MOSFET dosimetry in radiotherapy

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The Ottawa Hospital Regional Cancer Centre | L'Hopital d'Ottawa

Disclosure

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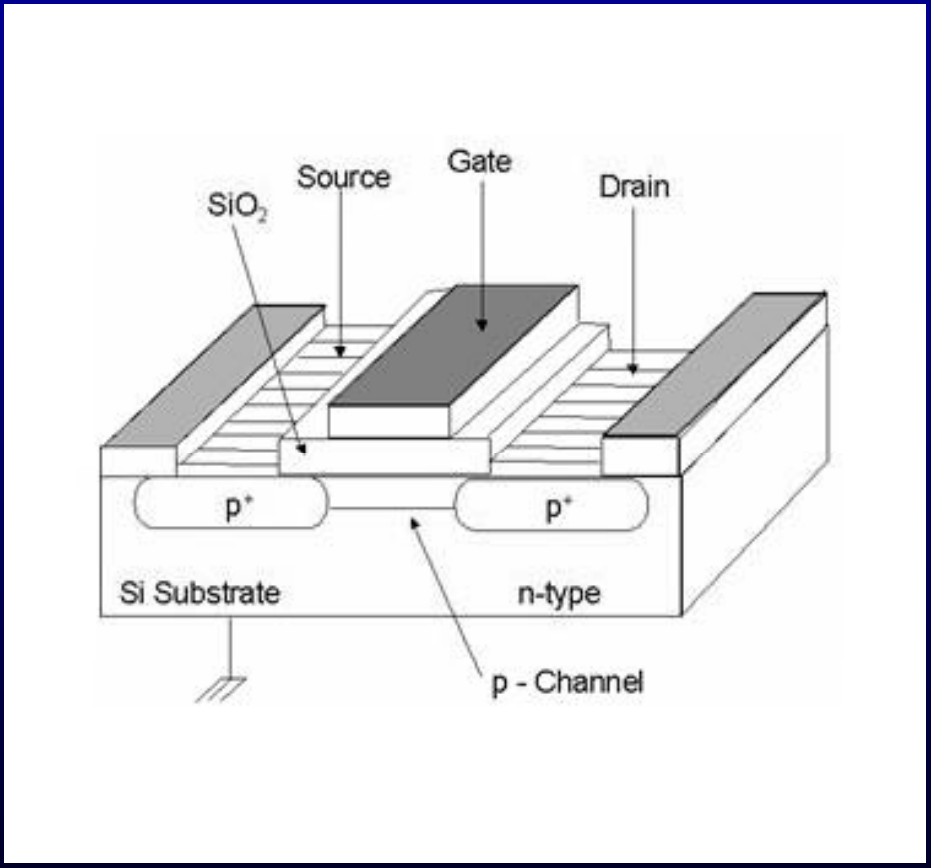
Outline

- Principles of MOSFET dosimetry
- Brief description of commercially available MOSFET systems
- Dosimetric characteristics of MOSFET detectors
  - Temperature dependence
  - Energy dependence
  - Dose and dose rate dependence
  - Time dependence (other than the dose-rate dependence)
  - Angular dependence
- Advantages and disadvantages
- Clinical dosimetry applications
- Summary

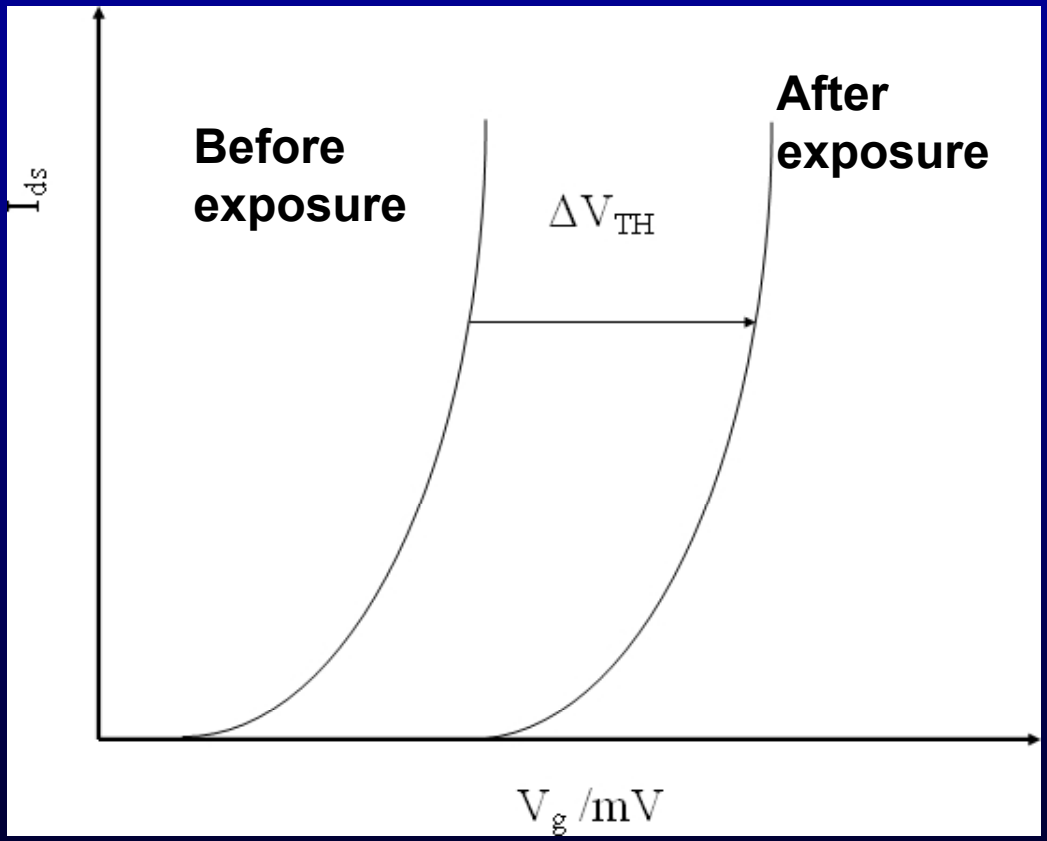
MOSFET structure

- **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor
- Capable of dose measurements immediately after irradiation or can be sampled in predefined time intervals (on-line dosimetry)
- Can operate in active (negative bias on gate during radiation) or passive mode



*Soubra, Cygler, Mackay, Med. Phys. **21(4)**, 567-572, 1994*

Threshold voltage shift / ΔVT



- ΔV_T is a function of absorbed dose
- That function is linear when the MOSFET operates in the biased mode during the irradiation
- Absorbed dose linearity region increases with the increase of the bias voltage

*Soubra, Cygler, Mackay, Med. Phys. **21(4)**, 567-572, 1994*

Types of MOSFETs available

Single bias, single MOSFET

- Temperature dependence
- Instability of response

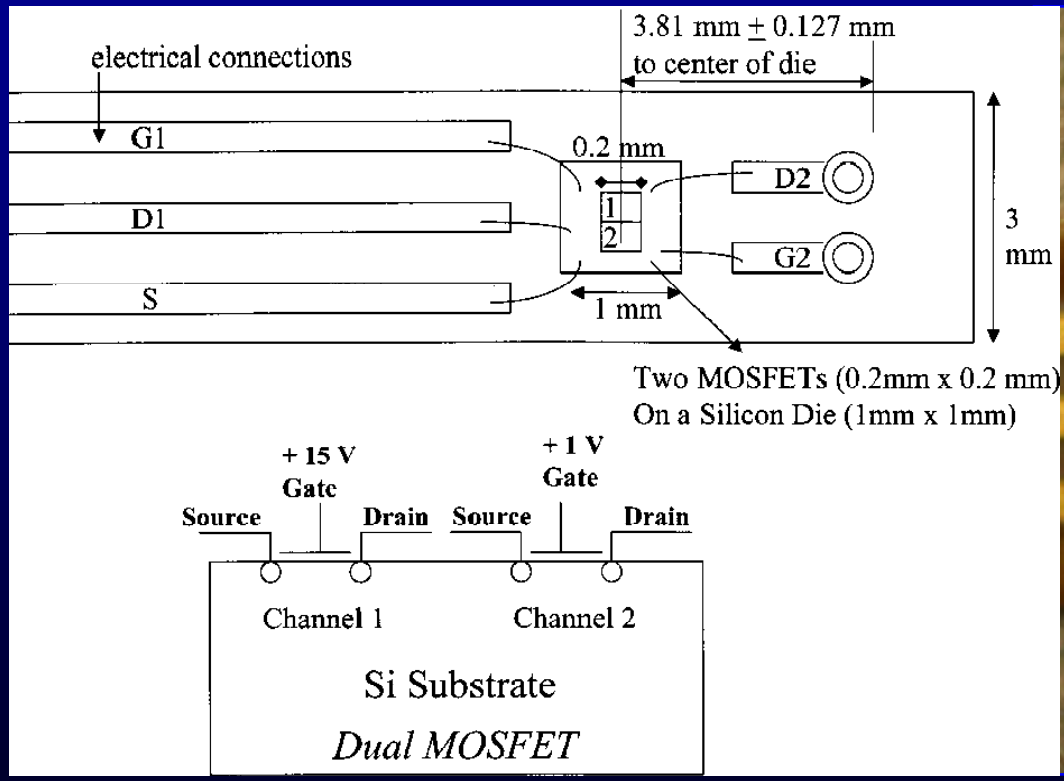
Dual-bias, dual-MOSFET

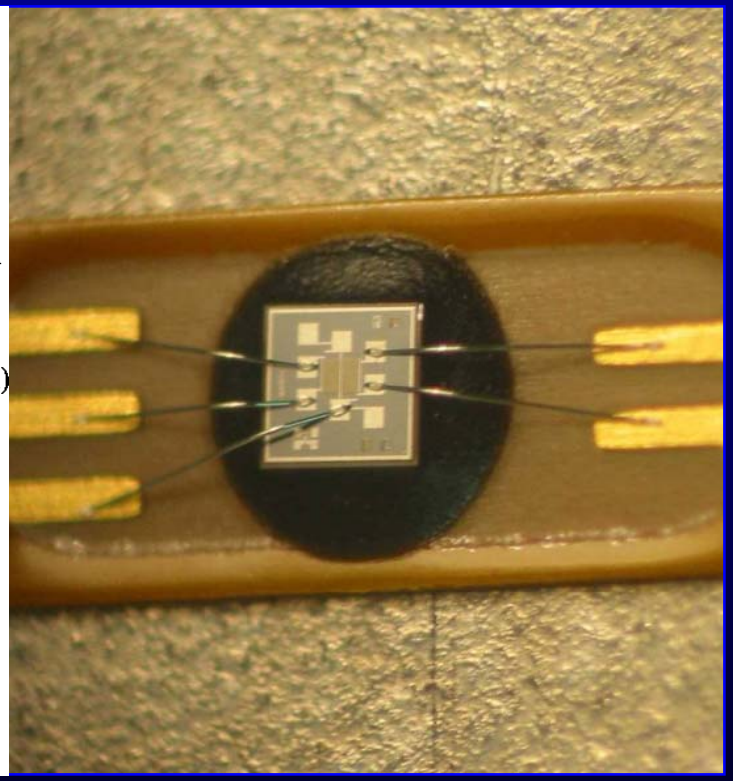
- Proposed by Soubra, Cygler et. al. in *Med. Phys.* (1994)
- Two MOSFETs on same silicon chip operating at two different gate biases
- Better sensitivity, reproducibility, and stability than single MOSFET
- Minimal temperature effects

Unbiased single MOSFET

- Temperature dependence
- Instability of response, frequently used as disposable detectors
- Shorter linearity range than biased MOSFETs

Dual-MOSFET-dual-bias detector



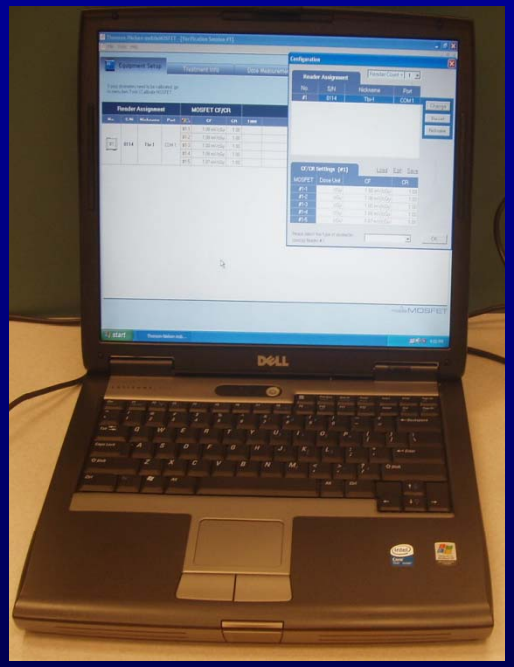


Courtesy of Ian Thomson

Commercial MOSFET systems available on the market

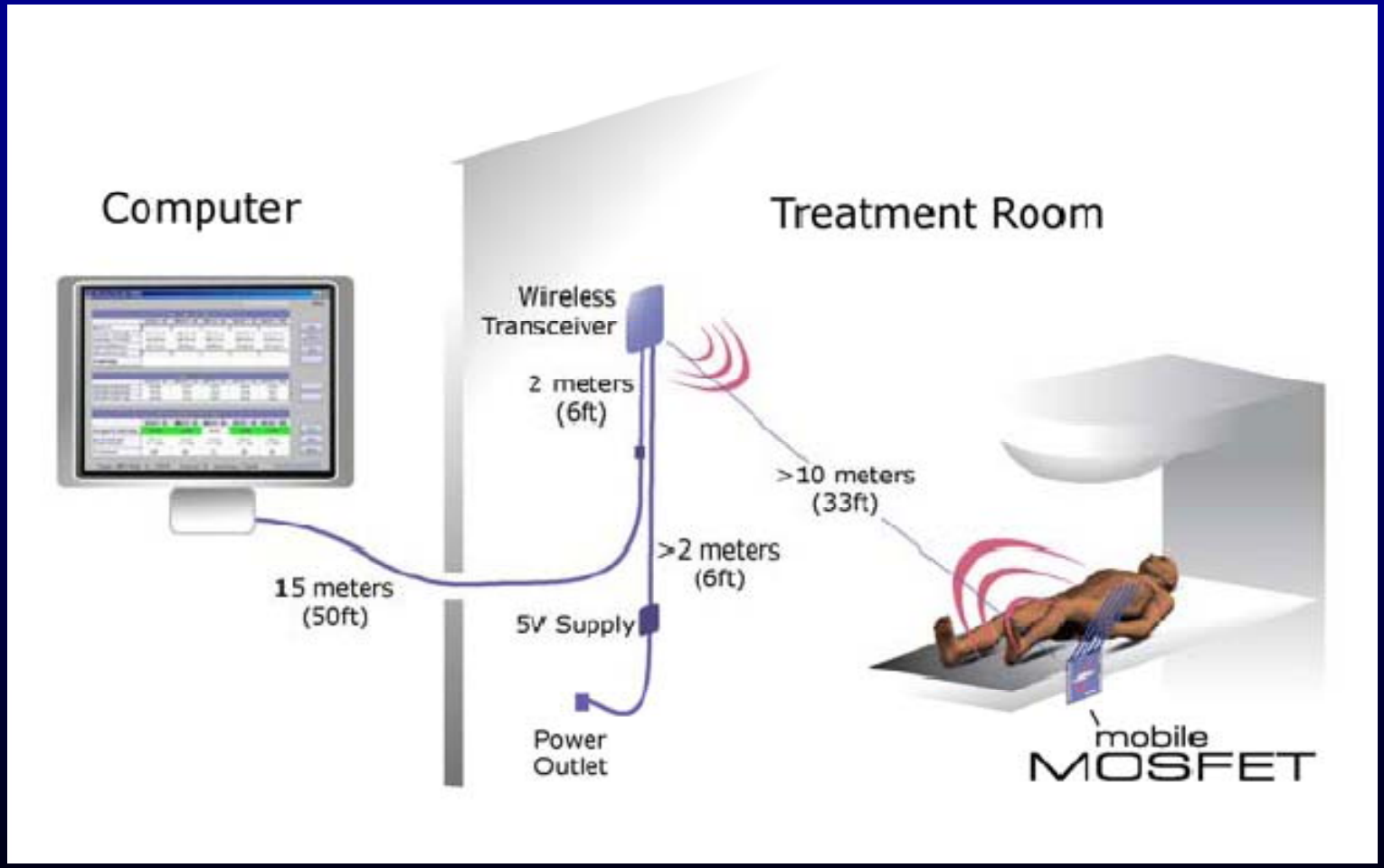
- BEST Medical (Thomson-Nielsen)
  - Mobile MOSFET system
- Sicel Technologies Inc.
  - OneDose system
  - DVS (Dose Verification System)

Mobile MOSFET system



TN detectors come in two physical sizes: standard and microMOSFETs, see Table 29-I

Wireless setup

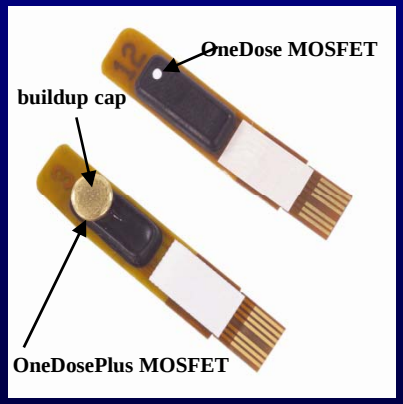


Nominal sensitivities in high-energy photon beams of various TN detector/bias combinations.

TN MOSFET type	Bias	Nominal sensitivity (mV/cGy)
Standard sensitivity	Standard	1
Standard sensitivity	High	3
High sensitivity	Standard	3
High sensitivity	High	9

OneDose MOSFET system

OneDose reader

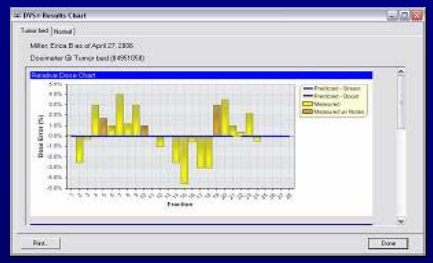


OneDose MOSFET detectors

Courtesy of Sicel Technologies

Dose Verification System Components

11-gauge needle



Implantable Dosimeter

Plan and Review Software

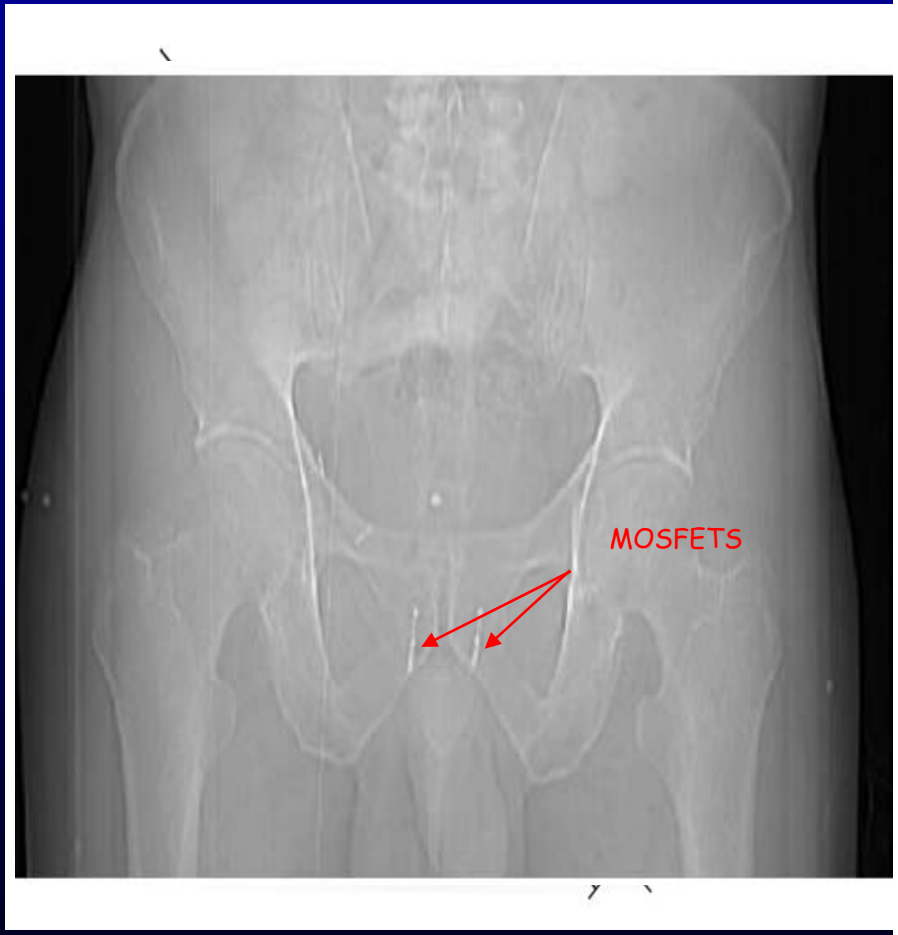
DVS®
Dose Verification System

DVS
Database

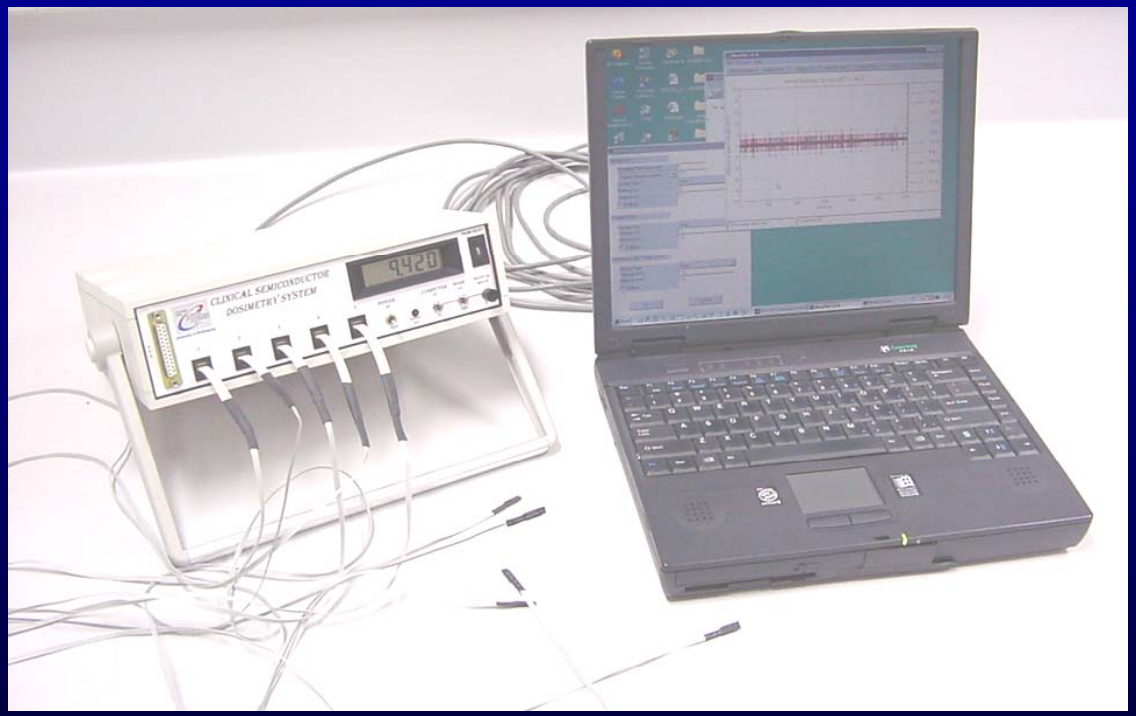
Courtesy of Sicel Technologies

Implantable MOSFET detector (DVS)

- Electronics assembly contains 2 MOSFETs and support circuitry
- Bi-directional antenna coil provides dosimeter power and communications channel
- Hermetically sealed in bio-compatible glass capsule
- Filled with medical grade epoxy



CMRP MOSFET Dosimetry System



MOSkin detectors, thickness 0.07 mm, see Table 29-III

MOSFET Clinical Dosimetry System:

designed and distributed by CMRP

Courtesy of Anatoly Rosenfeld

MOSFET calibration

- Purpose – to establish calibration coefficient of the detector

$$CF(Q) = \frac{D_0(Q)}{M_{\text{det}}(D_0, Q)}$$

Units: cGy/mV

$$S_{AD,w}(Q) = \frac{1}{CF(Q)}$$

Units: mV/cGy

$$M_{\text{det}}(D_0, Q) = \Delta V(D_0, Q)$$

$$D(Q) = CF(Q) * \Delta V_{th} * \prod_i k_i$$

Calibration process

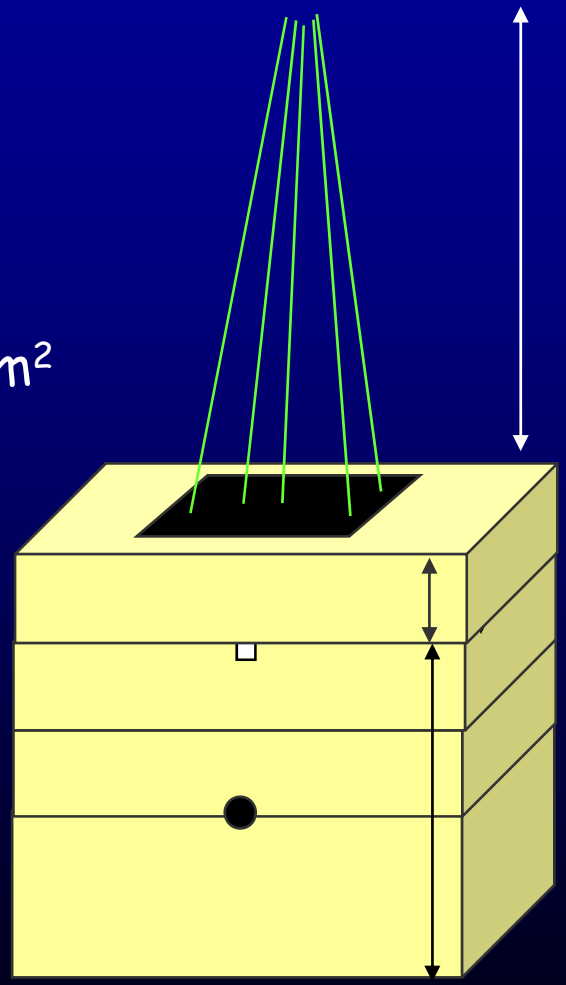
Calibration process ⟶ dosimetric characterization of detectors ⟶ calibration coefficient

- In principle, the users are responsible for the calibration of new detectors
- Some companies, e.g. Sicel sell pre-calibrated detectors.
  - the user is still responsible for checking the calibration coefficients, so errors are avoided in patient dosimetry

Dosimetric characterization of MOSFET detectors

- MOSFET detectors should be fully characterized before use
- How it is done, depends on the intended use of the detector
- Calibration in full buildup conditions
  - in phantom, at a standard depth, e.g. d_{max}, 5 cm, etc.
  - in a linac beam, simultaneous measurement of the detector and ionization chamber signals

SSD calibration set-up



SSD_1 = 80 cm (Co-60)

SSD_2 = 100 cm (linac)

Field Size = 10x10 cm^2

MOSFET depth = 5.0 cm

Ion chamber depth = 11.3 cm

Backscatter = 12.3 cm

*Diagrams not to scale

Clinical calibration process

- 50-100 MU delivered several times, threshold voltage recorded before and after each trial

- Simultaneous ion chamber measurement used to determine the dose $D_0(Q)$ for each trial

M_{raw} —*TG-51*→ Dose @ depth = 11.3 cm —*PDD curves*→ Dose to water at MOSFET location

$$CF = \frac{D_0(Q)}{\Delta V_{th}(D_0, Q)}$$

$$\left[\frac{cGy}{mV}\right]$$

Calibration Process for DVS

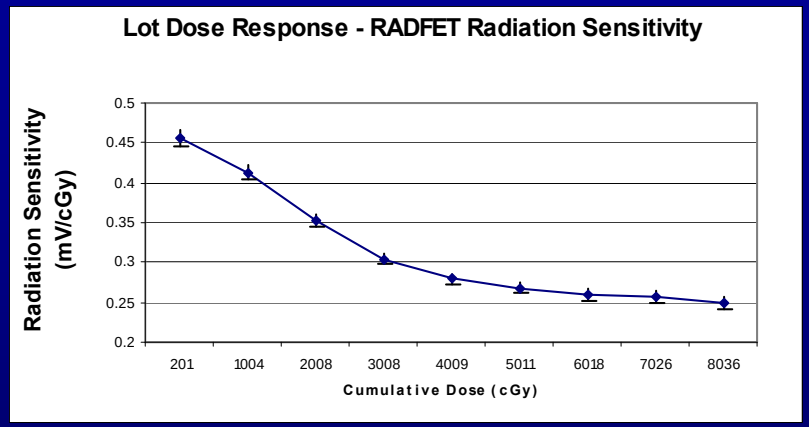
- Calibration performed by the manufacturer
- The response (or radiation sensitivity) of each dosimeter is first determined using a ^{60}Co source
- Calibration is performed in a phantom ("*in vitro*") at body temperature (37°C)

Sicel ^{60}Co Irradiator

In-Vitro Water Tank Testing

Courtesy of G. Beyer

Calibration Process for DVS *(cont.)*



Dose response curve

- *A cumulative dose response calibration curve is obtained for a specific lot by irradiating a statistically significant representative sample from the lot up to* **80Gy** (*maximum dose range of the dosimeter*).

- Verified by UW-ADCL (sample lot sent for testing)
- Calibration is valid for use with daily doses of 150-250 cGy
- Reported accuracy for each lot has a calibration certificate with values within:
  - <5.5% (2σ) up to 20 Gy
  - <6.5% (2σ) up to 74 Gy (accuracy decreases for doses > 74 Gy).

Courtesy of G. Beyer

Correction factors for MOSFETs

- Environmental – temperature (no pressure correction)
- Energy dependence
  - beam energy
  - modality (photons, electrons, particles)
- Accumulated dose
- Dose rate
- Field size
- SSD
- Directional dependence

Temperature dependence

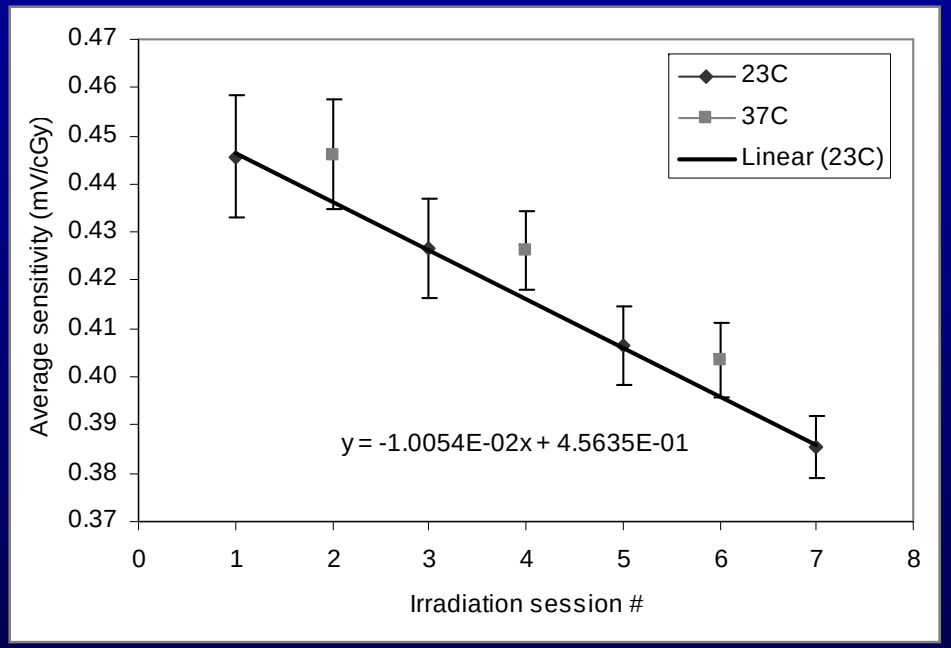
- TN dual-MOSFET-dual-bias detector – temperature independent

- Other currently available MOSFET detectors need corrections to be applied when used at a temperature different from the one at calibration

Temperature dependence

The DVS is calibrated at 37°C for use at body temperature.

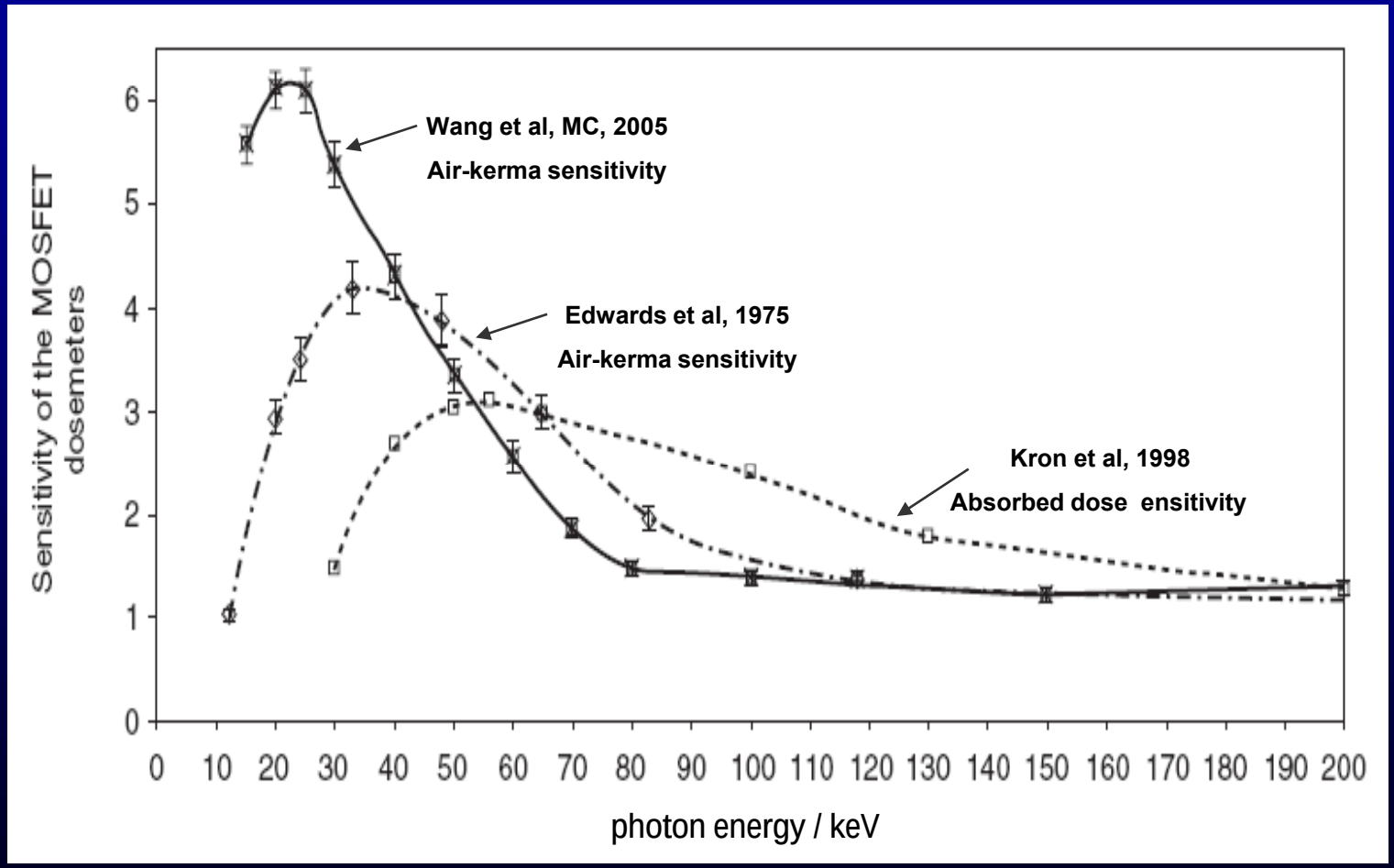
DVS dosimeter is approximately 3.3% more sensitive (higher dose reading for same applied dose) when irradiated at 37°C vs. 23°C



A multiplicative correction factor of 1.033 can be used for room temperature phantom measurements

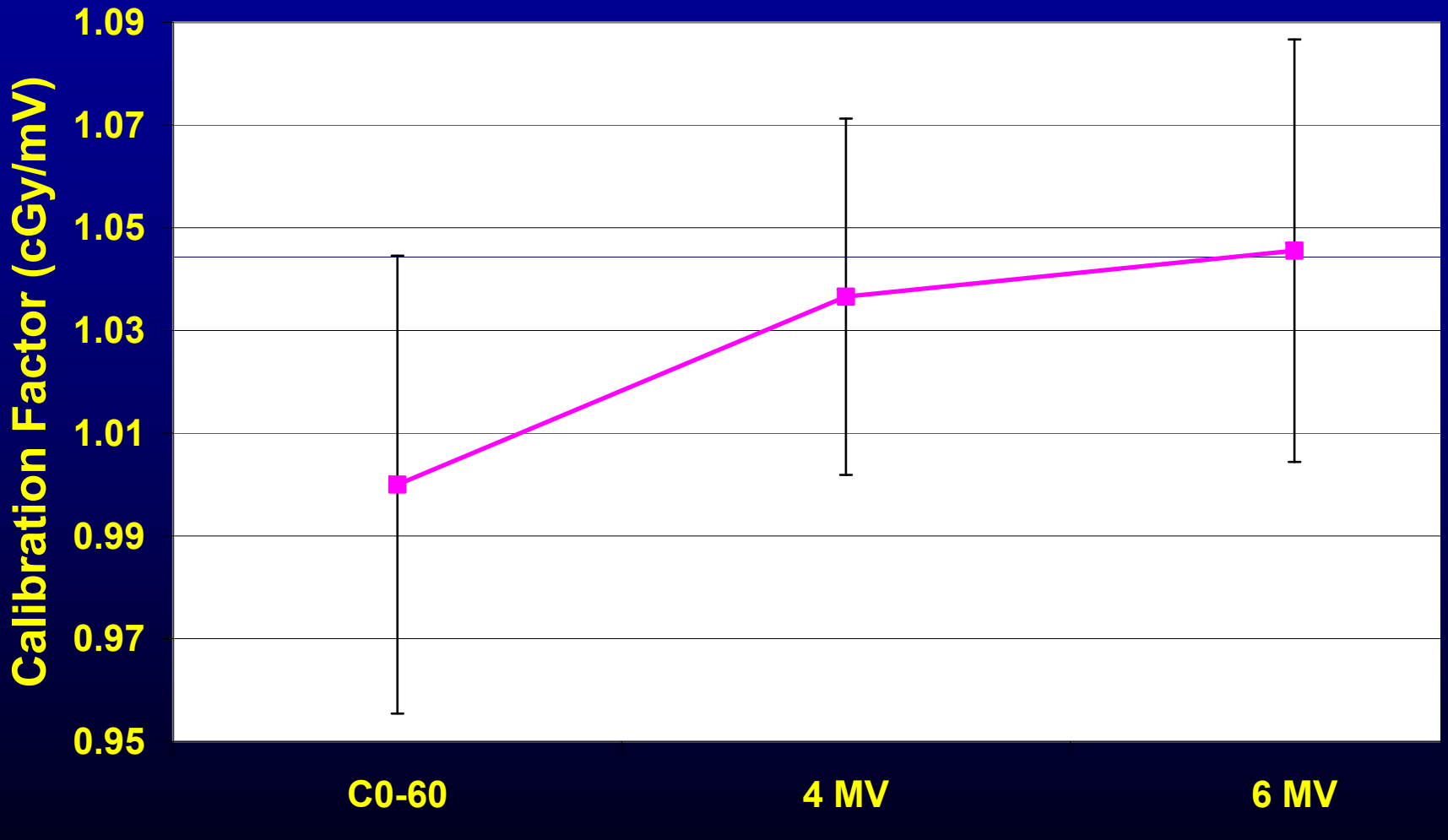
Courtesy of G. Beyer

MOSFET energy dependence



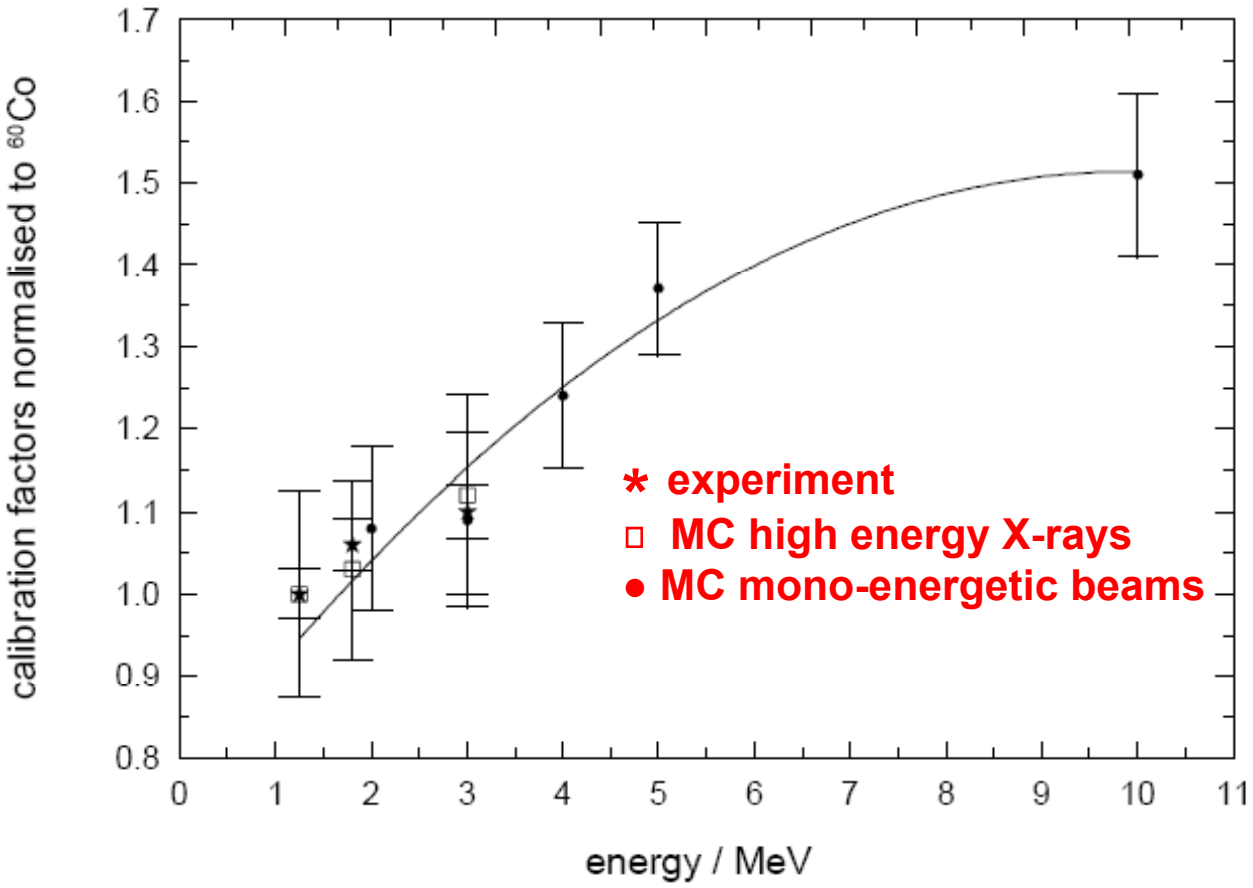
Wang et al Radiat. Prot. Dos. 2005

MOSFET energy dependence TN-502 RDM



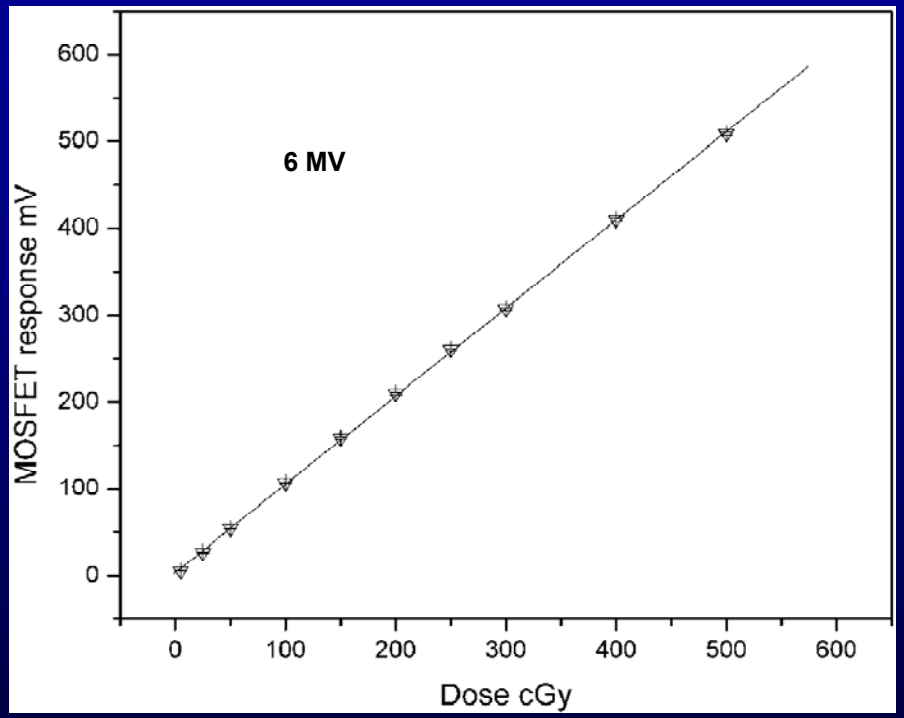
Courtesy of T. Woods

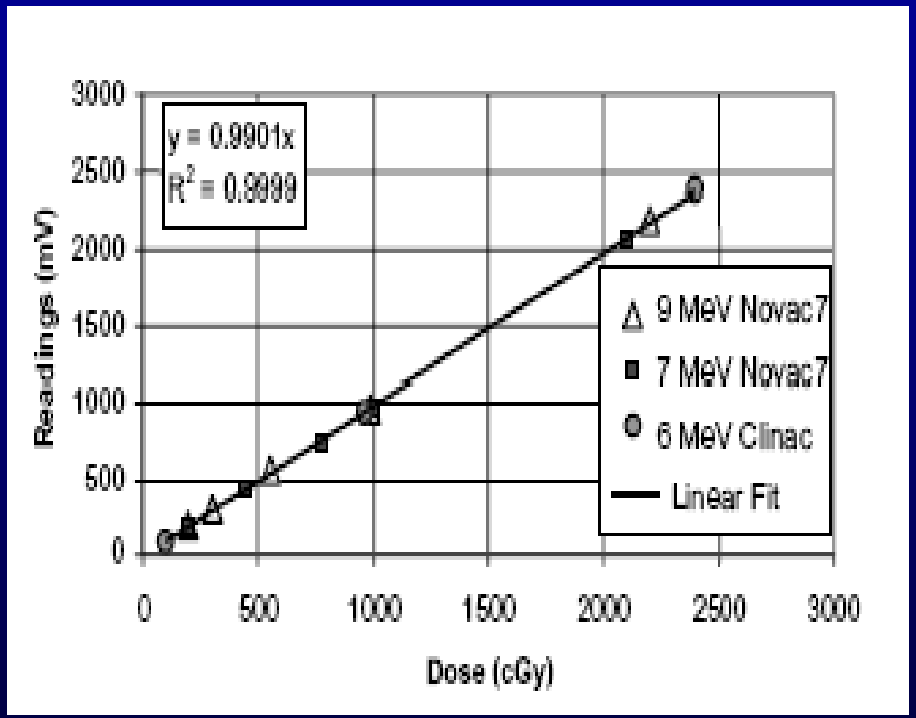
Energy dependence - TN-502-RD



Panettieri et al Phys Med Biol. 52(1):303-16.2007

Absorbed dose linearity - dual MOSFET-dual-bias

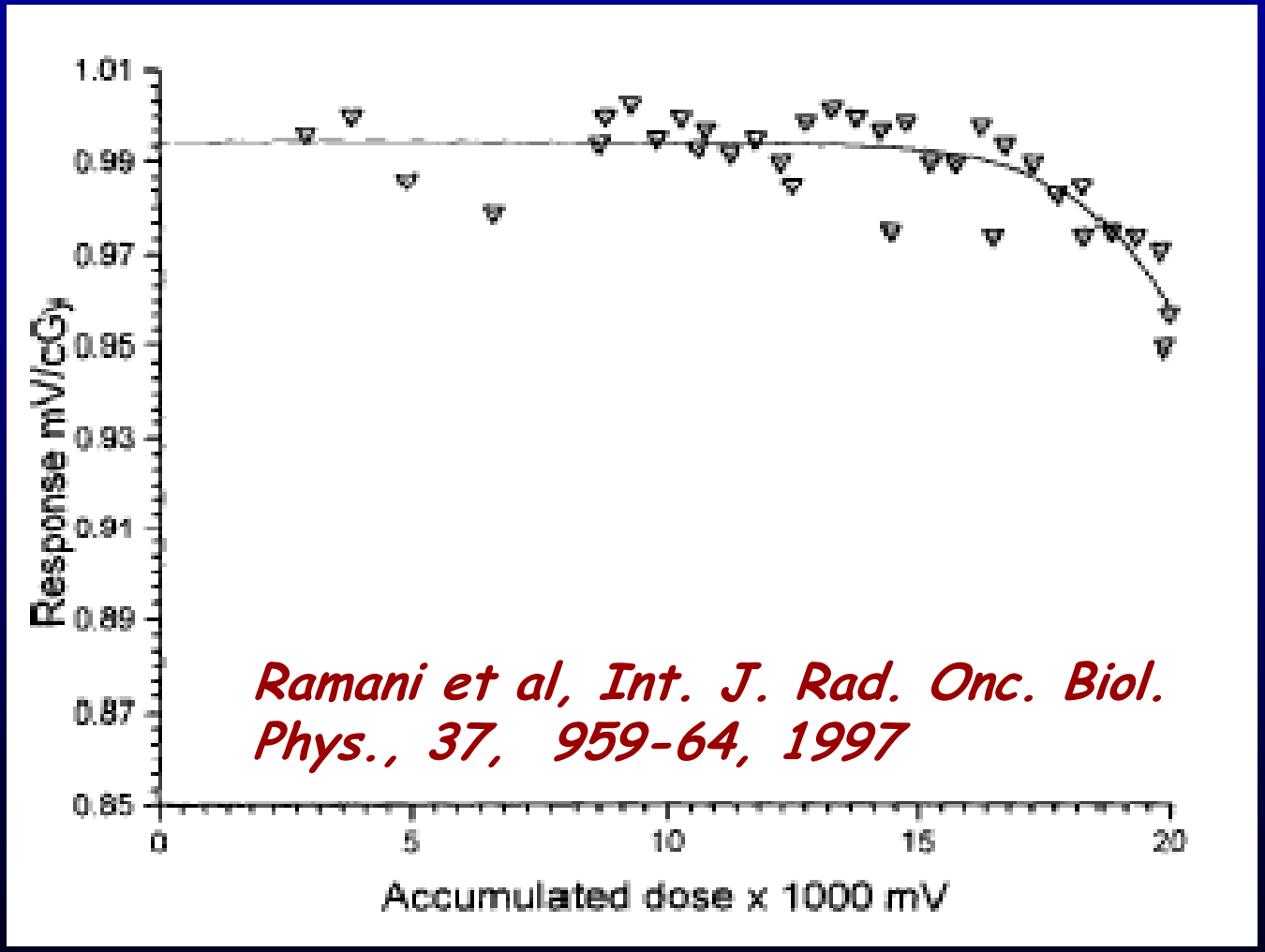




Ramaseshan et al, Phys. Med. Biol. 49 , 4031-4048, 2004

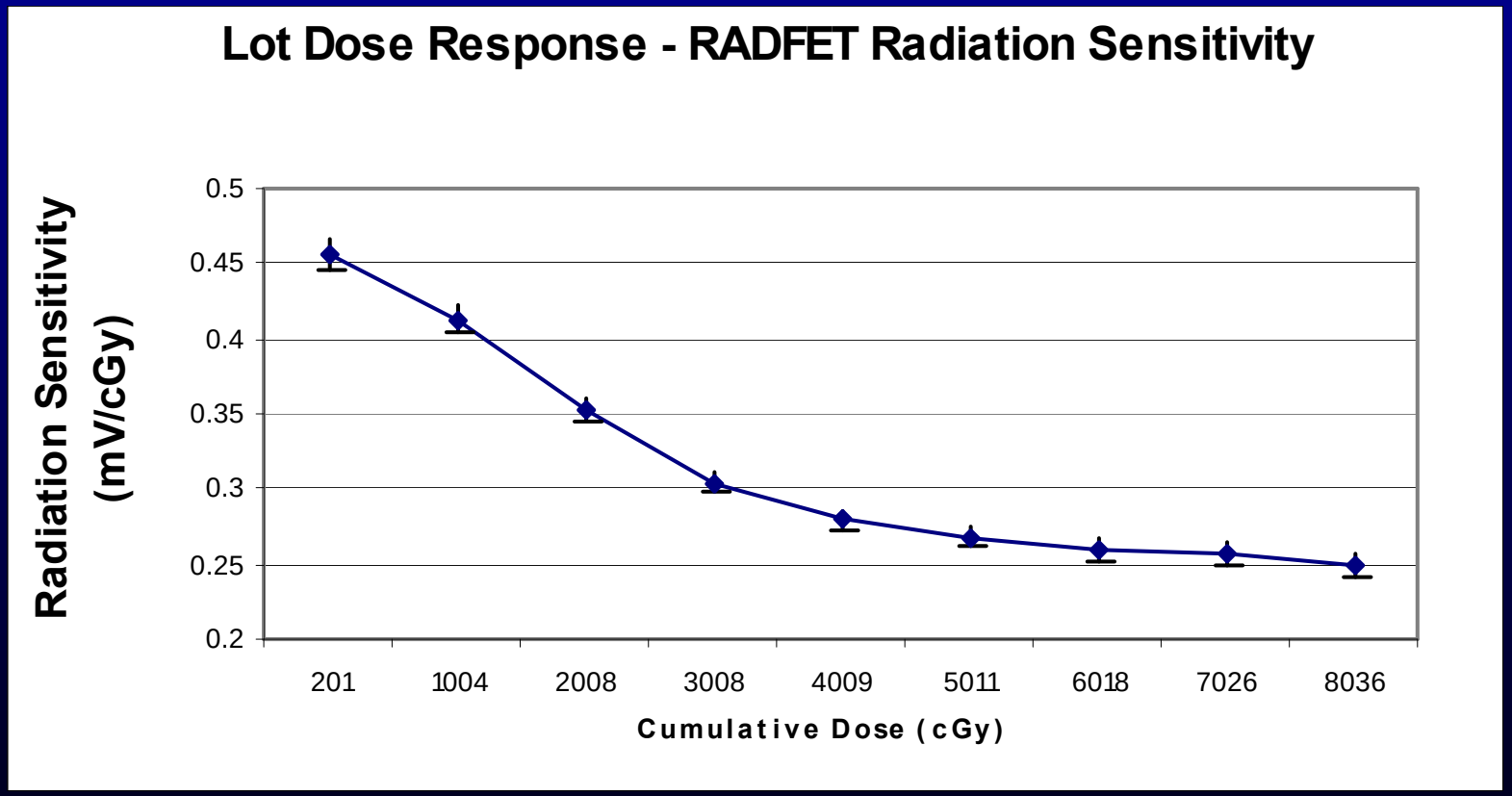
Consorti et al, Int. J. rad. Onc. Biol. Phys. 63, 952-60, 2005

Effect of accumulated dose



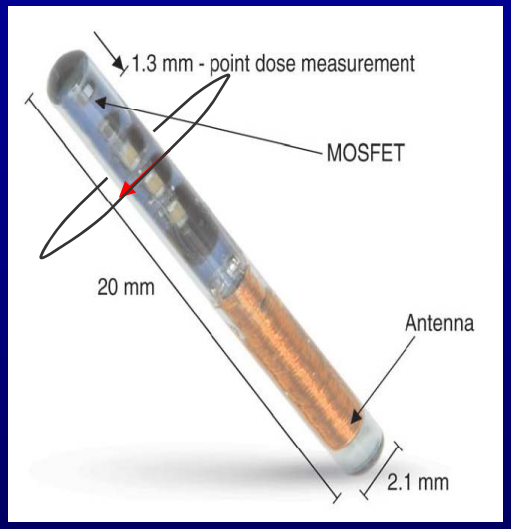
Ramani et al, Int. J. Rad. Onc. Biol. Phys., 37, 959-64, 1997

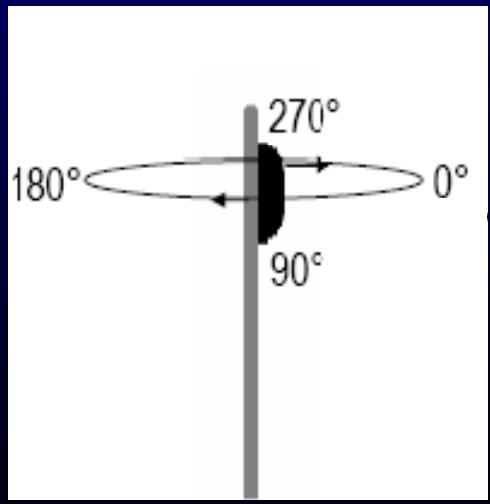
Effect of accumulated dose – unbiased MOSFET - DVS



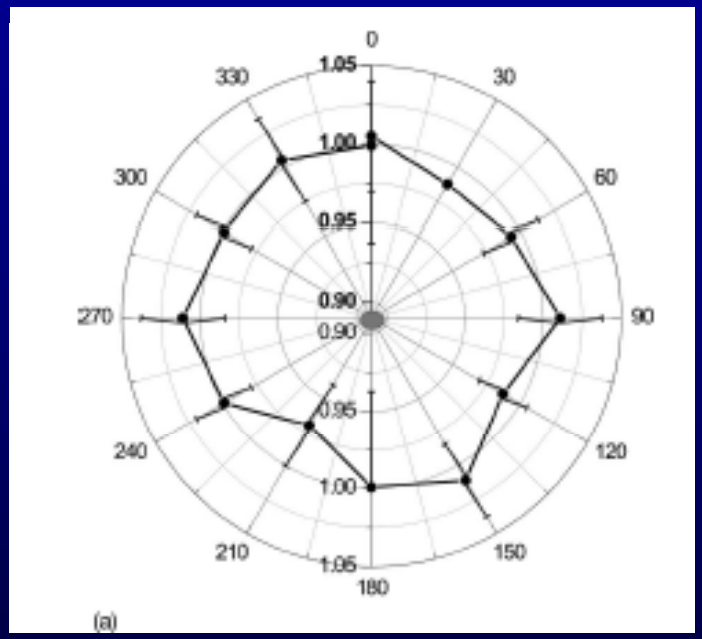
Directional dependence

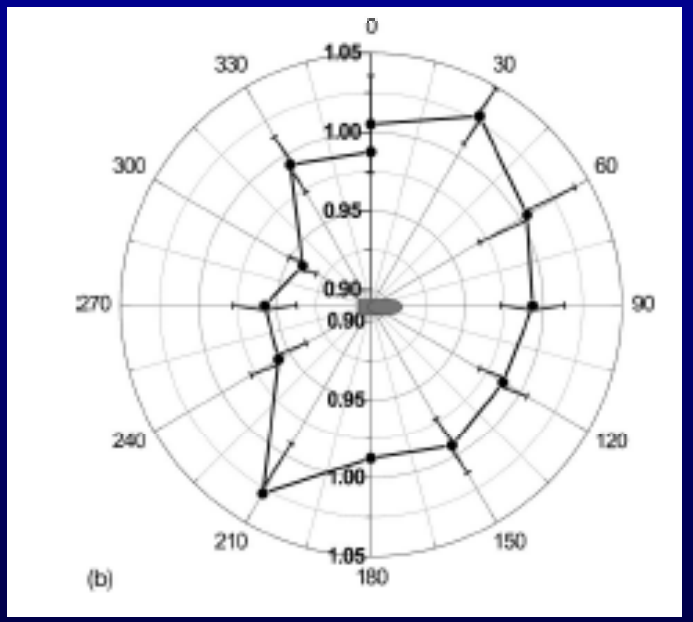
- Ideally it should be isotropic
- In practice, angular response of the detector depends on
  - its design
- It can be different for different energies
- Should be evaluated in-phantom to derive correction factors

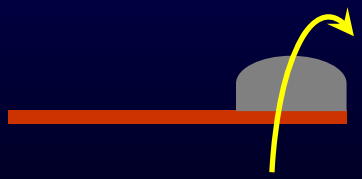


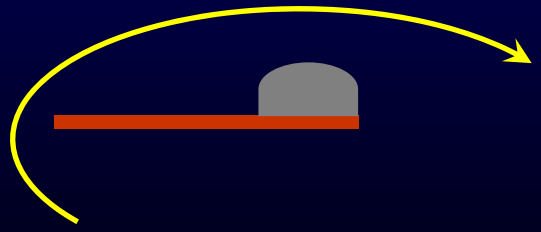


Directional dependence of microMOSFET









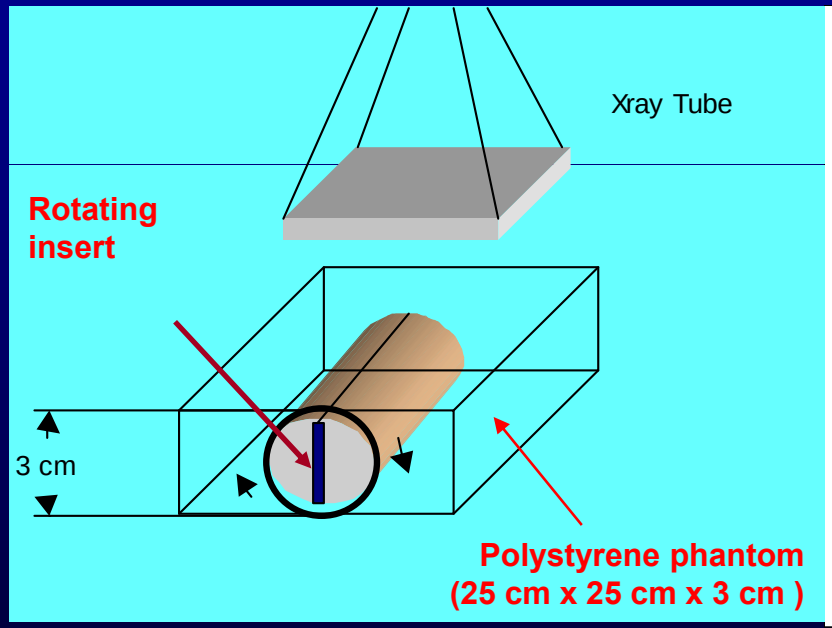
Rowbottom & Jaffray. Med. Phys. 31, 609-15, 2004

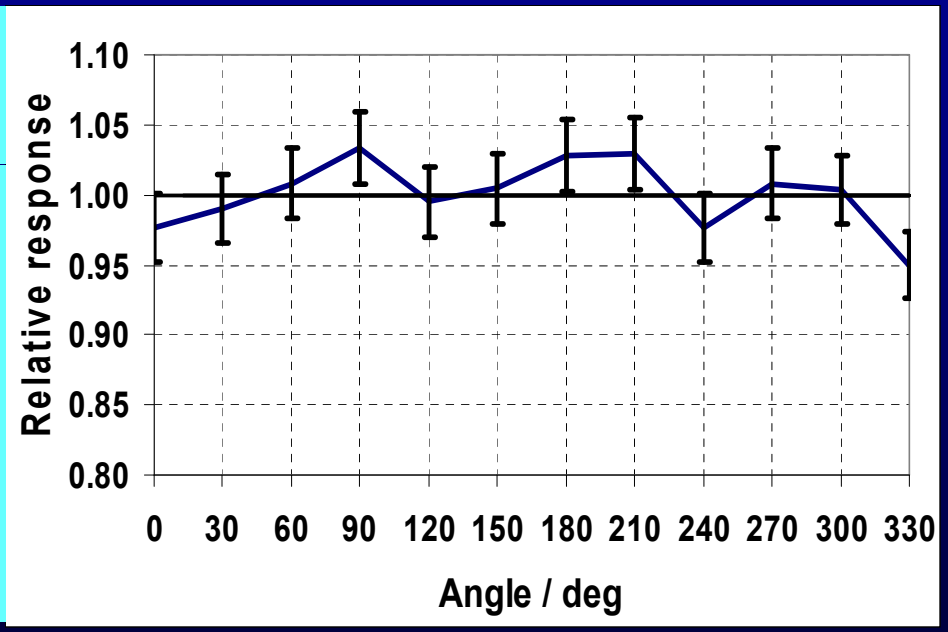
Directional dependence phantom

Example of a spherical phantom that can be used to measure angular dependence of MOSFET response

Directional dependence

Energy: 100 kVp , FS:10x10 cm^2 ,FSD:50 cm, Depth:1.5 cm





Cygler et al, Radiother. Onc. 80, 296-301, 2006

Isotropic within 2.5% (1SD)

Time dependence - Cyberknife

- Cyberknife: long treatment times
- High-dose DVS dosimeter initial design - significant dependence of response on irradiation time: 1-h and 2.5-h multiple irradiations caused mean over-responses of 4% and 8%, respectively, when compared to a single irradiation of ≈1.5 min.
- Improved DVS design - no time dependence (response within 2 %)

MOSFET detectors
Advantages *vs.* disadvantages

Advantages

- Very small active volume
- Dual-MOSFET-dual bias system eliminates most correction factors
- Instantaneous readouts (on-line dosimetry)
- Permanent dose storage (Can be read multiple times)
- Waterproof
- Efficient in use

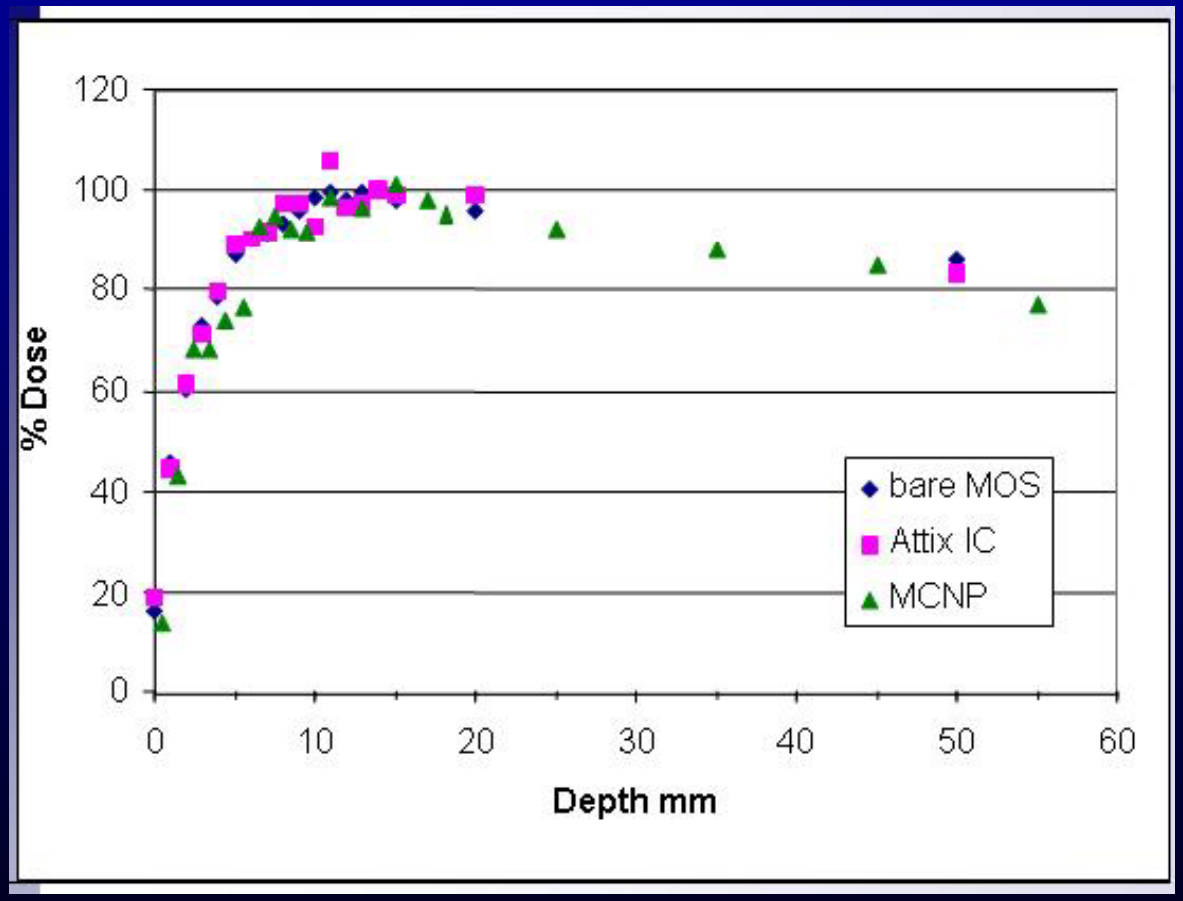
Disadvantages

- Finite lifetime(~100 Gy)
- Energy dependence
- Temperature dependence for single-MOSFET-detector
- Sensitivity change with accumulated dose for unbiased MOSFETs

Clinical applications

- In-phantom measurements
  - Build-up curves for high energy photon beams
  - Interface dosimetry
  - Small field output factors (radiosurgery)
- In-vivo dosimetry
  - External beam: entrance and exit doses, skin dose, peripheral dose, tumor dose
  - TBI
  - IMRT
  - IGRT
  - IORT
  - brachytherapy

Build-up depth dose curves 6 MV FS=10x10 cm^2, SSD=100 cm

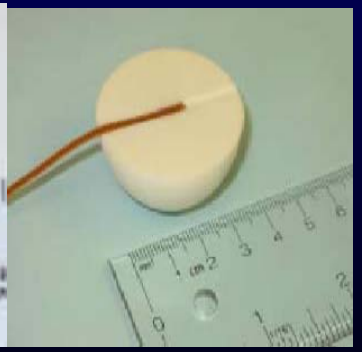


MOSkin chip developed at CMRP allows measurements of the surface dose at a depth of 0.07mm

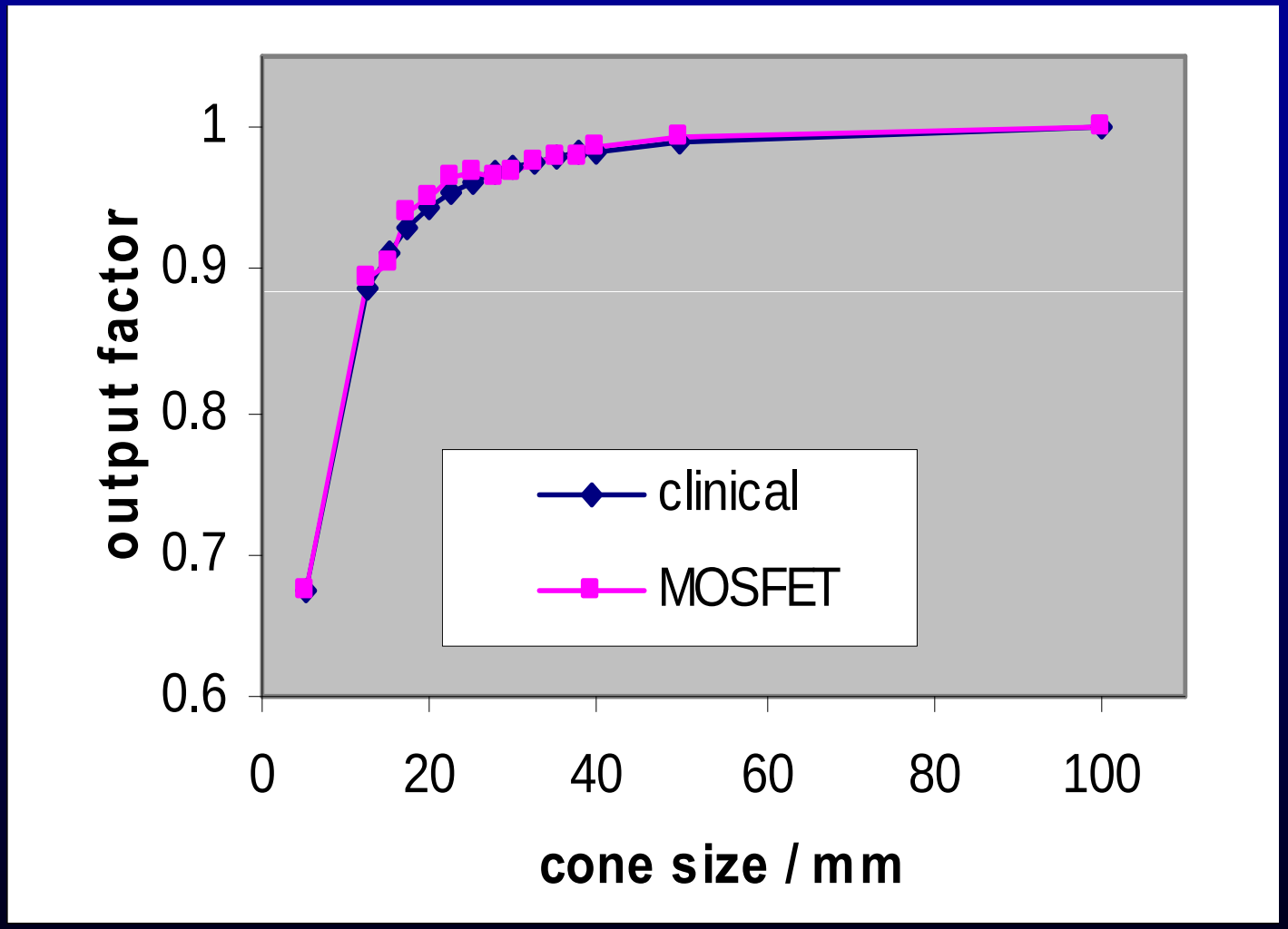
Courtesy of Anatoly Rosenfeld

Entrance and exit dosimetry

- Use of build-up caps is recommended
- OneDose Plus detectors – come equipped with caps
- TN MOSFETs – one can fit inside special buildup caps



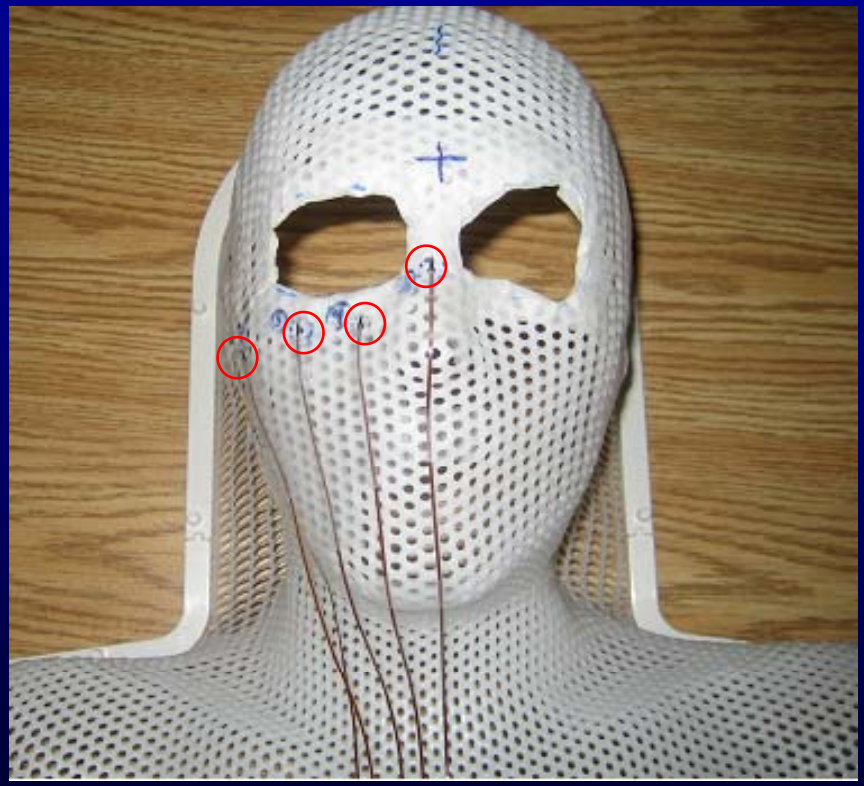
Radiosurgery dosimetry



Courtesy of J. Wojcicka

IMRT in vivo dosimetry

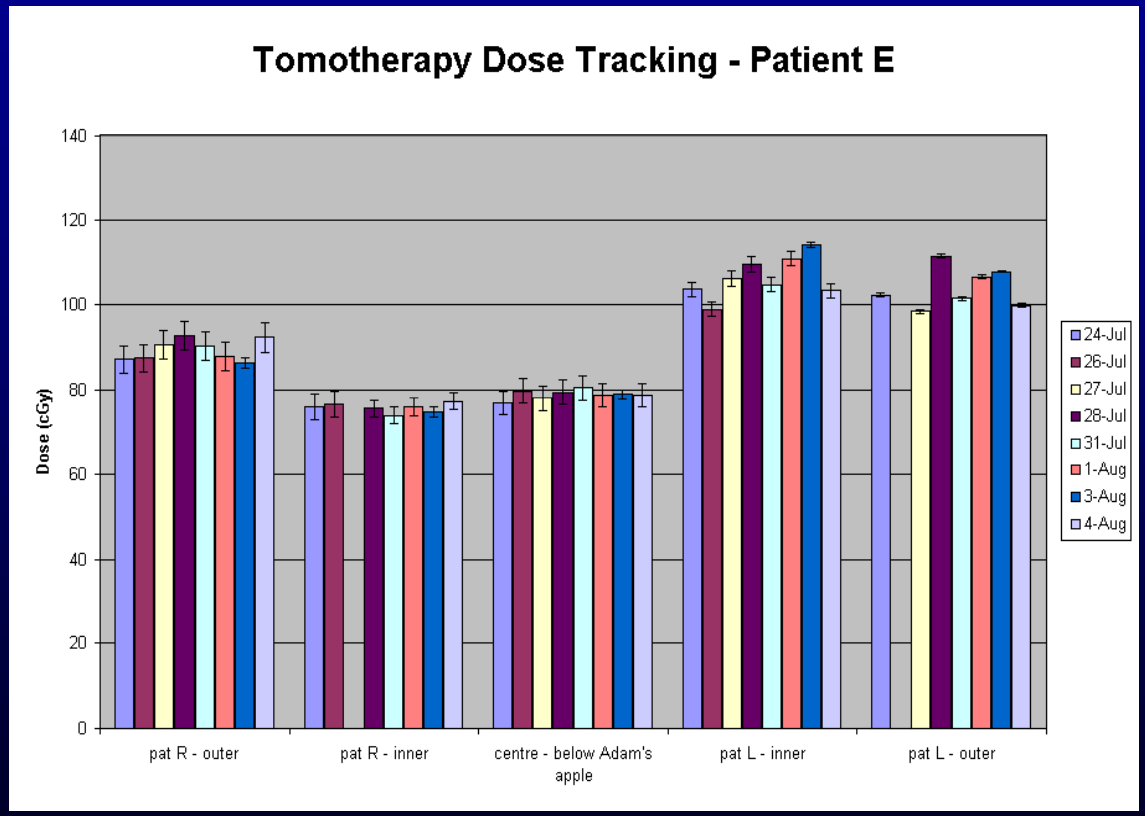
Marcie et al, Int. J. Rad. Onc. Biol. Phys., 61, 1603–6, 2005



- In some cases, BB's placed on top of patient's mask for original CT

Results from *in vivo* measurements Tomotherapy

Example: Patient E



Cherpak et al Radiother. Oncol. 86, 242-250, 2008

IORT

Pancreas treatment with Novac7

Consorti et al, Int. J. rad. Onc. Biol. Phys. 63, 952-60, 2005

Detector calibration for brachytherapy -TG-43 formalism

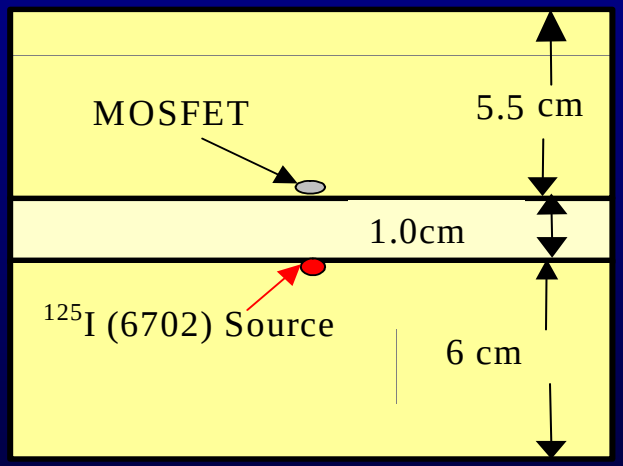
$$\dot{D}(r,\theta) = S_K \Lambda \left[G(r,\theta) / G(r_0,\theta_0) \right] g(r) F(r,\theta)$$

- Solid water phantom

Reference distance 1 cm

$$\dot{D}(r,\theta) = S_K \Lambda$$

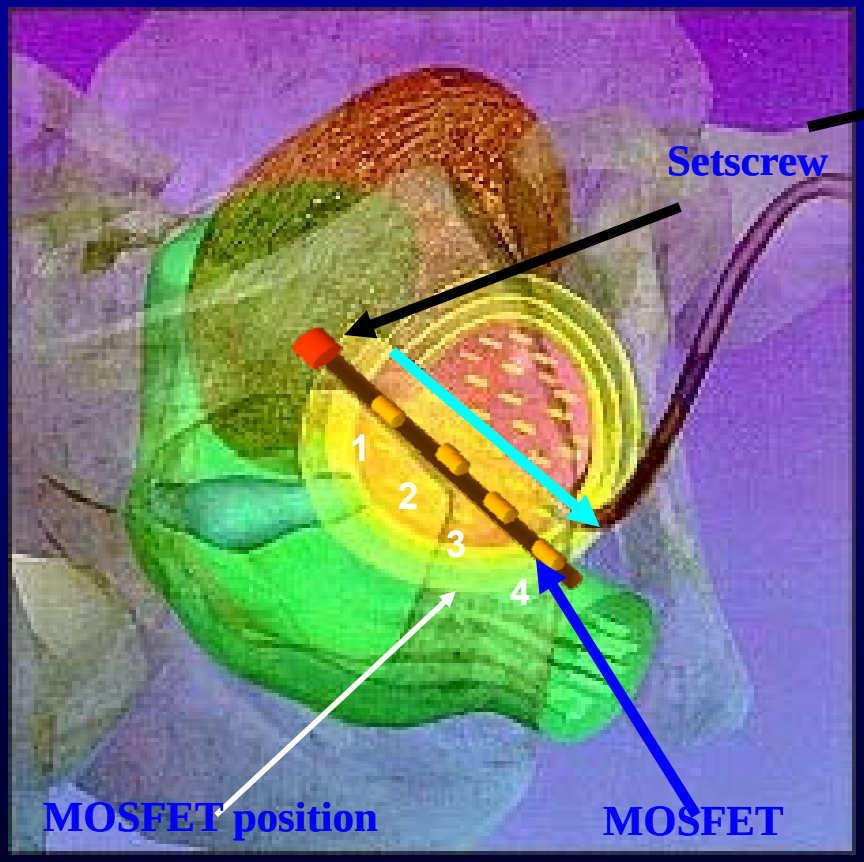
$$f_{cal} = \frac{Dose(cGy)}{\Delta V_{th}(mV)}$$

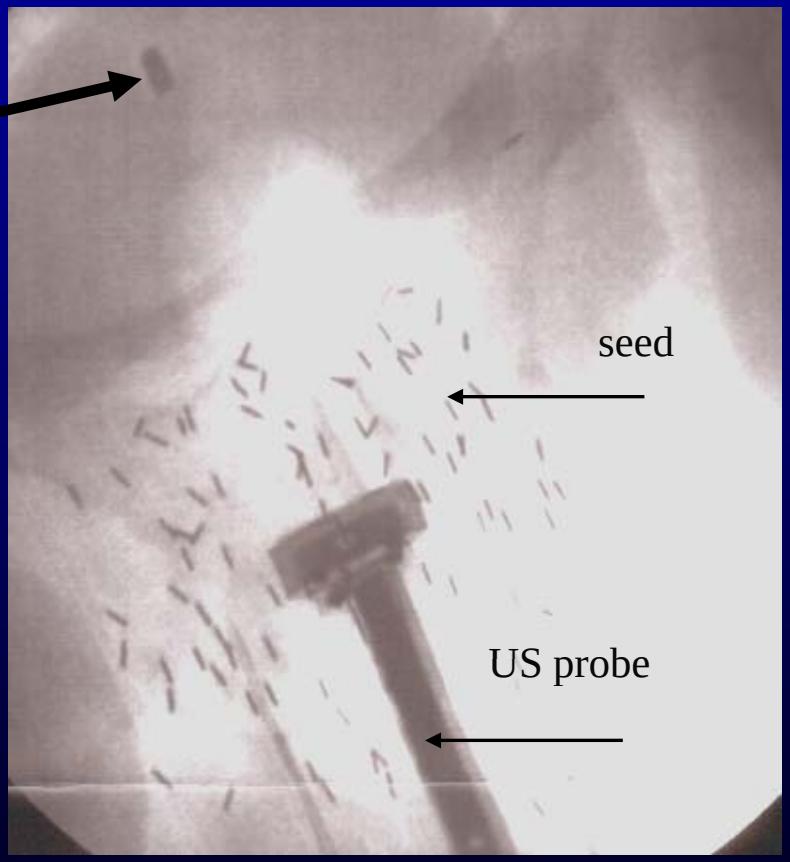


Energy Dependence:

Sensitivity (^{25}I/ ^{60}Co) ~ 3

In Vivo Measurements – prostate implants

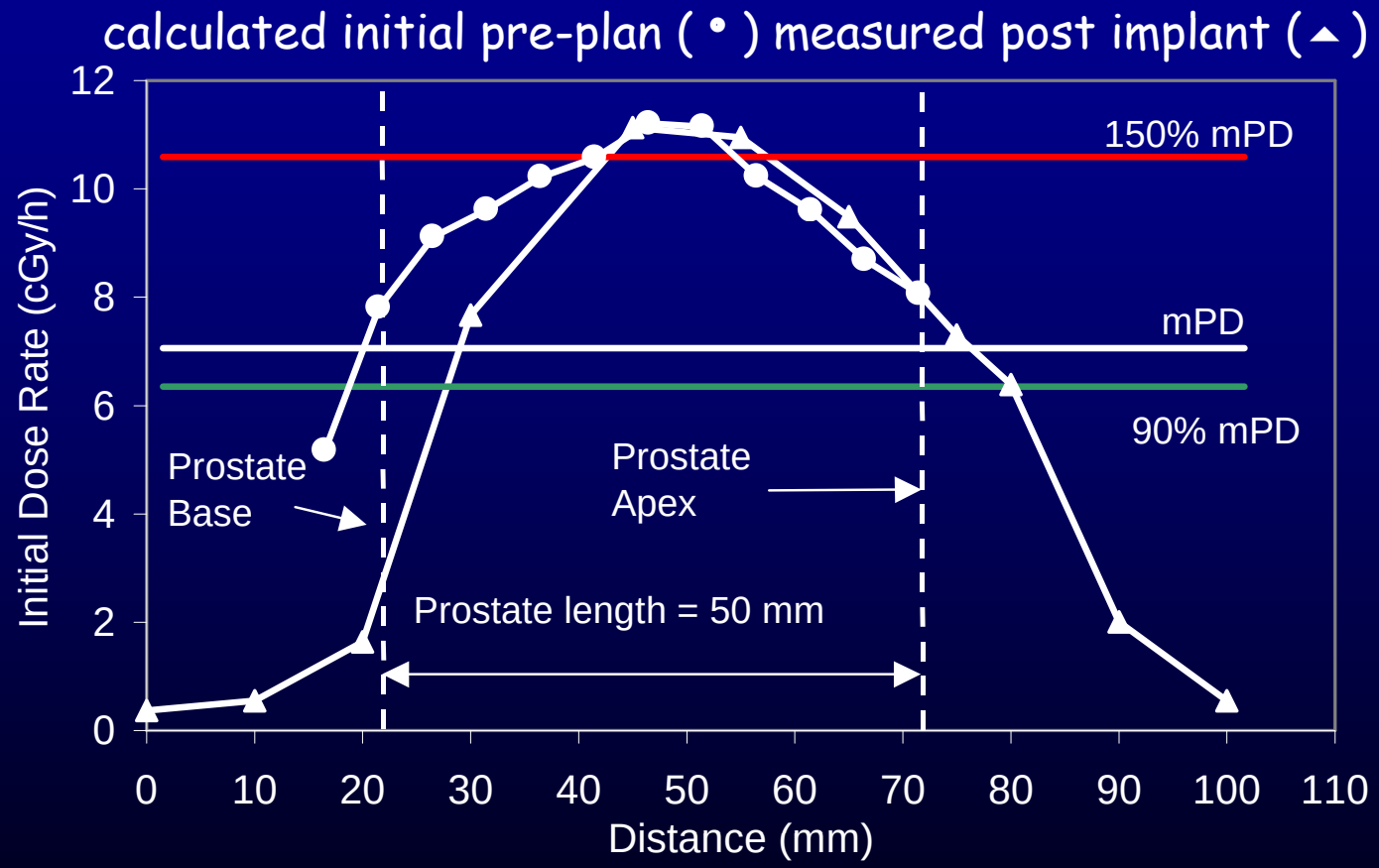




- MOSFET reading taken every 1cm

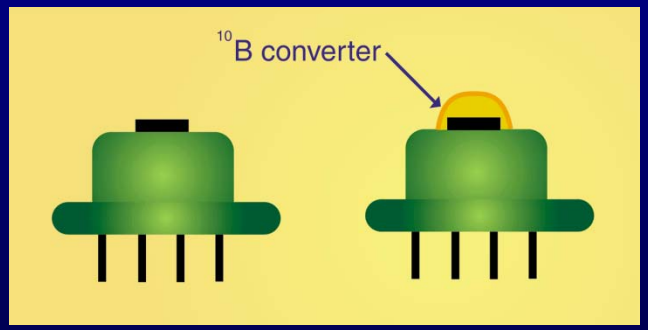
Fluoroscopy image of the prostate after implant

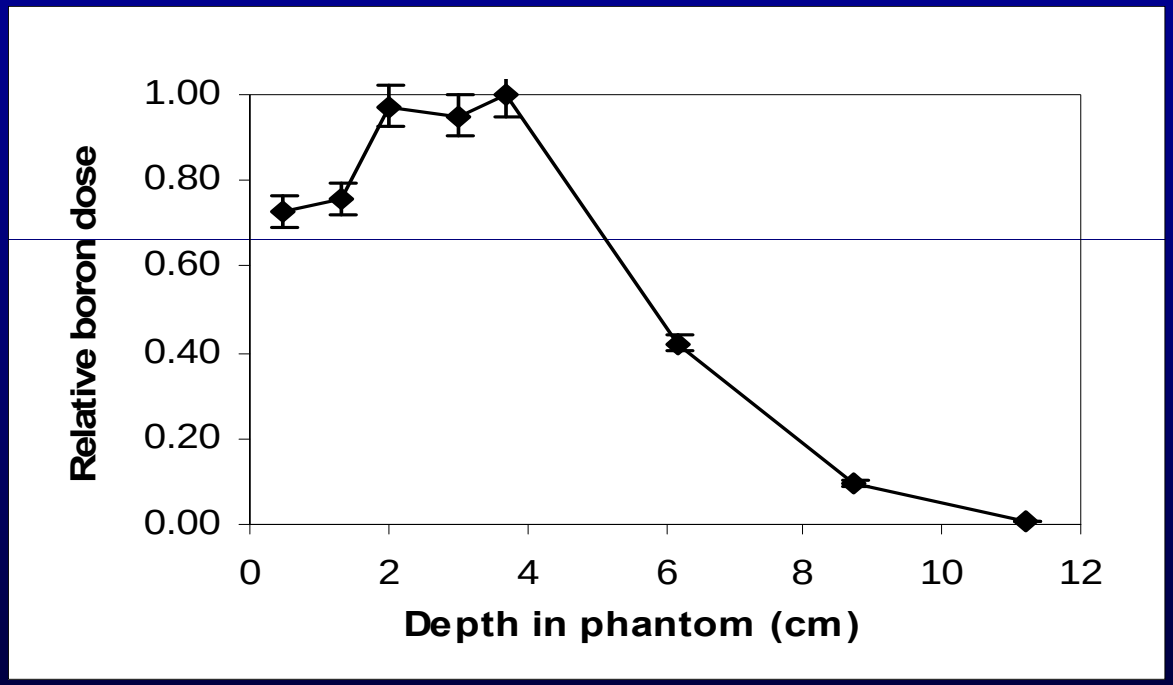
Use of MOSFET detectors during prostate implant procedure



Cygler et al Radiotherapy and Oncology 80: 296-301; 2006

BNCT at BNL medical research reactor





Thermal neutron depth dose distribution in a perspex phantom in a BNCT epithermal neutron beam facility at BNL obtained with paired MOSFET detectors with ^{10}B converter. Subtracting on-line the response of paired MOSFET eliminate effect of gamma dose.

Courtesy of Anatoly Rosenfeld

Conclusions

- MOSFET detectors are very useful for dosimetry, especially
  - High dose gradient fields
- Accurate if properly characterized and used
- Phantom (in vitro) dosimetry
- In vivo dosimetry in external beam and brachytherapy treatments

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