Radiation Protection – Design & Prevention

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Slides will be made available at
www.particle-therapy.com

Disclosures

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Meissner Consulting has design contracts Health Care Providers.

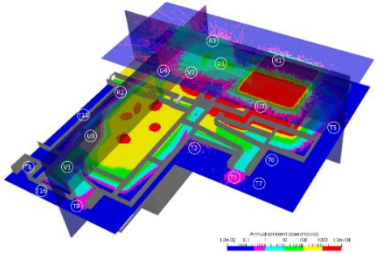
Learning Objectives

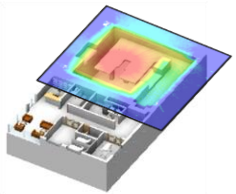
- physics of neutron shielding and its dependence on beam and material parameters.
- Apply workload data and conservative assumptions
- radiation protection regulations and distinguish regulatory limits from design criteria.
- Explain why shielding calculations are facility-specific in particle therapy facilities.
- Available Calculation Methods and Benchmarking
- Effect of FLASH and proton arc therapy on shielding requirements

Some Physics Background

Radiation Production Processes

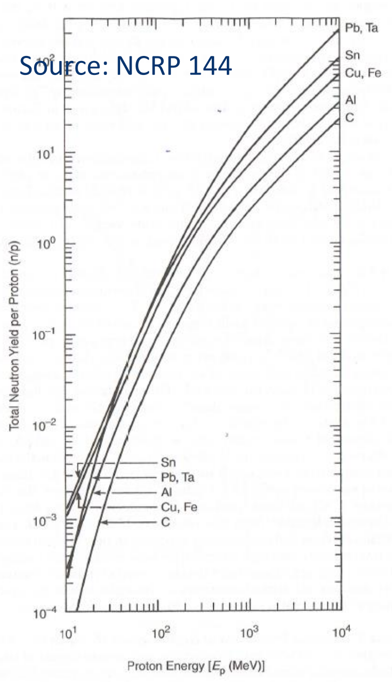
- Protons/Ions interact with material…
  - inside the accelerator,
  - Energy selection system and beamline,
  - Beam shaping at the patient: range shifters, collimators, modulators
    - PBS nozzles typically do not use these devices
  - patient, phantom
- …and create secondary radiation
  - Neutrons, charged particles, protons, gamma
  - Activation remains when the machine is off
- Shielding: Neutrons matter most





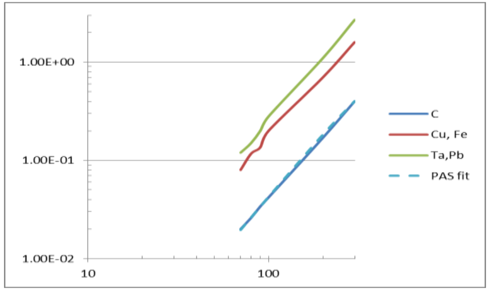
Neutron Yield (E_p,θ,material)

Source: NCRP 144

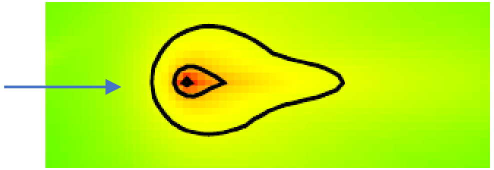


- Variation with Energy: Factor 10 in Yield between 70 MeV and 230 MeV

- Yield ~3-4x higher for Cu, Fe than for C or tissue

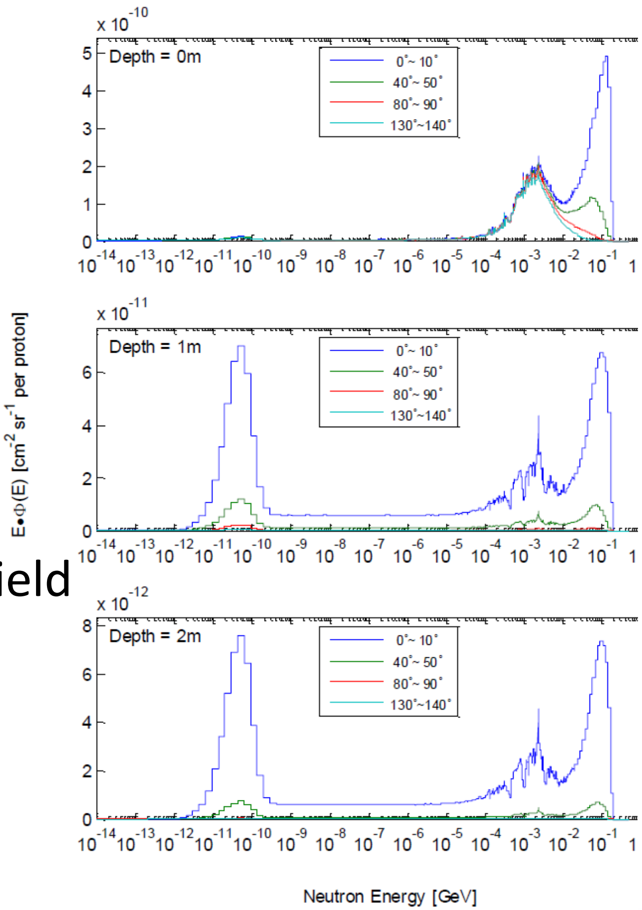


Flux is forward peaked



Neutron Field

- Direct neutrons, cascade neutrons
  - Typ > 20 MeV, up to incident p-Energy
  - continuously generate lower energy neutrons 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



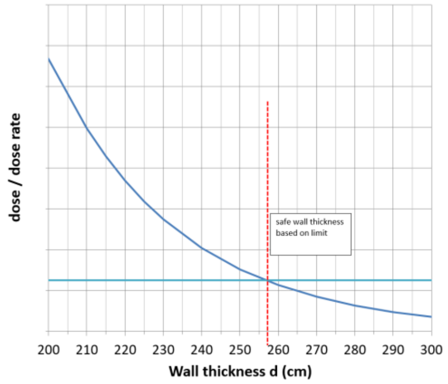
Why does this matter?
Attenuation!

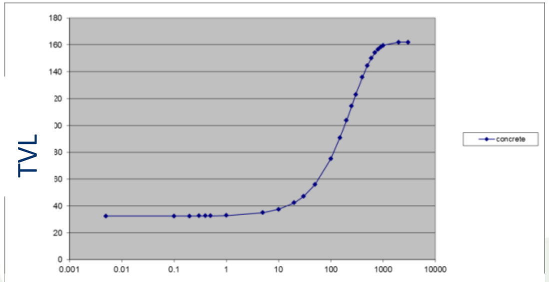
Measurement Instruments!
Neutrons Energy
thermal to 250 MeV

Source: Rong-Jiun Shu, RADSYNCH2013

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 !
  - Does not scale with density!

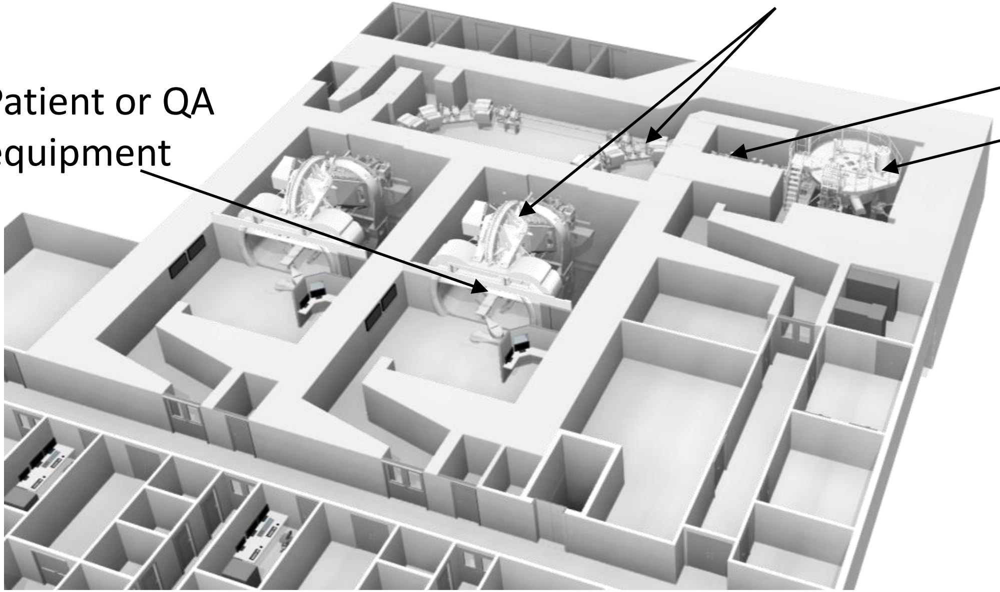




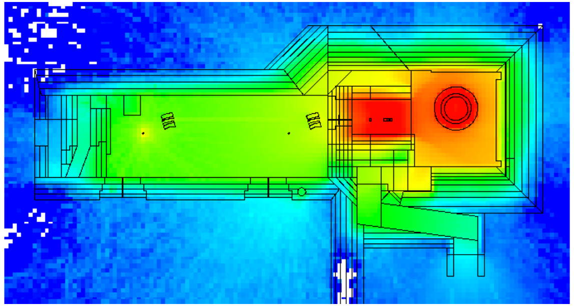
Neutron Energy (MeV)

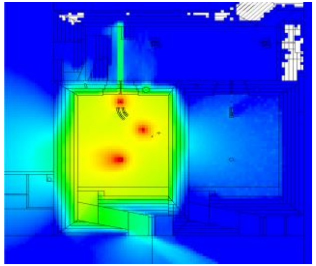
RT	PT
• Constant Energy	variable E_p and E_n
• 1 source	many source locations
• Workload: Gy/yr	proton losses & treatment plans
• θ dependence	θ dependence
• Constant TVL	variable TVL; Not ~ density

Complex Source Locations



Equipment courtesy of Varian Medical Systems

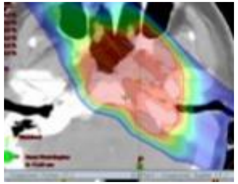


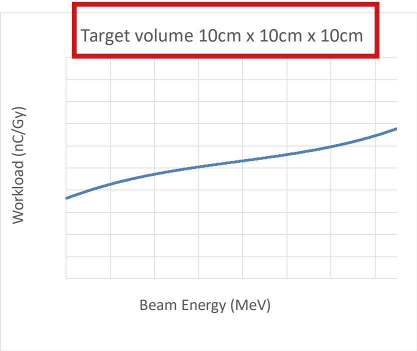


Dose map not to scale

From Gy or Gy-RBE and Treatment Plan data To nC(E) or protons/year (E)

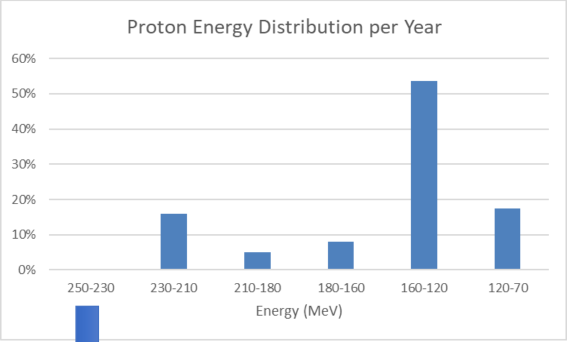
Indication Group Varian	% of treatments	Average of Dose (CGE)	Average of Volume (g/ml)
Head & Neck	31%	54	548
lung	16%	50	364
metastases	18%	42	1,660
prostate	5%	56	945
rectum & gyn	30%	61	1,344

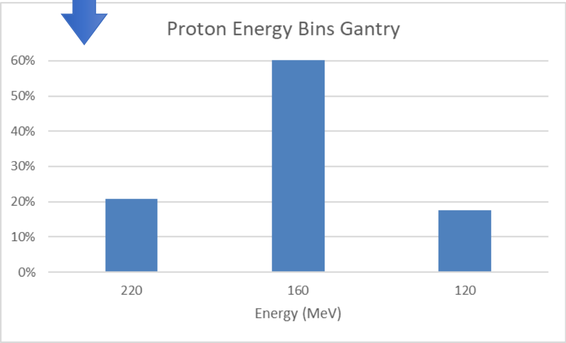




Process:

- Simplify Target to 1l box
- Scale Dose & Volume
- Gy → nC for each Indication Group, using distal energy

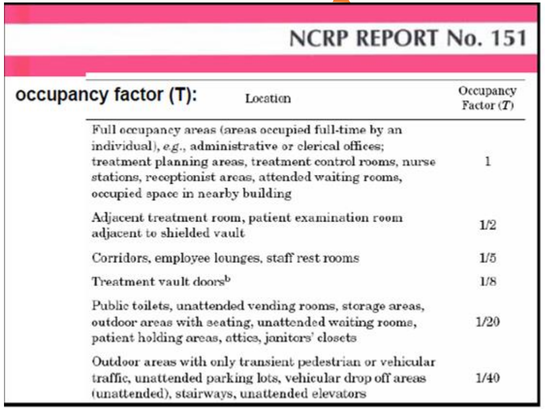




Regulatory: Effective Dose Limit (E)

- Annual or weekly 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
  - Singapore requires a safety margin of Factor 3 for Monte Carlo
  - UAE requires 0.1 mSv/a
  - Often the design target the regulatory body requires is not written explicitly in the regulations!

➔ Design for E, not for H*(10) nor Dose Rate



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

Design for Annual Dose or Instantaneous Dose Rate?

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Definitions

- IDR (instantaneous dose rate) introduced by some countries, without really specifying the "instant" or measurement technique.
- time averaged dose rate (TADR) – takes time in between irradiation into account

Examples

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

➔ Cost Efficient Design for E, not Dose Rate

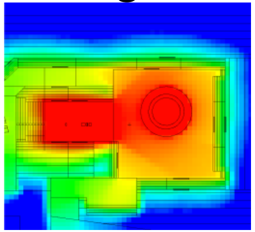
Regulatory: Activation & Decommissioning

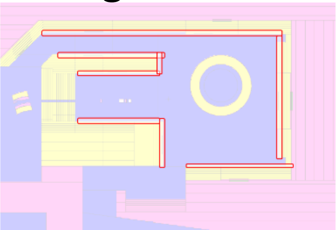
Limited Activation?

- Cooling water
- Exhaust air
- Ground Water and Soil

Likely activated beyond CL

- Equipment in cyclotron area
- Shielding walls near degrader





More than 100 PT centers worldwide

- More and more regulators considered decommissioning
- examples: Denmark, Norway, Germany, New York, New Jersey, Thailand, Singapore, UAE…
- RPTC decommissioning cost estimates > $15 million ➔ Bond? (2% p.a. = $300k)

Why Shielding Calculations are Facility Specific

Regulatory Environment
- Regulations differ
- dose rate limits ?
  - Hefei: 280cm
  - UPenn: 190cm
- Decommissioning
- Local rule interpretation

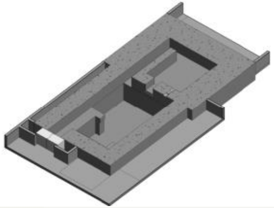
Workload per room
- Clinical hours
- Standard/hypo fractionation
- 3 fractions / hr; peds 2/hr
- ➔ 250 – 400 patients/yr
- Robustness of patient model

New Treatment Methods
- Flash, Arc, …

Facility
- Vendor specific
- Door vs maze
- Local concrete / density
- Ventilation and other penetrations
- Use of area around the vault

Other factors
- Futurization of patient model
- QA and Service
- Operating Hours increase





FLASH

Effect on Annual Dose

Treatment Room Considerations

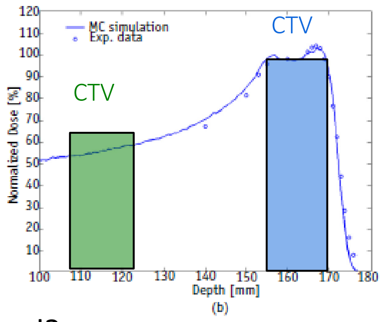
- Hypo Fractionation
  - To the extreme of applying full dose in one session
  - Theoretical capacity increase x 20?
- Fraction of Patients treated with Flash?
- Conformal or Transmission Method –
  - where is the beam stopped? patient, beam-stop, wall?
  - Maybe 2-3x more protons needed for the same 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

Set-up for FLASH irradiation of small animals 625

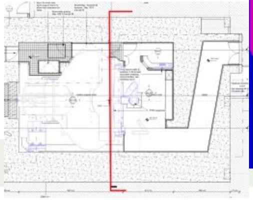


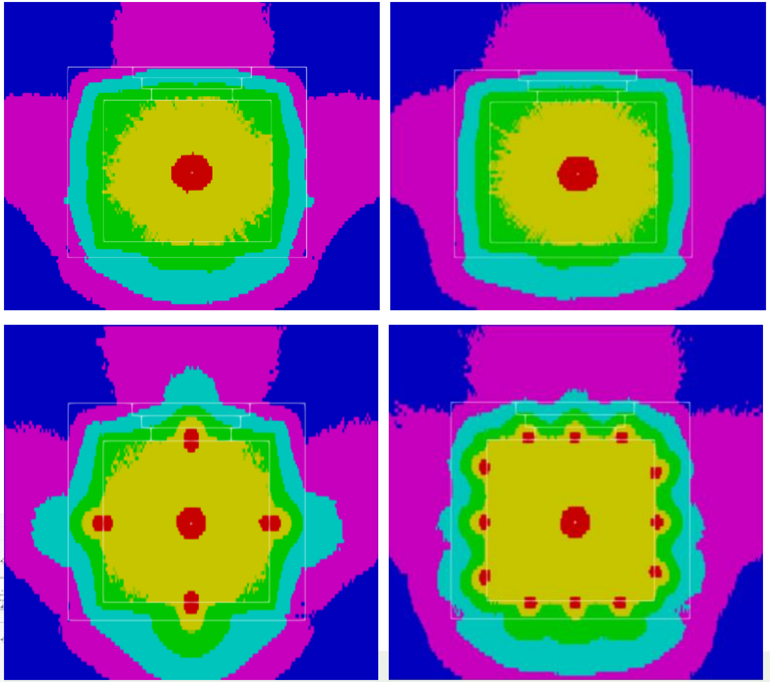
Source of inset: Int J Radiation Oncol Biol Phys, Vol. 102, No. 3, 2018

FLASH with Proton Arc

- Traditional PT: 2-3 fields
- Arc: many fields during rotation (approximated by using 12 angles)
- Conformal method
- Transmission Method (no beam stop)

➔Not dose rate, but Energy, Source Location, hypo fractionation



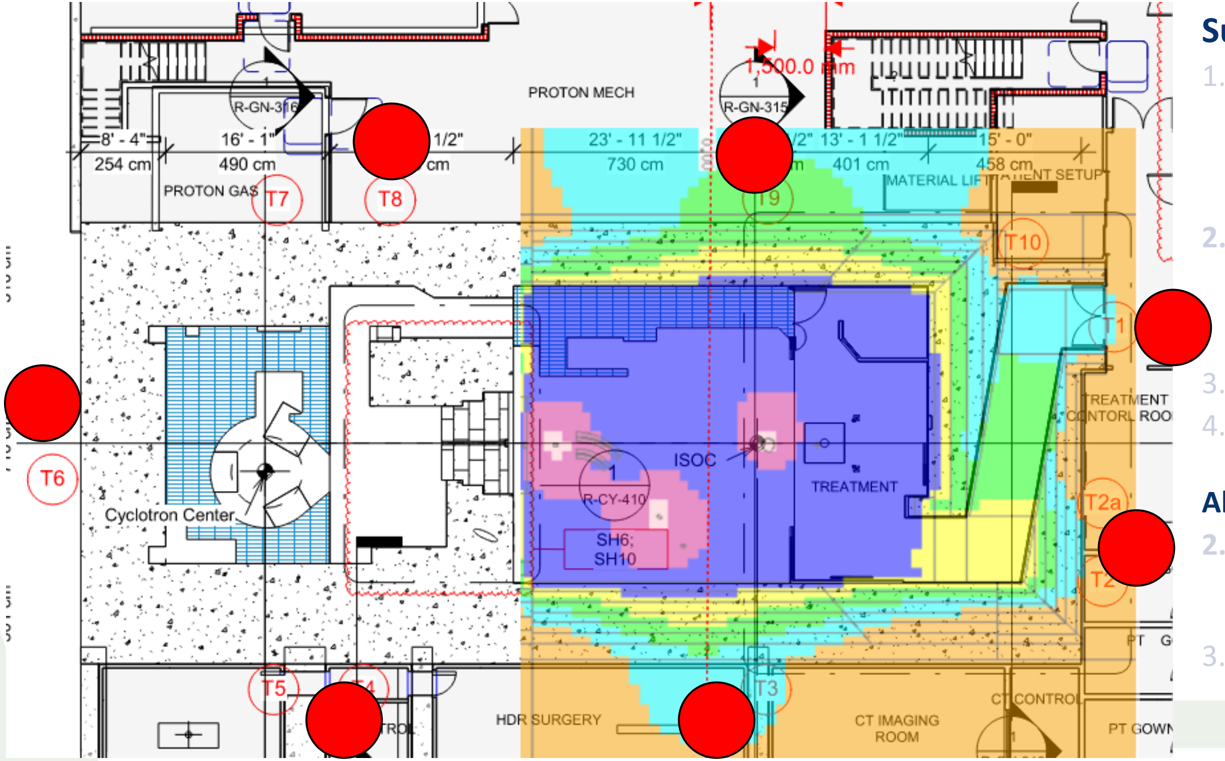


Gantry Room Sections through the ISOC; Rotation Plane

Verification & Survey

Risk based Facility Survey

Neutron and Photon Dose Survey – Define repeat frequency!



Survey Steps

1. Select several POI based on
   1. shielding report, use of location, experience.
   2. Ventilation ducts
2. **Physics Mode:** Measure neutron + photon accumulated dose over 3min (not IDR) @ fixed energy and fixed beam current (phantom at ISOC!).
3. Use clinical model to calculate annual dose.
4. Be sure to understand Energy/Intensity in clinical model.

Alternative Step 2 & 3:

2. **Treatment Mode:** Apply High Energy TP, max dose per fraction available from machine; measure accumulated dose/fraction
3. Scale fractional dose and # patients

Preventing Exposure – What Matters & what doesn't

Access to the cyclotron area

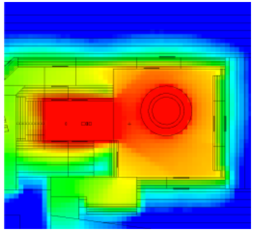
- High level activations
  - Pre-access survey
- Air activation
  - Activation calculations
- Cyclotron vs Synchrotron
- Waiting time? It depends…

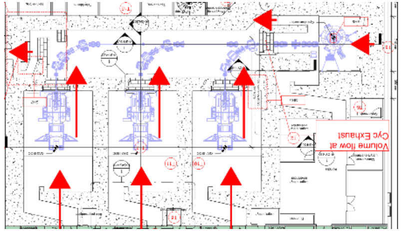
Access to the treatment area

- No significant activations
- No significant air activation
- Waiting time? No

Cyclotron area Activation

- Equipment in cyclotron area
- Shielding walls near degrader





- Air
  - Huge differences in regulations!
  - Activity level depends on ventilation design.
  - In Multiroom: up to 10min
  - In single rooms: rarely a factor

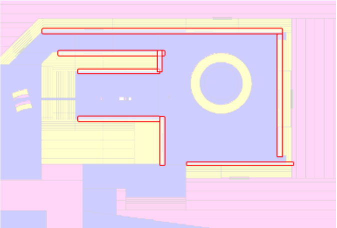
Preventing Exposure – What Matters & what doesn’t

Permanent Radiation Monitoring

- Inside Treatment room
  - Trust thy Interlock System
  - Adjacent room with beam?
    - Facility survey
    - Personnel dosimetry (OSL)
- Inside Cyclotron area
  - For what purpose?
  - Pre-access surveys!
  - Personnel dosimetry (OSL)
- Representative locations
  - Purpose: Audit / Record keeping, ambient dose
  - PE-sphere with OSL; official readout

Activation Monitoring & Mitigation

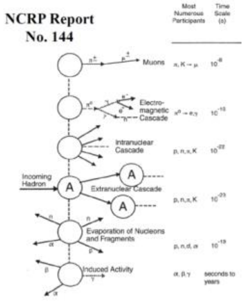
- Service Exposure
  - Pre-access survey (hand held survey meter)
- Reduce Long-term Waste
  - Shielding walls near degrader
  - Waste disposal & decommissioning concept
  - Sacrificial layer design; integrated monitoring
  - Low-Activation Concrete
- Emissions: Exhaust Stack
  - Ventilation design and exhaust calculation
  - validation measurement
  - No continuous monitoring

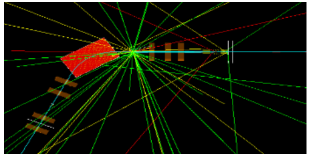


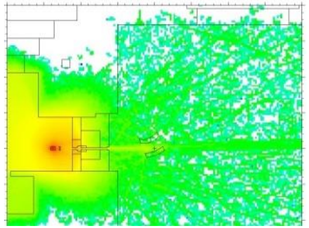
Calculation Methods

Monte Carlo – roll the dice for each proton

- Each particle is tracked by probability until a defined cutoff
- Each interaction is recorded, secondary particles are tracked.
- Physics cross sections available for all elements.
- All materials possible, 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

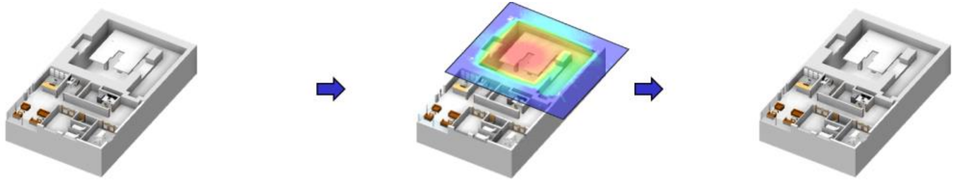






Monte Carlo Applied

- 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 or ICRP 116
  - Simulation of Source particles – CPU time intensive
- Step 3
  - Pretty up the output
  - Communicate output
- Benchmarking



Benchmarking Monte Carlo

Material

- Concrete ≠ concrete
- Density and Elemental Composition => TVL
- Physics model

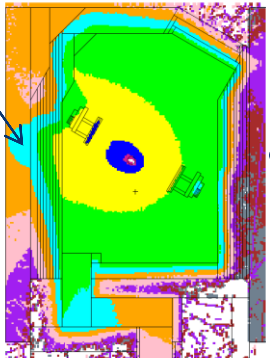
Source

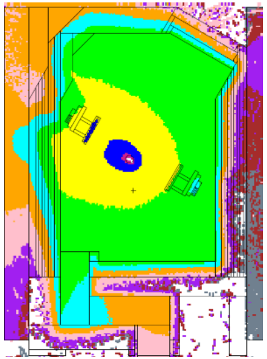
- How to model a cyclotron?
- How to model the beam loss positions?
- How to simplify and remain conservative?

Hotspot

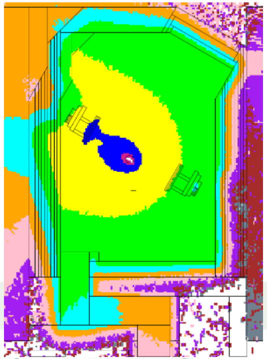
Some concrete | Portland Concrete (NIST)

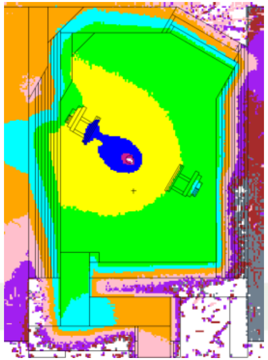
CEM03.03





Bertini / RAL / ISABEL





ρ= 2.35g/cm³

	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

Carbon Ion Therapy Shielding

PHITS (Particle and Heavy Ion Transport code System)

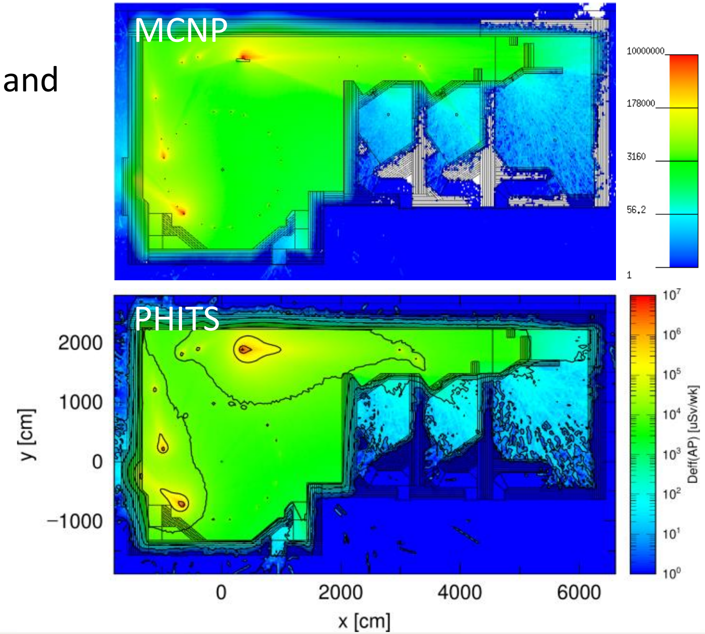
- general purpose Monte Carlo simulation code developed under collaboration between JAEA (Japan Atomic Energy Agency), RIST, KEK and several other institutes
- Commonly used for Carbon Therapy Shielding – 400 MeV/u

MCNP

- Ideal for neutron transport
- Requires benchmarking for Source Terms when using He, C or other heavy ion beams

Fluka

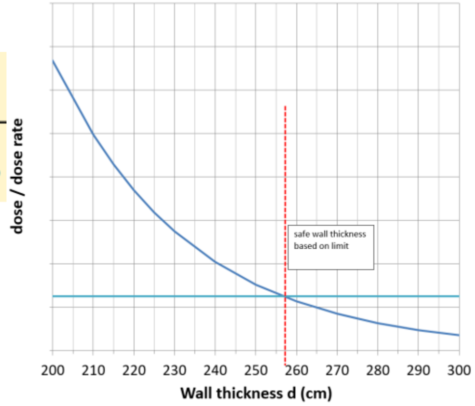
- Used by many for Carbon and Proton Therapy
- Commercial License necessary



Line-of-Sight - Analytical Explained – $1/r^2$

- Point-Source line-of-sight model

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



- Source term and attenuation length (TVL)
  - H_i from NCRP 144, other standards, or publications
  - choose energy bins and angles for each POI
  - Know your target materials
  - Only materials where λ_i (E, θ) is available

Needed:
H_i (E, θ) e.g. Yield
λ_i (E, θ) e.g. TVL

Source: Rong-Jiun Shu, RADSYNCH2013

Thank You!

Slides will be made available at
www.particle-therapy.com

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