Radiation safety considerations for electron and proton FLASH vaults: shielding, neutron production, and neutron activation

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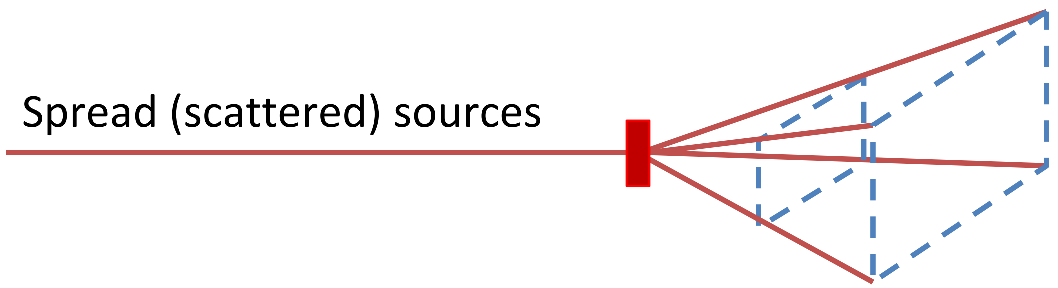
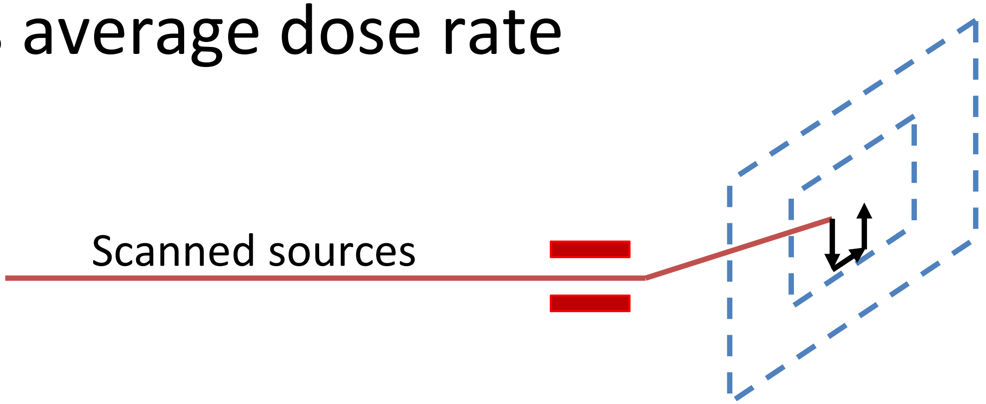
How is FLASH currently achieved?

- The two ingredients of FLASH: **Dose** and **Ultra-High Dose rate**
  - (Large single (>8 Gy) dose at >40 Gy/s average dose rate





- UHDR is produced through two methods
  - Increased beam current
    - Nozzle current for p^+, electron gun current + RF power for e^-
  - Decreased beam spread
    - Spread sources (photons/scattered e^-) : Reduce SSD
    - Scanned sources : reduce scanning area/use fewer beam energies

Varian FLASH Forward Consortium

- A consortium of several centers using Varian linear accelerators (e^{-} FLASH) or ProBeam proton PBS sources (p^{+}-FLASH)
- Two consortion radiation protection working groups have proposed recommendations for electron and proton UHDR sources

e^{-} FLASH

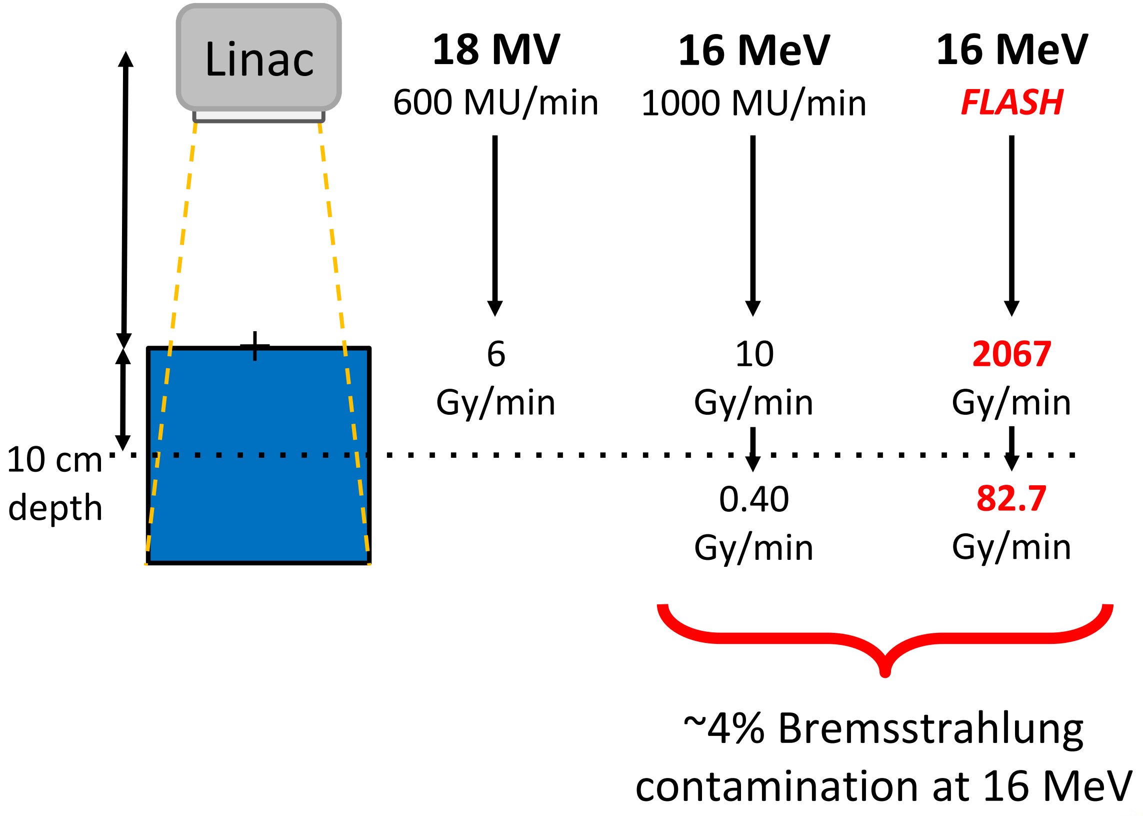
- Converted TrueBeam or Clinac 23EX
- 16 MeV
- 180 or 200 Hz
- ~200 Gy/s @ isocenter

p^{+} FLASH

- ProBeam® or ProBeam 360®
- Max energy (250/226 MeV)
- Mainly used in transmission mode (not Bragg Peak)
- ~200 Gy/s @ isocenter

Shielding for e^- FLASH sources

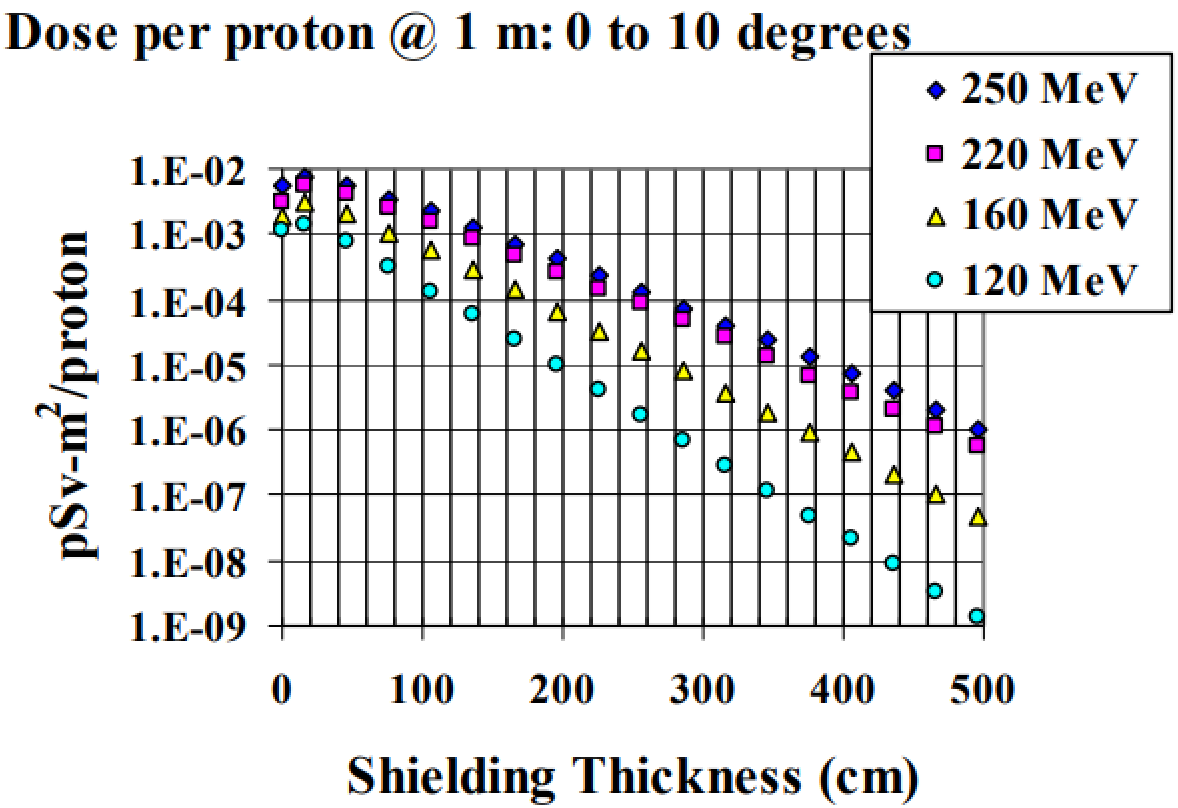
- Electrons typically an **afterthought**
  - Assumed it sufficient for electrons if designed & sufficient for photons
- These assumptions **break down** at FLASH-RT dose rates
  - ~1-4% bremsstrahlung contamination
  - For converted linac, ~82.7 Gy/min at isocenter from photon contamination alone
- Rooms with mixed lead/concrete shielding a concern for neutron production
  - Additional neutrons can be produced within lead shielding



Poirier et al, Med Phys, 2021

Shielding for p^+ FLASH sources

- Proton FLASH
  - Used at higher energies (250 MeV) and without SOBP (transmission flash)
  - Higher workload at high energies than used in shielding design
  - More neutron activation at 250 MeV
    - Neutron source in beam stopper vs nozzle
- Practical considerations
  - Use of a beam stopper to prevent irradiation of electronics
  - Consider neutron-activation of beam-stopper and other equipment



Shielding design considerations for proton therapy facilities, Nisy Elizabeth Ipe, PTCOG52

The impact of UHDR on Shielding

- All assumptions related to shielding calculations must be re-evaluated
  - Instantaneous and cumulative dose rates from leakage/transmission for primary and secondary barriers
  - In the USA – limit of 20 μSv in any 1 hour for uncontrolled areas, 1 mSv/year
  - Neutron production and activation
- Electrons
  - Typically not considered in shielding requirements due to finite range
  - UHDR bremmsstrahlung production alone can exceed that of 18 MV photons
- Protons
  - Used at higher energies (250 MeV) and without SOBP
  - Higher workload at high energies

Radiation protection assumptions

- Workload
  - Treatment/research workloads will be comparable to conventional
  - Commissioning/radiation survey workload likely to be much higher
    - Beam scanning, radiation surveys take time to find hotspot/stable reading
    - Dose to isocenter can easily exceed normal weekly workloads 10^3-10^4 Gy
- Shielding thickness
  - Transmission likely to be higher at FLASH vs CONV
    - p^+ Flash uses max (250 MeV) energy
    - e^- bremsstrahlung production in scattering foil exceeds conventional photon dose rates
- Neutron activation of accelerator or in-field components
  - Short delivery times allow operators to enter room while activation is higher

Radiation Surveys for e$^-$ FLASH (converted 23EX)

- Transmission dose rate from FLASH-RT e$^-$ **higher** than 18 MV Vault was designed for
  - Comparable at door/console, significantly higher in uncontrolled area (~2 orders of magnitude)
  - Highest dose for 16 MeV e$^-$ FLASH-RT was **outside primary shielding**

Energy	Exposure rate measured in location (μSv/h)					
	Door		Console		Uncontrolled area	
	Photons	Neutrons	Photons	Neutrons	Photons	Neutrons
18 MV photons	28	36	1.6	2	6.0	8.3
16 MeV e$^-$ – clinical	0.4	*not detectable*	0.2	*not detectable*	0.2	*not detectable*
16 MeV e$^-$ – FLASH (G180°:"*biology mode*")	65	45	3.0	4.0	430	350
16 MeV e$^-$ – FLASH (G0°:"*physics mode*")	31	38	2.0	8.0	1.0	0.3

US Federal limits:

20 μSv in any single hour

1 mSv yearly to non-NEWs

Poirier et al, Med Phys, 2021

- Uncontrolled Area: FLASH-RT in **biology mode** for ~1.5 min (~3180 Gy at isocenter)
  - At ~40 Gy per experiment, requires >80 experiments an hour
  - Impossible due to time for door, setup, etc…
  - **Rapidly achieved during beam tuning**

Neutron-activation of in-field materials

- Copper (alone or in brass) stands out as main source of concern
  - Combination of high cross-section and medium half-life
  - Used in collimators for both e^- and p^+
- Table below for e^- FLASH, but similar rationale for p^+ FLASH

Table 1: Induced radioactivity after ~**10s** (2000 Gy) irradiation using typical TrueBeam UHDR settings

Irradiated sample	Sample thickness (cm)	Most important radionuclide	Radionuclide lifetime	Radioactivated dose rate (initial, 0.3 m) (µSv/h)	Total dose (µSv)
Water	8	O-15	122 s	0.24	0.01
Solid water	8	O-15	122 s	0.10	0.00
Aluminum	4	Al-26m	6.3 s	32.30	0.08
Iron	1.2	Fe-53	8.5 min	0.1	0.02
Copper	**1**	**Cu-62**	**9.7 min**	**35.78**	**8.32**
Brass	1	Cu-62	9.7 min	14.32	3.33
Tungsten	0.5	Cu-62	9.7 min	0.71	0.17
Lead	0.8	Pb-203m	6.2 s	57.90	0.14

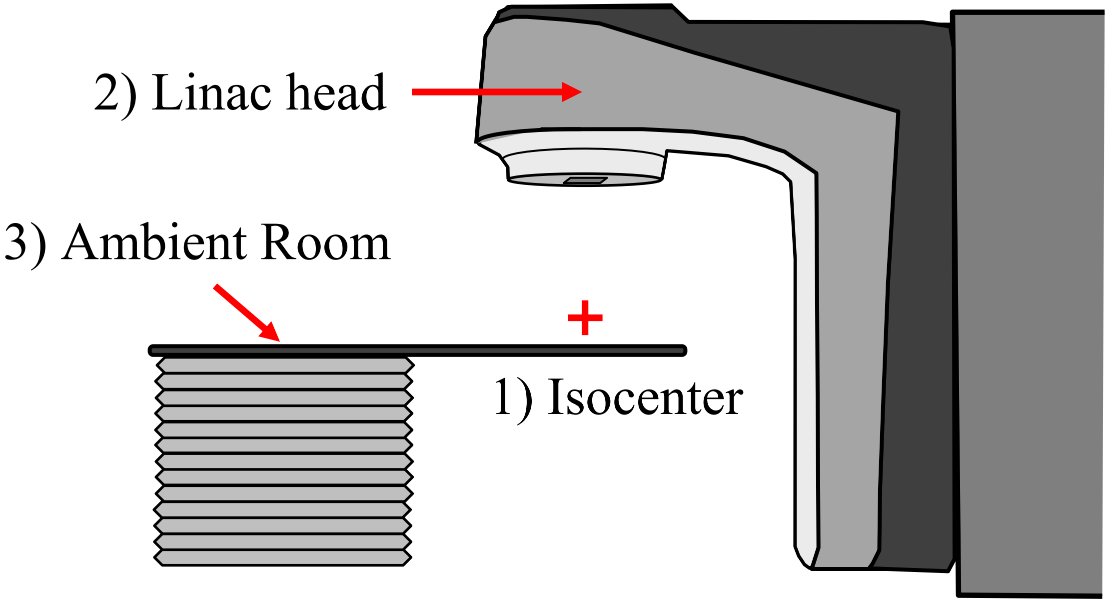
Præstegaard, Med Phys, 2024

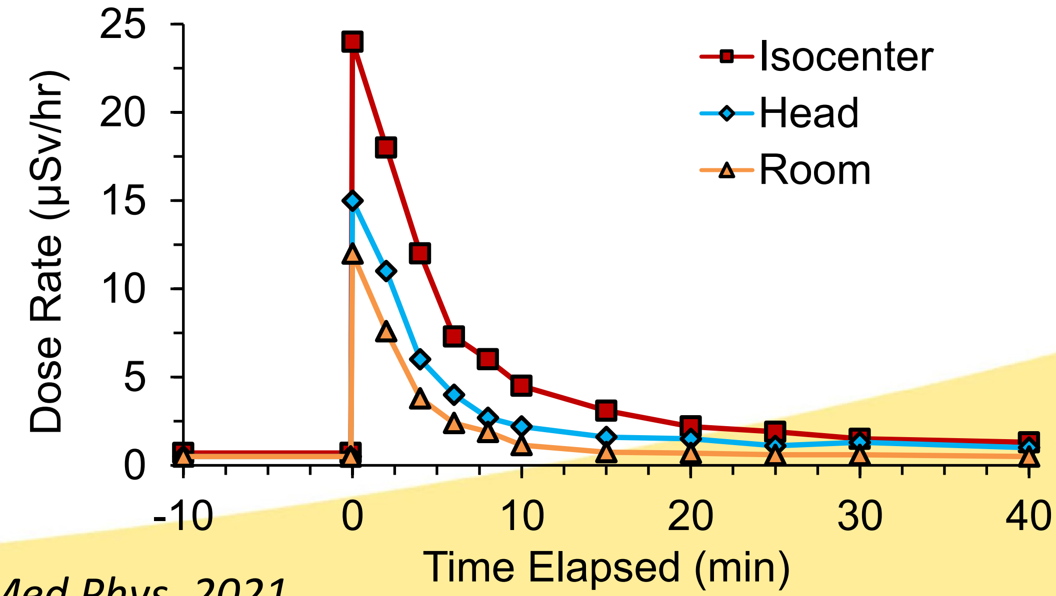
Neutron-activation of Linac Components for e⁻ sources

- Following a 110s irradiation (~4000 Gy at isocenter) typical of radiation surveys or beamscanning operation

- Dose is higher than expected, but quickly drops ~10-15 minutes following operation
  - Integrated over an hour: 1.5/2.4/3.9 µSv in the room/head/isocenter, respectively

- Not a major concern but operators should be cognizant following long (>2 minutes) FLASH-RT exposures





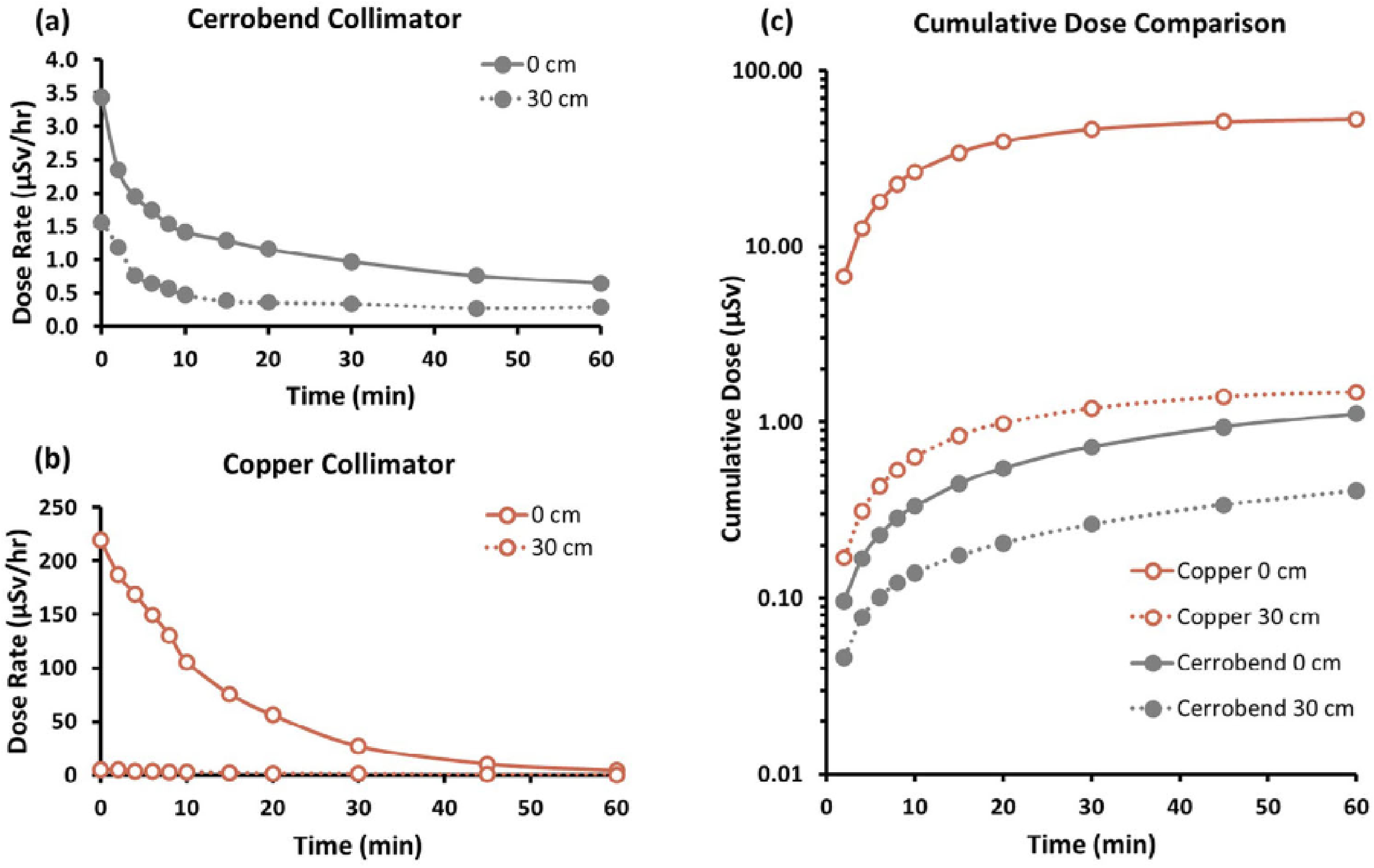
Poirier et al, Med Phys, 2021

Neutron-activation of collimators for e⁻ FLASH

- Neutron activation of Cu-containing accessories is highest concern
  - Collimators used for patient/biology studies
  - Dose equivalent measured using Fluke inovision survey meter for two collimators

- Even following a large (120 Gy) delivery, dose is below limits
  - Cumulative dose >20 µSv in 1 hr only if staff remain in contact with collimator for 1 hr post-exposure

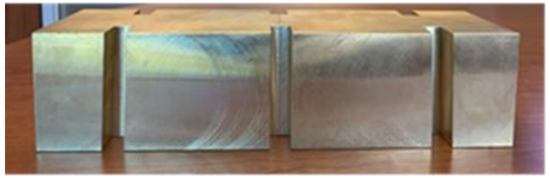
Dose Following ~120 Gy e⁻ Flash at isocenter

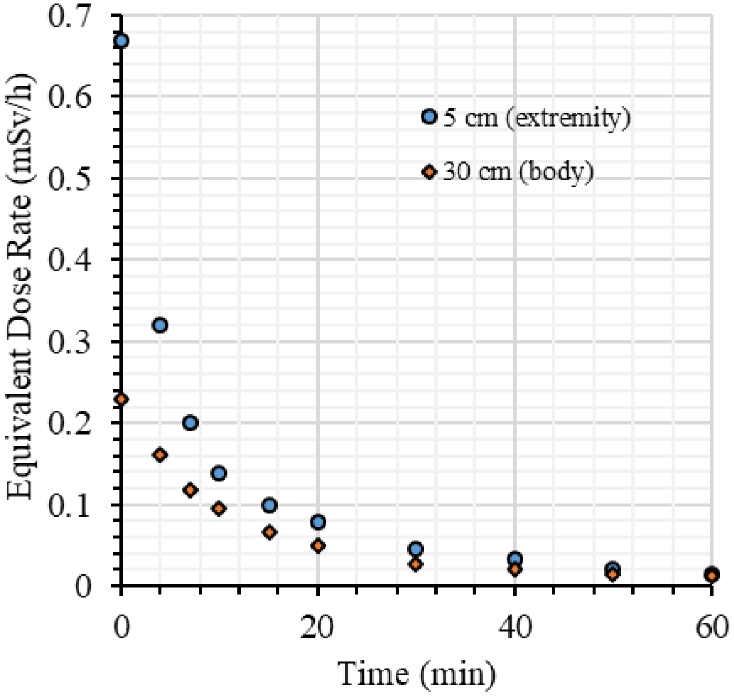


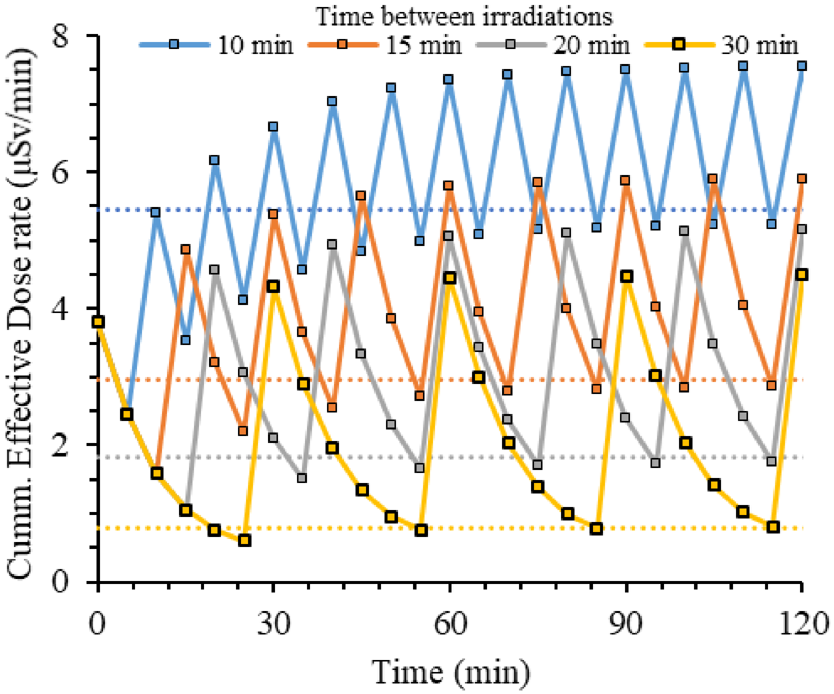
Byrne et al, Med Phys, 2024

Neutron-activation of collimators for p⁺ FLASH

- Pre-clinical study brass collimator activated by proton beam
  - Dose rate initially falls down very quickly ($T_{1/2}$ = 14 min)
- Over repeated irradiations, block does not decay before re-activation (right figure)
  - The minimum dose rate (to which staff is exposed) reaches a plateau (dashed lines)
  - By limiting time in the room, doses to staff can be kept ALARA







Mossahebi et al., Phys Med Biol, 2024

Radiation Protection Summary

- In FLASH radiotherapy, high dose rates are obtained in part by increasing beam current
  - Produces higher instantaneous dose rates, continuous workloads can be very high
- Compared to conventional beams, FLASH is typically operated at higher energies and in a shorter timeframe
  - Operated continuously, doses can exceed NRC hourly limit in uncontrolled areas
  - Neutron doses almost always below primary (photon/proton) doses through shielding
  - Staff can enter room quickly after irradiation and be exposed to neutron-activated components or accessories
  - Copper accessories are of highest concern, but fail to rise to regulatory limits with reasonable use and precautions
- Radiation safety program should be carefully re-evaluated after UHDR conversion
  - Copper-containing accessories should be carefully used when workloads will be high

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Thank you!