Dosimetry with silicon pixel detectors

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Part I

Dosimetry with Si diodes

With reference to external photon beam radiotherapy

1. Introduction
2. Operating principle
3. Dosimetric performances (sensor specific)
4. Solutions to improve radiation hardness
5. Dosimetric performances (device specific)

Introduction

Advantages and drawbacks of Si dosemeters

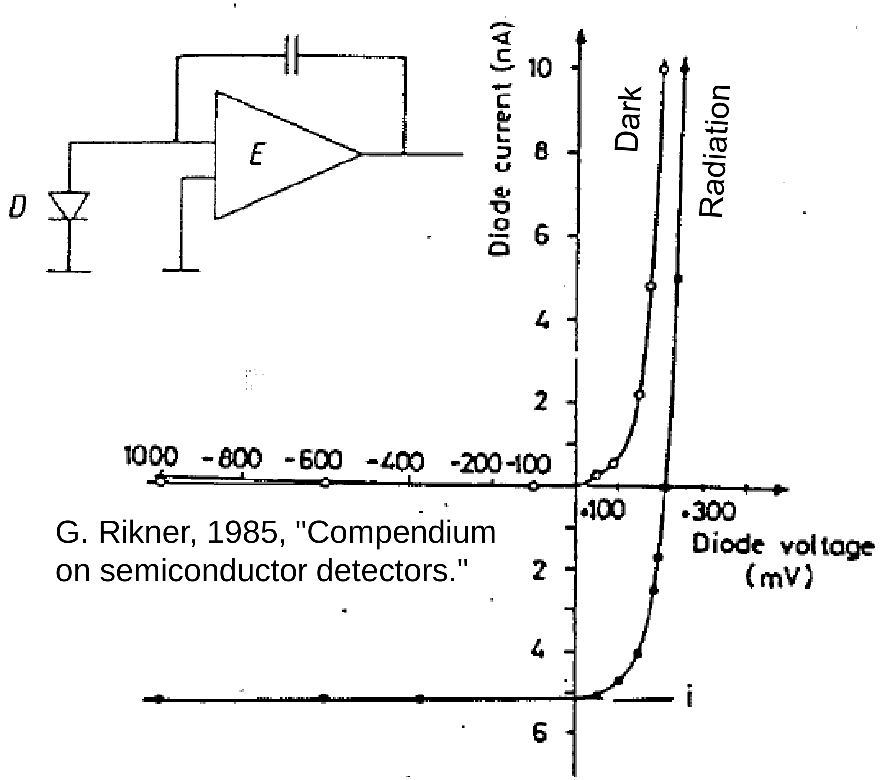
	Feature	Consequence
PRO	High specific sensitivity (~650nC/mm^3	Suitable for detectors with high spatial resolution
	Well developed (and cheap) manufacture technology	
	Photovoltaic mode (null bias)	Simplified design
CONS	Radiation Damage	Sensitivity drift with dose Dose rate linearity
	Not water equivalent (Z=14)	Energy dependence

Basic ideas are known since long; their exploitation still in progress...

See e.g. R. P. Parker et al, „Silicon PN junction surface-barrier detectors and their application to the dosimetry of X- and gamma-ray beams,Solid state and chemical radiation dosimetry in medicine and biology“, symposium proceedings, IAEA, 1967, p. 167.

Introduction

Readout scheme



G. Rikner, 1985, "Compendium on semiconductor detectors."

Features:

- "null bias" (to minimize leackage current; no concerns about signal strength and speed).
- DC coupling.
- Sampling time and reset fixed by electronics (usually T≥10ms).
- Only integrated charge is measured.

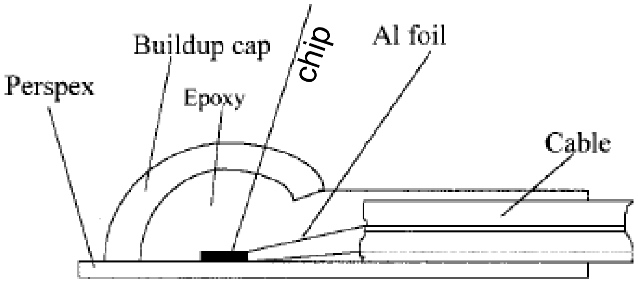
- o Situation is different for "single event" detectors, where one typically has:
- o diode bias at full depletion (full collection and speed).
- o AC coupling (to get rid of reverse current).

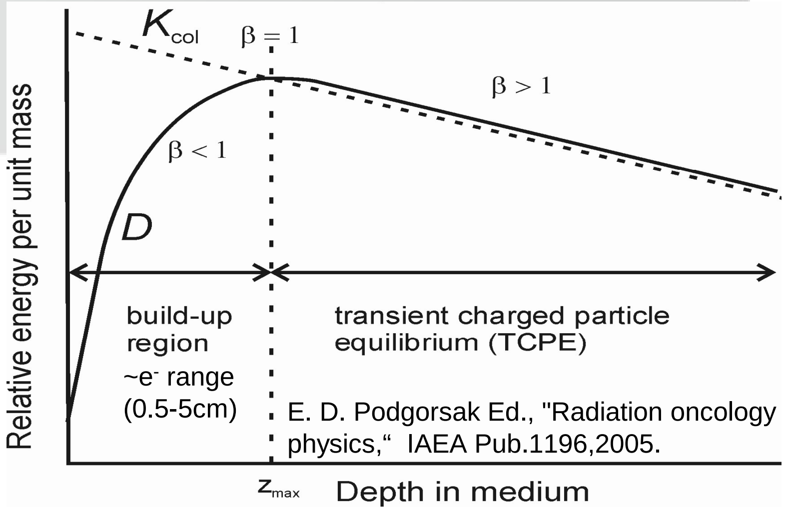
Null bias simplifies everithying (chip design, PCB layout, operation...)

Introduction

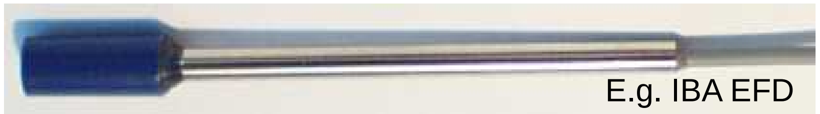
Basic geometries for single diode detectors

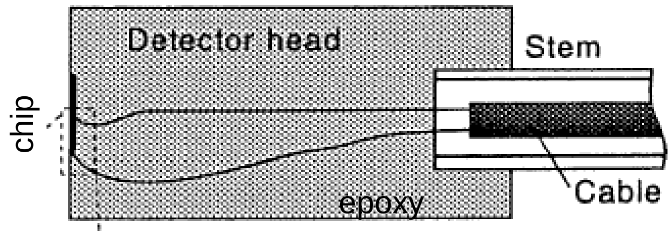
“**In-vivo detectors:**” to be attached to patient body
Buildup: “thicker & heavy” (e.g. Brass, Steel, W)





“**Field detectors:**” to characterize radiation fields
Buildup: water equivalent, as thin as possible
Additional buildup added by the user (H_2O or plastic)

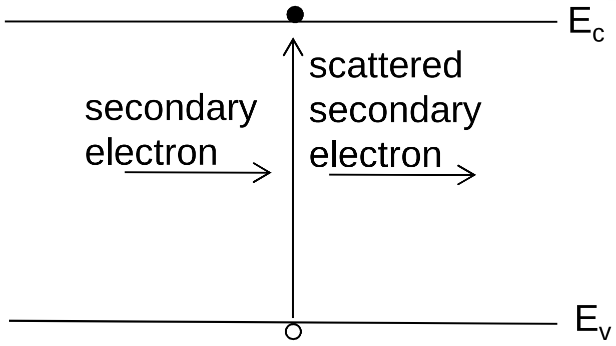




Null bias: a guard is not needed!

Operating principle

Excess carrier generation



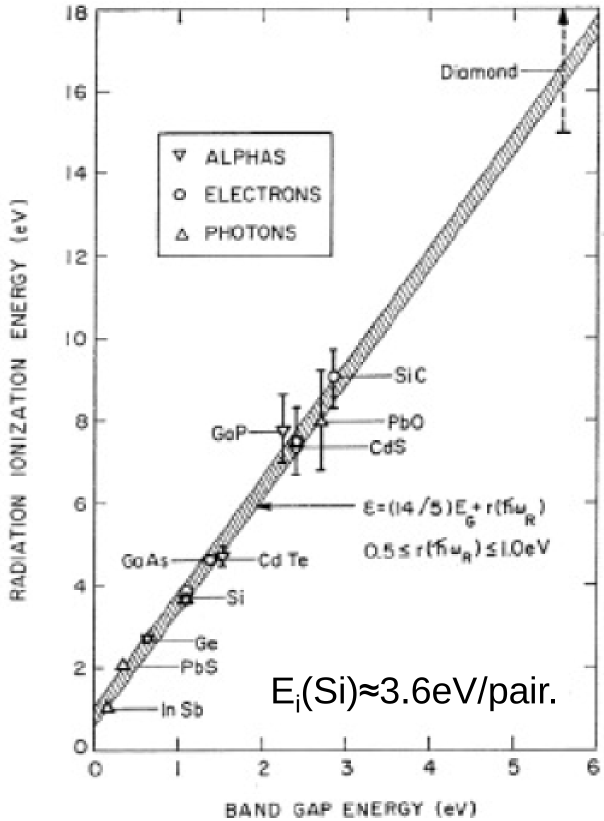
It gives high sensitivity!

$$G = R\rho_{Si} / E_i$$

$$s = \frac{Q}{D} = \frac{qG}{R} = \frac{q\rho_{Si}}{E_i} = 637\frac{nC}{Gy \cdot mm^3}$$

G,: carrier generation rate:
R,: dose rate;
ρ_{Si}: Si density;
E_i: mean ionization energy.

s: specific sensitivity
Q: released charge;
D: delivered dose;
q: elementary charge



E_i/E_{gap} constant (at fixed T) for many semiconductors under general conditions.

Operating principle

Carrrier diffusion (I)

Assumptions:

- o Excess carriers freely diffuse in the bulk.
- o Diffusion length is limited by recombination.
- o Minority carriers reaching depleted region edge, are swept by the field and generate a current.

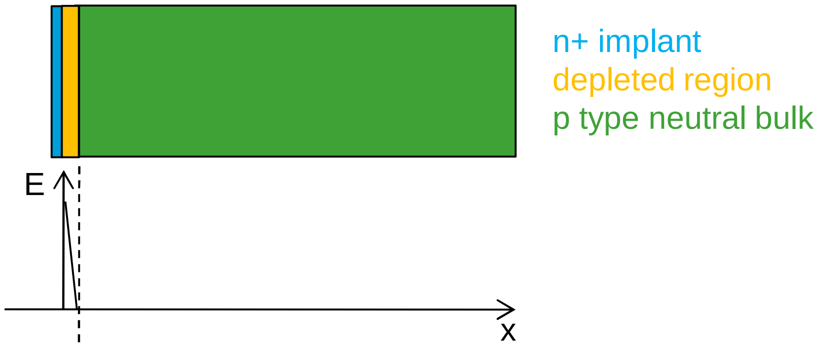
$$\frac{\partial^2 \Delta n}{\partial x^2} = \left(\frac{\Delta n}{\tau_e} - G \right) \frac{1}{D_e},$$ Diffusion equation

$$D_e = \frac{kT}{q} \mu_e = 37.6 cm^2 / s.$$ Diffusivity (at 300K)

Boundary condition (for a semi-infinite bulk):

$\Delta n(0)=0$

i.e. all the electrons approaching the depleted region are promptly swept by electric field.



A simple model (any drift is ruled out) even if very useful to interpret experimental results

Operating principle

Carrier diffusion (II)

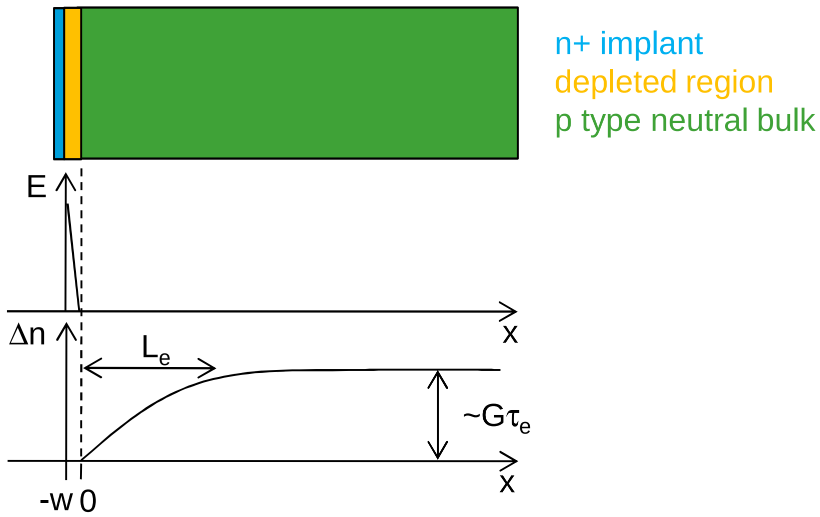
Solution of diffusion equation:

$$\Delta n = \frac{GL_e^2}{D_e}\left(1 - \exp(-x / L_e)\right).$$

$$L_e^2 = \tau_e D_e.$$

$$j_e(x) = qD_e \frac{\partial \Delta n}{\partial x} = qL_e G e^{-x/L_e}$$

$$j = j_e(0) = qL_e G.$$

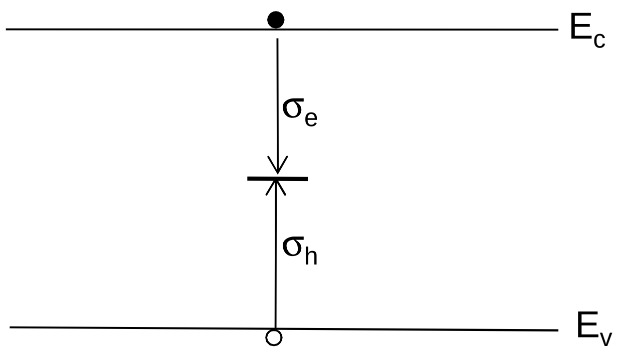


j, total current density
j_e, electrons current density
q, elementary charge
L_e, minority carriers diffusion lenght

Rule of the thumb:
"<u>All the minority carriers generated within a difffusion length from depleted region are collected</u>."

Operating principle

Carrier recombination



Indirect recombination via midgap levels is dominant in silicon.

It is a 2 steps process:
capture e, then capture h,
or viceversa.

Shi J., Simon W. E., 2003, Med. Phys. 30, 2509-19.
Shokley W., Read W. T. jr., 1952, Phys. Rev., 87, 835-42.

$$\tau'_e \approx \tau_e \left(1 + \frac{\tau_h + \tau_e}{\tau_e} \cdot \frac{\Delta n}{p_0}\right) \approx \left(1 + \cdot \frac{(\tau_h + \tau_e) G \rho_{Si}}{p_0 E_i} R\right)$$

$\tau_{e/h}$, carriers lifetime;
Δn, excess carriers concentration;
p_0, majority carriers equilibrium conc.

$$\tau_{e/h} = \frac{1}{\sigma_{e/h} v_{e/h} N_t}.$$

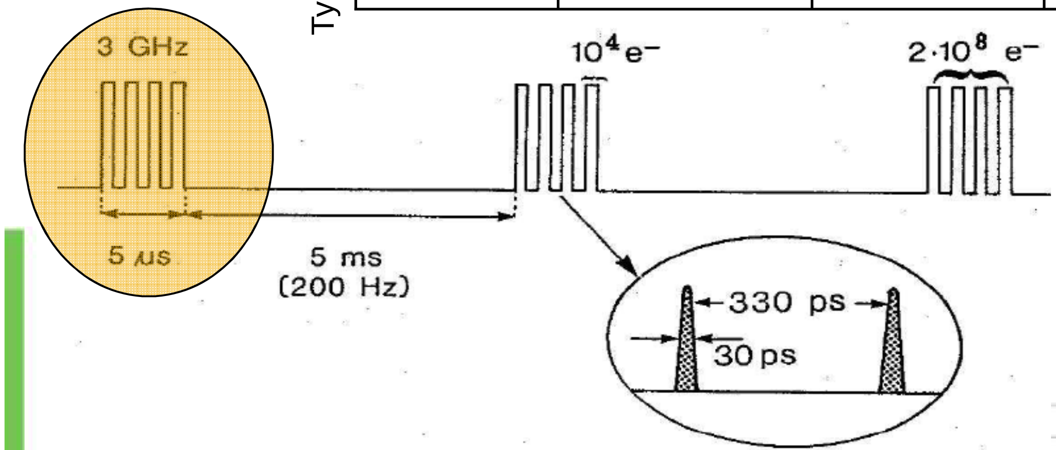
$\sigma_{e/h}$, center capture cross sections;
$v_{e/h}$, carriers thermal velocity;
N_t, center concentration.

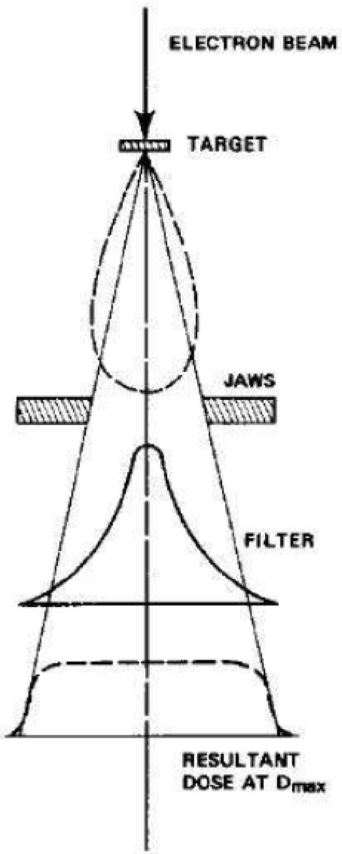
Dosimetric performances (sensor specific)

Dose rate dependence: context

Typical Macro-pulse parameter

Beam quality	4-18MV X	With target	
	4-18MeV e^-	No target	
PRF	50-400Hz		
Max Dose rate	6Gy/min	Flattened	X rays isocenter
	20Gy/min	Unflattened	
Dose per pulse	0.1-0.5mGy	flattened	X rays Depending on beam quality and SDD
	0.4-2mGy	Unflattened	





Dosimetric performances (sensor specific)

Dose rate dependence: basic theory

Sensitivity per unit area of the diode:

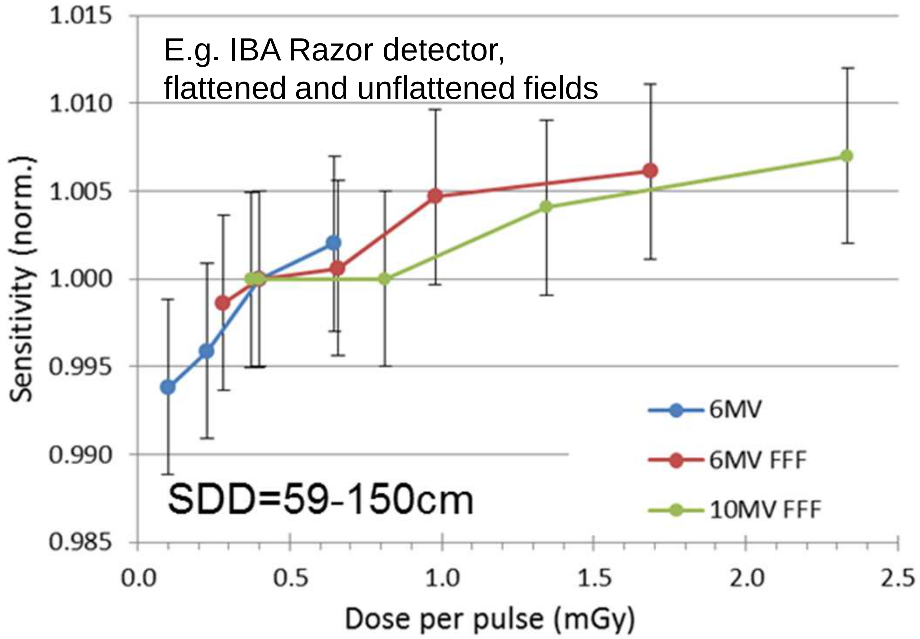
$$\frac{S}{A} = \frac{j}{R} = sL_e = \frac{q\rho_{Si}}{E_i} L_e .$$

$$\frac{S}{A} \approx \frac{q\rho_{Si}}{E_i} \sqrt{D_e \tau_e \left(1 + \frac{(\tau_h + \tau_e) G \rho_{Si}}{p_0 E_i} R \right)}$$

Dose rate non-linearity,
due to traps saturation.

Dose rate linearity is improved by:

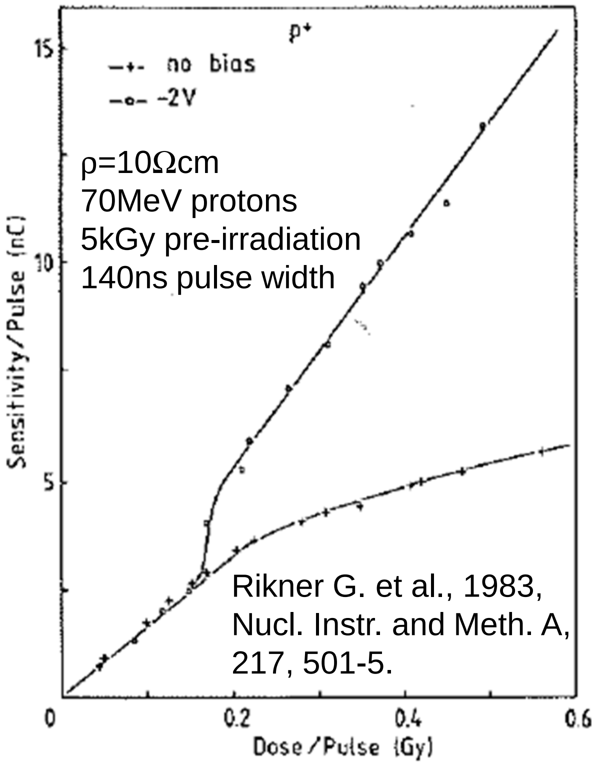
- high doping (i.e. high p_0);
- short lifetime.



Practically: this effect is seen only with pulsed radiation (very high instantaneous dose rate)

Dosimetric performances (sensor specific)

Dose rate dependence: an extreme case



$$p_{p0} = \frac{1}{q\mu_h \rho} = 1.3 \cdot 10^{15} cm^{-3},$$

$$\Delta n \approx \frac{GL_e^2}{D_e} = \frac{R\rho_{Si} L_e^2}{E_i D_e} \approx 5.5 \cdot 10^{15} cm^{-3},$$ (at 0.2 Gy/pulse)

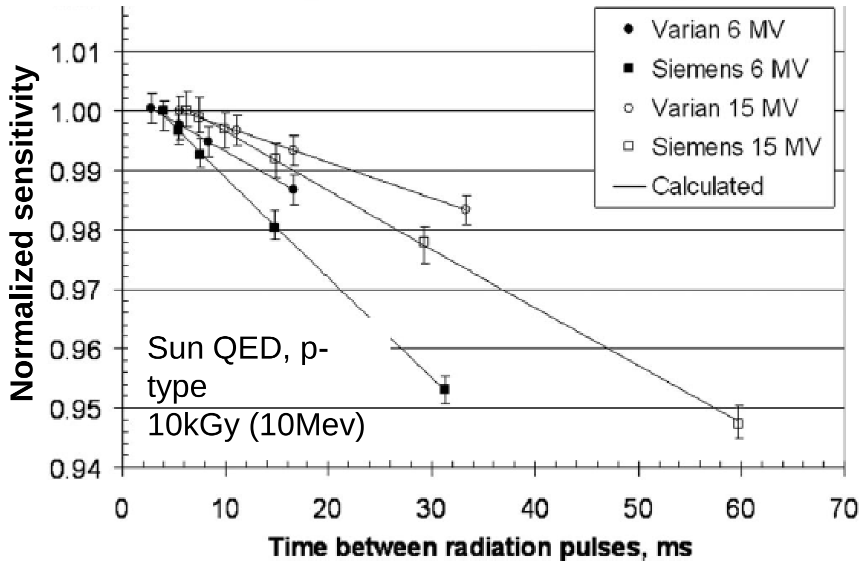
Sensitivity saturates when the excess carriers concentration is comparable to doping level.

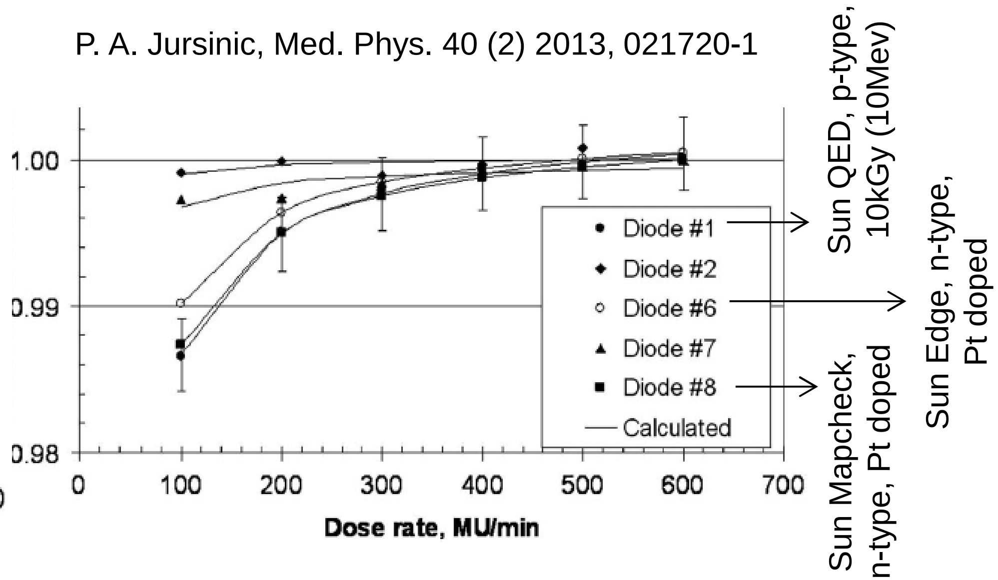
In this case the junction electric field is heavily modified.

Dose rate beyond the range of clinical applications.

Dosimetric performances (sensor specific)

Dose rate dependence: PRF related effects





- Observed in few detectors only
- Sensitivity decrease at low dose rate, more evident at low dose per pulse
- Proposed explanation: Release from traps slower than 1/PRF

Dosimetric performances (sensor specific)

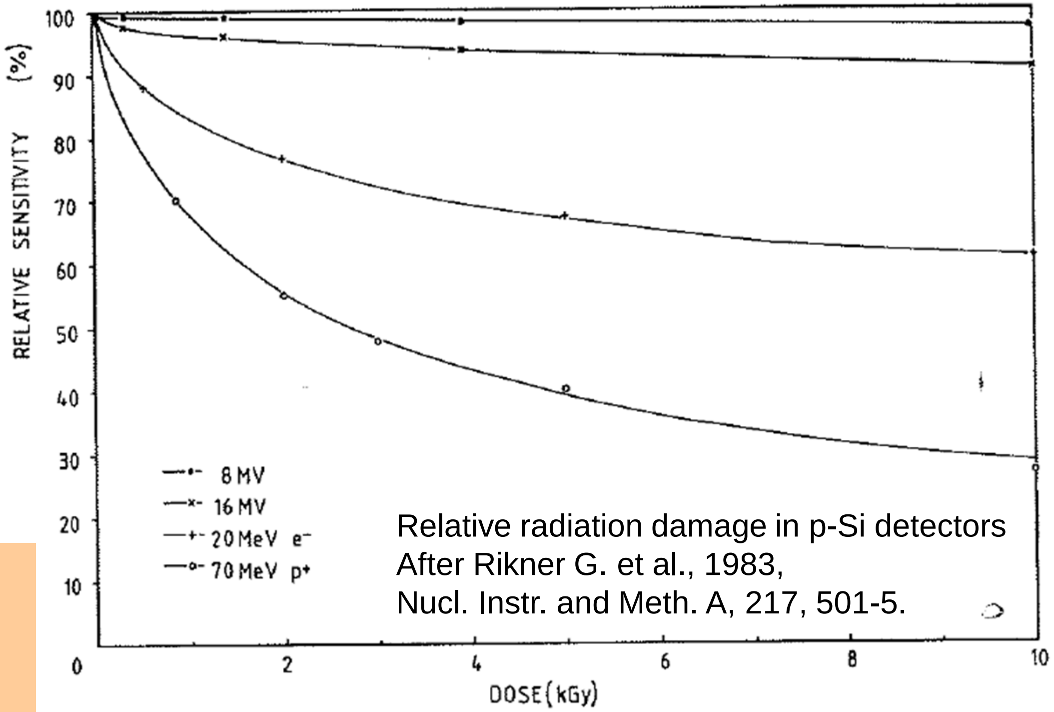
Sensitivity vs dose: basic theory

$$\frac{S}{A} \approx \frac{q\rho_{Si}}{E_i}\sqrt{D_e\tau_e\left(1+\frac{(\tau_h+\tau_e)G\rho_{Si}}{p_0E_i}R\right)}$$

If a single trap dominated,
Neglecting R-related term

$$\frac{S}{A} = \frac{q\rho_{Si}}{E_i}\sqrt{\frac{D_e}{\sigma_e v_e N_t}} \propto N_t^{-1/2}.$$

N_t grows with Dose, thus τ_e and L_e decrease
Consequences:
- o decrease of sensitivity S during use
- o need of priodic recalibration.



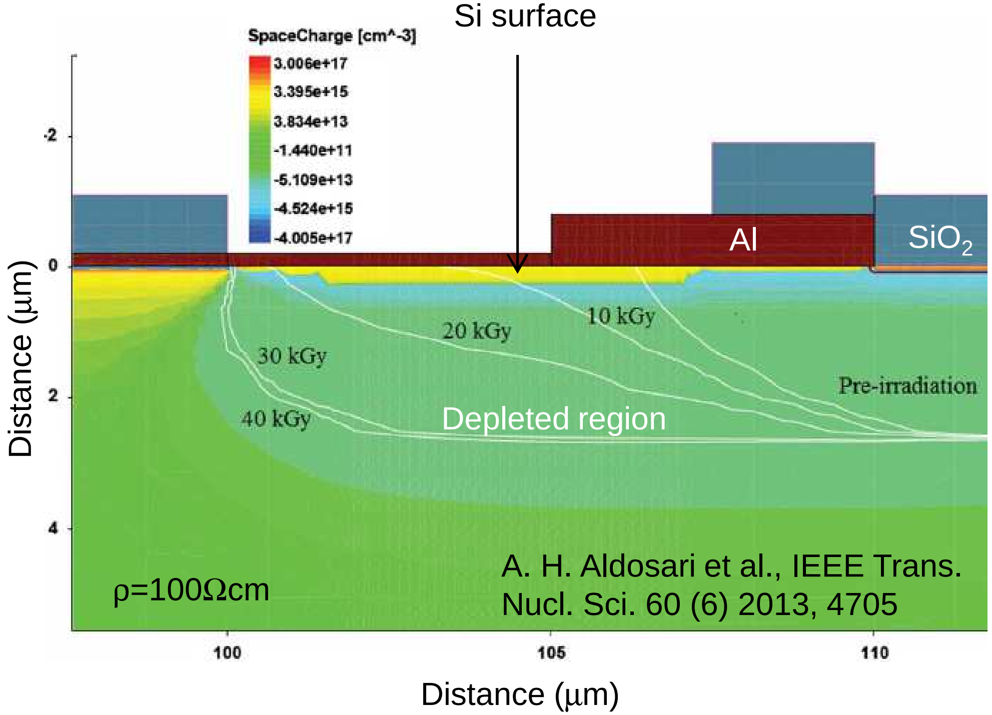
Relative radiation damage in p-Si detectors
After Rikner G. et al., 1983,
Nucl. Instr. and Meth. A, 217, 501-5.

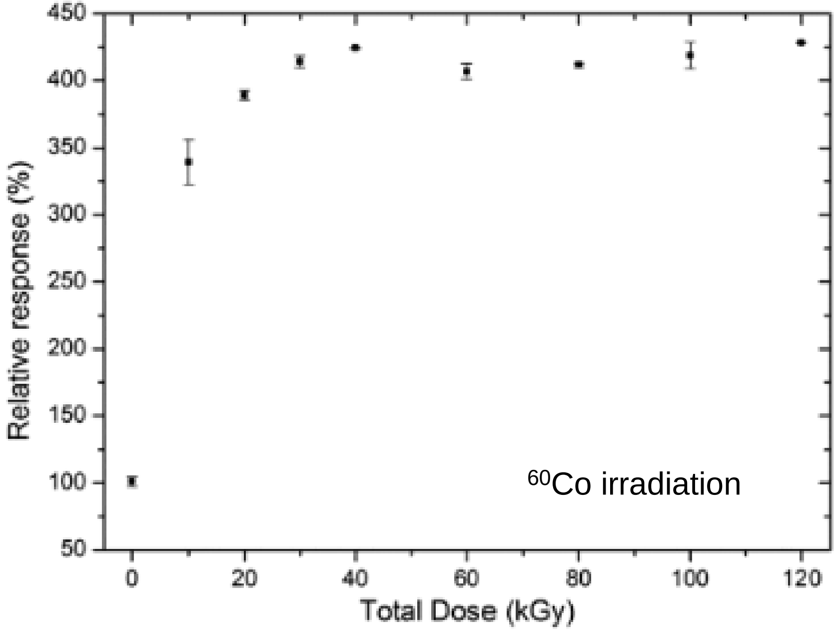
Essential for arrays: central pixel receive higher dose!!
Annealing play a big role!!

Dosimetric performances (sensor specific)

Sensitivity vs dose: oxide related effects

Oxide traps positive charge
A layer rich of electrons is created at Si surface





- Relevant for p-type Si only
- Determines sensitivity increase
- Visible only after low energy (e.g. ^{60}Co) irradiation
- Otherwise bulk damage dominates

Dosimetric performances (sensor specific)

Temperature dependence (I)

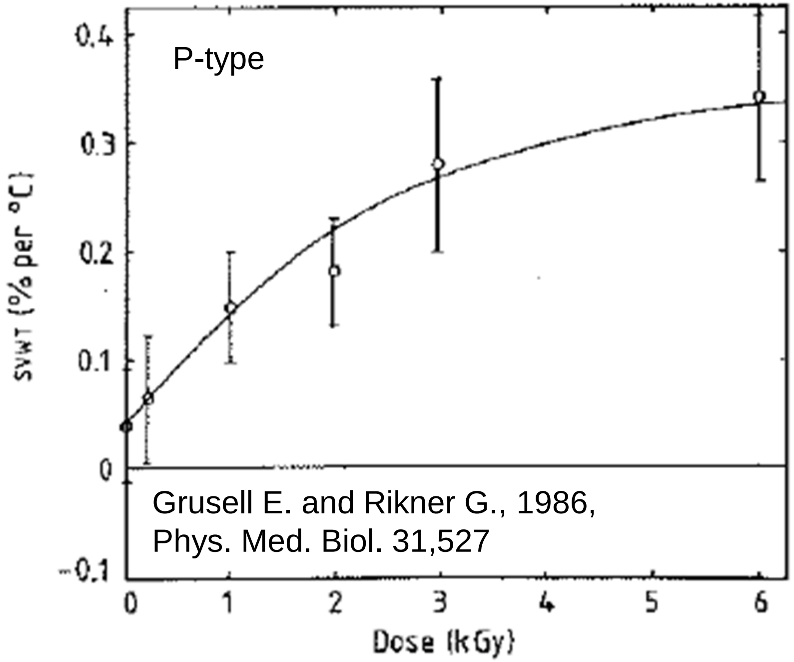
Important for in-vivo applications.
Accordingly to the outlined theory:

$$\mu_e \propto T^{\gamma}, \gamma \approx -2,$$

$$svwt = \frac{1}{S}\frac{dS}{dT} = \left(\frac{1}{4} + \frac{\gamma}{2}\right)\frac{1}{T} \approx -0.3\% \quad (@300K)$$

Actually, this is not the case...

- o svwt is usually positive
- o svwt is influenced by irradiation.
- o assumption of a single dominant deep level is probably not adequate



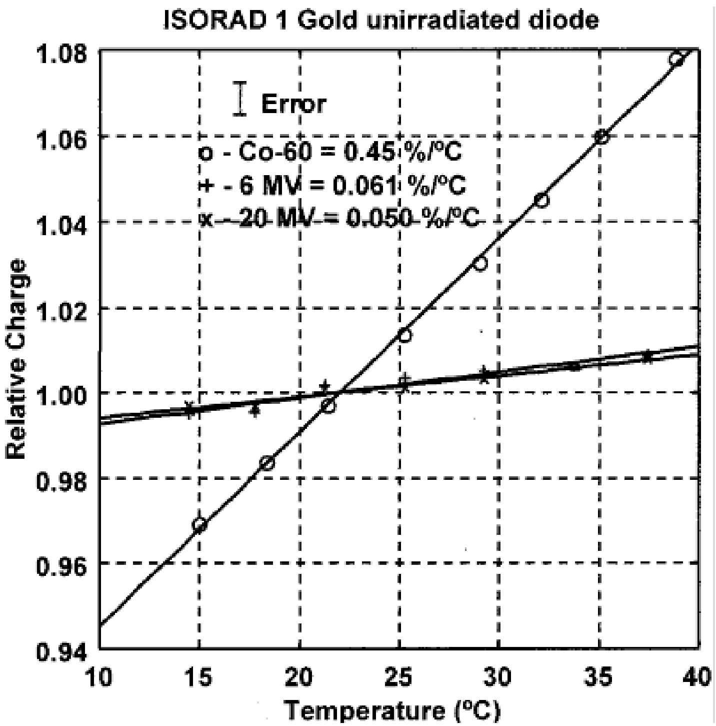
Diodes with most pronounced dose-per-pulse dependence exhibit the highest svwt
(Van Dam, Radiother. Oncol. 19, 245,1990)

Dosimetric performances (sensor specific)

Temperature dependence (II)

All diodes without Pt doping

Model	Type	ρ (Ωcm)	Pre-irradiation	Temp. Coeff. (%/K)		
			Dose 10MeV e- (kGy)	^{60}Co	6MV	15-20MeV
EDP10	p	0.2	8	0.36	0.38	0.33
EDP30	p	0.2	8	0.39	0.36	0.34
Isorad Gold	n	35	none	0.16-0.45	0.05-0.1	0.05-0.1
Isorad Red	n	35	10	0.37	0.22	0.21
QED Blue	p	0.8	10	0.30	0.30	0.31
QED Red	p	0.8	10	0.29	0.29	0.29
QED unirr.	p		None	0.34	0.25	0.27

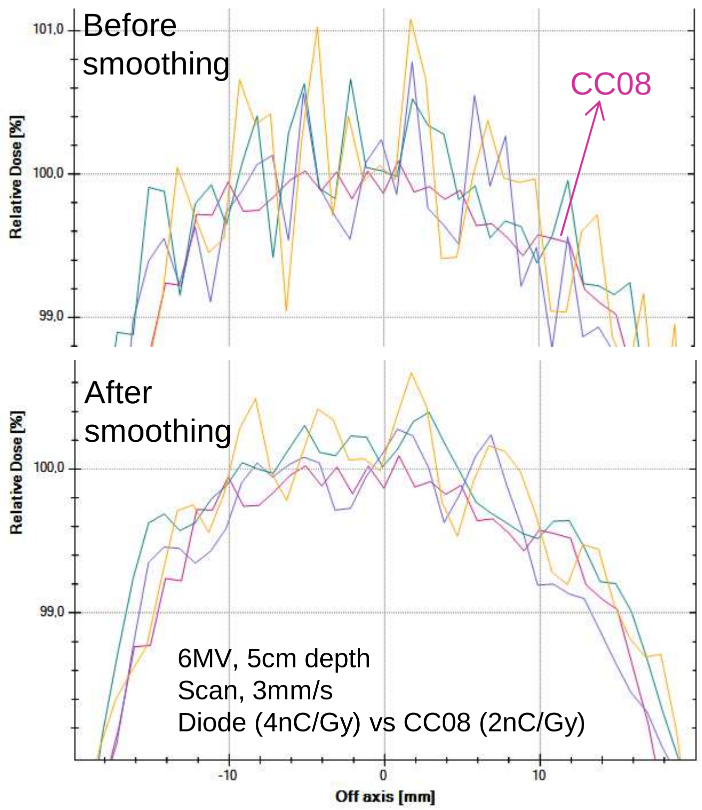


Saini A. S. and Zhu T. C, 2002, Med. Phy. 29, 622

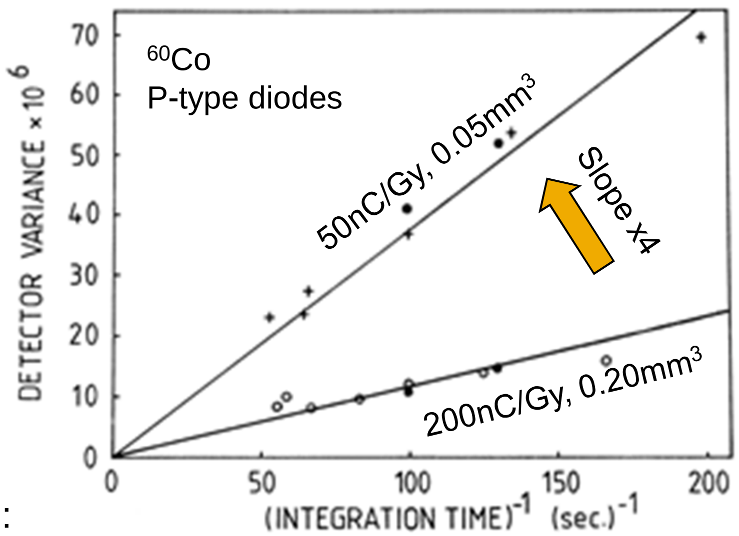
1. In most cases svwt=0.2-0.4%/K
2. Variation with beam energy only in unirradiatied diodes

Dosimetric performances (sensor specific)

Quantum noise



Rikner, G., et al. 1984. Acta Rad. Oncol., 23, 471.



Quantum noise:

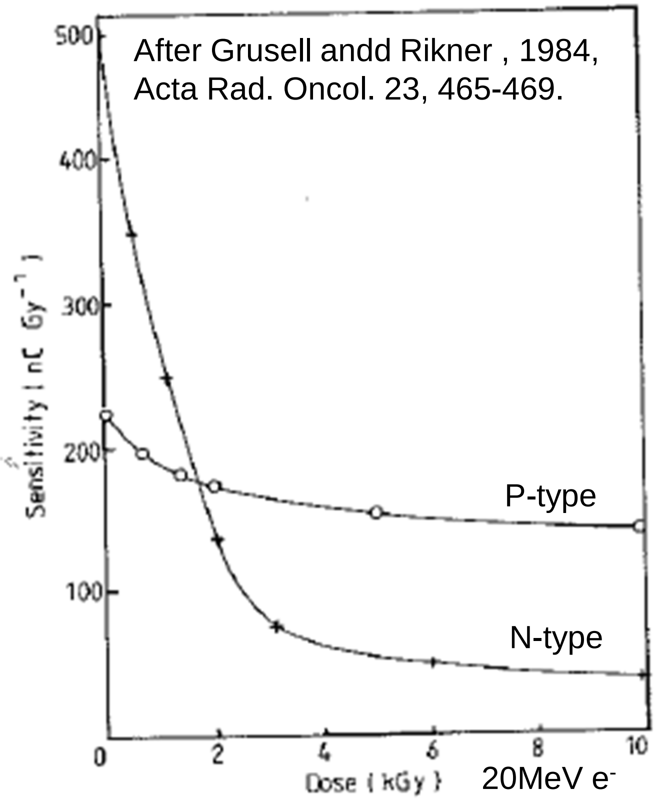
$$\frac{\sigma^2}{D^2} = \frac{1}{N}\left(1 + \frac{\sigma_F^2}{\langle z \rangle_F^2}\right)$$

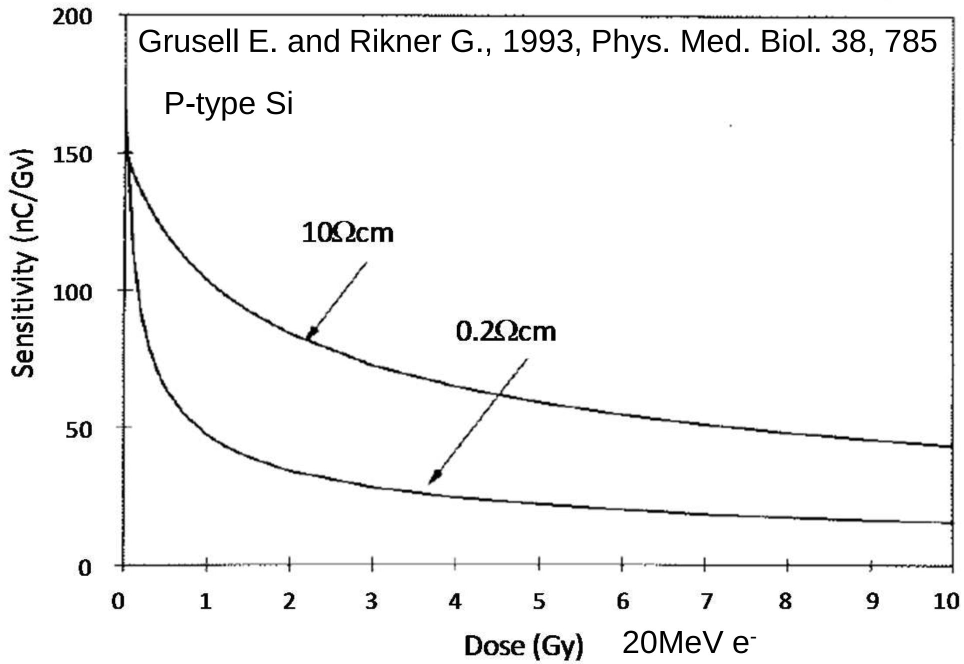
Smaller detectors may exhibit a „larger“ noise, in spite of absolute sensitivity

Important for scans with small diodes!

Solutions to improve radiation hardness

Recipe 1: preirradiation...

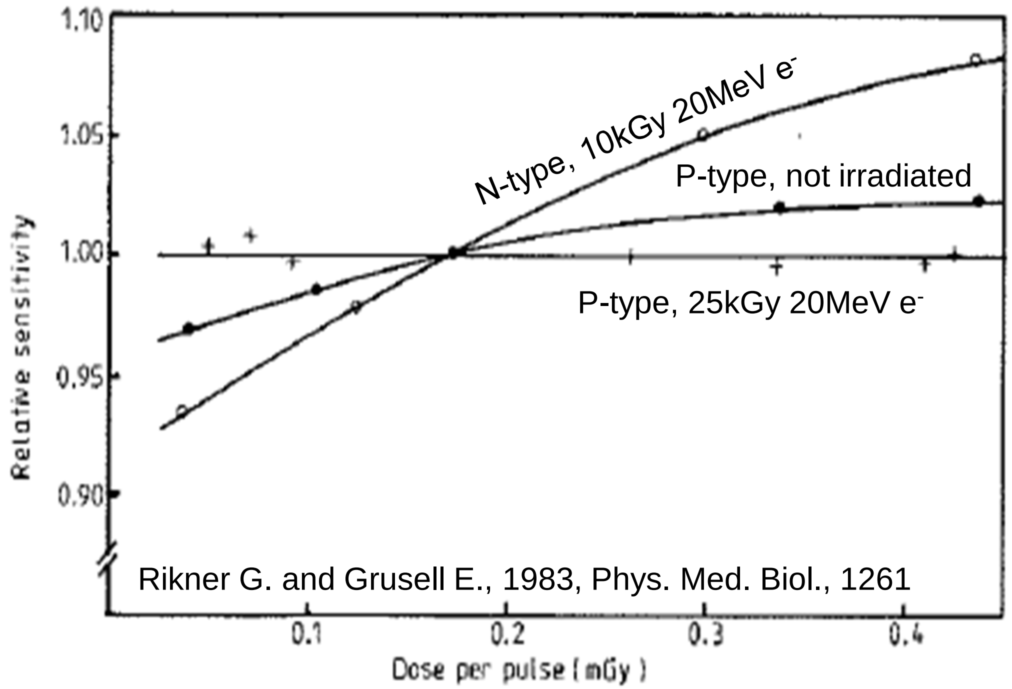




Since S decreases with dose ($S \sim N_t^{-0.5}$), pre-irradition reduces dS/dD slope

Solutions to improve radiation hardness

Recipe 1: ...p-type...



Dominant center produced by radiation (e-):

σ_e=1.62x10^{-16}cm^2,
σ_h=8.66x10^{-16}cm^2.

For this center it is easier to capture holes! Saturation is prevented if minority carriers are electrons:

$$\frac{\Delta\tau_e^{(rel)}}{\Delta\tau_h^{(rel)}} = \frac{\tau_h}{\tau_e} = \sqrt{\frac{m_h^*}{m_e^*}}\left(\frac{\sigma_e}{\sigma_h}\right) = \sqrt{\frac{0.38}{0.26}}\frac{1.62}{8.66} = 0.23,$$

$$\Delta\tau^{(rel)} = \frac{1}{S}\frac{dS}{dR}.$$

Shi J., Simon W. E., 2003, Med. Phys. 30, 2509 and cited refs.

Solutions to improve radiation hardness

Recipe 1: ...low resistivity.

Use of low resistivity improves recombination, as expected.
Even the effect of neutron-contaminated beams is negligible.

Table: "Φ factor" for diodes of two resistivities, at different pre-irradiation levels.

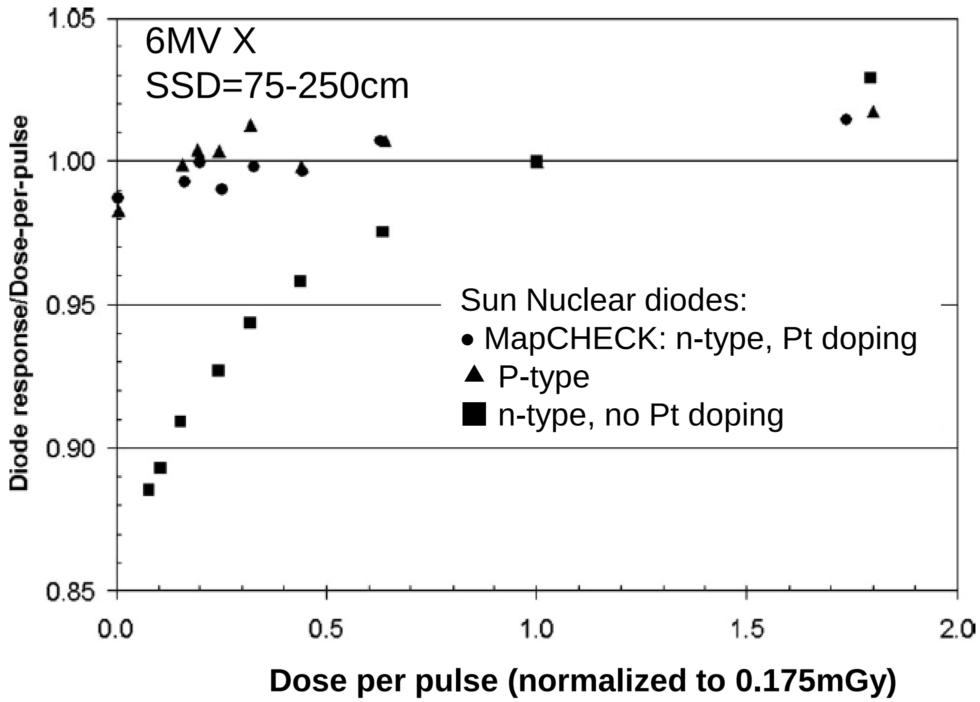
Detector type	Pre-irradition Dose (kGy)	Pre-irradiation Beam quality			
		8MV	21MV	20MeV e^-	70MeV p^+
10Ωcm	0	1.00	1.00	1.00	1.00
	3	1.0	0.96	0.97	0.95
	10			0.98	
	25			0.99	0.92
0.2Ωcm	0	1.00	1.00	1.00	1.00
	3	1.00	1.00		
	5			1.00	1.00
	10			1.00	
	50	1.00	1.00		1.00

Grusell E. and Rikner G., 1993, Phys. Med. Biol. 38, 785-792.

$$\Phi = \frac{S_{Si}(highR)}{S_{IC}(highR)} / \frac{S_{Si}(lowR)}{S_{IC}(lowR)}$$

Solutions to improve radiation hardness

Recipe 2: Pt doping



Pt introduces a recombination level at:

E_V+0.42eV,
σ_h=2.7x10^{-12}cm^2
σ_e=3.2x10^{-14}cm^2.

Large σ are effective in reducing $\tau_{e/h}$.

If center concentration is high enough:

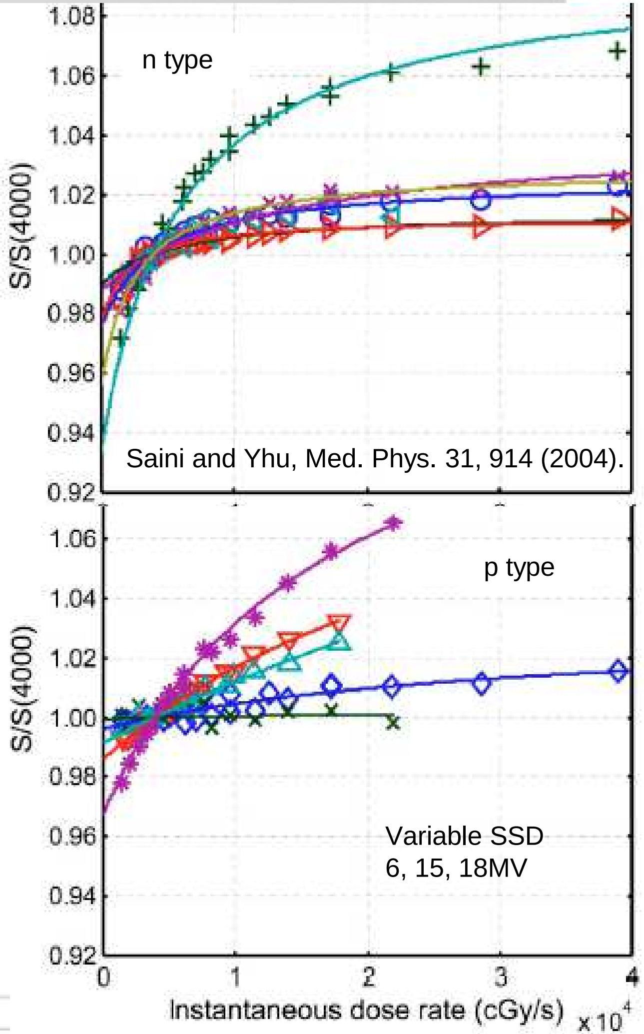
- o it dominates against radiation induced centers (S independent on dose);
- o traps saturation cannot be reached
- o (no dose rate dependence).

Jursinic P. A. and Nelms B. E., 2003, Med. Phys. 30, 870.
Baliga, Sun, 1977, IEEE Trans. Electron Devices 24, 685

Solutions to improve radiation hardness

Comparison of commercial detectors

	Manufacture	Model	Type	Pt	ρ (Ωcm)	Preirradiation	
						Dose (kGy)	Energy (MeV)
◁	Nuclear Ass.	Veridose Green	n	yes	NA	8	10
◇	Scanditronix	EDP10	p	no	0.2	8	10
X	Scanditronix	EDP20	p	no	0.2	confidential	
0	Sun Nuclear	Isorad Gold	n	no	35	none	
+	Sun Nuclear	Isorad Red	n	no	35	10	3
*	Sun Nuclear	Isorad-p Red	p	no	0.8	10	10
▷	Sun Nuclear	Isorad-3 Gold	n	yes	10	none	
X	Sun Nuclear	QED Red	n	yes	10	none	
▽	Sun Nuclear	QED Blue	p	no	0.8	10	10
△	Sun Nuclear	QED Red	p	no	0.8	10	10

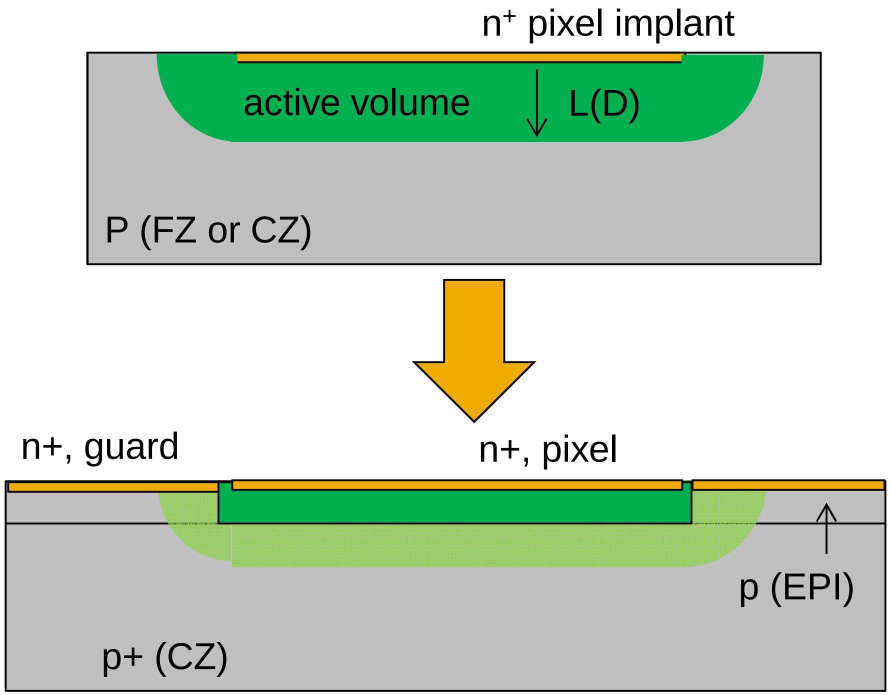


Low dose rate dependency and reproducibility is obtained with:
a) p type, pre-irradiated, low resistivity;
b) Pt doping.

Solutions to improve radiation hardness

Recipe 3: Epitaxial guarded diodes (I)

Example: p-type substrate



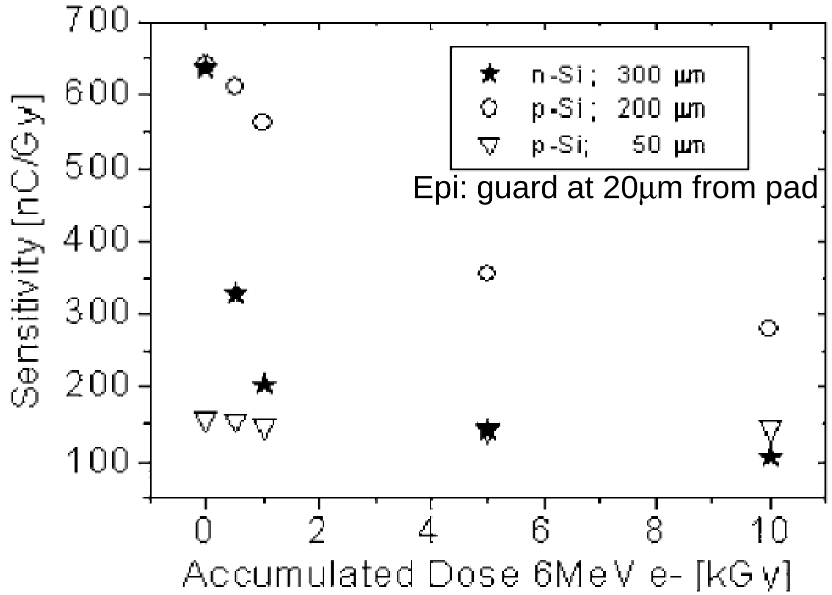
- e^- generated under the guard: collected by the guard
- e^- generated in the substrate: recombine (due to high doping)

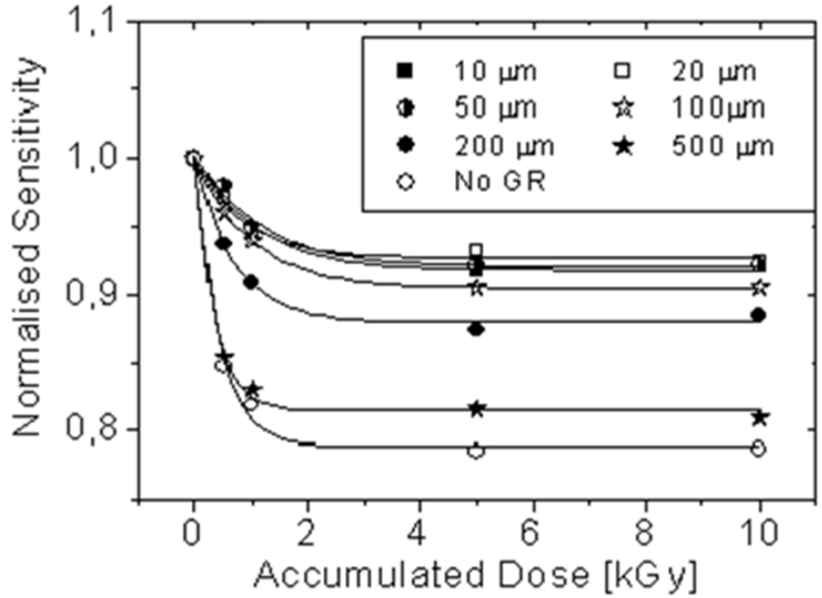
Active volume is geometrically defined!

M. Bruzzi et al., Appl. Phys. Lett., 90 (2007) 172109 1-3.

Solutions to improve radiation hardness

Recipe 3: Epitaxial guarded diodes (II)

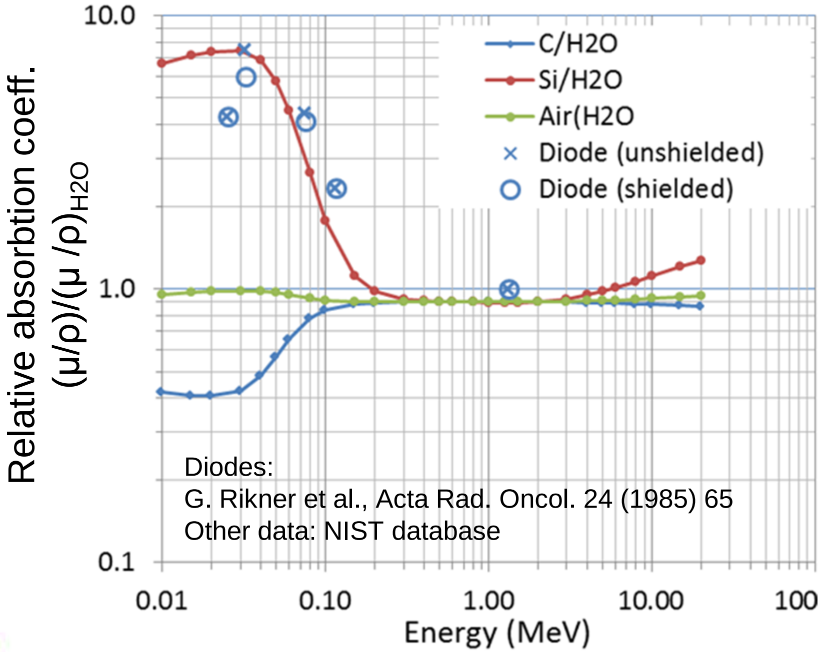


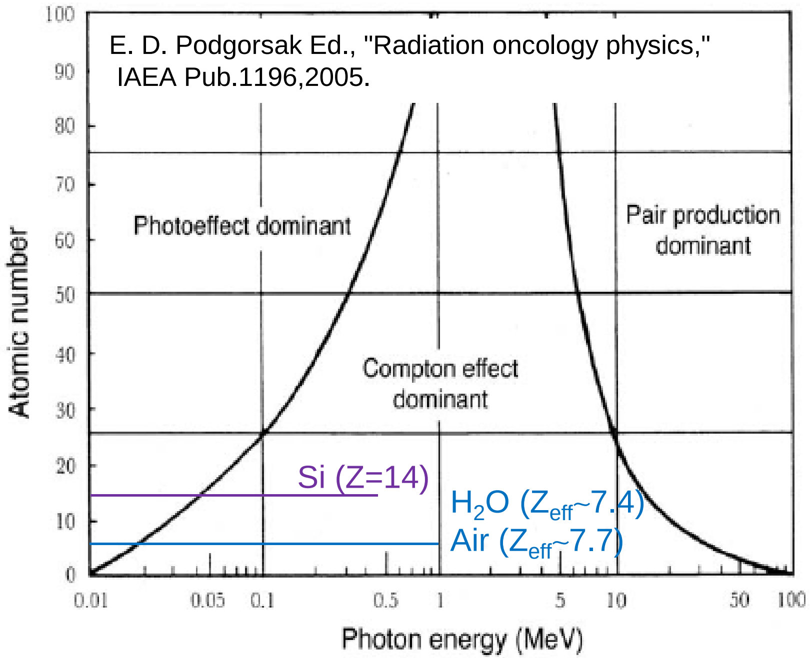


M. Bruzzi et al., Appl. Phys. Lett., 90 (2007) 172109 1-3.

Dosimetric performances (Device specific)

Energy dependence: origin

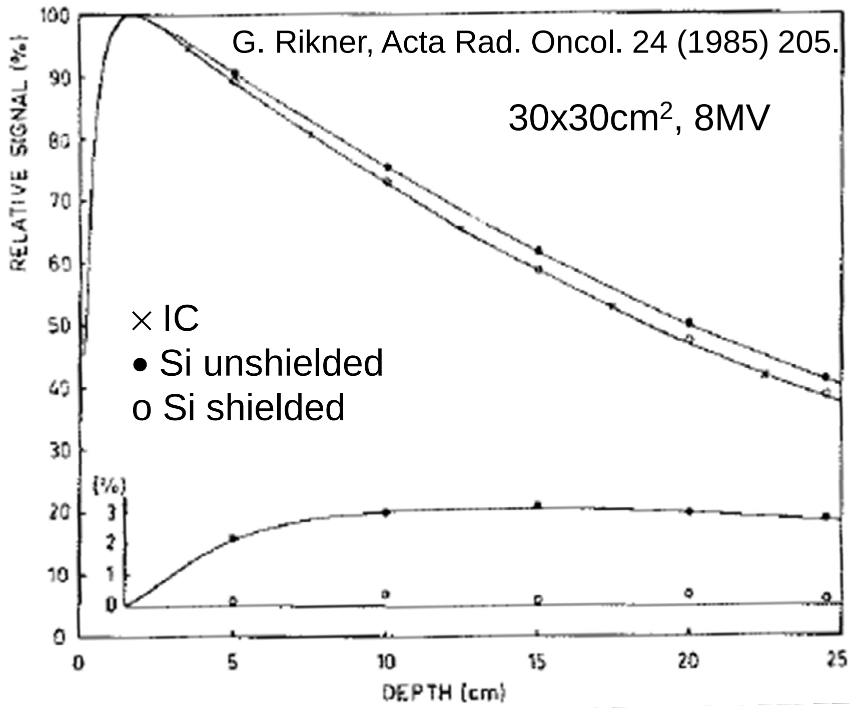


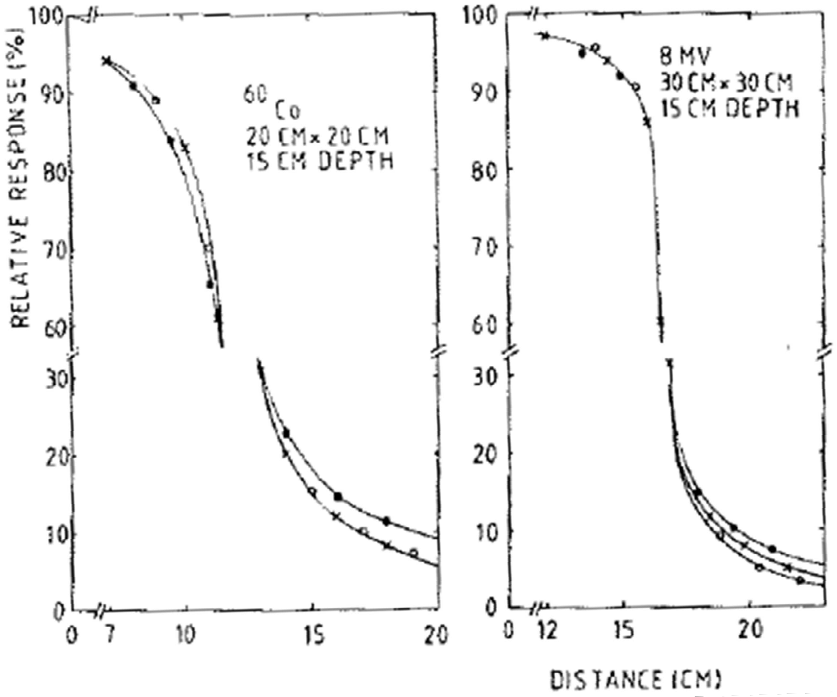


Si over-responds with respect to ionization chambers in conditions of high scattering
Due to excess of photoelectric effect with respect to air and water
Can be mitigated with a shield (e.g. Tungsten), absorbing low energy photons

Dosimetric performances (Device specific)

Energy dependence: effects on measurements



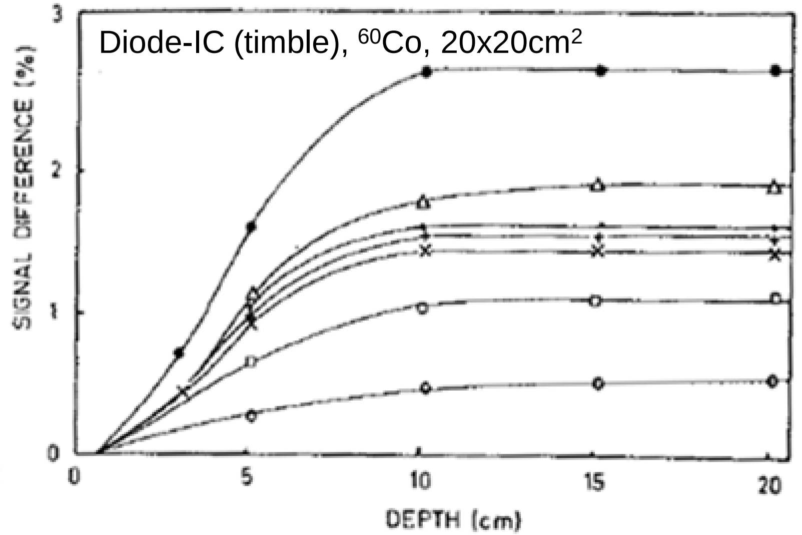


Overrespons is higher in depth, with large field sizes, at low energy

Dosimetric performances (Device specific)

Energy dependence: shield design

Rikner G. and Grusell E, 1985, Acta Rad. Oncol., 24, 65.

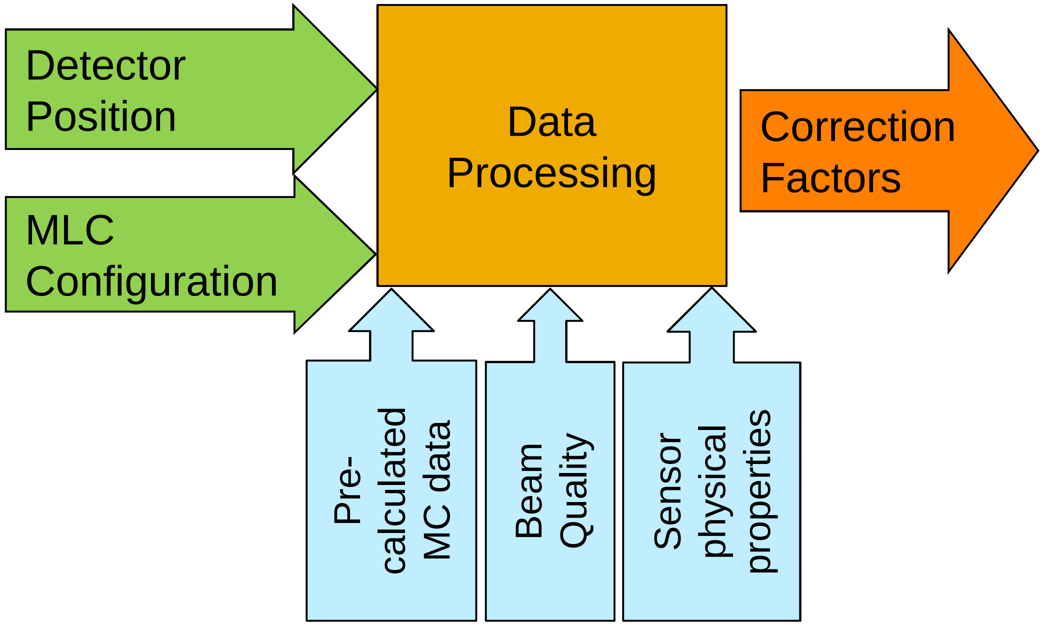


	Filter
●	none
△	0.5g/cm² Pb, 2mm cylinder
·	0.5g/cm² Pb, 6mm cylinder
+	0.5g/cm² Pb, 15mm cylinder
□	0.5g/cm² Pb, 15mm cylinder
×	1mm disk behind
O	1.0g/cm² W+epoxy behind

- A large improvement is obtained by shielding the chip from low energy backscattering
- Shielded diodes shall be used only when necessary (sub-optimal for small fields and electrons)

Dosimetric performances (device specific)

Energy dependence: software correction (I)



First-order calculation:

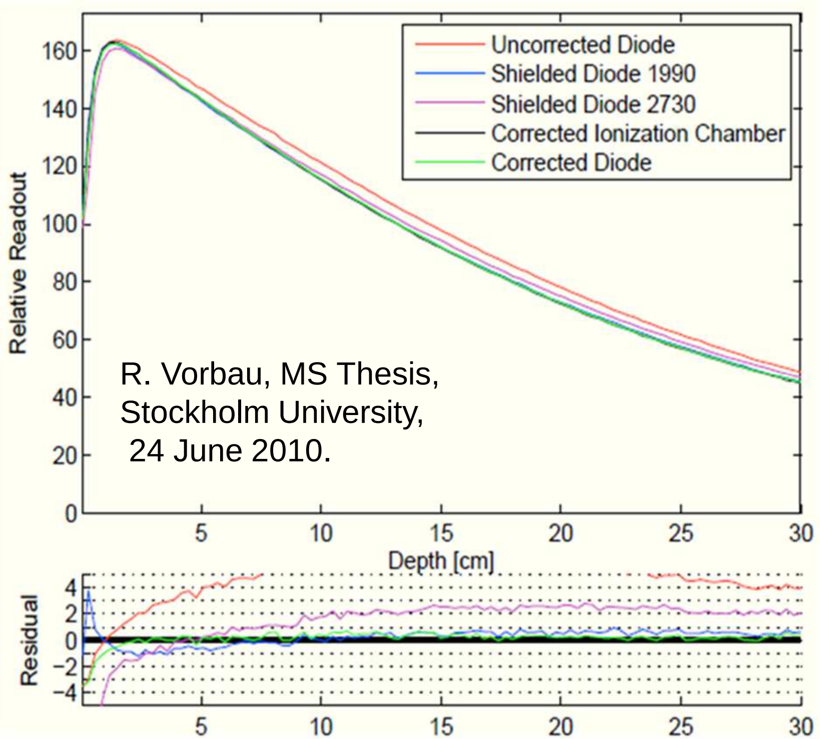
- o no scattering from MLC;
- o No beam divergency.

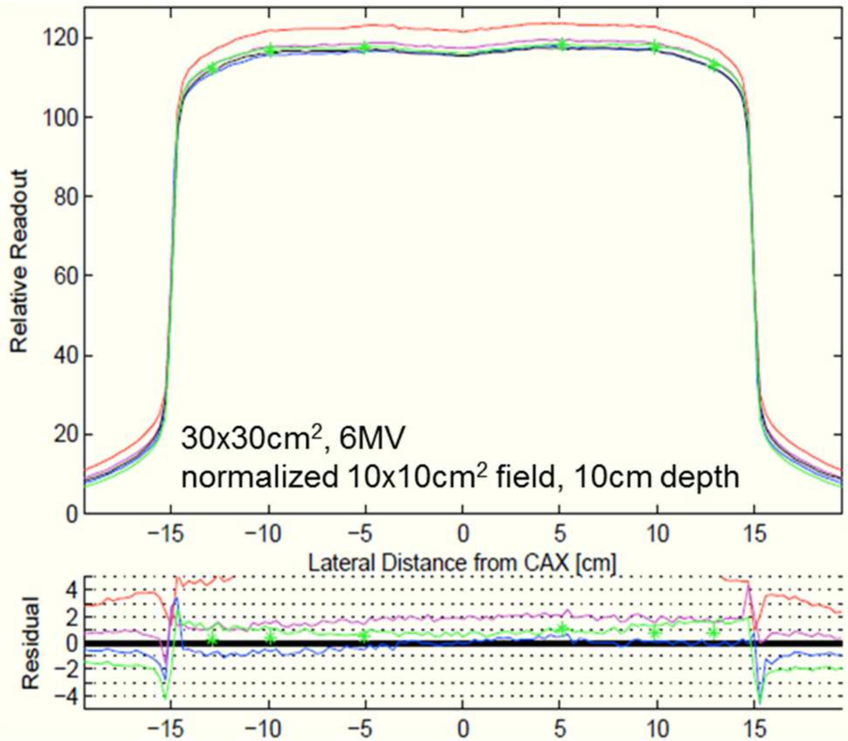
Based on pre-calculated MC pencil beams.

Eklund, K. & Ahnesjö, *Phys Med Biol* **54**, 6135 (2009).
Eklund, K. & Ahnesjö, A. *Med. Phys.* **37**, 6055 (2010).
Eklund, K. & Ahnesjö, A. *Phys. Med. Biol.* **55**, 7411–7423 (2010)
A. Ahnesjo et al, US 2009/0090870

Dosimetric performances (device specific)

Energy dependence: software correction (I)

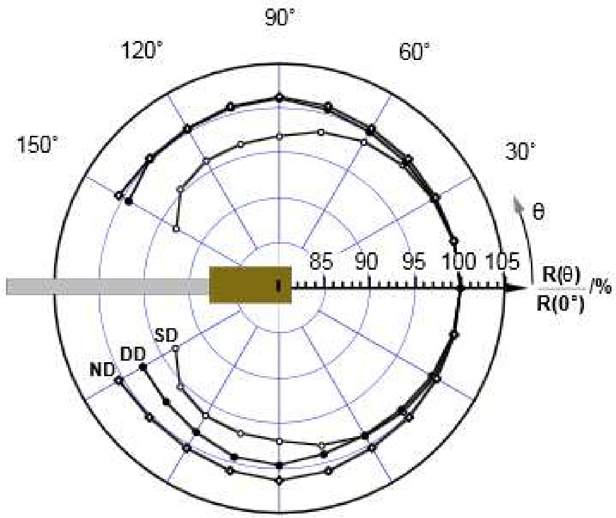


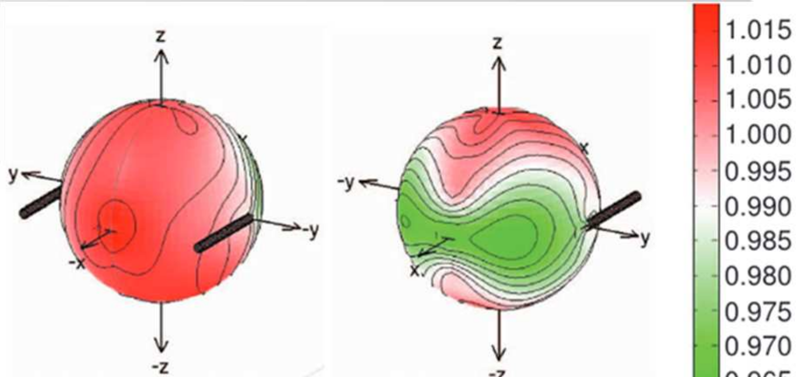


Dosimetric performances (device specific)

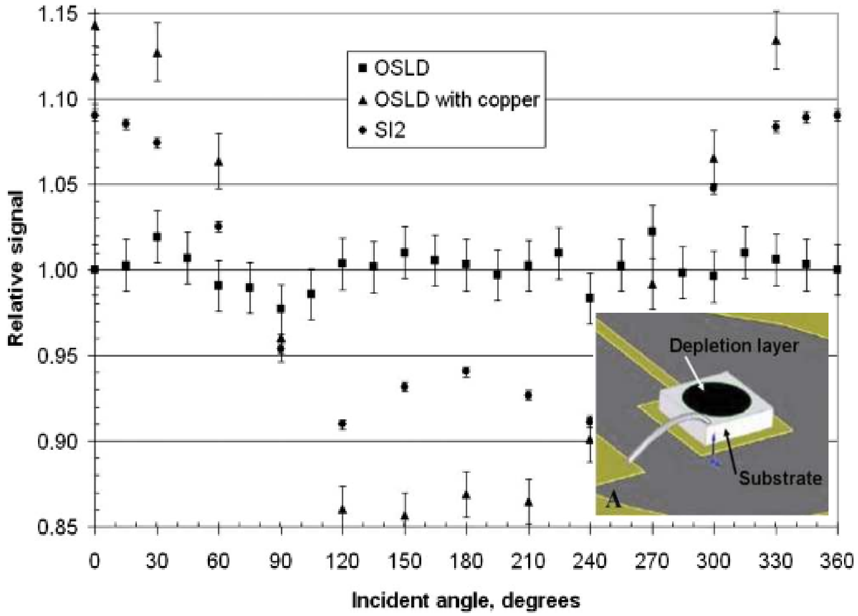
Angular dependence

Angular dependence is dominated by assembling
Almost no effect related to flat chip geometry





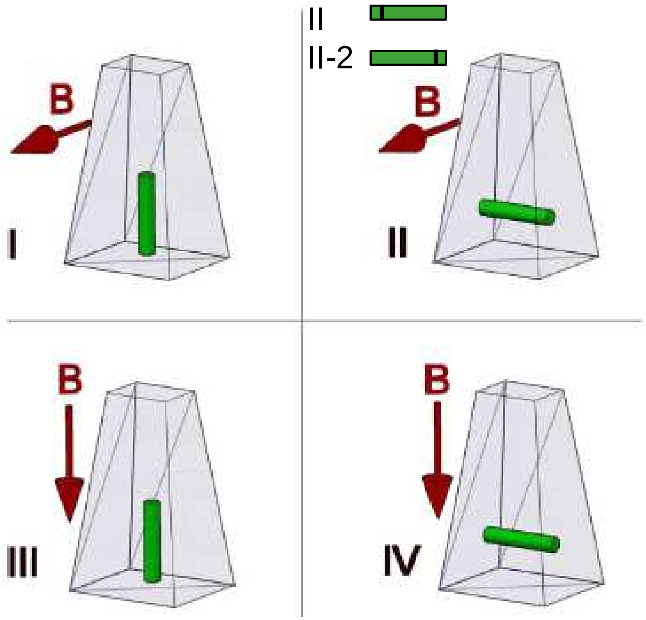
Sphelar® diode (for solar cells)

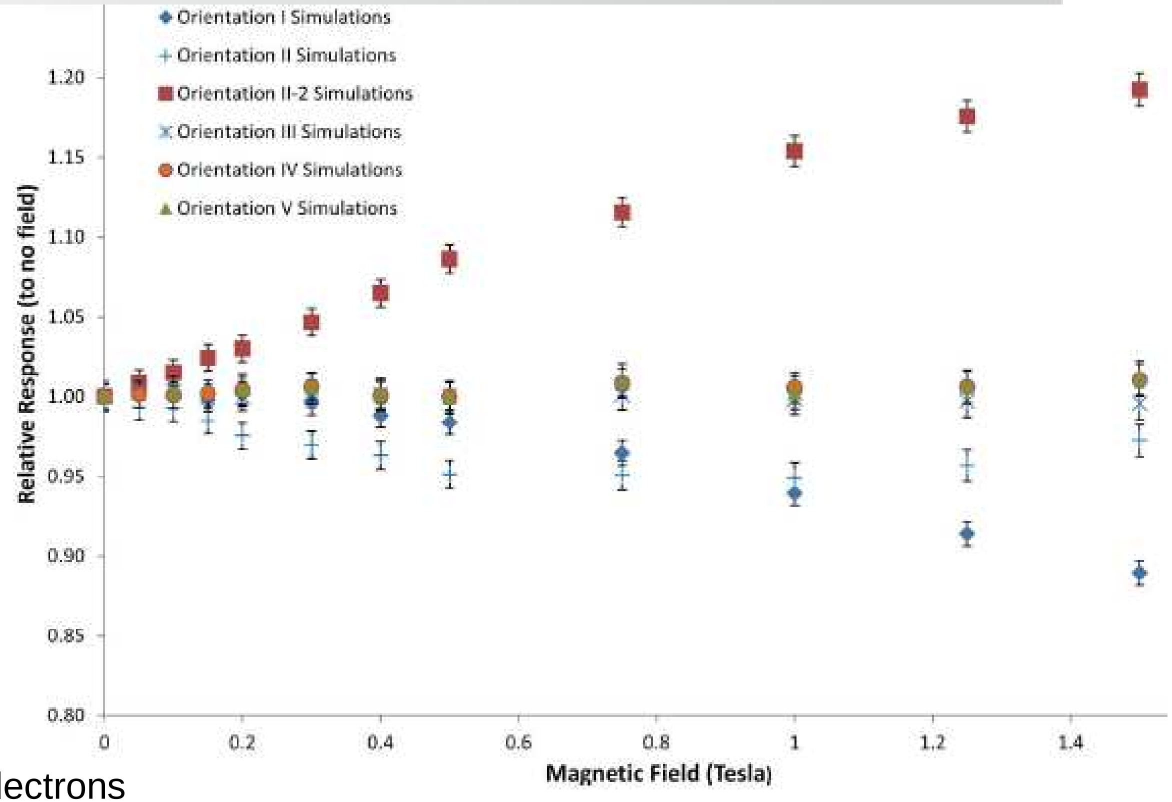


M. Westermark et al., Phys. Med. Biol. 45, 685, 2000.
P. Björk et al., Med. Phys. 27 (11), 2000
P. A. Jursinic, Med. Phys. 36 (6), 2171 (2009)
Barbés et al., Med. Phys. 41, 012102 (2014)

Dosimetric performances (device specific)

Performances in MRI LINACs





Dominant effect: bending of secondary electrons
Almost no effect when **B** is parallel to beam axis.
Need of correction if **B** is orthogonal to beam axis.

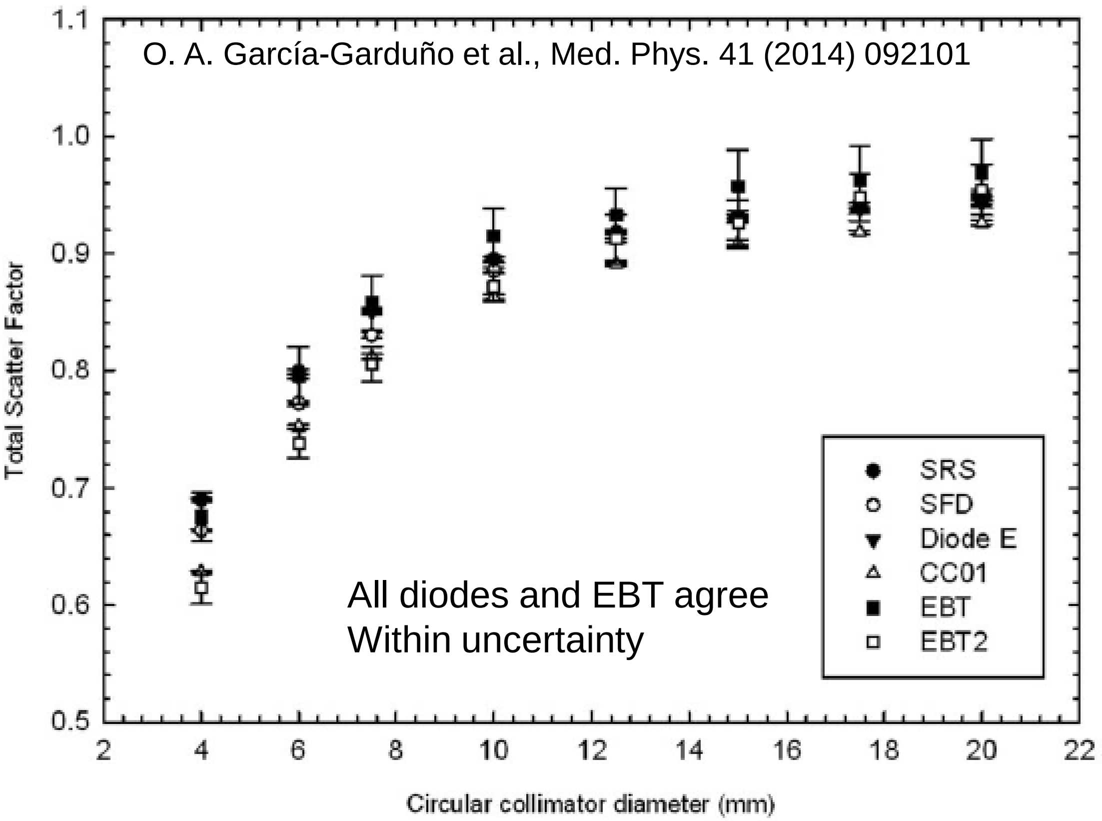
Dosimetric performances (device specific)

Small field dosimetry (I)

Very important applications (SBRT)
- o Better treatment of some tumors
- o Huge time and cost savings

Ideal for high resolution detectors
Specific features (below 2x2cm^2):
- Lack of lateral charged particle equilibriur
- Obstruction of X-ray source
- Detector perturbation

Silicon promising…
few points to be clarified:
a) How relevant is energy dependence?

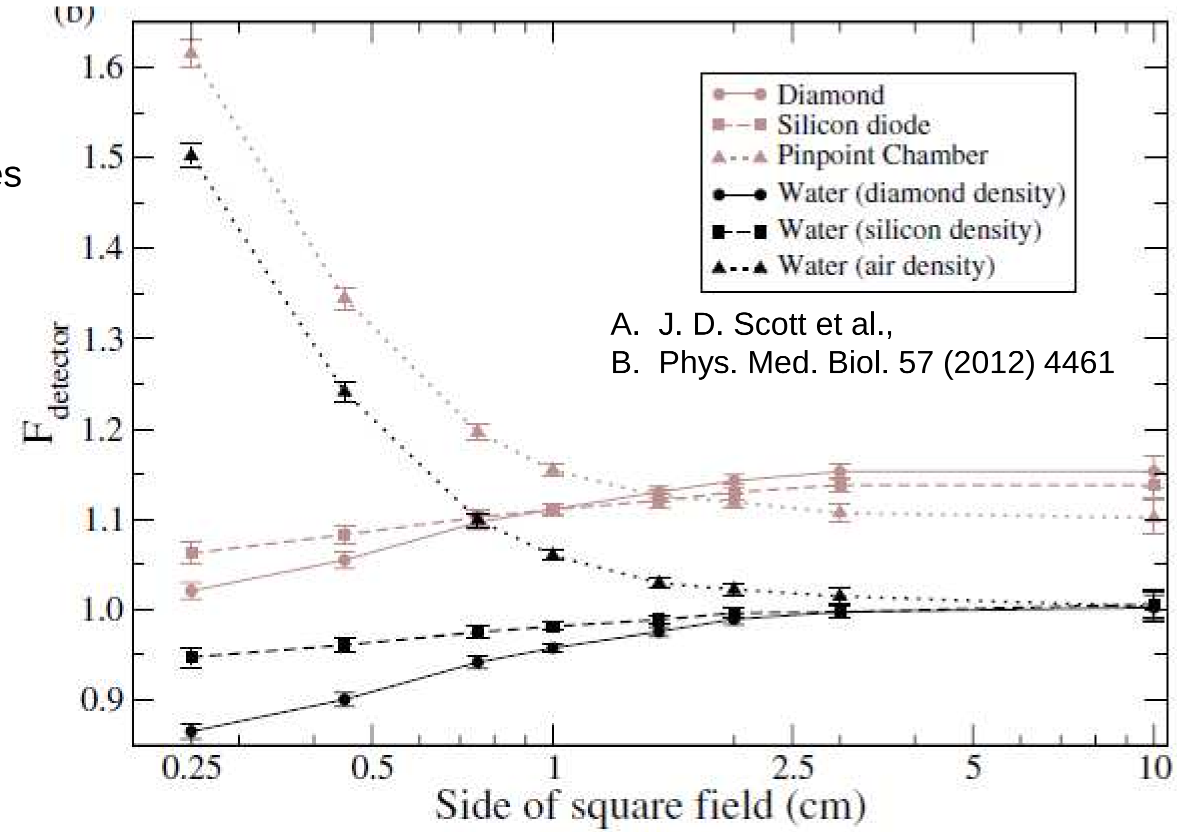


Dosimetric performances (device specific)

Small field dosimetry (II)

Silicon promising…
few points to be clarified:

a) How relevant is energy dependence?
b) Which physical parameters determines energy dependence (Z, density?)



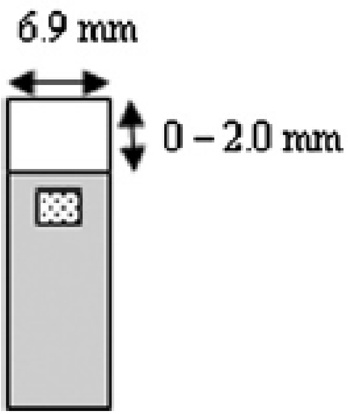
A. J. D. Scott et al.,
B. Phys. Med. Biol. 57 (2012) 4461

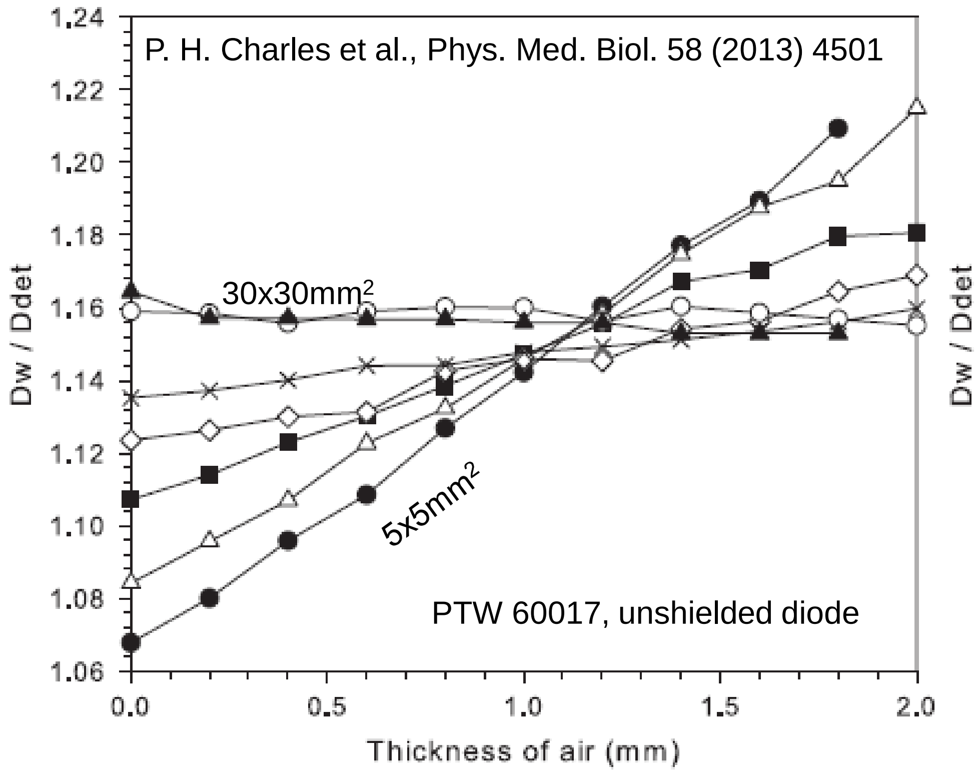
Dosimetric performances (device specific)

Small field dosimetry (III)

Silicon promising…
few points to be clarified:

a) How relevant is energy dependence?
b) Which physical parameters determines energy dependence (Z, density?)
c) Improvement with inhomogeneities in assembling (e.g. air volumes)?





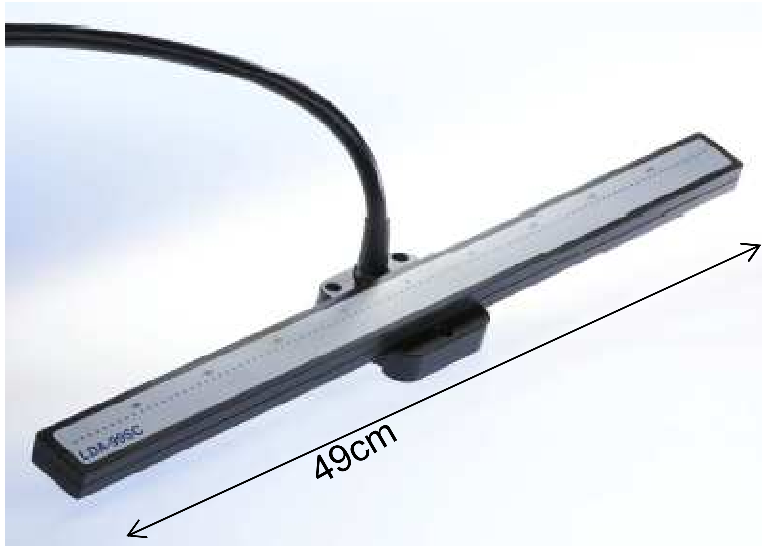
Part II

Diode arrays

- Commercial solutions
- Research prototypes

Commercial solutions

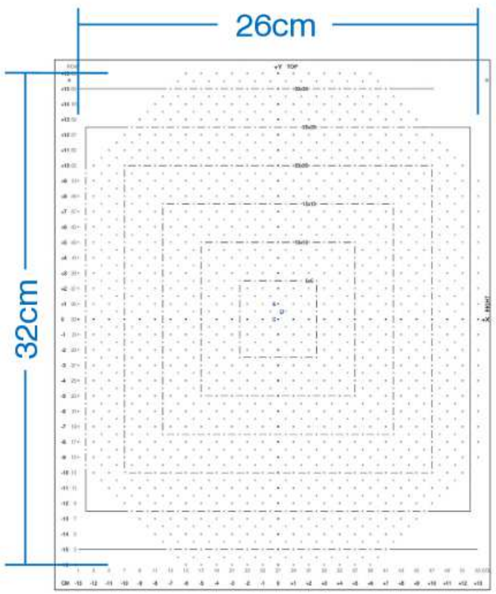
LINAC commissioning: LDA99 (IBA Dosimetry)

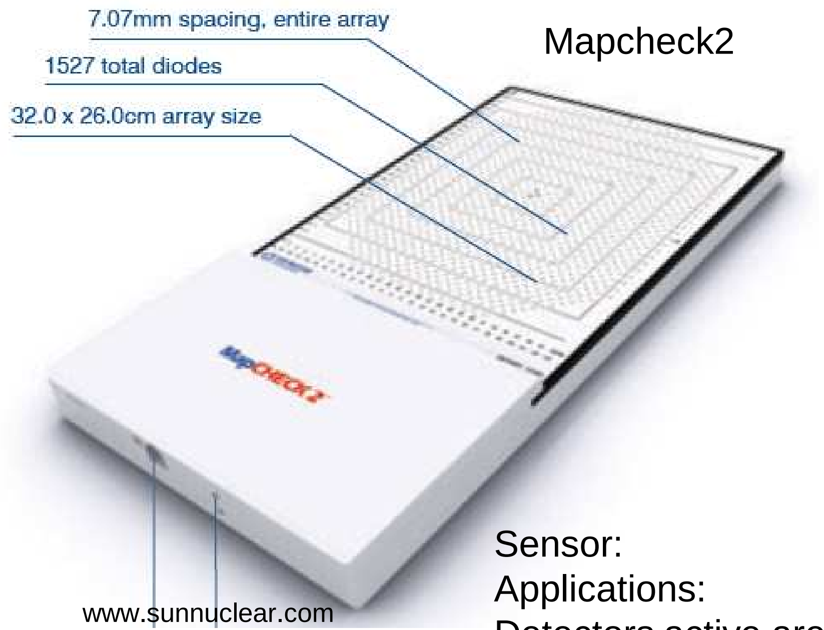


Sensor:	p-type diode, pre-irraidated;
Applications:	Relative dosimetry in a water phantom
Detectors active area:	3.1mm^2;
Active volume:	0. 15mm^3;
Sensitivity:	100nC/Gy;
Buildup:	~1mm

Commercial solutions

Multi purpose: MapCheck2 (Sun Nuclear)





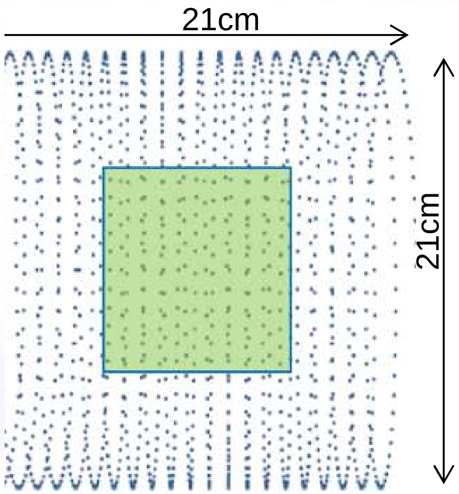
Mapcheck2

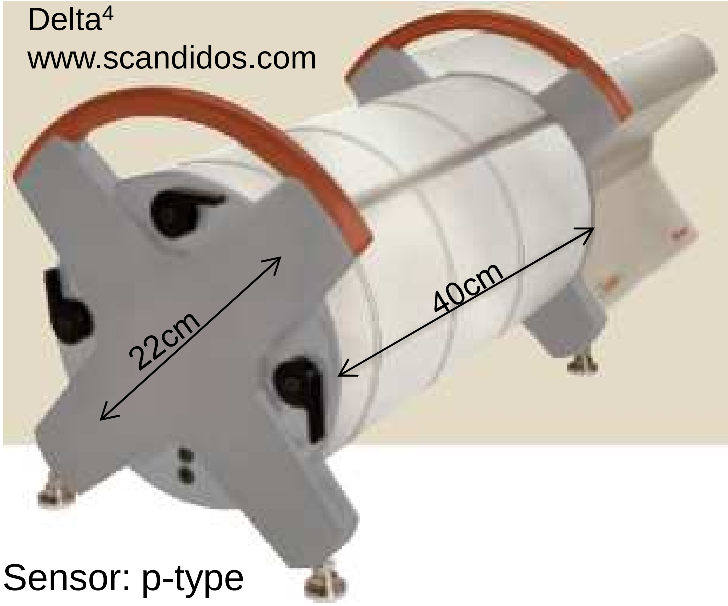
www.sunnuclear.com

Sensor:	n-type diode, Pt doped;
Applications:	mostly plan QA
Detectors active area:	$0.64mm^2$;
Active volume:	$0.019mm^3$;
Sensitivity:	32nC/Gy;
Buildup:	$2g/cm^2$

Commercial solutions

Patient plan QA: ArcCHECK (Sun), Delta[4] (Scandidos)



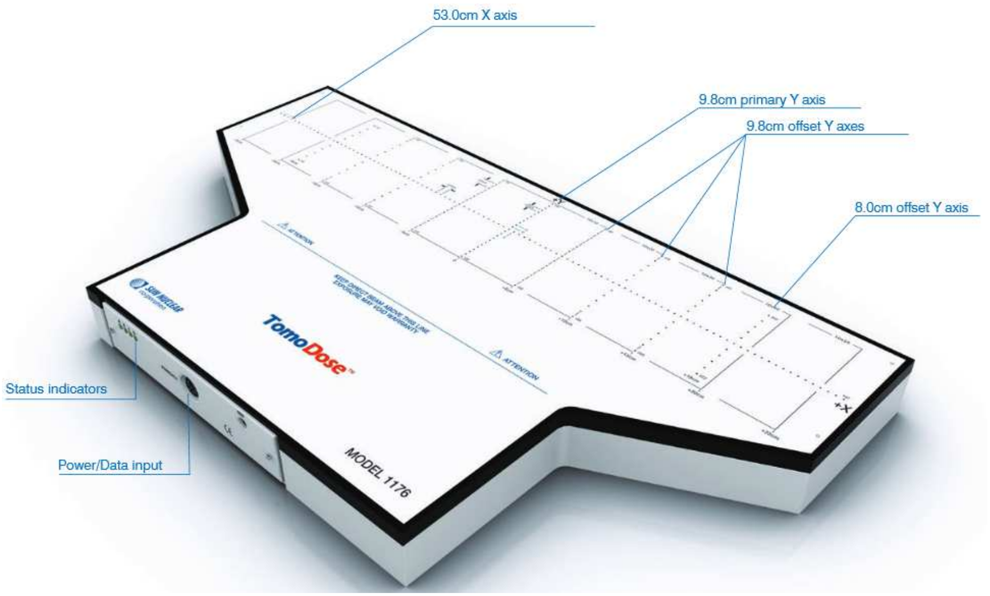


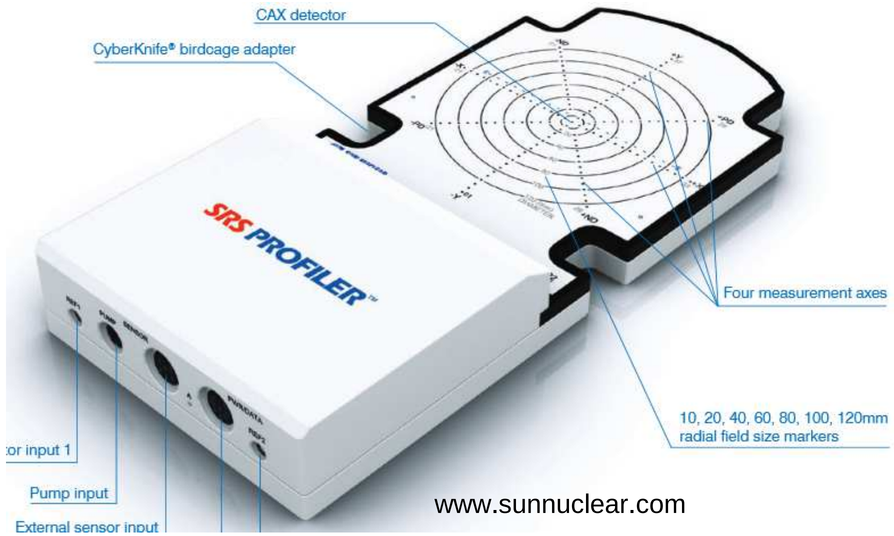
Sensor:	same as MapCheck2
Pixels:	1386
Buildup:	3.3g/cm^2

Sensor: p-type
Pixels: 1069
5-10 mm pitch (depending on region)
detectors on two planes at 90^o
Active area 0.78mm^2

Commercial solutions

LINAC QA: Tomo Dose and SRS profiler (Sun Nuclear)



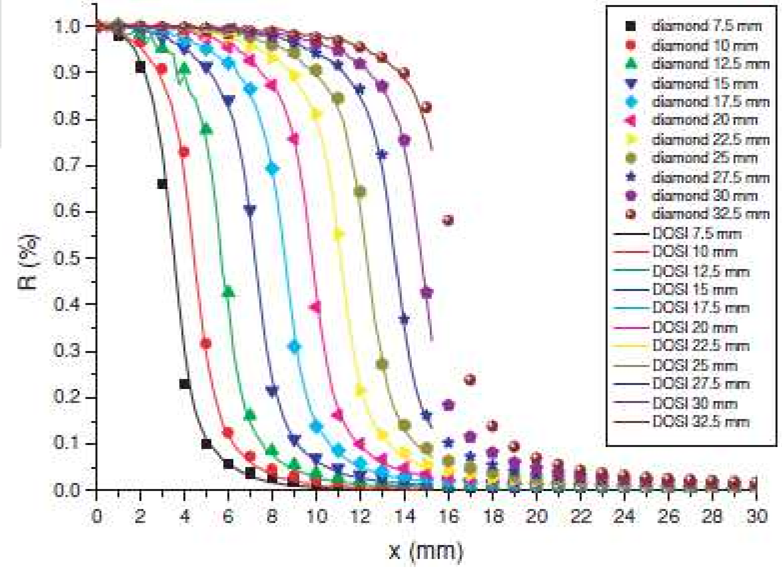


www.sunnuclear.com

Sensor:	same technology of MapCheck2;	Sensor:	same technology of MapCheck2;
Application:	specific for Tomotherapy	Application:	specific for CyberKnife
Pixels:	223, 4-8mm pitch	Pixels:	125, 4mm pitch
Buildup:	1.0g/cm^2	Buildup:	0.5g/cm^2

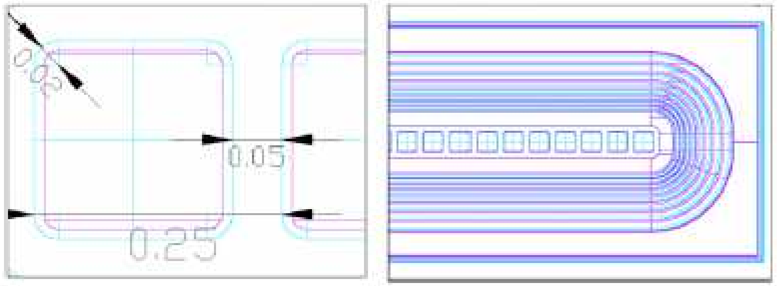
Research prototypes

ΔOSI



- First Si monolithic dosimeter
- Design mutuated from high-energy physics
- N-type silicon, 1-10kΩcm, 300μm thick.
- Readout based on X2CHIP integrator from RAL (UK)
- Detector is biased (V_{rev}=20V)

I. Redondo-Fernández et al., Nucl. Instr. Meth. A 563 (2006) 229.
Manolopoulos, S. et al., *Phys. Med. Biol.* **54**, 485 (2009).

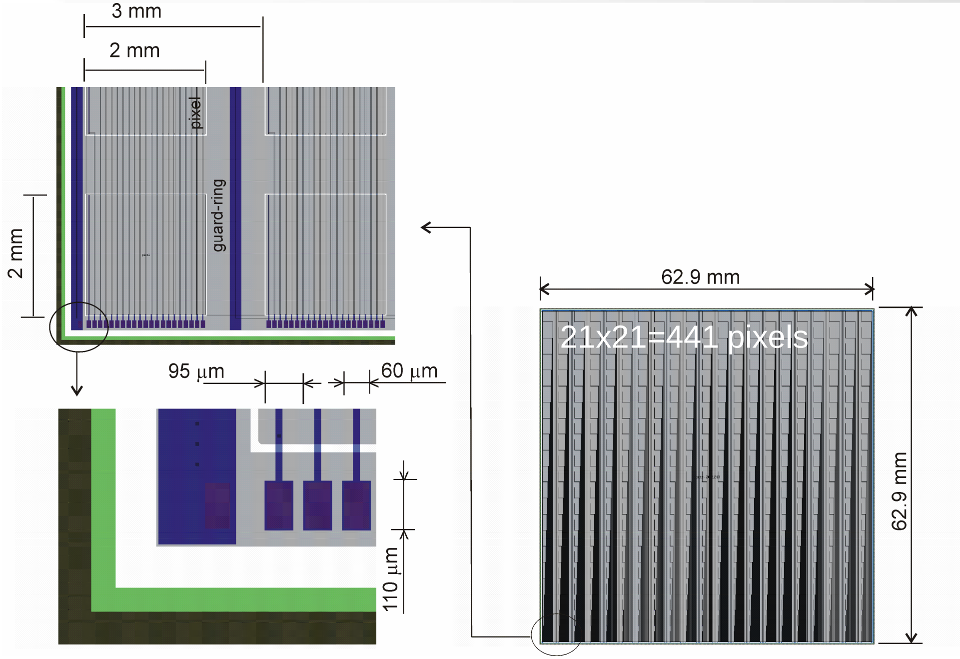


128 diodes, 250 μm pitch

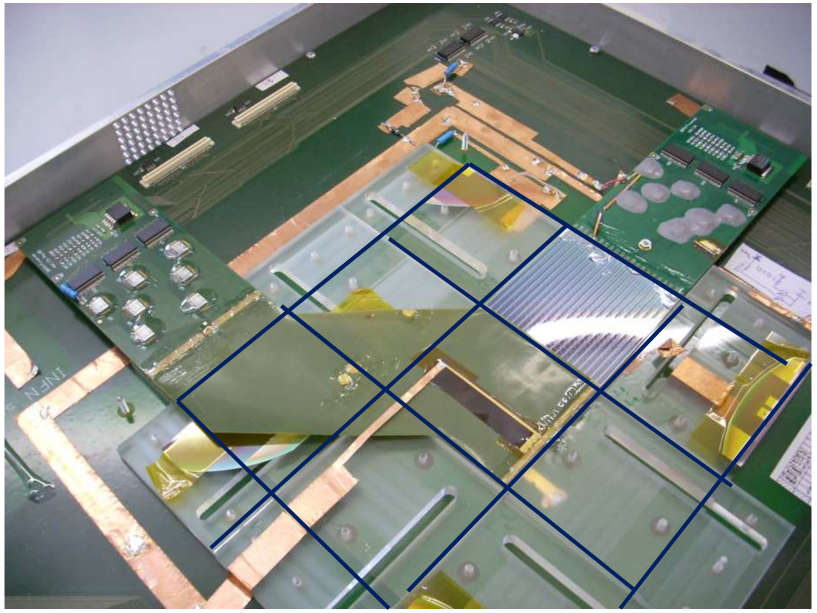
Research prototypes

„MAESTRO“ 2D array

D. Menichelli et al., Nucl. Instr. and Meth. A, 583, 109 (2007)
C. Talamonti et al., Nucl. Instr and Meth. A., 583 (2007) 114
C. Talamonti et al., Nucl. Instr. And Meth. A 658, 84 (2011)



Si Module:
p-type epitaxial diodes, 50 µm epi layer thickness
Overmetal strips to pads along one single side.
Diffused guardring structure.



Assembled detector:
Up to 3x3=9 modules (19x19cm^2)
TERA06 readout (INFN Turin)

Research prototypes
„MAESTRO“ 2D array

C. Talamonti et al., “2D Monolithic Epitaxial Silicon Detector for Application in Radiotherapy,” presented at RESMDD 2012, Florence, 10-12 October 2012.

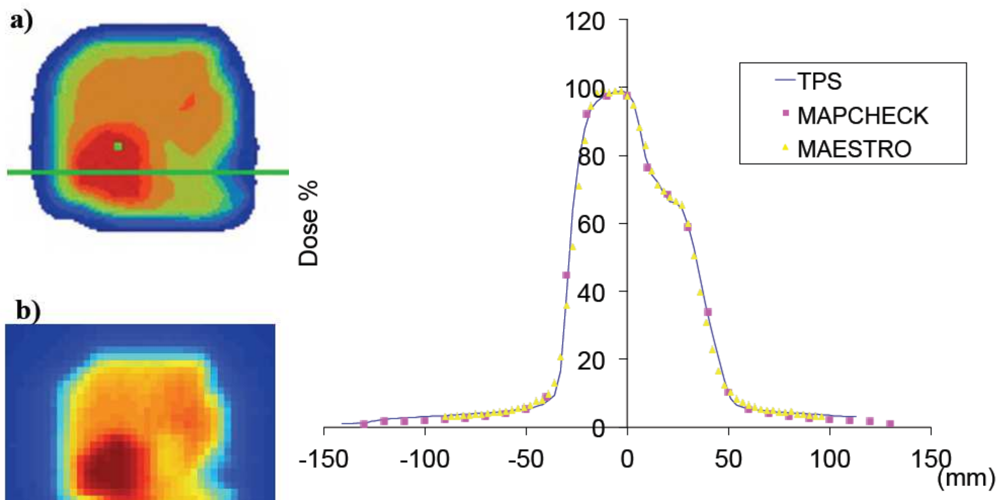
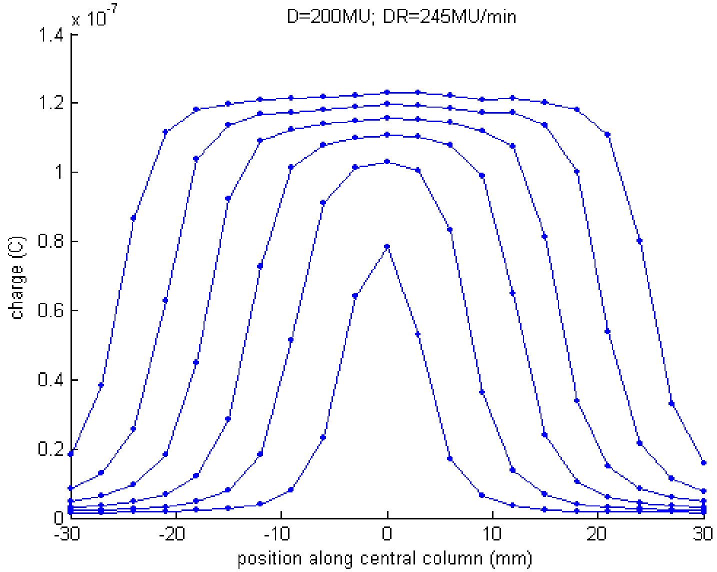


Fig.5 Profile comparison



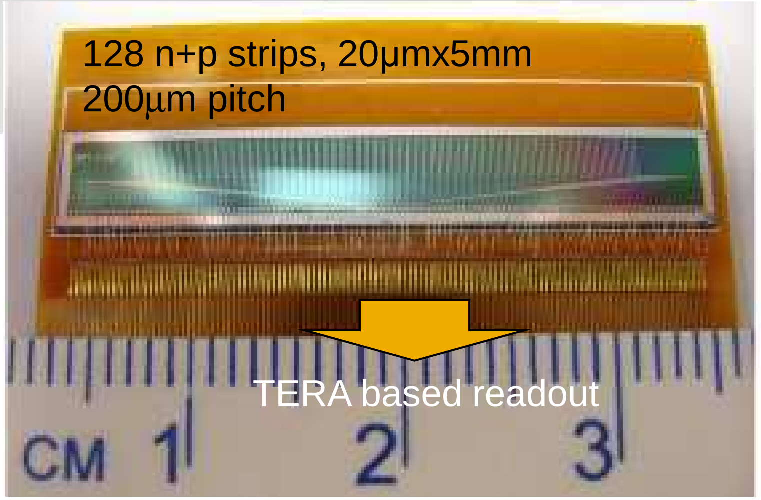
IMRT beam, 6MV

6MV, profiles of squared fields (0.8-4.8cm size)

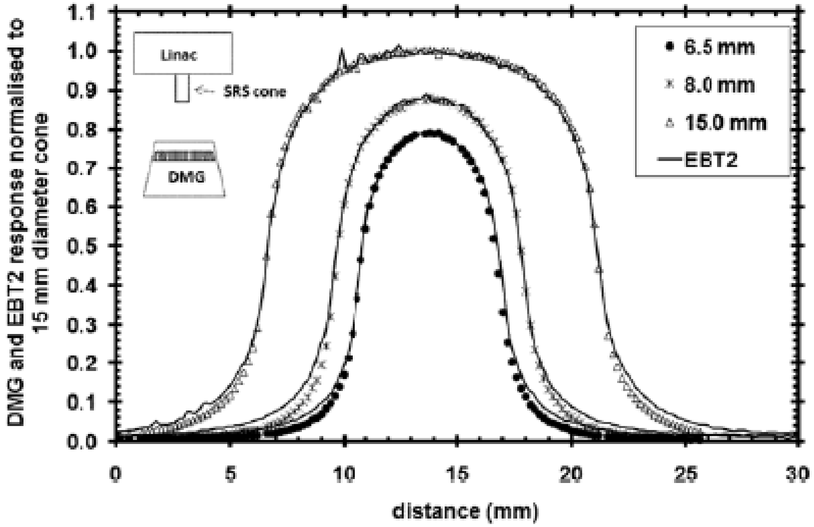
Research prototypes

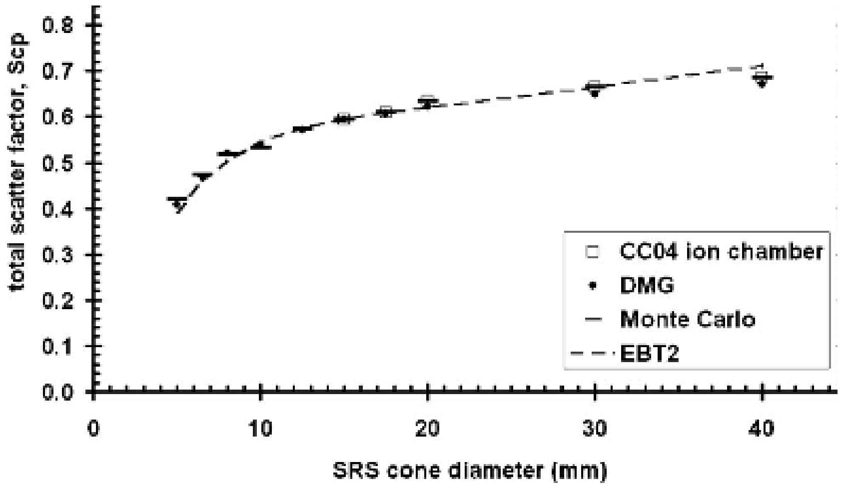
„Dose magnifying glass“

P-type silicon
ρ=5kΩcm (FZ), 10 Ωcm (CZK)
375µm thickness
Pre-irr: 15kGy (1MeV e^-)



J. H. D. Wong et al., Med. Phys. 37 (2) 2010, 428.
J. H. D. Wong et al., Med. Phys. 38 (3), 2011, 1226.
J. H. D. Wong et al., Rad. Meas. 46 (2011) 1615.

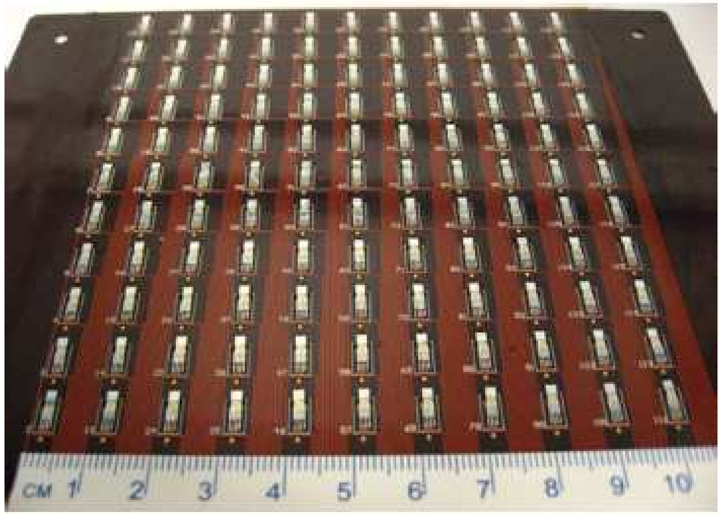


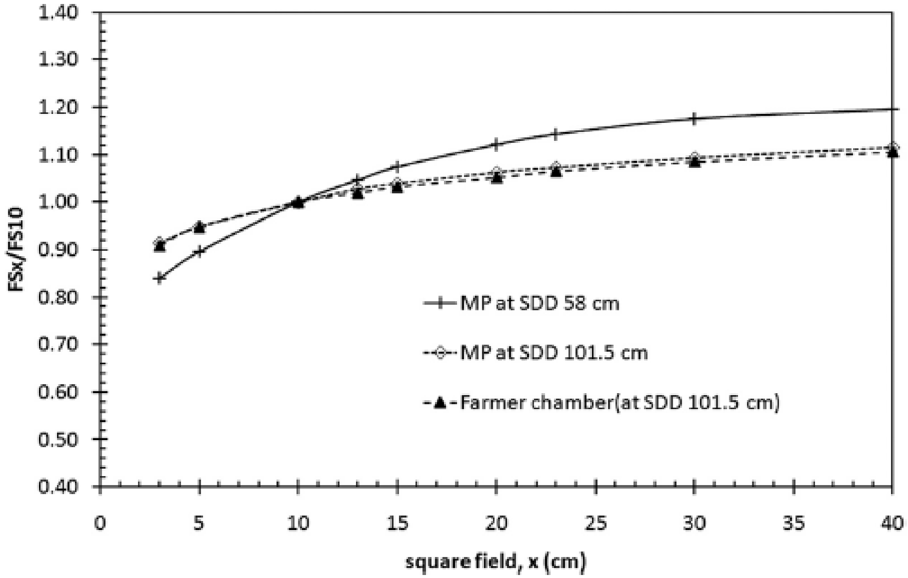


Research prototypes

„Magic Plate“ (Wollongong)

J. H. D. Wong et al., Med. Phys. 39 (5) 2012, 2544.
US2010/0164534 A1



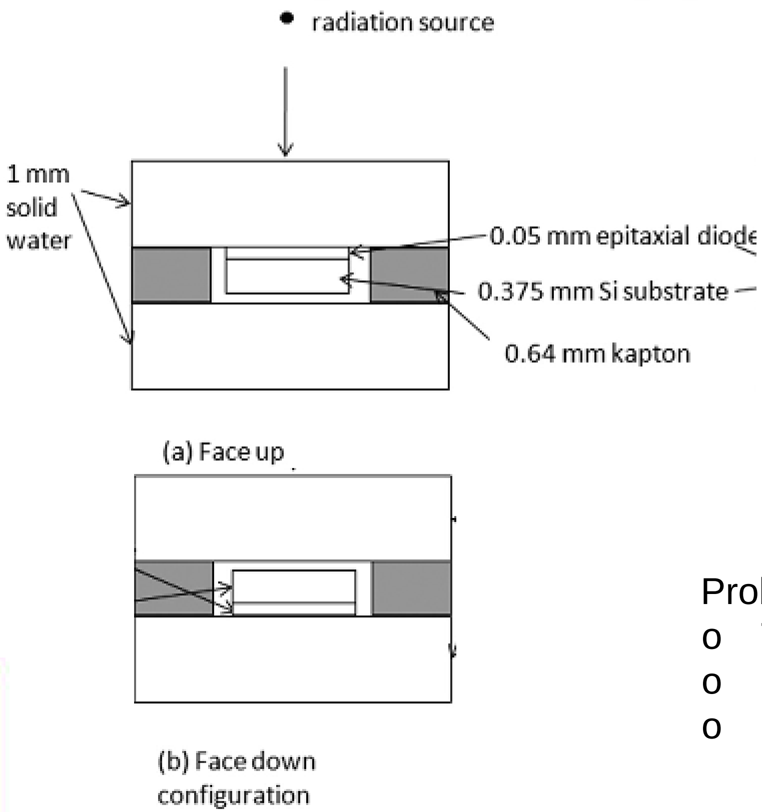


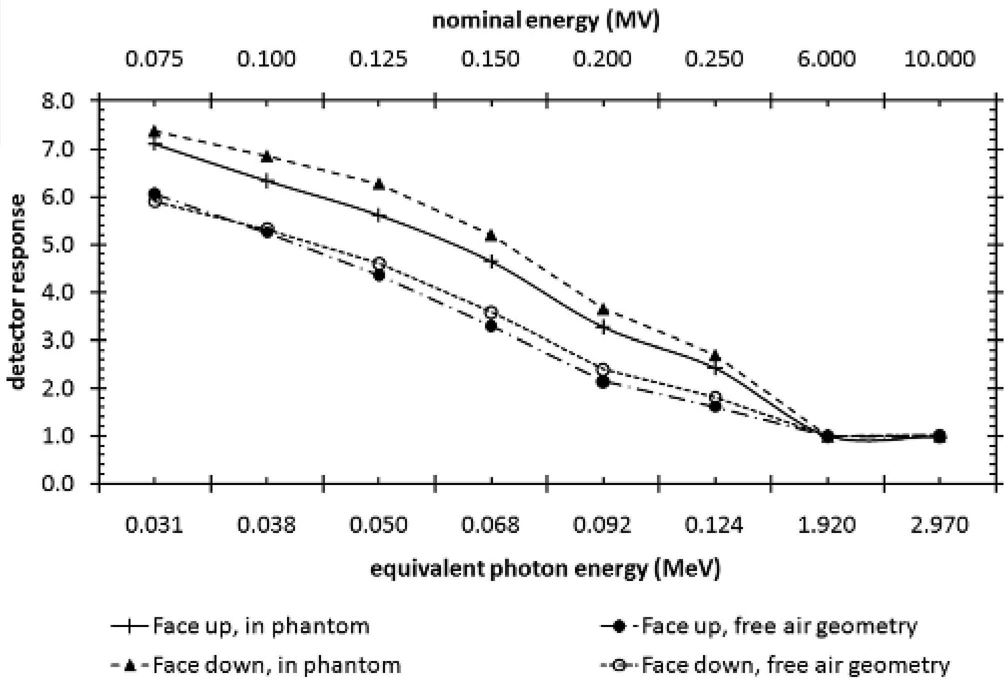
11x11 single diodes
P-type (100Ωcm), 50µm epi layer
$0.5x0.5mm^2$ active area
Pre-irradiation: 1.3kGy (6MV)+40kGy (^{60}Co)

Transmission or phantom detector mode
Chips embedded in thin plastic/kapton layers
(proprietary technology)
1cm pitch

Research prototypes

„Magic Plate“- encapsulation





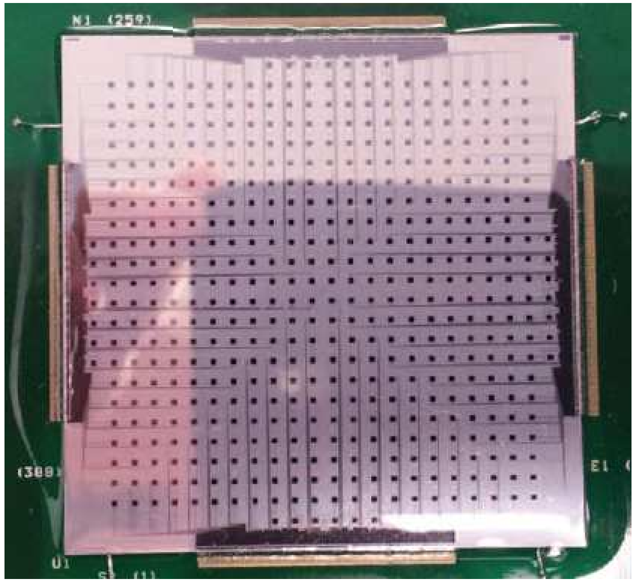
Problem:

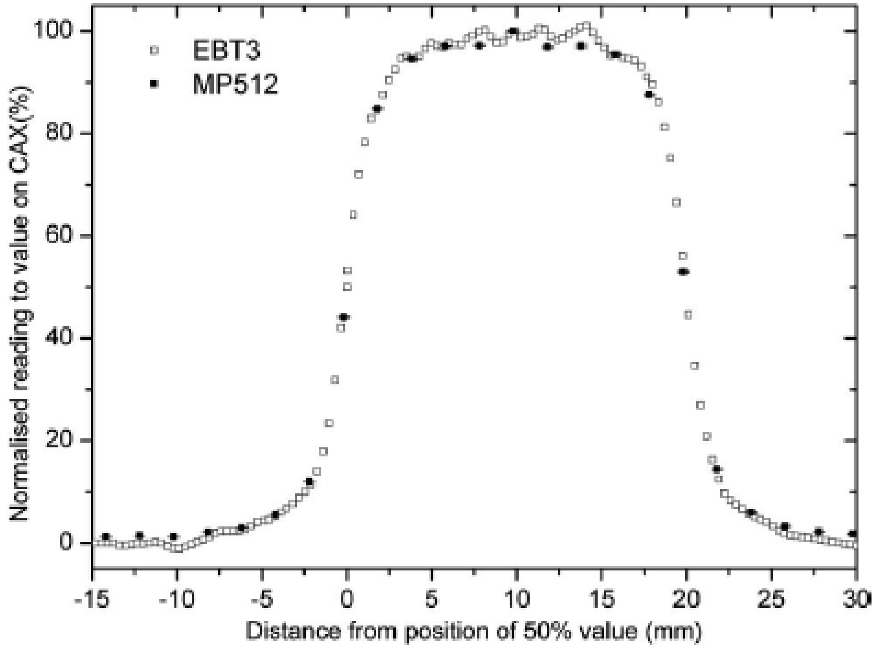
- Tight buildup (no lack of electronic equilibrium)
- No damage to Si, no skatches, no mechanical stress
- No additional energy dependence

Research prototypes

„Magic Plate-512“

A. H. Aldosari, Med. Phys., 41, 091707 (2014).





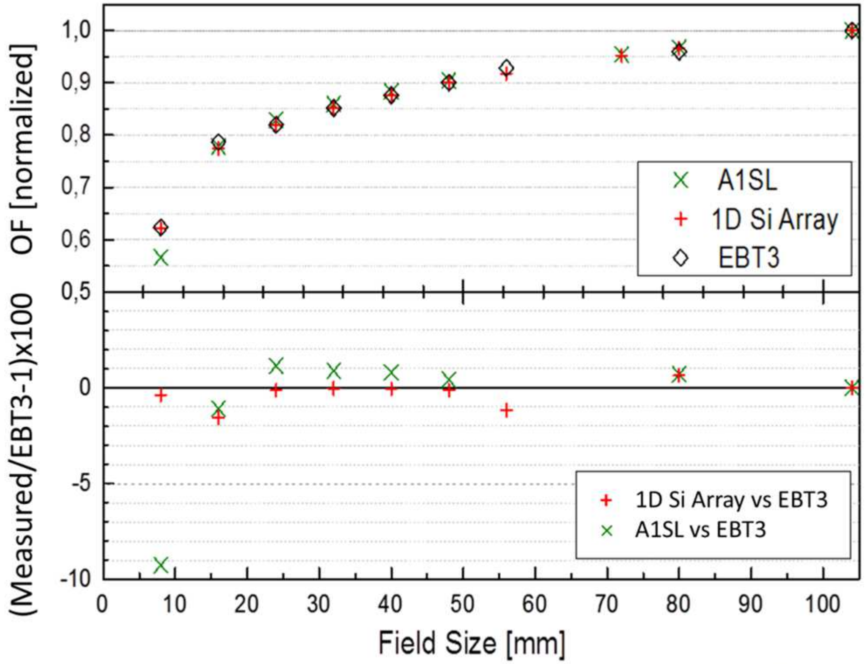
Monolithic Array,
Bulk p-type substrate
^{60}Co pre-irradiation
Readout based on Texas AFE0064
Mouted on flexible FR4, PMMA buildup

22x22 pixels,
0.5x0.5cm^2 pixel active area
52x52mm^2 area
2mm pitch

Research prototypes

IBA „1D Si Array"

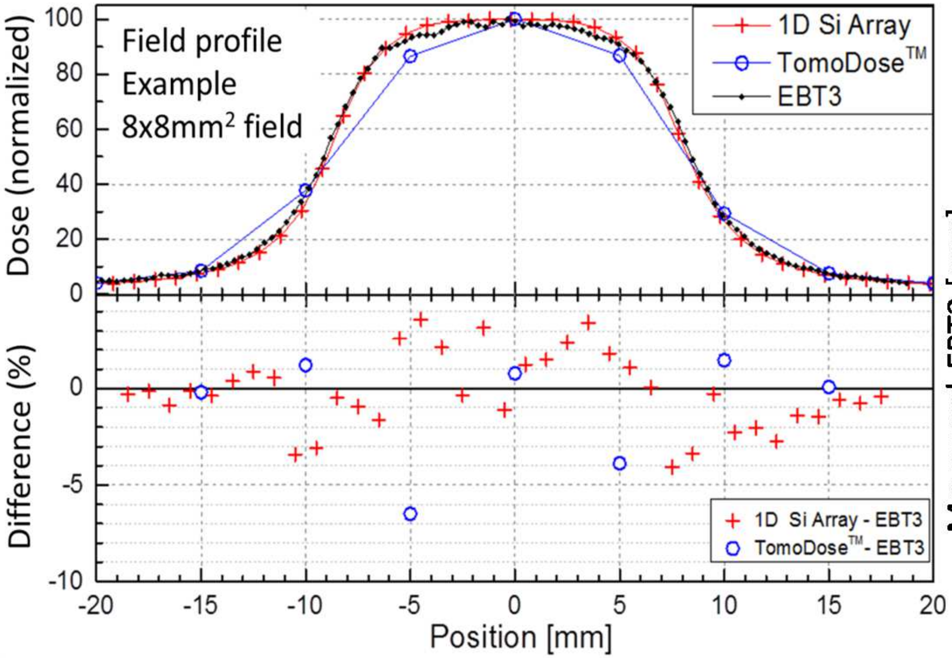
C. Talamonti et al., „Novel Silicon Array for quality assurance in photon and proton therapy," AAPM annual congress, Austin, July 2014.

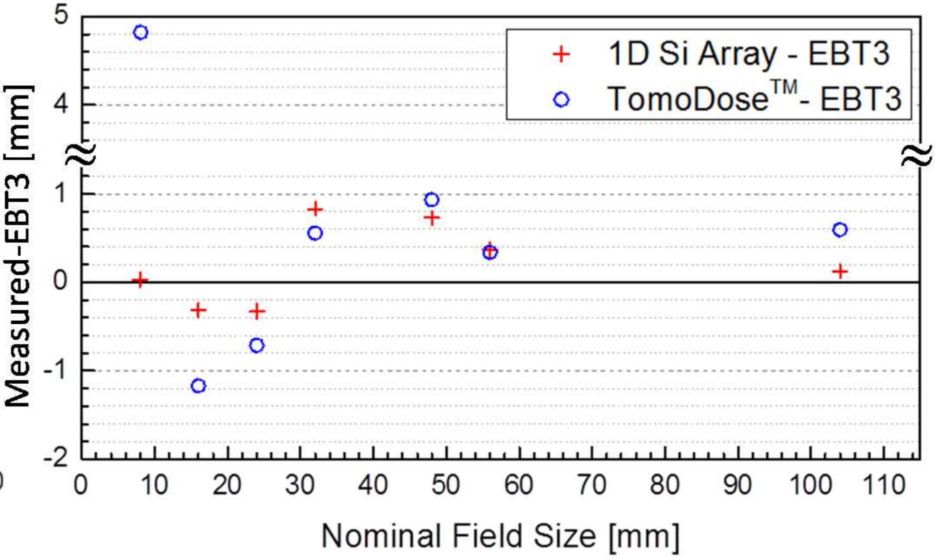


24cm active length, 1mm pitch
Assembling of 64 pixels monolithic modules
Connected to „Zebra" electrometer with a molti-pole shielded cable.

Research prototypes

IBA „1D Si Array“





Part III

Final remarks and future perspectives

- State of the art
- Semiconductor design
- System design
- Competing technologies*

*Huge bibliography; I can provide references about specific issues to the interested persons

Remarks and perspectives

State of the art summary

Present situation

- o Solutions available to manufactor high performances Si dosimeters
- o Consolidated readout scheme: photovoltaic, DC coupling, current integration, no bias
- o Single diodes are widely used for scanning, in-vivo and OF measurements (small fields)
- o Commercial Arrays (of single diodes) cover most applications but in-vivo (ScandiDos solution announced).
- o Current research: mainly exploiting high spatial resolution (typically with monolithic array)
- o Multichannel electrometers with ADC are available (e.g. INFN Tera0x, TI and Analog...)

Open issues

- Energy dependence
  large fields (>10x10cm^2): photoelectric effect;
  very small fields (<1x1cm^2) : unclear.
- Best use of high resolution possibilities offered by Si processing
  Trade off between area coverage, pixel pitch, cost, readout complexity

Remarks and perspectives

Semiconductor design

Diodes shall be radiation hard (recipes exist)

- Low dS/dD, to preserve calibration (a user calibration procedure must be given!);
- Low dose rate dependence (especially with unflattened beams)
- Quantum noise may be not negligible if pixels are very small (important for small fields).
- Angular and energy dependence shall be faced at system level.

Monolithic arrays or single diodes?

- Monolithic chips are convenient only if full area coverage is required;
- Monolithic: better uniformity; assembling is only conceptually easier.
- Array of single diodes cost effective if pitch is not too small, depending on assembling technology

If monolithic, which module size?

- Few full wafers? Many small chips? A tradeoff is needed.
- Large area chips are fashinating but: lower yeld, huge replacement costs.
- Attention to important axes (central axes covered with 3x3, not with 2x2...)
- Fan out is not obvious...

Final remarks and perspectives

System design

General rule

One shall have in mind the final application, and a consistent feedback from clinics!

Assembling

- o No energy dependence worsenign (minimal amount of high-Z materials, especially upstream)
- o Scattered photon shielding: may be a problem for electrons and small fields
- o Mechanical stability, even with temperature changes
- o No damage to chips (e.g. scratches)

Readout complexity

- Parallel readout needed by diodes (multiplexing available only with MAPS)
- Number of readout ICs and costs rise with #pixels
- Critical for 2D applications: #pixels$\propto$(1/pitch)^2, #pixels$\propto$(detector size)^2
- Integrating IC cannot placed inside clinical radiation field (parasitic signal generation)
- Reliability and power consuption are worsened by high complexity

Final remarks and perspectives

Competing technologies (already commercialized)

Air filled ionization chambers

- „Gold standard“ (highest dosimetric performances)
- E.g. IBA MatriXX and StarTreck, Sun IC Profiler, PTW Octavius 1500 and 729
- 7-10mm pitch, prototypes down to 3.5mm
- No cost problems in covering large surfaces

a:Si flat panels: (software for LINAC-embedded Epid)

- Large area (up to 40x40cm2) and high resolution (200µm) thanks to a:Si deposition and multiplexing.
- Pretty expensive, radiation hardnes not completely clear, few manufactures.
- Indirect detection (aim is imaging), need software correction
- EPIdose (Sun), EpiGray (Dosisoft), Dosimetry Check (Math Resolution), Epidos products
- Research about stand alone devices

Liquid filled ionization chambers (e.g. PTW Octavius SRS)

- Better spatial resolutions due to higher sensitivity (2.5mm available)
- „Gold standard“ attribute of air is lost;
- Problems with dose per pulse and stability

Scintillating detectors, coupled with cameras (e.g. IBA Lynx for protons)

- Prototypes developed for photons (including scintillating liquids/gel)

Final remarks and perspectives

Competing technologies (research stage)

Monolithic Active Pixel Sensors (MAPS)

- Cristalline silicon equivalent of a:Si flat panel
- Potentially more performing
- A lot of reasearch, no commercial applications.
- Size limited by cost and wafer size

Arrays of scintillating fibers, or of fibers coupled with scintillators

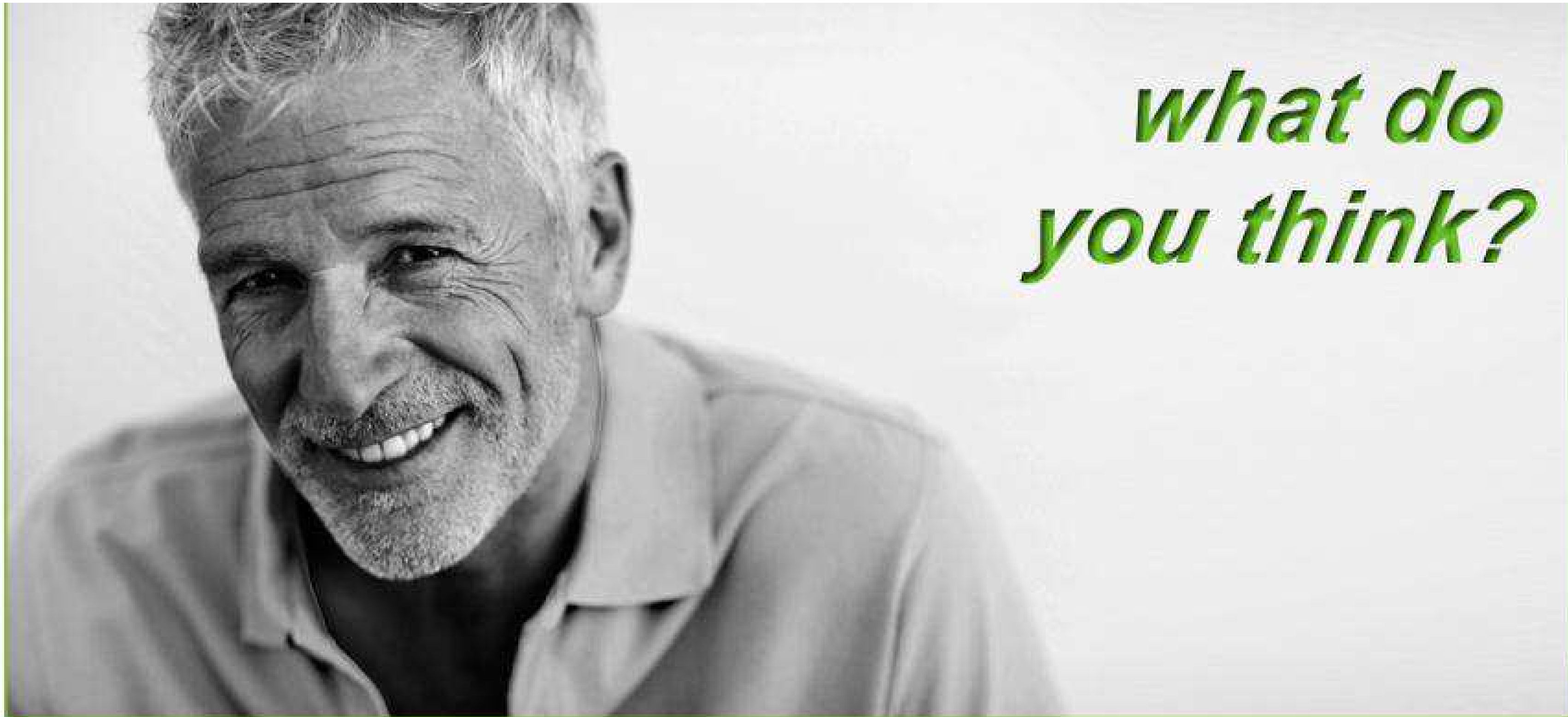
- Readout with cameras, photodiodes of PMT

GEM detectors,

- Usually coupled with pads or scintillator/optical systems
- Mainly proposed for proton- and hadron-therapy, or medical imaging.
- Few experiments with photons; advantages are unclear.

Diamond arrays

- Experiments with monolithic poly-cristalline diamond (to reduce cost) arrays
- Is diamond really better performing with small fields (which are the case of interest)?



Thank you