The future of nuclear data measurements at n_TOF, CERN

On behalf of the n_TOF Collaboration
Frank Gunsing

CEA Irfu, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

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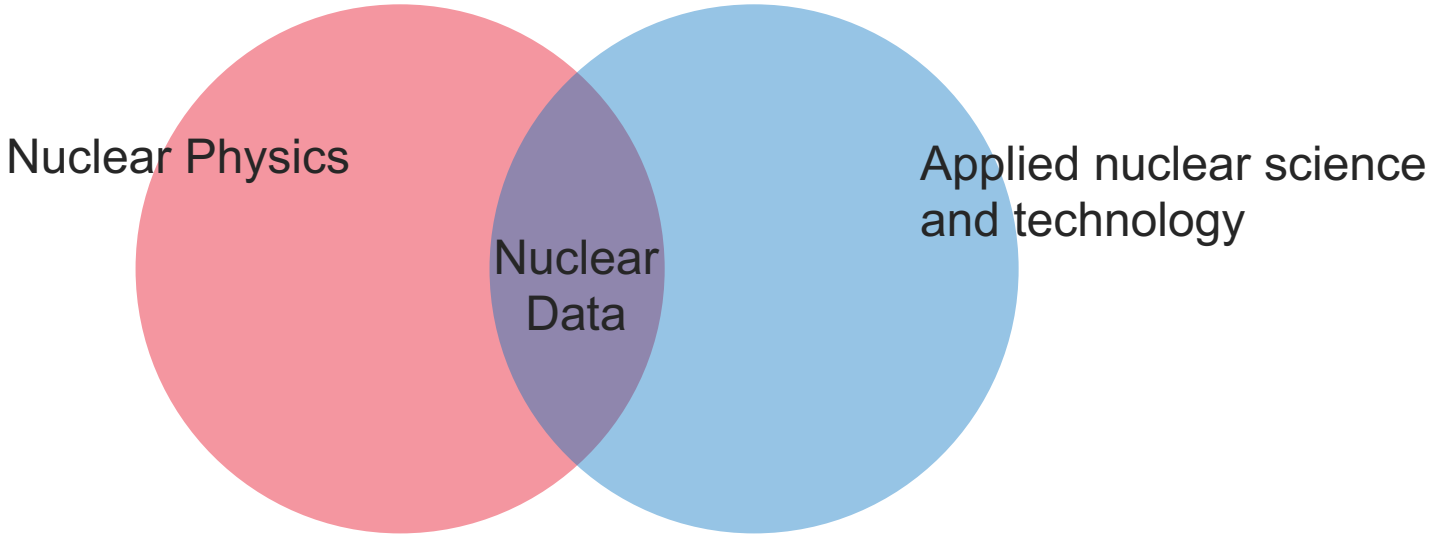
Much has already been covered by yersteday's presentation by **A. Manna**

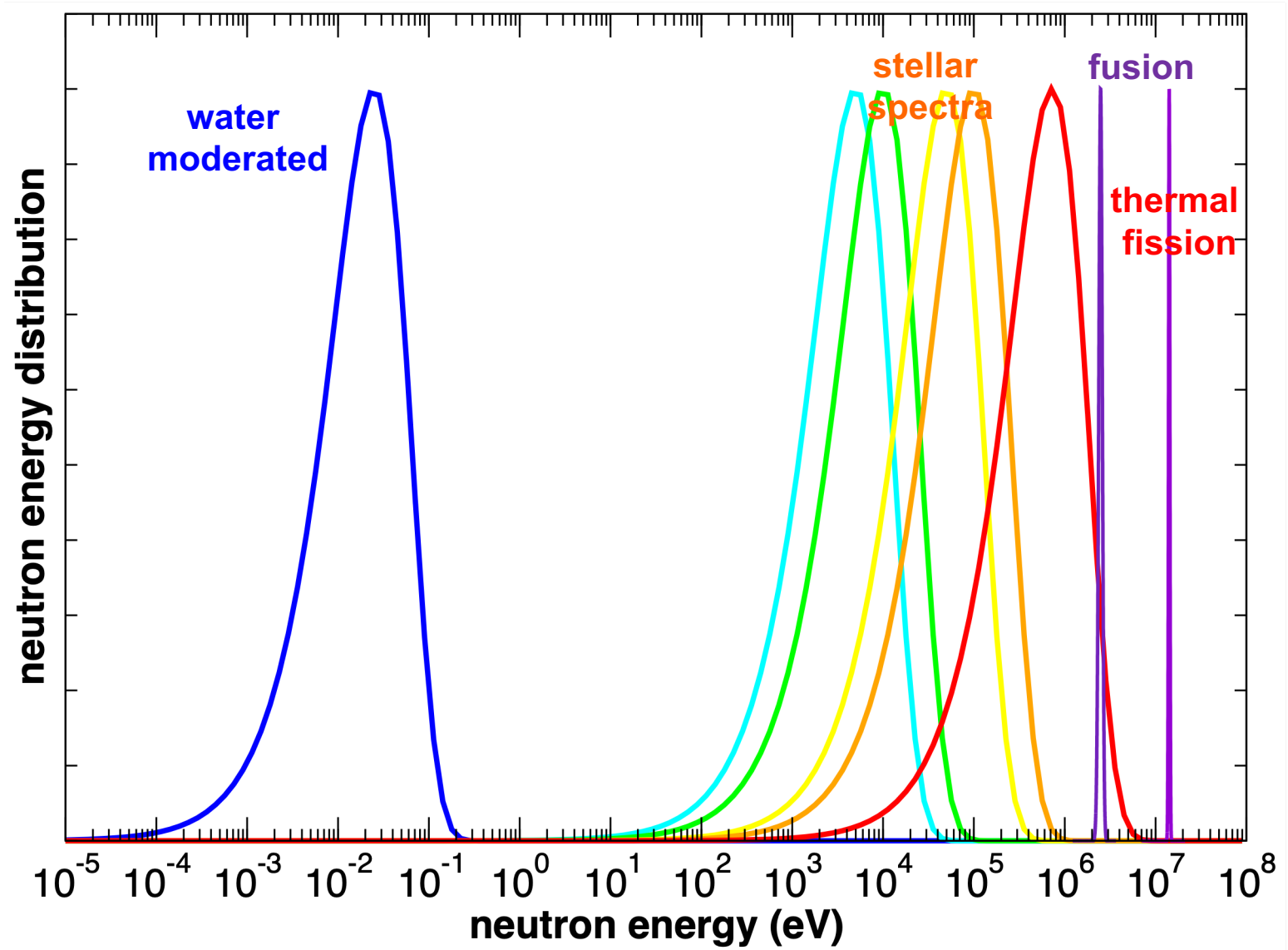
Nuclear Data – Nuclear Physics



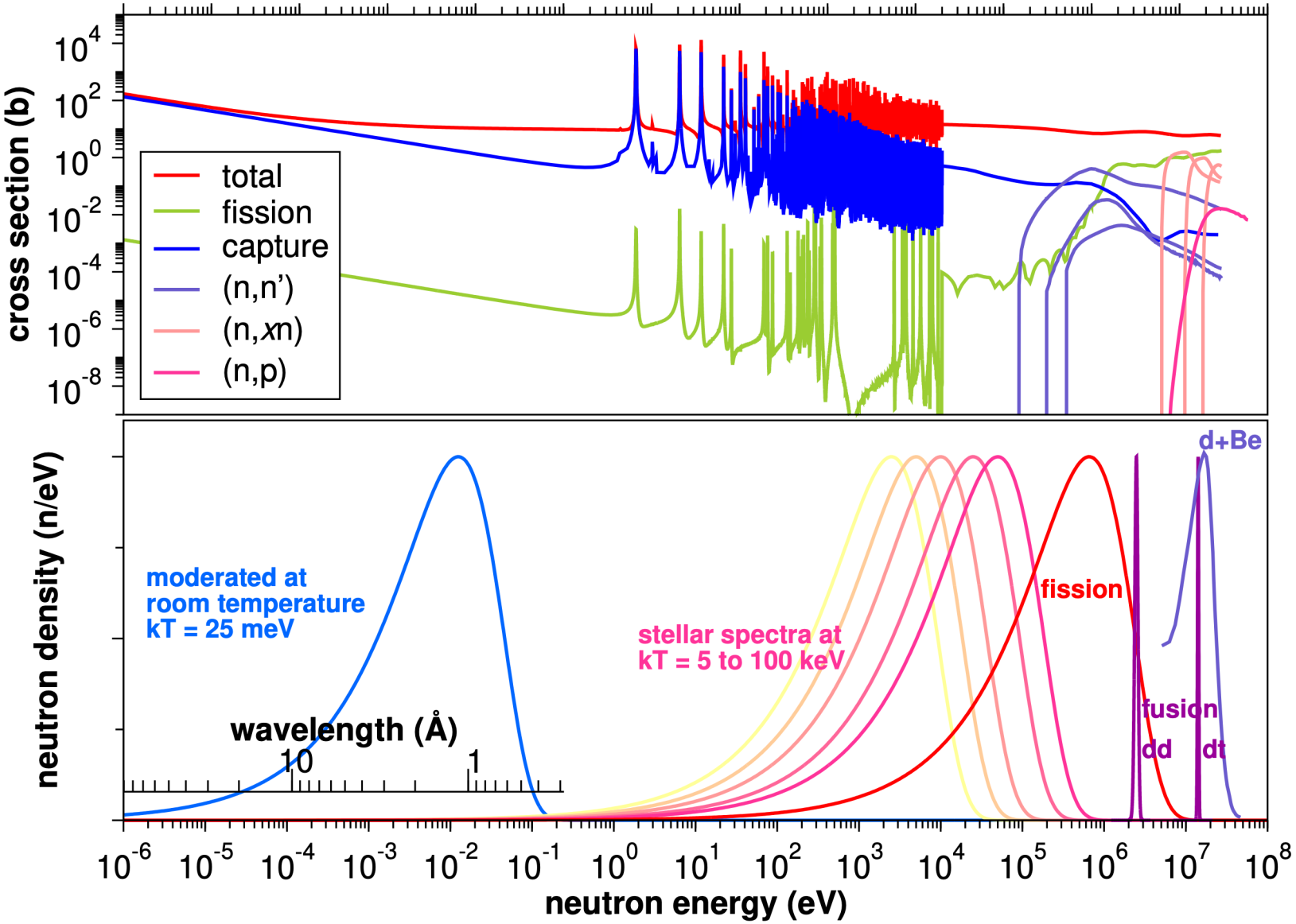
- Nuclear Data are at the intersection of nuclear physics and applied nuclear science and technology
- Includes cross sections, angular distributions, mutliplicities, fission yields, decay data
  - experimental data feed **experimental databases** for reactions (EXFOR) and structure (XUNDL)
  - which in their turn are used as input for evaluated nuclear data, ENDF (reactions) and ENSDF (structure)
- Neutron-induced cross sections have a central position in Nuclear Data

Neutron distributions

- Maxwell-Boltzmann distributions, conveniently scaled

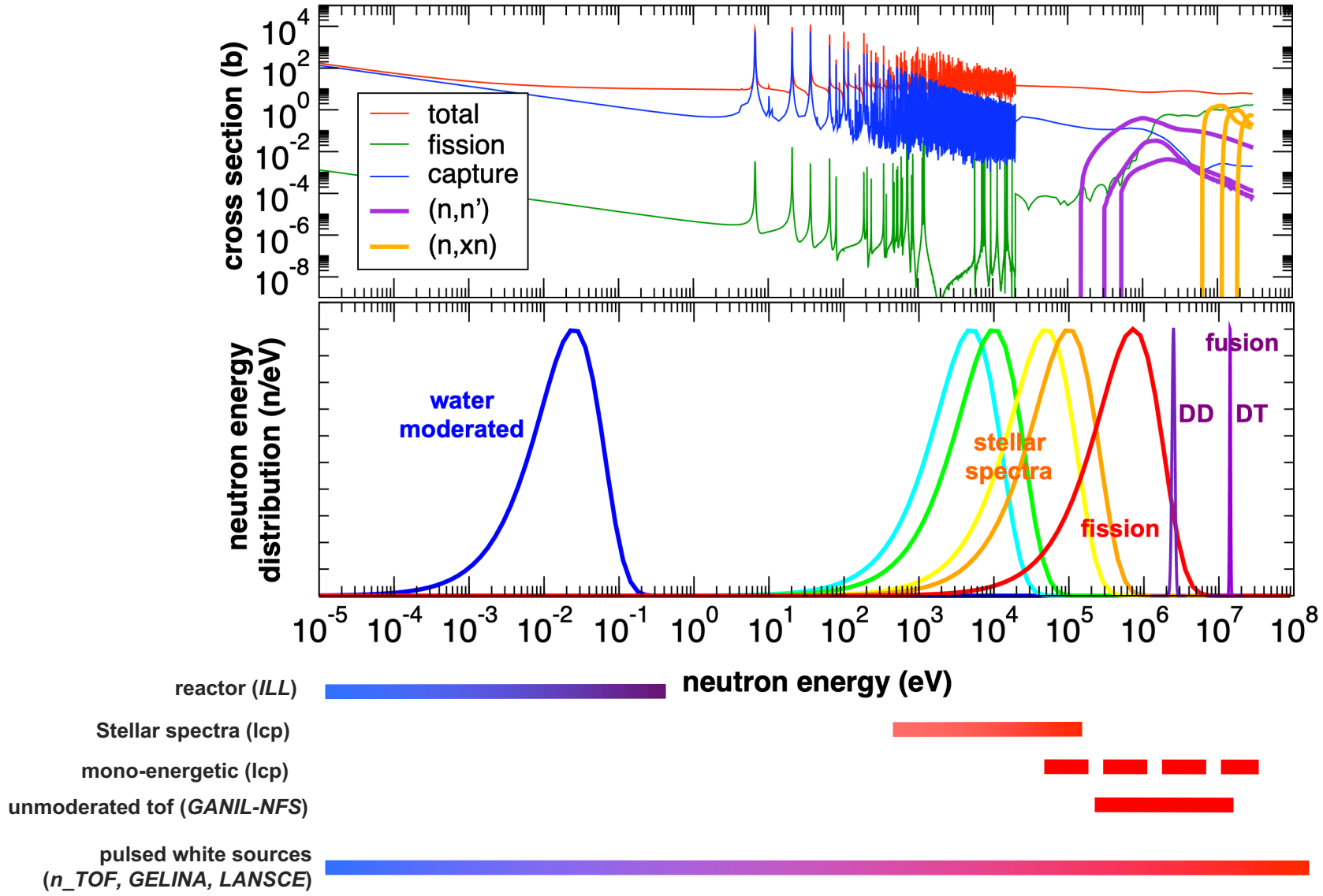


Neutron-induced reactions, nuclear data



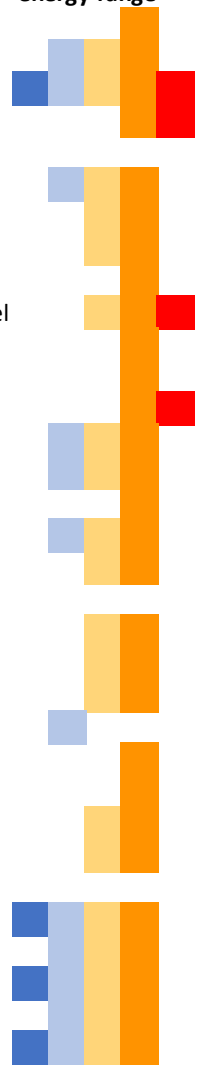
- Eur. Phys. J. Plus 133 (2018) 440
- NuPECC LRP2024

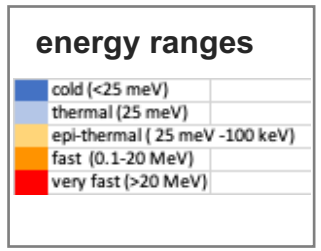
Neutron-induced reactions, nuclear data



European neutron facilities for nuclear physics

	facility	Institute
dedicated time of flight	nELBE	HZDR
	GELINA	JRC-Geel
	n_TOF	CERN
	NFS	GANIL Caen
p, d on light targets (p,D,T, Li,Be,C,N)	MONNET	JRC Geel
	AIFIRA	CNRS Bordeaux
	ALTO	CNRS Orsay
	GENESIS	CNRS Grenoble
	VdG	CEA, Bruyères-le-Chatel
	FNG	ENEA-Frascati
	PIAF	PTB Braunschweig
	FNG	UJF/NPI-Rez
	HISPANoS	CNA Sevilla
	VdG	NPL Teddington
	AMANDE	IRSN Cadarache
	CARAT	IRSN Cadarache
	Demokritos	NCSR Athens
upcoming	IFMIF-DONES	CIEMAT, U-Granada
	NEPIR	LNL Legnaro
	SPES, BELINA	LNL Legnaro
	AB-BNCT	INFN-Caserta
	JYFL	JYU Jyvaskyla
	NESSA	UU Uppsala
	FRANZ	Goethe U- Frankfurt
	SARAF-II	Soreq
reactor	BRR	MTA EK Budapest
	BR1	SCK-CEN Mol
	Triga	JGU Mainz
	LR-0/LR-15	CVR Rez
	RHF	ILL Grenoble





Information from
- ARIEL
- EuroLabs
- NuPECC

Pulsed white neutron sources, world-wide

Facility	Location	Beam	Energy (MeV)	Target	Pulse width (ns)	Beam power (kW)	rep. rate (Hz)
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
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	Lund, Sweden	p	2 000	W	2860	5000	14
SNS	Oak Ride, USA	p	1 000	Hg	700	1400	60
ISIS-TS1	Oxfordshire, UK	p	800	W	100	240	50
CSNS	Dongguan, China	p	1 600	W		100	25
NFS	GANIL, Caen, France	d	40	Be	<0.5	2	150k–880k

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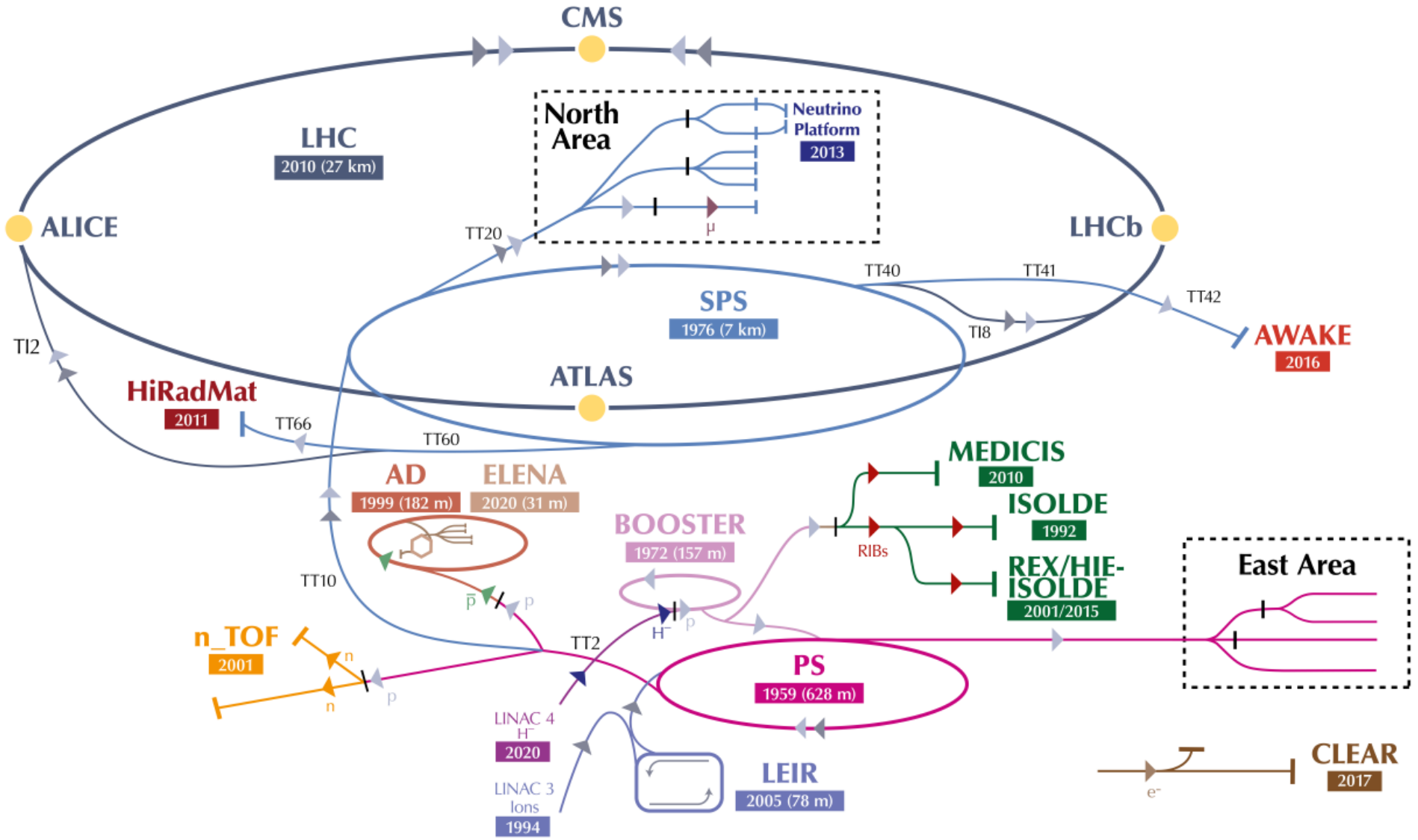
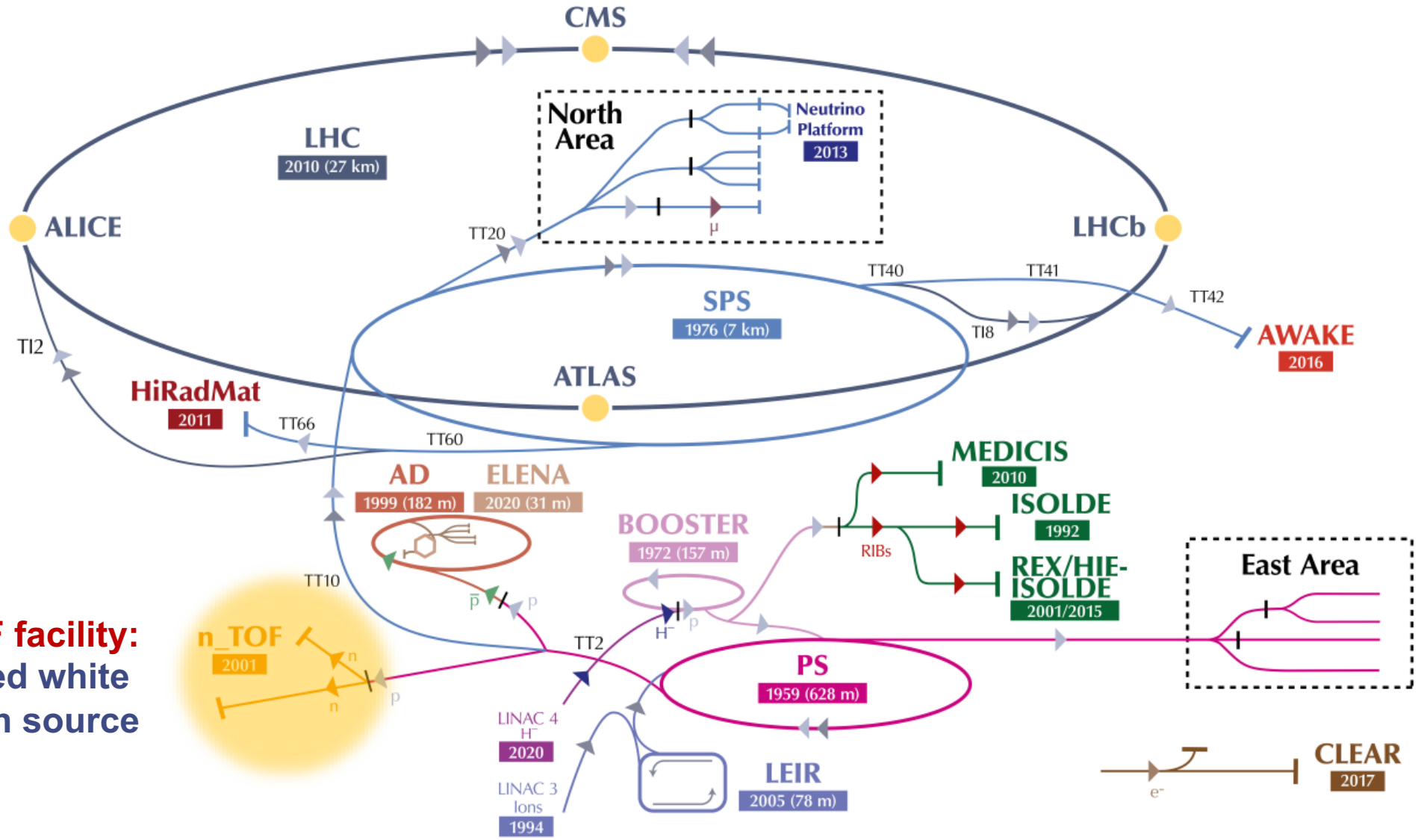
CERN accelerator complex

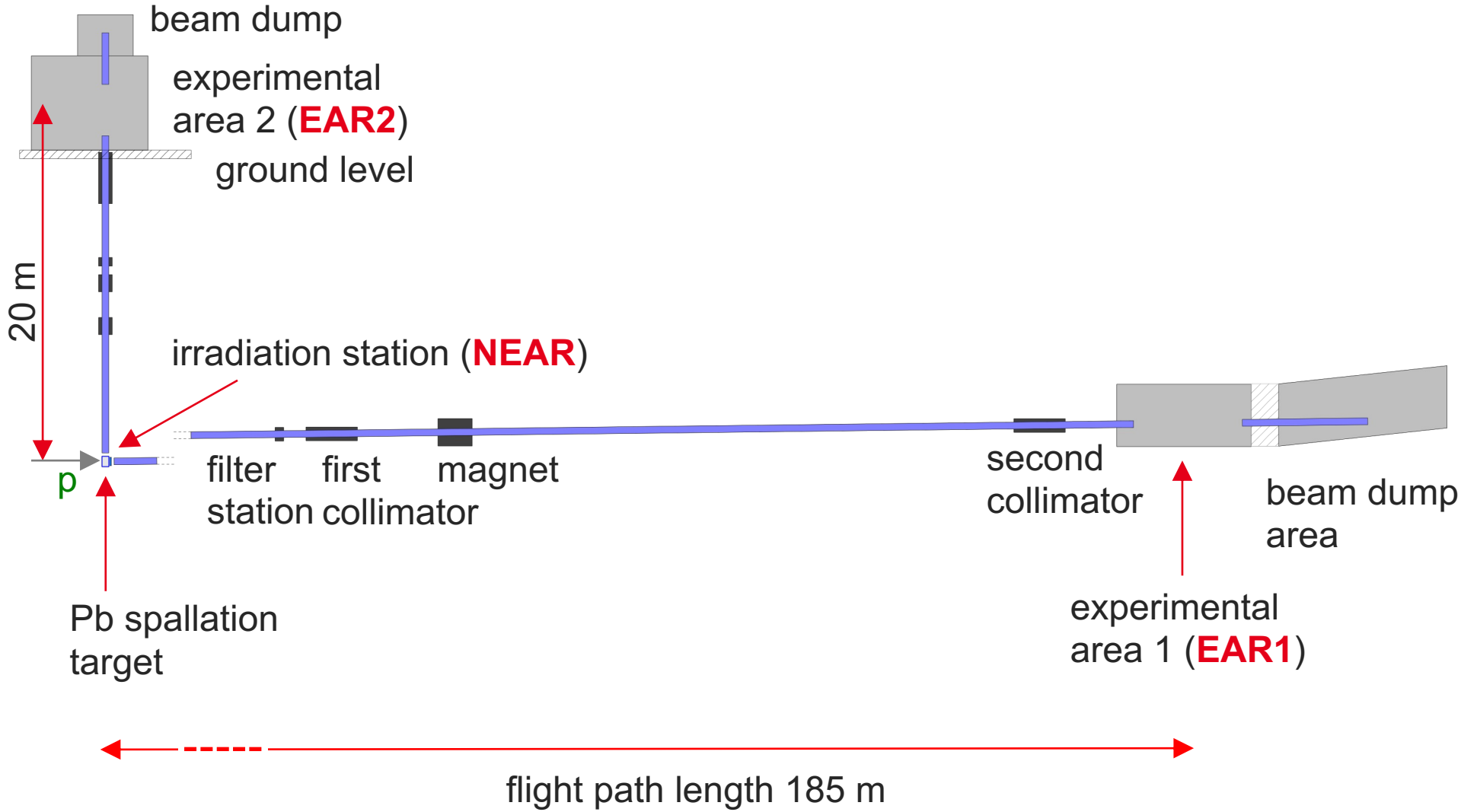


CERN accelerator complex



n_TOF facility:
a pulsed white neutron source

n_TOF at CERN



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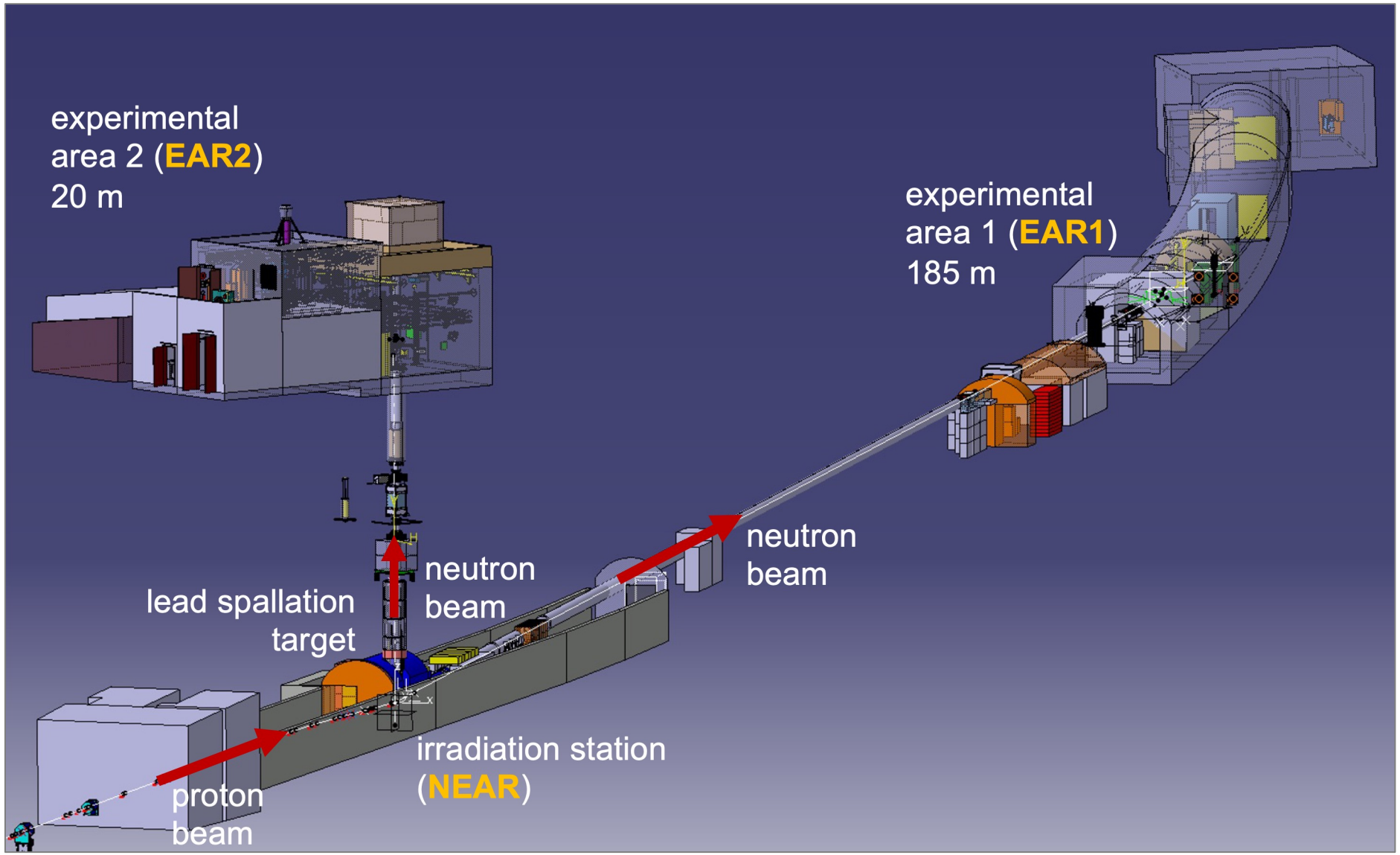
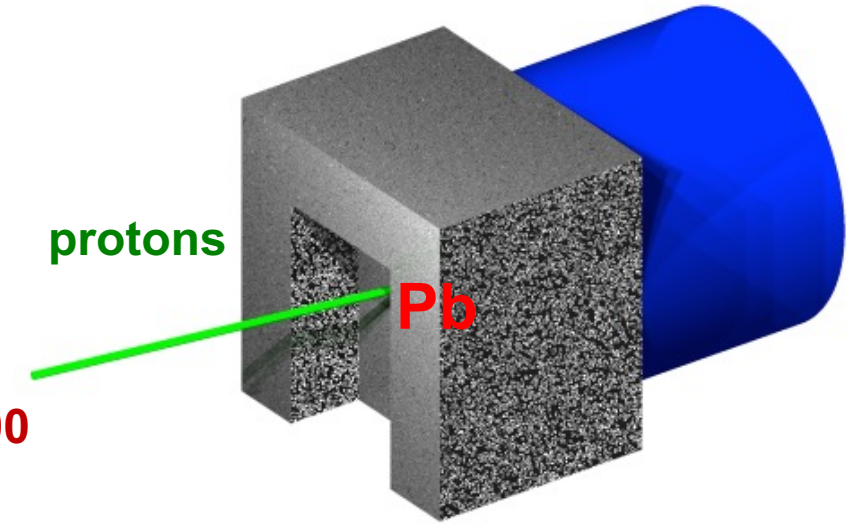
n_TOF at CERN


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

Spallation target 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: 7×10^{12} protons/pulse
- @source: 2×10^{15} neutrons/pulse
- @EAR1: $5 \cdot 10^{5}$(capture) – $5 \cdot 10^{7}$(fission) neutrons/pulse



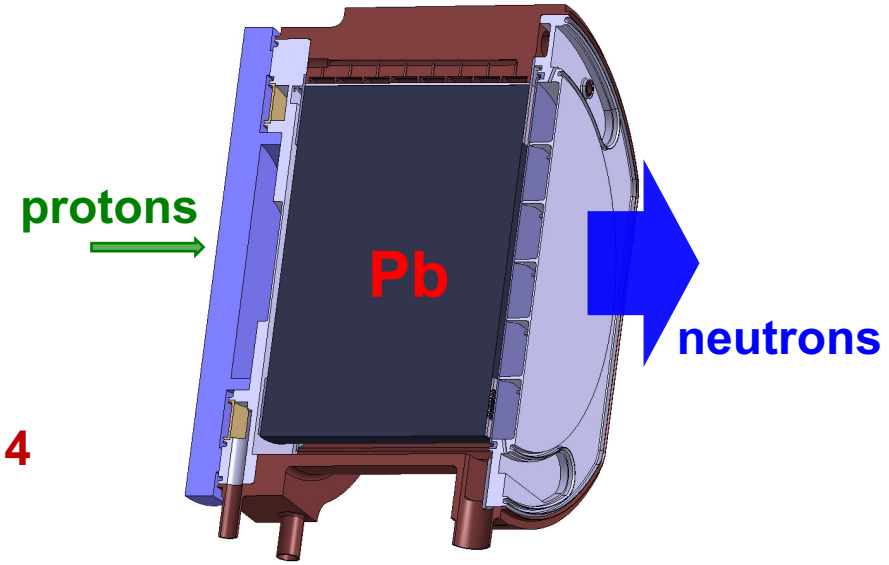
phase I target
2001-2004

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)

Spallation target 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



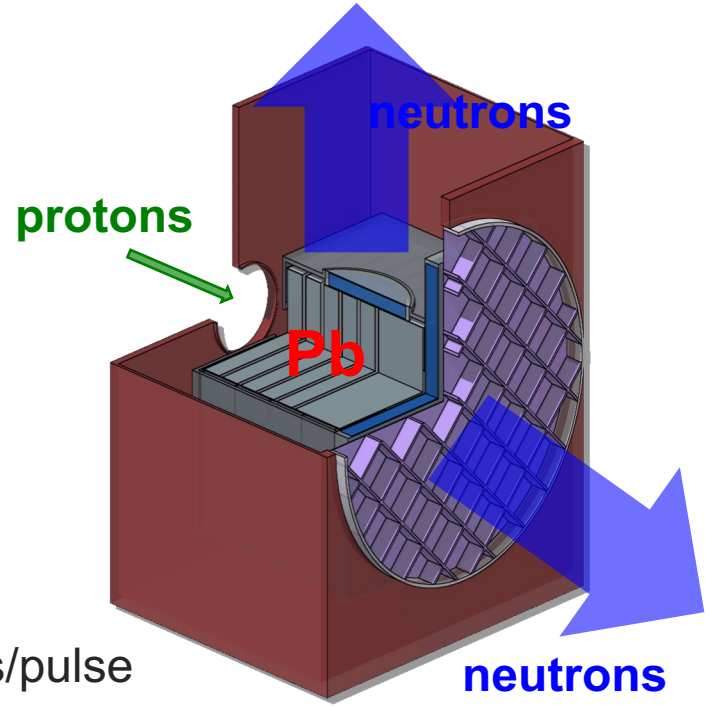
phase II-III target
2009-2018

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

Spallation target 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

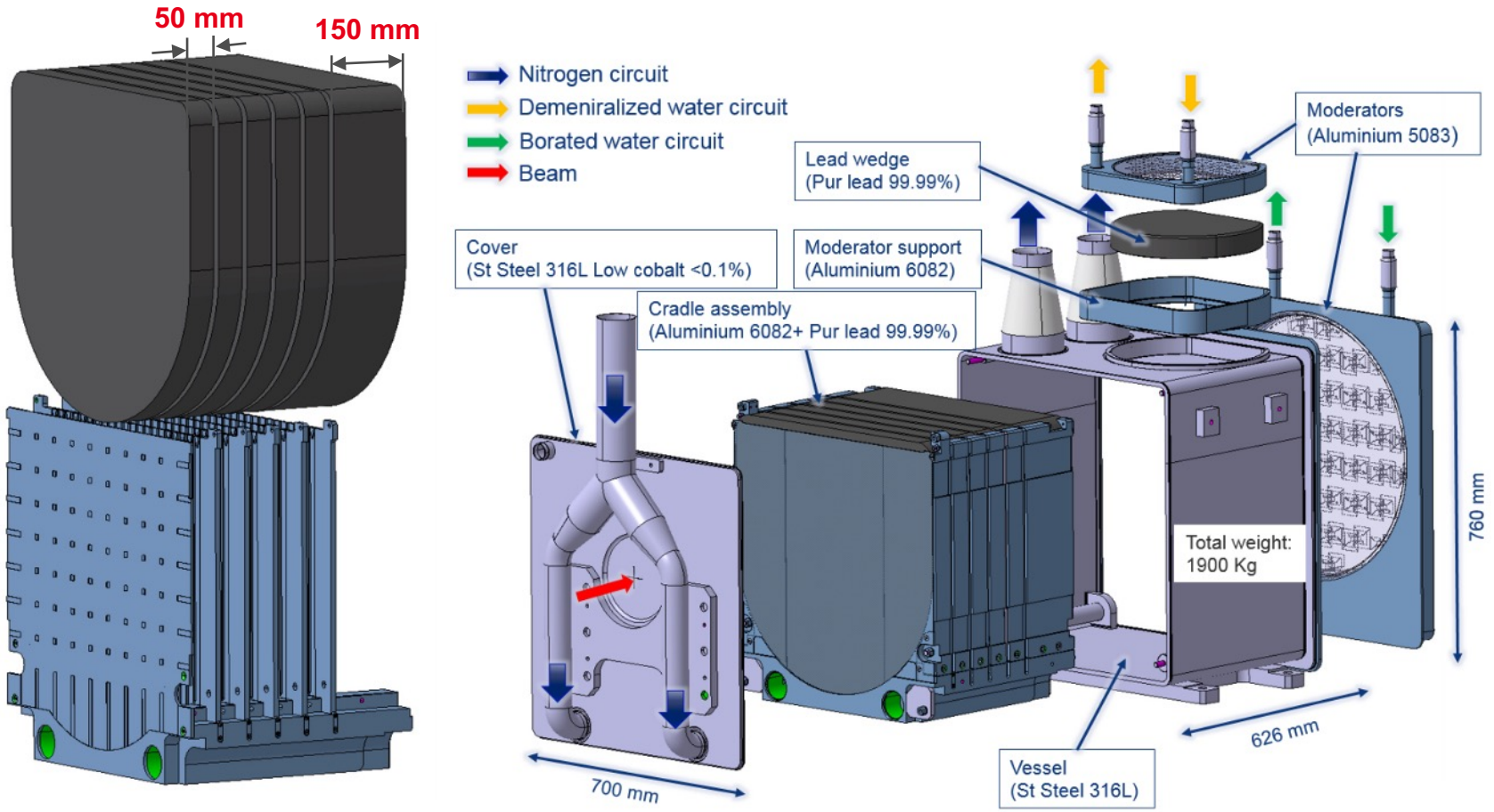


Main features:
- Large energy range available (0.01 eV – 1 GeV)
- Favorable signal to noise ratio for capture on radioactive isotopes (actinides, fission products)

phase IV target, N_2-cooled since 2021

Only moderator contains water

Spallation target n_TOF at CERN

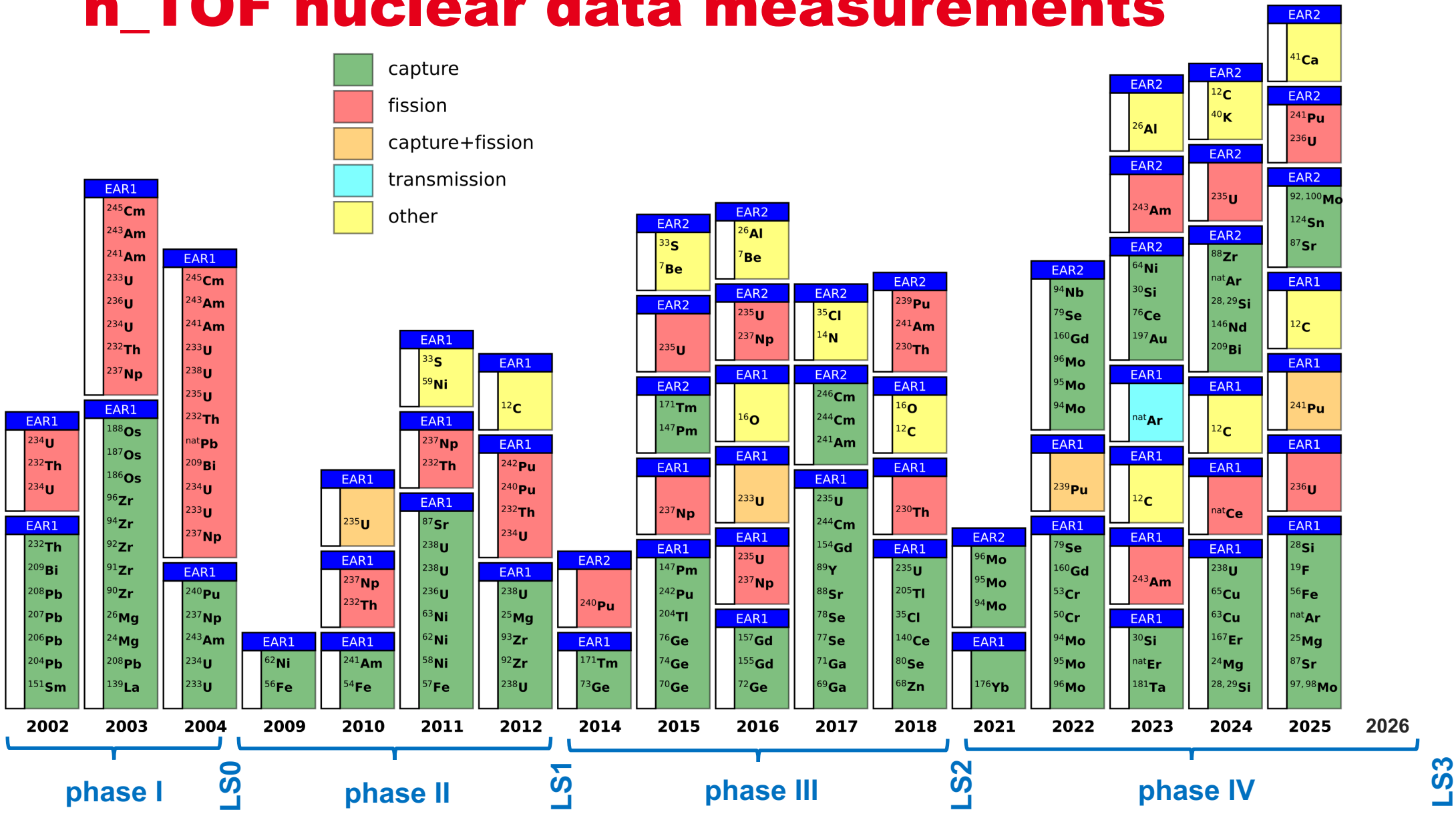


Al-6082-T6 supporting structure
(anti-creep and N_2 cooling channels)

5.4 kW (average)

ref: EDMS 2378651

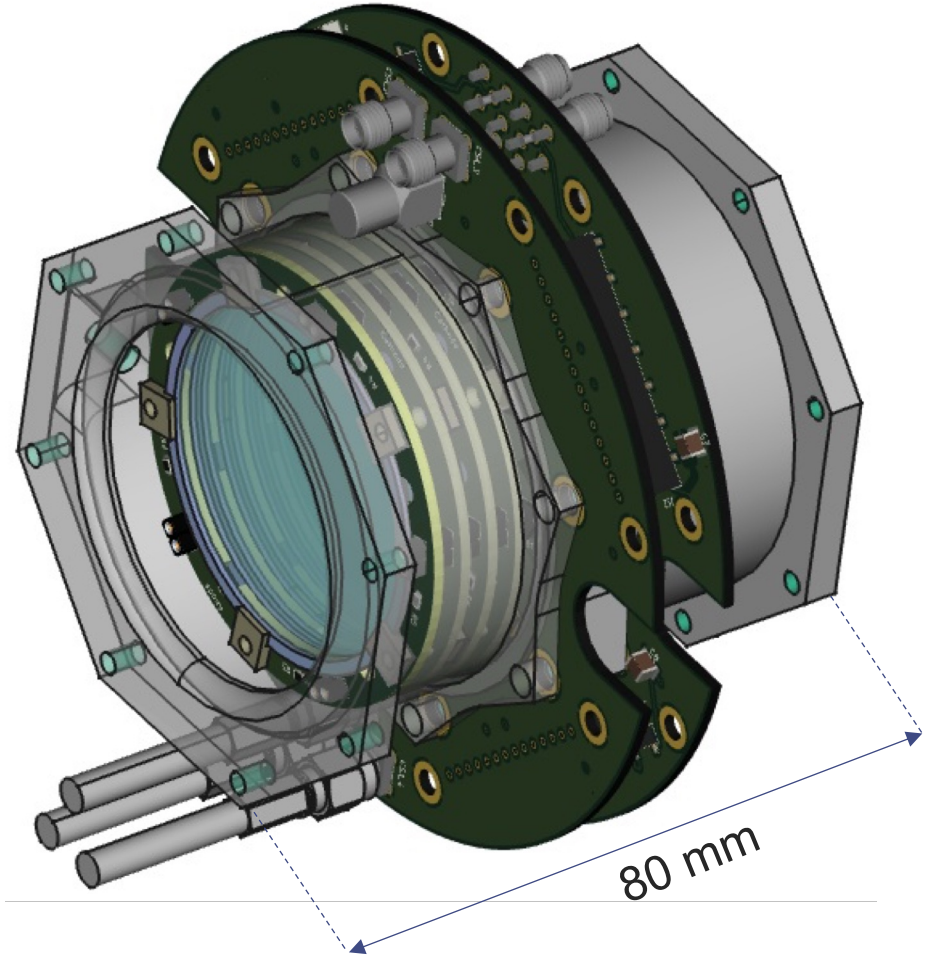
n_TOF nuclear data measurements

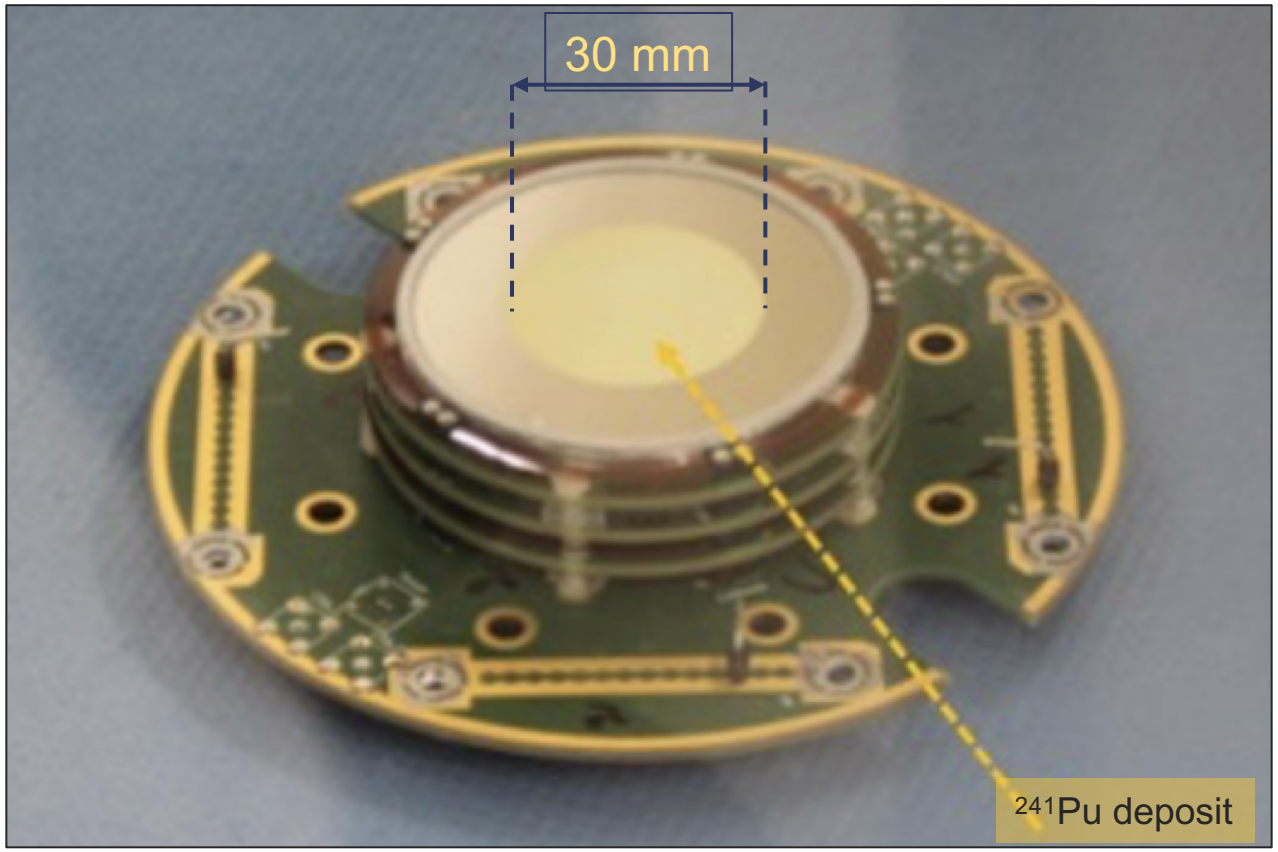


Example: ^{241}Pu capture and fission

- Initial contours of this project started in 2021
- Highly radioactive, ^{241}Pu decays to ^{241}Am (β^-, $T_{1/2}$ = 14 y), only one existing capture measurement (Weston and Todd 1978)
- Search for suitable sample material, including sample preparation, lead to JRC-Geel.
  Raw material from the 1970s available.
- A complex chemical sequence of purification to remove ^{241}Am, then ^{237}Np, and then residual uranium, was performed at JRC-Geel in collaboration with CEA DAM/DIF.
- Final samples: 8 deposits of 30 mm diameter of ^{241}Pu (54% enrichment),
  total mass **^{241}Pu 5.9 mg**, (total Pu 10.9 mg), activity β^- 23 GBq, α 34 MBq
- Design of new compact fission chamber, using fast electronics developed at DAM/DIF
- Fission chamber fits in the 4π total absorption calorimeter TAC at n_TOF
  - measurement done at n_TOF **EAR1** (L=185 m) and **EAR2** (L=20 m) in 2025
  - measurement ongoing at JRC-Geel (L=10 m)

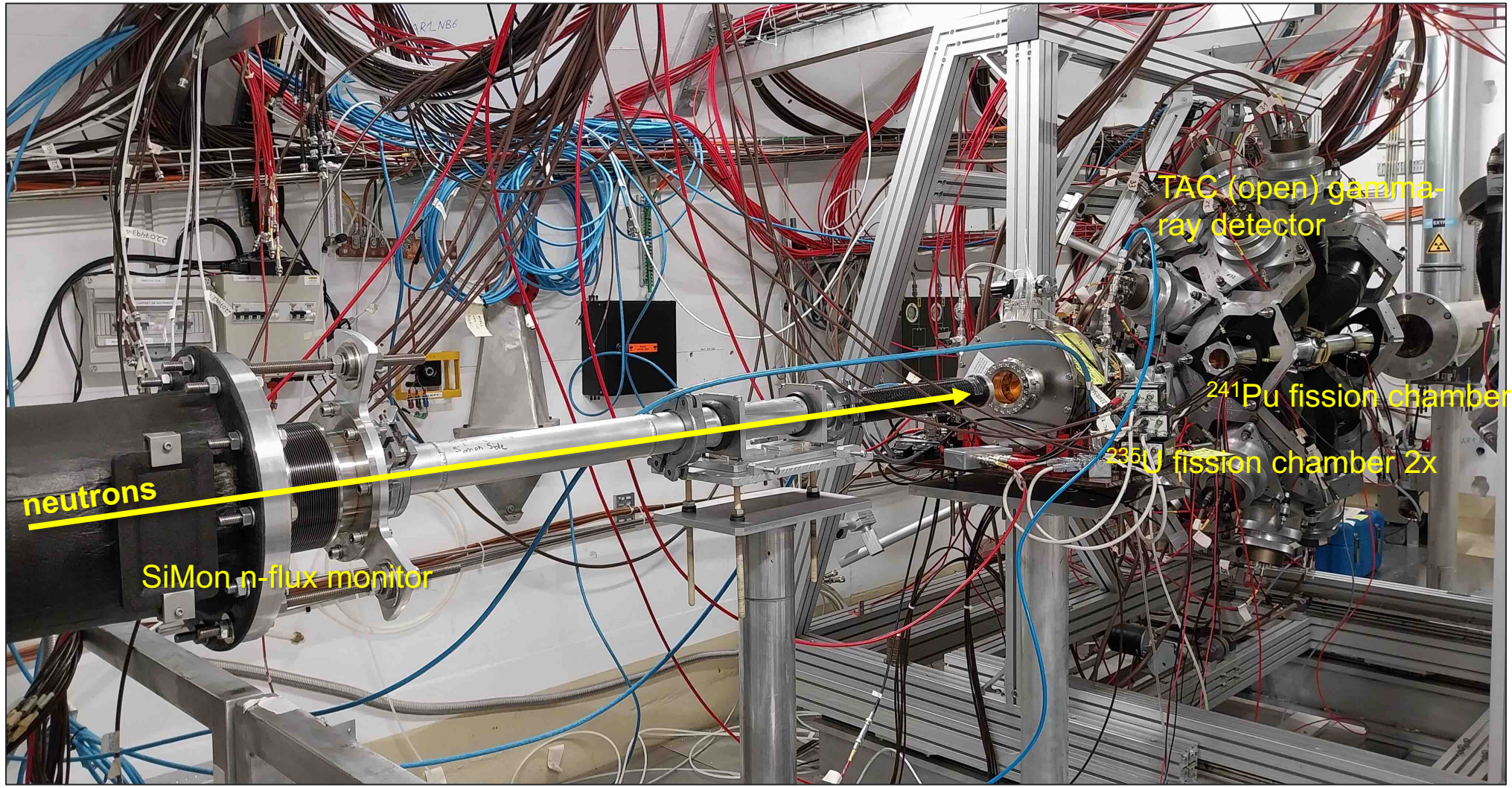
^{241}Pu fission chamber



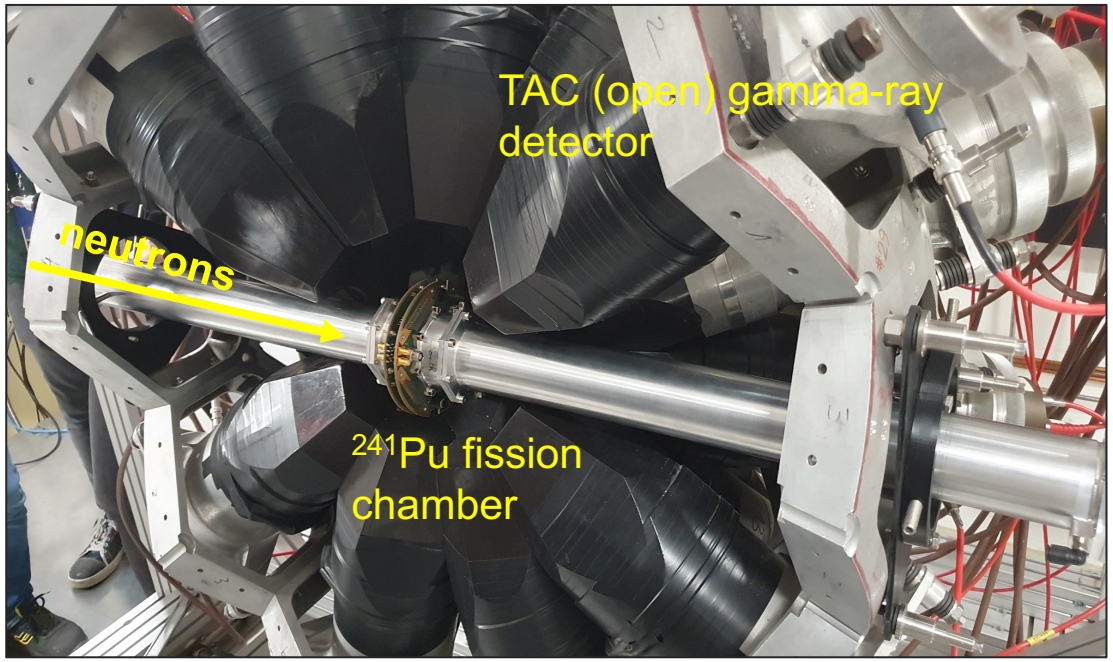


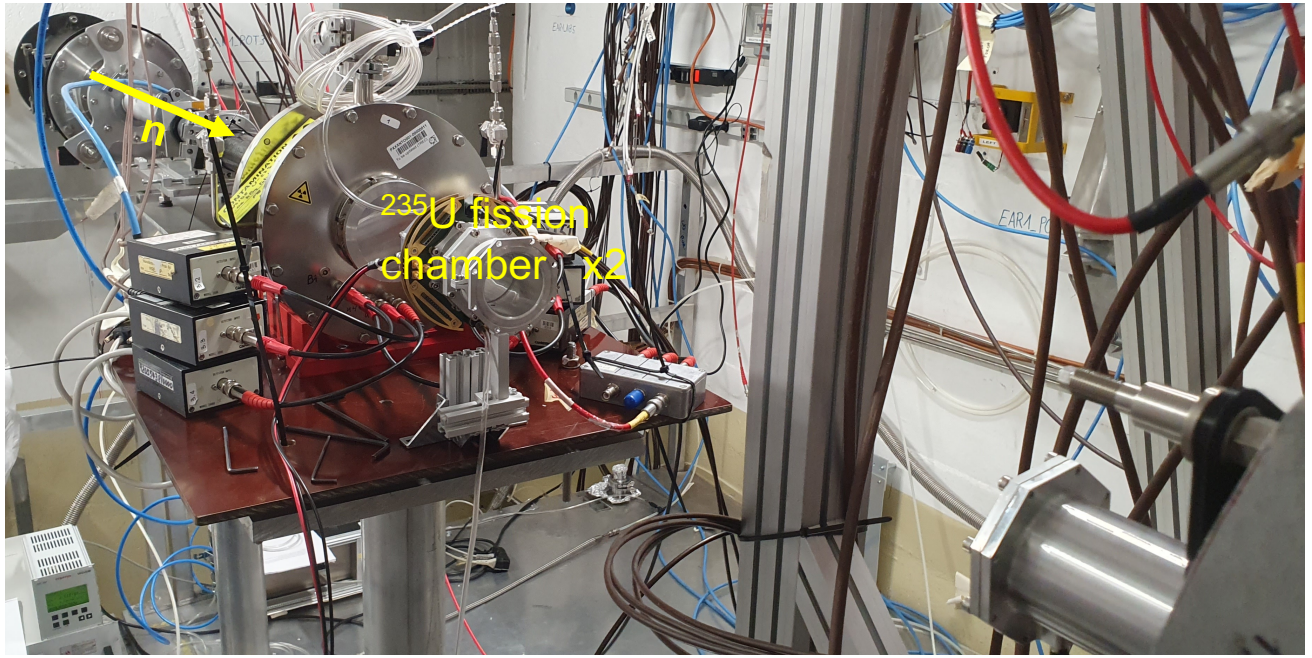
final design: E. Berthoumieux

^{241}Pu experiment at n_TOF EAR1



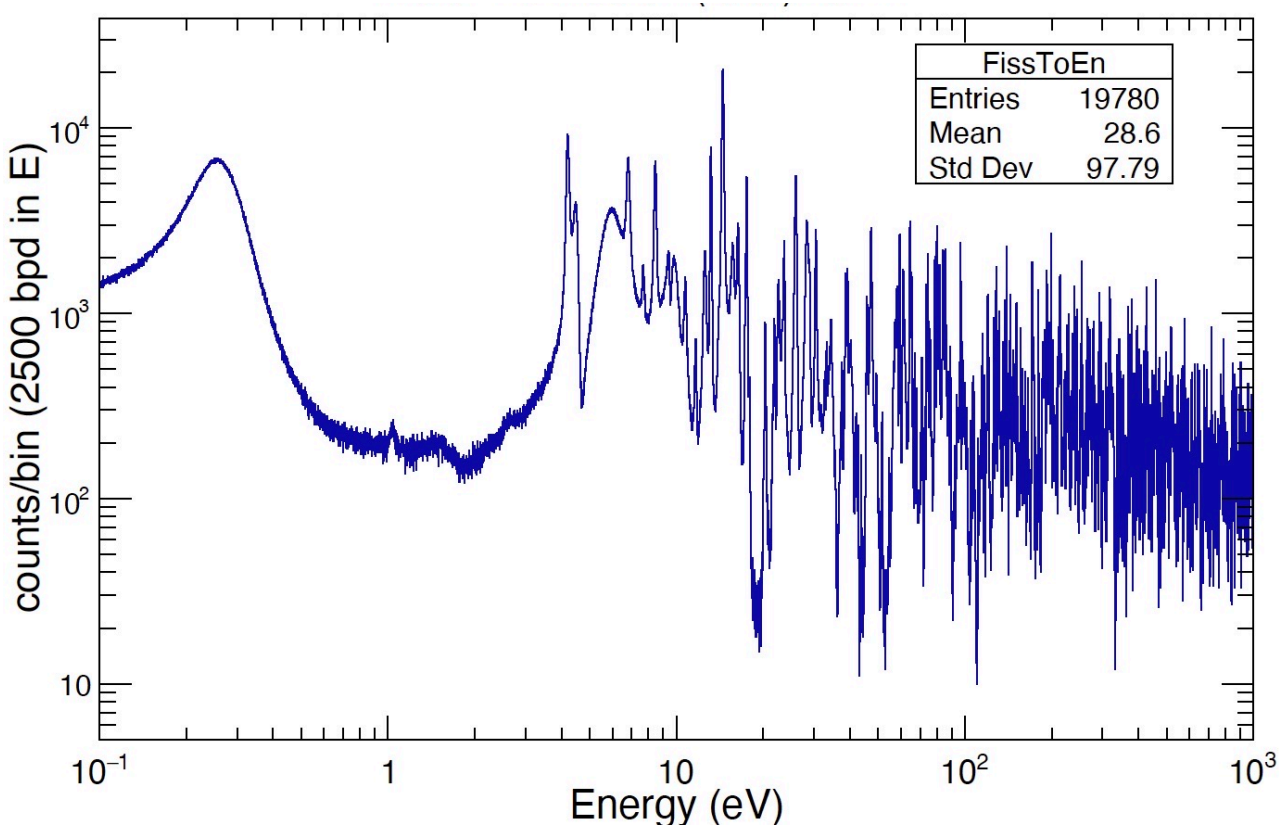
^{241}Pu experiment at n_TOF EAR1



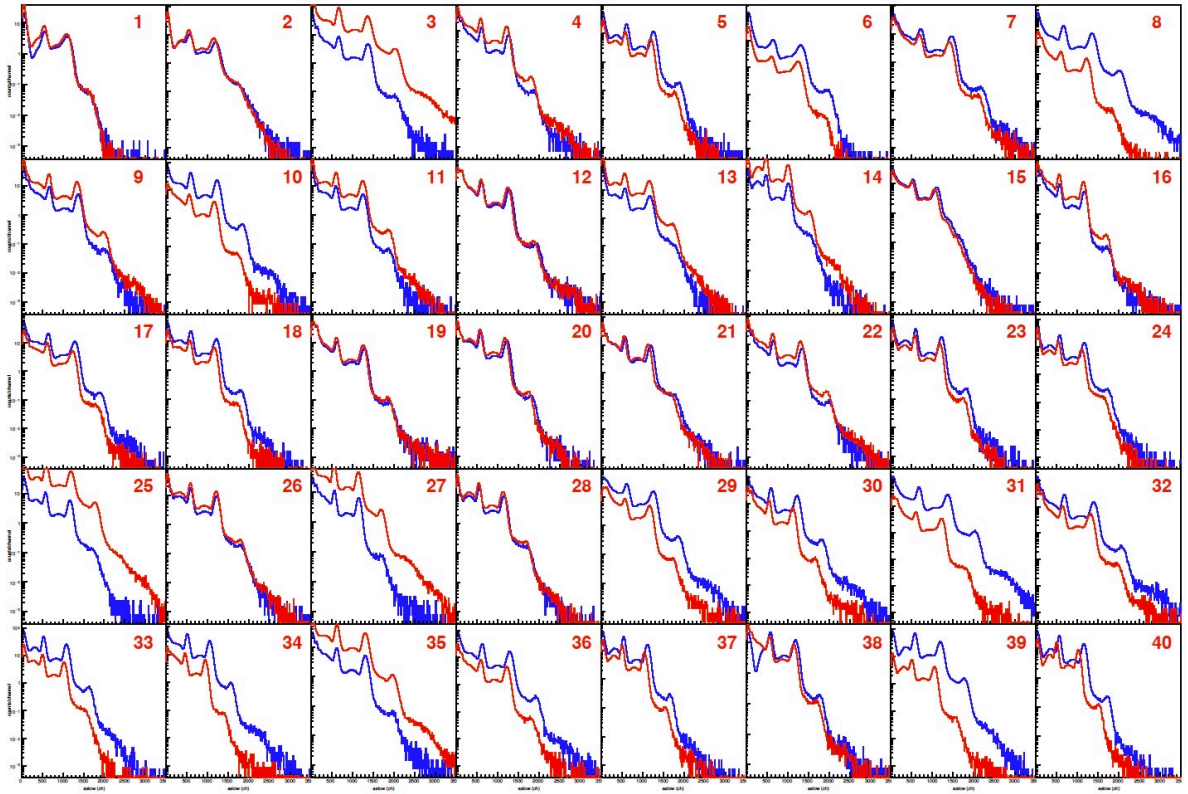


^{241}Pu experiment at n_TOF EAR1

fission chamber respons to neutrons



TAC response to ^{88}Y calibration source



PhD A. Cahuzac

^{241}Pu experiment at n_TOF EAR2

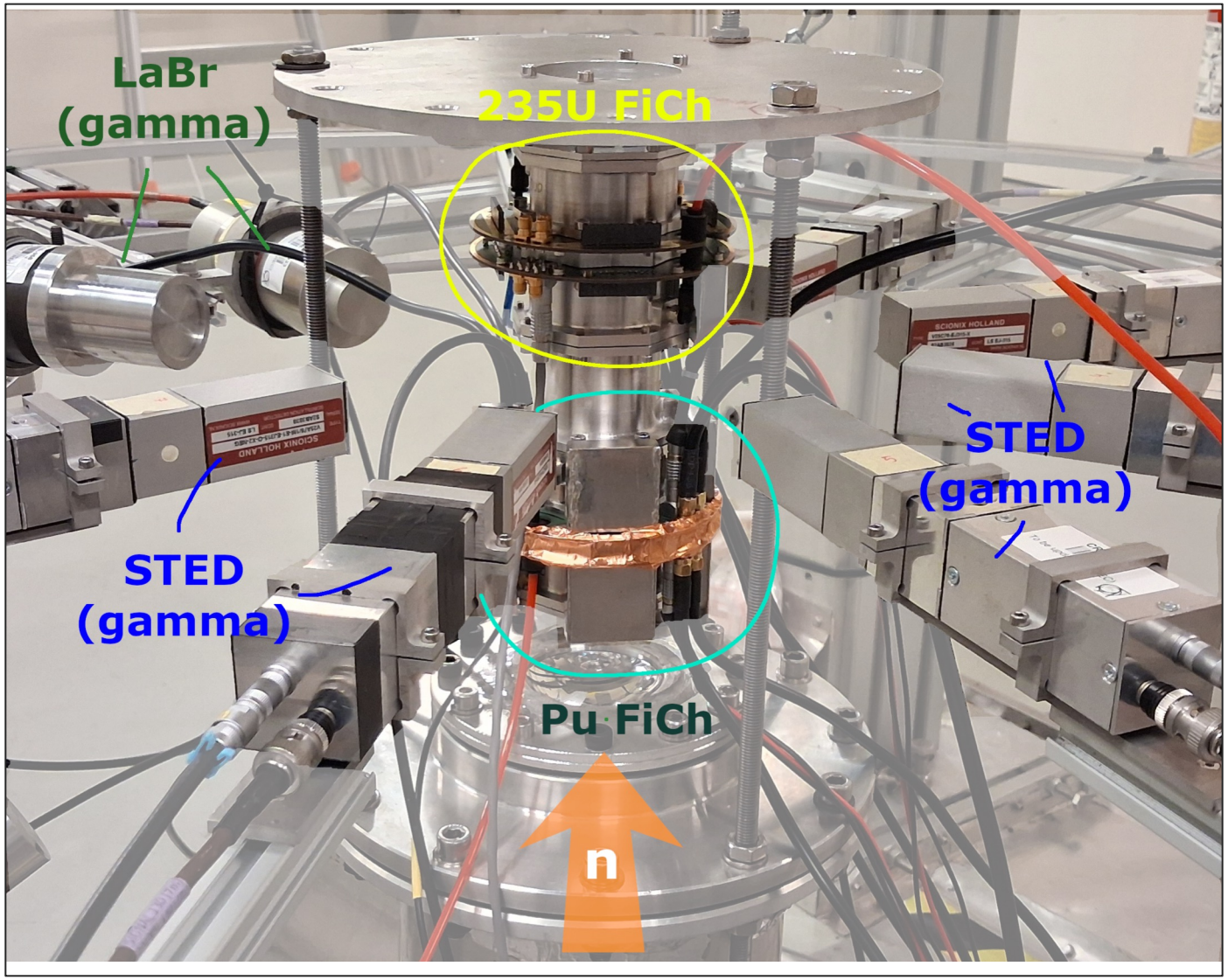
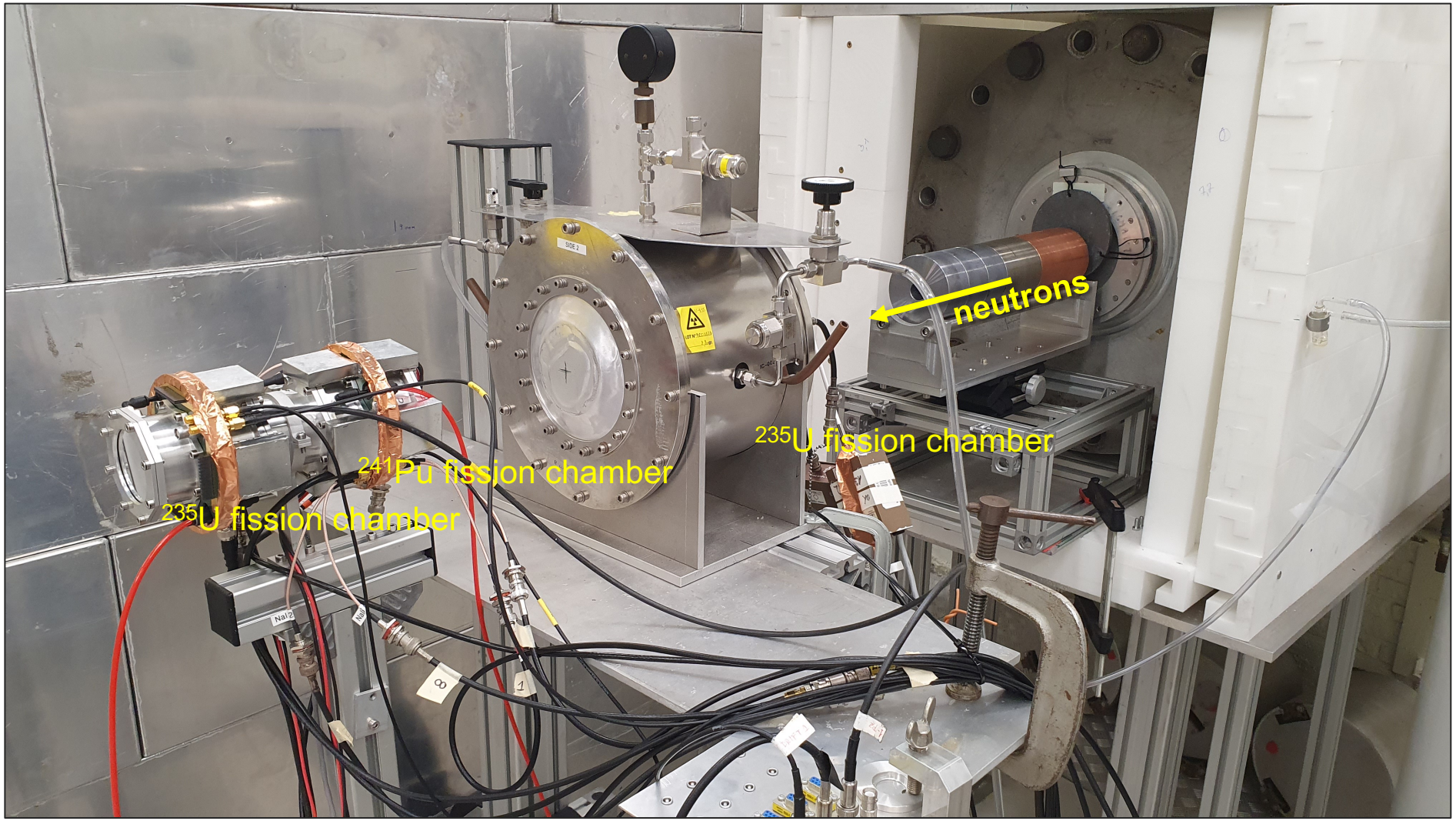


fig. A. Cahuzac

^{241}Pu experiment at JRC-Geel



Neutron-induced reactions at n_TOF - CERN

- **time-of-flight** measurements at **EAR1** and **EAR2**,
  - reaction cross sections $\sigma(E_n)$
  - (double) differential cross sections $d\sigma(E_n)/d\Omega$ $d\sigma(E_n)/dE_{out}$ $d^2\sigma(E_n)/d\Omega dE_{out}$
  - nuclear structure/reaction quantities
    level densities and **photon strength functions**

- **integral** quantities, flux-integrated cross sections $\int\sigma(E)\phi(E)dE$ measured by activation / transmutation at **NEAR** and the upcoming **BDF** (see later)

- Developments for detectors and experimental techniques, in support of nuclear data measurements

- Collaboration with more than 150 members from 40 countries

Neutron-induced reactions at n_TOF - CERN

- **n_TOF** is about **Nuclear Data**, in particular experimental **neutron-induced reaction data**, for
  - nuclear technology
  - nuclear astrophysics
  - nuclear science

- In addition, various detector developments, and non-nuclear data measurements (e.g. imaging)

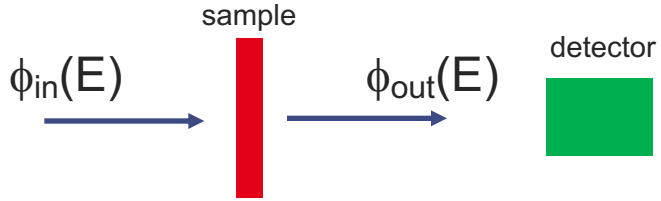
- Nuclear data measurements since 2001
  - neutron capture **(n,γ)**
  - neutron fission **(n,f)**

- Since several years also
  - light charged-particle emission **(n,α), (n,d), (n,p)**
  - total cross section σ_{tot} (sum of all partial reactions)

- Under development or on wish list
  - elastic scattering **(n,n)**
  - inelastic scattering **(n,n')** → **(n,n'γ)** γ-spectroscopy
  - neutron emission **(n,xn)** → **(n,xnγ)** γ-spectroscopy

Example: Transmission measurements

- The total cross section is an essential complementary quantity for the analysis of capture measurements, in particular for nuclei with large scattering cross sections.
- Is measured in terms of transmission: the neutron flux ratio with “sample in” over “sample out”

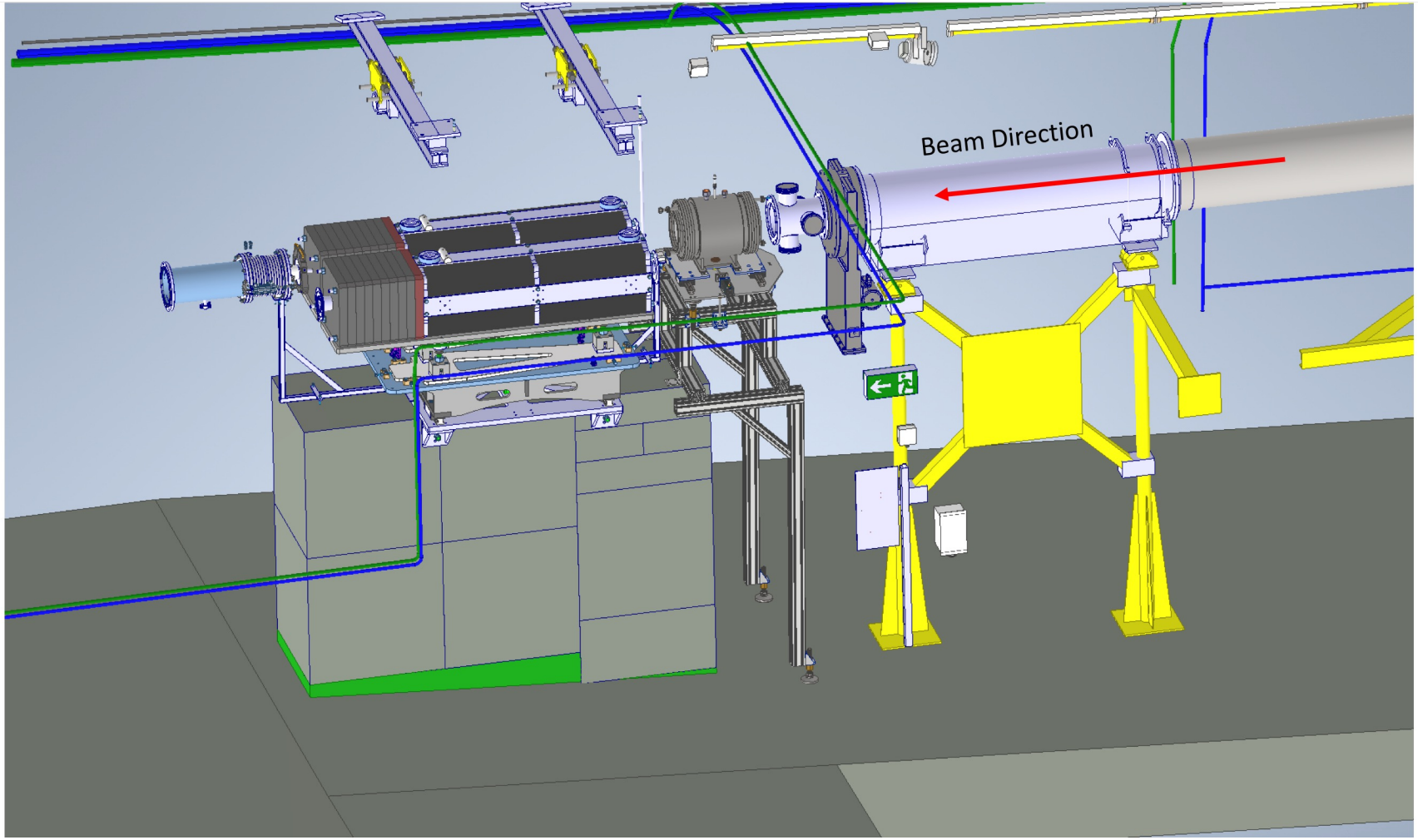


- Due to strong gamma flash at n_TOF, a compromise must be found between detection efficiency and gamma-flash sensitivity. Eventually, a low mass fission chamber is used
- Initial tests have been performed with high-pressure, gaseous ^{nat}**Ar**. Upgraded in 2025 with a dedicated transmission station with capability of cry-targets (**L-Ar**). Also used for conventional targets (^{nat}**Cu**).
- Improvement of transmission setup foreseen during LS3

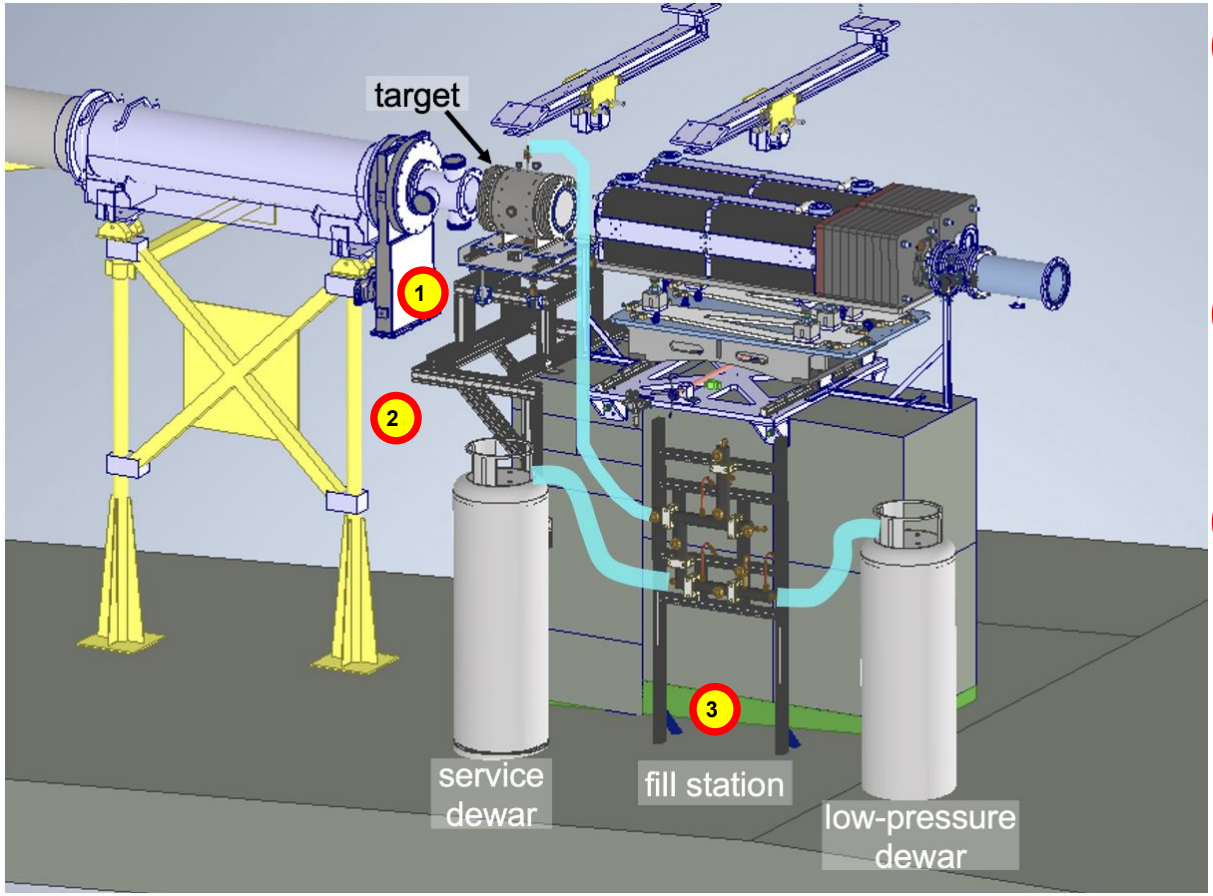
Dedicated transmission – cryo-target L-Ar

- Liquid argon sample and chamber designed, produced and tested at **LANL**

- Sample (liquid argon) placed before final collimation upstream in EAR1



Dedicated transmission – cryo-target L-Ar



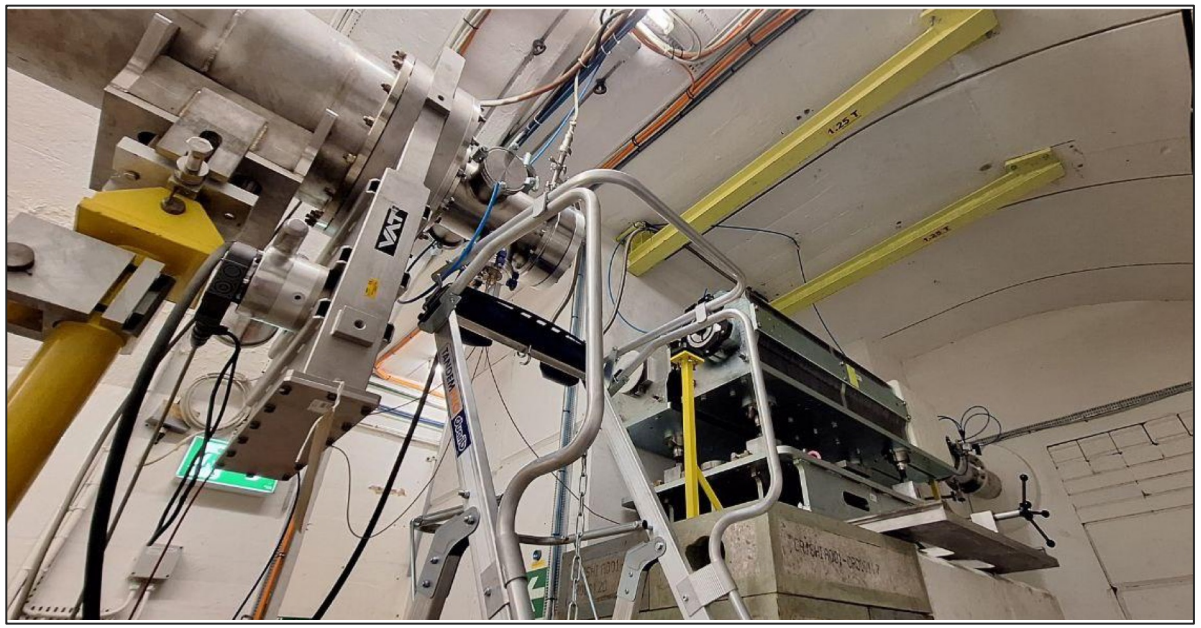
1. Motorized support table to assist in initial alignment (lateral movement)

2. Aluminum struts/beams for support

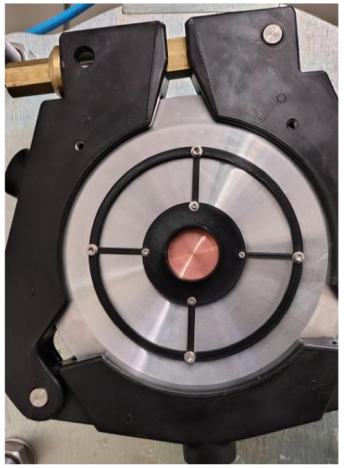
3. Automated cryogenic fill station
   - Uses cryogenic flow meter and solenoid valves for fully remote operation
   - Under construction and testing at LANL

fig. A. Mengoni

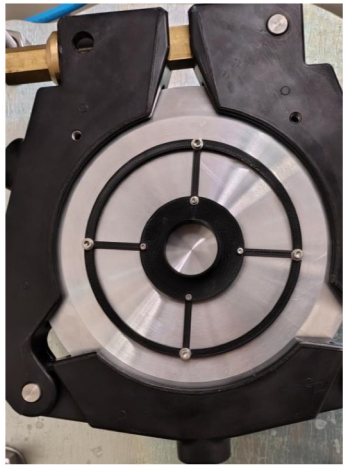
Transmission measurement of ^{nat}Cu



transmission station
n_TOF EAR1



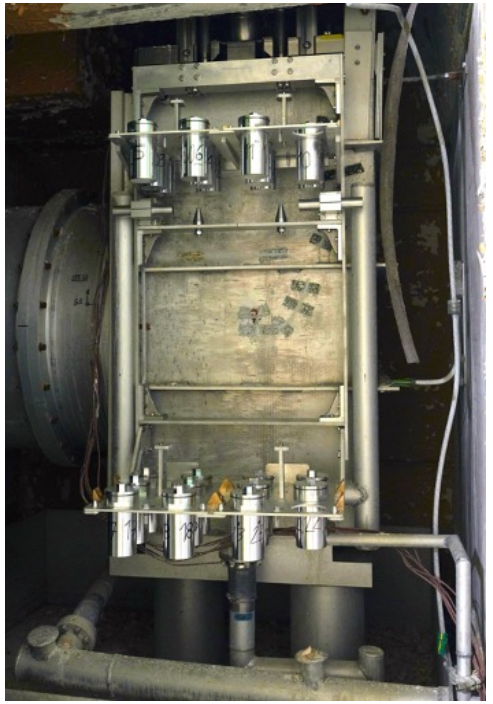
“sample in”
6 mm thick ^{nat}Cu

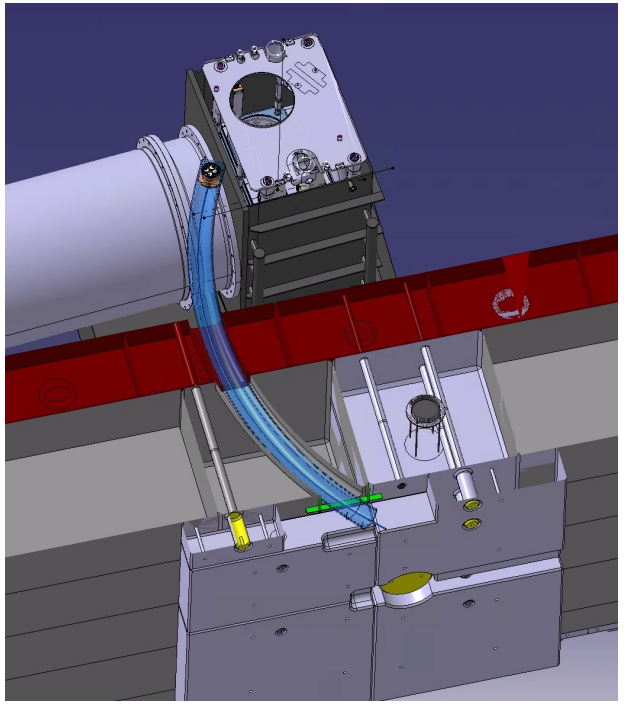


“sample out”

PhD A. Berardi

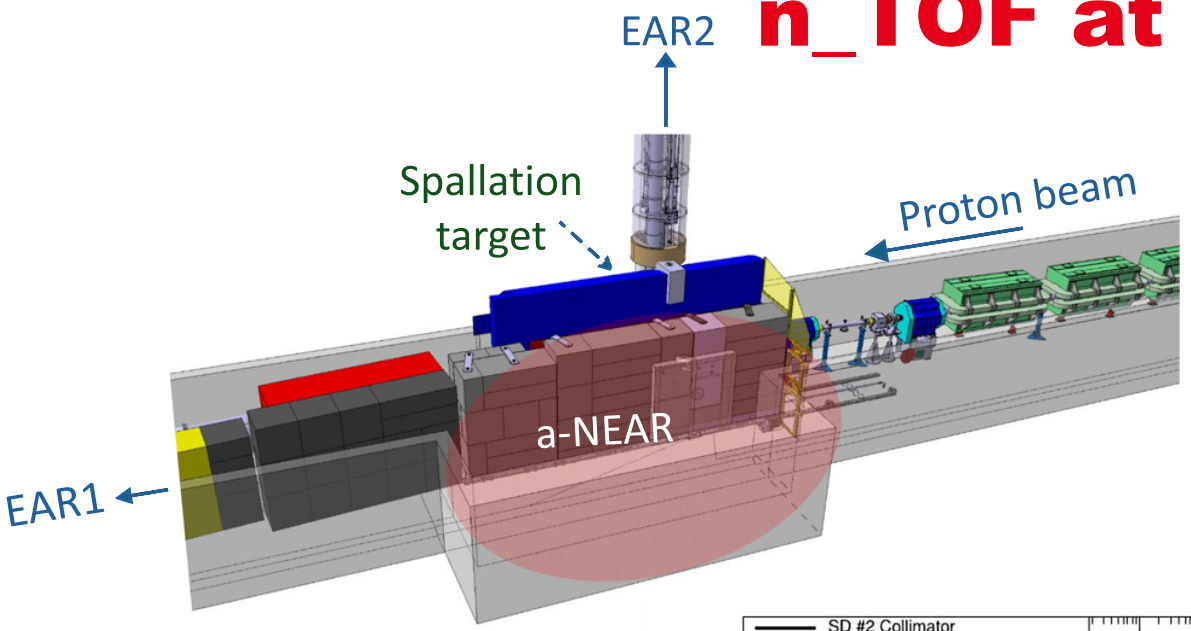
n_TOF at CERN, NEAR

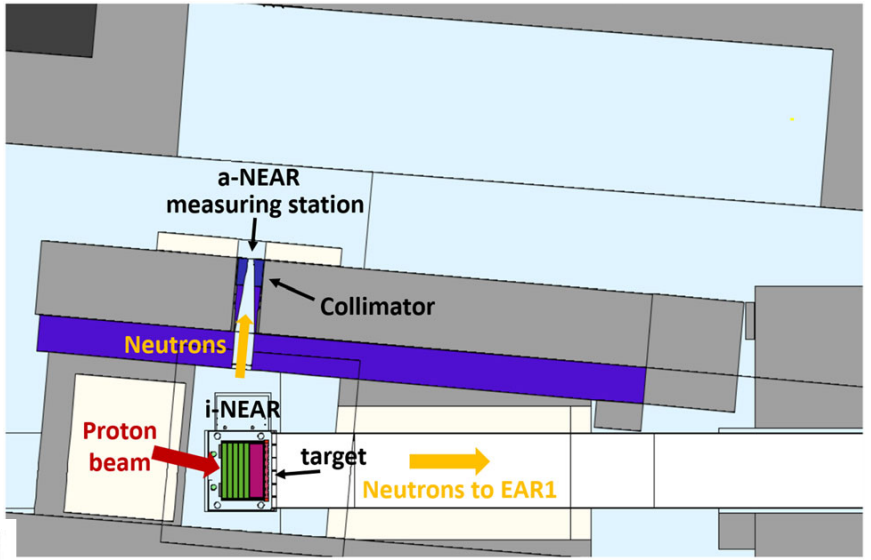


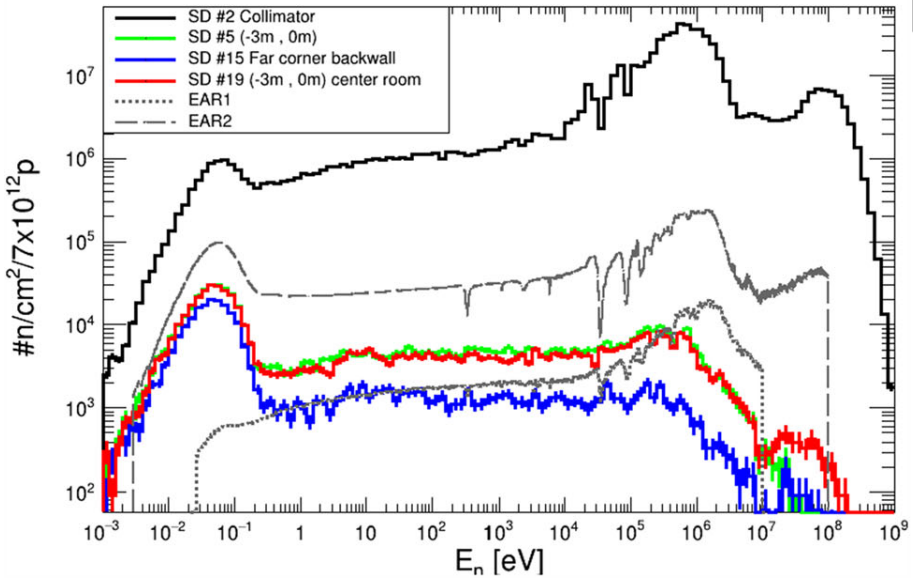


- Irradiation (i-NEAR) and Activation (a-NEAR) areas
- (almost) no time of flight
- spectrum-averaged cross section (SACS) measurements $\int\sigma(E)\phi(E)dE$

n_TOF at CERN, NEAR

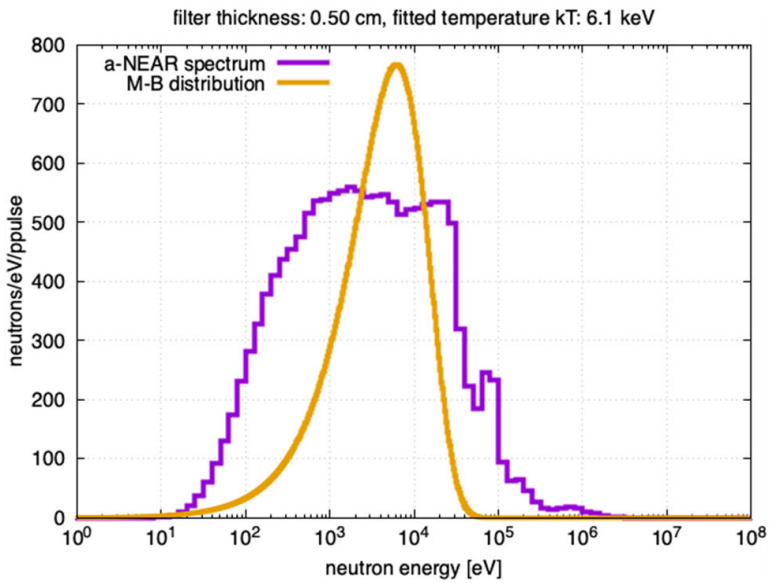


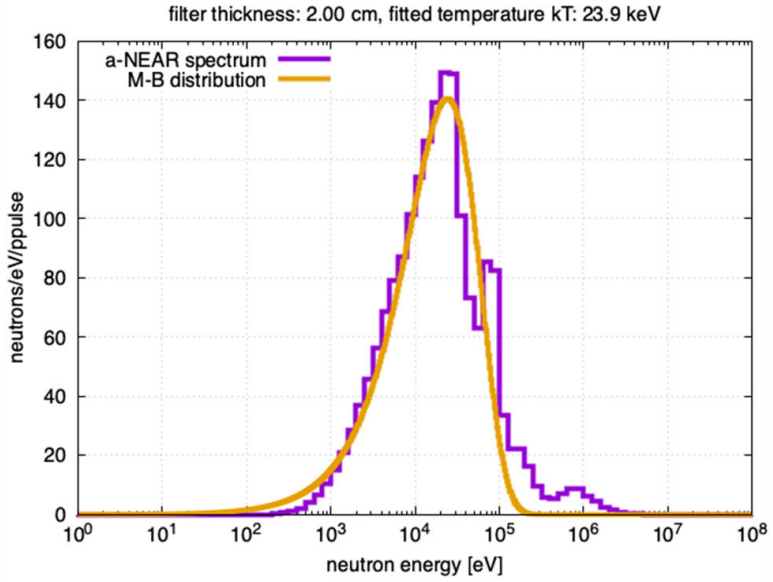


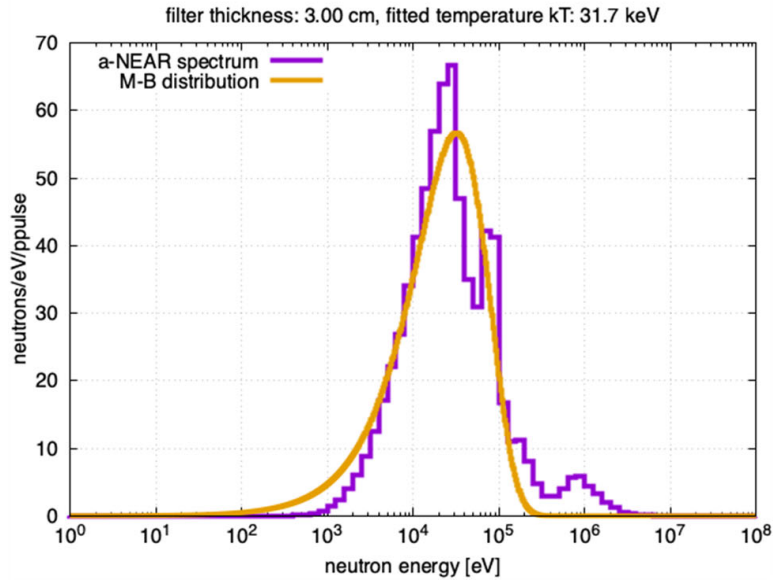


from: N. Patronis et al.
Eur. Phys. J. A (2025) 61:215

Neutron spectral shaping: SACS



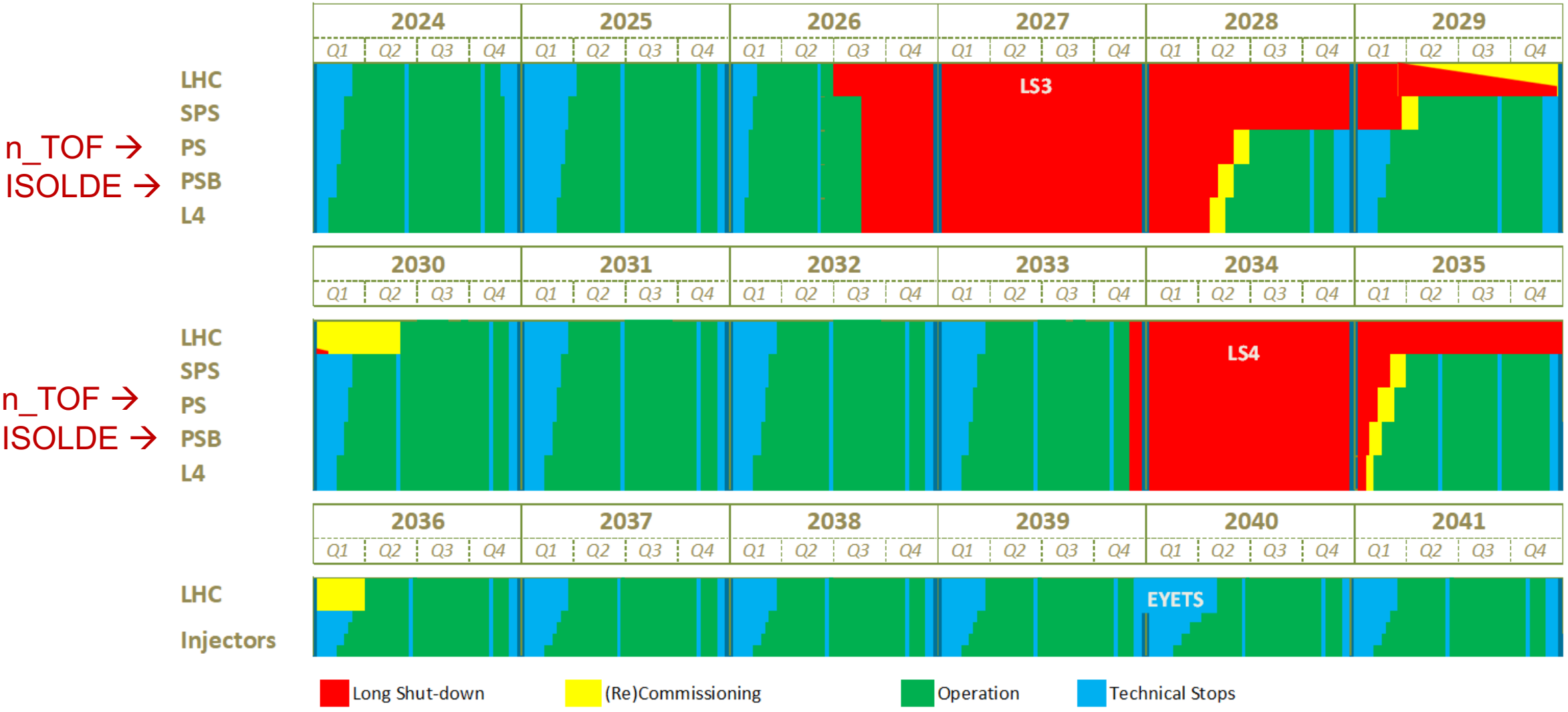




- combinations of AlF_3 moderator together with $^{10}B_4C$ filter to shape initially fast spectrum into a Maxwellian spectrum

from: N. Patronis et al.
Eur. Phys. J. A (2025) 61:215

Future of n_TOF: CERN's accelerator schedule



from: https://edms.cern.ch/document/2311633/5.0 (2025-02-19)

New: proposal for neutron source at CERN n_ACT @ BDF

- **Proposal** at CERN to use the SPS Beam Dump Facility (BDF): **n_ACT@BDF**
  The BDF will host the Search for Hidden Particles (**SHiP**) experiment

- Neutrons from spallation reactions from p+W. Proton beam 400 GeV/c, 4e13 p/pulse (350 kW)

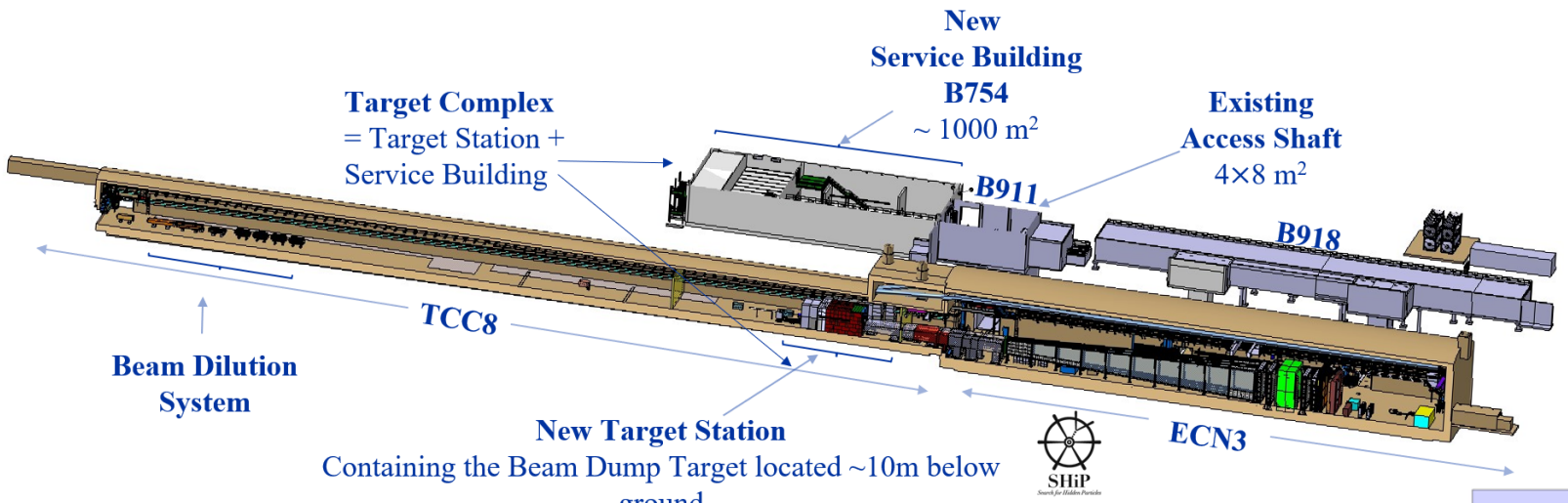
- Measure flux-integrated neutron cross sections of radioactive nuclei ($T_{1/2}$ > few minutes)

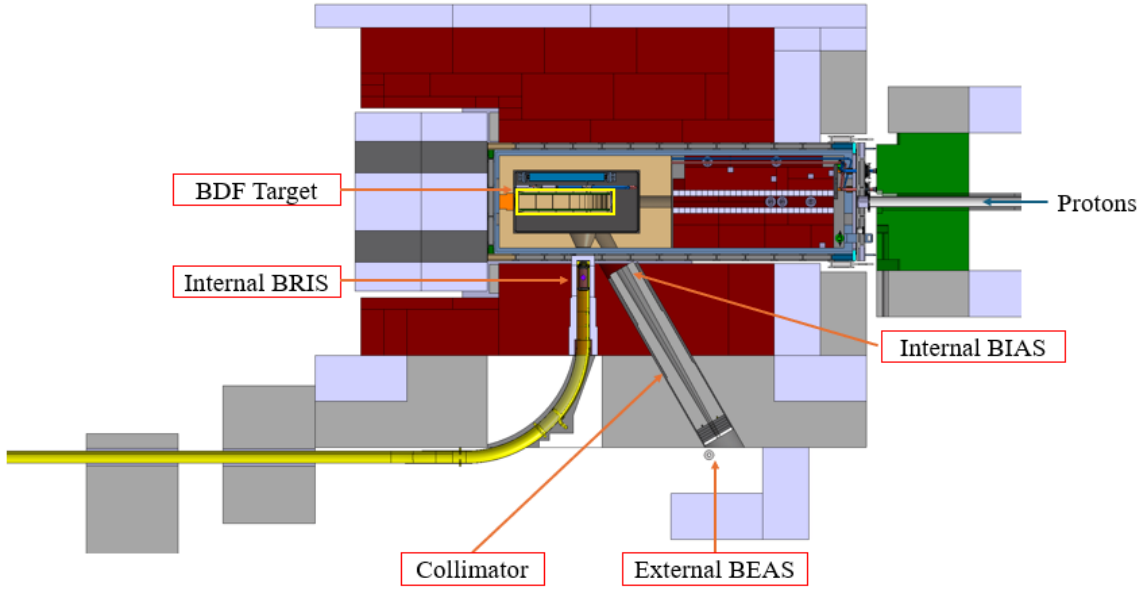
- Three measurement stations foreseen
  - BIAS (internal, highest flux)
  - BEAS (external, collimated neutron beam)
  - BRIS (pneumatic transfer between irradiation point and surface lab)

- Shaping of neutron spectra into quasi-Maxwellian spectra using filters/moderators

- Isotope production ISOLDE envisaged

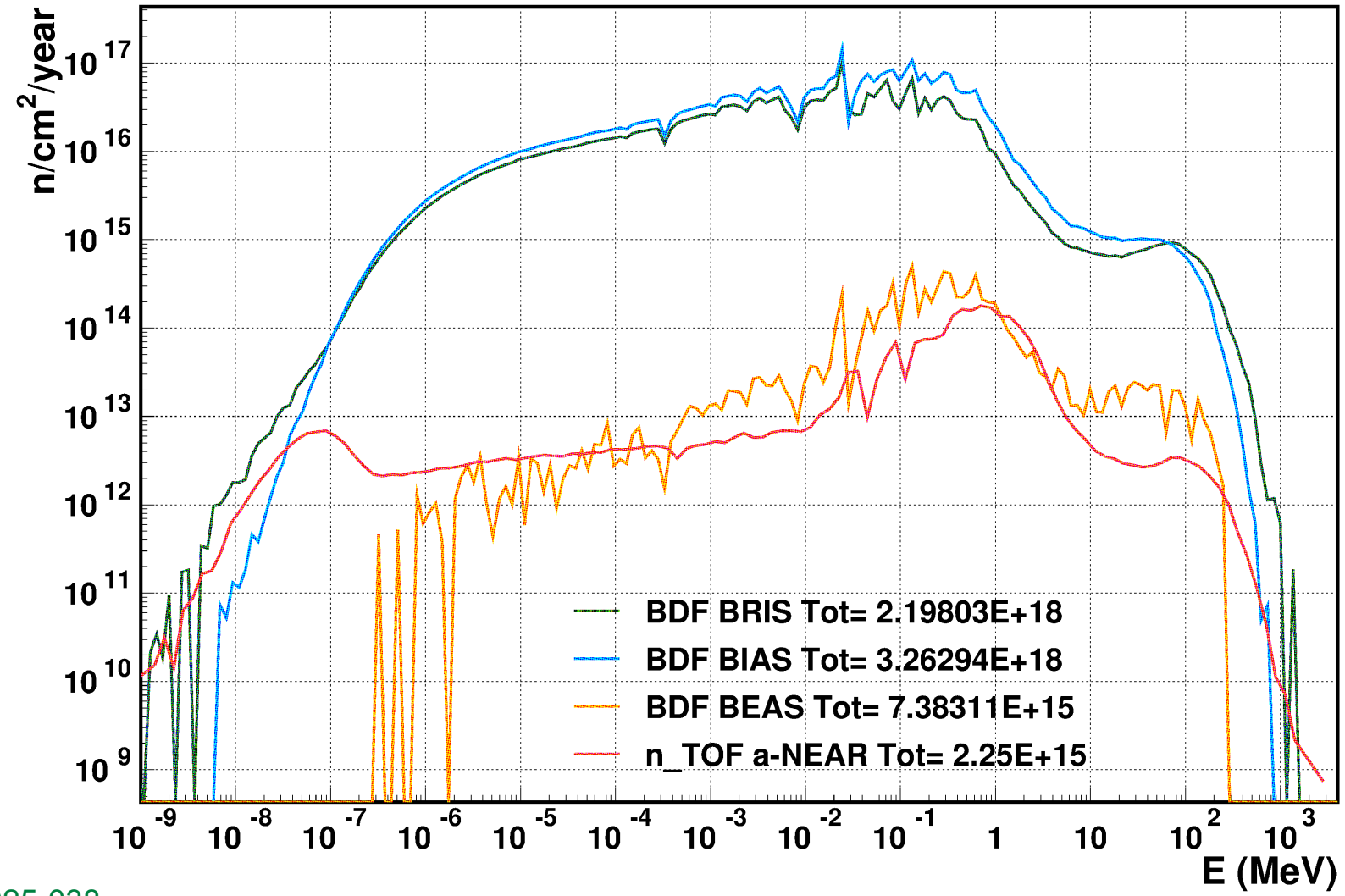
- Staged deployment from 2032 on





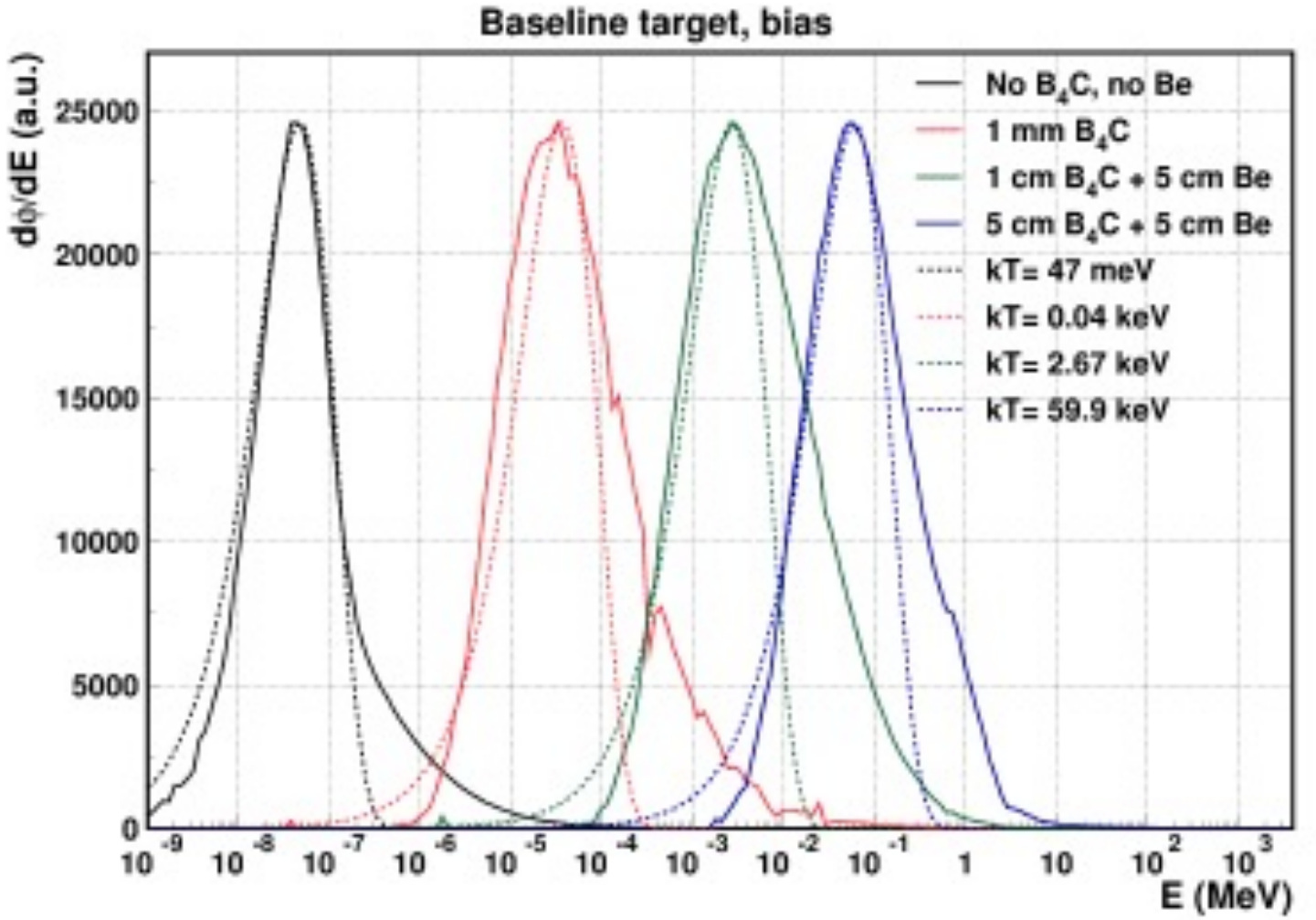
C. Lederer et al.,
proposal CERN-SPSC-2025-038
SPSC-P-375

n_ACT @ BDF



C. Lederer et al.,
proposal CERN-SPSC-2025-038
SPSC-P-375

n_ACT @ BDF, Mawellian-shaped fluxes



C. Lederer et al.,
proposal CERN-SPSC-2025-038
SPSC-P-375

Conclusions (1/2)

- Neutron capture: cross sections, level densities, photon strength functions from high-resolution measurements

- Cross sections:
  - high resolution using time of flight $\sigma(E_n)$
  - flux-integrated $\int\sigma(E)\phi(E)dE$

- New **n_TOF - NEAR** station can work with microgram-level samples

- Output of n_TOF available here:
  - List of publciations: https://twiki.cern.ch/NTOFPublic/ListOfPublications
  - By nucleus, with link to EXFOR: https://twiki.cern.ch/NTOFPublic/DataDissemination

- Recurrent issue of sample (is target) availability

- Possible future initiative **n_ACT @ BDF** can work with very short-lived isotopes

Conclusions (2/2)

- Short term plans
  - **2026:** running from 5-2-2026 to 31-8-2026
  - all experiments already approved by the INTC

- LS3 for n_TOF (2027)
  - several technical improvements/updates (including FIRIA)
  - considerable amount of data to be analyzed
  - preparing an outline of possible experiments for phase V (2028-2033)

- Between LS3 and LS4, and post-LS4
  - experimental program with focus on nuclear astrophysics, advanced nuclear technologies and basic nuclear science and applications
  - plan construction of next generation spallation target
  - planning of the post-LS4 experimental program

The n_TOF Collaboration in 2026

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