

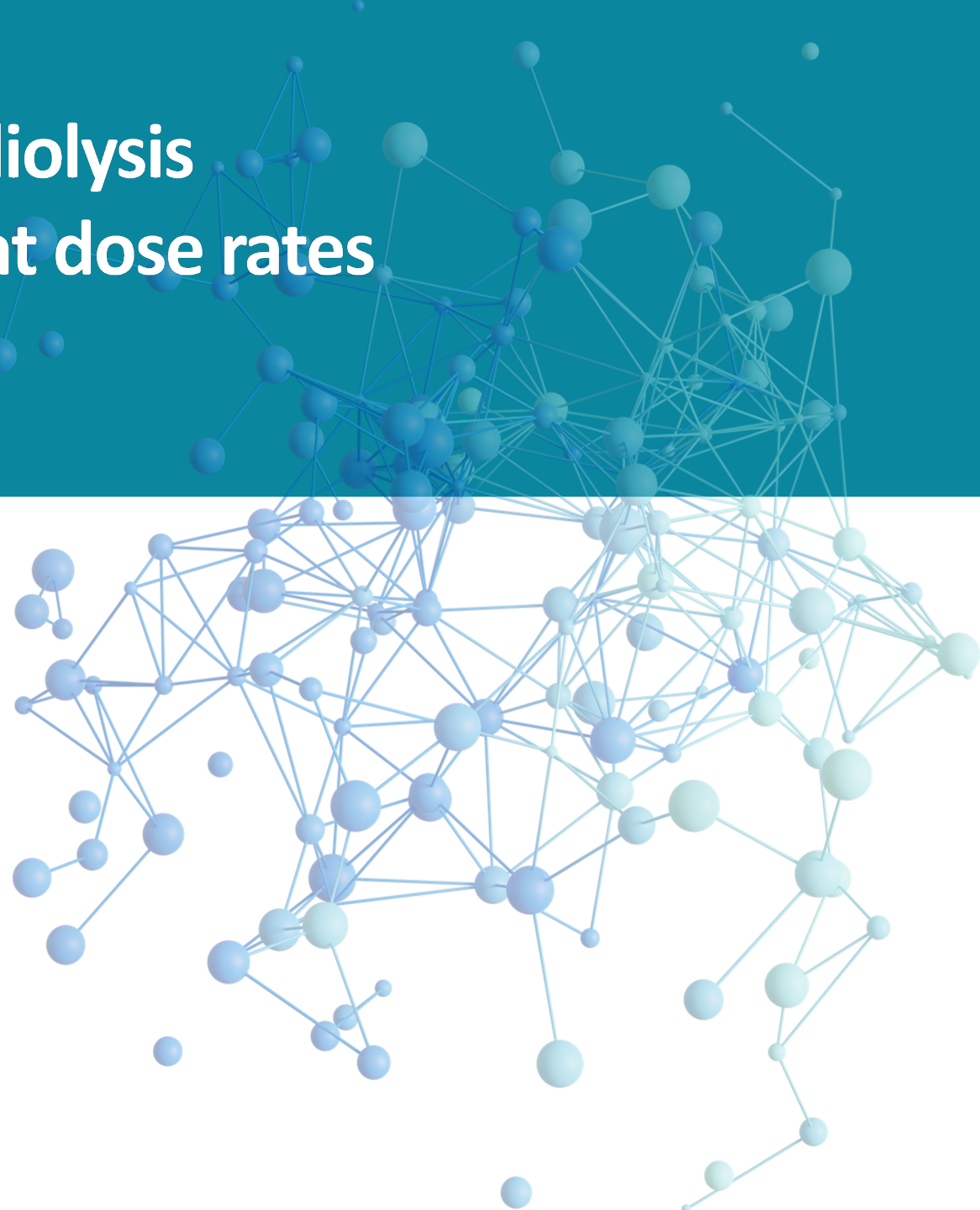
Monte Carlo simulation of Water radiolysis induced by Ion Beams under different dose rates

30 June 2026, GDR

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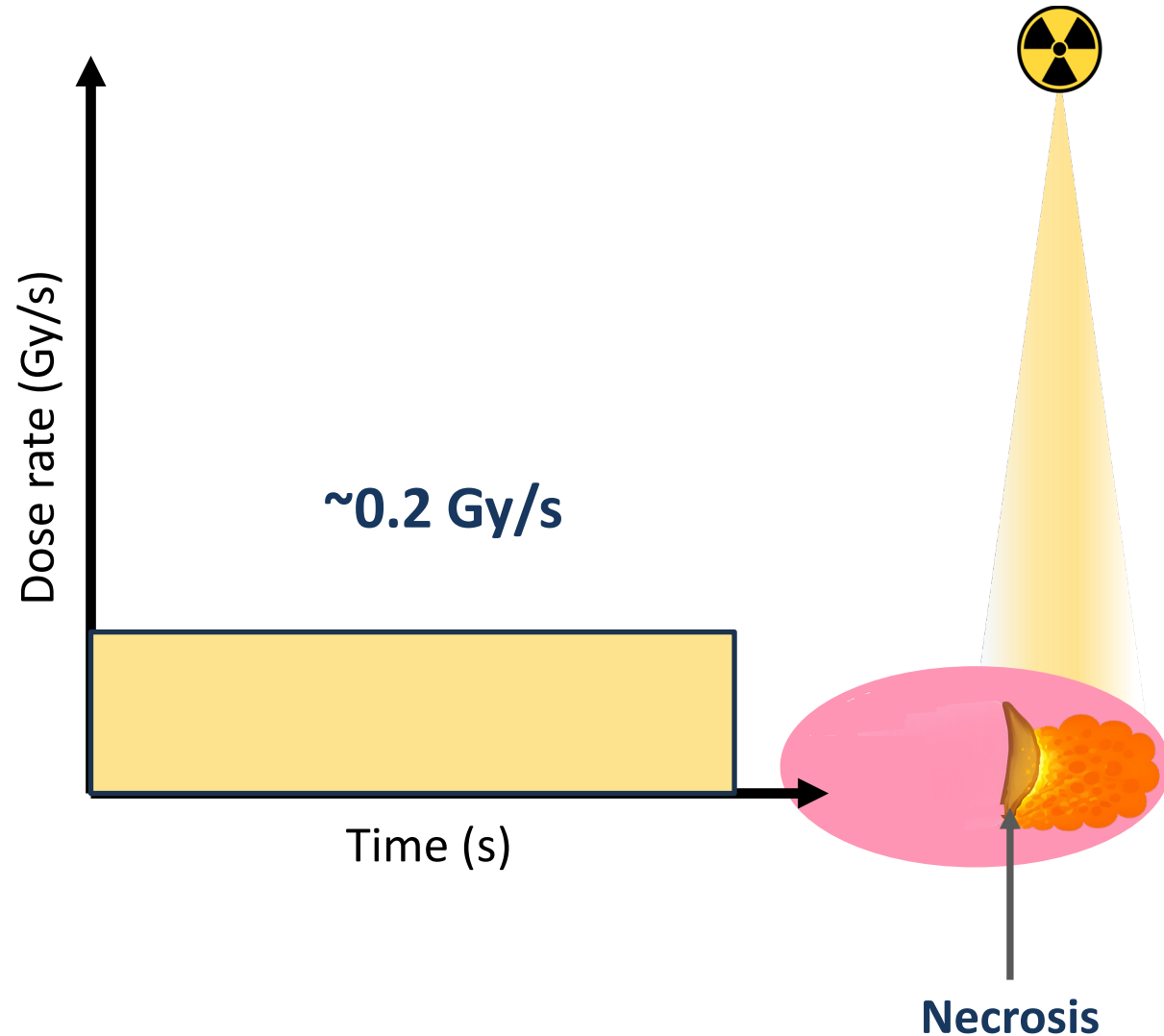
The background of the slide features a complex, abstract network diagram. It consists of numerous small, light blue circular nodes connected by thin, light blue lines. Some nodes are larger and have a double-circle outline, while others are smaller and have a single-circle outline. The connections form a dense, interconnected web that fills the corners and sides of the slide, leaving a central white area for the text.

Background

What is FLASH Radiotherapy ?

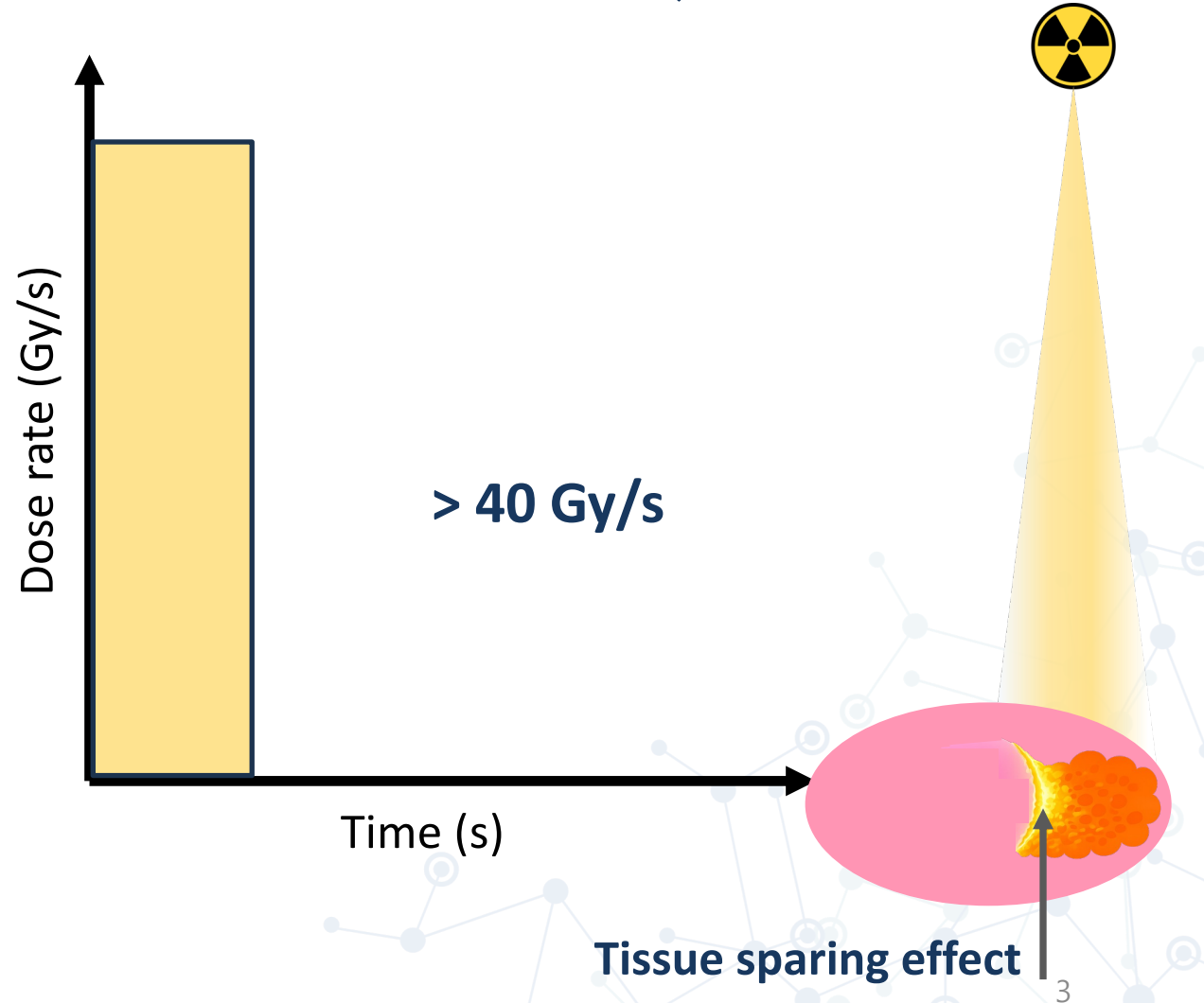
Conventional (Lower intensity of beam)

Timescale → min

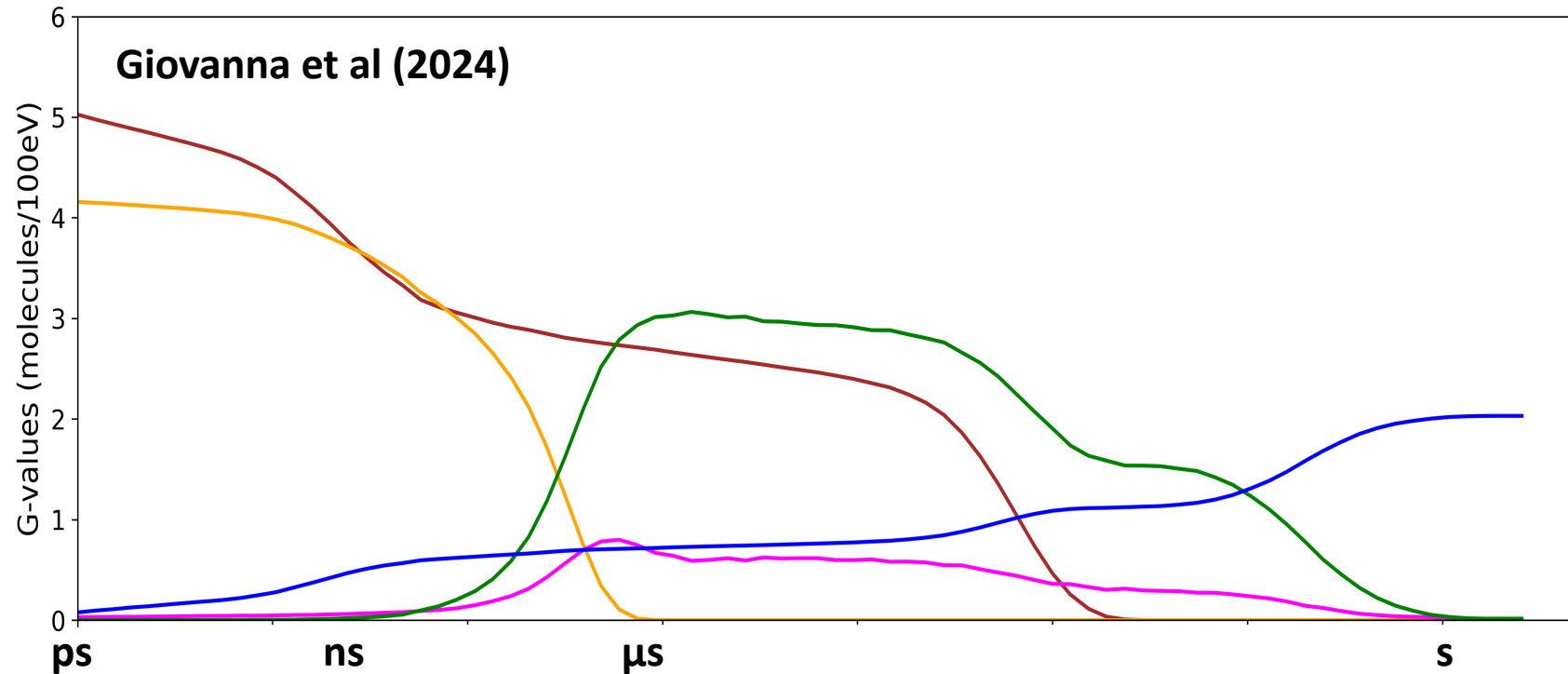
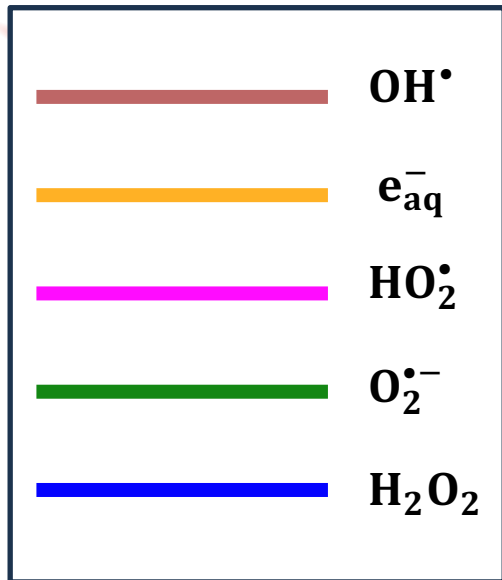
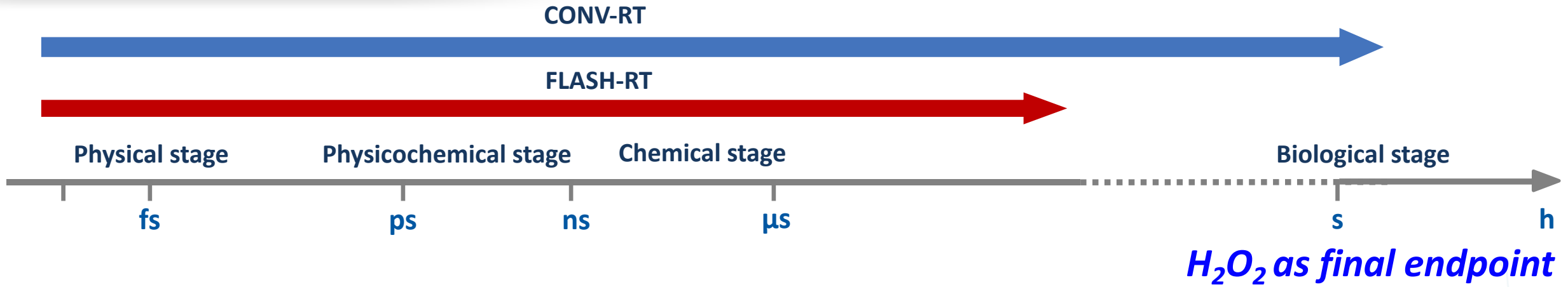


FLASH (Higher intensity of beam)

Timescale → ms



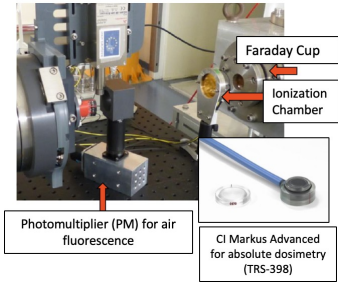
The chemical basis: From Radiolysis to Tissue sparing



A multidisciplinary project

Arronax
Nantes

Subatech



^{12}C (95 MeV) [0,01 Gy/s – 100 Gy/s]

H^+ (16–25 MeV) [0,1 Gy/s – 300 Gy/s]

GANIL

Caen

Strasbourg

IPHC
Institut Pluridisciplinaire
Hubert CURIE
STRASBOURG



Nantes

Clermont-Ferrand

QST

+ Japan (HIMAC)

He^{2+} (21 MeV) [0,067 Gy/s – 600 kGy/s]

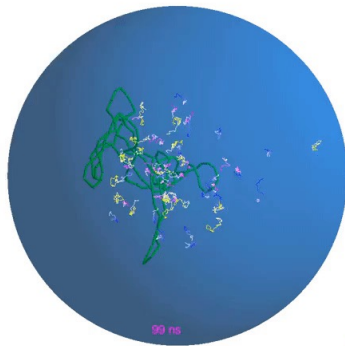
LP2i
Bordeaux

GATE

Bordeaux

GEANT4-DNA
A SIMULATION TOOLKIT

LPC



Experiment



Simulation

DB gathering GATE digital twins of the beam lines



Activity Map



Attenuation Map



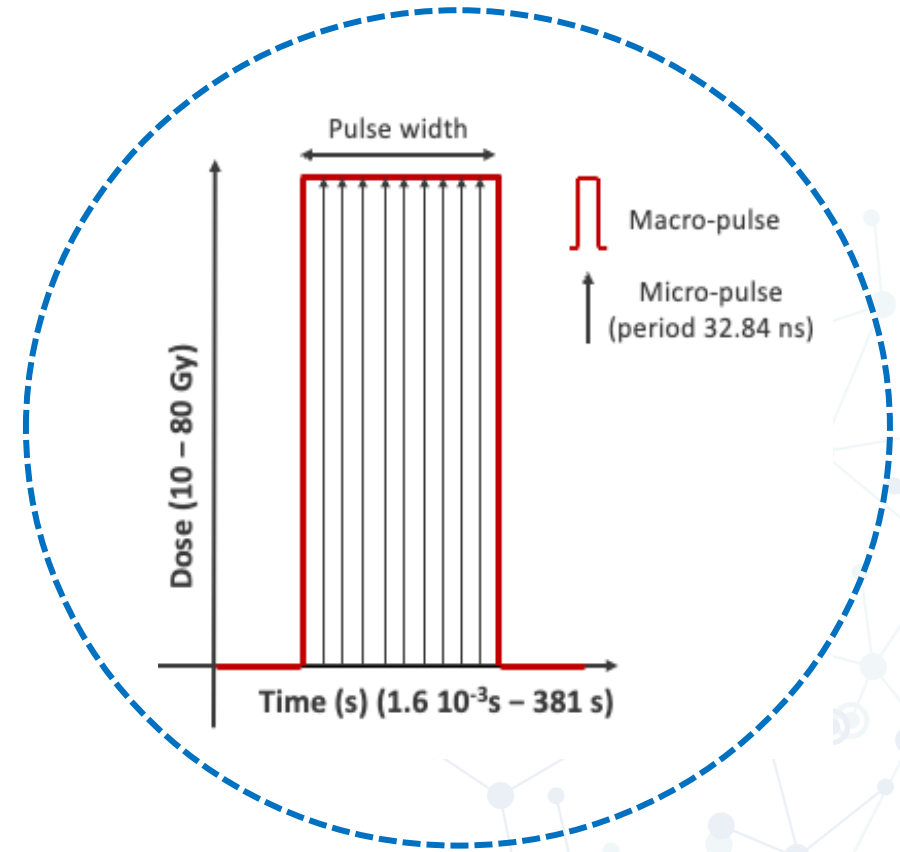
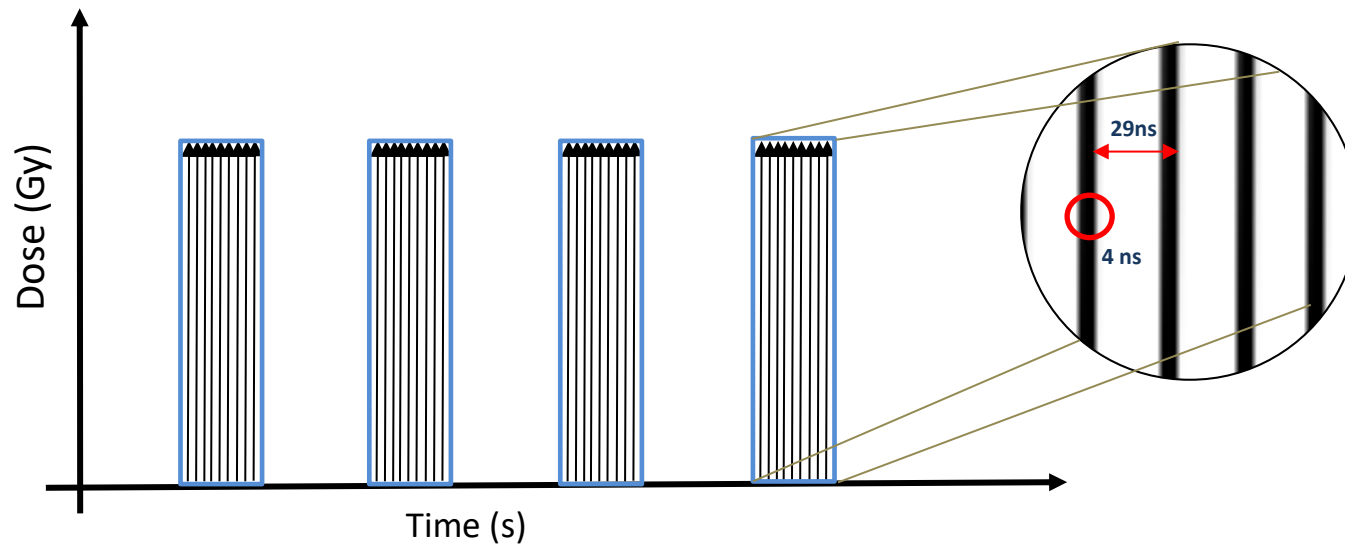
Dose Map



Experimental and simulated H_2O_2

Beam Production In ARRONAX

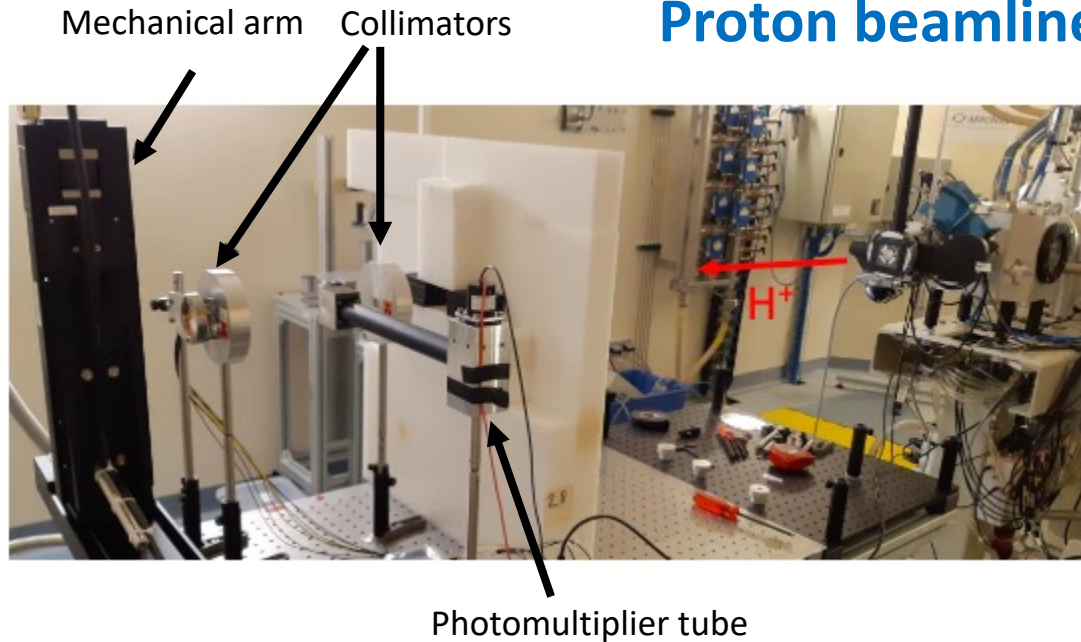
The time pulse structure



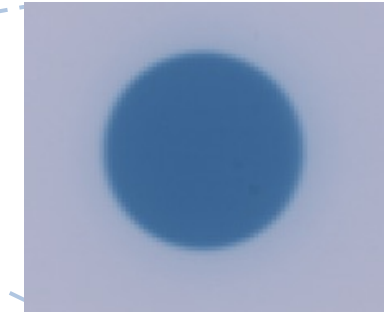
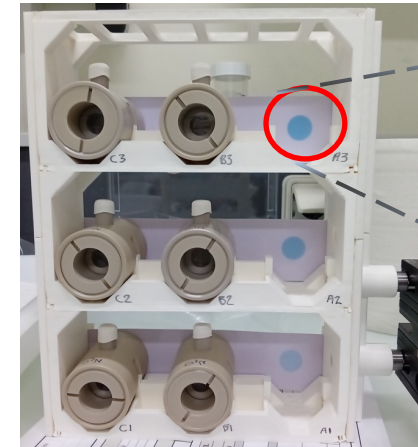
Measurement of Hydrogen Peroxide



Proton beamline



3D-printed cellholder



Film Orthochromatic OC-1 (Confirmation dose)



Beamline production

67.5 MeV proton beam

Intensity: 1 pA ~ 350 μ A

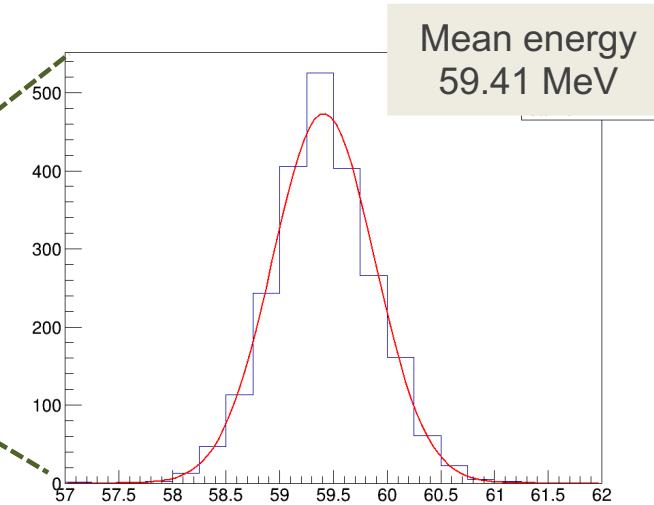
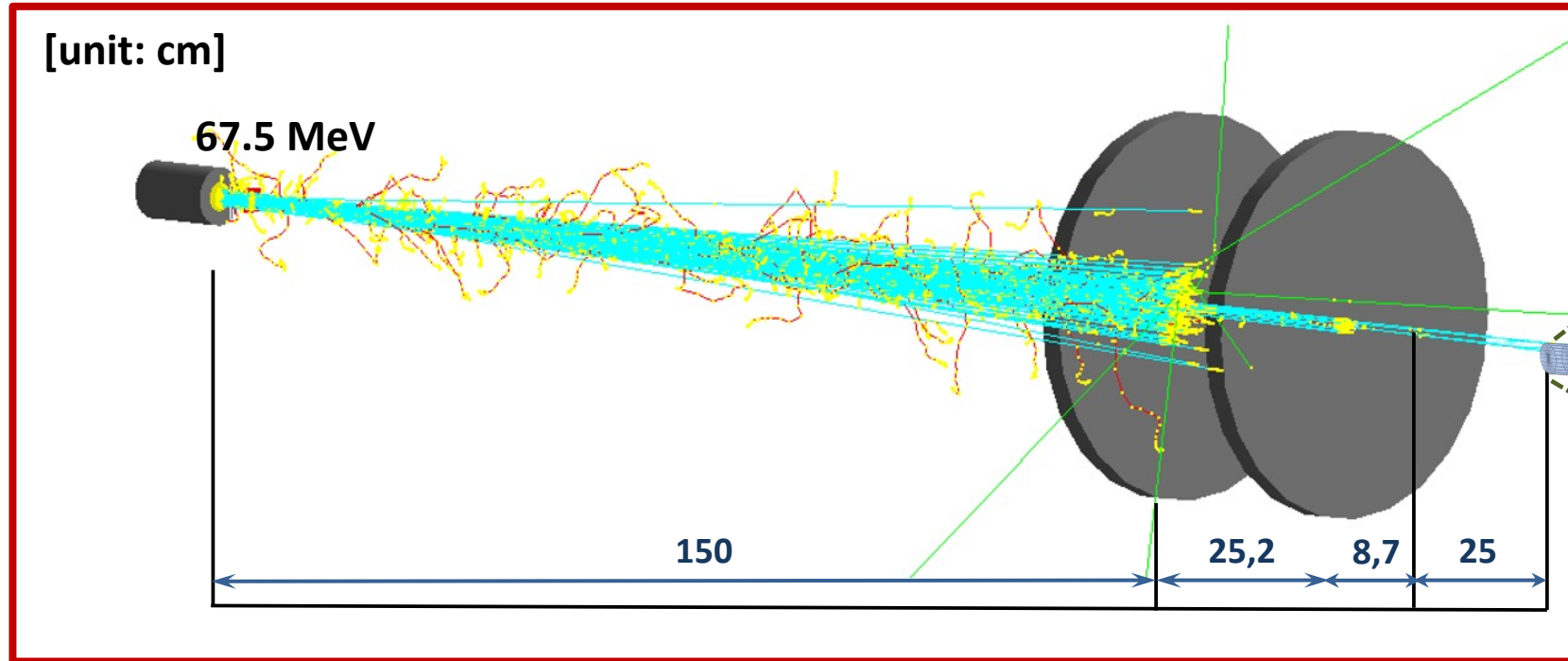
Dose rate: 0.2 ~ 6000 Gy/s

Parameters in measurement

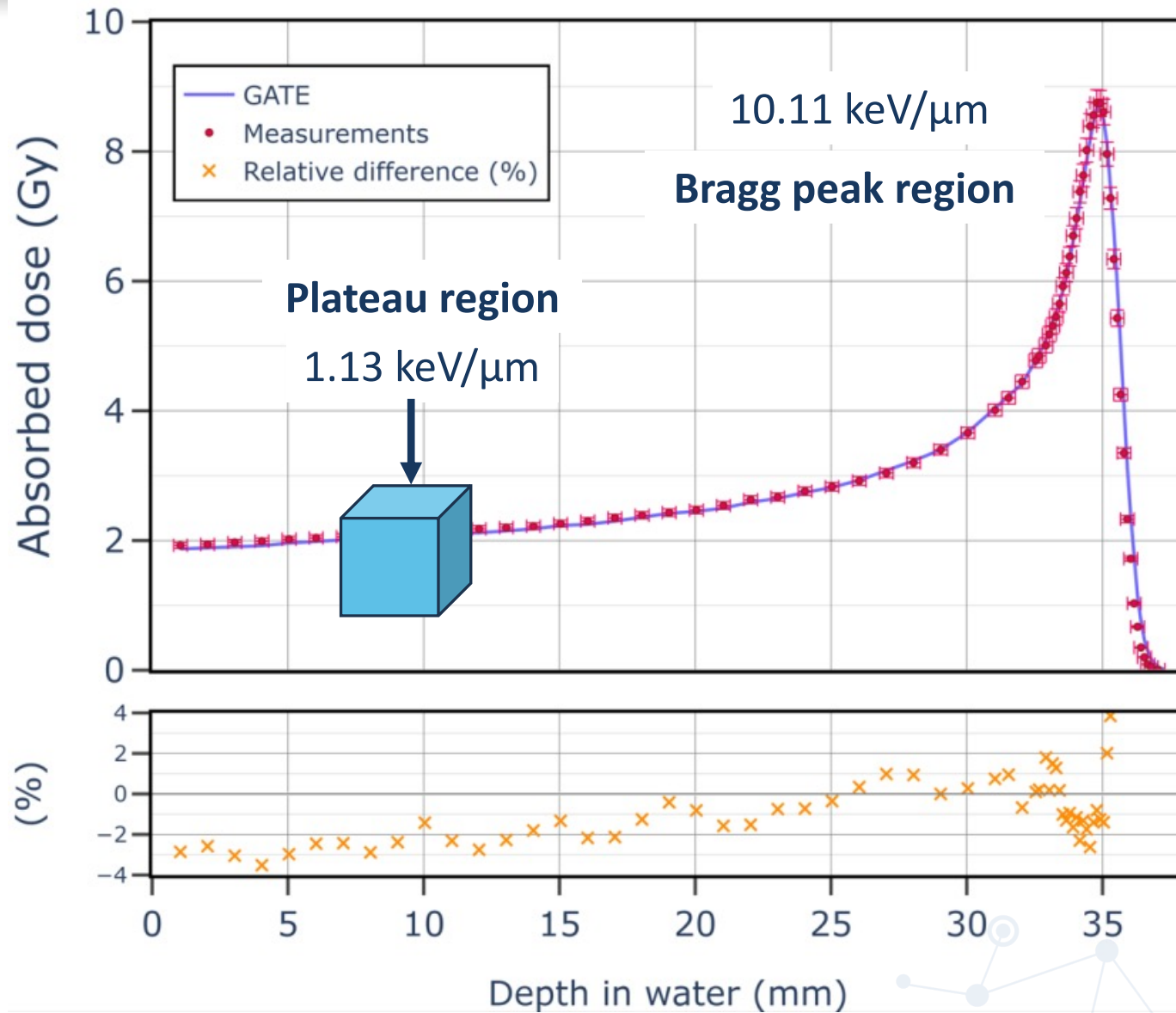
O₂ levels: Air (1% $\pm$ 0.6% and 21%)

pH : 5.5 $\pm$ 0.3 (pure water condition)

A macro – level digital twin of ARRONX proton beamline

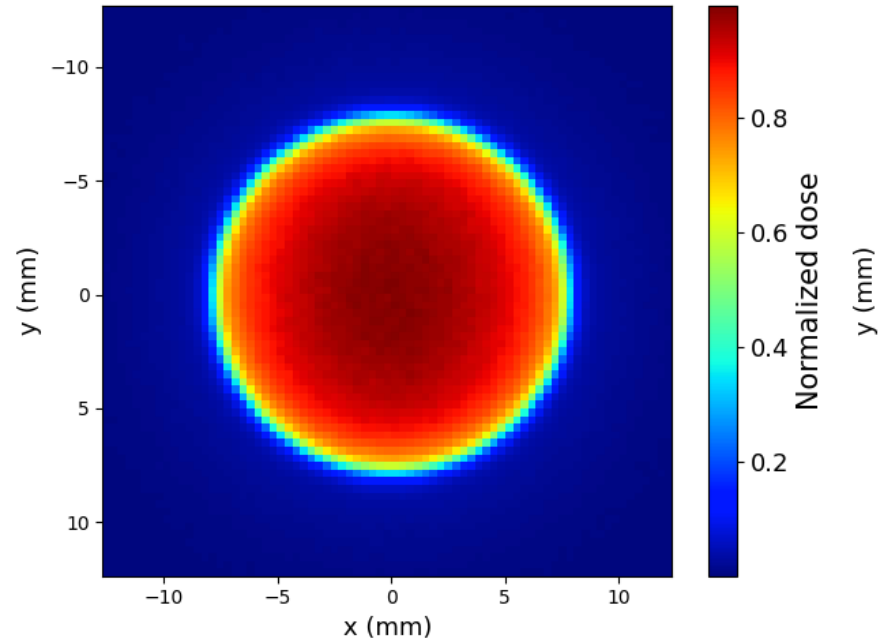


ARRONAX Proton beamlines using GATE 10

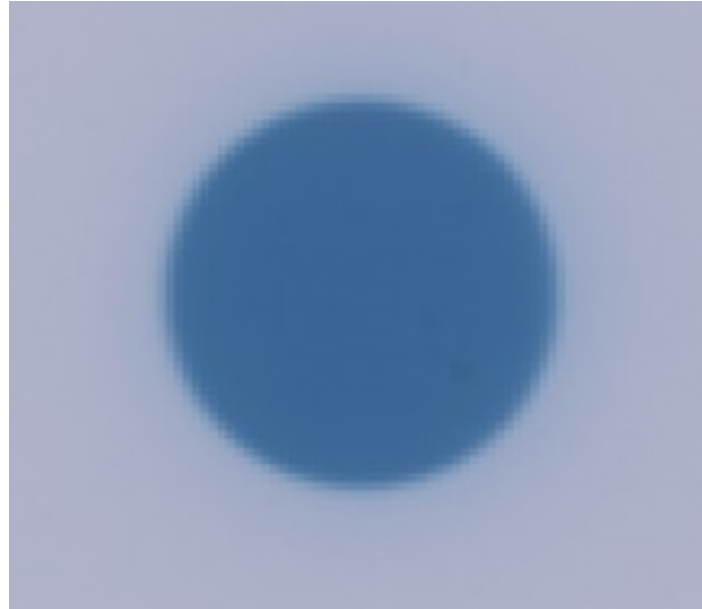


Film dosimetry validation: simulation vs Experiment

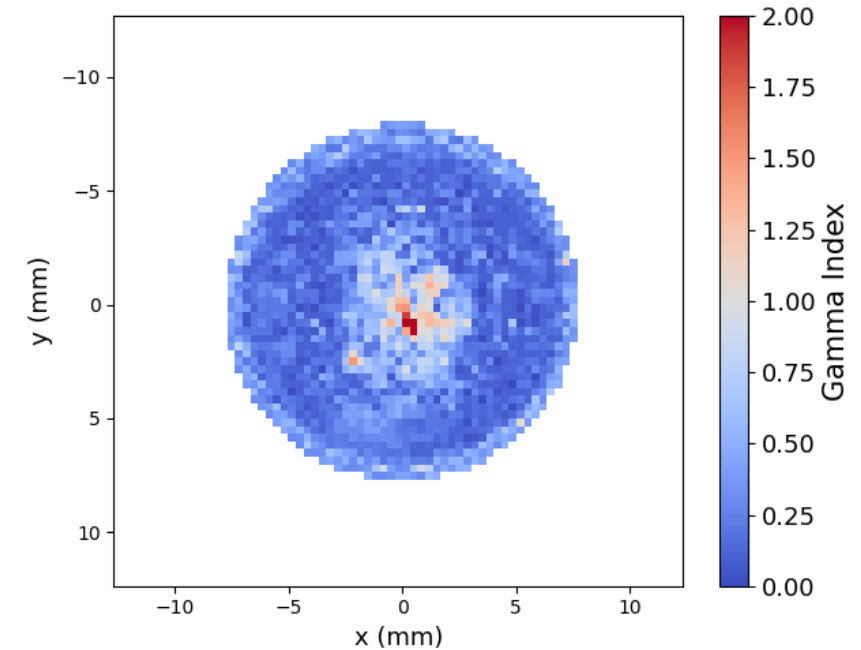
Simulated film



Film measurement



Comparison (97.43%)



Film resolution: 75 x 75

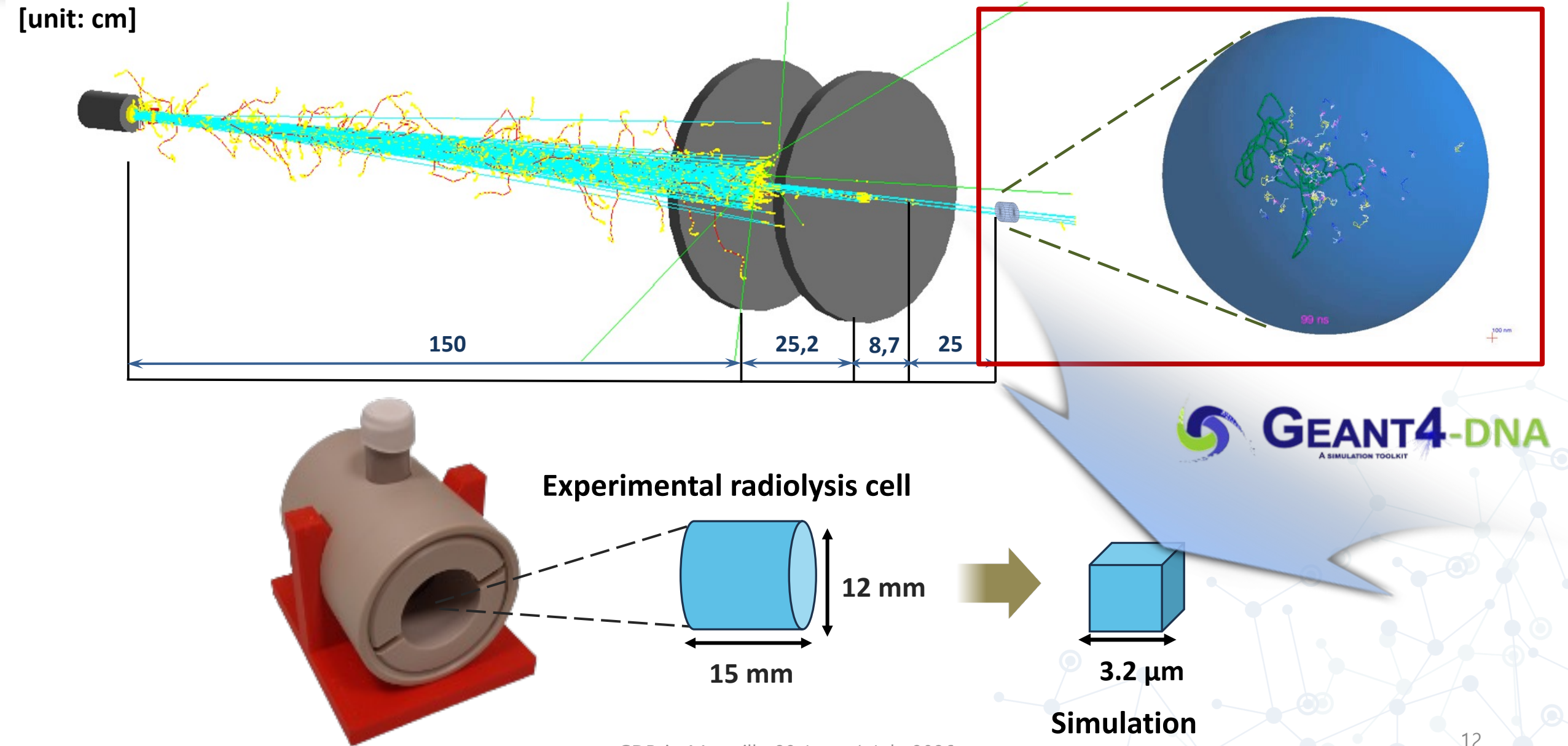
Pixel size (mm): 0.34 x 0.34

Gamma-index analysis

Dose/distance: 2%/2mm

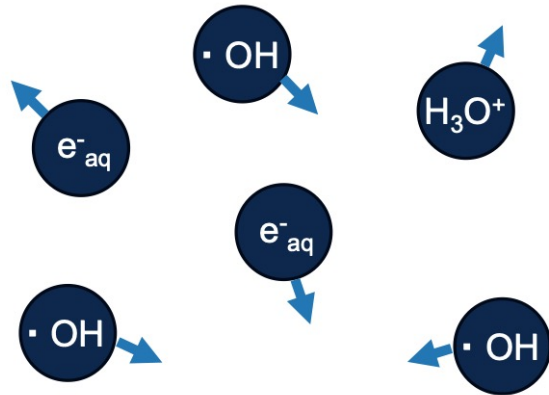
Dose threshold: 10%

A micro – level digital twin of water radiolysis



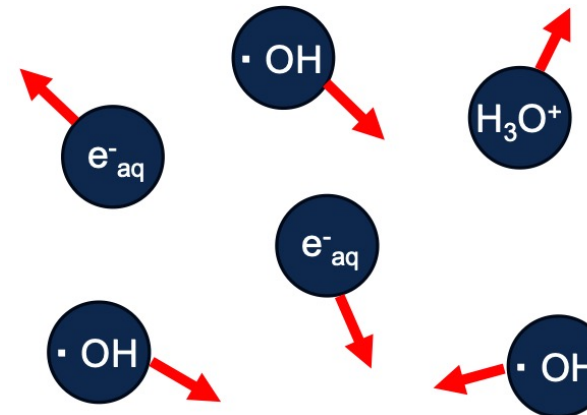
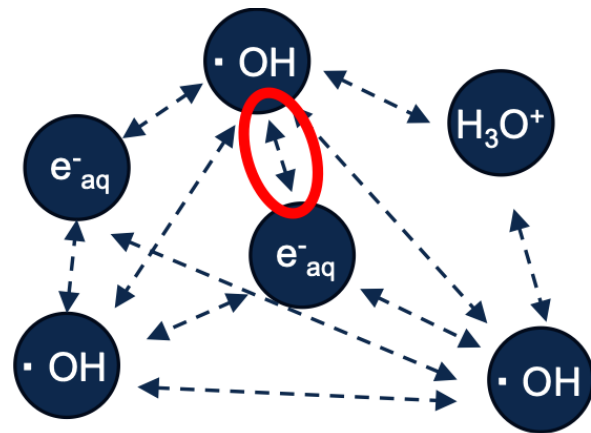
Geant4-DNA: Chemical stage

SBS (Step by step)

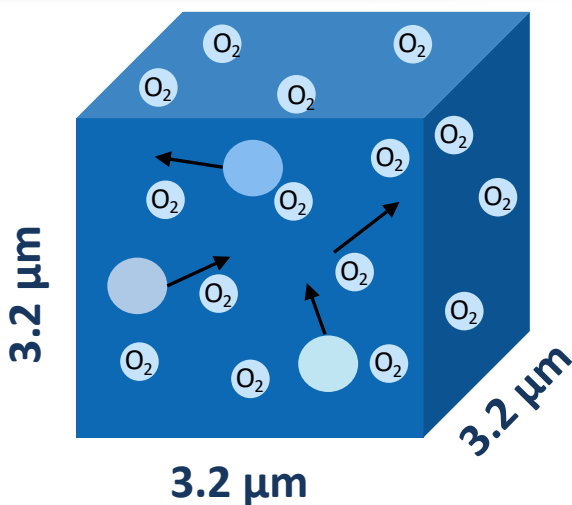


- Diffuse molecules with fixed T-step (time step)
- Time step must be always short enough

IRT (Independent Reaction time)



Digital twins in micro-scale simulation



Parameters in simulation

- O₂ levels: 1% ± 0.6% and 21%
 - CO₂ level: 0.042 %
 - pH: 5.5 ± 0.3
- } Reaction with Scavenging molecule

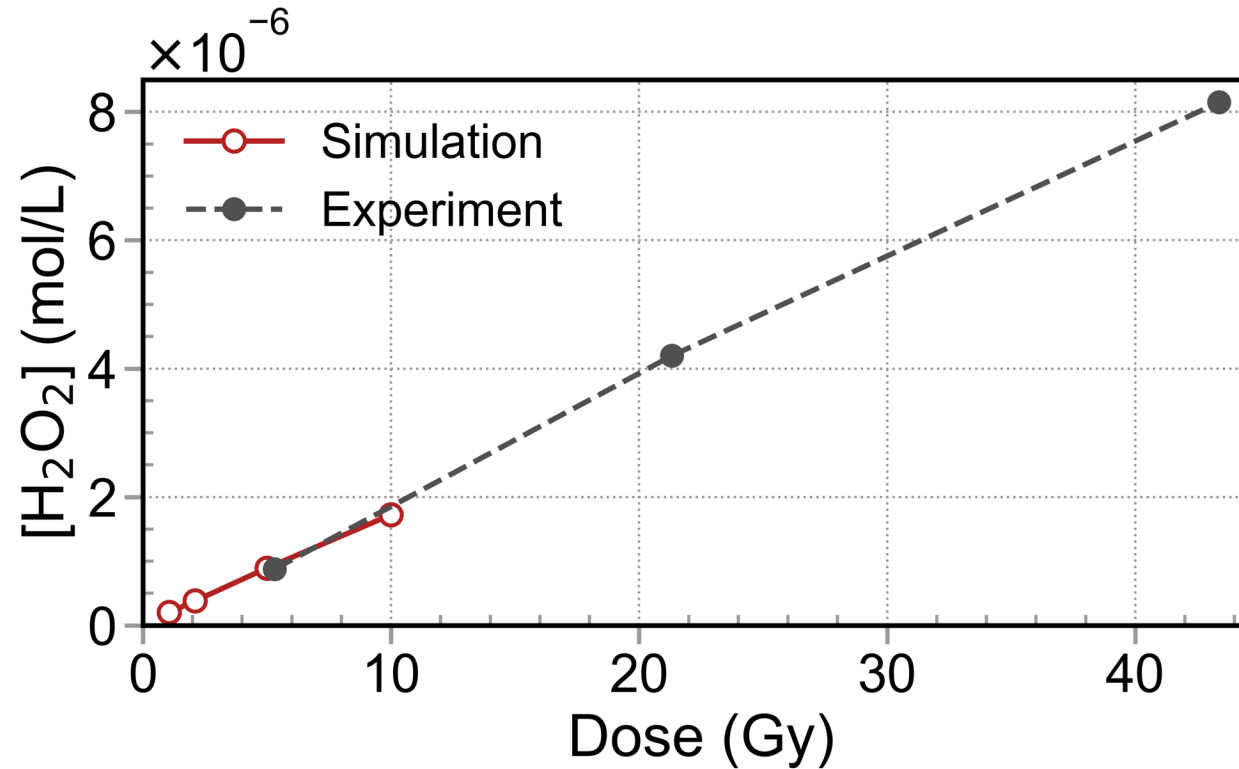
Experiment

Mean dose rate (Gy/s)	Pulse duration (ms)	Dose to the target (Gy)
0.2	[6.3 10 ⁻³ – 1.9]	[10, 20, 30, 40, 60, 80]
8		
40		
50		
110		

Simulation

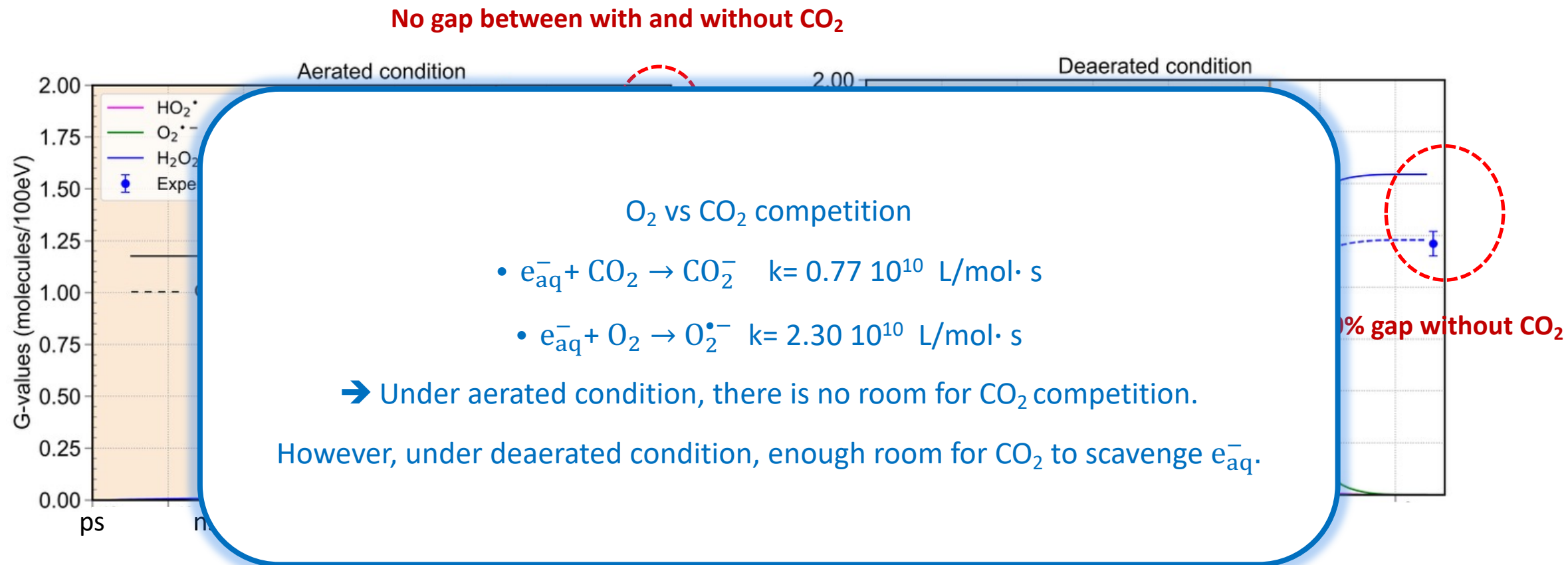
Mean dose rate (Gy/s)	Pulse duration (ms)	Dose to the target (Gy)
0.2	50	0.01
8		0.4
40		2
50		2.5
110		5.5

H₂O₂ linearity with dose at 100 Gy/s

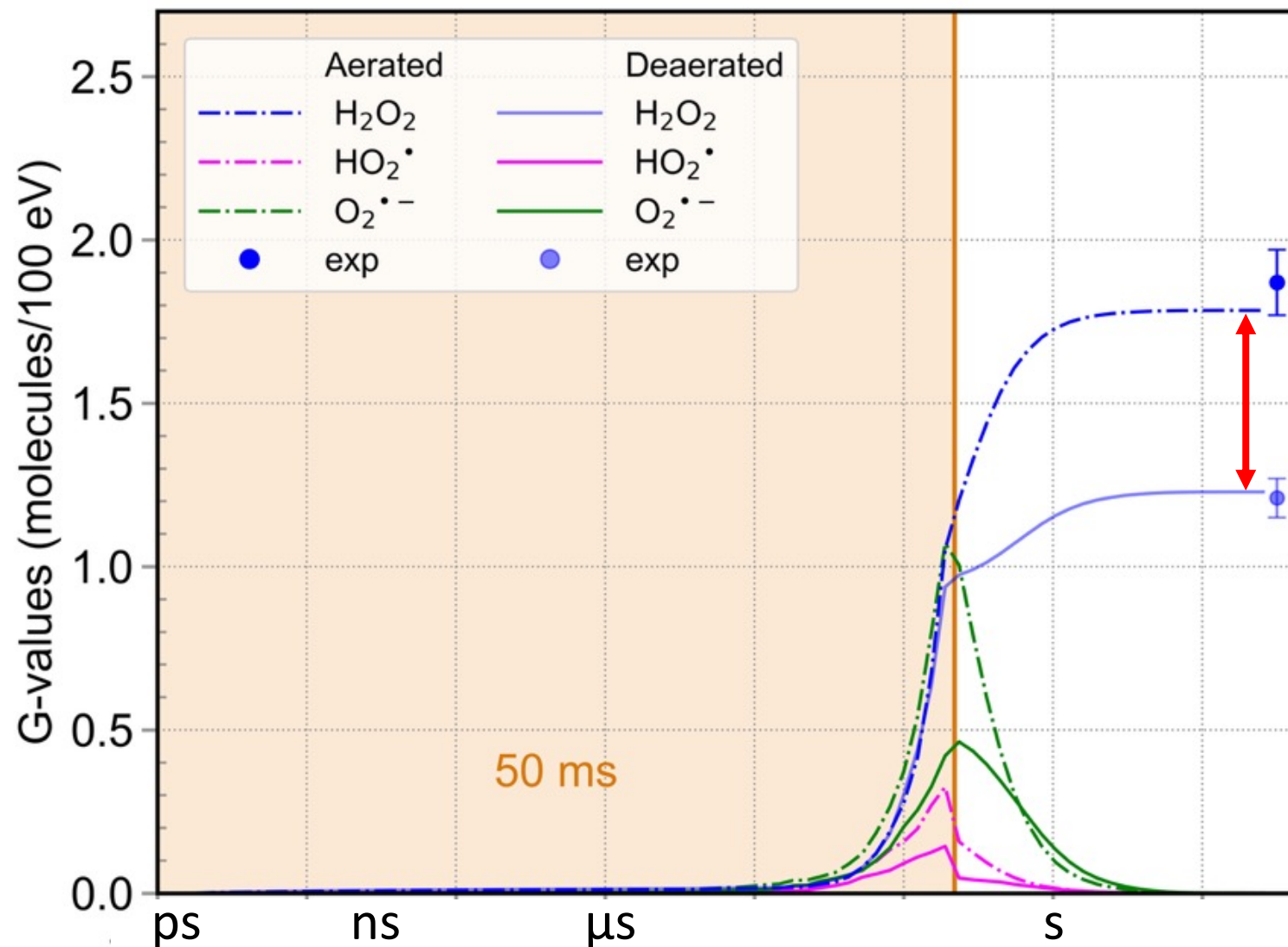


→ Simulated data (red open circles) are shown at 1.1, 2.1, 5 and 10 Gy ($R^2=0.9997$) and experimental data (grey filled circles) at 5.3, 21.3 and 43.4 Gy ($R^2=0.9994$).

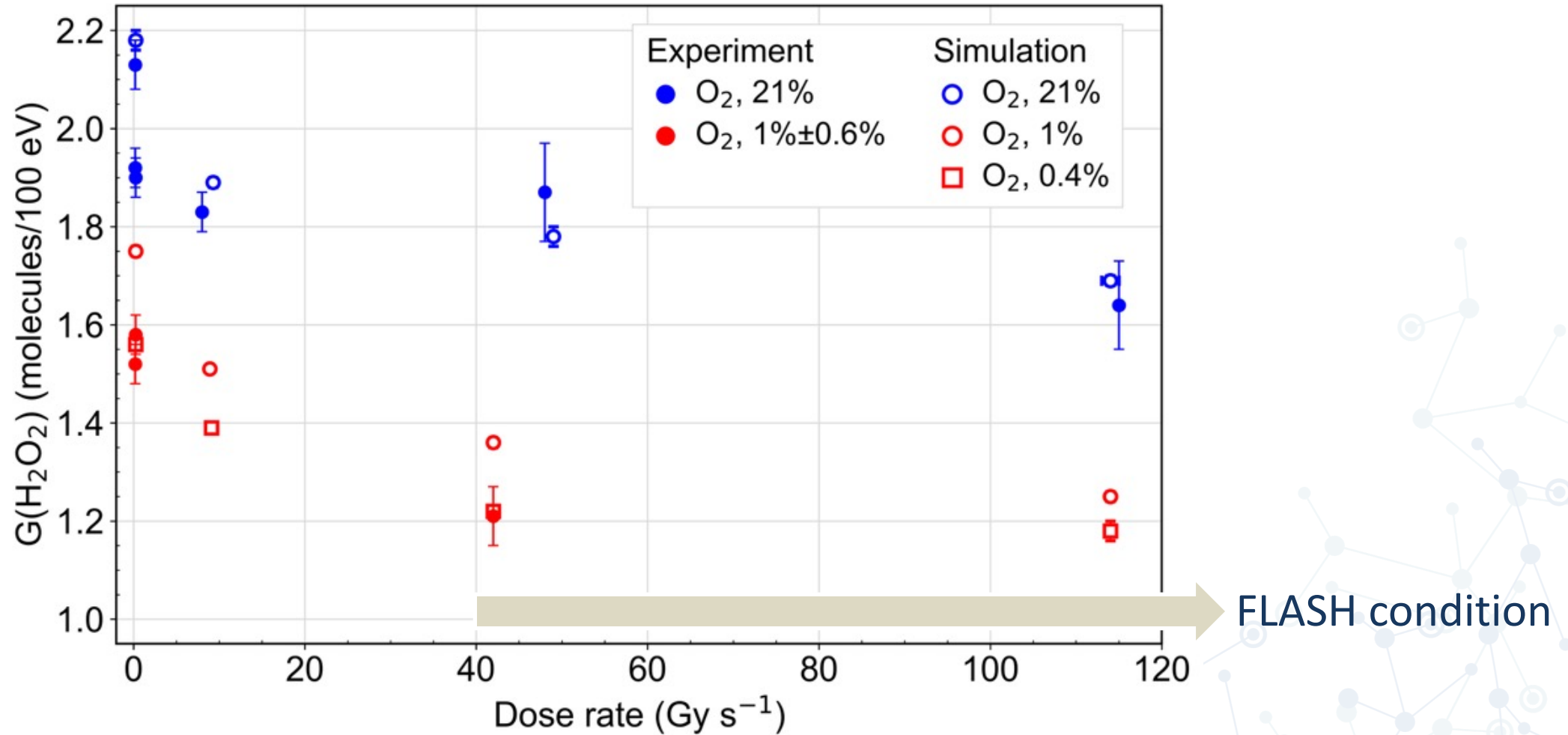
Impact of CO₂ on the radical formation



Impact of O₂ on the radical formation at 42 Gy/s



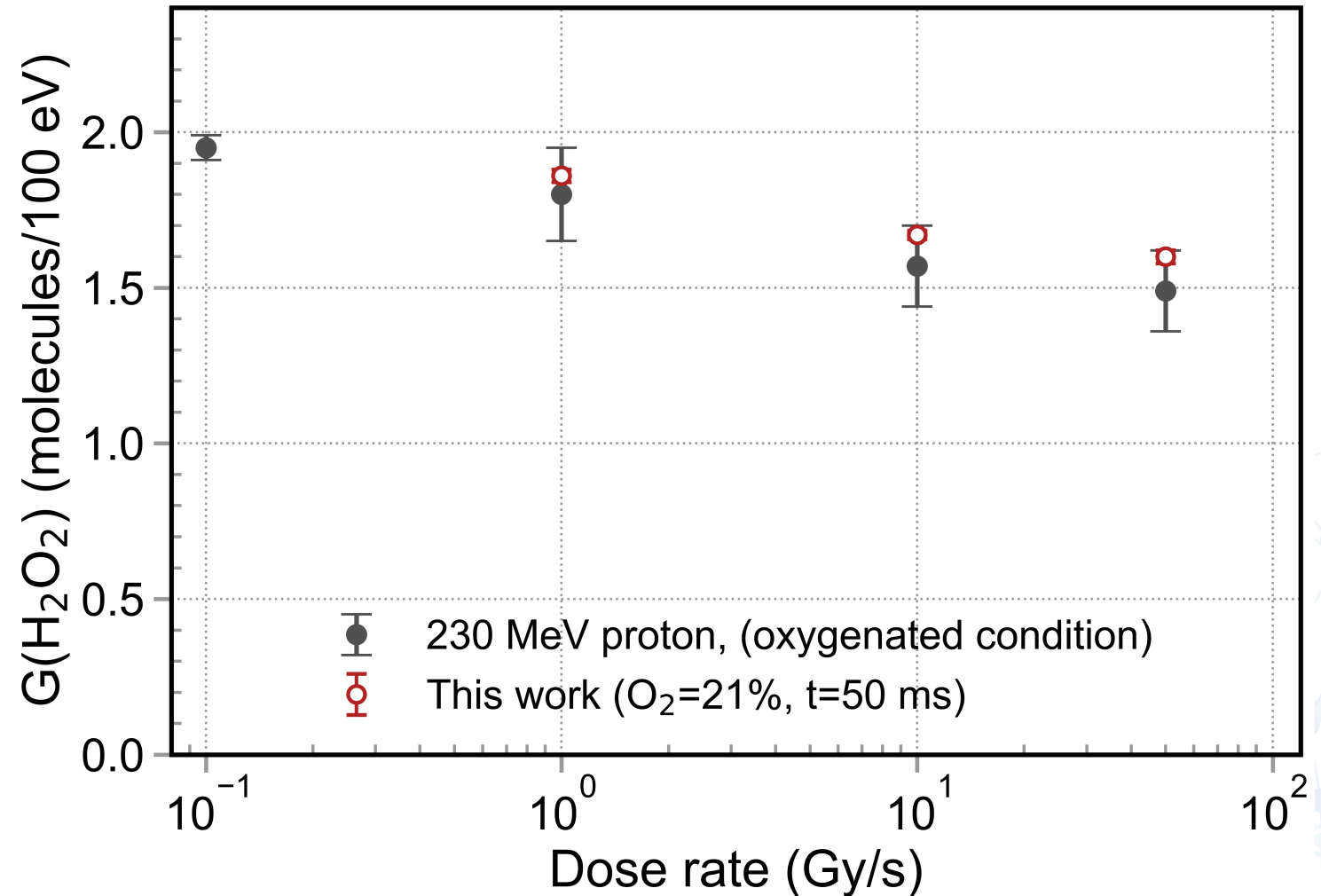
Comparison of simulated and experimental $G(\text{H}_2\text{O}_2)$



Digital twin with other experimental data



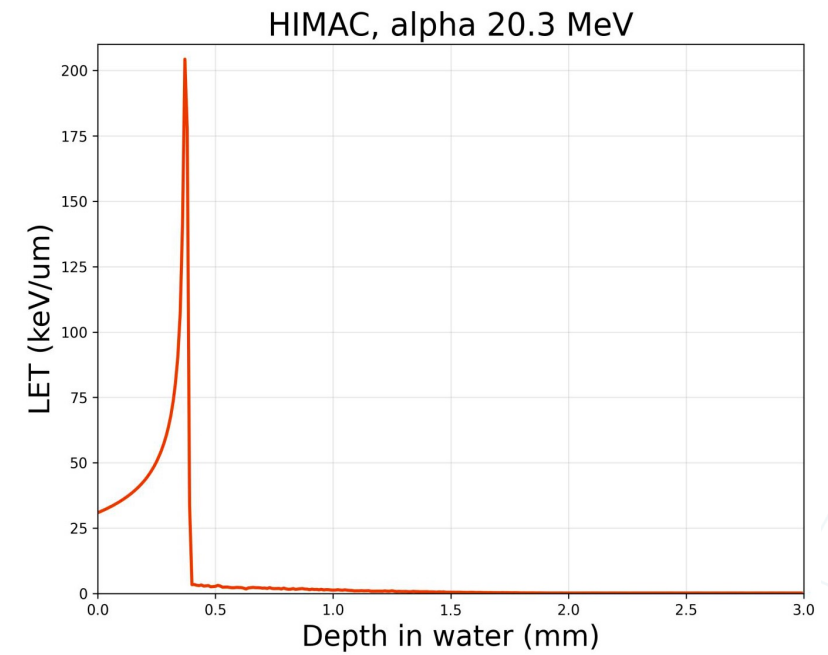
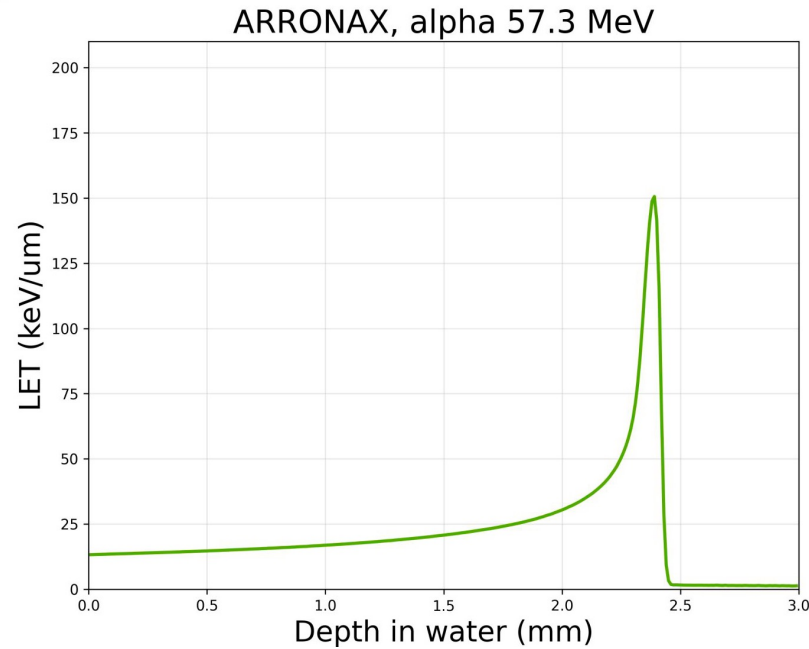
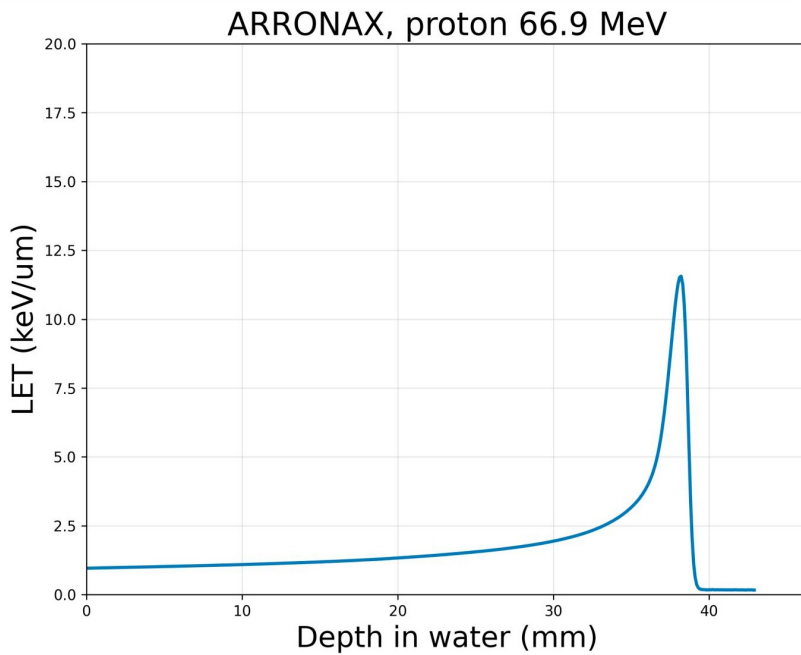
Kusumoto et al., 2024





Digital twin of the ARRONAX and HIMAC beamlines for e_{aq}^-

Digital twin of the ARRONAX and HIMAC beamlines for e_{aq}^-



Beamlines	Deposite energy in the sample (Gy)	O ₂ levels (%)	Measured time of e_{aq}^- (ns)	Pulse structure	Mean dose rate (kGy/s)
ARRONAX proton	0.4 ± 0.03	0.04 to 21	2000	2 μ s (seperated by 10 ms)	190
ARRONAX alpha	0.56	0.04 to 4	2000	2 μ s (seperated by 10 ms)	260
HIMAC alpha	400	< 0.0002	74	700 μ s (seperated by 1.65s)	20 or 200

The background of the slide features a complex, abstract network diagram. It consists of numerous small, light blue circular nodes connected by thin, light blue lines. These nodes and lines are distributed across the slide, with a higher density in the top-left and bottom-right corners, creating a sense of connectivity and complexity. The central text is positioned within the less dense middle area of the network.

Conclusion and perspectives

Conclusion and Perspectives

Validation of FLASH irradiation @ ARRONAX from physics to Chemistry ✓

D. Kwon et al, accepted in Med. Phys., June 2026

- The role of dissolved CO_2 in scavenging e_{aq}^-
- Longer time radiolysis; key radicals: $\text{HO}_2^\bullet$ and $\text{O}_2^{\bullet-}$
- Good agreement between simulation and experiments



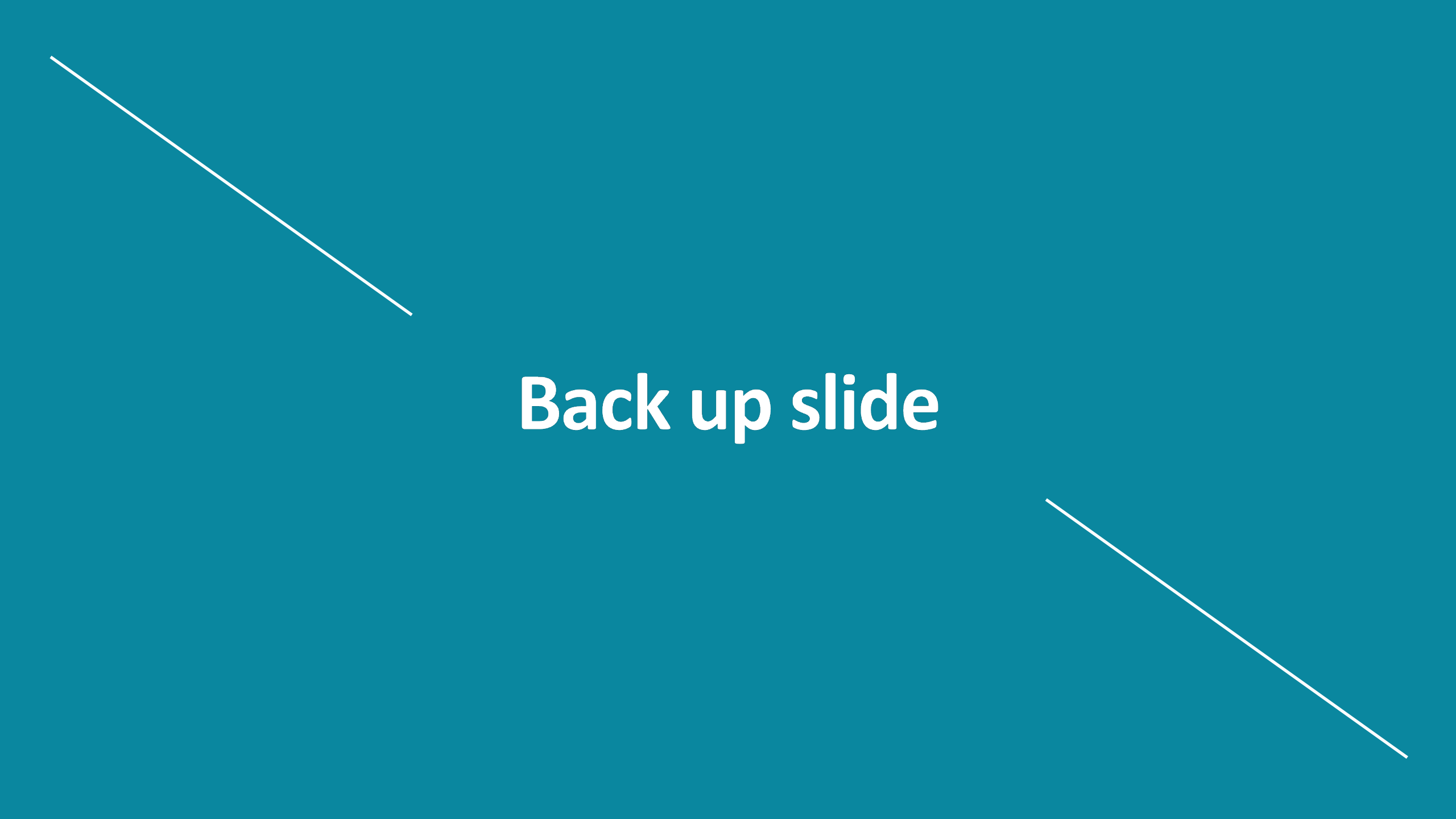
Extend the work to other French beam lines
Other comparison with HIMAC He^{2+} irradiations (IPHC)

More detailed information will be provided at the PhD defense in October



Thank you for your attention



The background is a solid teal color. Two thin white diagonal lines are present: one in the upper-left quadrant and one in the lower-right quadrant, both pointing towards the center.

Back up slide