Applications of Nuclear Physics: Future Trends

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Applications Using Particle Beams

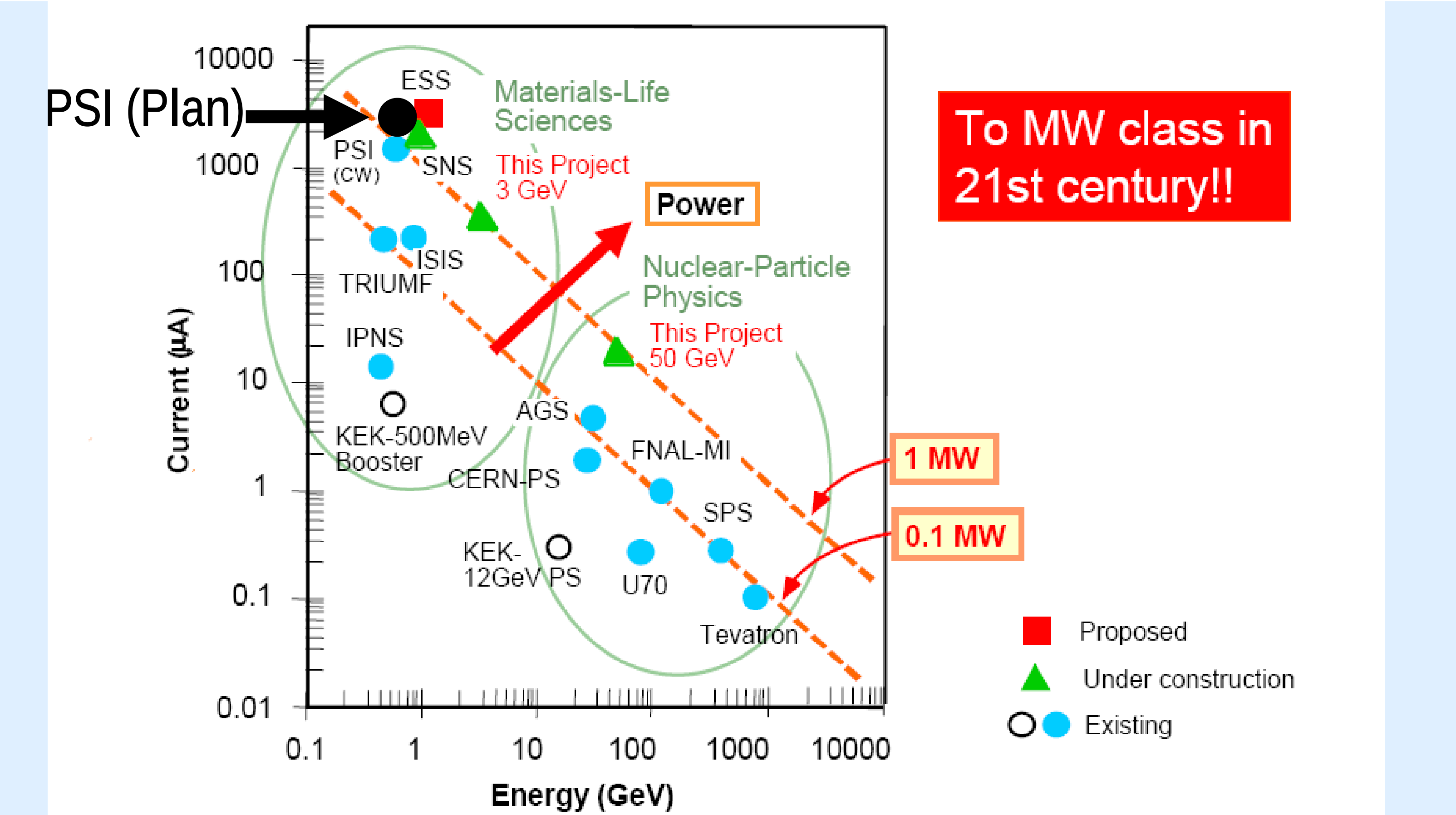
Neutron Radiography

- Applications in nuclear and car industry, archaeology
- Complementary to x-ray tomography

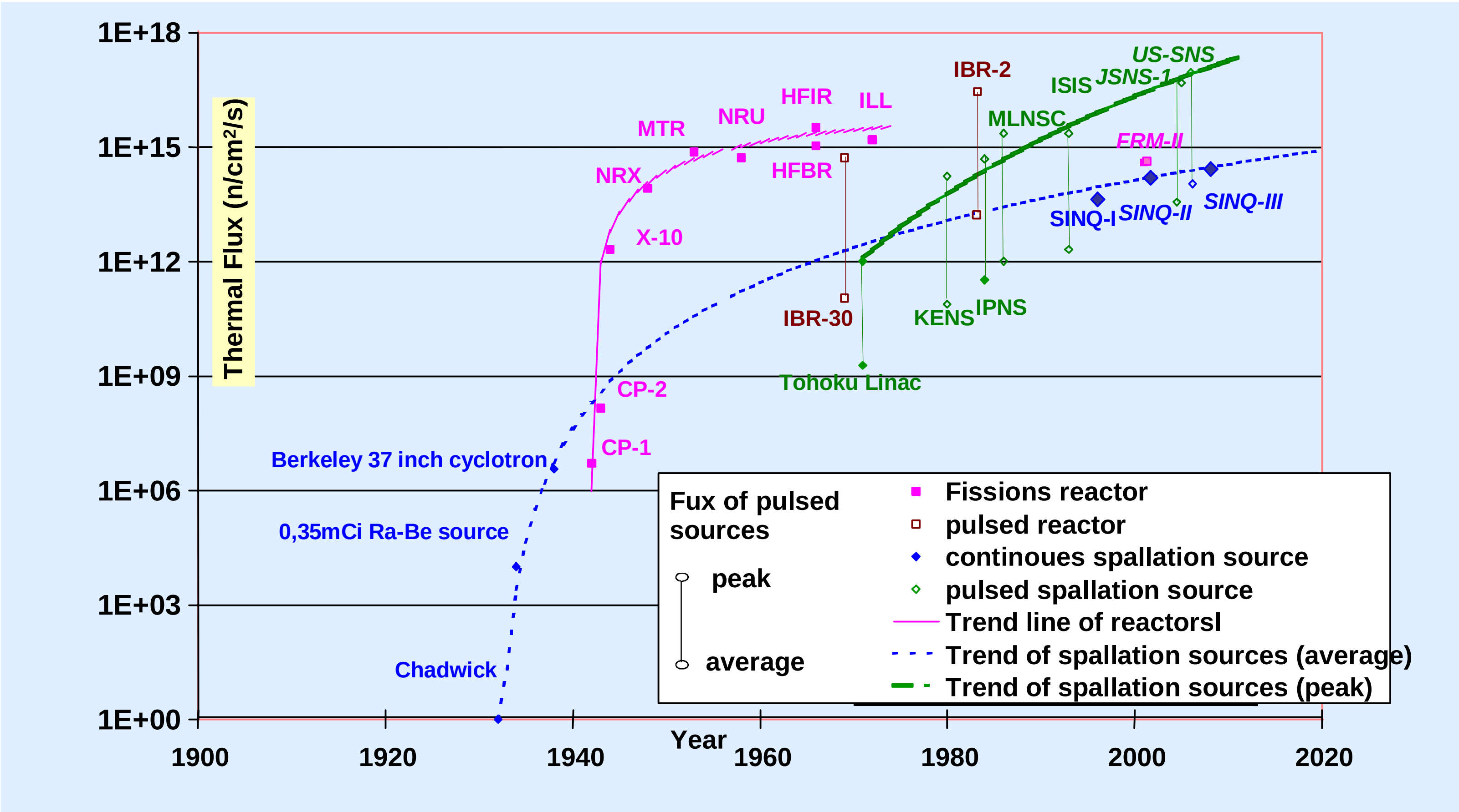
Accelerator Mass Spectroscopy

- Applications in nuclear non proliferation, climate research, archaeology, food industry
- Trend to table top devices

Comparison of High Intensity Accelerators



Comparison of Neutron Sources for Research



Neutron Radiography

Non Destructive Analysis

- Material composition (pellet integrity, fuel enrichment)
- Check of homogeneity (distribution of glue)

Tomography

- 3D visualisation
- The use of mathematical algorithm for the reconstruction of volume (density) data (voxel matrix) from n single projections (n ~ 200)

Methods and Facilities

- Transmission radiography with digital imaging methods
- Quantification
- Phase contrast imaging with cold neutrons

Attenuation Coefficients with Neutrons [cm^{-1}]

Attenuation coefficients with neutrons [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
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
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 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	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
Fr	Ra 0.34	Ac	Rf	Ha													
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75			
**Actinides	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 neut.			

Legend

thermal neutrons

$$\text{Attenuation coefficient [cm?}^{1}\text{]} = \frac{\sigma\text{-total} * \text{sp.gr.} * 0.6023}{\text{at.wt.}}$$

σ-total: JEF Report 14, TABLE OF SIMPLE INTEGRAL NEUTRON CROSS SECTION DATA FROM JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 AND CENDL-2, AEN NEA, 1994.
and Special Feature: Neutron scattering lengths and cross sections, Varley F. Sears, AECL Research, Chalk River Laboratories Chalk River, Ontario, Canada KOJ 1JO, Neutron News, Vol. 3, 1992, http://www.ncnr.nist.gov/resources/n-lengths/list.html.

sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

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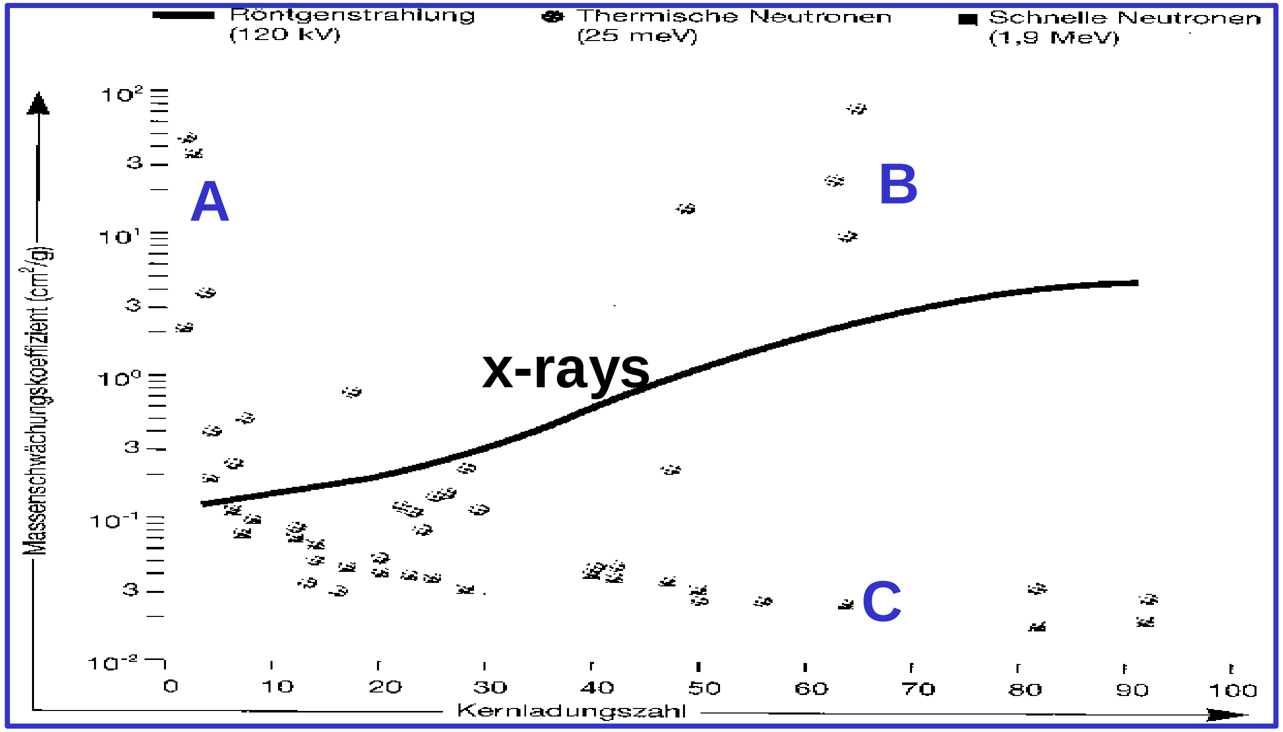
Comparison between the Interaction Probabilities for (Thermal) Neutrons and X-Ray



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B: especially strong neutron absorbers Gd, Cd, Dy, In
C: heavy materials like Pb, Bi, U , Th

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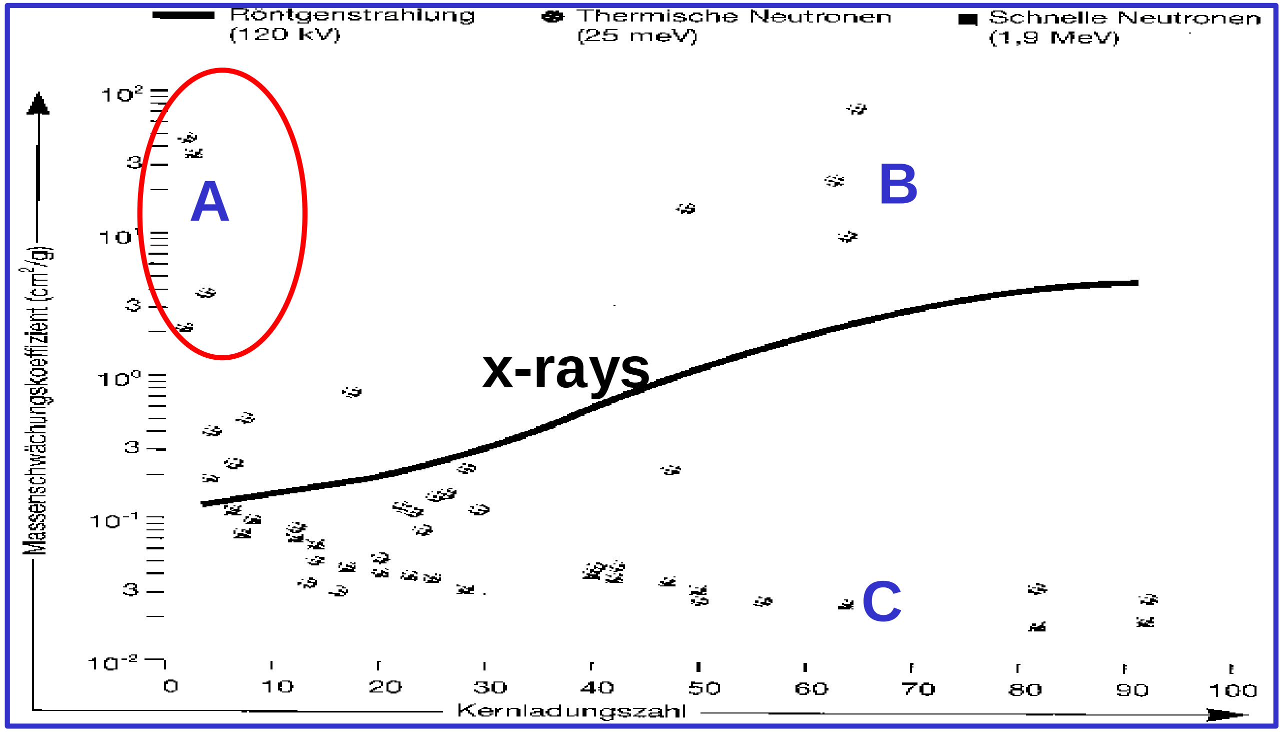

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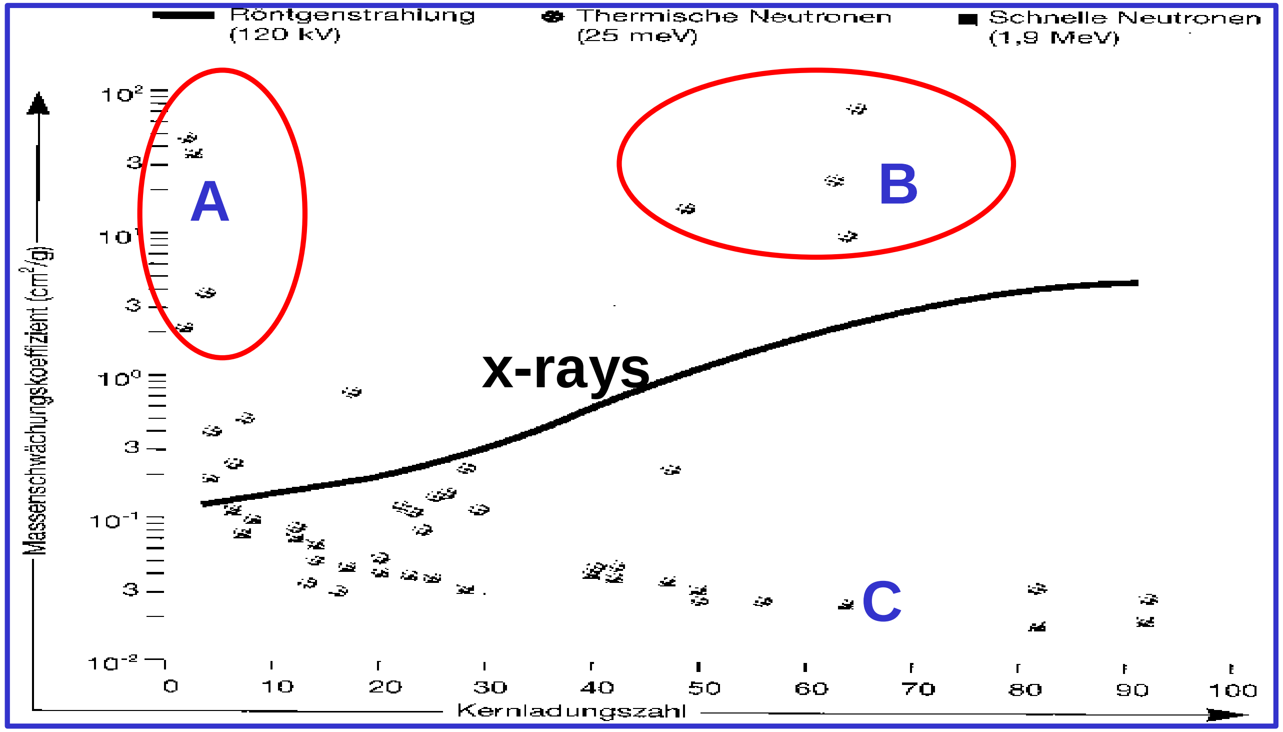

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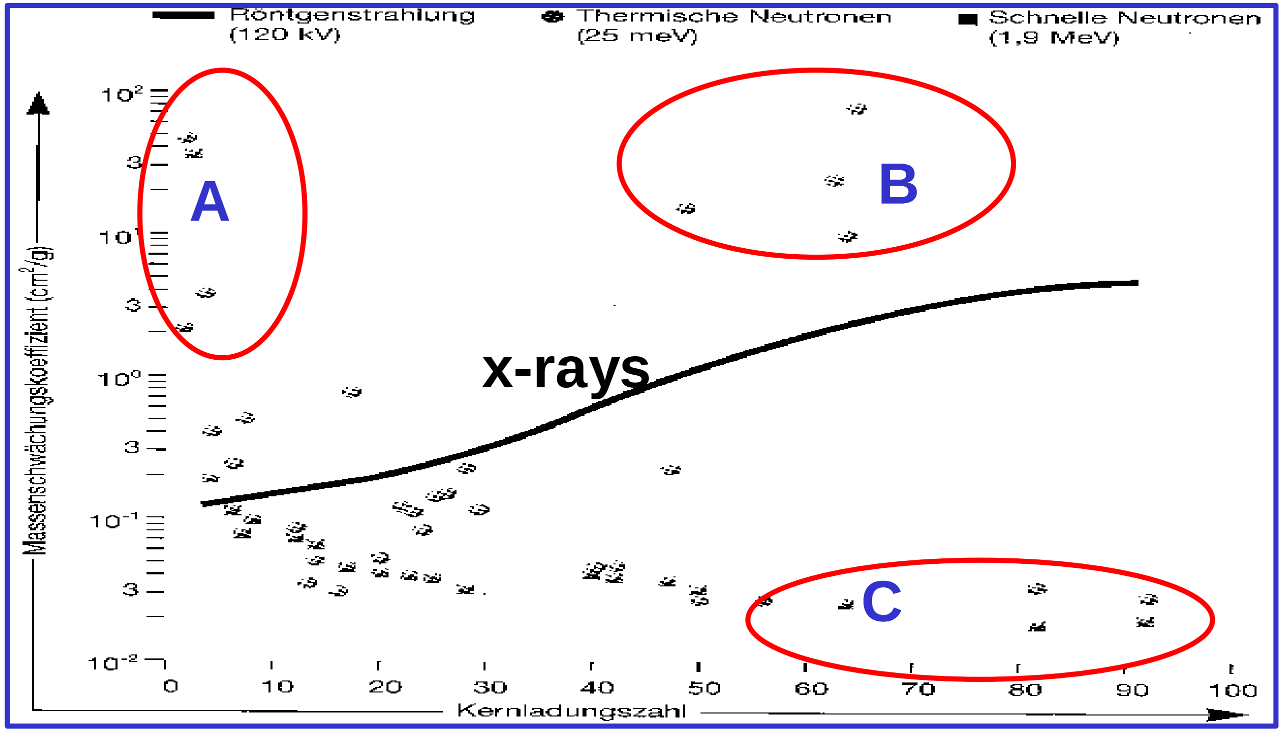

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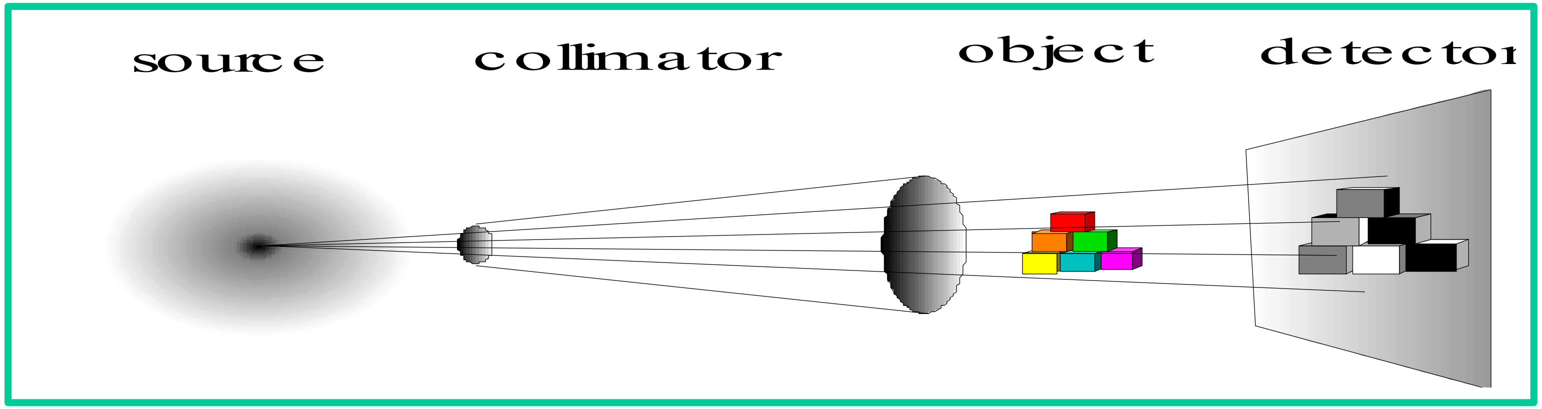
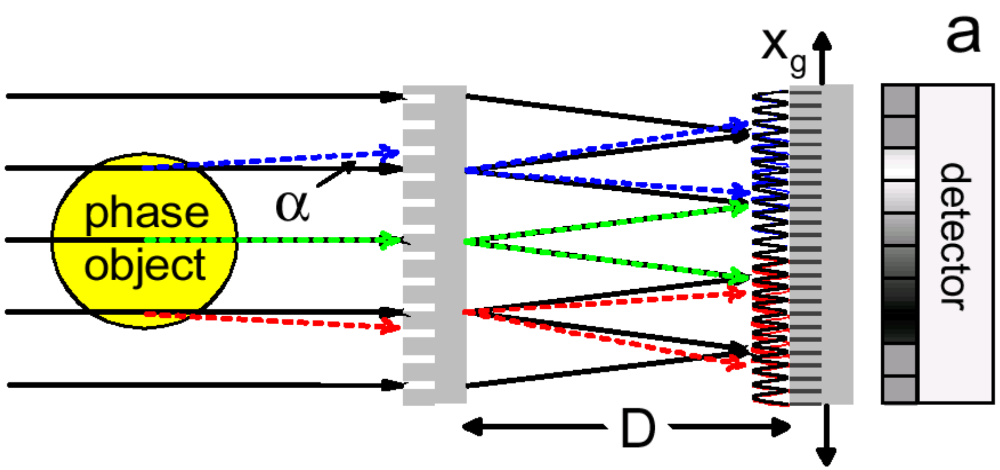
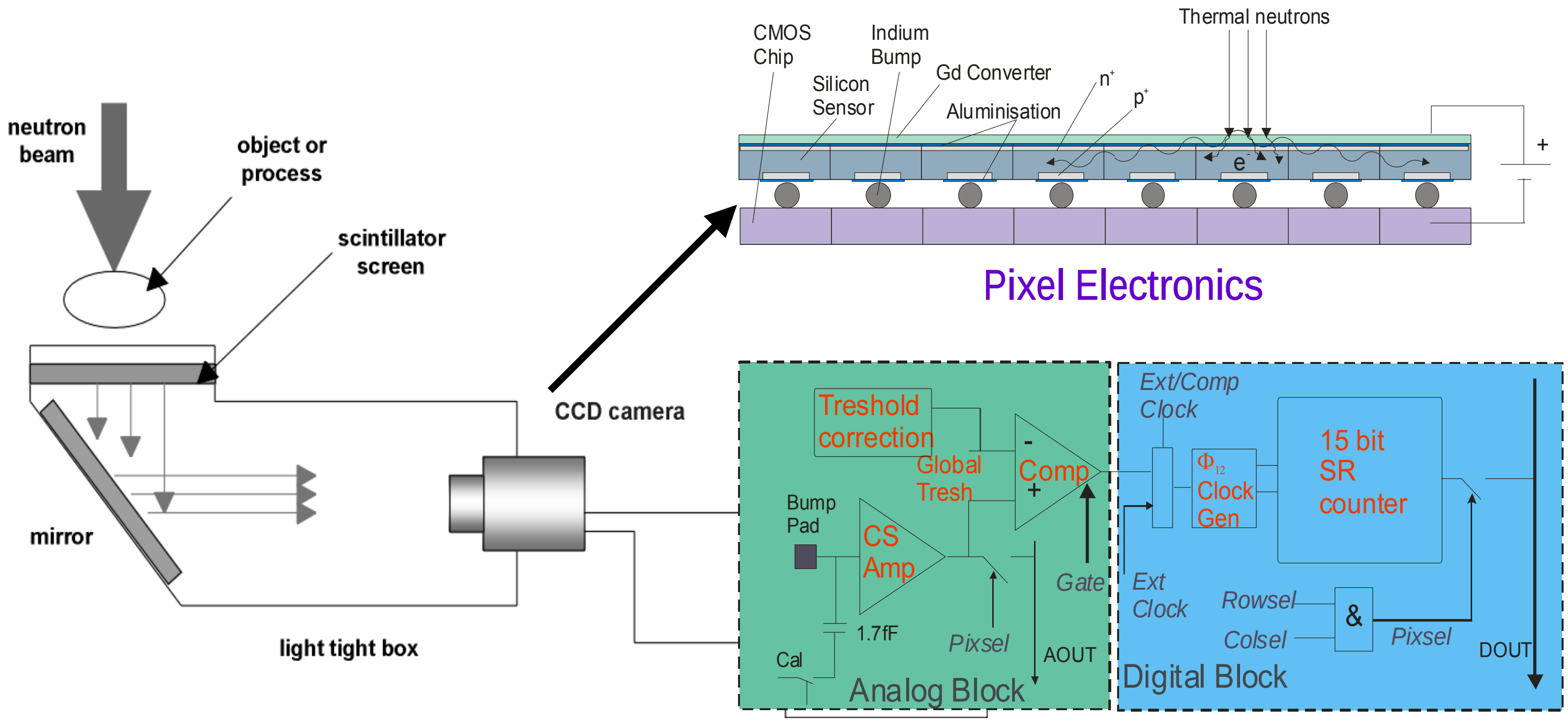
The Principle: Transmission (top), Shearing Interferometer (bottom)





CCD-Camera or Pixel Detectors

Neutrons are hitting the scintillator and the emitted light will be detected by the high sensitive camera.



Determination of the U-235 Content (Enrichment) in Nuclear Fuel Elements

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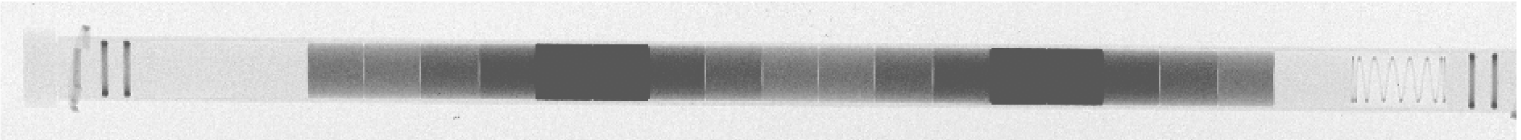

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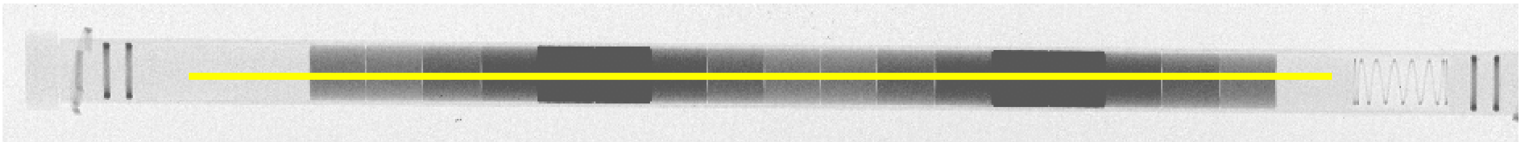

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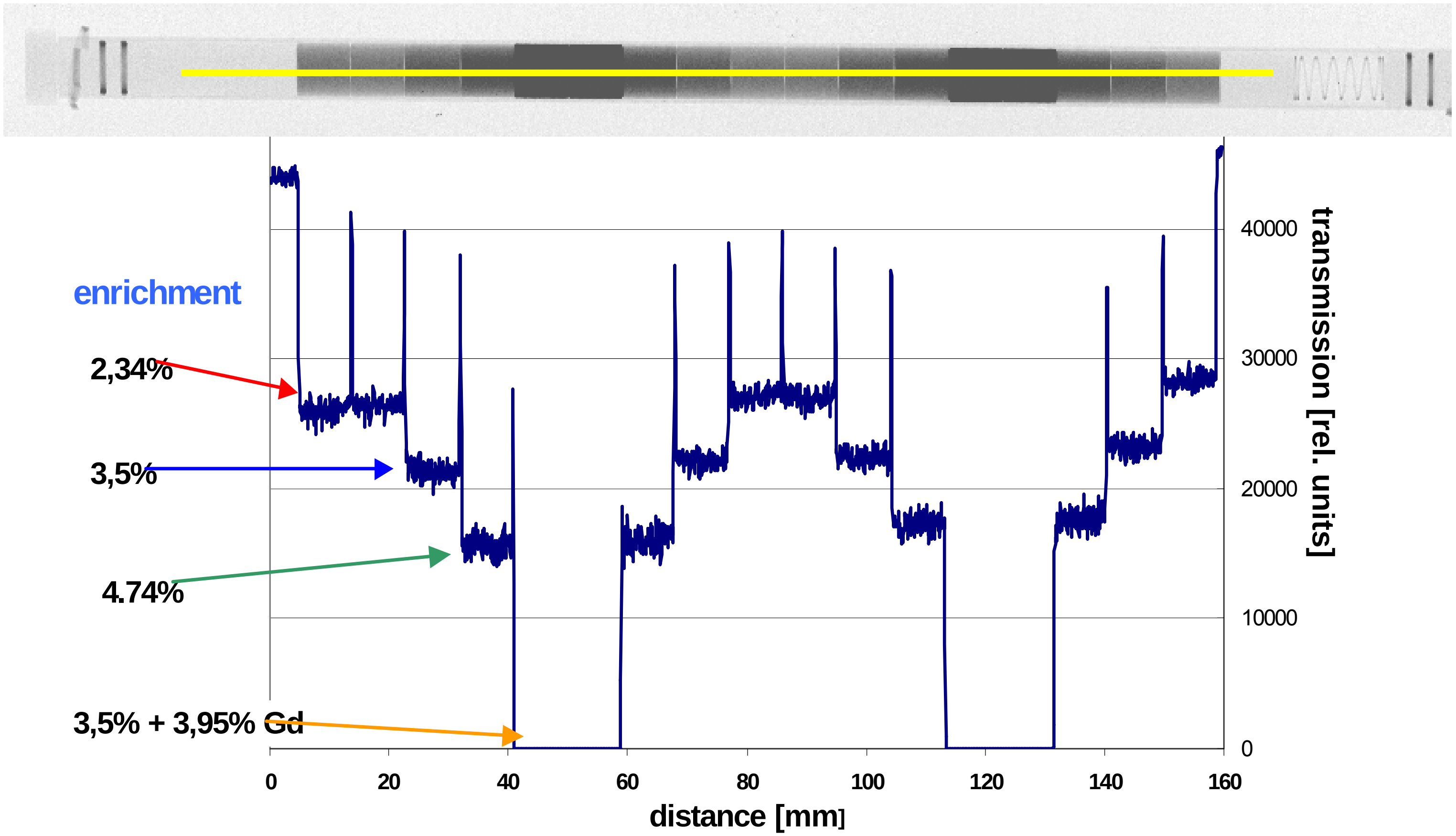
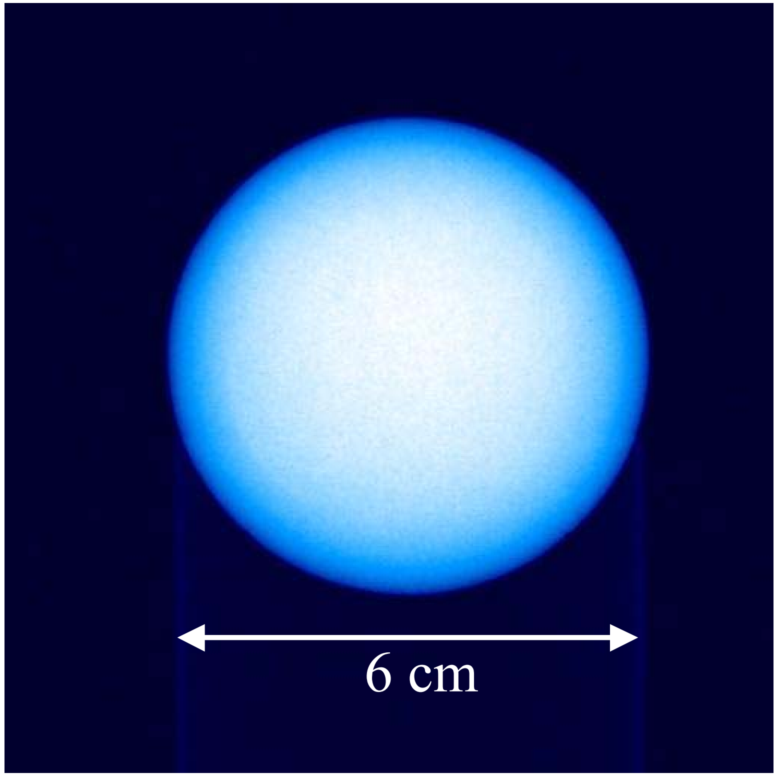


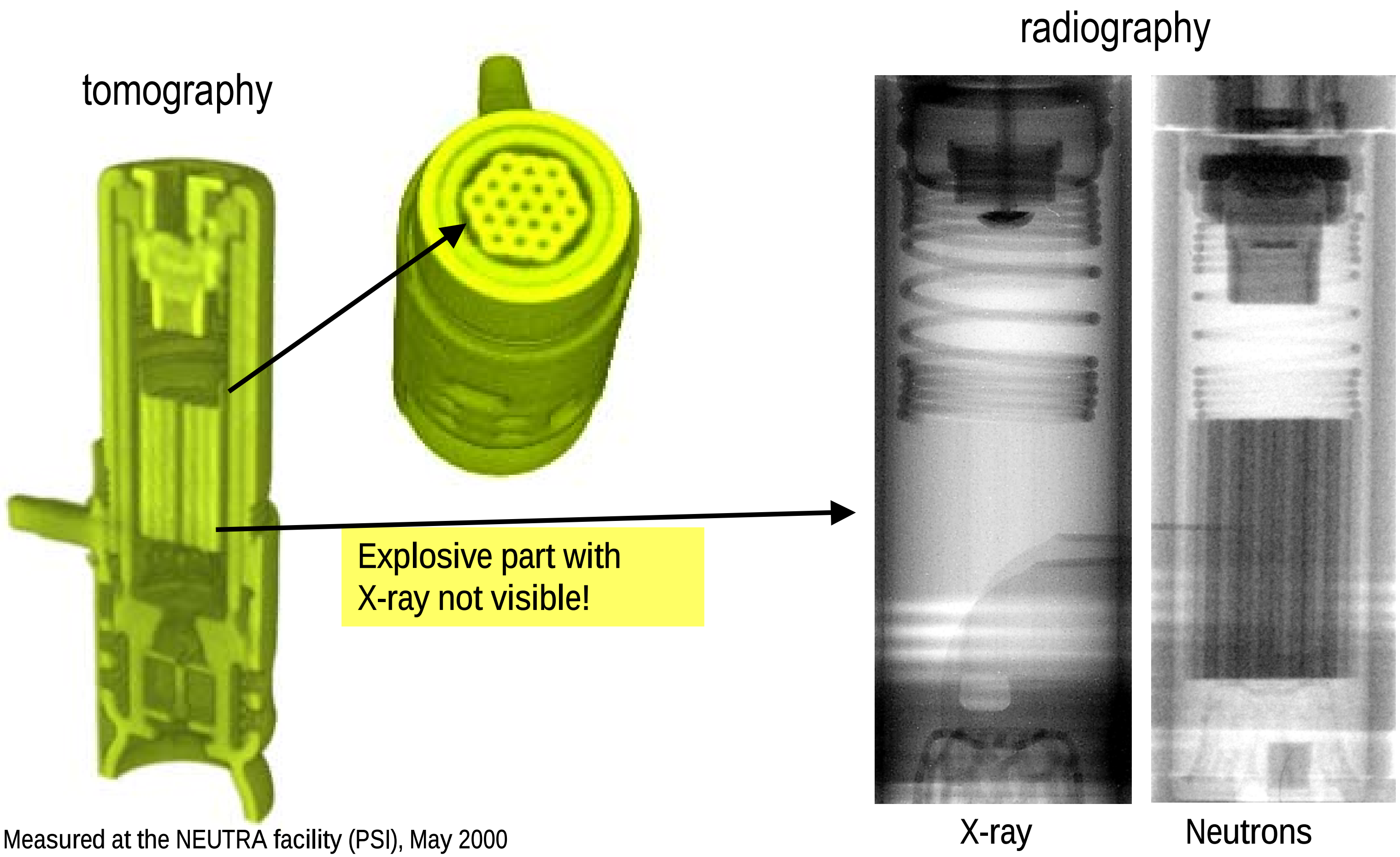
Tomography: Investigation of HTR Fuel Sphere



Transmission image (single projection)

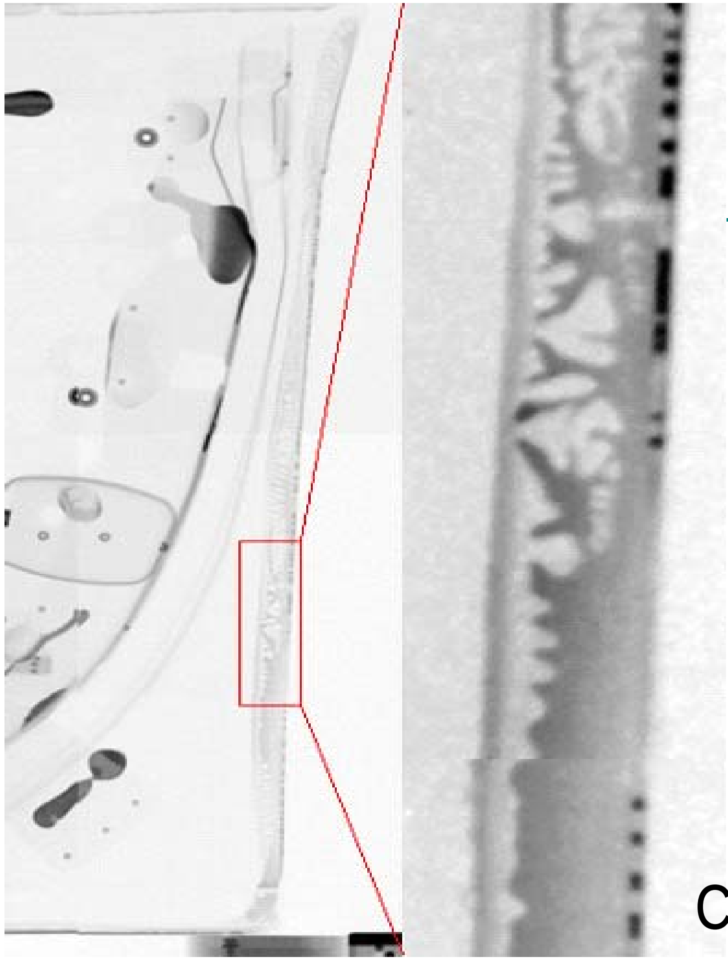
Tomography slice of one layer with CP

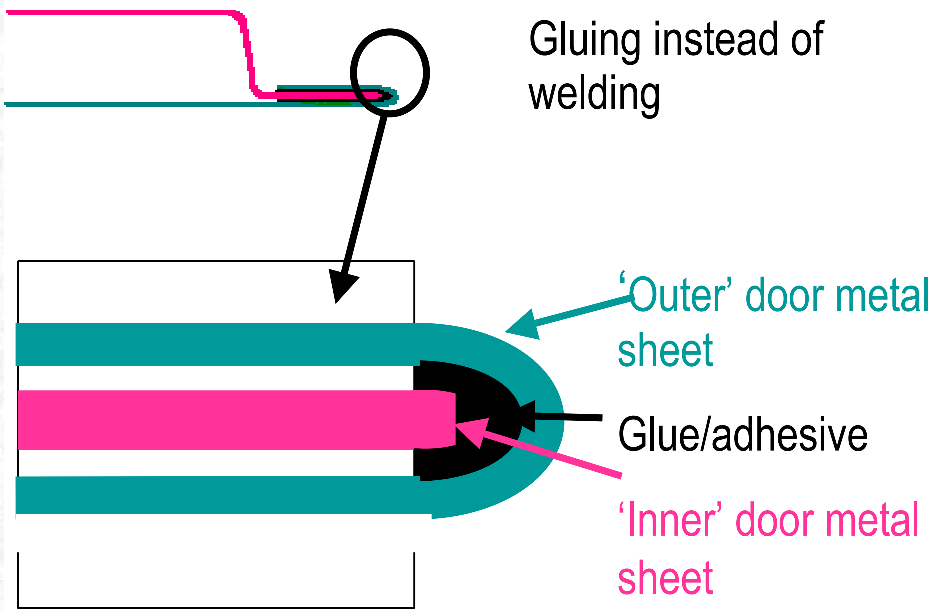
Non Destructive Inspections: Airbag Actuator



© Measured at the NEUTRA facility (PSI), May 2000

Detailed Inspection of Adhesive in a Car Door





Corrosion when not filled with glue

Neutron Phase Shift Mechanisms

Table 1.3 Neutron interferometric measured phase shifts

Interaction	Potential	Phase shift
Nuclear	$\frac{2\pi\hbar^2}{m} b_c \delta(\boldsymbol{r})$	$-N b_c \lambda D$
Magnetic	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(\boldsymbol{r})$	$\pm \frac{\mu B m \lambda D}{2\pi\hbar^2}$
Gravitation	$m\boldsymbol{g} \cdot \boldsymbol{r}$	$\frac{m^2 g \lambda A \sin\alpha}{2\pi h^2}$
Coriolis	$-\hbar\boldsymbol{\omega}(\boldsymbol{r} \times \boldsymbol{k})$	$\frac{2m}{\hbar} \boldsymbol{\omega}_e \cdot \boldsymbol{A}$
Aharonov–Casher (Schwinger)	$-\boldsymbol{\mu} \cdot (\boldsymbol{v} \times \boldsymbol{E})/c$	$\pm \frac{2\mu}{\hbar c} \boldsymbol{E} \cdot \boldsymbol{D}$
Scalar Aharonov–Bohm	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(t)$	$\pm \frac{\mu B T}{\hbar}$
Magnetic Josephson	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(t)$	$\pm \omega \cdot t$
Fizeau	—	$-N b_c \lambda D \left(\frac{w_x}{v_x - w_x} \right)$
Geometry (Berry)	—	$\Omega/2$

m: neutron mass
λ: neutron wavelength
D: sample thickness
B: magnetic field strength
g: gravitational acceleration
A: normal area enclosed in the coherent beams
α: angle between the horizontal and the area A
$\omega_e = 0.727 \times 10^{-4} s^{-1}$: angular rotation velocity of the Earth
E: electric field
$\hbar\omega$: energy transfer due to the time-dependent field $\boldsymbol{B}(t)$
T: time during which the constant field B is switched on,
w_x, v_x: velocity components of the phase shifter and the neutrons of the phase shifter
Ω: solid angle subtended by a closed circuit in parameter space

From H. Rauch, *Neutron Interferometry*, Oxford University Press, New York (2000).

Phase Contrast Imaging

<u>Nuclear phase shift:</u> $\Delta\Phi = 2\pi\delta D/\lambda$

Complementary information

2D imaging & 3D tomography of both the real (δ) and imaginary (β) part of the refractive index n

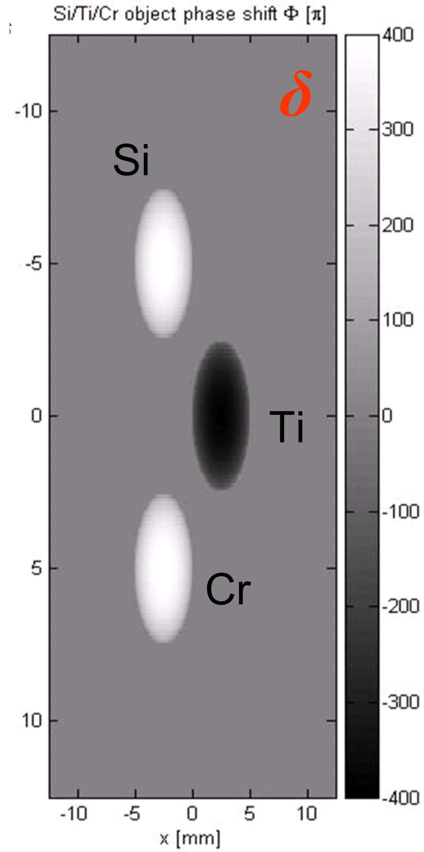
Increased contrast & sensitivity

for some materials $\delta >> \beta$,

=> S/N improvement by $10^2 – 10^3$

Field of view: 20-50 mm

Resolution: 100 μm



Si would be invisible in transmission tomography.

Neutron Imaging of Magnetic Domain Structures
a Future Dream

<u>Magnetic phase shift:</u>

$$\Delta\Phi = 2\pi\mu Bm\lambda\, D/h^2$$

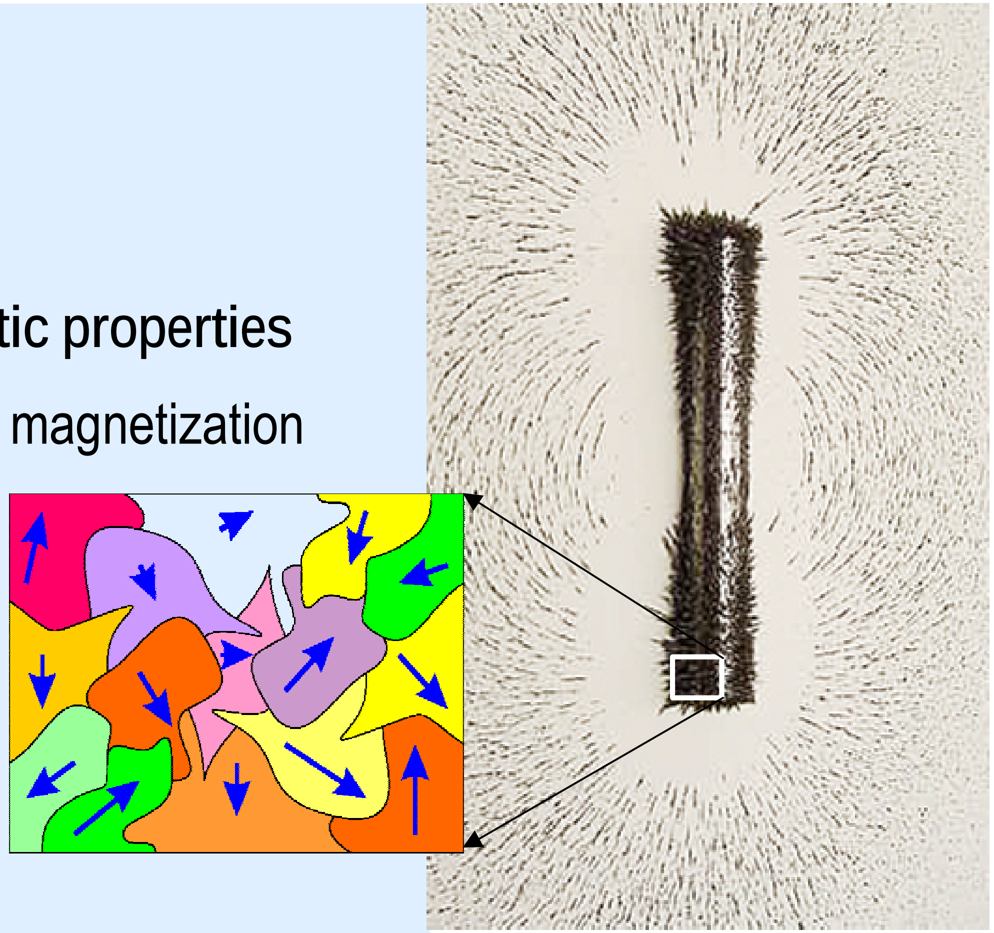
Information about magnetic properties

2D (& 3D) mapping of the magnetization

<u>inside</u> materials

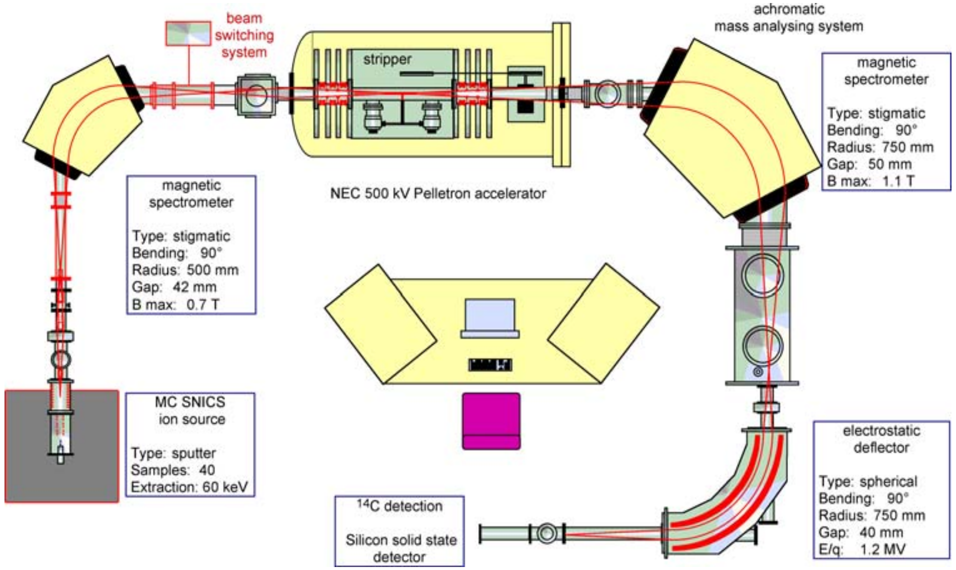
Field of view: 20-50 mm

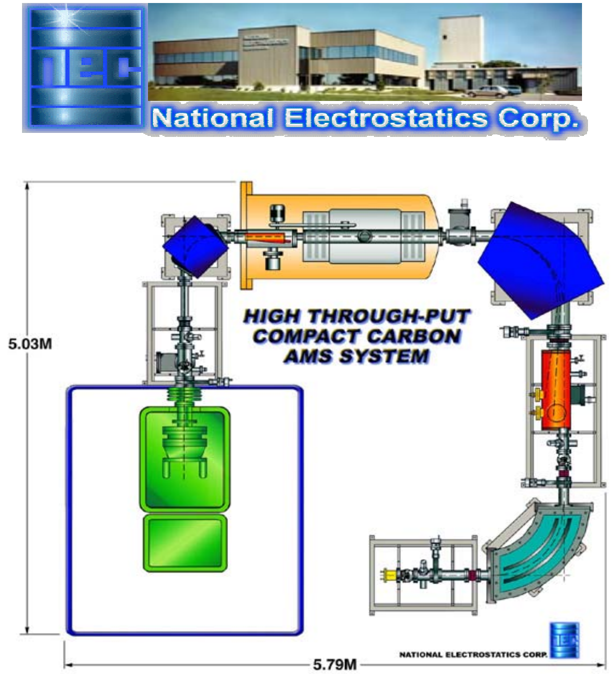
Resolution: 100 µm



Development of a Compact AMS System

PSI/ETH Compact AMS facility (600 kV)

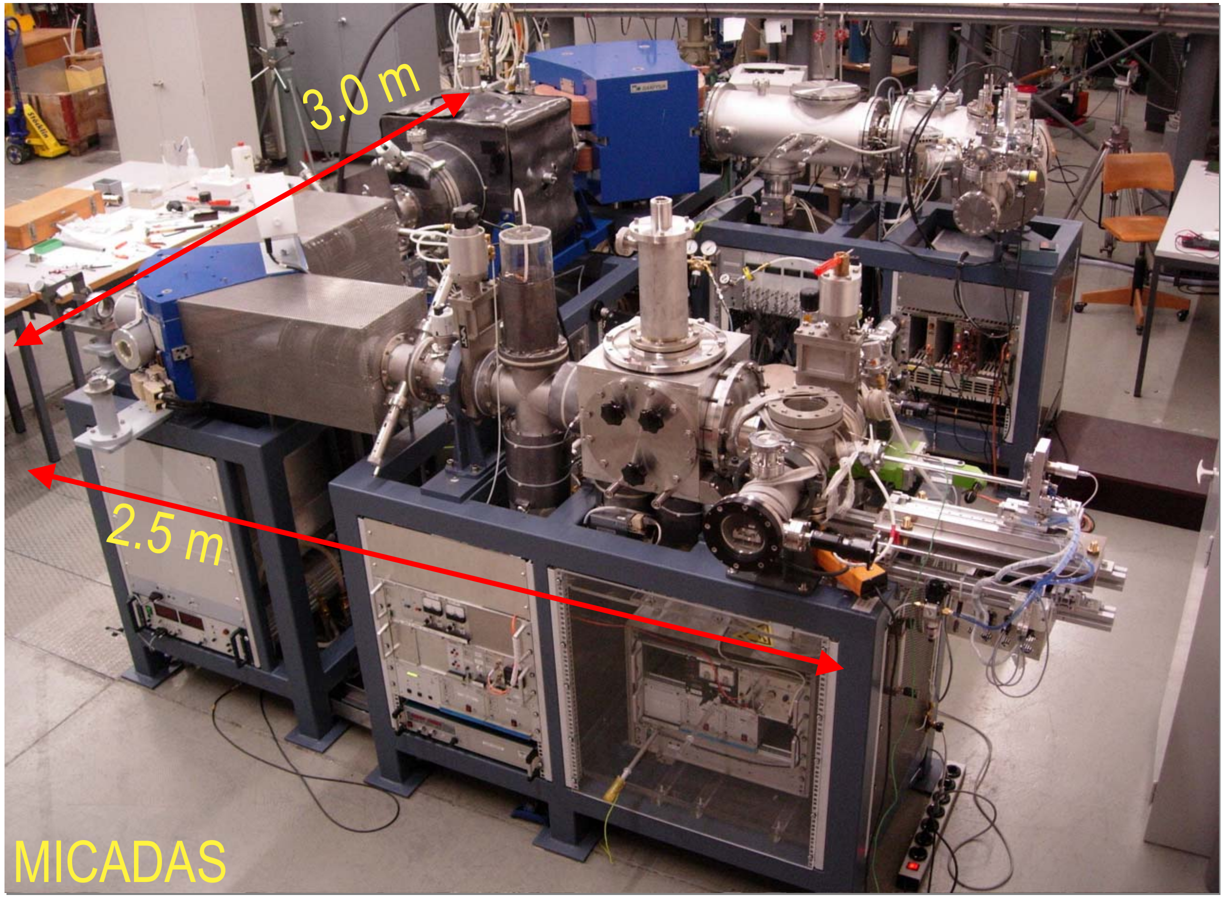




NEC manufactures a commercial Compact AMS System based on the technology developed at PSI/ETH

MIni radioCArbon DAting System: Overview

The next generation of AMS instruments



Key features

Sputter ion source:
spherical ionizer
multi cathode
sample changer

200 kV Accelerator:
vacuum insulated
high voltage platform

HE end:
achromatic
mass spectrometer

Gas ionization detector:
high energy resolution

Performance of MICADAS

Prototype of the “next generation” of radiocarbon dating systems

- Vacuum insulated high voltage platform (200kV)
- Gas stripper (differential pumping)

Ion source

- 50 µA from graphite targets (20 - 30 µA for measurements)
- Up to 5 µA from CO_2 gas (≈2 % negative Ion yield)

Transmission

- ≈ 40 % (more than 80 % ion optical)

Background

- No surviving molecules

Blank values

- Processed ^{14}C Blank are measured at 40 - 50 kyrs

High precision radiocarbon dating measurements

Compilation of Low Energy AMS Performance

Nuclide	Beam	Background 10^{-12}	Transmission %	Acc.voltage kV	Application	Status
^{14}C	C	<0.005	40-50	460	radiocarbon dating	✓
^{10}Be	BeF	0.005-0.01	50	550	earth sciences	✓
^{26}Al	Al	0.01	28	500	earth sciences/biomed	✓
^{41}Ca	CaF_3	1	7	530	biomed	✓
^{129}I	I	0.04-0.10	3	500	earth sciences	✓
Pu	PuO	fg	12	360	nuclear safegards	✓
^{14}C	C	<0.005	40	200	radiocarbon dating	✓
^{10}Be	BeF	0.01	50	200	earth sciences	✓
^{36}Cl	Cl	1	5	200	experimental AMS	?
^{41}Ca	CaF_3	1		200	biomed	?
Pu	PuO	fg		200	nuclear safegards	?

Two Examples

- C^{14}-marker in food is stored in human body for several years. If test-person stops eating, the C^{14} is transferred to CO_2 in the breathing air and can be measured. Level of radioactivity is equivalent of 1h flight in 10’000 m altitude.
- U^{236} and Pu^{236} could be measured in the environment from the B-52 military air plane crash in Spain in 1962.