Neutron Diffraction - Neutron Imaging Instruments and Application & An overview of the Italian Users Community

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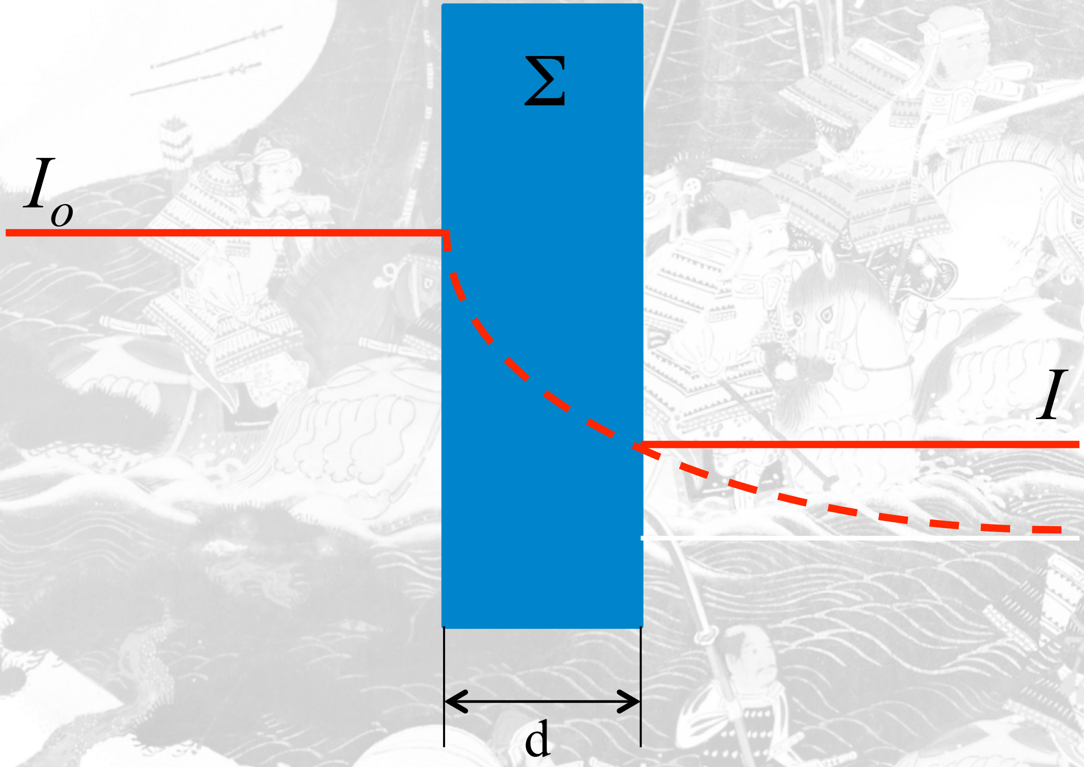
Neutron Imaging: principles



$$I = I_0 e^{-\Sigma d}$$

Lambert-Beer law

$$T = \frac{I}{I_0}$$

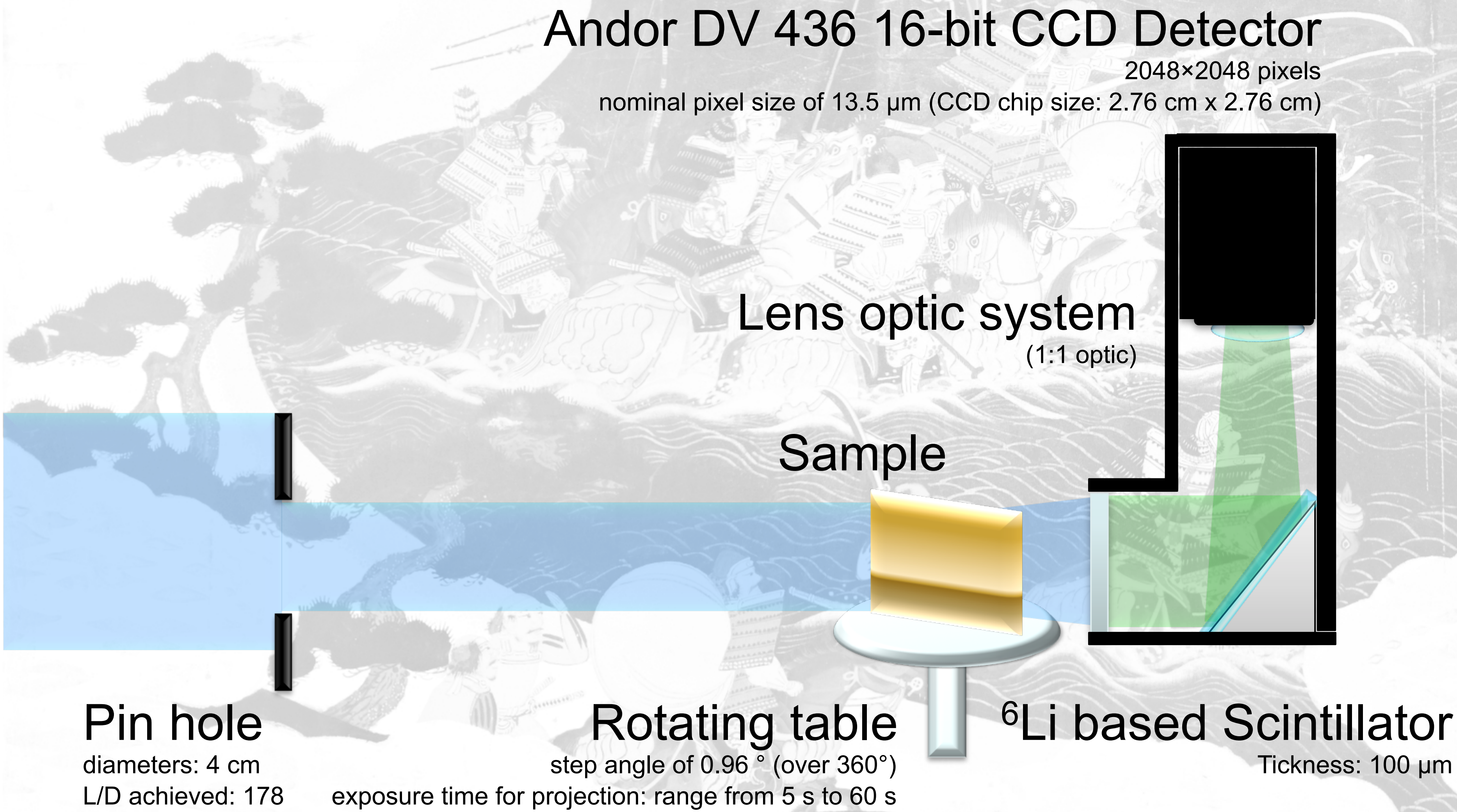
Trasmittance

$$-\ln(T) = \Sigma d$$

& $\Sigma = \sigma n$

Contrast:
material (σ) and thickness(d)

Instrumental set-up



Atomic Absorption cross sections

X Ray

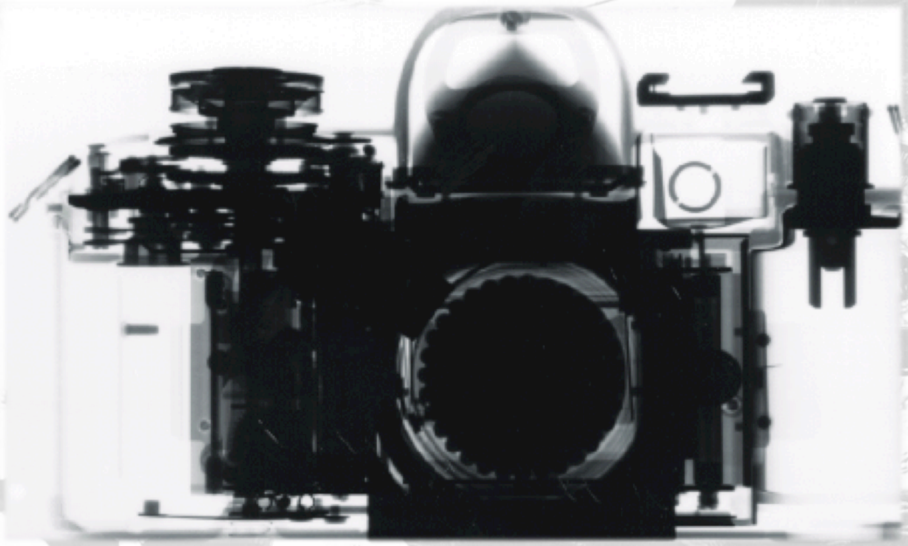
Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 0.02																	He 0.02
2	Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
3	Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
4	K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
5	Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
6	Cs 1.47	Ba 2.73		Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At -	Rn 9.77
7	Fr -	Ra 11.80		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 5.04	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.17	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
Actinides				Ac 24.47	Th 28.95	Pa 39.65	U 49.08	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

Neutron

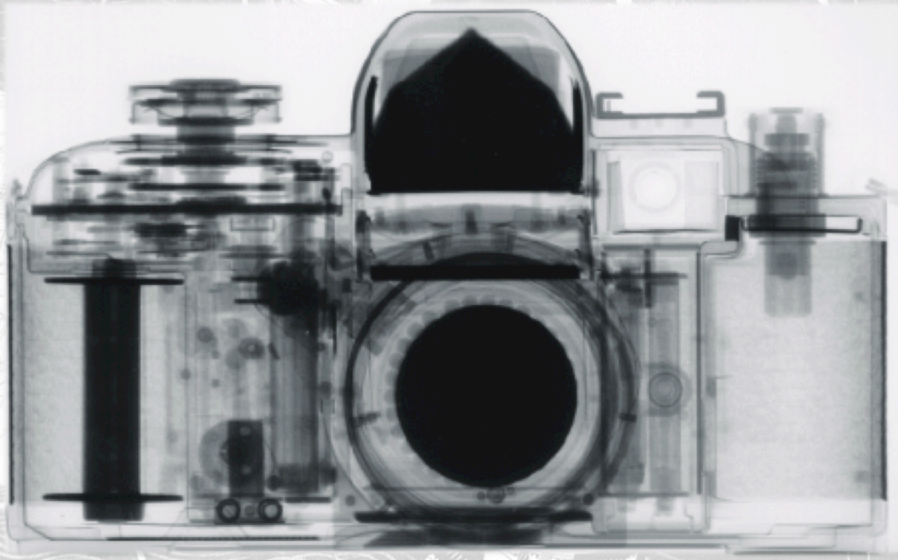
Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 3.44																	He 0.02
2	Li 3.30	Be 0.79											B 101.6	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
3	Na 0.09	Mg 0.15											Al 0.1	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
4	K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
5	Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.1	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
6	Cs 0.29	Ba 0.07		Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po -	At -	Rn -
7	Fr -	Ra 0.34		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 0.52	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.0	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
Actinides				Ac -	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

Courtesy E. Lehmann – PSI(CH)

Complementary x-ray / neutron imaging results



X-Ray



Neutron

Neutrons are optimal for:
-light elements,
-metals

Courtesy PSI(CH)

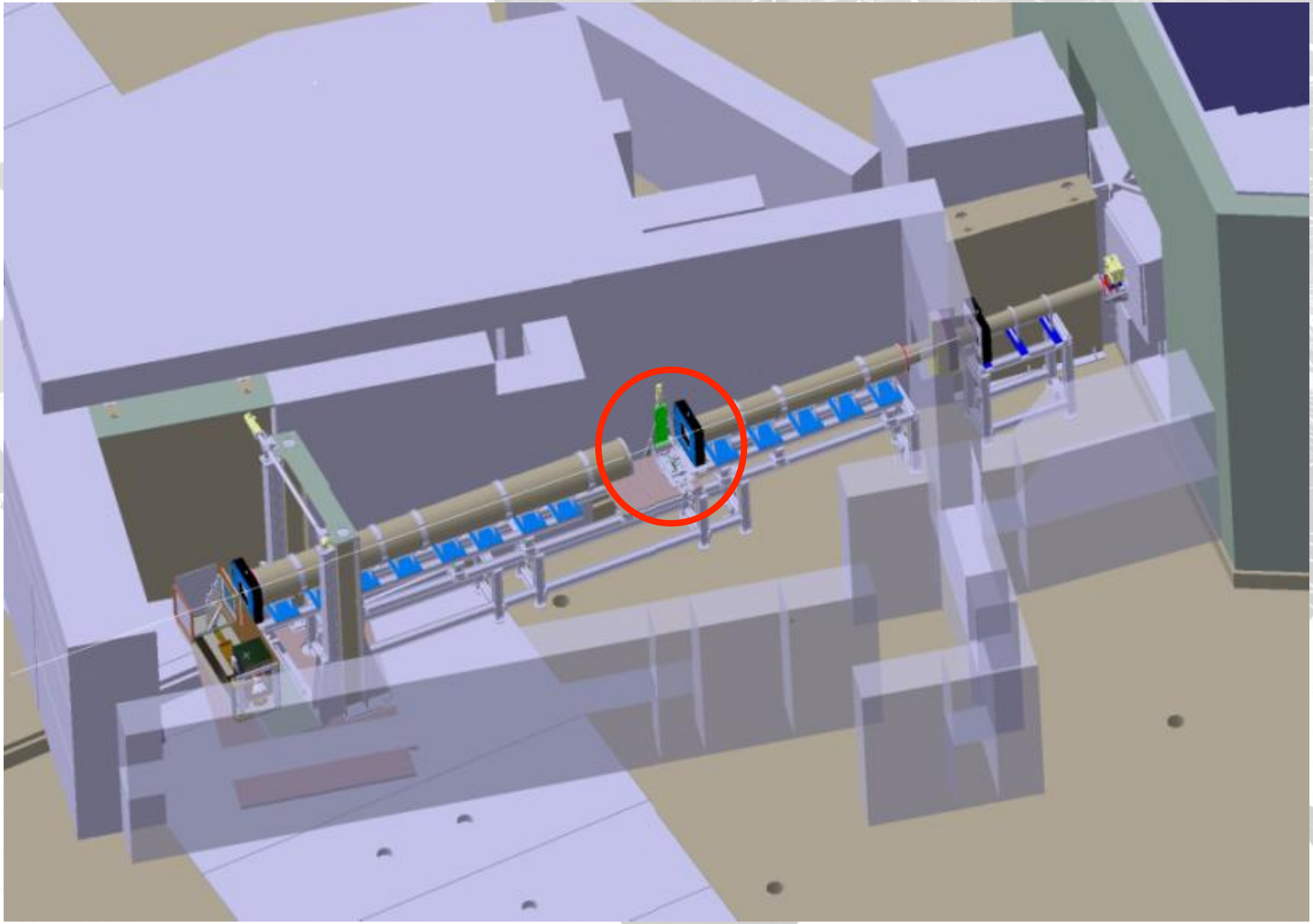
Neutron imaging beamlines in Europe (with open access user program)

NEUTRA	thermal neutrons	Paul Scherrer Institut (CH)
ICON	cold neutrons	Paul Scherrer Institut (CH)
CONRAD	cold neutrons	Helmholtz Zentrum (De)
ANTARES	thermal neutrons	TUM-FRM2 (De)
NECTAR	epithermal neutrons	TUM-FRM2 (De)

Neutron imaging future beamlines in Europe

IMAT (under constr.)	thermal neutrons	ISIS (UK)
ODIN (approved project)	cold neutrons	European Spallation Source (Sw)

An example:
ICON beamline at SINQ - PSI



Beamline components

- Moderator

- Flight tube under vacuum

- Pin hole: resolution is proportional to L/D parameter
  (L: distance diaphragm-sample, D: diaphragm aperture)

- Rotating stage (for tomographies)

- Scintillator (GdO, LiF+ZnS)

- Optics (mirror, lens)

- CCD camera

- Image processing software

A few numbers

- **Resolution** is a function of L/D, scintillator type and thickness, CCD camera pixel size.

Typical values range from 20 to 300 μm

- **Brigthness** and **contrast** depends on moderator type, neutron flux, scintillator type and thickness, CCD camera dynamic range

Typical measuring time for a radiography ranges from 2 to 120 s

- **Field of view** ranges from 20x20 mm^2 to 350x350 mm^2

- **Neutron flux** ranges from $1*10^5$ to $5*10^7$ $n/cm^2/s$

- World **user community** comprehends about 2000 scientists in the last 5 years

- **Proposed** vs **accepted** experiments **ratio** in Europe is more than 3:1

Applications

Non-destructive Testing

Traditional applications: detection of cracks, lunkers, explosives etc.

Nuclear technology: fuel inspection

Scientific Applications

Environmental research: soil physics, wood science, plant physiology ...

Electro-chemistry: fuel cell research, battery technology ...

Combustion engineering: fuel injection, exhaust gas treatment ...

Geoscience

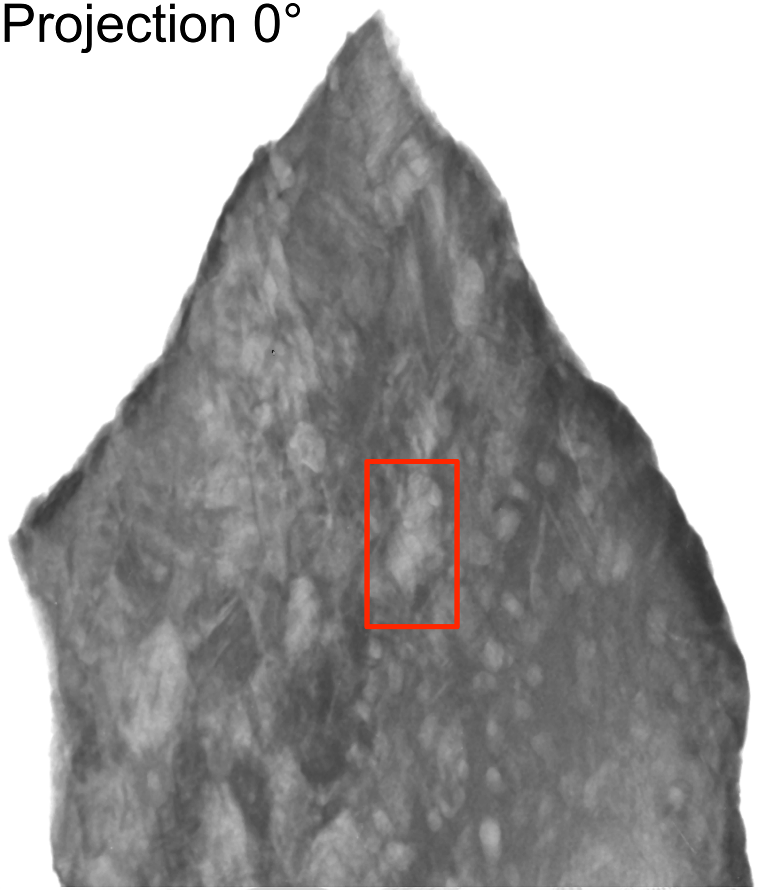
Archaeology and Cultural Heritage

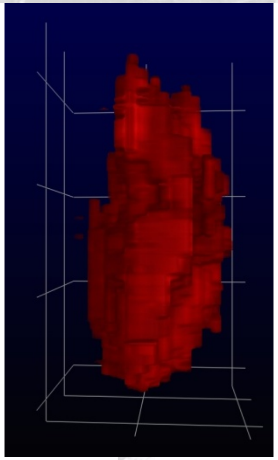
Construction engineering

Time resolved coffee making

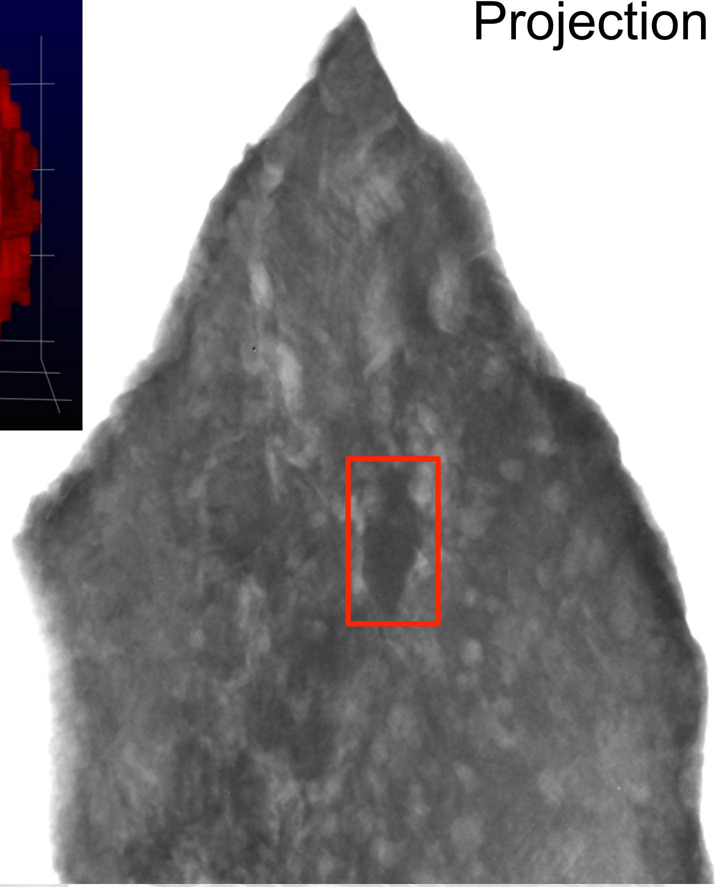
Tomographic reconstruction of single crystal grains in meteorites using monochormatic neutron tomography

Projection 0°



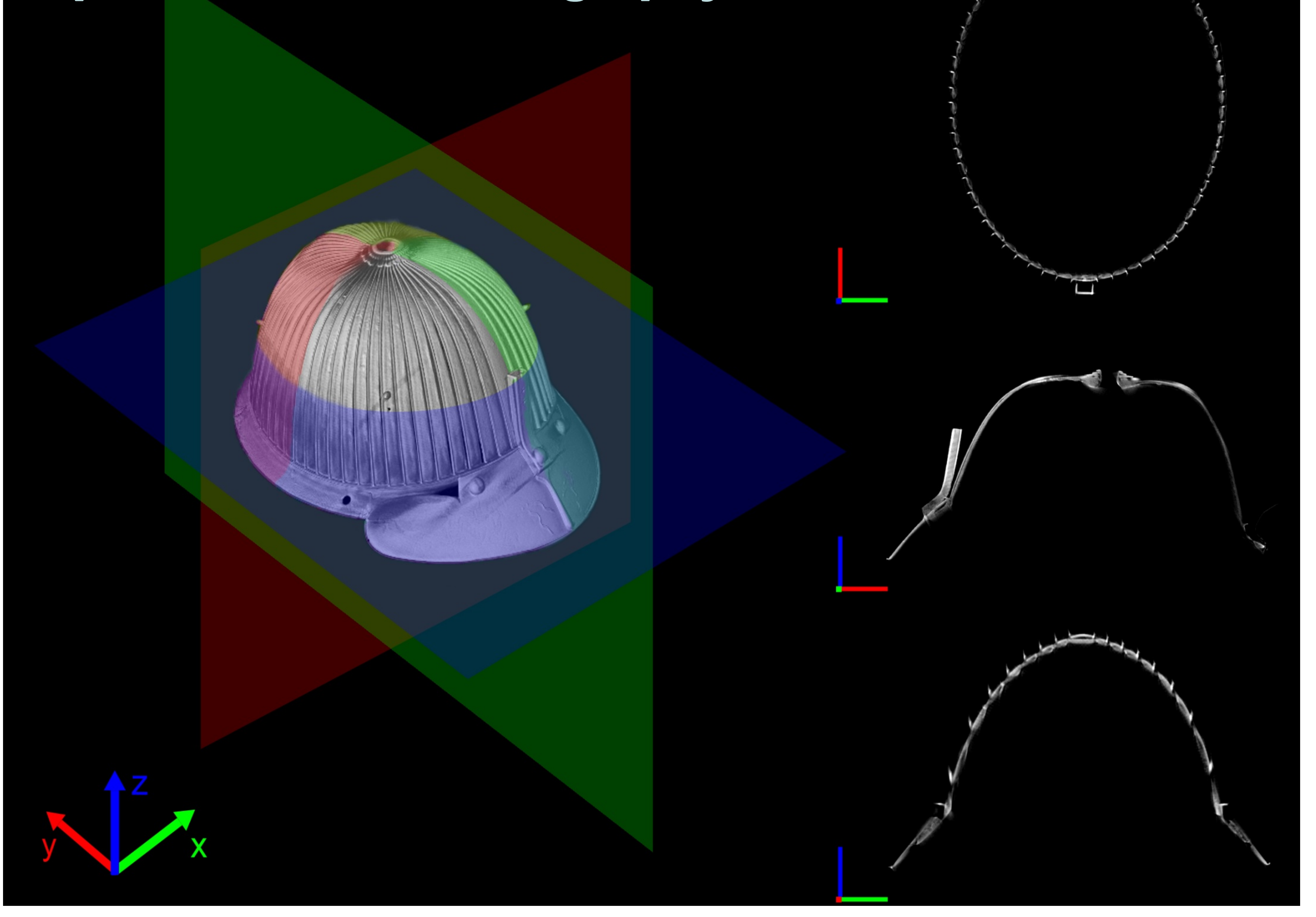


Projection 21.5°



Kaczmarz method (S. Peetermans - PSI)

Japanese helmet tomography



Neutron Powder Diffraction: principles

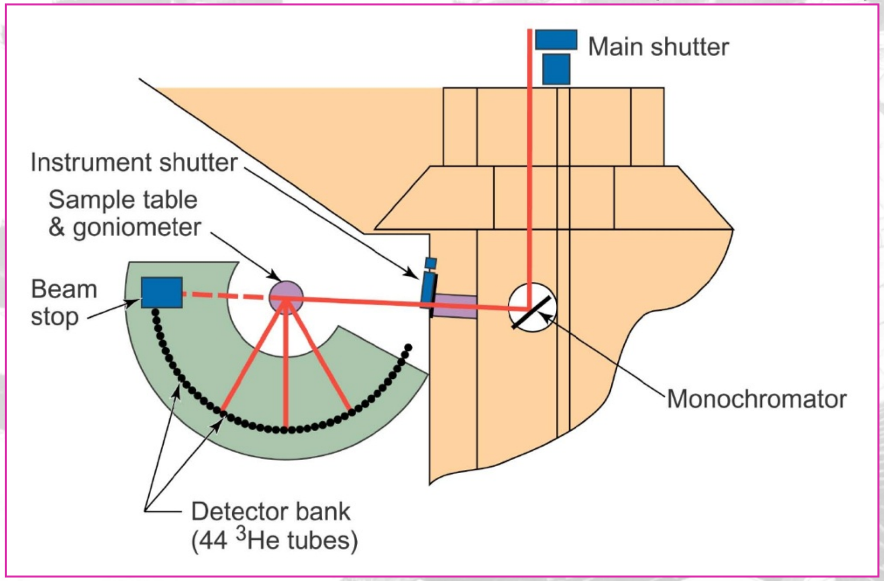
Bragg law: $$d = \frac{\lambda}{2\sin\vartheta}$$

Constant Wavelength (CW) diffraction $\lambda = const, d = f(\sin\vartheta)$

Time of Flight (ToF) diffraction $\sin\vartheta = const, \lambda = f(t), d = g(t)$

Instrumental set-up (Constant Wavelength)

HB-2A neutron powder diffractometer (ORNL, USA)



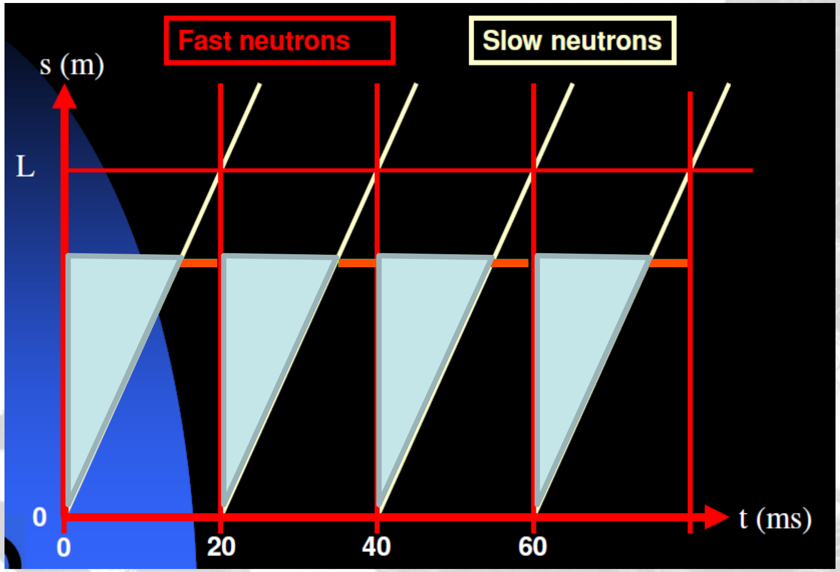
2 axis instrument

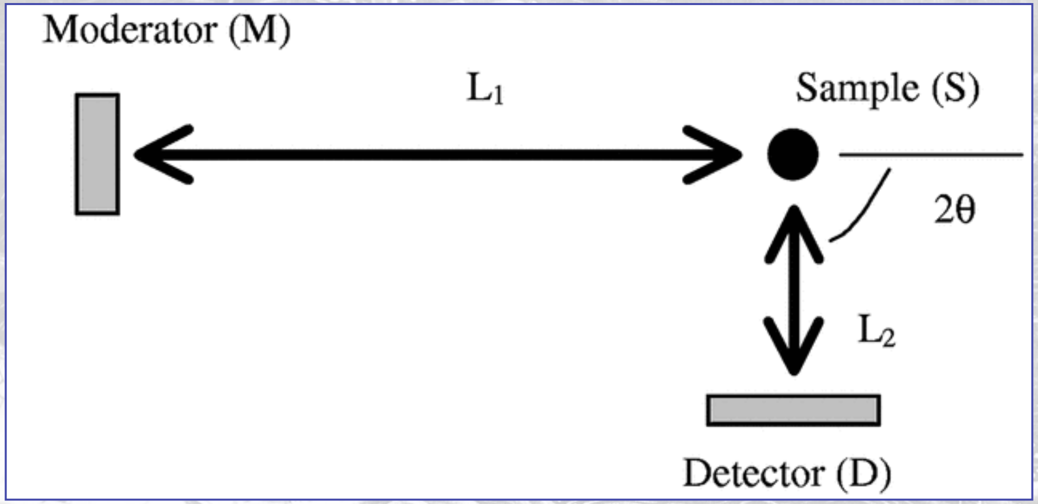
Constant

$$d = \frac{\lambda}{2\sin\vartheta}$$

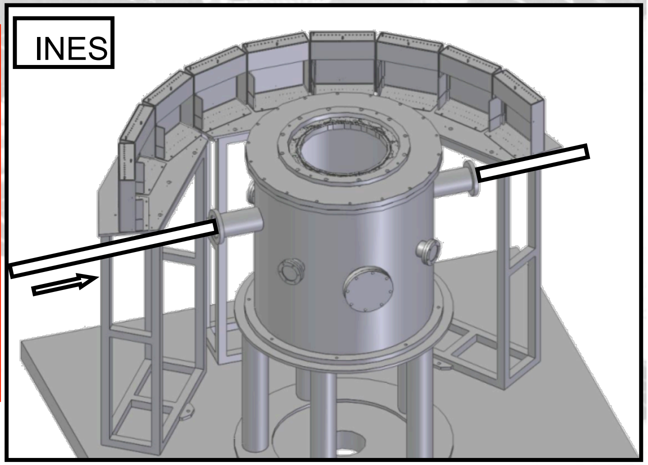
Variable

Instrumental set-up (Time of Flight)





INES (ISIS, UK)



ToF Equation:

$$d(\AA) = \frac{h}{2m_n}\frac{t(\mu s)}{L(m)\sin\Theta} = \frac{1}{505{,}56}\frac{t(\mu s)}{L(m)\sin\Theta}$$

ToF

Flight Path Length

Scattering Angle

Neutron Diffraction beamlines in the main European Facilities

(with open access user program)

ILL (Fr)	**13** diffraction beamlines (**CW**)
ISIS (UK)	**11** diffraction beamlines (**ToF**) + **1** in construction (**ToF**)
SINQ-PSI (CH)	**5** diffraction beamlines (**4 CW, 1 ToF**)
FRM2 (De)	**6** diffraction beamlines (**CW**) + **2** in construction (**ToF**)
HZB (De)	**9** diffraction beamlines (**CW**)
LLB (Fr)	**9** diffraction beamlines (**CW**)
KFKI (Hu)	**3** diffraction beamlines (**2 CW, 1 ToF**)
LVR15 (Cz)	**4** diffraction beamlines (**CW**)

Beamline components

- Moderator (all)
- Flight tubes or guides (all)
- Monochromators (CW)
- Chopper (ToF)
- Sample environment (all)
- Detectors (all)
- Data acquisition electronic (all)

A few numbers

- **Resolution** is a function of the geometric parameters and of incident wavelength(s).

  Typical Δd/d resolution ranges from 0.02 (low res) to 0.0005 (high res)

- **Brigthness** depends on moderator type, source neutron flux, presence of neutron guide, detector type, area and efficiency

  Typical measuring time for a diffraction measurement ranges from 3 minutes to ≈10 hours

- **Neutron flux** ranges from $1*10^4$ to $5*10^8$ $n/cm^2/s$

- World **user community** comprehends about 3000 scientists in the last 5 years

- **Proposed** vs **accepted** experiments **ratio** in Europe is more than 2:1

Applications

- determination of the atomic and/or magnetic structure of a material

- determination of the structure of crystalline solids

- indexing of new crystalline phases

- determination of the static structure factor of gases, liquids or amorphous solids

- mapping of 2^{nd} type residual strain in crystalline solids

The Italian Neutron User Community (a quick overview)

- More than 500 italian users in the neutron facilities in the last 10 years

- Italian neutron users: tot pub 3684, 167 pub/y since 1990
  (average last 5 years: 219 pub/y)

- There are about 340 frequent users (at least 5 papers in 10 years, 2002-2011)

- Società Italiana di Spettroscopia Neutronica (SISN) is the reference society for the largest part of the users community (about 250 associates in the last 10 years)

-Scientific cooperation agreements with ILL and ISIS facilities (managed by CNR) to provide access for Italian users

- Well established (since '80s) Italian expertise in beamline construction at ISIS and ILL

-Three beamlines (BRISP, IN13 and INES) managed by CNR at ILL and ISIS

The Italian Neutron User Community