國家同步輻射研究中心
National Synchrotron Radiation Research Center

Radiation Safety Considerations for the TPS Accelerators

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NSRRC, Taiwan

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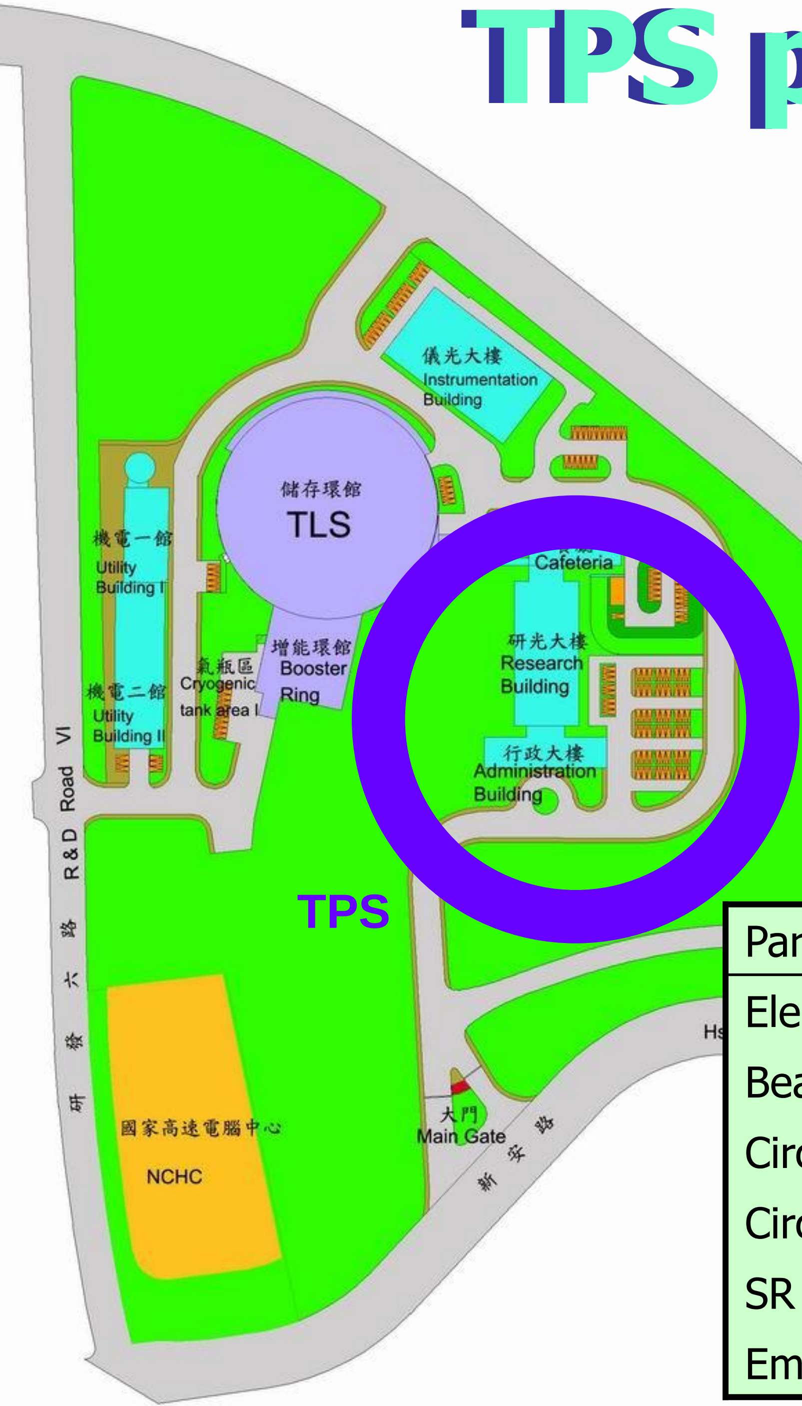
TPS project in NSRRC

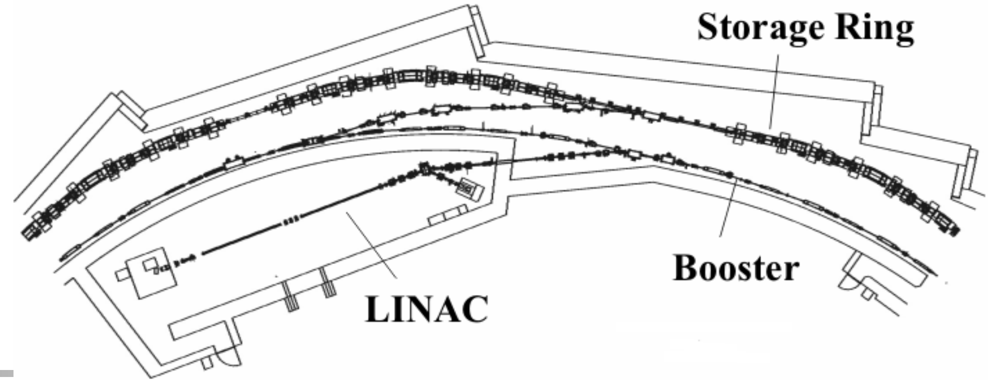


Parameters	TLS	**TPS**
Electron Energy	1.5 GeV	**3.0 GeV**
Beam Current	300 mA (Top-up)	**400mA** (Top-up)
Circ. (Str. Ring)	120 m	**518.4 m**
Circ. (Booster)	72 m	**499.2 m**
SR Lattice	6-cell TBA	**24-cell DBA**
Emittance	< 20 nm.rad	**< 2 nm·rad**

Outline

- Beam Loss Estimation
- Shielding Configuration
- Tools and Models for Design/Analysis
- Dose Assessment for TPS Operation
- Maximum Credible Radiation Incidents
- Radiation Streaming through Penetrations
- Induced Activity and Residual Dose
- Radiation Safety System
- Summary

Beam Loss Assumption



SLS Operation: Extraction/Transfer/Ramping/Injection Efficiency (SLS Handbook)

LINAC 0.9W → 80% → Booster (95%) → 90% → BTS → 90% → Storage Ring (I=400mA, τ=10Hr)

62%

81%

TPS Operation: Extraction/Transfer/Ramping/Injection Efficiency

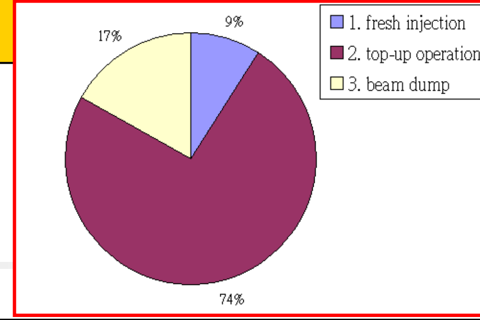
LINAC 2.25W → 90% → LTB (90%) → 90% → Booster (90%) → 90% → BTS (90%) → 90% → Storage Ring (I=400mA, τ=7Hr)

48%

73%

Reference Beam Loss → Operation Envelope → Safety Envelope

A estimate of total electron loss per year is **7.71×10^{15}** [e^-/y], based on the assumption of 6000 hours operation in 300 days. For a typical daily operation: one fresh injection to 400 mA, top-up operation for 20 hours, and then the beam dump.



Beam Loss Estimation

Beam Loss Analysis for TPS Normal Operation

Location		Electron (e^-/s)	Electron (W)	Operation	Loss (e^-/s)	Loss (W)	Shielding	Loss (e^-/s)[d]	Loss (W)
GUN	inlet	n/a	n/a	Start	n/a	n/a	LINAC Room	Inj. 4.58E+10 Str. 0.00E+00	Inj. 0.48 Str. 0.00
	outlet	1.30E+11	1.88E-03	Ext./Inj.	2.60E+10	3.75E-04			
LINAC	inlet	1.04E+11	2.50	Ramping	1.04E+10	0.25			
	outlet	9.38E+10	2.25	Ext./Inj.	9.38E+09	0.23			
LTB	inlet	8.44E+10	2.03	Transfer	8.44E+09	0.20	Shared Tunnel	Inj. 3.95E+10 (2.43E+10)[e] Str. 1.71E+08	Inj. 11.67 Str. 0.0823
	outlet	7.59E+10	1.82	Ext./Inj.	7.59E+09	0.18			
Booster	inlet	6.83E+10	32.81	Ramping	6.83E+09	3.28			
	outlet	6.15E+10	29.52	Ext./Inj.	6.15E+09	2.95			
BTS	inlet	5.54E+10	26.57	Transfer	5.54E+09	2.66			
	outlet	4.98E+10	23.91	Ext./Inj.	4.98E+09	2.39			
Storage Ring	inlet[a]	4.48E+10	21.52	Storage[b]	1.71E+08	8.23E-02			
	outlet	n/a	n/a	Dump[c]	4.32E+12 (e^-)	2073.6 (J)			

a. It will take 96.34 seconds to fill the storage ring in 400 mA.

b. Estimating electron loss rate during beam storage, we assume 400 mA top-up operation and the corresponding lifetime is 7 hours.

c. For a beam dump event, we assume 400 mA maximum stored beam current.

d. Inj. stands for the electron loss rate during beam injection period and Str. for electron loss rate during beam storage period.

e. Shielding design is determined by power-normalized electron loss rate, since electrons lost inside the shared tunnel during injection are not in the same energies.

Safety and Operation Envelopes

ANSI N43.1 Standard:
Radiation safety for the design and operation of particle accelerators

- **Safety Envelope (SE)**: The limiting parameters within which the accelerator is required to operate. These generally include the maximum beam energy and current, maximum beam losses, the dose limits to workers and public etc.
  - Max beam power ≦ E=3.0GeV I=400mA
  - Max deliverable beam power from LINAC ≦ 2.25W
  - Max personnel dose ≦ 1.0 mSv for 2000h working time
  - Max environment dose ≦ 0.5 mSv for 6000h operation

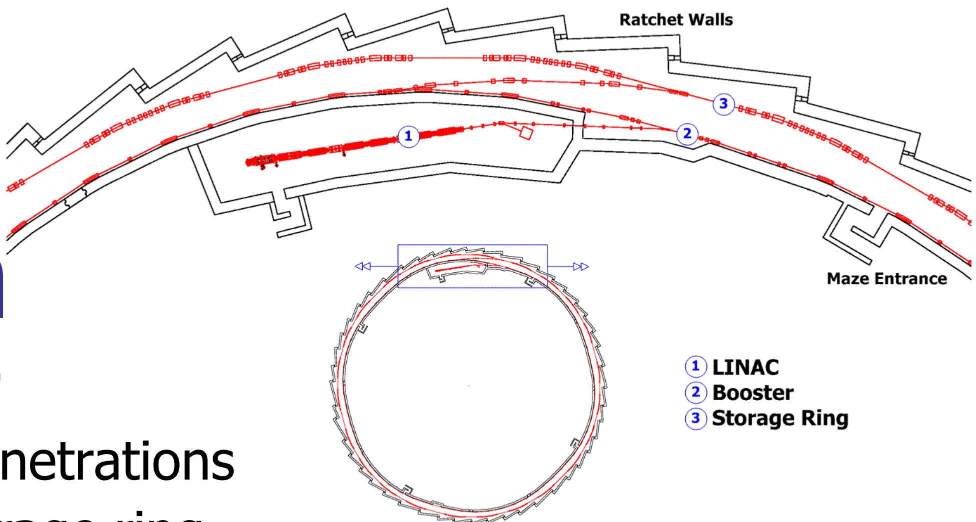
Interlock /Inhibit

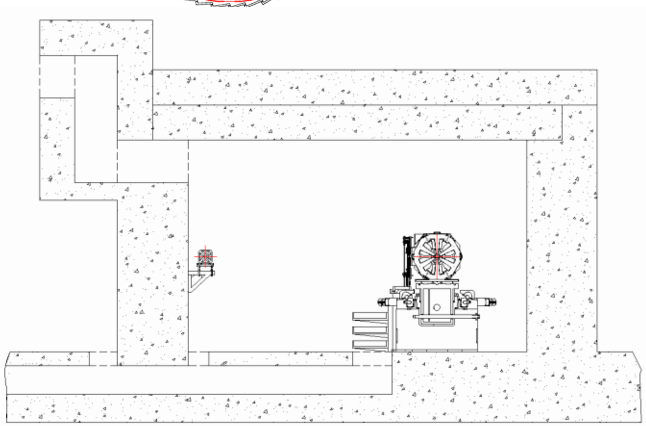
- **Operation Envelope (OE)**: The limiting parameters and/or conditions within which the accelerator is expected to operate to maintain an acceptable level of risk to both workers and the general public. The OE must be within the SE. A beam loss in excess of the OE is called abnormal beam loss.
  - Beam loss estimation for TPS normal operation (reference)
  - Operational bounding conditions:
    max electron loss rate at each stage ≦ **5 x** normal beam loss
  - Accelerator operation outside the OE shall require approval by the operation manager and the radiation safety officer, safety procedures for handling exceptional conditions will be established.

Interlock /Alarm

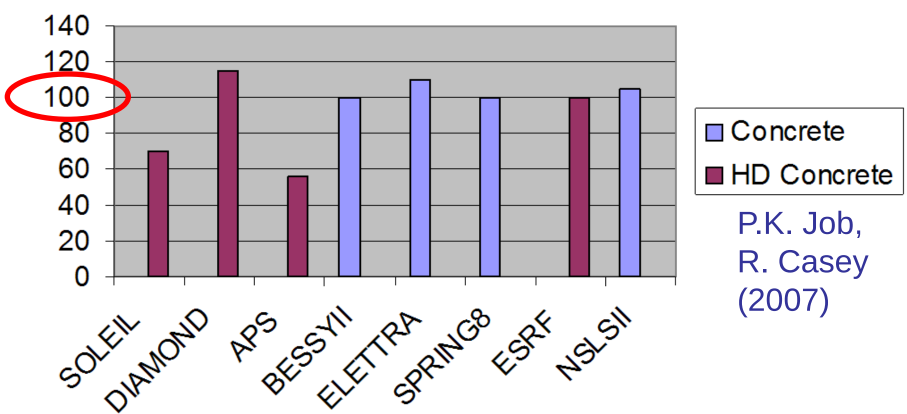
Shielding Configuration

- Ratchet-style shielding & some penetrations
- Shared tunnel for booster and storage ring
  - Inner/outer walls and roof: 100 cm concrete
  - Injection area: 120 cm concrete
  - Ratchet end wall: 120 cm concrete
- Independent LINAC room
  - Walls and roof: 100 cm concrete
  - Beam dump for LINAC alone operation
- Special-designed local shielding
  - Mazes and trenches
  - BL openings
  - Frontends and beamlines
  - SRF waveguide
  - IDs cryogenic piping
  - Possible hot spots



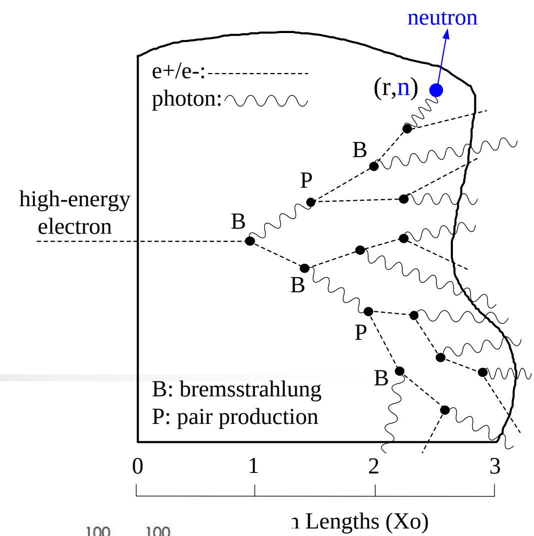


Bulk Shield at Experimental Floor Side

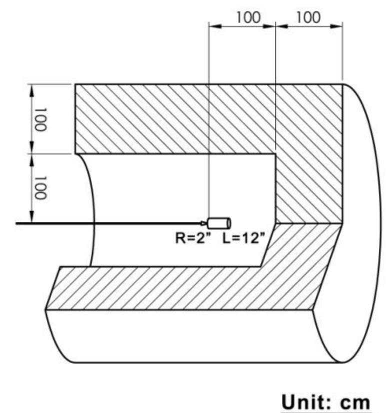


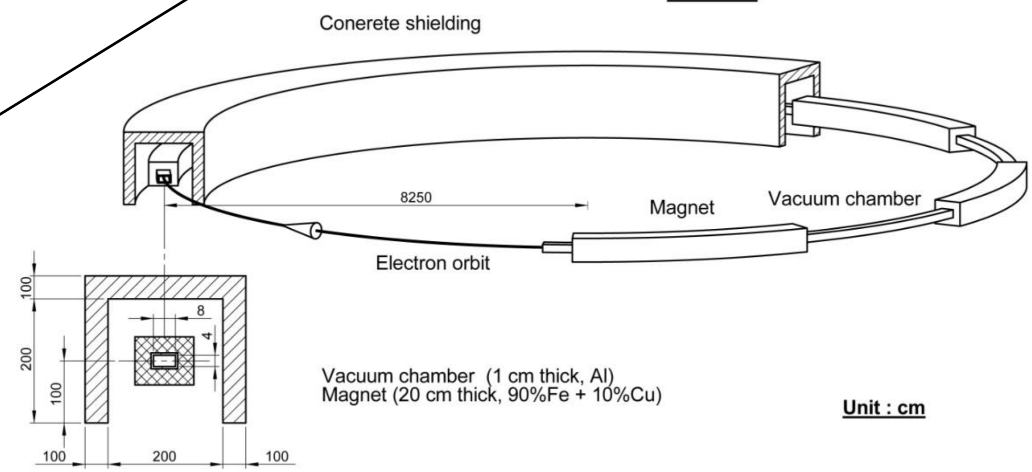
P.K. Job, R. Casey (2007)

Tools and Models for Design/Analysis

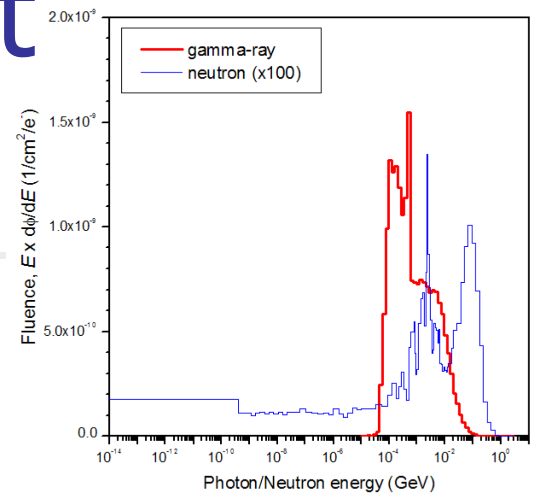


- Tools
  - **SHIELD11** code:
    semi-empirical analytical method (SLAC)
  - **FLUKA** code:
    Monte Carlo method (INFN/CERN/SLAC)
  - **MCNPX** code:
    Monte Carlo method (LANL)
- Models
  - Point loss:
    localized beam loss
  - Uniform loss:
    distributed beam loss

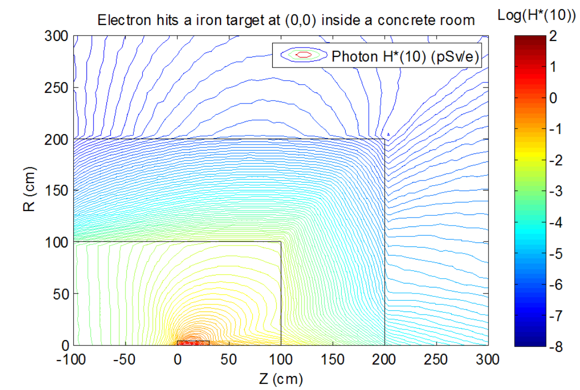




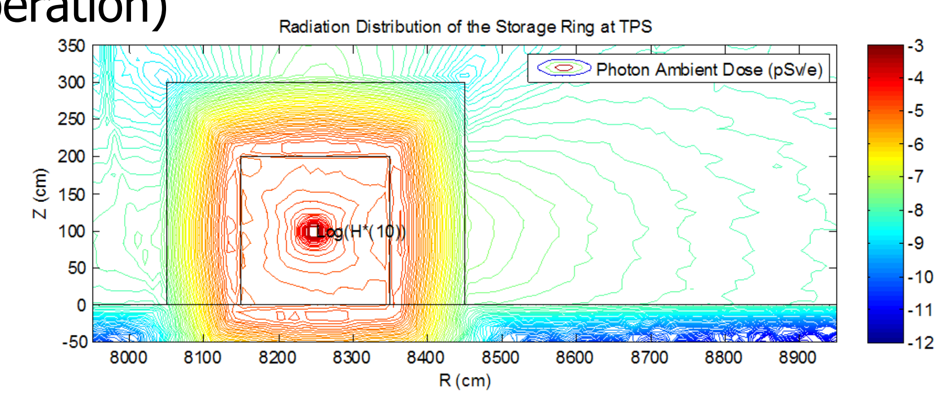
Dose/rate Assessment for TPS Operation



- Energy & spatial distributions of prompt radiation fields (γ, n, μ)
  - photon ~ neutron (~50%)
  - high-energy neutron dominates neutron contribution
  - muon negligible (<1%)

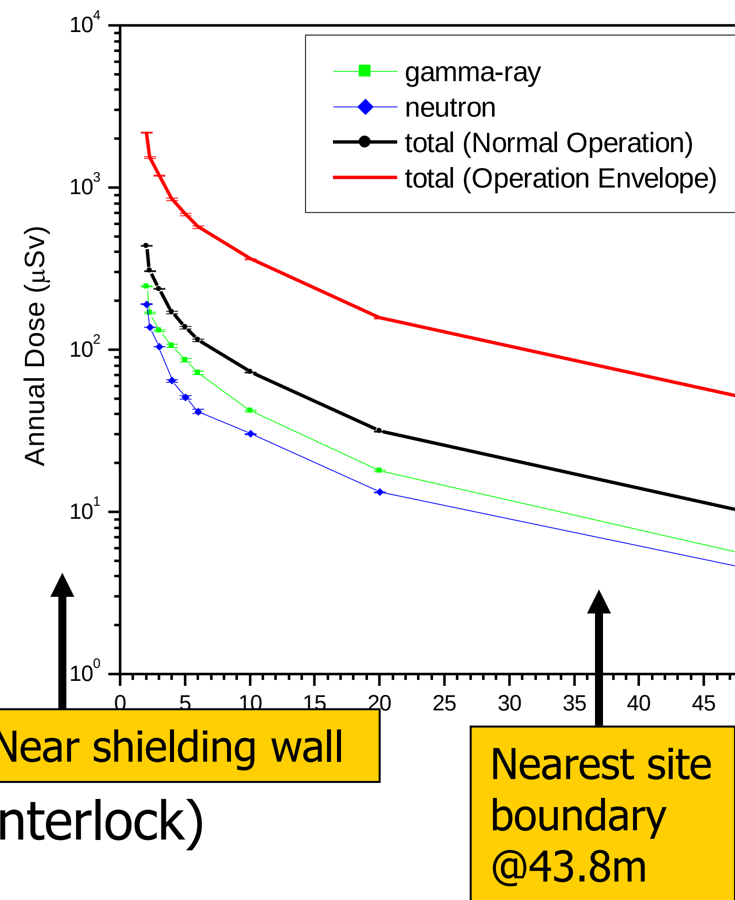


- Independent LINAC room
  target w/wo local shielding (OE: 2.25W LINAC)
  - 0-degree: 0.1 ~ 83 μSv/h
  - 90-degree: 1.1 ~ 14 μSv/h
- Shared tunnel for booster and storage ring
  uniform/point beam losses (normal operation)
  - Beam injection (injeff*~48%): 3.4 ~ 128 μSv/h
  - Beam storage (I=400mA, τ=7h): 0.02 ~ 1.7 μSv/h
  - Full beam loss event (400mA): 0.2 ~ 12 μSv



Annual Dose Assessment for TPS Operation

- Assumed operation schedule
  - 6000h operation in 300 days
  - Daily operation:
    - one fresh injection to 400mA,
    - top-up operation for 20h,
    - and then the beam dump.
- Normal operation
  - @wall: 0.44 mSv/y
  - @43.8m: 14 μSv/y
- Operation envelope
  - @wall: 2.2 mSv/y
  - @43.8m: 70 μSv/y
- Safety envelope (Design limit)
  - Personnel: 1.0 mSv for 2000h
  - Environment: 0.5 mSv for 6000h



→ Reasonably achievable (shielding & interlock)

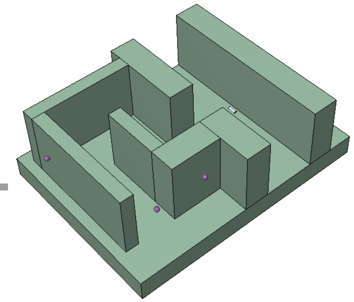
Maximum Credible Radiation Incidents and Controls

P.K. Job, R. Casey (2007)

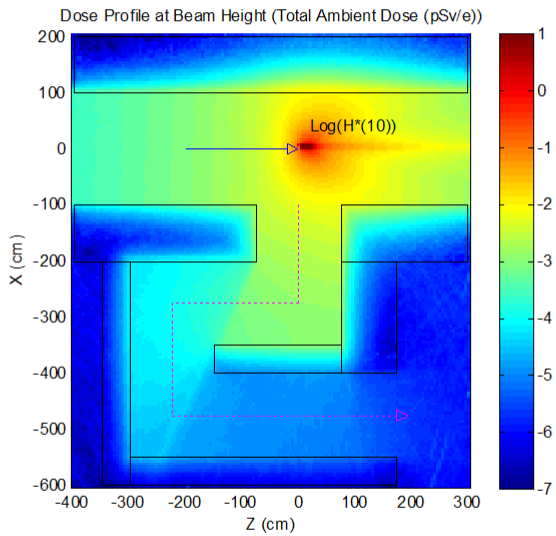
- Maximum credible radiation incidents
  - 100% of max accelerated beam is lost continuously in the LINAC
    → 0.08 mSv/h (at the exterior of the 0°shield on contact)
  - 100% injected beam is lost continuously at any location in the storage ring
    → 0.45 mSv/h (at the exterior of the exp. floor wall on contact)
  - 100% injected beam is lost continuously at a BL frontend due to a dipole failure
    → 3.55 mSv/h (at the exterior of the ratchet end wall on contact)
  - 100% of stored beam is lost at a point
    → 0.012 mSv/event (at the exterior of the exp. floor wall on contact)

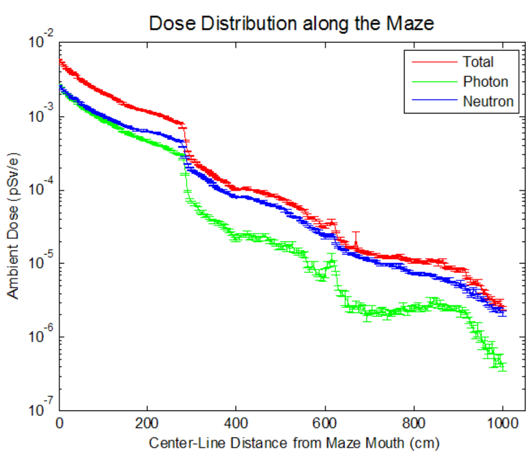
- Mitigation/controls to prevent significant exposure
  - Area radiation monitors with injection shut off capability
  - Realtime beam loss or transfer efficiency monitors
  - Additional supplementary shielding
  - Operating procedures and administrative access controls

Radiation Streaming through Maze

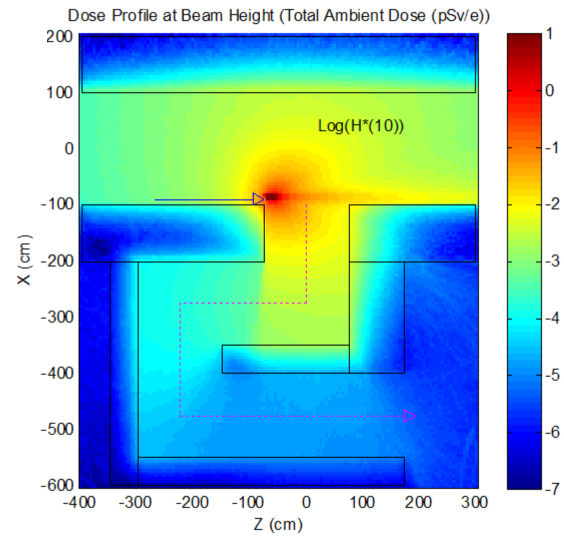


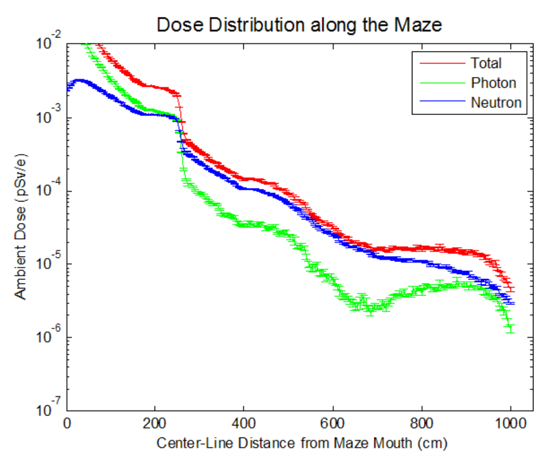
Beam Loss: Storage Ring



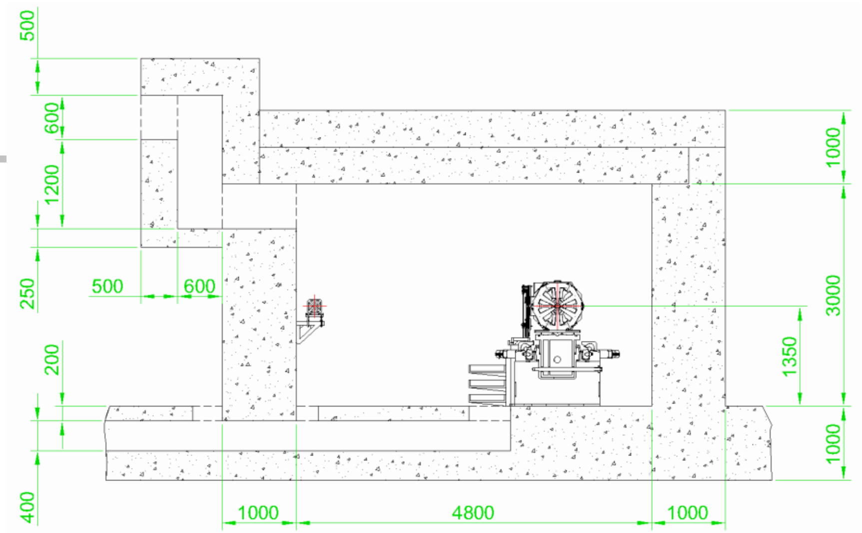


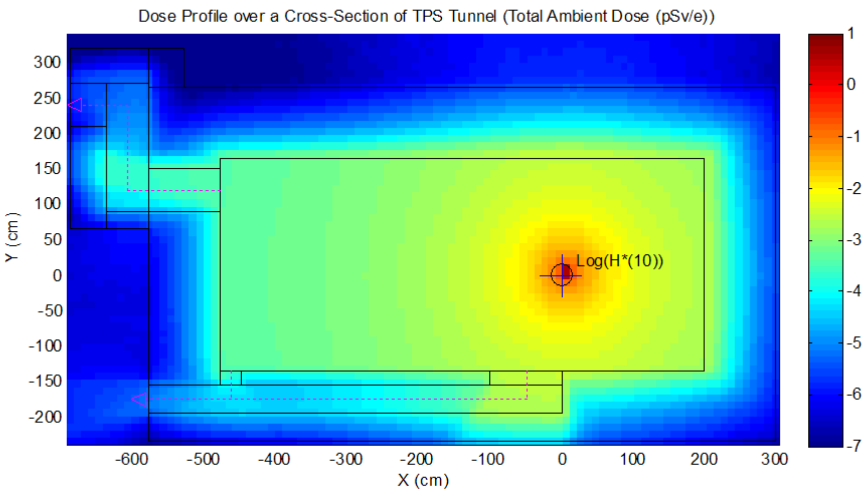
Beam Loss: Booster



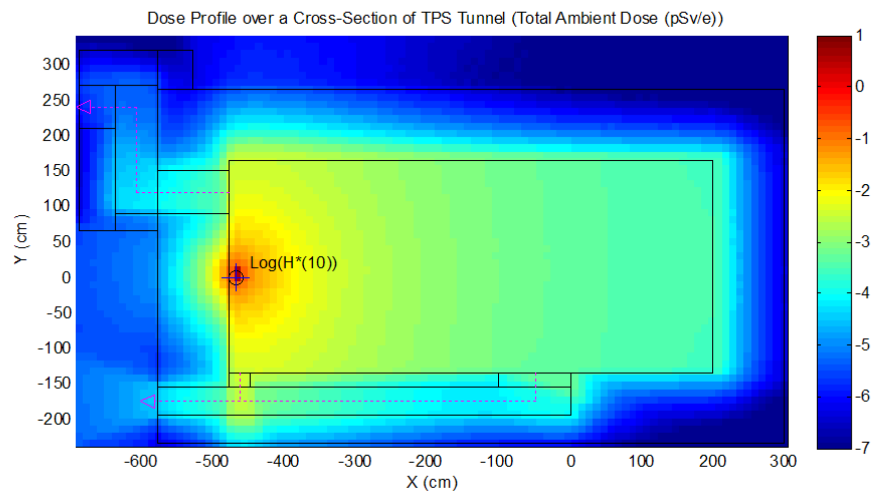


Radiation Streaming through Duct & Trench



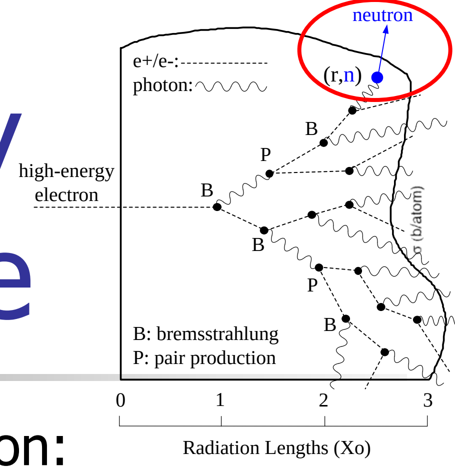


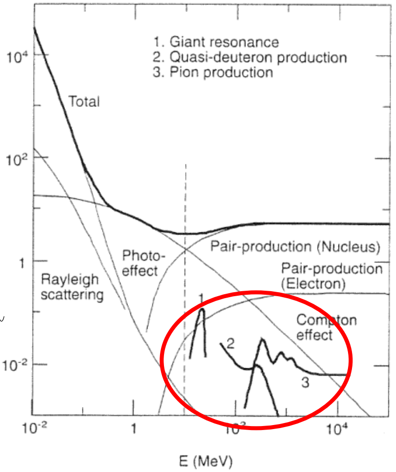
Beam Loss: Storage Ring



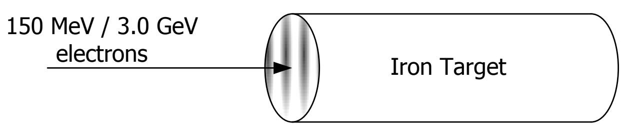
Beam Loss: Booster

Induced Activity & Residual Dose





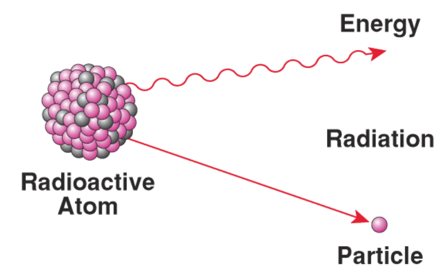
- Mechanism for material activation:
  - EM cascade → Photonuclear reaction → n & activated nuclei
- Estimation of induced activity and residual dose
  - FLUKA Monte Carlo code

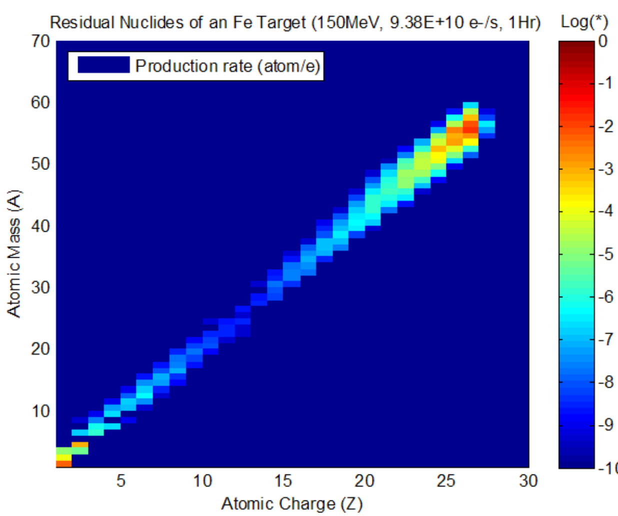


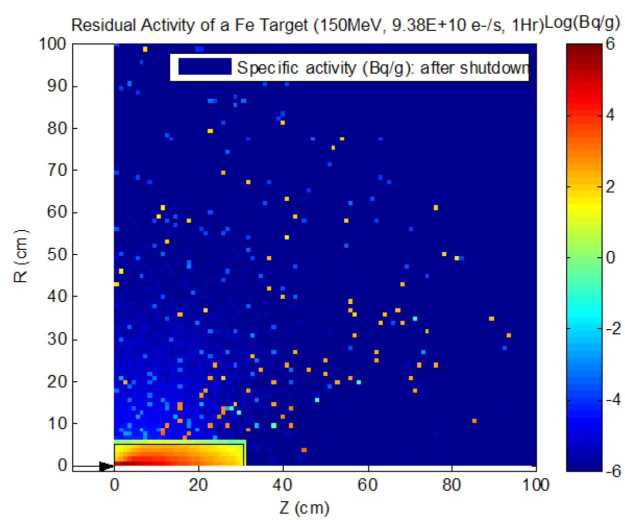
(1). Nuclides produced (Z,A)

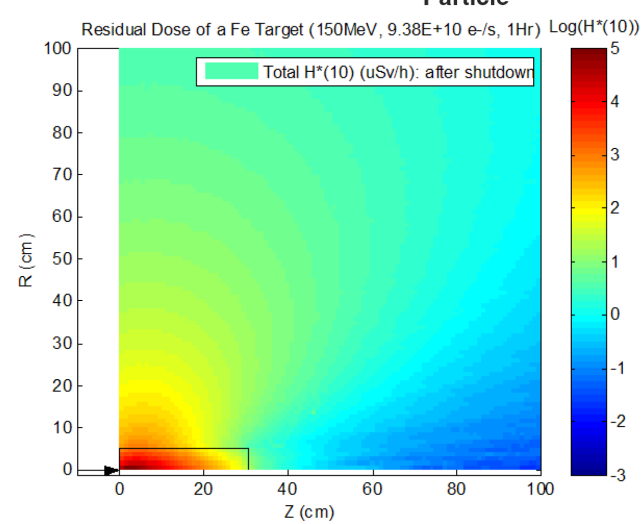
(2). Residual activity (Bq/g)

(3). Remnant dose (μSv/h)

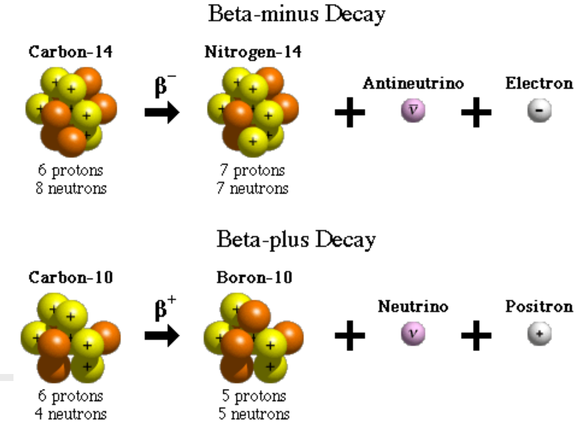








Exemption Limits for Radioactive Material



- Atomic Energy Council in Taiwan
- Concept of exemption limits (LE), i.e. threshold values of specific activity for every i radionuclides
- One need to list all the produced radionuclides and calculate the ratio **R**=?
- **R > 1** is a radioactive waste!

附表　　一定活度或比活度以下放射性廢棄物之限值

一、單一核種：廢棄物含單一核種之限值依下列各欄之一

限值 / 核種	每年外釋廢棄物活度限值 (貝克)	每年外釋超過一公噸之廢棄物比活度限值 (貝克/克)	每年外釋一公噸以下之廢棄物比活度限值 (貝克/克)
H-3	1.E+9	1.E+2	1.E+6
Be-7	1.E+7	1.E+1	1.E+3
C-14	1.E+7	1.E+0	1.E+4
F-18	1.E+6	1.E+1	1.E+1
Na-22	1.E+6	1.E-1	1.E+1
Na-24	1.E+5	1.E+0	1.E+1
Si-31	1.E+6	1.E+3	1.E+3
P-32	1.E+5	1.E+3	1.E+3
P-33	1.E+8	1.E+3	1.E+5
S-35	1.E+8	1.E+2	1.E+5
Cl-36	1.E+6	1.E+0	1.E+4
Cl-38	1.E+5	1.E+1	1.E+1

限值 / 核種	每年外釋廢棄物活度限值 (貝克)	每年外釋超過一公噸之廢棄物比活度限值 (貝克/克)	每年外釋一公噸以下之廢棄物比活度限值 (貝克/克)
Mn-54	1.E+6	1.E-1	1.E+1
Mn-56	1.E+5	1.E+1	1.E+1
Fe-52	1.E+6	1.E+1	1.E+1
Fe-55	1.E+6	1.E+3	1.E+4
Fe-59	1.E+6	1.E+0	1.E+1
Co-55	1.E+6	1.E+1	1.E+1
Co-56	1.E+5	1.E-1	1.E+1
Co-57	1.E+6	1.E+0	1.E+2
Co-58	1.E+6	1.E+0	1.E+1
Co-58m	1.E+7	1.E+4	1.E+4
Co-60	1.E+5	1.E-1	1.E+1
Co-60m	1.E+6	1.E+3	1.E+3

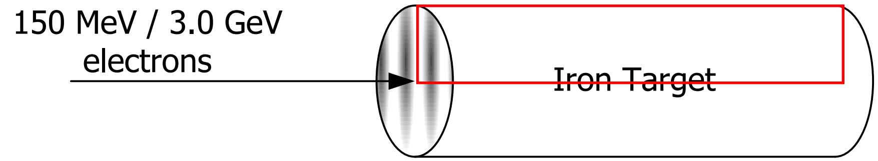
Pu-241	1.E+5	1.E+1	1.E+2
Pu-242	1.E+4	1.E-1	1.E+0
Pu-243	1.E+7	1.E+3	1.E+3
Pu-244	1.E+4	1.E-1	1.E+0
Am-241	1.E+4	1.E-1	1.E+0
Am-242	1.E+6	1.E+3	1.E+3
Am-242m	1.E+4	1.E-	[illegible]
Am-243	1.E+3	1.E-	[illegible]
Cm-242	1.E+5	1.E+	[illegible]
Cm-243	1.E+4	1.E+	[illegible]
Cm-244	1.E+4	1.E+	[illegible]
Cm-245	1.E+3	1.E-	[illegible]
Cm-246	1.E+3	1.E-1	1.E+0
Cm-247	1.E+4	1.E-1	1.E+0
Cm-248	1.E+3	1.E-1	1.E+0
Bk-249	1.E+6	1.E+2	1.E+3

Fm-255	1.E+6	1.E+2	1.E+3
其他未列之放射性核種	1.E+3	1.E-1	1.E-1

二、多核種：廢棄物含有多核種時，應符合下列公式之要求

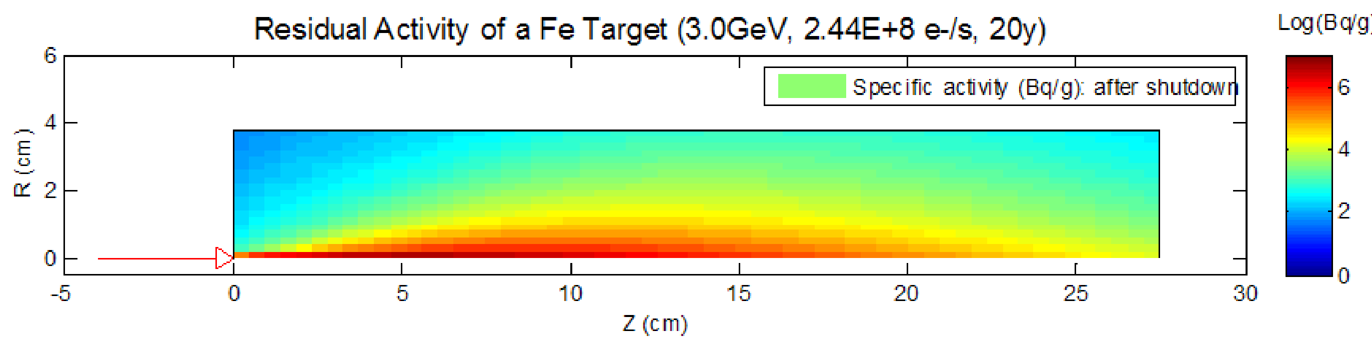
$$R = \sum_{i=1}^{n} \frac{A_i}{LE_i} \leq 1.0$$

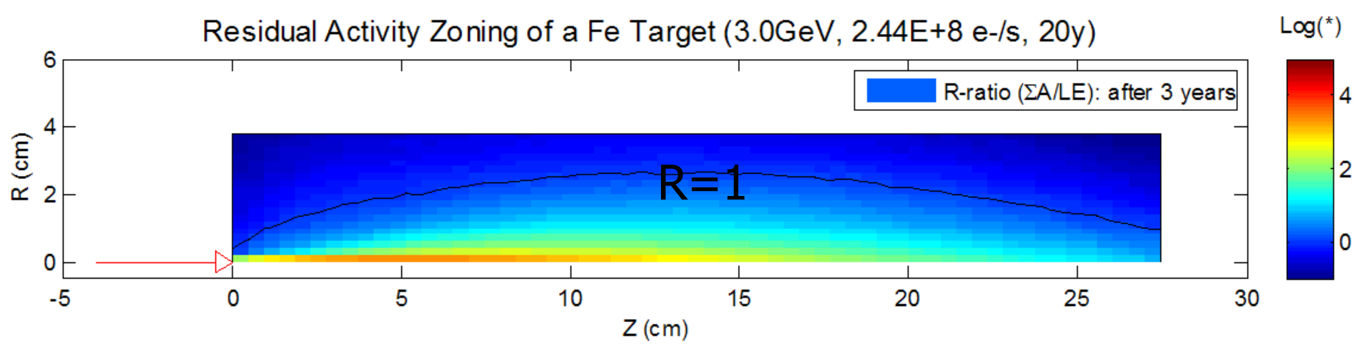
n ：所含核種的數目

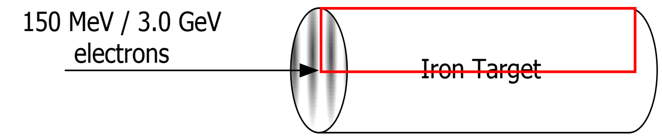


Activation Analyses

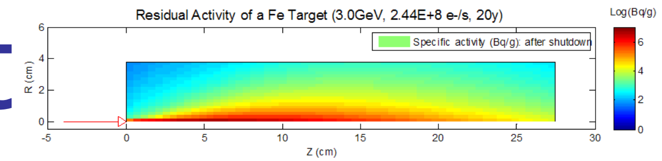
- Two extreme irradiation conditions for TPS operation:
  - 20y irradiation, 7.71×10^{15} e^{-}/y ~ 0.12W
  - 1Hr irradiation, 4.48×10^{10} e^{-}/s ~ 21.5W
- Target materials: Al, Fe, Cu, W, Pb, SS304
- Radioactive waste zoning





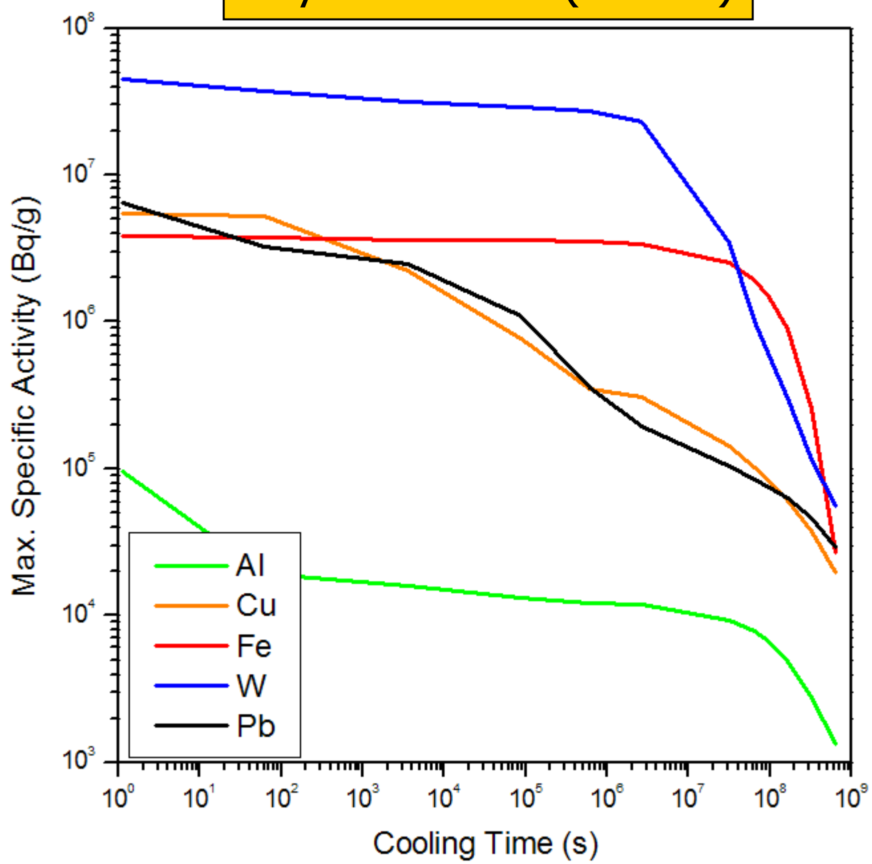


Activation in Target

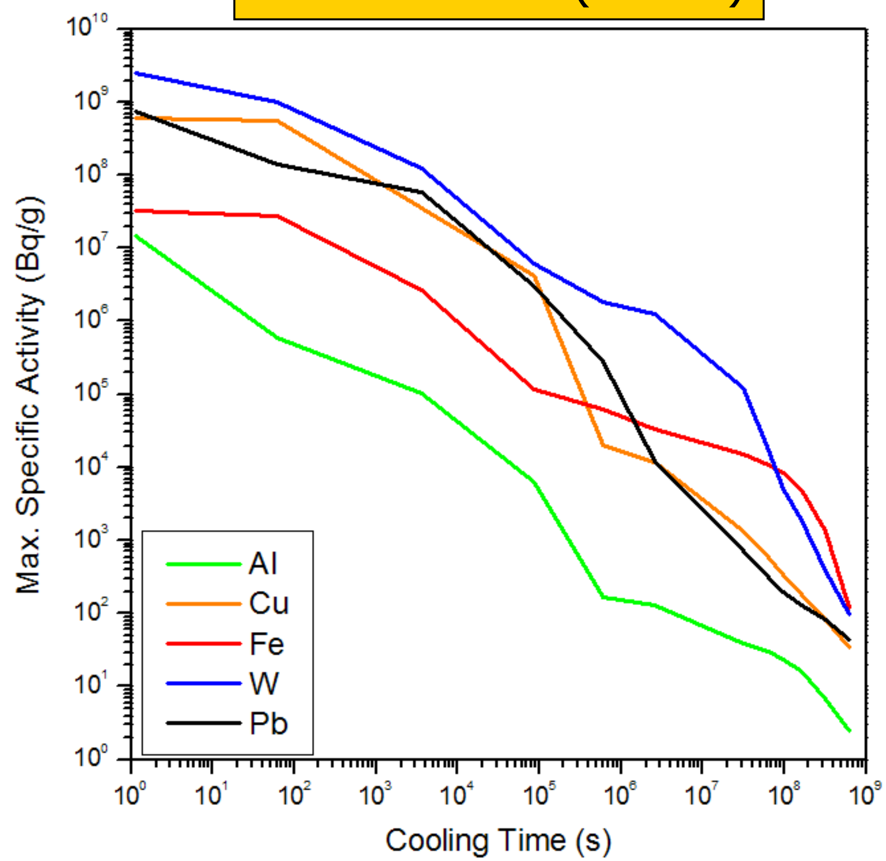


- Max. activity in target

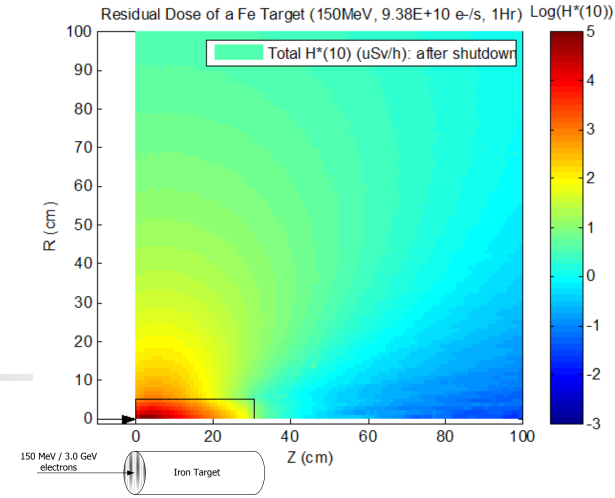
20y irradiation (0.12W)



1Hr irradiation (21.5W)

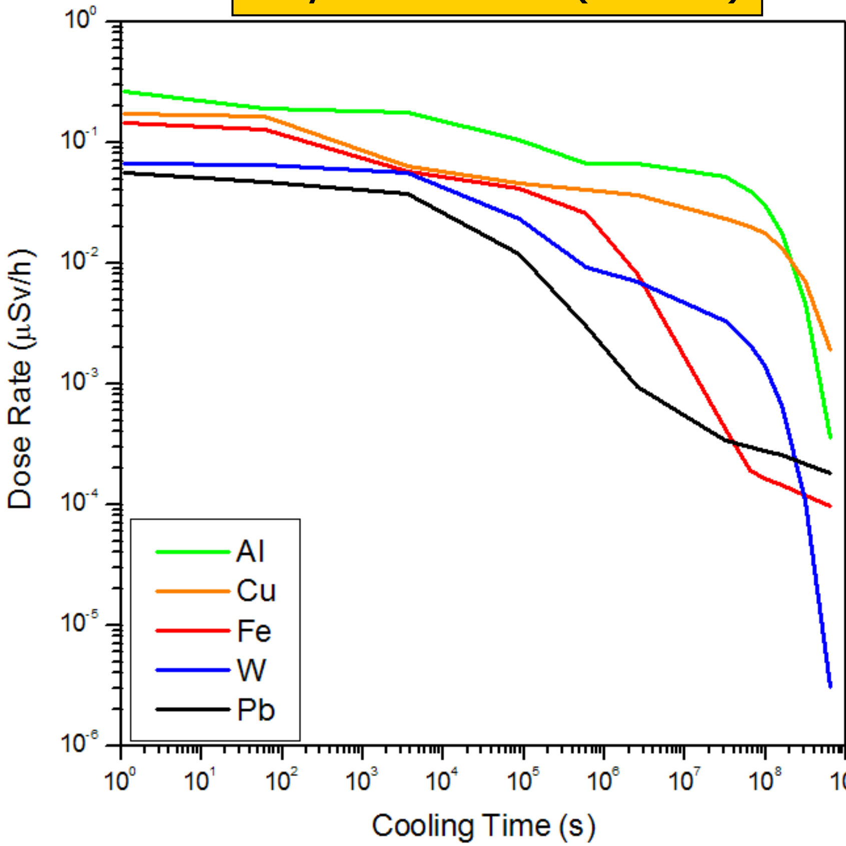


Activation in Target

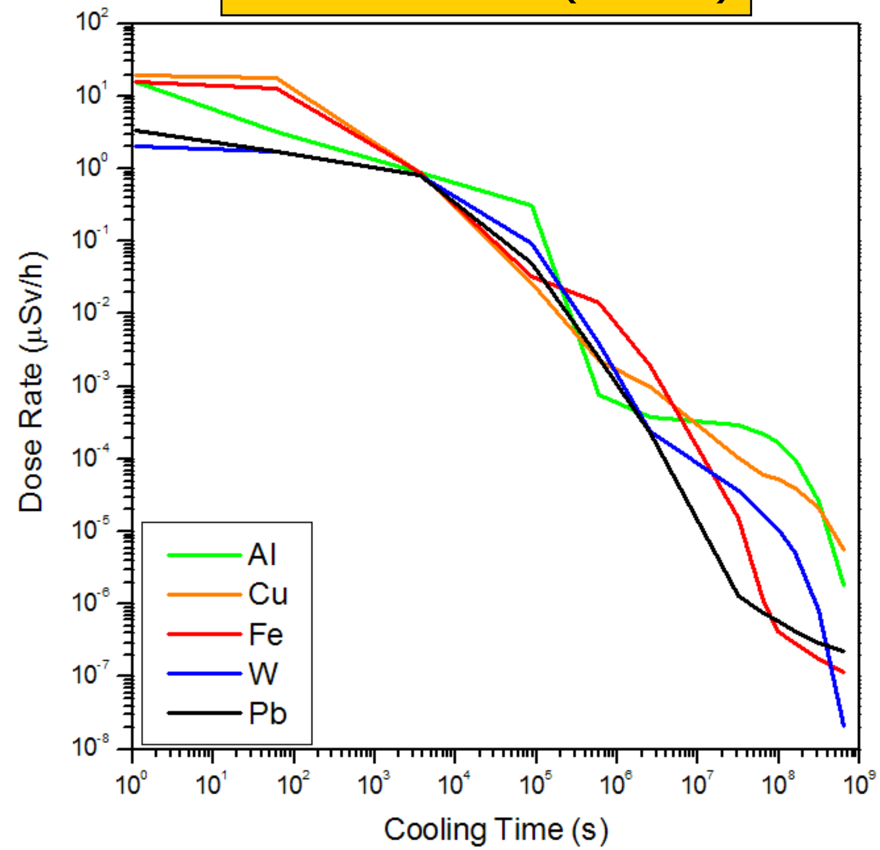


- Remnant dose at 1m from target

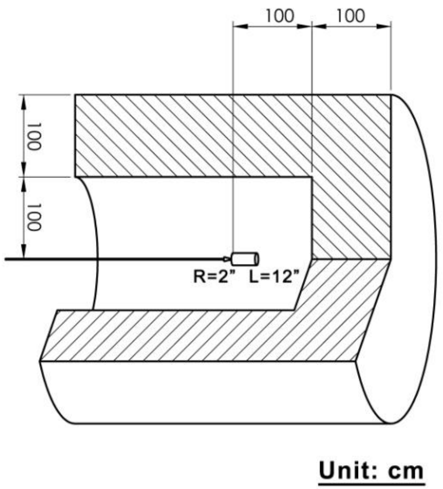
20y irradiation (0.12W)



1Hr irradiation (21.5W)

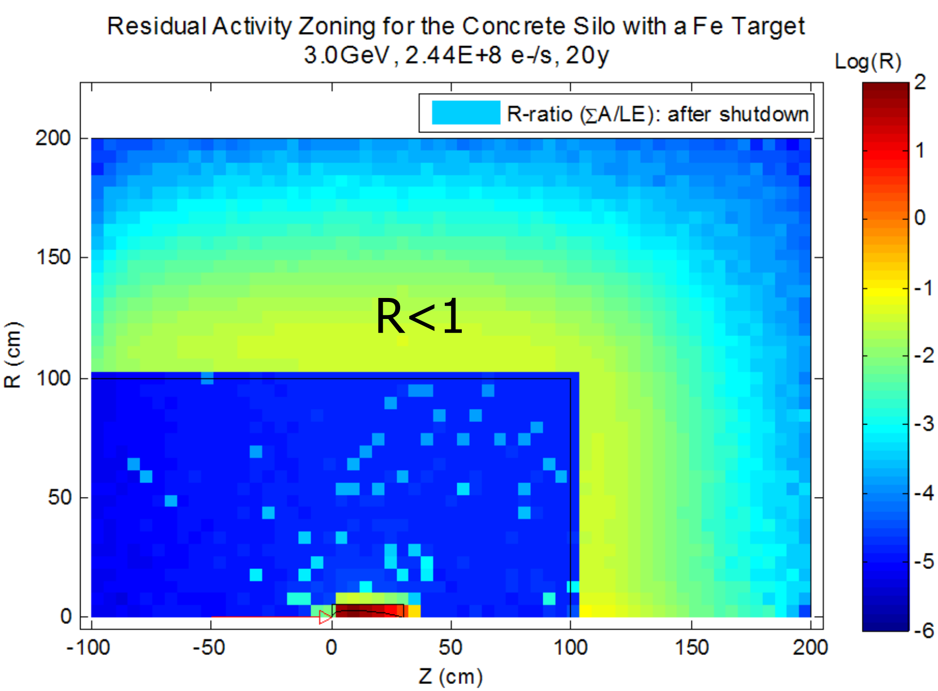


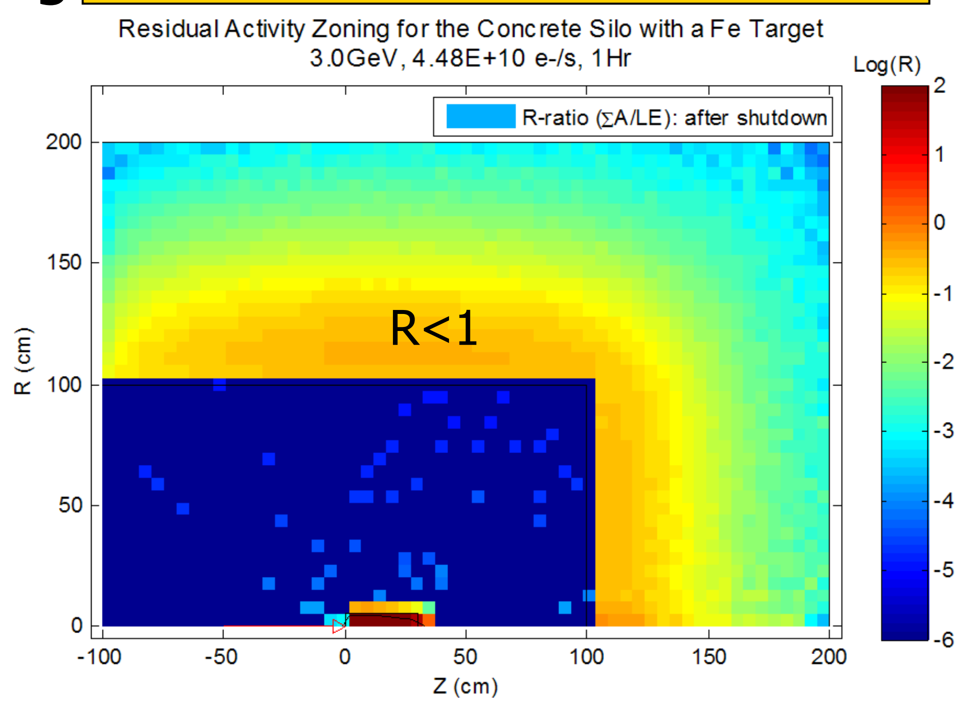
Activation in Concrete Shielding



- Two extreme Irr. conditions:
  - 20y irradiation, 7.71×10^{15} e^-/y ~ 0.12W
  - 1Hr irradiation, 4.48×10^{10} e^-/s ~ 21.5W
- Target materials: iron and concrete shielding walls
- Radioactive waste zoning

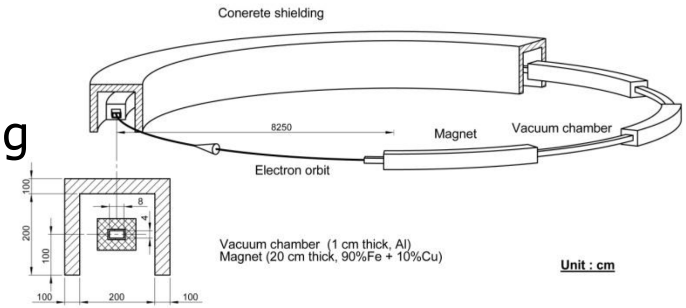
R<1 → Concrete walls are not radioactive waste!



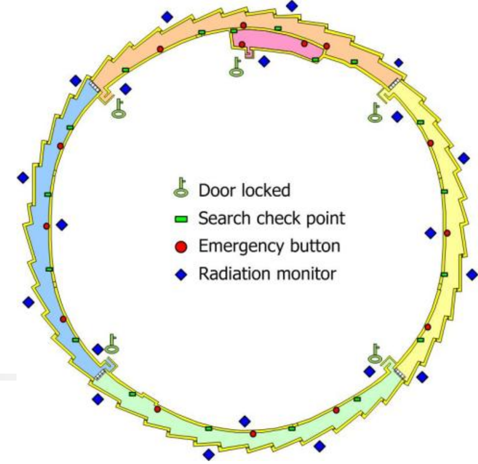


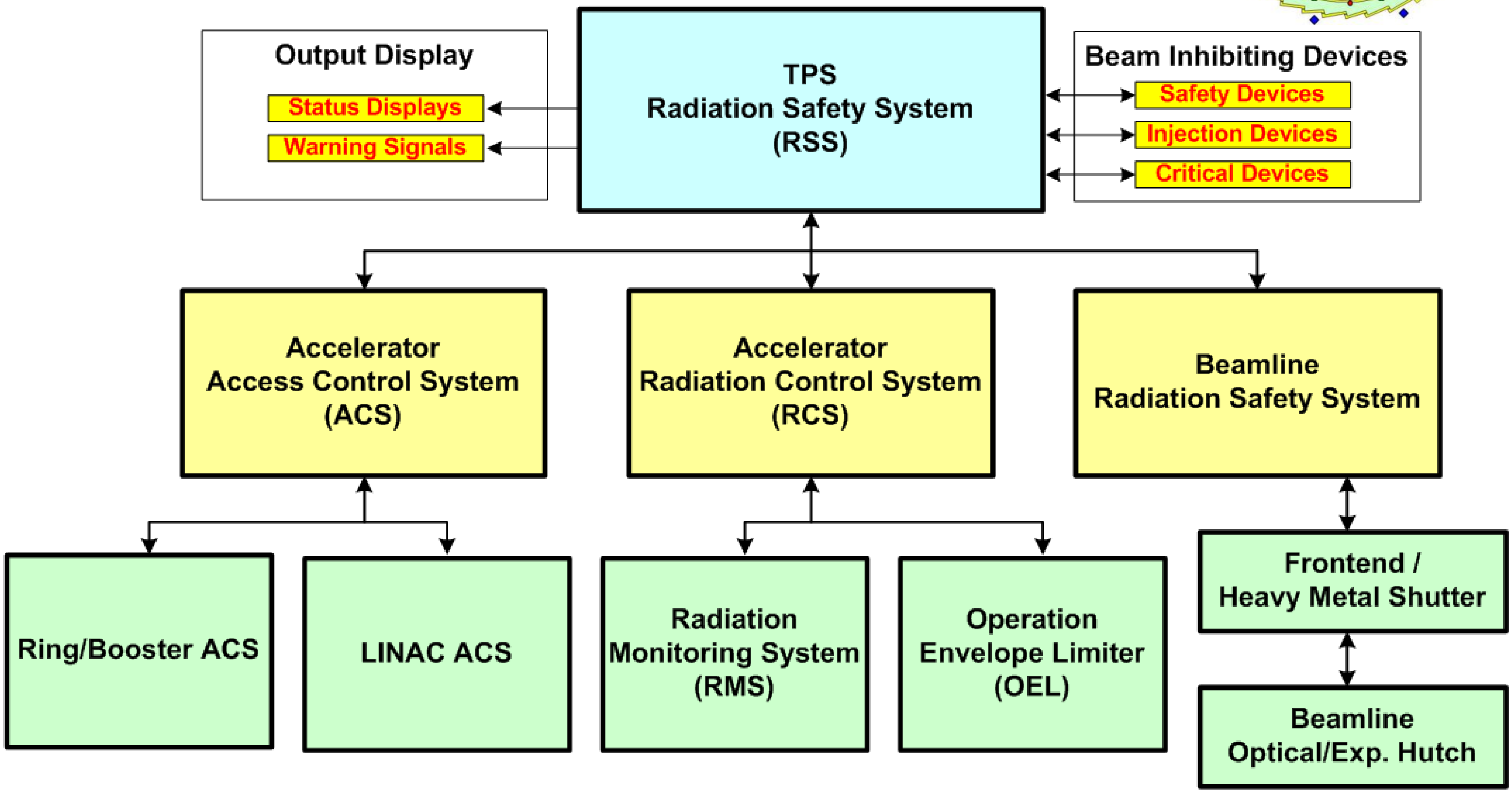
Possible Activation of Air and Cooling Water in Tunnel

- Most important radionuclides induced in air and cooling water
  - Air/Water:
    - ^{13}N ($\beta+$, $T_{1/2}$=9.96min), $^{14}N(\gamma,n)^{13}N$ for Eγ≧10.55 MeV
    - ^{15}O ($\beta+$, $T_{1/2}$=123sec), $^{16}O(\gamma,n)^{15}O$ for Eγ≧15.67 MeV
- FLUKA-calculated results (saturated activities)
  - Air in tunnel:
    - ^{13}N ~ 4.52×10^{-3} ± 34% (Bq/g/W)
    - ^{15}O ~ 2.47×10^{-3} ± 31% (Bq/g/W)
  - Hypothetical water pipe around the ring ~20cm to beam orbit:
    - ^{15}O ~ 1.85×10^{-2} ± 33% (Bq/g/W)
- Max. injection power?
  - ~ 21.5W in the shared tunnel
- Exemption Limits of AEC:
  - ^{13}N & ^{15}O = 1.00×10^{2} (Bq/g)
- TPS is still a fairly low power facility, activation of air and cooling water and their environmental releases should be negligible!



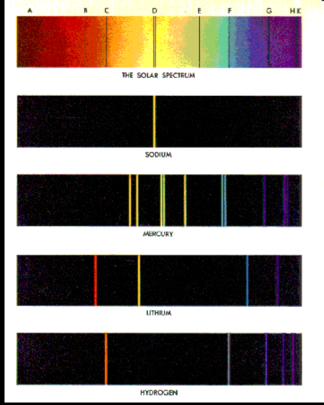
Radiation Safety System





Summary

- Radiation safety design and analysis of the TPS is approaching its final version.
- Anticipated beam losses for normal operation have been established for design reference. Operation envelope has been defined accordingly (x5). The design dose limits (safety envelope) should be practically achievable under the present shielding and interlock configuration.
- Max credible radiation incidents have been identified and the corresponding controls will be established to prevent significant exposure.
- Material activations have been analyzed and their management program will be set up accordingly for routine operation.
- A robust radiation safety system will be established to prevent exposure of individuals to non-permissible prompt radiation.
- 3-stage review process for TPS licenses is required by AEC and finishing the radiation safety analysis report is our first priority.



Taiwan Photon Source (**TPS**)

Thank you!