Status of Cyclotron Laboratory at Institute for Nuclear Research and Nuclear Energy

- Project goals
- Cyclotron @ INRNE
- ^{18}F production & activation of components

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INRNE-BAS

Key Points about the Cyclotron Project

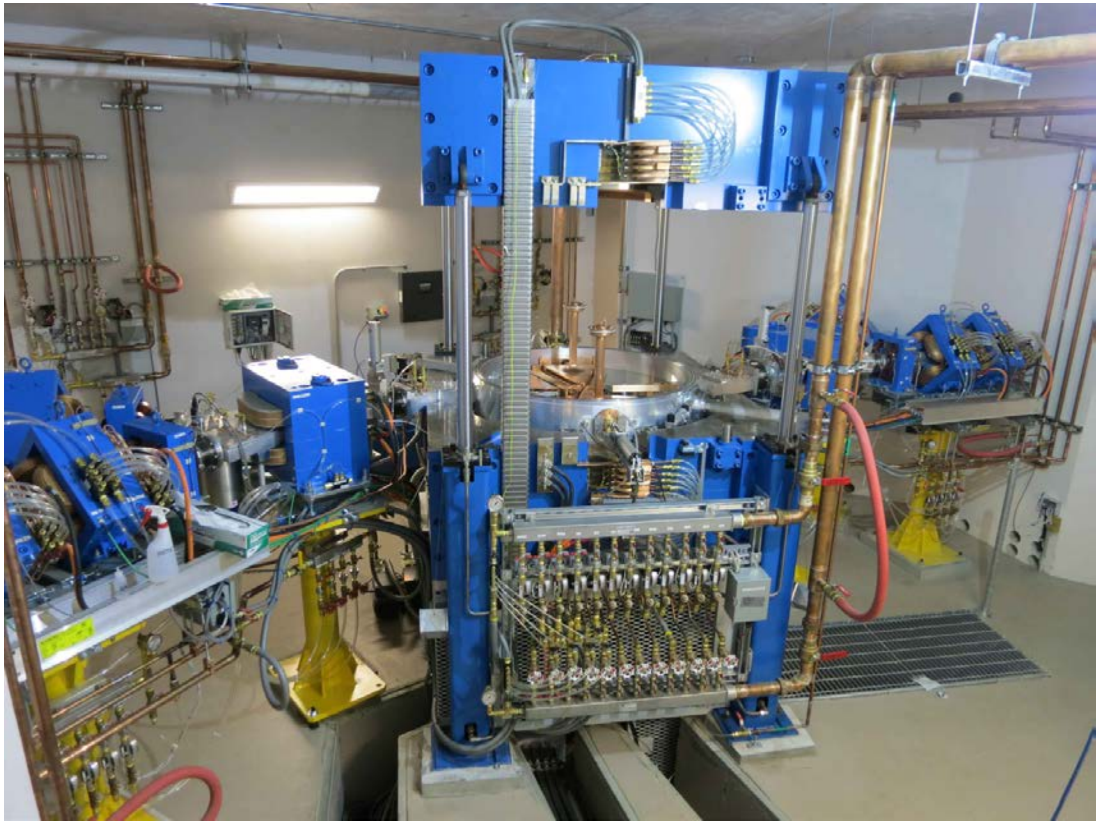
- A “green field” market oriented infrastructure for GMP production of medical radioisotopes and radiopharmaceuticals with major R&D activities in the fields.

- Enables high level fundamental and applied research with radioisotopes/radiotracers in life sciences, industry, pharmacy and medicine. A contribution of the nuclear and particle community to the other fields of science in Bulgaria.

- With basic capabilities for materials and electronics irradiation, beam diagnostics, detector testing, experimental equipment development.

- Training within the R&D program in radiochemistry, radiation protection, and experimental nuclear physics for the nuclear energy and radioactive waste management industry and nuclear medicine in Bulgaria.

TR-24, ACSI (EBCO), Canada



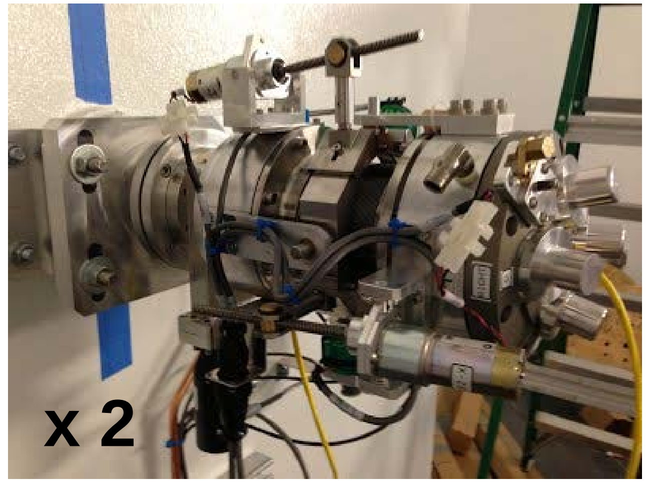
- Accelerates H- ions
- Extraction by stripping foils
- Beam Energy: 15 – 24 MeV
- Beam Current: 400 µA
- Upgradeable to 1 mA

- Dual Beam Extraction
- External CUSP ion source
- Turbomolecular and cryo vacuum pumps
- Vacuum: 5.10-7 – 10-6 Torr

PET: ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{124}I, ^{64}Cu, ^{68}Ge

SPECT: ^{123}I, ^{111}In, ^{67}Ga, ^{57}Co, ^{99m}Tc

Beamlines, targets and target stations for PET&SPECT radioisotopes production



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Financial Support for the Project

“АЕЦ КОЗЛОДУЙ” ЕАД
KOZLODUY NPP PLC

Donations from DOE of USA and Kozloduy NPP.

Government support

Business plan showing the feasibility of such a facility (2015).

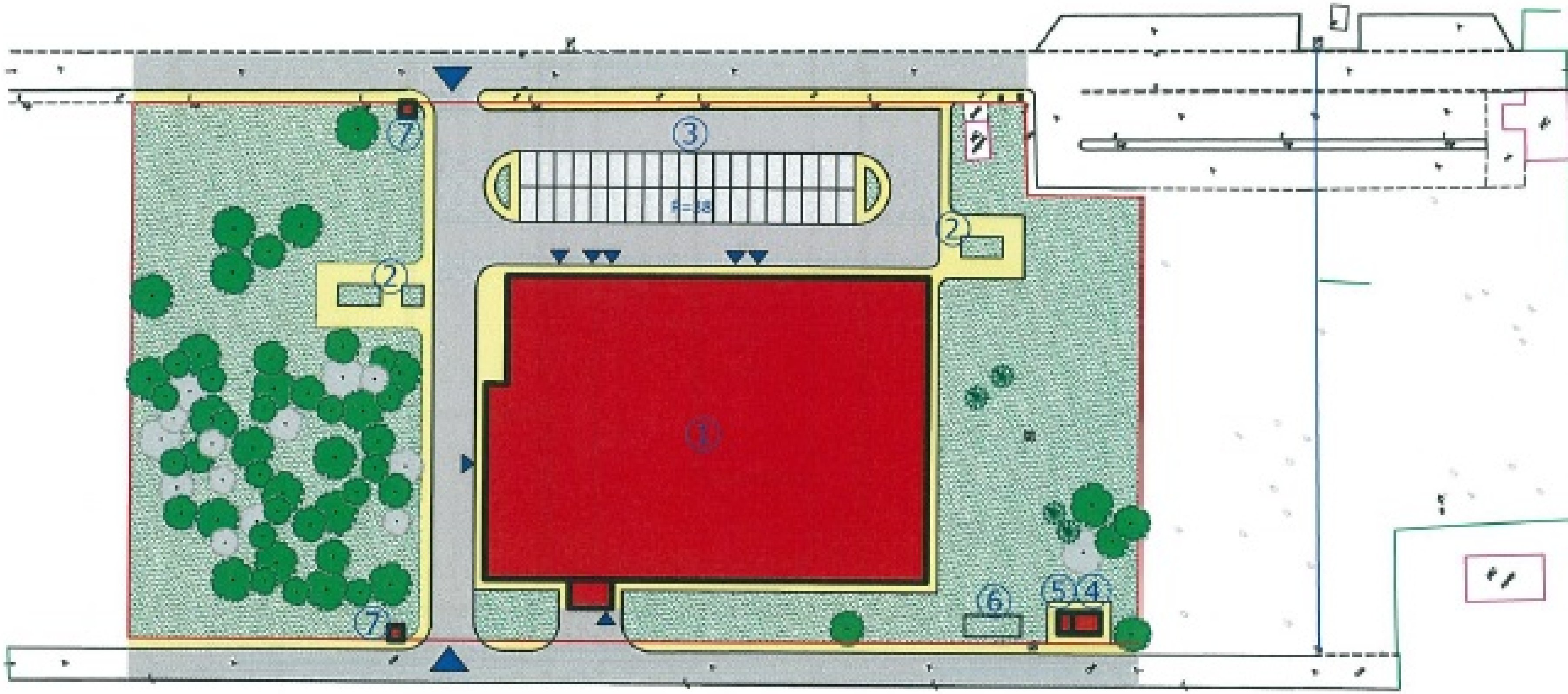
Cyclotron (1)

- FAT done in August 2015

Cyclotron (2)

- Delivery – January 2016

Vision for the building layout

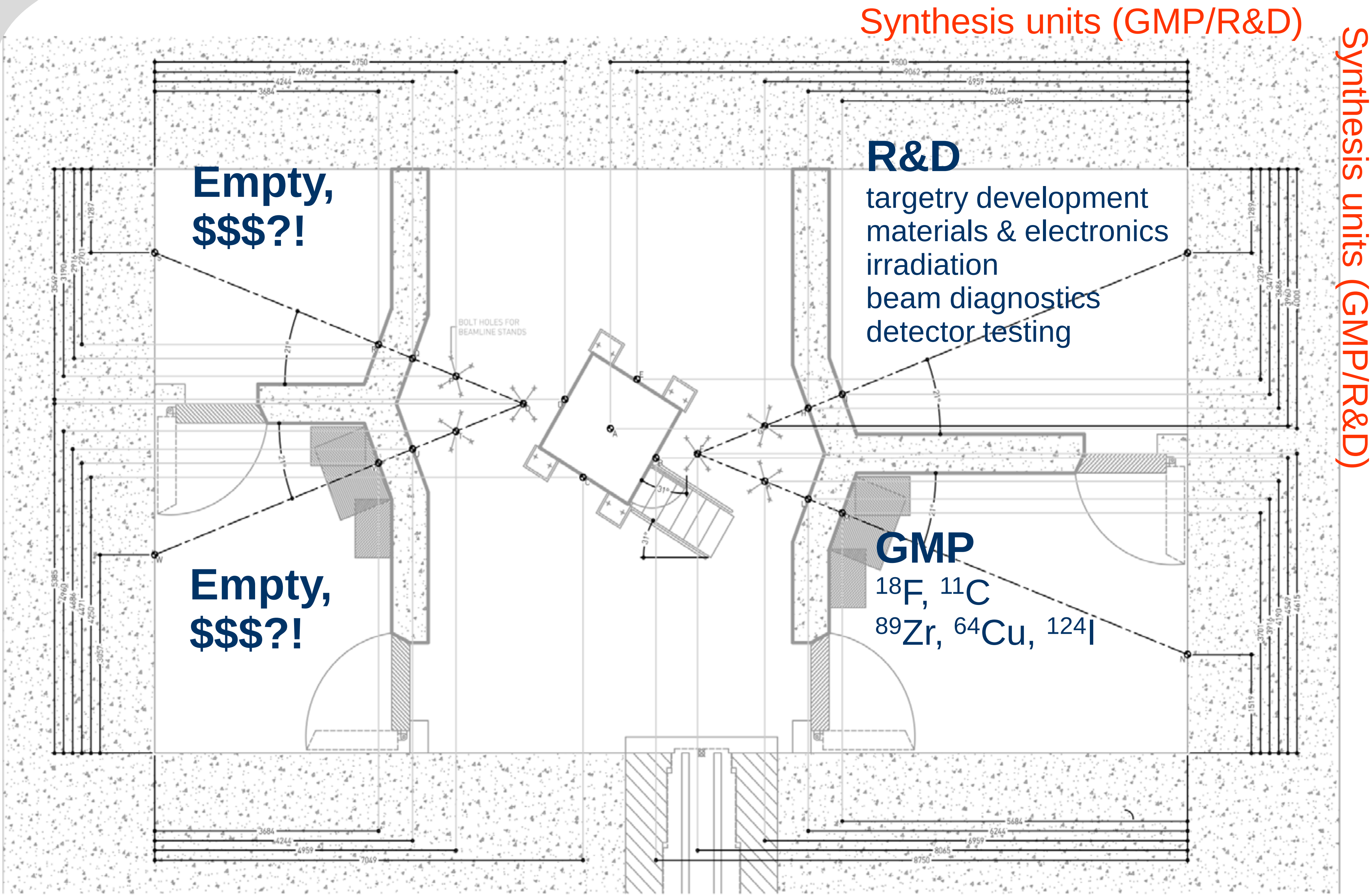


Former research reactor

INRNE

Close to major roads – 4 hospitals nearby, airport, highways to N/E part of Bulgaria.

Cyclotron vault layout



Radioisotopes & radiopharmacy at INRNE

Till 1989 radioisotopes production at the Research Nuclear Reactor IRT-2000:

› Sealed radioactive sources: 60Co, 75Se and 192Ir used for gamma-defectoscopy control, charging of gamma relays in testing equipment.

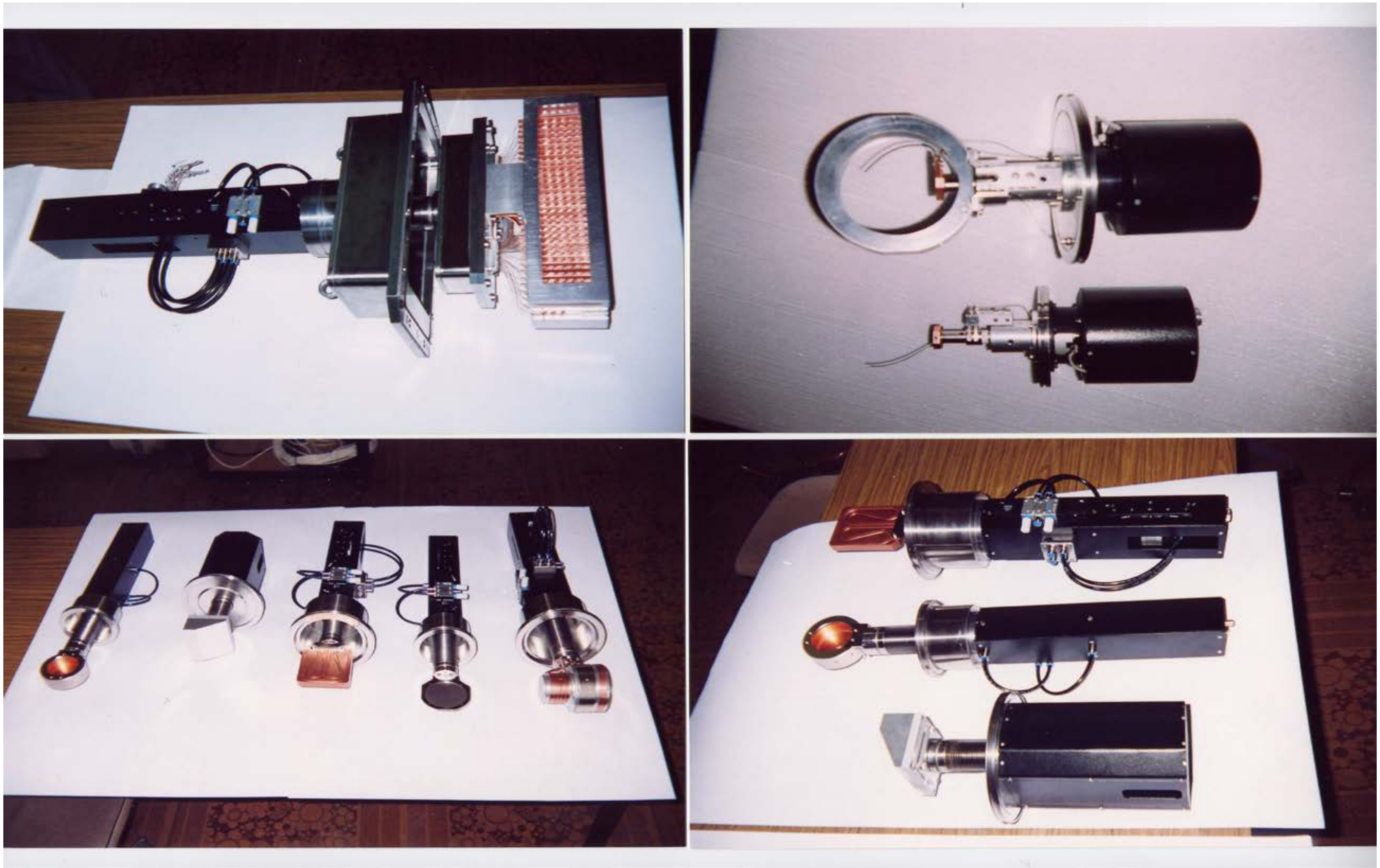
› Short living isotopes: 18F, 42K, 24Na, 64Cu, 82Br, 140La for application in industry, criminology, biology, medicine, etc.

› Radioactive sources of 198Au, 90Y, 182Ta, 192Ir for treatment of certain types of malignant tumors.

› 12 products of great value for medical usage.

› Before EU GMP, INRNE used to produce cold kits for 99mTc and distribute them to hospitals (**MDP** for skeletal metastases, **MDP-RPC** for labeling of **RBC, PYROPHOSPHATE** for myocardial imaging, etc).

Beam Diagnostics Modules. In-house technical design. Workshop for Development and Production/Physics.



Radiological characterization

Evaluate internal hazards:

- Nuclides in target body
- Define nuclides expected to be produces over the operation time of the machine and the vault
- Check vault radiation specs w.r.t. neutrons and gamma rays
- Define cooling time - short lived nuclides (airborn ^{41}Ar?)
- Check operators dose rate

Monte-Carlo approach

FLUKA used for simulations

FLUKA

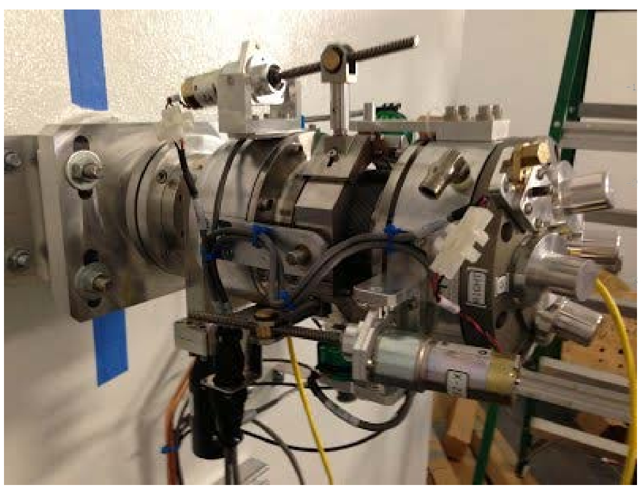
- Emission and transport of secondary particles due to primary nuclear reaction
  - low energy neutron transport
  - takes into account the geometry of the impinging beam (e.g. point source)
- Assessment of the produced residual nuclei
- Possibility to score the same physics process at different irradiation & cooling times
  - buildup and decay of waste

- Not possible to include missing X-section libraries

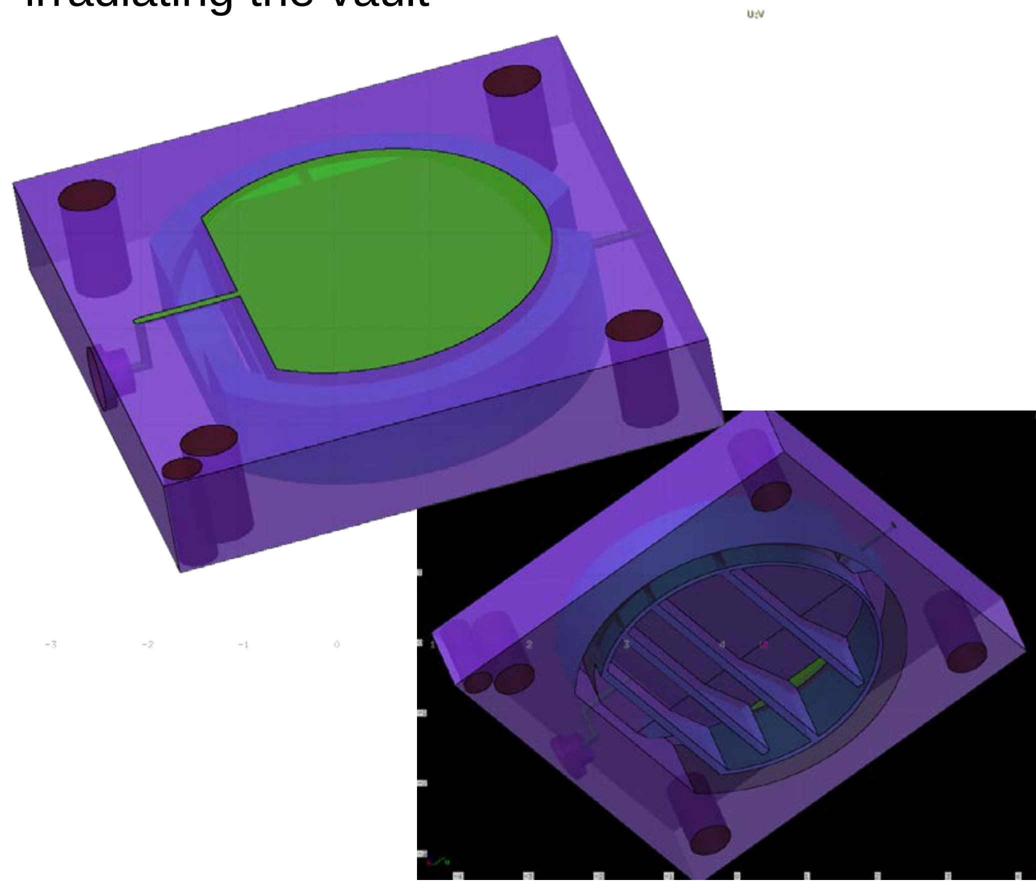
Two-step approach to estimate fluence/waste within the vault

- Simulate target irradiation, assess secondary particles
  - (p, n), (p, γ)
- Use secondary particles as source irradiating vault components

^{18}F high-current liquid target

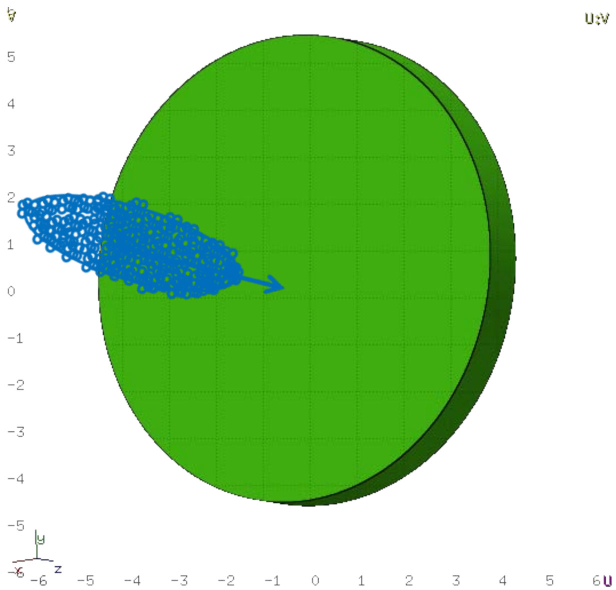


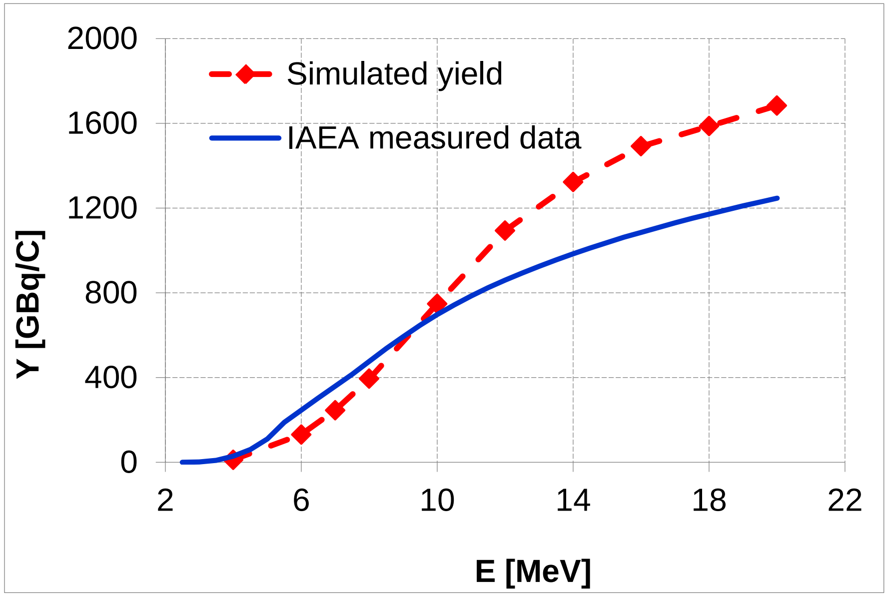
- Delivered 3.8 mL targets
- Check thick target yield in $^{18}O(p, n)^{18}F$
- Pipe secondary particles to be used as source irradiating the vault



Check the FLUKA Monte-Carlo methodics

A proton beam (various E, fixed I) impinges on a simple target





Thick target – the reaction takes place with the volume of enriched water.

The lower the beam energy, the better the agreement:

» Real beam not gaussian in any plane, not point-like, no experimental data on phase space

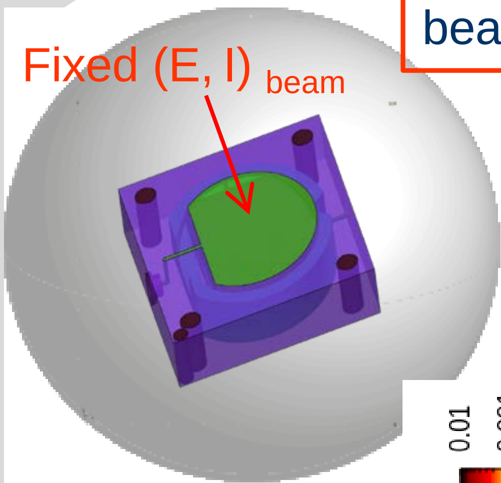
» The FLUKA model is limited in terms of energy

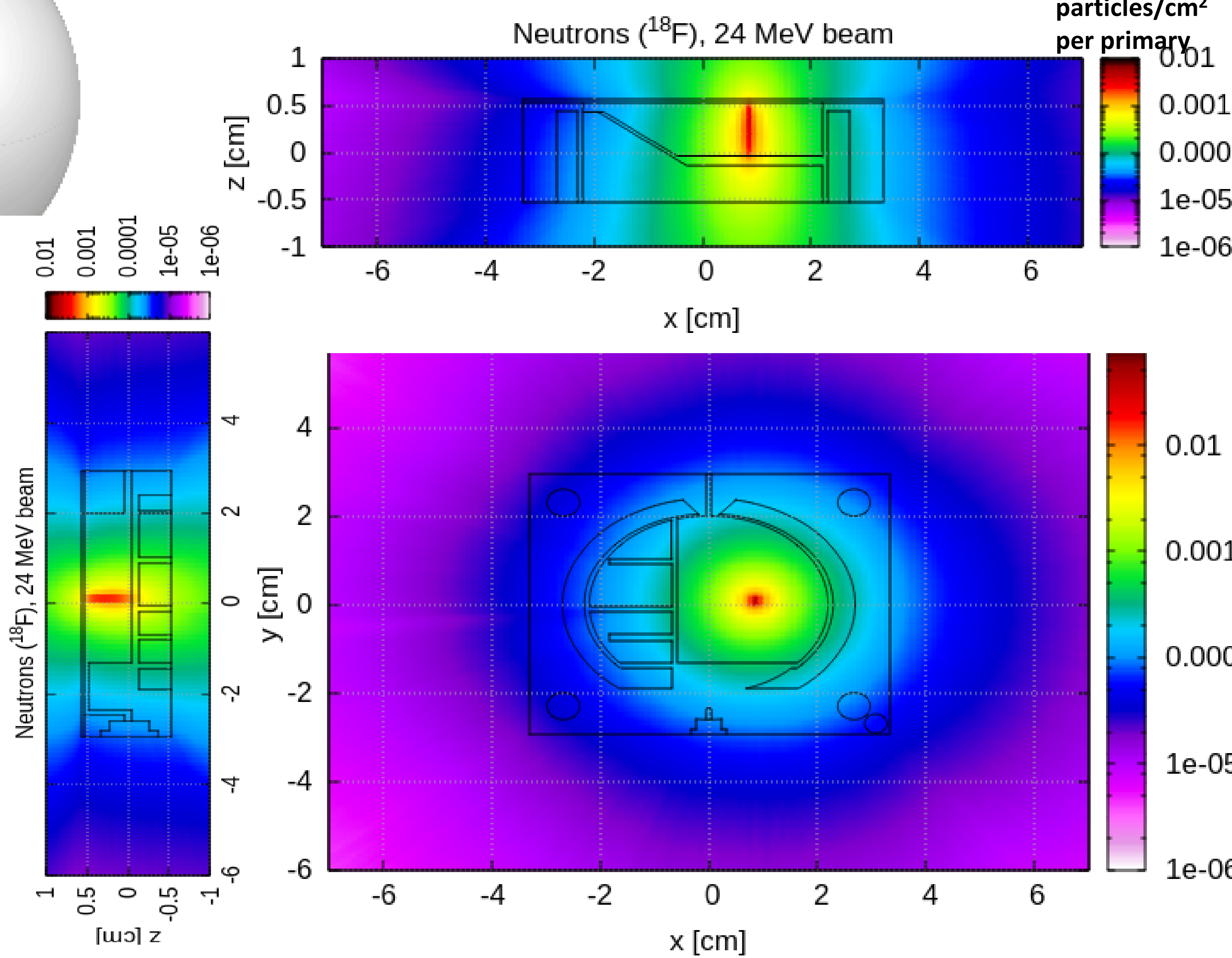
Secondary particles – real target

A. Density distribution

beam orientation w.r.t. target

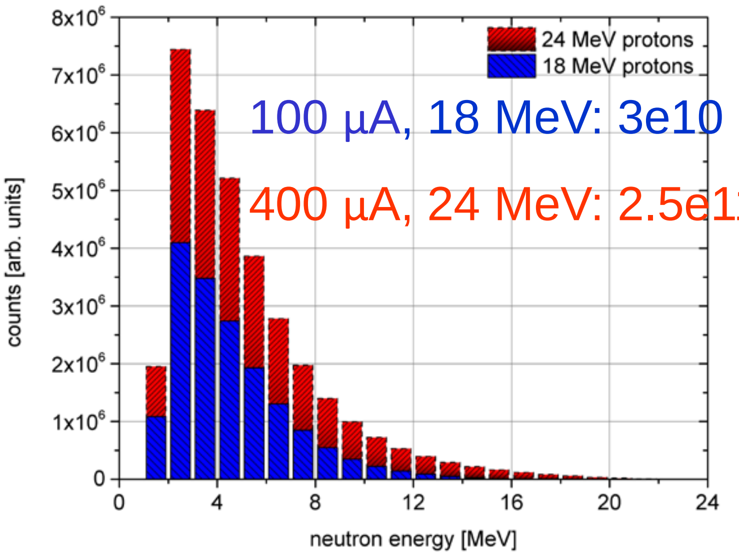
rate of emission of secondaries





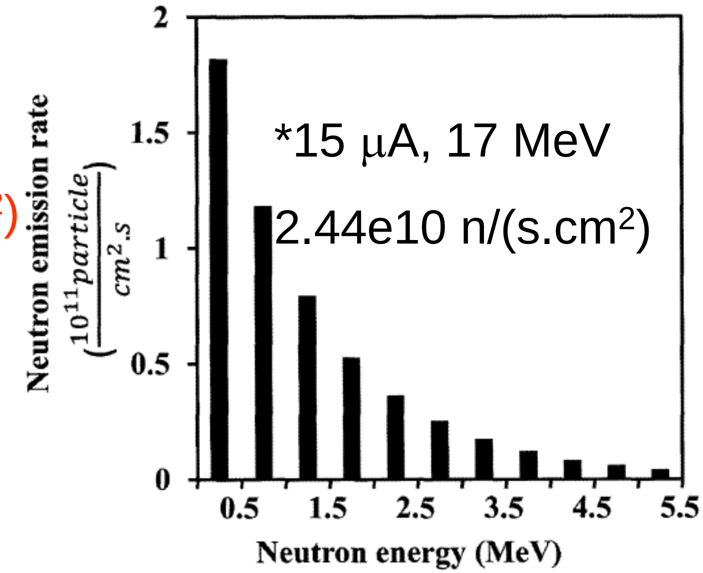
Secondary particles – real target

B. Energy spectrum



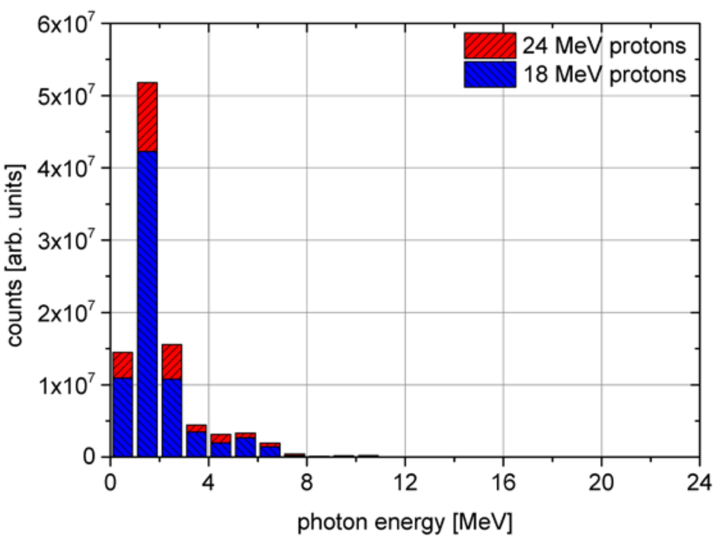
100 µA, 18 MeV: 3e10 n/(s.cm²)

400 µA, 24 MeV: 2.5e11 n/(s.cm²)



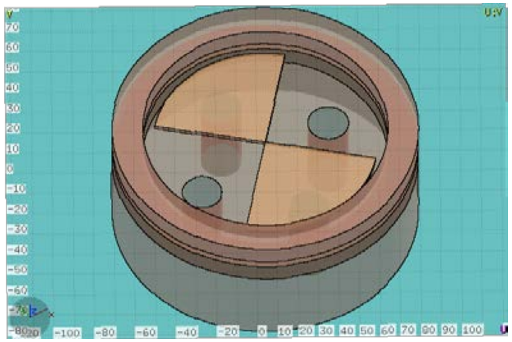
*15 µA, 17 MeV

2.44e10 n/(s.cm²)

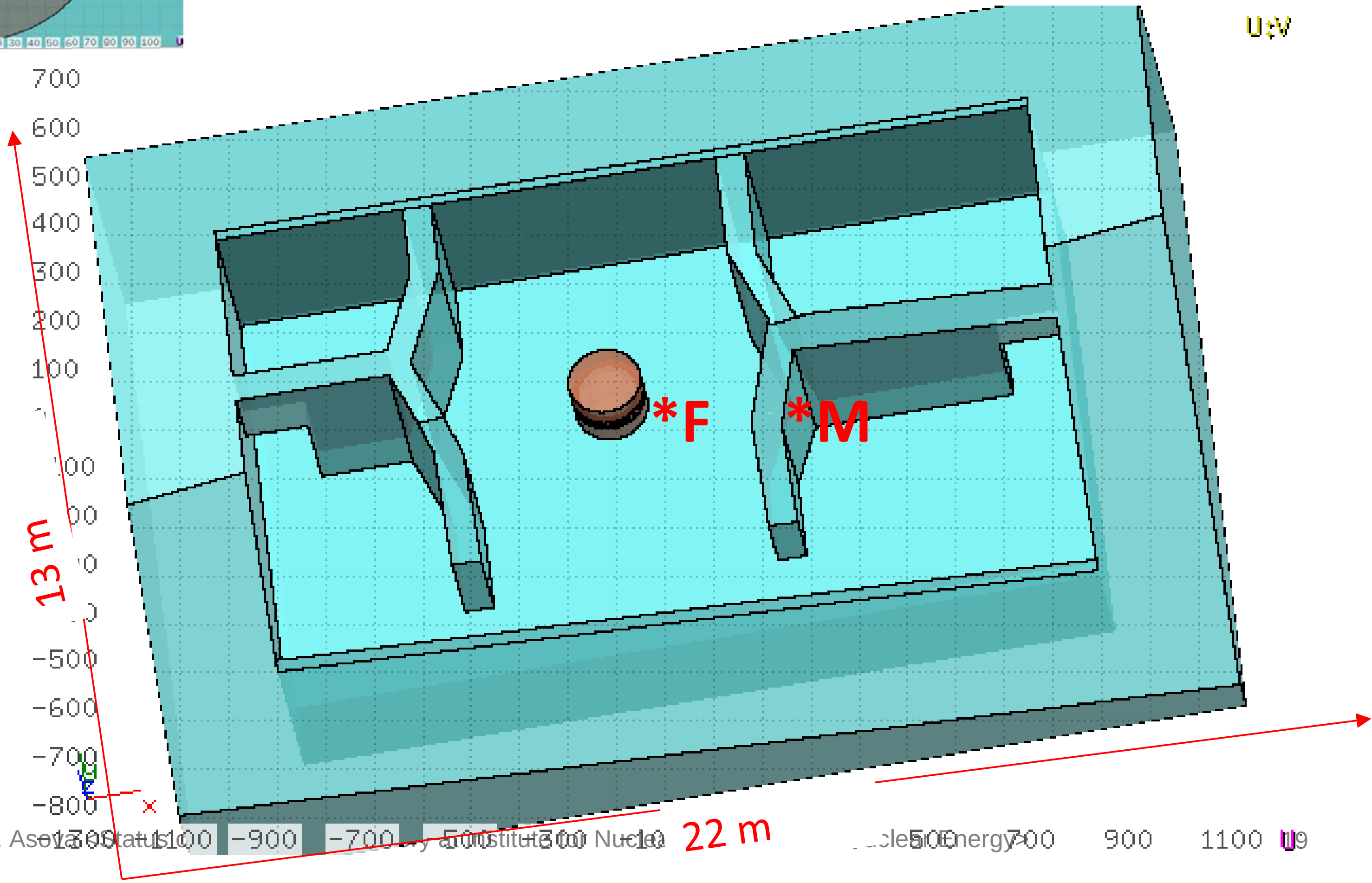


*Sadat-Eshkevar et al, Assessment of the staff absorbed dose related to cyclotron operation and service in the production of ^{18}F radiopharmaceuticals, *Nukleonika 2012; 57 (3):407-410*

The vault with the cyclotron



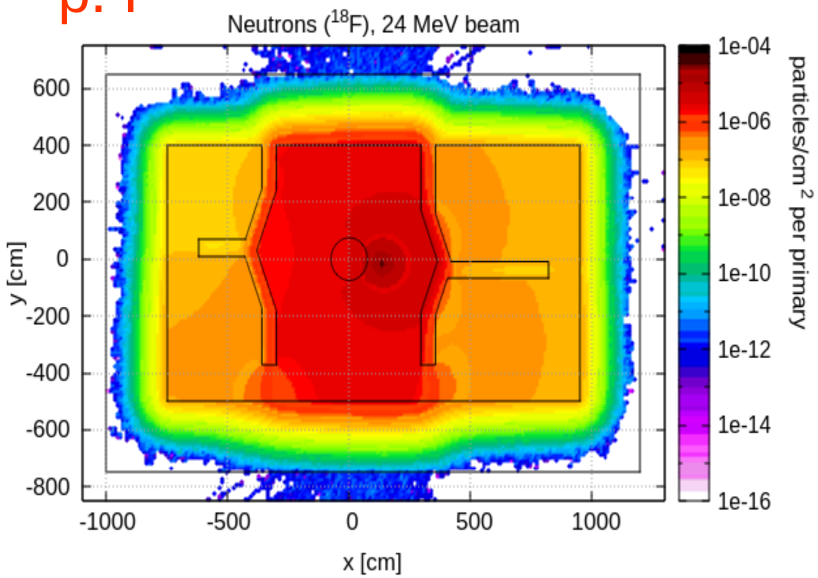
External targets in a ^{18}F-dedicated cave (*)



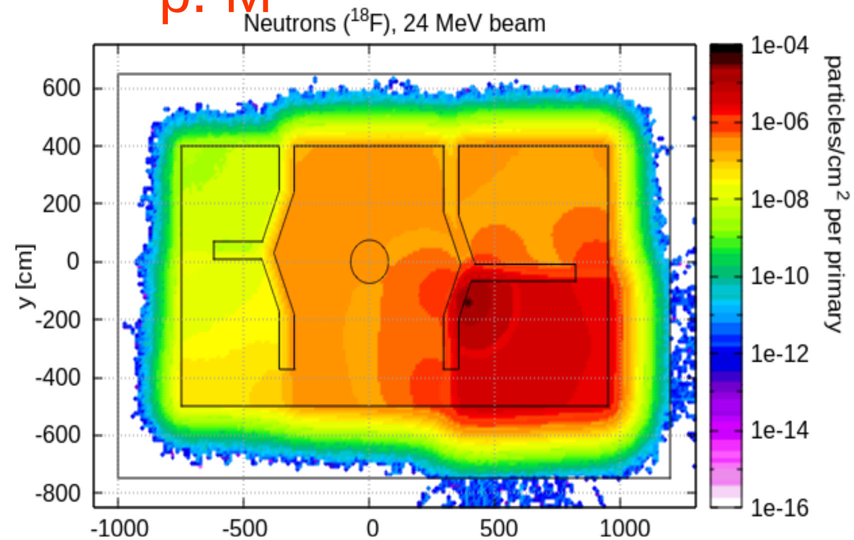
Neutron fields

No additional shielding around the targets. High-density concrete used.

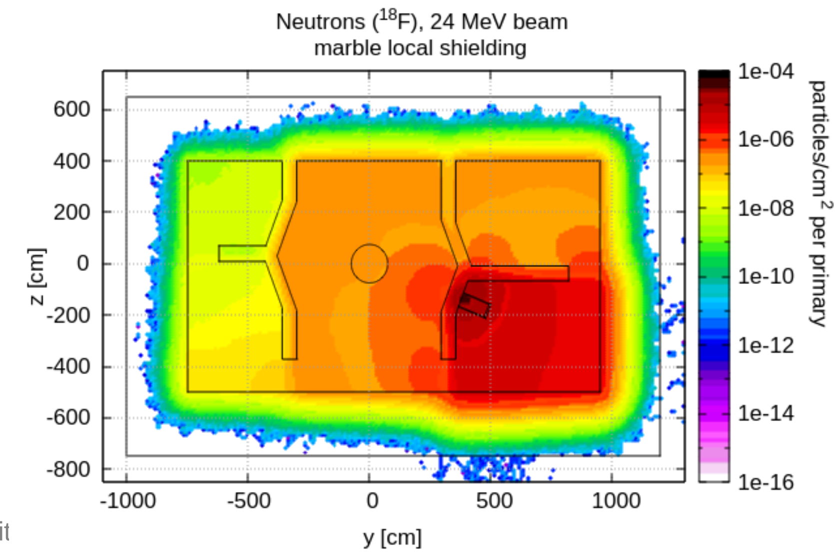
p. F



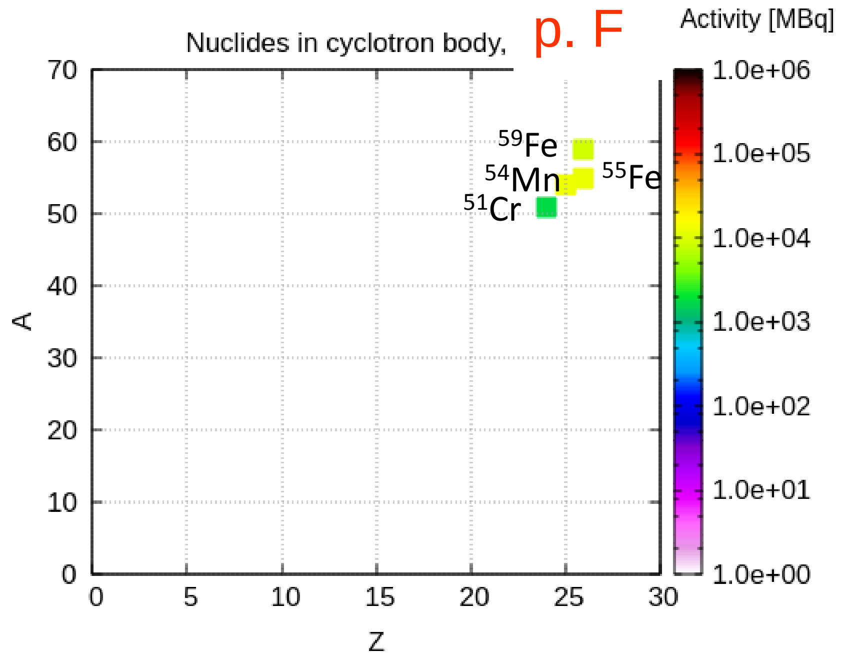
p. M

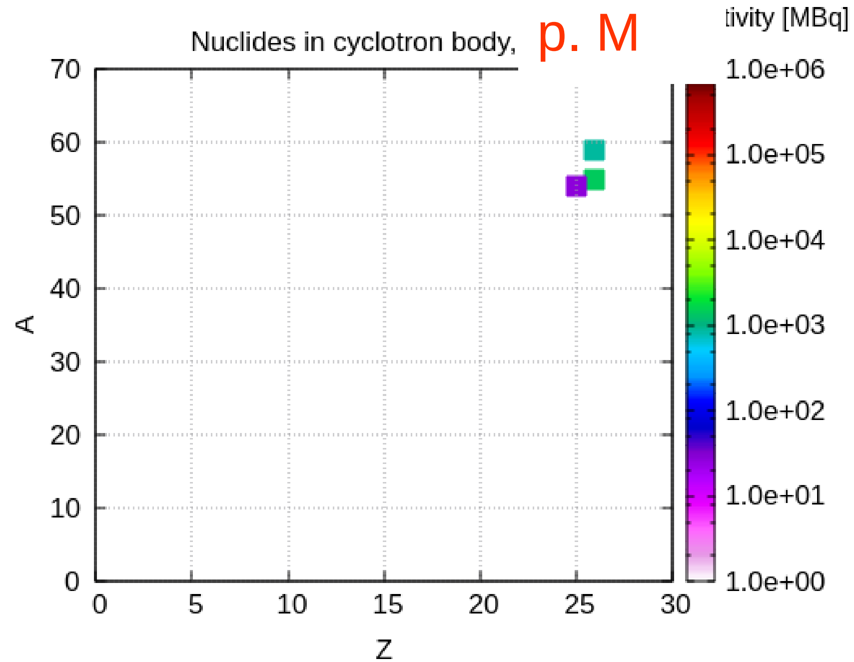


Marble-enriched shielding around the target. Thickness not optimized!



Nuclides in cyclotron, irradiation for 6 h/d for a month @ 400 μA, 24 MeV





^{55}Fe ($t_{1/2}$ = 2.7 y)

^{53}Mn ($t_{1/2}$ = 3.7e6 y)

^{56}Mn ($t_{1/2}$ = 2.6 h)

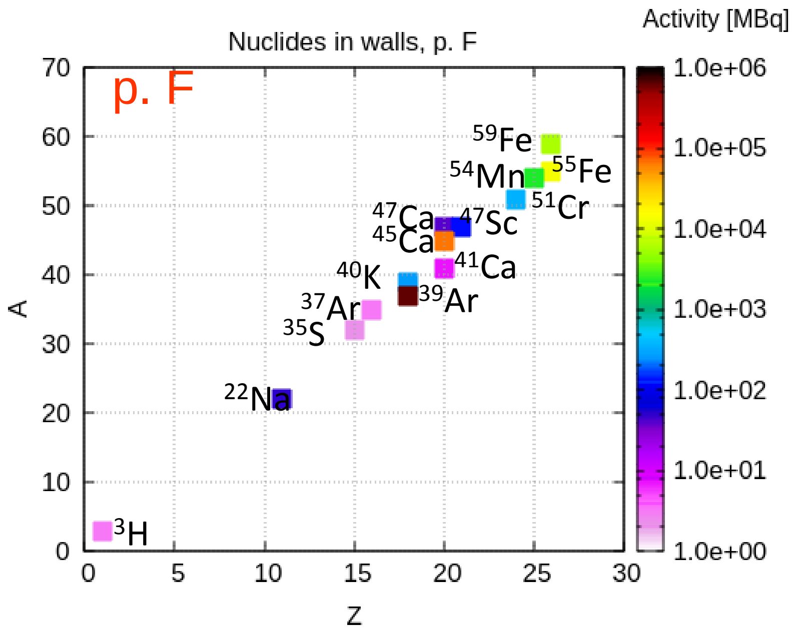
^{59}Fe ($t_{1/2}$ = 44.5 d)

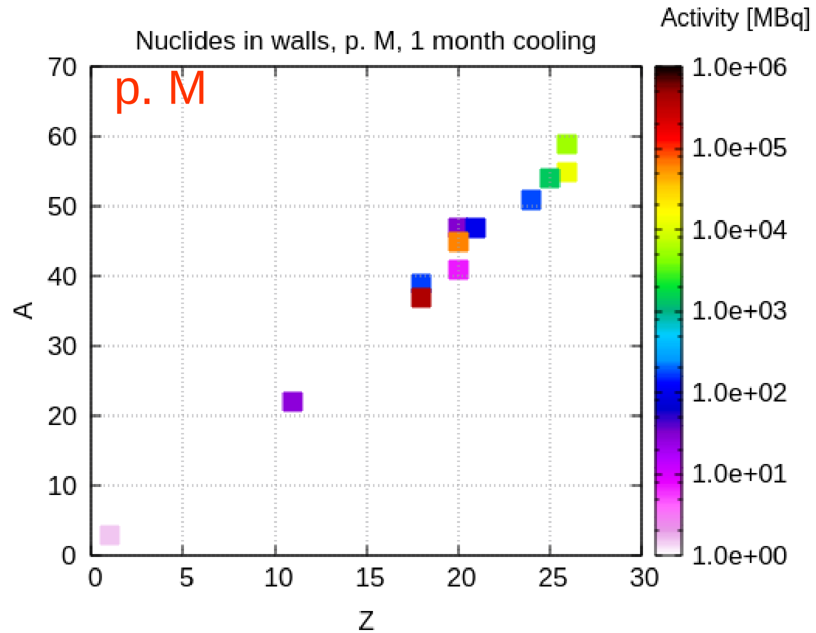
^{54}Mn ($t_{1/2}$ = 312 d)

…

p. M preferable w.r.t. cyclotron contamination.

Nuclides in vault, irradiation for 6 h/d for a month @ 400 μA, 24 MeV





^{59}Fe ($t_{1/2}$ = 44 d)

^{53}Mn ($t_{1/2}$ = 3.7e6 y)

^{45}Ca ($t_{1/2}$ = 163 d)

^{51}Cr ($t_{1/2}$ = 27 d)

^{54}Mn ($t_{1/2}$ = 312 d)

^{37}Ar ($t_{1/2}$ = 35 d)…

Almost no difference in walls contamination between p. M and p. F (score outer walls?).

Nuclides in vault, irradiation for 6 h/d for a month @ 400 μA, 24 MeV

walls

		after EOB	3 weeks cooling	
^{59}F	44 d	8 GBq		
^{56}Mn	2.6 h	0.6 GBq		
^{55}Fe	2.7 y	13 GBq		
^{54}Mn	312 d	1.4 GBq		
^{53}Mn	3.7e6 y	15 Bq		
^{51}Cr	28 d	0.3 GBq		1 year
^{49}Sc	57 m	1 MBq		
^{47}Sc	3 d	1.9 GBq		
^{47}Ca	4.5 d	2 GBq		
^{45}Ca	163 d	69 GBq		
^{41}Ca	1e5 y	6.7 MBq		
^{43}K	22 h	0.3 GBq		
^{42}K	12.4 h	858 GBq		
^{39}Ar	269 y	167 MBq	4.6 kBq	
^{41}Ar	**109 m**	**10 MBq**	**42 MBq / 1 GBq**	1 day

Summary

- Major problem – "researchers dislike wasting time and inspiration on infrastructure projects". They also lack skills and knowledge required to run an infrastructure investment project. The solution:
    - seek consultants until "BEAM-ON" time and partnership with well established radiopharmaceutical companies and foreign R&D institutions
- Land for the facility granted by BAS, geological survey done.
- The building for the cyclotron facility – ongoing call for public tenders.

- Monte-Carlo procedure needed for Bulgarian Nuclear Regulatory Agency
    - model of the vault complete unless something changes
    - more simulations to come
        - vault with local target shielding, with marble concrete, activation in depth in the walls, etc.
        - more isotopes to be checked – $^{67,\,68}$Ga, ^{111}In, ^{64}Cu, etc.

- Design a solid target station capable to work with the beam load delivered by the cyclotron – far future.
- Nuclear physics – far future.

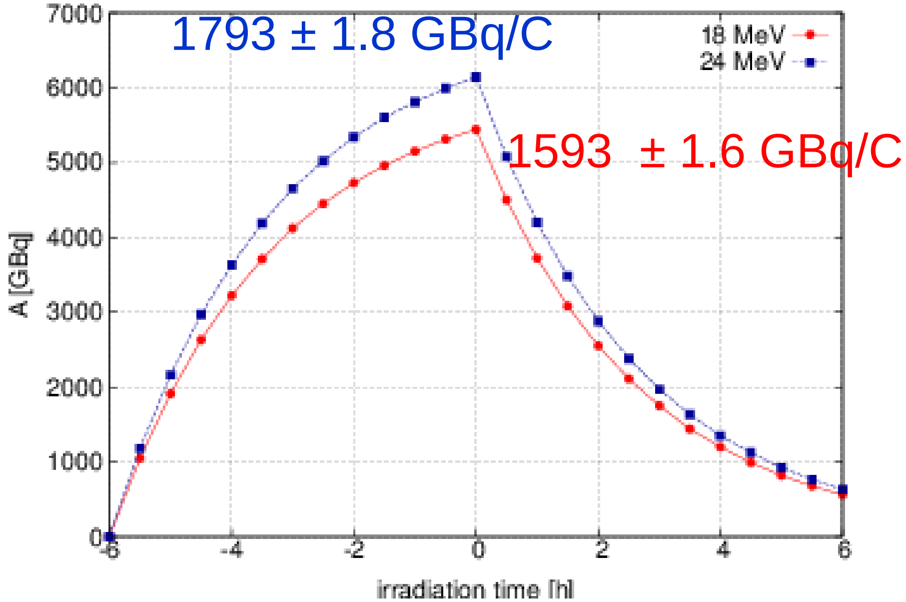
Thank you for the attention!

Thick target yield

Cross-check FLUKA calculations with published experimental data

- 100 and 400 μA for 18 and 24 MeV
  - results normalized to particle charge ($Y_{100\ \mu A} \sim Y_{400\ \mu A}$ depending on the beam energy)

400 μA



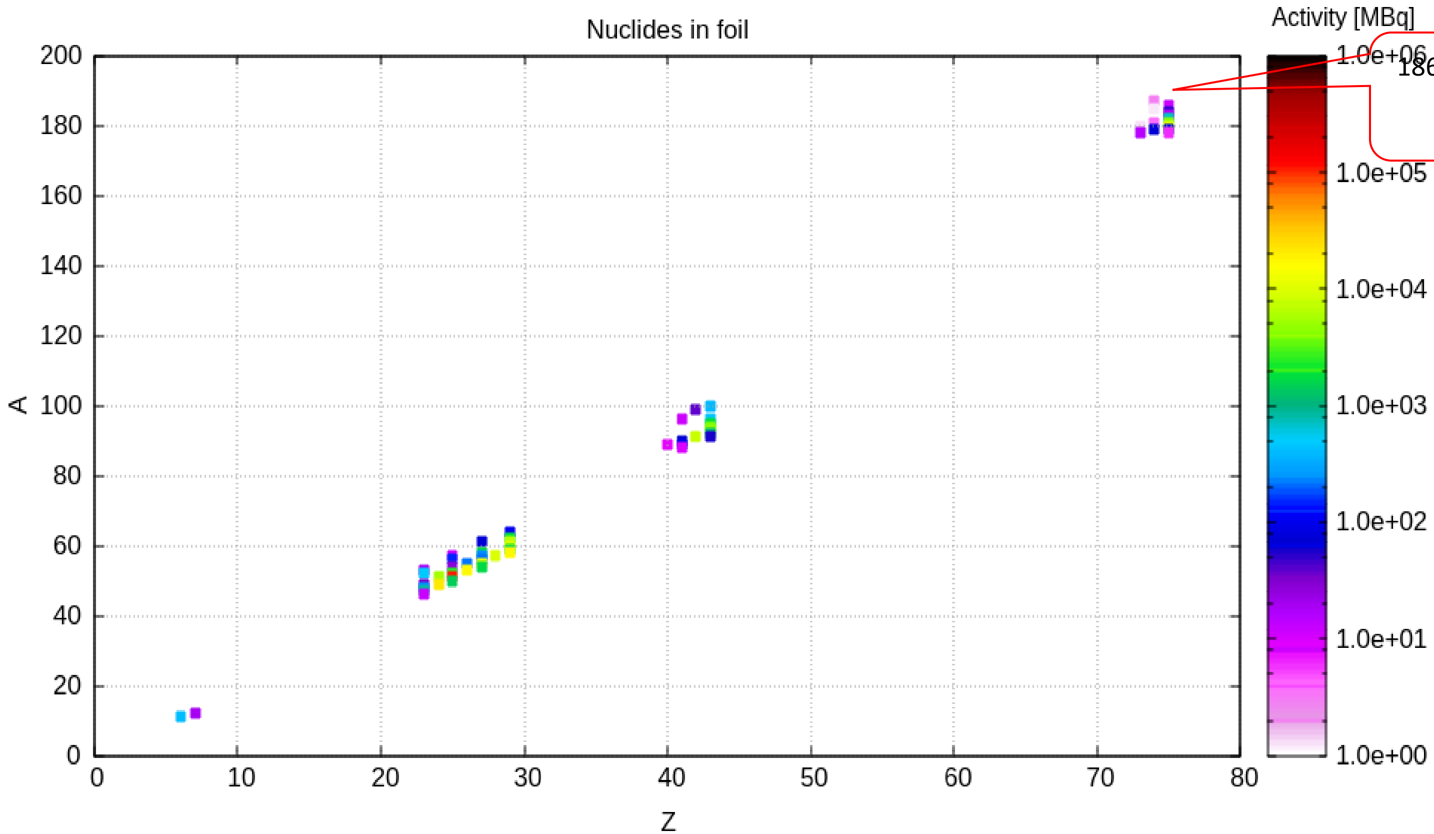
IAEA data (IAEA-TECDOC-1211):

18 MeV: 1171 GBq/C measured

24 MeV - no data.

Nuclides in Havar foil

After irradiation with 400 μA @ 24 MeV, 6 h



^{186}Re, $t_{1/2}$ = 89.25 h

^{186}W (p, n) ^{186}Re – liver cancer treatment

^{93}Mo ($t_{1/2}$ = 4e3 y)

^{57}Co ($t_{1/2}$ = 272 d)

^{55}Fe ($t_{1/2}$ = 2.7 y)

Nuclides in Havar foil

After irradiation with 400 μA @ 24 MeV, 6 h

Exemption limit

^{185}W	75 d	5.6 MBq / 10 MBq
^{181}W	121 d	7 MBq / 10 MBq
^{96}Tc	4.3 d	126 MBq / 1 MBq
^{93}Mo	4e3 y	0.6 Bq / 0.1 GBq
^{59}Fe	44 d	558 MBq / 1 MBq
^{58}Co	71 d	2.7 MBq / 1 MBq
^{56}Mn	2.6 h	18 MBq / 0.1 MBq
^{56}Co	77 d	0.1 MBq / 0.1 MBq
^{55}Fe	2.7 y	0.03 MBq / 1 MBq
^{54}Mn	312 d	0.7 MBq
^{52}Mn	5 d	71 MBq / 0.1 MBq
^{51}Cr	28 d	23 MBq / 10 MBq
^{3}H	12.3 y	88 MBq / 1 GBq

137 days in storage