RBWH Nuclear Medicine

Hospital Cyclotrons: Radiation Safety Aspects

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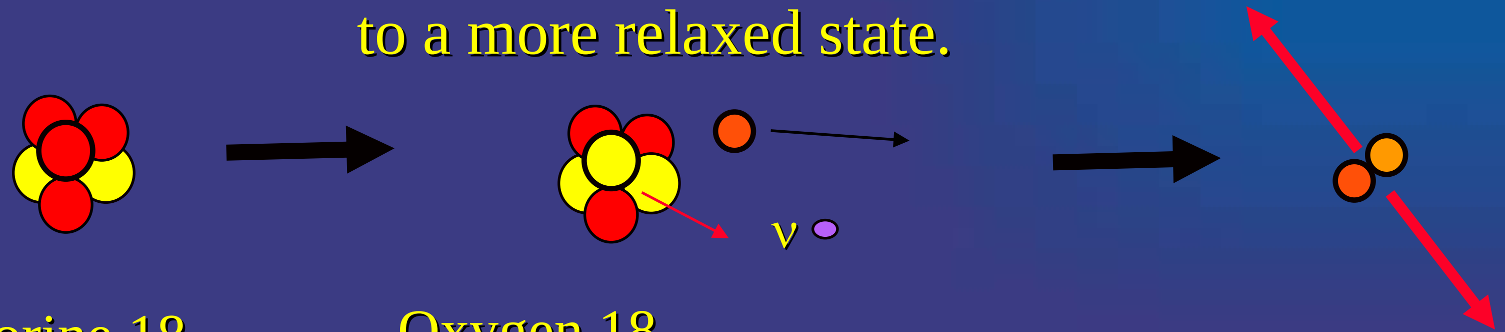
Isotope Production.

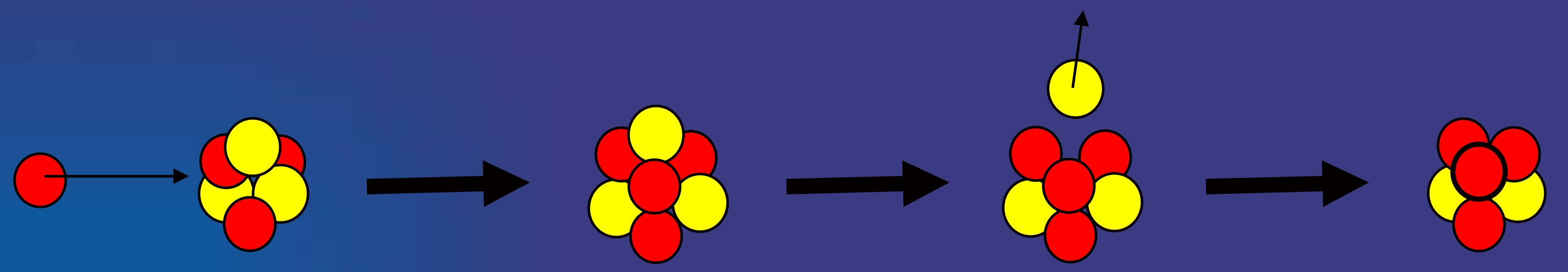
Positron decay is a way for an atom with too many protons to get to a more relaxed state.



Fluorine 18
excess Proton

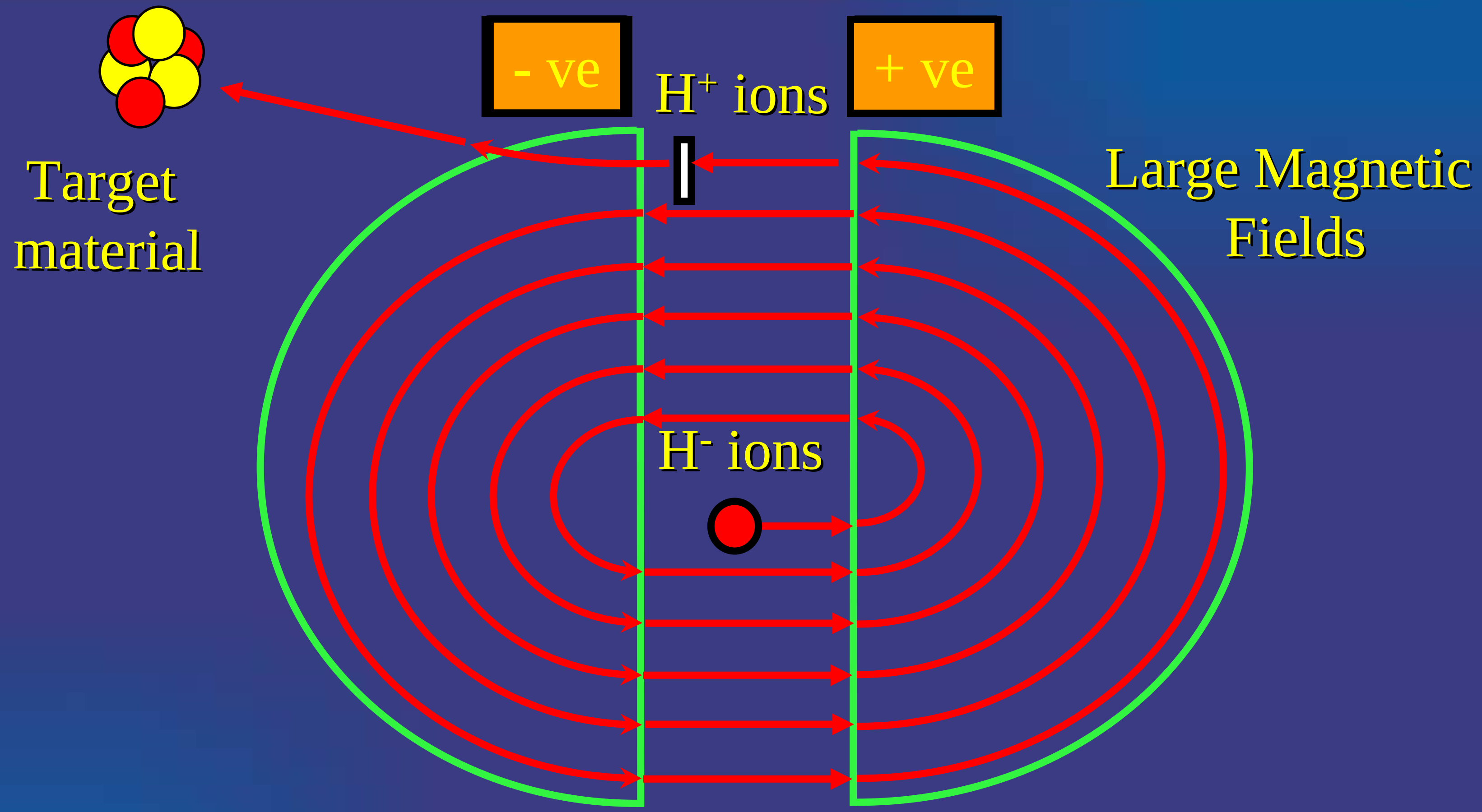
Oxygen 18
Neutron, Neutrino,
Positron and Gamma rays

Production: Take a stable target atom and add a proton.



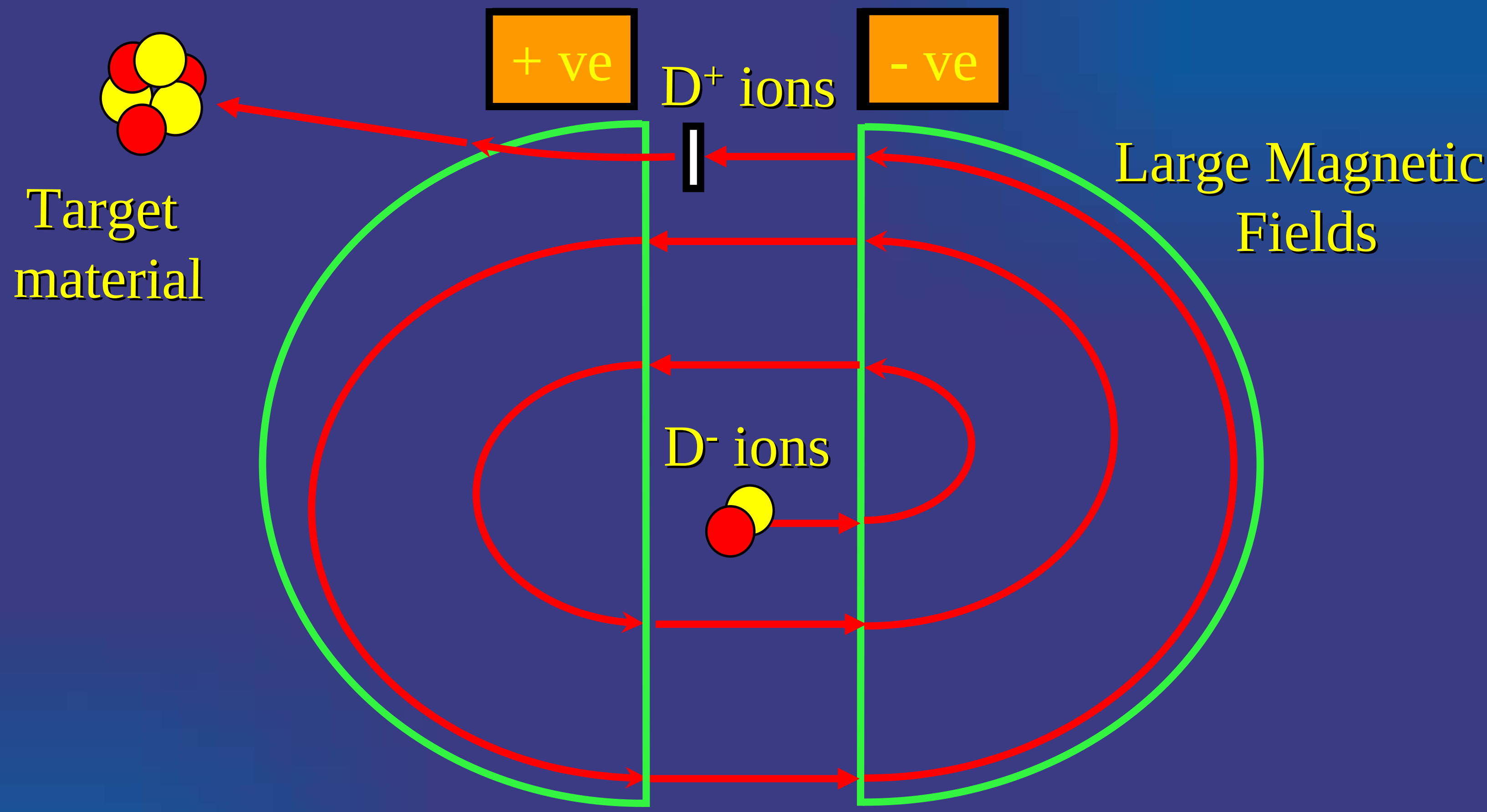
O^{18}_{8} (p,n) F^{18}_{9}

Cyclotron



Electric potentials accelerate ions.
Magnetic fields cause ions to travel in circles.

Cyclotron



Electric potentials accelerate ions.
Magnetic fields cause ions to travel in circles.

Cyclotron

Not a Nuclear Reactor.

Needs no radioactive fuel.

Does not produce radioactive waste or emissions.

An electrical device that can be turned off.

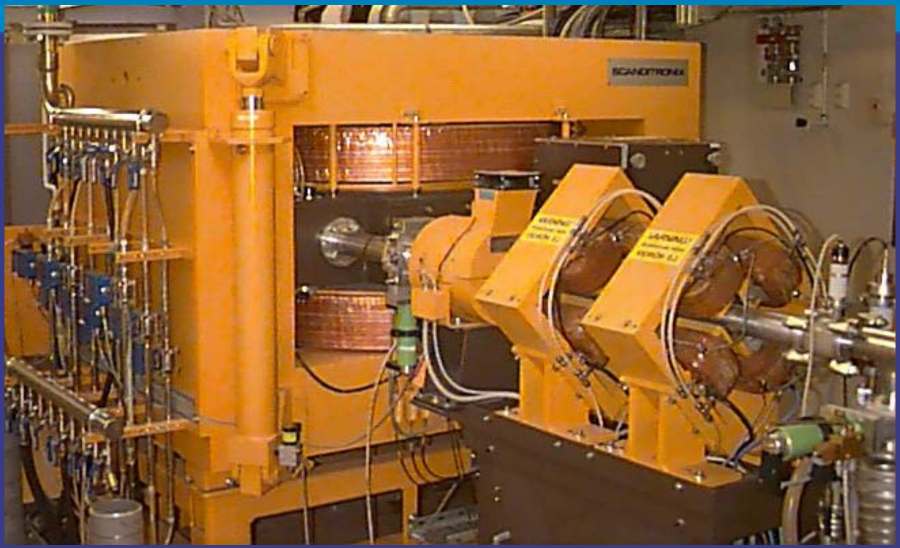
(Very big brother to a TV set)

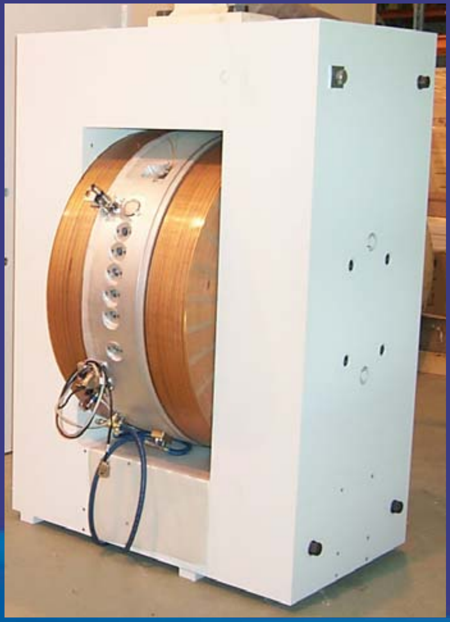
Requires a small amount of a stable material as a target.

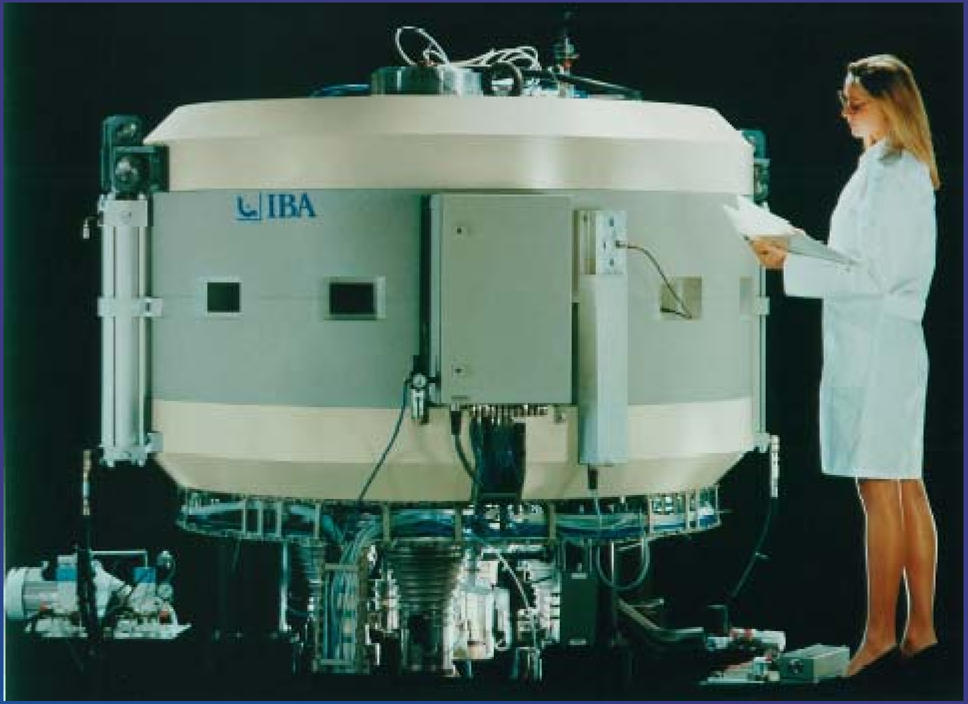
Produces a small volume of a highly specific radioactive product.

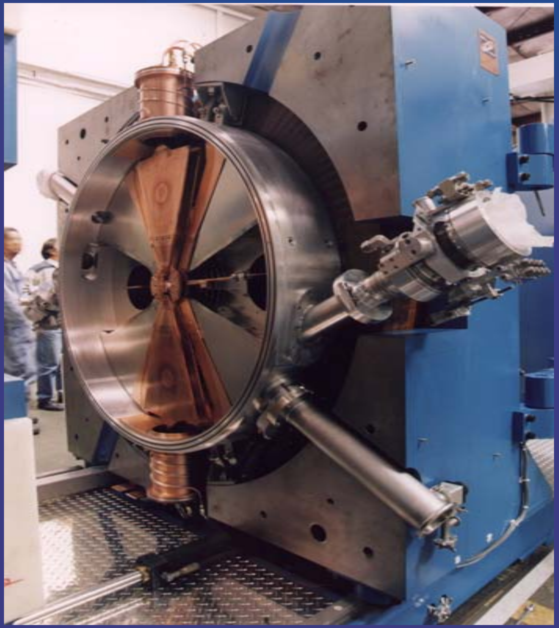
Does not become radioactive.

CYCLOTRONS






IBA

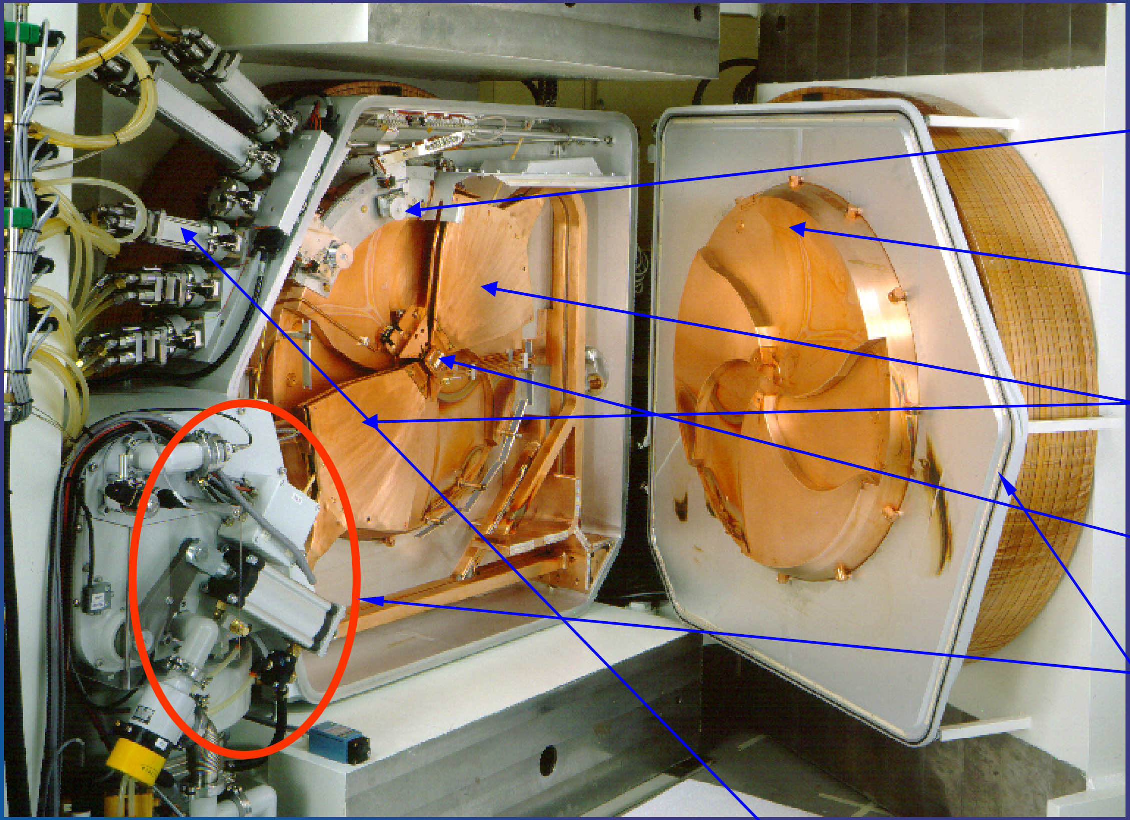


Cyclotron subsystems

- Magnet system
- RF system
- Ion source system
- Extraction system
- Diagnostic system
- Vacuum system
- Control System
- Target system
- Cooling system

Courtesy of GE Medical systems

Cyclotron subsystems



Extraction system

Magnet pole

RF system (Dee's)

Ion source

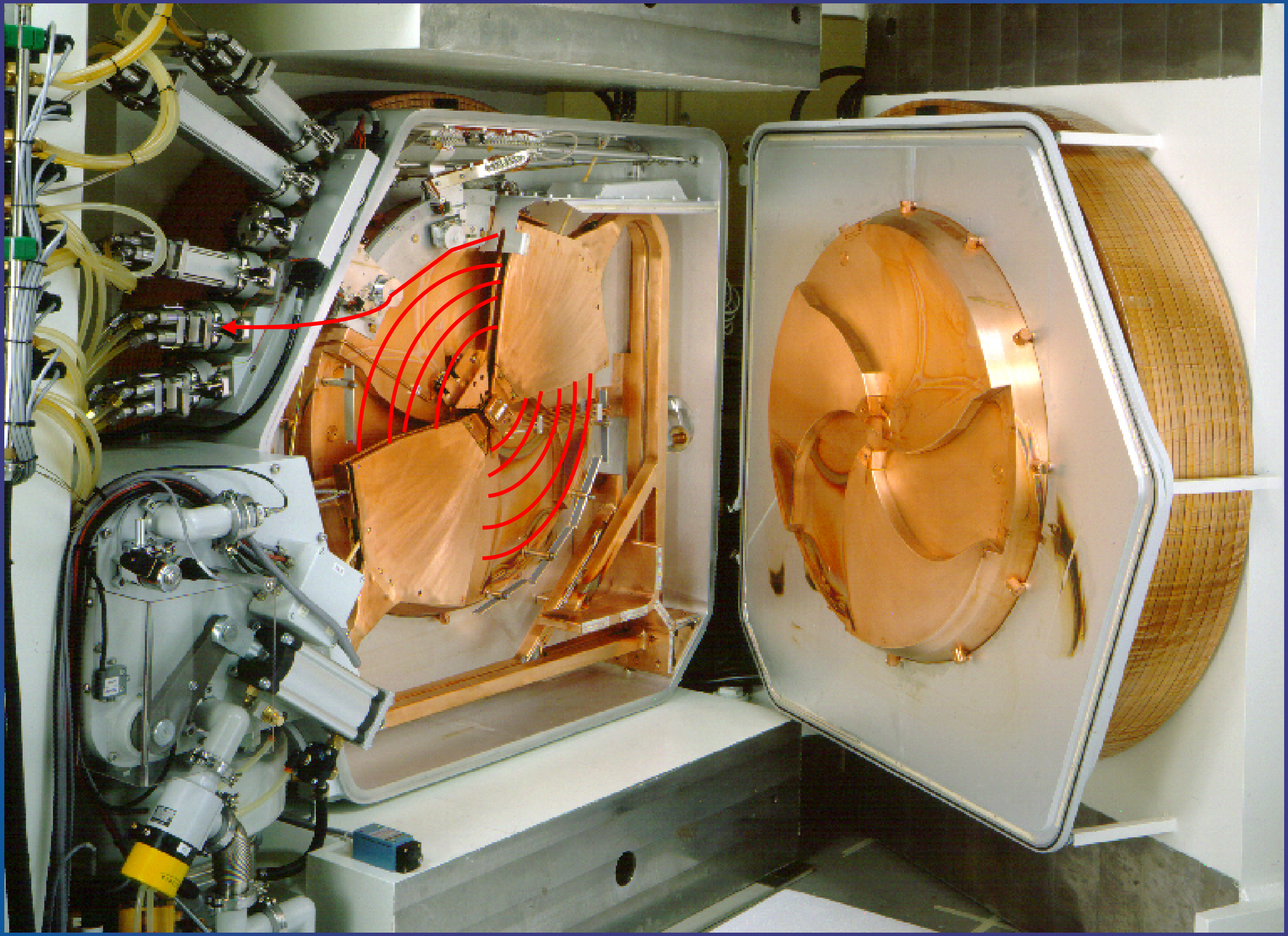
Vacuum system

Targets

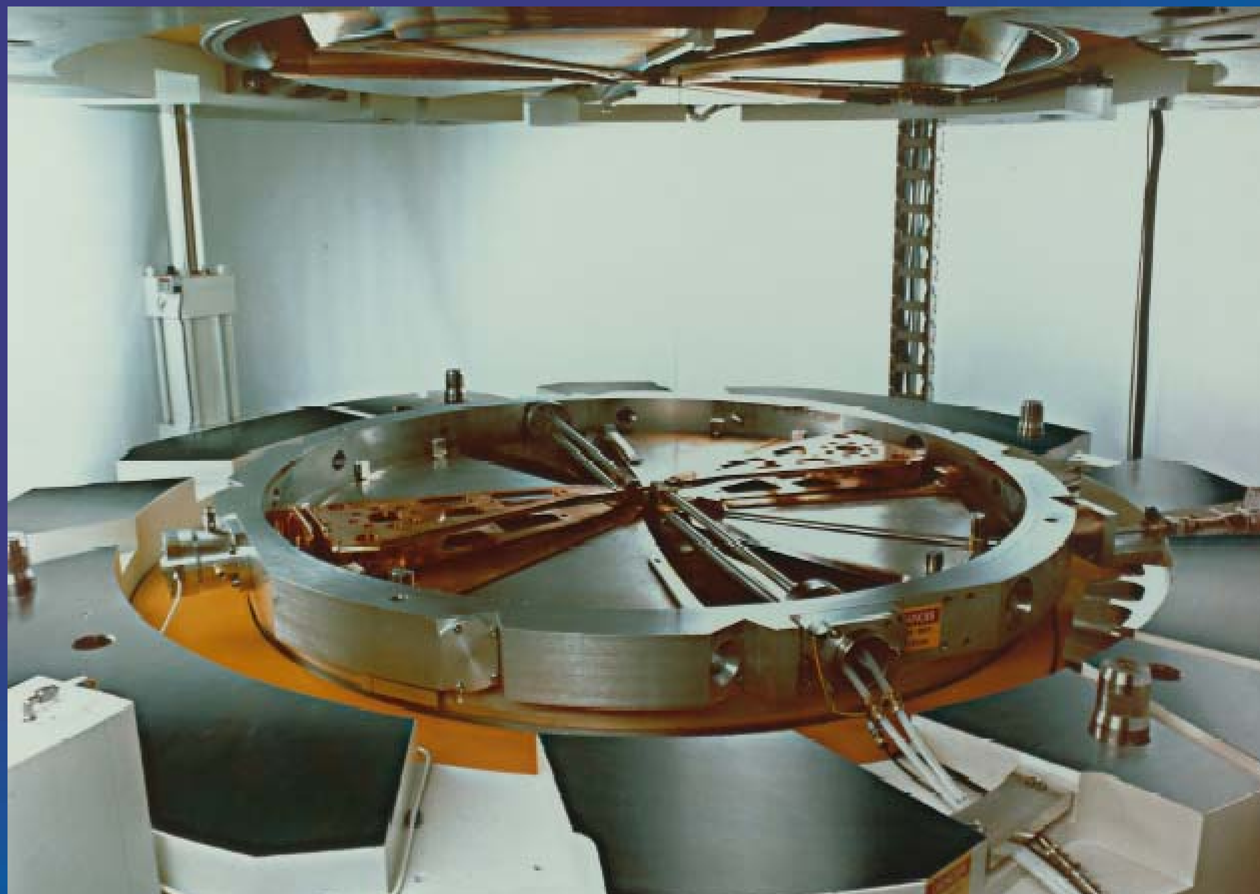
Courtesy of GE Medical systems

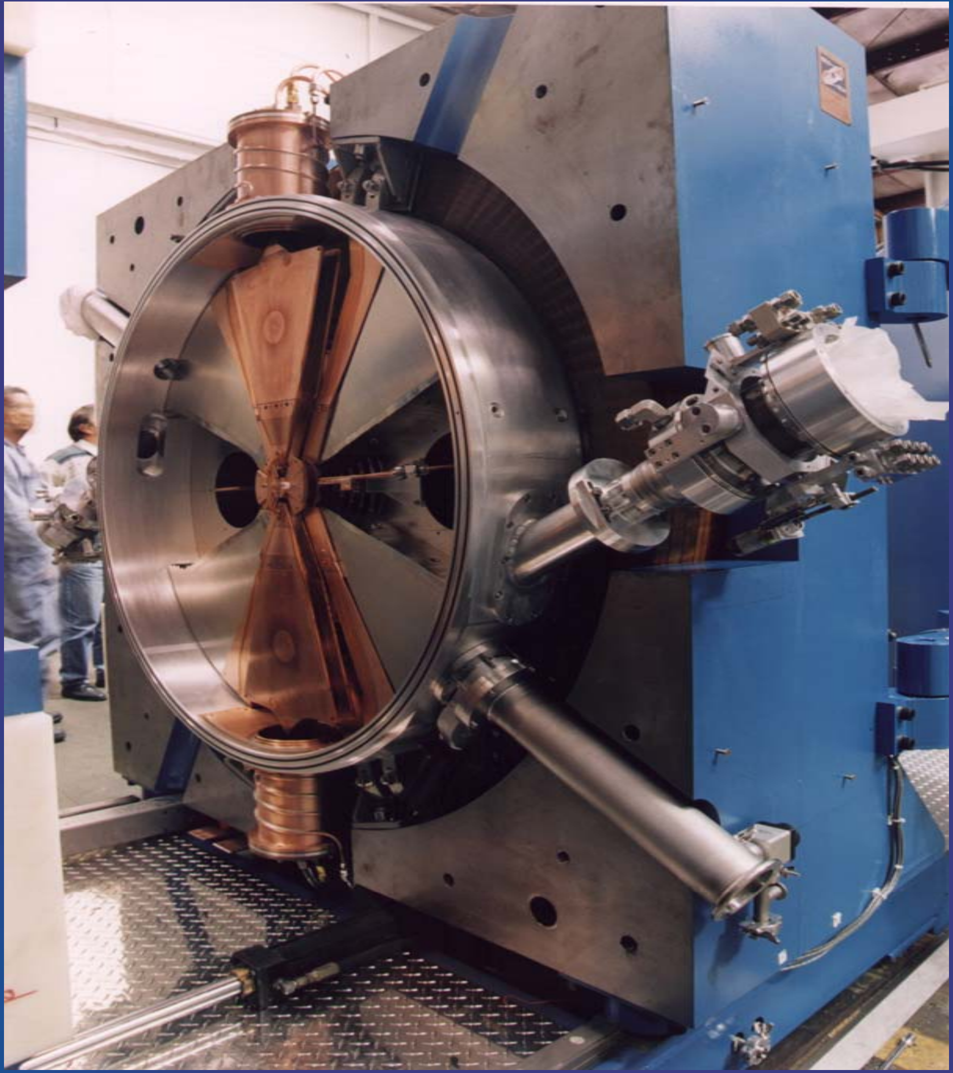
Beam acceleration

Beam

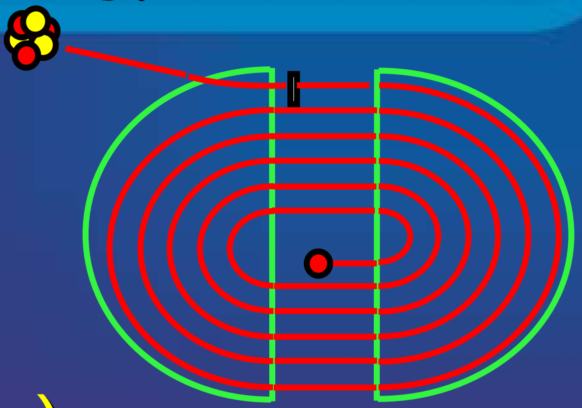


Courtesy of GE
Medical systems





Cyclotron Radiation Source Terms:



- Proton acceleration

lost protons

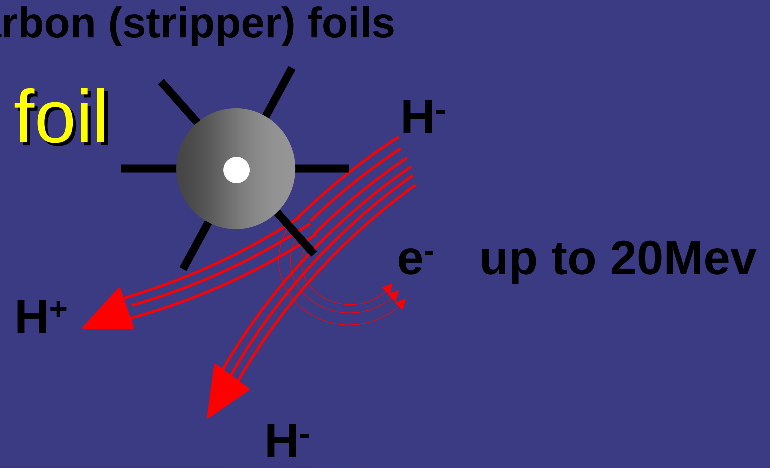
(40% due to electron loss)

(p,<u>x</u>) + <u>γ</u> with vacuum chamber

x = neutrons duterons tritons alphas

electrons after stripper foil

<u>x rays</u>



Cyclotron Radiation Source Terms:

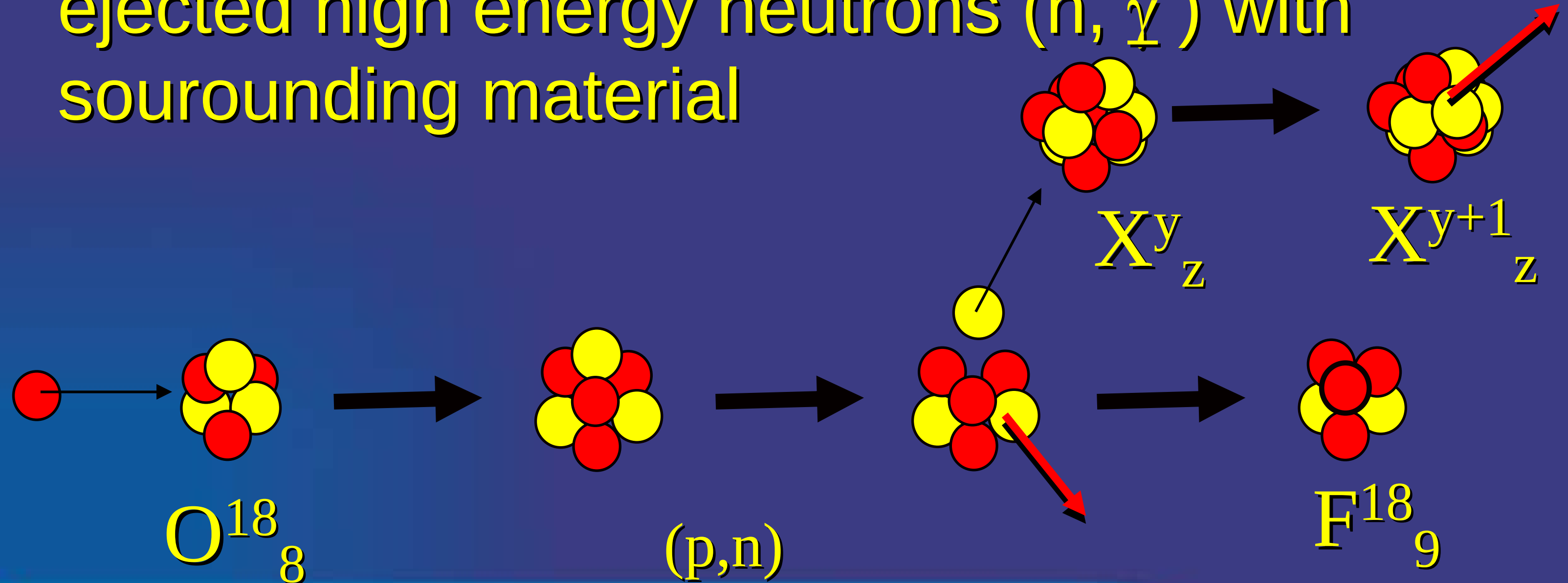
- Bombardment

  (p,<u>n</u>) + γ from target material

  (p,<u>x</u>) + γ from target body + collimators

  x = neutrons duterons tritons alphas

ejected high energy neutrons (n, γ) with souraounding material



Cyclotron Radiation Source Terms:

Proton attenuation	μA	no./s	MeV
•Lost H- with a range of energies	32	2.0×10^{14}	0-16.5
•Protons leaving the acceleration	48	3.0×10^{14}	16.5
•Tantalum collimator losses	8	5.0×10^{13}	16.5
•Foil 20μm, He 30mm, Foil 50μm			15
Havar (Co 42.5%, Cr 20%, Mn 1.6%, Mo 2%, Ni 13%, W 2.8%, Fe 18.1%)			
•^{18}O (5% ^{16}O)	40	2.5×10^{14}	15

•Some will impact on back of target (silver)

$H_2{}^{18}O$ target for ^{18}F 40 μA of 15 MeV protons (GE PET trace)

Cyclotron Radiation Source Terms:

- Proton interactions

Material	Proton flux [1/s]	Yields [particles/s] Neutrons	Deutrons	Tritons	Alfa	Gamma	Neutron energy E_{av} [MeV]
Al (p,x)	4.0E+13	2.8E+09	6.3E+07	0.0E+00	2.8E+10	6.1E+10	2.45
Si (p,x)	1.5E+14	2.8E+09	1.0E+09	2.1E+06	2.1E+09	2.3E+11	2.02
Cu (p,x)	1.0E+13	3.6E+09	4.7E+06	5.2E+04	1.1E+09	1.5E+10	1.96
Ta (p,x)	5.0E+13	1.0E+11	3.3E+07	2.4E+06	7.0E+07	2.2E+11	1.38
Havar (p,x)	2.5E+14	2.8E+11	2.4E+09	1.9E+08	4.4E+09	4.4E+11	2.29
$H_2{}^{18}O$ (p,x)	2.5E+14	3.2E+11	3.2E+09	0.0E+00	6.4E+11	2.2E+12	1.93
$H_2{}^{16}O$ (p,x)	2.5E+14	0.0E+00	1.2E+06	0.0E+00	4.2E+10	3.2E+11	
$^{14}N_2$ (p,x)	2.5E+14	1.1E+10	2.1E+10	0.0E+00	2.6E+11	1.3E+12	3.40
Al dummy	2.5E+14	1.3E+11	8.6E+09	0.0E+00	6.3E+11	2.3E+12	2.92

7.13E+11 total
1.41E+11 forward
5.72E+11 isotropic

$H_2{}^{18}O$ target
40 μA, 15 MeV protons
(GE PET trace)

•Gamma source terms
(energy per second)
prompt gamma from (p,x) and (n,γ) reactions)

Material	(p,x) [MeV/s]	(n,g) [MeV/s]
Ta	1.7E+11	
Si	6.5E+11	
Pb		1.0E+10
Ag		6.6E+09
Cu + Others	2.4E+10	6.9E+11
Al	1.5E+11	1.7E+10
Fe + SS		5.8E+11
Concrete		3.5E+12
H_2O + Oil		2.0E+09
Havar	6.2E+11	
Target - $H_2{}^{18}O$	3.8E+12	
Target - $H_2{}^{16}O$	1.9E+12	
Target - ${}^{14}N_2$	3.9E+12	
Target - Dummy (Al)	6.6E+12	

Net dose rate

- Gamma: Sieverts per hour

- Neutron: tens of Sieverts per hour

QLD design criteria 1 μSv/hr

Reducing the radiation to safe levels

- Attenuation
- Minimize + localize the neutron interactions (n,γ) (n,2n) (n,α)

Two basic choices

- Self shielded cyclotron
- Cyclotron vault

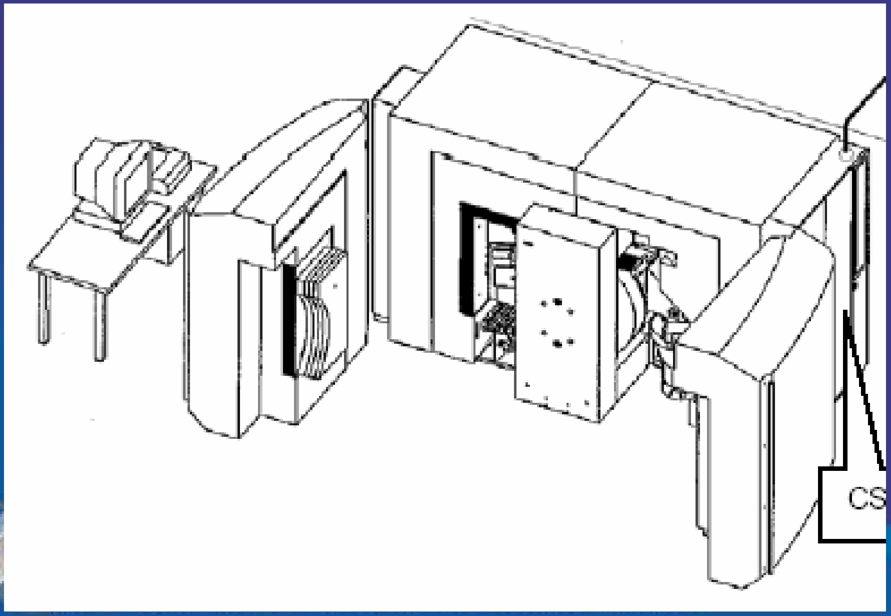
Self Shielded

Shielding encases cyclotron

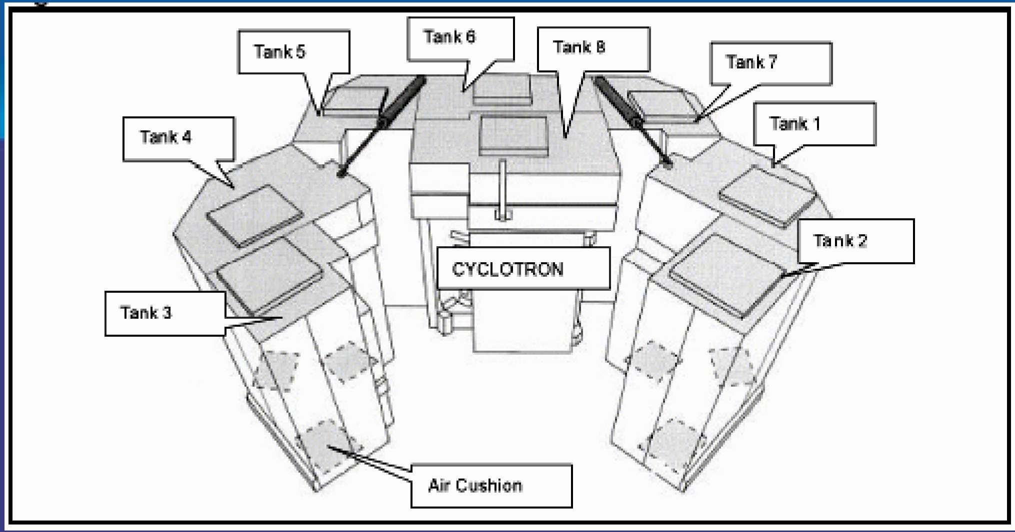
- Moderate the neutrons.
  Polyethylene water wax
- Absorb neutrons with min activation and γ rays.
  Boron
- Attenuate γ rays
  Lead Concrete

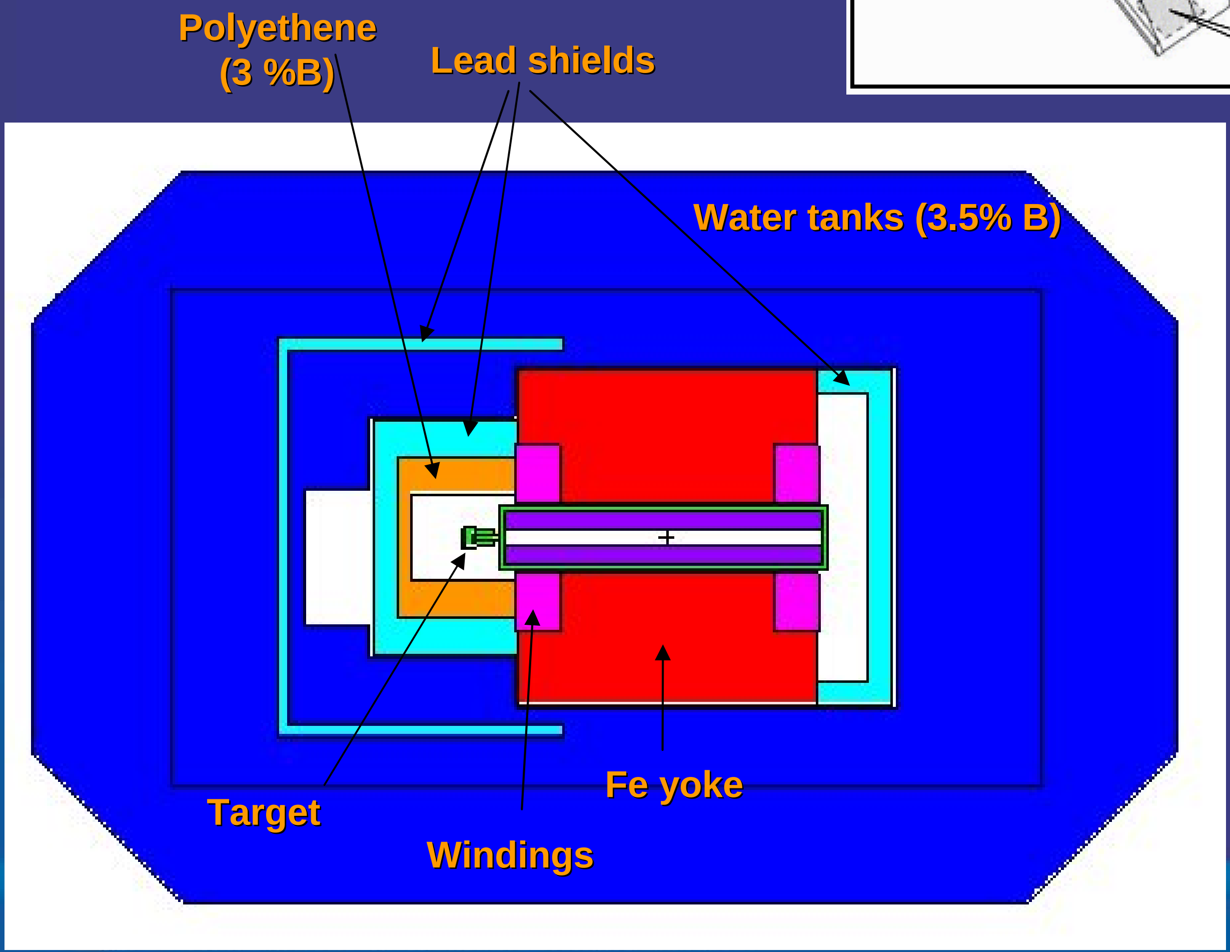
- Still may require thick walls 50-300 mm

GE MiniTrace



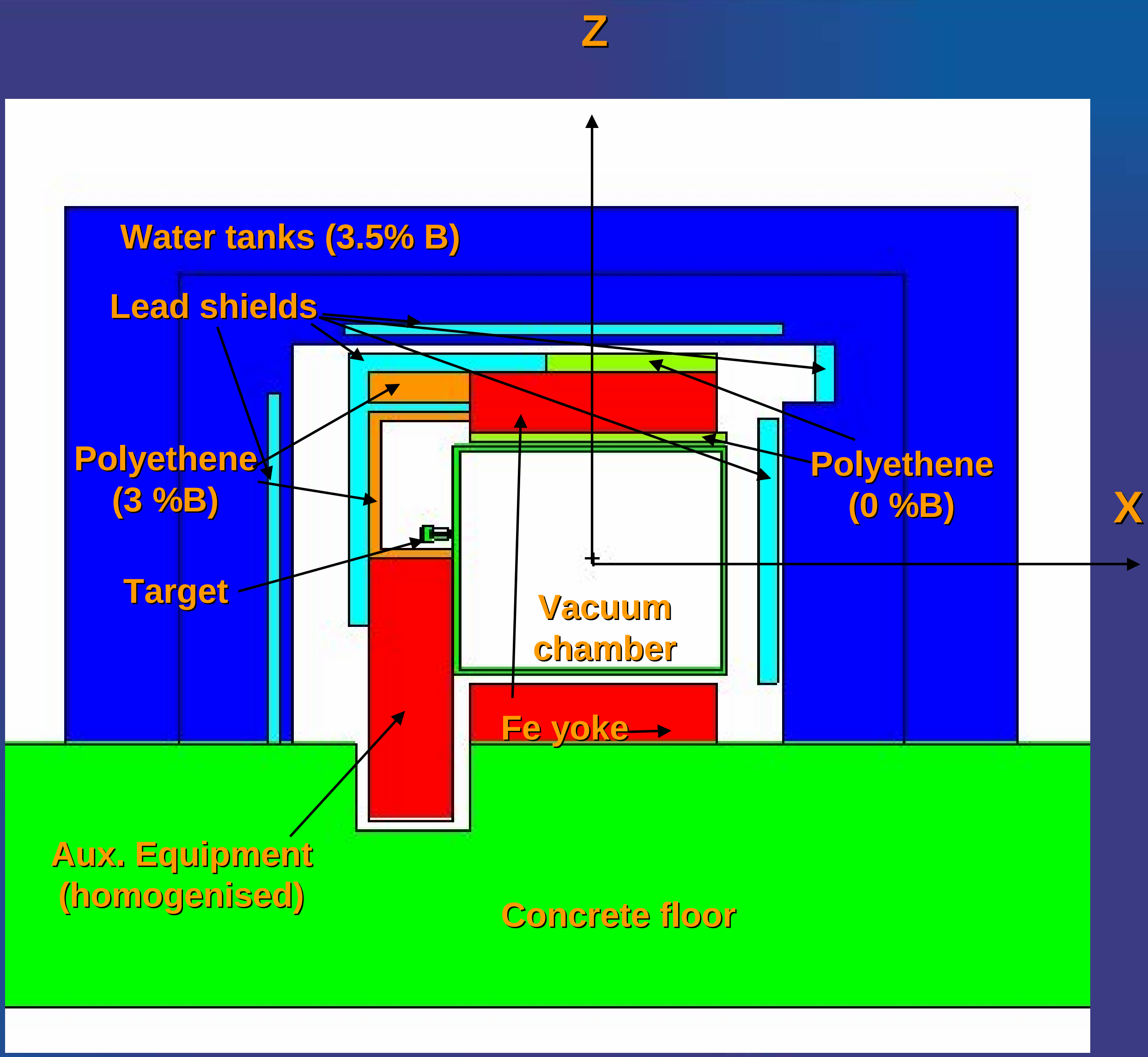
PETTrace





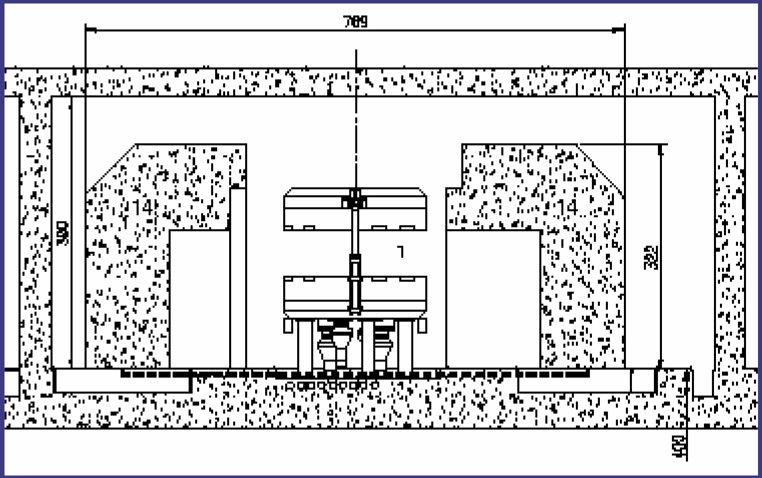
47 000 kgs

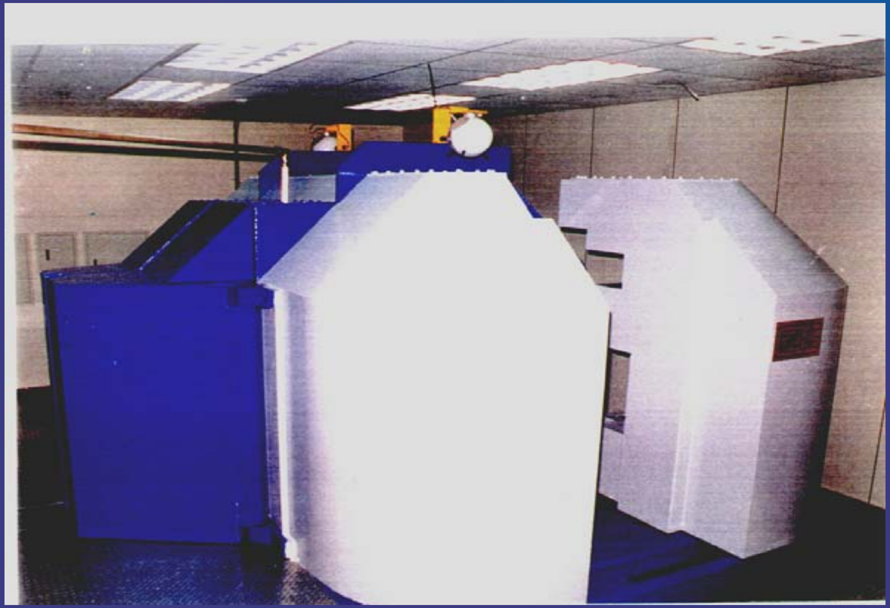
GE PETtrace


Z
X
Water tanks (3.5% B)
Lead shields
Polyethene
(3 %B)
Target
Polyethene
(0 %B)
Vacuum
chamber
Fe yoke
Aux. Equipment
(homogenised)
Concrete floor

IBA

EBCO





2 x45 000 kgs

60 000 kgs

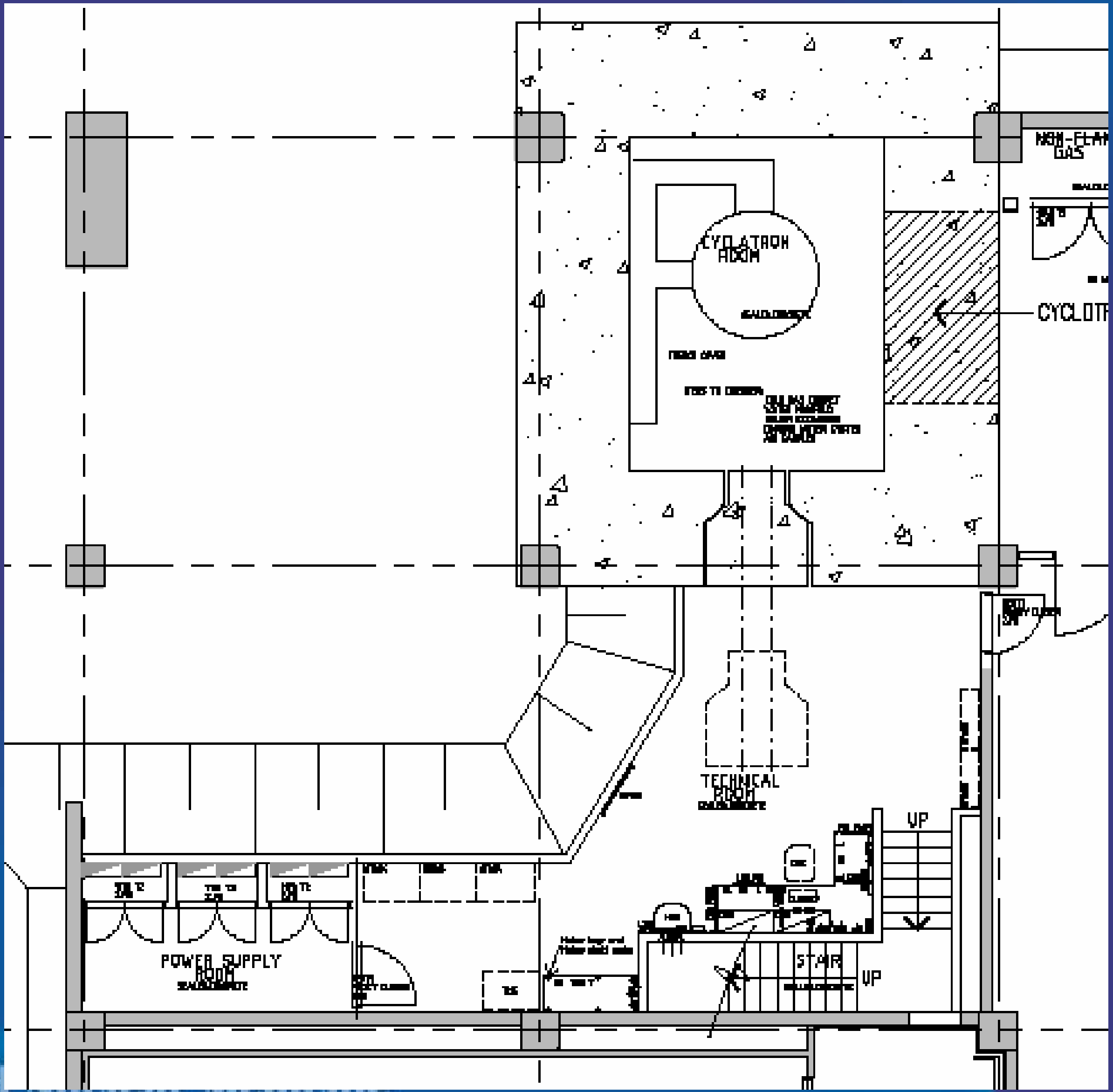
Cyclotron Vault

Place cyclotron in shielded enclosure

- Use bulk material to attenuate Neutron and Gamma dose.
  Usually concrete, 1.6 - 2.0 m
  Can use additives to increase neutron capture

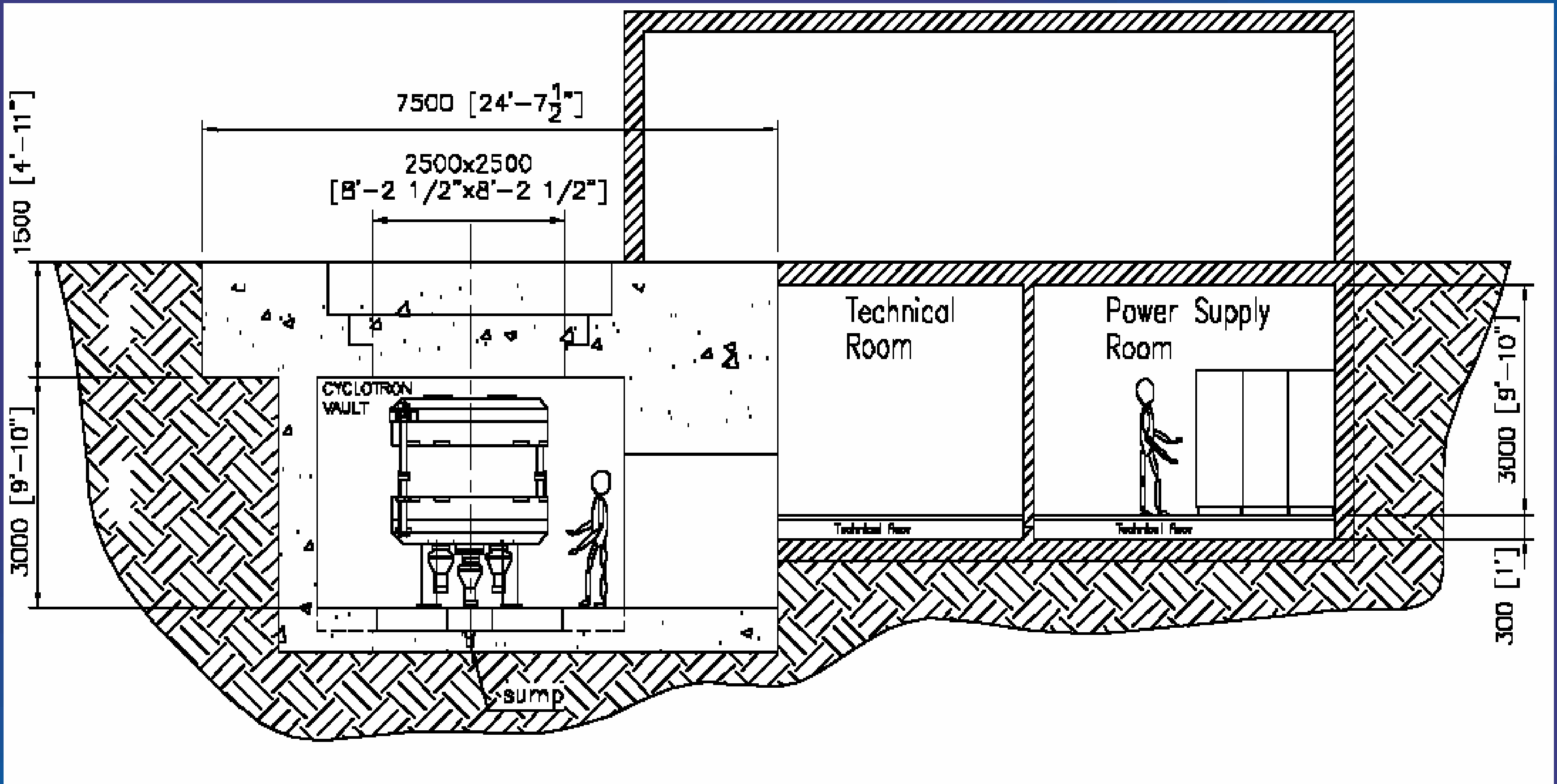
- Access via either a maze or a door (plug)

Vault



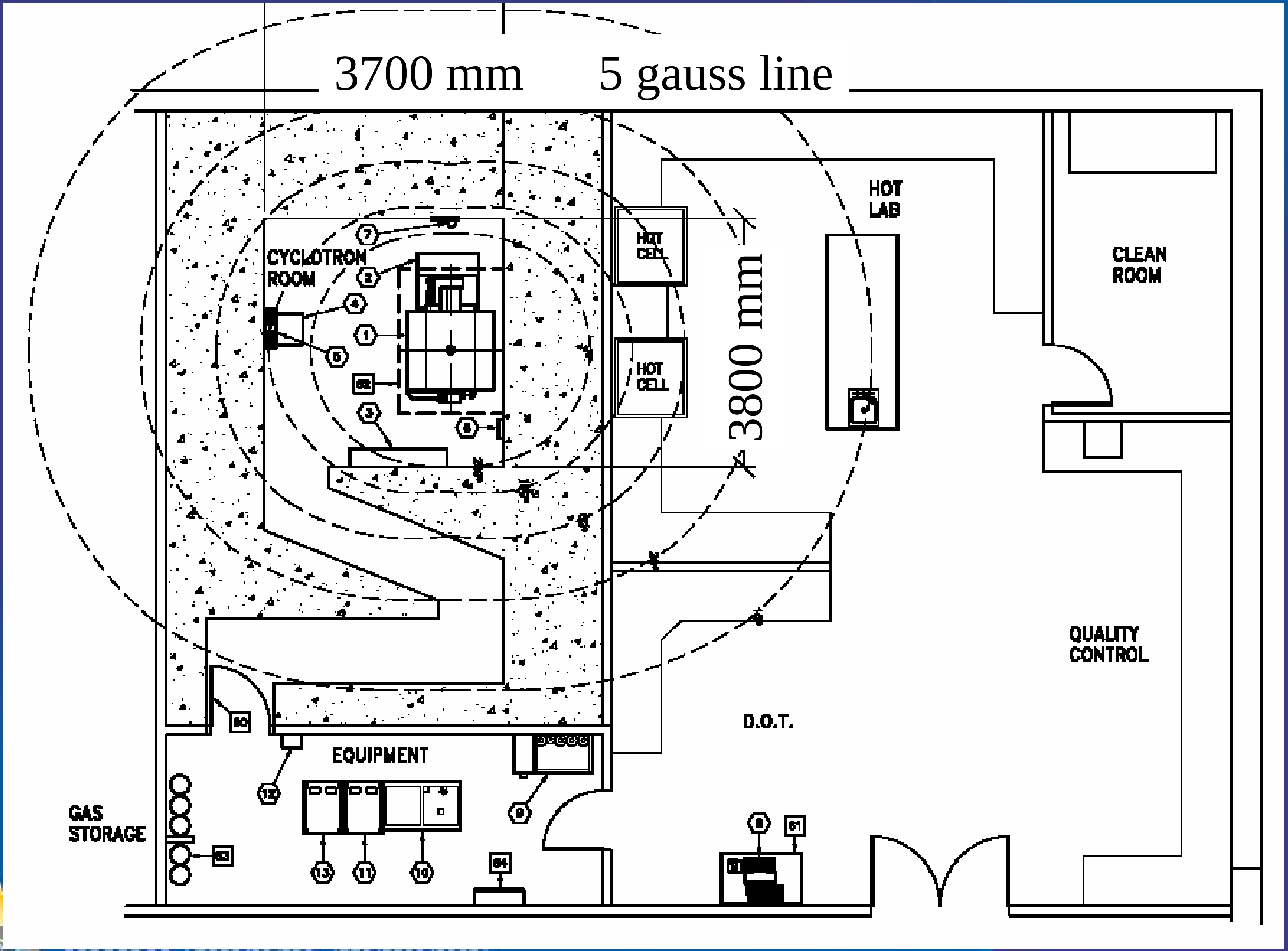
CYCLOTRON ROOM
CYCLOTR
NON-FLAM GAS
TECHNICAL ROOM
POWER SUPPLY ROOM
STAIR
UP
UP

Partially underground vault



Bunker Doors

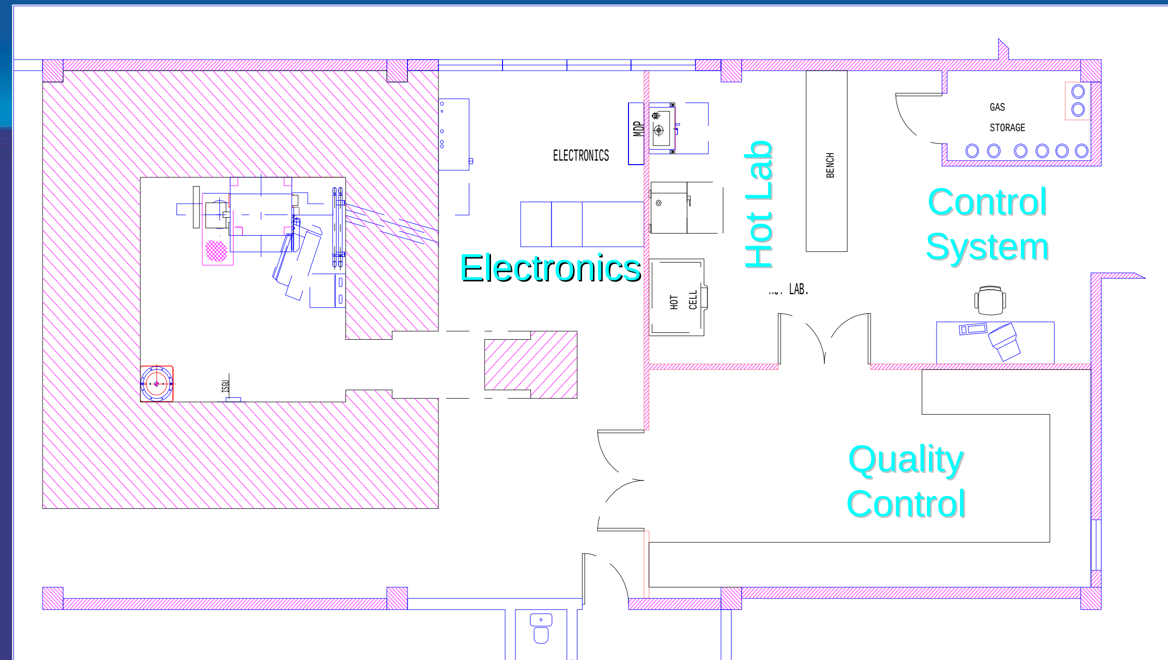
Maze entrance

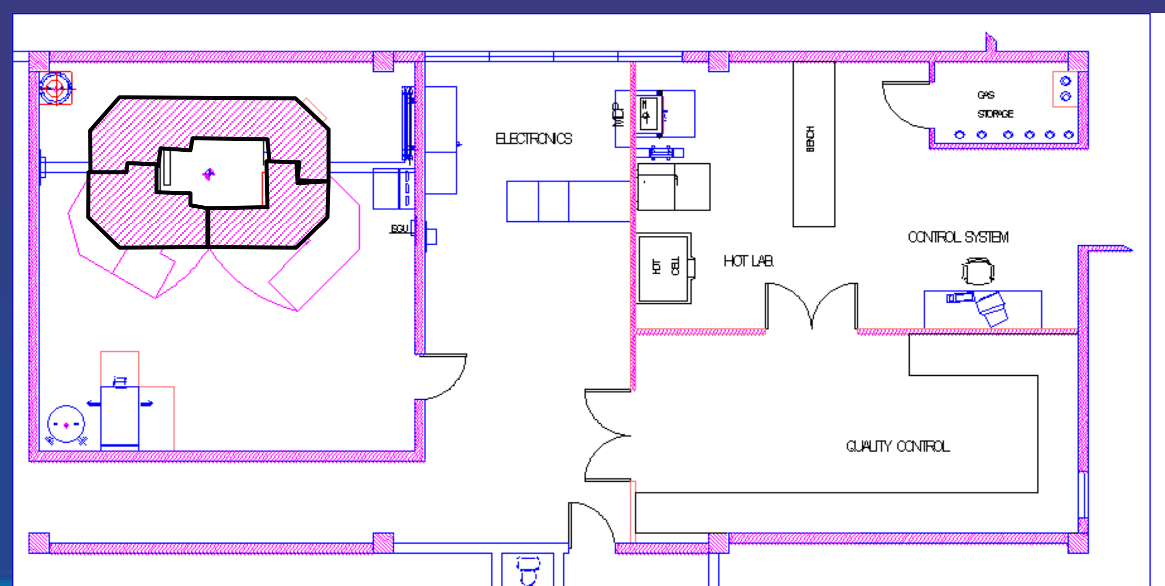


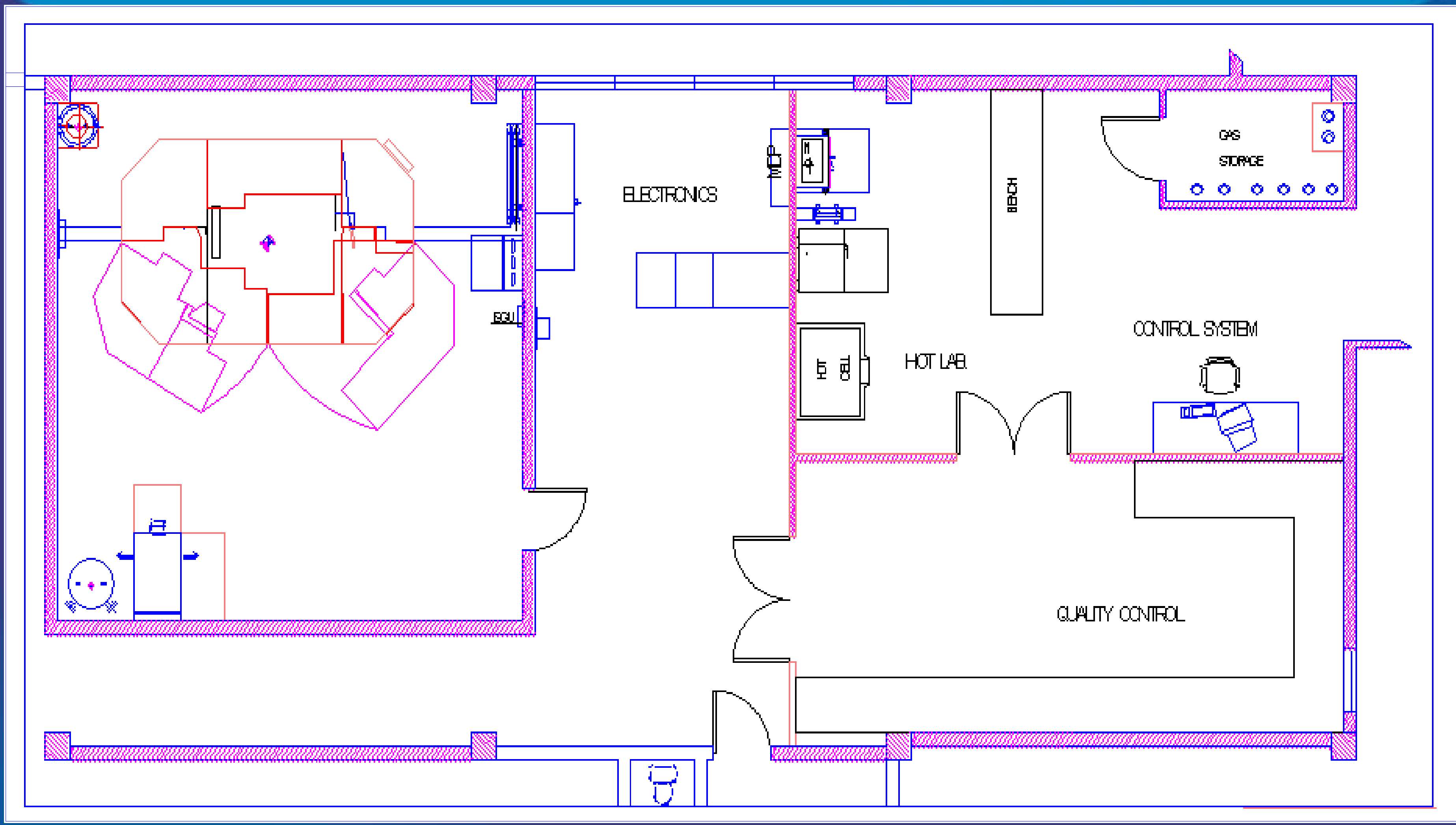
Cyclotron vault

vs

Self shield






ELECTRONICS
GAS
STORAGE
BENCH
CONTROL SYSTEM
HOT LAB
QUALITY CONTROL

Vault vs Self Shield

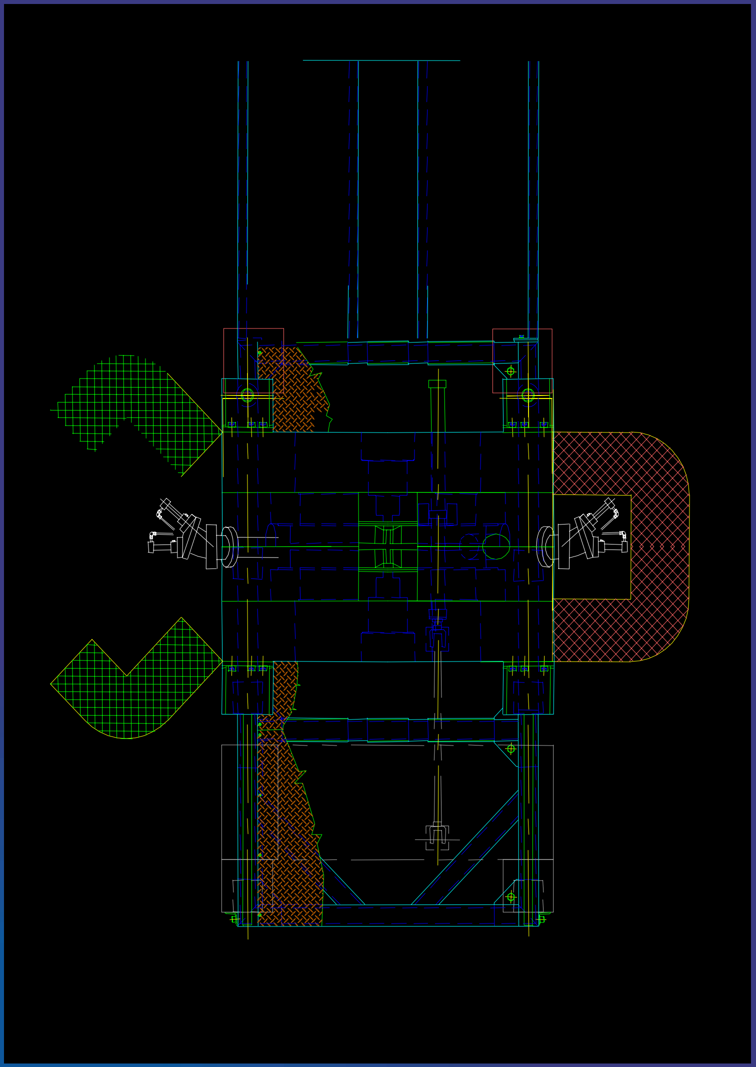
Vault

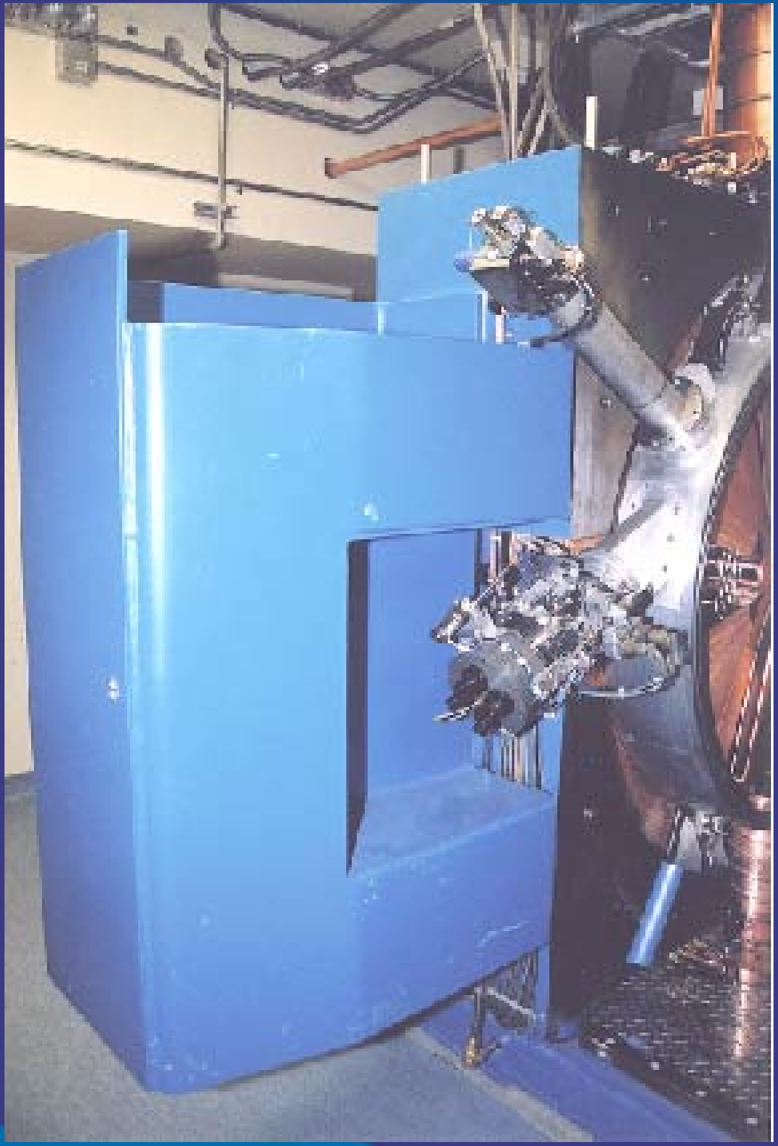
- future growth, beam lines
- maintenance access
- may cost less
- site specific radiation calcs (neutrons)

Self Shield

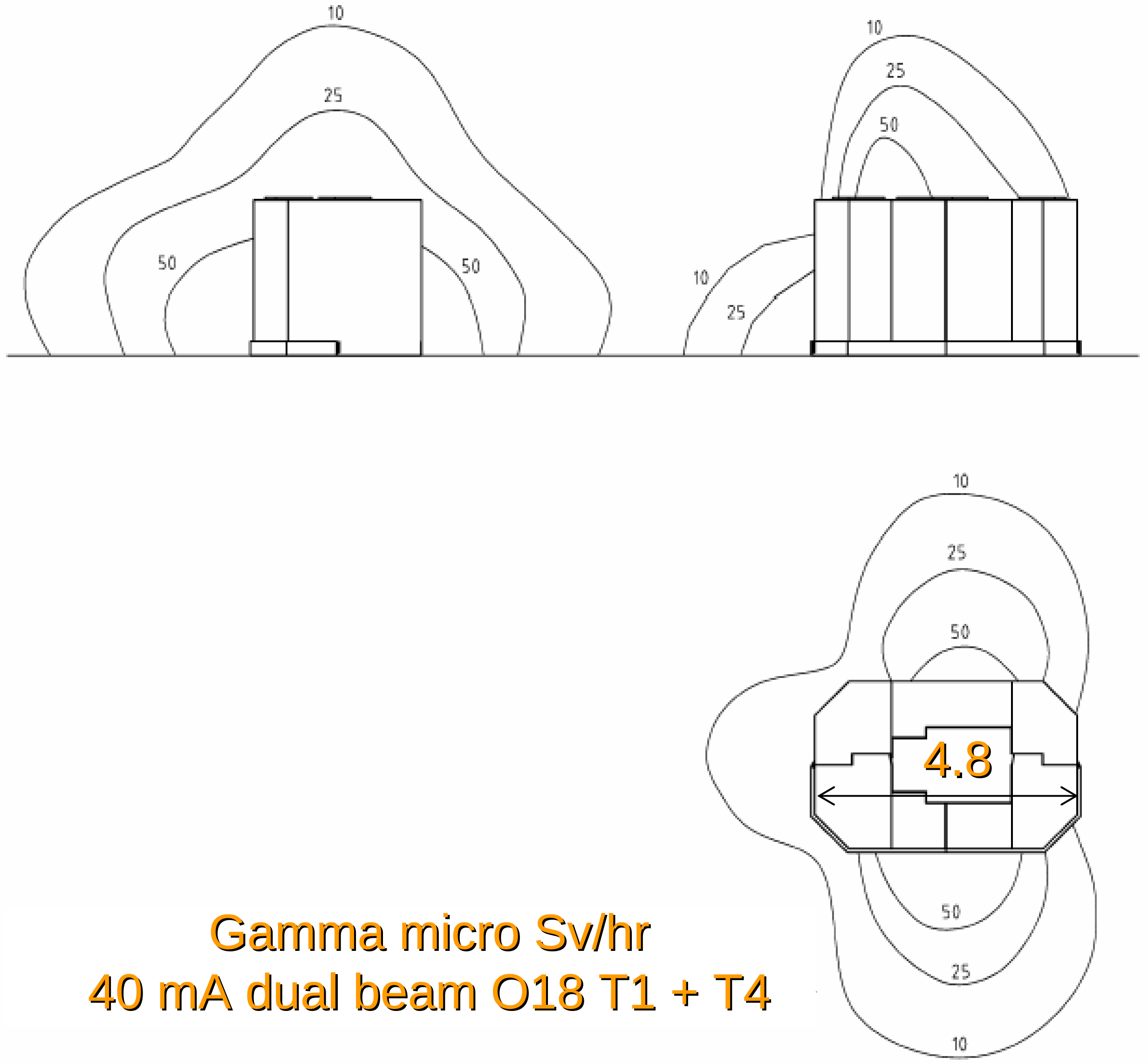
- limited additional targets
- limited maintenance access
- known radiation source
- smaller in height

Limited Local Shielding + Light Vault



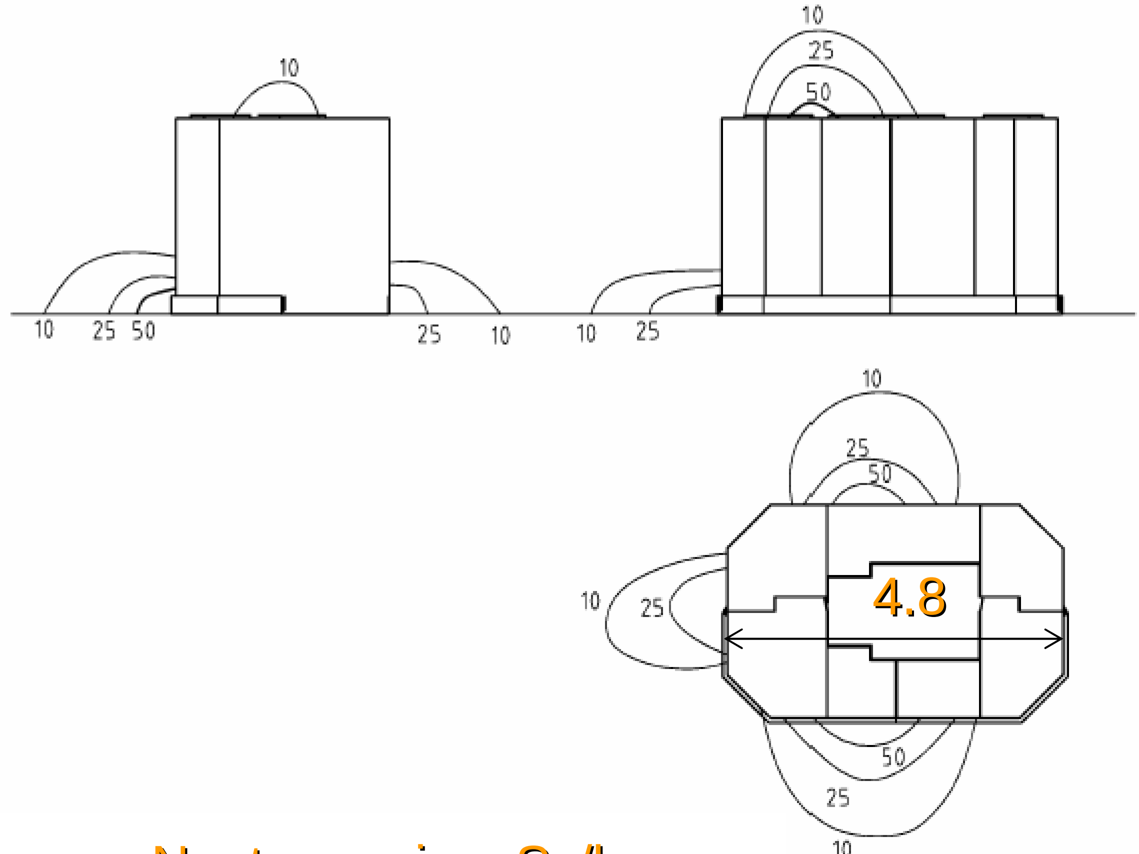


PETtrace isodose curves



Gamma micro Sv/hr
40 mA dual beam O18 T1 + T4

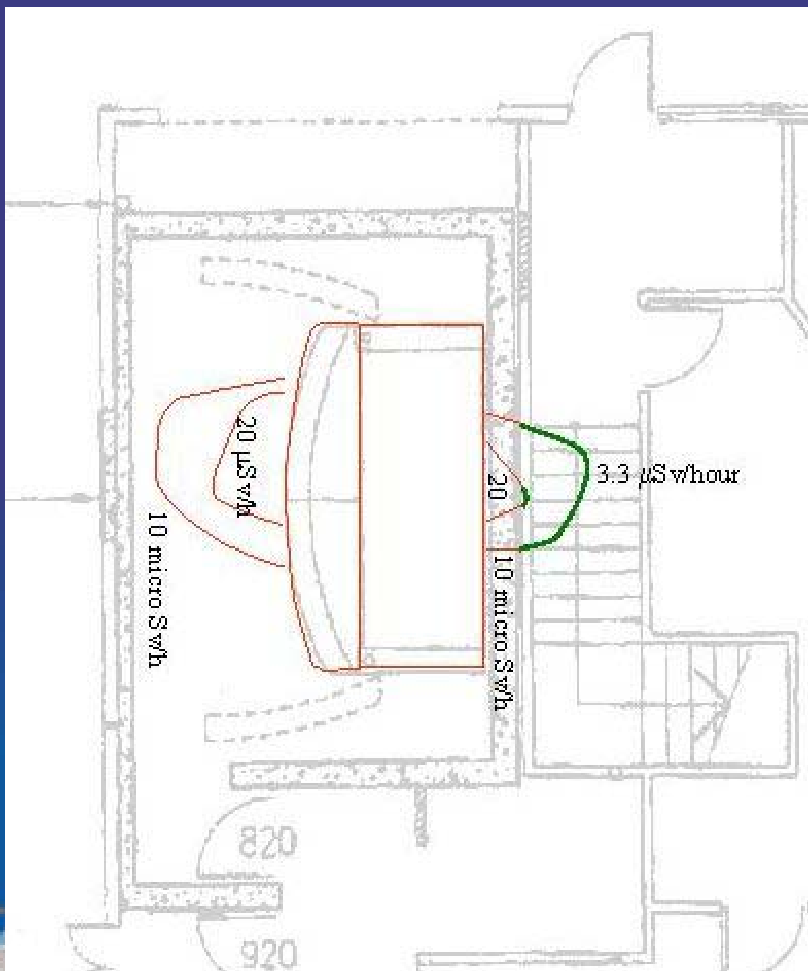
PETtrace isodose curves



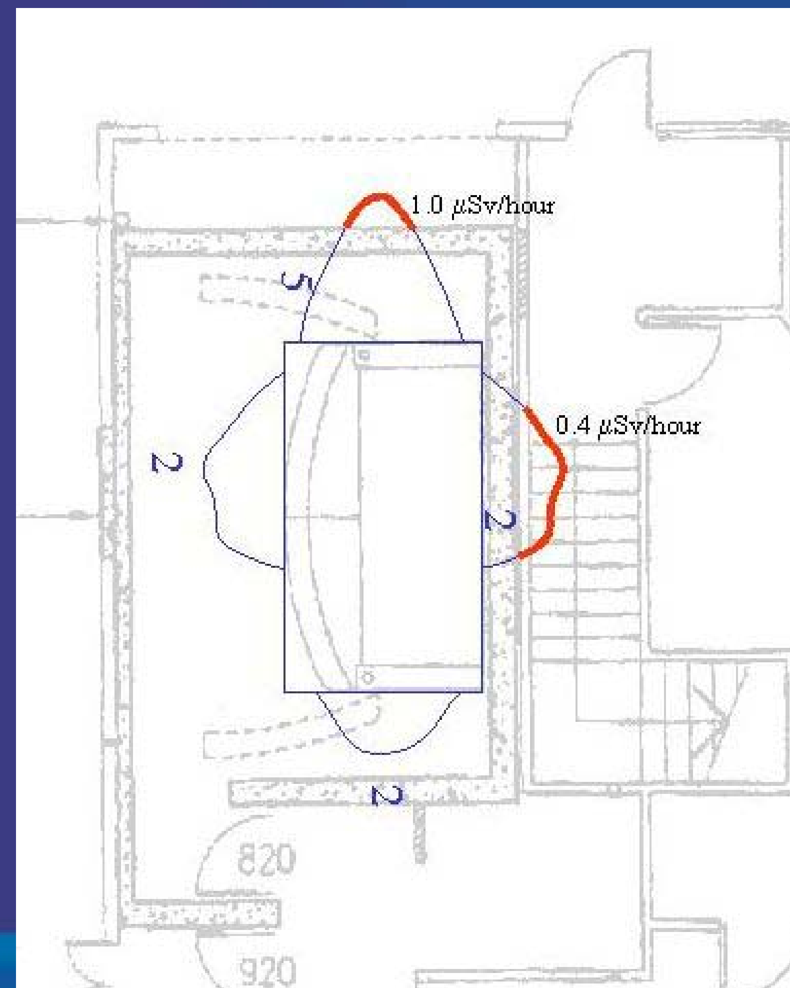
Neutron micro Sv/hr
40 mA dual beam O18 T1

Minitrace placed with in an existing building with additional 300 mm precast concrete walls

Gamma



Neutron



Radiation Attenuation and Vaults

- Prompt Gammas are easy.
  Find source terms and effective energy and look up the attenuation values in references.

- Neutrons are not easy.
  The nature of, and likelihood of interaction depends on energy and material. Cross section for scatter and capture are energy dependent.

Neutrons

- Fast neutron are elastically scattered loosing energy. They do not get absorbed much. H rich compounds are good moderators.
- Thermal neutrons have lost most of their energy and are elastically scattered until they are absorbed.
- Thermal neutrons in air are often described as a neutron gas and to a degree will diffuse like a gas.
- Elements with large capture cross sections act as neutrons sinks.

Neutron capture

- Generally a (n,γ) reaction.
  The γ rays are not trivial.

  Boron approx. 0.3 MeV

  Hydrogen 2 MeV

  Iron approx. 7 MeV

These become a diffuse gamma source where ever the neutron stops, for instance partly through the vault wall,

Adding to the complexity of the gamma shielding.

Neutron Attenuation / Dose Calculation

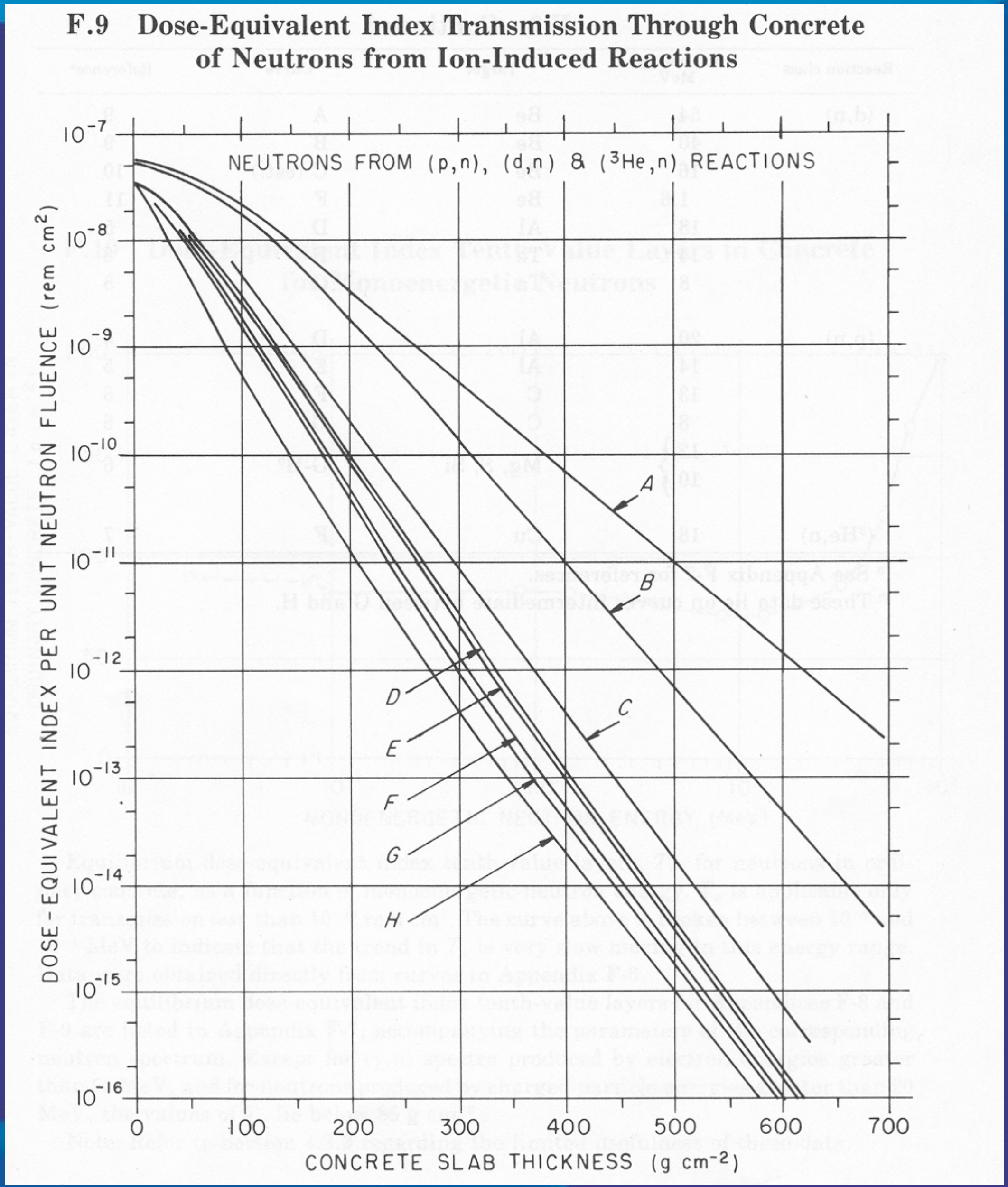
- Empirical (for some materials)
  requires knowledge (assumptions) of neutron flux, energy and concrete density.

- Monte Carlo simulation of cyclotron in vault.
  Requires knowledge of neutron source terms, energy distribution and relative elemental composition of cyclotron and vault.

Empirical

NCRP Report No. 51 - Radiation Protection Design Guideline for 0.1 to 100 MeV: Particle Accelerator Facilities

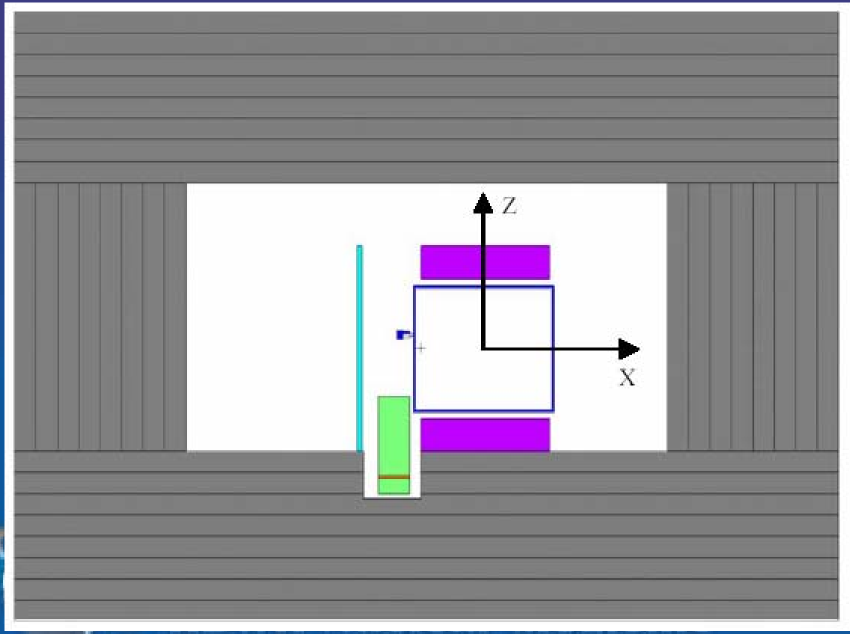
Dose, including gamma from (n,g) reactions in concrete rem cm^2 per unit neutron fluence

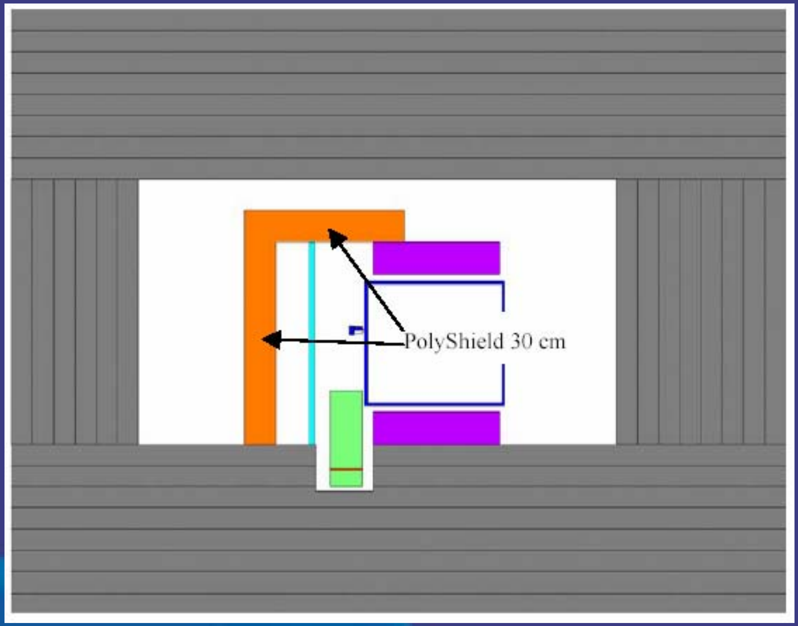


Monte Carlo

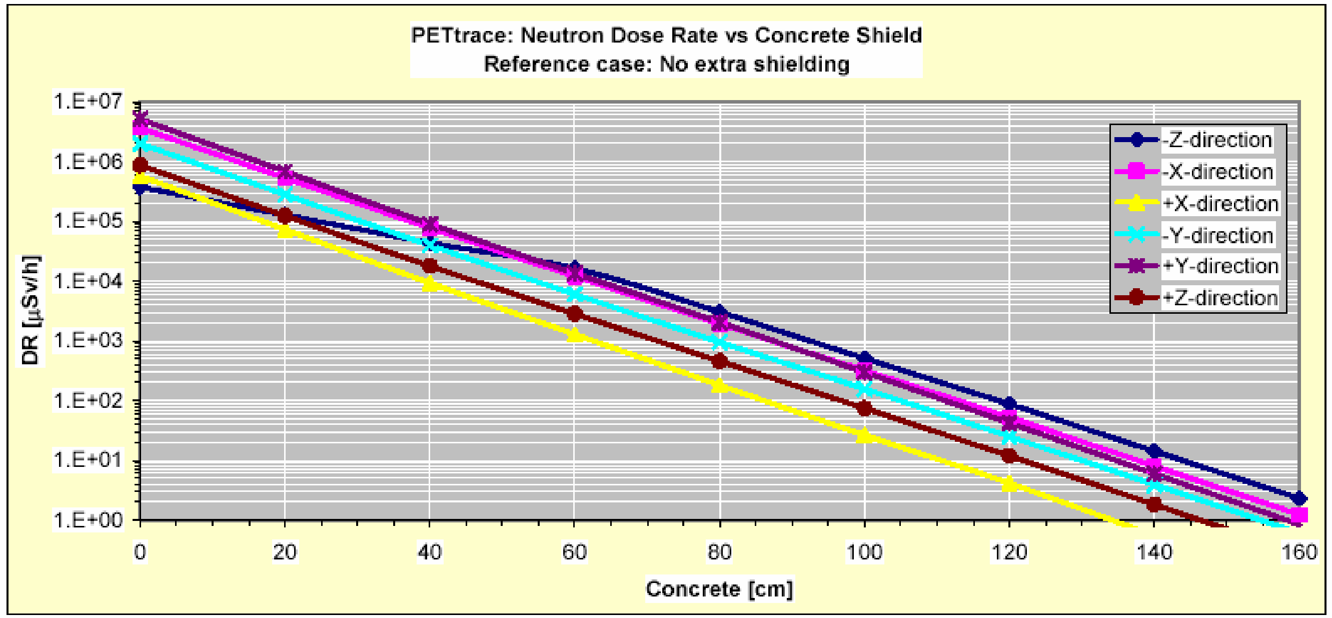
- Source neutron terms, energy and direction.
- Geometry of vault.
- Elemental composition of surrounding material eg cyclotron steel concrete target material etc
- Cross section at various energies for elements
- Run simulation to see the evolution of gamma and neutron dose.

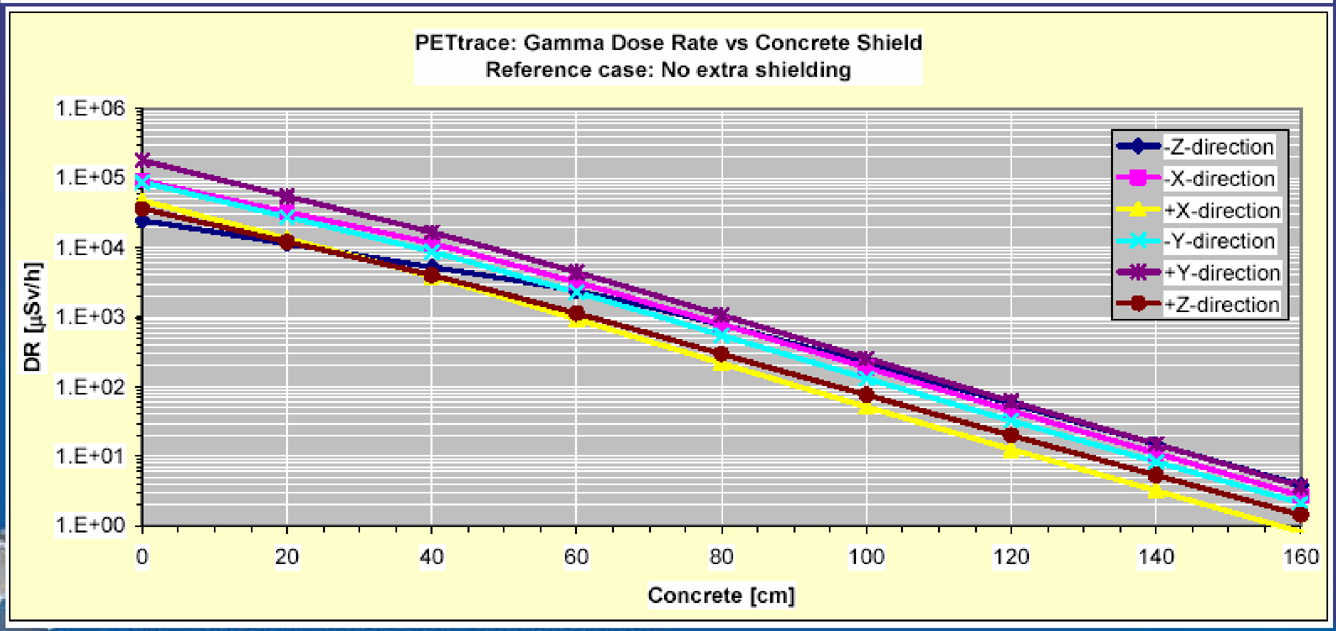
GE PET trace simulation dose in 20 cm slabs for typical F18 run.





Monte Carlo





$H_2{}^{18}O$ target
40 µA, 15 MeV protons
(GE PET trace)

Monte Carlo

- Your vault will not be the same dimensions as the published simulation
- It is too hard to re do it your self
- The composition of the concrete will not be the same.

Shielded or vault:

Get as much information as possible

Use a Semi Empirical approach.

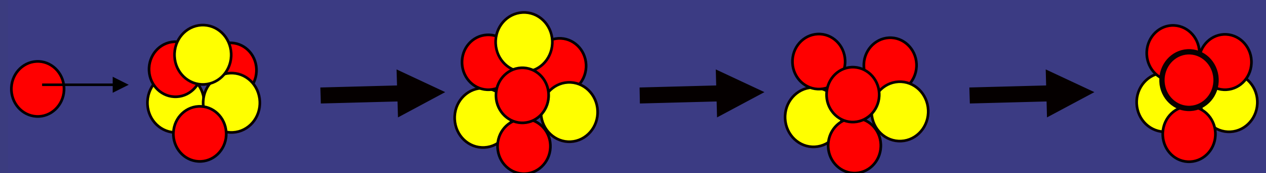
1) Apply judicial fudge factors to the data you have, then add at least an extra 1/2 value.
2) Make sure at least two approaches produce a shielding value with in the same order of magnitude.
3) Check with other installations

Consequences of stopping all those neutrons?

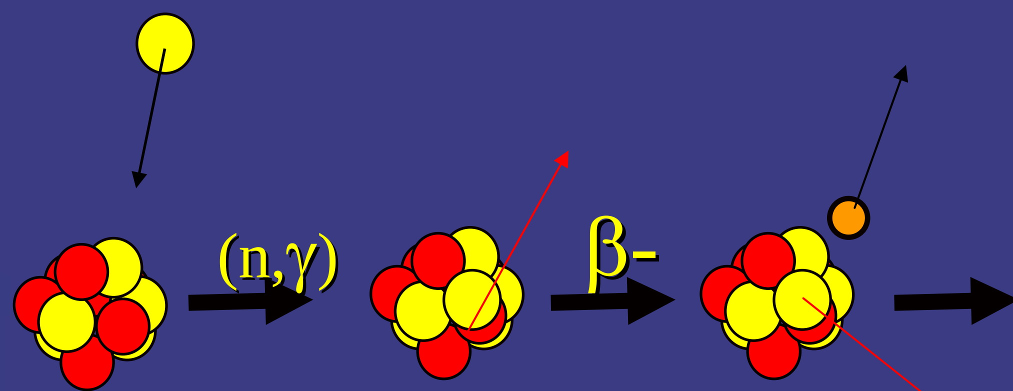
Activation.

After capturing a neutron the atom may not be stable

O^{18}_{8} (p,n) F^{18}_{9}



Typical but not only reaction also (n,2n), (n,α) etc



X^{y}_{z} (n,γ) X^{y+1}_{z} β- X^{y+1}_{z+1} ?

1/2 life ? 1/2 life ?

Activation occurs every where

Air

N14 →	N15 →	N16 →	O16
(n,γ)	(n,γ)	(β-)	
stable	stable	7 sec 1/2 life	
		6 MeV gamma ray	
		2 MeV beta	

Negative pressure around cyclotron

slow passage up stack.

Activation after production

Induced activity in the cyclotron

A cocktail of radioactive isotopes will be formed in the cyclotron with a range of cross-sections and half-lives.

After a weekend most of low energy gamma radiation has decayed.

After isotope production, wait for at least two hours before entering the cyclotron room or opening shields. mSv per hour

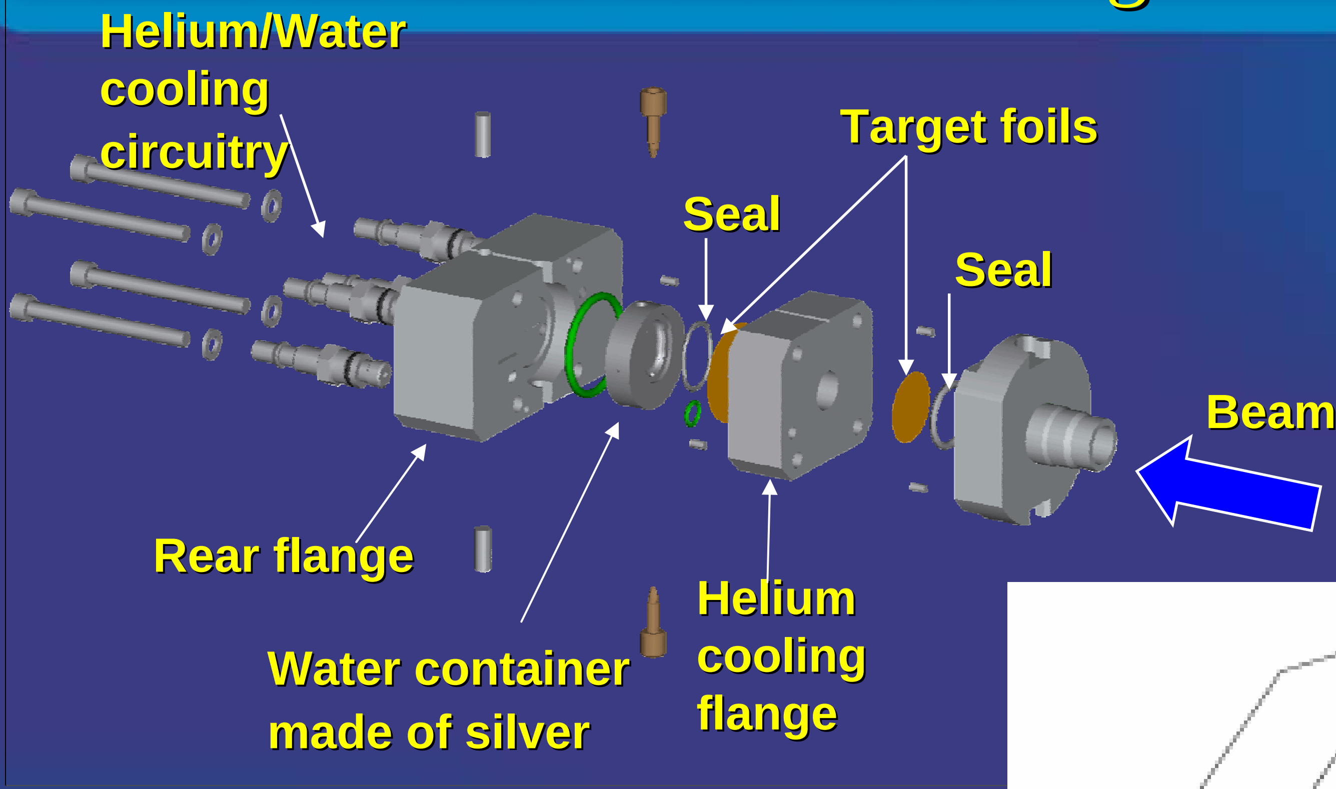
Maintenance: a radiation measurement to see if work is appropriate. Plan the work. Prepare tools if needed. Stop and re assess if not going to plan.

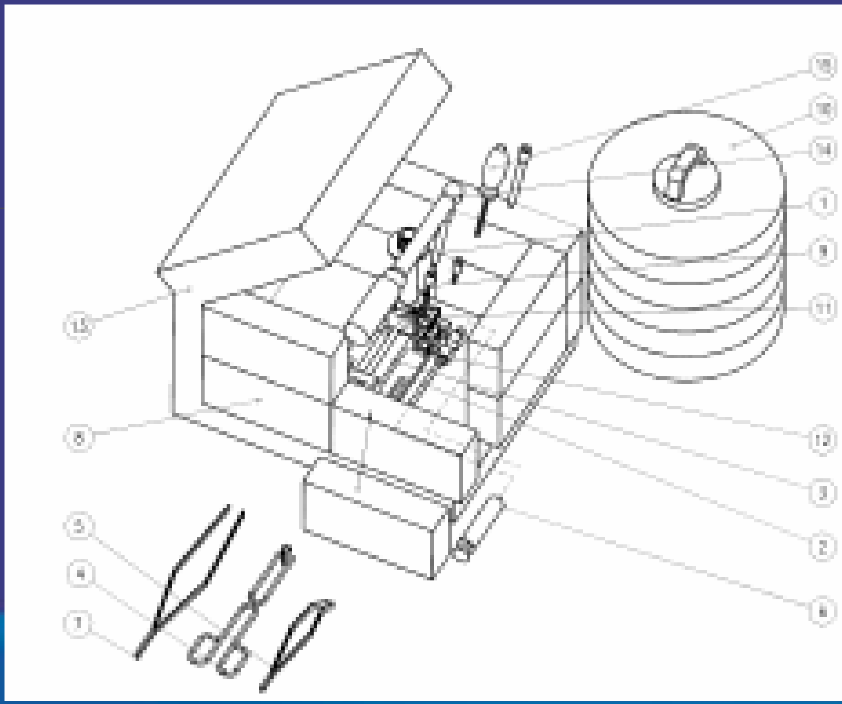
Maintenance

Protective measures

- Electronic dosimeter at all times
- Gloves
- Lab coat
- Plastic safety glasses, protection from β's
- Use of shielding where appropriate
- Long tweezers and tongs
- Treat all components as hot, waste store.
- Do not mill or sand materials

Target Maintenance





Long Term Activation: Protons

- Most cyclotron components are not exposed to proton beam.
- Notable exception are the Havar target foils.

Co 42.5%, Cr 20%, Mn 1.6%, Mo 2%, Ni 13%, W 2.8%, Fe 18.1%

- and the Collimators

Long Term Activation: Protons

Isotope	Half-life	Activity [Bq]	Main components
Al26	717 ky	1.3E+03	Silica, Alumina
V49	330 d	1.4E+08	Havar foil
Cr51	27.7 d	3.8E+07	Havar foil
Mn52	5.51 d	2.2E+08	Havar foil
Mn53	3.74 My	4.5E+03	Havar foil
Mn54	312.3 d	2.5E+09	Havar foil
Fe55	2.73 y	7.9E+07	Havar foil
Co56	77.27 d	7.2E+09	Havar foil
Co57	271.74 d	2.5E+08	Havar foil
Co58	70.86 d	1.8E+08	Havar foil
Ni57	6.077 d	1.4E+06	Havar foil
Ni59	76 ky	4.4E+06	Havar foil
Ni63	100.1 y	7.6E+04	Havar foil
Zn65	244.26 d	3.4E+08	Copper
Ta179	1.82 y	4.7E+05	Ta Collimator
W181	121.2 d	1.7E+10	Ta Collimator

20 years of operation, 20% utilisation followed by a 30 day decay period

Long Term Activation: Neutrons

- Most cyclotron components are selected to have low activation profiles and or short 1/2 life products.

Isotope	Half-life	Activity [Bq]	Main components
Cr51	27.7 d	2.5E+07	Aux. Equipment
Mn54	312.3 d	4.8E+07	Acc. Cell, Iron yoke
Fe55	2.73 y	5.4E+08	Acc. Cell, Iron yoke
Fe59	45.1 d	1.3E+07	Acc. Cell, Iron yoke
Co58	70.86 d	1.1E+07	Aux. Equipment
Co60	5.27 y	9.8E+07	Aux. Equip., Iron yoke
Ni59	76 ky	1.6E+04	Aux. Equipment
Ni63	100.1 y	3.7E+06	Aux. Equipment
Ag108m	418 y	7.9E+05	Target holder (Ag)
Ag110m	249.9 d	7.2E+07	Target holder (Ag)

Un-shielded PET trace

20 years of operation, 20% utilisation followed by a 30 day decay period

Long Term Activation: Neutrons

Shielded PETtrace

Isotope	Half-life	Activity [Bq]	Main components
H3	12.33 y	7.8E+07	Concrete floor
Be10	1.6 My	8.0E+01	Polyethylene (3% B)
C14	5730 y	1.5E+03	Concrete floor
Ca41	103 ky	2.0E+04	Concrete floor
Cr51	27.7 d	2.0E+07	Aux. Equipment
Mn54	312.3 d	3.7E+07	Acc. Cell, Iron yoke
Fe55	2.73 y	4.3E+08	Acc. Cell, Iron yoke
Fe59	45.1 d	1.0E+07	Acc. Cell, Iron yoke
Co58	70.86 d	8.8E+06	Aux. Equipment
Co60	5.27 y	8.0E+07	Aux. Equip., Iron yoke
Ni59	76 ky	1.3E+04	Aux. Equipment
Ni63	100.1 y	2.9E+06	Aux. Equipment
Ag108m	418 y	6.1E+05	Target holder (Ag)
Ag110m	249.9 d	5.6E+07	Target holder (Ag)
Eu152	13.32 y	2.3E+06	Concrete floor
Eu154	8.6 y	2.1E+05	Concrete floor

20 years of operation, 20% utilisation followed by a 30 day decay period

Long Term Activation: Neutrons

Un Shielded PETtrace Vault Walls

	Specific activity [Bq/kg]					Total
Nuclide	0-20cm	20-40cm	40-60cm	………....	140-160cm	[Bq]
Co60	3.1E+03	1.0E+03	2.3E+02	………..		2.2E+08
Cs134	5.0E+02	1.1E+02	2.2E+01	……….		3.2E+07
Eu152	4.2E+03	1.5E+03	3.6E+02			3.2E+08
Eu154	2.8E+02	8.0E+01	1.7E+01			1.9E+07
Fe55	1.2E+04	4.4E+03	1.0E+03			9.0E+08
Fe59	2.0E+02	7.2E+01	1.6E+01			1.5E+07
H3	6.3E+04	2.3E+04	5.2E+03			4.7E+09
K40	6.2E+02	6.2E+02	6.2E+02			3.9E+08
Th232	3.2E+01	3.2E+01	3.2E+01			2.0E+07
U238	2.5E+01	2.5E+01	2.5E+01			1.5E+07
Total	**8.5E+04**	**3.1E+04**	**7.6E+03**			**6.7E+09**

20 years of operation, 20% utilisation followed by a 30 day decay period

Planning for decommissioning at installation

- Long term activation in cyclotron
  - (organise storage in advance)
- Long term activation of self shield
  - (organise storage in advance)
- Long term activation of floor
  - Limestone mix in sacrificial topping over slab
- Vault walls / ceiling
  - Limestone mix in sacrificial topping over slab
  - and or neutron moderators absorbers around targets

Production

- Products
  - small volumes of material
  - well shielded in trenches / ducts running to hot cells
  - typically 50 mm of lead
- Chemistry in Hot cells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Production

- 2/3 of cyclotron problems are due to blockages, leaks, faulty valves, clogged filters and material getting where it shouldn't.

Radiation Monitoring

Continueous monitoring + logging

- Gamma in vault or near self shield
- Gamma outside vault
- Stack monitoring
- Air concentration
- Gamma in hot lab.

- Periodic Gamma + Neutron surveys