Science with neutrons flying at IFMIF-DONES

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Nuclear Innovation Unit – CIEMAT

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

Introduction

Accurate modeling 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
- …

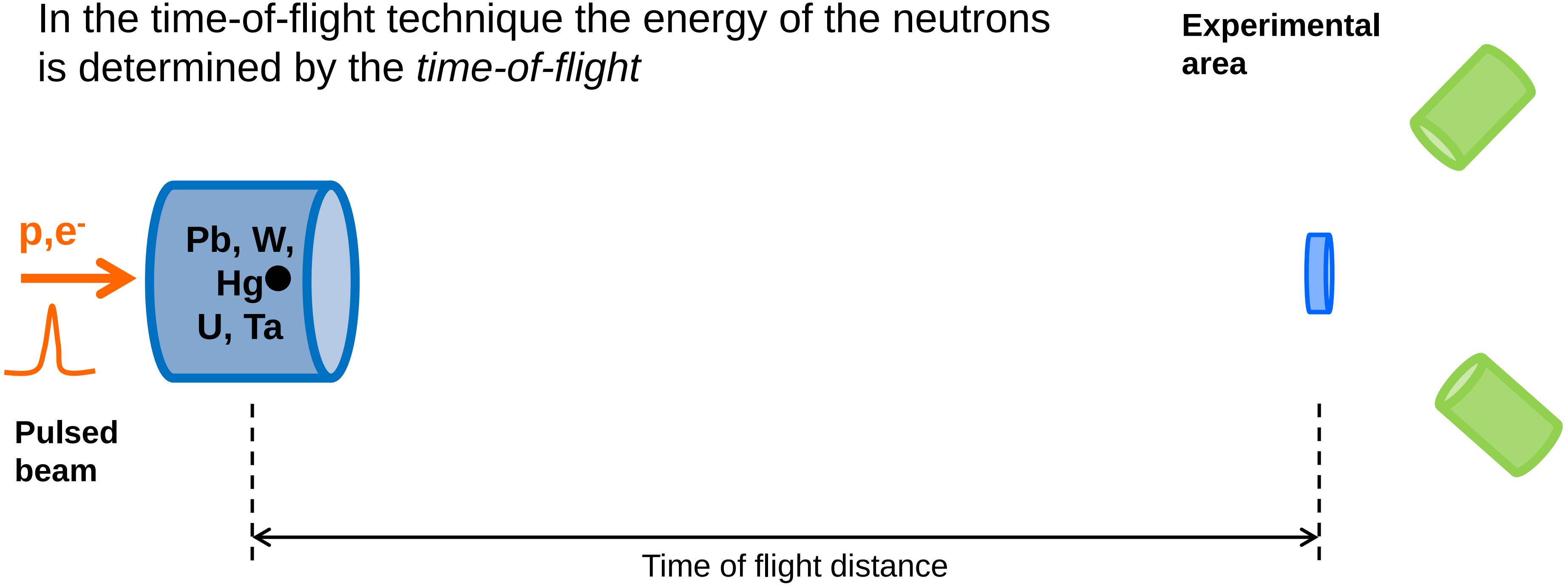
Actual nuclear models have a limited accuracy and predictive capabilities → experimental data is needed.

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*



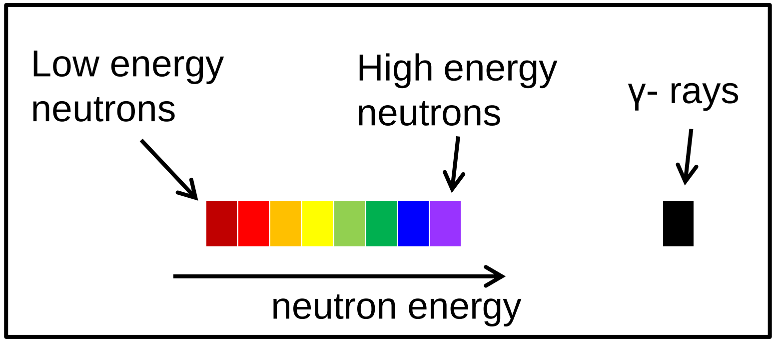
Experimental area

p,e$^-$

Pb, W, Hg● U, Ta

Pulsed beam

Time of flight distance



Low energy neutrons

High energy neutrons

γ- rays

neutron energy

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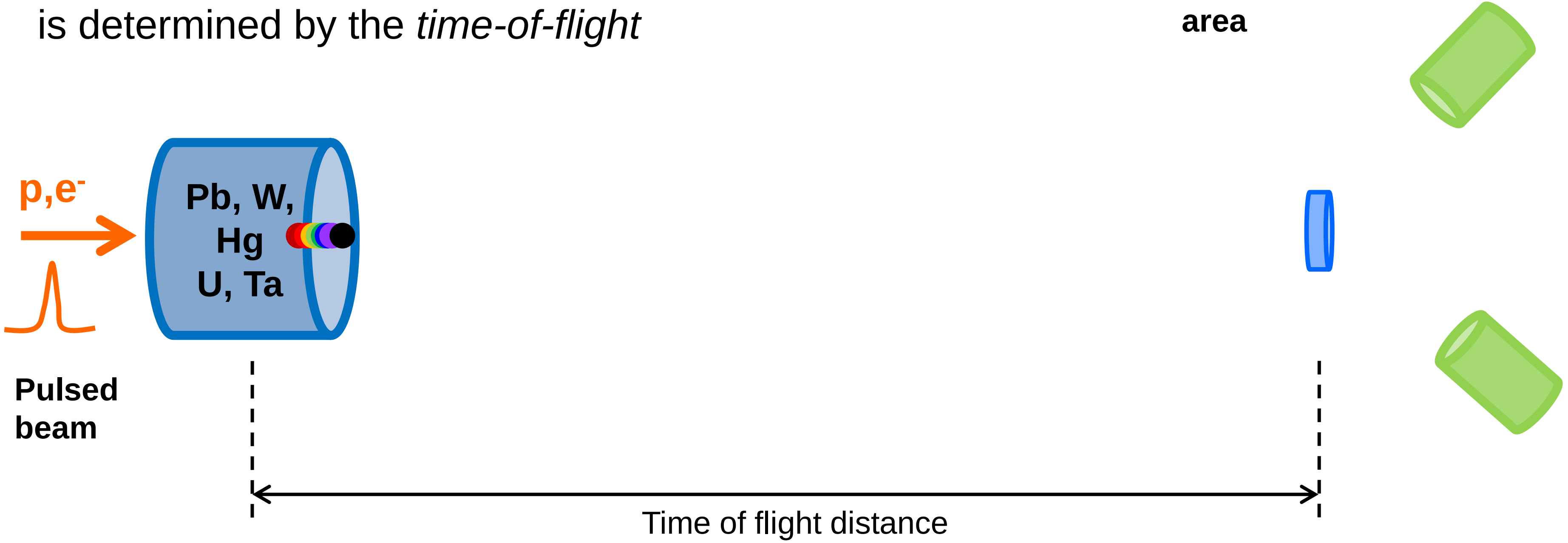

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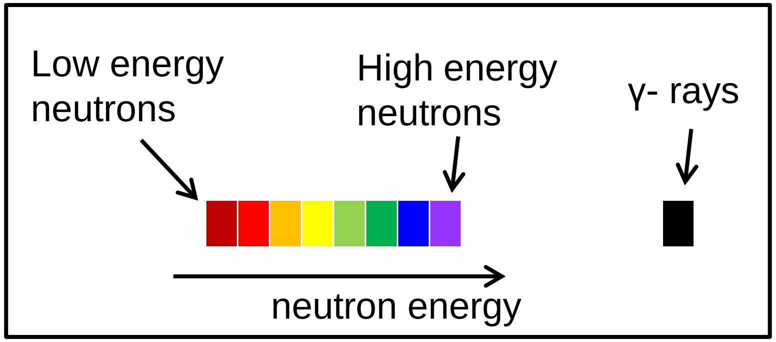

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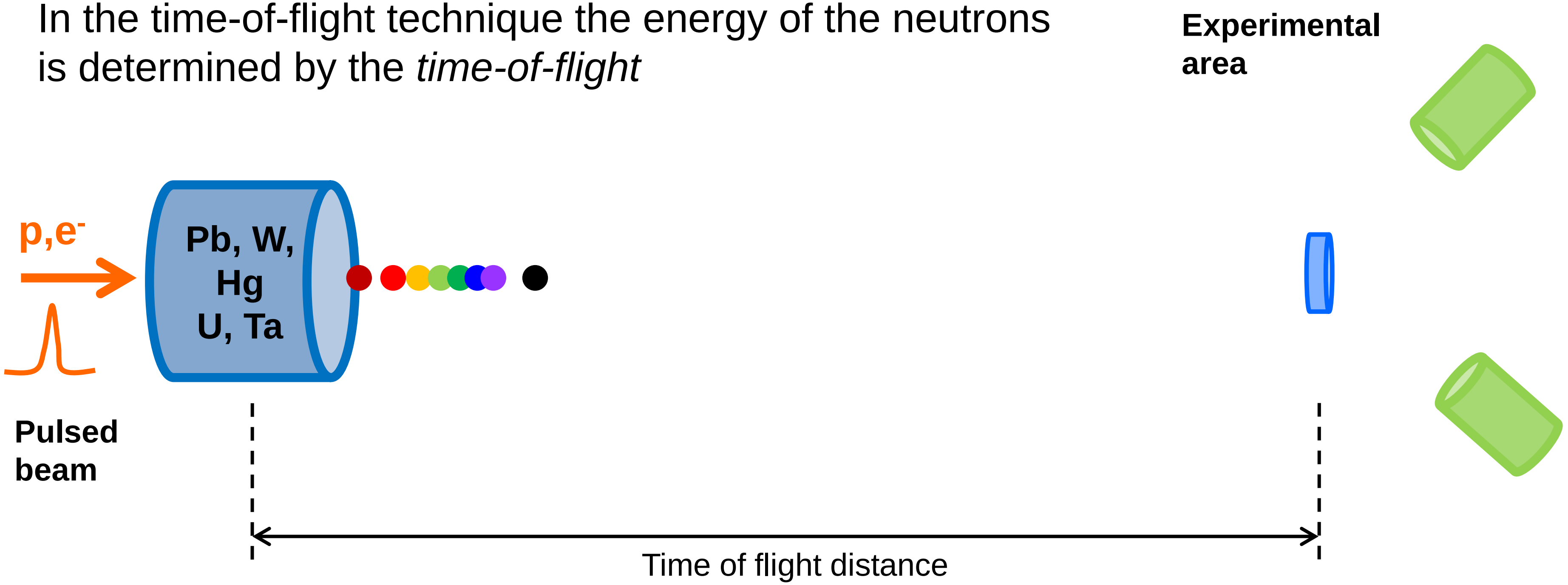

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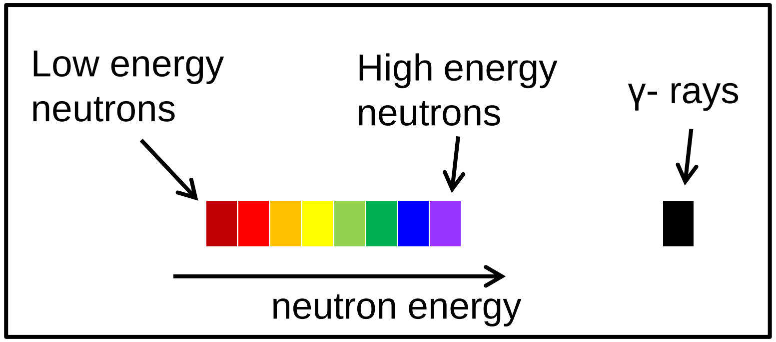

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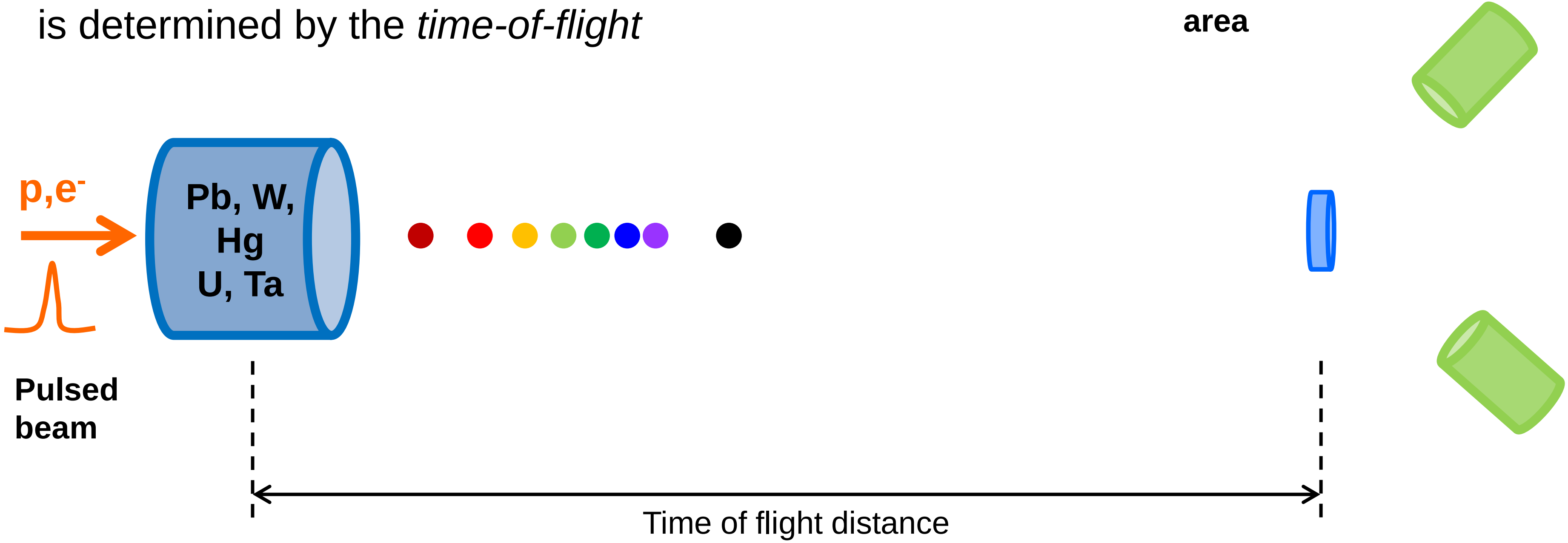

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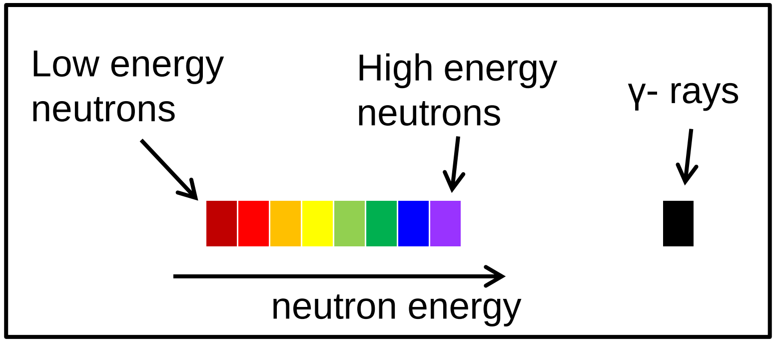

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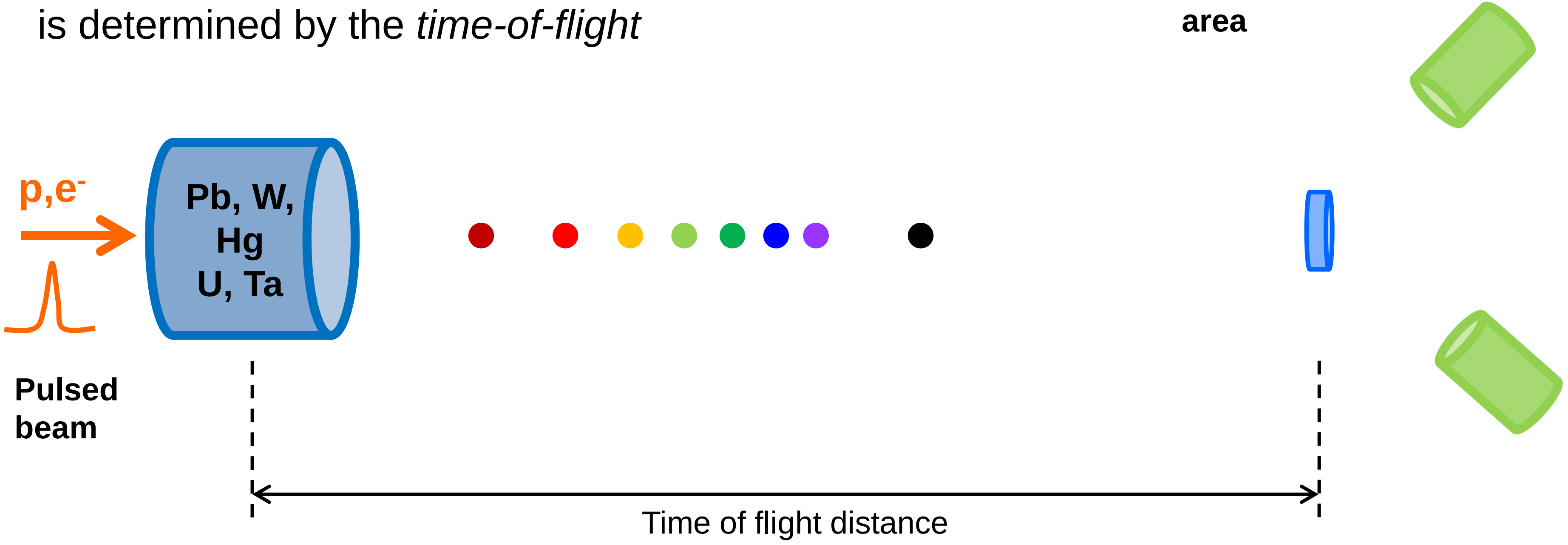

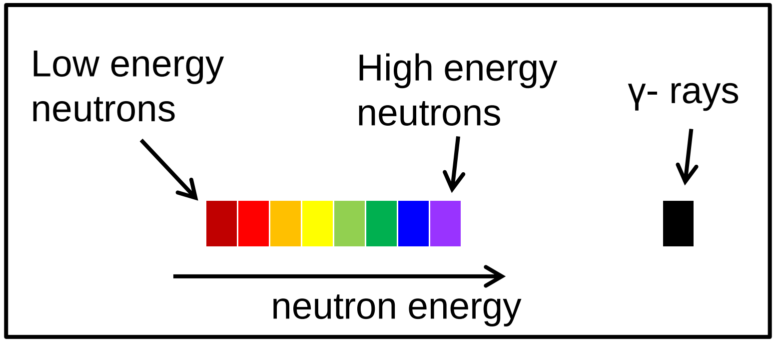

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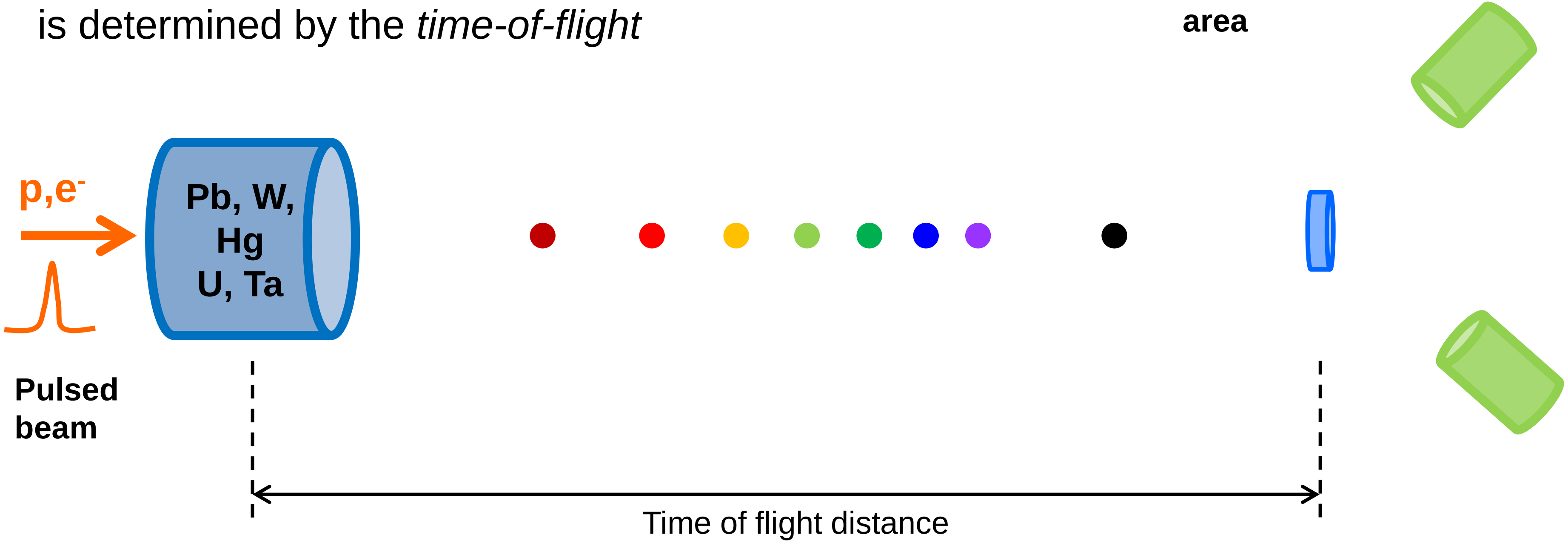

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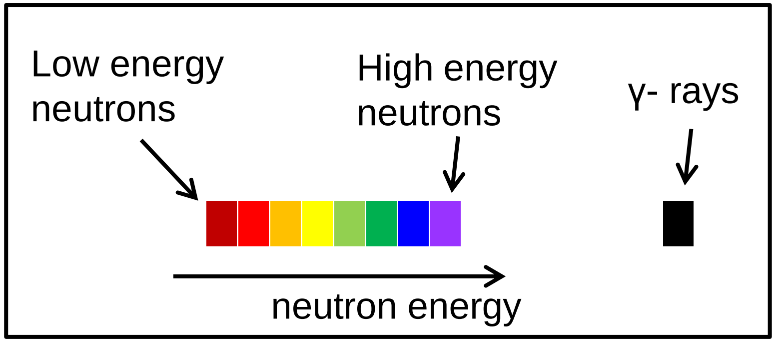

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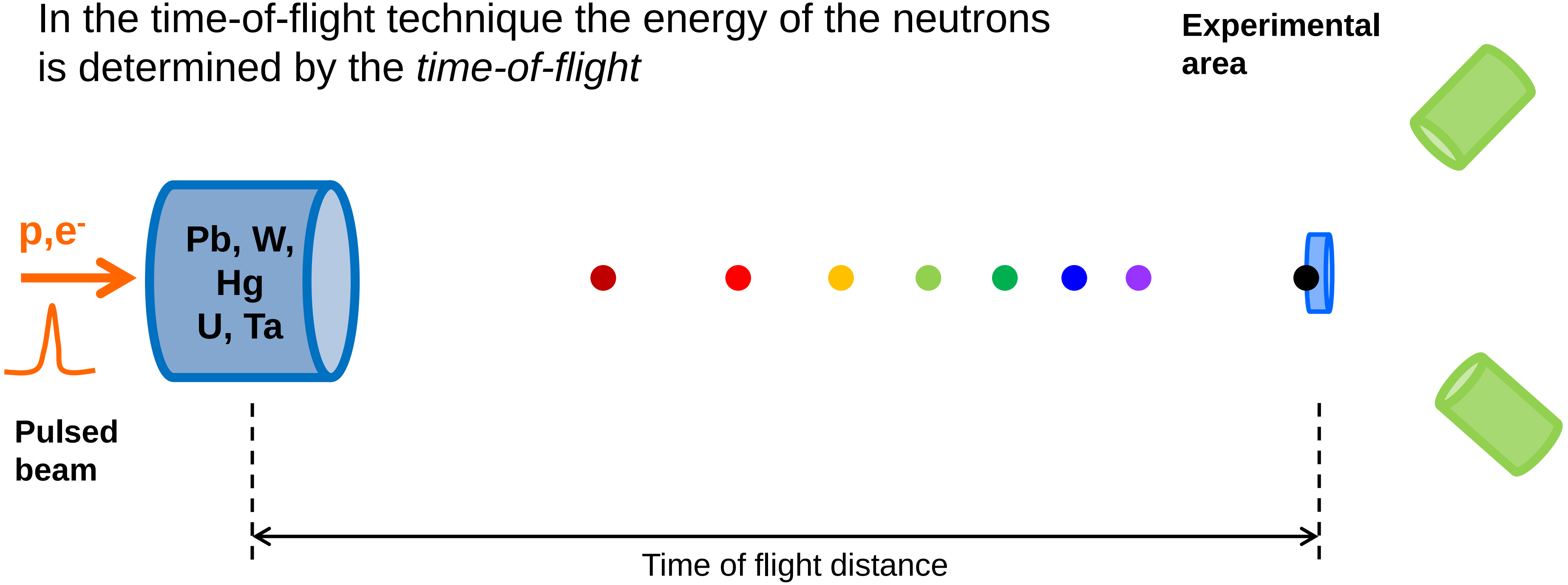

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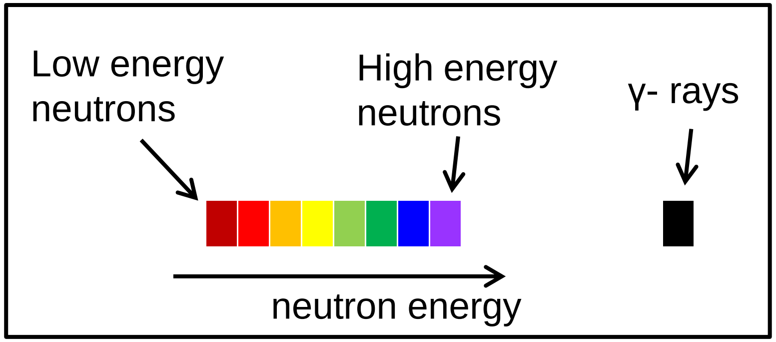

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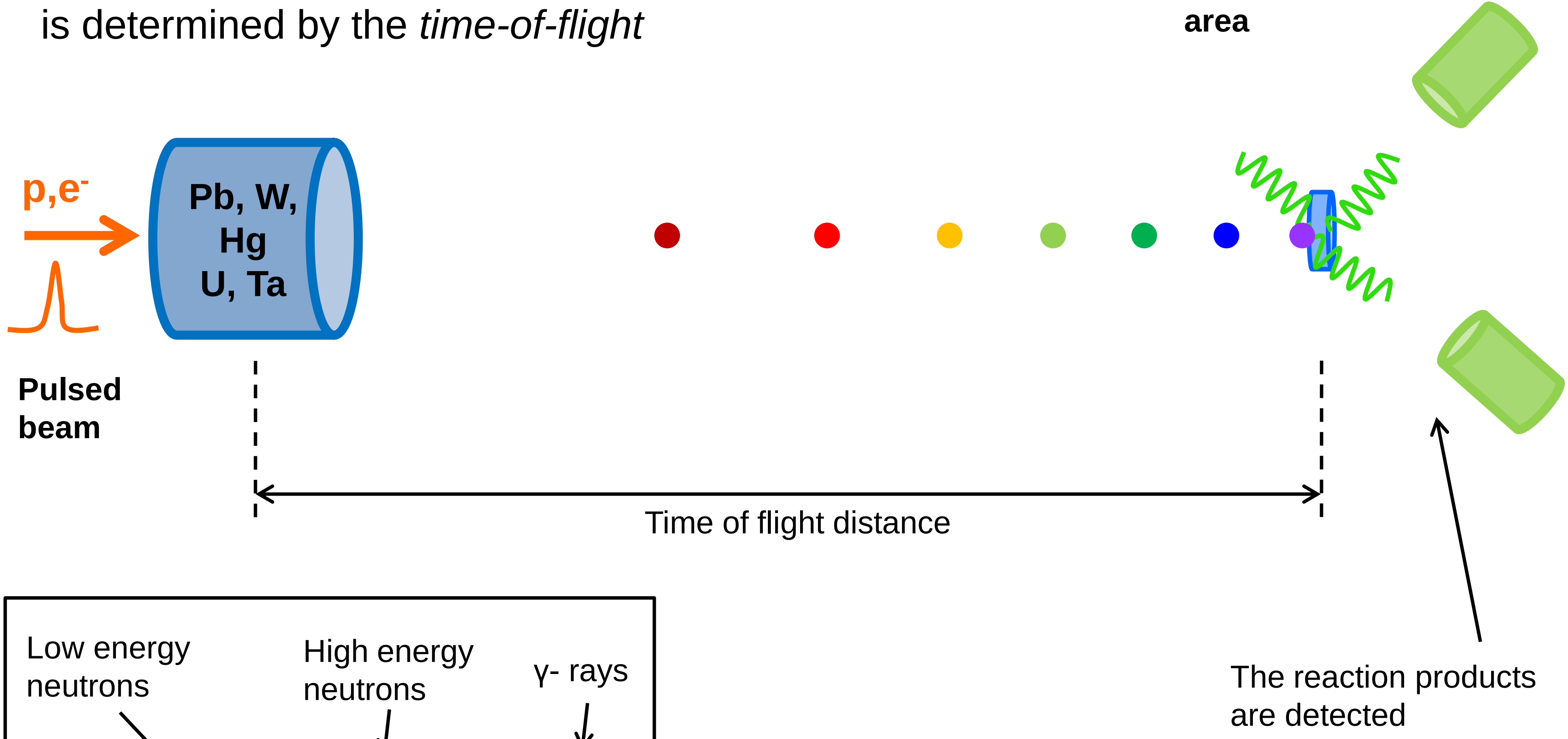

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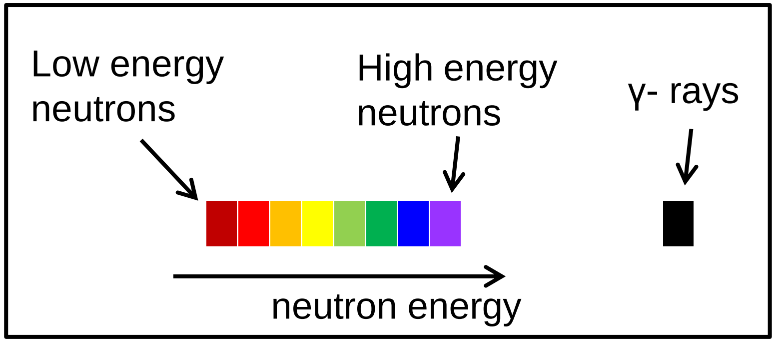
Pulsed beam

Time of flight distance

The reaction products are detected



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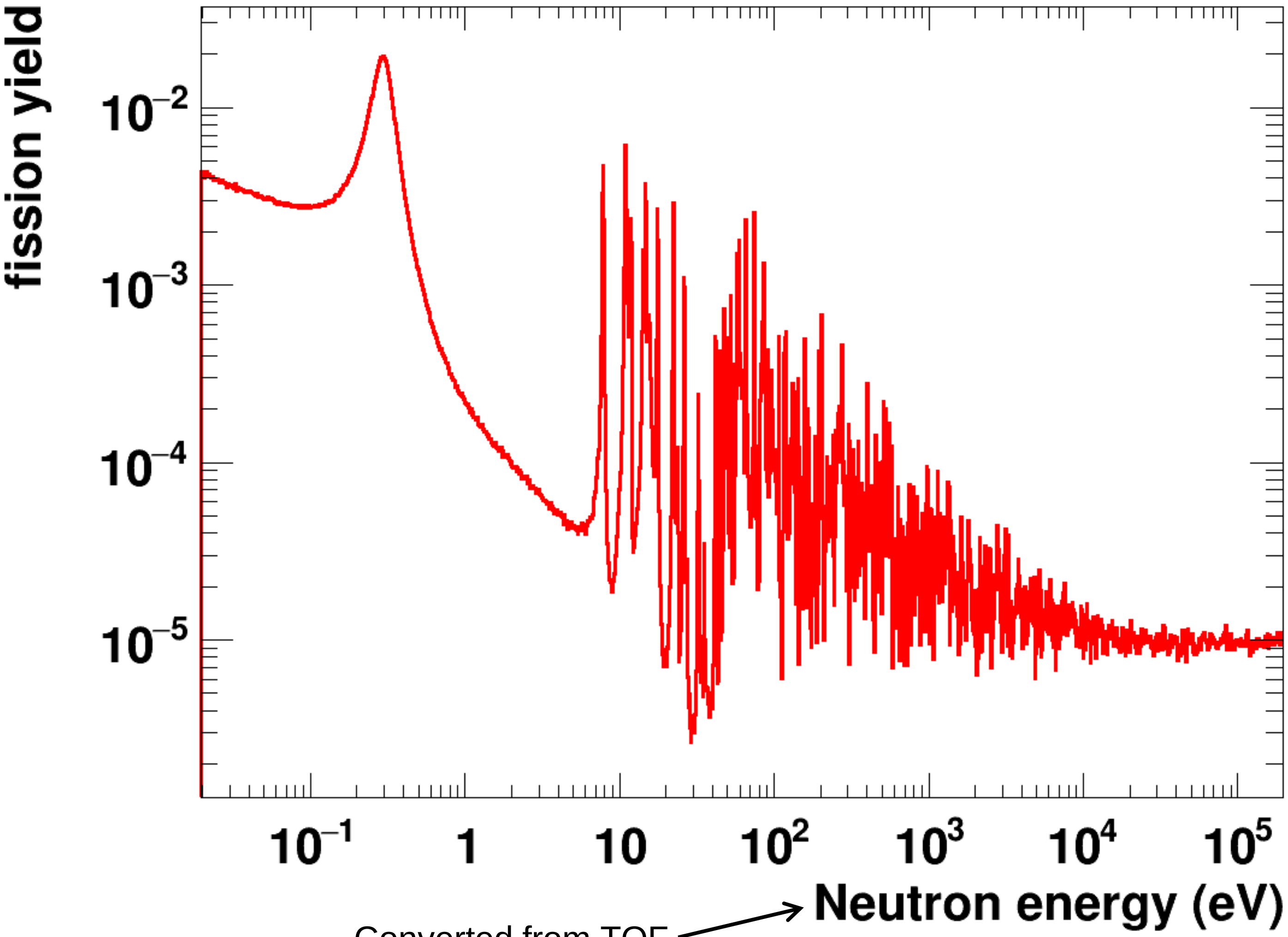
Example

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



Converted from TOF →

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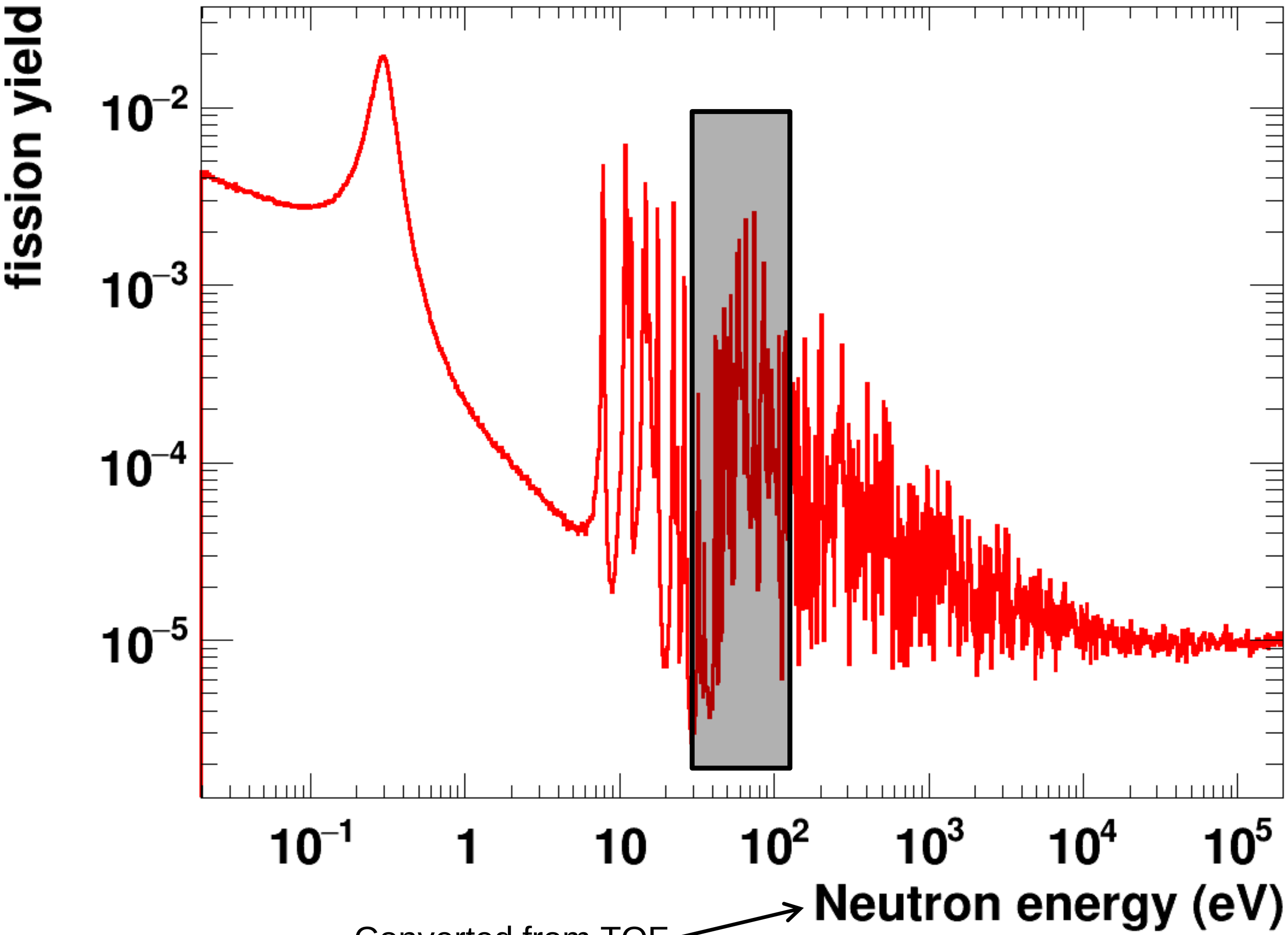

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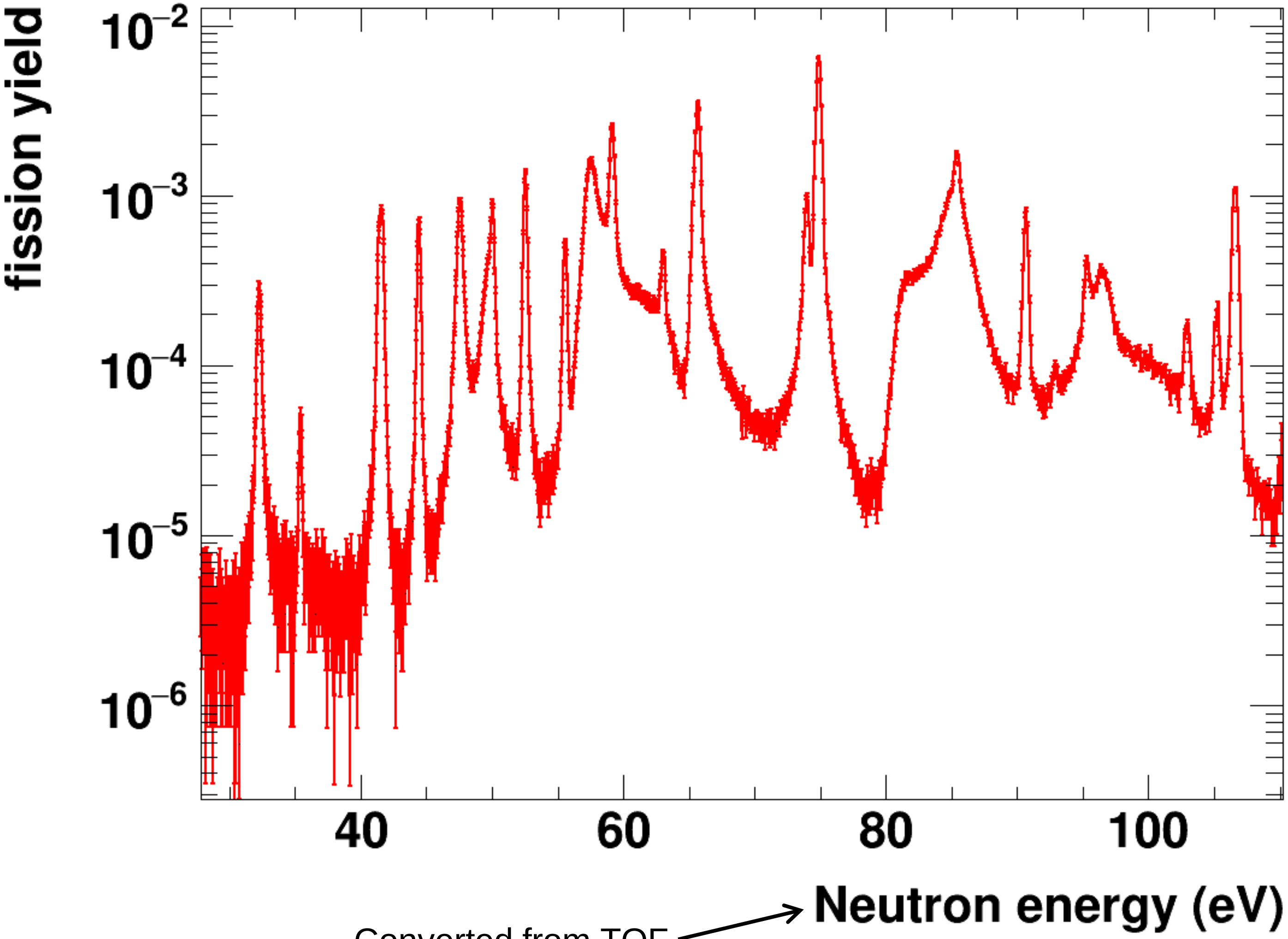

Converted from TOF

Examples of neutron time-of-flight facilities

- LANSCE (Los Alamos, New Mexico, US)
- RPI (New York, US)

- n_TOF – CERN (Geneva, Switzerland)
- GELINA (Geel, Belgium)
- NFS – GANIL/SPIRAL-2 (Caen, France)
- nELBE (Dresden, Germany)

- J-PARC (Tokai, Japan)

- Back-n - CSNS (Dongguan, China)

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Strong presence of Spanish institutions (~20%)

- J-PARC (Tokai, Japan)

- Back-n - CSNS (Dongguan, China)

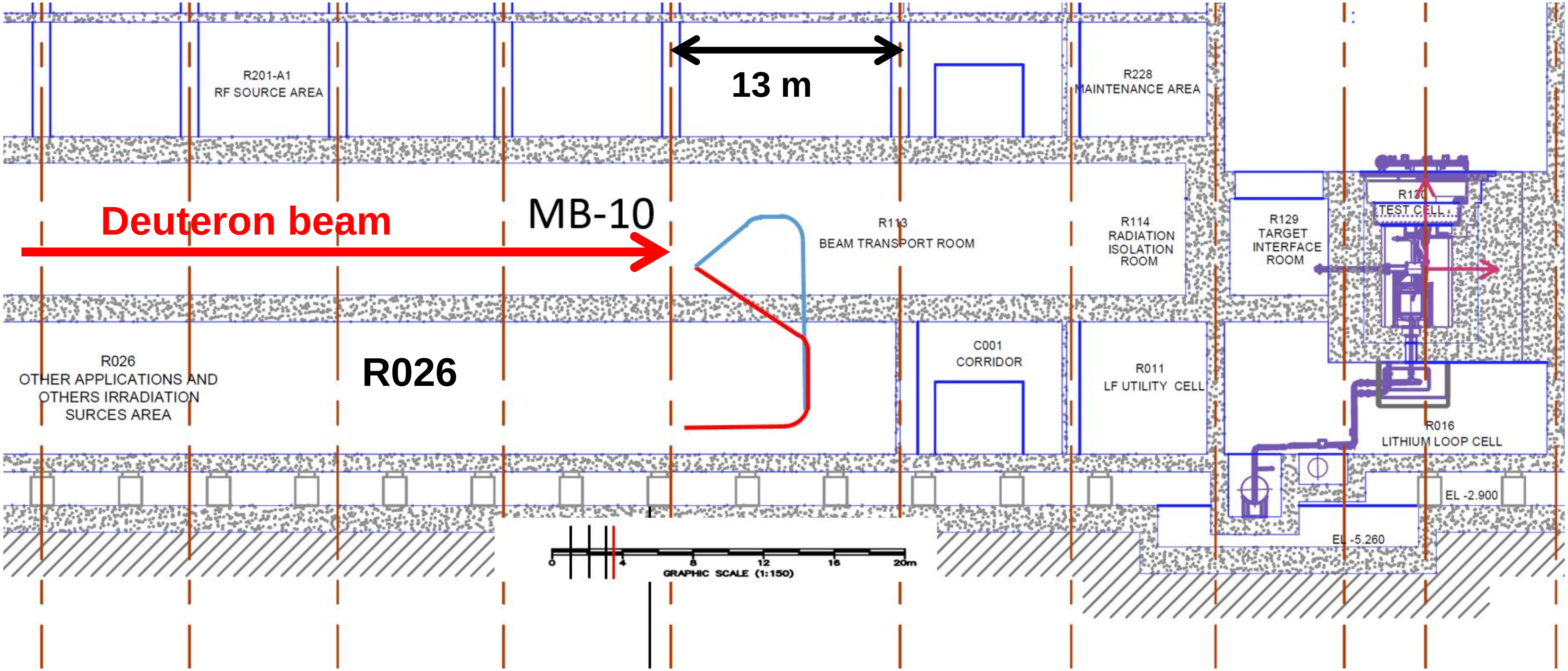
n_TOF measurements lead by Spanish institutions

- **^{94}Nb(n,γ)**: J. Balibrea-Correa et al., EPJ Web of Conferences **279**, 06004 (2023).
- **^{244,246,248}Cm(n,γ)**: V. Alcayne et al., EPJ Web of Conferences **284**, 01009 (2023).
- **^{232}Th(n,f),^{233}U(n,f)**: D. Tarrío et al., Physical Review C **107**, 044616 (2023).
- **^{14}N(n,p)**: P. Torres-Sánchez et al., Physical Review C **107**, 15 (2023).
- **^{176}Yb(n,γ)**: F. García-Infantes, EPJ Web of Conferences **284**, 09001 (2023).
- **^{80}Se(n,γ)**: V. Babiano-Suarez et al., EPJ Web of Conferences **284**, 01001 (2023).
- **^{171}Tm(n,γ)**: C. Guerrero et al., Physical Review Letters **125**, 142701 (2020).
- **^{235}U(n,γ)**: J. Balibrea-Correa et al., Physical Review C **102**, 044615 (2020).
- **^{204,205}Tl(n,γ)**: A. Casanovas et al., J. Phys.: Conf. Ser. **1668**, 012005 (2020).
- **^{242}Pu(n,γ)**: J. Lerendegui-Marco et al., Physical Review C **97**, 024605 (2018).
- **^{241}Am(n,γ)**: E. Mendoza et al., Physical Review C **97**, 054616 (2018).
- **^{33}S(n,α)**: J. Praena et al., Physical Review C **97**, 064603 (2018).
- **^{238}U(n,γ)**: T. Wright et al., Physical Review C **96**, 064601 (2017).
- **^{238}U(n,f)/^{235}U(n,f)**: C. Paradela et al., Physical Review C **91**, 024602 (2015).
- **^{243}Am(n,γ)**: E. Mendoza et al., Physical Review C **90**, 034608 (2014).
- **^{237}Np(n,γ)**: C. Guerrero et al., Physical Review C **85**, 044616 (2012).

n_TOF measurements lead by Spanish institutions

- **^{nat}Pb(n,f), ^{209}Bi(n,f)**: D. Tarrío et al., Physical Review C **83**, 044620 (2011).
- **^{234}U(n,f), ^{237}Np(n,f)**: Physical Review C **82**, 034601 (2010).
- **^{204}Pb(n,γ)**: C. Domingo-Pardo et al., Physical Review C **75**, 015806 (2007).
- **^{206}Pb(n,γ)**: C. Domingo-Pardo et al., Physical Review C **76**, 045805 (2007).
- **^{209}Bi(n,γ)**: C. Domingo-Pardo et al., Physical Review C **74**, 025807 (2006).
- **^{207}Pb(n,γ)**: C. Domingo-Pardo et al., Physical Review C **74**, 055802 (2006).

Extraction of the deuteron beam



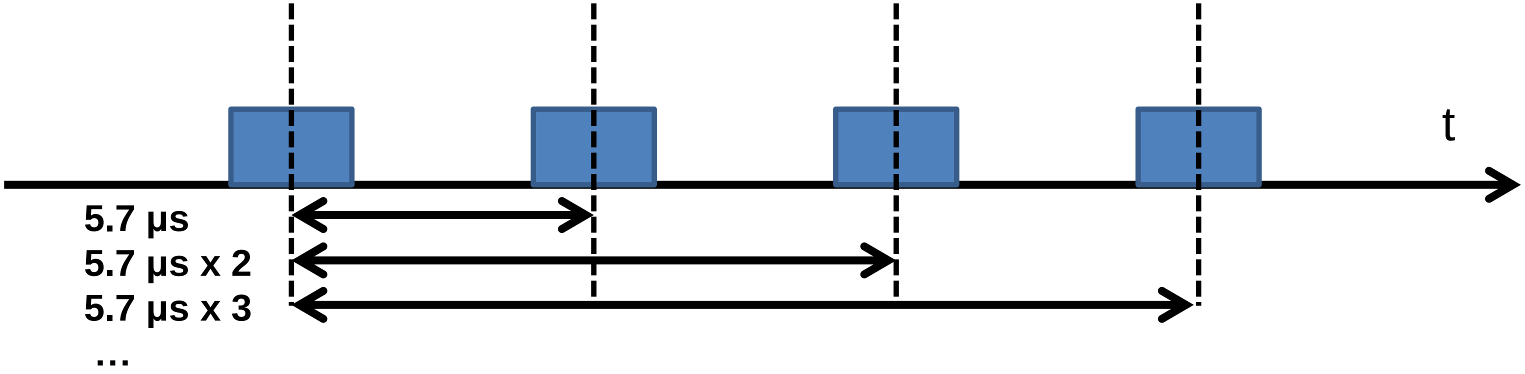
Dimensions of **R026**: ~ 60 x 36 x 8 m^3

0.1% duty cycle maximum

Structure of the deuteron pulses

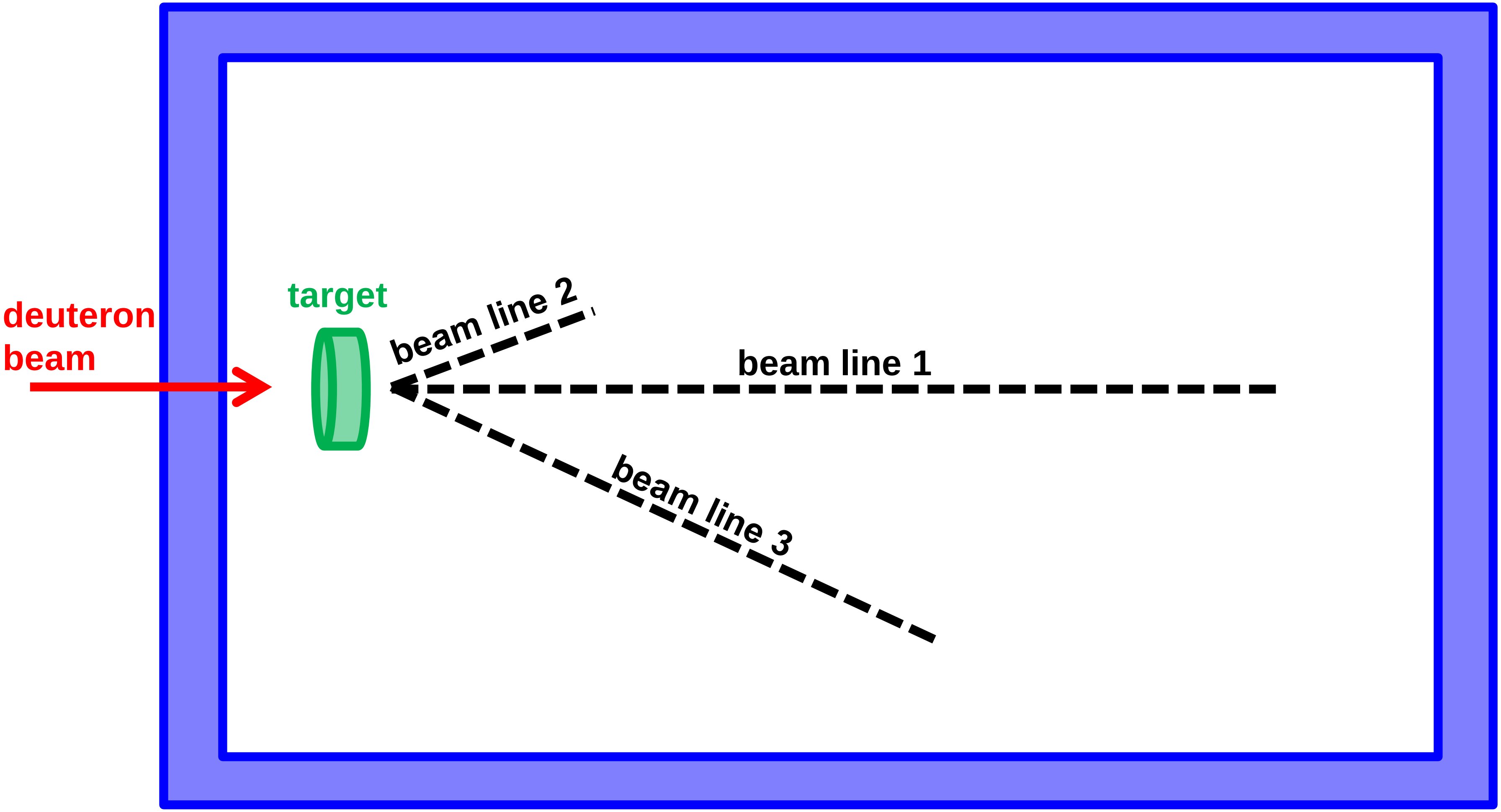
- Pulse width: ~ 5.6 ns

- Separation between pulses: 5.7(x n) μs , with n = 1, 2, 3 … → 175/n kHz



Design of a neutron time-of-flight facility at DONES

- Dimensions of R026 → ~ $60 \times 36 \times 8\ m^3$



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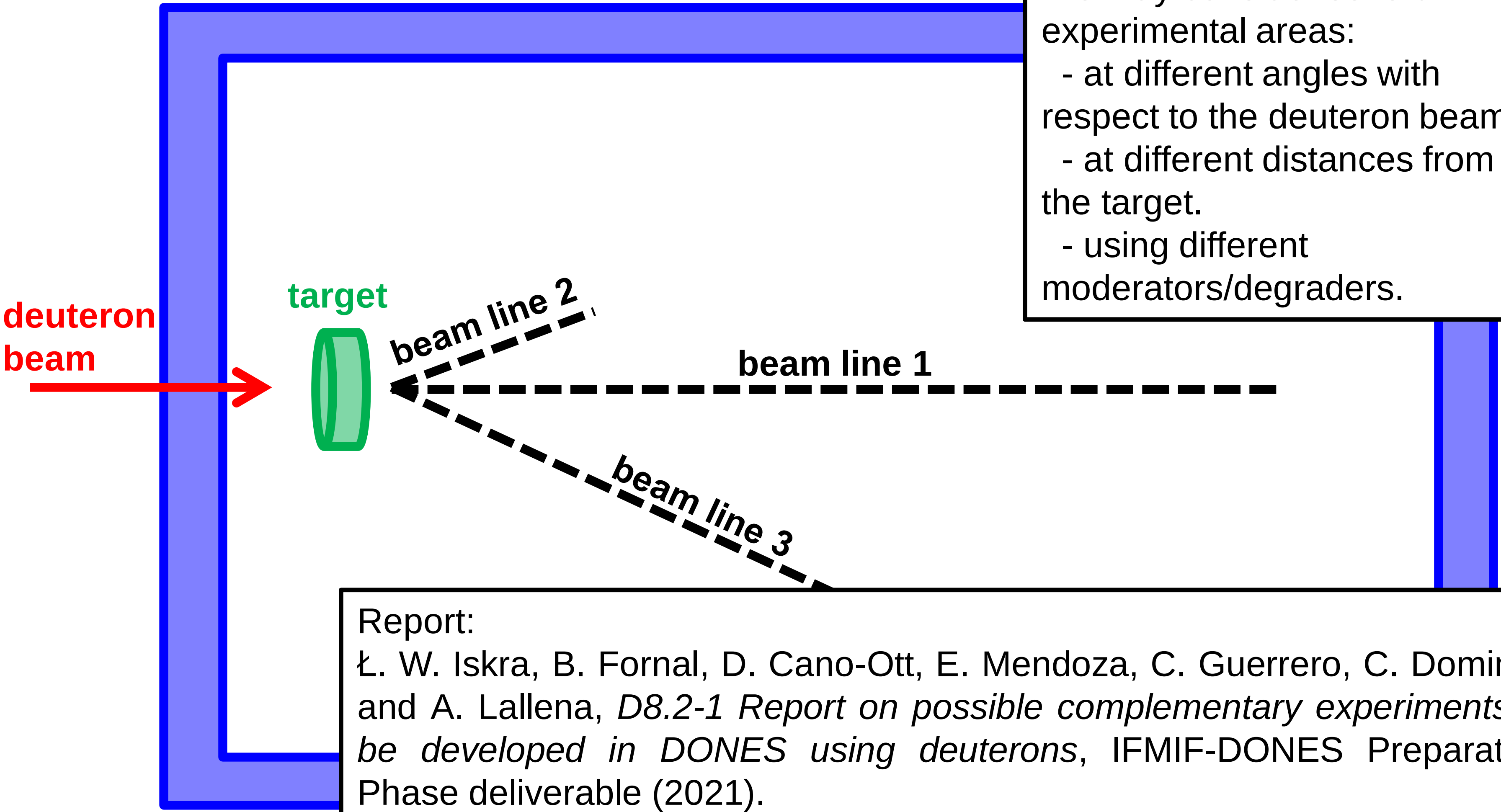


We may consider several experimental areas:
- at different angles with respect to the deuteron beam.
- at different distances from the target.
- using different moderators/degraders.

Report:
Ł. W. Iskra, B. Fornal, D. Cano-Ott, E. Mendoza, C. Guerrero, C. Domingo and A. Lallena, *D8.2-1 Report on possible complementary experiments to be developed in DONES using deuterons*, IFMIF-DONES Preparatory Phase deliverable (2021).
https://cordis.europa.eu/project/id/870186/results/es

Neutron production by 40 MeV deuterons

We have investigated different possibilities for producing neutrons in a secondary target of the TOF DONES time-of-flight facility:

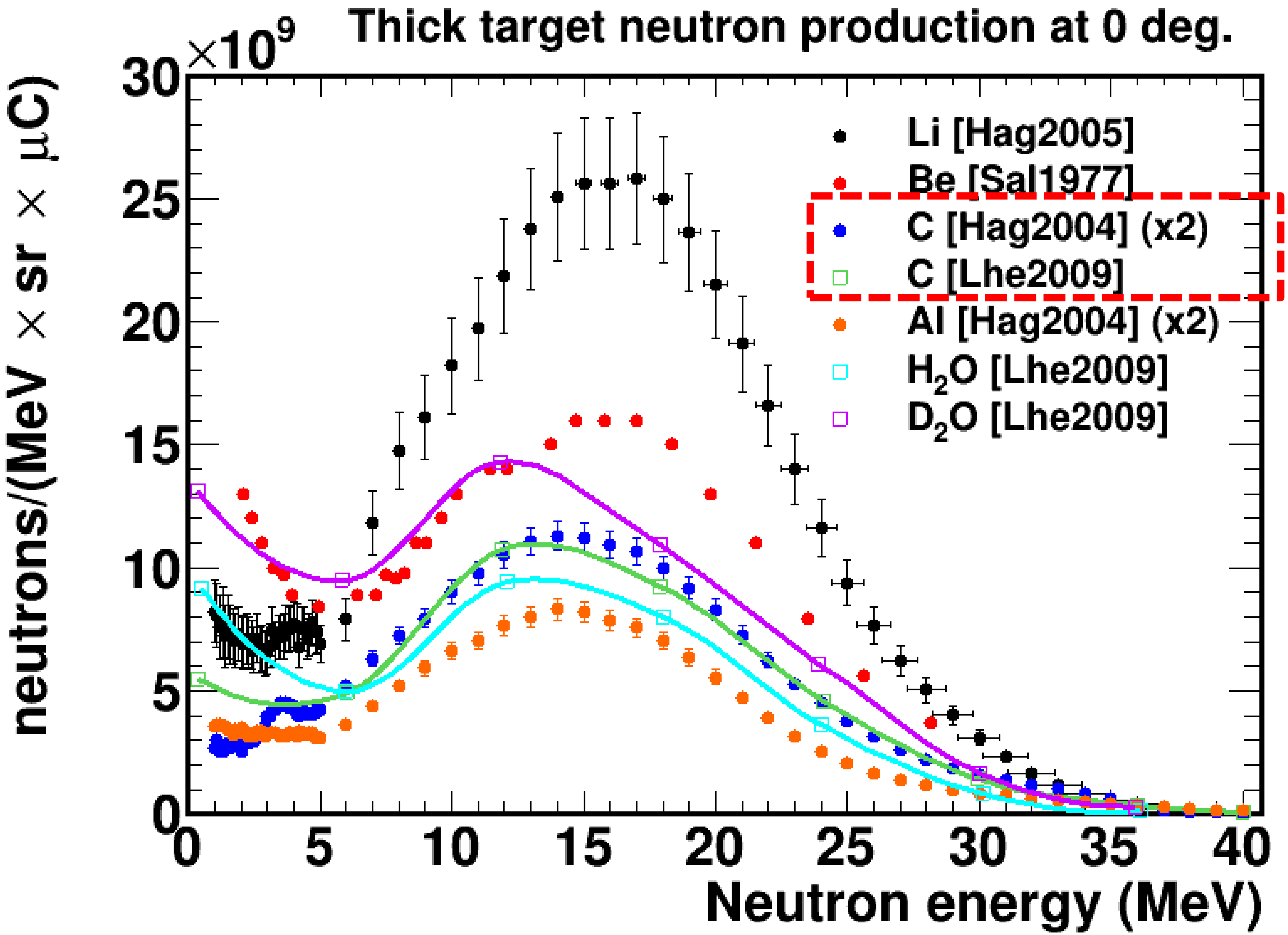
- Thick target neutron production yields and energy spectra at forward angles
- Nuclear data for 40 MeV deuterons from the EXFOR database.

→ realistic event generators based on experimental data.

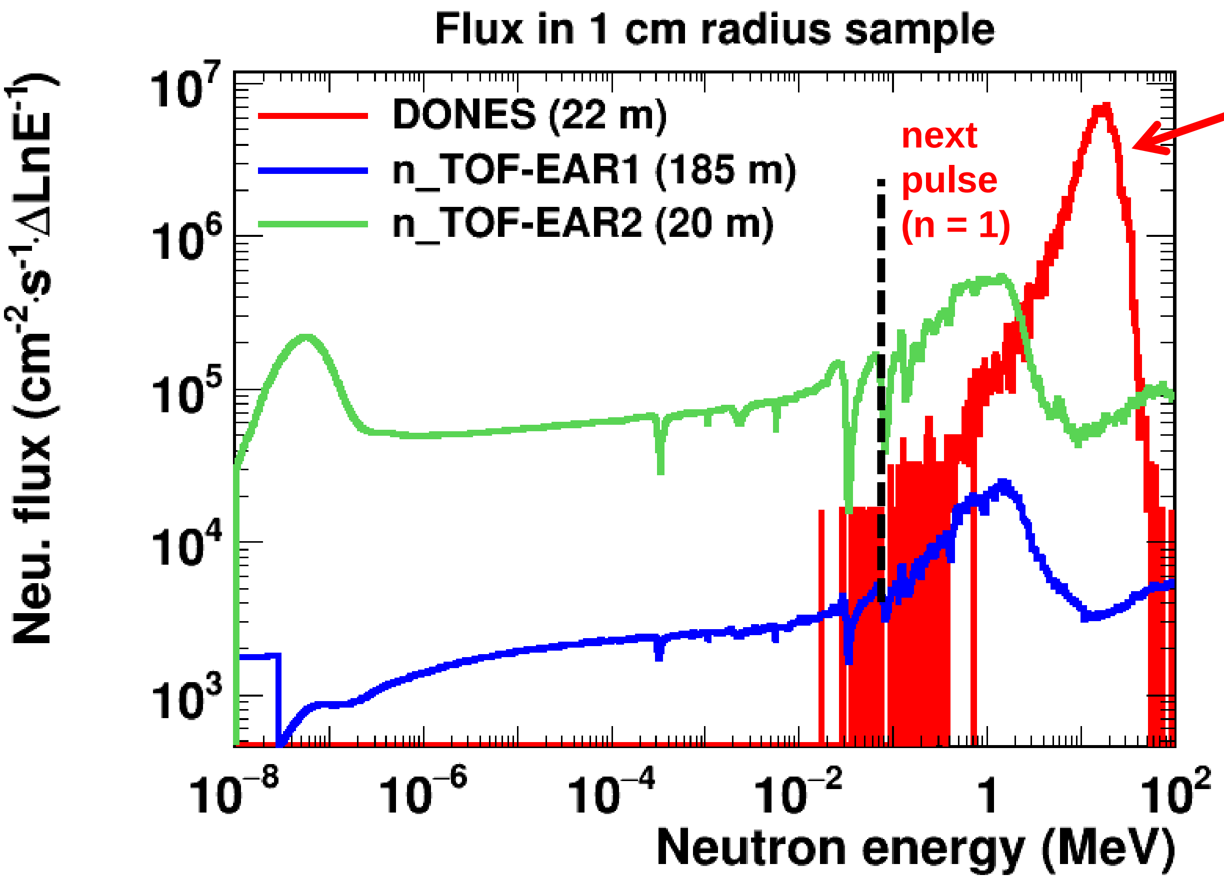
Target	**Reference**	**EXFOR entry**	**neutron yield (forward) (n/(sr·µC))**
Li	[Hag2005]	http://www-nds.iaea.org/EXFOR/E1986.002	$4.52\cdot10^{11}$ (11%)
Be	[Sal1977]	http://www-nds.iaea.org/EXFOR/C1832.003	$3.09\cdot10^{11}$ (15%)
C	[Hag2004]	http://www-nds.iaea.org/EXFOR/E1985.002	$2.02\cdot10^{11}$ (--%) (*)
C	[Lhe2009]	http://www-nds.iaea.org/EXFOR/E1985.002	$1.85\cdot10^{11}$ (12%)
Al	[Hag2004]	http://www-nds.iaea.org/EXFOR/E1985.003	$1.44\cdot10^{11}$ (--%) (*)
H_2O	[Lhe2009]	http://www-nds.iaea.org/EXFOR/O1746.004	$1.64\cdot10^{11}$ (15%)
D_2O	[Lhe2009]	http://www-nds.iaea.org/EXFOR/O1746.003	$2.82\cdot10^{11}$ (12%)

(*) The values for C and Al from Hagiwara have been multiplied by a factor of 2 following the recommendation from the evaluator

Neutron production by 40 MeV deuterons



Simulations of a time-of-flight facility at DONES

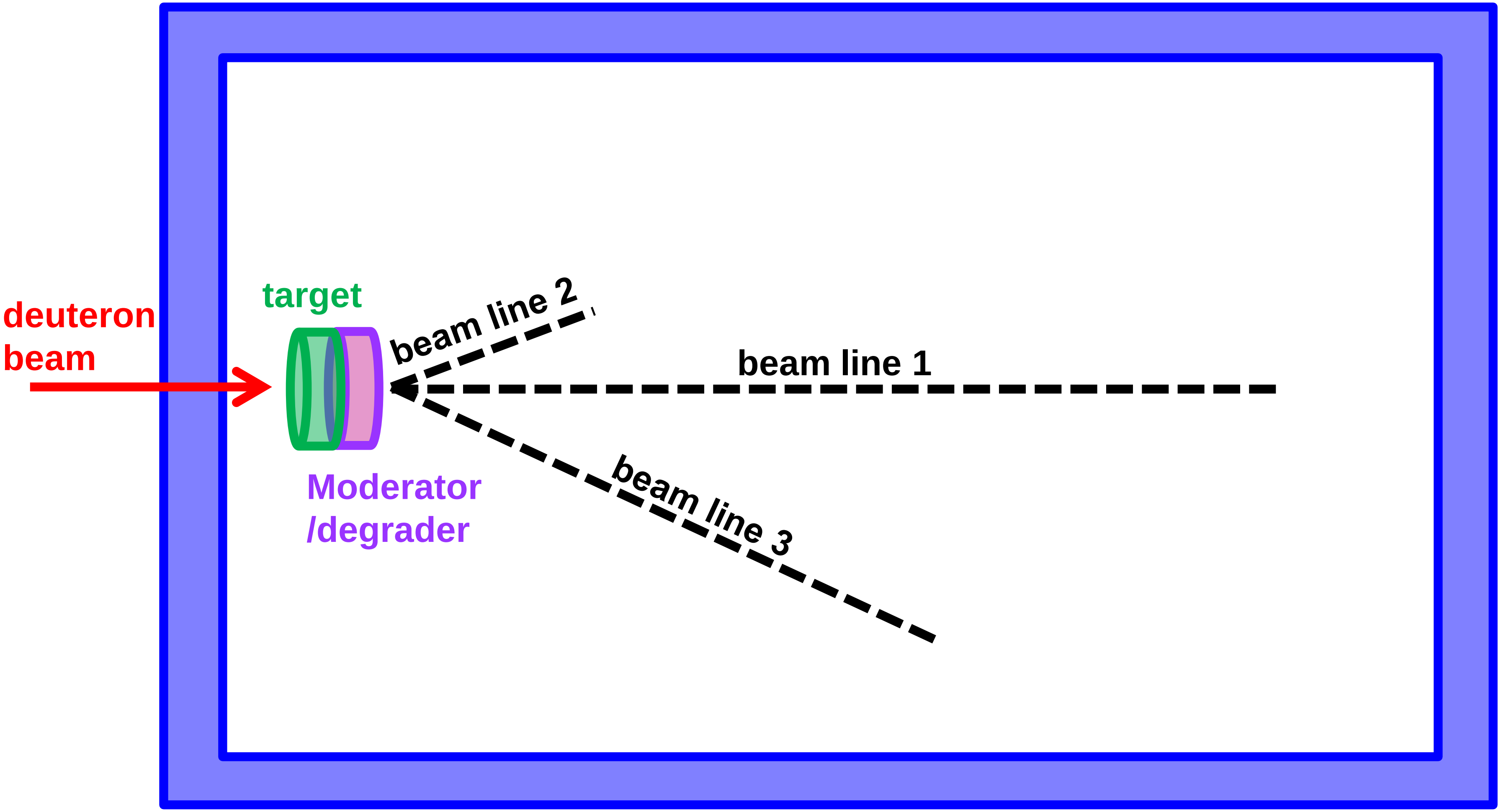


7.4·10^6 n/(cm^2·s)

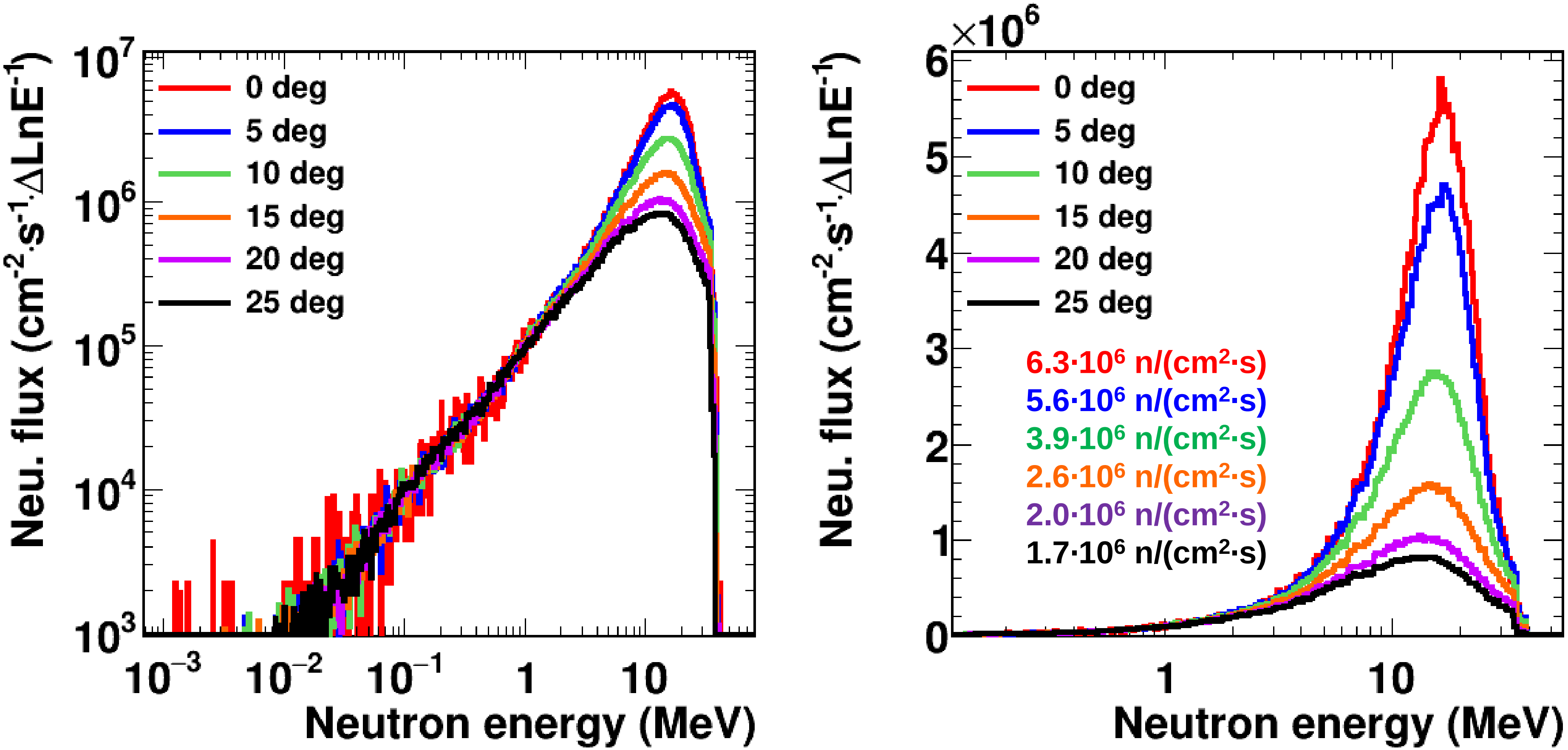
Neutron flux per unit lethargy at the sample position (22 m) compared with n_TOF (capture collimator). n_TOF has 0.83 pulses per second. A duty cycle of 10^{-3} has been assumed for DONES.

Design of a neutron time-of-flight facility at DONES

- Dimensions of R026 → ~ 60 x 36 x 8 m



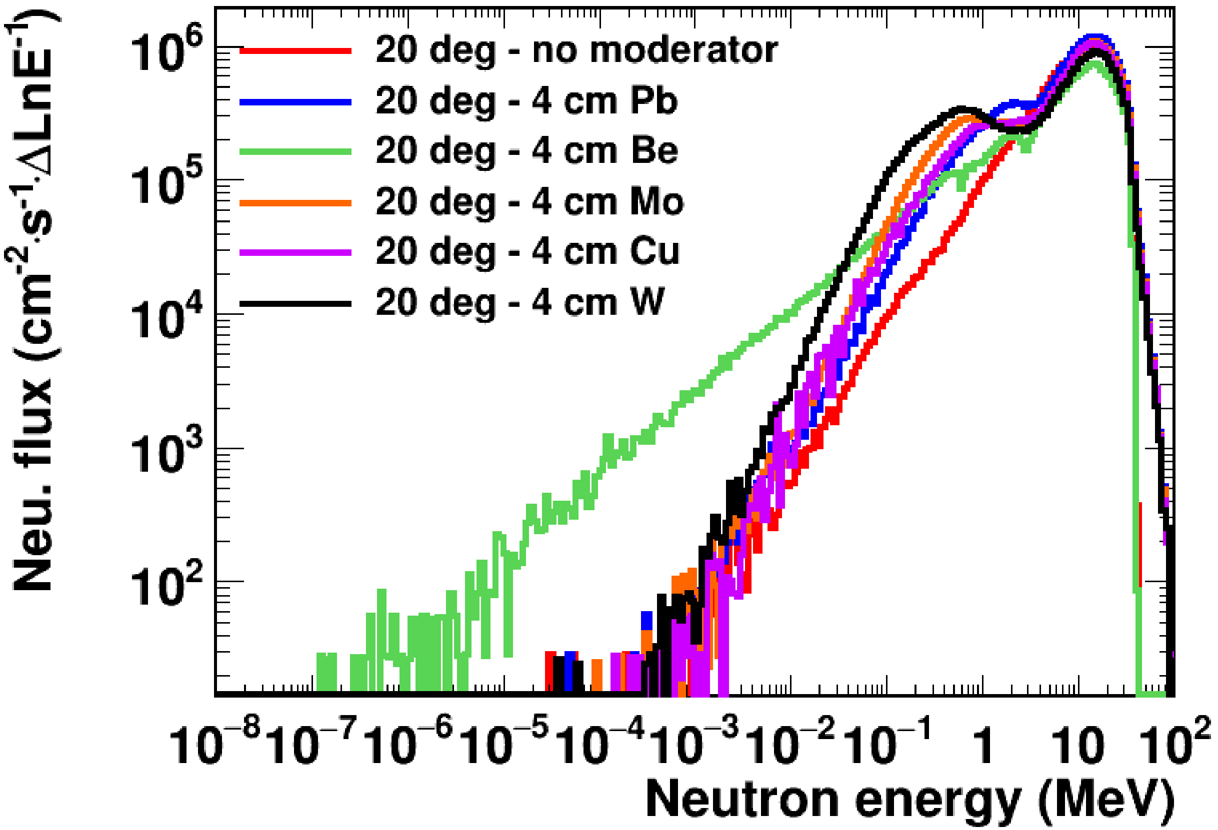
Neutron emission at different angles (thick graphite target)



6.3·10^6 n/(cm^2·s)
5.6·10^6 n/(cm^2·s)
3.9·10^6 n/(cm^2·s)
2.6·10^6 n/(cm^2·s)
2.0·10^6 n/(cm^2·s)
1.7·10^6 n/(cm^2·s)

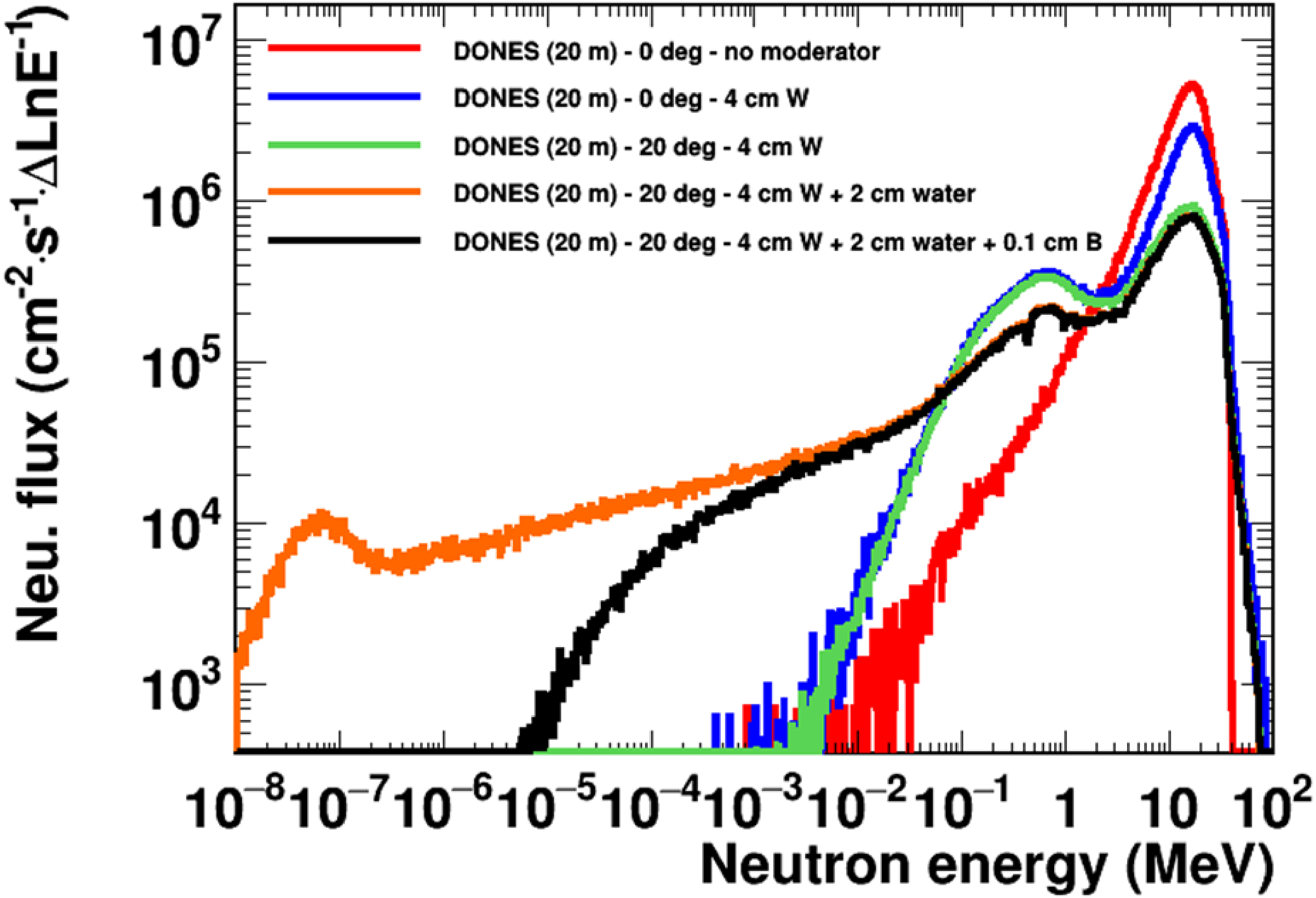
Neutron flux at **20 m TOF distance**, as a function of the neutron energy, at different angles generated by a 40 MeV deuteron beam of 125 μA impinging on a thick graphite target. The values have been obtained from MCNP6.2 using the JENDL/DEU-2020 deuteron incident data library (validated with experimental data).

Moderation/degradation of the neutron beam



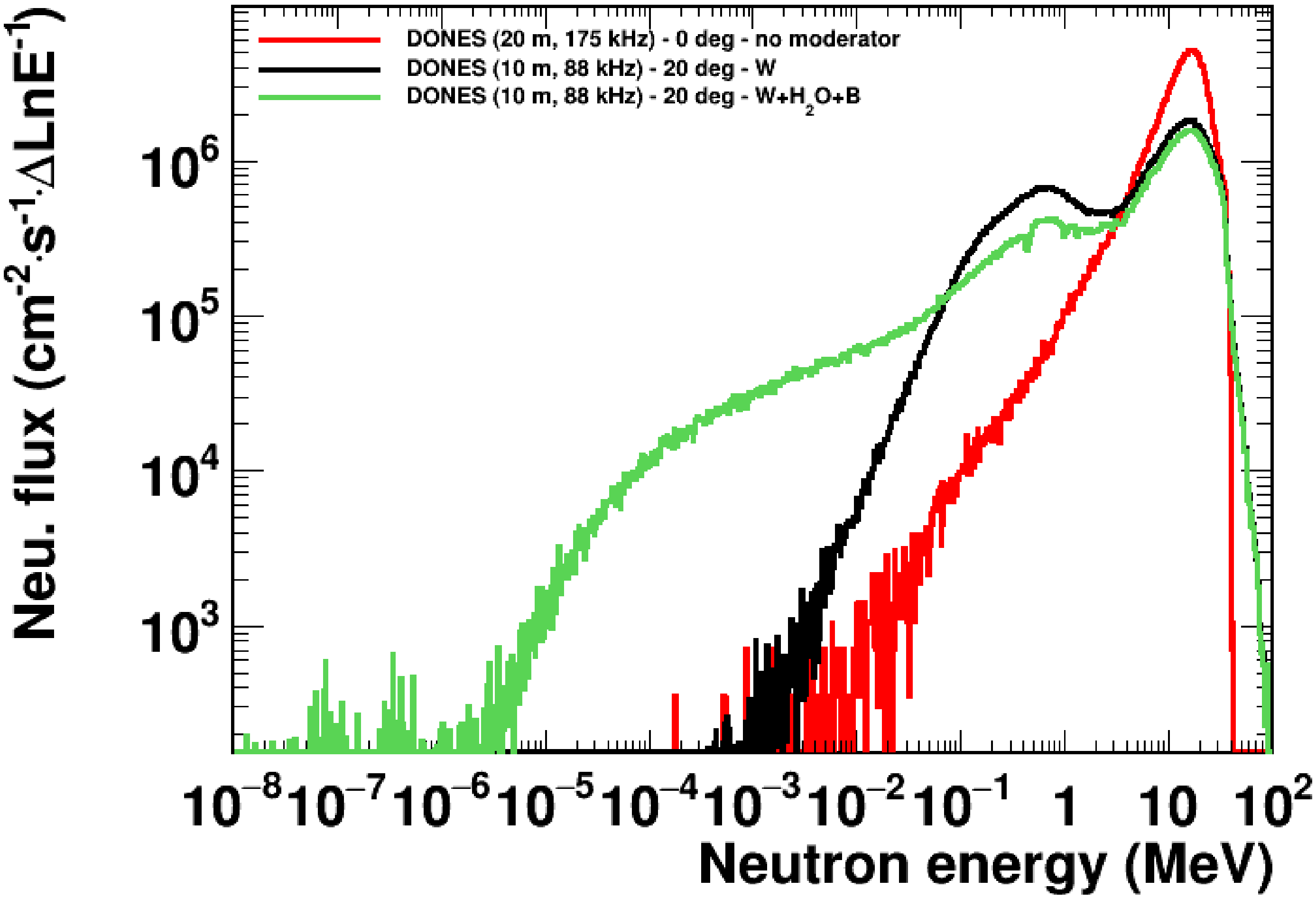
Neutron flux at **20 m TOF distance**, as a function of the neutron energy, at 20 degrees with respect to the deuteron beam. Different moderators/degraders have been placed after the graphite target.

Moderation/degradation of the neutron beam

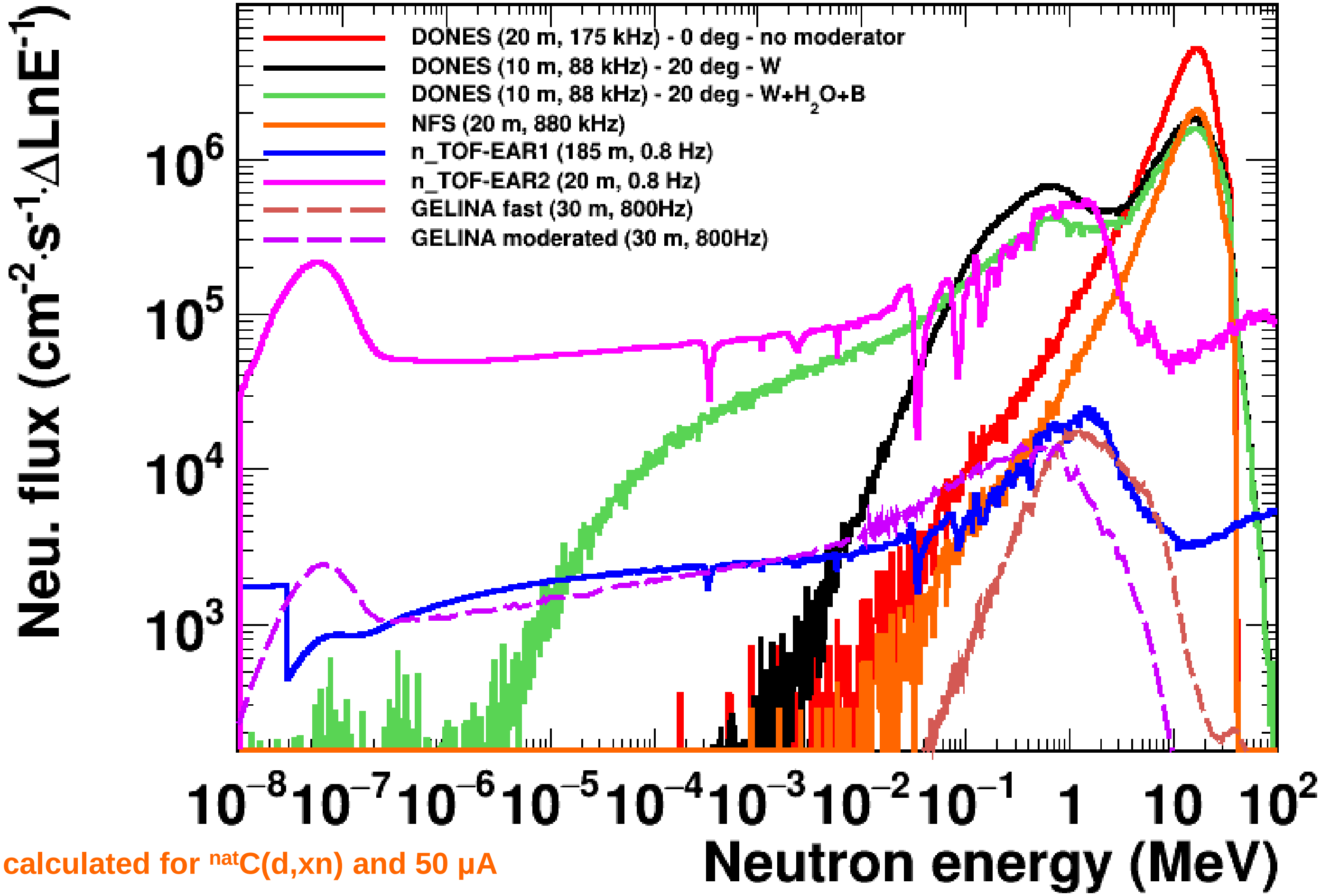


Neutron flux per unit lethargy at the DONES time-of-flight facility for different configurations, all of them at 20 m from the graphite target and using the maximum beam intensity of 125 mA (175 kHz).

TOF-DONES neutron fluxes



Comparison of TOF-DONES with other facilities



NFS value calculated for ^{nat}C(d,xn) and 50 μA

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)

There is a program that requires decades of beam time (thee is room for complementary facilities like n_TOF, NFS, nELBE, GELINA).

TOF-DONES experimental program

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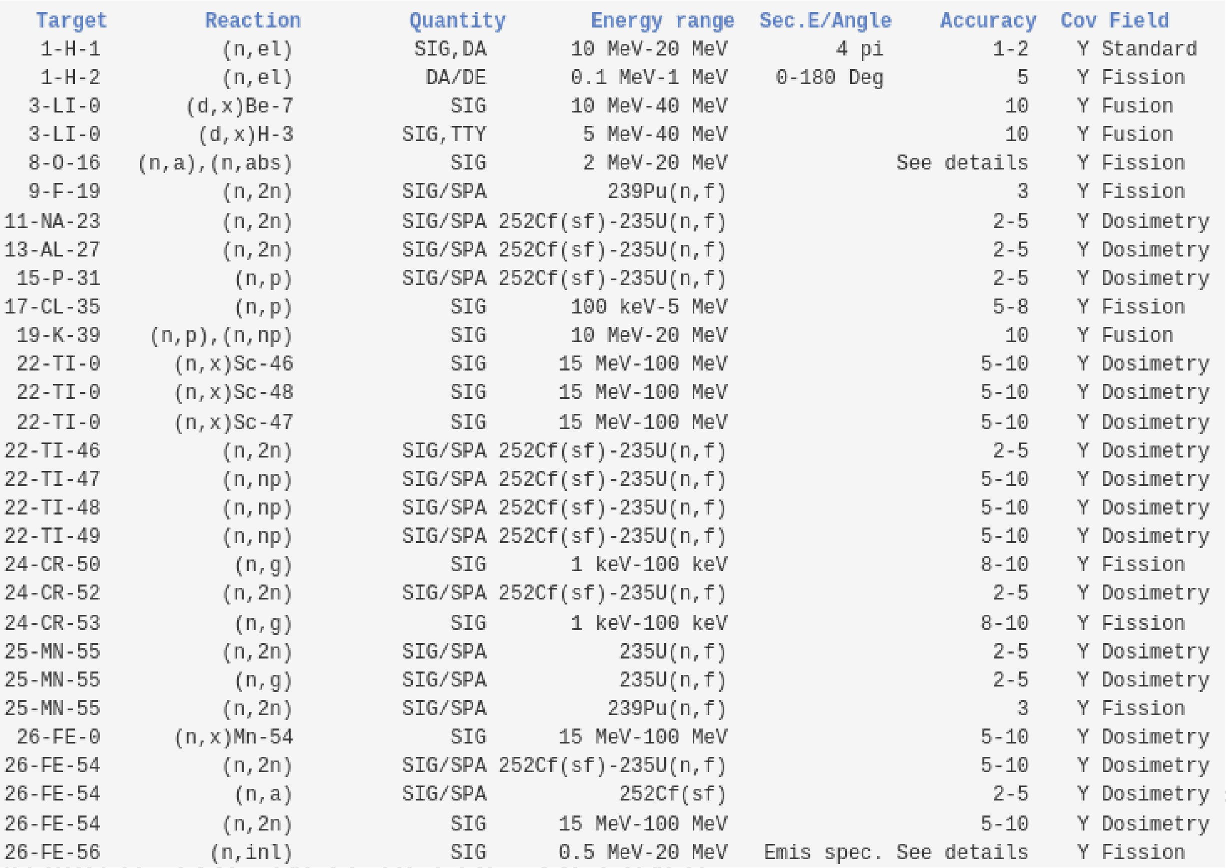

Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy	Cov	Field
1-H-1	(n,el)	SIG,DA	10 MeV-20 MeV	4 pi	1-2	Y	Standard
1-H-2	(n,el)	DA/DE	0.1 MeV-1 MeV	0-180 Deg	5	Y	Fission
3-LI-0	(d,x)Be-7	SIG	10 MeV-40 MeV		10	Y	Fusion
3-LI-0	(d,x)H-3	SIG,TTY	5 MeV-40 MeV		10	Y	Fusion
8-O-16	(n,a),(n,abs)	SIG	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

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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).

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 (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).

- Mark R Gilbert, J. Phys. Energy 5 034002 (2023)

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

There is a program that requires decades of beam time (thee is room for complementary facilities like n_TOF, NFS, nELBE, GELINA).

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)

There is a program that requires decades of beam time (thee is room for complementary facilities like n_TOF, NFS, nELBE, GELINA).

In summary …

We have an excellent opportunity for building a world leading neutron time-of-flight facility at IFMIF-DONES.

The TOF-DONES facility will provide *good* nuclear data 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
- …

The Spanish Nuclear Physics community has the necessary expertise and skills for making the facility a great success.

Future actions & activities

This work will be continued as part of the DONES-ConP1 project. For a successful completion of the activity we will need to:

- Create a task force for the design of the TOF-DONES facility (nuclear physics community + however is interested).
- Strengthen the interaction with the DONES design teams (engineering, safety, …)
- Establish a collaboration with the experts who have already built neutron production targets for high intensity neutron beams → our colleagues GANIL/SPIRAL-2.
- Interact with the accelerator design team. The kicker is a key element and a prototype of the kicker seems to be necessary.

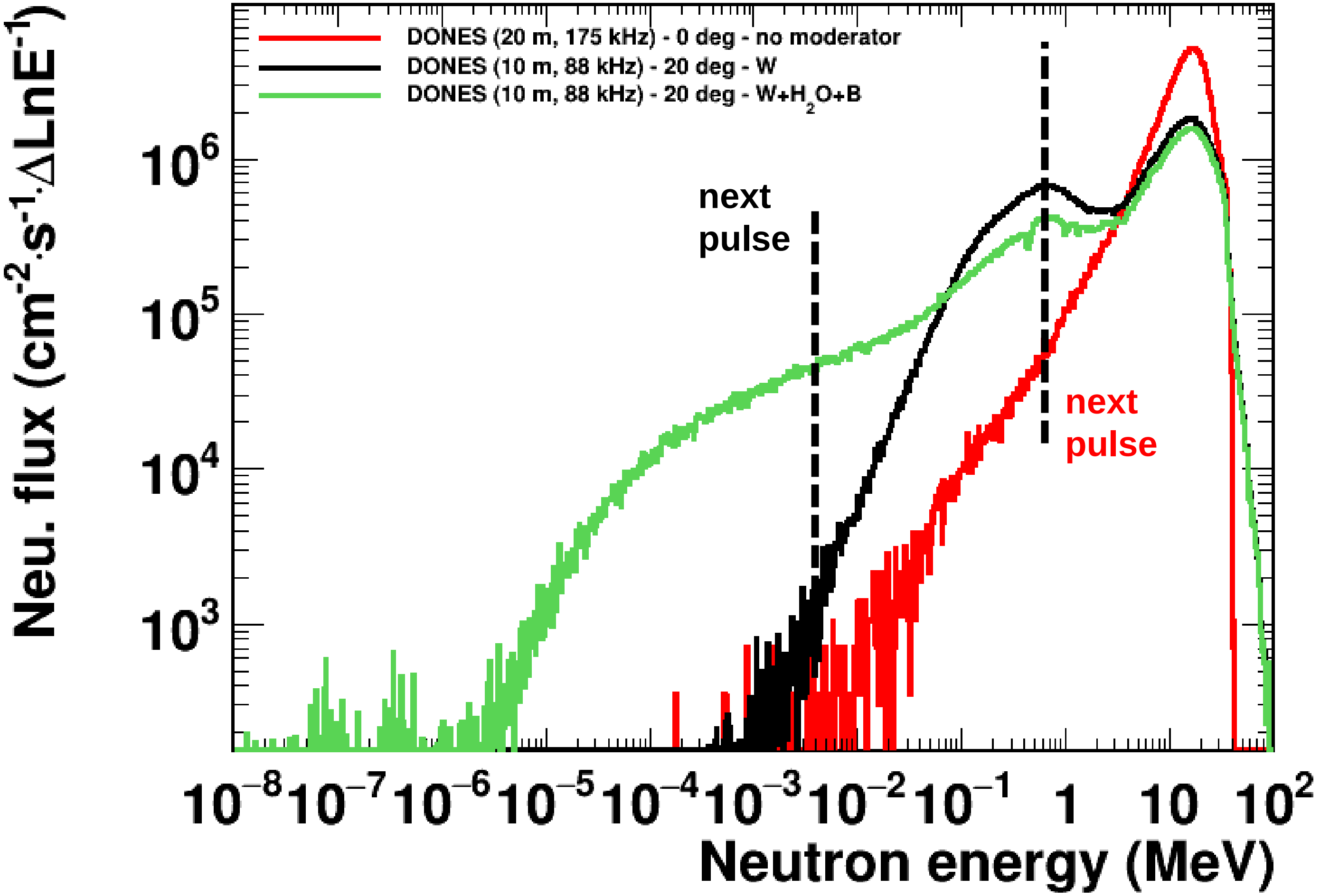
Backup slides

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

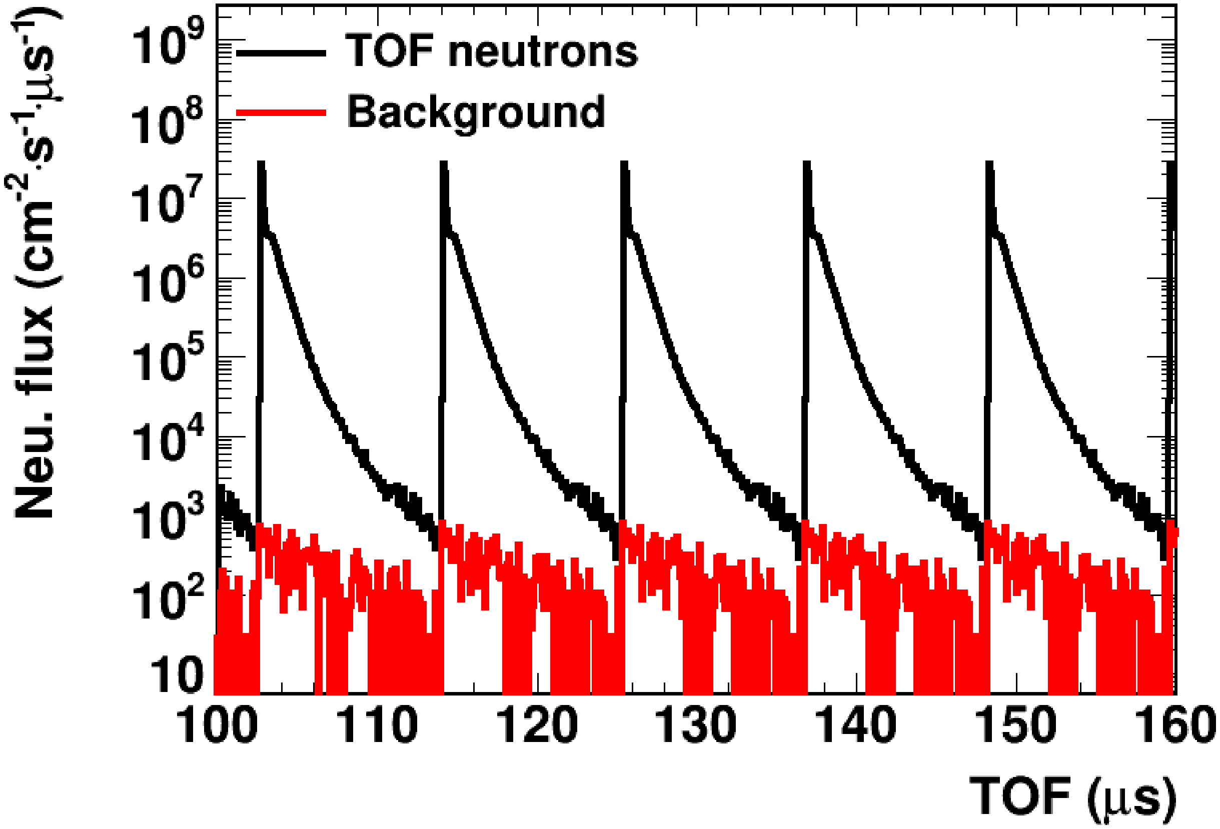
TOF-energy (in **keV**) of the neutrons at the time of overlapping with the next pulse, at the sample position → minimum neutron energy for TOF measurements.

TOF-DONES neutron fluxes



Time structure of the neutron beam

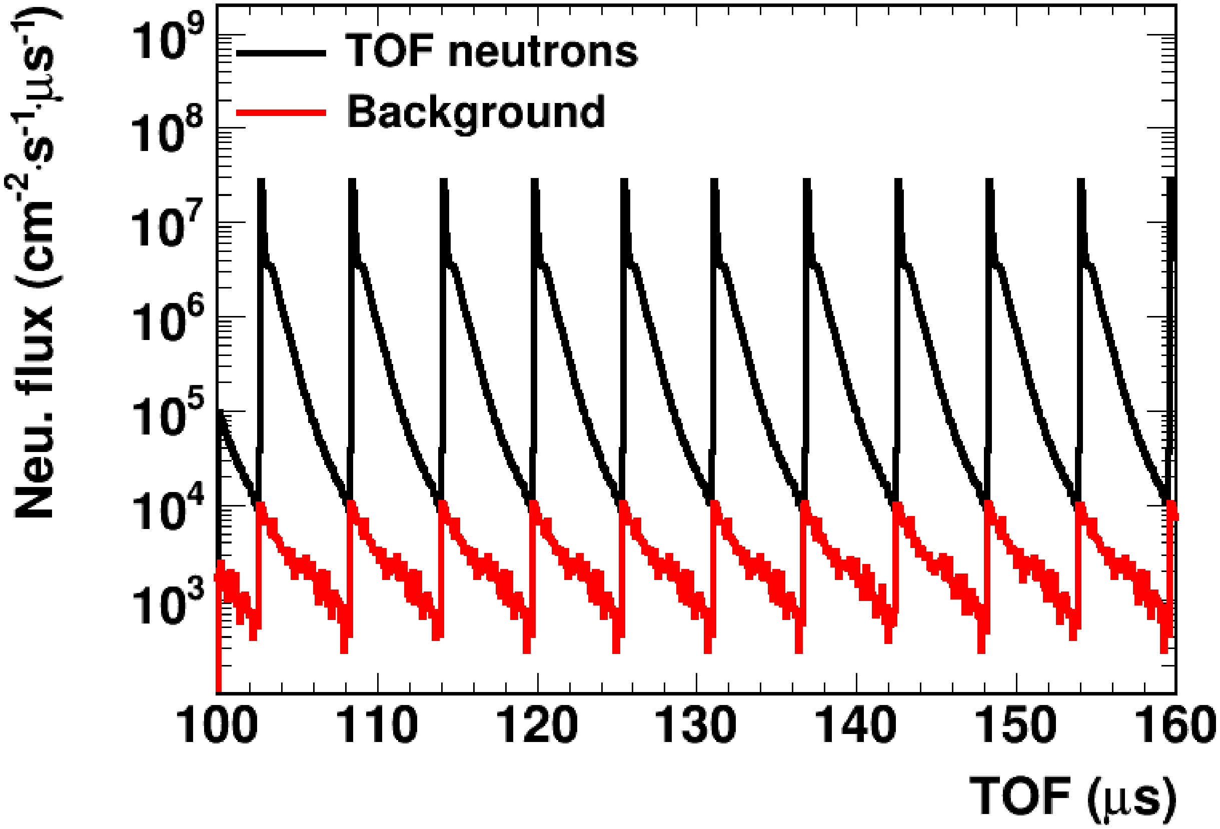
10 m – 20 deg - 4 cm W – 88 kHz (n=2)



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 = 2 and the distance between pulses 11.4 μs (88 kHz).

Time structure of the neutron beam

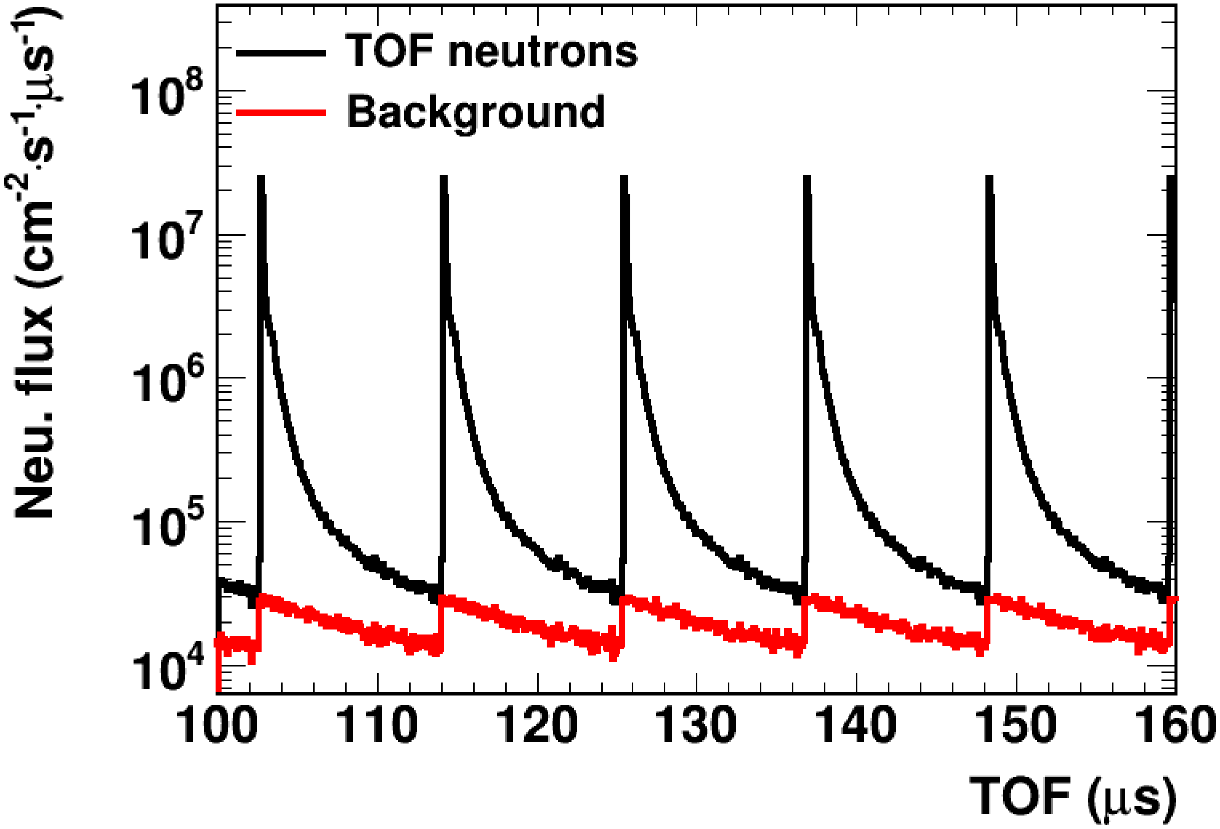
10 m – 20 deg - 4 cm W – 175 kHz (n=1)



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).

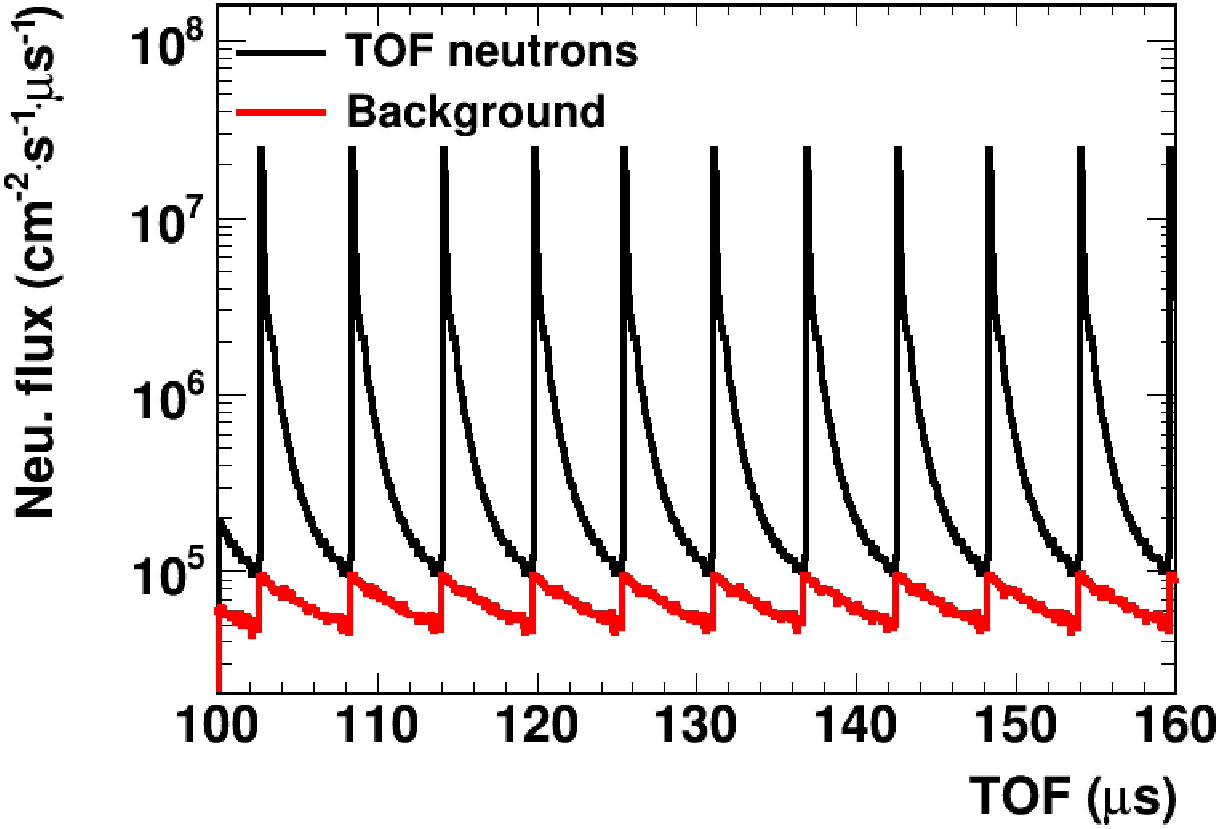
Time structure of the neutron beam

10 m – 20 deg – W+H_2O+B – 88 kHz (n=2)



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 = 2 and the distance between pulses 11.4 μs (88 kHz).

Time structure of the neutron beam



10 m – 20 deg – W+H_2O+B – 175 kHz (n=1)

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).

Energy resolution of TOF-DONES