South East European International Institute for Sustainable Technologies

Radiation shielding - before touching a computer and TR1H beamline

Mariusz Sapinski*

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* GSI and SEEIIST

Radiation Protection - Legal requirements

- SEEIIST - nuclear installation.
- Bodies issuing radiation safety recommendations:
  - International Atomic Energy Agency (IAEA)
  - International Commission on Radiation Units and Measurements (ICRU)
  - Intern. Commission on Radiological Protection (ICRP)
- Recommend dose to public less then 1 mSv/year (natural 2.4 mSv/year).


IAEA TECDOC SERIES

IAEA-TECDOC-1891

IAEA-TECDOC-1891

Regulatory Control
of the Safety of Ion
Radiotherapy Facilities

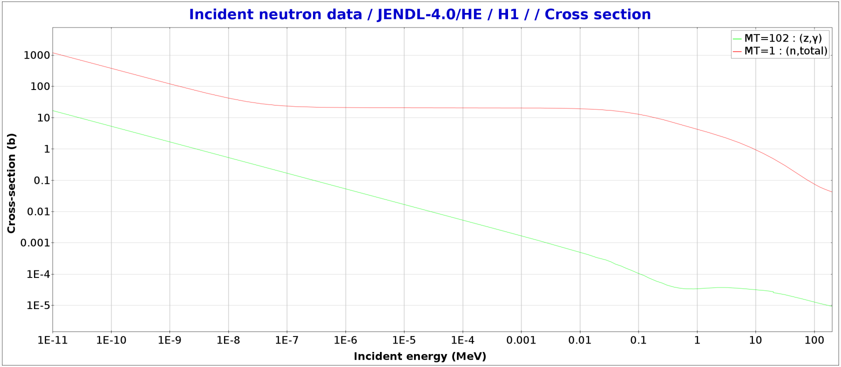
- IAEA document specific for Ion Therapy Centers (issued in 2020(!))

  - Permanent presence assumed (8760 hours/year).
  - There are more regulations, but this is the first one to consider.

Radiation Protection - physics

- All Carbon ions loose energy interacting with body electrons and producing the cancer-killing Bragg-peak.
- In addition a lot of nuclear reactions takes place, eg:
  - fragmentation: $^{12}\mathrm{C(p,^6 Li)^7Be}$, $^{12}\mathrm{C(p,^4 He)^9B}$, etc.
  - prompt gamma emission (used for in-situ imaging): $^{12}\mathrm{C(p,\gamma)^{13}N}$, $^{12}\mathrm{C(p,p'\gamma)^{12}C}$, $^{12}\mathrm{C(p,4He)^{6m}Li \rightarrow \gamma +^6 Li}$
  - neutron production eg: $^{12}\mathrm{C(^{12}C,n)^{23}Mg}$, $^{12}\mathrm{C(p,n)^{12}N}$; most neutrons are produced in spallation eg. $^{12}\mathrm{C(p,3p3n)^7Be}$
- No dominant processes - use of a computer code at this stage is a big help, otherwise: tables/databases (eg. JANIS4) of nuclear reactions.
- Radiation hazard is mainly due to high-energy (HE) neutrons.
- Rule of thumb: 5 neutrons (1 high energy) produced per $^{12}\mathrm{C}$ at 430 MeV/u, moving in the beam direction (narrow cone).

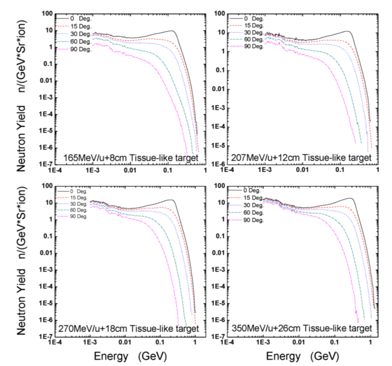
Neutron scattering and capture cross-section



(using JANIS 4.0 nuclear database)

Neutron spectra

- General rule: neutrons must be slowed down to thermal energies (meV) and then they are captured in nuclear reactions.
- So: shielding depends on maximum neutron energy.
- Max neutron energy depends on beam energy.
- Those reactions often produce gammas which must be shielded as well; for instance: $^{1}\mathrm{H}(\mathrm{n},\gamma)^{2}\mathrm{H},\ \mathrm{E}_{\gamma}=2.2\ \mathrm{MeV}$



FLUKA simulations from arXiv:1702.08332 [physics.med-ph]

Shielding

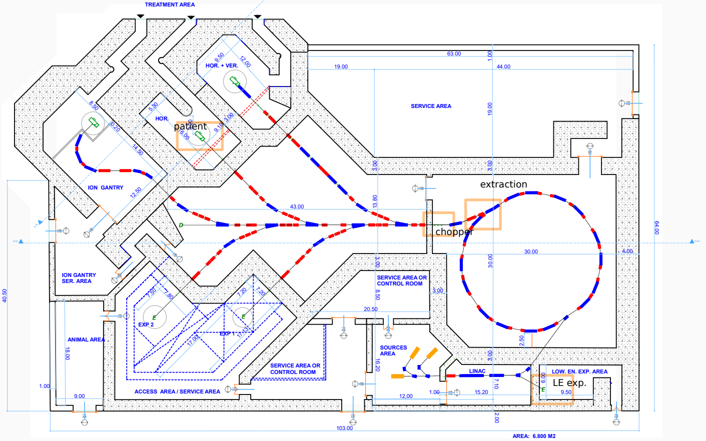
- Concrete (various types) can slow down and absorb neutrons and shield gamma rays $\rightarrow$ the most popular material.
- High-density poliethylene (high concentration of hydrogene) often used.
- For neutron above 100 MeV a layer of high-Z material (Fe, Pb) used, but I don't think it is used in therapy centers.
- Schaeffer Equation (1973, before computers era):

$$D = D_O \cdot exp(-\Sigma_R \cdot d) \ \ (+50 \ cm \ of \ hydrogenous \ material) \tag{1}$$

where:

- D_0, D - dose before and after shield,
- d- shield thickness,
- Σ_R - neutron removal cross-section, concrete 0.0945 $[cm^{-1}]$,
- in addition a buildup factor R=5 due to geometry (pencil beam source).

Beam losses in SEEIIST



Conservative assumption: all shots in TR2 (1 shot of 10^{10} Carbon ions at 430 MeV/u every 10s): $3.2 \cdot 10^{16}$ per year! The same number of high energy (300 MeV) neutrons. Lower energies neglected as they will be stopped by the same shielding.

Dose in the Treatment Room TR2

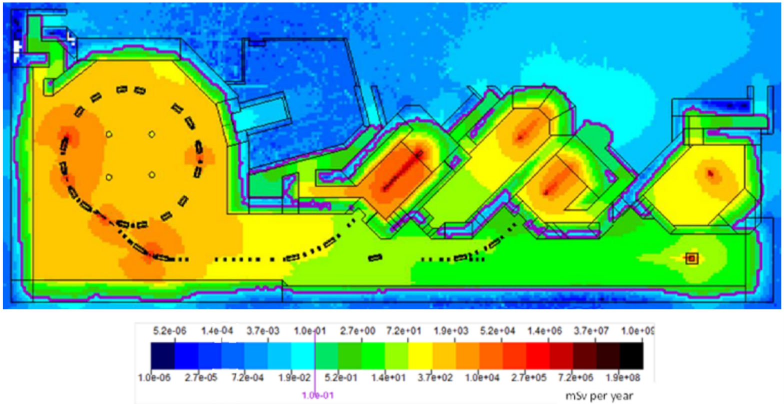
Back-of-an-envelope calculation:

- total HE neutron number: $\mathrm{N} = 3.2 \cdot 10^{16}$
- average elastic scattering cross section: $\sigma_\mathrm{s} =$ 1 barn,
- in each scattering process neutron loses half of energy ($\mathrm{Q_{av}} = 150$ MeV) to a proton,
- tissue density: $\rho = 1\ \mathrm{g/cm^3}$,
- atomic density of hydrogen in tissue: $\mathrm{n} = 6 \cdot 10^{22} \mathrm{cm^{-3}}$,
- irradiated area: $\mathrm{S} = 20 \times 20\ \mathrm{cm^2}$,
- High-energy neutron dose: $\mathrm{D} = \mathrm{R} \cdot \mathrm{N} \cdot \frac{\mathrm{n} \cdot \sigma_\mathrm{s} \cdot \mathrm{Q_{av}}}{\mathrm{S} \cdot \rho}$

yearly dose (fast neutron component): 500 kGy $\approx$ 2500 kSv

Radiation shielding thickness

- Initial dose from fast neutrons: 2500 kSv/year.
- We have to reduce it to 1 mSv/year ($25 \cdot 10^9$ times).
- Result is 3.0 meters of concrete.
- Reduction to 0.1 mSv/year (as in MedAustron) - 3.3 meters

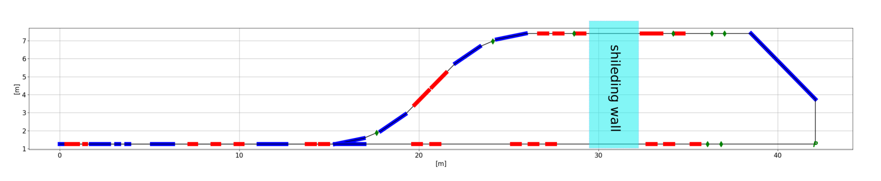


Radiation Shielding Summary

- Basic radiation shielding requirement: 1 mSv/year dose to public.
- Back-of-an-envelope calculation confirm 3-meter concrete, compatible with MedAustron simulations.
- This kind of calculation can be used for basic scalling, but...
- FLUKA/Geant4 simulations are necessary for assessment of real radiation fields (IAEA fellow + expert consultant).
- Other tools: G4beamline, BDsim (MADX input), MCNP and many more.
- Input needed for estimation of shielding in TR:
  - conservative but realistic operational scenarios (beam energies, scanning area, time per patient, number of patients per year, etc),
  - yearly dose to public condition (local regulations).
  - 1 W/m condition (hands-on maintenance).
- Experiments' requirements are less predictible - more shielding?

TR1 beam lines

Since it was decided for having H and V beamlines in TR1, the layout and optics of TR1H changed. The current layout:



Vertical part of beam line is from Marco Pullia (CNAO). It uses slightly different magnets then SEEIIST baseline.

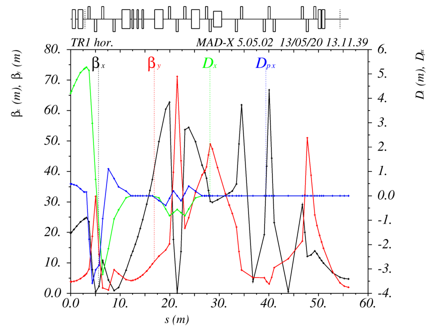
Dipole rendering is poor (eg. 90 deg dipole).

TR1H optics solutions

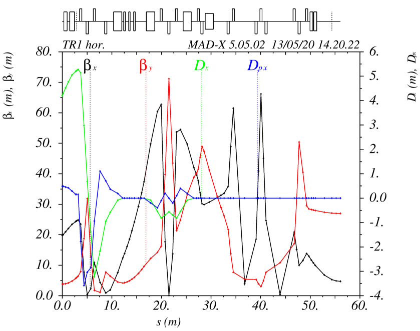
$$\text{constraint, range} = \text{patient}, D_X = 0.0, D'_X = 0.0, \beta_X = 5.0, \alpha_X = 0.0, \alpha_Y = 0.0, \mu_X = 2.7;$$

$$\text{constraint, range} = \text{mq5.1/mq3.8}, \beta_X < 60, \beta_Y < 50;$$

$\beta_Y = 2$ m



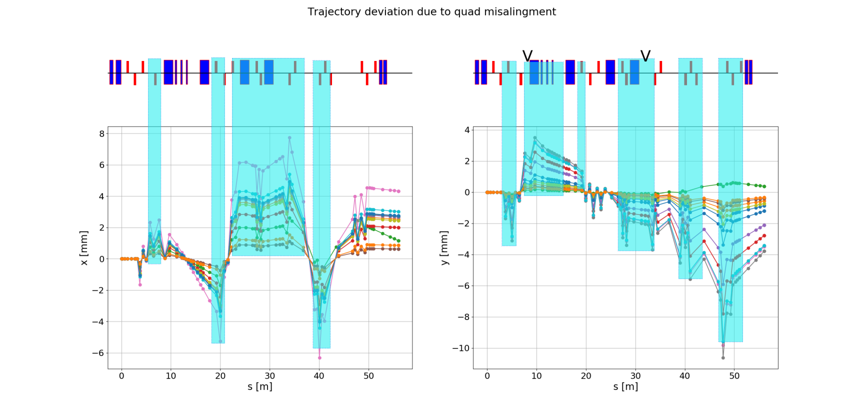
$\beta_Y = 27$ m



Quadrupole misalingment study

Random misalingment of all quadrupoles by up to 2 mm.

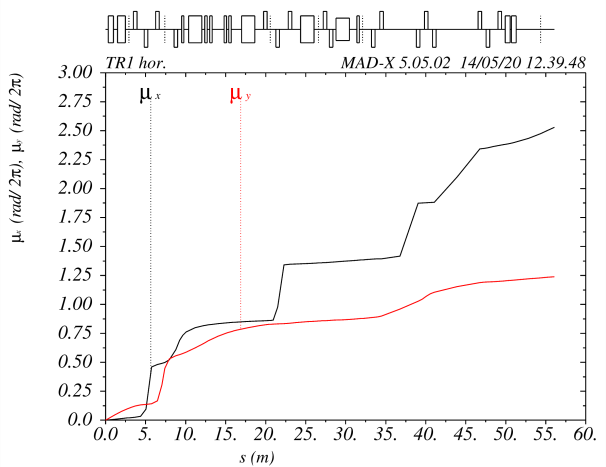
EALIGN, DX := 0.002*RANF(), DY := 0.002*RANF();



Horizontal steering: by tuning the main dipoles.

First idea: only two vertical steerers.

Preliminary complete layout



To do: demonstration of position correction (probably more steerers needed), estimation of steerers' strength.