Fermilab

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Radiation Protection At Accelerator Facilities

Matthew Quinn, PhD

Radiation Physicist, Fermilab ESH&Q Section

American Nuclear Society Student Section

University of Wisconsin, Madison

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Fermilab is America's particle physics and accelerator laboratory

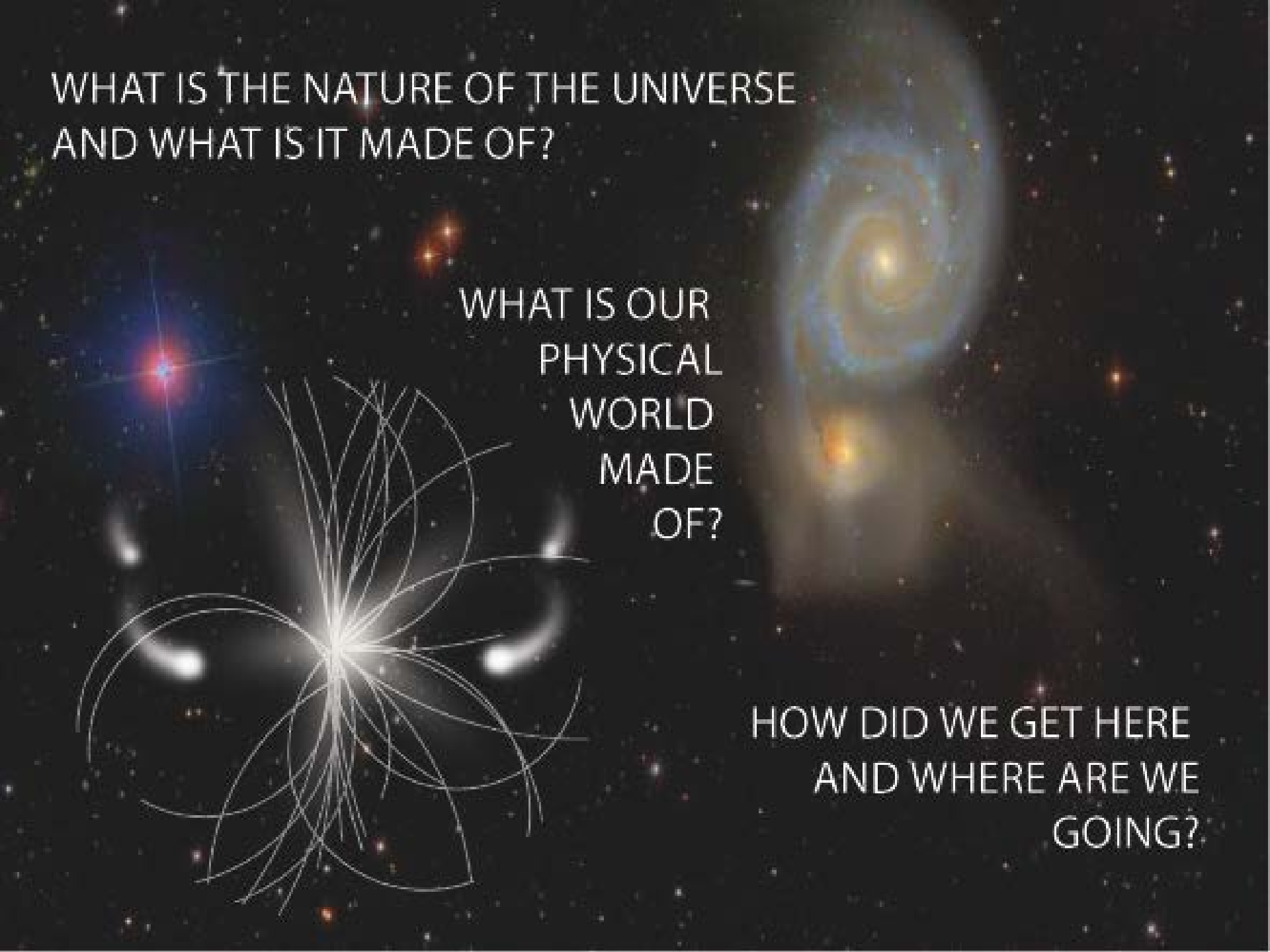
Our vision is to solve the mysteries of matter, energy, space and time for the benefit of all. We strive to:

- **lead the world in neutrino science with particle accelerators**
- **lead the nation in the development of particle accelerators and their use for scientific discovery**
- **advance particle physics through measurements of the cosmos**

Our mission is to drive discovery by:

- **building and operating world-leading accelerator and detector facilities**
- **performing pioneering research with national and global partners**
- **developing new technologies for science that support U.S. industrial competitiveness.**

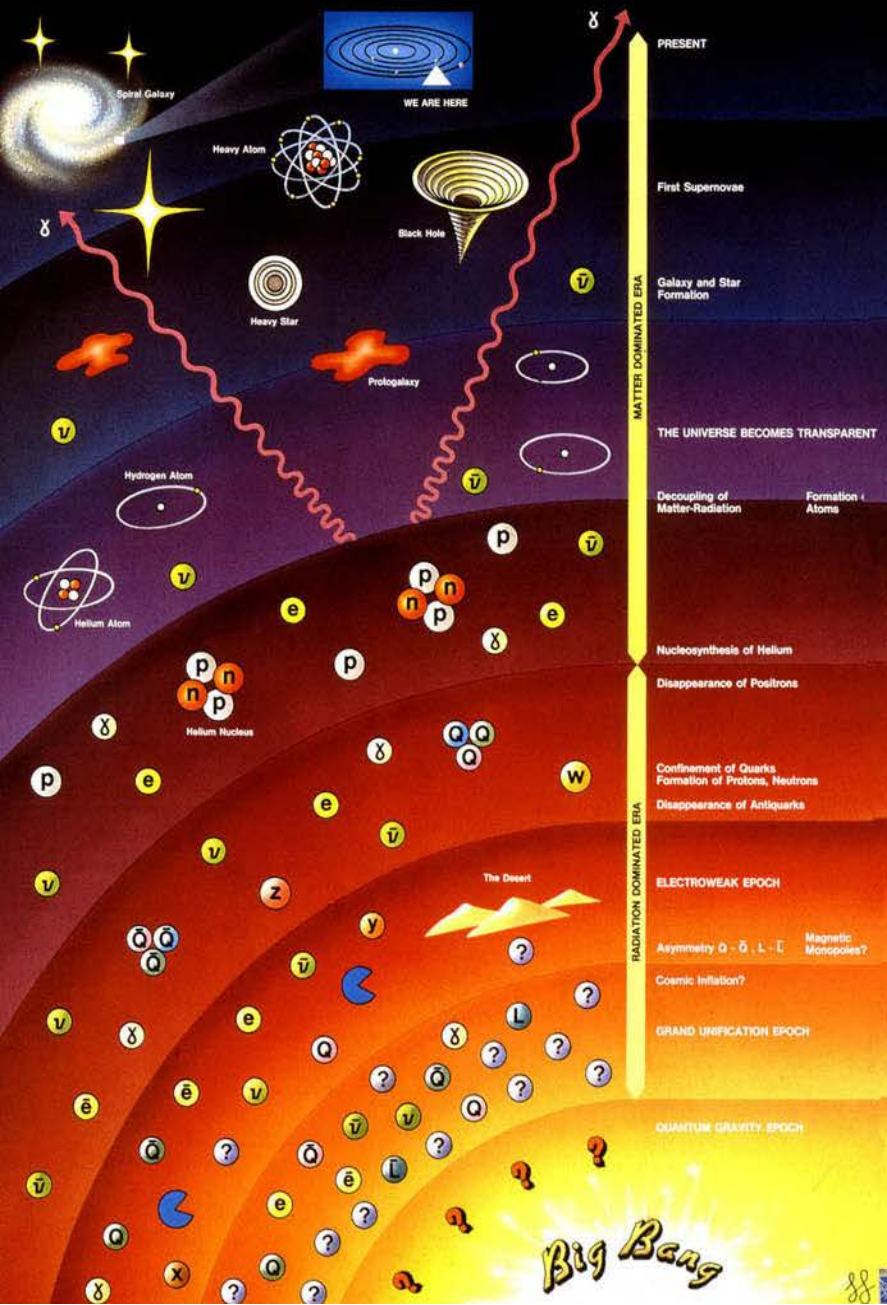
WHAT IS THE NATURE OF THE UNIVERSE AND WHAT IS IT MADE OF?



WHAT IS OUR PHYSICAL WORLD MADE OF?

HOW DID WE GET HERE AND WHERE ARE WE GOING?

History of the Universe



Now
(13.7 billion years)

Stars form
(1 billion years)

Atoms form
(380,000 years)

Nuclei form
(180 seconds)

Nucleons form
(10^{-10} seconds)

Quarks differentiate
(10^{-34} seconds?)

??? (Before that)

The Periodic Table of Elementary Particles and Forces

Three Generations of Matter (Fermions)

	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	⅔	⅔	⅔	0
spin→	½	½	½	1
name→	u up	c charm	t top (truth)	γ photon (electromagnetic)
Quarks	4.8 MeV, -⅓, ½, d down	104 MeV, -⅓, ½, s strange	4.2 GeV, -⅓, ½, b bottom (beauty)	0, 0, 1, g gluon (strong force)
	<2.2 eV, 0, ½, ν_e electron neutrino	<0.17 MeV, 0, ½, ν_μ muon neutrino	<15.5 MeV, 0, ½, ν_τ tau neutrino	91.2 GeV, 0, 1, Z^0 weak force
Leptons	0.511 MeV, -1, ½, e electron	105.7 MeV, -1, ½, μ muon	1.777 GeV, -1, ½, τ tau	80.4 GeV, ±1, 1, $W^\pm$ weak force
				115-185 GeV, ±1, 0, $H^\pm$ higgs boson

Bosons (Forces)

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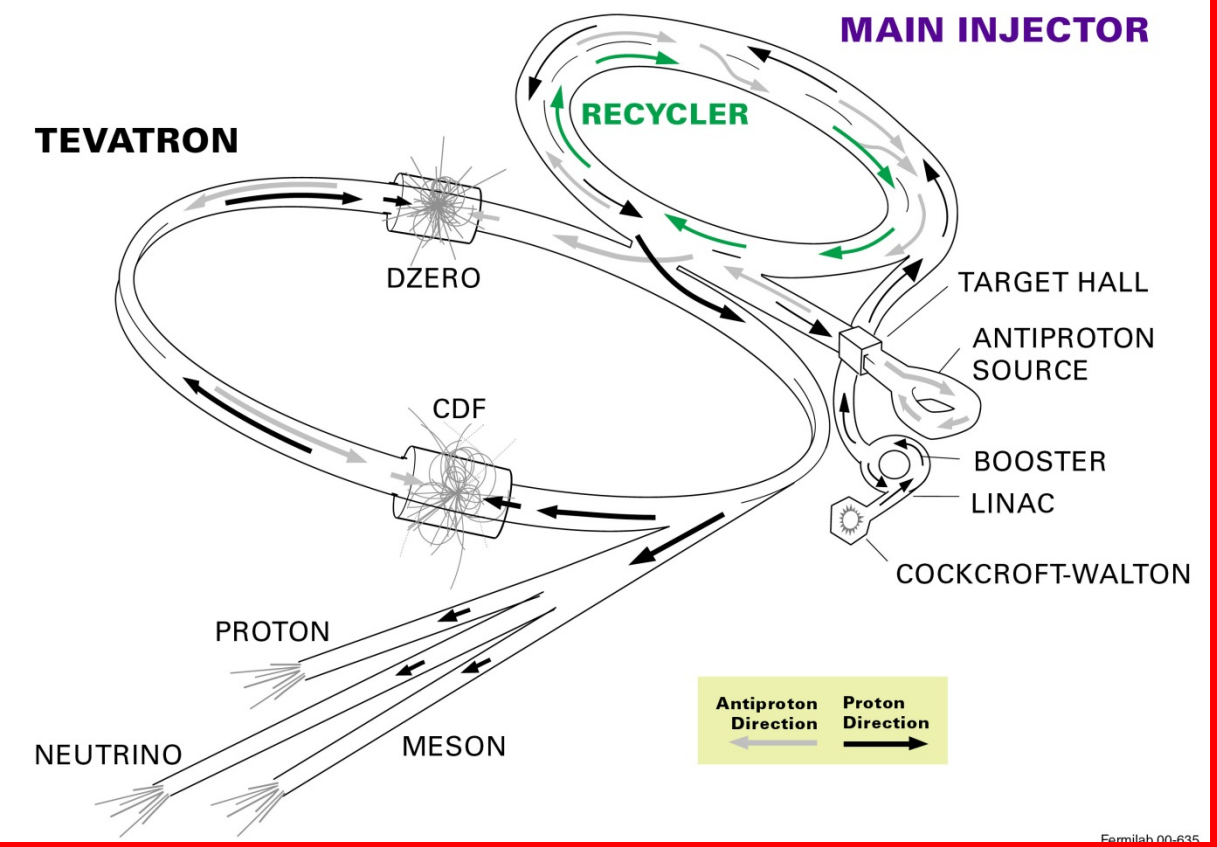
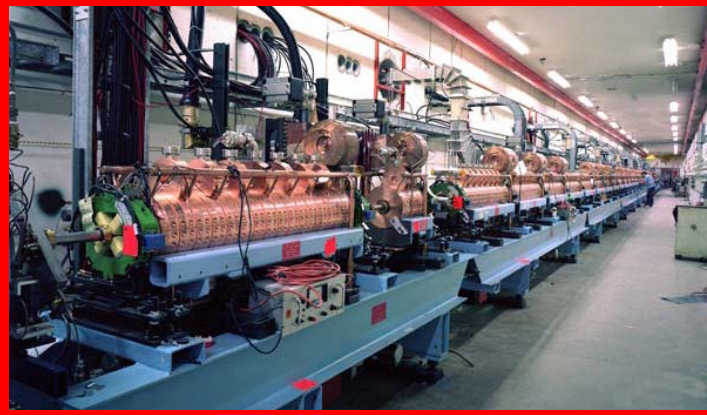
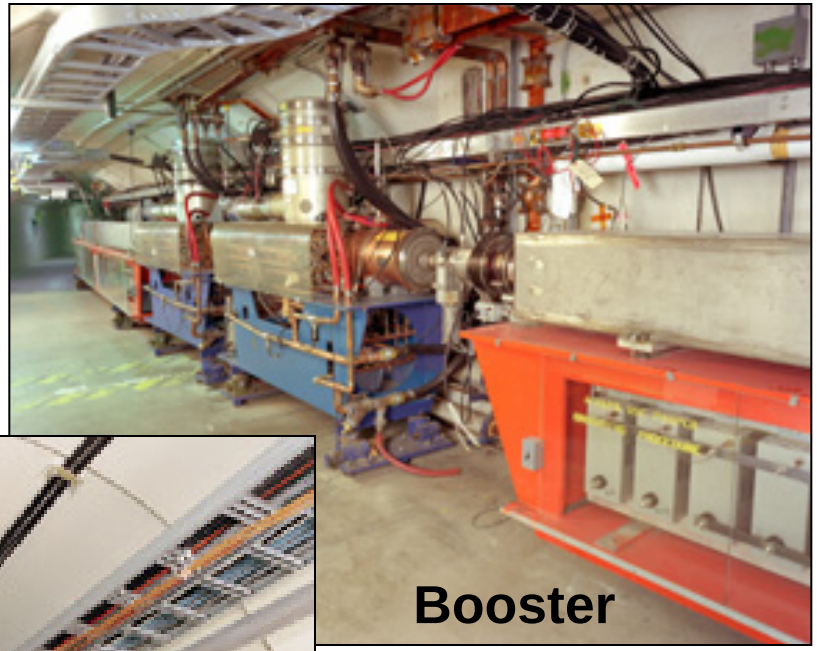
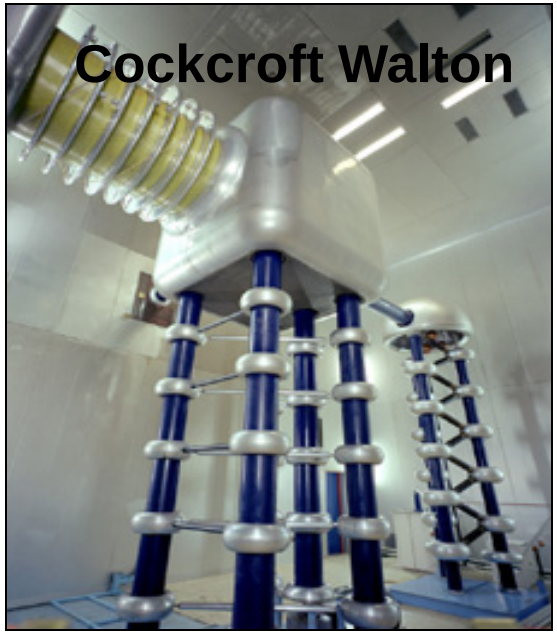
Fermilab Campus

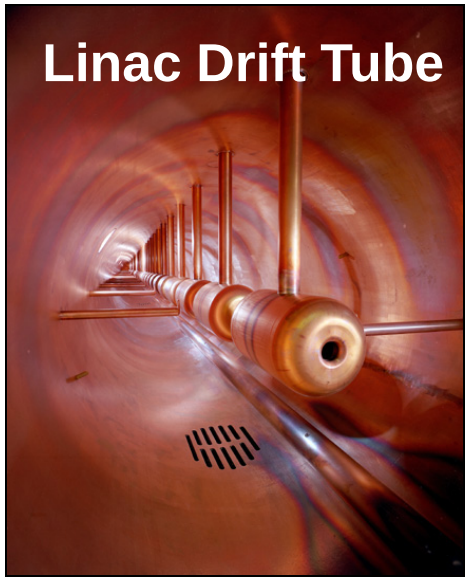
FERMILAB'S ACCELERATOR CHAIN



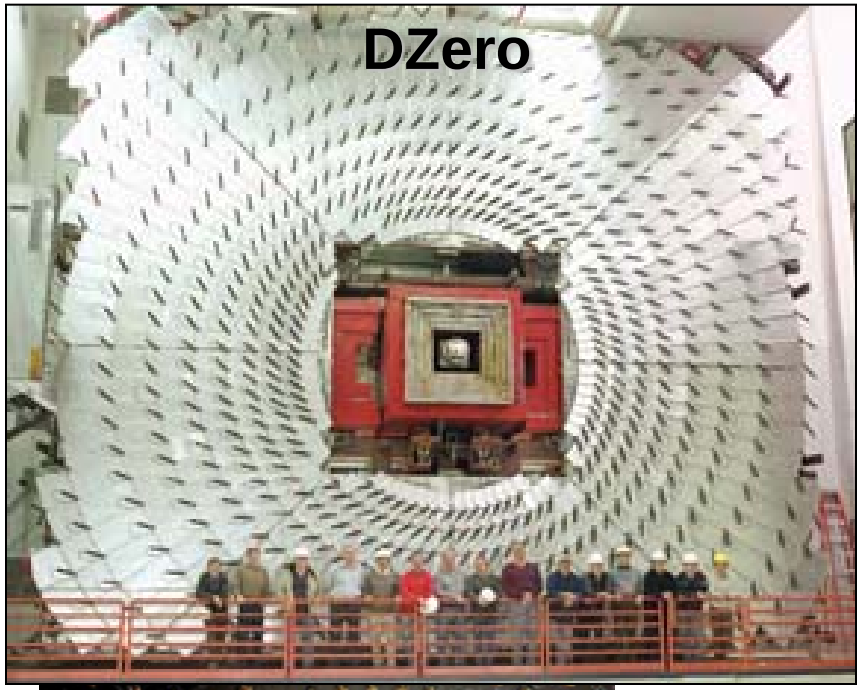


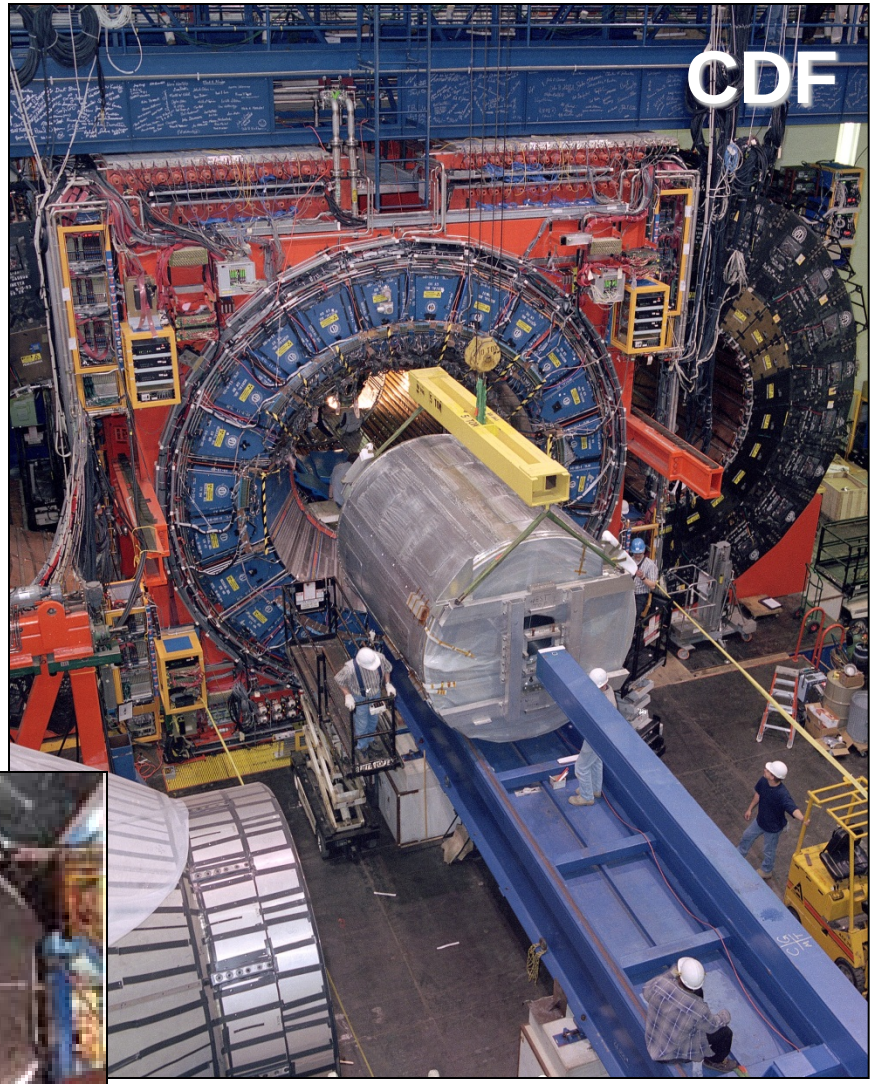


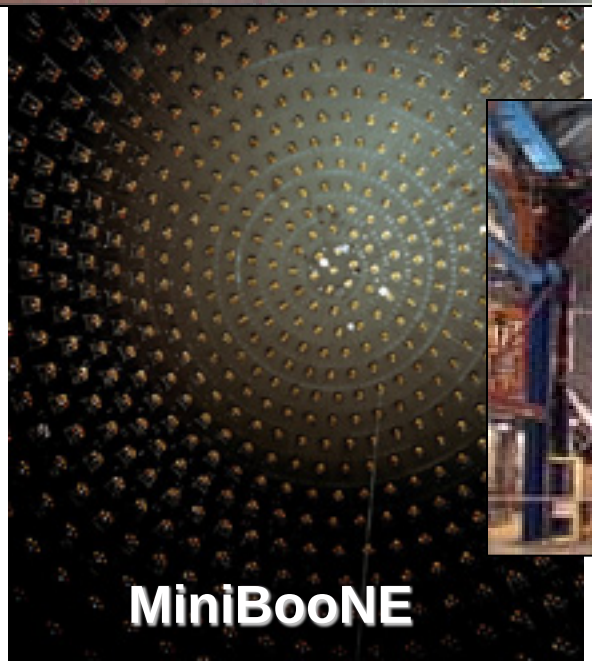




Fermilab Accelerators







Fermilab Detectors

Goals of Radiation Protection

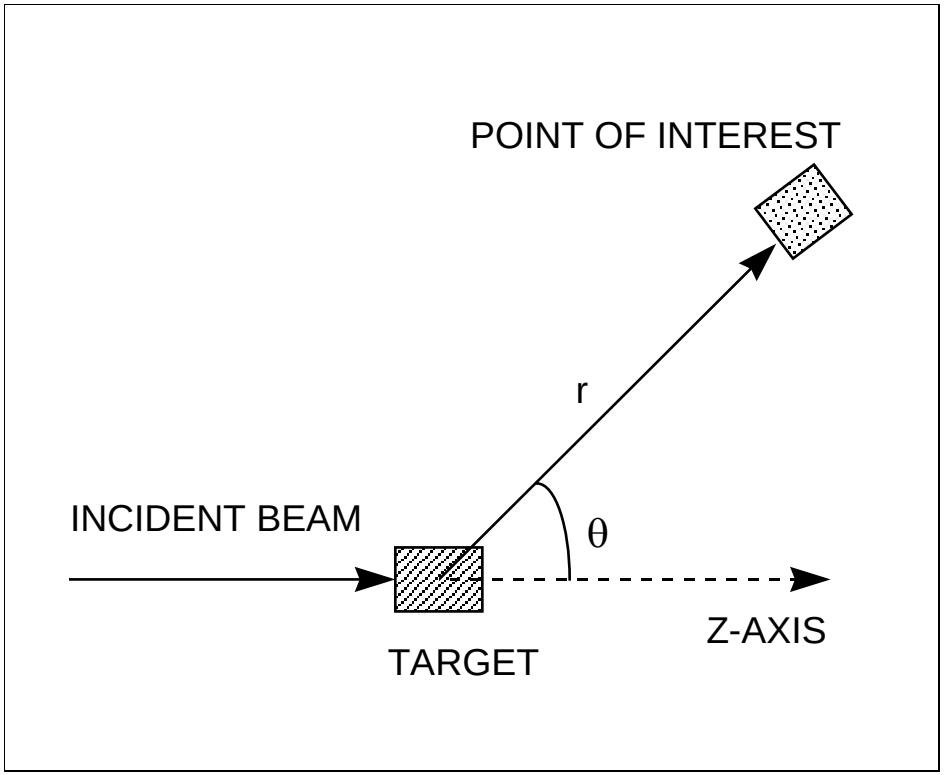
We want to protect people from:

- Normal running losses
- Accidental beam losses
- Activated components
- Activated air, soil and water

What limits do we have to be concerned with?

- 10CFR835 (radiation workers) 5000(DOE)/1500(FNAL)mrem/y
- DOE Order 458.1 (members of the public) 100mrem/y
- EPA regulations (environmental discharge)

Basic Problem for Rad Protection



Can We Calculate Doses by Hand?

In general, we discuss differential yields that depend upon:

- target material and thickness
- particle type
- particle energy (strong dependence)
- emission angle (strong dependence)

One could start with differential cross sections for the process,

$$\frac{d\sigma(E,\theta)}{d\Omega}$$

to get the yield, Y.

Such a calculation is limited by

- targets are not always thin
- secondary particles are produced in the targets
- knowledge of cross sections is incomplete
- all of these limit the ability to perform the needed integrations.

Radiation Transport

The primary tool for determining the amount of radiation reaching a given location is the *stationary form* of the **Boltzmann equation.**

The density of radiation in a volume of phase space may change in 5 ways:

Uniform translation;

Collisions;

Continuous slowing down;

Decay; and

Introduction;

Radiation Transport

$$\tilde{\mathrm{B}} f_i(\vec{x}, E, \vec{\Omega}, t) = Q_{ij} + Y_i$$

$$\tilde{\mathrm{B}}_i = \vec{\Omega} \cdot \nabla + \sigma_i + d_i - \frac{\partial S_i}{\partial E}$$

Y_i is the number of particles of type i introduced by a source per unit area, time, energy, and solid angle;

σ_i is the absorption cross section for particles of type i.;

d_i is the decay probability per unit flight path of radioactive particles of type i ;

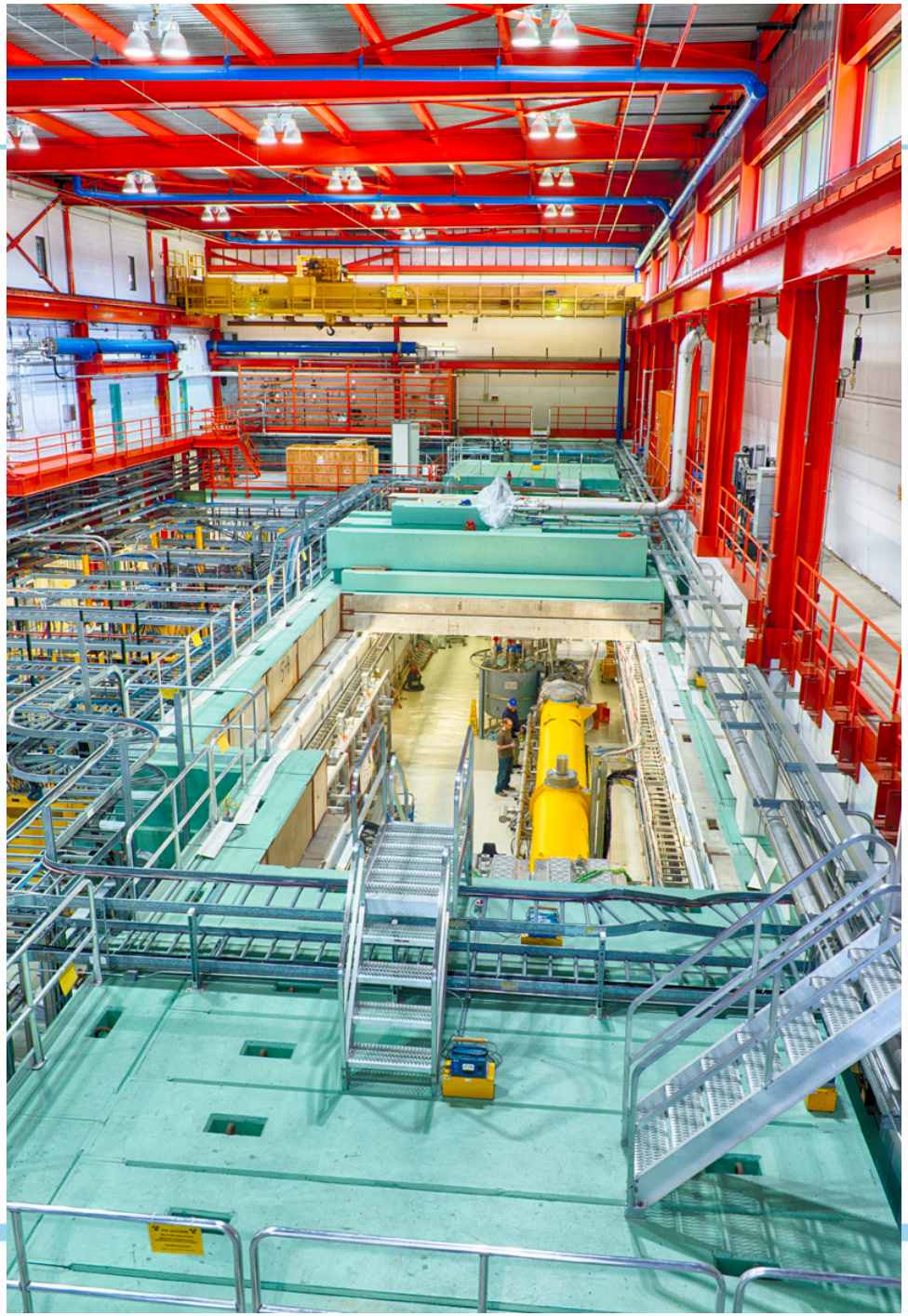
S_i is the stopping power for charged particles of type i (zero for uncharged particles);

Q_{ij} is the "scattering-down" integral, the production rate of particles of type i with a direction , an energy E at a location , by collisions with nuclei or decay of j -type particles having a direction at a higher energy E_B;

Monte Carlo Methods

- Let a computer do this accounting.
- Select a random number, corresponding to a random distance the particle travels in a material.
- Cross sections for all possible processes determine the probabilities for interactions.
- Construct the history (series of interactions) for each particle. This includes the energy deposited in each material.
- Do this lots of times, but remember your simulation is only as good as your random number generator.

- Commonly used codes include: MARS, FLUKA, MCNP, EGS



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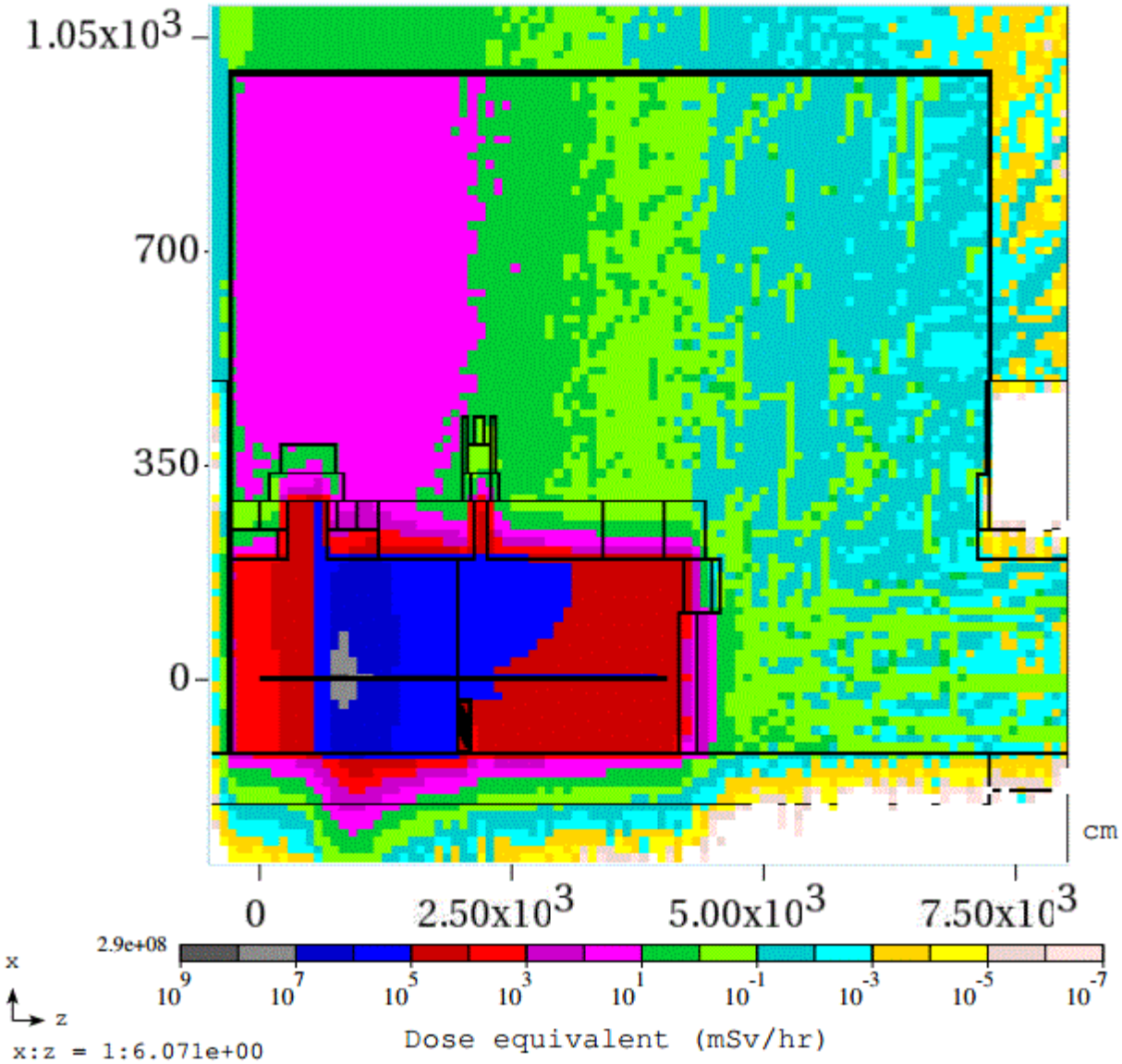
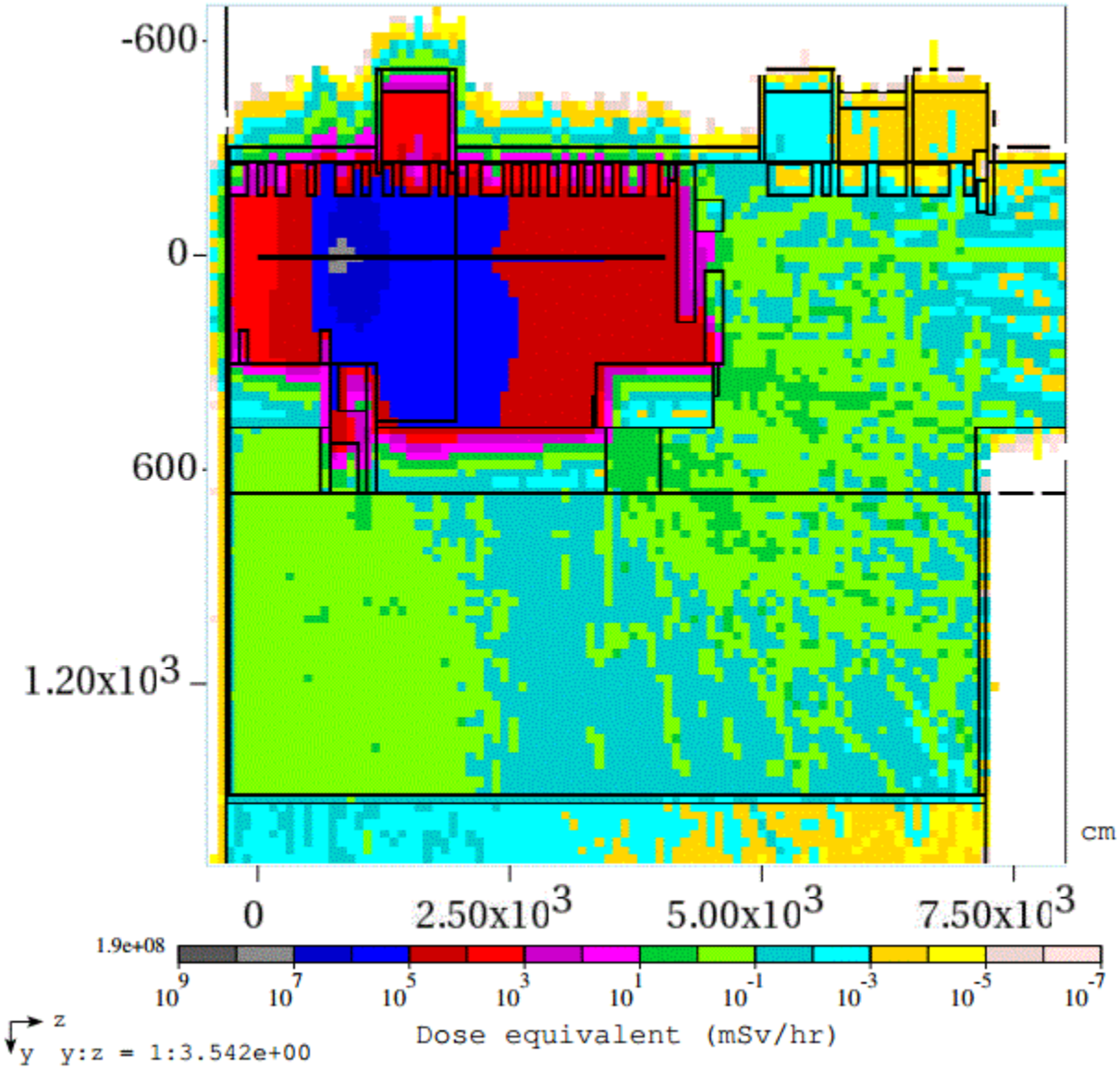
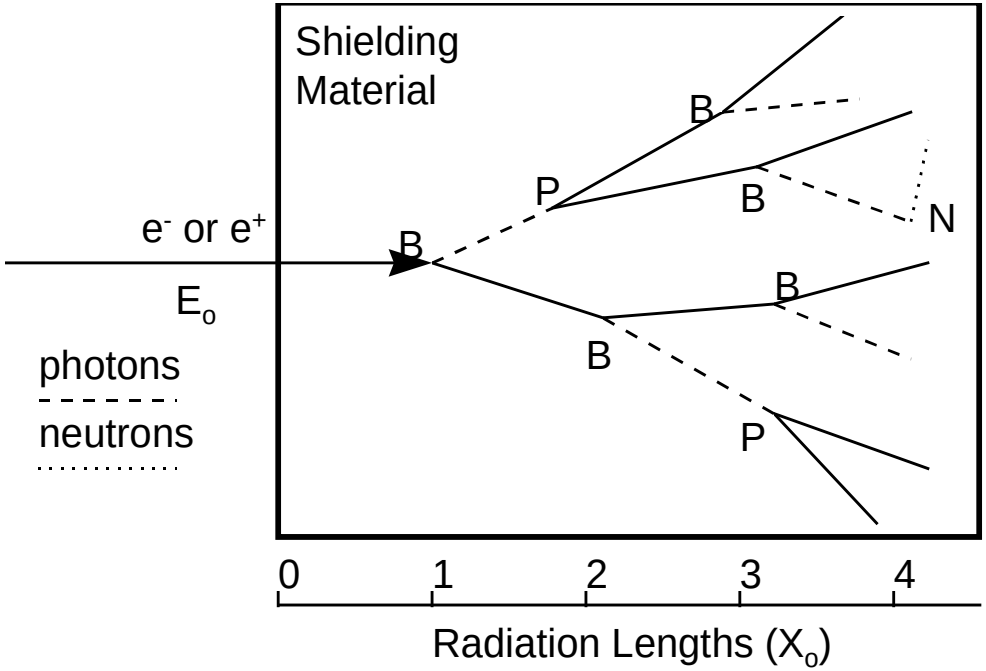
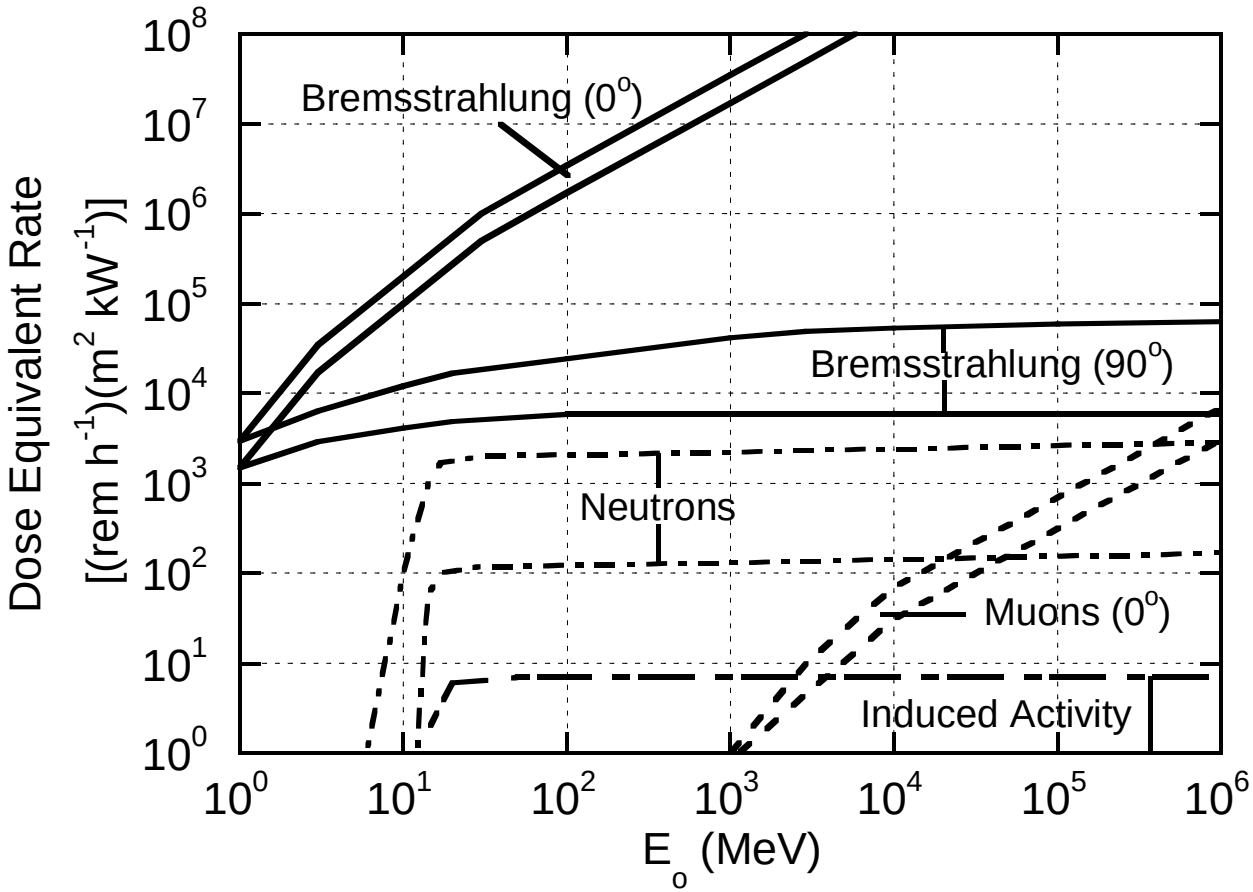

1.05x10^3
700
350
0
cm
0
2.50x10^3
5.00x10^3
7.50x10^3
2.9e+08
10^9
10^7
10^5
10^3
10^1
10^-1
10^-3
10^-5
10^-7
x
z
x:z = 1:6.071e+00
Dose equivalent (mSv/hr)


-600
0
600
1.20x10^3
cm
0
2.50x10^3
5.00x10^3
7.50x10^3
1.9e+08
10^9
10^7
10^5
10^3
10^1
10^-1
10^-3
10^-5
10^-7
Dose equivalent (mSv/hr)
z
y
y:z = 1:3.542e+00

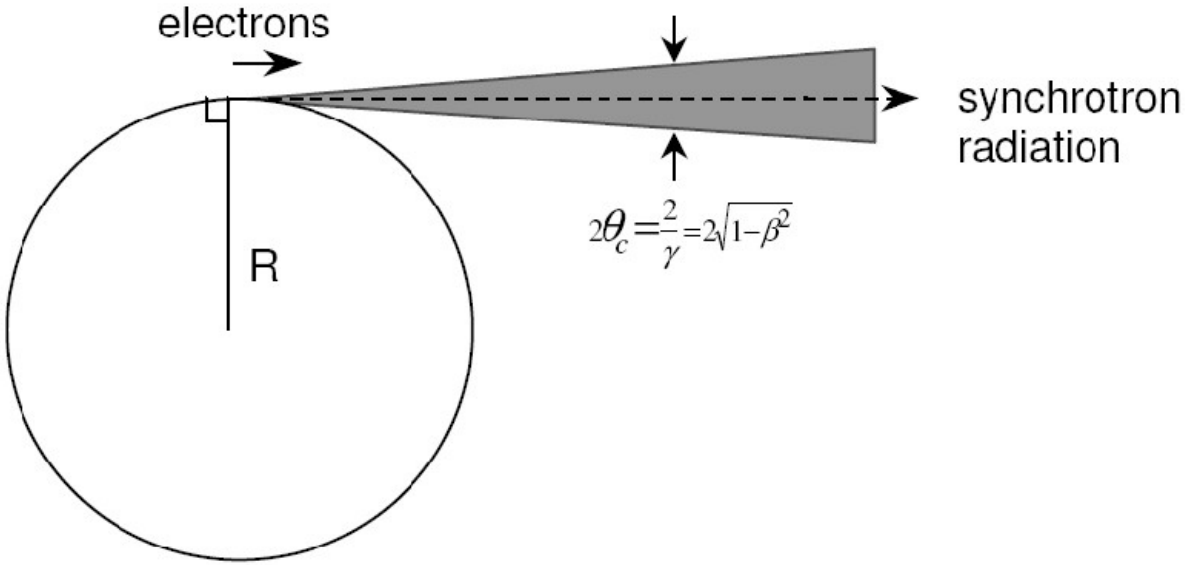
Electron Interactions



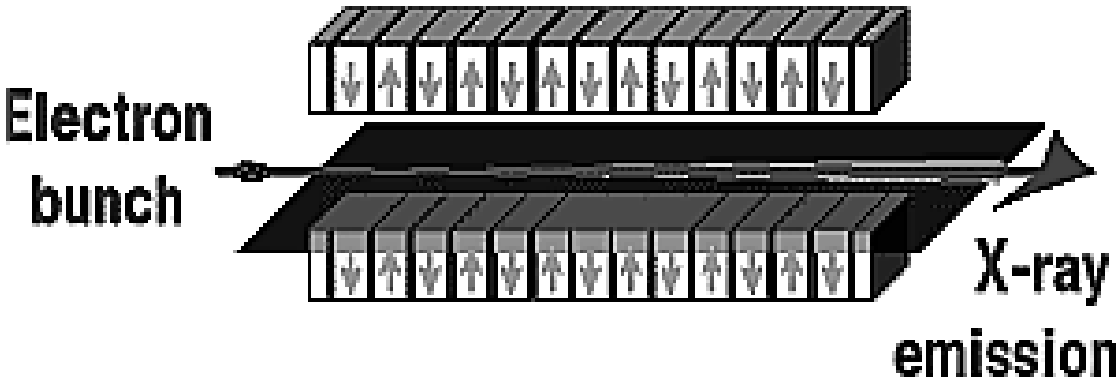
Electron Doses

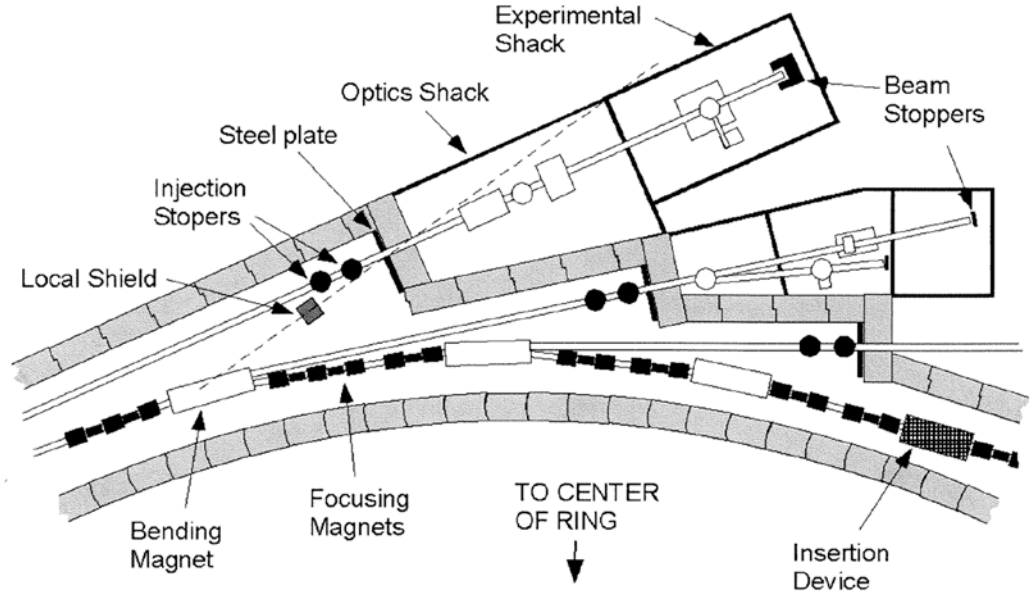


Synchrotron Radiation

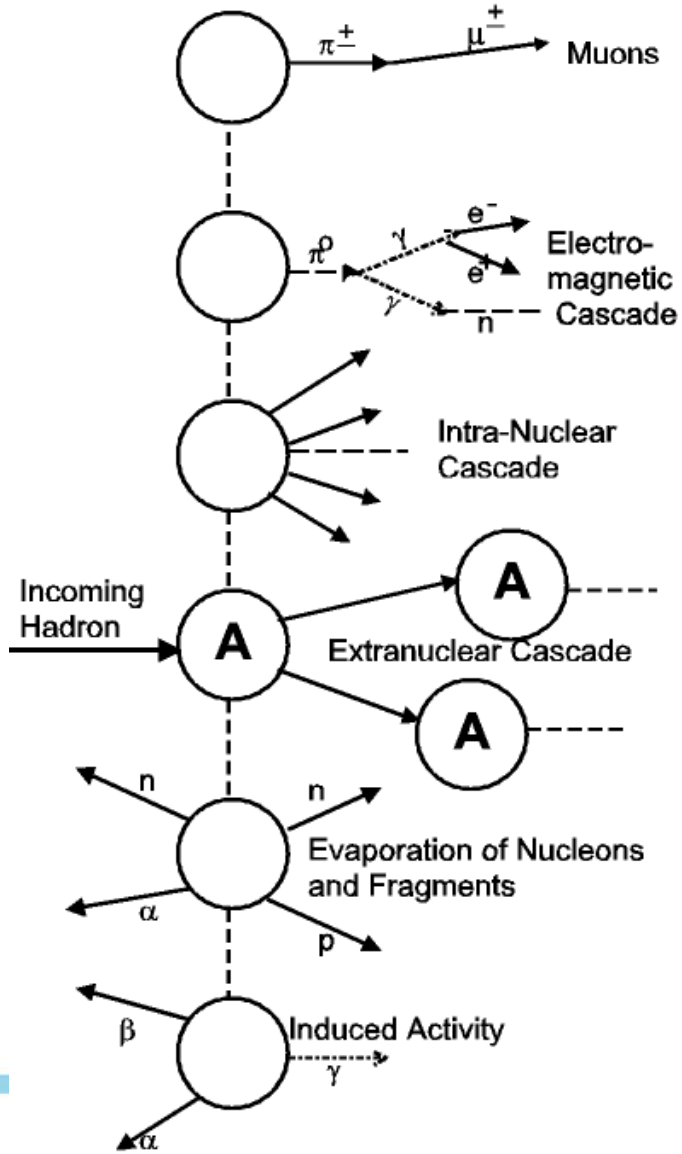


Synchrotron Facilities





Hadron Interactions



Most Numerous Participants	Time Scale (seconds)	Typical Energy per Particle (MeV)	Per Cent of Energy Deposition
π, K -> μ	10^{-8}	any	10
π^0-> e,γ	10^{-16}	any	20
p, n, π, K	10^{-22}	<200	30
p, n, π, K	10^{-23}	>200	30
p, n, d, α	10^{-19}	<30	10
α, β, γ	seconds to years	<10	<1

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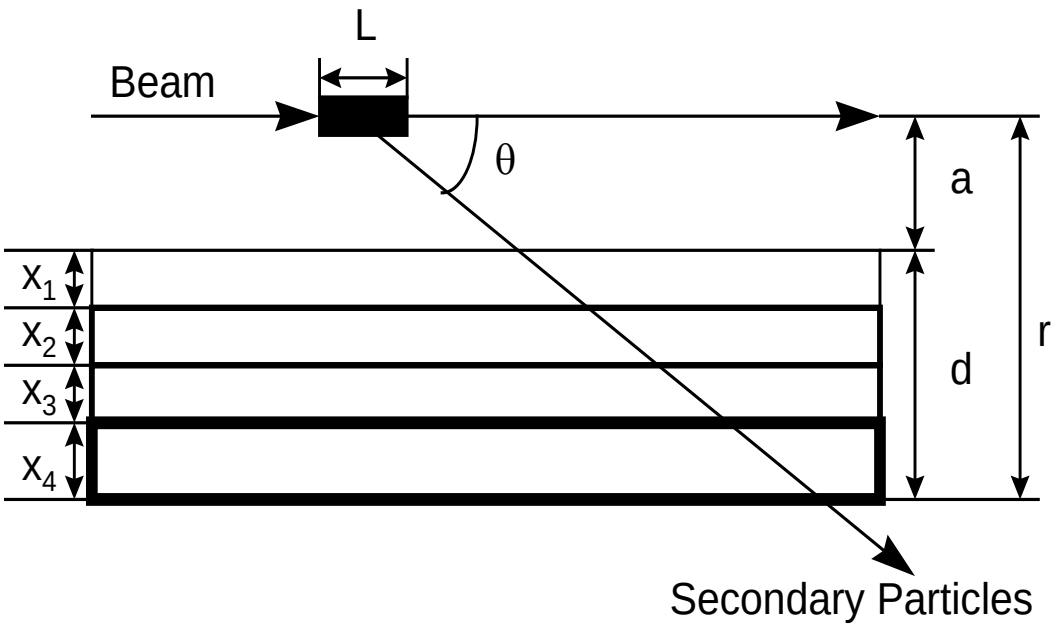
Simple Cases

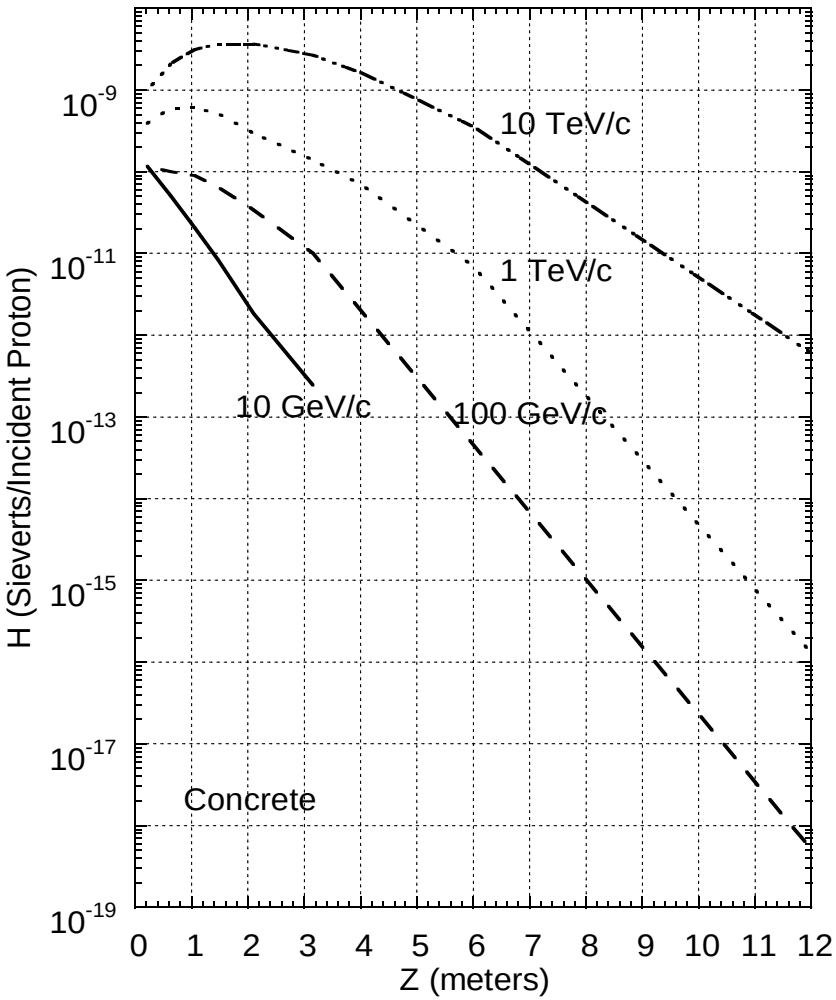


$$H_{equiv} \propto \frac{N_p}{(a+d)^2 \csc^2\theta} \exp\left(-\frac{d\csc\theta}{\lambda}\right)$$

Typical Shielding Materials

Material	Density	Removal Mean Free Path	Removal Mean Free Path
	(grams cm-3)	(grams cm-2)	(cm)
hydrogen gas @ STP	9.00×10^{-5}	43.3	4.81×10^{5}
beryllium	1.85	55.8	30.16
carbon	2.27	60.2	26.58
aluminum	2.70	70.6	26.15
iron	7.87	82.8	10.52
copper	8.96	85.6	9.55
lead	11.35	116.2	10.24
uranium	18.95	117.0	6.17
air @ STP	1.29×10^{-3}	62.0	4.81×10^{4}
water	1.00	60.1	60.10
concrete (typical)	2.50	67.4	26.96
silicon dioxide (quartz)	2.64	66.5	25.19
plastics (polyethylene)	0.93	56.9	61.29

Simple Cases



Variations of the dose equivalent per proton, H, on the longitudinal axis vs. depth Z in the shield for proton-induced cascades in CONCRETE of density 2.4 g cm-3. The curves are the result of CASIM calculations for incident proton momenta of 100 GeV/c, 1 TeV/c, and 10 TeV/c and FLUKA results for 10 GeV/c.

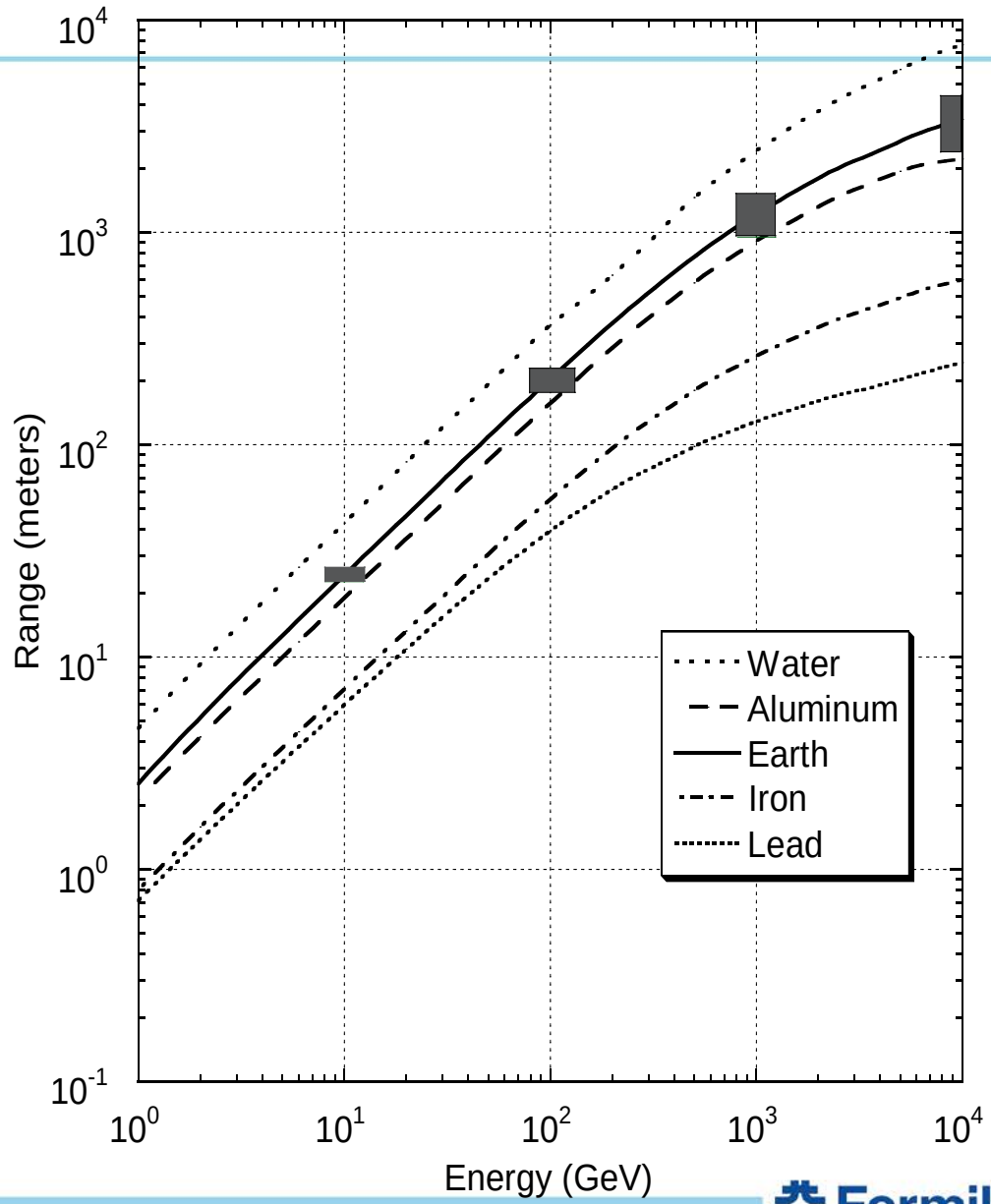
Muon Interactions

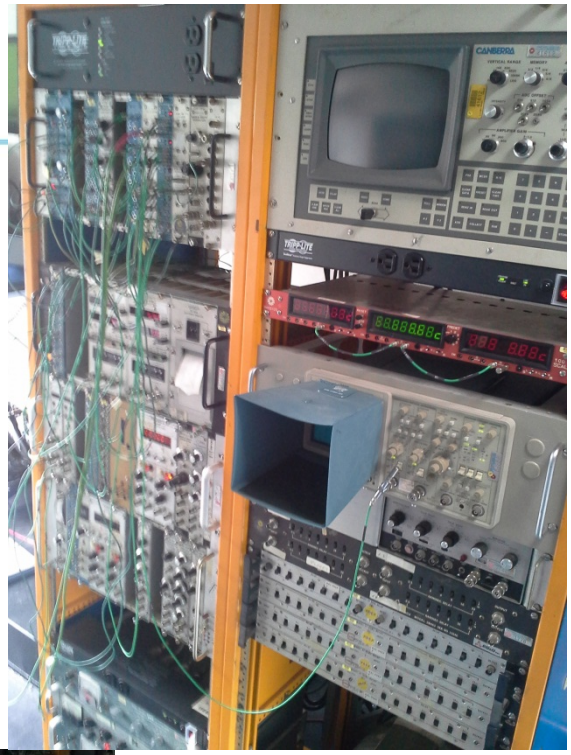
For muons (μ's) the situation is rather unique.

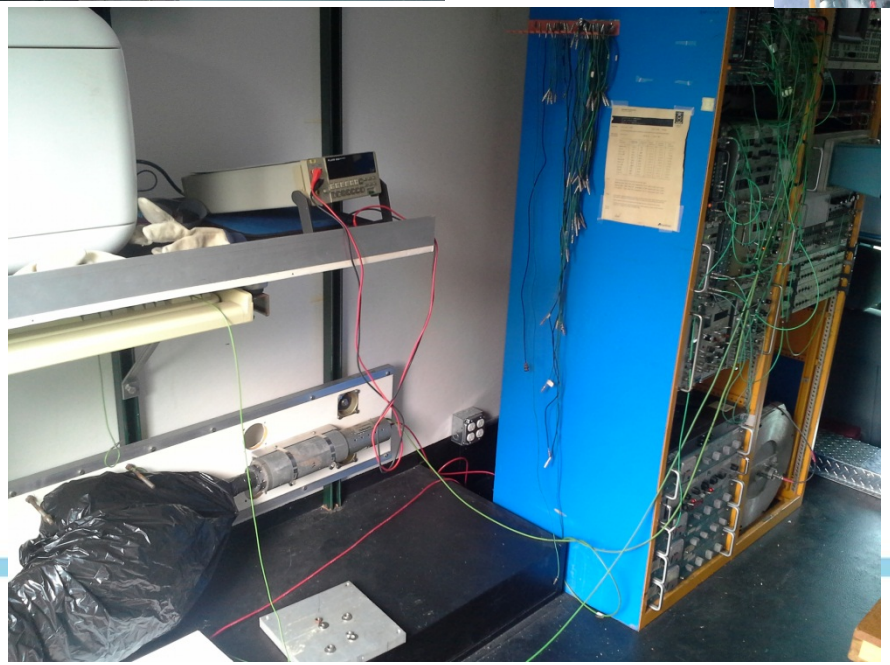
The muon rest energy is 105.66 MeV,
The mean-life *t* =2.1970x10-6 s,

The mean-life times the speed of light *ct* =658.65 m.
Muon ranges are very long.

Muons are far less susceptible to radiative effects.







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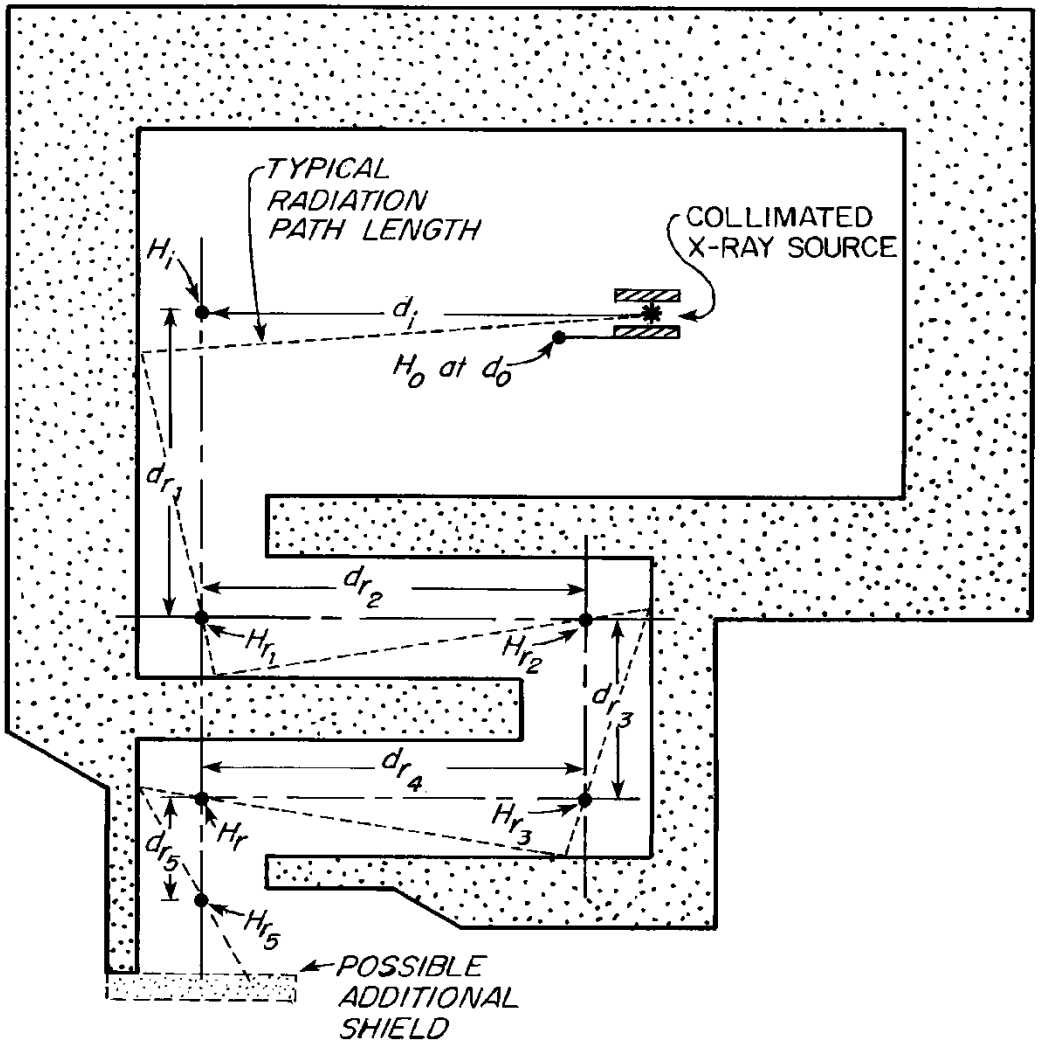
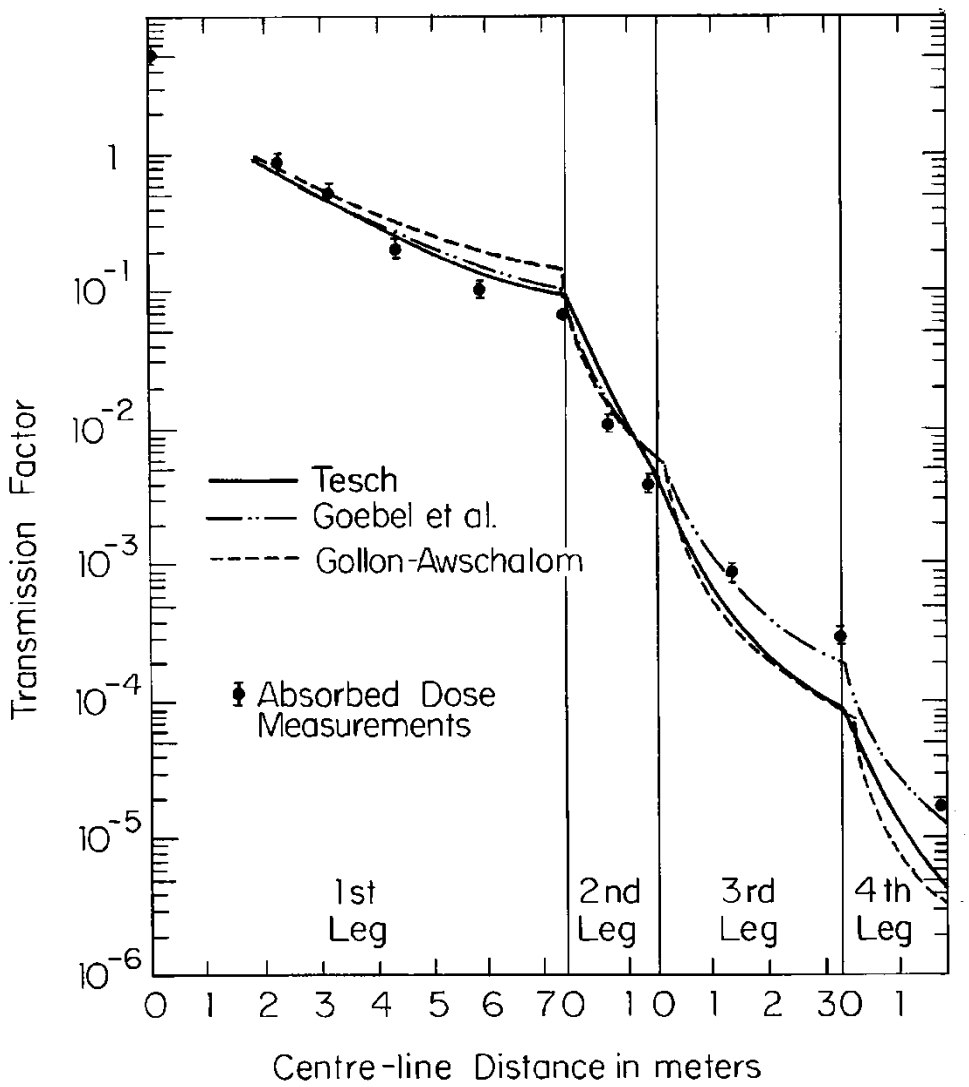
Labyrinths and Penetrations



Labyrinths and Penetrations



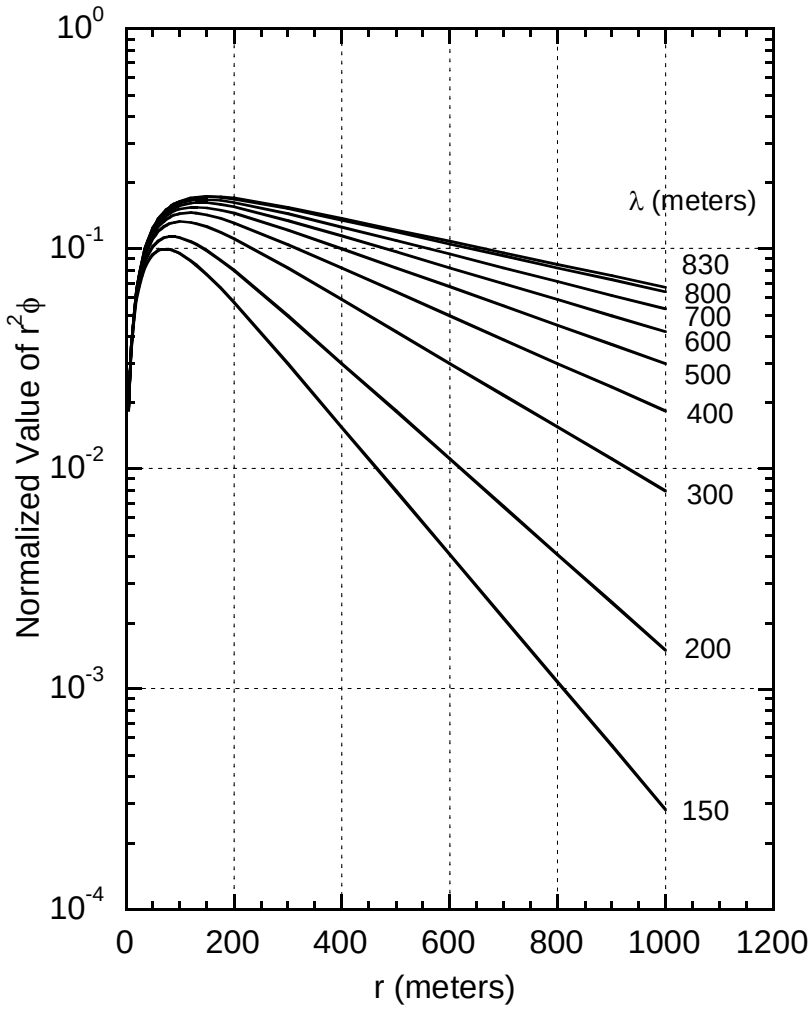
Skyshine

The phenomenon, known as **skyshine**, is the situation in which the roof of some portion of the accelerator or an associated experimental facility is shielded more thinly than are the sides of the same enclosure that directly view the radiation source.

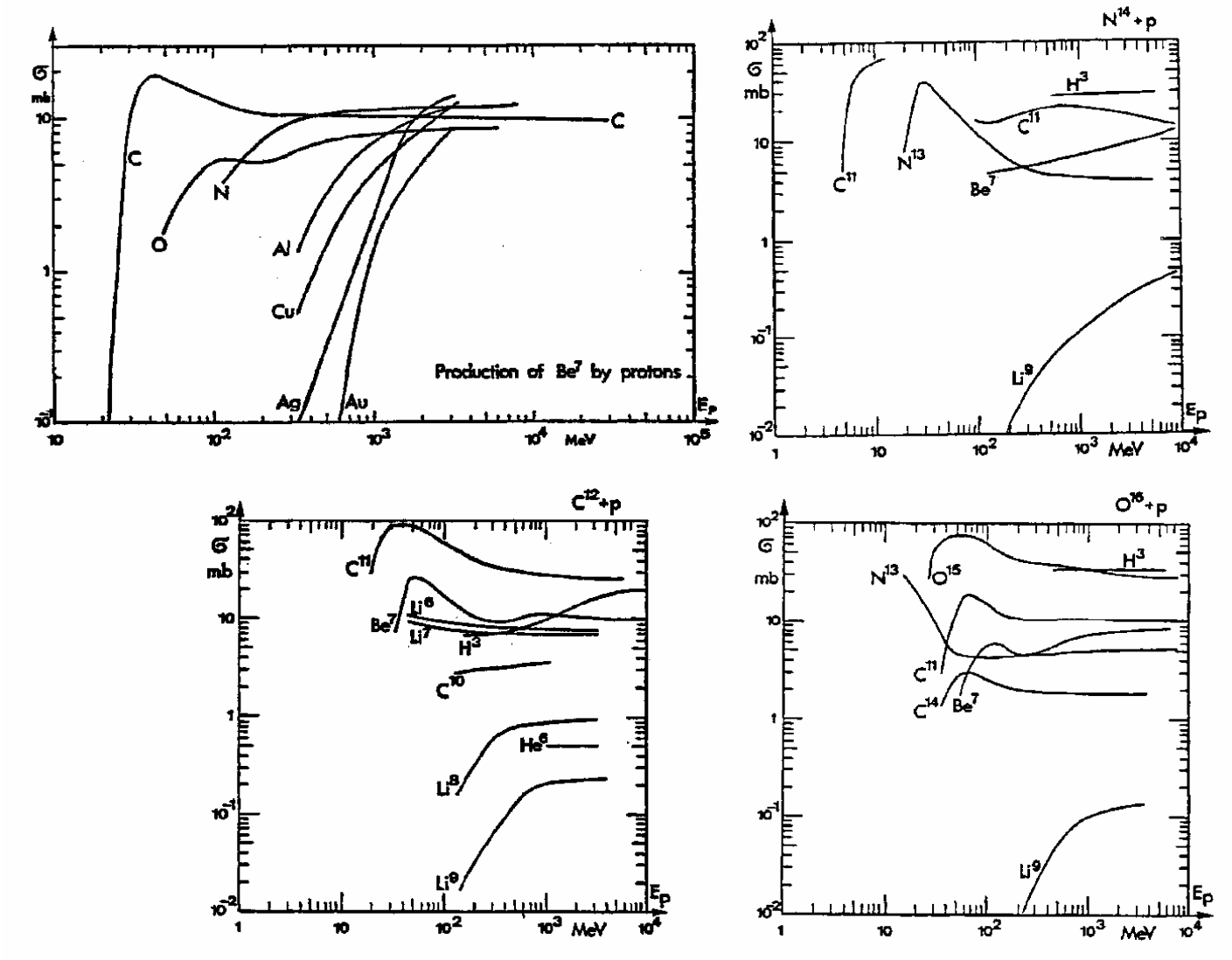
Neutron skyshine has been encountered at nearly all major accelerators.

$$\Phi(r) = \frac{aQ}{4\pi r^2}\left(1 - e^{-r/\mu}\right)e^{-r/\lambda}$$

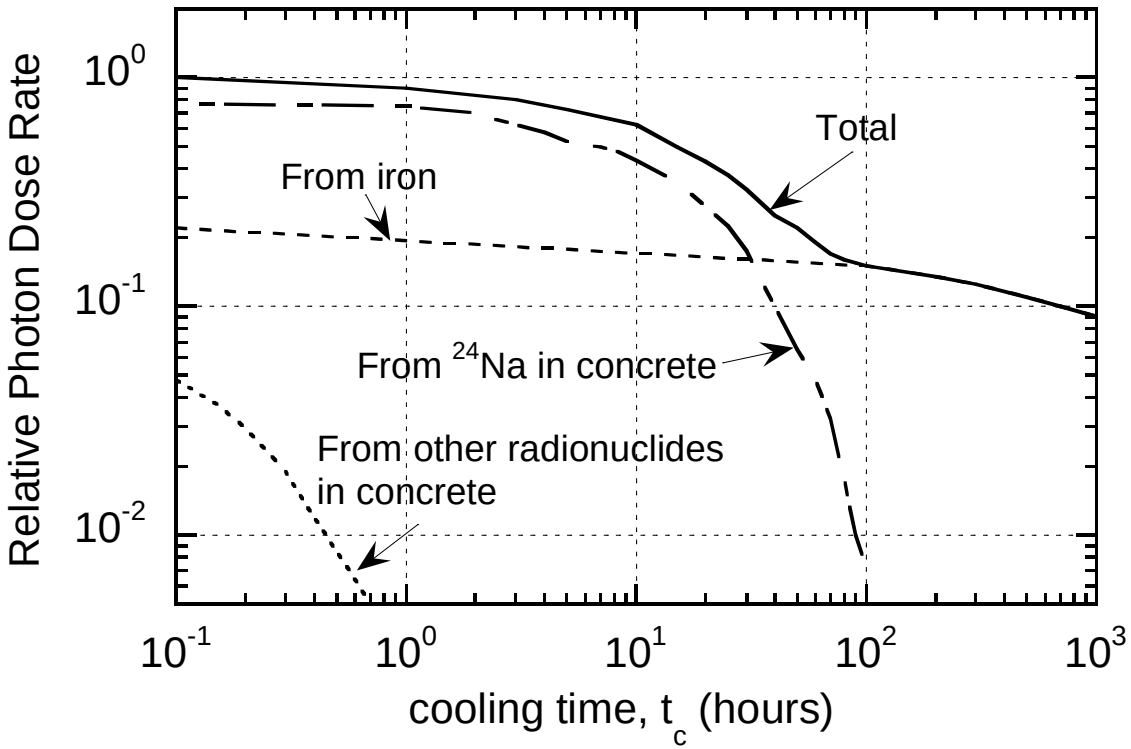
Skyshine


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Normalized Value of $r^2\phi$
0
200
400
600
800
1000
1200
r (meters)
λ (meters)
830
800
700
600
500
400
300
200
150

Induced Activity



Induced Activity



Environmental Protection

Environmental Protection

Environmental Protection

Environmental Protection

Air Protection

Air and water activity limits are set by the EPA. Fermilab is regulated by the Illinois EPA.

Annual dose rate due air emissions to a maximally exposed individual are calculated using EPA CAP88 software. Activity from emission stacks and stack flow rate are inputs to this code, in addition to local meteorological data. The EPA limit is 10mrem/y for members of the public. Fermilab is well below this every year.

Air doses in buildings and tunnels are governed by DOE limits.

In both cases, ventilation systems are designed to allow activity to decay before it is released. Entrance to tunnels may be delayed to allow decay of airborne activity before work begins.

11C, 13N, 15O along with 41Ar (produced by thermal neutron capture) are the nuclides most frequently seen

Water Protection

Surface water limits for Tritium : 1900pCi/ml (~100mrem/y)

Drinking water limits for Tritium: 20pCi/ml (~4mrem/y)

Sanitary sewer limit: 9500pCi/ml (5Ci annual total)

Soil, geological media, and water in soil can be activated by proton beams.

3H, 7Be, 22Na, 45Ca, 46Sc, 48V, 51Cr, 54Mn, 55Fe, 59Fe, and 60Co are seen. A few isotopes (3H, 22Na, 45Ca, and 54Mn) can leach from soil into water.

Calculations are done to make sure that experiments/facilities won't exceed these limits. An analytical model is also used to calculate any possible flow to ground water in the area.

Thank you