Radiation Shielding

PTCOG 58 – Manchester, UK (2019)

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Disclosures

This work is not funded by third parties with a commercial interest in the topic.

Meissner Consulting has shielding design contracts with Varian Medical Systems, Health Care Global and University of Pennsylvania, and other HP.

Learning Objectives

- Basic understanding of Neutron Physics as it is affected by
  - Energy, Incident Angle, Target and Shielding Material
- How to use Workload data effectively and conservatively
- Regulatory Overview
  - Regulatory Limits vs Design Criteria
  - Understand why Shielding Calculations are Facility Specific
- Available Calculation Methods and Benchmarking, with some how-to guidelines
- Effects of FLASH and Proton Arc on shielding

Big Picture Goals

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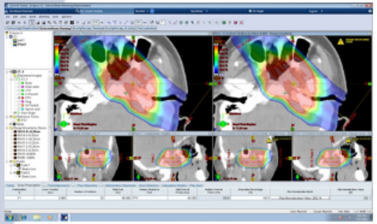
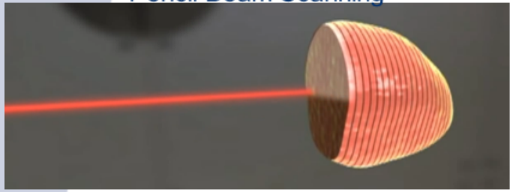
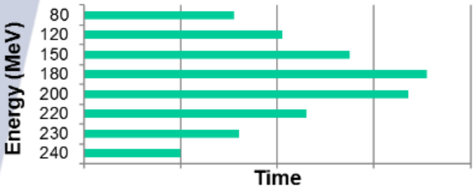
Proton Therapy Treatment Plan



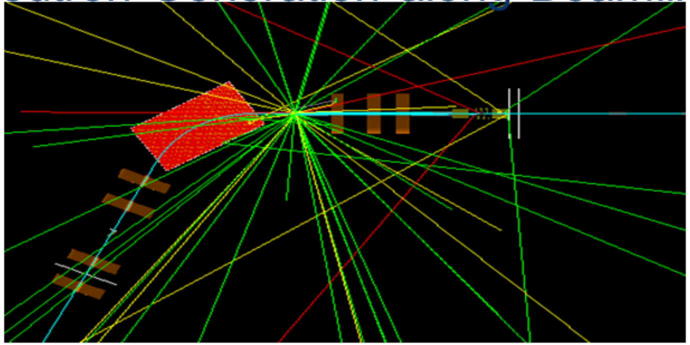
Pencil Beam Scanning



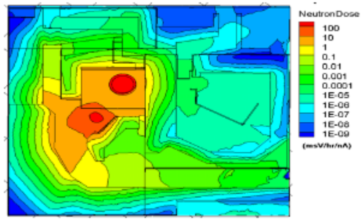
Depth ⇔ Energy



Neutron Generation along Beamline

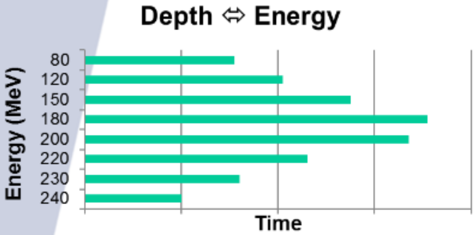


Neutron Radiation Dose



Courtesy: Varian Medical Systems

Big Picture Goals



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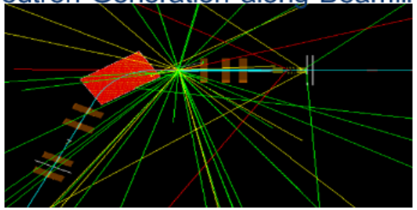
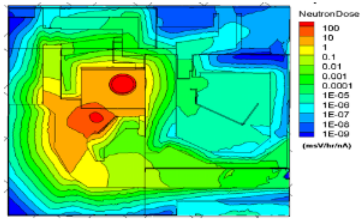


Neutron Radiation Dose



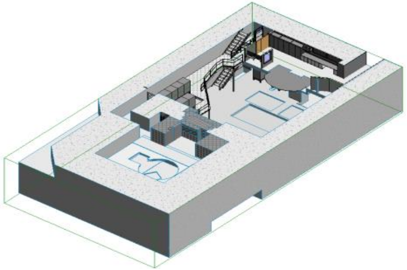
Courtesy: Varian Medical Systems

Future Proofing and Margins

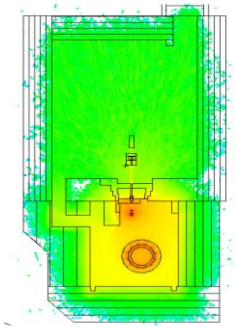
- Quality Assurance
  - Daily, weekly, quarterly checks
  - Treatment plan verifications
- Change of patient capacity
  - More efficient treatment
  - Operating hour extension
- Robustness
  - change in patient population on E vs proton loss, and then on annual dose
- Service processes
- New treatment methods or R&D

Ideal Shielding Design Process

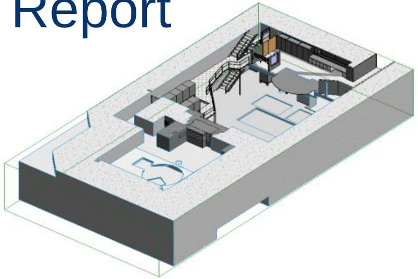
Input:
Revit™ 3D model
Source Terms
Clinical Use Case



Shield Optimization



Output:
Revit™ 3D model
Safe Shield
Report



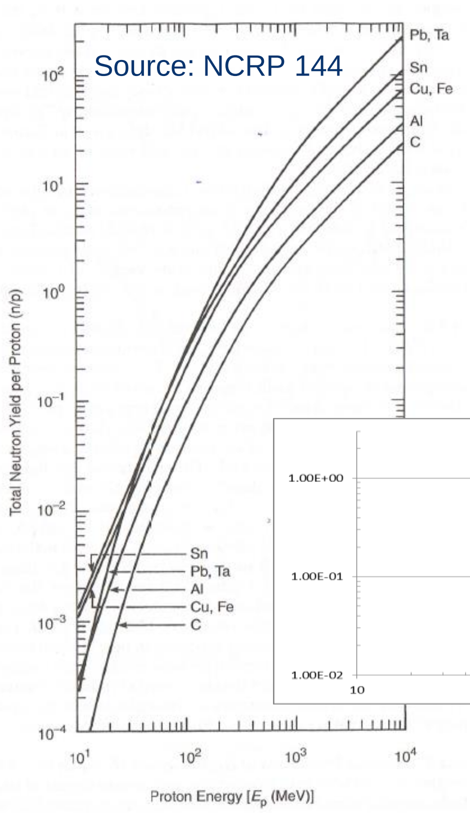
- Fast
- No Misunderstandings about Shield-Geometry
- Validate Shield Penetrations (Ventilation etc)

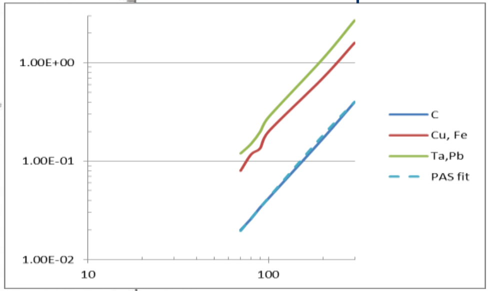
Some Physics Background

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

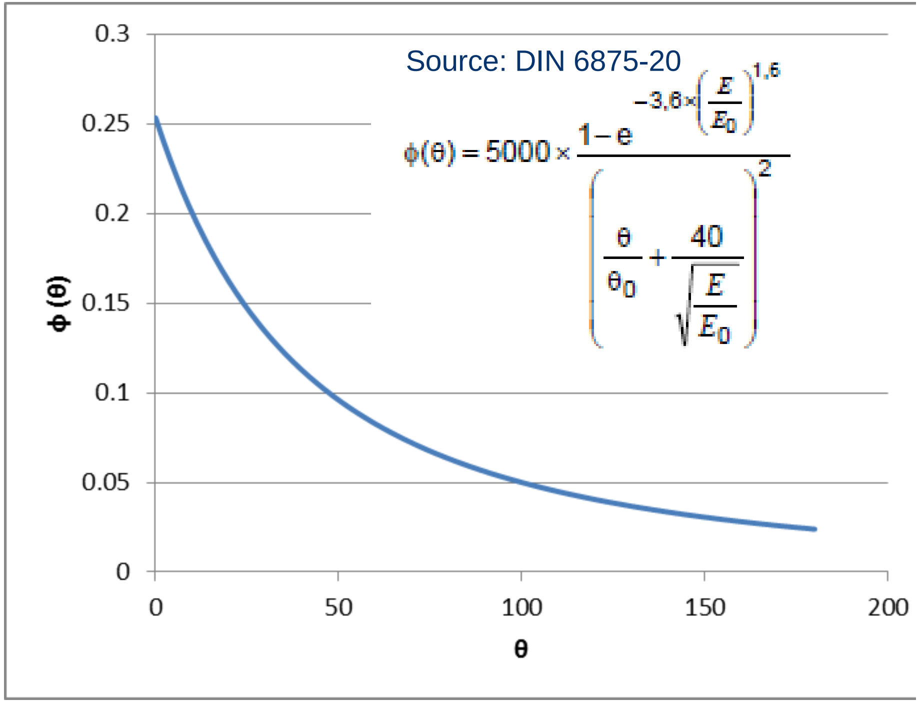
Neutron Yield (E_p,θ,material)



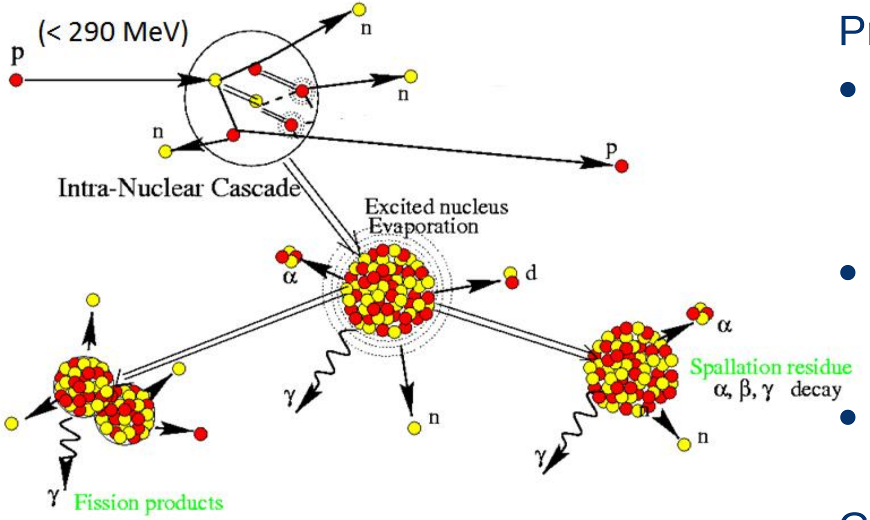


Note:

- 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



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

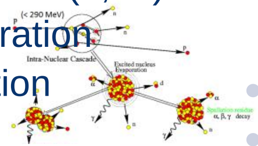
➔ neutrons, gamma

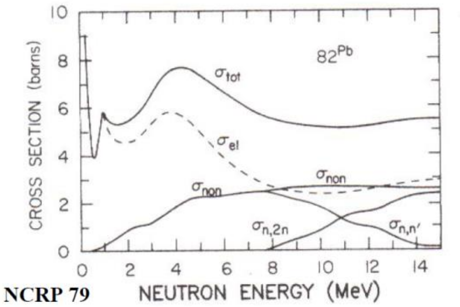
Attenuation Processes in the shield

Shielding Wall

Relativistic and Fast Neutrons

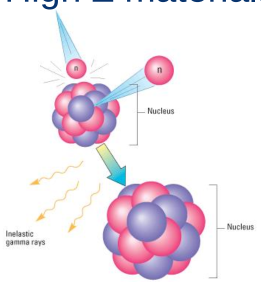
- >> 20 MeV
- Cascades
- Spallation (n,2n)
- Evaporation
- activation





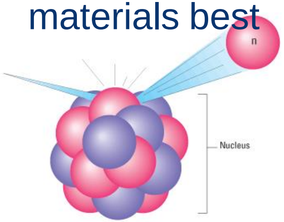
Inelastic Scattering

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



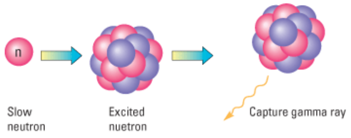
Elastic Scattering

- 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

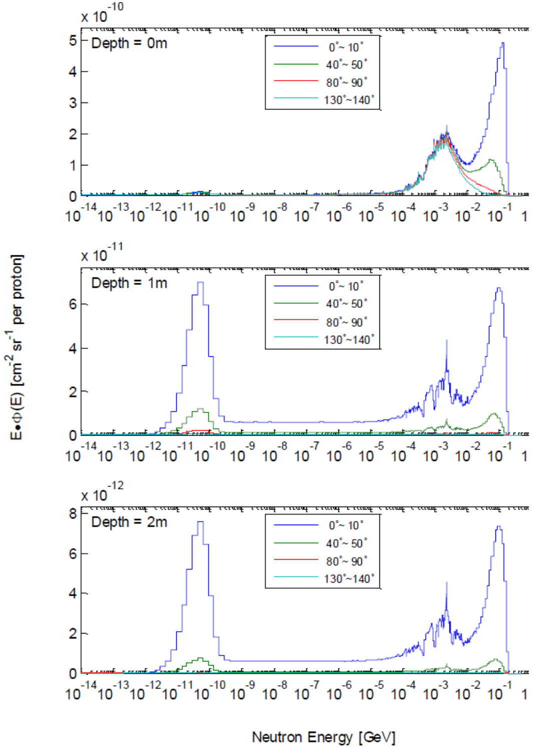
- 0.025 eV to ~ keV
- Thermal absorption
- Resonant absorption
- Emission of gamma ray
- Good materials:
  Hydrogen (2.2 MeV)
  Boron (0.478 MeV)



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

Neutron Field

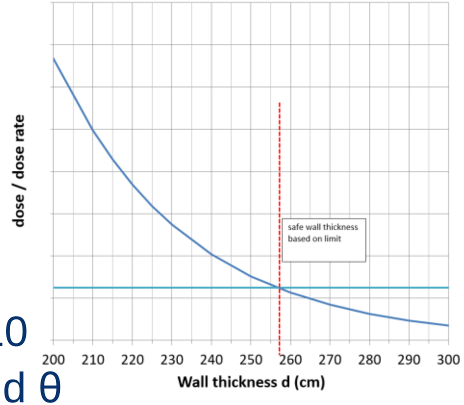
- Direct neutrons, cascade neutrons
  - Typ > 20 MeV, up to incident p-Energy
  - lower energy neutrons continuously generated in shield
  - Forward focused
- Evaporated neutrons:
  - 1-10 MeV, peak 1-2 MeV, isotropic
  - Elastic and inelastic scattering
- Few thermal Neutrons in unshielded field
- After shielding, dominantly thermal, 2 MeV and 100 MeV peaks

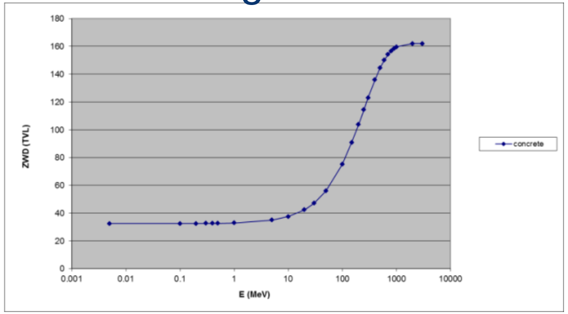


Source: Rong-Jiun Shu, RADSYNCH2013

Effect of Shielding

- Shielding of neutrons “attenuates”
- Exponential attenuation curve
- 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
  - TVL for neutrons from 250 or 150 MeV protons in concrete ranges from*
    - 114cm or 91cm at θ = 0°
    - 83 cm or 66cm at θ ~ 45° - 90°
    - 56 cm or 45cm at θ ~ 90° - 135°
    - 43 cm or 35cm at θ > 135°

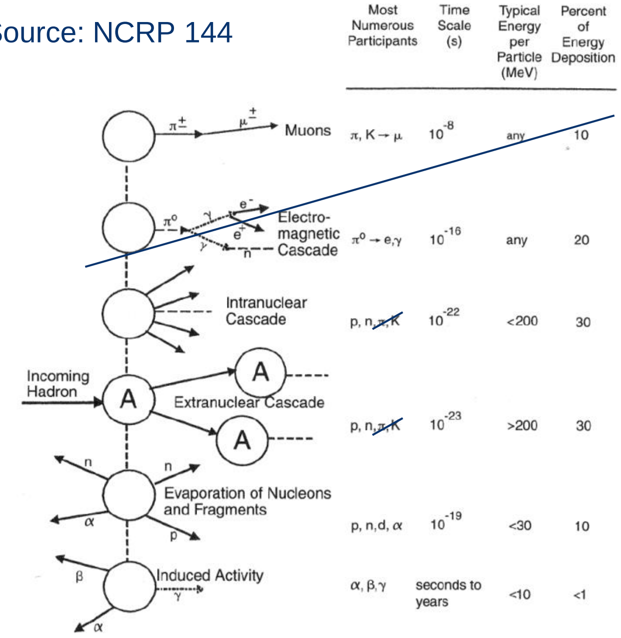




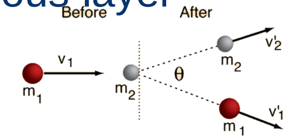
* Source: DIN 6875-20

Summary of Physics

Source: NCRP 144



- 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 (except maybe at the end of mazes)
  - high-Z without hydrogenous layer following



Regulatory Overview

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

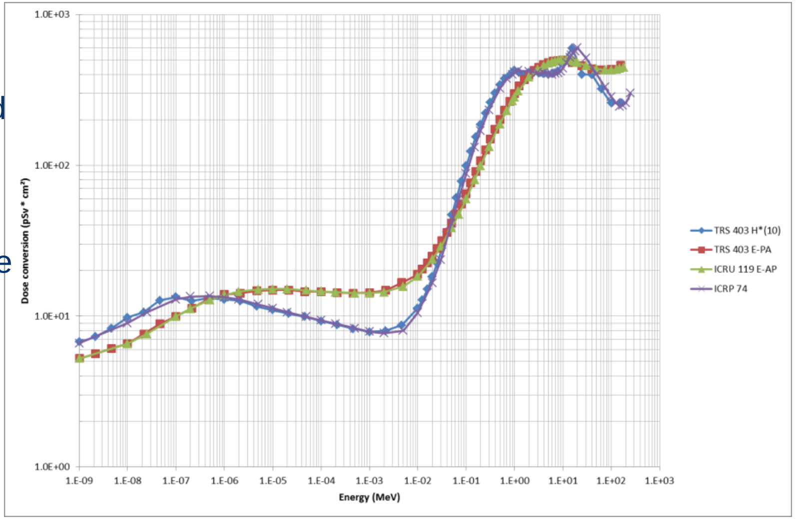
NCRP REPORT No. 151

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

Ambient Dose equivalent *H*(10)*

- Defined as
  - simulates the human body through a phantom (the ICRU sphere, a sphere of 300 mm in diameter made of tissue equivalent material)
  - H*(10) is the dose equivalent at a depth of 10 mm inside that sphere
  - Considers the quality factor Q for the type of radiation
  - Used for strong penetrating radiation
- Used for
  - Operational quantity: Monitored quantity, measured by radiological protection instruments.
  - Used for Effective Dose *E*
  - for neutron fields in proton therapy, requires special instruments with large neutron energy range
- Use how
  - Convert from neutron fluence, common practice to use ICRP 74
  - Used by standards such as DIN, NCRP, GBZ
  - Measure with Instruments



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?
  - Italy: 10µSv per year
  - 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 – instantaneous!
- 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?

Calculation Methods

Vendor's Source terms

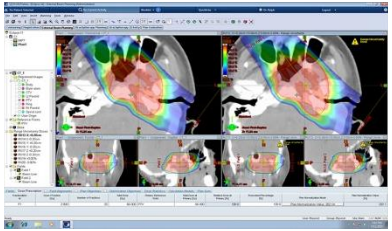
- Very different from the X-ray world!
- Instead of dose rate
  - Proton losses / Beamline transmission
  - Materials
  - Equipment geometry
- PBS vs Passive Scattering
  - Typ difference in proton losses: factor 5-10

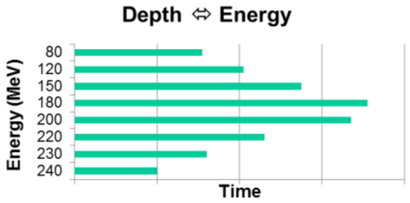
Clinical Use Model

- User Input
  - Number of patient p.a.
  - Tumor sites and frequency
  - Treatment plans
- Converted to Protons lost at each
  - Location
  - Energy

➔ Neutron Yield

Site	% GA	% with Range shifter	Imaging Procedure	% of fractions for CBCT	Average No. fields	Total no. of patients	% of total treatments	total no. #	Average tumour volume (cc)	Fraction dose (CGE)	total dose (CGE)
Brain		70	kV daily	25	2	400	33	30	315	1.8	50-54
Paeds Brain	30				2-3	95		30	508	1.8	54
H&N		80	kV daily	25	3	410	30	32	567	2.0	70
Paeds H&N	30				3-4	40		33	275	1.8	66
Pelvic		50	kV daily	100	2-3	193	14		1549	2.0	50-66
Paeds Pelvis	30				3	17		20-30		1.5-1.8	30-54
Whole CNS		80	kV daily	25	4	45	9	30	2376	1.8	54(24-36Gy whole CNS)
Whole CNS Paeds	30				3-4	90		30	1922	1.6-1.8	54(24-36Gy whole CNS)
Thorax		100	kV daily	100	2	44	4	30	821	2	50-66
Paeds Thorax	30				3	16		30		1.5-1.8	20-54
Abdomen		100	kV daily	100	3-4	112	10	30	880	2	50-66
Paeds Abdomen	30	100			3-4	38		30		1.5-1.8	20-54

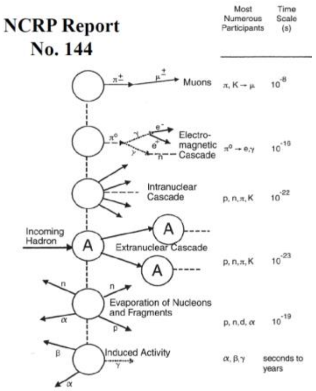


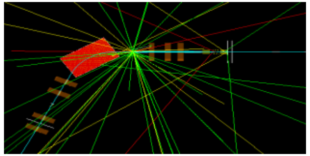


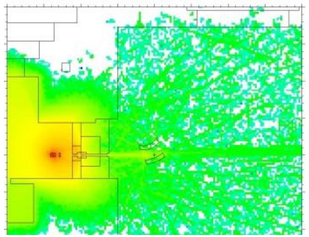
Courtesy: Varian Medical Systems

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, increase need for benchmarking
  ➔ 10^6 to 10^8 protons (still CPU days)

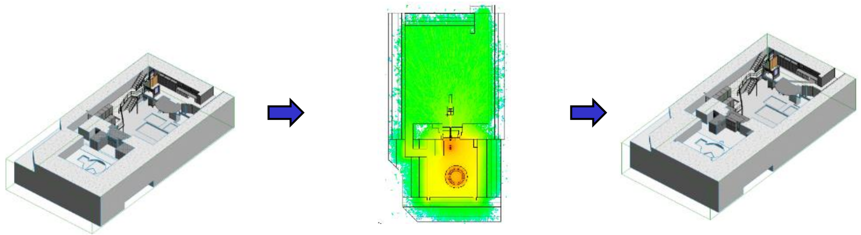






Monte Carlo Applied

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



Analytical Explained

- Point-Source line-of-sight model

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

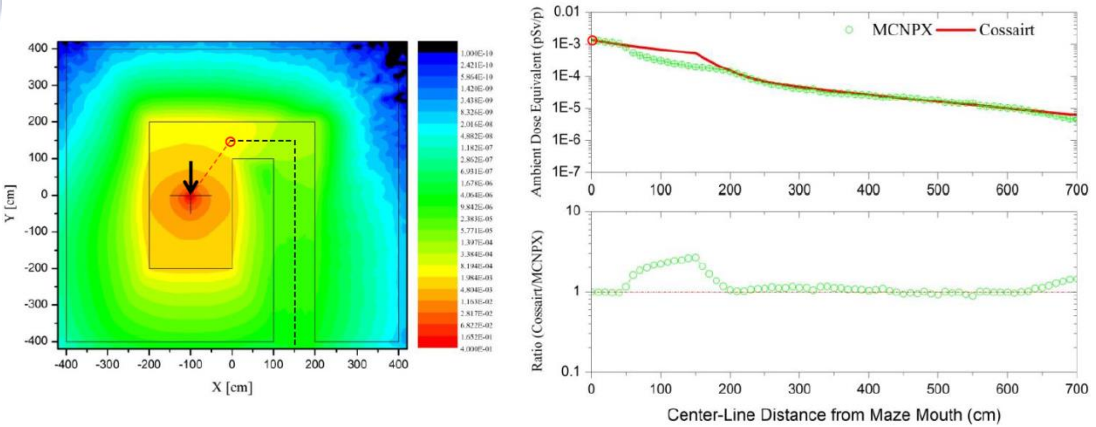
- Source term and attenuation length (TVL)
  - H_i from NCRP 144 or other
  - choose energy bins and angles
  - Target materials
  - Shielding materials

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

Source: Rong-Jiun Shu, RADSYNCH2013

Maze Calculations

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



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

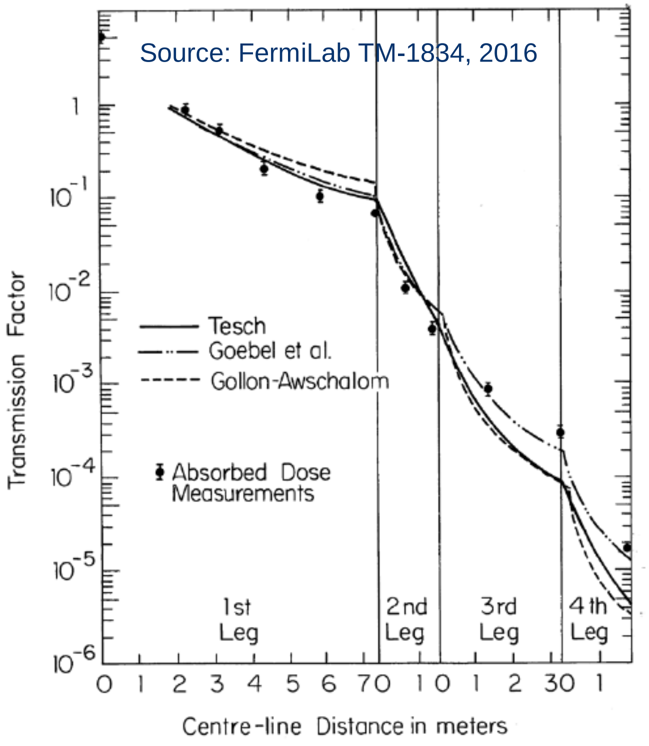
$$H_i(\delta_i) = \left\{\frac{e^{-\delta_i/a} + Ae^{-\delta_i/b} + Be^{-\delta_i/c}}{1 + A + B}\right\} H_{i-1}(\delta_{i-1}) \quad \text{for } i^{th} \text{ leg } (i > 1)$$

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

Maze Calculations



Maze Basics:

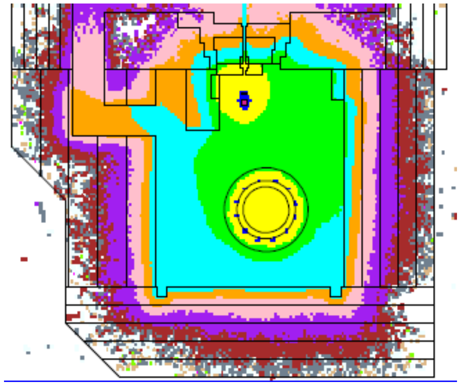
- Avoid direct beam at maze mouth
- Leg # more important than length
- Several approaches in literature, benchmarked for experimental cases
- Dominated by thermal or near thermal neutrons after first leg
- First leg has least effect

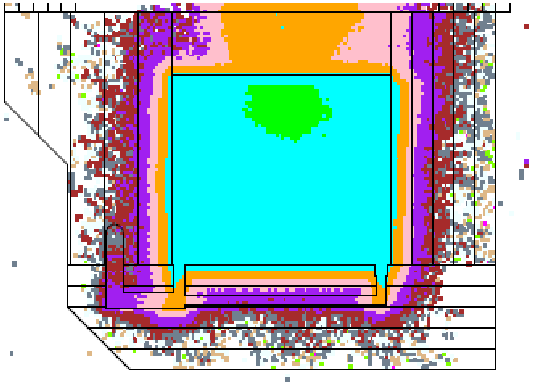
Refer to Literature Sources

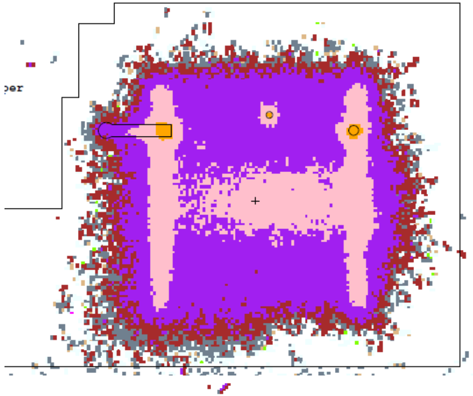
- FermiLab TM-1834, 2016
- NCRP 144
- DIN PAS 1078

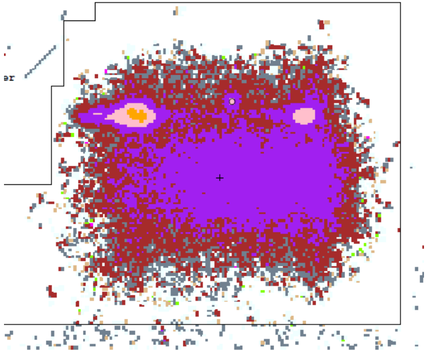
Maze Calculations

Ventilation Ducts are Mazes



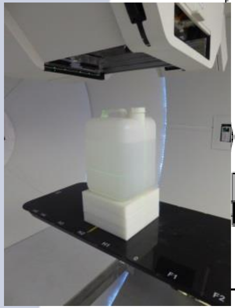


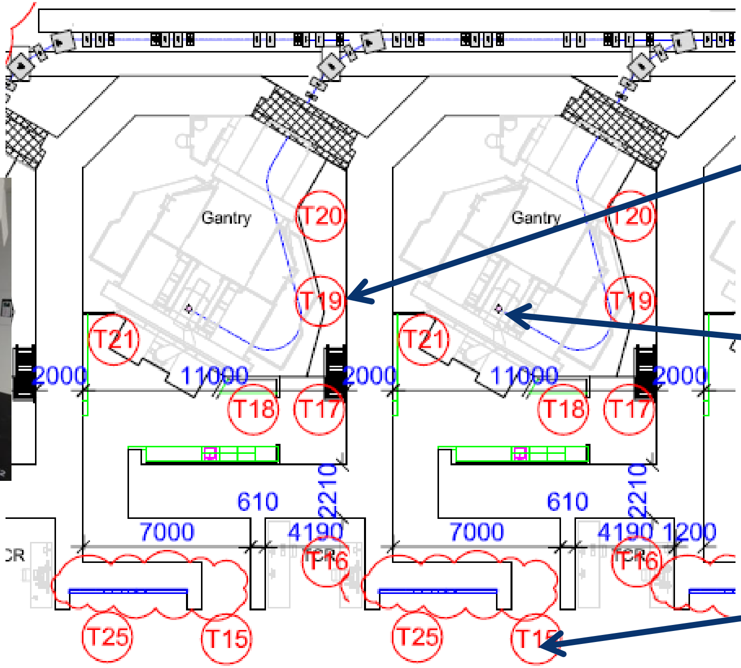


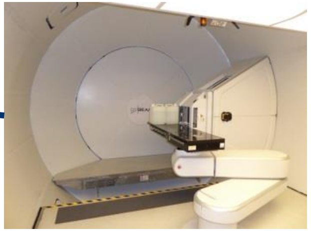


Benchmarking

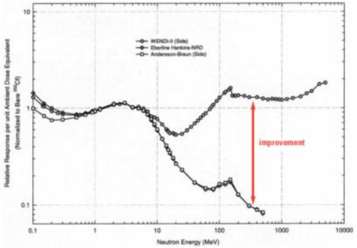
Benchmarking any Calculation





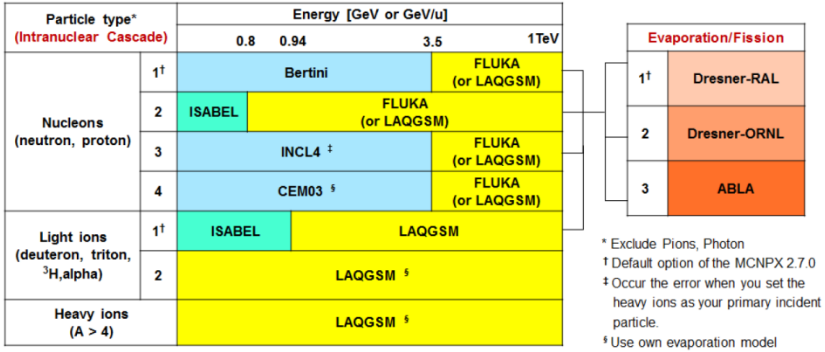


We used:
FHT 762 Wendi II
Neutrons: thermal to 5 GeV
Gamma rejection
High sensitivity due to large He-3 tube
Tungsten Core



Benchmarking Monte Carlo

- Physics Models
  - Spallation
  - INC
  - Fission-evaporation
  - light ion interactions
  - Choice?
    - Become a theoretical nuclear physicist, or look at literature:
    - (*)ARIM LEE et al.: COMPARISON OF PHYSICS MODEL FOR 600-MEV PROTONS, Journal of Radiation Protection and Research (2016)
    - MCNP6™ USER'S MANUAL



* Exclude Pions, Photon
† Default option of the MCNPX 2.7.0
‡ Occur the error when you set the heavy ions as your primary incident particle.
§ Use own evaporation model

Fig. 1. Physics models in MCNPX 2.7.0.

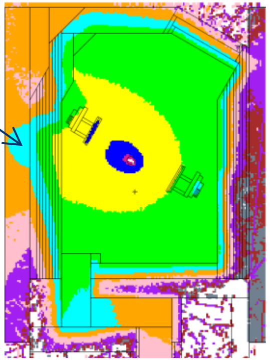
Source: (*)

Benchmarking Monte Carlo

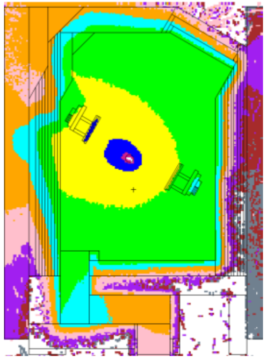
Some concrete | Portland Concrete (NIST) | ρ= 2.35g/cm³

Hotspot

CEM03.03

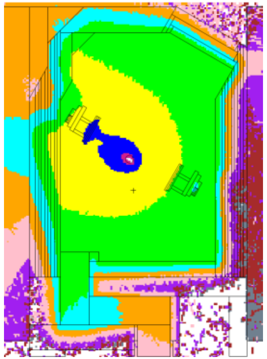


Test 001

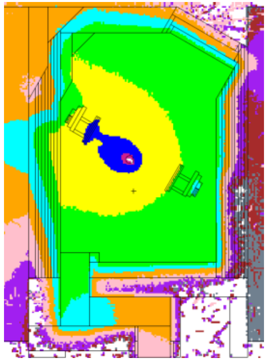


Test 003

Bertini / RAL / ISABEL



Test 002



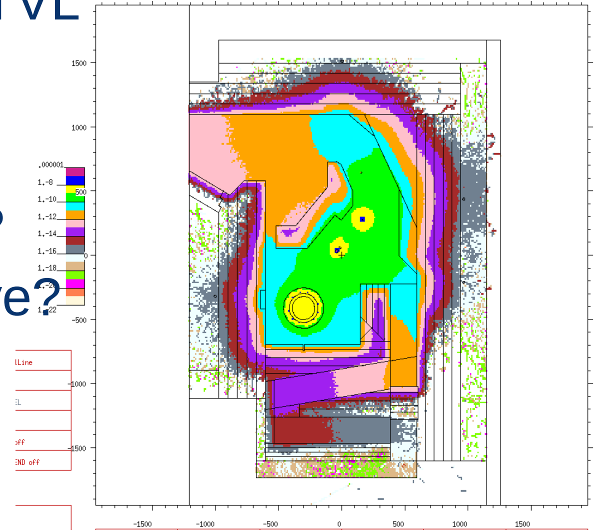
Test 004

	Some concrete	Portland Concrete (NIST)
CEM03.03	17.6	14.9
Bertini / RAL / ISABEL	26.7	23.4
Measured Value	5.7	

	Maze exit
CEM03.03	0.89
Measured Value	0.1

Benchmarking

- Material
  - Concrete ≠ concrete
  - Density and Elemental Composition = TVL
- Source
  - How to model a cyclotron?
  - How to model the beam loss positions?
  - How to simplify and remain conservative?

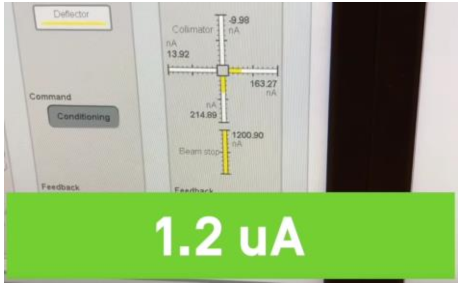


FLASH

FLASH with Protons

- Shielding Challenge
  - Understanding Source Terms
  - Understanding Workload
- Very high dose rate at ISOC
  - High extracted current
  - Low beamline losses
  - High currents in the Nozzle (> 40Gy/s)
  - Very short beam-on (< 1s)

Source: IBA Press Release
08 Mar 2019

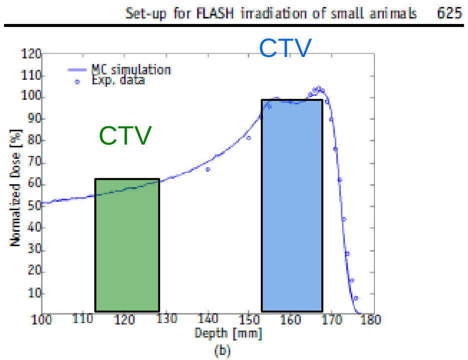


Cyclotron Current 1.2µA

University Medical Centre Groningen
IBA Site at UMCG
IBA Research & Development
IBA Innovation Laboratory

FLASH with Protons

- Reportedly, FLASH dose rates are less toxic to normal tissue
  - High dose rate pulses 40-200 Gy/s, < 1s
  - Reduced toxicity:
    - Irradiated Volume accuracy not as critical?
    - Bragg Peak or Transmission?
    - Hypo Fractionation, maybe single dose?

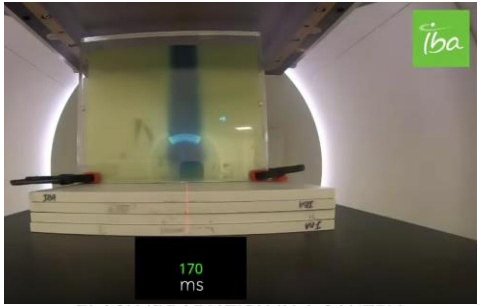


- Technology
  - Very fast energy variation, typically close to the patient
  - High energy beam in treatment room
  - At least in the beginning, small volumes
- R&D: clinical and technology

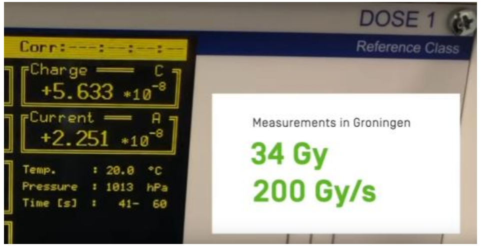
FLASH with Protons (IBA)

- Demo at Groningen
- Taking a closer look at the Press Release (08 Mar 2019)
- For Research

Source: IBA Press Release
08 Mar 2019



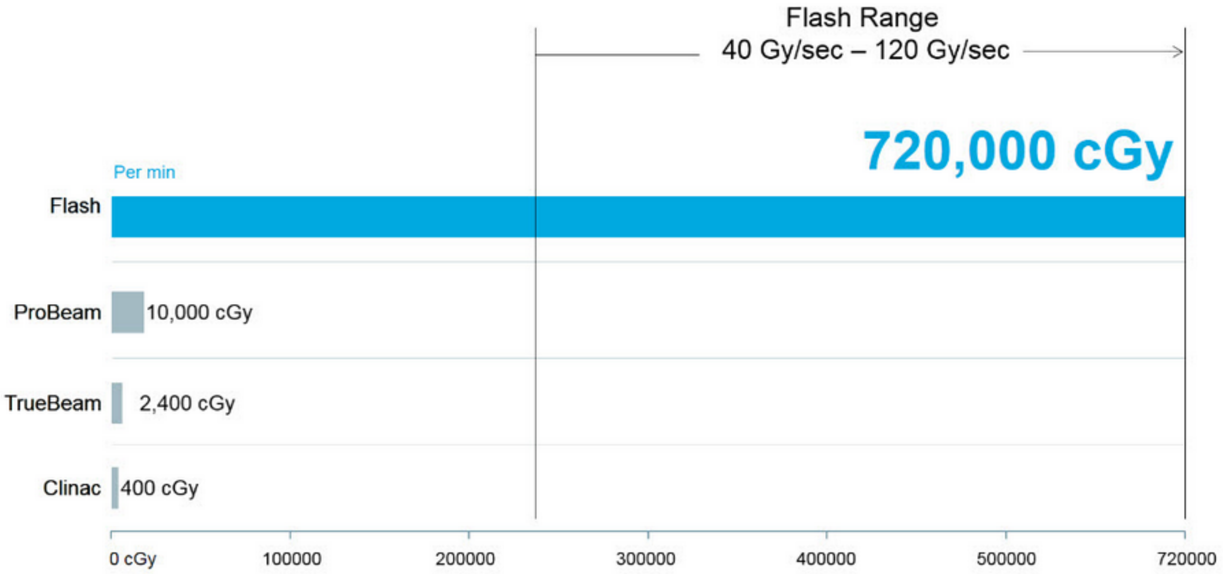
FLASH IRRADIATION IN A GANTRY
Cube 2x2x2 [cm3]



ISOC Current: 22.5nA for 170ms

FLASH with Protons (Varian)

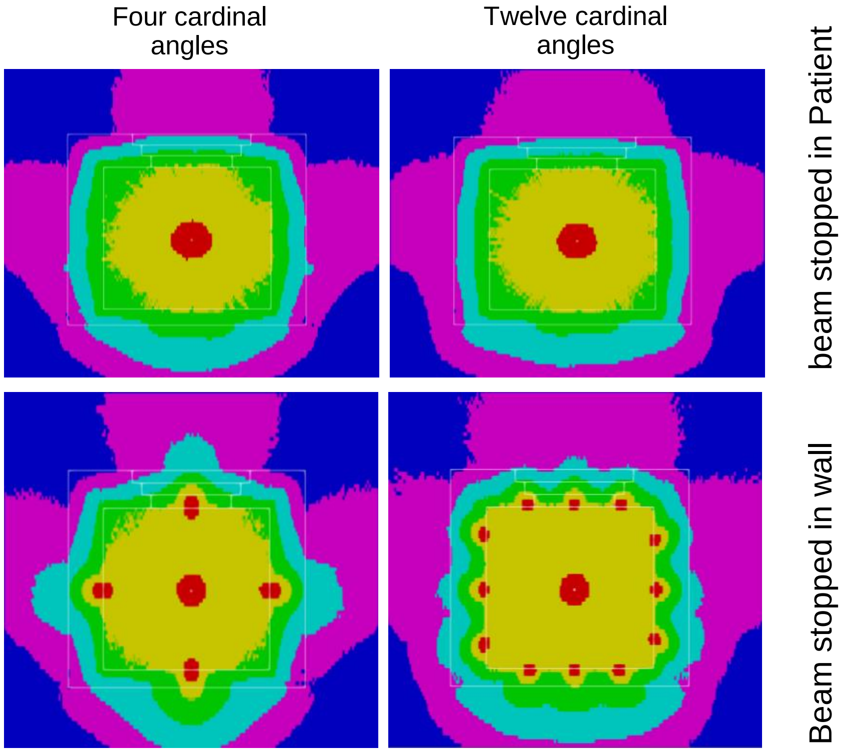
- Flash Forward Consortium
- For Research



Source: https://www.varian.com/oncology/solutions/proton-therapy/flashforward-consortium

FLASH with Proton Arc

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

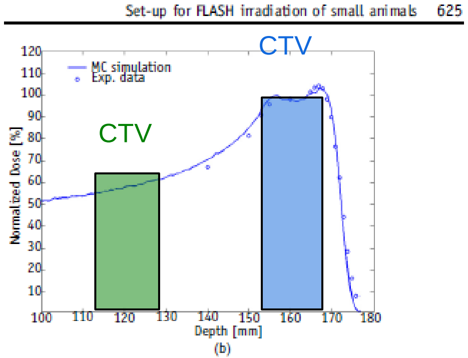


Gantry Room Sections through the ISOC; Rotation Plane

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

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.

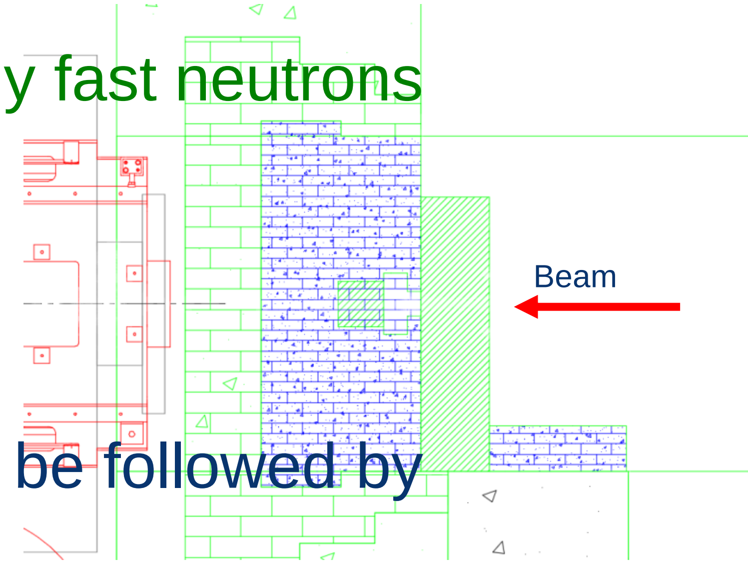
- Safety criteria is dose, not by IDR. Not all regulations reflect that.
- Choice of averaging time for IDR – 1 or 2 min, any one hour, dose per week?
- Locations where the requirements have to be met
  - also inside adjacent gantry room?
  - Only in public areas?

Learning Objectives

- Neutron Physics and Concept of Attenuation Lengths (=HVL/TVL) and their Dependence on:
  - Energy, observing Angle, Target and Shielding Material, Density
- Shielding Calculations need to Facility specific
  - Regulatory Limits vs. Design Criteria
  - Occupancy, Assumptions on Operating Parameters
- 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

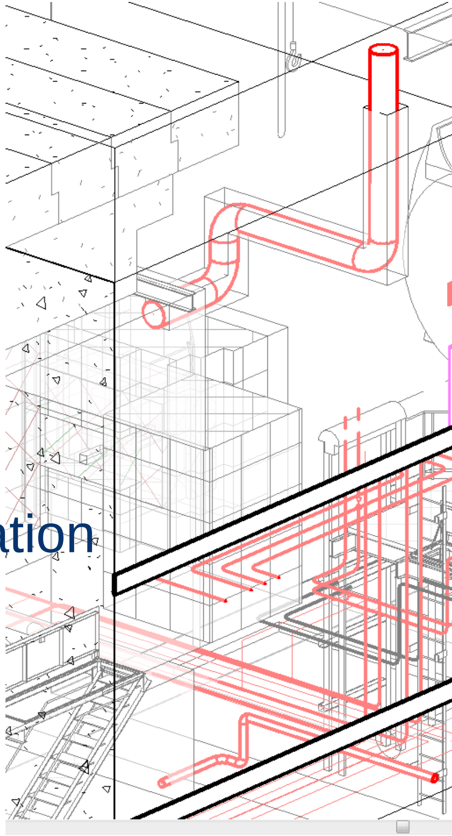
How-To:
Shielding Materials

- Iron – fast neutrons only
- High Density Concrete – mainly fast neutrons
  - Up to 5 kg/dm³
- **Standard Concrete**
  - **Typ 2.35 kg/dm³**
- Earth
- Sandwich order: Iron/HD must be followed by hydrogenous material.
- Bound water content 3%-5% typ. in concrete



How-To:
Ventilation - Guidelines for A&E team

- Each duct is a maze:
  - minimize cross section,
  - ≥ 2, often 3 legs
  - 1st leg is least effective – can be short
  - Opening not in forward beam direction
    - Avoid beamline height openings
    - Back of gantry rooms
- Avoid Duct run in line-of-sight direction from radiation source
- Avoid Duct with too little concrete coverage
- Verify individually by shielding consultant



How-To:
Conduits - Guidelines for A&E team

- Keep parallel conduit separated by ~3-4x diameter
- Conduit run not in line-of-sight direction from radiation sources
- Min 2 bends, max 4 bends (NEC),
  typical 2-3 bends

Thank You!