Status of the design of the TOF-DONES

E. Mendoza
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 (see talk by Lukasz Iskra in this session)
- Production of radioisotopes for medical and technological applications
- …

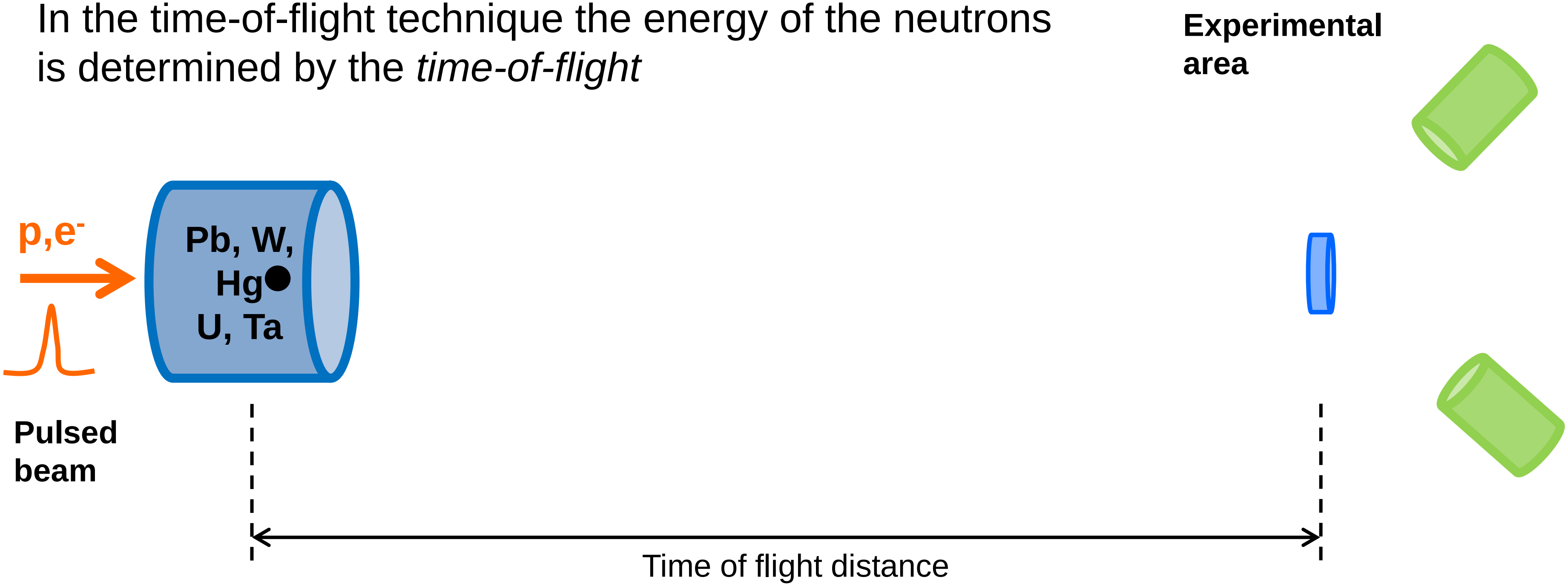
Actual nuclear models have a limited accuracy and predictive capabilities → experimental data is needed.

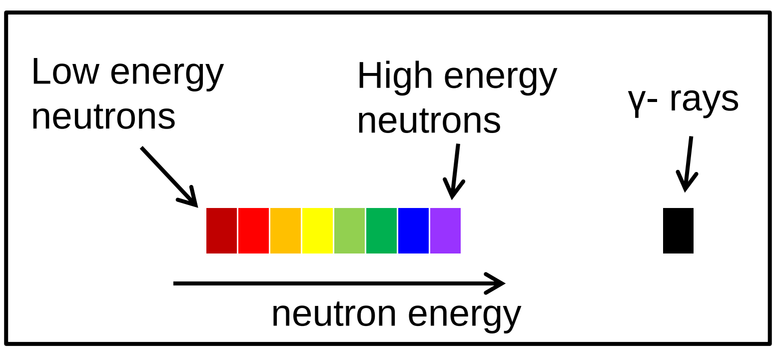
Neutrons cannot be accelerated nor deflected → the most widely used facilities to study neutron induced reactions as a function of the neutron energy are time-of-flight facilities.

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

The time-of-flight technique

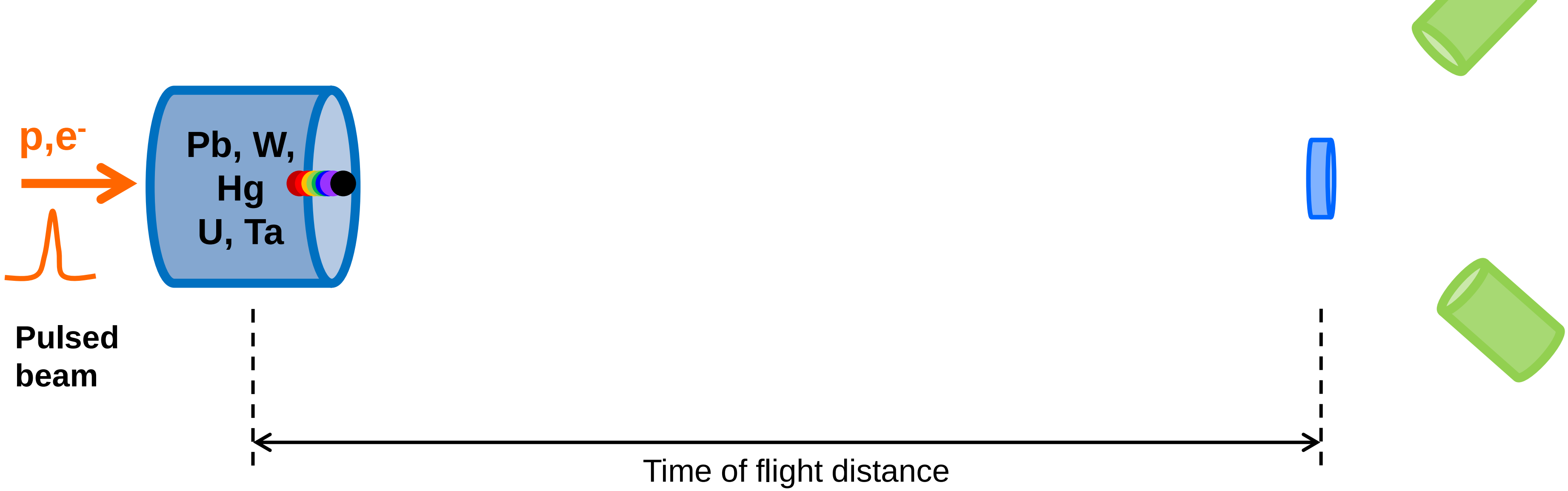
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*

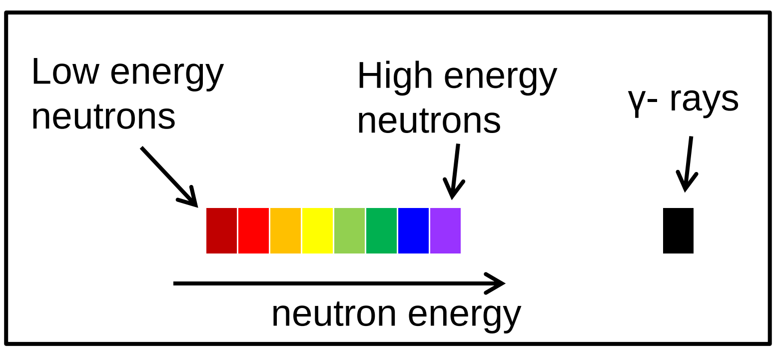




The time-of-flight technique

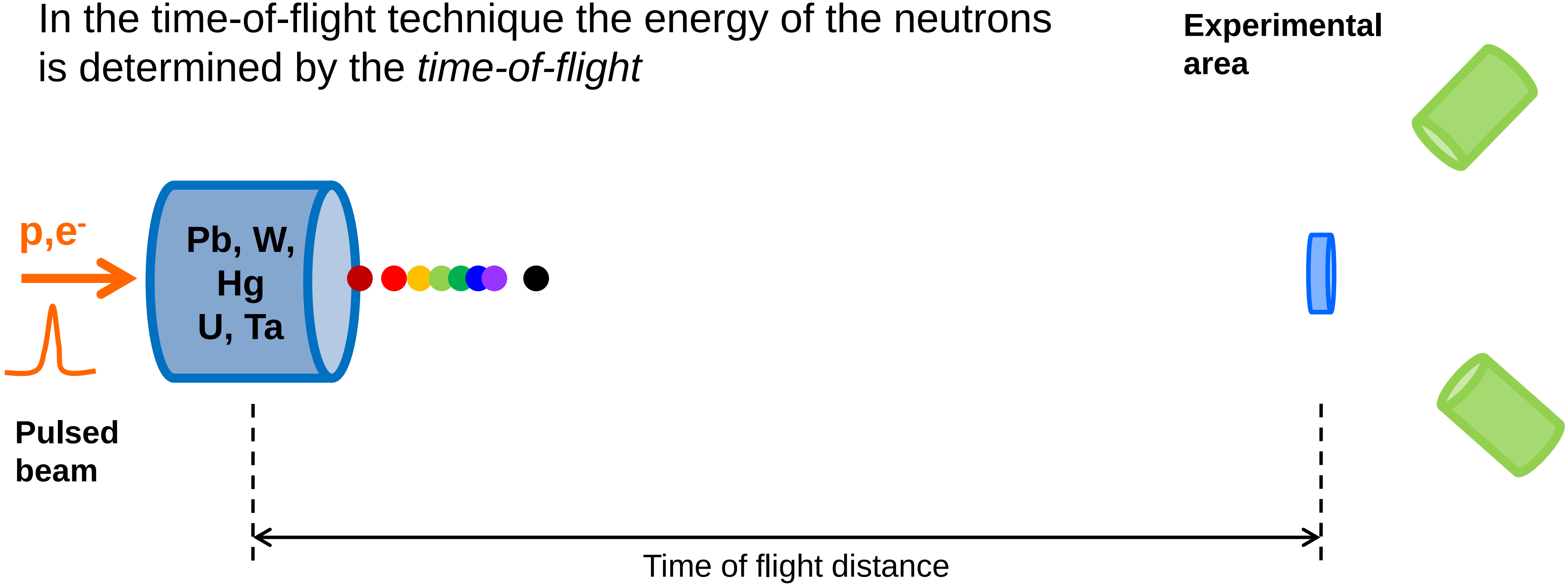
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*

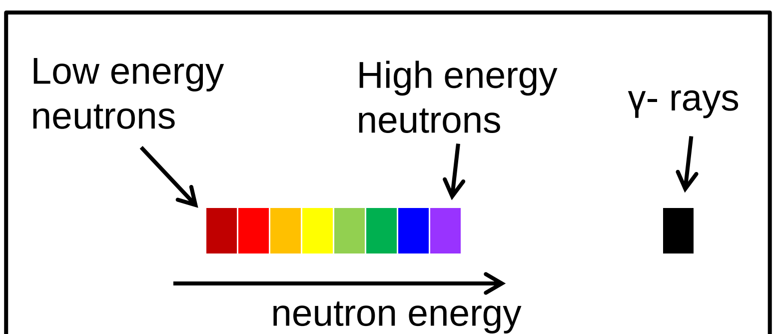




The time-of-flight technique

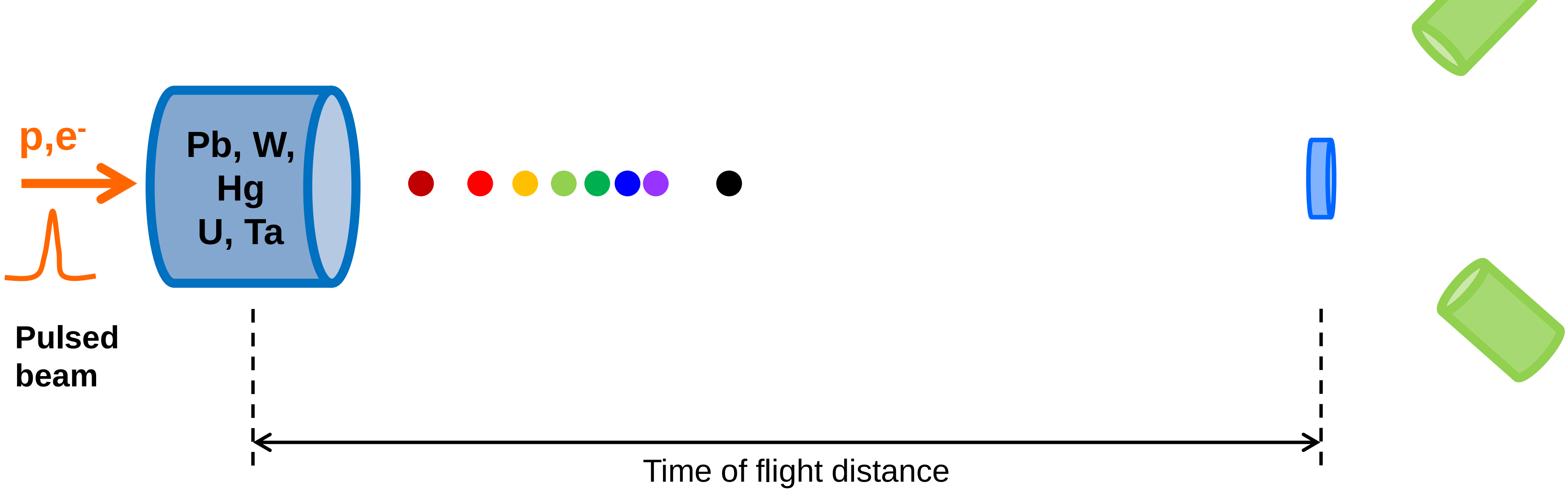
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*

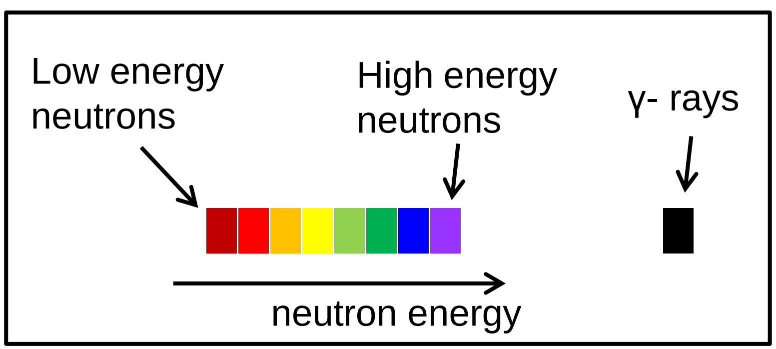




The time-of-flight technique

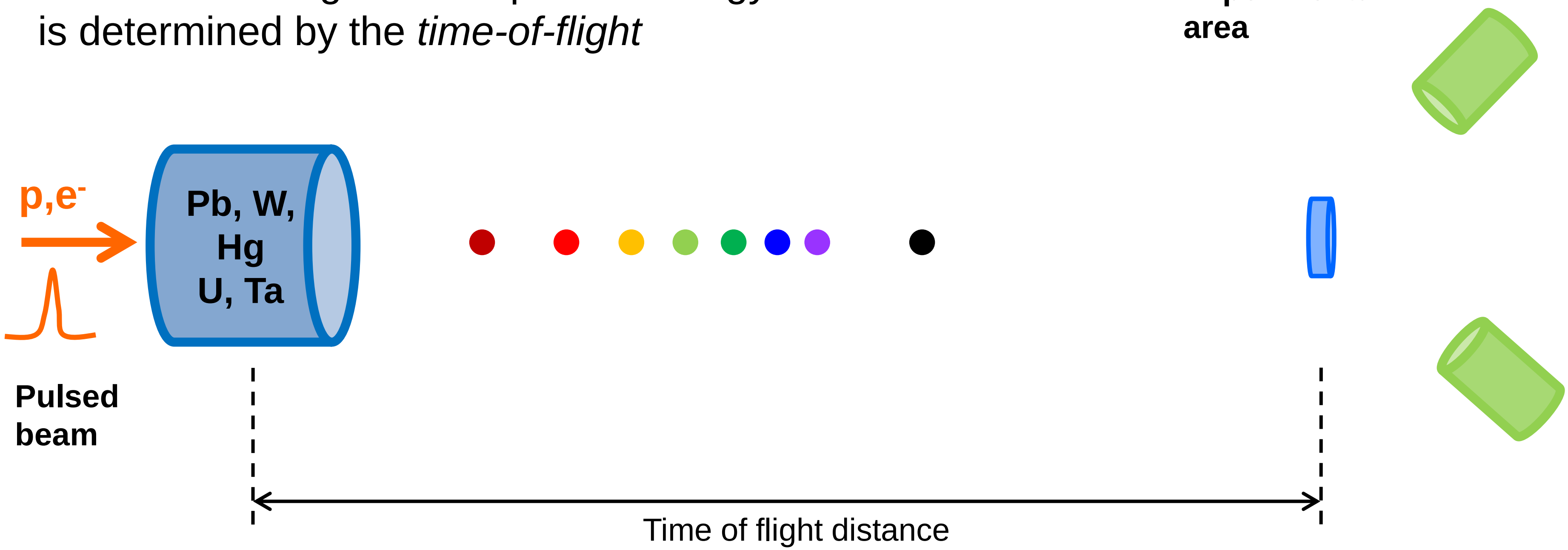
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*

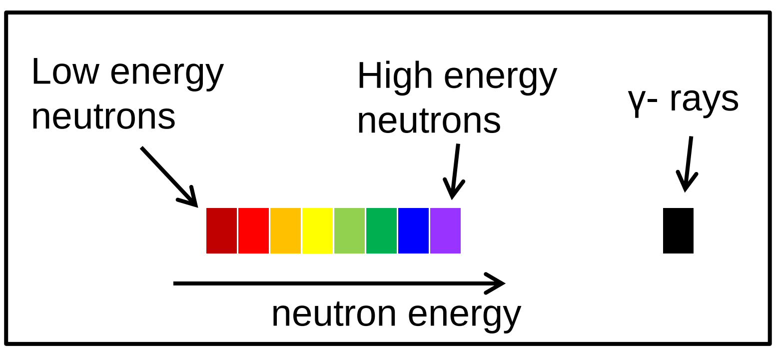




The time-of-flight technique

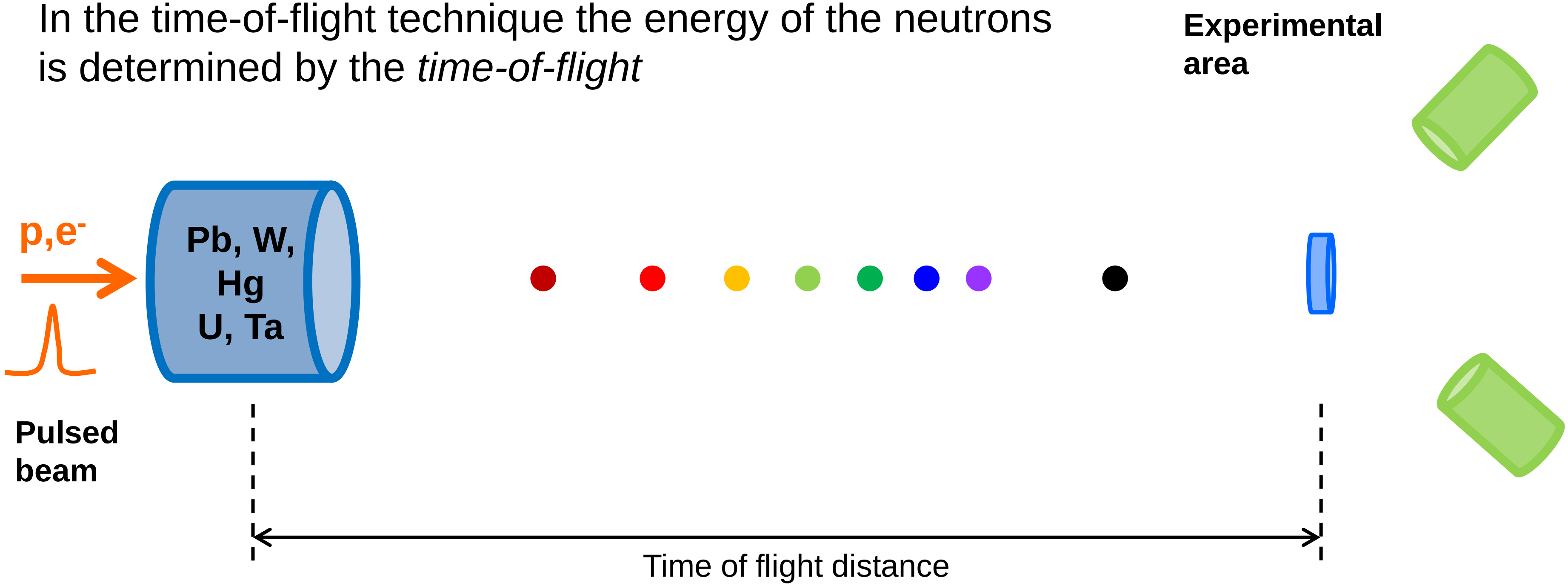
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*

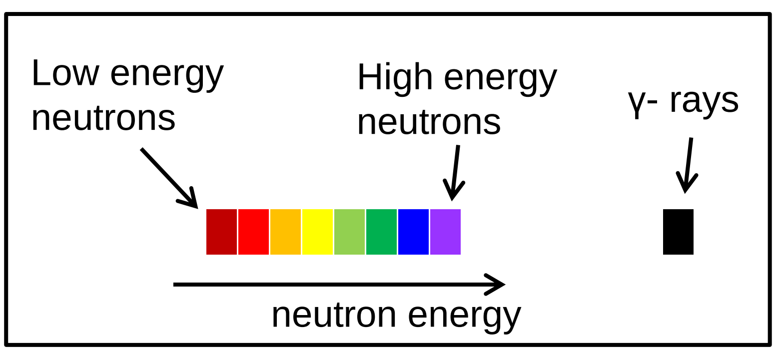




The time-of-flight technique

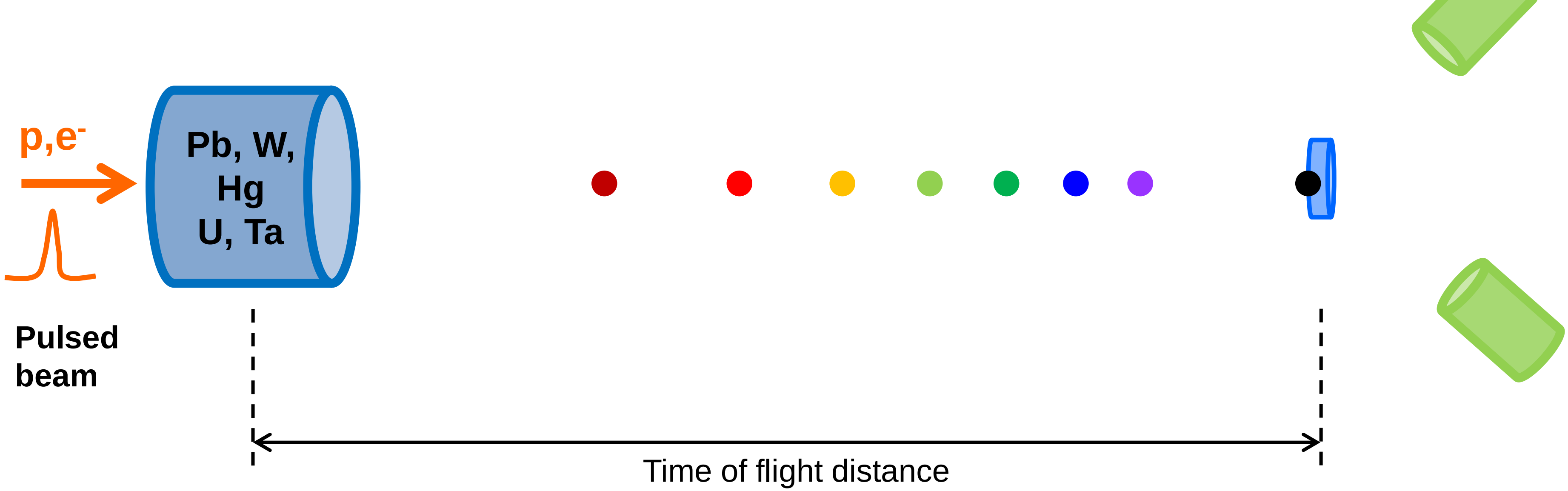
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*

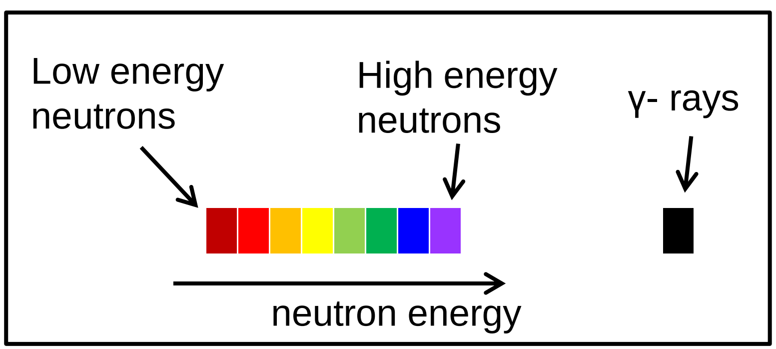




The time-of-flight technique

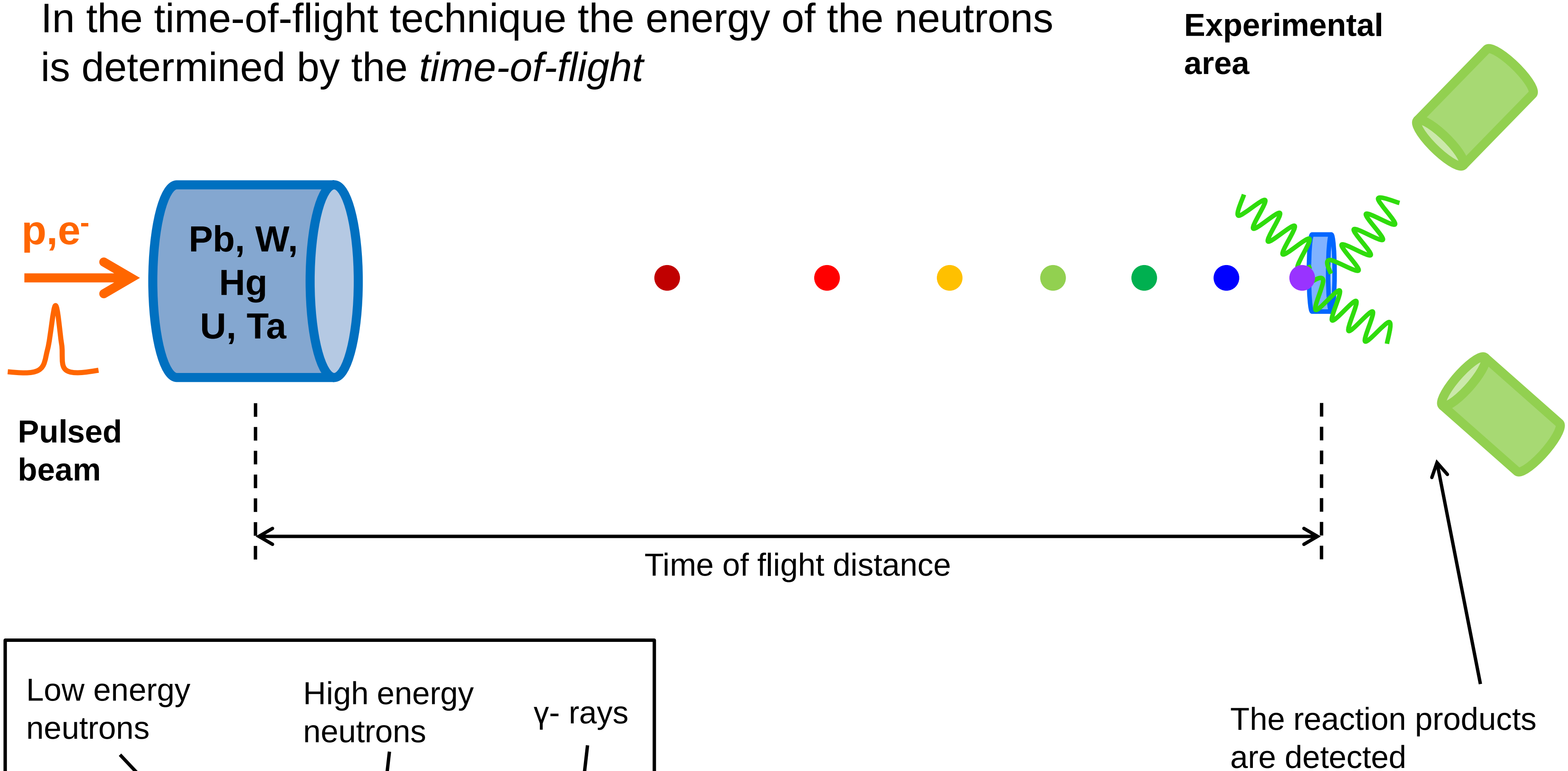
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*

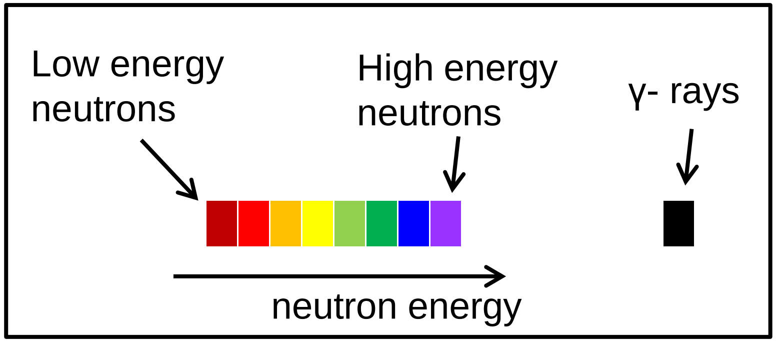




The time-of-flight technique

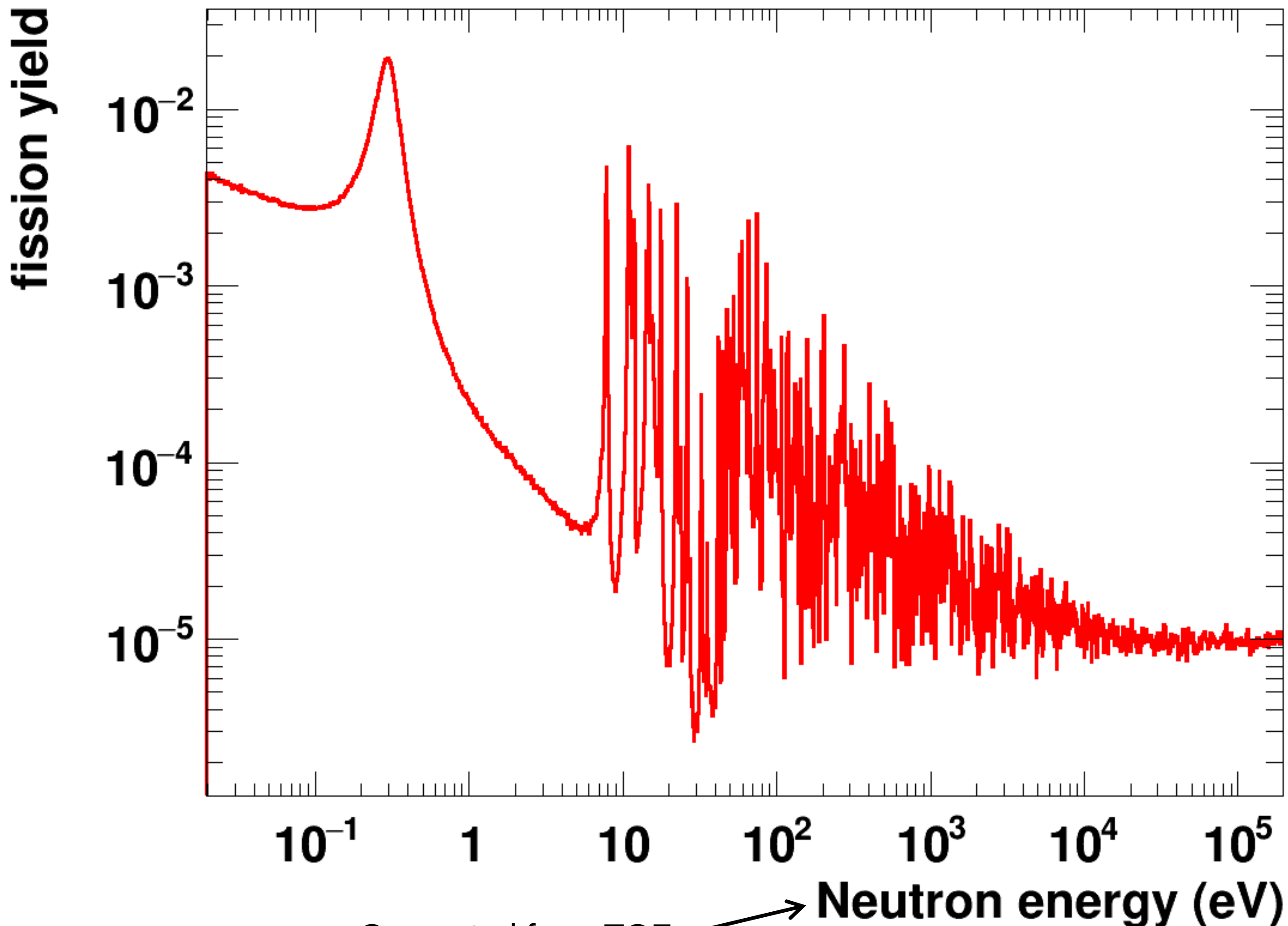
In the time-of-flight technique the energy of the neutrons is determined by the *time-of-flight*





Example

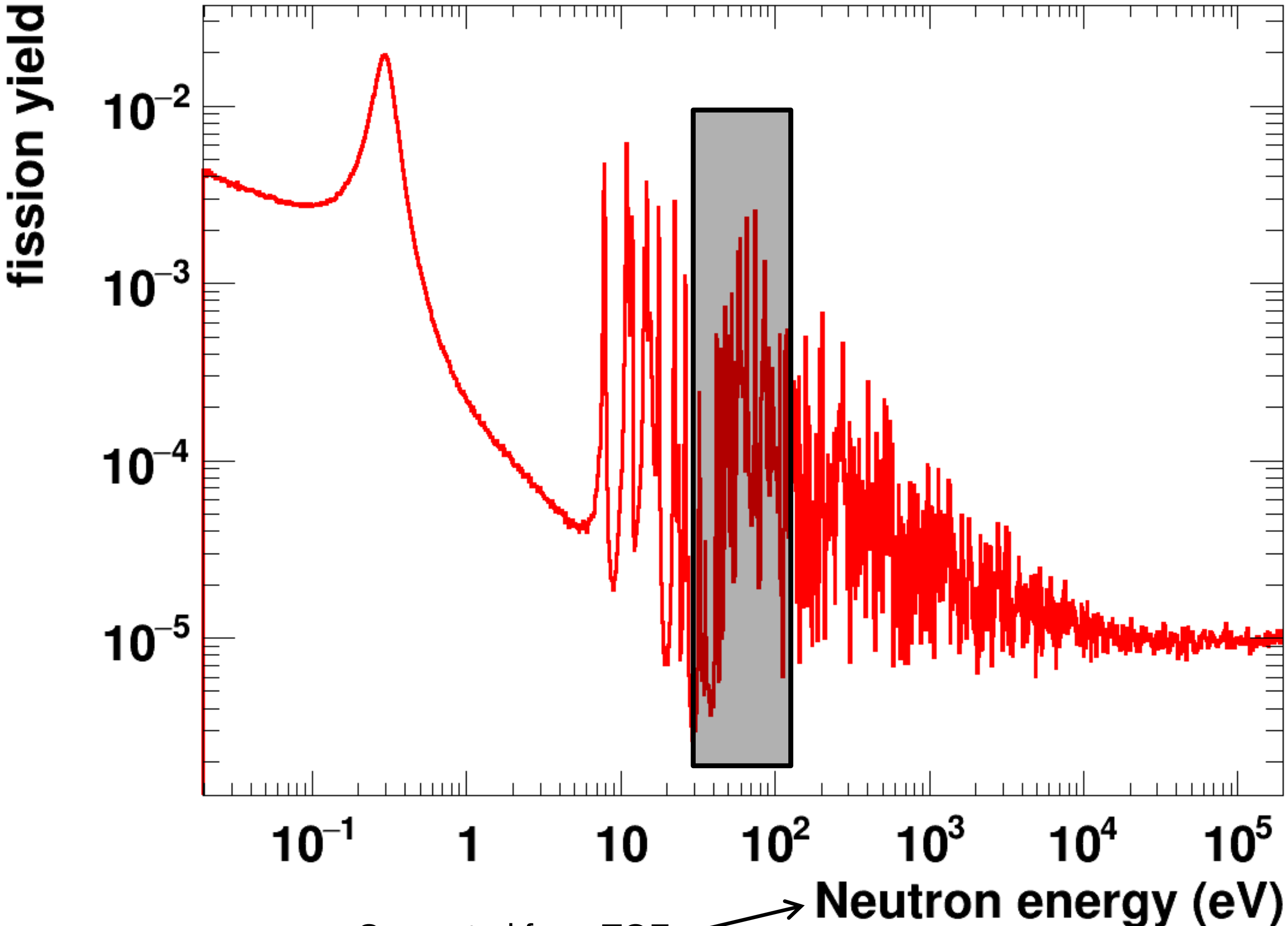
^{239}Pu(n,f) cross section measured at n_TOF-CERN (2022)



Converted from TOF

Example

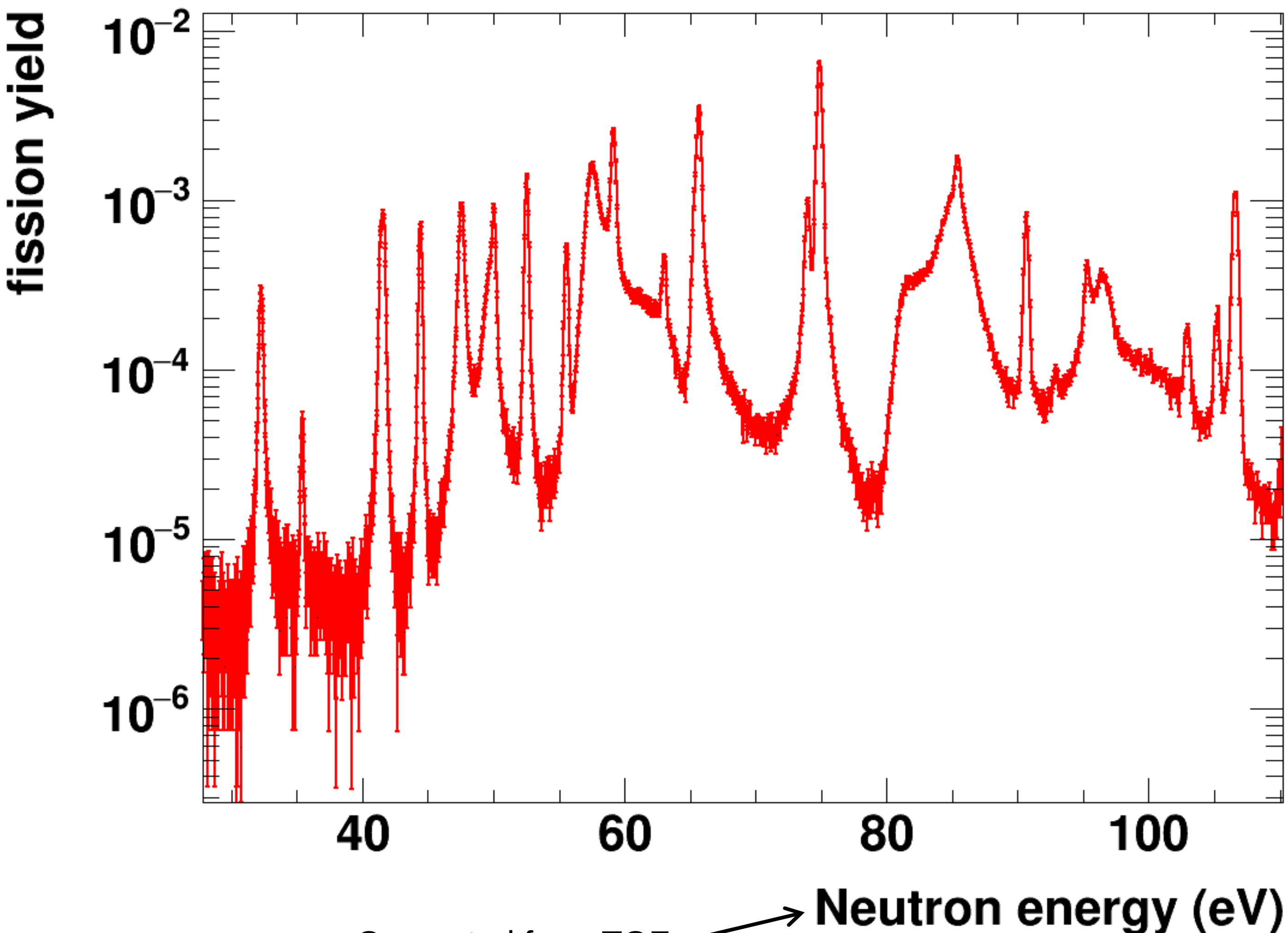
^{239}Pu(n,f) cross section measured at n_TOF-CERN (2022)



Converted from TOF

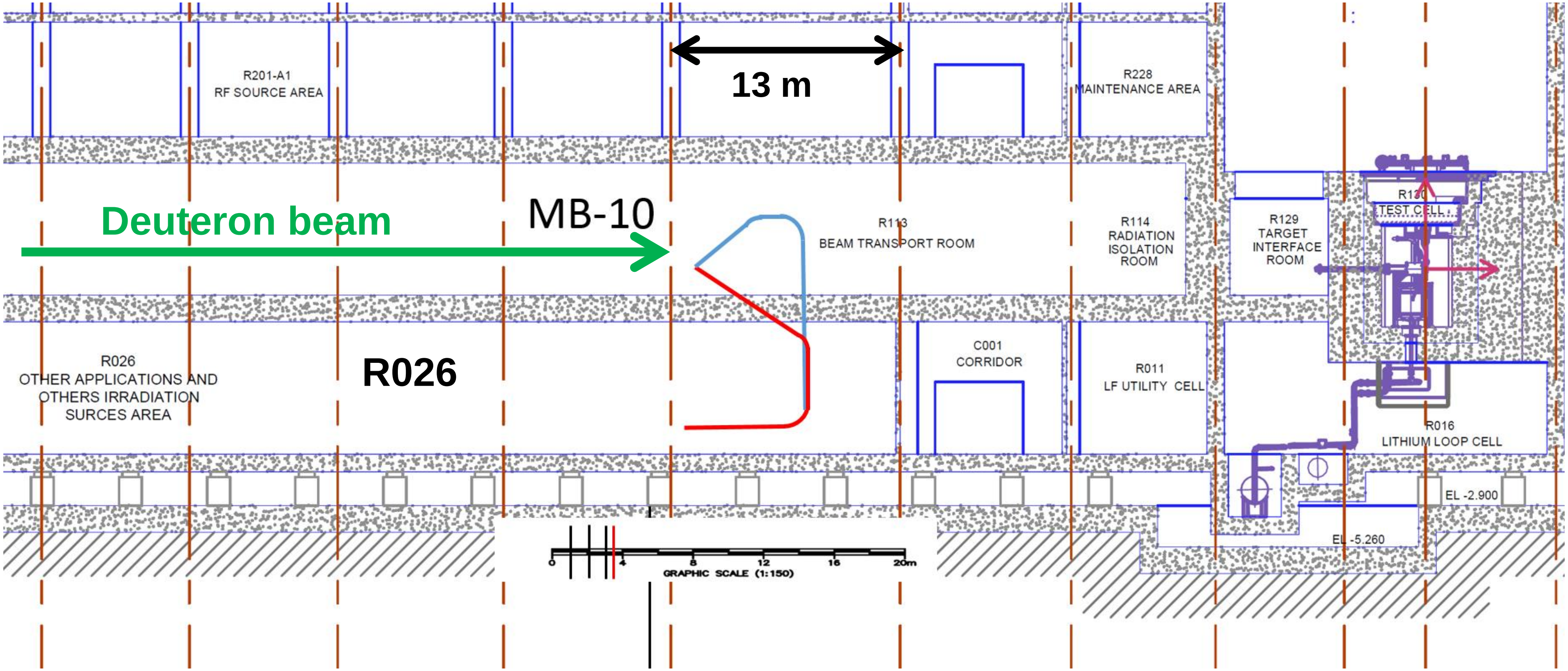
Example

$^{239}Pu(n,f)$ cross section measured at n_TOF-CERN (2022)



Converted from TOF → Neutron energy (eV)

Extraction of the deuteron beam



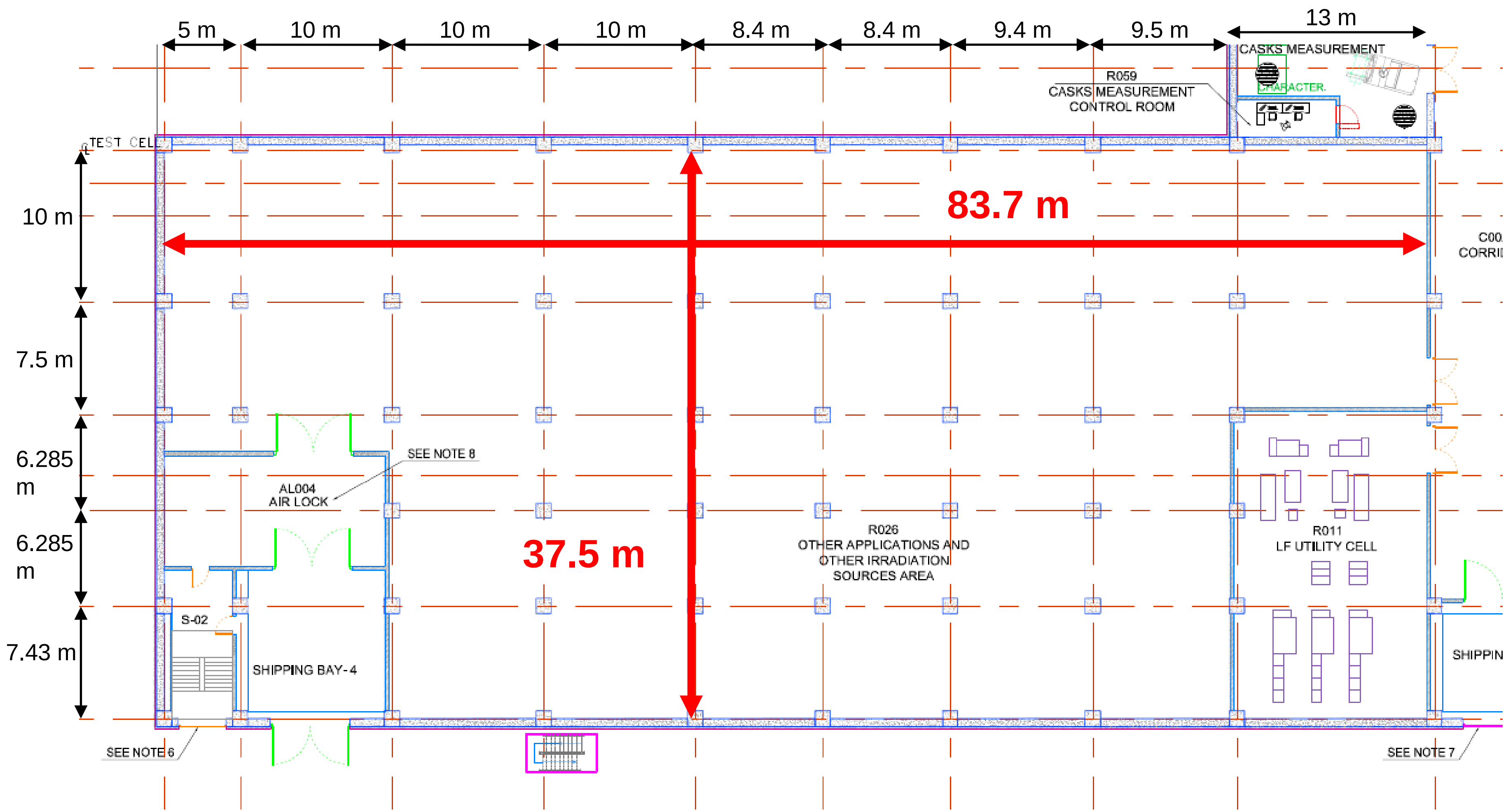
Vertical view

Dimensions of **R026**: ~ 60 x 36 x 8 m³

0.1% duty cycle maximum

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

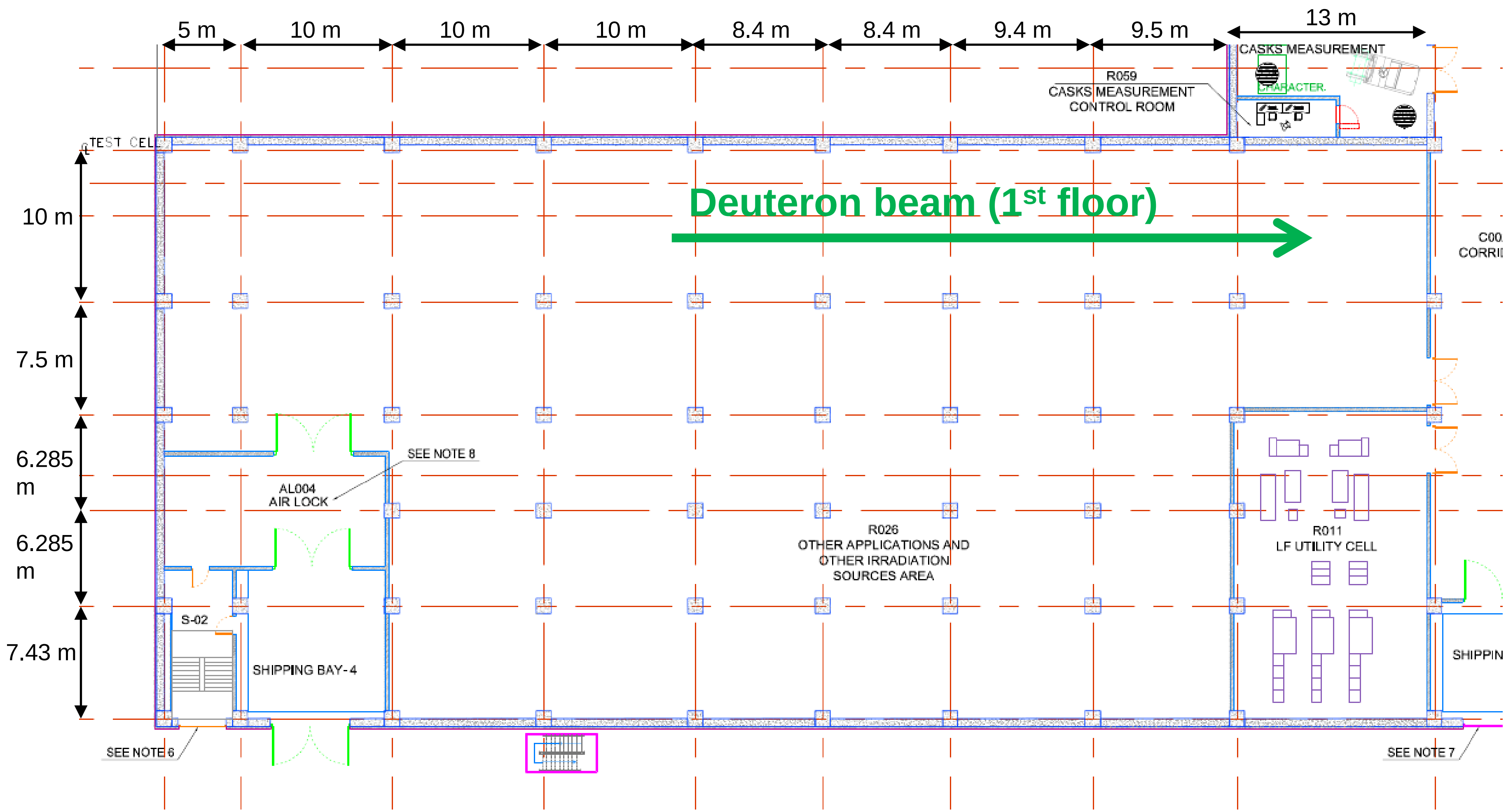
Dimensions of R026



Horizontal view

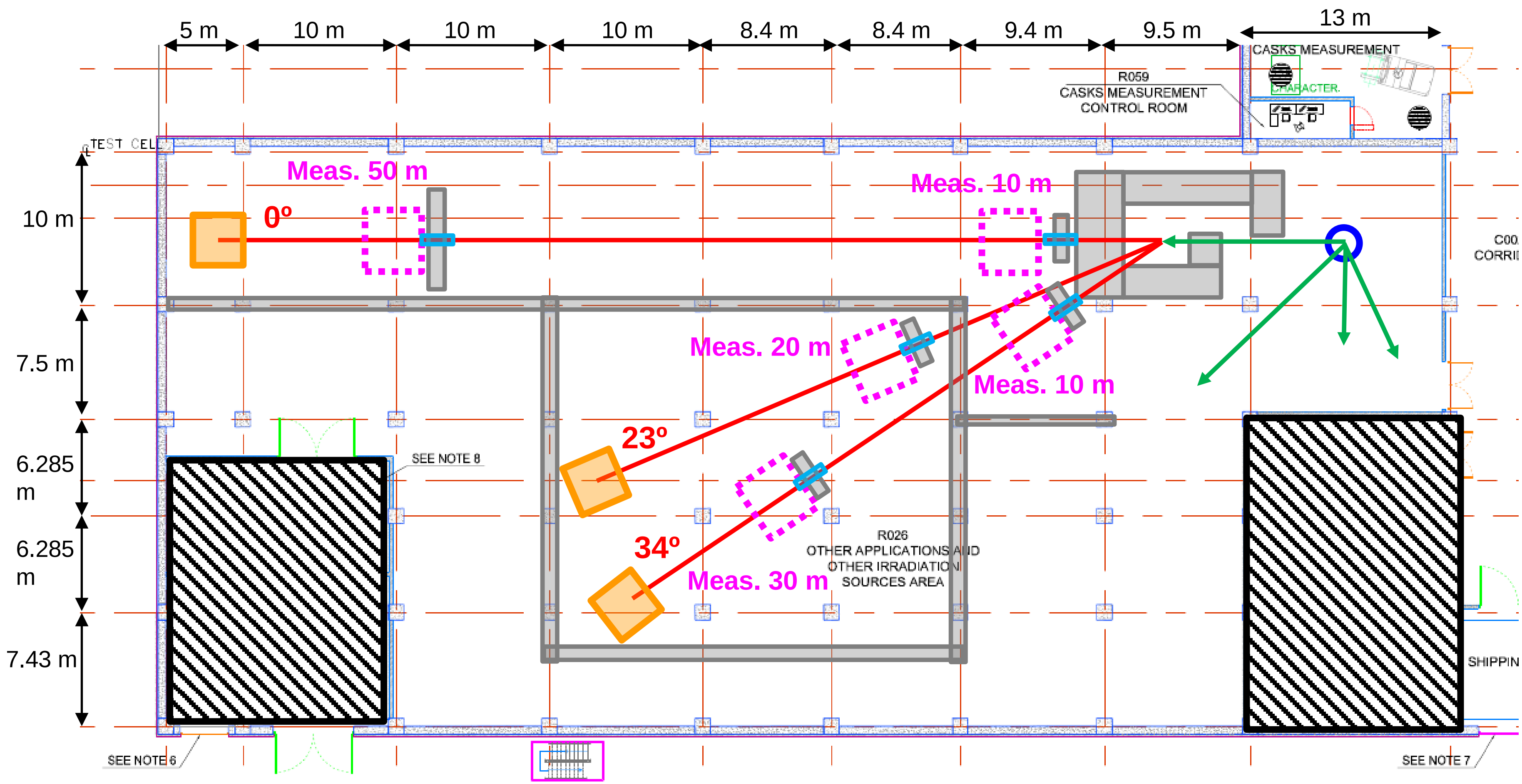
The height of the room is 8 m

Dimensions of R026

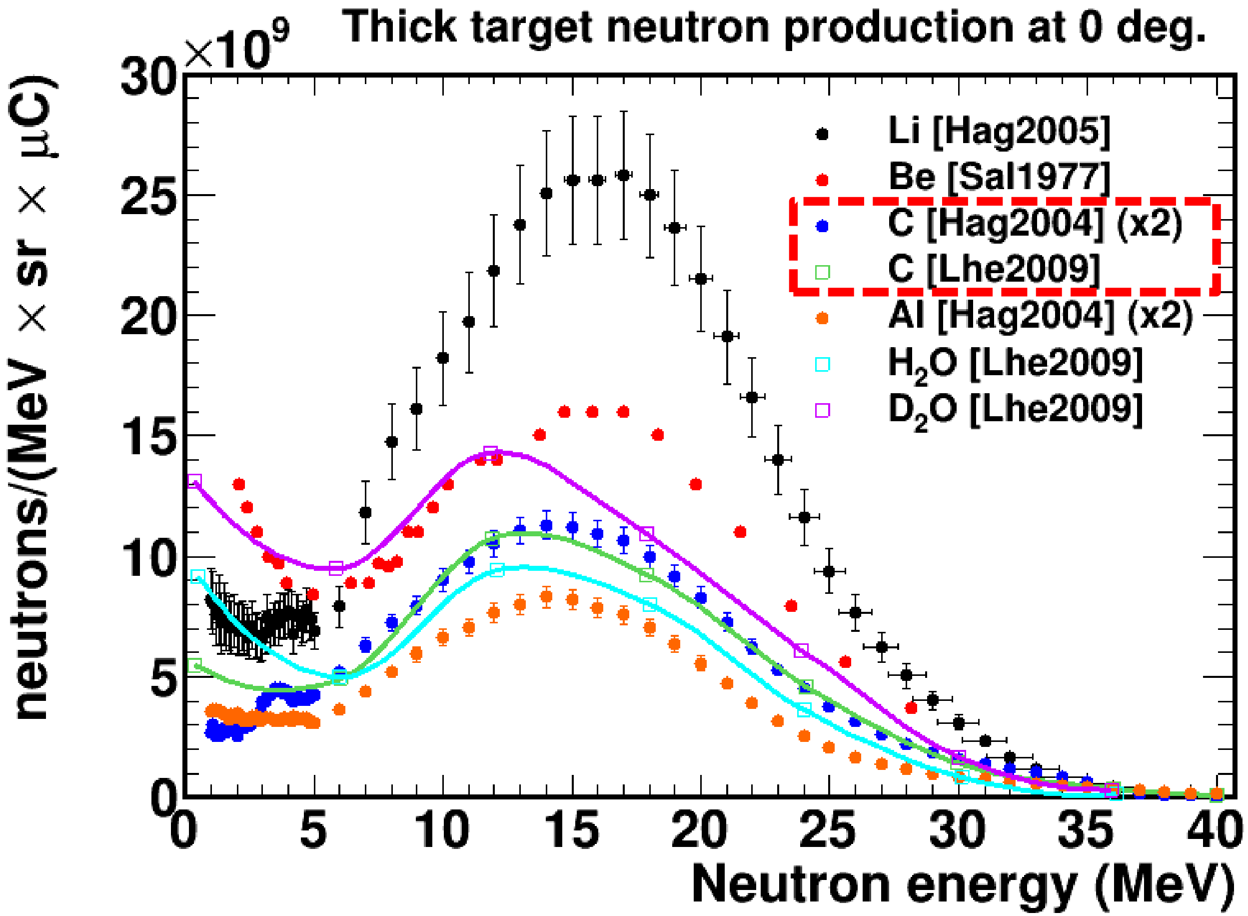


The height of the room is 8 m

Design of the DONES-TOF facility

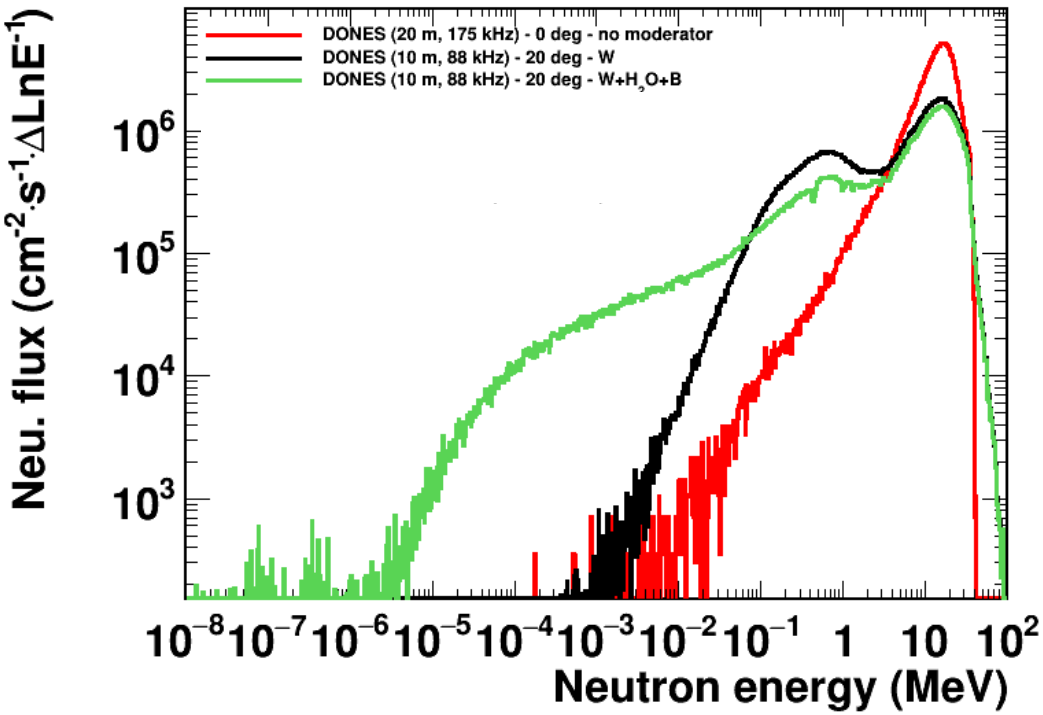


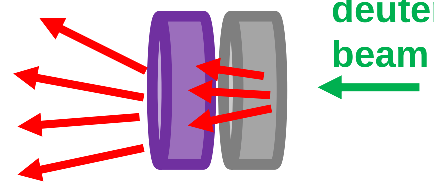
Neutron converter



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).

Degrader



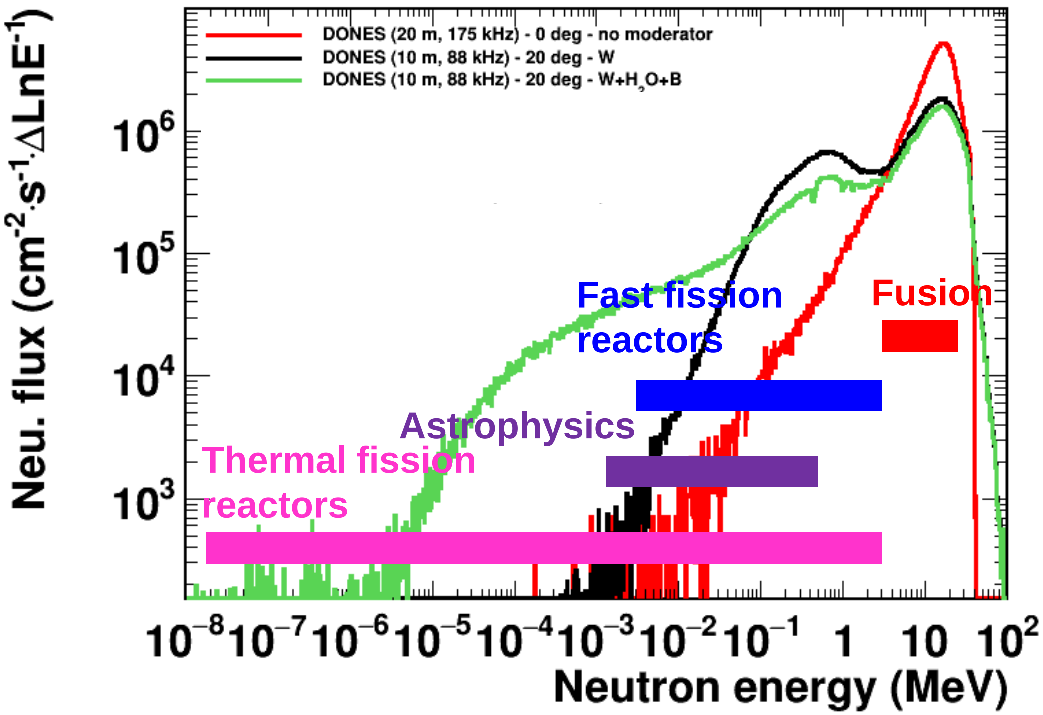


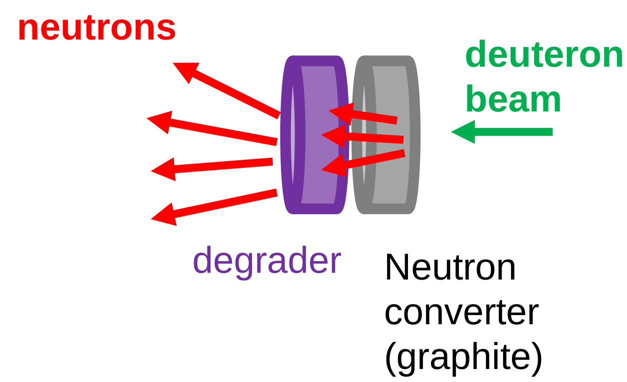
A neutron degrader located just after the neutron converter may allow to perform measurements in the keV region.

The neutron converter still needs to be properly designed (rotating converter may be not the best idea).

MC calculations → neutron generator is needed.

Degrader





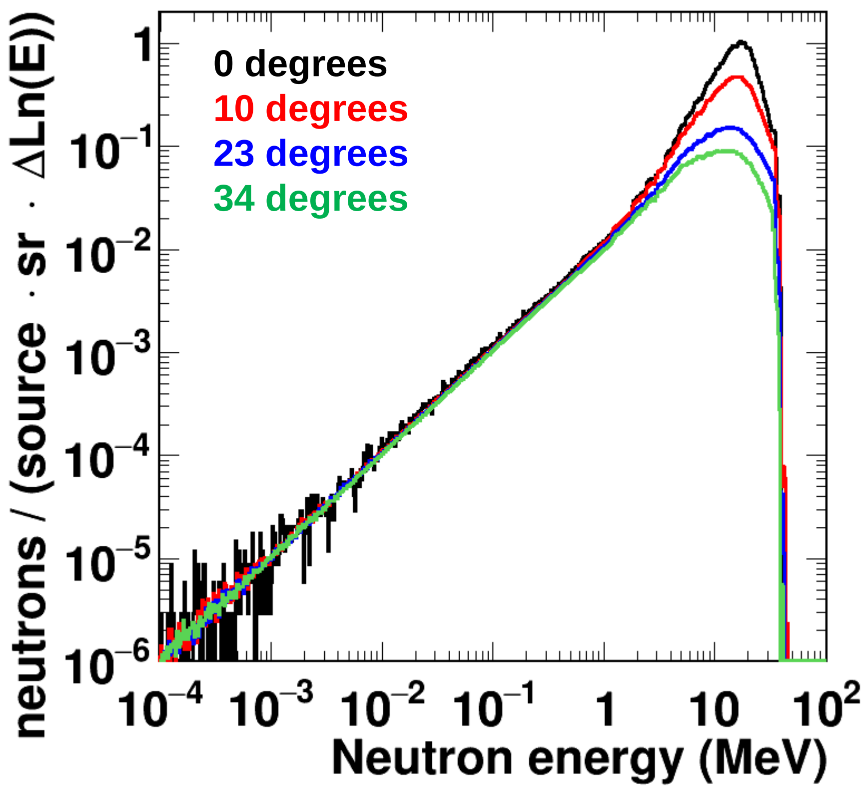
A neutron degrader located just after the neutron converter may allow to perform measurements in the keV region.

The neutron converter still needs to be properly designed (rotating converter may be not the best idea).

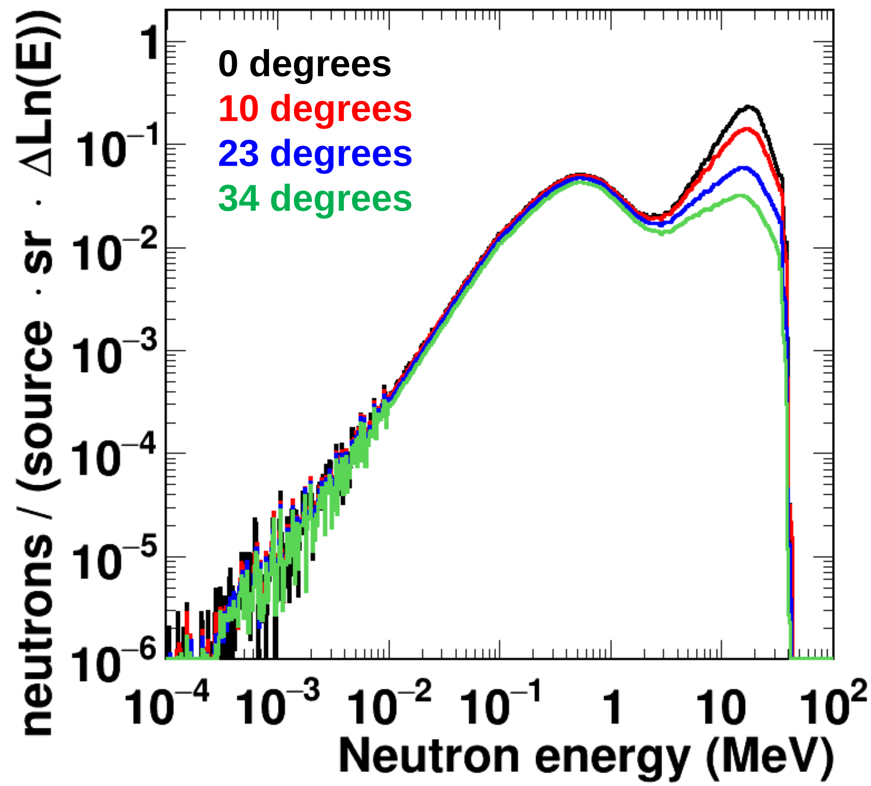
MC calculations → neutron generator is needed.

Angular distribution of the neutron source

No degrader

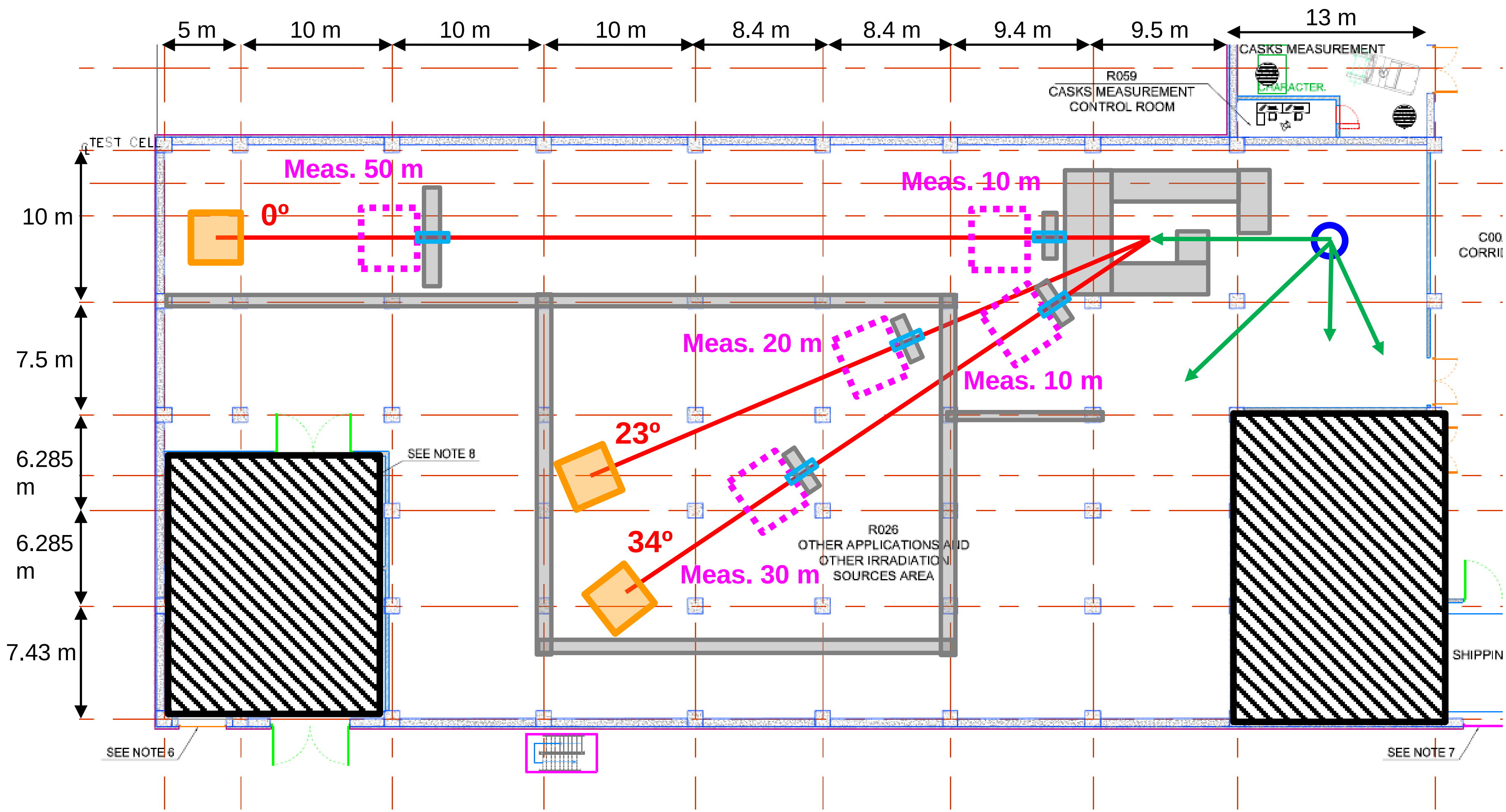


6 cm W degrader



Neutrons emitted at different angles, when placing just the graphite converter (left), and when placing the graphite converter + 6 cm W degrader (right).
The MeV part of the spectra decreases with the angle, but the keV region does not decrease much.

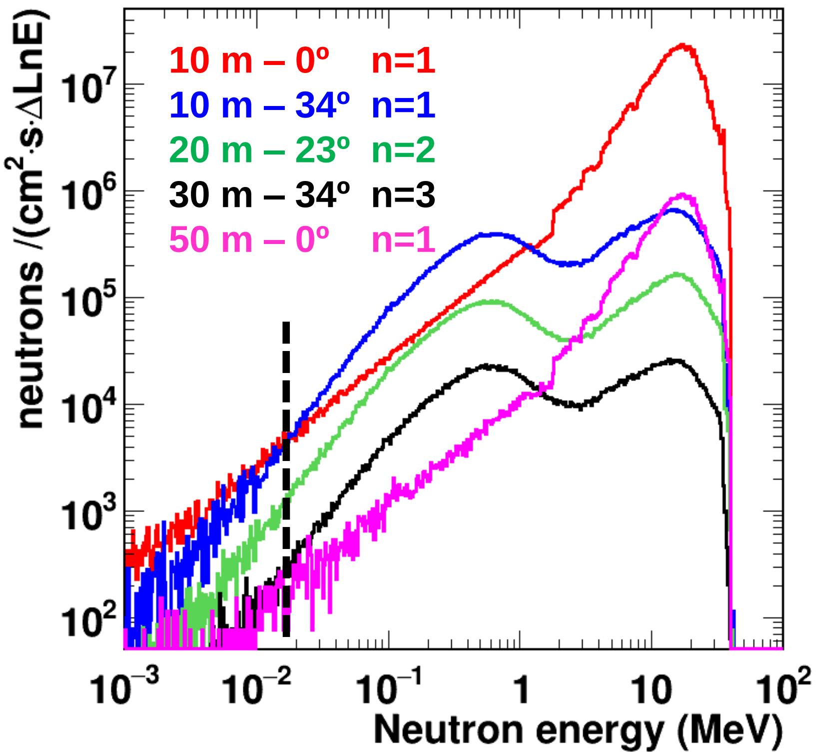
Design of the DONES-TOF facility



Design of the TOF-DONES facility

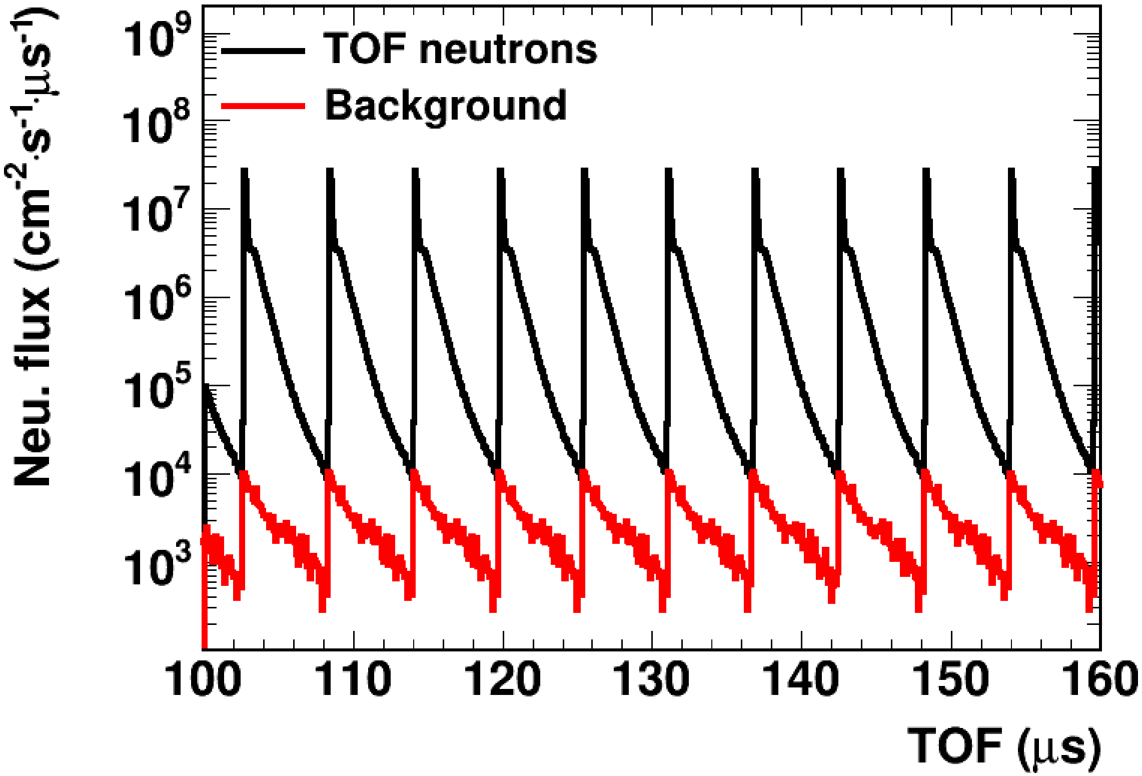
In summary, we have defined 5 different measuring stations, at:

- 10 m, 0 degrees
- 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



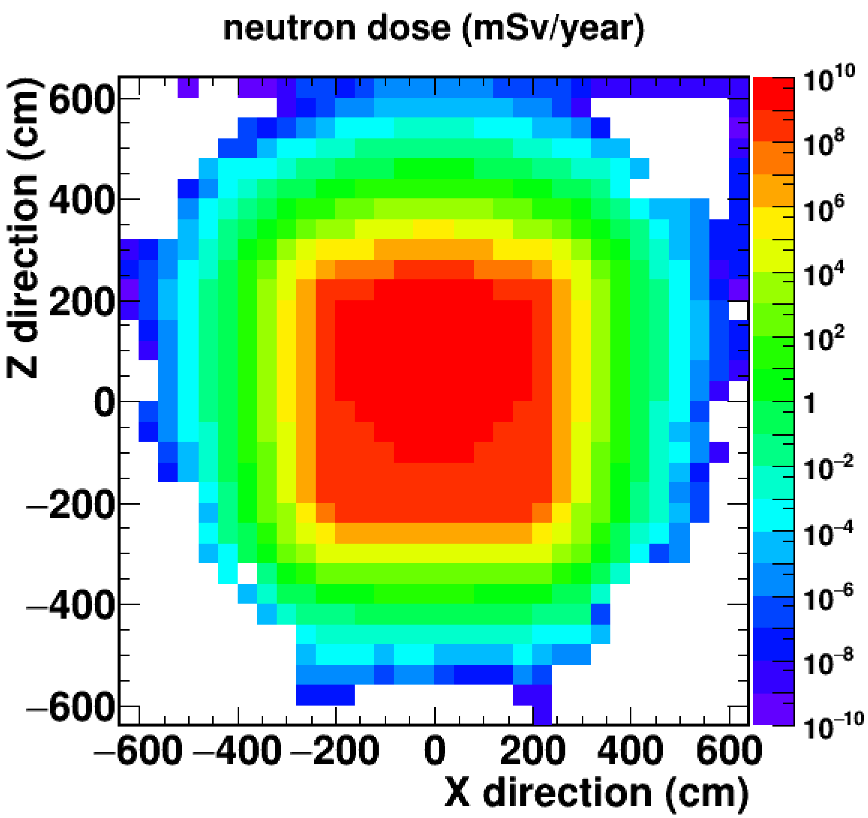
Neutron fluxes, as a function of the neutron energy, at the 5 different measuring stations, without (red and magenta) and with a 6 cm W neutron degrader (blue, green and black), and using different beam frequencies.
We have assumed that for the lines at 20 and 30 m, respectively we take 1/2 (n=2) and 1/3 (n=3) of the pulses, to avoid overlapping between pulses.

Time structure of the neutron beam

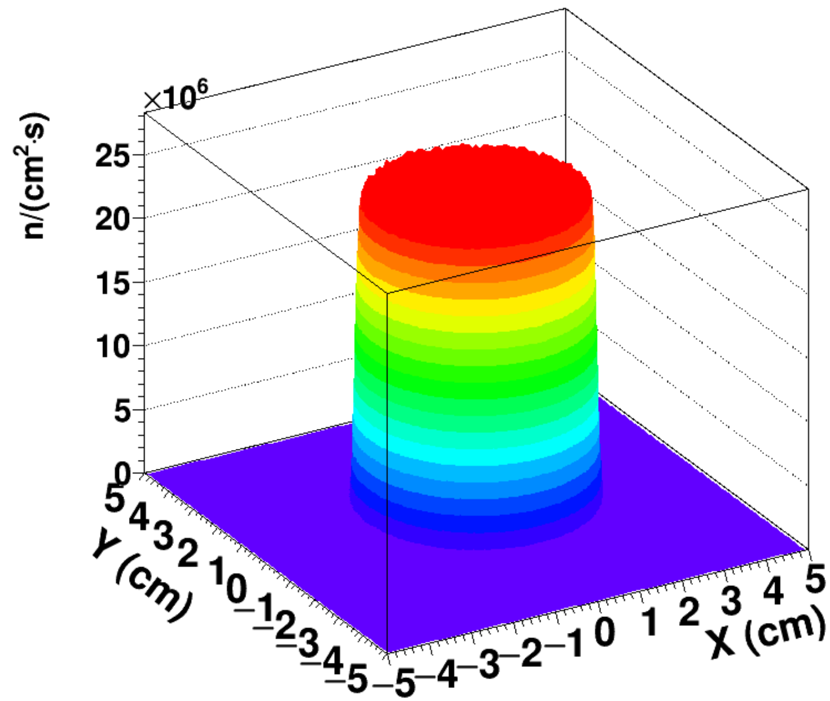


In the neutron beam, there will be some neutrons coming with the desired TOF-Energy relation (black) and other neutrons from other pulses → background (red). In the picture, n = 1 and the distance between pulses 5.7 μs (175 kHz).

Design in progress

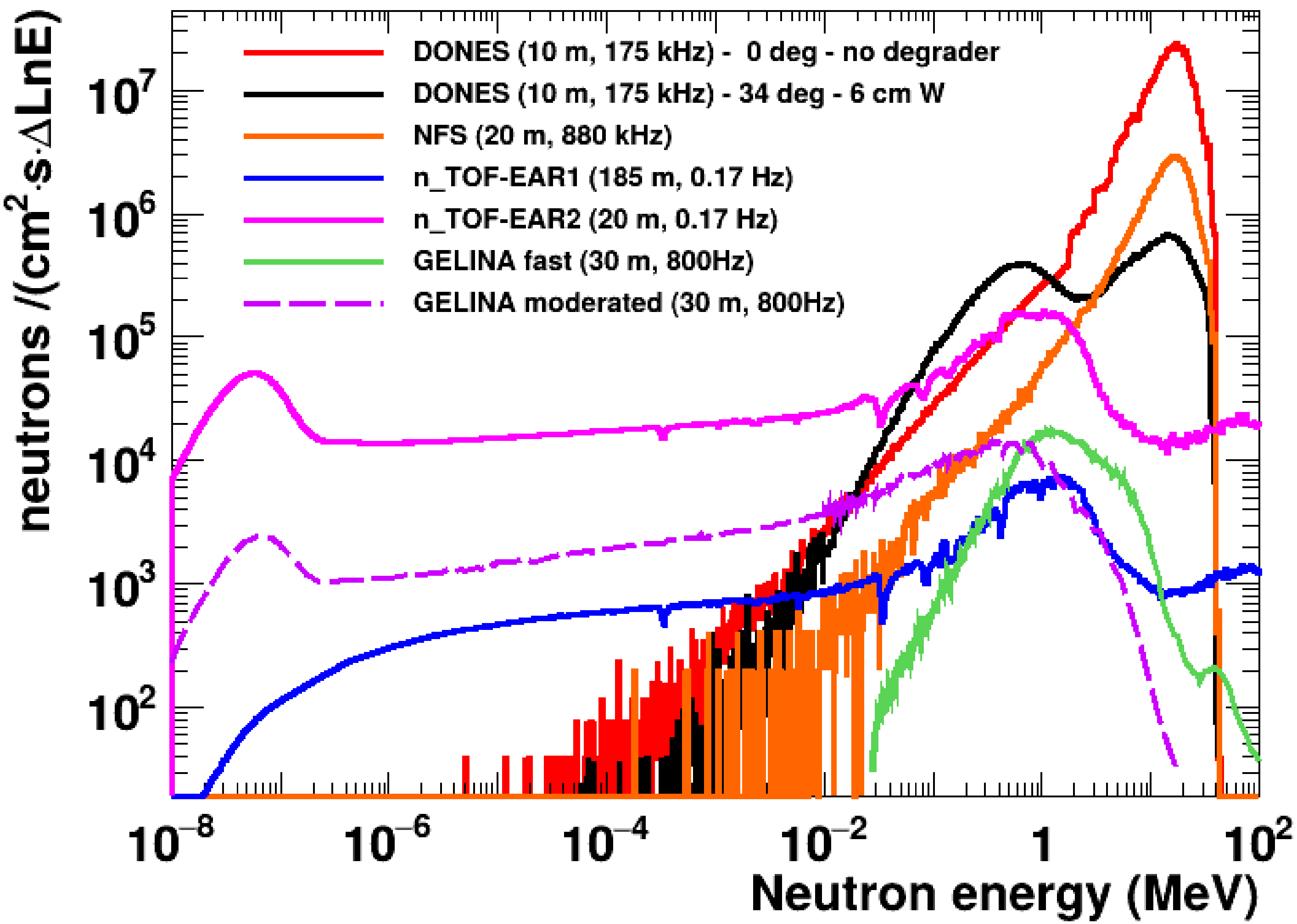


Shielding calculations

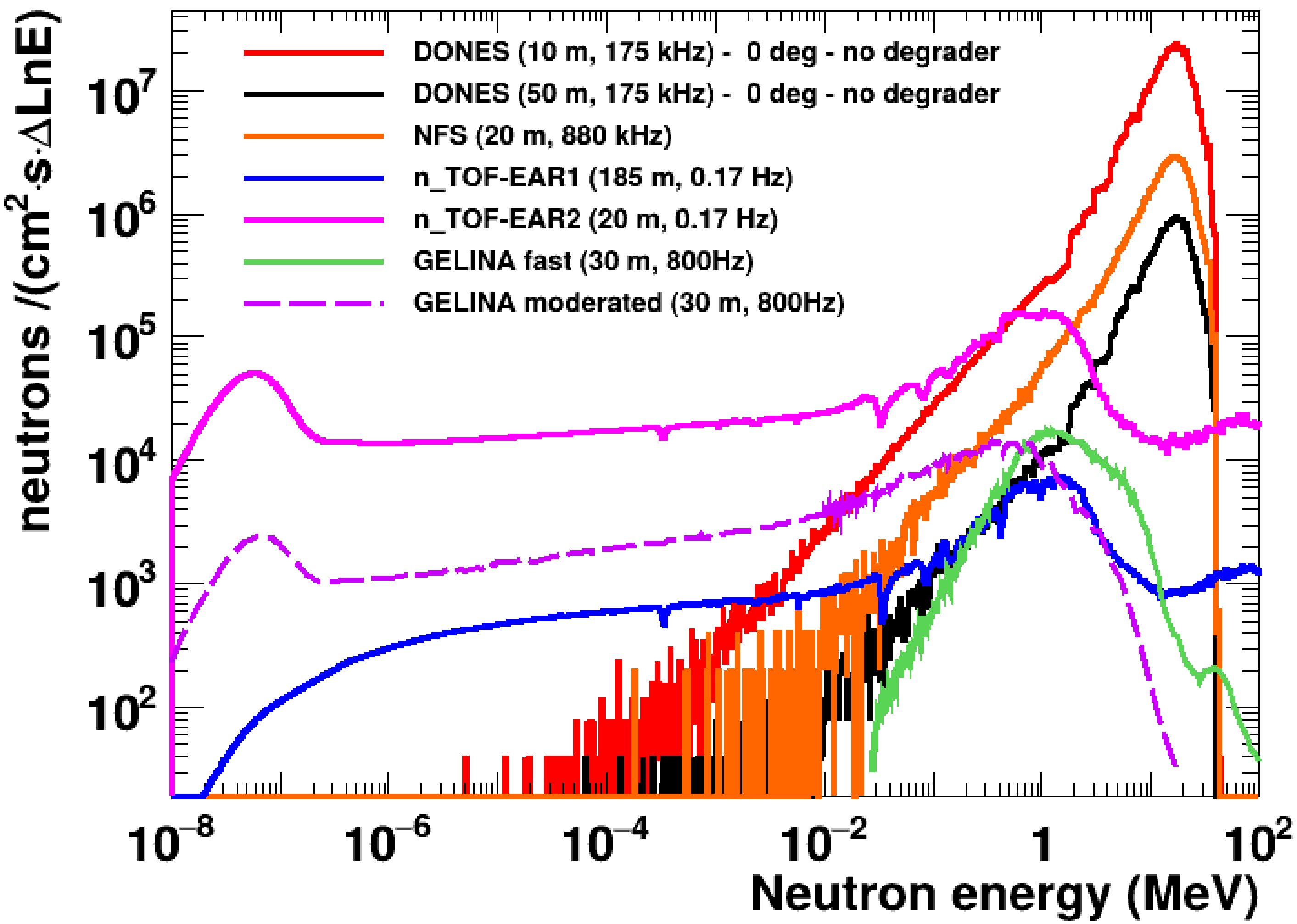


Collimators

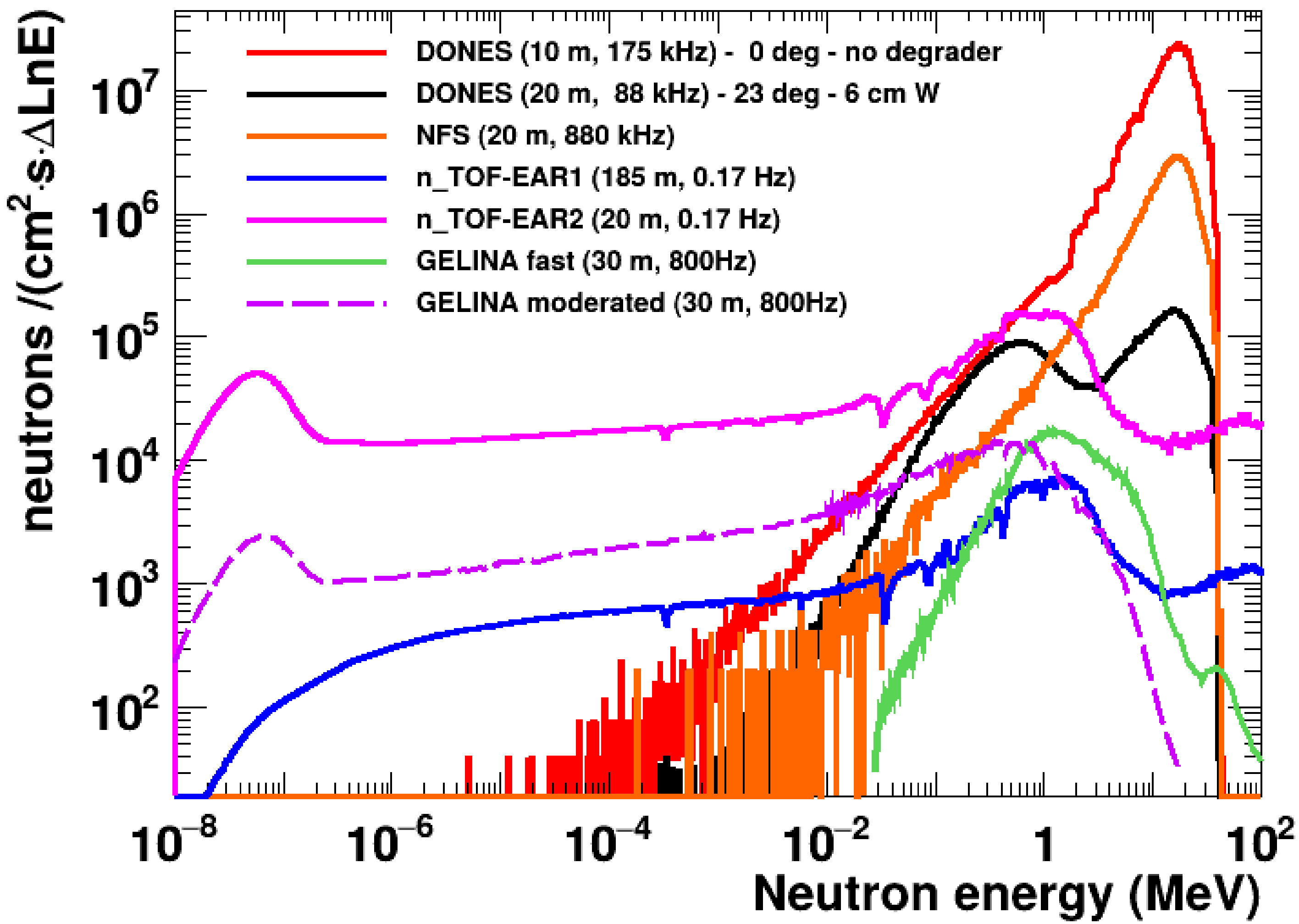
Comparison with other facilities



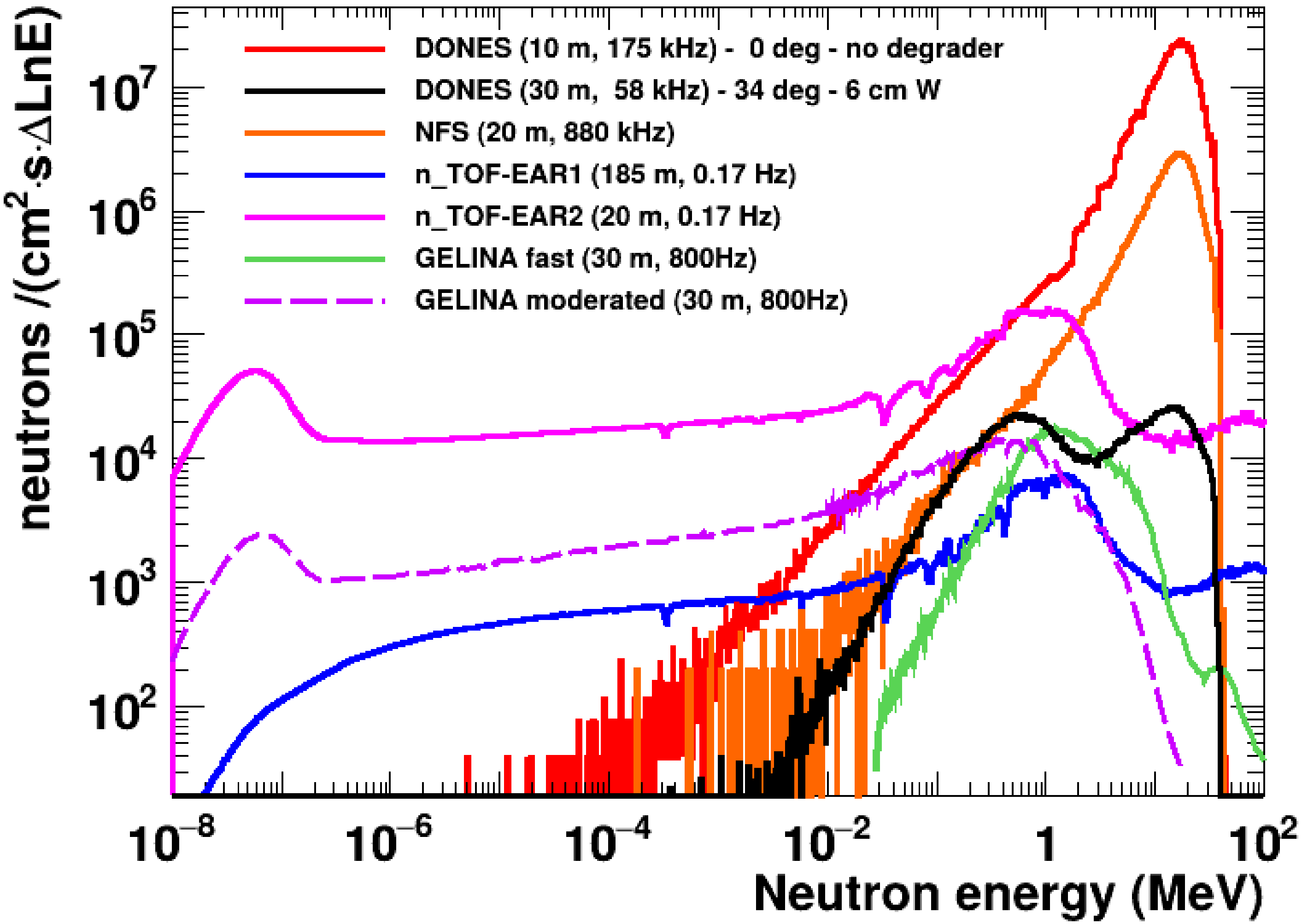
Comparison with other facilities



Comparison with other facilities



Comparison with other facilities



Visit to a similar and existing facility: SPIRAL2-NFS

A delegation of the IFMIF-DONES project (A. Ibarra, D. Cano-Ott, W. Krolas, I. Podadera, C. Torregosa, E. Mendoza) visited the SPIRAL2-NFS facility (Caen, France) two weeks ago (many thanks to Marek Lewitowicz, Xavier Ledoux and colleagues).

We had several technical meetings on the operation of the accelerator, beam diagnostics, neutron production targets, operation of NFS and relevant safety aspects. A forma collaboration between IFMIF-DONES and GANIL was discussed, and several topics of common interest were identified:

- Construction of a prototype of the kicker (IFMIF-DONES) and testing at SPIRAL2.
- Training of personnel at GANIL, to acquire valuable experience in the operation of the different parts of the facility.
- Development of a joint experimental program at NFS. 4 IFMIF-DONES related proposals have been submitted (activation analysis, charged particle production...).

See talk by X. Ledoux in this session.

TOF-DONES experimental program

Nuclear data needs for **nuclear technologies** (fission, fusion, dosimetry, waste management with accelerator driven systems...) → NEA/OCDE High Priority Request List → https://www.oecd-nea.org/dbdata/hprl/

Nuclear data needs for **nuclear astrophysics**:

- F. Käppeler et al., Rev. Mod. Phys 83 (2011)
- N. Nishimura et al., MNRAS 489, 1379–1396 (2016)
- G. Cescutti et al., MNRAS 478 4101 – 4127 (2018)

Nuclear data needs for nuclear **fusion**:

- U. Fischer et al., EPJ Web of Conferences 146, 09003 (2017)
- Mark R Gilbert, J. Phys. Energy 5 034002 (2023)
- Dedicated session to fusion during the last USA workshop on nuclear data (WANDA 2024 https://conferences.lbl.gov/event/1403/)

There is a program that requires decades of beam time -> there is room (and need) for complementary facilities like n_TOF, NFS, nELBE, GELINA).

TOF-DONES experimental program

Nuclear data needs for **nuclear technologies** (fission, fusion, dosimetry, waste management with accelerator driven systems...) → NEA/OCDE High Priority Request List → https://www.oecd-nea.org/dbdata/hprl/

Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy	Cov	Field
1-H-1	(n,el)	SIG,DA	10 MeV-20 MeV	4 pi	1-2	Y	Standard
1-H-2	(n,el)	DA/DE	0.1 MeV-1 MeV	0-180 Deg	5	Y	Fission
3-LI-0	(d,x)Be-7	SIG	10 MeV-40 MeV		10	Y	Fusion
3-LI-0	(d,x)H-3	SIG,TTY	5 MeV-40 MeV		10	Y	Fusion
8-O-16	(n,a),(n,abs)	SIG	2 MeV-20 MeV		See details	Y	Fission
9-F-19	(n,2n)	SIG/SPA	239Pu(n,f)		3	Y	Fission
11-NA-23	(n,2n)	SIG/SPA	252Cf(sf)-235U(n,f)		2-5	Y	Dosimetry
13-AL-27	(n,2n)	SIG/SPA	252Cf(sf)-235U(n,f)		2-5	Y	Dosimetry
15-P-31	(n,p)	SIG/SPA	252Cf(sf)-235U(n,f)		2-5	Y	Dosimetry
17-CL-35	(n,p)	SIG	100 keV-5 MeV		5-8	Y	Fission
19-K-39	(n,p),(n,np)	SIG	10 MeV-20 MeV		10	Y	Fusion
22-TI-0	(n,x)Sc-46	SIG	15 MeV-100 MeV		5-10	Y	Dosimetry
22-TI-0	(n,x)Sc-48	SIG	15 MeV-100 MeV		5-10	Y	Dosimetry
22-TI-0	(n,x)Sc-47	SIG	15 MeV-100 MeV		5-10	Y	Dosimetry
22-TI-46	(n,2n)	SIG/SPA	252Cf(sf)-235U(n,f)		2-5	Y	Dosimetry
22-TI-47	(n,np)	SIG/SPA	252Cf(sf)-235U(n,f)		5-10	Y	Dosimetry
22-TI-48	(n,np)	SIG/SPA	252Cf(sf)-235U(n,f)		5-10	Y	Dosimetry
22-TI-49	(n,np)	SIG/SPA	252Cf(sf)-235U(n,f)		5-10	Y	Dosimetry
24-CR-50	(n,g)	SIG	1 keV-100 keV		8-10	Y	Fission
24-CR-52	(n,2n)	SIG/SPA	252Cf(sf)-235U(n,f)		2-5	Y	Dosimetry
24-CR-53	(n,g)	SIG	1 keV-100 keV		8-10	Y	Fission
25-MN-55	(n,2n)	SIG/SPA	235U(n,f)		2-5	Y	Dosimetry
25-MN-55	(n,g)	SIG/SPA	235U(n,f)		2-5	Y	Dosimetry
25-MN-55	(n,2n)	SIG/SPA	239Pu(n,f)		3	Y	Fission
26-FE-0	(n,x)Mn-54	SIG	15 MeV-100 MeV		5-10	Y	Dosimetry
26-FE-54	(n,2n)	SIG/SPA	252Cf(sf)-235U(n,f)		5-10	Y	Dosimetry
26-FE-54	(n,a)	SIG/SPA	252Cf(sf)		2-5	Y	Dosimetry
26-FE-54	(n,2n)	SIG	15 MeV-100 MeV		5-10	Y	Dosimetry
26-FE-56	(n,inl)	SIG	0.5 MeV-20 MeV	Emis spec.	See details	Y	Fission

TOF-DONES experimental program

^{63}Ni(n,γ), ^{79}Se(n,γ), ^{81,85}Kr(n,γ), ^{95}Zr(n,γ), ^{134,135}Cs(n,γ), ^{147}Nd(n,γ), ^{147,148}Pm(n,γ), ^{151}Sm(n,γ), ^{154,155}Eu(n,γ), ^{153}Gd(n,γ), ^{160}Tb(n,γ), ^{163}Ho(n,γ), ^{170,171}Tm(n,γ), ^{179}Ta(n,γ), ^{185}W(n,γ).

Nuclear data needs for **nuclear astrophysics**:

- F. Käppeler et al., Rev. Mod. Phys 83 (2011)
- N. Nishimura et al., MNRAS 489, 1379–1396 (2019)
- G. Cescutti et al., MNRAS 478, 4101 – 4127 (2018)

^{60}Zn(n,p) , ^{64}Ge(n,p), ^{68}Se(n,p), ^{59}Zn(n,p), ^{63}Ge(n,p), ^{72}Kr(n,p), ^{77}Sr(n,p), ^{75}Sr(n,p), ^{76}Sr(n,p), ^{100}Pd(n,γ), ^{97}Rh(n,γ), ^{113}In(n,γ) , ^{117}In(n,γ), ^{57}Ni(n,p), ^{85}Mo(n,p), ^{80}Sr(n,γ), ^{93}Tc(n,γ) , ^{80}Zr(n,p), ^{86}Mo(n,p).

^{72}Ge(n,γ), ^{74}Ge(n,γ), ^{75}As(n,γ), ^{78}Se(n,γ), ^{84}Kr(n,γ), ^{85}Kr(n,γ)

TOF-DONES experimental program

[…] Not only are further experiments needed to address the outstanding issues for key fusion materials, but also more careful development of inventory nuclear data libraries to target the specific and unique needs of fusion (e.g. fission reactors are unlikely to be impacted by the He production channels in Fe and C, which are only 'open' at fusion relevant neutron energies). Both integral experiments, for example of decay-heat, and differential cross section measurements are needed. Differential data needs should be guided by the identified priority reaction channels for fusion, such as those identified for W [21] and Mo [37], which should be recorded in an appropriate database of 'needs' such as NEA's High Priority Request List. Whether fusion specific cross section libraries, which previously existed (i.e. EAF) but have now become obsolete, are needed will depend on whether future evolutions of modern general purpose libraries such as TENDL, ENDF/B, and JEFF, will consider more proactively the fusion-relevant energy ranges alongside the ongoing needs of future nuclear fission developments.

- Structural materials and coolants: ^{16}O, ^{54,56,57,58}Fe, and ^{90,91,92,94,96}Zr neutron reaction data.
- Shielding and tritium breeding: ^{1}H, ^{6}Li, ^{7}Li, ^{9}Be, ^{16}O, ^{28,29,30}Si, ^{54,56}Fe, ^{52}Cr, ^{58}Ni and ^{182,183,184,186}W
- …

Nuclear data needs for nuclear **fusion**:

– U. Fischer et al., EPJ Web of Conferences 146, 09003 (2017)
– Mark R Gilbert, J. Phys. Energy 5 034002 (2023)
– Dedicated session to fusion during the last USA workshop on nuclear data (WANDA 2024 https://conferences.lbl.gov/event/1403/)
– Talk by D. Leichtle in this session.

Conclusions

TOF-DONES will be an **international facility** to perform a large variety of nuclear physics experiments:

- Pulsed neutrons
- Pulsed deuterons (program under discussion)

The characteristics of TOF-DONES make it a **world leading neutron time-of-flight facility**.

More than one experiment may run at the same time → **high scientific production**.

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.

Backup slides

Energy range of the TOF measurements

	10 m	20 m	30 m	40 m	50 m	60 m
n = 1	16	64	144	250	400	580
n = 2	4	16	36	64	100	144
n = 3	1.8	7.1	16	28	44	64
n = 4	1	4	9	16	25	36
n = 5	0.64	2.5	5.8	10	16	23
n = 10	0.16	0.64	1.44	2.5	4	5.8
n = 20	0.04	0.16	0.36	0.64	1	1.44
n = 50	0.0064	0.025	0.058	0.10	0.16	0.23
n = 100	0.0016	0.0064	0.0144	0.025	0.04	0.058

TOF-energy (in **keV**) of the neutrons at the time of overlapping with the next pulse, at the sample position → minimum neutron energy for TOF measurements.