Presentation of TOF-DONES

E. Mendoza, D. Cano-Ott
Nuclear Innovation Unit – CIEMAT

on behalf of the Spanish Nuclear Physics Network
fNUC@DONES study group

Introduction

Accurate modelling of **neutron induced reactions** are important in various fields:

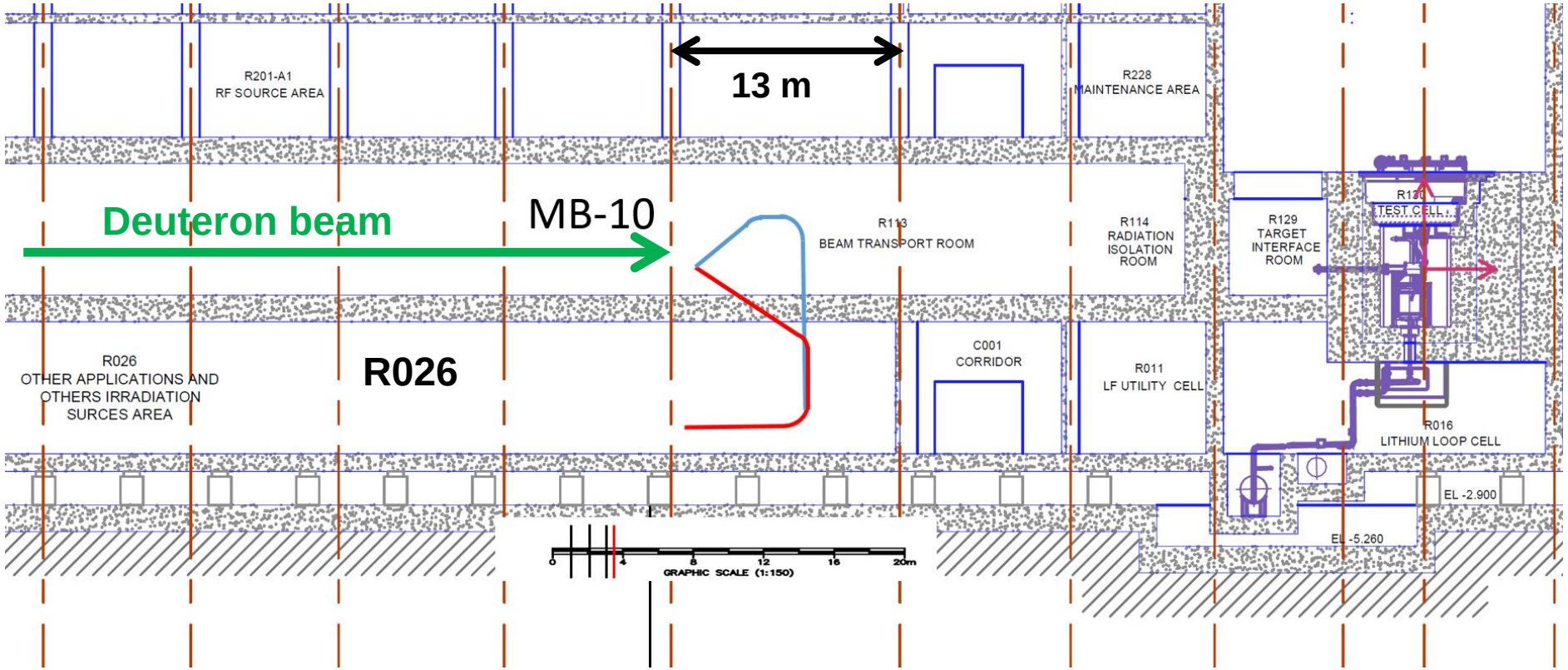
- Nuclear reactors
- Nuclear fusion
- Nuclear waste management strategies
- Nuclear inspection techniques
- Dosimetry
- Nuclear astrophysics
- Nuclear structure
- Production of radioisotopes for medical and technological applications
- …

Nuclear data underpin every application involving neutron transport. Actual nuclear models have a limited accuracy and predictive capabilities → experimental data is needed.

Neutrons cannot be accelerated nor deflected → the most widely used facilities to study neutron induced reactions as a function of the neutron energy are time-of-flight facilities.

The exceptional characteristics of the IFMIF-DONES accelerator offer a unique opportunity for building a world leading neutron time-of-flight facility.

Extraction of the deuteron beam



Vertical view

Deuteron beam → 0.1% duty cycle maximum
Deuteron pulses separated by 5.7 μs → 175/n kHz (n=1, 2, 3 …)

From the technical point of view, the extraction of the deuteron beam is probably the most challenging task for TOF-DONES

Extraction of the deuteron beam

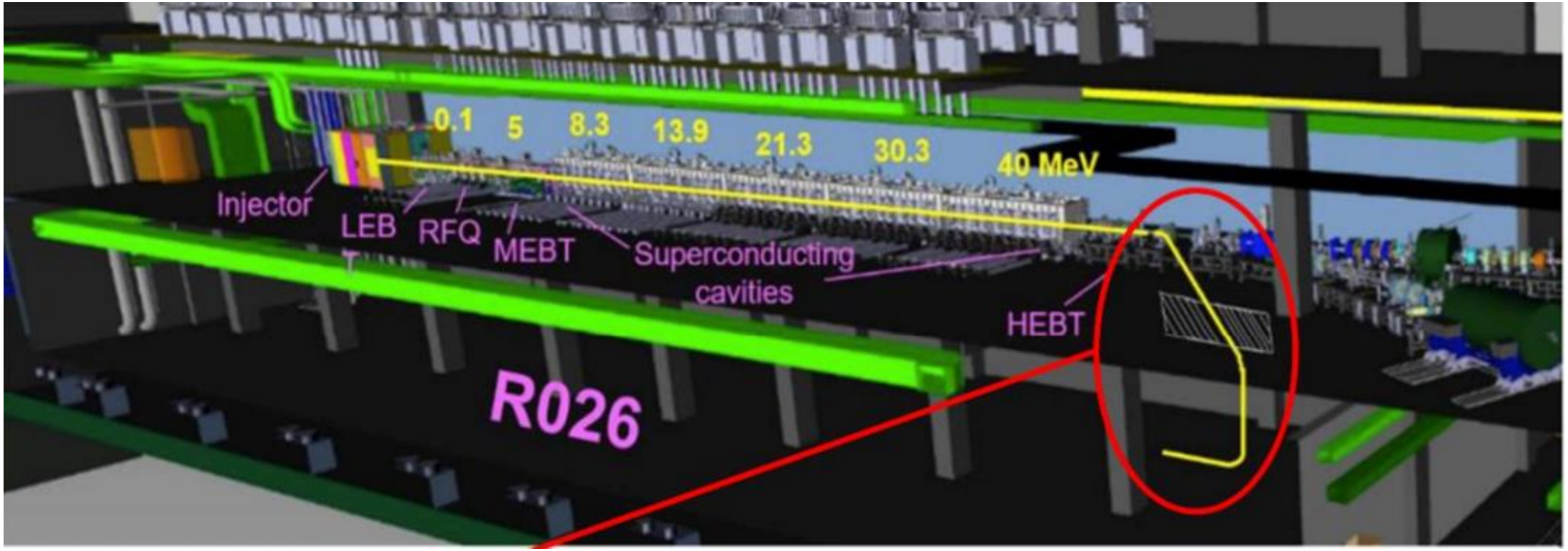
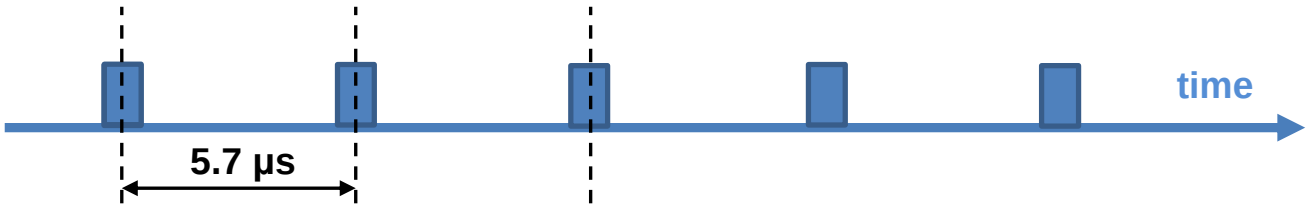
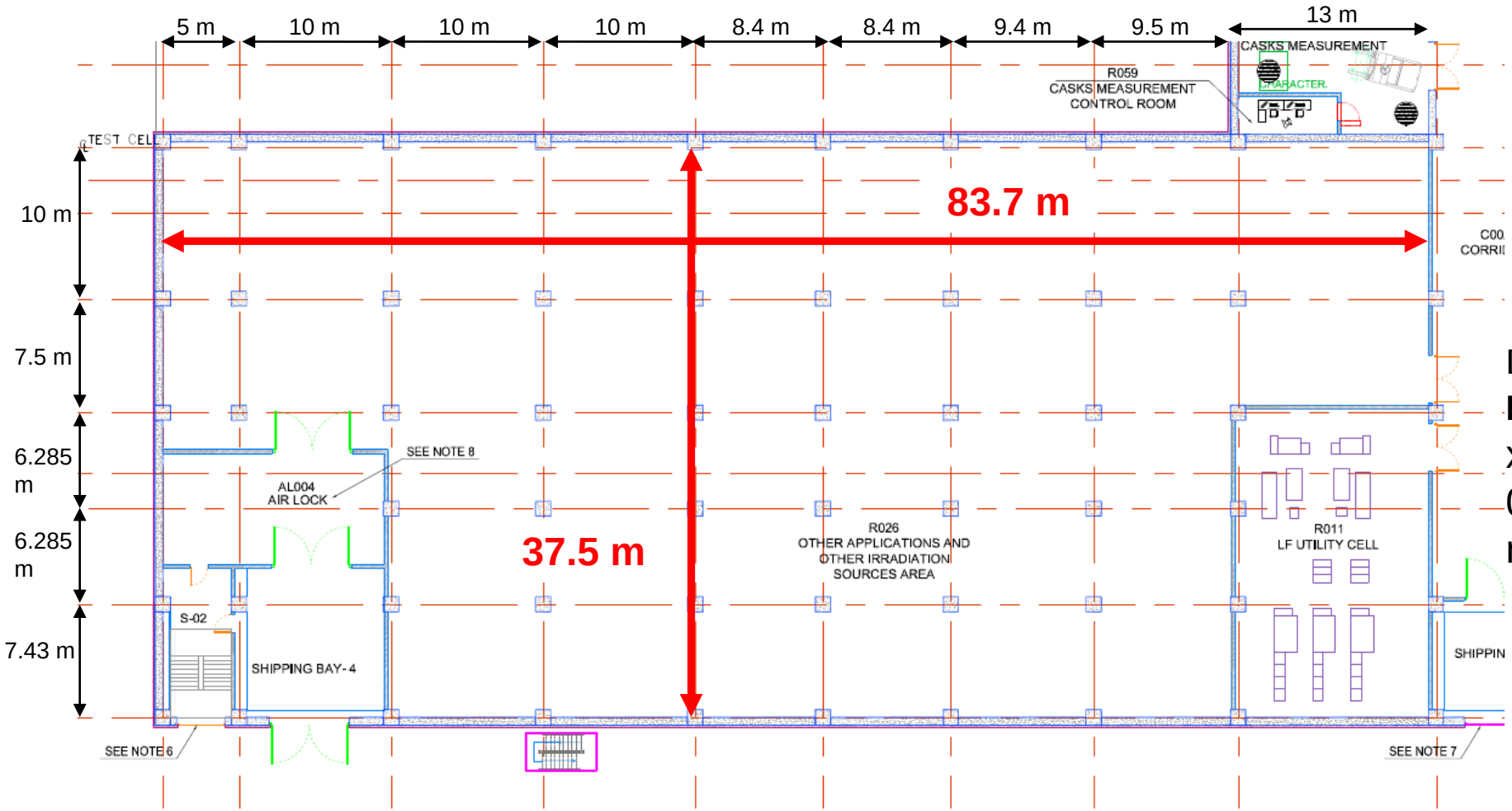


Figure from A. Maj et al., DONES non-Fusion Experimental Programme, DONES con P1 Deliverable 2.5 (2025).



From the technical point of view, the extraction of the deuteron beam is probably the most challenging task for TOF-DONES

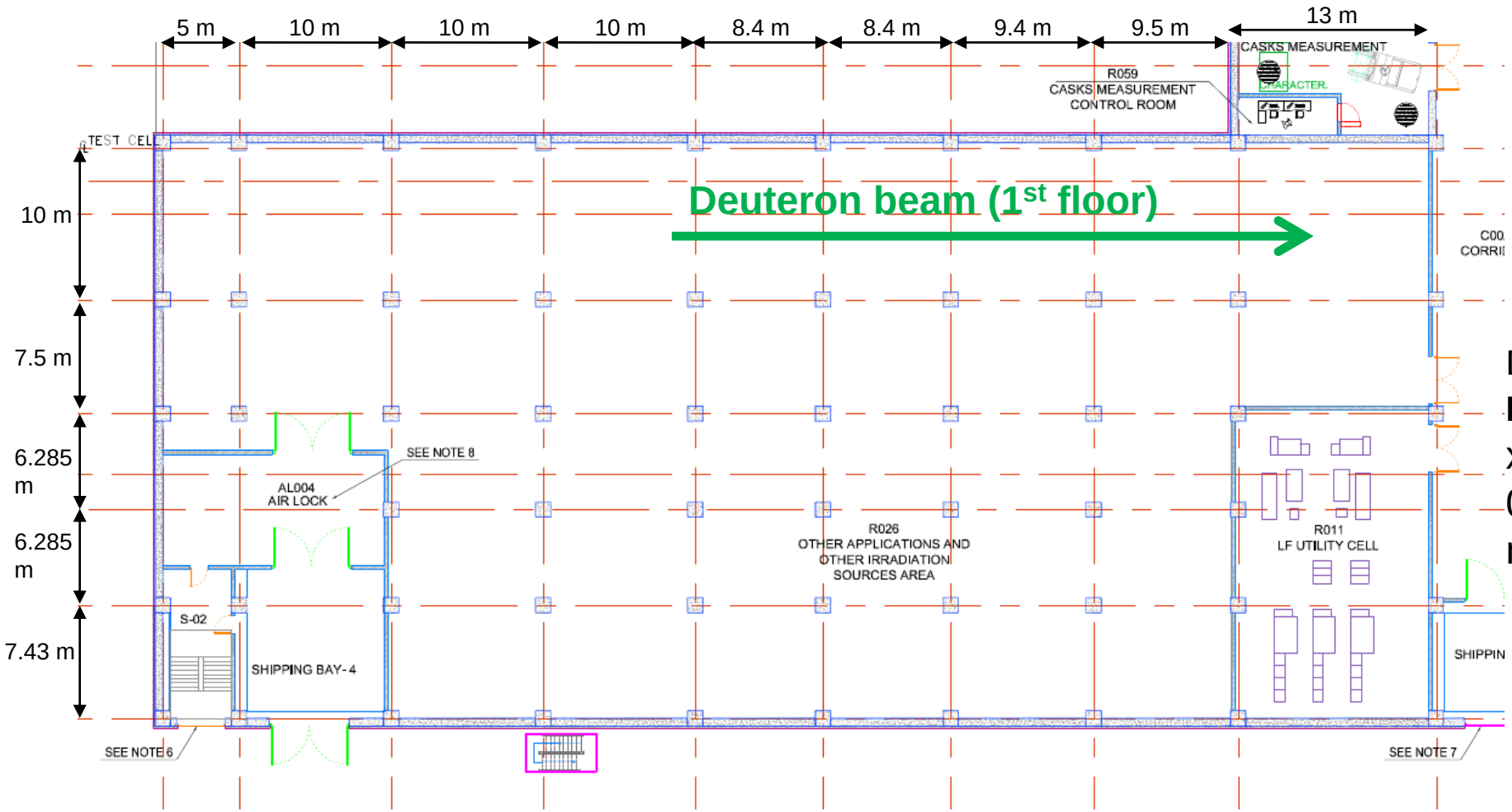
Dimensions of R026



Dimensions of **R026**: ~ 80 x 36 x 8 m^3
0.1% duty cycle maximum

The height of the room is 8 m

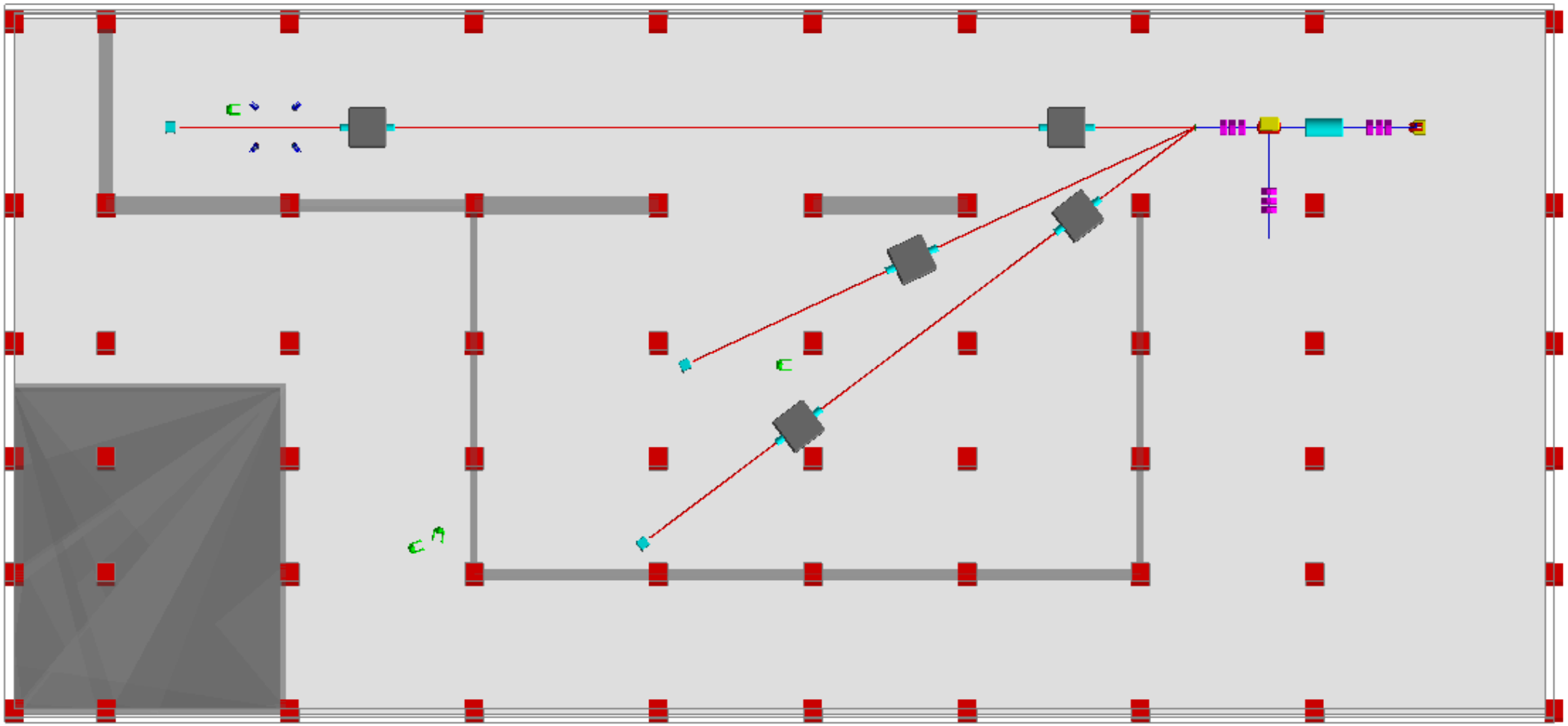
Dimensions of R026



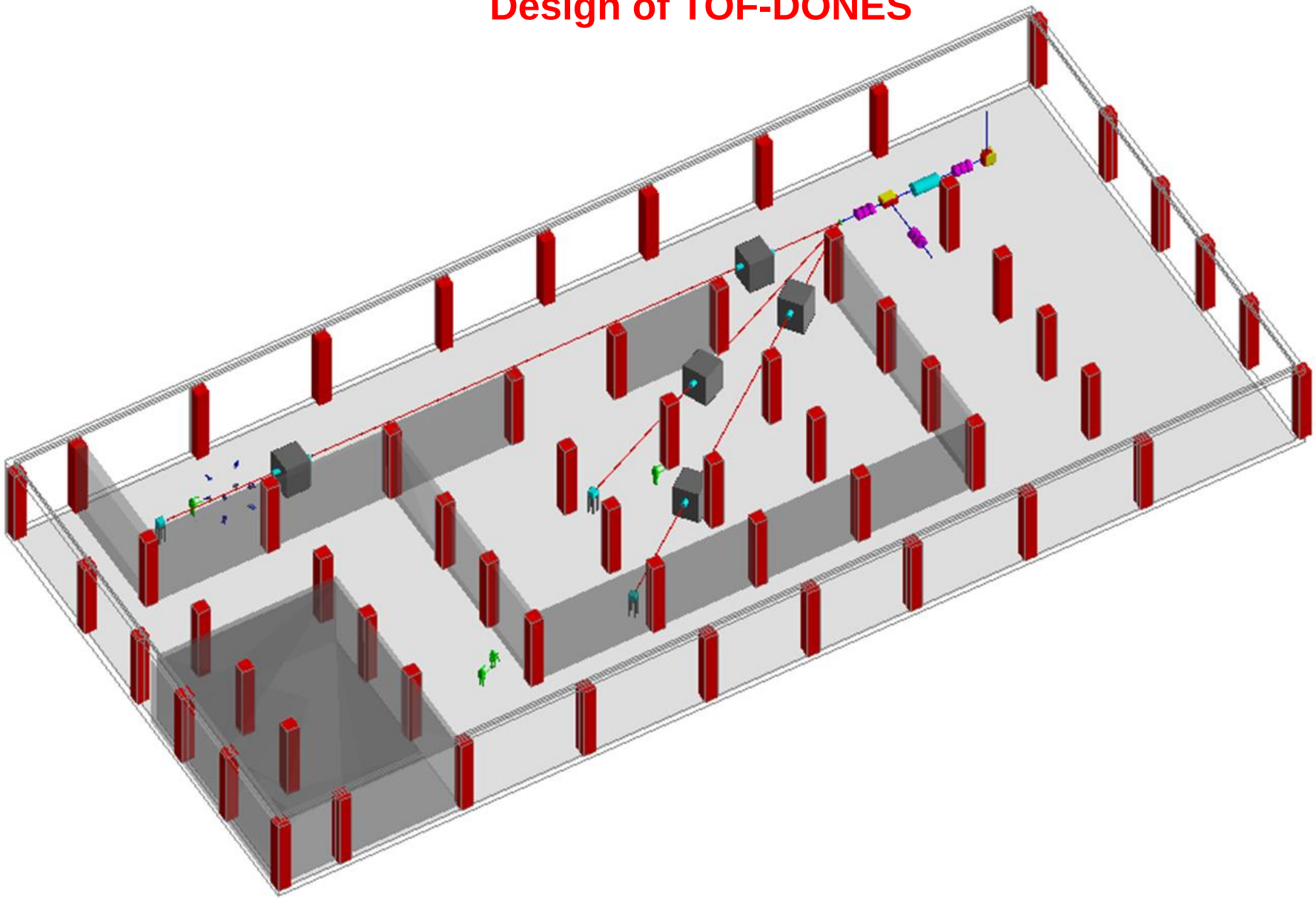
Dimensions of **R026**: ~ 80 x 36 x 8 m^3
0.1% duty cycle maximum

The height of the room is 8 m

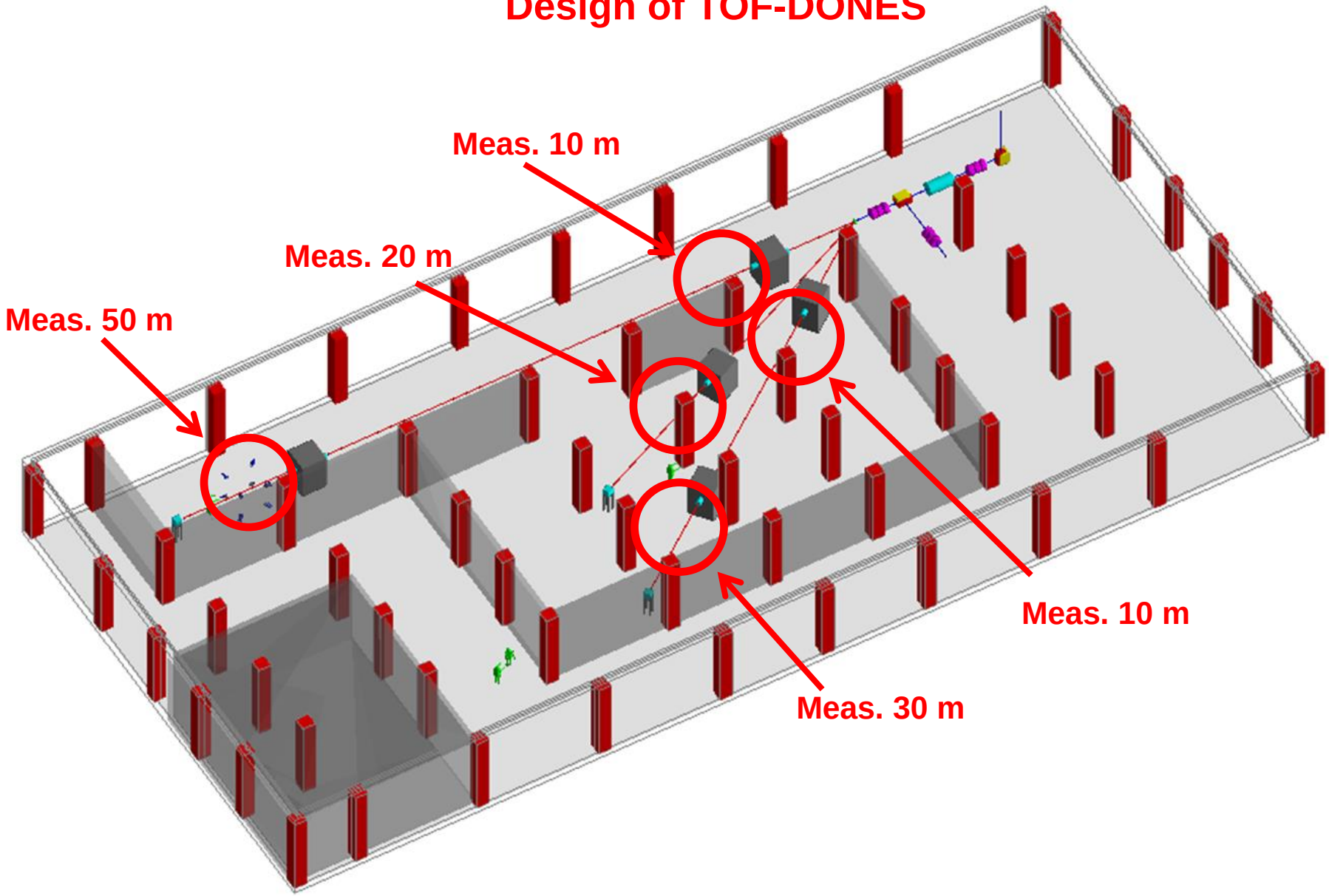
Design of TOF-DONES



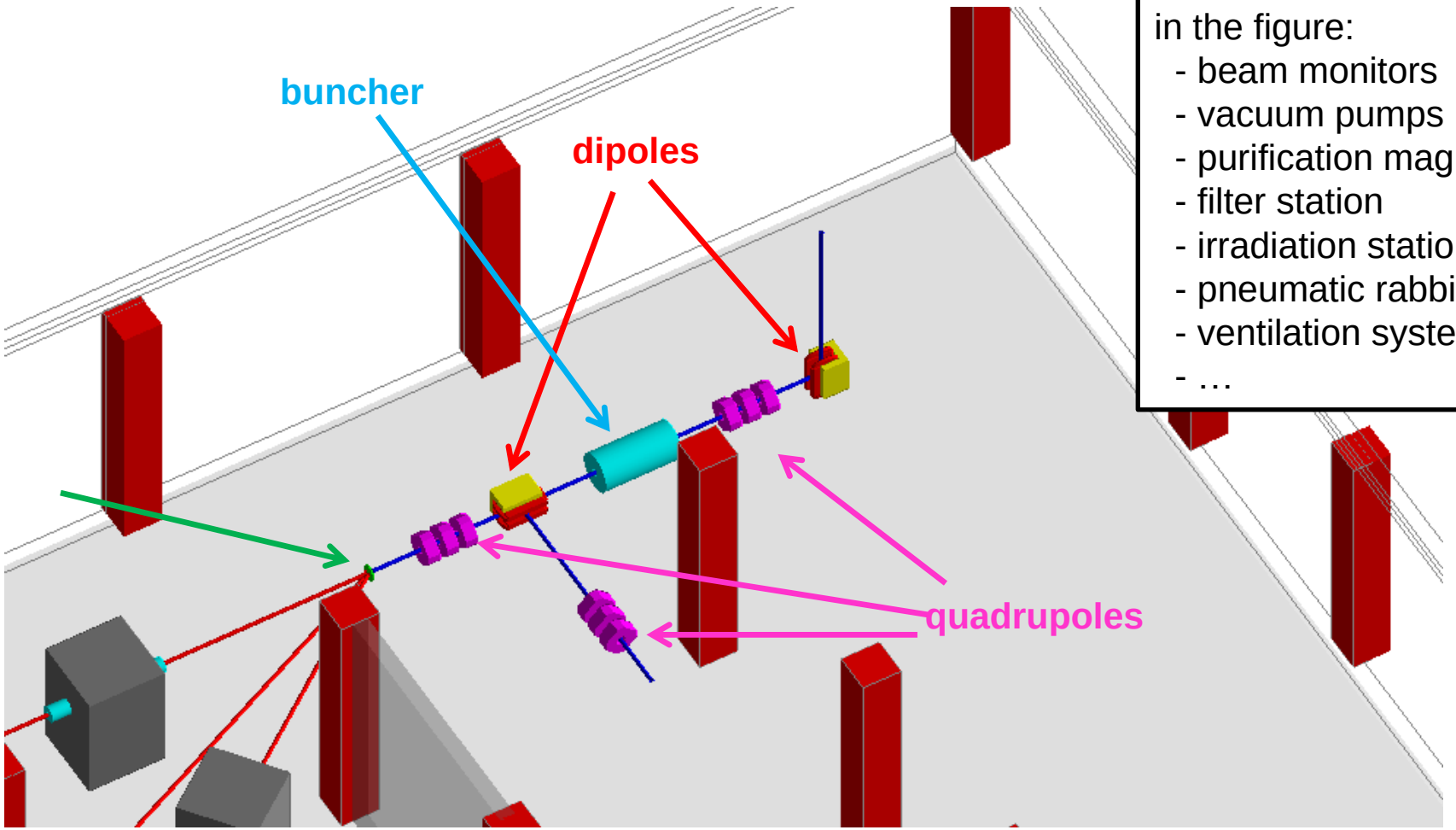
Design of TOF-DONES



Design of TOF-DONES

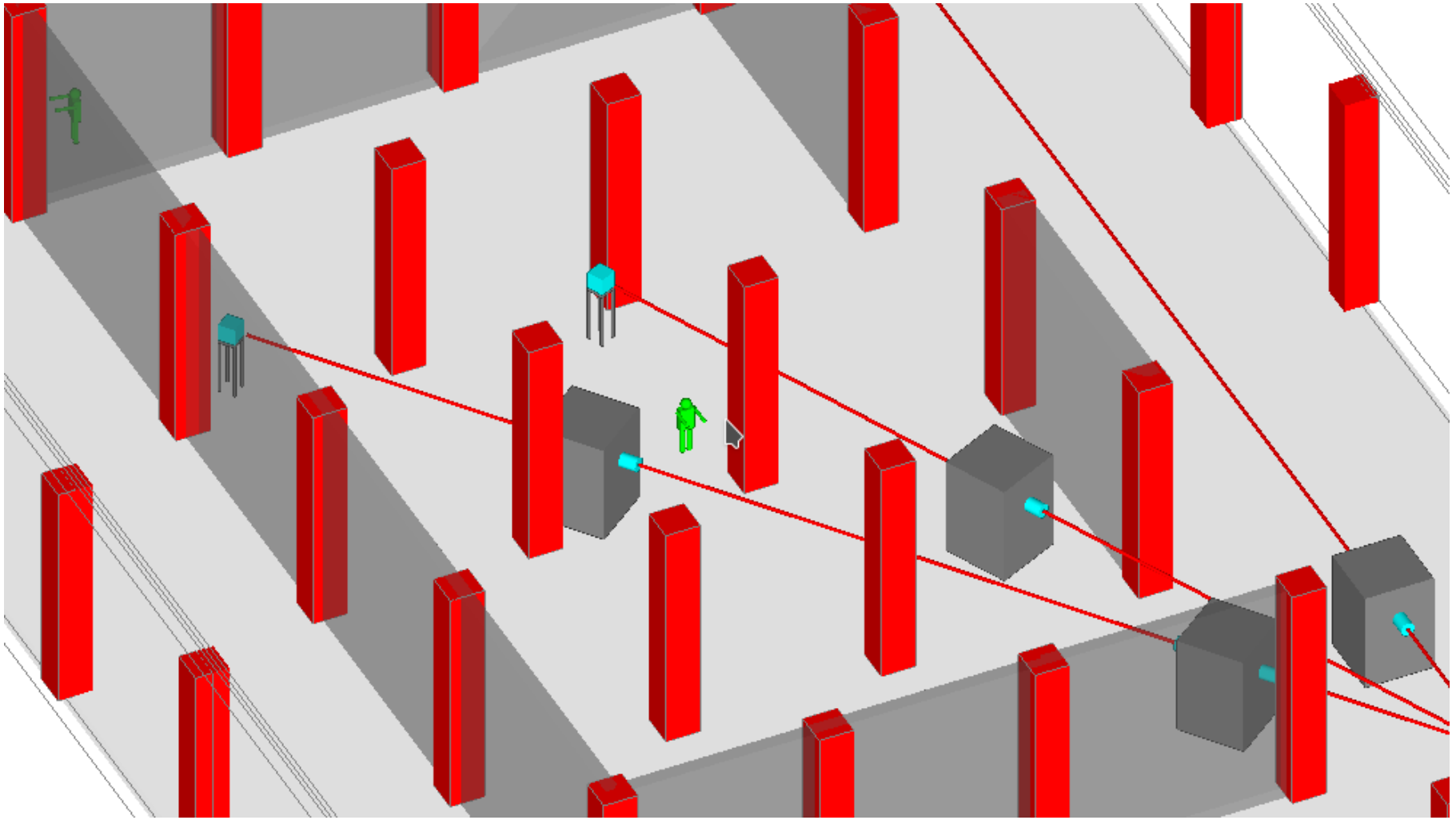


Design of TOF-DONES

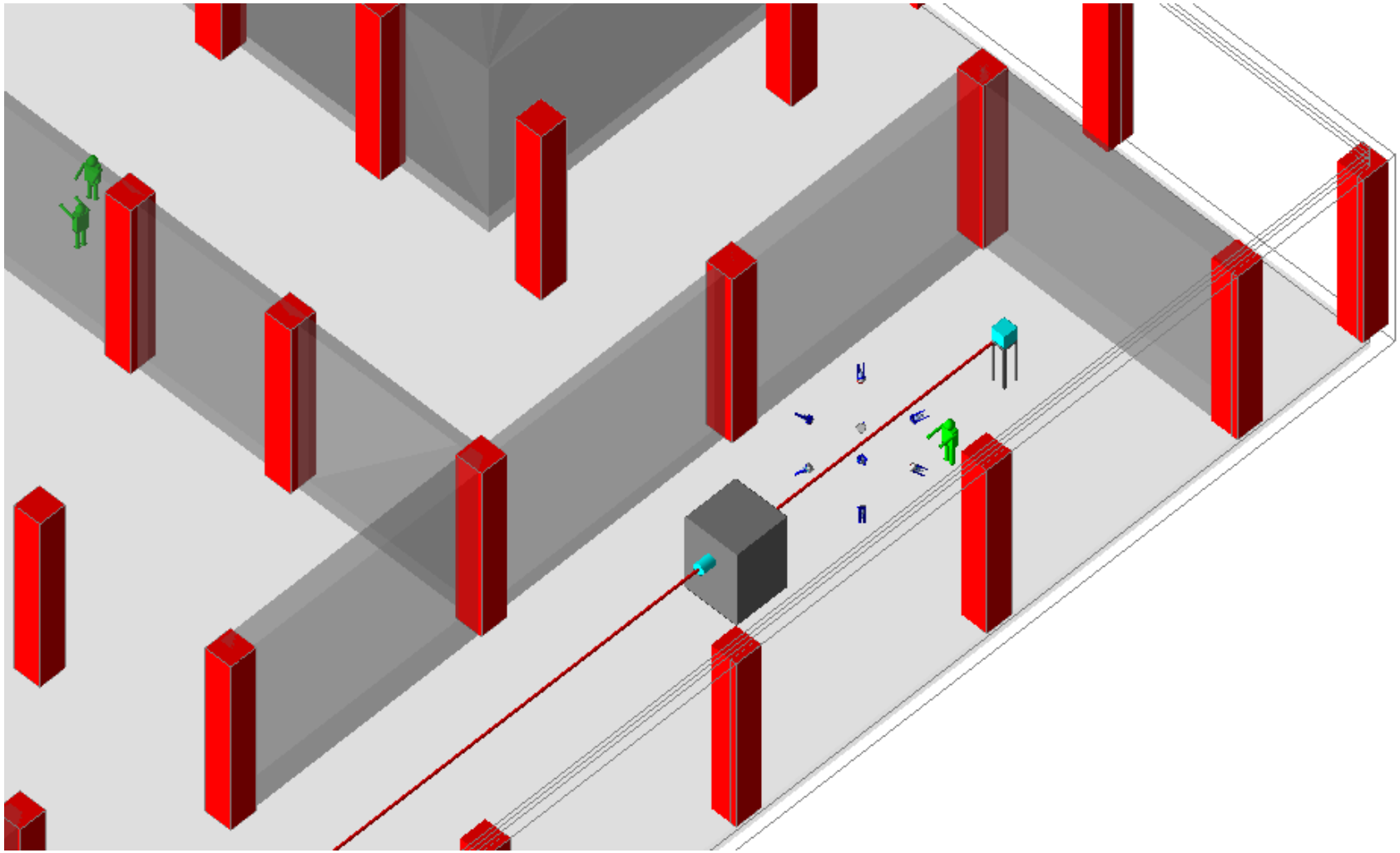


Other elements not included in the figure:
- beam monitors
- vacuum pumps
- purification magnets
- filter station
- irradiation station
- pneumatic rabbit system
- ventilation system
- …

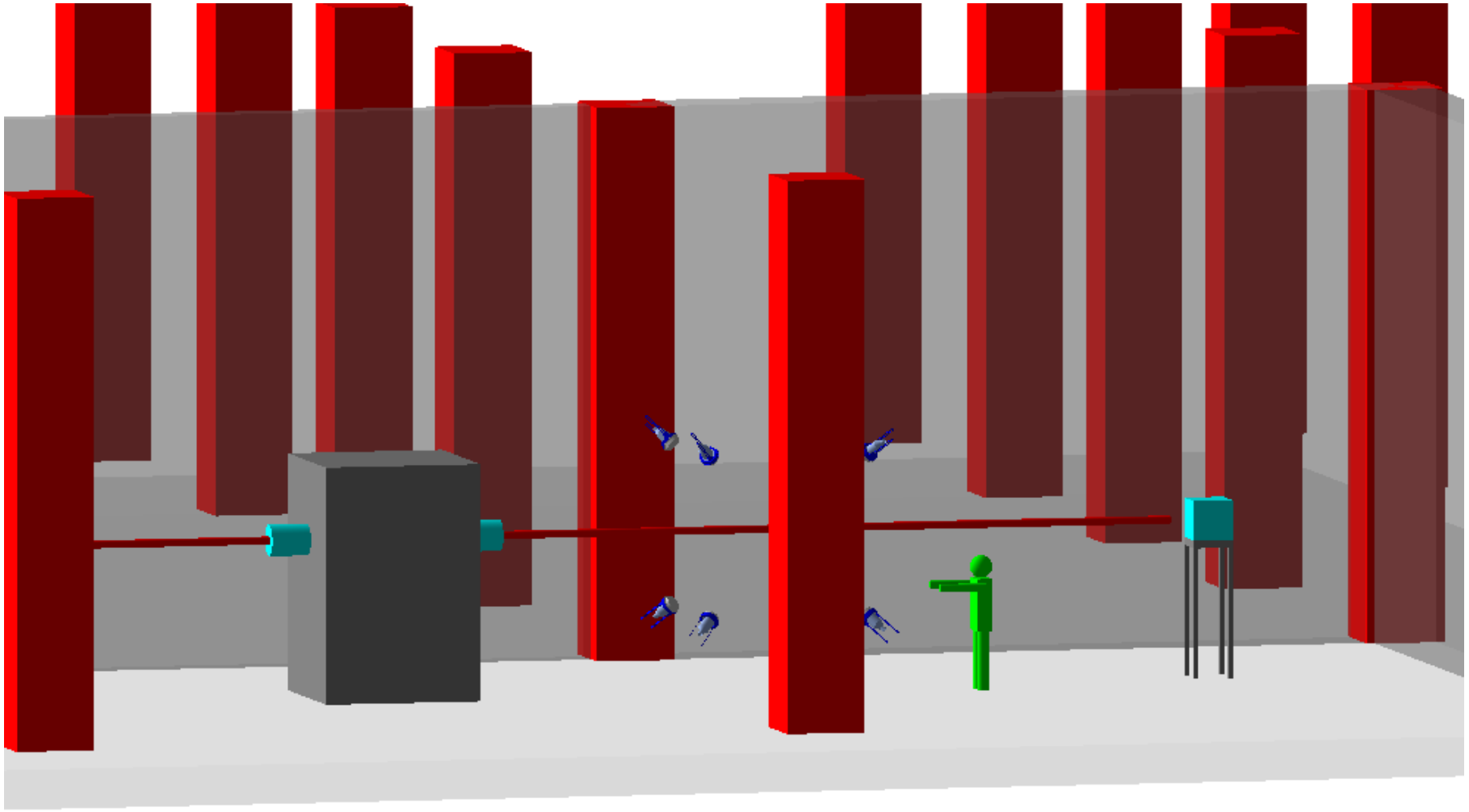
Design of TOF-DONES



Design of TOF-DONES



Design of TOF-DONES



Design of TOF-DONES

We have defined 5 different measuring stations, at:

- 10 m, 0 degree
- 10 m, 34 degrees

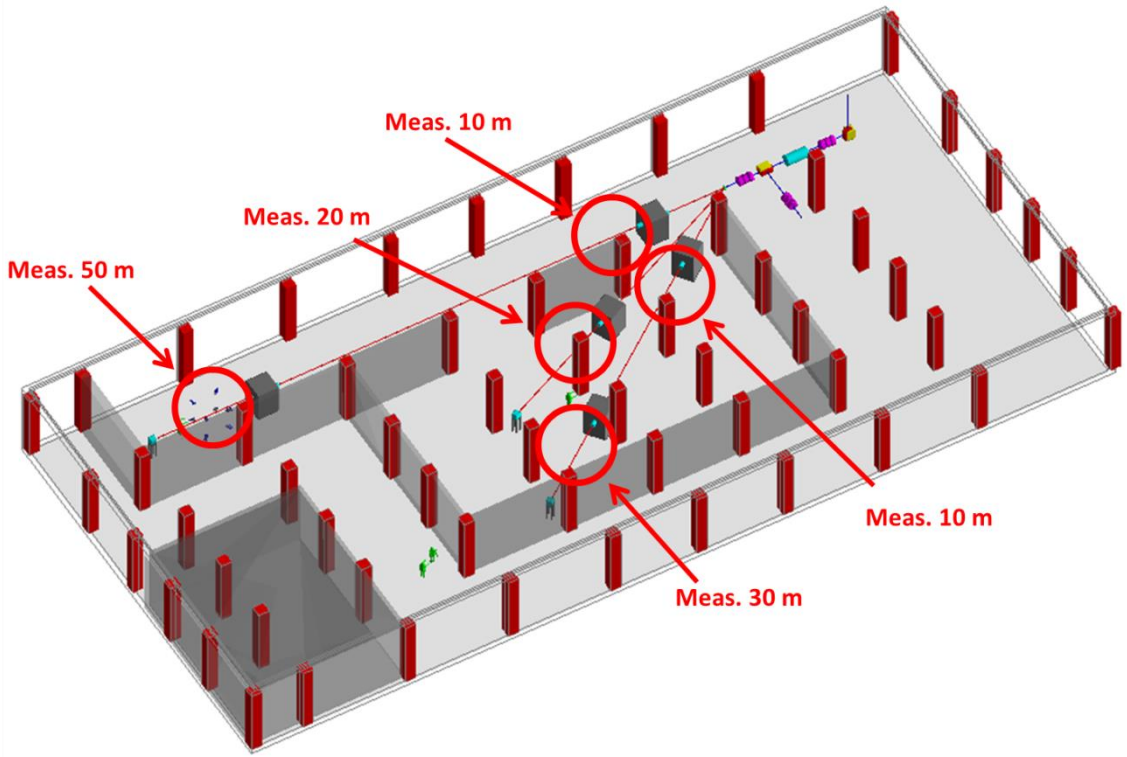
} High flux

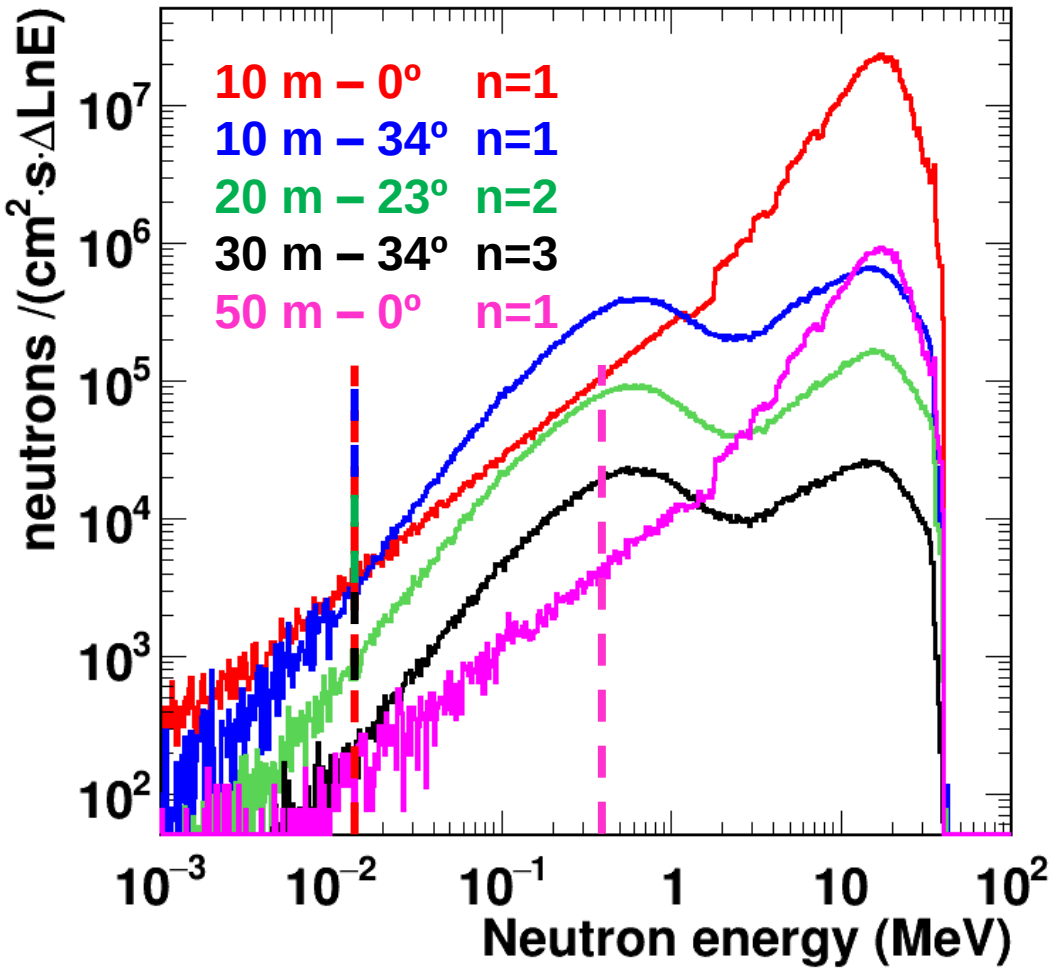
- 20 m, 23 degrees
- 30 m, 34 degrees

} Intermediate flux and energy resolution

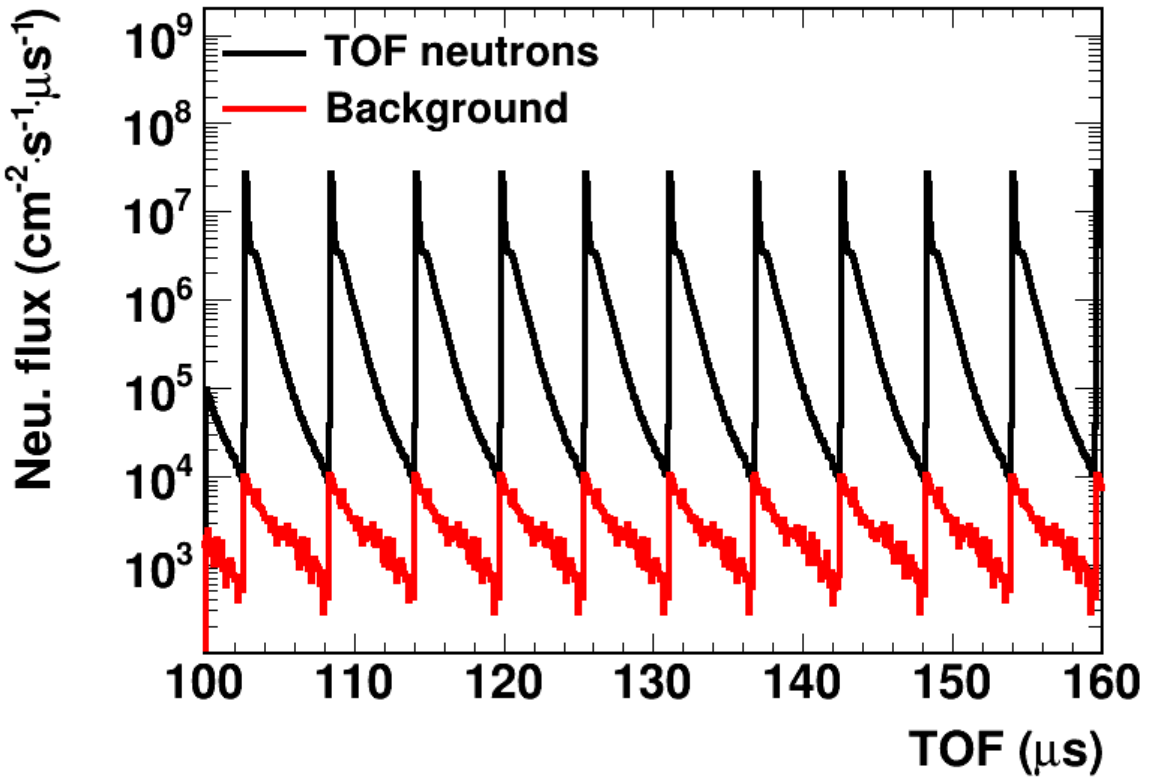
- 50 m, 0 degrees

} High energy resolution



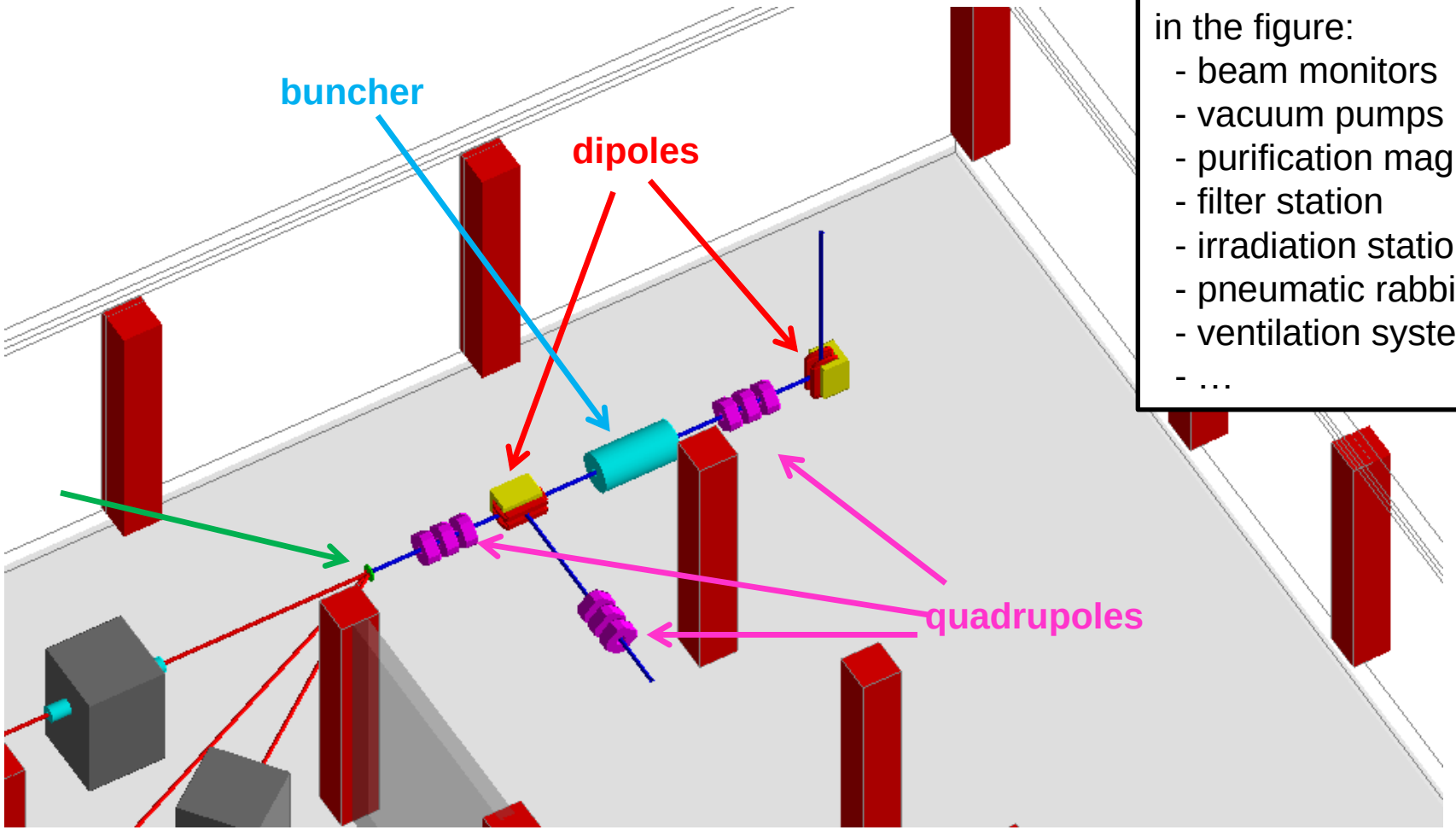


Time structure of the neutron beam



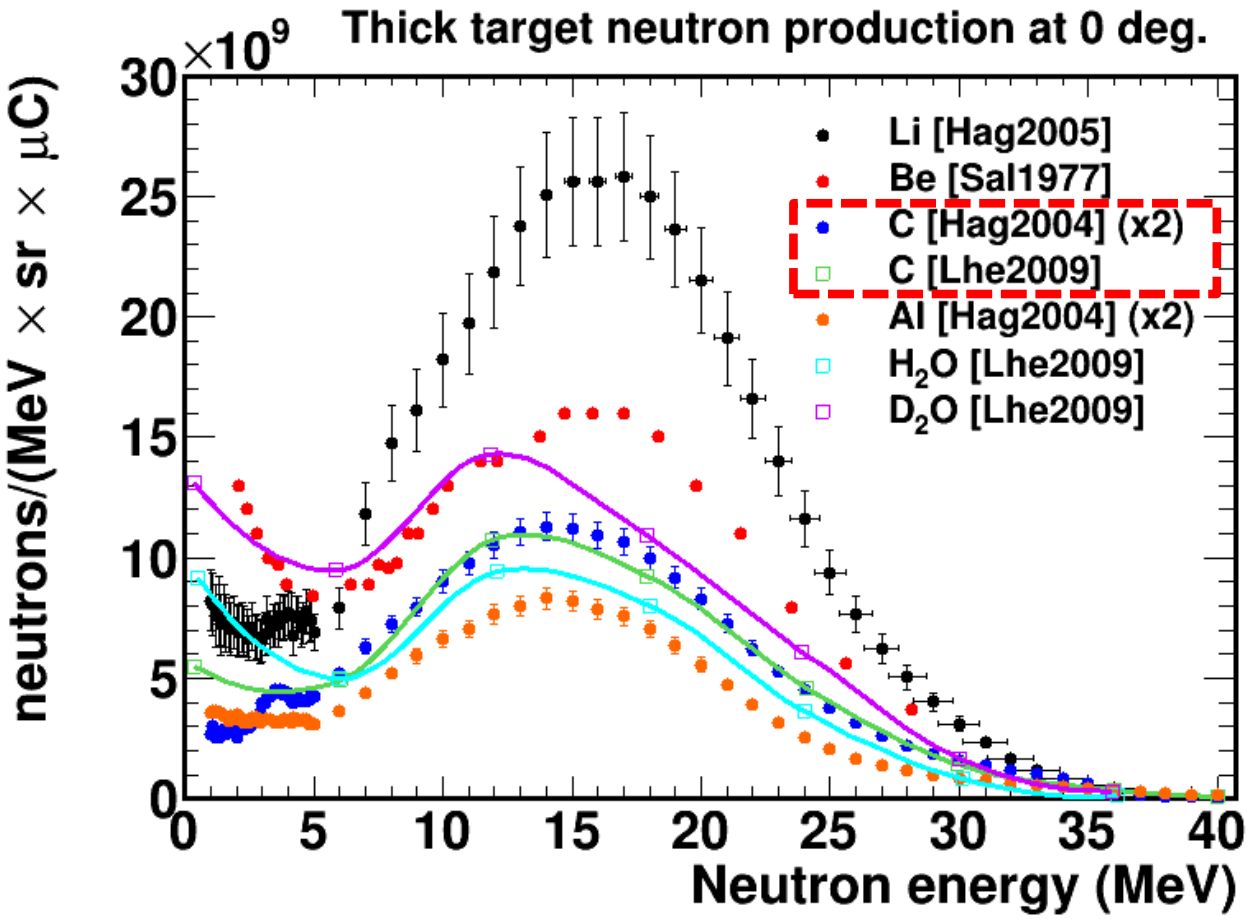
In the neutron beam, there will be some neutrons coming with the desired TOF-Energy relation (black) and other neutrons from other pulses → background (red). In the picture, n = 1 and the distance between pulses 5.7 μs (175 kHz).

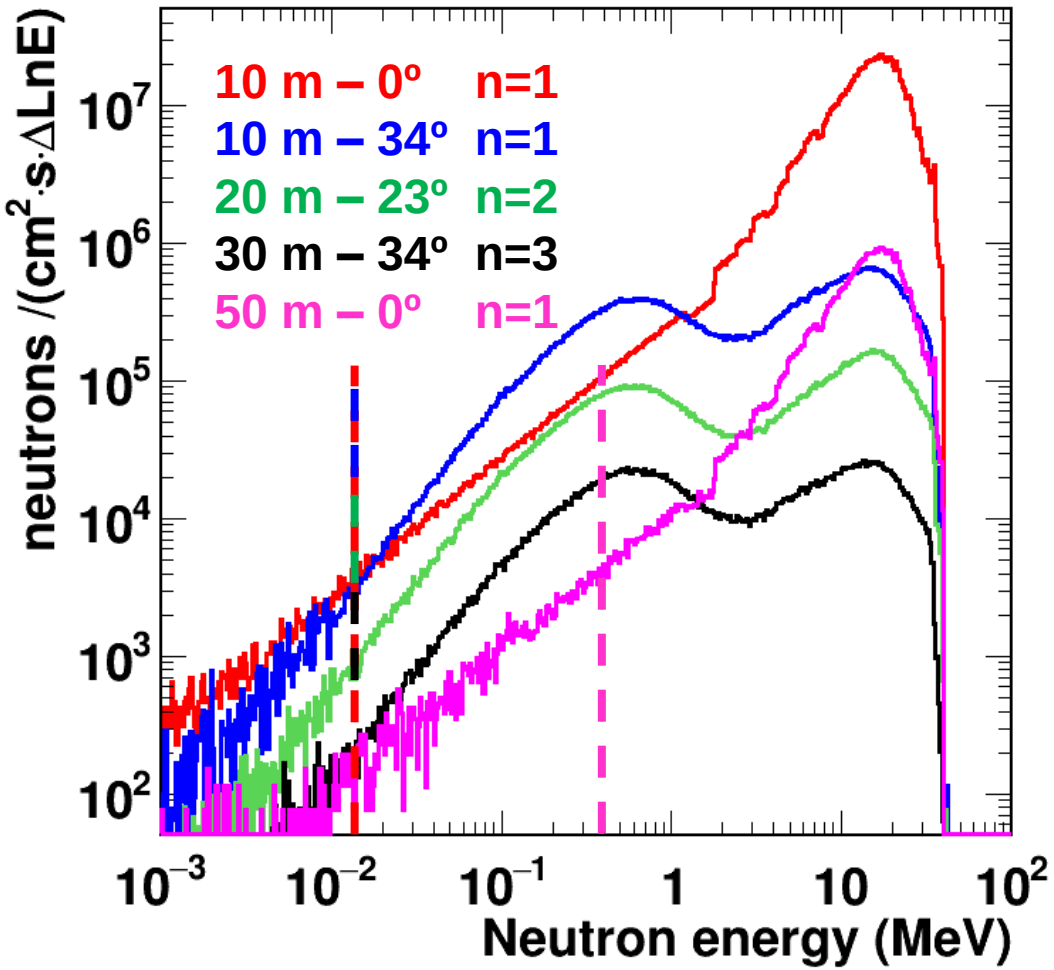
Neutron converter



Other elements not included in the figure:
- beam monitors
- vacuum pumps
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- …

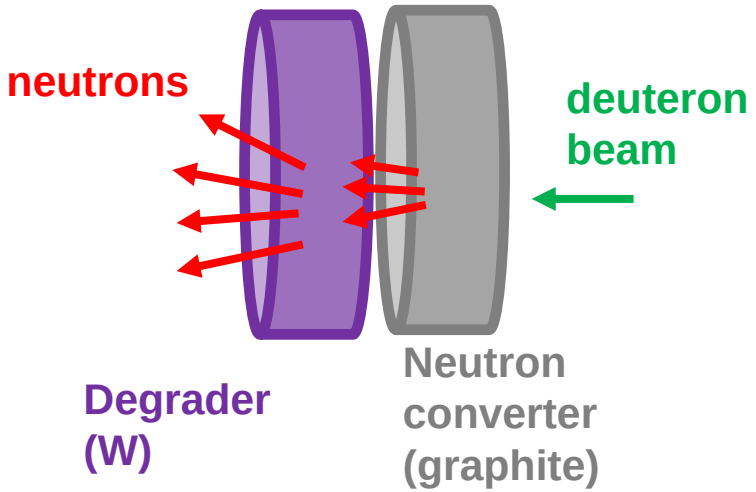
Neutron converter



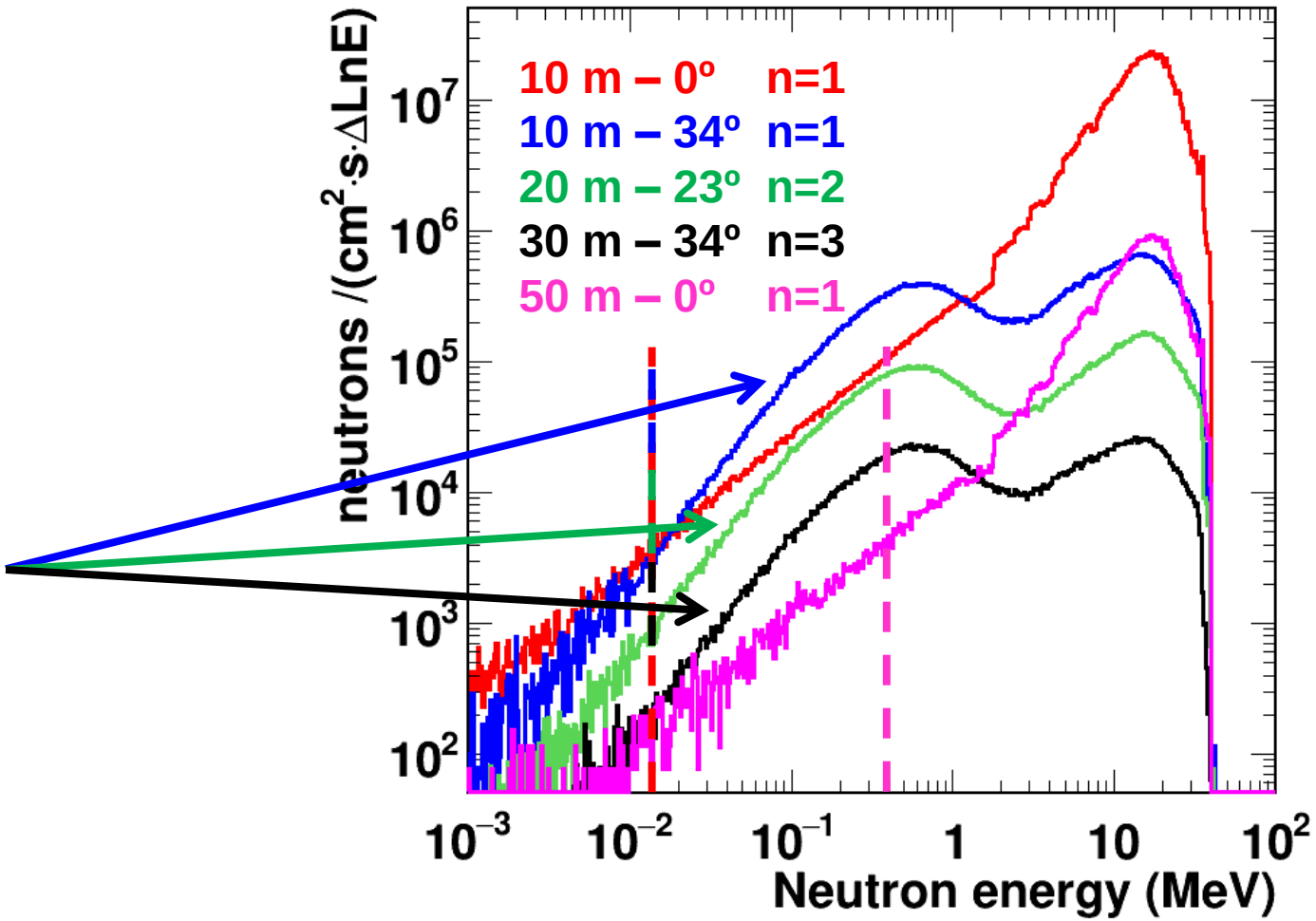


For the moment we have performed the calculations taking Carbon (graphite) as neutron converter. Be will be another possibility (x1.5 in neutron production but more difficult to handle).

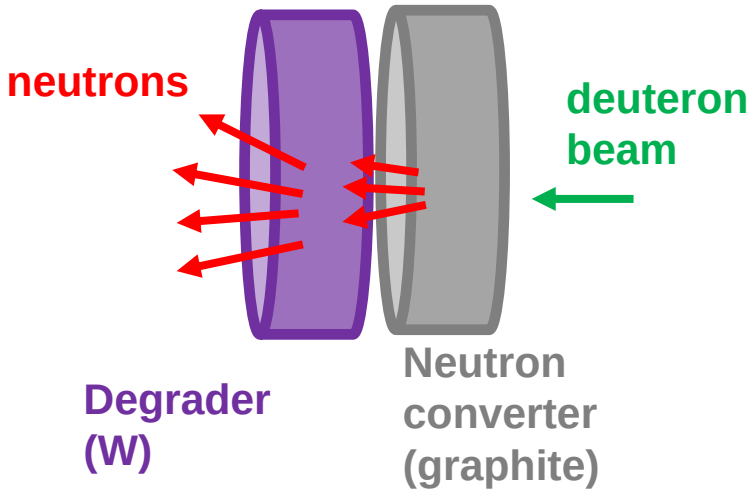
Neutron degrader



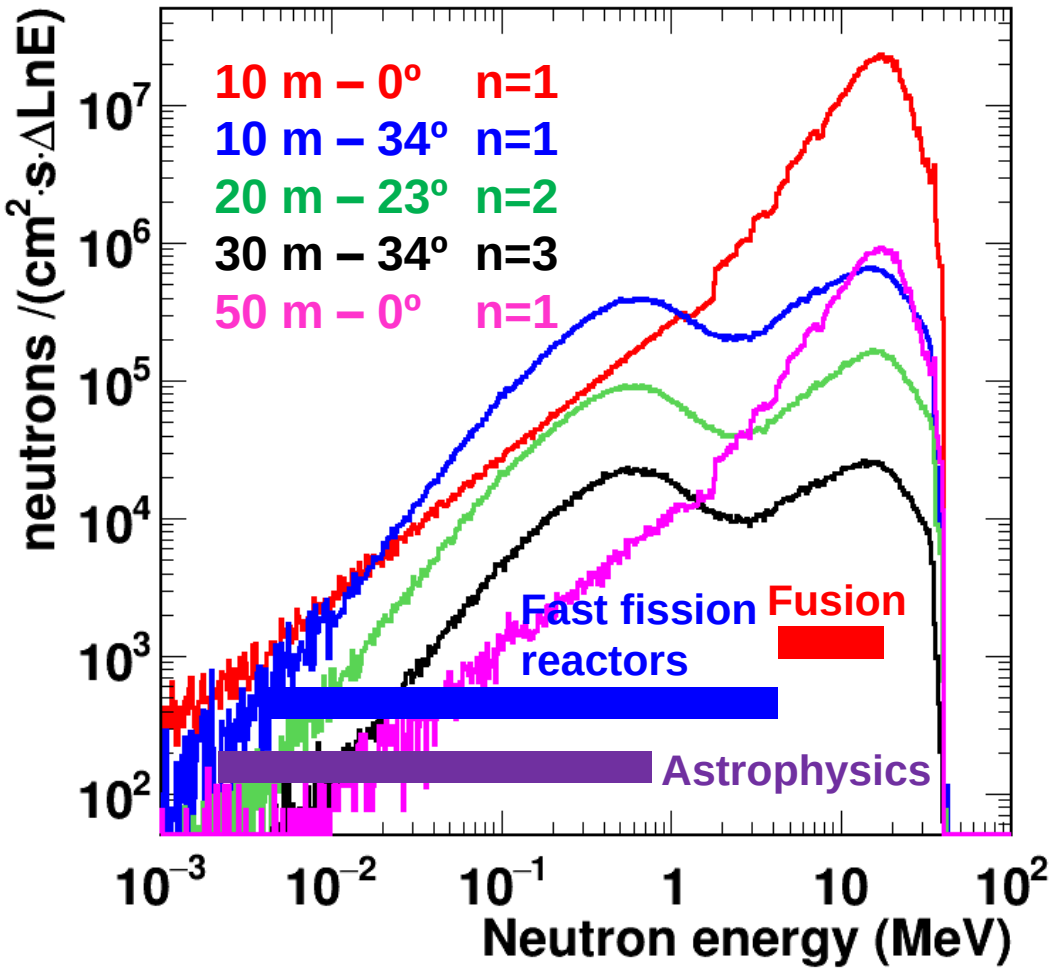
A neutron degrader located just after the neutron converter may allow to perform measurements in the keV region.



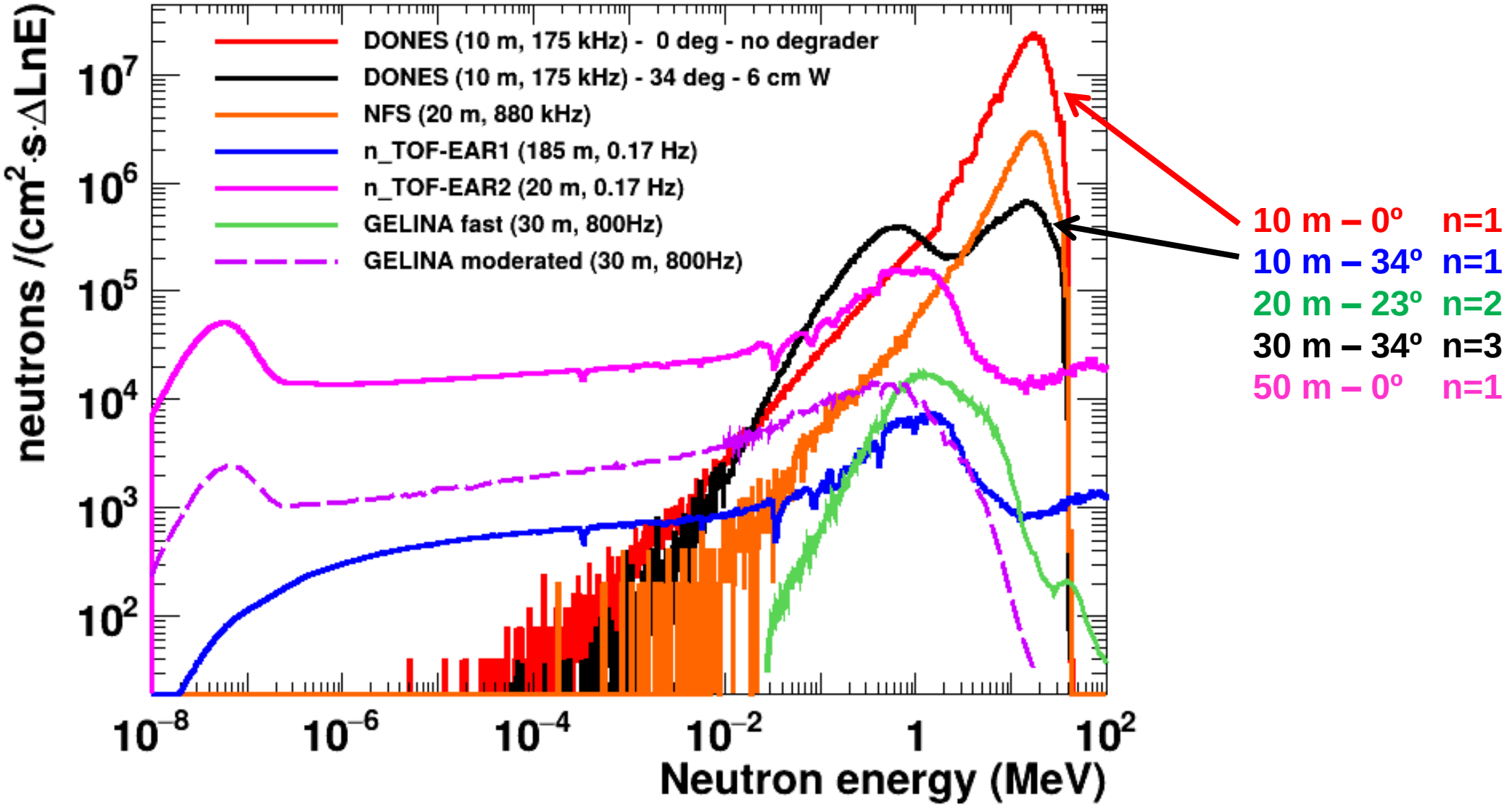
Neutron degrader



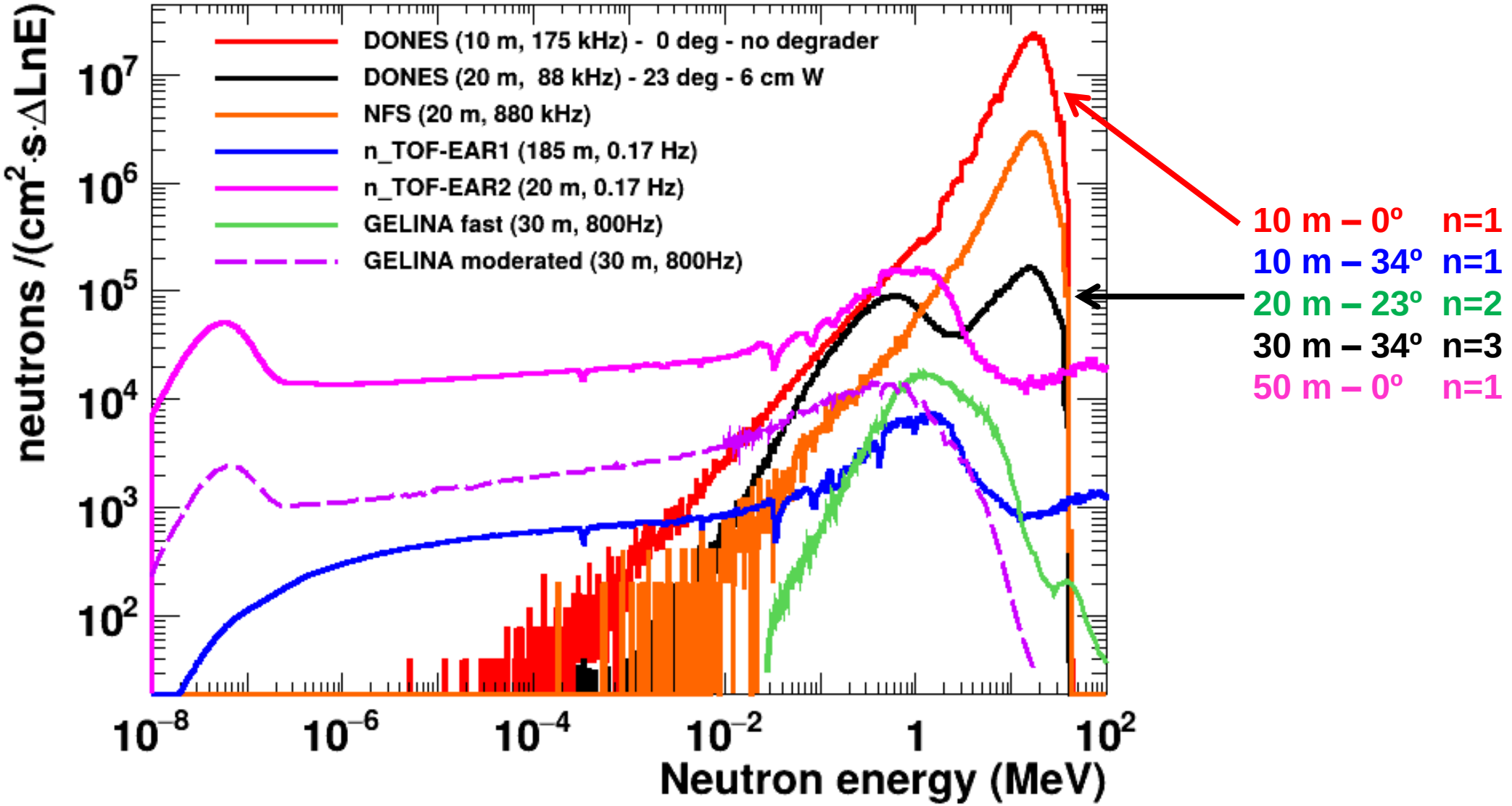
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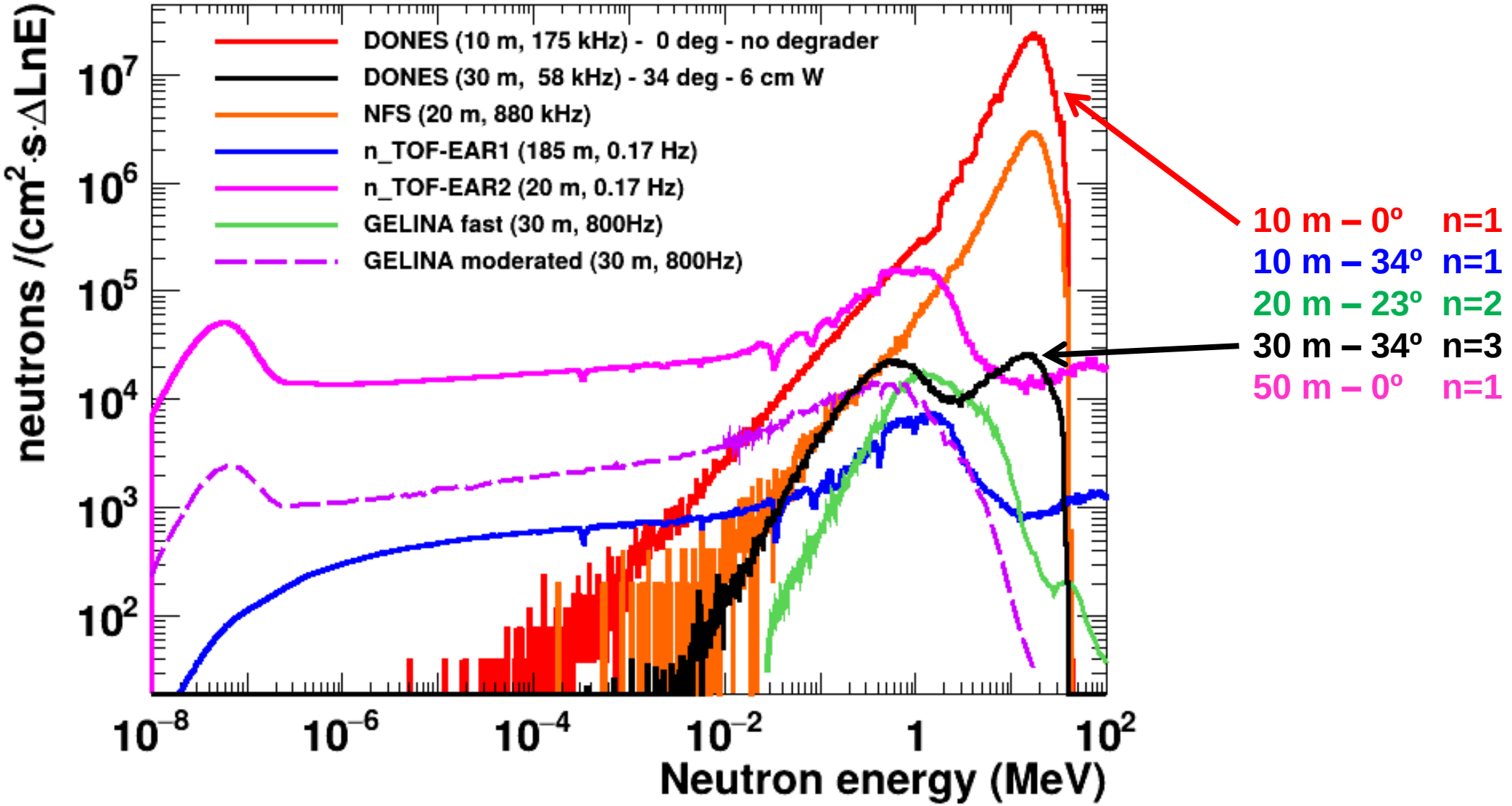
Comparison with other facilities



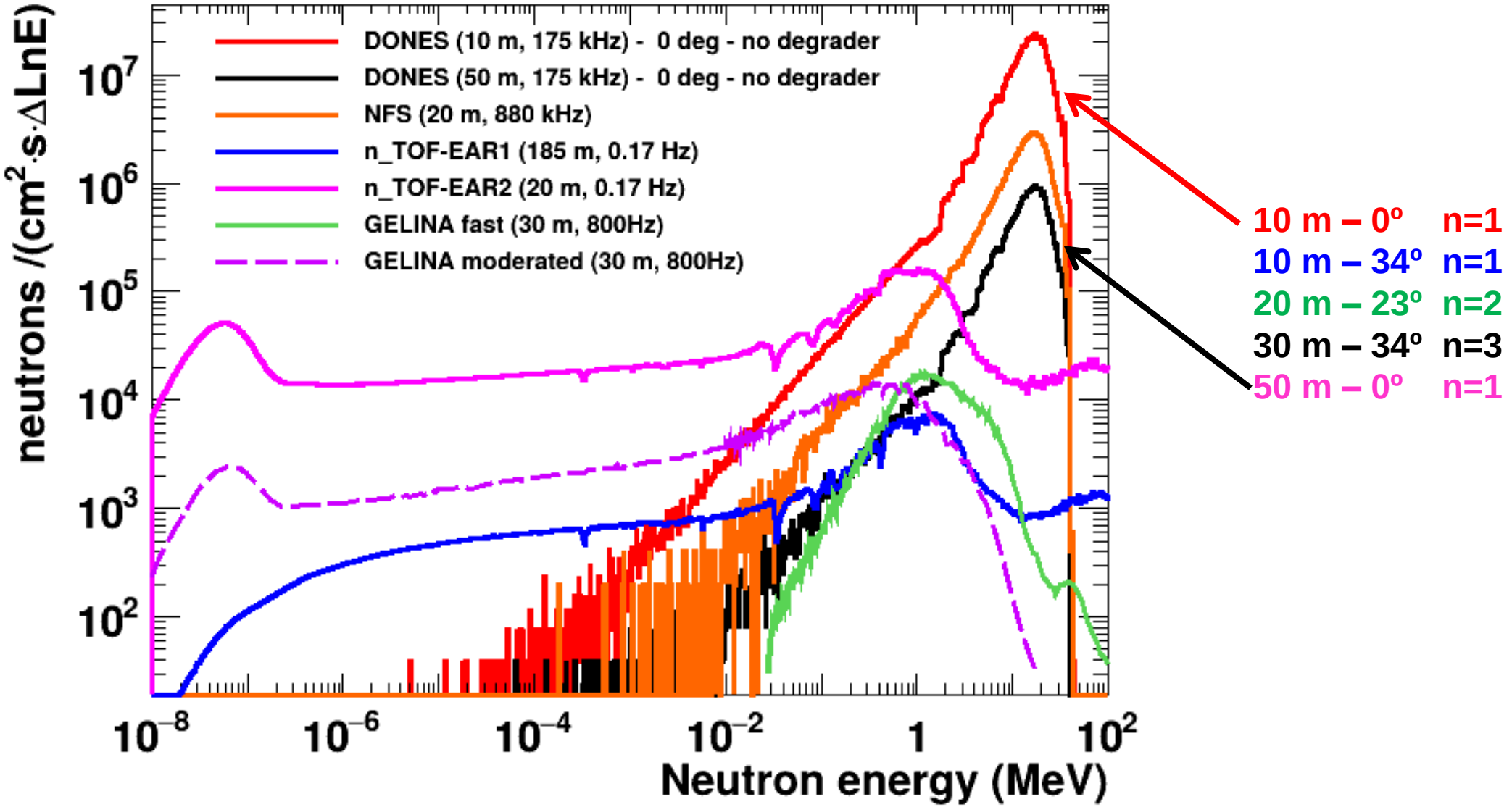
Comparison with other facilities



Comparison with other facilities



Comparison with other facilities



TOF-DONES experimental program

Energy range of TOF-DONES: from tens of **keV to tens of MeV**.

Experimental programme for the coming decades, including data relevant for:

Fission

New designs, waste manag., fuel cycle …

Fusion

Damage, activation, gas production, heating …

Astrophysics

New designs, waste manag., fuel cycle …

Medicine

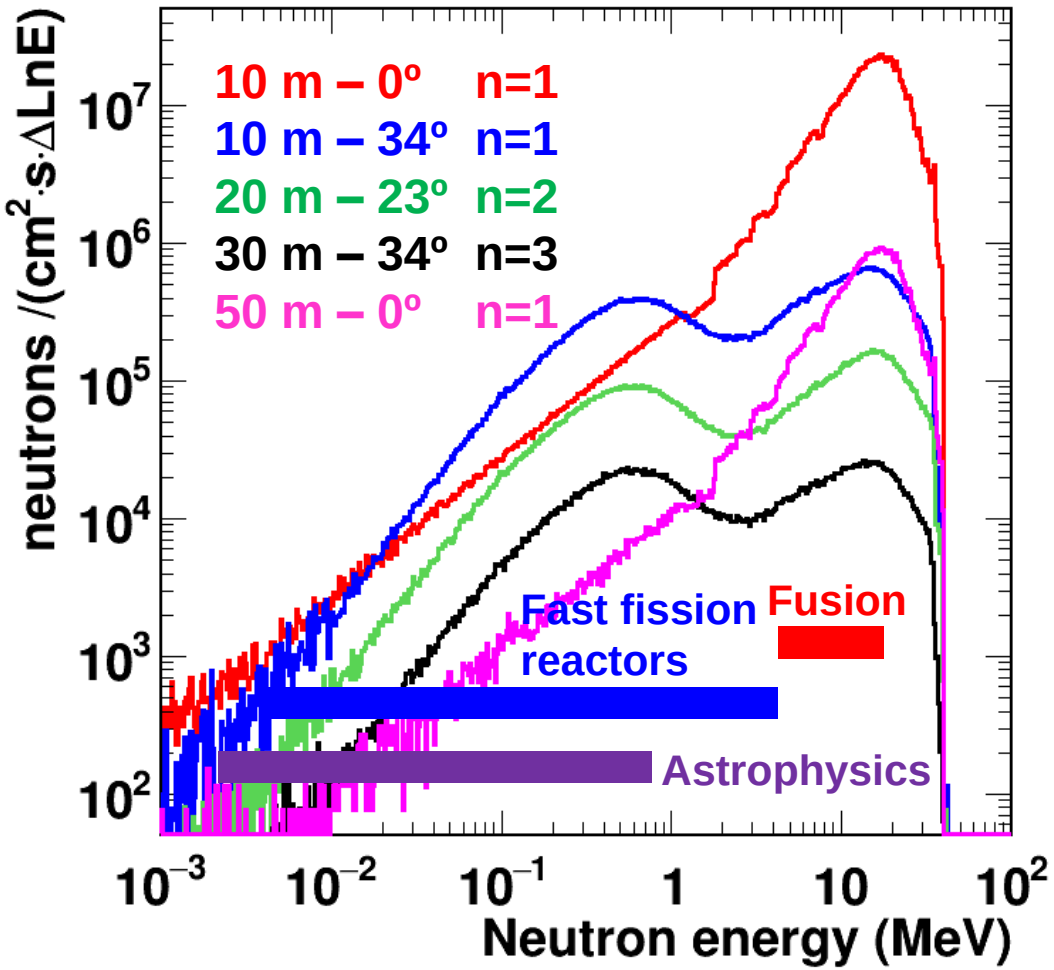
Production data for medical radioisotopes …

Space

Radiation transport, astronaut shielding …

Fundamental physics

Nuclear structure …



TOF-DONES experimental program

Programme definition: five complementary reaction channels

NEUTRON CAPTURE (n,γ)
Actinides, stable isotopes, radioactive fission products.

FISSION (n,f)
Cross sections plus other physical observables: fission fragment, neutron and γ-rays.

LIGHT CHARGED PARTICLE (n,lcp)
(n,p), (n,α), …: gas production, material damage, decay heat, tritium breeding, medical ...

SCATTERING (n,n'), (n,n)
Multi-particle detection systems. Reactor simulations, shielding, γ-ray production data …

TRANSMISSION (n,tot)
Resonance parameters, constrain evaluations.

(n,γ) measurements

Motivation and scientific relevance:

- Fundamental nuclear physics:
  - Nuclear level densities
  - Photon strength functions
  - Nuclear de-excitation mechanism
- Fission and fusion technologies: In fission and fusion energy systems (n,γ) affects fuel burn-up, isotopic evolution, and activation.
  - Fission: reactivity coefficients, breeding ratios, and decay heat.
  - Fusion: material activation, tritium breeding performance, and transmutation rates of structural materials exposed to high-energy neutrons.
- Nuclear astrophysics: synthesis of heavy elements in stars through the slow (s-) and rapid (r-) neutron capture processes.
- Medical sector: (n,γ) reactions are fundamental to the production of radioisotopes used in diagnostics and therapy.
- Space research: (n,γ) reactions influence material activation and radiation shielding design for spacecraft and satellites. These data are also vital for calibrating neutron and gamma detectors on planetary missions and for radiation protection of astronauts in deep-space environments.
- Material science: neutron activation analysis (NAA) to determine elemental compositions with extreme sensitivity and accuracy.

(n,f) measurements

Motivation and scientific relevance:

Neutron-induced fission is a fundamental nuclear process that governs the stability and energy release of heavy nuclei. High-precision measurements of fission observables—including fission cross sections, prompt fission neutron multiplicities (PFNMs), prompt fission neutron spectra (PFNS), and prompt fission gamma-ray emission (PFGS)—are essential for both basic research and a broad range of technological applications.

- Fission cross sections: Accurate fission cross sections are among the most important nuclear data for criticality, reactor design, and safety analysis. From a fundamental standpoint, they provide direct constraints on the fission barrier height, level densities, and competition between fission and other reaction channels. For fission reactors, these data determine neutron economy, reactivity coefficients, and fuel burn-up predictions.
- Prompt Fission Neutron Multiplicities (PFNMs) and spectra (PNFS): PFNMs are critical for calculating chain reaction behavior, delayed neutron fractions, and reactivity feedback in nuclear systems. In fundamental studies, PFNM data test the energy partition between fission fragments and the emission-time distribution of prompt neutrons.
- Prompt Fission Gamma-Ray Spectra (PFGS): They are directly relevant for decay heat calculations, radiation transport simulations, and nuclear forensics. In fundamental science, they constrain the statistical properties of the fragment cascade and help benchmark microscopic models of the fission process.

(n,lcp) measurements

Motivation and scientific relevance:

- Fundamental nuclear physics: Measurements of neutron-induced charged-particle reactions — such as (n,p), (n,d), (n,t), (n,α) — provide direct information on the underlying nuclear interaction mechanisms and reaction cross sections over a broad energy range → nucleon–nucleus optical model potentials and reaction theory (Hauser-Feshbach, direct and pre-equilibrium models), determine level densities, angular distributions, and spectroscopic factors of residual nuclei.
- Fission and fusion nuclear technologies: quantifies gas production, predict radiation damage evolution and support the design of radiation-resistant materials for fission, fusion, and spallation systems.
- Space applications: in spacecraft materials and electronics, neutron-induced reactions can produce charged-particle emissions that lead to single-event upsets (SEUs) and cumulative radiation damage.
- Astrophysics: Charged-particle emission reactions also contribute indirectly to stellar nucleosynthesis and neutron-burning cycles. In particular, (n,p) and (n,α) reactions on light and intermediate-mass nuclei influence the branching ratios in the s-process and r-process, affecting isotopic abundances.
- Other applications: production of therapeutic radioisotopes in medical physics. In detector development provides benchmark data for radiation-hard semiconductor and scintillator materials.

(n,n') measurements

Motivation and scientific relevance:

- Fundamental nuclear physics: inelastic scattering measurements enable the study of nuclear structure and reaction mechanisms. They provide experimental access to excitation energies, level schemes, transition probabilities, and decay pathways of nuclei across a wide mass and energy range.
- Fission and fusion nuclear technologies: In fission reactors, accurate (n,n′γ) cross sections are necessary for reactor dosimetry, shielding design, and fuel cycle optimization. For fusion devices, particularly those based on deuterium–tritium or deuterium–lithium reactions, inelastic scattering data are essential for predicting neutron-induced activation and damage in first-wall materials, blanket structures, and diagnostic systems.
- Space and astrophysics applications: Data from inelastic scattering help improve transport codes used to predict radiation exposure for satellites and crewed missions. In nuclear astrophysics, such measurements support reaction rate calculations needed to model stellar nucleosynthesis and the synthesis of heavy elements in extreme astrophysical environments.
- Other applications: Accurate cross sections support the design of neutron-based therapy systems and advanced imaging techniques. In homeland security, knowledge of neutron-induced gamma-ray signatures is essential for non-destructive assay and detection of illicit materials.

(n,tot) measurements

Motivation and scientific relevance:

- Fundamental nuclear physics: total cross-section measurements provide integral constraints on the reaction mechanisms governing neutron–nucleus interactions. They are used to benchmark optical model potentials, compound nucleus formation probabilities, and scattering theories.
- Fission and fusion technologies: total cross sections are fundamental inputs for neutron transport calculations and reactor core simulations. They define neutron attenuation in fuel, moderator, and structural materials, directly impacting the neutron economy, shielding design, and safety margins in both fission and fusion systems.
- Astrophysics: total neutron cross sections play an indirect but essential role in modeling stellar environments. They serve as reference data for normalizing resonance parameters and for improving neutron reaction rate calculations used in stellar nucleosynthesis models.
- Industrial, medical, and space applications: In medical physics, they are required for neutron dosimetry, radiation shielding, and design of neutron-based therapeutic and imaging systems. In materials science and engineering, transmission measurements enable characterization of neutron attenuation in alloys, composites, and shielding materials. In space applications, total cross-section data help model the interaction of cosmic-ray-induced neutrons with spacecraft materials and electronics.

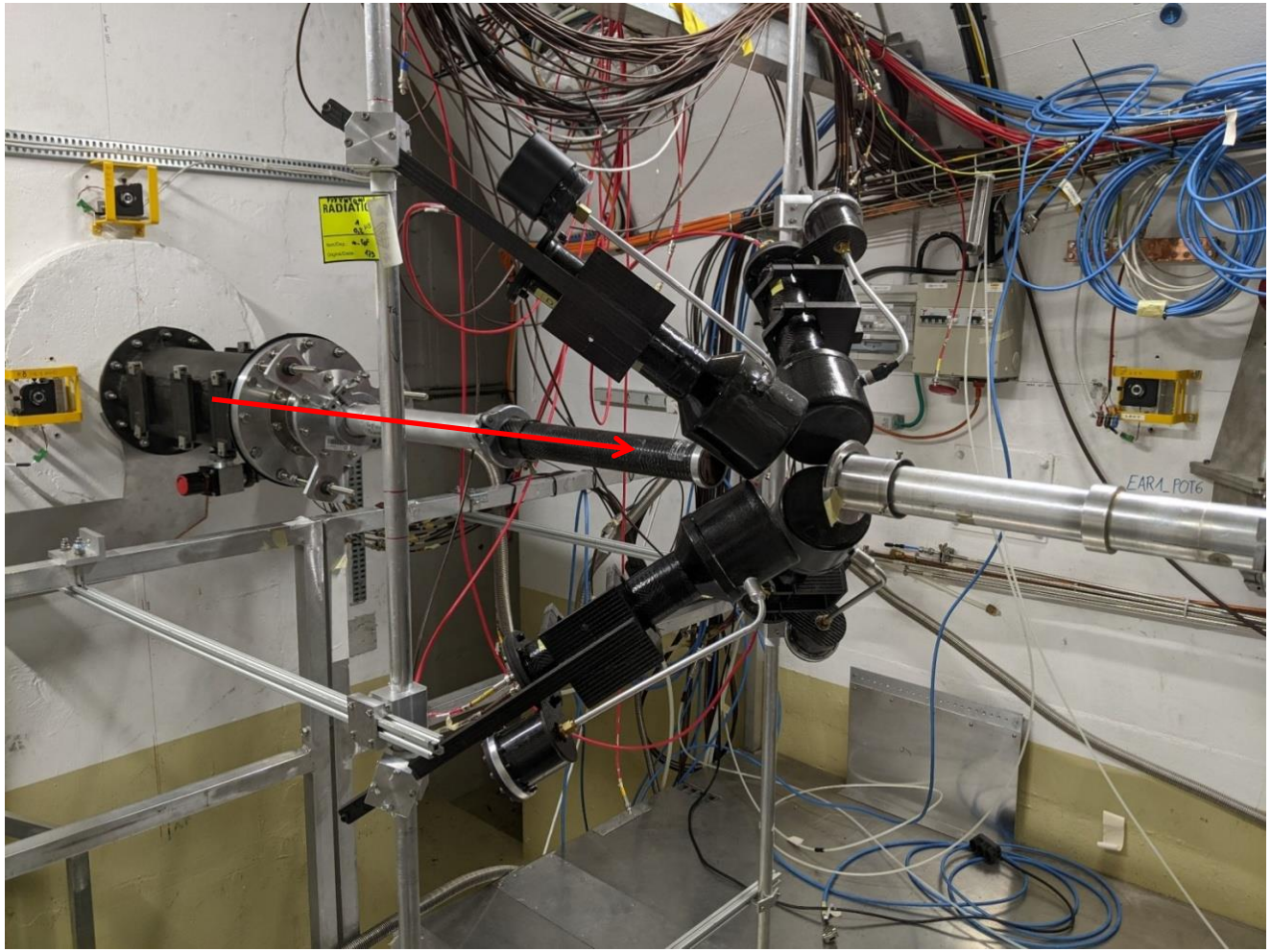
Other experiments with pulsed neutrons

- Nuclear structure studies using neutrons as probes
- Neutron Spectroscopy and reference cross-section measurements
- Calibrate neutron detectors
- Develop new neutron spectrometers for nuclear, medical, and fusion facilities
- Non-destructive elemental analysis using neutron-induced prompt gamma-ray activation analysis (PGAA): measures elemental compositions via characteristic γ-ray lines emitted immediately after neutron capture
- Neutron imaging
- Benchmark experiments
- Dosimetry foils for activation mapping relevant to the design of reactor and accelerator shielding, nuclear waste facilities, and radiation protection barriers
- Neutron-Induced Isomeric ratio
- Delayed gamma measurements
- Radiation Hardness and Material Testing
- …

Measurement techniques

(n,γ) measurements:

→ detection of the γ-rays emitted after neutron capture: liquid scintillators, HPGe, $LaBr_3(Ce)$, $CeBr_3$ …



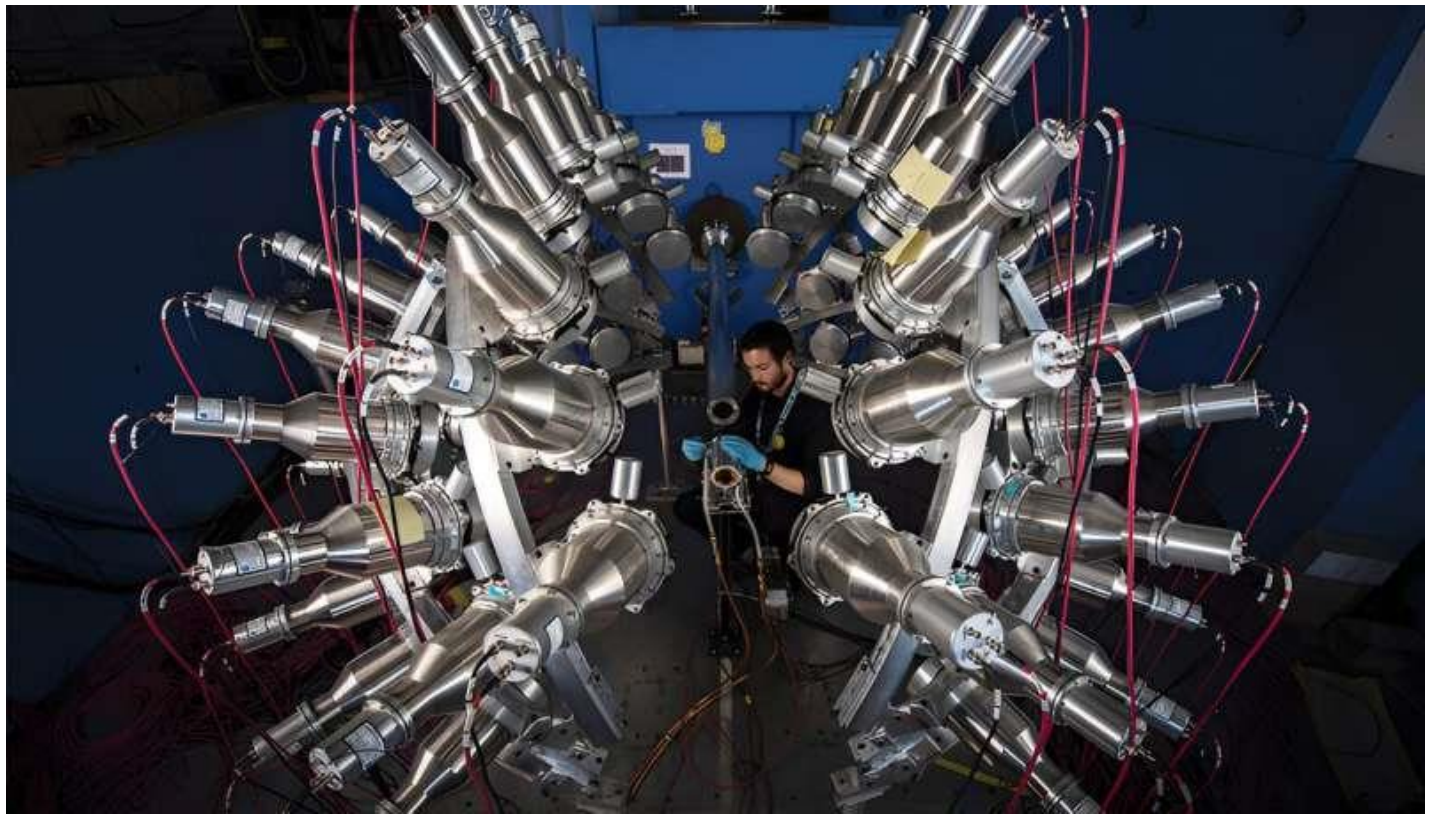


Experimental setup for $^{238}U(n,\gamma)$ cross section measurement at n_TOF (CERN)

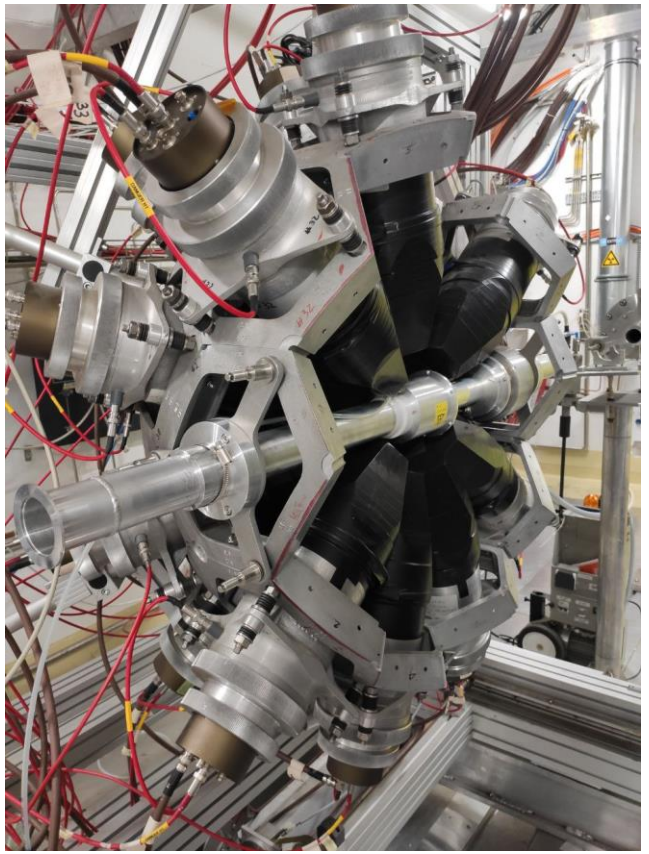
Measurement techniques

(n,f) measurements:

→ detection of the fission fragments, neutrons and γ-rays emitted after fission: micromegas, PPACs, liquid scintillators, HPGe, $LaBr_3(Ce)$, $CeBr_3$ …



Chi-nu detector at LANL (picture from https://phys.org/news/2023-09-chi-nu-bolsters-nuclear-energy-reactors.html)

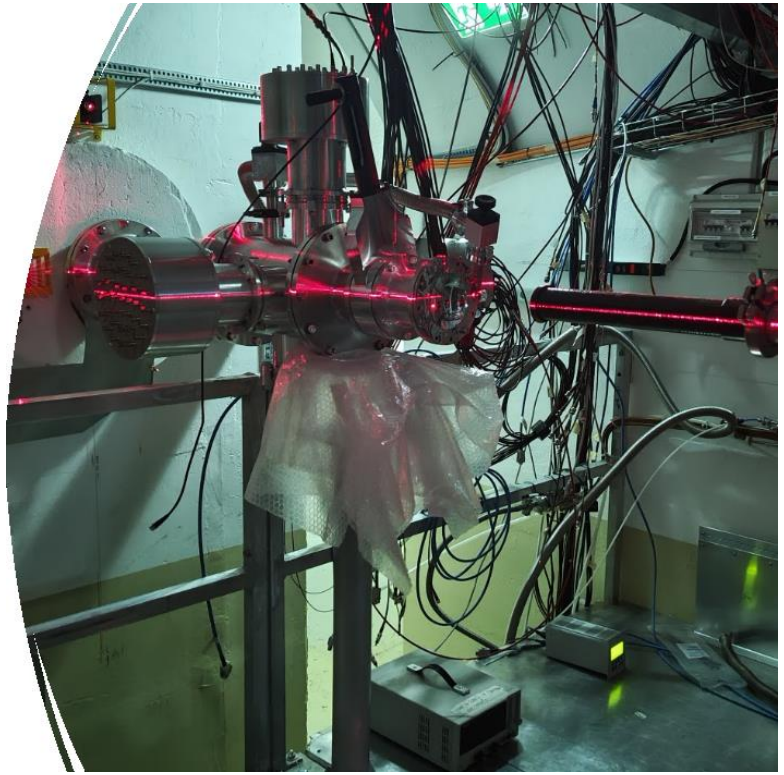


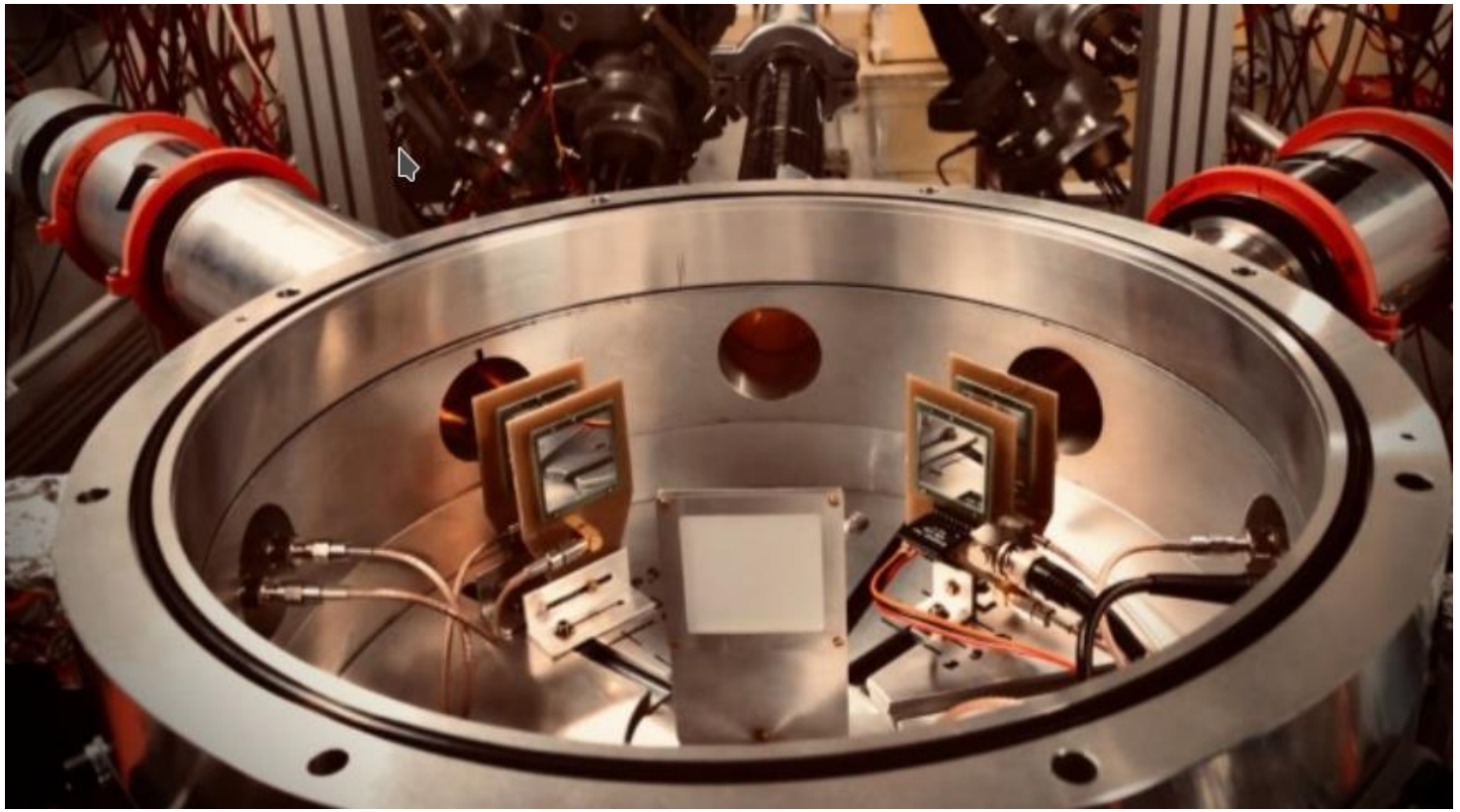
^{239}Pu(n,f)+(n,γ) measurement at n_TOF

Measurement techniques

(n,lcp) measurements:

→ detection of p, d, t, α alpha particles: semiconductor detectors, scintillator detectors, gaseous detectors.





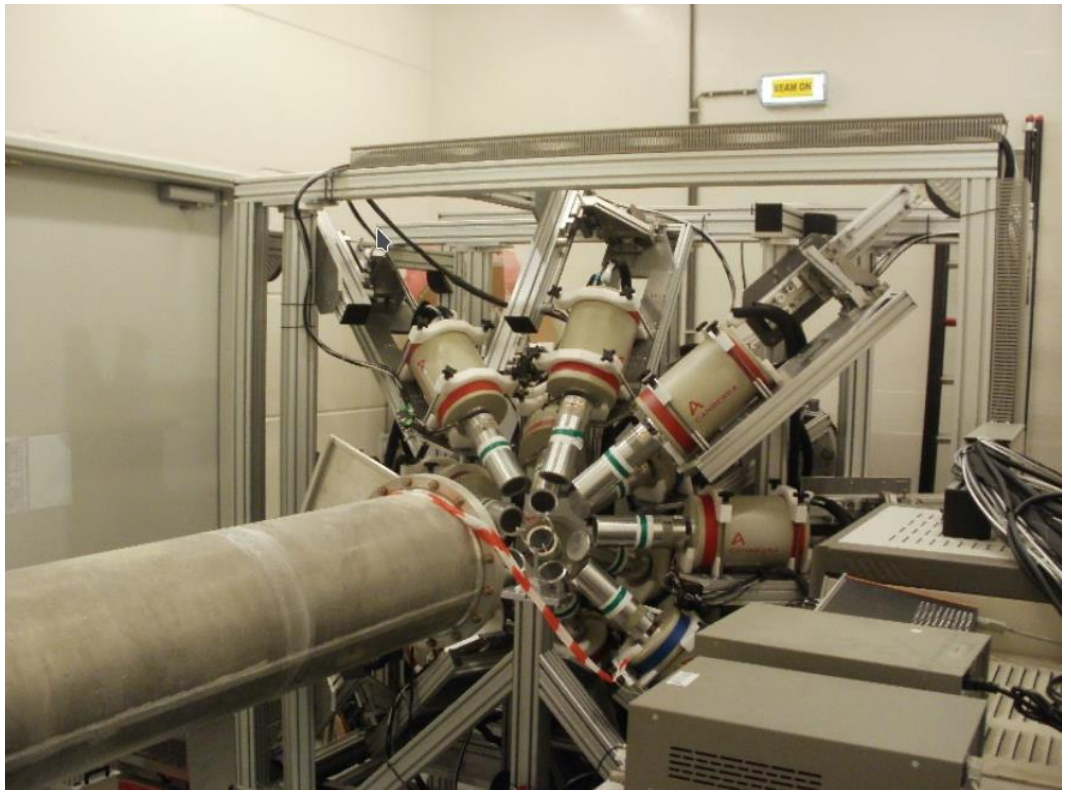
Measurement techniques

(n,n') measurements:

→ detection of the γ-rays or both neutrons and γ-rays: γ-ray detectors with high energy resolution HPGe, $LaBr_3(Ce)$ or $CeBr_3$; and neutron detectors.



^{140}Ce(n,n') measurement at NFS-GANIL, using PARIS and MONSTER.



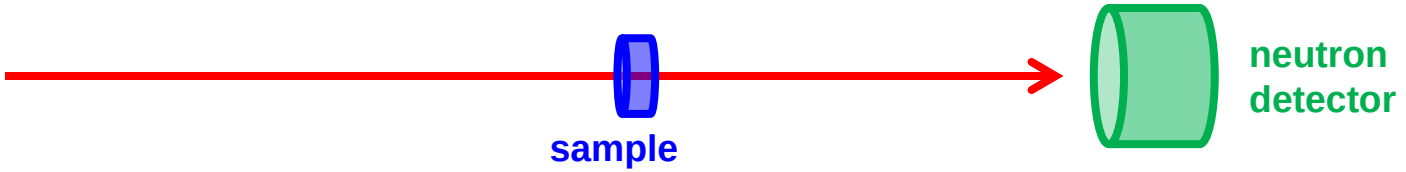
GAINS spectrometer at GELINA. Picture obtained from A. Olacel et al. EPJ Web of Conferences 284, 01007 (2023).

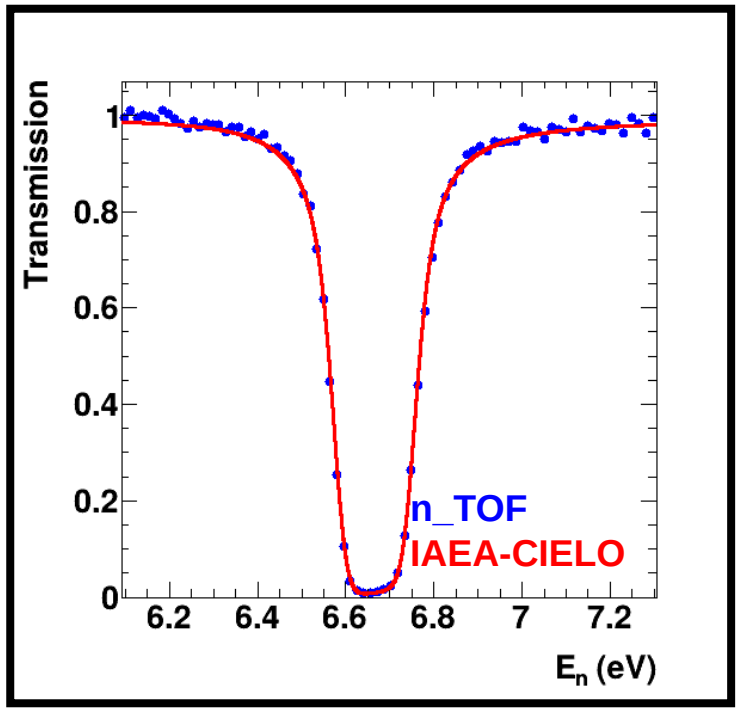
Measurement techniques

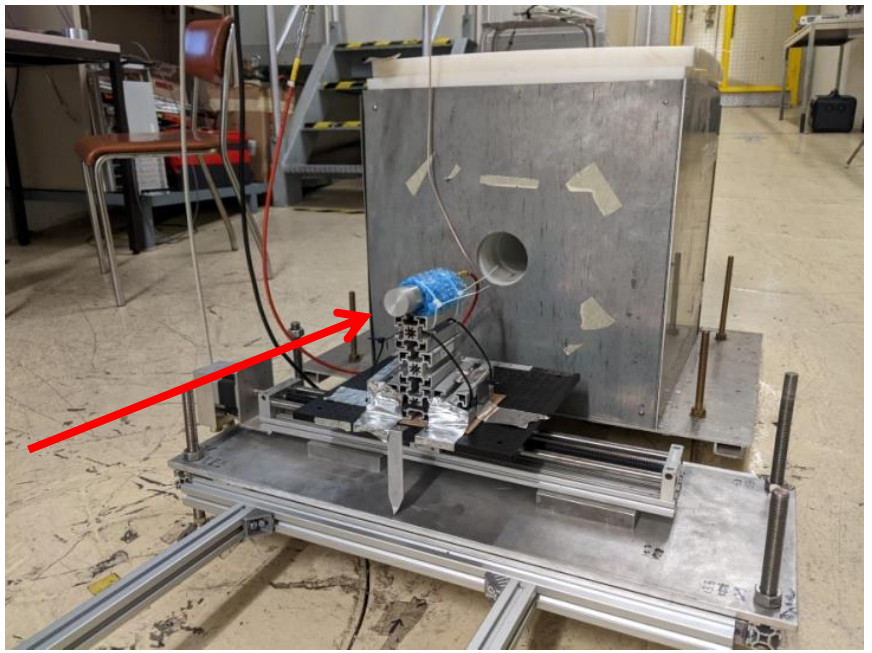
(n,tot) measurements (transmission):

→ sample-in / sample-out technique: neutron detectors.

$$\sigma_{tot} = -\frac{1}{n} Ln(T_{exp}) = -\frac{1}{n} Ln\left(\frac{R_{in}}{R_{out}}\right)$$







^{238}U(n,tot) measurement at n_TOF

Nuclear data needs

Isotopes relevant for fission technologies (many of them also for fusion, shielding, space, etc.)

Actinides: ^{232}Th, ^{233,234,235,236,238}U, ^{237}Np, ^{238,239,240,241,242}Pu, ^{241,242m,243}Am, ^{242,243,244,245,246,247,248}Cm.

Stable isotopes:

Dopants and poisons in the nuclear fuel: ^{27}Al, ^{28,29,30}Si ^{46,47,48,49,50}Ti, ^{50,52,53,54}Cr, ^{93}Nb, ^{154,155,156,157,158,160}Gd, ^{166,167,168,170}Er, ^{176,177,178,179,180}Hf, ^{160,161,162,163,164}Dy …

Coolants, claddings and reflectors: ^{1,2}H, ^{6,7}Li, ^{9}Be, ^{12,13}C, ^{16}O, ^{19}F, ^{23}Na, ^{24,25,26}Mg, ^{35,37}Cl, ^{39,41}K, ^{90,91,92,94,96}Zr, ^{92,94,95,96,97,98,100}Mo, ^{181}Ta, ^{204,206,207,208}Pb, ^{209}Bi …

Structural materials: ^{50,52,53,54}Cr, ^{55}Mn, ^{54,56,57,58}Fe, ^{59}Co, ^{58,60,61,62}Ni, ^{63,65}Cu …

Stable fission products: ^{83,84,86}Kr, ^{85,87}Rb, ^{88}Sr, ^{89}Y, ^{101,102,104}Ru, ^{103}Rh, ^{105,106,108}Pd, ^{109}Ag, ^{130}Te, ^{131,132,134,136}Xe, ^{133}Cs, ^{137,138}Ba, ^{139}La, ^{140,142}Ce, ^{141}Pr, ^{143,144,145,146}Nd, ^{147,149,150,152}Sm …

Radioactive fission products: ^{85}Kr, ^{90}Sr, ^{93m}Nb, ^{95}Zr, ^{102}Rh, ^{106}Ru, ^{108m}Ag, ^{109,113m}Cd, ^{119m,121m,123}Sn, ^{124,125}Sb, ^{127m}Te, ^{134,137}Cs, ^{144}Ce, ^{146,147}Pm, ^{151}Sm, ^{152,154,155}Eu, ^{158}Tb, ^{166m}Ho, ^{171}Tm …

Nuclear data needs

Nuclear-data requirements are compiled and prioritized by international and national organizations that connect data users in reactor technology, medicine, and safety with experimental laboratories. Examples include the OECD Nuclear Energy Agency (NEA), through its High Priority Request List (HPRL), and the U.S. Nuclear Data Program (USNDP).

HPRL → https://www.oecd-nea.org/jcms/pl_68746/hprlapp

USNDP → https://www.nndc.bnl.gov/usndp/

Nuclear data measurements have long been extensively conducted for fission technologies, but the same level of data has not yet been established for fusion. Historically, research and modeling have heavily favored traditional fission reactors due to their commercial deployment. However, as fusion energy technology advances and moves closer to practical realization, **the demand and interest in precise nuclear data specific to fusion applications will inevitably increase.**

Conclusions

- We have an excellent opportunity for building a **world leading** neutron time-of-flight facility at **IFMIF-DONES**.
- The TOF-DONES facility will provide **accurate nuclear data necessary for many applications**: nuclear reactors, **nuclear fusion**, nuclear waste management strategies, nuclear inspection techniques, dosimetry, nuclear astrophysics, nuclear structure, production of radioisotopes for medical and technological applications.
- More than one experiment may run at the same time → **high scientific production**.
- The **Spanish Nuclear Physics community** has the necessary expertise and skills for making the facility a great success.
- More info about TOF-DONES and its experimental programme can be found in → A. Maj et al., DONES non-Fusion Experimental Programme, DONES con P1 Deliverable 2.5 (2025). https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5268ca43b&appId=PPGMS