BEL V

Belgian TSO

Cyclotron dismantling – International experience

Content

- Context-foreword
- Situation worldwide and in Belgium
- Characterization - elaboration of the radioisotopics vectors – streams segregation
- Second hand market - Decay
- Recycling – Final storage
- Sampling size - concrete activation
- Good practices
- Recommendations for new facilities
- Conclusions

Dismantling of low energy cyclotrons (≤ 30 MeV) Foreword

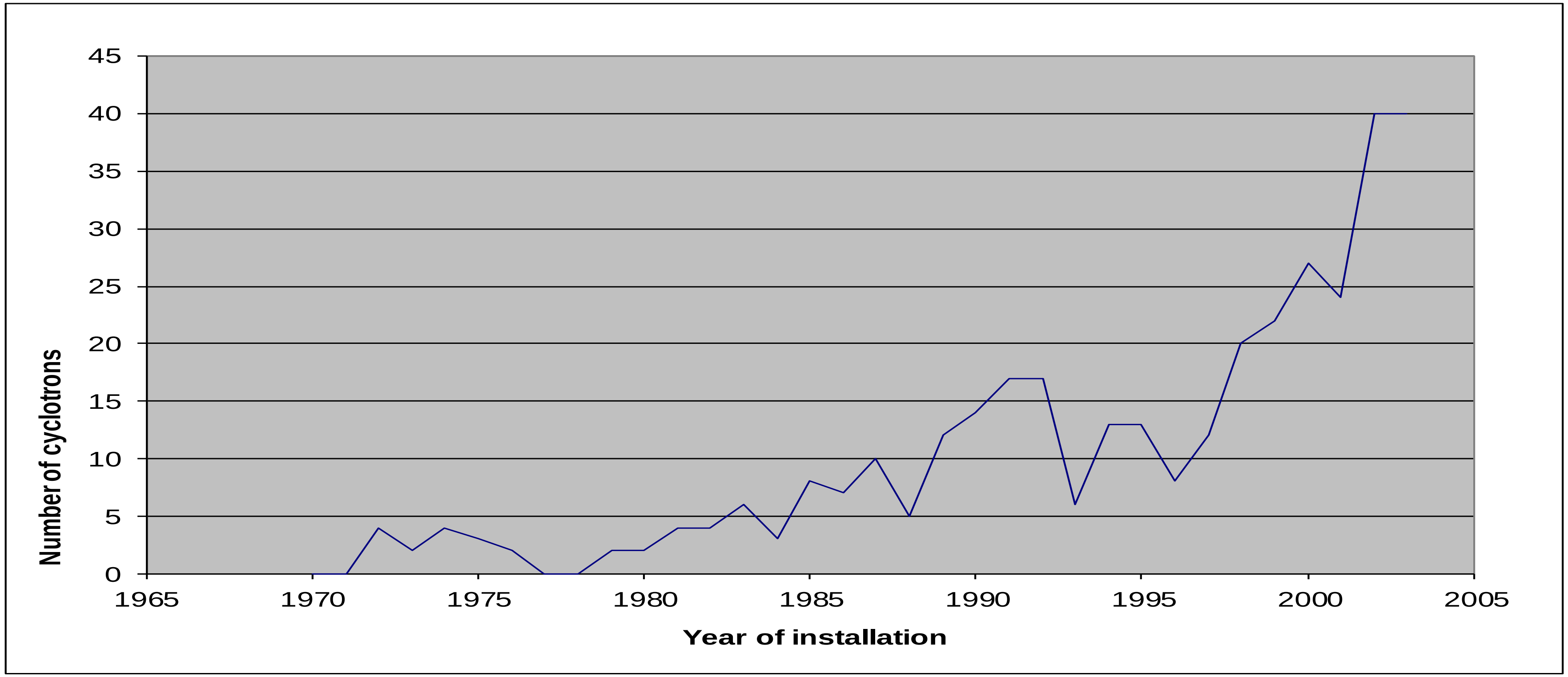
- **Bel V workshop (1, 2016):** Dismantling cyclotron, Application of international REX to Belgian situation
- **R&D program (2020):** Accelerator decommissioning
- **Eurosafe meeting (1, 2021):** Challenges raised by the dismantling of an accelerator used for radio-isotopes production
- **Mirdec meetings (5, 2021-2022):** Situation in Belgium, Situation-regulatory framework, Decommissioning of low energy cyclotrons in Belgium, Decommissioning of low energy cyclotrons (≤ 30 MeV).
- **IBA meetings (4, 2021-2022):** Situation-regulatory framework, Database construction, Concrete characterization-design improvments, Recycling fluxes (recycling rate > 95 % ?)

- **Protons accelerator of low energy (≤ 30 MeV) (can theoreticaly be extended to ≤ 70 MeV)**
- **International dismanting experience (no domestic file)**
- **Dismantling file, datas, scientific litterature survey**

IAEA, NW-T-2.9, Decommissioning of particle accelerator

IAEA, TRS 44, Decommissioning of small medical, industrial and research facilities

Situation worldwide



2002 : 246 cyclotrons.
2006 : 262 cyclotrons registred, 350 believed to be set up.
Since then +/- 50 machines are believed to be set up per year.
2022 : +/- 1300 accelerators
10 % market growth until 2025

IAEA Tecdoc-1007.
IAEA-Directory of cyclotrons used for radionuclide production in member states 2002.
IAEA-Directory of cyclotrons used for radionuclide production in member states 2006.
IAEA-Directory of cyclotrons used for radionuclide production in member states 2019.

Situation in Belgium

Localisation	Type of cyclotron
IBt > Bebig > Telix (Seneffe)	Cyclone-14+ (S0), Cyclone-14+ (S1)
UCL (LLN)	Cyclone-30, Cyclone-44 and 100 (LLN)
Erasme (Brussel)	Cyclone-30
Ulg (Liège)	Cyclone-18/9, CGR MeV
VUB (Brussel) UZB	CGR MeV, Kiube
KUL (Leuven)	Cyclone-18/9, Protheus 1, Protheus 2
UG (Gent) INW	Cyclone-18/9, CGR MeV
UZA (Antwerpen)	RDS 111
Onsf… (Fleurus)	Cyclone-30, CGR MeV
IRE-Elit (Fleurus)	Cyclone-AE
St Luc (Woluwe)	Cyclone-18/9

+ Kiube Ulg (IBA), Proteus 1 Charleroi (IBA), Ikon 30 IRE (IBA), Smart IRE (ASML), Ac 225 SCK (IBA), Minerva SCK
+ Cyclone « Key » (IBA) ?, « Mini trace » (GE) ?

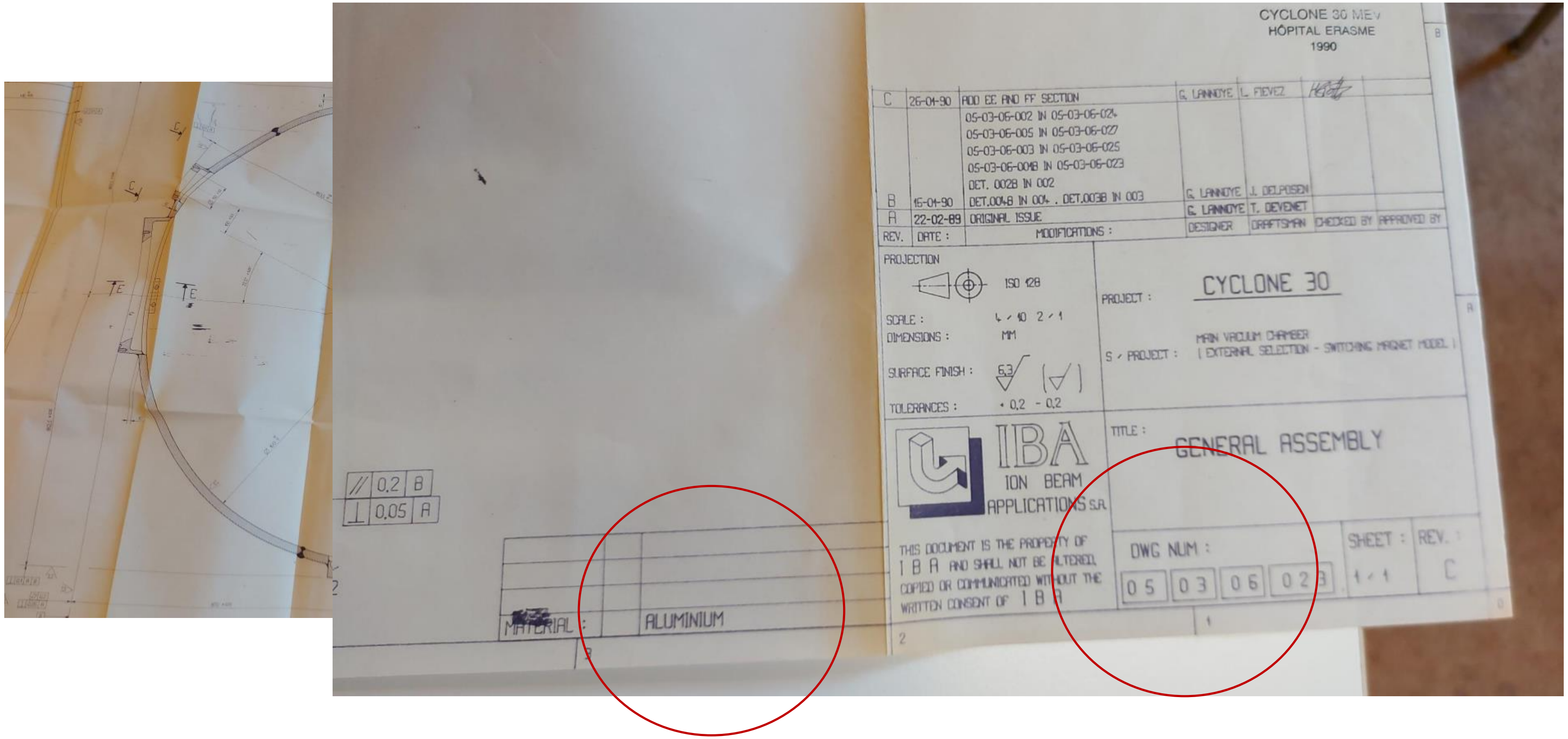
Decommissioning of low energy cyclotrons (≤ 30 MeV)

Material <>Activation

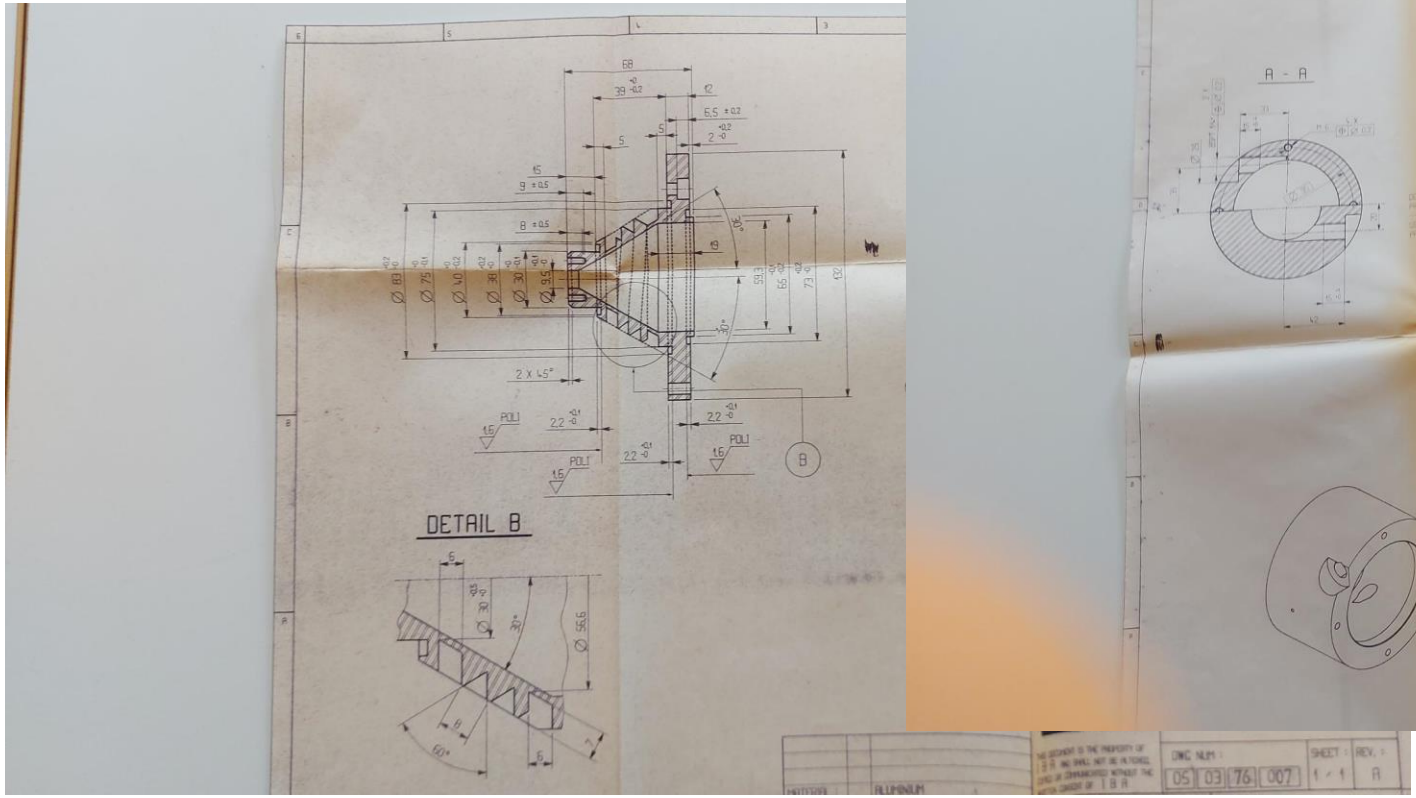
Al (4-10 %), Steel (82-84 %), Cu (8-10 %), Polymers, concrete

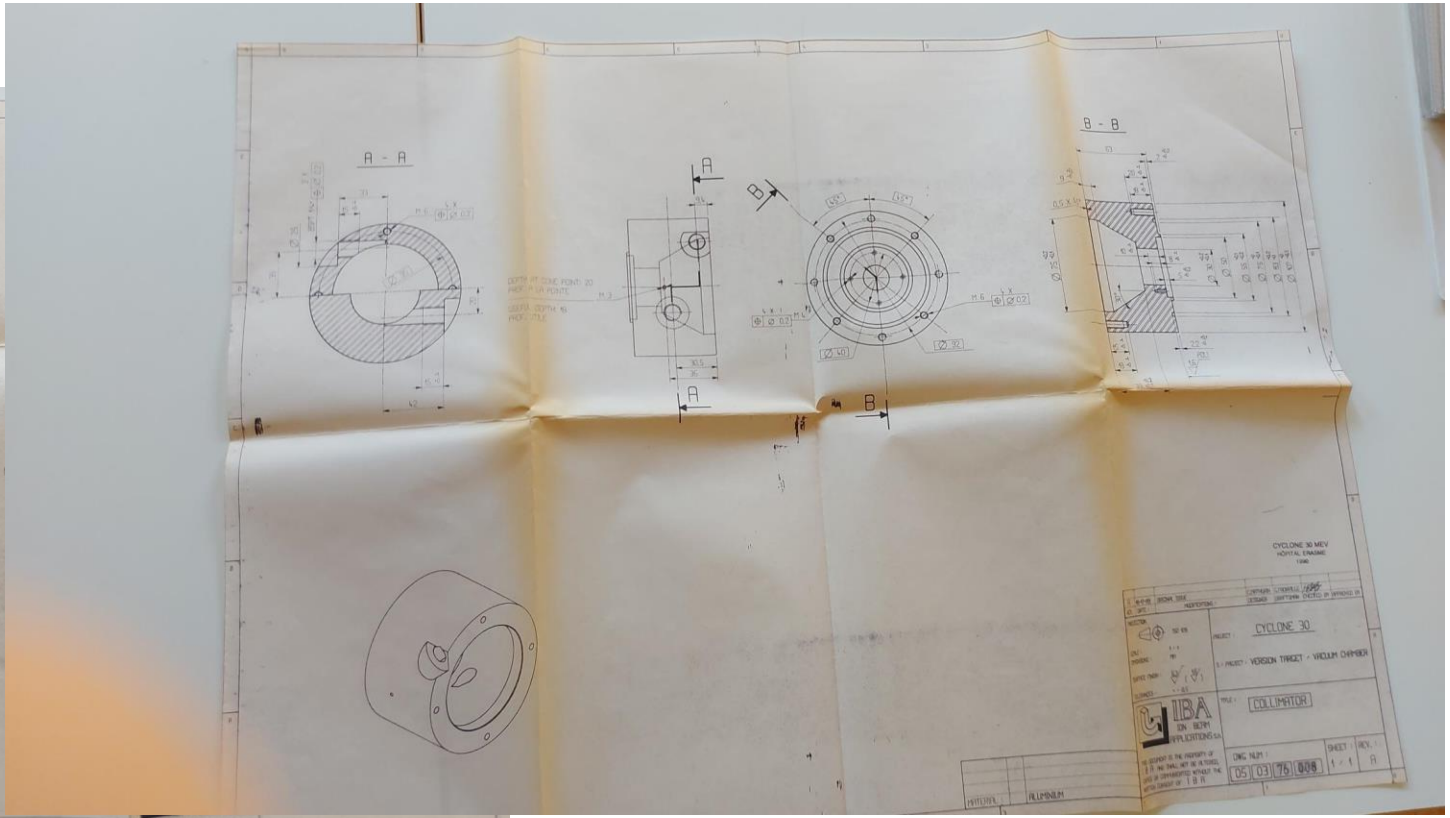
	Material	Primary beam (protons)	Secondary beam (neutrons)
Yoke	Steel		X
Sector	Steel	X	X
Beam line	Al	X	X
Ion sources	Cu	X	X
Dees	Cu	X	X
Coils	Cu		X
Collimator, stripper fork, …	Al	X	X
Bunker	Concrete, steel rebars		X
Isolation material	Polymers	X	X

Material traceability



Localisation of the sub systems > primary beam, secondary beam





Decommissioning of low energy cyclotrons (≤ 30 MeV)

Copper

Co-60, Ag-110m, Ni-65, Ni-63, Cu-64, Ag-110, Ag-108m, + …

Radioisotope	Co-60	Ag-110m	Ni-63	Ag-108m
Nuclear reaction	63Cu(n,α)60Co	109Ag(n,ɣ)110mAg	63Cu((n,ɣ)63Ni	107Ag(n,ɣ)108mAg
Quantification	0.1-20 Bq/gr	0.05-0.2 Bq/gr	0.5-100 Bq/gr	0.09 Bq/gr

Radioisotope	Co-60	Ag-110m	Ni-63	Cd-109	Ag-108m	Zn-65
Nuclear reaction	63Cu(n,α)60Co	109Ag(n,ɣ)110mAg	63Cu((n,ɣ)63Ni	109Ag(p,n)109Cd	107Ag(n,ɣ)108mAg	65Cu(p,n)65Zn
Quantification						

Calandrino R. et al., Decommissioning procedure and induced radiation levels, calculations and measurements in an 18 MeV medical cyclotron, Journal of Radiological Protection, 2021, Volume 41, 4.
Bonvin V. et al, Detailed study of the distribution of activation inside the magnet coils of a compact PET cyclotron, Applied Radiation and Isotopes, Volume 168, February 2021, 109446.
Calandrino et al, Decommissionng procedures for an 11 MeV self-shielded medical cyclotron after 16 years of working time, Health Physics, Volume 90, June 2006, 6.

Calculation code > Radioisotope vector benchmarking

BEL V
Belgian TSO

Radioisotope (RI)	Half-life (year)	Cross section (Barn)	Nuclear reaction
^{152}Eu	13,3	9198	$^{151}Eu(n,\gamma)^{152}Eu$
^{154}Eu	8,8	312	$^{153}Eu(n,\gamma)^{154}Eu$
^{60}Co	5,3	37	$^{59}Co(n,\gamma)^{60}Co$
^{134}Cs	2,1	29	$^{133}Cs(n,\gamma)^{134}Cs$

Eu-152 Co-60 H-3 Fe-59 Cr-51 Ce-141 Eu-154 Mn-54 Be-7 Na-22 Sc-46 Ba-133

RI	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
^{152}Eu	x	x	x	x	x	x	x	x	x	X
^{154}Eu										
^{60}Co	x	x	x	x	x	x	x	x	x	x
^{134}Cs										

Masaharu K., et al, Journal of Nuclear Science and Technology, Vol 39, N°3, pg 215-225 (march 2002), Correlation between H-3 and Eu-152 induced in various type of concrete by thermal neutron irradiation

Shiomi T. et al., Measurement of residual radioactivity of machine element and concrete on the cyclotron decommissioning, Journal of Nuclear Science and Technology, Supplement 1, March 200.

« Second hand » market or decay

Cyclotron type	Initial set-up place	Re export to	Decay
CS 22 (TCC)	Berkeley (US)	Beijing (China)	
CP 42 (TCC)	Houston (US)	Denton (US)	
Cyclone-10/5 (IBA)	Leuven (Belgium)	Vietnam	
MC 40 (SCX)	Minneapolis (US)	Bimingham (UK)	
Cyclone-18/9 (IBA)	Ulm (Germany)	Russia	
CS 30 (TCC)	Edimburgh (UK)	Aberdeen (UK)	
CS 30 (TCC)	Miami (US)	Shanghai (China)	
RDS 111 (Siemens)			Milano
Cyclone-18/9 (IBA)			Milano
MC 40 (SCX)			Hammersmith*

Carroll L., *et al*, Carroll & Ramsey Associates, Berkeley CA, USA, Decommissioning and recommissioning cyclotrons.
Carroll L.R., *et al*, Decommissioning and recommissioning cyclotrons, 9th International Workshop on Targetry and Target Chemistry, Turku, 2002.
Calandrino R. *et al*., Decommissioning procedure and induced radiation levels, calculations and measurements in an 18 MeV medical cyclotron, Journal of Radiological Protection, 2021, Volume 41, 4.
Calandrino *et al*, Decommissionng procedures for an 11 MeV self-shielded medical cyclotron after 16 years of working time, Health Physics, Volume 90, June 2006, 6.
*https://www.youtube.com/watch?v=LlSynde5fCI

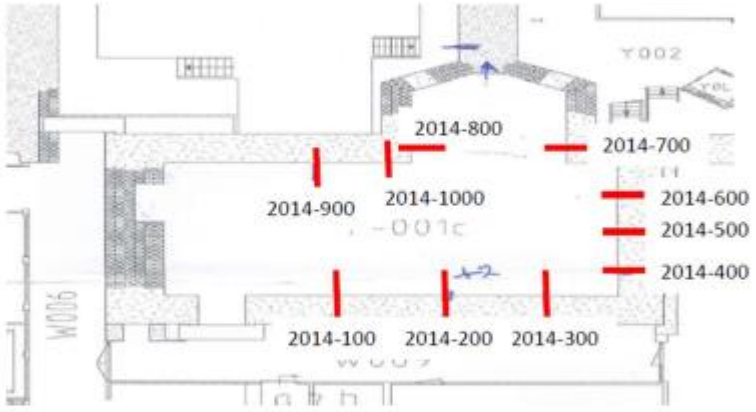
Decommissioning of low energy cyclotrons (≤ 30 MeV)

Recycling or final storage

- https://www.siempelkamp.com/en/products-and-technologies/nuclear-technology/
  - Cu, Al, Steel
- https://www.energysolutions.com/clive-disposal-facility/
  - Steel,
- https://www.studsvik.com/what-we-do/waste_mgmt_tech/waste_analysis/waste-repositories/
  - Steel
- https://www.cyclife-edf.com/cyclife/notre-marque/cyclife-une-marque-de-services-dediee/
  - Steel
- Polymers: unconditional release after mesurement (volumic measurement)
  - PP, PE, PEEK, PU, … : Ok.
  - PVC, electrical cable insulation material : Ok/Nok ?
- Final storage
  - Steel
  - Cu
  - Al
  - Polymers

Calculation code > Sampling size (> 40 cm) ?

Site	Cyclotron vault	Target vault 1	Target vault 2	Target vault 3	Target vault 4	Target vault 5	Total site	Average/vault
1	15	6	4	4	5		34	7
2	9						9	9
3	3						3	3
4	11						11	11
5	4	4	4				12	4
6	5	5	5	5	5	5	30	5
7	5						5	5
8	4	3	3				10	3



Van Driel A., et al, Cyclotron decommissioning-Vrij Universiteit Amsterdam, IRAP 2018.

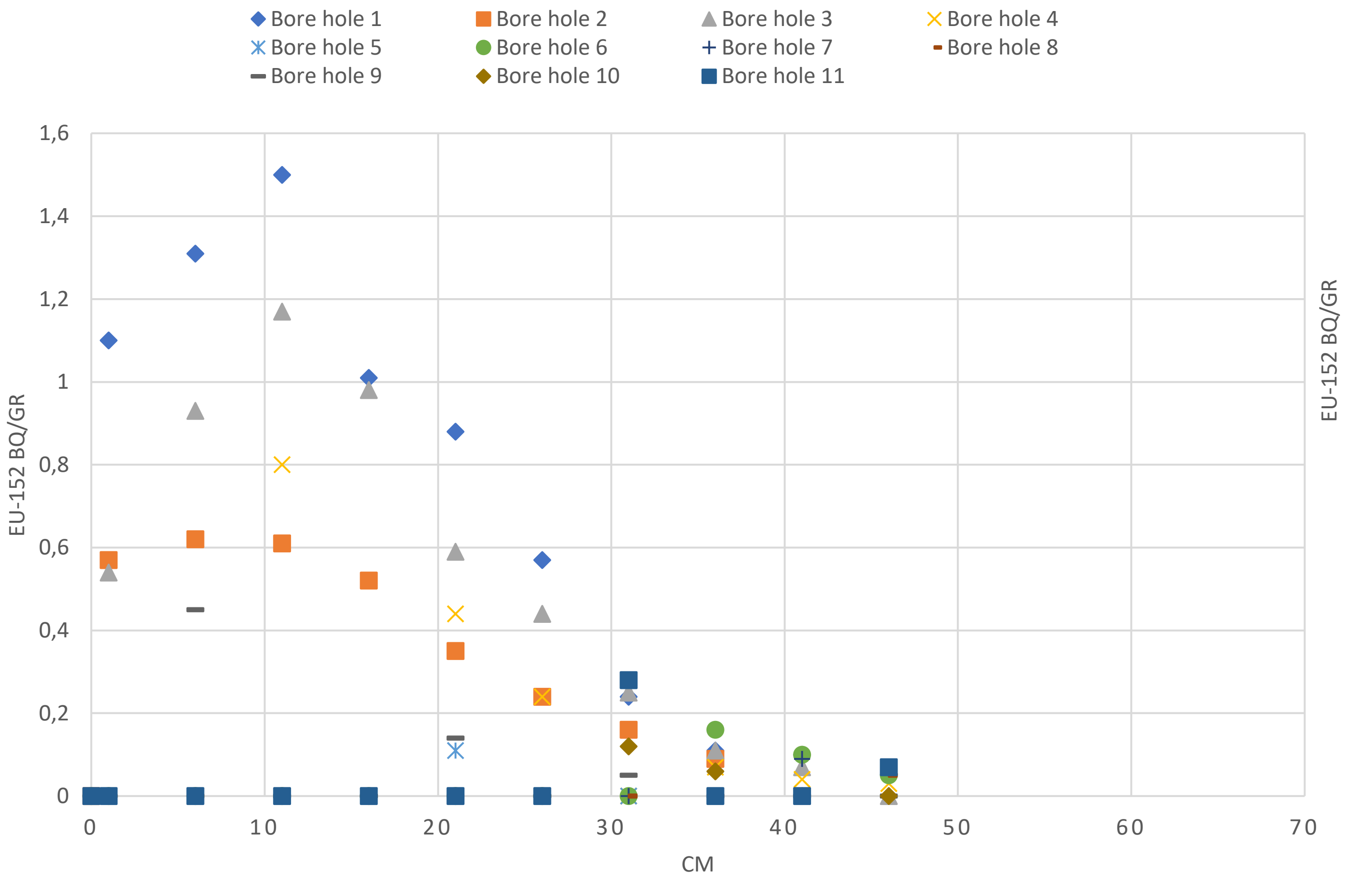
Neutrons energy (+/- = 10 MeV)

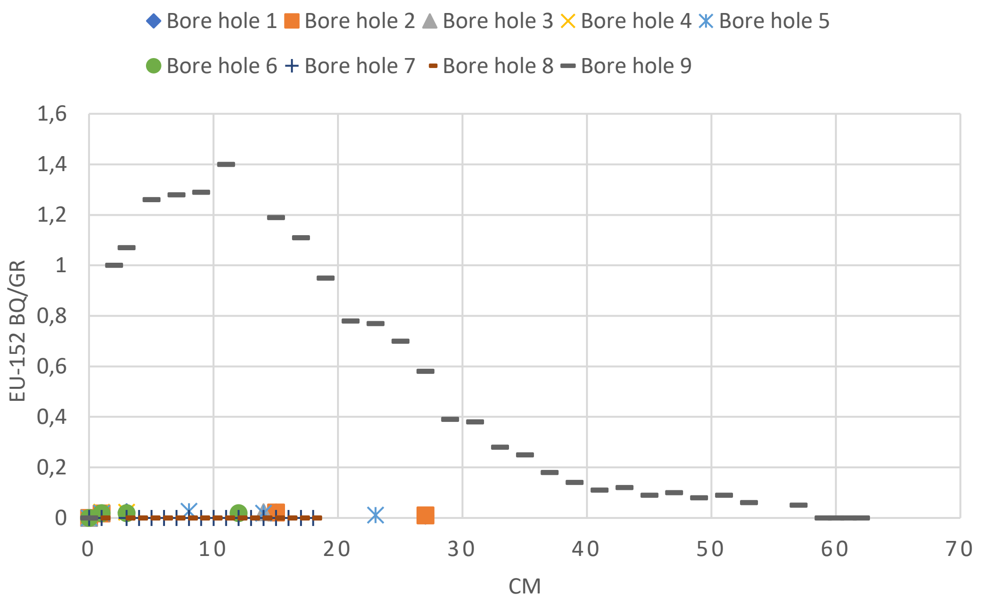
Site	Nuclear reaction 1	Nuclear reaction 2	Nuclear reaction 3	Nuclear reaction 4	Nuclear reaction 5	Nuclear reaction 6
1	203Tl(p,3n)201Tl	127I(p,5n)123I	59Co(p,2n)57Co	68Zn(p,2n)67Ga	Ga69(p,2n)68Ge	112Cd(p,2n)111In
2	203Tl(p,3n)201Tl	124Xe(p,2n)123I	59Co(p,2n)57Co	18O(p,n)18F		
3	103Rh(p,n)103Pd					
4	103Rh(p,n)103Pd					
5	103Rh(p,n)103Pd	18O(p,n)18F				
6	14N(p,alpha)11C	18O(p,n)18F	15N(p,n)15O	56Fe(p,2n)55Co	82Kr(p,2n)81Rb	
7	18O(p,n)18F	16O(p,alpha)13N	14N(p,alpha)11C	16O(p,pn)15O		
8	18O(p,n)18F	103Rh(p,n)103Pd	203Tl(p,3n)201Tl	78Se(p,2n)77Br		
9	59Co(p,2n)57Co	18O(p,n)18F	14N(p,alpha)11C	16O(p,alpha)13N	86Sr(p,n)86Y	16O(p,pn)15O
10	82Kr(p,2n)81Rb	203Tl(p,3n)201Tl	124Xe(p,2n)123I	18O(p,n)18F	68Zn(p,2n)67Ga	14N(p,alpha)11C
11	82Kr(p,2n)81Rb	18O(p,n)18F	14N(p,alpha)11C	14N(d,n)15O	78Se(p,2n)77Br	124Te(p,n)124I
12	18O(p,n)18F	16O(p,alpha)13N	14N(p,alpha)11C	16O(p,pn)15O	203Tl(p,3n)201Tl	124Xe(p,2n)123I
13	18O(p,n)18F	16O(p,alpha)13N	14N(p,alpha)11C	15N(p,n)15O		

IAEA TRS 468, Cyclotron produced radionuclides: Physical characteristics and production methods.

Neutrons energy (+/- = 10 MeV)

BELV Belgian TSO





Concrete streams

Concrete : Unconditional release, Conditional release, Radioactive waste.

Scenarios	Advantage	Drawbacks
Recycle 15 cm of the activated concrete	Controled recycling of concrete	Specialised demolition technique
	Separation of activated rebars	Time consuming and higher doses for the workers
		Final structure « still radioactive »
Recycle all concrete	Controled recycling of concrete	More difficult to separate activated and non activated rebars
	Final product has a concentration of < 0,1 Bq/gr Eu-152	
	Use of conventional demolition technique	
	Low exposure of workers	

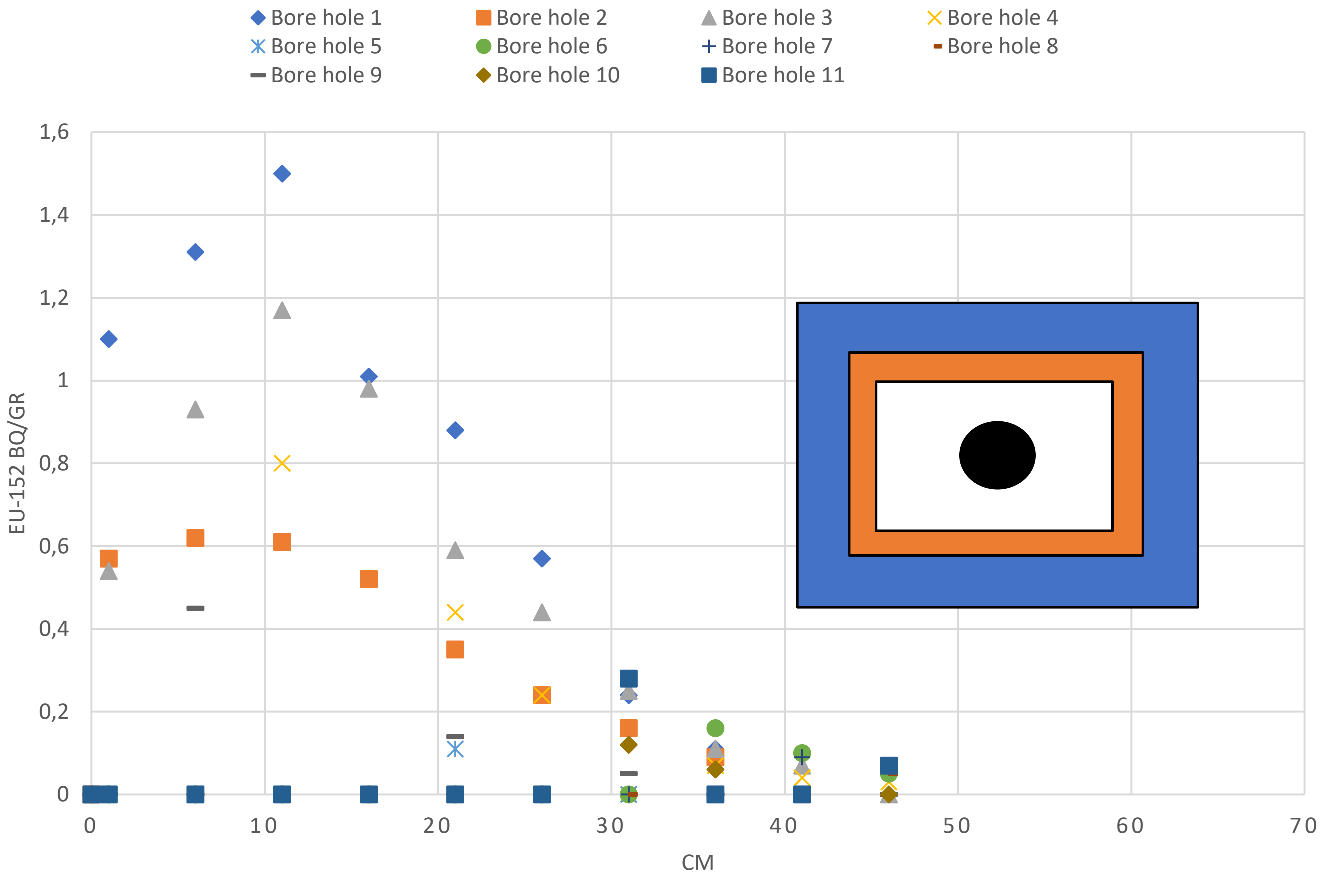
Van Driel A., et al, Cyclotron decommissioning-Vrij Universiteit Amsterdam, IRAP 2018

Reduction of beam loss by correctly tuning the beam

- Neutron activation study
- Transmission ratio ↑
  - Ion source (µA)/extraction mechanism (µA)
- Beam transport optimisation ↑
- Extraction ratio ↑
  - Extraction mechanism (µA)/target (µA)
- Vaccuum level ↓
  - Cyclotron off
  - Beam on

Milton B.F., et al, Commercial compact cyclotrons in the 90's, Proceedings of the 14th conference on cyclotrons and their applications, Cape Town, South Africa, 1995.

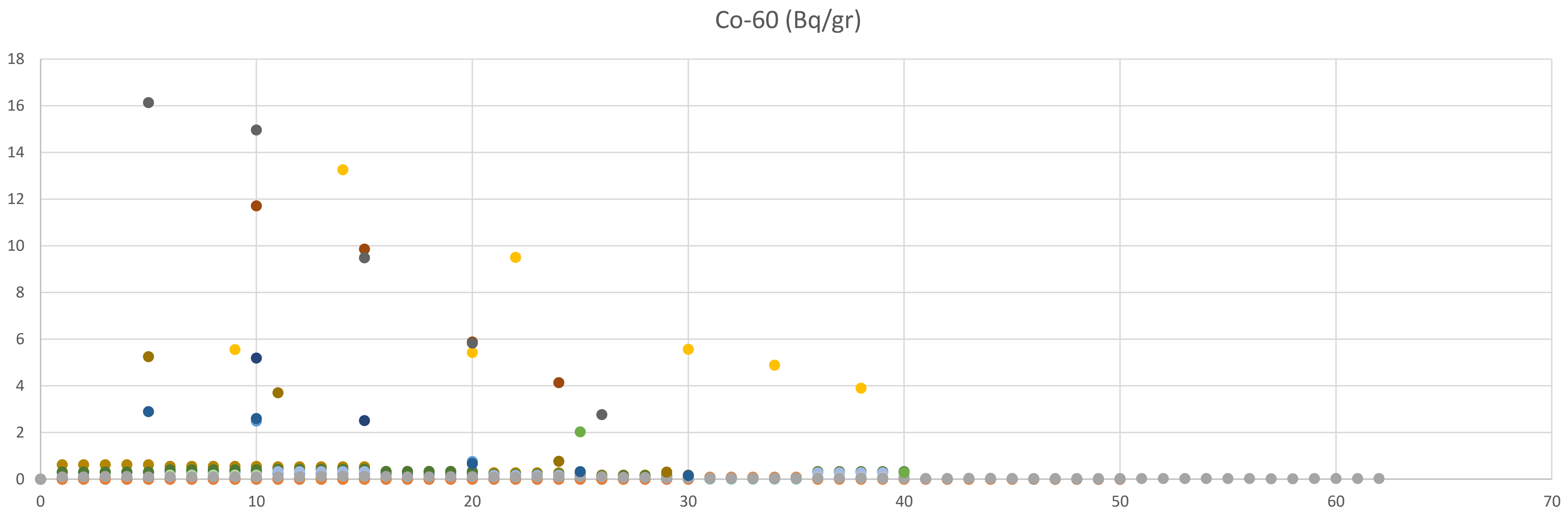
Facility design improvements (new site)



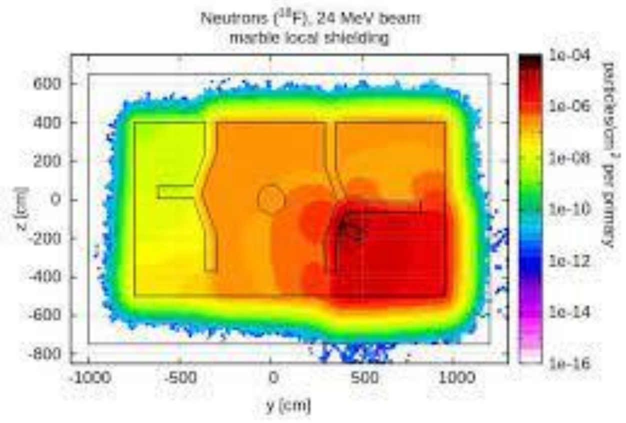
- LAC (Low Activation Concrete) inner layer, Fiberglass rebars structure instead of steel rod for concrete reenforcement (Co-60)
- Physical separation between the two concrete layers (LAC/rest)
- Removable bore hole with an harmonization of bore hole sizes (length 10 > 280 cm, diameter 4 > 7.4 cm, cutting position in depth 2 > 10 cm (n=65))
- Lego bricks
- Stable Eu concentration measurement

European Patent 3 266 754 A (Eu-152)
Kinno M., *et al*, Raw materials for low-activation concrete neutron shields, Journal of Nuclear Science and Technology, Volume 39, December 2002, 12.

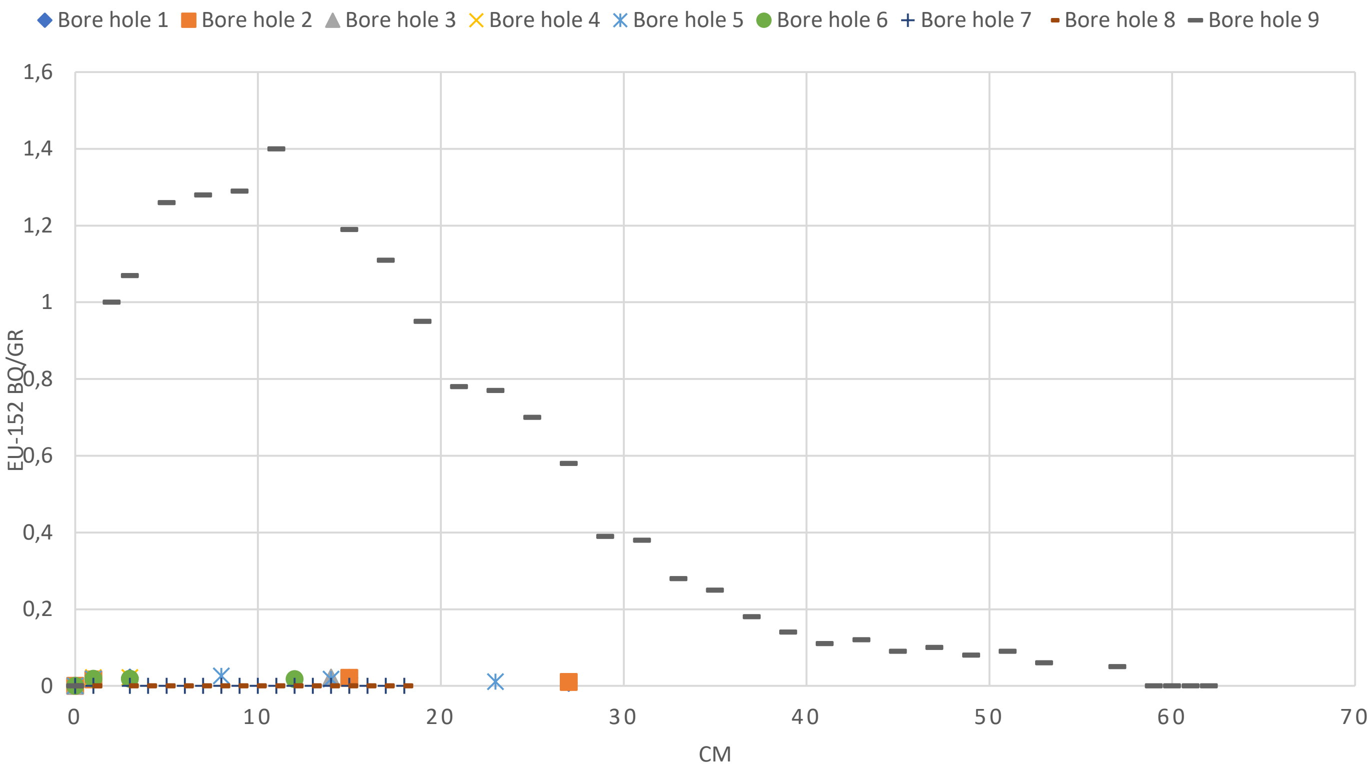
Facility design improvements (new site) – steel rebars



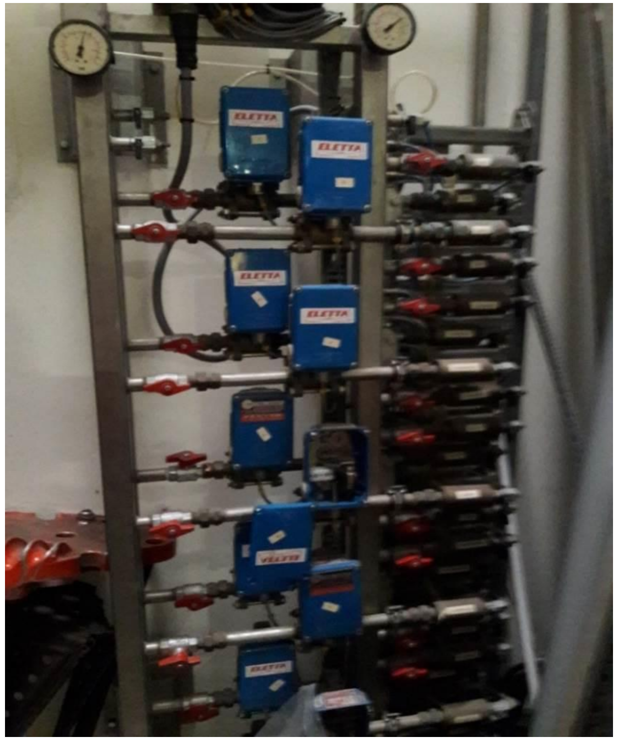
Optional advantages – sacrificial shielding (new site)



Asova G. et al, Status of simulation for the cyclotron laboratory at the institute for nuclear research and nuclear energy, IOP Conf.Series: Journal of physics. Conf.Series 1023 (2018) 012008, doi : 10.1088/1742-6596/1023/1/012008



Design improvements, cyclotron and auxiliary equipment (new site)



IMPROVED DESIGN SUGGESTION AUXILARY EQUIPMENT?

- General tools
- Dedicated tools for maintenance
- Water manifold
- Water pump
- Ion exchange resin
- Heat exchanger
- Waste pit
- False floor
- Addition of sacrificial shielding layer around the target
- …

Worldwide REX

	SCX MC 40	Argonne	Cyclone 30	RDS 111
D&D file	1 year	18 months	1 year	1 year
D&D field work	1 year	13 months	1 year	1 year
External dose	No problem occured	No problem occured	No problem occured	No problem occured
Dose rate of equipment			0-100 µSv/h-0.5 m 1 mSv/h contact	
Contamination	Residual risk	Residual risk	Residual risk	Residual risk
Mid term survey of the zone	Yes	Yes	Partial (set-up of a new cyclotron)	No
Classical risk	High	High	High	High

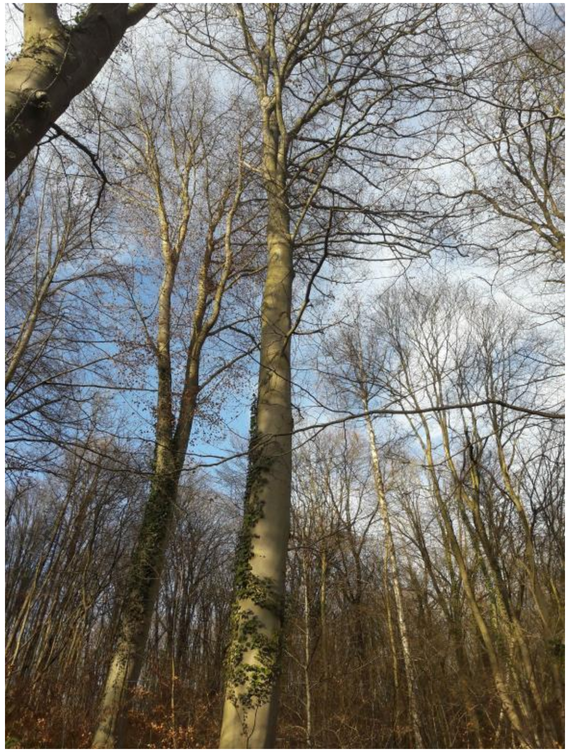
Bolt/unbolt, screw/unscrew, no cutting

A.Garcia, et al, Ansto Camperdown project public presentation.
P.Maharaj, et al, ARPS, Melbourne Decommissioning and dismantling of the national medical cyclotron – a radiation protection perspective.

Future-conclusions

- International survey (no domestic dismantling file)
- Development, publication of a guidance
  - Good practices, …
- Continuous data accumulation
  - Sampling size, sampling standardization (with AIEA ?);
  - Radioisotopic vector characterization, ...
- Relative cost estimation
  - Second hand market; transport;
  - Total or partial recycling; final storage, ...

Questions ?



CONTACT

Schmitz Frédéric

Project Manager

Frederic.schmitz@belv.be