PAUL SCHERRER INSTITUT

CCMX Competence Centre for Materials Science and Technology

IAEA International Atomic Energy Agency

Wir schaffen Wissen – heute für morgen

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Neutron Sources

(for imaging)

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OUTLINE

1. Introduction
2. Properties of the free neutron
3. How to get neutrons as free particles and beams
4. Fission
5. Spallation
6. Other (accelerator driven) reactions
7. Thermal and cold neutrons ← moderation
8. Typical neutron – matter interactions
9. Materials of relevance in neutron research
10. Mono-energetic neutrons ?

Introduction

too small

too fast

no charge

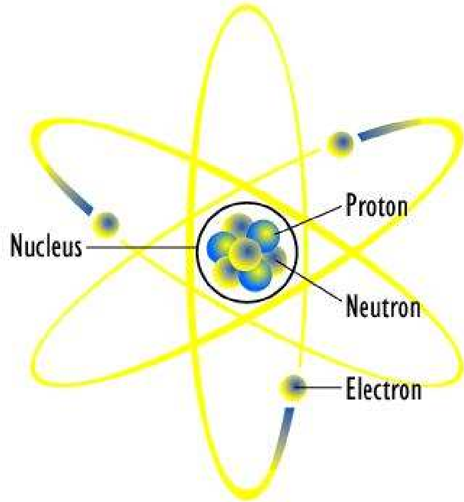
Have you ever seen a neutron?

Does it really exists?

no human sensor

no human sensor

Properties of the free neutron



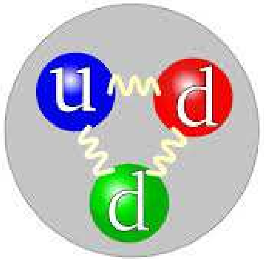
Size: $1.6 * 10^{-15}$ m

Mass: $1.674927351(74) * 10^{-27}$ kg

Charge: 0

Spin: ½ (two states possible)

Velocity: few m/s (ultra cold) to speed of light (very fast)



Elementary composition: 3 Quarks up-down-down

Magnetic moment: $-1.913\ \mu_N$

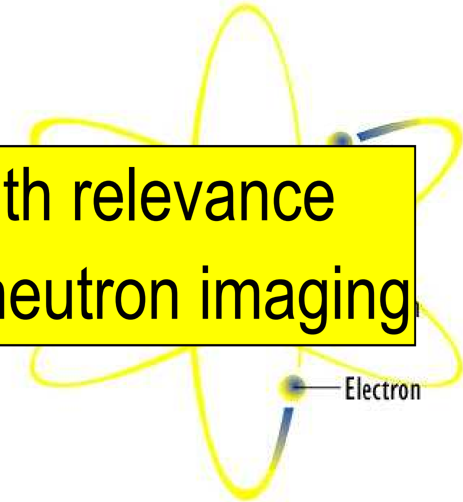
Interaction with matter: nuclear reactions: absorption, scattering, fission

Classification: Baryon, Fermion

Half-life: 881.5 s

Properties of the free neutron

with relevance
for neutron imaging



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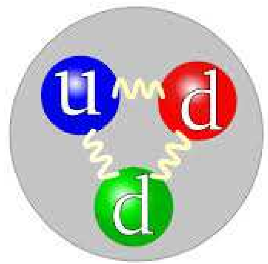

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NEUTRONS vs. X-RAYS

thermal neutrons

- wavelength: ~ 2 Å = 0.2 nm
- energy: 25 meV
- mass: 1.674927351(74) · 10^{-27} kg
- charge: no
- spin: ½
- magnetic moment: **- 1.91 μ_N**
- interaction with nuclei via scattering and absorption

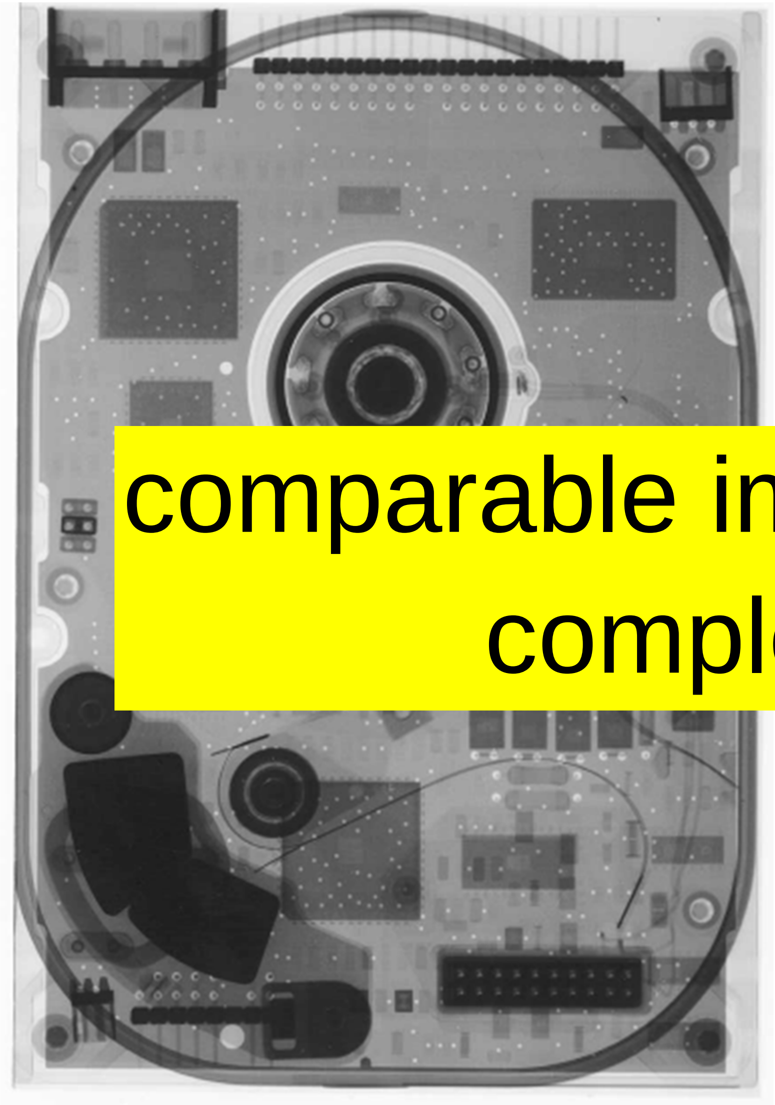
X-rays (e.g. 100 keV)

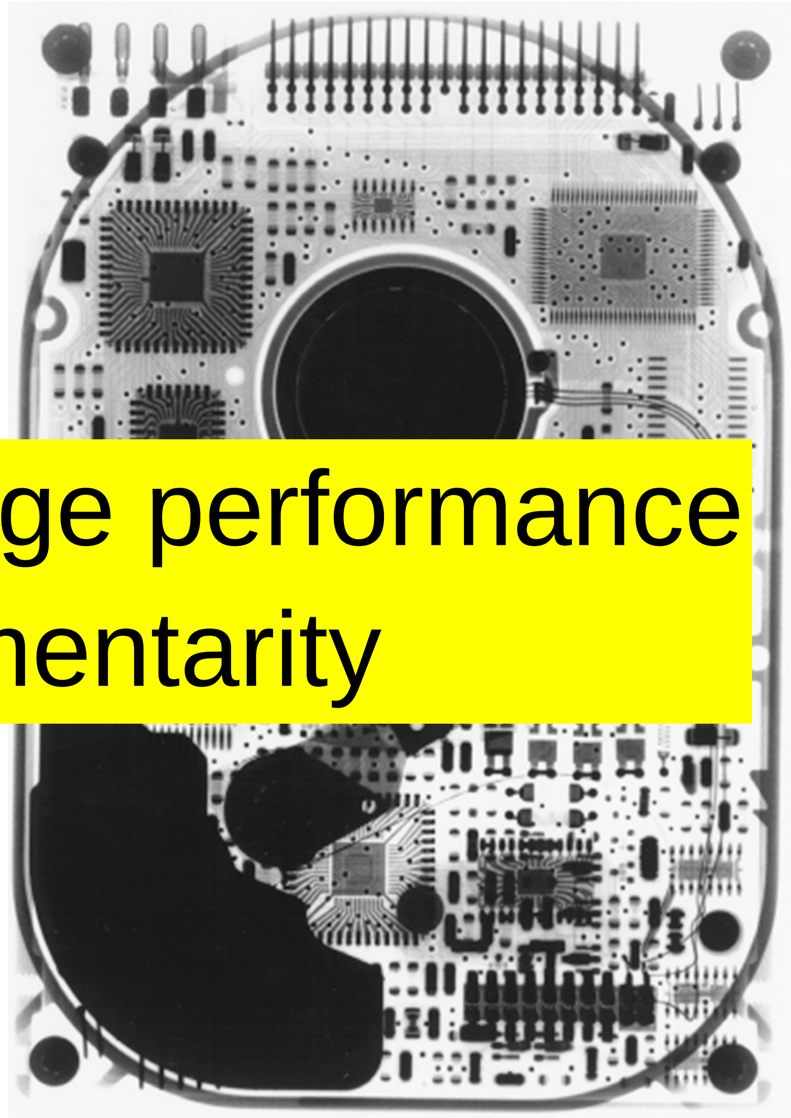
- wavelength: 1 keV ~ 1.24 nm
- energy: eV to MeV (E=h*c/λ)
- mass: no
- charge: no
- spin: 1
- magnetic moment: no
- interaction via electrons in the atomic shell (Photo-, Compton-Effekt)

Comparison N / X (hard disk)

thermal neutrons

X-rays (100 keV)





comparable image performance

complementarity

How to get neutrons as free particles and beams

- A NUCLEAR reaction is needed to break the binding forces in suitable atoms

- It is on the order of MeV/particle

- The options are:

- *radioactive decay (Cf-252); Am-Be*
- *Fission (research reactor)*
- *bombardement with accelerated particles (spallation source)*

How to get neutrons as free particles and beams

- A NUCLEAR reaction is needed to break the binding forces in suitable atoms

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- The options are: (with relevance for neutron imaging)

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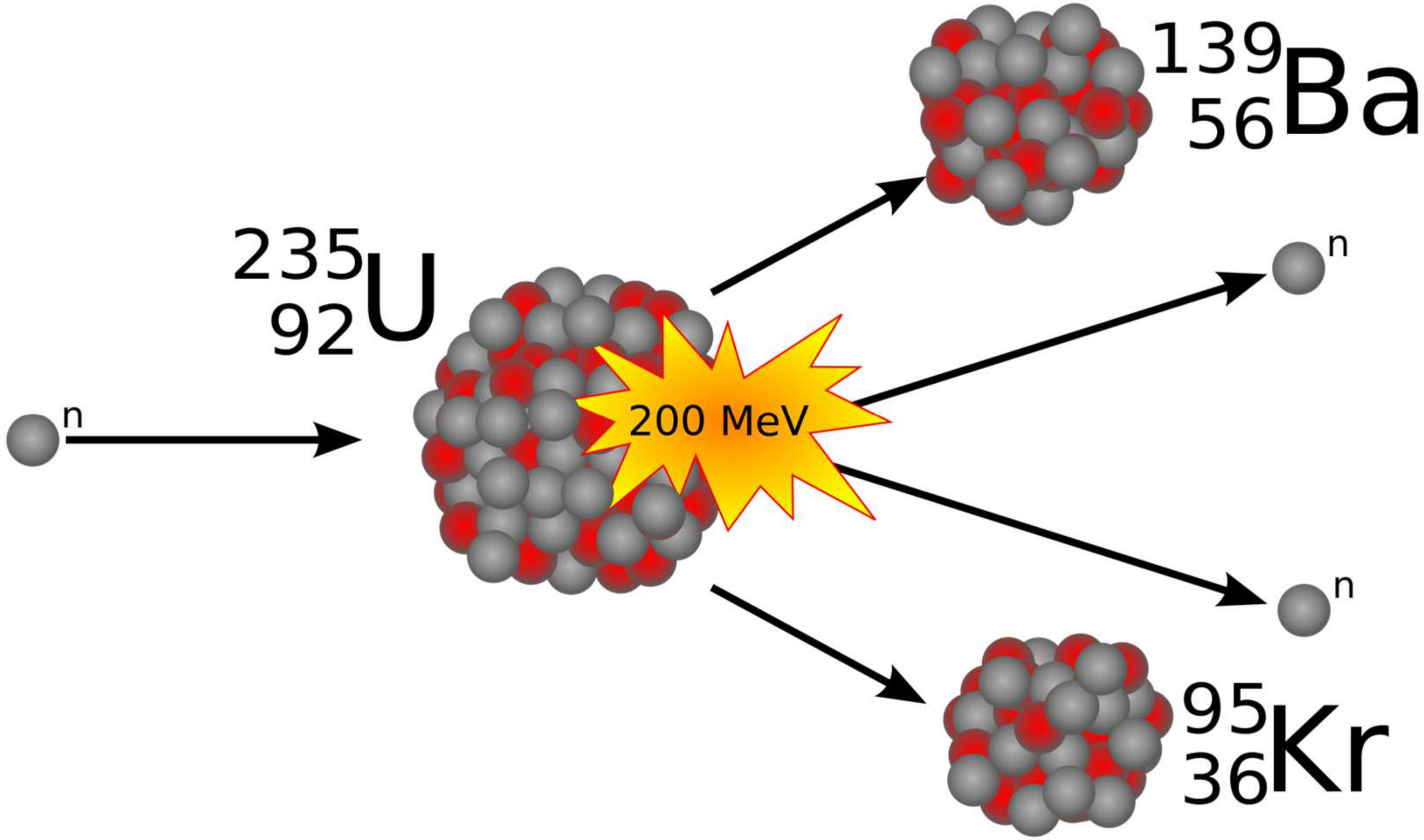
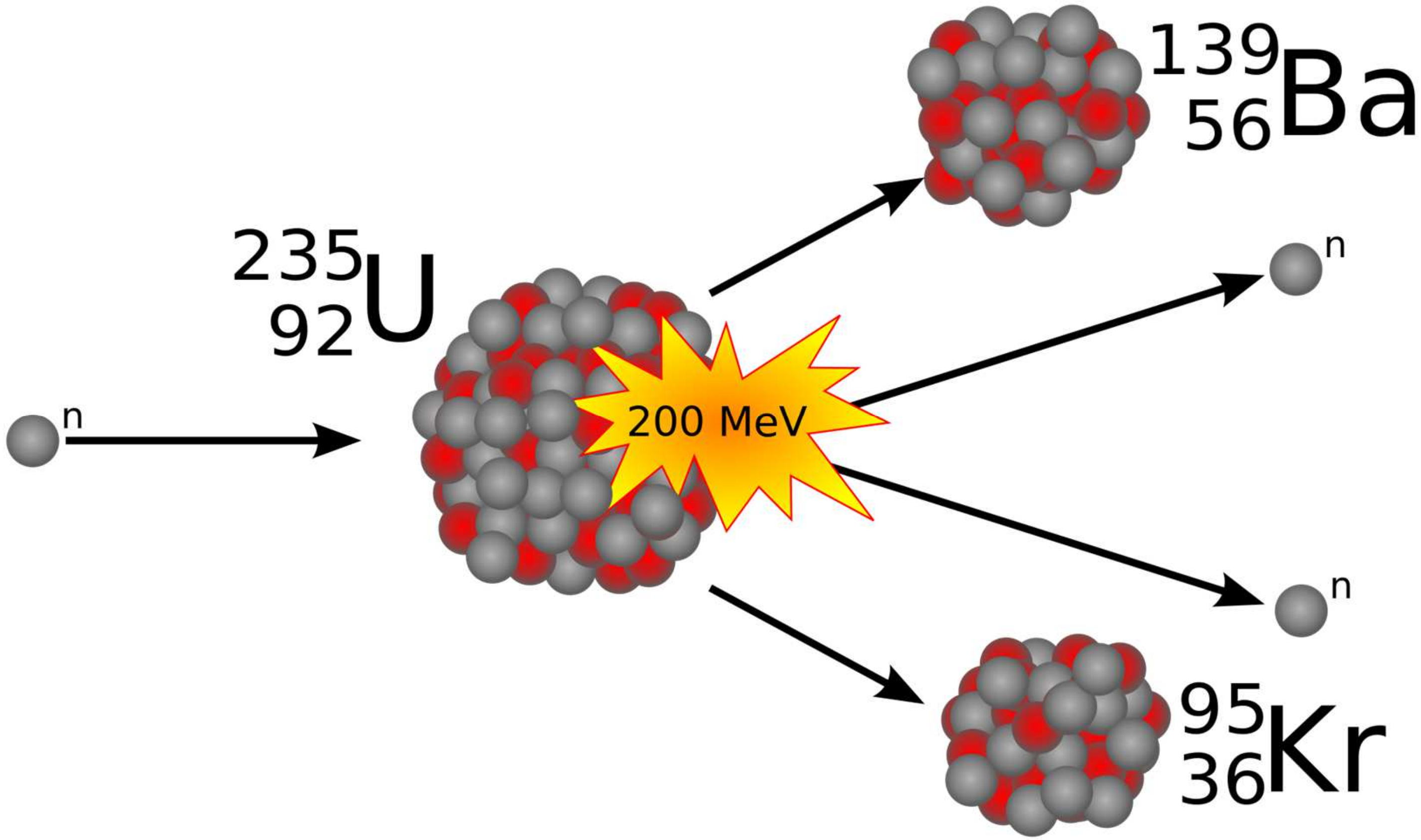
Fission



1. Fissionable material required: **U-235** (in nature available), Pu-239, U-233, Pu-241
2. More neutrons out than in: chain reaction possible - multiplication
3. High energy release: nuclear energy
4. Fission products: unsymmetrical mass distribution

Fission



1. Fissionable material required: U-235 (in nature available), Pu-239, U-233, Pu-241
2. More neutrons out than in: chain reaction possible
3. ~~High energy release: nuclear energy~~ **drawback for a neutron source**
4. Fission products: unsymmetrical mass distribution

Fission

	Research Reactor	**Nuclear Power Plant**
aim	neutron output	energy production
design	compact core	large core
enrichment	as high as possible	only few %
inventary	few kg only	many tons
power limit	100 MW	3000 MW
temperature	low: 40 °C	high: above boiling
pressure	low	high: 70 bar

Data Base of IAEA: world-wide overview (2015)

https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx

Operational: 248 of 285 total

Power > 1 MW: 117

Age < 40 years: 103 Age > 40 years: 160

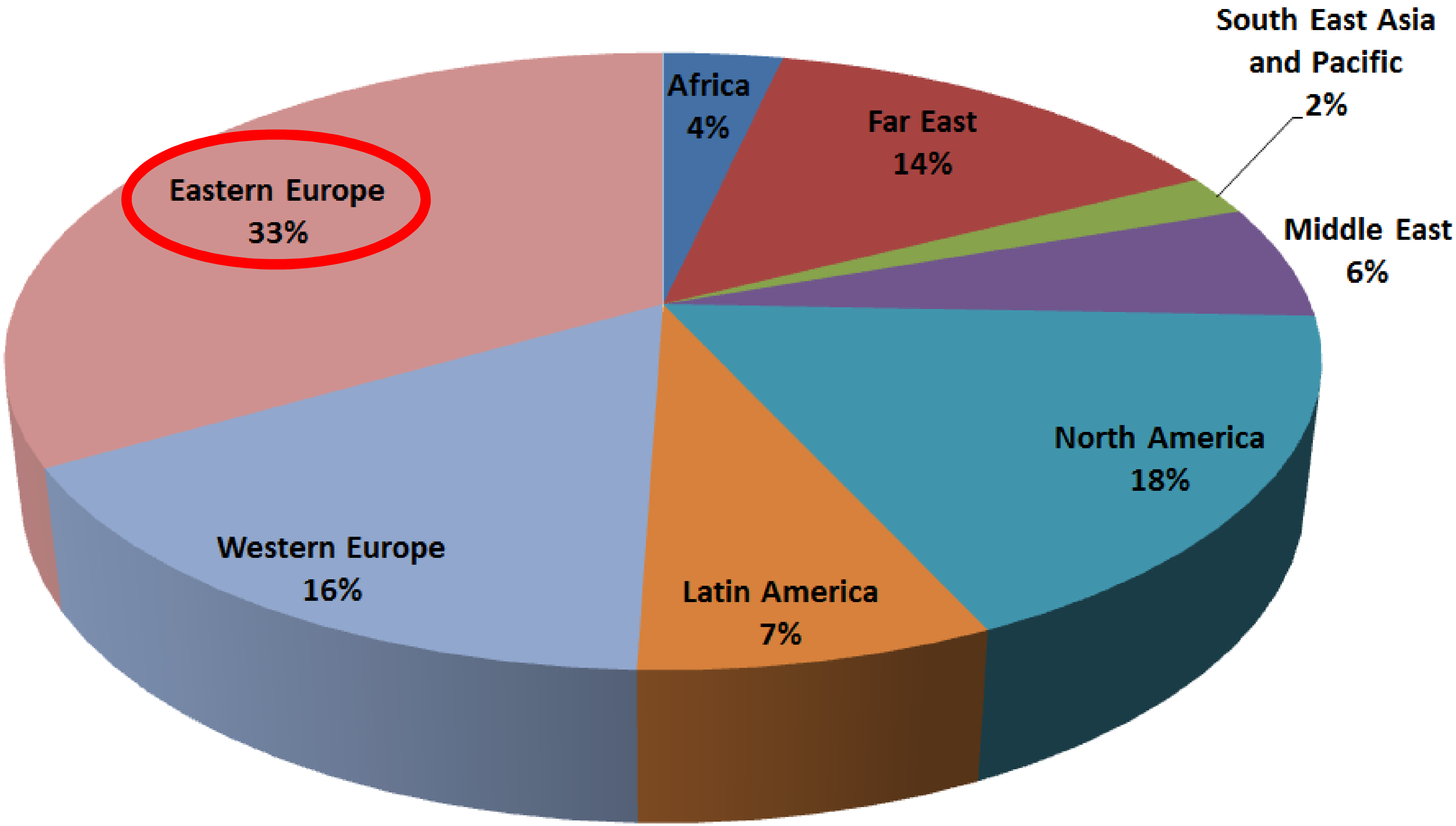
Planned/Construction: 18

Neutron Radiography: 74 **(ISNR/IAEA-Data Base: 47), but only 15 are «state-of-the-art»**

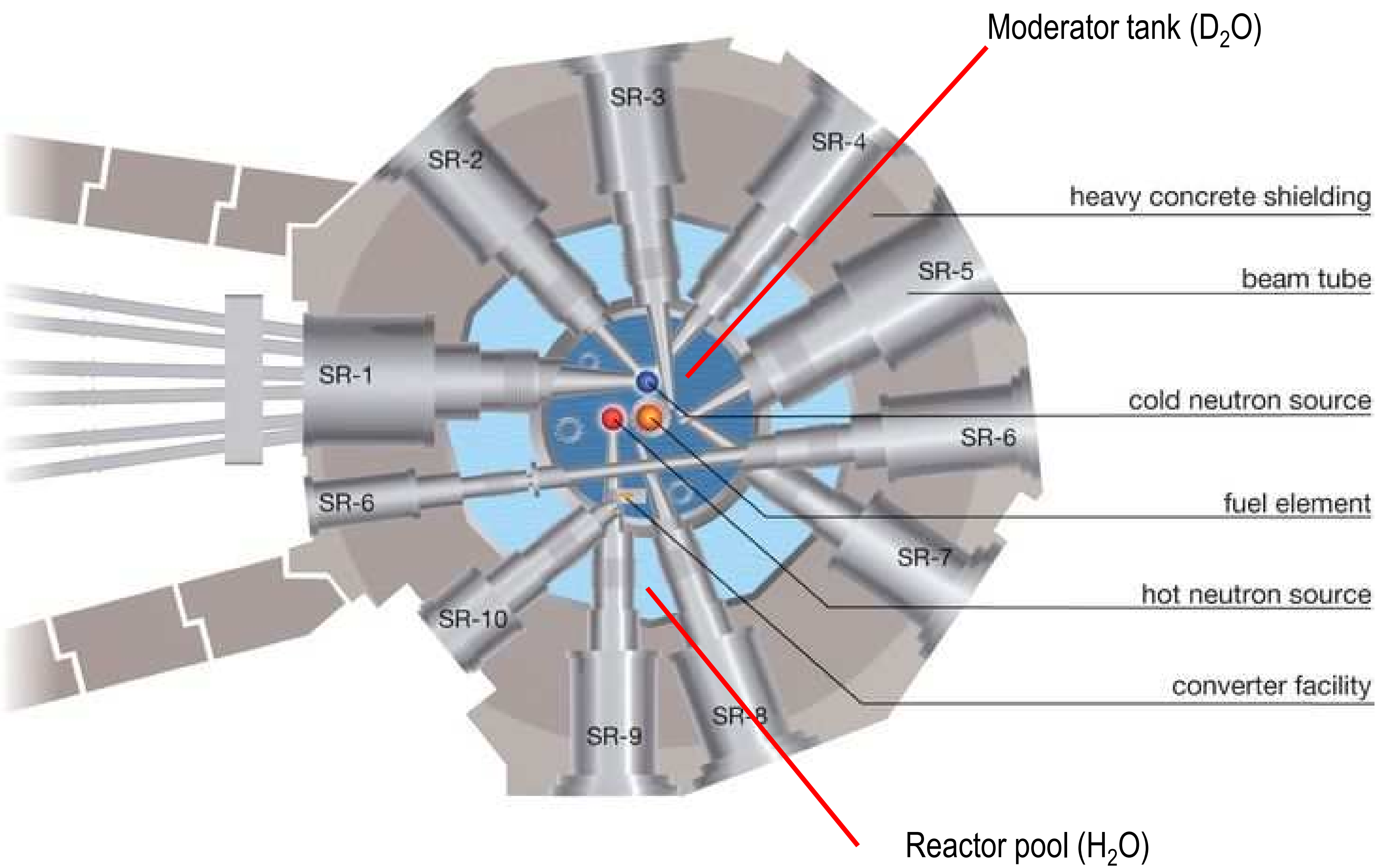
Neutron Scattering: 54

Research Reactors

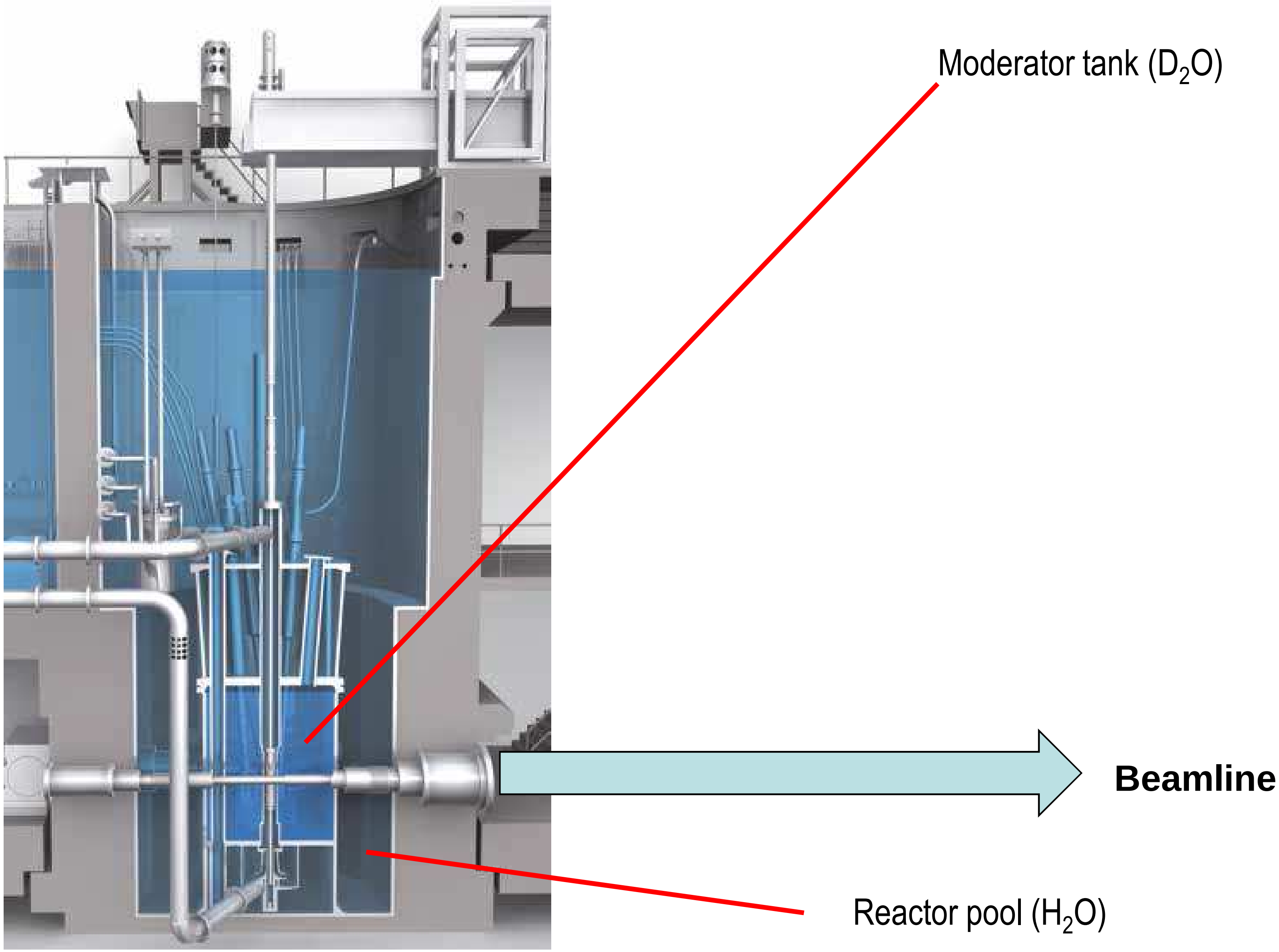
Research Reactor Distribution around the globe



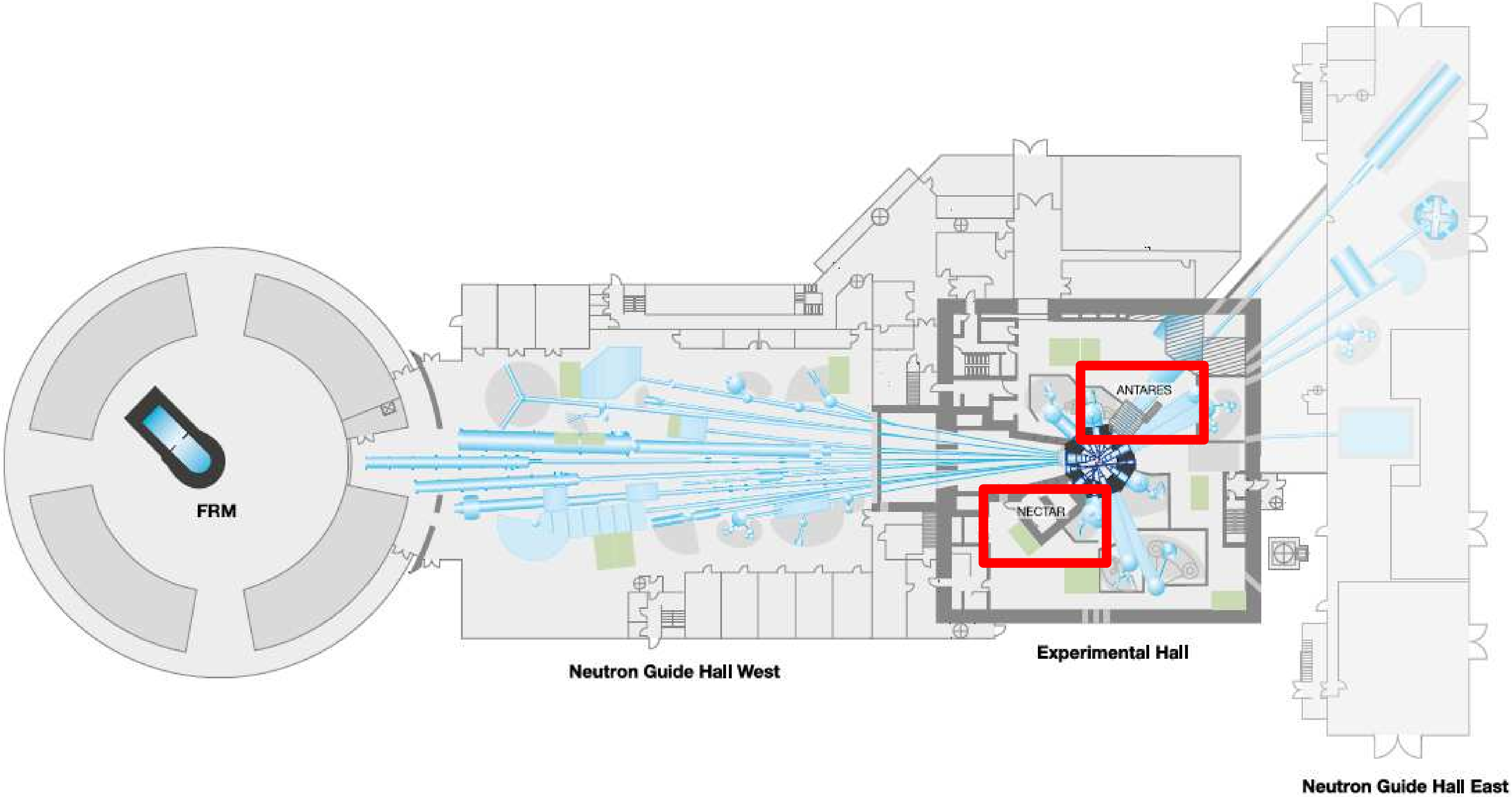
Research Reactors – Design (example FRM-2)



Research Reactors – Design (example FRM-2)



ANTARES and NECTAR @ FRM-2



Spallation Sources

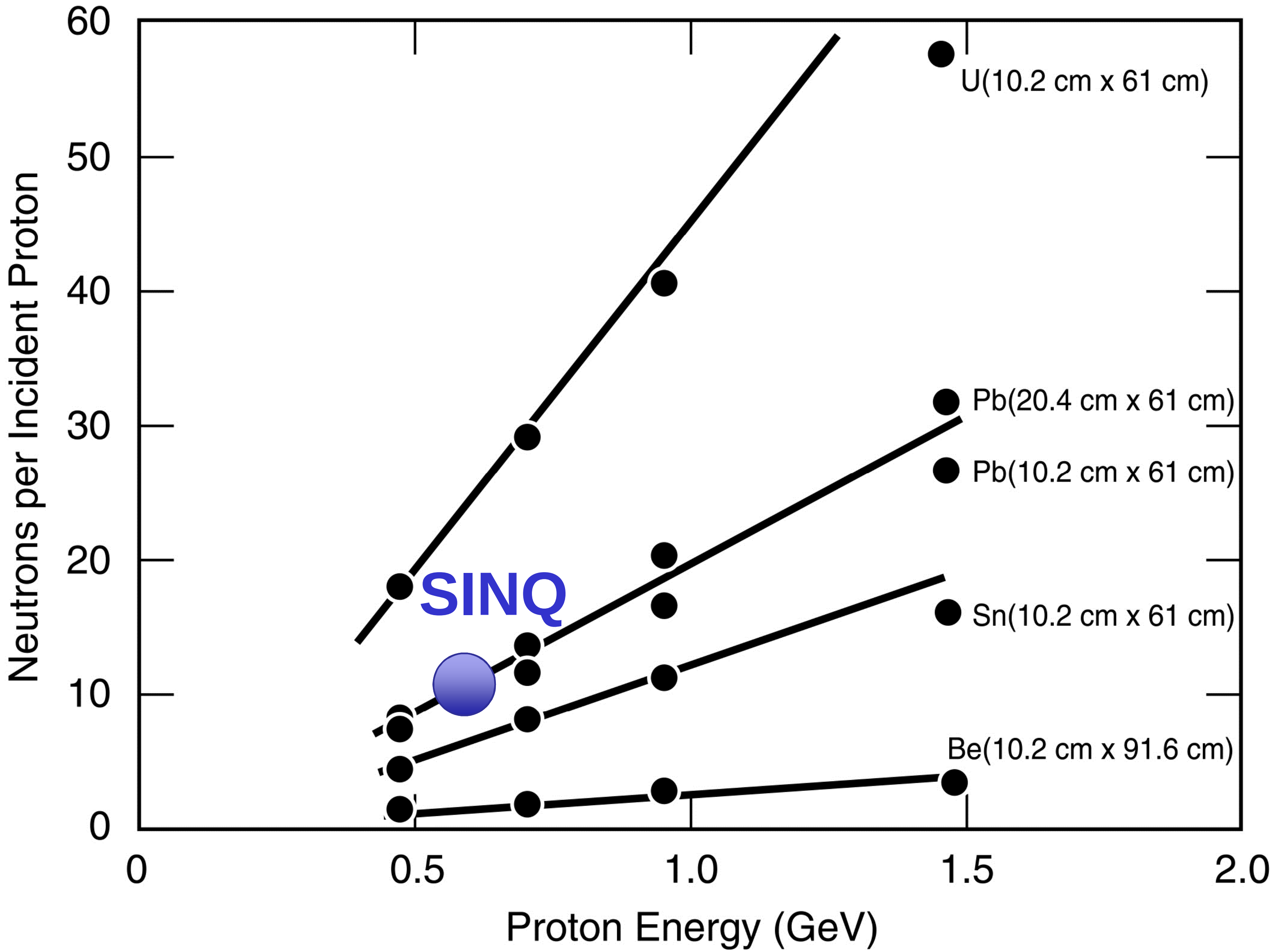
Spallation: Destruction of heavy nuclei by high energy particle (protons) exposure

Neutron emission: since the lower mass spallation products needs less neutrons for stability, 10-15 neutrons are «available»

Neutron yield:
- ▸high target mass (Pb, W, U, Pb-Bi alloy, …)
- ▸compact structure (problem: heat removal)
- ▸high proton energy (GeV order)
- ▸high beam intensity (mA, corresp. MW power)

Neutron energy: initially in MeV region → moderation needed to get thermal and cold neutrons

Measured Neutron Yield vs. Proton Energy for Various Targets



From Fraser *et al.*, measurements at Brookhaven Cosmotron

Overview HIPA

Injector II Cyclotron
72 MeV, 160kW

Cockcroft Walton
870keV, 10kW

Isotope Production

dimensions:
120 x 220m^2

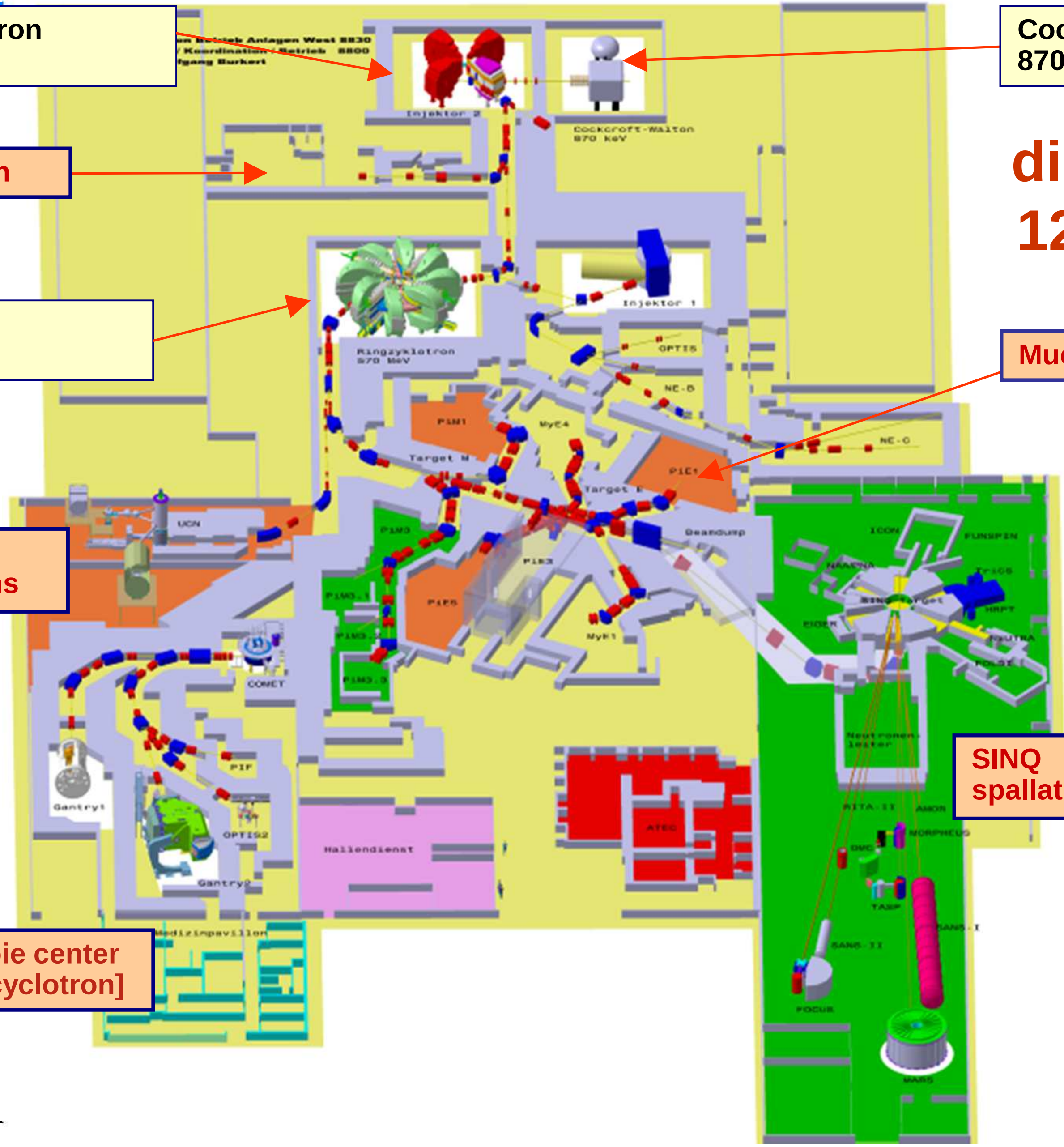
Ring Cyclotron
590 MeV, 1.3MW

Muon Beamlines

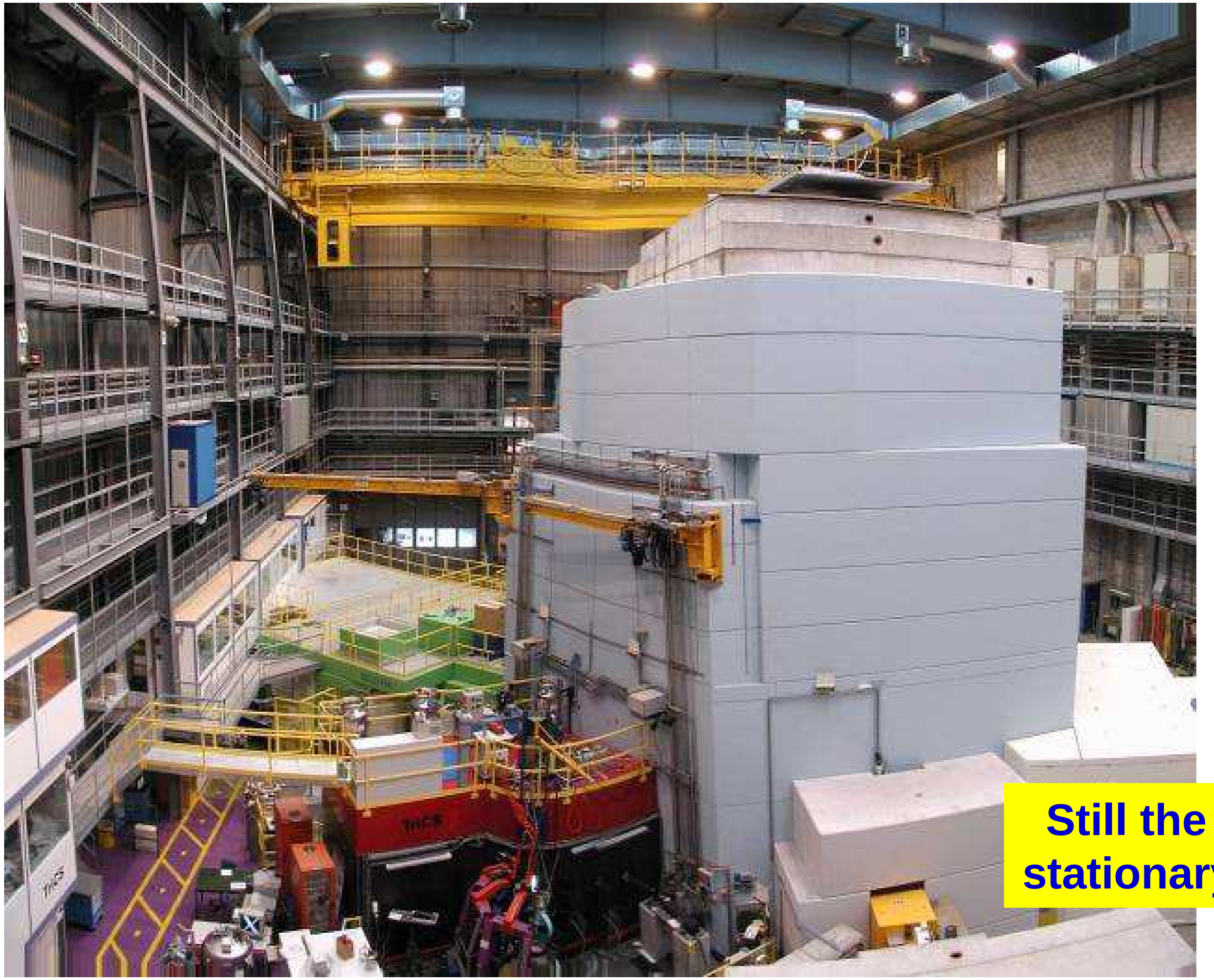
UCN
Ultra-Cold Neutrons

SINQ
spallation source

proton therapie center
[250MeV sc. cyclotron]



Spallation neutron source SINQ @ PSI

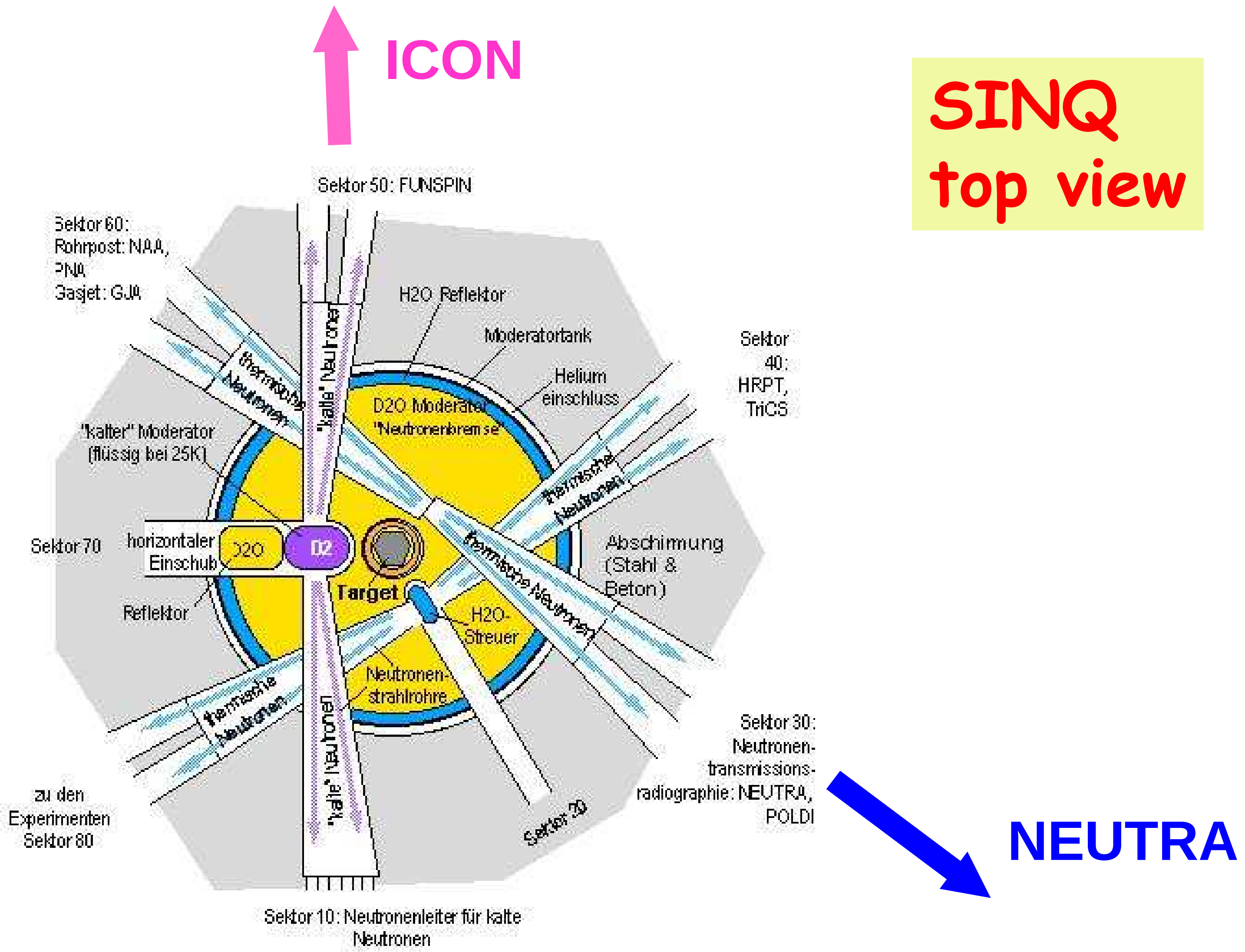


- In operation since 1997
- Driven by 590 MeV protons on a Pb target
- Intensity about 1.2 mA, corresponding to 1MW thermal power
- Installations for research with thermal and cold neutrons

Still the world‘s strongest stationary spallation source

Beamlines layout

SINQ
top view



Spallation

Spallation facilities (with homepage)

European Spallation Source Lund, SE
ISIS neutron source, Oxford, UK
J-PARC, Mito, Japan
LANSCE Los Alamos, USA
PSI Spallation Neutron Source (SINQ), CH
Spallation Neutron Source Oak Ridge, USA
Chinese Spallation Source

Spallation

Spallation facilities (under construction) – other: operational

European Spallation Source (ESS), Lund, SE
ISIS neutron source, Oxford, UK
J-PARC, Mito, Japan
LANSCE, Los Alamos, USA
PSI Spallation Neutron Source (SINQ), CH
Spallation Neutron Source (SNS), Oak Ridge, USA
Chinese Spallation Source

Spallation

Spallation facilities (pulsed)

European Spallation Source (ESS), Lund, SE
ISIS neutron source, Oxford, UK
J-PARC, Mito, Japan
LANSCE, Los Alamos, USA
PSI Spallation Neutron Source (SINQ), CH
Spallation Neutron Source (SNS), Oak Ridge, USA
Chinese Spallation Source

Spallation

Spallation facilities (imaging options exist)

European Spallation Source (ESS), Lund, SE
ISIS neutron source, Oxford, UK
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Spallation

Spallation facilities (imaging options exist, planned)

European Spallation Source (ESS), Lund, SE
ISIS neutron source, Oxford, UK
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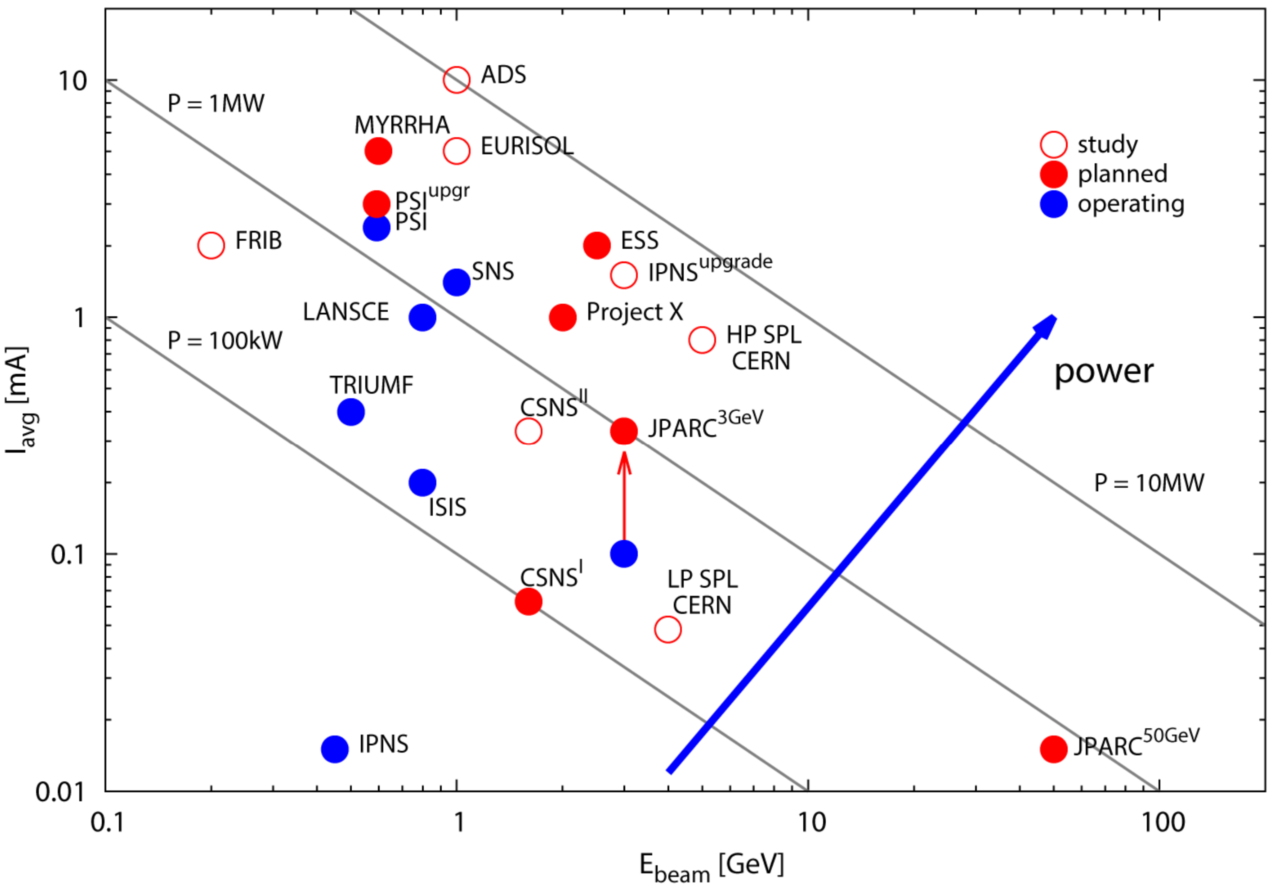
PSI HIPA in the international context

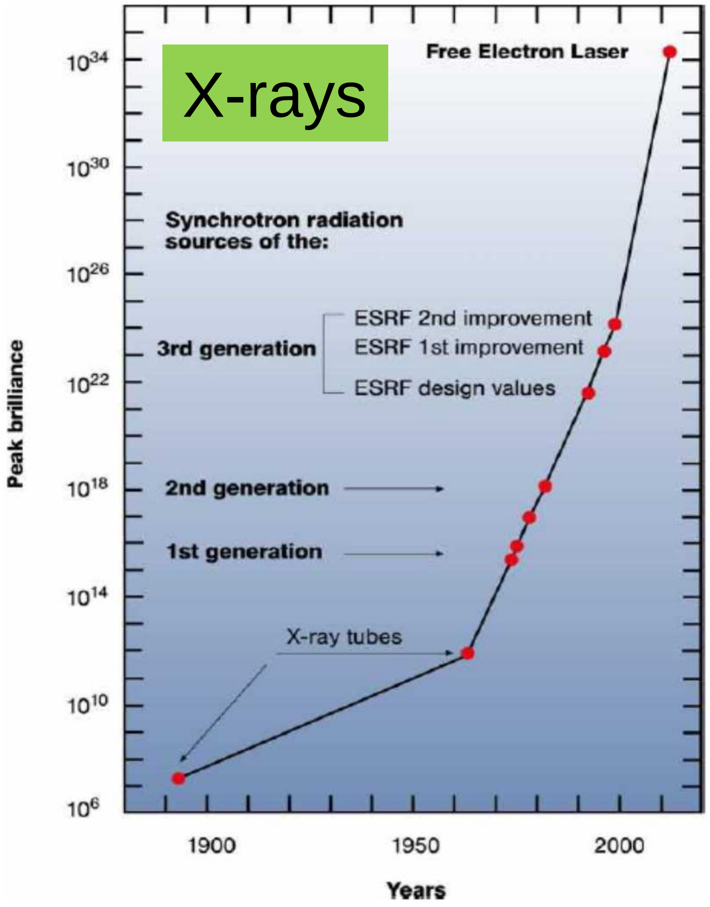


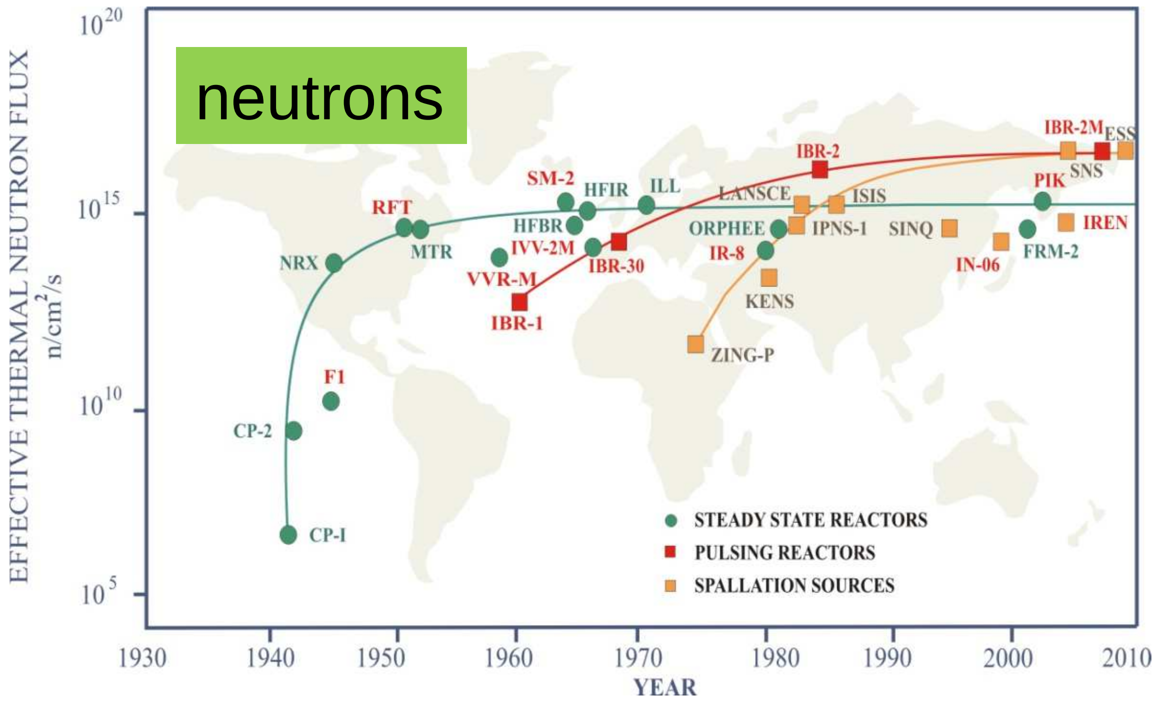
Neutron Sources:

	Energy [GeV]	Power [MW]
ISIS	0.8	0.18
J-Parc	3.0	0.3 (1.0)
SNS	1.0	1.4
PSI	0.59	1.4
ESS	2.5	5.0
CSNS	1.6	0.1…0.5

“Brilliance” of synchrotron and neutron sources

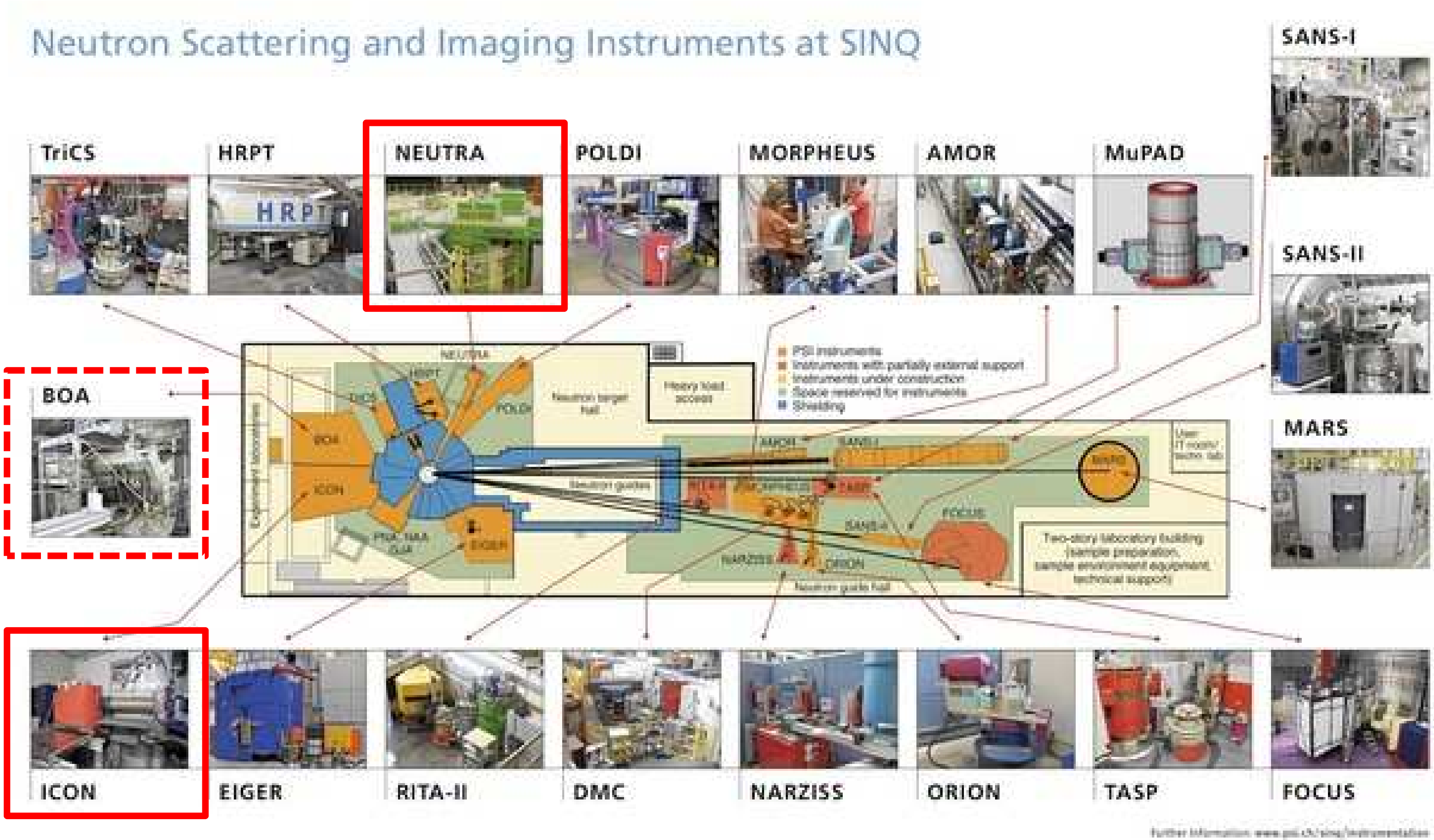
Limitations in Neutron Imaging: Intensity!
(influencing: collimation, coherence, acquisition time, resolution…)



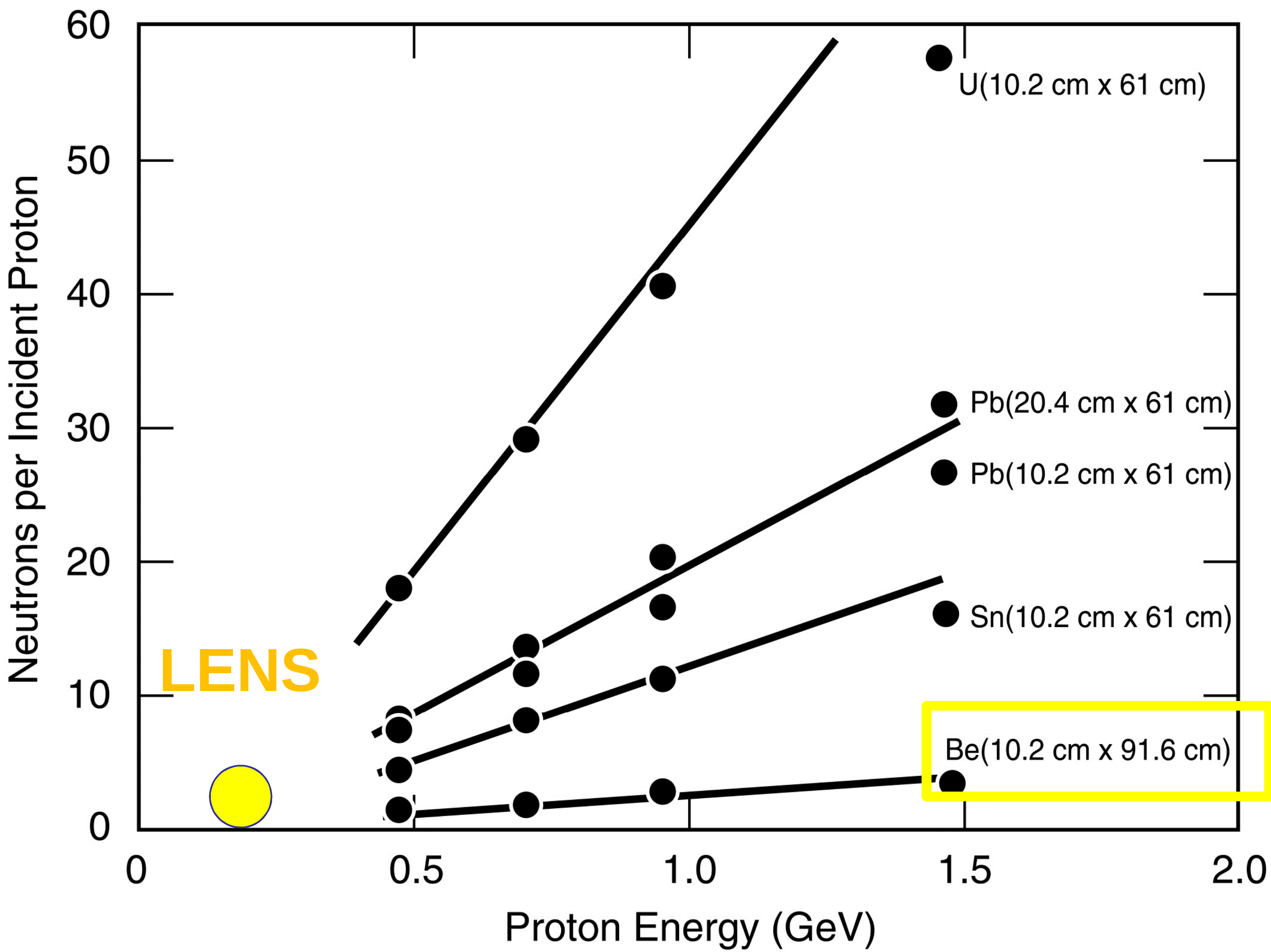


source: Anatoly M. Balagurov
Frank Laboratory of Neutron Physics, JINR, Dubna, Russia

Spallation neutrons at SINQ



Measured Neutron Yield vs. Proton Energy for Various Targets



From Fraser *et al.*, measurements at Brookhaven Cosmotron

Other (accelerator driven) reactions

p (13 MeV) + Be-9 → n + B-9 LENS (Indiana University)

$D + T \rightarrow n + {}^4He \quad E_n = 14.1\ MeV$

$D + D \rightarrow n + {}^3He \quad E_n = 2.5\ MeV$

source strength on the order of 10^{10} n/s into 4π
but high losses during the moderation process
and the beam formation

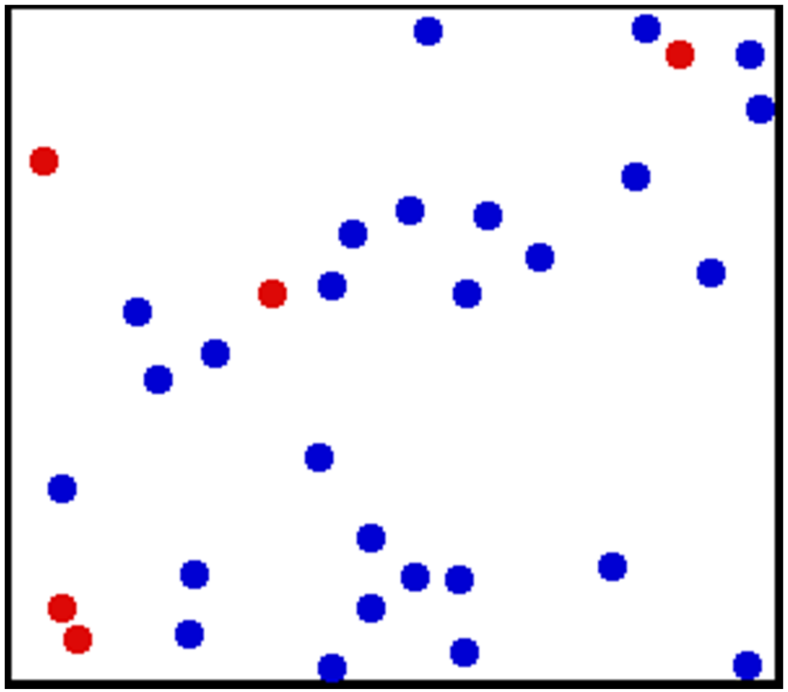
Thermal and cold neutrons ← moderation

Moderation: slowing down process
of initially fast (fission/spallation) neutrons (MeV)
to the thermal equilibrium (with the moderator) (meV)

→ over 9 orders of magnitude
→ by elastic collisions with moderator nuclei (H, D, C)

thermal neutrons
(moderator on 40° C)

cold neutrons
(moderator on -250° C)



thermal equilibrium
between neutrons and
moderator molecules

Thermal and cold neutrons ← moderation

Moderation: best moderation power: H - since the mass is same as of the neutron; drawback: neutron absorption

D is the best compromise between moderation and absorption; drawback: D costs, scattering range

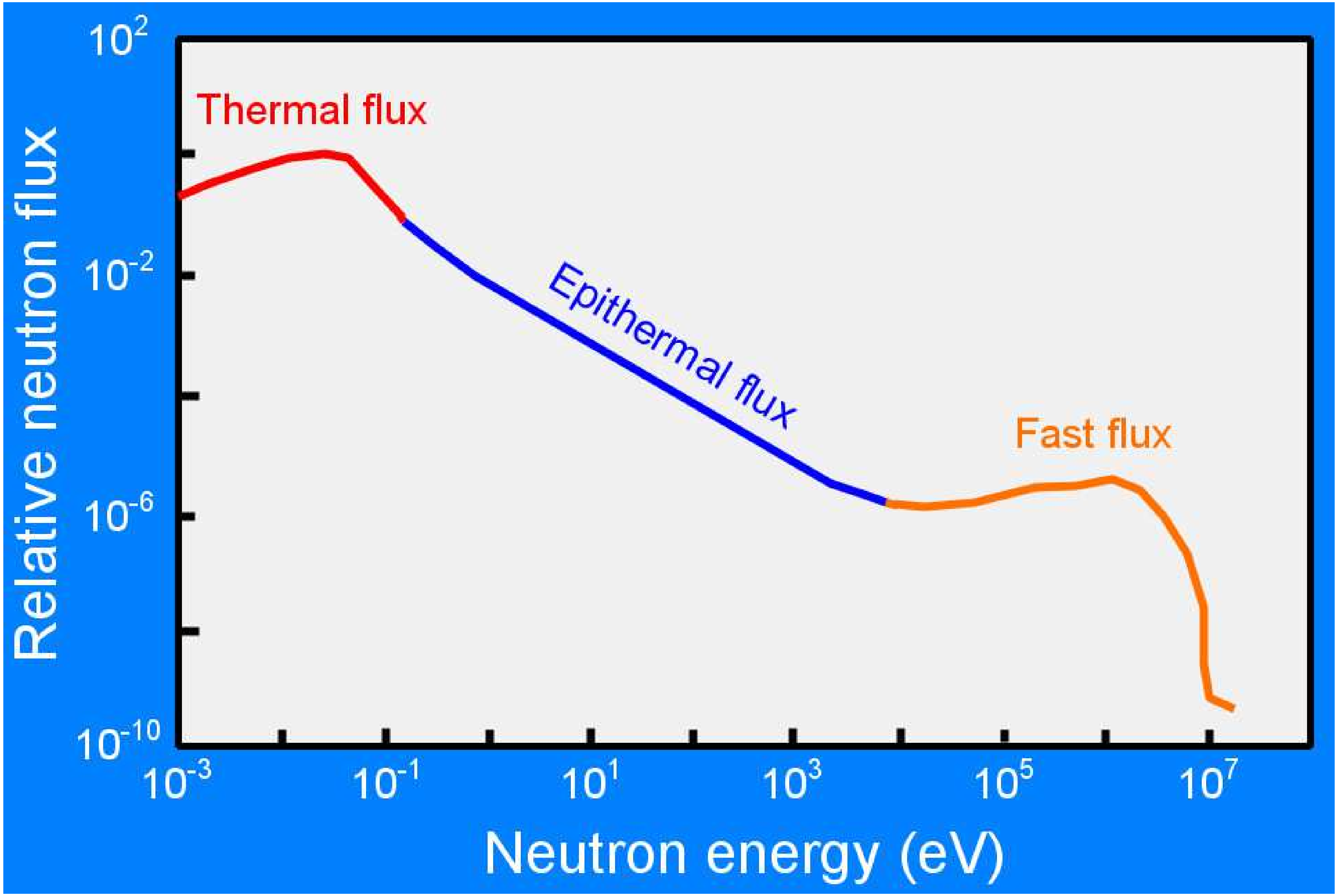
	Hydrogen	Deuterium	Beryllium	Carbon	Oxygen	Uranium
Mass of kernels u	1	2	9	12	16	238
Energy decrement	1	0.7261	0.2078	0.1589	0.1209	0.0084
Number of Collisions	18	25	86	114	150	2172

Thermal and cold neutrons ← moderation

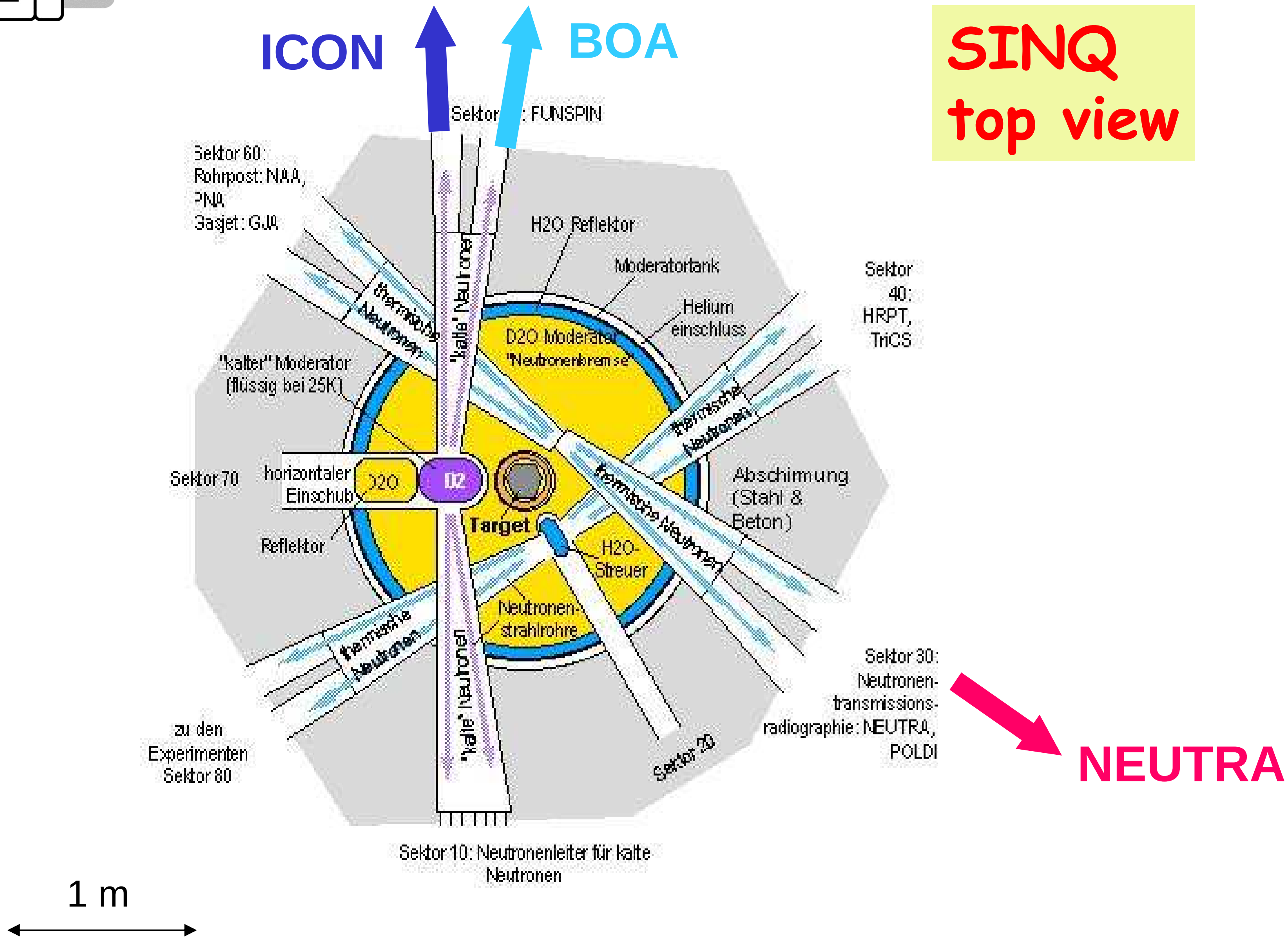
Nuclear Power Plant Moderators

Moderator	Reactors	Design	Country
none (fast)	1	BN-600	Russia (1)
graphite	29	AGR, Magnox, RBMK	United Kingdom (18), Russia (11)
heavy water	29	CANDU	Canada (17), South Korea (4), Romania (2), China (2), India (2), Argentina, Pakistan
light water	359	PWR, BWR	27 countries

Final spectral distribution

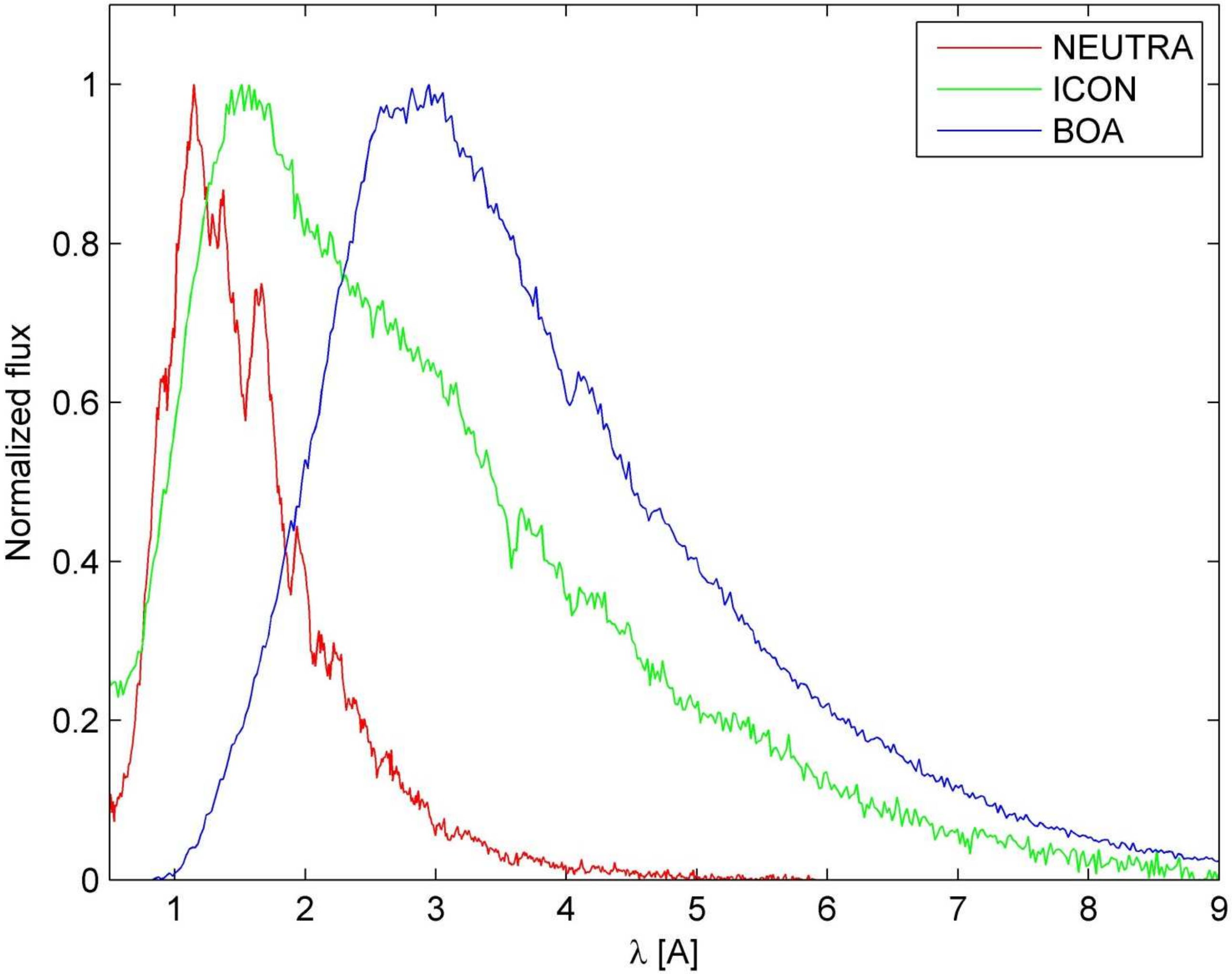


SINQ top view



Nomalized neutron spectra in comparison

(peak value = 1)



Typical neutron – matter interactions

Neutron absorption: important for detection, shielding and collimation; **activation**: emission of secondary radiation (mostly gamma) – ***nuclide card***

Neutron scattering: happens at all energies, own research topic with cold and thermal neutrons

Nuclear fission: only with fissile materials possible

«exotic» reactions: mostly in the high-energy range, (n,α), (n,xn); (n,pn), …

Materials of relevance in neutron research

for detection : He-3, B-10, Li-6, Gd-157

for shielding: Cd, B+plastics, Gd, H_2O (in concrete)

for sample holders, windows: Al, Zr, Si

As samples: e.g. organics within metal cases

Mono-energetic neutrons ?

1. Better quantification: no average over large spectral range (talk: P. Vontobel)

2. Resolving the behaviour near Bragg edges of structural materials (talk: S. Peetermans)

3. Grating interferometry (talk: B.Betz)

4. Imaging with polarized neutrons (talk: N. Kardjilov)

5. Diffractive imaging (of polycrystalline materials) (talk: M. Raventos)

Idealized conditions for a neutron imaging beam

- Quasi-parallel (high L/D-ratio)
- Beam size adequate to sample dimensions
- High intensity
- Narrow energy band (thermal or cold)
- No background from gamma rays or fast neutrons
- Flat beam profile
- No interference from back-scattered neutrons (and gammas)

→ **All optimization steps result in limited intensities**

Light excitation (scintillator)

Photo-stimulated Luminiscence (IP)

Have you ever seen a neutron?

How to see a neutron ?

Charge excitation (counter)?

Film blackening

Summary

- Even if some neutron imaging is possible with relatively weak sources (1E4 cm-2 s-1), for advanced neutron imaging we need access to highest beam intensities possible
- This is important for either spatial, time or energy resolution …and for best possible image quality.
- Time-of-flight (TOF) with pulsed sources is a new approach we still have to exploit for practical applications in the right manner
- Fission sources are dominant for neutron imaging facilities, but new approaches for accelerator based systems have to be supported … and considered as options … until «mobile» sources
- All exiting reactor based facilities should be upgraded with «reasonable effort» for imaging purposes. Experts Meeting foreseen in March 2016.