Radiation Protection & Shielding

PTCOG 61 – Madrid

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Learning Objectives

- Basic understanding of Parameters that matter
  - Energy, Incident Angle, Target and Shielding Material
- How to use Workload data effectively and conservatively
- Regulatory Compliance
  - Regulatory Limits vs Design Criteria
  - Activation
  - Understand why Shielding Calculations are Facility Specific
- Monte Carlo vs Point Kernel
- Effects of FLASH and Proton Arc on shielding

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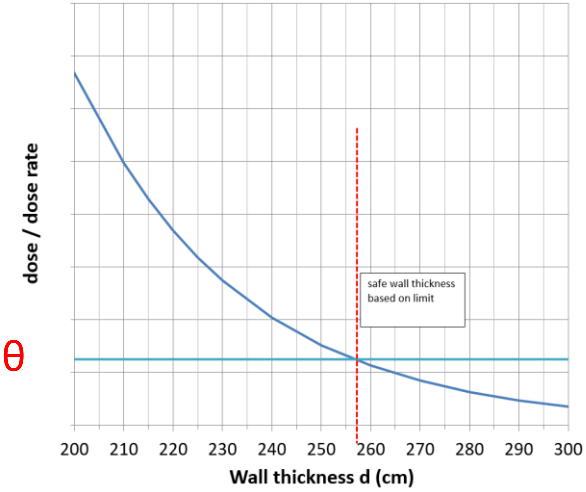
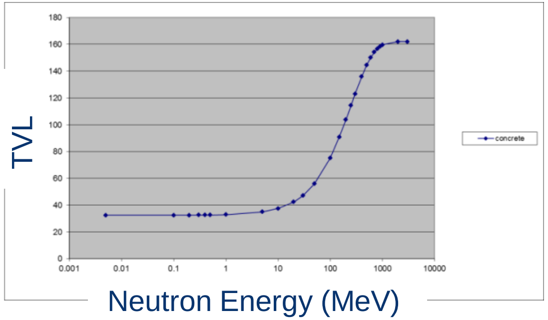
Some Physics Background

Similarities to RT: TVL Concept

- Shielding of neutrons “attenuates” dose rate
- Exponential attenuation curve
- We customarily define:
  Half-value (HVL) or tenth-value layer (TVL)
  - Each TVL of shielding material reduces the dose by 1/10
  - TVL depend on neutron energy, and therefore on E_p and θ
  - Neutron TVL range from 35cm to >100 cm !





Source: DIN 6875-20

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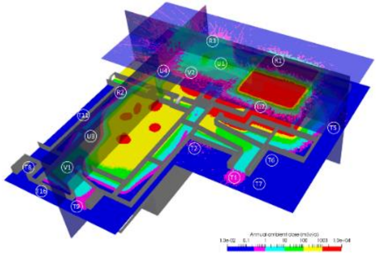
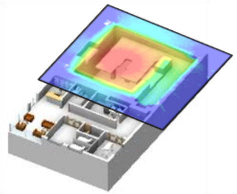
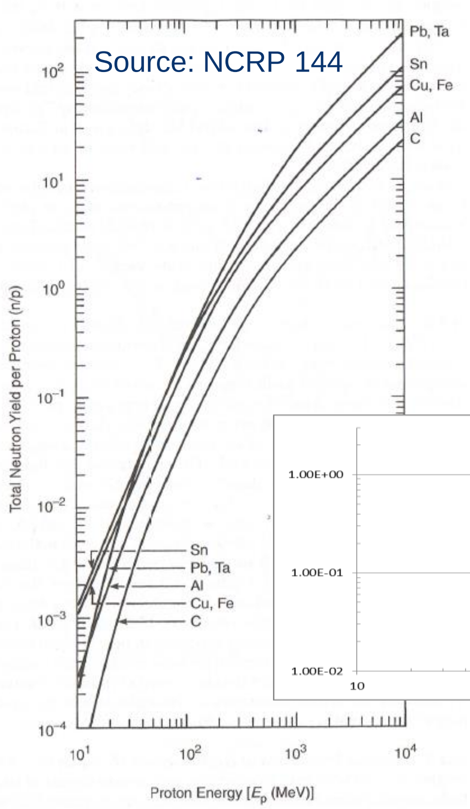
Radiation Production Processes

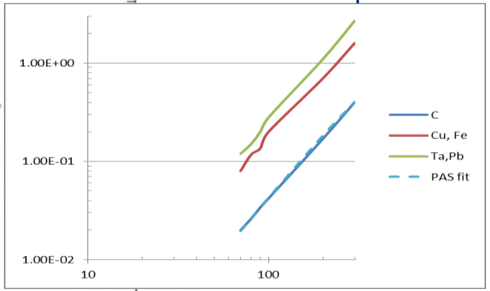
- Protons interact with material…
  - inside the accelerator,
  - Energy selection system and beamline,
  - Beam shaping at the patient: range shifters, collimators, modulators
    - PBS nozzles typically do not use these devices
  - patient, phantom
- …and create secondary radiation
  - Neutrons, charged particles, protons, gamma - only if the machine is on.
  - Activation remains when the machine is off (gamma and beta)
- Radiation shielding is concentrating on neutrons





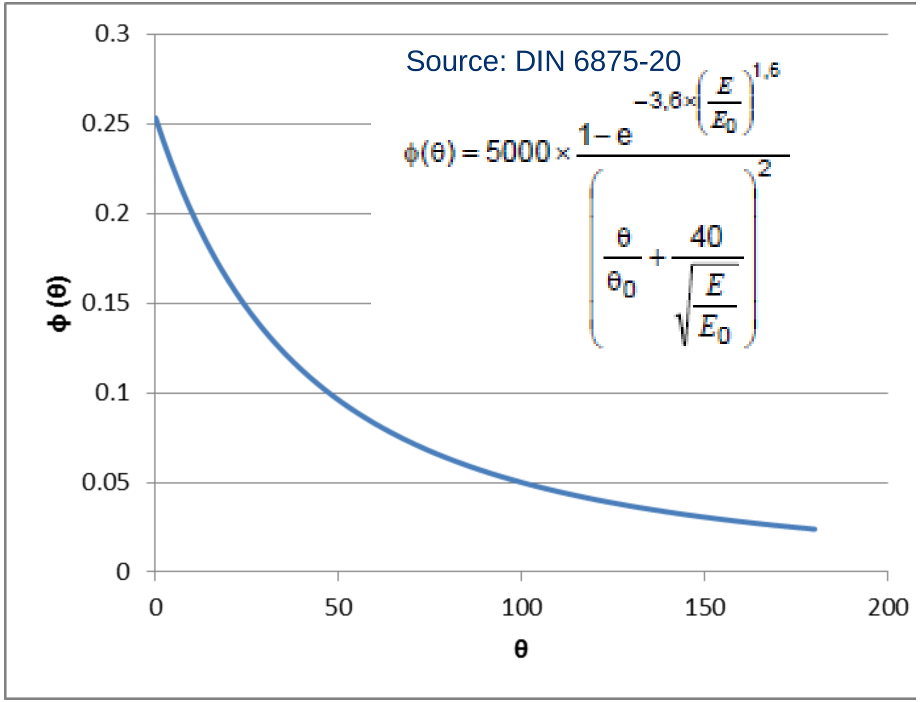
Neutron Yield (E_p,θ,material)





Note:

- Yield ~3-4x higher for Cu, Fe than for C or tissue
- Yield ~4-6x higher for Ta than for C or tissue
- Variation with Energy: Factor 10 between 70 MeV and 250 MeV
- Forward peaked



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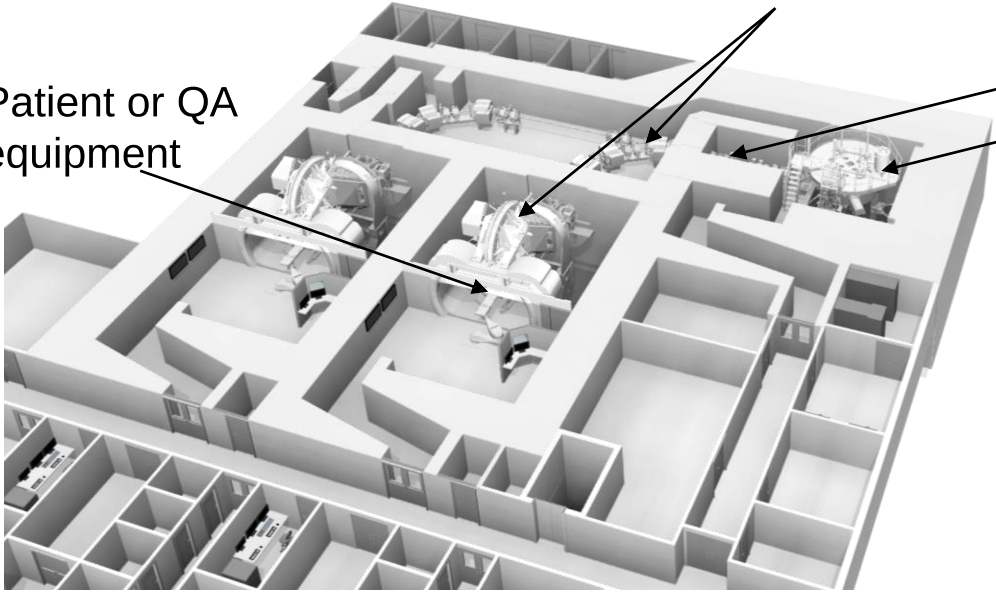
Complex Source Locations

Beam transport

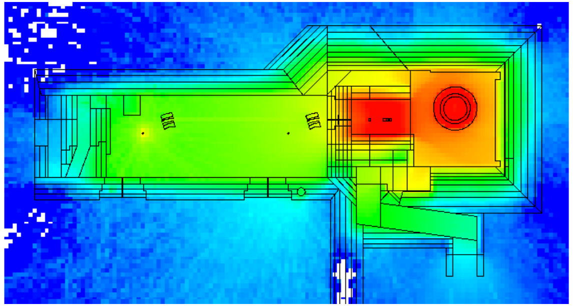
ESS / Degrader

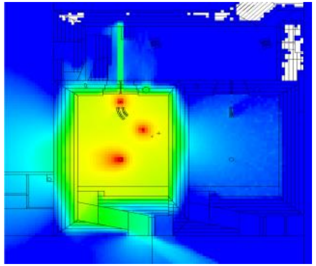
Accelerator

Patient or QA equipment



Equipment courtesy of Varian Medical Systems

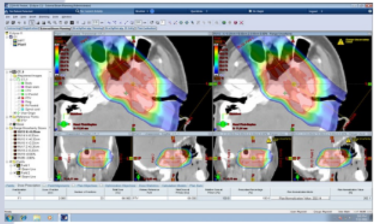




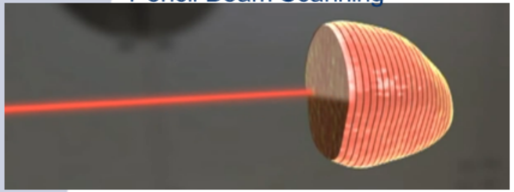
Dose map not to scale

Big Picture Goals

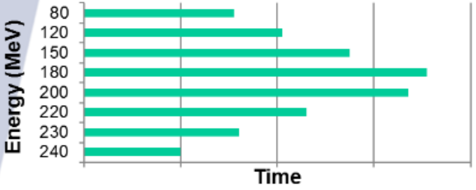
Proton Therapy Treatment Plan



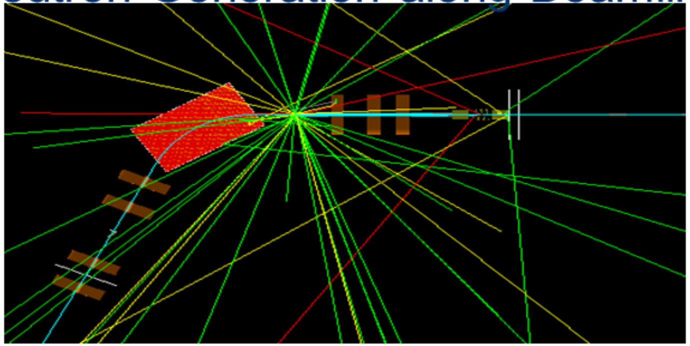
Pencil Beam Scanning



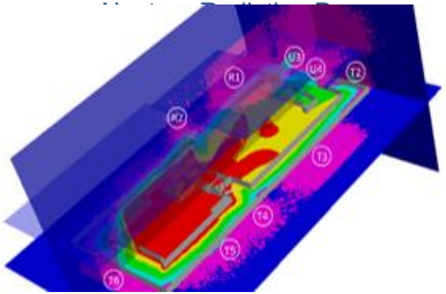
Depth ⇔ Energy



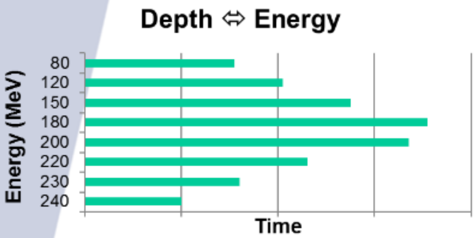
Neutron Generation along Beamline



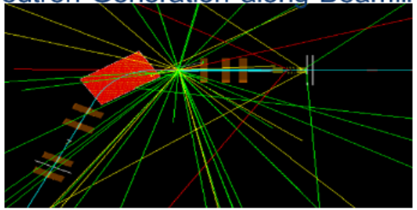
Neutron Radiation Dose



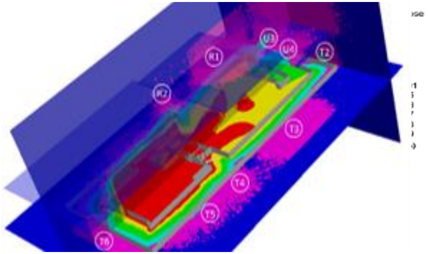
Big Picture Goals



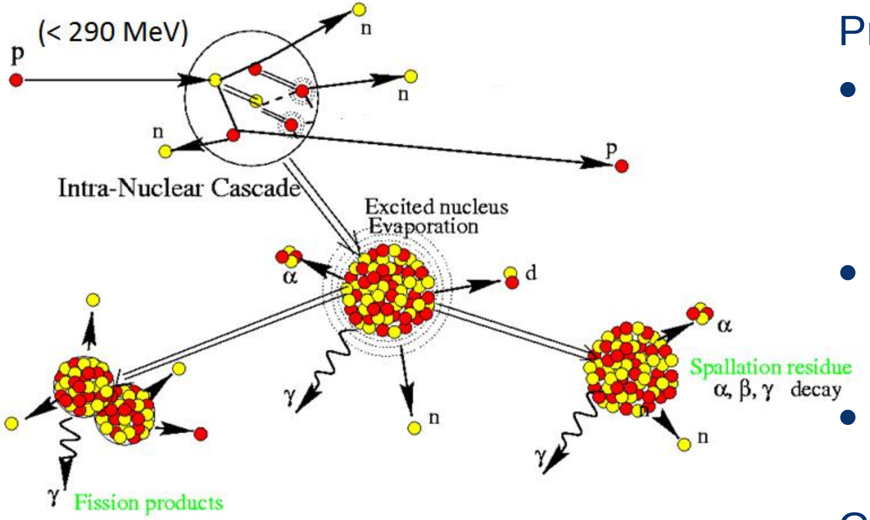
Neutron Generation along Beamline



Neutron Radiation Dose



Radiation Production Processes



Source: modified from irfu.cea.fr

Proton hits target Nucleus

- Intra-Nuclear Cascade (INC)
  - Cascade of reactions within nucleus
  - Large fraction of E transferred to few nucleons
  - Forward peaked nucleon emissions, new INC
- Evaporation of Nucleons and Fragments
  - Isotropic emissions (n, α, d, γ)
- Activation and decay

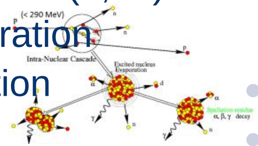
Charged particles are quickly stopped
➔ neutrons, gamma

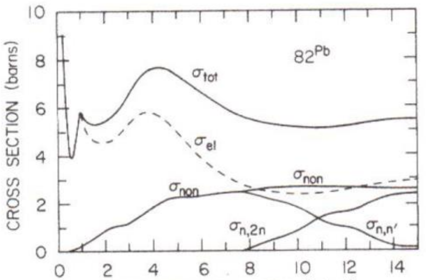
Attenuation Processes in the shield

Shielding Wall

Relativistic and Fast Neutrons

- >> 20 MeV
- Cascades
- Spallation (n,2n)
- Evaporation
- activation

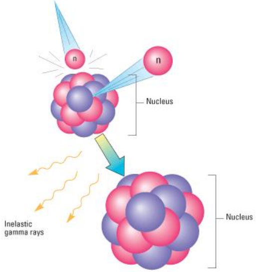




NCRP 79

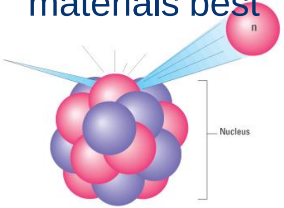
Inelastic Scattering

- Dominant 10 MeV < E < 50 MeV
- Neutron kinetic energy is lost in collision to excite nucleus
- Gamma ray
- High Z materials



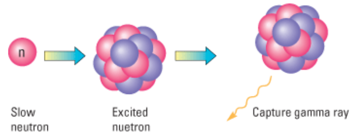
Elastic Scattering

- Dominant < 1 MeV for concrete and PE; < 10 MeV for other materials
- Neutron kinetic energy lost is transferred to nucleus
- Hydrogenous materials best



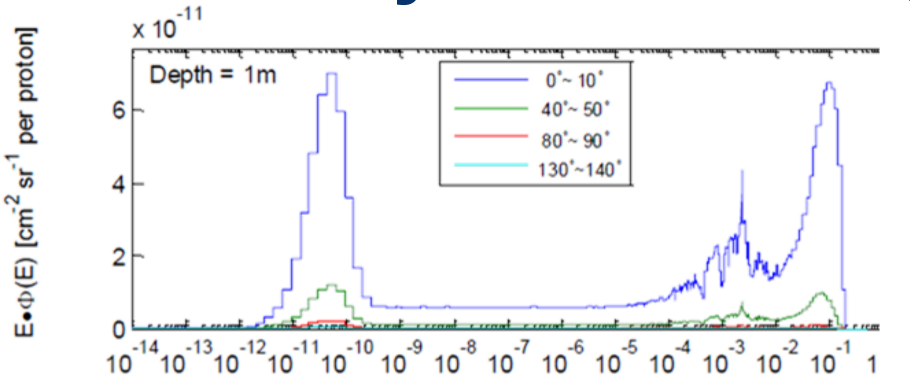
Neutron Capture

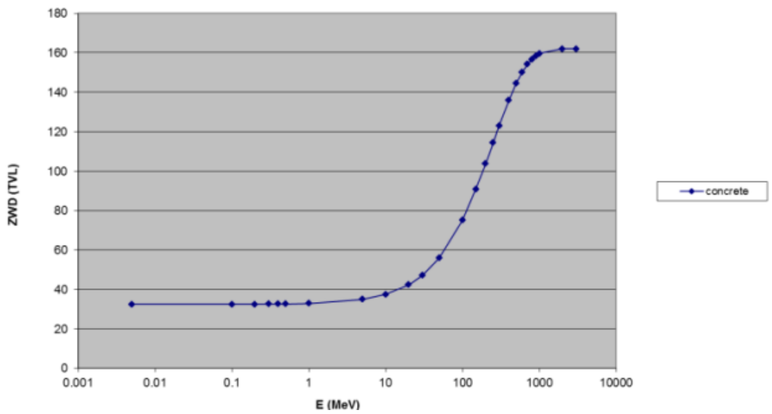
- 0.025 eV to ~ keV
- Thermal absorption
- Resonant absorption
- Emission of gamma ray
- Good materials:
  Hydrogen (2.2 MeV)
  Boron (0.478 MeV)



Source: http://www.glossary.oilfield.slb.com/Terms

Summary of Shielding Physics





- Y(E_p, θ,material); TVL(E_p, θ)
- High Energy Neutrons
  - 100 MeV, 2 MeV
- Good shielding Materials:
  - Concrete
  - sandwich of high-Z with concrete
  - High density
- Not suitable for shielding:
  - PE (only for low energy)
  - high-Z without hydrogenous layer following

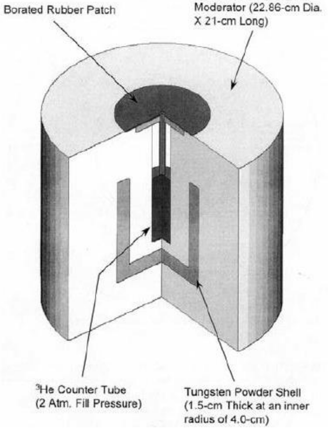
Neutron Dose Rate Measurement Instrumentation

Suitable to comply with GBZ/T 201.5-2015 section 7.2

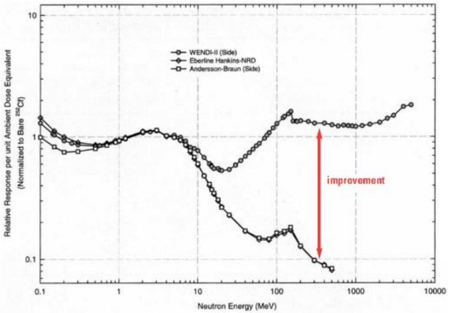
- Response to High Energy Neutrons; thermal to 250 MeV
- Low dose rate: > 0.1µSv/h
- Reliable low dose rate measurements require 1-3 min measurement time.

- FHT 762 Wendi II

FHT 762 Wendi II
Neutrons: thermal to 5 GeV
Gamma rejection
High sensitivity due to large He-3 tube
Tungsten Core




FHT 762 Wendi-2 with FH 40 G survey meter



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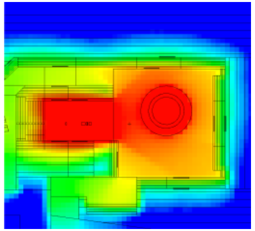
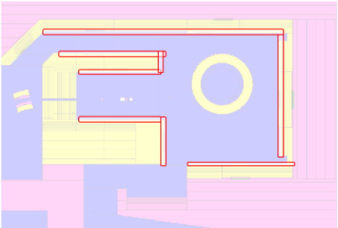
Activation & Decommissioning

- More and more, regulators pay attention to decommissioning
- Regulatory limits differ from country to country
- Calculations sometimes required
- Measurements during operation recommended (as calculations are typ conservative)

Likely activated

- Equipment in cyclotron area
- Shielding walls near degrader





Limited Activation? Safety Concepts!

- Cooling water
- Exhaust air: N-13, O-15, C-11, Ar-41
- Ground Water and Soil

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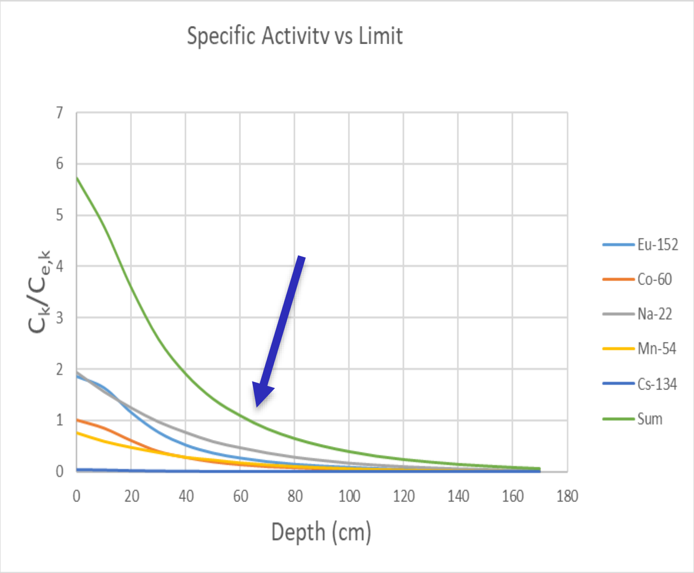
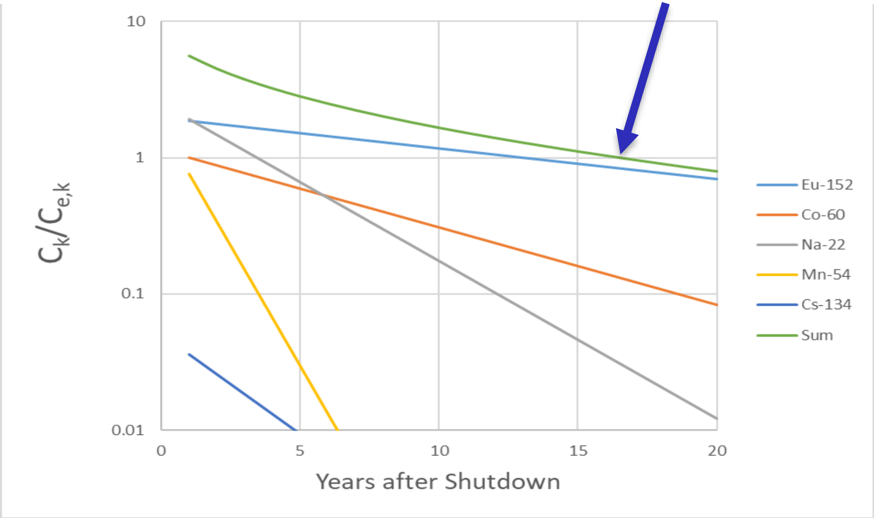
Activated Wall Materials Decay time



First layer

18yrs?



The important question:

How much Material is activated and how much does it **cost** to dispose of it after 30-50yr operation?

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Regulatory Compliance

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Influencing factors

Capacity per room

- 3 fractions / hr; peds 2/hr
- 8-10 clinical hours per day
  5.5 day week
- Average 20-25 fractions per patient
- ➔ 250 – 400 patients/yr

New Treatment Methods

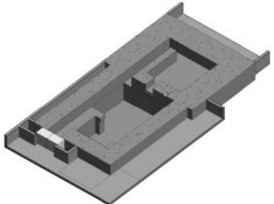
- Hypofractionation
- Flash
- Arc

Other factors

- Daily, weekly, monthly QA, service
- Treatment Plan Verifications
- Operating Hours increase
- Robustness of patient model

Facility

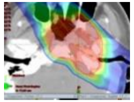
- Vendor building requirements
- Workload and Regulatory

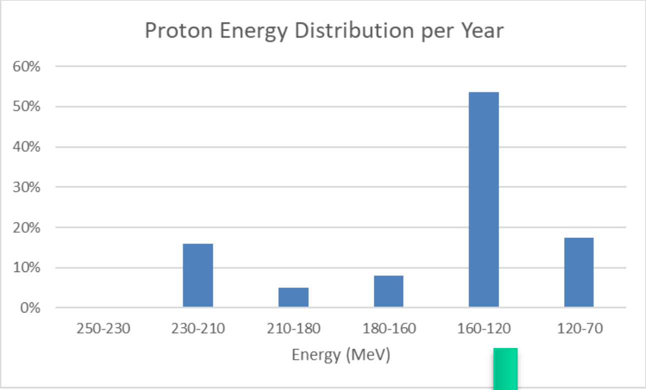


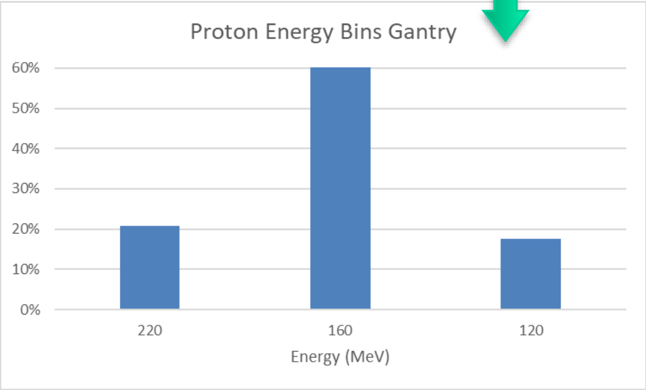
Indications and standard TPs

	dose	Volume	Proximal Energy from MeV	Proximal Energy to MeV	distal Energy from MeV	distal Energy to MeV
prostate	75	200	116.3	150.5	210	220
brain	60	300	69.2	119.9	81.7	127.2
base of skull	70	200	69.2	112.8	109.3	146.4
lung	60	2000	69.2	154.8	84.4	163.8
rectum & gyn	54	2500	79	163.8	159.8	220
head & neck	70	1500	69.2	146.4	69.2	146.4
Ped. Tumors	40	1000	69.2	138.4	69.2	138.4
metastases	30	2000	69.2	154.8	84.4	163.8

Indication Group	% of treatments	Average of Dose (CGE)	Average of Volume (g/ml)
Head & Neck	31%	54	548
lung	16%	50	364
metastases	18%	42	1,660
prostate	5%	56	945
rectum & gyn	30%	61	1,344







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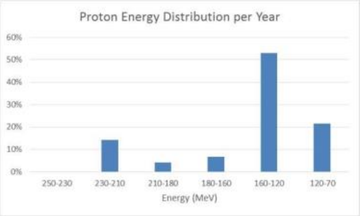
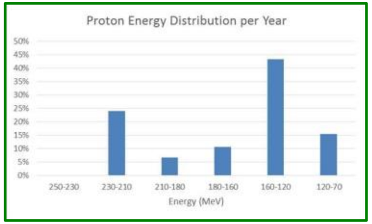
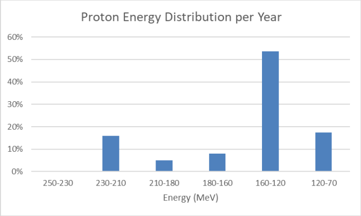
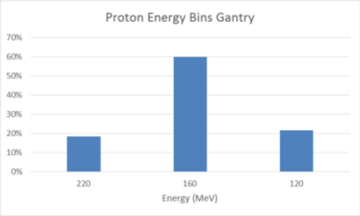
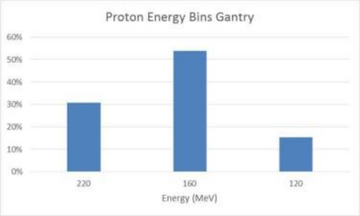
Robustness of patient models

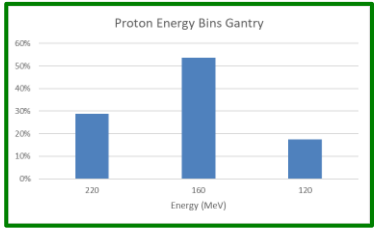




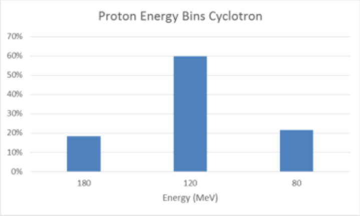


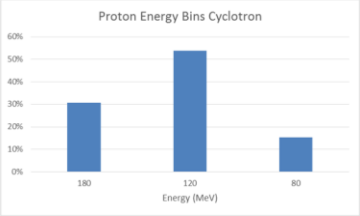


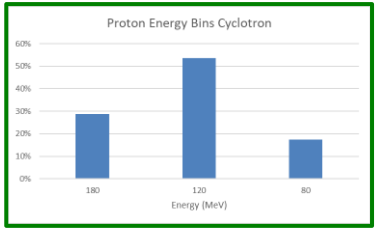




Energy binning more conservative than before in gantry room







Brain heavy | Abdomen heavy | Kazakhstan 2006

Regulated: Effective Dose *E*

- tissue-weighted sum of the equivalent doses in all specified tissues and organs of the human body
- Effective Dose *E* cannot be measured, cannot be used as quantity for radiation monitoring
- Operational Quantity *H*(10)* is used for assessing *E*
- Ambient dose *H*(10)* vs Effective Person dose
  - Occupancy factors T

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occupancy factor (T):

Location	Occupancy Factor (*T*)
Full occupancy areas (areas occupied full-time by an individual), *e.g.*, administrative or clerical offices; treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, occupied space in nearby building	1
Adjacent treatment room, patient examination room adjacent to shielded vault	1/2
Corridors, employee lounges, staff rest rooms	1/5
Treatment vault doors[b]	1/8
Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitors' closets	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators	1/40

➔ Design for E, not for H*(10) or DR

Effective Dose Limit

- Annual or weekly limits, dose rate limits
- Per person – not per facility
- IAEA and in most countries – Annual Dose Limit [E ~ T ▪ H*(10)]
  - Members of the public: 1mSv/a
- BUT for a facility
  - Denmark and Belgium enforce 0.3 mSv/a
  - Sweden is very sensitive on childcare facilities – 0.1mSv/a?
  - Often the limit the regulatory body requires is not written explicitly in the regulations!
  - Occupancy Factors (range T=0.1 to 1.0)

Dose Rate

Definitions

- Technically, all dose limits are time averaged dose rates (TADR) like “mSv per year”; the shorter the averaging period the more complex.
- IDR (instantaneous dose rate) introduced by some countries, without really specifying the “instant” or measurement technique.

Examples

- IAEA: advice that there may be some countries that regulate TADR for short intervals or IDR.
- USA/Thailand: 20µSv in any one hour
- Germany: 20µSv per week; but < 3mSv/h IDR
- China: 2.5 µSv per hour IDR – <u>instantaneous!</u>
- UK: 7.5µSv per hour IDR; averaged over 1min by ACOP
- Singapore: 10µSv per hour IDR “outside the X-ray room”

Mitigating IDR

Example

- Typical field application time ~1-2min, PBS, going through all energy layers.
  - Largest annual dose contribution comes form the energy range 130-160 MeV
  - Highest dose rate is reached at distal edge of deep lying tumor irradiations; 30-60s?
  - Measurement: specialized equipment, like a Wendi II with tungsten core. Today's detectors need about 1 minute to see enough counts to provide a reliable measurement result – outside the shield

Mitigation by negotiation with the regulatory body.

- Choice of averaging time for IDR – 1 or 2 min?
- Locations where the requirements have to be met
  - also inside each adjacent room?
  - Only in public areas?

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Calculation Methods

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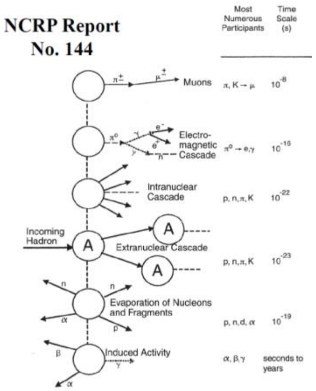
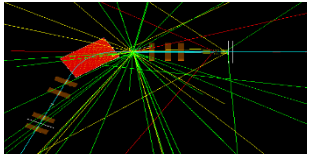
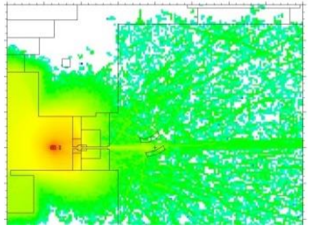
Monte Carlo Explained

- Each particle is tracked until a defined cutoff
- Each interaction is recorded, secondary particles are tracked.
- Physics cross sections available for all elements.
- Materials are defined as mass ratios of elements.
- Quick math: 1p ➔ 0.1 n; attenuation 10^{-6}; for $\frac{\sqrt{N}}{N}$=10%, N=100 neutrons at protected locations
  ➔ 10^{9} protons to be simulated
- Biasing methods can reduce calculation time,
  ➔ 10^{6} to 10^{8} protons (still CPU days)
- Need for benchmarking







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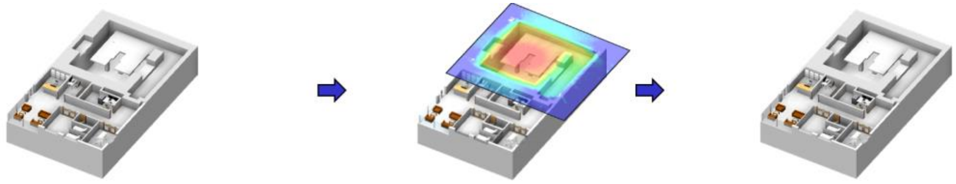
Monte Carlo Applied

- Step 1:
  - Geometry Modelling – can be time intensive
  - Proton loss definition (➔ Neutron Yield)
- Step 2:
  - Biasing (geometry, weight factors, …)
  - Calculate fluence, convert to dose using ICRP 74
  - Simulation of Source particles – CPU time intensive
- Step 3
  - Pretty up the output
  - Communicate output
- Benchmarking



Analytical Explained

- Point-Source line-of-sight model

$$H(E_p,\theta,d/\lambda) = \boxed{\frac{H_1(E_p,\theta)}{r^2}\exp(-\frac{d}{\lambda_1(E_p,\theta)})} + \frac{H_2(E_p,\theta)}{r^2}\exp(-\frac{d}{\lambda_2(E_p,\theta)})$$

- Source term and attenuation length (TVL)
  - H_i from NCRP 144 or other
  - choose energy bins and angles
  - Target materials
  - Shielding materials

Needed:
$H_i\ (E, \theta)$
$\lambda_i\ (E, \theta)$

Source: Rong-Jiun Shu, RADSYNCH2013

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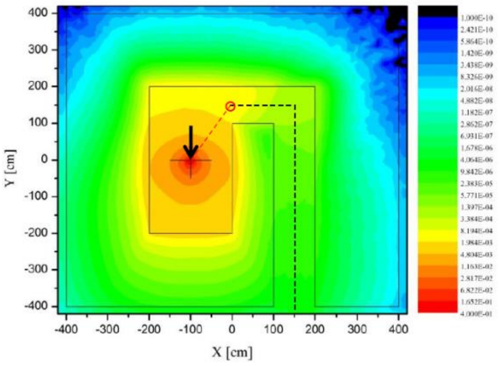
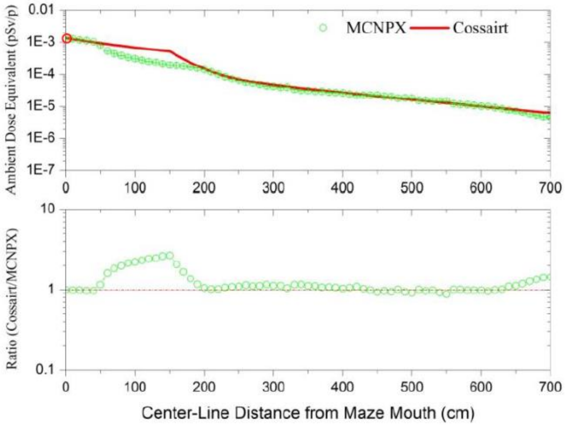
Maze Calculations

Comparison of MCNPX and Cossairt’s formula (FermiLab TM-1834, 2016)





$$H_1(\delta_1) = \left[\frac{r_0}{\delta_1 + r_0}\right]^2 H_0(R) \quad \text{for } 1^{st} \text{ leg}$$

$$H_i(\delta_i) = \left\{\frac{e^{-\delta_i/a} + Ae^{-\delta_i/b} + Be^{-\delta_i/c}}{1 + A + B}\right\} H_{i-1}(\delta_{i-1}) \quad \text{for } i^{th} \text{ leg } (i > 1)$$

where $\delta_i = d_i/\sqrt{A}$ and the fitting parameters are:

$r_0 = 1.4,\ a = 0.17,\ b = 1.17,\ c = 5.25,\ A = 0.21,\ B = 0.00147$

Source: Rong-Jiun Shu, RADSYNCH2013

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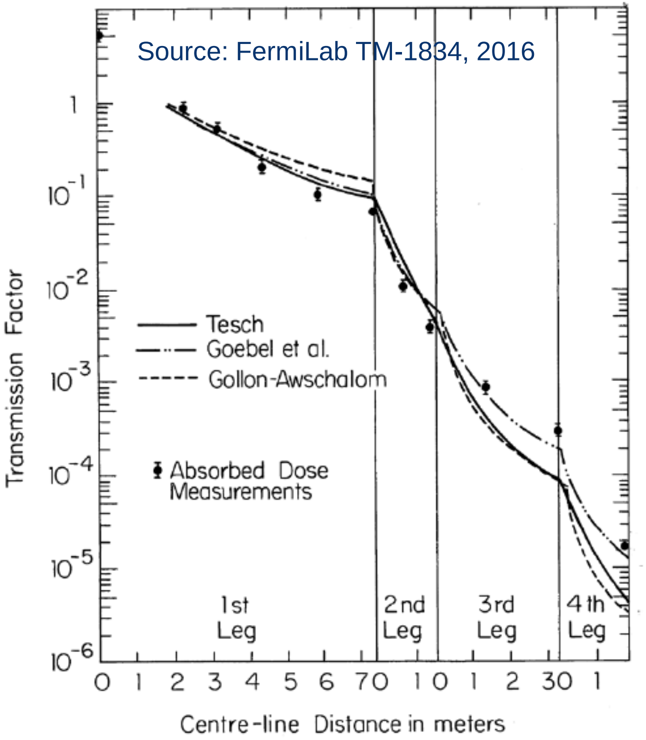
Maze Calculations



Maze Basics:

- Avoid direct beam at maze mouth
- Leg # more important than length
- Several approaches in literature, benchmarked for experimental cases
- Dominated by thermal or near thermal neutrons after first leg
- <u>First leg has least effect</u>

Refer to Literature Sources

- FermiLab TM-1834, 2016
- NCRP 144
- DIN PAS 1078

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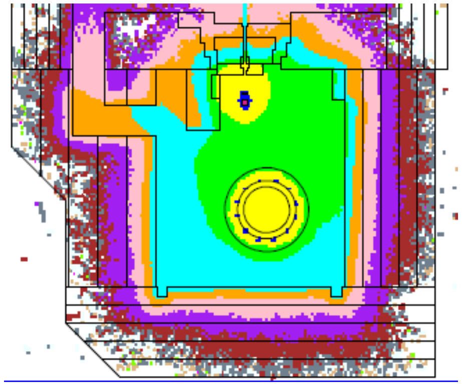
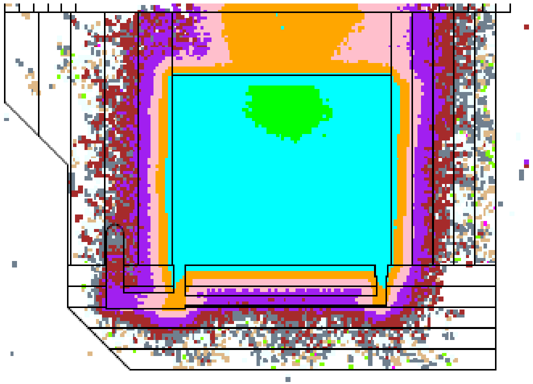
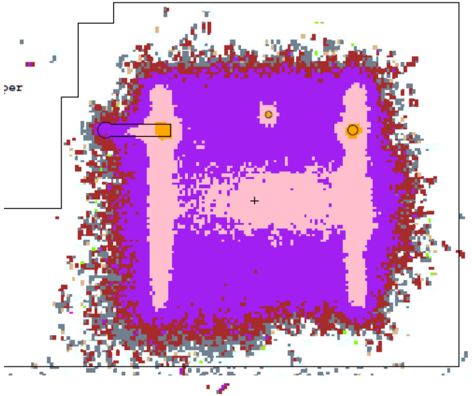
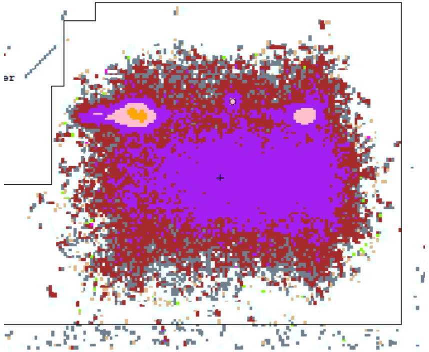
Maze Calculations

Ventilation Ducts are Mazes









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FLASH

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Status of FLASH R&D

physicsworld
25 Oct 2022

- Clinical Trials in Cincinnati
  - In-human trials for metastatic bone cancer (FAST-01)
  - Enrolement for thracic bone mestatates (FAST-02)
- IBA ConformalFLASH® R&D in several places
  - Pre-clinical radiobiology
  - Development of FLASH protocols
  - Groningen, Seattle, Penn Medicine, …
- SBRT and hypofractionation at New York Proton Center
  - Clinical use of 5-fraction prostate treatment
  - R&D Bragg-Peak based FLASH for lung cancer
- …

➔ lots of excitement, lots of R&D, the future will tell…

➔ Better to consider this for future shielding needs!

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Effect on Annual Dose

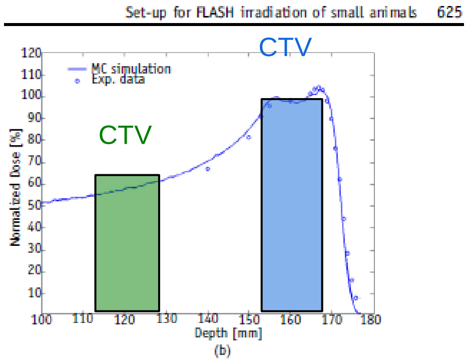
Treatment Room Considerations

- Hypo Fractionation
  - To the extreme of applying full dose in one session
  - Theoretical capacity increase x 20?
- Fraction of Patients treated with Flash?
- Bragg Peak or Transmission Method –
  - where is the beam stopped? patient, beam-stop, wall?
  - Maybe 2-3x more protons needed for the same CTV dose in transmission method?
  - (Near) full energy into the treatment room - Most neutrons generated at E_{max} ?

➔ Radiation source location

➔ Workload per year

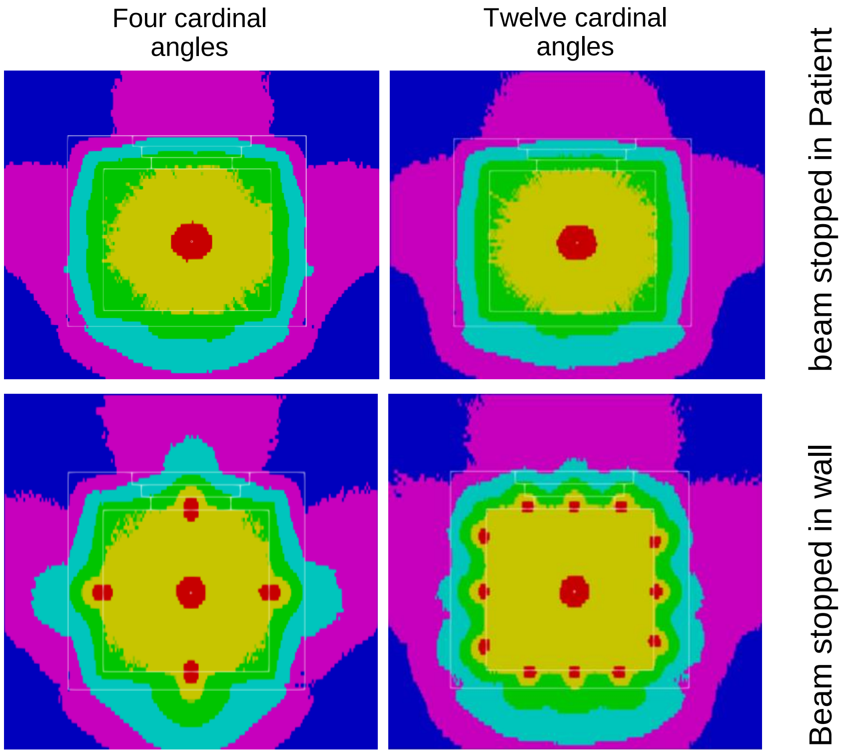
➔ Instantaneous Dose Rate – regulation dependent



Source of inset: Int J Radiation Oncol Biol Phys, Vol. 102, No. 3, 2018

FLASH with Proton Arc

- Traditional PT: 2-3 fields
- Arc: many fields during rotation
- Bragg Peak method
- Transmission Method (Bragg Peak outside patient)



Gantry Room Sections through the ISOC; Rotation Plane

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Mitigating IDR for FLASH

Example

- Typical field application time < 1s, max E at nozzle entrance.
  - ~100-200 Gy/s at the tumor,
  - IDR even higher where the beam is stopped if using the transmission method.
  - Measurement: are there neutron monitors that can measure this fast?

Mitigation by negotiation with the regulatory body.

- Safety criteria is dose, not by IDR. Not all regulations reflect that.
- Choice of averaging time for IDR – 1 or 2 min, any one hour, dose per week?
- Locations where the requirements have to be met
  - also inside adjacent gantry room?
  - Only in public areas?

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Learning Objectives

- Neutron Yield and Shielding depend on:
  - Energy, Angle, Target- and Shielding-Material, Density
- Shielding Calculations need to be Facility specific
  - Regulatory Limits and Interpretations vary – devil is in the detail
  - Occupancy, Assumptions on Operating Parameters
  - Influencing Factors
- Principles of Monte Carlo Simulations, Point-Kernel Calculation Methods, and the Necessity for Benchmarking.
  - Shield Barrier Transmission Attenuation
  - Maze Attenuation
- The shield can change for FLASH – but there is a lot of guesswork involved for future developments

Thank You!

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