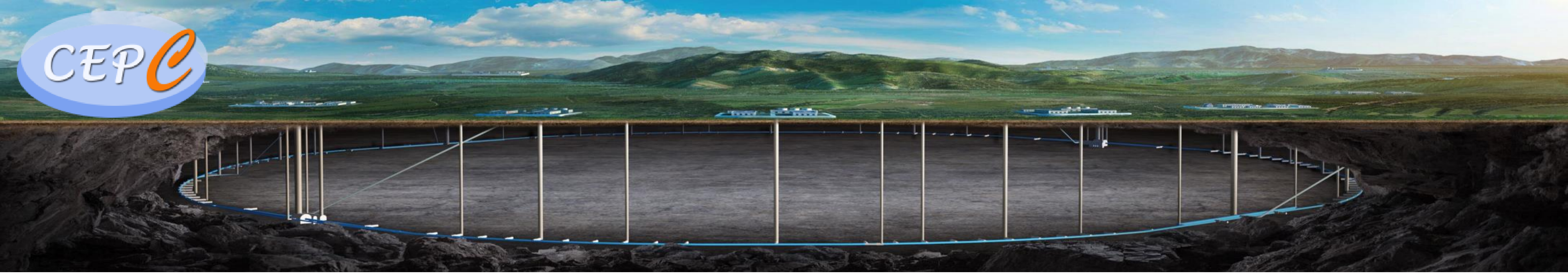

CEPC radiation protection and beam dumps

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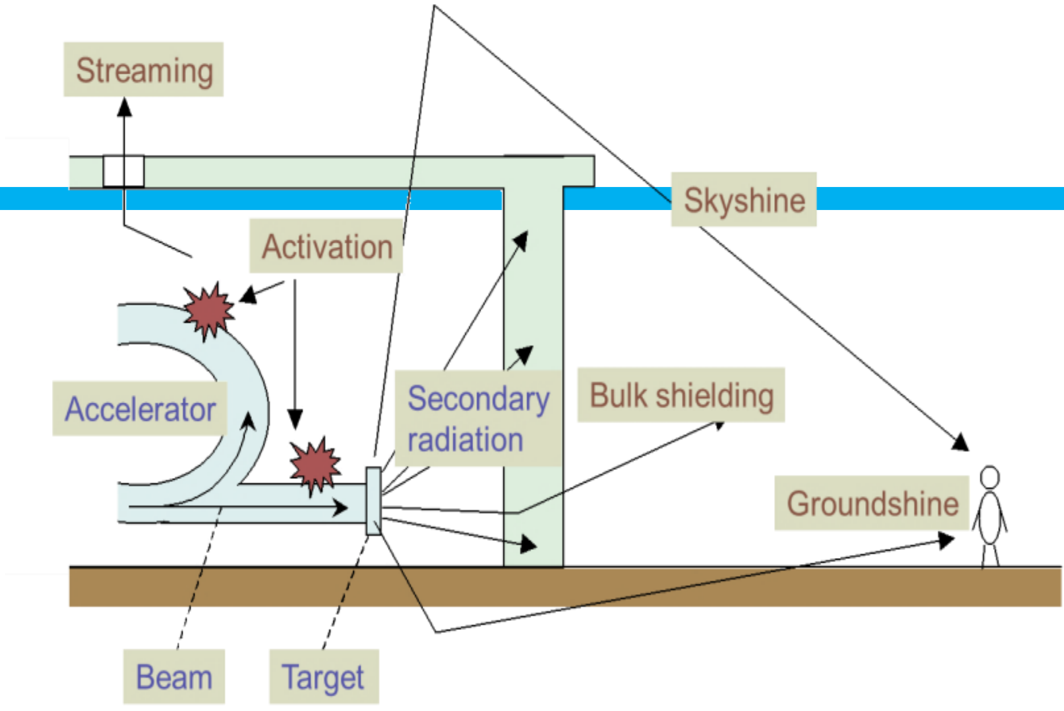
Chinese Academy of Sciences

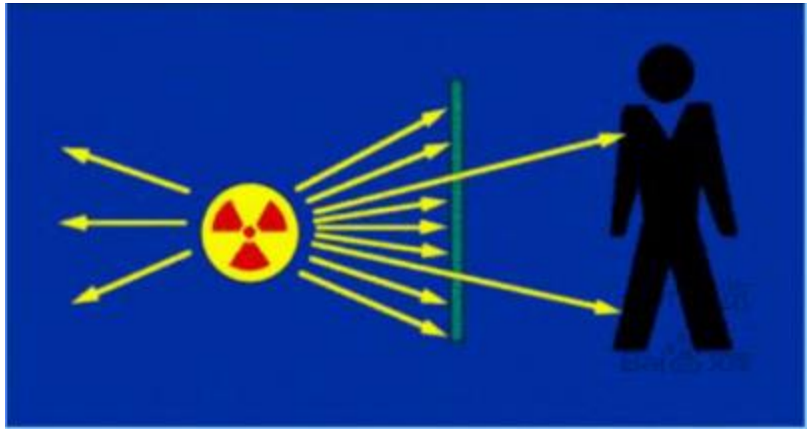
Content

- Introduction
- Synchrotron radiation shielding
- Radionuclide production estimation
- Collider dump design
- Linac hot spots and beam losses shielding
- Environment, health and safety
- Summary and outlook

RP concepts

- Source:
  - beam, target (hot spot), synchrotron radiation, ...
- Radiation can cause damage to equipment and pose risks to health.
- How to estimate the damage:
  - For material: absorbed dose, unit: Gray (Gy)
  - For health: personal/ambient dose equivalent, unit: Sievert (Sv)
- How to reduce radiation damage:
  - Shorten exposure time
  - Increase distance
  - Shield
    - High Z: iron, lead, tungsten, ...
    - Hydrogen-containing: water, paraffin wax, ...





Shielding Design Criteria

- Basic Rules of Radiation Protection
  - Justification, Optimization, Limitation
- Constrains:

  Individual dose for worker:
  - < 2.5 uSv/h (working 2000 hours)

  Induced radioactivity:
  - (Specific) activities of isotopes in Chinese mandatory standard GB18871
  - Empirical constrain: prompt dose equivalent < 5.5 mSv/h

  Toxic gases:
  - O_3 < 160 ug/m^3
  - NO_2 < 40 ug/m^3.

  Collective dose limits
  - site dependence

- Annual individual dose limit adopted by different owners

Owners	Public	Radiation workers	
		B	A
Eu-Directive	< 1 mSv/year	< 6 mSv/year	< 20 mSv/year
CERN from 2004	< 0.3 mSv/year	< 6 mSv/year	< 20 mSv/year
China	< 1 mSv/year	< 20 mSv/year	
IHEP	< 0.1 mSv/year	< 5 mSv/year	

Radiological Impact

- Main consideration aspects

Impact factors		Characteristics
Prompt radiation	Synchrotron radiation	Radiation damage to magnets coils, electronics; Over heat load to ventilation system; Formation of ozone and nitrogen oxides in the air; Slightly activation to the material around;
	Random beam loss	Cause secondary radiation inside/outside the tunnel; Determine the bulk shielding thickness;
	Hot spot	MDI, collimators, collider/linac dumps, injection/extraction points;
Radiological impact on environment (induced radiation)		Dose from stray radiation emitted during machine running Radionuclides in the cooling water, underground water, tunnel air, soil/rock. Radioactivities in the solid components and waste

Radiological Impact

<table>
<tr><th>sector</th><th colspan="2">Impact factors</th><th>Optimize/estimate</th></tr>
<tr><td rowspan="4">Linac</td><td rowspan="3">Prompt</td><td>Random beam losses</td><td>Bulk shielding</td></tr>
<tr><td>Hot spots (dumps, positron target)</td><td>Local shielding</td></tr>
<tr><td>Toxic gases</td><td>Production estimation</td></tr>
<tr><td colspan="2">Induced: radioactive isotopes</td><td>Production estimation: in the air</td></tr>
<tr><td rowspan="5">Collider + Booster</td><td rowspan="4">Prompt</td><td>Random beam losses</td><td rowspan="3">Local shielding</td></tr>
<tr><td>Synchrotron radiation</td></tr>
<tr><td>Hot spots(dumps, collimators, MDI)</td></tr>
<tr><td>Toxic gases</td><td>Production estimation</td></tr>
<tr><td colspan="2">Induced: radioactive isotopes</td><td>Production estimation: in the air/water/environment</td></tr>
</table>

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- Introduction
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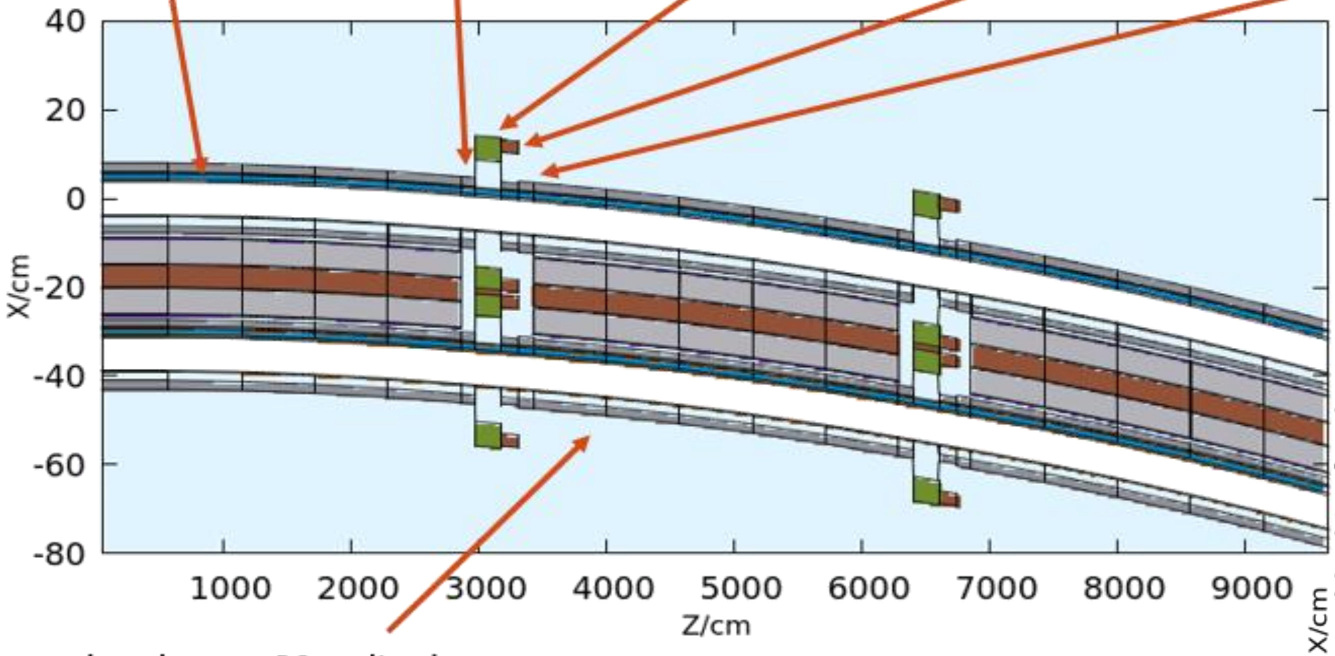
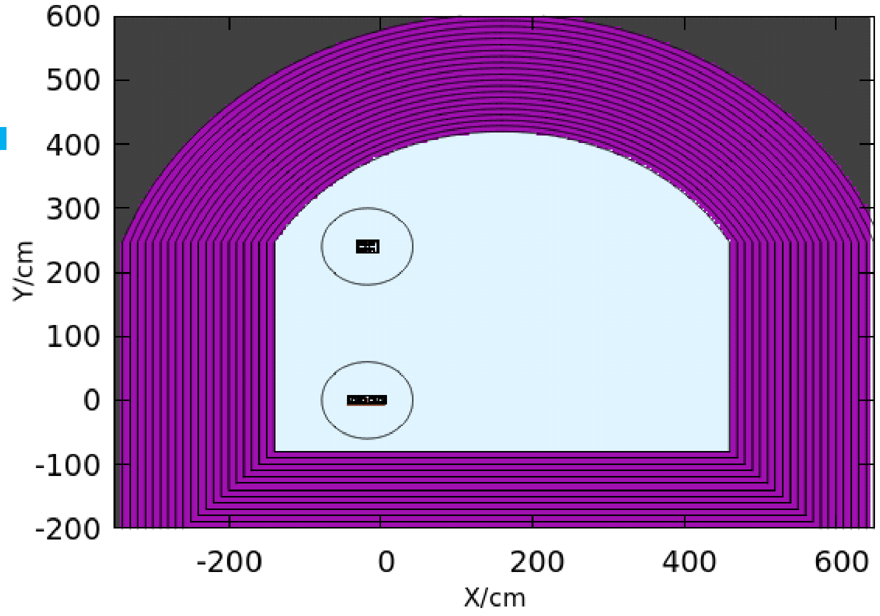
Simulation Setup

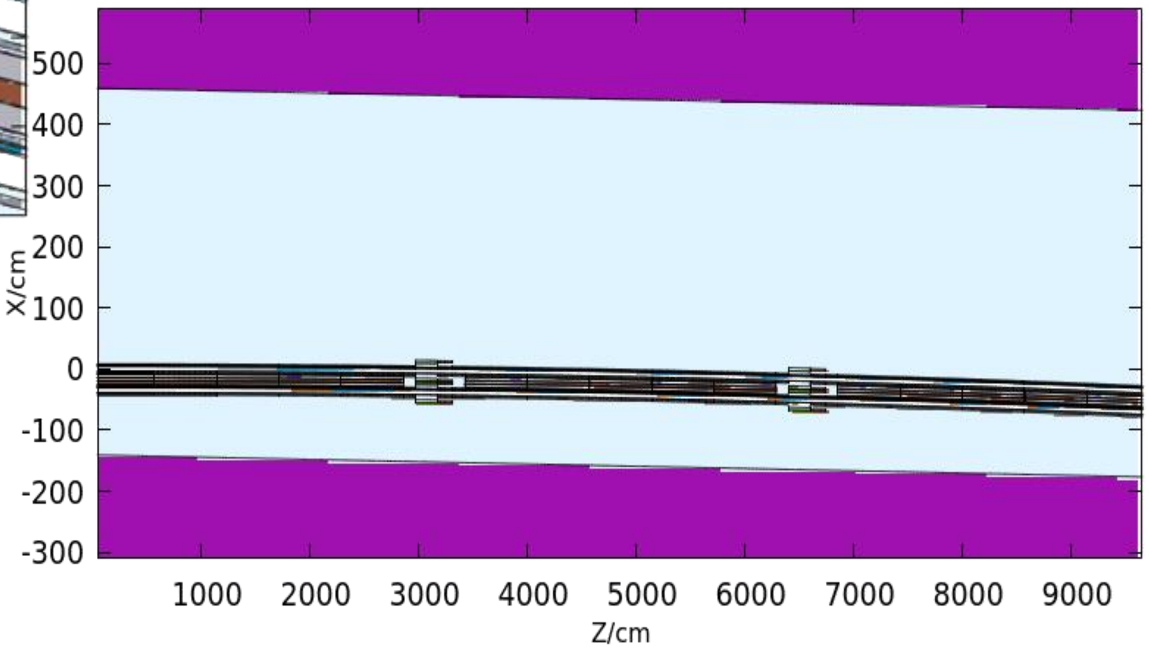
- Tunnel geometry

▪ 28m dipole -> 1.1m drift chamber -> 2m quadrupole -> 1.4m sextupole -> 1.1m drift



chamber -> 28m dipole -> ......

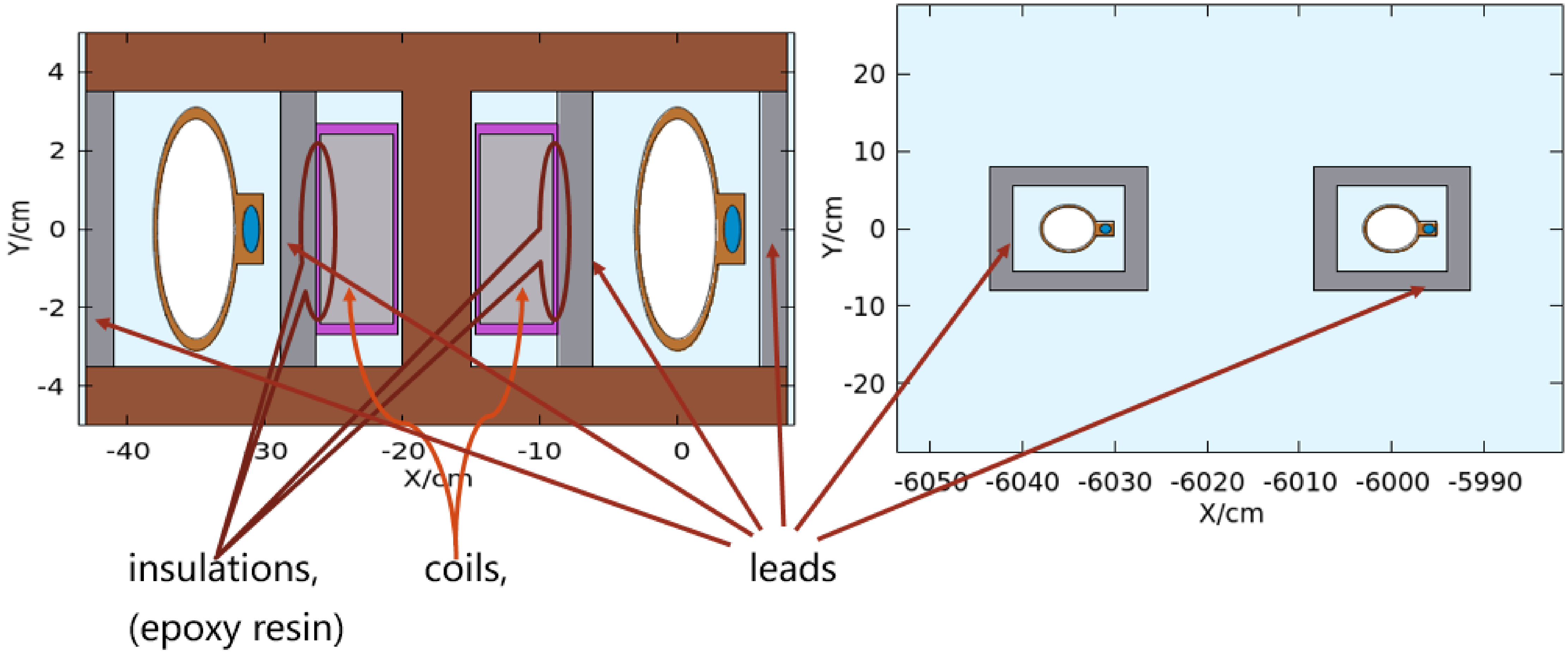




- Length: 100m
  - 3 dipoles;
  - 2 quadrupoles;
  - 2 sextupoles;

Simulation Setup

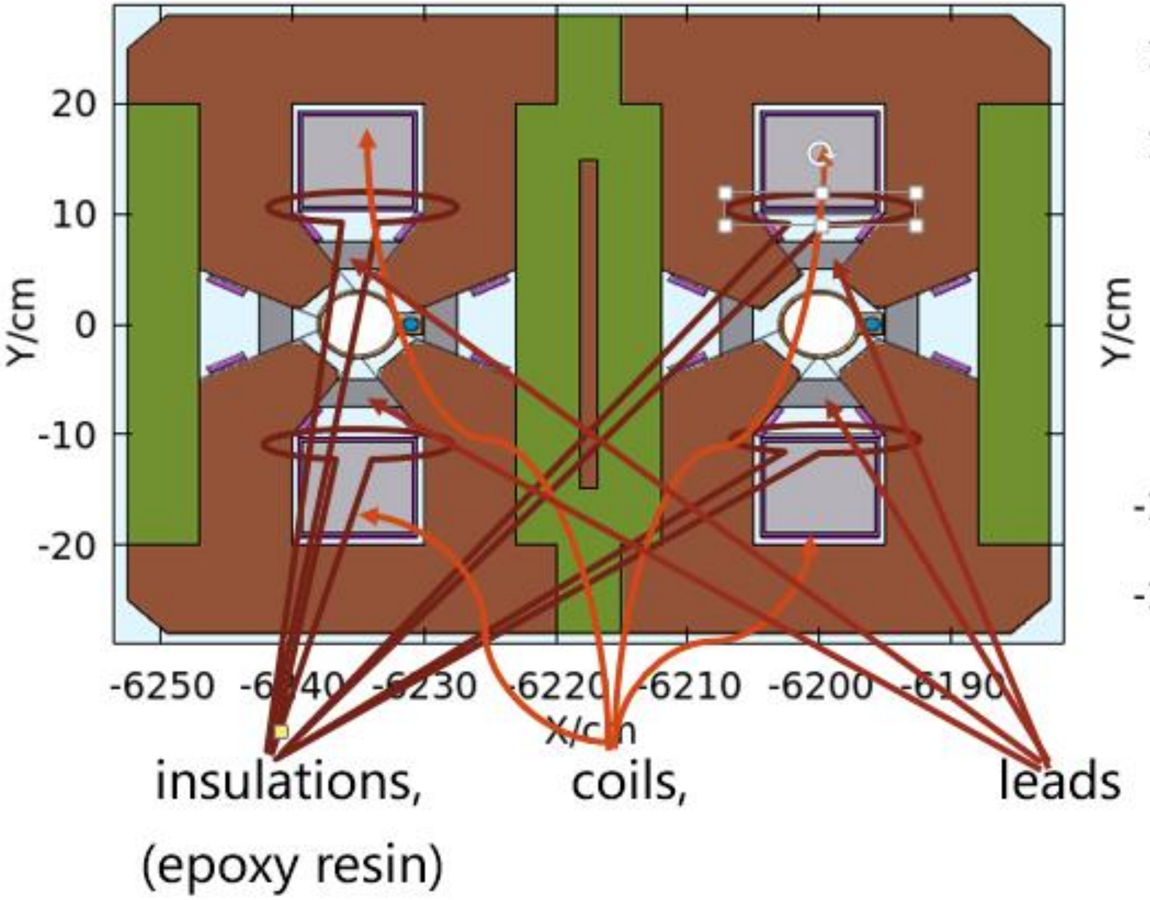
- Dipole
- Drift chamber



- Insulations is added in the model. Both beam-pipes are made of copper.
- In the cross-section, area of lead: $70cm^2$
- Area of lead: $270cm^2$

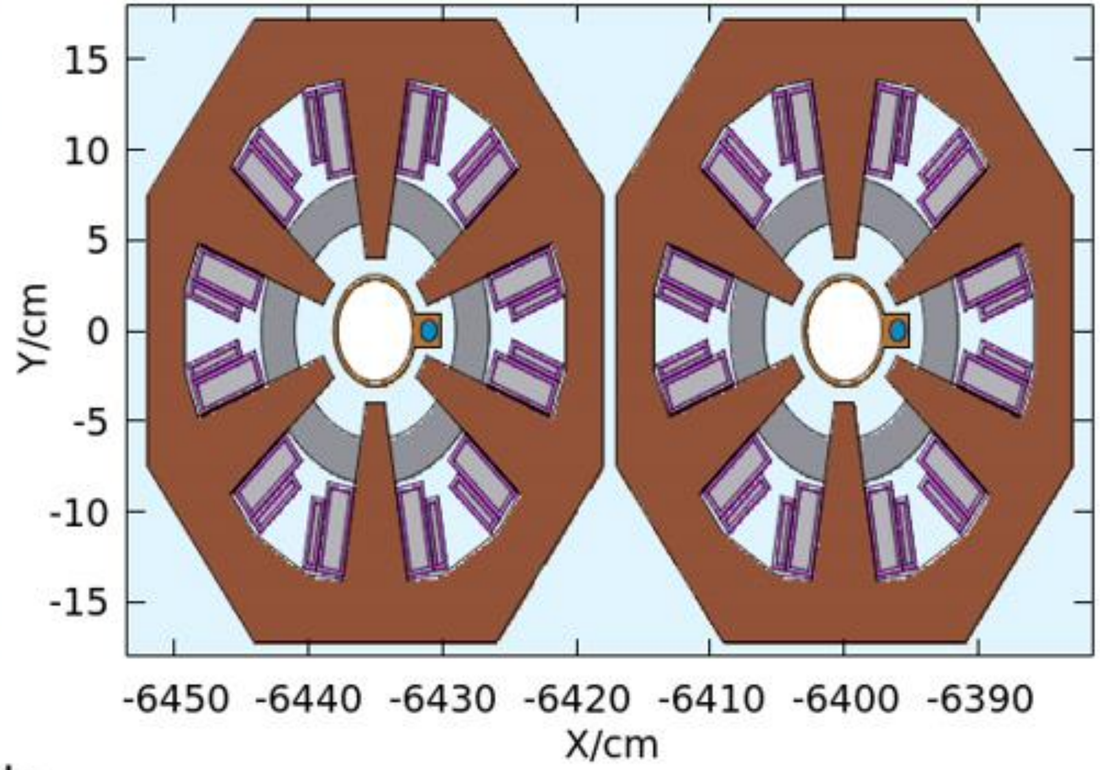
Simulation Setup

- Quadrupole



- Area of lead: $140cm^2$

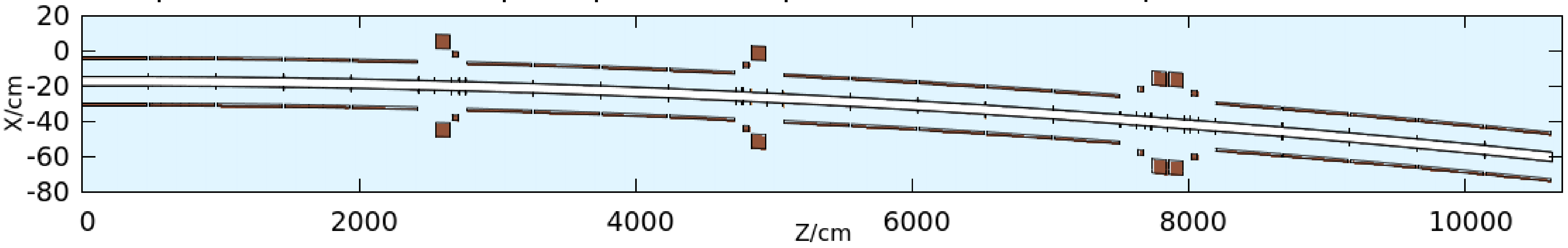
- Sextupole



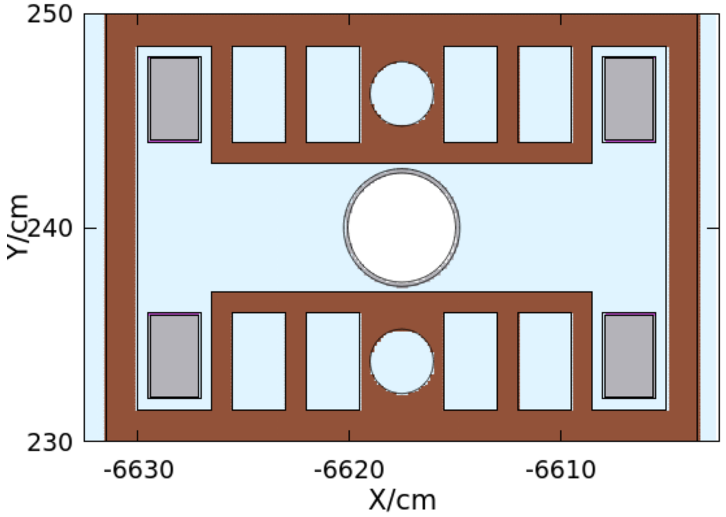
- Area of lead: $270cm^2$

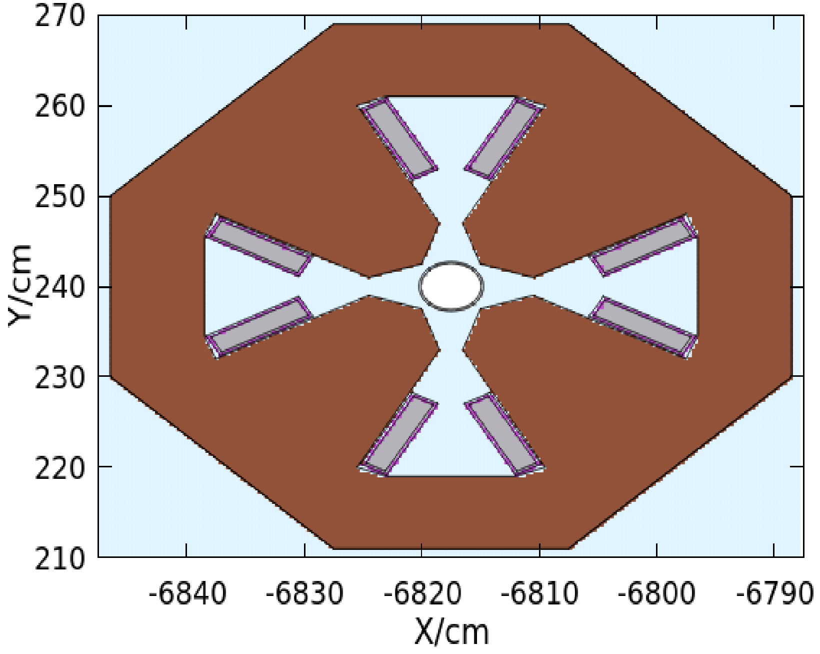
Booster

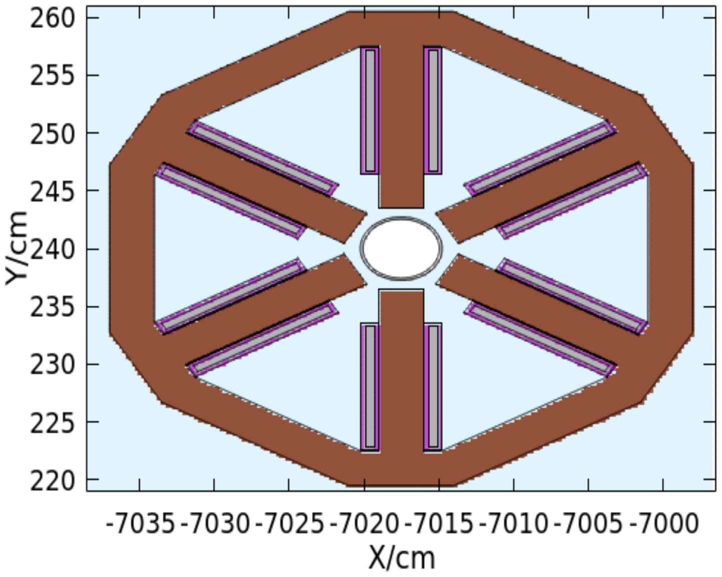
- dipole ->drift chamber ->quadrupole -> sextupole ->drift chamber ->dipole …



- Magnets







Parameters: 50MW

- Collider

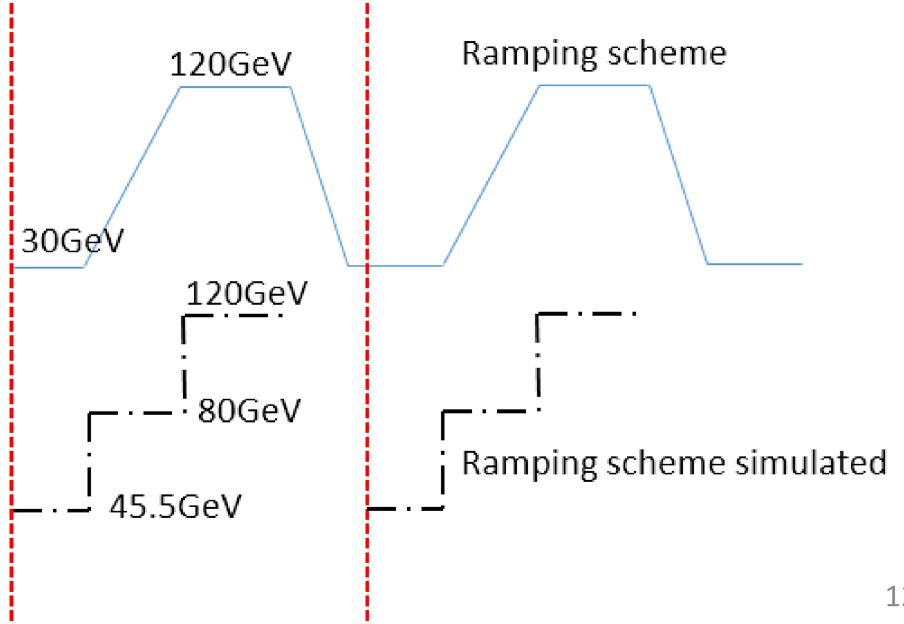
	Higgs	WW	Z	ttbar
Beam energy/GeV	120	80	45.5	180
Ne/bunch/10^{10}	14	13.5	14	20
Number of bunches	415	2162	19918	58
Number of photons/114m	4.7e18	1.6e19	8.4e19	1.4e18

- The ramping simulation is more critical than reality.
  - Overestimate dose to booster

- Booster

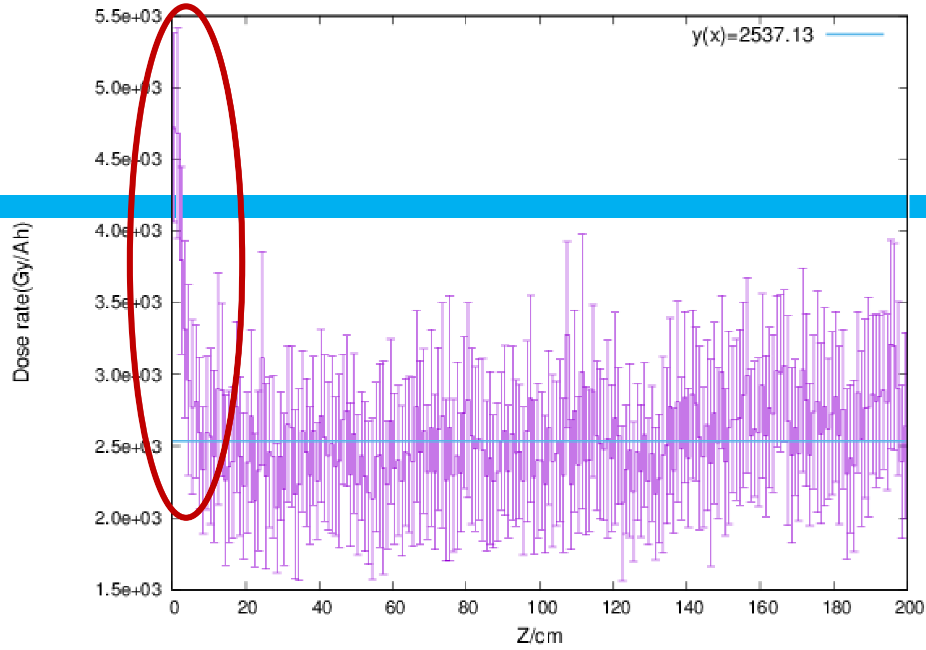
	Higgs	WW	Z	ttbar
Current(mA)	1	2.69	14.4	0.12
Injection duration(s)	32.8	39.3	134.7	30
Injection interval(s)	38	155	153.5	65

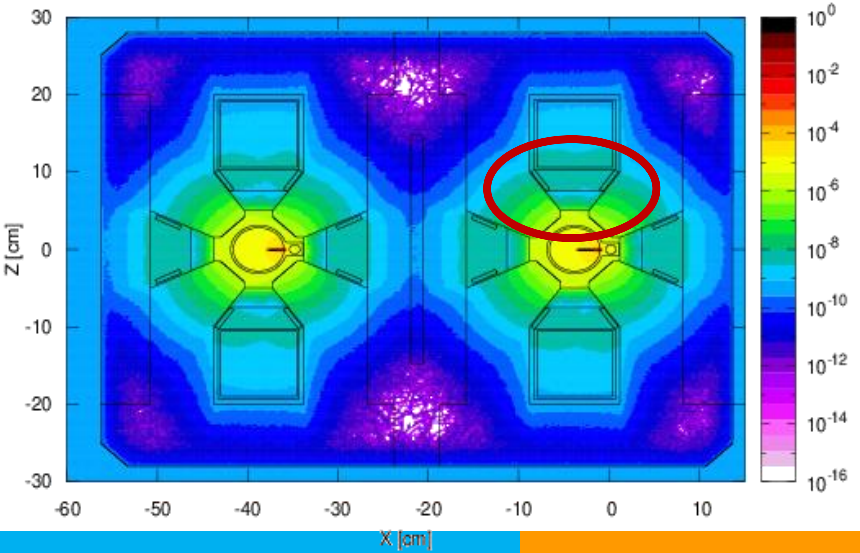
- Ramping simulation: example @Higgs

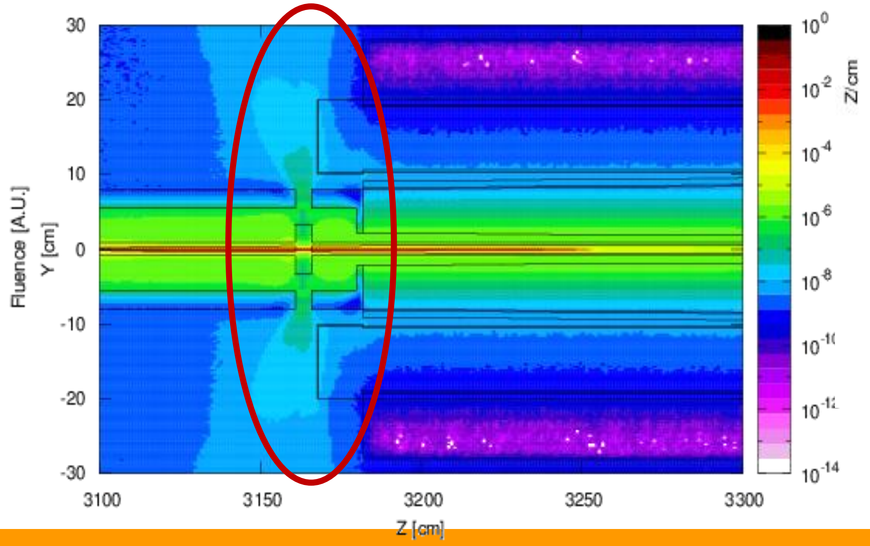


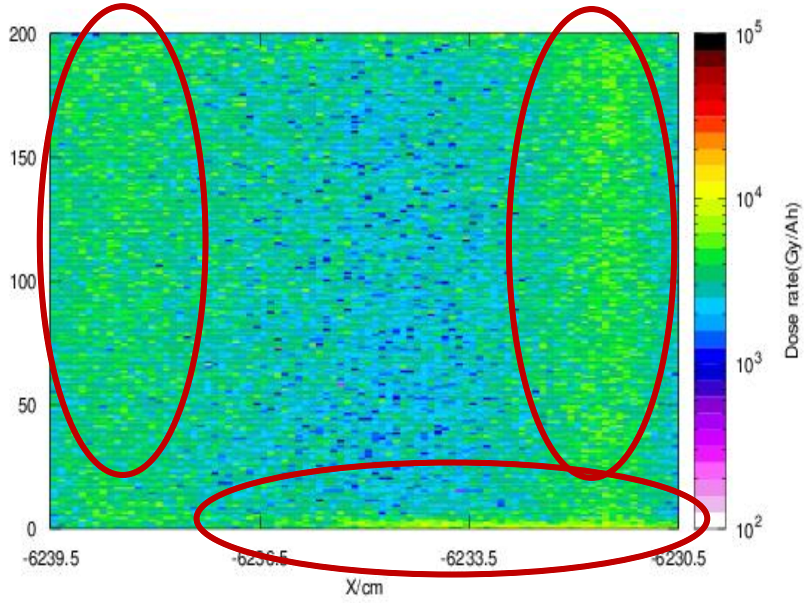
Dose to Insulations

- Dose values are equal in middle of magnet, not in both ends of magnet.
- “Hot spots” in insulation because:
  - The shielding between magnets are not designed well.
  - SR hits the iron close to beam pipe and bypasses lead.
- Hot spots shielding will be considered in next stage.
- Dose in uniform regions are summarized in the following pages.



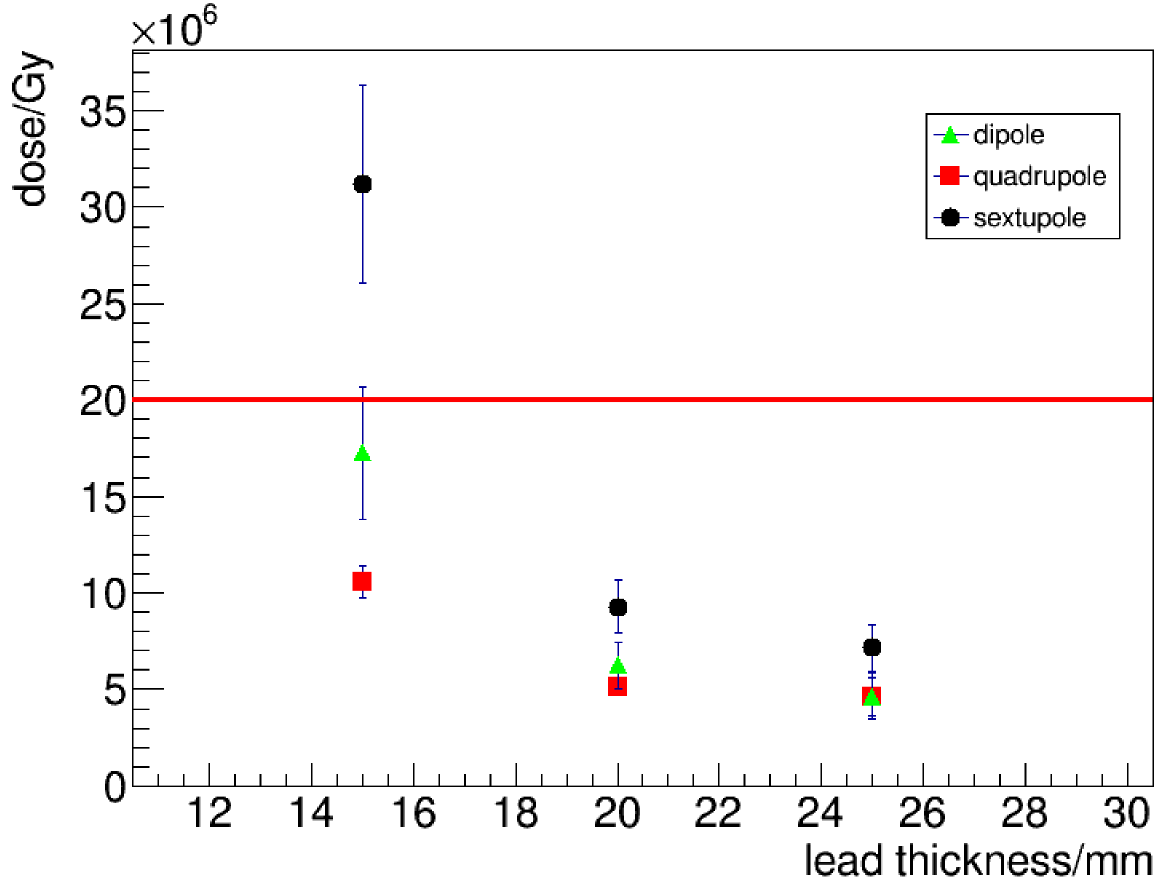






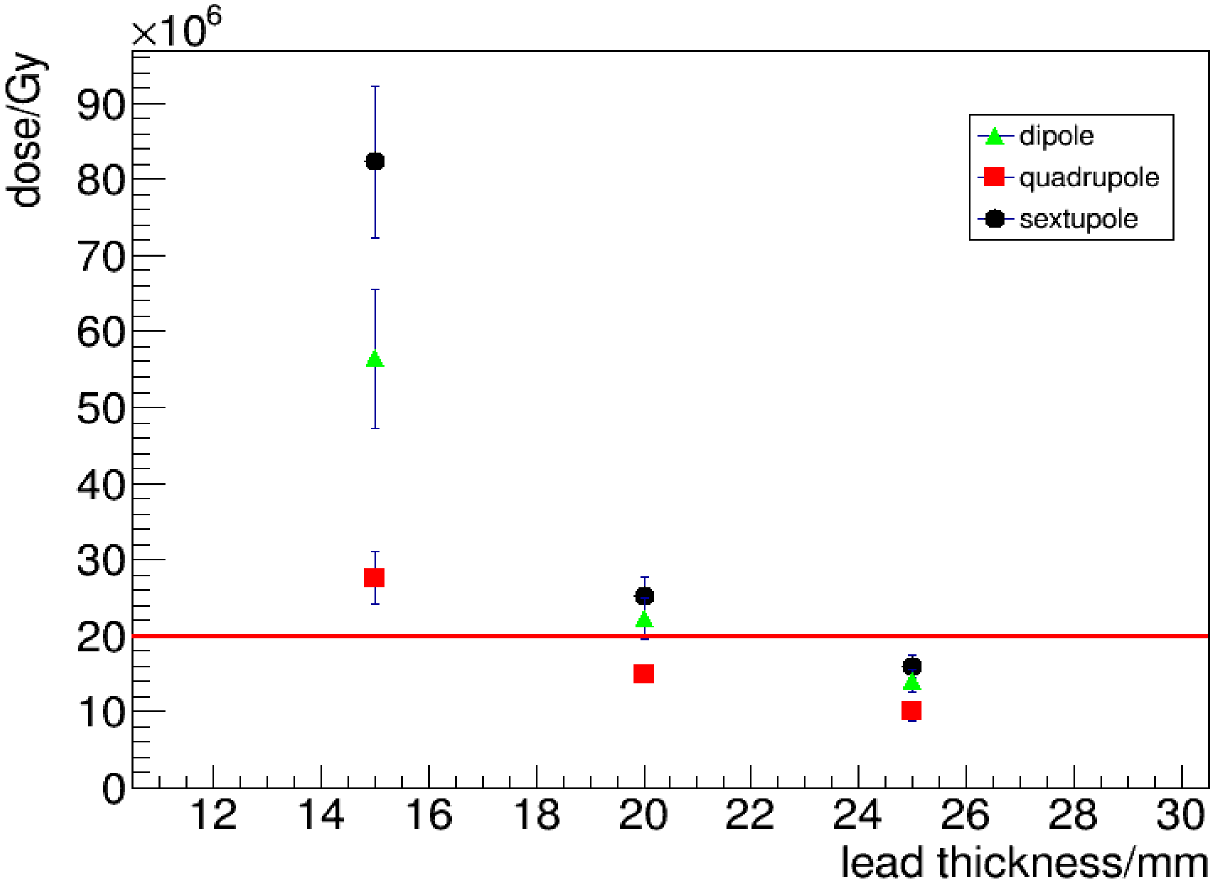
Dose vs Lead Thickness: 50MW

- While running @Higgs/Z/WW (13 years),



  - Possible to reduce 2cm lead if no ttbar run;

- While running another 5 years @ttbar

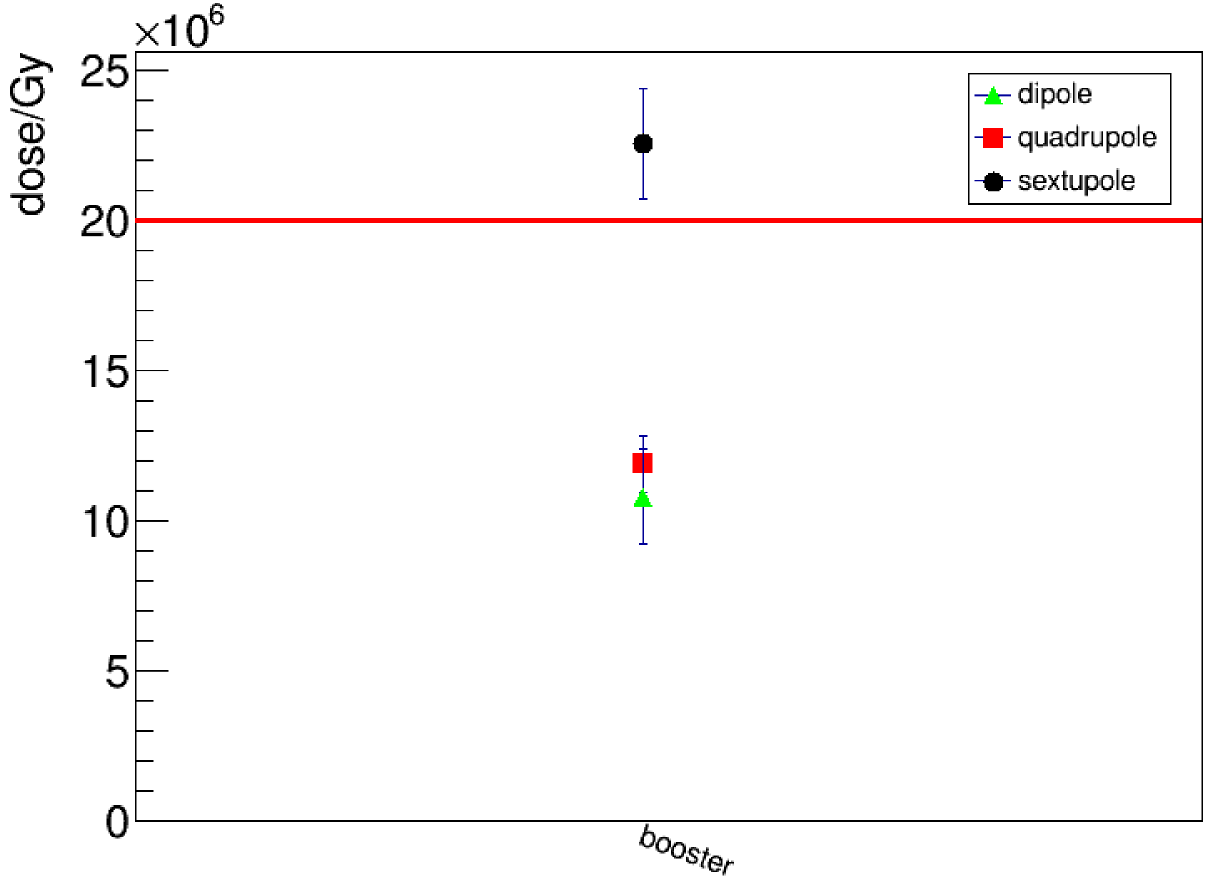


  - 2.5cm lead is needed for dipole, quadrupole and sextupole.

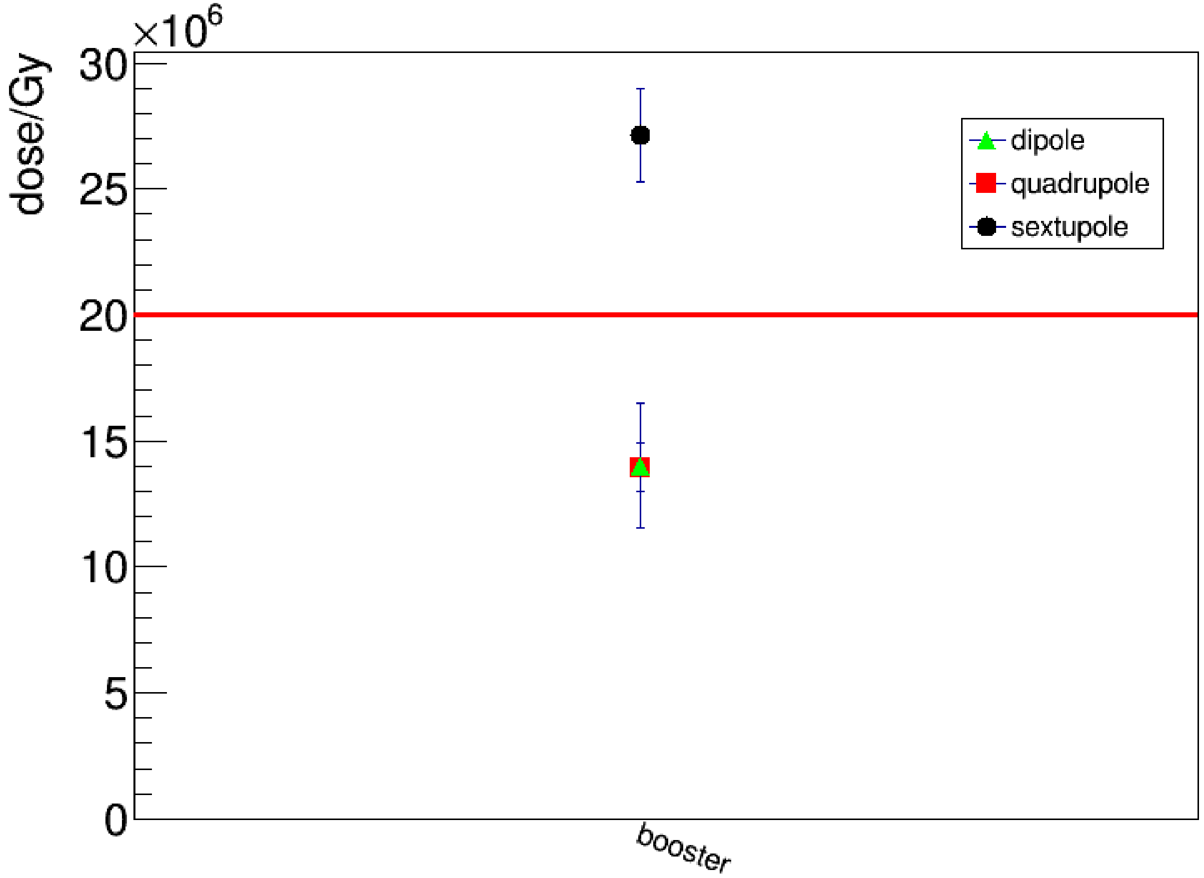
- Lead thickness is constrained by the operation schedule.

Dose to Booster Insulations: 50MW

- While running @Higgs/Z/WW (13 years),



- While running another 5 years @ttbar



- The dose to dipole and quadrupole is smaller than upper limit based on our simulation scheme.
- Maybe local shielding for sextupoles: iron/lead sheets.
- We will simulate more precisely, with accurate time scheme and beam energy.

Electronics in the tunnel

- Dose and 1-MeV neutron equivalent fluence in the tunnel
- Electronics in the tunnel and auxiliary tunnel should be protected.
  - Magnet and kicker powers, BPMs, vacuum pumps
- The labyrinth and shielding doors are designed at the entrances of auxiliary tunnels. Lead and organic materials (polyethylene or paraffin wax) would be put around the electronic cabinets.

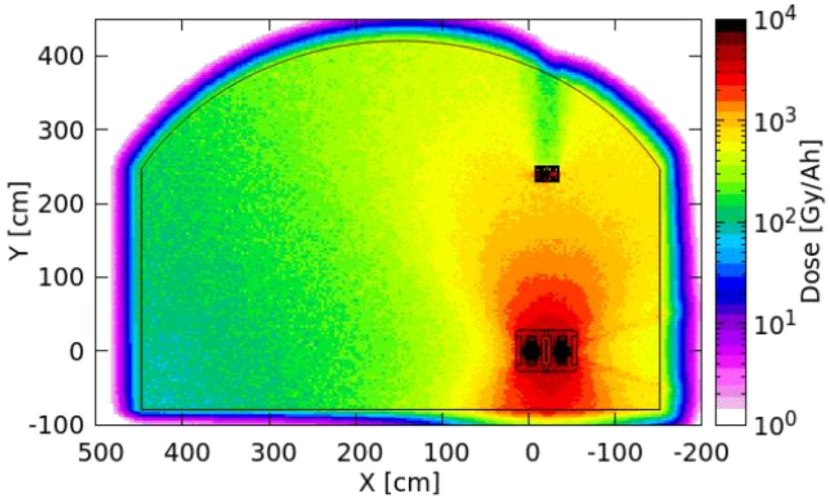


Figure 4.2.4.18 Absorbed dose distribution in the tunnel.

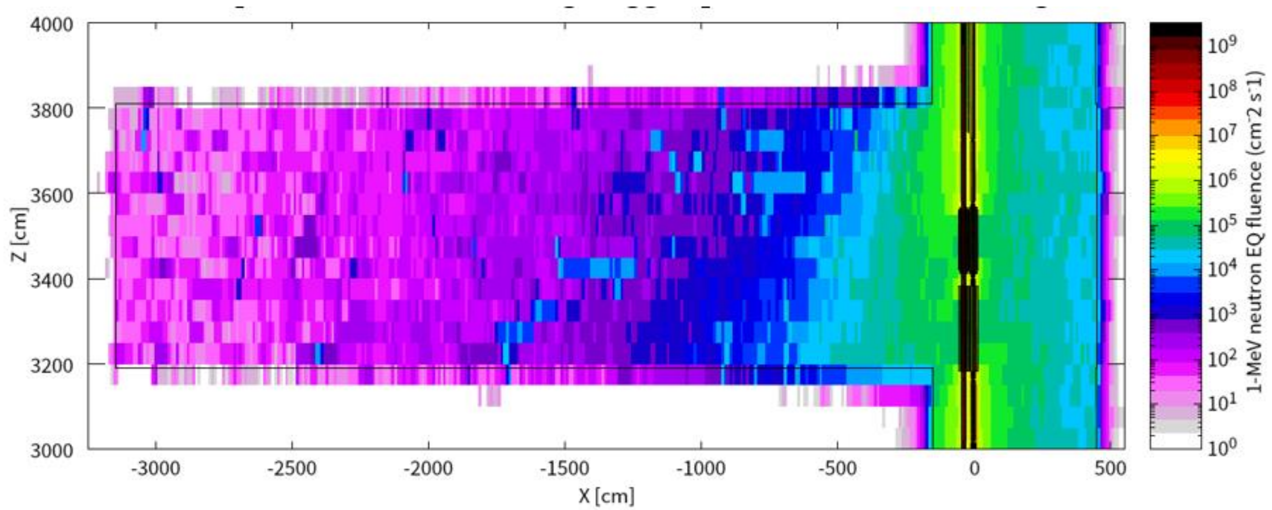


Figure 7.3.7: The 1−MeV neutron equivalent fluence in the tunnel and the nearby auxiliary tunnel.

Radionuclides Simulation

- Lost beam & SR photon of energy >6MeV

		Higgs	WW	Z	ttbar
Beam energy/GeV		120	80	45.5	182.5
Ne/bunch/10^{10}		14	13.5	14	20
Number of bunches	50MW	415	2162	19918	58
Number of SR photons >6MeV	50MW	1.4e10	1e-7	negligible	1.3e15
Life time	50MW	0.33	0.91	1.33	0.30
Lost beam /114m	50MW	5.5e7	1.0e8	6.7e8	1.2e7

- FLUKA options

PHOTONUC Type: ▾ All E: On ▾
E>0.7GeV: off ▾ Δ resonance: off ▾ Quasi D: off ▾ Giant Dipole: off ▾
Mat: BLCKHOLE ▾ to Mat: @LASTMAT ▾ Step:
PHYSICS Type: EVAPORAT ▾ Model: New Evap with heavy frag ▾
Zmax: 0 Amax: 0
PHYSICS Type: COALESCE ▾ Activate: On ▾
PHYSICS Type: PEATHRES ▾ Nucleons: 1000. Pions: 1000.
Kaons: 1000. Kaonbars: 1000. AntiNucleon: 1000. (Anti)Hyperons: 1000.
RADDECAY Decays: Active ▾ Patch Isom: ▾ Replicas: 3.
h/μ Int: ignore ▾ h/μ LPB: ignore ▾ h/μ WW: ignore ▾ e-e+ Int: ignore ▾
e-e+ LPB: ignore ▾ e-e+ WW: ignore ▾ Low-n Bias: ignore ▾ Low-n WW: ignore ▾
decay cut: 0.0 prompt cut: 0.0 Coulomb corr: ▾

- Wall material:
  - Case 1: water as wall
  - Case 2: rock as wall

- Simulate two critical cases:
  - SR @ttbar; Lost beam @Z

Soil/Rock

- Widely used material: soil
- Now use average components of rocks near site candidates.
- Simulate productions of residual nuclei after one year running in:
  - Cooling water
  - Air in tunnel
  - Water around tunnel
  - Rock (leachable isotopes)
- Compared with Chinese mandatory standard GB18871.

		Soil	components of different rocks
density		1.6g/cm^3	1.2~3.3g/cm^3
Major element (wt%)	C	1.0	---
	N	0.12	---
	O	34	30~70
	Na	0.50	0.1~2.9
	Mg	0.52	0.4~3.7
	Al	8.0	3.5~9.7
	Si	40	26~39
	P	---	0.02~0.16
	K	2.36	1.8~3.7
	Ca	2.26	0.2~4.8
	Ti	1.0	0.09~0.8
	Mn	0.24	0.02~0.12
	Fe	9.6	0.8~6.3

Radionuclide Production

- Densities of Long half-life isotopes are lower than mandatory standard, GB18871.

		Half-life	Cooling water	
			Specific activity/GB18871	Stat. error (%)
Beam loss@Z-pole	O15	122s	2.44	10
	C14	5700a	3.5e-7	23
	Be7	53d	1.3e-2	34
	H3	12a	2.3e-6	22
SR @ttbar	None			

		Half-life	Air in tunnel	
			Specific activity/GB 18871	Stat. error (%)
Beam loss@ Z-pole	O15	122s	2.7e-4	52
	C14	5700a	7.7e-7	1
	Be7	53d	1.1e-5	57
	H3	12a	3.5e-9	32
	P32	14d	---	---
	P33	25d	1.9e-8	100
	Cl36	3e5a	---	---
	Cl38	37m	---	---
	Ar37	35d	6.1e-9	59
	Ar41	1.8h	1.4e-3	12
SR @ttbar	C14	5700a	6.5e-6	2
	Ar41	2h	1.5e-2	20

Radionuclide Production

- Densities of Long half-life isotopes are lower than mandatory standard.

		Half-life	Water wall	
			Specific activity/GB18871	Stat. error (%)
Beam loss@Z-pole	O15	122s	2e-3	2
	C14	5700a	5e-10	4
	Be7	53d	3e-5	5
	H3	12a	6e-9	3
	F18	2h	5e-6	52
SR @ttbar	C14	5700a	2e-12	99
	H3	12a	1e-10	71

- Only leachable isotopes are listed:
  - ^{3}H, ^{22}Na, ^{45}Ca, ^{54}Mn

		Half-life	Rock wall	
			Specific activity/GB18871	Stat. error (%)
Beam loss@Z-pole	Mn54	312d	6.94E-04	1.8
	Ca45	163d	5.49E-06	0.3
	Na22	2.6y	7.20E-04	1.4
	H3	12a	5.90E-09	0.9
SR @ttbar	H3	12a	1e-10	71

- According to site candidates, investigate if radionuclides would transport to drinking water.

Production of Toxic Gases

- Saturated concentrations of ozone and oxides of nitrogen. [Hoefert, 1986]

For long irradiation times, *i.e.*, $t \to \infty$ the saturation concentrations are given by:

$$N_{sat} = \frac{gI}{\alpha + \kappa I + Q/V} . \quad (6.39)$$

N = number of ozone molecules per unit volume at time t (m^{-3})
I = energy deposited in air per unit volume and unit time ($eV\ m^{-3}\ s^{-1}$)
g = number of ozone molecules formed per unit energy (eV^{-1})
α = rate of decomposition of ozone molecules (s^{-1})
κ = number of ozone molecules destroyed per unit energy and volume ($eV^{-1}\ m^{-3}$)
Q = ventilation rate of irradiated volume ($m^3\ s^{-1}$)
V = irradiated volume (m^3)

	Number of SR photons/ 114m	Deposited energy from photon (GeV)	O3 mass [ug/m^3]
Higgs	4.7e18	2.8e-8	8.3e-6
WW	1.6e19	1.8e-9	8.3e-6
Z	8.4e19	6.0e-9	8.3e-6
ttbar	1.4e18	7.6e-8	8.3e-6

- O3: 8.3e-6 ug/m^3; NO2: 4.0e-6 ug/m^3
- Concentration limit
  - O3: 160 ug/m^3; NO2: 40 ug/m^3.
  - Lower than the concentration limits.

outline

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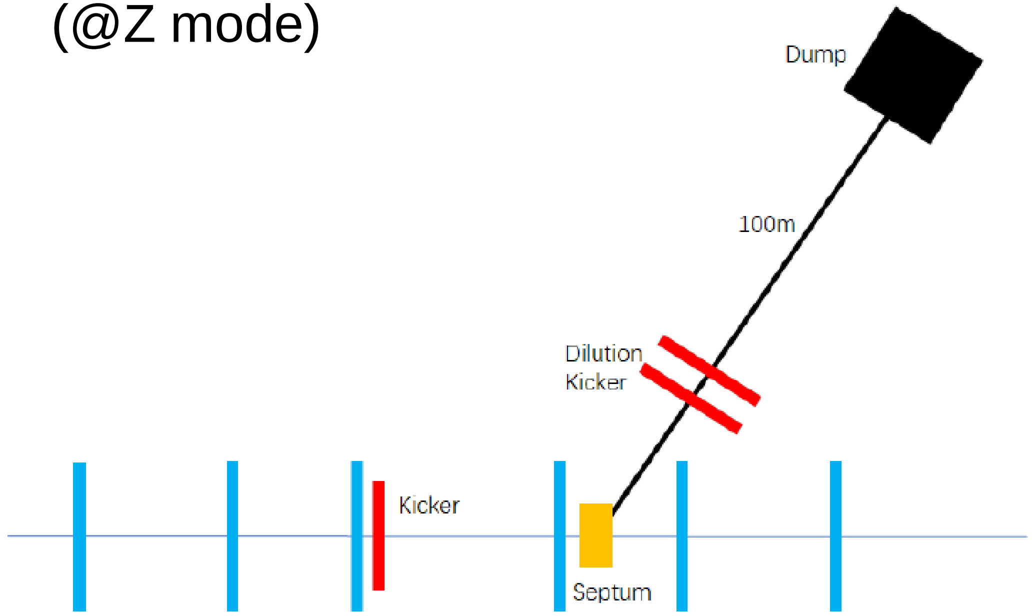
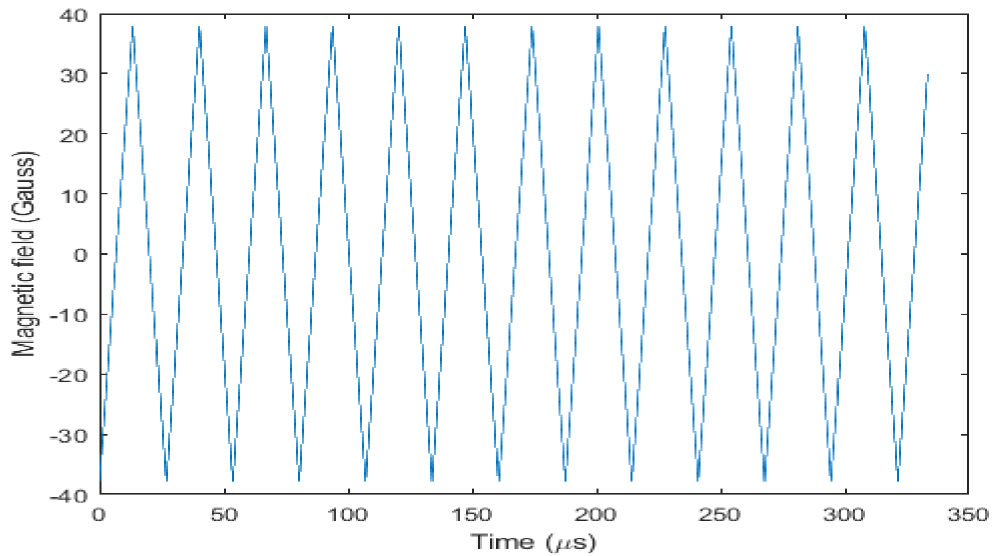
Collider Dump

- A set of kicker magnets is used to dilute the beam horizontally and vertically.
- The length of transfer tunnel is about 100m The volume of cavern will be determined after the design of the equipment installation.
- The area of bunch distribution at dump entrance is optimized to be 6cm x 6cm (@Z mode)

		Extraction kicker	Septum	Dilution kickers
Length (m)		2	20	10
Magnetic flux density (Gauss)	Z	280	2600	40 (Max.)
	WW	493	4700	
	Higgs	740	7000	
	ttbar	1110	10500	





Dilution kicker requirement:

1. Vertical kicker should periodic oscillate 12.5 times in 300 us

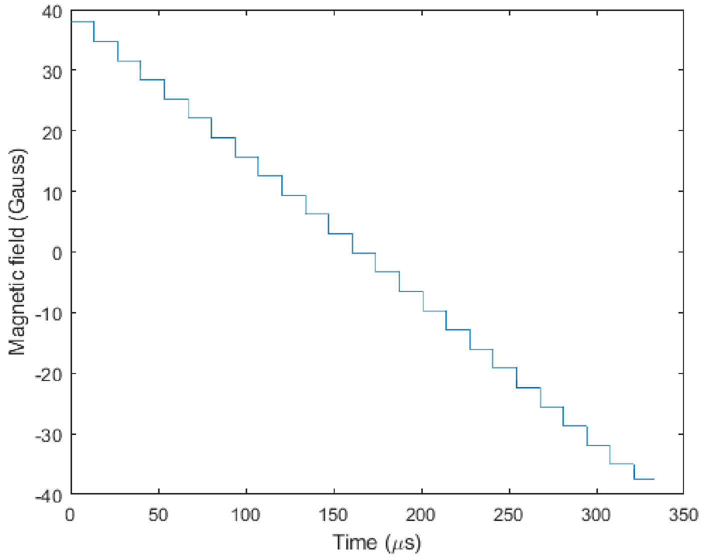
From Xiaohao Cui

Bunch Distribution: 50MW

- The bunch distributions at the dump entrance is simulated.
  - Bunch size: $\sigma_x > 7mm; \sigma_y > 40\mu m$;

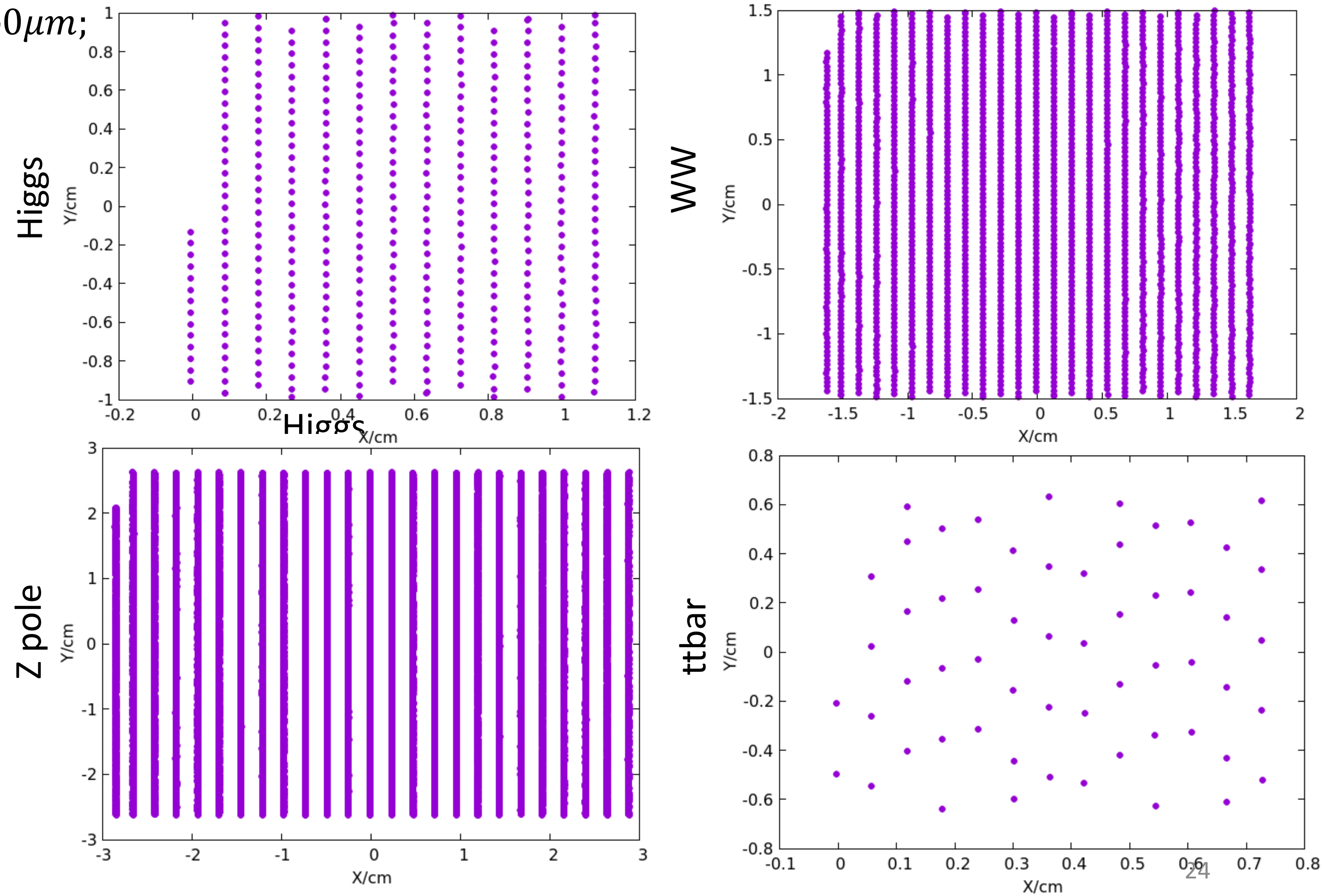
From Xiaohao Cui

① Simulate energy deposition in dump core.
② Find the maximum energy deposition. And calculate maximum temperature rise.
③ Optimize dump dimensions



Dilution kicker requirement:

2. Horizontal kicker should reduce step by step from max. to min. in 300 us



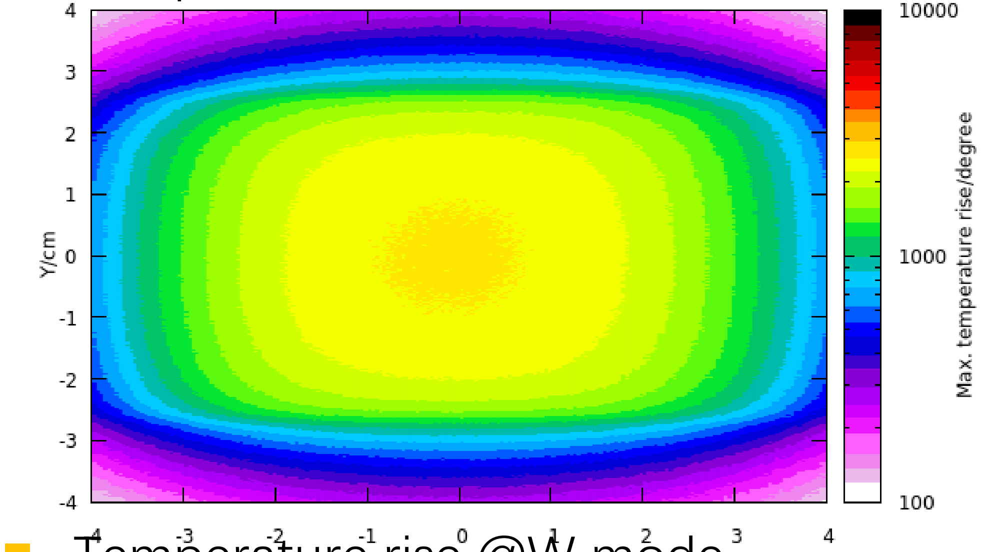
Instantaneous Max. Temperature Rise: 50MW

- Example: graphite core (dumping once)

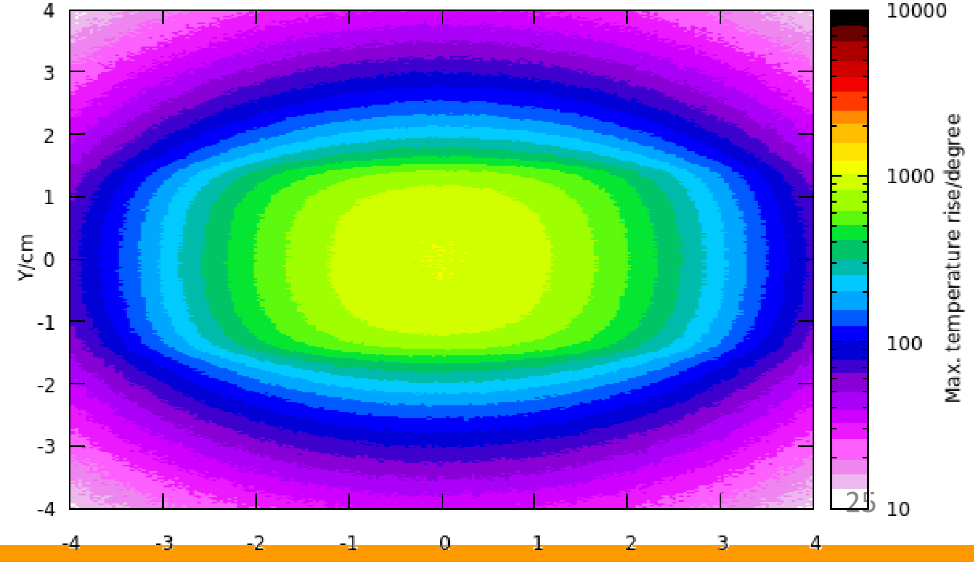
	Higgs	WW	Z	ttbar
Beam energy/GeV	120	80	45.5	180
Ne/bunch/10^{10}	14	13.5	14	20
Bunch number (50MW)	415	2162	19918	58
Max. temperature rise	510 ± 15℃	1020 ± 30℃	2620 ± 15℃	194 ± 2℃
Max. temperature rise by one bunch	7.31 ± 0.03℃	5.38 ± 0.03℃	3.76 ± 0.02℃	10.08 ± 0.04℃

- Max. temperature rise is smaller than graphite melting point. Inert gas will be used to stop fire and chemical reaction.
- Dimension (graphite + Iron): R~2.3m, L~8m; constrained by the condition dose-eq < 5.5mSv/h.

- Temperature rise @Z mode

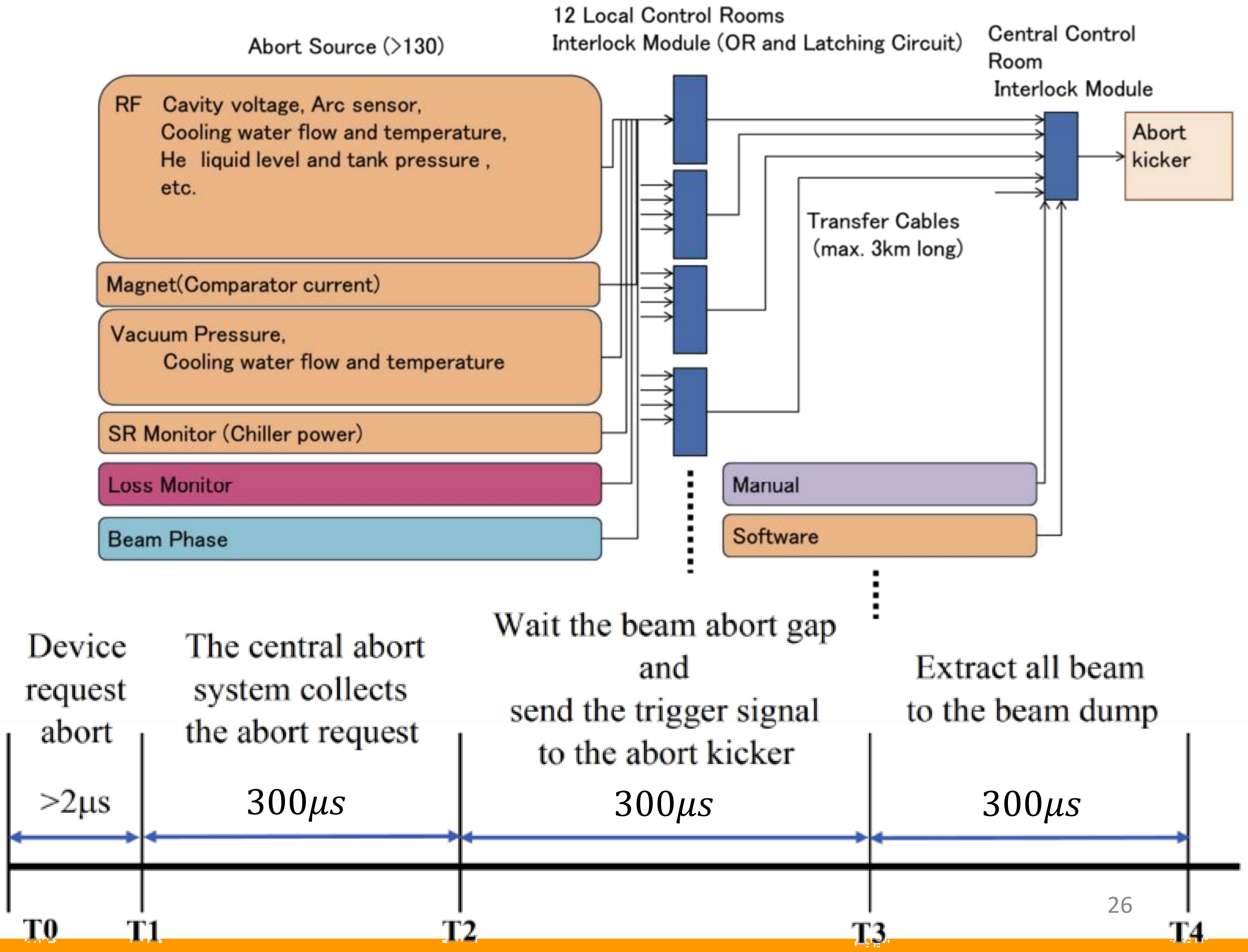


- Temperature rise @W mode



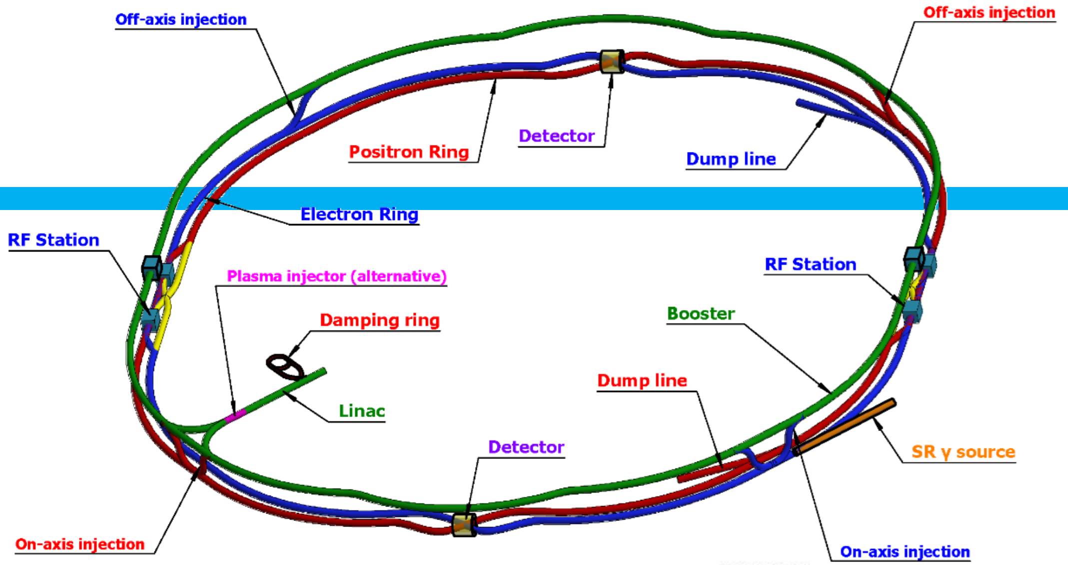
Response Time

- Abort request:
  - Beam loss monitors
  - Synchrotron oscillation phase monitor
  - Hardware components
  - Manual abort
- Time interval
  - Device request -> local control
  - Local control -> central control
  - Central control -> dump system
  - Extract all beam.
- Collider dump response time ~ 1ms.



More about Dump

- Abort beam in booster and collider
  - For normal operations and machine tuning
- Study feasibility to build extraction line from booster to dump.
- Build in the straight sections. One for electron beam and one for positron beam.
- Temperature decrease to 40 ℃ in 1h.
- Will study reliability (or alternative design).
- Need absorber to protect machine elements from incorrect dumping.
- Response time ~ 1ms.
- Need collimators to deal with beam loss faster than 1ms.
  - fault cases.



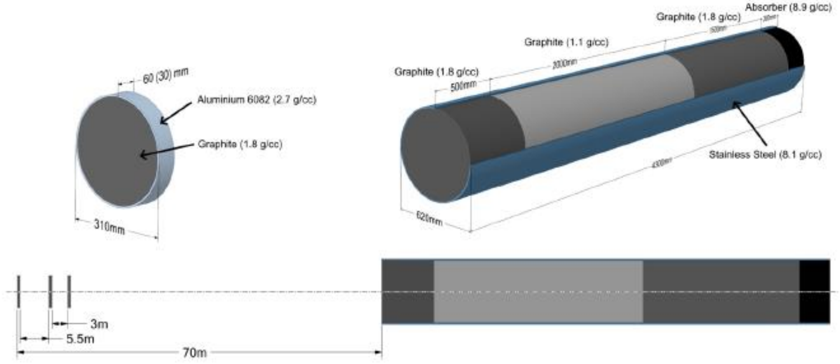


Figure 4 Overview of the geometry used in FLUKA simulations. Different spoiler configurations were simulated: 1 × 6 cm, 2 × 3 cm and 3 × 3 cm long spoilers

Krainer, A. et.al., *EPJ Techn Instrum* **9,** 3 (2022)

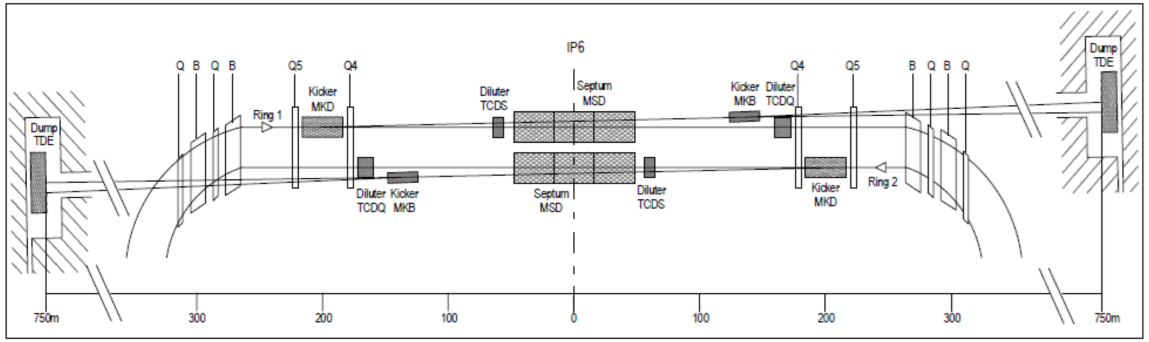


Figure 17.1: Schematic layout of beam dumping system elements around LHC point 6.

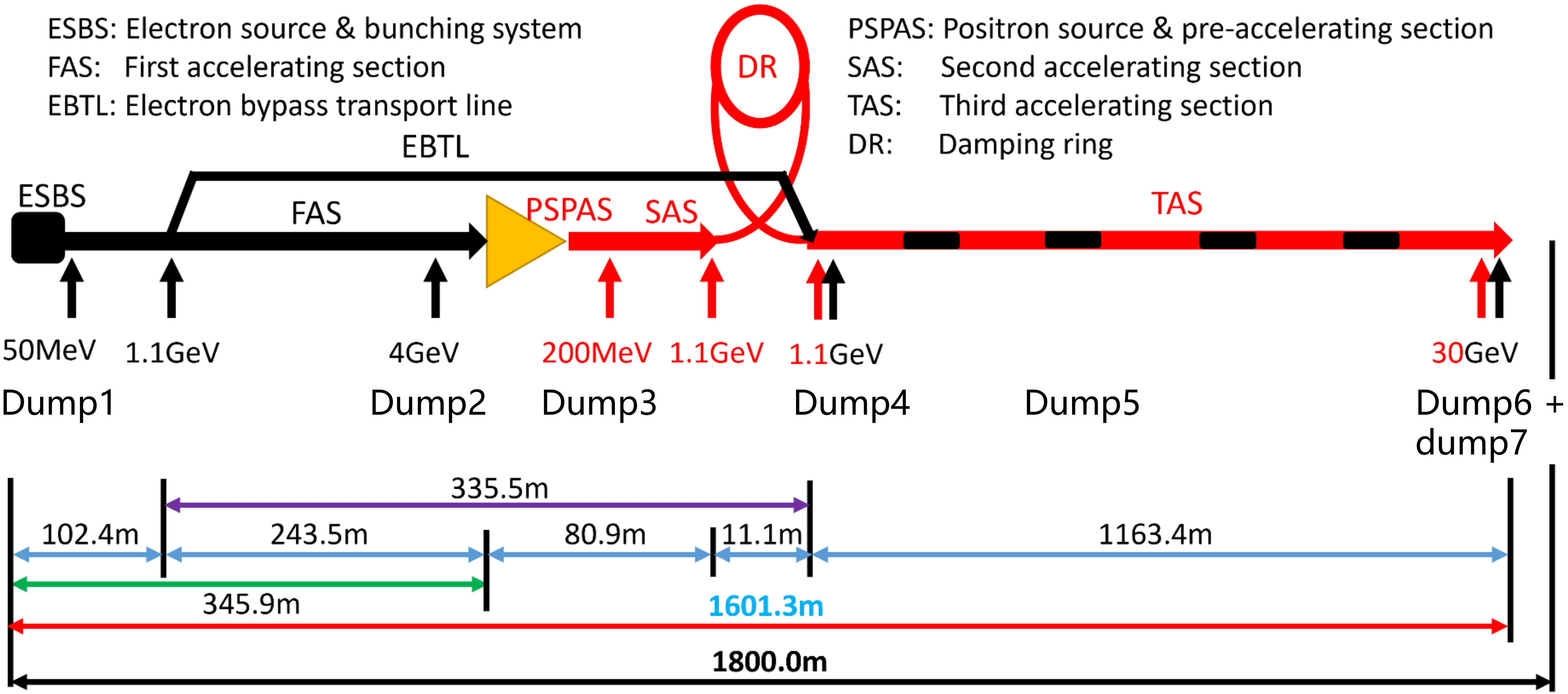
LHC design report Ch.17

Outline

- Introduction
- Synchrotron radiation shielding
- Radionuclide production estimation
- Collider dump design
- Linac hot spots and lost beam shielding
- Environment, health and safety
- Summary and outlook

CEPC Linac

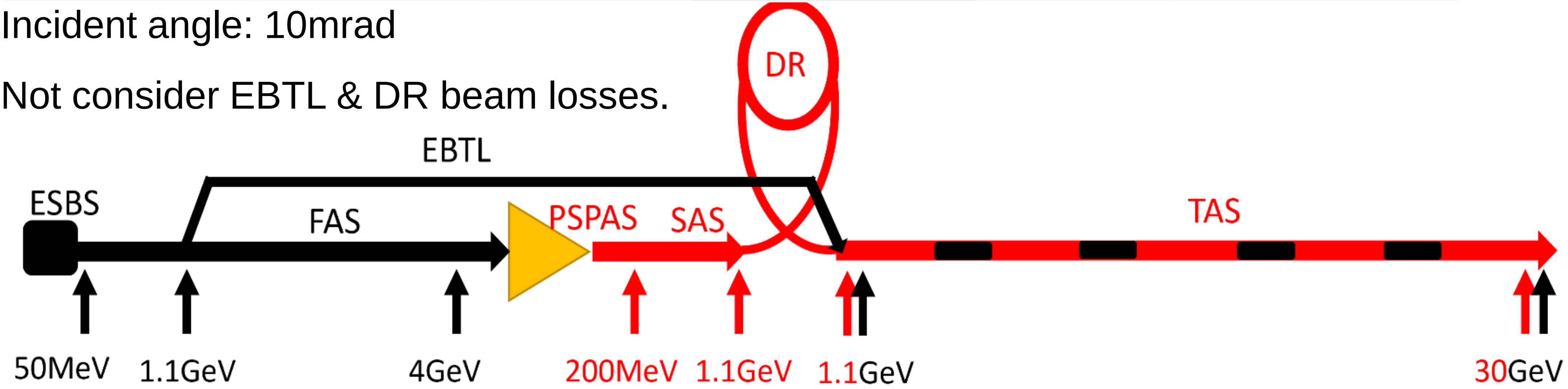
- Length: 1601.3m; 7 dumps and 1 positron target;



Linac Beam Loss Assumptions

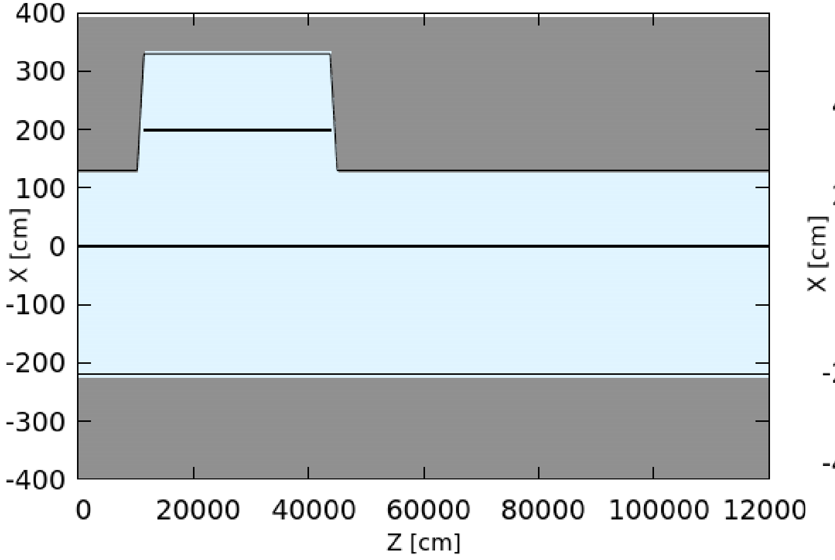
Position	Length	Beam energy	Number of bunches [s^{-1}]	Beam loss/bunch [nC]	Number of particles [10^{10}/s]
FAS	100m	300MeV	200	0.5	62.5
Positron target	15mm	4GeV		10	1250
PSPAS	15m	5~200MeV		10	1250
SAS	3m	300MeV		2	250
	30m	600MeV		0.2	25
TAS	1163m	1.1~30GeV		0.1	12.5

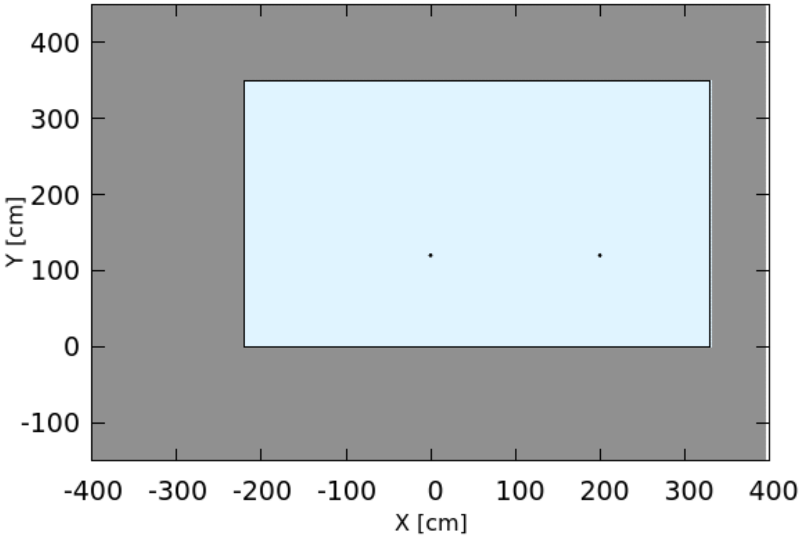
- Incident angle: 10mrad
- Not consider EBTL & DR beam losses.



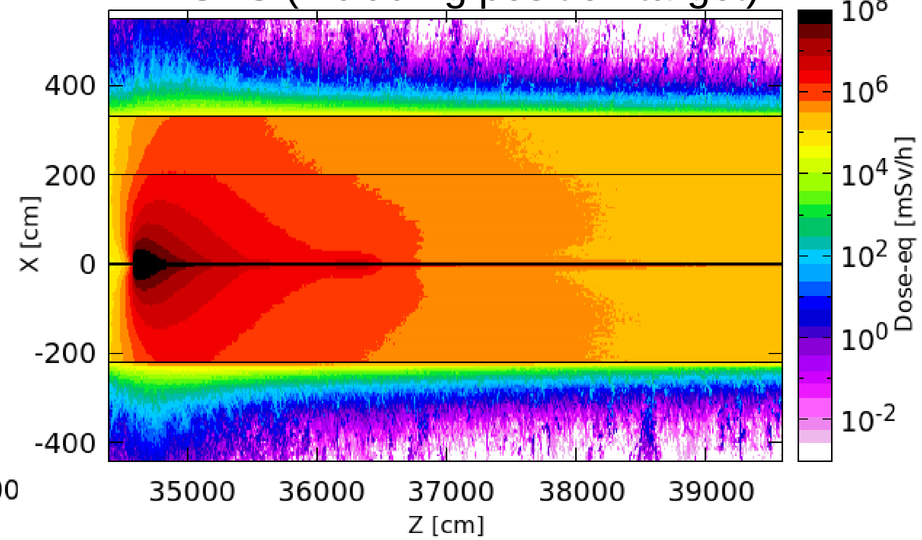
Simulation Setup

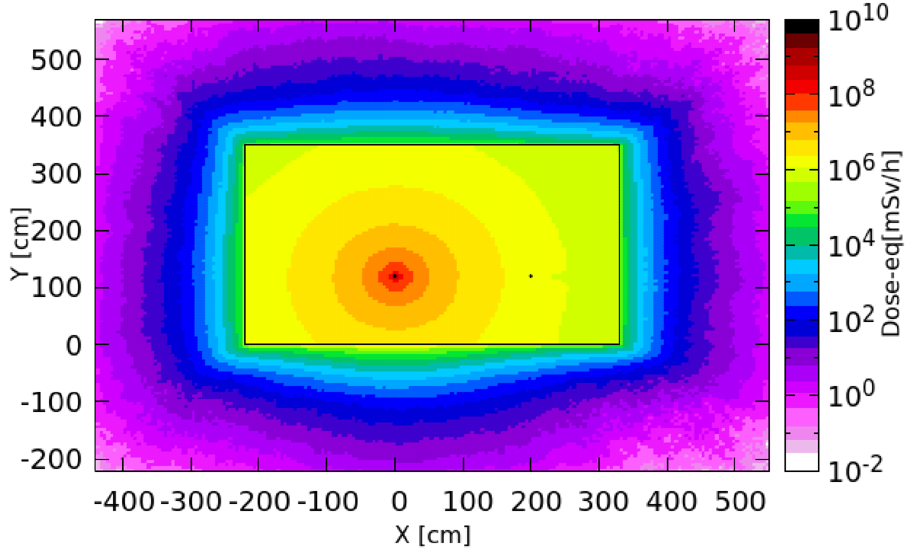
- Beam pipes and concrete wall





- Dose-eq distribution
  - SAS (including position target)



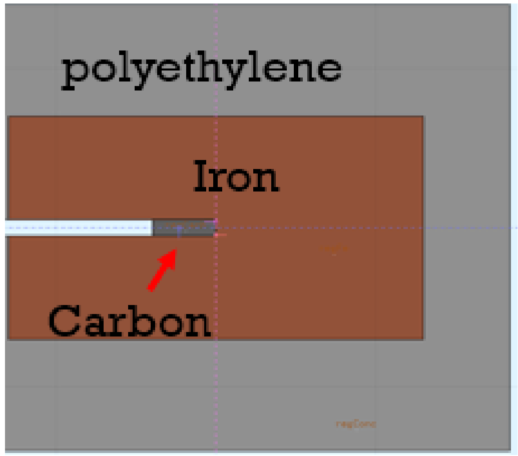


- Thickness of Shielding wall according to upper limit 5.5mSv/h (left/right/bottom) or 2.5uSv/h(top).

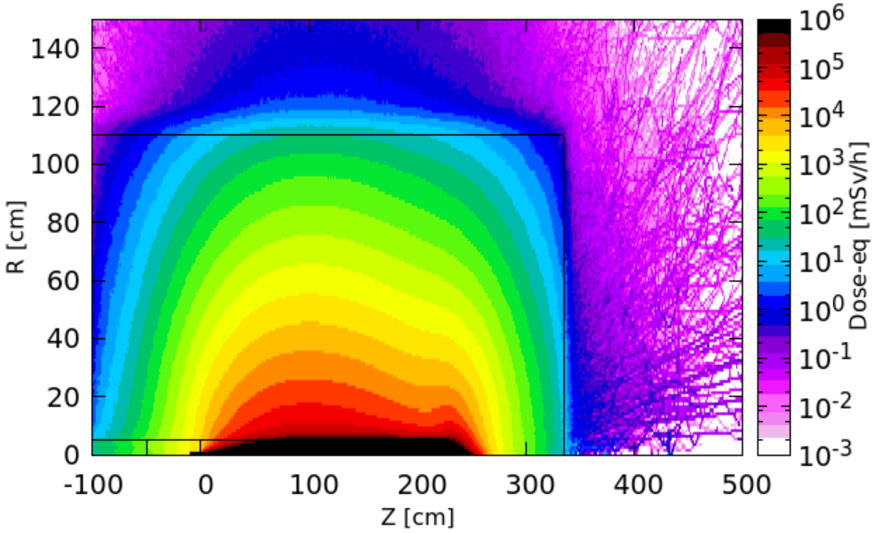
Wall thickness	FAS	SAS	TAS
Left	0.3m	1.9m	0.3m
Right	0.2m	1.9m	0.3m
Bottom	0.3m	2.1m	0.3m
Top	1.3m	4.1m	2.0m

Local Shield Design for Hot Spots

- Carbon and iron is selected as the absorber material, surrounded by the polyethylene as local shielding.
- 5.5mSv/h is set as upper limit to decide the thickness of local shielding.



Absorber geometry and local shielding:
Size for carbon and iron for different beam energy, adopt from other projects, is suitable but haven't been optimized.



Local size selection (20GeV dump as example):
2D map of dose distribution is obtained using FLUKA, the dose rate alone Z or R axis was averaged by 1x1cm^2 area, the shielding size can be selected by setting dose rate limit.

Beam energy	R/m	Length/ m
60MeV	0.7	1
4GeV	1.2	2.6
250MeV	0.55	1
1.1GeV	0.85	1.7
6GeV	1	2.5
30GeV	1.3	3.8

Preliminary design results for different beam energy analysis station:
Radiation level nearby each energy analysis station was figured out, also specify a roughly space for the future local shielding.

- The thickness of shielding will be optimized combined with Linac tunnel geometry in the next stage.

Radionuclides and Toxic Gases in Linac

- Densities of Long half-life isotopes in Linac air are lower than mandatory standard.

	Half-life	Specific activity/GB18871
Ar41	1.8h	0.13
Ar37	35d	3.4×10^{-7}
Cl38	37m	0.41
Cl36	3e5a	3.1×10^{-10}
S35	88d	3.4×10^{-5}
P33	25d	4.6×10^{-6}

	Half-life	Specific activity/GB18871
P32	14d	4.6×10^{-5}
Si31	2.6h	4.3×10^{-4}
F18	1.8h	2.7×10^{-4}
O15	2.0m	2.58
C14	1.2m	7.8×10^{-5}
Be7	53d	3.8×10^{-2}
H3	12a	1.3×10^{-5}

- O3: $1.0 \times 10^{-6} \mu g/m^3$.
  NO2: $4.8 \times 10^{-7} \mu g/m^3$.
- Toxic gas concentration limit
  - O3: 160 ug/m^3; NO2: 40 ug/m^3.
  - Smaller than the concentration limits.

For long irradiation times, *i.e.*, $t \to \infty$ the saturation concentrations are given by:

$$N_{sat} = \frac{gI}{\alpha + \kappa I + Q/V}. \qquad (6.39)$$

N = number of ozone molecules per unit volume at time t (m^{-3})
I = energy deposited in air per unit volume and unit time ($eV\ m^{-3}\ s^{-1}$)
g = number of ozone molecules formed per unit energy (eV^{-1})
α = rate of decomposition of ozone molecules (s^{-1})
κ = number of ozone molecules destroyed per unit energy and volume ($eV^{-1}\ m^{-3}$)
Q = ventilation rate of irradiated volume ($m^3\ s^{-1}$)
V = irradiated volume (m^3)

outline

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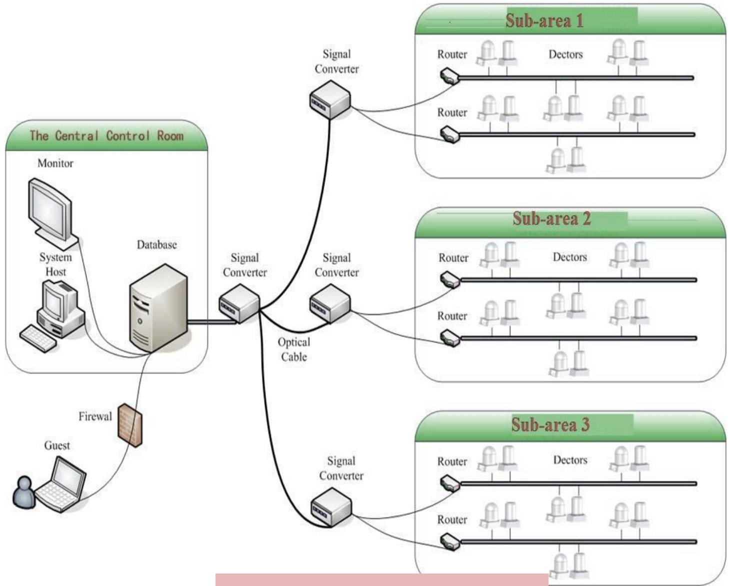
Radiation Dose Monitor System (RDMS)

- Goal: guarantee the radiation level of workplace and the environment around comply with relevant regulations.
- State of the art system: once radiation level exceeds the set critical value, monitors would give an alarm.
- Main includes:
  - Data acquisition program
  - Workplace monitoring program
  - Environmental monitoring program
  - Personal dose monitoring program
  - Management of radioactive components

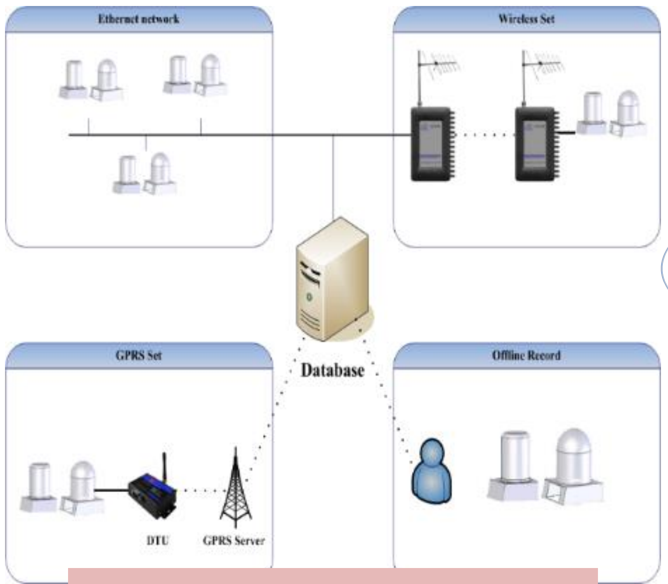
RDMS & PPS

RDMS provides remote supervision, long term database storage.

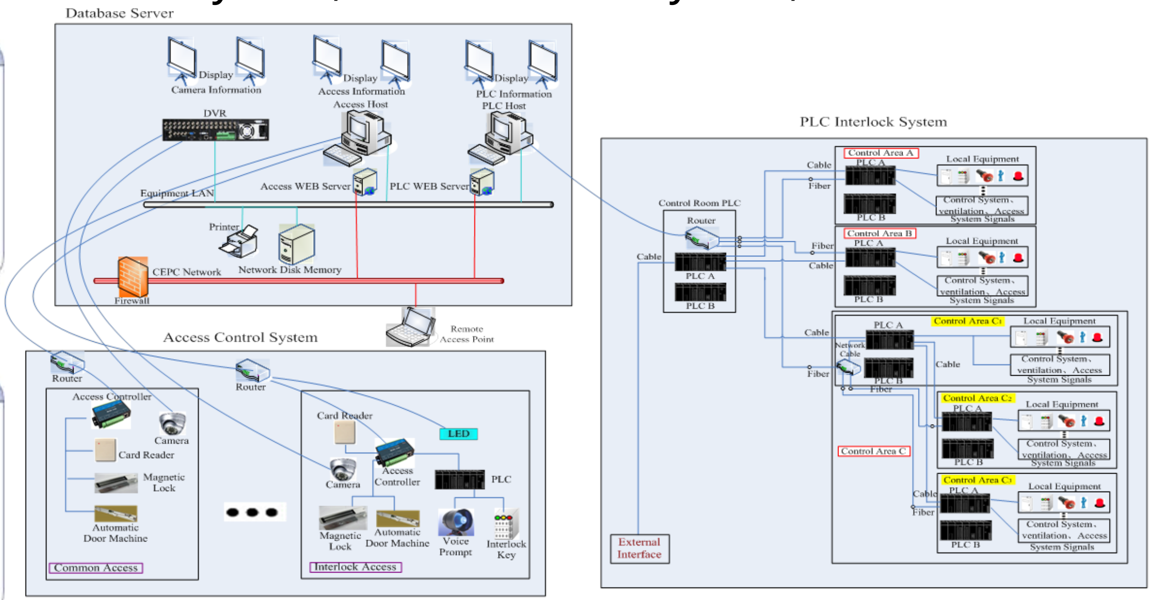
PPS (Personal Protection System) Includes programmable logic controller system, access control system, database.



System framework



Date communication methods



Schematic diagram of the PPS

- A pre-research project was established to solve the problem of saturation for neutron measurement at high instantaneous dose rate.
- More radiation field detection methods was also investigated and co-researched for future radiation detection

Environment, Health and Safety

- Before construction
  - Environmental impact assessment document, safety analysis document
  - Considering:
    - Training:
      - Radiation safety and protection
      - Occupational health training
      - Special job/equipment operation
      - …
    - Access Control, work Permit and Notification
- During construction
  - Blasting Vibration
  - Noise
  - Water environment
  - Water and soil conservation
- During operation
  - Groundwater and cooling water release
  - Radioactivity and toxic gases release
  - Radioactive waste management
  - Radiation impact to the public
  - Radiation level
  - Safety
    - Fire
    - Cryogenic and oxygen Deficiency
    - Electrical
    - Non-ionization radiation
    - General safety
    - Traffic and vehicular safety

Summary

- The main part of shielding design finished
  - Prompt radiation shielding
    - SR shielding
    - Linac hot spots and bulk shielding
    - Collider dump design
  - Radionuclides productions and toxic gases estimation.
- All RP designs will be finished in the next 2 years.

Thank you