Scuola Nazionale
"Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica ed Applicazioni Spaziali"
INFN-Laboratori Nazionali di Legnaro
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Qualification of radiation hard electronic devices: reference standards and irradiation facilities at ENEA-Casaccia Research Centre (Rome).

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SUMMARY

* Hostile radiation environments;

HEP experiments

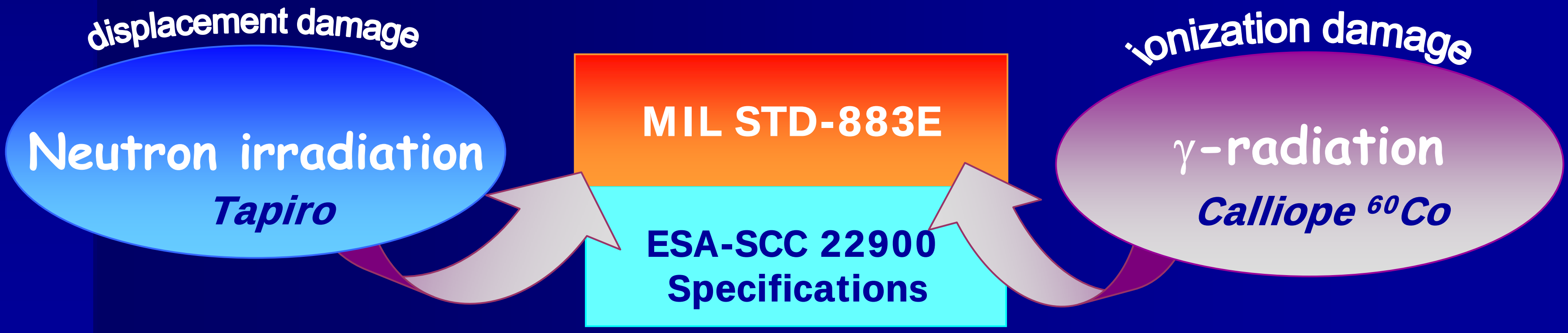
(leptons, hadrons, γ)

Space radiation environment:

(electrons, protons, γ & heavy ions)

* Ionization & Displacement Damage;

* Qualification of radiation damage at irradiation facilities:



displacement damage

Neutron irradiation

Tapiro

MIL STD-883E

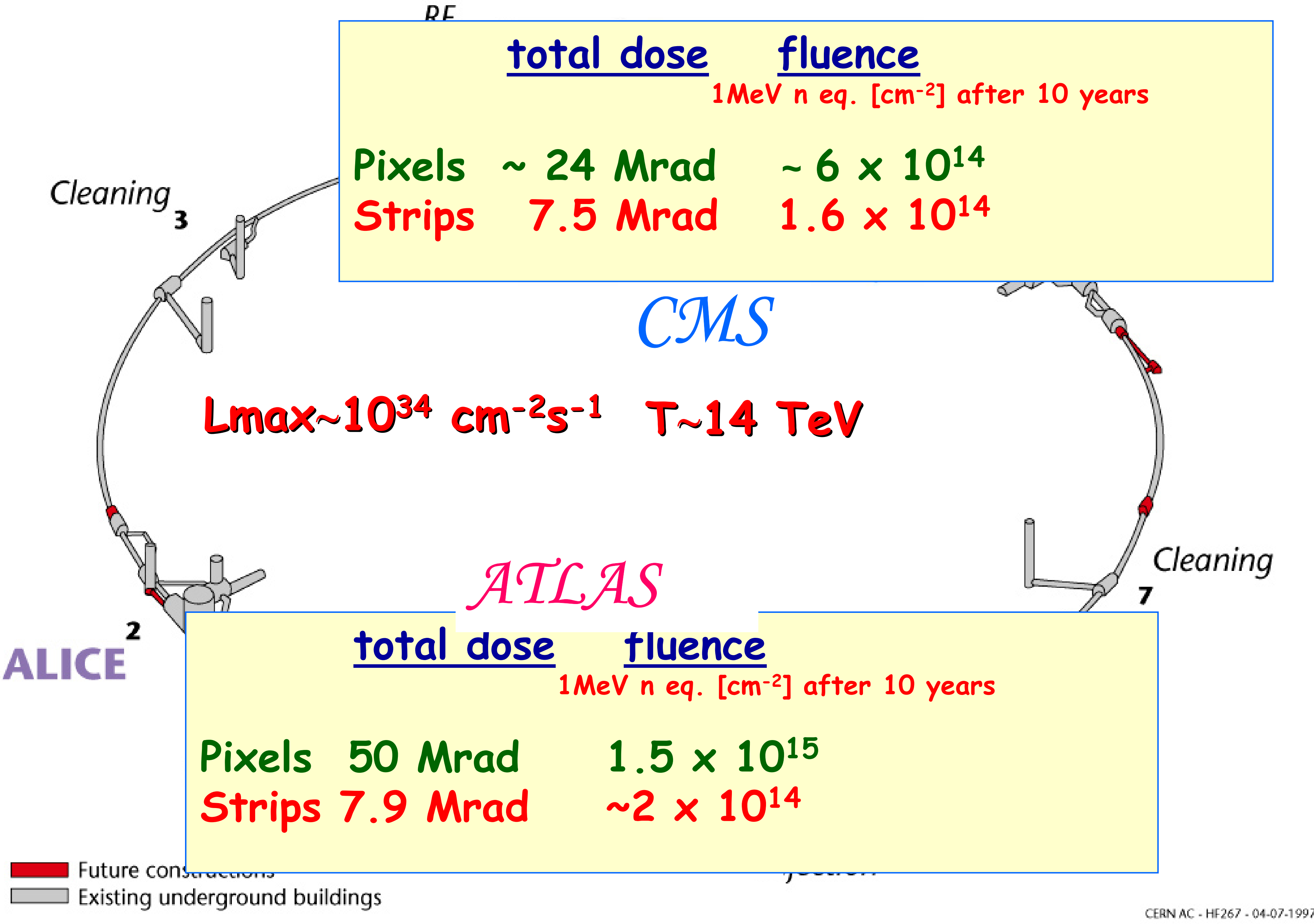
ESA-SCC 22900 Specifications

ionization damage

γ-radiation

Calliope ^{60}Co

High Energy Physics Experiments



	total dose	fluence 1MeV n eq. [cm^{-2}] after 10 years
Pixels	~ 24 Mrad	~ 6 x 10^{14}
Strips	7.5 Mrad	1.6 x 10^{14}

CMS

Lmax~10^{34} cm^{-2}s^{-1} T~14 TeV

ATLAS

	total dose	fluence 1MeV n eq. [cm^{-2}] after 10 years
Pixels	50 Mrad	1.5 x 10^{15}
Strips	7.9 Mrad	~2 x 10^{14}

Space Radiation

1) *Galactic cosmic rays:* charged particles originating from sources beyond our solar system (87% protons, 12% α-particles, 1% heavy ions)=> $10 \text{ MeV} < E < 10^{12} \text{ MeV}$.

2) *Solar particles events:* high fluxes of charged particles encountered during rare but intense coronal mass ejections and solar flares (electrons, protons, heavy charged particles up to iron).

3) *Van Allen Belts:*
energetic electron and protons trapped in the geomagnetic field and making up the Earth's radiation Belts.

VAN ALLEN BELTS or the Earth's trapped radiation belts

- Trapped electrons occur in two belts or zones.

  The first inner zone extends to about 2.4 Earth radii and consists mostly of electrons with energies less than 5 MeV.

  The second or outer zone extends from about 2.8 to 12 radii and contains electrons with energies up to about 7 MeV. Electron flux is about an order of magnitude greater in the outer zone than in the inner.
- Trapped protons occur only in a single region that decreases in intensity as a function of distance from the Earth. They extend in energy between 150 and 250 MeV.

Earth Orbiting Missions

Typical radiation levels < 20 krad (Si) (altitude, inclination, SAA)

For space vehicles or satellites

Low inclination LEO (<28°) in both Northern and Southern hemispheres:

10^2-10^3 rad(Si)/year.

Higher inclination LEO (20°<I<85°) in both Northern and Southern hemispheres:

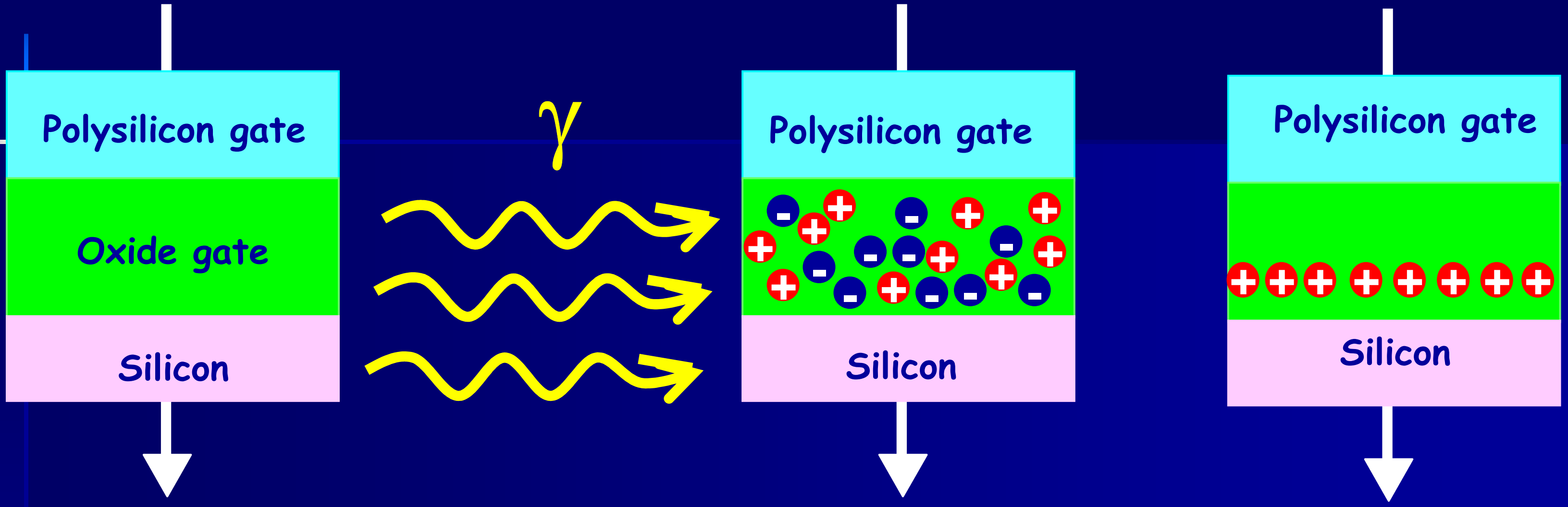
10^3-10^4 rad(Si)/year.

Interplanetary Missions

Jupiter & Saturn

Very high radiation levels
> 1 Mrad(Si)

Ionization damage:
Due to e^--h pairs generated in silicon dioxide and other insulator.

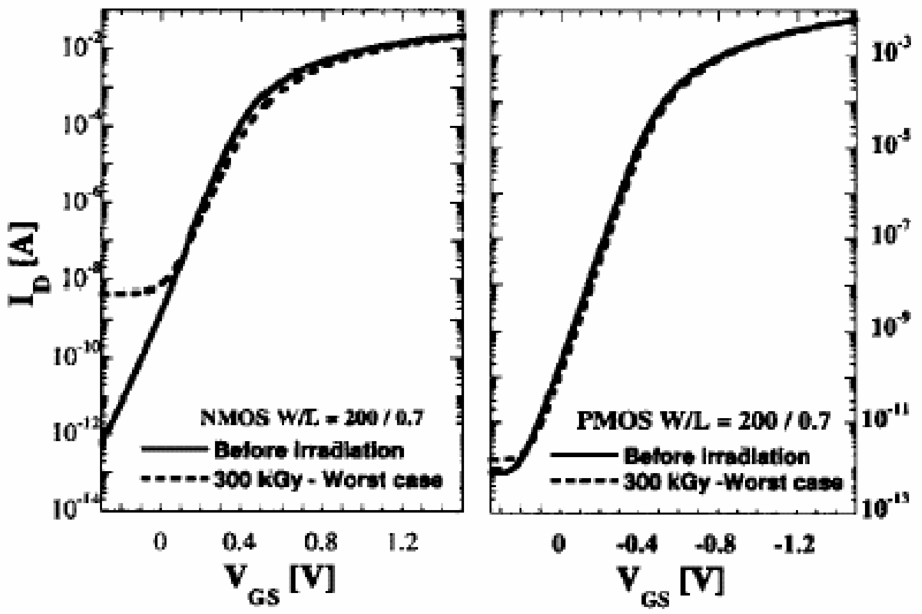


BEFORE IRRADIATION

AFTER IRRADIATION

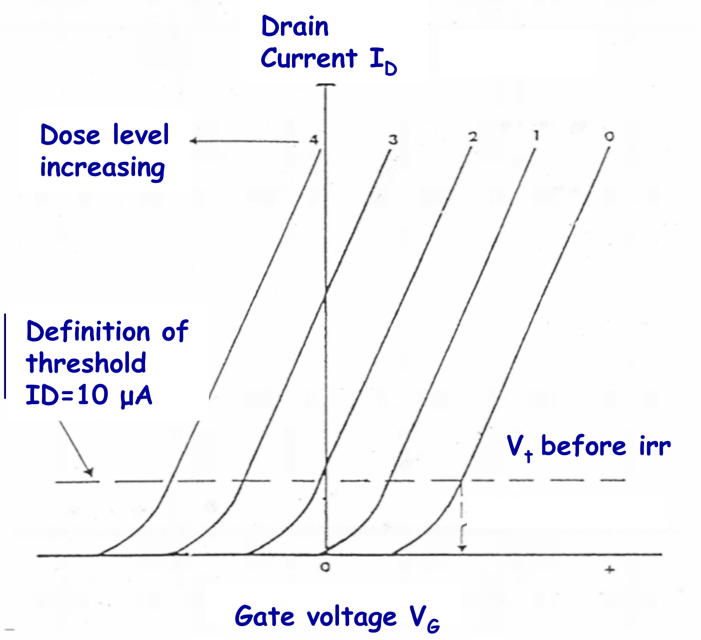
- e^--h creation and separation
- e^- drift outside the oxide
- h migration and trapping in the near the Si-SiO_2 interface

Macroscopic effects of ionization damage



M. Manghisone et al., Nuclear Physics B (2003)

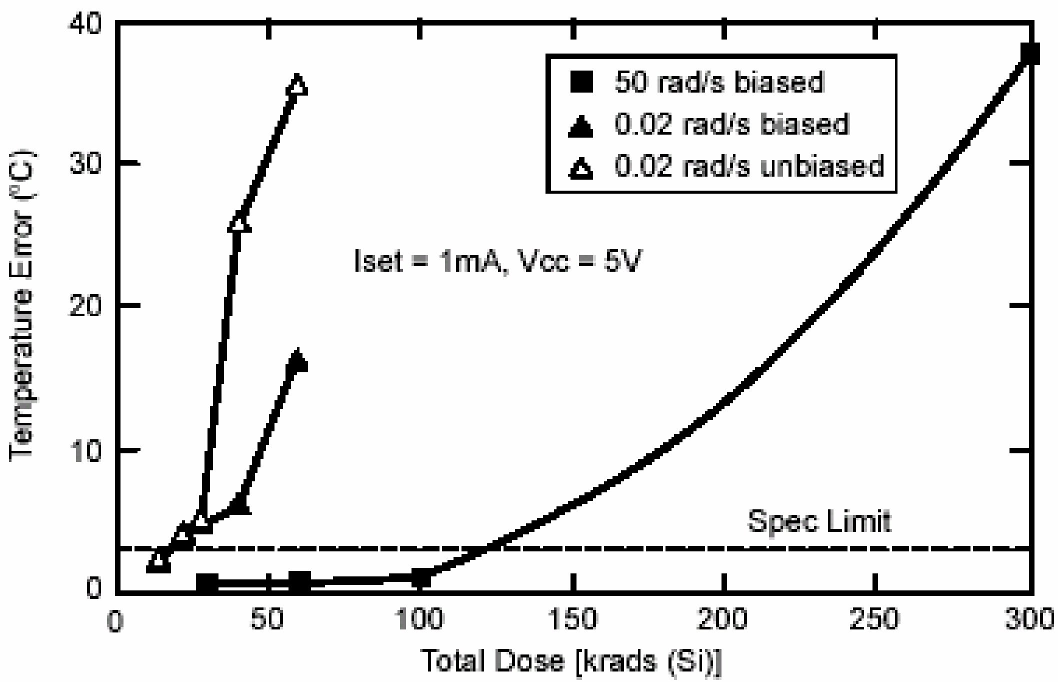
Threshold voltage shift



R.R. Brown, Boeing Report D2-90570 (1964).

Enhanced Degradation at Low Dose Rate (ELDR)

A higher damage occurs at the low dose rates in space compared to the damage observed at high dose rates typically used for laboratory testing.



A.H. Johnston, Internal Note, 1999.

Possible explanation: *build-up* of internal fields due to charge trapped at regions near the interface as well as extremely slow transport of trapped holes in oxides where the electric field is low.

Possible test procedures for *ELDR*

(F.Faccio, Cern)

TID> 30 krad:

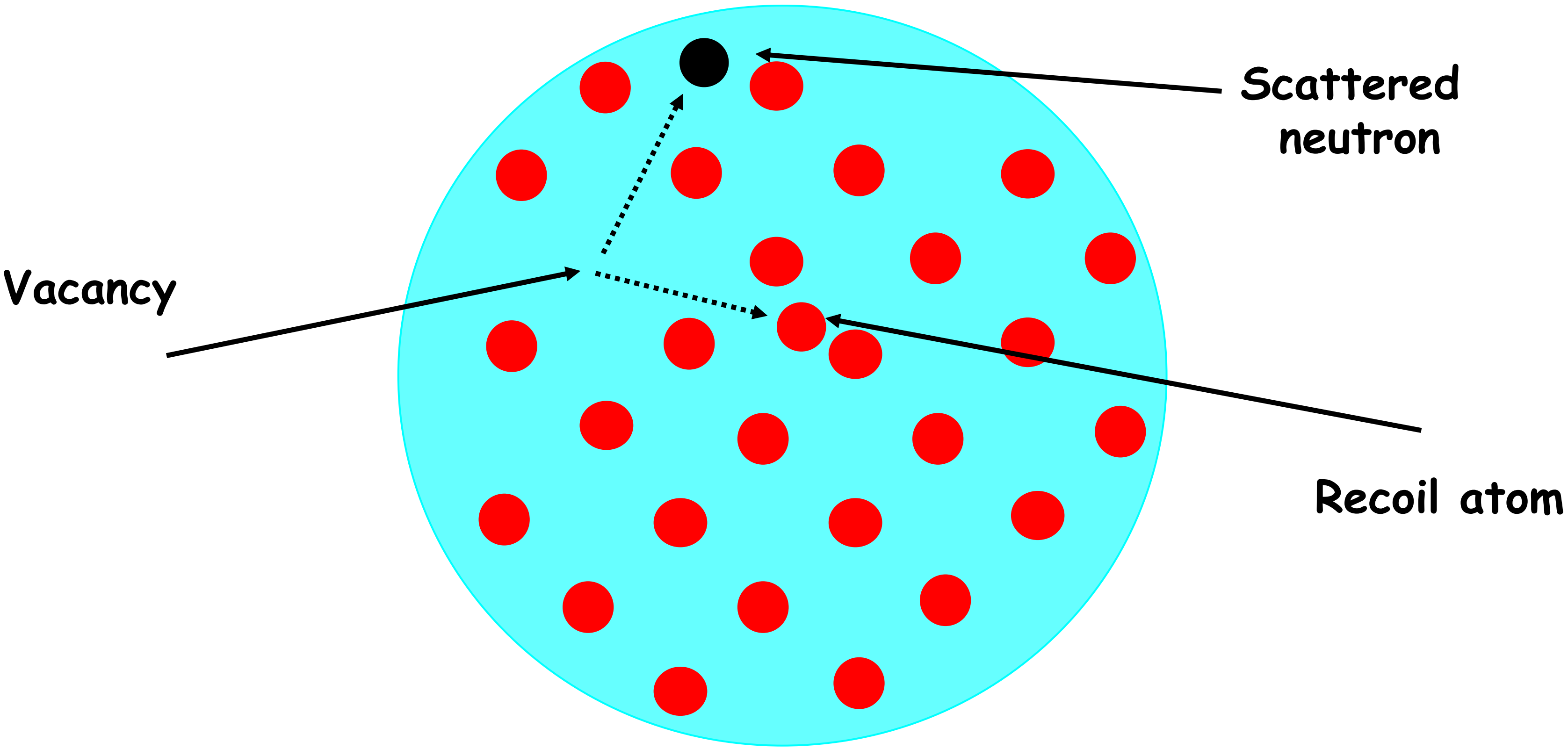
it is necessary to accelerate the damage mechanism by using high temperature during irradiation at high dose rate (0.5-2 rad/s). T= 90°C

TID< 30 krad:

Test at both high dose rate (50 rad/s) and low dose rate (preferably 0.005 rad/s).
If the part fails at 1.5 times the foreseen TID in any of the tests, the component should not be used.

Displacement damage:

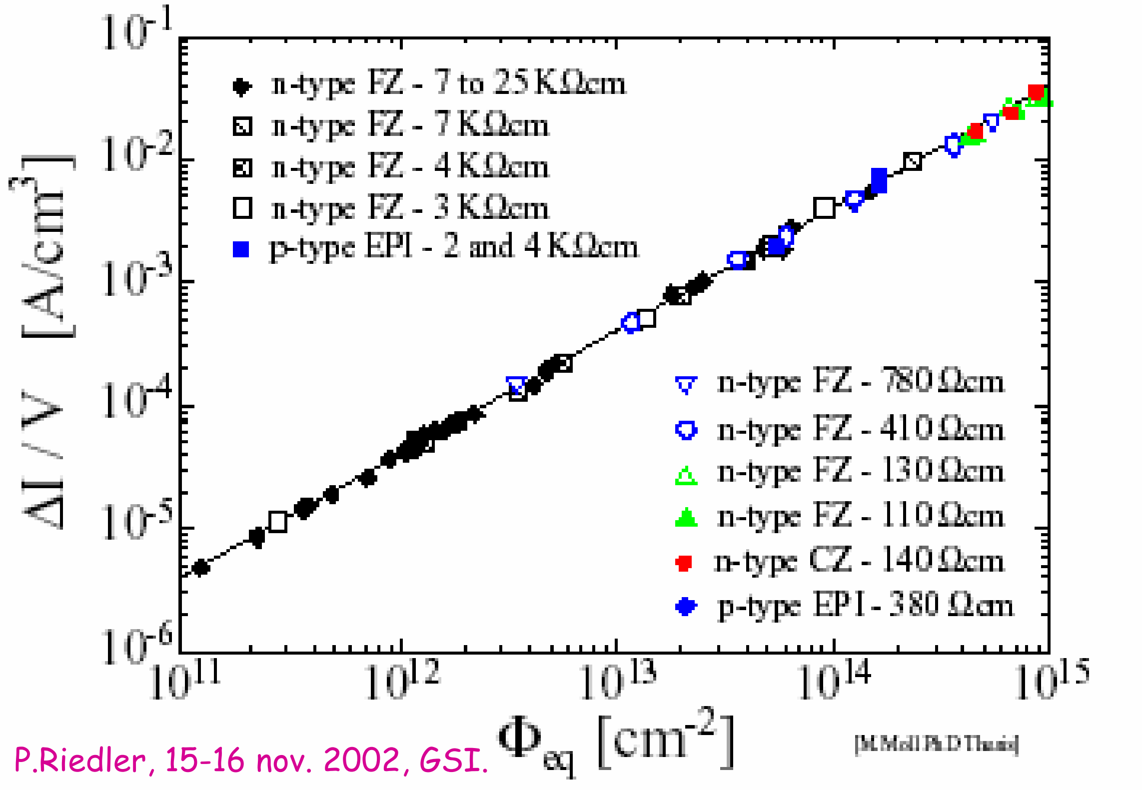
Caused by lattice collisions between energetic protons or electrons that transfer sufficient energy to the lattice to move an atom out of its normal position.



Bulk damage is proportional to Kinetic Energy released in Matter (KERMA) relatevely to the damage induced by 1 MeV neutrons

Macroscopic effects of displacement damage

Leakage current increase $\Delta I_{leak} = \alpha \times \Phi \times V$



Minority carrier Lifetime decrease

After irradiation

Before irradiation

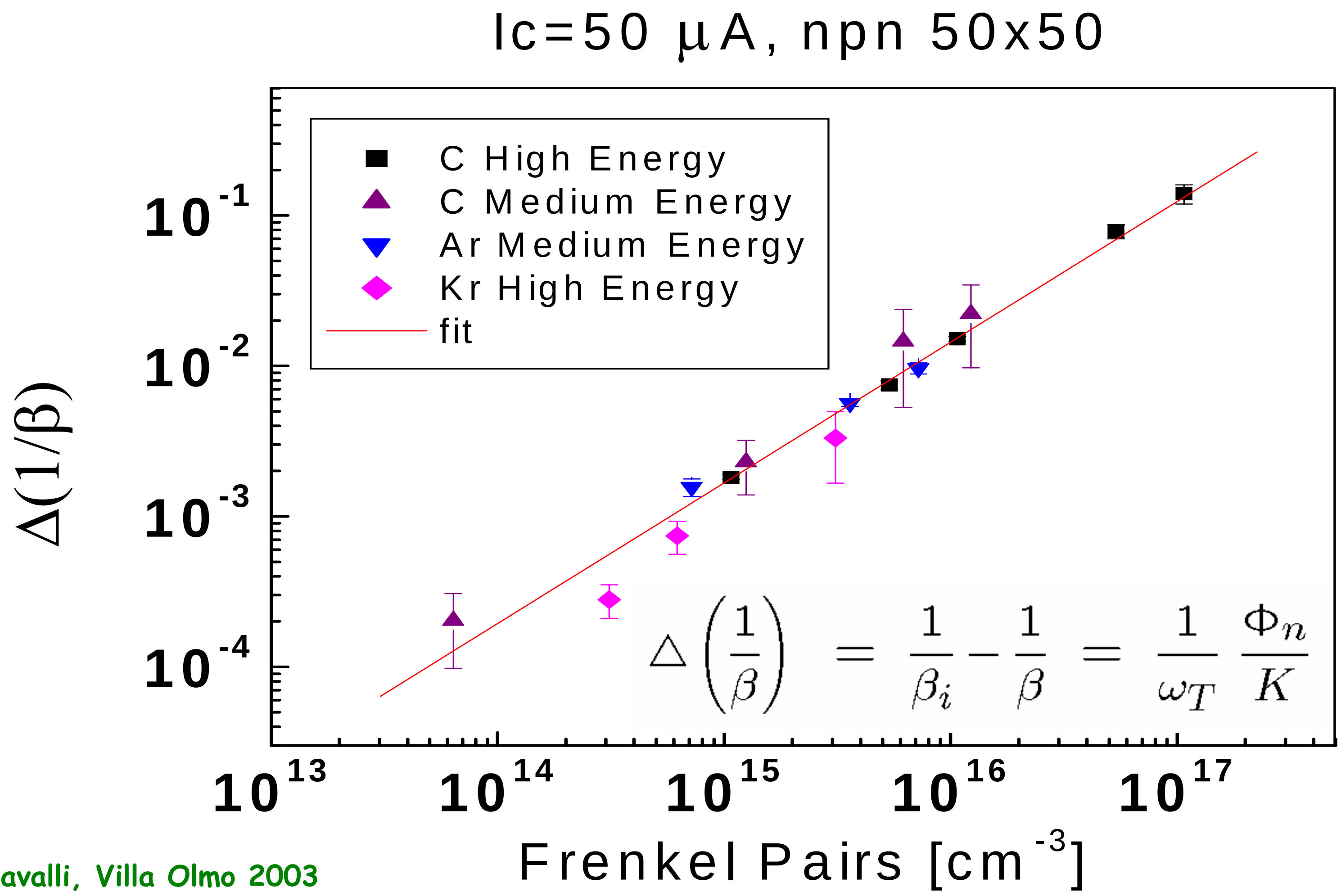
fluence

$$\frac{1}{\tau} = \frac{1}{\tau_i} + K_\tau \Phi$$

Relevant damage constant

Macroscopic effects of displacement damage

Reduction of common emitter current gain



A.Favalli, Villa Olmo 2003

Irradiation tests of electronic devices can be performed according to:

MIL-STD-883E

This procedure establishes uniform methods, controls, and procedures for testing microelectronics devices suitable for use within Military and Aerospace electronic systems including basic environmental tests to determine resistance to deleterious effects of natural elements and conditions surrounding military and space operations.

ESA/SCC BASIC SPECIFICATION No. 22900

This specification defines the basic requirements applicable to the steady-state irradiation testing of integrated circuits and discrete semiconductors suitable for space applications.

DISPLACEMENT DAMAGE QUALIFICATION

MIL-STD-883E

Method 1017.2

Radiation source: *Triga* Reactor

Dosimetry equipment: fast neutron threshold activation foils (^{32}S, ^{54}Fe and ^{58}Ni) and CaF_2 for γ-ray component;

ESA/SCC BASIC SPECIFICATION No. 22900

Radiation source: electron accelerator with sufficient energy to ensure that the energy at the surface of the chip is at least 2.5 MeV; protons, neutrons;

Safety requirements: handling and storage of test specimens shall be governed by the local Radiation Safety Officer or Health Physicist;

Exposure: All exposure shall be made at 20 ±10 °C and correlated ot 1 MeV equivalent fluence;

Tests: They shall be made within 24 hours after the completion of exposure and eventually extended to 1 week in case of residual radioactivity.

MIL-STD-883E

(Method 1019.4)

Ionising radiation (total dose) test procedure

PURPOSE: Definition of the requirements for testing packaged semiconductor integrated circuits for ionising radiation total dose effects. In addition, the procedure provides an accelerated aging test for estimating low dose rate ionising radiation effects on devices.

Radiation source: ^{60}Co gamma source, with an intensity uncertainty no more than ±5% and a radiation field uniformity within ±10% in the volume where devices are irradiated.

Radiation dose rate:

A) Standard condition: 50<dose rate<300 rads(Si)/s [0.5 & 3 Gy(Si)/s]± 10%

B) For some bipolar & biCMOS devices to space-level dose rates, if the maximum rate is <50 rads(Si)/s in the intended application, the parties to the test may agree to perform the test at dose rate≥ maximum rate of the intended application.

C) As an alternative, the test may be performed at the dose rate of the intended application if this is agreed by the parties to the test.

Lead/Aluminium container: Test specimens shall be enclosed in a Pb/Al container in order to minimise dose enhancement effects caused by low-energy, scattered radiation. A minimum of 1.5 mm Pb, surrounding an inner shield of at least 0.7 mm Al, is required. This Pb/Al container produces an approximate charged particle equilibrium for Si.

Temperature requirements: Devices under test shall be irradiated in an ambient temperature of 24±6 °C and electrical measurements shall be performed in an ambient temperature of 25±5 °C.

Post irradiation procedure: electrical measurements shall be performed within 1 h from the stop of irradiation; Between the prior and the next irradiation test there can not be more than 2 hours.

Accelerated aging under bias: 100°C±5°C under bias for 168±12 hours.

ESA/SCC BASIC
SPECIFICATION No. 22900

IONIZATION DAMAGE QUALIFICATION

Radiation source: ^{60}Co gamma source or an electron accelerator beam or an alternative source which can be correlated to these source with a dose and uniformity field no more than 10%.

Radiation level: test devices shall be exposed to within 10% of the specified radiation dose level or fluence. If multiple exposures are required for a set of test devices, then:

a) Electrical parameters shall be measured after each exposure;

b) Unless differently specified, there shall be a minimum of 3 exposures, for which the increments in dose level shall be in ratios of 1/3, 1 and 3 times the radiation level of interest specified in the plan.

Radiation levels (Si):

(M) 3 krad;	(D) 10 krad;
(E) 20 krad;	(F) 50 krad;
(R) 100 krad;	(H) 1 Mrad.

Two dose rate windows are specified:

1)The standard dose rate: 3.6 krad to 36 krad/h (36 to 360 Gy/h);

2) The low dose rate: 36 to 360 rad/h (0.36 to 3.6 Gy/h).

Total exposition time shall be <96 hours, but longer periods at low dose rate may be used in certain case with the agreement of all the parties.

Lead/Aluminium container: Test specimens shall be enclosed in a minimum of 1.5 mm Pb, surrounding an inner shield of at least 0.7 mm Al container.

Post irradiation measurements within 1 hour of completion of exposure.

Temperature requirements: irradiation test at 20±10 °C and electrical measurements at 25±3 °C.

Annealing treatment:

a) 25°C annealing under bias with measurements performed after 12, 24 and 168 hours.

b) Accelerated ageing under bias: Devices shall be baked at 100 °C under bias for 168 hours.

Differences
ESA/SCC BASIC SPECIFICATION No. 22900- MIL-STD-883E

MIL-STD-883E

50< dose rate<300rads(Si)/s
(0.5 and 3 Gy(Si)/s) ± 10%

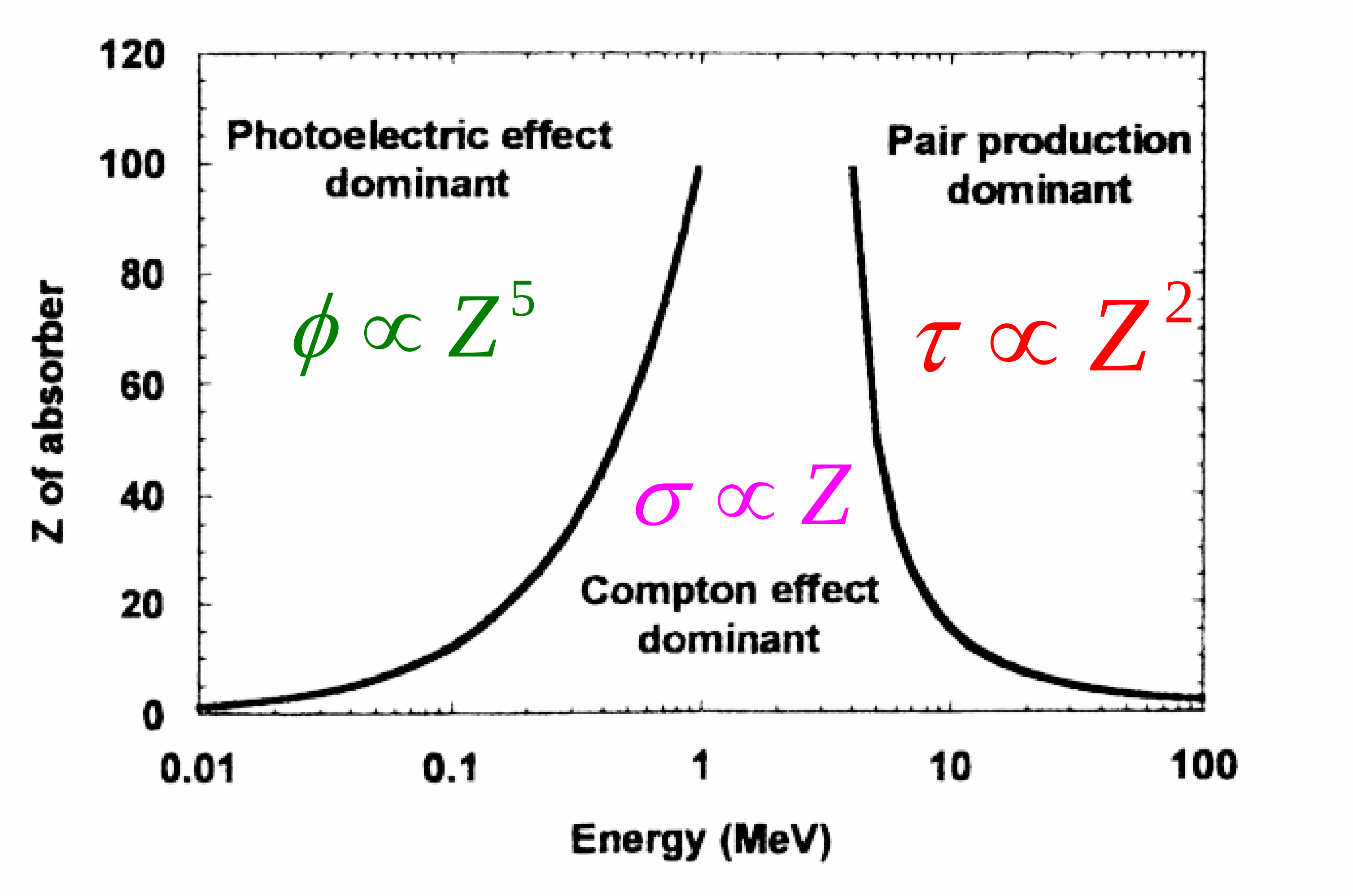
Temperature:
Irradiation: 24±6 °C;
Measurements: 25±5 °C.

ESA/SCC BASIC SPECIFICATION No. 22900

Two dose rate windows:
1)The standard dose rate:
3.6 krad to 36 krad/h
(36 to 360 Gy/h);
2) The low dose rate:
36 to 360 rad/h
(0.36 to 3.6 Gy/h)

Temperature:
Irradiation:20±10 °C;
Measurements: 25±3 °C.

Interaction of γ rays with matter



$\phi \propto Z^5$

$\sigma \propto Z$

$\tau \propto Z^2$

Absorption

The intensity of a monoenergetic beam of gamma rays entering a detector of thickness d is reduced in intensity accordinto to

$$I(E) = I_0(E)e^{-\mu d}$$

where

total linear attenuation coefficient μ (E)=N/Aσ_{tot}

↑

$\sigma_{\text{photoelectric effect}} + \sigma_{\text{Compton interaction}} + \sigma_{\text{pair production}}$

Interaction of radiation with matter

Gamma Rays

Photoelectric process

a photon is completely absorbed in a collision with an electron and the elctron is ejected from the atom.

If $E_{p.e.} = E_{photon} - E_{binding}$

↘

X o e^- Auger

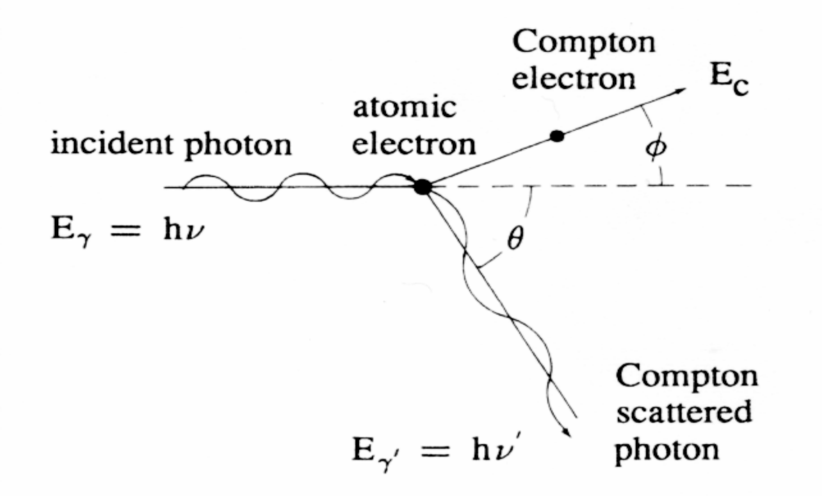
↘ 2°p.e.

COMPTON EFFECT

Applying the conservation laws of energy and momentum, it turns out that the energy transferred to electron is given by:

$$E_{\gamma'} = \frac{E_\gamma}{1+\alpha\left(1-\cos\theta\right)}$$

where $\alpha = \frac{h\nu}{mc^2} = \frac{E_\gamma}{0.511}$, and E_γ e $E_{\gamma'}$ are expressed in MeV.



The Compton electron kinetic energy is equal to :

$$E_c = E_\gamma - E_{\gamma'} = \frac{\alpha\left(1-\cos\theta\right)}{1+\alpha\left(1-\cos\theta\right)} E_\gamma$$

From these relations one evicts that the Compton electron energy spectrum extends from 0 (corresponding to θ=0°) up to a maximum value(for θ=180°) given by the following relation:

$$E_{c(\max)} = \frac{E_\gamma}{1+\frac{0.511}{2E_\gamma}} MeV$$

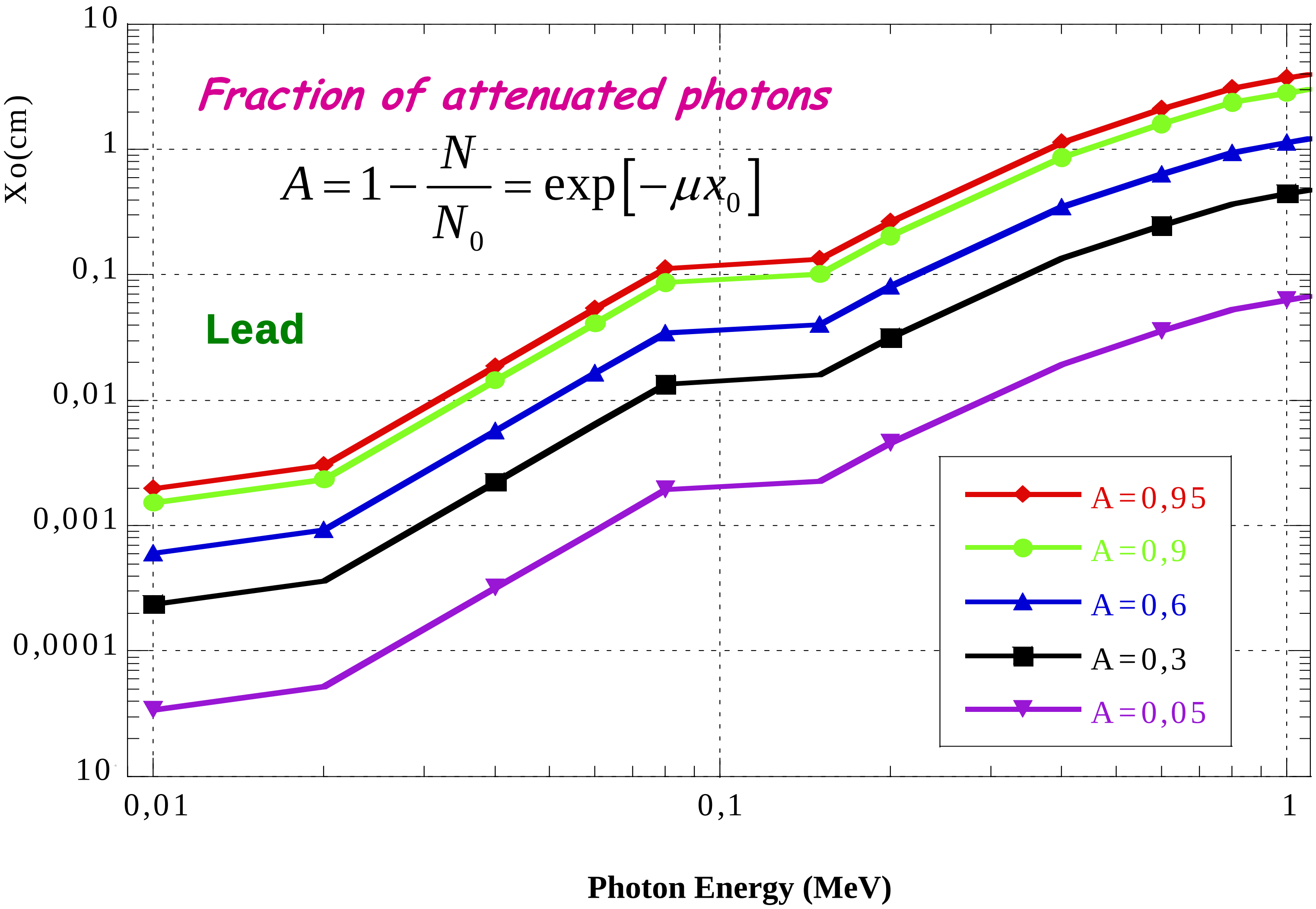
Pair Production –

If E_{photon} = twice the rest mass of an electron
(0.511 MeV)
can occur the pair-production process
($E_{minimum}$ 1.02 MeV)
$e^{-}\ e^{+}$
↓ 2 γ da 0.511 MeV
e^{-}

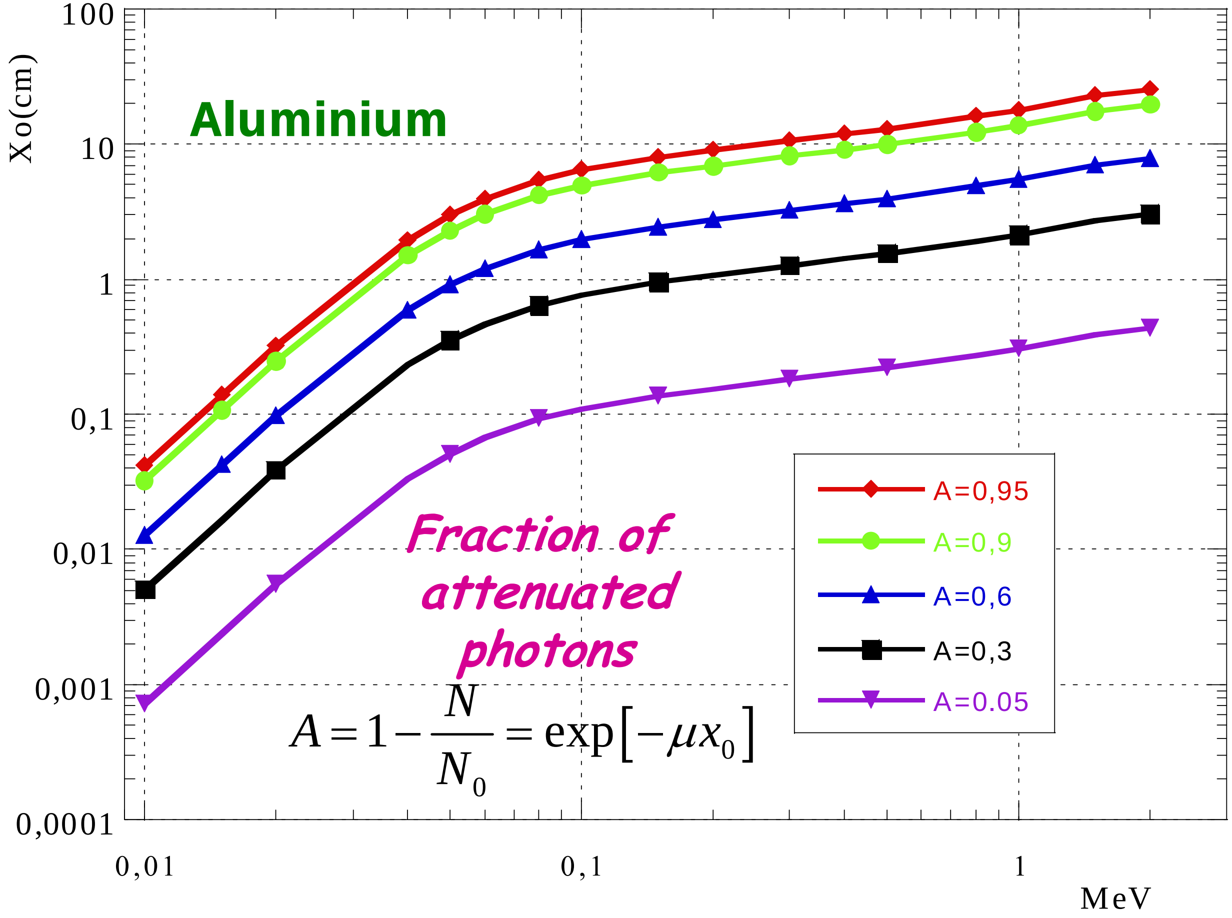
During test devices it is strictly required that:

a) only one interaction process between γ photons and matter is dominant;

b) the conditions of charge particle equilibrium are verified.



$$A = 1 - \frac{N}{N_0} = \exp\left[-\mu x_0\right]$$

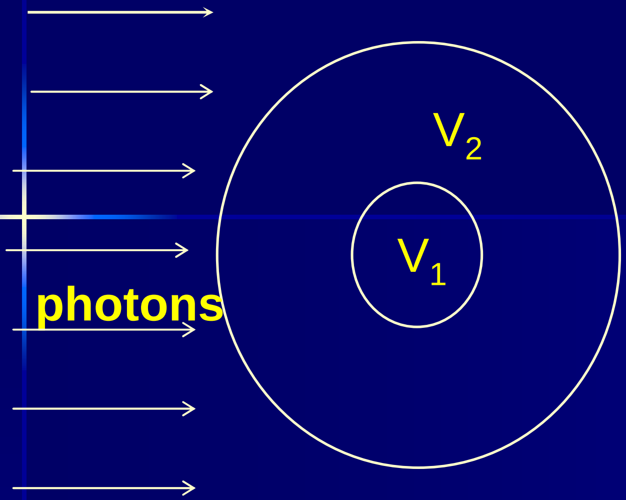


A minimum of 1.5 mm *Pb* layer surrounding an inner shield of at least 0.7 mm *Al* is required, in fact:

-Pb layer absorbs 95 % of γ < 150 keV

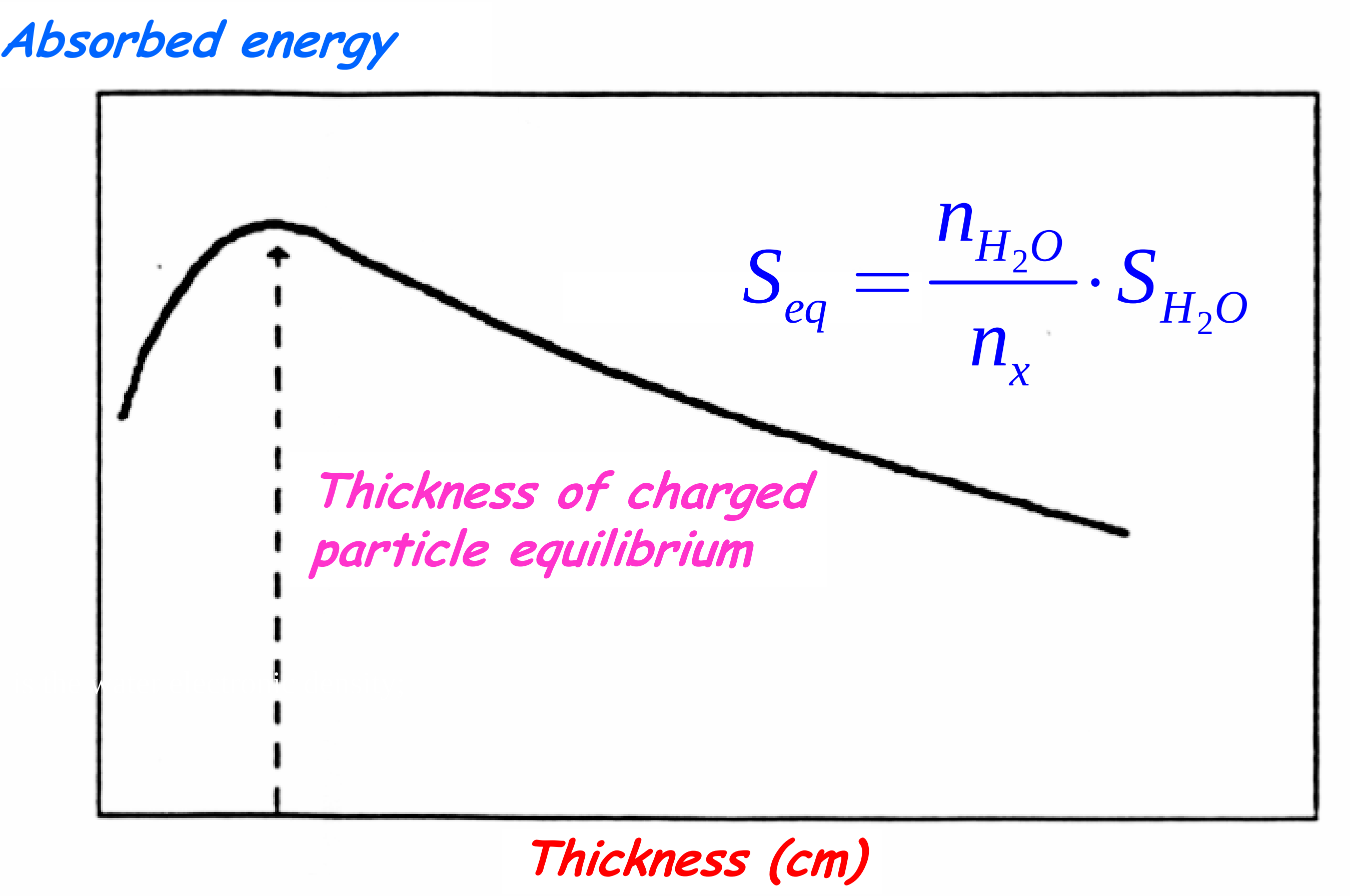
-Al layer absorbs 99 % of γ < 15 keV

COMPTON EFFECT IS DOMINANT.



To realize the charged particle equilibrium conditions during an irradiation sample under irradiation should be surrounded with an absorber of suitable thickness, defined as the *charged particle equilibrium thickness*. The thickness value depends on sample electron density and on the energy of impinging radiation. In the curve representing the course of absorbed dose vs. sample depth its value corresponds to the thickness where the curve achieves its highest value. This curve is characterised by an initial increasing course due to fluency increment of the electrons coming from foregoing layer.

This Pb/Al container produces an approximate charged particle equilibrium for Si.



$$S_{eq} = \frac{n_{H_2O}}{n_x} \cdot S_{H_2O}$$

$$n_x = \rho \frac{N_A}{M} \sum_i Z_i$$

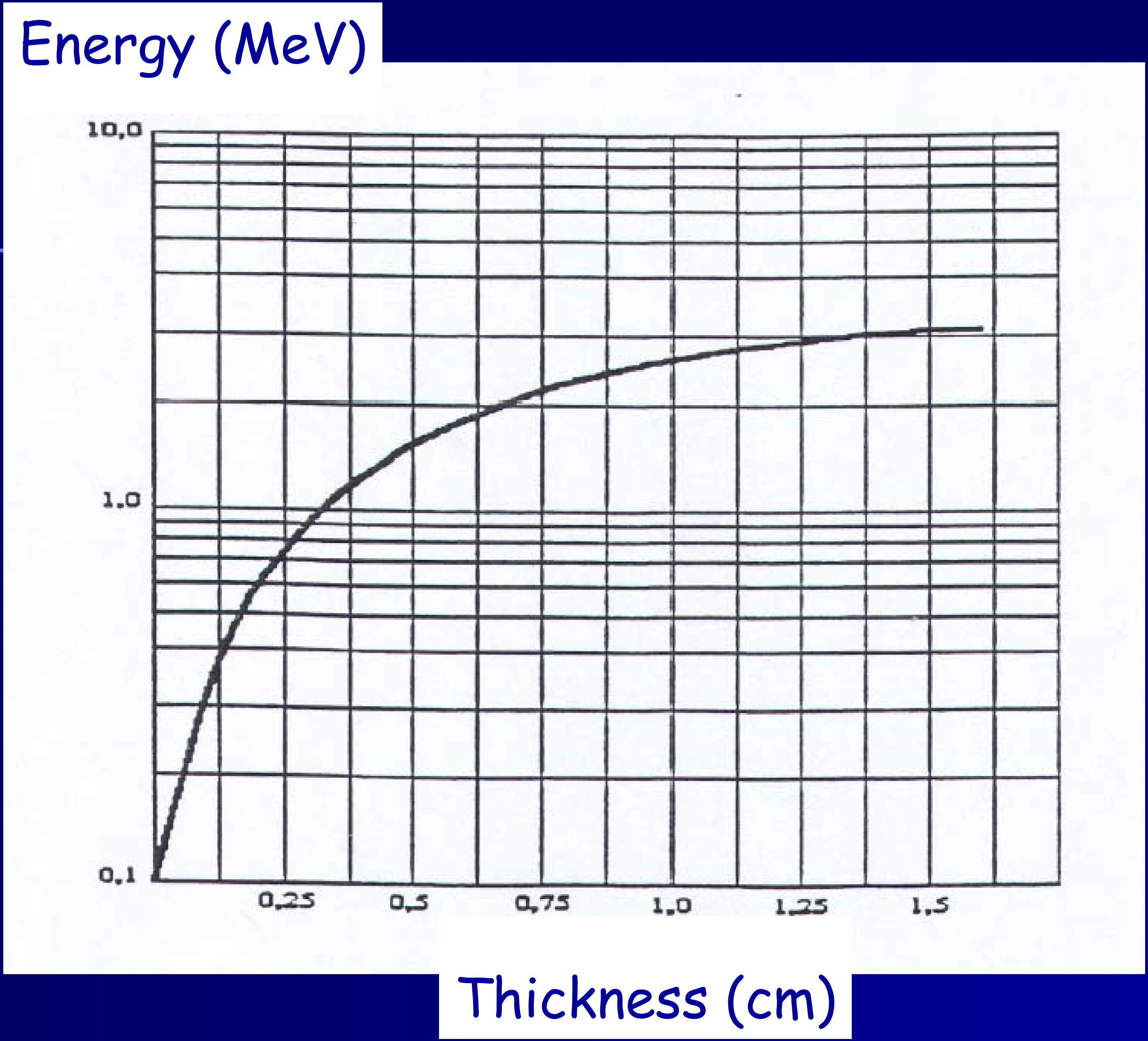
electron density

- ρ is the material density [Kg m^{-3}];
- N_A is the Avogadro number [6.023*10^{23} moli-1];
- M is the molecular mass [Kg moli-1];
- Z_i is the atomic number of the i-material;
- ΣZ_i is the total number of electron per molecule.

Next, as the depth increases, photon attenuation causes an electronic fluence decrease and consequently a decrease of absorbed dose. The equivalent thickness of a certain material can be obtained by the following relation:

$$S_{eq} = \frac{n_{H_2O}}{n_x} \cdot S_{H_2O}$$

Where n_{H_2O} is the water electronic density; S_{H_2O} is the electronic equilibrium thickness for water and n× is the electronic density of the material.

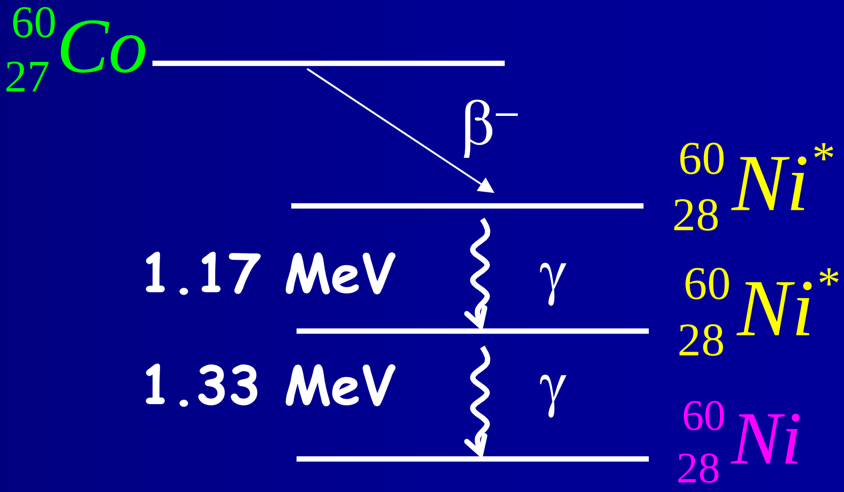

Energy (MeV)
10,0
1.0
0,1
0,25
0,5
0,75
1,0
1,25
1,5
Thickness (cm)

Calliope ^{60}Co radioisotope source

Irradiation cell dimensions:
7x6x3.9 m

Maximum allowed activity:
3.7×10^{15} Bq (100kCi)

Present activity (January 2004):
7.7×10^{14} Bq (20 kCi)



$^{60}_{27}Co$

β^-

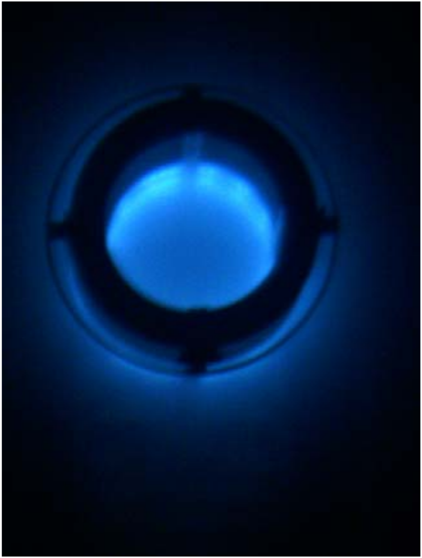
$^{60}_{28}Ni^*$

1.17 MeV γ

$^{60}_{28}Ni^*$

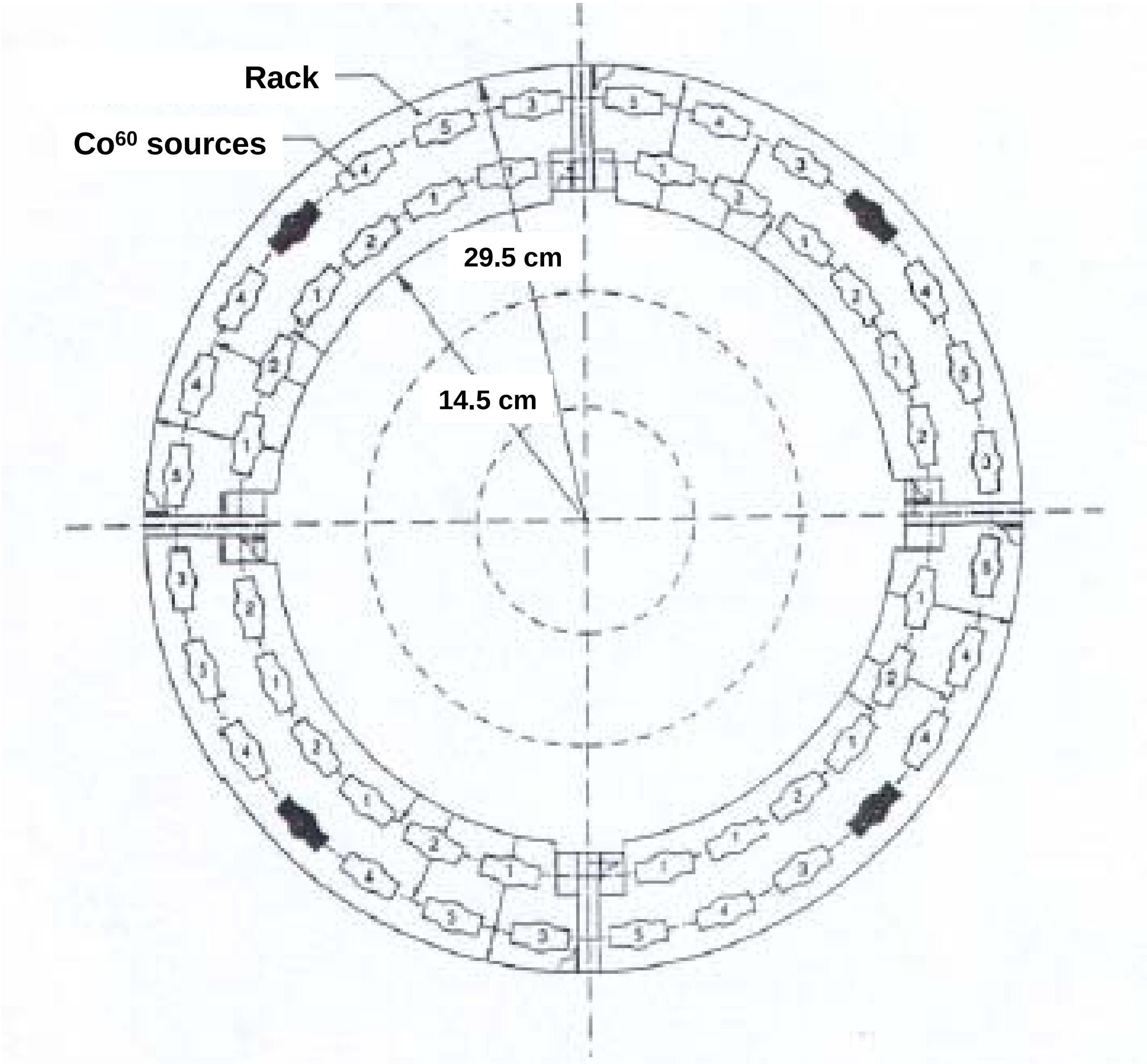
1.33 MeV γ

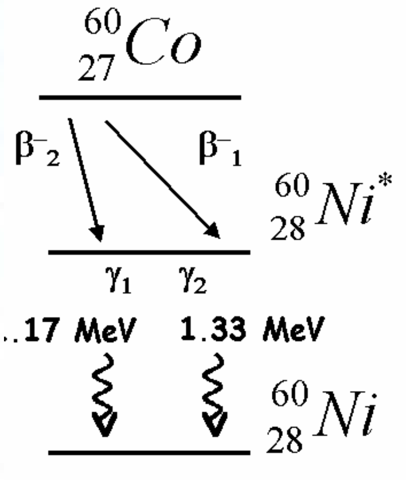
$^{60}_{28}Ni$



Rack with ^{60}Co sources

Available dosimetry methods:
1. *Fricke absolute dosimetry (20-400 Gy);*
2. *Alanine dosimetry (1 Gy-500 kGy);*
3. *Red Perspex dosimetry (5-40 kGy).*


Rack
Co60 sources
29.5 cm
14.5 cm


$^{60}_{27}Co$
β^-_2
β^-_1
$^{60}_{28}Ni^*$
γ_1
γ_2
..17 MeV
1.33 MeV
$^{60}_{28}Ni$

Dosimetric methods at CALLIOPE plant

Fricke dosimeter (20-400Gy)

$Fe^{2+} + H_2O_2 + \gamma \Rightarrow Fe^{3+} + HO^- + OH^\bullet$

$Fe^{2+} + OH^\bullet + \gamma \Rightarrow Fe^{3+} + OH^-$

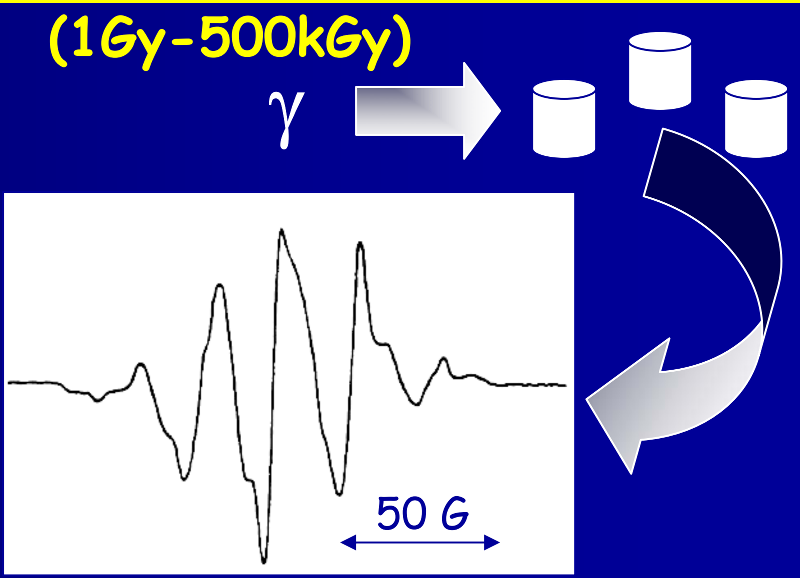
Spectrophotometer
UV-VIS

Red-Perspex dosimeter(5-40kGy) and radiochromic (1kGy-3MGy)

Polimetilmetacrilate
and radiocromic film + γ

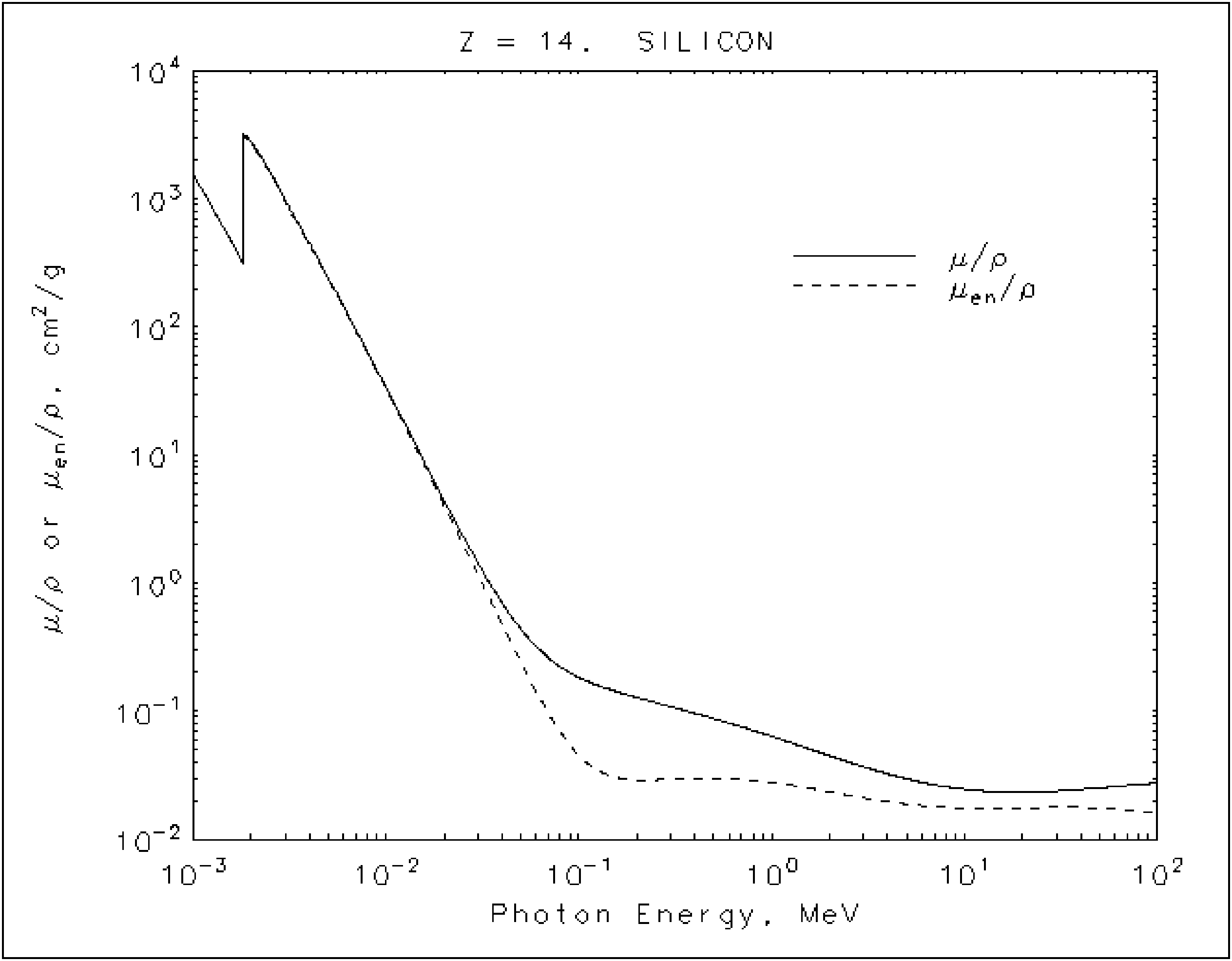
Spectrophotometer UV-VIS
And radiocromic analyser
(510-600 nm)

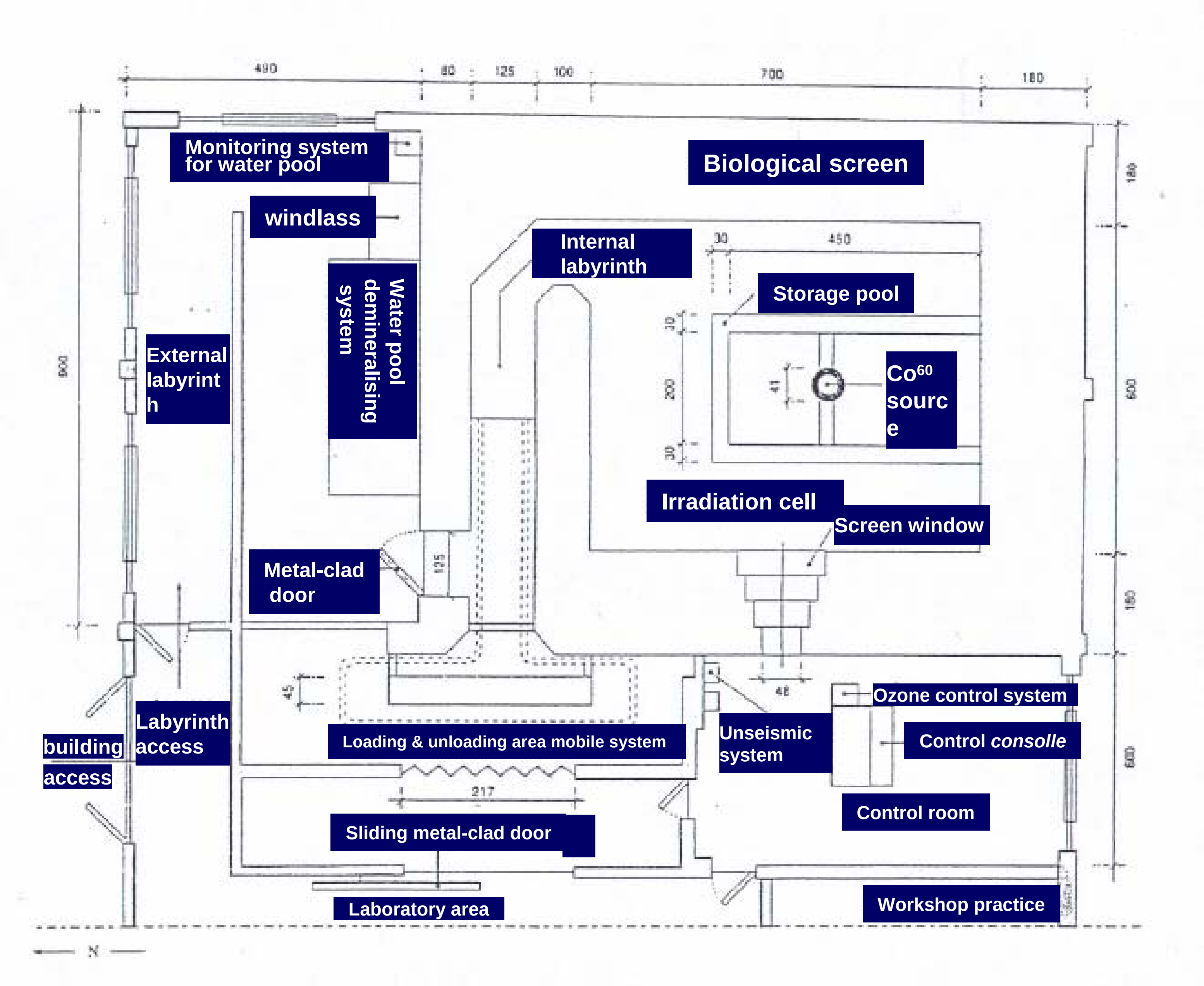
ESR dosimeter with alanine (1Gy-500kGy)



Calculation of the dose absorbed in Silicon

$$D_{Si} = \frac{\left(\frac{\mu_{en}}{\rho}\right)_{Si}}{\left(\frac{\mu_{en}}{\rho}\right)_{H_2O}} \times D_{H_2O} = \frac{2.652*10^{-2}(cm^2/g)}{2.965*10^{-2}(cm^2/g)} = 0.894*D_{H_2O}$$





Monitoring system for water pool

Biological screen

windlass

Internal labyrinth

Storage pool

Water pool demineralising system

External labyrinth

Co^{60} source

Irradiation cell

Screen window

Metal-clad door

Ozone control system

Labyrinth access

building access

Loading & unloading area mobile system

Unseismic system

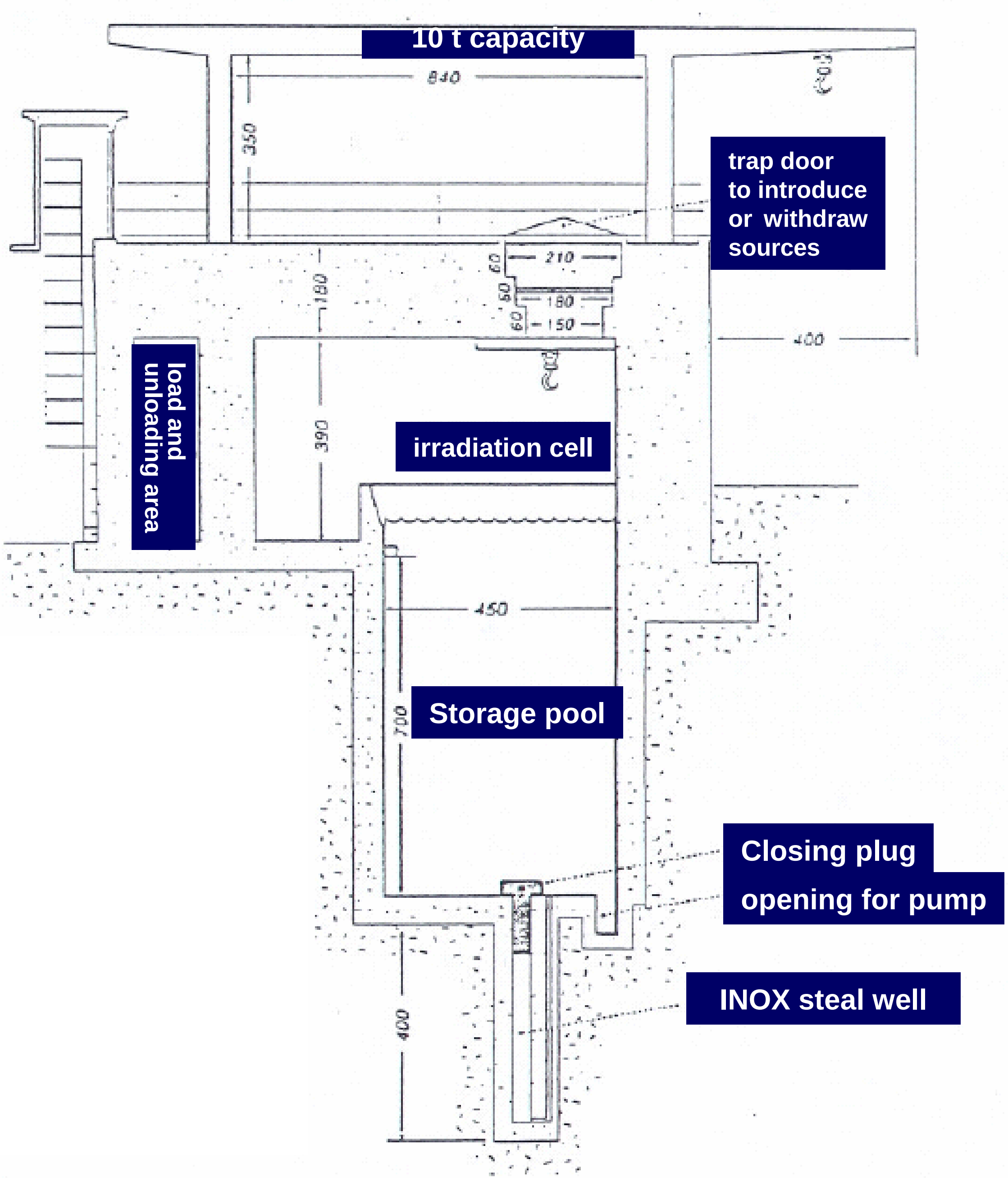
Control *consolle*

Control room

Sliding metal-clad door

Workshop practice

Laboratory area



10 t capacity

trap door to introduce or withdraw sources

load and unloading area

irradiation cell

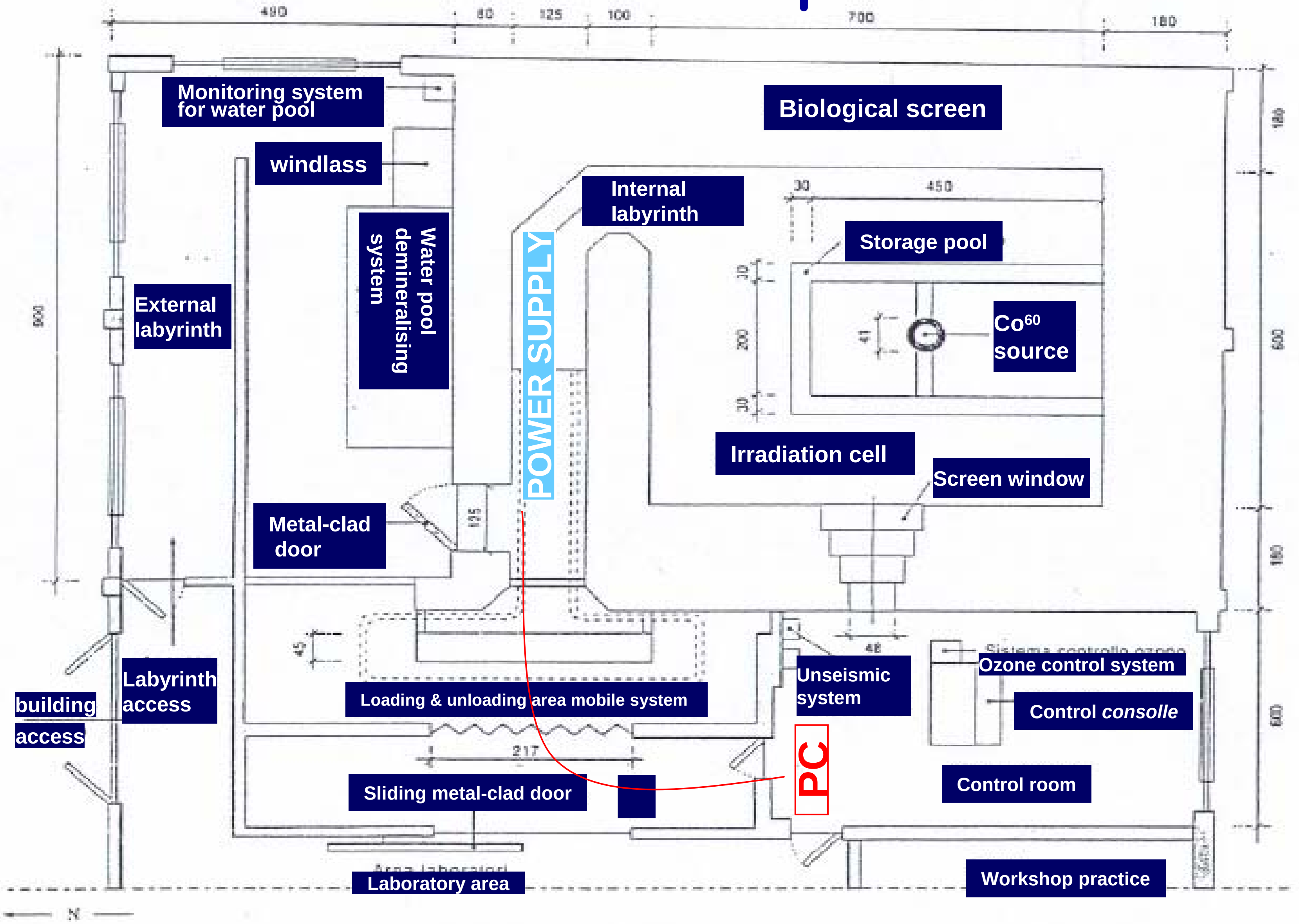
Storage pool

Closing plug

opening for pump

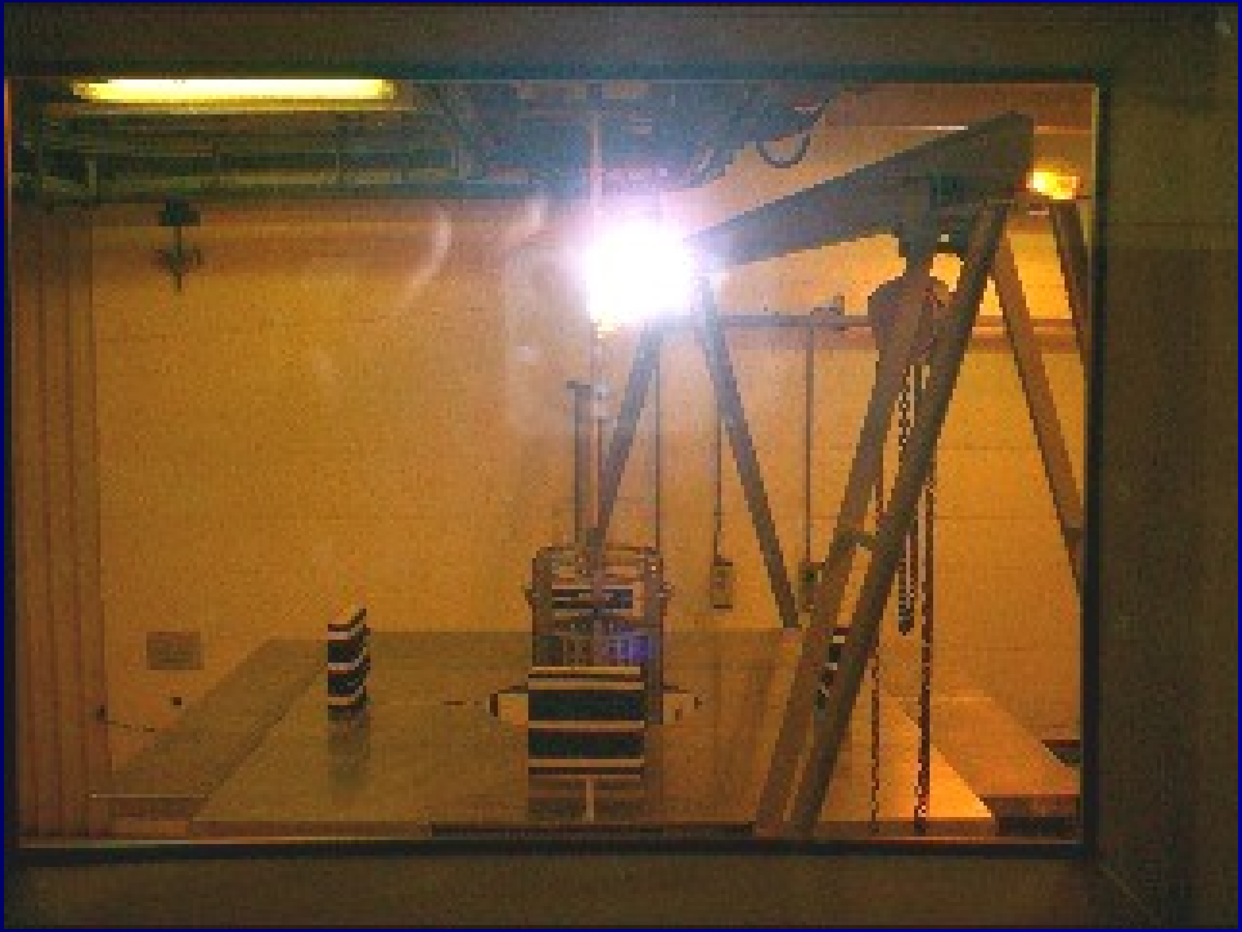
INOX steal well

CALLIOPE plant

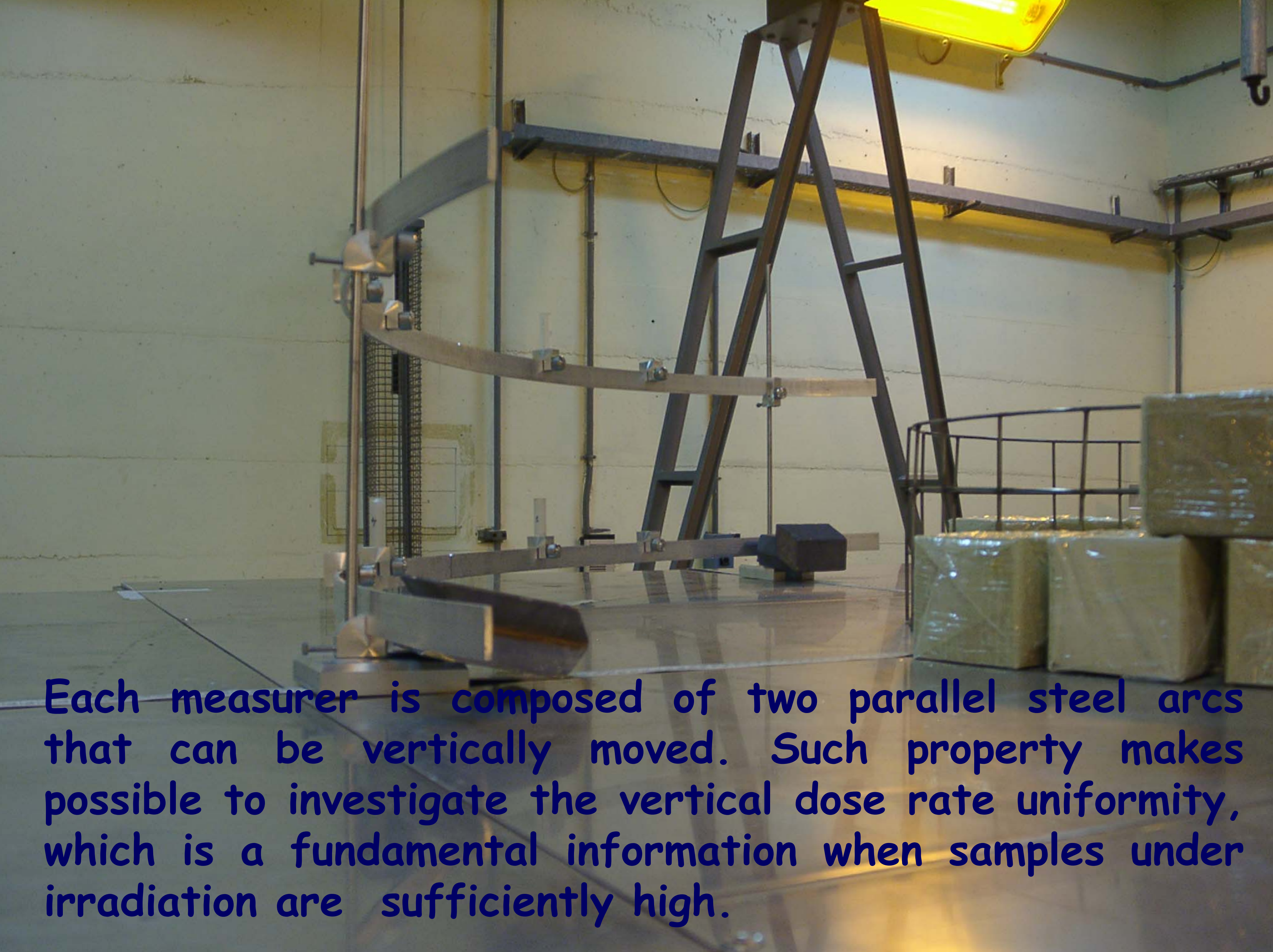


Recent modifications:

a steel platform was projected and realised, covering the pool and characterised by a central circular aperture for the passage of the source, thanks to which materials can be irradiated in isodose positions surrounding the source rack.



That platform is equipped with movable arc measurers describing isodose positions on the platform and provided with compartments for the housing of dosimeters.



Each measurer is composed of two parallel steel arcs that can be vertically moved. Such property makes possible to investigate the vertical dose rate uniformity, which is a fundamental information when samples under irradiation are sufficiently high.

Besides previously described devices, 4 steel movable mountings were projected and realised which can be moved in different dosimetric positions of the irradiation cell and which allow the repeatable sample positioning.

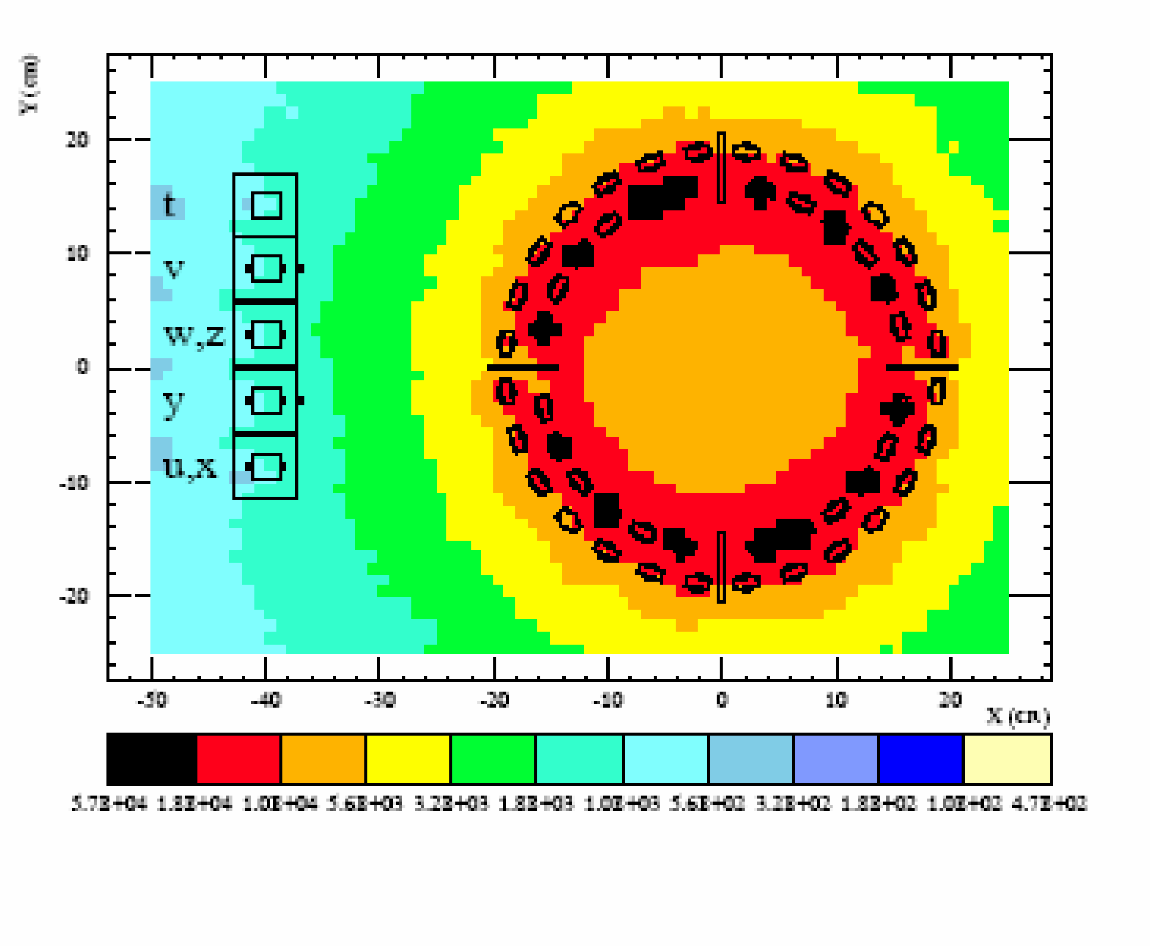
Simulation of γ radiation field inside the cell.

To map the γ radiation field inside the irradiation cell, we have performed a simulation of Calliope dose rate profile by using FLUKA code.

Such code includes a good description of the electromagnetic physics down to about 1\,keV and its models are adapted and extended versions of the *EGS4* shower code.

Knowing accurately the properties of ^{60}Co decay and the material distribution in the source and its surroundings, an accuracy of better than 10 percent can be expected from such a simulation.

Simulation results of the radiation field inside the ^{60}Co pencil rack and in the region closest to the source.



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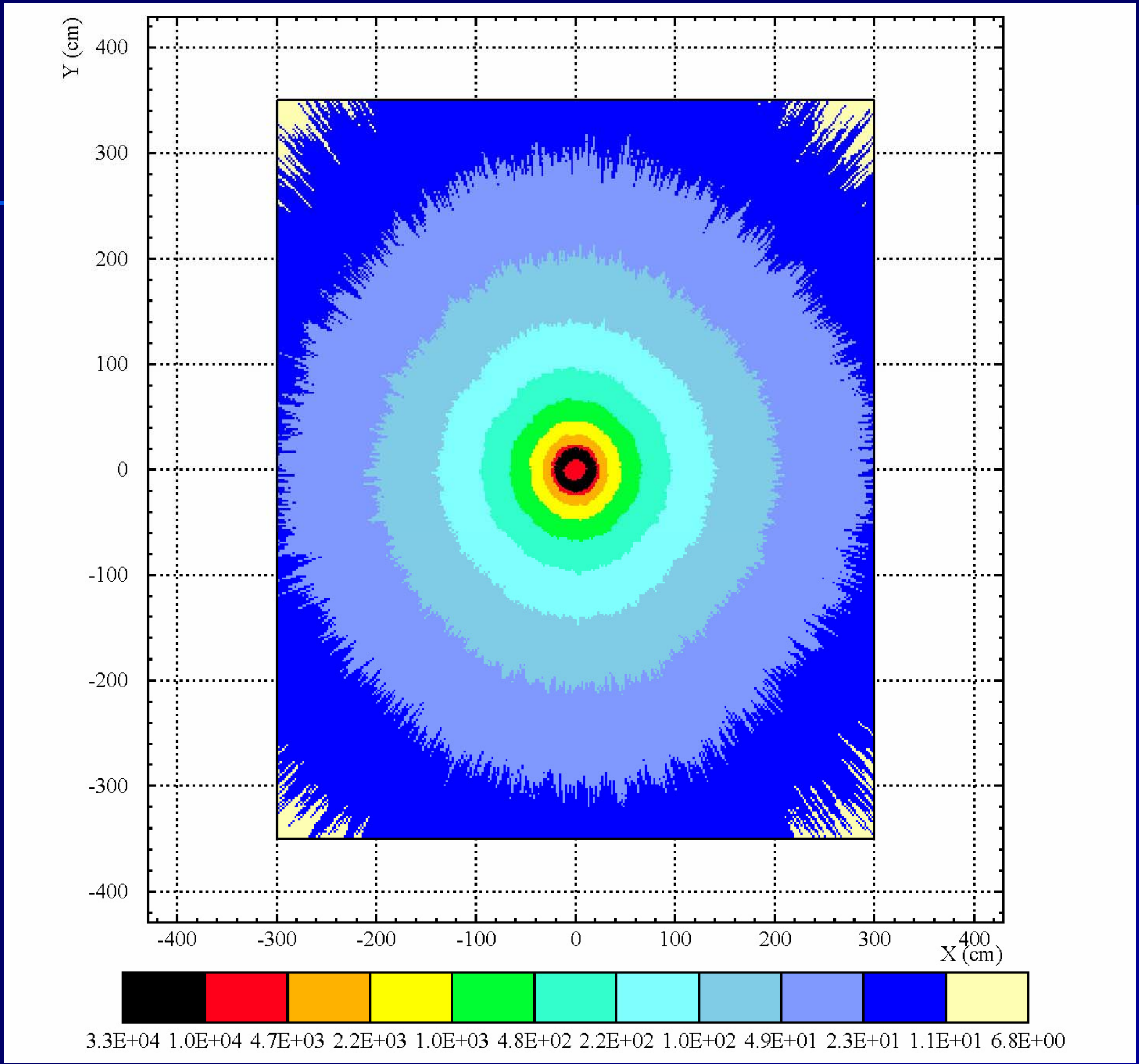
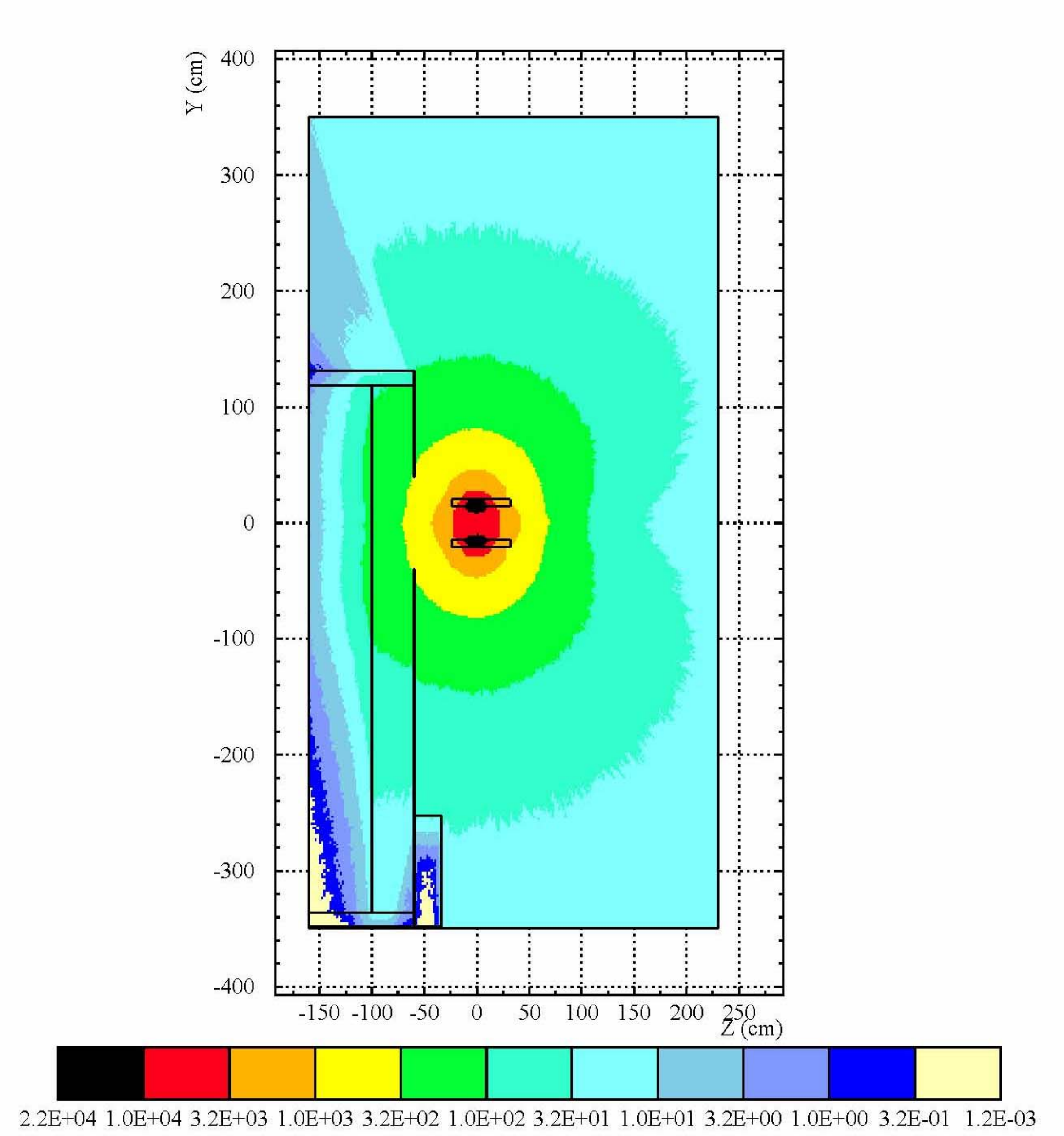
Top view x-y of the dose rate profile inside the radiation cell



M. Hutinen

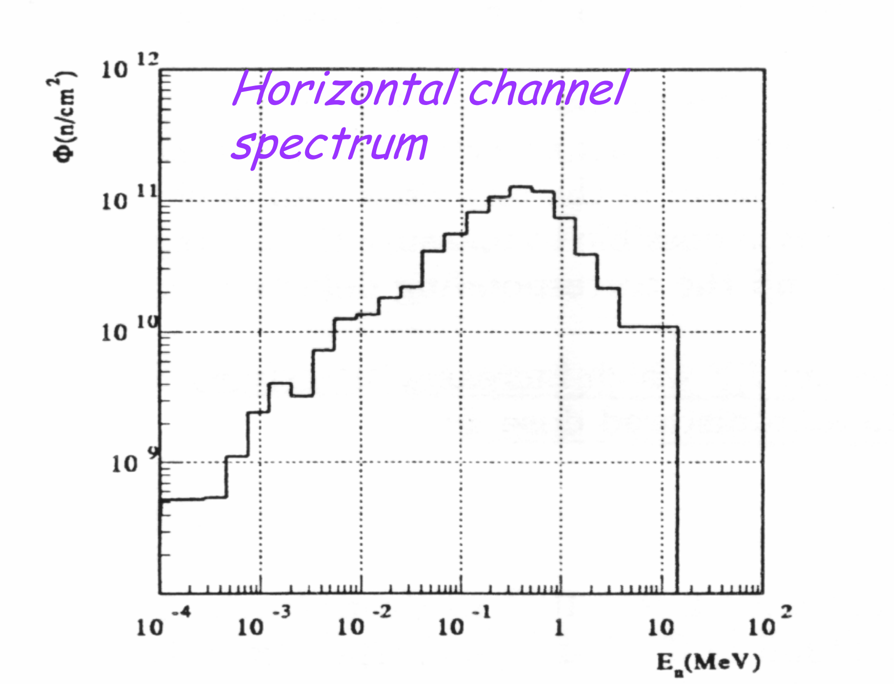
Lateral y-z dose rate profile inside the radiation cell



M. Hutinen

Tapiro reactor

- Maximum nominal power= 5 kW therm
- Maximum neutron flux at the core centre is $2.2 \cdot 10^{12}$ n/cm$^2 \cdot$s.



- Cylindrical core (r=6.20 cm, h=10.87 cm).
- Fuel: metal alloy (U 98.5%, Mo 1.5%)with a fully enriched ^{235}U (93.5%).
- Critical mass is 21.46 kg.

BIOLOGICAL SHIELD	High density concrete: 1.75 m thickness
CONTROL RODS	▪ 2 Shims ▪ 2 Safety ▪ 1 Regulation
SHUTDOWN SYSTEM	Core and Reflector separation
IRRADIATION FACILITIES	▪ 1 cavity ▪ 2 radial channels ▪ 1 piercing channel ▪ 1 horizontal channel ▪ 1 vertical channel ▪ 1 large thermal cave (1.6 m^3 volume)

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REACTOR TYPE	Fast source
MAX THERMAL POWER	5 kW
MAX NEUTRON FLUX	$4 \cdot 10^{12}$ n cm^{-2} s^{-1}
MAX GAMMA DOSE RATE	20 kGy/h
CORE	Cylindrical: diameter 125.8 mm
FUEL	U-Mo alloy (98.5% - 1.5%) Enrichment: 93.5% U^{235}
CLADDING	Stainless steel
REFLECTOR	Copper
COOLING SYSTEM	forced He + double heat exchanger
BIOLOGICAL SHIELD	Overall Height:

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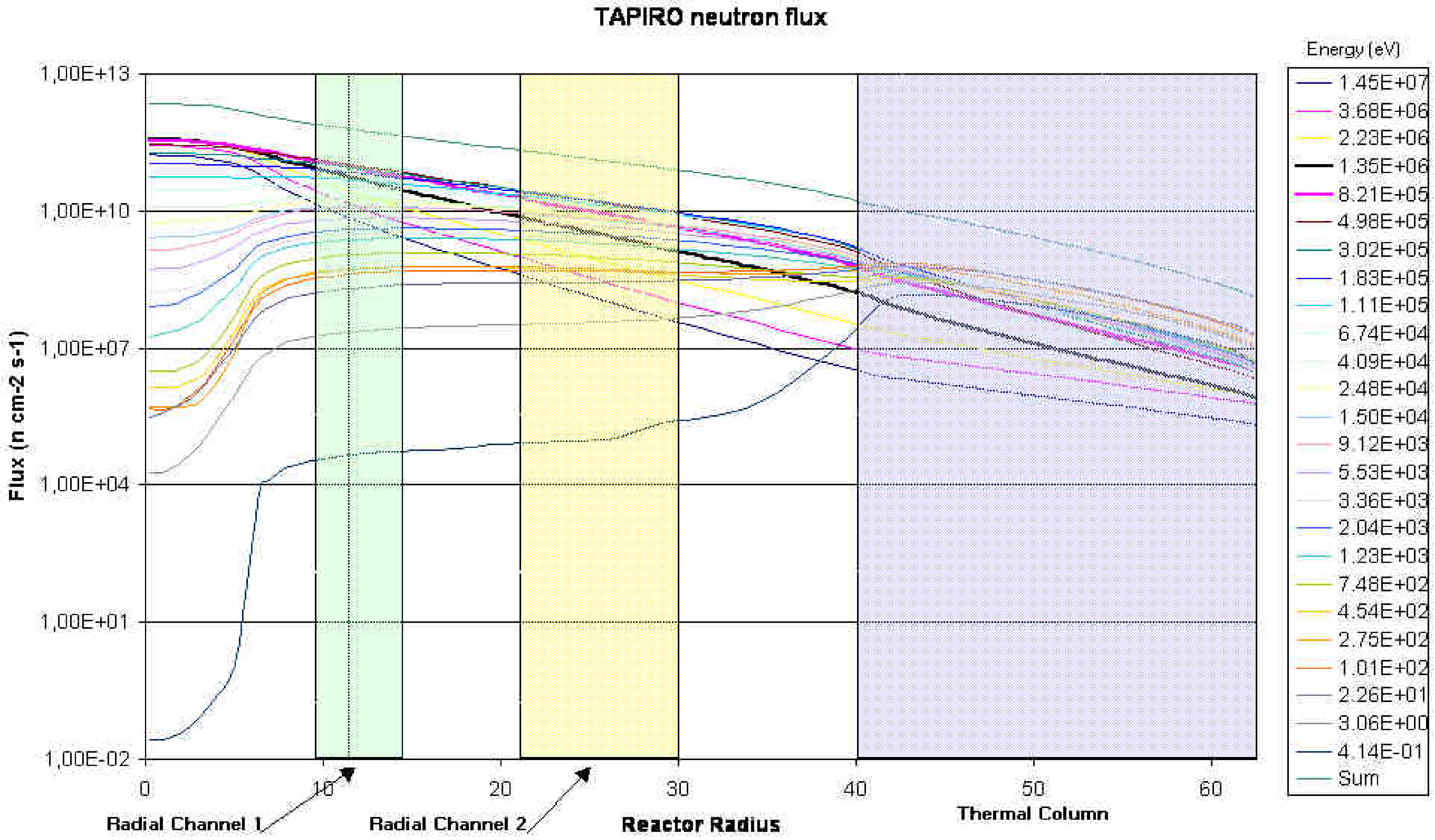

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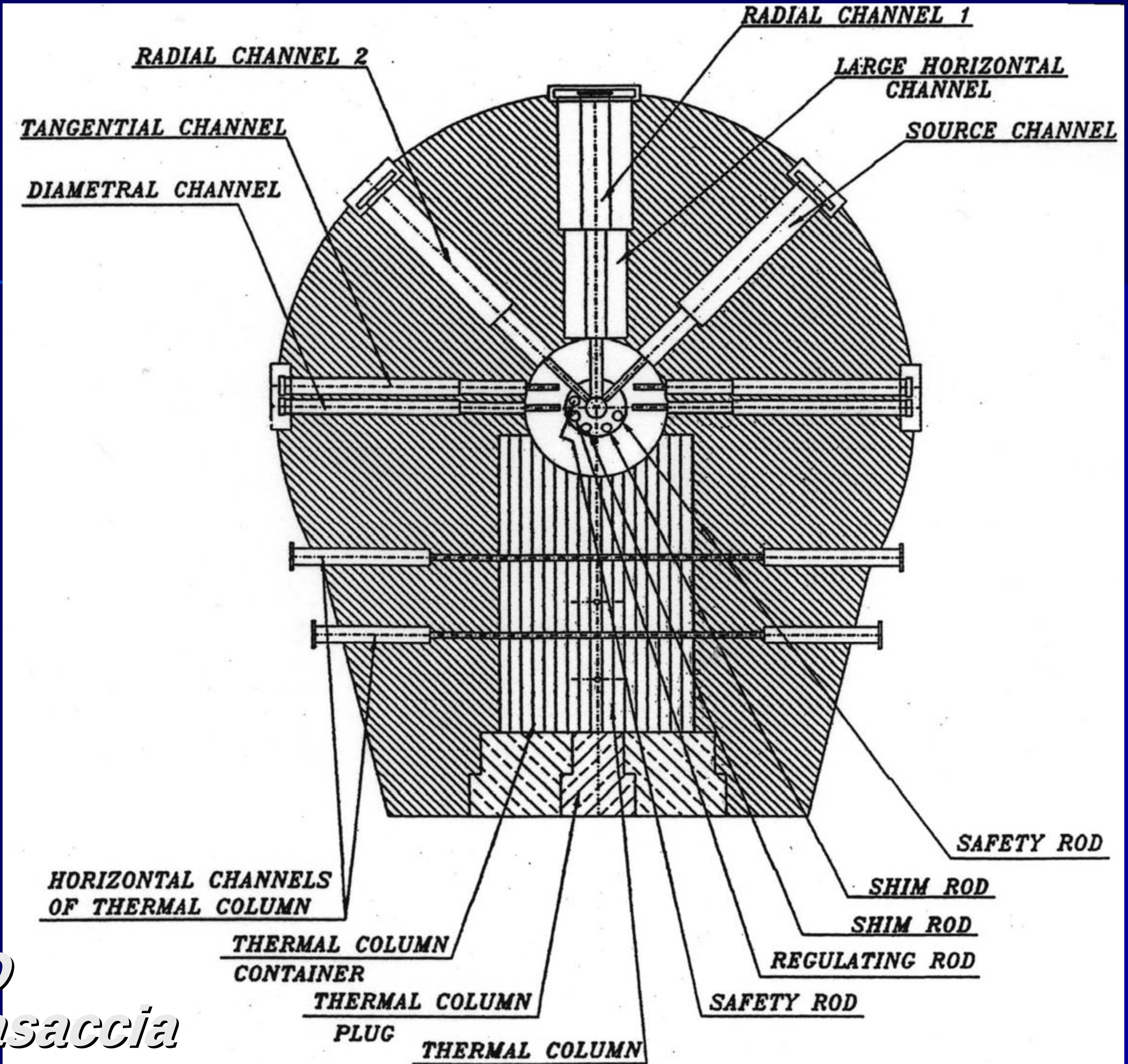

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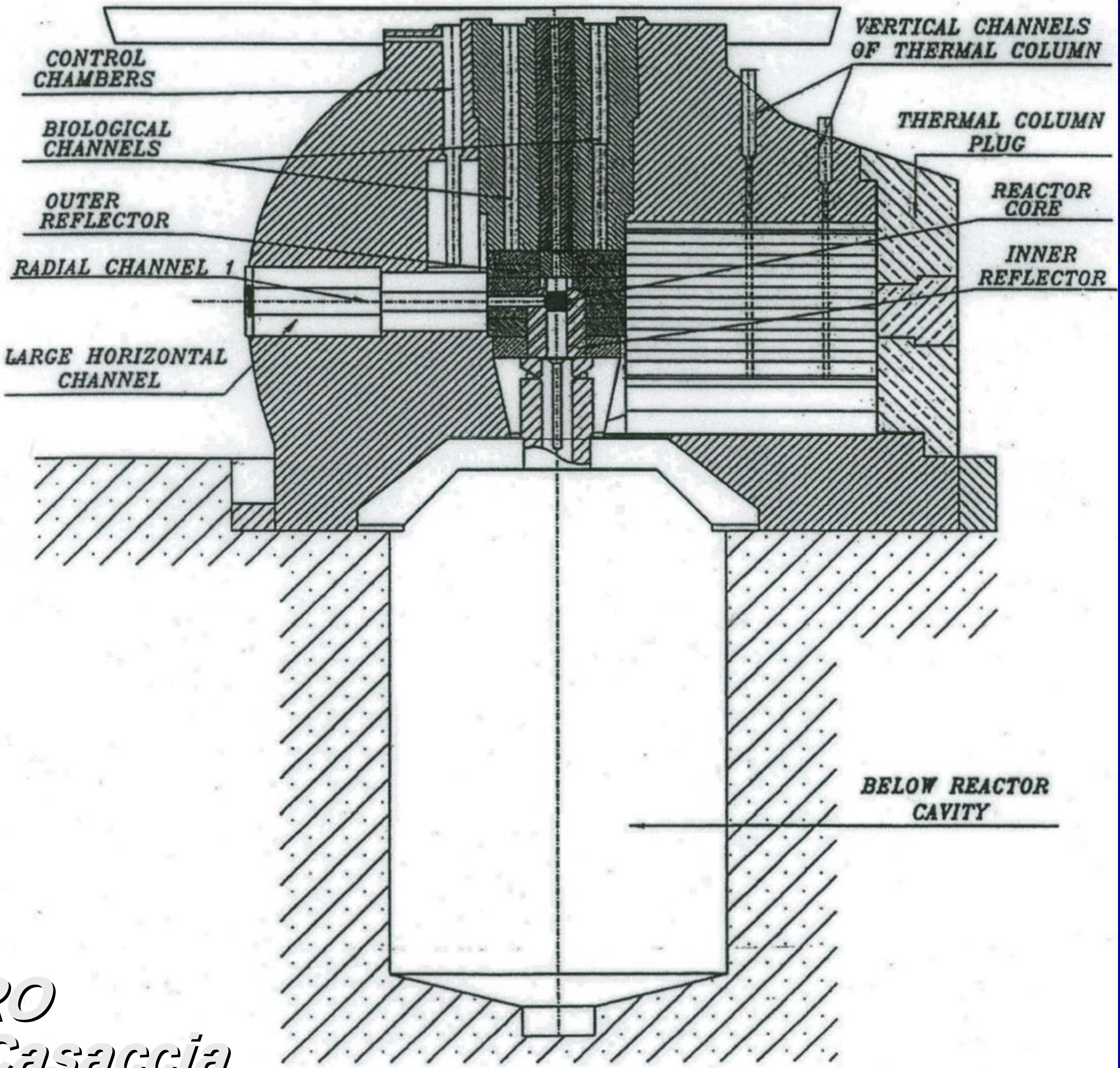

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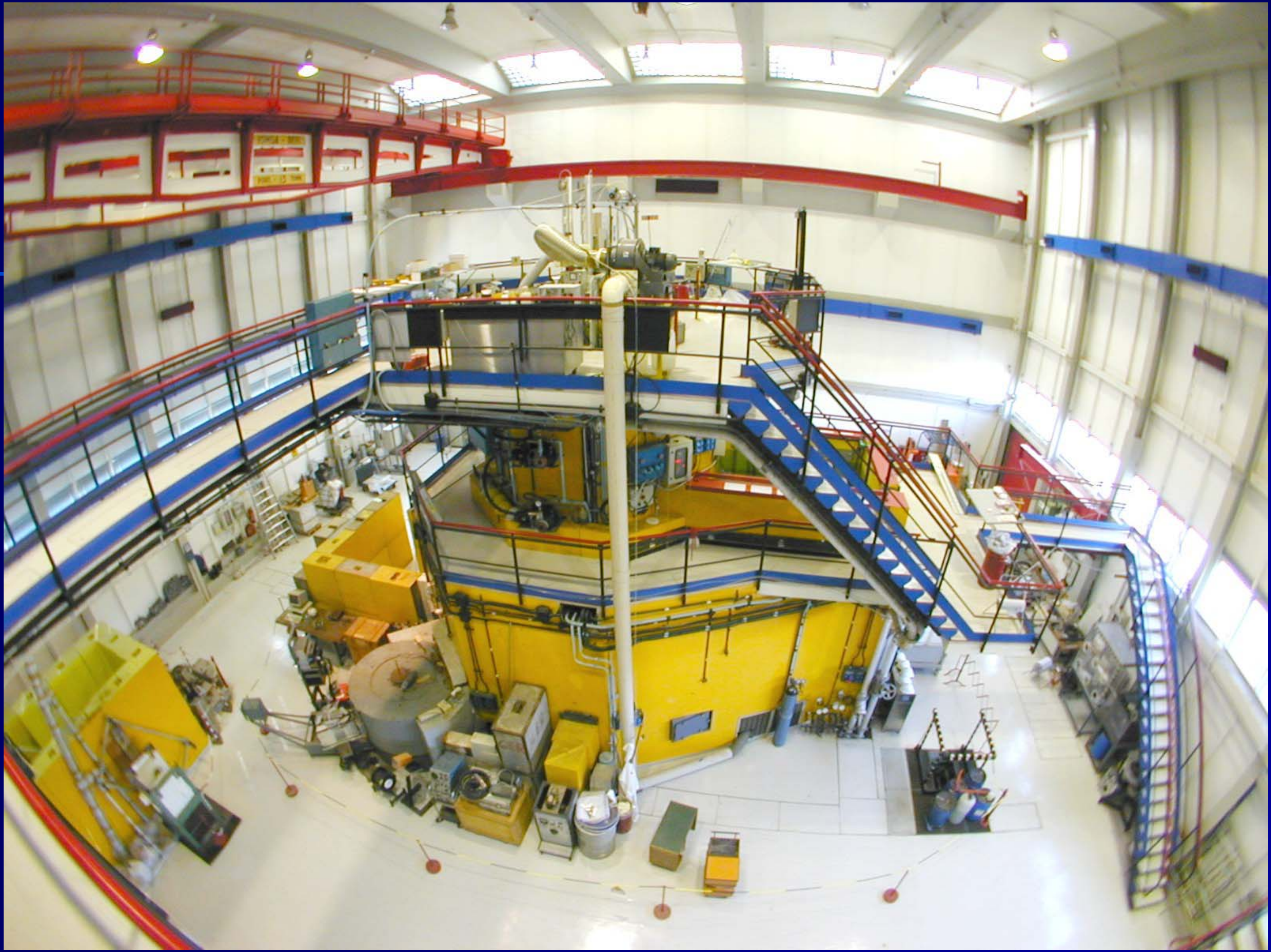
Thermal Column

1.6 m^3 volume



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Pool thermal reactor

Fuel: cylindrical element formed by a ternary alloy of Zr-H and 20 % uranium enriched 235U (about 4.5 kg of 235U).

The reactor is controlled by four rods: 2 shims, 1 safety and 1 regulating rod.

Maximum exercise power= 1 MW.

Highest neutron thermal flux is $3 \cdot 10^{13}$ n/cm^{2}s (central thimble).

Highest gamma dose rate is 1.03 MGy/h (central thimble).

Neutron Facilities

- Central Channel (1 location): $\Phi_{th} \cong 3 \cdot 10^{13}$ n cm^{-2} s^{-1}
- Rotating drum (40 locations) : $\Phi_{th} \cong 2 \cdot 10^{12}$ n cm^{-2} s^{-1}
- Rabbit (1 location): $\Phi_{th} \cong 1.3 \cdot 10^{13}$ n cm^{-2} s^{-1}
- Thermal column neutron collimator: $\Phi_{th} \cong 5.0 \cdot 10^{6}$ n cm^{-2} s^{-1}
- Tangential channel neutron collimator: $\Phi_{th} \cong 1.0 \cdot 10^{8}$ n cm^{-2} s^{-1}

Cadmio ratio $\cong 3$

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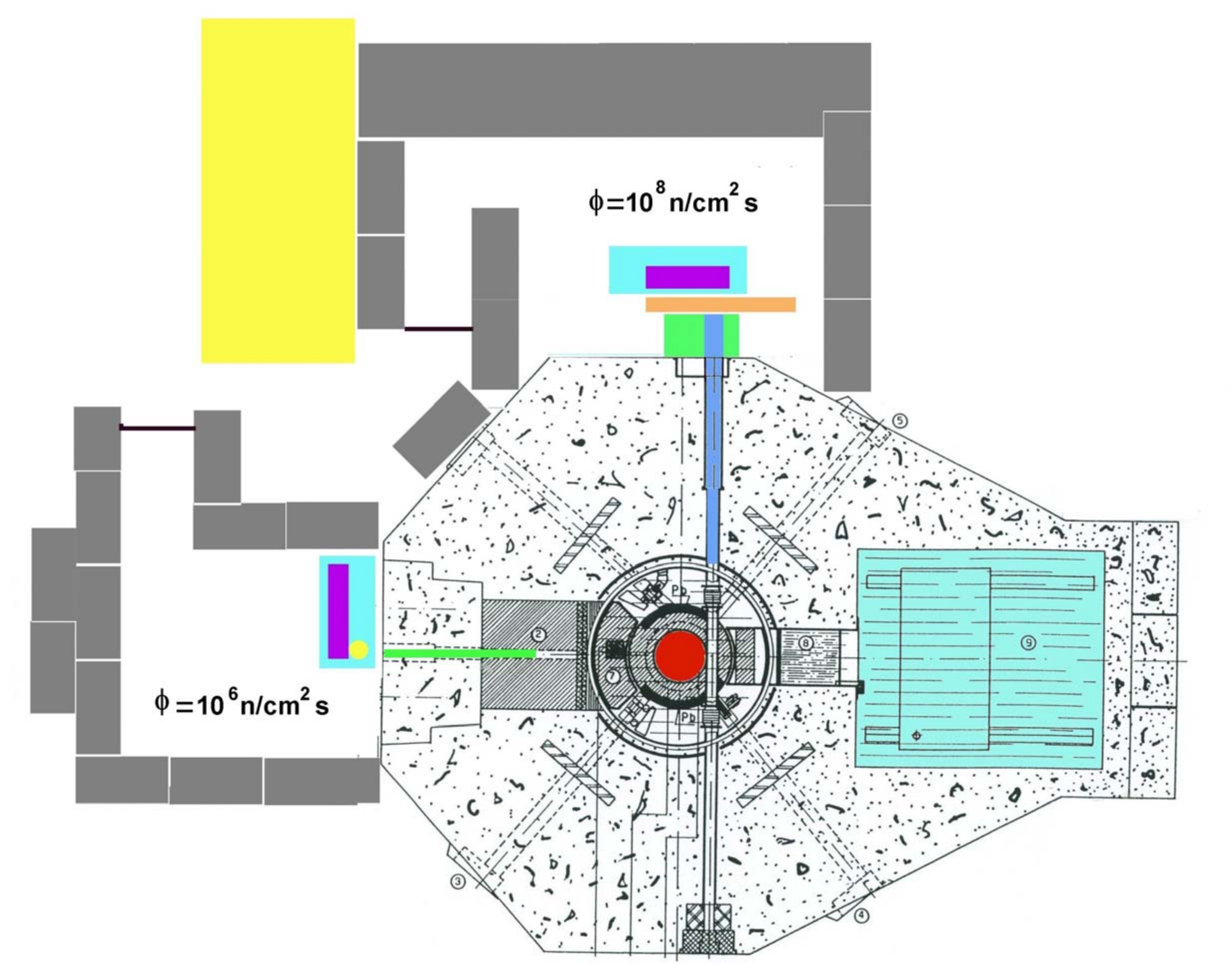

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Conclusions

There are two major types of radiation damage for silicon devices working in hostile radiation environments:

Surface effects due to such phenomena as charge trapping at oxide interfaces

the important parameter is the ionization, quantified in the Si radiation dose

Bulk damage due to displacement of ions

it can be correlated with the non-ionizing energy loss, which scales differently with energy and particle type than does the radiation dose

To establish the ionising dose or the particle fluence that a device can tolerate

RADIATION DAMAGE TESTS with β^-, γ-rays and heavy particles (n, Ar, Kr, C).

As previously described, at our RC Casaccia it is possible to perform the electronic device qualification under γ & n irradiations.