
- 部件划分
  - 探测器束流管（单管）
  - 加速器真空盒（双管）
  - 由于交叉角存在，两者坐标系不一致



探测器束流管的设计要求

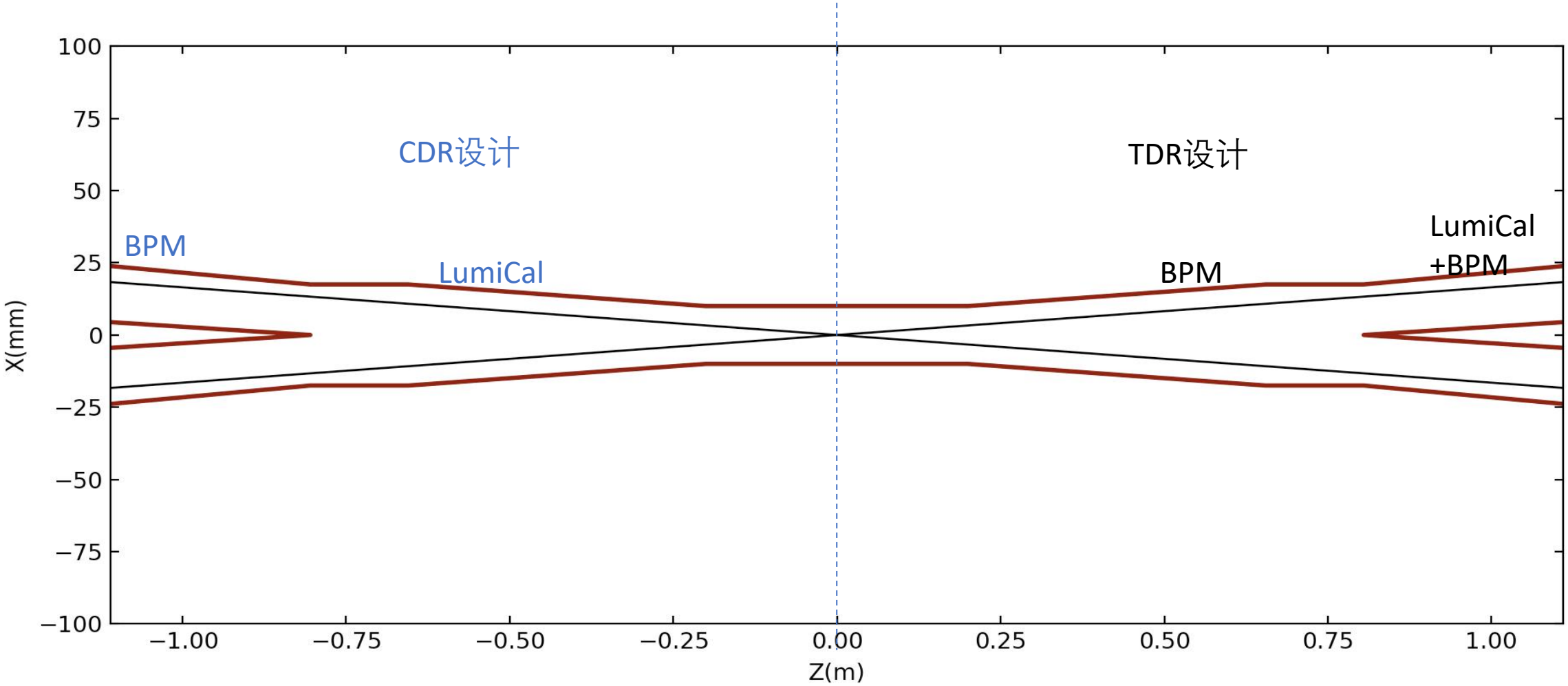
- 物理要求
  - 中心束流管 —— 辐射长度上限，越薄越好；孔径越小越好
  - 外延管 —— 满足相关物理系统的要求
- 机械要求
  - 力学稳定性
  - 热学稳定性
- 实际实现——平衡
  - 中心束流管孔径——本底与信号；物理与机械 等
  - 外延管厚度及材料——探测器本底和亮度探测器

当前束流管物理设计——对撞区



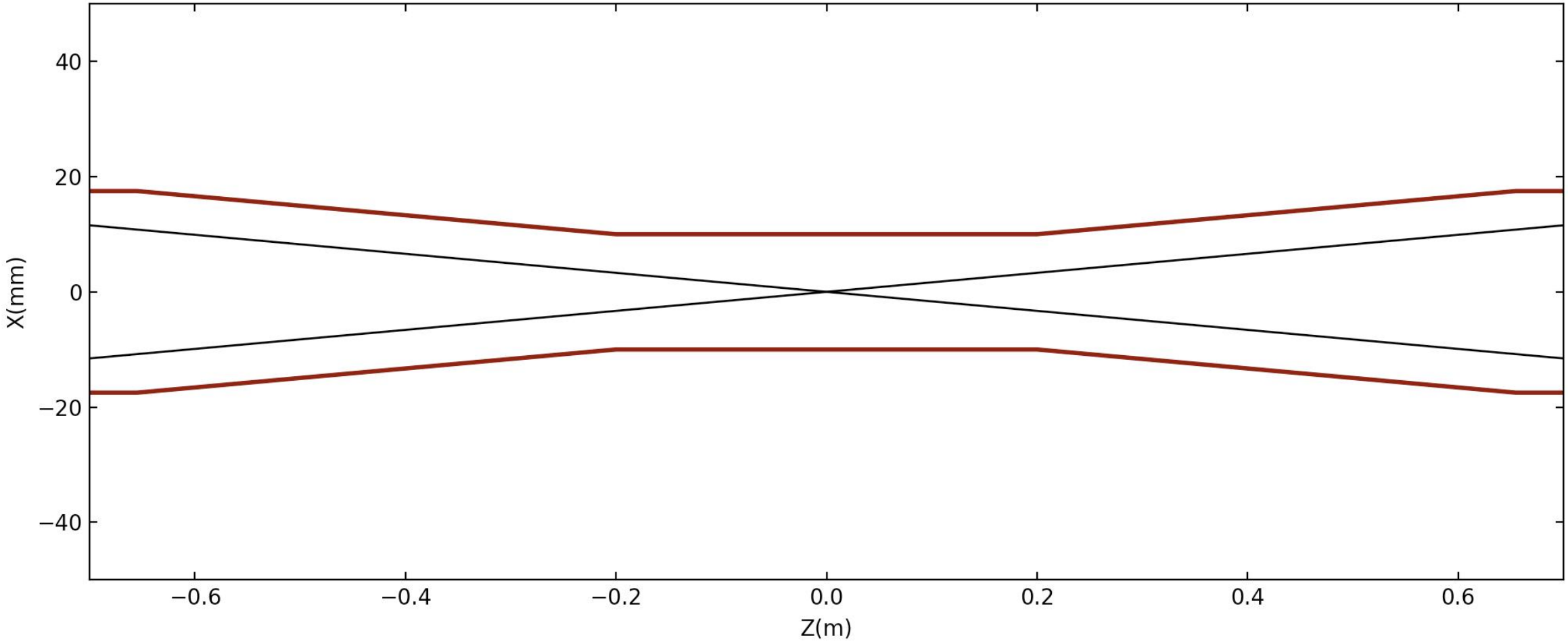
TDR 阶段对撞区的范围是 -7m~7m

当前束流管物理设计



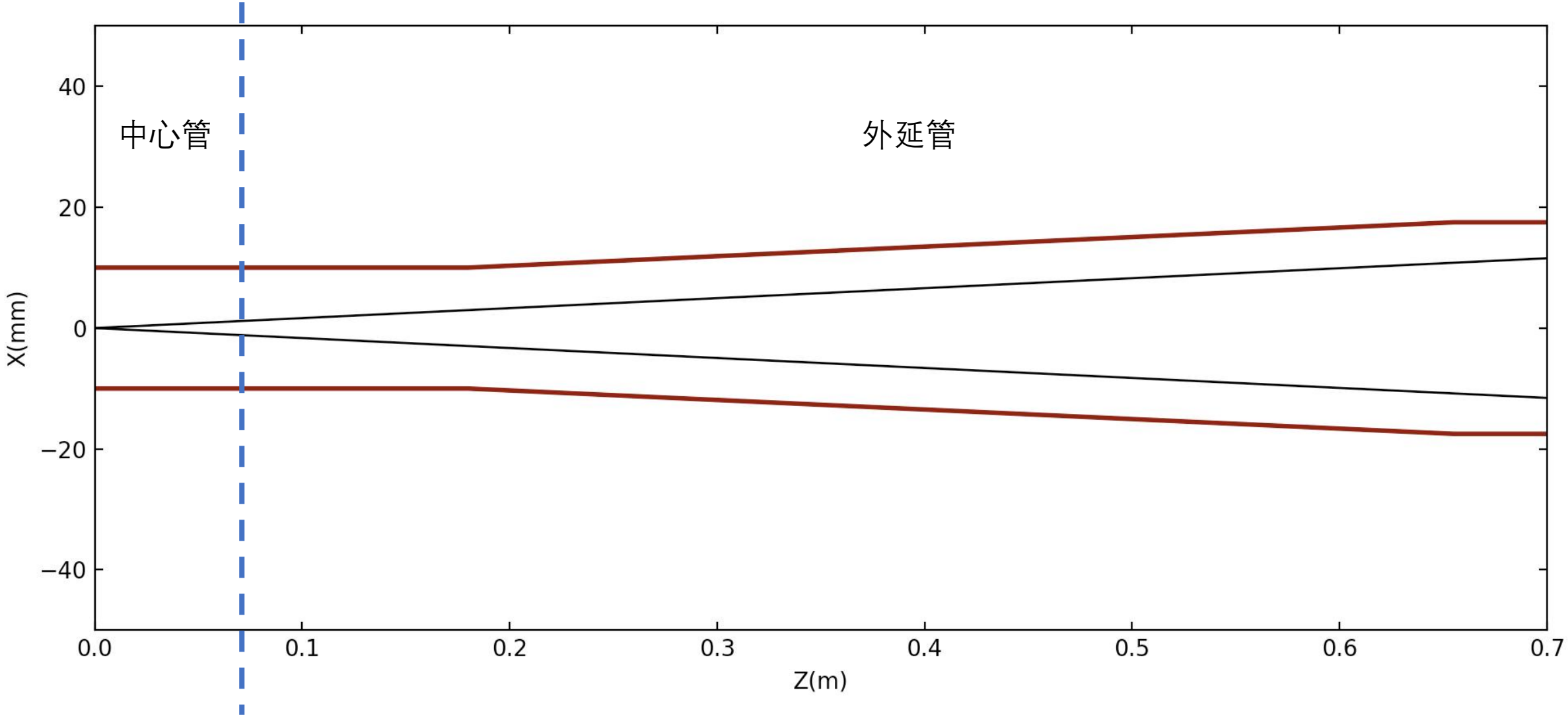
非恒温器内中心区域的范围是 -1.1m~1.1m

当前束流管物理设计



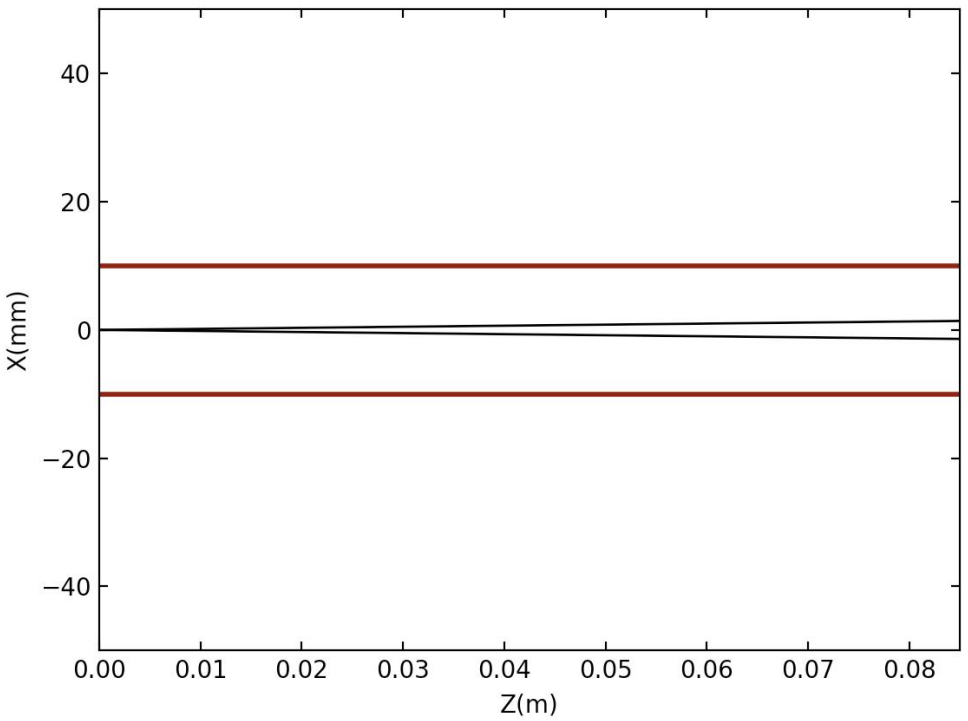
对称设计，以 0 ~ 700 为例，存在口径扩张

当前束流管物理设计

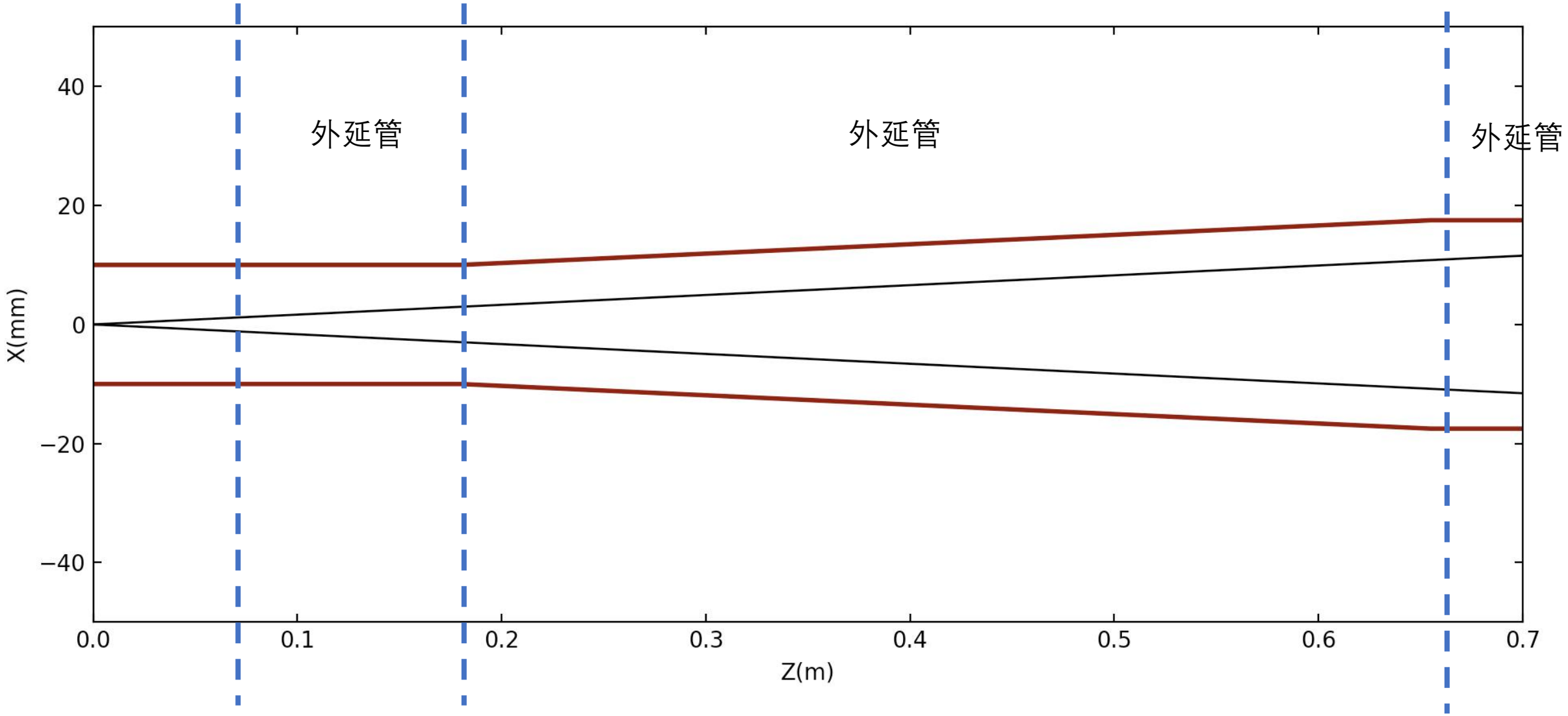


中心管——20mm 内径，铍

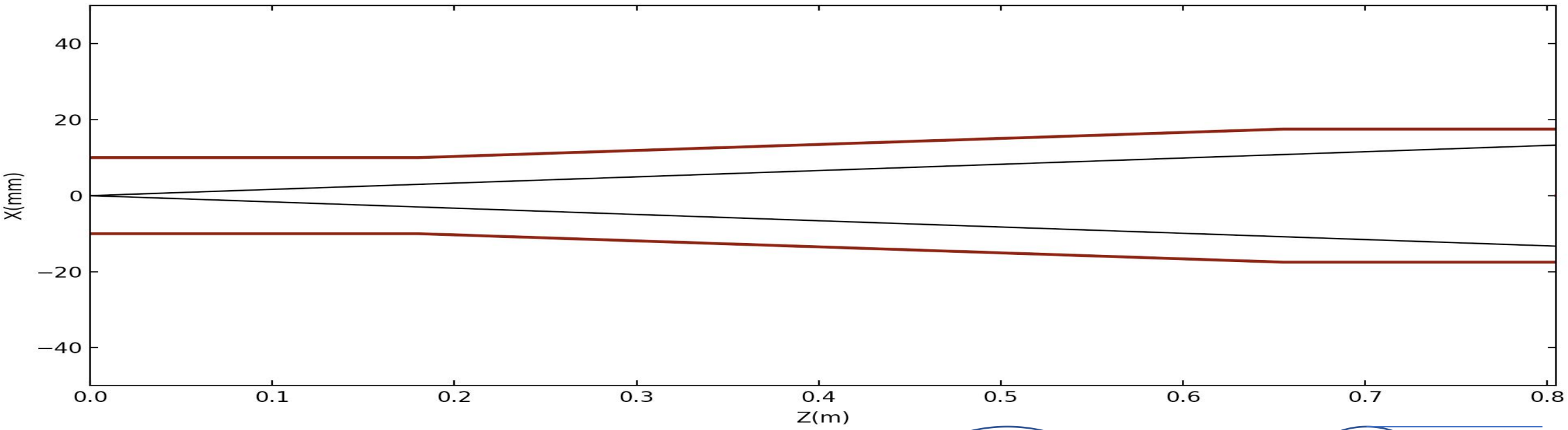
- 物理要求
  - 孔径：Ø28 mm ---> Ø20mm（下限 Ø9.52mm）
    - 顶点探测器性能提升
    - 本底增加
  - 材料：铍
  - 厚度：0.15% 辐射长度——0.5mm
  - 长度：85mm（下限 70 mm）
  - 圆形束流管



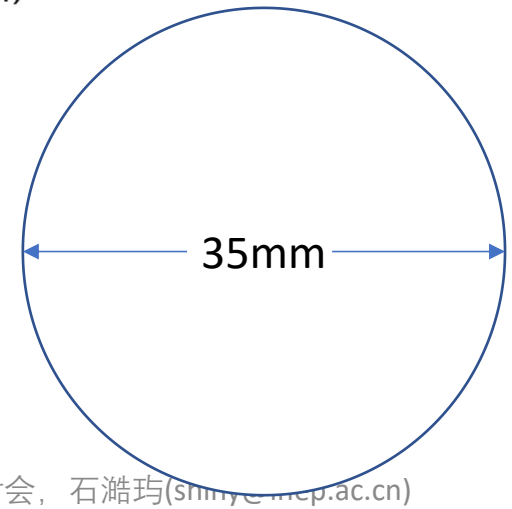
当前束流管物理设计

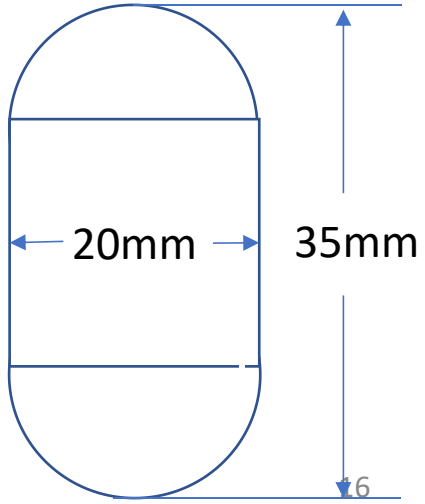


外延管——内径35，铝，跑道型

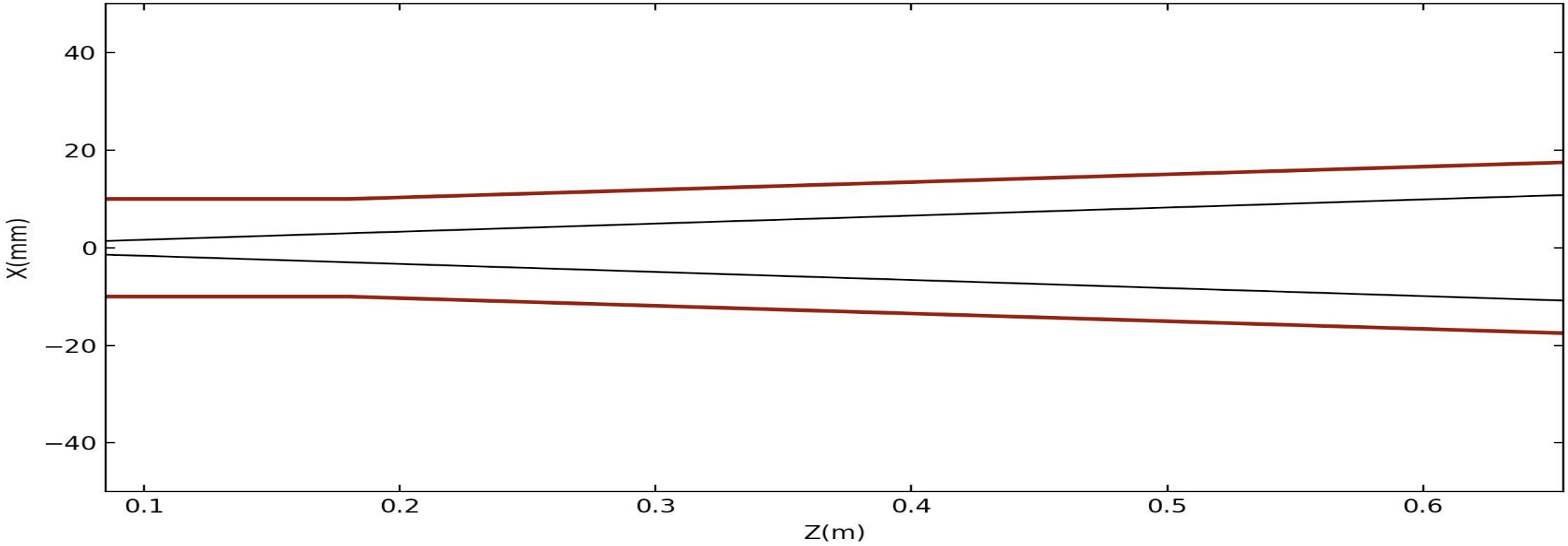


- 内径 35mm，由同步辐射决定
- 截面跑道型，由 HOM 热决定
  4097.23w→1150.1w



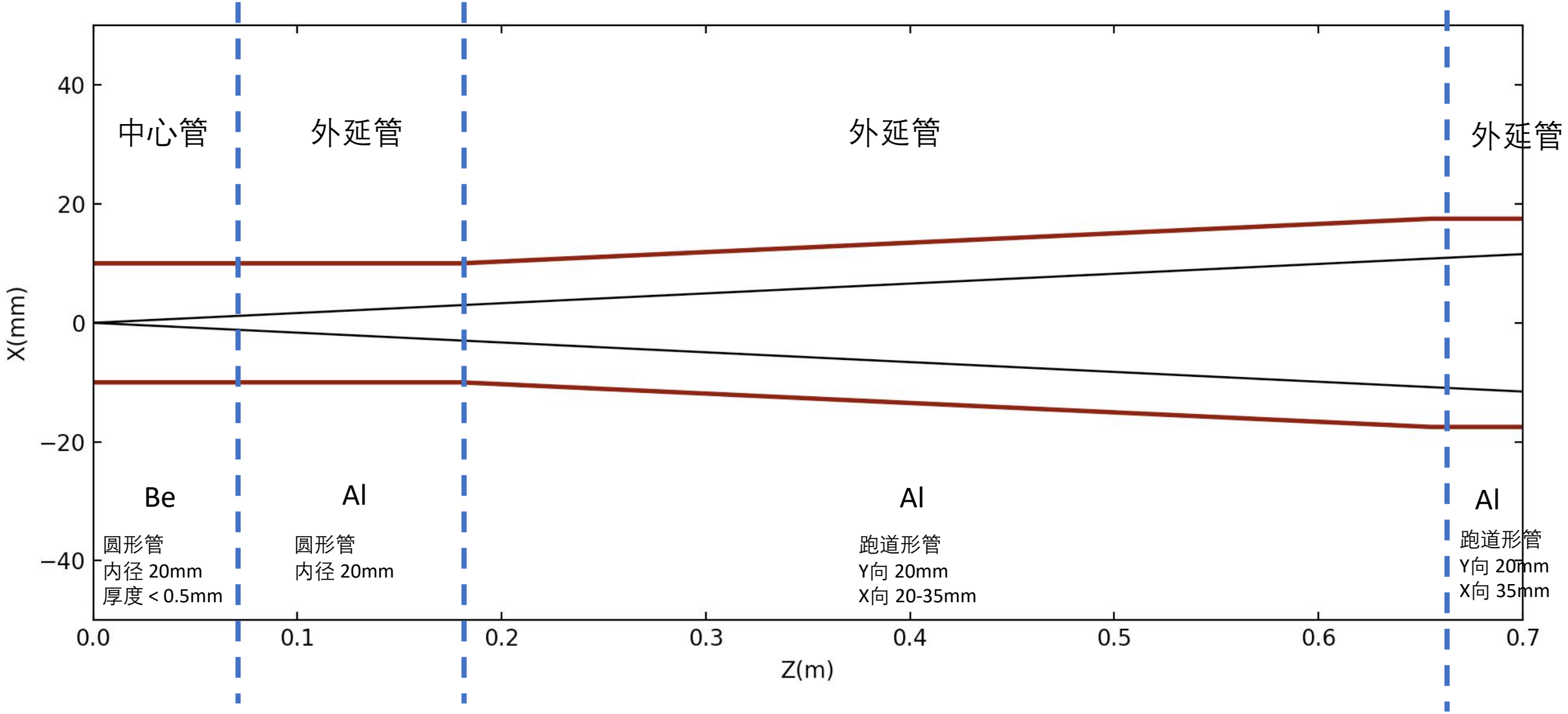


外延管——铝，过渡段



- 长度影响条件
  - 本底考量：斜率不大于束流自身斜率
  - HOM 考量：坡度越缓越好

当前束流管物理设计


中心管
外延管
外延管
外延管
Be
圆形管
内径 20mm
厚度 < 0.5mm
Al
圆形管
内径 20mm
Al
跑道形管
Y向 20mm
X向 20-35mm
Al
跑道形管
Y向 20mm
X向 35mm
X(mm)
Z(m)
40
20
0
−20
−40
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

总结与展望

- 已经有了基线物理设计，考虑了以下因素
  - 本底（包括同步辐射和丢失粒子）
  - 束流动力学孔径和束流清晰区
  - 探测器要求（顶点、LumiCal 等）
  - 加速器要求（BPM等）
  - 分工和接口
- 作为基线设计推进研究
  - 模拟工作
  - 工程设计
- 收集问题，集中改进
  - 动态优化
  - 版本概念

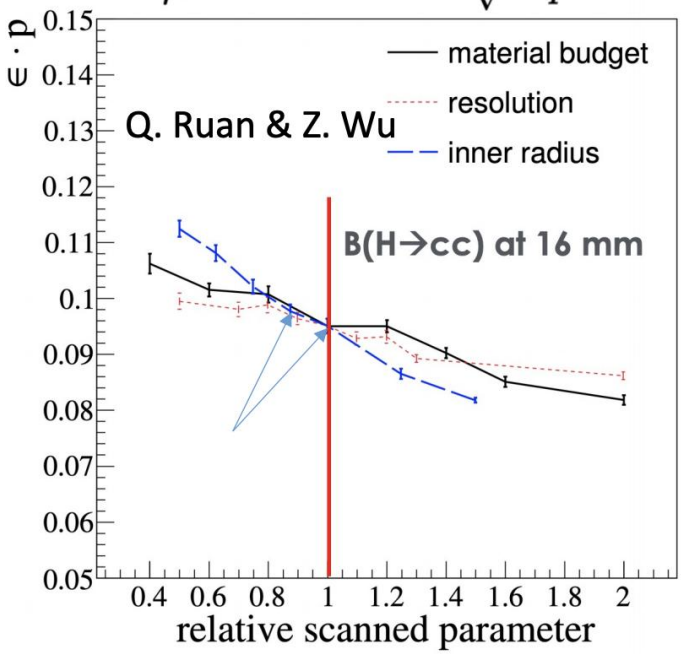
谢谢各位老师

Backup

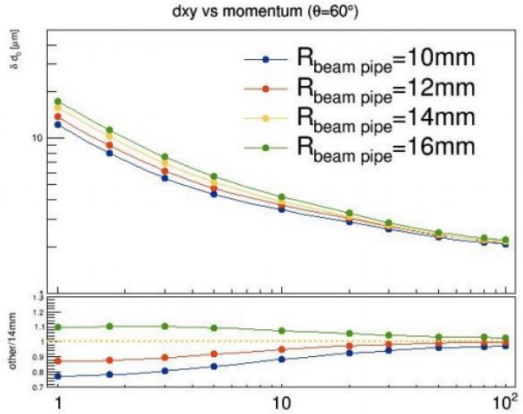
Physics Gains for 20mm Be

- First estimates made with fast simulation and scaling

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



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



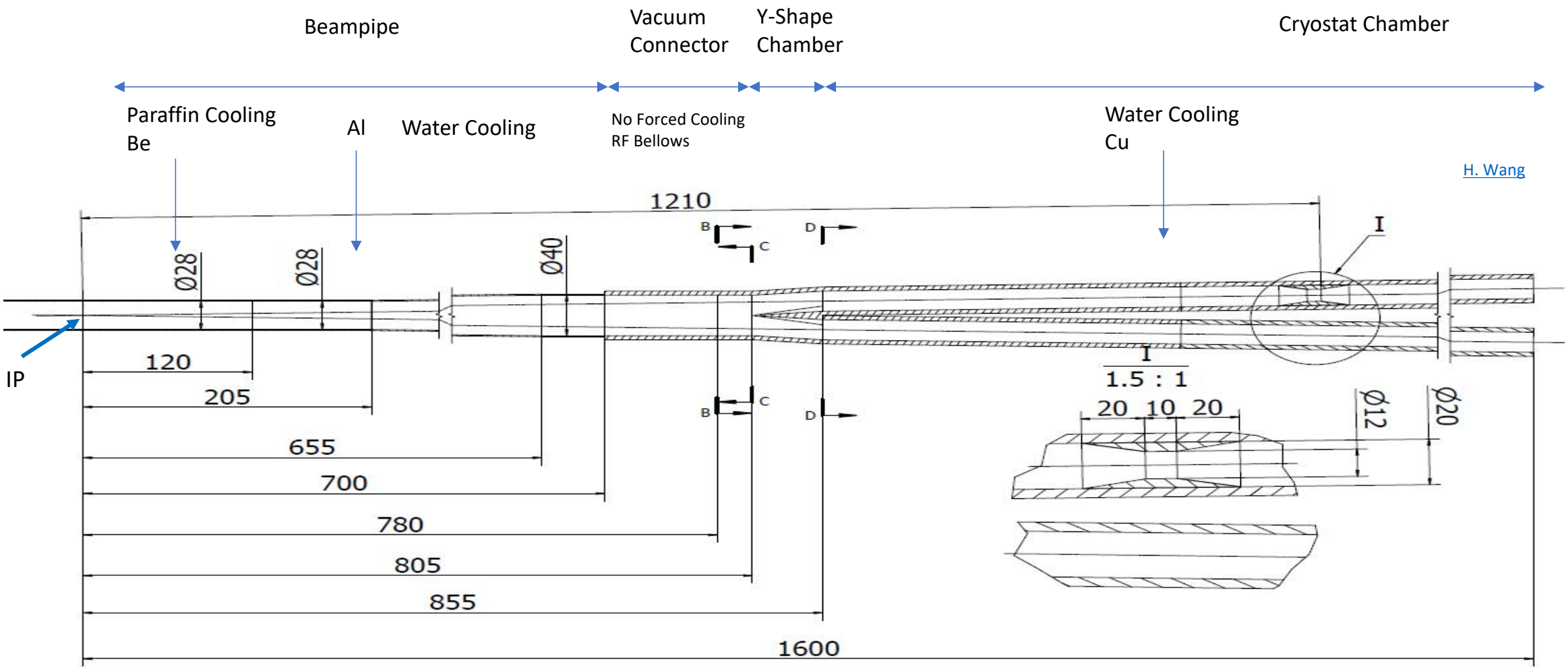
H. Zeng

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

G. Li

The cdr beampipe design

Nearly 20 versions tried in since last summer



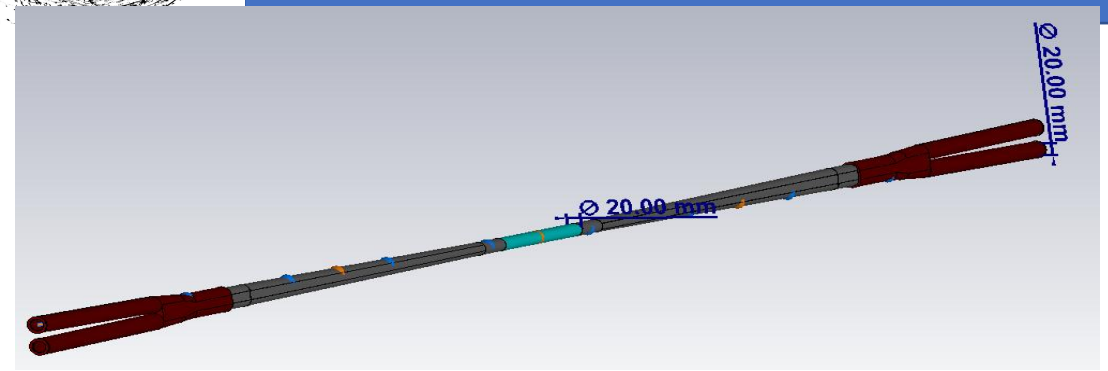
The new central beampipe design

- If we still keep the cylinder design, the HOM heat would be unacceptable: P: H/W/Z/tt: 84.78w/413.6w/4097.23w/23.54w

Yudong Liu

Position	Position Start-end (mm)	material	Length (mm)	Higgs(w) & (w/cm²)	W (w) & (w/cm²)	Z(w) & (w/cm²)	ttbar （w） & (w/cm²)
Be pipe (w)	0-85	Be	85	3.99 & 0.075	19.72 & 0.369	**195.16 & 3.65**	1.10 & 0.021
Be pipe transition(w)	85-130	Al	45	2.17 & 0.077	10.41 & 0.368	**103.34 & 3.66**	0.61 & 0.021
Transition pipe (w)	130-655	Al	525	24.90 & 0.055	121.70 & 0.268	**1205.51 & 2.66**	6.91 & 0.015
Transition （w）	655-700	Al	45	2.17 & 0.044	10.41 &0.210	**103.34 & 2.09**	0.61 & 0.012
RVC bellow （w）	700-780	Cu	80	1.85 & 0.021	8.93 & 0.102	**88.24 &1.00**	0.50 & 0.006
Transition on Y-crotch	780-805	Cu	25	0.57 & 0.02	2.77 & 0.095	**27.61 & 0.95**	0.18 & 0.006
Y- crotch (w)	805-855	Cu	50	1.18 &0.016	5.55 & 0.076	**55.15 & 0.75**	0.32 & 0.004
Quadrupole pipe(w)	855-1100	Cu	245	5.59 & 0.017	27.30 & 0.085	**270.33 & 0.84**	1.53 & 0.005
Total	0-1100	-	1100	42.39 &0.039	206.80 & 0.189	**2048.69 & 1.87**	11.76 & 0.011

Transition region: Racetrack (including materials)& power distribution



Yudong Liu

σ_z=5mm: Two beam in the IR

Loss factor Trap in IR @k_trap: 0.032v/pc

P_{trap}: H/W/Z/tt: 23.8w/116.1w/1150.1w/6.61w

Position	Position Start-end (mm)	material	Length (mm)	Higgs(w) & (w/cm²)	W (w) & (w/cm²)	Z(w) & (w/cm²)	ttbar (w) & (w/cm²)
Be pipe (w)	0-85	Be	85	1.12 & 0.02	5.535 & 0.104	**54.781 & 1.02**	0.31 & 0.005
Be pipe transition(w)	85-130	Al	45	0.61 & 0.02	2.923 & 0.104	**29.008 & 1.02**	0.17 & 0.007
Transition pipe (w)	130-655	Al	525	6.99 & 0.017	34.16 & 0.085	**338.39 & 0.83**	1.94 & 0.005
Transition （w）	655-700	Al	45	0.61 & 0.014	2.923 & 0.069	**29.008 & 0.69**	0.17 & 0.003
RVC bellow （w）	700-780	Cu	80	0.52 & 0.007	2.508 & 0.035	**24.77 & 0.33**	0.14 & 0.002
Transition on Y-crotch	780-805	Cu	25	0.16 & 0.007	0.778 & 0.031	**7.7492 & 0.31**	0.05 & 0.002
Y- crotch (w)	805-855	Cu	50	0.33 & 0.005	1.557 & 0.024	**15.481 & 0.24**	0.09 & 0.002
Quadrupole pipe(w)	855-1100	Cu	245	1.57 & 0.005	7.663 & 0.024	**75.883 & 0.24**	0.43 & 0.002
Total	0-1100	-	1100	11.9 & 0.012	58.05 & 0.057	**575.07 & 0.57**	3.3 & 0.003

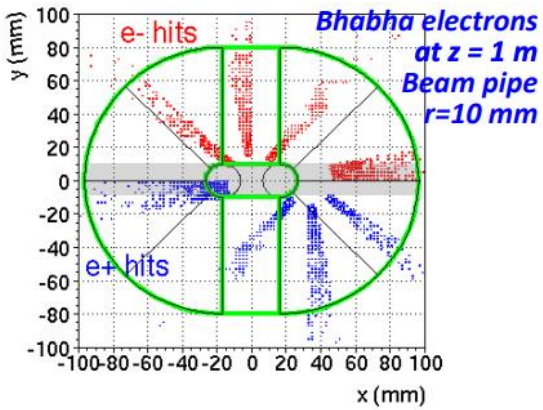
The new LumiCal position

Suen Hou

BHlumi X-section

flat beam pipe, y= ±10 mm

Bhlumi counting electrons in fiducial region at z = 1m



Lab round r>20 mRad, |y|>20 mm

CMS 10 ~ 80 mRad		LAB detect *ONE* electron		LAB detect *both* electrons	
BARE1		R>20 mRad full phi coverage	R>20 mRad cut off ±20mm	R>20 mRad full phi coverage	R>20 mRad cut off ±20 mm
Nevents	457232	274420	53724	93311	51360
Xsec (nb)	1168.3	701.2	137.3	238.4	131.2

Lab round r>15 mRad, |y|>15 mm

CMS 10 ~ 80 mRad		LAB ONE electron		LAB both electrons	
BARE1		R>15 mRad full phi coverage	R>15 mRad cut off ±15mm	R>15 mRad full phi covearge	R>15 mRad cut off ±15mm
Nevents	457232	330952	100152	204263	96221
Xsec (nb)	1168.3	845.6	255.9	521.9	245.9

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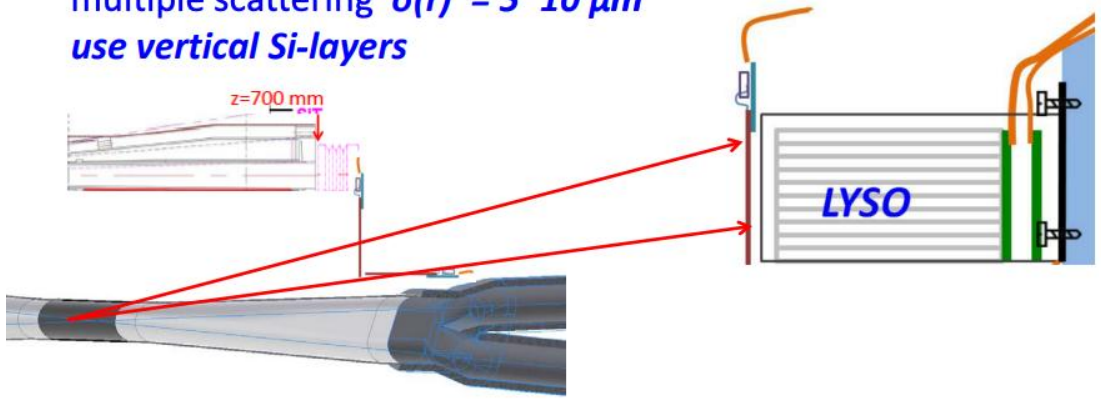
Electron @ 15 mRad

Beampipe= $0.5^{Al}+0.5^{Air}+0.35^{Al}$
Distance dz in beampipe=
1.35/tan(0.015 mRad) = 90 mm

- Electrons at ϑ_{min} = 15 mRad needs a Si-layer attached on beam-pipe to minimize multiple scattering expansion
  σ(Z) ~ 200 μm, σ(ϑ) ~ 20 μRad,
- Inner tracker region z = 400~700 mm
  (ϑ range 15 ~35 mRad)
  multiple scattering ***σ(r) = 5~10 μm***
  use vertical Si-layers



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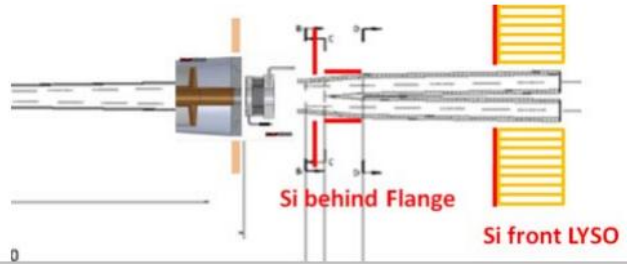
Alignment error less than $1\mu m$

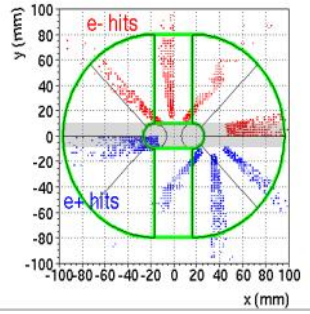
The new central beampipe design

Summary, tube-pipe
Fixed r_y= ±10mm, split-x to dual-pipes

Suen Hou

- **Bhabha cross-section** with both electrons detected in Lab frame of Θ_{min} >15 mRad, |y|>15mm
  ➔ X-section ~250 nb
- **LumiCal simplified** (need detailed GEANT study)
  - fiducial range cut off x-axis for mechanical and probes
  - Si-layers outside Flange
    two horizental flat layers upon/below beam-pipe ➔ θ_{min} edge
    vertical layers to beampipe for θ coverage





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- HOM and LumiCal both prefer the racetrack design
- LumiCal wants to change the material to Al as much as possible
- IP BPM will be added to single beampipe part