CEPC SR system feasibility design

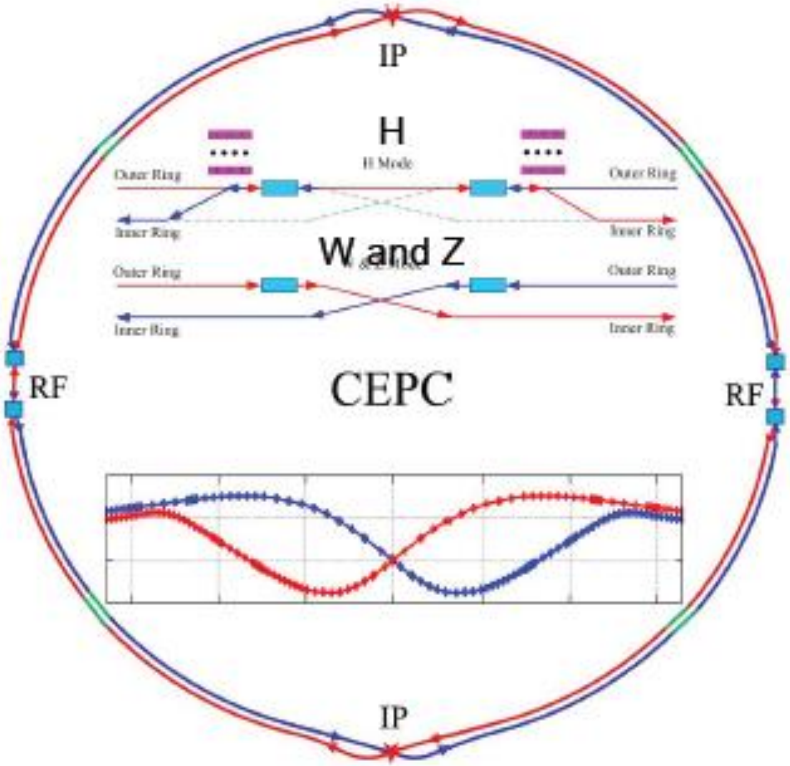
CEPC SR study group

2020.06.15

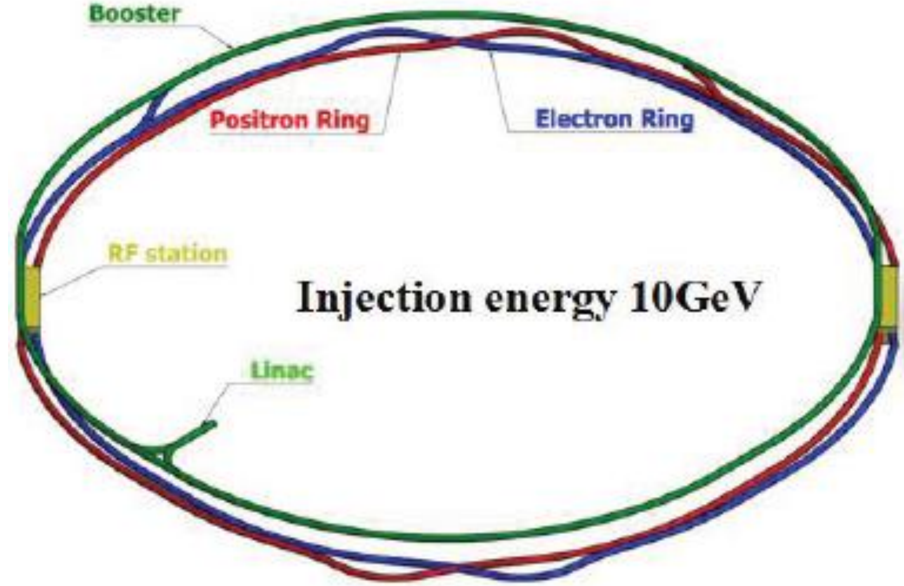
Outline

- CEPC CDR: parameters and baseline layout
- SR design in the CEPC CDR
- The new design: parameters, baseline and the applications
- The vacuum chamber design and the requirement to the bend magnetic
- Tunnels, halls and vertical shafts for the SR stations
- The challenges and the next works
- Summary

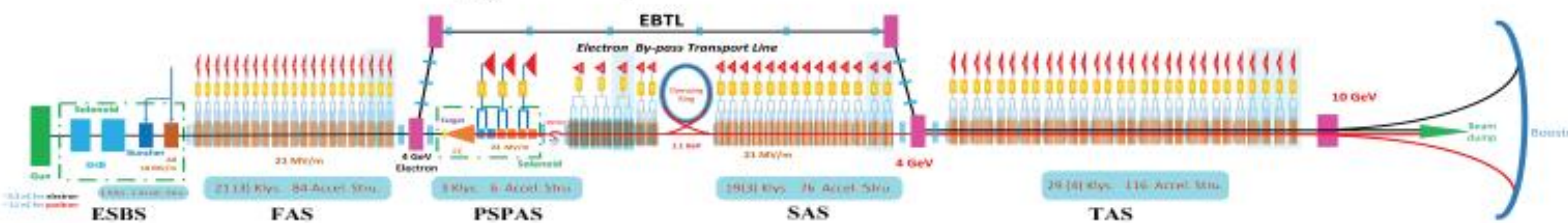
CEPC CDR baselines layout



CEPC collider ring (100km)



CEPC booster ring (100km)



CEPC Linac injector (1.2km, 10GeV)

CEPC CDR 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	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (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 $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**10.1**	**16.6**	**32.1**

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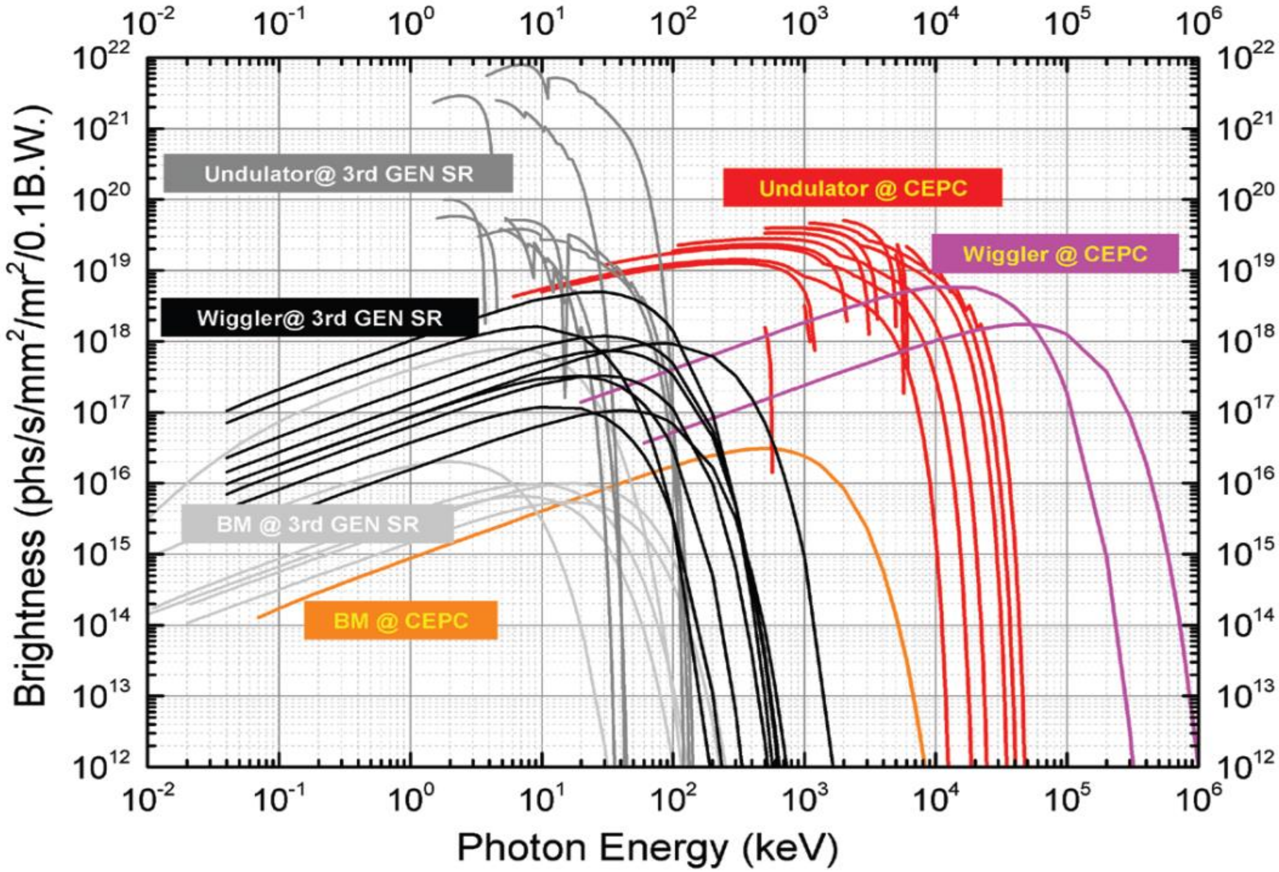


Brightness of the SR from bent iron, torsion, oscillator and low-K undulators in future high-energy particle colliders(CEPC-CDR)

The torsion pendulum has a characteristic gamma energy of 19.2 MeV and a high flux radiant energy of 300 MeV. The gamma light energy produced by the undulator can reach 20 MeV at high flux. Moreover, in the energy region greater than 100 keV, the brightness and flux of the future high energy particle collider synchrotron source are higher than those of the third generation synchrotron radiation source.

Central intensity of Synchrotron radiation,[photon/s/mrad2/0.1%b.w.]

$$\left.\frac{d^2F_{bm}}{\mathrm{d}\theta d\psi}\right|_{\psi=0} = 1.327\times10^{13}E^2[GeV]I(A)H_2(y)$$

F_{bm} , flux; I, the curent of the ring, $\mathrm{H_2(y) = y^2K^2_{\frac{2}{3}}(y/2)}$, K, the second Bessel function;

$\mathrm{y} = \epsilon/\epsilon_c$, ϵ,the photon energy, $\epsilon_c = 0.665E^2[GeV]B[T] = 358.2\mathrm{keV}$.

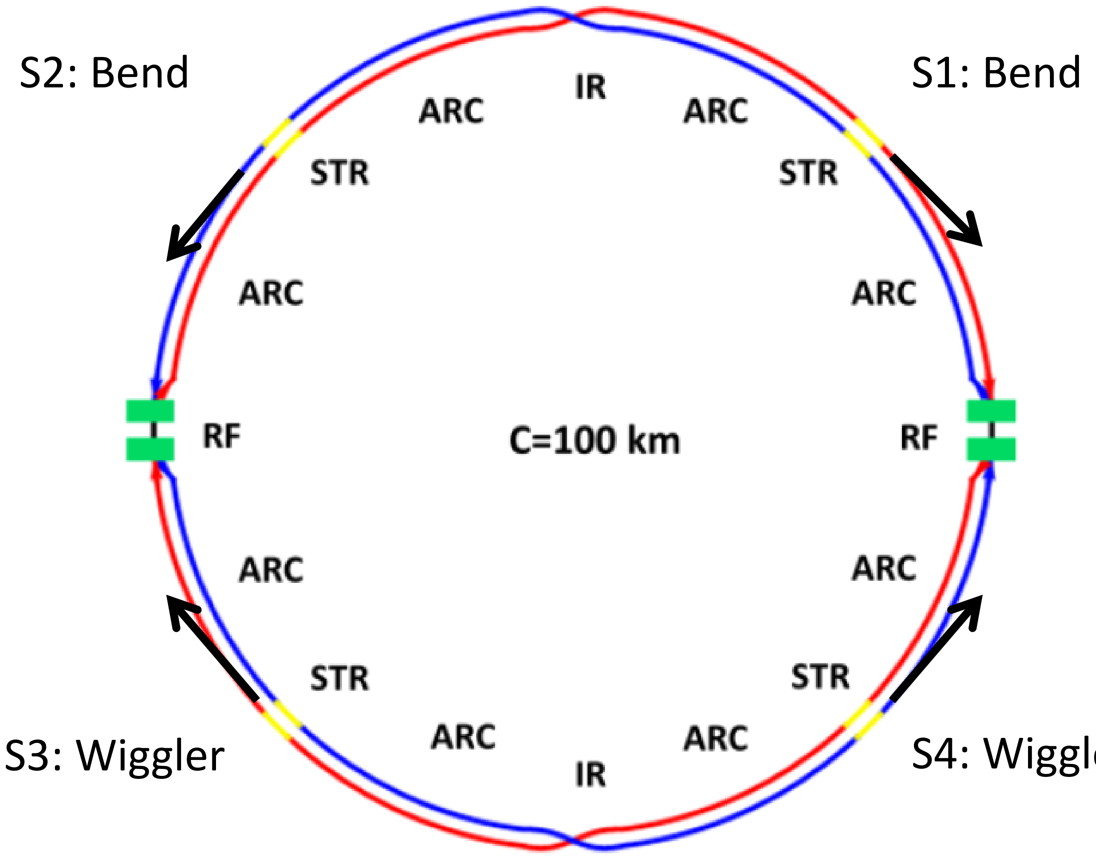
Table A6.1: Performance comparison between a CEPC gamma source and the main laser gamma sources in the world.

Source	CEPC BM	CEPC Undulator	CEPC Wiggler	SSRF (China)	TUNL-HIGS (USA)	TERAS (Japan)	ALBL (Spain)
Gamma energy rang (*MeV*)	0.1~5	0.1~10	0.1~100	0.4-20 330-550	2-100	1-40	0.5-16 16-110 250-530
Energy resolution (*ΔE/E*)	continuous	~1%	continuous	5%	0.8~10%		
Flux (*phs/s*)	$>10^{12}$ @0.1%	$>10^{13}$ @0.1%	$>10^{16}$ @0.1%	10^6	10^8	10^4~10^5	10^5~10^7

Total design of the SR stations

- **Four beamlines：**
- **S1,S2: two bending magnetic field lines： 0.1-5MeV, >10^12@0.1%,**
- **High energy X-ray diffraction/scattering/transmission beam line**
- **Hard X-ray micro/nano probe beamline**
- **High voltage extreme condition beam line**

- **S3,S4:two wiggler beamlines：0.1-100MeV,>10^14@0.1%**
- **Photon-nuclear physics science**
- **Others high energy gamma-ray station, GRB simulations**



S1,S2: SR from bending magnetic field：0.1-5MeV, >10^12@0.1%

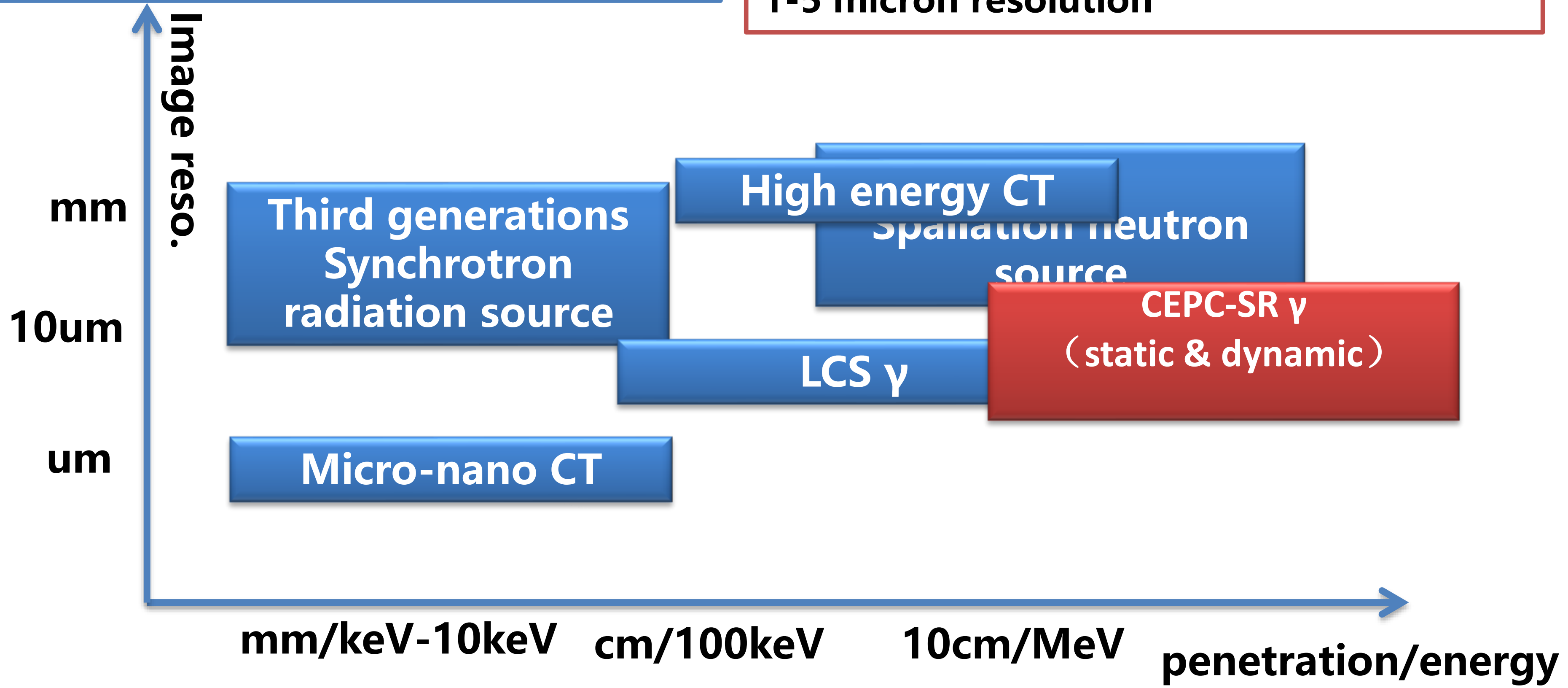
- **High energy X-ray diffraction/scattering/transmission beam line**
  - In-situ observation and structural analysis of aircraft engine blade growth process
  - Structural changes of special steel
  - Observation of special welds
- **Hard X-ray micro/nano probe beamline**
- **High voltage extreme condition beam line**
  - Structural changes of special materials under dynamic and high pressure conditions of 1000GPa
  - Study on the equation of state of special materials under static high pressure and high temperature/low temperature

CEPC high-flux γ beamlines

Complementary with the third generations of synchrotron sources, spallation neutron sources, industrial CT, and LCS gamma sources:
7.5cm steel penetration, several micron resolution, high flux fast imagination

Static imaging - engine blade inspection: 6cm thick steel, 1-5 micron resolution

Dynamic imaging---metal phase change process-droplet solidification/seawater corrosion mechanism: us, 6cm thick steel, 1-5 micron resolution

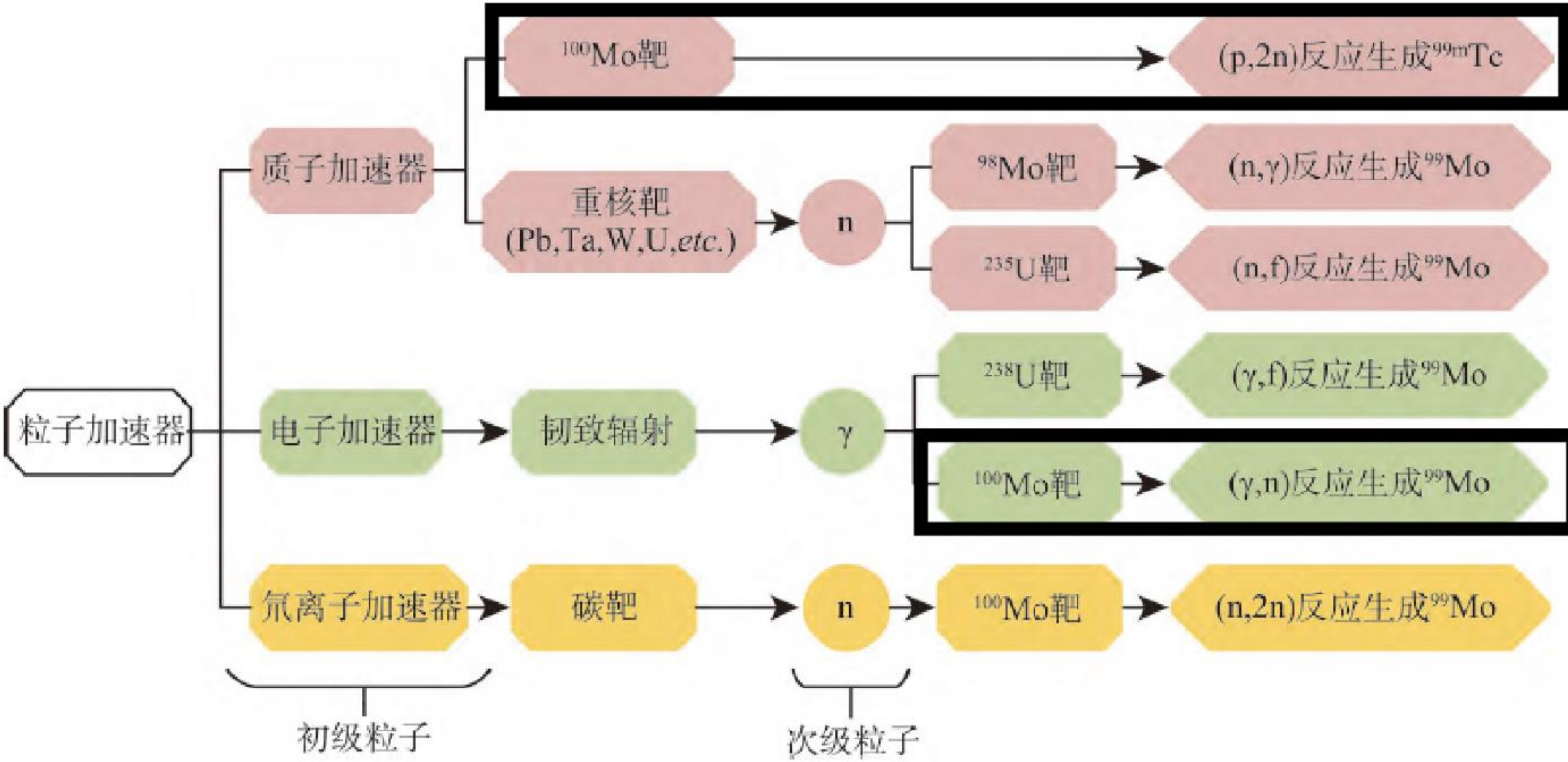


S3,S4: SR from wiggle magnetic field: 0.1-100MeV, >10^14@0.1%

- **Photon-nuclear physics science**
- **Gamma assisted transmutation**
- **Giant resonance,**
- **Nuclear resonance fluorescence**
- ***a "mini" giant dipole resonance it is often called pygmy dipole resonance (PDR).***
- **$^{12}C(\alpha,\gamma)^{16}O$ reaction: the "Holy Grail" of nuclear astrophysics.**
- **Others high energy gamma-ray station, GRB simulations**
- **radio-pharmaceuticals production**

紧缺放射性医用同位素制备

技术路线



放射性医用同位素需求量大，国内技术迫切需要

放射性同位素需求

- 据统计，我国常用放射性同位素^{18}F、^{60}Co、^{89}Sr、^{99}Mo、^{125}I、^{131}I、^{192}Ir等的年总消耗值近10亿元，其下游产业(同位素制品、核医学等)总产值能达到数百亿元。

- 目前国内反应堆生产同位素除了^{60}Co和^{131}I外，其他同位素基本依赖于进口。

- 而全球同位素生产反应堆大多由于运行年限长，面临退役，届时可能会影响国内放射性同位素的供应，因而有必要在国内开展重要同位素品种的自主生产。

- 我国可用于放射性同位素生产的七座研究堆均未进行放射性同位素的常规生产。

- 在加速器同位素制备技术方面，近年来发展很快，主要的同位素品种，如^{11}C、^{18}F、^{64}Cu、^{111}In、^{123}I等，我国都掌握了商品化生产技术，但缺少70MeV以上能量加速器制备同位素的技术。

同位素品种	^{99}Mo(^{99m}Tc)	^{131}I	^{125}I	^{60}Co	^{192}Ir	^{75}Se	^{3}H	^{241}Am	^{137}Cs
放射性活度(万 Ci)	3.51	2.05	0.18	11.8	24.7	6.0	0.45	0.09	0.01

中国目前无法生产Mo99

（1）99mTc发生器的母体核素，反应过程
^{98}Mo（n，γ）^{99}Mo，^{235}U（n，f）^{99}Mo。
（2）制备^{99}Tc，用于内脏器官造影。
（3）制造发射γ射线的医用同位素。
（4）作为示踪核素，用于土壤肥料方面科学研究。

钼-99，核素符号^{99}Mo，半衰期为65.94h。

货源

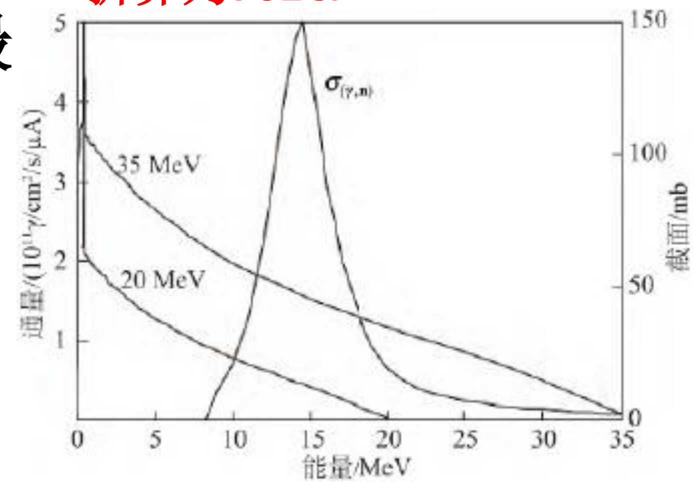
- 医用放射性核素来源
  - ✓ 核反应堆生产 ✓ 加速器生产 ✓ 从核燃料后处理废液中分离纯化
- 目前反应堆生产的医用核素全球供应依赖于少数几个医用研究堆。
- 以^{99}Mo为例，南非NTP公司、澳大利亚ANSTO公司、荷兰Mallinckrodt-Covidien公司和比利时IRE公司四个供应商2018年市场占比分别为21%、21%、37%、21%。

国家	反应堆	建堆时间	临界时间	计划关闭时间	年产量/Ci
荷兰	HFR	1957	1961	2024	187 200
加拿大	NRU	1952	1957	2018 已关闭	187 200
法国	OSIRIS	1964	1966	2015 已关闭	62 400
比利时	BR2	1958	1961	2026	156 000
捷克共和国	LVR-15	?	1957	2028	84 000
南非	SAFARI-1	1961	1965	2025	130 700
波兰	MARIA	1969	1974	2030	42 900
澳大利亚	OPAL	1956	2006	2055	42 900
俄罗斯	SM-3	1956	1961	?	少量
美国	HFIR	1961	1965	?	少量
美国	MURR	1963	1966	2026	少量
韩国	HANARO	1987	1995	?	少量
中国	CARR	2002	2010	?	计划生产

利用wiggler 伽玛束能区、通量非常合适

- γ射线诱发100Mo(γ,n)反应，反应阈值约为9 MeV；在14.5 MeV 下出现截面最大，约为150 mb。
- S=$\frac{N_A(0.693)}{MT} = 1.96 \times 10^{13} Bq/mg$
- 1Mo99=1.66*10^-25kg=1.66*10^-19mg
- 1mg=6*10^18Mo99

1h 10^14 通量可产生1.44mg
折算为762Ci



性能参数	短期技术				中期技术	
	反应堆裂变法	中子活化法	溶液堆裂变法	回旋加速器质子反应法	加速器驱动光子诱导法	低浓缩铀加速器驱动裂变法
核反应	$^{235}U(n, f)$	$^{98}Mo(n, \gamma)$	$^{235}U(n, f)$	$^{100}Mo(p,2n)^{99m}Tc$	$^{100}Mo(\gamma, n)$	$^{235}U(n, f)$
靶材	HEU	高纯 ^{98}Mo 靶	硝酸铀酰溶液	高纯 ^{100}Mo 靶	高纯 ^{100}Mo 靶	硫酸铀酰溶液
技术成熟度	***	**	**	**	*	**
产量	***	*/**	**	*/**	***	*/**
废物管理	*	***	**	**/***	**	**
其他同位素共产生可能性	***	*	**	*	*	***
审批困难度	***	**/***	**	***	**	*
经济成本	**	**	***	**/***	**	**

注：这些技术通过三级评级系统进行评估。***是最积极的结果，*是最不积极的结果。

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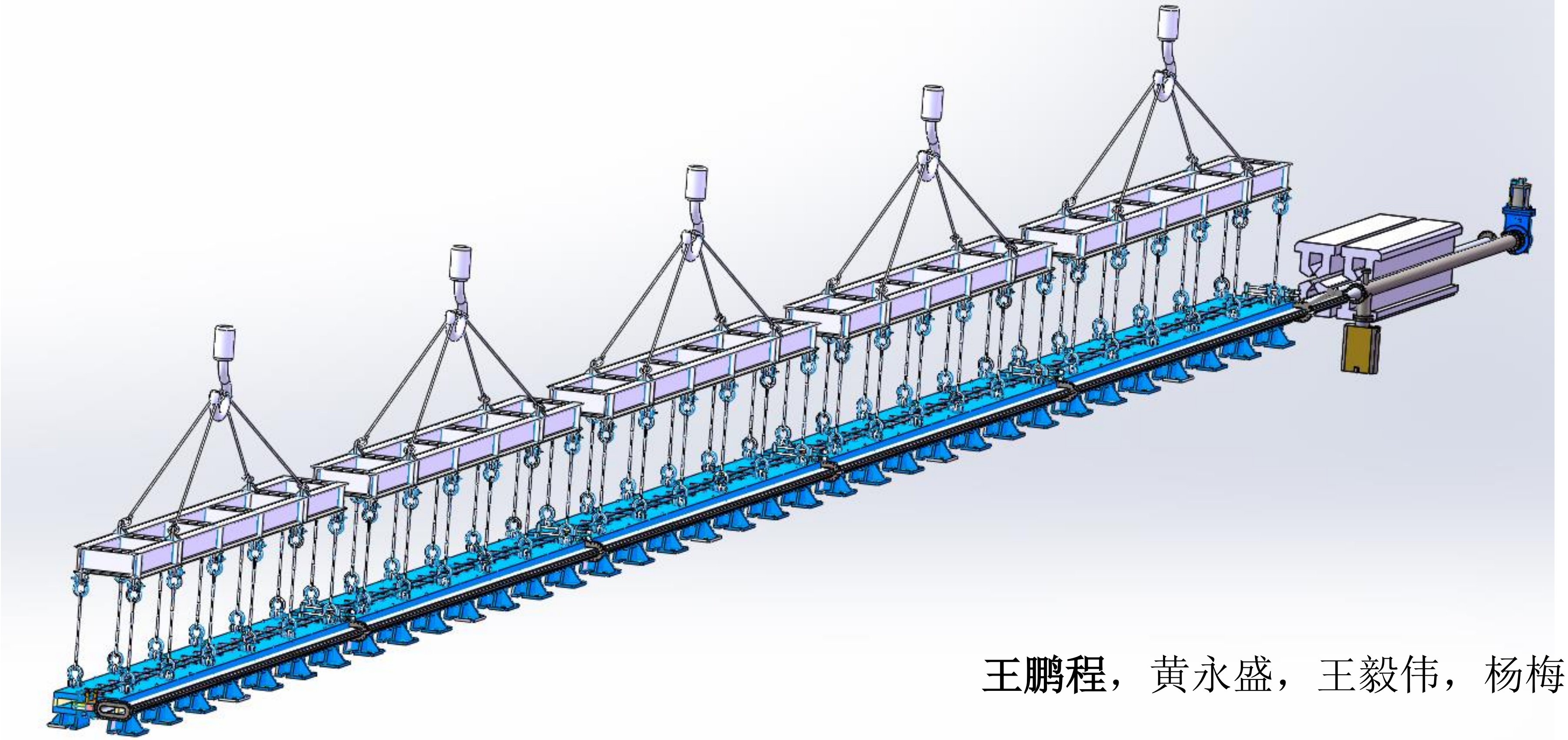
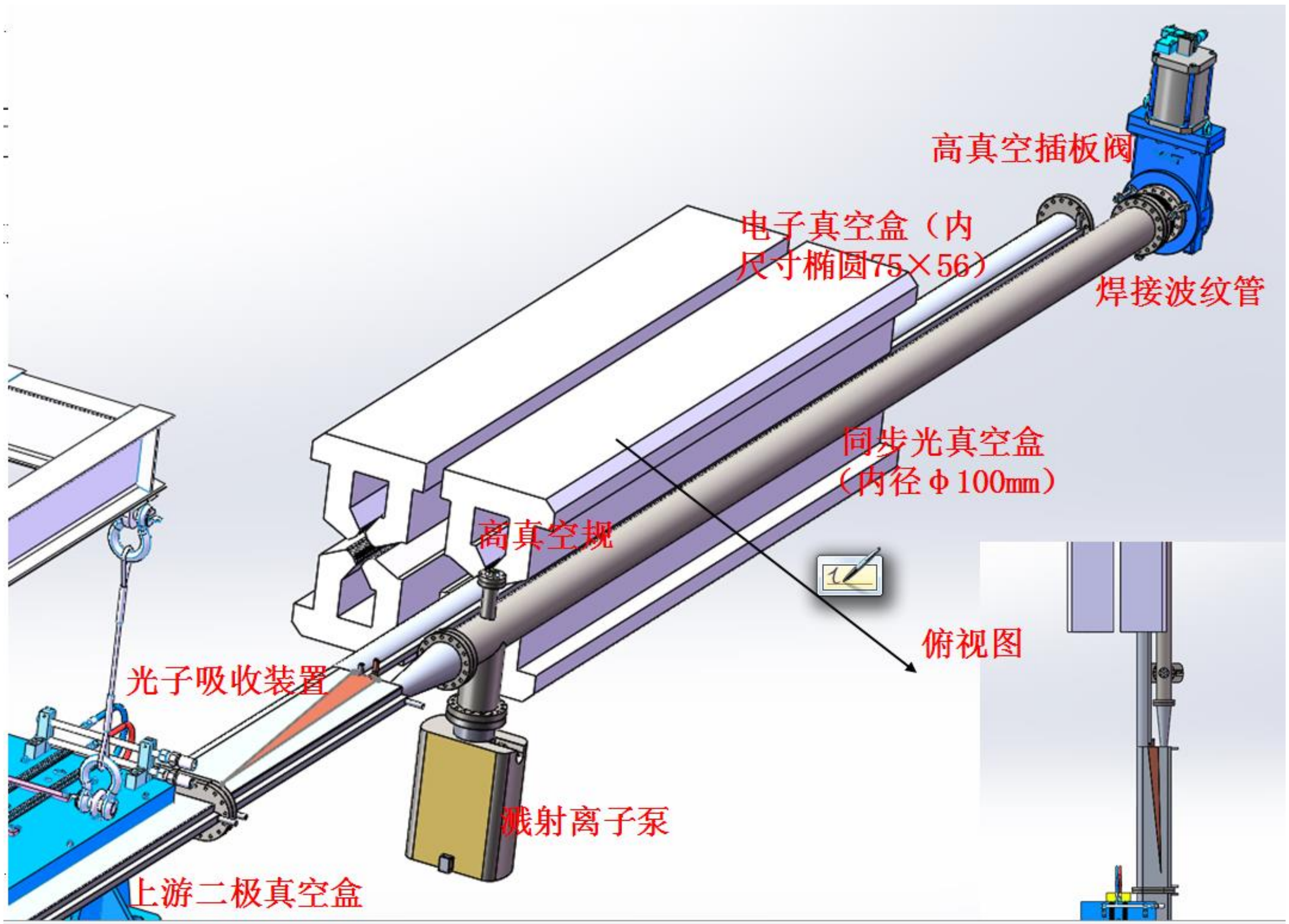
The vacuum chamber design

- The first diode vacuum box in the first 28-meter diode vacuum box
- The first meter diode vacuum box remains unchanged
- The second meter diode vacuum box needs to be extended by 150mm

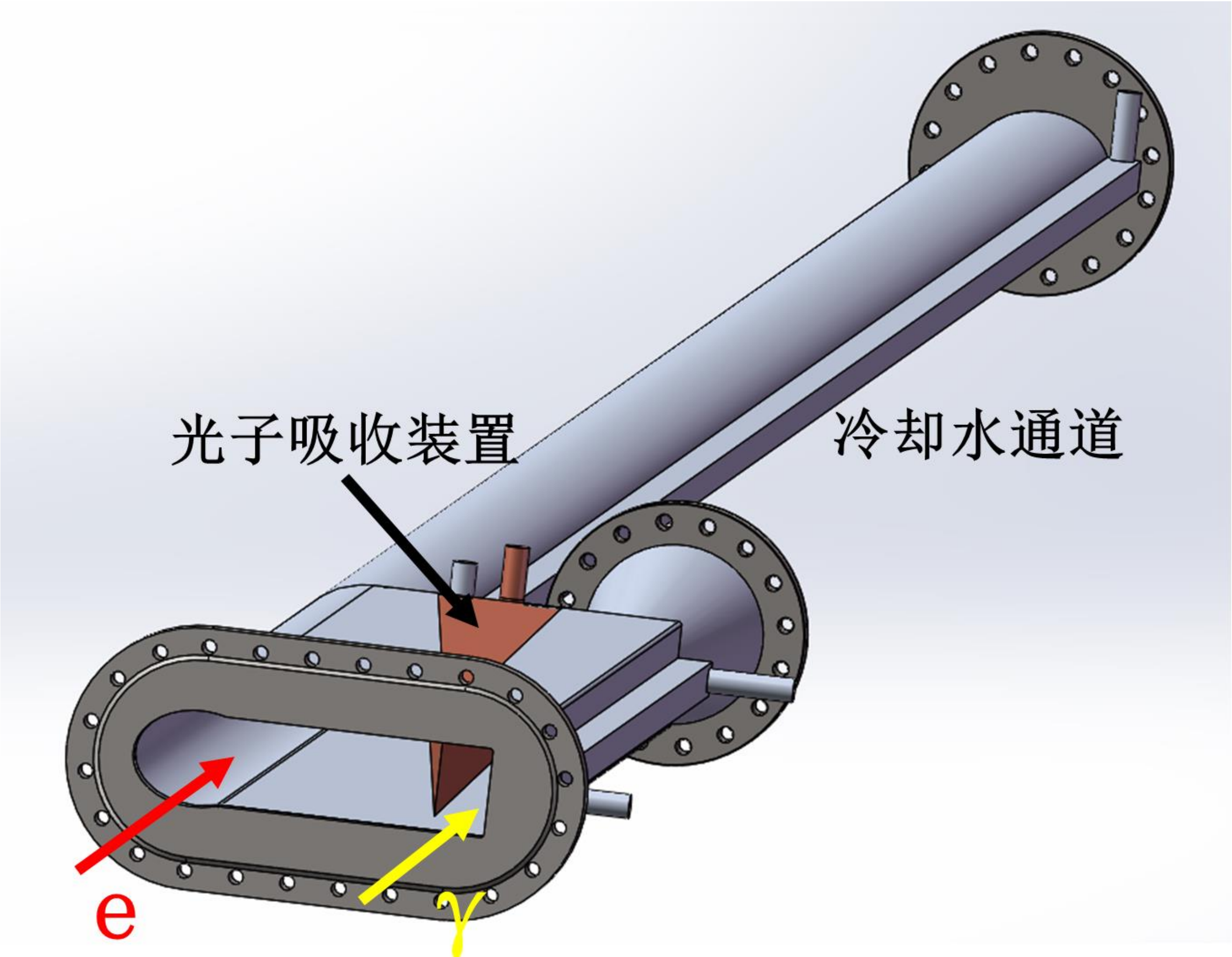


王鹏程，黄永盛，王毅伟，杨梅

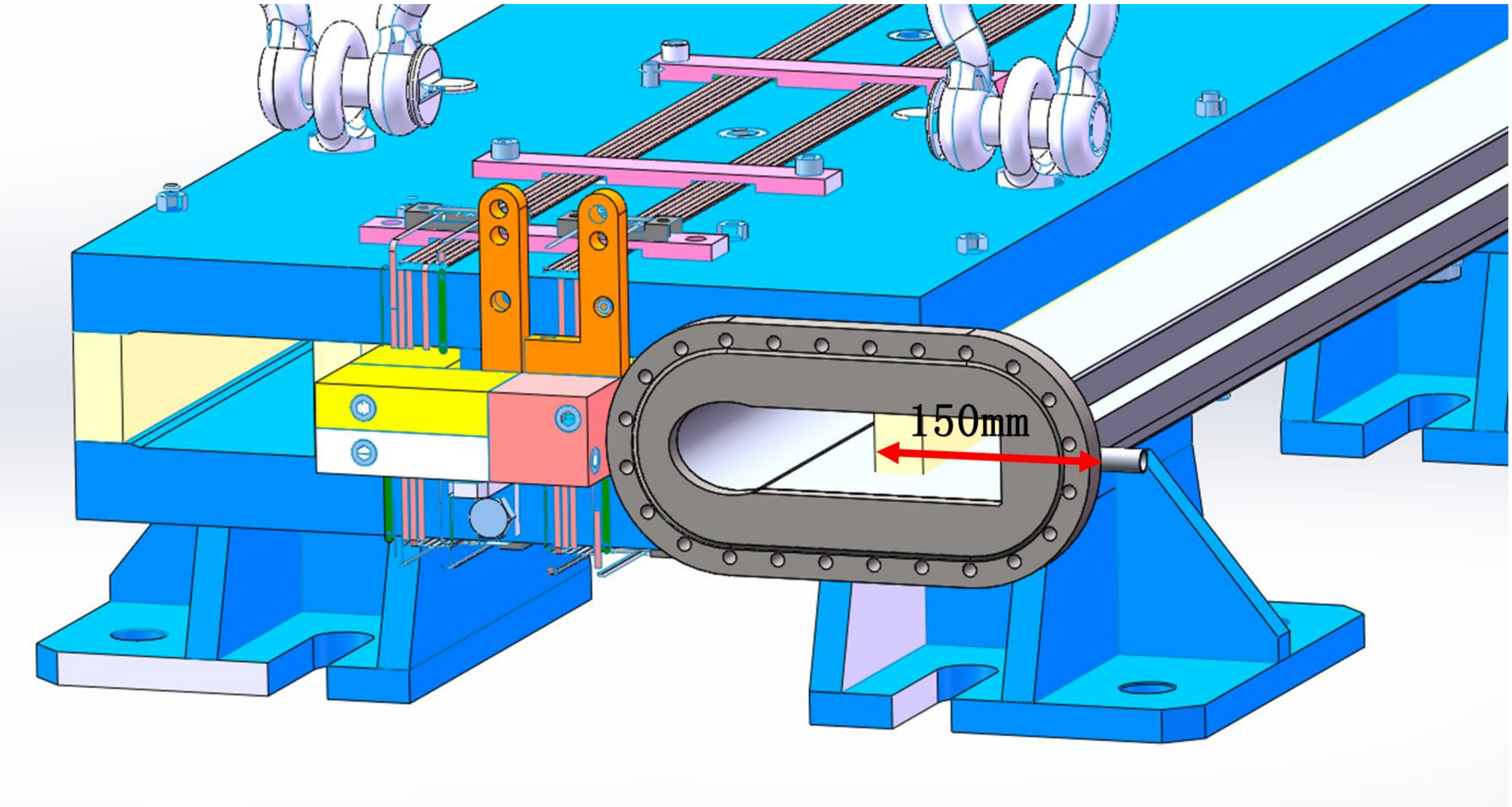
真空管分叉、二级铁末端与四级铁



The vacuum chamber design



二级铁中的真空管道以及对二级铁侧端的要求



The discussions

1.光束线长度超过700米，其真空系统建议采用吸气剂膜（NEG films）+离子泵构成。

2.全部束线可以分成8个区段，每个区段使用全金属超高真空阀门隔离开（9台阀门），每个区段留有单独的粗抽口和充气口，同时每个区段均布5-10台离子泵（用于抽除CH_4等吸气剂薄膜不易抽除的气体），全部真空盒内壁镀NEG films。

3.真空盒材料可以采用304不锈钢（其内尺寸为φ100，壁厚3mm）。

4.真空测量采用每个区段留有2个测量点，采用冷阴极真空规进行测量。

5.在光子准直区域需要在附近真空盒布置测温点，监测真空盒外壁温度变化。

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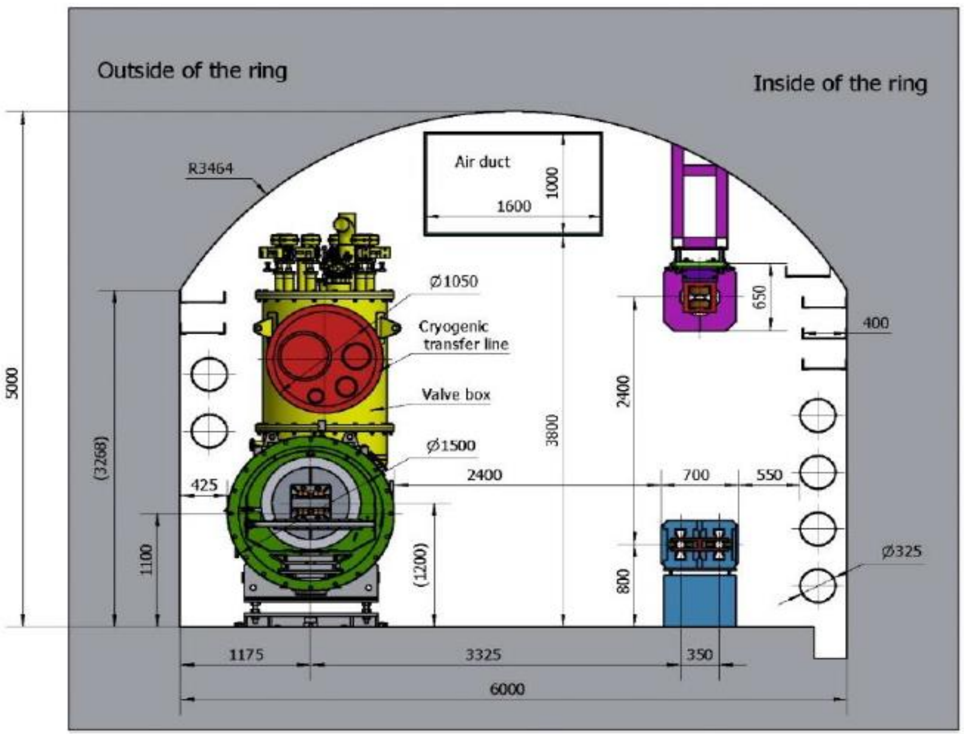
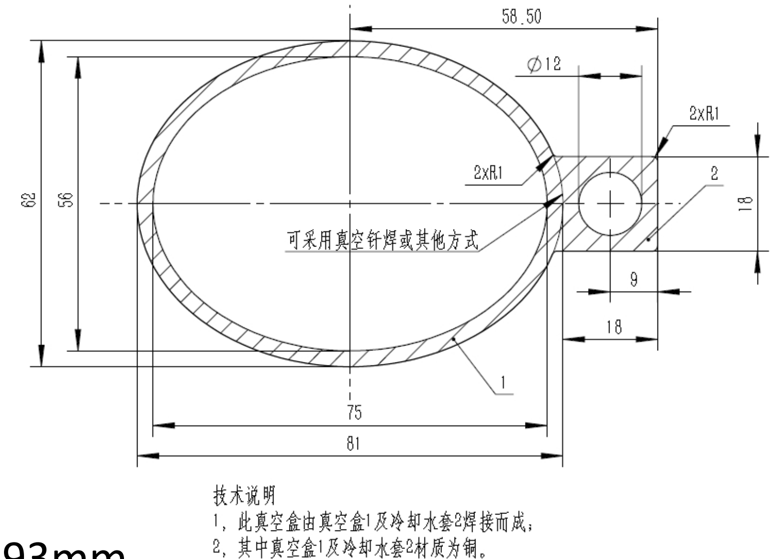
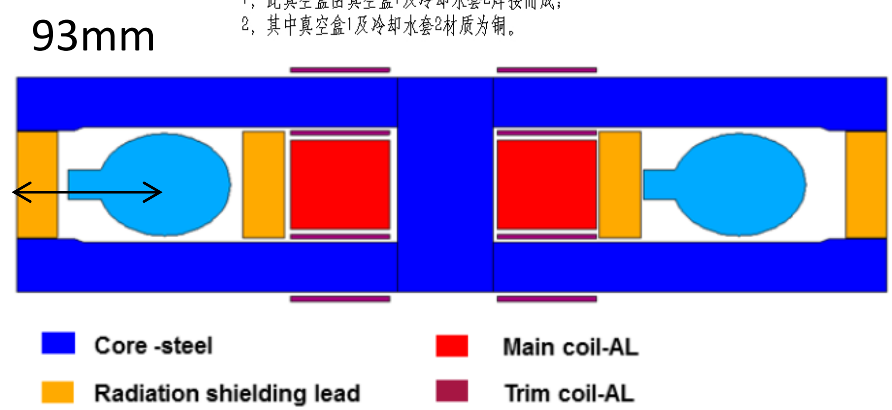
Vacuum chamber, dipole and tunnel





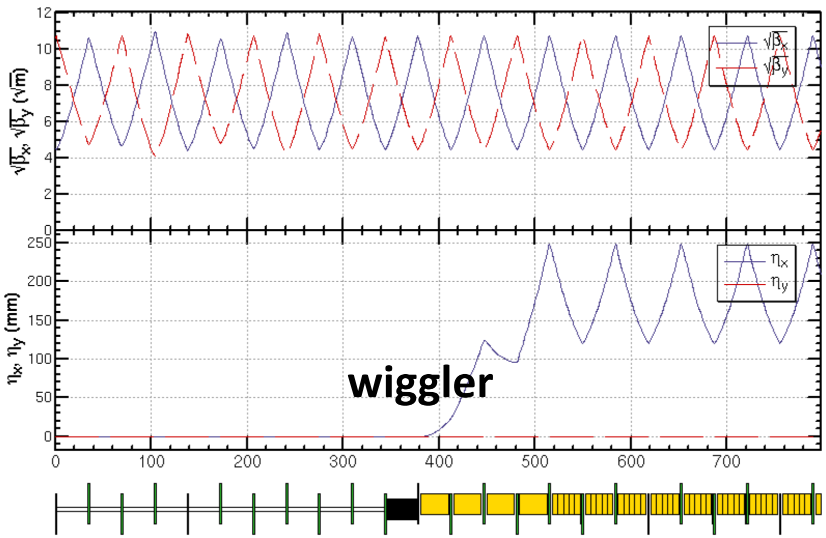


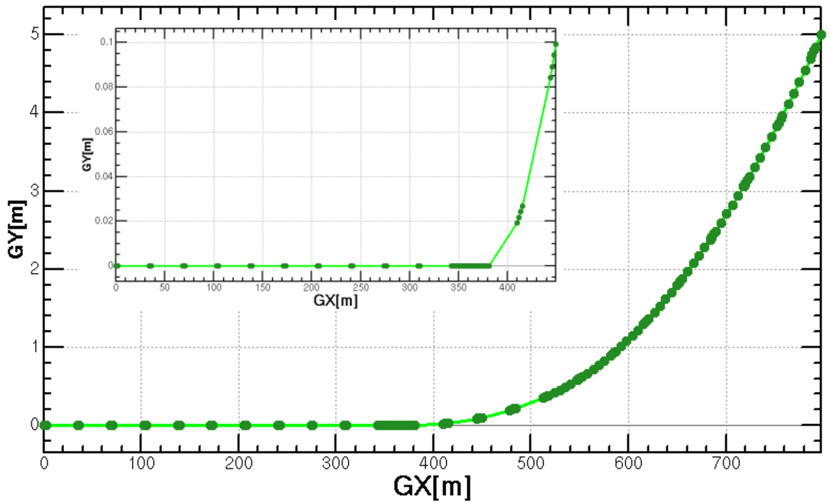
dvc=0.075/2 m; ! distance from the gamma ray to the inner wall of vacuum chamber
dwall=4.5 m; ! distance from the gamma ray to the wall

4500

Add Wiggler

Lp=0.32m, Np=4, L=1.28m, B=2.0T

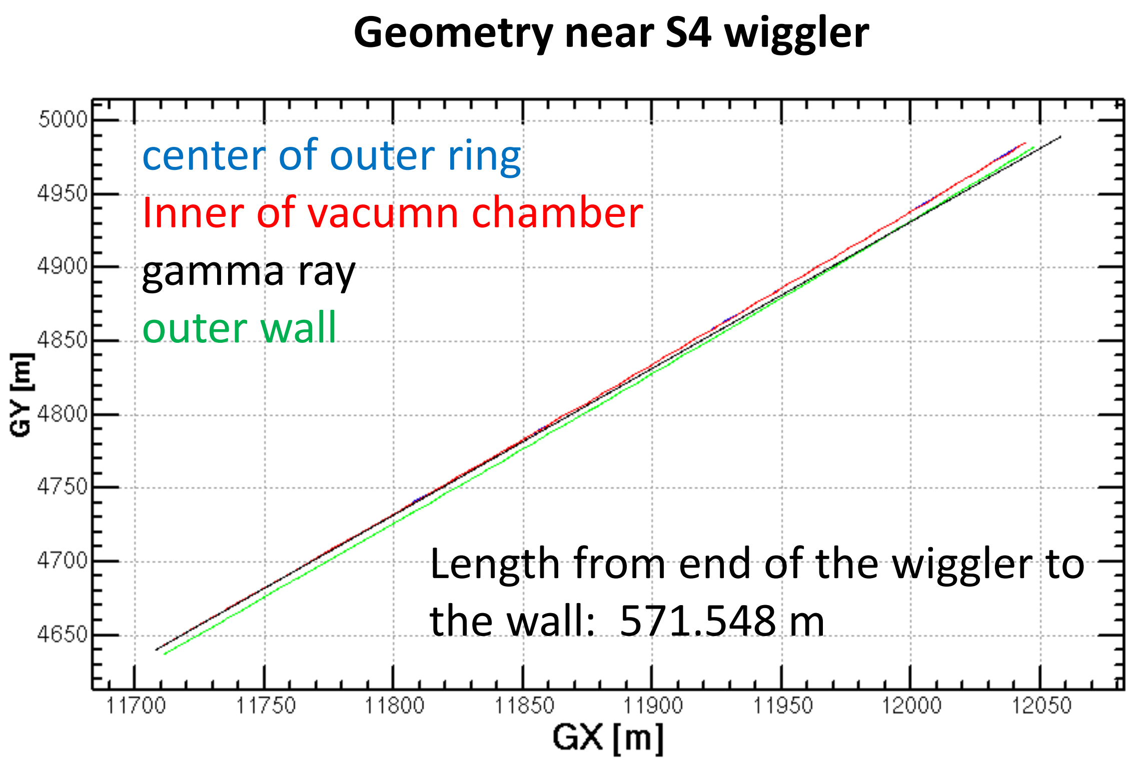




dvc=0.075/2 m; ! distance from the gamma ray to the inner wall of vacumn chamber
dwall=4.5 m; ! distance from the gamma ray to the wall

- The angle between gamma ray and the vacumn chamber and bend is very small.
- The vacumn chamber, bend at these regions need to be carefully design to solve the problem of geometry conflict and impedance.

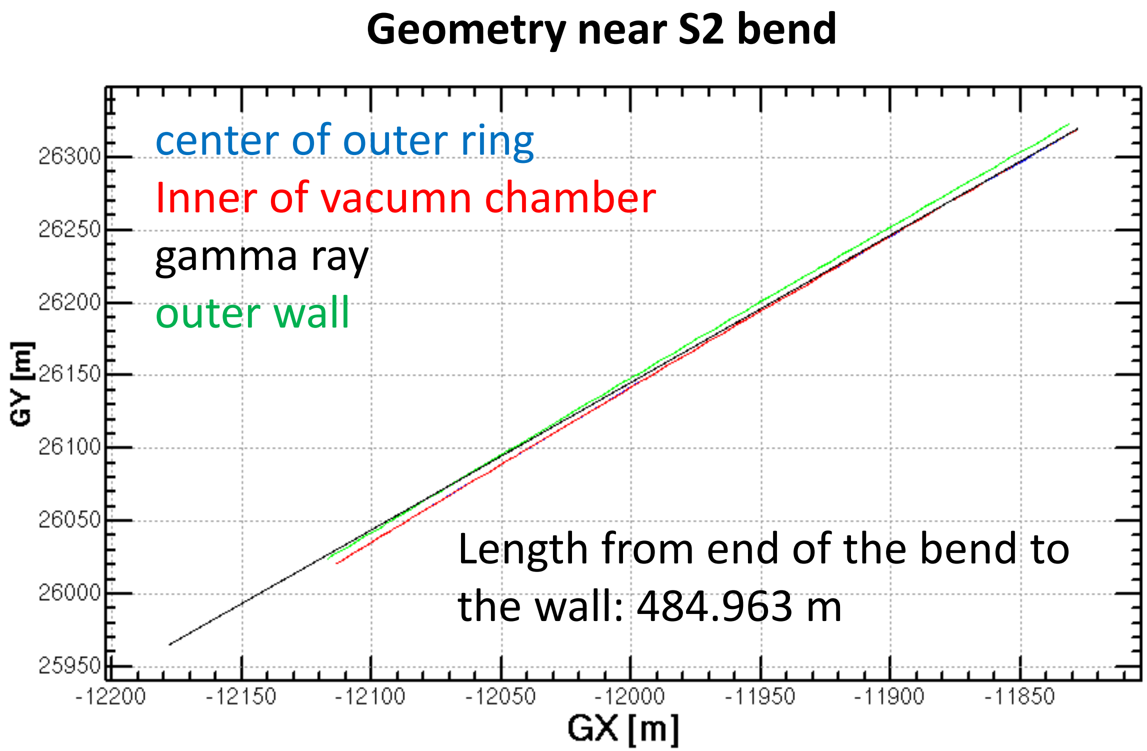
Geometry near S3 and S4 wiggler



gamma ray at the end of **S4 wiggler**:
{11708.067 m, 4640.366 m}
gamma ray at the wall:
{11994.183 m, 4925.771 m}

gamma ray at the end of **S3 wiggler**:
{-11708.067 m, 4640.366 m}
gamma ray at the wall:
{-11994.183 m, 4925.771 m}

Geometry near S1 and S2 bend



gamma ray at the end of S2 bend:
{-11827.872 m,26319.878 m}
gamma ray at the wall:
{-12068.740 m,26075.755 m}

gamma ray at the end of S1 bend:
{11827.872 m,26319.878 m}
gamma ray at the wall:
{12068.740 m,26075.755 m}

四条光束线：S1、S2、S3、S4

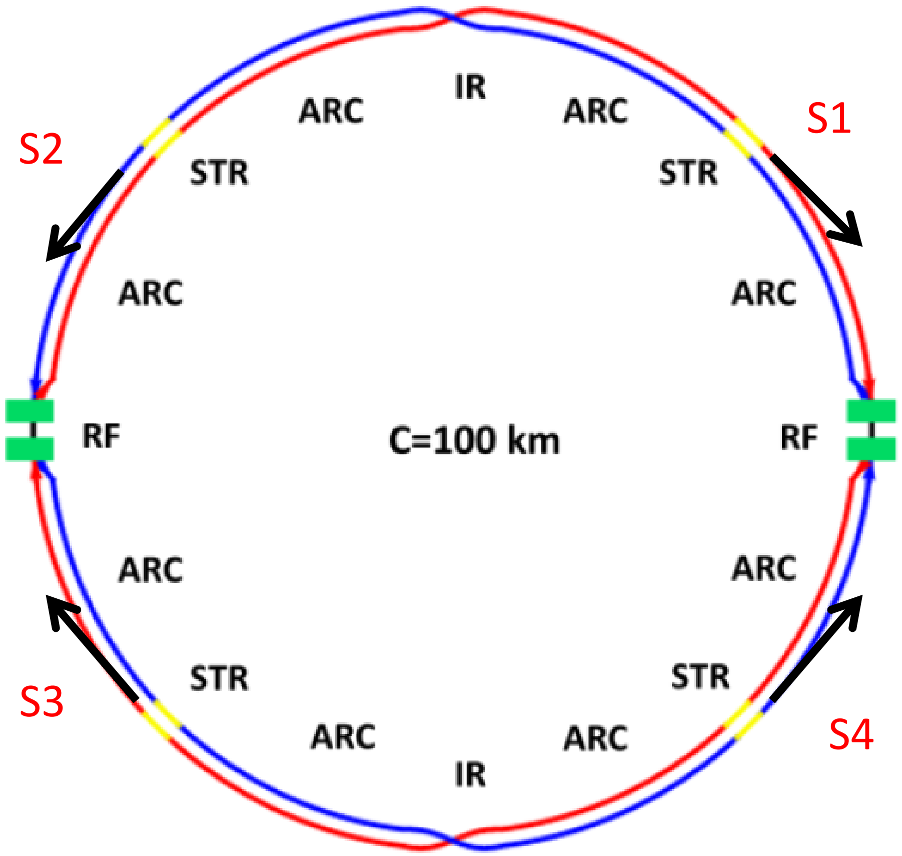
其起始点坐标分别如下：

S1 :
{11827.872 m,26319.878 m}
{12319.514m, 25821.592m} 700m

S2:
{-11827.872 m,26319.878 m}
{-12319.514m, 25821.592m }700m

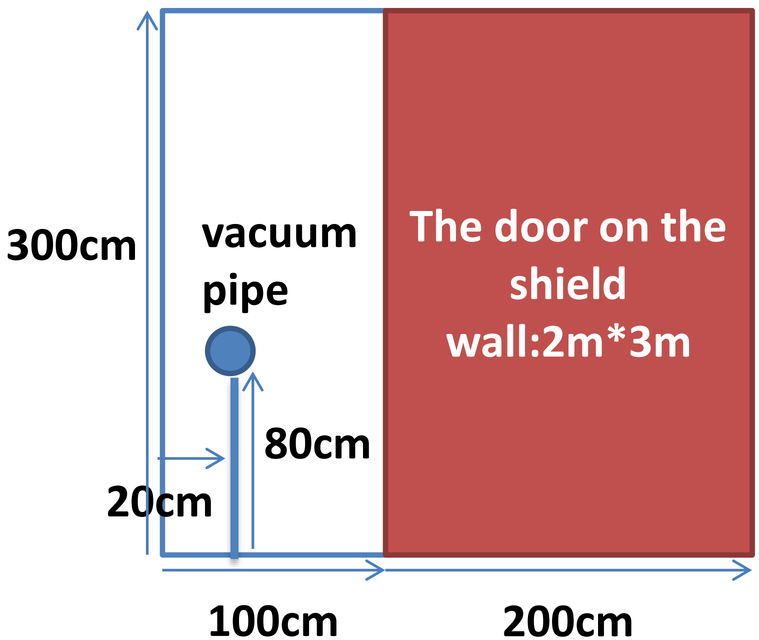
S3 :
{-11708.067 m, 4640.366 m}
{-12203.657m, 5134.725m} 700m

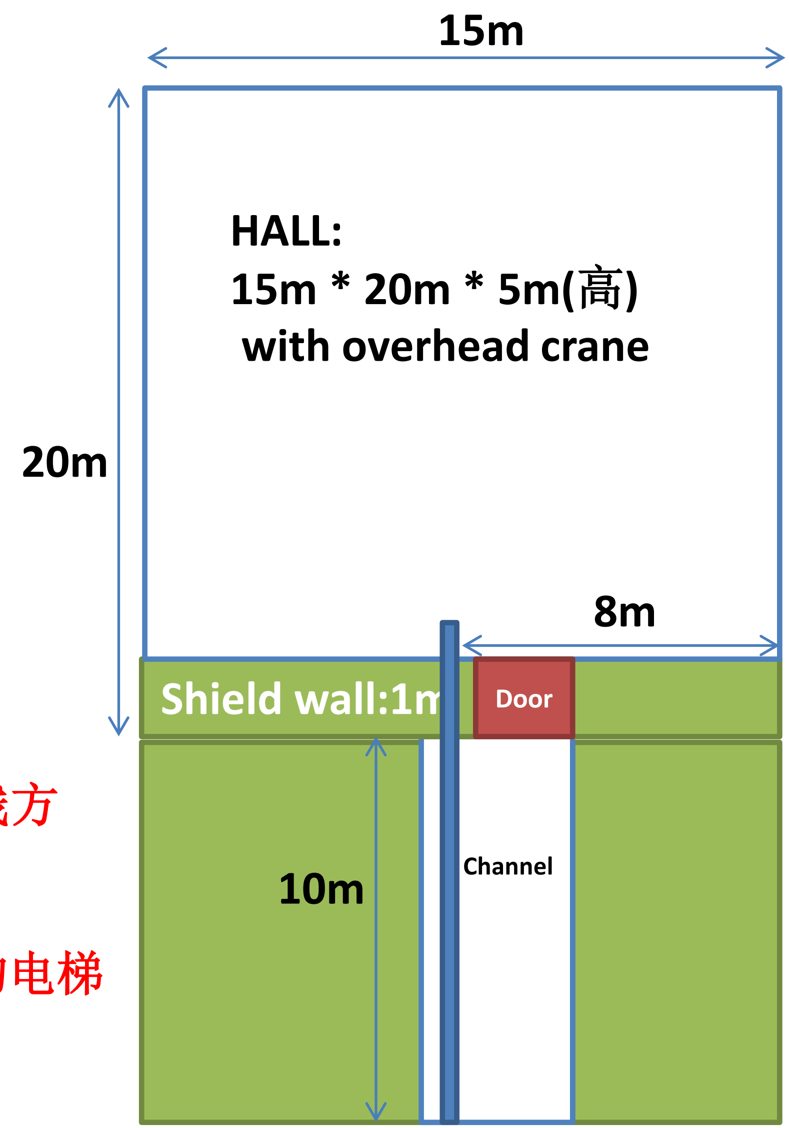
S4 :
{11708.067 m, 4640.366 m}
{12203.657m, 5134.725m} 700m



Tunnels, halls and shafts

Tunnel cross section :3m * 3m





上一页各束线的终点坐标，从这个点开始，沿着束线方向，向岩石内挖3X3米的隧道，

挖到10米处是防护门，然后是大厅。见右图。

束线S1和S2的大厅处，需分别有吊装竖井和载小货物电梯

电梯：2m*2m*3m，称重>2顿。

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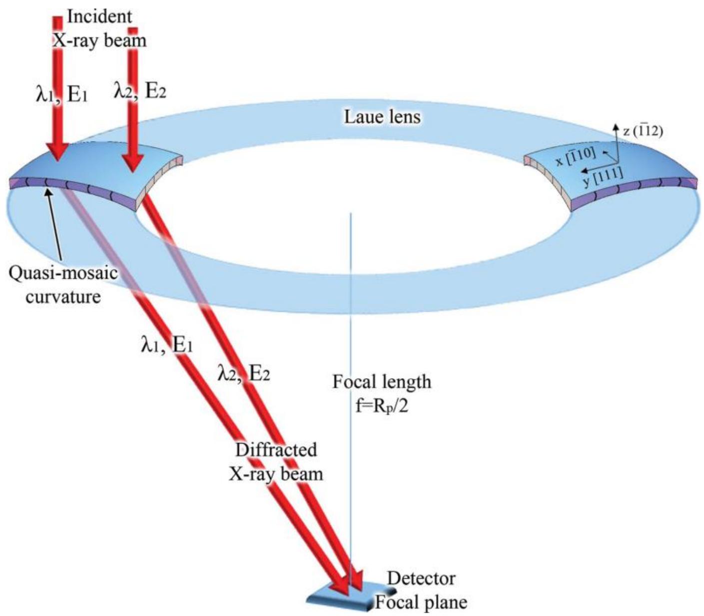
The challenges and the next to do

1) The focalization of gamma-ray: larger than MeV

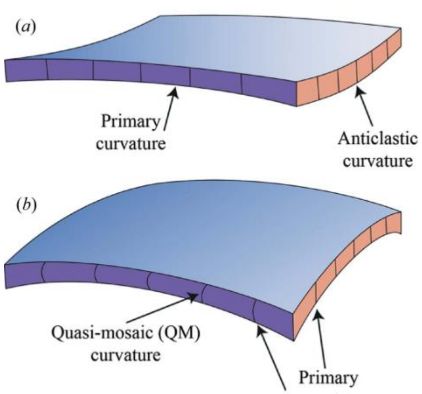
2) The detection of the energy distribution and the spatial distribution of the SR from bending magnetic and wiggler

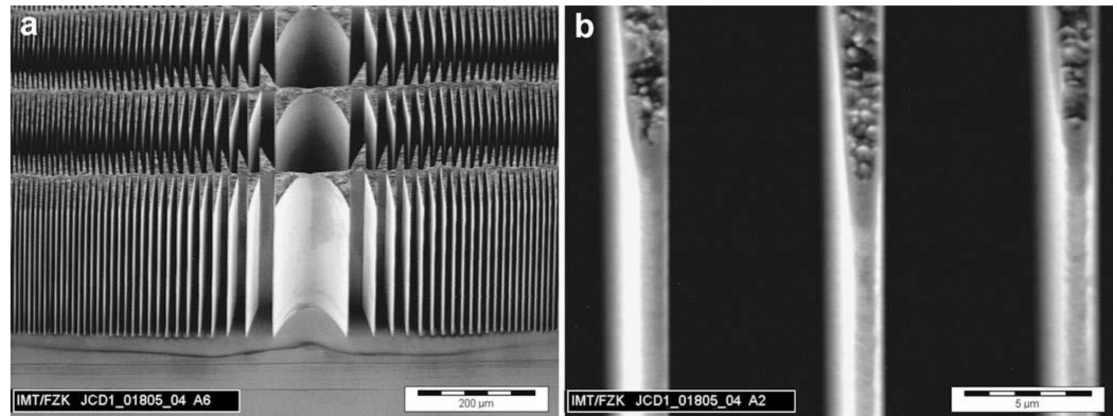
3) The Mechanical design drawings and equipment, and cost estimates

The focalization of hard x-ray
And soft gamma-ray 100keV-1MeV, 1MeV still problem?

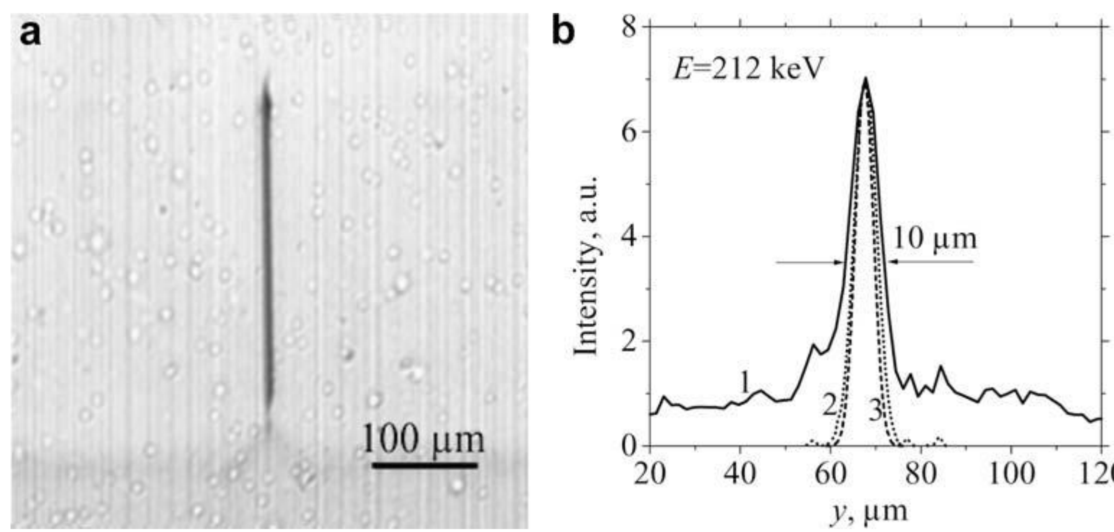


Schematic representation of a Laue lens based on QM crystals. J. Appl. Cryst. (2015). 48, 977–989





LIGA fabrication of X-ray Nickel lenses 100keV-1MeV : Microsystem Technologies 11 (2005) 292–297

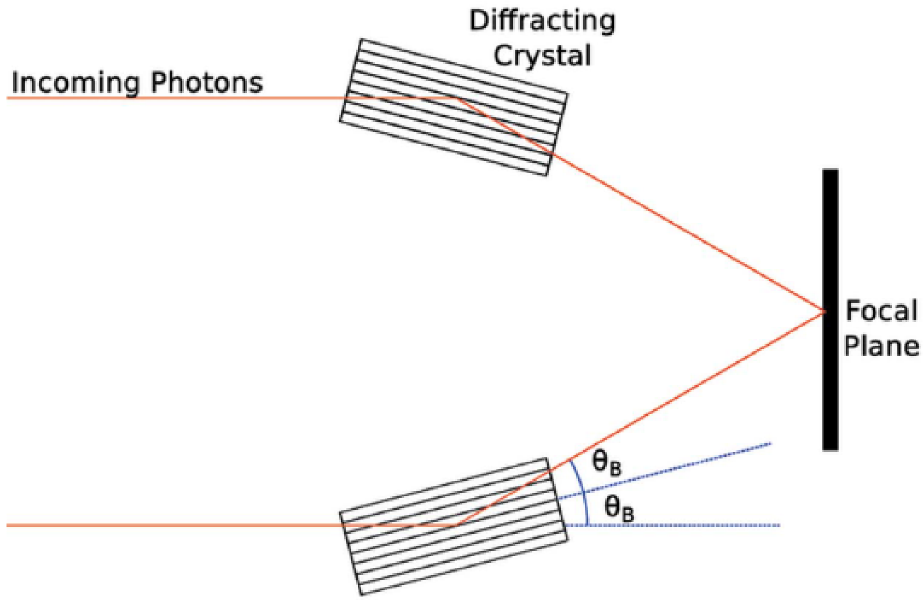


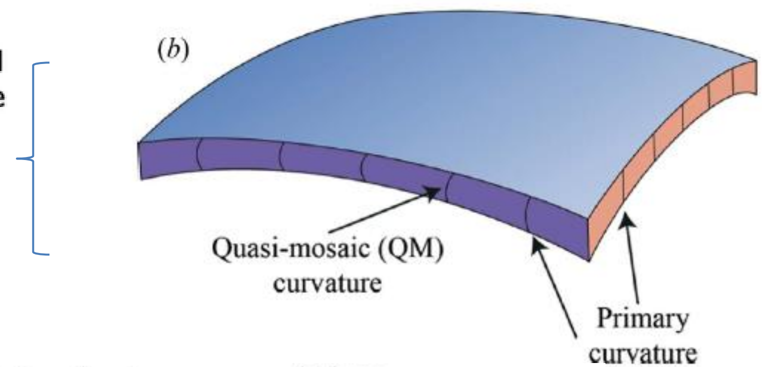
For high-energy photons, the Bragg angle is very small, and even in small beams the crystal must be large to diffract. Therefore, Laue geometry represents a more convenient choice.

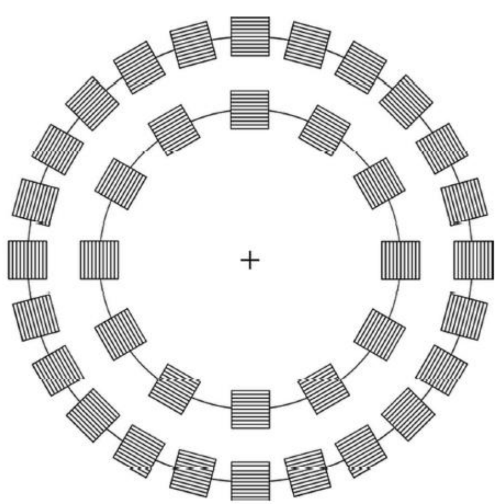
Perfect crystal, mosaic crystal, the maximum reflectivity is 1/2

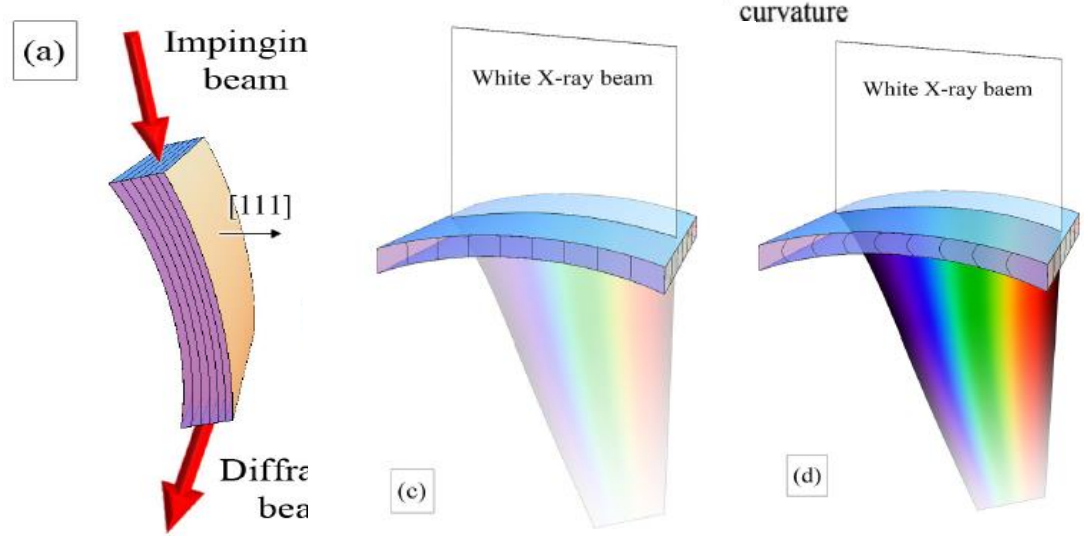
Curved diffraction plane crystal (CDP), quasi-mosaic (QM) crystal, peak reflectance is not limited by 1/2

$$R = \left[1 - \exp\left(\frac{-\pi^2 d_{hkl}}{\Lambda_0^2}\frac{T_0}{\Omega}\right)\right]\exp\left(-\frac{\mu T_0}{\cos\theta_B}\right)$$





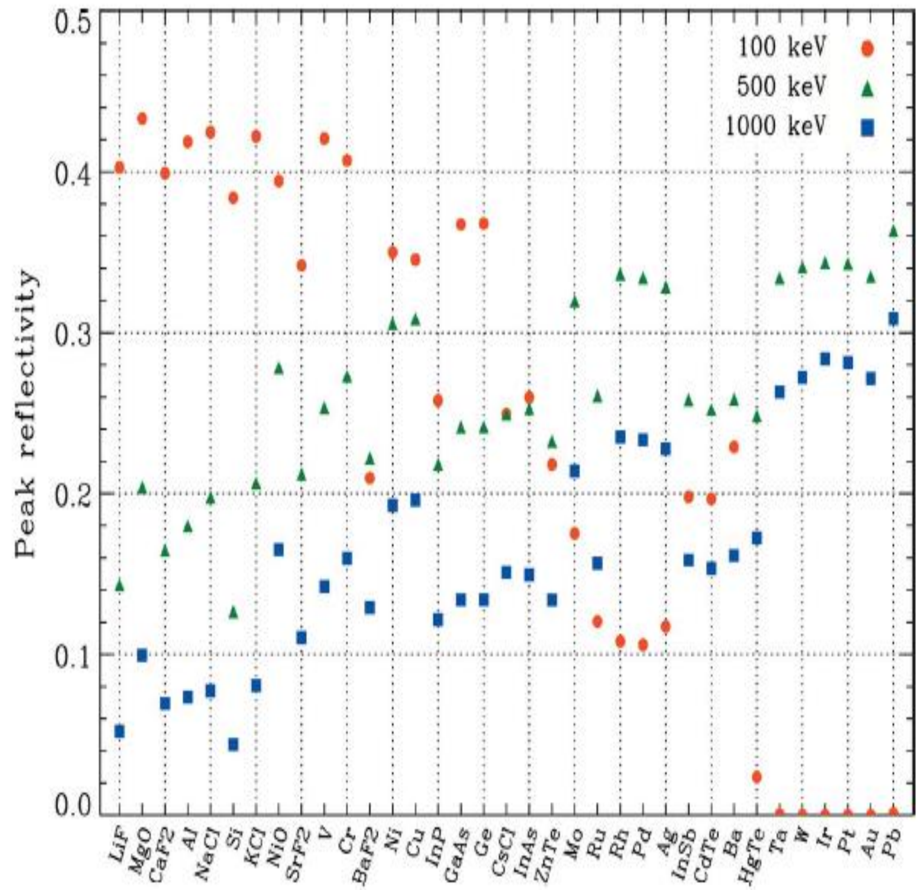




Choice of crystal

For various crystals, the peak reflectance at 100 keV, 500 keV, and 1 MeV energies, Z (atomic number) increases from left to right.

As can be seen from the figure on the right, at high energy, the higher reflectance is a crystal with higher Z; on the other hand, at low energy, the higher reflectance is a crystal with lower Z.



MeV聚焦透镜的材料选择：Pb，Au

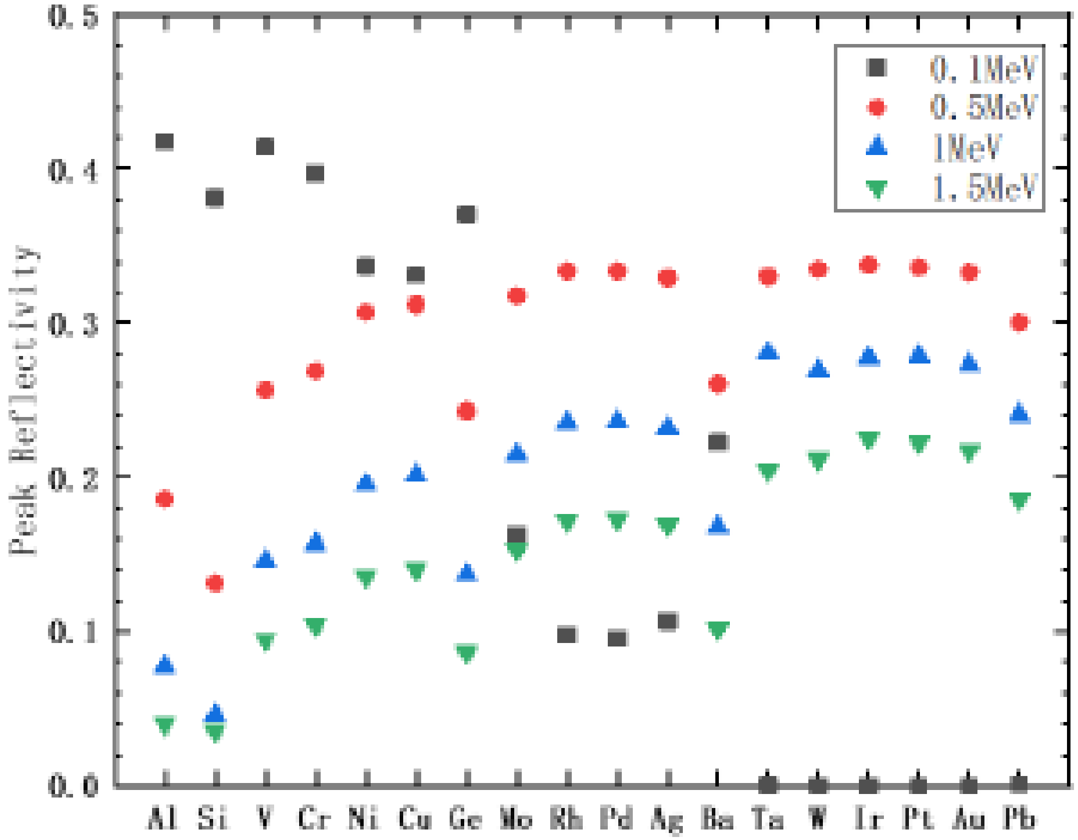


图 : 18 种晶体的能量分别在 0.1MeV、0.5 MeV、1 MeV 和 1.5 MeV 时的峰值反射率，按原子序数从左到右逐渐增加排列。假设是镶嵌晶体，镶嵌度 Ω 为 30arcsec，微晶厚度 t0 为 5μm，晶体厚度 T0 可由 (3.11) 式算出，但被限制在 1～25mm 范围内。

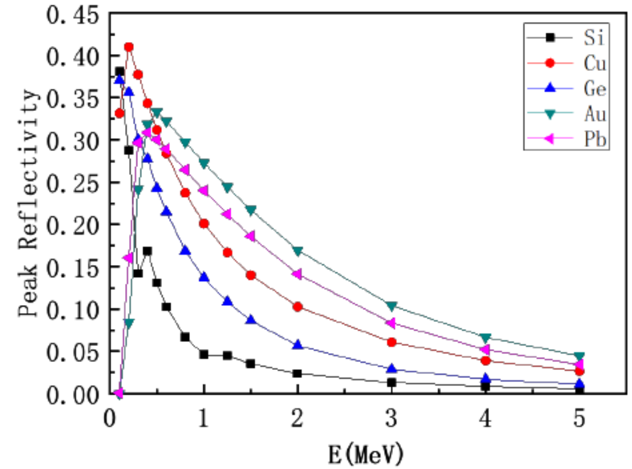


图 : 假设是镶嵌晶体，镶嵌度 Ω 为 30arcsec，微晶厚度 t0 为 5μm，晶体厚度 T0 可由 (3.11)式算出，但被限制在 1～25mm 范围内。Si、Ge、Cu、Au 和 Pb 峰值反射率随能量的变化。

MeV聚焦透镜初步方案

- 选择劳厄透镜的焦距为 20m，因为 20m 是天体物理学应用中通常会考虑到的焦距。
- 所以可以算出，当能量为 0.8MeV 时，半径最大为 131.66mm，当能量为 1.2MeV 时，半径最小为 87.78mm。晶体环排列越紧密，相邻环的能量重叠越多，劳厄透镜衍射的能量越平滑，则这个劳厄透镜由 5 个晶体环组成，且每个环上都排列尽可能多的
- 晶体，这可以使得劳厄透镜的有效面积最大。
- 估价-100万左右

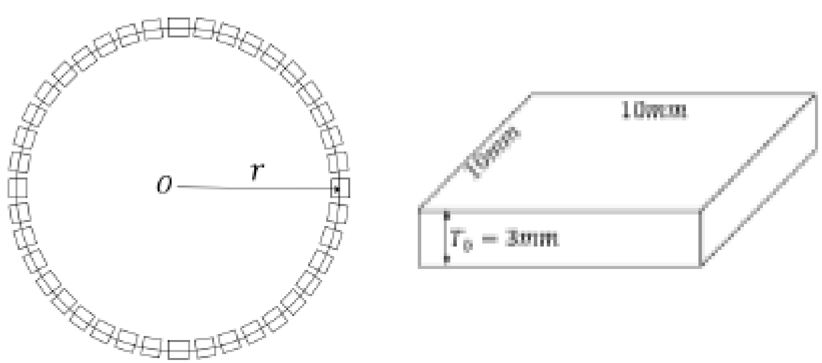


图 1: (a) 每个环上 Au 晶体的排列，(b)Au 晶体的尺寸，(10×10×3)mm2

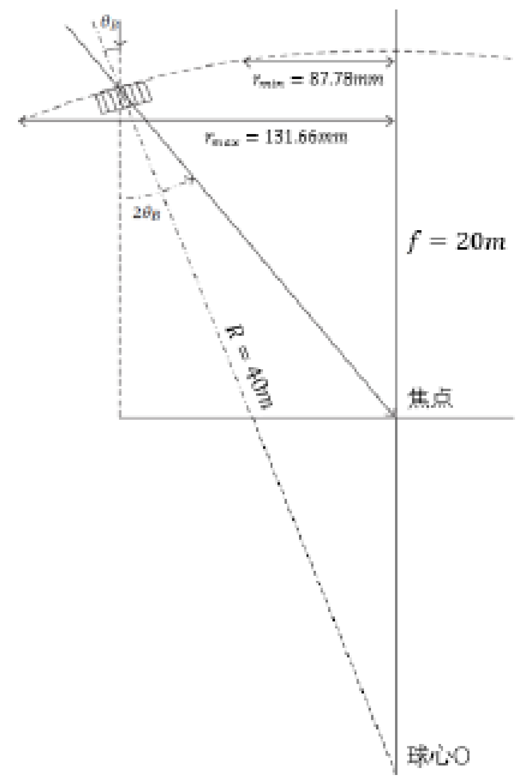
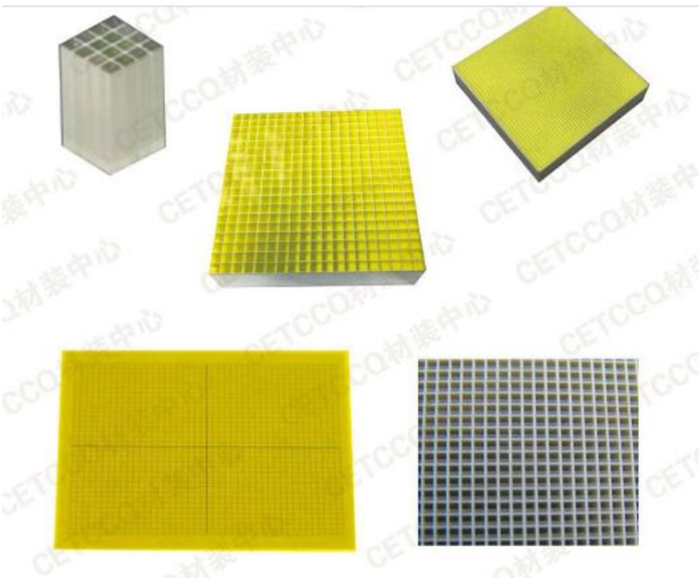
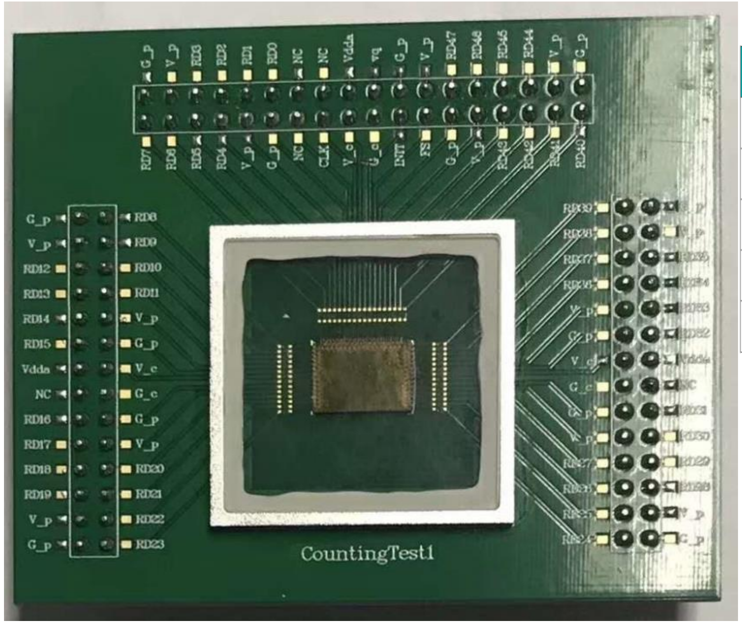


图 2: 0.8-1.2MeV 劳厄透镜的几何图

MeV阵列伽玛探测器 1000万

- 探测器：阵列GAGG：150mm*150mm，0.2mm一个单元
- 电子学：SiPM阵列 0.2mm像素 实现阵列像素4块75mm*75mm的拼接





参数	数值
像素数量	64×48
像素 Pitch	113.8um
SPAD 尺寸	50μm×50μm
光子计数深度	4 bits
PCB 尺寸	71mm×59mm

Summary

- **Considering the layout of CEPC, the radiation power and the possible polarization requirement, four beamlines are designed;**
- **The basic parameters of the wigglers are given;**
- **The possible applications of the beamlines are discussed, especially for the gamma-ray imagination ;**
- **The key challenges need to be study are proposed: the focus of MeV gamma-ray beam and the detection design.**

Thanks go to CEPC-SppC team!