A neutron source at FCC-ee?

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on behalf of the n_TOF Collaboration

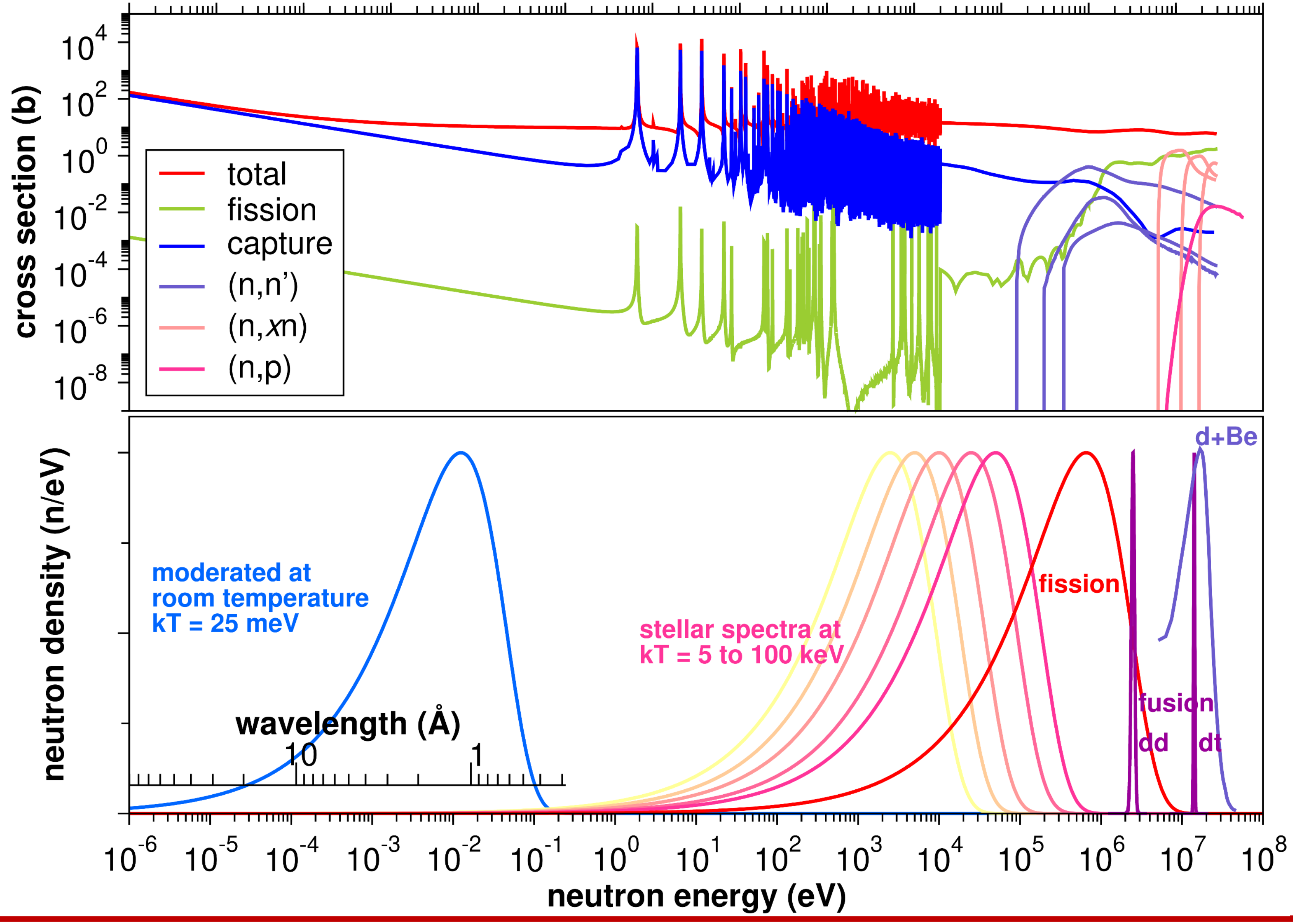
Neutron sources for nuclear physics

- Wide range of research and industrial application fields, including
  - nuclear physics,
  - nuclear astrophysics
  - solid-state physics
  - chemistry
  - biology
  - material science
  - cultural heritage
  - metrology
  - medical applications
  - others

- Many facilities for neutrons are available, mainly for “scattering” measurements, not for nuclear physics

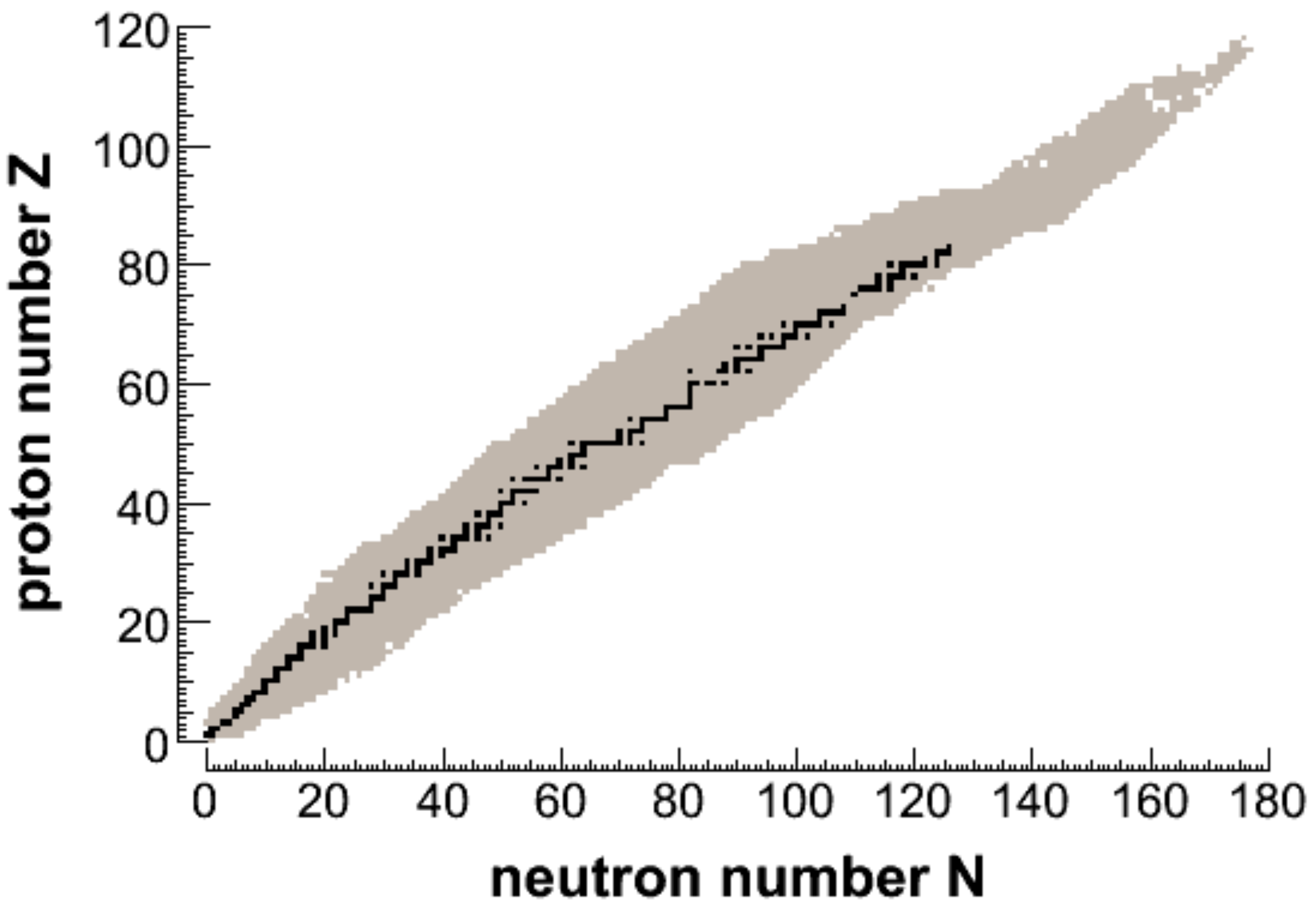
- Only a few of them are suited for nuclear physics including *nuclear data*

Neutron cross sections



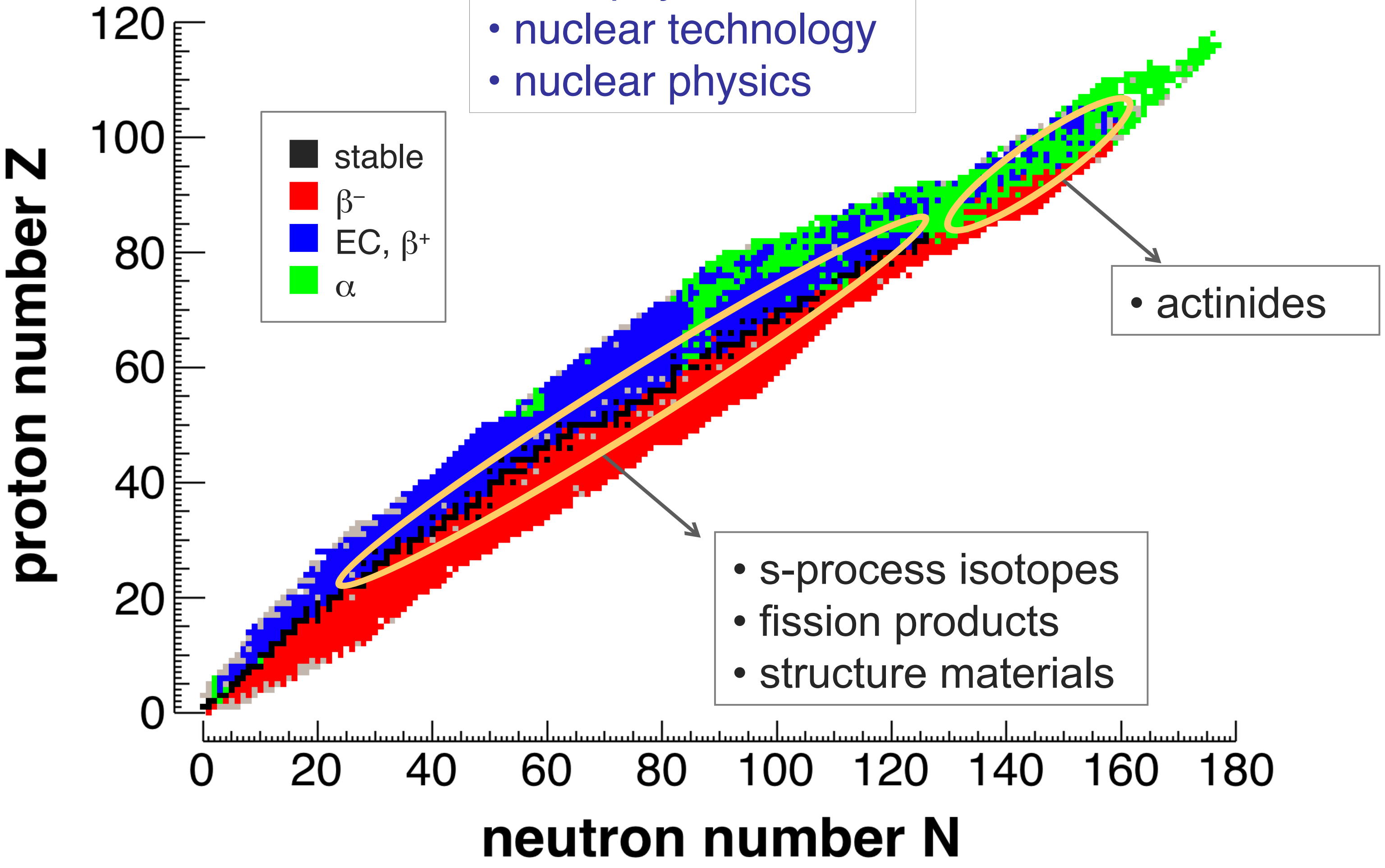
NuPECC LRP2024

Neutrons and nuclei

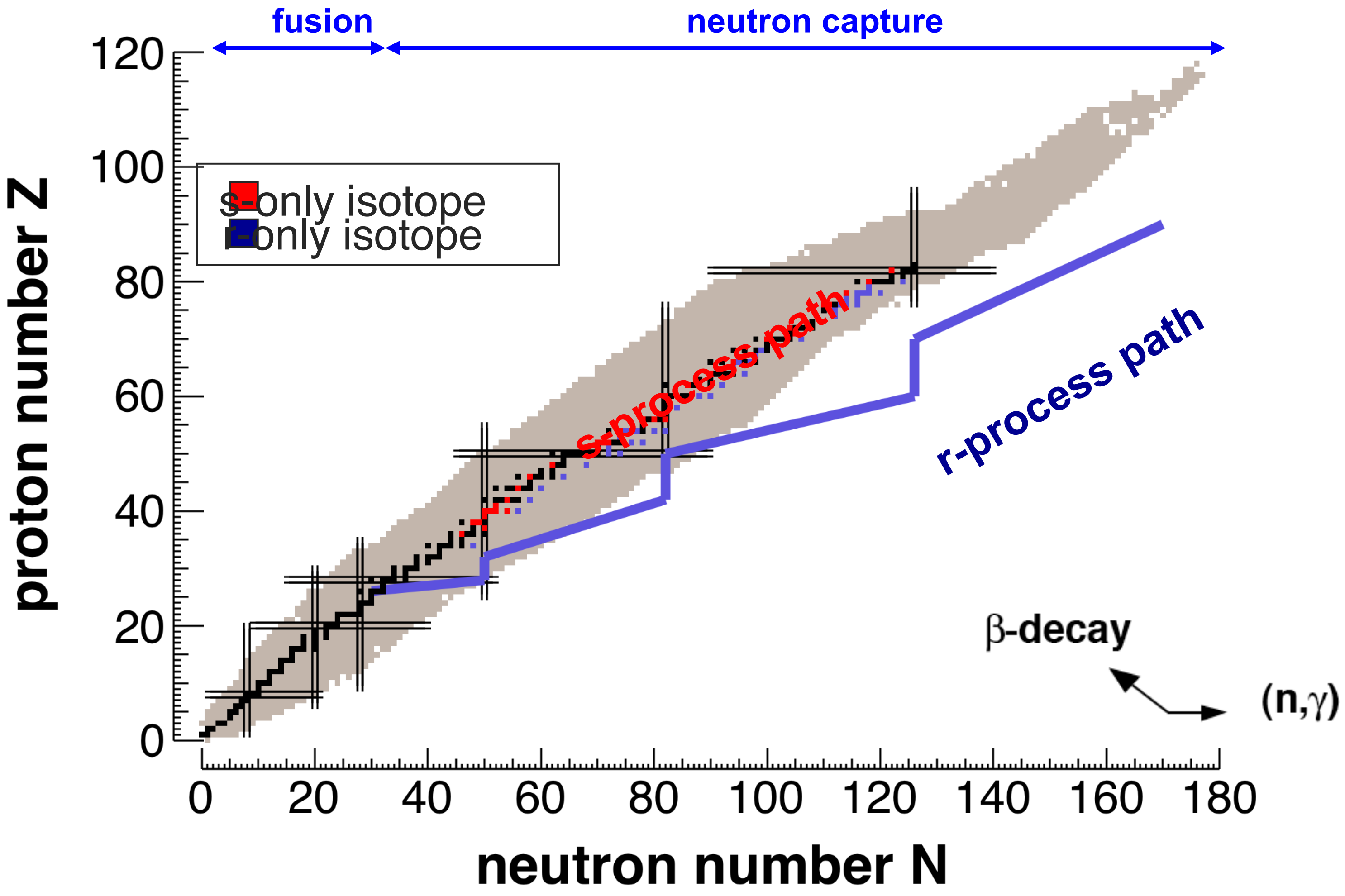


Neutrons and nuclei

Nuclear data for
- astrophysics
- nuclear technology
- nuclear physics



Neutrons and nuclei



Neutron sources for nuclear physics

- Nuclear fission research reactors
- Accelerator based neutron sources
  - wide spectrum or quasi mono-energetic neutrons
    light ions (p,d,α) on light targets Li, Be) : for example **^{7}Li(p,n)**
    quasi Maxwellian spectra, activation, CANS, others
    continuous or pulsed.
  - dedicated pulsed TOF (time-of-flight) neutron sources
    - electron based, on heavy target, **Bremsstrahlung**, (γ,n) (γ,f)
    - proton based, on heavy target, **spallation** reactions
    - deuteron based, on light target (Li, Be)

time-of-flight needs a pulsed beam with short (ns) pulses and long flight paths, in the order of tens of meters.

Pulsed white neutron sources

	Facility	Location	Beam	Energy (MeV)	Target	Pulse width (ns)	Beam power (kW)	rep. rate (Hz)
(γ,n) + (γ,f)	RPI	Troy, USA	e	60	Ta	5	0.45	500
			e	60	Ta	5000	>10	300
	ORELA	Oak Ridge, USA	e	180	Ta	2–30	60	12–1000
	GELINA	Geel, Belgium	e	100	U	1	10	40–800
	nELBE	Rossendorf, Germany	e	40	L-Pb	0.01	40	500 000
	IREN	Dubna, Russia	e	30	W	100	0.42	50
	PNF	Pohang, Korea	e	75	Ta	2000	0.09	12
	KURRI	Kumatori Japan	e	46	Ta	2	0.046	300
			e	30	Ta	4000	6	100
spallation	LANSCE-MLNSC	Los Alamos, USA	p	800	W	135	800	20
	LANSCE-WNR	Los Alamos, USA	p	800	W	0.2	1.44	13 900
	n_TOF	Geneva, Switzerland	p	20 000	Pb	6	10	0.4
	MLF-NNRI	Tokai, Japan	p	3 000	Hg	1000	1000	25
	ESS c	Lund, Sweden	p	2 000	W	2860	5000	14
	SNS	Oak Ride, USA	p	1 000	Hg	700	1400	60
	ISIS-TS1 c	Oxfordshire, UK	p	800	W	100	240	50
	CSNS	Dongguan, China	p	1 600	W		100	25
(d,n)	NFS	GANIL, Caen, France	d	40	Be	<0.5	2	150k–880k

c in Europe

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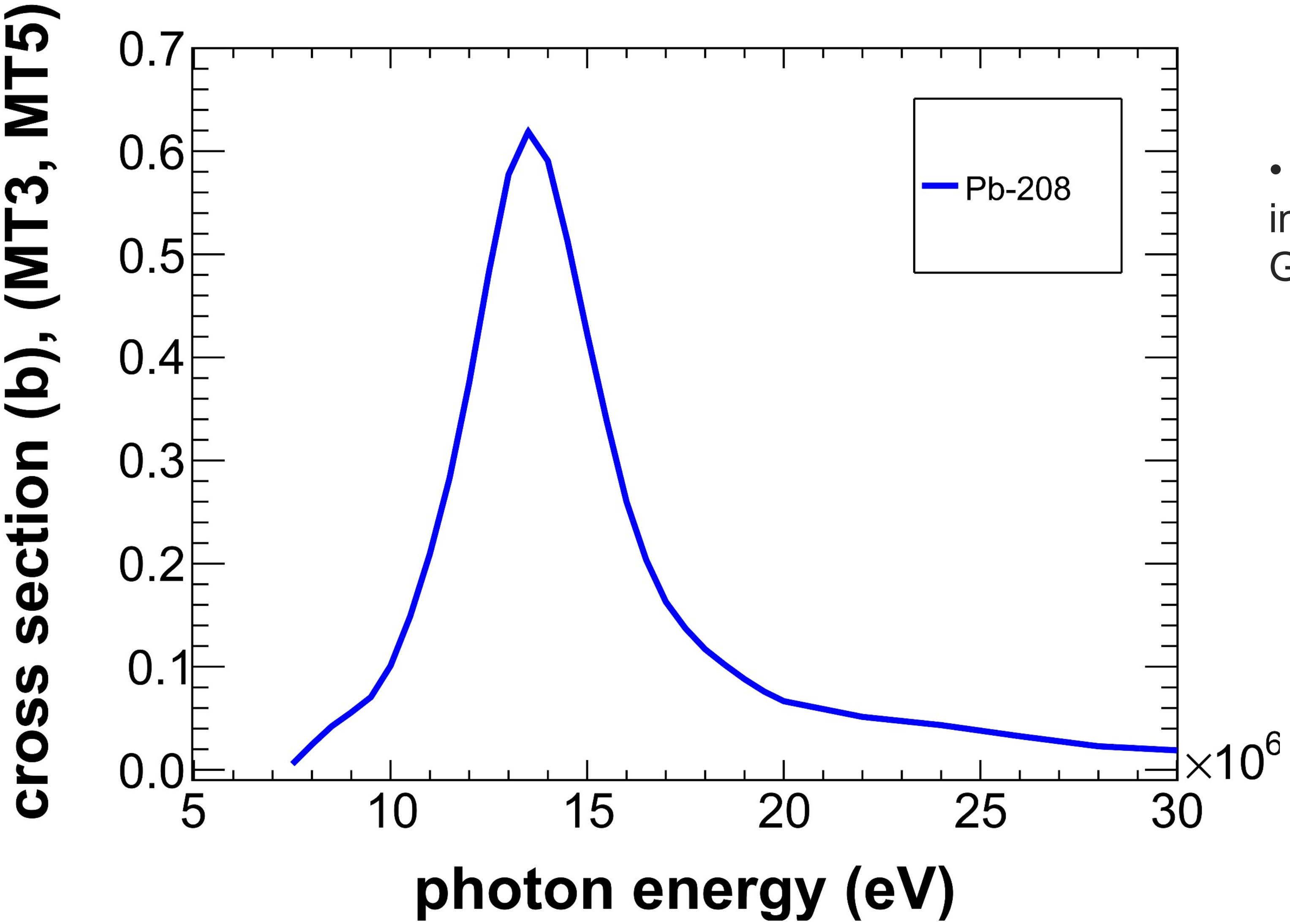
Photo-nuclear neutron production

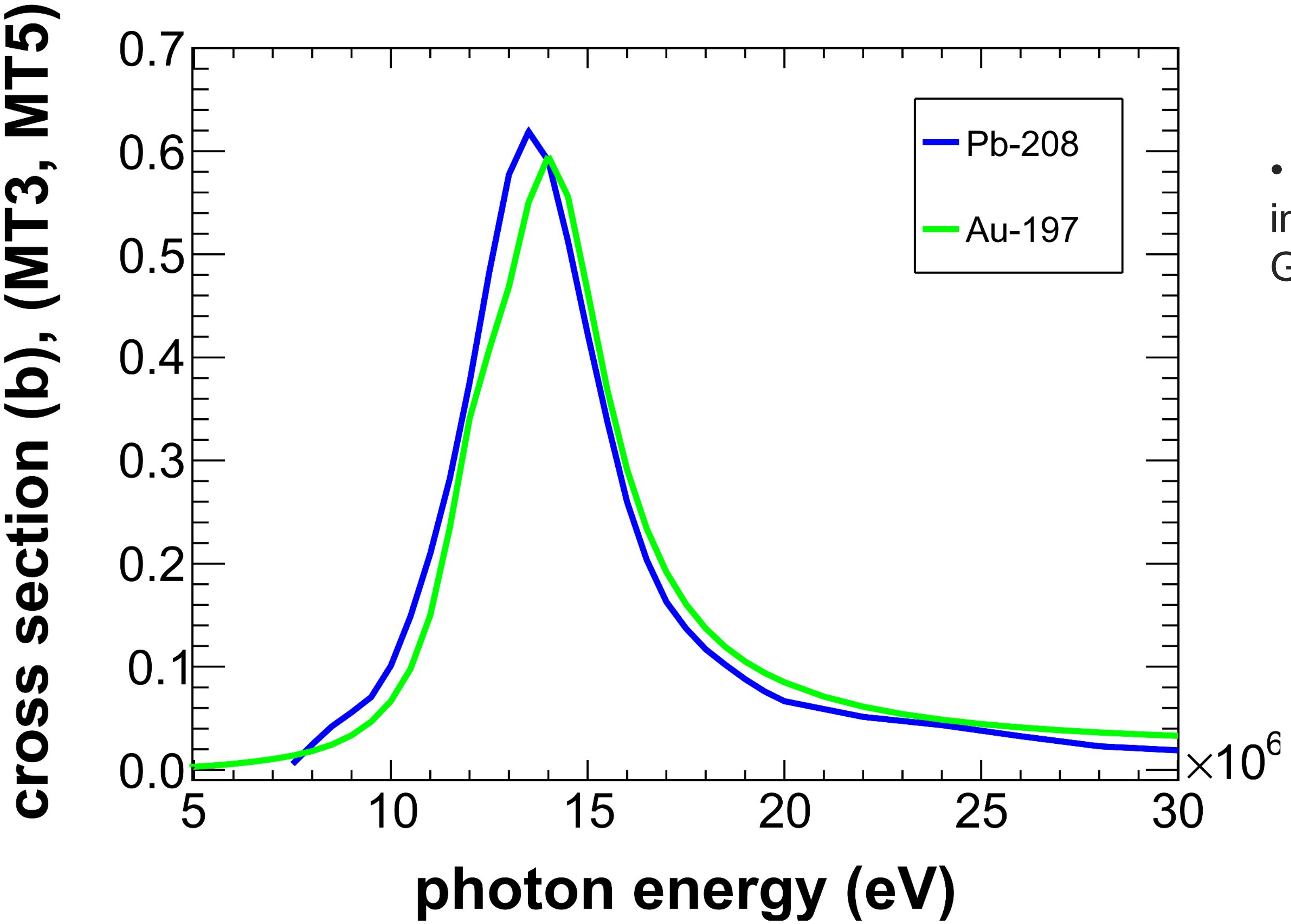
Data from
ENDF/B-VIII.1



- Very strong increase in cross section at GDR, Giant Dipole Resonance

Photo-nuclear neutron production

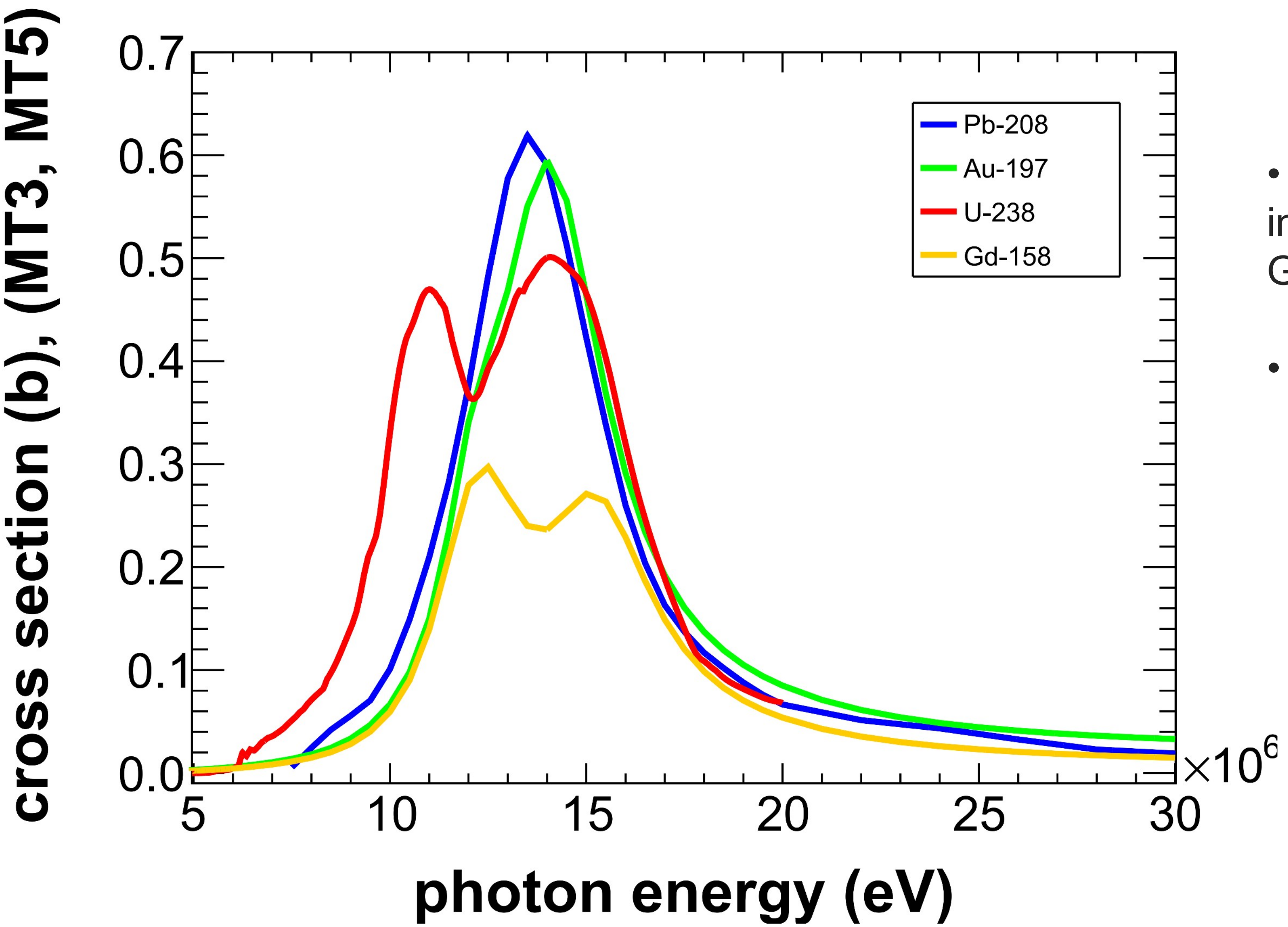
Data from
ENDF/B-VIII.1



- Very strong increase in cross section at GDR, Giant Dipole Resonance

Photo-nuclear neutron production

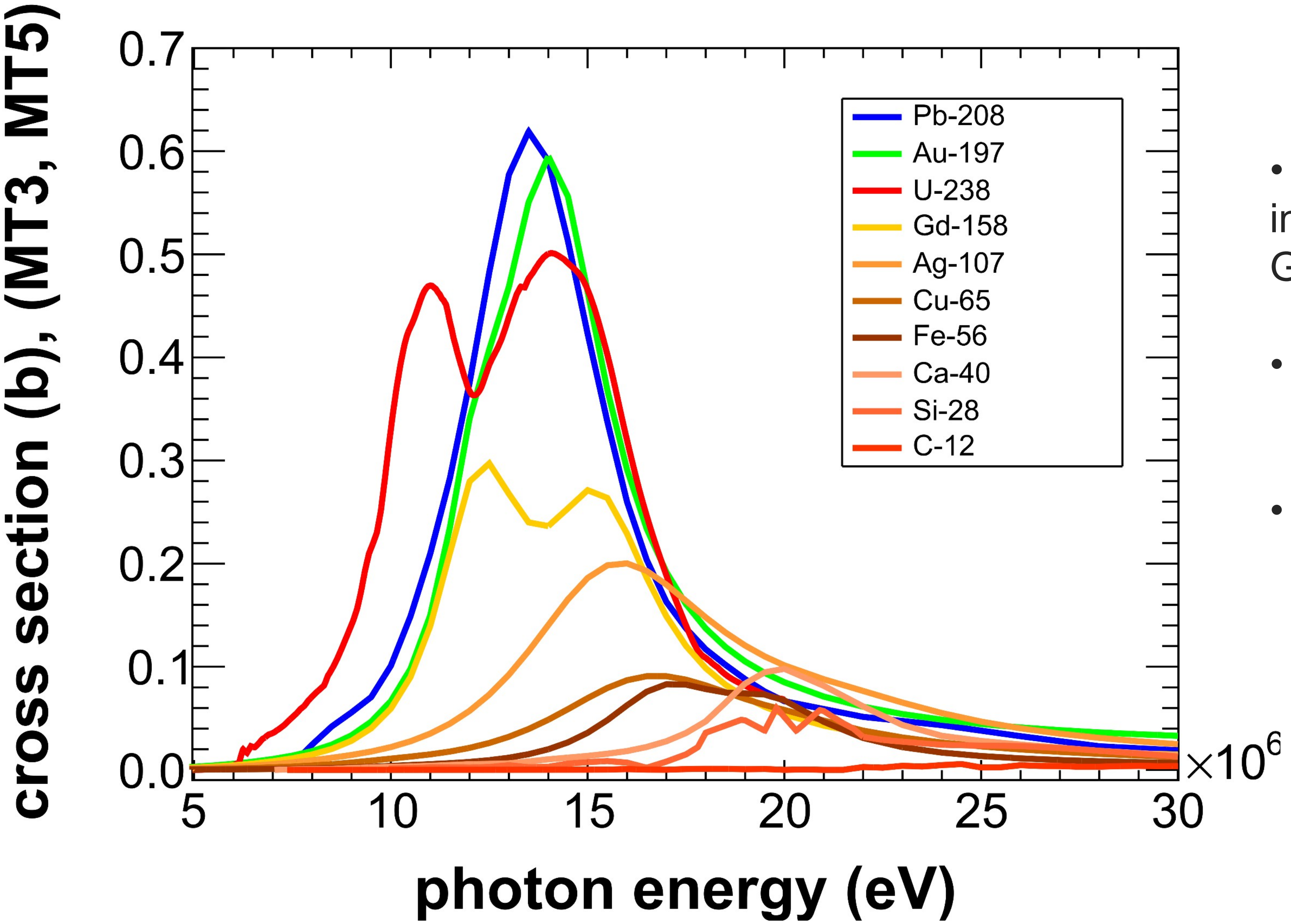
Data from ENDF/B-VIII.1



- Very strong increase in cross section at GDR, Giant Dipole Resonance
- For deformed nuclei, two GDRs

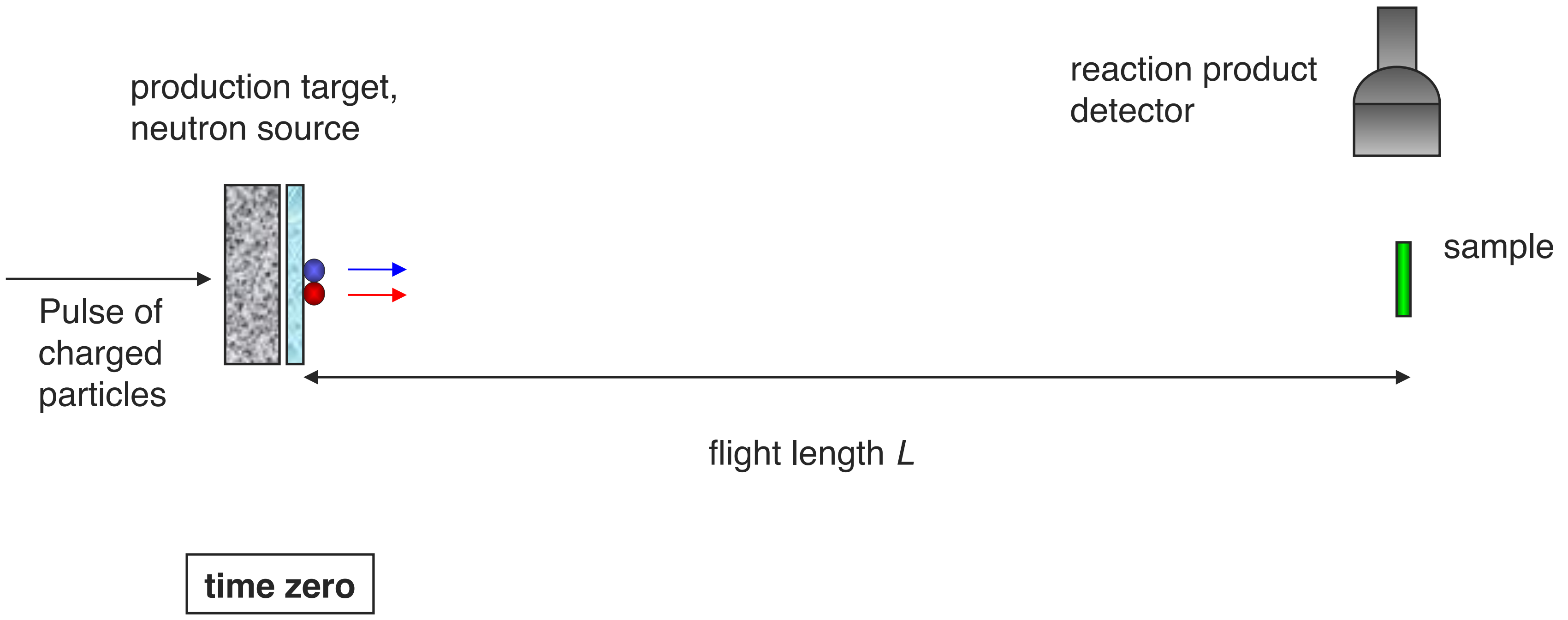
Photo-nuclear neutron production

Data from
ENDF/B-VIII.1

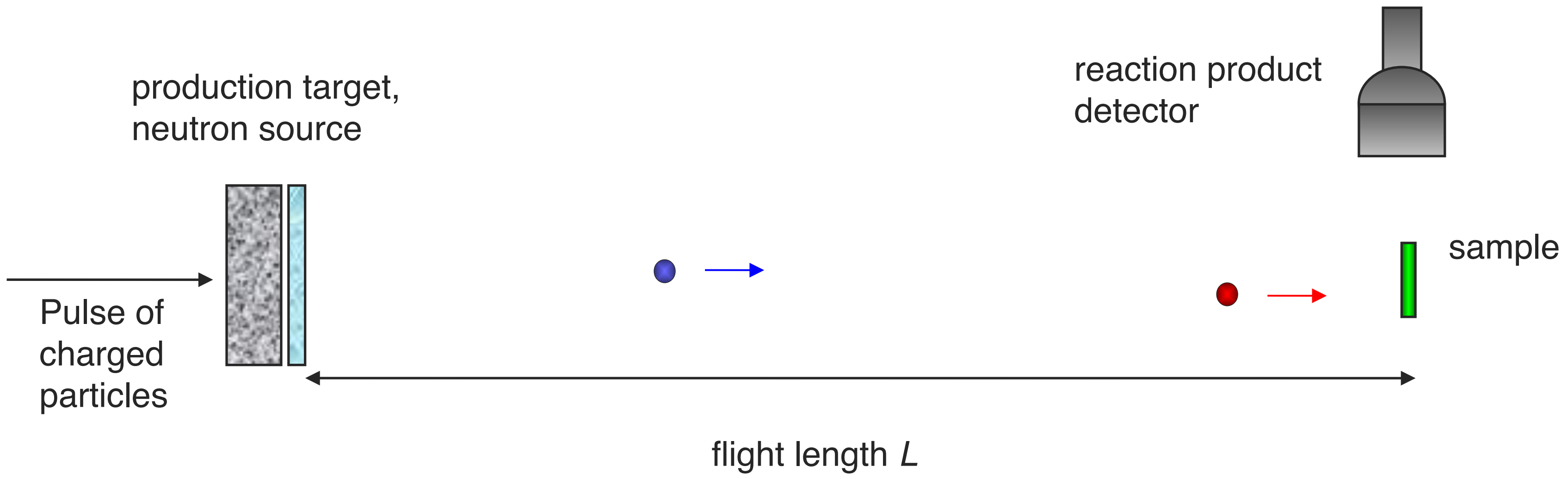


- Very strong increase in cross section at GDR, Giant Dipole Resonance
- For deformed nuclei, two GDRs
- In general, photo-induced neutron production is favoured in heavy targets

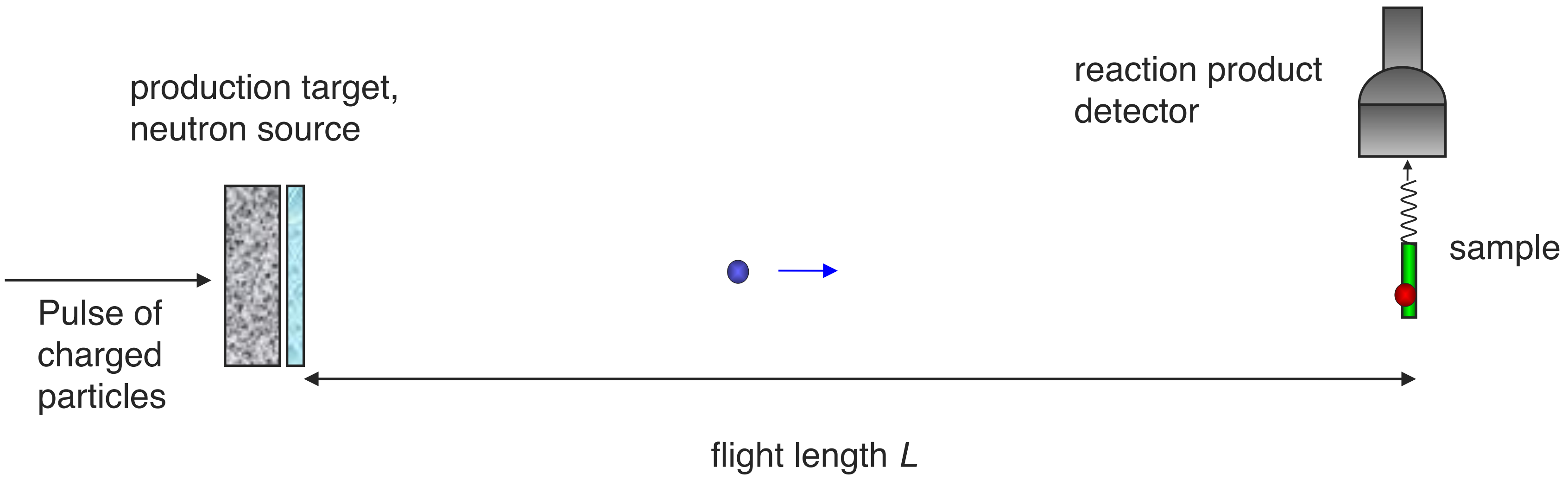
Neutron time of flight



Neutron time of flight



Neutron time of flight



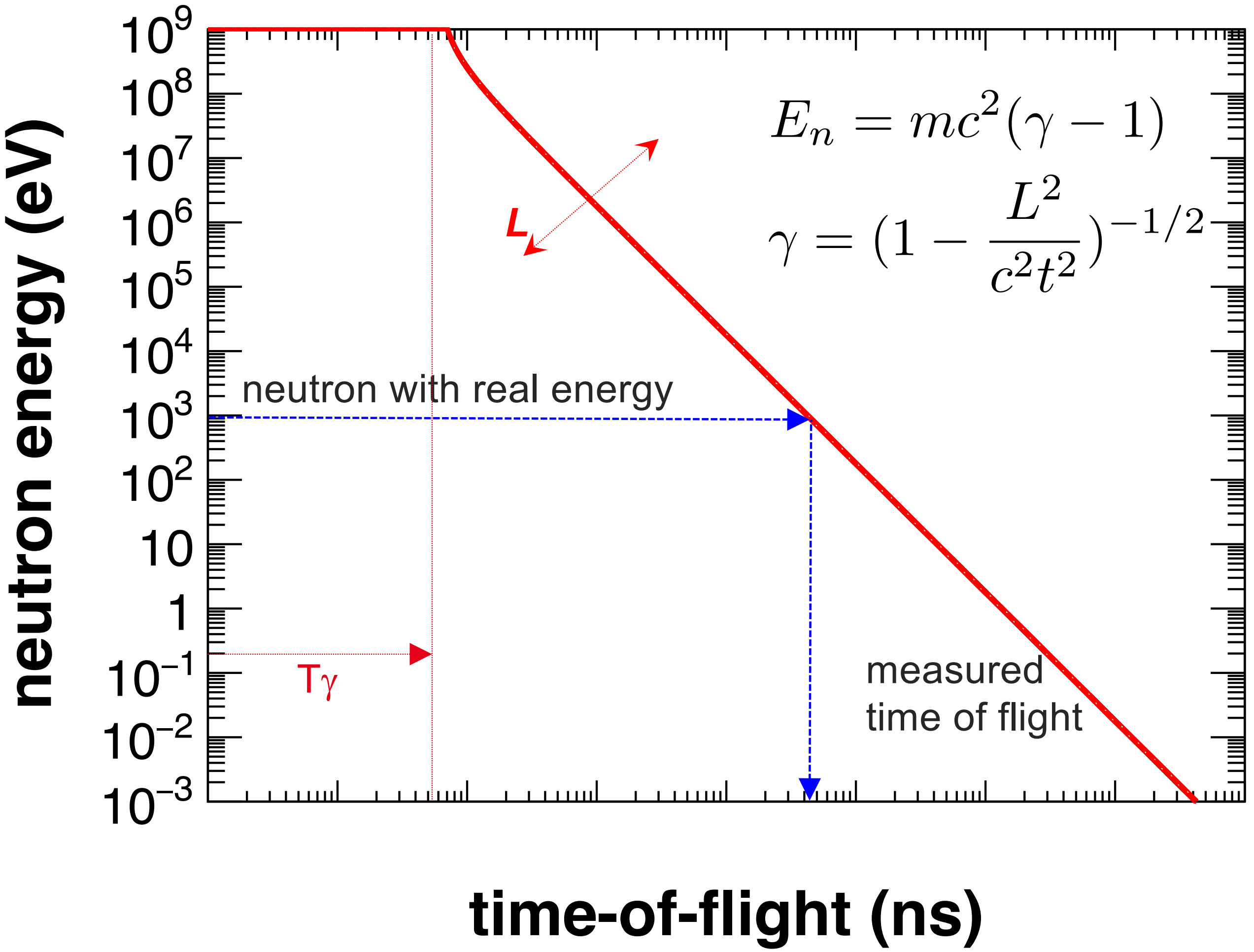
time of flight *t*

Deduce kinetic energy from neutron by time-of-flight:

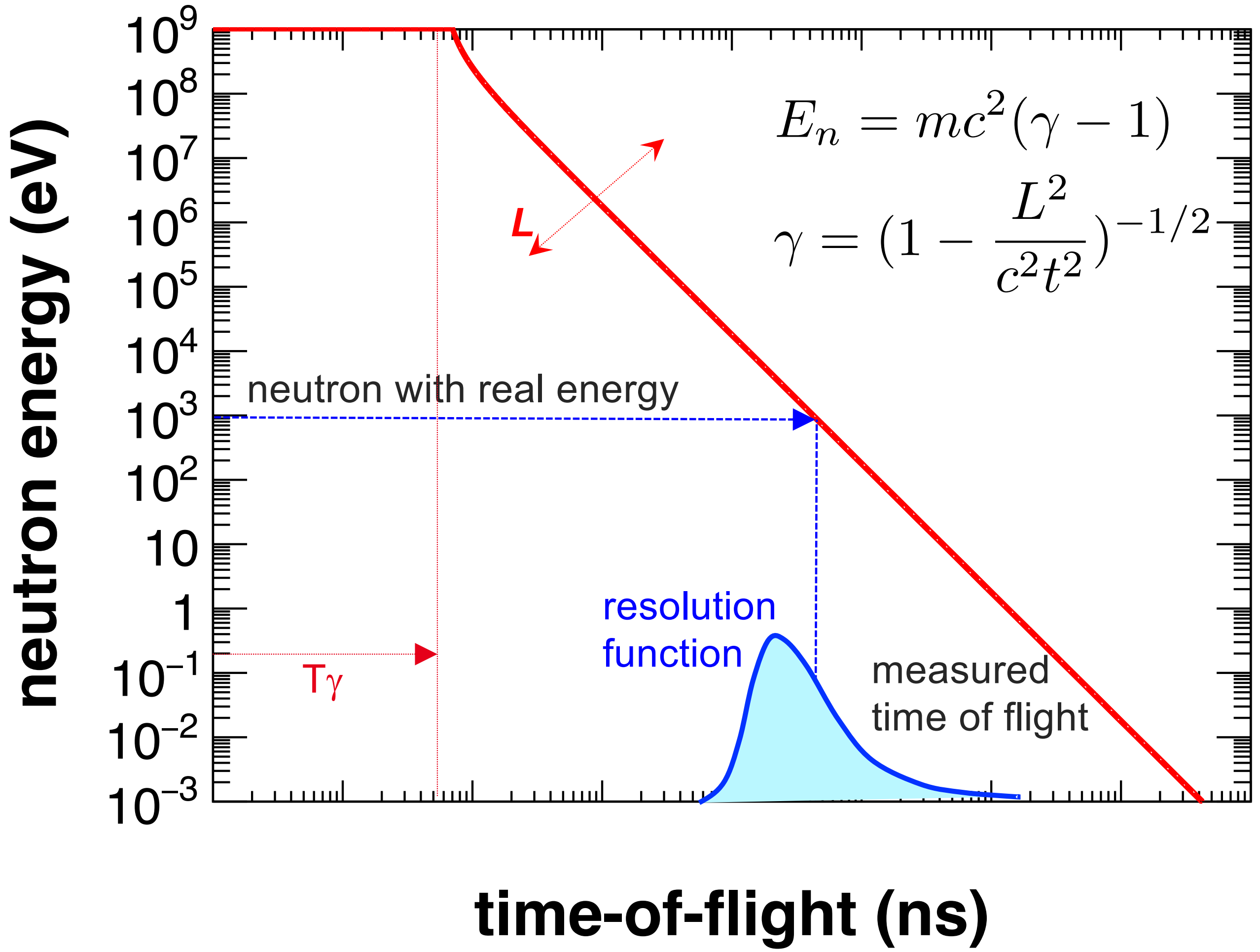
$$E_n = mc^2(\gamma - 1)$$

$$\gamma = (1 - \frac{L^2}{c^2t^2})^{-1/2}$$

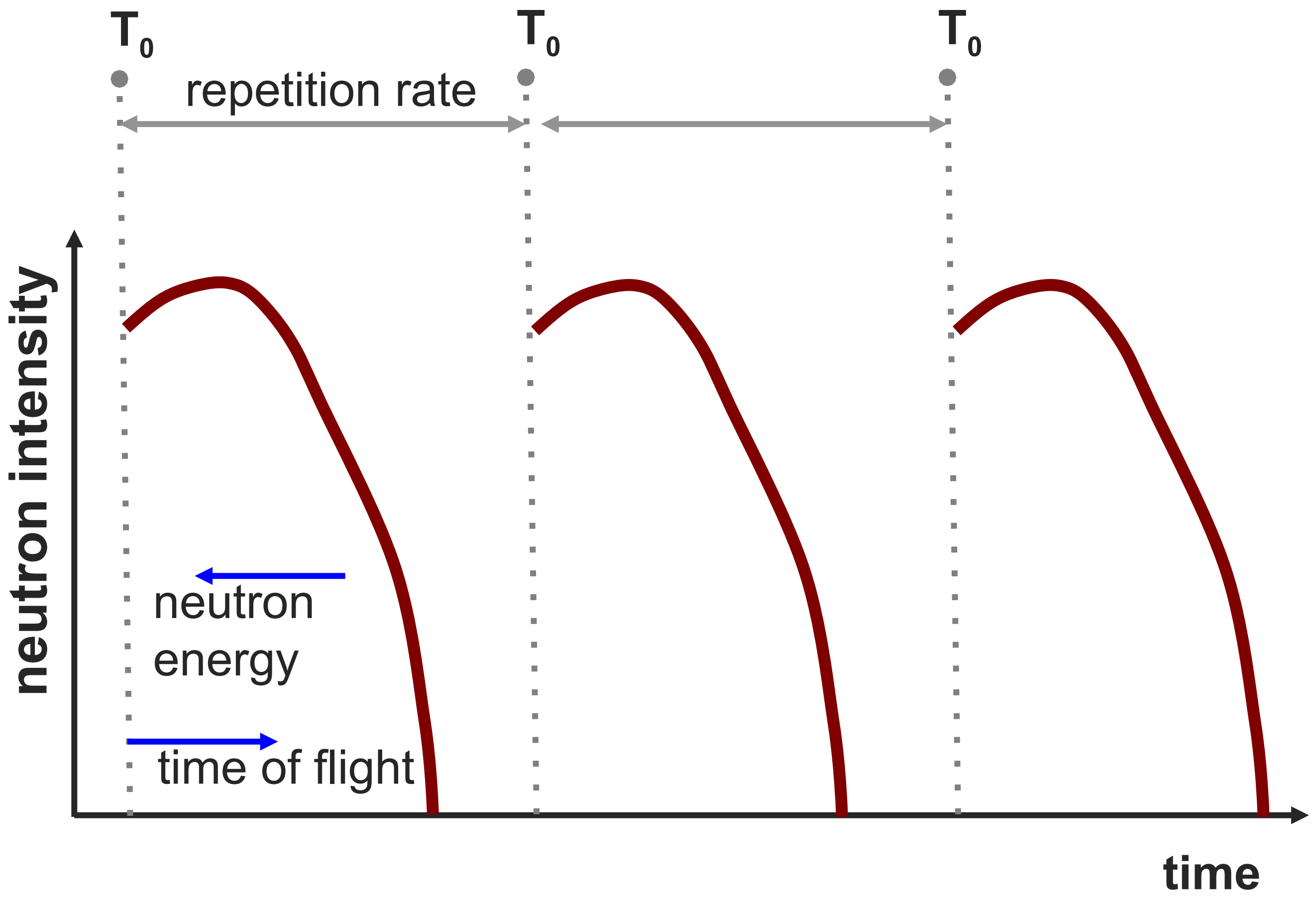
Neutron time of flight



Neutron time of flight

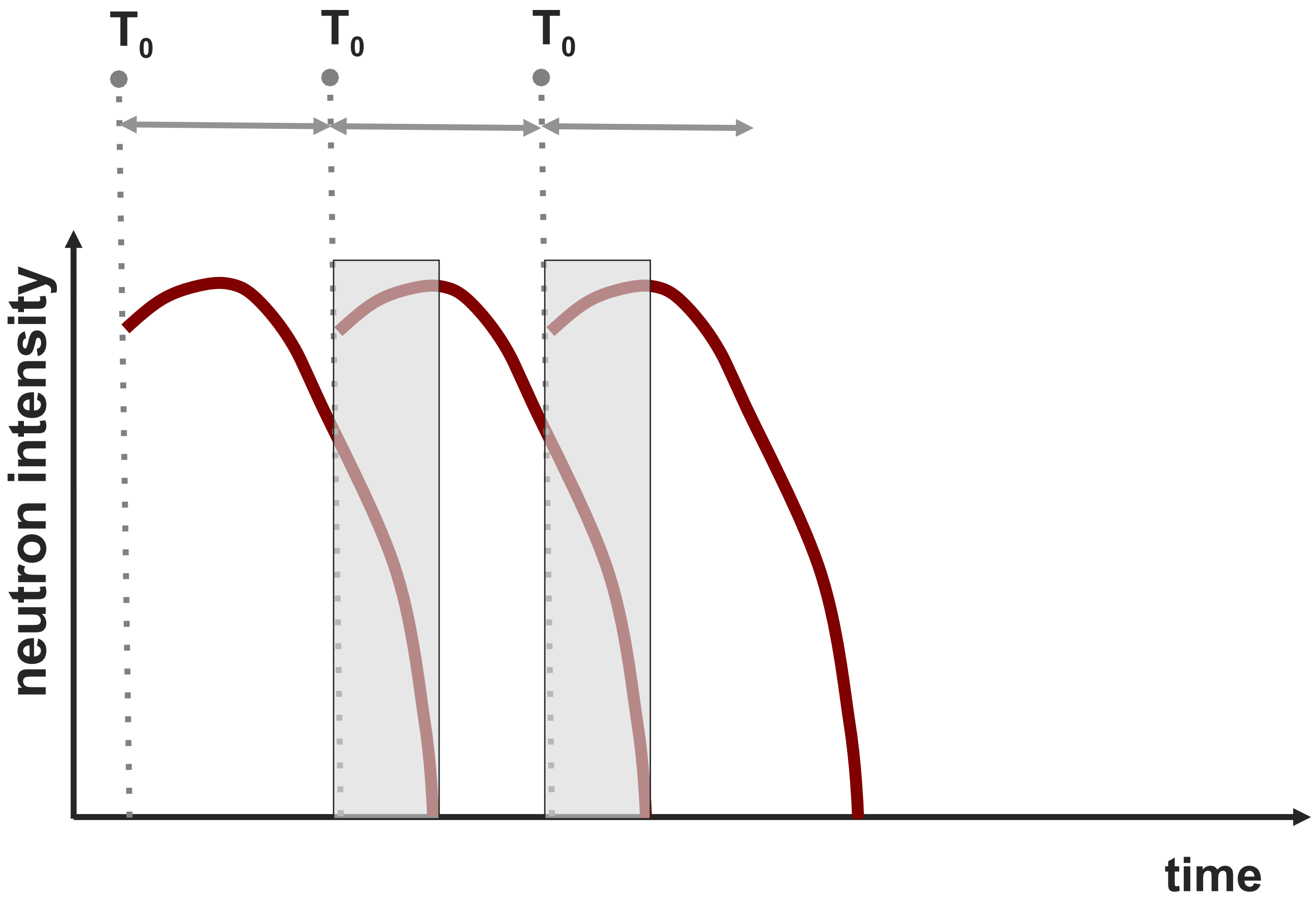


Neutron time of flight



White neutron spectrum, with moderator, for several TOF cycles

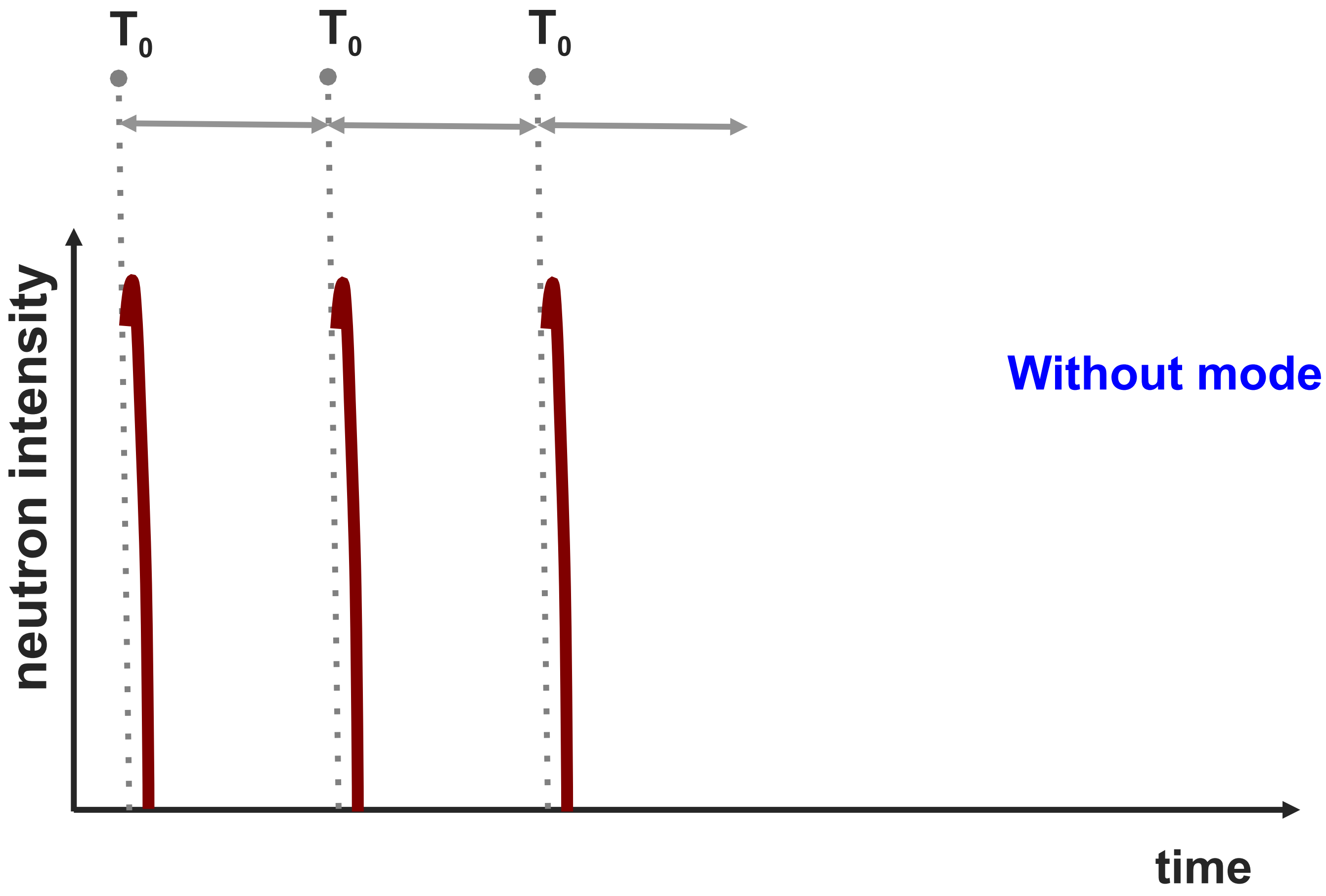
Neutron time of flight



White neutron spectrum, with moderator, for several TOF cycles

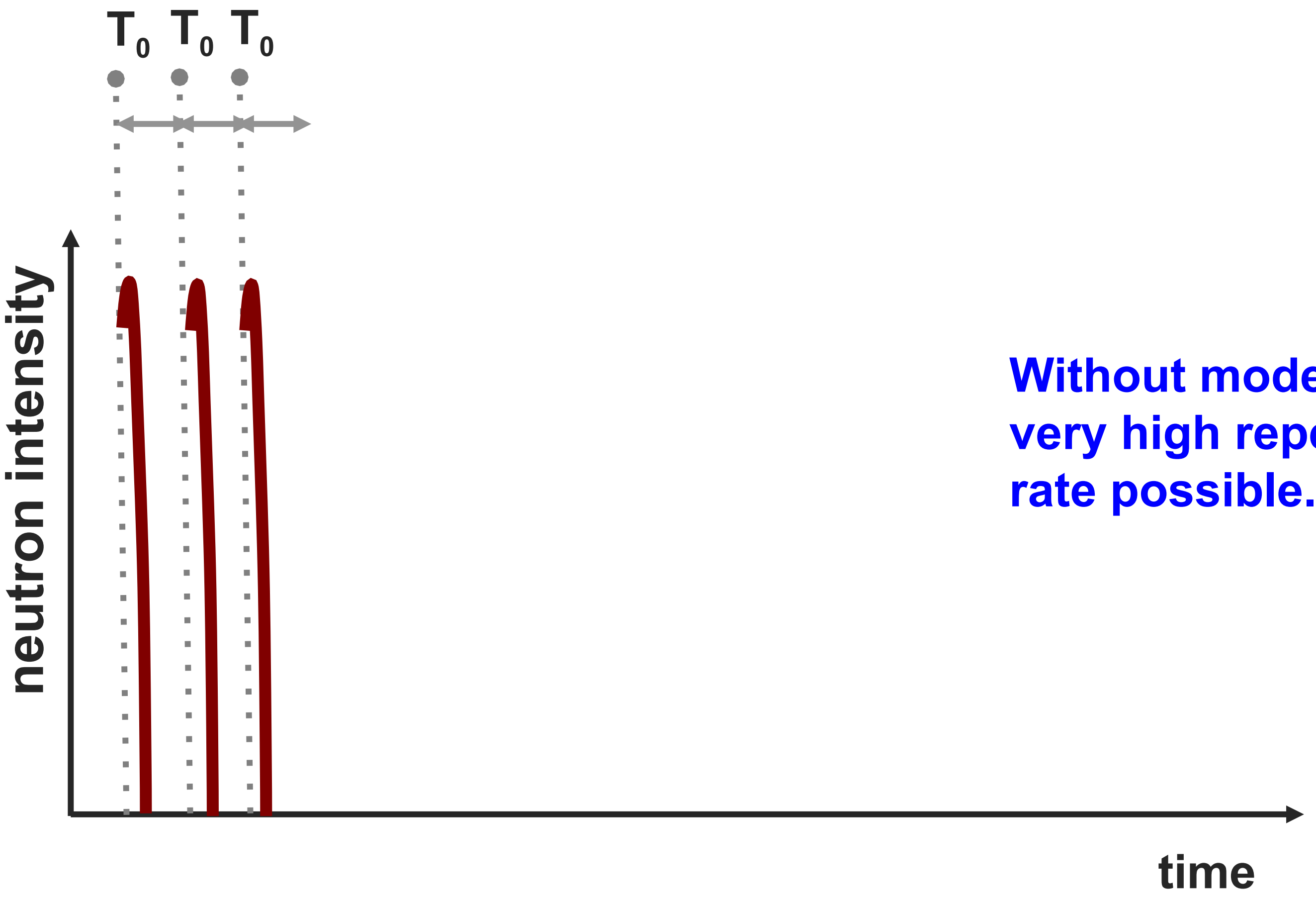
Cycle overlap if repetition rate too high

Neutron time of flight



Without moderator

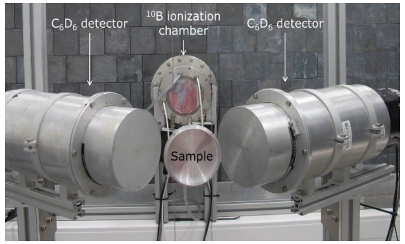
Neutron time of flight

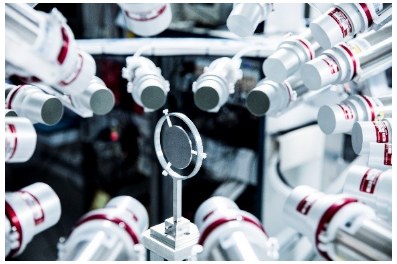


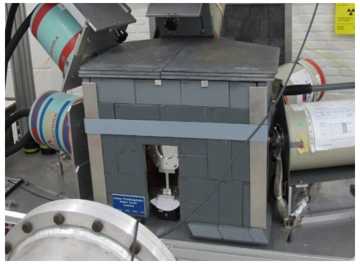
Without moderator, very high repetition rate possible.

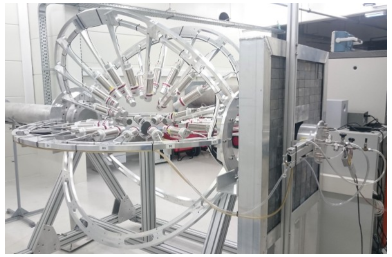
GELINA at JRC-Geel

- Transmission
  - 10 m, 30m, 50 m
- Capture
  - 10 m, 30 m, 60 m
- Elastic sattering
  - 30 m
- In-elastic scattering
  - 30 m, 100 m
- Fission, (n,p), (n,α),
  - 10 m

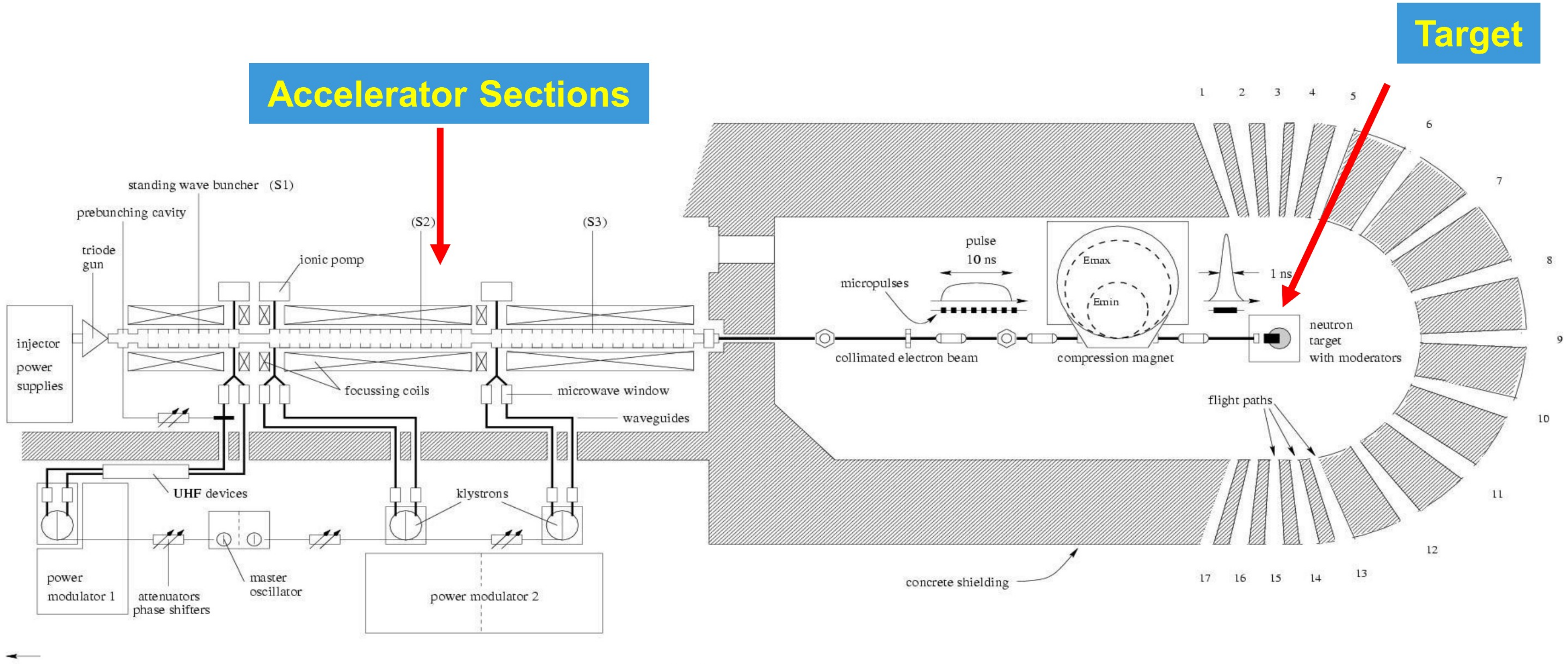








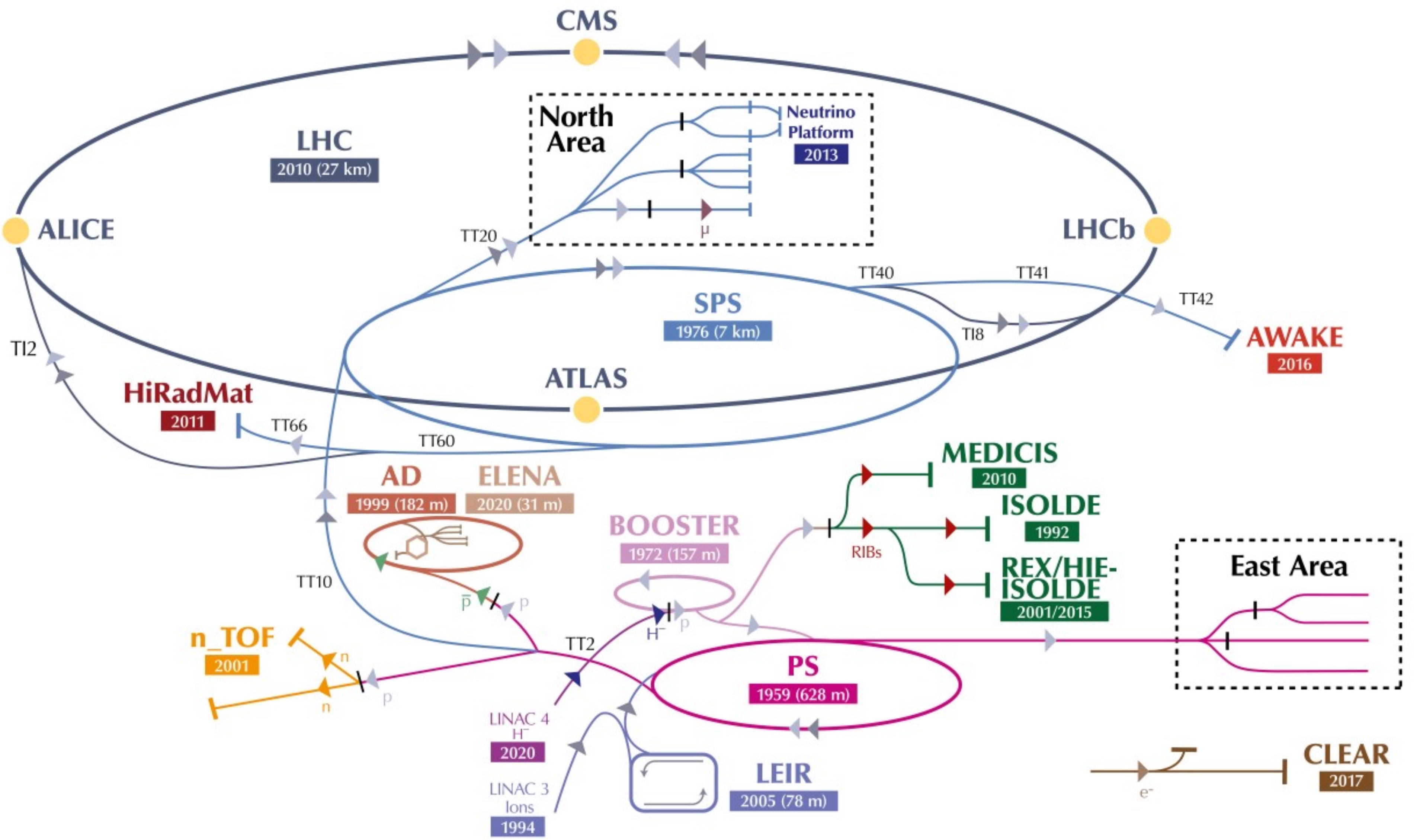
GELINA at JRC-Geel



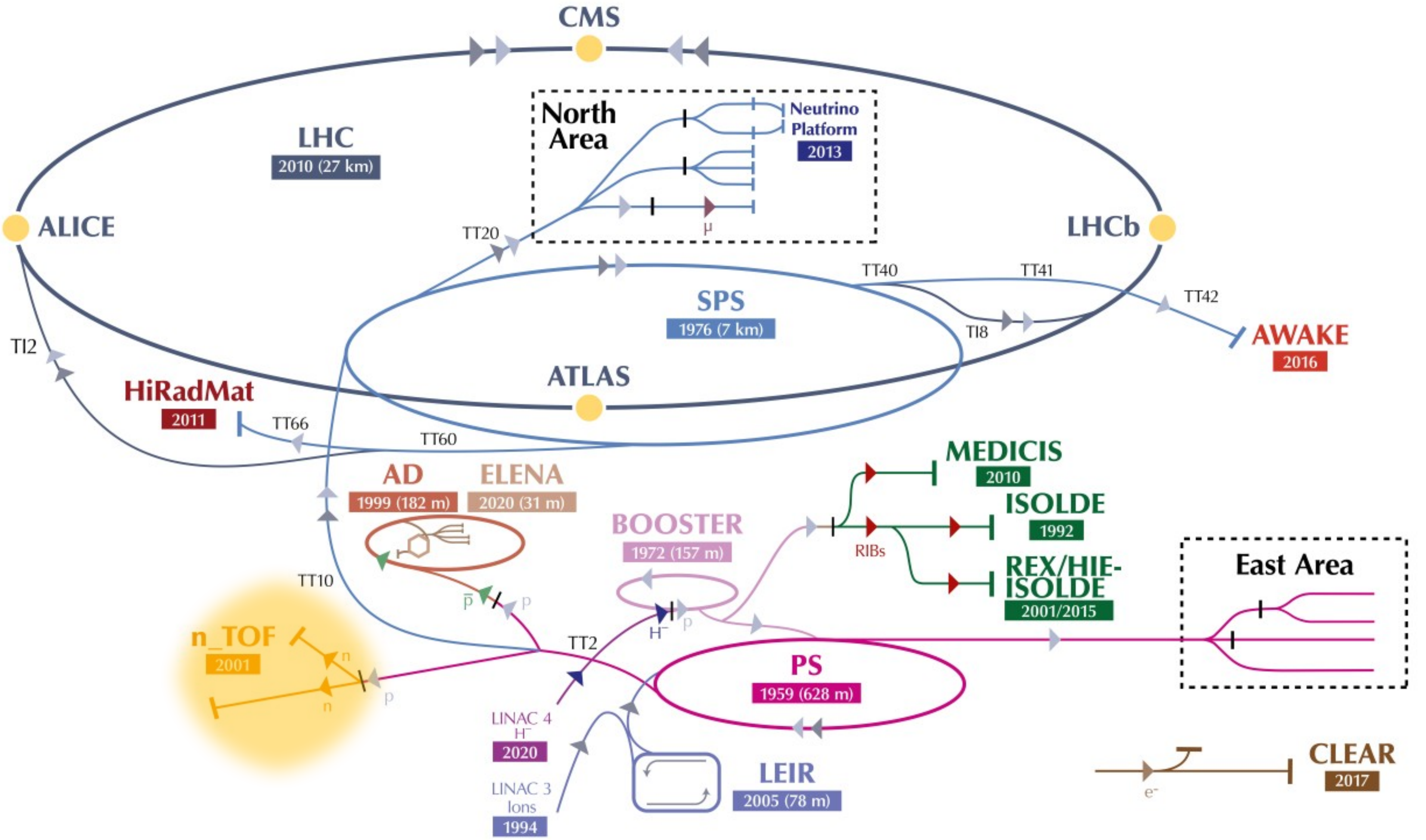
Normal Operating Parameters

Average Current	: 70 μA	Frequency	: up to 800 Hz
Maximum Electron Energy	: 130 MeV	Pulse Width	: 1-2 ns
Mean Power	: 7 kW	Neutron Flux	: 2 x 10^{13} 1/s

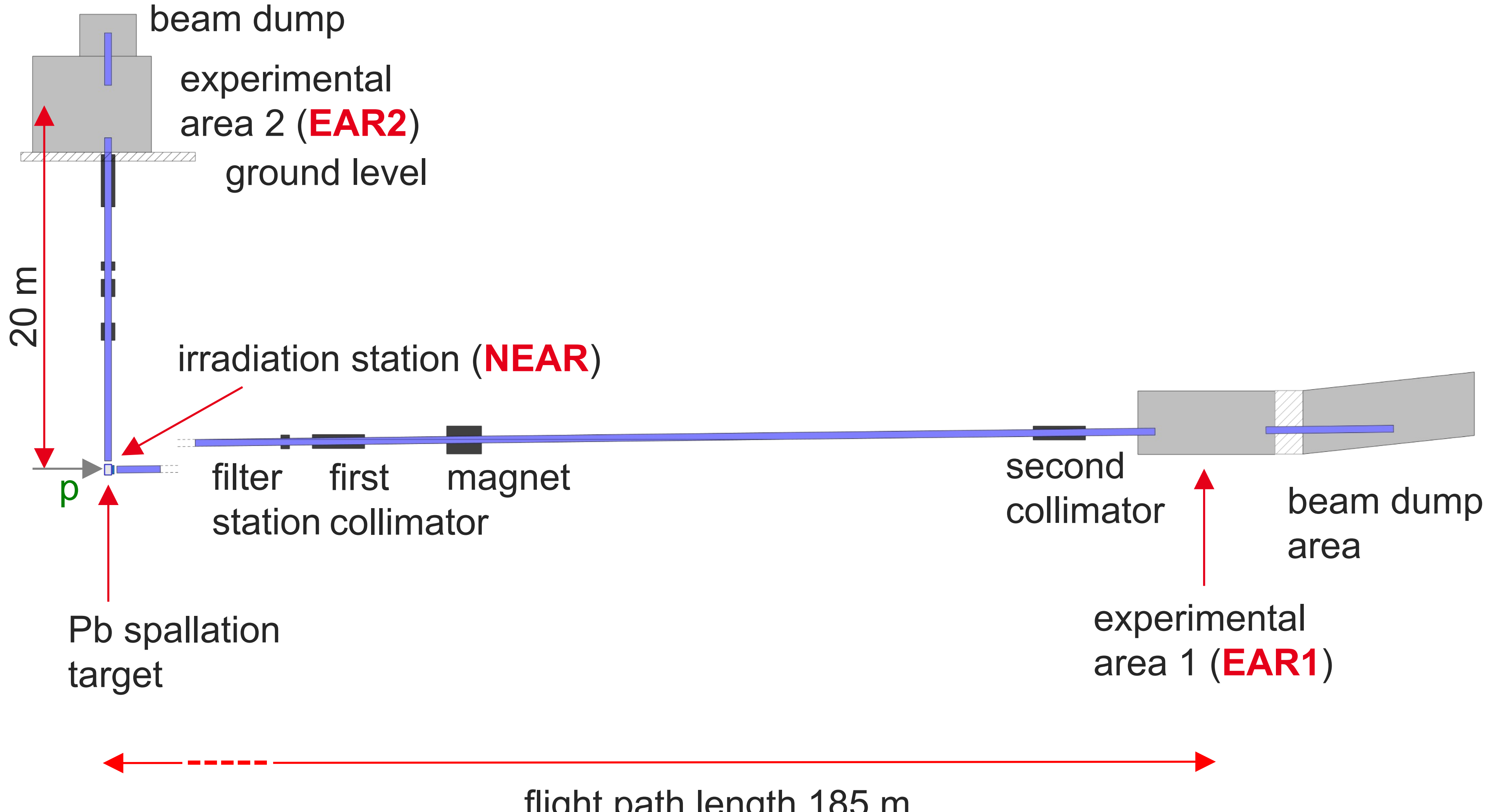
CERN accelerator complex



CERN accelerator complex



n_TOF at CERN



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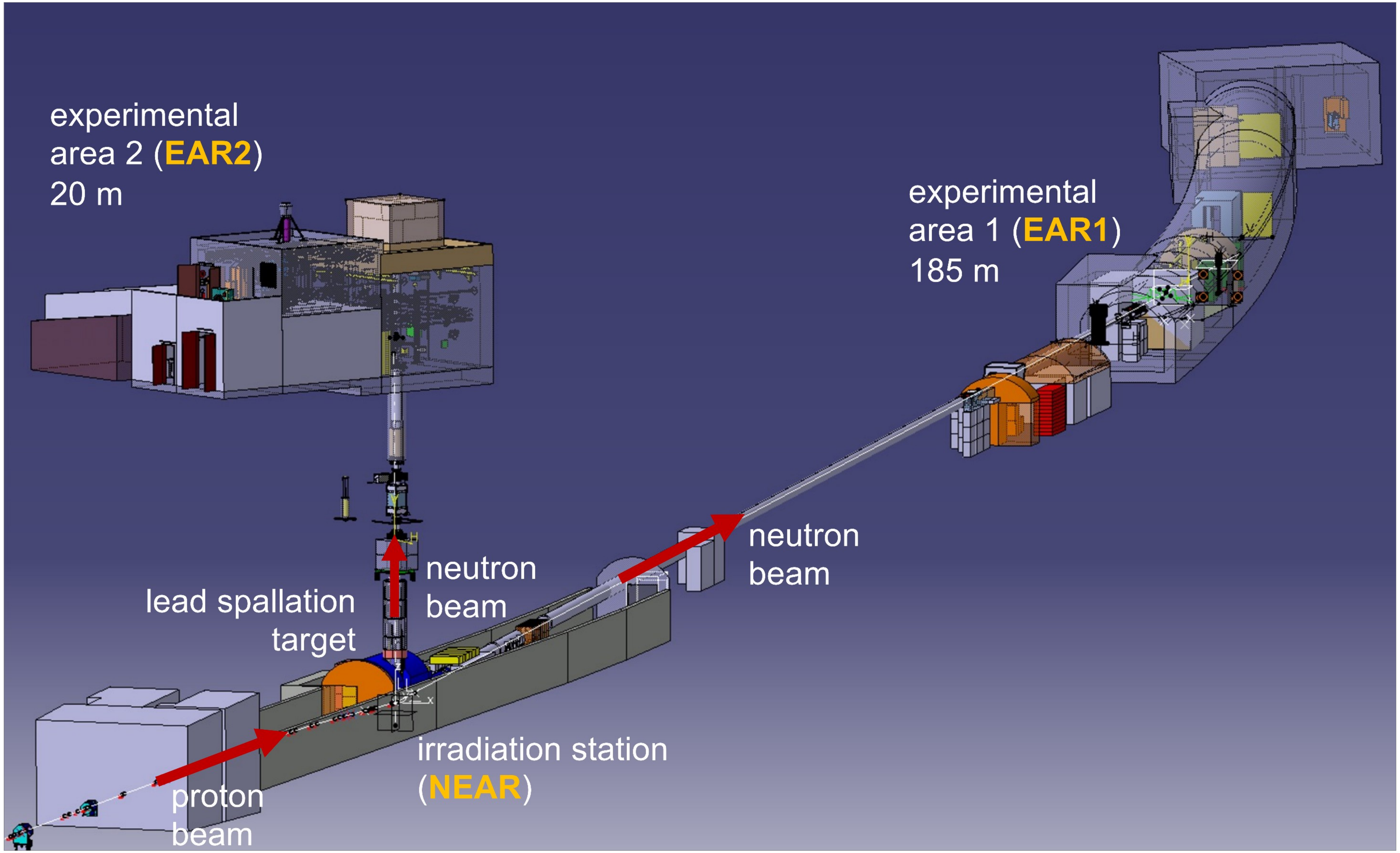
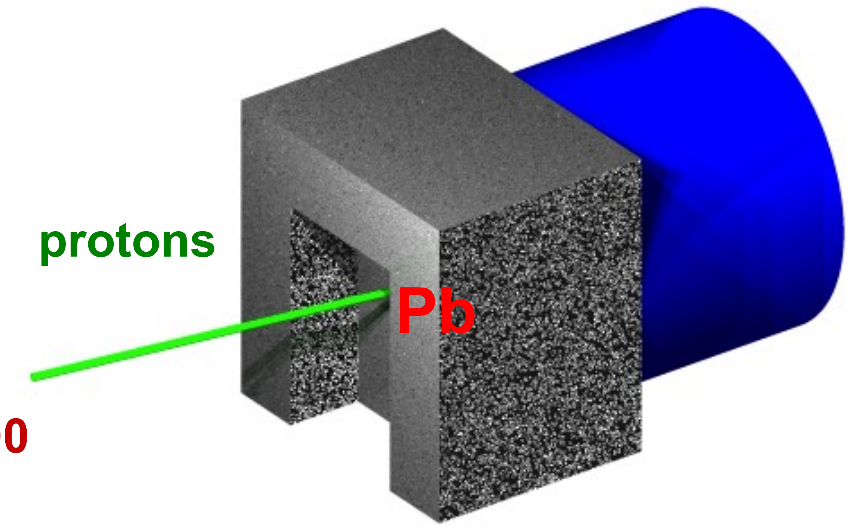
n_TOF at CERN


experimental
area 2 (EAR2)
20 m
experimental
area 1 (EAR1)
185 m
neutron
beam
lead spallation
target
neutron
beam
irradiation station
(NEAR)
proton
beam

n_TOF at CERN

Pulsed white neutron source:

- **20 GeV/c** protons
- neutrons from spallation
- **7 ns** rms pulse width
- frequency **1 pulse/2.4** seconds
- separate cooling and moderation
- flight path length EAR1: **185 m, since 2000**
-
- @source: $7\mathrm{x}10^{12}$ protons/pulse
- @source: $2\mathrm{x}10^{15}$ neutrons/pulse
- @EAR1: $5 \cdot 10^5$(capture) – $5 \cdot 10^7$(fission) neutrons/pulse



phase I target 2001-2004

Single water volume coolant and moderator

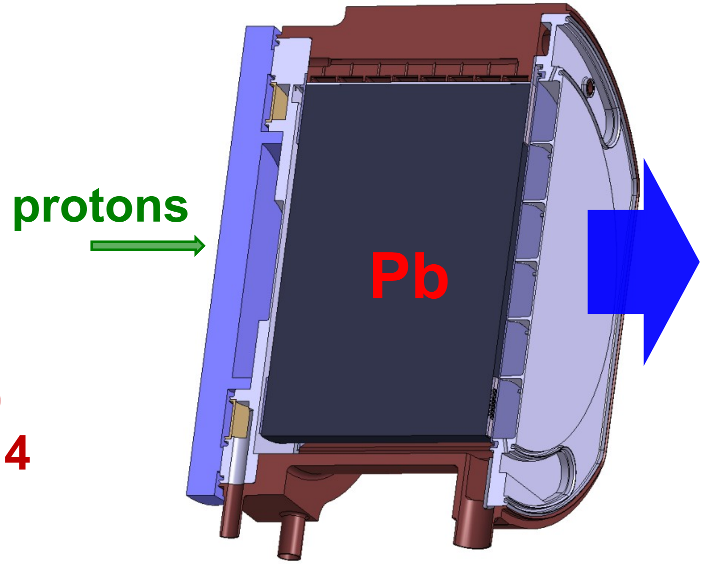
Main features:

- Large energy range available (0.01 eV – 1 GeV)
- Favorable signal to noise ratio for capture on radioactive isotopes (actinides, fission products)

n_TOF at CERN

Pulsed white neutron source:

- **20 GeV/c** protons
- neutrons from spallation
- **7 ns** rms pulse width
- frequency **1 pulse/2.4** seconds
- separate cooling and moderation
- flight path length EAR1: **185 m, since 2000**
- **flight path length EAR2: 20 m, since 2014**
- @source: 7×10^{12} protons/pulse
- @source: 2×10^{15} neutrons/pulse
- @EAR1: $5 \cdot 10^5$(capture) – $5 \cdot 10^7$(fission) neutrons/pulse



phase II-III target 2009-2018

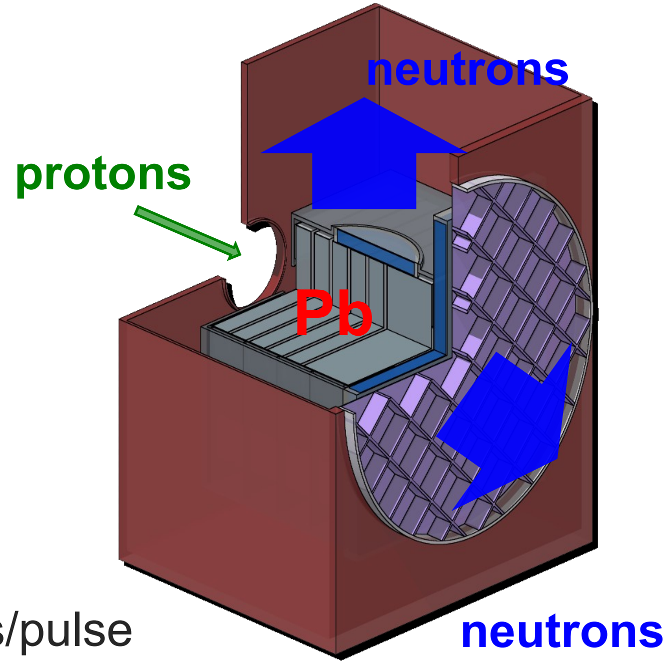
Main features:

- Large energy range available (0.01 eV – 1 GeV)
- Favorable signal to noise ratio for capture on radioactive isotopes (actinides, fission products)

Moderator separated from water coolant

n_TOF at CERN

Pulsed white neutron source:
- **20 GeV/c** protons
- neutrons from spallation
- **7 ns** rms pulse width
- frequency **1 pulse/1.2** seconds
- separate cooling and moderation
- flight path length EAR1: **185 m, since 2000**
- **flight path length EAR2: 20 m, since 2014**
- @source: 7×10^{12} protons/pulse **nominal**
- @source: 2×10^{15} neutrons/pulse **nominal**
- @EAR1: $5 \cdot 10^{5}$(capture) – $5 \cdot 10^{7}$(fission) neutrons/pulse

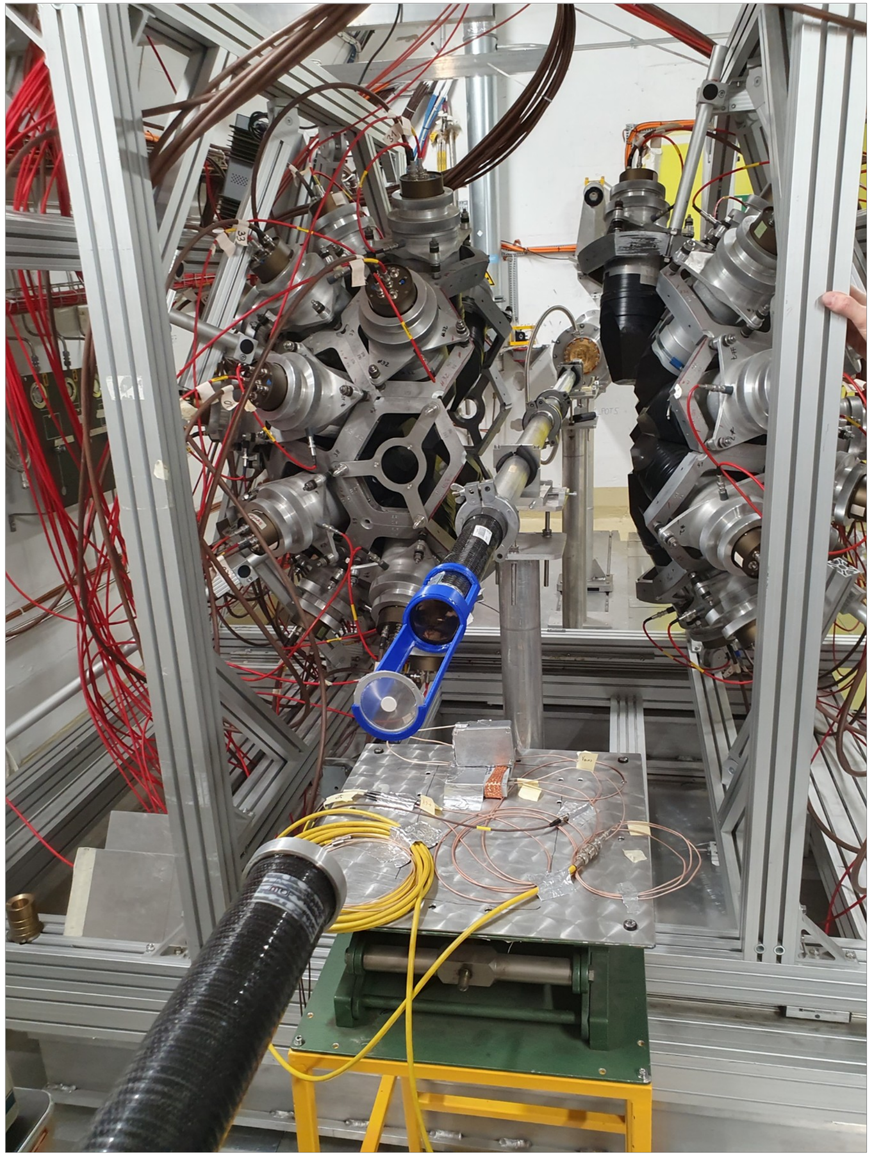


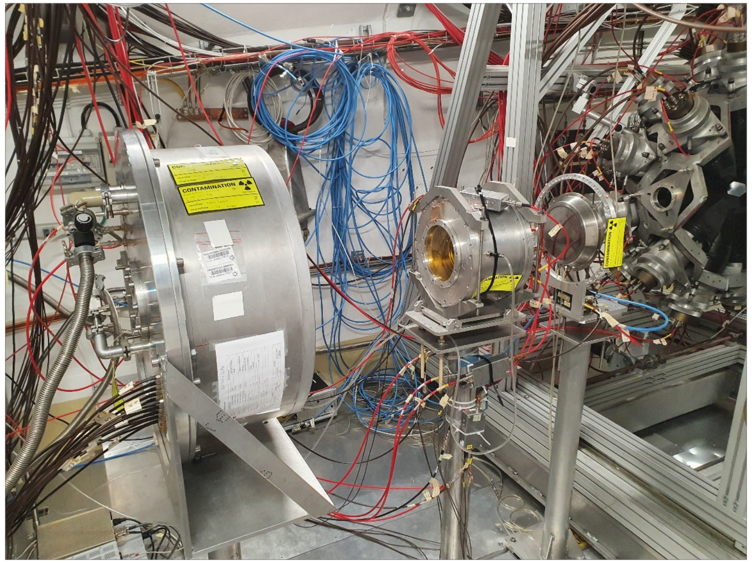
phase IV target,
N_2-cooled
since 2021

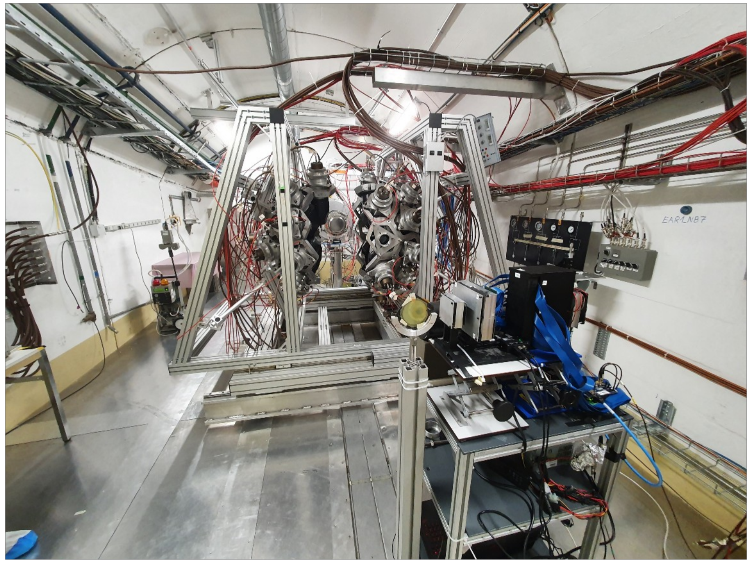
Only moderator contains water

Main features:
- Large energy range available (0.01 eV – 1 GeV)
- Favorable signal to noise ratio for capture on radioactive isotopes (actinides, fission products)

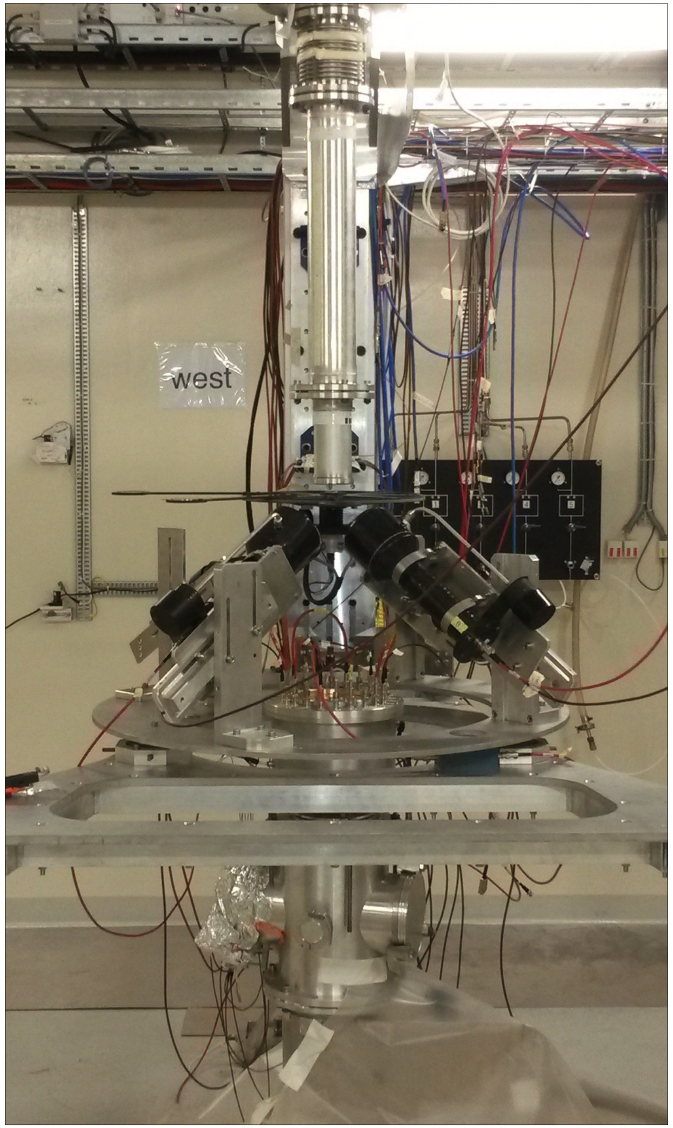
n_TOF at CERN, EAR1

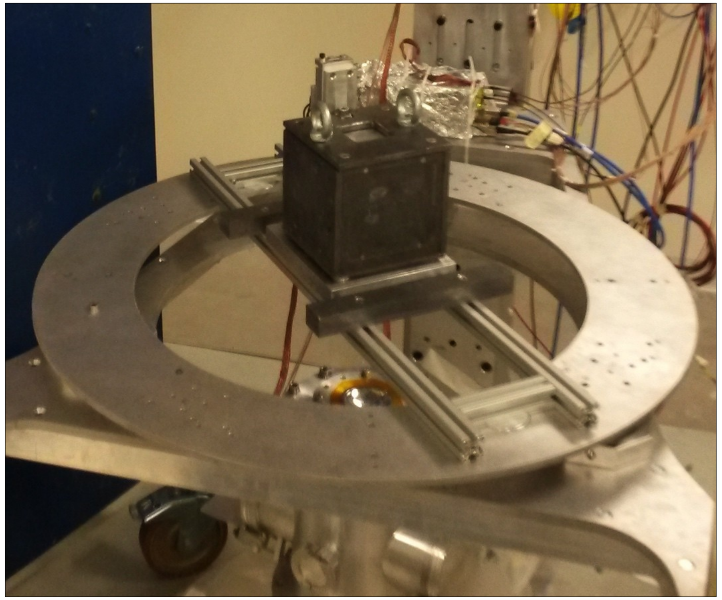


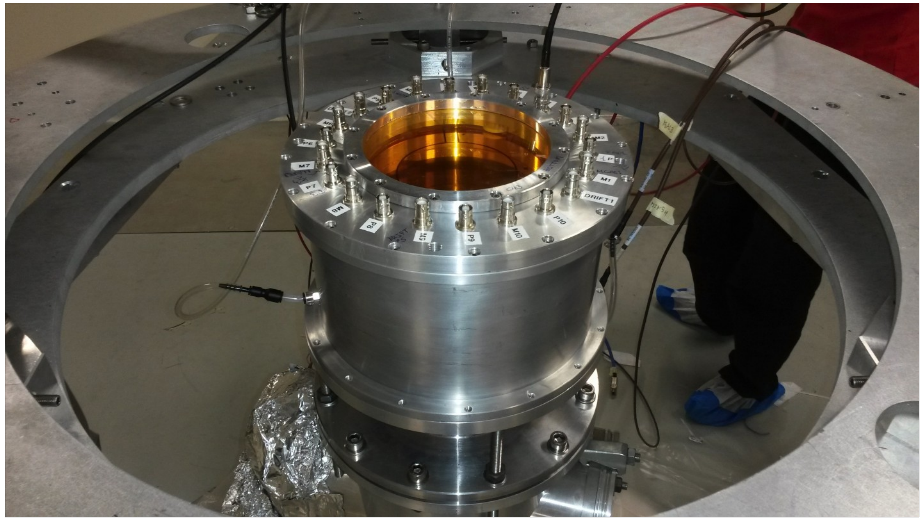




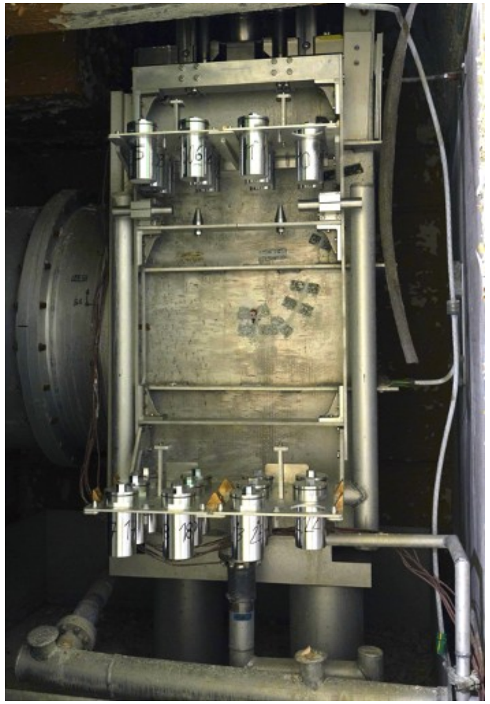
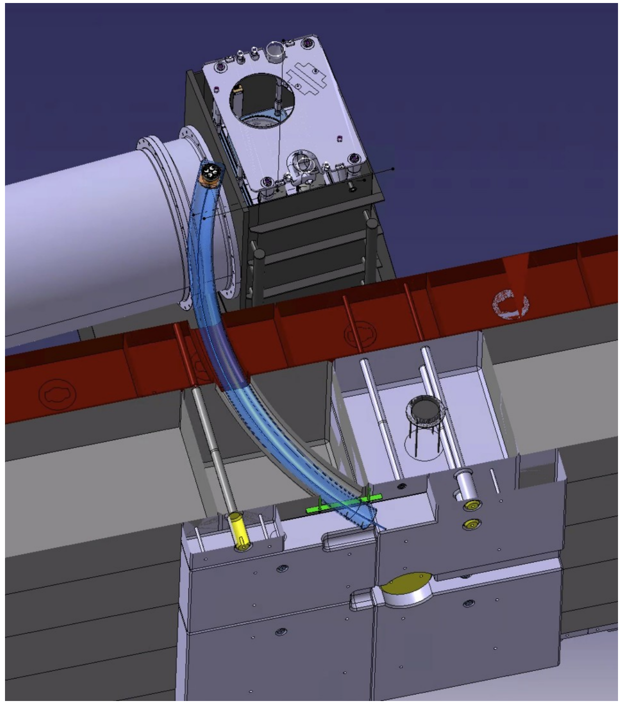
n_TOF at CERN, EAR2







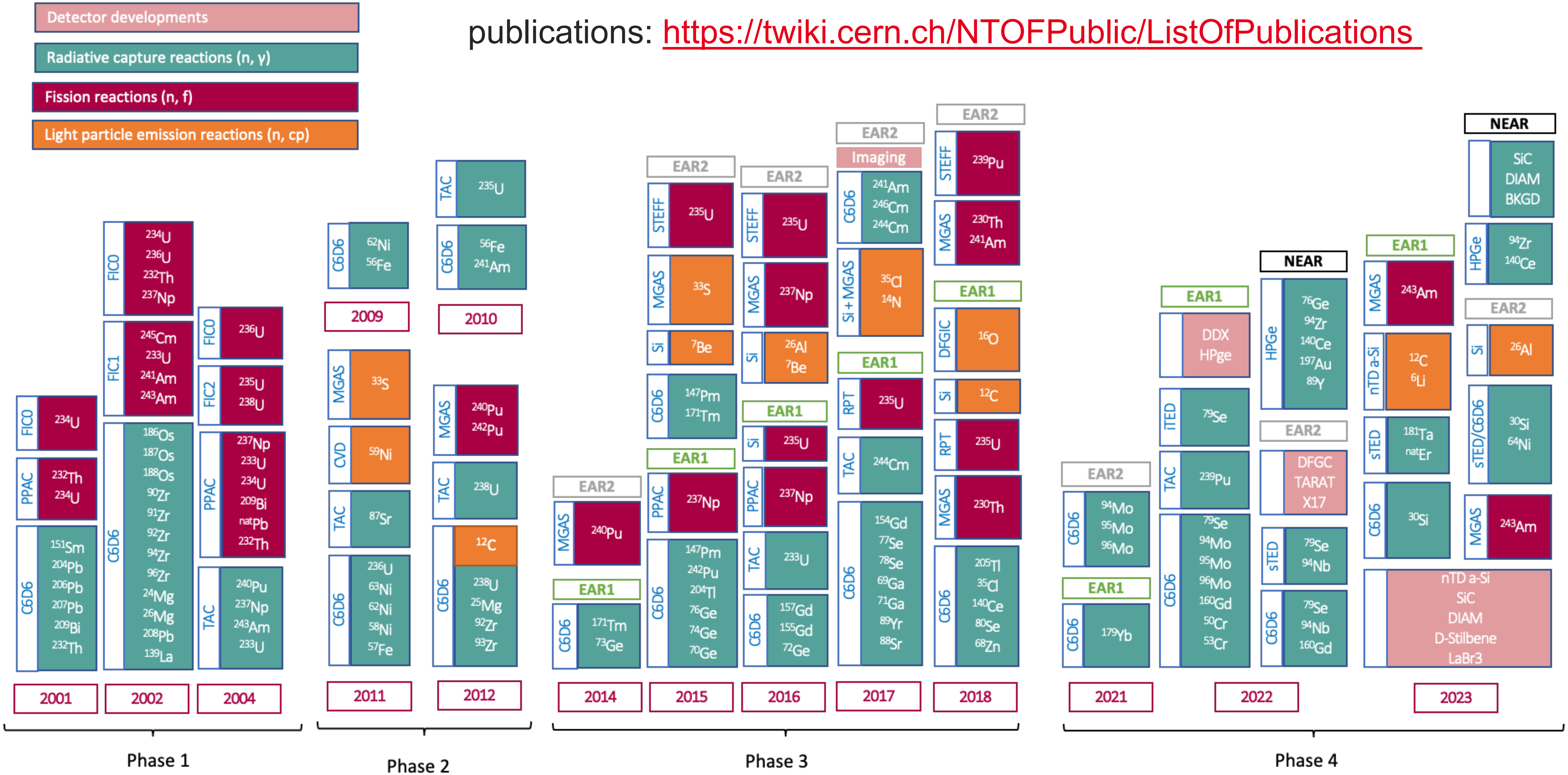
n_TOF at CERN, NEAR

- Irradiation (i-NEAR) and Activation (a-NEAR) Areas
- (almost) no time of flight
- spectrum-integrated cross section measurements

n_TOF, measurements, publications

publications: https://twiki.cern.ch/NTOFPublic/ListOfPublications



n_TOF data dissemination

Target	Reaction	Data Taking	Area	Detector	Energy Range (eV)	Main Reference	Data Status	EXFOR Entry
4-Be-7	(n,p)	Phase-III (2016)	EAR2	Si ΔE-E	2.53E-02 - 3.25E+05	2018 - PRL 121,042701 (arXiv) 2017 - EPJ/CS 146,01012	Final	23399 (full entry in text) 23399 (subentries sorted) O2394 (full entry in text)
4-Be-7	(n,α)	Phase-III (2015)	EAR2	Si	2.53E-02 - 1.00E+04	2016 - PRL 117,152701 (arXiv)	Final	23312 (full entry in text) 23312 (subentries sorted)
6-C-12	(n,p)B-12	Phase-II (2012)	EAR1	C6D6	[1.0E+07 - 1.0E+10]	2016 - EPJ/A 52,101 (arXiv) 2014 - PR/C 90,021601 (arXiv)	Final	23259 (full entry in text) 23259 (subentries sorted)
6-C-12	(n,p) (n,d)	Phase-III (2018)	EAR1	Si ΔE-E	1.50E+07 - 2.50E+07	-	Prelim	-
7-N-14	(n,p)	Phase-III (2017)	EAR2	MGAS+DSSD	2.53E-02 - 1.00E+06	-	Prelim	-
								23163 (subentries sorted)
95-Am-243	(n,γ)	Phase-I (2004)	EAR1	TAC	7.00E-01 - 2.50E+03	2014 - PR/C 90,034608 (arXiv)	Final	23254 (full entry in text) 23254 (subentries sorted)
96-Cm-244	(n,γ)	Phase-III (2017)	EAR2	C6D6	1.00E+00 - 5.50E+02	2019 - EPJ/CS 211,03008	Prelim	-
96-Cm-244	(n,γ)	Phase-III (2017)	EAR1	TAC	7.67E+00	2019 - EPJ/CS 211,03008	Prelim	-
96-Cm-245	(n,f)	Phase-I (2004)	EAR1	FIC1	3.00E-02 - 1.00E+06	2012 - PR/C 85,034616	Final	23168 (full entry in text) 23168 (subentries sorted)
96-Cm-246	(n,γ)	Phase-III (2017)	EAR2	C6D6	1.00E+00 - 5.50E+02	2019 - EPJ/CS 211,03008	Prelim	-

- Full list of experiments and EXFOR status on
  https://twiki.cern.ch/NTOFPublic/DataDissemination

n_TOF at CERN

- CERN's Nuclear Physics activities (including **n_TOF** and **ISOLDE)** well represented in **NuPECC**'s **Long Range Plan 2024** (https://www.nupecc.org/)

- **NuPECC** Nuclear Physics European Collaboration Committee

- **APECC** Astroparticle Physics European Consortium

- **ESPPU** European Strategy for Particle Physics

Conclusion

- **n_TOF** at CERN is a pulsed white neutron source (PS, **20 GeV/c** protons on lead, pulse width **6 ns**, rep. rate **1.2 s**, water moderated).
- Wide neutron energy range available for science, spanning 11 orders of magnitude, from meV to GeV.
- Operational since 2001, collaboration of 130 members from 40 countries
- Very high instantaneous (per pulse) neutron flux, favorable signal/noise ratio for radioactive samples
- Today, **n_TOF** is one of the largest contributors to experimental nuclear data, with a solid publication track record
- **FCC-ee** could drive a new additional neutron source, or a possible successor of **n_TOF** in case of discontinuation of CERN's PS, with specifications depending on beam power, pulse width and repetition rate.
- First simulations (V. Vlachoudis) confirm a R=20 cm, H=50 cm cylinder of Pb, W or U, fully absorbs the e-beam up to 20 GeV and gives a neutron yield scaling with beam power.