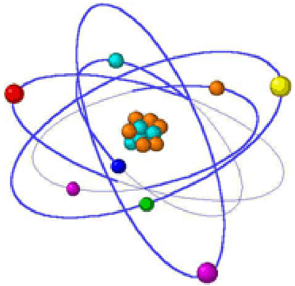
Radioisotope and Radiation Applications (FS2013)



NEUTRA / ICON Facilities at PSI (Week 6c, Seminar)

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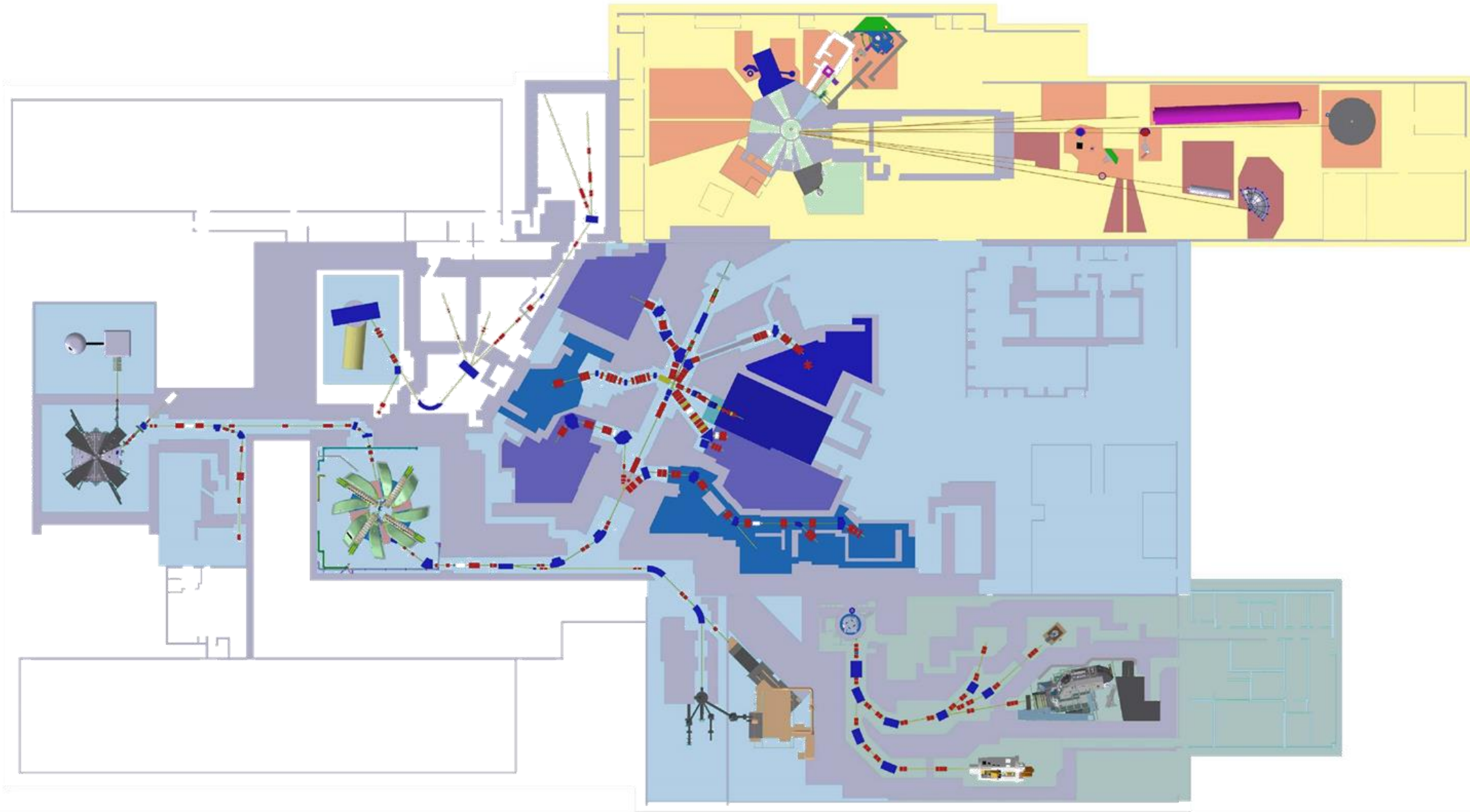
NEUTRA / ICON Facilities at PSI: Outline

- The Spallation Neutron Source SINQ at PSI
- The NEUTRA Beam Line
- The ICON Beam Line
- Types of Detectors
- Neutron Activation Service at PSI
- Literature / WWW-References

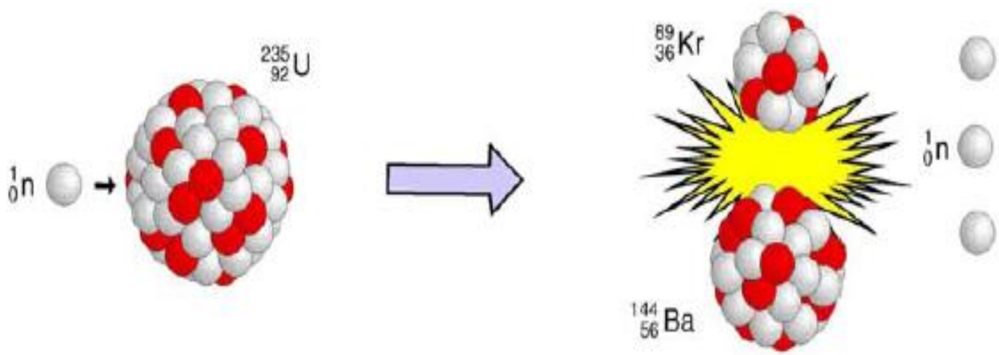
Proton-Accelerator and Experimental Areas (1)

Proton-Accelerator and Experimental Areas (2)

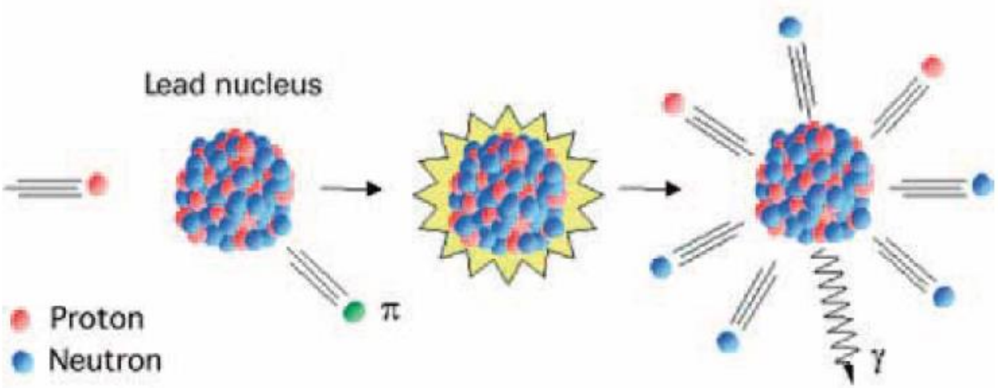
Location of the Spallation Neutron Source SINQ



Sources: Fission and Spallation at PSI

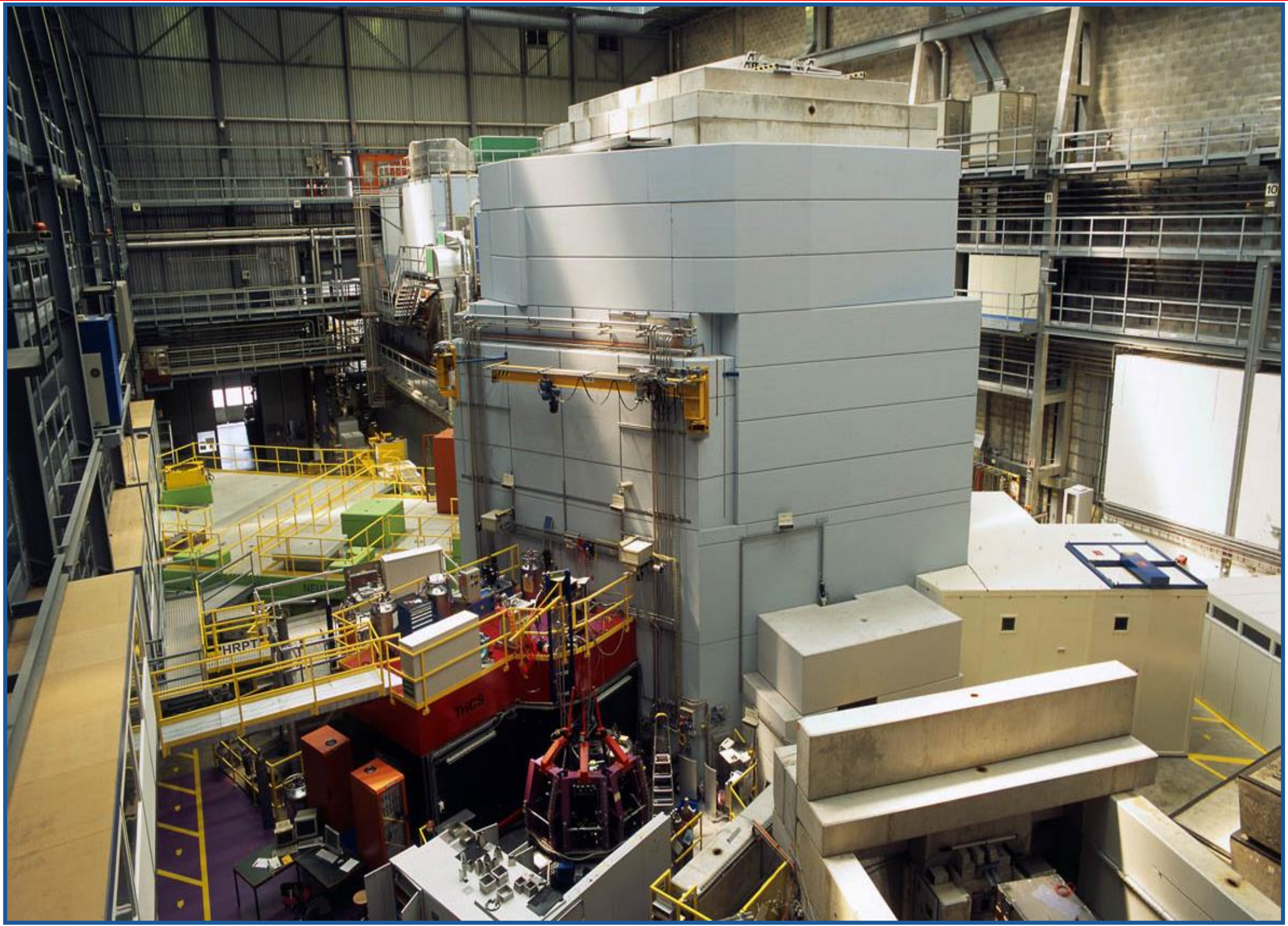


$$^{235}_{92}U + ^1_0n \longrightarrow ^{89}_{36}Kr + ^{144}_{56}Ba + 3^1_0n + 210\ \text{MeV}$$

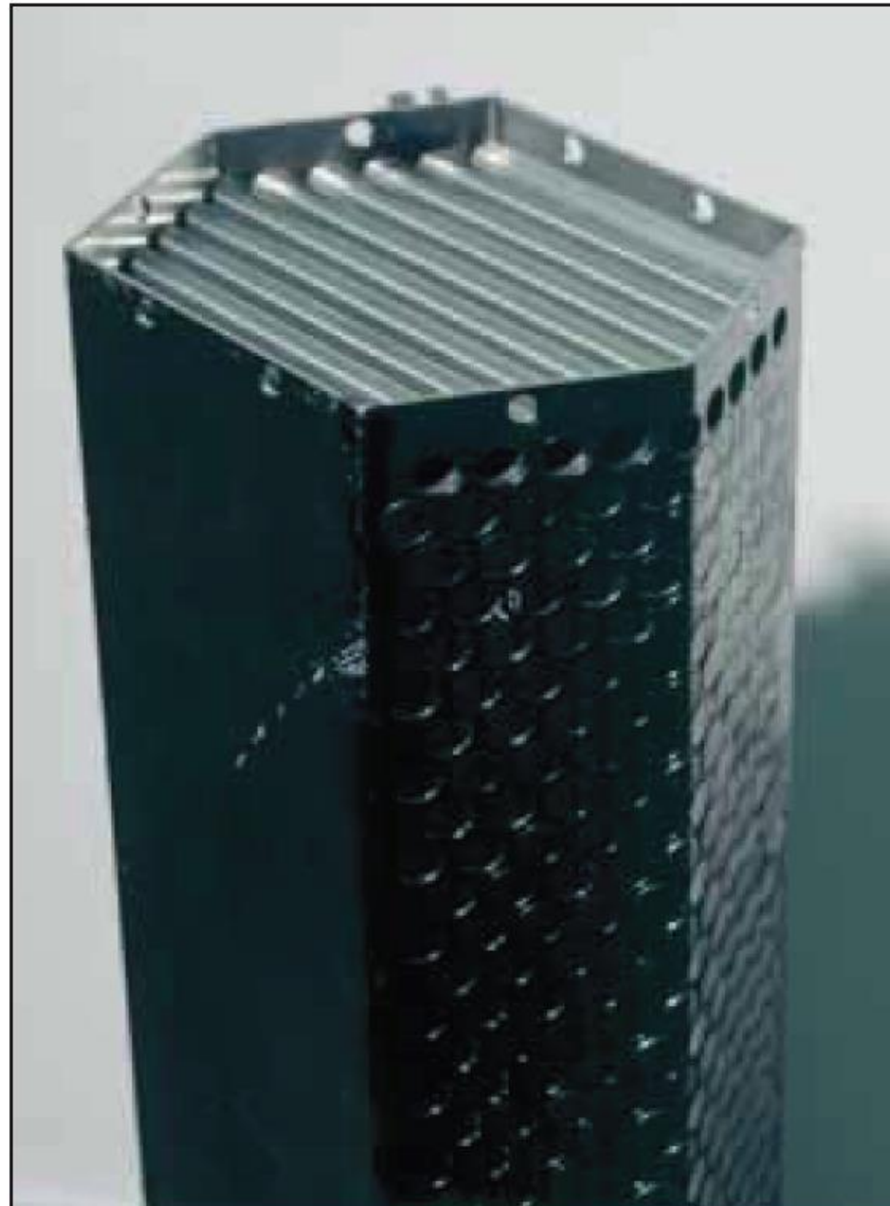


- Nuclear fission and spallation are the two most important nuclear processes producing free neutrons.
- **Neutron sources have been operated at PSI since many years**:
  - The research reactor **SAPHIR** was commissioned in 1957.
  - It has been replaced in 1996 by the spallation neutron source **SINQ**.
- The fast neutrons (~ 20’000 km/s) from the SINQ are slowed down to thermal energies (~ 2’200 m/s) in a heavy water filled moderator tank.
- Cold neutrons are produced by scattering thermal neutrons on cold molecules (liquid heavy hydrogen at 250 °C).
- In the future: ultra cold neutrons (UCN) by scattering on liquid deuterium $^2H_2$.

Spallation Neutron Source SINQ



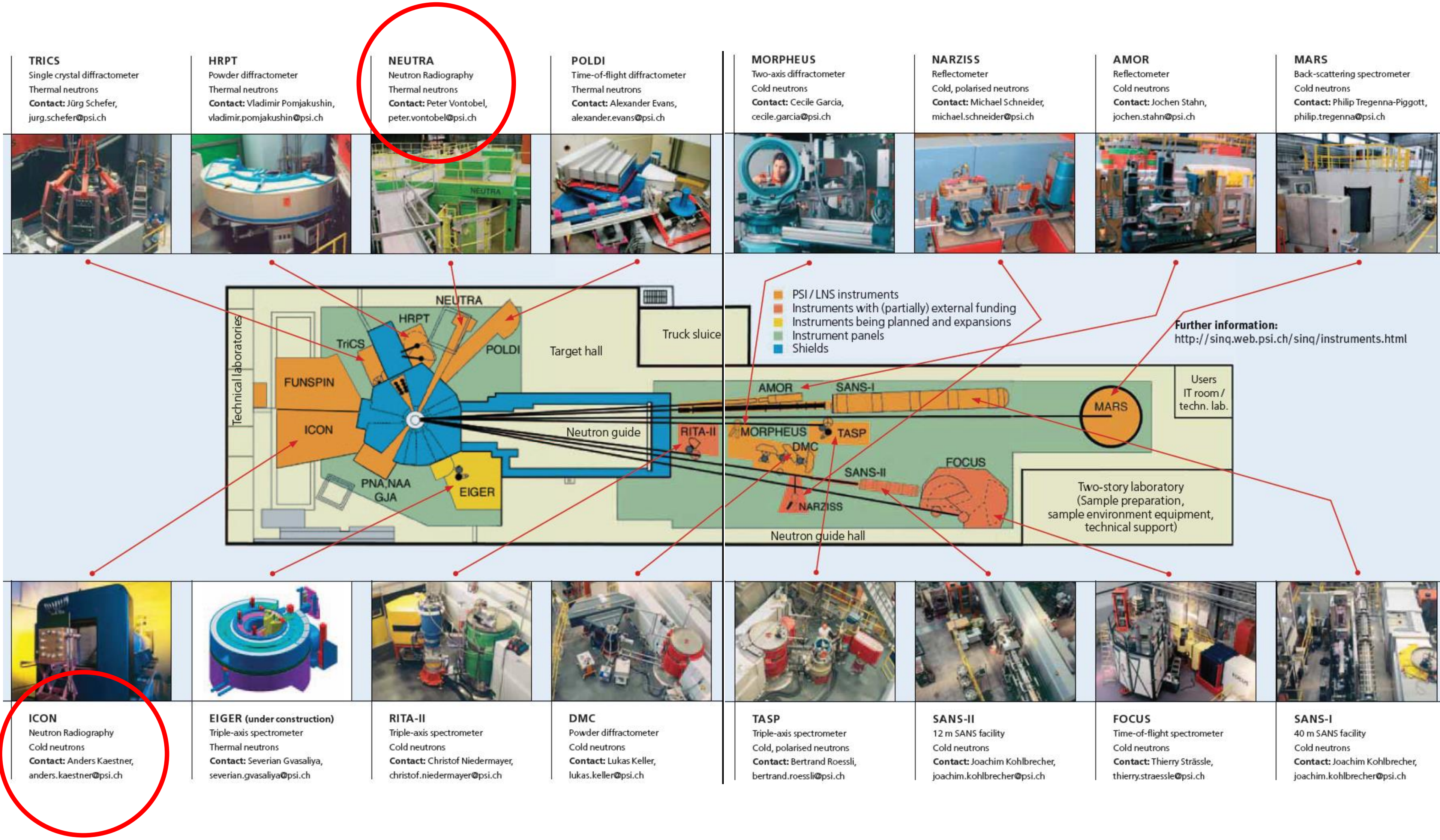
SINQ: Model and Target



The Particular Strengths Associated with Neutrons

NEUTRON PROPERTIES:	EXCEPTIONALLY WELL-SUITED FOR:
• **Wavelength compatibility** with the distance between atoms	Research into atomic structures
• **Energy compatibility** with the kinetic energy of atoms	Research into atomic dynamics
• **Electrical neutrality,** achieves deep penetration into matter, hardly any damage	Thick samples, biological substances
• **Scattering contrast**	Differentiation between elements with very small differences in mass
• **Hydrogen detection**	Samples containing water, biological substances
• **Microscopic bar magnet**	Research into structure and movement in magnetic substances

The SINQ Instruments

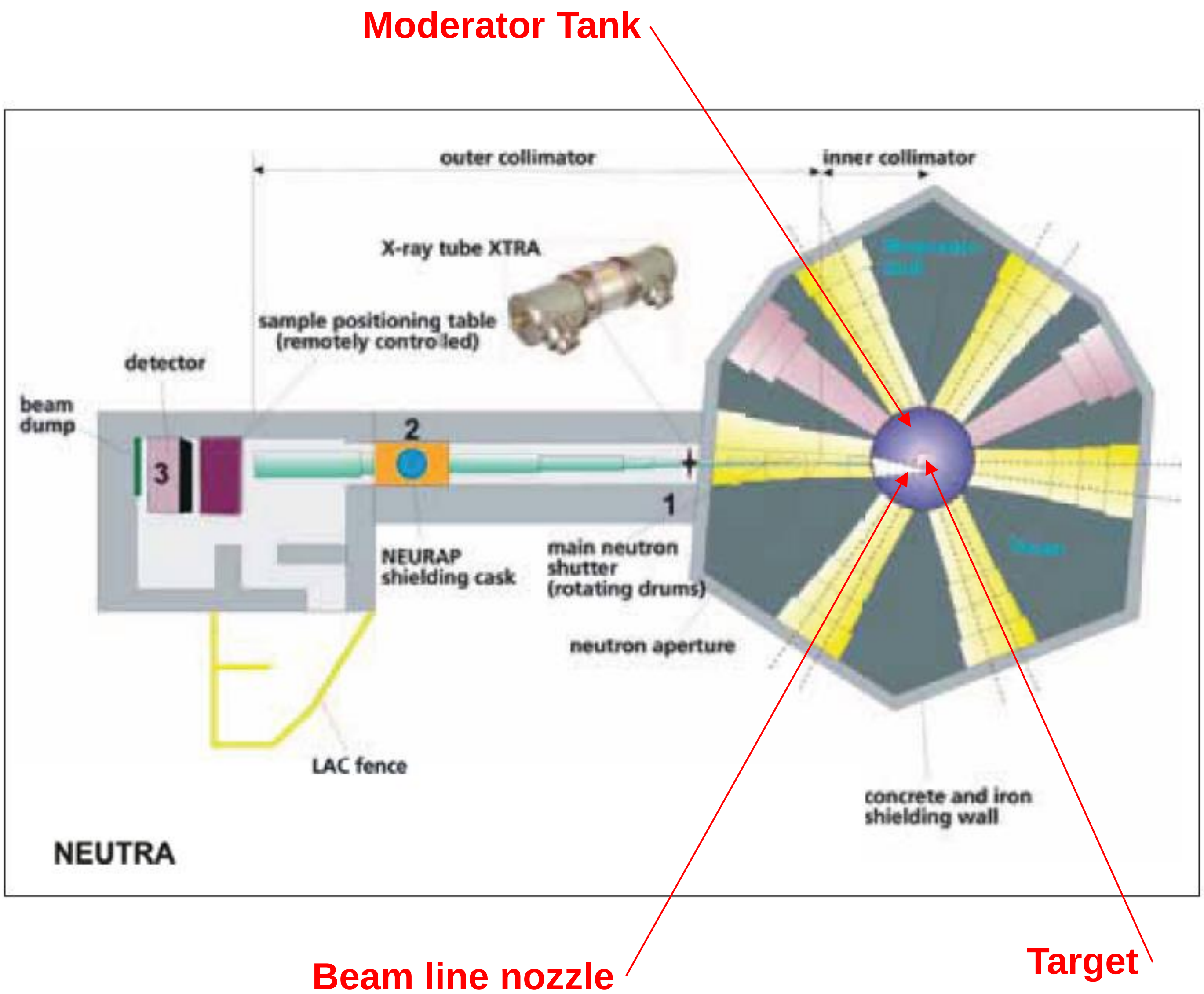


Neutron Guides

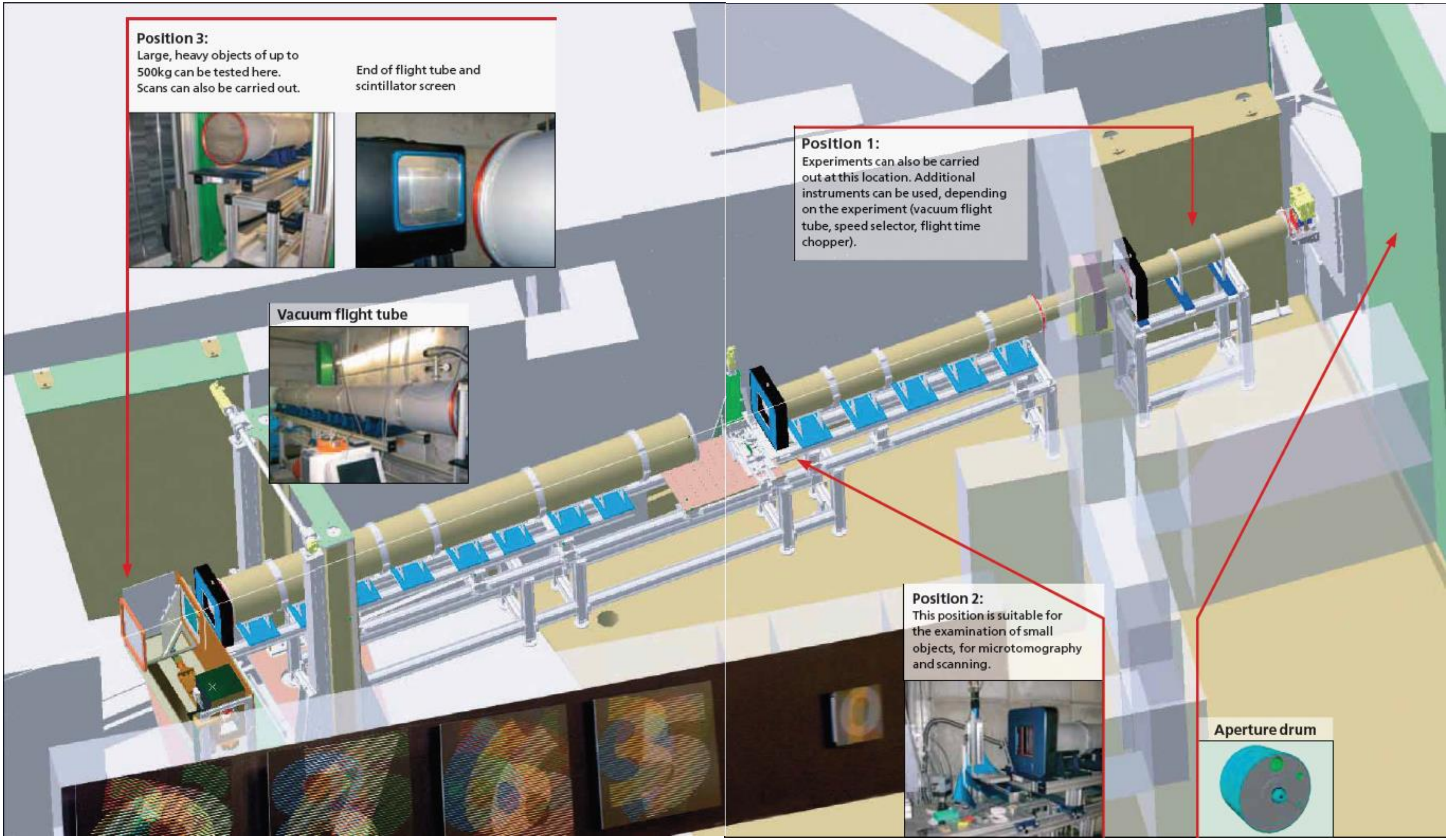
- The wave nature of cold neutrons is so pronounced that they can be directed by total reflection on suitable material surfaces (like light by mirrors).
- Neutron guides are specially mirrored glass ducts that can transport neutrons over large distances (50m or more) without any significant losses.

Facilities at PSI: NEUTRA (Neutron Transmission Radiography)

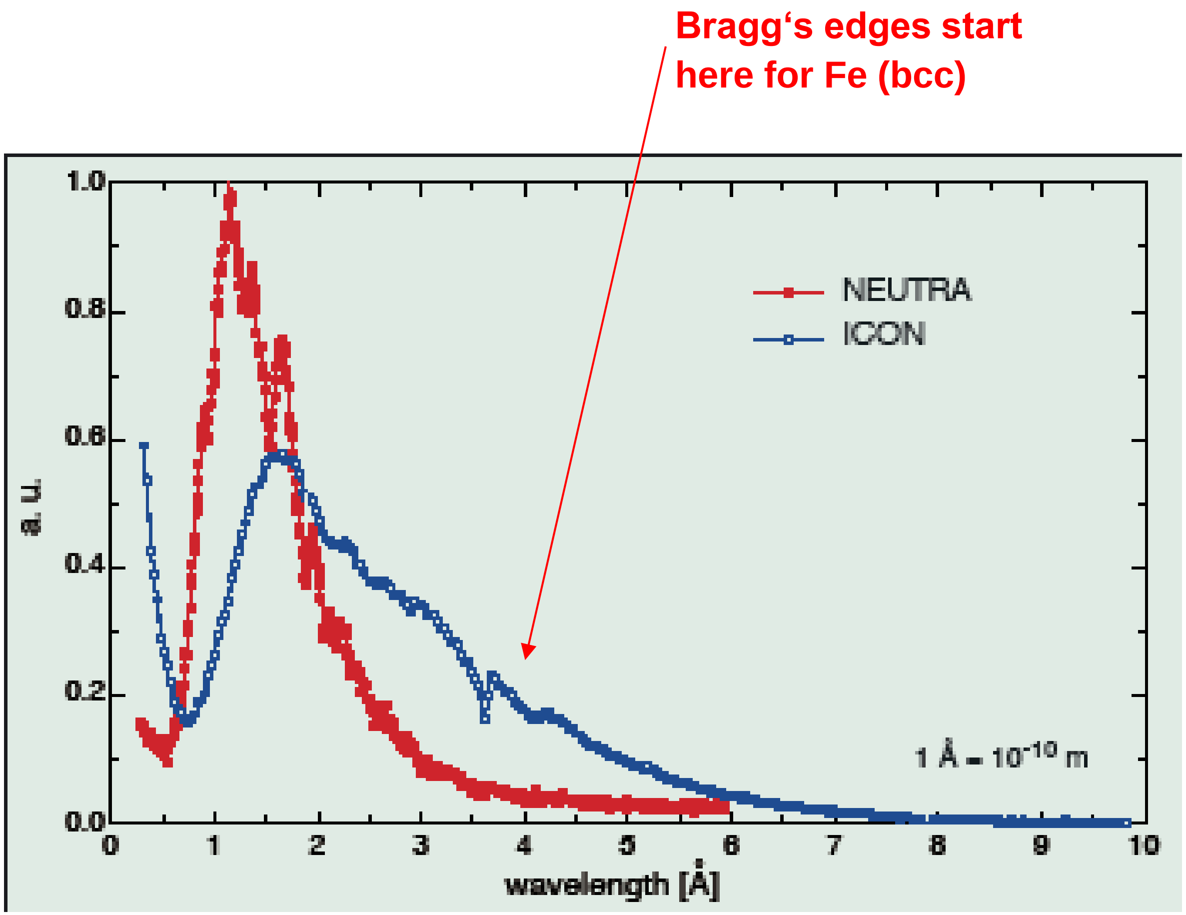
Internal view of NEUTRA (shielding partially removed). Right: graphic representation of NEUTRA.



Facilities at PSI: ICON (Instrument for Cold Neutron Radiography)



Facilities at PSI: NEUTRA versus ICON (1)



- Contrary to NEUTRA the ICON flight tube is located near the cold source box containing liquid heavy hydrogen at -250°C.
- Thus the neutron wave-length spectra of the two facilities are different.
- **The distinct spectra induce different penetration and image contrasts**, because:
  - Scattering of cold neutrons by thin layers (containing H) is enhanced.
  - Bragg edges due to cold neutron scattering on lattice structure.
  - Phase contrast enhanced RG for cold neutrons preferably.
  - Higher spatial resolution achievable by the use of thin scintillators.

Facilities at PSI: NEUTRA versus ICON (2)

	NEUTRA	ICON
Neutron aperture D	fixed: ø 20 mm	variable: ø 1,0 – 80 mm
Collimation ratio L/D	200, 350, 550	numerous stages: 90 – 10 000
Neutron flux (n/cm²/s/mA) (L = 7,1 m, D = 2 cm)	$7{,}5\ 10^6$	$9{,}2\ 10^6$
Filter for γ and fast neutrons	Bismut	no filter
Tomograpy setup	“large” samples	includes microtomography
Beryllium filter	none	available
Energy selector	none	available
Combination with X-ray	XTRA	no X-ray tube
Setup for highly-active samples	NEURAP	weakly-active samples only

Detectors applied in Neutron Imaging (Overview)

$^{6}Li + {}^{1}n \Rightarrow {}^{3}H + {}^{4}He + 4.79\ MeV$

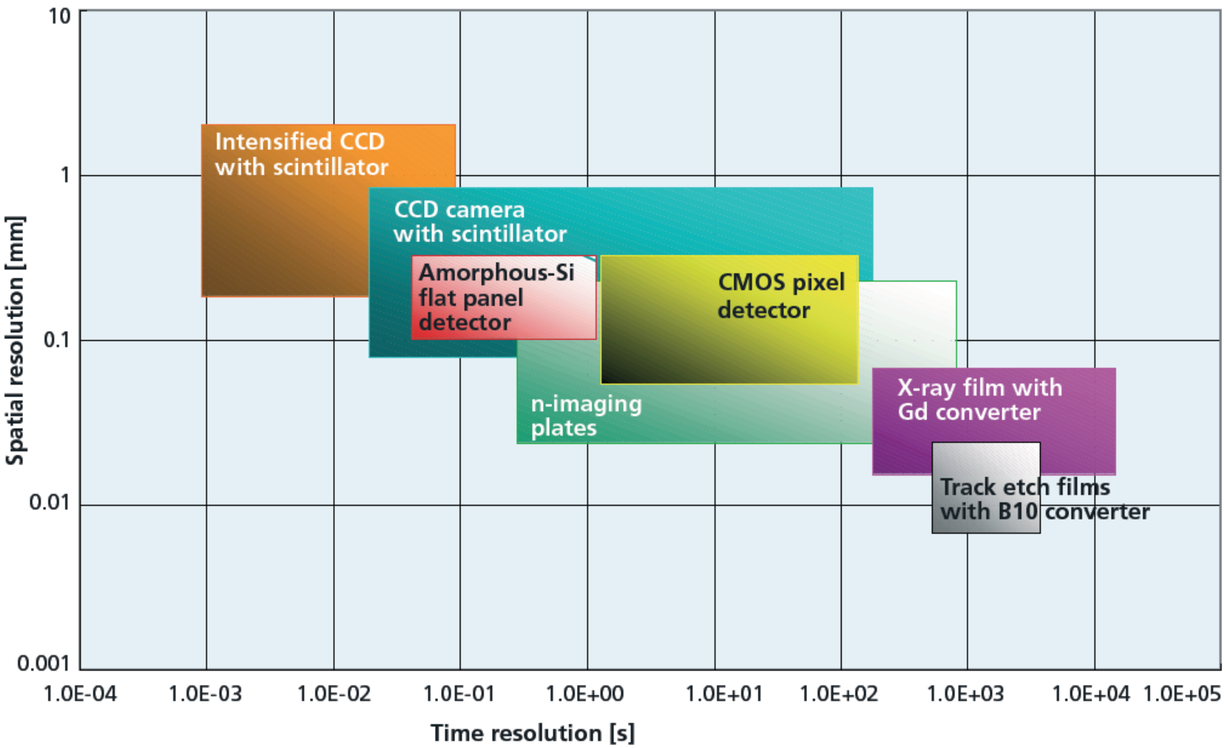
$^{10}B + {}^{1}n \Rightarrow {}^{7}Li + {}^{4}He + 2.78\ MeV$ (7%)

$\Rightarrow {}^{7}Li^{*} + {}^{4}He + 2.30\ MeV$ (93%)

$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma's + CE's$ (7.9 MeV)

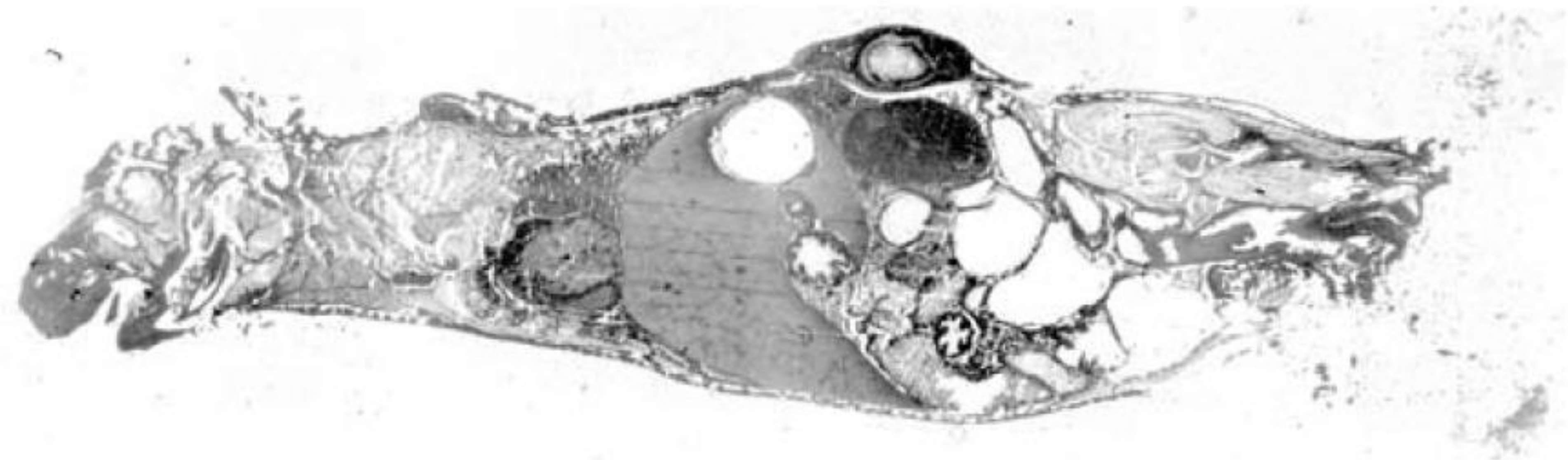
$^{157}Gd + {}^{1}n \Rightarrow {}^{158}Gd + \gamma's + CE's$ (8.5 MeV)

- Neutron detection is based on the creation of charged particles by reactions on nuclei with a high neutron capture cross section:
  - ^{6}Li, ^{10}B, Cd, Gd-isotopes



- Various detector types covering a range of time and spatial resolutions are used:
  - Film based detectors.
  - Neutron scintillation screen and CCD camera.
  - Silicon flat panel detector (array of small photodiodes).
  - Imaging plates.
  - CMOS pixel detector.

Detectors: Film Based Methods

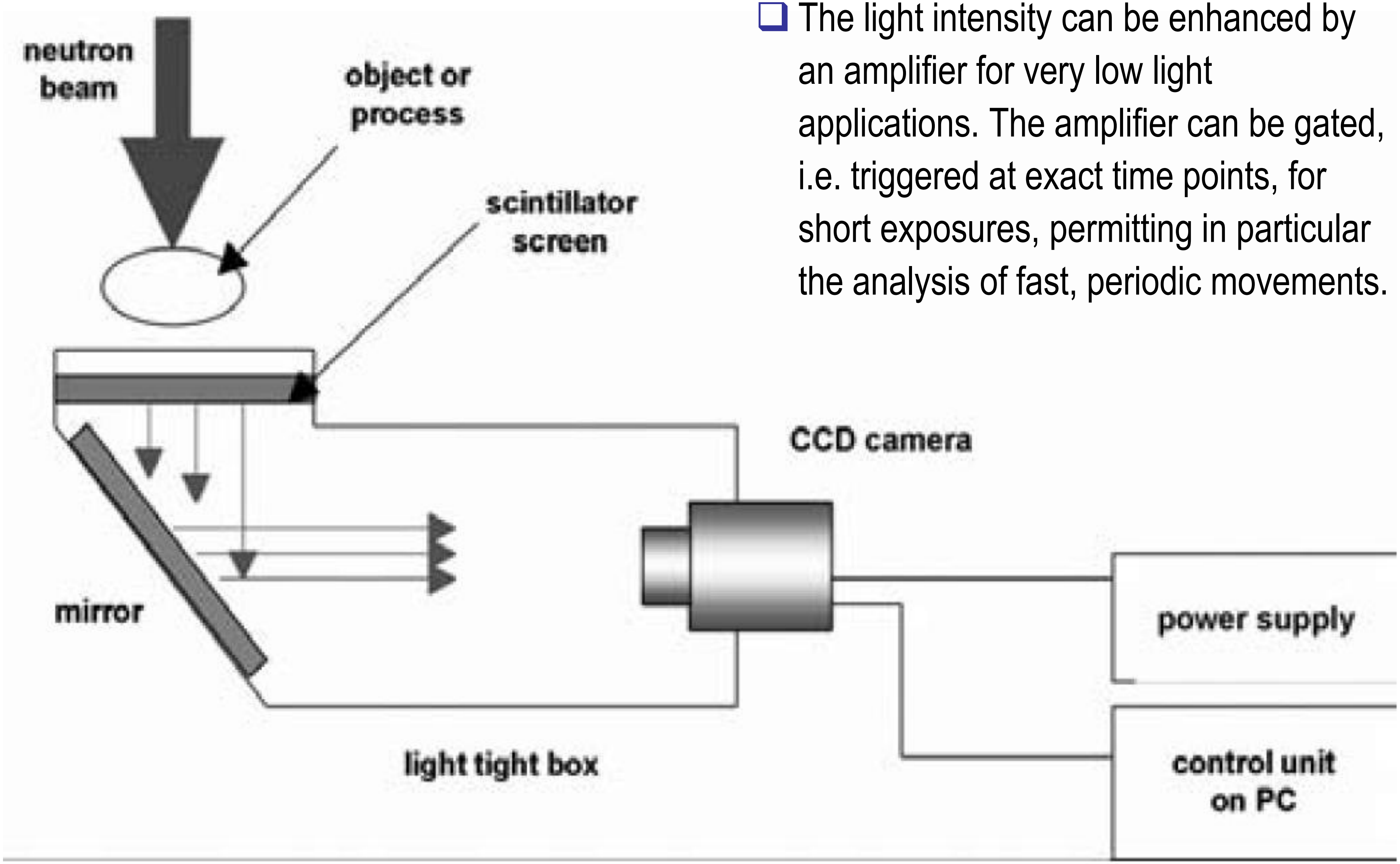


- X-ray films and special “track-etch foils” provide analogue images of high spatial resolution, but require long neutron exposures and film-development times.

Detectors: CCD Camera with Scintillator

- The cooled, light-sensitive CCD chip of the camera captures the light emitted from the neutron-sensitive scintillation screen. Optical lenses fitted to the camera head capture variably sized fields-of-view from 4 to 40 cm. This detector is especially useful for neutron tomography.

Detectors: CCD Camera with Light Amplifier



- The light intensity can be enhanced by an amplifier for very low light applications. The amplifier can be gated, i.e. triggered at exact time points, for short exposures, permitting in particular the analysis of fast, periodic movements.

Amorphous Silicon Flat Panel Detector

- Light emitted from the neutron scintillation screen is captured by a narrow array of small photodiodes in direct contact with the screen. The diodes accumulate charges, which can be read out at high frequency, permitting “real-time” neutron imaging.

Detectors: Imaging Plates

- These large-area, thin, plastic-like foils capture neutrons in a matrix containing gadolinium isotopes mixed with a barium, fluorine, europium. Electron-hole pairs are generated, which, by laser irradiation, induce light emission. This photostimulated luminescence can be recorded with high spatial resolution using a laser scanning device.

CMOS Pixel Detector

- An array of pixels collects the charges generated by neutron capture. Each pixel has its own amplifier and digital converter, permitting low-noise acquisition of multiple neutron events and fast detector read-out.

Comparison of Detectors

Detector system	Field of view (typical)	Pixel size [mm]	Dynamic range [greylevels]	Typical exposure time [s]	Read-out time [s]	Read-out rate [1/s]	Special prop.
Film + converter	18 cm * 25 cm	0.02	100	approx. 1000	approx. 2000	not relevant	
Track-etch foil + B10	10 cm * 10 cm	0.02	100	approx. 2000	approx. 2000	not relevant	
CCD-camera + scintillator	25 cm * 25 cm	0.05–0.2	65536 (16 Bit)	1 to 20	1 to 5	0.1 – 0.5	
intensified CCD + scintillator	25 cm * 25 cm	0.05–0.3	4096 (12 Bit)	0.001 to 1	1 to 5	0.1 – 0.5	trigger
n-sensitive imaging plate	20 cm * 40 cm	0.05	65536 (16 Bit)	approx. 10	approx. 300	not relevant	multiple use
amorph-Si flat panel	20 cm * 25 cm	0.127	4096 (12 Bit)	0.03 to 2	continuous	1 to 30	
Pixel-detector	3 cm * 8 cm	0.25	unlimited	> 1	< 1		

- **The requirements and aim of the investigation determine which system should be used.**
- By their nature, digital images allow numerical processing, i.e.:
  - Statistical or systematic image distortions can be eliminated by methods of digital image analysis like noise filtering and contrast enhancement.
  - Multiple images can easily be compared or transformed (e.g. divided) into new images.

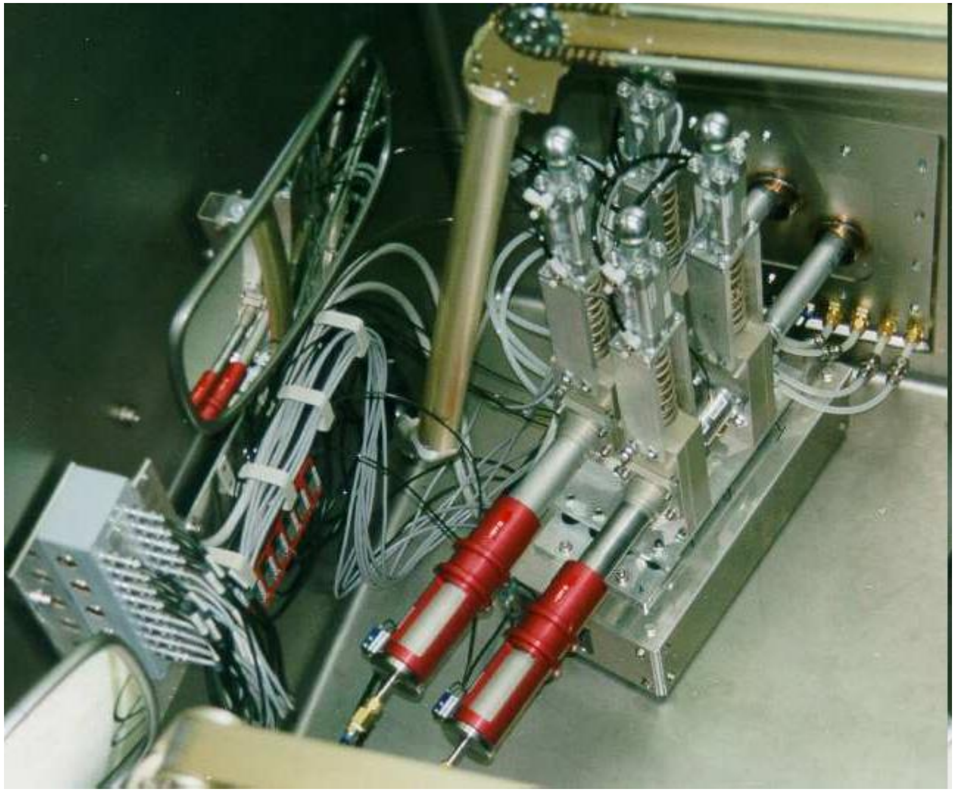
Neutron Activation Service at PSI

- The neutron activation service at PSI provides two facilities:
  - **Preparative Neutron Activation (PNA) for the production of isotopes, and**
  - **Neutron Activation Analysis (NAA).**
- At both facilities probes can be irradiated with thermal neutrons from the SINQ with fluxes in the range from $1 \cdot 10^6$ to $1.5 \cdot 10^{13}$ n/(cm^2 sec). In detail the following fluxes can be provided:

Irradiation Position	Thermal Flux [n/(cm^2 sec)]	Type of irradiation capsule	Irradiation time	Decay time
PNA1	up to $1.5 \cdot 10^{13}$	PNA (Al)	2 to 10'000min	up to ~120min
PNA2	up to $1.5 \cdot 10^{13}$	PNA (Al)	2 to 10'000min	up to ~120min
NAA1	up to $0.3 \cdot 10^{13}$	NAA (PE)	10 to 7'200sec	up to ~60sec
NAA2	up to $0.3 \cdot 10^{13}$	NAA (PE)	10 to 7'200sec	up to ~60sec
NCR(cold n)	up to $4.5 \cdot 10^{8}$	(PE-foil)	2 to 10'000min	up to ~10min
PNA(photo-n)	up to $1.2 \cdot 10^{6}$	PNA (Al)	2 to 10'000min	up to ~30min
NAA(photo-n)	up to $1.2 \cdot 10^{6}$	NAA (PE)	10 to 7'200sec	up to ~60sec

PNA Facility

- For irradiation in the PNA facility the material is encapsulated in a silica glass ampule.
- The ampule is wrapped in a protective foil and shrink-wrapped in an Aluminum capsule.
- The capsules have a length of 60mm, a diameter of 20mm, and can incorporate up to 10g of material. The material to be irradiated must be dry and temperature resistant (up to 200°C).
- By pneumatic delivery in a He-loop the capsules are transported to the irradiation position.

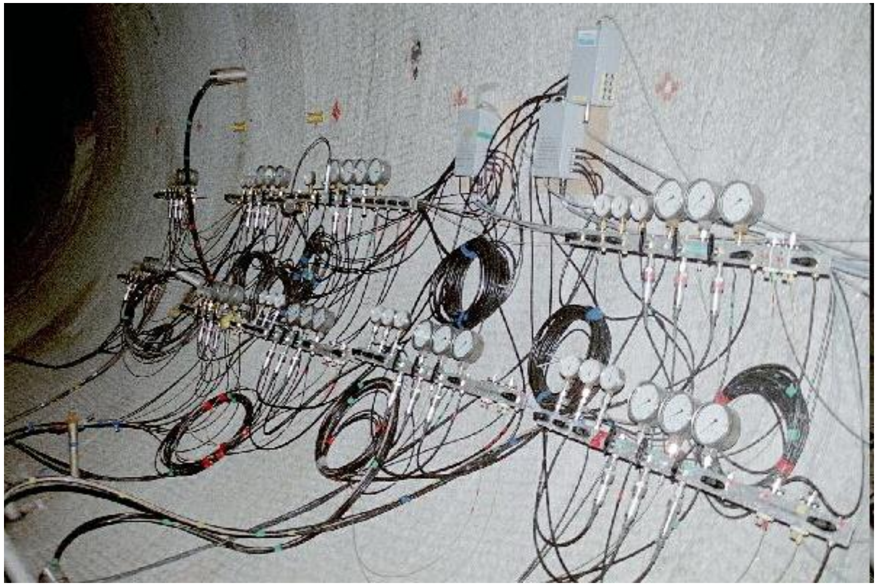


NAA Facility

- For irradiation in the NAA facility the material is put in a polyethylene bottle.
- The polyethylene bottle is again encapsulated in a polyethylene capsule.
- The capsules have a length of 30mm, a diameter of 15mm, and can incorporate up to 5g of material. The material to be irradiated must be dry and temperature resistant (up to 80°C).
- By pneumatic delivery in a He-loop the capsules are transported to the irradiation position.

Applications of PNA / NAA

- ^{82}Br is used as a tracer to study the dispersion of radionuclides in rock (geological disposal).
- At the hazardous waste deposit in Kölliken (Switzerland) ^{82}Br is used as a tracer to investigate the flow of the ground water.
- With ^{24}Na two-phase-flow studies are performed to measure the mass flow in NPP Beznau.



Literature / WWW-references

- *PSI-Brochures: (available in English, German and French)*
  - **Neutron Imaging** / How neutrons create pictures, (Villigen PSI, November 2007)
  - **Neutrons for Research** / The Spallation Neutron Source SINQ at the Paul Scherrer Institute, (Villigen PSI, January 2009)
- Neutron Imaging and Activation Group at PSI: http://neutra.web.psi.ch