Radiation safety at CNAO

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*On behalf of the CNAO RP group

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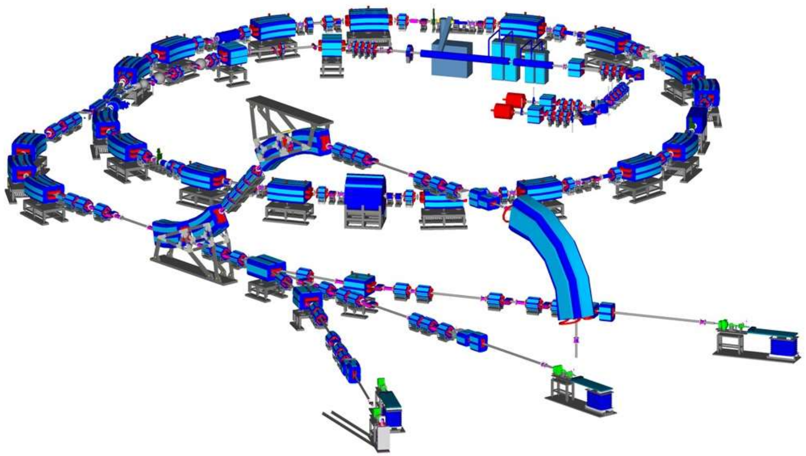
fondazioneCNAO
Centro Nazionale di Adroterapia Oncologica

- Ion synchrotron (in operation)
- Proton synchrotron (in commissioning)
- BNCT (coming soon)



- Operational radiation protection
- Radiation Protection

- Radiation physics (facility design and RP engineering)

R&D ongoing

- methods for radiation fields study, activation nd contamination assessment
- Innovative detectors for RP in hadron accelerator environment

fondazione CNAO ⇔ research and industrial partners

Master and PhD students @ CNAO RP group

R&D ongoing - methods for dose and contamination assessment

- Study of Monte Carlo modeling of the facility ⇔ study of the CNAO radiation fields with different ions

- Study of the basic physics for BNCT (e.g. monte Carlo neutron transport, photon generation in FLUKA and MCNPX)

- Activations studies: synchrotron - BNCT

- Study of the radioactive gas production, and their transport in the surrounding areas

-Evaluation of emergency (e.g. fire) scenarios (BNCT)

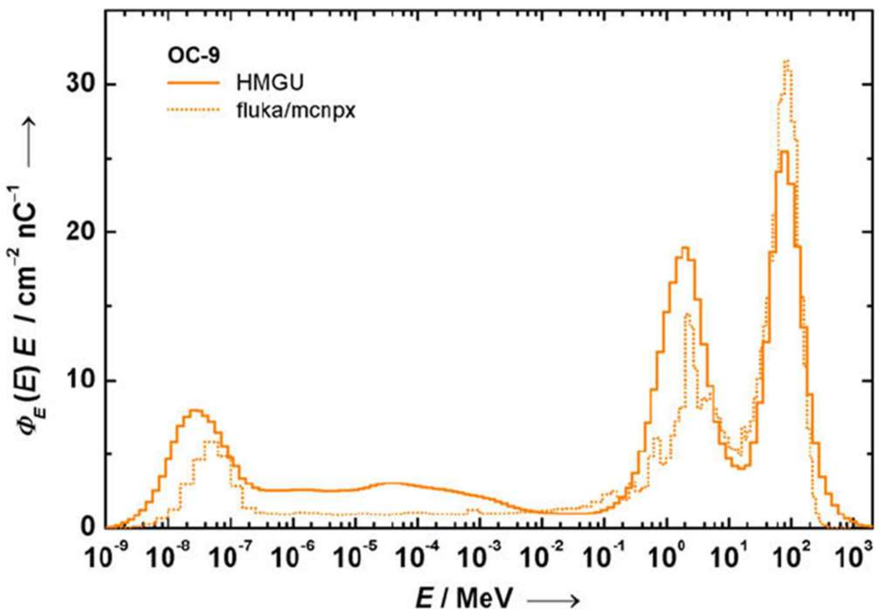
Shielding/facility design

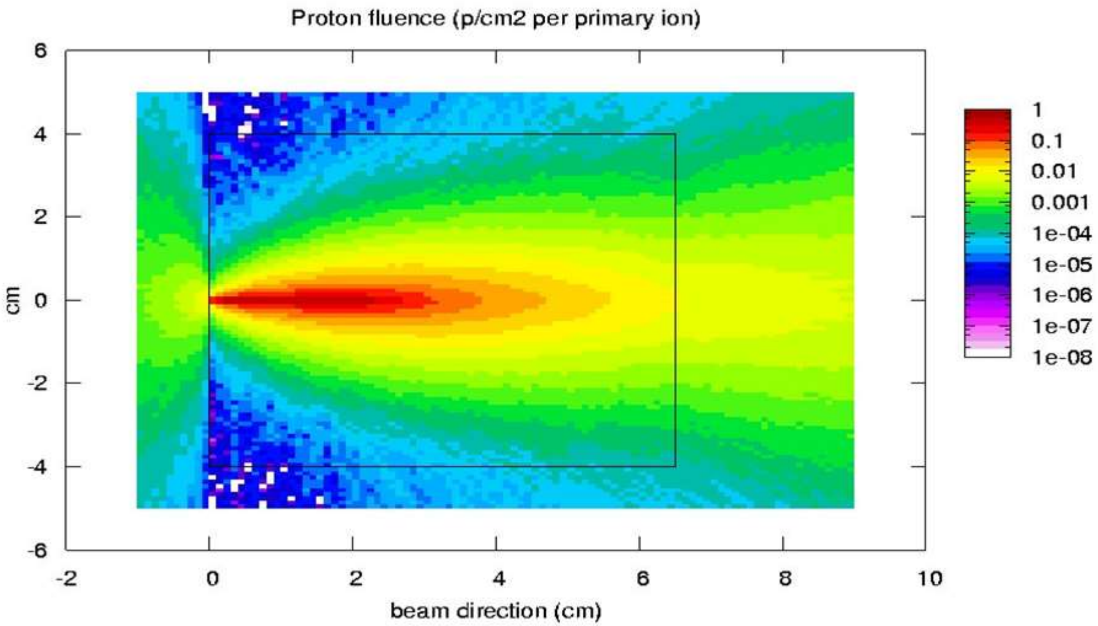
For intermediate energy hadron accelerators, the problem is secondary radiation

Intermediate energy protons and ions impinging on any material give rise to a complex mixed field (where many particles can be found, such as neutrons, protons, photons, nuclear fragments etc…)

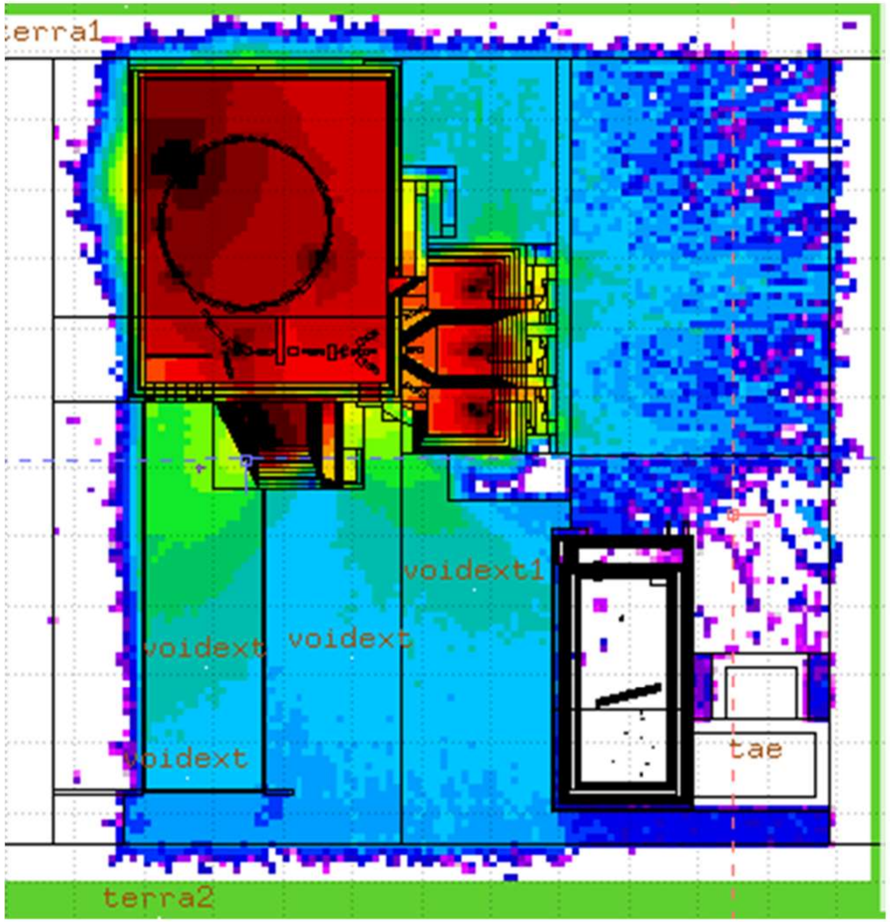
The radiation field outside the shielding is dominated by neutrons.

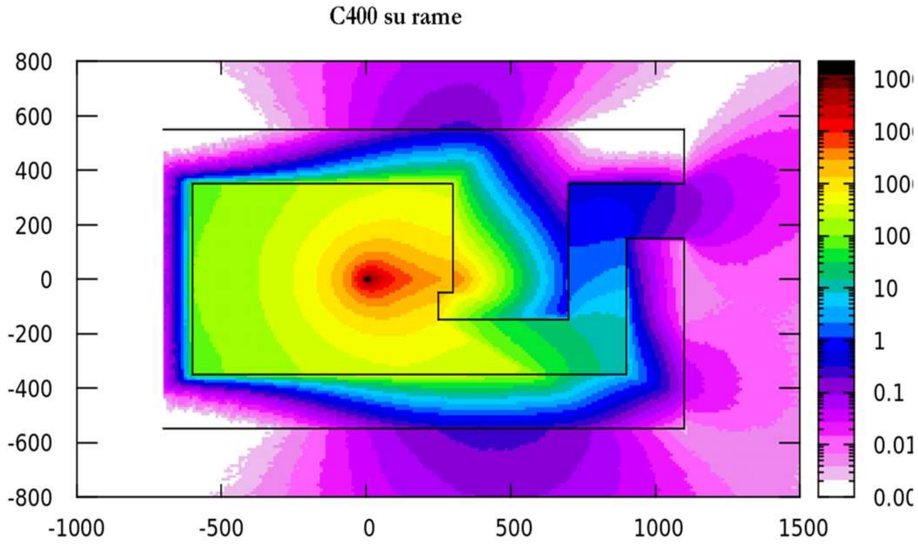
The field inside the treatment or accelerator vault is dominated by heavy charged particles .

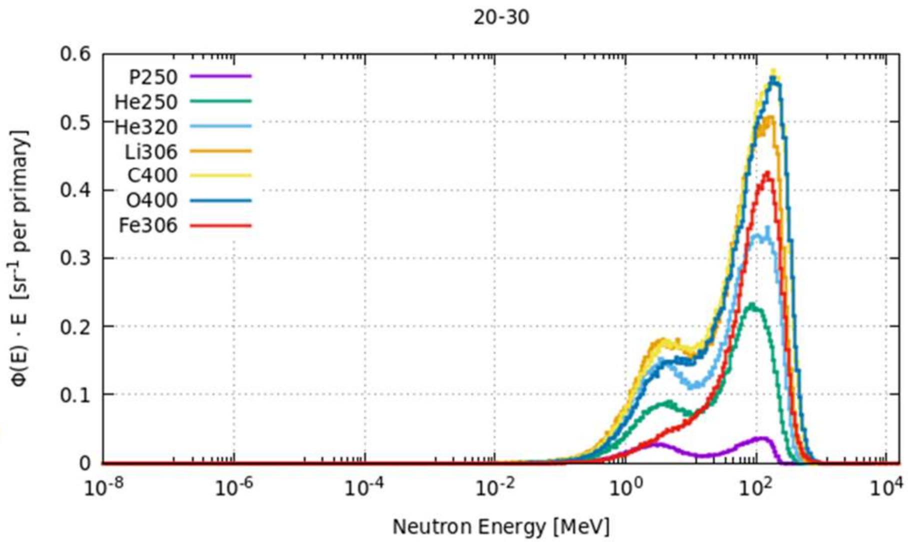




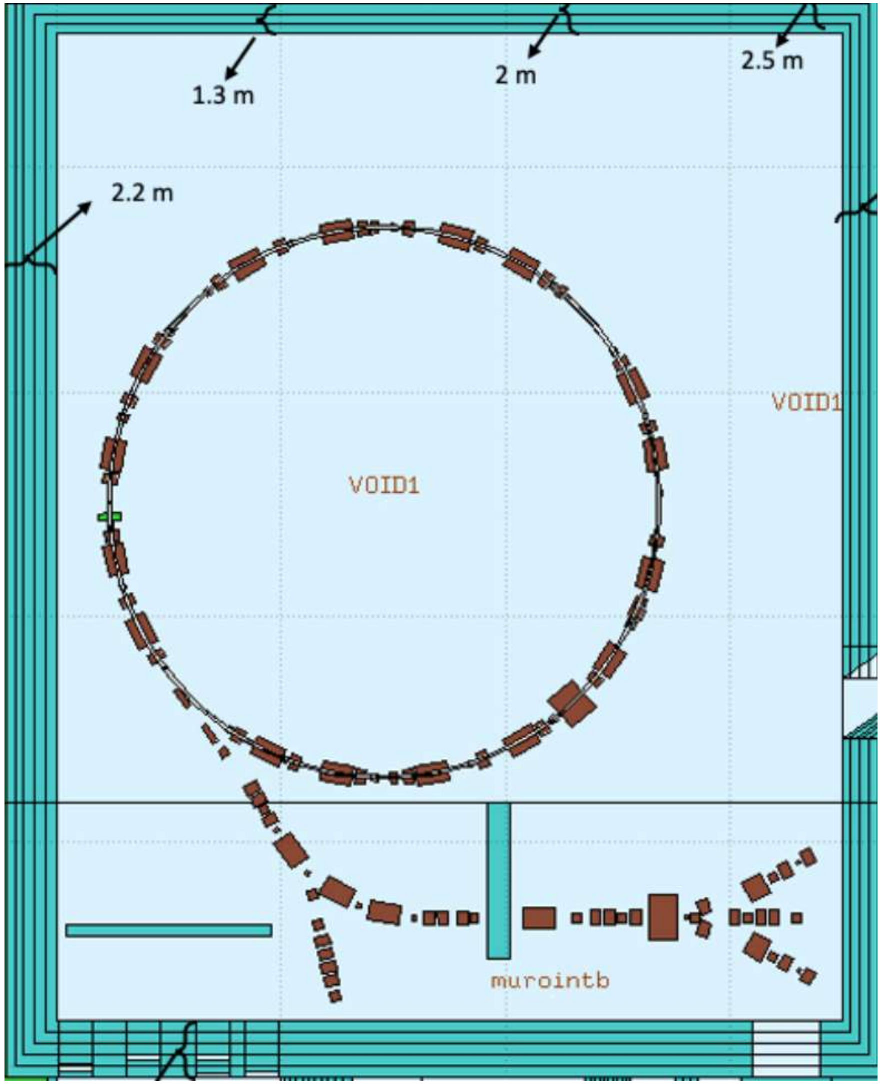
Study of Monte Carlo modeling of the facility ⇔ study of the CNAO radiation fields with different ions







New ions (He-4, Li-7, O-16, F-56)



Verify approximations effects

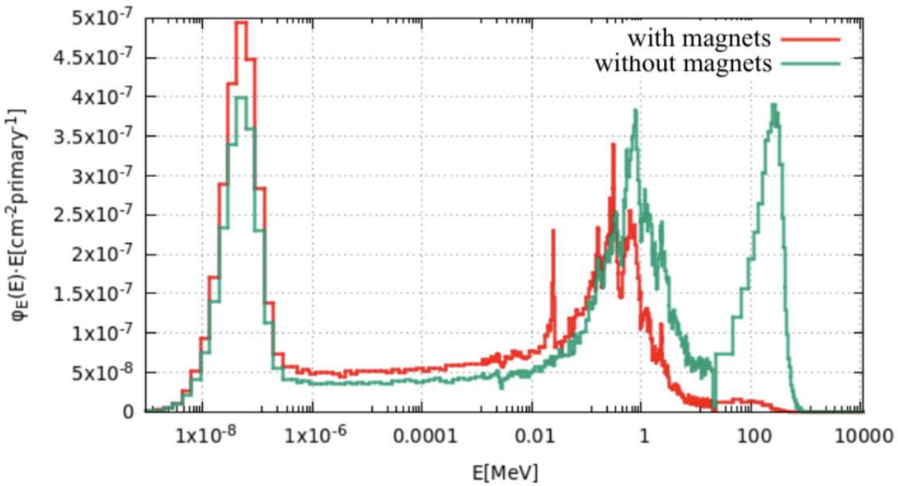


Figure 1.6: Neutron spectra generated inside the synchrotron room with and without magnets [5].

S.Dibartolomeo, master thesis, UniMi, 2021

Table 2.19: Values of the current ratio between a selected ion beam and carbon ions in the worst case and in the case adopted for dose maps.

Ion	Beam Energy [MeV/u]	Worst Case Current Ratio	Adopted Current Ratio
^{4}He	250	2.75	2.5
^{7}Li	306	1.19	0.83
^{16}O	400	0.63	0.13
^{56}Fe	306	1.16	0.07

PhD Thesis F.Bonforte – UniBas 2023

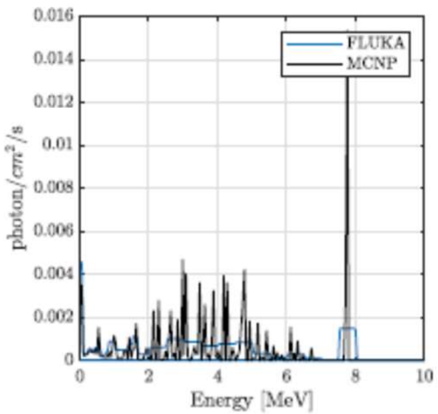
Ion gantry

Preliminary design – preliminary RP studies

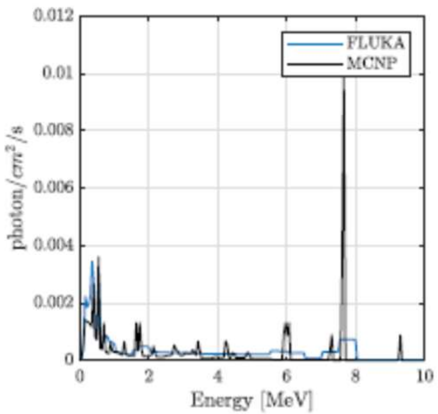
Study of the basic physics for BNCT (e.g. monte Carlo neutron transport, photon generation in FLUKA and MCNPX)

Calculating shielding, activations etc… for a BNCT is a very tricky issue.
The shielding depends on capture gammas, and they depend on the materials inside the facility.

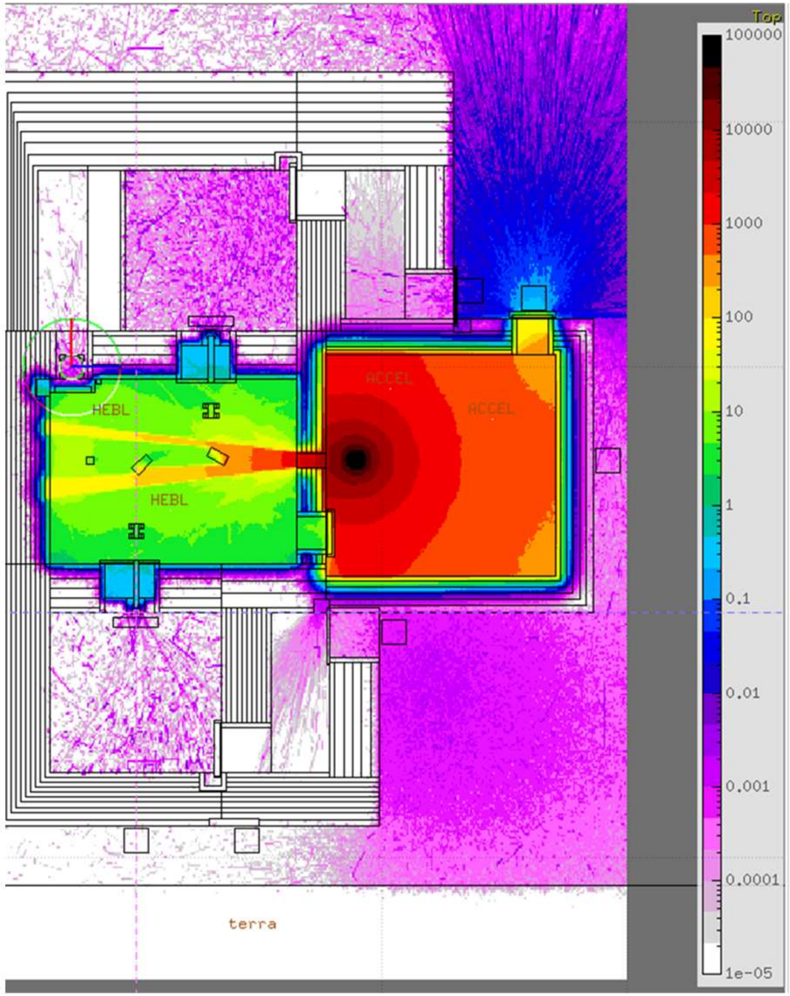
It requires a deep understanding of the neutron transport modeling, and a significant trust in the capture photon generation engine of the Monte carlo code used



(a) Al27 prompt gamma spectrum

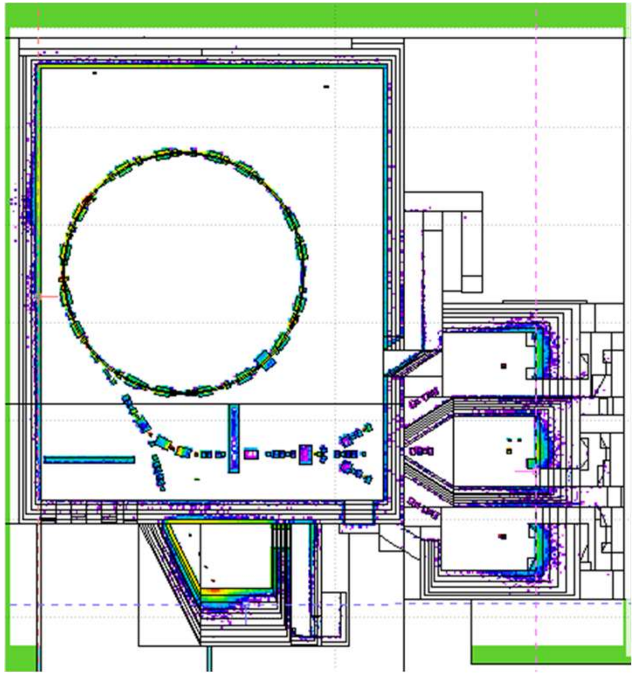


(b) Natural Fe prompt gamma spectrum



G:Mazzola Master thesis, PoliMi, 2021

Activations/decommissioning

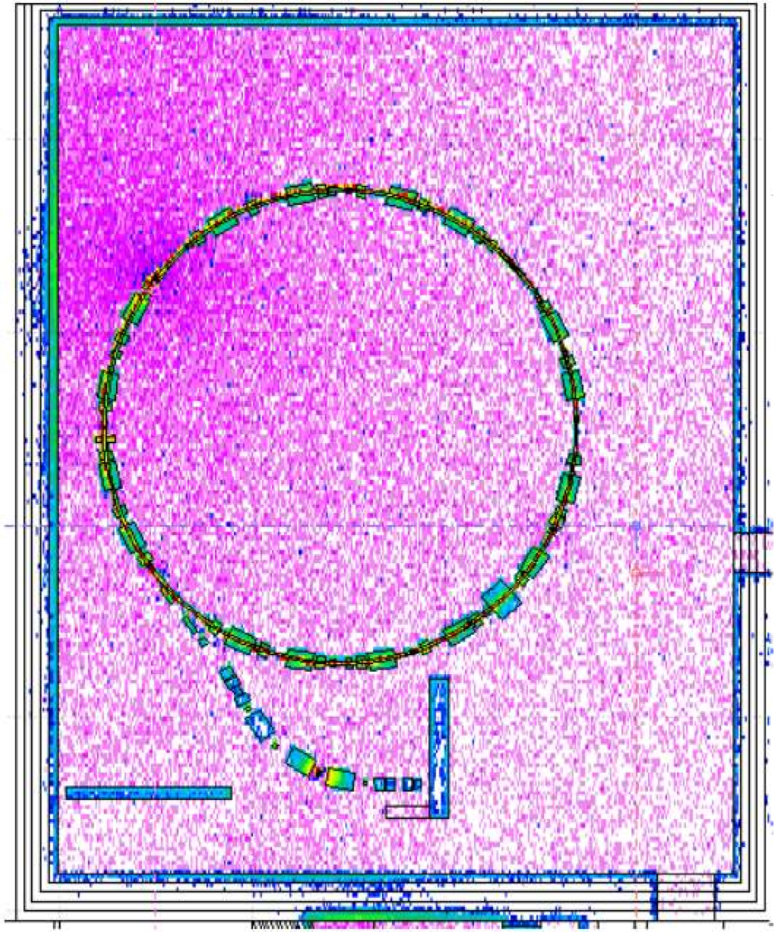


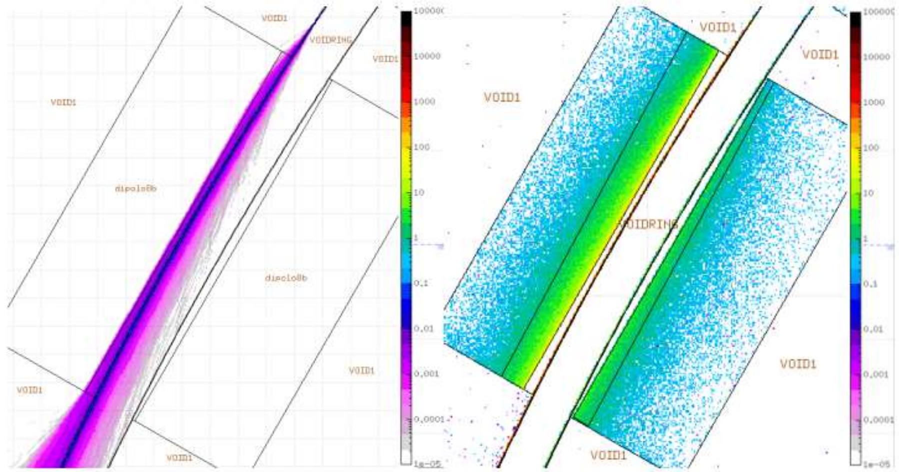
Activations are to be taken into account for the disposal of machine parts, but also for handling any irradiated material (not only filters and bolts, but also the patients' positioning masks, sheets etc…). Materials charachterization issues (e.g. gamma/beta scaling factors)

At the moment, activations on the machine lines provide a negligible dose to the operators. It will have to be taken into account for materials handling, clearence and (in the future, but not only) decommissioning.

Also the air gets activated (mainly short-lived beta+ emitters and Ar-41)

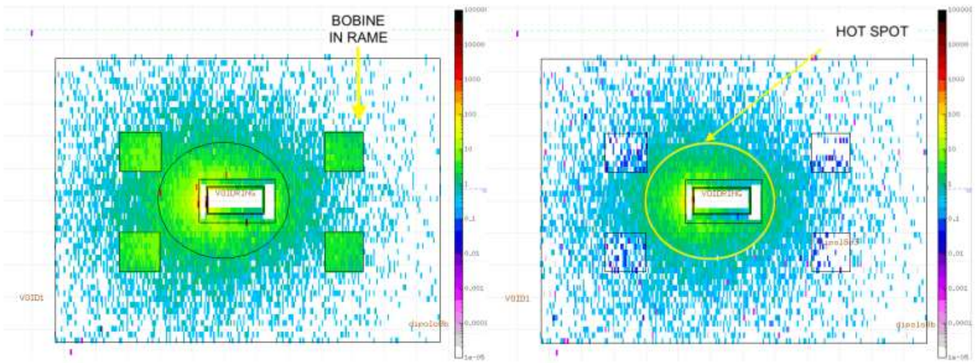
Activation studies / decommissioning - ion synchrotron





(a) *Scoring BEAMPART nel dipolo* (b) *Scoring di ACTIVITY nel dipolo*

Figura 6.5. Visualizzazione grafica del fascio e dell'attività indotta nel magnete



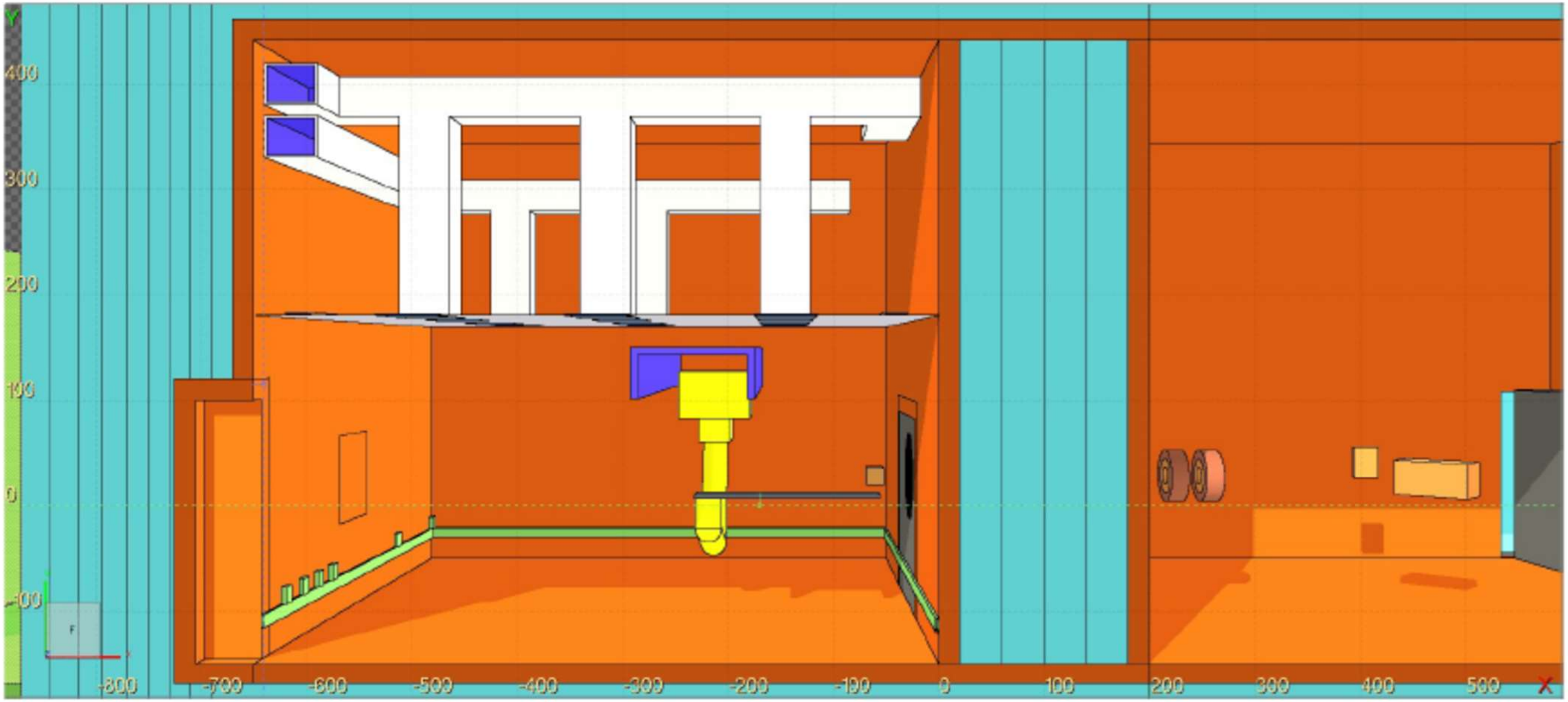
(a) *Scoring ACTIVITY frontale a 60s* (b) *Scoring ACTIVITY frontale a 1 anno*

Figura 6.6. Visualizzazione frontale dell'attività indotta nel magnete

A.Formento, Master thesis, PoliMi, 2021
R.Loguercio, Master thesis, UniPv 2025

V.Montaina, Master Thesis, PoliMi 2026

Activation studies / decommissioning - BNCT

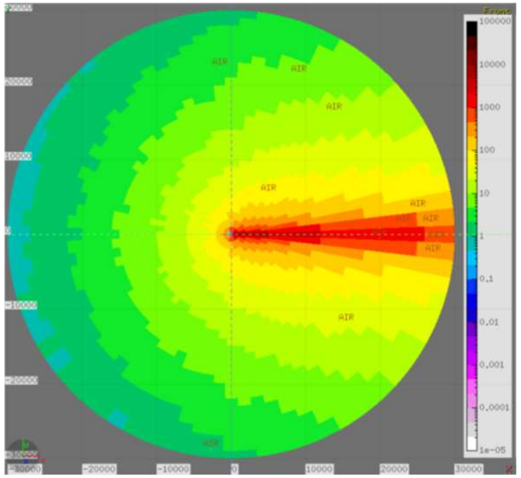


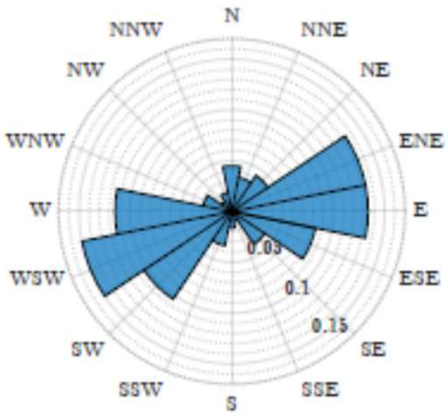
The study of activations in the BNCT requires the construction of a very detailed Monte Carlo model (systems, false ceilings, etc.) – and study of materials and their impurities.
Small amount of impurities (e.g. Eu in concrete, Mn in steel and aluminum etc..) lead the game

Study of the radioactive gas production, and their transport in the surrounding areas

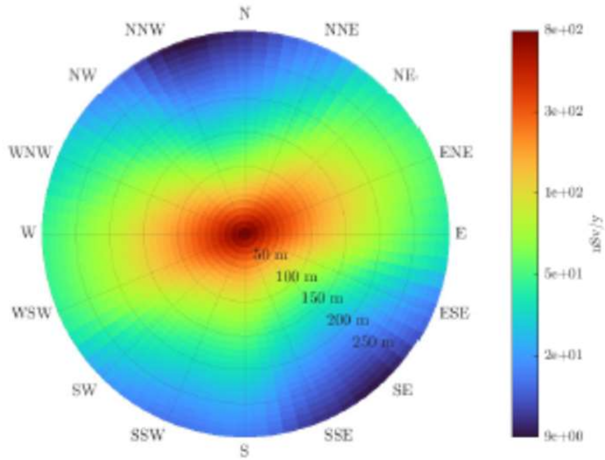
Hadrontherapy centers are usually in crowded city areas, and campus size is usually small.

Doses due to activated air in the immediate neigborhood are a significant issue to be handled, and require significant modeling effort.





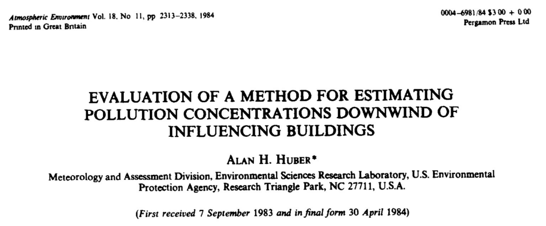
(a) *Distribuzione in frequenza dei venti*



G.Garlaschelli, mater thesis, PoliMi, 2019
T.Lorenzon Master thesis, PoliMi, 2021

Study of the effects of building disturbance on the diffusion of contaminants in near field

The models used in literature to keep this effect into account date back to the 1980s


Atmospheric Environment Vol. 18, No. 11, pp. 2313–2338, 1984
Printed in Great Britain

0004-6981/84 $3.00 + 0.00
Pergamon Press Ltd

EVALUATION OF A METHOD FOR ESTIMATING POLLUTION CONCENTRATIONS DOWNWIND OF INFLUENCING BUILDINGS

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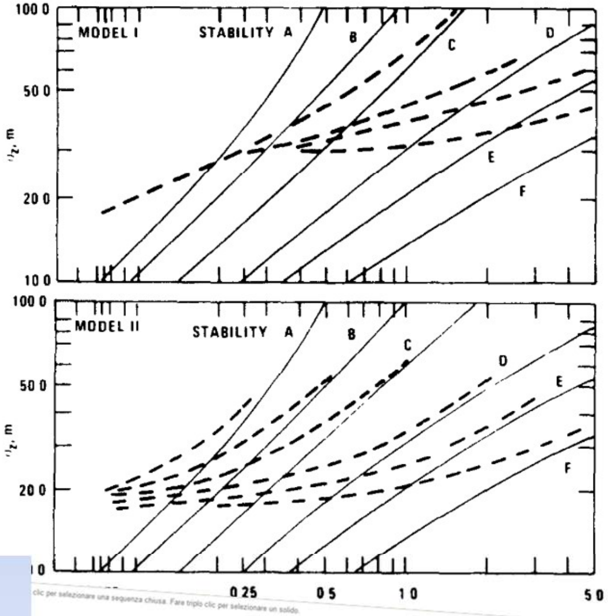
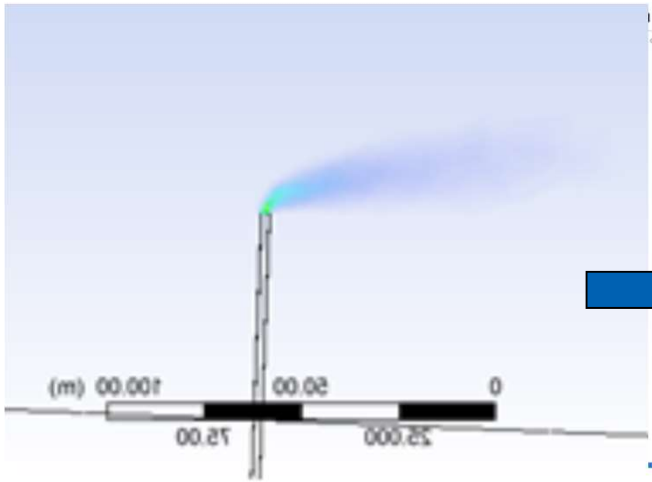
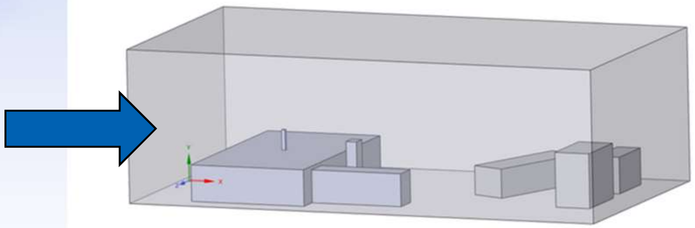
Meteorology and Assessment Division, Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, U.S.A.

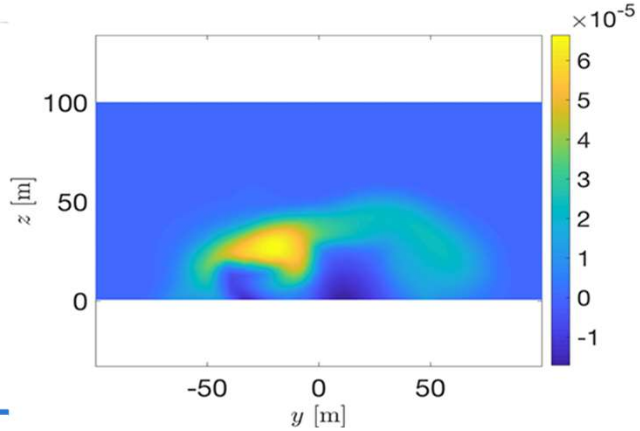
(*First received 7 September 1983 and in final form 30 April 1984*)



Study with Ansys Fluent (UniBas coll.) of the propagation and diffusion of radioactive gases emitted from the CNAO chimneys





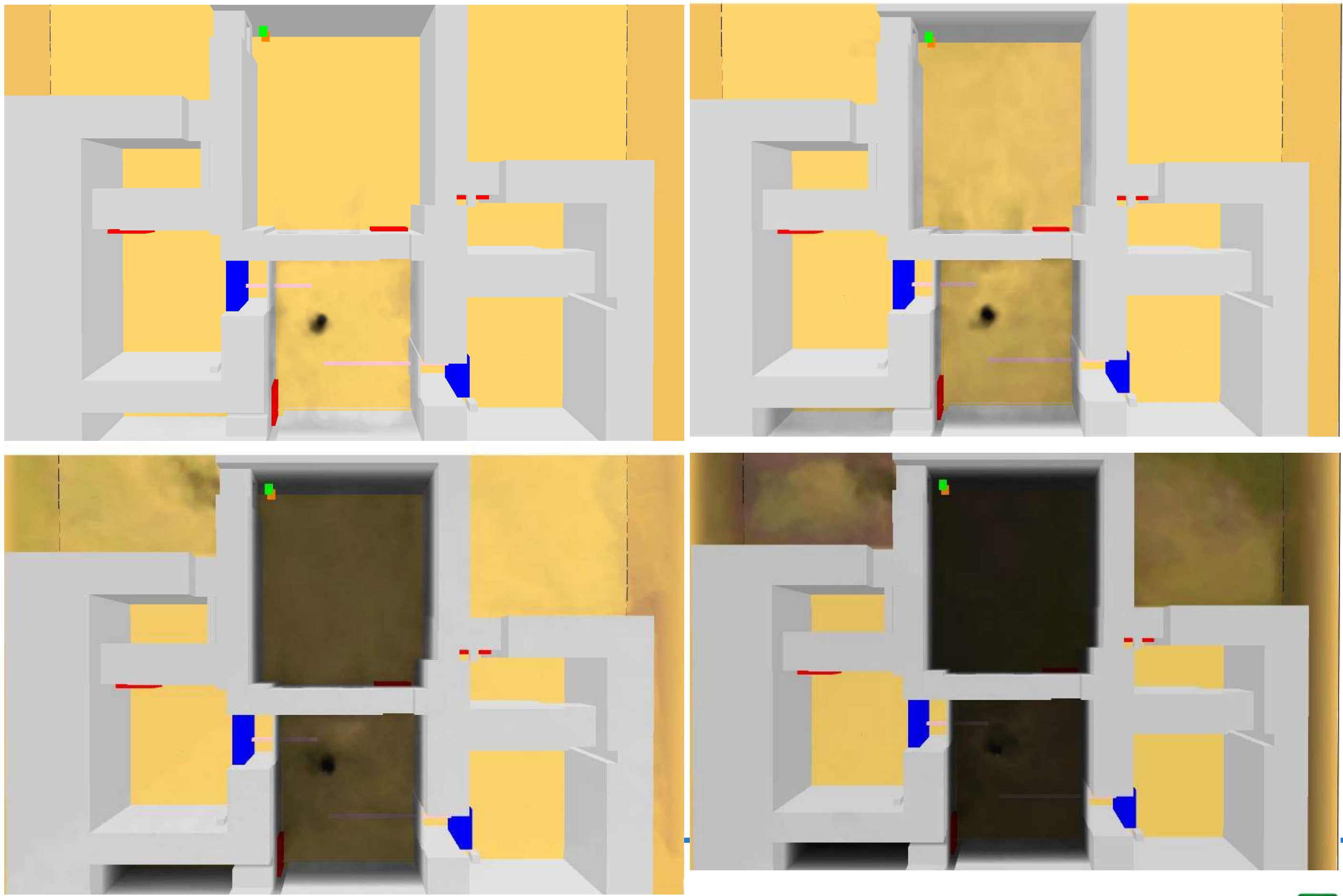


CFD model of the diffusion of radiactive gases during operation (Ph.D thesis, G.Giannattasio)

Fire safety issues ⇔external emergency plan -materials damage/dispersion

the "five-factor" formula: **MAR*ST* DR* ARF*RF*LPF**

ST is the source term (Bq), MAR is the total available material-at-risk (Bq), DR is the damage ratio (no units), ARF is the airborne release fraction (no units), RF is the respirable fraction (no units), and LPF is the leak path factor (no units).



Direct calculation od LPF with FDS (Fire Dynamics Simulator), simulating the actual smoke dispersion with Navier/stokes equations

F.Schirinzi Master thesis - PoliMi

R&D ongoing - detectors

Need for:

-Passive (⇔ inexpensive) area dosemeters for environmental dosimetry (low dose rates integrated over a long time, eg. 3 months)

-Passive dosemeters fit for personal dosimetry of high energy mixed fields (low weight, reasonable LDL, wide energy range, able to detect high energy charged particles)

-Active area dosimeters able to work in pulsed/very intense fields

- Low budget (for wide dissemination all throughout the plant) photon and neutron detectors

fondazione CNAO ⇔ 20 years research pipeline with research and industrial partners (CERN, Polimi, UniPv, UniMi, MiAm, Else nuclear, etc…)

Neutron Detectors (commercial & homemade) for environmental dosimetry

Figure 3.6: On the left the monitor of a raspberry is shown, on the right the driver board interface indicates the total measured counts

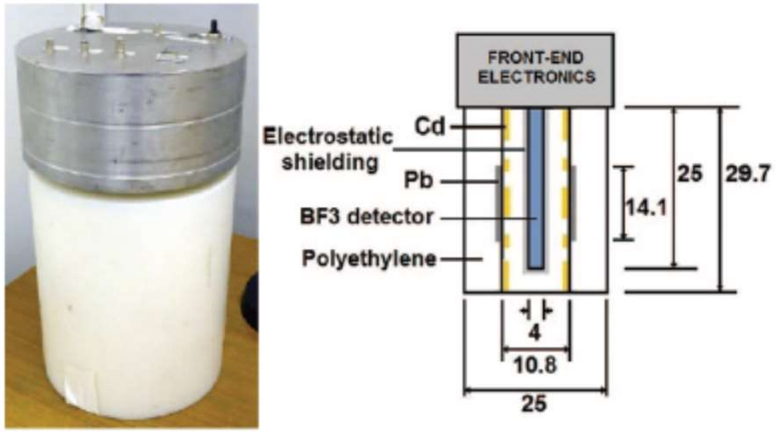
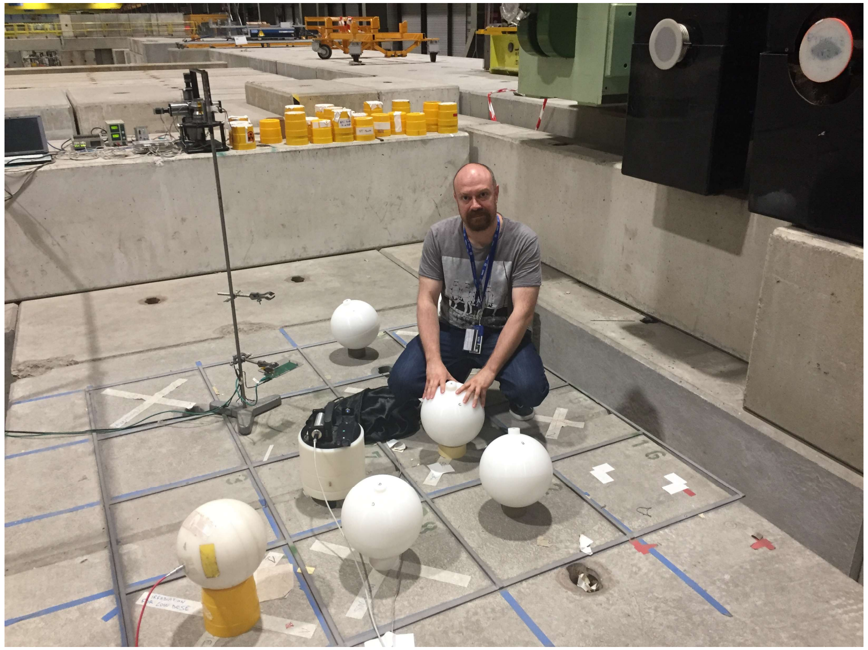


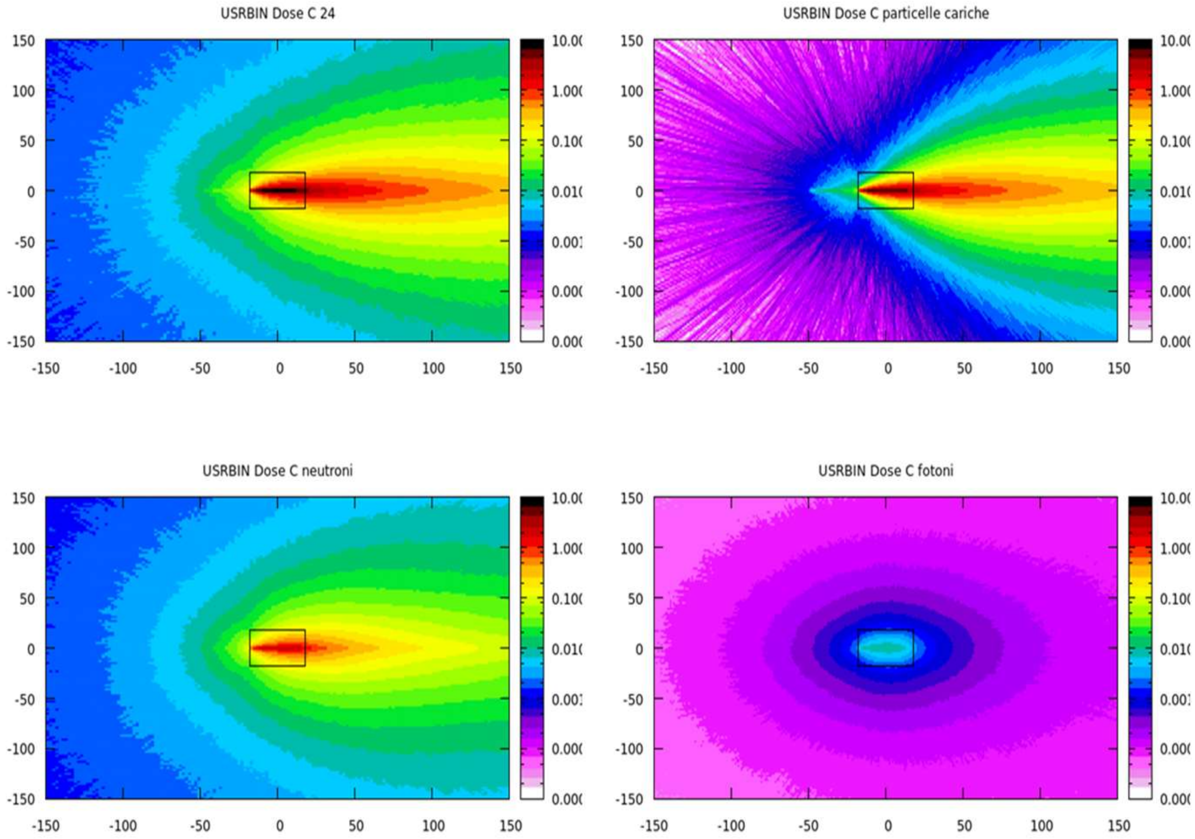
Figure 3.7: Photography of the LUPIN and its scheme

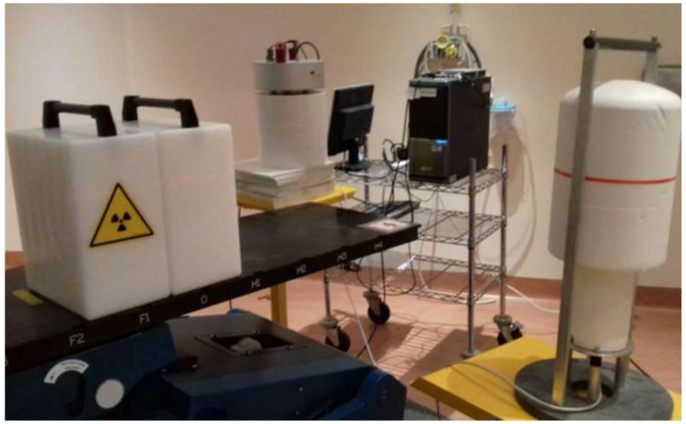
G.Manessi, PhD thesis, 2013



Test of detectors @CERN

Detectors response in high energy, very intense (or very low intensity), pulsed, mixed fields



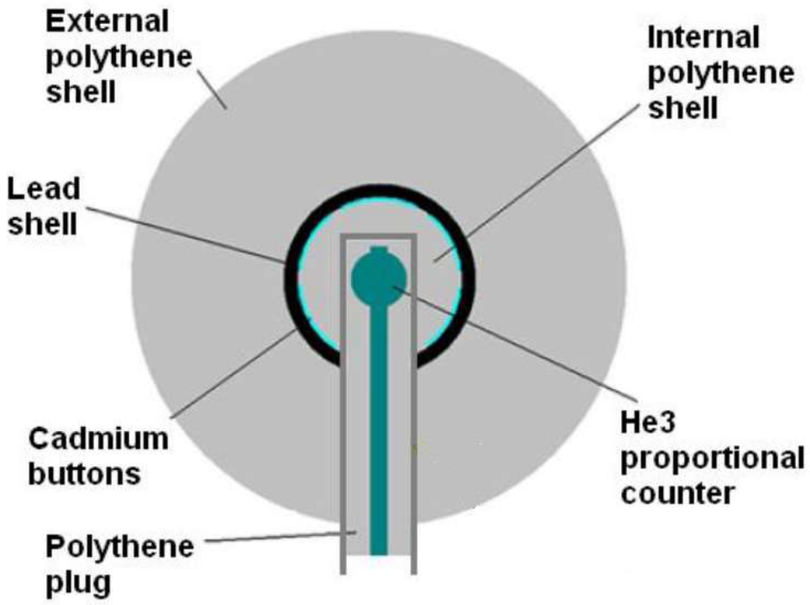


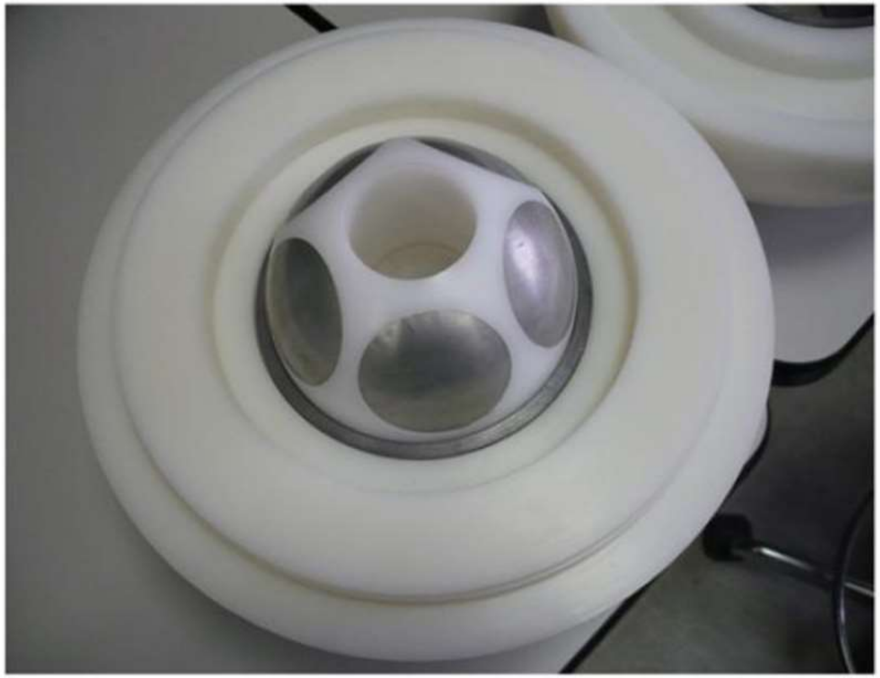
Instruments don’t (only) measure the particles they are designed for.

Outside the shielding, the main contribution to the ambient dose equivalent is due to the neutron component of the radiation field.

Inside the shielding, the dose due to secondary radiation is mainly due to charged particles.

F.Ferrulli, Master Thesis, PoliMi, 2019





0,025 eV-1 GeV

LDL ~ 3 μSv (passive version)

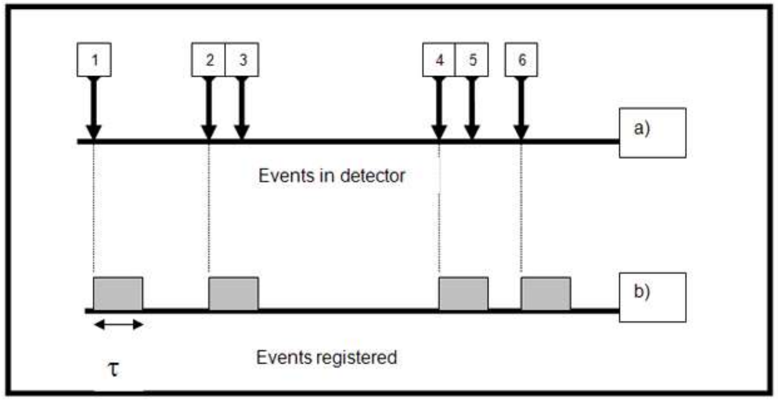
LDL ~ 3 nSv/h (active version)

It provides a cheap and reliable system for environmental neutron dosimetry

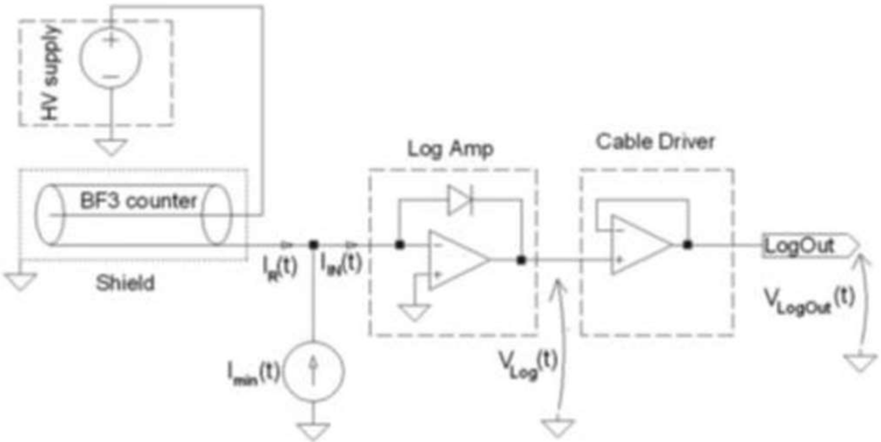
At CNAO a dense network of measuring points has been deployed

Saturation – very intense and pulsed fields

- **Pulse – operated active detectors (e.g. proportional counters) suffer from saturation due to dead-time effects . This is a typical issue in accelerator environment, where pulsed fields are very common.**



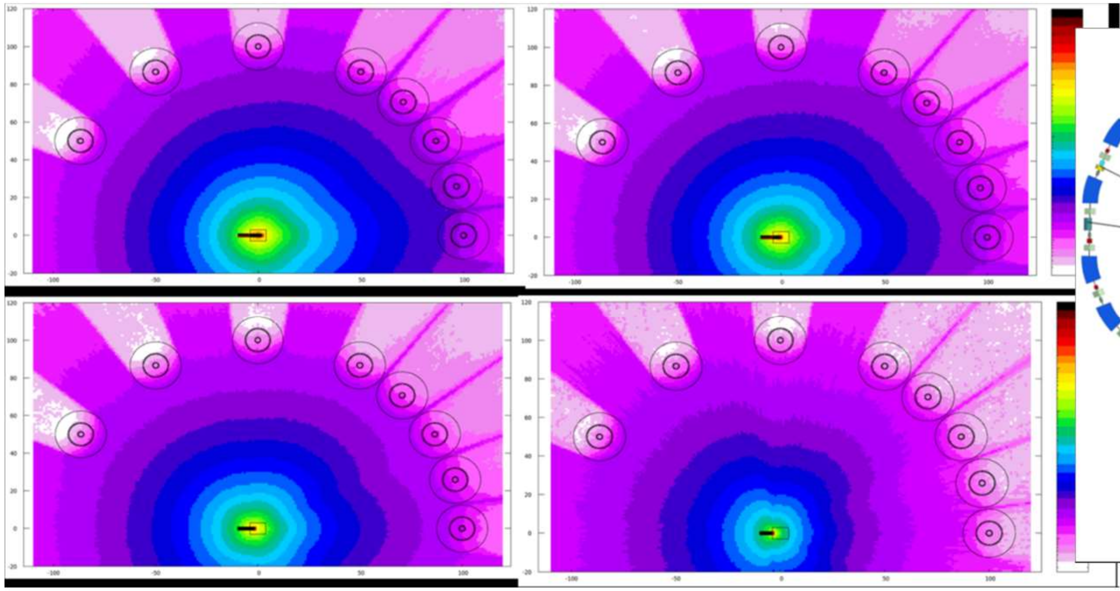
LUPIN (Long interval Ultra wide dinamic Pile-up free Neutron detector)



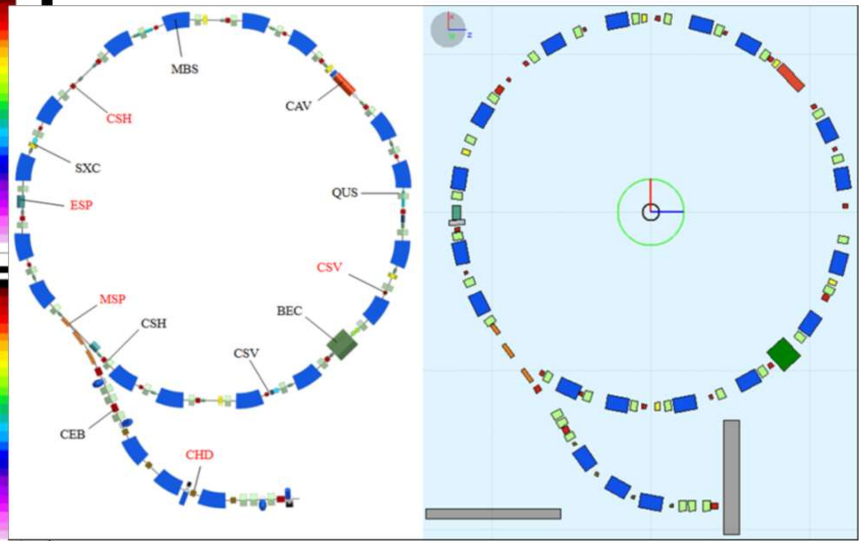
The BF3 detector is placed inside a cylindrical polyethylene moderator with a diameter of 35 cm.

The current released in a proportional counter creates a signal through a log Amplifier based front-end electronic. It is then sampled and integrated

Beam loss Monitoring



Picture FLUKA model



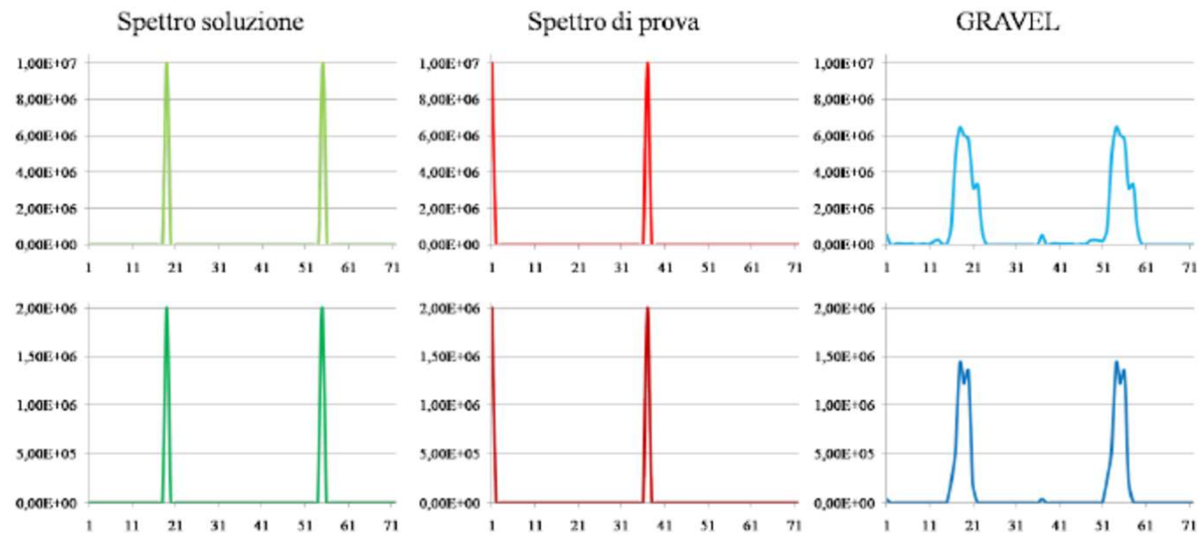
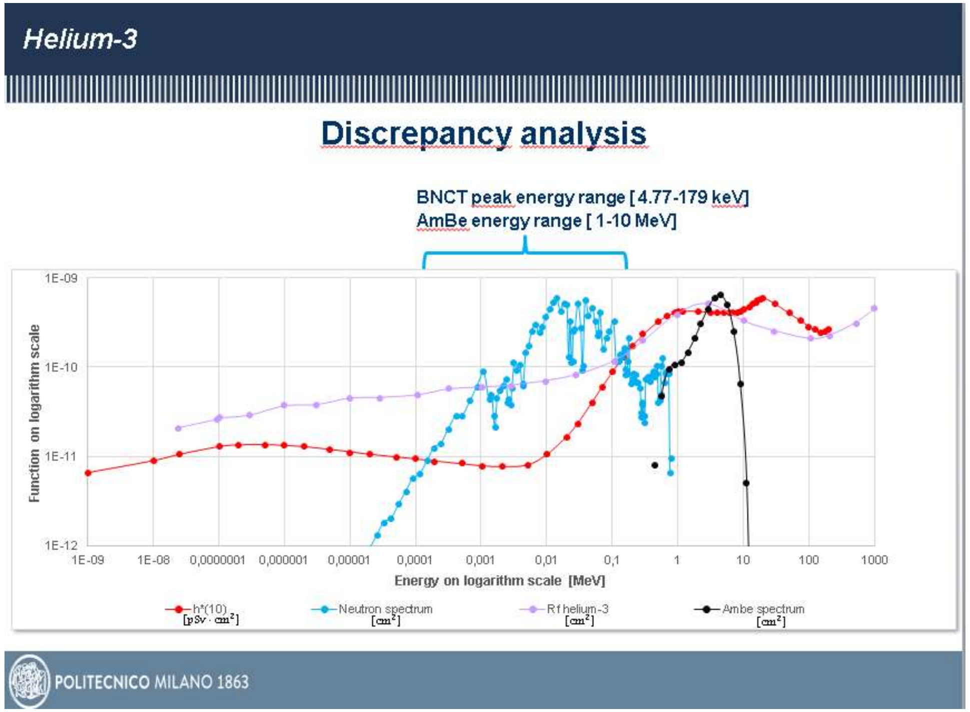


Figura 5.15. Risultati ottenuti con GRAVEL con perdita doppia sull'anello per spettro di default con perdite posizionate in 1 e 37 per protoni (in alto) e ioni carbonio.

Unfolding tecnique for beam loss monitoring based on neutron generation

M.Frosini, master Thesis, PoliMi, 2020

BNCT radiation fields: very intense, mixed (photon/neutron) radiation fields, atypical neutron energy range,



Conventional detectors in the (mixed - intense) BNCT range suffer from saturation, pile-up, and work in an atypical energy range.

Their response is not straightforward

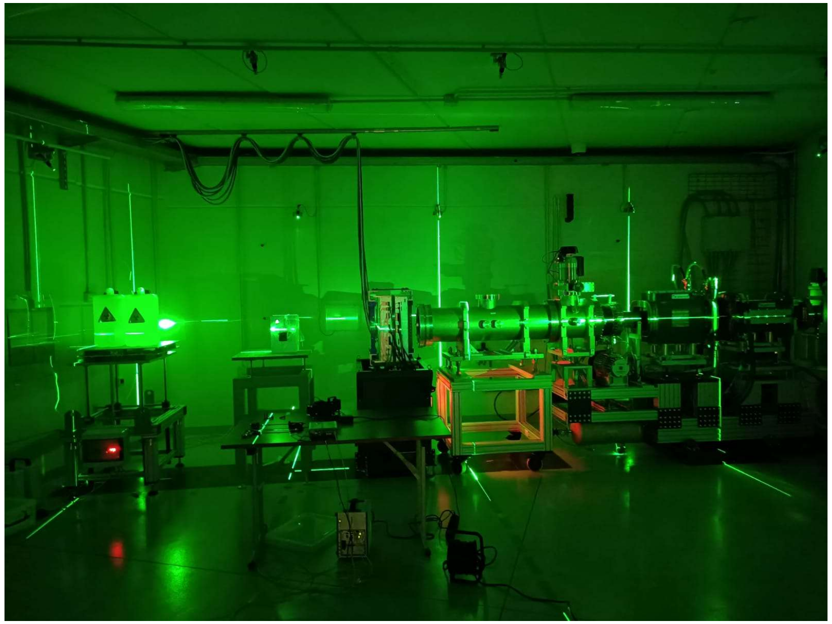
Kind of neutron detectors to be used inside a BNCT

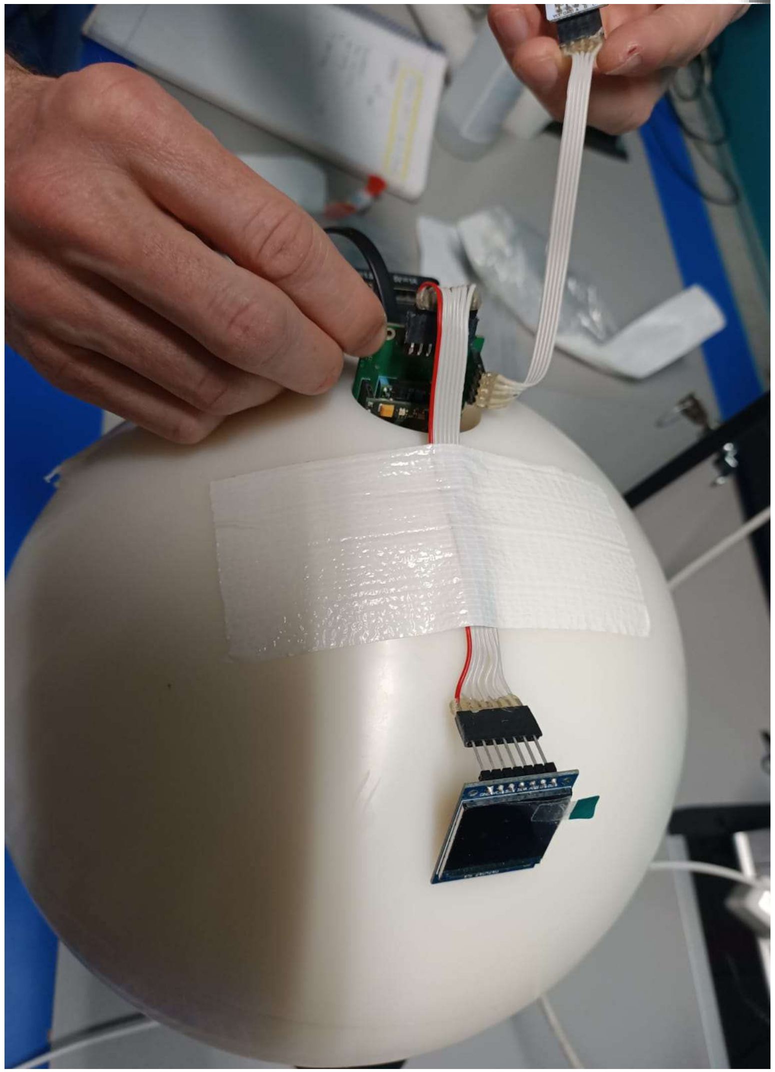
	Diode	LUPIN		Helium-3
		Streaming	Derivative	
Calibration Coefficient	To be recalculated	To be recalculated	To be recalculated	To be recalculated
Neutron interaction rate	Saturation	Adequate	Dead time losses	Saturation
Neutron-γ discrimination	Fail	Success	Not studied	Success

Table 6.1: Summary of the behaviour of the studied REM COUNTERs

SEAMUS? (IN2P3 collaboration)

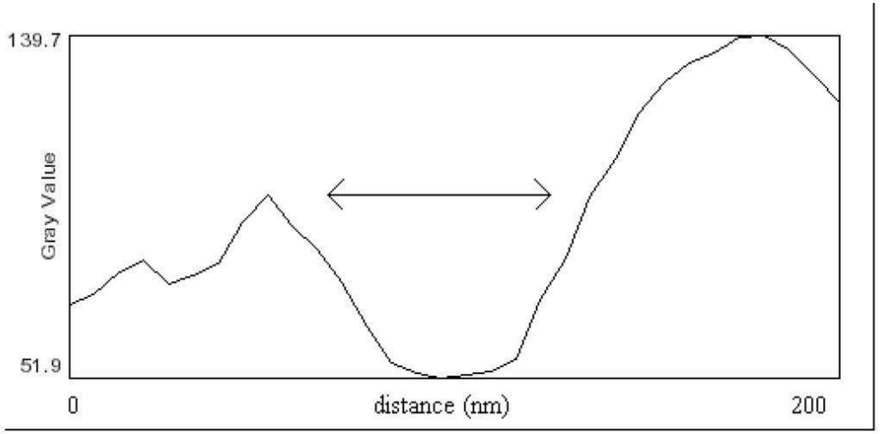
- Thought for low thermal neutron sensitivity
- Preliminary tests in CNAO XPR in April 23

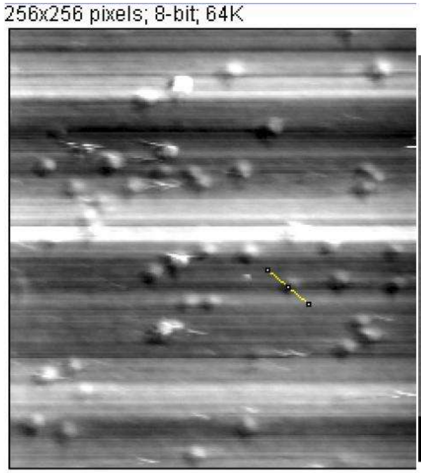


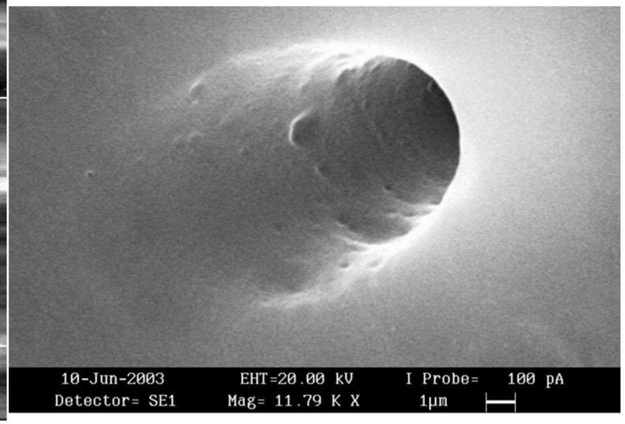


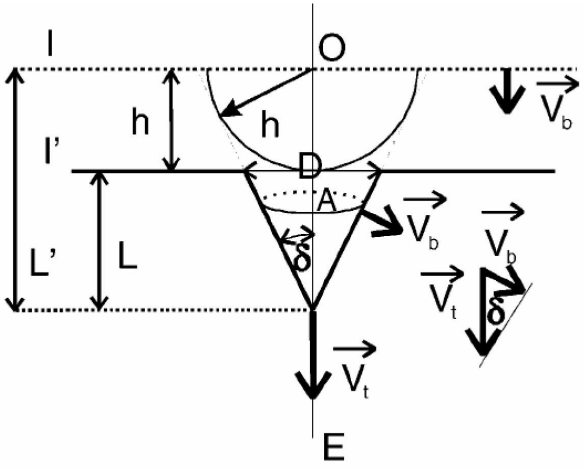
- Choice of the neutron converter ongoing

Nuclear track detectors









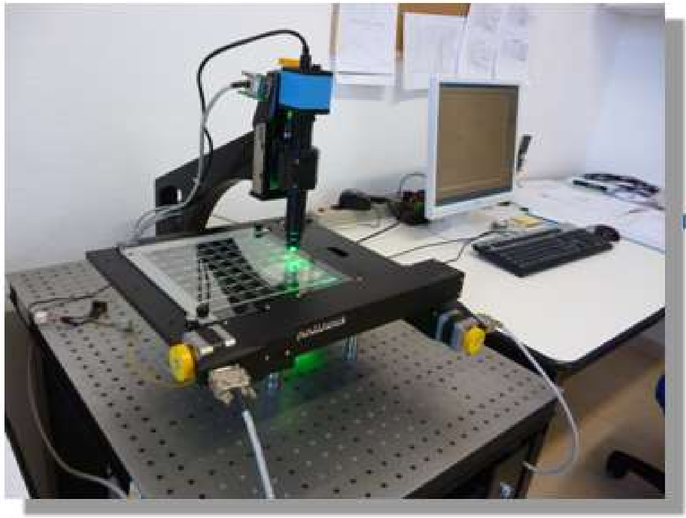
Sensitive to high LET radiation ⇔ heavy charged particles.
The particles create a column of damage in the material

The damaged area in the material is chemically etched and becomes a visible track (~20-70 µm)

Track Analysis and LET determination

www.cnao.it

CNAO PoliMi-Mi.Am srl cooperation

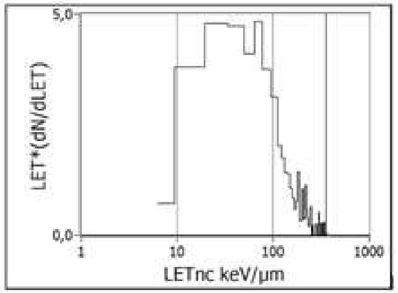


(a) Politrack™ SSNTD automatic reader

(b) Raw image captured with Politrack

(c) On line image analysis

(d) Measurement of D and d



(e) *LET* distribution (the suffix nc indicates that it is a quantity measured with Nuclear track detector CR39)

They can be used for personal dosimetry

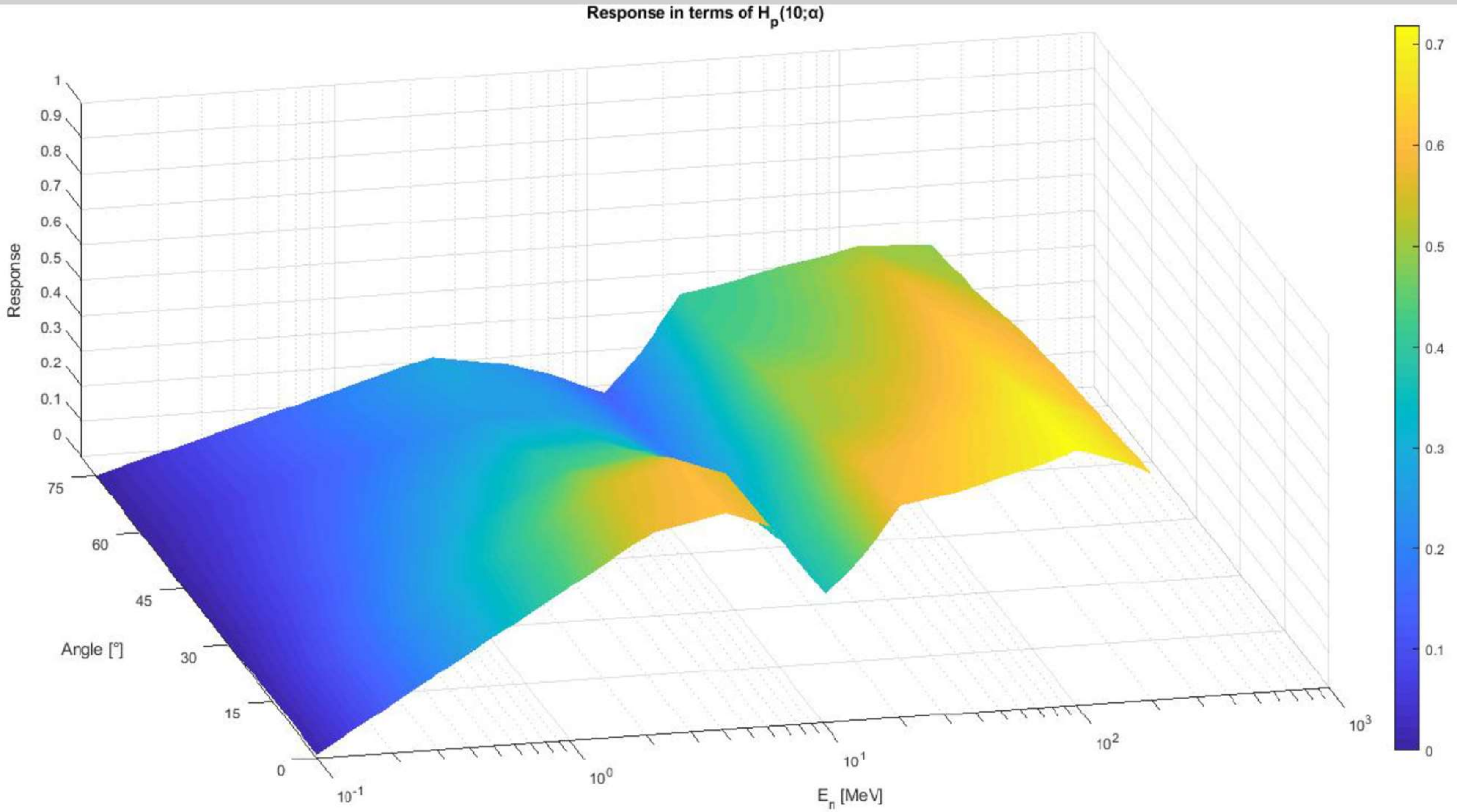
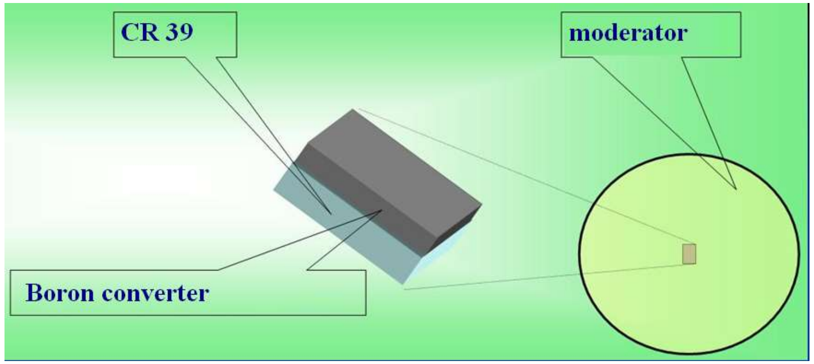


Figure 6.4 – *Dosimeter response in terms of* $H_p(10;\alpha)$ *as a function of angle and energy. The response value are shown both on the z-axis and through color. This 3D plot was drawn using MATLAB®. Notice that the ideal response would be a plane of equation* $z = 1$.

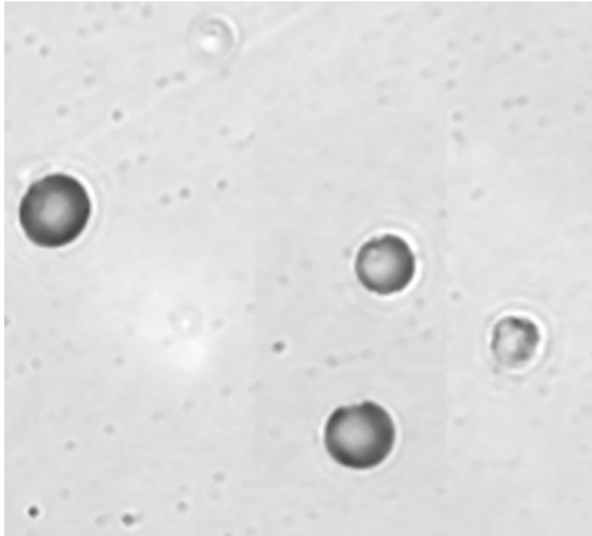
M.Bolzonella, master thesis, PoliMi, 2019

For environmental dosimetry- Passive rem counter



- The track detector is coupled to a boron converter, as thermal neutron detector (exploiting the n,α reaction on ^{10}B).

- The neutron is detected by the 1.47 MeV α particle. The number of tracks is proportional to the thermal neutron fluence at the center of the Rem counter



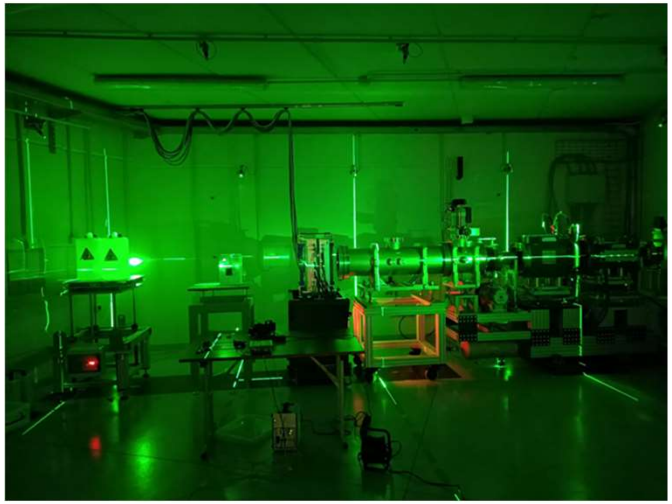
What’s going on?

- Radiation physics studies for BNCT (UniPv/LENA collaboration)
  (Master thesis, S.Azzolari 3/2026)
- OOF neutron dose evaluation and measurements in BNCT and Hadrontherapy treatment (E.Costanza, Master thesis, exp. 4/2027)
- Personal dosimetry with track detectors (coll. Mi.Am S.r.l)
- Environmental dosimetry high-intensity mixed neutron fields – radiation physics and neutron detectors design. (Progress Project, A.Martelengo, Else Solutions)
- Exhaust distribution evaluation with CFD (UniBas collaboration)
- Evaluation of special concretes for BNCT shielding
  (PoliMi collaboration, RadChem grup, + E. Truxi, master thesis, 3/20206)
- AI applications in RP evaluations and documentation
- (M.Grondona, Master thesis, exp. 11/2026)

Irradiations at CNAO.

At CNAO we have a list of possible beams ref. Sandro Rossi presentaton) with different parameters and (coming soon) epithermal neutron BNCT field. RP group, as researcher:,

- can provide several kind of instruments for cross check
- can provide a significant Monte Carlo dataset for the radiation field
- We are willing to cooperate for any radiation mesurements and detection experiments



As RPO office, for researchers coming to CNAO, we will have to ask for:

- The RP papers of the involved personnel (certiticates for medical fitness, RP training, classification, employers' authorization etc…)
- Parameters of the experiments, irradiated materials, etc..
- We will ask you to attend the CNAO online RP training

IRRADIATIONS @CNAO – Materials clearance

We operate all of our facilities under a national Licence, with prescriptions, ad we have very strict prescriptions about materials clearance.

For any irradiated object (and any object that has been exposed to a significant secondary radiation field) we must:

- Assess the activation, with a radionuclide inventory (also HTM, estimated by Monte Carlo simulations)
- Verify the estimates with HPGe measurements (i.e. estimating the HpGe efficiency via Monte Carlo simulations)
- Check the surface contamination of any metallic object

Pls. beware: it takes some time.

- A Fluka Monte Carlo model of the experiment can help
- A detaild materials list can help
- By now, we are not authorized to release liquids

- What we cannot release in clearance regime requires a radiation transport

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Thanks for your attention

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