Verres de silice en milieux radiatifs

du durcissement pour le spatial à l'application en dosimétrie médicale

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SILICA FIBERS AND USUAL DOPANTS

CORE DOPANT	Role
Ge	Increases refractive index (RI) for total internal reflection
Er	Stimulated emission (fiber amplifiers and lasers)
Yb	Stimulated emission (fiber amplifiers and lasers)
P	Increases RI, lowers fusion point, improves solubilty of RE ions, reduces OH abs.
Al	Increases RI, improves solubilty of RE ions, stabilizes host matrix around dopants
Luminescent ions	RE ions (Yb, Ce, Gd…), Cu, N… for radioluminescence

CLADDING DOPANT	Role
F	Decreases RI for total internal reflection
B	Decreases RI

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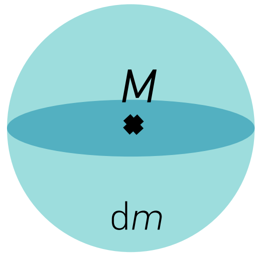
DOSE AND DOSE RATE

Dose *D* « absorbed » to a material

Energy deposited by particles in the medium per unit mass

- In unit of **GRAYS** → 1 Gy = 1 J kg^{-1} (i.e. 1 m^2 s^{-2} in fundamental units)
- Determined by the fluence of incident ionizing particles (cm^{-2})
- Former unit (still used in space community) = **rad**, acronym for «radiation absorbed dose» → 1 rad = 0.01 Gy

Elementary volume d*V* around M



$$D(M) = \frac{dE_{\mathrm{abs}}(M)}{dm}$$

Harold GRAY
1905-1965
Radiobiologist

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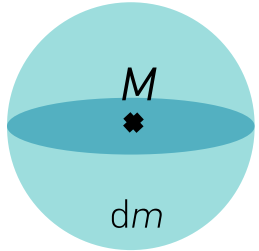

$$D(M) = \frac{dE_{\mathrm{abs}}(M)}{dm}$$

Orders of magnitude

- Therapeutic dose = **60 Gy** but controls should measure < 1 Gy
- Cumulated dose over a 15-year satellite mission = **300-500 Gy**
- Dose létale corps entier **DL50 = 4 Gy**

DOSE AND DOSE RATE

Dose rate *D'* « absorbed » to a material :

The rate of dose absorption, which depends on the particle **fluence rate** ($cm^{-2}\ s^{-1}$)

$$D'(M) = dD(M)/dt \quad (Gy\ s^{-1},\ Gy\ h^{-1}...)$$

Orders of magnitude

- Space = $10^{-6} < D' < 10^{-3}$ Gy h^{-1}
- Therapeutic irradiaiton ; from **a few cGy s^{-1}** (conventional) to **a few thousands Gy s^{-1}** (flash)

OUTLINE

1. Radiation effects on silica glasses
2. Why should we mitigate? How can we exploit?
3. Space Applications (*low dose rates*)
   - 3A – Silica-based fibers in space
   - 3B - The space harsh environment
   - 3C – Radiation hardening techniques (against RIA)
   - 3D – How to take advantage of low dose rates in active fibers
4. Medical Applications in radiation-therapy (*low doses*)
   - 4A – Radiation-therapy and dosimetry
   - 4B – The promises of « flash » therapy and related needs
   - 4C – Why silica-based fibers can help?
   - 4D – Topical example: high-energy proton therapy (HEPT)

1 ● RADIATION EFFECTS ON SILICA GLASSES

A (very) brief overview

1 – RADIATION EFFECTS ON SILICA GLASSES

- Ionizing radiation ?

In physics: if the radiation energy exceeds the ionization energy

- In wide-band gap materials: $E > E_G$ (mean energy for a pair ~2.8 E_G)
- Gases, liquids: Mean ionization energy about **30 eV**
- ...

In radiobiology: a radiation capable of damaging DNA
(photons are non-ionizing particles!)

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- Radiation types

Photons (X rays, gamma rays), **light charged particles** (electrons), **heavy charged particles** (protons, ions).

Neutrons are specific, out of the scope of this talk.

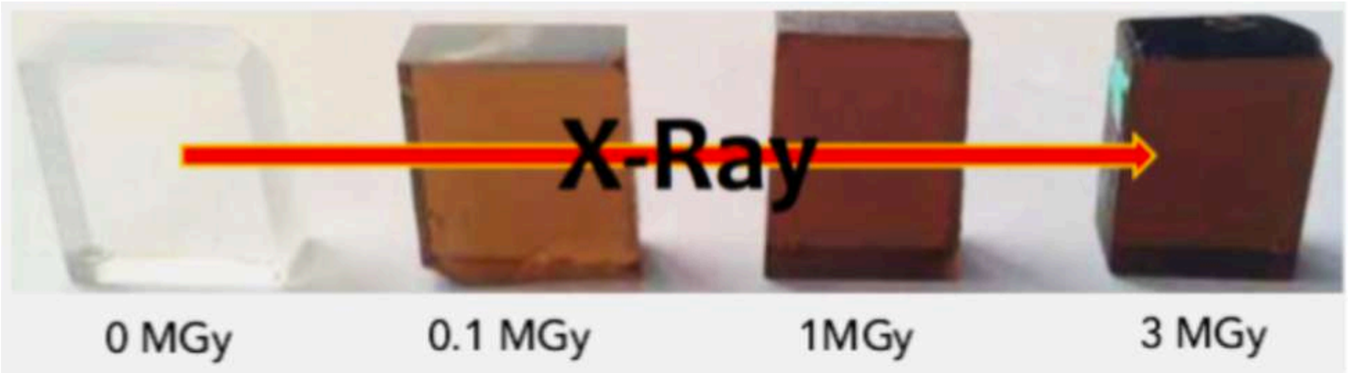
1 - RADIATION EFFECTS ON SILICA GLASSES

3 major effects

- 1A – **Radiation-Induced Attenuation** or RIA: development of optical loss
- 1B - **Radiation-Induced Emission** or RIE: Cerenkov + Radioluminescence (RL)
- 1C - **Radiation-Induced Refractive Index Change** or RIRIC: compaction and RIA

1A – RIA (radiation-induced attenuation)

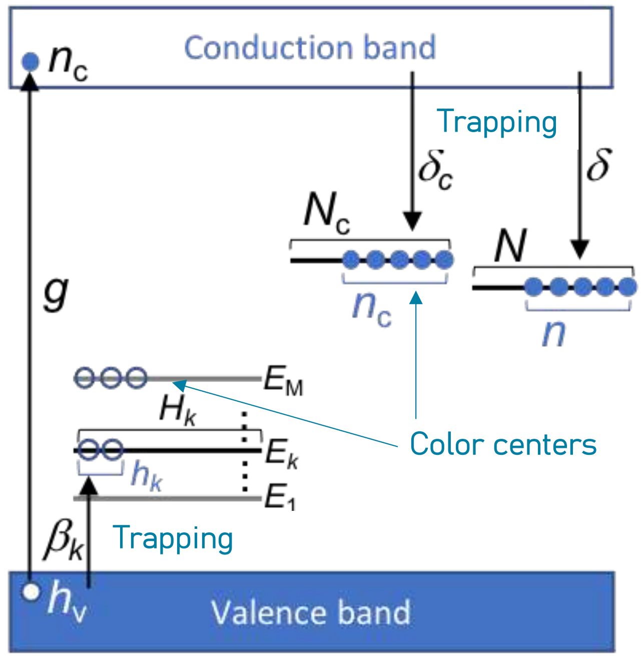
Induced optical absorption, « **darkening** », on a very broad spectral range



RIA level depends on the **dose D** but also, a priori, on the **dose rate** *D'*

1A – RIA (radiation-induced attenuation)

- Ionization → production on **electron-hole pairs** (« free » band carriers)
- Free electrons and holes can **trap** at
  - **Intrinsic defect** sites
    for ex. oxygen deficient centers
    as ≡Si–Si≡ + h⁺ → SiE' (i.e. ≡Si●)
    or ≡Si–Si≡ + e⁻ → =Si:e⁻



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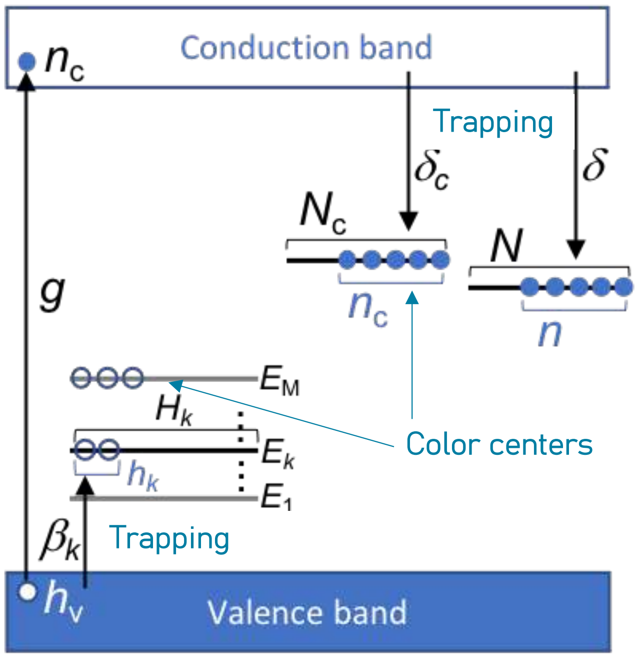
    or ≡Si–Si≡ + e^- → =Si:e^-
  - **Dopants-related** sites
    for ex. ≡Al $^+$Si≡ + e^- → AlE' (i.e. ≡Al●)
    or ≡Al–O–Si≡ + h^+ → Al-OHC (i.e. ≡Al●)
    or Yb^{3+} + e^- → Yb^{2+}
- Formation of COLOR CENTERS
  → **optical absorption (OA) bands**



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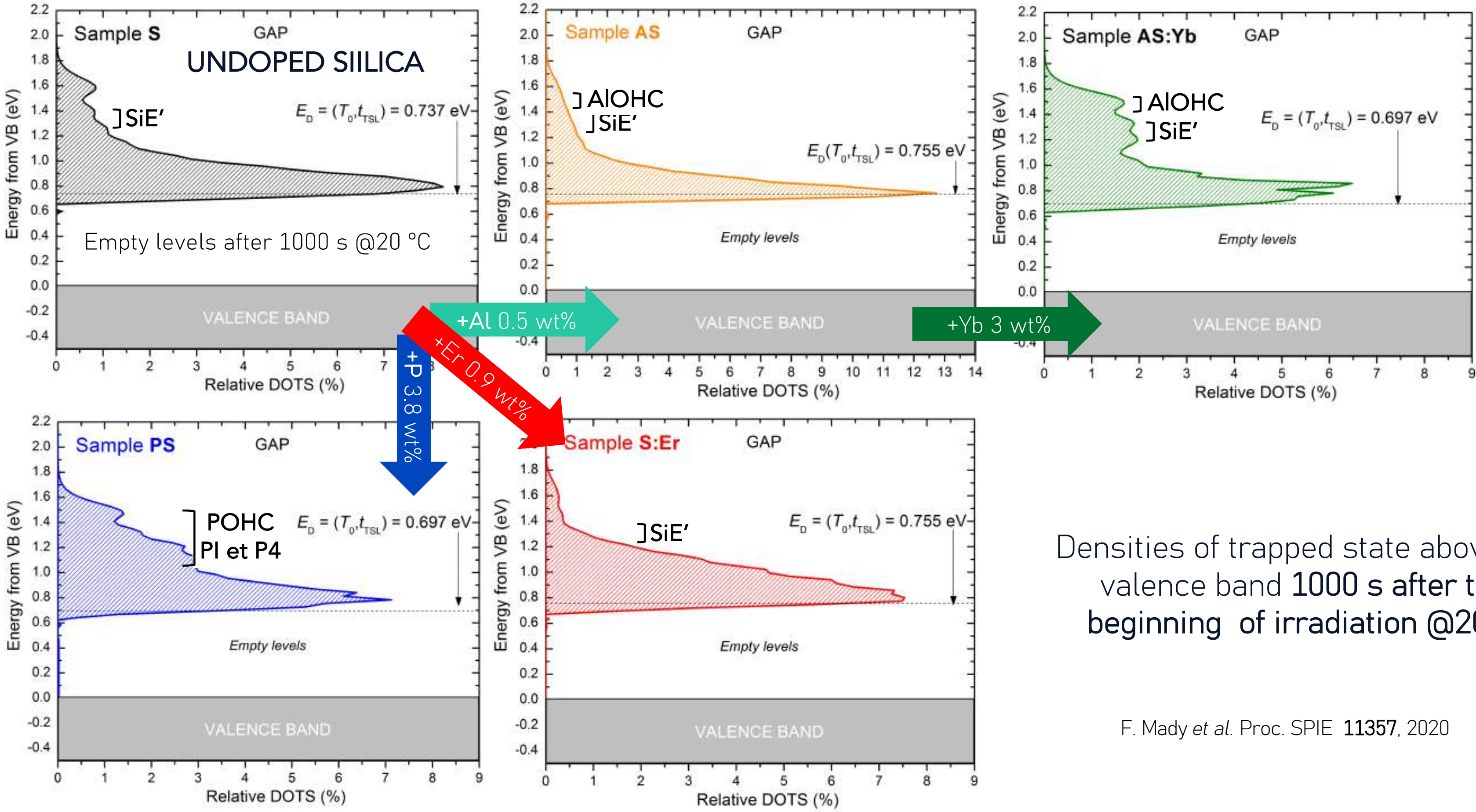
1A – RIA (radiation-induced attenuation)

Quasi-continuous distribution of trapped-hole states with **activation energies < 2 eV**



Densities of trapped state above the valence band **1000 s after the beginning of irradiation @20°C**

F. Mady *et al.* Proc. SPIE **11357**, 2020

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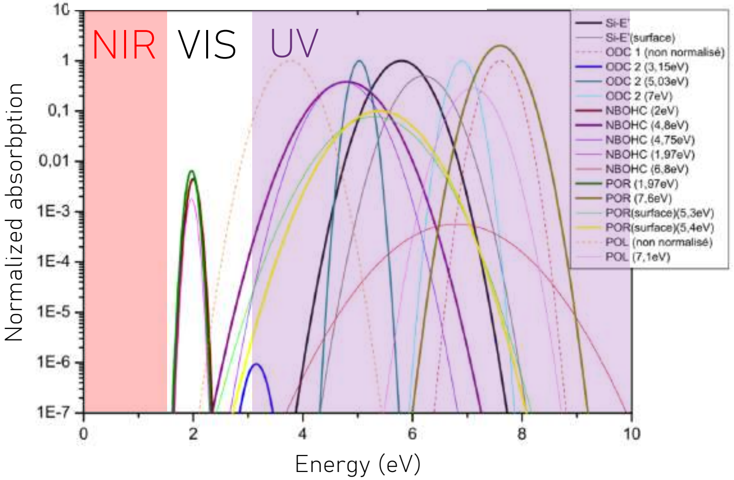
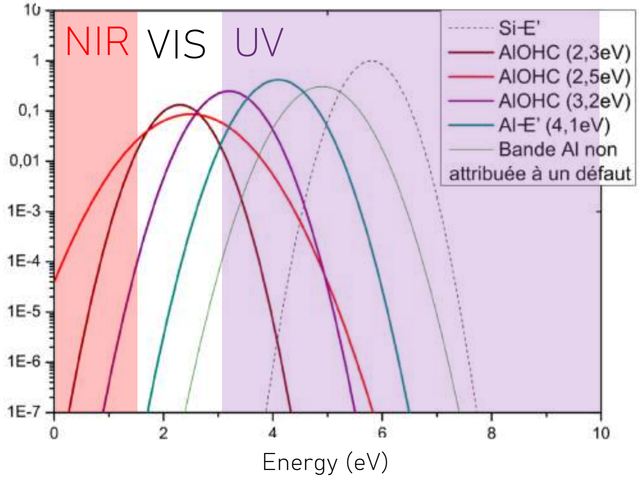
1A – RIA (radiation-induced attenuation)

Well-known (gaussian) OA bands attributed to carriers trapped at defects

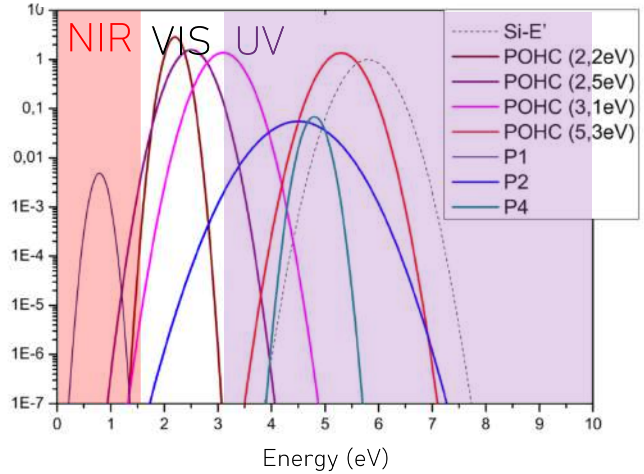
Intrinsic OA bands



Al-related OA bands



P-related OA bands



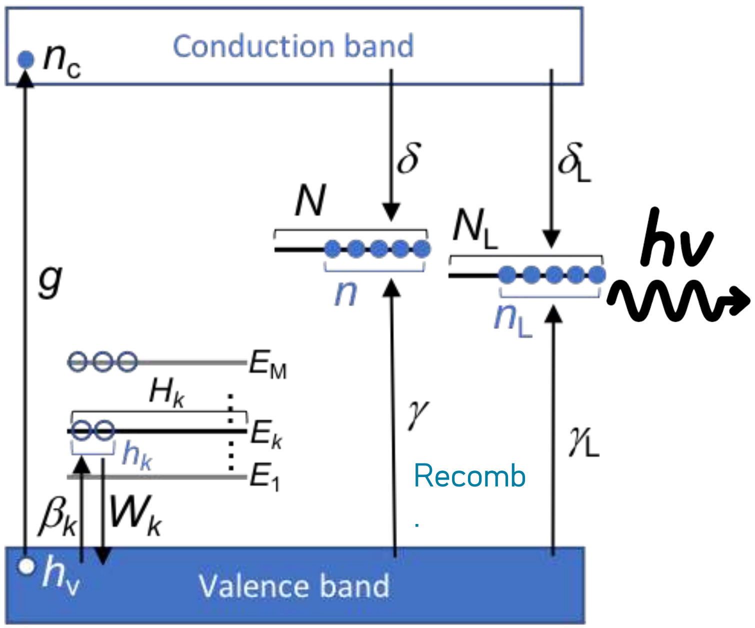
- **No OA band** peaking in the **NIR** range (notable exception of the **P1 centers**) 😫😫
- **Undoped silica is RIA-resistant** in the NIR range (but still has RIA…??)
- Al-OHC bands have significant tails in the NIR → **detrimental role of Al**

1B – RIE (radiation-induced emission)

2 contributions

1. Inorganic scintillation = **radioluminescence** (RL)
   - **Recombination of free carriers** at trapped states of opposite polarity (direct generation or thermal/optical detrapping)
   - Part of recombination is **radiative →** RL
   - In silica: free h^+ recombine with trapped e^-
   - Scintillating from the glass matrix is **weak.** It must be « **activated** » by **doping with**

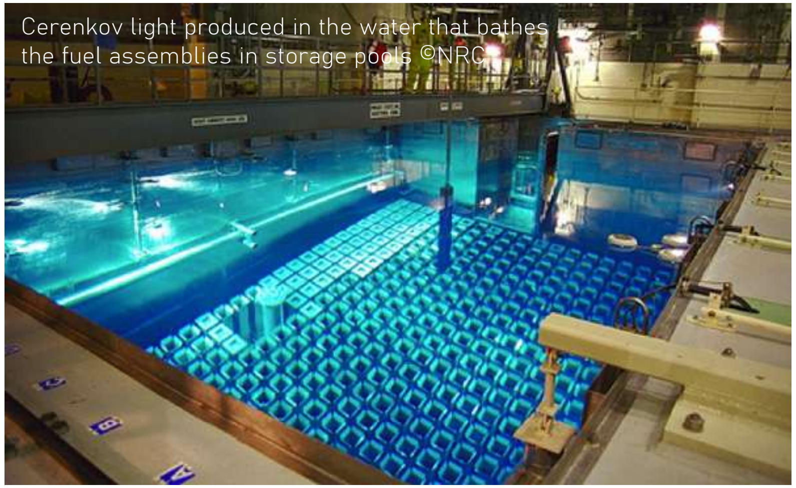
     Rare-earth ions (Ce, Yb, Gd…), Ge, Cu, N, P…



1B – RIE (radiation-induced emission)

2 contributions

2. Cerenkov emission
   - Only for **charged particles travelling faster than light** in the medium
   - Most often due to **secondary electrons** set in motion by photons or protons!


Cerenkov light produced in the water that bathes the fuel assemblies in storage pools ©NRC

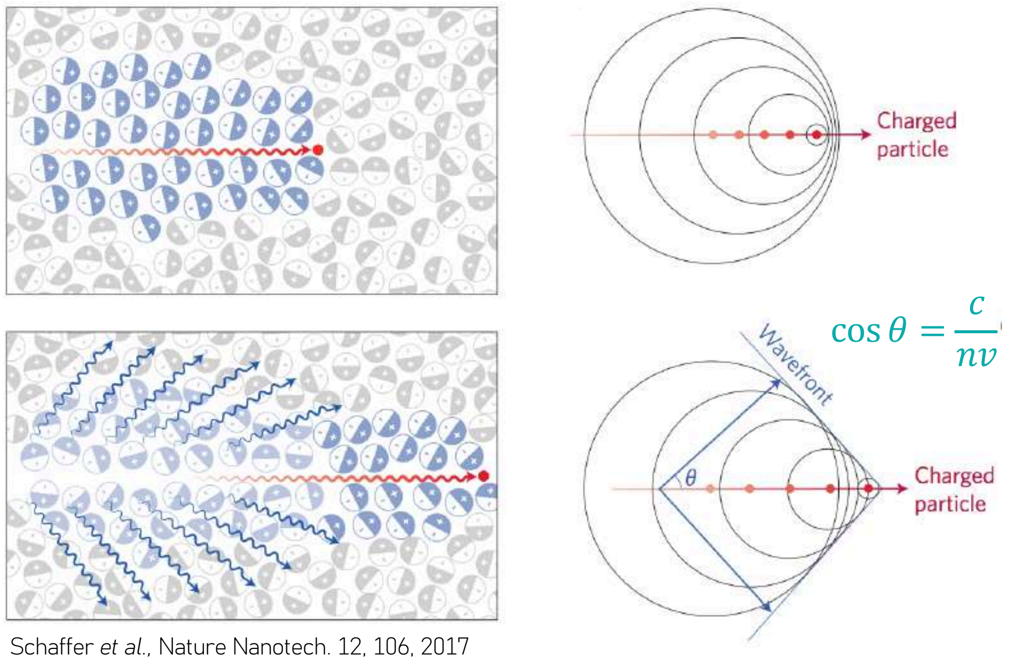
1B – RIE (radiation-induced emission)

Cerenkov emission (optical equivalent to sonic boom)

- Charged particle in a **dielectric medium** (ref. index $n > 1$) with $v \geq \frac{c}{n}$
  - Kinetic energy threshold

    $$E \geq mc^2 \left(\frac{1}{\sqrt{1 - \frac{1}{n^2}}} - 1 \right)$$

  - Thresholds in silica
    350 MeV for **protons**
    190 keV for **electrons**
    Relativistic particles



Schaffer *et al.*, Nature Nanotech. 12, 106, 2017

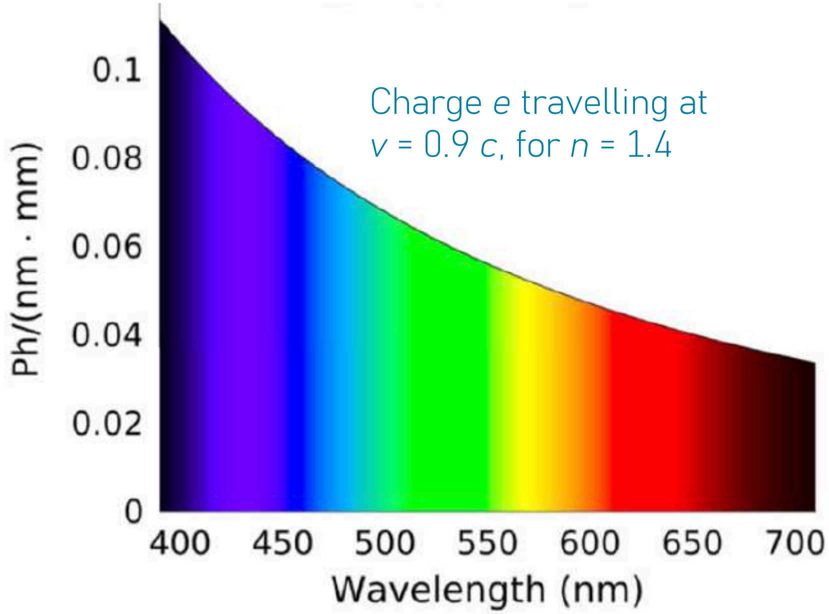
1B – RIE (radiation-induced emission)

Cerenkov light spectrum: Frank-Tamm's formula

Spectral density of energy radiated at **wavelength λ** per **unit path length dx** of a charged particle moving at **velocity v** in a medium with **refractive index $n(\lambda)$**

$$\frac{\partial^2 E}{\partial x \partial \lambda} = \frac{e^2}{4\pi\varepsilon_0} \times \frac{1}{\lambda^3} \times \left(1 - \frac{c^2}{n^2(\lambda)v^2}\right)$$

- Mainly **violet-blue luminescence**
- Enhanced intensity when v increases (above threshold)
- Continuous spetrum decreasing in $\sim 1/\lambda^3$ from UV to NIR.



Giarrocchi and Belcari, EJNMMI Physics **4**, 14, 2017

1C – RIRIC (radiation-induced refraction index change)

The refractive index *n* of a dielectric medium relates to:

- The volume density of polarisable units *N*, following the **Clausius-Mossoti's law**

$$\frac{n^2-1}{n^2+2}=\frac{N\alpha}{3\varepsilon_0}$$

- The optical absorption coefficient α of the medium (due to **Kramers-Kronig's relation** applied to electric susceptibility)

$$n(\omega)=1+\frac{c}{\pi}\int_0^\infty \frac{\alpha(\omega')}{\omega'^2-\omega^2}\mathrm{d}\omega'$$

1C – RIRIC (radiation-induced refraction index change)

2 contributions to RIRIC

$$\frac{n^2 - 1}{n^2 + 2} = \frac{N\alpha}{3\varepsilon_0}$$

- The compaction **of the material increases** *N* **and** *n*
  - Silica: if *N* increases by **1%,** *n* increases by **~5×10^{-3}**
  - Requires high **proton, neutron** or **electron** fluences (~1×10^{19} cm^{-2})
  - For example: doses of a few **GGy** under 2.5 MeV electrons (N. Ollier *et al.*, Sci. Reports **13**, 13657, 2023)

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- RIA increases the absorption coefficient α of the medium and therefore n
  - Main cause of RIRIC **under photons** (« moderate » doses)

$$n(\omega) = 1 + \frac{c}{\pi}\int_0^\infty \frac{\alpha(\omega')}{\omega'^2 - \omega^2}\,\mathrm{d}\omega'$$

  - Limited effect in silica
    n rises by **~5×10^{-6}/kGy** under gamma rays (^{60}Co) in germanosilicate fibers

2 ● WHY SHOULD WE MITIGATE?
HOW CAN WE EXPLOIT?

2A – RIA
2B – RIE
2C - RIRIC

2A – RADIATION-INDUCED ATTENUATION (RIA)

Adverse effects

- Darkening: light transmission ↘
  - Shortens transmission distances
  - Wavelenght-dependent effect (distortion in multi-wavelenghts systems)
  - SNR degradation
- In fiber lasers/amp.: GAIN ↘
  - Due to excess attenuation
  - Loss of active ions
    (RE^{3+} ions converted into RE^{2+} ions)

All effects
- Are almost permanent
- Increase with ionizing dose

Exploitable properties

RIA grows with cumulated dose (*almost always*) → DOSIMETRY

- Various models (n^{th} order or fractal kinetics…)

$RIA = kD^f$ with $0 < f < 1$

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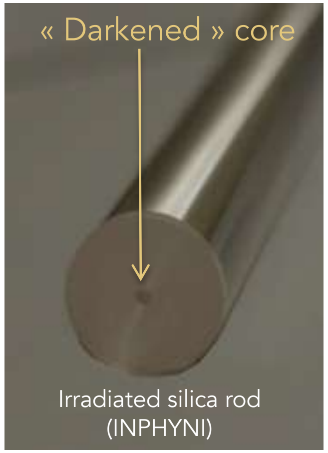
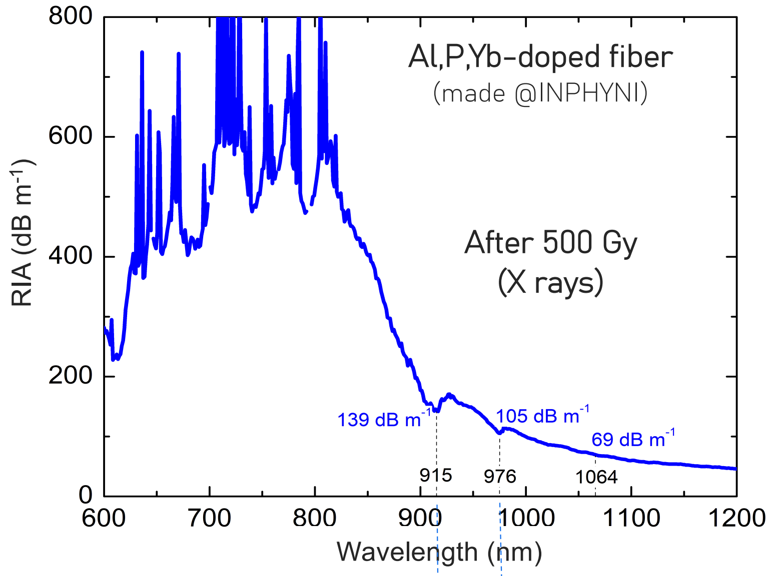
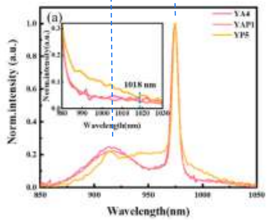


F. Mady *et al.*, Opt. Letters **35**, 3541, 2010



Absorption spectra of Yb^{3+} ions in various silica glasses



H. Dong *et al.*, Opt. Mat. **122**, 111761, 2021

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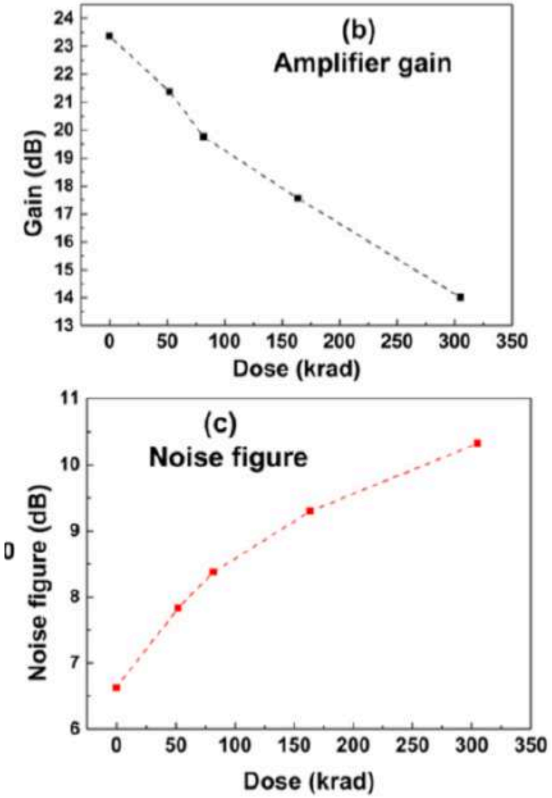
Gain and noise figure of an **Er-doped fiber amplifier** (EDFA) as a function of dose (simulation)



S. Girard *et al.*, *J.* Opt. **20**, 093001, 2018

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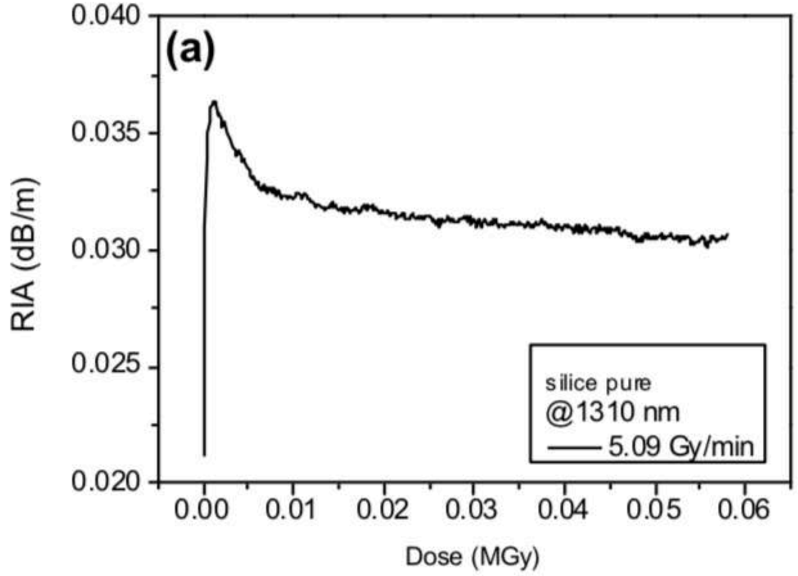
RIA = kD^f with $0 < f < 1$

2A – RADIATION-INDUCED ATTENUATION (RIA)

In-core RIA @1310 nm of a **pure silica core fiber (PSCF)** under ^{60}Co γ-irradiation



CERTYF PROJECT – UJM-IRSN

Non monotonic variation *at low dose rate*…
but the origin of this **weak RIA** *is not* a color center

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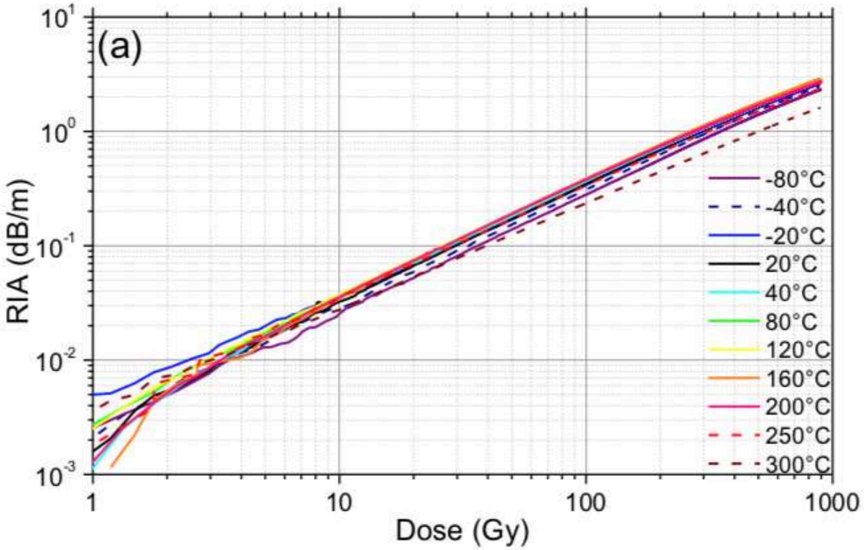
2A – RADIATION-INDUCED ATTENUATION (RIA)

In-core RIA @1550 nm of a **P-doped silica** fiber
under X-ray irradiation (1 Gy s^{-1})



A. Morana *et al.*, IEEE Trans.. Nucl. Sci. **68**, 906, 2021

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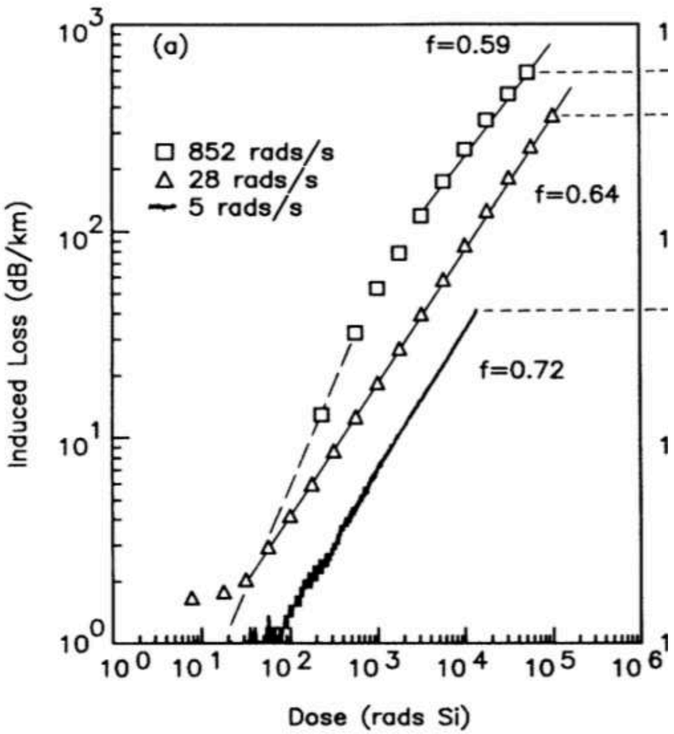
2A – RADIATION-INDUCED ATTENUATION (RIA)

In-core RIA @1300 nm of a **germanosilicate** fiber under ^{60}Co γ-irradiation



D. Griscom *et al.*, Phys. Rev. Lett. **71**, 1019, 1993

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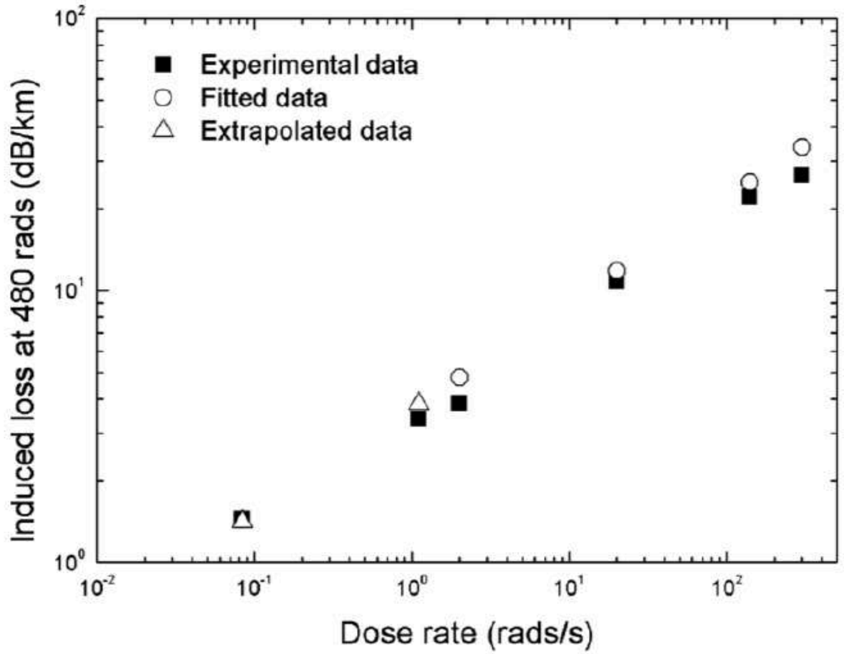

O. Gilard *et al.*, J. Appl. Phys. **108**, 093115, 2010

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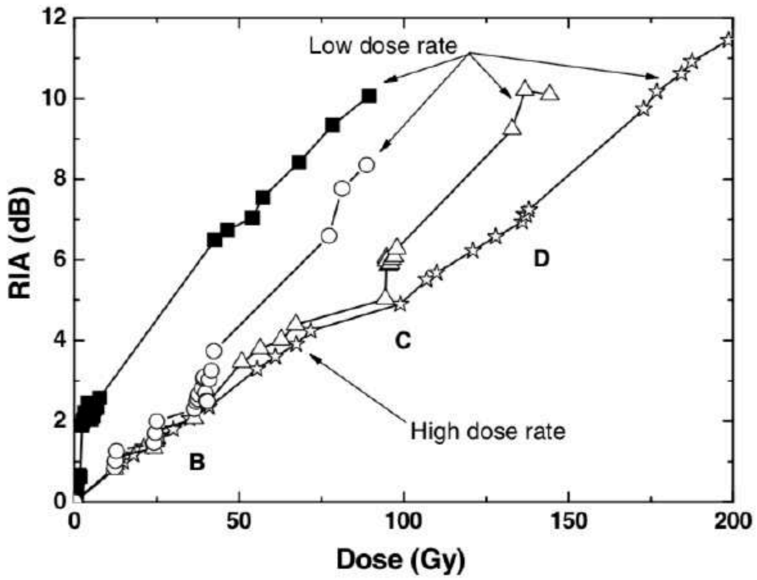
2A – RADIATION-INDUCED ATTENUATION (RIA)

In-core RIA @1550 nm of an **Er-doped fiber**
under ^{60}Co γ-irradiation

« *Enhanced low-dose rate sensitivity* » (ELDRS)



O. Gilard *et al.*, Appl. Opt. **51**, 2230, 2012

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… some ELDRS are reported

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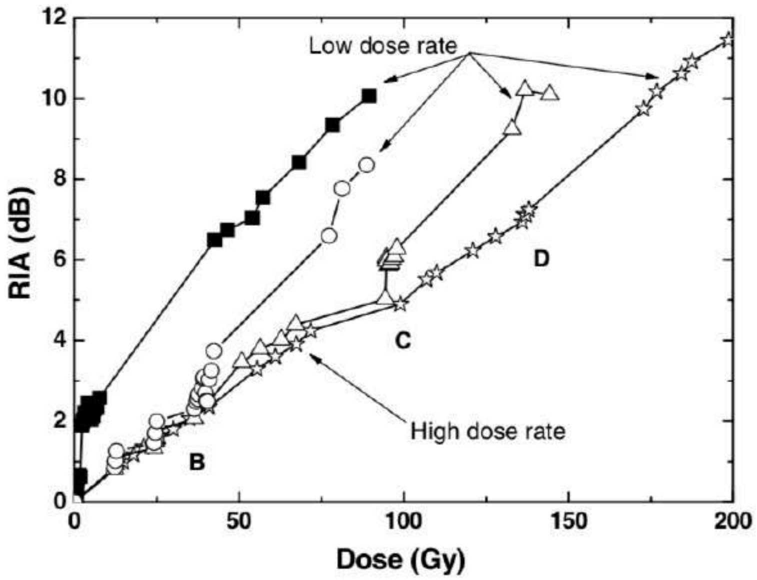

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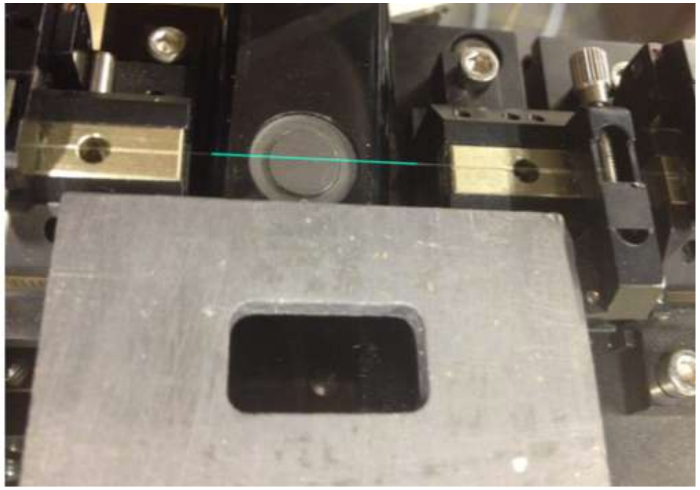
2A – RADIATION-INDUCED ATTENUATION (RIA)

How to measure RIA?

By subtracting attenuation coefficients (during/after irrad. – before irrad.)

- 'Local' measurements: **short pieces** (a few mm-cm) **of fibers** or **preform slices**
  → OK for UV-VIS range, *not for NIR* where RIA is weak

Preform slice (INPHYNI)



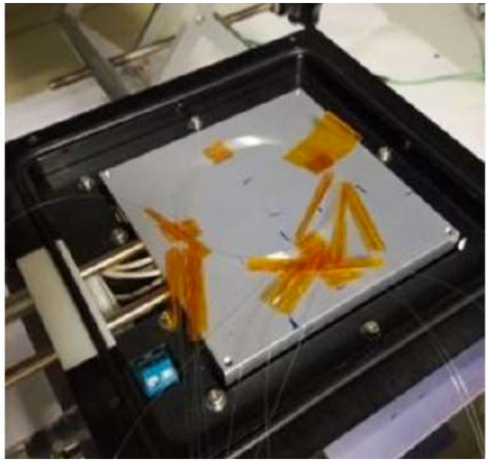
Pumped Yb-doped fiber irradiated through a 1-cm long aperture (INPHYNI)

2A – RADIATION-INDUCED ATTENUATION (RIA)

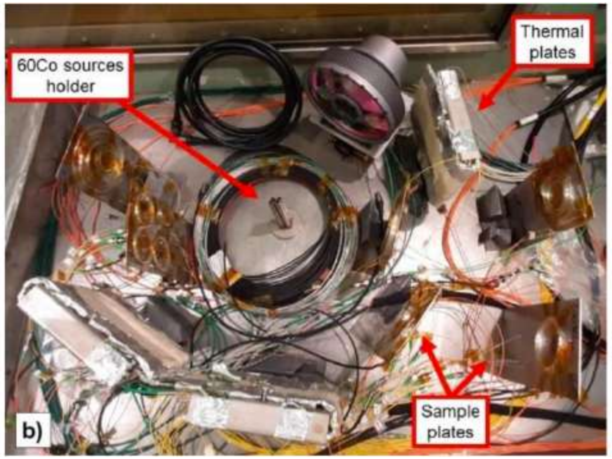
How to measure RIA?

By subtracting attenuation coefficients (during/after irrad. – before irrad.)

- Measurements over long fibers to better assess RIA in the NIR range
  → mean RIA over the fiber length (fiber coiled in an *homogeneous* radiation field)



Fiber coil to be irradiated in an X-ray generator (UJM, *CERTYF* Projet)

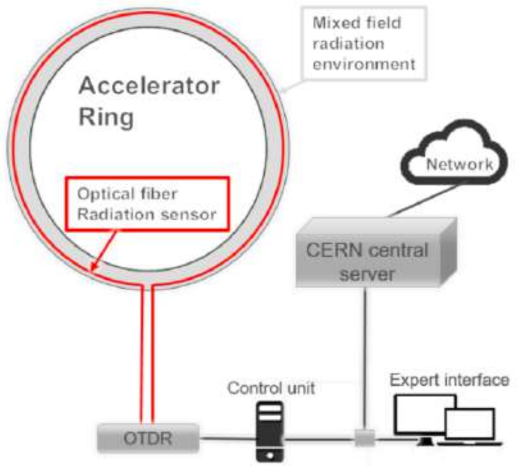


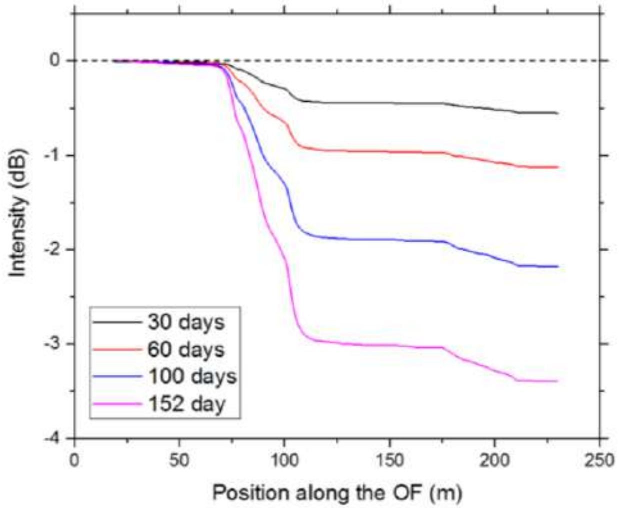
Arrangement of coils to be irradiated at the IRMA ^{60}Co γ-ray irradiator (IRSN, *CERTYF* Project)

2A – RADIATION-INDUCED ATTENUATION (RIA)

How to measure RIA?

« Distributed measurement » by reflectometry in the time domain (OTDR)
Allows « coarse » spatial resolution along « long » fibers but only at selected NIR wavelength (830, 1310, 1550 nm)





M. DiFrancesca *et al.*, IEEE Trans. Nucl. Sci. **65**, 1639, 2018

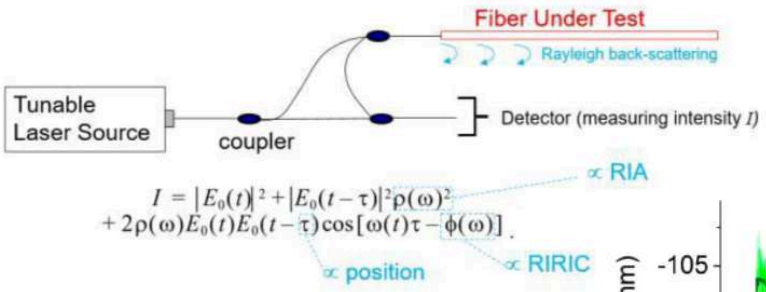
- **P-doped fiber** (NIR RIA due to P1 centers) implemented at the proton synchrotron booster at CERN for **dosimetry**
- Sensitivity = **4 dB km^{-1} Gy^{-1}** @830nm
- **RIA,** as a function of the position along the fiber, given by the plot **derivatives**
- **Fiber lentgh:** a few hundreds of meters
- **Spatial resolution**: ~1 m

2A – RADIATION-INDUCED ATTENUATION (RIA)

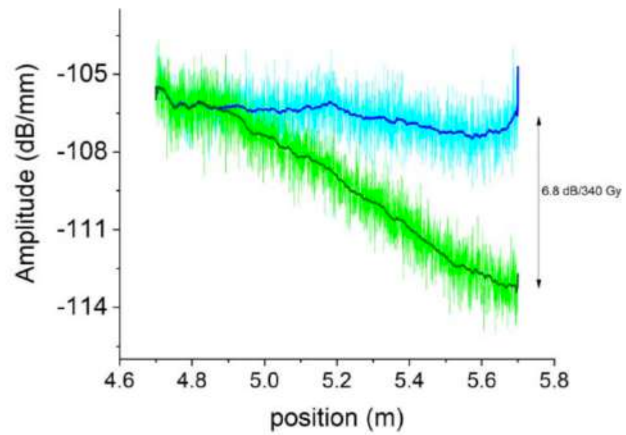
How to measure RIA?

By reflectometry in the frequency domain (OFDR)

Allows « high » spatial resolution along « short » fibers but only at selected NIR wawelength (around 1310, 1550 nm, C telecom band)



M. Olivero *et al.*,
IEEE Trans. Inst. Meas.
70, 7003909, 2021



- **Al-doped and Mg-doped NP fibers** (INPHYNI)
- Sensitivity = **20 dB km^{-1} Gy^{-1}** @1550nm
- **RIA,** as a function of the position along the fiber, given by the plot **derivatives**
- **Fiber lentgh:** a few meters (1 m here)
- **Spatial resolution**: < 10 μm for a 88 nm-scanning width around 1550 nm
- Also allows **« smooth » RIRIC** to be measured!
- Suitable for **medical applications**

2B – RADIATION-INDUCED EMISSION (RIE)

Adverse effects

Parasitic light produced *under exposure.* It may

- Be partly guided in fibers
- Mask weak signals
- Raise the noise floor (SNR lowering)
- Stimulate or quench emission in fiber amplifiers
- …

RL and Cerenkov equilibrium intensities proportional to the fluence rate

RL, Cerenkov ∝ Nb of particles $cm^{-2}\ s^{-1}$

VERY ROBUST PROPERTY

2B – RADIATION-INDUCED EMISSION (RIE)

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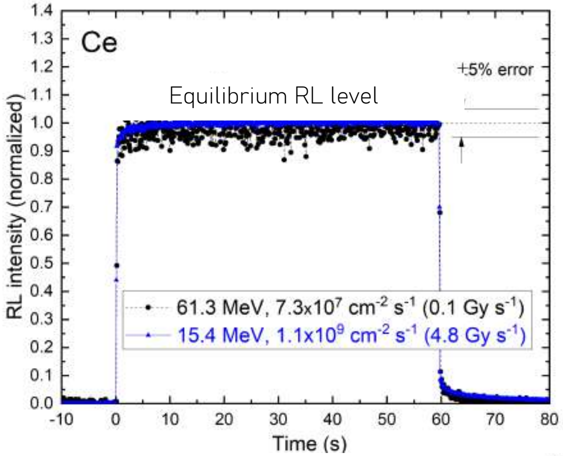
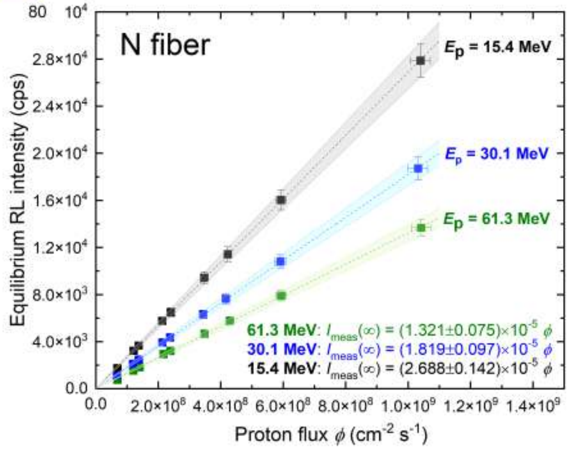
VERY ROBUST PROPERTY

Under protons (CAL-INPHYNI)



R&D proton beamline (max. 65 MeV, CAL Nice)

Examples:
Ce- and N-doped silica fibers



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2B – RADIATION-INDUCED EMISSION (RIE)

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- Stimulate or quench emission in fiber amplifiers
- ...

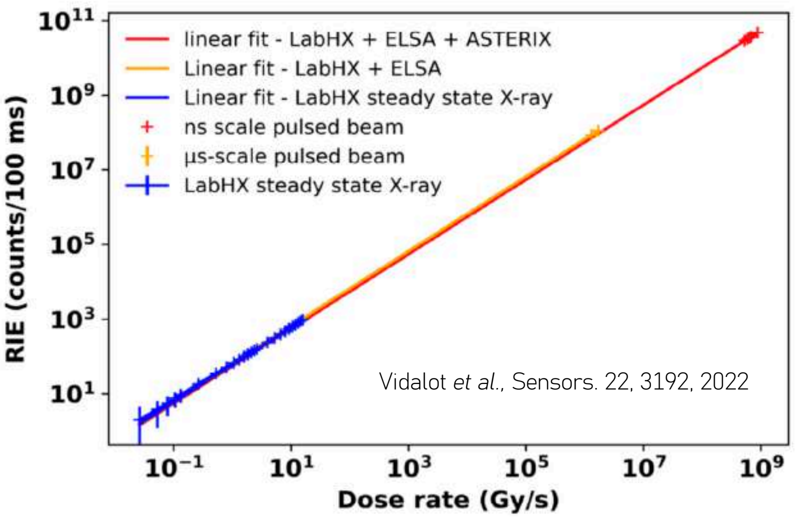
RL and Cerenkov equilibrium intensities proportional to the fluence rate

RL, Cerenkov ∝ Nb of particles cm^{-2} s^{-1}

VERY ROBUST PROPERTY

Under X rays (photons)

Dose rate proportional to fluence rate



Linearity over 10 decades, *at least*

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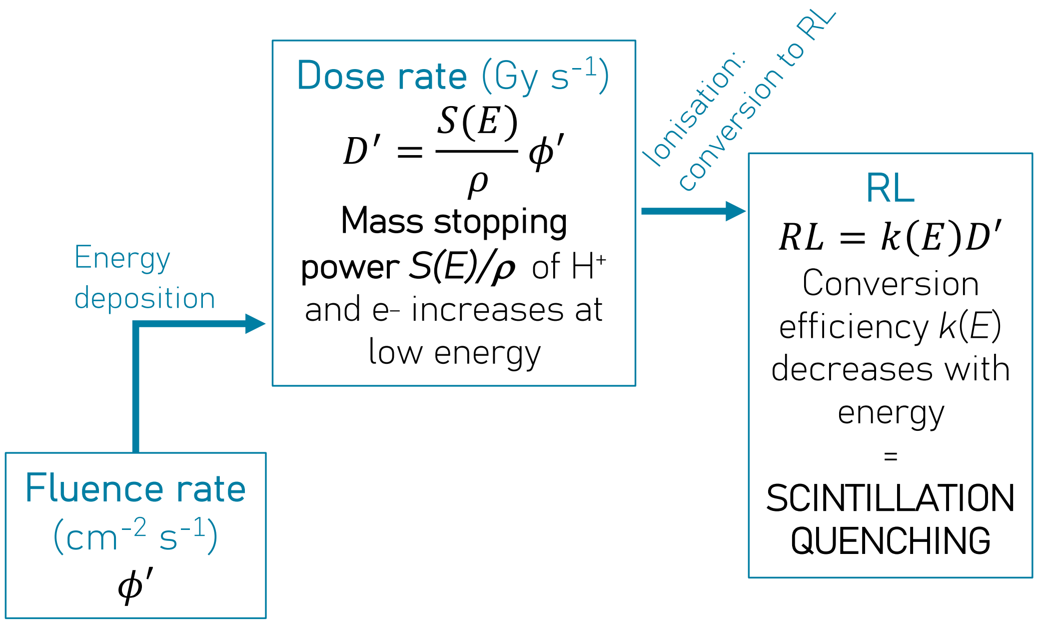
2B – RADIATION-INDUCED EMISSION (RIE)

Exploitable properties

Extended linearity
→ REALTIME «DOSIMETRY»

- Metrology of fluence rate ?
- Not directly the *dose rate*…
- Pb with measuring *dose* or *dose rate* **as a function of depth**

2B – RADIATION-INDUCED EMISSION (RIE)



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2B – RADIATION-INDUCED EMISSION (RIE)

Fluence rate (cm^{-2} s^{-1})
ϕ'

Energy deposition

Dose rate ($Gy\ s^{-1}$)

$$D' = \frac{S(E)}{\rho}\phi'$$

Mass stopping power $S(E)/\rho$ of H^+ and e- increases at low energy

Ionisation: conversion to RL

RL

$$RL = k(E)D'$$

Conversion efficiency $k(E)$ decreases with energy
=
SCINTILLATION QUENCHING

Dielectric excitation by charged particles

Cerenkov emission

$$CE = C(E)\phi'$$

CE–fluence rate coefficient $C(E)$ decreases with E (Frank-Tamm's formula)

Exploitable properties

Extended linearity
→ REALTIME «DOSIMETRY»

- Metrology of fluence rate ?
- Not directly the *dose rate*…
- Pb with measuring *dose* or *dose rate* as a function of depth

2B – RADIATION-INDUCED EMISSION (RIE)

- Cerenkov intensity **does not result from the absorbed dose rate**. Only provides a measure of the fluence rate of charged particles (above threshold), but with a decreasing in-depth sensitivity.

Exploitable properties

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2B – RADIATION-INDUCED EMISSION (RIE)

- Cerenkov intensity **does not result from the absorbed dose rate**. Only provides a measure of the fluence rate of charged particles (above threshold), but with a decreasing in-depth sensitivity.

- RL intensity: **a consequence of the absorbed dose rate.**
  - **Photons: penetrate the material at constant energy** (only their fluence decreases).

    → No depth dependence of the RL-dose rate coefficient (RL sensitivity)
  - **Protons are stopped:** their energy decreases as they penetrate the medium

    → RL sensitivity loss (scint. quenching)

Exploitable properties

Extended linearity

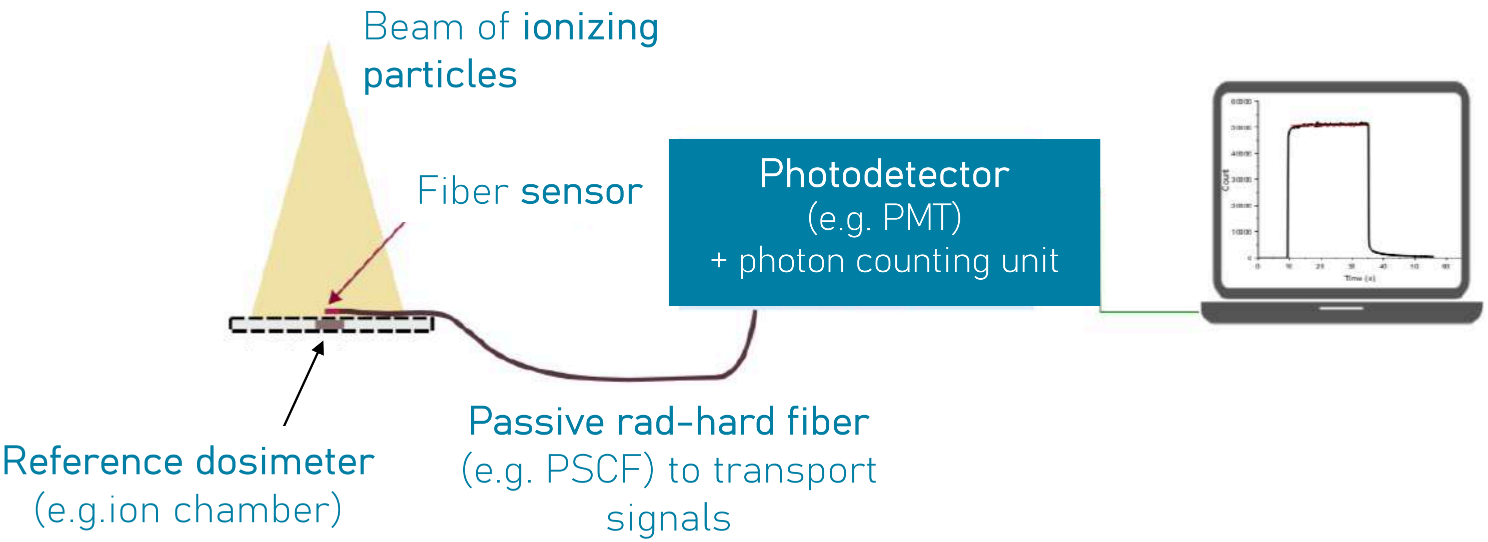
→ REALTIME «DOSIMETRY»

- Metrology of fluence rate ?
- Not directly the *dose rate*…
- Pb with measuring *dose* or *dose rate* **as a function of depth**

2B – RADIATION-INDUCED EMISSION (RIE)

How to measure RIE?

Very straightforward technique!



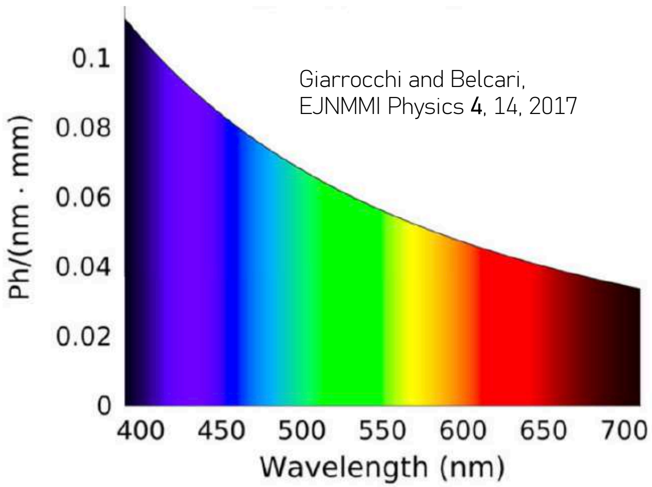
2B – RADIATION-INDUCED EMISSION (RIE)

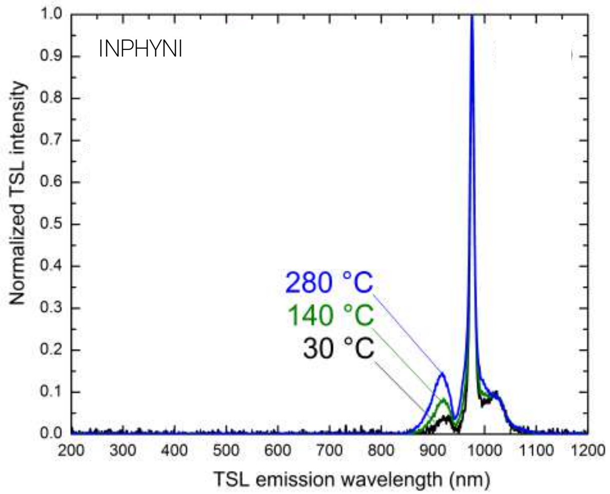
How to separate RL from Cerenkov light (when it does exist)?

- Spectral filtering

  Choose activator ions (dopants) that preferentially emit sharp lines in the NIR range (as Yb^{3+} ions), **well separated from the broad Cerenkov spectral range** (rather in the UV-blue).
  Then, use an **optical filter**.

  😫 Some Cerenkov light remains in the filtered signal…





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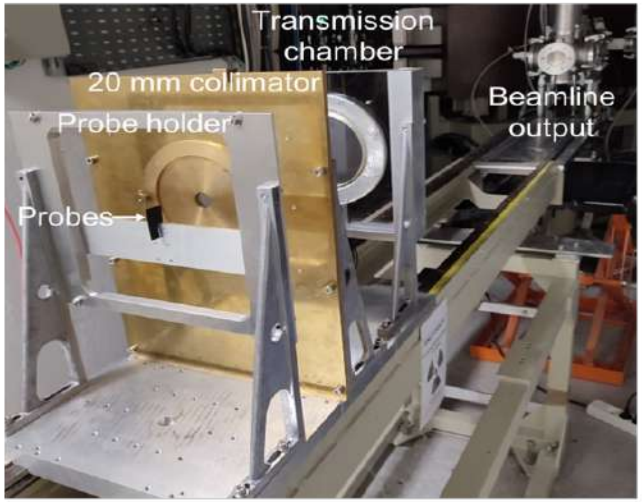
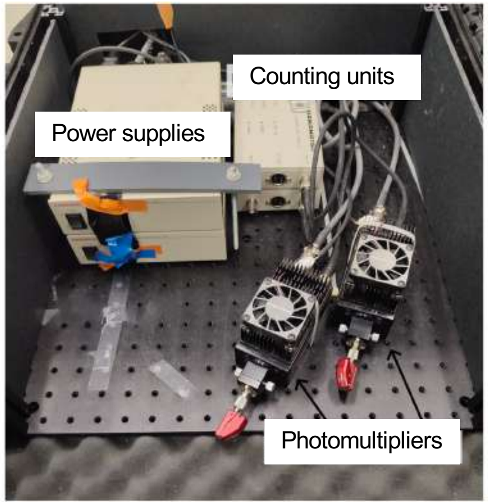
2B – RADIATION-INDUCED EMISSION (RIE)

How to separate RL from Cerenkov light (when it does exist)?

- Signal subtraction
  Use two acquisition channels in the same irradiation field: 1 with an RL activated sensor, the other with an undoped sensor that only measures the Cerenkov light.
  Then, **subtract** the two signals to remove the Cerenkov contribution.
  😫 The 2 measurement channels must be striclty identical + you also remove RL from matrix…





Marjorie GRANDVILLAIN PhD dissertation, INPHYNI-CAL
RL measurements under protons at CAL Nice, *FIDELIO Project*

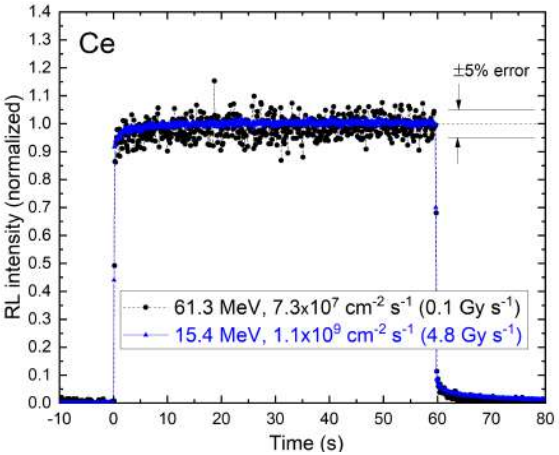
2B – RADIATION-INDUCED EMISSION (RIE)

How to separate RL from Cerenkov light (when it does exist)?

- Time gating in the time-resolved detection of pulsed irradiations
  - Cerenkov is **prompt**, appearing in ps to ns;
  - Inorganic RL has a long **transient growth (ms)** and **decays slowly (phosphorescence)**

  Using a **fast photodetector**, it is possible to detect the Cerenkov during the pulse and to **delay the RL measurement** after the prompt signal has faded.

😫 Requires an enhanced and very sensitive time-resolved detection + measures phosphorescence rather than RL.



Marjorie GRANDVILLAIN PhD dissertation, INPHYNI-CAL
RL under protons from a Ce-doped silica fibers

2C – RADIATION-INDUCED REFR. INDEX CHANGE (RIRIC)

Adverse effects

Opto-geomatrical parameters of the fibers can be modified

- Numerical aperture
→ Cutoff wavelength
→ Risk of fundamental mode loss

- Bragg wavelenght shift in FBG sensors

Increase with RIA and density, so a priori with the absorbed dose

Exploitable properties

→ Opportunities for DOSIMETRY

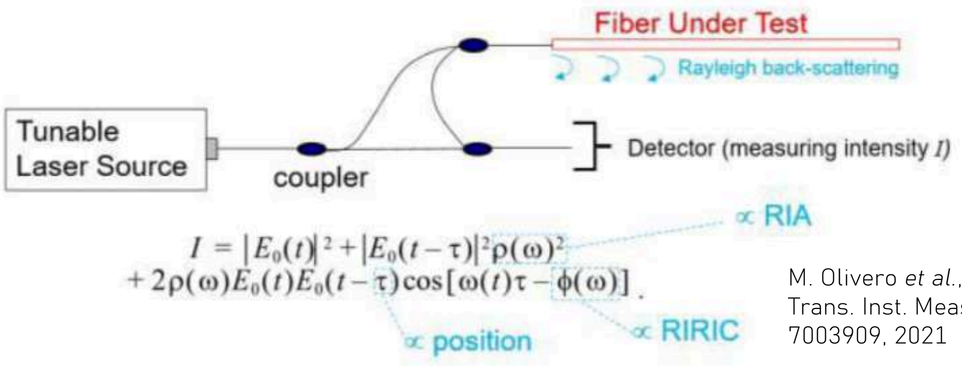
Difficulty under photons and low particle fluences, because RIRIC can be hard to measure

2C – RADIATION-INDUCED REFR. INDEX CHANGE (RIRIC)

How to measure RIRIC?

Most simple **realtime techniques** are the **reflectometry-based** ones, namely **OTDR** and **OFDR**.

- **OTDR** senses backscattered power, not directly phase or index.
  Only detects **large (> 10^{-3})** and **localized change** in the refractive index as, e.g., those causing Fresnel reflection.
- **OFDR** is a phase-resolved measurement technique, inherently sensitive to RIRIC. **Detects both sharp and smooth small changes in the refractive index**, with good spatial resolution.

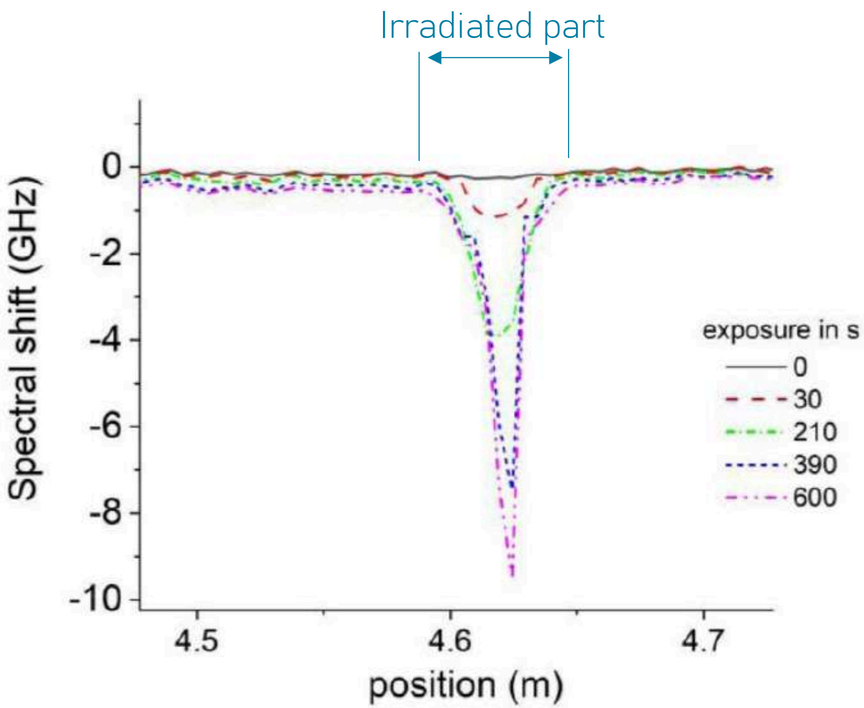


M. Olivero *et al.*,IEEE Trans. Inst. Meas. **70**, 7003909, 2021

Can also probe the RIRIC through the spatially-resolved **shift of the Rayleigh spectra**

2C – RADIATION-INDUCED REFR. INDEX CHANGE (RIRIC)

How to measure RIRIC?



Spectral shift of the Rayleigh spectrum along an Al-doped fiber under soft X rays @ 700 Gy min^{-1}

M. Olivero *et al.*,IEEE Trans. Inst. Meas. **70**, 7003909, 2021

→ One of the rare (unic?) examples of time- and spatially-resolved RIRIC monitoring under soft X rays (**weak RIRIC**), with high spatial resolution

→ Sensitivity to be improved to meet requirements of medical applications (dose level ~1 Gy).

3 ● SPACE APPLICATIONS

- RIA is the main issue
- Low dose rates
- Fibers should be « radiation-hardened »

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- RIA is the main issue
- Low dose rates
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3A – Silica-based fibers in space
3B - The space harsh environment
3C – Radiation hardening techniques (against RIA)
3D – How to take advantage of low dose rates in active fibers

3A – SILICA FIBERS IN SPACE

Mainly: active fibers: doped with Er, Yb, or co-doped ErYb (also Al, P)

- High-speed data transfer with high output-power lasers
  - Optical links (LEO-GEO, LEO-LEO, down link, up link)
  - Sensing, mapping (LIDAR: topography, detection)

- Fiber-optics gyroscopes (FOGs)
  - Erbium-doped fiber amplifier (broadband 1550 nm ASE source)

- Scientific instruments
  - Active spectrometers to Mars, Venus…
  - Stabilized lasers for space optical clocks
  - …

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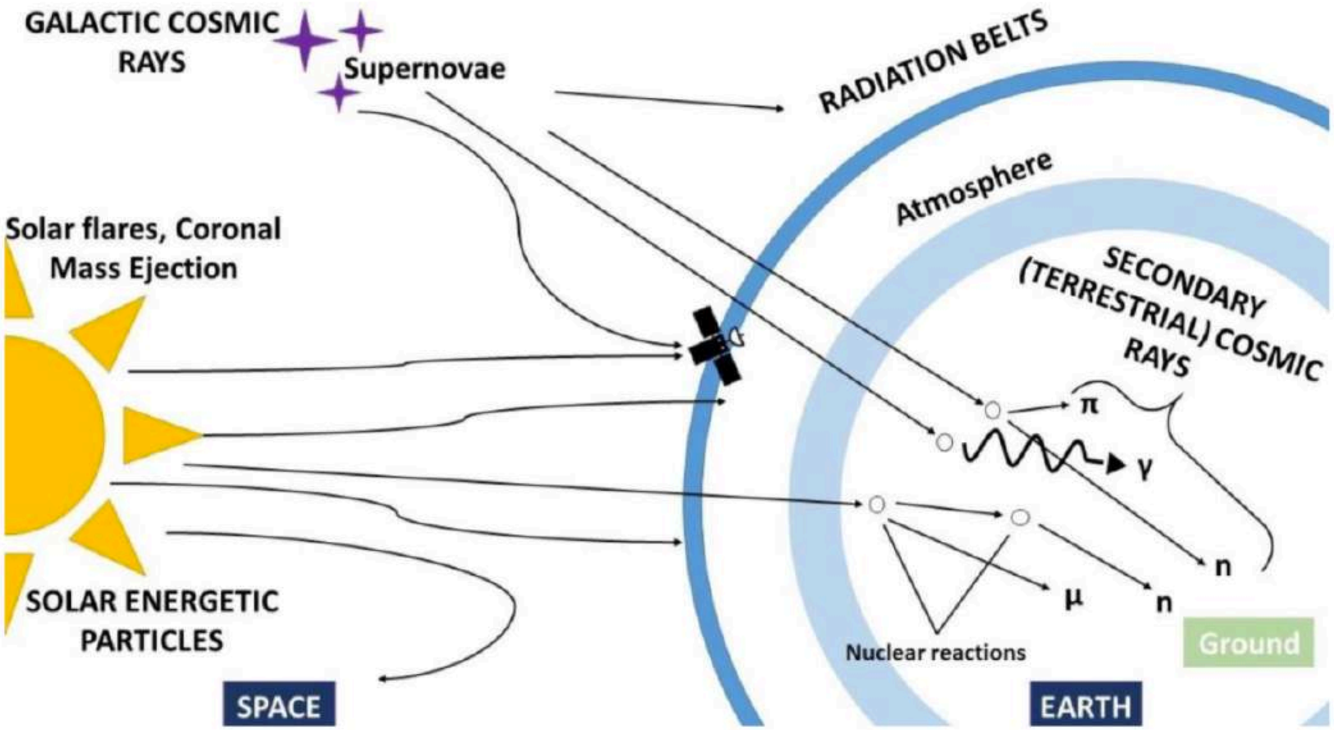
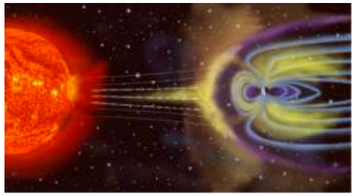
- Scientific instruments
  - Active spectrometers to Mars, Venus…
  - Stabilized lasers for space optical clocks
  - …

Passive fibers (Sagnac fibers in FOGs, signal or laser transport…)

3B – THE SPACE HARSH ENVIRONMENT





GCR
Protons (~87 %)
Alpha particles (~12 %)
Electrons and other heavy ions (~1%)
Up to a few GeV or even TeV per nucleon

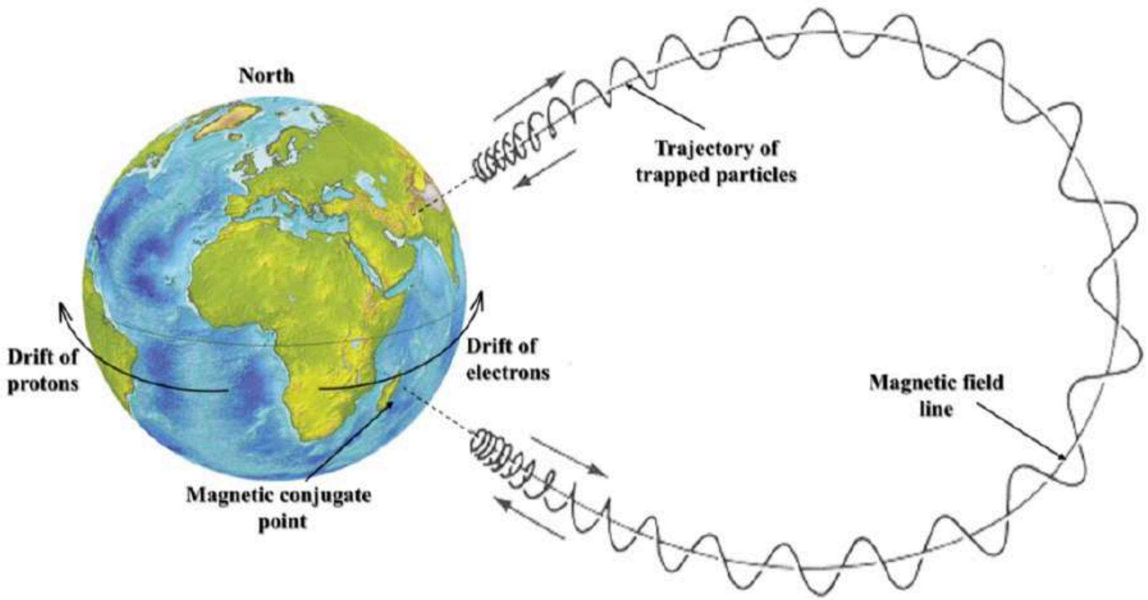
SEP
Protons
Alpha particles
Other heavy ions
From 10 to several hundreds of MeV

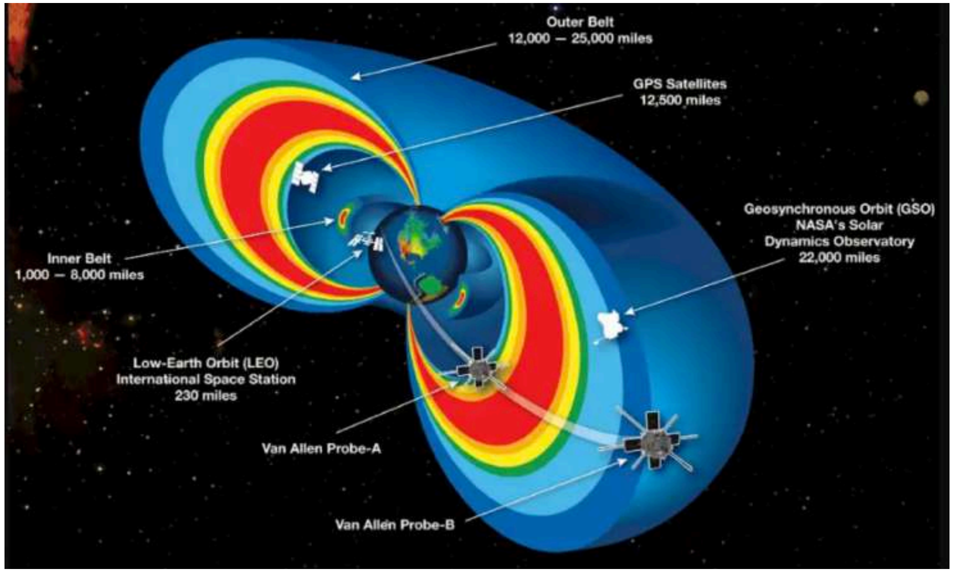
Energetic photons
Gamma rays (from nuclear reactions)
X rays (from stopping particles)
From keV to a few MeV

3B – THE SPACE HARSH ENVIRONMENT

For space applications (satellites)

→ Van Allen belts (protons and electrons trapped by the magnetic fied of Earth)





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For space applications (satellites)

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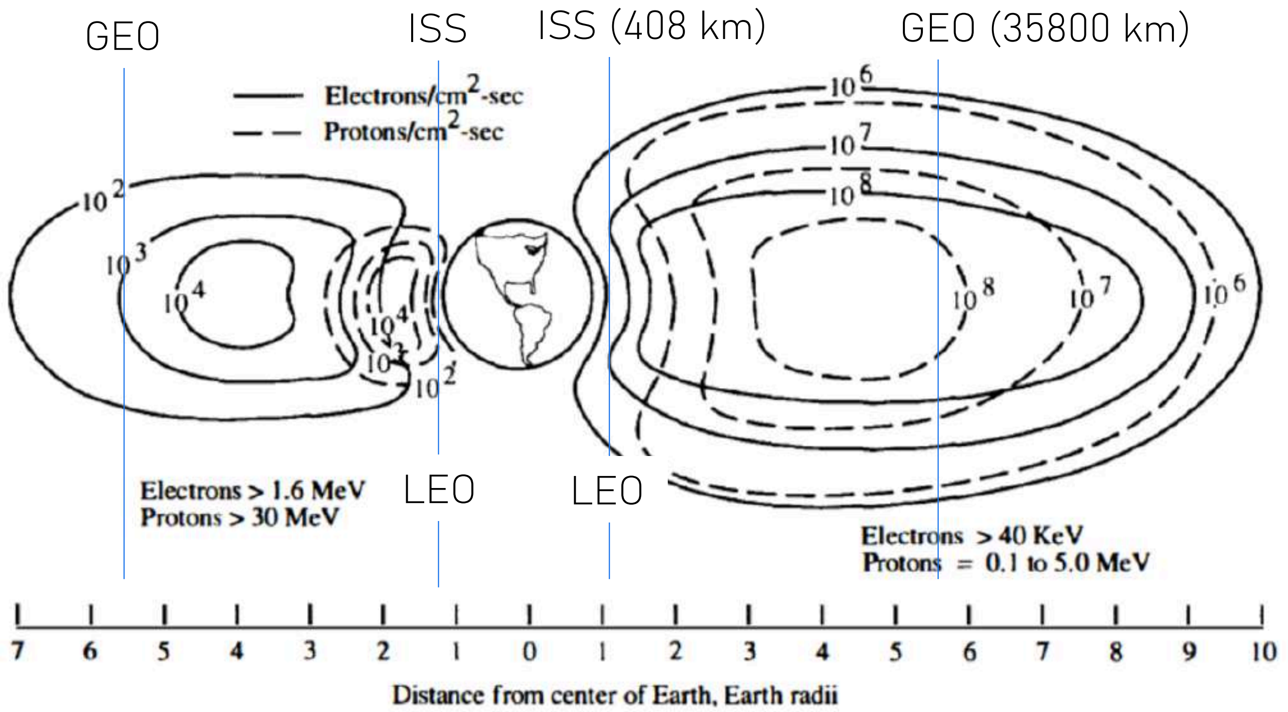


LEO

High energy protons

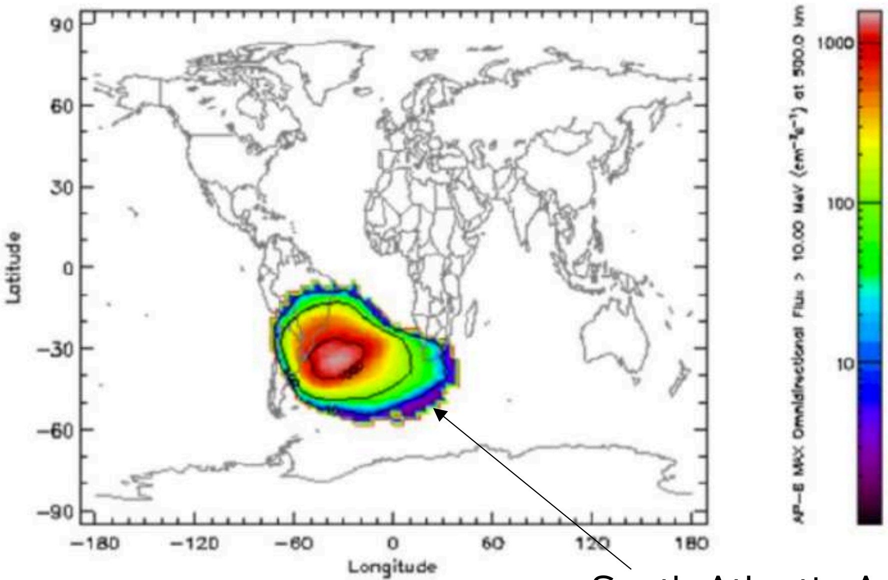
Low energy electrons

3B – THE SPACE HARSH ENVIRONMENT

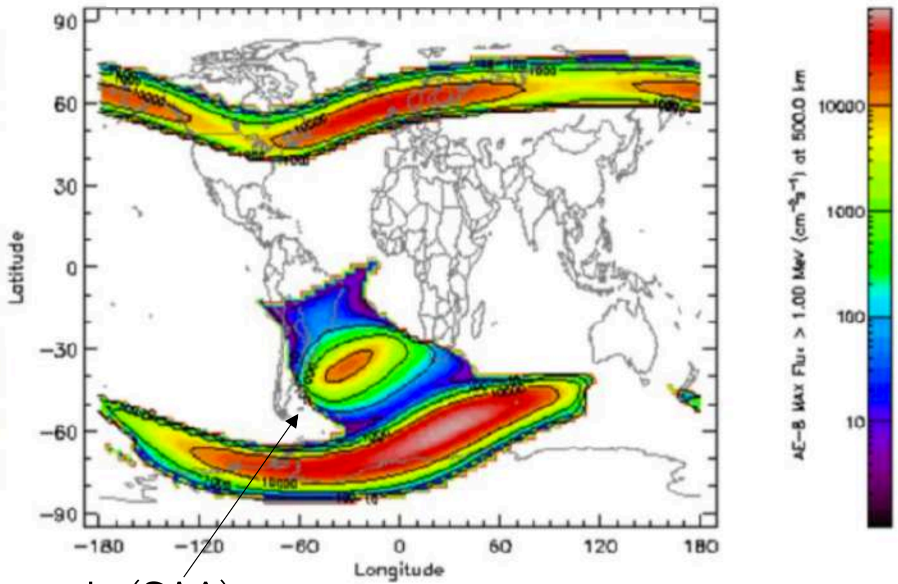
For space applications (satellites)

→ Fluence rates depend on the strength of the magnetic field (SAA)

Proton flux > 10 MeV @500 km



Electron flux > 1 MeV @500 km



South Atlantic Anomaly (SAA)
Weaker magnetic field
(axis is tilted 11° vs rotation axis)

3B – THE SPACE HARSH ENVIRONMENT

Typical dose rate and dose over a mission

Dose rate by charged particles $D' = \frac{S(E)}{\rho}\phi'$ i.e.

$$D'(\text{Gy h}^{-1}) = 5.77\times10^{-7}\times\frac{S(E)}{\rho}(\text{MeV cm}^2\text{ g}^{-1})\times\phi'(\text{cm}^{-2}\text{s}^{-1})$$

Orbit	Proton energy (MeV)	Stop. Power silica (MeV cm^{-1})	Flux (cm^{-2} s^{-1})	Dose rate @max. flux (Gy h^{-1})	15-year DOSE @max. flux (Gy)
LEO	< 500	> 2.302	< 10^4	**> 0.013**	1700
GEO	< 5	> 61.76	< 10^8	**> 3562**	4.7×10^8

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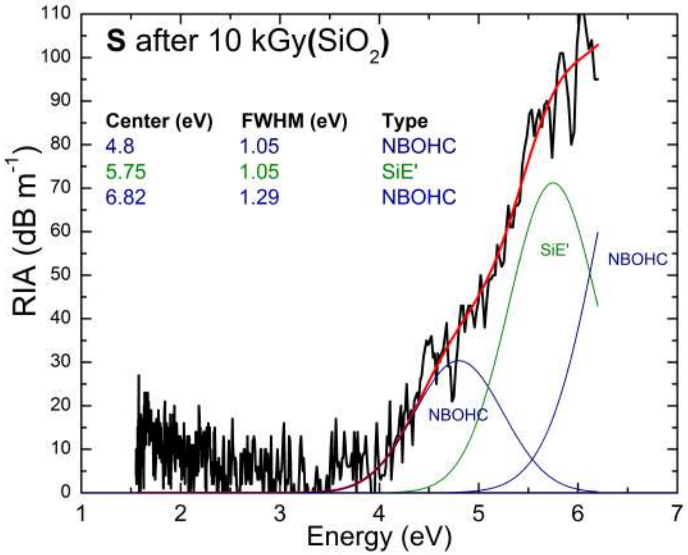
Usually considered values: $10^{-6} < D' < 10^{-3}$ Gy h^{-1} and $1 < D_{15y} < 10^3$ Gy
Depends on orbit, shielding, solar events…

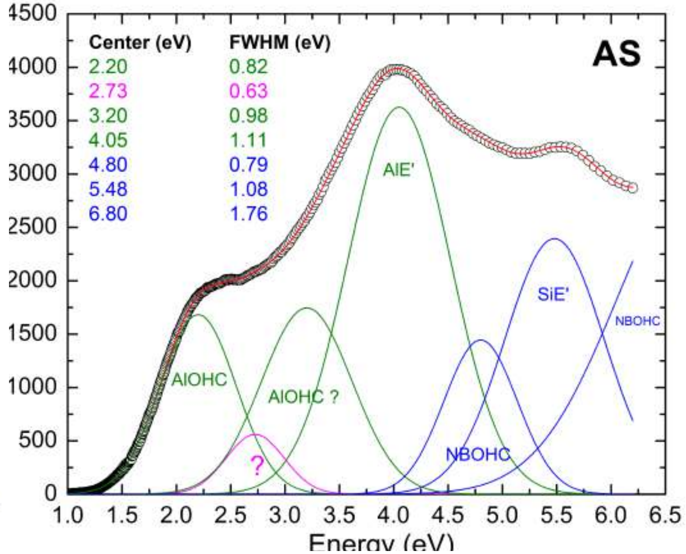
3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by component

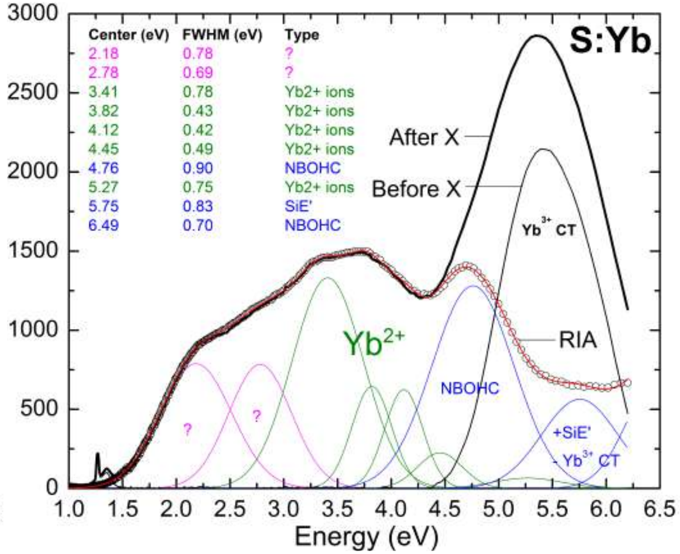
« Pure » (undoped) silica very resistant to RIA



Undoped silica
after 10 kGy



Al-doped silica (0.5 wt%)
after 10 kGy



Yb-doped silica (1.2 wt%)
after 10 kGy

F. Mady *et al.*, Opt. Mat. Express **9**, 2466, 2019

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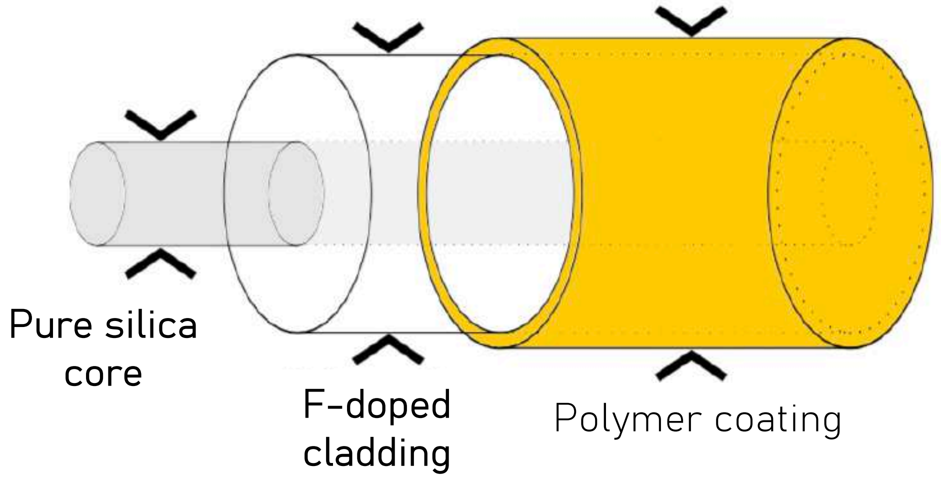
3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by component

- Pure silica core fibers (PSCF) can serve as **rad-hard passive fibers**



Note:
Also works if the core is F-doped

- The level of radiation-hardening depends on the operating spectral range and on impurities (Cl, OH groups: 'wet' vs 'dry' silica).

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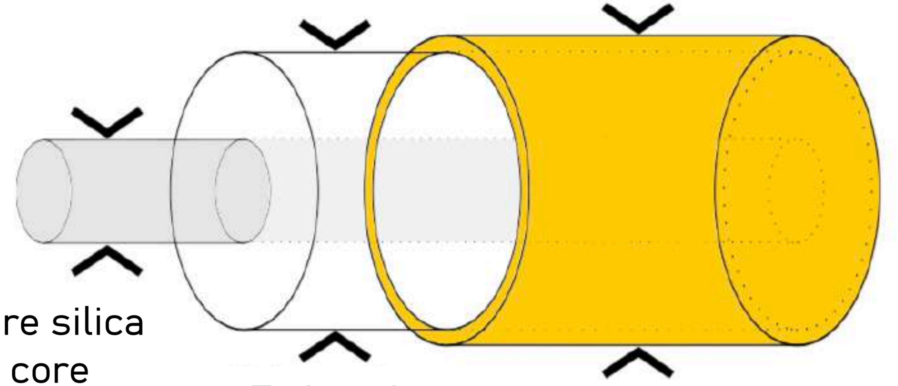

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What about **active fibers**?

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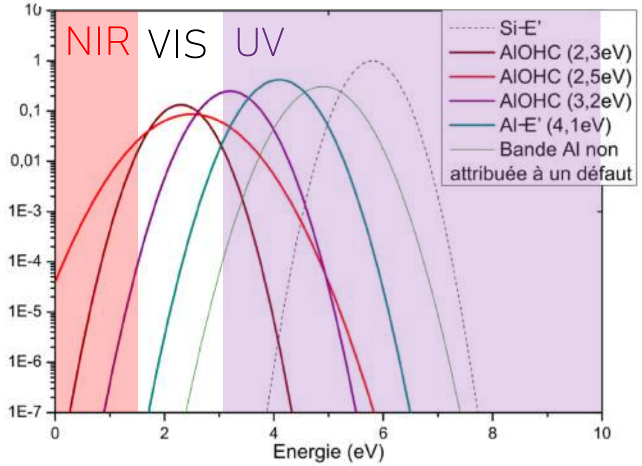
3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by component

Active fibers (Er- or/and Yb-doped)

- Most often contain Al which induces RIA in the NIR region because of broad **Al-OHC absorption bands** peaking at 3.2 eV (**388 nm**) and 2.3 eV (**539 nm**).

Al-related OA bands



3C – RADIATION-HARDENING TECHNIQUES (against RIA)

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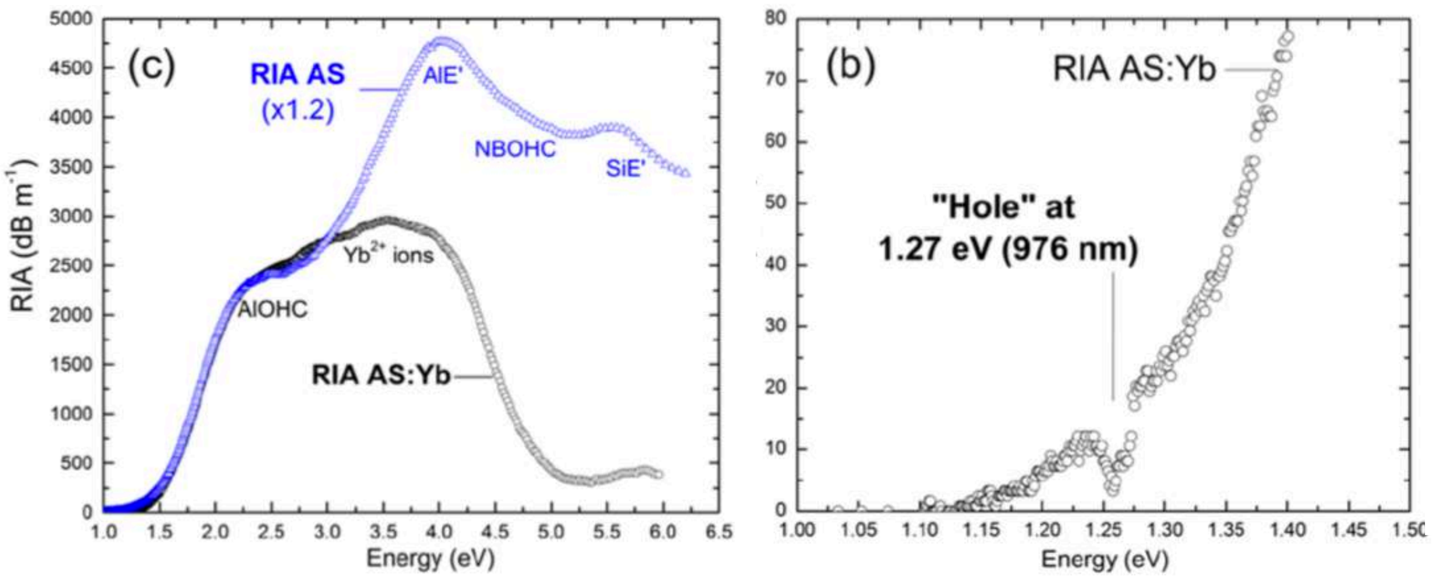


Yb,Al-doped silica (3;0.6 wt%)
after 10 kGy

F. Mady *et al.*, Opt. Mat. Express **9**, 2466, 2019

- Yb strongly suppresses AlE' centers at constant [Al-OHC]
- Electrons are rather captured by Yb^{3+} (then reduced into Yb^{2+} ions)

3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by component

Hardening of active fibers by cerium co-doping

An « **old empirical recipe** » (J.S. Stroud, J. Chem. Phys. **37**, 836, 1962)

The twofold benefit of Ce doping

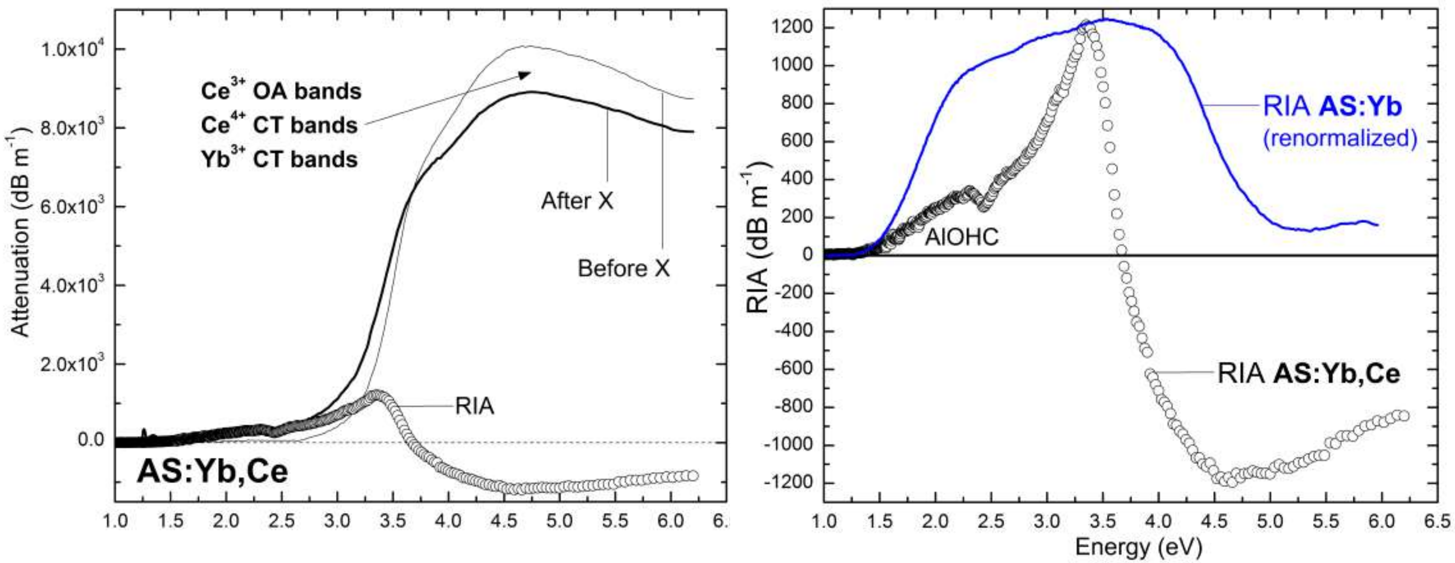
→ Strongly **reduces the NIR RIA** under irradiation (density of Al-OHCs)

→ Accelerates post-irradiation recovery of the optical absorption
(fast RIA decay @RT)

3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by component

Hardening of active fibers by <u>cerium co-doping</u>



Yb,Al,Ce-doped silica (1.5;1.3;1 wt%) after 10 kGy

F. Mady *et al.*, Opt. Mat. Express **9**, 2466, 2019

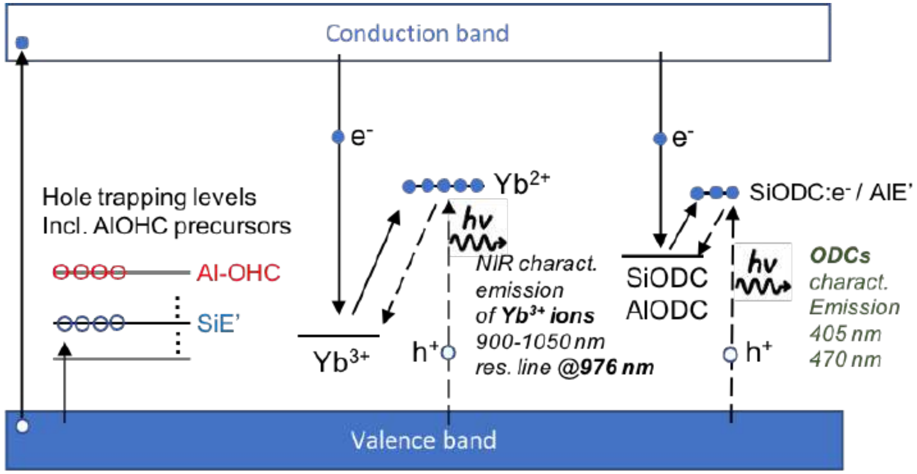
- Ce^{3+} ions disappear under irradiation.
- At similar [Yb^{2+} ions] formed, much less Al-OHC
- Holes rather captured by Ce^{3+} ions (then Ce^{4+})

3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by component

Hardening of active fibers by cerium co-doping

F. Mady *et al.*, Opt. Mat. Express **9**, 2466, 2019



Degradation:

- Electron trapping forms stable Yb^{2+} ions
- Hole trapping forms SiE', Al-OHC…

Annealing: Thermally released holes recombine with electrons in Yb^{2+} ions, reforming Yb^{3+} ions

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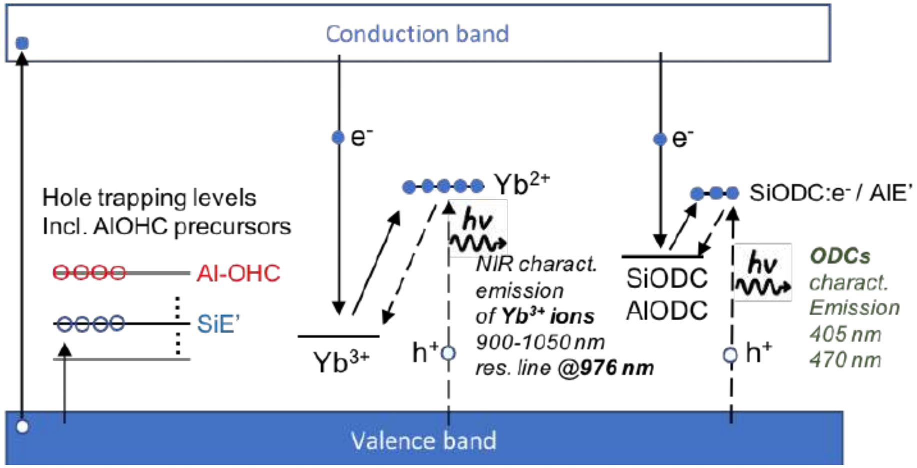

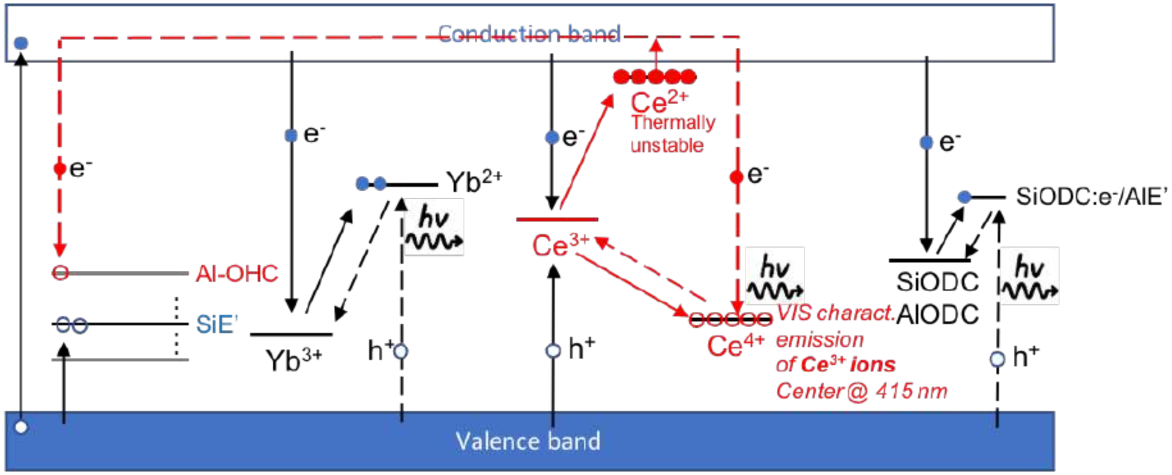

Degradation:

- Electron trapping forms stable Yb^{2+} ions
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Degradation: as before + amphoteric trapping at Ce^{3+} ions

- Ce^{4+} ions are formed instead of Al-OHC
- Highly unstable Ce^{2+} are formed instead of stable Yb^{2+}

Annealing: as before + detrapped electrons recombine to Al-OHC (swift post-irrad. decay) and to Ce^{2+}, reforming Ce^{3+}

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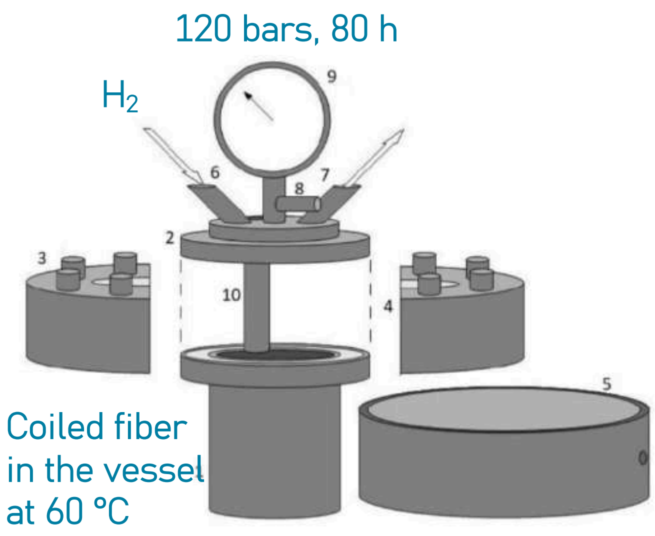
3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by pre-treatment

Loading fibers (PSCF mainly) with H_2 or D_2

→ Reduces precursor sites for the formation of *certain* color centers



C. Campanella, PhD dissertation, 2022

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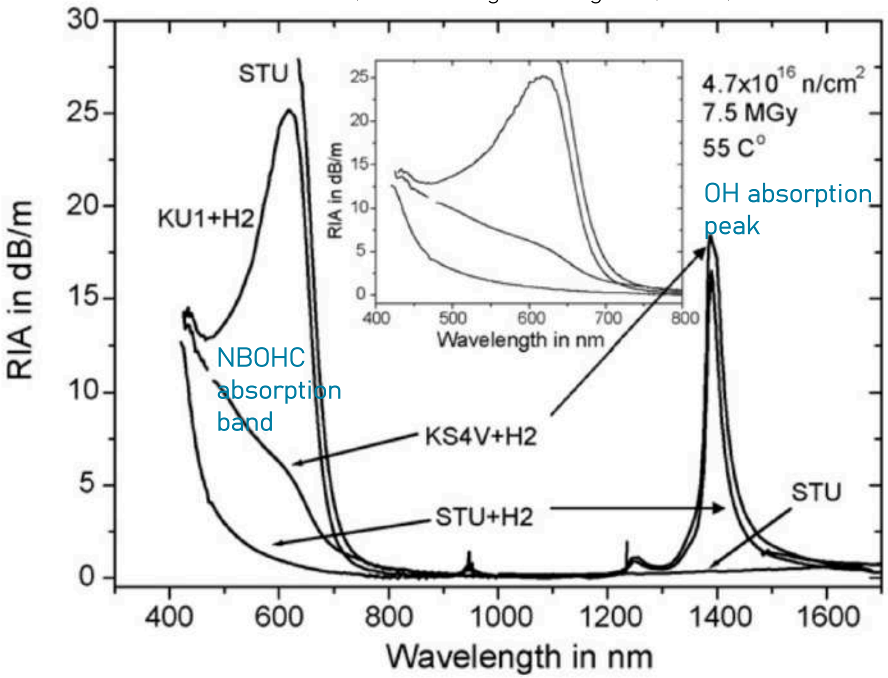
3C – RADIATION-HARDENING TECHNIQUES (against RIA)

Hardening by pre-treatment

B. Brichard *et al.*, Fusion Engin. Design **82**, 2451, 2007



Main benefit

Reduces the visible RIA due to **NBOHC**, around **610 nm**

$$2\ Si{-}O\bullet + H_2 \rightarrow 2\ Si{-}O{-}H$$

NBOHC — Hydroxyl termination

Main drawbacks

- Hydroxyl groups increase **optical absoprtion in the NIR range**
- H-related defects H(I) and H(II) **absorb in the UV region**
- **Transient benefit**: hydrogen out-diffuse within a few days
- **Carbon or metal coating** required to significantly extend this period

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3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Active fibers (fiber amplifiers, lasers) are pumped during operation!

- **Yb-doped fibers:** pump responsible for **photo-darkening (PD)**
  - Cooperative de-excitation of 3 Yb^{3+} ions (UV) absorbed in the first CT band of another Yb^{3+} ion → Yb^{2+} ion + trapped hole (Al-OHC) (F. Mady *et al.*, AIP Conf. Proc. **1624**, 87, 2014)
  - Trapped hole centers **are the same as those induced by ionizing radiation** (F. Mady *et al.*, Opt. Lett. **35**, 3541, 2010)
  - Radiation-induced and pump-induced effects can compete…

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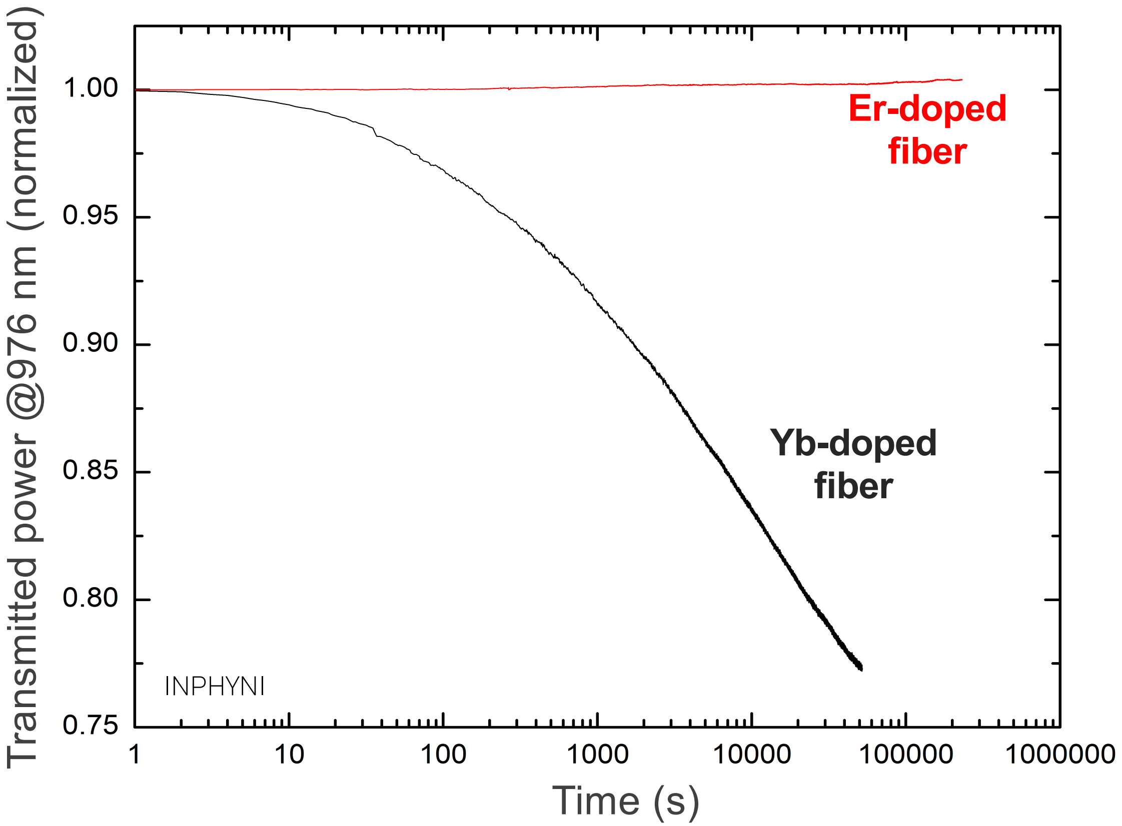
  - Trapped hole centers **are the same as those induced by ionizing radiation** (F. Mady *et al.*, Opt. Lett. **35**, 3541, 2010)
  - Radiation-induced and pump-induced effects can compete…

- **Er-doped fibers:** no significant PD reported
  - The pump can only « bleach » radio-induced darkening

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

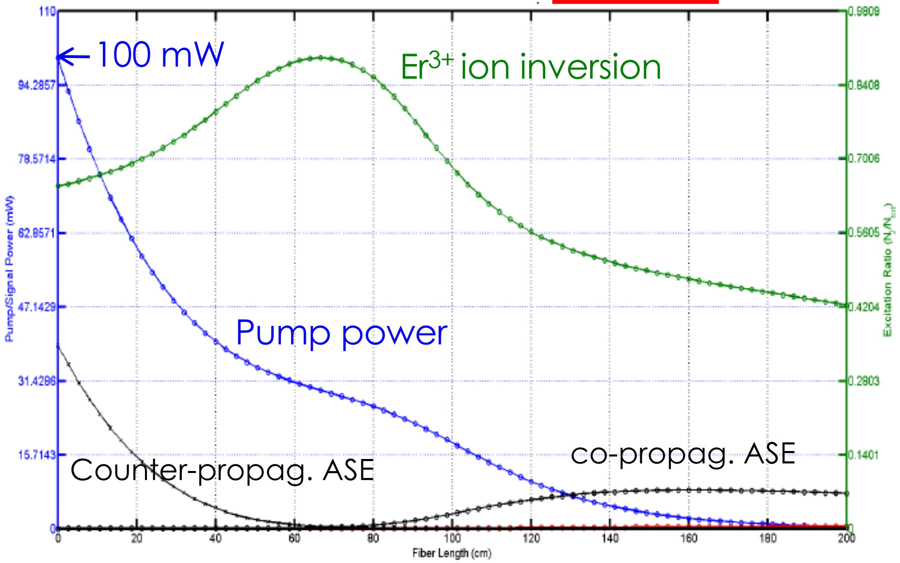
Active fibers (fiber amplifiers, lasers) are pumped during operation!



3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Proper characterization of pump effects: short fiber pieces!

Er fiber, $P_{p\ launched}$ = 100 mW L = 2 m



Inhomogeneous pump power
→ Iimpact on the RIA depending on *L*…

No intrinsic characterization of 'physics'

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3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

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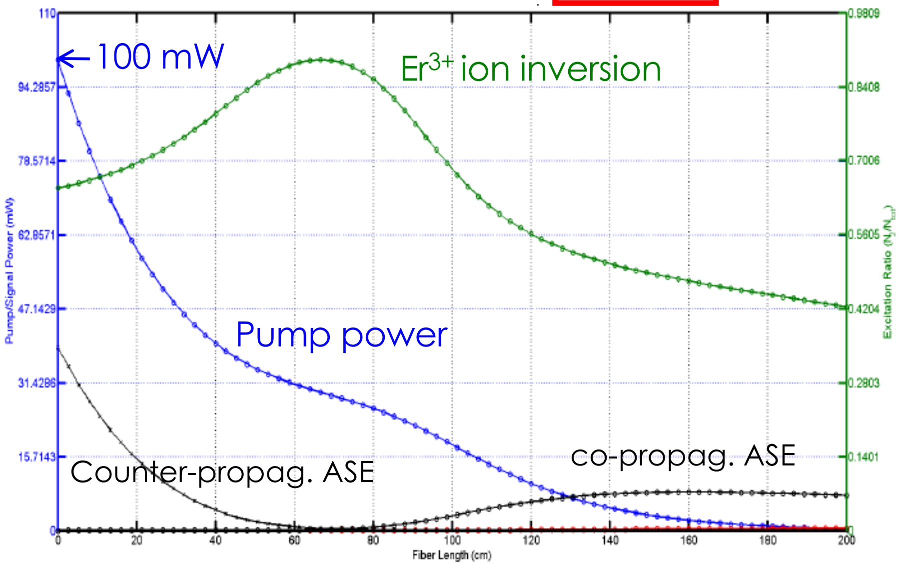

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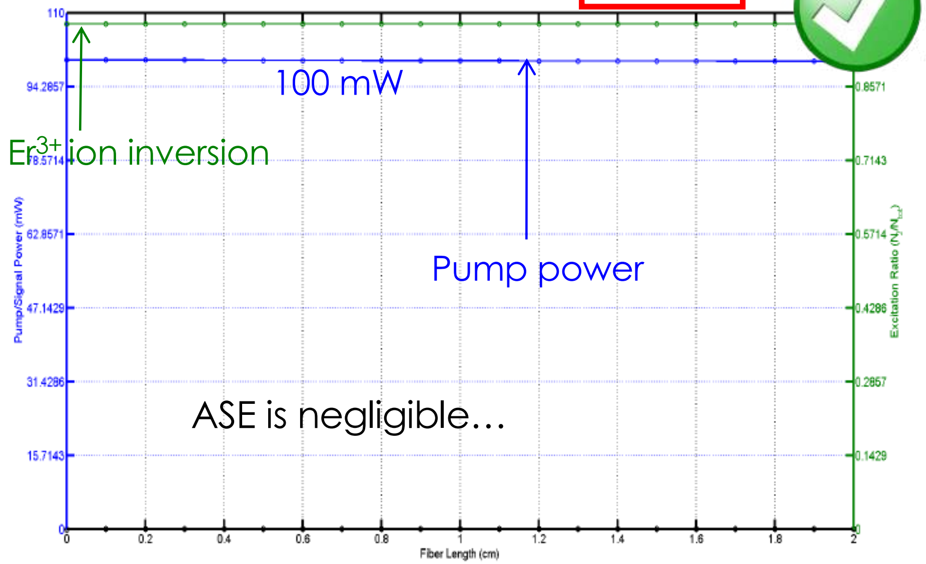


Homogeneous pump power and inversion

Pump-induced effets fully characterized by the well-controled launched power

Intrinsic characterization of the pump power effect

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Proper characterization of pump effects: short fiber pieces!

- Both pump power and dose rate can be varied during experiments
- Realtime monitoring of the dose rate and cumulated dose

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

« Home made » and commercial samples

	Er-doped fibers	Yb-doped fibers
Fibers made at INPHYNI, Nice (MCVD + solution doping)	M04 $[Er^{3+}]$ = 2,8 x 10^{19} cm^{-3} 72 dB m^{-1} @ 1530 nm	K10 $[Yb^{3+}]$ = 4,5 x 10^{19} cm^{-3} 575 dB m^{-1} @ 976 nm
Commercial fibers « COTS »	Er80 (Liekki) $[Er^{3+}]$ = 3 x 10^{19} cm^{-3} 80 dB m^{-1} @ 1530 nm	Yb1200 (Liekki) $[Yb^{3+}]$ = 9,4 x 10^{19} cm^{-3} 1200 dB m^{-1} @ 976 nm

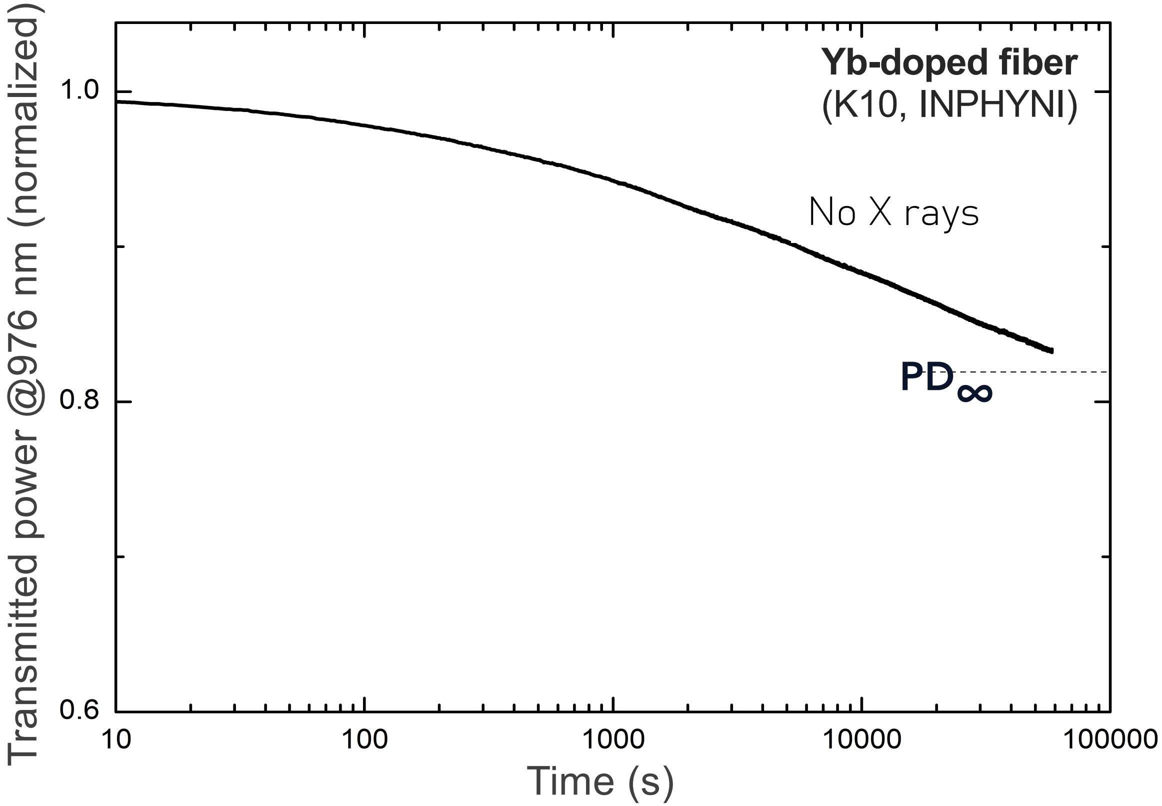
INPHYNI samples: aluminosilicate matrix with [Al] ≈ 1 wt. %

Commercial samples: undisclosed composition (Yb1200 contains Ce)

Both « home-made » and COTS fibers behave exactly in the same way

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Pure photo-darkening in Yb-doped fibers (pump only)

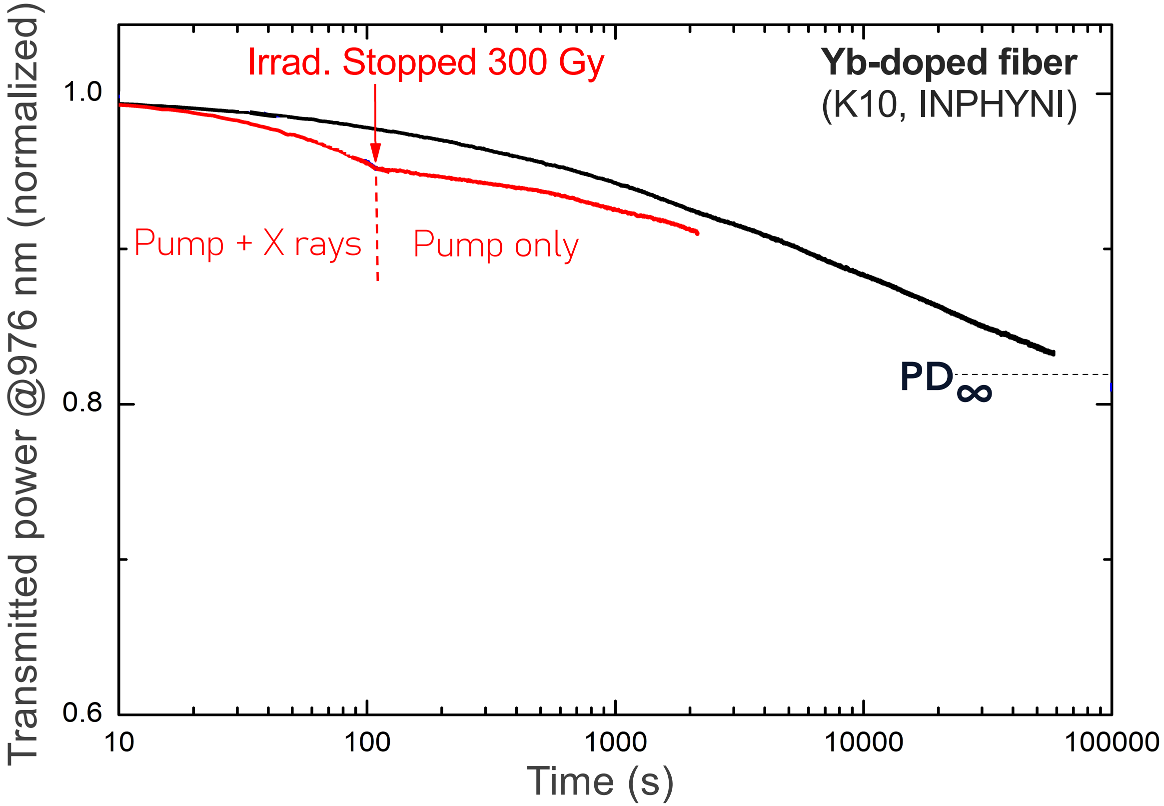


Strong PD for Yb fibers

Transmission decays towards an equilibrium level PD_∞ ~ 0.82 here

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Role of the pump (976 nm) under X rays



- Increased degradation rate
- Irradiation stops before PD_∞ is reached → The pump continues to photodarken the fiber towards PD_∞

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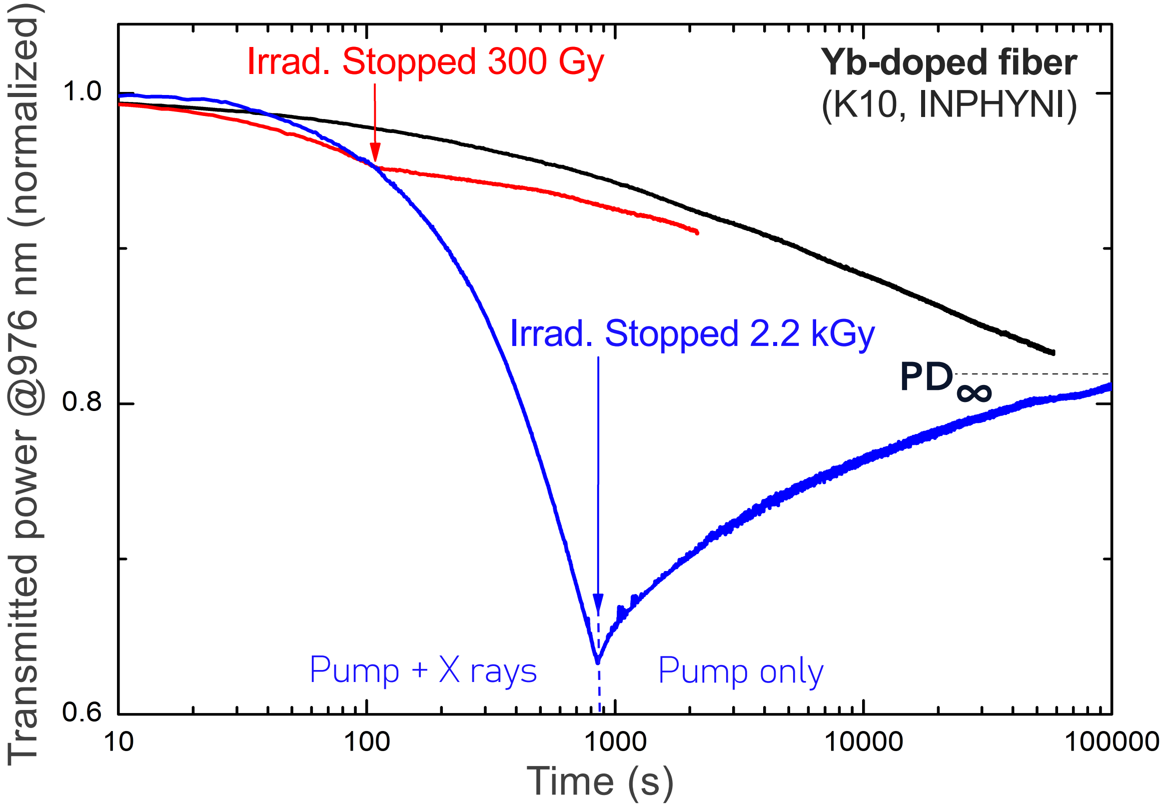
3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Role of the pump (976 nm) under X rays



- Increased degradation rate
- Irradiation stops before PD_∞ is reached → The pump continues to photodarken the fiber towards PD_∞
- Irradiation stops after PD_∞ is excedeed → The pump bleaches the fiber towards PD_∞

PhotoBleaching = PB

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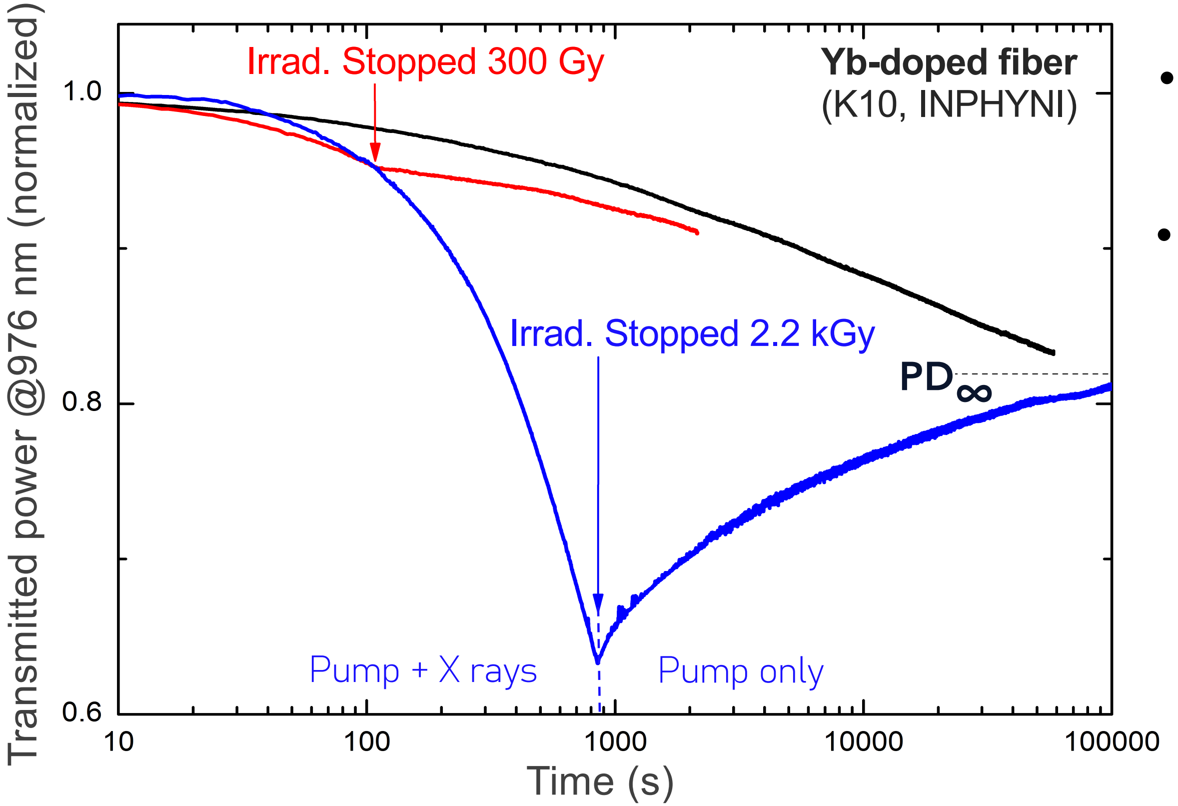
3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

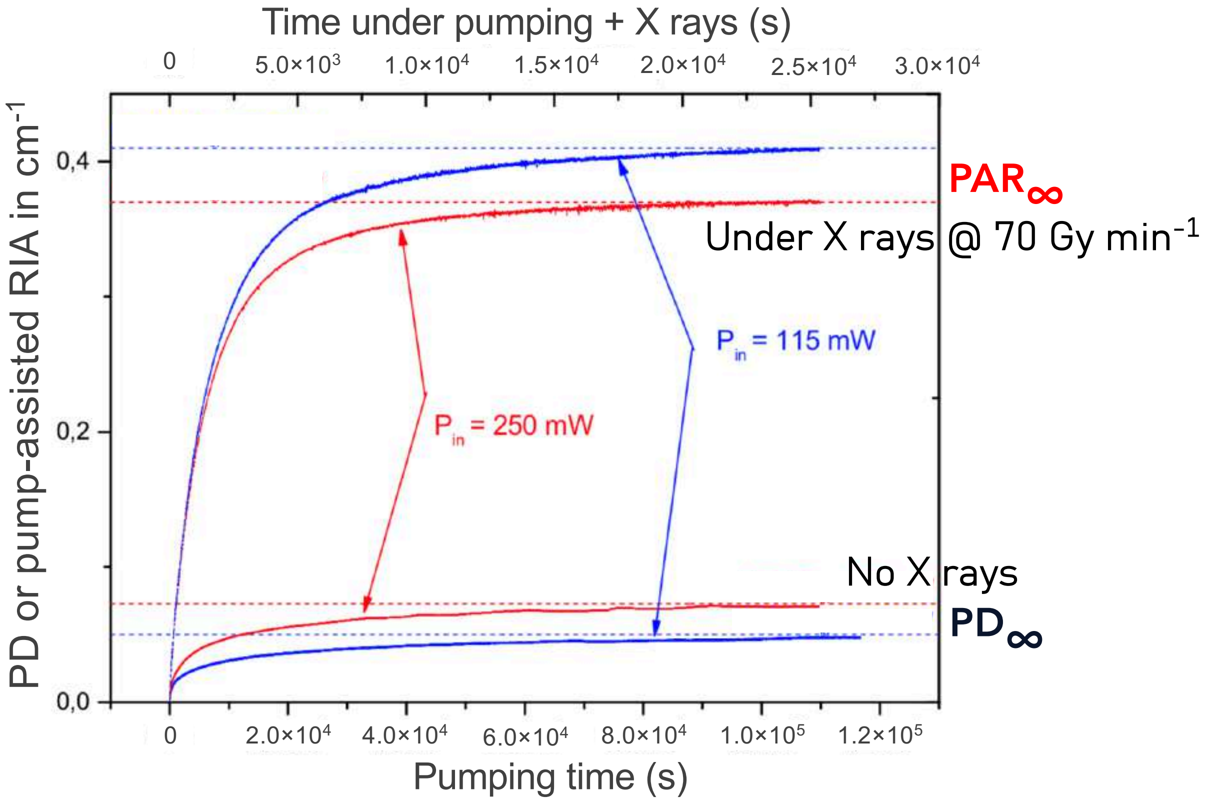
Role of the pump (976 nm) under X rays



- The pump, *responsible for PD*, can also be a **mitigation agent against RIA** !
- PD + PB → PD_{∞} is well an equilibrium level, *not saturation*

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Role of the pump (976 nm) under X rays



Pump + Irradiation:

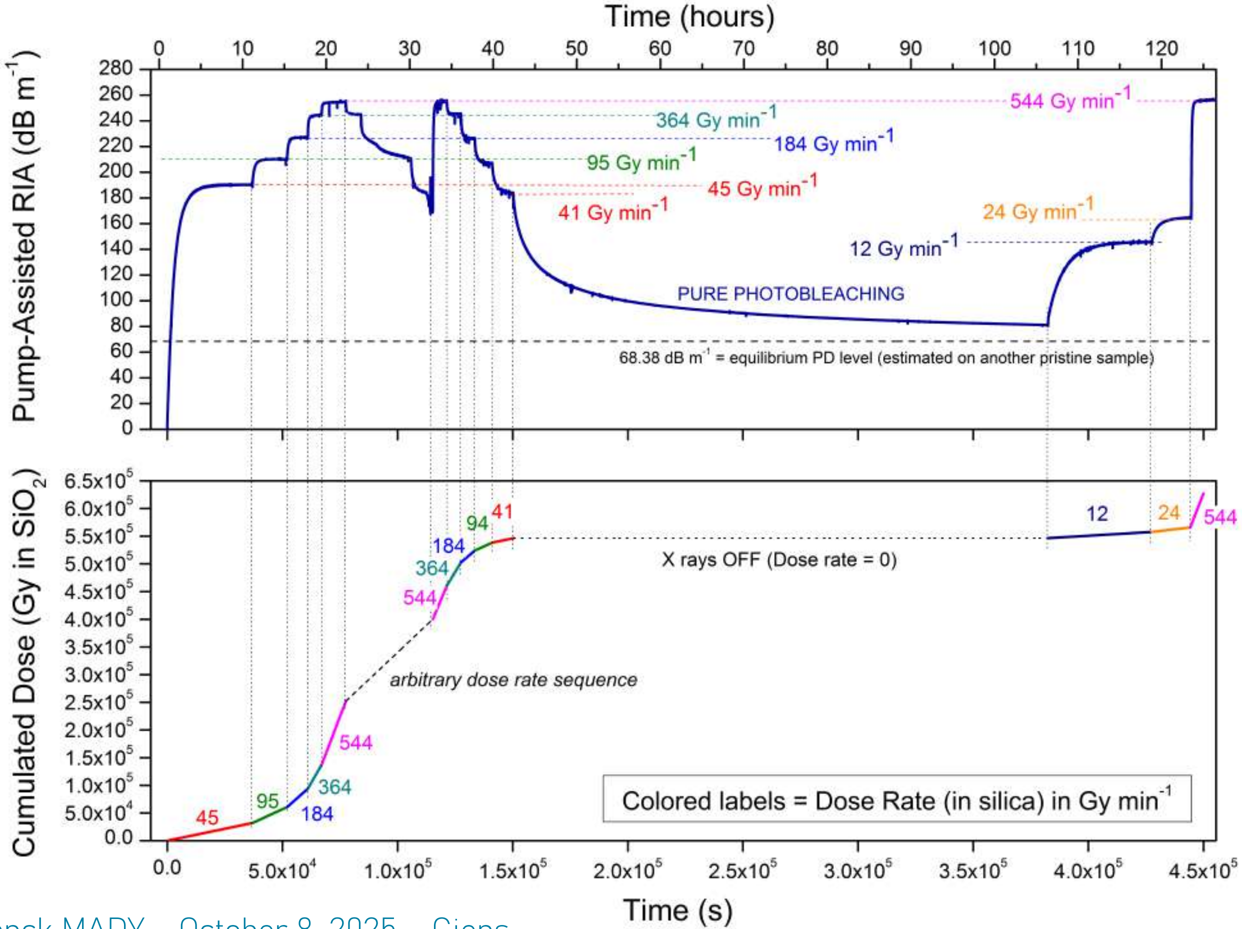
- RIA balanced by pump-induced PB

→ Equilibrium level of the « Pump-Assisted-RIA » (PAR)

- PAR_∞ decreases when Pp increases (increased power → increased PB)

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Equilibrium degradation levels in Yb-doped fibers



Continuous experiment > 130 h on a single **Yb fiber sample** (INPHYNI K10, L = 2 cm)

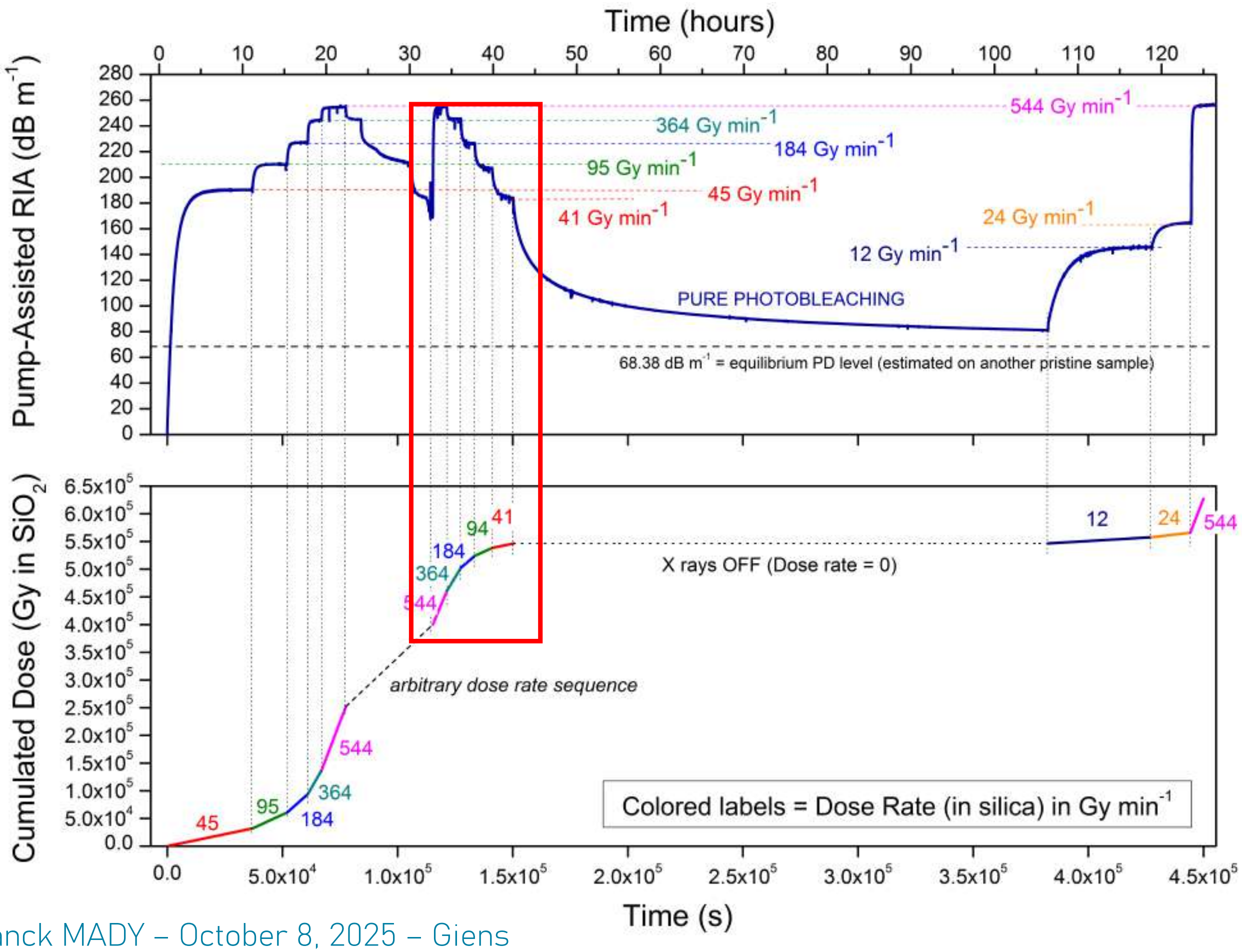
Total cumulated dose > 640 kGy

Constant P_p (368 mW) but dose rate switched as soon as a PAR_∞ is reached

Identical experiments done where pump power is switched at fixed dose rate

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Equilibrium degradation levels in Yb-doped fibers



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Total cumulated dose > 640 kGy

Constant P_p (368 mW) but dose rate switched as soon as a PAR_∞ is reached

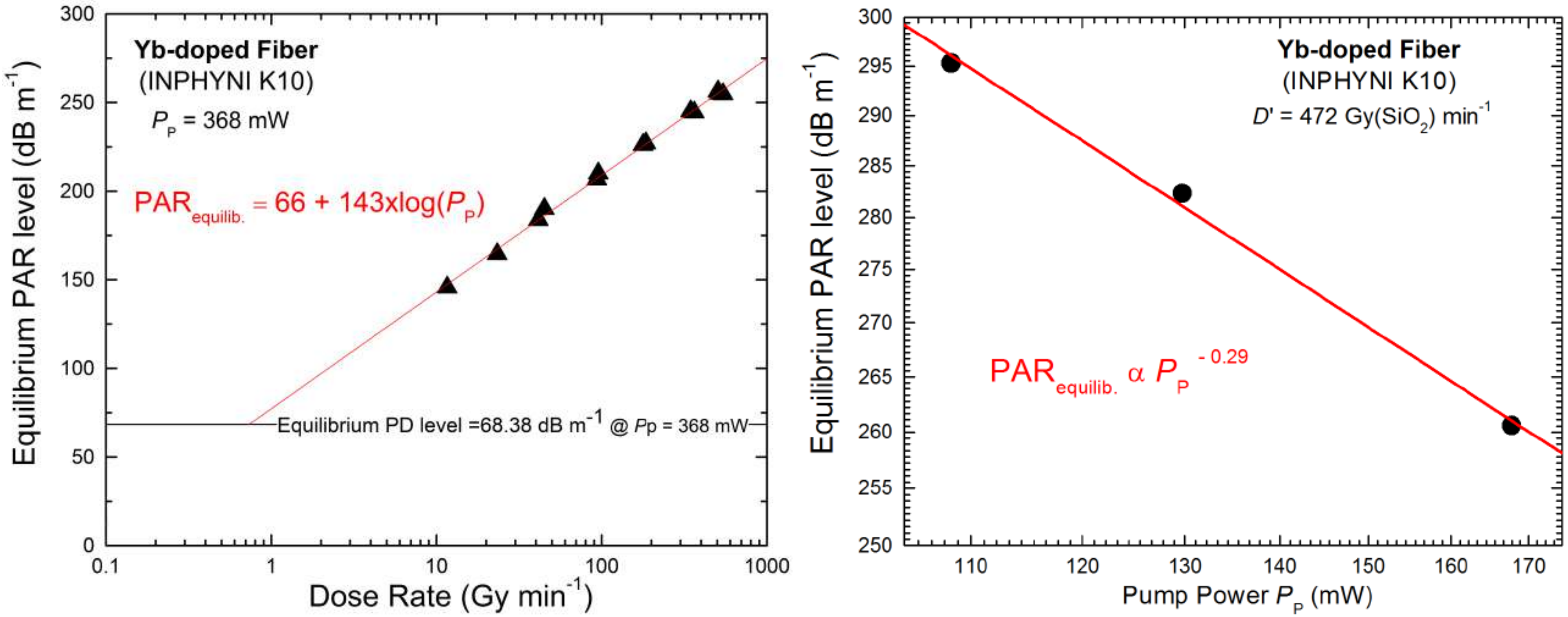
Identical experiments done where pump power is switched at fixed dose rate

Local equilibrium PAR_∞ levels **are:**

- **Reversible, tunable**
  Degradation can decrease while the dose is increased!
- **Determined by the dose rate/pump power**
  Not by the irradiation history or the cumulated dose!

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

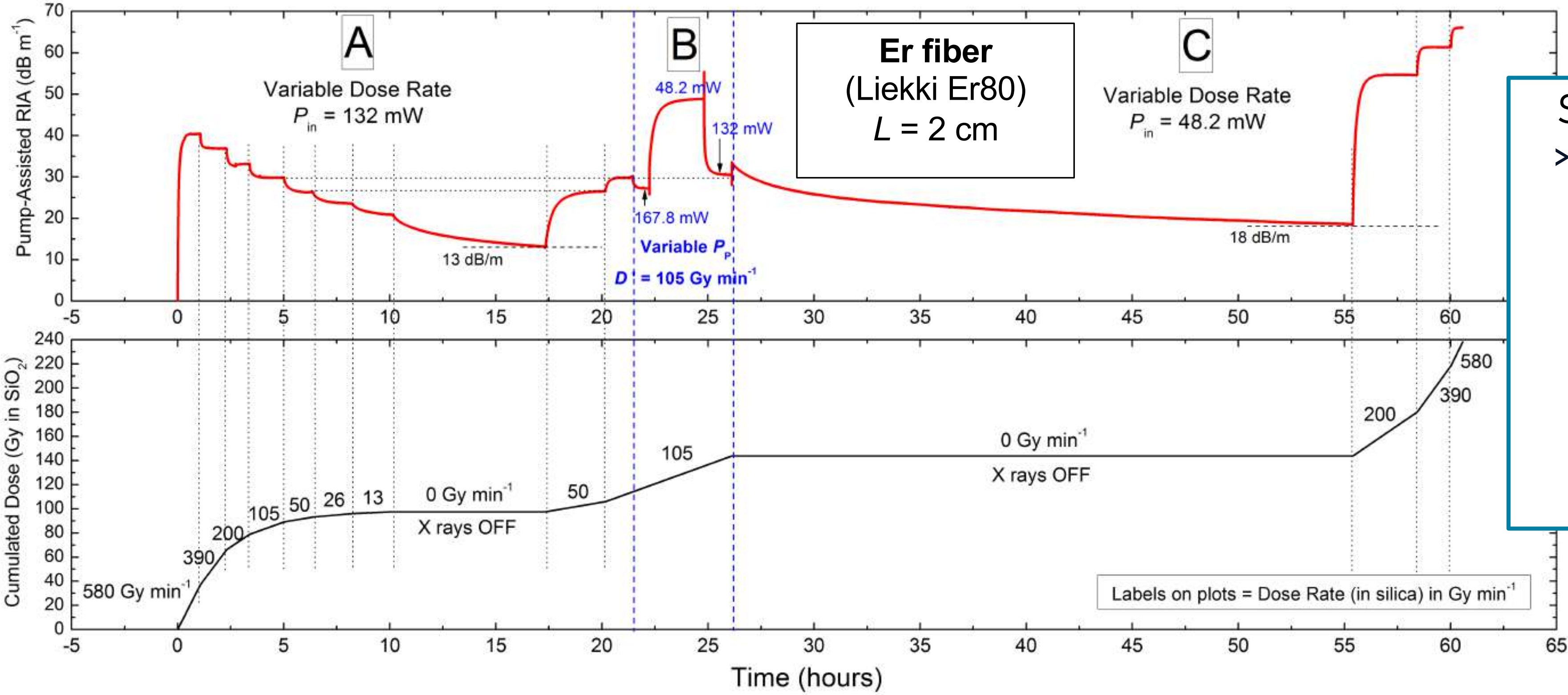
Equilibrium degradation levels in Yb-doped fibers



- Local degradation level only determined by the local **(P_p,D') couple**
- Identical properties for **COTS fibers**

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Similar results for Er-doped fibers



Switching exp.
> 60 h, 240 kGy

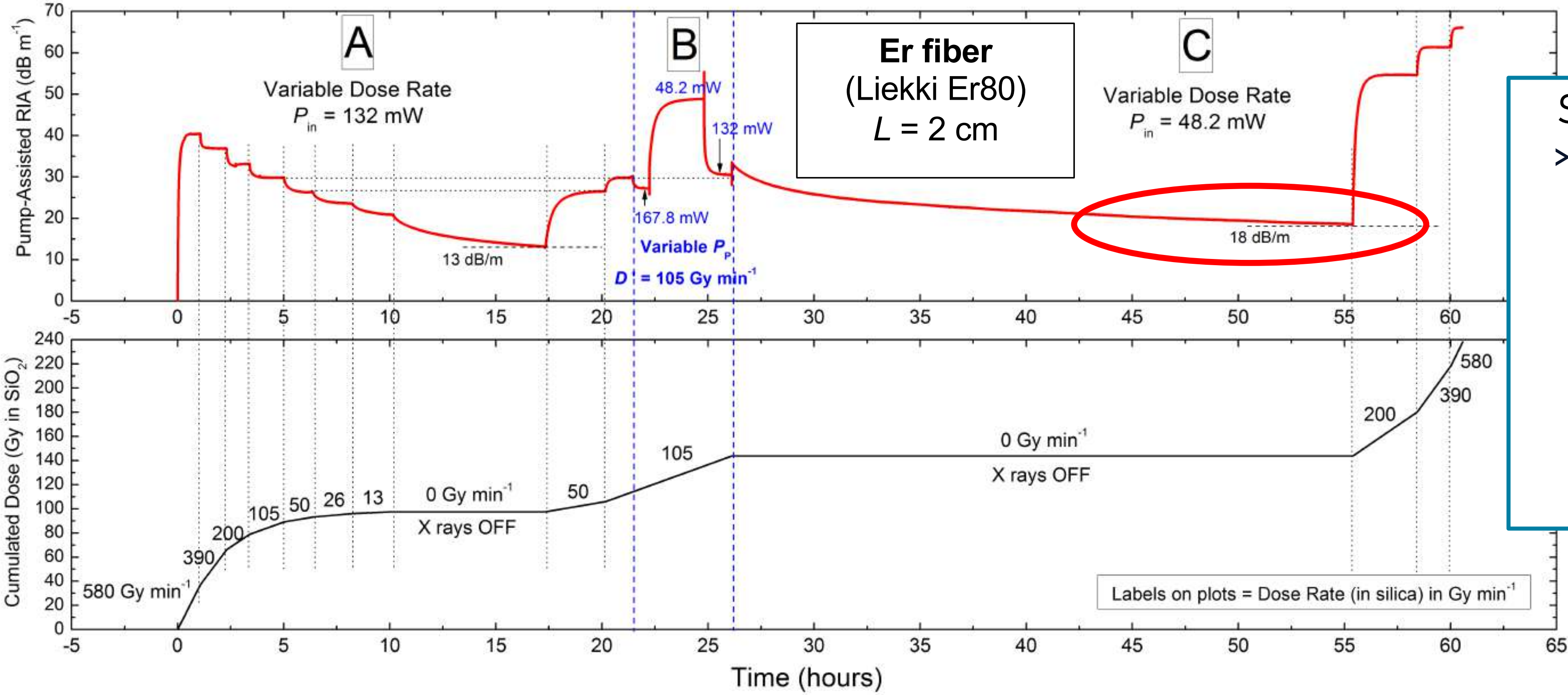
Zones A & C :
D' switched @ constant P_p

Zone B :
P_p switched @ constant *D'*

Again, reversible equilibrium degradation levels, fully determined by the local couple (D', P_P)

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Similar results for Er-doped fibers



Switching exp.
> 60 h, 240 kGy

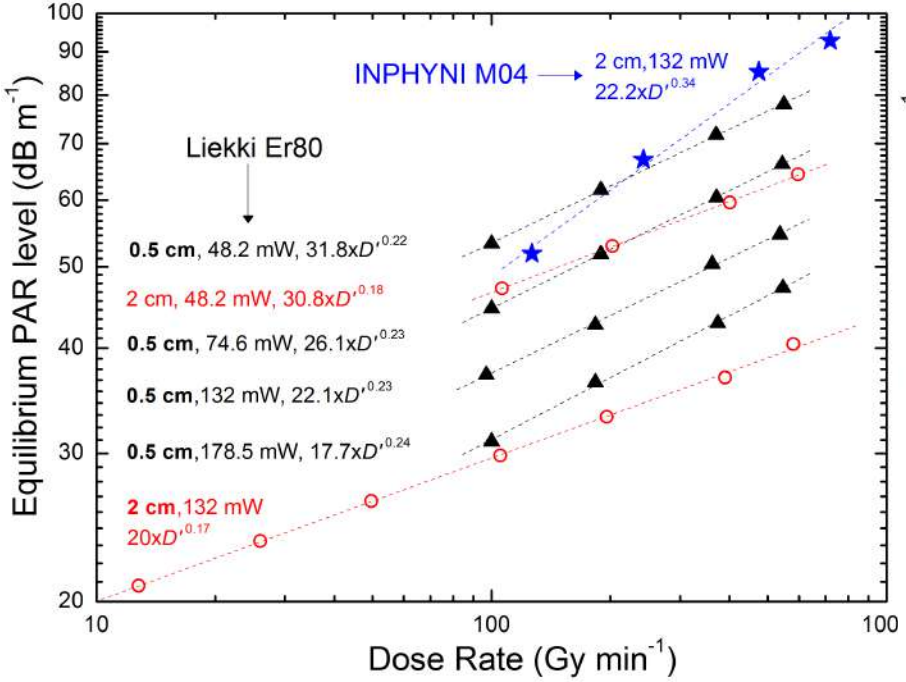
Zones A & C :
D' switched @ constant P_p

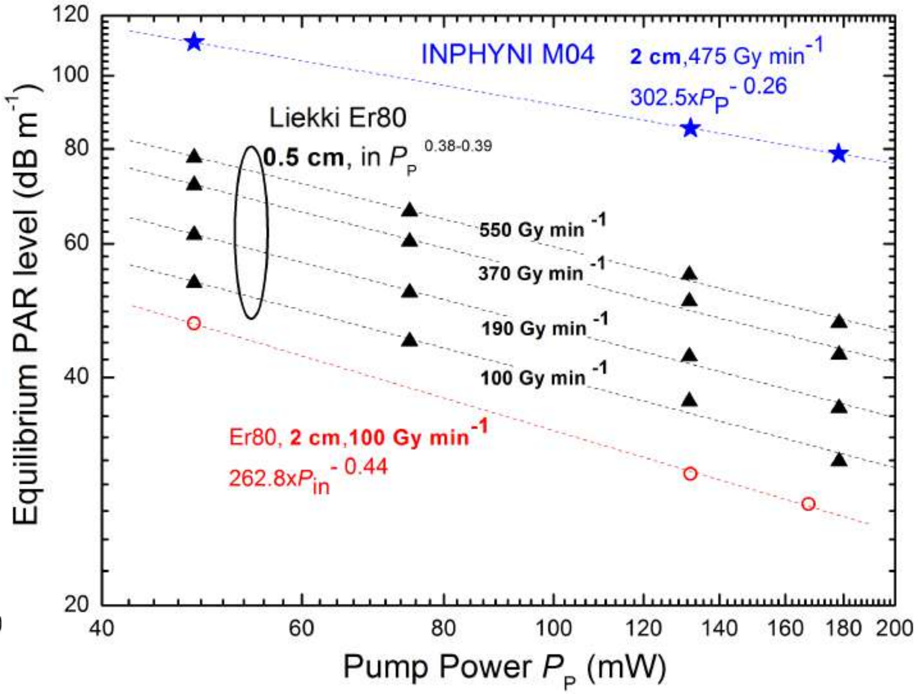
Zone B :
P_p switched @ constant *D'*

Pump only: no PD but residual RIA → Part of color centers absorbing @976 nm not bleached

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Similar results for Er-doped fibers

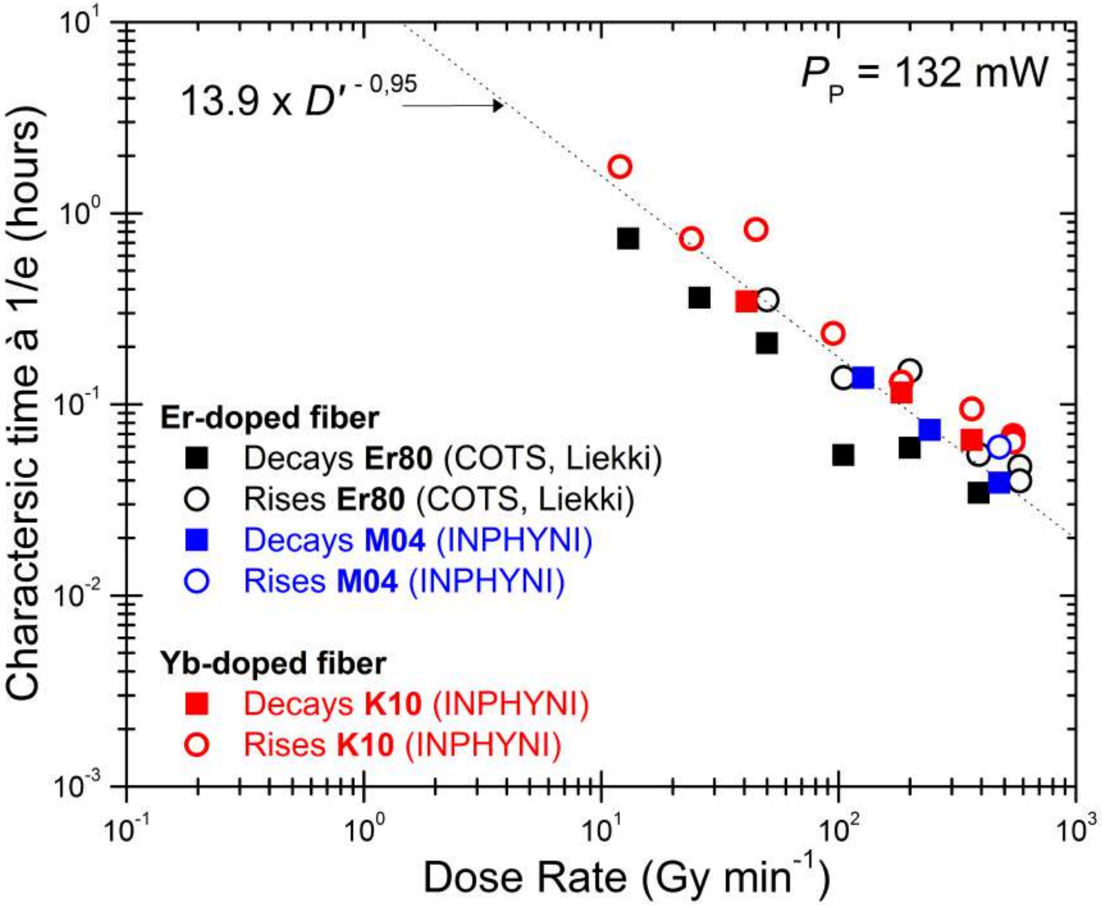




Equilibrium pump-assisted RIA (PAR) $\propto D'^{\alpha} P_p^{-\beta}$

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

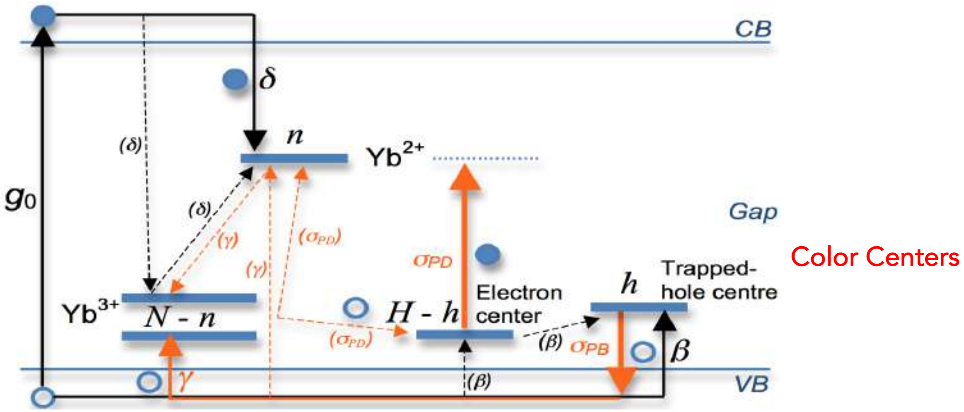
Transient kinetics towards PAR_∞ for Yb- and Er-doped fibers



- **Similar kinetics** for Yb and Er fibers
- **Similar kinetics** for « home-made » and COTS fibers
- **Characteristic times** approx. inversely proportional to the dose rate
- **Decays** tend to be faster than rises

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Modeling for Yb-doped fibers



- g_0 = Dose rate
- n_c = Electron concentration in CB
- h_v = Hole concentration in VB
- x_{inv} = inversion rate of Yb^{3+} ions (P_p)
- τ = Radiative lifetime of Yb^{3+} ions
- N_V = Equivalent DOS of the VB
- σ_{PD} = PD coefficient
- σ_{PB} = Photoionization and PB coefficient

$$\frac{dn_c}{dt} = g_0 - \delta\, n_c (N-n)$$

$$\frac{dn}{dt} = \delta\, n_c (N-n) + \sigma_{PD} \frac{x_{inv}^4 (N-n)^4}{\tau^3} (H-h) - \gamma\, h_v n$$

$$\frac{dh}{dt} = \beta\, h_v (H-h) + \sigma_{PD} \frac{x_{inv}^4 (N-n)^4}{\tau^3} (H-h) - \sigma_{PB} \frac{x_{inv}^2 (N-n)^2}{\tau^2} N_V h$$

$$\frac{dh_v}{dt} = g_0 - \beta\, h_v (H-h) + \sigma_{PB} \frac{x_{inv}^2 (N-n)^2}{\tau^2} N_V h - \gamma\, h_v n$$

PD involves 4 excited Yb^{3+} ions

PB triggered by 2 excited Yb^{3+} ions

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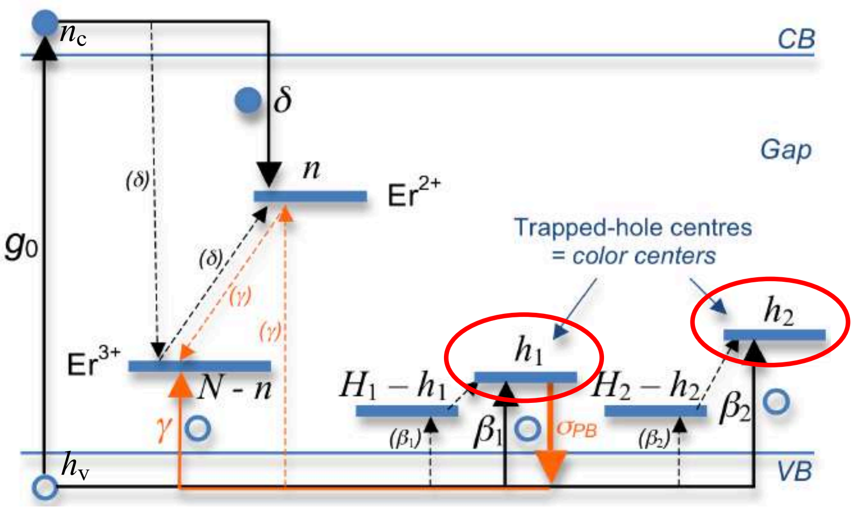
3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Modeling for Er-doped fibers



$$\frac{\partial n_c}{\partial t} = g_0 - \delta n_c(N-n)$$

$$\frac{\partial n}{\partial t} = \delta n_c(N-n) - \gamma h_v n$$

$$\frac{\partial h_1}{\partial t} = \beta_1 h_v(H_1 - h_1) - \sigma_{PB} P_p^2 N_v h_1$$

$$\frac{\partial h_2}{\partial t} = \beta_2 h_v(H_2 - h_2)$$

$$\frac{\partial h_v}{\partial t} = g_0 - \beta_1 h_v(H_1 - h_1) - \beta_2 h_v(H_2 - h_2) + \sigma_{PB} P_p^2 N_v h_1 - \gamma h_v n$$

PB triggered by
2 pump-photon
absorption

- no PD
- Existence of an additional, deep « unbleachable » hole level
- PB not triggered by de-excitation of active ions, but by 2 pump photons

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Implementation in PDE for short fibers

Without degradation (standard PDE for <u>short samples</u>)

No signal, no ASE

→ Pump power ***P(z,t)*** and inversion $\boldsymbol{x_{inv}(z,t)}$ only

$$\frac{\partial x_{\mathrm{inv}}(z,t)}{\partial t} = \frac{\sigma_{\mathrm{P}}\Gamma}{Sh\nu_{\mathrm{P}}} P(z)[1 - x_{\mathrm{inv}}(z,t)] - \frac{x_{\mathrm{inv}}(z,t)}{\tau}$$

$$\frac{\partial P(z,t)}{\partial z} = -\sigma_{\mathrm{P}}\Gamma P(z,t) N(z)[1 - x_{\mathrm{inv}}(z,t)]$$

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$$\frac{\partial x_{inv}(z,t)}{\partial t} = \frac{\sigma_P \Gamma}{Sh\nu_P} P(z)[1 - x_{inv}(z,t)] - \frac{x_{inv}(z,t)}{\tau}$$

$$\frac{\partial P(z,t)}{\partial z} = -\sigma_P \Gamma P(z,t) N(z)[1 - x_{inv}(z,t)]$$

With pump- and radiation-induced degradation

$$\frac{\partial x_{inv}(z,t)}{\partial t} = \frac{\sigma_P \Gamma}{Sh\nu_P} P(z)[1 - x_{inv}(z,t)] - \frac{x_{inv}(z,t)}{\tau} + \frac{x_{inv}(z,t)}{N(z)\left[1 - \frac{n(z,t)}{N(z)}\right]} \frac{\partial n(z,t)}{\partial t}$$

$$\frac{\partial P(z,t)}{\partial z} = -\sigma_P \Gamma P(z,t) N(z)[1 - x_{inv}(z,t)] \left[1 - \frac{n(z,t)}{N(z)}\right] - \sigma_{CC} \Gamma P(z,t) h(z,t)$$

$$\frac{\partial n_c(z,t)}{\partial t} = g_0(z) - \delta n_c(z,t) N(z) \left[1 - \frac{n(z,t)}{N(z)}\right]$$

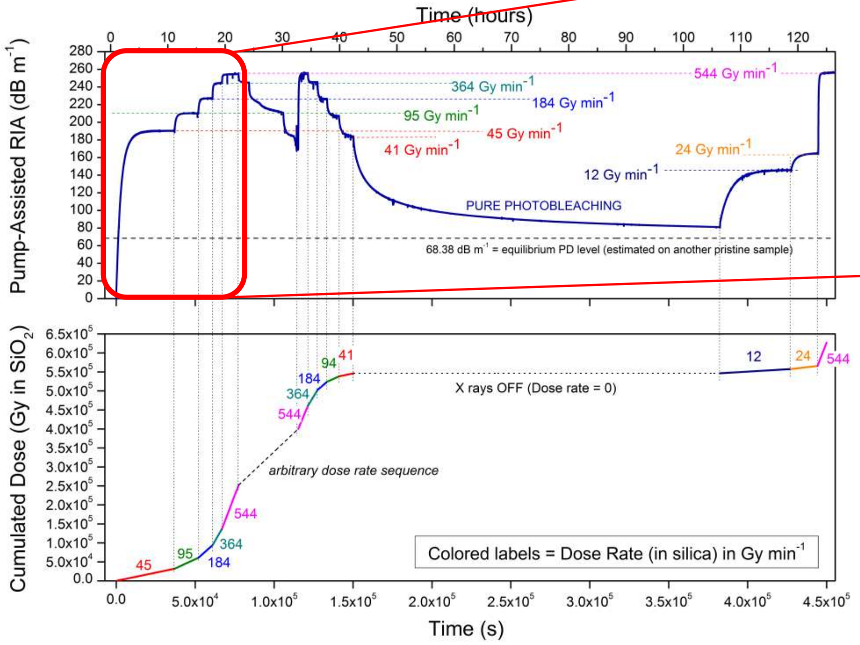
$$\frac{\partial n(z,t)}{\partial t} = \delta n_c(z,t) N(z) \left[1 - \frac{n(z,t)}{N(z)}\right] + \sigma_{PD} \frac{x_{inv}^4(z,t)}{\tau^3} N(z)^4 \left[1 - \frac{n(z,t)}{N(z)}\right]^4 H(z) \left[1 - \frac{h(z,t)}{H(z)}\right] - \gamma h_v(z,t) n(z,t)$$

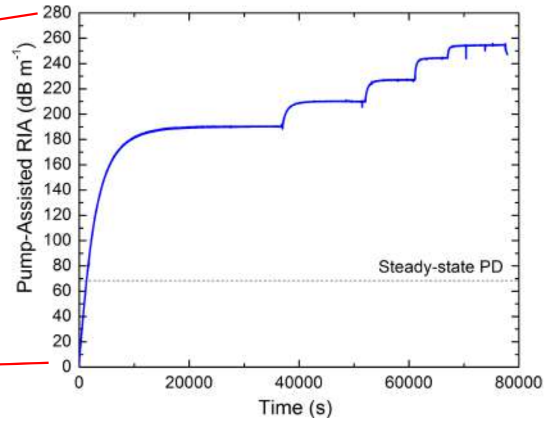
$$\frac{\partial h(z,t)}{\partial t} = \beta h_v(z,t) H(z) \left[1 - \frac{h(z,t)}{H(z)}\right] + \sigma_{PD} \frac{x_{inv}^4(z,t)}{\tau^3} N(z)^4 \left[1 - \frac{n(z,t)}{N(z)}\right]^4 H(z) \left[1 - \frac{h(z,t)}{H(z)}\right] - \sigma_{PB} \frac{x_{inv}^2(z,t)}{\tau^2} N(z)^2 \left[1 - \frac{n(z,t)}{N(z)}\right]^2 N_v h(z,t)$$

$$\frac{\partial h_v(z,t)}{\partial t} = g_0(z,t) - \beta h_v(z,t) H(z) \left[1 - \frac{h(z,t)}{H(z)}\right] + \sigma_{PB} \frac{x_{inv}^2(z,t)}{\tau^2} N(z)^2 \left[1 - \frac{n(z,t)}{N(z)}\right]^2 N_v h(z,t) - \gamma h_v(z,t) n(z,t)$$

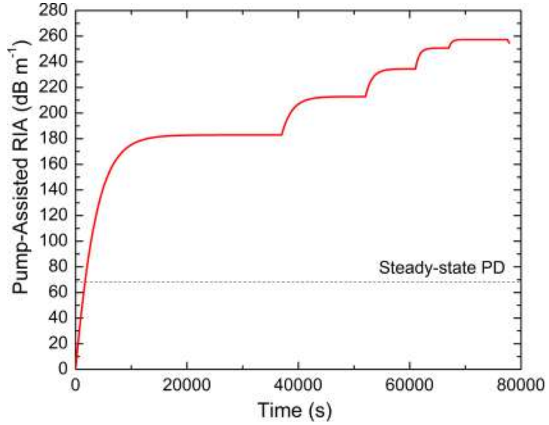
3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Model validation: Yb-doped fibers





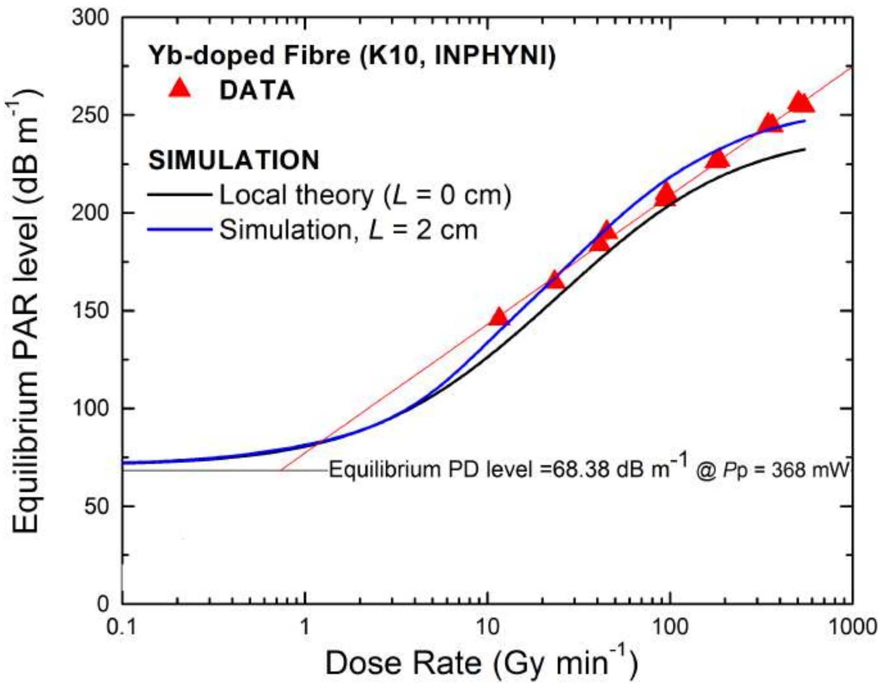
Experiment

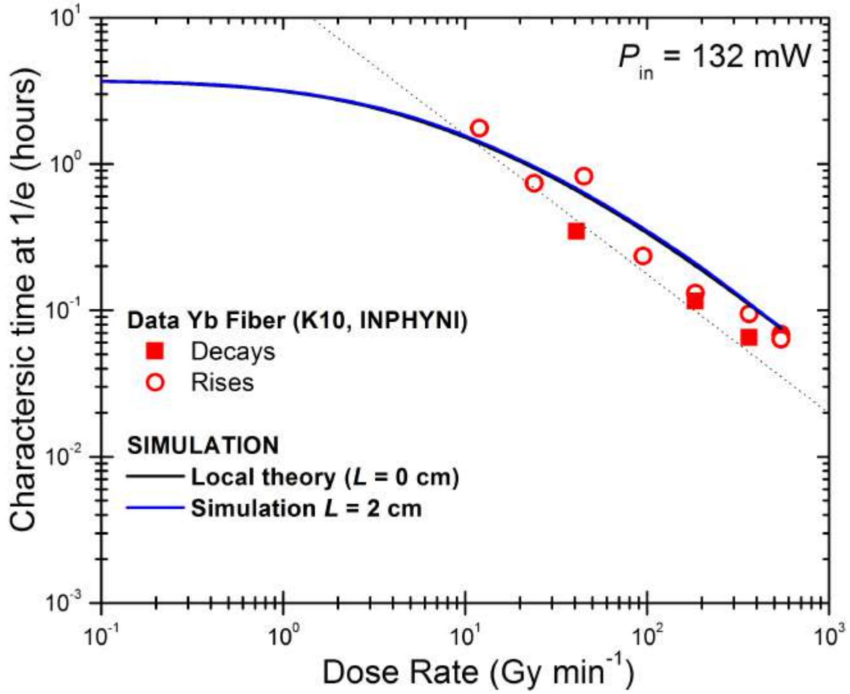


Simulation at identical P_p and D' values

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

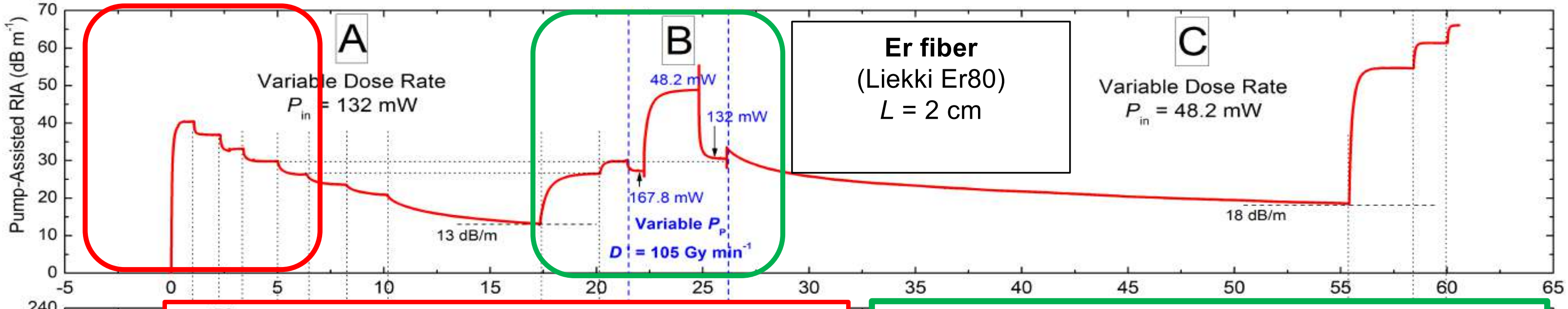
Model validation: Yb-doped fibers



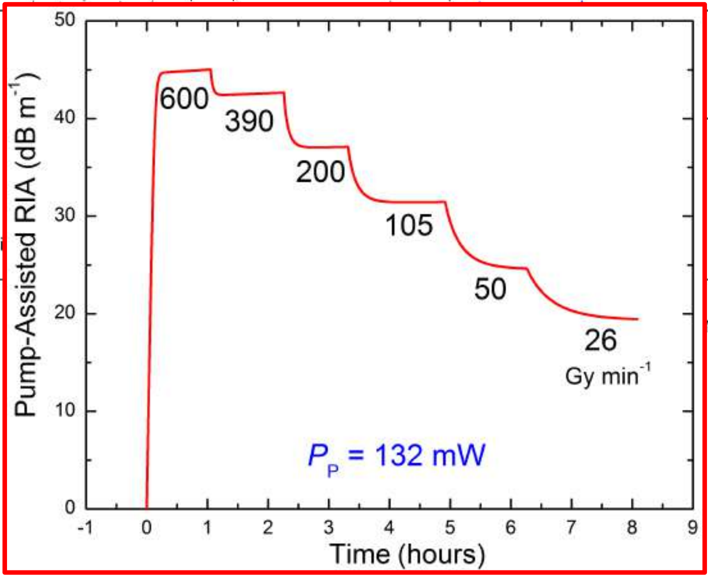


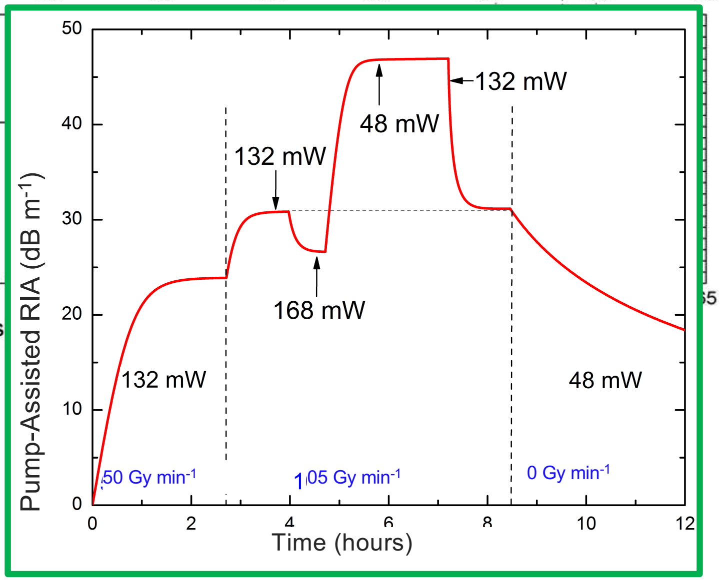
3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Model validation: Er fibers



Experiment



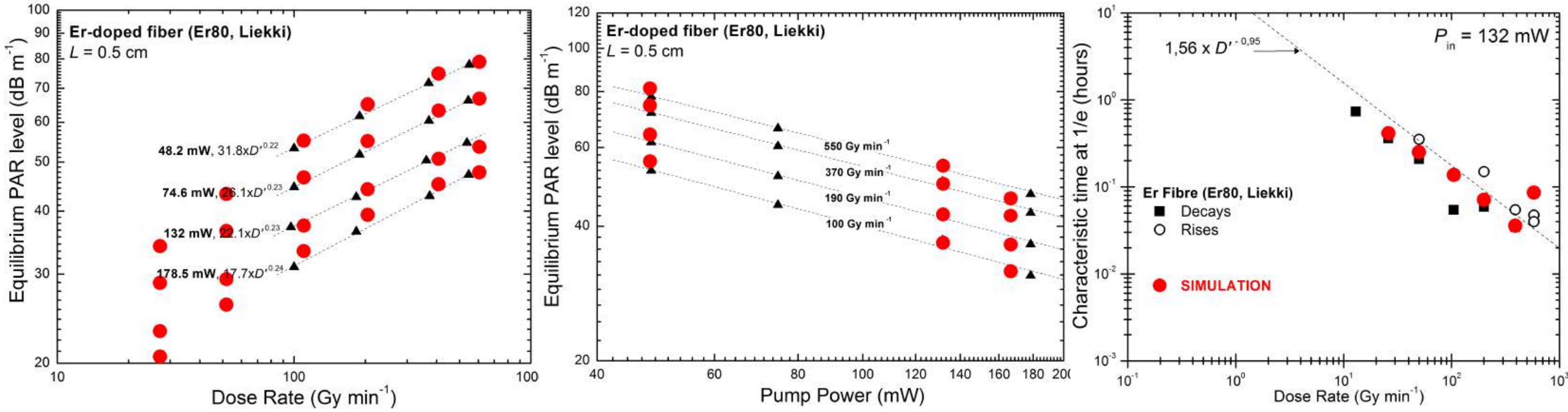


Simulation at identical P_p and D' values

3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

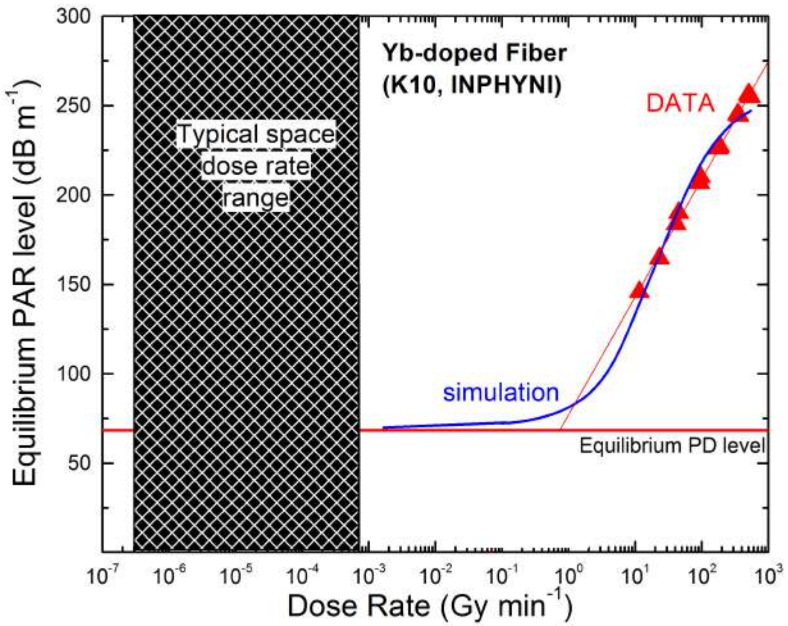
Model validation: Er fibers

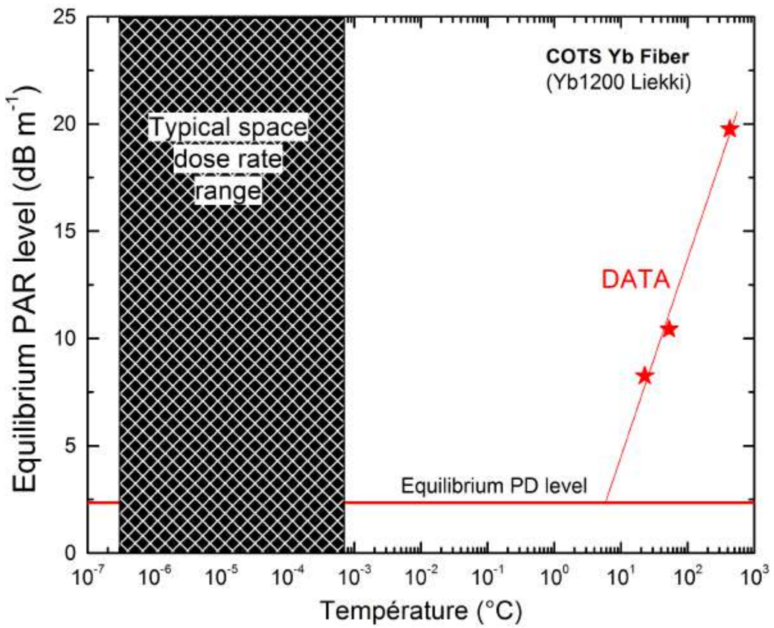
Simulation: red dots for L = 0.5 cm



3D – HOW TO TAKE ADVANTAGE OF LOW DOSE RATES?

Extrapolation to typical space dose rates





Very low dose rates → Very slow RIA development → Each time RIA exceeds the PD_∞ level, the pump has time to bleach back to PD_∞ (*regulation*)…

Pump-assisted RIA cannot exceed PD_∞ in Yb-doped fibers or the residual loss level in Er-doped fibers (in active conditions: **pump ON**). **But both depend on the local pump power**.

4 • MEDICAL APPLICATIONS

- Low dose levels
- Mainly RIE (radioluminescence)

4 • MEDICAL APPLICATIONS

- Low dose levels
- Mainly RIE (radioluminescence)

4A – Radiation-therapy and dosimetry
4B – The promises of « flash » therapy and related needs
4C – Why silica-based fibers can help?
4D – Topical example: high-energy proton therapy (HEPT)

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

What is RT?

- A modality included in more than 50% of the treatments given to cancer patients
- Use of **ionizing radiation** to **kill** malignant cells (tumors)

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

What is RT?

EXTERNAL

- High-energy X rays (> 6 MV)
- Protons (65-230 MeV), *less common*

~120 RT Centers in France use X rays...

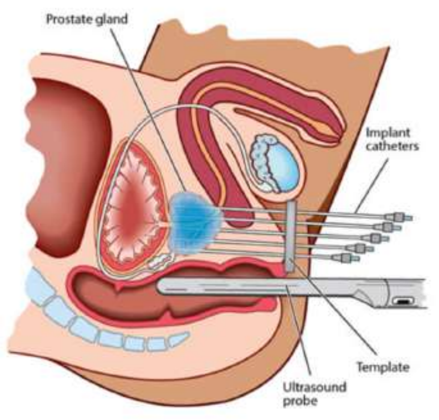
... **but only 4 cyclotrons:** 2 in Nice + 1 Orsay + 1 Caen

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

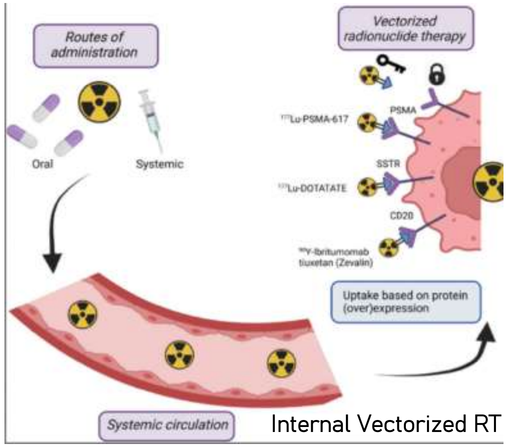
What is RT?

INTERNAL (low energy gamma rays from radionuclides)

- Brachyterapy
- Internal vectorized radiotherapy



Prostatic brachytherapy

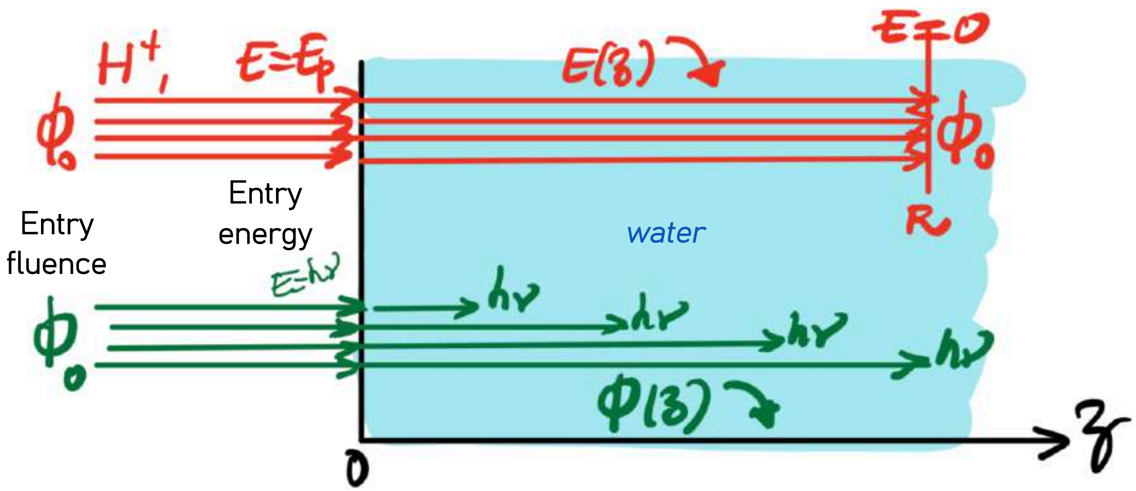


Internal Vectorized RT

Hot TOPIC!
^{117}Lu-PSMA

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Differences between photons and protons

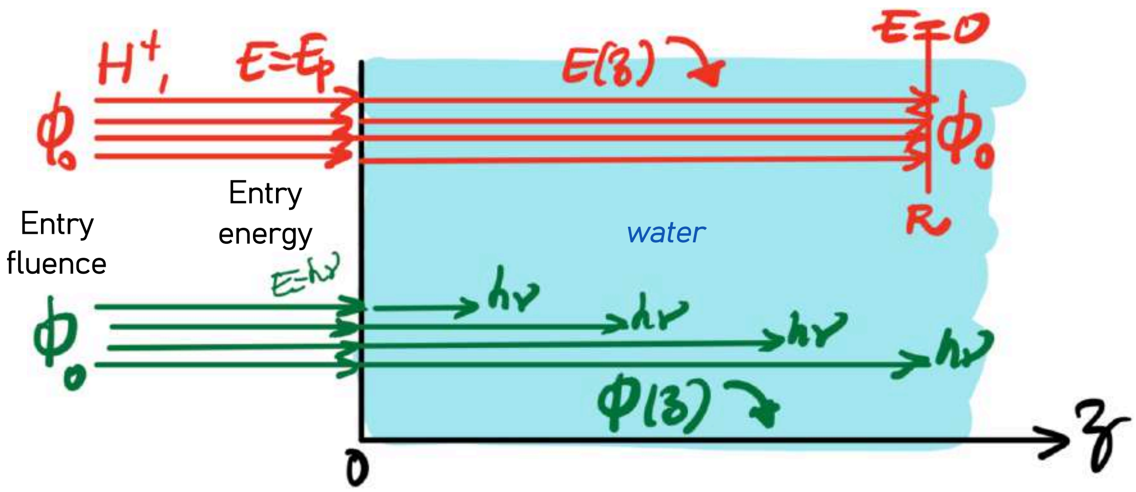


Proton stopping is deterministic

- Protons are stopped (slowed down) by **a huge number of small energy transfers**, mainly to electrons
- Their **fluence remains roughly constant** until they come to complete stop

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Differences between photons and protons



Proton stopping is deterministic

- Protons are **stopped** (slowed down) by **a huge number of small energy transfers**, mainly to electrons
- Their **fluence remains roughly constant** until they come to complete stop

Photon attenuation is stochastic

- Photons can travel without interacting with the medium. They disappear upon interaction.
- The **energy** of the **primary beam remains constant,** but its **fluence decreases**.

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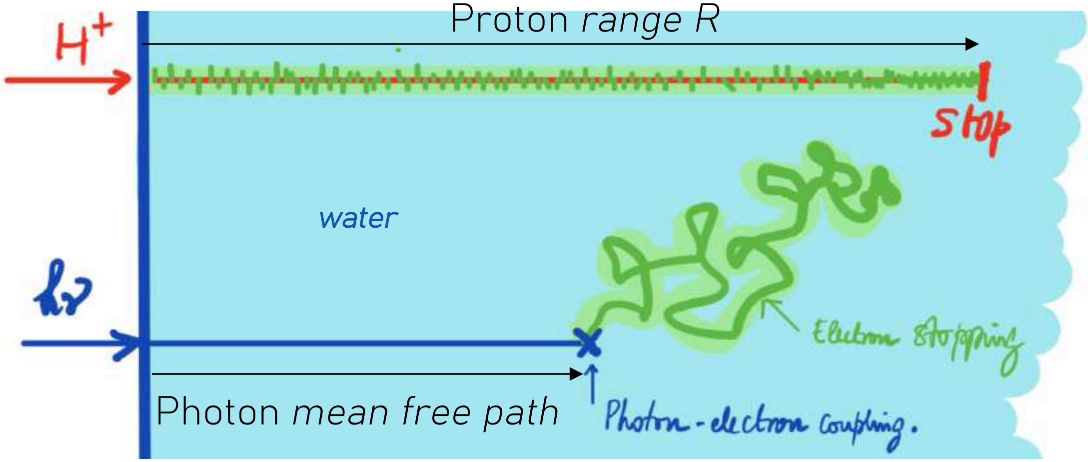
4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Differences between photons and protons



Huge number of proton-electron interactions

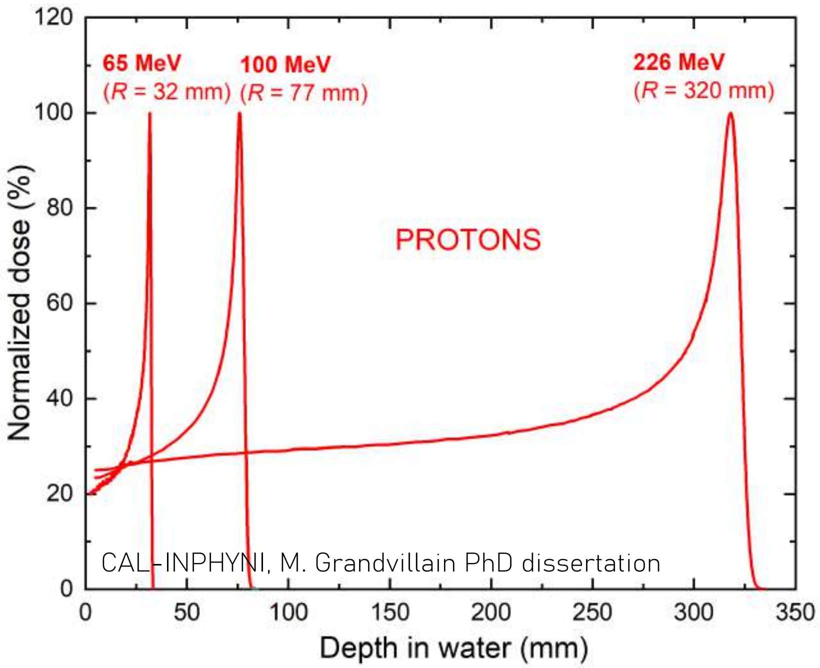
- On average a **few hundreds eV** transferred to electrons at each interaction
- Electrons are stopped within 10-20 nm. Energy deposited right next to the interaction point
  → **Local dose absorption**

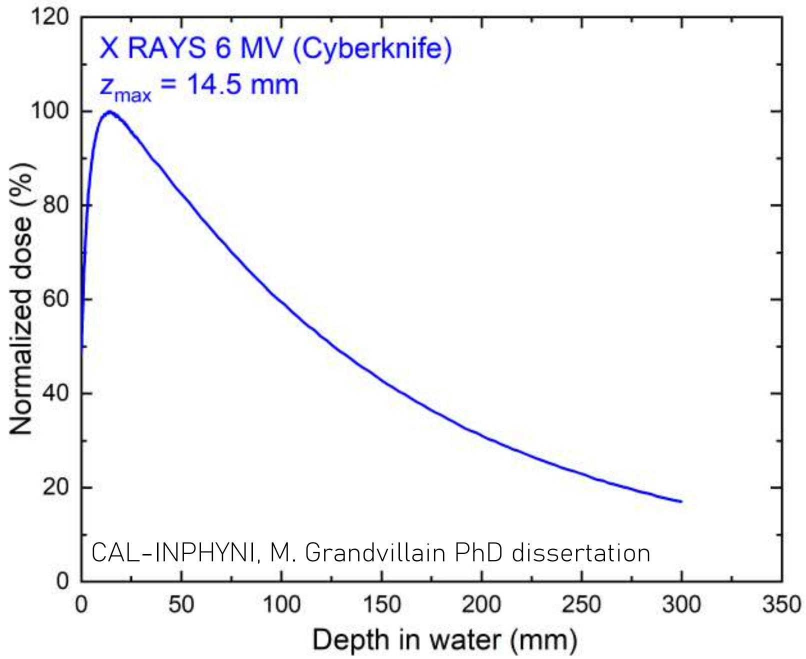
Only one photon-electron coupling

- High transferred energy: 80 to 100% of $h\nu$, **of the order of 1 MeV** for high energy X rays
- Long electron range (cm): **energy** deposited far away from the coupling point…
  → **Distant dose absorption**

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Consequences on depth-dose profiles



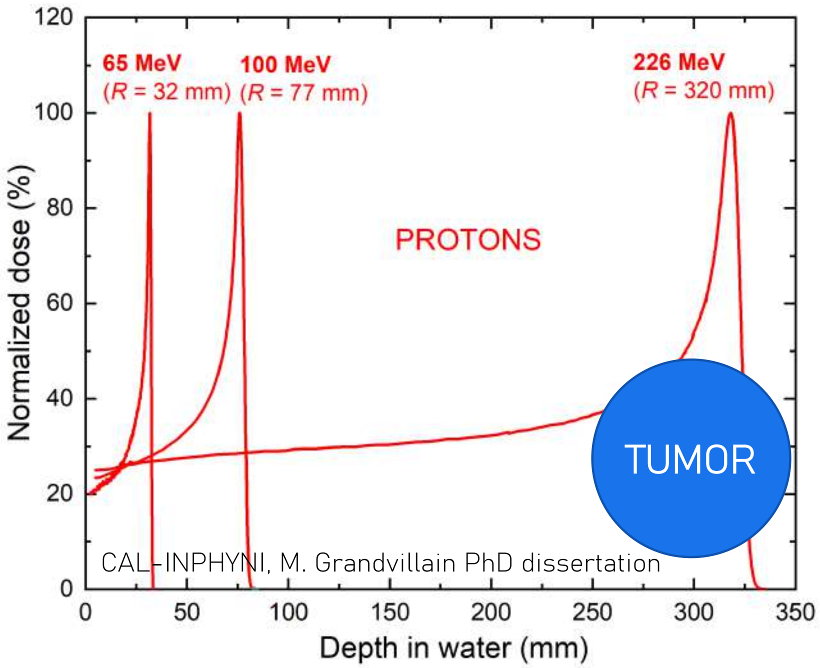


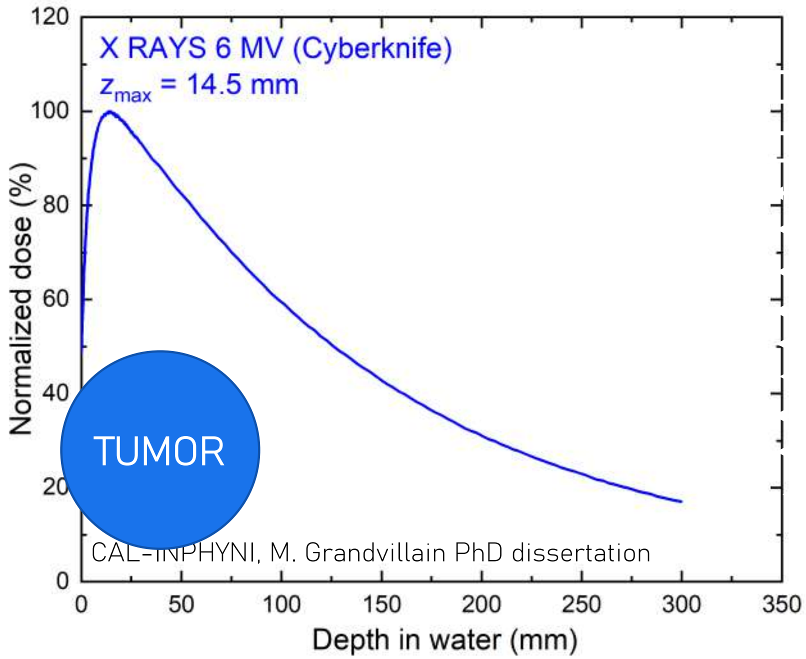
- Sharp maximum = BRAGG PEAK
- Virtually no dose at depth > R

- Significant doses absorbed before and after the maximum

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Consequences on depth-dose profiles





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4A – RADIATION-THERAPY (RT) AND DOSIMETRY

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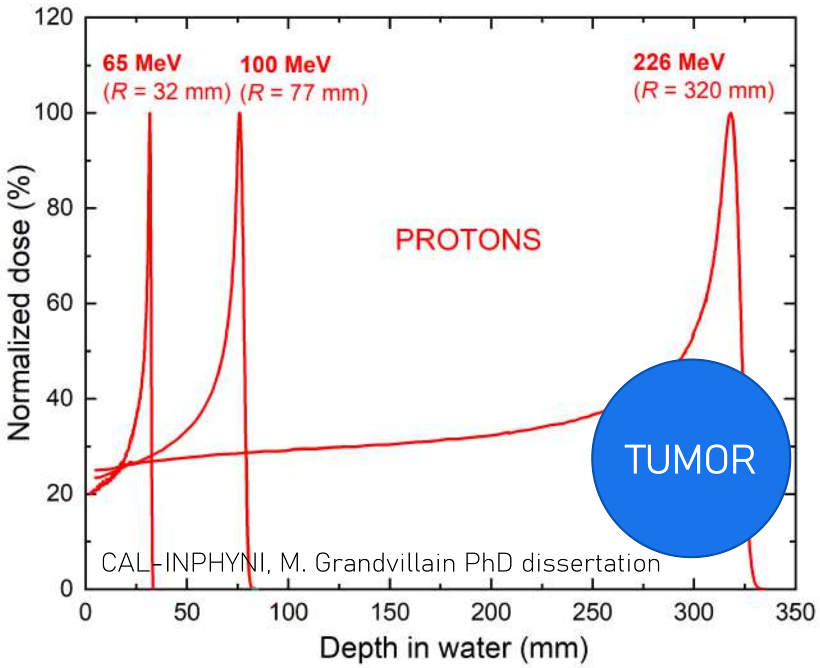

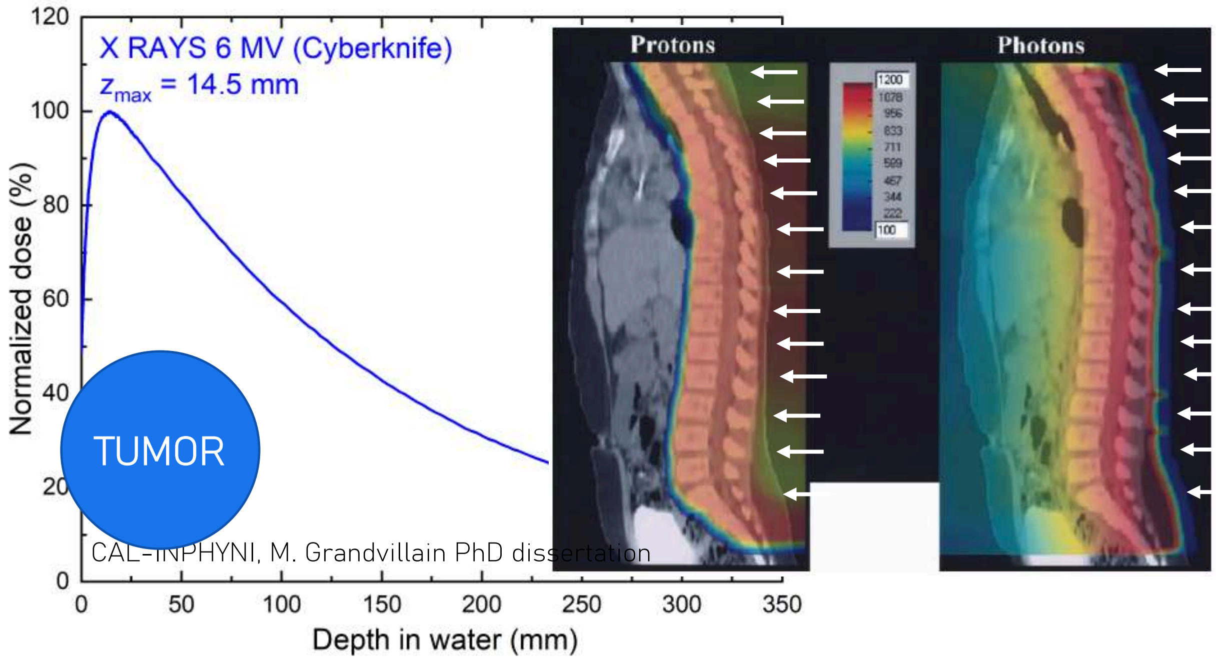

- Sharp maximum = **BRAGG PEAK**
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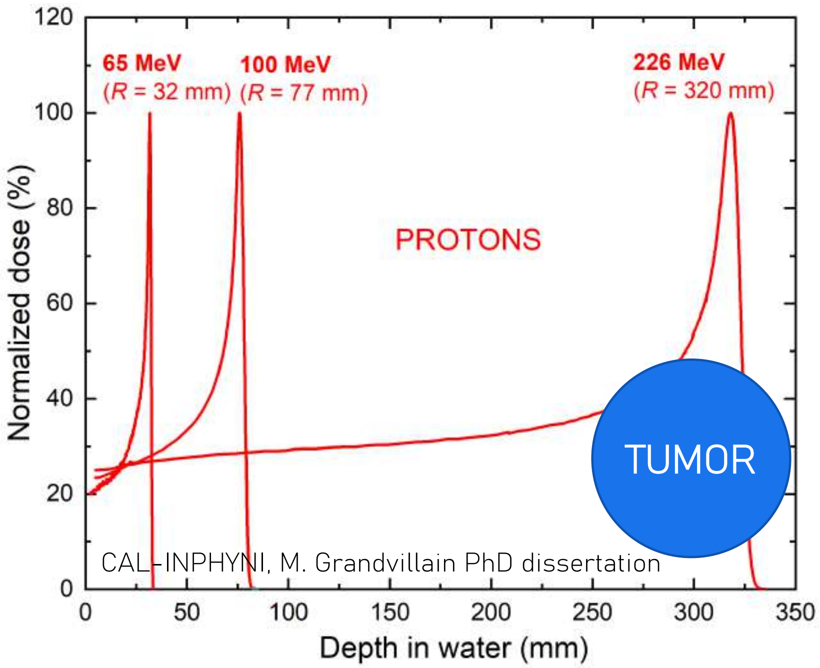
4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Consequences on depth-dose profiles



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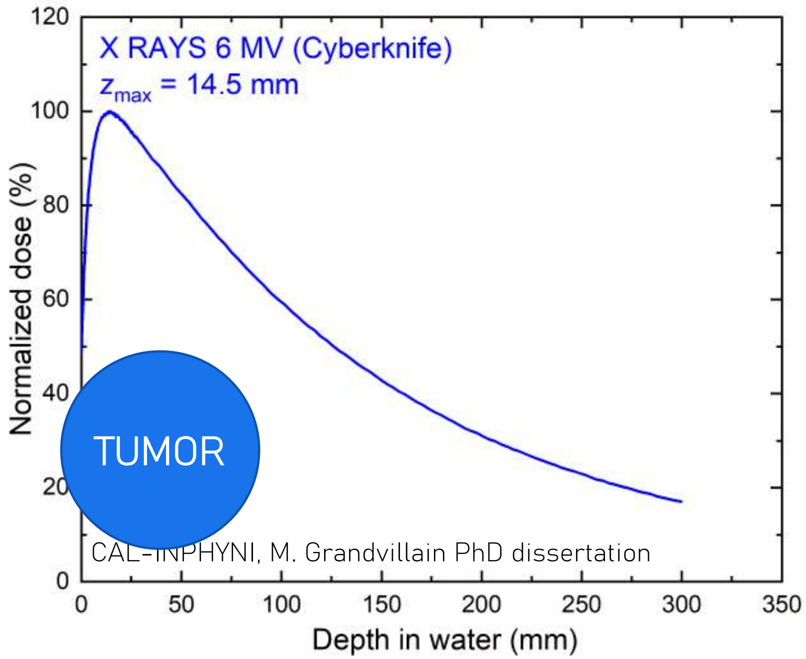


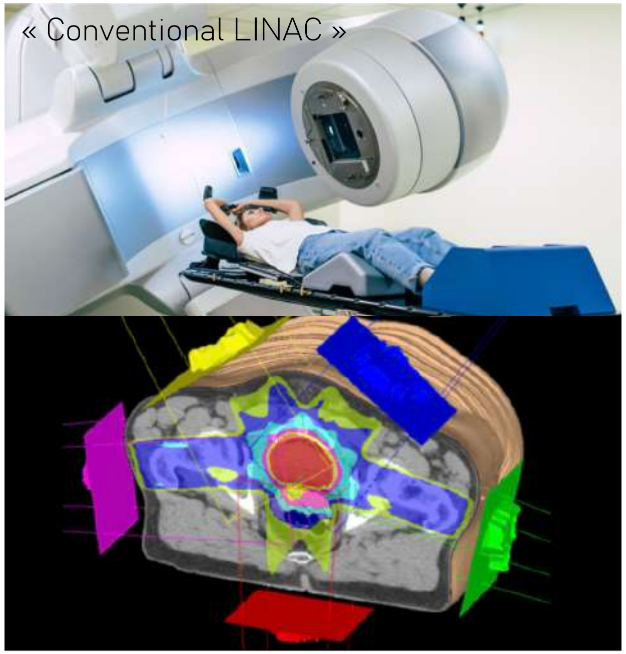
- Significant doses absorbed before and after the maximum

- Impossible to target only the tumor
- Surrounding **healthy tissues receive dose** (side effects)

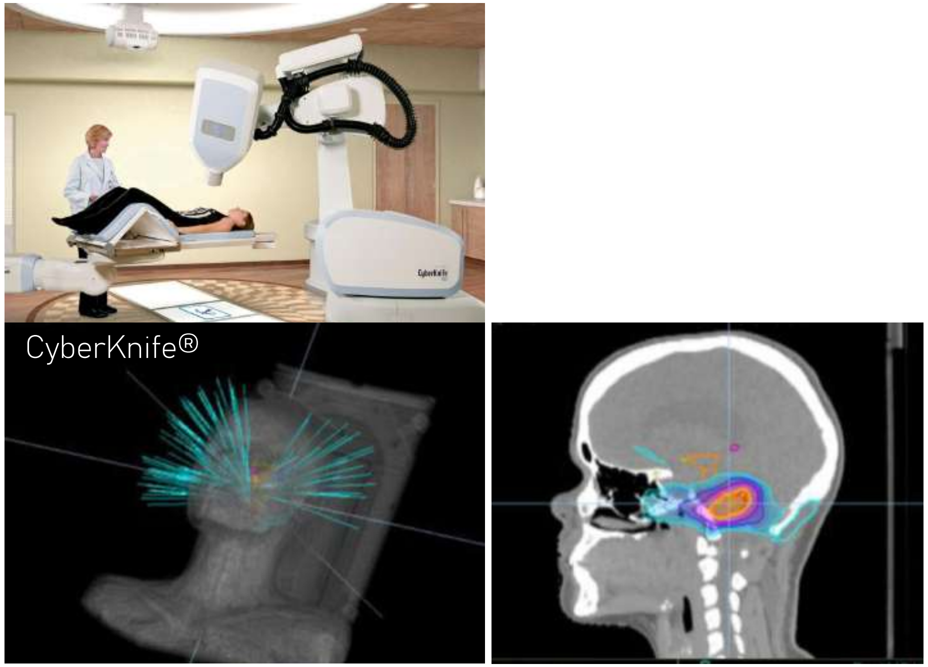
4A – RADIATION-THERAPY (RT) AND DOSIMETRY

How to limit the dose at healthy tissues and side effects?

1 – Use of multiple « entry points » (multiple converging beams)



A few coplanar beams....



...or a lot of non-coplanar microbeams

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

How to limit the dose at healthy tissues and side effects?

2 – Treatment (dose) delivered in a fractionated manner

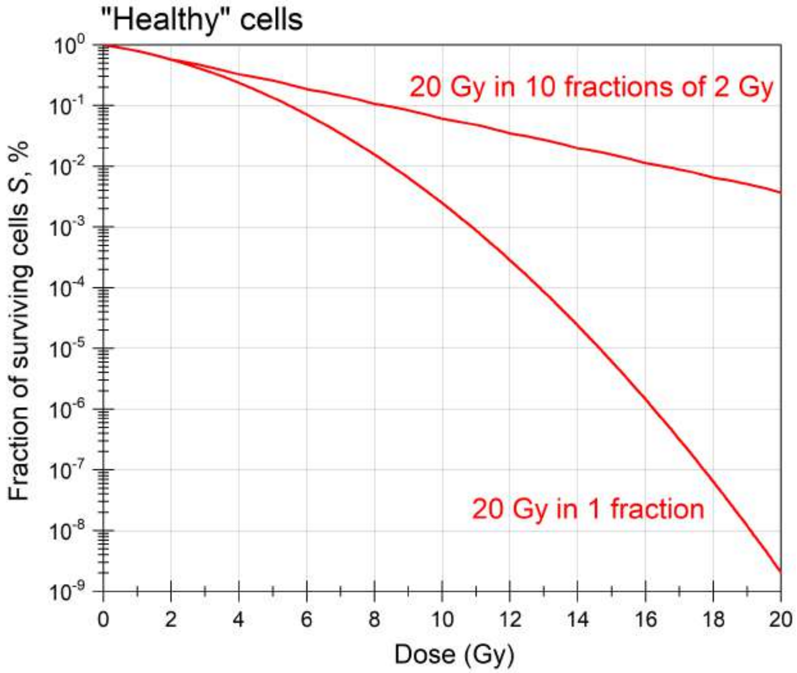
- Typical therapeutic dose: **60 Gy** to the « target volume »
- Delivered into **30 fractions** of **2 Gy** each.
- 1 fraction per day during several (6) weeks

😡 Source of fatigue for the patient
😡 Socioeconomic costs (medical transport, number of sessions…)

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

How to limit the dose at healthy tissues and side effects?

2 – Treatment (dose) delivered in a fractionated manner

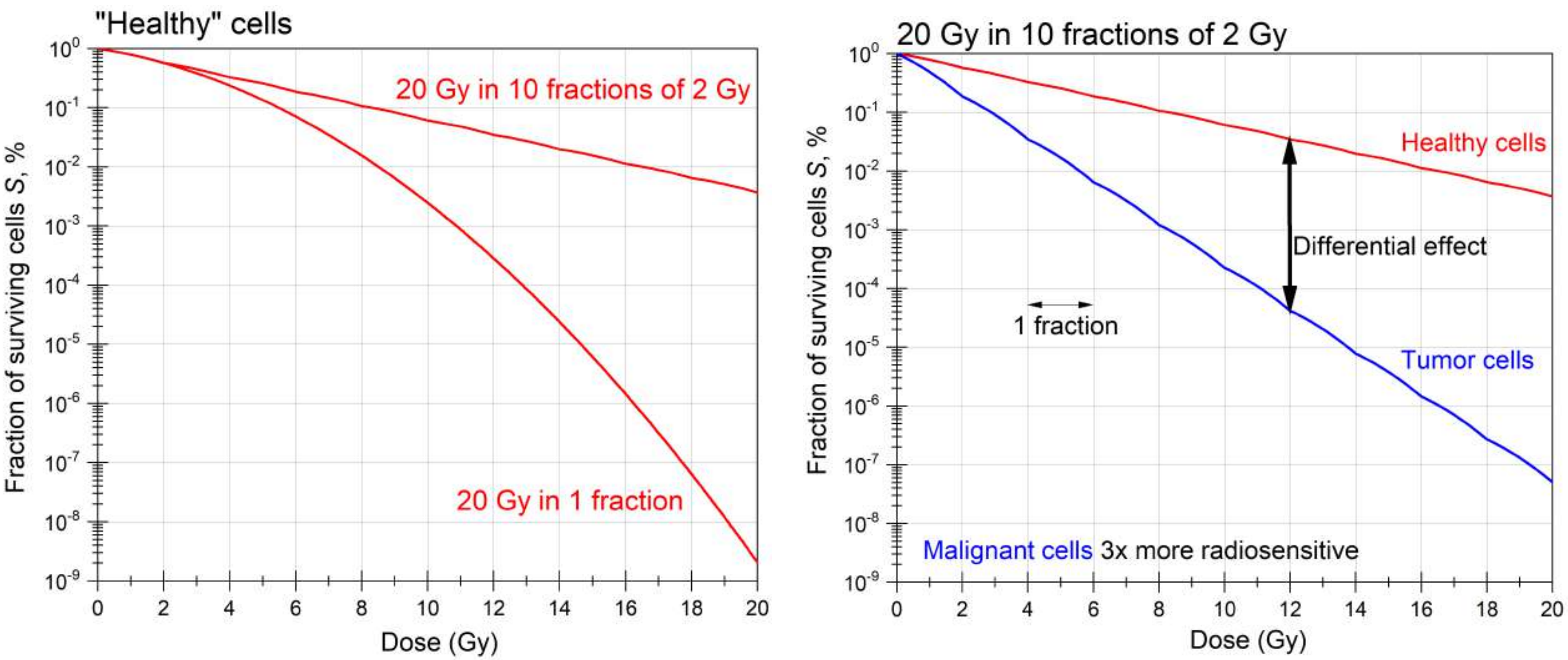


But **tumor cells are more radio-sensitive**
(high mitotic activity)

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

How to limit the dose at healthy tissues and side effects?

2 – Treatment (dose) delivered in a fractionated manner



4A – RADIATION-THERAPY (RT) AND DOSIMETRY

How to limit the dose at healthy tissues and side effects?

2 – Treatment (dose) delivered in a fractionated manner

If improved irradiation techniques allow:

- **An enhanced targeting** of the tumor (better sparing of surrounding tissues)
- **Less side effects** on healthy tissues

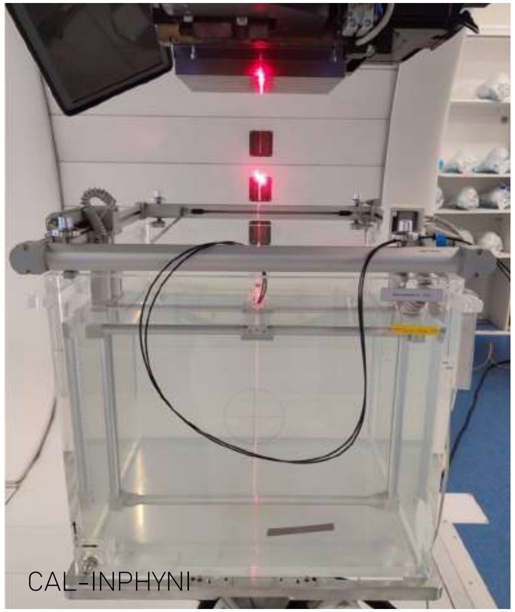
Treatments can be **HYPOFRACTIONATED** (less fractions, increased per-fraction dose)
'Perfect' targeting → 1 fraction = « *radiosurgery* »

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Dosimetry for Quality Assurance (QA)

Need to control:

- **Beams** to check proton range *R*, photon z_{max}, dose per MU… in water tanks



4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Dosimetry for Quality Assurance (QA)

Need to control:

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- **Treatment plans**, checked in « phantoms » to make sure that the treatment plan delivers the planned dose at the right place in the patient

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Dosimetry for Quality Assurance (QA)

Need to control:

- **Beams** to check proton range *R*, photon z_{max}, dose per MU… in water tanks

- **Treatment plans**, checked in « phantoms » to make sure that the treatment plan delivers the planned dose at the right place in the patient

- **Treatment on patient (in-vivo dosimetry)** To check the dose actually given to the patient during one fraction (dosimeter at patient's skin)

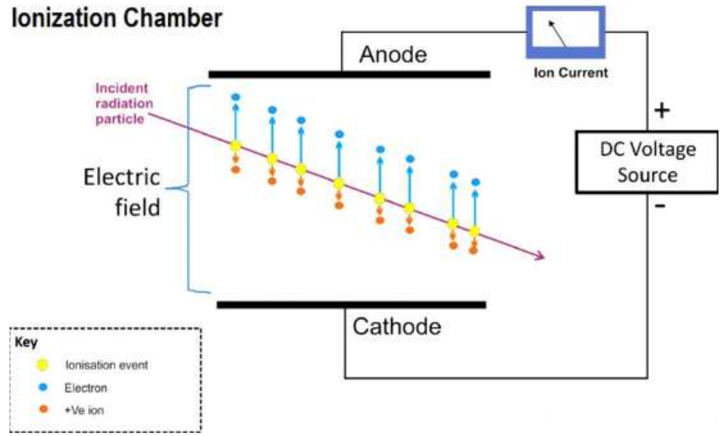
MA Ghadi *et al.*, Austin Oncol. Case Rep. **1**, 1004, 2016

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Dosimetry for Quality Assurance (QA)

Usual dosimeters

- **Ion chambers** are calibrated by reference institutes
  - Active dosimeters (realtime dosimetry).
  - Serve as reference dosimeter to calibrate others
  - Used for beam controls



PTW DOSIMETRY

Bragg Peak Chamber 34080

Waterproof plane-parallel chamber for use as a thin window reference chamber in particle therapy dosimetry

Farmer Ionization Chamber 30010

Classical therapy chamber for reference dosimetry in high-energy photon, electron and proton beams

4A – RADIATION-THERAPY (RT) AND DOSIMETRY

Dosimetry for Quality Assurance (QA)

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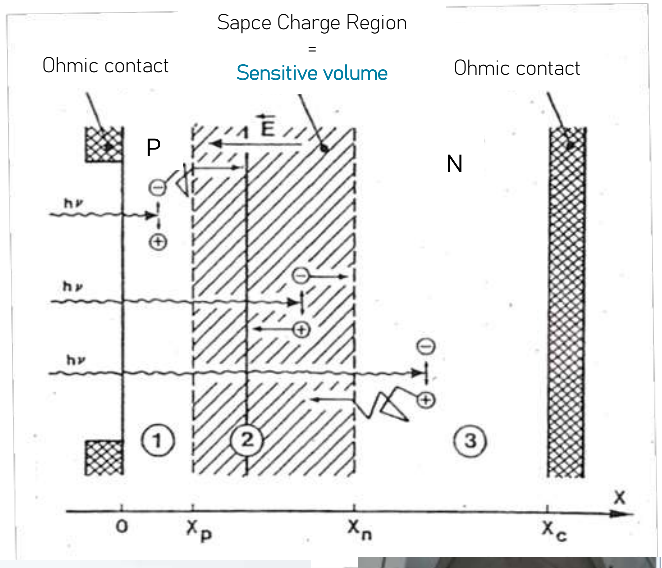
- **Ion chambers** are calibrated by reference institutes
  - o Active dosimeters (realtime dosimetry).
  - o Serve as reference dosimeter to calibrate others
  - o Used for beam controls
- Semi-conducting diodes
  - o Active dosimeters (realtime dosimetry)
  - o A kind of *solid equivalent* of ion chambers
  - o Used for beam, plans and patient controls



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4A – RADIATION-THERAPY (RT) AND DOSIMETRY

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  - Used for beam controls
- Semi-conducting diodes
  - Active dosimeters (realtime dosimetry)
  - A kind of *solid equivalent* of ion chambers
  - Used for beam, plans and patient controls
- Less common modalities using luminescent detectors
  - TLD /OSL (passive), RL (active)

4B – THE PROMISES OF FLASH THERAPY and related needs

« Flash » therapy?

A radically new approach to external RT treatments

- So-called « **flash effect** » first reported by Favaudon *et al.* in **2014**
  (V. Favaudon et al., Sci. Transl. Med. **6**, 3008973, 2014)
- Use « **short pulses** » (< 500 ms) at **ultra-high dose rate** (UHDR)

Benefits:
Seems to allow **better sparing of normal tissues** while **maintaining tumor control**

	Dose rate	Per-fraction dose	Number of fractions
Conventional RT	Typ. **0.03** Gy s^{-1}	Typ. **2 Gy** (in 60 s)	Typ. **30**
Flash RT	**40 – 200** Gy s^{-1}	**8-20** Gy ?	**3 to 5 ?** (hypofractionated)

Hypofractionation → **great benefits** to patients but **QA controls must be flawless**

4B – THE PROMISES OF FLASH THERAPY and related needs

State of affairs

- **Feasible and promising**
  Early human studies showing that FLASH is feasible and safe. But very small cohorts for selected indications (e.g., superficial lesions, bone metastases).

- **Not yet standard of care**
  Widespread clinical adoption requires larger trials, robust dosimetry/QA

- **Mechanisms unresolved**
  Multiple plausible mechanisms exist (oxygen depletion among the leading hypotheses), but none fully explains all observations
  Still an active area of basic research.

4B – THE PROMISES OF FLASH THERAPY and related needs

Challenges

- Dosimetry
  Reliable QA at UHDR remains complex (detector saturation).
- Beam delivery: Most clinical linacs not designed for FLASH; limited to superficial/transmission setups.
- Reproducibility: Tissue-dependent, dose-dependent; not all normal tissues show sparing.
- Clinical evidence: Current human data limited (small N, short follow-up). No randomized phase III yet.

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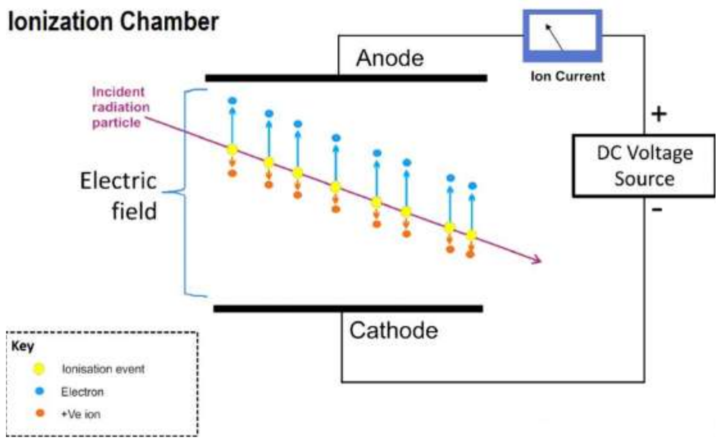
4B – THE PROMISES OF FLASH THERAPY and related needs

Challenge in dosimetry



Usual state-of-the-art dosimeters (ICs, diodes):

Ionisation → **e-/ion** or **e-/h+** pairs
→ **drift** under electric field (conduction)
→ current in the polarization circuit.

Steady-state current proportionnal to the absorbed dose rate
under « normal voltage » (200-300 V)

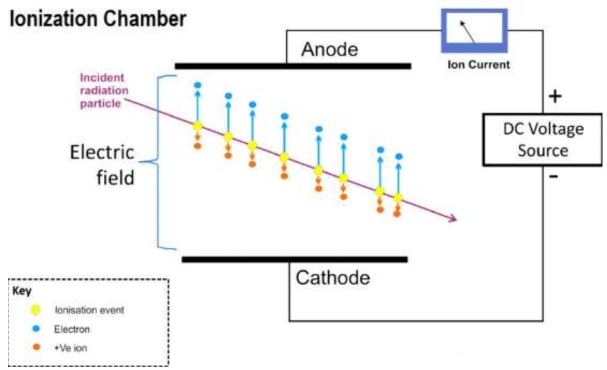
- Sufficiently high to **collect all created pairs** (they must escape recomb.)
- Sufficiently low **not to induce electron multiplication** or cascade

4B – THE PROMISES OF FLASH THERAPY and related needs

Challenge in dosimetry

Such dosimeters are not suited for operation under high dose rates !

Too much pairs (e-/ion or e-/h+) created at once



- Recombination favored
  → Sensitivity loss
- Space-charge limited current
  → Electric field induced by free charges may screen the applied field
  → Reduced effective drift velocity
  → Sensitivity loss

→ *Need for increasing polarization but detector then **operated out of specifications***

4B – THE PROMISES OF FLASH THERAPY and related needs

Needs

Novel dosimeters that maintain their sensibility at high dose rates

→ Luminescent dosimeters

Active, realtime dosimeters to resolve beam time structure

→ Metrology based on Radioluminescence (RL)

4B – THE PROMISES OF FLASH THERAPY and related needs

Needs

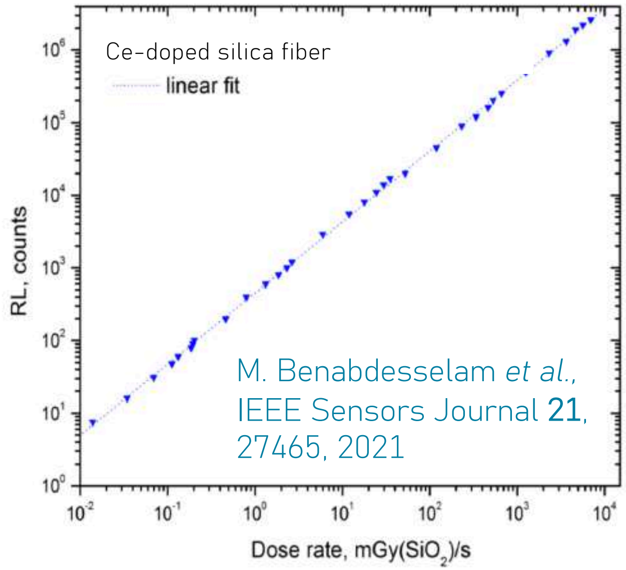
Novel dosimeters that maintain their sensibility at high dose rates

→ Luminescent dosimeters

Active, realtime dosimeters to resolve beam time structure

→ Metrology based on Radioluminescence (RL)

- Steady-state RL intensity is **proportional to the particle fluence,** hence **to dose rate** at constant energy
- **No theoretical limitations.** **Very robust property** (no saturation effect)



M. Benabdesselam *et al.*, IEEE Sensors Journal **21**, 27465, 2021

4C – WHY SILICA-BASED FIBERS CAN HELP?

…instead of plastic fibers?

	Plastic fibers	Silica fibers
🙂	– Water equivalent (Z = 6.5 for PMMA, 5.7 for PE) – Organic scintillation is rapid	
😠	– Thick (1 mm in diam.), rigid – Limited emission range (mainly UV-blue) – Scintillation quenching	

Water: Z = 7.42
Silicon: Z = 14

Lot of « plastic fiber dosimeters » in fact consist in inorganic scintillator attached to PMMA fibers…

Z can be 30+ !!

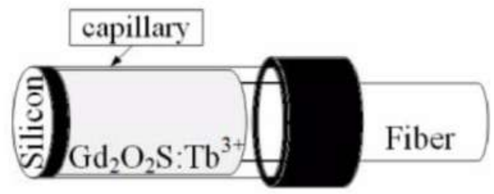


Fig. 1 (a) The schematic diagram of sensor

Fig. 1 (b) The picture of the entity of the sensing element

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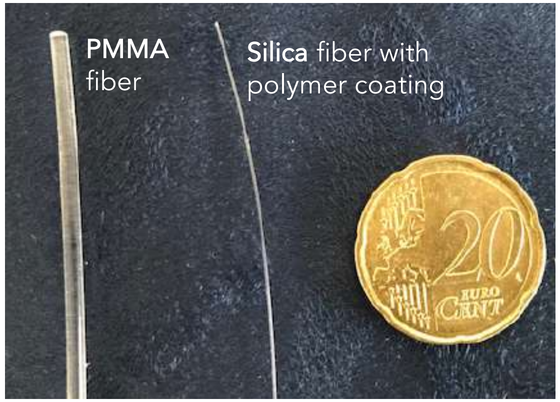
4C – WHY SILICA-BASED FIBERS CAN HELP?

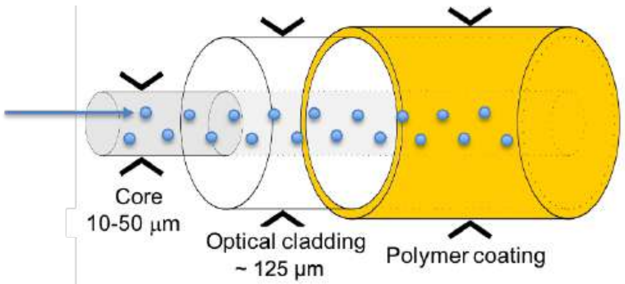
…instead of plastic fibers?

	Plastic fibers	Silica fibers
🙂	– Water equivalent (*Z* = 6.5 for PMMA, 5.7 for PE) – Organic scintillation is rapid	– Nearly water equivalent (*Z* = 10) – Thin and flexible, « bendable » – Tunable emission wavelength (according to dopant) – The fiber itself is the scintillator, possibly over very long length
😠	– Thick (1 mm in diam.), rigid – Limited emission range (mainly UV-blue) – Scintillation quenching	– Inorganic scintillation is « slow » – Scintillation quenching

Water: Z = 7.42
Silicon: Z = 14



In-core luminescent ions Cu^{+}, Gd^{3+}, Tb^{3+}, Ce^{3+}, Sm^{3+},… or Ge

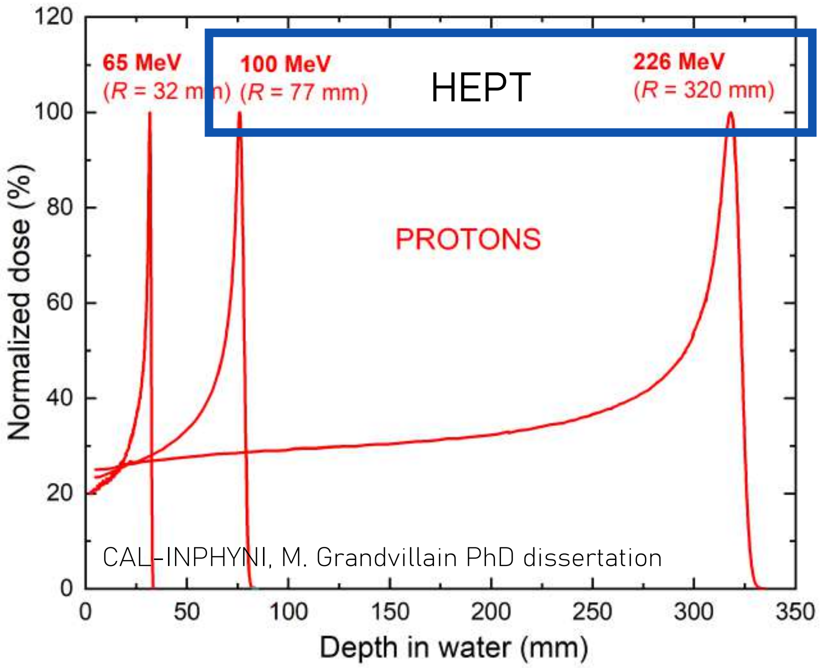


Silica fibers offer opportunity of:

- In-vivo dosimetry
  - at patient's skin
  - In brachyterapy catheter
- Distributed sensing

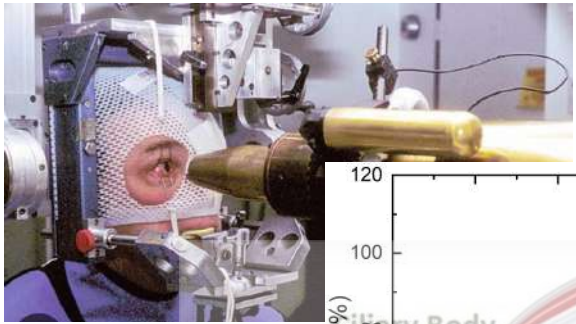
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

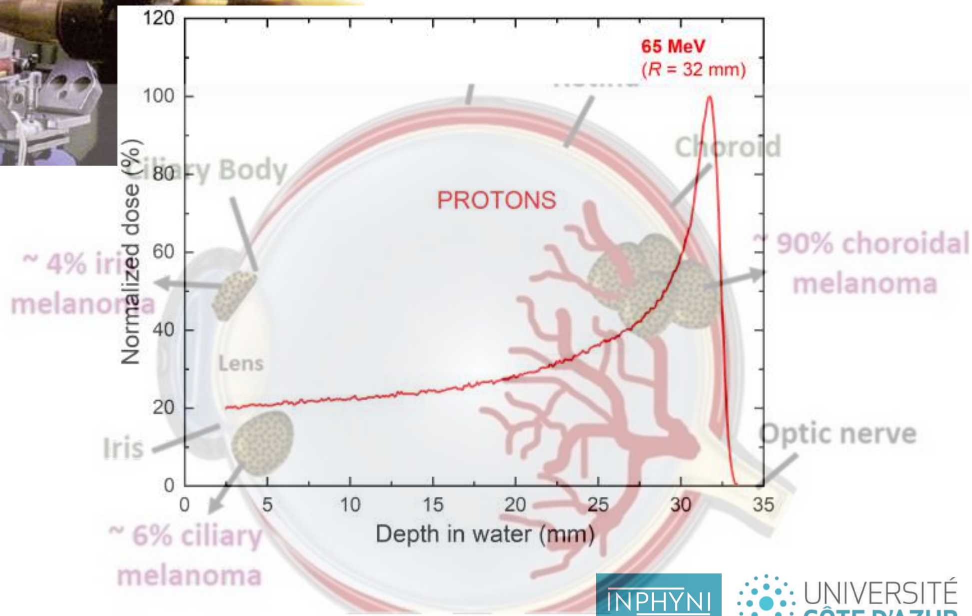
What is HEPT?



65 MeV : protons penetrate up to 3,2 cm in soft tissue

→ Can only treat ocular (uveal) melanoma





4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

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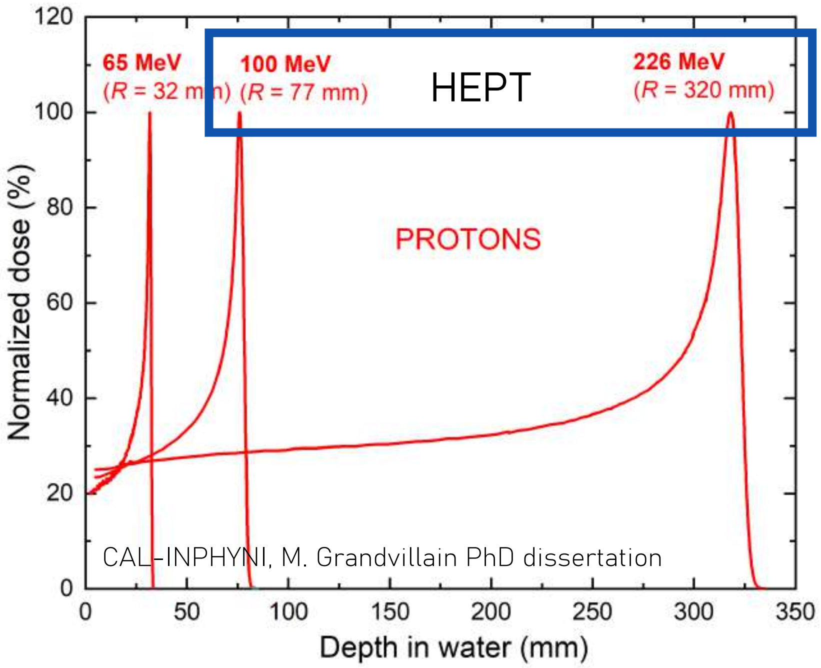


CAL–INPHYNI, M. Grandvillain PhD dissertation

65 MeV : protons penetrate up to 3,2 cm in soft tissue
→ Can only treat ocular (uveal) melanoma

Energy up to 226 MeV, range = 32 cm in soft tissue
→ Protons can pass trough human body
→ Can reach all tumors.

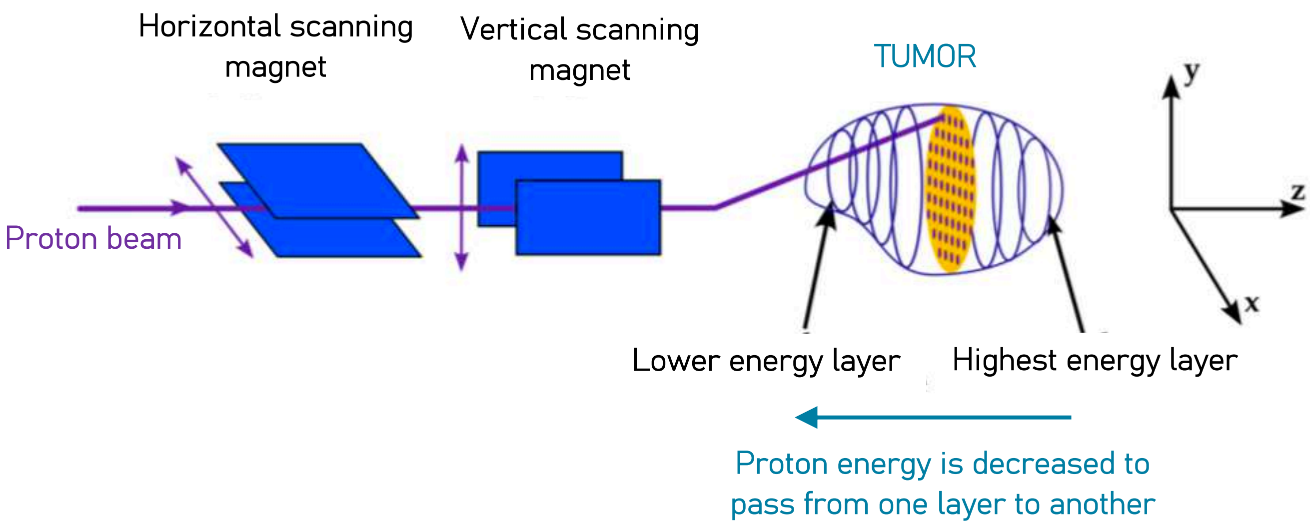
Superconductor SynchroCyclotron (S2C2)

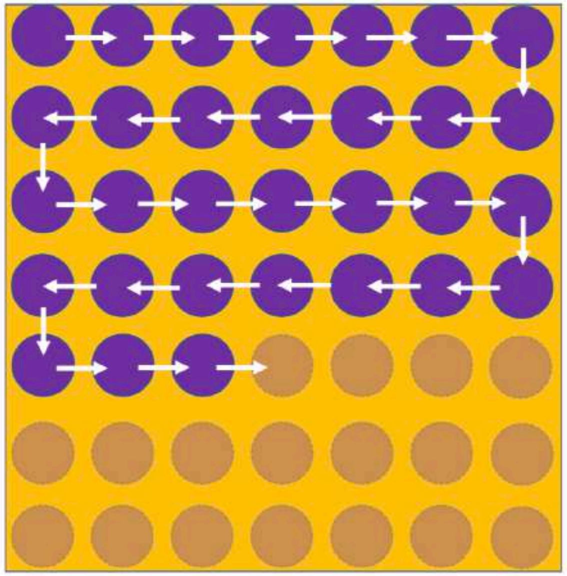
S2C2 IBA ProteusOne, CAL, Nice

ProteusOne, Gantry, CAL, Nice

4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

« Pencil Beam Scanning » (PBS) is used to irradiate the tumor with mm-size spots, layer by layer





Transverse scanning of a layer

CAL-INPHYNI, M. Grandvillain PhD dissertation

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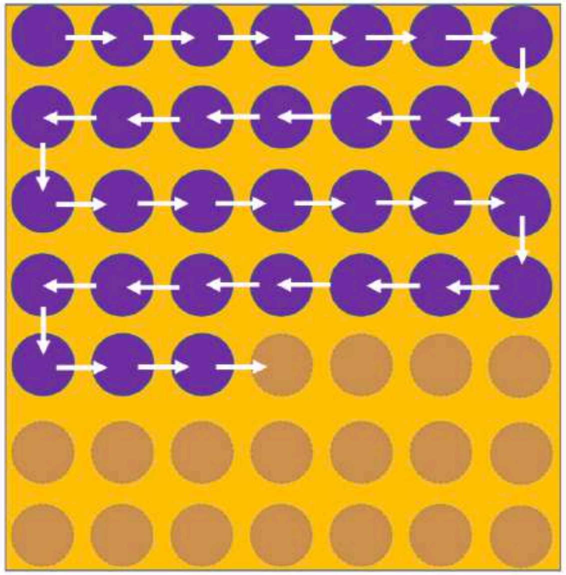
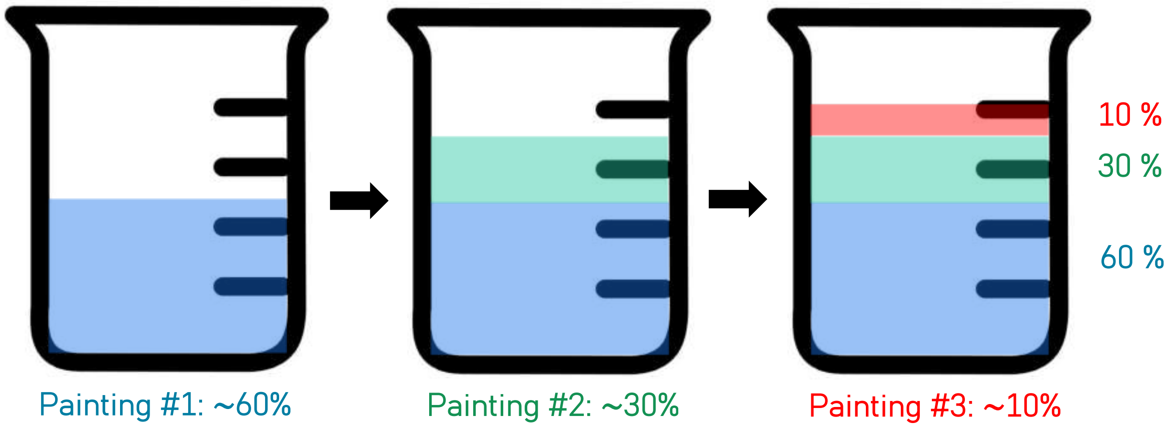
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

« Pencil Beam Scanning » (PBS) is used to irradiate the tumor with **mm-size spots, layer by layer**



Transverse scanning of a layer

On each layer, the planned proton fluence is **delivered in three successive scanning (« paintings »)** for better accuracy

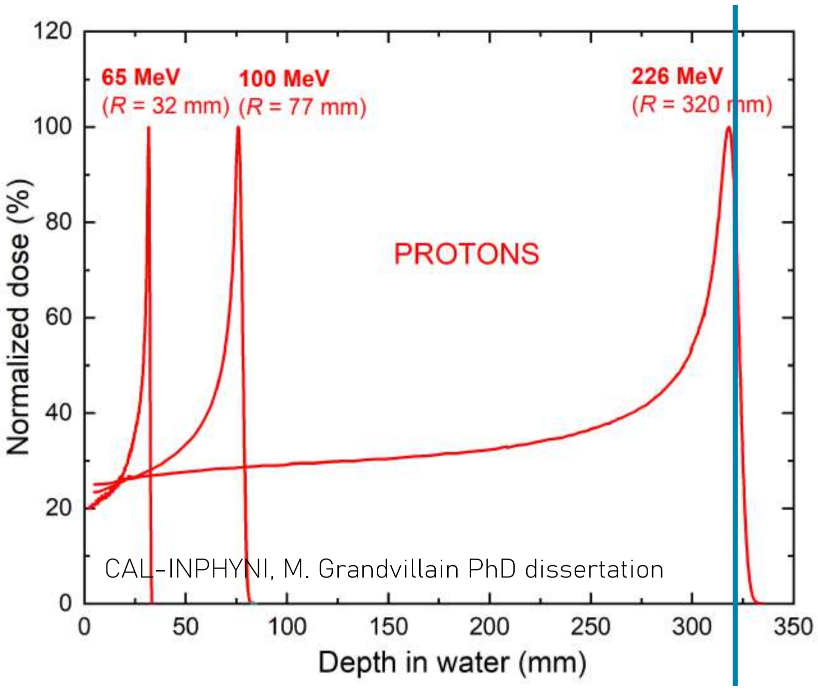


« Blind golfer algorithm » is used to adjust each painting

4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

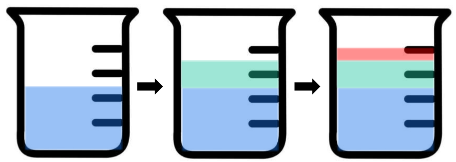
Crucial QA controls

F

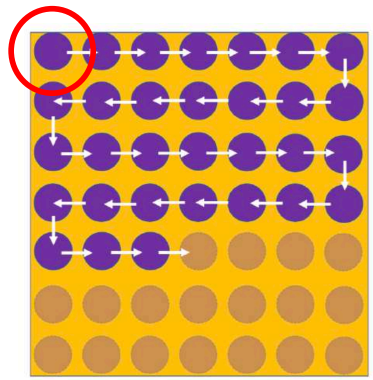


Depth-dose profiles

RANGE *R*



Painting sequence



Spot size

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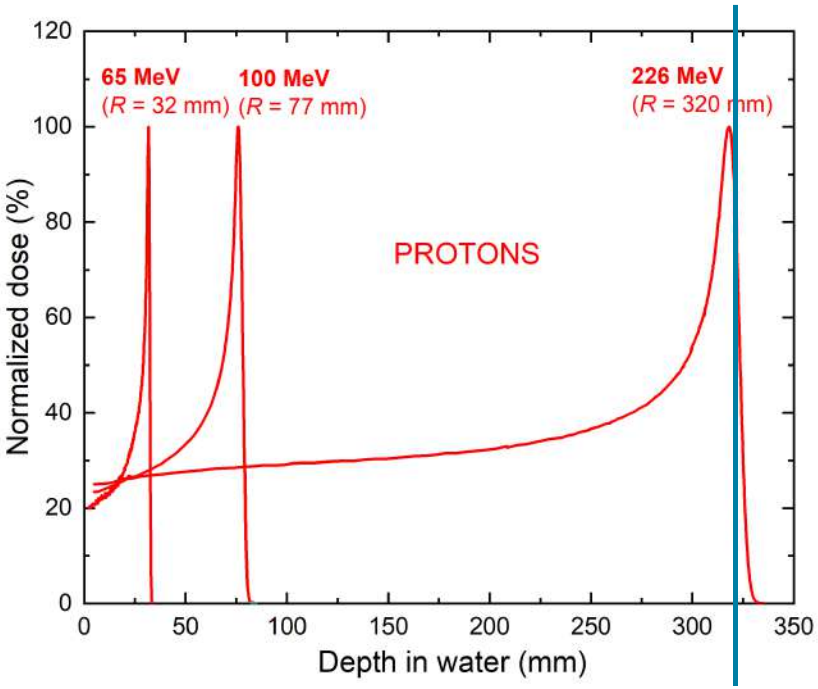
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

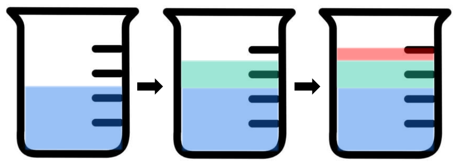
Crucial QA controls

F

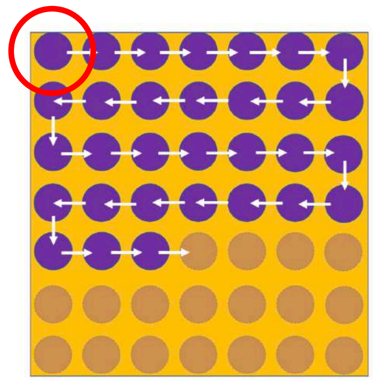


Depth-dose profiles RANGE *R*

Already done (ion chambers, diodes)



Painting sequence

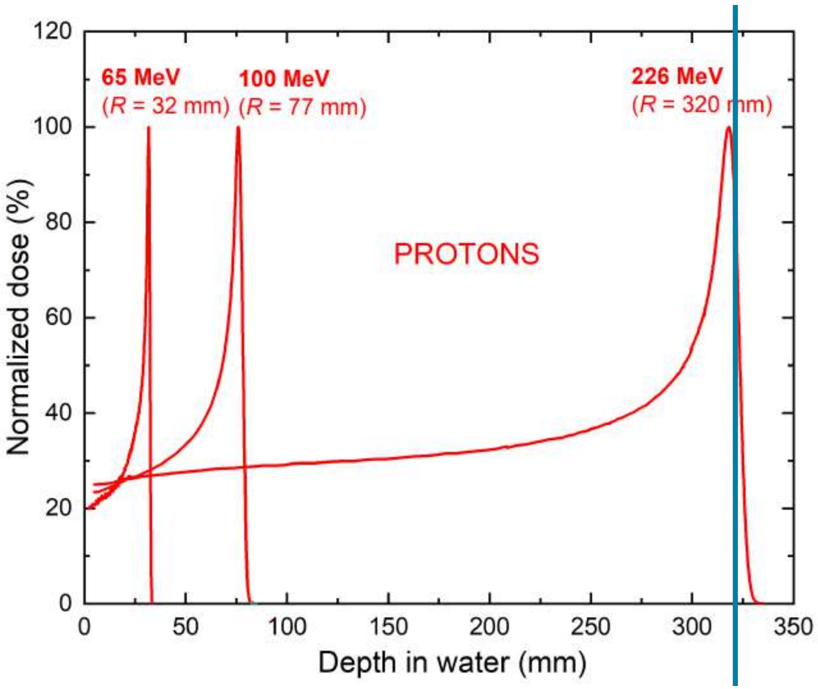


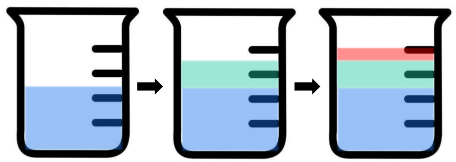
Spot size

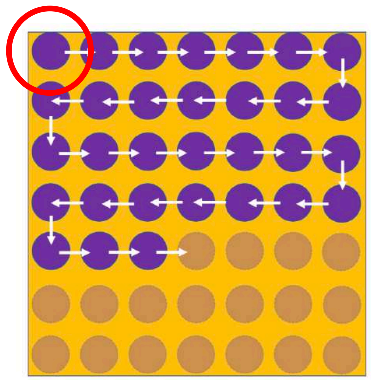
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Crucial QA controls

F







Depth-dose profiles RANGE *R*

Already done (ion chambers, diodes)

Painting sequence NEW

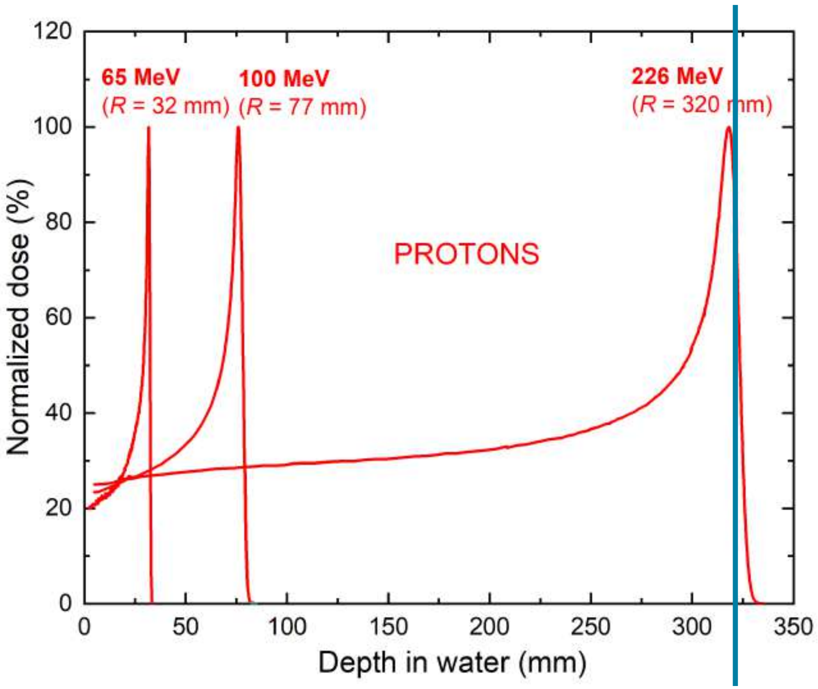
Not feasible with state-of-the-art sensors

Spot size

4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

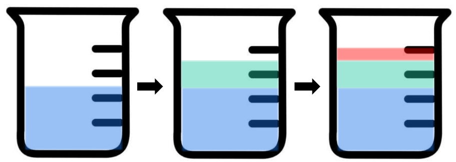
Crucial QA controls

F



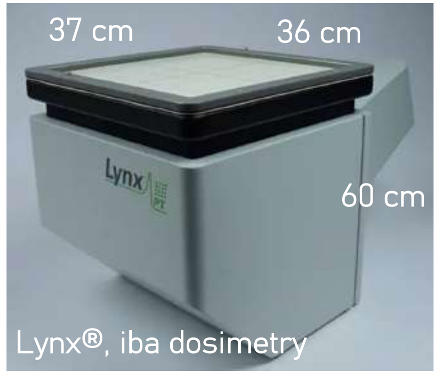
Depth-dose profiles RANGE R

Already done (ion chambers, diodes)



Painting sequence NEW

Not feasible with state-of-the-art sensors



Spot size NEW

Already done (Lynx®), but at water surface only

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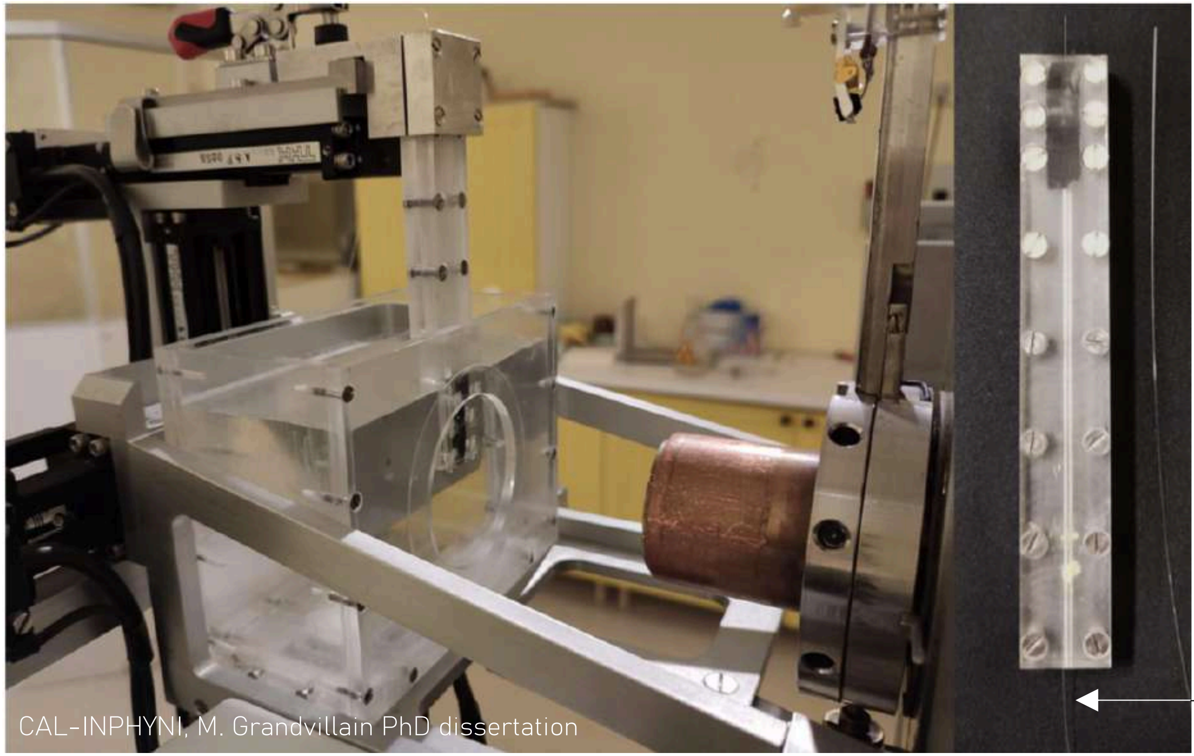
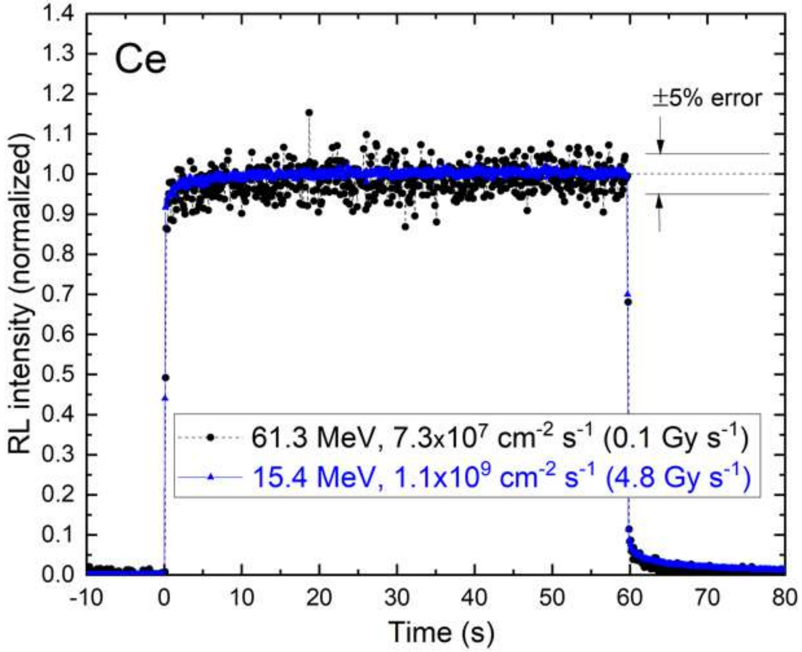
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Depth-dose profiles

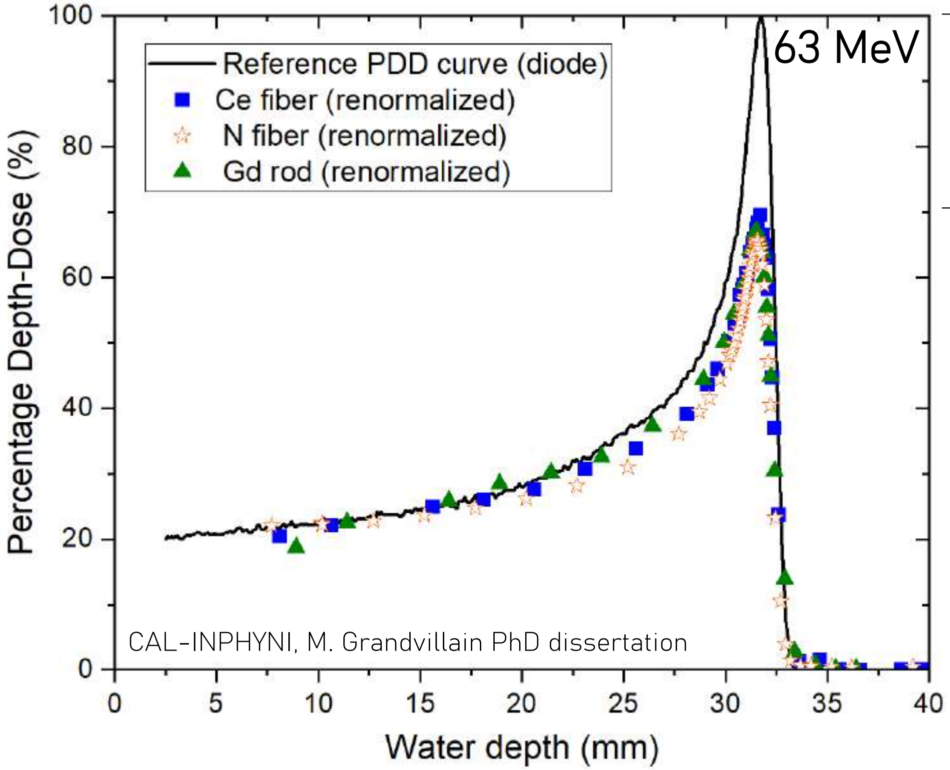




Radioluminescent fiber probe (nitogen doped), 1 cm long

4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Depth-dose profiles



Scintillation quenching
Dose underestimation

Fluence rate (cm^{-2} s^{-1})
ϕ'

Energy deposition

Dose rate (Gy s^{-1})

$$D' = \frac{S(E)}{\rho}\phi'$$

Mass stopping power $S(E)/\rho$ of H^+ and e- increases at low energy

Ionisation: conversion to RL

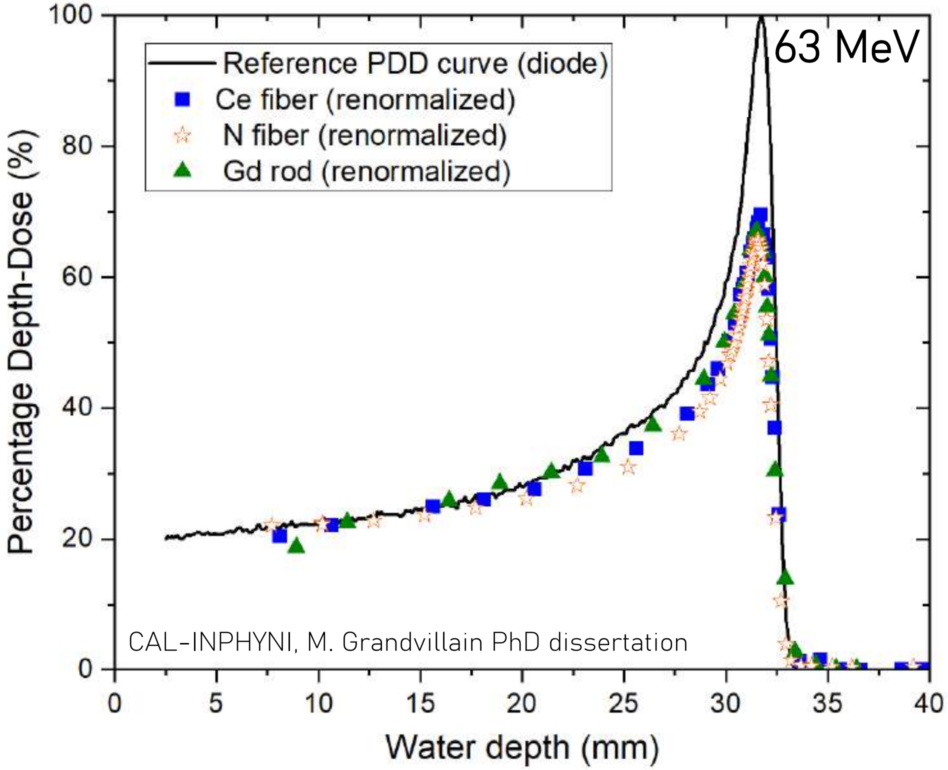
RL

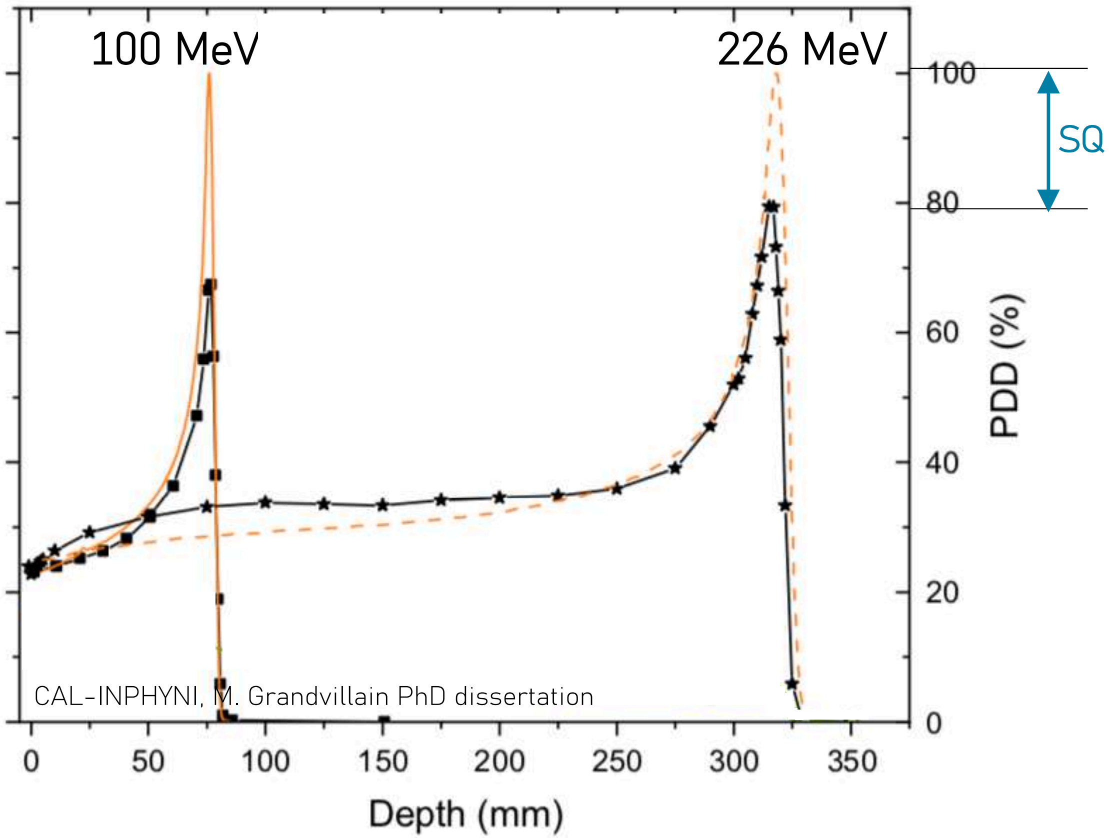
$$RL = k(E)D'$$

Conversion efficiency $k(E)$ decreases with energy
=
SCINTILLATION QUENCHING

4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Depth-dose profiles





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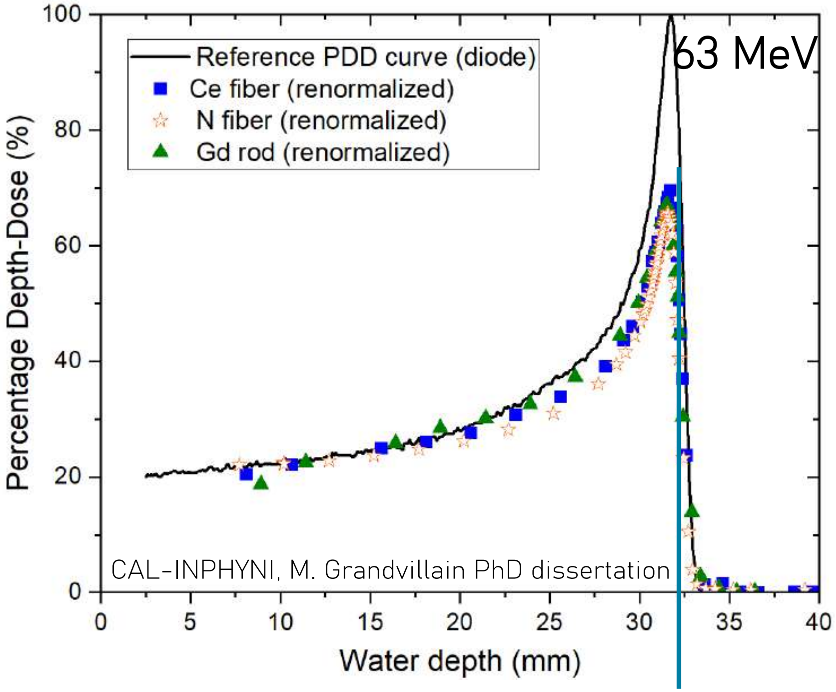
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Range



@ 10% off after peak

R90 values from silica-fibers related PDD curves (mm)

	Reference	N-doped	Ce-doped	Gd-doped
63 MeV	32.05	31.9	32.02	31.9
100 MeV	77	77.3	–	–
226 MeV	320	319	–	–

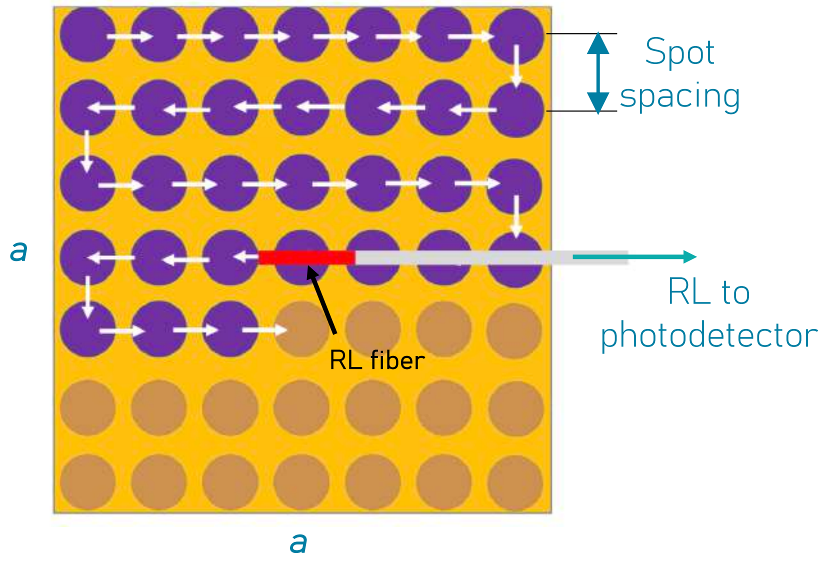
Relative deviation from reference

	Reference	N-doped	Ce-doped	Gd-doped
63 MeV	0	-0.47 %	-0.09 %	-0.47 %
100 MeV	0	+0.39 %	–	–
226 MeV	0	-0.31 %	–	–

Very good range estimate across the whole range of clinical energies, **despite SQ**

4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Painting sequence NEW



In QA control conditions (not real patient's plan)

- Square irradiation field, side length ***a*** **= 10.2 cm**
- **1-cm long RL** silica fiber (N-doped), centered
- Scanning with spot spacing of 2, 4, 6 or 8 mm

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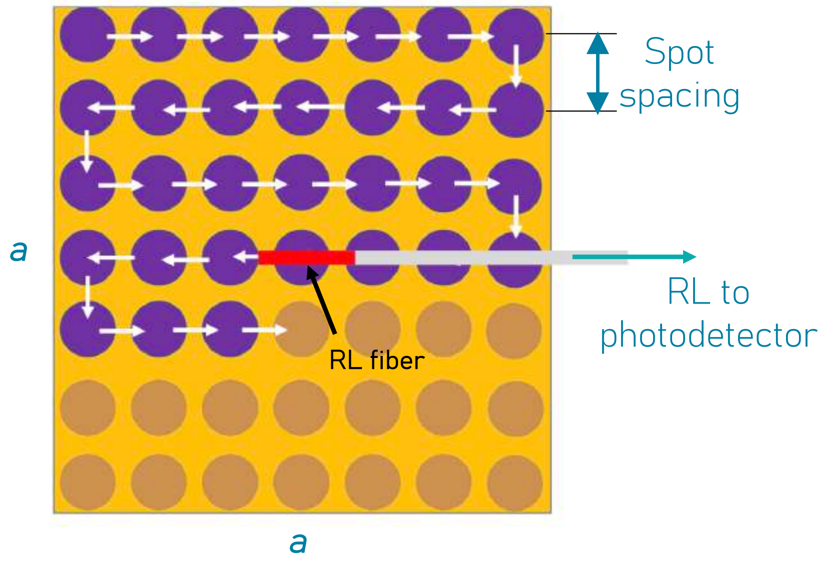
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Painting sequence NEW



CAL-INPHYNI, M. Grandvillain PhD dissertation

In QA control conditions (not real patient's plan)

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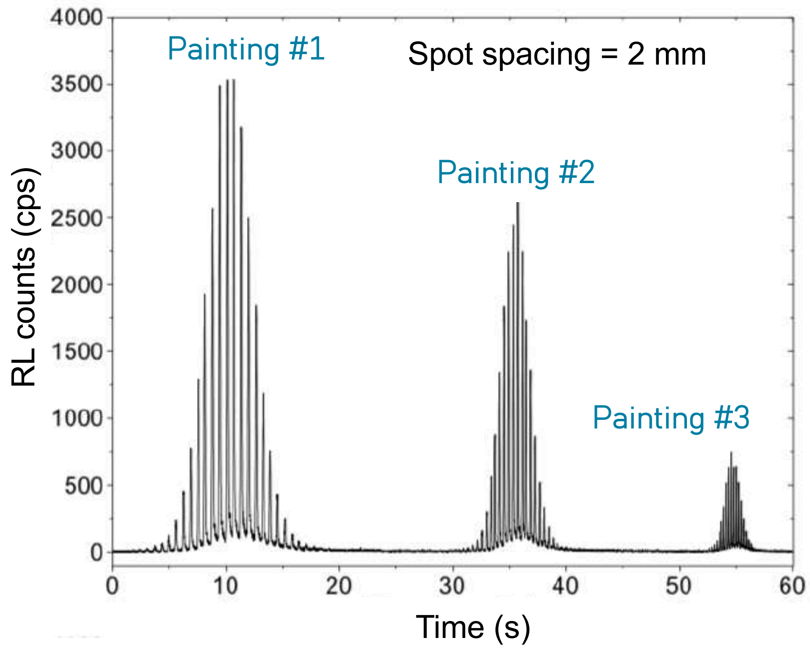

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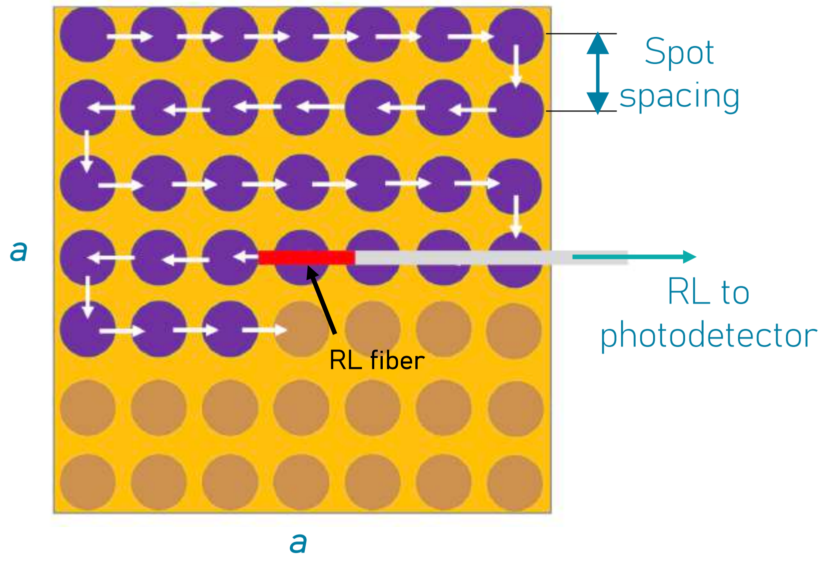
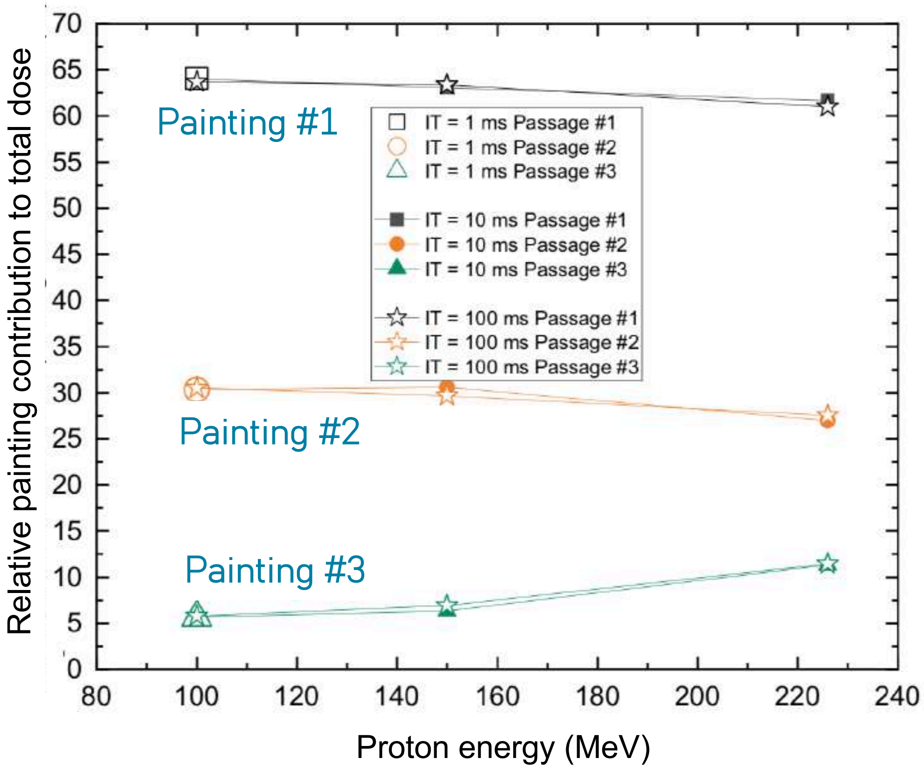
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Painting sequence NEW



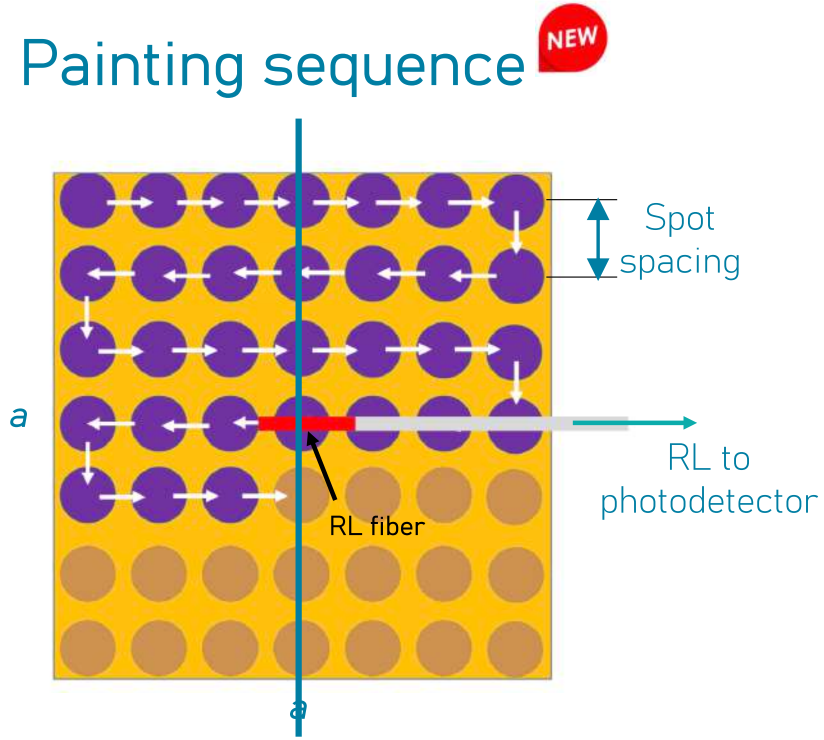
CAL-INPHYNI, M. Grandvillain PhD dissertation

Control of the relative dose given by each painting



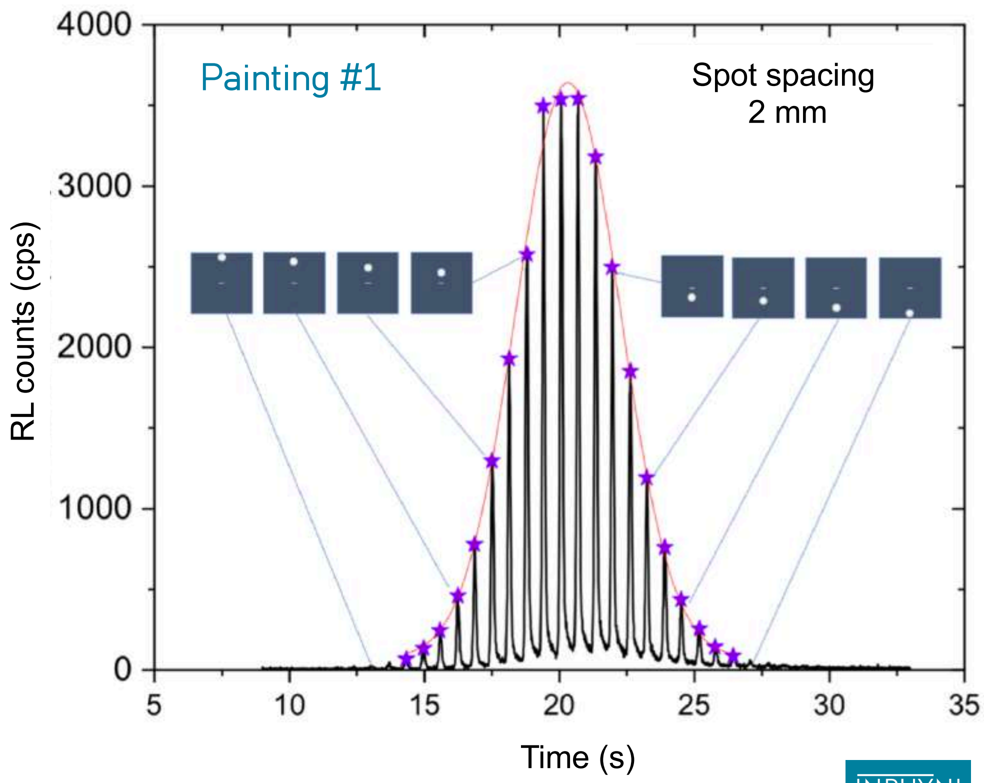
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Painting sequence



CAL-INPHYNI, M. Grandvillain PhD dissertation

Sub-peaks pass **relative maxima** each time the spot intercepts the **transverse axis** of the fiber probe



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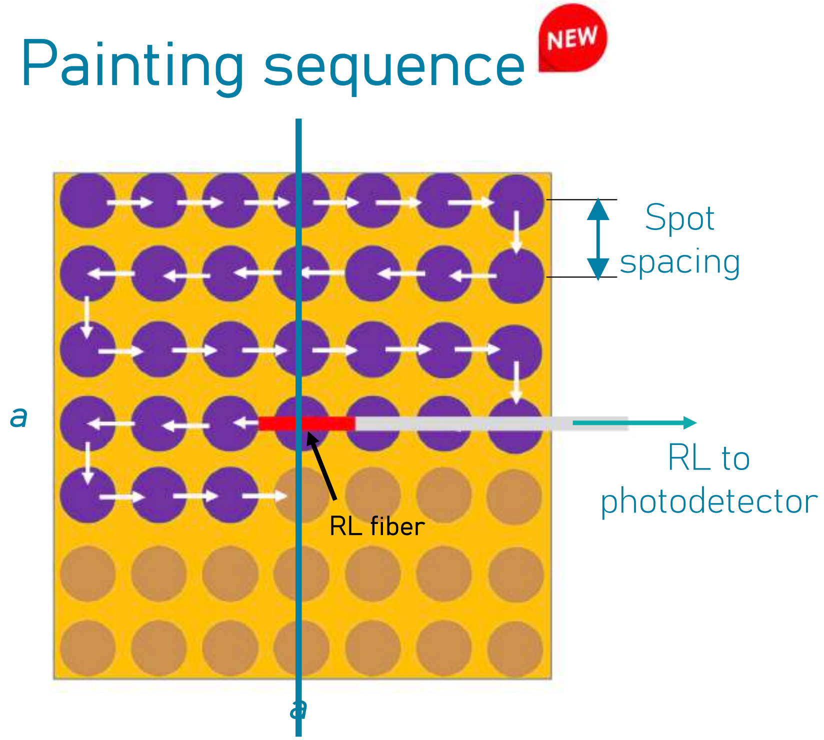
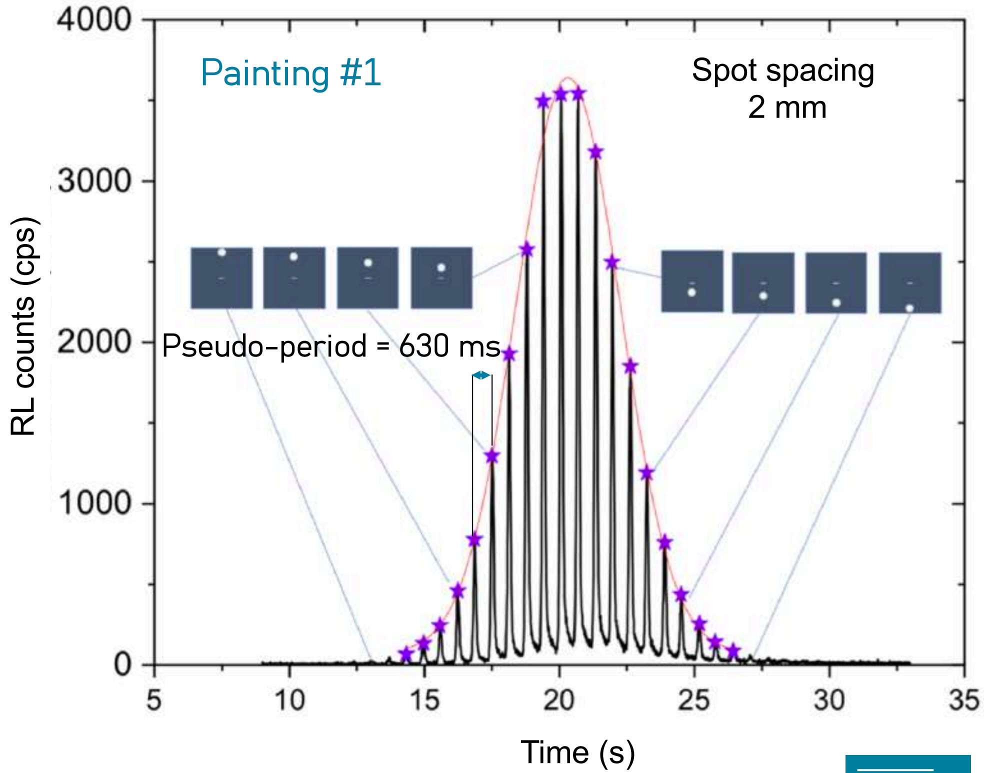
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Painting sequence



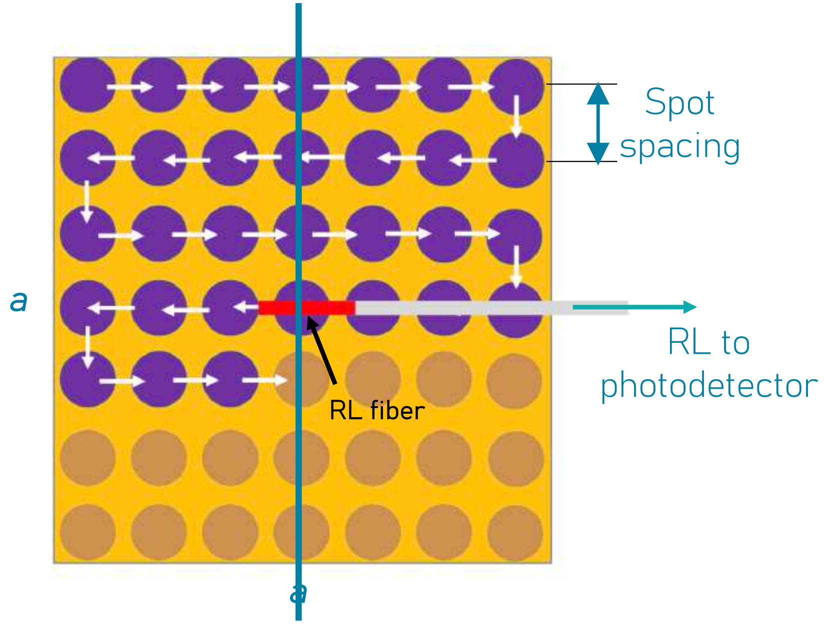
Pseudo-period between 2 subpeaks
= time for the spot to travel the distance *a*
→ **Control of the scanning speed**

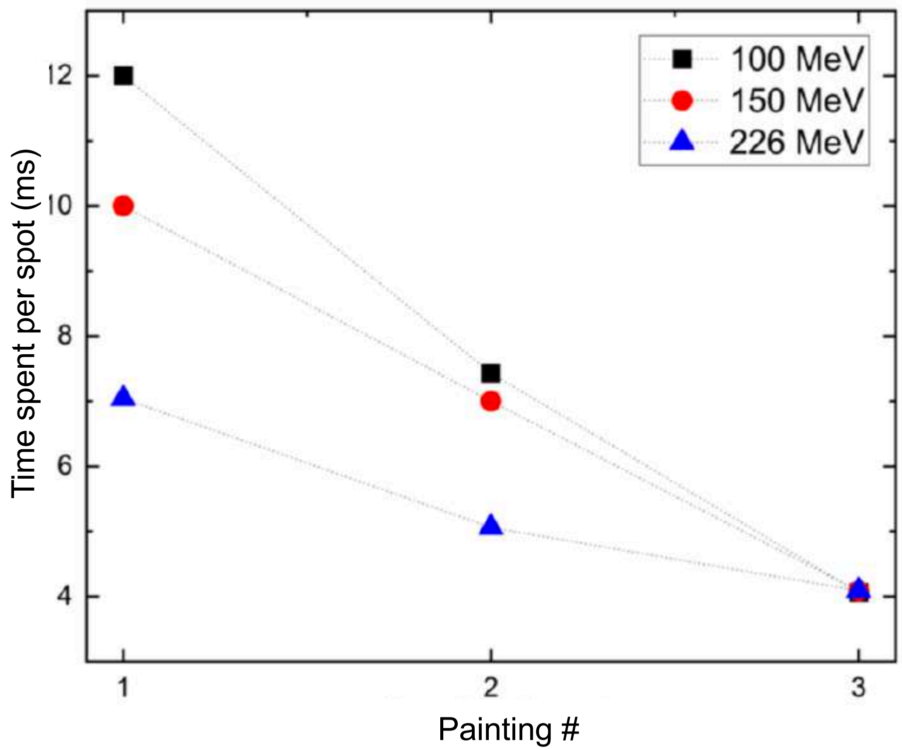
Sub-peaks pass **relative maxima** each time the spot intercepts the **transverse axis** of the fiber probe



4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Painting sequence





Pseudo-period between 2 subpeaks
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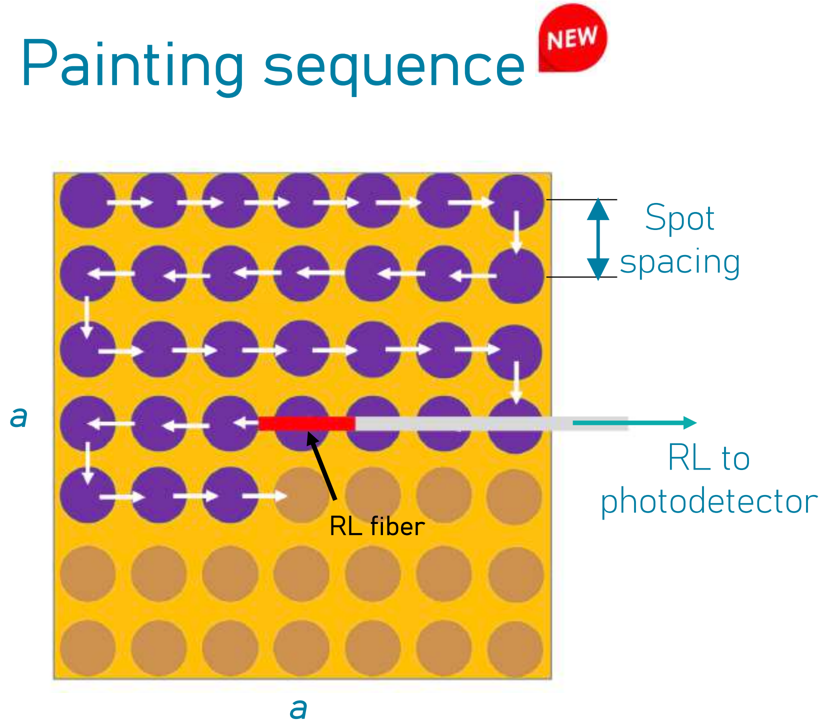
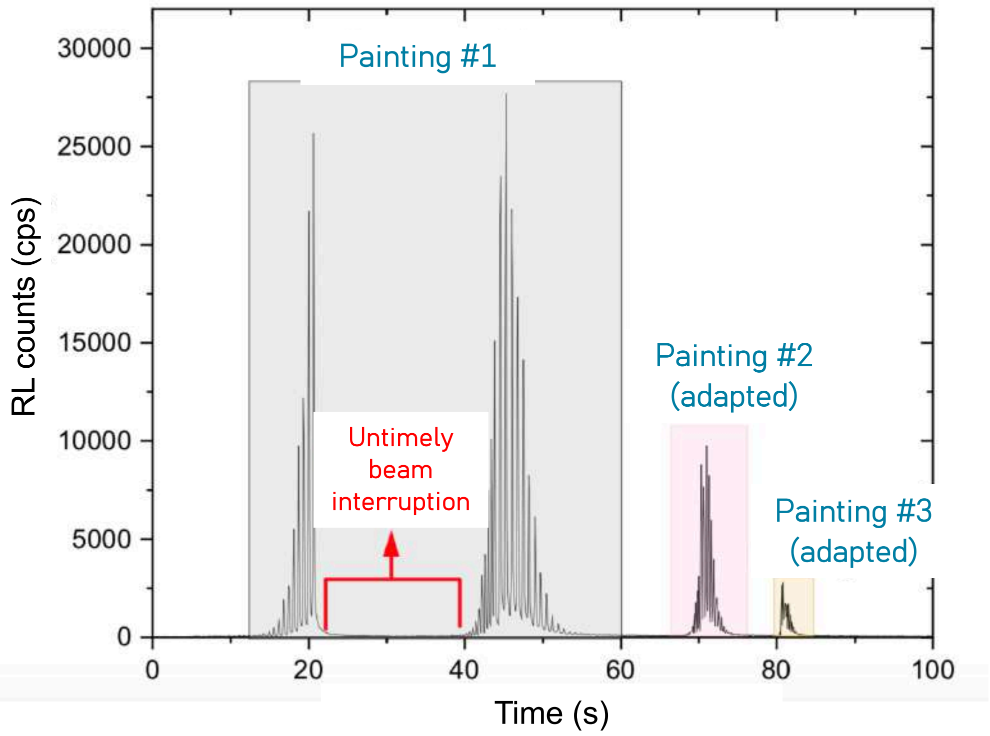
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Painting sequence



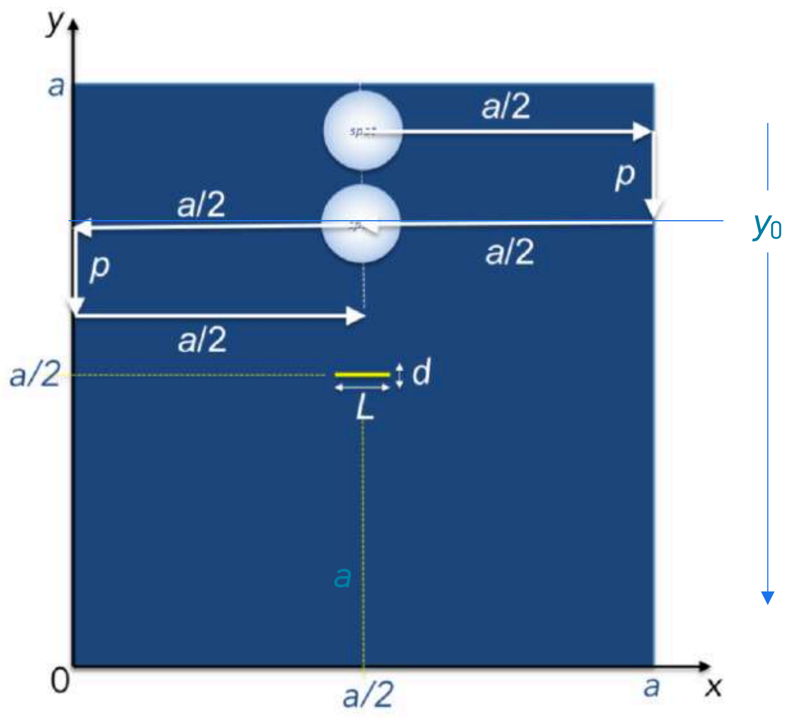
CAL-INPHYNI, M. Grandvillain PhD dissertation

In real treatment conditions: **detection of beam interruption** and control of the **dose delivery adaptation**



4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Spot size σ NEW



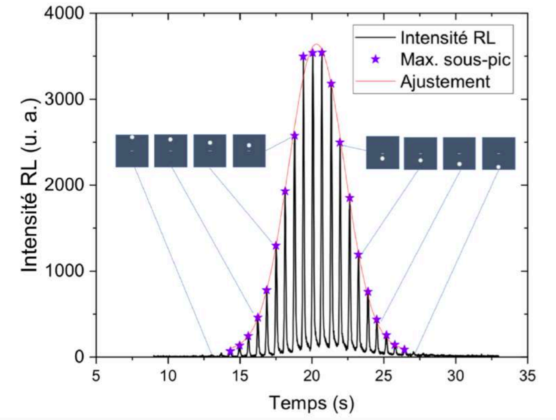
Spot fluence is spatially distributed following a gaussian distribution

- If spot center @(x_0, y_0), fluence @ (x, y) is

$$\Phi(x,y) = \Phi_0 \times \exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}\right)$$

- Fluence on the fiber probe at subpeak max.

$$\overline{\Phi}_{\text{subpeak}}(y_0) = \frac{\Phi_0\sigma^2\pi}{Ld} \times \text{erf}\left(\frac{L}{2\sqrt{2}\sigma}\right) \times \left[\text{erf}\left(\frac{a+d-2y_0}{2\sqrt{2}\sigma}\right) - \text{erf}\left(\frac{a-d-2y_0}{2\sqrt{2}\sigma}\right)\right]$$



- Time → Space coordinate:

$$y_0(t) = \frac{a}{2} - \frac{p}{T}(t - t_{\max}).$$

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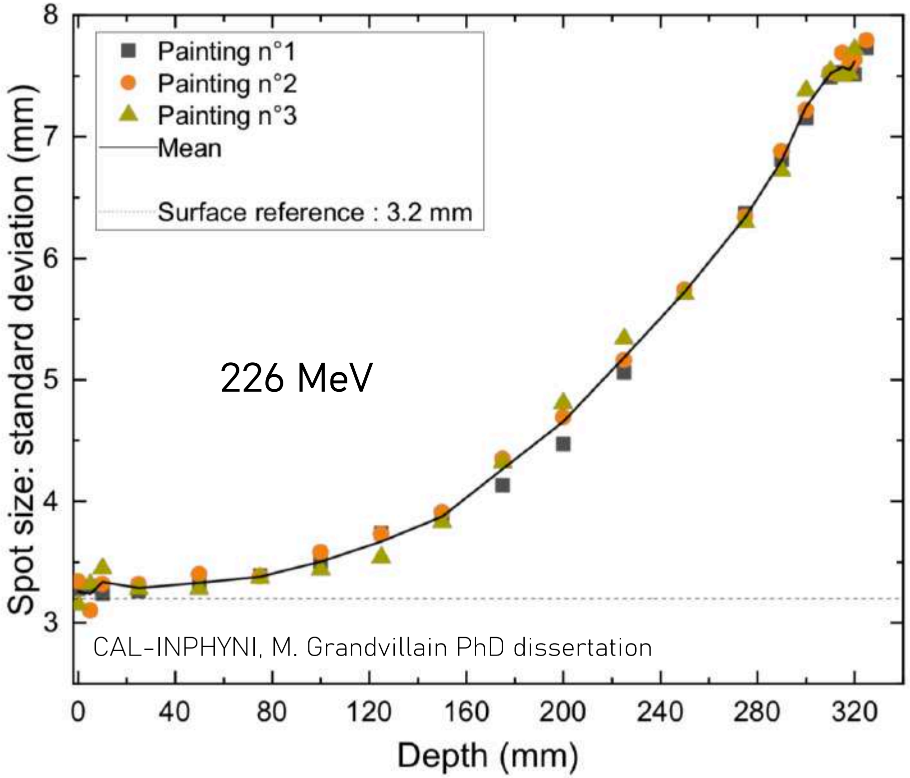
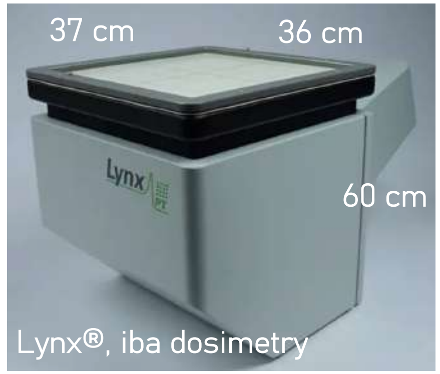
4D – TOPICAL EXAMPLE: HIGH ENERGY PROTONTHERAPY

Spot size σ NEW



- **In-depth monitoring of spot size** with a small fiber (1cm x 125 microns)

- **Much better (and much cheaper) that the « big » LYNX** that cannot be immersed in water!



- **All innovative controls (relative painting contributions, scanning speed, spot size) are made during the measurement of the depth-dose profile →** ALL IN ONE MEASUREMENT !

😁 😁 😁

- Silica fibers, used as RL dosimeters, are « flash ready»

- They offer important new opportunities to achieve enhanced QA controls in innovative, highly-precise treatment modalities (as HEPT)

- Other important opportunities
  - for brachyterapy (in-vivo dosimetry, with fibers in catheters)
  - for external RT: in-vivo 2D dose mapping
  - for internal vectorized RT (in vivo dosimetry)

- Next important step: distributed but « cheap » sensors (i.e. not based on OFDR).