Overview of Dosimetry and its Applications

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Outline

- Introduction-What is it Dosimetry?
- Medical Dosimetry-Applications
  - Dosimetry in radiation therapy
  - Internal dosimetry
  - Dosimetry in radiology
- Radiation Protection Dosimetry-Applications
  - Dosimetry in mixed fields (accelerators, avionic, space)
  - Biological dosimetry
  - Microdosimetry
  - Nanodosimetry
  - Simulation dosimetry

What is it dosimetry?

- **Dosimetry is the determination of the delivery of energy to matter**
- Radiation dose (absorbed dose)has a specific meaning which is connected to the absorbed energy per unit mass, Gy
- Dosimetry is possible only if one knows relation between the dosimetric quantity and measurable quantities (e.g. spectra and composition of radiation field)
- Ionizing energy impartation can be described as stochastic or deterministic quantity depends on object size and time delivery (e.g.energy delivered to kidney is deterministic while to the cell in a kidney is probabilistic)

Why do we need dosimetry?

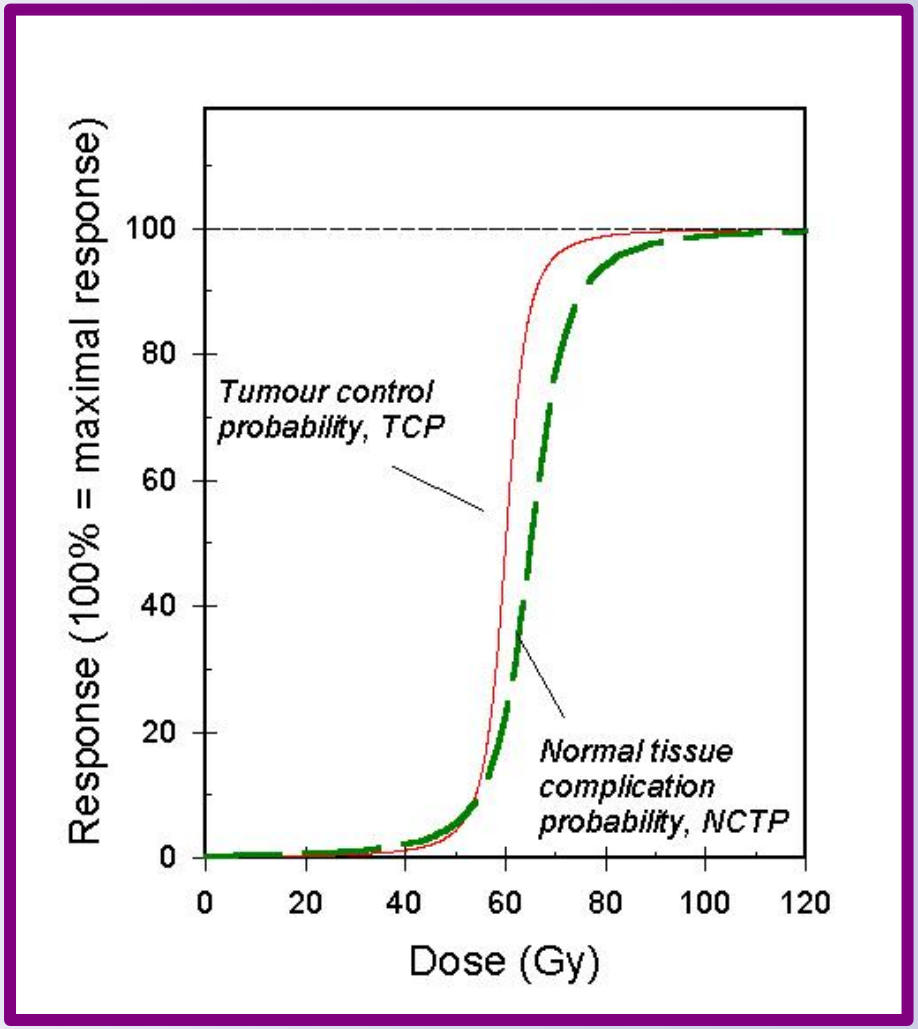
Radiation Protection Goals: NCRP Report No. 116

1. prevent the occurrence of clinically significant radiation-induced deterministic effects by adhering to dose limits that are below the apparent threshold levels; and

2. limit the risk of stochastic effects, cancer and genetic effects, to a reasonable level in relation to societal needs, values, benefits gained and economic factors

Required dose uncertainty in radiotherapy

- Depends on steepness of the dose response curve
- 5% difference in dose make a 15% difference in tumour control probability in head and neck patients - this is clinically detectable



Dose should be accurate

- To target:
  - 5% too low - may result in clinically detectable reduction in tumour control (eg. Head and neck cancer: 15%)
- To normal tissues:
  - 5% too high - significant increase in normal tissue complication probability = morbidity = unacceptable side effects

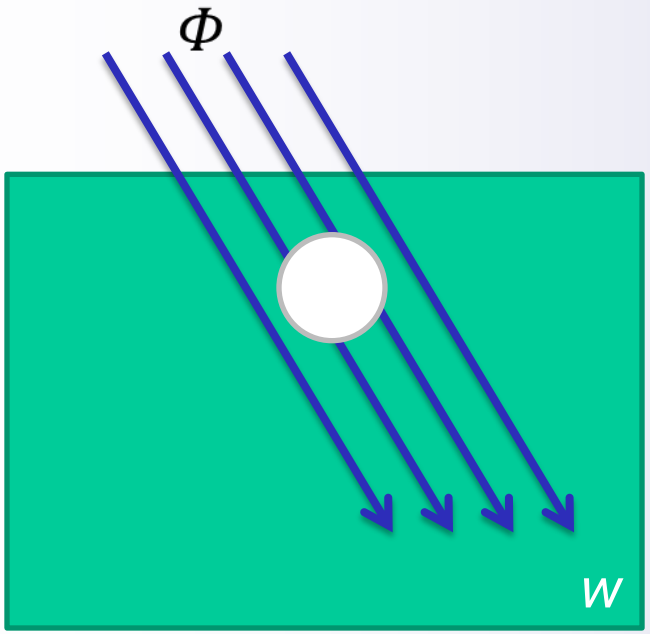
Delivery of dose within +/-5%

- Sources of uncertainty:
  - Absolute dosimetry/calibration
  - Relative dosimetry (%depth dose, profiles, output factors)
  - Treatment planning (estimated uncertainty of the order of +/- 2%)
  - Machine performance on the day (+/- 2%)
  - Patient set-up and movement (+/- 3%)

Not much room for error in dosimetry...

Bragg-Gray Cavity Theory

For a sufficiently small cavity *g*, within a different medium w and incident flux Φ, the dose to the water, D_w may be determined through use of the mean mass-stopping power ratio:



$$D_g = \left(\frac{dT}{\rho dx}\right)_g \quad \text{and} \quad D_w = \left(\frac{dT}{\rho dx}\right)_w$$

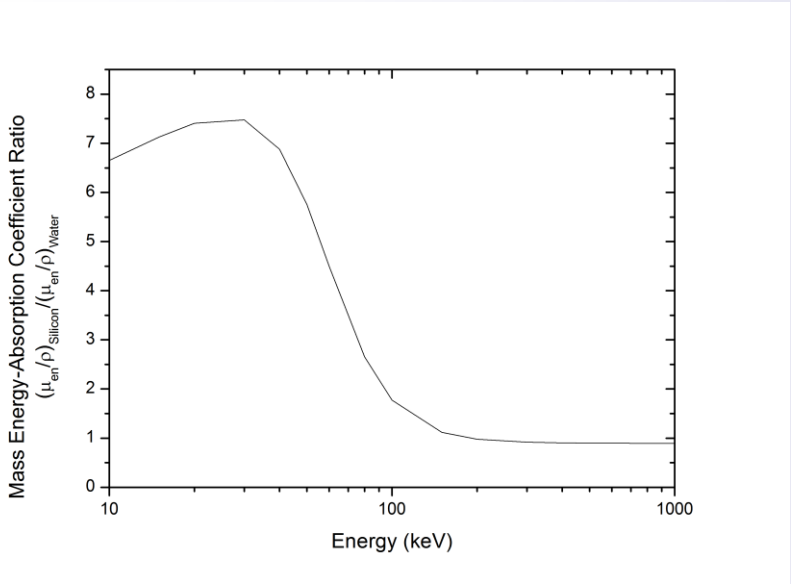
$${}_m\bar{S}_x = \frac{1}{\Phi}\int_0^{T_{\max}} \Phi \left(\frac{dT}{\rho dx}\right)_x dT = \frac{D_x}{\Phi}$$

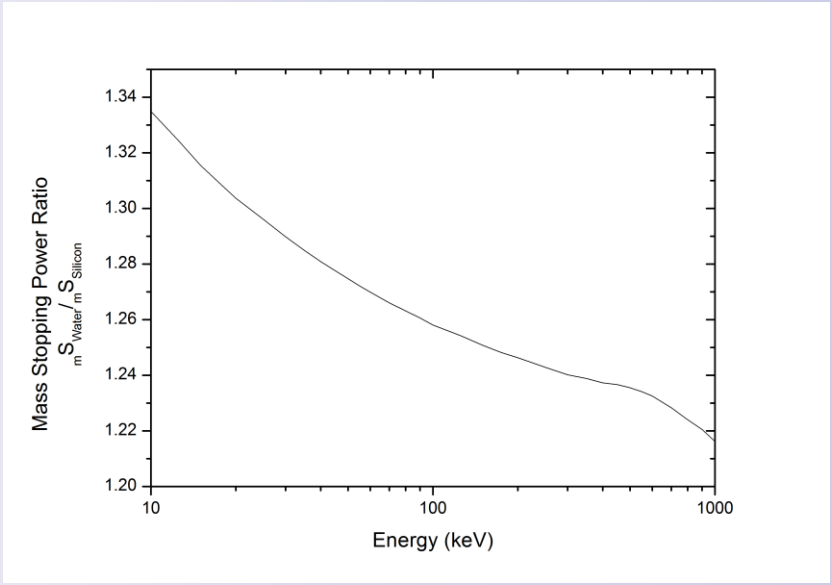
For transient charged particle equilibrium:

$$\frac{D_w}{D_g} = \frac{{}_m\bar{S}_w}{{}_m\bar{S}_g} \equiv {}_m\bar{S}_g^w$$

$$\therefore \boldsymbol{D_w = D_g \cdot {}_m\bar{S}_g^w}$$

Dosimetric Ratios of Silicon-to-Water





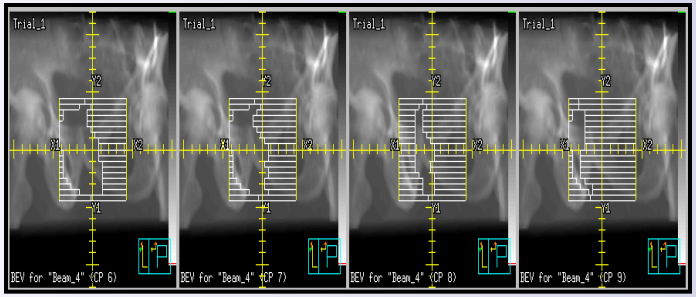
Mass-Energy Absorption Coefficient Ratio for Silicon to Water

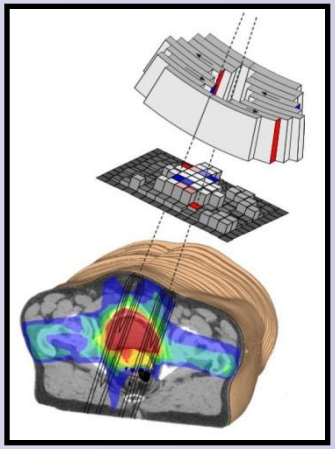
Mass Stopping Power Ratio for Silicon to Water

- The energy response of Si detector which is satisfying B-G cavity theory and placed in water will be relatively flat in a wide energy range
- Silicon is not water equivalent in free air geometry or in case of a range of secondary electrons in Si is smaller than Si cavity

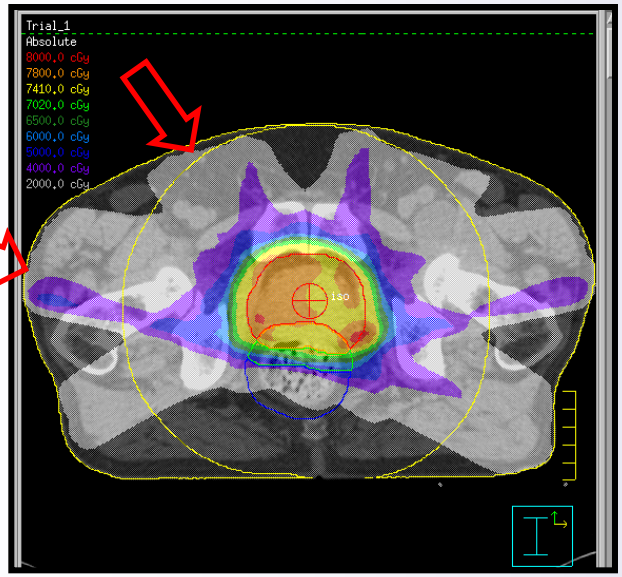
Static Gantry Modulation

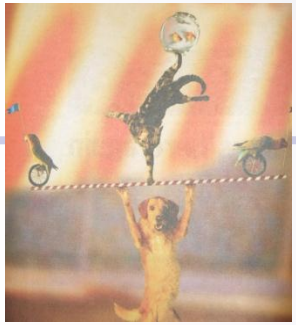
- "Static gantry modulation"
- (sg-IMRT)





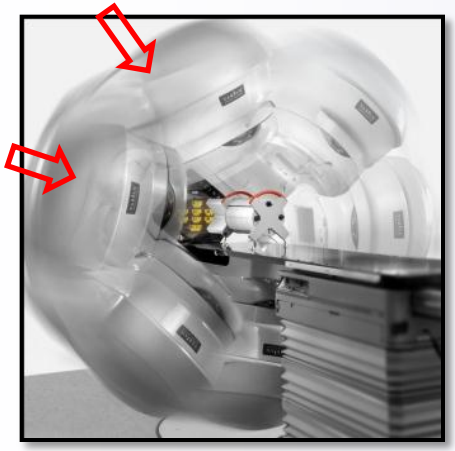
Courtesy Ahnesjo PMB 06



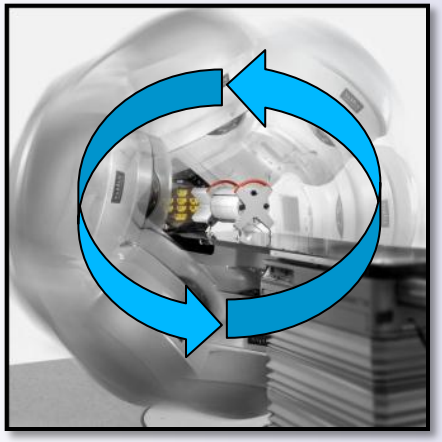


Arc Gantry Modulation

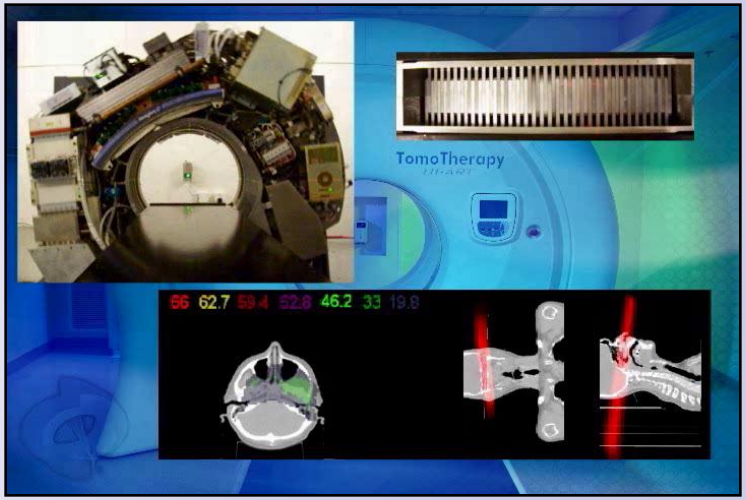
Static gantry-IMRT



VMAT

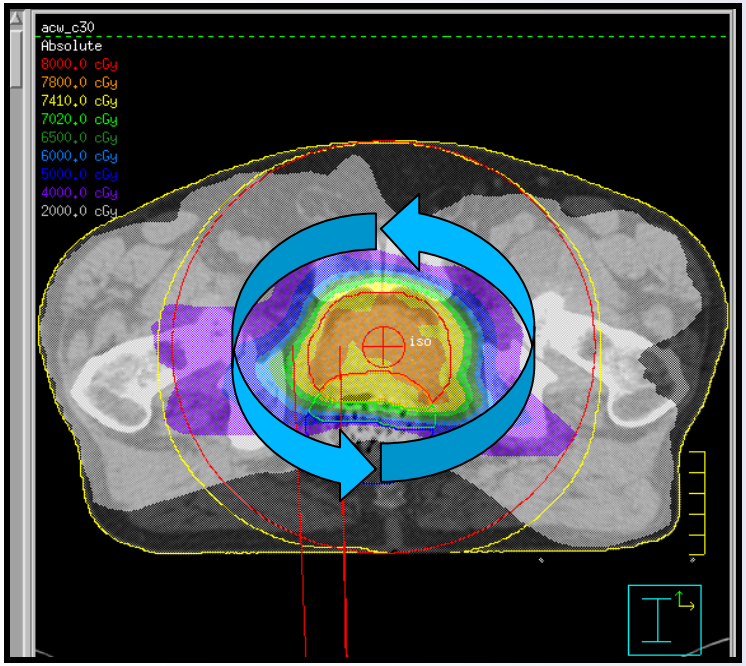


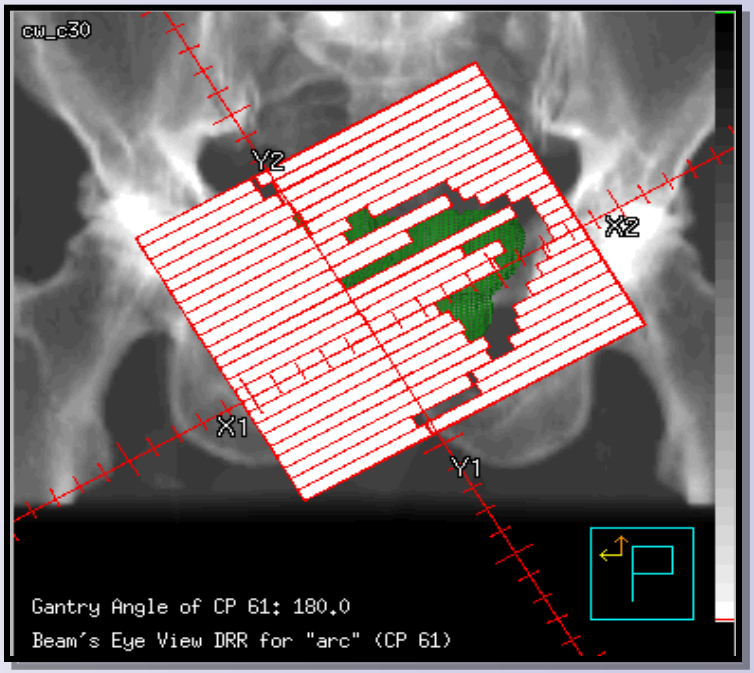
Tomotherapy



Arc Gantry Modulation

- Arc Gantry Modulation
- “Volumetric Modulated Arc Therapy”
- (VMAT)



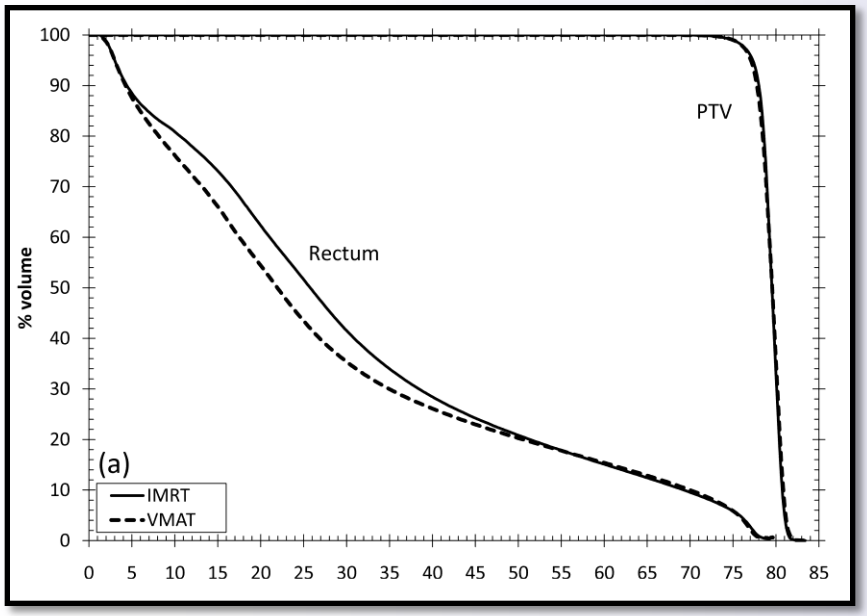


Beams Eye View

Plan Comparisons

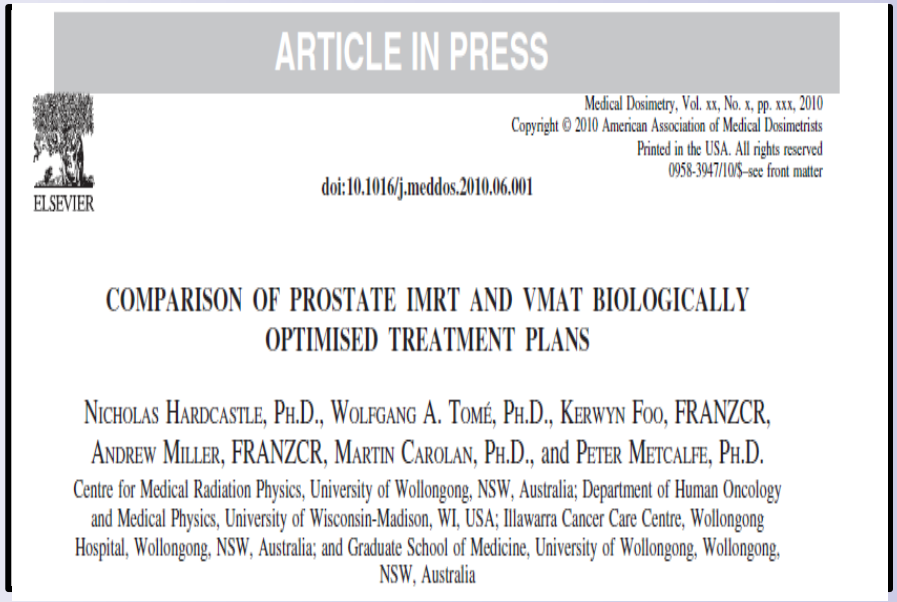
- Arc modulation vs static gantry modulation

Dose Volume Histogram



Dose (Gy)

Normal Tissue Complication



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COMPARISON OF PROSTATE IMRT AND VMAT BIOLOGICALLY OPTIMISED TREATMENT PLANS

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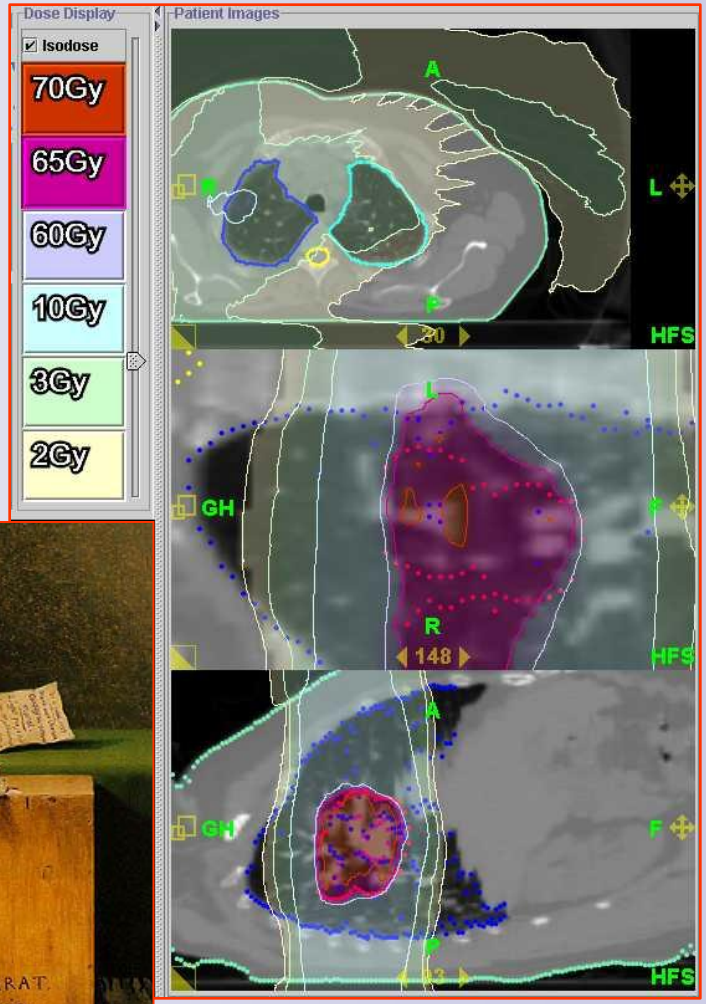
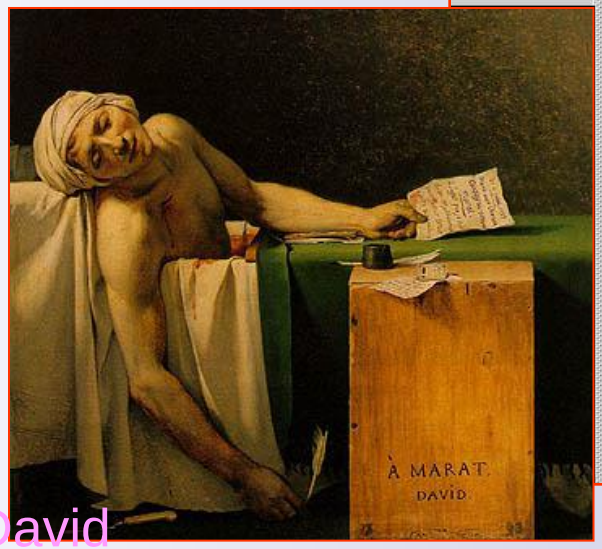
*average over 10 patients

The dose bath...

- Due to increased MU per Gray there is more leakage
- Due to more beams dose is spread through larger volume
- Out of field dosimetry is important



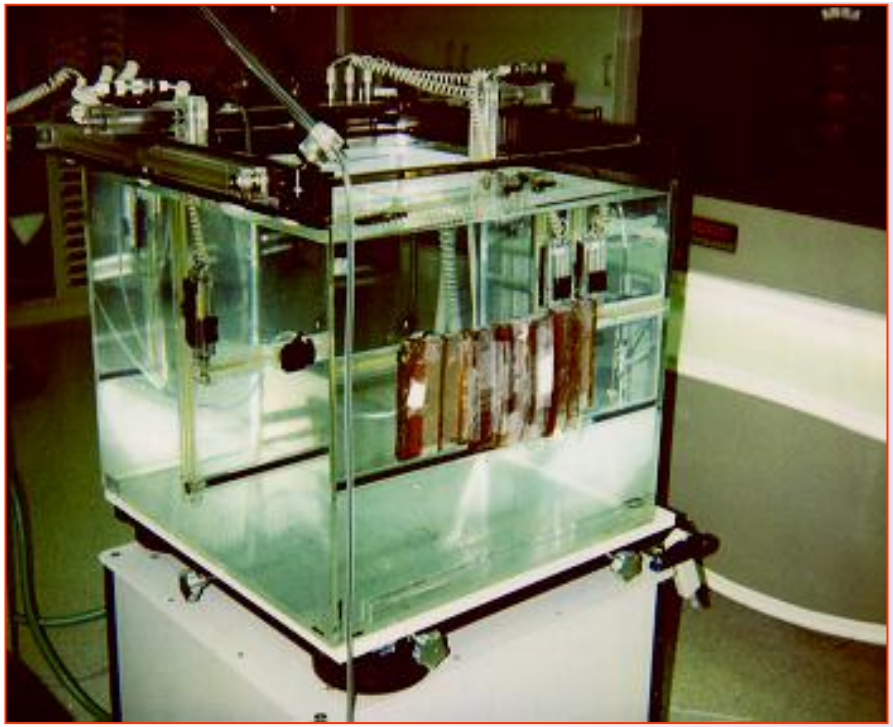


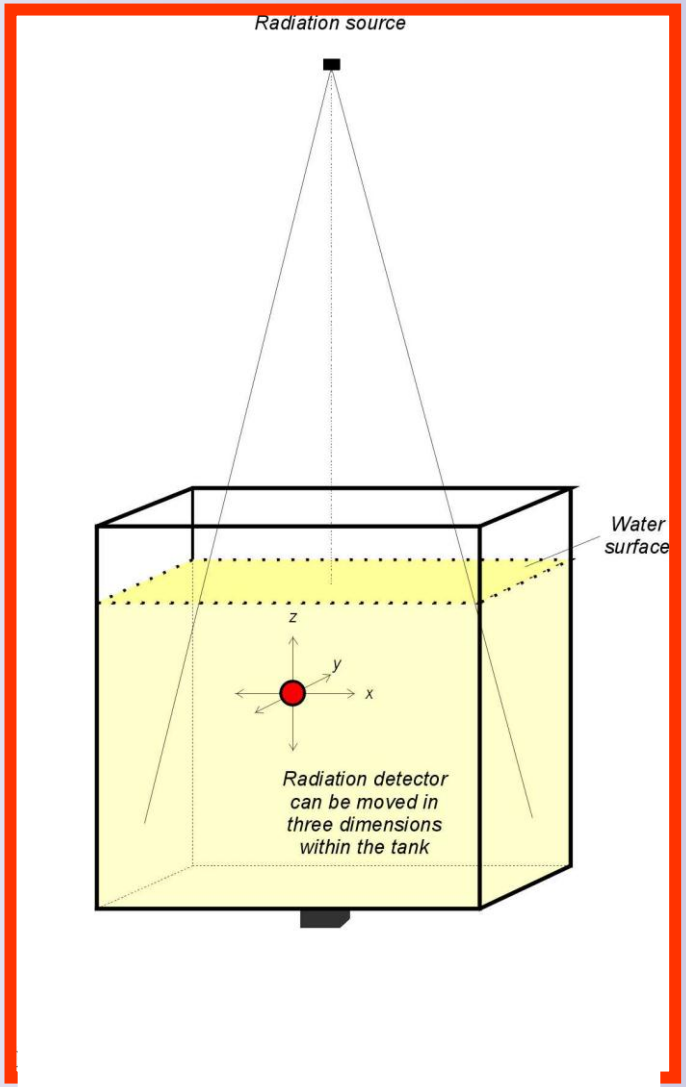
David

The dosimetric environment:

- Phantoms:
  - A phantom represents the radiation properties of the patient and allows the introduction of a radiation detector into this environment, a task that would be difficult in a real patient.
  - A very important example is the scanning water phantom.
  - Alternatively, the phantom can be made of slabs of tissue mimicking material or even shaped as a human body.

Scanning water phantom





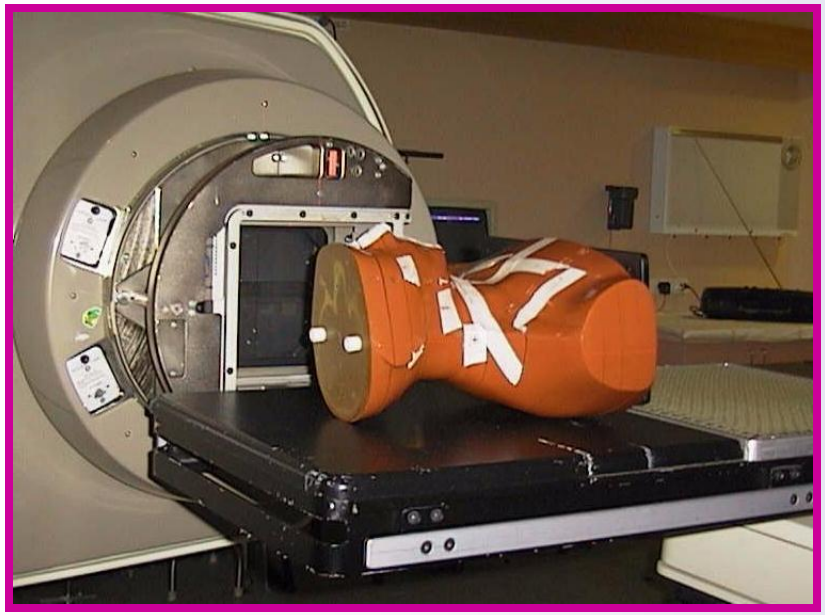
Slab Solid Water phantom

Tissue equivalent materials

- Many specifically manufacturer materials such as solid water (previous slide), white water, plastic water, …
- Polystyrene (good for megavoltage beams, not ideal for low energy photons)
- Perspex (other names: PMMA, plexiglass) - tissue equivalent (TE) composition, but with higher physical density - correction is necessary.

TE for X-ray not necessary TE for other radiation fields

Anthropomorphic phantom

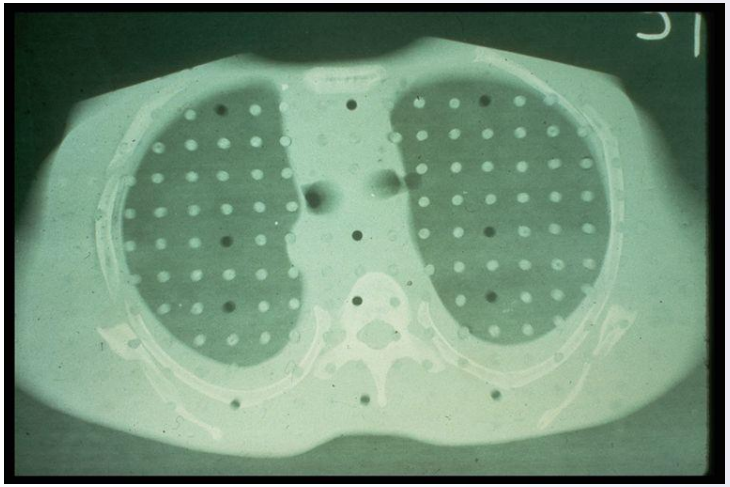


Whole body phantom: ART

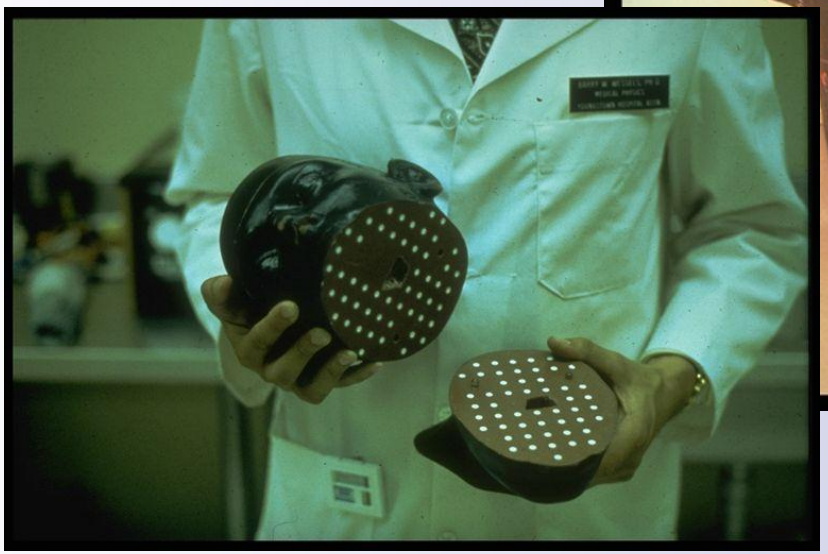
Allows placement of radiation detectors in the phantom

Includes inhomogeneities

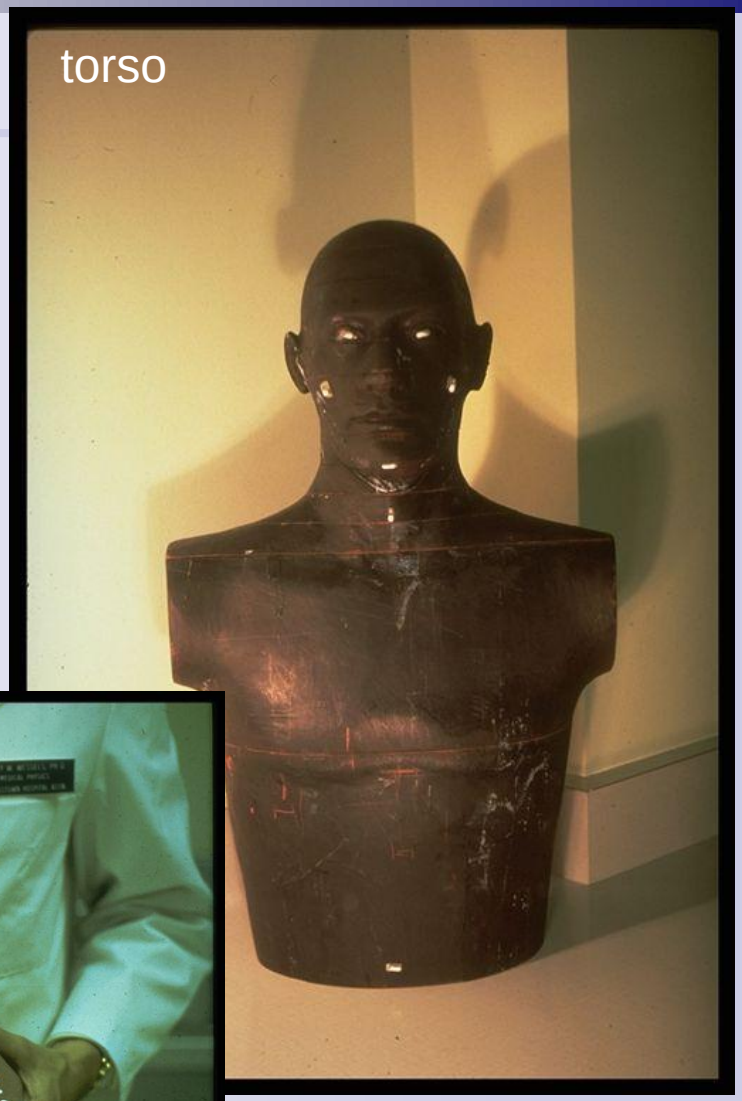
RANDO phantom



CT slice
through lung

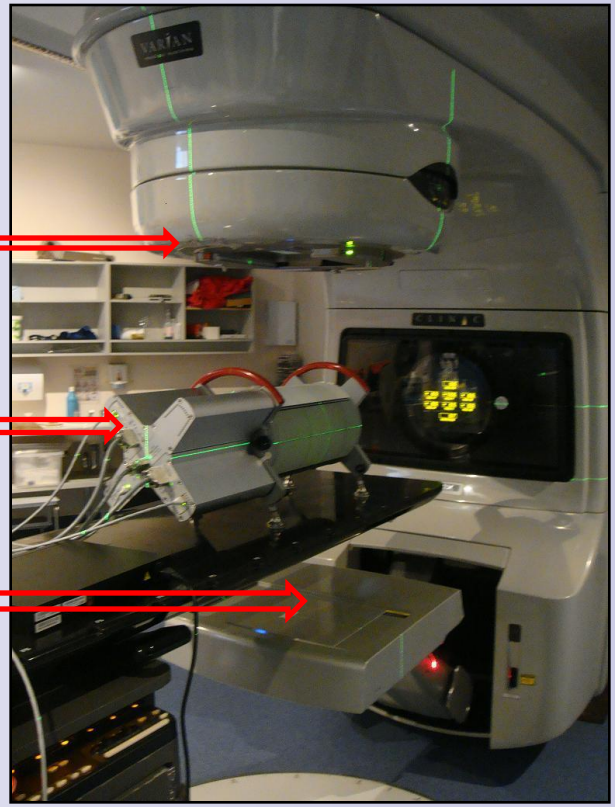


Head with
TLD holes



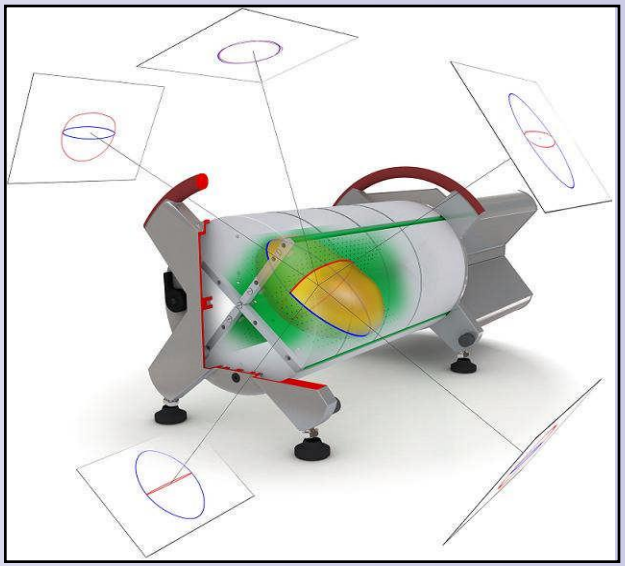
Physics Dosimetry Options for QA

- Fluence array detector
  - Magic Plate (CMRP)
- Phantom on couch
  -2D diode array (Delta4)
- Exit detector – e.g. EPID



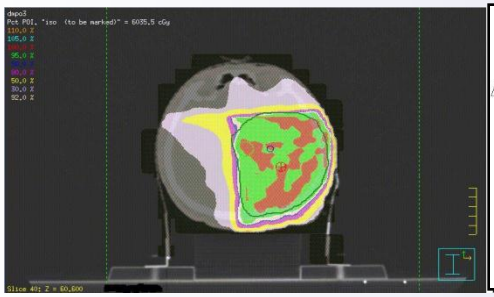
Dosimetry Media- Delta^4

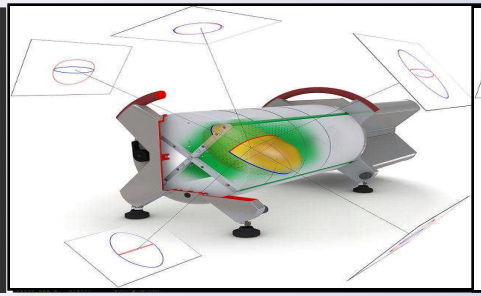
- 2D diode array 1069 detectors
- Angle offset 90 degree
- Detector spatial resolution 1mm
- Diode separation 5mm, 10mm
- Acrylic Phantom 20cm Cylinder

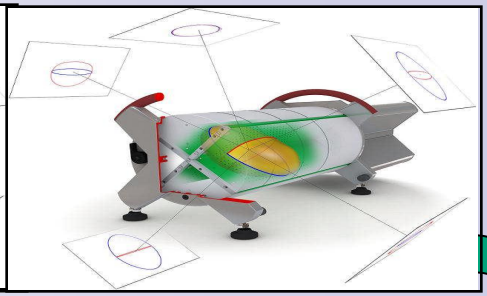


Physics Dosimetry Process

- Deemed requirement for all “modulation” methods
- These checks not required for conformal (3DCRT)
- Research question what does Delta^4 bring to... party?

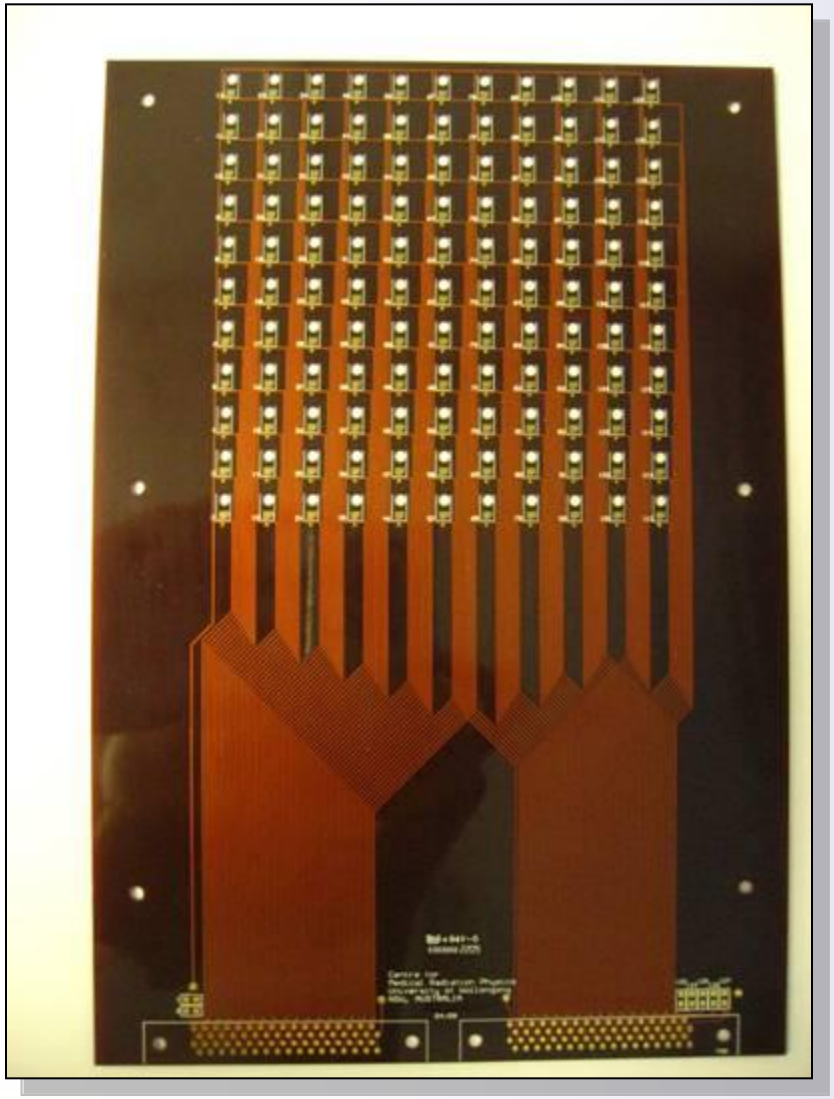






Treat

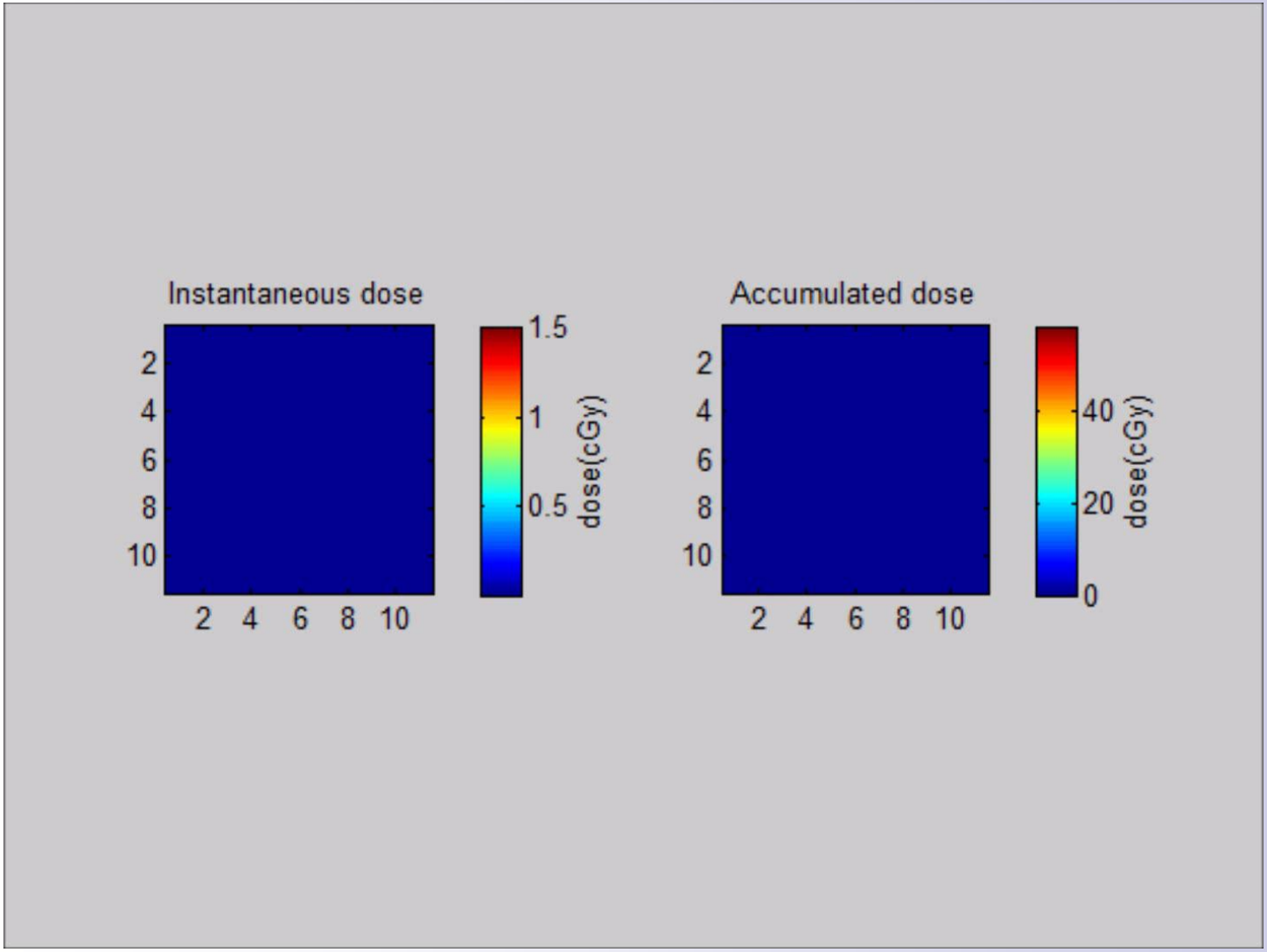
Magic Plate (MP)



- Two dimensional 11 x 11 cm Si diode array
- 50 μm thick Si
- Area: 0.5 x 0.5 mm^2
- Pitch 1 cm and 0.5cm

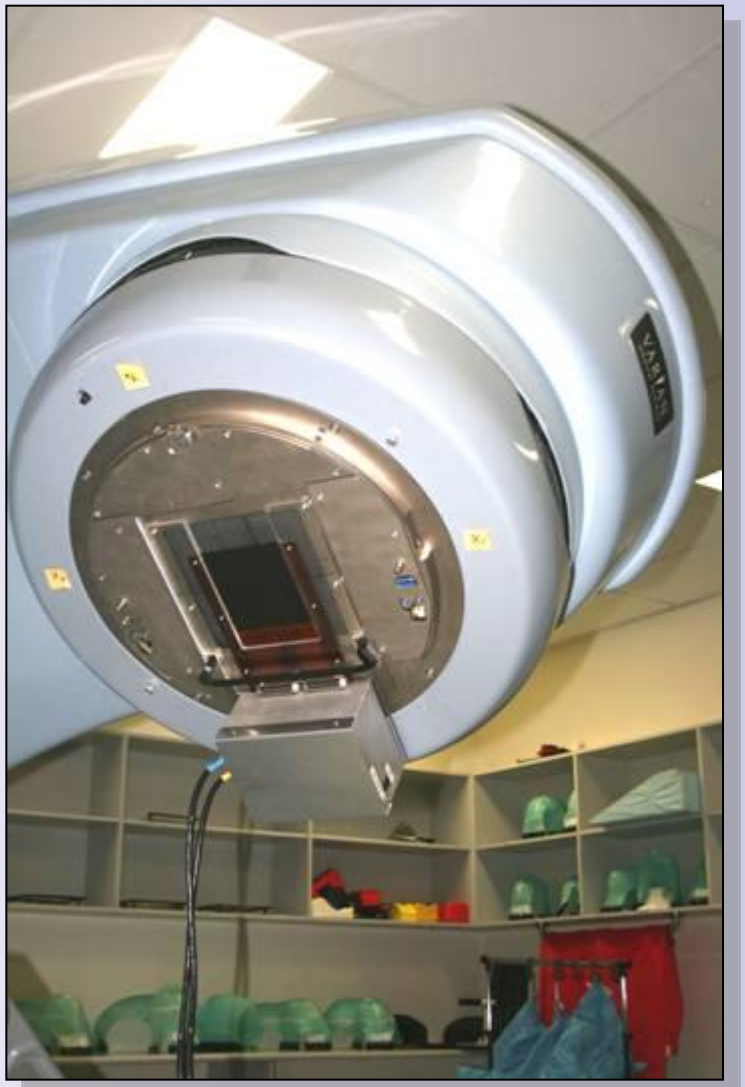
Transmission 99.8%

Real-time dose display

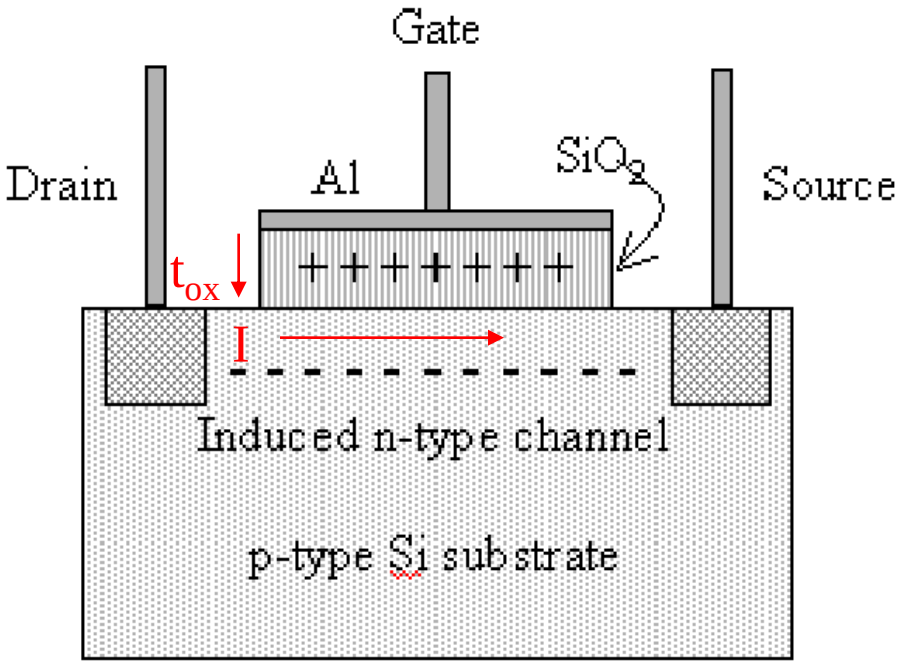


Magic Plate mounting on a Linac gantry

From in a phantom QA
to
In vivo real time fluence verification
in RapidArc RT and IMRT



Advanced MOSFET Dosimetry-Principle of Operation



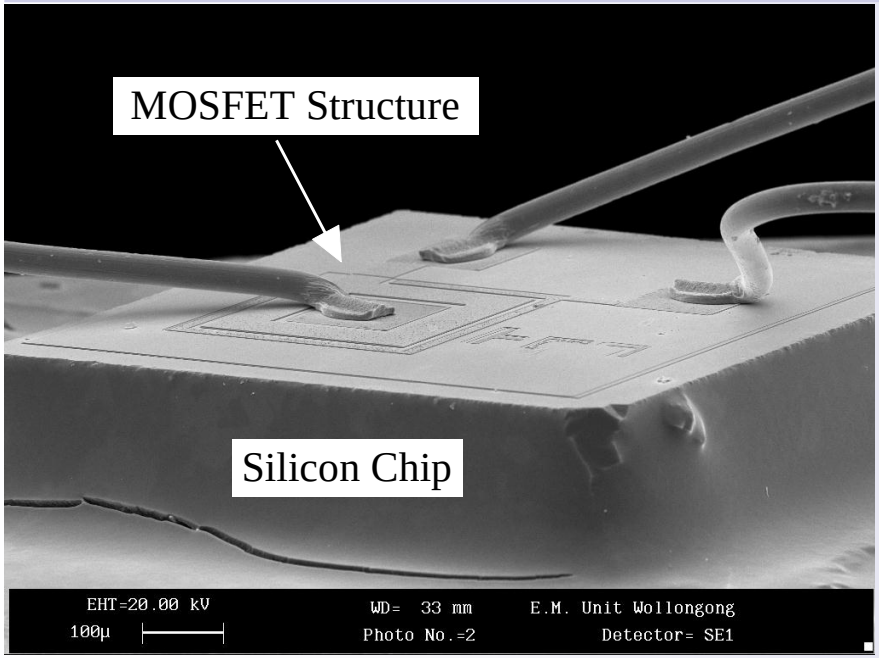
- Generation of electron-hole pairs in silicon oxide by ionizing radiation
- Trapping of holes on the SiO_2-Si interface
- Shift in the IV characteristics leading to a change in the threshold voltage under constant channel current

Passive mode - $\Delta V_{th} \sim 0.0022\ D^{0.4}\ t_{ox}^{2}\ f$

Active mode - $\Delta V_{th} \sim 0.04\ D\ t_{ox}^{2}\ f$

Active mode has a positive bias on the gate during operation

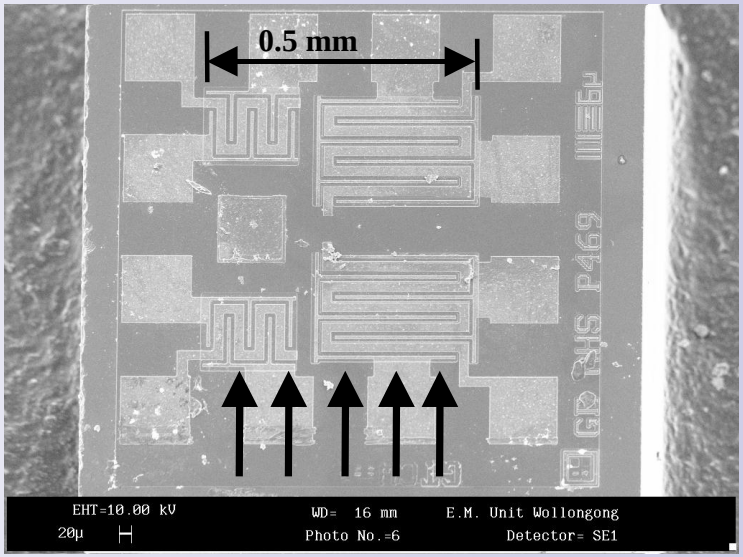
MOSFET Chips



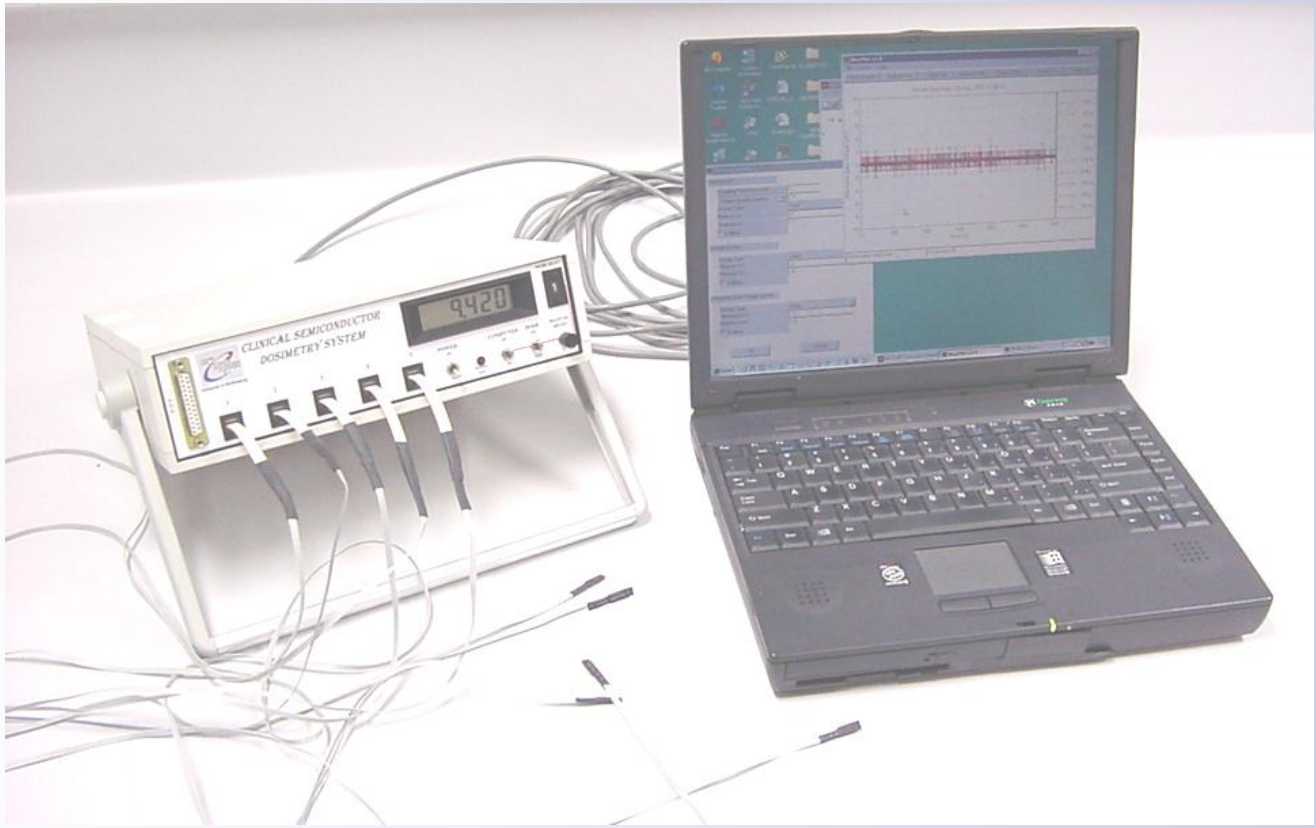
Single CMRP MOSFET detector

Advantage of MOSFET detectors-Extremely thin sensitive volume (<1mm)

Quadruple MOSFET detector RADFET REM Oxford



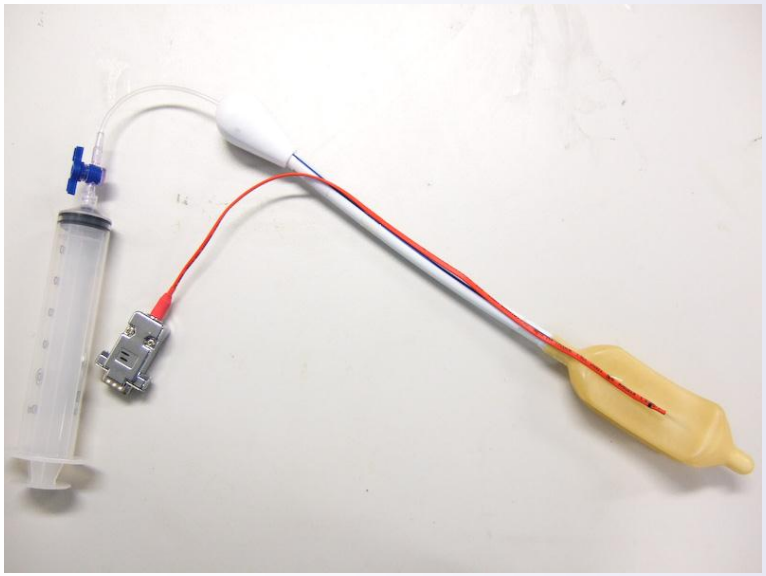
Online MOSFET Dosimetry System



MOSFET Clinical Dosimetry System with MOSPLOT DAQ: designed and distributed by CMRP

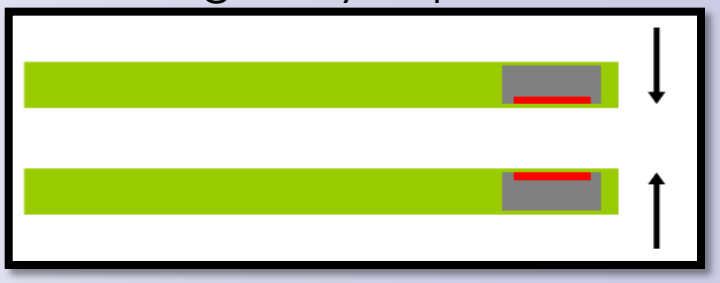
PDR Brachytherapy: Clinical Trials

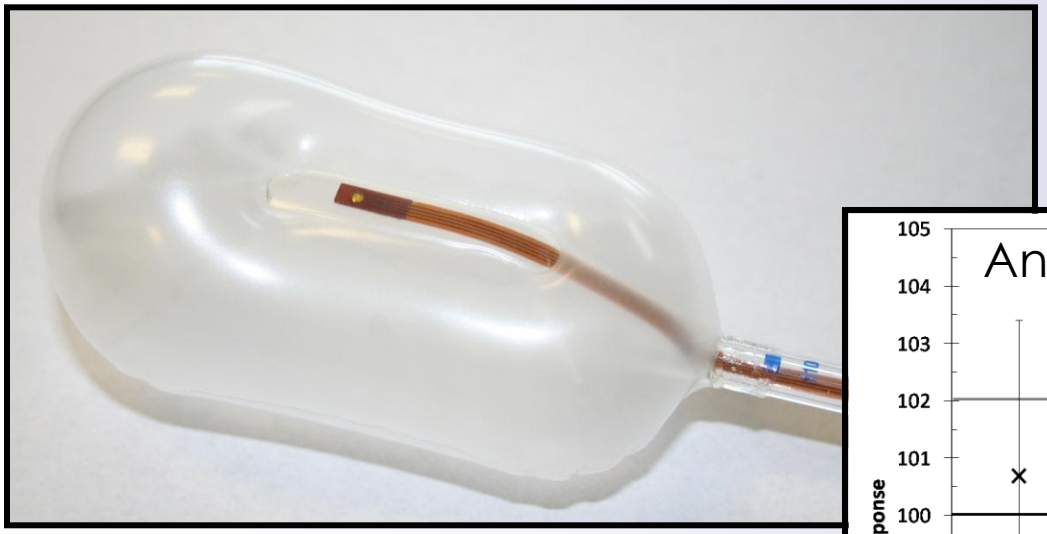
- Telesis 5 silicone adhesive is used to secure the MO*Skin* against the balloon.
- Two condoms are placed over the balloon before 60 ml of air is injected into the balloon.
- The trial has gained TGA approval.
- The MO*Skin* has earned sterilization approval, which encompasses all the materials used in the detector, the type of sterilization performed, and the handling procedures.

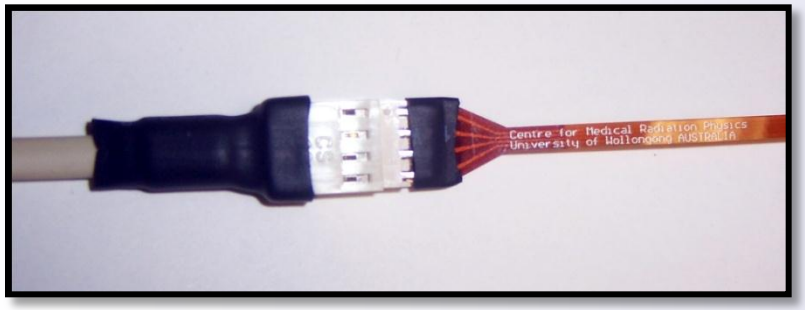


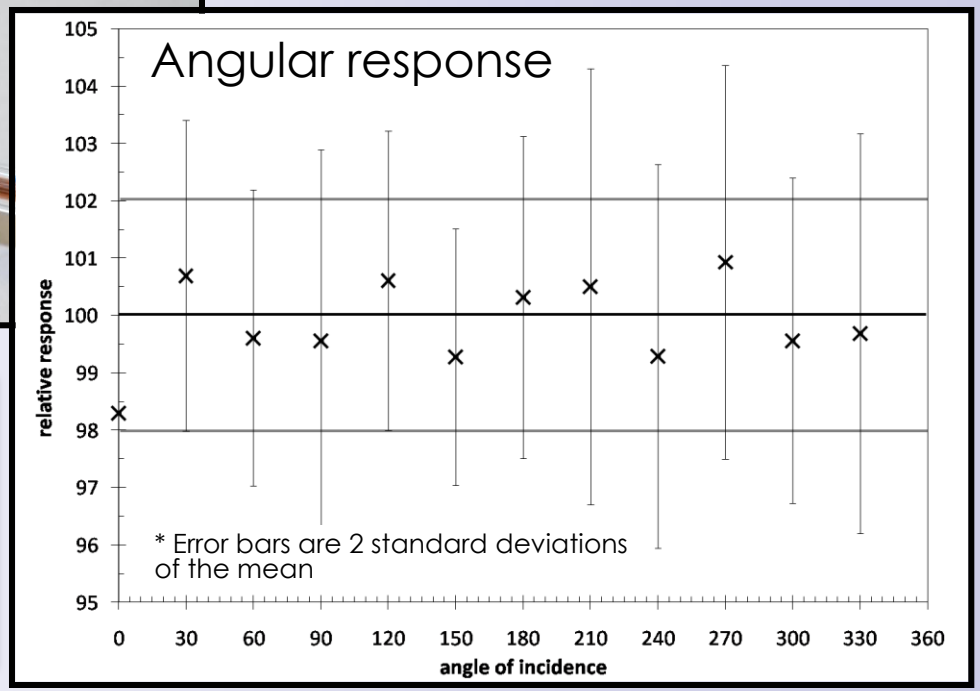
Dual MO*Skin* + rectal balloon

- The *MOSkinTM* Dosimeter angular response has been greatly improved through the use of a dual FET design



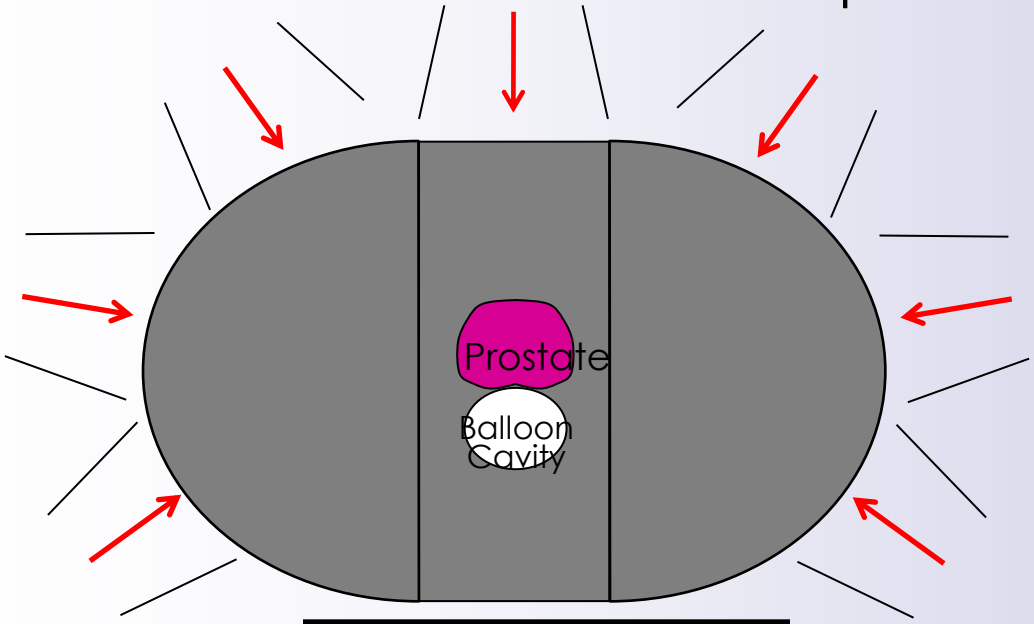


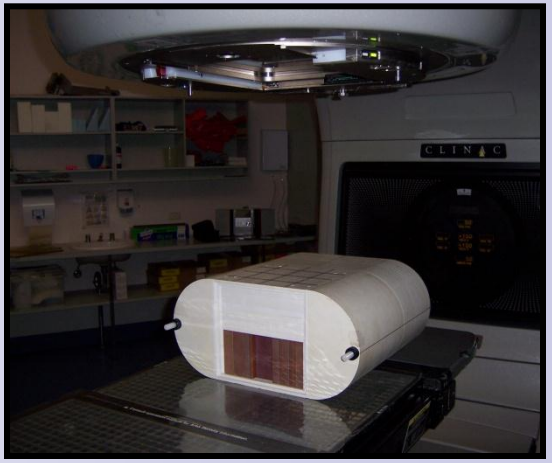


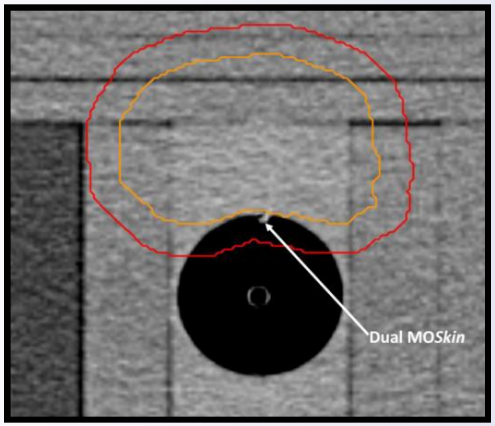


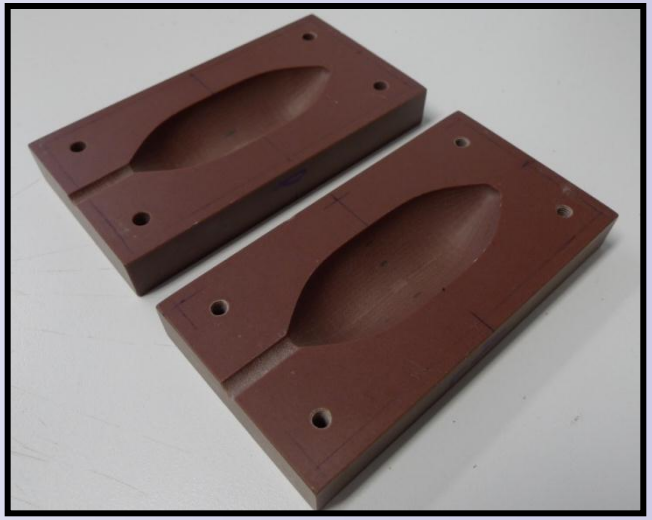
Real-time rectal wall dosimetry: dual *MOSkin*

- Seven field 3DCRT and IMRT plans:



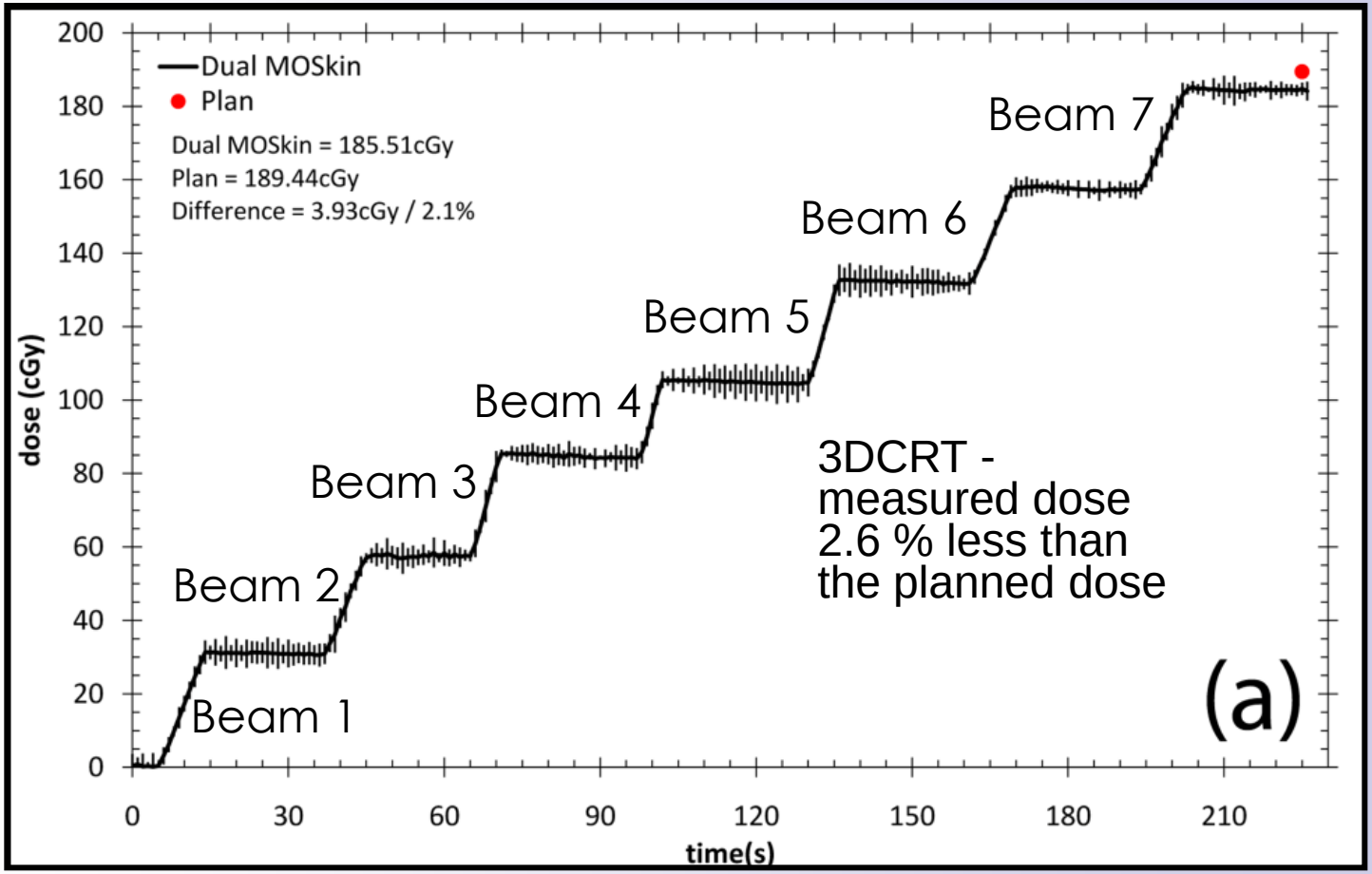






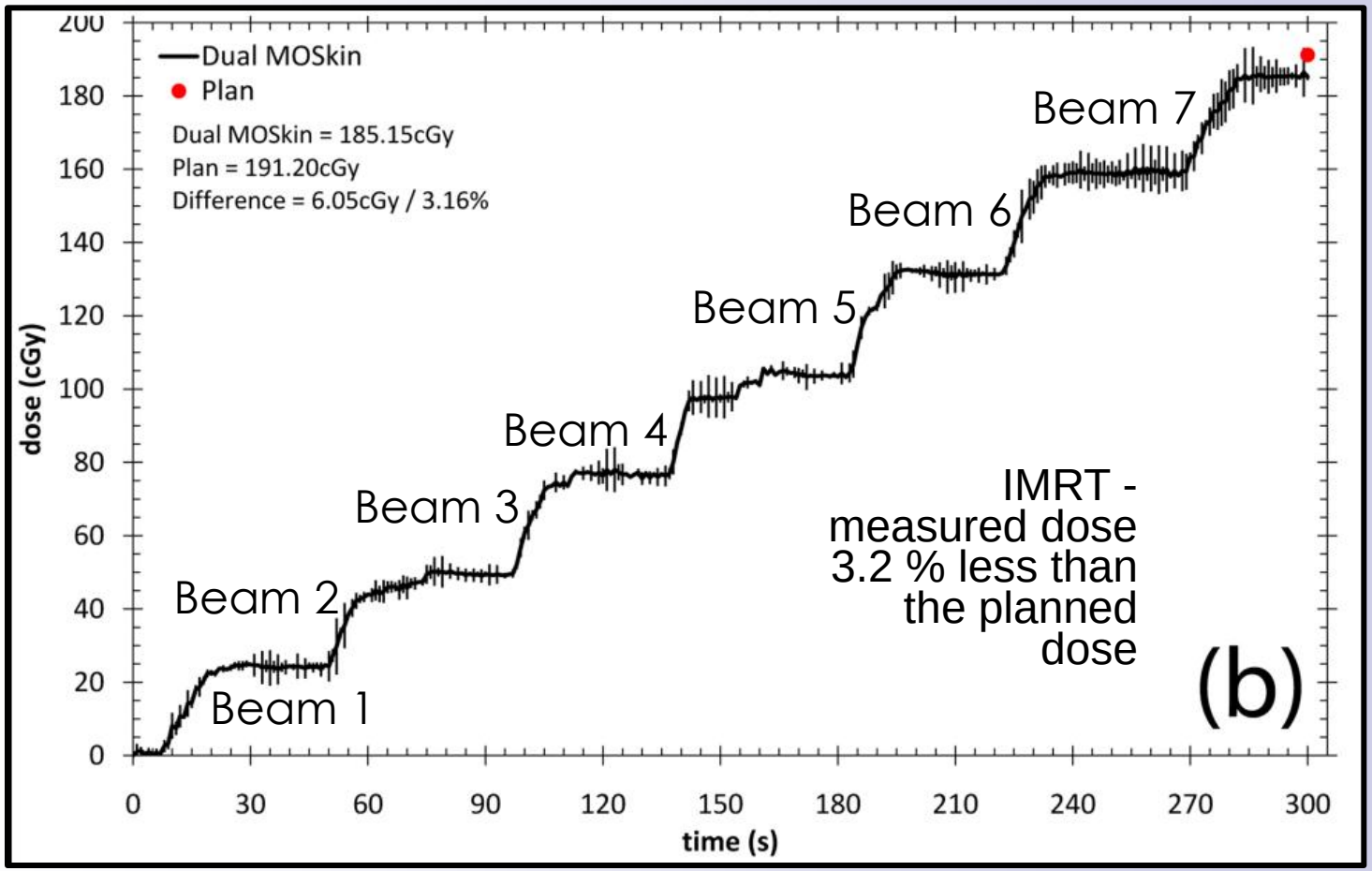
Dual MOSkin

- Seven field 3DCRT plan:



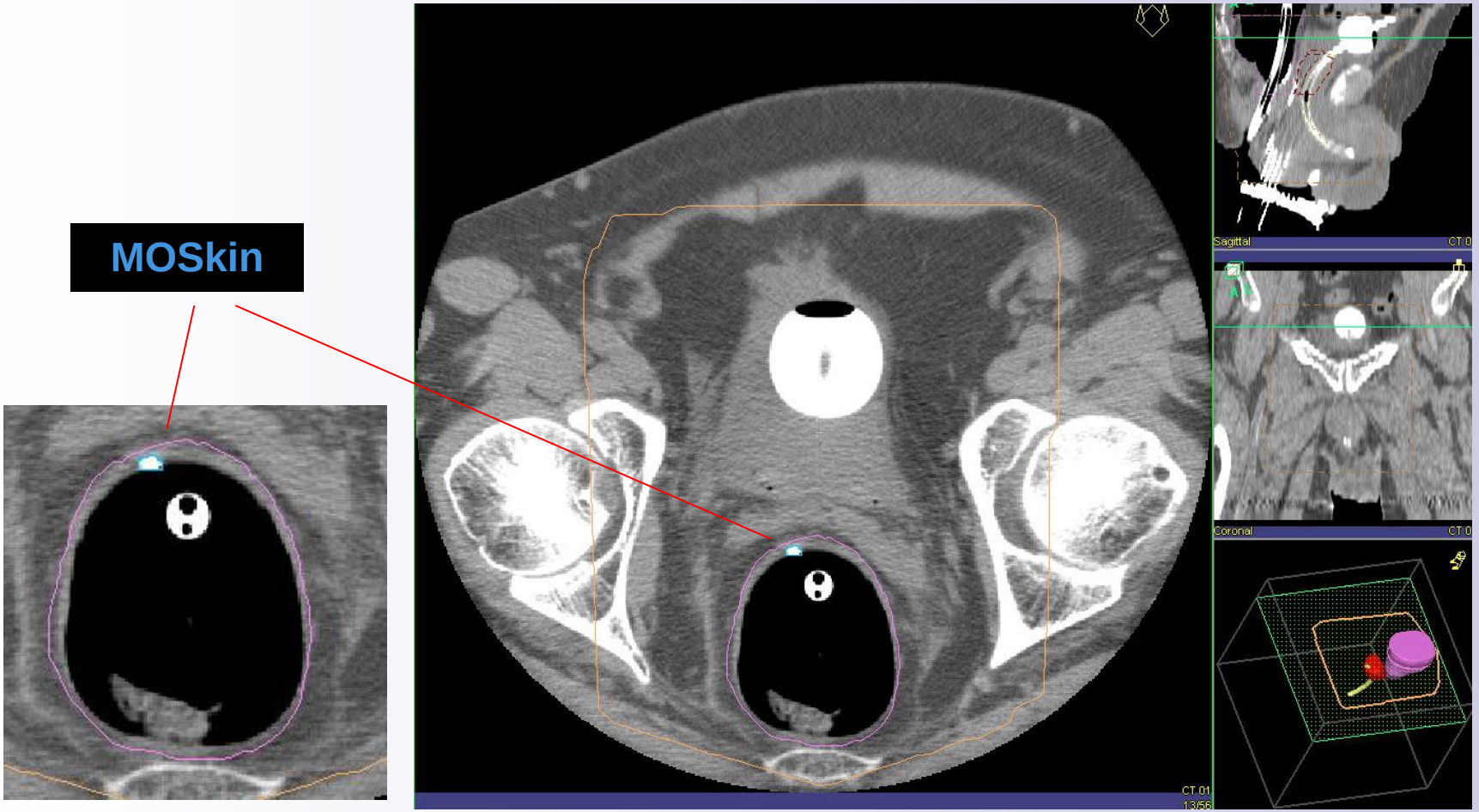
Dual MO*Skin* + rectal balloon

- Seven field IMRT (modulated delivery) plan:

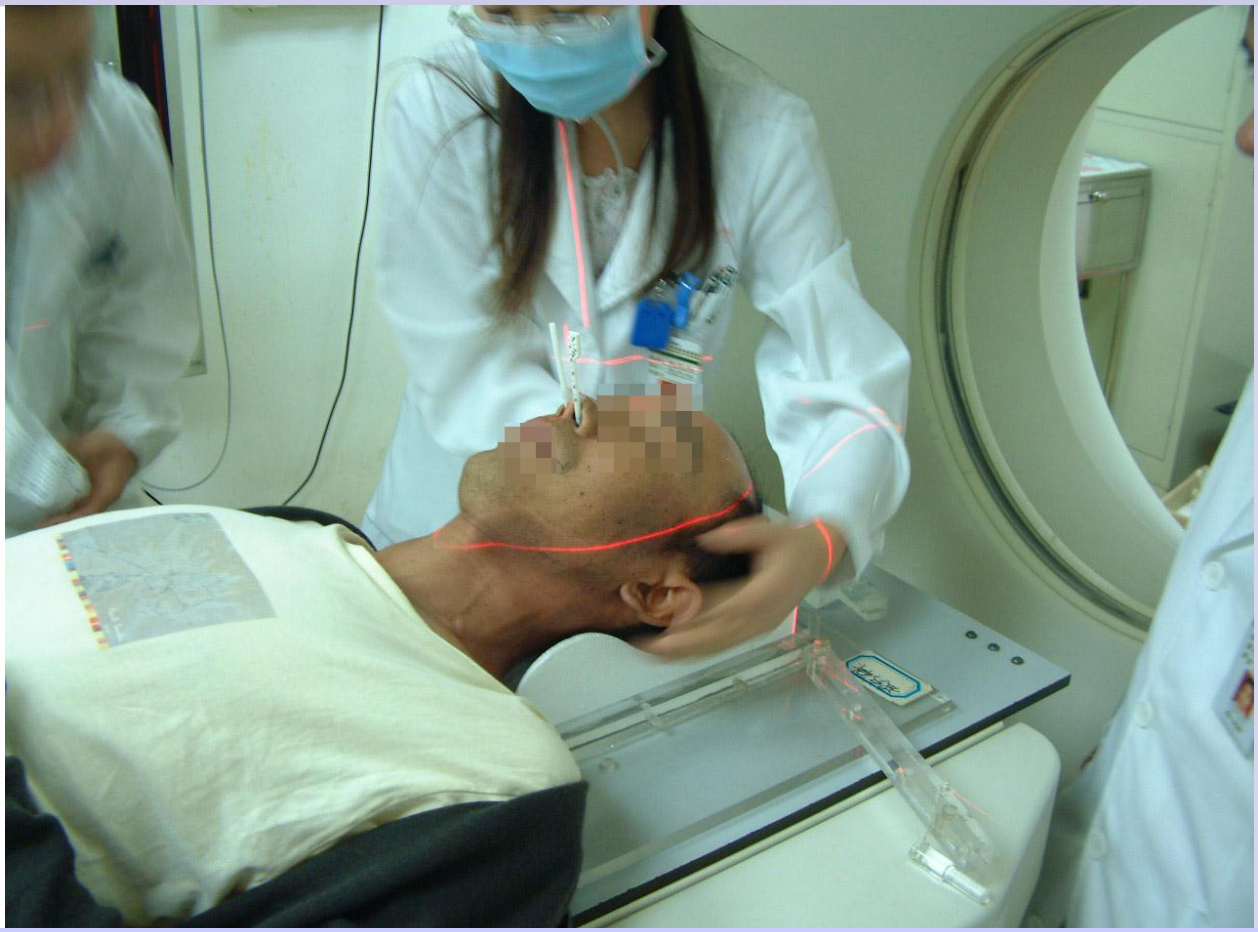


In vivo QA point dosimetry

Visualization of *MOSkin* using CT



QA in HDR for Nasopharyngeal Carcinoma

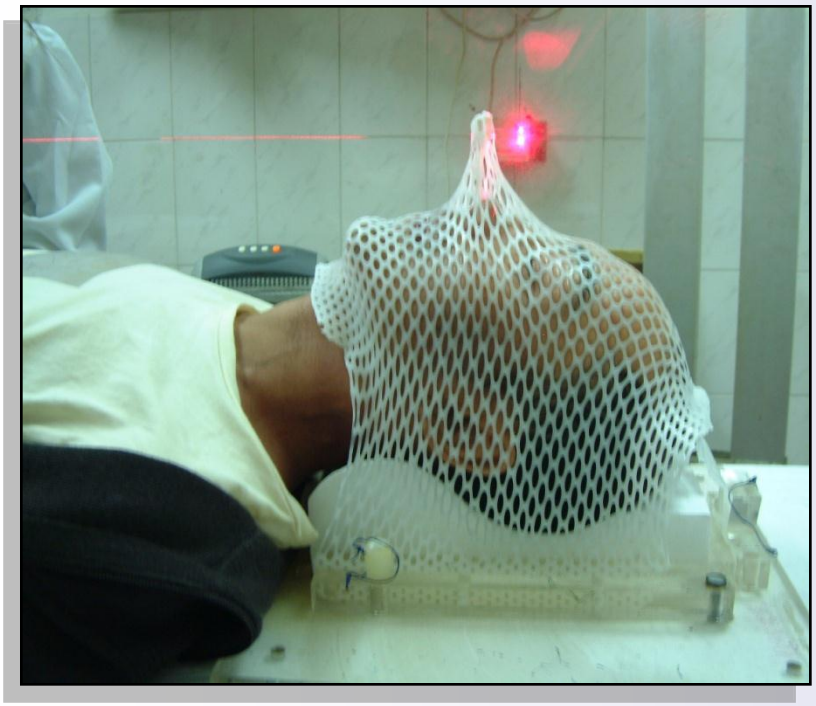


- MO*Skin* detectors are placed inside the left nostril whilst an Ir-192 source is stepped through the right nostril

QA in HDR for Nasopharyngeal Carcinoma

- A thermoplastic mask was used for patient immobilization and was also used to fix the applicator

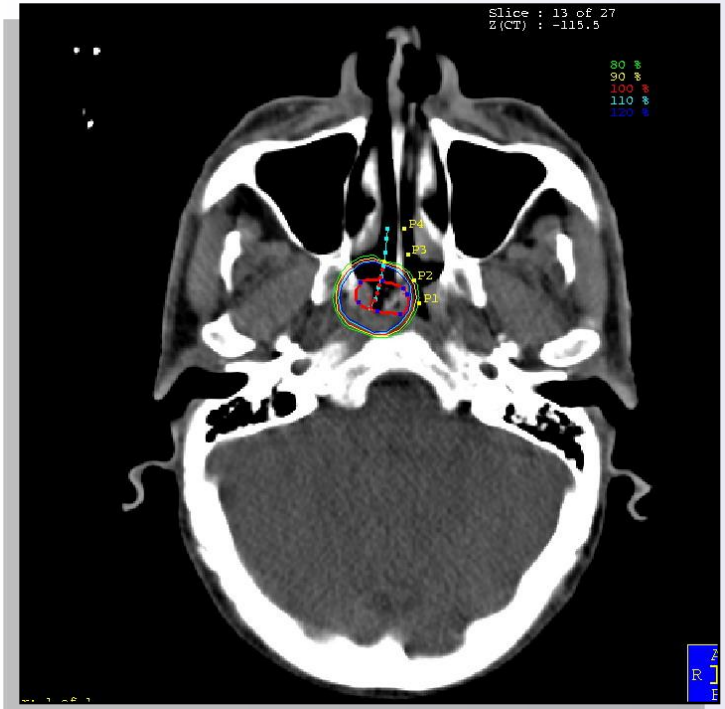
nasopharyngeal applicator



- A CT scan is used to identify the MOS*kin* detector locations
- *In vivo* real time dose measurements were performed using MOSkin detectors during treatment.

QA in HDR for Nasopharyngeal Carcinoma

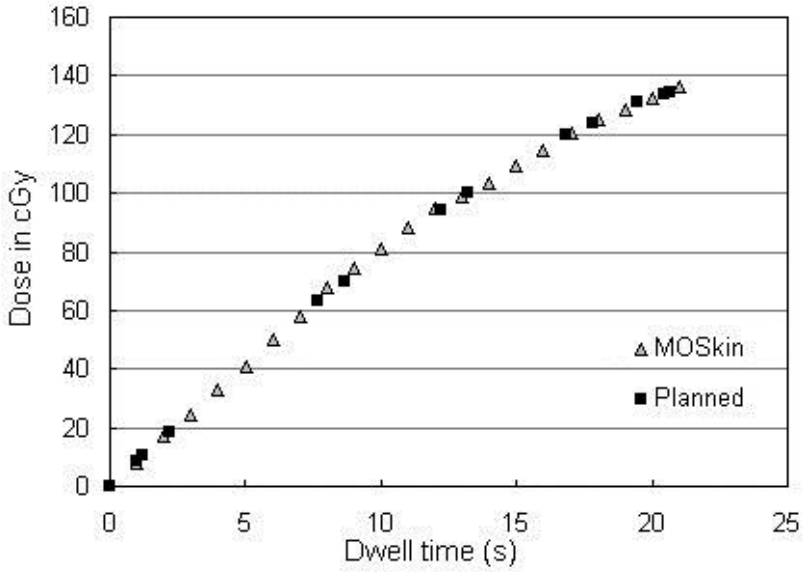
- CT images were acquired with the carriers inserted -- 3mm slice thickness.

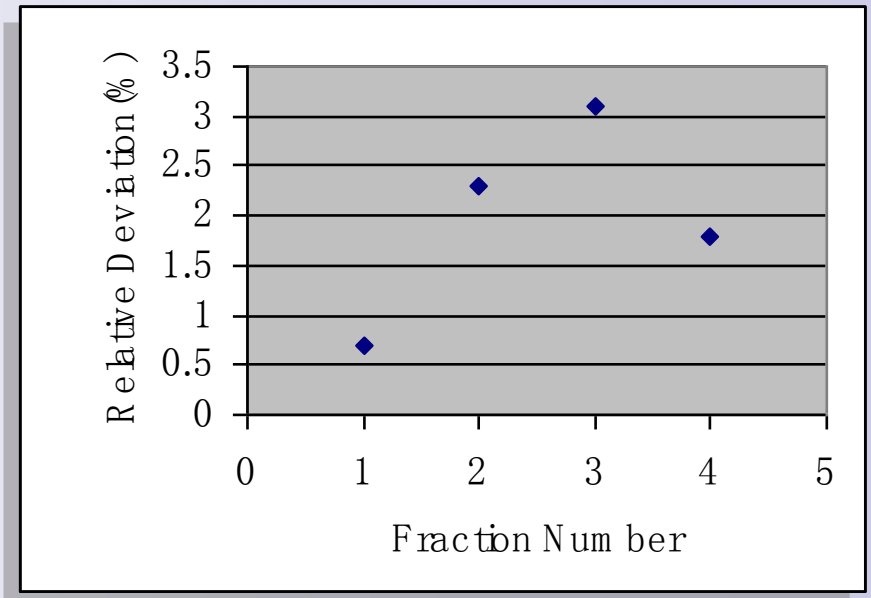


- Point P1 represents the location of the MOSkin, while P2, P3, and P4 are opaque markers. The Ir-192 source is inserted down the carrier and through the other nostril.

QA in HDR for Nasopharyngeal Carcinoma

- A total of 7 patients were measured using the *MOSkin* detector. The average deviation was within ±5% of the predicted dose, with the maximum deviation less than 10%.
- The relative deviation (%) of the measured doses from the treatment plan for four fractions is shown for one patient.





Real-time comparison of *in vivo* measurements with TPS in agreement within 5%

MOSkin: Dose verification in serial IMRT treatment (NPC)

Taste dysfunction and oral mucous reaction are major radiation sequel in NPC patients receiving radiotherapy.

Clinical trial is ongoing to explore the role of a molded oral plate in sparing the normal oral tissues by pushing tongue away from radiation field during radiotherapy for some NPC cases.

Total dose 68Gy, 30 fractions.

Real time measurements were carried out of surface dose on a tongue with 2 MOSkins placed on interface

tongue -plate, **MOSkin dose was readout each second during IMRT delivery with MOSPLOT4.1 software**

Measurements were usually performed during the first treatment session and once a week thereafter.

A total of 8 NPC patients and 48 dose points have been currently measured *in vivo*.

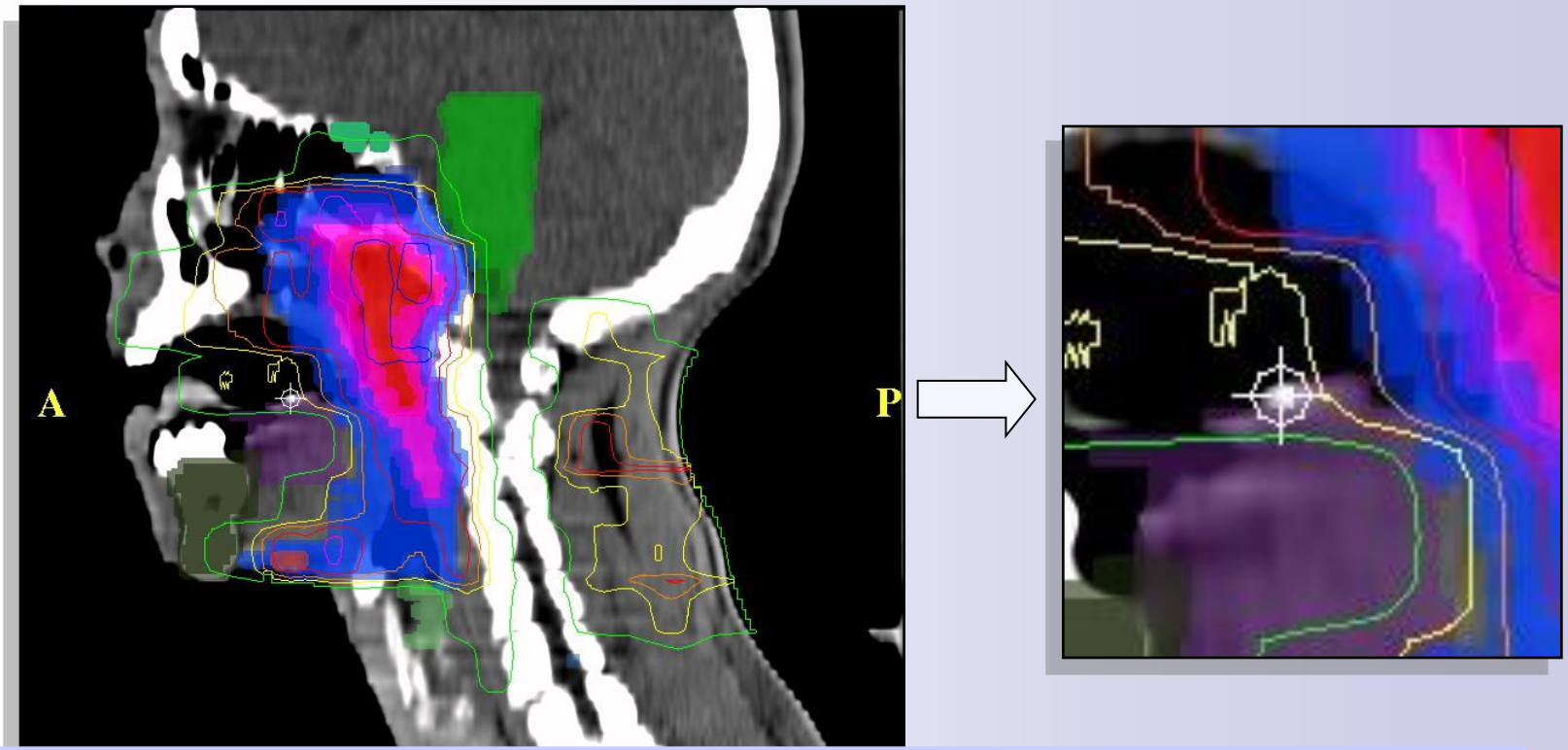
a b

The custom-made oral plate produced for each patient to keep MOSkin on a surface of the tongue .

a: top view b: bottom view

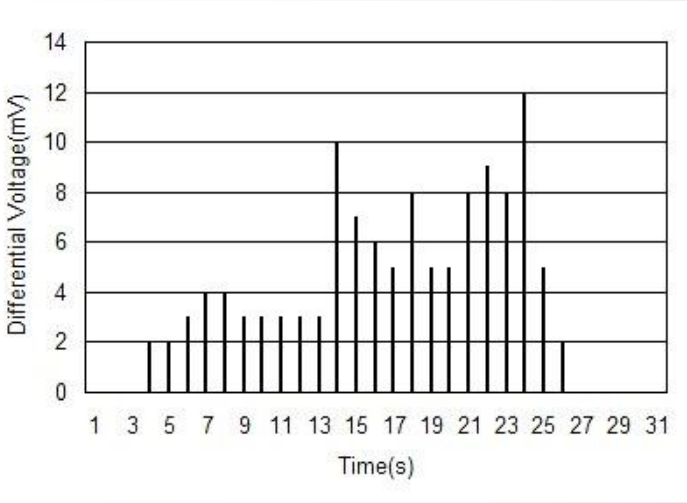
Dosimetry in IMRT

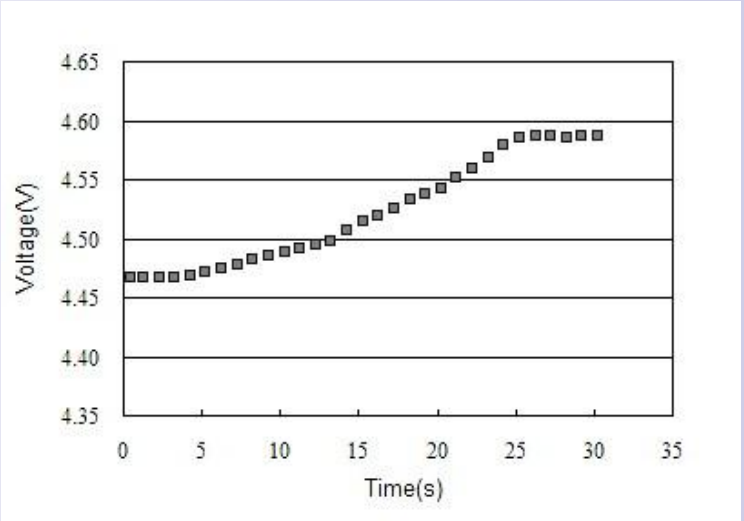
- MOSkin has also been used for dose verification during IMRT



- A special *mouth plate* was designed by a dentist to keep the MOSkin detector against the surface of the mouth.

MOSkin: Dose verification in serial IMRT treatment (NPC)



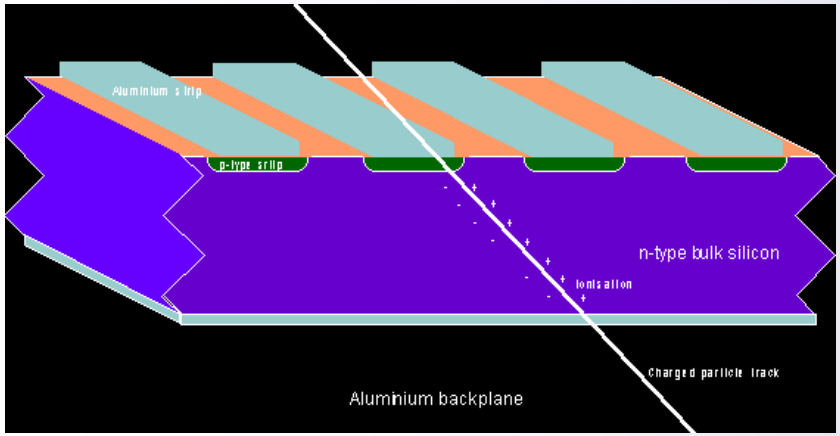


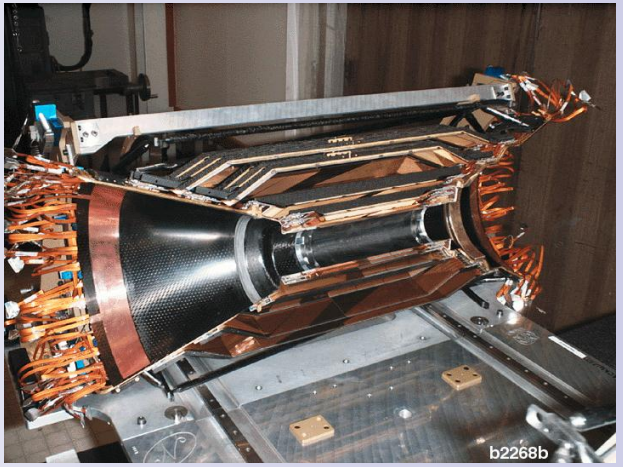
- ***In vivo* MOSkin in differential readout mode provide each second temporary map of IMRT delivery (1 cGy is corresponding to 2.45mV)**
- ***In vivo* MOSkin in integral mode provide total dose immediately after delivery**
- **Measured total dose on a surface of the tongue for particular treatment fraction and patient was 48.96 cGy while TPS predicted dose was 47.90 cGy and agreed within 2.2%**

Conclusion 1

- While the ionizing chamber is always the gold standard in radiation therapy, semiconductors diode and MOSkin are the future of online *in vivo* dosimetry
- MOSFET dosimetry is unique for skin and surface dosimetry
- MOSkin is a new MOSFET suitable for many RT applications where skin dose is an issue
- Design of diodes and its packaging is critical for their response and not trivial

Strip Si detectors: from HEP to Radiation Oncology

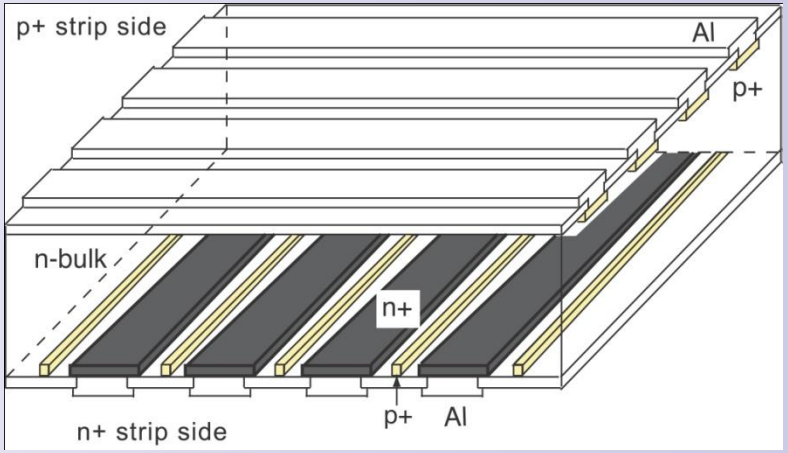




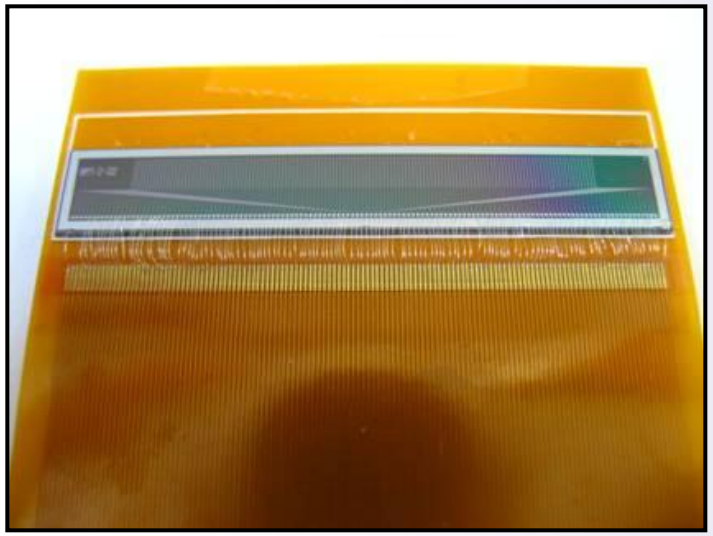
Strip detectors are used in HEP in Vertex Detectors for m.i.p. tracking with micron spatial resolution 1D and 2 D.

Charge deposited by particle is shared between strips (p-n junctions) allowing determination "centre of mass" and particle coordinate

Technology exist for Mega-strips readout



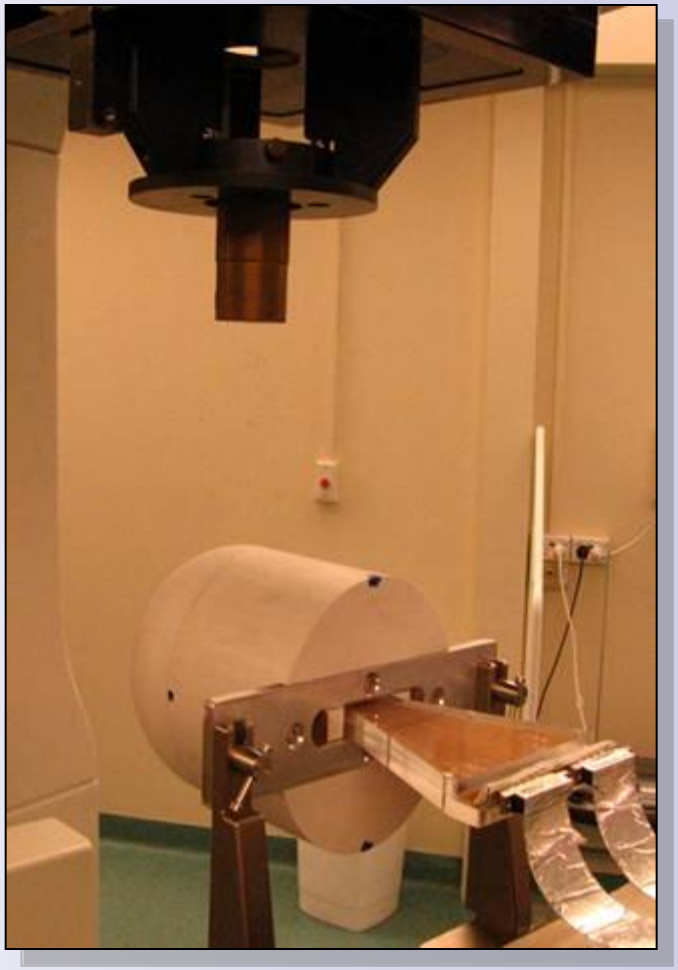
Dose Magnifying Glass (DMG)



- 128 channels Si strip detector
- Area: 20 x 5000 μm
- Thickness: < 0.4 mm
- Kapton thickness: 0.1 mm

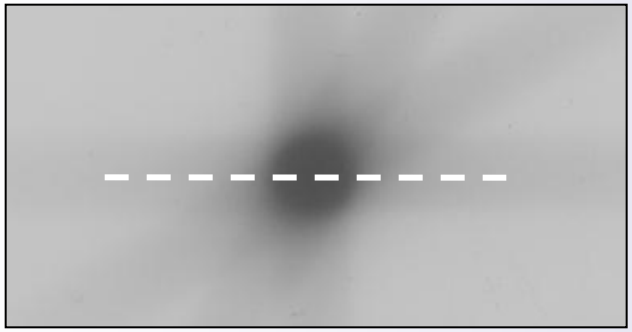
Dosimetry of small radiation fields-SRS

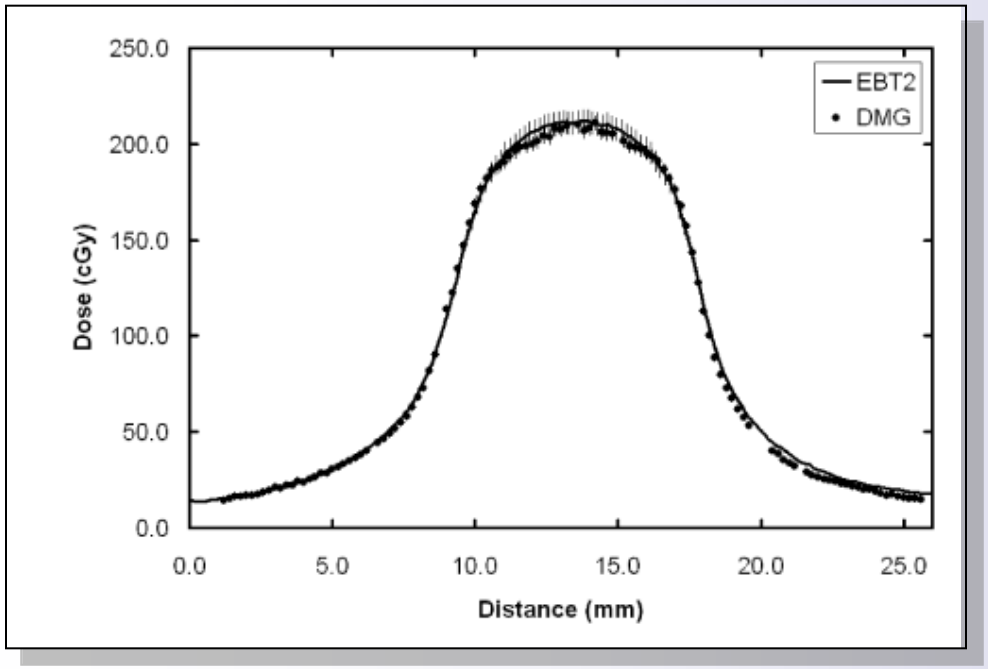
Lucy Phantom from Standard Imaging +DMG is an optimal QA for real time dose verification in SRS



SRS dose verification in Real Time

DMG: SRS delivery verification

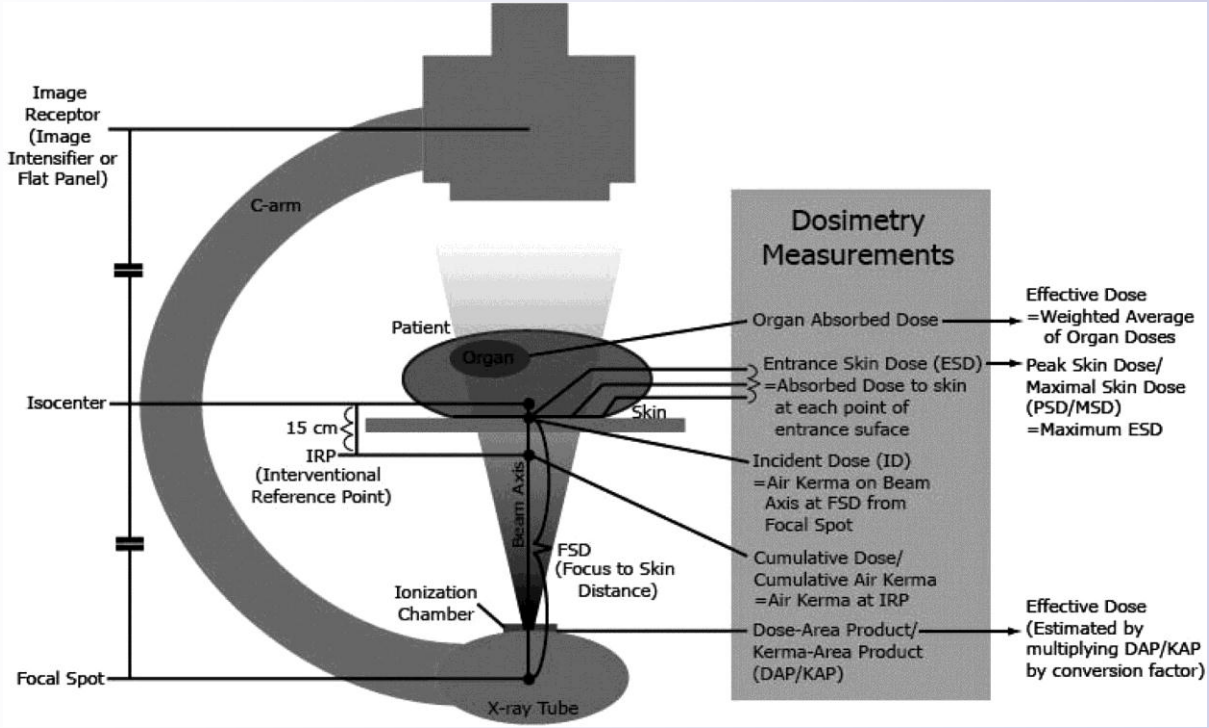




- 4 SRS arcs of 180° angles
- Couch angles: 270°, 300°, 330°, 360°.
- average difference = 4.1 ± 6.7%.

DMG-fast and accurate QA in SRS with 0.2 mm spatial resolution

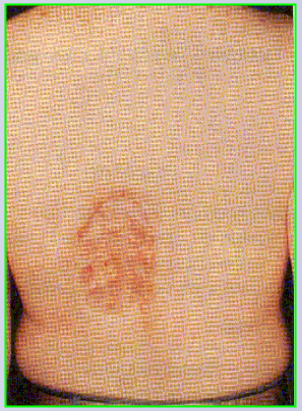
MO*Skin* dosimetry in diagnostic radiology : C-arm



- Interventional radiology procedures associated with high skin doses up to 4Gy
- Real time *in vivo* dosimetry for *Maximum Skin Dose* (MSD) monitoring is required
- Detector on a patient should not obstruct the image

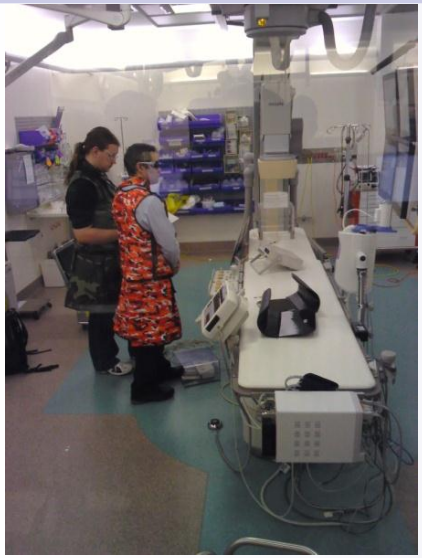
Interventional Radiology- Skin reactions

Injury	Threshold Dose to Skin (Sv)	Weeks to Onset
Early transient erythema	2	<<1
Temporary epilation	3	3
Main erythema	6	1.5
Permanent epilation	7	3
Dry desquamation	10	4
Invasive fibrosis	10	
Dermal atrophy	11	>14
Telangiectasis	12	>52
Moist desquamation	15	4
Late erythema	15	6-10
Dermal necrosis	18	>10
Secondary ulceration	20	>6

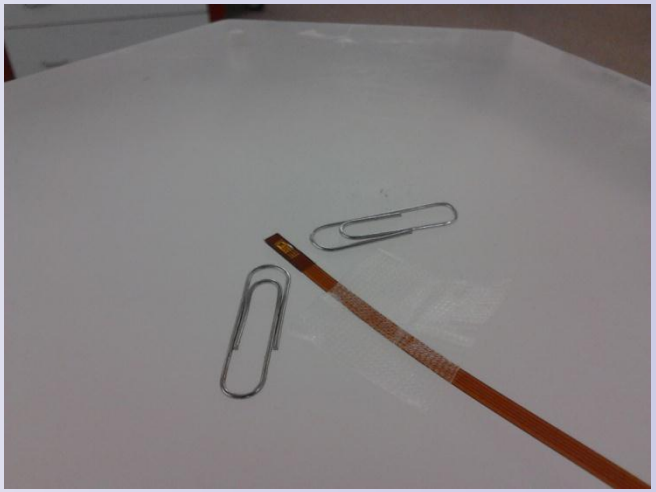


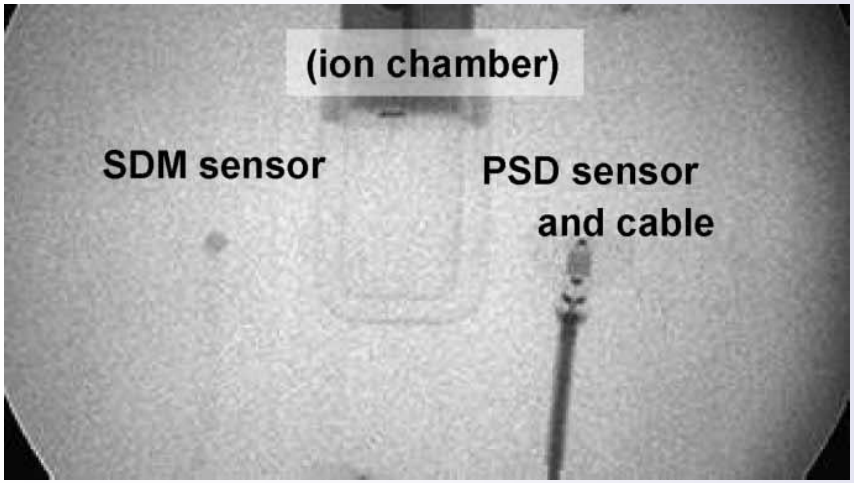
Skin damage from prolonged fluoroscopic exposure

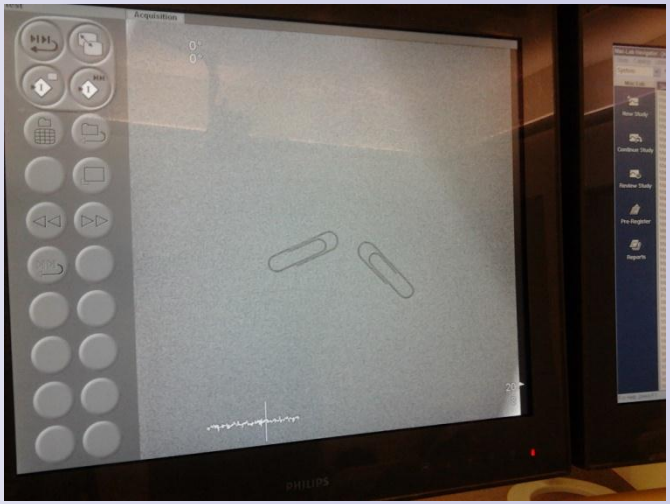
MO*Skin* Dosimetry in Interventional Radiology



- "Invisible MO*Skin*" X-ray beam 78KVp, 15 frames/s
- MO*Skin* do not change C-arm parameters





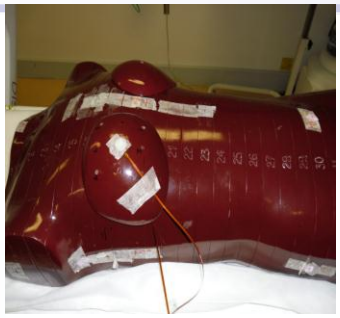


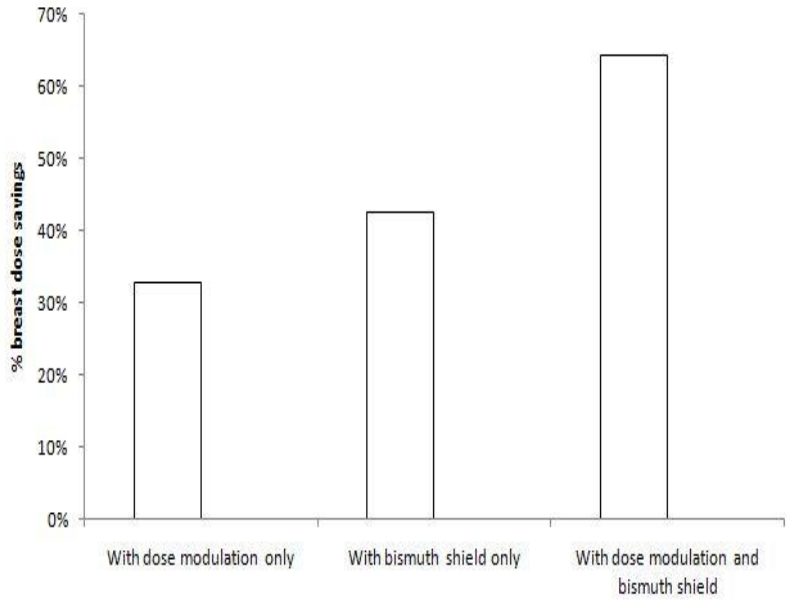
C.Chida *et al*. Acta Radiologica, 2009

Radiation Exposure to the Australian Population - Medical Exposures

- Multidetector (multislice) computed tomography (MDCT) procedures have become the dominant contributor to the radiation dose to the population from diagnostic radiology.
- ARPANSA surveyed radiation doses from MDCT in 1994, 2002 and estimated contemporary doses in 2008 for standard MDCT procedures.
  - In Australia the per head radiation dose from CT for 2002 was approximately 0.9 mSv, in 2008 this has increased to an estimated 1.2 mSv, a growth of 50 %.
- ARPANSA is planning a national web based survey of common MDCT procedures and doses to start in early 2010, which will reflect the dose impact of new MDCT platforms and new types of procedures.
- A major aim of the survey is to measure the impact of new technologies and procedures on patient doses in CT. The survey of doses will be put to practical use in the development of national DRLs.

Application of the MO*Skin* in the assessment of breast dose





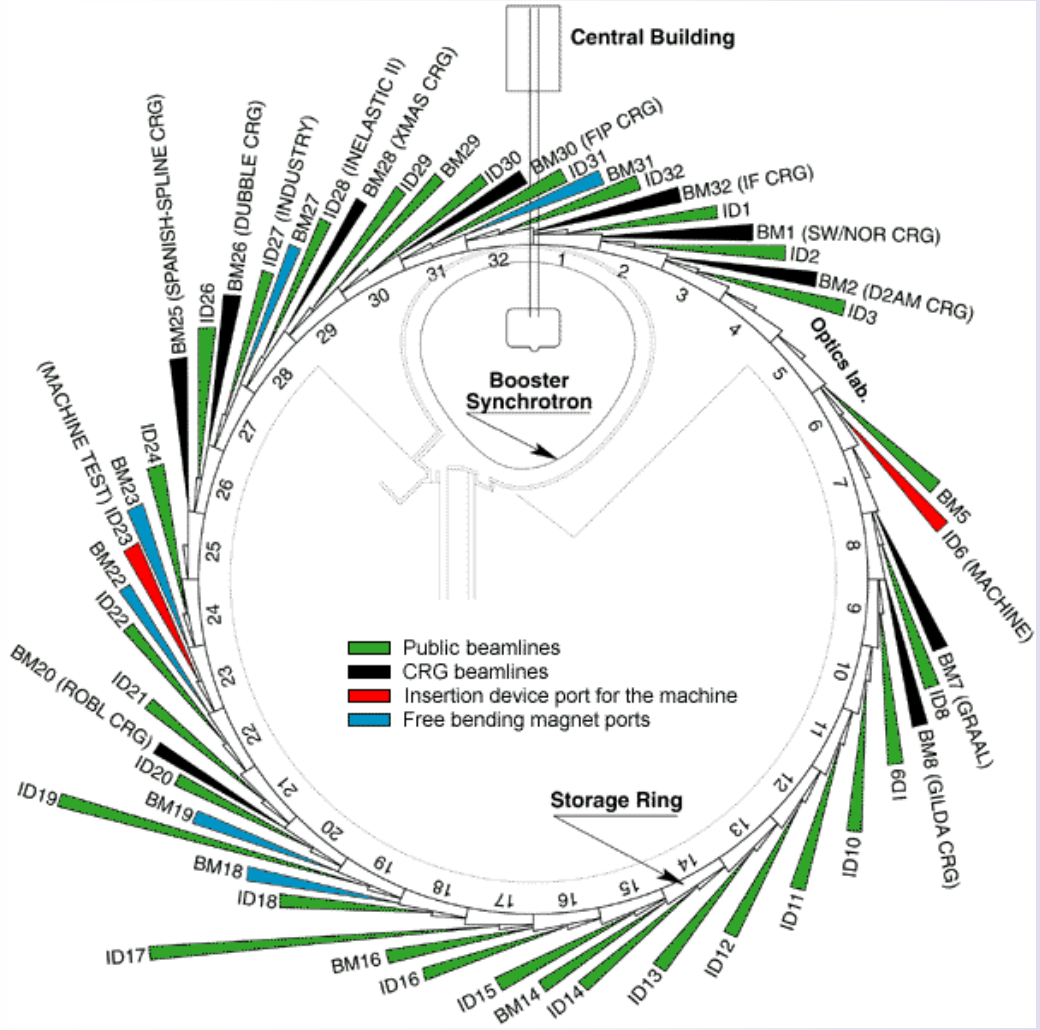
A MO*Skin* study on the effect of dose reduction strategies (tube current modulation and breast shield) on breast dose

<u>Findings</u>

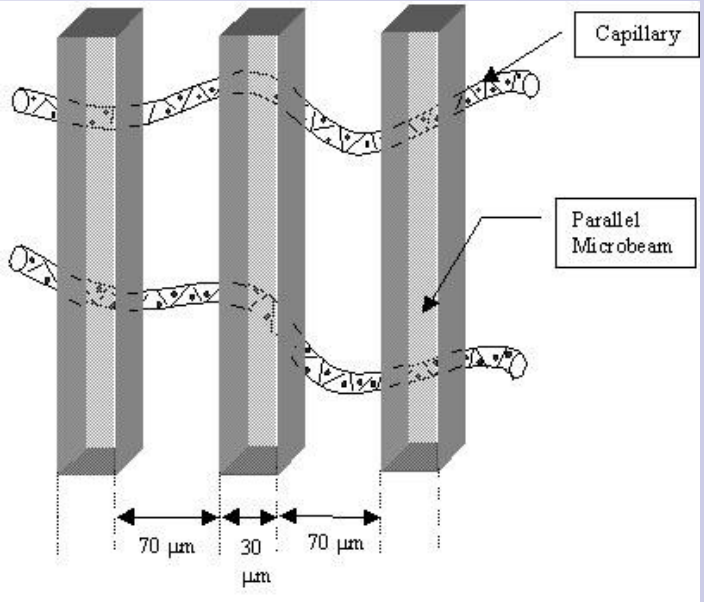
MO*Skin* and film results were comparable to within +/-5 mGy

Up to 64% breast dose savings with tube current modulation and use of the bismuth breast shield

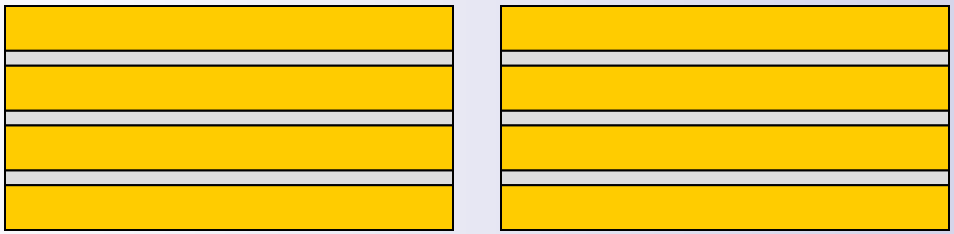
Dosimetry in Microbeam RT, ESRF , France



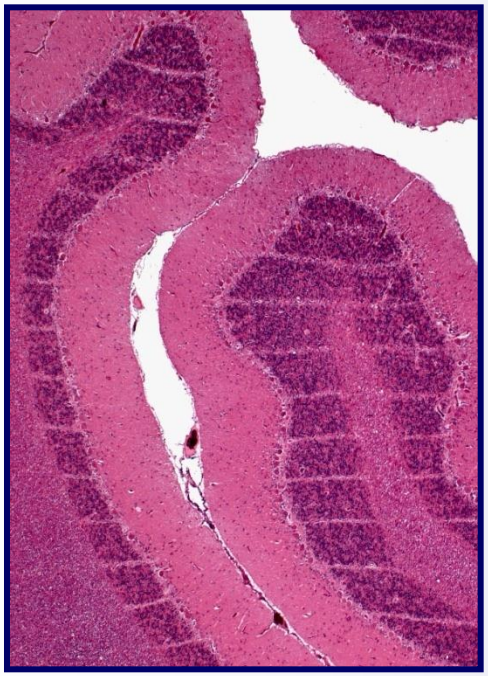
ID17 is a medical beam line dedicated to MRT and imaging.



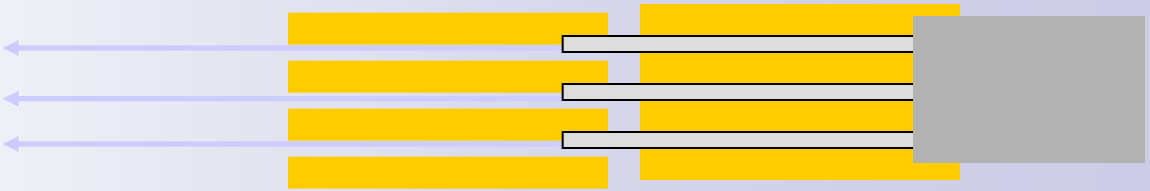
Multislit collimator



Two stacks of foils: Al (50 mm thick) and Au (155 mm thick)



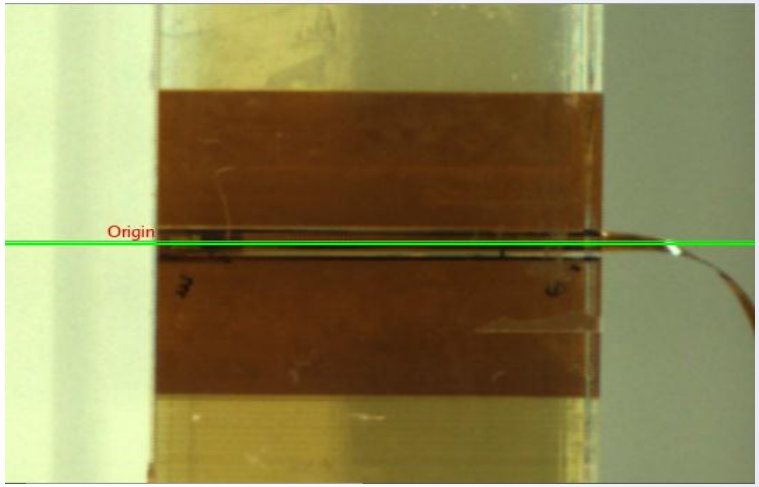
Beam width control
by translation of a stack
(from 1 mm to 50 mm)



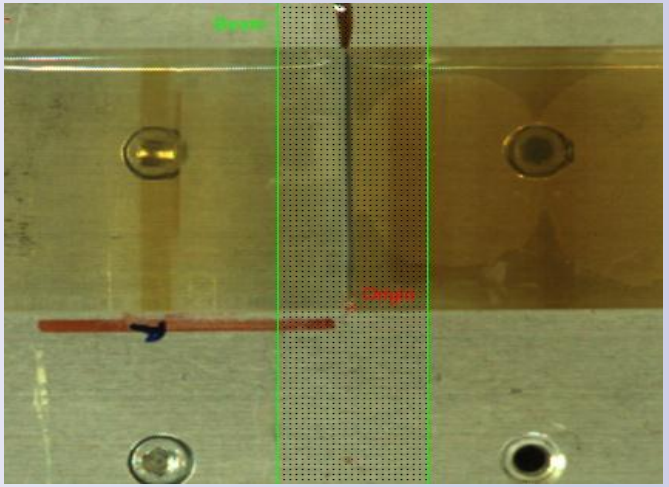
Courtesy of ESRF

Edge-on Microstrip SingleDetector

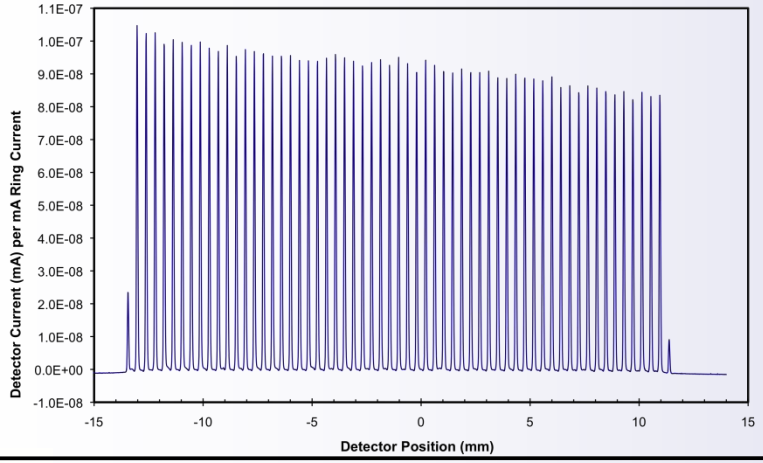
Side-view of detector in phantom



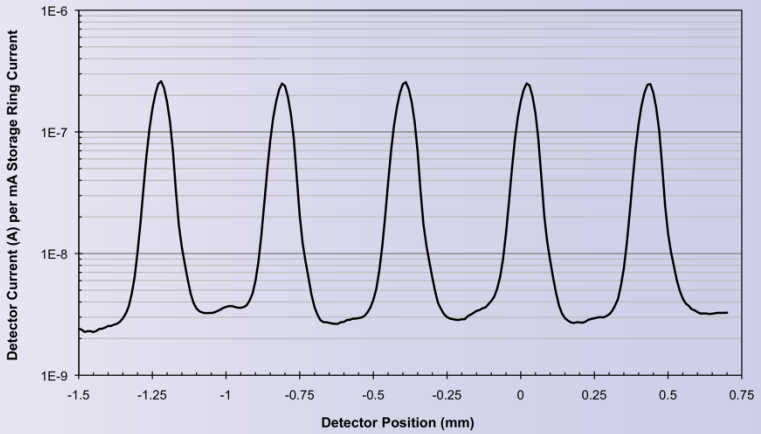
Top-view



Lateral scan of 25mm microbeam array in 10 micron increments



Detailed view of microbeams

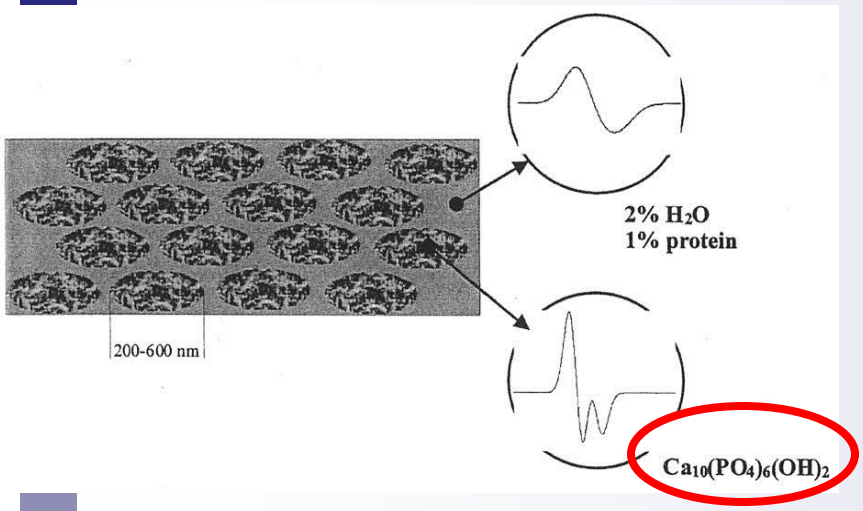


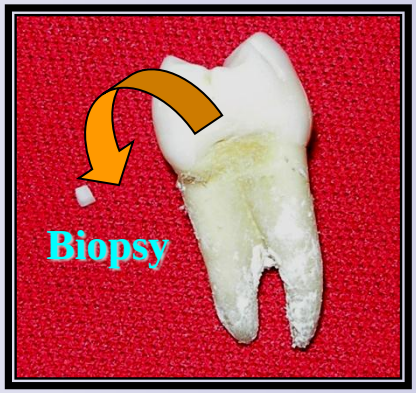
Biological Retrospective Dosimetry

What is Electron Paramagnetic Resonance (EPR) ?

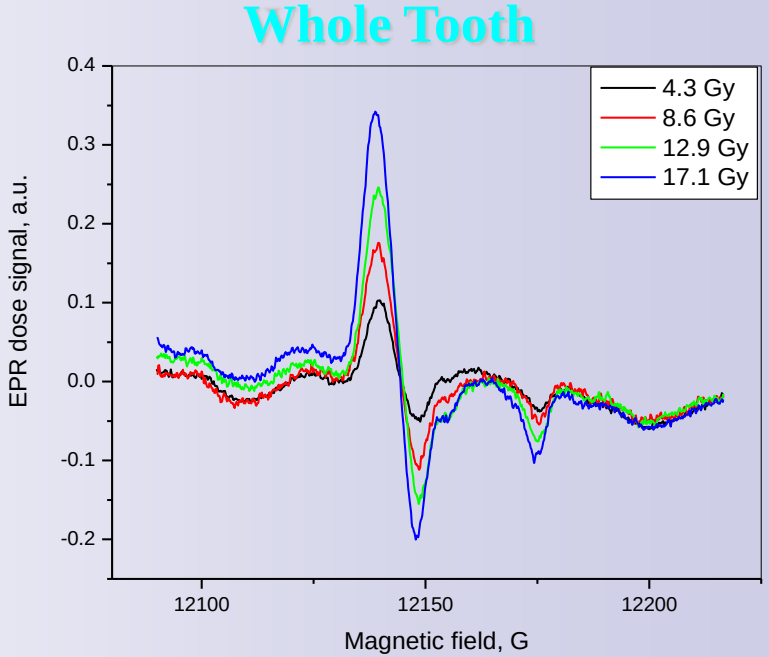
- Non-destructive magnetic resonance technique used to detect and quantify unpaired electrons.
- Absorption of ionizing radiation generates unpaired electrons (i.e., paramagnetic centers).
- The concentration of radiation-induced paramagnetic centers is proportional to the absorbed dose.

EPR Biodosimetry (Teeth)



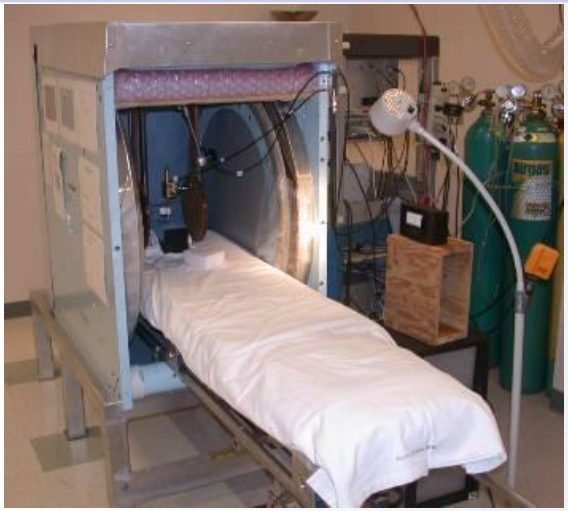


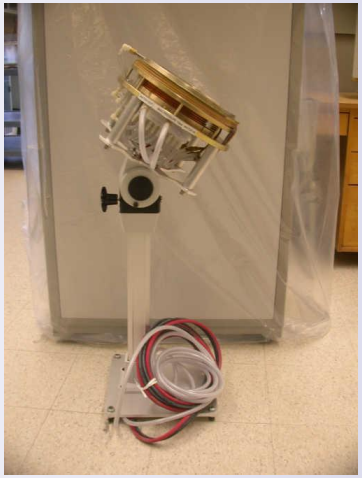
- Hydroxyapatite constitutes:
  - ~95% by weight of tooth enamel
  - 70-75% of dentin
  - 60-70% of compact bones

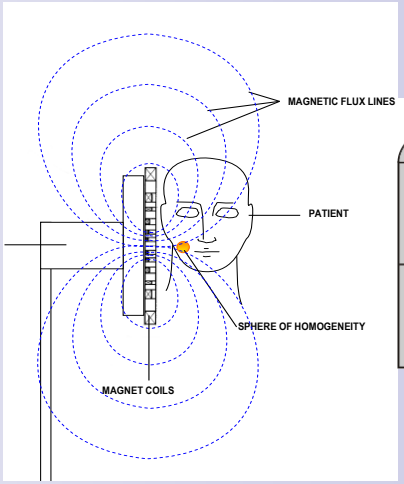


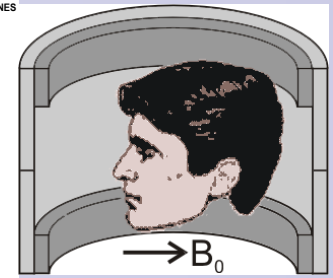
Romanyukha, et. al, Appl. Radiat. Isot. (2000) and IAEA-TECDOC-1331

Clinical EPR Spectrometers

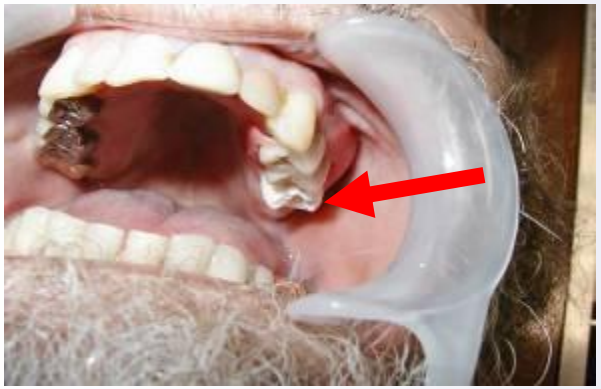




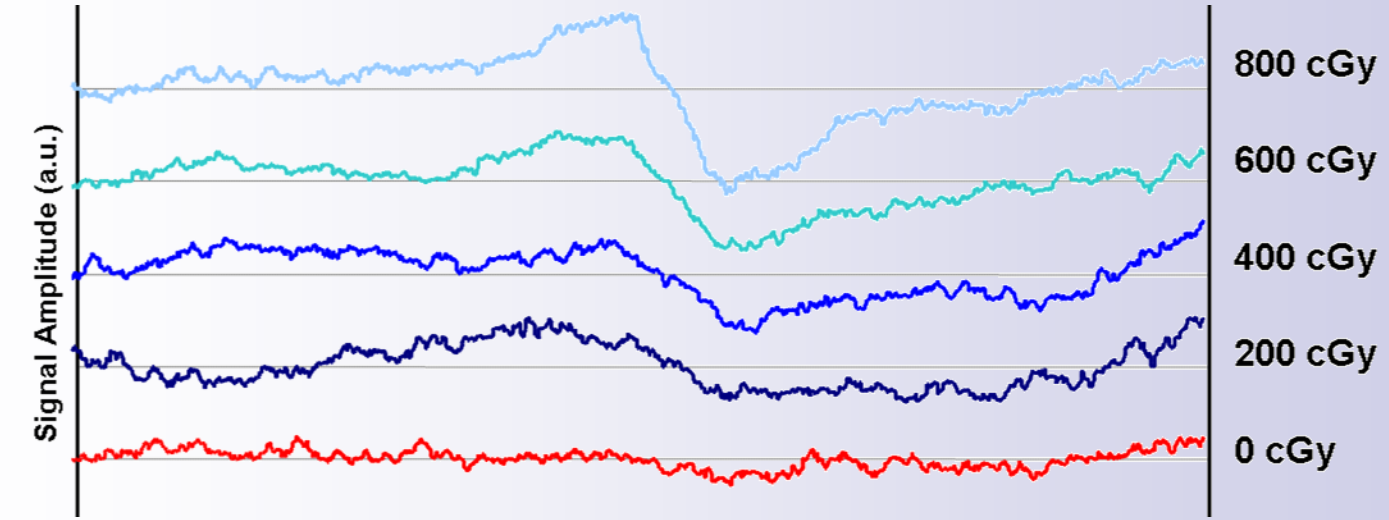


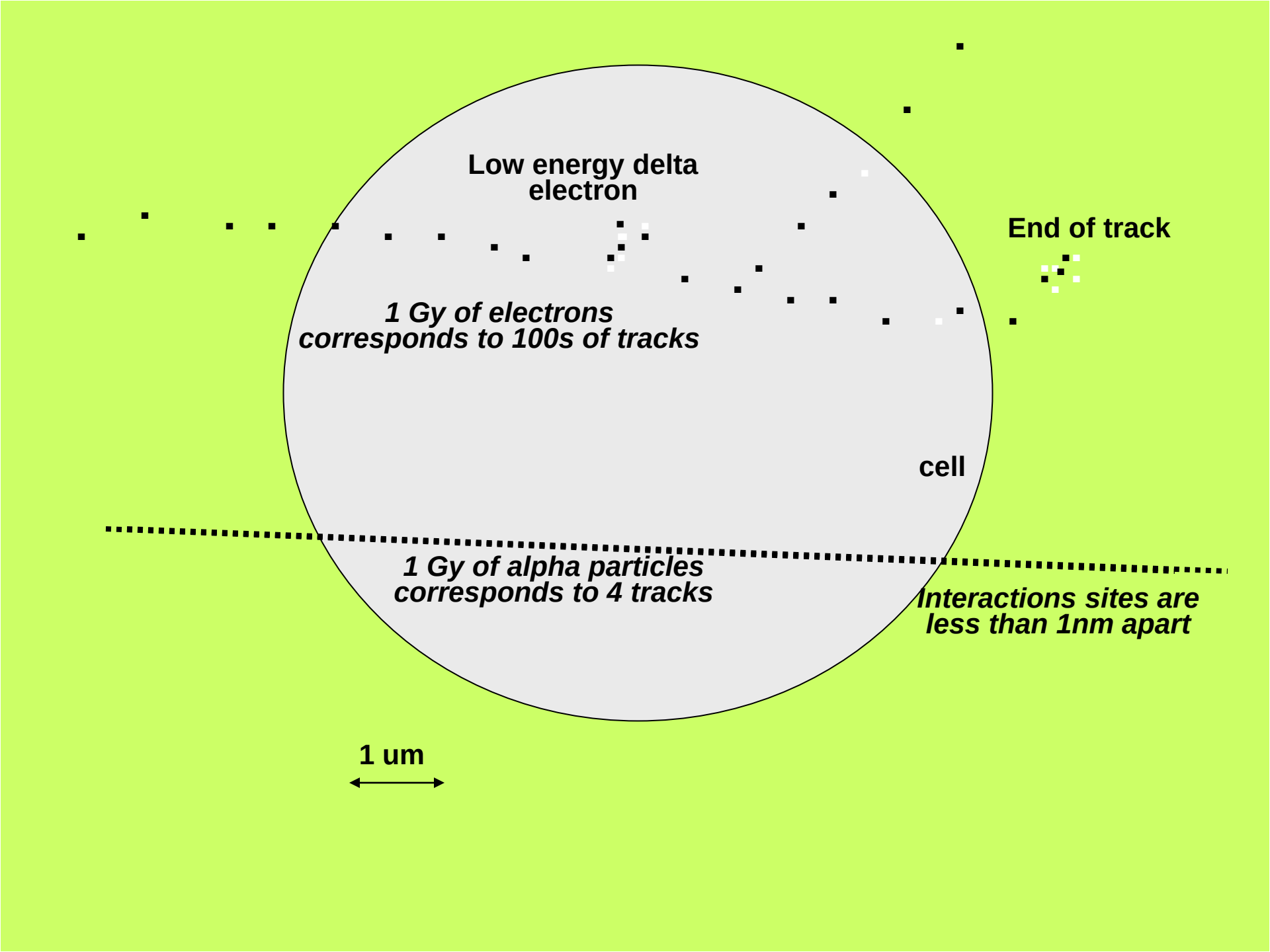


In Vivo EPR Radiation Dosimetry



Under practical conditions with an irradiated tooth in the mouth of a volunteer, the dose dependent signal amplitude is clearly observed. (Acq. time = 4.5 minutes/spectrum)



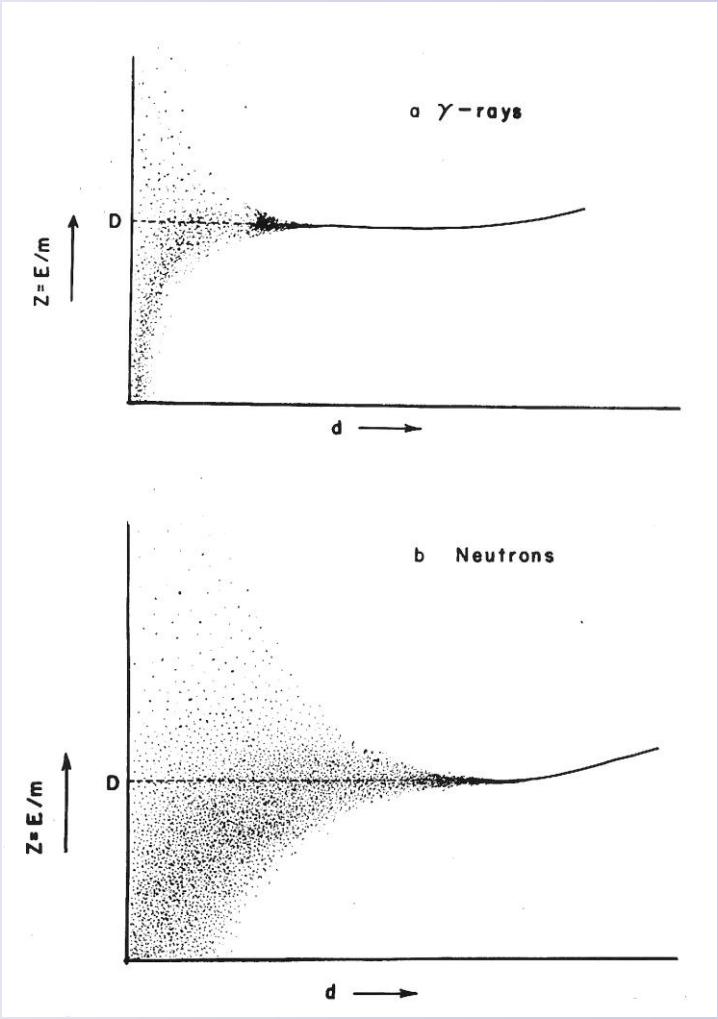

Low energy delta electron
End of track
1 Gy of electrons corresponds to 100s of tracks
cell
1 Gy of alpha particles corresponds to 4 tracks
Interactions sites are less than 1nm apart
1 um

Concept of Microdosimetry

Energy per unit mass vs mass for *constant* dose.

Reducing of the target is changing deterministic deposition of energy to stochastic. Each radiation type has own signature.

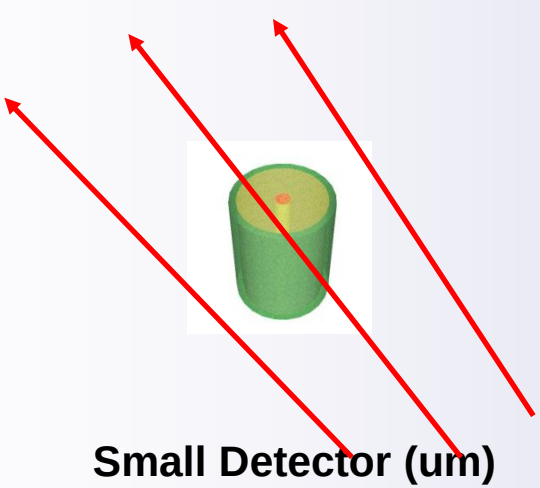
E/m= specific energy



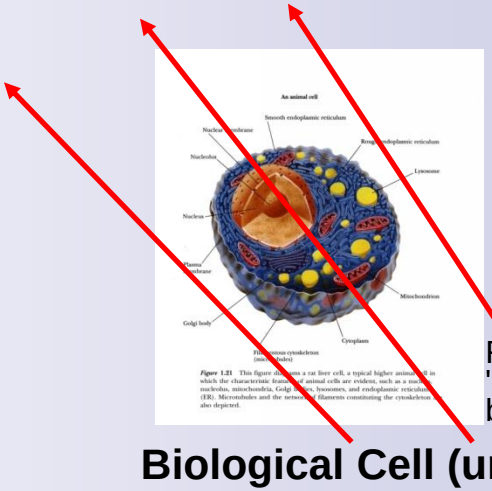
Microdosimetry and Equivalent Dose

- **Microdosimetry**
  - Assumes the weighting factor is related to the energy deposited in the cell nucleus: ε
  - Measure this for each particle that crosses detector
  - Formulate dose distribution: $d(\varepsilon)$
  - Integrate with weighting factor to give **Equivalent Dose**: $H = \int Q(\varepsilon)d(\varepsilon)\,d\varepsilon$
  - Equivalent Dose can be used to accurately predict biological effect of radiation

- **We require detectors with dimensions commensurate with cell nuclei**



Small Detector (um)



Biological Cell (um)

From Garret and Grisham, "Biochemistry" Copyright 1995 by Sauders College Publishing

Microdosimetry and Fluence approach for stochastic events

Microdosimetry

Measure distribution of ionisation events in microscopic volume
Derive quality factor and equivalent dose estimate

$$H = \int Q(y)d(y)dy$$

Fluence based approach

Measure types and energy distribution of all particles
Integrate product of risk cross section a fluence over energy
Sum over all particles to directly obtain risk estimate

$$R = \sum_i \int_r \sigma_i(E)\phi_i(E)dE$$

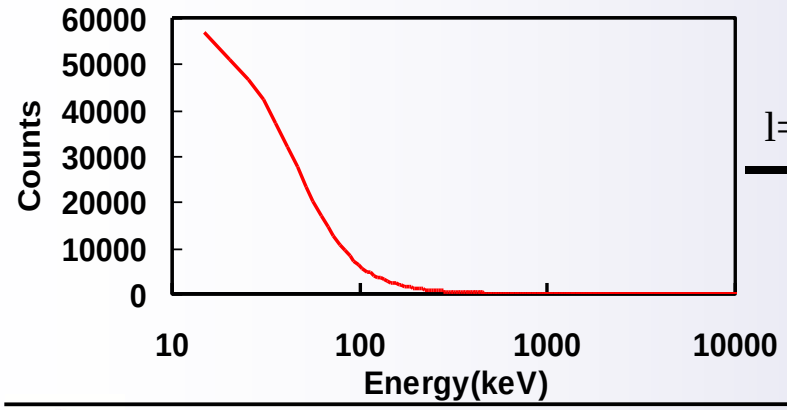
Q(y), Q(L) and $\sigma(E)$ were modified recently , ICRU 92 and NCRP 137
Quality coefficient for low doses neutrons is still uncertain

All above characteristics are relevant to Radiation Protection only

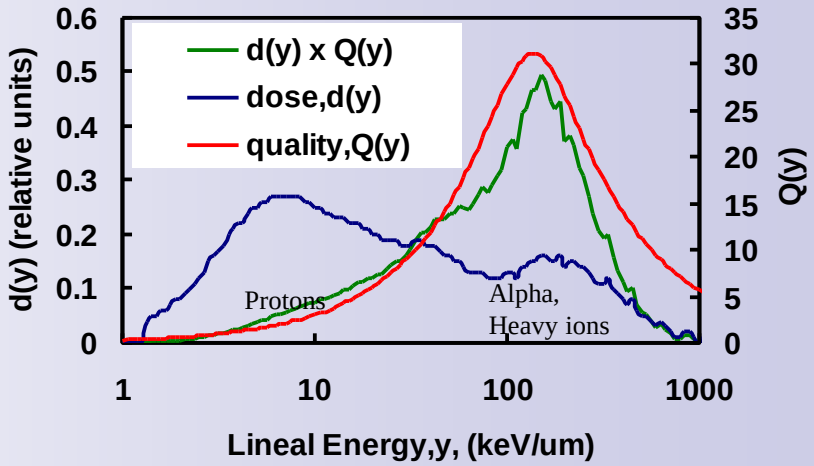
Si microdosimetry

- **Microdosimeter measures the energy deposition events in a small (cell-sized) volume due to radiation interactions.**
  - Produces spectra of counts versus energy (E).
  - Divide energy by mean chord length (l) gives lineal energy spectra f(y)
  - Dose distribution d(y) ✪ yf(y) where y=lineal energy=E/l
- **Motivation**:
  - Radiobiological effectiveness depends upon LET or lineal energy
  - Distribution of dose (d(y)) with lineal energy gives dose equivalent (H)

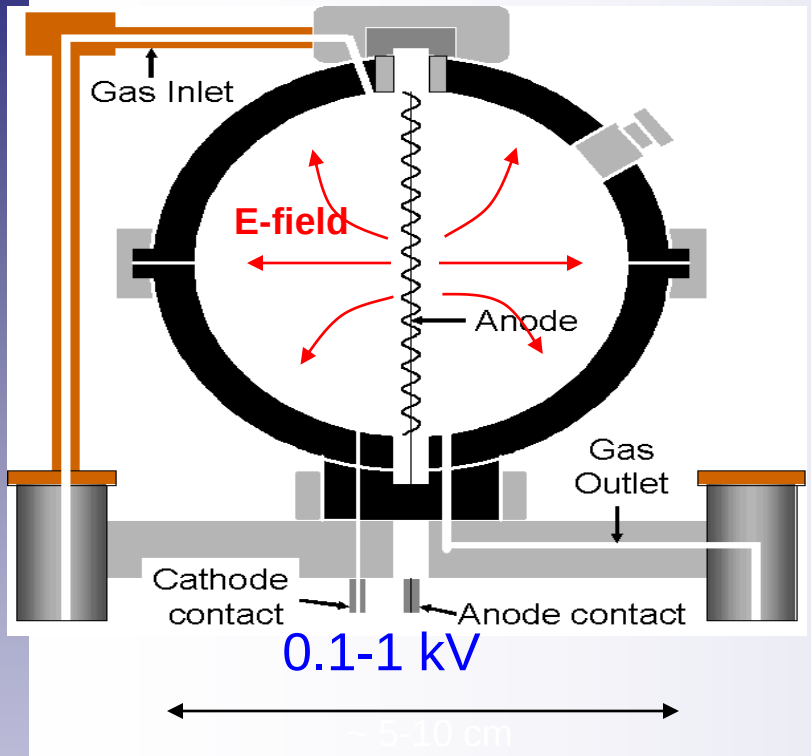
$$H = \int_0^\infty d(y)Q(y)dy$$

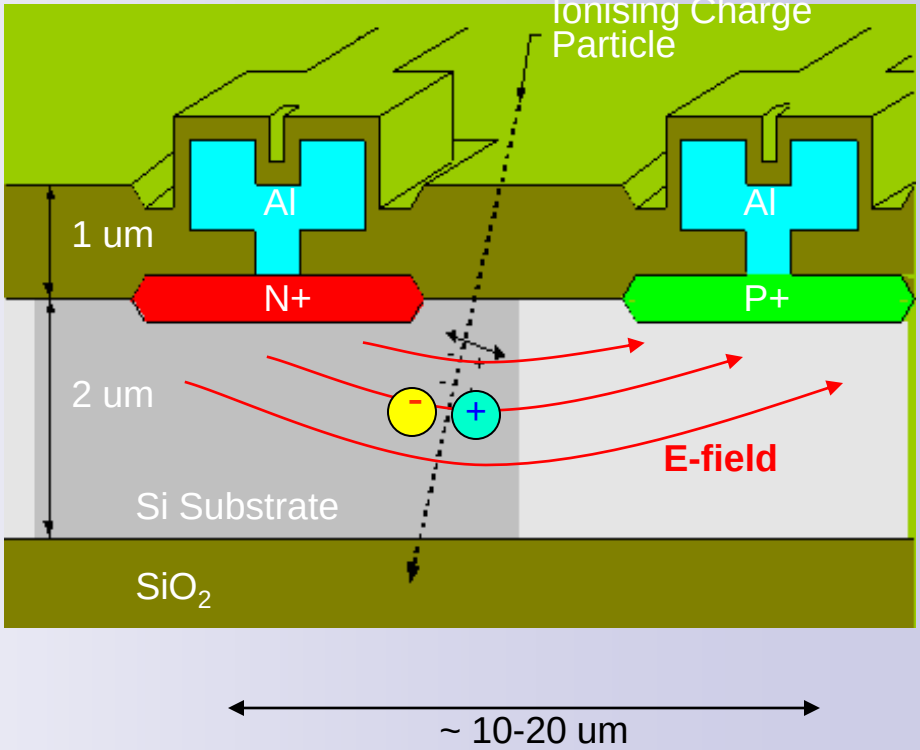


l=10um



Tissue Equivalent Proportional Counter and Silicon Microdosimeter

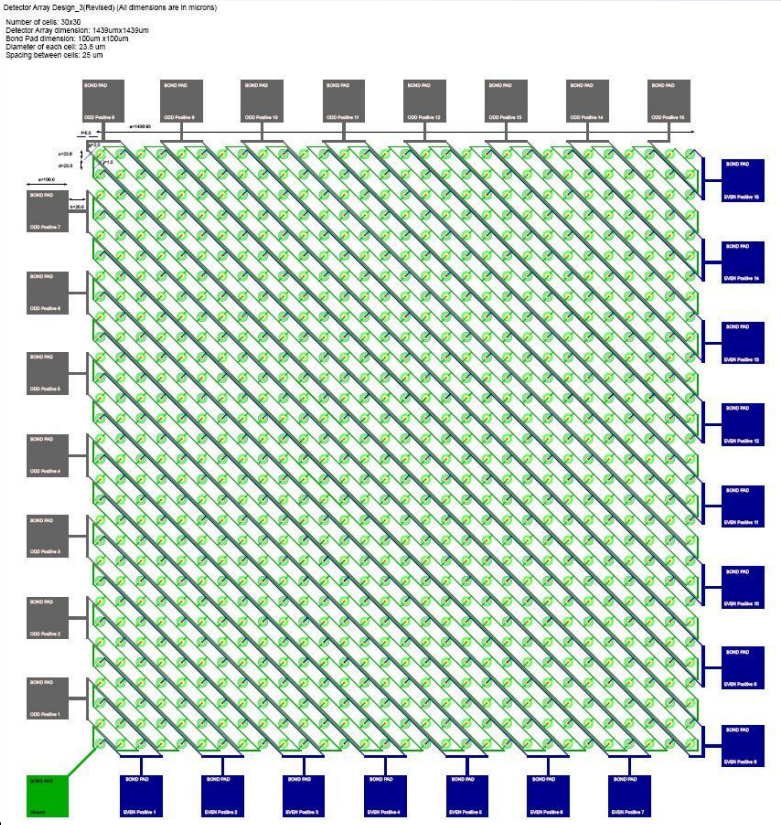


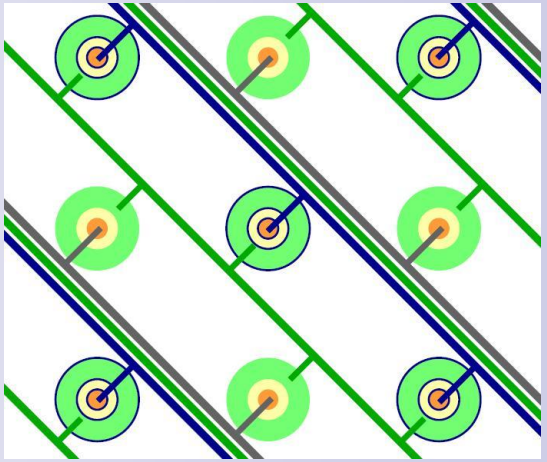


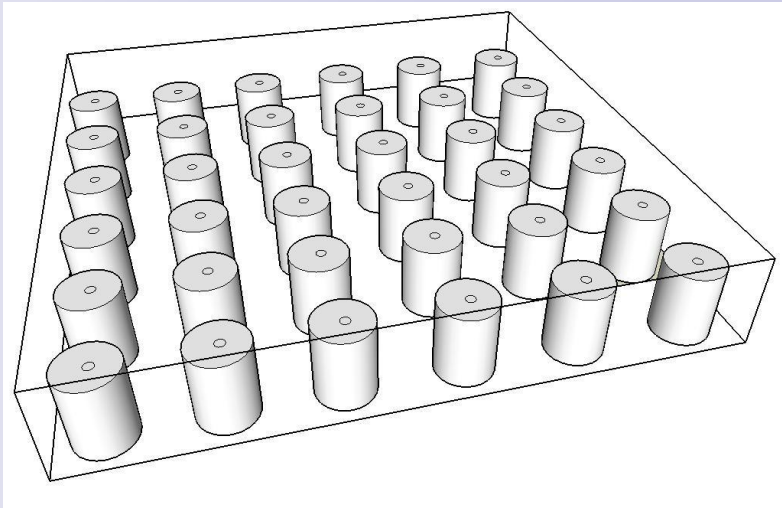
- **Rossi Tissue Equivalent Proportional Counter**
- **Silicon Microdosimeter**

3D SOI silicon microdosimetry

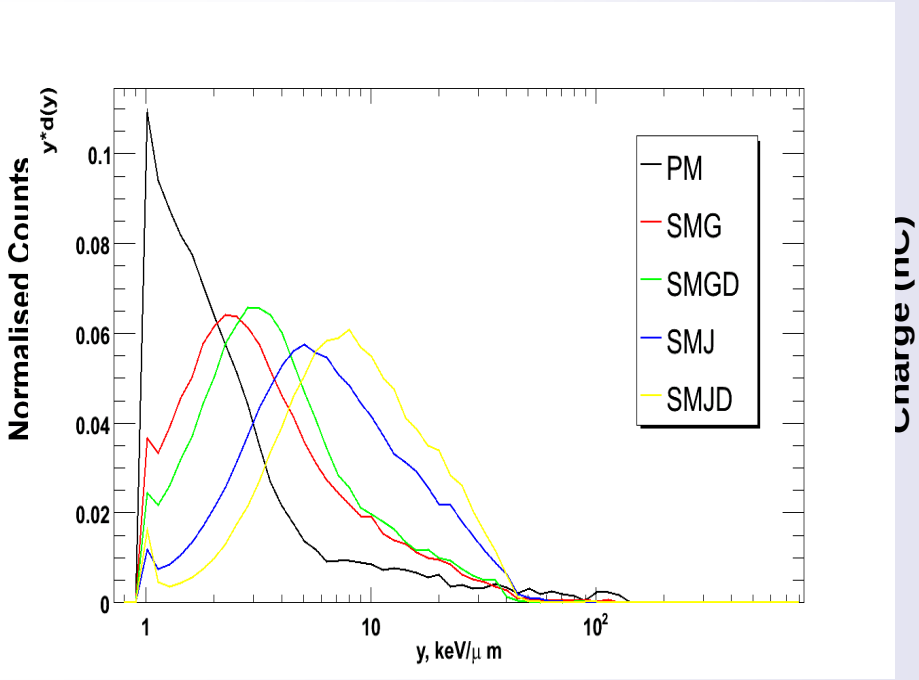
- 3D silicon cell array for modeling of energy deposited in biological cells event by event by secondaries
- Each Si cell is 6x10 microns

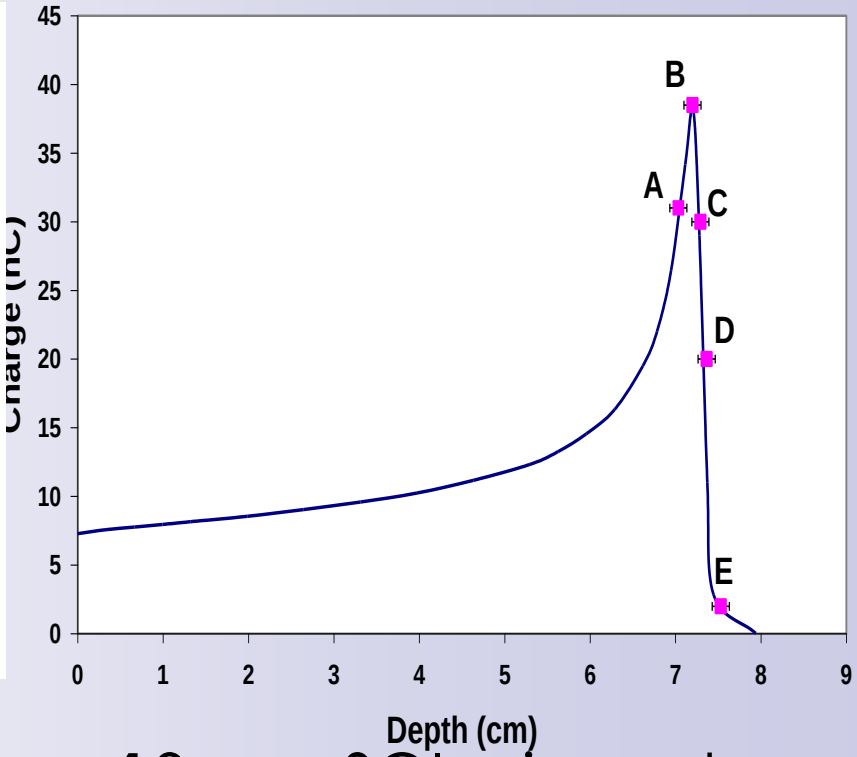






SOI Microdosimertry on 100 MeV Proton Therapy





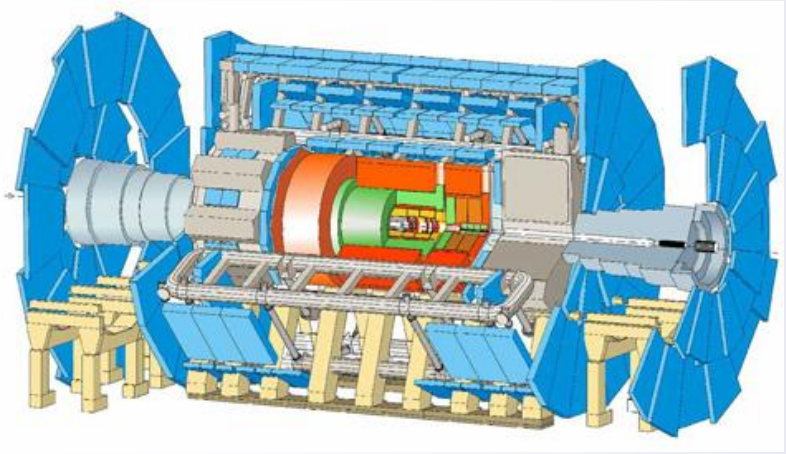
- Microdosimetric spectra from 10 mm SOI micro at consecutive positions in a Bragg Peak
- Possibility to estimate Q of the beam

For more details see: A Rosenfeld "Electronic Dosimetry in Radiotherapy", Rad. Meas., 41, 134-153, 2007

Particle Accelerators

Accelerator	Colliding Particles	Total Energy	Major Accomplishment
Stanford Linear Collider (SLC) in Palo Alto	electron, positron	100 Gev	provided first look at Z^0
Large Electron Positron Collider (CERN-LEP) in Geneva	electron, positron	200 Gev	discovered Z^0, W in 1983; shut down in 2002
Relativistic Heavy Ion Collider (BNL-RHIC) in Brookhaven	heavy ions	200 Gev	created quark-gluon plasma (Mini Big Bang)
Tevatron (FNAL) in Chicago	proton, antiproton	2 Tev	confirmed Z^0, W, discovered top quark
Large Hadron Collider (CERN-LHC) in Geneva	proton-proton; ion-ion	14 Tev	planned for 2008 - LEP replacement

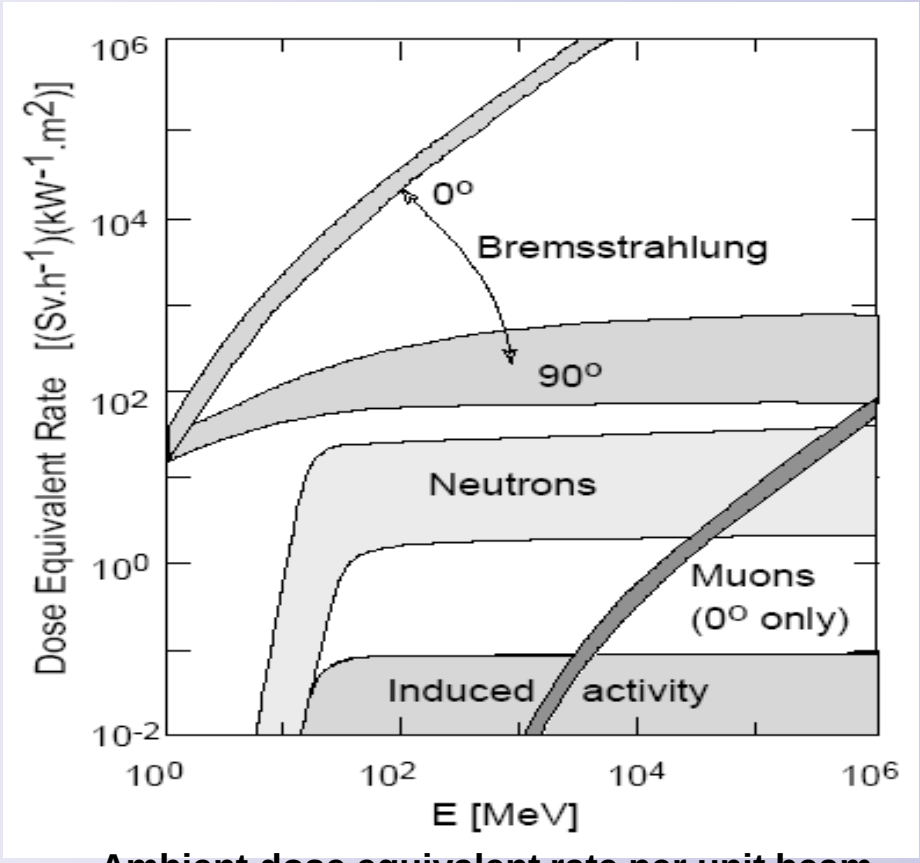
Mixed radiation field in workplace in research high energy accelerator



Interaction of the primary beam with accelerator structure generates photons and neutrons field especially :

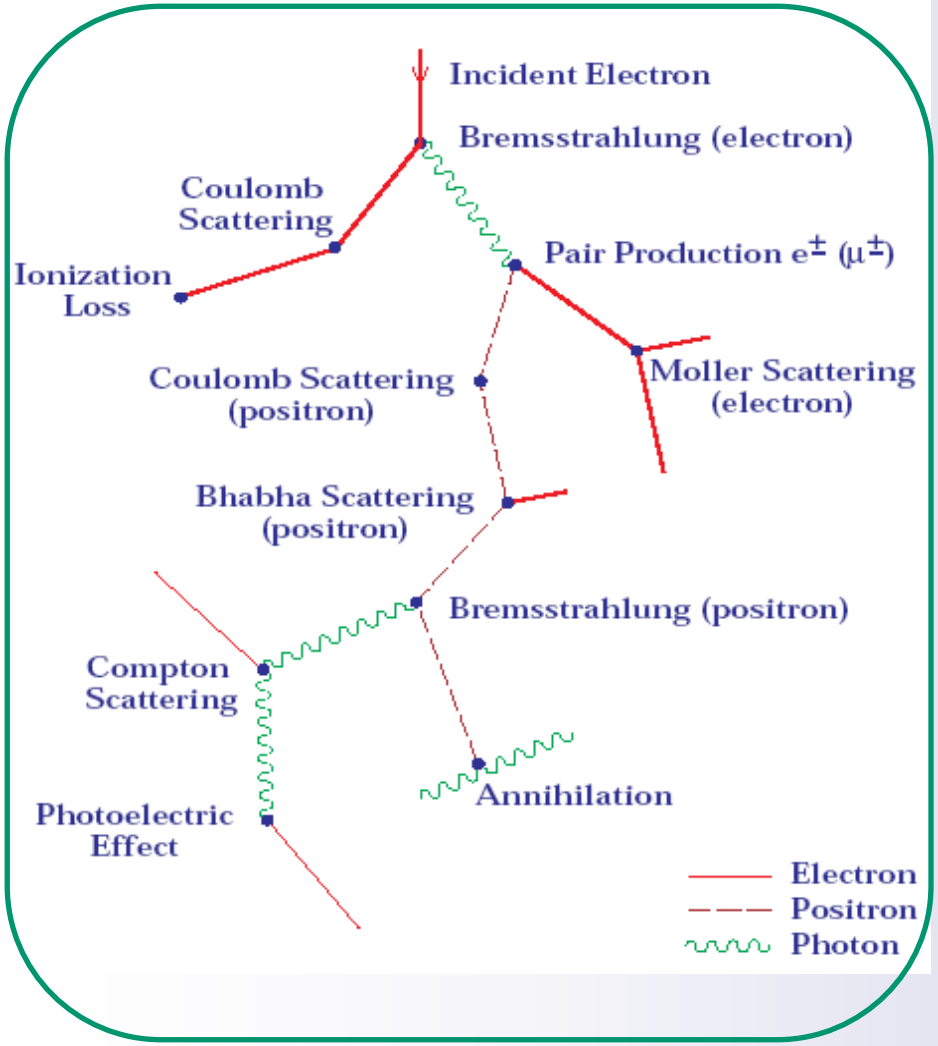
- *with injection sections*
- *collimators*
- *large angle bending magnets*
- *scrapers and beam stoppers…*

Radiation field in electron accelerator in unshielded condition (Vylet. et al, 2002)



Ambient dose equivalent rate per unit beam power at 1m from high Z target

The Electromagnetic Cascade Processes



- **Electromagnetic cascade:** *Interaction of electrons striking target material at energy of 100MeV*

$$dE = -\frac{E}{X_0}dx$$

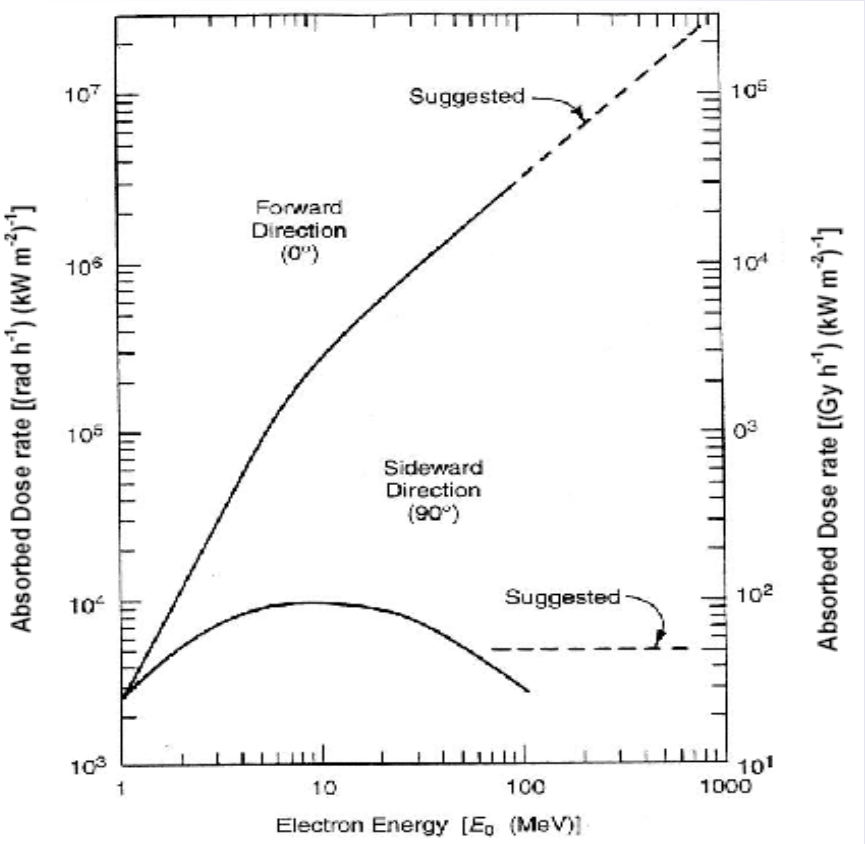
E: electron energy

dE: energy decrement

dx: infinitesimal material thickness

X_o: const of attenuation process

PHOTON FIELD



Thick target bremmstrahlung yield from high Z target . For incidence angles of 0° and 90 ° (NCRP, 2004)

- **Photon field:** *produced when electron beam striking high Z target*

Rules of thumb (Swanson 1979)

dD/dt: Absorbed dose rate at 1m (Gy/h.kW)

1) $\frac{dD}{dt} = 20 \cdot E_0^{\,2} \quad (\theta = 0° \text{ and } E_o < 20 \text{ MeV})$

2) $\frac{dD}{dt} = 300 \cdot E_0 \quad (\theta = 0° \text{ and } E_o > 20 \text{ MeV})$

3) $\frac{dD}{dt} \approx 50 \quad (\theta = 90° \text{ and } E_o > 100 \text{ MeV})$

NEUTRON FIELD

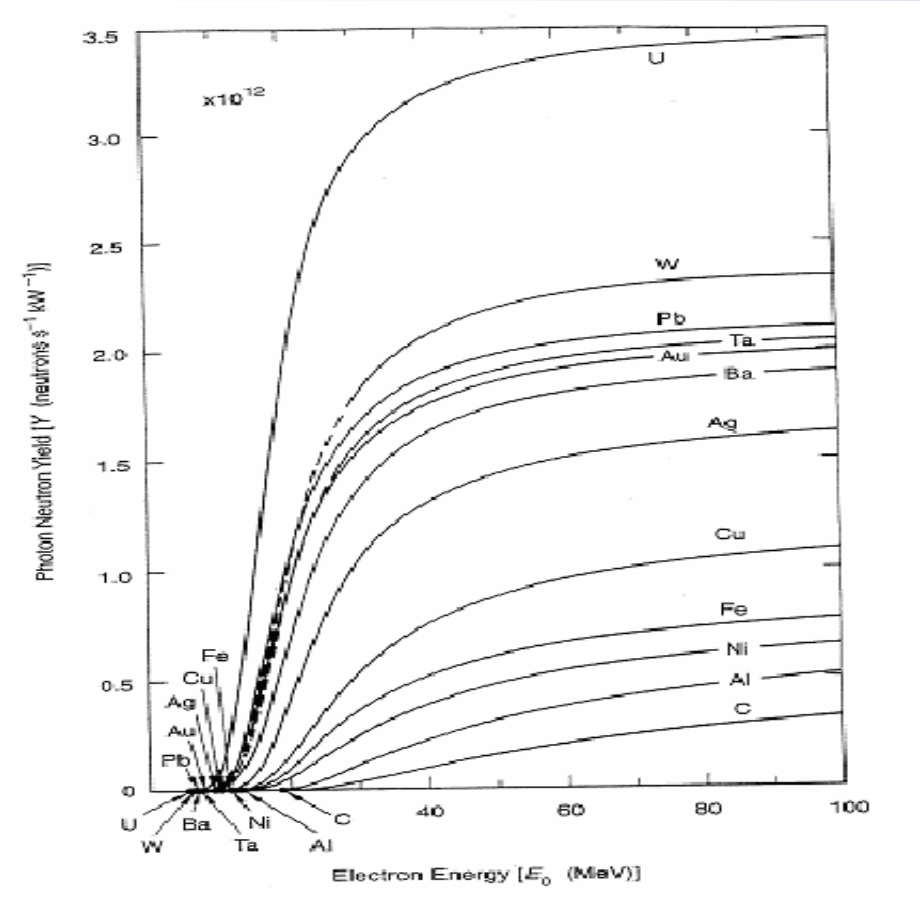


Photo-neutron yield of electromagnetic cascade on thick targets. (NCRP, 2004)

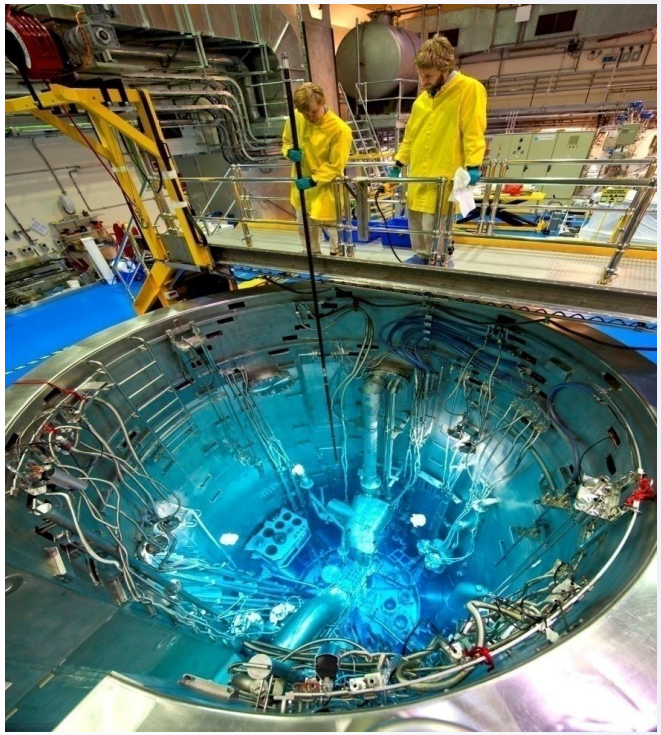
- **Neutron field:** *produced by photonuclear reactions :*
  - (γ,n) (γ,2n)
  - (γ,pn)
  - Electro –nuclear (e,e'n)

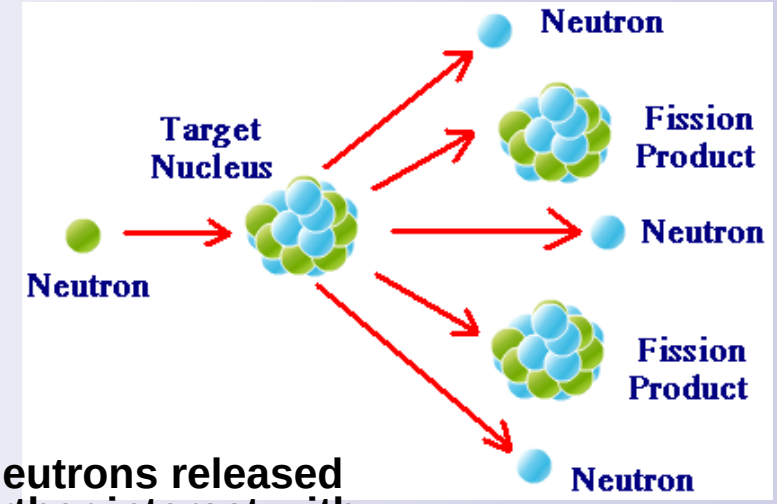
At energies > 100MeV , neutron production is energy independent (saturation effect) for medium-high Z materials(Z >50)

Lighter material reach saturation at energies >500MeV

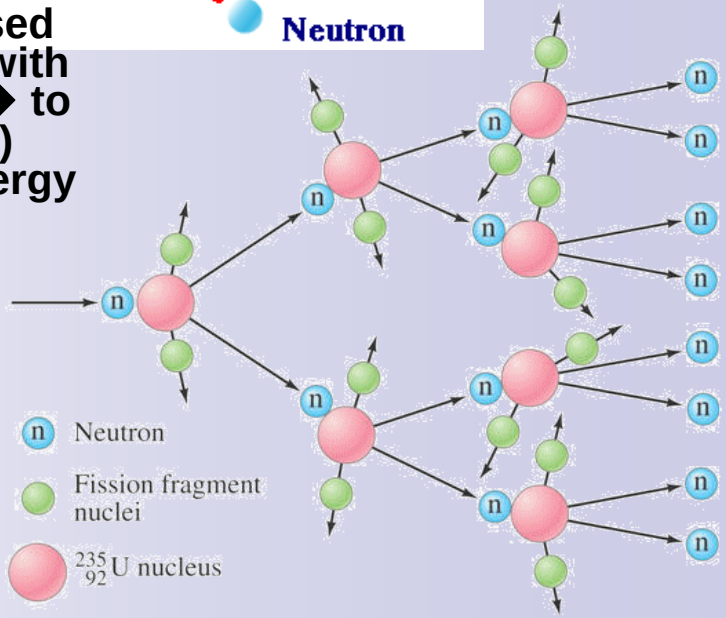
Nuclear Reactor

$^{235}U + n \rightarrow [^{236}U] \rightarrow {}^{A}X + {}^{B}Y + 2 \text{ to } 3\ n + \text{Energy}$





Neutrons released further interact with fissile element ➔ to chain (fission) reaction with energy release



- Low n flux: $<10^{13}$ ^{24}Na, ^{32}P, ^{82}Br
- Medium n flux: 2-8 X 10^{13} ^{82}Br, ^{99}Mo, ^{125}I, ^{35}S, ^{131}I, ^{153}Sm, ^{177}Lu, $^{186/188}Re$, ^{192}Ir
- High n flux: $>10^{14}$ ^{60}Co, ^{192}Ir, ^{75}Se, ^{89}Sr, ^{177}Lu, ^{99}Mo, ^{188}W

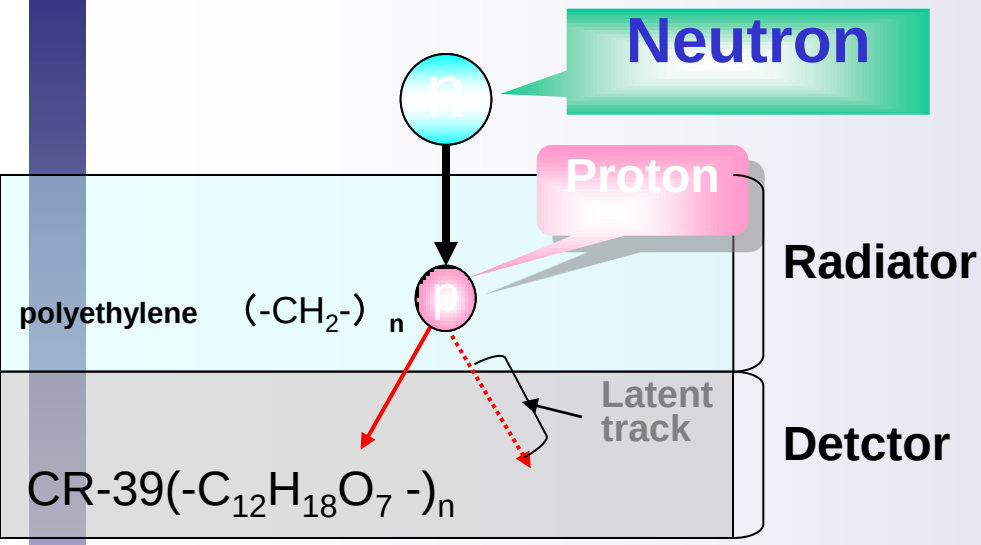
NUCLEAR SAFETY IN WORKPLACES IN NUCLEAR REACTOR

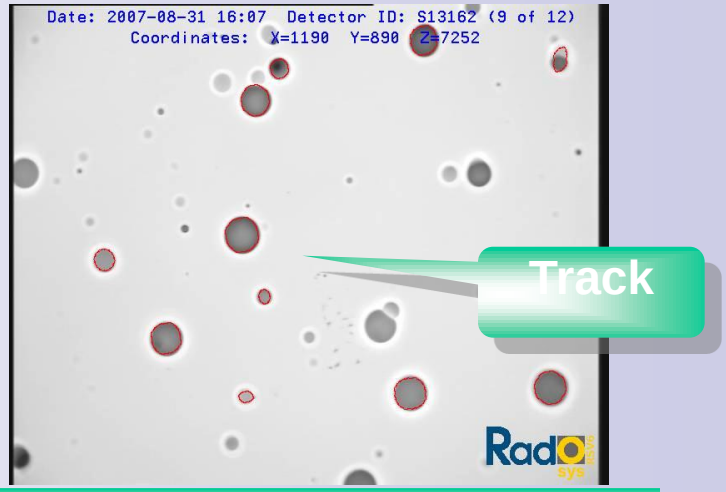
Monitoring system in control room

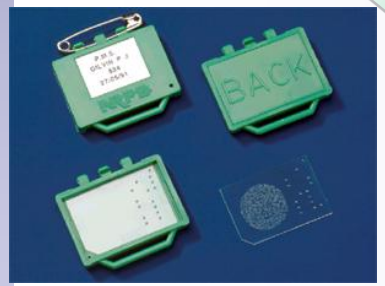
Management of nuclear waste

Monitoring system in laboratory

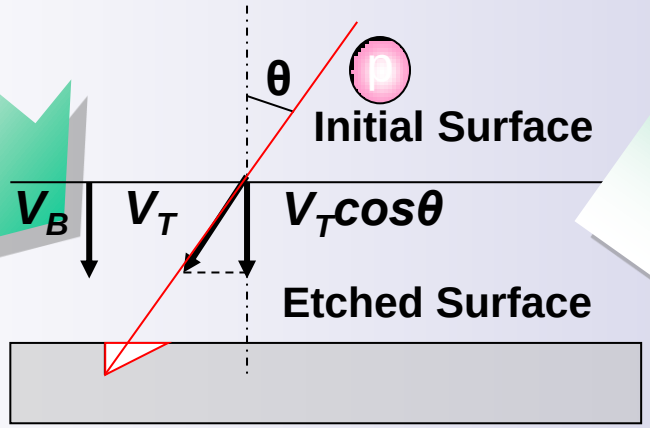
Neutron Dosimetry with CR-39







Etching



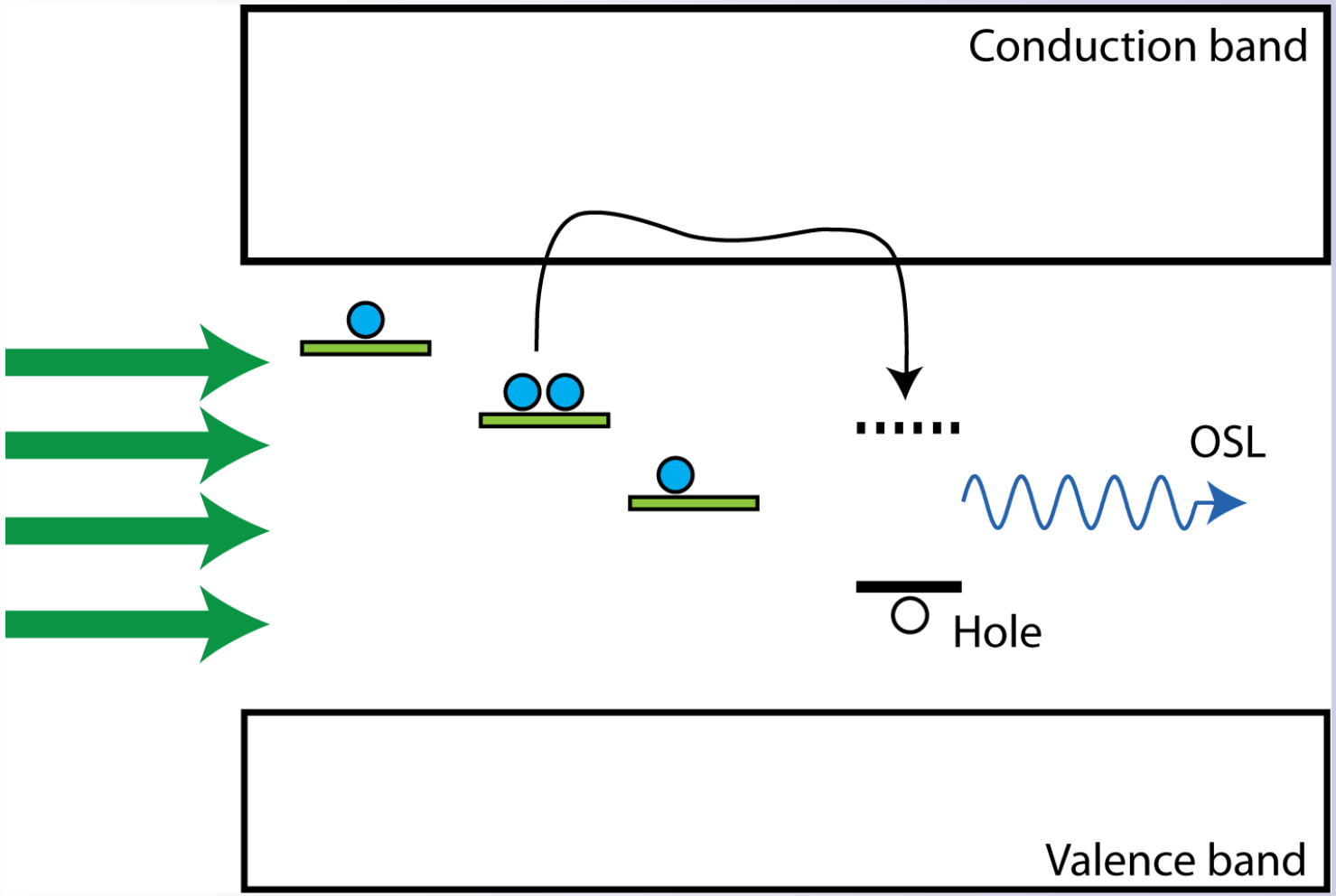
Critical angle condition

$V_B < V_T COS\theta$

V_T : Track etching velocity

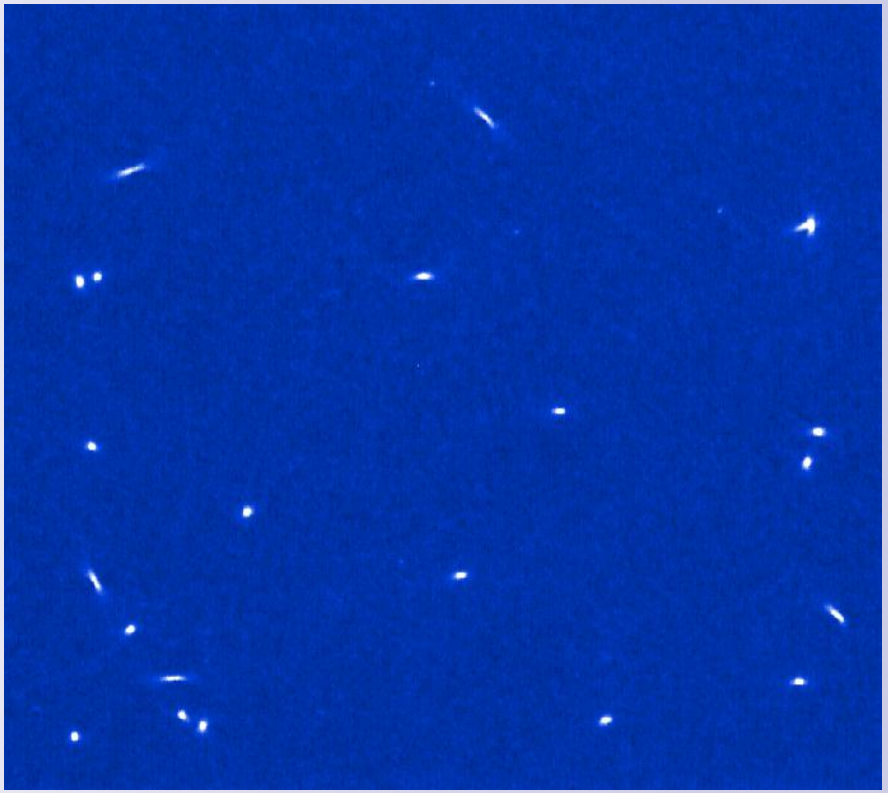
V_B : Bulk etching velocity

Principle of OSL Dosimetry



Novel Fluorescent Nuclear Track Detector Technology for measuring neutrons, photons and HCP

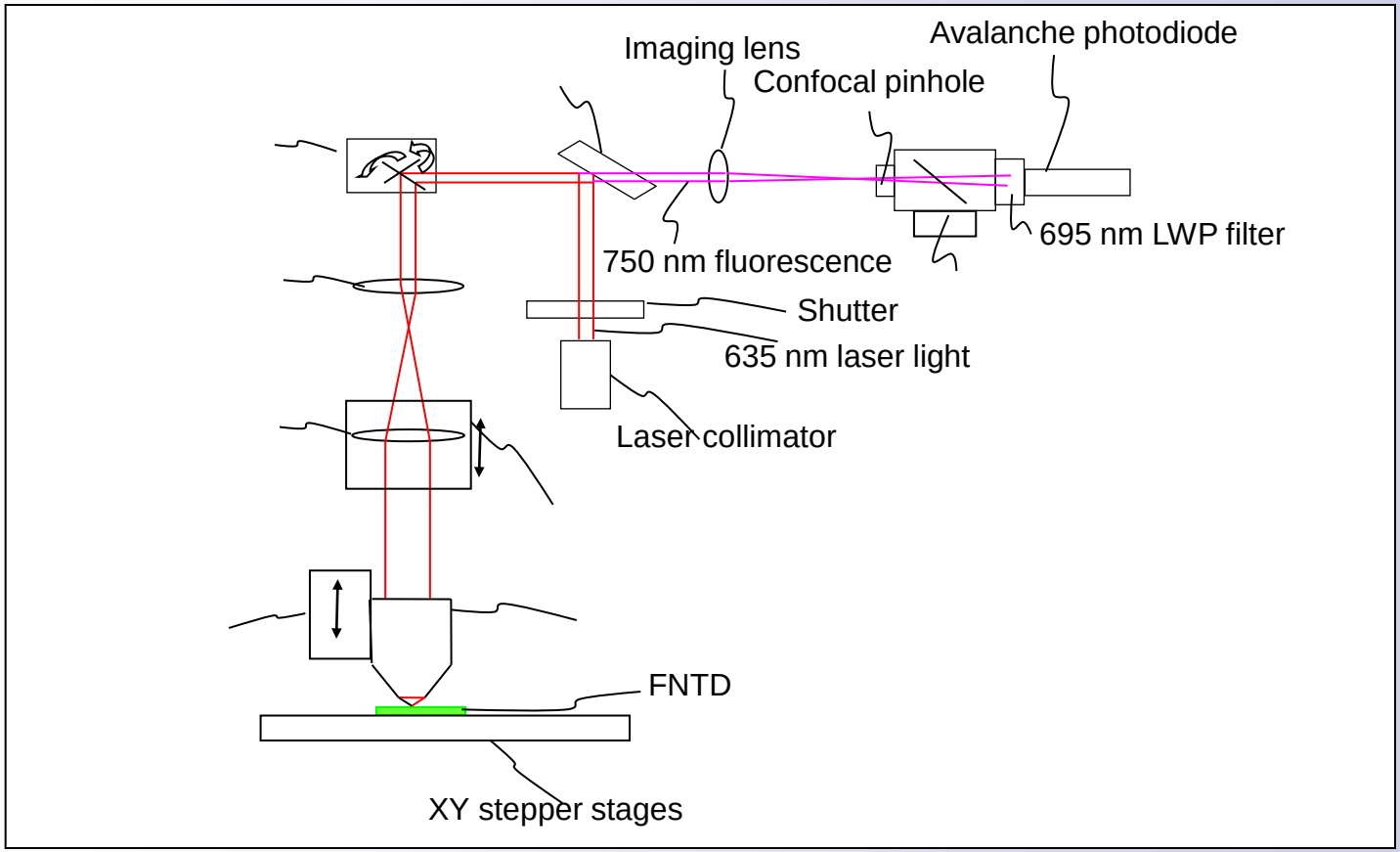
- Problems of dosimetry of protons and neutrons
- Optical properties of novel Al_2O_3:C,Mg crystals
- Optical technique and instrumentation
- Performance of FNTD in mixed neutron-gamma fields
- Preliminary results after irradiations with protons



Courtesy of Dr M Akselrod

Fluorescent image of neutron induced recoil protons

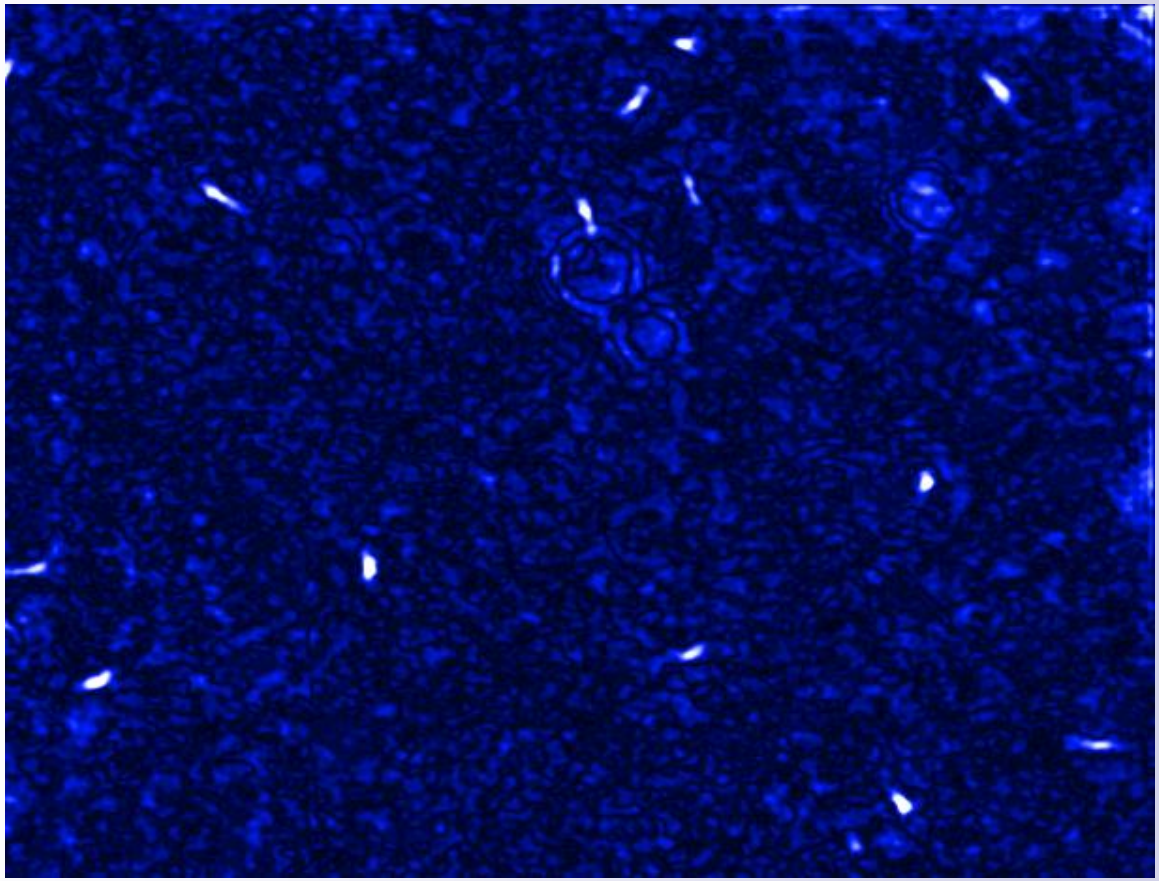
Optical diagram of imaging system



- The imaging system is based on a concept of a confocal laser scanning microscope.
- The system is designed for fast scanning and nondestructive readout of the detector.

Courtesy of Dr M Akselrod

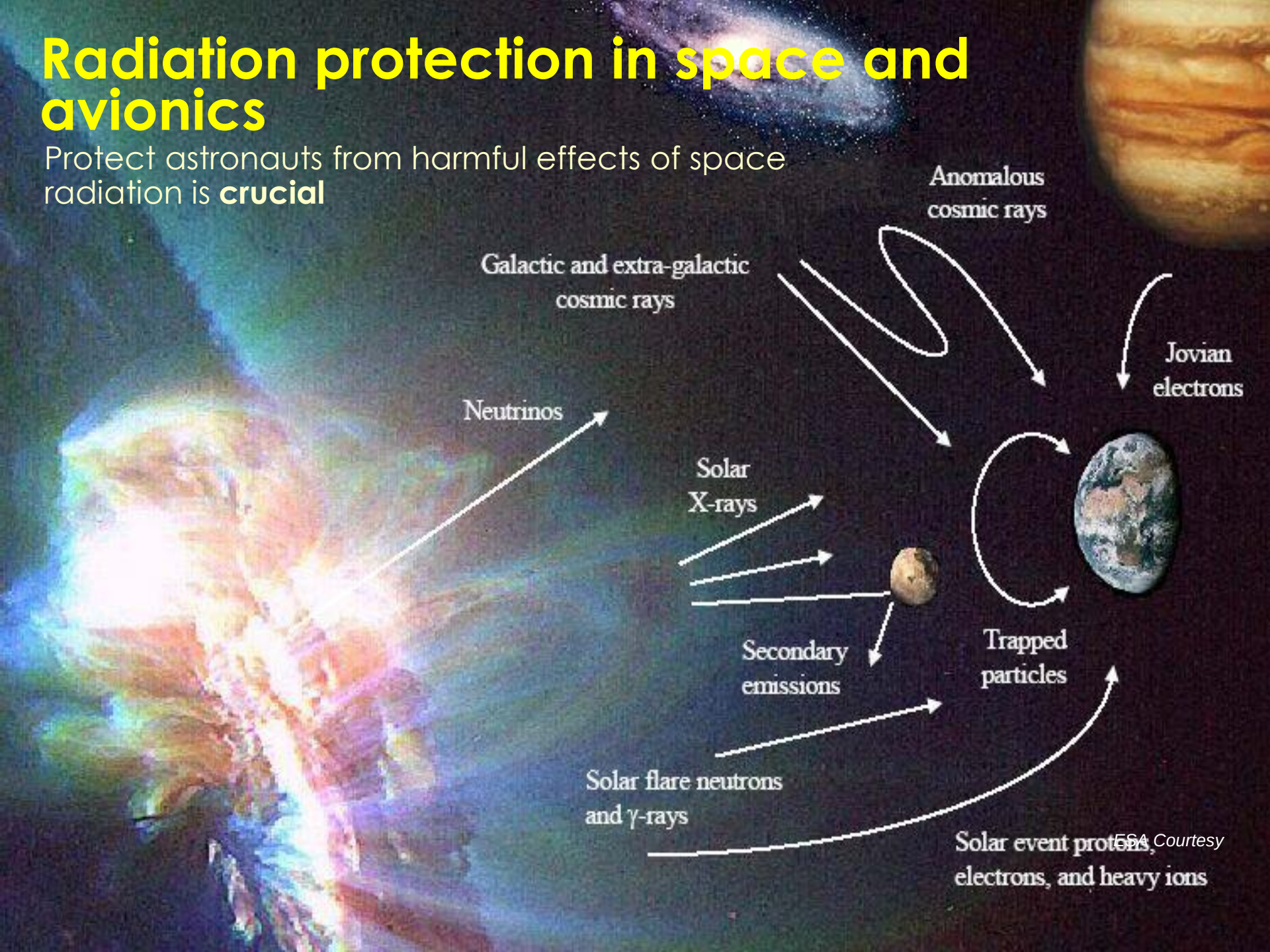
Recoil protons propagating through the crystal detector



Courtesy of Dr M Akselrod

Radiation protection in space and avionics

Protect astronauts from harmful effects of space radiation is **crucial**



ESA Courtesy

Space Radiation Environment

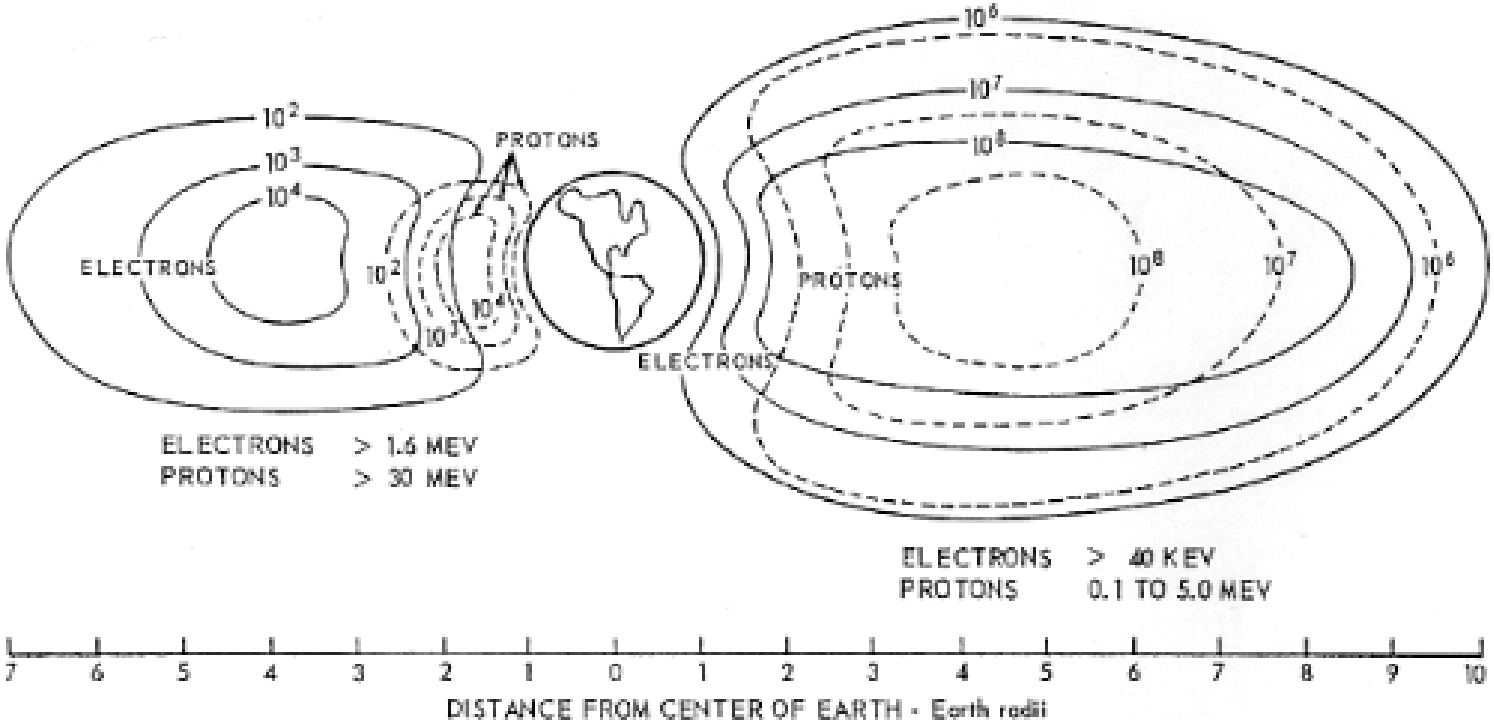
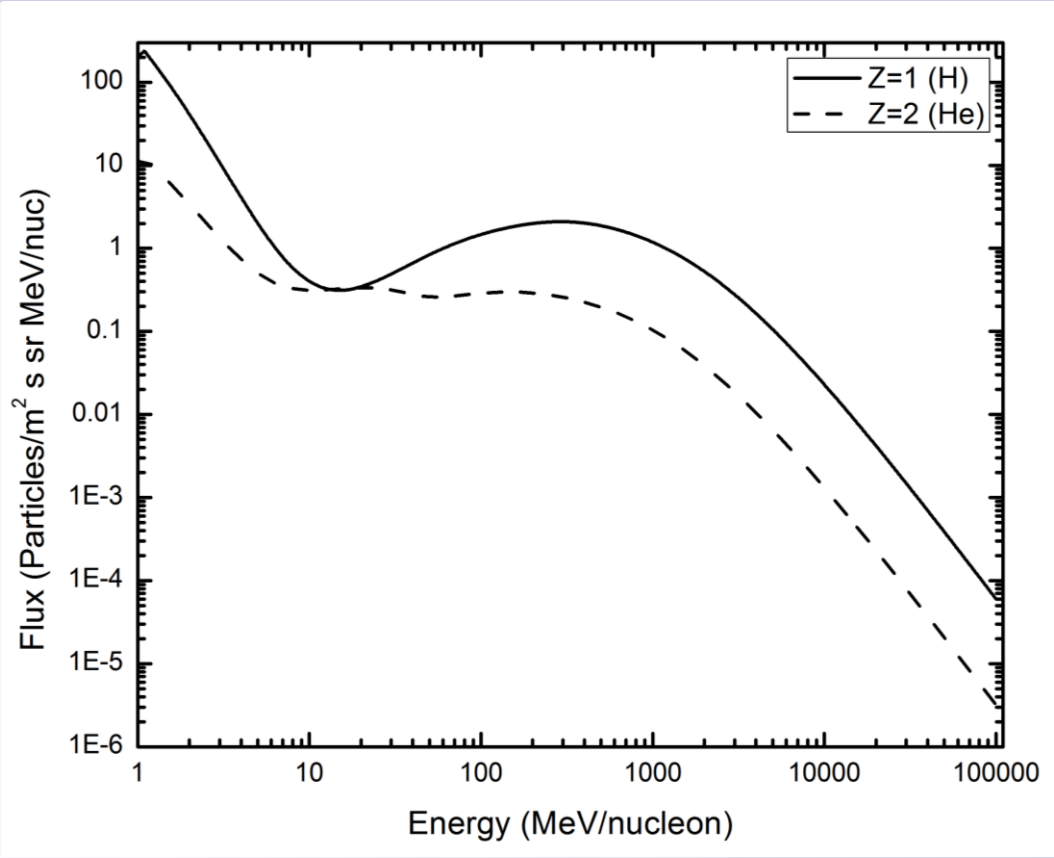


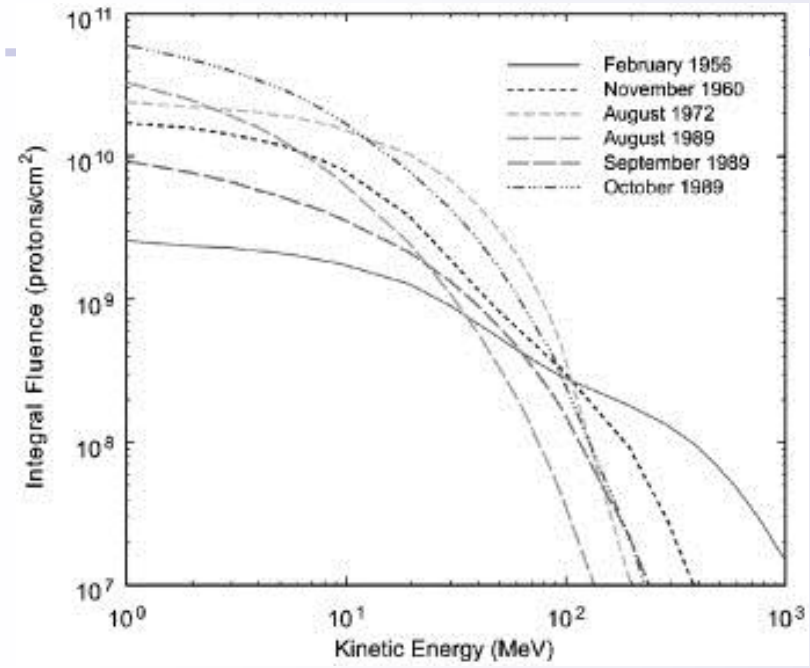
Figure 1. Trapped radiation belts as a function of energy and distance from the earth.

Space Radiation Environment

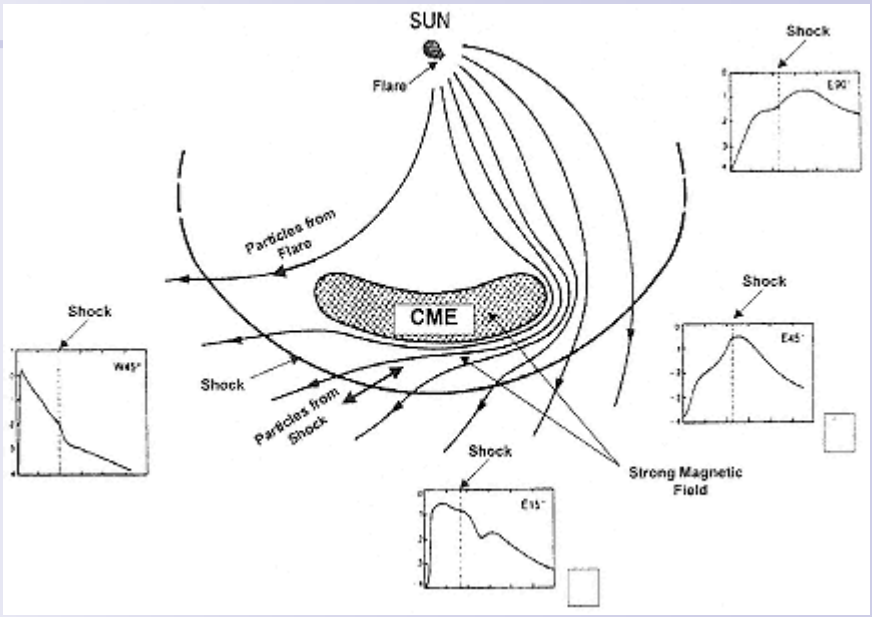


Galactic Cosmic Rays (GCR) for proton and alpha at 1AU. Taken from CREME96 database

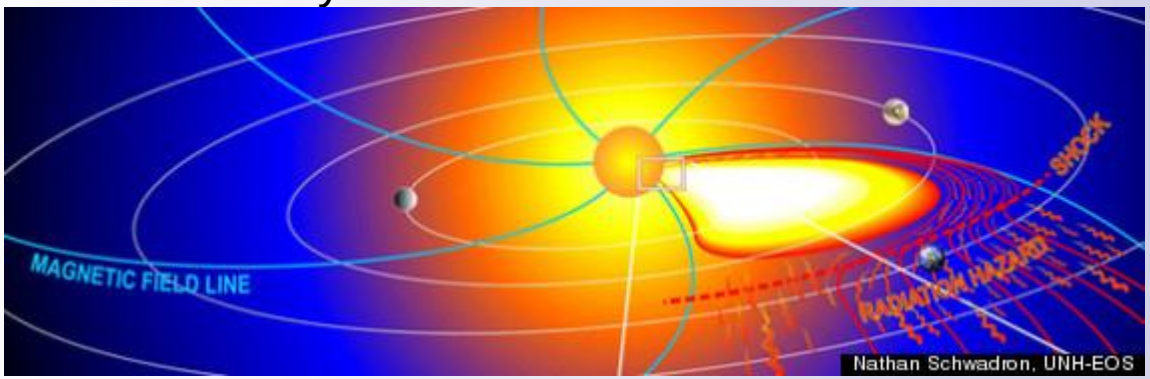
Space Radiation Environment



Integral proton fluences for several major SPEs over the last four solar cycles

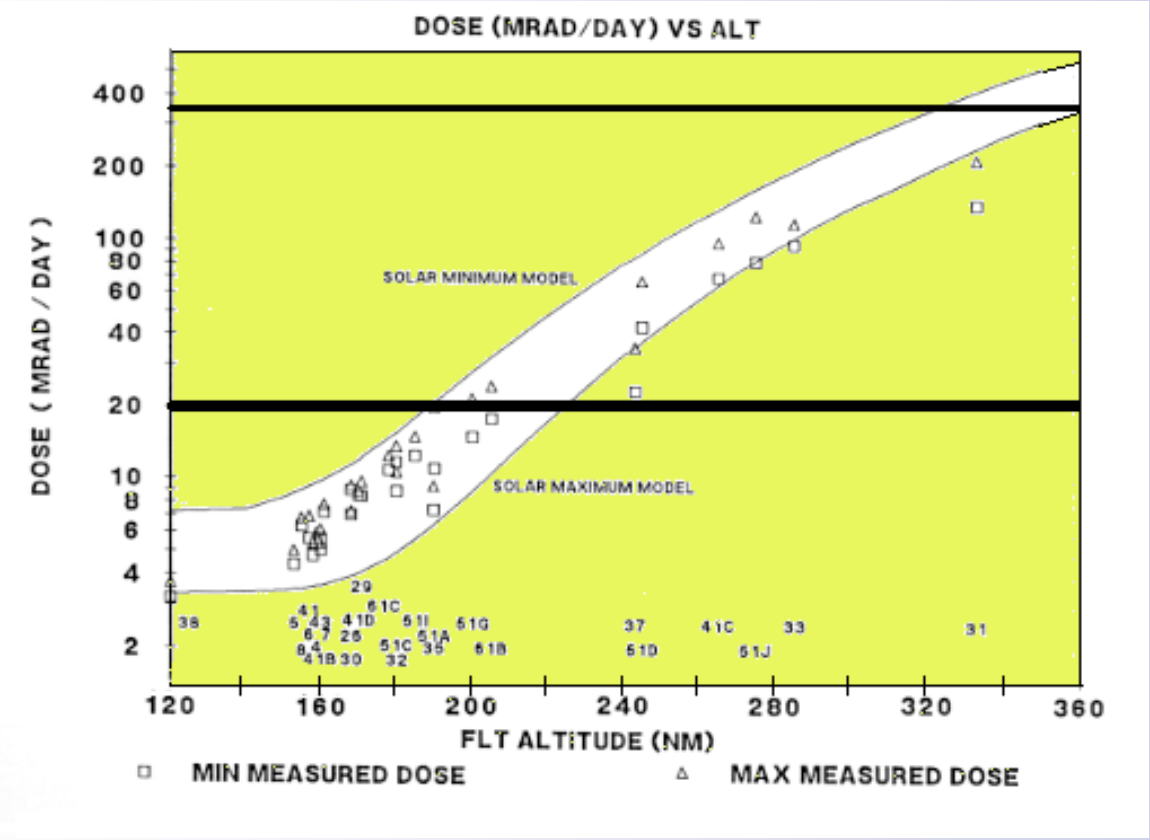


This figure illustrates the rise and fall of fluxes of solar energetic particles during an SPE.



Human missions in space

The amount of radiation received by astronauts depends on several factors including orbital inclination, altitude, position in the solar cycle, and mission duration.



The figure above shows the radiation dosages encountered by Space Shuttle astronauts during various missions indicated by the numbers near the bottom of the graph. The average altitude of space shuttle orbits is 170 Nautical Miles corresponding to 9 milliRad/day.

LIMITS ON OCCUPATIONAL DOSES (ICRP)

	Annual Dose Limit (mSv)
Effective dose, worker	**20**
Equivalent dose to lens of eye	**150**
Equivalent dose to skin	**500**
Equivalent dose to hands and feet	**500**
Effective dose to embryo or fetus	**1**
Effective dose, public	**1**

- Effective dose of 20 mSv per year— averaged over a period of 5 years
- Should not exceed 50 mSv in any one year
- Equivalent skin dose of 500 mSv per year—Limit is set on basis of avoiding deterministic effects
- Dose limits do not apply to radiation dose employee receives as part of personal healthcare

Dosimeters for spacecraft crew

The Pille dosimeter system

the first and to date only TLD system designed specifically for use by cosmonauts and astronauts while travelling in space.

Figure 15. Space Shuttle Dosimetry.

Figure 14. Charged particle directional spectrometer (CPDS).

Figure 13. Tissue equivalent proportional counter (TEPC).

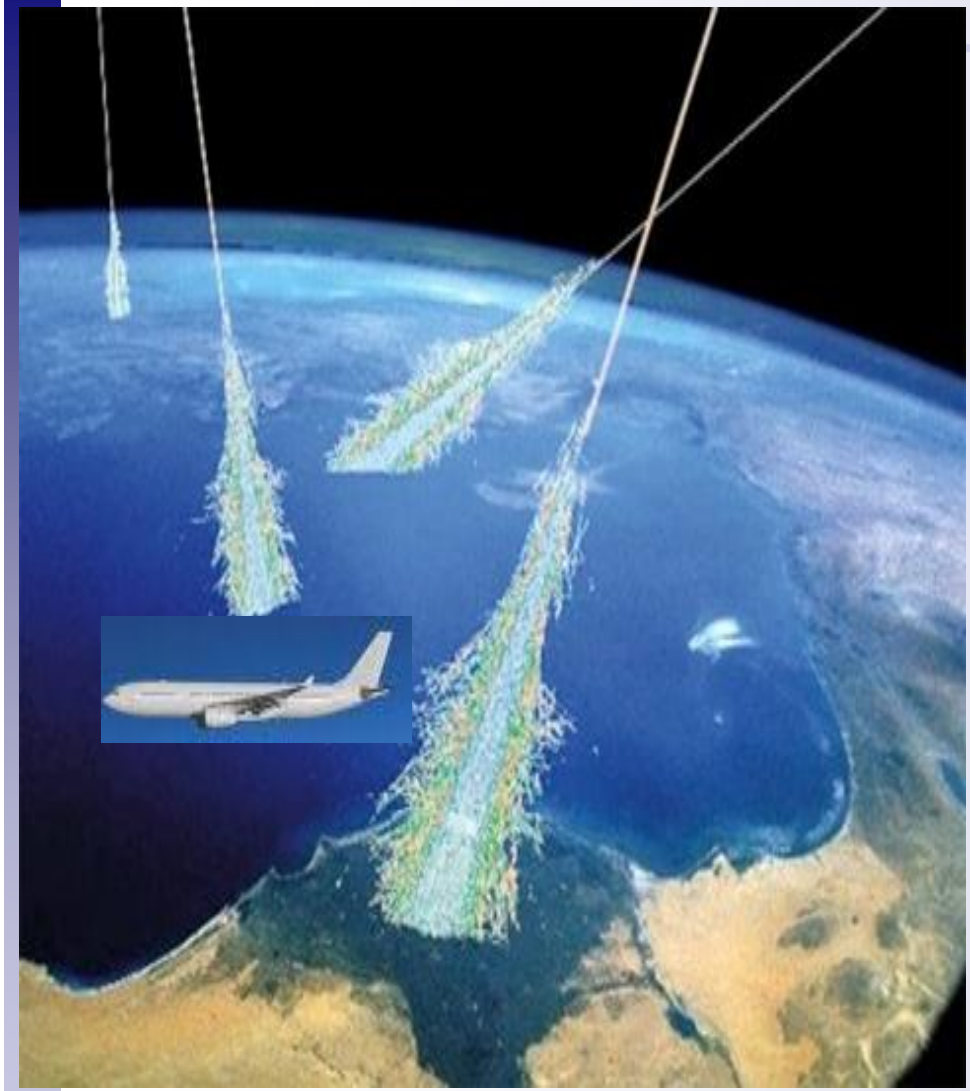
Hazards in Space and Avionics

The most critical health risks for astronauts , those classified by NASA as ranked as 1(I), are:

- **Carcinogenesis caused by radiation**
- **Loss of bone mass or density**
- **Human Performance: Poor psychosocial adaptation**
- **Clinical Manifestations: Trauma or acute medical problems**

NASA's Critical Path Roadmap (April, 2003)

RADIATION PROTECTION IN AVIATION



Mixed Radiation Field: Protons, Neutrons, Electrons, Gammas, Muons, Pions.

- ❑ Doses are affected by…
  - Altitude,
  - Latitude and
  - Solar activity
- ❑ Typical dose rate: 5-6μSv/h at 10.67 km (35.000 ft)

Dose limits for aircraft crew members:

- ❑ Considering usual total annual flight times of crew members (≤1000 hours).

DOSIMETRY and RECORDS are REQUIRED

Atmospheric depths (g cm $^{-2}$)Aircraft heights (km)

25

30

Private jet (15 km)

20

100

15

SST (18-20 km)

Commercial (10 km)

10

300

5

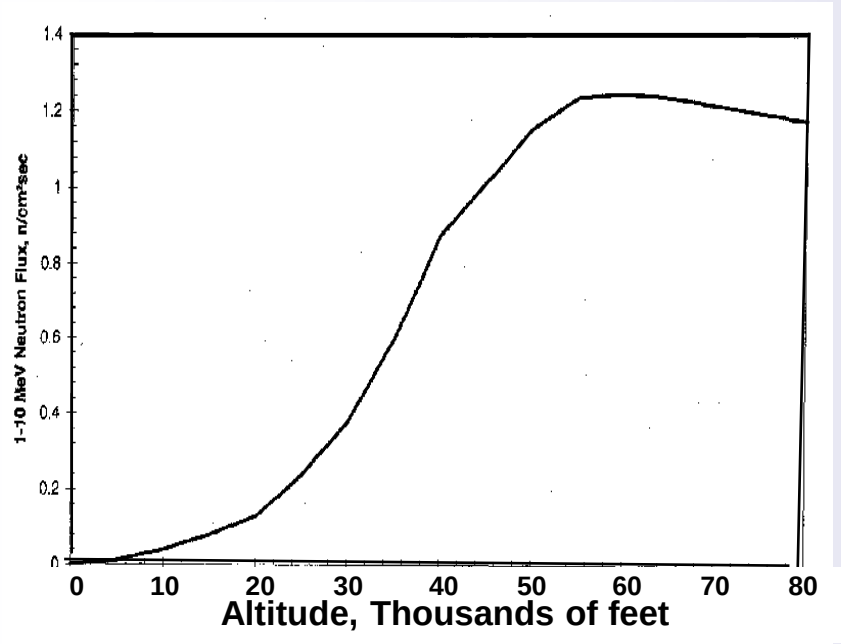
1000

Tibet (3.7 km)

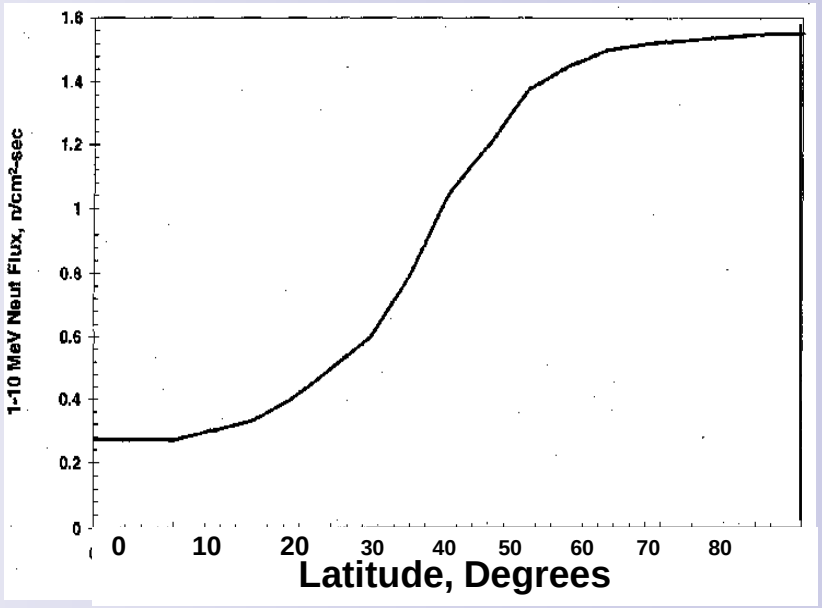
Kendall et al, 2000

Dosimetry in aviation – Neutron flux (1-10MeV)

1-10MeV atmospheric neutron flux as a function of altitude based on aircraft and balloon measurements



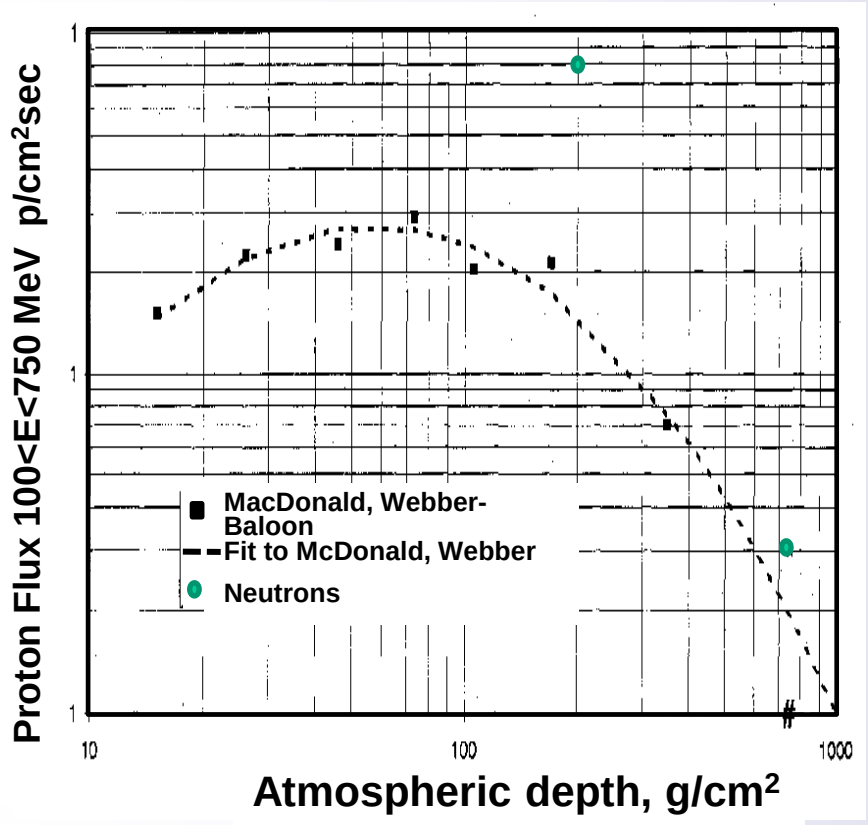
1-10MeV neutron flux as a function of geographical latitude based on aircraft measurements



A. Taber, et al, IEEE 1993

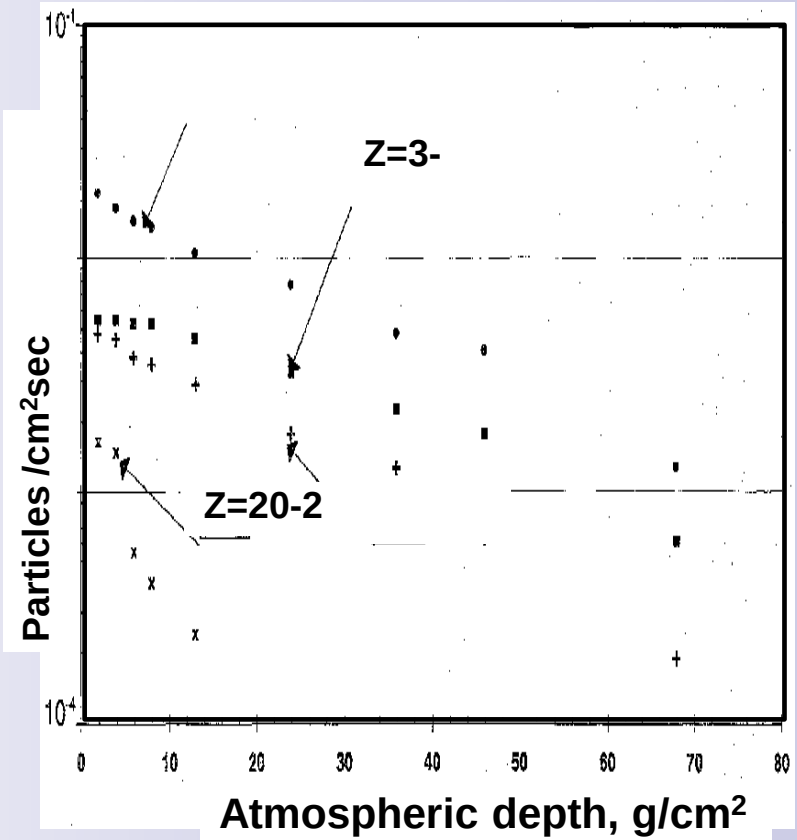
DOSIMETRY IN AVIATION – PROTON AND ION FLUX

Comparison of measured atmospheric proton flux 100<E<750MeV as function of depth)



H. B. Barber, T. Brown et al, Phys. Review 1980

Fall-off verticle ion flux with depth for ions of energy>200MeV/nucleon)

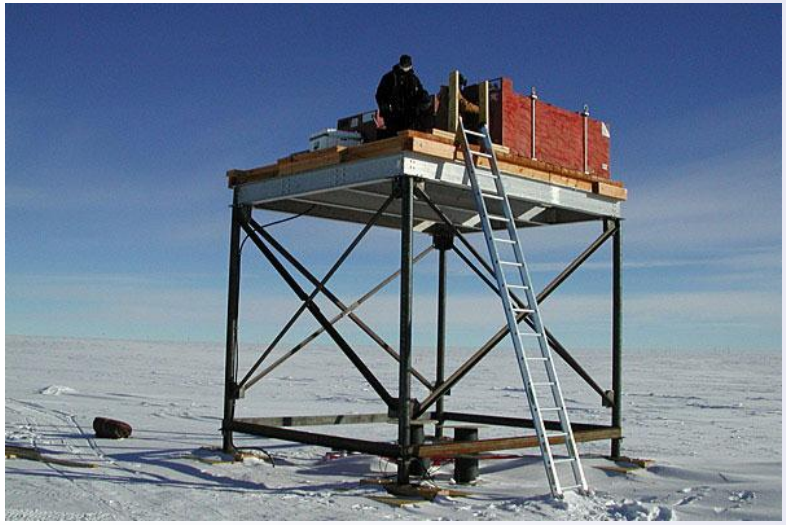


Leukemia or Cancer risk for aircrew

	< 1000hours	1000-5000 hours	>5000hours
Leukemia	0	0	1.9
Acute Myeloid Leukemia	0	0	5.1
CLL	0	0	1.3
Melanoma	0	0	2.8
Other Skin	0	0	3.0

Gundestrup et al, 1999

DOSIMETRY IN AVIATION



Ground based neutron monitoring station at the South Pole

Ground based neutron monitoring stations:

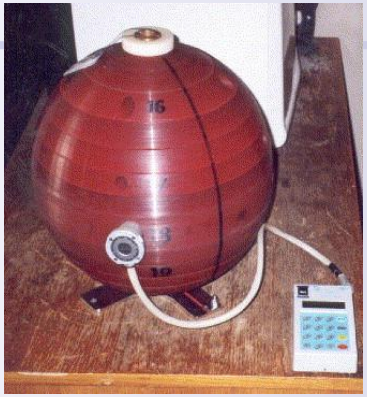
✓ provides data for analysis of solar and cosmic events

✓ but it is not clear if this type of monitoring provides sufficient protection for airborne aircrew in significant events.

Personal real time Dose Equivalent dosimetry is required for air crew

- **Measurement of neutrons on aircraft** with TEPC and Brookhaven National Laboratory dose equivalent meter (DEM) with two sets of Bonner sphere moderators. [NASA ,1976]

SPECTROMETERS AND DETECTORS FOR DOSIMETRY IN AVIATION

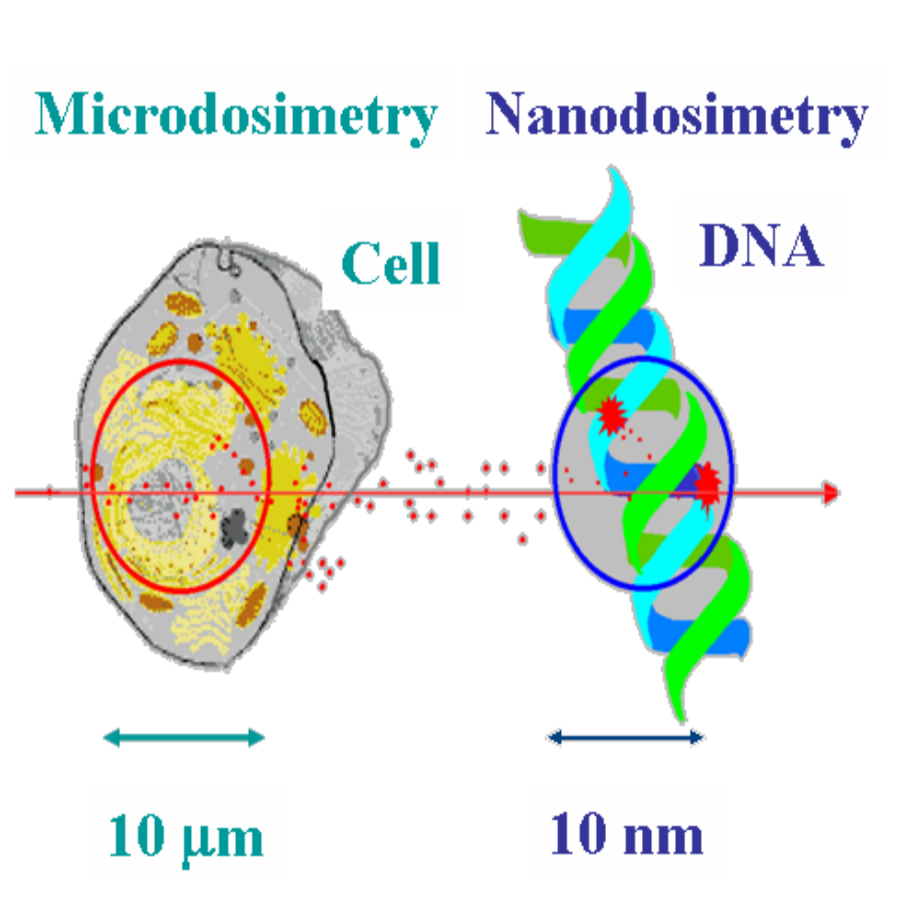


TEPC (Hawk2) **Luilin** **Bubble detector**

Detector	Capabilities	Weight [g]	Battery Requirement
TEPC	Dosimetry Information	5000	6V DC D-Cells
Luilin	Spectral Information	550	12V pack (15h)
FH41B	Gamma and Protons	200	19V (5months)
Bubble Detector	Neutrons	----	-----

Nanodosimetry vs Microdosimetry

- Volume of interest:
  - Cell versus DNA
- Statistical Fluctuations:
  - much larger in ND
- Empty Events
  - common in ND
  - uncommon in MD
- Choice of Gas
  - unrestricted in ND
  - restricted in MD



Why Nanodosimetry?

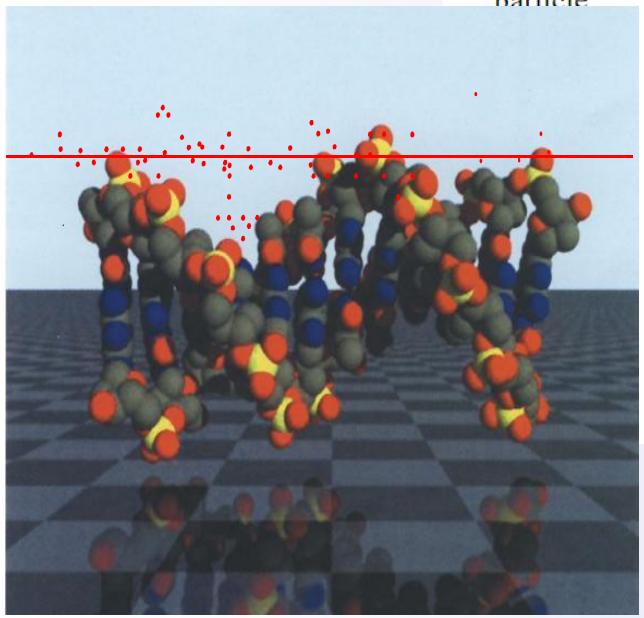
- Ending point in cell desactivation is DNA damage
- Clustered DNA lesions are difficult to measure *in vivo*
- Relative number of clustered lesions probably determines RBE
- RBE changes with depth of therapeutic hadron beams are usually subtle (for protons)
- Increasing number of patients treated with hadrons requires better definition of RBE values

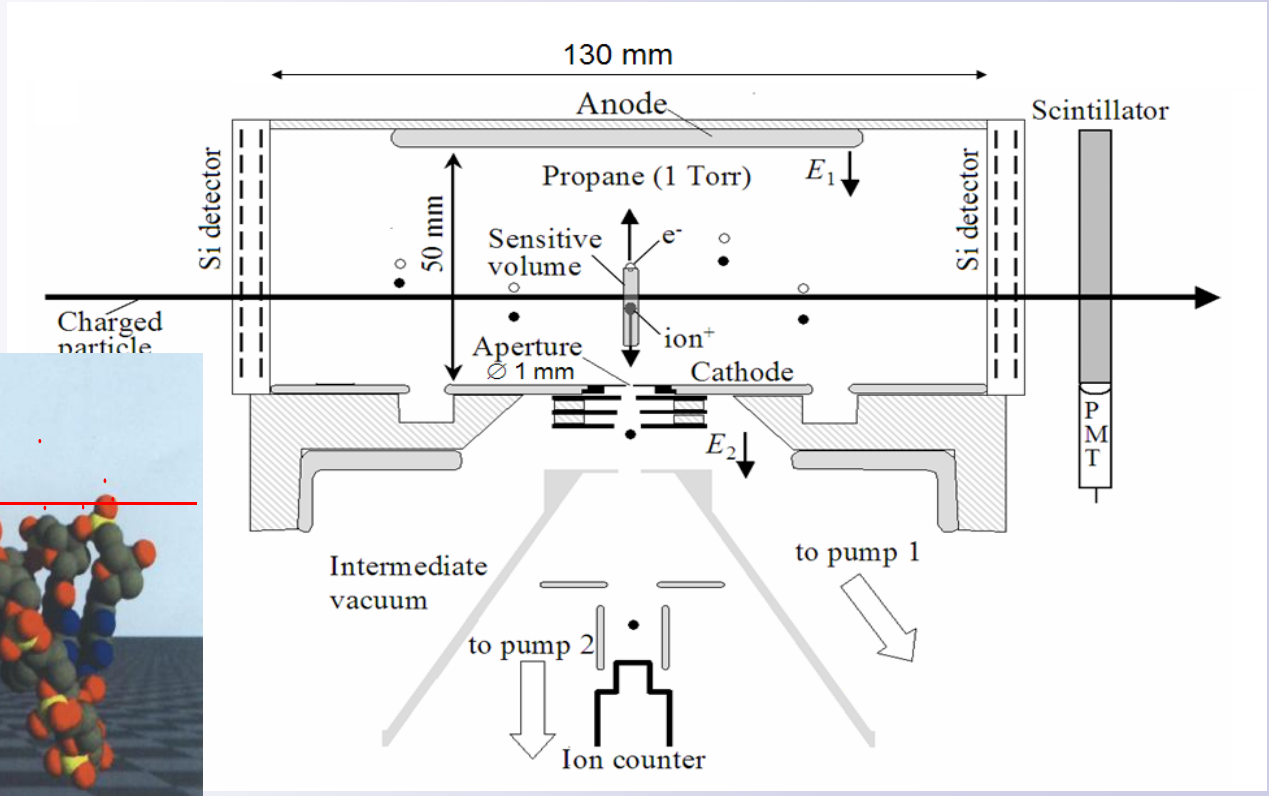
Efforts in Nanodosimetry

- Significant effort has been invested into the development of numerical simulation codes modeling particle track structure on the nanometer scale
- Experimental validation is an important step for such codes
- Experimental efforts in this direction are scarce but one such option is low pressure gas counter which measures individual ionisations of charged particle tracks

Low-Pressure Gas Nanodosimetry

Loma Linda Uni Medical Centre nano-dosimetry facility

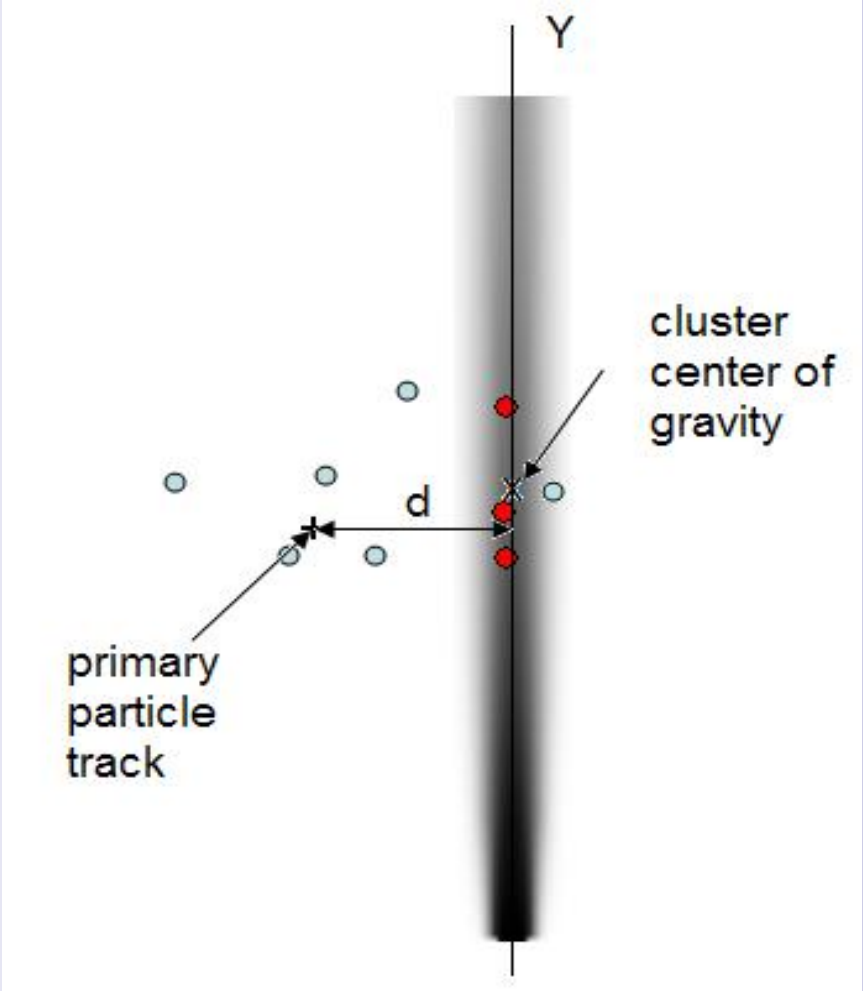




Millimeter size TE gas volume represent nm size /DNA fragment due to low gas pressure

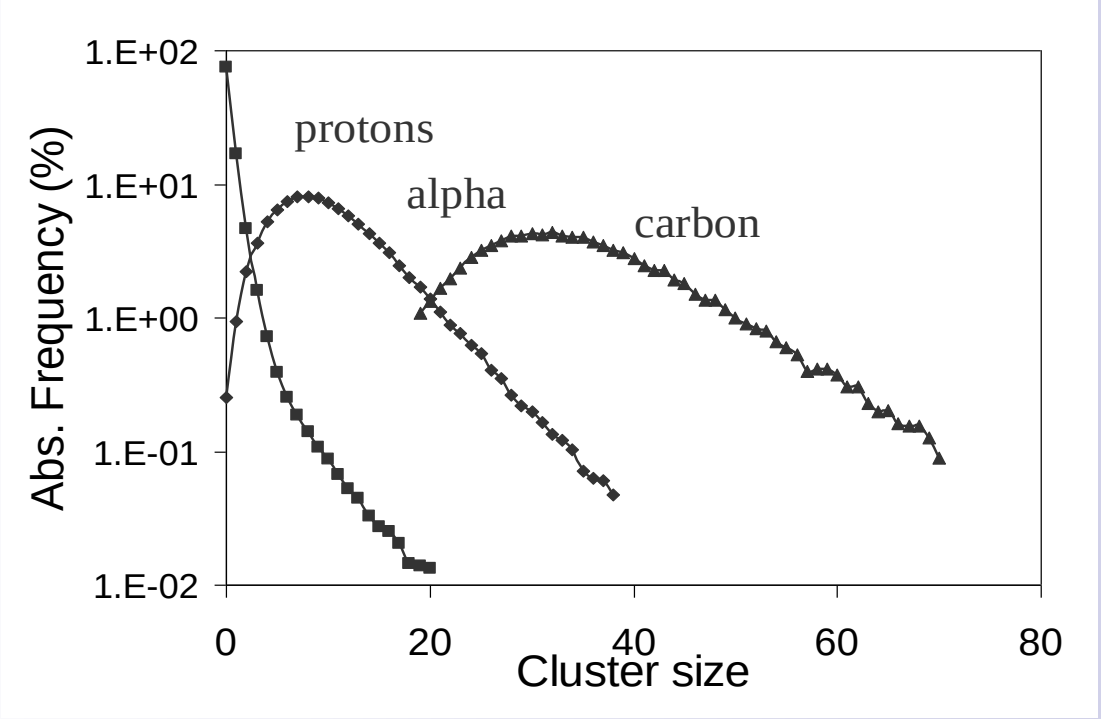
Cluster Size Definition

- Cluster size is the number of ionizations detected or simulated within a SV representative of a segment of double-stranded DNA that occur within 10nm of one another.

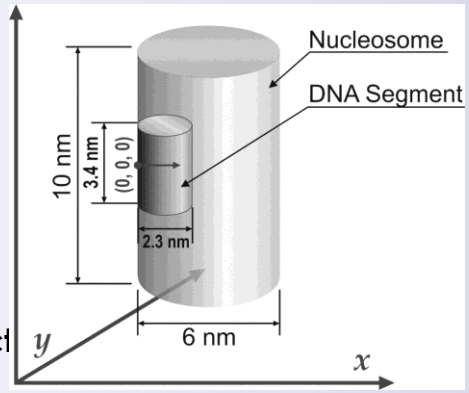


Cluster size measured for different ions

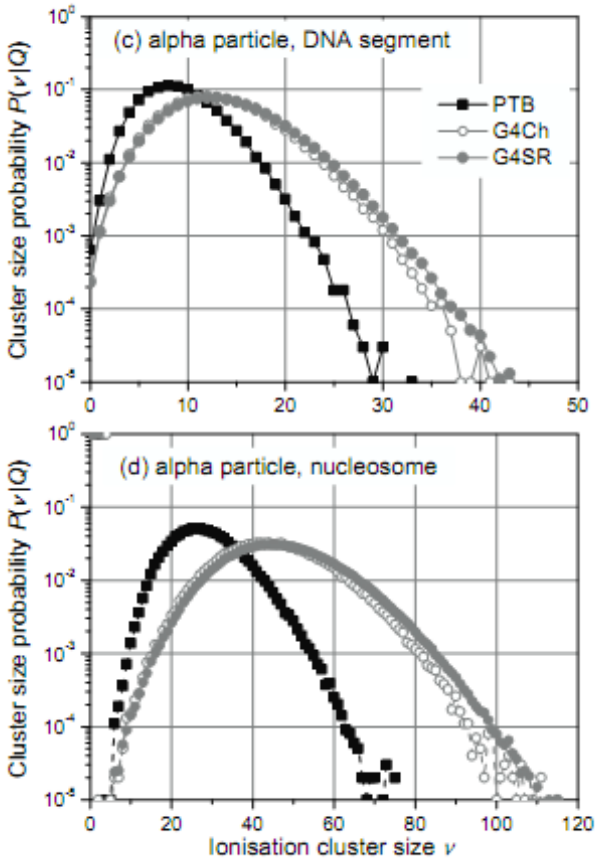
- Using radiobiological model based on a cluster size and simulating by MC GEANT 4 secondary ions possible improvement of RT planning. Experimental cluster sizes will be used



Monte Carlo computational Nano-Dosimetry



- **Nanodosimetric approach**
  - **Study the spatial distribution of interact on a DNA scale**
- **DNA segment** ~10 base pairs long
  - **Size of a Double Strand Break (DSB)**
  - **Represents** direct DNA damage
- "**Nucleosome**" represents distance free radicals can diffuse into DNA
  - **Represents** indirect DNA damage
- **Liquid water** medium
  - Commonly used to represent biological materials



Geant4-DNA and PTra for nanodosimetry

Lazarakis *et al.*, Phys. Med. Biol. **57** (2012) 1231–1250

Monte Carlo is a powerful method in radiation dosimetry

Dosimetry of Radiopharmaceuticals for Diagnostic and Therapeutic Nuclear Medicine

MIRD DOSIMETRY

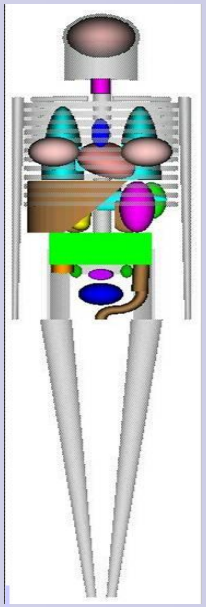
A STANDARD FORMALISM FOR INTERNAL DOSIMETRY IN NUCLEAR MEDICINE WAS DEVELOPED IN THE 1960'S AND BECAME KNOWN AS THE MIRD SYSTEM OF INTERNAL ABSORBED DOSE CALCULATION

The absorbed dose to a target organ from a radionuclide located within \ a source organ can be calculated as:

$$D_T = \tilde{A}_S \Sigma_i n_i E_i \varphi_i / m_T$$

n_i is the number of radiations with energy E_i per disintegration,
φ_i is fraction of energy emitted by the source region that is absorbed in the target)
m_T is the mass of the target organ,
$\tilde{A}$ is the cumulative activity, changing with time

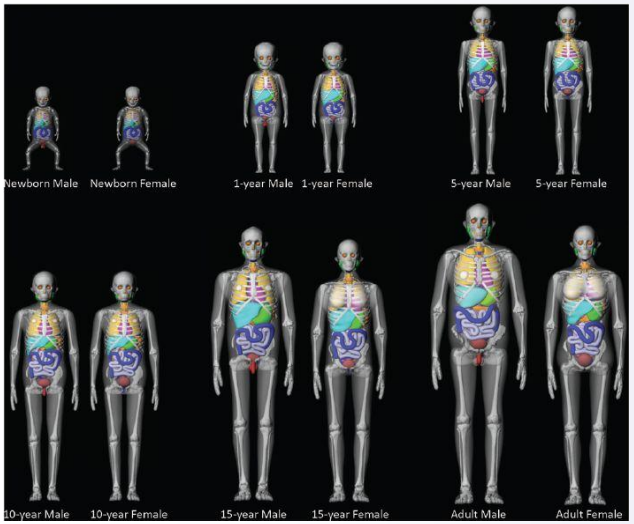
The absorbed fractions were calculated from an anthropomorphic mathematical model of the human body which has become known as the MIRD phantom



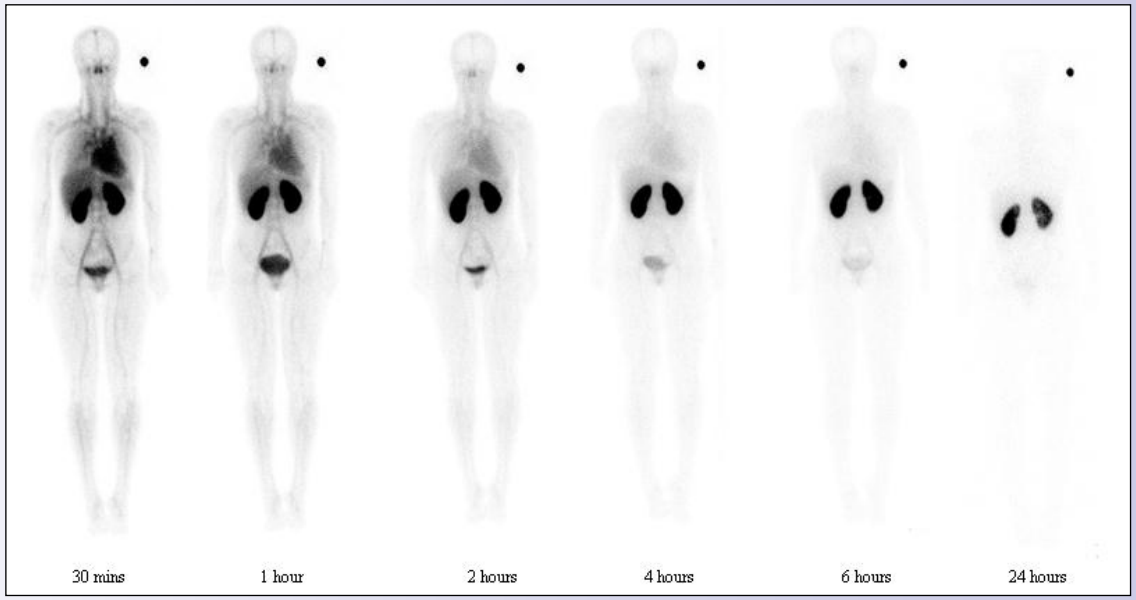
The mathematical phantom used by the MIRD
http://www.doseinfo-radar.com/RADARphan.html

Dosimetry of Radiopharmaceuticals for Diagnostic and Therapeutic Nuclear Medicine

There are now more than 50 voxel CT based phantoms available representing Chinese, Japanese and Korean persons as well as Caucasian, and representing babies, children as well as both male and female adults.



The University of Florida family of reference voxel phantoms



Anterior whole body images obtained after intravenous administration of ^{99m}Tc jn female subject over a 24 hour period.
Effective dose was found to be 8.6 mSv and 9.4 mSv for males and females respectively, for an administered activity of 750 MBq

Conclusion

- Radiation Dosimetry is a very interesting field of research with multiple range of applications from Occupational Radiation Protection to advanced Radiation Therapy Quality Assurance
- Too many questions are still to be answered and major is "do we know what parameter of radiation field can predict accurately biological effect"
- Development of dosimetry instrumentation with response to predict biological effect in any radiation field is a challenge to be addressed by ARDENT

Acknowledgement

- ARDENT
- CMRP colleagues and PhD students
- Prof Tomas Kron ,Dr Alex Romanyukha and Dr David Schauer for sharing some slides

Recommended Reading.

Rosenfeld A.B. Kron T. ,. d'Errico F, and. Moscovitch M. editors "*Concepts and trends in medical radiation dosimetry*", American Institute of Physics ,ISBN:978-0-7354-0901-9 (2011)

Metcalfe P.; Kron T.; Hoban P. *The physics of radiotherapy X-rays from linear accelerators*. 1997.

MMND and IPCT 2012

Mini-Micro-Nano-Dosimetry Workshop and Modern Technologies of Prostate Cancer Treatment

Centre for Medical Radiation Physics
University of Wollongong

6-9 December, 2012

Centre for Medical Radiation Physics