Quality Assurance for small beam radiotherapy and HDR brachytherapy :

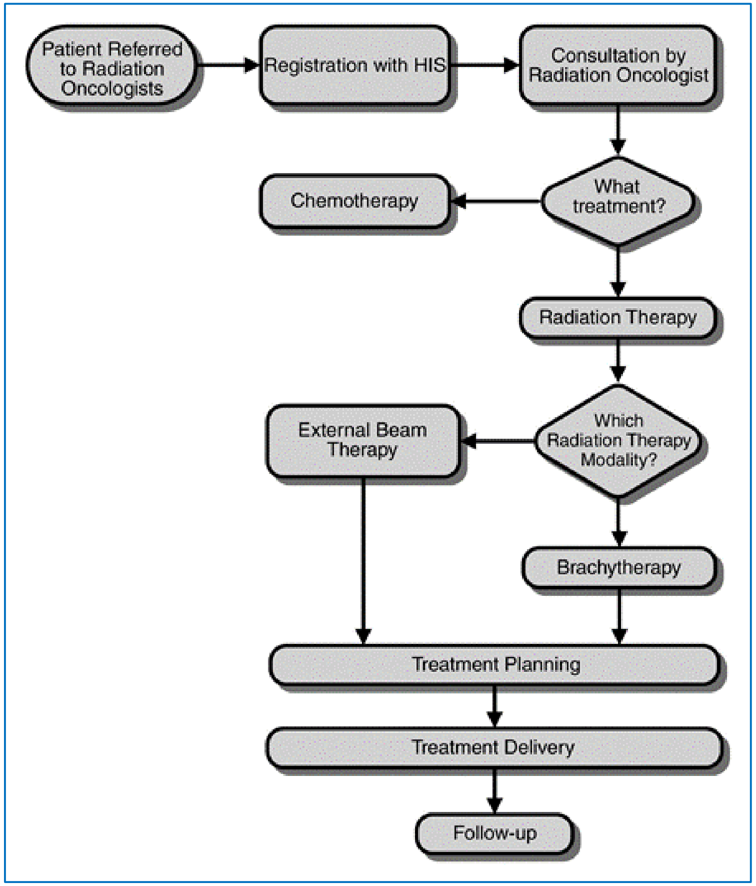
Context, Instrumentation challenges and On-going research to tackle these challenges

P. Pittet,

European School of Instrumentation in Particle & Astroparticle Physics – 11 march 2021

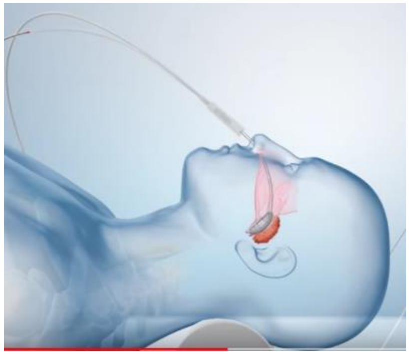
Radiotherapy :

- ✓ one of the main types of cancer treatment.
- ✓ ionizing radiation used to destroy cancer cells and limit their growth.
- ✓ be delivered externally or internally.

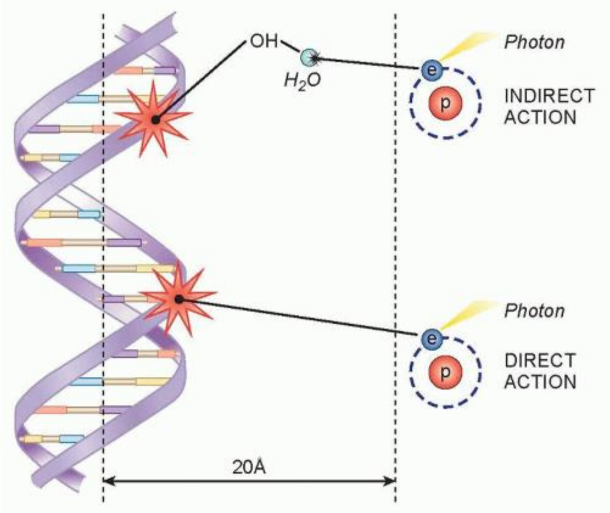


External beam radiotherapy (**EBRT**) ➔ Beams externally created through the use of a linear accelerator or a cobalt unit are directed towards the treatment site.

B**rachytherapy (BT)** ➔ small and encapsulated radioactive sources placed directly into or near the volume to be treated.



How Radiation Therapy Works Against Cancer

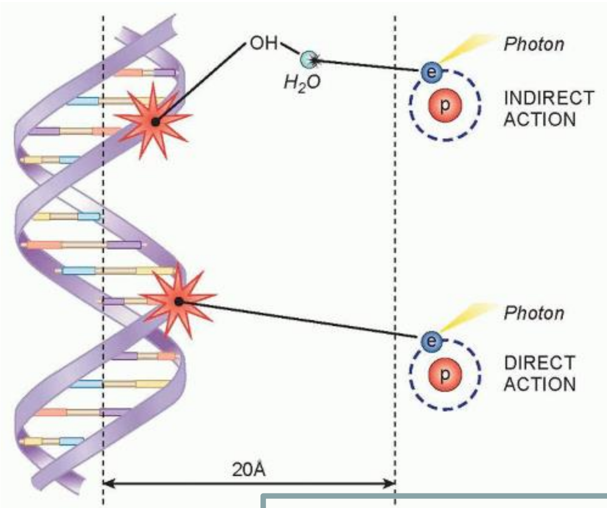


Incident photons (X, Gamma) ➔ free electrons (Compton scattering)

Electrons produce damage :

- ➢ by direct interaction with DNA
- ➢ by H_2O-based free radical formation resulting from electron/water interaction

How Radiation Therapy Works Against Cancer



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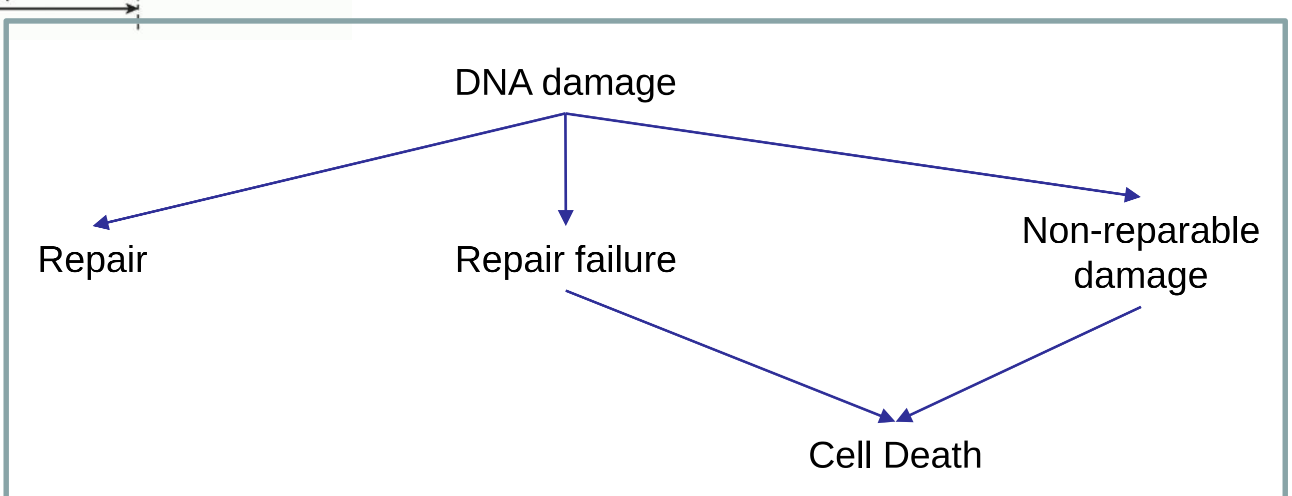


How Radiation Therapy Works Against Cancer

Treatment effect relies on :

- absorbed dose in Gray (1 Gy = 1 J/kg)
- Relative Biological Effectiveness (RBE), i.e., the ratio of the doses required by two radiations to cause the same level of effect

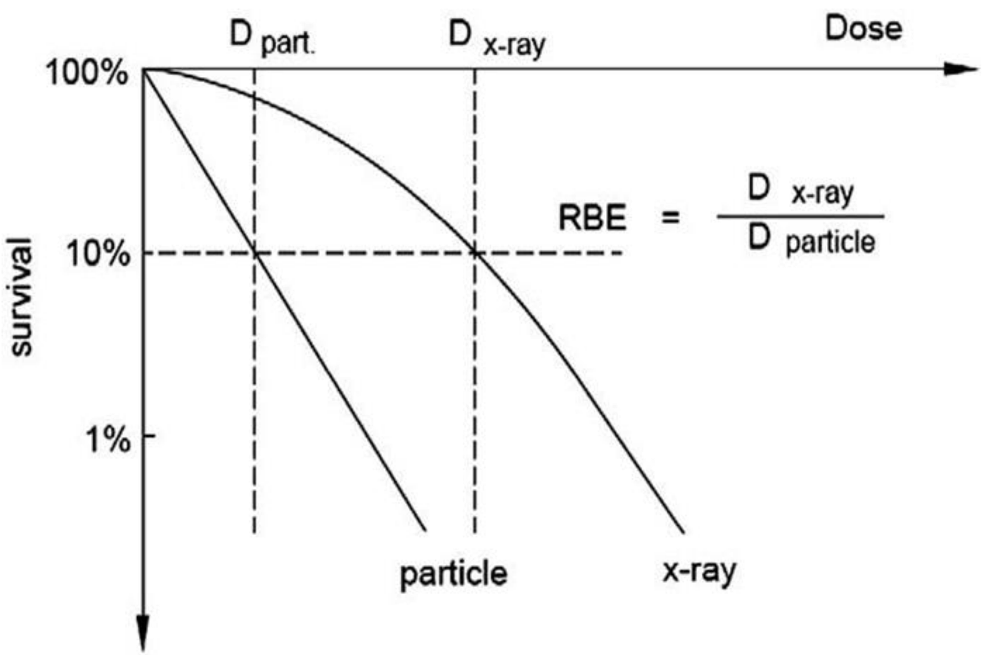


TABLE 32-3 Relative Biological Effectiveness, RBE, for Different Types of Radiation

Type of radiation	RBE
Heavy ions	20
α rays	10–20
Protons	10
Fast neutrons	10
Slow neutrons	4–5
β rays	1.0–1.7
γ rays	1
200-kev X-rays	1

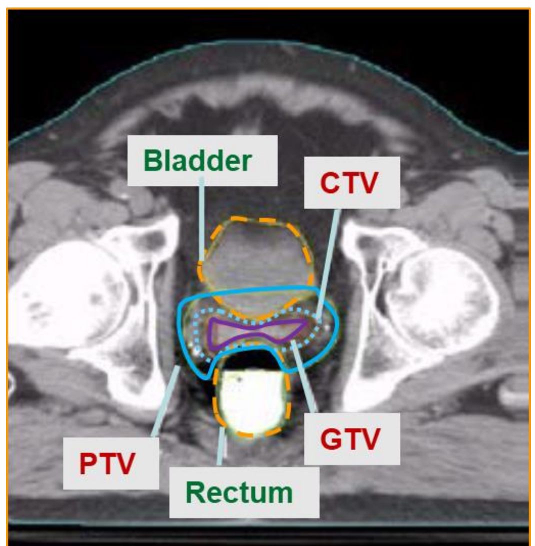
The treatment site and associated volumes

- **The Gross Tumor Volume (GTV)** = visible location and extent of the malignant growth
- **The Clinical Target Volume (CTV)** = tissue volume including GTV(s) and/or potential subclinical malignant

  CTV need to be treated adequately.
- **The Planning Target Volume (PTV)** surrounds the CTV with an additional margin (treatment uncertainties)

Others important sites for radiotherapy

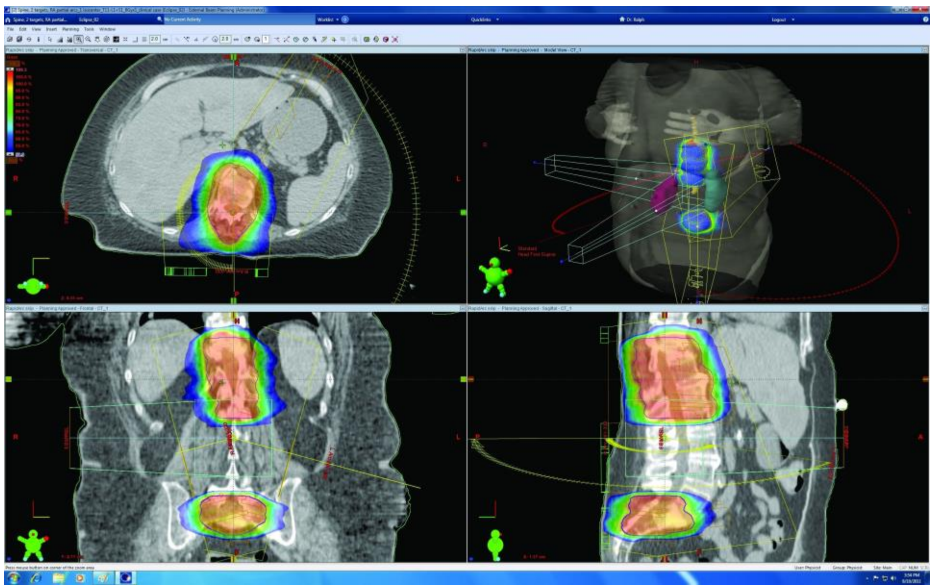
Organs at Risk (OARs) = normal tissues with radiation sensitivity

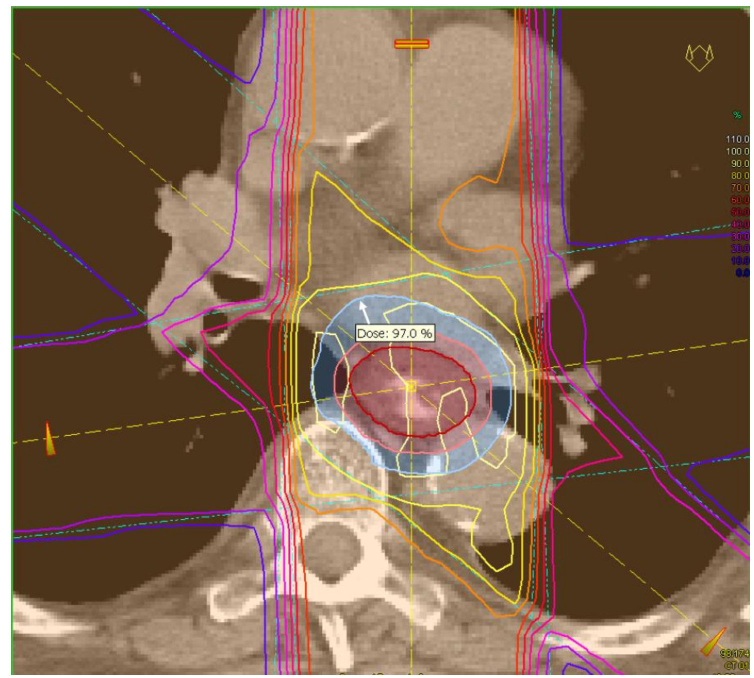


Target volume and organs at risk (Bladder and rectum) for a prostate treatment.

Treatment Planning System (TPS) on patient CT scan *:*

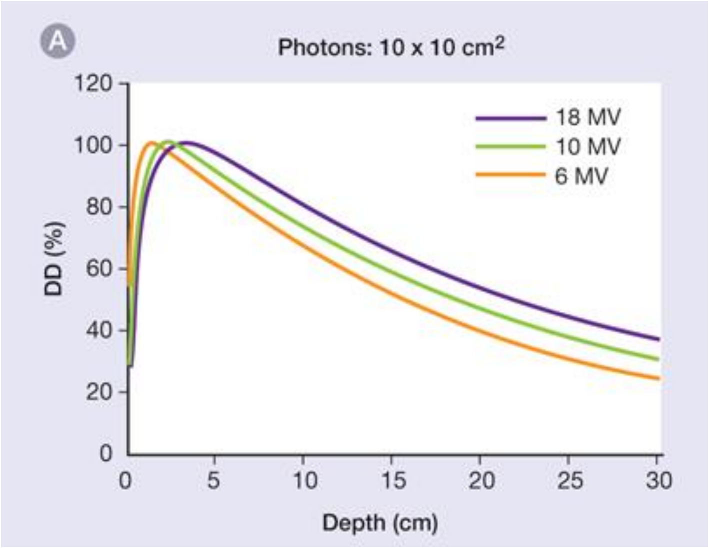
- *To deliver the appropriate dose at the* ***PTV***
- *To maintain an acceptable dose at* ***OAR****s*

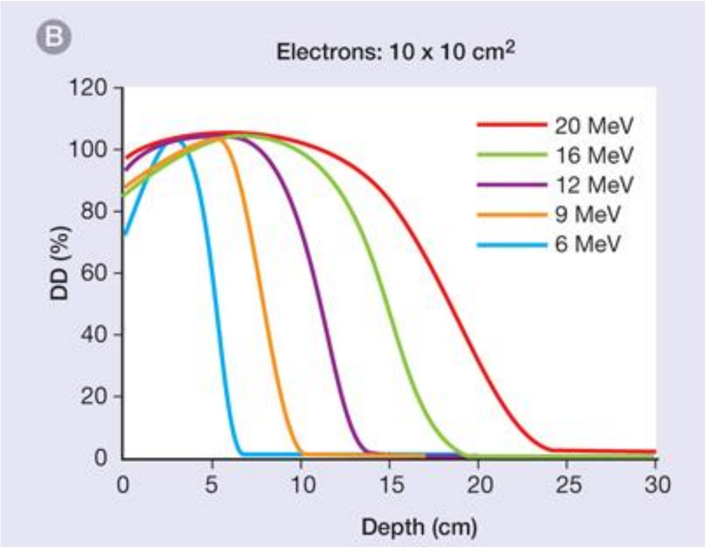


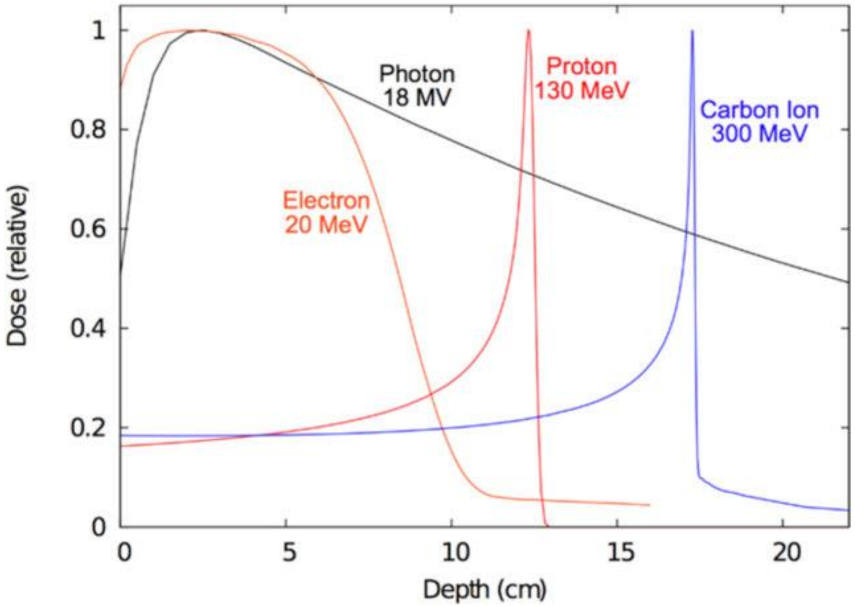


RT particles for efficient and safe treatment

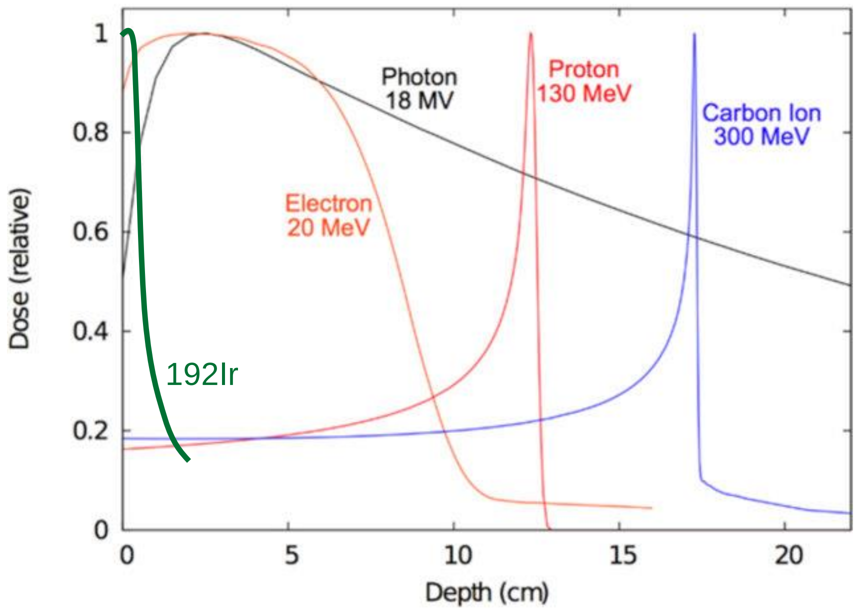
- RBE
- Depth-Dose curve (OARs)

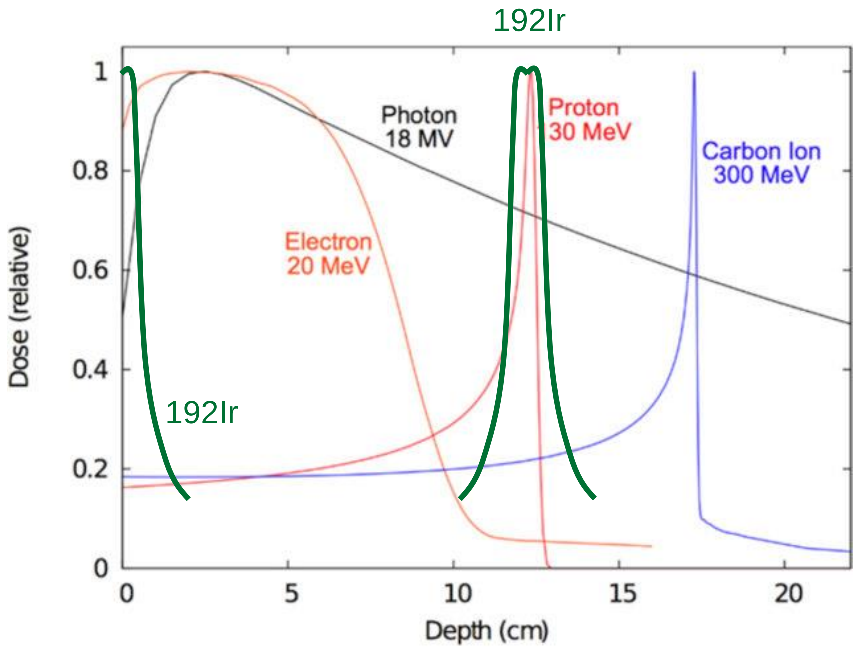






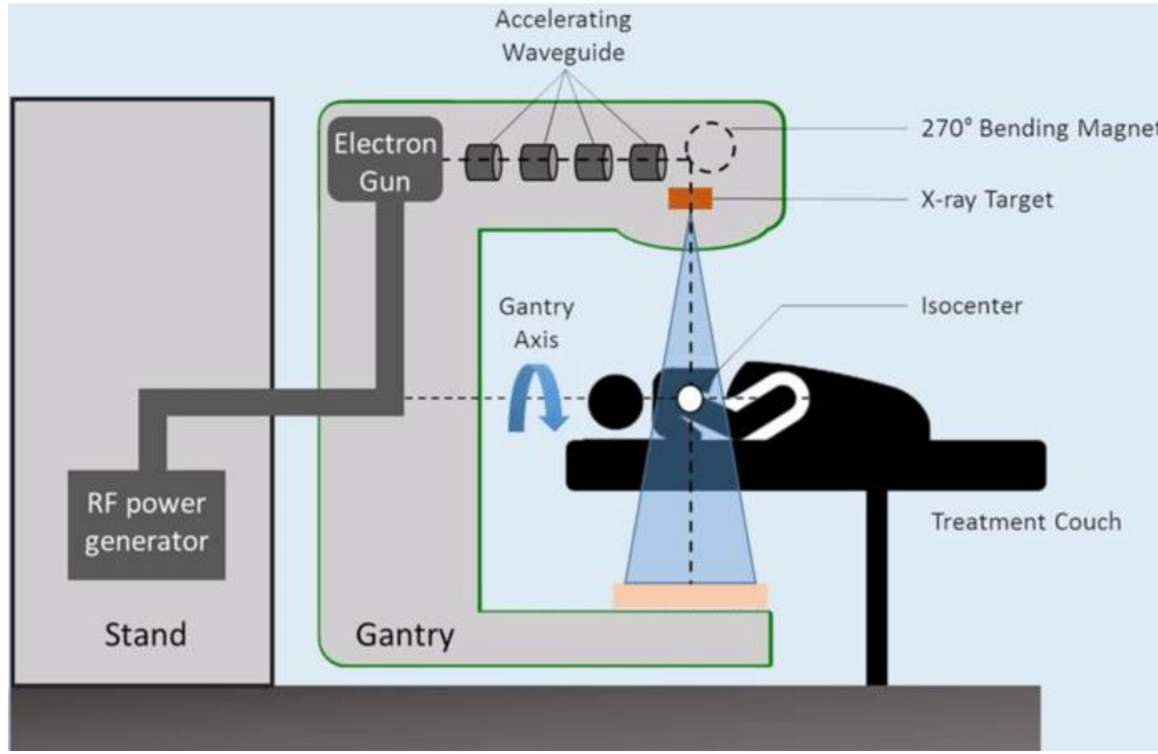
Adapté de *Kaiser, A. et al. , A. Proton Therapy Delivery and Its Clinical Application in Select Solid Tumor Malignancies. J. Vis. Exp. (144), e58372, doi:10.3791/58372(2019).*


Photon
18 MV
Proton
130 MeV
Carbon Ion
300 MeV
Electron
20 MeV
192Ir
Dose (relative)
Depth (cm)
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20

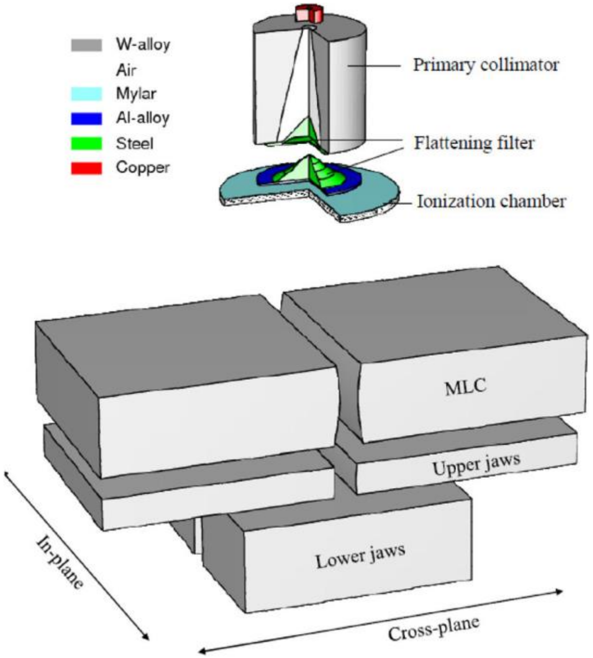


The treatment modality is chosen according to the tumor location (depth, distance from natural cavities..)

External beam radiotherapy (EBRT) : LINAC



External beam radiotherapy (**EBRT**) : LINAC Collimation



MLC

Efficient and safe EBRT treatment delivery:

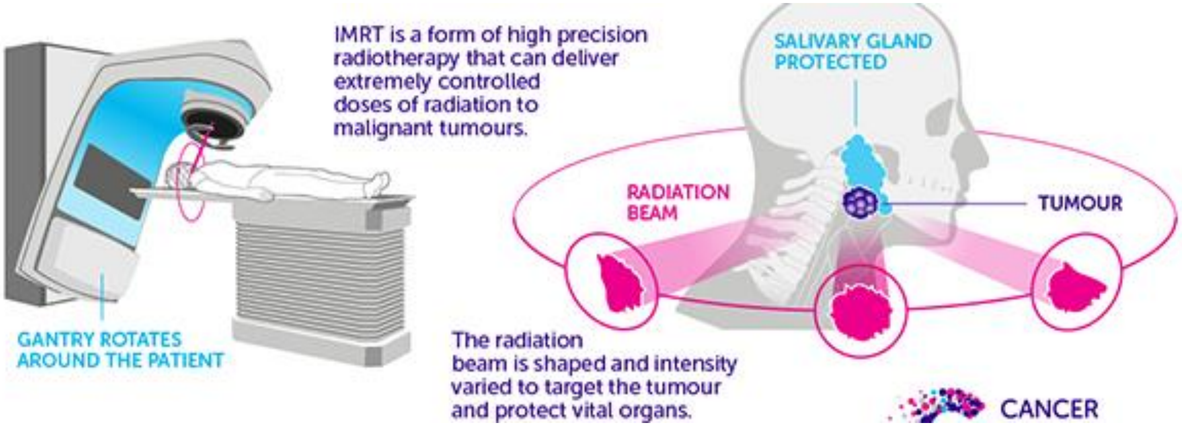
1. planned dose accurately delivered at the **PTV**

2. dose @ **OARs** as low as possible

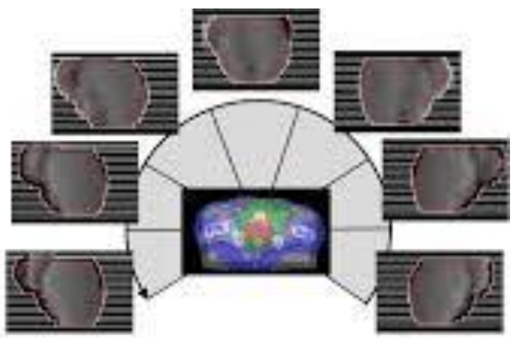
☞ accurately positioning of Patient anatomical (laser, X-ray, MRI)

☞ reliable LINAC system to deliver the planned treatment (QA, QC)

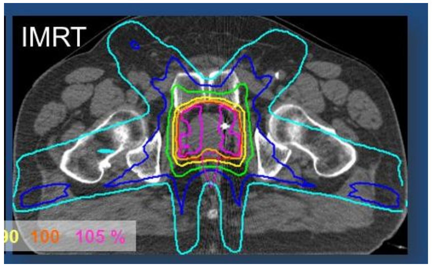
External beam radiotherapy (EBRT) :
Intensity Modulated Radiation Therapy (IMRT)



The intensity of each beam can be modulated by using the multileaf collimator

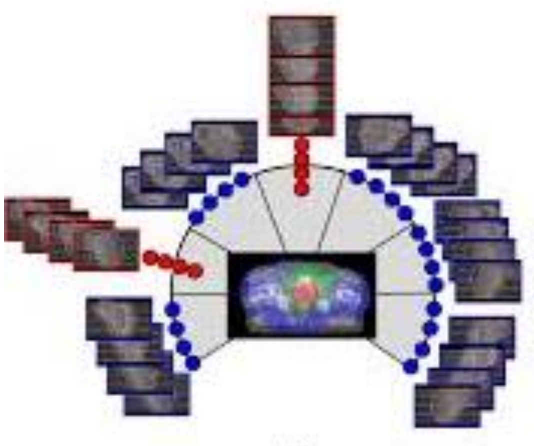


IMRT

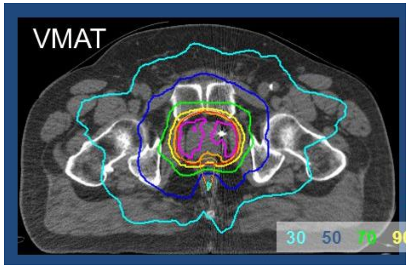


External beam radiotherapy (EBRT) :
Volumetric modulated arc therapy - VMAT

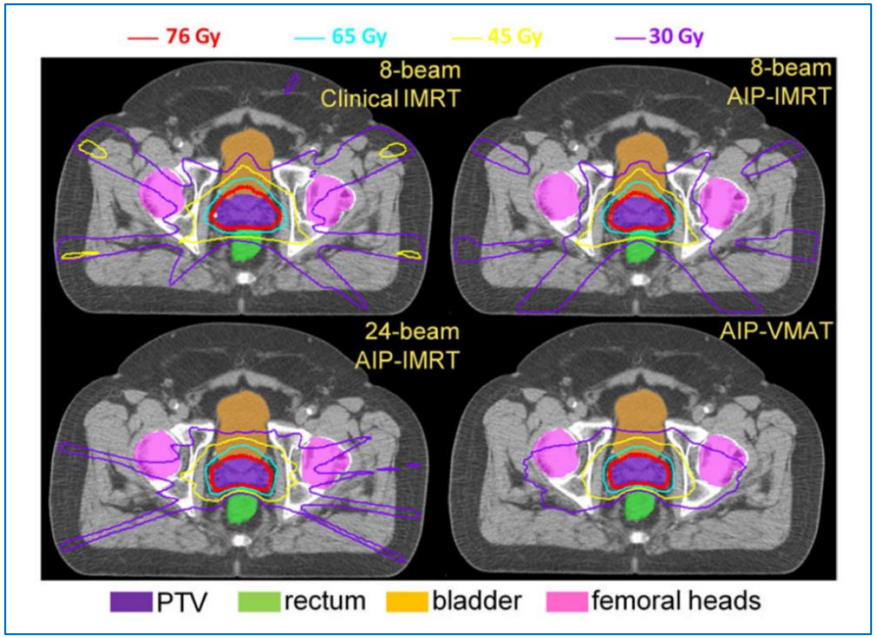
Dose delivered dynamically during rotation of the gantry



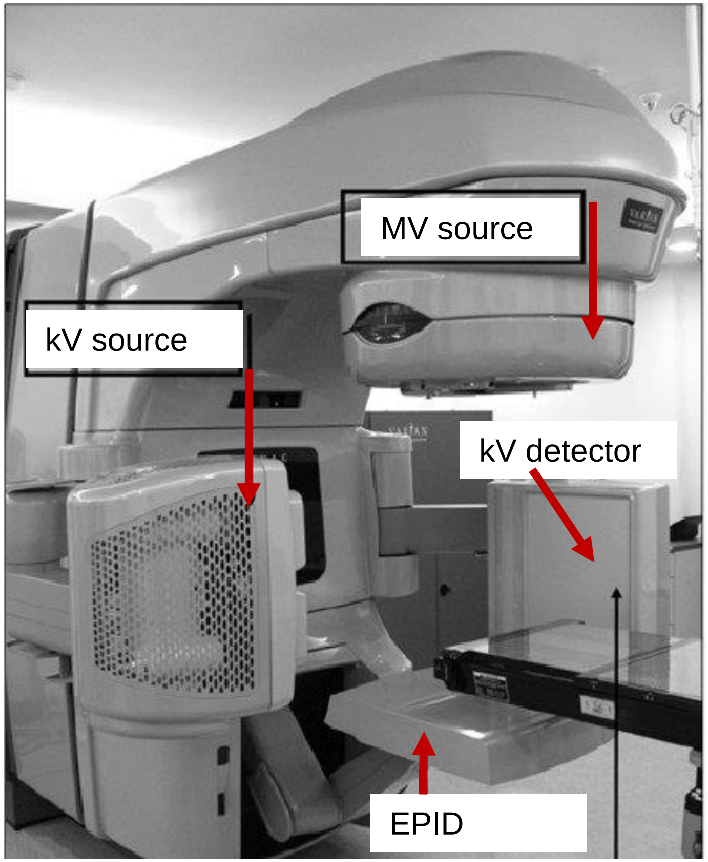
VMAT
(ArcTherapy, Tomotherapy)



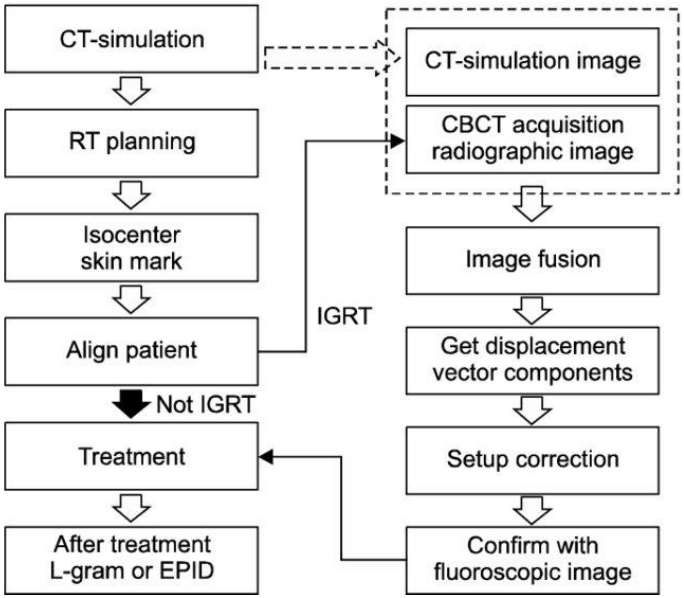
External beam radiotherapy (**EBRT**) : VMAT versus IMRT



EBRT: Image Guided Radiotherapy

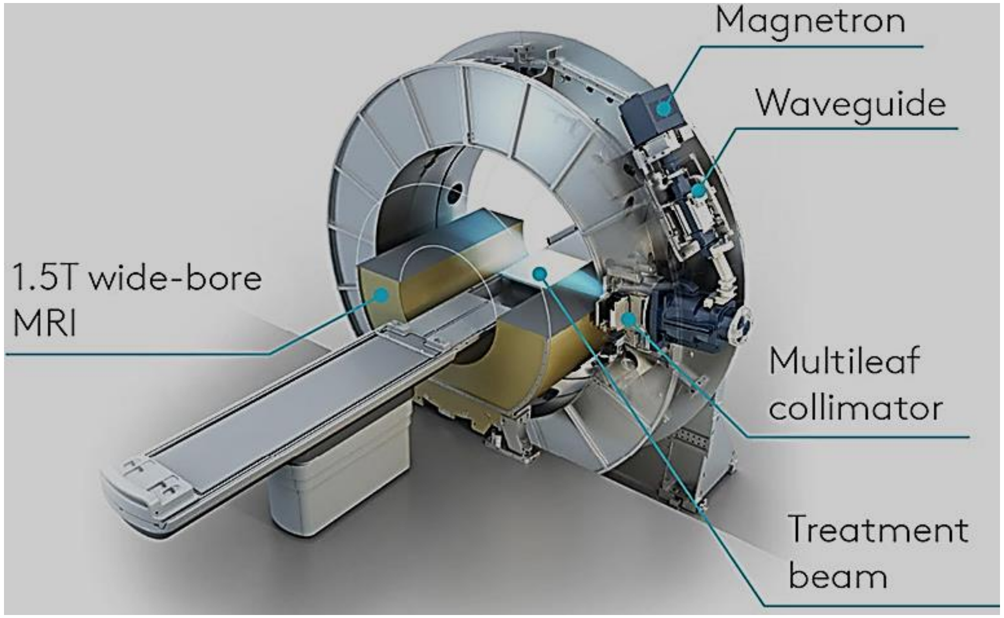


Adapted from Radiat Oncol J. 2008;26 (2): 118-125.



External beam radiotherapy: MRI-Guided Linear Accelerator (MRI-LINAC)

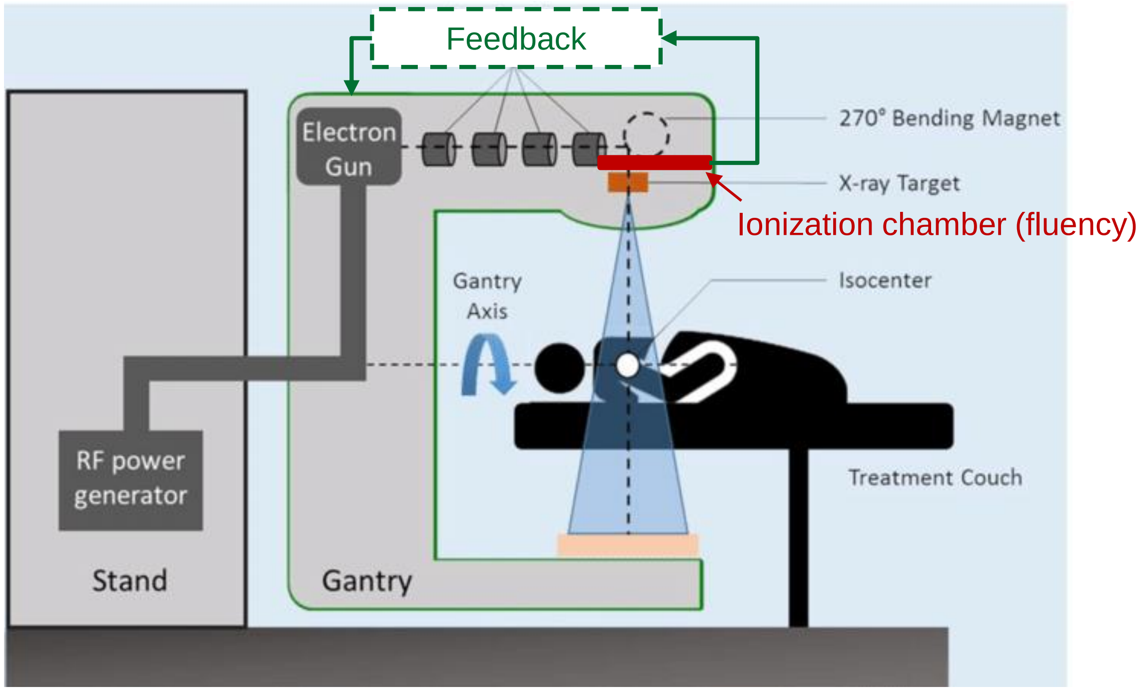
MRI-based imaging → better visualization of GTV and OARs for treatment setup and delivery



External beam radiotherapy:

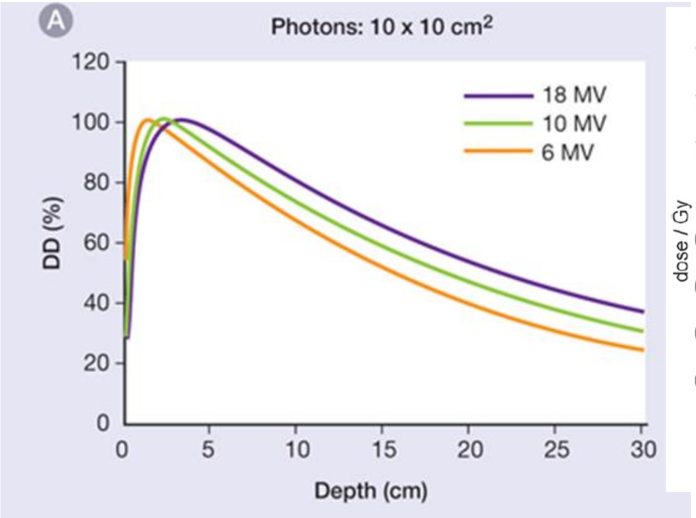
LINAC, a Closed-loop system ?

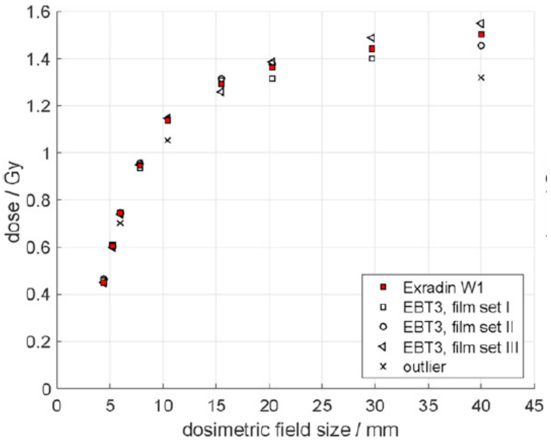
- **YES for the particle fluency** by using a monitor ionization chamber (dose and dose rate in monitor units)
- **NO for the absorded dose in PTV and OARs**



External beam radiotherapy: LINAC, a Closed-loop system ?

Monitor unit to Gy conversion depends on several physical parameters (field size, target depth, beam spectrum, tissue heterogeneity…) ☞ Quality Assurance, dosimetry





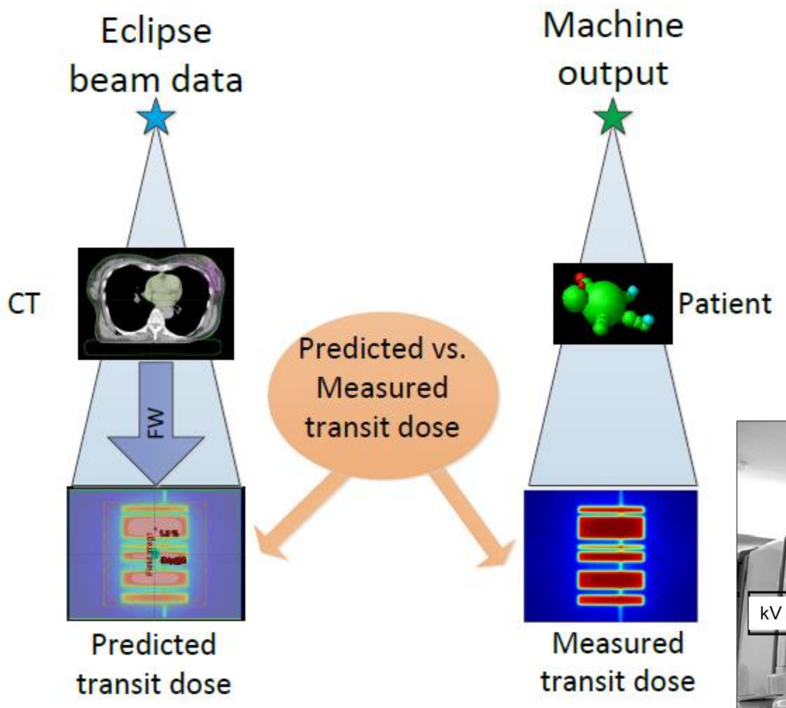
D. Poppinga et al.
Med Phys 28 (2018)

External beam radiotherapy: QA

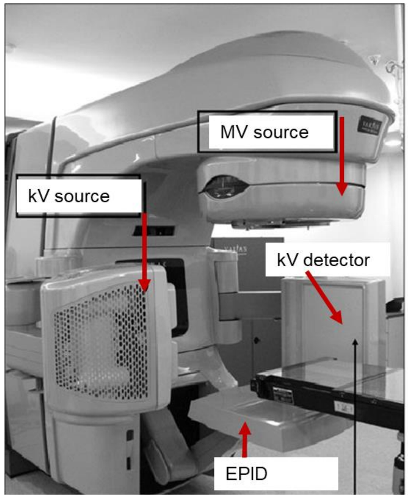
Motorized 3D water phantom system for dose distribution measurement

Delta4 phantom instrumented with 4040 diodes (5mm resolution at isocenter)

EPID Dosimetry

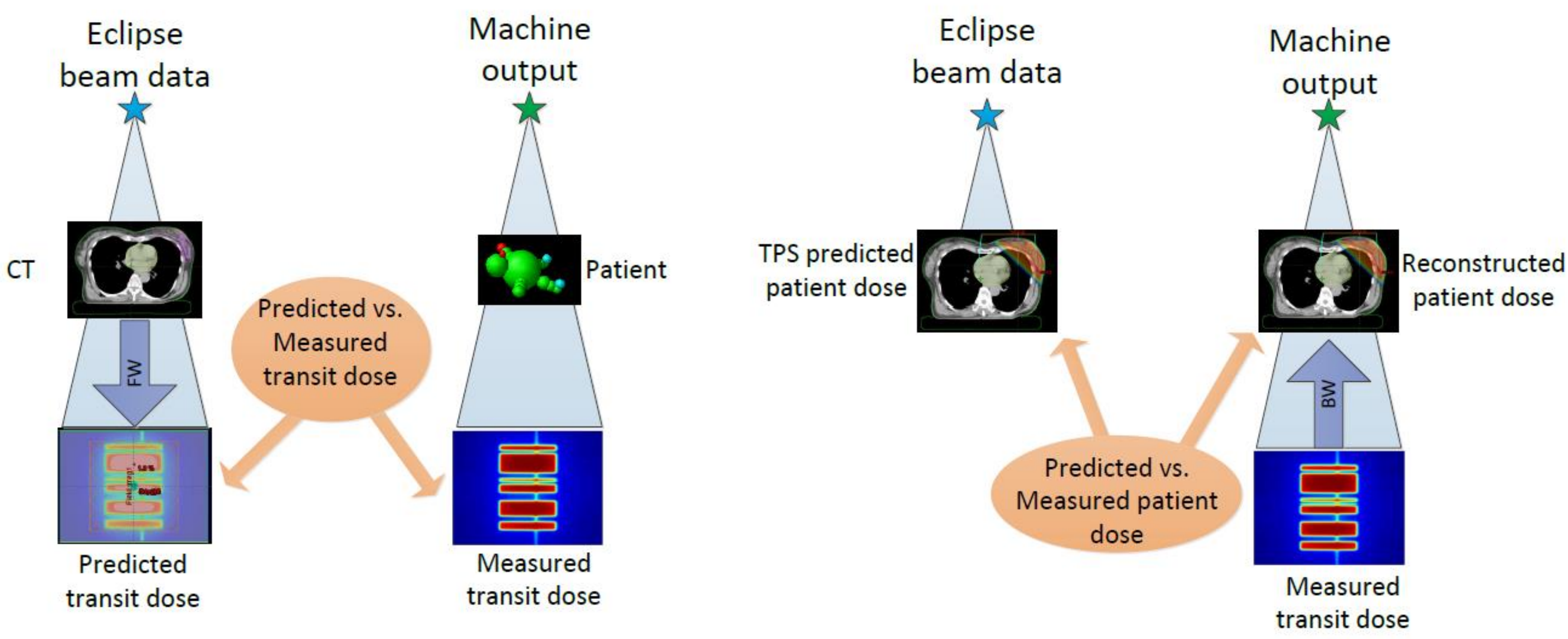


(a) Forward approach



J. Bertholet, Master Thesis LPHE-EPFL,2013

EPID Dosimetry



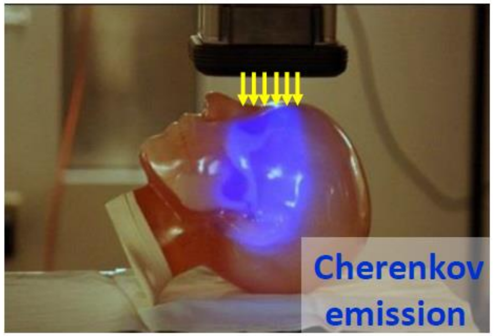
(a) Forward approach

(b) Backward approach

J. Bertholet, Master Thesis LPHE-EPFL,2013

Cherenkov Imaging

Cherenkov emission occurs when a **charged particle** passes through a dielectric medium at **a speed greater than the phase velocity of ligh**t in that medium.



Adapted from "Treatment Verification From Cherenkov Imaging During Radiation Therapy", B. Pogue, 2020 Joint AAPM | COMP Virtual Meeting.

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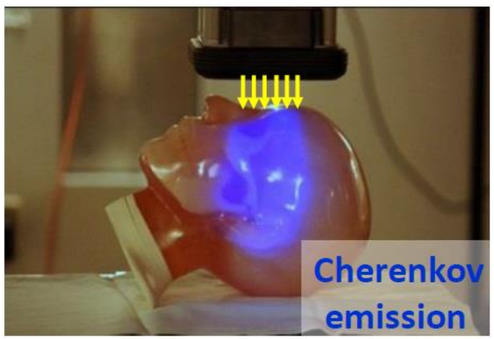
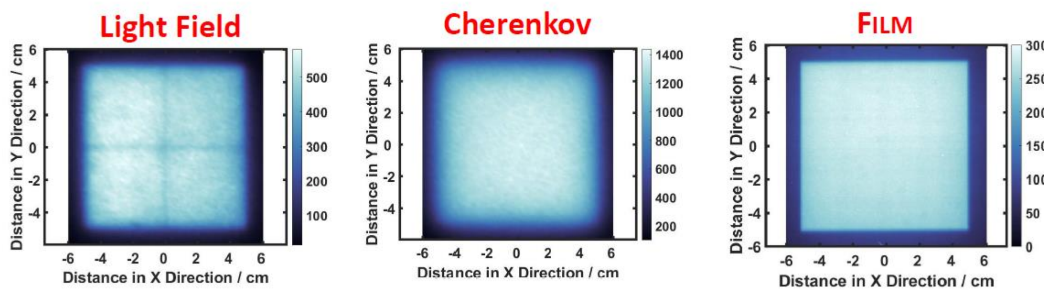
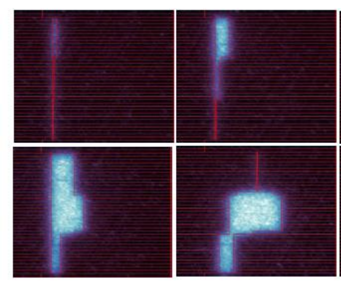


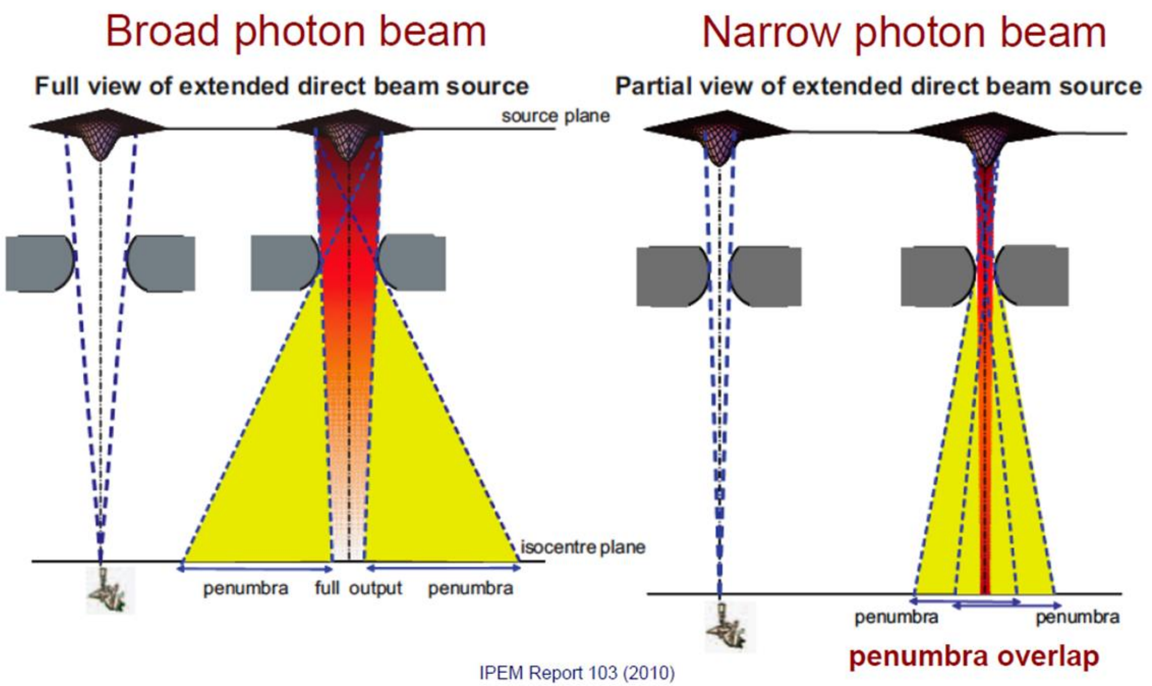




Adapted from “Treatment Verification From Cherenkov Imaging During Radiation Therapy”, B. Pogue, 2020 Joint AAPM | COMP Virtual Meeting.

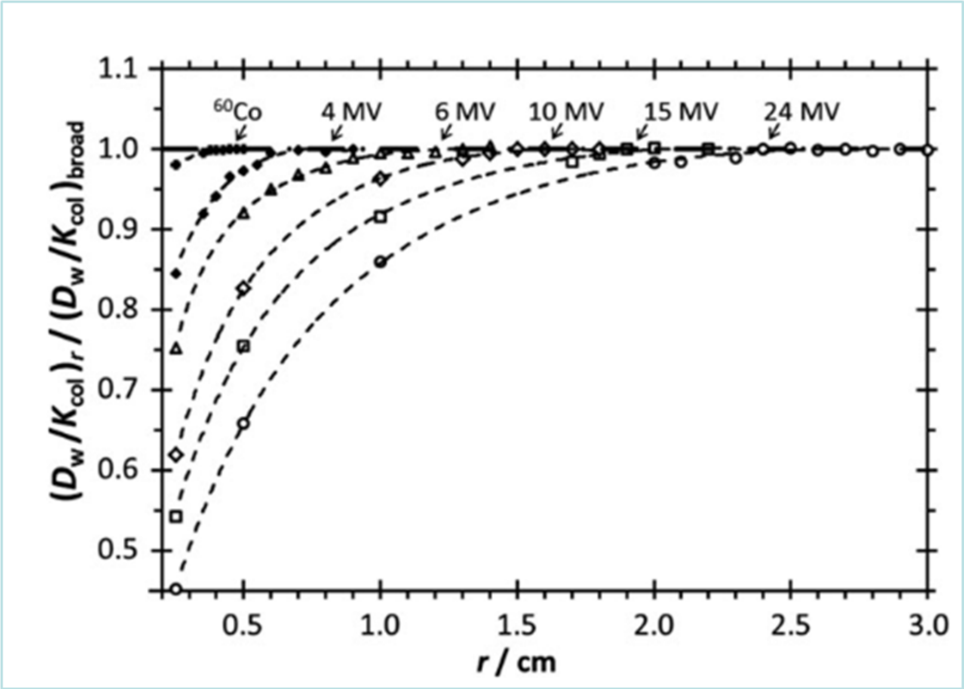
Remaining Challenges : Small field QA

Palmans et al. “Dosimetry of small static fields used in external photon beam radiotherapy: Summary of TRS-483, the IAEA-AAPM international Code of Practice for reference and relative dose determination.” Medical physics vol. 45,11 (2018)



1. Penumbra plays a major role in dose distribution
2. Penumbra energy spectrum is different as compared to the in-field spectrum)

Remaining Challenges : Small field QA

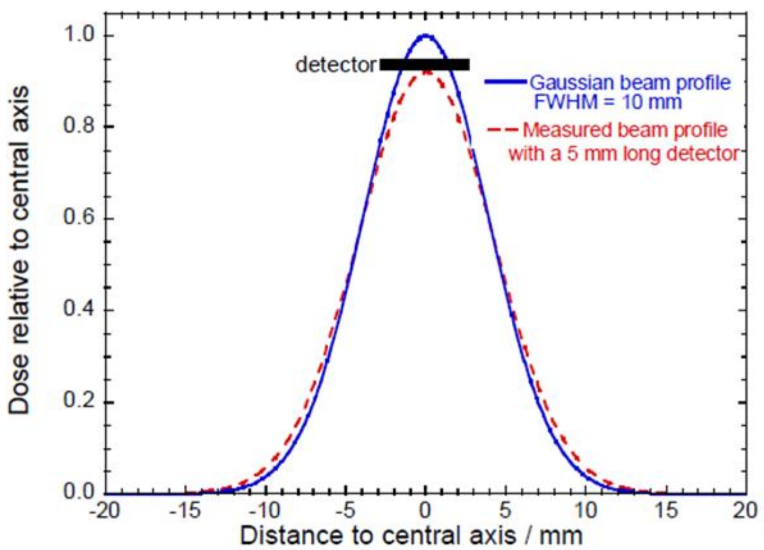


Palmans et al. Medical physics vol. 45,11 (2018)

1. For a given particle fluency, dose on beam axis in a small field is lower than in a broad field due to loss of lateral charge particle equilibrum and of partial source occlusion

Remaining Challenges : Small field QA

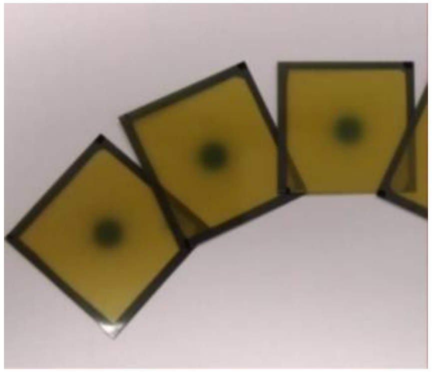
Fluence over detector not uniform

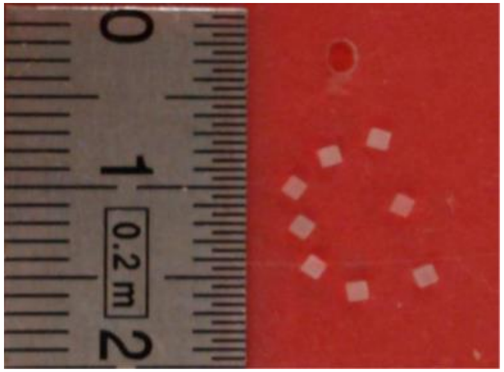


Wuerfel *Med Phys Int* 1 (2013) 81

Small field QA requires small size (sub-millimeter) and tissue equivalent detector

Remaining Challenges : Small field QA

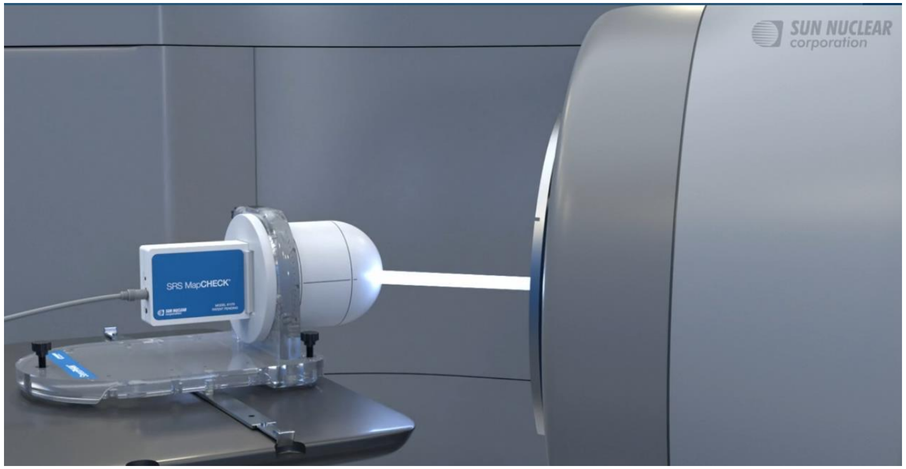


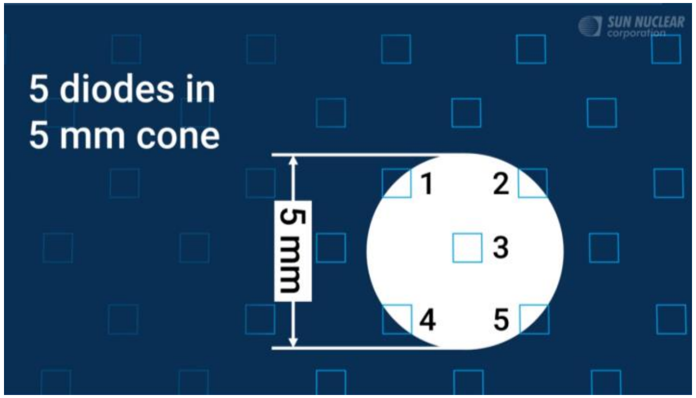


IRSN protocol (standard in France) : EBT3 radiochromic film + 1mm² Thermoluminescent Dosimeters
Institute for Radiological Protection and Nuclear Safety (IRSN) – Rapport N° PSE-SANTE/SDOS/2018-00035 -

Film-based and TLD–based methods [Bassinet et al. *Med. Phys., 2013*]
are suitable for commissioning but not for daily QA procedures
(time consuming and not real time).

Filmless patient QA





Diode are not tissue equivalent (Z_{si}=14) and requires compensation factor and sufficient spacing (2.47mm)

Main goals of the QASYS research project

1. Highly spatially resolved 2D dosimeter (sub-millimeter)
2. Tissue equivalent dosimeter (no need for energy compensation)
3. Real-time QA
4. Optical transduction for MRI-LINAC compatibility

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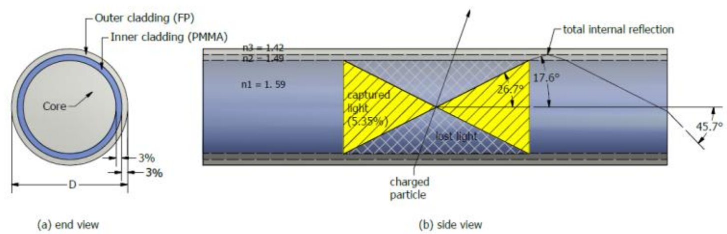
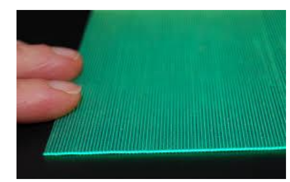
Approach implemented for the QASYS research project

1. Scintillating Fiber technology





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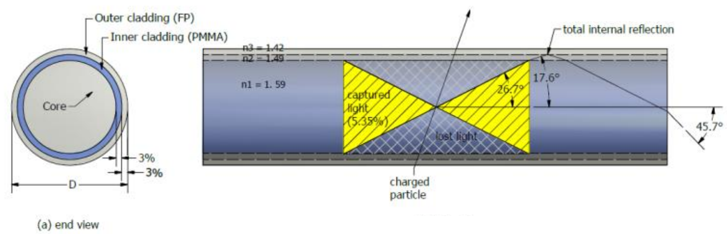
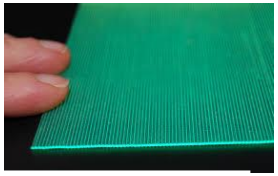
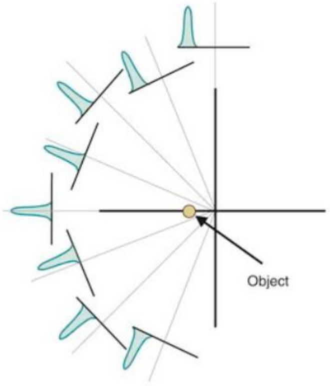
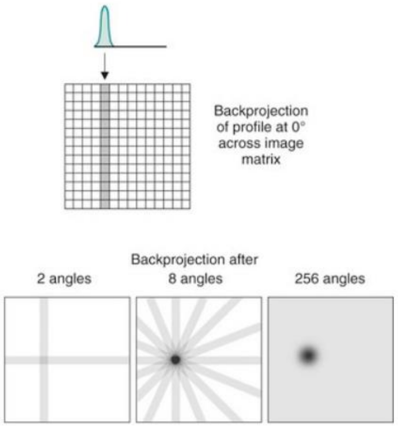




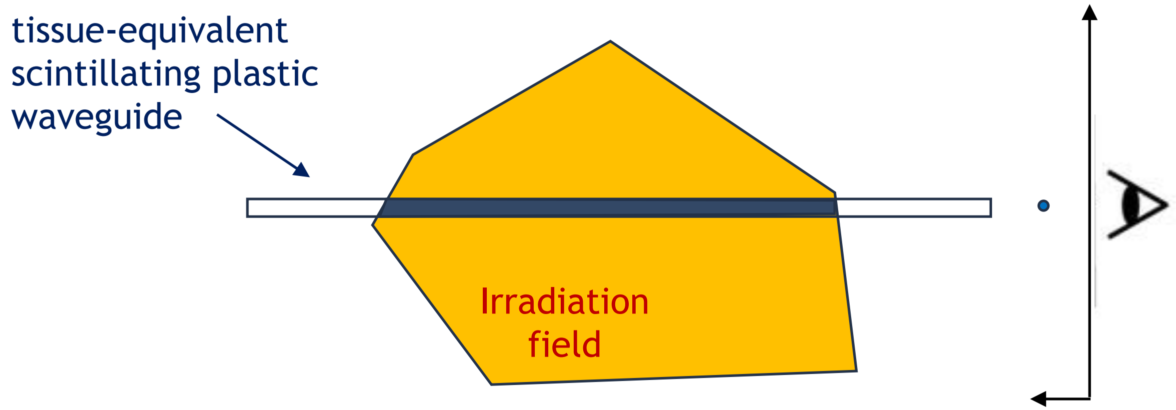
2. Tomographic dosimetry





https://radiologykey.com/tomographic-reconstruction-in-nuclear-medicine/

QASYS detector for real-time SRS QA : principle

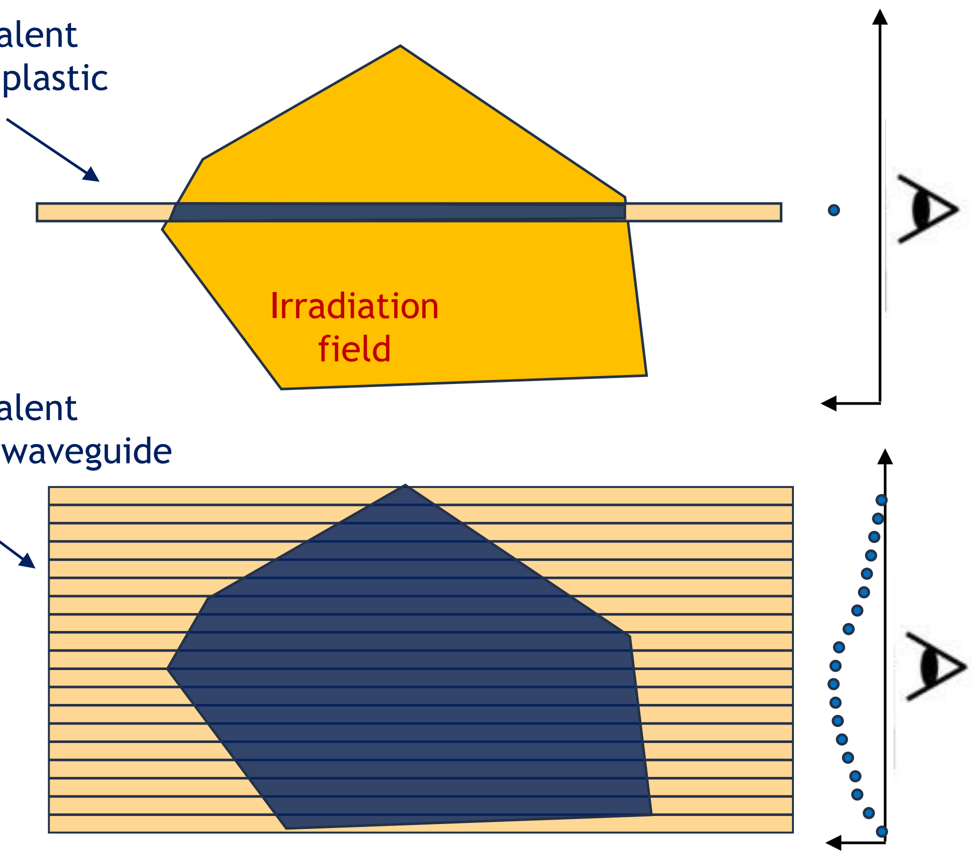


Signal is proportional to the dose integrated over the irradiated segment of waveguide

Goulet M et al., " High resolution 2D dose measurement device based on a few long scintillating fibers and tomographic reconstruction", Med Phys. 2012

QASYS detector for real-time SRS QA : principle

tissue-equivalent scintillating plastic waveguide



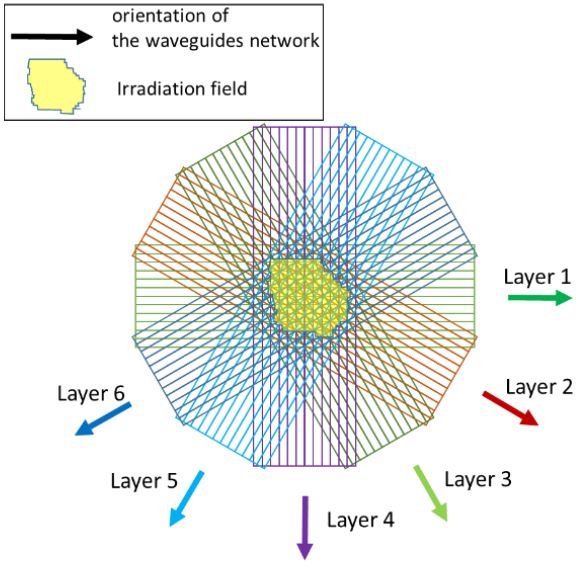
Signal is proportional to the projected dose along the waveguide (i.e. length of the irradiated segment)

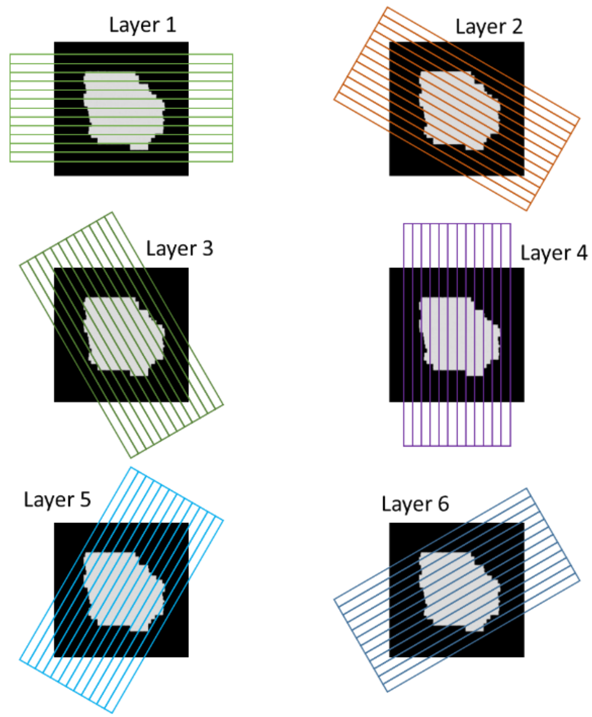
tissue-equivalent scintillating waveguide ribbon

Signal at ribbon output gives the projected profile of the irradiation field

QASYS detector for real-time SRS QA : principle

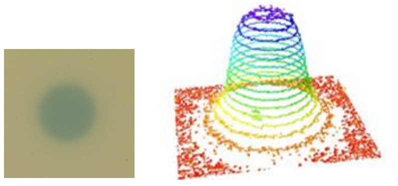
Detector based on stacked tilted 2D waveguide layers for tomographic field reconstruction :





O. Pivot et al. "Estimation of radiotherapy dose fields from a few projections: how many projections will ensure uniqueness?", 2020 IEEE NSS-MIC, Boston USA

QASYS detector : Field reconstruction method



Dose distribution (EBT3 film)

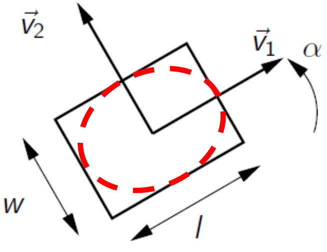
A priori knowledge and assumptions:

Isodose lines share the same geometry
this geometry is related to the collimator

Step 1 : Geometric tomography (width, length and orientation) [1]

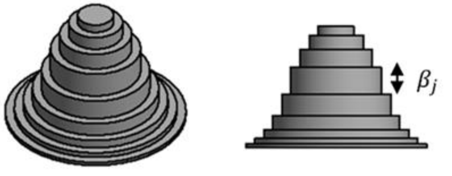
Step 2 : Dose distribution modeled by the superimposition of dose *slices* with *thicknesses* (β_j) determined by a least-squares estimation [2].

Step 1



Step 2

Dose distribution model



[1] L. Desbat et al., "Geometric tomography for measuring rectangular radiotherapy fields from six projections," 2019 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), UK, 2019.

[2] P. Pittet et al., « SciFi detector and associated method for real-time determination of profile and output factor for small fields in stereotactic radiotherapy », Medical Physics, 2020

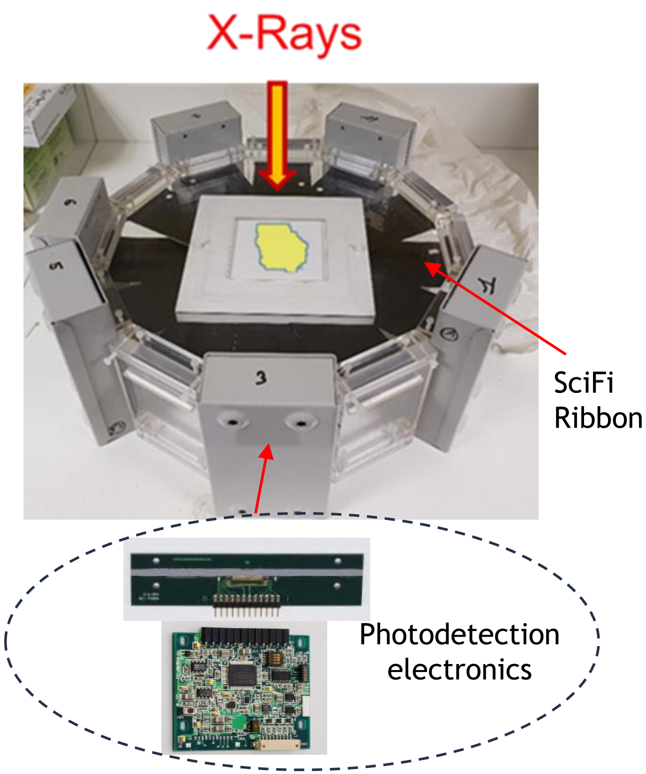
QASYS detector for real-time SRS QA : Material and Method

Cross section of the 2D scintillating fiber ribbon (developed for the LHCb SciFi Tracker project) consisting of tissue equivalent material.

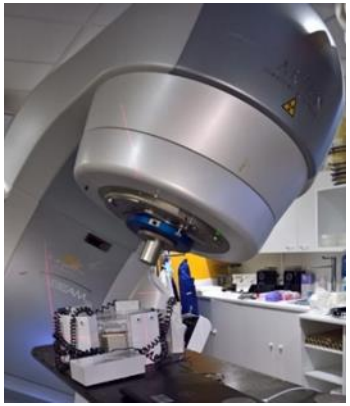
The signal at the ribbon output is acquired by a 128 silicon photodiode linear array combined with signal processing IC

The fiber diameter of 250µm and the readout channel pitch of 400µm allows for an excellent spatial resolution.

QASYS detector prototype (6 tilted layers)

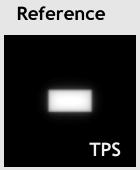


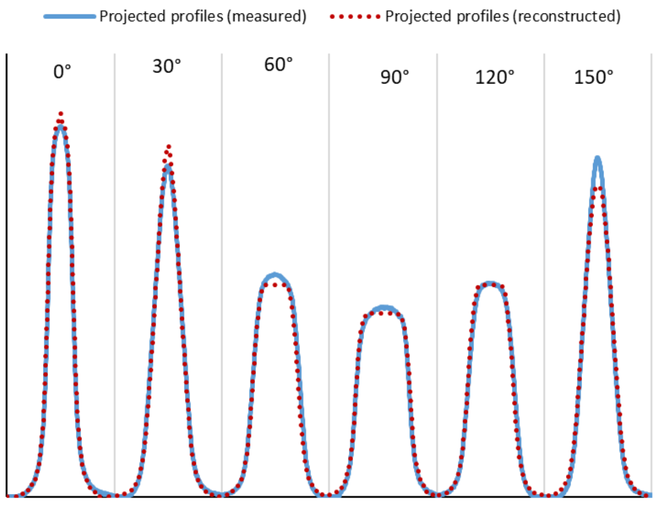
Number of SciFi Ribbon	6 (tilt 30°)
Lateral resolution (for each orientation)	0.4 mm
Number of scintillating fibers	4800 (6x800)
Number of photodetection channels	768 (6x128)
Active area	50 mm in diam.
Detector depth in RW3	1.4 cm

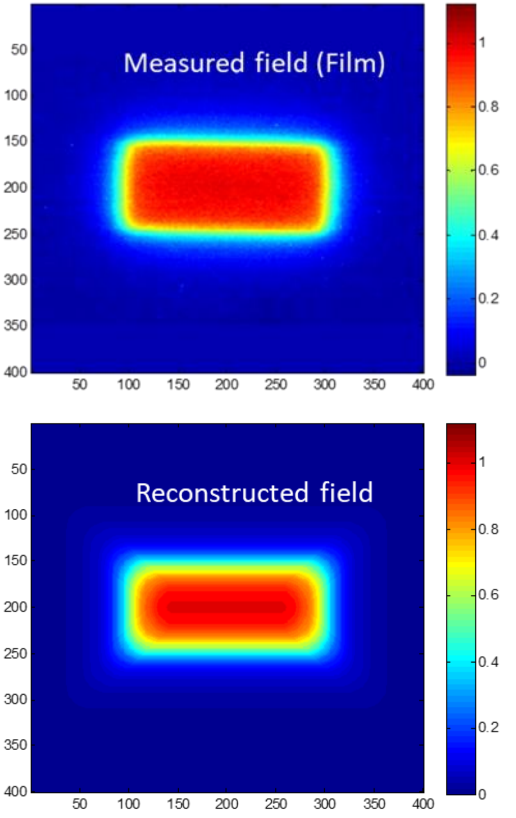


Testing Setup:

Novalis TrueBeam X 6MV- Dose rate 600 MU/min
Source to Surface distance: 98.6cm - Detector @ dmax
Field size : **20mmx10mm**







Gamma index criterion

$$\gamma(\vec{r}_c, \vec{r}_m) = \sqrt{\frac{|\vec{r}_c, \vec{r}_m|^2}{DTA^2} + \frac{|D(\vec{r}_m)\text{-}D(\vec{r}_c)|^2}{\Delta D^2}} \qquad (1)$$

where:

$|\vec{r}_c, \vec{r}_m|$ – distance between analyzed points,

$|D(\vec{r}_m)\text{-}D(\vec{r}_c)|$ – dose difference,

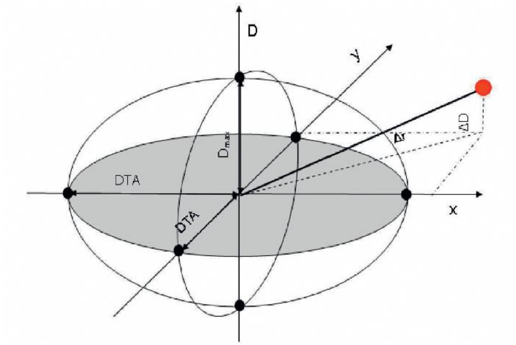
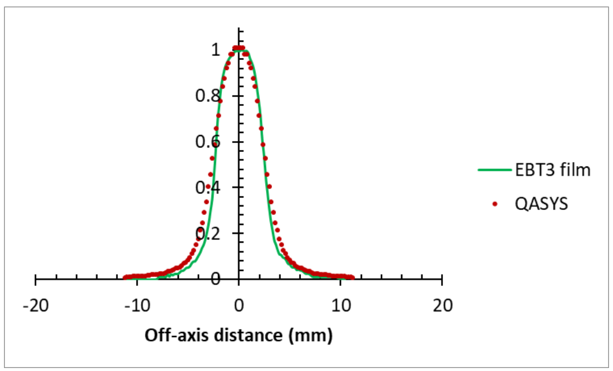


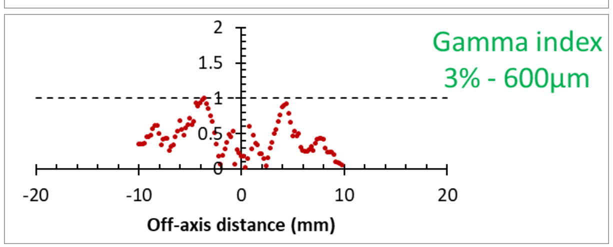
Fig. 3. The concept of gamma verification [5]: x, y, D – spatial and dose dimensions; DTA – distance-to-agreement; D_{max} – max dose deviation; Δr, ΔD – local spatial and dose divergence of the analyzed point

Testing Setup:
Novalis TrueBeam X 6MV- Dose rate 600 MU/min
Source to Surface distance: 98.6cm - Detector @ dmax
Field defined by a **5mm stereotactic cone**

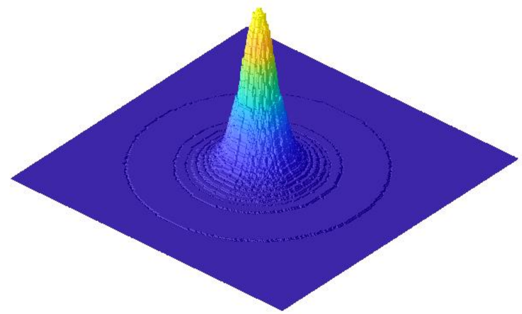
Reference

Reconstructed profile





Reconstructed field



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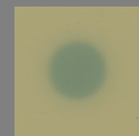
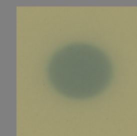
Testing Setup:

Novalis TrueBeam X 6MV- Dose rate 600 MU/min
Source to Surface distance: 98.6cm - Detector @ dmax
Field defined by a **10mm stereotactic cone**

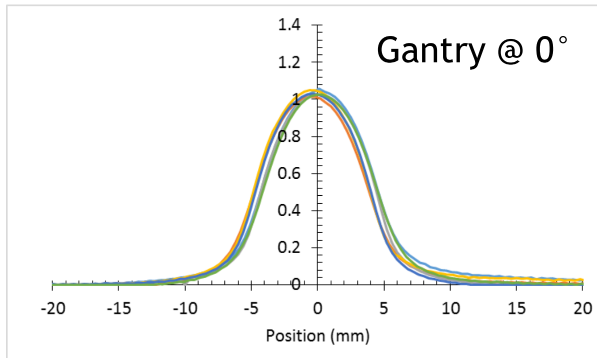
Gantry @ 0°

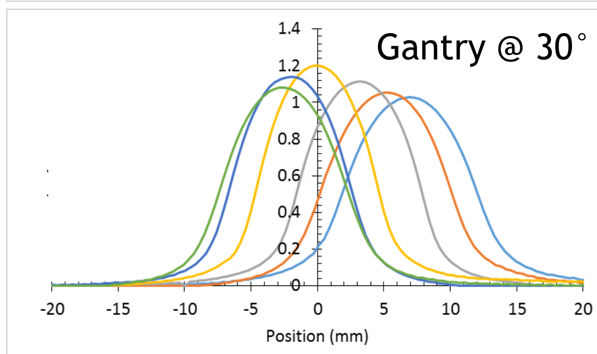


Gantry @ 30°



6 projected profiles (QASYS)





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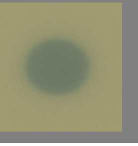
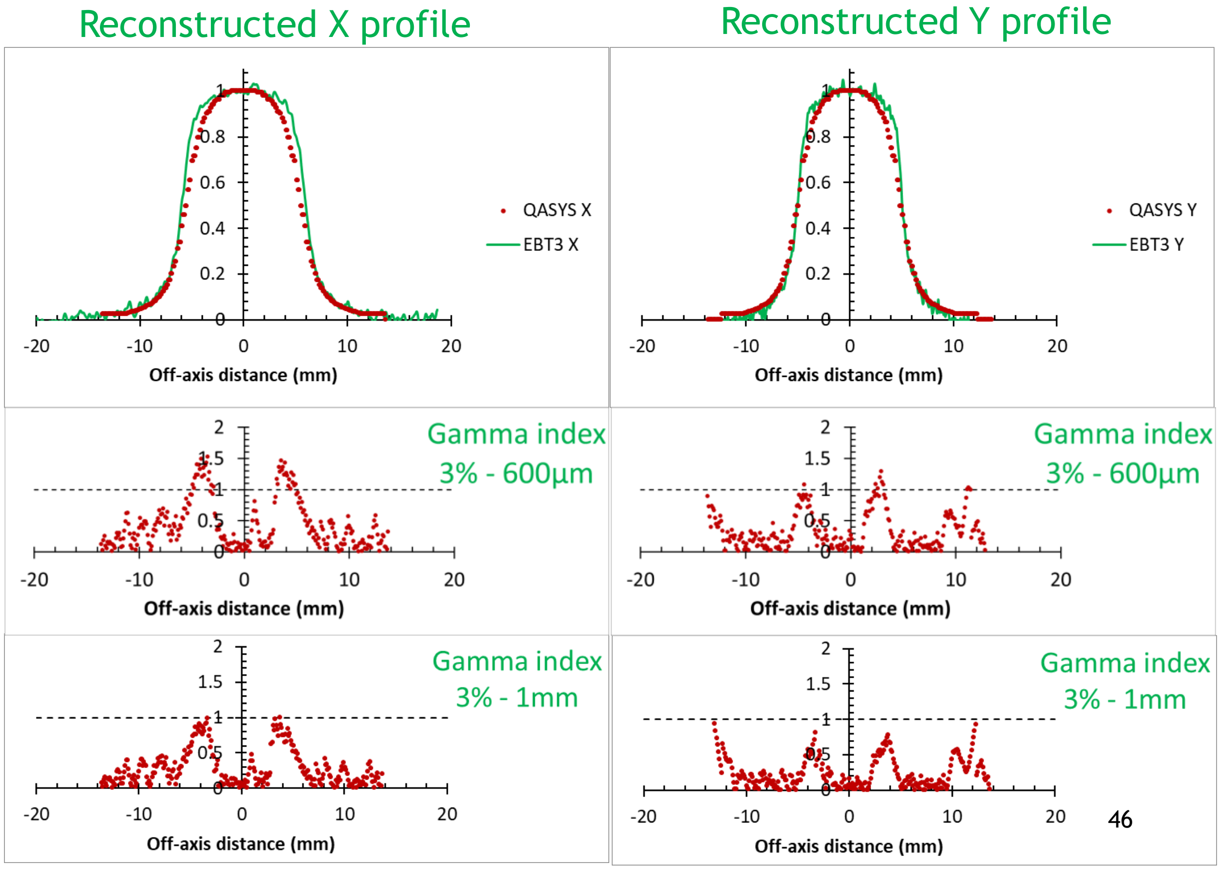
Testing Setup:

Novalis TrueBeam X 6MV- Dose rate 600 MU/min
Source to Surface distance: 98.6cm - Detector @ dmax
Field defined by a **10mm stereotactic cone - Gantry 30°**

Gantry @ 30°





Reconstructed field

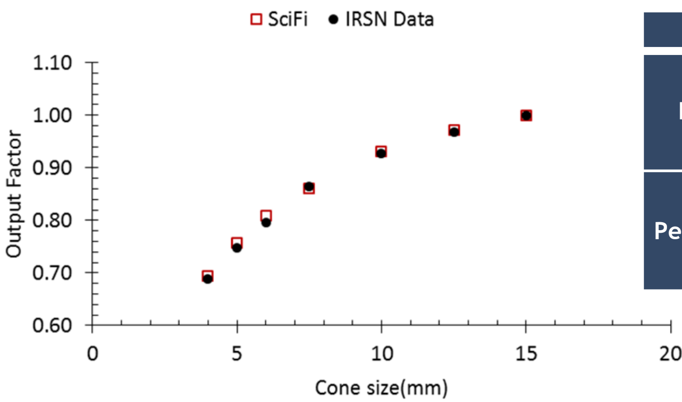
	Expected	Measured
Minor axis	10.00mm	10.26mm
Major axis	11.55mm	11.35mm
Aspect ratio	0.866	0.905

Testing Setup:

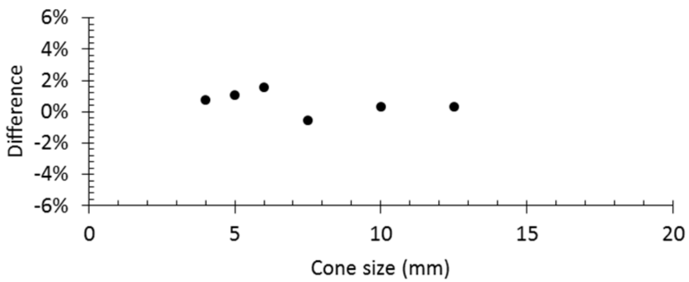
Novalis TrueBeam X 6MV- Dose rate 600 MU/min
Source to Surface distance: 98.6cm - Detector @ dmax
4, 5, 6,7.5, 10, 12.5 and 15mm stereotactic cones

References

IRSN Data
EBT3 film and TLD



Cone (mm)		4	5	6	7.5	10	12.5	15
FWHM (mm)	QASYS	4.03	4.92	5.82	7.61	9.85	12.53	14.77
	EBT3	NA	5.08	6.10	7.79	9.99	12.53	15.07
	difference	NA	-0.16	-0.28	-0.18	-0.14	0.00	-0.30
20%-80% Penumbra width (mm)	QASYS	1.57	1.57	1.57	1.79	2.01	2.01	2.24
	EBT3	NA	1.27	1.52	1.52	1.69	2.03	2.03
	difference	NA	0.30	0.04	0.27	0.32	-0.02	0.21



P. Pittet et al., « SciFi detector and associated method for real-time determination of profile and output factor for small fields in stereotactic radiotherapy », Medical Physics, 2020

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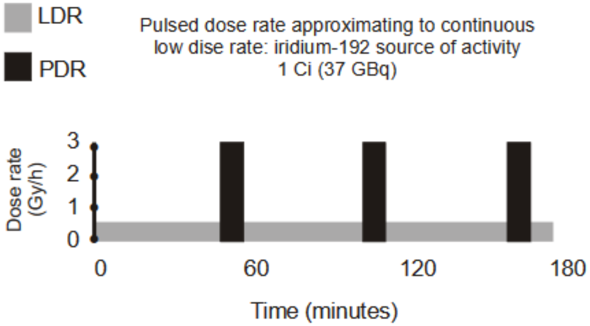
Brachytherapy is a method of delivering radiation to tumors by **placing radioactive sources either within or immediately adjacent to tumor tissue**. Because the radiation source is very close to the tumor, therapeutic radiation can affect the tumor directly while minimally affecting normal tissue.

Depending on the length of time the radioactive sources remain in place, brachytherapy can be provided using :

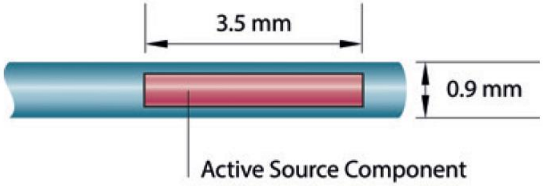
- low dose rate (LDR) ^{125}I ^{103}Pd ^{137}Cs ^{192}Ir seed and wire
- pulsed dose rate (PDR) ^{192}Ir 1Ci
- high dose rate (HDR) techniques ^{192}Ir 10Ci – ^{60}Co 2Ci



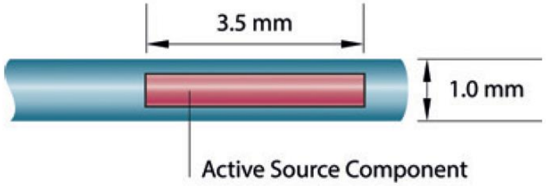
Rep. Pract. Oncol. Radiother. 6 (4) 2001²

PDR / HDR afterloader

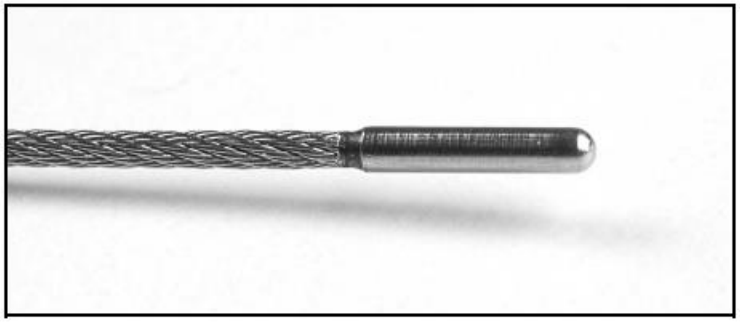
PDR / HDR afterloader



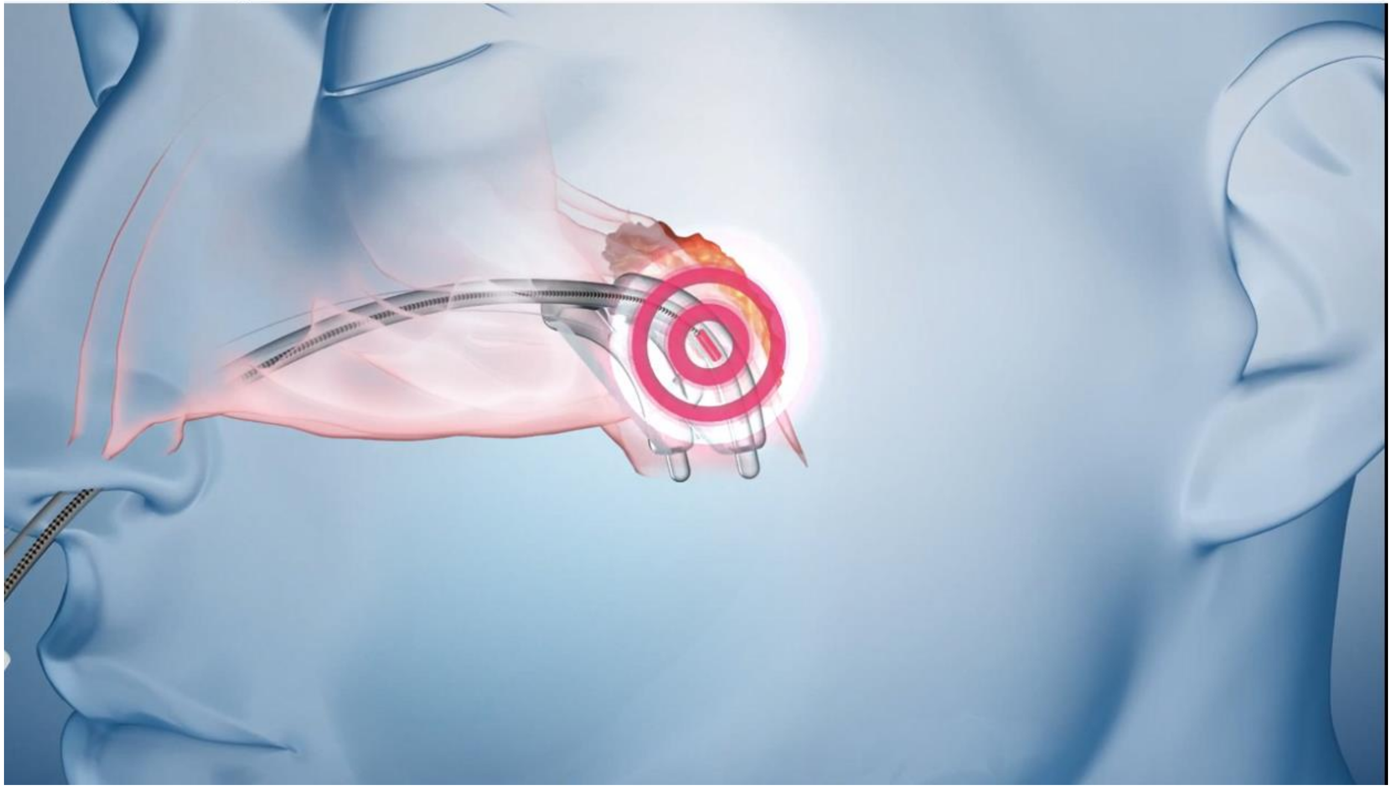
Miniaturized Ir-192 source



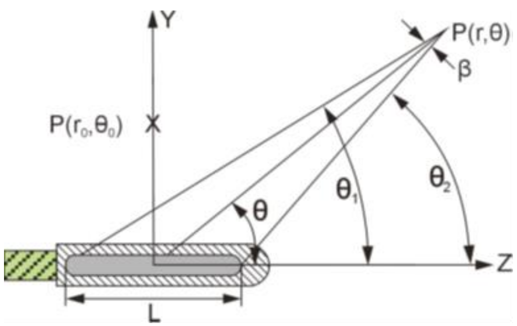
Miniaturized Co-60 source



Nucletron microSelectron V2 ^{192}Ir 370 GBq HDR brachytherapy source

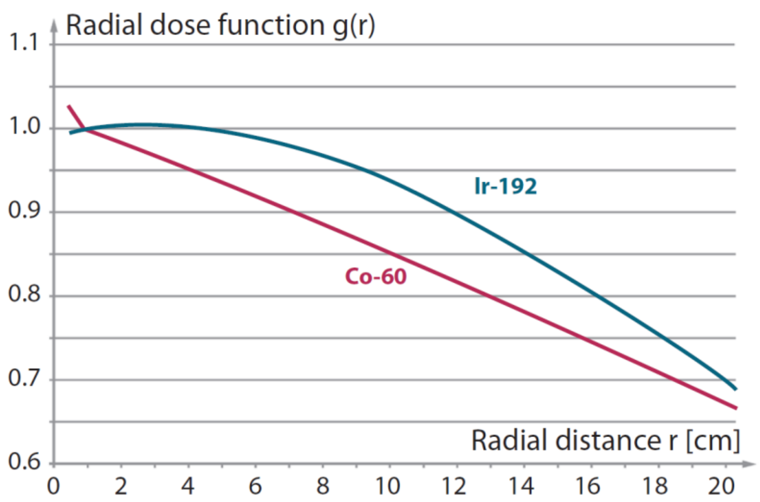


TG-43U1 formalism is conventionally used for dose rate in water calculation

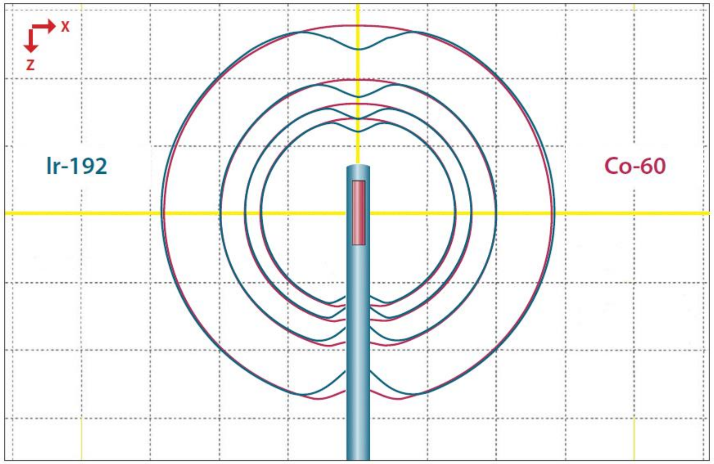


$$\dot{D}(r,\theta) = S_k \Lambda \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} g_L(r) F(r,\theta)$$

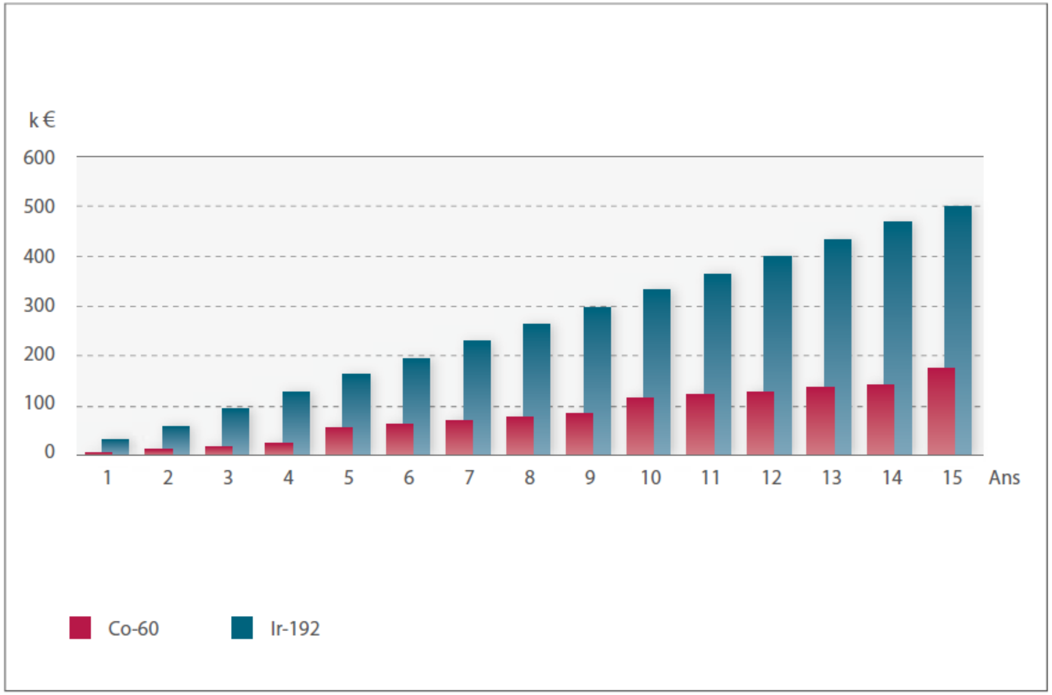
S_k Air-kerma strength
Λ Dose rate constant in water
$G_L(r,\theta)$ Geometry function
$g_L(r)$ Radial dose function
$F(r,\theta)$ 2D anisotropy function



Source Anisotropy

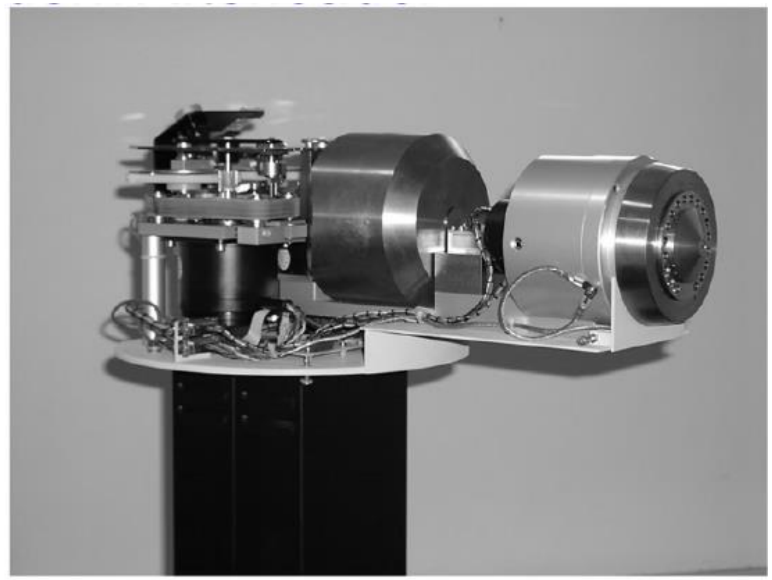


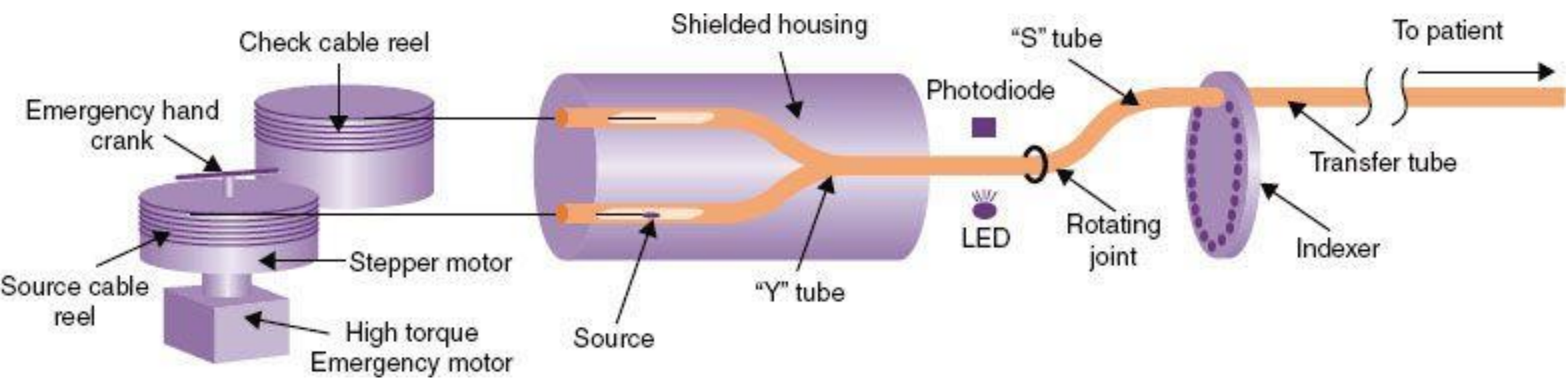
Nuclide	Average energy (in MeV) of the emitted photons	Half life	First HVL in lead (in mm)	TVL in lead (in mm)	TVL in concrete* (in cm)
^{198}Au	0.42	2.7 d	3	11	
^{60}Co	1.25	5.3 y	12	42	22
^{137}Cs	0.66	30.2 y	6.5	22	17.5
^{125}I	0.028	59.4 d	0.025	-	-
^{103}Pd	0.021	17 d	0.02	-	-
^{192}Ir	0.38	74.0 d	6	16	14.7
^{226}Ra**	0.83	1600 y	16	45	23.4



^{192}Ir source is replaced every 3 months while ^{60}Co every 60 months

PDR / HDR afterloader





Efficient and safe HDR BT treatment delivery relies on :

1. Accurate knowledge of the current source activity
2. Accurate transfer tubes length and connection
3. Accurate source positioning (within ± 1mm)
4. Accurate dwell time management
5. Accurate positioning of the treatment vector (applicator, needle, catheter)

ESTRO Booklet No. 8	Frequency	Tolerance
Source calibration	Source exchange	< 5%
Source position	dayly	< 2mm
Length of treatment Tubes	Annualy	< 1mm
Irradiation timer	Annualy	< 1%
Date,time, source strength	Dayly	-
Transit time effect	Annualy	-

Accurate knowledge of the current source activity

The activity is verified by using an IC (Well-type chamber) after each source change :

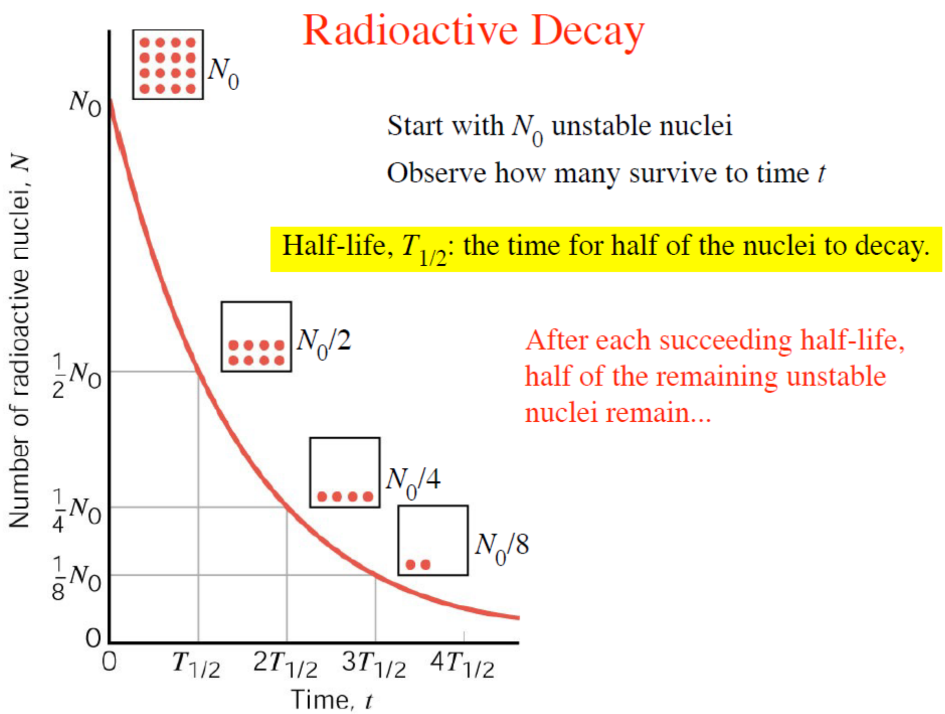
Standard imaging HDR100+
vented well-type chamber
Revue Française de Métrologie,
N°10, 2007

PTW SourceCheck 4pi chamber

Specification	
Type of product	vented well-type chamber
Application	calibration of afterloading sources
Measuring quantities	air kerma strength, apparent activity, exposure strength
Calibration	^{192}Ir, others upon request
Nominal sensitive volume	200 cm^3
Design	vented sensitive volume
Reference point	84.5 mm below chamber top
Chamber voltage	400 V nominal 500 V maximal
Change of response with source positioning change of ± 1 cm	< 1 %
Leakage current	≤ 0.5 pA

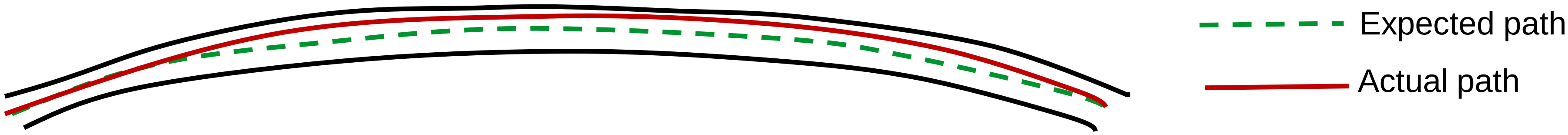
Accurate knowledge of the current source activity

The current source activity is computed in the TPS by using the radioactive decay law with the known activity at a given date (certificate or measurement at installation of the source) and the current date



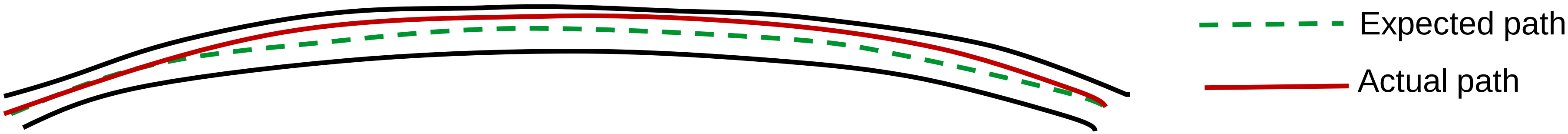
Adverse event on source positioning

1. Path deviation in bended transfer tube

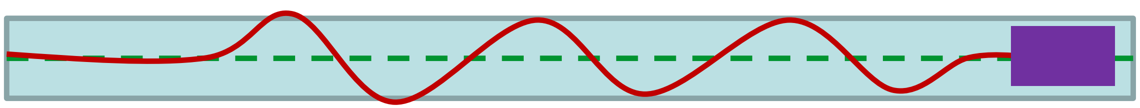


Adverse event on source positioning

1. Path deviation in bended transfer tube

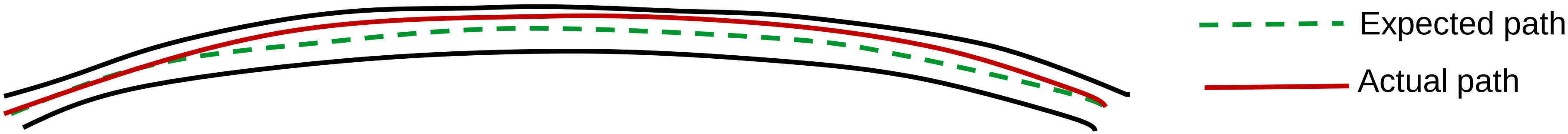


2. Snaking effect in applicator : The source-cable is curled



Adverse event on source positioning

1. Path deviation in bended transfer tube



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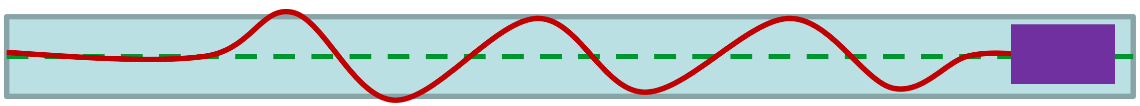
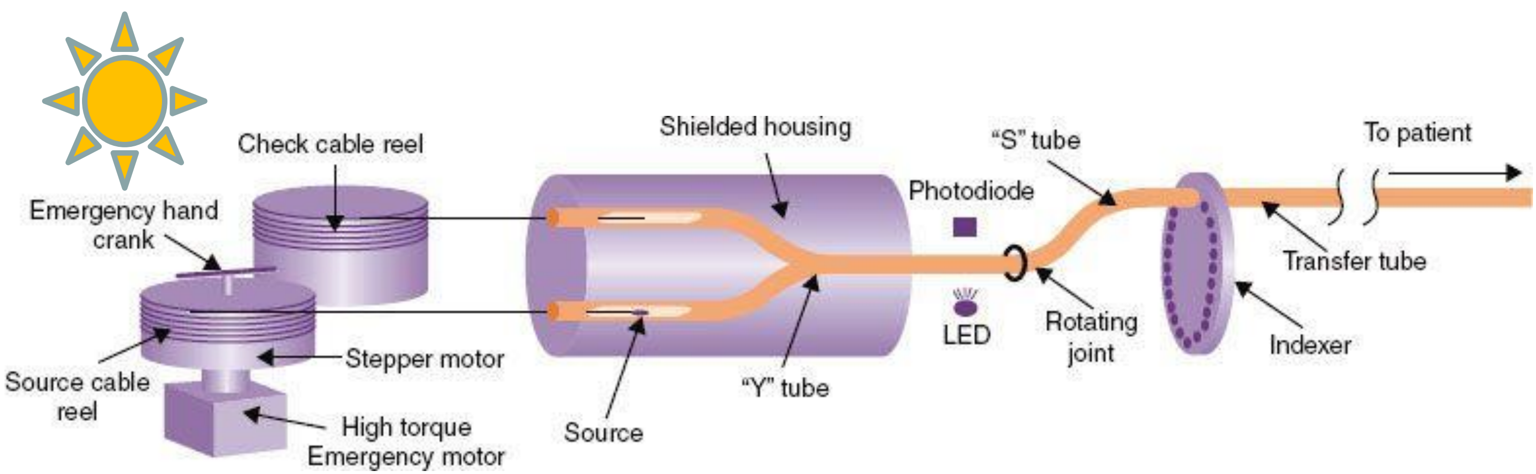
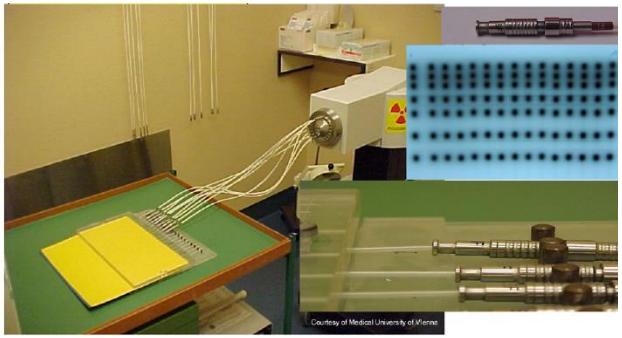


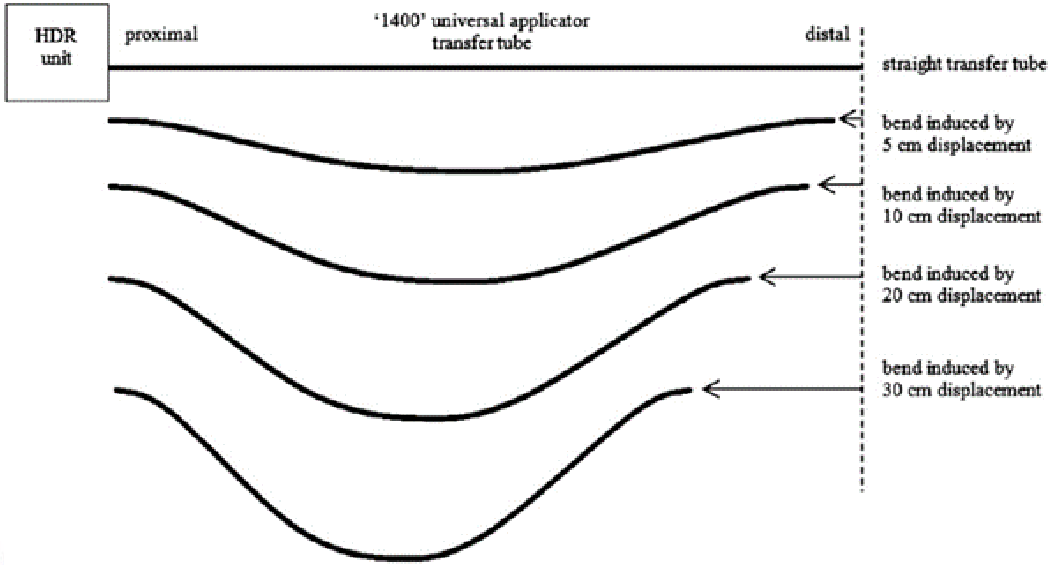
3. Thermal expansion of the source-cable (~0.01‰ per K, i.e. Δl >1mm for ΔT=10°C)

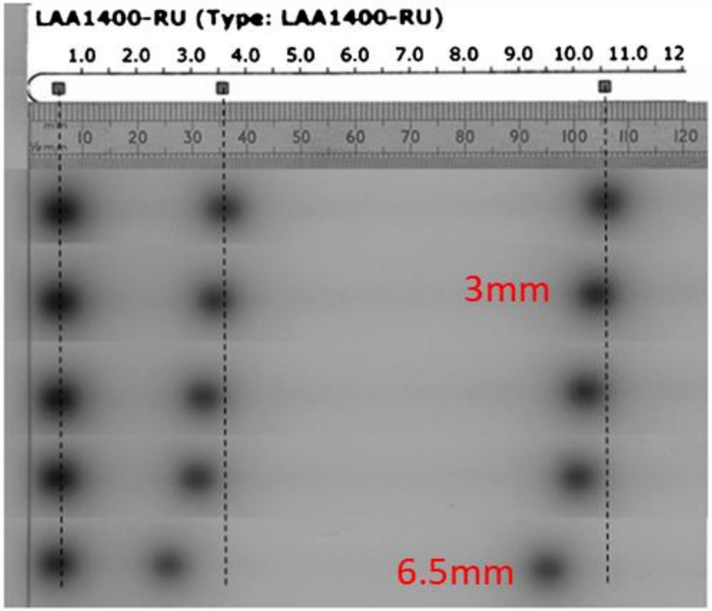


QA : Source positioning accuracy and Transfer tube length verification

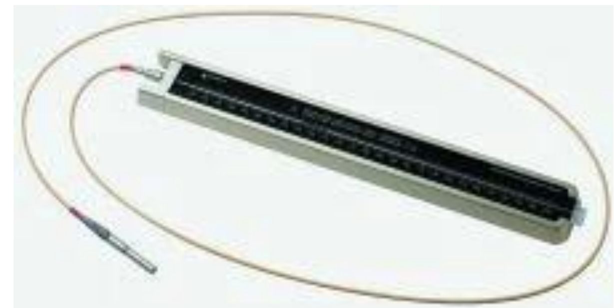


Adapted from Palmer et al. Phys. Med. Biol. 54 (2009)





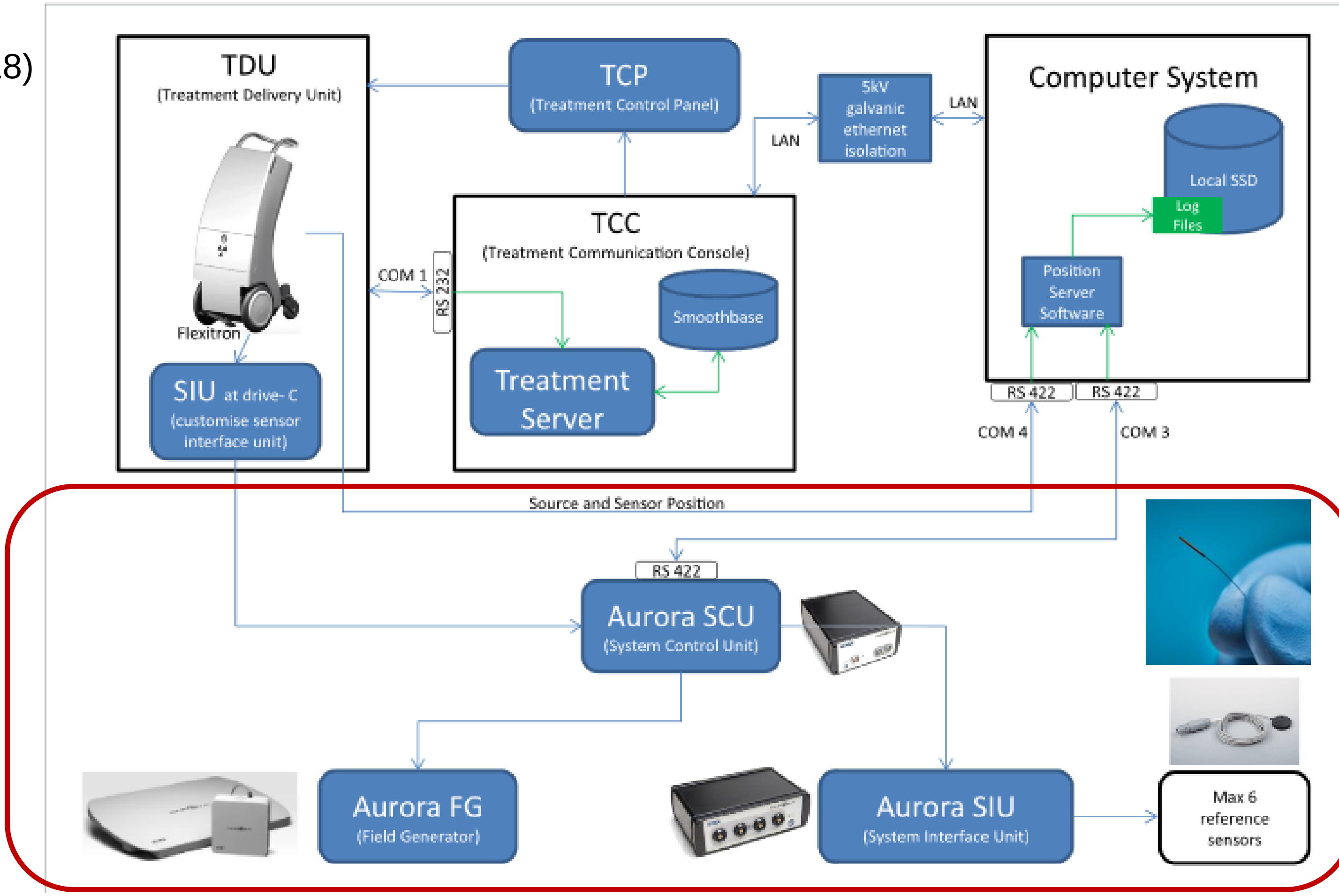
QA : Source positioning accuracy and transfer tube length verification



QA : Source positioning accuracy and transfer tube length verification

Hybrid Treatment Delivery System (HTDS),
which integrates Electromagnetic Tracking System (EMTS) into an afterloader system

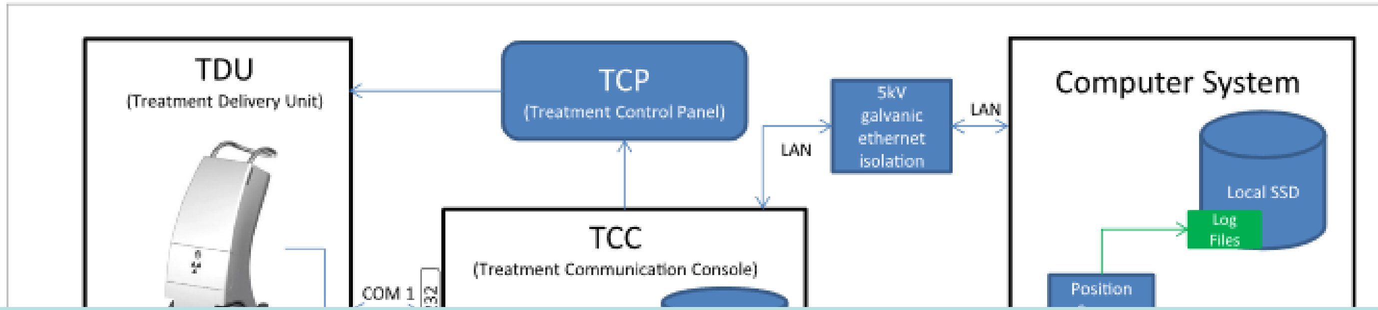
Phys. Med. Biol. 63 (2018)



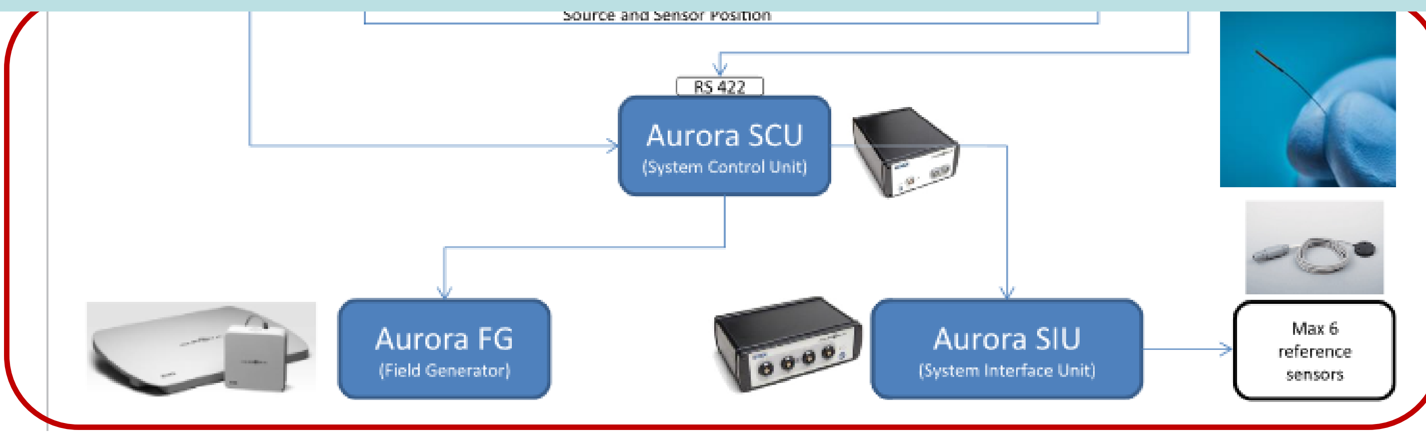
QA : Source positioning accuracy and transfer tube length verification

Hybrid Treatment Delivery System (HTDS),
which integrates Electromagnetic Tracking System (EMTS) into an afterloader system

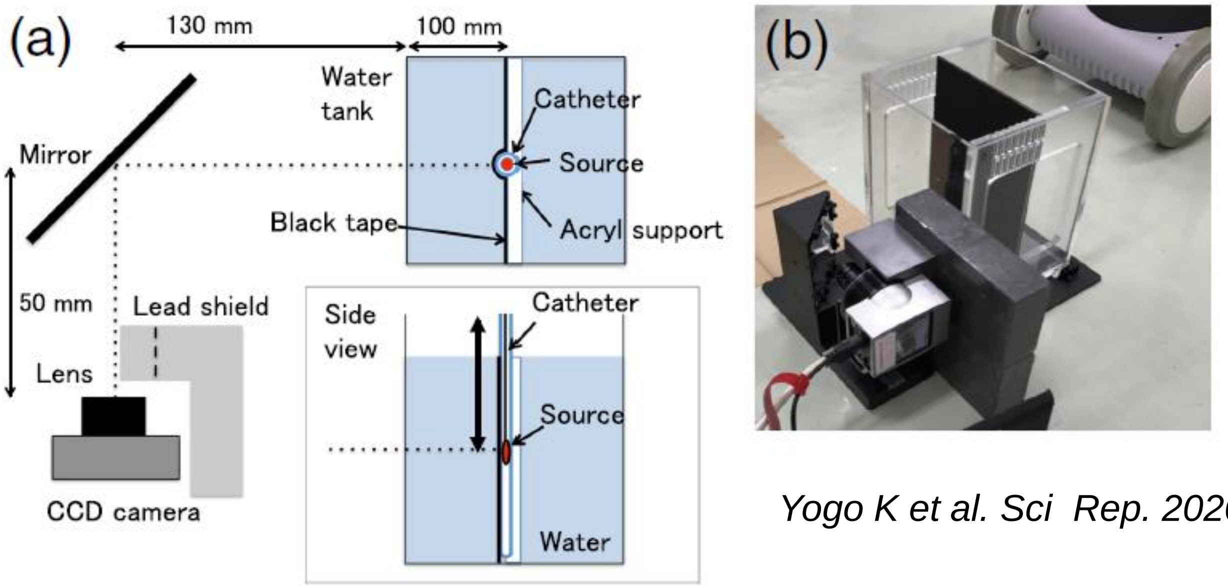
Phys. Med. Biol. 63 (2018)



"[…] **Large treatment planning errors** such as partial swaps and tip/connector end swaps and large treatment delivery errors such as catheter swaps **could easily be detected and differentiated visually**.[…] **small changes** in the indexer length or the offset value in the treatment plan or catheter shifts **<1.1 mm can be difficult to differentiate** " *Phys. Med. Biol. 64 (2019)*



Imaging Cherenkov emission for QA of HDR brachytherapy



Yogo K et al. Sci Rep. 2020

The observed light is primarily Cherenkov emissions produced by Compton-scattered electrons from the γ-rays.

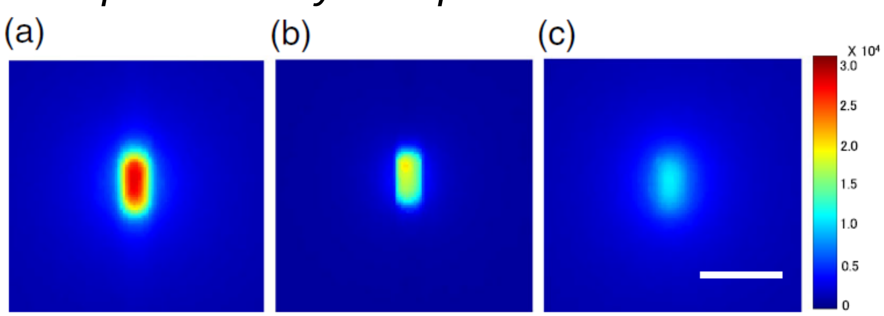
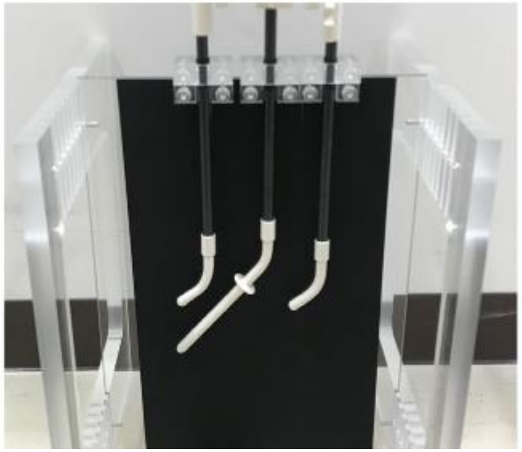


Figure 2. Images of light emission from water irradiated with ^{192}Ir source. (**a**) Image of light from pure water and catheter irradiated with source. (**b**) Image of light from the catheter in air when irradiated with source. (**c**) Image of light from pure water irradiated with source after the catheter was covered with tape. Scale bar: 5 mm. Exposure time was 58 s. Images are expressed in grey values in 16-bit scales as in colour bars.

Imaging Cherenkov emission for QA of HDR brachytherapy



Medical Physics, 48 (1), January 2021

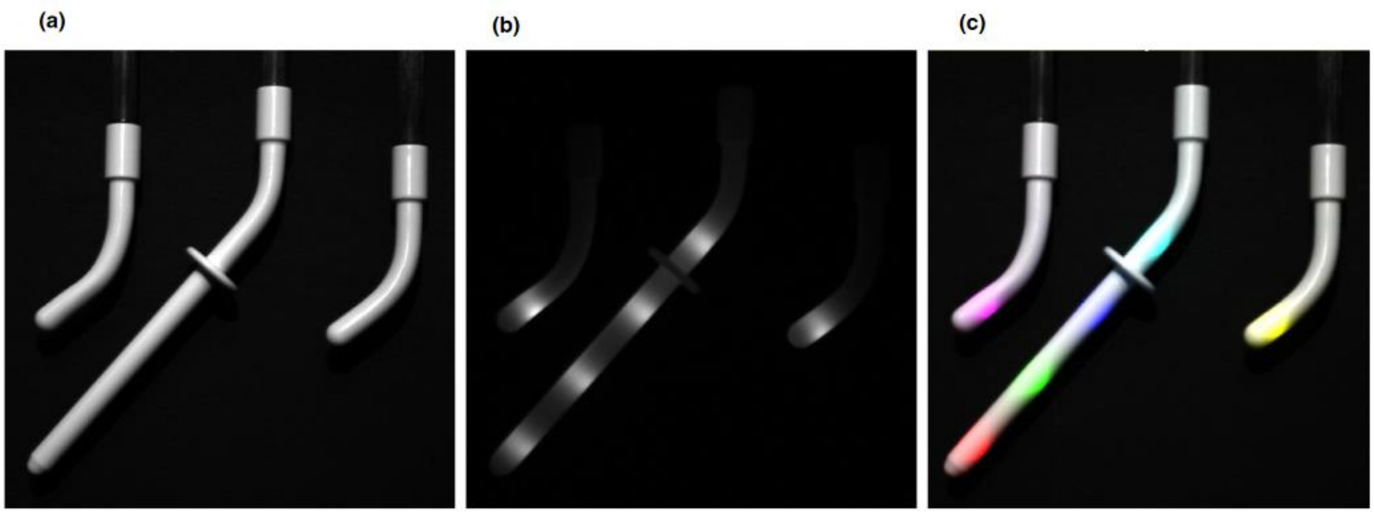
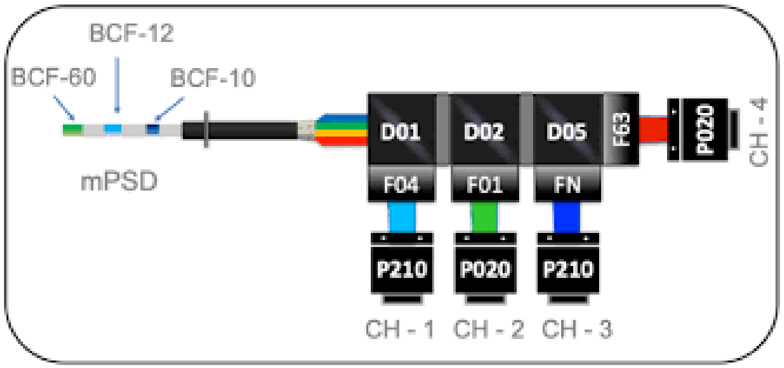


FIG. 2. Images of light emission from plastic applicator irradiated with an ^{192}Ir source. (a) Image captured under light room. (b) Image of Cherenkov emission captured under dark room for 30 s. (c) Merge of images (a) and (b). Note that the window level of the images was modified. Cherenkov emissions in (c) are presented in pseudo-colors. [Color figure can be viewed at wileyonlinelibrary.com]

Source detection by using point detectors



Medical Physics, 46 (5), May 2019

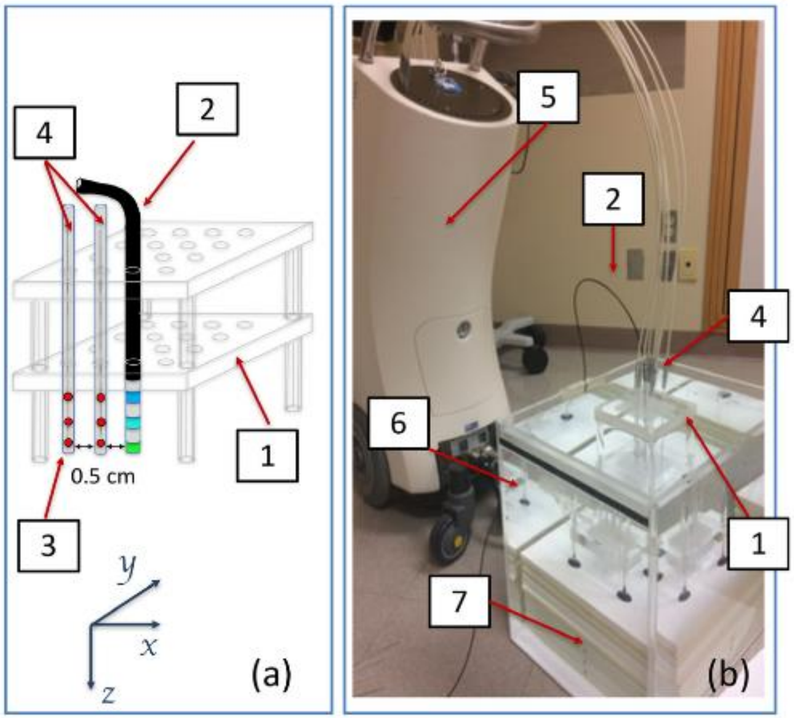


FIG. 2. (a) Schematic of the poly(methyl methacrylate) (PMMA) phantom constructed for HDR brachytherapy measurements with an multipoint plastic scintillator detector (mPSD). The catheter positioning allowed source displacement parallel to the mPSD. (b) Experimental set-up for HDR brachytherapy measurements. (1) PMMA phantom, (2) mPSD, (3) ^{192}Ir source, (4) 30-cm catheters, (5) Flexitron HDR afterloader unit, (6) $40 \times 40 \times 40\text{-cm}^3$ water tank, (7) solid-water slabs.

Source detection by using point detectors

ISD : single inorganic crystal (CsI:Tl).

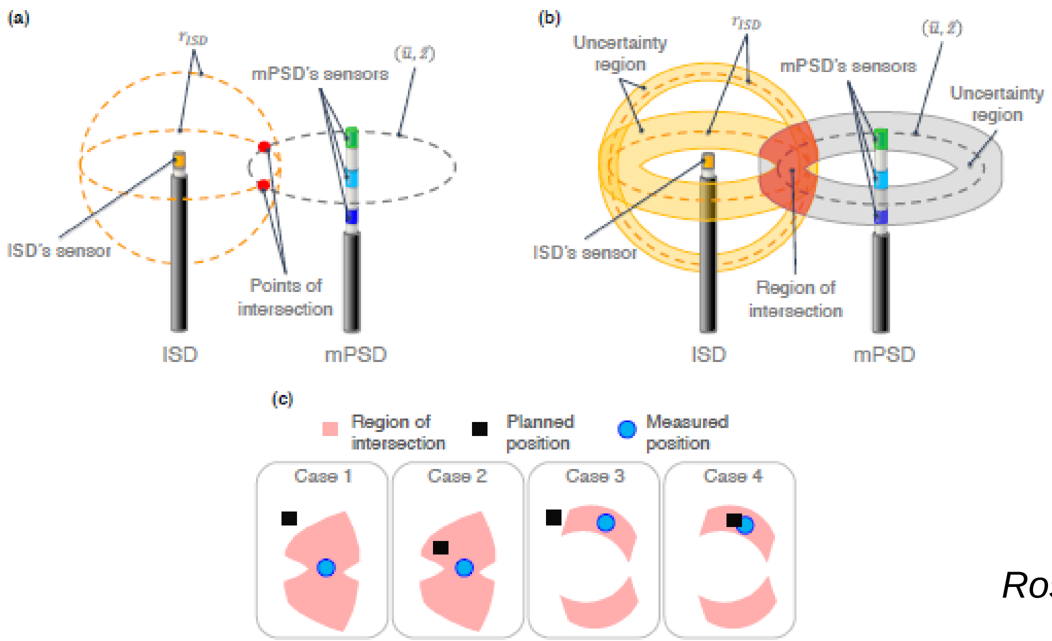


FIG. 3 Schematic that illustrates the combination of mPSD-ISD responses to determine the source position using no uncertainties (a) and non-zero uncertainties (b), and possible cases (c) that can arise when extracting the intersection region in (b).

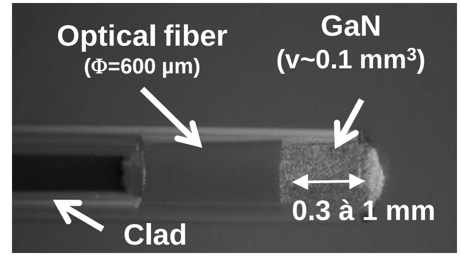
Rosales et al, Med. Phys. In press

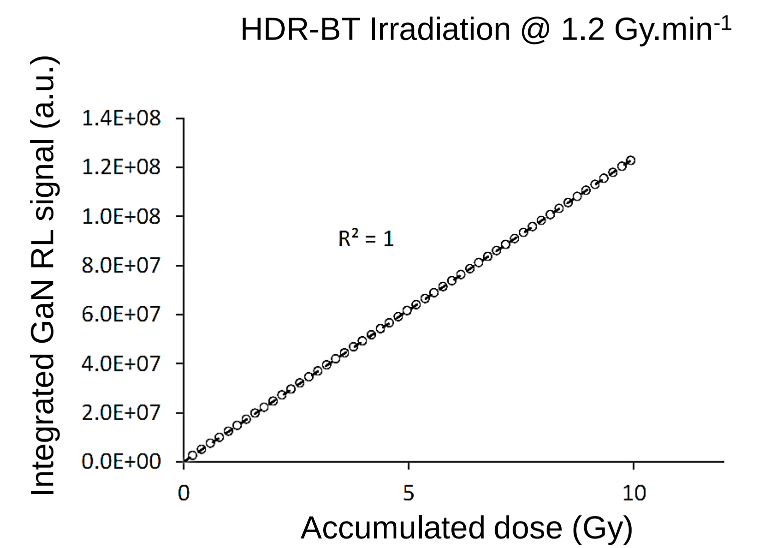
[…] The agreement between the source's reconstructed and expected positions was generally within 3 mm for a range of distances to the source up to 50 mm […]

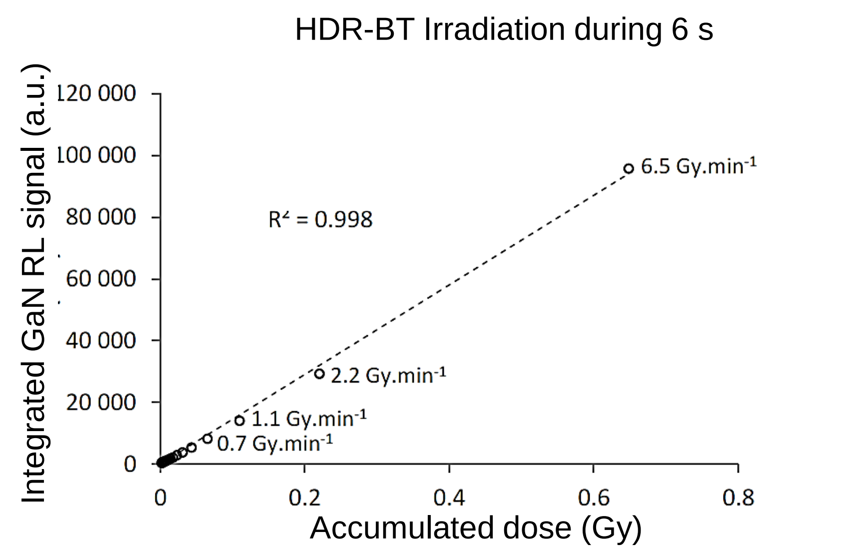
Source detection by using point detectors

GaN detector probe

Photodetection module

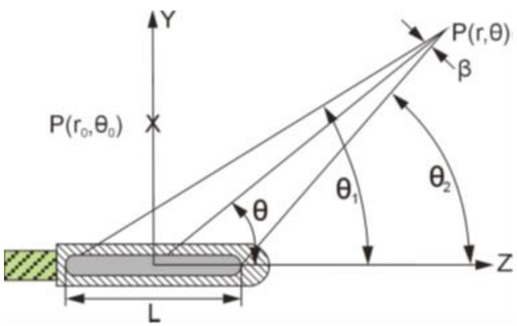






☺ Miniaturized GaN detector is suitable **for measurements in steep dose gradient regions** and **over extended dose rate ranges (real time RL response is linear and dose rate independent)**

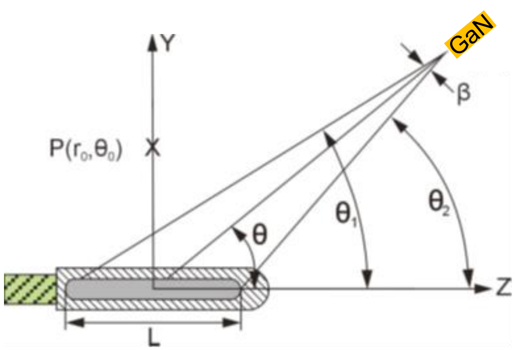
TG-43U1 formalism is conventionally used for dose rate in water calculation



$$\dot{D}(r,\theta) = S_k \Lambda \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} g_L(r) F(r,\theta)$$

S_k Air-kerma strength
Λ Dose rate constant in water
$G_L(r,\theta)$ Geometry function
$g_L(r)$ Radial dose function
$F(r,\theta)$ 2D anisotropy function

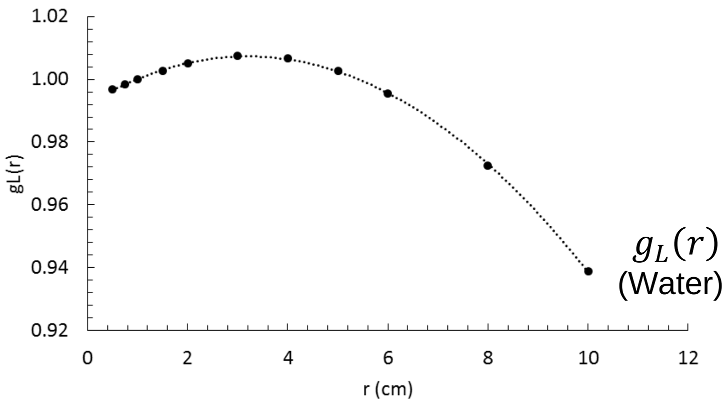
TG-43U1 formalism is can be extended and applied for detector instantaneous response calculation

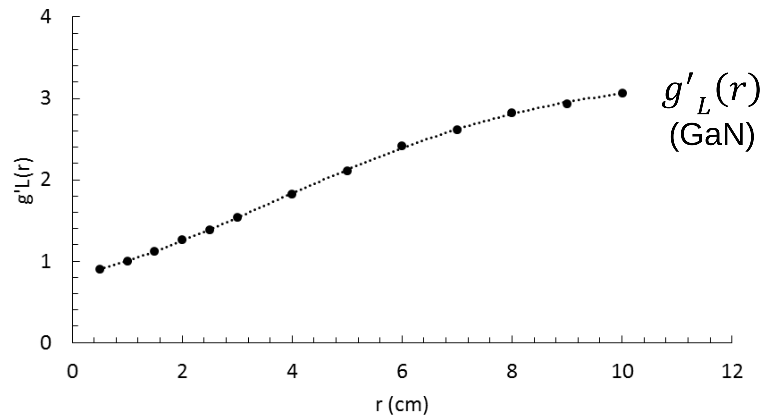


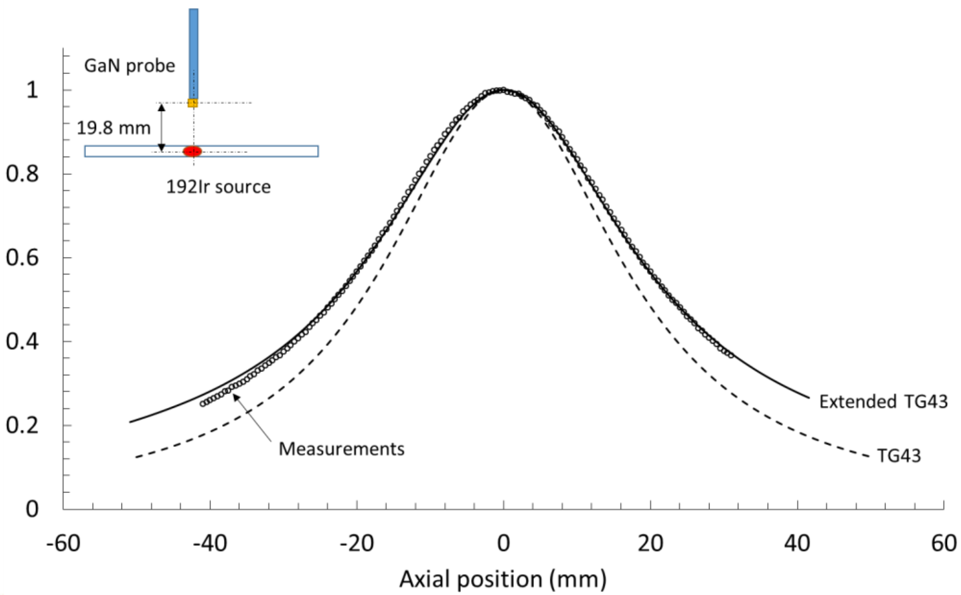
$$\dot{R}(r,\theta) = S_k \Lambda \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \boldsymbol{g'_L(r)} F(r,\theta) \boldsymbol{F'(r,\theta)}$$

$\boldsymbol{g'_L(r)}$ extended radial dose function
(accounts for response variations on the transverse axis to photon scattering and attenuation and transducer non tissue equivalence)
$\boldsymbol{F'(r,\theta)}$ detector anisotropy function
(accounts for the anisotropy of transducer response and, eventually for stem effect)

The extended radial dose function, $g'_L(r)$, is evaluated by MC simulations (PENELOPE).



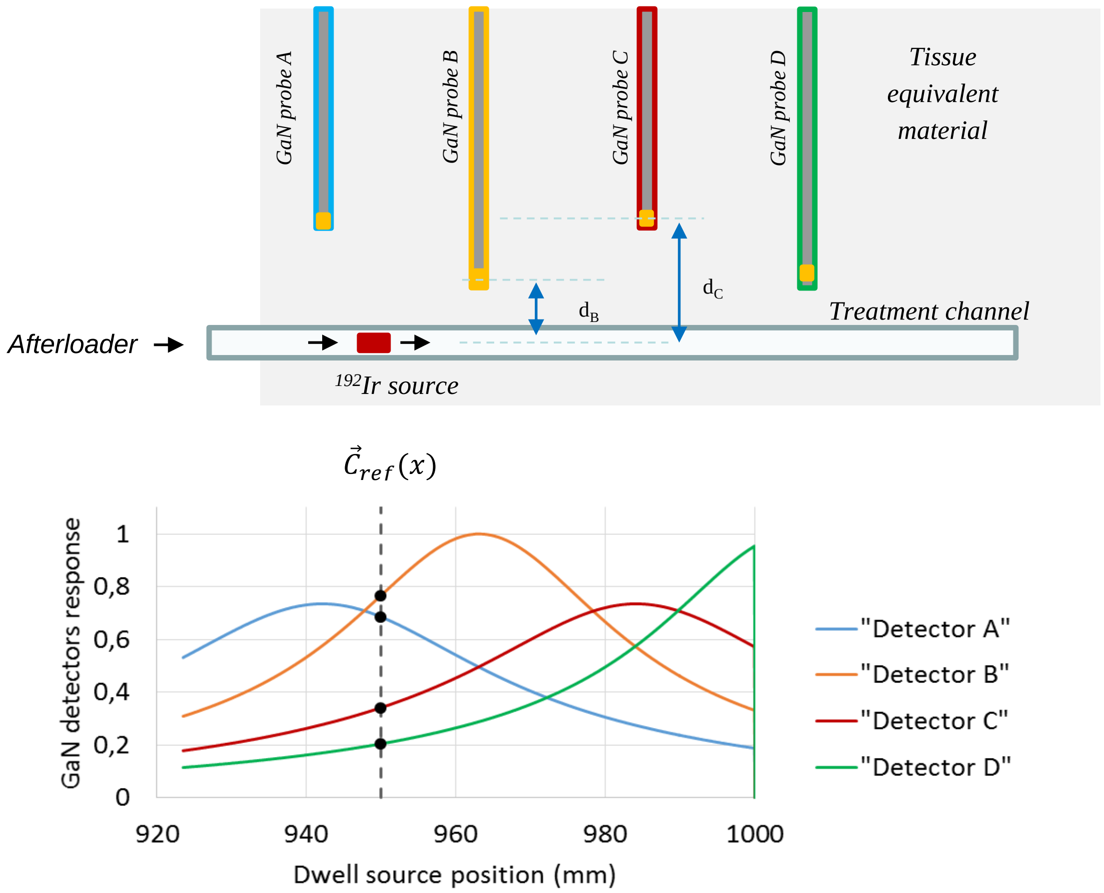


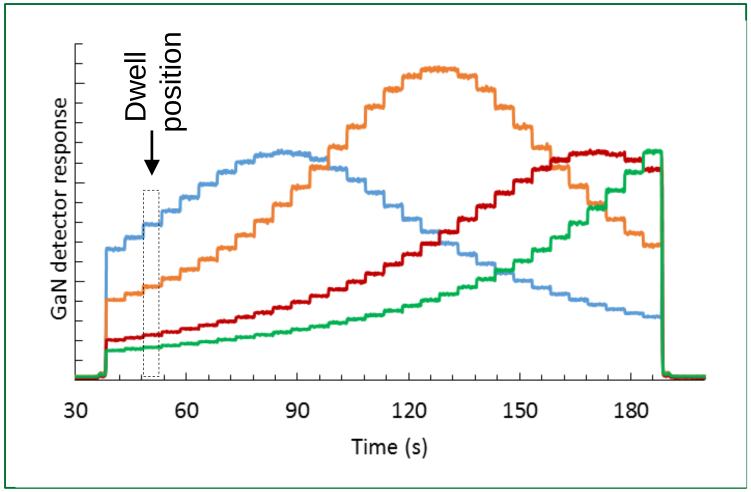


- $Z_{GaN} > Z_{Tissu} \Rightarrow g'_L(r) > g_L(r)\ for\ r > 1$
- Model is in good agreement (±4%) with measurements over [30mm,+30mm]
- Detector anisotropy needs to be corrected (not yet implemented)

Principle

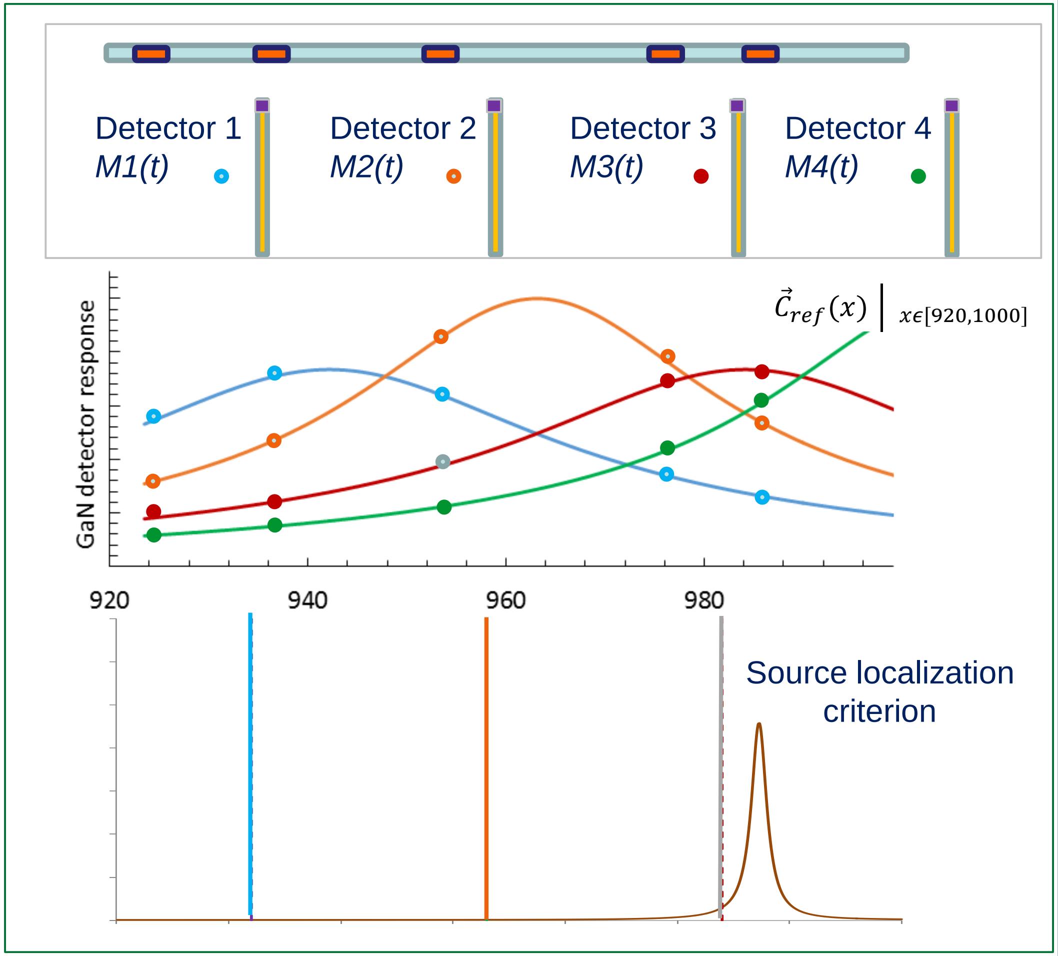
Highly spatially resolved measurements with 4 GaN-based detectors distributed along the treatment channels





Source position is search in real time by using measurements and a look-up table $\vec{C}_{ref}(x)\ |_{x\epsilon[x_{min},x_{max}]}$

P. Guiral et al., Medical Physics, 43, 2016.



Current source activity verification

Current activity

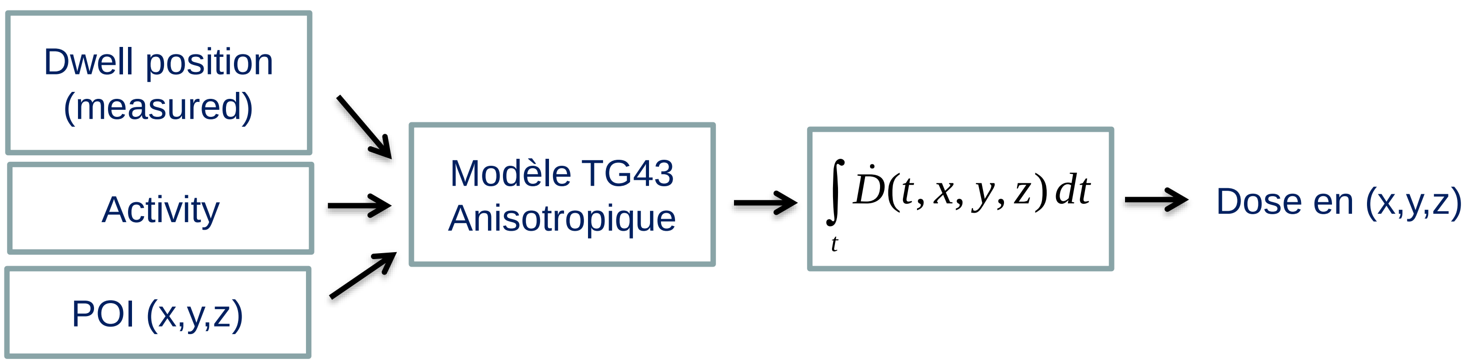
Activity at calibration

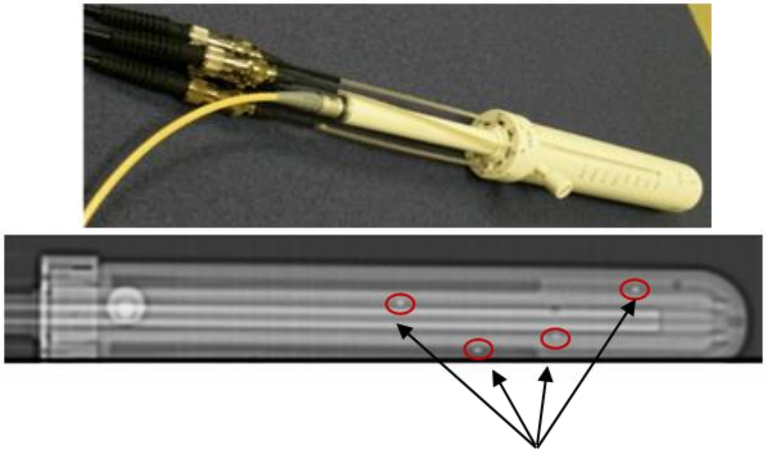
Current GaN response

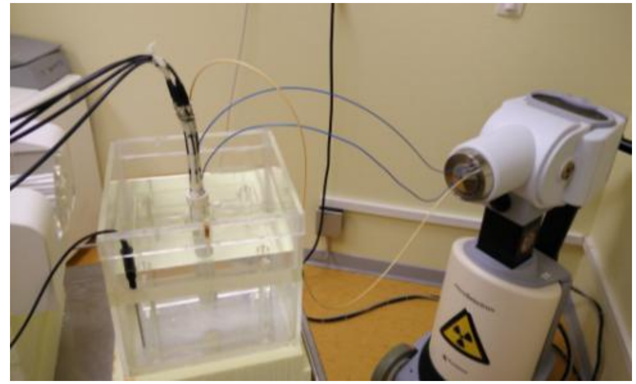
$$\mathbf{A(t)} = A_0 \frac{\left\|\vec{\mathbf{R}}(\mathbf{Z}, \mathbf{A}(t))\right\|}{\left\|\vec{T}(\mathbf{Z}, \mathbf{A_0}(t))\right\|}$$

GaN response at calibration

Dose at Point Of Interest

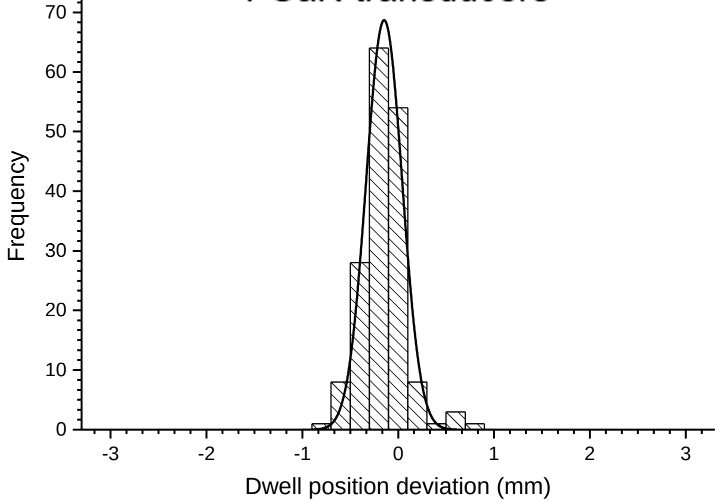




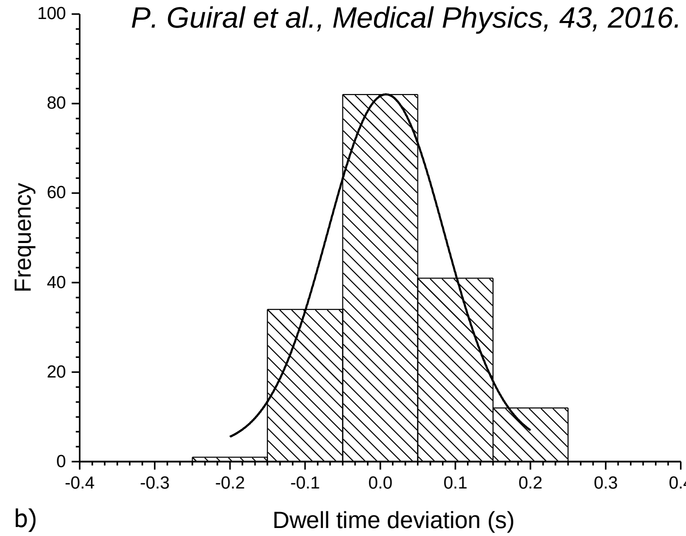


4 GaN transducers

P. Guiral et al., Medical Physics, 43, 2016.



a)



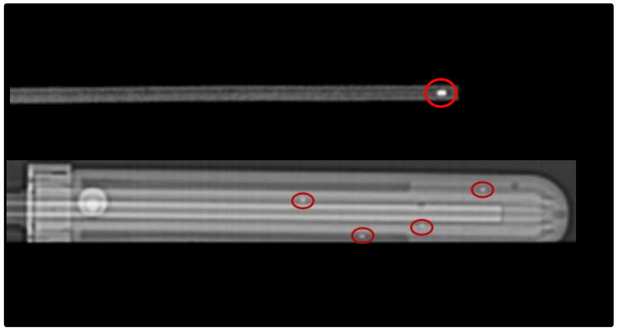
b)

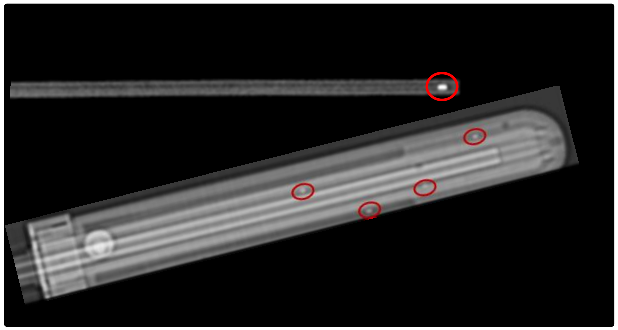
0.01±0.42 mm (1 SD)

0.02±0.08 s (1 SD)

(ESTRO recommendations : Dwell position 2mm – Dwell time 1%)

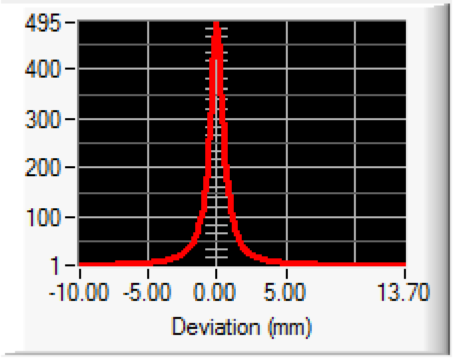
Applicator motion detection by the use of an additional probe in the urethral channel

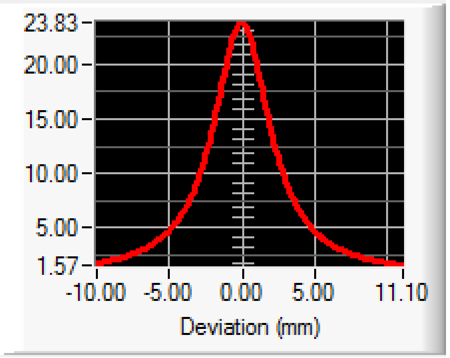




The look-up reference table $\vec{C}_{ref}(x)$, is build considering the 5 GaN transducers as a rigid body

Applicator / urethral probe ⇨ loss in correlation between $\vec{C}_{ref}(x)$ and measurements





Criterion : Magnitude ⬂ and FWHM ⬀

Questions and open discussion…