CEPC Synchrotron Radiation

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Outline

Introduction

Synchrotron radiation from bending magnets

Monte Carlo simulation

Energy deposition caused by SR

Dose estimation for the main ring

Radiation damage

Harm of synchrotron radiation

Synchrotron radiation will induce lots of problems

Heating of the vacuum chamber

Radiation damage to machine elements

Formation of ozone and nitrogen oxides in the air

Leading to corrosion of machine components and health hazards for personnel

Radioactivity induced in components

Other issues……

Apart from electronic components and metals, the organic materials are the ones that are most sensitive to radiation. The insulation materials of the magnet coils consists of partial organic materials.

The upper dose limit of materials

Materials	Upper dose limit in Gy
Acylic scintillator	10^2-10^4
Butyl rubber	5×10^4
Electronics components (active)	10^2-10^3
Optical fibre	10-10^2
Perfluoro ethylene-propylene	5×10^4
Phenolic resin, unfilled	10^4
Polyacryl (Plexiglas)	10^5
Polyamide (Nylon)	10^5
Polyester resin, unfilled	5×10^4
Silicone oil	5×10^5
Silicone rubber	5×10^5
Teflon (PTFE)	10^3
Viton	1-2×10^5
Araldite D (epoxy resin, cured at ambient temperature)	
Chlorosulfonated PE (Hypalon, CSP)	
Cross-linked PE (XLPE)	
Ethylene-acylate rubber (EAR)	
Ethylene-propylene rubber (EPR)	
Ethylene vinyl acetate (EVA)	
Flamtrol (polyolefin)	1-2×10^6
Halar (CTFE)	
Hytrel (PETP copolymer)	
Lupolen (PE)	
Polychloroprene (Neoprene)	
Polyolefin	
Polyvinyl chloride (PVC)	

Materials	Upper dose limit in Gy
Araldite B (epoxy resin)	
Araldite F (epoxy resin)	
Epikote (epoxy resin)	
Epoxy Novolac	
Epoxy resin, aromatic hardener	
Glass-fibre reinforced EPR-hoses	
Mineral oil	1-2×10^7
Paints based on epoxy or polyurethane resins	
Polyimide resin	
Special radiation resistant lubricants	
Special radiation resistant motors	
Cerium-doped glass	
Ryton (PPS)	
Inorganic filled resins:	
-Epoxy, aromatic hardener	
-Phenolic	1×10^8
-Polyester	
-Polyimide	
-Polyurethane	
-Silicone	
Aluminium oxide	
Magnesium oxide	
Metals	$>10^8$
Mica	
Glass fibre	
Quartz	

Theory and parameters

SR critical energy

$$E_c = 2.218\frac{E(GeV)^3}{\rho(m)}$$

SR Power

$$P(W/m) = 14.08\frac{E(GeV)^4 I(mA)}{\rho(m)^2}$$

SR spectrum

$$S\left(\frac{\omega}{\omega_c}\right) = 0.4652\frac{\omega}{\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(\eta)d\eta$$

Solid degree

$$\varphi = \frac{1}{\gamma} = \frac{m_0 c^2}{E}$$

Number of photons (Method 1)

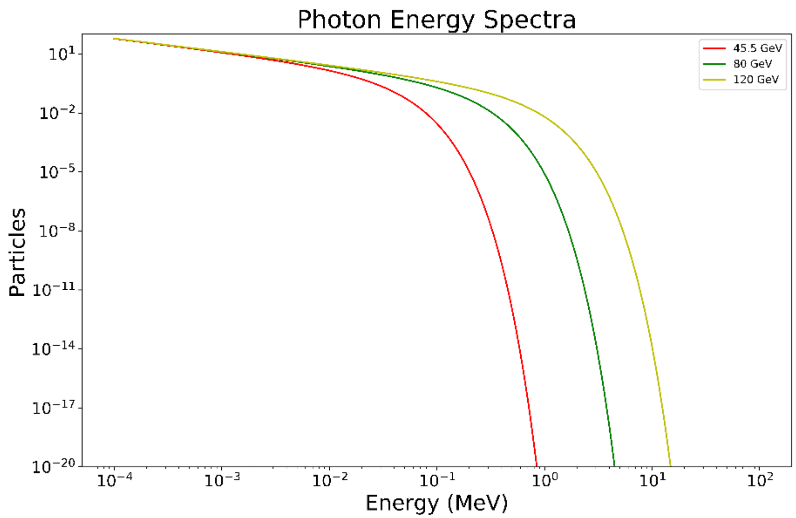
$$N_{photon} = \frac{P}{E_{ave}}\cdot t$$

Number of photons (Method 2):

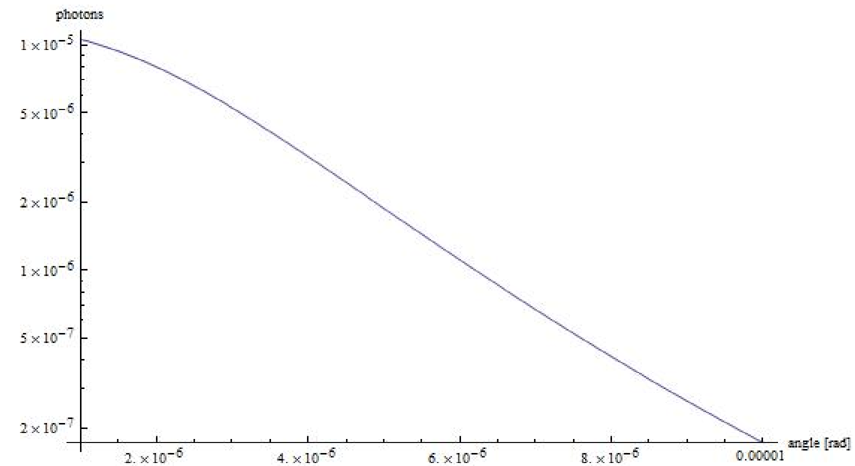
$$\frac{dN}{ds} = \int_0^{\infty} E_c\left(\frac{d^2N}{d\varepsilon ds}\right)dr =$$

$$3.936\left(\frac{E}{\rho}\right)\int_0^{\infty}\int_r^{\infty} K_{5/3}(\eta)d\eta dr = 19.4\frac{E}{\rho}$$

Theory and parameters



Energy spectrum distribution



Angular distribution

- The total number of photons emitted by an electron per metre and MeV.
- The results were crosschecked by a script written in Python and Mathematics.
- The lowest energy of incident photons is assumed to be 1 keV, and the energy spectrum is also the interval of 1 keV.
- The average energy of photons is 116 keV.

1st method: $2.363\times10^{16}m^{-1}s^{-1}$ 2nd method: $2.351\times10^{16}m^{-1}s^{-1}$

Theory and parameters

Parameters determining synchrotron radiation in CEPC

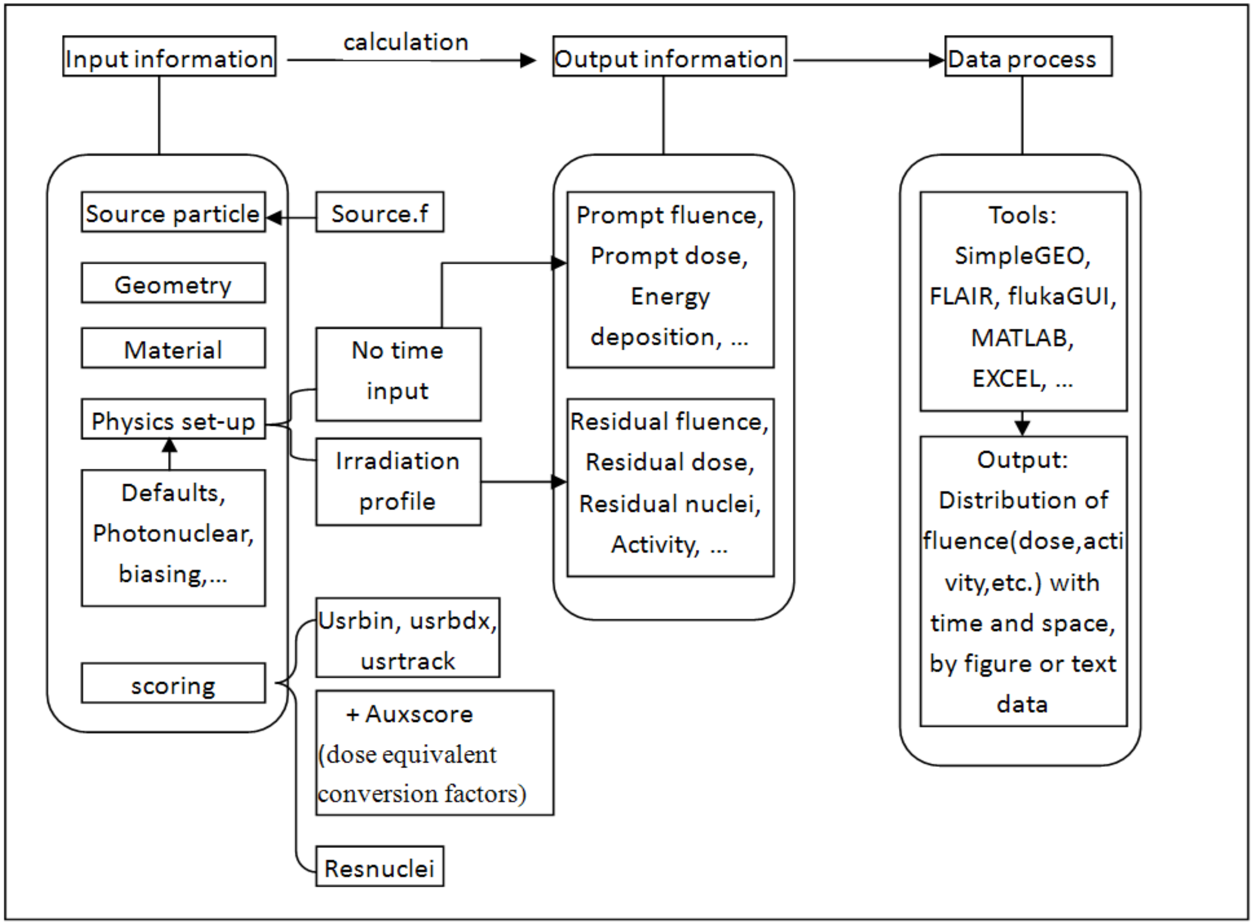
Parameters		CEPC energy in GeV		
		45.5	80	120
I (per beam)	mA	183.1	88.1	17.4
Critical energy	keV	19.7	107.1	361.6
Radiated power	W/m	98	435	435

Parameters of synchrotron radiation at 120 GeV

Parameters	Symbols	Values	Units
Beam energy	E	120	GeV
Beam current	I	17.4	mA
Bending radius	ρ	10600	m
Power per unit length	P	435	W/m
Critical energy	E_c	361.6	keV
Bending angle	θ	2.844	mrad
Opening angle	φ	4.258	μrad

Monte Carlo simulation

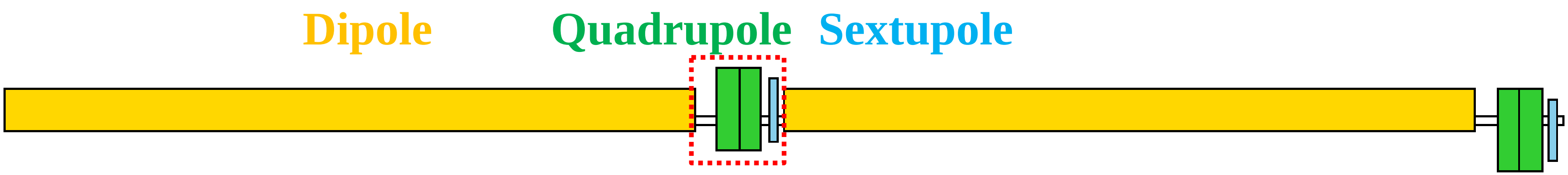
Universal Monte Carlo software：FLUKA MCNP

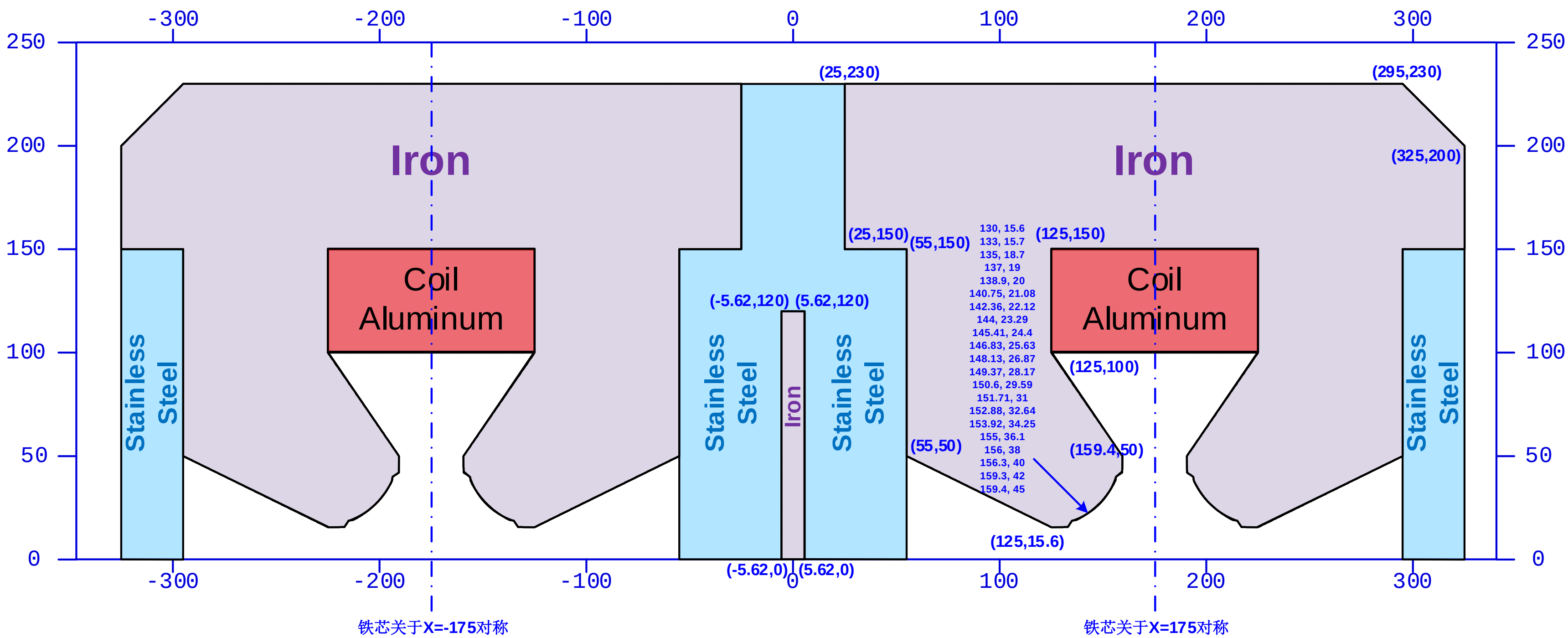


We have a standard procedure to calculate radiation by using FLUKA.

It is used to calculate prompt dose rate, residual dose rate, and activity.

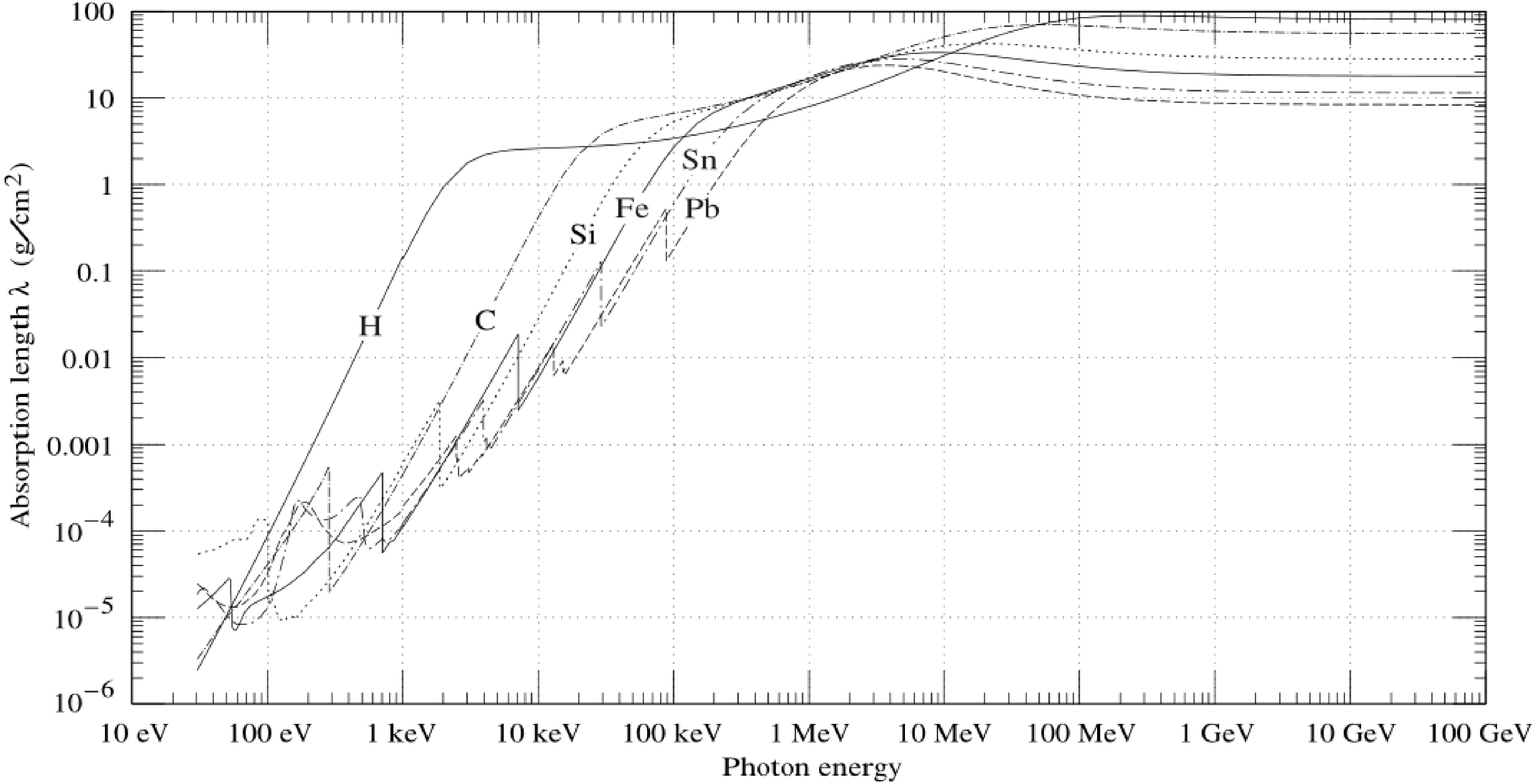
Magnets design





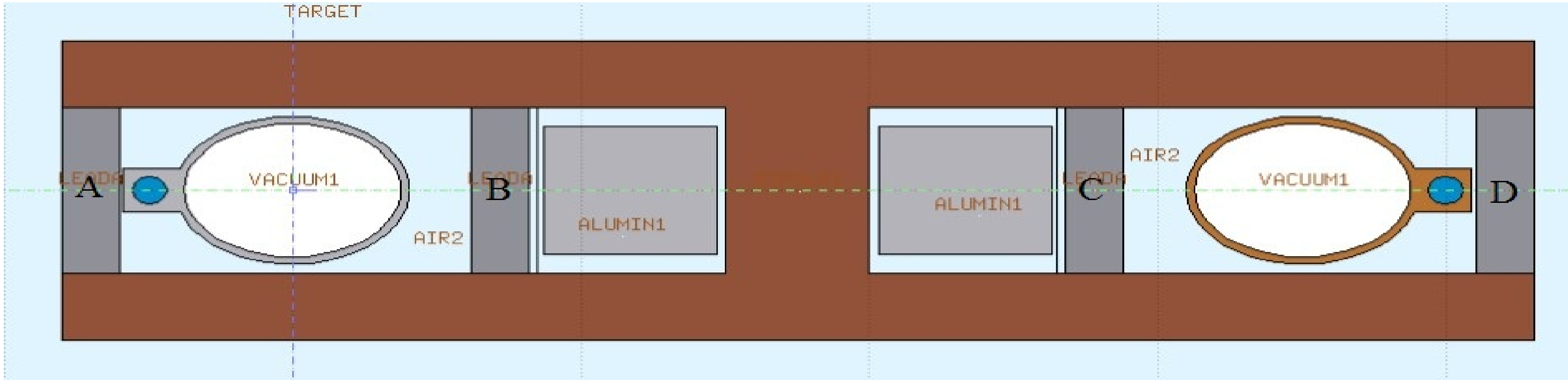
The thickness is only three millmeters, which is composed by aluminum or copper with a simple elliptical cross section, 75mm×56mm. The coils are exposed to radiation.

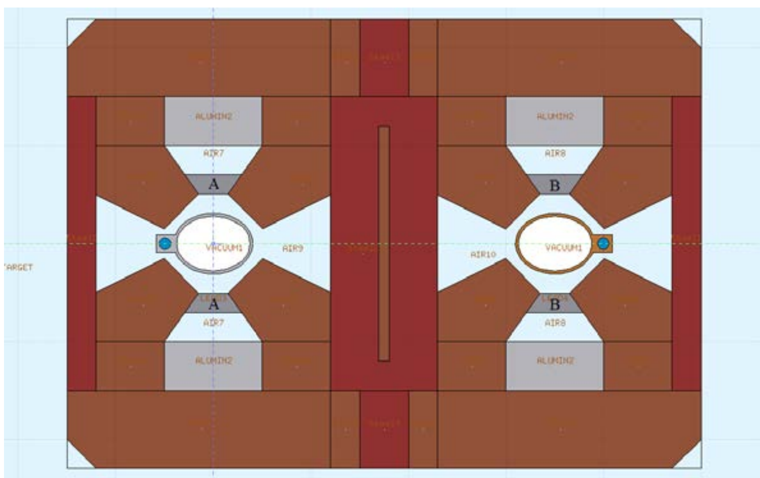
Photon attenuation length

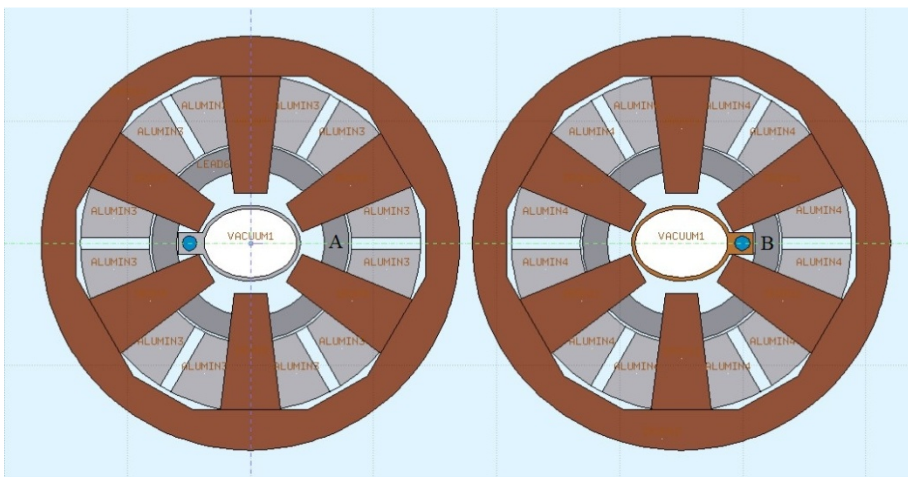


The photon mass attenuation length for various elemental absorbers as a function of photon energy. High energy photons in synchrotron radiation are difficult to shield. Lead is a good material, because it is cheap and has a high density.

Shielding design for magnets







Multiple pieces of 20 mm thick lead placed outside of vacuum chamber

To protect magnet coils from radiation damage

To prevent radiation and heat entering the tunnel

Energy deposition

Energy deposition in dipole without shielding

Beam direction: left W/m		Beam direction: right W/m	
Al chamber	199	Al chamber	186
Cu chamber	309	Cu chamber	332
Dipole	255	Dipole	252

Energy deposition in dipole with shielding

Beam direction: left W/m		Beam direction: right W/m	
Al chamber	199	Al chamber	186
Cu chamber	308	Cu chamber	332
Dipole	186	Dipole	182
Lead A	60.6	Lead A	29.2
Lead B	33.5	Lead B	80.0
Lead C	46.8	Lead C	18.8
Lead D	14.3	Lead D	20.4

The total power of synchrotron radiation is 870 W/m for two beam.
Radiation from bending magnets affects downstream quadrupole and sextupole.

Energy deposition

Energy deposition in quadrupole with shielding

Beam direction: left W/m		Beam direction: right W/m	
Quadrupole	279	Quadrupole	268
Lead A	37.8	Lead A	36.4
Lead B	18.1	Lead B	21.7

Energy deposition in sextupole with shielding

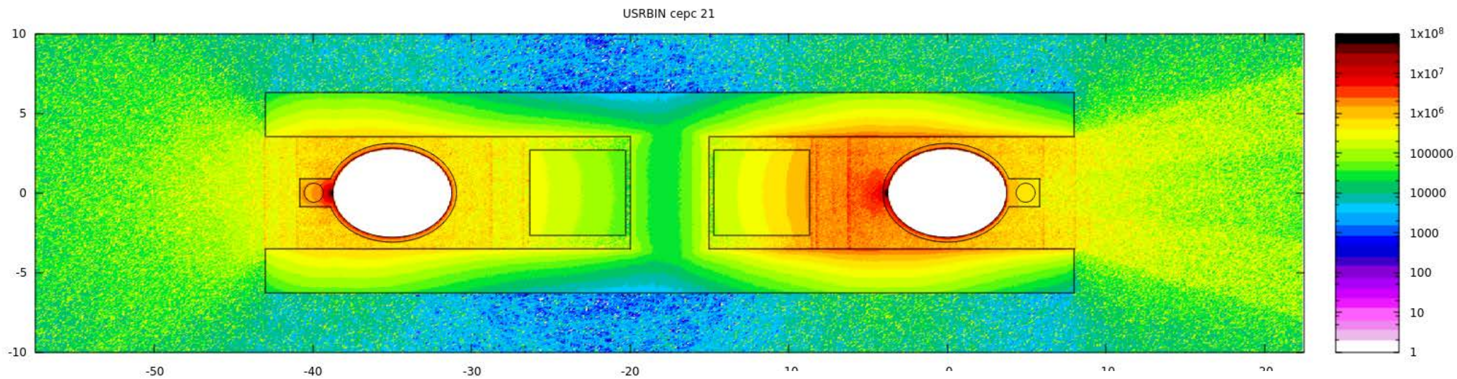
Beam direction: left W/m		Beam direction: right W/m	
Sextupole	179	Sextupole	174
Lead A	95.1	Lead A	107
Lead B	60.3	Lead B	43.1

Gap between the magnets with shielding

Beam direction: left W/m		Beam direction: right W/m	
Lead A	235	Lead A	248
Lead B	126	Lead B	102

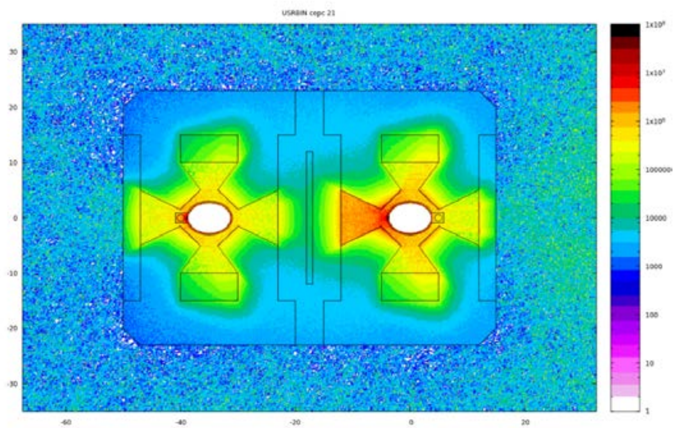
After shielding, less than 5% of radiation is directly into the tuntel.
This effectively reduces the radiation and the yield of harmful gases in the tunnel.

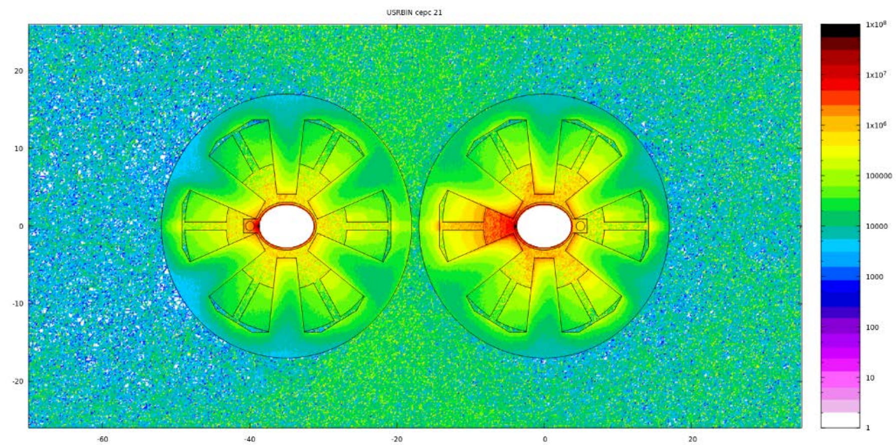
Radiation dose around the coils



Dose:
5.11E5 Gy/Ah

2.34E6 Gy/Ah



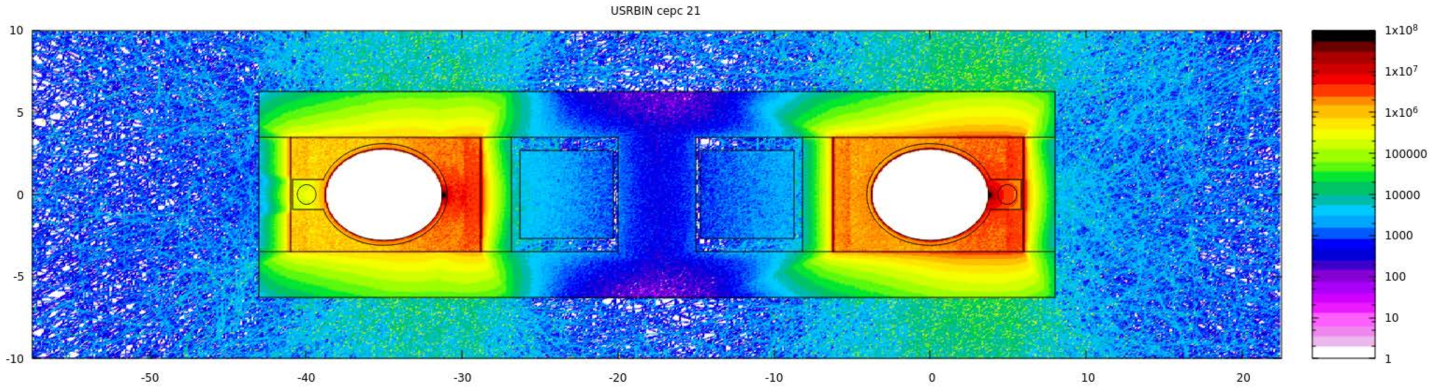


Dose: 3.27E5 Gy/Ah   4.69E5 Gy/Ah

Dose: 5.14E5 Gy/Ah   3.25E6 Gy/Ah

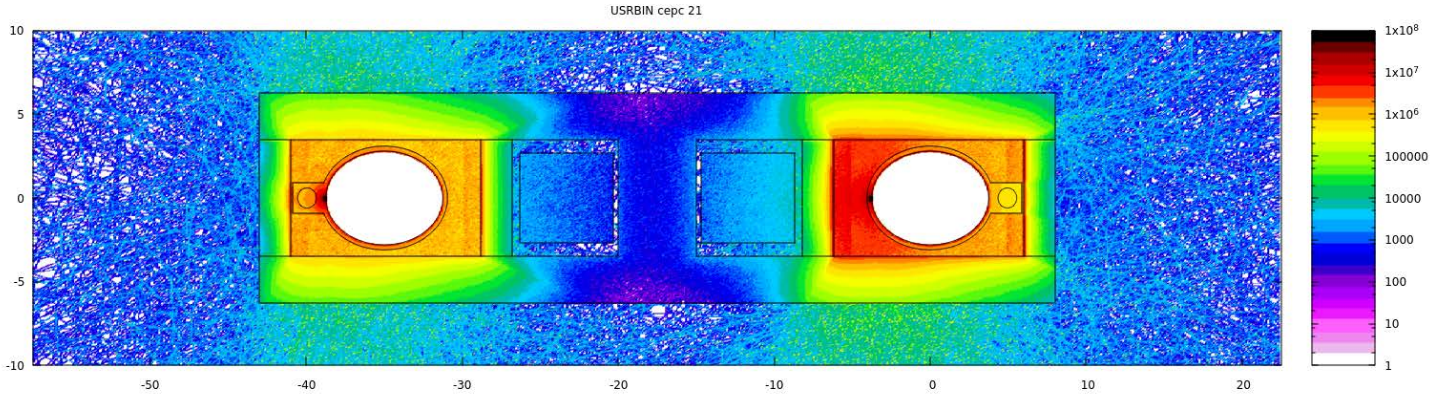
The dose distribution around the coils without lead shielding is simulated by using FLUKA program. The doserate is very high, the absorbed dose of the air is large.

Radiation dose around the coils



Max dose:
1.75E4 Gy/Ah

1.31E4 Gy/Ah

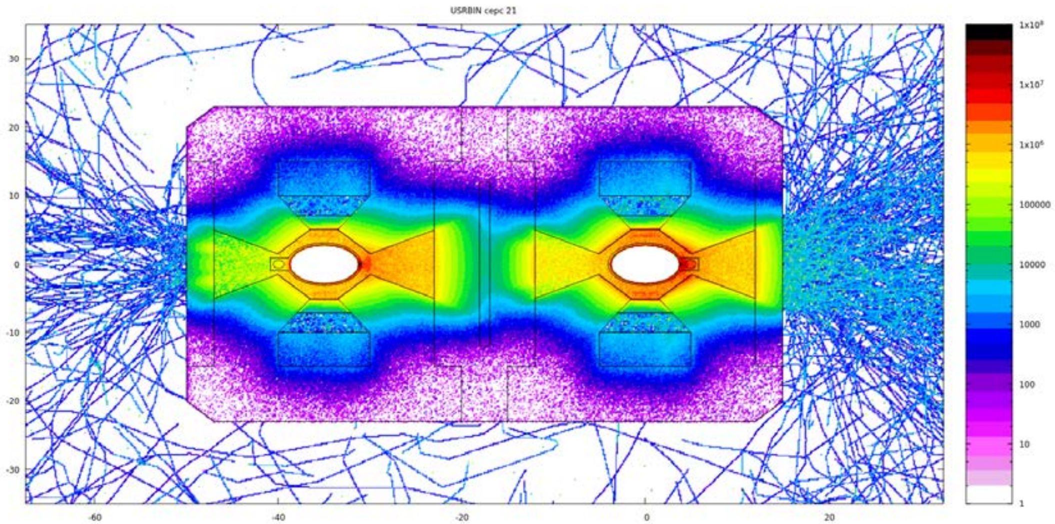


Max dose:
1.27E4 Gy/Ah

1.89E4 Gy/Ah

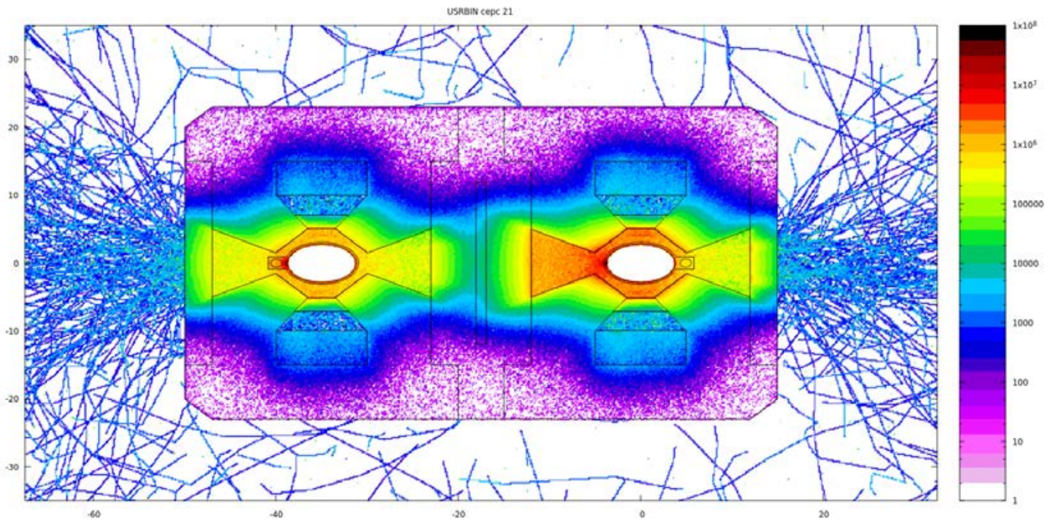
The dose distribution around the dipole coils with lead shielding in different beam directions.
This max dose means the maximum air absorbed dose between shielding and coil.

Radiation dose around the coils



Max dose:
0.51E4 Gy/Ah

0.73E4 Gy/Ah

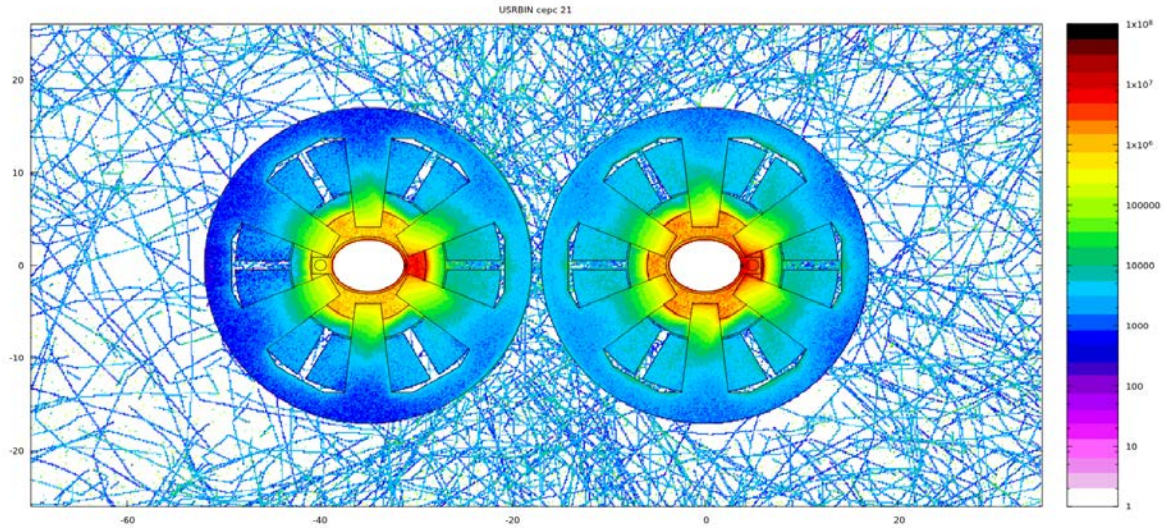


Max dose:
0.46E4 Gy/Ah

0.82E4 Gy/Ah

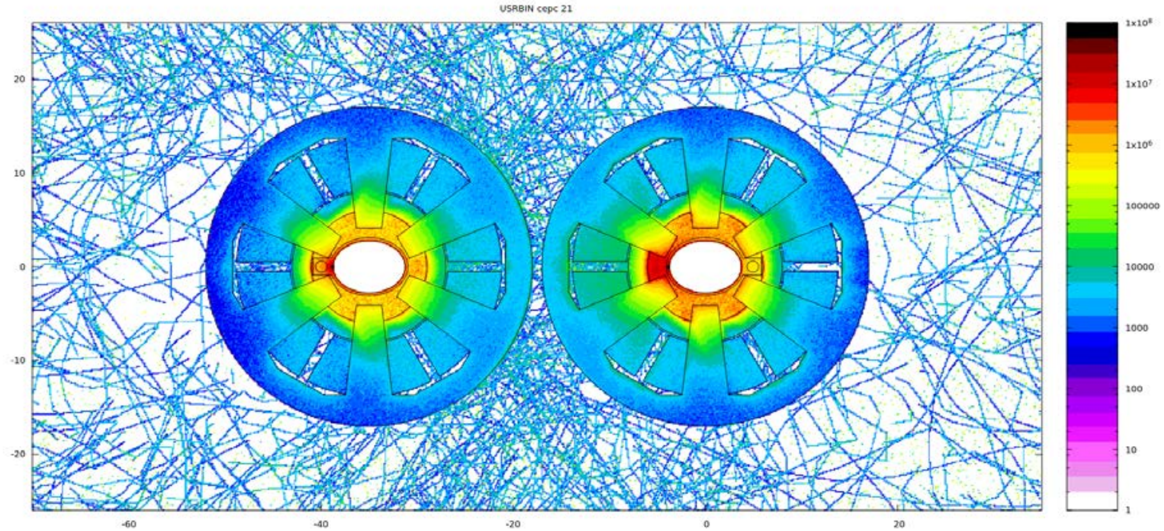
By adding shielding, the radiation dose around quadrupole is significantly reduced.

Radiation dose around the coils



Max dose:

0.23E4 Gy/Ah
1.25E4 Gy/Ah
1.11E4 Gy/Ah
1.67E4 Gy/Ah



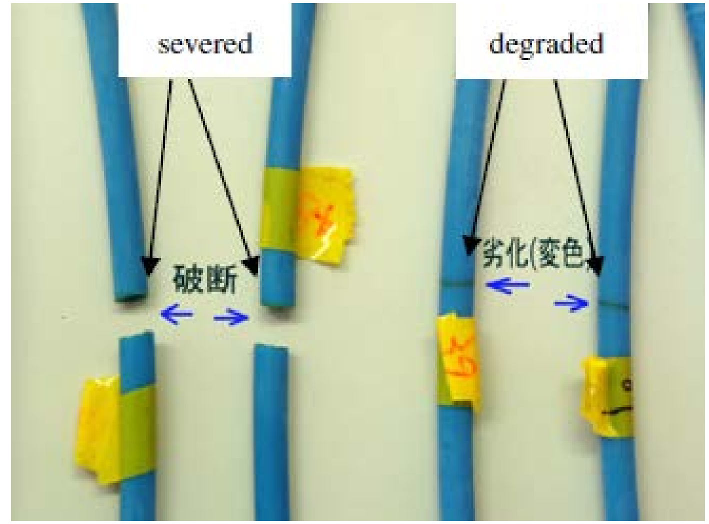
Max dose:

0.28E4 Gy/Ah
0.79E4 Gy/Ah
1.36E4 Gy/Ah
0.86E4 Gy/Ah

The radiation dose around sextupole coils does vary widely.

Radiation damage

Radiation damage research in LEP

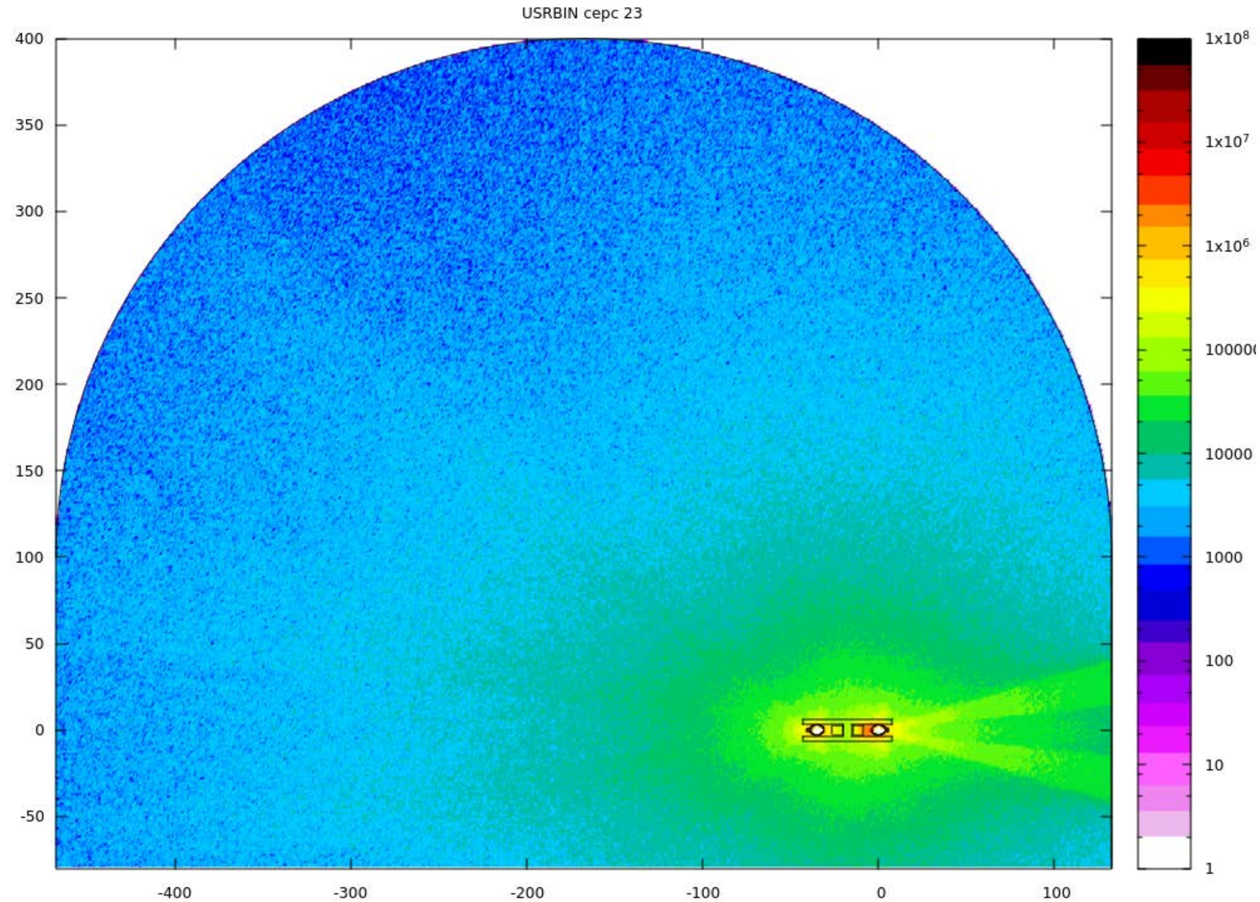


Cable severed and degraded in Spring-8

Lifetime for materials of magnets coils

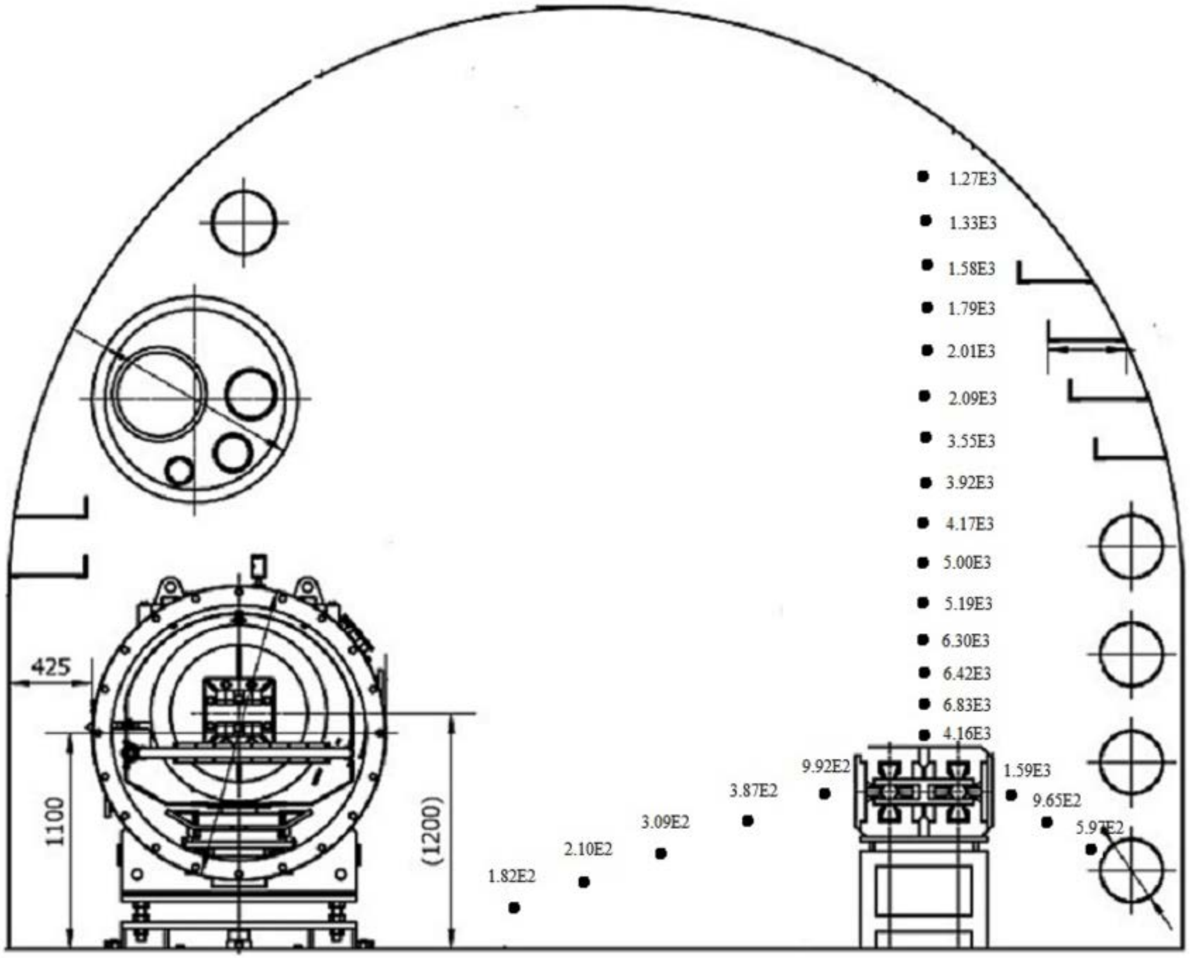
Materials	Upper dose limit in Gy	Radiation dose in Gy/Ah	Time in h
Fiberglass	10^8	1.89×10^4	2.99×10^5
Semi-organic coating	10^8	1.89×10^4	2.99×10^5
Epoxy resin	2×10^7	1.89×10^4	5.98×10^4

Radiation dose in the tunnel



Dose distribution in Gy/Ah at 120 GeV in a dipole section without shielding.
The radiation dose around specific equipment such as control electronics, control and instrumentation cable which came closer to the beam line has been estimated.

Radiation dose in the tunnel



Dose distribution in Gy/Ah at 120 GeV in a dipole section with shielding
Radiation dose of the other sections are lower than dipole section.

Neutron problem

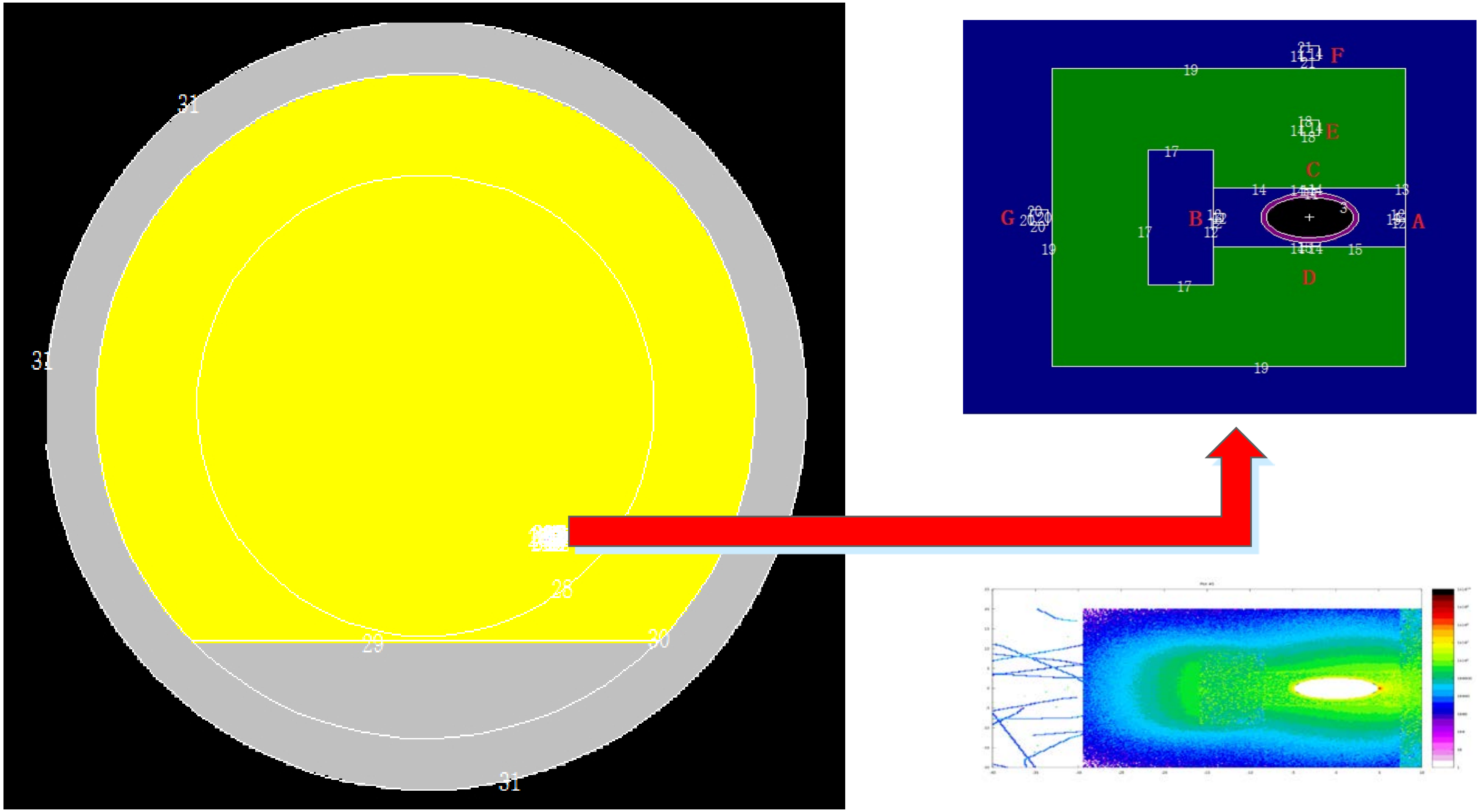
Properties of four accelerator materials

Materials	Iron	copper	Aluminium	Lead
Isotope abundance	Fe-56 91.8% Fe-54 5.8% Fe-57 2.1%	Cu-63 69.2% Cu-65 30.8%	Al-27 100%	Pb-206 24.1% Pb-207 22.1% Pb-208 52.4%
Melting point ℃	1538	1084	660.0	327.5
Photonuclear reaction threshold MeV	11.20 13.38 7.65	10.85 9.91	13.06	8.09 6.7 7.37
Thermal Conductivity W/m·K	68	401	237	35

$$\varepsilon = \frac{\int_{\omega}^{100} K_{5/3}(\eta)d\eta}{\int_{0}^{100} K_{5/3}(\eta)d\eta} \xrightarrow{\omega = \frac{6.7MeV}{E_c}} \varepsilon = 1.81 \times 10^{-5}$$

The share of high-energy photons could be calculated by the above formula.

Results from MCNP



A simple check between FLUKA and MCNP in Pre-CDR: S=54 km, R=6094 m, I=16.6 mA. Differences between the results do not exceed 10%.

Summary

- Lead is used as shielding material to protect the magnets, equ-ipments, cables. The simulated results could meet the require-ments of current main ring of CEPC.
- The parameters of synchrotron radiation are calculated. They are used as radiation items to complete simulation.
- The results calculated by FLUKA are consistent with MCNP's.
- There still has a space for luminosity upgrade.
- We will consider influence of magnetic field in the future.
- Further optimization is undergoing.

Thanks for your attention！