中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

CEPC RADIATION PROTECTION (RP) STUDY

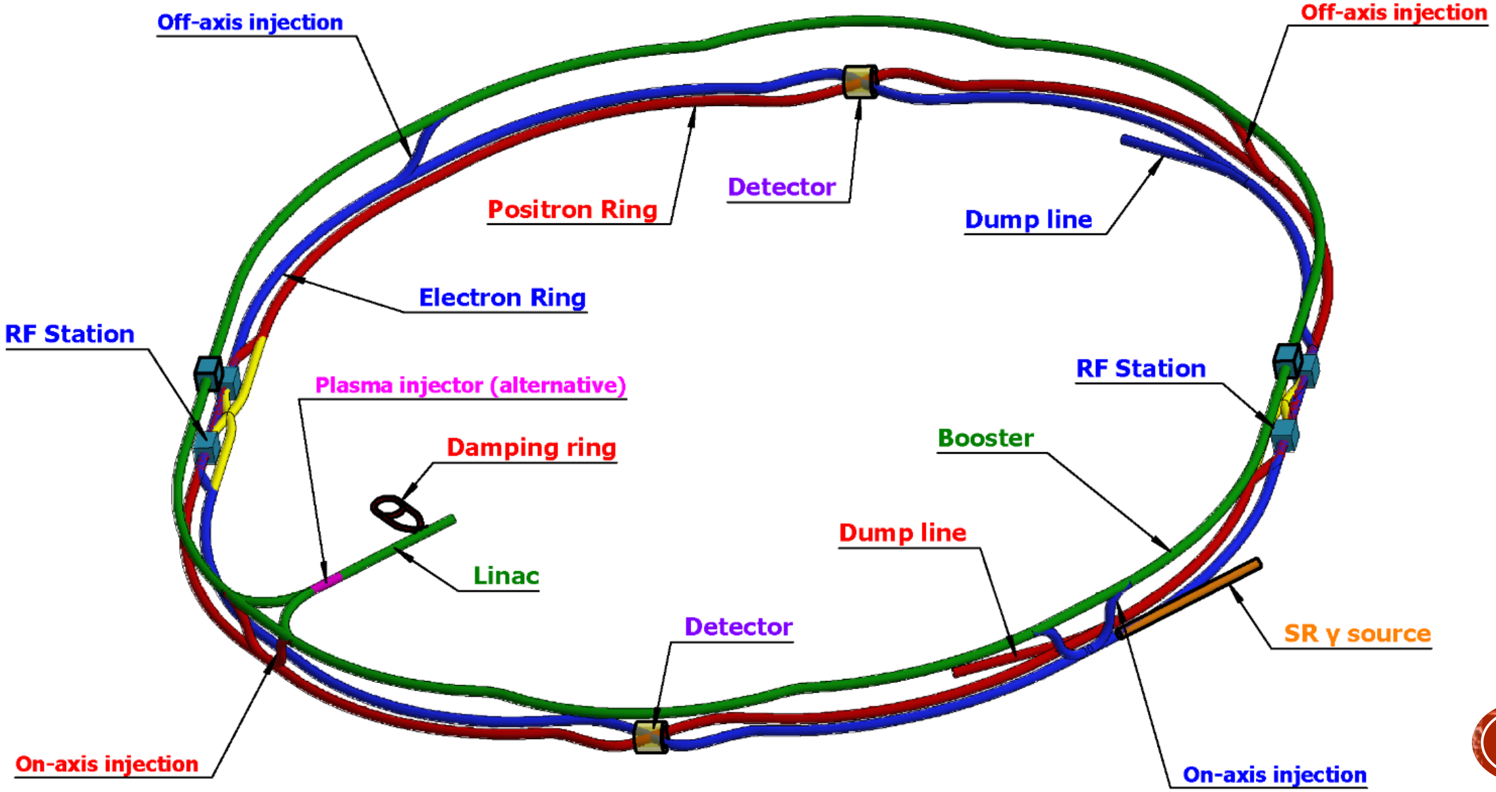
Guangyi Tang on behalf of CEPC RP Group

IAS Program on High Energy Physics, 2023/2/14

OUTLINE

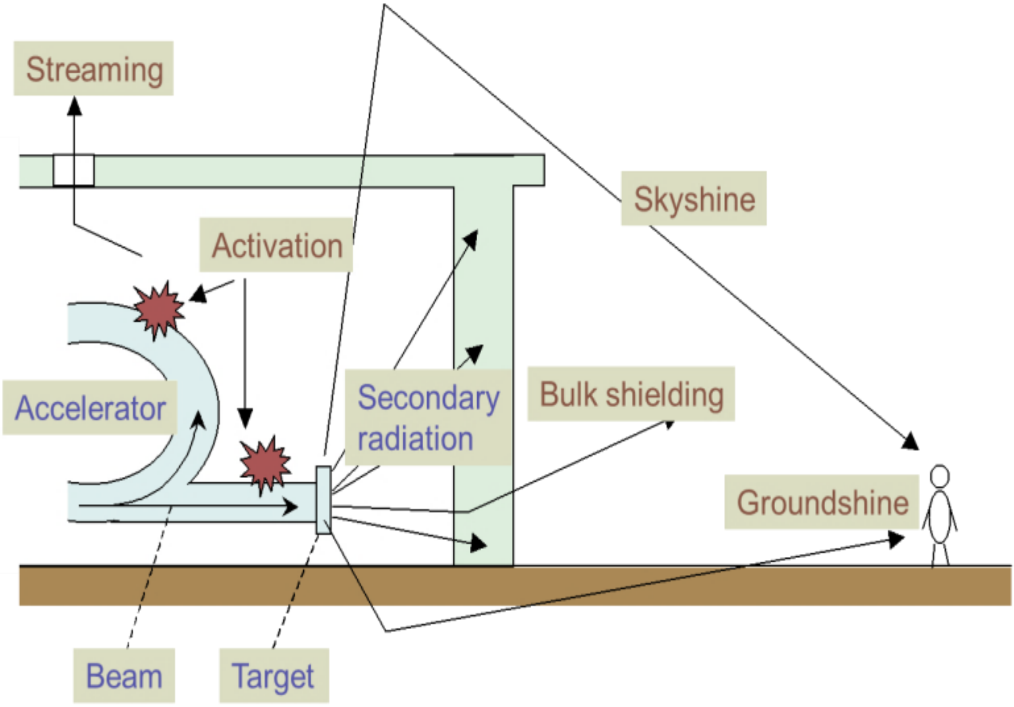
- Introduction
- Synchrotron radiation shielding
- Radionuclide production estimation
- Collider ring dump design
- Linac hot spots and beam losses shielding
- Summary and outlook

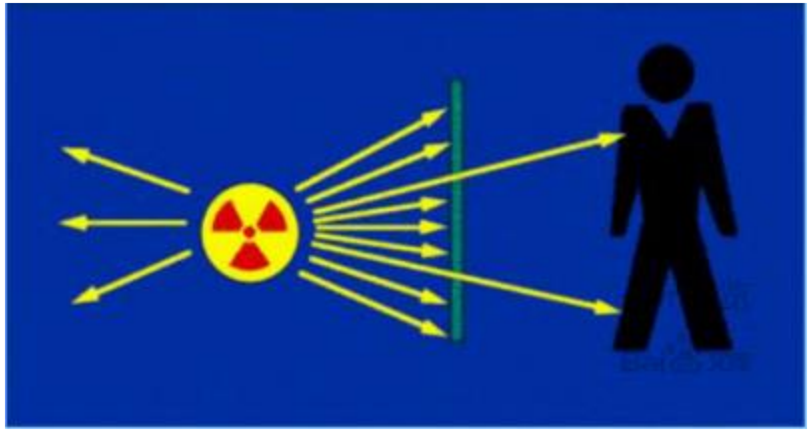
Simulation Using FLUKA, Flair.



RP CONCEPTS

- Source:
  - beam, target (hot spot), synchrotron radiation, …
- Radiations may damage equipment and health.
- How to estimate the damage
  - For material: absorbed dose, unit: Gray (Gy)
  - For health: 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, …





RADIOLOGICAL IMPACT

- Main consideration aspects

Impact factors	Characteristics
Synchrotron radiation	Radiation damage to magnets coils; 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 the tunnel; Determine the bulk shielding thickness;
Hot spots	MDI, Collimation locations, collider/linac dumps, injection/extraction points;
Radiological impact on environment	Dose from stray radiation emitted during machine running Radionuclides in the cooling water, underground water, tunnel air, soil. Radioactivity analysis for the solid components and waste
Machine protection	Active/passive protection

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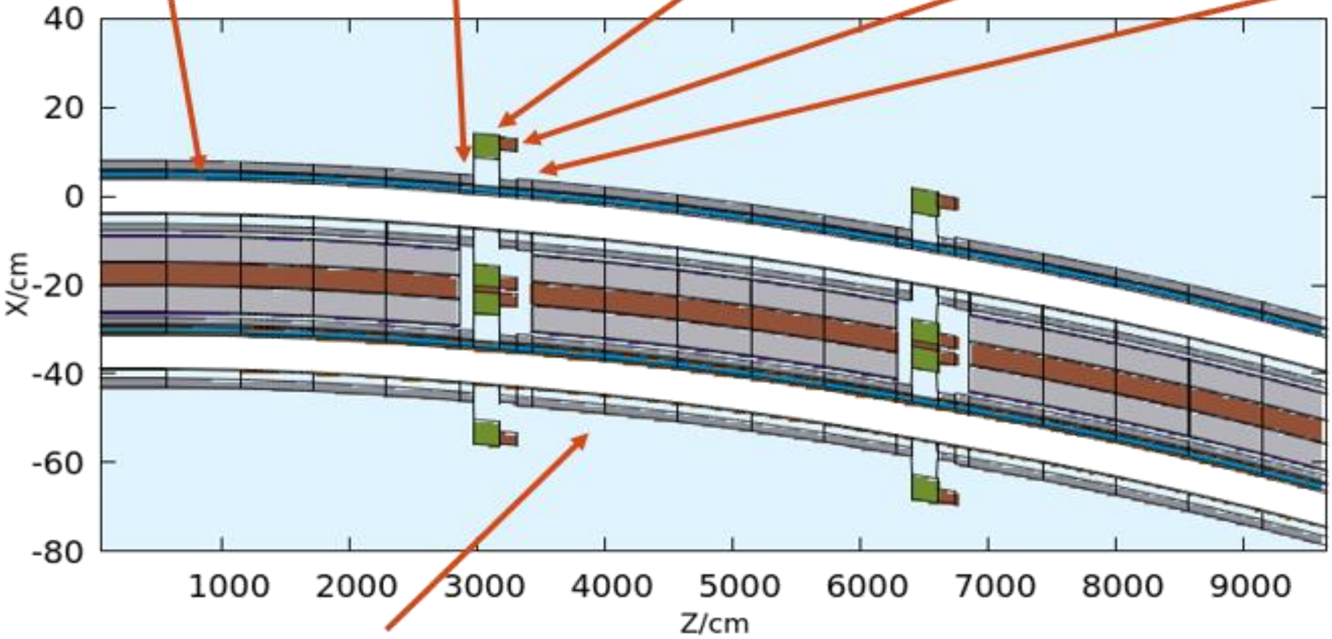
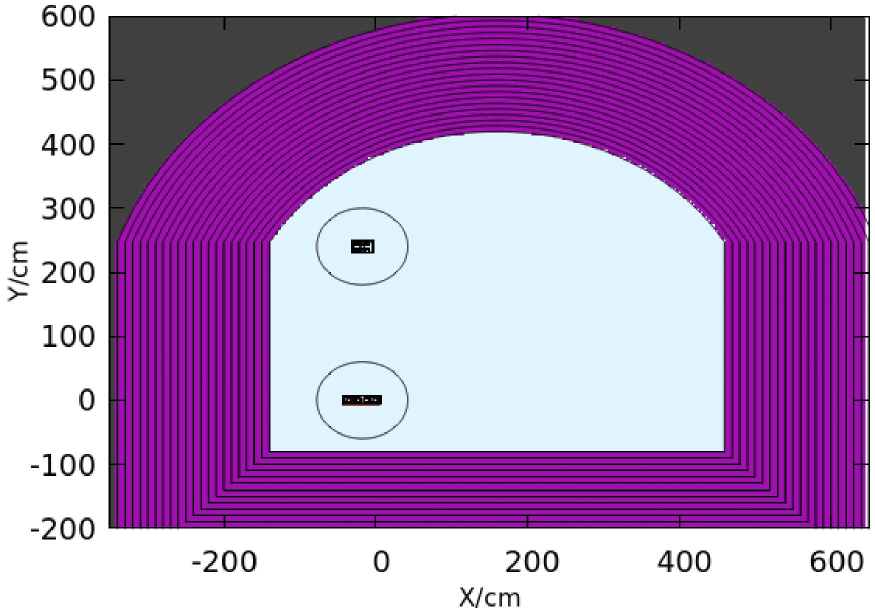
SIMULATION SETUP

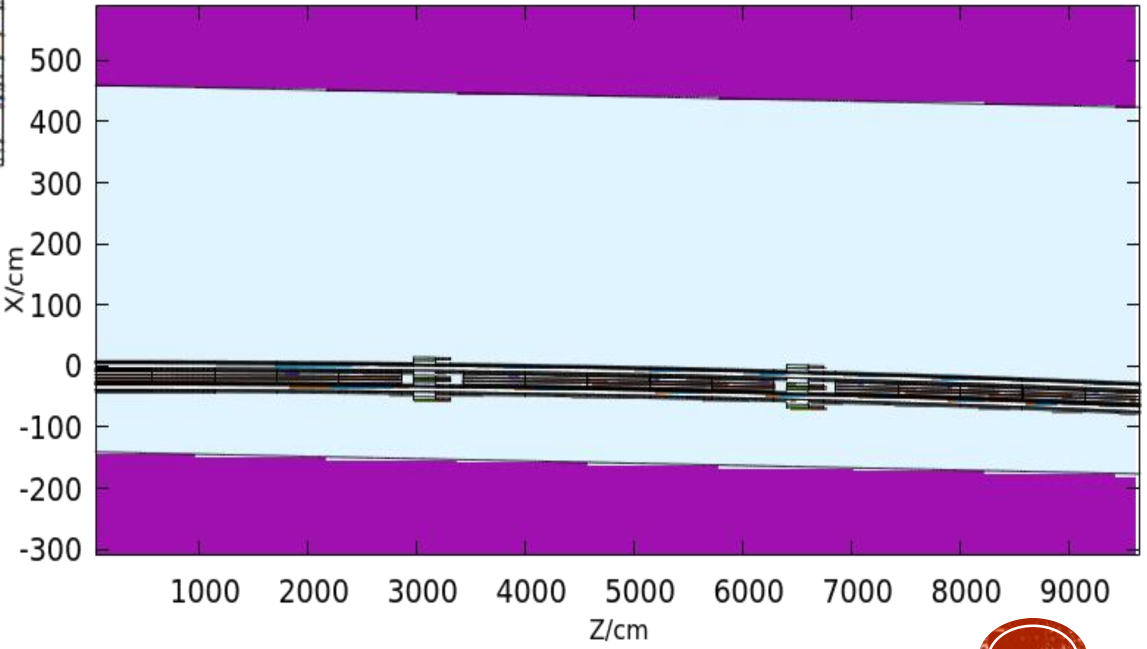
- Tunnel geometry
  - 28m dipole -> 1.1m drift chamber -> 2m quadrupole -> 1.4m sextupole -> 1.1m drift



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

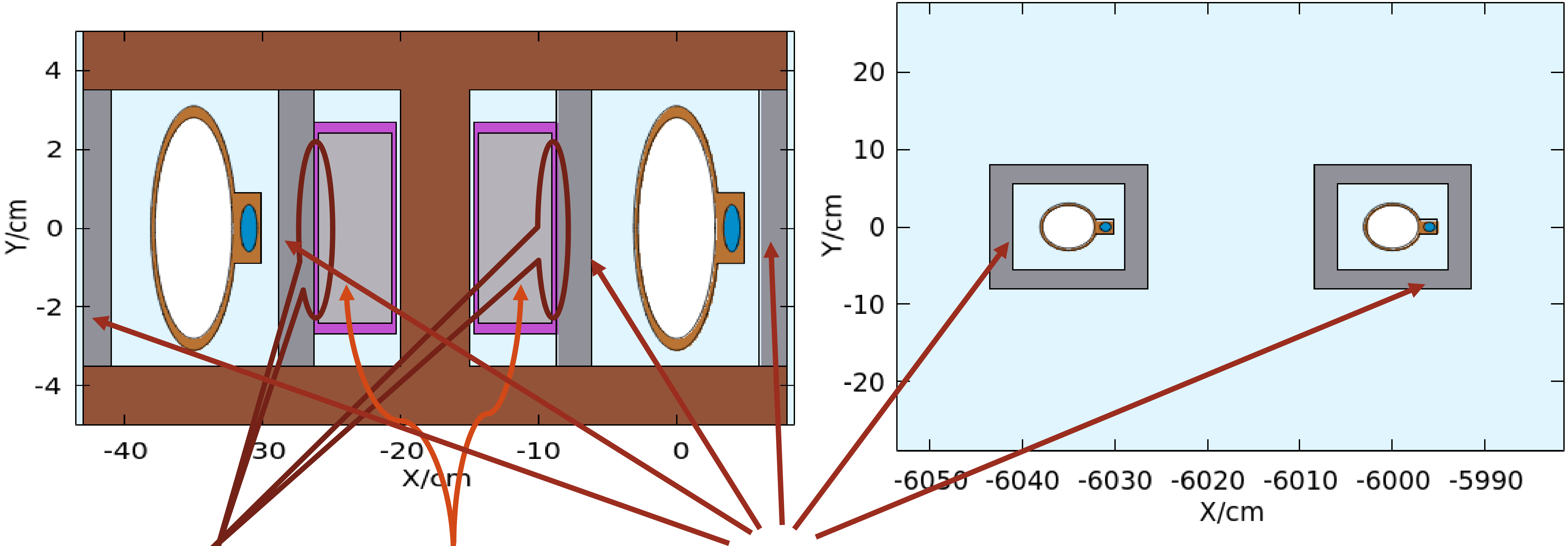
- Length: 100m;
  - 3 dipoles;
  - 2 quadrupoles;
  - 2 sextupoles;





SIMULATION SETUP

- Dipole
- Drift chamber



insulations, (epoxy resin)

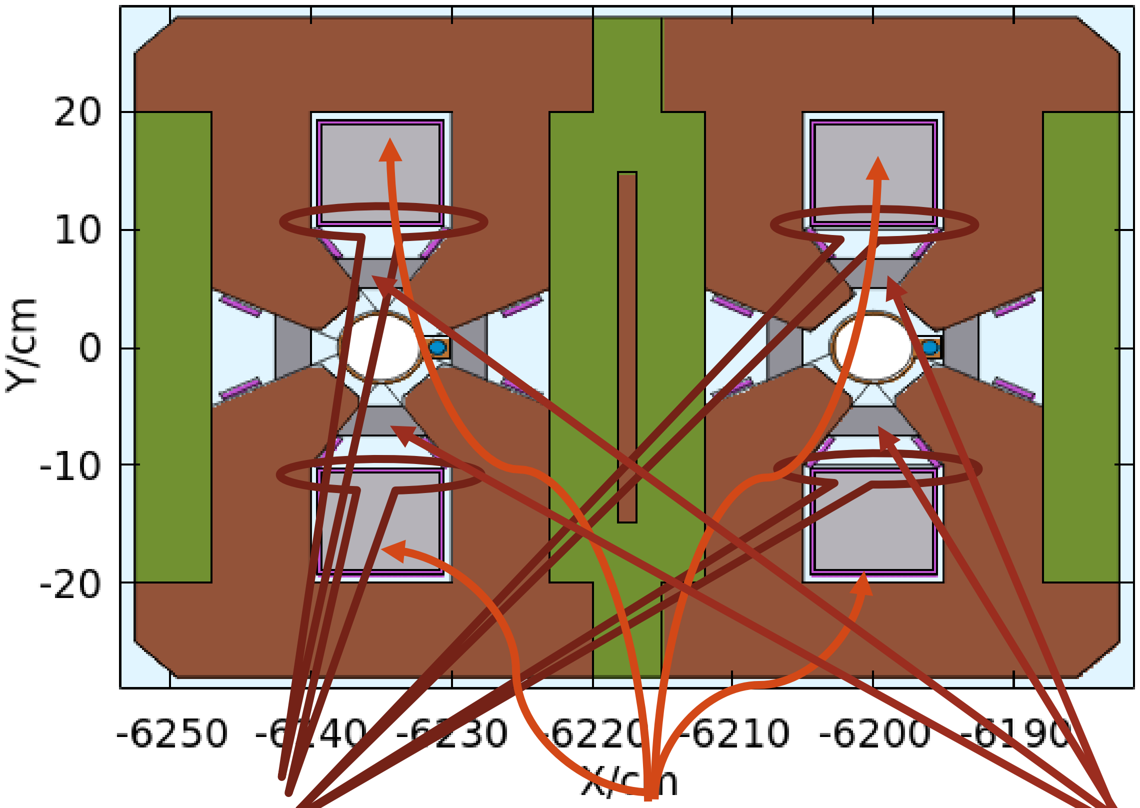
coils,

leads

- Insulations is added in the model. Both beam-pipes are made of copper.
- In the cross-section, area of lead: $56cm^2$
- area of lead: $216cm^2$

SIMULATION SETUP

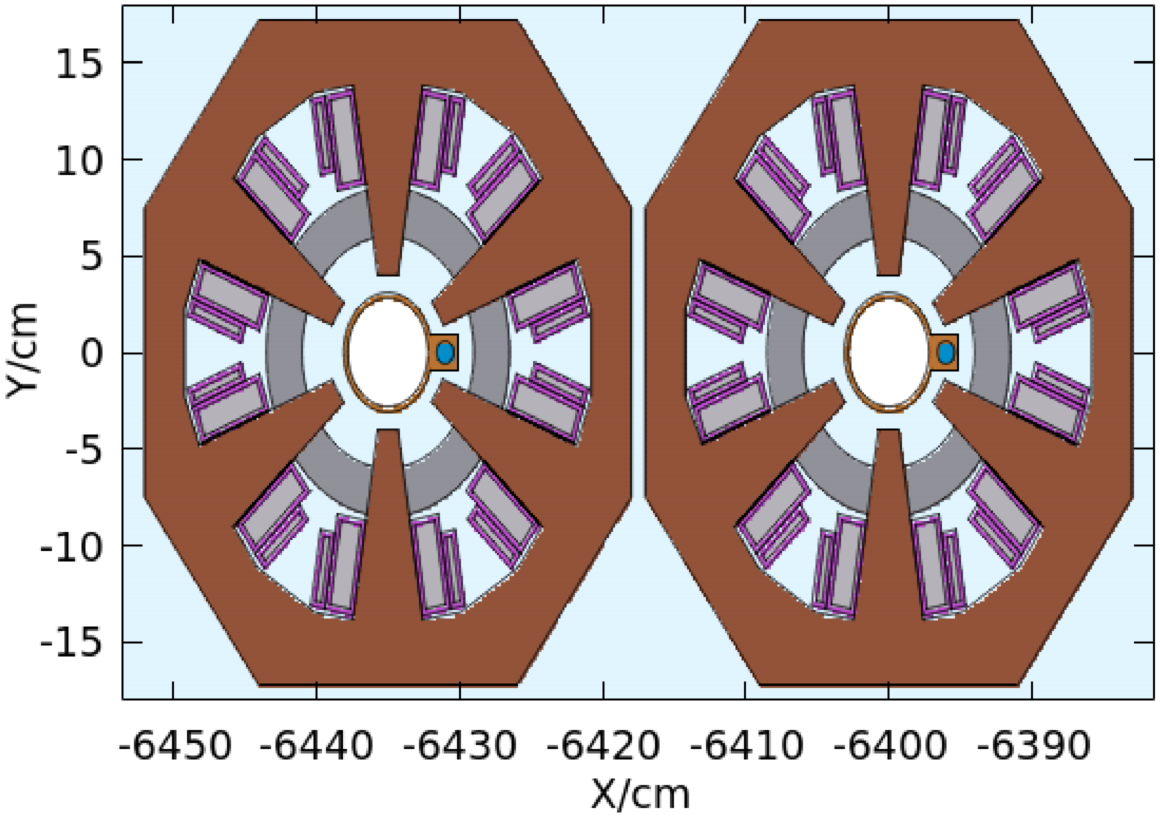
- Quadrupole



insulations, coils, leads

(epoxy resin)

- Sextupole

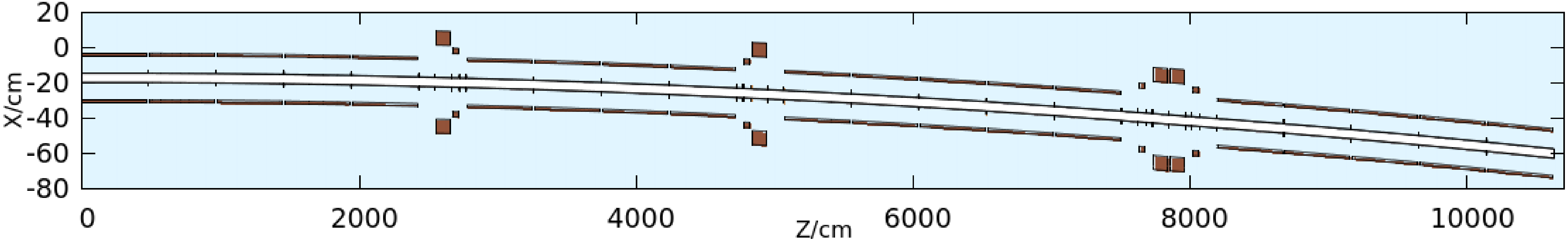


- area of lead : $96cm^2$

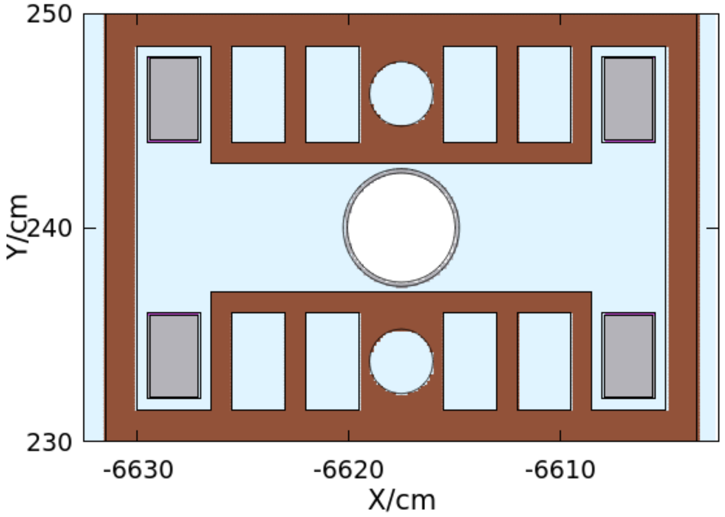
- area of lead : $100cm^2$

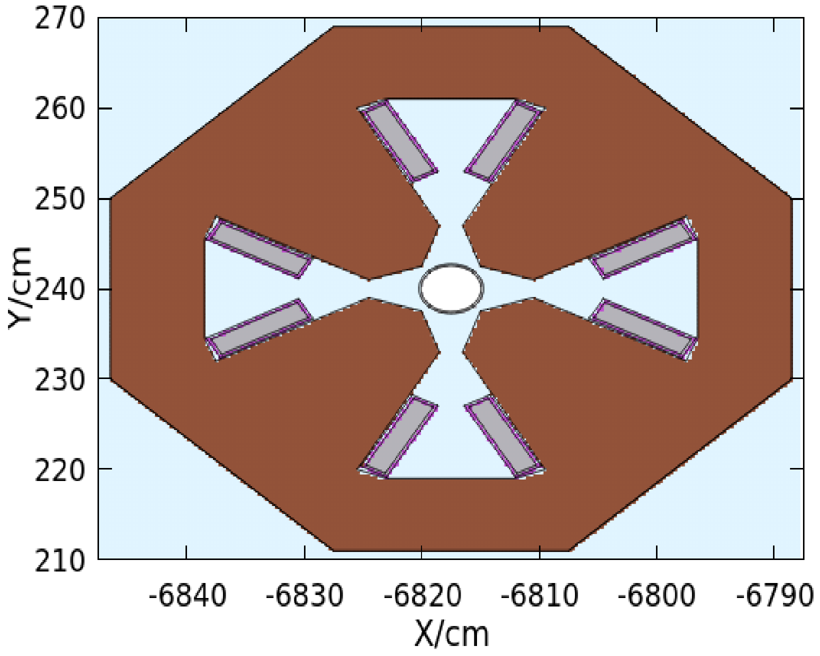
BOOSTER

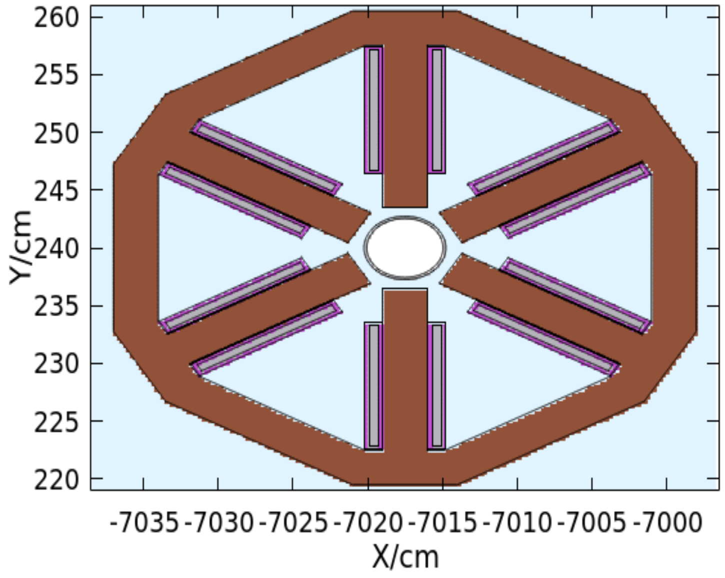
- dipole ->drift chamber ->quadrupole -> sextupole ->drift chamber ->dipole ...



- Magnets







PARAMETERS: 50MW

- Collider

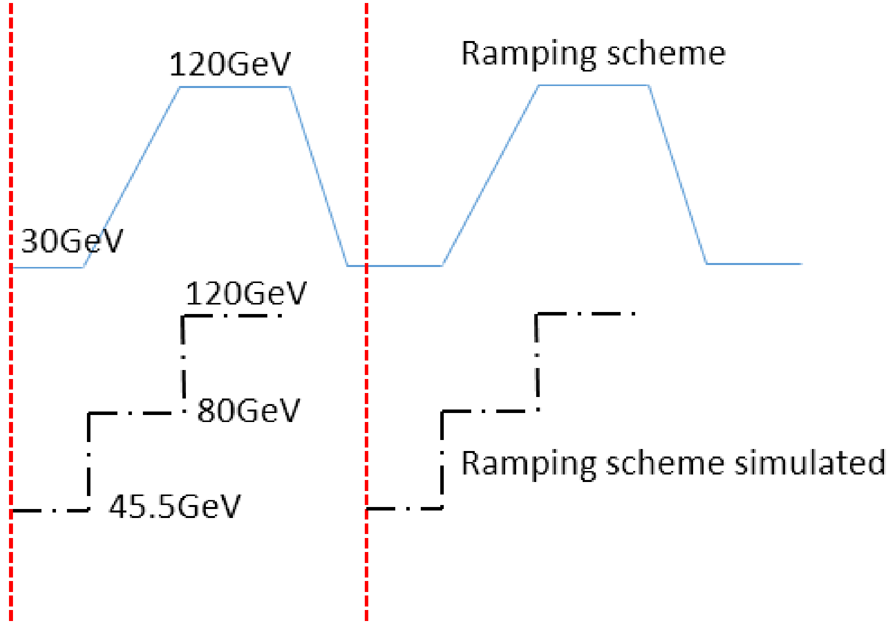
	Higgs	WW	Z	ttbar
Beam energy/GeV	120	80	45.5	180
Ne/bunch/10^{10}	14	13.5	14	20
Number of bunches	415	2162	19918	58
Number of photons/114m	4.7e18	1.6e19	8.4e19	1.4e18

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

- Booster

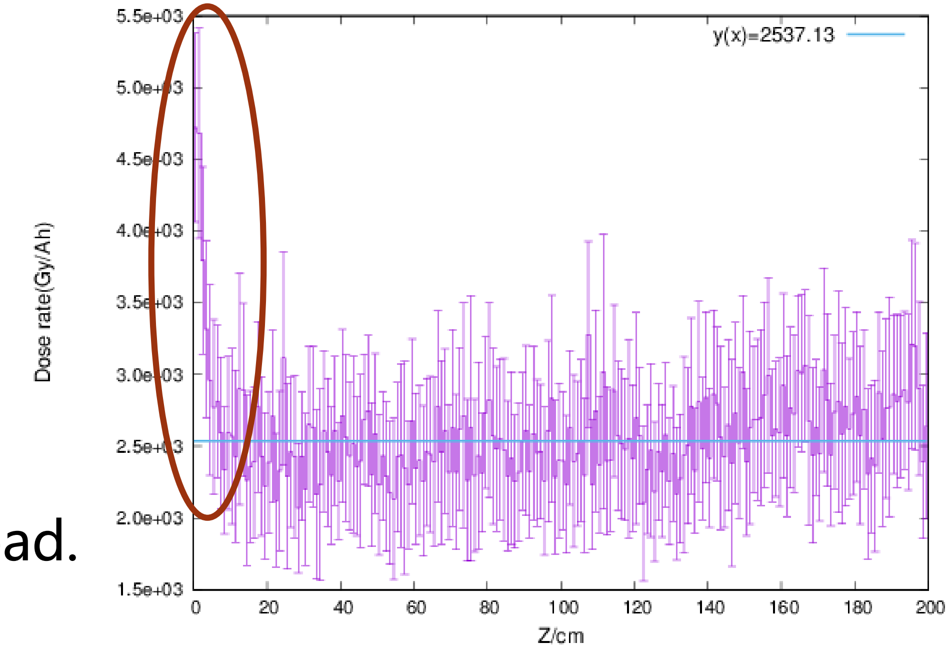
	Higgs	WW	Z	ttbar
Current(mA)	1	2.69	14.4	0.12
Injection duration(s)	32.8	39.3	134.7	30
Injection interval(s)	38	155	153.5	65

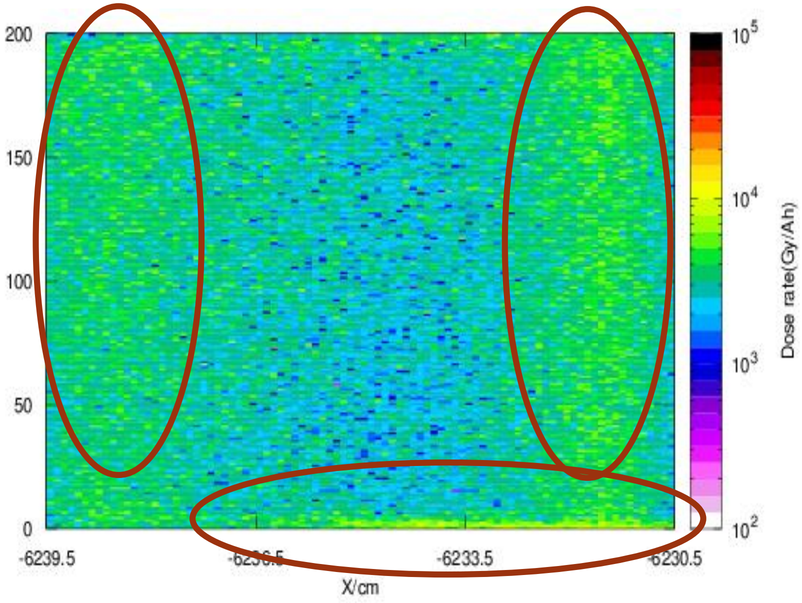
- Ramping simulation: example @Higgs

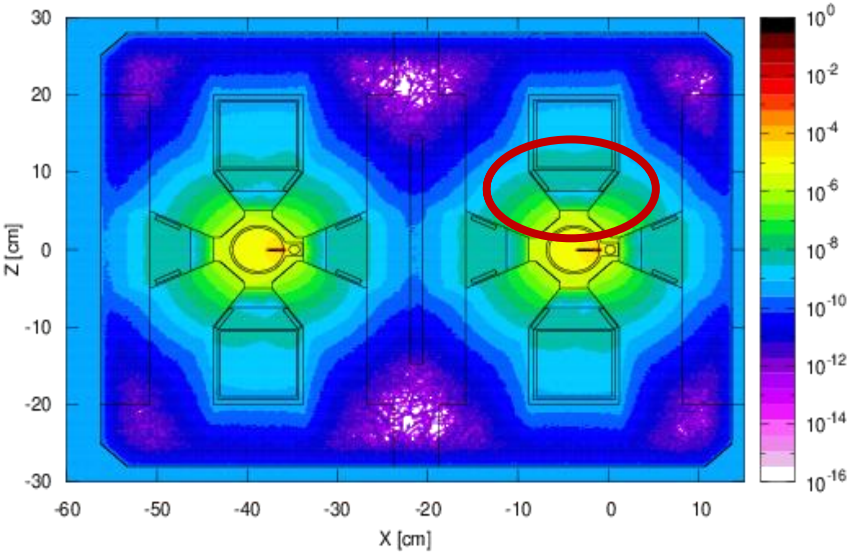


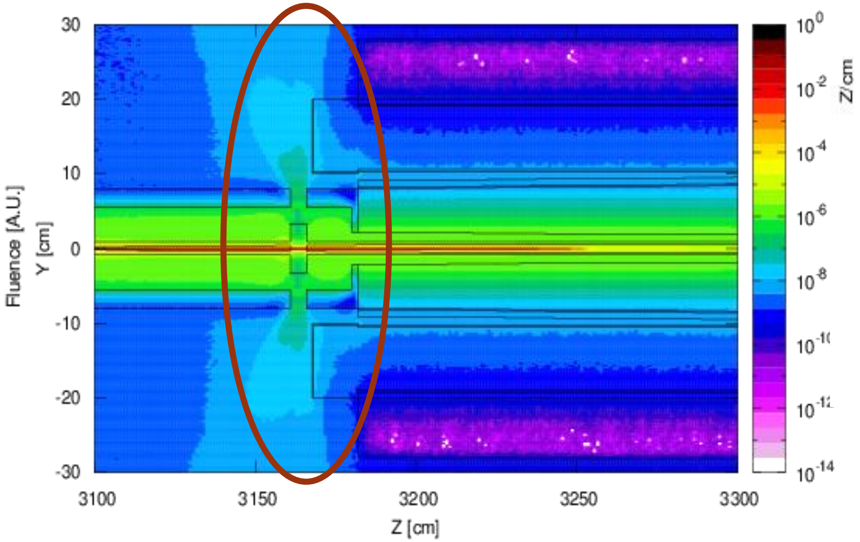
DOSE TO INSULATIONS

- 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.



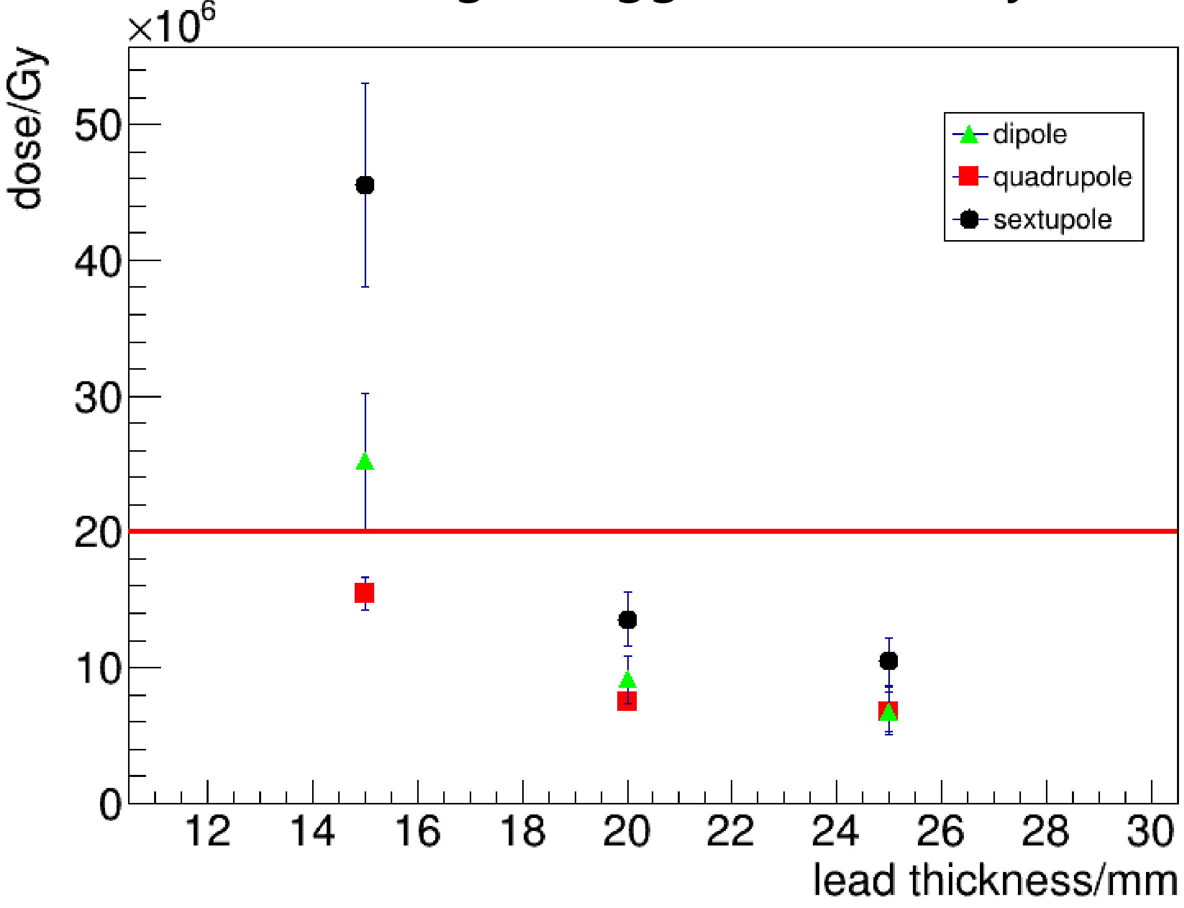






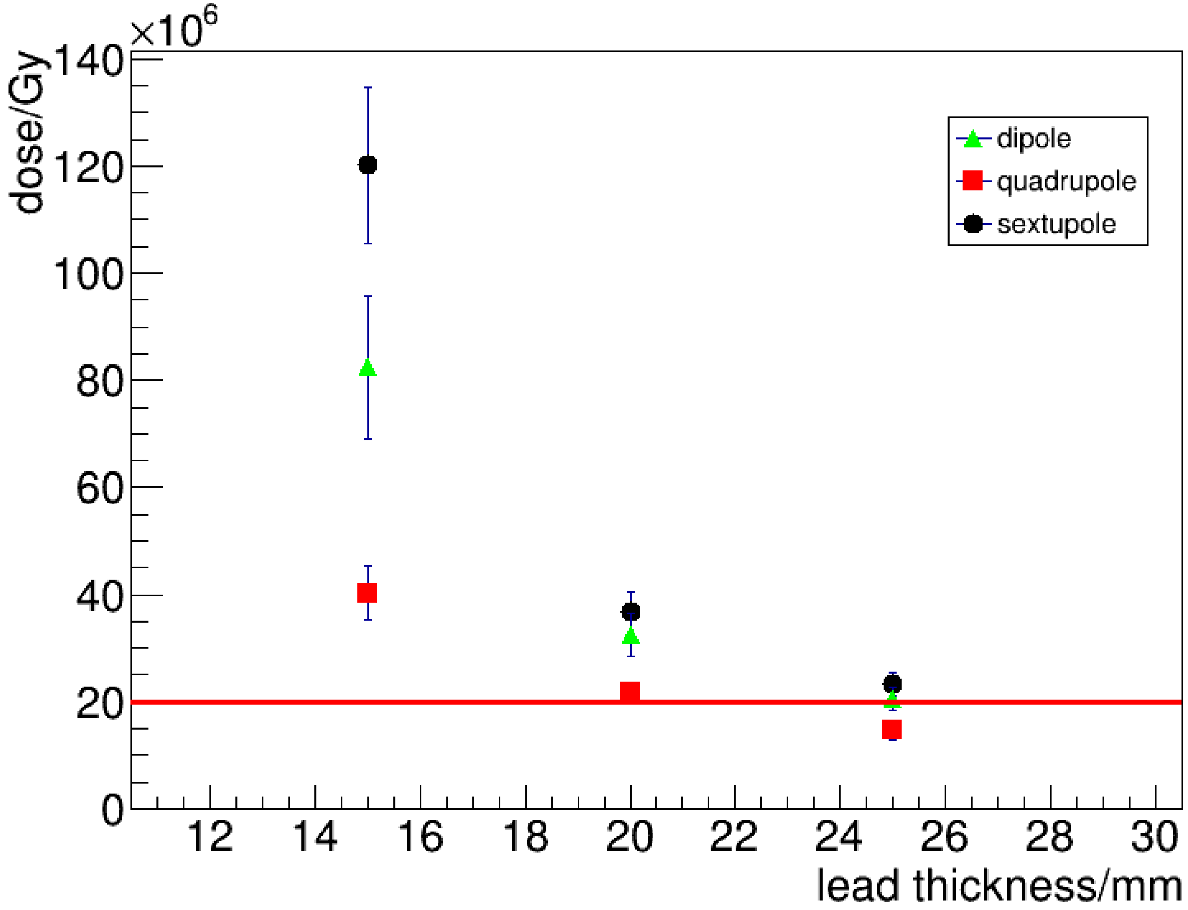
DOSE VS LEAD THICKNESS: 50MW

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



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

- While running another 5 years @ttbar ,

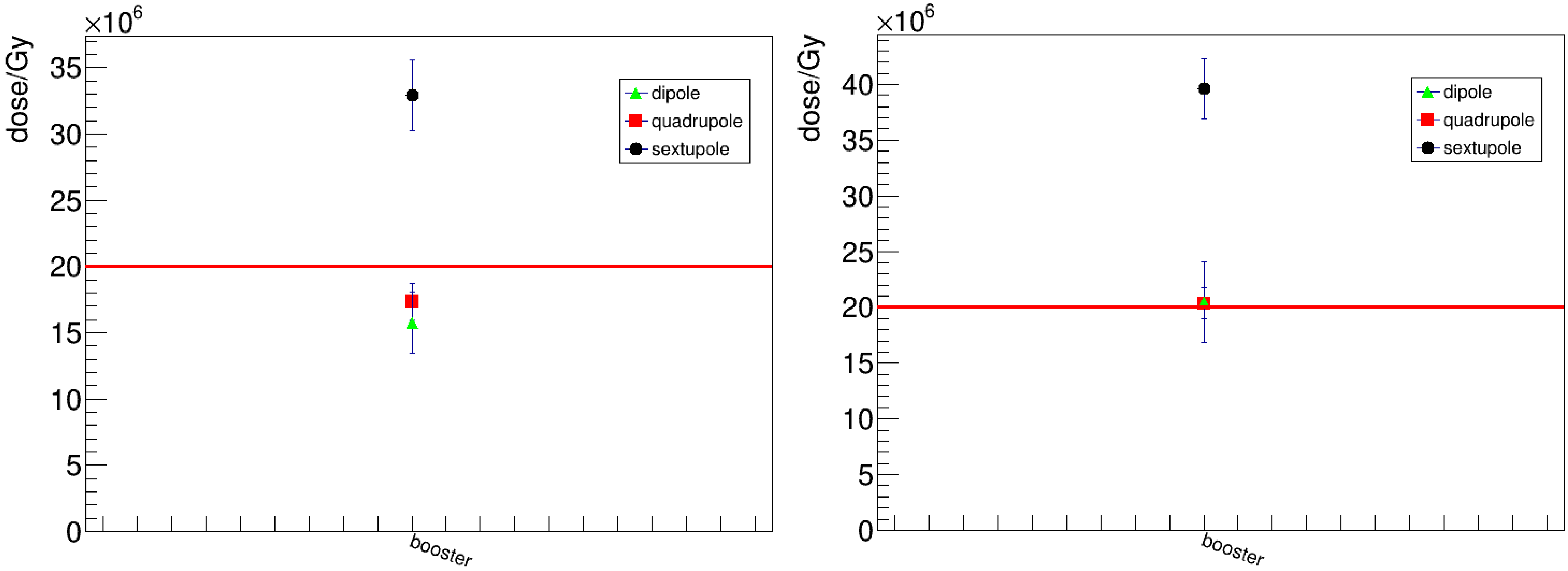


  - 2.5cm lead is needed for dipole and quadrupole, more for sextupole.

- Lead thickness is constrained by the operation schedule.

DOSE TO BOOSTER INSULATION: 50MW

- While running @Higgs/Z/WW (13 years),
- While running another 5 years @ttbar ,



- The dose to dipole and quadrupole is slightly higher than upper limit based on our simulation scheme.
- Pay attention to sextupoles. We will simulate more precisely, with accurate time scheme and beam energy.

RADIONUCLIDES SIMULATION

- Beam losses & 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
Beam losses/114 m	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:
  - Case1: water as wall
  - Case2: rock as wall

- Simulate two critical cases:
  - SR @ttbar and beam losses @Z

SOIL/ROCK

- In previous study, use soil as tunnel wall.
- Now use average components of rocks in each site candidate.
- Simulate productions of residual nuclei after one year running in:
  - Cooling water
  - Air in tunnel
  - Water outside 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

RADIONUCLIDES PRODUCTION

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

		Half-life	Cooling water	
			Specific activity/GB18871	Stat. error (%)
Beam losses @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/GB18871	Stat. error (%)
Beam losses @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	2h	1.4e-3	12
SR @ttbar	C14	5700a	6.5e-6	2
	Ar41	2h	1.5e-2	20

RADIONUCLIDES PRODUCTION

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

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

		Half-life	**Water wall**	
			Specific activity/ GB18871	Stat. error (%)
Beam losses @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

		Half-life	**Rock wall**	
			Specific activity/ GB18871	Stat. error (%)
Beam losses @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

- Should 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.*, $t \rightarrow \infty$ the saturation concentrations are given by:

$$N_{\text{sat}} = \frac{gI}{\alpha + \kappa I + Q/V} . \tag{6.39}$$

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

	Number of SR photons/ 114m	**Deposited energy from photon**	**O3 mass [ug/m^3]**
Higgs	4.7e18	2.8e-8	1.8e-6
WW	1.6e19	1.8e-9	1.5e-6
Z	8.4e19	6.0e-9	9.7e-7
ttbar	1.4e18	7.6e-8	1.1e-6

- Concentration limit
  - O3: 160 ug/m^3; NO2: 40 ug/m^3.
  - Smaller than limits in CEPC cases.

OUTLINE

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- Collider ring dump system
- Linac hot spots and beam losses
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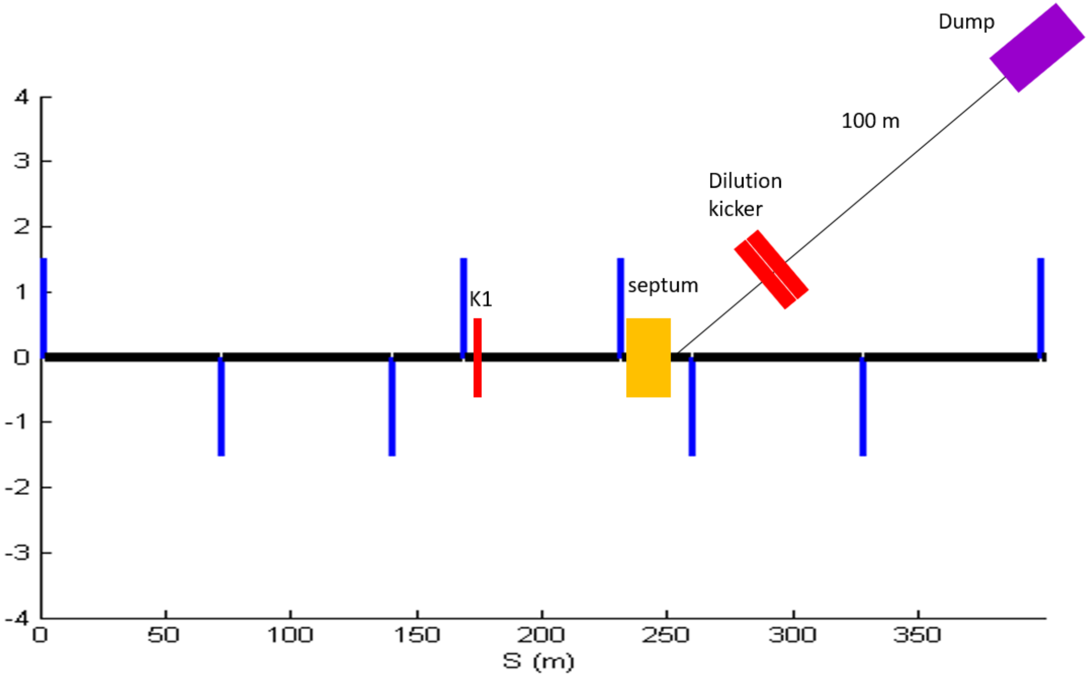
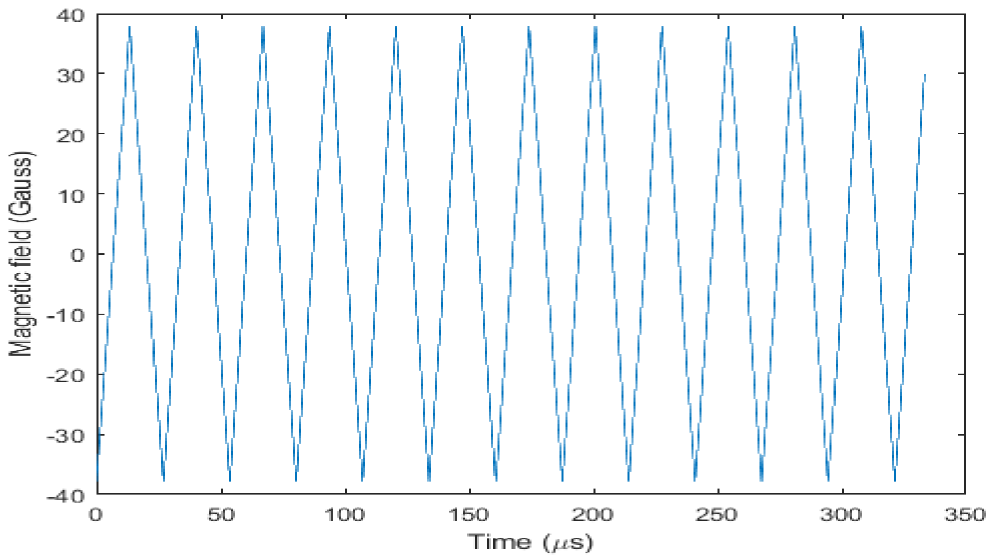
COLLIDER DUMP

- 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 hall 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

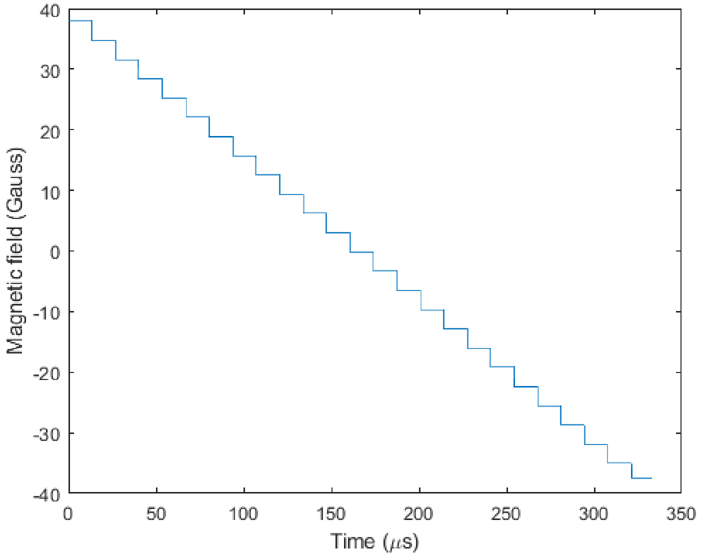
From Xiaohao Cui

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

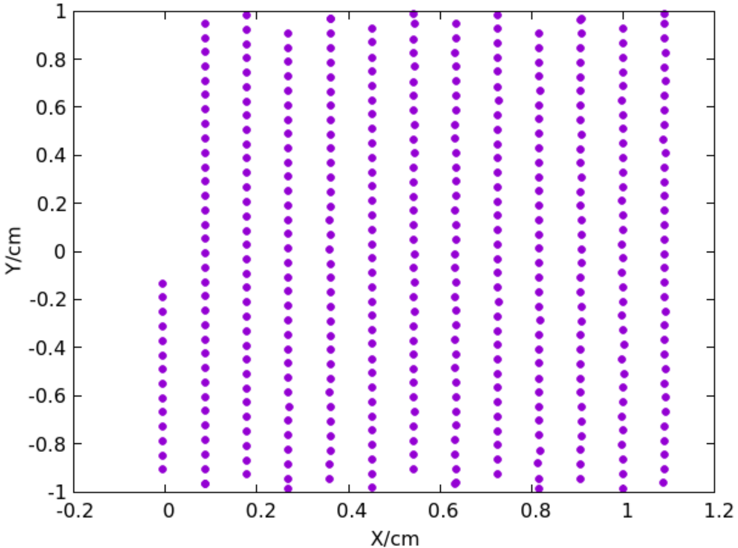
① Simulate energy deposition in dump core.
② Find the maximum energy deposition. And calculate maximum temperature rise.
③ Optimize dump dimensions



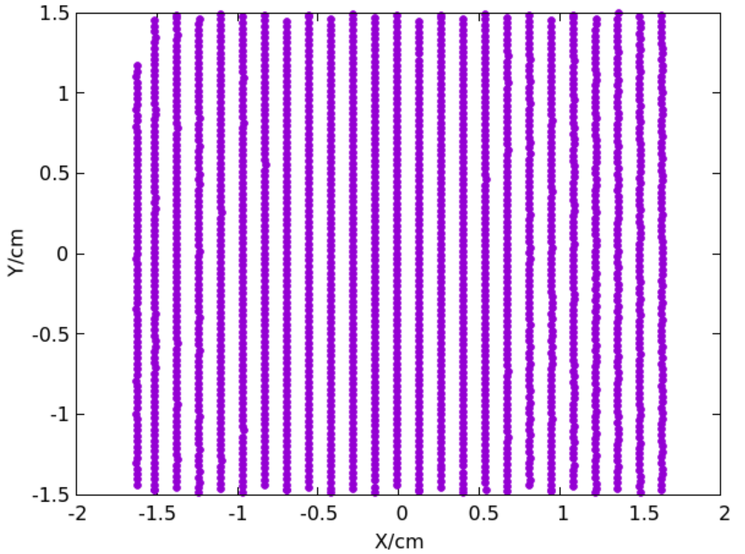
Dilution kicker requirement:

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

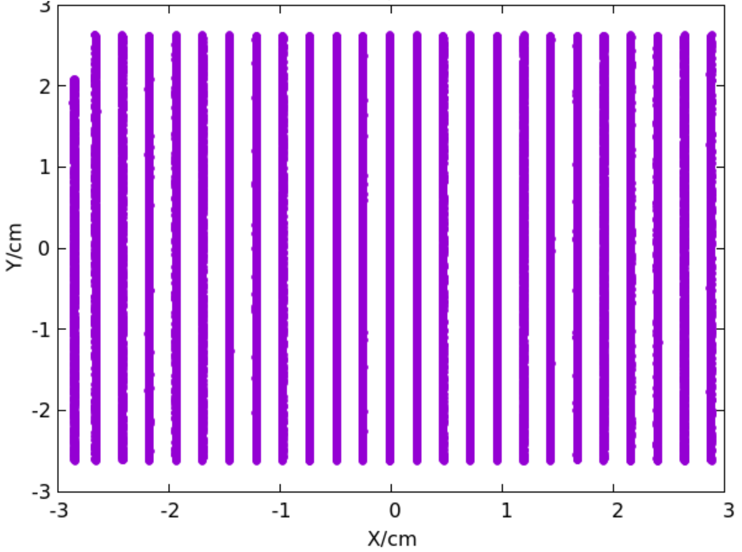
Higgs



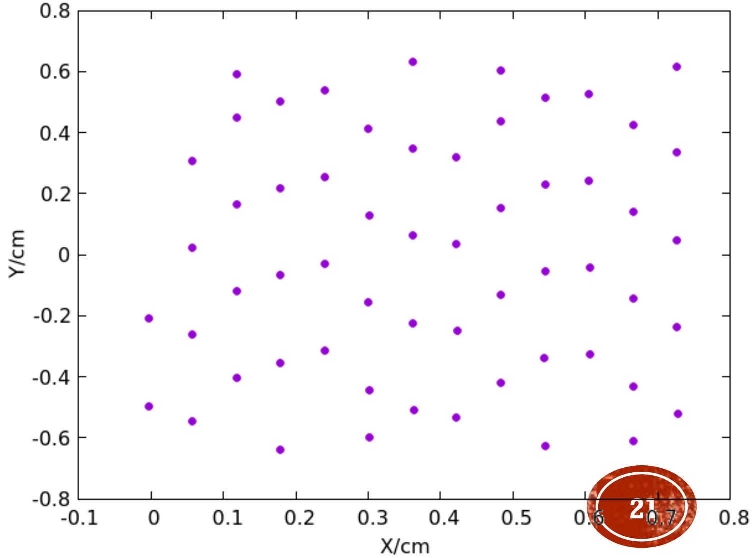
WW



Z pole



ttbar



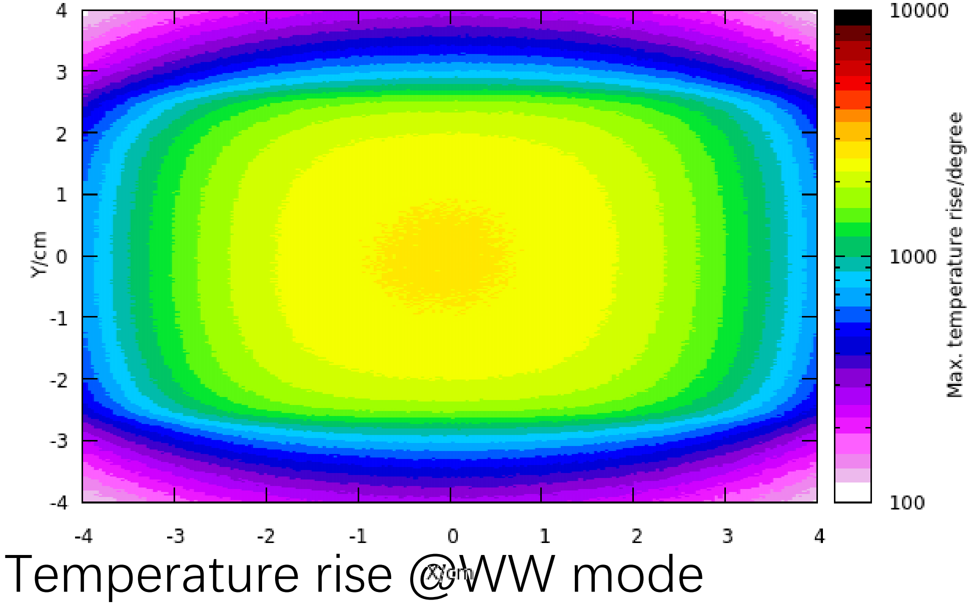
MAX. TEMPERATURE RISE: 50MW

- Example: graphite core

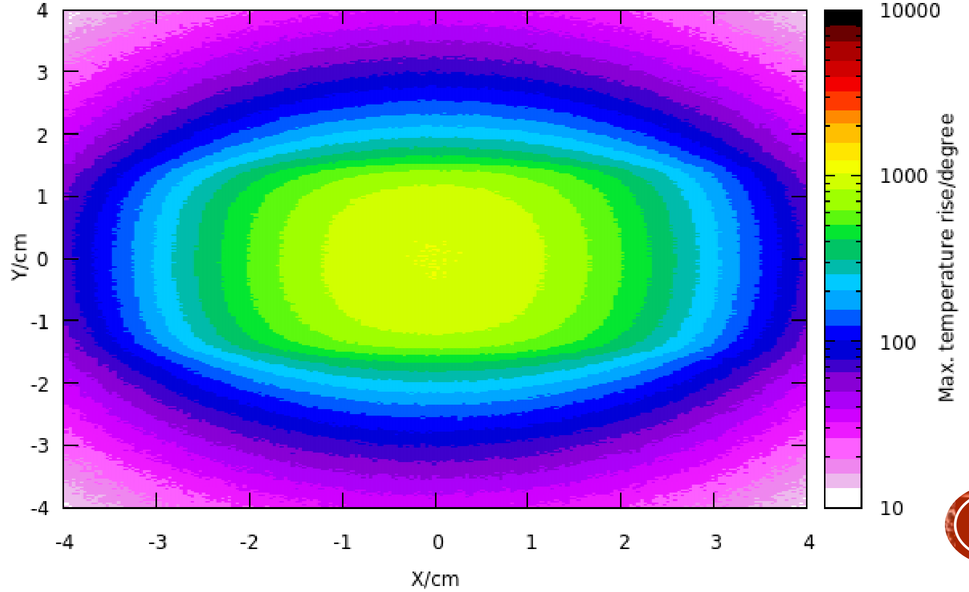
	Higgs	**WW**	**Z**	**ttbar**
Beam energy/GeV	120	80	45.5	180
Ne/bunch/10^{10}	14	13.5	14	20
Bunch number (50MW)	415	2162	19918	58
Max. temperature rise	510 ± 15℃	1020 ± 30℃	2620 ± 15℃	194 ± 2℃
Max. temperature rise by one bunch	7.31 ± 0.03℃	5.38 ± 0.03℃	3.76 ± 0.02℃	10.08 ± 0.04℃

- 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 that dose-eq is smaller than 5.5mSv/h.

- Temperature rise @Z mode

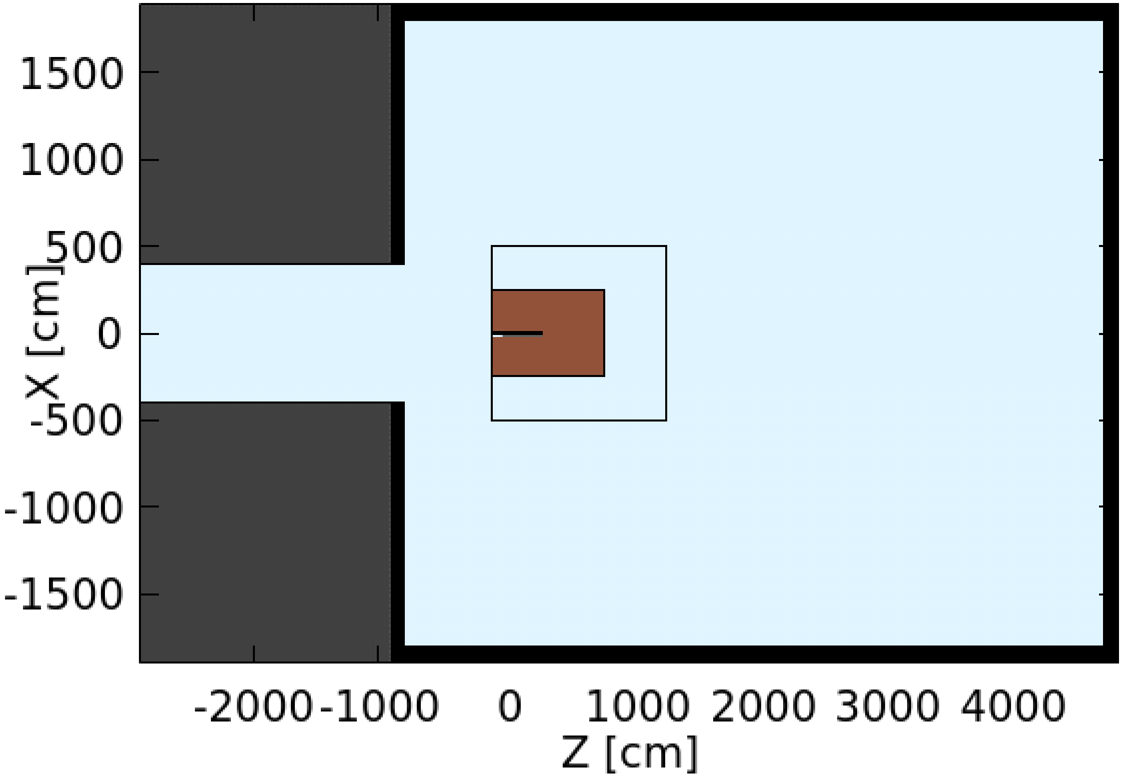


- Temperature rise @WW mode



RADIONUCLIDES PRODUCTION IN DUMP HALL

- A dumping hall geometry in the below.
- Assume dumping beam one time per day
- The radionuclide production is simulated. Meet Chinese mandatory standard.



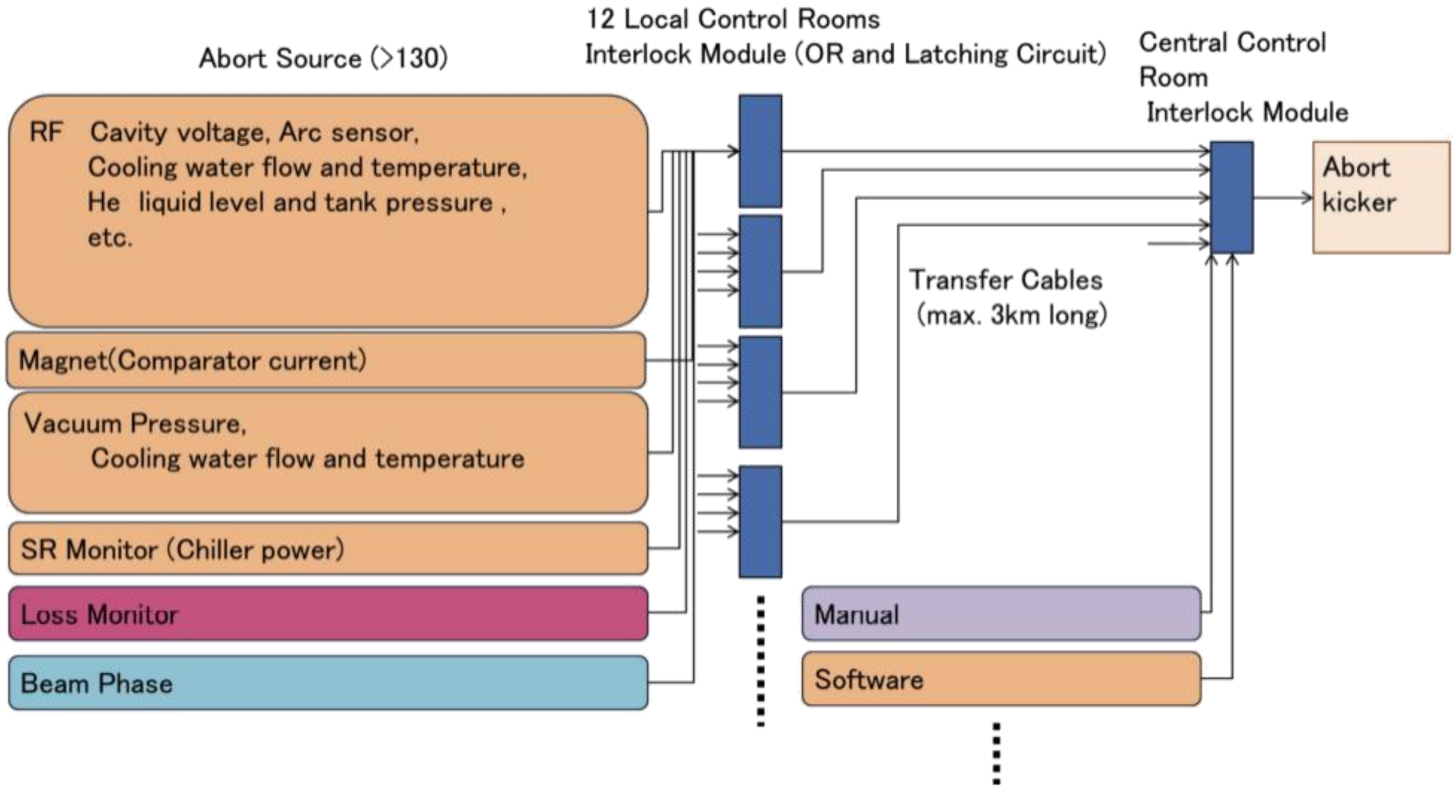
	Half-life	**Concrete wall**	
		Specific activity/GB1 8871	Stat. error (%)
Ca47	4.5d	4.9e-9	100
Ca45	163d	3.1e-9	17
Na24	15h	1.0e-4	5
Na22	2.6y	1.4e-8	100
H3	12a	1.6e-13	56

	Half-life	**Air in dump hall**	
		Specific activity/GB1 8871	Stat. error (%)
C14	5700a	3.1e-9	7
H3	12a	1.5e-11	49
Ar41	2h	5.6e-10	33

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.

SuperKEKB Design Report



Abort Source (>130)

12 Local Control Rooms
Interlock Module (OR and Latching Circuit)

Central Control Room
Interlock Module

RF Cavity voltage, Arc sensor, Cooling water flow and temperature, He liquid level and tank pressure, etc.

Magnet(Comparator current)

Vacuum Pressure, Cooling water flow and temperature

SR Monitor (Chiller power)

Loss Monitor

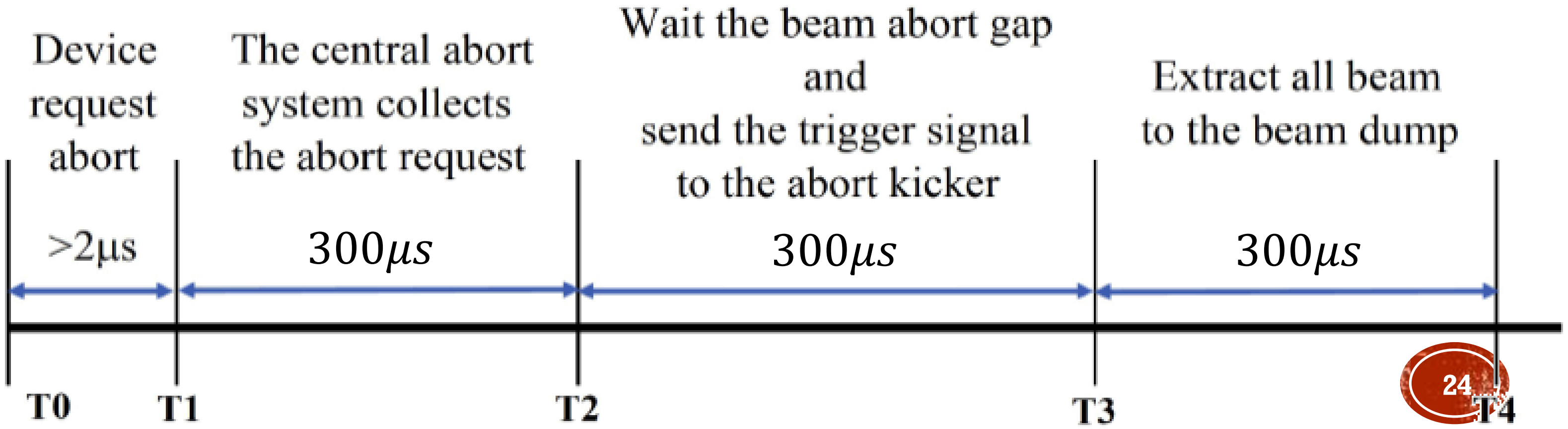
Beam Phase

Transfer Cables (max. 3km long)

Manual

Software

Abort kicker



Device request abort

>2μs

The central abort system collects the abort request

$300\mu s$

Wait the beam abort gap and send the trigger signal to the abort kicker

$300\mu s$

Extract all beam to the beam dump

$300\mu s$

T0

T1

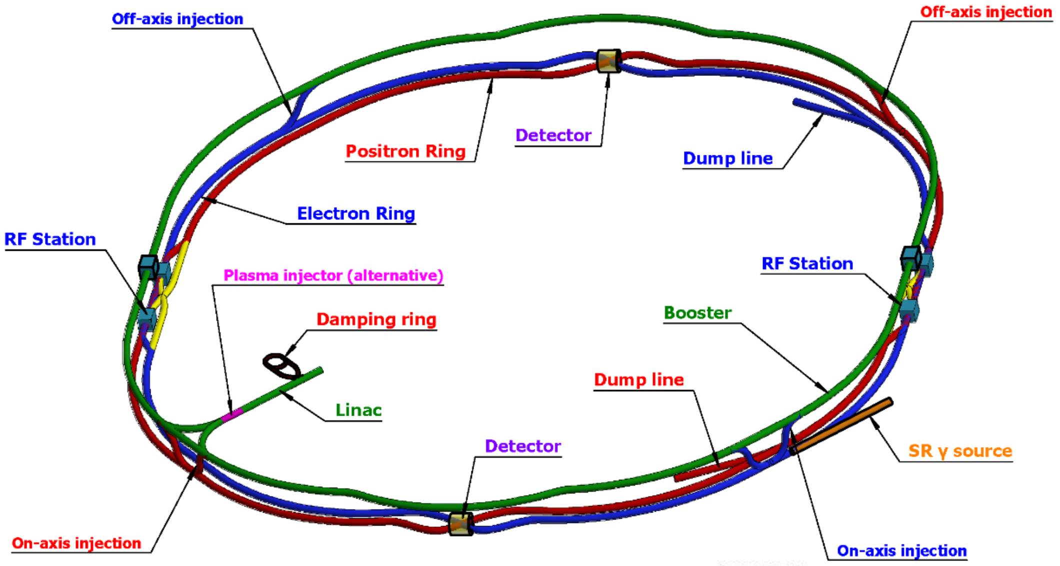
T2

T3

T4

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.



- Will study reliability (or alternative design).
- Need absorber to protect machine elements from incorrect dumping.

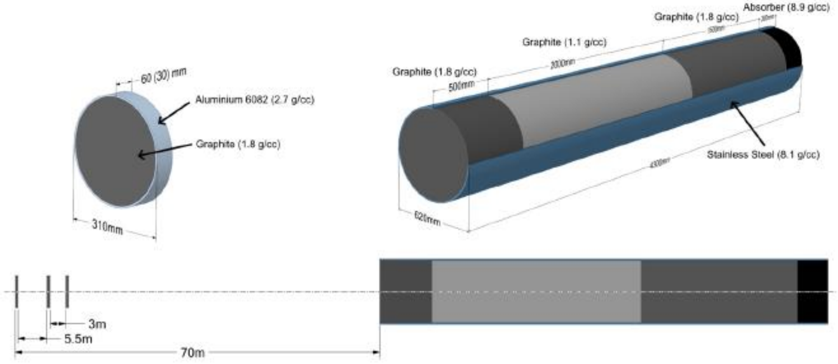


Figure 4 Overview of the geometry used in FLUKA simulations. Different spoiler configurations were simulated: 1 × 6 cm, 2 × 3 cm and 3 × 3 cm long spoilers

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

- Response time ~ 1ms.
- Need collimators to deal with beam losses faster than 1ms.
  - fault cases.

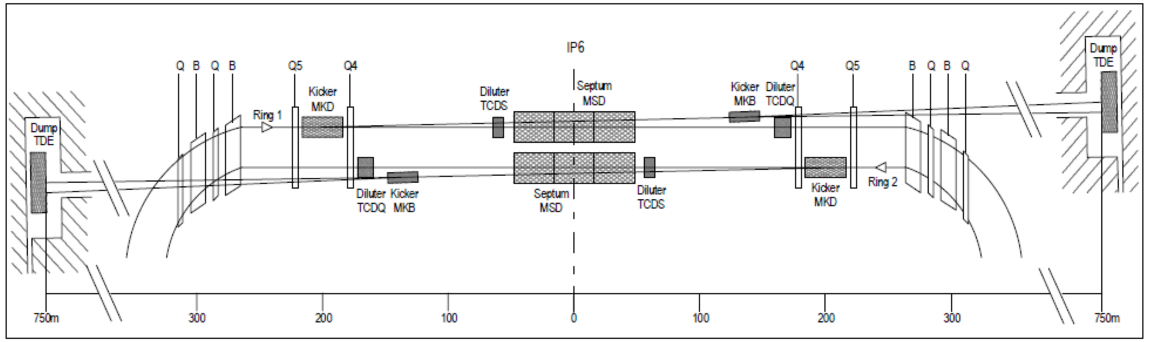


Figure 17.1: Schematic layout of beam dumping system elements around LHC point 6.

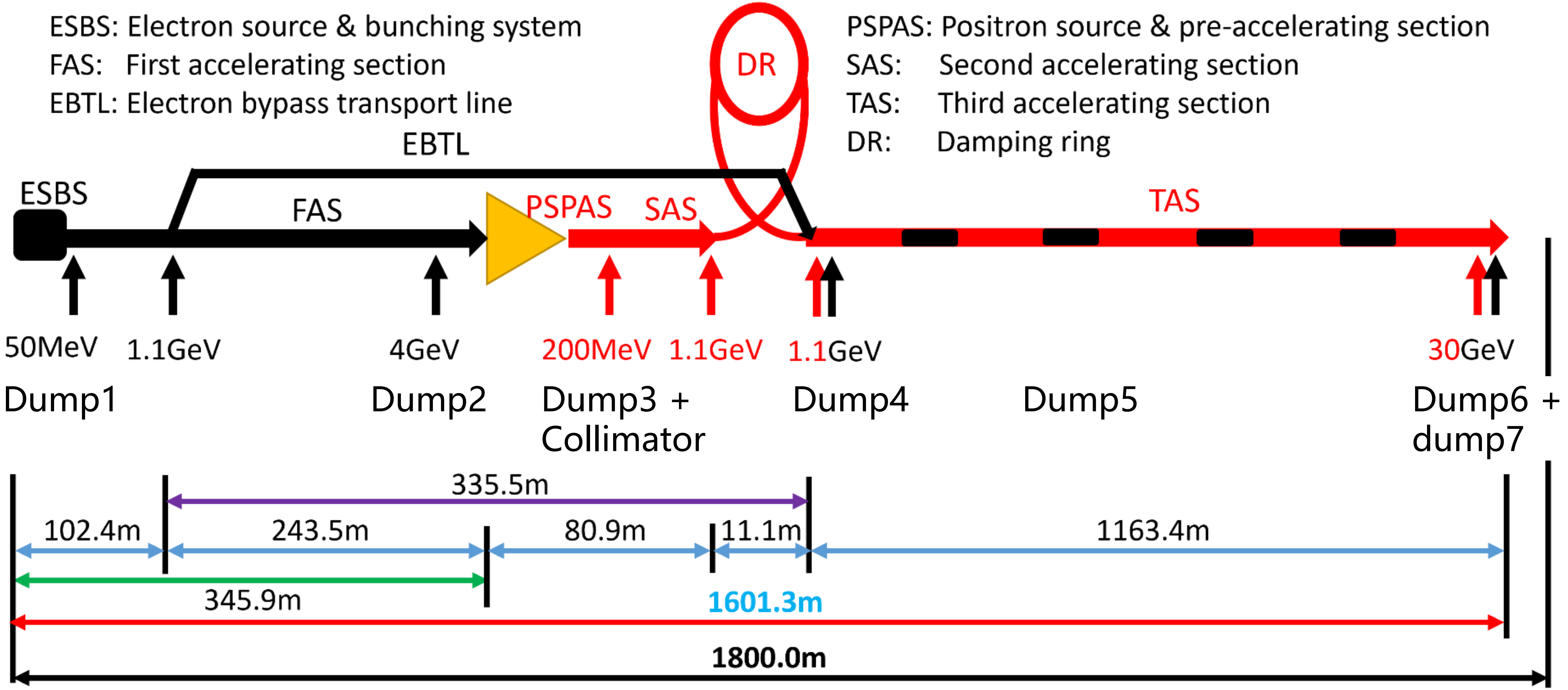
LHC design report Ch.17

OUTLINE

- Introduction
- Synchrotron radiation shielding
- Radionuclide productions
- Collider ring dump system
- Linac hot spots and beam losses
- Summary and outlook

CEPC LINAC

- Length: 1601.3m; 7 dumps and 1 collimator;



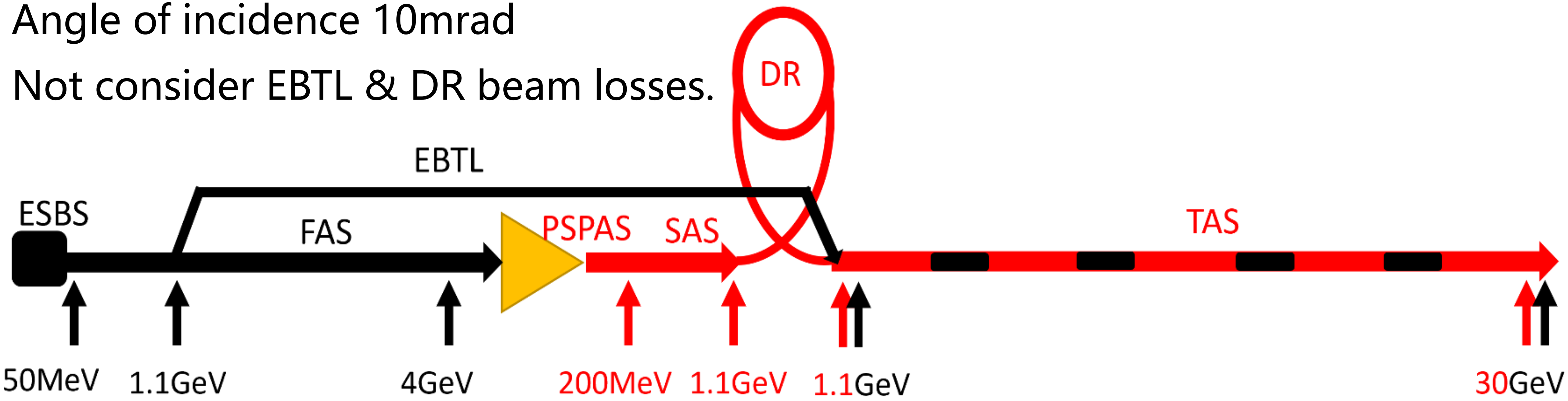
ESBS: Electron source & bunching system
FAS: First accelerating section
EBTL: Electron bypass transport line

PSPAS: Positron source & pre-accelerating section
SAS: Second accelerating section
TAS: Third accelerating section
DR: Damping ring

LINAC BEAM LOSSES ASSUMPTIONS

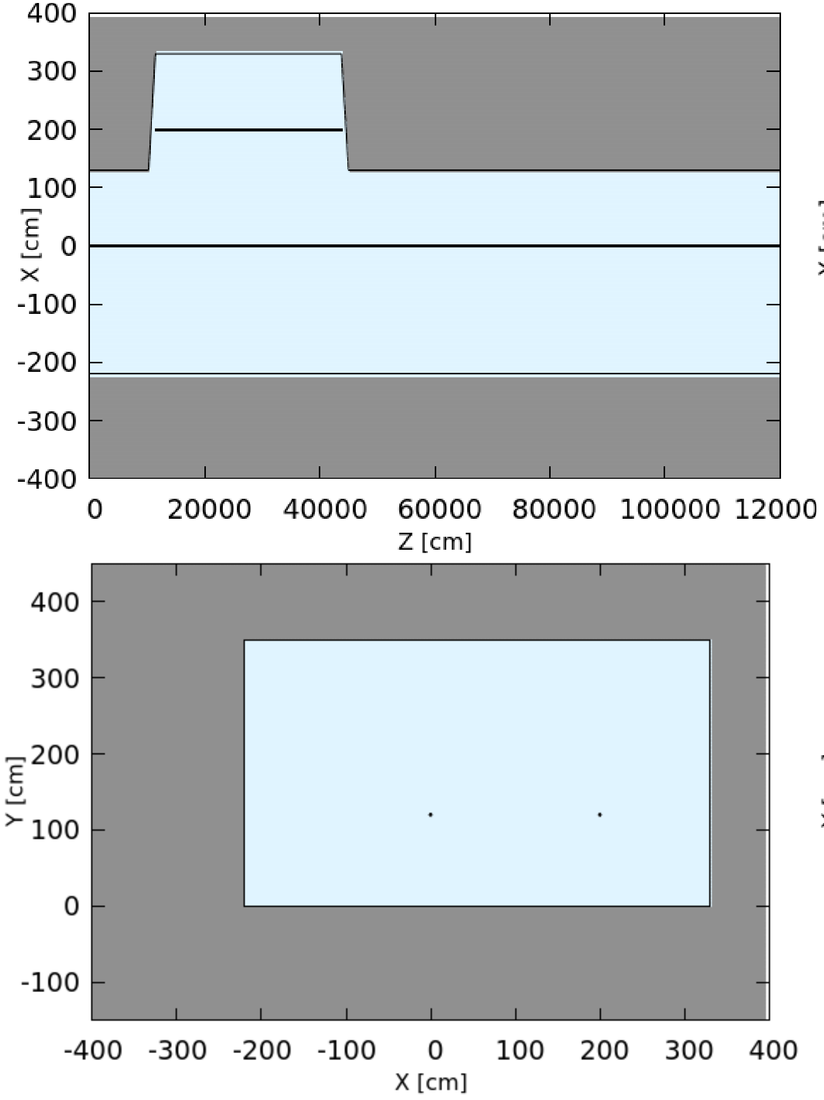
Position	Length	Beam energy	Number of bunches [s^{-1}]	Beam loss/bunch [nC]	Number of particles [10^{10}/s]
FAS	100m	300MeV	200	0.5	62.5
Positron target	15mm	4GeV		10	1250
PSPAS	15m	5~200MeV		10	1250
SAS	3m	300MeV		2	250
	30m	600MeV		0.2	25
TAS	1163m	1.1~30GeV		0.1	12.5

- Angle of incidence 10mrad
- Not consider EBTL & DR beam losses.

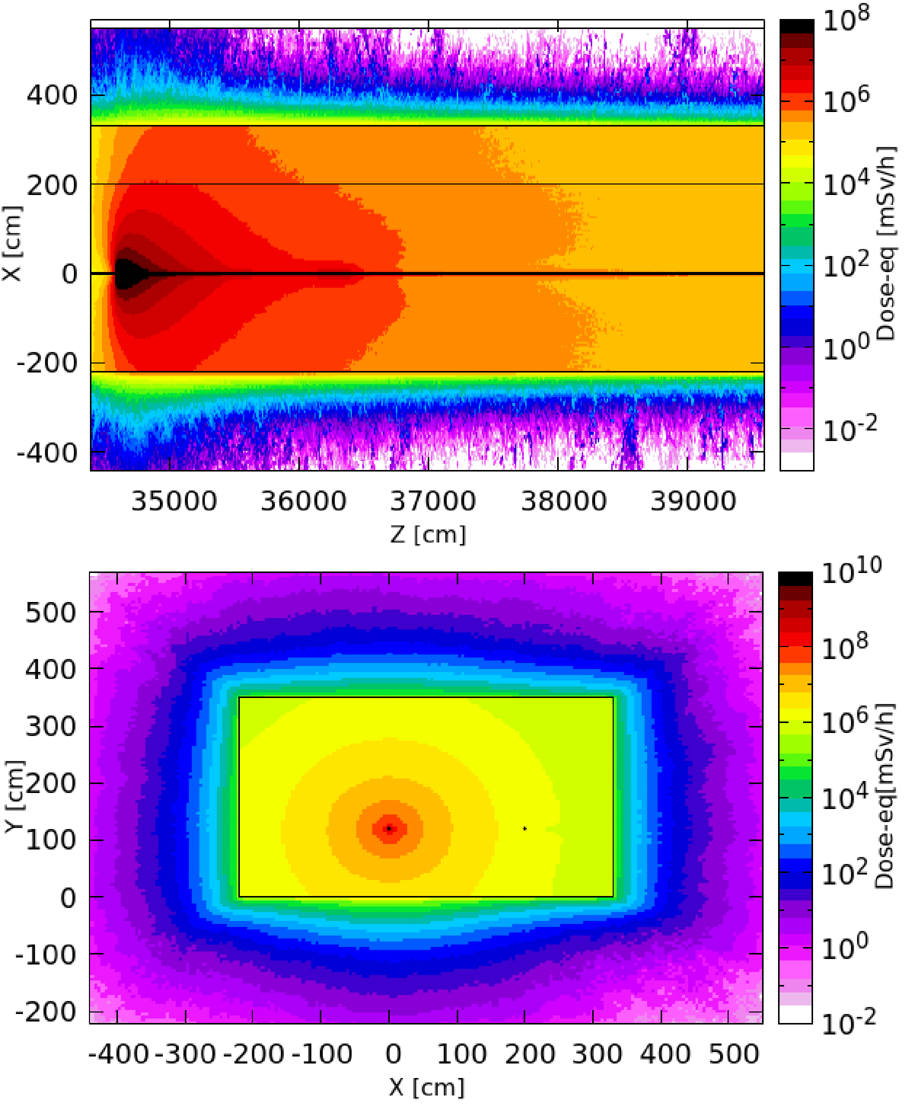


SIMULATION SETUP

- Beam pipes and concrete wall
- Top/side view



- Dose-eq distribution example: SAS

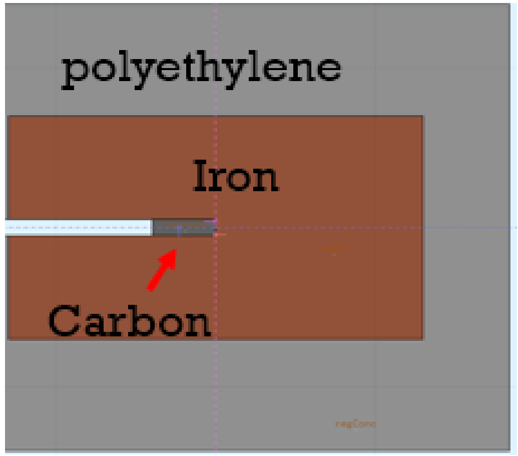


- Thickness of Shielding wall according to upper limit 5.5mSv/h (left/right/bottom) or 2.5uSv/h(top).

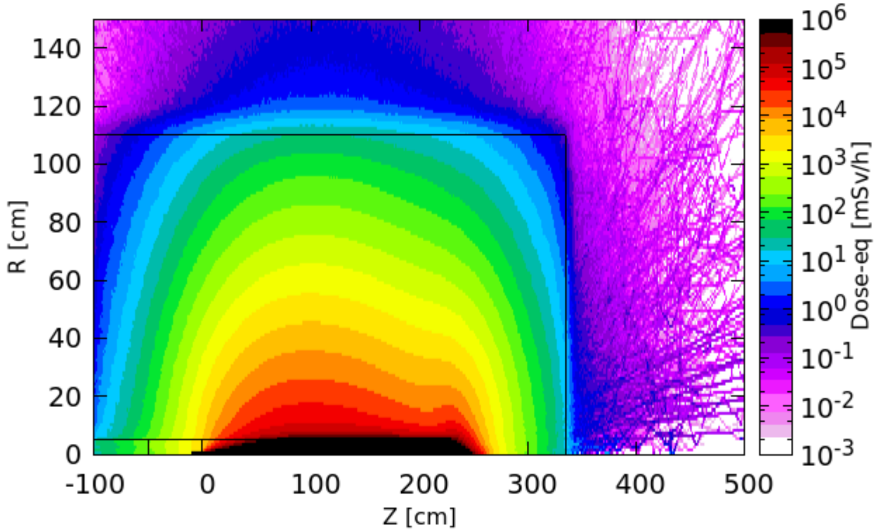
Wall thickness	**FAS**	**SAS**	**TAS**
Left	0.3m	1.9m	0.3m
Right	0.2m	1.9m	0.3m
Bottom	0.3m	2.1m	0.3m
Top	1.3m	4.1m	2.0m

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

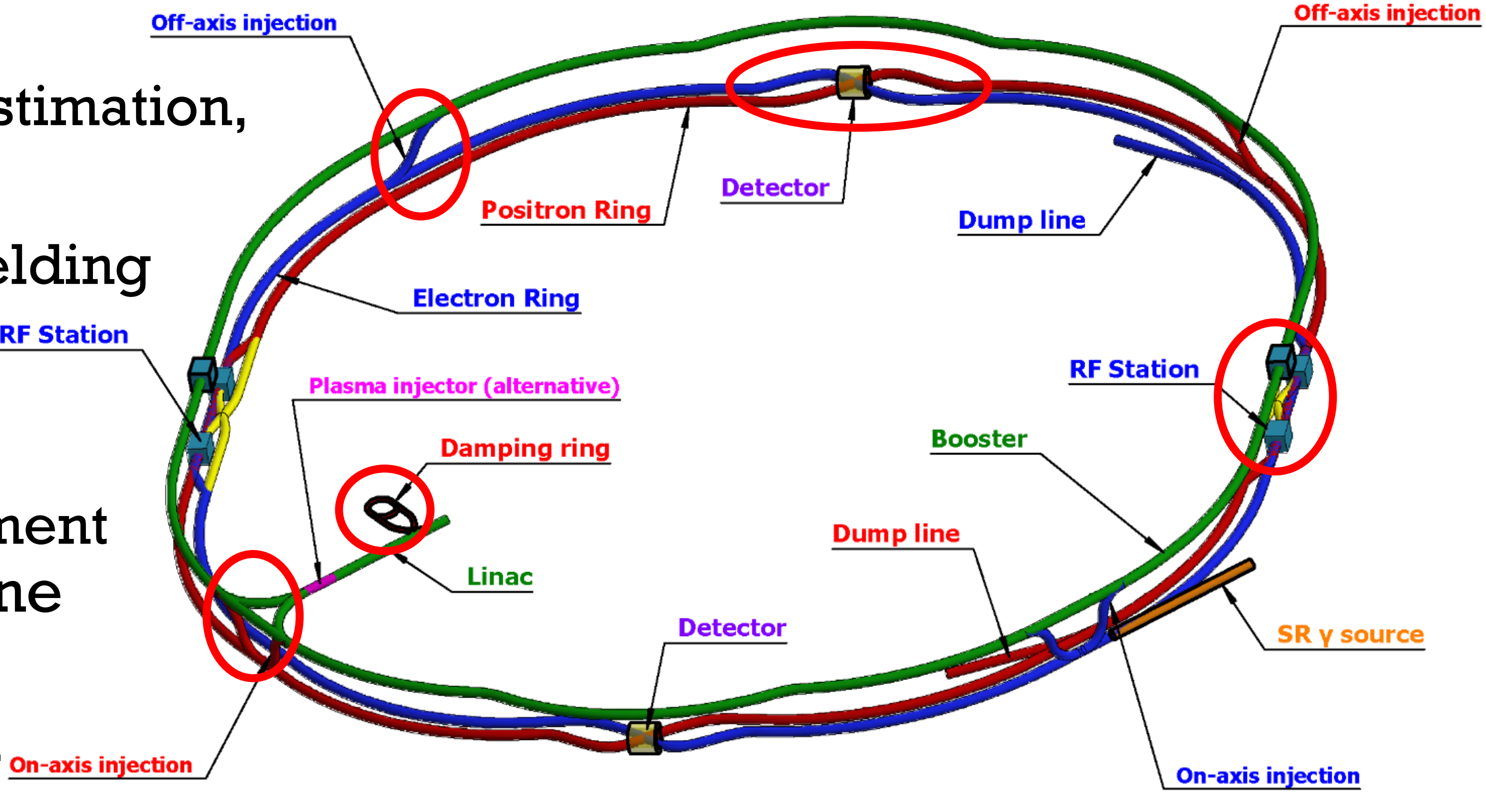
Preliminary design results for different beam energy analysis station:
Radiation level nearby each energy analysis station was figured out, also specify a roughly space for the future local shielding.

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

SUMMARY

- Have studied:
  - lead shielding design,
  - radionuclides productions estimation,
  - Collider dump design,
  - Linac hot spots and bulk shielding

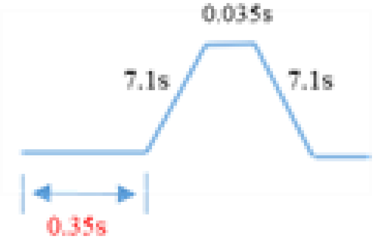
- Go on:
  - Shielding design for experiment hall/RF hall/DR/transport line
  - Reliability study for dump.
  - Machine protection: fault cases.



Thank you

BACKUP

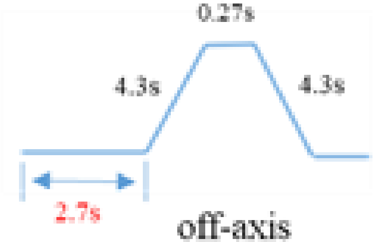
tt



1 cycles/beam

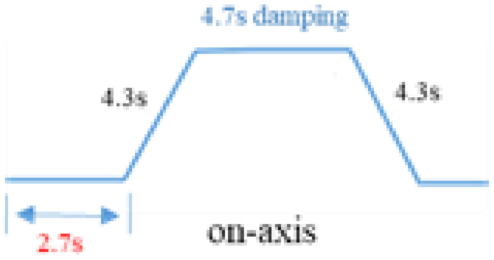
0.35s+7.1s+0.035s+7.1s=14.6s

Higgs



off-axis

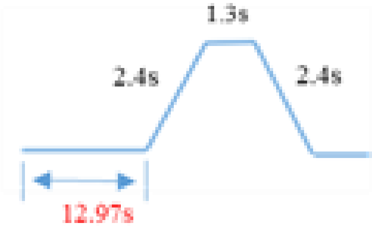
1 cycles/beam



on-axis

2.7s+4.3s+4.7s+4.3s=16.0s

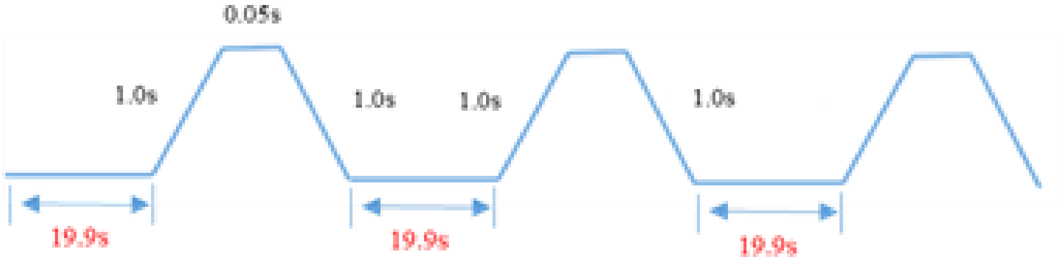
W



1 cycles/beam

12.97s+2.4s+1.3s+2.4s=19.1s

Z



(19.9s+1.0s+0.05s+1.0s)*3=65.9s

3 cycles/beam