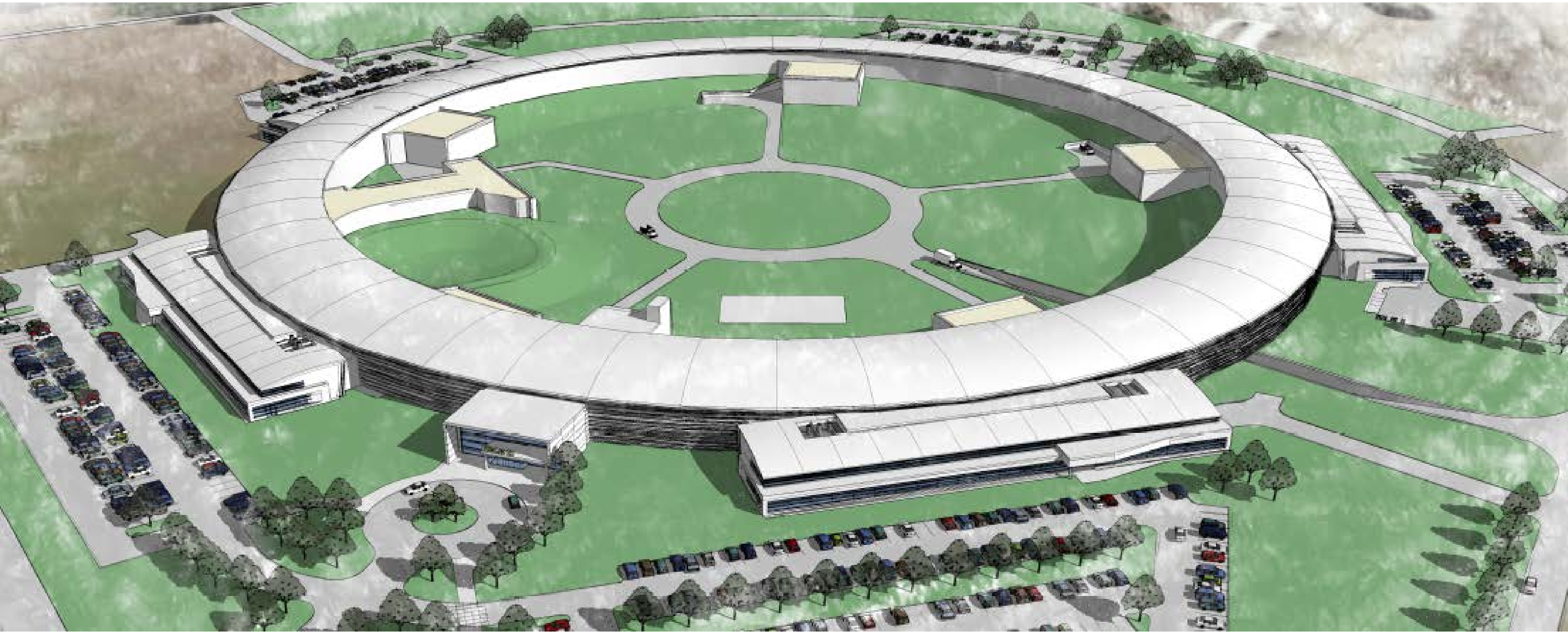
Soil Activation around Electron Accelerators



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Outline

- Beam Losses in Electron Accelerators.
- Secondary Interaction and Photo-neutron Production.
- High energy neutron flux estimates.
- Analytical methodology to calculate activation.
- Cross section data for Isotope production in soil.
- Soil composition at long Island.
- Na22 and H3 significant isotopes Production.
- Comparison with FLUKA activation calculations.

Beam Loss Assumptions at SR Facilities

Accelerator system SR/Linac Energy (GeV)	NSLS2 (%) 3/0.200	ALBA (%) 3/0.130	Diamond (%) 3/0.100	AusLS (%) 3/0.300	Spear3 (%) 3	APS (%) 7/0.450
Linac - general	10 (distri.)	10	10	50/20		5.5
- Momentum slit	50	-	-	-		
- Beam dumps	100	100	100	100		100
Booster - general	2	15	10 (distri.)	15 (distri.)		2
- injection septum	50	20	50	20		50
- extraction septum	20	15	50	20		
Storage Ring – gen.	~6	30 (distri.)	20	45.5 (distri.)	3	10 (distr.)
- injection septum	~ 20	40	50	12.5	16	50
- injection region	70		80			

High Energy Neutron Production

- 100% Beam Loss at dump (part of the operation time).
- Secondary interaction and neutron generation in the dump.
- The high energy neutron (HEN) component in the transverse direction of the beam loss location on a thick target is provided as (Fasso);

1.3×10^{-3} n/ GeV/ electron/ steradian

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Neutron Flux Estimate in the Soil

$$\Phi(0) = \frac{1.3\times10^{-3}}{R^2} N_e \times E \times e^{-r/\lambda} \quad \text{neutrons/cm}^2\text{.s} \qquad (1)$$

Where N_e = Number of electrons interacting with the target material / sec

E = Energy of the electron in GeV

R = Distance of the flux point from the source in cm

r = Thickness of the concrete shield in g/cm^2

λ = Attenuation length of HEN in concrete in g/cm^2 (115 g/cm^2)

High Energy Neutron Interaction Cross Sections in the Soil

Parent Nucleus	Weight (%) In soil	^{3}H Production Threshold (MeV)	^{3}H Production Cross section (mb)	^{22}NaProduction Threshold (MeV)	^{22}NaProduction Cross section (mb)
^{16}O	51.3	15.0	3.07		
^{23}Na	0.0196	20.0	6.81	15.0	36.6
^{24}Mg	0.21	25.0	6.48	25.0	28.2
^{27}Al	1.65	25.0	8.23	50.0	14.5
^{28}Si	45.1	50.0	3.54	50.0	14.5
^{39}K	0.063	50.0	3.56		
^{40}Ca	0.058	50.0	3.0		
^{55}Mn	0.012	50.0	2.0		
^{56}Fe	1.44	50.0	1.65		

Average Neutron Flux in the Soil

$$\Phi_{av} = \frac{\int \Phi(x) dx}{\int dx} = \frac{\int \Phi(0) e^{-\Sigma x} dx}{\int dx}$$

Where Φ(0) is the flux at the external surface of the concrete shield and the integration is carried out for 300 cm of the soil thickness. Integrating equation **for 300 cm of soil and substituting for Σ of the** soil,

Σ = Neutron removal cross section in the soil (0.016 cm^{-1})

It can be shown that;

Φav (soil) = 0.2066 Φ(0)

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Analytical Methodology to Calculate Activation

If σ = Neutron cross section of the element for activation;

The number of atoms of the radionuclide of interest (n) per unit volume is governed by the following differential equation during the period of irradiation:

$$\frac{dn}{dt} = -\lambda_R n + \Phi_{av} N \sigma$$

The equation has the following solution applying the boundary condition when n = 0, t=0;

$$n(t) = \frac{\Phi_{av} N \sigma}{\lambda_R} (1 - e^{-\lambda_R t})$$

where

λ_R = Decay constant of the radioactive isotope

t = Irradiation time (A conservative annual irradiation time of 500 hours is considered for the dumps).

Thus the specific activity (Bq/cm^3) induced in the soil as a function of time by this nuclide of interest;

$$A(t) = \Phi_{av} N \sigma (1 - e^{-\lambda_R t}) \quad Bq/cm^3$$

Parameters for Analytical Calculations

- Distance of the Floor from the dumps 100 cm
- 50 cm of normal density concrete floor (2.35 g/cm^3) between the dump and the floor.
- 500 hours of Linac and 500 hours of Booster Study (fill and dump), continuous operation.
- 15 nC/s Fill and dump is assumed for 500 hours.

Summary of Analytical Results

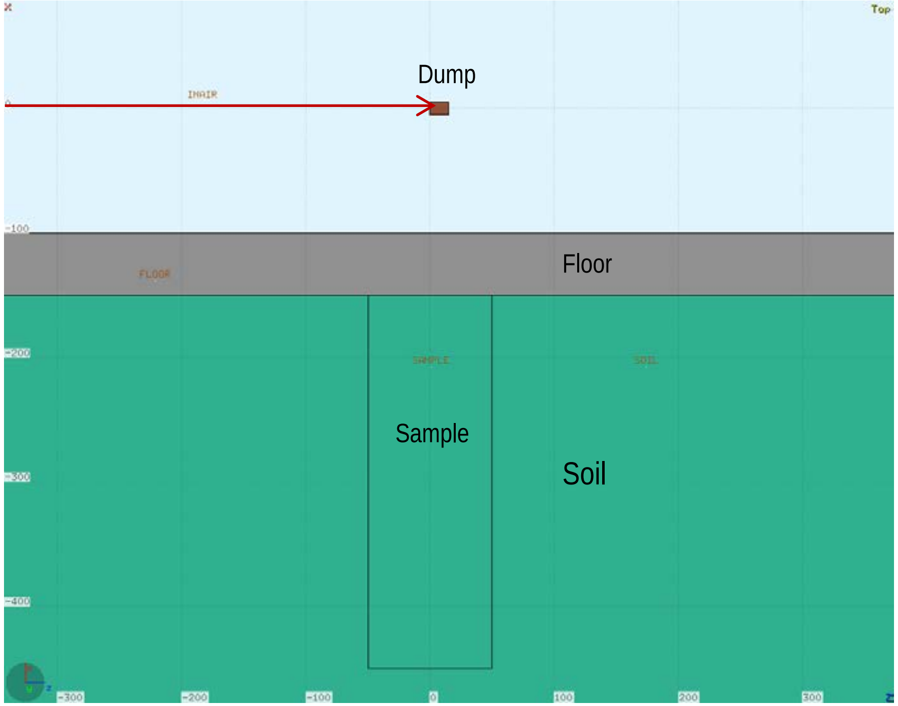
Soil location	Electron loss (e/s) (15 nC/s)	Neutron flux ($n/cm^2.s$)	^3H (pCi/L)	^{22}Na (pCi/L)
Linac Dump 230MeV	9.36E10	3.0E2	0.014	0.52
Booster Dump 3 GeV	9.36E10	3.9E3	0.13	0.46

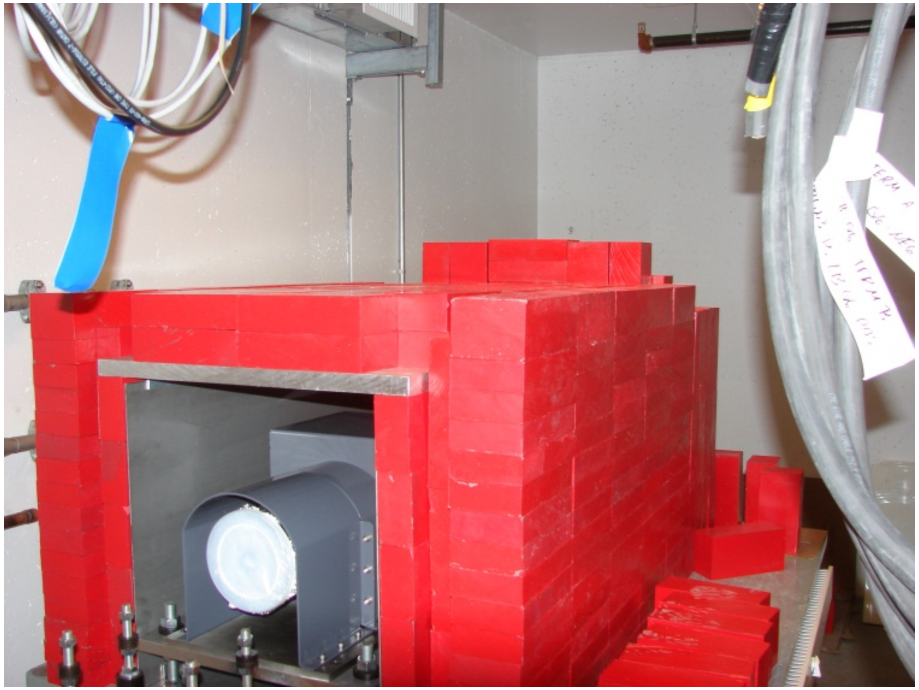
FLUKA Calculations

FLUKA calculations have been performed to validate the analytical results of activation with the same input parameters;

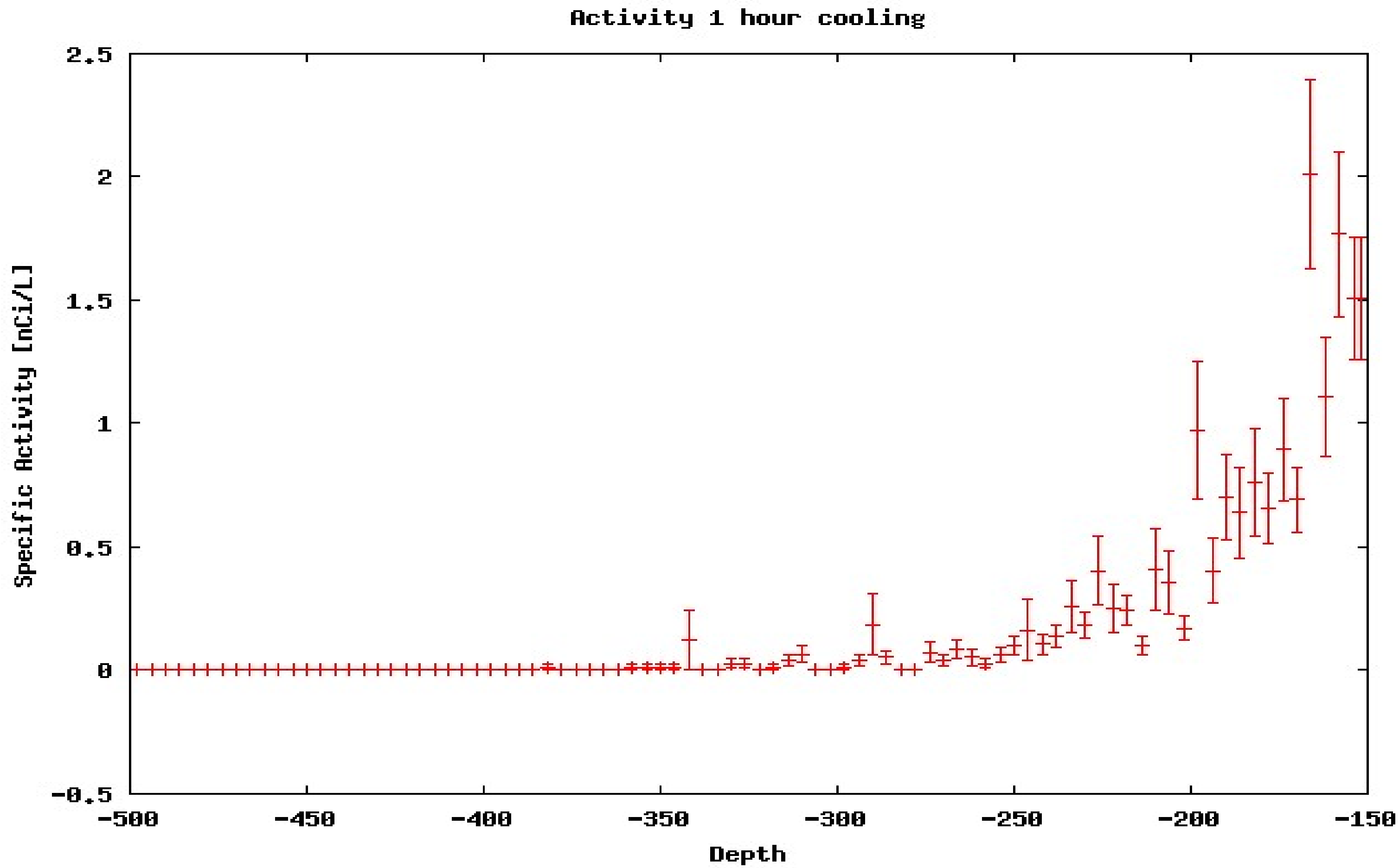
- Distance of the Floor from the dumps is 100 cm.
- 50 cm of normal density concrete floor between the dump and the floor.
- 500 hours of Linac and 500 hours of Booster Study (fill and dump), distributed over three month periods of operation with one month maintenance period in between is assumed over one year.
- 15 nC/s Fill and dump is assumed during the irradiation period.
- Beam dump is of 10 cm radius and 15 cm long Fe cylinder.

FLUKA Geometry for Soil Activation

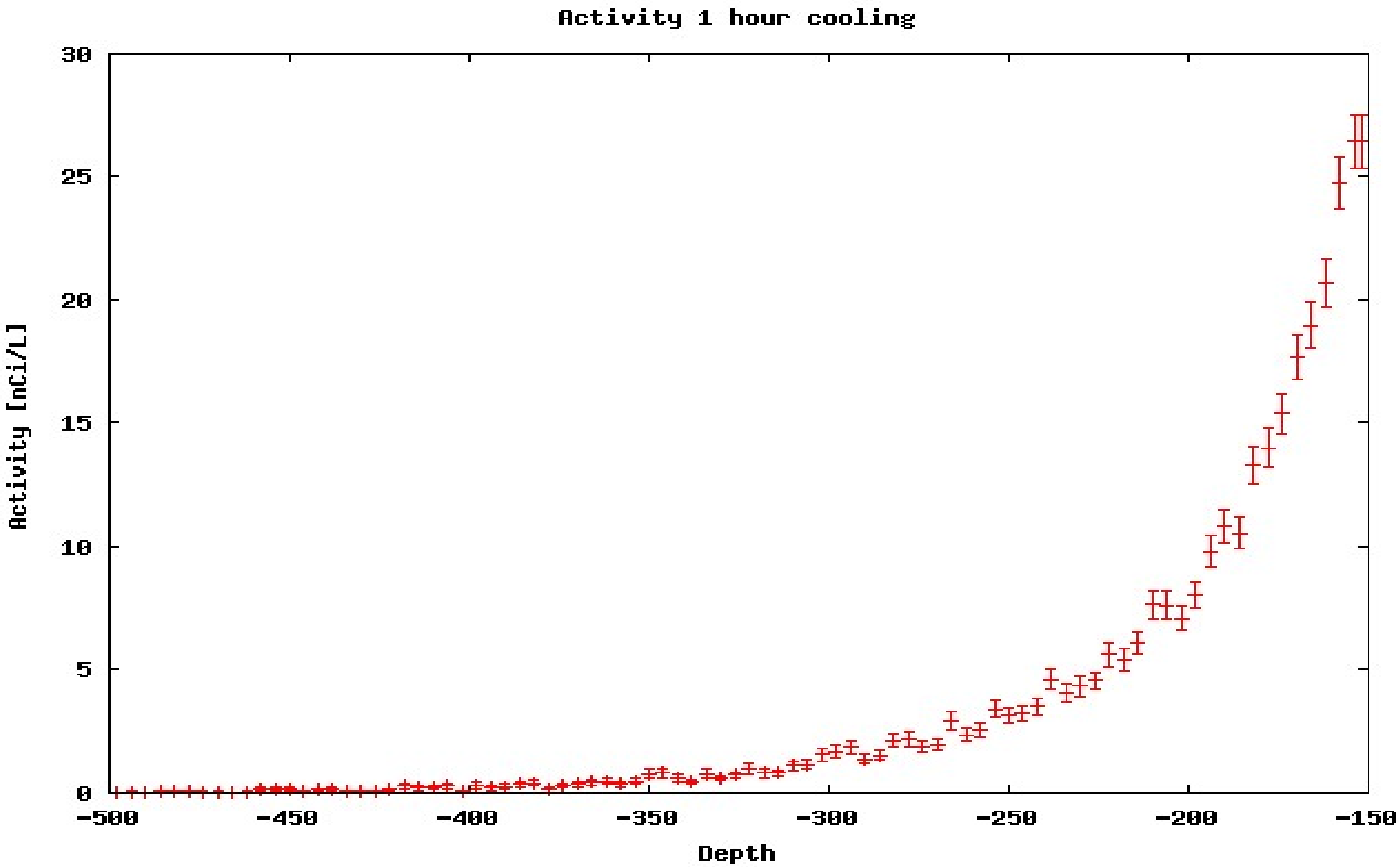




Total Activity near Linac Dump



Total Activity near Booster Dump



Summary of FLUKA Results

Soil Location	Electron Loss (e/s)	Neutron Flux ($n/cm^2.s$)	^3He (pCi/cm^3) Analytical	^3He (pCi/cm^3) FLUKA	^{22}Na (pCi/cm^3) Analytical	^{22}Na (pCi/cm^3) FLUKA
Linac Dump	9.36E10 230 MeV	3.0 E2	0.014	0.02	0.52	0.25
Booster Dump	9.36E10 3 GeV	3.9 E3	0.13	0.70	0.46	1.05

Observations and Conclusions

- Analytical estimates are quick and easy.
- In general FLUKA predicts higher activation compared to the current analytical methodology.
- Analytical calculations does not consider neutron slowing down effects in concrete.
- Analytical calculations use mono-energetic neutron cross sections, unlike FLUKA.
- FLUKA incorporates irradiation profiles.