γ-ray station at SSRF@SINAP (SLEGS)

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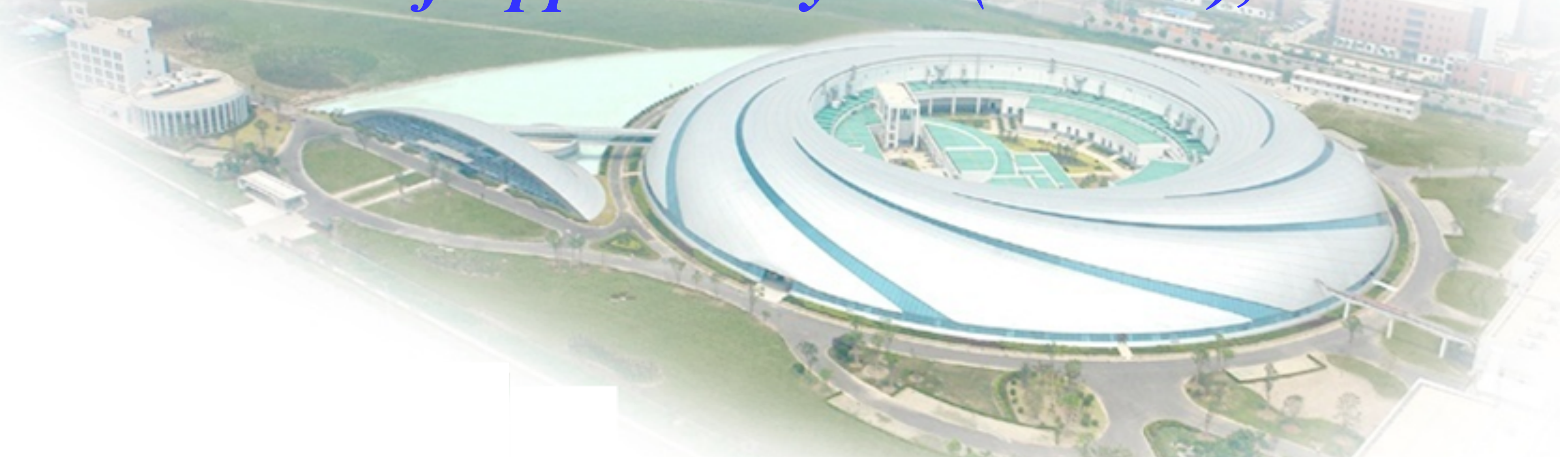
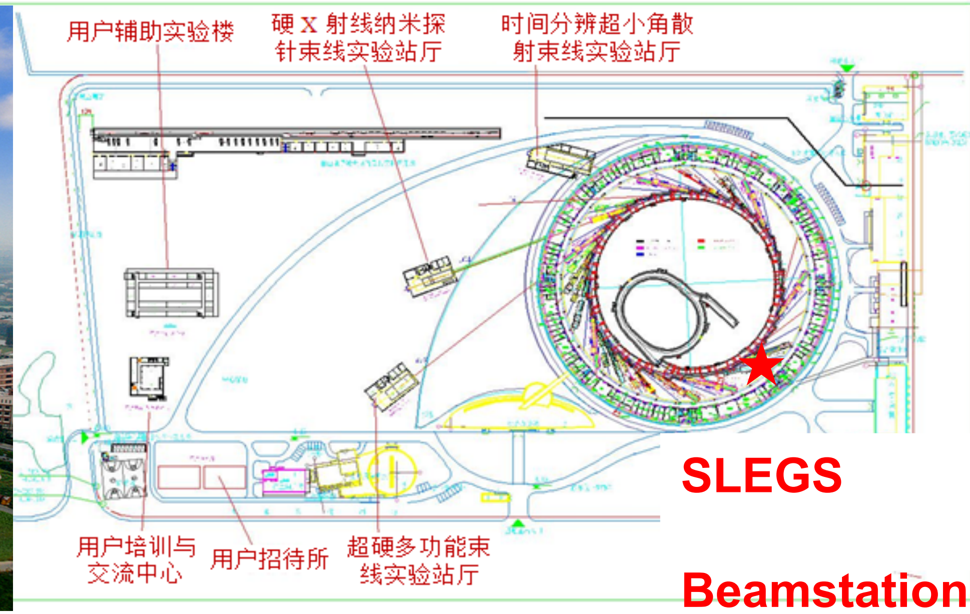


ICFA Mini-workshop on Future γγ collider, Apr. 23-26, 2017; THU

Outline

1. ***SLEGS @ SSRF-SINAP***
2. ***Properties & Scientific goals***
3. ***Design of Gamma source***
4. ***Design of Beamline***
5. ***Design of End station***
6. ***Summary & Outlook***

1. SLEGS @ SSRF



SINAP is a national research institute for particle accelerator physics and engineering, nuclear science and technology, and interdisciplinary studies. It constructed and operates a 3.5GeV third generation synchrotron light sources – the Shanghai Synchrotron Radiation Facility (SSRF).

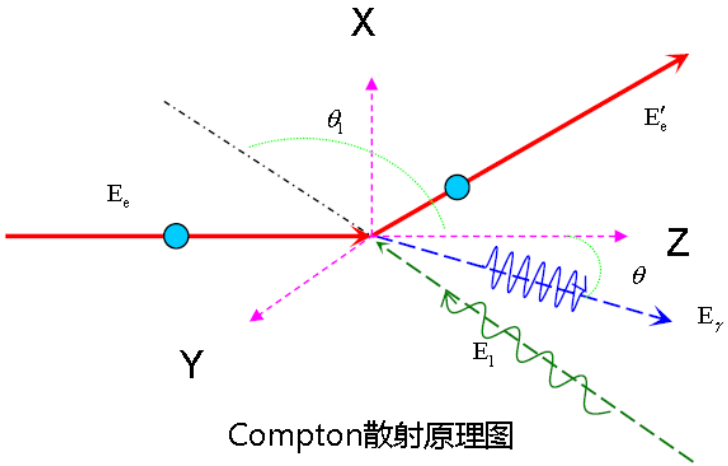
It also conducts state-of-the-art R&D in Thorium Molten Salt Reactor (TMSR).

Other key scientific endeavour includes Nuclear Physics, Physical Biology and Water Science & Technology.

SLEGS as one of 16 new SSRF Phase II beamlines, was approved by central government in 2015 and expected to be completed in 2021.

SLEGS is the first laser-Compton scattering based gamma-ray source in China, aiming at the frontier researches in nuclear structure physics, nuclear astrophysics, nuclear photonics, and etc. SLEGS will be opened for users in 2022.

1. SLEGS @ SSRF



Compton散射原理图

Compton scattering of an electron and a photon

Photon/Gamma energy as:

$$E_\gamma = \frac{E_l\left(1-\beta\cos\theta_L\right)}{1-\beta\cos\theta+\dfrac{E_l\left\{1-\cos\left(\theta_L-\theta\right)\right\}}{E_e}}$$

$$\beta = v_e / c$$

$$\lambda = E_e / m_e c^2$$

$$\beta = \sqrt{1-\lambda^2}$$

E_γ gamma photon energy ; E_e electron energy ;
E_l incident laser photon energy,
θ_l incident angle of laser photon
θ emission angle gamma photon
V_e electron Velocity; m_e electron mass and $m_e c^2$ = 0.511MeV

According Eq, three methods to change the gamma energy:

1) change the energy of incident laser photon E_l;
2) change the energy of electron beam E_e
3) change the incident angle of laser photon θ_l.

SLEGS will be operated in back scattering and slanting-scattering mode to produce the low energy (0.4-20 MeV) γ-ray.

Backward Compton Scattering:

$$\theta = 0,\quad \theta_l = 180,\quad E_\gamma^{max} = \frac{4E_e^2 E_l}{m_e^2 c^4 + 4E_e E_l}\ \text{(BCS)}$$

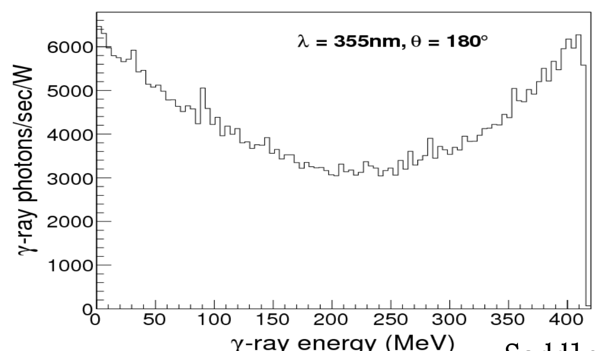
Features of LCS gamma source:

1、tunable Energy and Frequency.

2、High flux >10^6 photon/s(depend on laser power).

3、Ultrafast pulse width, ps or fs duration.

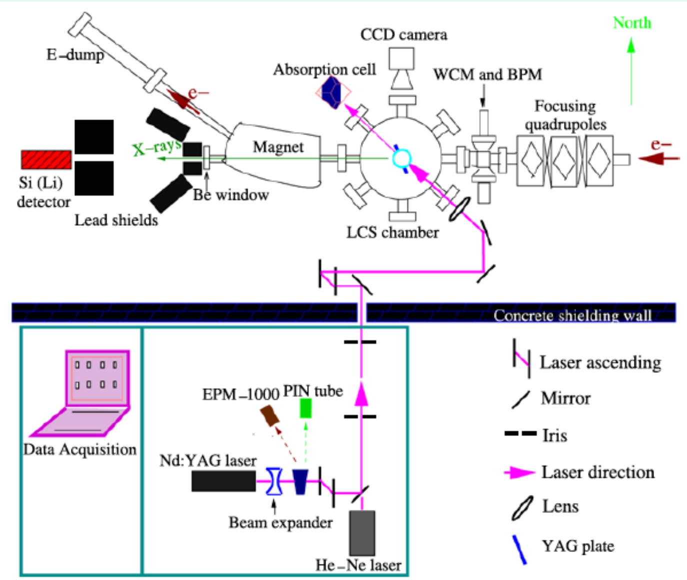
4、High polarization,~100%.



Saddle shape gamma energy distribution

Laser-electron X-ray @ SINAP-100MeV e-Linac, 2010

Laser-electron X-ray @ SINAP-100MeV e-Linac



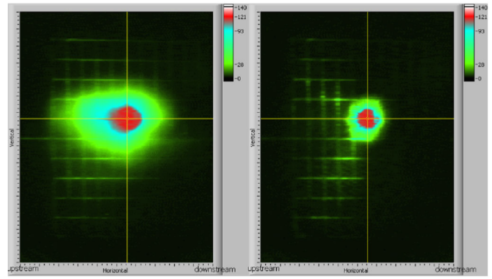


Fig. 3 Spot images of the electron beam (*left*) and the He–Ne laser beam (*right*) at the center of the LCS chamber (the interaction point) observed with the 16-bit CCD camera

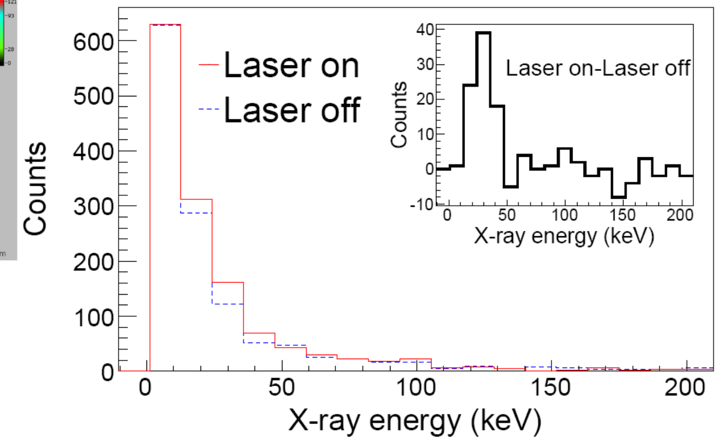
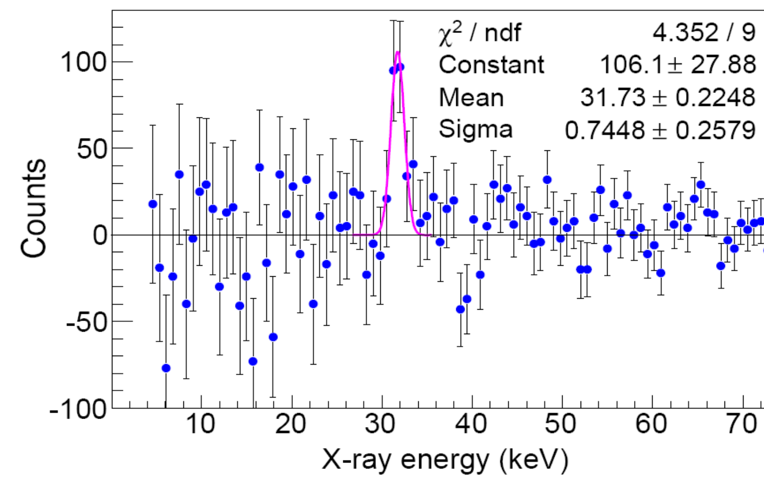


Table 2 The LCS experimental parameters including the generated LCS X-rays

Parameter	SINAP I	SINAP II
Electron beam		
Macropulse energy (MeV)	108	112
Macropulse charge (nC)	~0.1 (1.0)	0.027 (1.0)
Pulse length (rms) (ns)	0.95	0.9
rms spot size at focus (σ_{ex}/σ_{ey}) (mm)	3.1/2.5	1.5/1.9
Nd: YAG laser		
Wavelength (nm)	1064	1064
Pulse energy (J)	0.113	0.9 (2.0)
Pulse duration (FWHM) (ns)	21	7.8
rms spot size at focus (σ_{lx}/σ_{ly}) (mm)	<0.5/<0.5	<0.2/<0.2
Laser incident angle	42°	44±2°
Relative time jitter at interaction point (ns)	1.3	1.0
X-rays		
Peak energy (keV)	$29.1 \pm 4.4_{stat} \pm 2.1_{syst}$	$31.73 \pm 0.22_{stat} \pm 1.64_{syst}$
Peak width (keV)	$7.8 \pm 2.8_{stat} \pm 0.4_{syst}$	$0.74 \pm 0.26_{stat} \pm 0.03_{syst}$
Photons/sec (total spectrum)[c]	$(5.2 \pm 2.0) \times 10^2$	$(1.7 \pm 0.3) \times 10^3$



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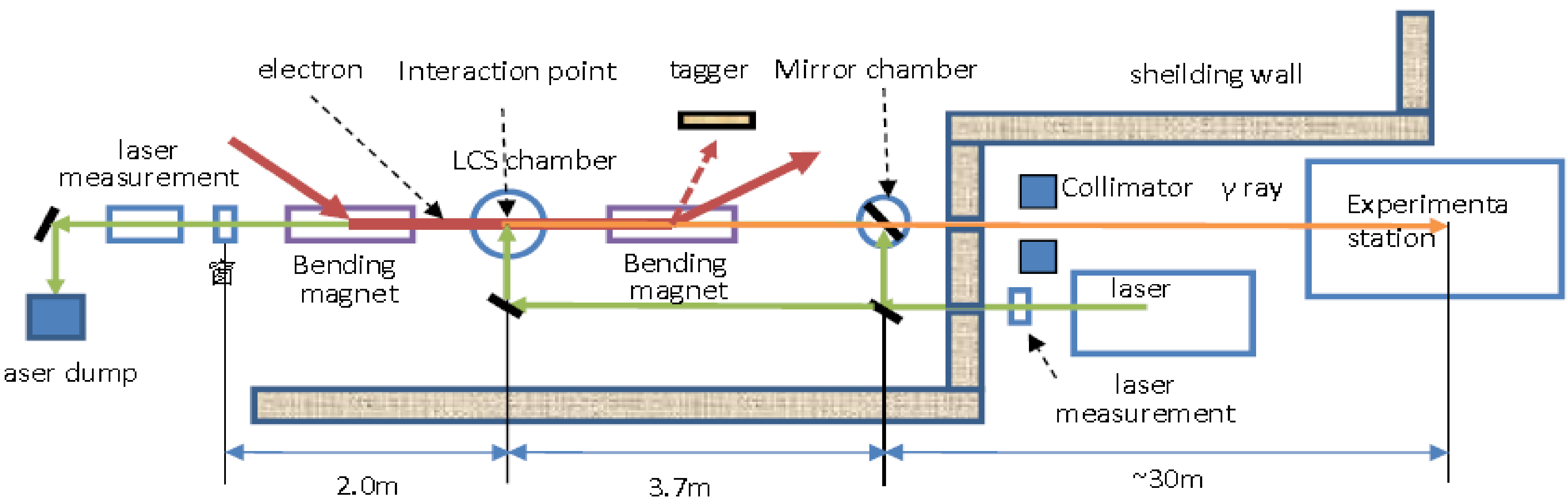
pulse on and off. The Nd:YAG laser and the electron beam repetition rates are 2.5 Hz and 5 Hz, respectively. We use

2. Properties & Scientific goals

Design properties

- Energy range： 0.4-20 MeV
- Energy resolution ： ~5%
- Divergence angle： 0.5mrad (milli-radian)
- Flux： $(0.2\text{-}4.2)\times10^{7}$ phs/s



2. Properties & Scientific goals

Properties ---Comparison with similar beamline

Beamline name	**SSRF-SLEGS (China)**	TUNL-HIGS (USA)	UVAOR–II (Japan)	ETL/AIST (Japan)	NewSUBARU (Japan)	Spring-8 LEPSII (Japan)
Energy region (MeV)	**0.4-20**	2-100 (158)	<6.6	1-40	1.7-73	1500-2900 1500-2400
Resolution ($\Delta E/E$)	**<5%**	0.8-10%	-	-	-	<0.5%
Flux (phs/s)	**$0.2*10^5$-$0.2*10^7$**	10^8	$>10^7$	10^4-10^5	10^6	10^6-10^7
Status	**2020**	running	running	running	running	running

Similar operating beamlines as SLEGS:

(1) Same production mode: LEPS/LEPS2, external laser scattered by electrons of storage ring.

(2) Similar Gamma energy region: ETL/AIST-LCS(1.6–40MeV), NewSUBARU(3.9–73MeV) and HIGS(1–158MeV).

Feature of SLEGS:

(1) Back and slant scattering mode: Incident laser angle tuned from 20° to 160°, Energy also can tunded by Laser Type

(2) Gamma Energy: Cover important region of nuclear physics and astrophysics

(3) Gamma resolution and the flux: Reaching the advanced level of the current beamlines.

2. Properties & Scientific goals

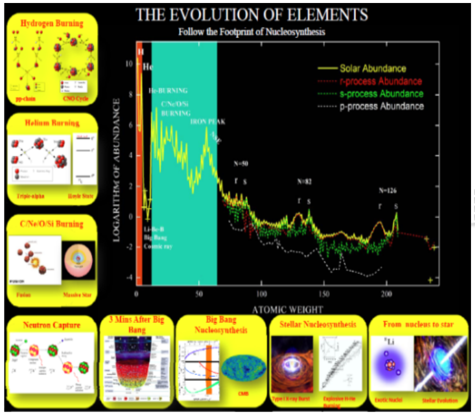
•Photo−nuclear physics:

- Nuclear Astrophysics： nuclear reactions which have a critical impact on stellar evolution and nucleosynthesis of elements
- Nuclear structure GDR and NRF, etc.

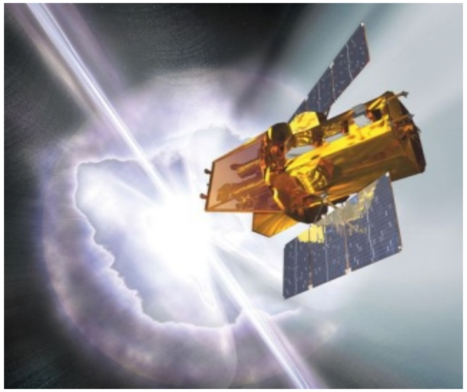
•Research on the anti-γ radiation properties of aerospace device and calibration for the X/γ detector equiped on aerospace device

•Nuclear waste transmutation research and nuclear safety,

•Gamma-ray imaging techniques (in particular: isotope imaging technology), etc.

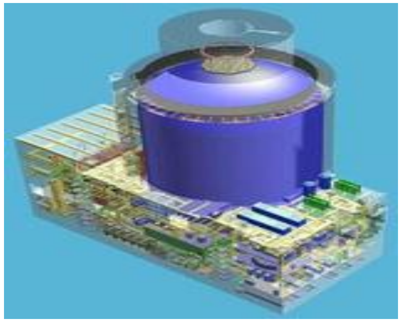


Space (radiation hardened)



Nuclear technology and data

nuclear explosion

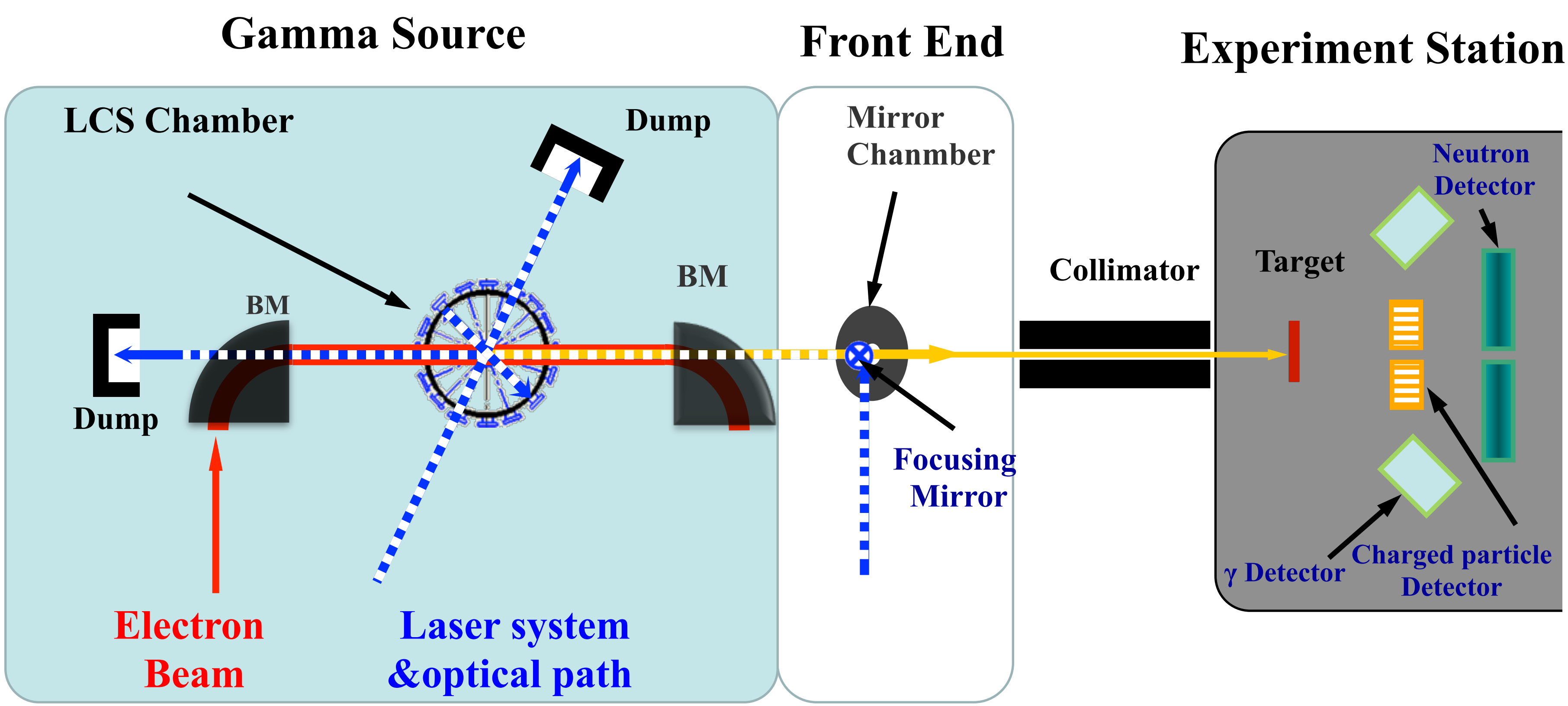


Nuclear reactor

Isotope Detection

3. Gamma source design

3.1 Operation mode



LCS Mode 1
Slanting Scattering

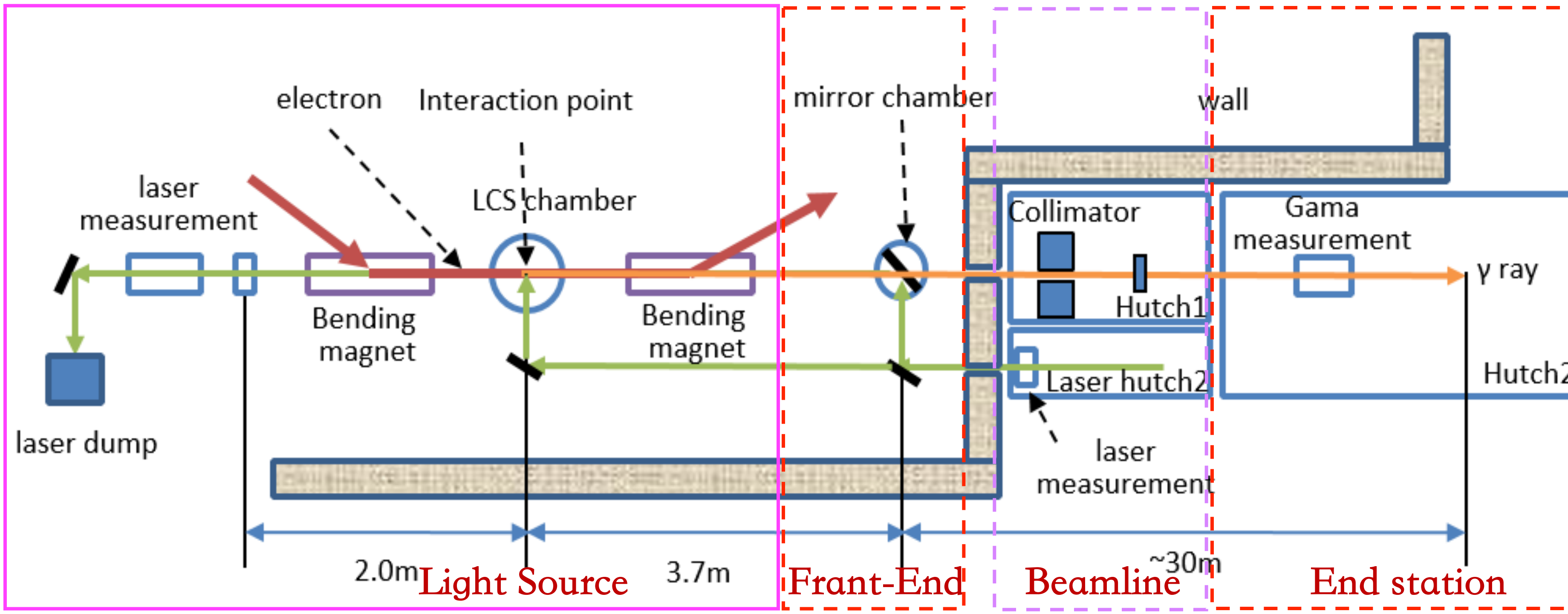
LCS Mode 2
Backward Scattering

Alternative mode

Reset

3. Gamma source design

3.2 Layout



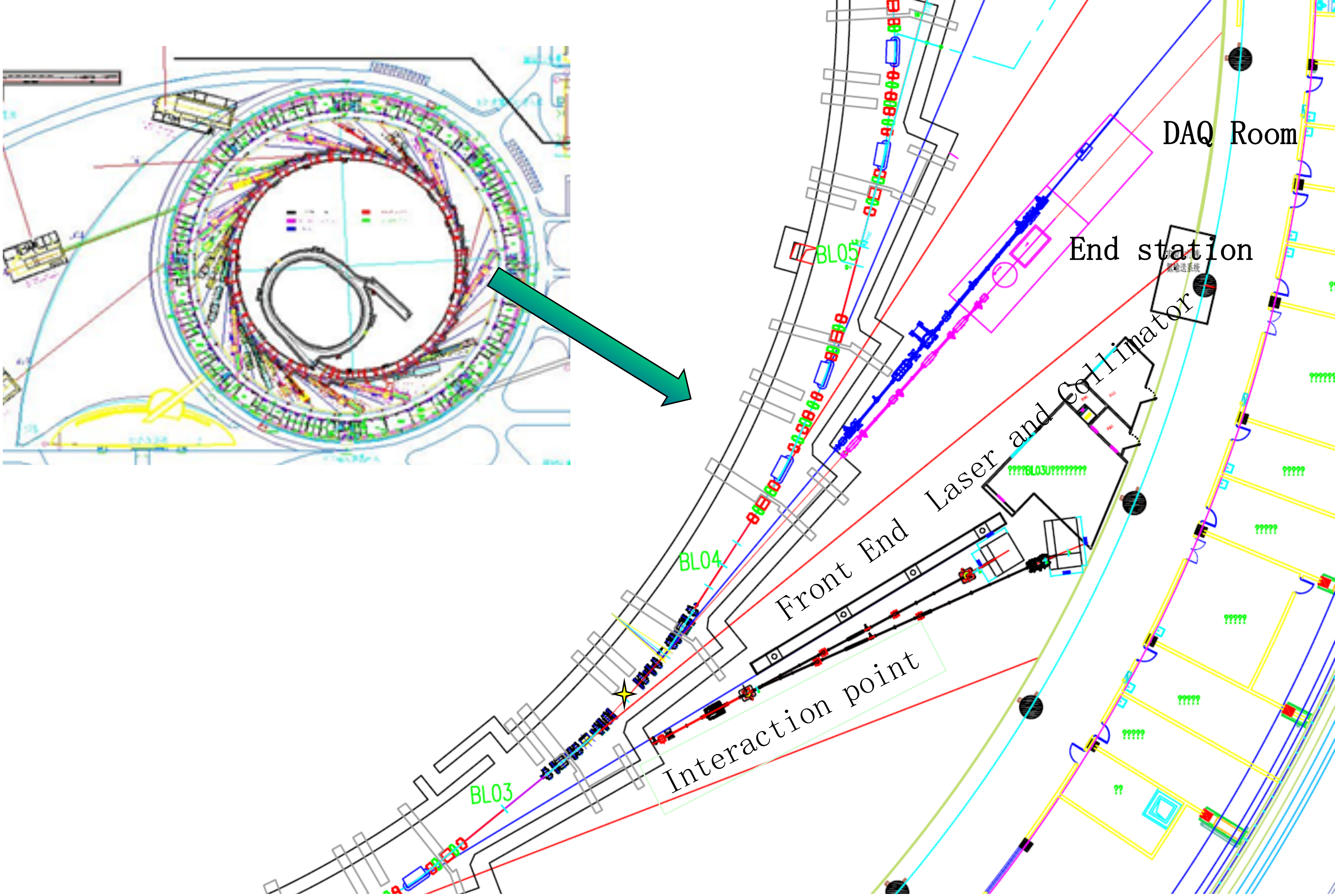
(1) light source: Electron, Laser, LCS chamber (slanting mode), mirror chamber (back scattering).

(2) Front end of Beamline.

(3) Beamline: gamma collimator, absorber, bend magnet, gamma monitor, gamma dump.

(4) End station.

The Position of SLEGS (BL03SSID) @SSRF



3. Gamma source design

3.3 Gamma source-components-SSRF storage ring

Energy	**3.5 GeV**
Beam Size σ_x	276.9 um
Beam Size σ_y	12.24 um
Pulse RMS	3 mm
Current	**300 mA**
Q_e	1.44 nC
Emittance $\varepsilon_x/\varepsilon_y$	2.59 / 2.59E-2 nmrad
Divergence η_x/η_y	0. 207 / 0 m
β_x/β_y	14. 86 / 5. 78 m
Energy spread	0. 944E-3
Pulse Number	500

Issues related to storage ring:

（1）**Interaction LCS chamber**

（2）**Laser injection and gamma ray extraction**

3. Gamma source design

3.3 10.64um CO_2 Laser

Diamond GEM-100A (10.6 μm)

Air-Cooled RF-Excited OEM Industrial CO_2 Laser

Features

- Outstanding beam quality and stability
- Direct air-cooling
- Linear polarization
- Highly compact
- Low-cost OEM configuration
- Fast rise/fall time
- Up to 100% duty cycle operation
- All-metal seals for long life
- Interchangeable laser heads and RF power supplies
- Wide operating power range

Diamond GEM-100L (10.6 μm)

Liquid-Cooled RF-Excited OEM Industrial CO_2 Laser

Features

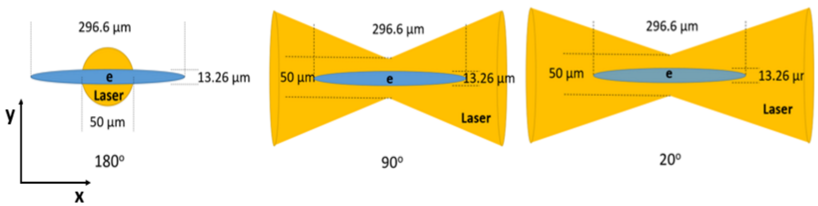
- Outstanding beam quality and stability
- Highly compact and lightweight, two-piece package
- All-metal seals for long life
- Low-cost OEM configuration
- Interchangeable laser heads and RF supplies
- Linear polarization
- Wide operating power range
- Fast rise/fall time
- Up to 100% duty cycle operation

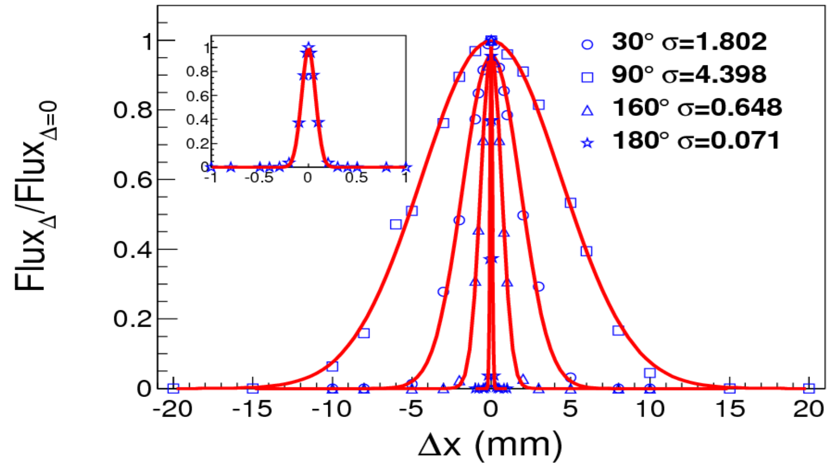
System specification	Parameters
Wavelength(μm)(fixed)	10.55 to 10.63
Output power(W)	**100**
Power stablity(%)	± 5
Mode Quality	>90% TEM_{00} M^2<1.3
Beam size(mm)	3.8 ± 0.4mm
Beam Divergence(mrad,full angle)	<5.0
Polarization(fixed liner)	>100 to 1
Weight of head(kg)	11.8
Weight of power supply(kg)	8.2
Dimensions(mm^3)	591.9×150.4×163.3
Facilities Requirements	
Input power	48VDC 50A
Laser head (heat dissipation)(W)	1200
RF power supply(heat dissipation)(W)	800
Tempture(°C)	5-40
Altitude（m）	< 2000
Humidity	Non-condensing

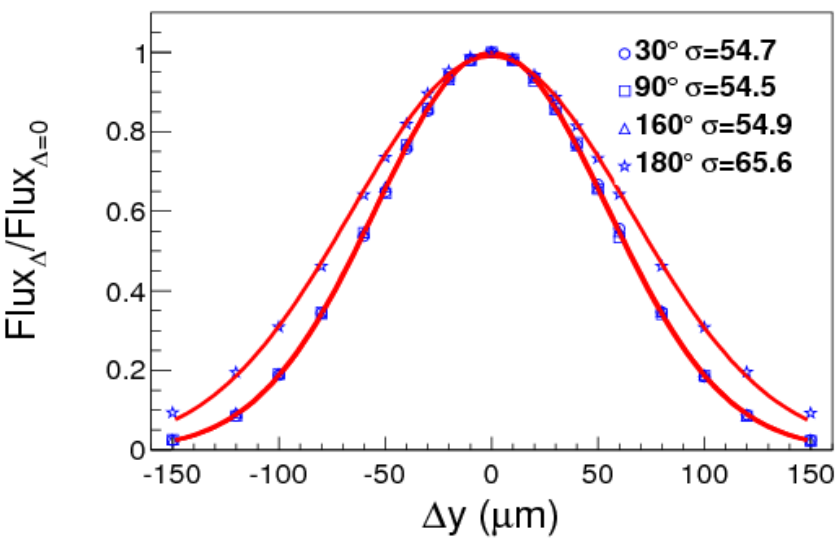
3. Gamma source design

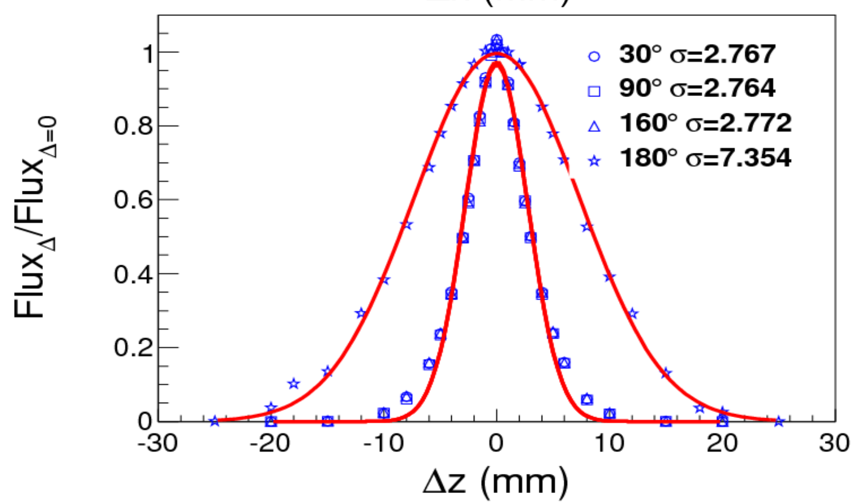
3.3 Gamma source-simulation

The position deviation of laser vs photon Flux @ collision point, slanting scattering





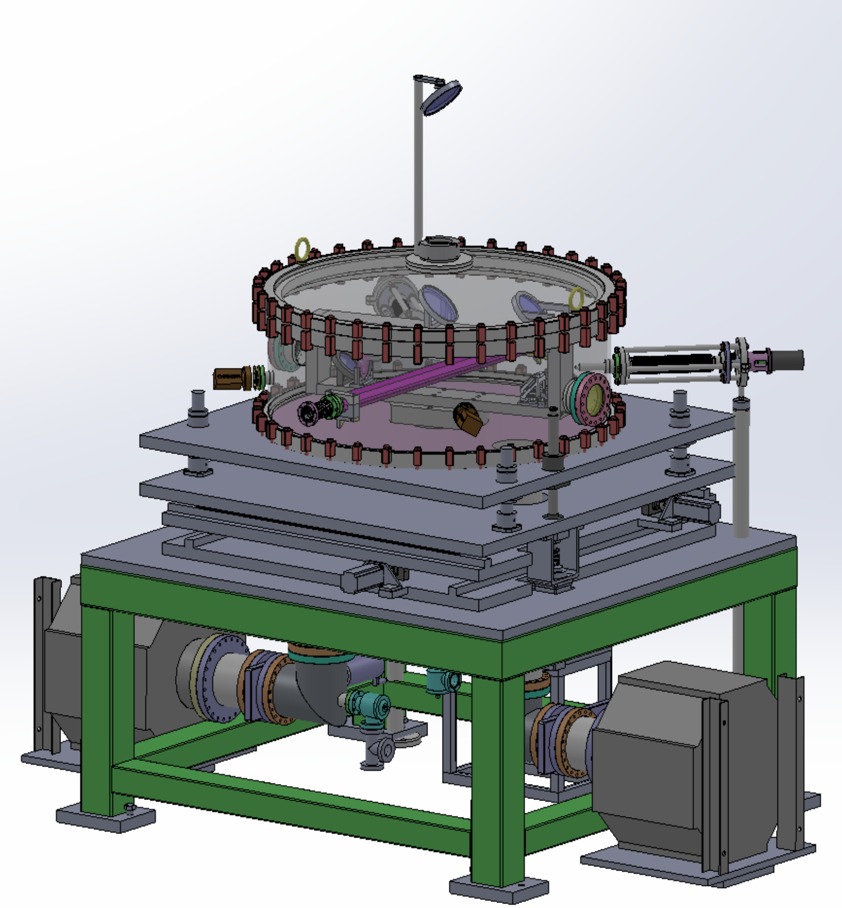


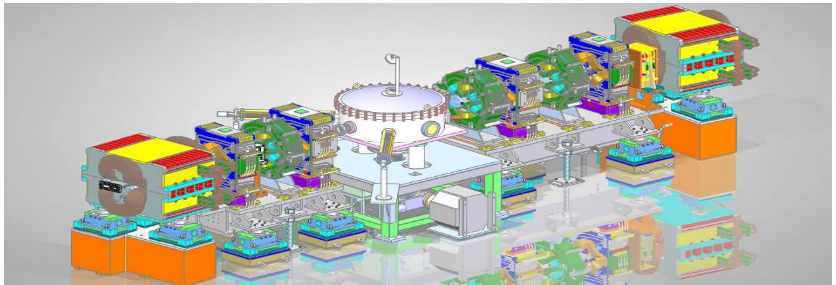


Requirement of position fine adjustment @ Slanting Scattering

3. Gamma source design

3.4 LCS chamber





The main function：

1) Rotatable optical system can adjust the angle between laser and electron beam from 20° to 160°;

2) Vacuum system can keep the LCS chamber at a 10^{-8} Pa ultra -high vacuum environment;

3) Finger shielding is set to match the chamber's impedance and storage ring's impedance;

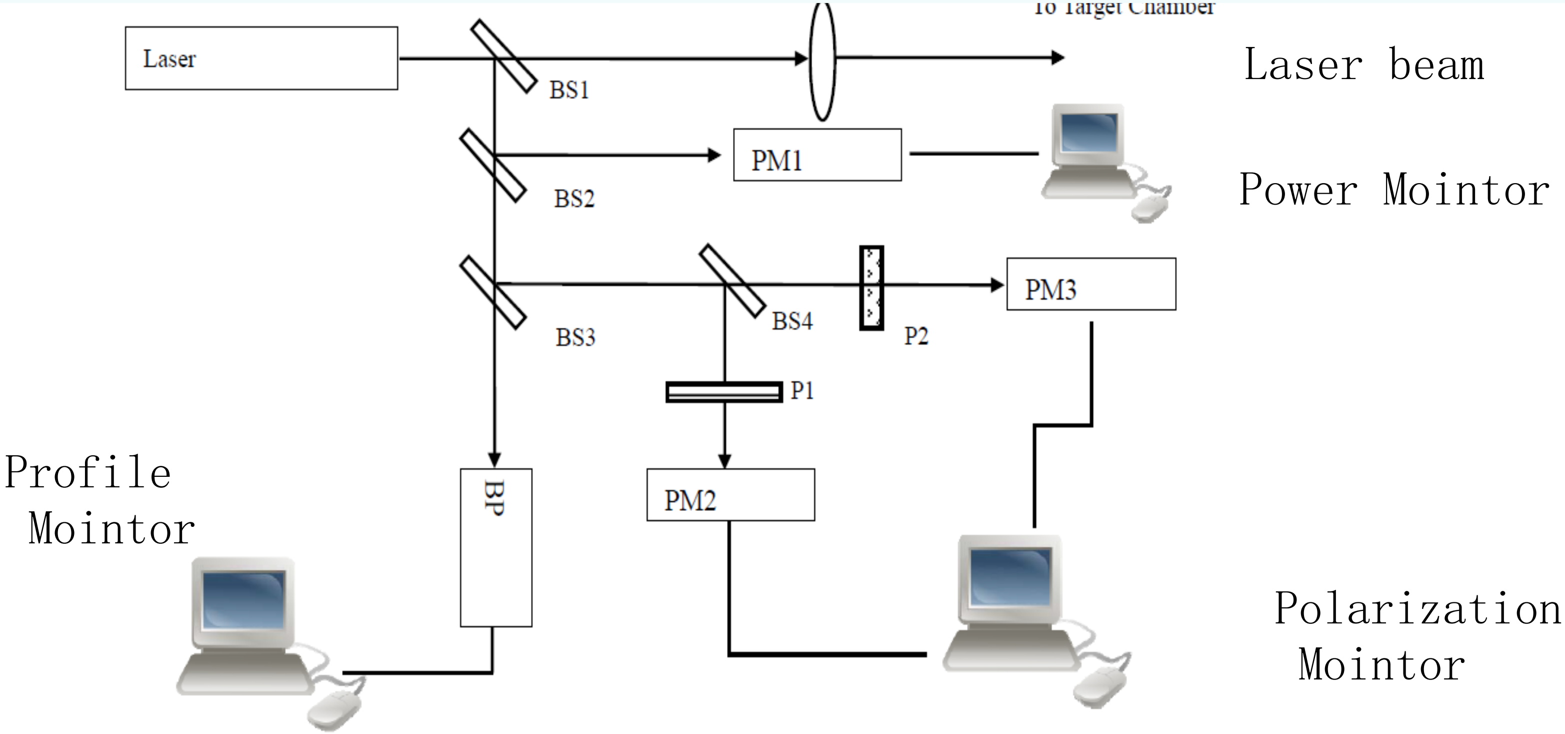
4) 3D moving platform which is under the LCS chamber in air can help to adjust the relative position of laser with resolution of 5 μm;

5) Flexible holder in the LCS chamber can achieve the electron bunch and laser's relative position adjustment with resolution of 5 μm.

Subsystem	Function and Purpose
3D moving platform	**5 μm**
Rotatable optical system	0.01°
Vacuum system	**10^{-8} Pa**
Finger shielding	impedance matching

3. Gamma source design

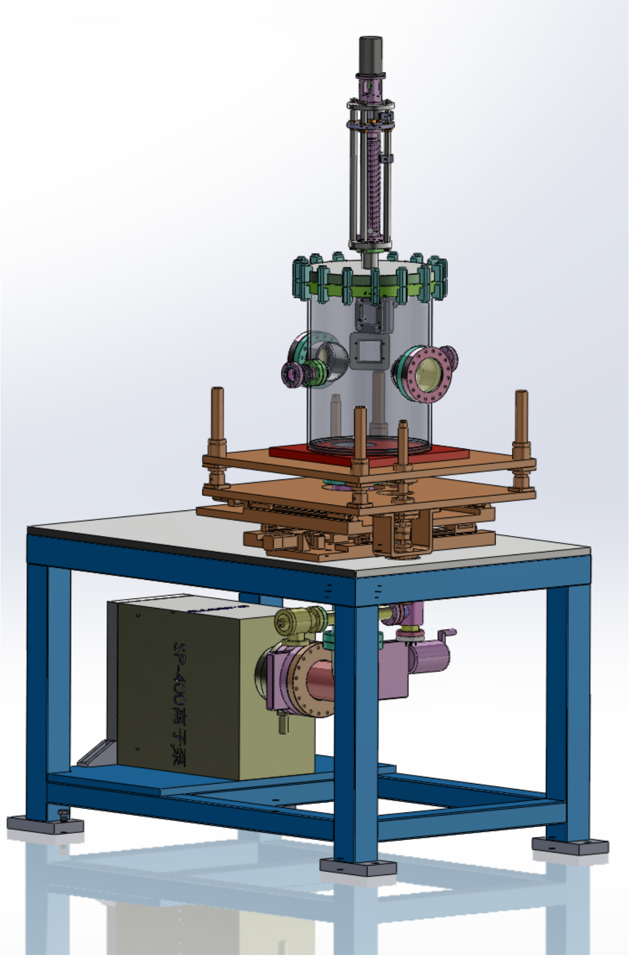
3.3 Laser Monitor



The Laser is divided by beam splitter (BS1, 1:99) into many parts.
mainly be used to interact with electron.
One is used to laser power monitoring.
One is used to conduct beam analysis by beam profiler (BP),
Another is used to measure the polarization.

3. Gamma source design

3.5 Mirror chamber



The main function：

keeping the electron beam and laser beam waist coincident within a maximum deviation of 10 μm in every direction in the 10^{-8} Pa ultra-high vacuum environment.

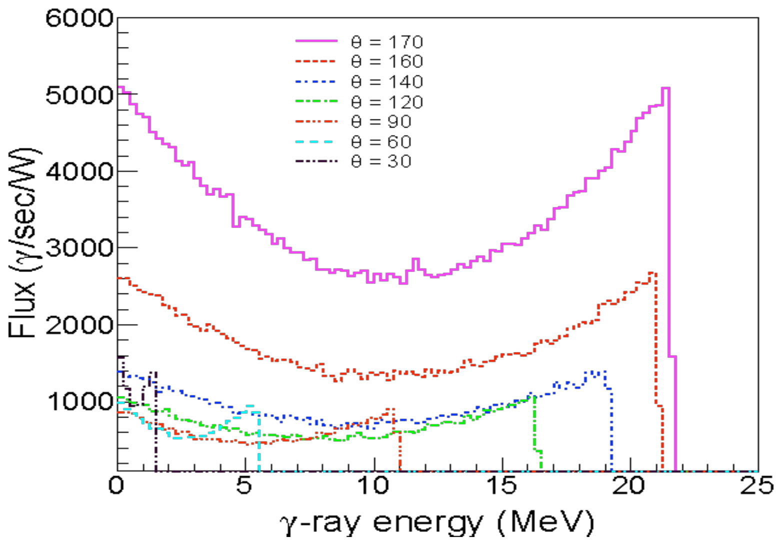
Compents：

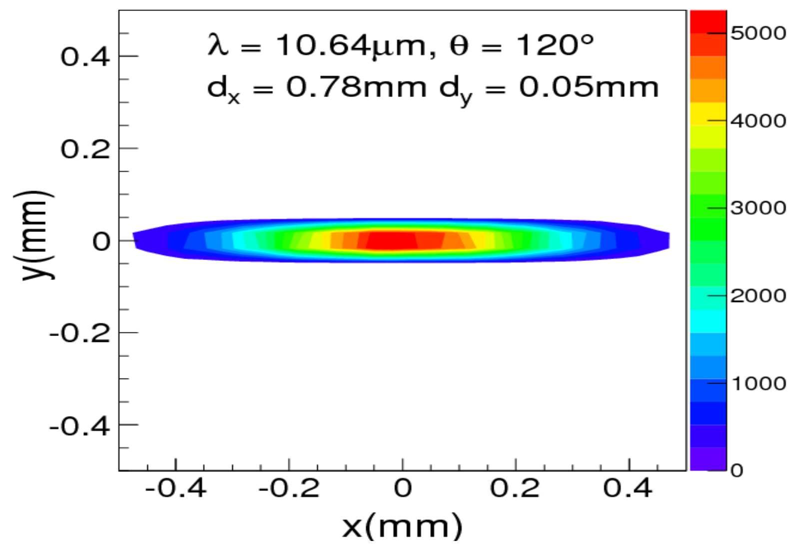
It includes optical system, vacuum system, 3D moving platform to adjust the spot position and flexible holder.

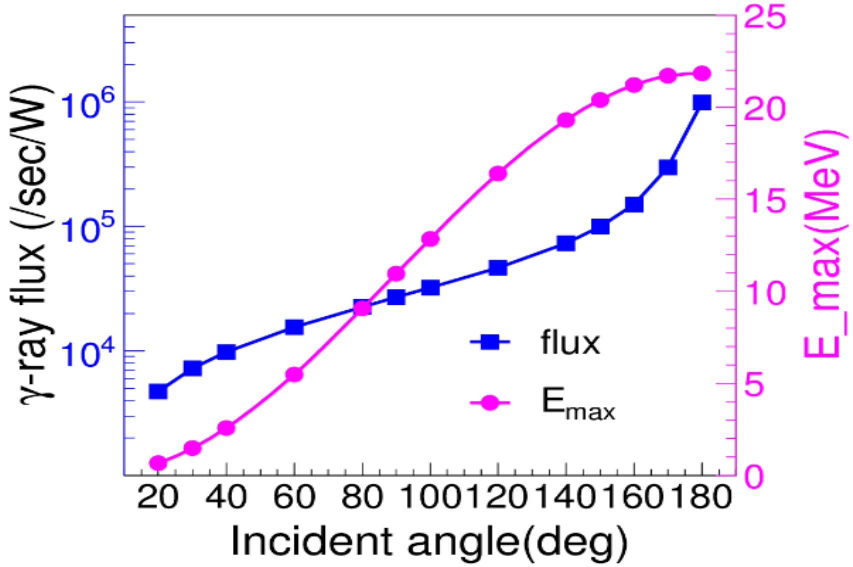
Sub-system	Function and Purpose
3D moving platform	**5 μm**
Optical system	Focusing laser
Vacuum system	**10^{-7} - 10^{-8} Pa**
Water cooling system	Cooling the lens

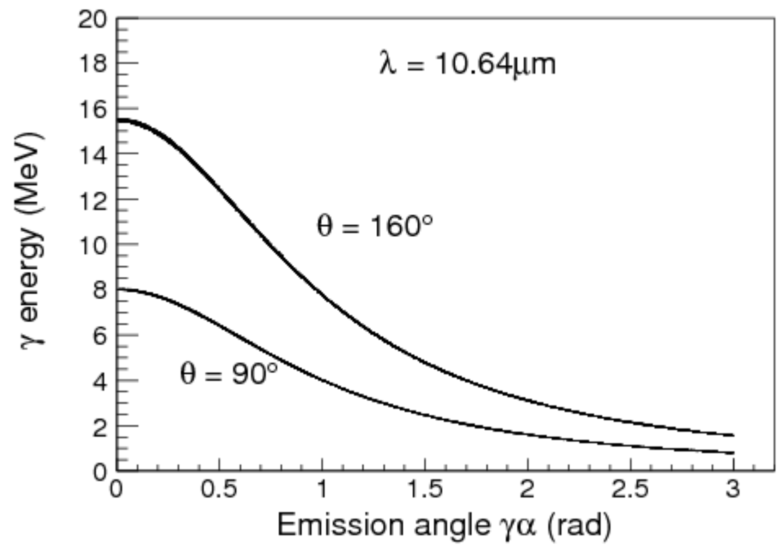
3. Gamma source design

3.6 Gamma properties @ Gamma source



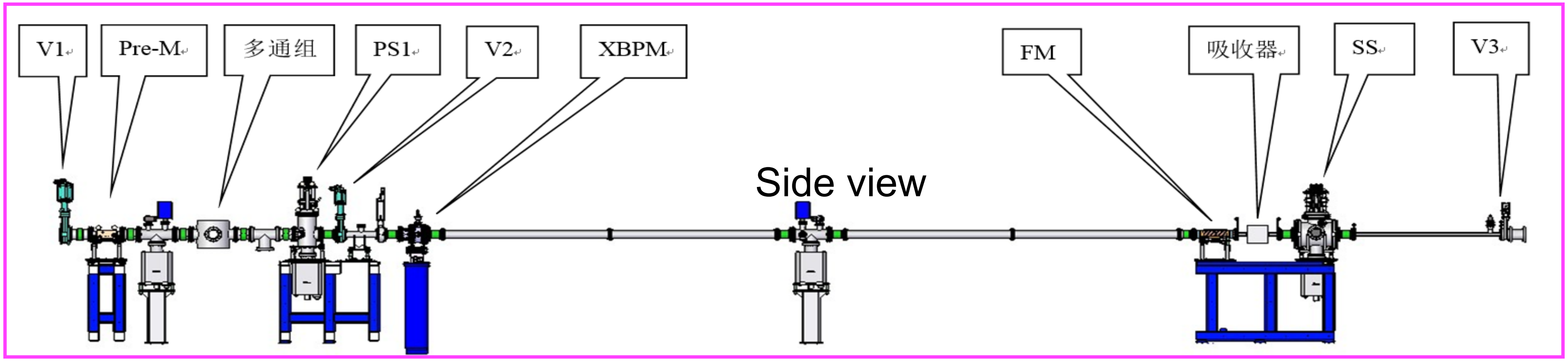






3. Gamma source design

3.7 Front End



Include: Valve1 (V1), Pre-Mask (Pre-M), Mirror chamber, Photon shutter1 (PS1), Valve2 (V2), Beam Position Monitor1(XBPM1), Fixed Mask1(FM1), Absobor,Safe shutter(SS), Valve3(V3).

Working mode of Front end：

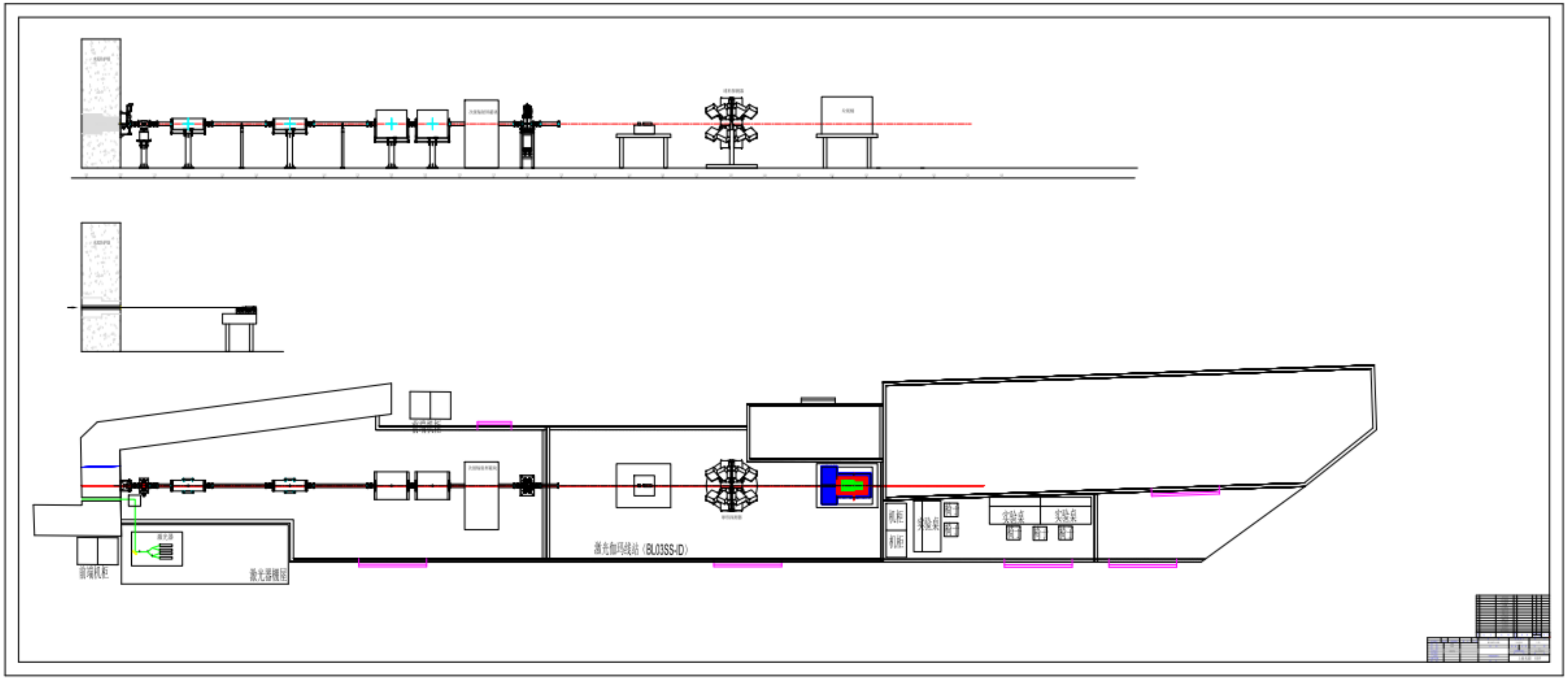
(1) Normal working mode；

(2) Waitting Mode when user enter Laser hutch；

(3) Stoping mode when front-end error occour

4. Beamline design

4.1 Beamline layout



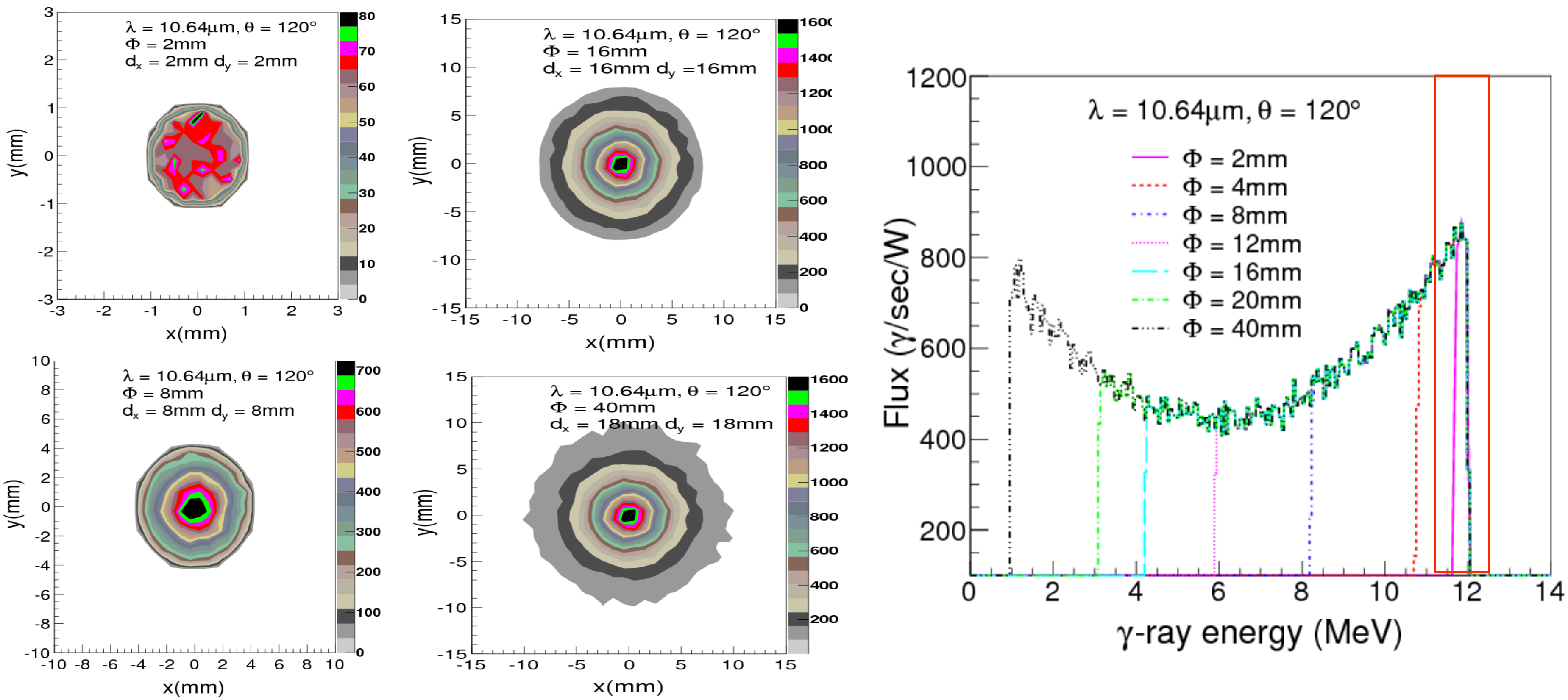
Include：

Collimators, Attenuator, Bend magnet, Radiation shielding,

Monitor detector (Energy, position, flux detector) and gamma absorber

4. Beamline design

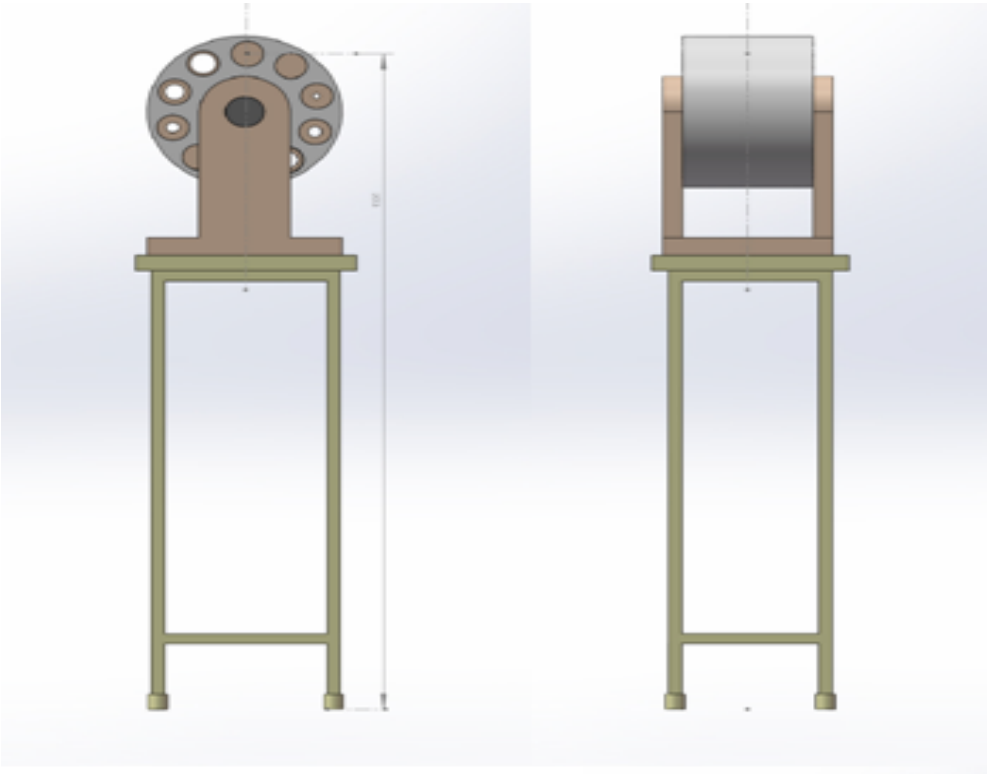
Gamma properties： Beam radius and collimater @ Beamline

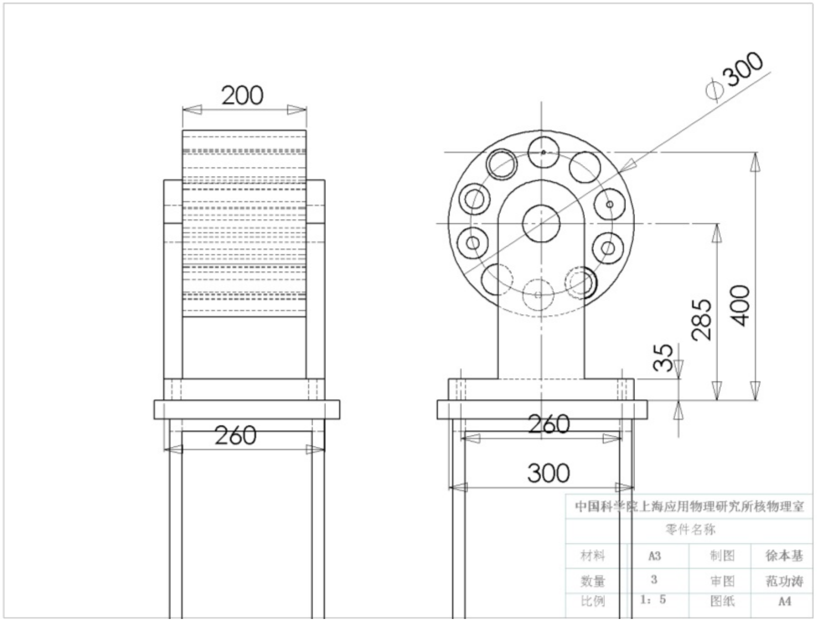


4. Beamline design

4.2 Rough collimator

For security consideration, the rough lead collimators will be shaped into 200 mm long hollow cylinders with external radius of 100 mm and inner radius of 8 optional size: 5, 10, 15, 20, 25, 30, 35, 40 mm. They are used for a rough selection of gamma energy。



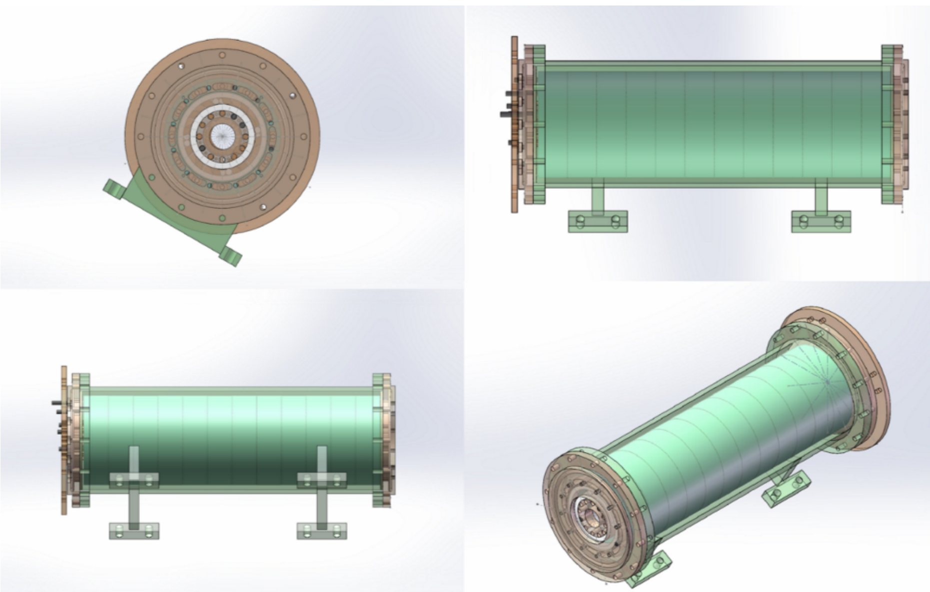


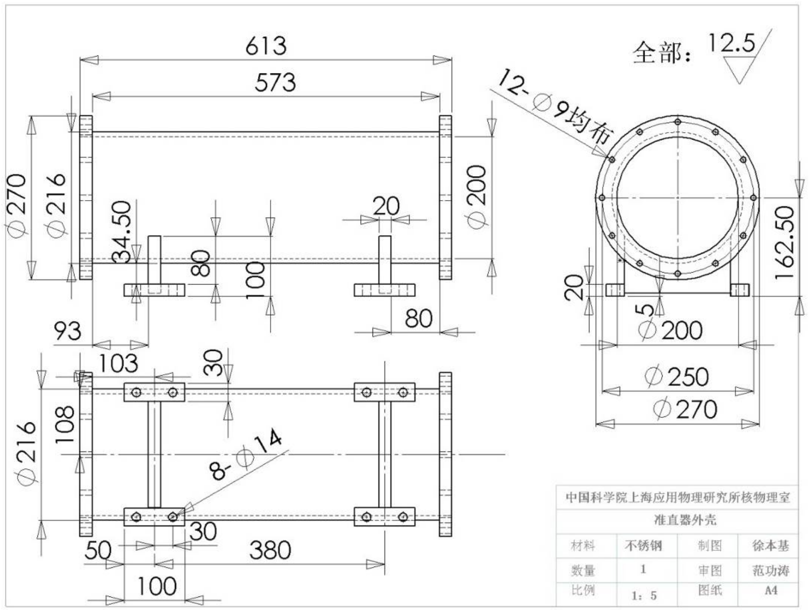
Rough collimator	
Material	Pb
Outside diameter（mm）	100
Inner diameter （mm）	5，10，15，20，25，30，35，40
Long（mm）	200

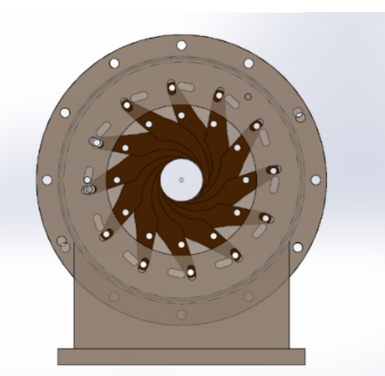
4. Beamline design

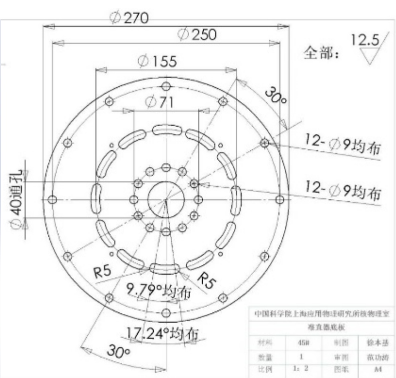
4.3 Fine collimator

The fine collimator's inner radius can be continuously adjusted from 0 to 40 mm to perform a fine selection of γ-ray's spot. like a carema shutter.







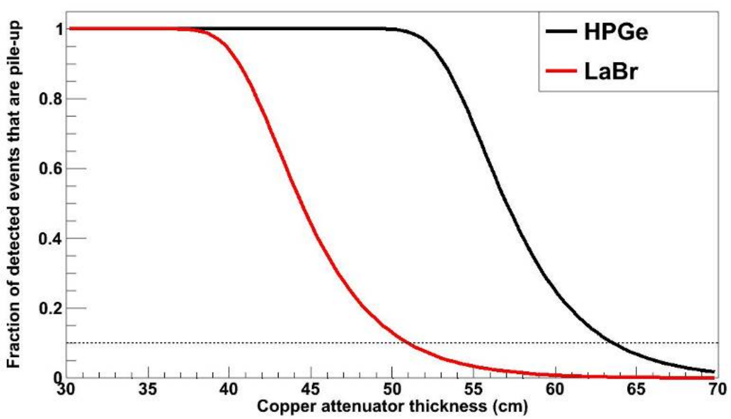


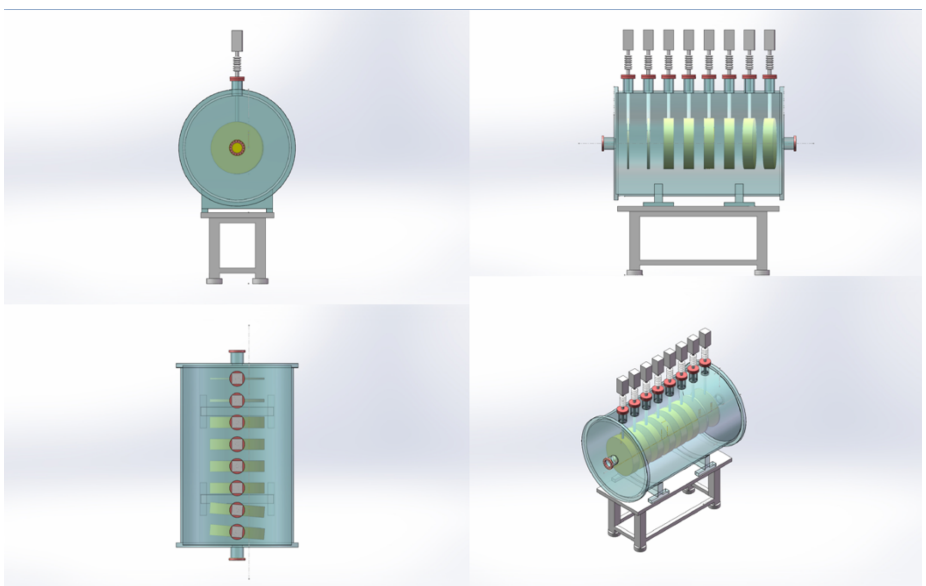
Fine collimator	
Material	Pb
Outside diameter（mm）	100
Inner diameter （mm）	0-40continuously adjustable
Long（mm）	200

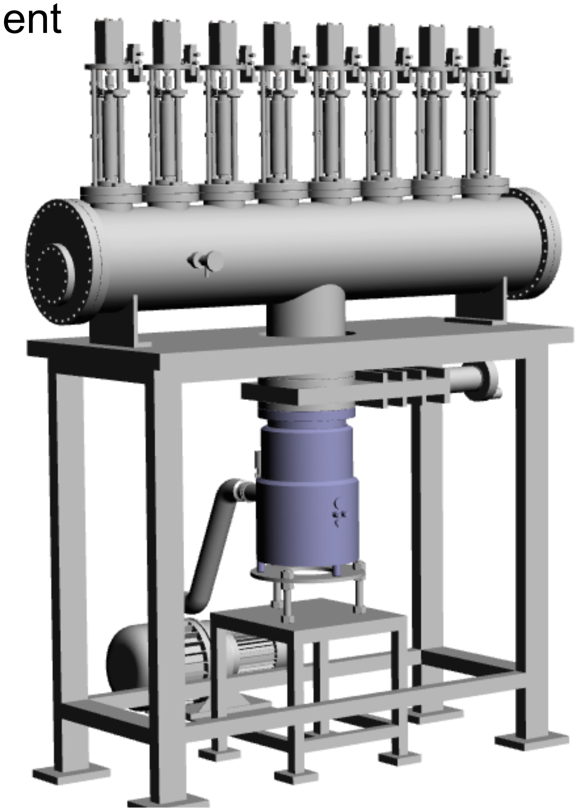
4. Beamline design

4.4 Attenuator

Used for reduced gamma flux for HpGe and LaBr measurement







Material	Cu		
Material purity	>99.9%		
Outside diameter（mm）	50		
Inner diameter （mm）	100	25	15
Numaber	6	1	1

5. End station design

5.1 Physics and Experiment

Correspondence between GDR and α cluster configurations

- ✓ GDR spectrum is highly fragmented into several apparent peaks due to the α structure
- ✓ The different α cluster configurations in ^{12}C and ^{16}O have corresponding characteristic spectra of GDR
- ✓ The number and centroid energies of peaks in the GDR spectra can be reasonably explained by the geometrical and dynamical symmetries of α clustering configurations

PRL **113,** 032506 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

Giant Dipole Resonance as a Fingerprint of α Clustering Configurations in ^{12}C and ^{16}O

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(Received 6 May 2014; published 17 July 2014)

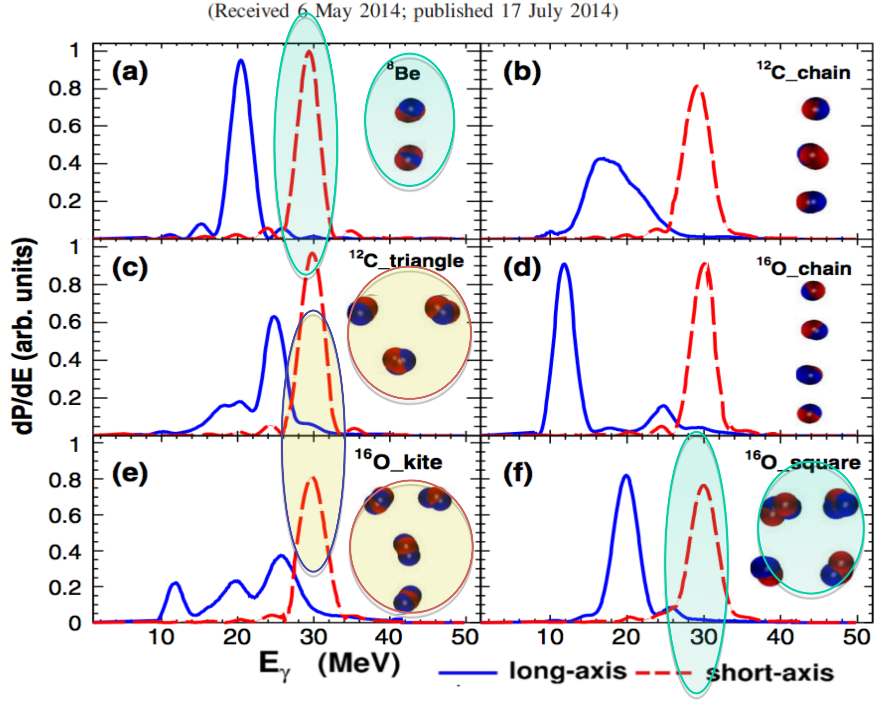
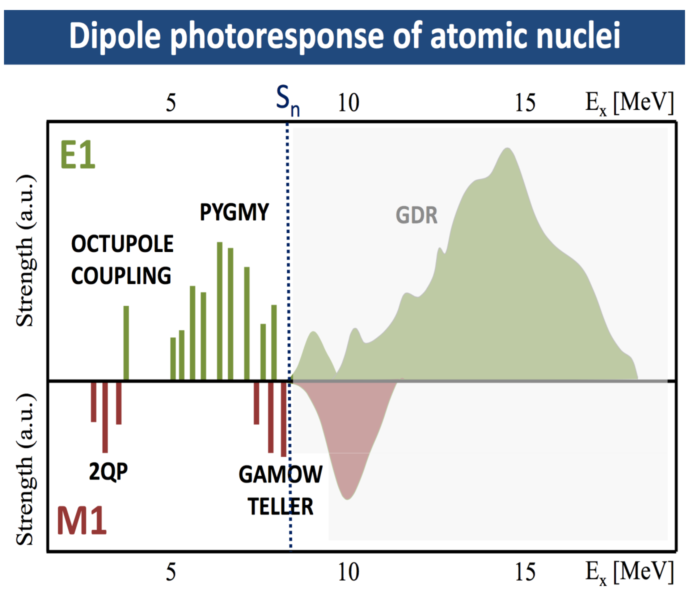
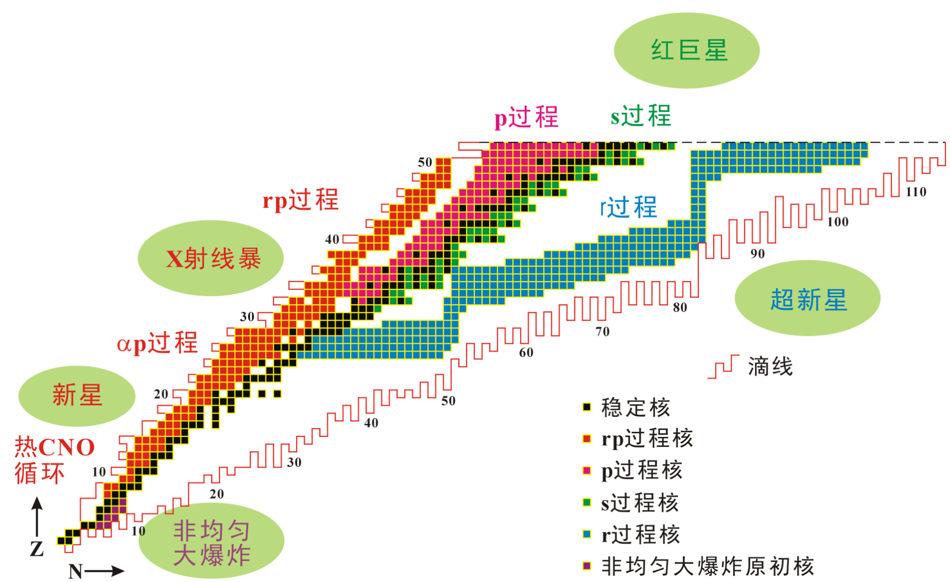


FIG. 2 (color online). ^{8}Be, ^{12}C, and ^{16}O GDR spectra with different cluster configurations. The corresponding α cluster configuration in the present EQMD model calculation is drawn in each panel, in which blue and red balls indicate protons and neutrons, respectively. The dynamical dipole evolution of ^{8}Be, ^{12}C, and ^{16}O with linear-chain configurations are shown in [51].

The p-process nuclei and GDR study

- p-nuclei: Containing more protons relative to other stable isotopes of the same element, stable nuclides with mass numbers A⩾ 74.
- Aboundance are a factor of ≈100 smaller to adjacent s- and r-nuclei.
- Their synthesis is still uncertain.
- Scenarios is Type-II supernovia
- Underproduction of species as ^{92}Mo, ^{94}Mo, ^{113}In, ^{115}In
- Strong ependence on (γ, p) cross section, as ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92}Mo, ^{96}Ru.





Nuclear Energy for TMSR (Gen-IV Reactor) & Gamma transmutation

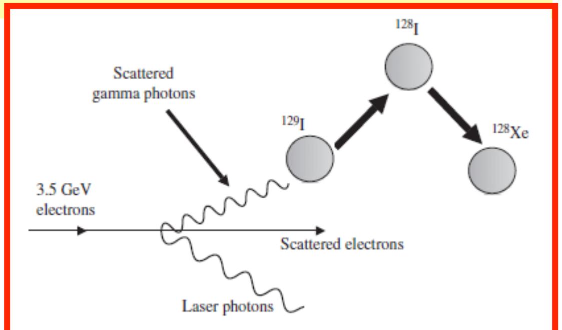
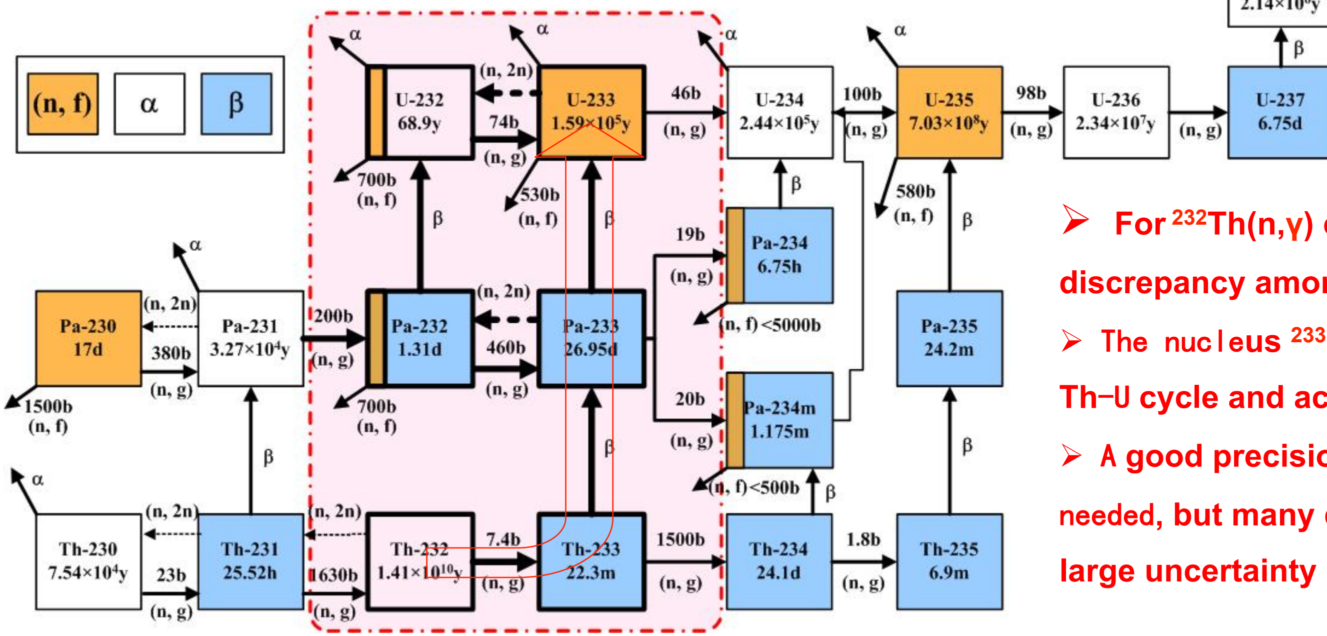
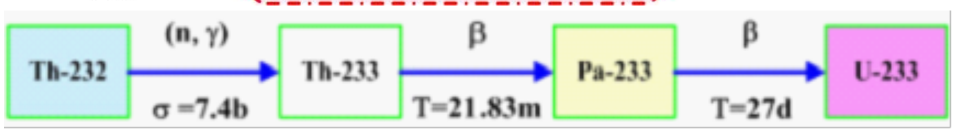


Fig. 1. The Compton scattering process between a laser photon and a relativistic electron as well as the transmutation of ^{129}I via the (γ, n) reaction.

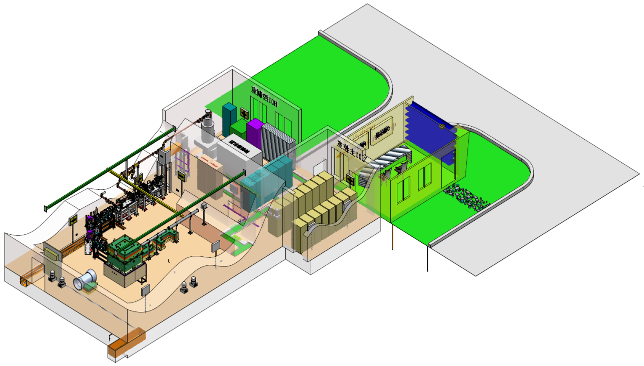
Scheme of Thorium-Uranium cycle





- For ^{232}Th(n,γ) capture reaction, it shows that discrepancy among data published is around 20-30%。
- The nucleus ^{233}Pa(protactinium) plays a key role in Th-U cycle and acts as a precursor
- A good precision of an order of few percent(~1%) needed, but many data shows large discrepances or large uncertainty

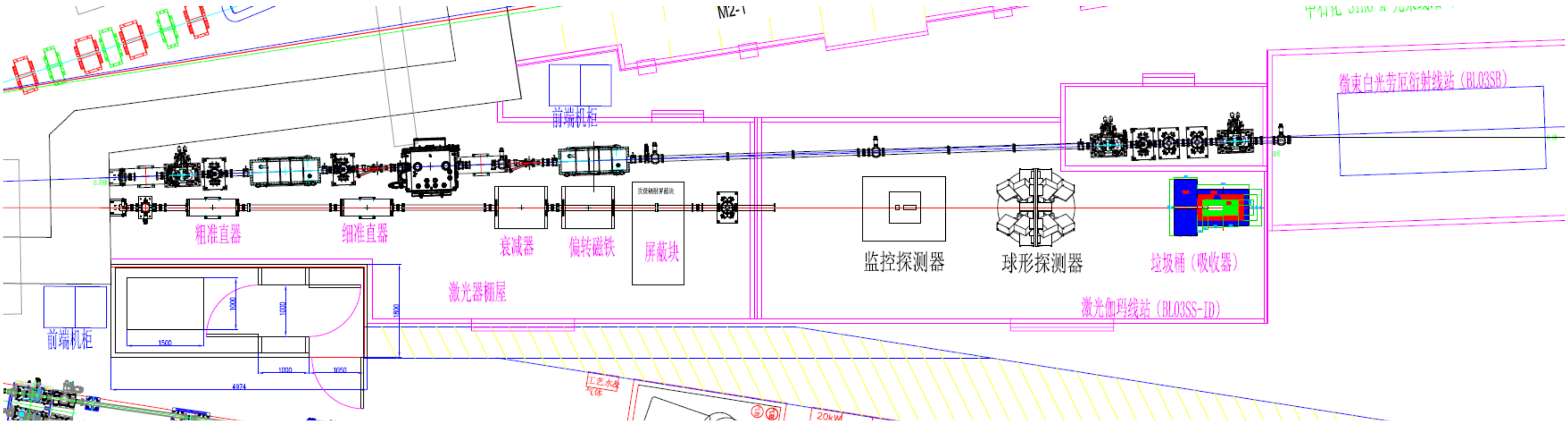
Photo-neutron white Source(Prototype)
@ SINAP-TMSR



key reaction in inverse process (γ,n): ^{233}U(n, γ)^{234}U(n, γ)^{235}U(n, γ)^{236}U, ^{230}Pa(n, γ)^{231}

5. End station design

5.2 Layout

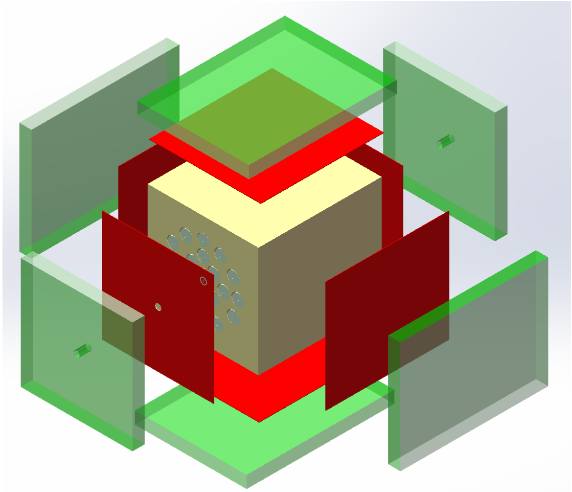


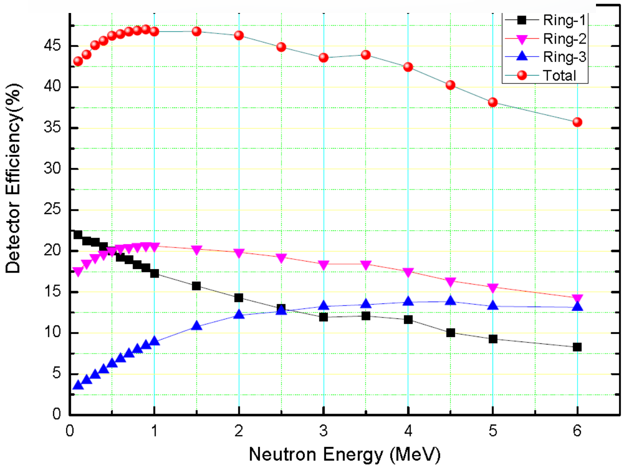
- (γ, n) Neutron detector
- (γ, p/α) Charged particle detector
- (γ, γ) Gamma detector

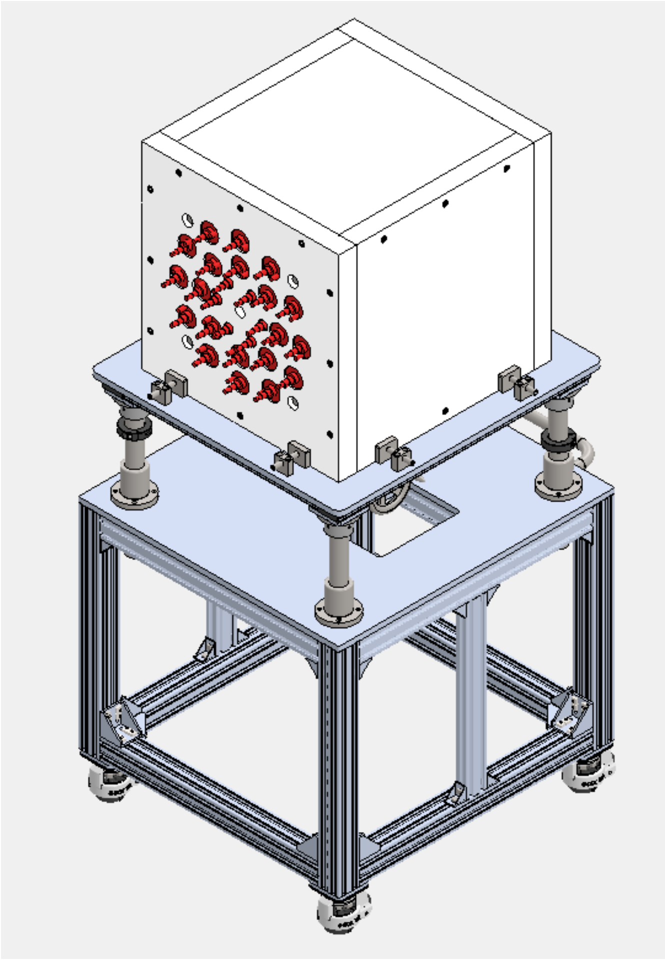
5. End station design

5.3 ^{3}He tube for 4π neutron detector

- 4π ^{3}He proportional counter：
- Energy rang: 1keV~ 5MeV；
- Efficiency ： ~ 45%@1keV~ 500keV，~35%@5MeV







5. End station design

5.4 Fast neutron detector

- BC702/EJ426(^{6}LiF • ZnS):

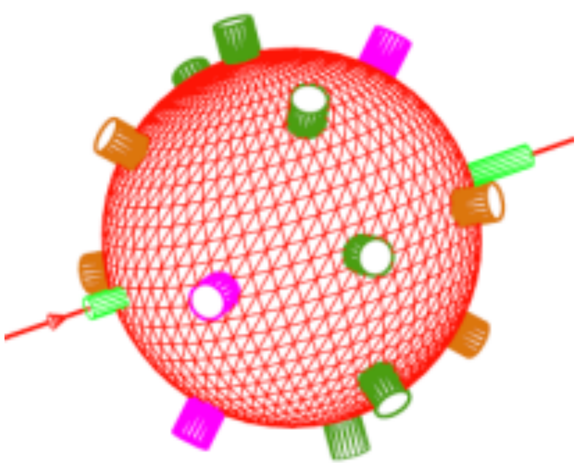
  Energy rang : 0.025eV-1keV; Efficiency: ~ 60%@Thermal neutro,

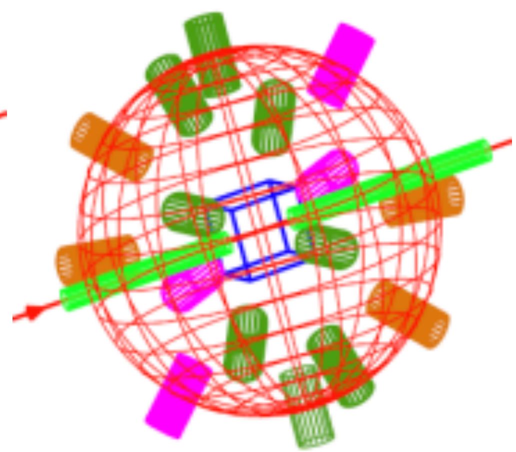
- Lithium glass GS20:

  Energy rang : 1keV-1MeV, Efficiency:~ 20%@^{252}Cf

- Liquid/Plastic scintillation detector BC501A/EJ301:

  Energy rang :1-5MeV, Efficiency:~ 10%@^{252}Cf

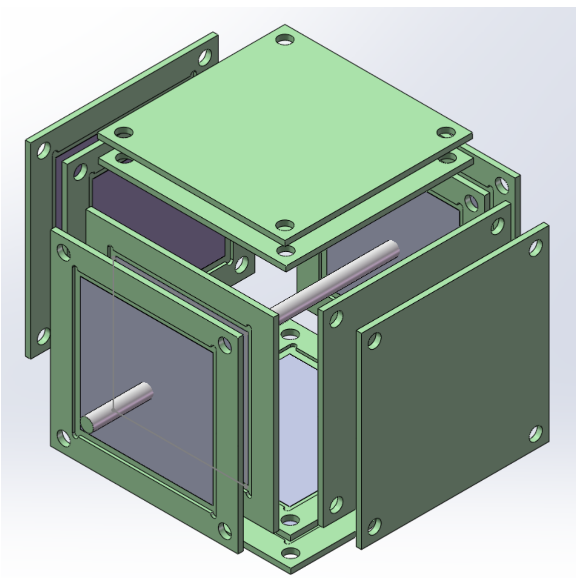


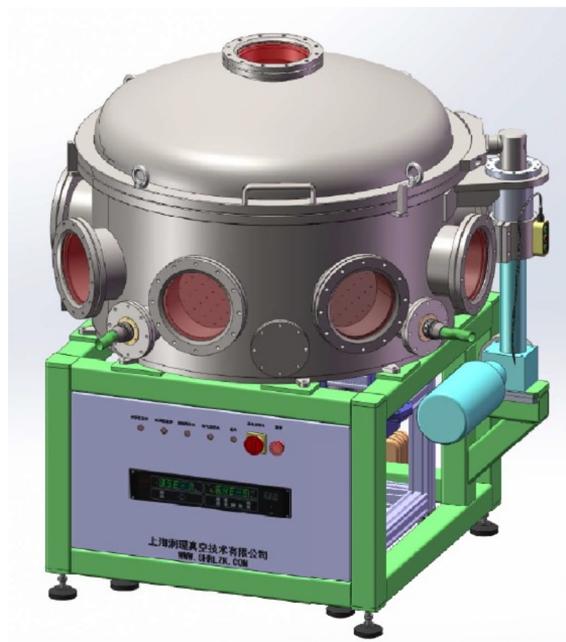


5. End station design

5.5 Si strip detector & Vacuum Chamber

- Sensitive area :50mm×50mm;
- Thickness:100um-300um, Resolution:~ 0.1%@5.5MeV, Position resolution ~3mm；
- Thickness: 500-1500um， Resolution: ＜ 1.5%@5.5MeV;
- Thickness of the non-position sensitive detector :1mm， Resolution: ＜ 2.5%。





5. End station design

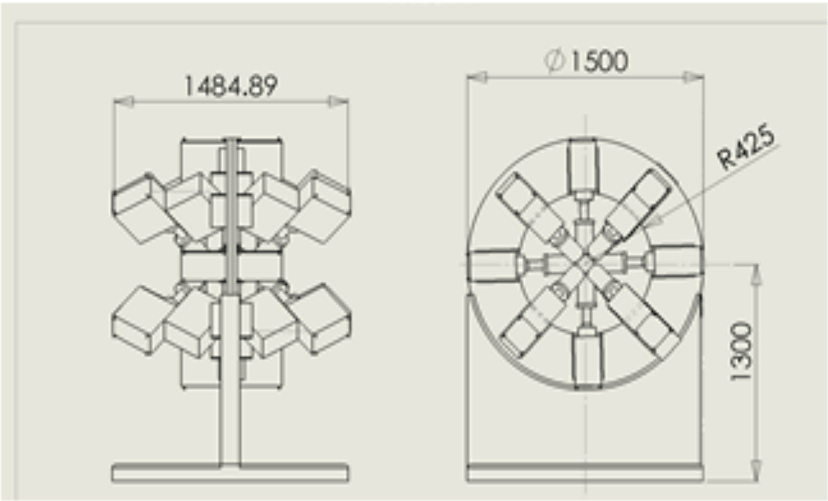
5.2 HPGe & $LaBr_3$ detectors

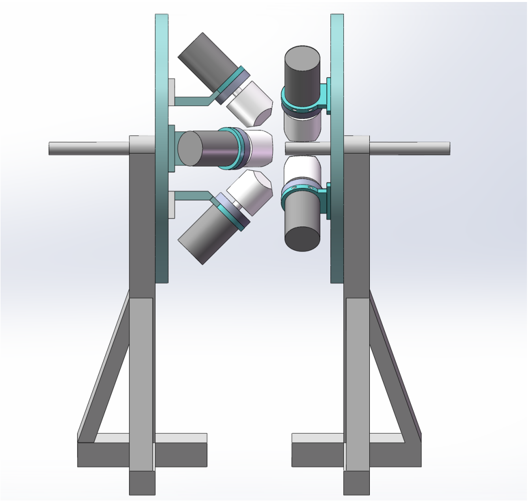
- Resolution （0. 1% ~ 0. 2%），
- Relative Efficiency＞ 90%@5MeV，
- High coincidence detection efficiency，
- Granularity：Clover HPGe +LaBr

LaBr:

Size 76mm×50mm，

Resolution ＜10%@1. 3MeV；





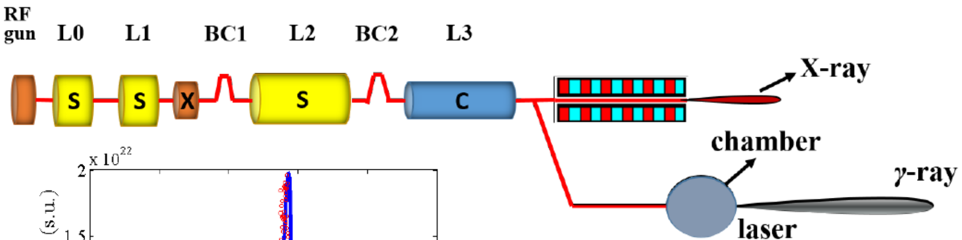
6. Summary

- SLEGS is one of the high quality gamma sources based on Laser Compton Scattering（LCS）at SSRF.
- The energy region and flux of SLEGS are 0.4-20 MeV and 10^5-10^7 phs/s, respectively.
- Based on the method of photonuclear reaction, SLEGS aims to nuclear structure researches such as NRF and GDR, nuclear astrophysics, measurement of nuclear data, atomic physics, and radiation physics.
- SLEGS also plans to carry out the applied research relating to aerospace, national defense, nuclear energy and other strategic demands of China, such as space radiation effect research of the aerospace electronic components, and accurate calibration of the gamma detector for aerospace.
- SLEGS will be constructed from this year, and be expected to open for users from 2022.

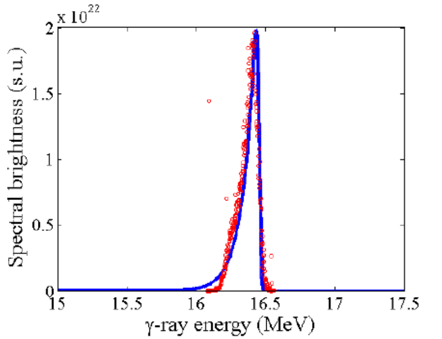
Outlook 1: LCS Gamma Sources at SxFEL@SINAP

A new proposal for LCS Gamma Source similar to ELI-NP @ SXFEL

Gamma Energy： 3.7MeV ~ 38.9MeV



Schematic layout of the gamma source at SXFEL



Main parameters of the SXFEL project.

Parameters	Baseline	Upgrade	Unit
e- beam energy	0.84	1.3	GeV
e- energy spread	<0.15%	<0.15%	
e- bunch charge	0.5	0.5	nC
e- normalized emittance	<1.5	<1.5	mm mrad
e- pulse length (FWHM)	<1	< 1	ps
e- beam current	500	500	A
e- repetition rate	10	10	Hz
FEL wavelength	8.8	3	nm
FEL power	>100	>100	MW
FEL pulse length	<150	<150	fs

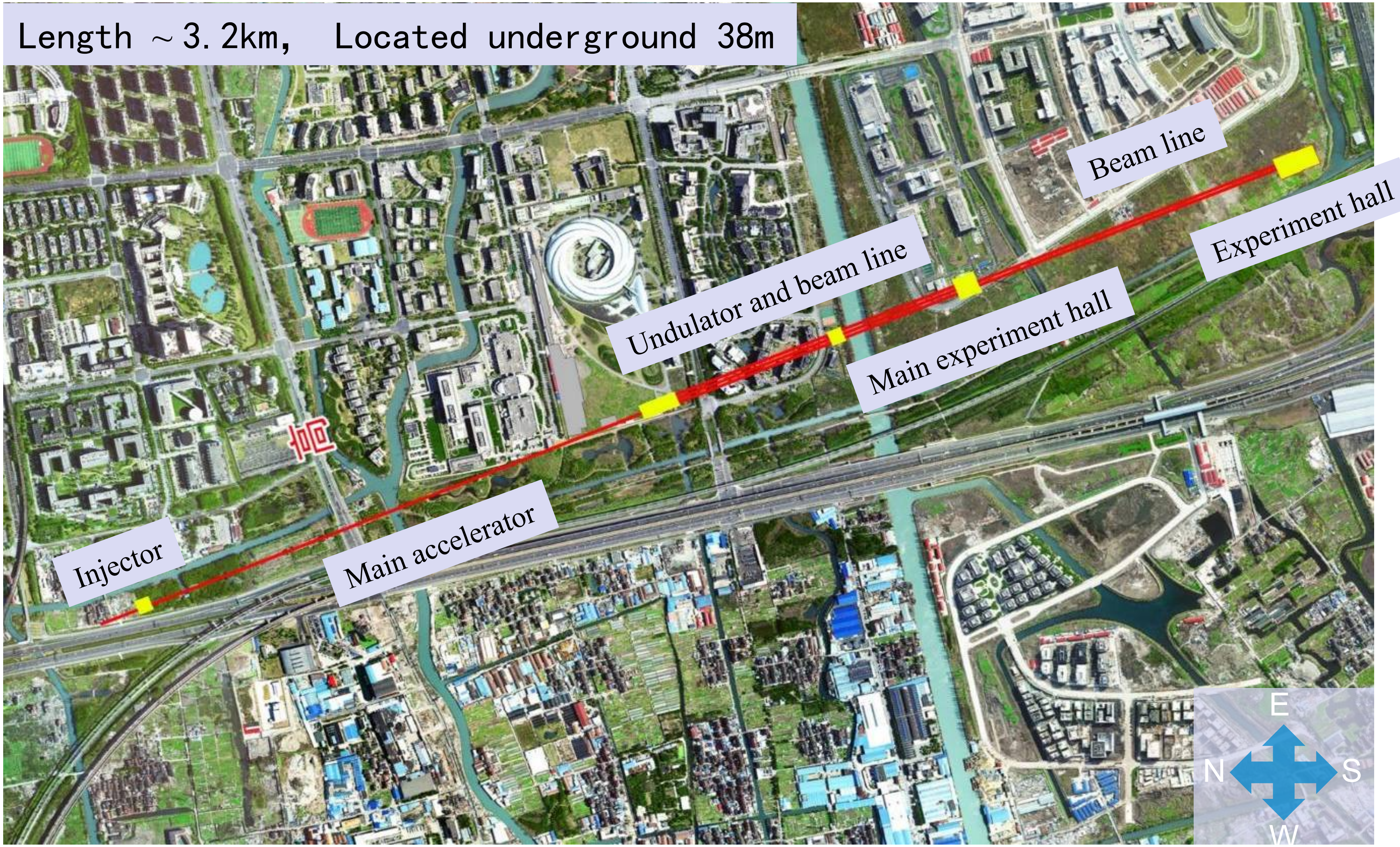
Main parameters of the gamma source at SXFEL and ELI-NP

Parameters	LCS@SXFEL	ELI-NP [62]	Unit
Photon energy	3.7–38.9	0.2–19.5	MeV
Spectral density	4–39	$0.8–4 \times 10^4$	ph/(s eV)
Bandwidth	< 0.5%	< 0.5%	
Photons/shot within FWHM BW	$< 4.54 \times 10^6$	$< 2.6 \times 10^5$	photons/pulse
Photons/sec within FWHM BW	$< 4.54 \times 10^7$	$< 8.3 \times 10^8$	photons/second
Source size (rms)	12	10–30	μm
Source divergence (rms)	0.8	0.03-0.2	mrad
Peak brightness	$4 \times 10^{21}–5 \times 10^{22}$	$10^{20}–10^{23}$	s.u.
Pulse length (rms)	0.86	0.7–1.5	ps
Repetition rate	10	100	Hz

Wu H et al. Nuclear Science and Techniques, Vol.26 (2015) 050103

New Opportunity in Hard X-ray FEL

Layout of the HXFEL: from SINAP to ShanghaiTech



New Opportunity in Hard X-ray FEL

Electron Parameters of HxFEL@ Shanghai

Parameter	Values
Electron Energy (GeV)	8
charge per pulse (pC)	20-200
Norlimalize Perpendicularslice eiitance (mm·mrad)	≤0.4
Peak current (A)	≥3000
Slice energy spread (rms)	<0.01%
Pulse duration (ps)	0.7
Frequency (MHz)	1
Beam bunchs diameter (um)	50
Energy dispersion	0.01%

The last four parameters are used to Laser Compton Gamma source calculation based on the Monte Carlo Code developed by our group.

Beam energy (GeV)	8
Peak current (kA)	4.4
Slice emittance	0.77
Slice energy spread	7.1e-5
Total charge (nC)	0.29
Bunch width (fs, FWHM)	55
Beam size at ID exit (um, rms)	35
Repetition rate (Hz)	60 (max) to 1 (min)

1] Design Report of Shanghai Coherent Light Facility (SCLF- Hard X-ray FEL) ,2016.11.
[2] Nuclear Instruments and Methods in Physics Research A, Vol.726 (2013)67.

Outlook 2: Proposed LCGS @ HxFEL

Calculation based on the Different Lasers

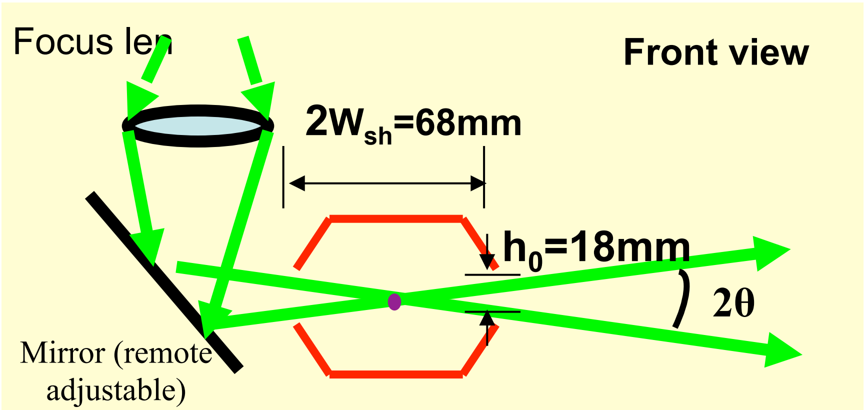
Laser wavelength um/nm	Type	Power /W	Duration fs/ps	Frequency /Hz	Single Pulse /J	Gamma Energy /MeV	Gamma flus photons/s/W
10.64um	CW	1				112.7	3.95×10^{1}
1.64um	CW	1				999.8	3.55×10^{2}
800nm	Pulse		50fs	10Hz	5J	1277.4	3.6×10^{5}
355nm	CW	1				2397.8	1.09×10^{3}
266nm	CW	1				2908.0	4.19×10^{4}
0.1keV@FEL	FEL		0.7ps	1MHz		7398.6	2.18×10^{14}
1.0keV@FEL	FEL		0.7ps	1MHz		7937.8	4.13×10^{16}

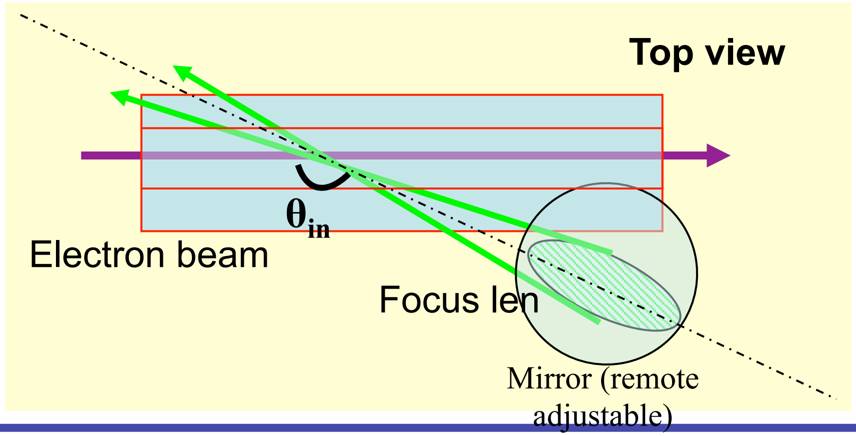
Preliminary calculation

（a）Use optical Laser，we can get 0.11-2.9 GeV gamma ray，and gamma fluxs per Watt from 10^{1} - 10^{4} phs/s/W
（b）Use X-ray FEL, we can get ~ 8GeV high energy Gamma ray，and integral gamma fluxs per pulse 10^{14} -10^{16} phs/s/pulse


Thanks for your attention

The max allowed width of the slit on the shield give restriction on the infimum of laser waist radius





derivation process

Laser waist radius $w_0\downarrow$

Envelope divergence half-angle $\theta\uparrow$

Laser incident angle $\theta_{in}\uparrow$

The edge of slit of shield blocks laser

The infimum of Laser waist radius w_0≈50μm

Specific restrictions applied in the calculation

Half width of shield W_{sh}	34mm
Max allowed width of slit h_0	18mm
Laser incident angle θ_{in}	165°
Laser wavelength λ	10640nm