JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Radiation protection for operators at JYFL Accelerator Laboratory

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Radiation Safety Officer @ JYFL

Contents

- Ionizing radiation
- Radiation dose
- Biological effects
- Radiation dangers at JYFL Acc Lab
- Radiation shielding
- Safety system
- Other dangers
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Ionizing radiation

- Radiation with sufficient energy to cause ionization in atoms or moleules by removing bound electrons from them is called ionizing radiation
- Types of ionizing radiation:
  - Electromagnetig radiation: X-ray, gamma
  - Charged heavy particles: alpha, proton, heavy ion
  - Charged light particles: beta, (electron, positron)
  - Neutral massive particle: neutron
- These all are produced directly or as secondary radiation with a particle accelerator
- Other sources of ionizing radiation include
  - Radioactive substances both natural and artificial
  - Cosmic rays from the Sun or outer space
  - Other technical devices such as X-ray machines, nuclear reactors, …

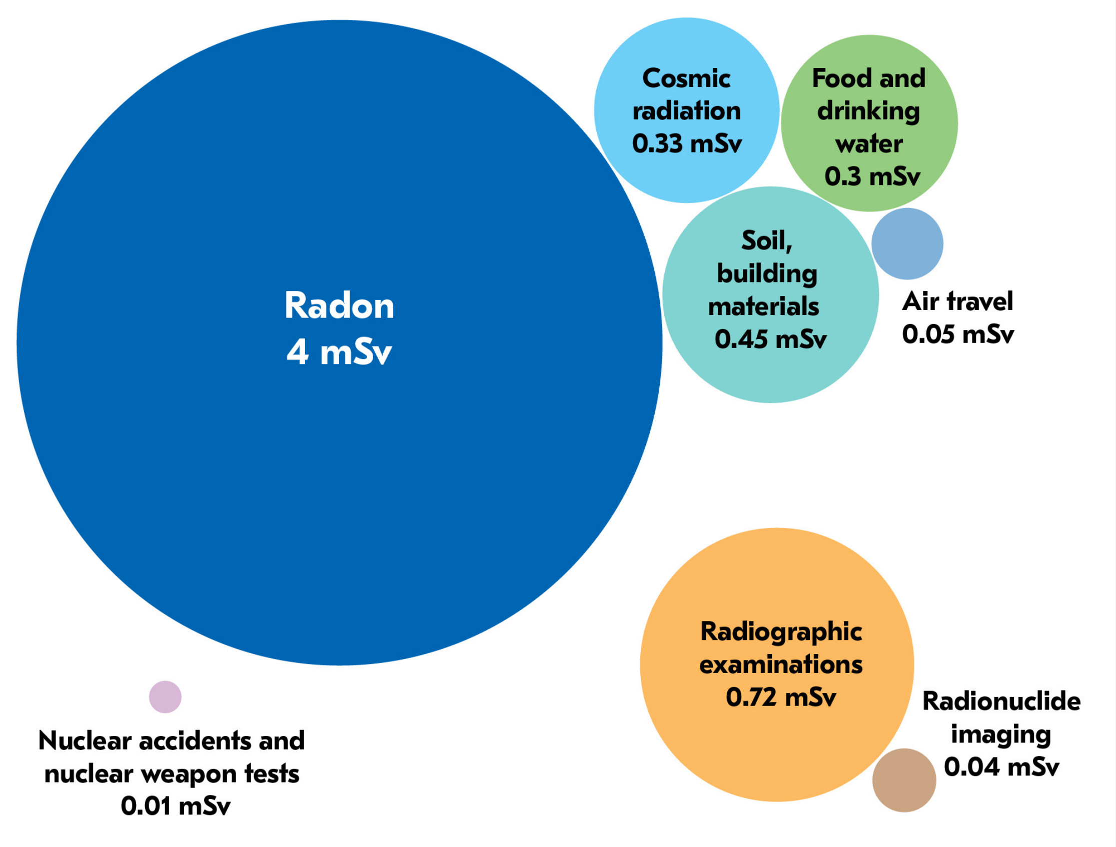
Radiation dose

- **Absorbed dose (Gy)**
  - Amount of energy deposited by radiation in a mass (J/kg => Gy).
- **Equivalent dose (Sv)**
  - Describes the biological effect of ionising radiation to tissue or an organ.
  - Depends on the type of radiation; gamma, beta, alpha, neutron, (and energy).
- **Effective dose (Sv)**
  - Describes the full health detriment due to ionising radiation.
  - Weighted sum of equivalent doses of different organs/tissues.

The unit is sievert (Sv)

1 mSv = 0.001 Sv

Average effective dose in Finland
(5,9 mSv 2018)



Ref. STUK-A263

Dose limits
(RA §99 and GD chapter 3 & 7)

Type of limit	Dose limit, in mSv per year		
	Occupational	16-17 year old students and trainees *	Public
Efective dose	20	6	1
Equivalent dose -Lens of the eye -Skin (ave 1 cm^2) -Hand and feet	 20 ** ! 500 500	 15 ! 150 150	 15 50 (50)

* Below 18 year old can not be radiation worker unless it is directly related to his/her occupational training.
** 100 mSv in five consecutive years. Max 50 mSv during a single year.
! Old limit for category A worker: 150 mSv/year and cat B worker: 45 mSv/year !

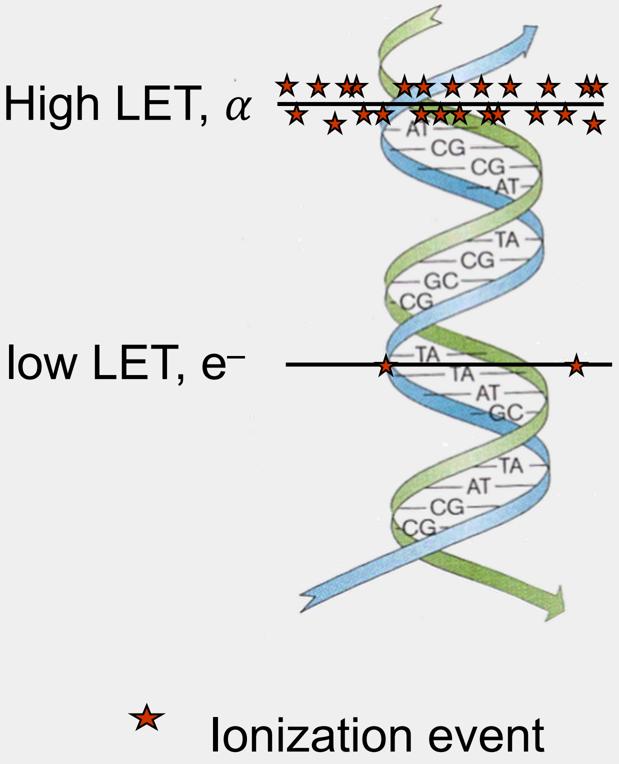
Dose examples

• Transatlantic flight	0.05 mSv
• Annual dose limit for a member of public	1 mSv
• Thorax x-ray	0.1 mSv
• Natural background radiation	3 mSv
• Annual dose limit of a radiation worker	20 mSv
• Interventional radiology (skin dose)	1000 mSv
• Slight acute radiation damage	2000 mSv
• Radiotherapy, local dose	> 6000 mSv

JYFL rad. workers' personal doses << 1 mSv per year

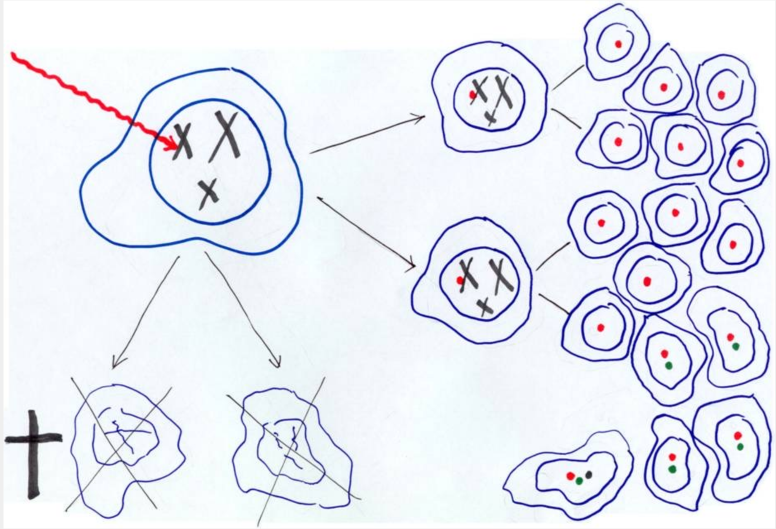
Biological impacts of ionizing radiation

- Direct impact on DNA
- Chemistry mediated damage: Free radicals (O•, OH•)
- DNA repair
- Mutations
- Apoptosis, programmed cell death



Biological effects

- Deterministic effects (high dose)
  - Threshold dose above which effect is certain
  - Dose rate affects both threshold and severity
  - Cell death, negrosis
- Stochastic effect (low dose)
  - Probability of the effect occuring is directly proportional to the dose
  - Severity does not depend on the dose
  - Individual effects rare
  - Population wide collective dose important
  - Combined effect with other causes (eg. smoking)

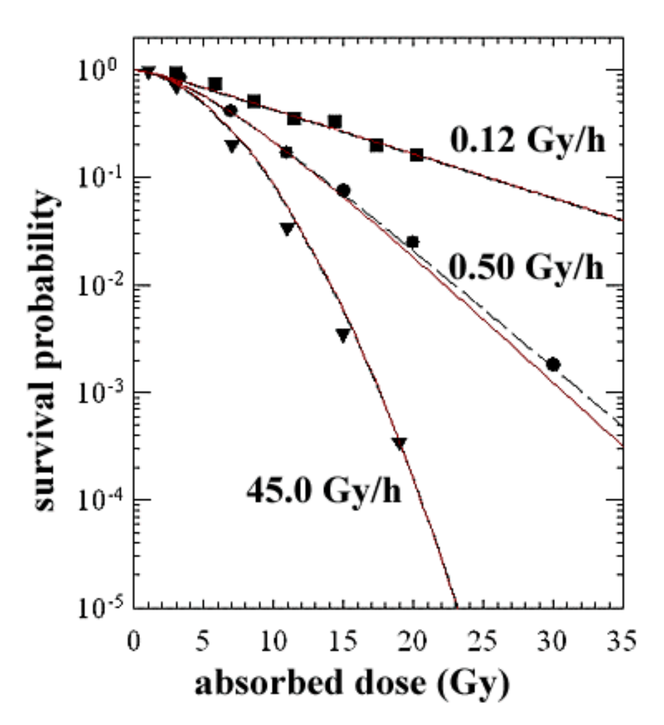


Cancer cell

Two mutations

Dose rate matters

- Chinese hamster ovary cells
- Survival probability with three different dose rate
- With higher rate the survival probability is lower even with same total dose
- Less time for self repair the damage



Dose and dose rate meters (1)

- RDS-200 /RADOS (dose rate/dose)
- Portable, meant for radiation users
- Learn how to operate
- Storage locations:
    - S106
    - S150
    - S2 101 (IGISOL and MCC30)

- DGM 1500 Turva /KATA
- Fixed dose rate monitoring in the controlled area

Dose and dose rate meters (2)

Wedholm 2222A
- Fixed location neutron dose rate monitoring in the controlled area
- S106 / portable neutron dose rate meter for radiation users

Measurement quantities for radiation dose

- Effective dose can not be measured
- Measurement quantities are defined separately
  - Deep dose (Hp(10); 10 mm deep)
  - Surface dose (Hp(0.07); 0.07 mm deep)
  - Eye dose (Hp(3); 3 mm deep)
- Measurement quantities give good estimate of equivalent dose for skin and eye and deep dose -> effective dose

-> Dosimeter

Thermoluminescense dosimeter

- Radiation excites electrons in a LiF crystal to trapped states in the lattice.
- When the crystal is heated those trapped states de-excite by emitting visible light. Intensity of light is proportional to radiation dose that the crystal has received.
- One time readable!
- Usage as personal and finger dosimeter.

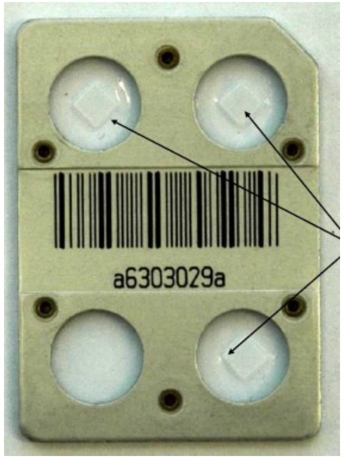
TLD dosimeter

TLD-100:
LiF-crystals, 3 pcs

Deep dose
4.1 mm Teflon and
1.0 mm ABS-plastic

Surface dose
0,064 mm aluminised mylar foil

Used in energy discrimination
0.1 mm copper and
2.3 mm ABS-plastic



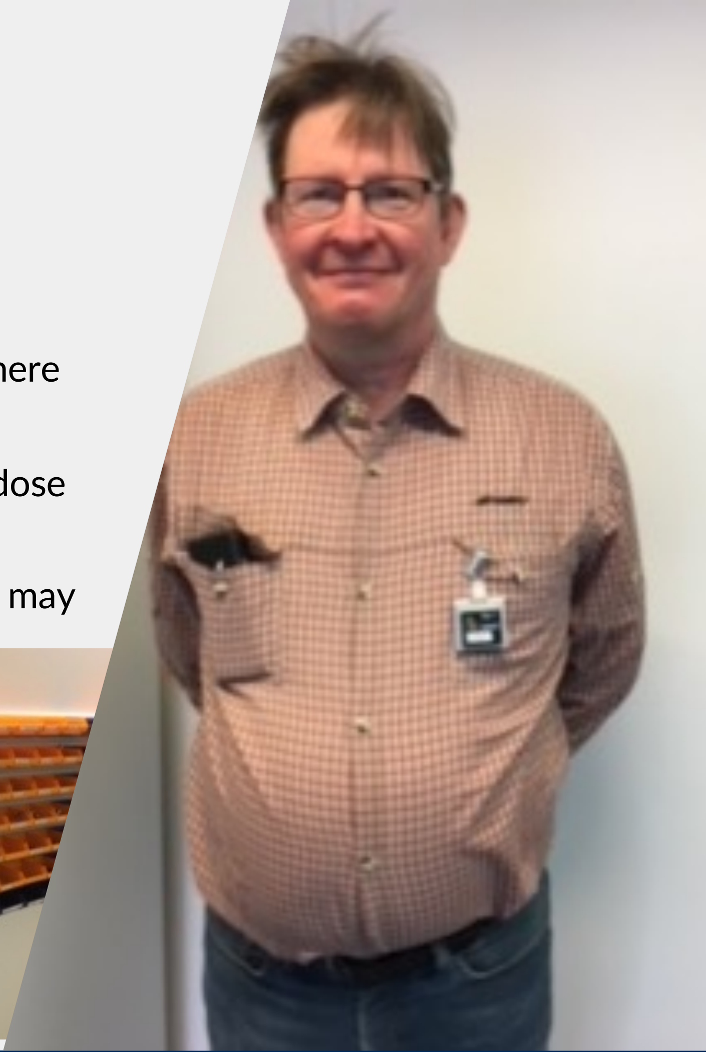
Internal plate

LiF-crystals

Photons and beta radiation 0.1 – 1000 mSv
Photon: Hp(10) and Hp(0.07); 20 keV – 1.3 MeV
Beta: Hp(0.07); 0.8 -2.3 MeV

Use of dosimeter

- Placing at the breast level, right way around (absorbers)!
- Storage at the boxes on the wall when not in use (this is the place where the background is determined).
- Be careful not to put your dosimeter to washing machine (recorded dose will be erased). In other words DON'T TAKE IT TO HOME!
- Don't keep the dosimeter in a pocket with keys etc. the thin window may get damaged.



JYFL accelerators (1)

- Cyclotron K=130 (Scanditronix, Uppsala).
  - Beams: from proton to gold (A=197).
  - Energy: about 10 MeV -> 1 GeV ; $E = (K\, q^2/A)$ MeV
- Cyclotron K=30 (MCC30/15; Efremov Institute).
  - Beams: proton, deuteron
  - Energy: p 18 – 30 MeV, d 9 – 15 MeV
- Pelletron 5SDH 2; Tandem-accelerator; (USA / VTT).
  - Beams: proton, helium, heavy ions Li -> U
  - Energy: $E = (n+1)eU$; n ion charge state, U terminal voltage (0,1 – 1,7 MV)

JYFL accelerators (2)

- Linear accelerator (Varian Clinac 2100 C/D)
  - Photons max 6 MeV and 15 MeV; maximum intensity 600 MU/min
  - Electrons 6, 9, 12, 16 and 20 MeV; maximum intensity 1000 MU/min
  - (MU Monitor Unit; 1000 MU corresponds 10 Gy)

- ECR-ion sources (JYFL)
  - The maximum energy of electrons in a plasma hundreds of keV -> 1 MeV.
  - Extraction voltage < 30 kV.
- Other ion sources (LIISA, Pellis)
  - Extraction voltage < 20 kV.
- Isotope separator on-line and JYFLTRAP (IGISOL)
  - Extraction voltage < 40 kV.
- MARA electric deflector ± 250 kV.

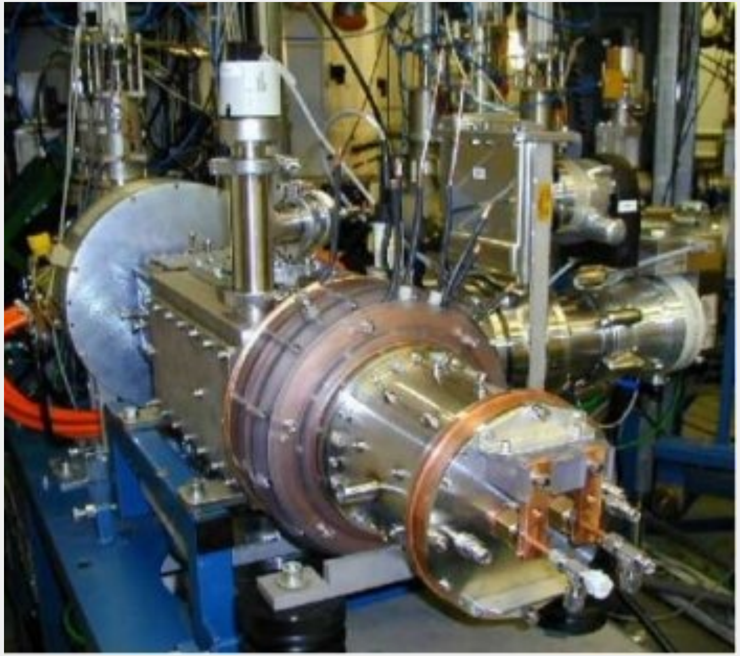
Cyclotron K=130

- Beams from proton to gold
- Energy: about 10 MeV -> 1 GeV ; $E = (K q^2/A)$ MeV;
  q charge state of ions
  A mass number of ions

K130/ ECR1 6 GHz, ECR2 14 GHz, ECR3 18 GHz

Liisa(s) and Pellis

- K130/K30/Pelletron
- H^- and D^-
- Multicusp
- Extraction voltage < 20 kV



Radiation hazards in the accelator laboratory

1. Accelerated beam itself
2. Prompt secondary radiation induced by the accelerator beam
3. Residual radiation from activated parts
4. Activation of air and cooling water
5. X-ray radiation from accelerated electrons

Radiation hazards in the accelerator lab (1) – Accelerated beam

- *Accelerated beam*
  - Direct exposure must be always prevented; Ion beam can instantly drill through tissue!
  - Taking the cyclotron beam out of the vacuum volume requires always safety considerations.
  - Fortunately ion beam is stopped in a reasonable layer of metal (beam tube wall or wall of a vacuum chamber).

Example

– Consider proton beam with a cross sectional area of 1 cm^2, energy 30 MeV and intensity 50 μA.
  - In tissue beam is absorbed in 1 cm distance (mass about 1 g).
  - Let's estimate an upper limit for dose absorption rate:

$$\dot{D} = 50 \cdot 10^{-6} \frac{C}{s} \frac{1}{1{,}6 \cdot 10^{-19}} \frac{p}{C} 30 \frac{MeV}{p} 1{,}6 \cdot 10^{-13} \frac{J}{MeV} \frac{1}{0{,}001\,kg}$$

$$= 1{,}5 \cdot 10^{6} \frac{J}{kg\,s} = 1{,}5 \cdot 10^{6} \frac{Gy}{s} = 5{,}4 \cdot 10^{9} \frac{Gy}{h}$$

  - Dose rate is **immense!**

Radiation hazards in the accelerator lab (2) Prompt secondary radiation

- Directly created *prompt secondary radiation* (n and γ) is the next highest potential danger.
  - When colliding with matter high energy beam will generate nuclear reactions.
    - New charged particles and **neutrons** will be created.
    - Reaction products typically release excitation energy via emission of **gamma radiation.**
  - Dose rate due to prompt radiation can be **Sv/h** (without shielding).
  - Dose rate decreases immediately when the beam is switched off.
  - Radiation shields are typically concrete (several meters).

Radiation hazards in the accelerator lab (3)

- The third highest radiation danger is caused by so called ***residual activity/radiation***.
  - Ion beam can cause nuclear reactions when impinging on structures of the system. Reaction products are often unstable (radioactive); (p,xn) and (p,xα) -reactions.
    - E.g. ^{22}Na(2,6 a), ^{56}Co(77 d), ^{60}Co(5,3 a), …
  - Neutrons generate radioactive nuclides in large area far away from their origin; (n,γ) -reactions.
    - E.g. ^{64}Cu (13 h), ^{24}Na (15 h), ^{65}Zn (245 d), ^{60}Co(5,3 a) (Eu in concrete)
  - Dose rates can rise easily to tens of **mSv/h**.
  - Local shielding (Pb; e.g. power-FC)
  - Equipment design and operation important in minimising!
    - Select materials and minimise their amount.
    - Avoid hitting beamlines with the beam.

Table 4.2. Principal radioactive isotopes produced in accelerator structures by spallation reactions and their gamma dose rate constant (dose rate at 1 m per disintegration per second).

Isotope	Half-life	Decay mode	$fSv.h^{-1}.Bq^{-1}$ at 1 m
^{7}Be	53 d	EC	7.8
^{11}C	20 min	$ß^{+}$	140
^{18}F	1.8 h	$ß^{+}$	132
^{22}Na	2.6 y	$ß^{+}$	298
^{24}Na	15 h	$ß^{-}$	560
^{46}Sc	84 d	$ß^{-}$	283
^{48}Sc	1.8 d	$ß^{-}$	455
^{48}V	16 d	$ß^{+}$	397
^{51}Cr	28 d	EC	4.3
^{52}Mn	5.7 d	$ß^{+}$	326
^{54}Mn	303 d	EC	114
^{56}Co	77 d	$ß^{+}$	350
^{60}Co	5.3 y	$ß^{-}$	340
^{65}Zn	245 d	EC	76

Table 4.5. Isotopes that could contribute to accelerator radioactivity by thermal neutron activation. The dose rates at 1 m are per Bq of the active isotope and per g of the natural parent element irradiated to saturation in a thermal neutron flux of 1 $n.cm^{-2}.s^{-1}$.

Parent isotope	Natural (%)	σ (barn)	Active isotope	Half-life	$fSv.h^{-1}$ at 1 m per Bq	$fSv.h^{-1}$ at 1 m per g
^{23}Na	100	0.53	^{24}Na	15 h	560	7.7
^{40}Ar	99.6	0.61	^{41}Ar	1.8 h	150	1.4
^{44}Ca	2.0	0.70	^{45}Ca	165 d	–	–
^{50}Cr	4.3	17	^{51}Cr	28 d	4	0.04
^{55}Mn	100	13	^{56}Mn	2.6 h	250	35
^{59}Co	100	37	^{60}Co	5.3 y	340	128
^{63}Cu	69	4.5	^{64}Cu	13 h	28	0.84
^{64}Zn	49	0.46	^{65}Zn	245 d	76	0.16
^{121}Sb	57	6.1	^{122}Sb	2.8 d	60	1.0
^{123}Sb	43	3.3	^{124}Sb	60 d	200	1.4
^{133}Cs	100	31	^{134}Cs	2.1 y	116	17
^{151}Eu	48	8700	^{152}Eu	12 y	45	750
^{153}Eu	52	320	^{154}Eu	8 y	286	190
^{186}W	28	40	^{187}W	1 d	73	2.6

Radiation hazards in the accelerator lab (4)

- The fourth most important potential exposure source is *activation of laboratory air or cooling water.*
  - Nuclides: ^{14}O (71 s), ^{15}O (122 s), ^{13}N (10 min) and ^{11}C (20 min) these are produced only in direct interaction of proton beam with air or cooling water.
  - Primary beam is not usually taken to the air.
  - ^{41}Ar (1.8 h), is produced in the air via: $^{40}Ar+n_{th}$
  - Closed cooling water circulation to eliminate the effect of induced activity (K130: extraction and beginning of the beam line, MCC30).

Table 4.10. Principal radioactive isotopes produced in air and water. All β^+ emitting isotopes are assumed also to emit 2×0.511 MeV photons.

Isotope	Half-life	Emission beta/gamma	*k* gamma ($fSv.h^{-1}.Bq^{-1}$ at 1 m)	Production cross section(mb) N	Production cross section(mb) O
^{14}O	1.2 min	1.8 MeV β^+ 2.3 MeV γ	450	–	1
^{15}O	2.1 min	1.7 MeV β^+	140	–	40
^{13}N	10 min	1.2 MeV β^+	140	10	9
^{11}C	20 min	.97 MeV β^+	140	10	5
^{7}Be	53 d	EC 10.3% 0.48 MeV γ	8	10	5
^{3}H	12.3 y	19 keV β	–	30	30
^{41}Ar	1.83 h	1.2 MeV β 1.3 MeV γ	150	Th n 610 mb in ^{40}Ar	

Radiation hazards in the accelerator lab (5)

- The fifth most important radiation danger is caused by *X-ray radiation* caused by electrons accelerated in different ways.
  - In the cyclotron and after it this radiation is hidden under other ionising radiation.
  - ECR ion source generates bremsstrahlung up to MeV energy (plasma). Thick Pb layer to shield (holes).
  - Pelletron generates X-ray radiation; shielded with Pb layer.
  - MARA electric dipole, sparking danger, ± 250 kV; sides shielded with Pb layer.

Reducing external exposure

Three principles:

- Minimize the exposure **time**
- Maximize the **distance**
- Use **shielding**

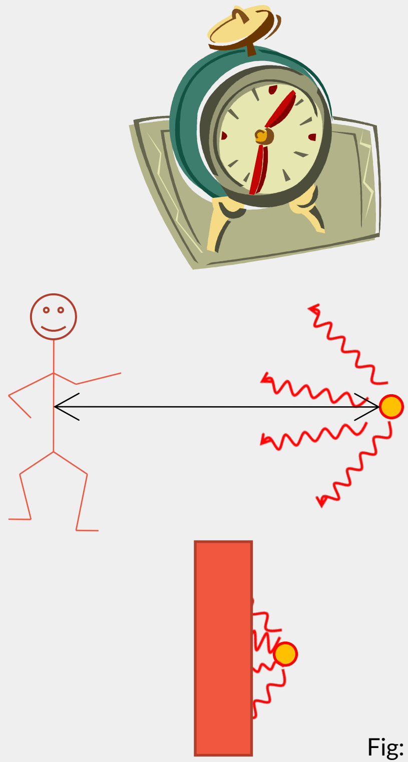
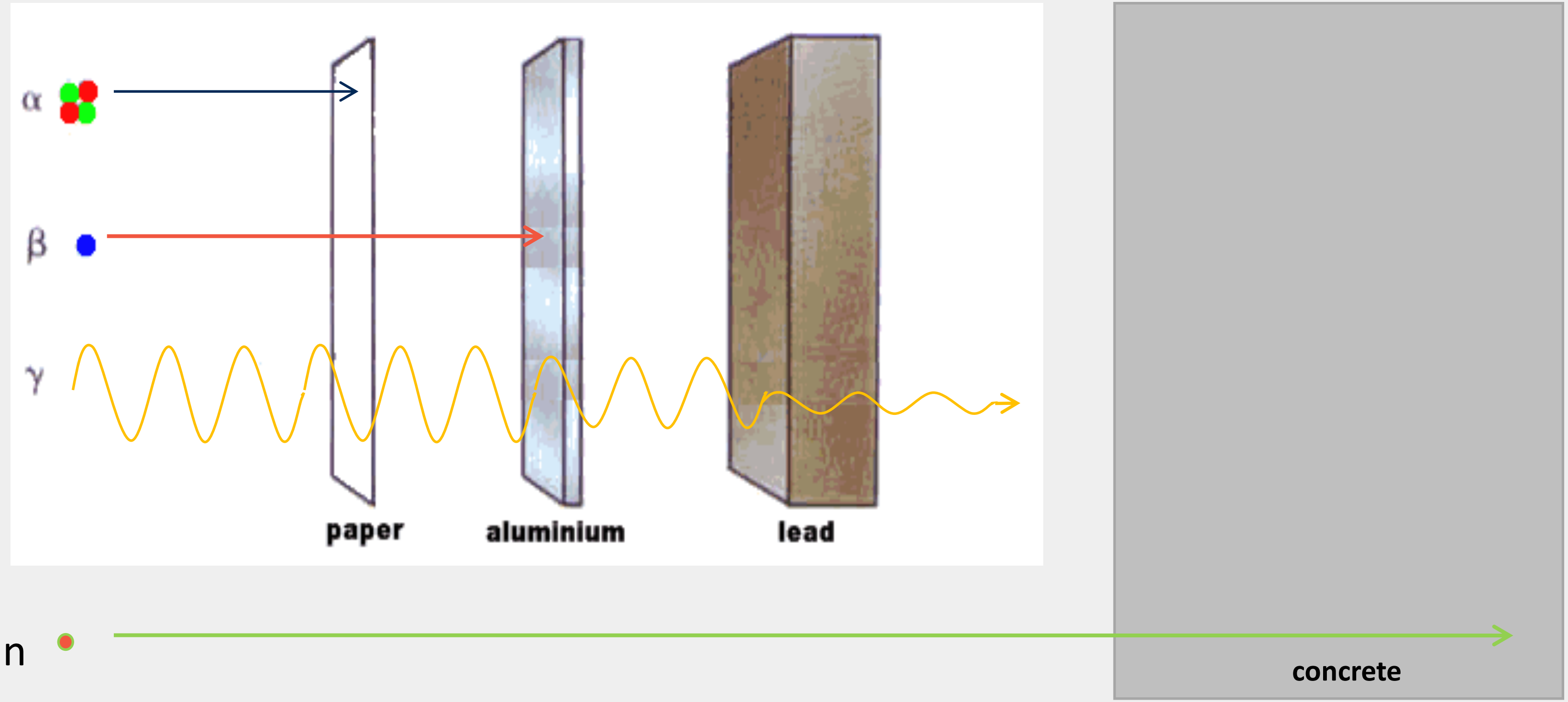


Fig: K.Helariutta, HYRL

Radiation shielding



Shielding

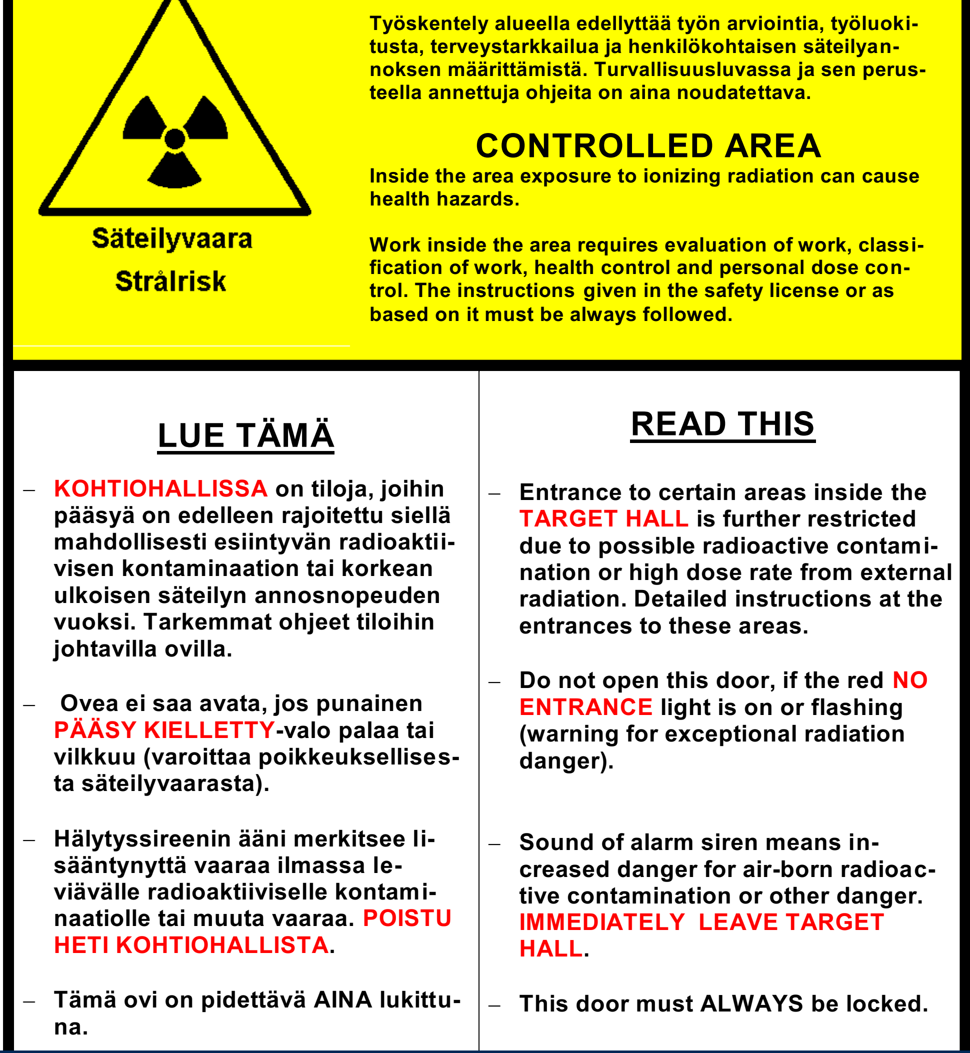
- As close to the source as possible –> minimize shielding material and possible activation
- Distance helps: $1/r^2$
- Any openings should have maze or chicanes to prevent radiation from escaping
- Lower pressure in rooms where air may be activated (ventilation)
- Separate water cooling circiut for water that might get activated
- Proper choice of materials and order of materials
  - Thermalization of fast neutrons first then capture, shielding of radiation released in n-capture, …
  - Best material depends on neutron energy (Plastic, Fe, ^{10}B, …)
- Concrete in general good shielding material for n and gamma (cheap, solid, contains H2O and heavier elements)

Radiation monitoring system

- Monitoring the working conditions in the radiation controlled area
- KATA gamma monitors
- Wedholm neutron monitors
- Part of the safety system of the accelerator
  - The beam is switched off if radiation level exeeds the set threshold, typically >0.5 uSv/h outside swept and closed areas
  - Sometimes false alarms
- Good to check levels also in the closed areas as high levels may tell that the beam is not going through optimally

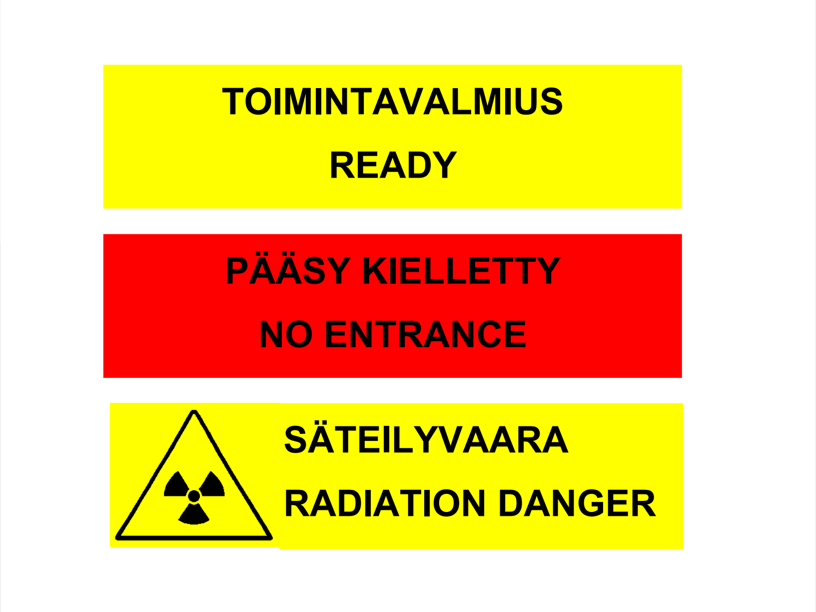
Controlled area

- Controlled access
- Personal dose monitoring
- No food or drinks
- High radiation areas markesd separately. General rule: Don’t access!

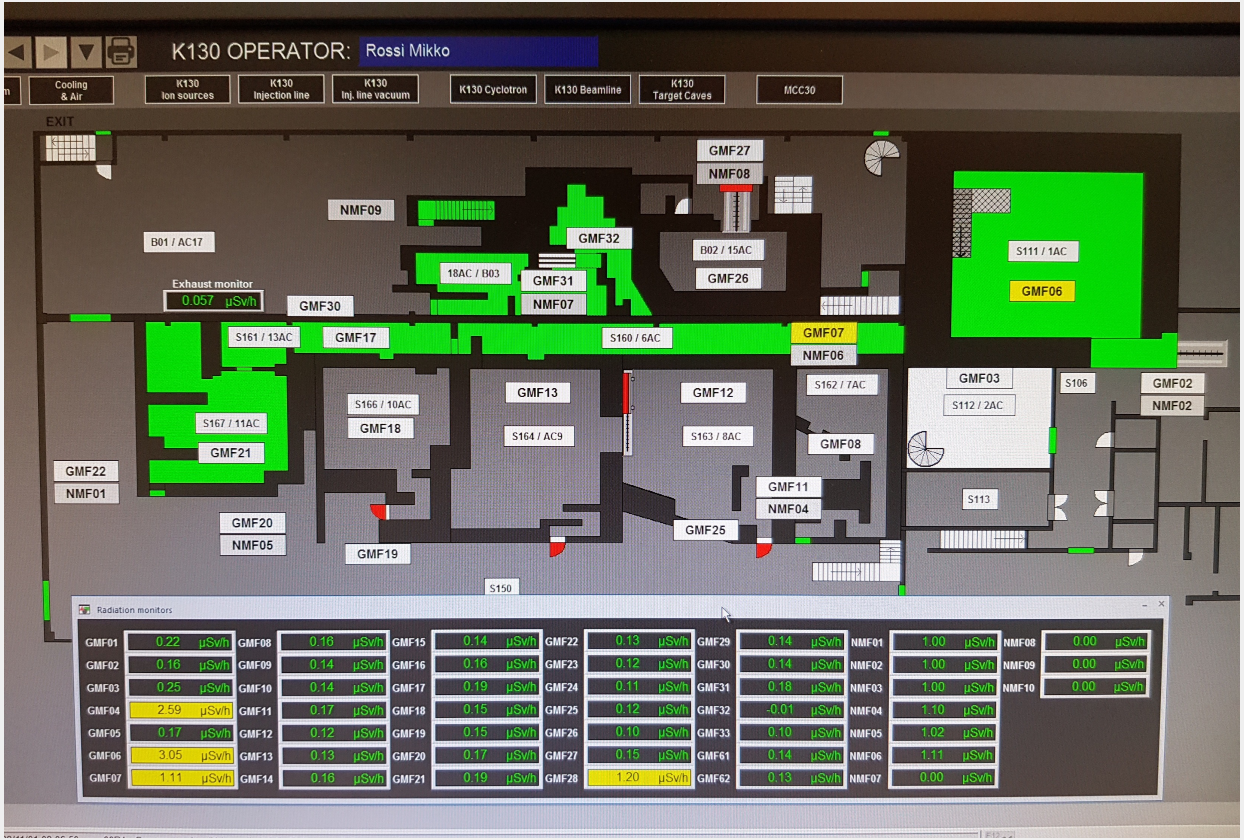


Access to radiation areas

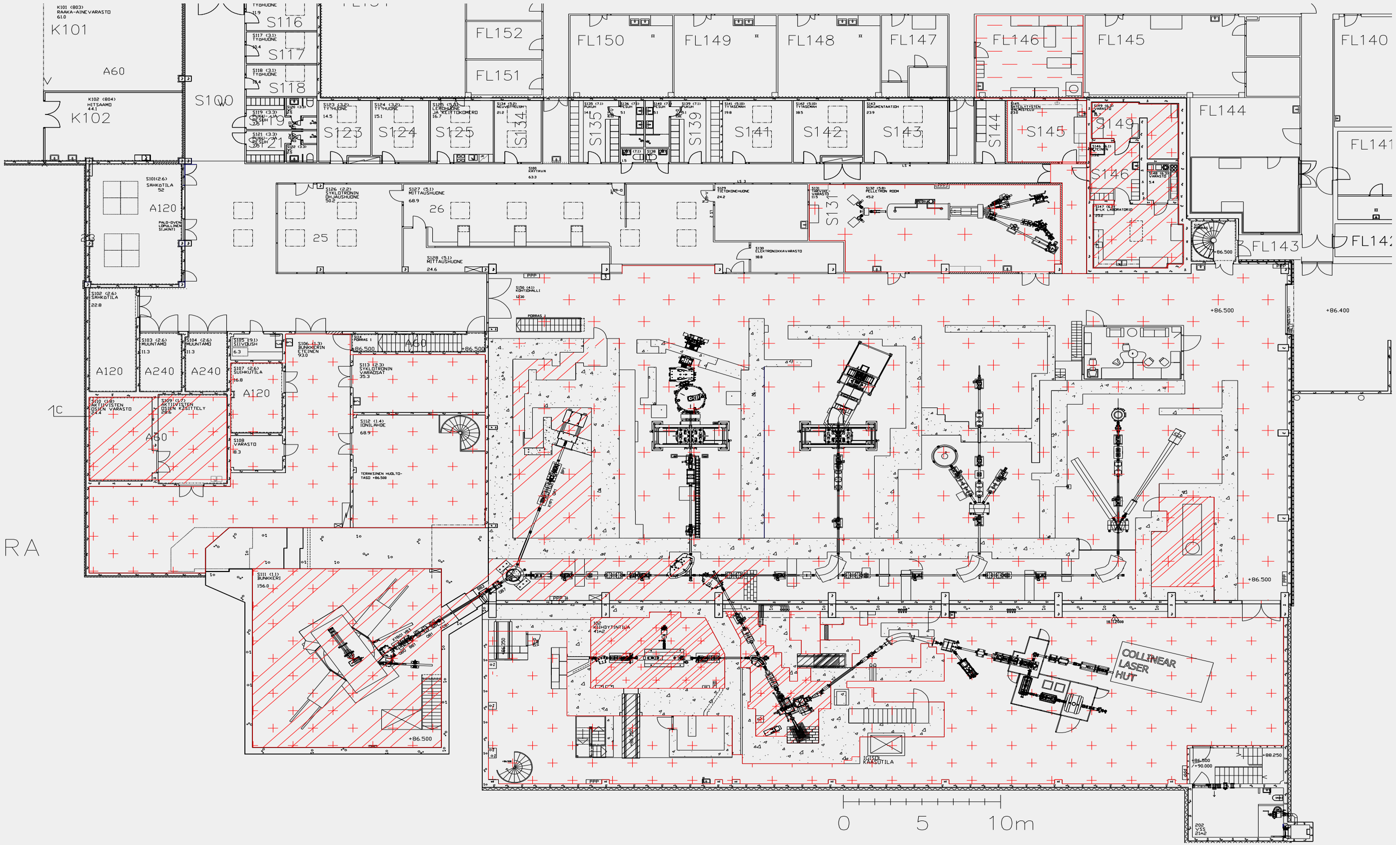
- Warning lights signal about closure status, equipment readiness and radiation danger.
- Red “No entrance” is lit when the area is swept and closed
  - Sweeping means that person closing the room/cave checks that nobody is left in
  - Sweeping sequence requires certain acknowledgement buttons to be pressed and doors to be shut
- “Radiation danger” light is on when dose rate inside is > 0,5 µSv/h
- When the room is swept and closed the safety system allows beam to be transported there



Control system safety view



1st floor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K102
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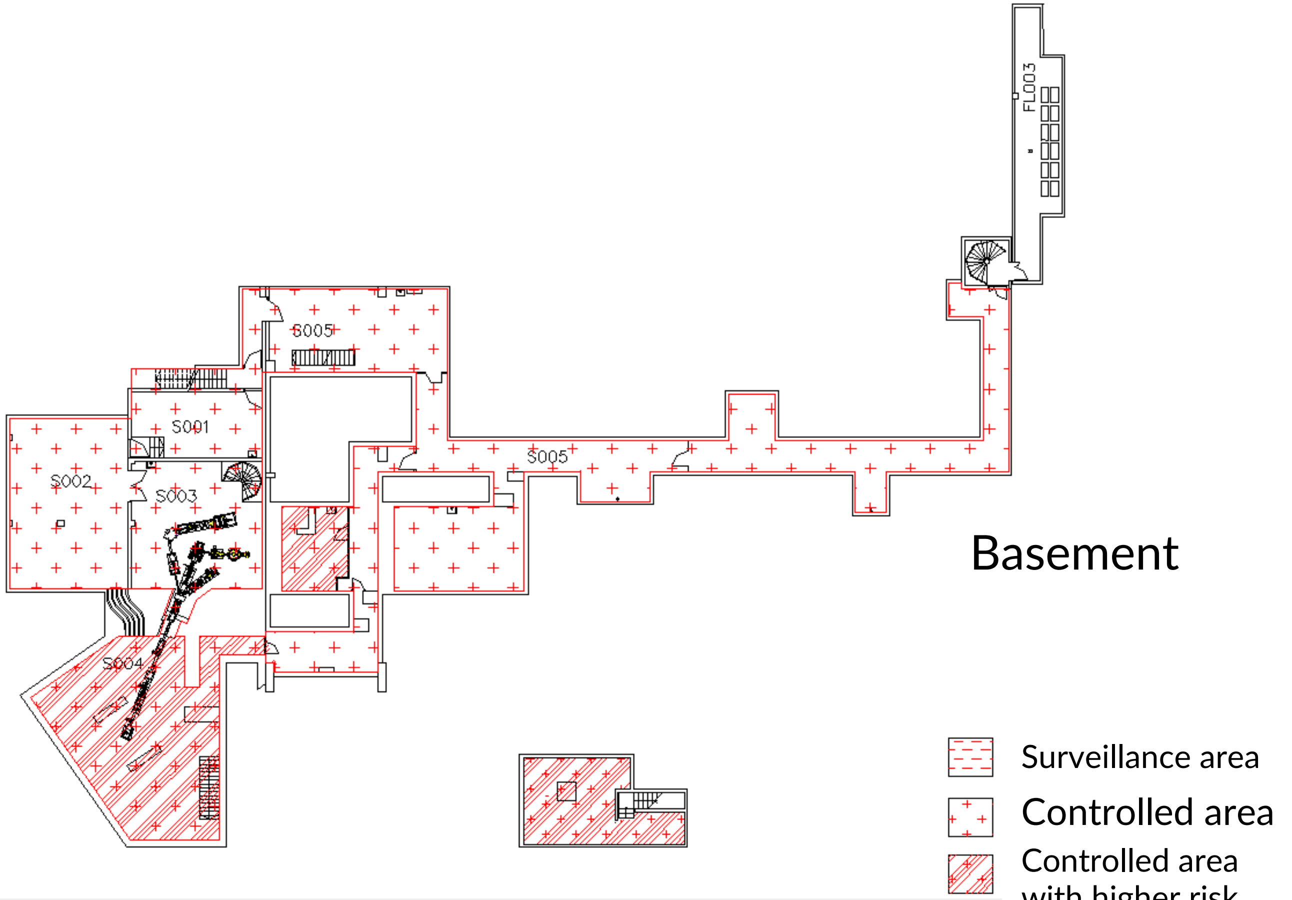
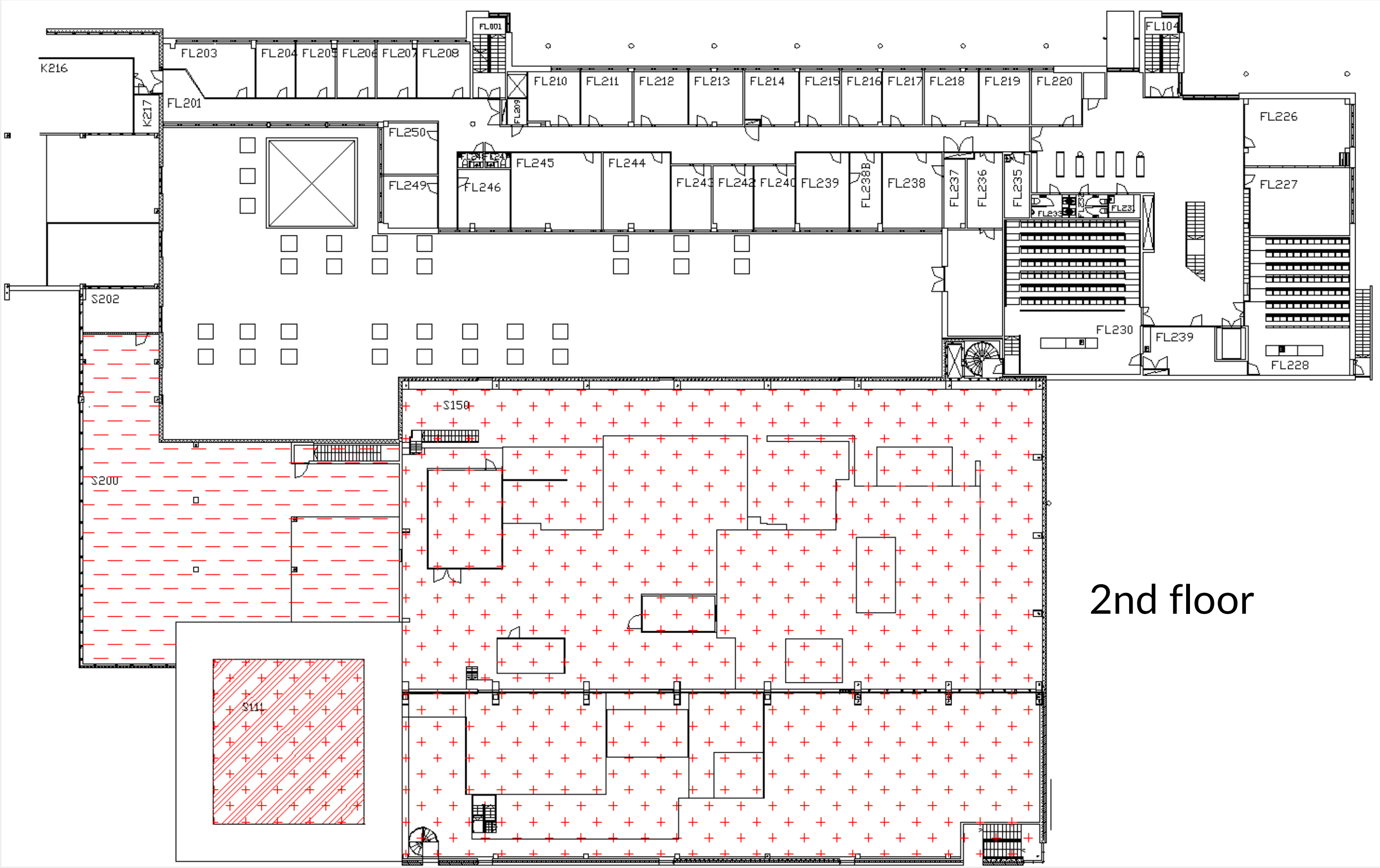


Basement

Surveillance area

Controlled area

Controlled area with higher risk



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FL236
FL235
FL230
FL239
FL228
S202
S150
S200
S111

2nd floor

Warning signs

- Signs and warning lights at the controlled area border
- Signs and/or warning lights at the equipment room doors
- Warning sign of

  ionising radiation:

  Must not be used needlessly!

Other dangers

- Magnetic and electric fields
- Laser equipment (S2 101-hall, Pelletron)
- Liquid nitrogen vessels and lines (S150, S2 101)
- Nitrogen gas
- Gas bottles
- Mechanical workshop
- Electrical workshop
- Crane lifting (only trained persons)

Fire

- Alert other people in the laboratory
- If the fire alarm is not on, press alarm button to strat it.
- Call 112 for help.
- It takes about 5 to 10 minutes for fire brigade to arrive.
- Shut down the system in the necessary extent. At least switch off the beam by pressing the emergancy switch on the control table.
- If possible try to distinguish the fire with portable fire distinguisher or fire hose. Do not risk yourself.
- Guide the fire fighters to the location

Oxygen alarm at MARA/RITU

In case of an oxygen alarm in the control system:

- Check from the CCTV MARA and/or RITU caves for possible problems or people in danger
- The area from which the alarm is coming must not be entered as there is a danger of losing consciousness and even death due to lack of oxygen
- Also the basement should be avoided if there is a liquid nitrogen leak in the MARA/RITU area as cold nitrogen tend to flow downsairs
- If somebody is seen collaped in the cave call 112.
- Try to stop liquid nitrogen flow from the main valve at the big tank or by pressing emergancy switch for detector filling system
- With two other persons at the door of the cave one can enter with a portable oxygen alarm to try to save person in danger in the cave

Operator’s responcibilities

- Starting from ion sources and ending to the beam delivery point at the research equipment. Research group takes care of their research equipment.
- To make sure that everybody has left the dangerous areas, the areas are closed and the control system of the accelerator has taken the area under surveillance in its safety system.
- To make sure that the conditions for safety of operation are met before starting the equipment.
- Operate the accelerator equipment according to the instructions and safety regulations.
- Make necessary notes related to the operation to the logbook.
- Make notes of the equipment failures, malfunctions, or other events that disturbed the operation or affected the radiation safety to the logbook and notify the radiation safety officer.
- At the change of operator inform the next operator about the necessary operation details.
- Find out in case of malfunction or danger as quickly as possibly the reason and meaning of the disturbance.

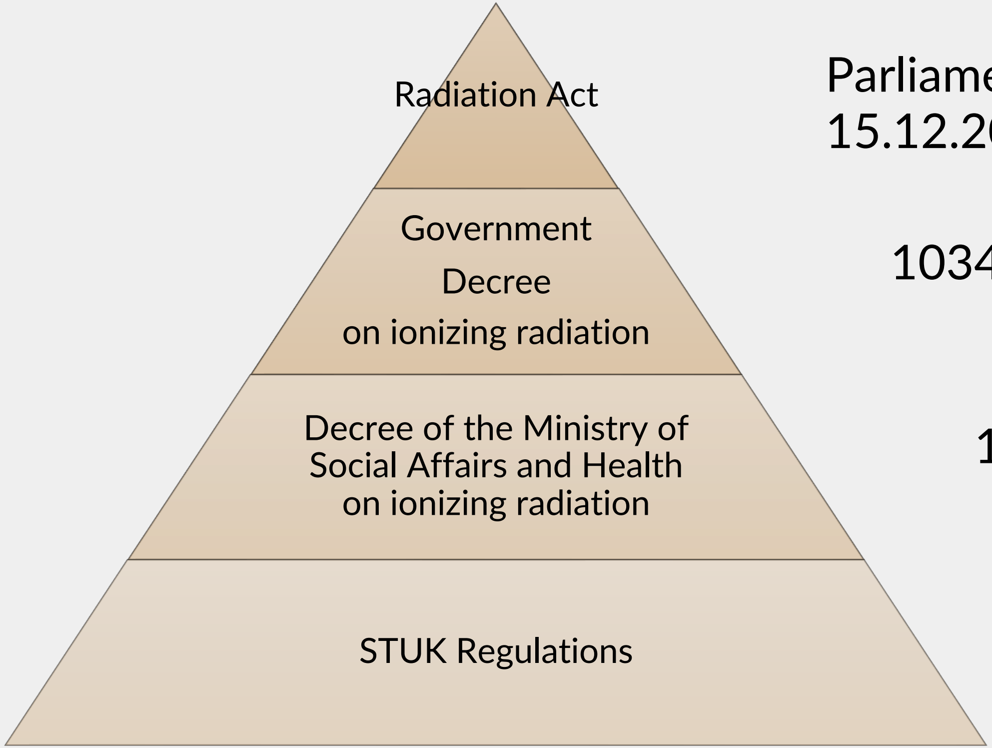
Operator's responcibilities 2

- Give the instructed alarms and alert the RSO at site if needed.
- In case of danger shut down the equipment in the extent demanded by the situation and lead the countermeasures until the RSO releaves him/her.
- Verify that the beam is off if the safety system alerts about loss of area closure and confirm the reclosure before redirecting the beam back to the area.
- Follow the shut down procedure instructed at the end of the use.
- Take cere of the safety according to instructions during the service and test use.
- Control the access to the controlled area.
- Report any disturbance or dangerous events to RSO.
- Report any deficiencies and suggest improvements to RSO in order to optimise the radiation safety.

Further information

- www.stuk.fi pages links to radiation act, radiation decree and regulations (in Finnish)
  - ’For professionals’ section is meant for the users of radiation
- Sammio is STUK’s search engine to legistlation sammio.stuk.fi
- In Finnish: http://www.stuk.fi/julkaisut/sateily-ja-ydinturvallisuus-kirjasarja
  - Includes 7 parts (ionising and non-ionising radiation)
  - References to ST-instructions partly outdated –> check from the new act, decrees and regulations.

Legislation related to use of radiation



Parliament enacts,
15.12.2018 new act 859/2018

1034/2018

1044/2018

New law: Regulations;
former RS guides not valid
anymore

Legislation related to use of radiation

- Radiation Act (859/2018)
  - General principles of radiation protection
  - Competent authority (STUK)
  - Liability and responsibility of the operator
  - Safety licence system
  - Principles of protection of workers
  - Registers of STUK
  - Inspection rights
  - Enforcement and sanctions
  - General requirements for different activities (radiation sources, medical use, non-ionizing radiation, natural radiation, radioactive waste)

Licencing system

Radiation Act 48-54 §

- It is obligatory to have a license for use of radiation
- License is granted by STUK based on written application

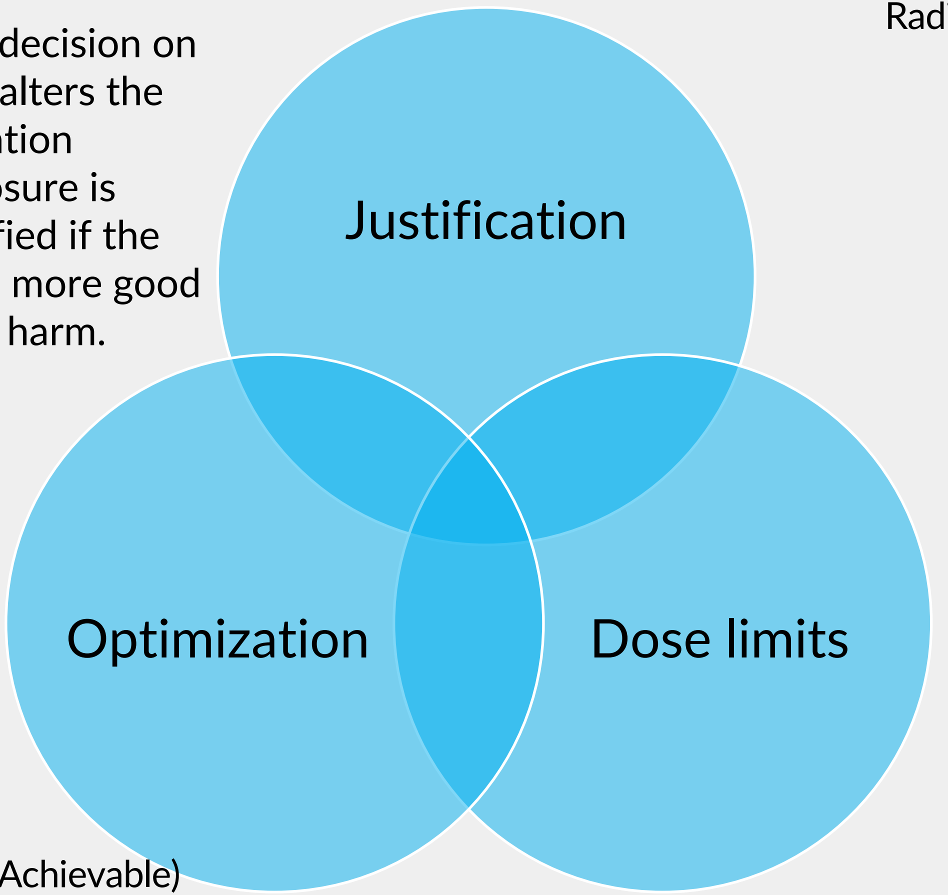
Principles of the radiation act (chapter 2) must be fulfilled:

- The Principle of Justification
- The Principle of Optimisation
- The Principle of Application of Dose Limits

Radiological protection general principles

Radiation Act 5-12 §

Any decision on that alters the radiation exposure is justified if the does more good than harm.



Occupational and public exposure to ionizing radiation should be as low as reasonably achievable (# of people, magnitude of individual doses)

ALARA-principle
(As Low As Reasonable Achievable)

Protection of individuals.
In planned exposure occupational and public dose must stay below the dose limit. (Gov Decree)

Operating organisation

- A person or organisation that uses ionising radiation
  - Applies for a safety licence for operation.
  - **Is responsible of safe operation. Responsibility is not transferrable. (RA 22 §)**
- University of Jyväskylä, Department of Physics
  - Safety licence No. 4294
  - Head of department (T. Sajavaara)
  - Head of accelerator lab (P. Greenlees)
  - Chief engineer (P. Heikkinen)

Other responsible persons

- Radiation safety officer RSO and radiation safety expert RSE (STV/STA)
  - S. Rinta-Antila,
    deputies P. Heikkinen / T. Kalvas
- All forepersons, group leaders
- Accelerator operators
- Members of research groups, users of radiation

- Persons in groups responsible of radiation sources:
  - J. Uusitalo, P. Ruotsalainan (RITU/MARA)
  - H. Penttilä (IGISOL)
  - H. Kettunen, M. Rossi (RADEF)
  - W. Trzaska (HENDES/LSC)
  - T. Sajavaara (Pelletron)
  - P. Heikkinen (Accelerator)
  - H. Koivisto (Ion source)
- X-ray tomography (J. Parkkonen)
- Student laboratory (P. Ruotsalainen)

JYFL safety licence

- Particle accelerators
  - Use; Installation, service, repair and manufacturing
- X-ray tomography devices and X-ray tubes;
  - Use; Trade, import, export; Installation, service, repair and manufacturing
- Radioactive sources (sealed and open sources)
  - Use; Trade, import, export
- Radioactive substances (open sources)
  - Use; S146-149 rad chem, FL146 bio phys, FL307 student lab

- Nuclear matter (U/Th/Pu) related licences separately (Nuclear power act/Nuclear power act)

Duties of licence holder

- Follow **Legislation and regulations** in its practice.
- Valid **safety licence** for use of ionising radiation.
- Qualified **responsible persons** (RSO) are named and a **management system** is appropriate and functional. A **radiation safety expert** is available.
- **Risks** related to the practice are identified and being prepared for **radiation protection incidents** and **safety assessments** are done.
- **Quality assurance program** drafted and implemented.
- Safety of **workers and public** is controlled.
- **Radiation sources** are protected against damage, disappearance and illegal actions.
- Radioactive **waste** is appropriately taken care of.
- **Training/orientation and supplementary training** has been taken care of.
- **Notifications and reporting** to STUK has been done.
- Management approved mode of operation emphasizes safety (**safety culture and safety leadership**).

Radiation safety at the work place

- Estimation of the exposure
- Limiting the dose
- Classification of the areas (controlled and supervised area)
- Category for workers (A/B)
- Protection of external workers
- Supplying information and organising training
- Radiation protection of the public
- Preparation for abnormal incidents

Obligations of the worker

- Obeying instructions
- Act responsible way (pay attention to safety of others too)
- Responsibility of protecting fetus and child.
  - It is recommended that radiation worker informs the radiation safety officer about her pregnancy and breastfeeding as early as possible

Radiation safety vs. security

Radiation safety

- Protecting workers and members of public
- Recording exposure
- Preparing for abnormal incidents
- Warning signs

Both

- Classification of areas
- Source records
- Safe construction of the sources
- Emergency and safety equipment
- Instructions
- Training
- Quality assurance

Security

- Physical barriers
- Access control using technical means
- Alarm systems
- Information security