Comparison of radiation damage effects in plastic scintillators after ultra-high dose rate irradiations of 9-MeV electrons, 200-MeV electrons, and 87-MeV protons

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Cloé Giguère,

Uwe Titt, Arthur Lalonde, Luc Beaulieu and Sam Beddar

IC3DDose 2026 | June 17th

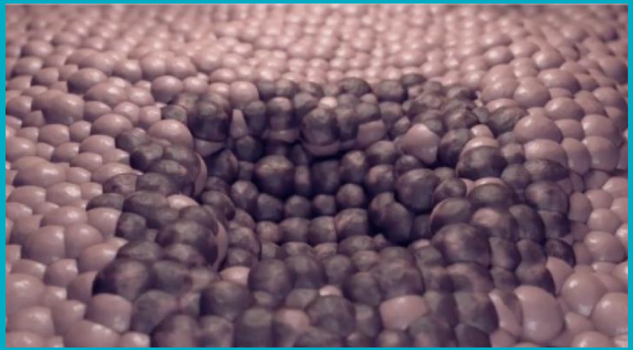
Novel dosimetry for the clinic today and for the emerging irradiation modalities of tomorrow

FLASH-RT: The Future of Radiotherapy?

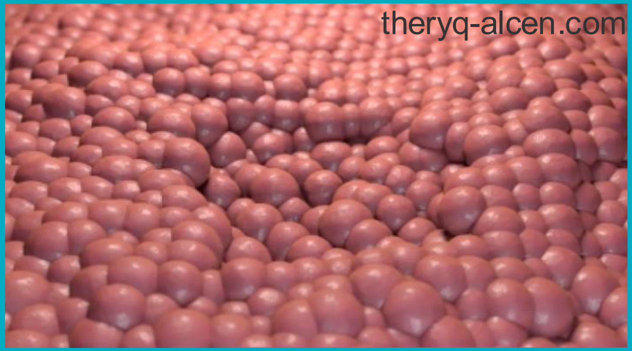
What

Radiotherapy using ultra-high dose rates (UHDR)

- > 100 Gy/s VS ~0.1 Gy/s current clinical standard



Conventional Radiotherapy
Possible side effects



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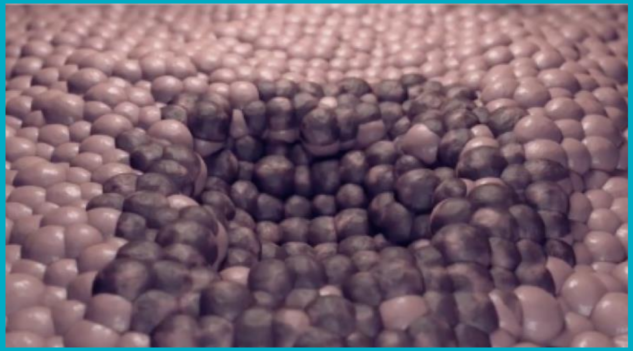
The FLASH effect appears at UHDR
- ↓ of healthy tissue toxicity
- = anti-tumour response

Discovered in 2014 by Favaudon *et al.*



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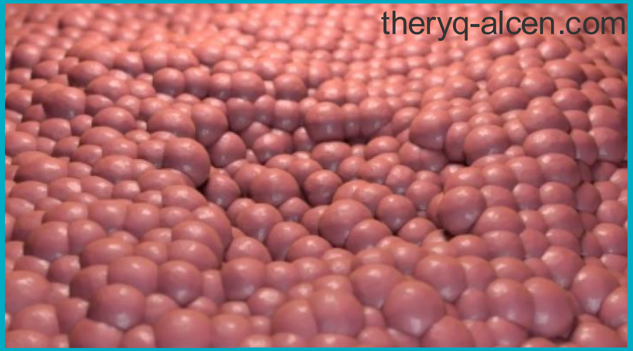

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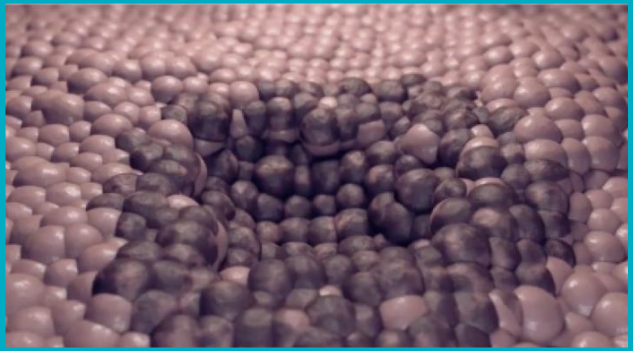
- ↓ of fractions/treatments
- ↓ of irradiation time



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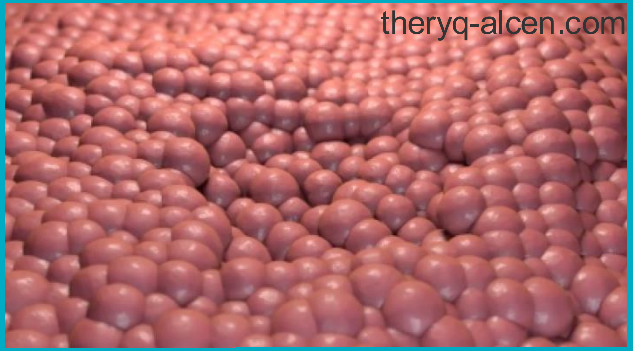

FLASH Radiotherapy
Less side effects

FLASH-RT: Challenges Before the Clinic

1 FLASH mechanism: how/why does it work?

- Oxygen depletion, reactive oxygen species, radicals, DNA damage, immune & inflammatory responses, ... ?

FLASH-RT: Challenges Before the Clinic

1 FLASH mechanism: how/why does it work?
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2 What are the factors influencing the FLASH effect?
- Treatment parameters: dose ≥10 Gy, single fraction or multiple, tissue sensitivity
- Beam delivery parameters: modality (photons, protons, electrons), energy, instantaneous dose rate, average dose rate, dose per pulse, duration, etc.

≥ 40 Gy/s ≠ always FLASH effect!

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≥ 40 Gy/s ≠ always FLASH effect!

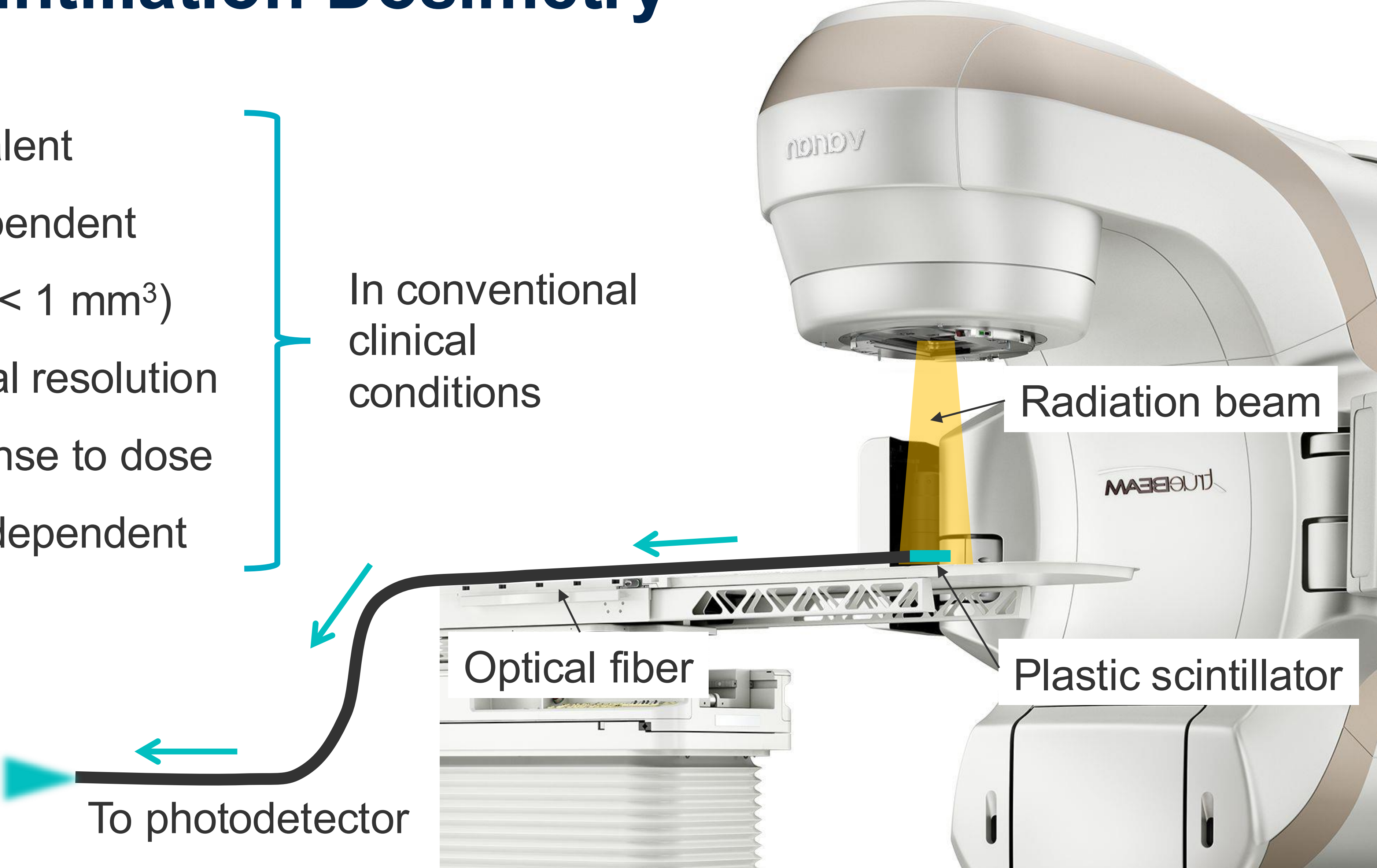
3 Quality assurance & patient safety: What dosimeters can we use in UHDR?

→ Plastic scintillation detectors (PSDs)

Plastic Scintillation Dosimetry

- ✓ Water equivalent
- ✓ Energy independent
- ✓ Small sized (< 1 mm^3)
- ✓ High temporal resolution
- ✓ Linear response to dose
- ✓ Dose rate independent

In conventional clinical conditions



Plastic Scintillation Dosimetry

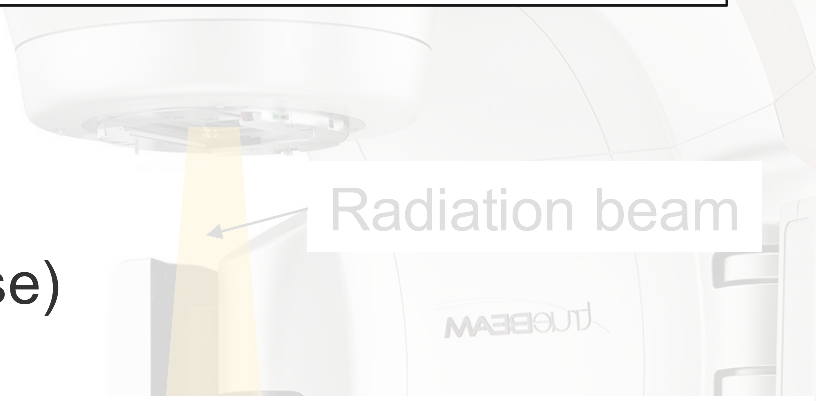
Submitted to Physics in Medicine and Biology,
in second round of reviews

Characterization of radiation damage sensitivity in plastic scintillators and optical fibers for proton FLASH real-time dosimetry

Cloé Giguère[1,2,3], Uwe Titt[3,4], Luc Beaulieu[1,2*] and Sam Beddar[3,4*]

- ✓ Water equivalent
- ✓ Energy independent
- ✓ Small sized (< 1 mm^3)
- ✓ High temporal resolution
- ✓ Linear response to dose (up to ~45 Gy in a single pulse)
- ? Dose rate independent
- ✗ Sensitive to radiation damage

In FLASH?



Scintillation light ∝ dose!

To photodetector

Scan to read

PAPER • OPEN ACCESS

Radiation damage and recovery of plastic scintillators under ultra-high dose rate 200 MeV electrons at CERN CLEAR facility

Cloé Giguère, Alexander Hart, Joseph Bateman, Pierre Korysko, Wilfrid Farabolini, Yoan LeChasseur, Magdalena Bazalova-Carter* and Luc Beaulieu

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DOI 10.1088/1361-6560/adc234

Article PDF

GOAL:

Study the effect of radiation type on PSD radiation damage and recovery processes, by comparing UHDR irradiations of

- 200 MeV very high energy electrons (VHEEs)
- 9 MeV electrons
- 87 MeV spread-out Bragg peak (SOBP) protons

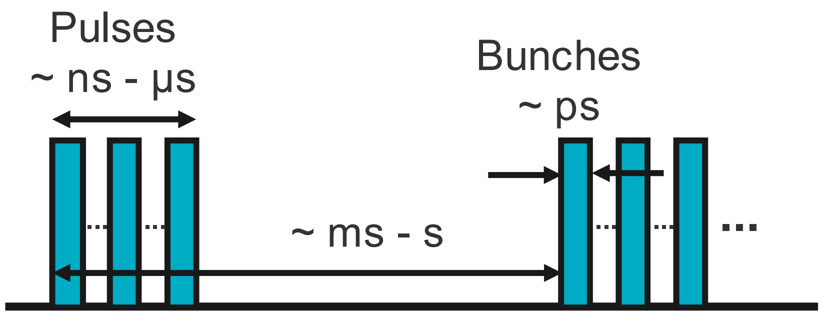
Methods

UHDR irradiation parameters

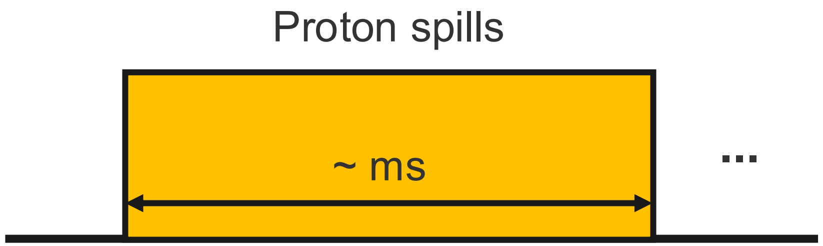
Particle type	Beamline	Energy (MeV)	
VHEEs	CERN CLEAR	200	Linear electron accelerator
Electrons	CHUM Mobetron	9	Linear electron accelerator
SOBP protons	MD Anderson PTC 1	87	Synchrotron

UHDR irradiation parameters

Particle type	Beamline	Energy (MeV)	Pulse or spill length (ns)	
VHEEs	CERN CLEAR	200	1-125	~ns
Electrons	CHUM Mobetron	9	$(1\text{-}3.78)\times10^{3}$	~μs
SOBP protons	MD Anderson PTC 1	87	$(27\text{-}71)\times10^{7}$	~ms



Pulsed linear accelerator (CLEAR & Mobetron)



Synchrotron

UHDR irradiation parameters

$$\text{Dose rate} = \frac{\text{Dose per pulse or spill}}{\text{Pulse or spill length}}$$

Particle type	Beamline	Energy (MeV)	Pulse or spill length (ns)	Dose per pulse or spill (Gy)	Dose rate (Gy/s)
VHEEs	CERN CLEAR	200	1-125	~5-90	$(0.22\text{-}4.60)\times10^{9}$
Electrons	CHUM Mobetron	9	$(1\text{-}3.78)\times10^{3}$	0.90-3.39	$(8.86\text{-}9.19)\times10^{5}$
SOBP protons	MD Anderson PTC 1	87	$(27\text{-}71)\times10^{7}$	7-18	252-259

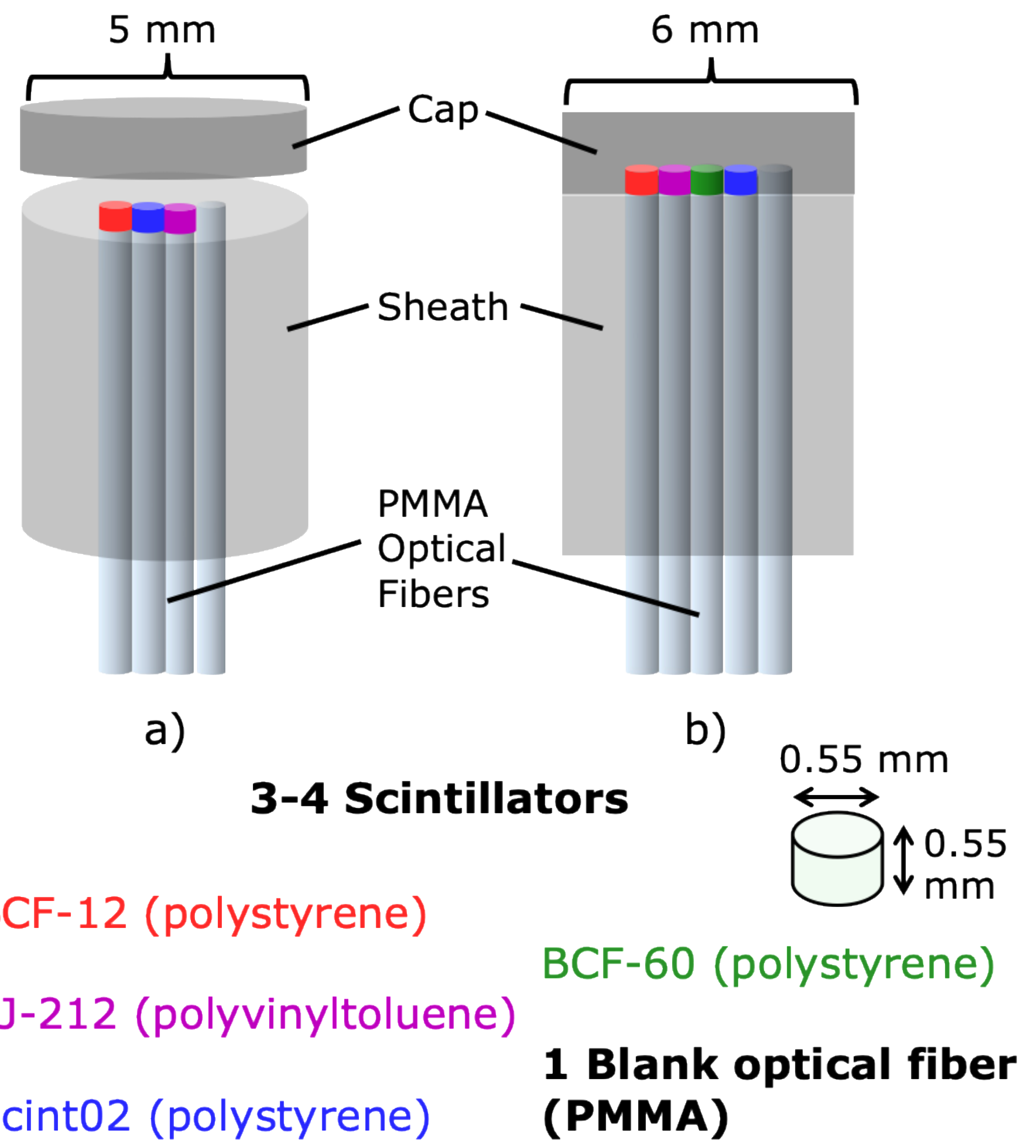
UHDR irradiation parameters

Particle type	Beamline	Energy (MeV)	Pulse or spill length (ns)	Dose per pulse or spill (Gy)	Dose rate (Gy/s)	Cumulative dose (kGy)
VHEEs	CERN CLEAR	200	1-125	~5-90	$(0.22\text{-}4.60) \times 10^{9}$	37.2
Electrons	CHUM Mobetron	9	$(1\text{-}3.78) \times 10^{3}$	0.90-3.39	$(8.86\text{-}9.19) \times 10^{5}$	2.2
SOBP protons	MD Anderson PTC 1	87	$(27\text{-}71) \times 10^{7}$	7-18	252-259	10.4

Experimental set-up

- **(a)** VHEEs & 9 MeV: 4-channel PSD
- **(b)** Protons: 5-channel PSD
- Last channel without a scintillator for stem-effect light removal
- Light acquisition with the Medscint Hyperscint RP-200 dosimetry platform

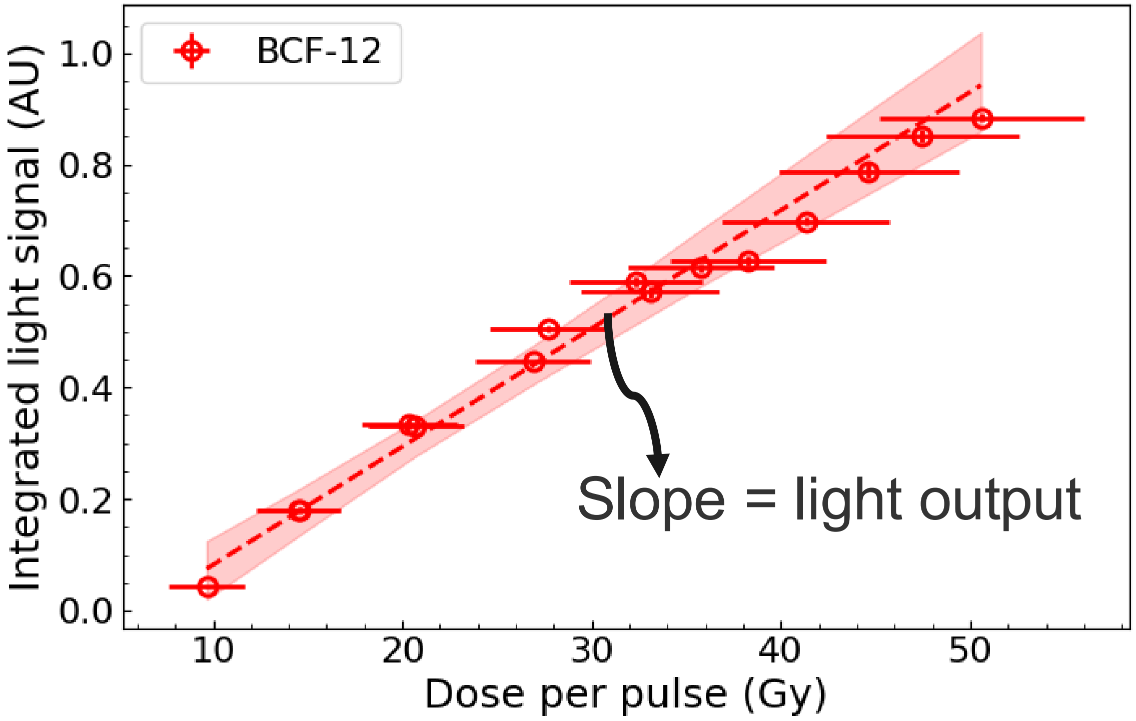
4-5 channel PSD



Evaluation of Radiation Damage

<u>Light output decrease</u>

- Linearity response of scintillators to varying dose per pulse or spill
- Slope of linear fits = light output
- Repeat of linearity measurements + high dose irradiations
- Light output tracked with cumulative dose
- Short-term rest (hours-days)

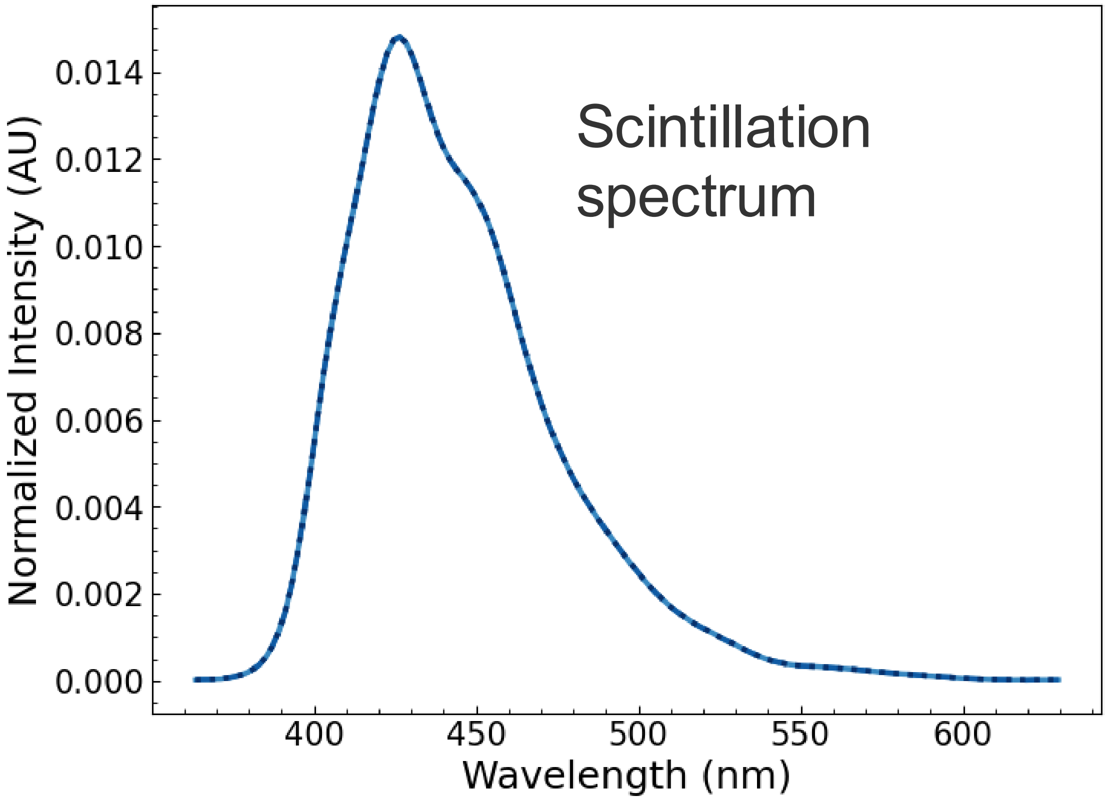


Evaluation of Radiation Damage

Spectral changes

- Spectral centroid (SC): average over the spectrum's wavelength bins ($\lambda(n)$), weighted by the intensity values ($\mathrm{I}(n)$)

$$SC = \frac{\sum_{n=0}^{N=136} I(n)\lambda(n)}{\sum_{n=0}^{N=136} I(n)}$$



Long-term Recovery Measurements

Light output

- 6 MV photon beam of TrueBeam Linac
- 500 MUs, 10 cm depth in solid water

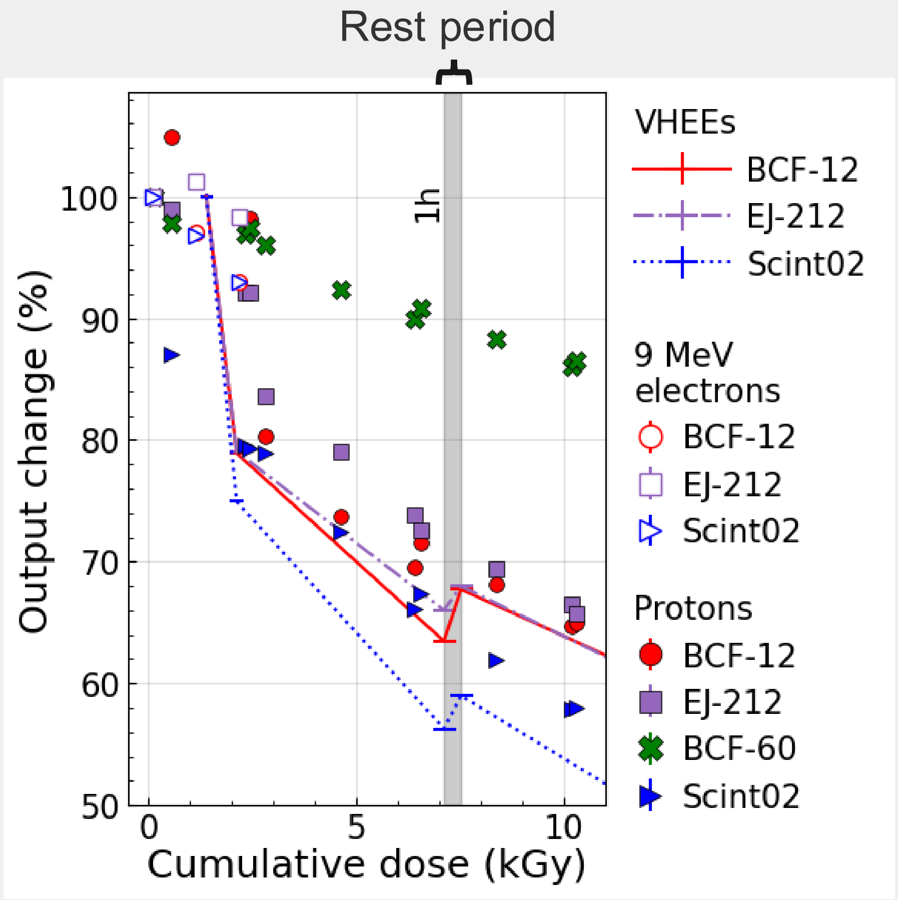
Scintillation spectrum

- 90 kV tube of TrueBeam Linac

Tracked with recovery time (50-300 days)

Results

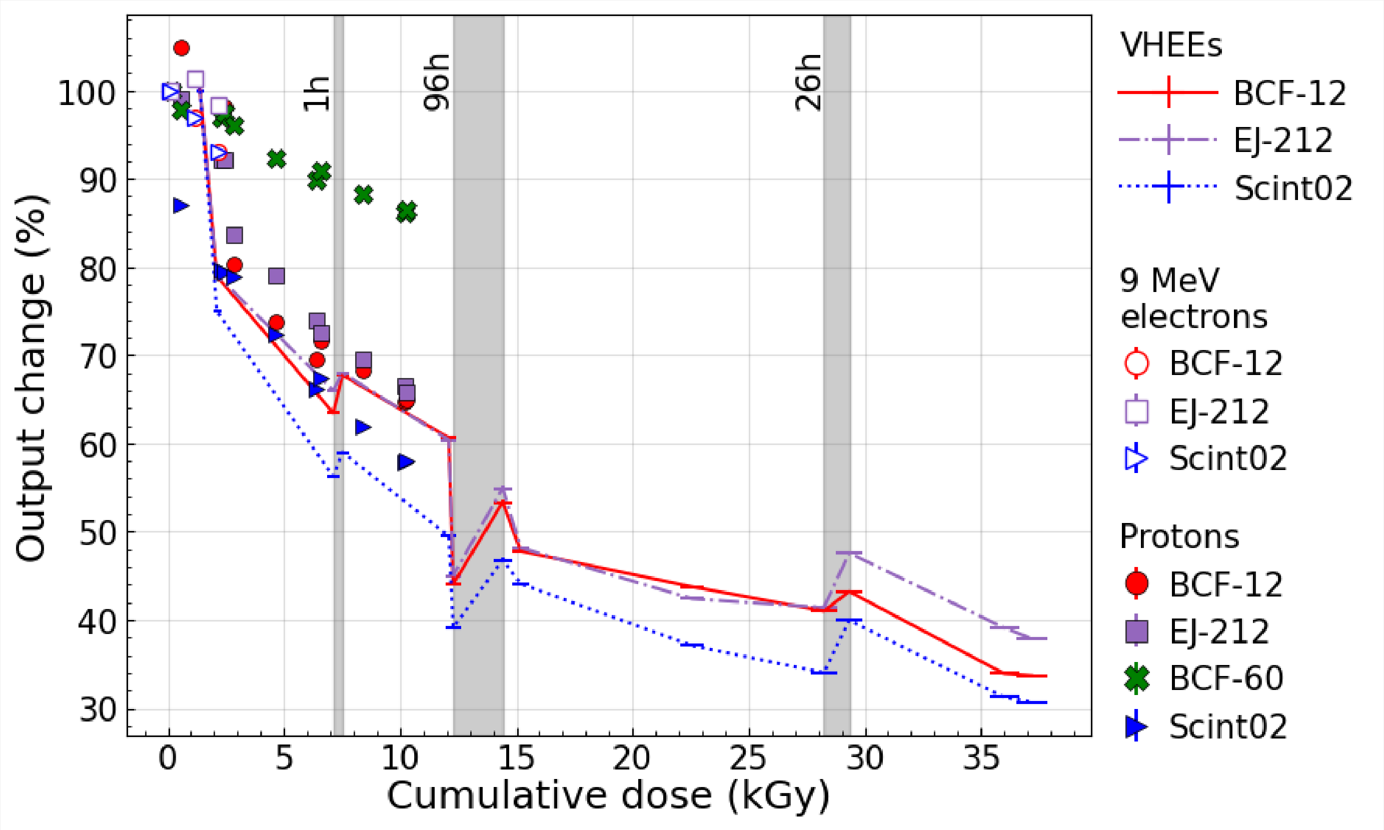
Light Output Decreases



First 10 kGy of cumulative dose

- Similar decreases for VHEEs, protons and 9 MeV electrons
- Recovery of output after 1 hour rest for VHEEs
- No short-term recovery observed for protons (15 min, 7 days, 20 days)

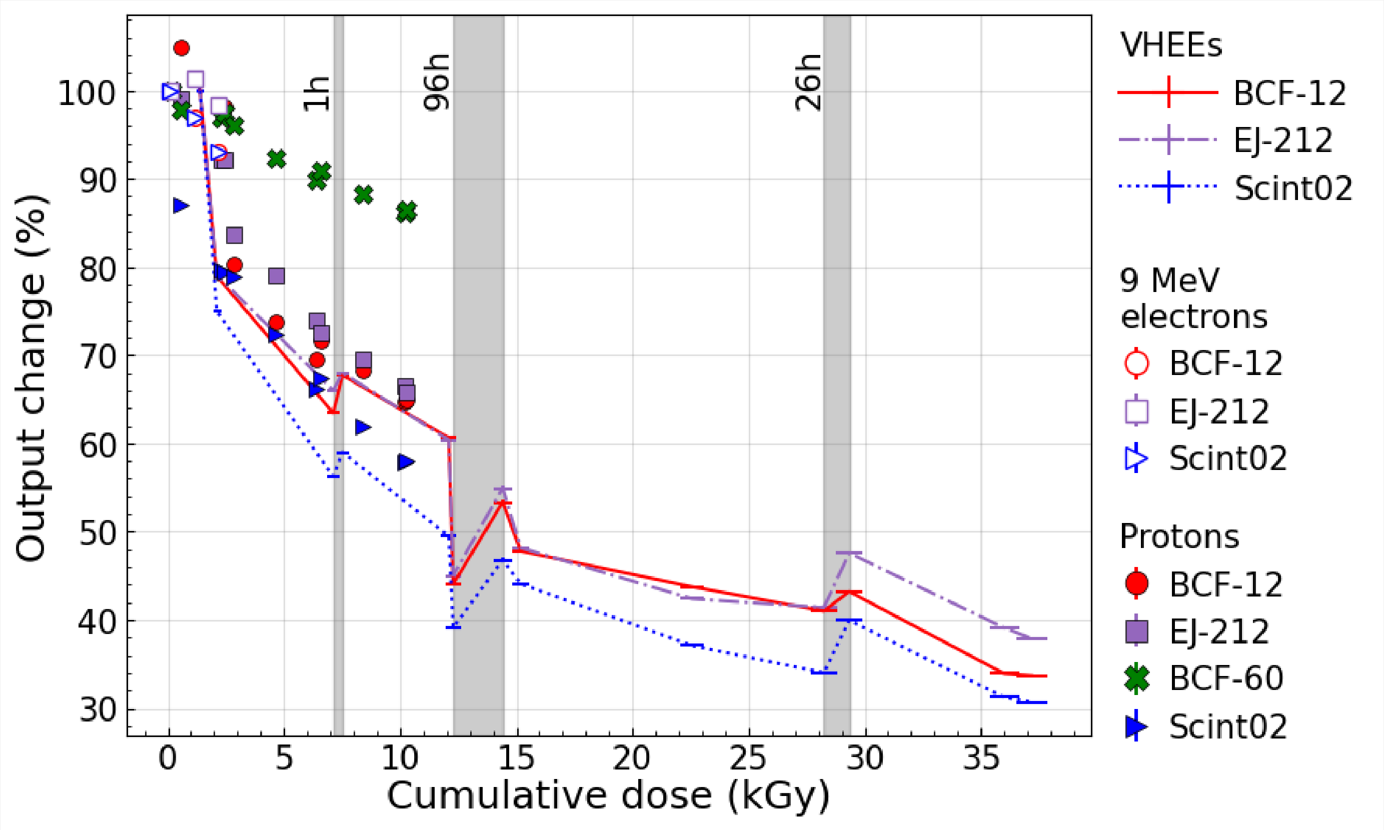
Light Output Decreases



Full range of cumulative dose

- After ~10 kGy of dose, VHEE data transitions to slower decrease
- Similar trend for protons and 9 MeV electrons?
- Recovery of output after 96h and 26h hour rest for VHEEs

Light Output Decreases

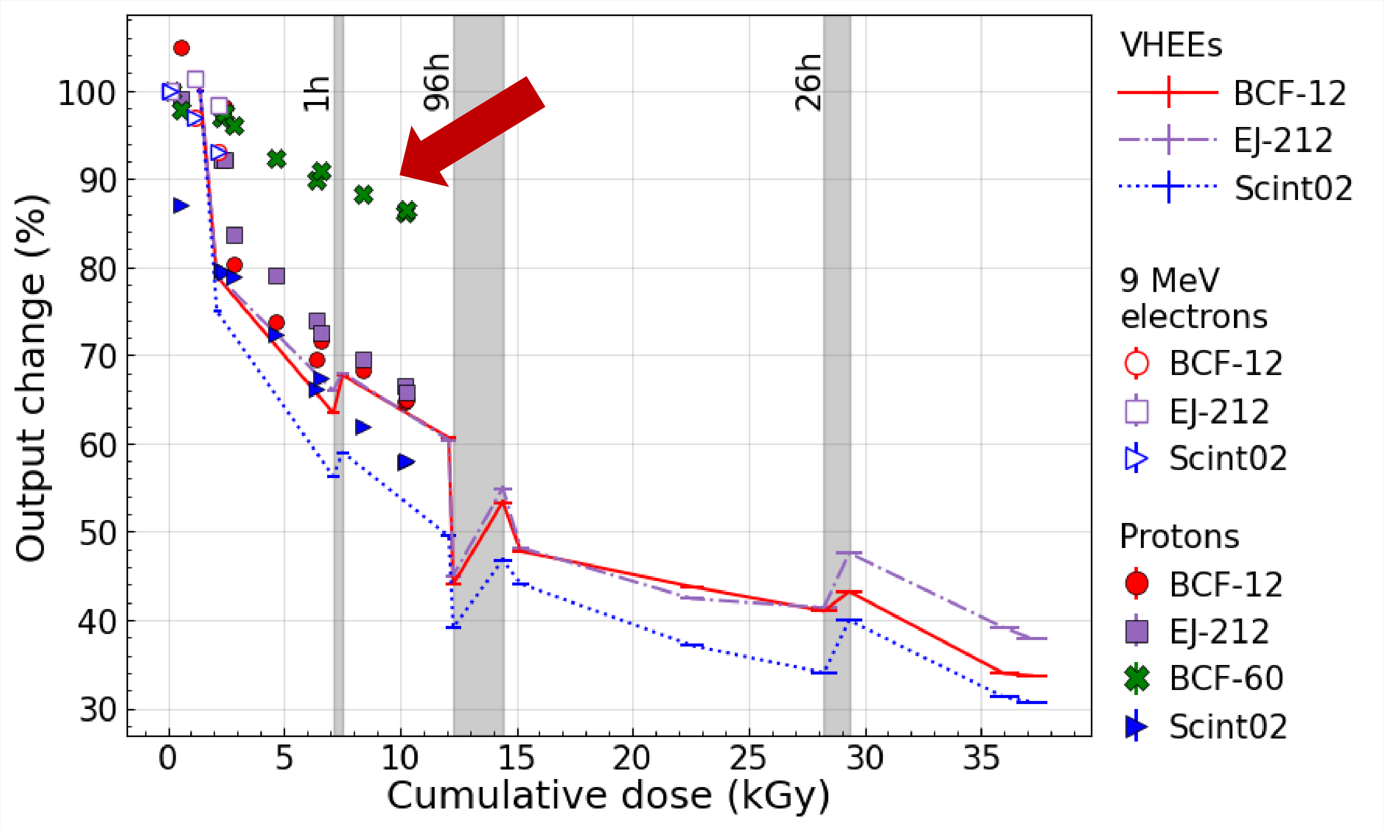


Average light output decreases (%/kGy)

	VHEEs	SOBP protons	9-MeV electrons
BCF-12	1.78	3.40	3.20
EJ-212	1.67	3.32	0.78
BCF-60	-	1.31	-
Scint02	1.86	4.08	3.24

~x2 average decreases for protons & 9 MeV electrons compared to VHEEs

Light Output Decreases



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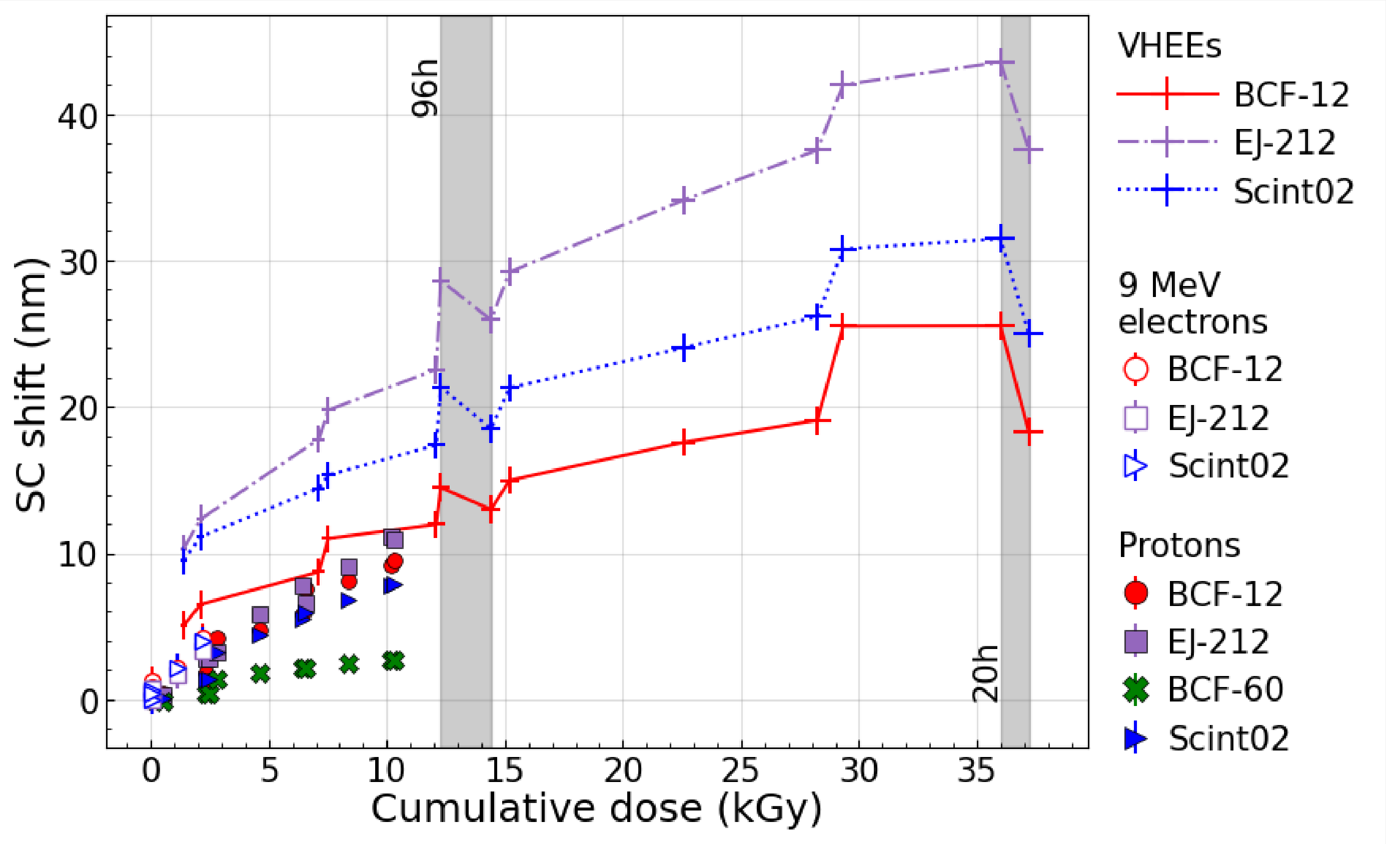
Superior radiation hardness of BCF-60 scintillator with green emission (~550 nm)

(Bross and Pla-Dalmau, 1992; Zorn, 1993; Kharzheev, 2019).

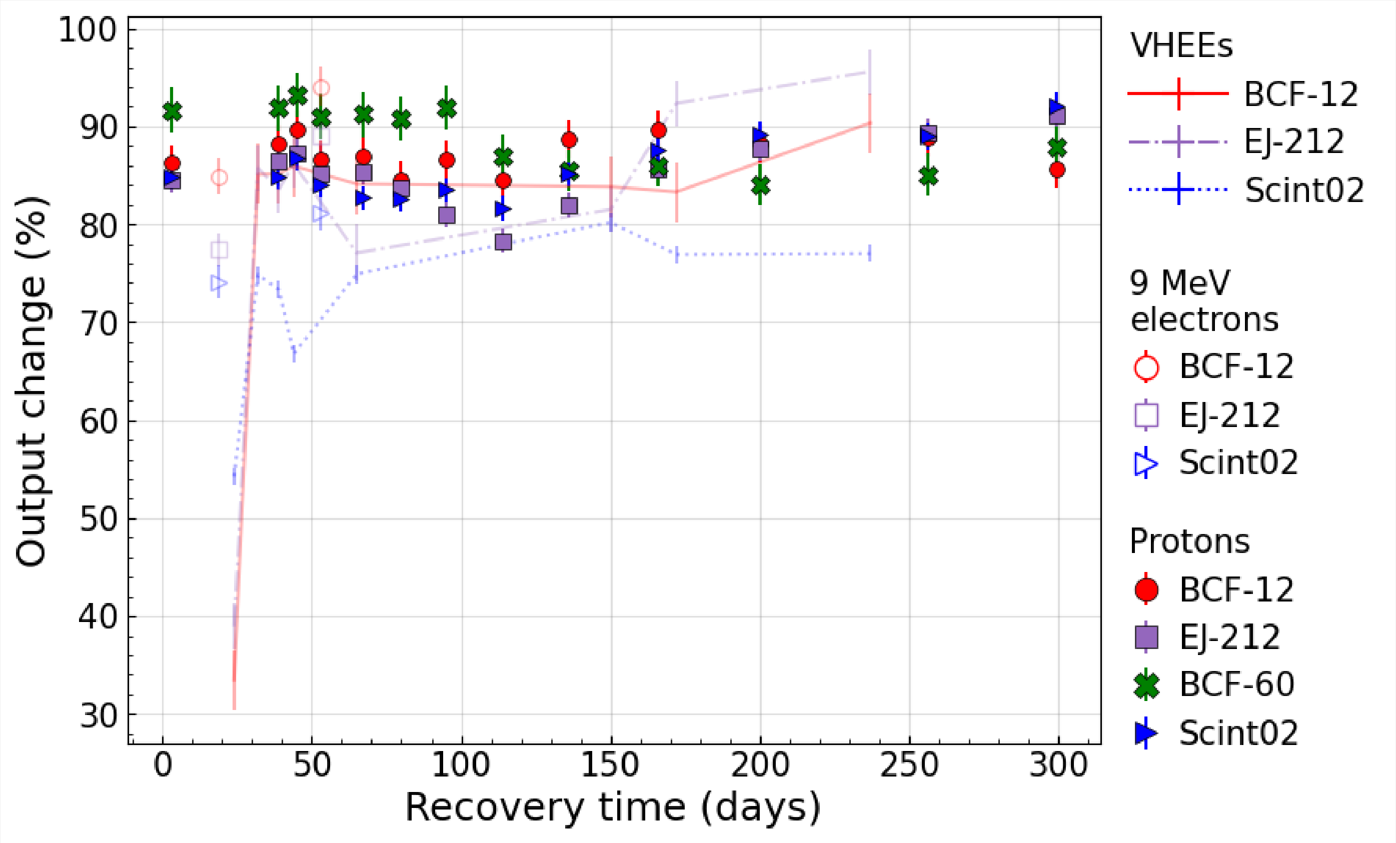
Spectral Changes



Spectral centroid shift increases

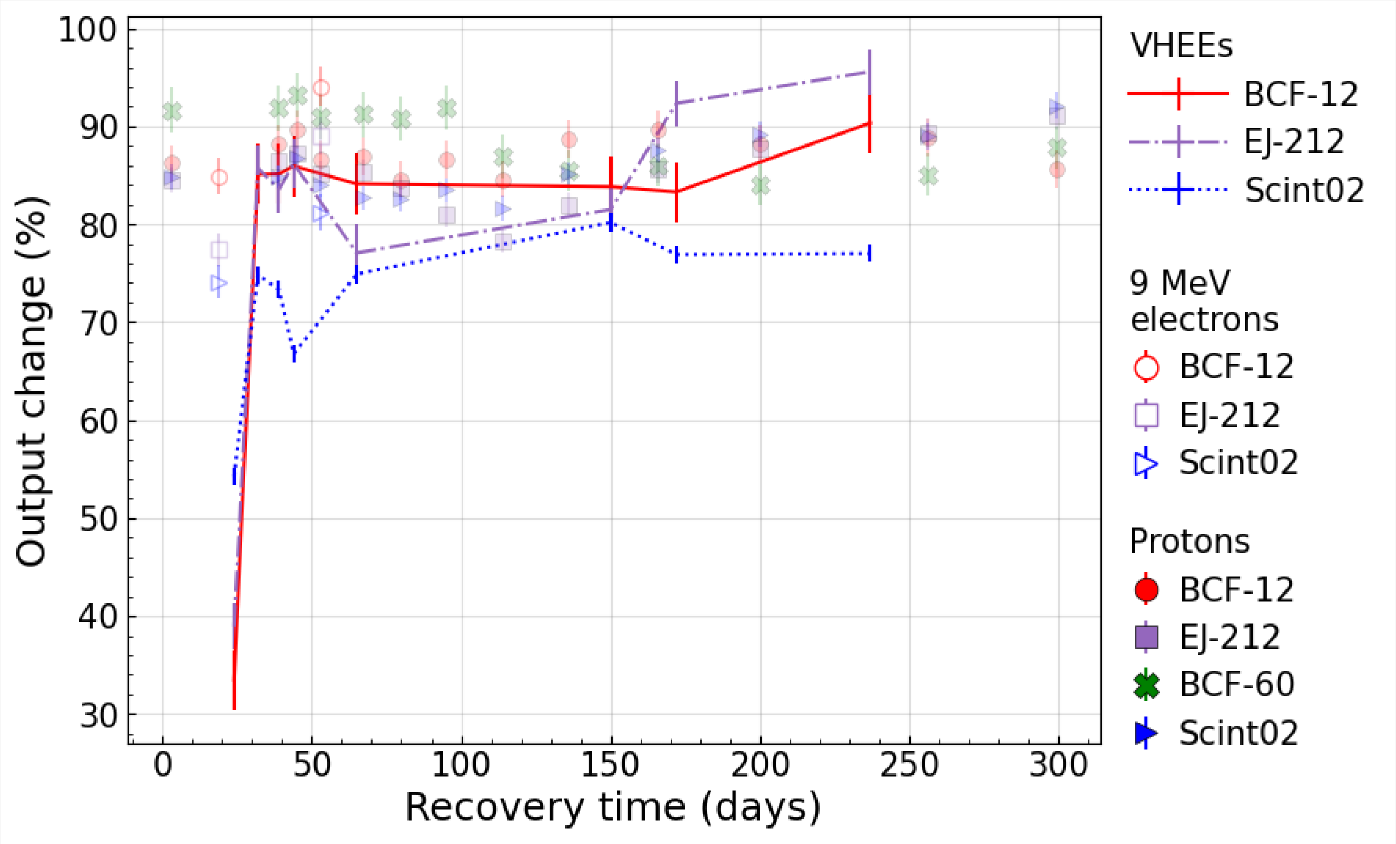
- Similar spectral changes between VHEEs, protons and 9 MeV electrons
- Recovery of spectral changes for VHEEs, after 96h and 20h rest

Long-term Recovery of Light Output



- Minimal light output recovery for protons
- Significant recovery of light output for VHEEs after 32-172 days
- Significant recovery around 50 days for 9 MeV electrons

Long-term Recovery of Light Output



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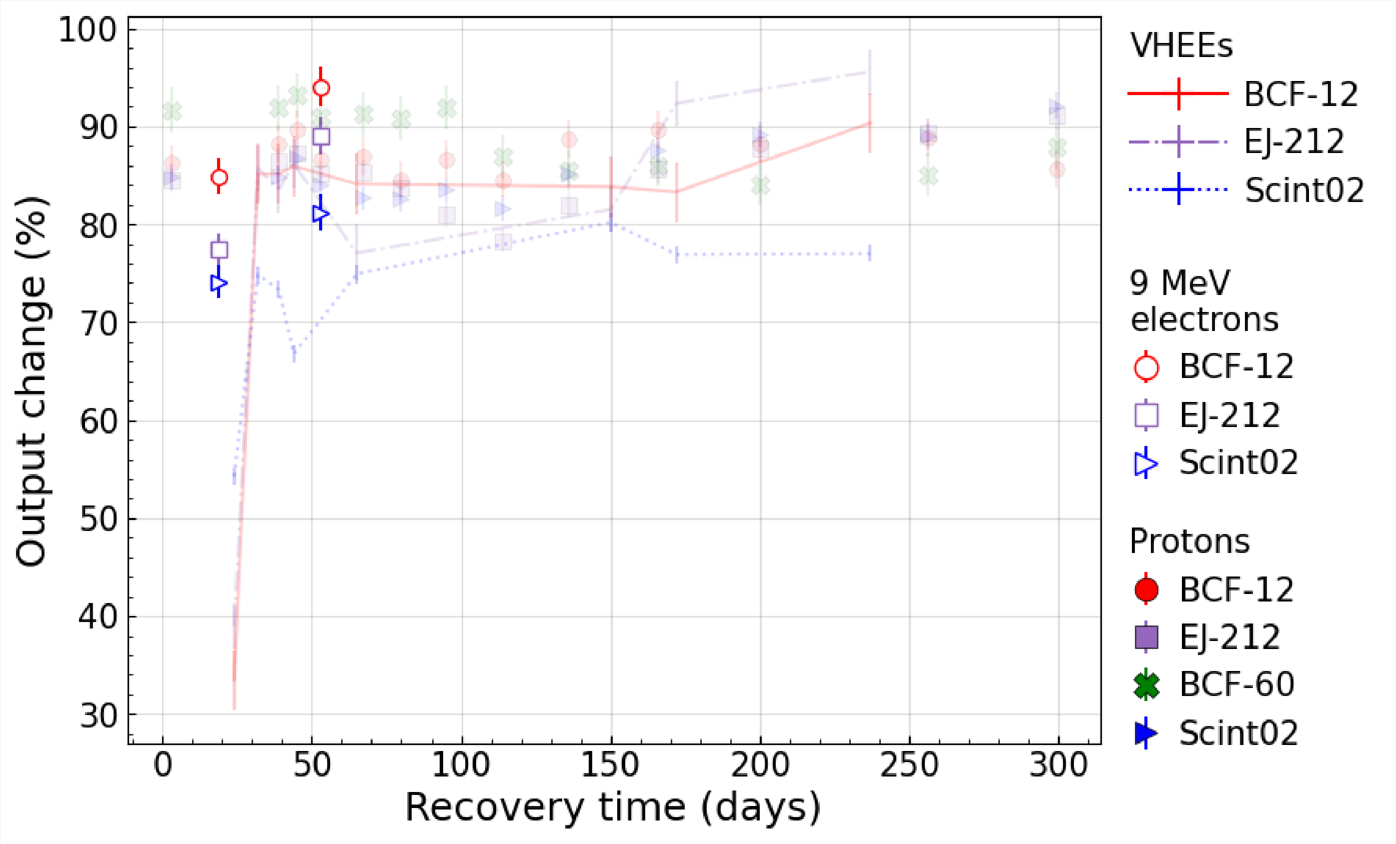

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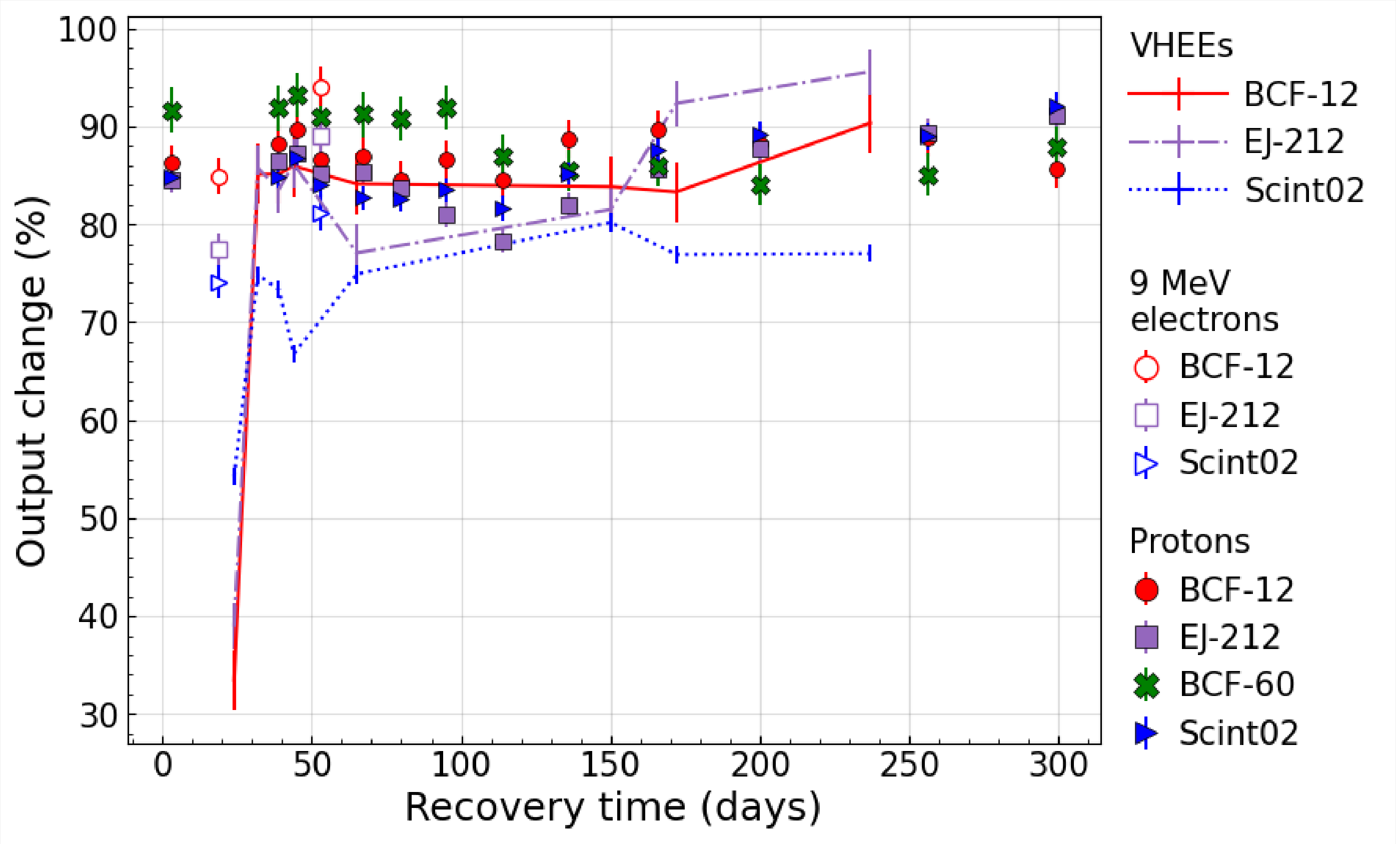


Effect of linear energy transfer (LET)

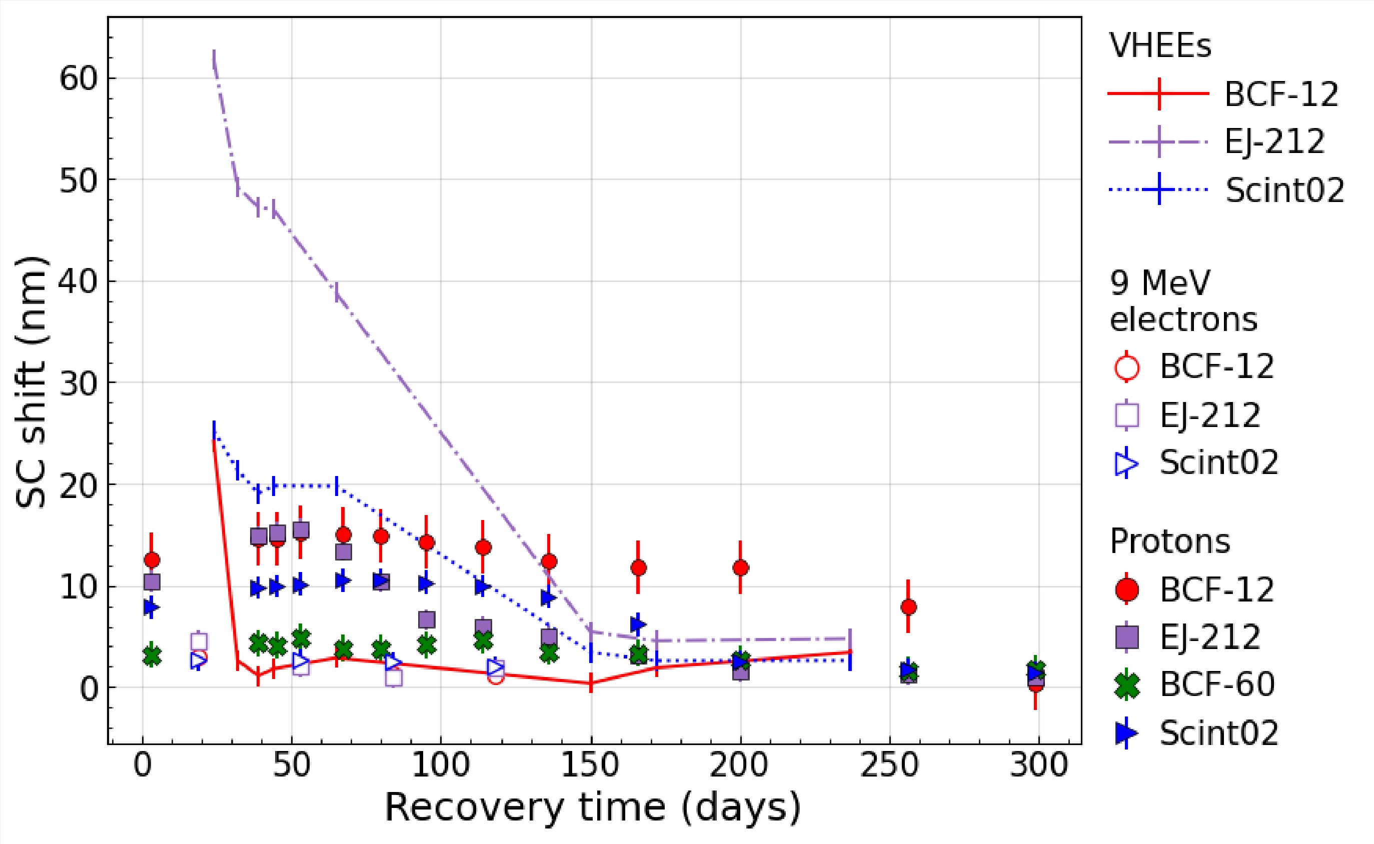
- High-LET radiation creates higher density of radicals
- Enhanced reactions between radicals
- Shown to lead to more permanent radiation damage (not recoverable)

Possible effect of beam time structure

- Pulsed vs near-continuous

(Bodmann et al., 2001 & 2003)

Long-term Recovery of Spectral Changes



Spectral shift

- Complete recovery of spectral changes for all modalities
- Very slow (~300 days) for protons

Conclusions

Conclusions

Radiation damage

- First ~10 kGy: Similar effects for all modalities
- After ~10 kGy: VHEE-irradiated scintillators become more radiation-hard

Recovery

- Minimal for protons, but significant for electrons
- High-LET protons create more permanent damage

Takeaways

- Type of radiation influences radiation damage and recovery processes
- Green-emitting BCF-60 is more radiation-hard

Thank you!

Merci!

cloe.giguere.1@ulaval.ca

Thank you to my collaborators from CERN CLEAR, CHUM and MD Anderson!

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ICCR 2027 - XXIth International Conference on the use of Computers in Radiation Therapy

Quebec Congress Centre • July 4-8, 2027

ICCR is one of the longest-running conferences in radiation therapy. Held only every three years, it attracts medical physicists, clinicians, and academic scientists from across the globe who are using computers to drive advances in radiation therapy. Many important innovations have been unveiled at ICCR and the conference enjoys a very high standing in the international radiation oncology community.

We look forward to welcoming you in Québec in July 2027!

Thank you!

Merci!

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Université Laval GRPM The University of Texas MD Anderson Cancer Center Making Cancer History clear

Centre de recherche sur le cancer de l'Université Laval CRCHUM Centre de recherche Centre hospitalier de l'Université de Montréal Centre de recherche CHU de Québec Université Laval

Experimental set-up

VHEEs:

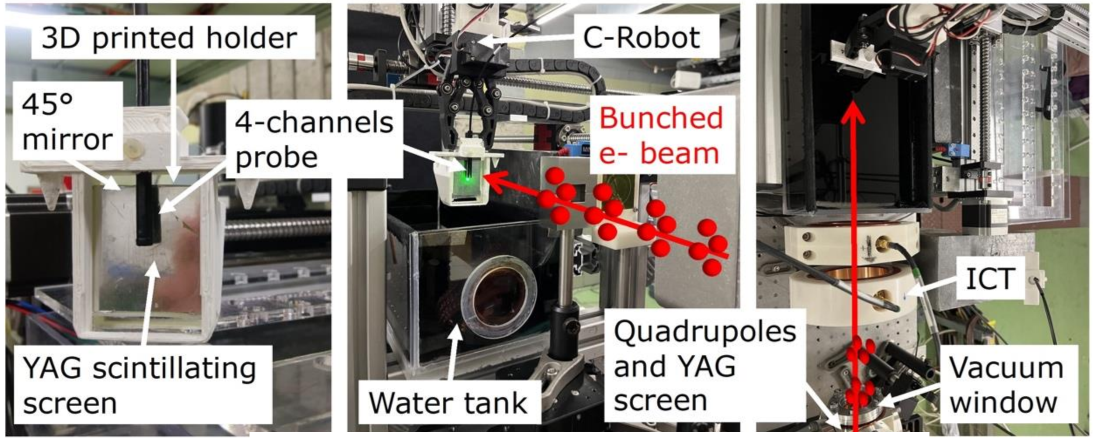
- ICT & MD-V3 films
- Water tank, 4 cm depth

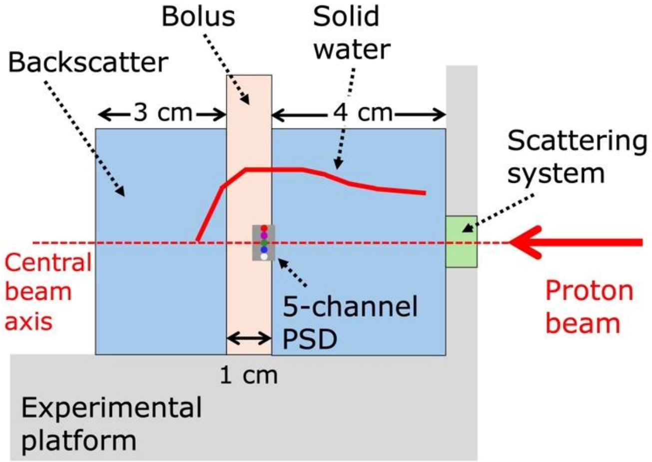
Protons:

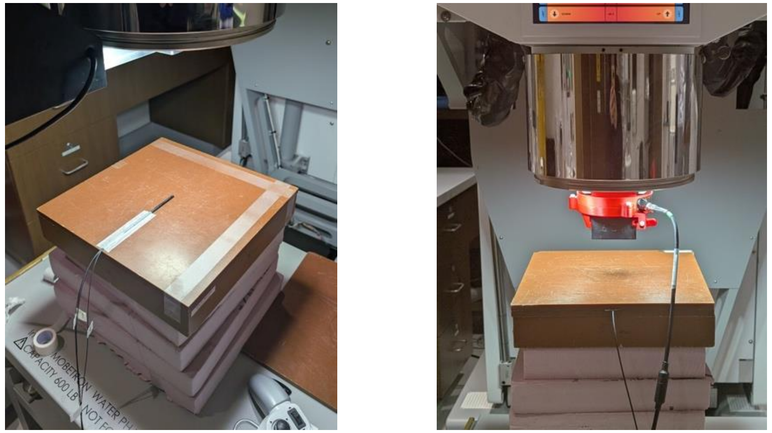
- Advanced Markus chamber
- Solid water, 4 cm depth (plateau region)

9 MeV electrons:

- BCT
- Solid water, 1 cm depth







Dosimetry in UHDR conditions

Chemical dosimeters

Radiochromic films, alanine

- Dose-rate independent
- Can measure high doses
- Passive measurement only

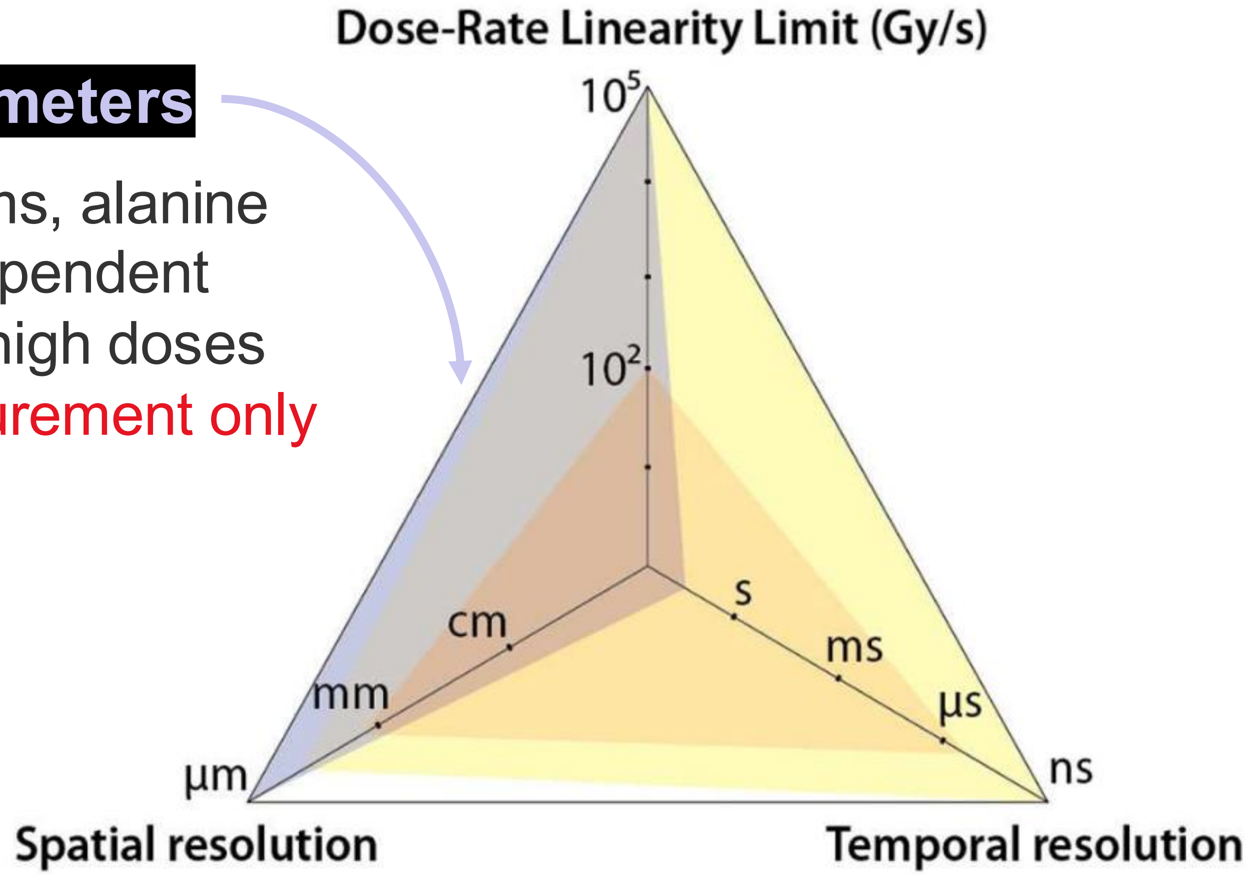


Figure from (Ashraf *et al.*, 2020)

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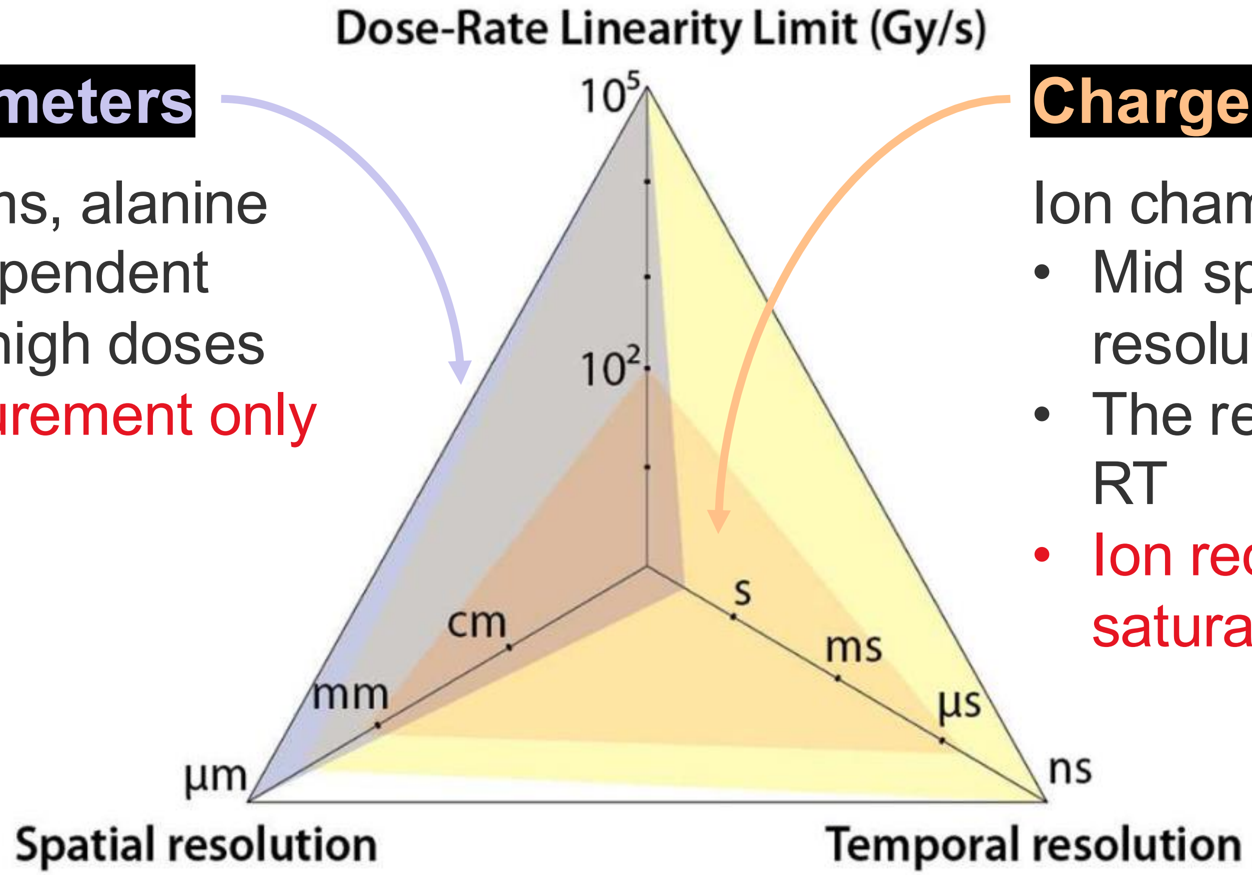

Charge-based dosimeters

Ion chambers
- Mid spatial and high temporal resolutions
- The reference dosimeter in RT
- Ion recombination & saturation at UHDR

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Figure from (Ashraf *et al.*, 2020)

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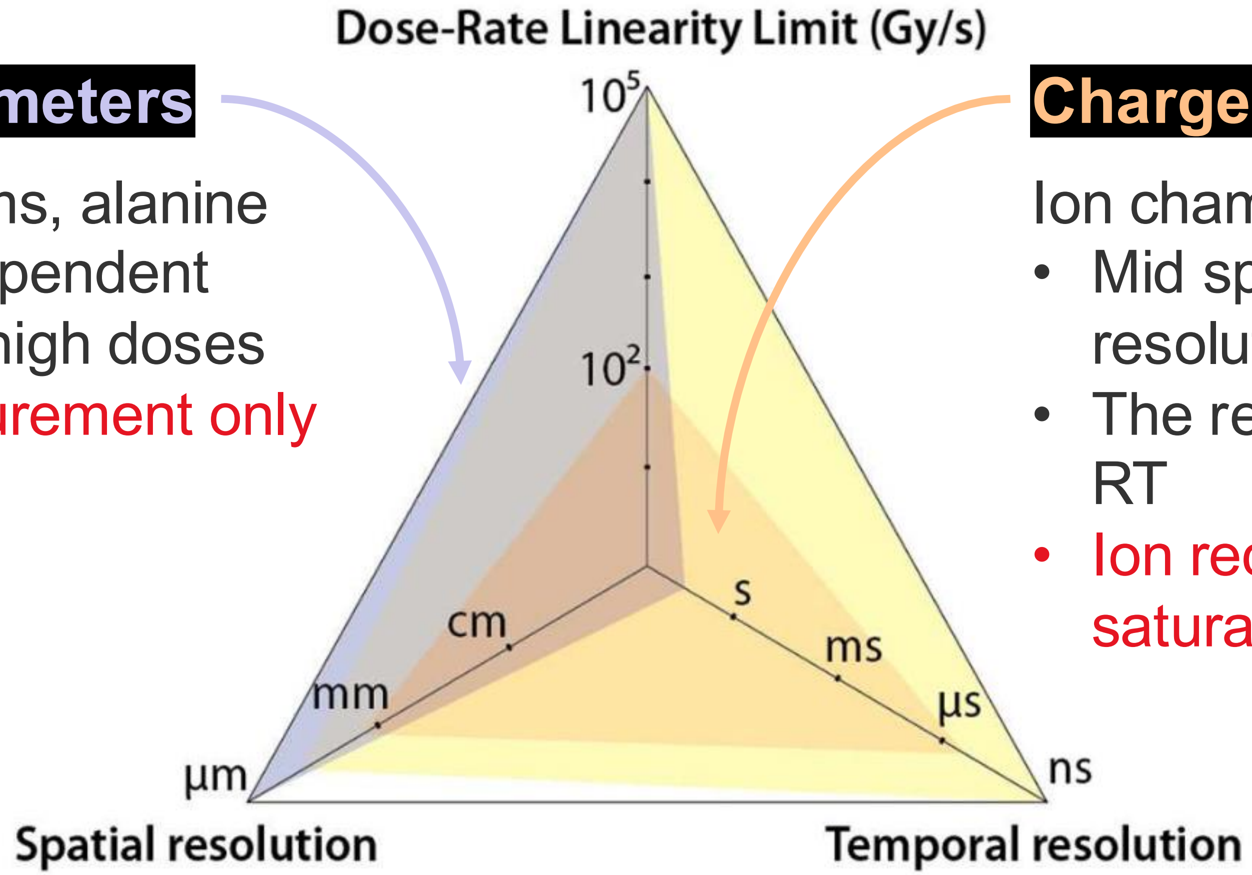

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Luminescence-based dosimeters

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Figure from (Ashraf *et al.*, 2020)

Light Output Decreases

Mechanism of radiation damage

- Creation of free radicals in the polymer base: colour centers
- Absorption of scintillation photons and loss of transmittance
- Loss of light output and yellow discoloration

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(Bross and Dalmau, 1992; Zorn, 1993; Kharzheev, 2019)

Spectral changes

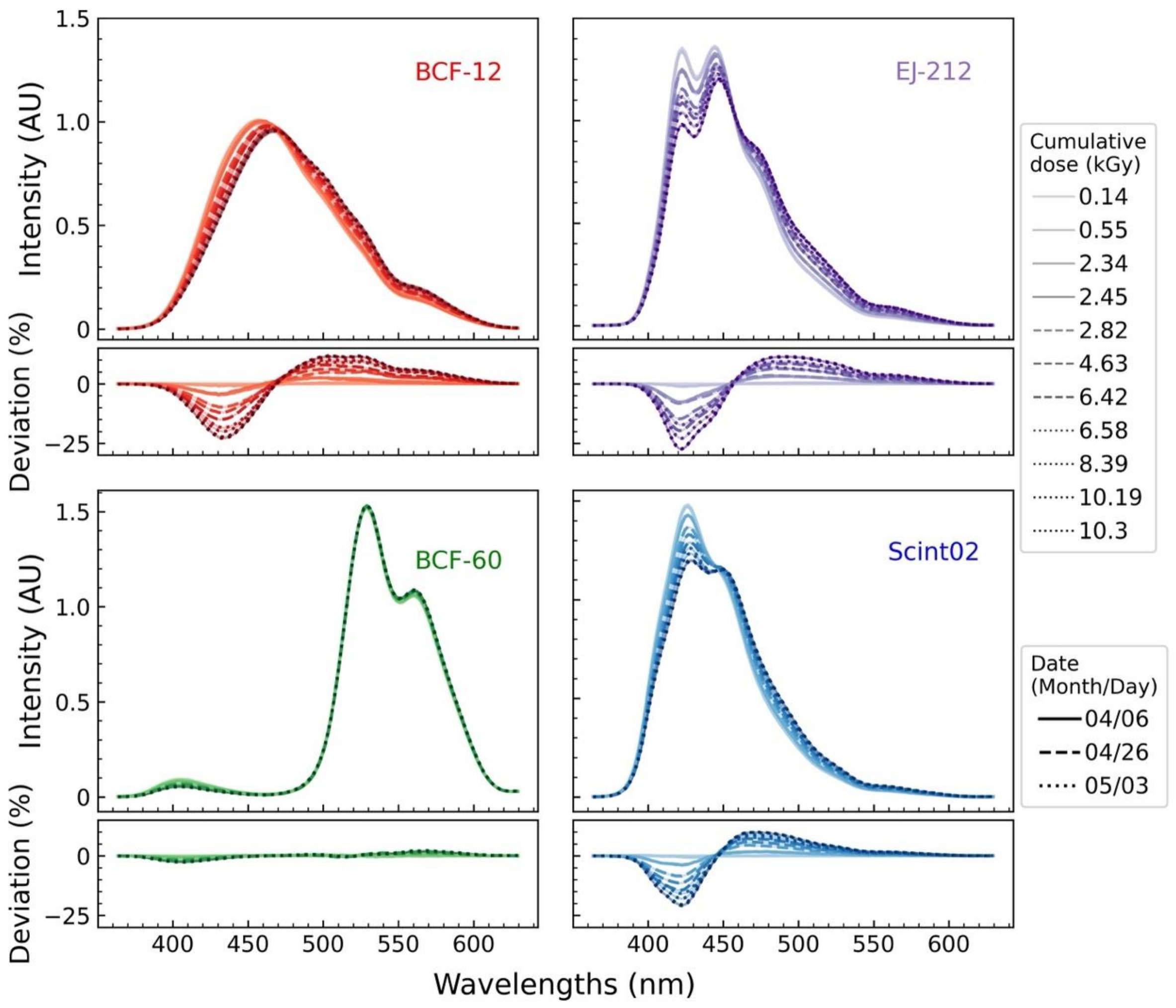

Fig.2: Scintillation spectra at increasing cumulative dose, for proton irradiations.

- Decrease of scintillation emission mostly in the UV-blue (380-500 nm) region
- Shift of spectrum towards yellower wavelengths
- BCF-60 emits above the most affected spectral region

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LET effect in radiation damage of plastics

Bodmann et al. 2001 & 2003

- High LET radiation lead to higher density of reactive intermediate species in the longitudinal track structure and to an overlapping of radicals along the path of the ionizing particle. Could cause enhanced interactions like reactions between radicals or recombination of radicals.

- Permanent damage in PS and PVT after recovery in air is larger for neutron than for gamma

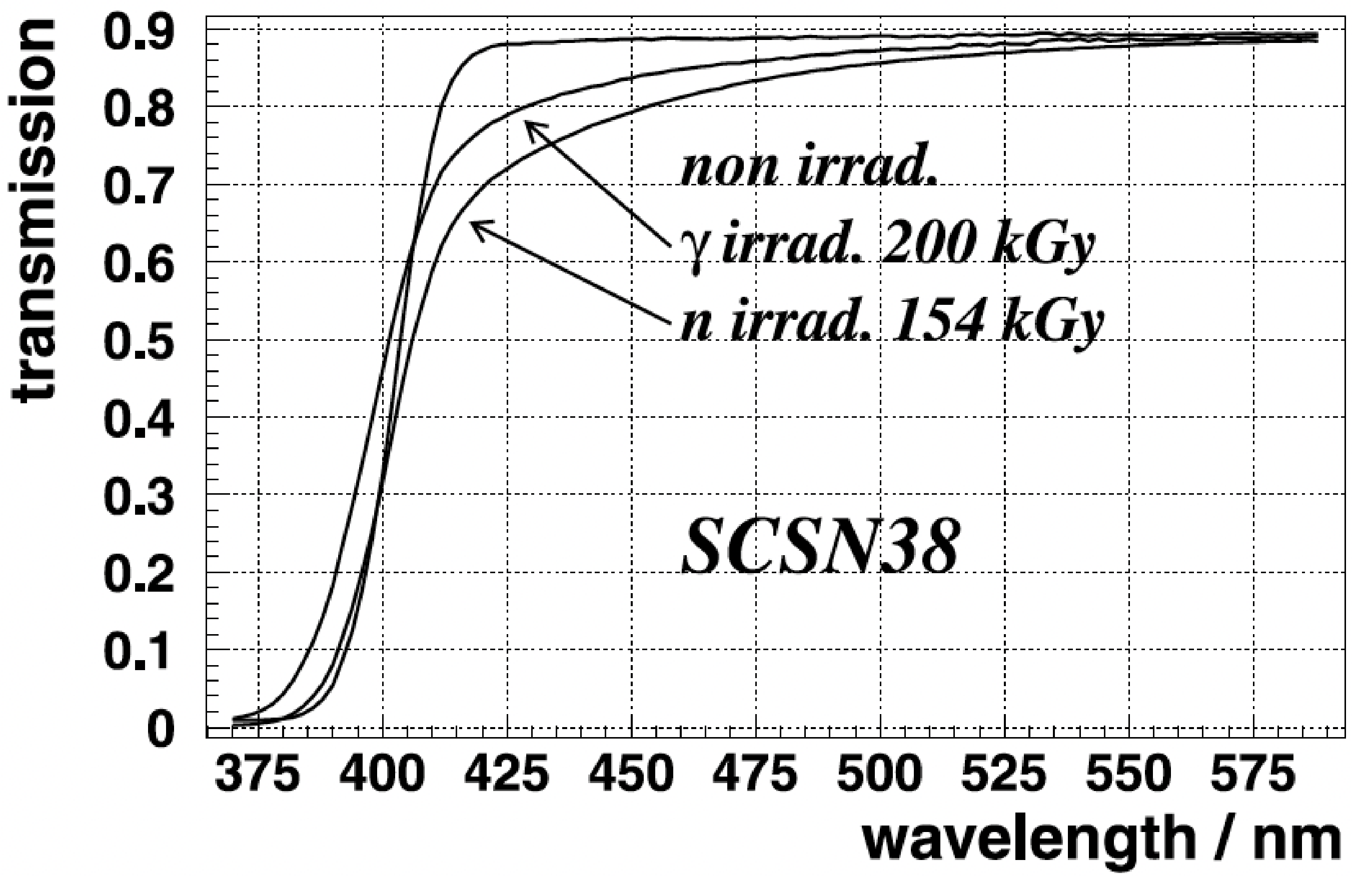
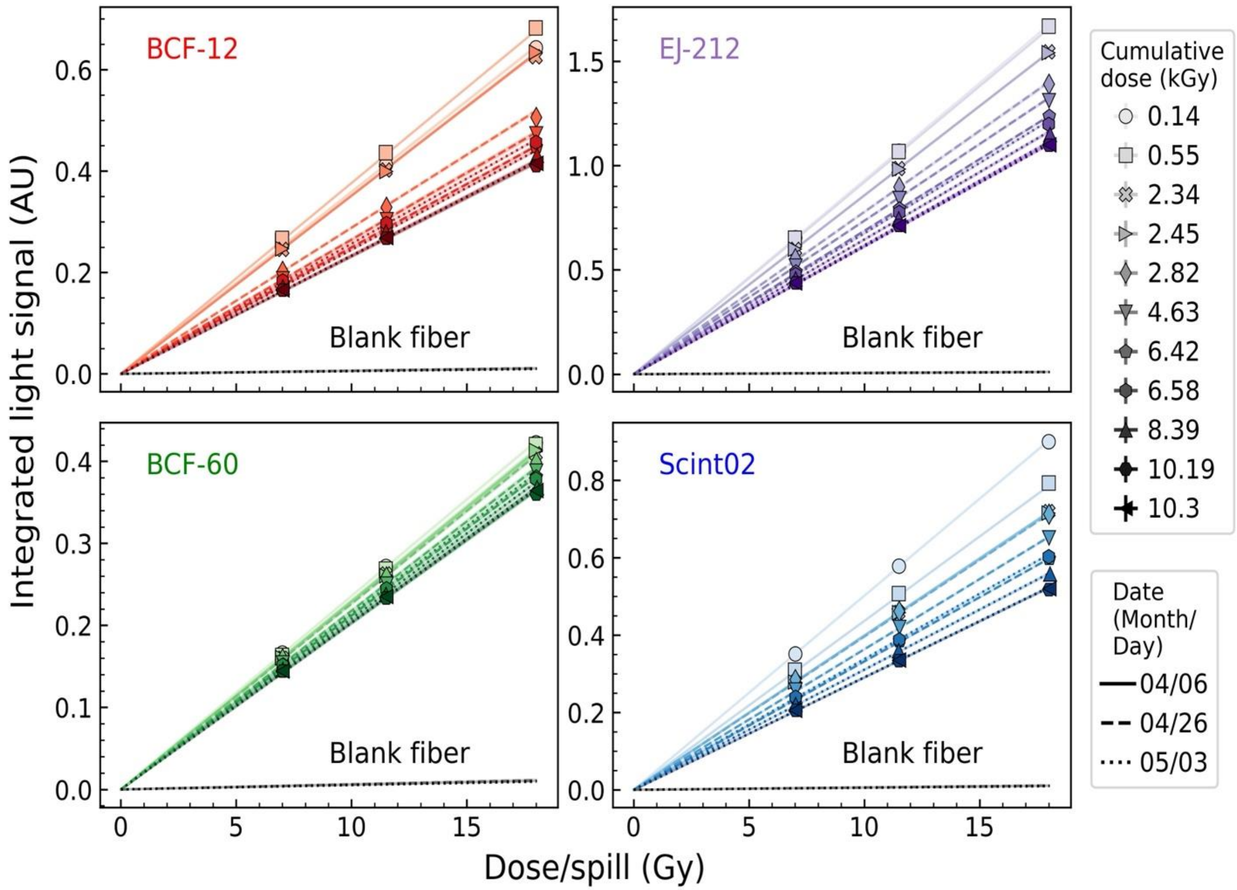


Fig. 2. Spectral transmissions of 2.6 mm thick SCSN38 samples before and after irradiation with 200 kGy γ and 154 kGy neutron (reactor) after complete annealing.

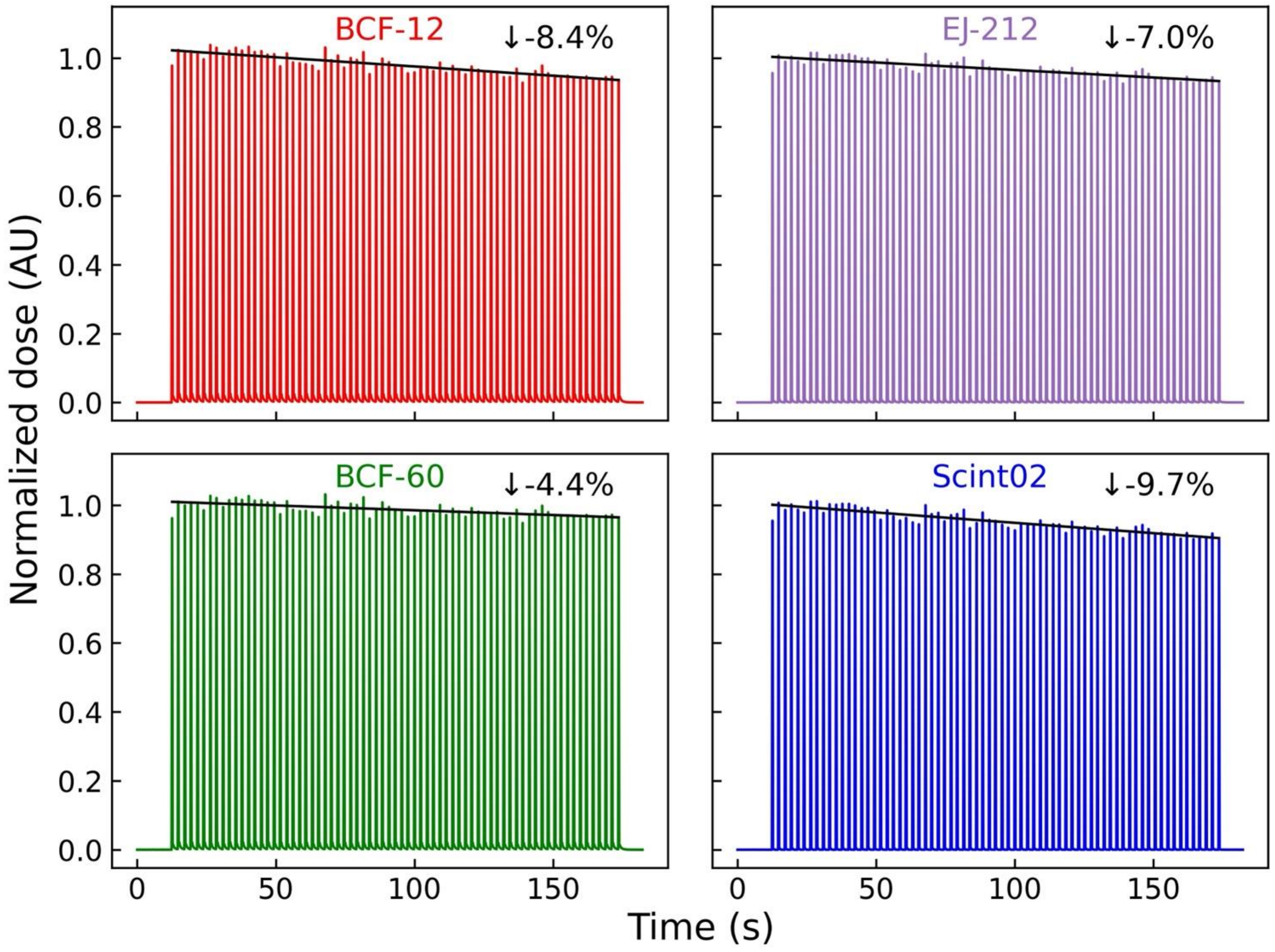
Protons Linearity Measurements

- Response linearity to dose per spill of 7, 11.5 and 18 Gy
- Repeated multiple times across the three experiment days
- Excellent linearity (R^2>0.999)
- Light output decrease with accumulation of dose



Protons High Dose Irradiations

- Five ~1680 Gy irradiations
  - Delivered in spills of ~18 Gy, sent out every 2 s (~3 min total)
- Important decreases in this short time



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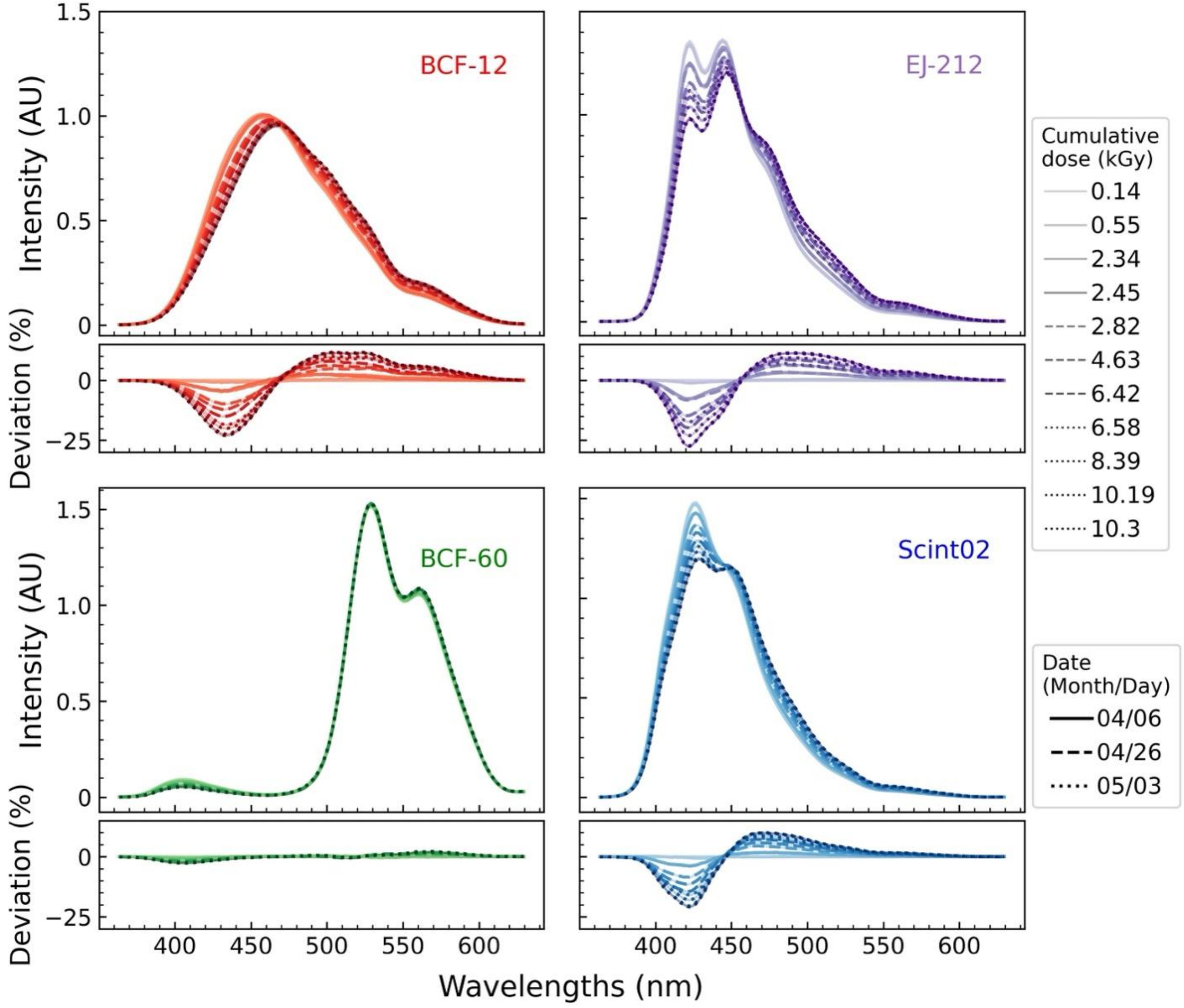
Protons Spectral changes

- Spectra measured at spills of ~11.5 Gy, normalized by area under the curve (AUC)
- Shift towards longer yellower wavelengths
- Decrease of light emission preferentially in the 380-500 nm region (blue)

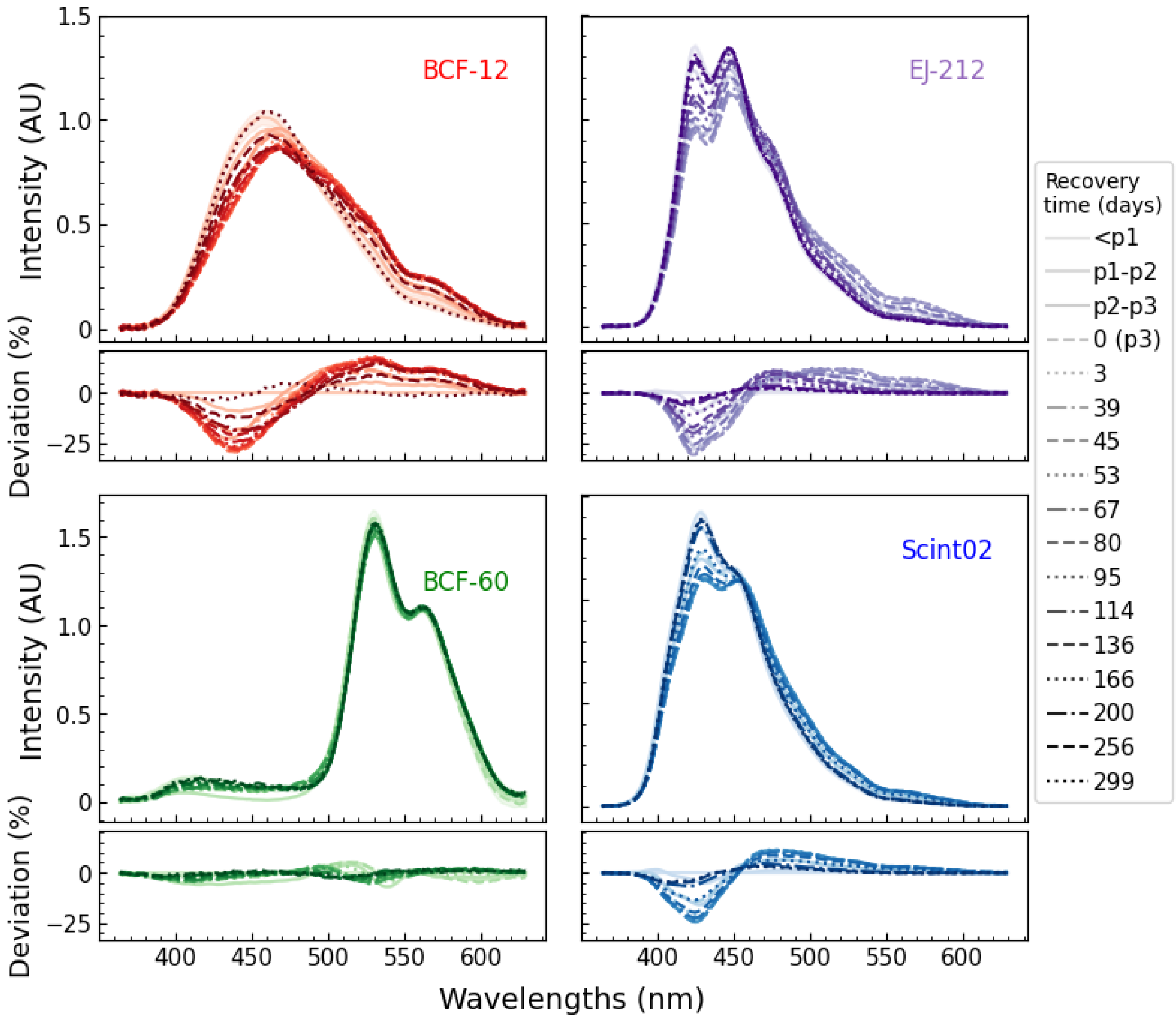


Long-term Recovery

Spectral recovery

- Slow (> 100 days) process
- Near complete recovery for Scint02 and EJ-212 (will continue tracking)

< p1: before 1st proton experiment
p1-p2: between proton experiments 1 and 2
p2-p3: between proton experiments 2 and 3



PSDs in FLASH VHEEs

Main takeaways:

- Blank fiber linear over whole dose range
- Scintillators lose linearity at ~45 Gy/pulse

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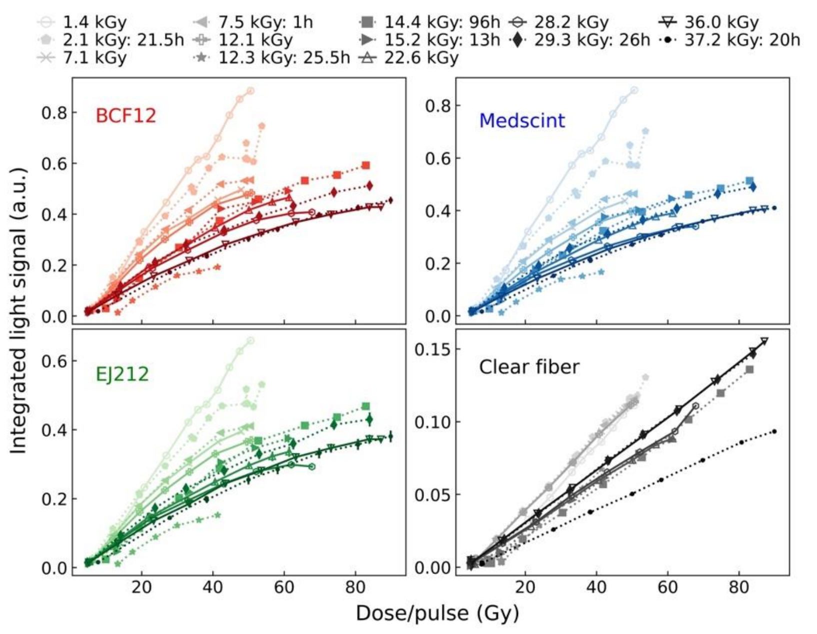

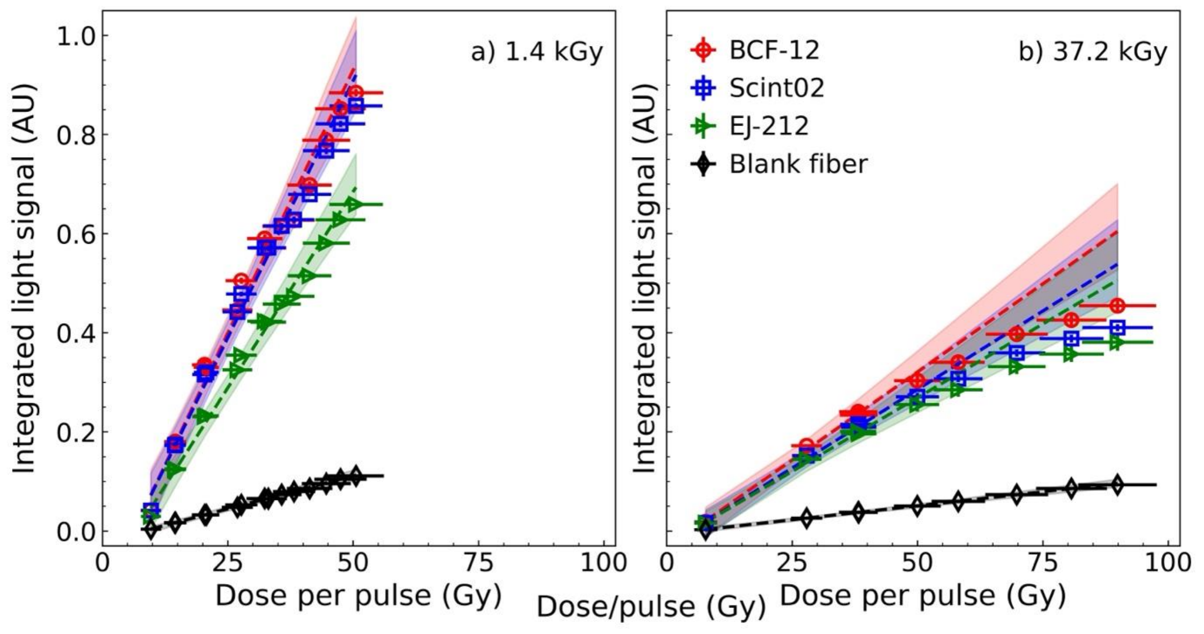

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- Radiation damage causes decrease of light output (≤1.87%/kGy) and shift of spectra towards yellow

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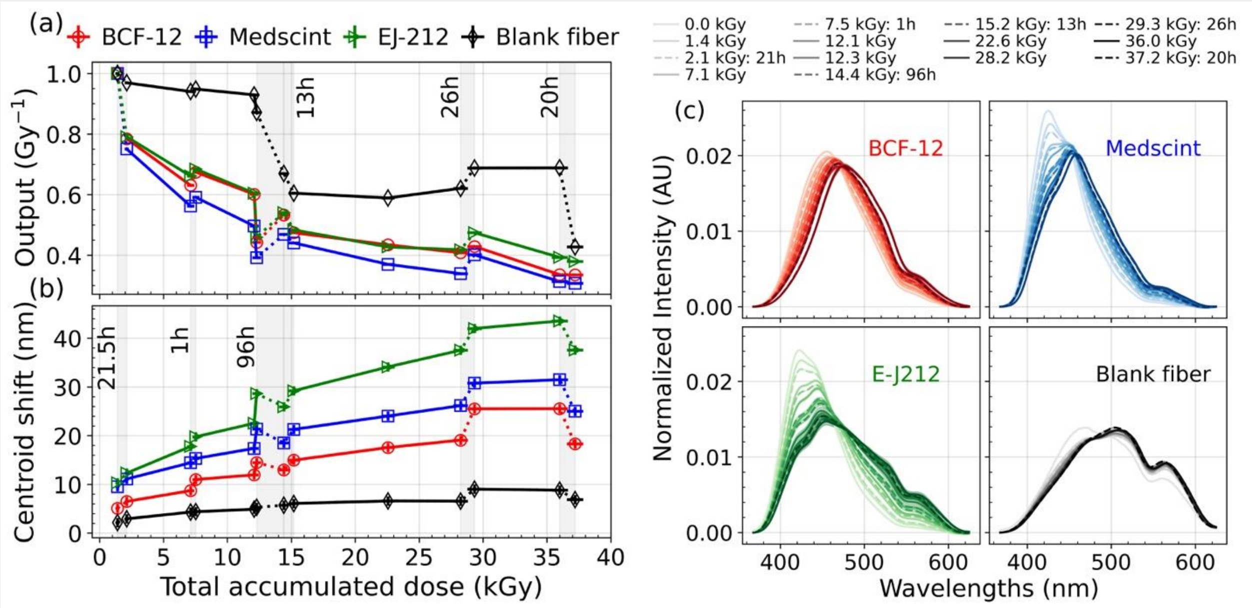
		BCF-12	Medscint	EJ-212	Blank fiber
Output (%)	Last irradiation (±0.2)	33.4	30.4	37.8	42.7
	Recovery[a] (±2)	85	78	94	89
Centroid shift (nm)	Last irradiation (±1)	18	25	38	7
	Recovery[a] (±1)	2	3	5	2

[a] Recovery values are mean values measured after stabilization of response.



PSDs in FLASH VHEEs

Main takeaways:

- Blank fiber linear over whole dose range
- Scintillators lose linearity at ~45 Gy/pulse
- Radiation damage causes decrease of light output (≤1.87%/kGy) and shift of spectra towards yellow
- Short-term (<100h) recovery observed
- Long-term (<172 days) recovery observed with partial output recovery (6-22% damage remaining after stabilization) and complete spectral recovery

		BCF-12	Medscint	EJ-212	Blank fiber
Output (%)	Last irradiation (±0.2)	33.4	30.4	37.8	42.7
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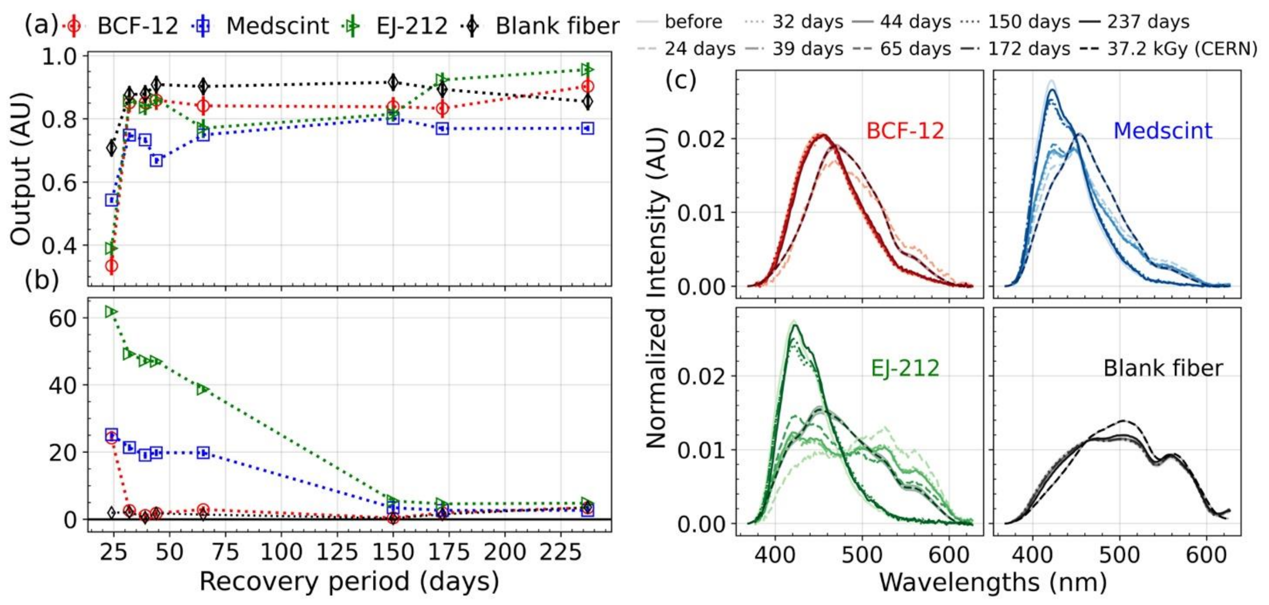
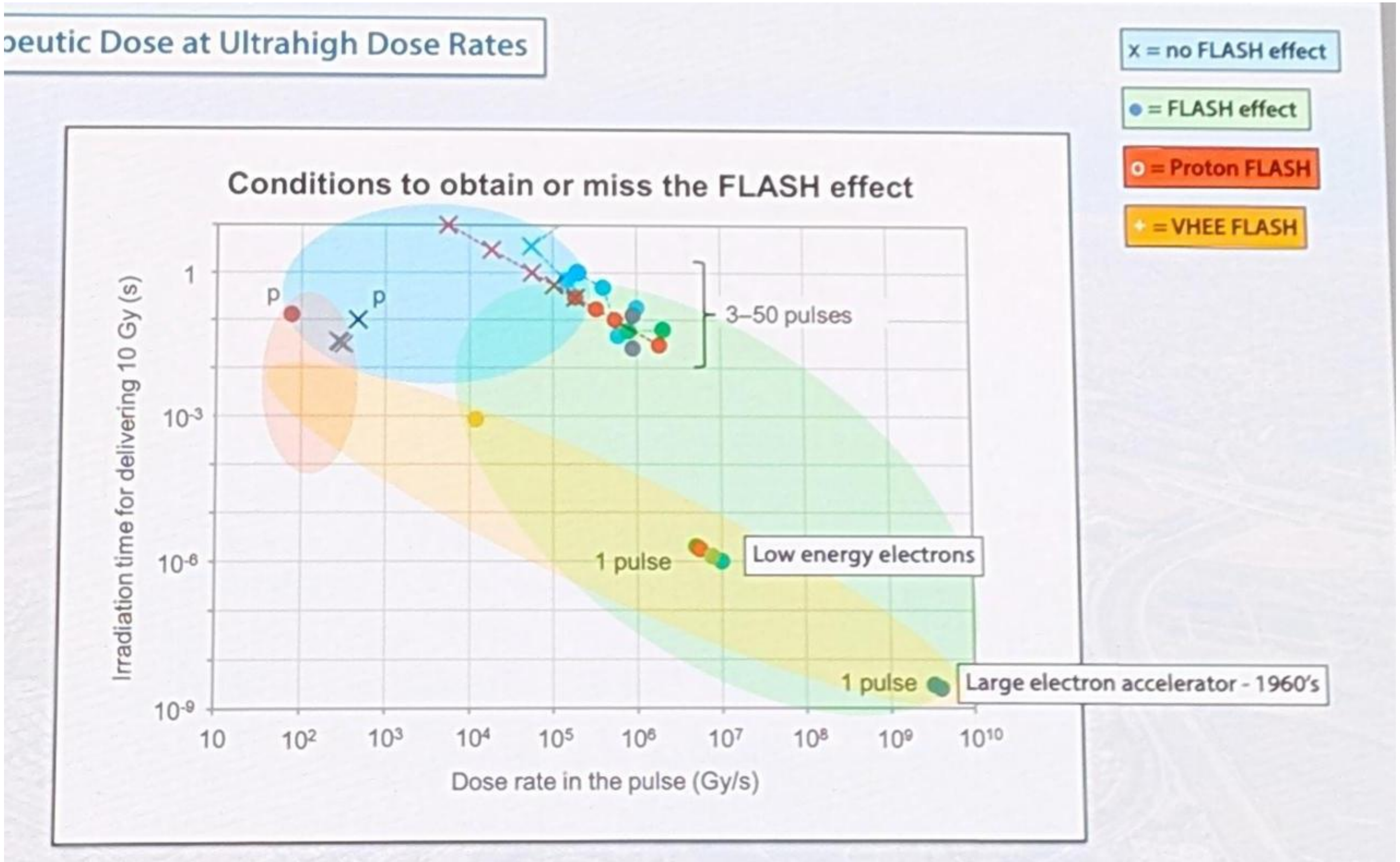
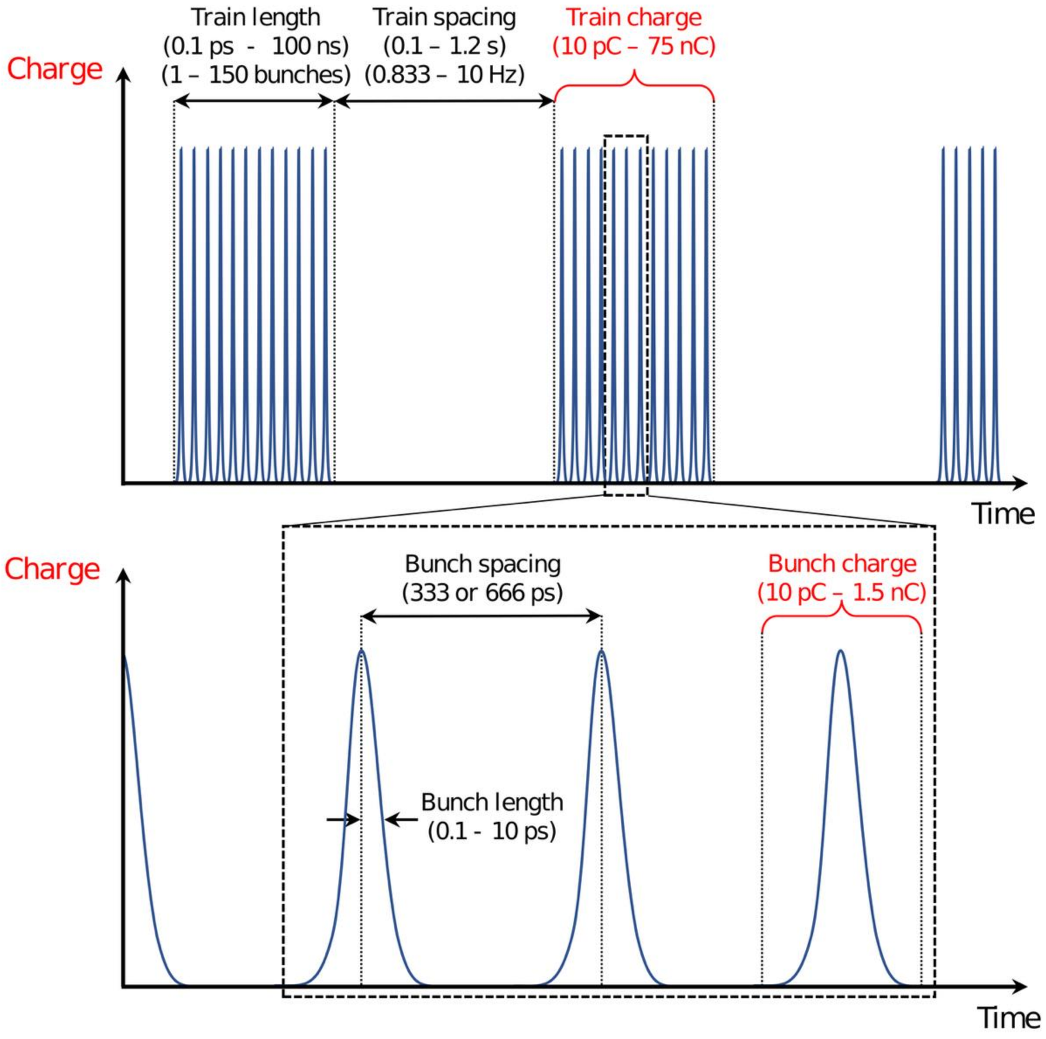


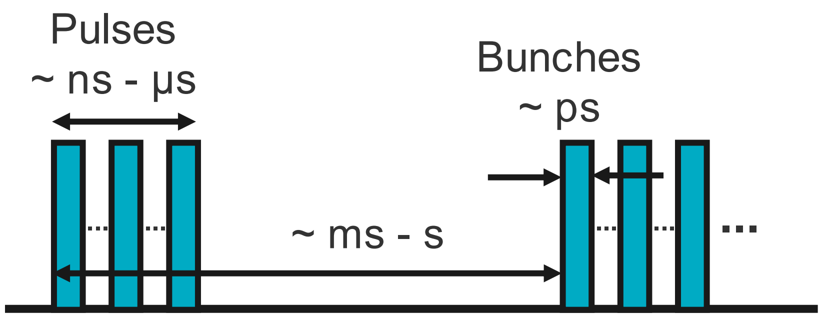
Conditions for FLASH



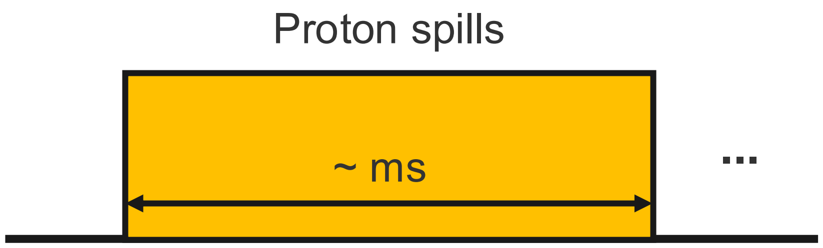
Beam Time structure



a) Pulsed linear accelerator (CLEAR & Mobetron)



b) Synchrotron



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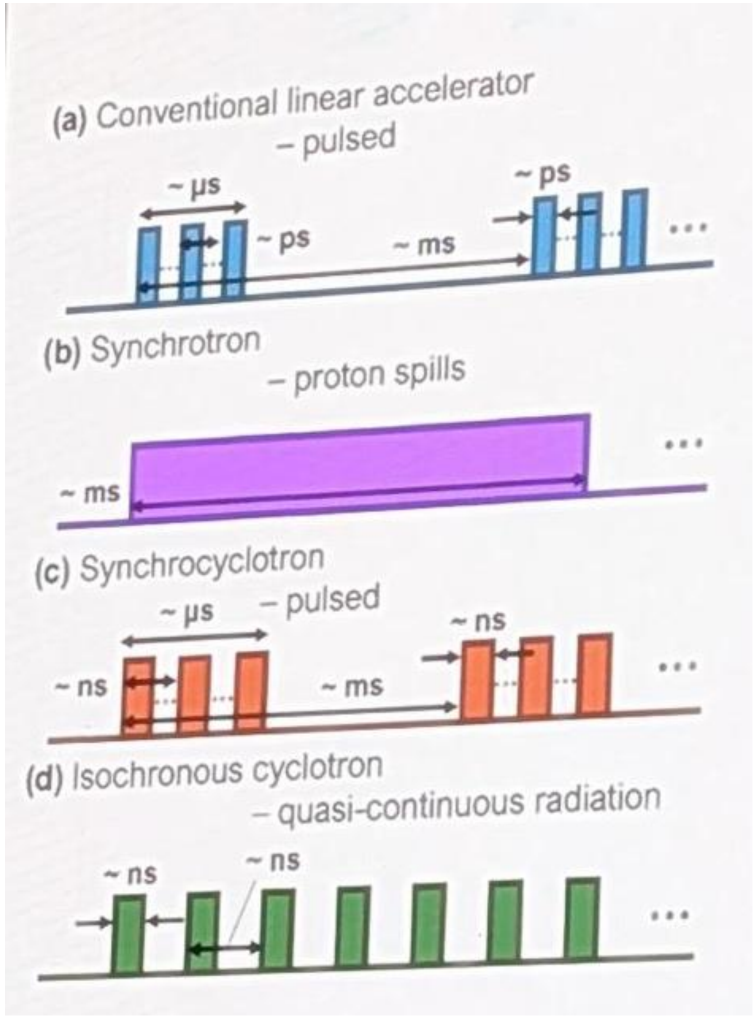
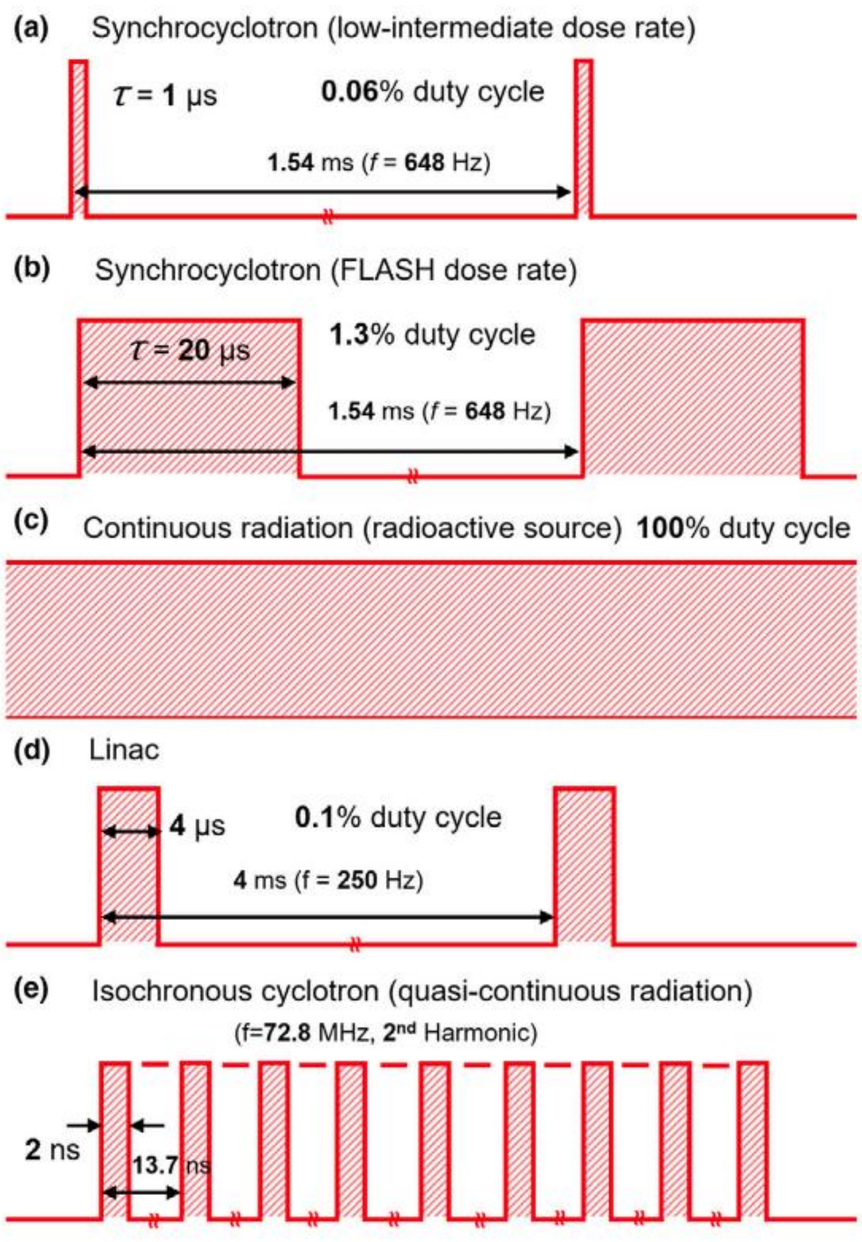
Beam Structure



Diffenderfer et al. 2022



Beam Parameters in UHDR

$\bar{\dot{D}}$: Average dose rate (DR)

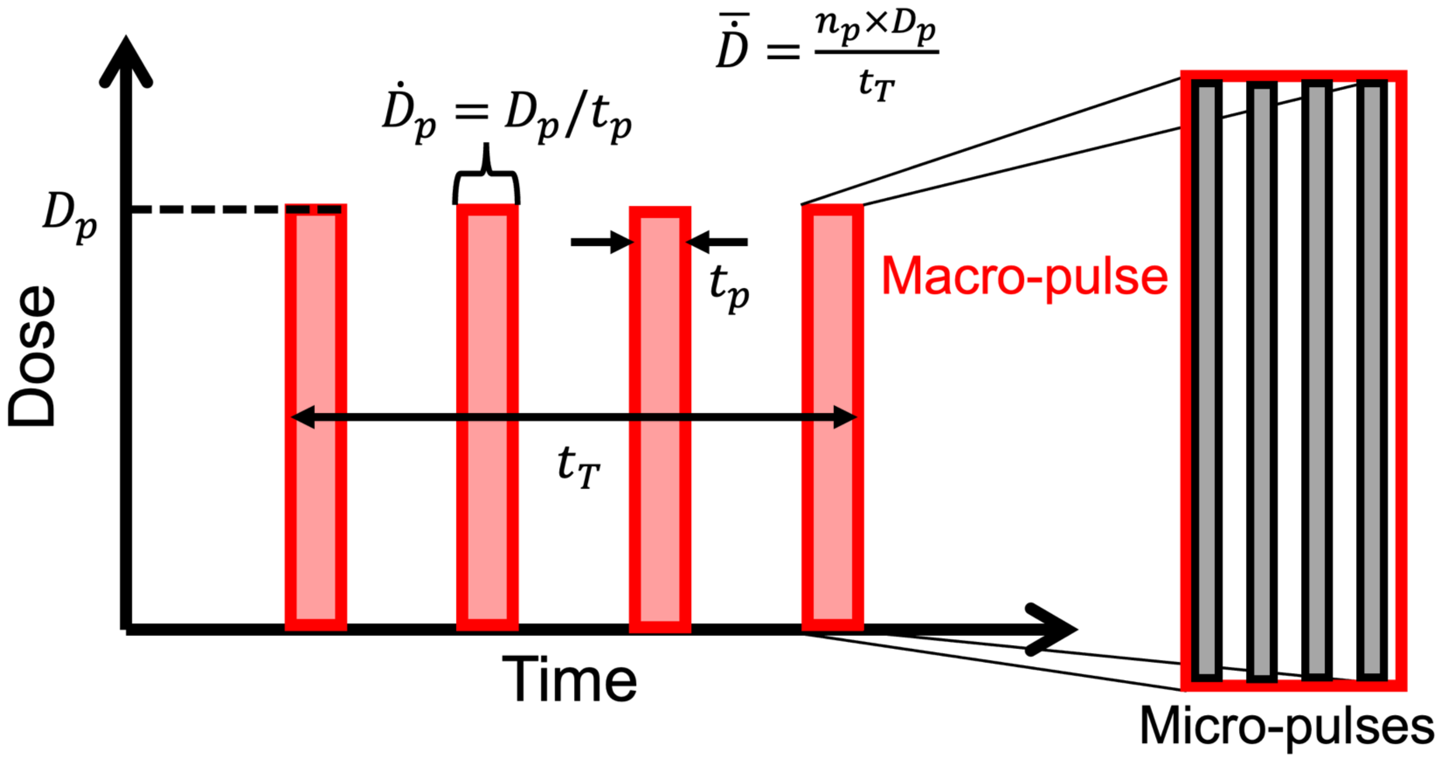
$\dot{D}_p$: Instantaneous DR

n_p: # of pulses

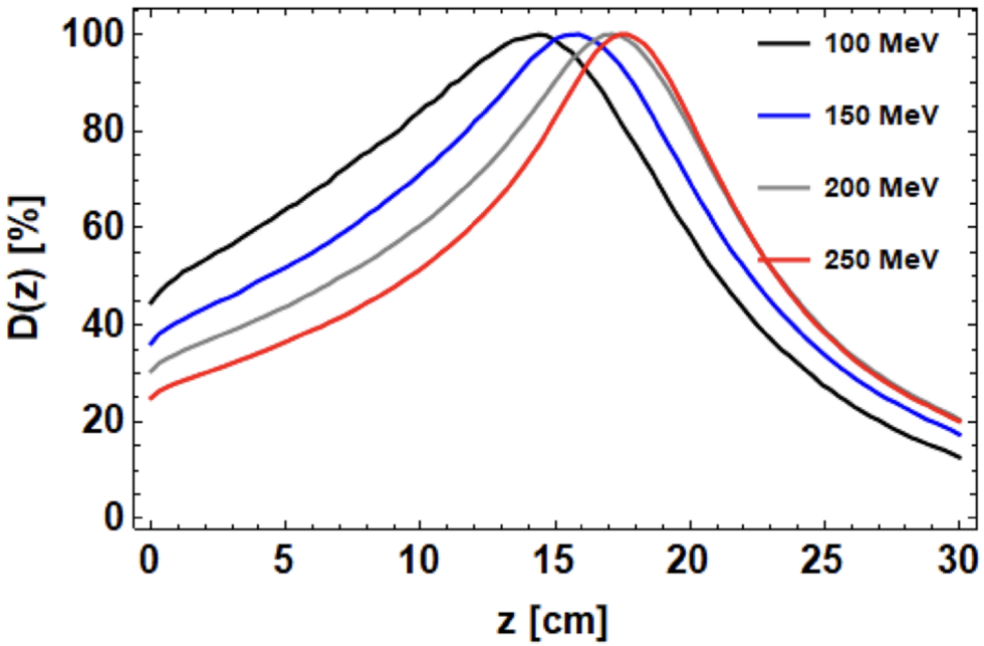
D_p: Dose per pulse

t_p: Pulse duration

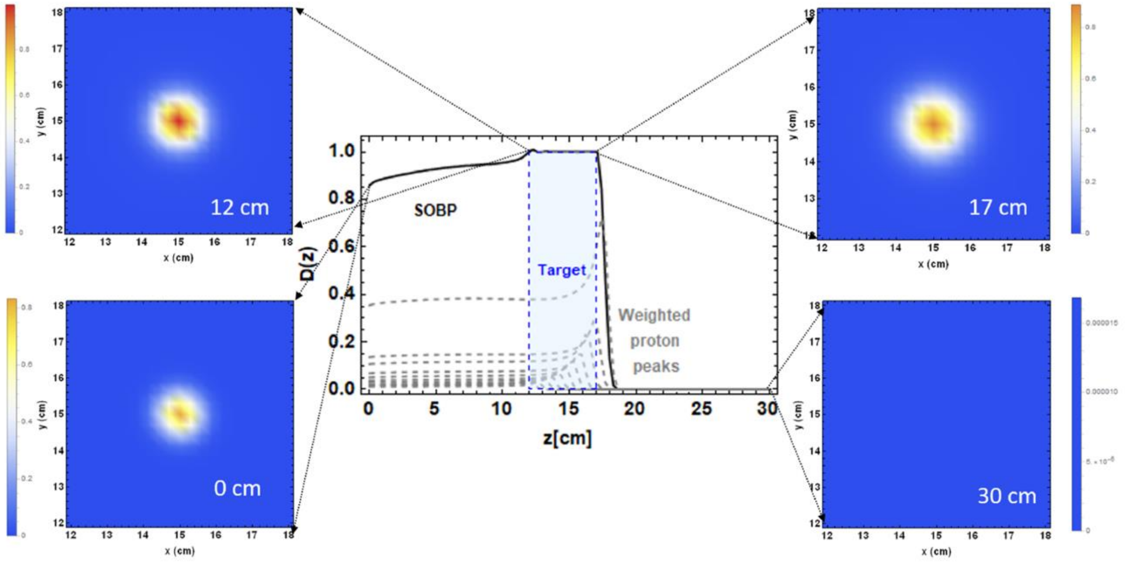
t_T: Total treatment time



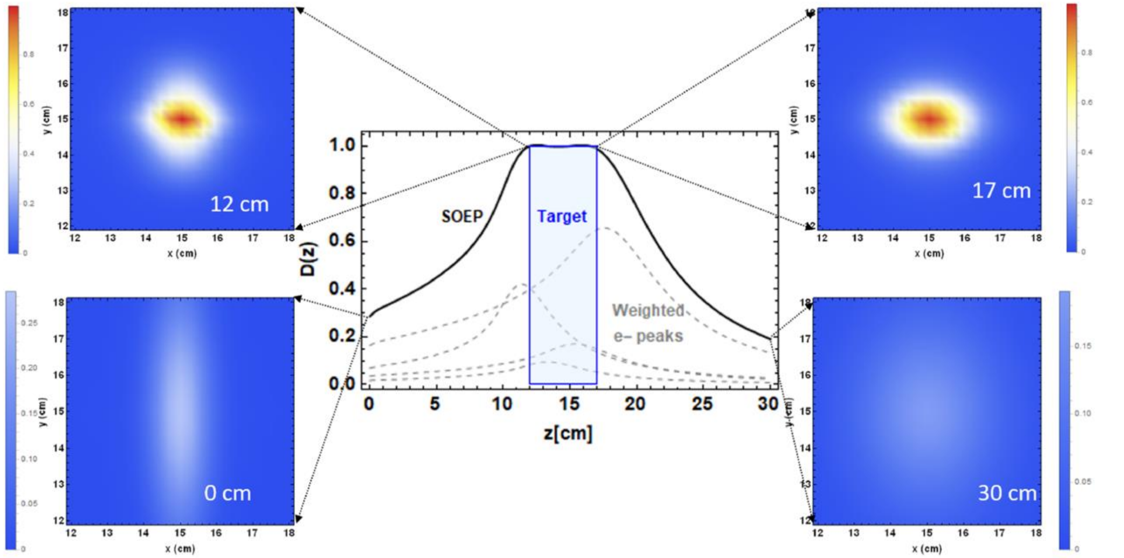
Focused VHEEs VS protons



TOPAS-based Monte Carlo simulations of the on-axis dose plots for 100, 150, 200 and 250 MeV asymmetrically focused VHEE beams in water. Differences in focusing is due to the increasing penetration power and reduced scattering of VHEE with beam energy.



(a) SOBP with 11 contributing proton peaks, with the transverse dose at entrance, 12 cm, 17 cm and exit of phantom shown.



(b) SOEP with 4 contributing electron peaks, with the transverse dose at entrance, 12 cm, 17 cm and exit of phantom shown.

Inhomogeneities VHEE VS protons