PAUL SCHERRER INSTITUT PSI

CCMX Competence Centre for Materials Science and Technology

IAEA International Atomic Energy Agency

Wir schaffen Wissen – heute für morgen

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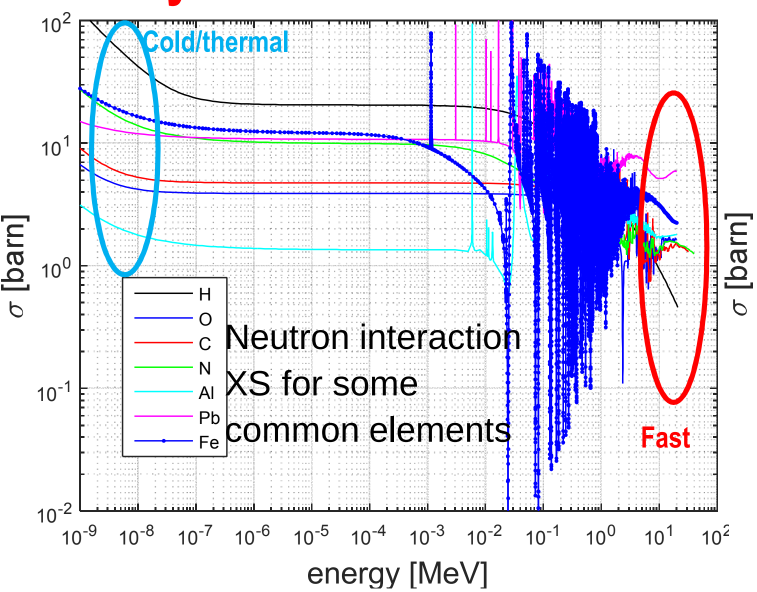
Neutron Imaging with Fast Neutrons

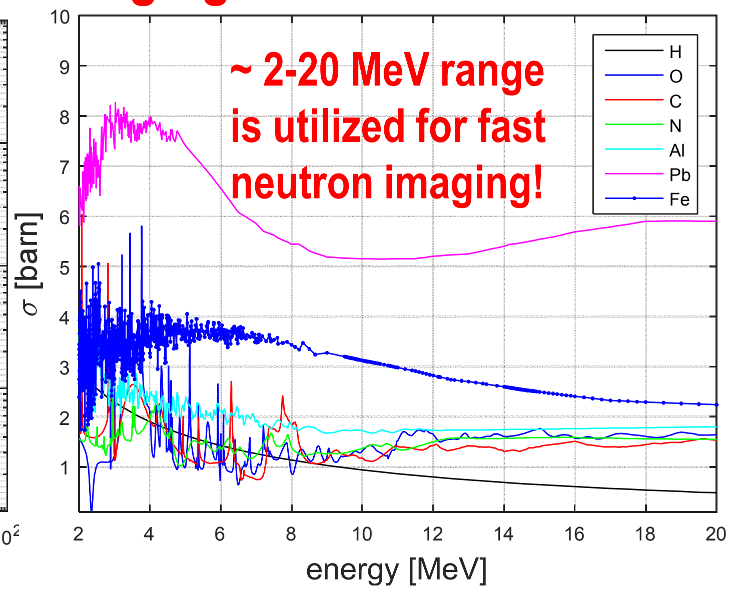
OUTLINE

1. Introduction: Fast neutron imaging vs. other modalities
2. Production of fast neutrons
3. Detector options
4. Imaging with fast neutrons at large-scale sources
5. Fast neutron imaging using compact sources
6. Application examples:
   Fast Neutron Resonance Radiography (FNRR)
   Time resolved imaging
7. Conclusions and Outlook

INTRO: FAST NEUTRON IMAGING vs. OTHER MODALITIES

Why to use fast neutrons for imaging?





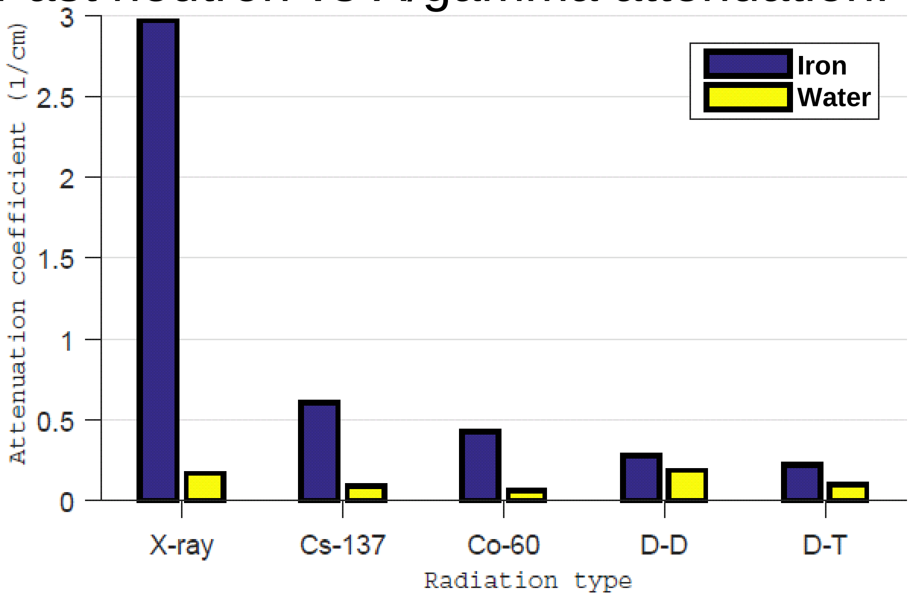
Compared to thermal neutrons:

1. XS show quite weak Z dependence

2. generally lower XS values

3. XS vary with E but no such pronounced resonances as for e.g. epithermal

Fast neutron vs X/gamma attenuation:



Compared to X/γ rays

1. XS show quite weak Z dependence (low-Z vs high-Z)

2. generally lower XS values

Consequence of 1.:
Samples containing practically any mixture of elements (low-Z hidden in high-Z or vice versa) can be imaged with similar good contrast!

Consequence of 2.:
Robust, voluminous samples can be imaged!

PRODUCTION OF FAST NEUTRONS

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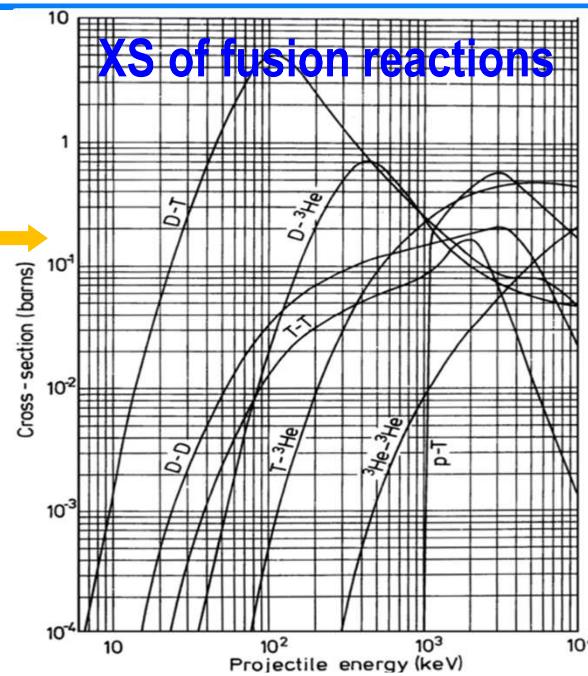
Overview of reactions for fast neutron production:

Fusion reactions:

- ${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{2}He$ (0.82MeV)+ n (2.45MeV in C.M.) mono E, Q>0
- ${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He$ (3.5MeV)+ n (14.1MeV) mono E, Q>0
- ${}^{3}_{1}T + {}^{3}_{1}T \rightarrow {}^{4}_{2}He$ + 2n (0-9.5MeV) broad E spec, Q>0

compact



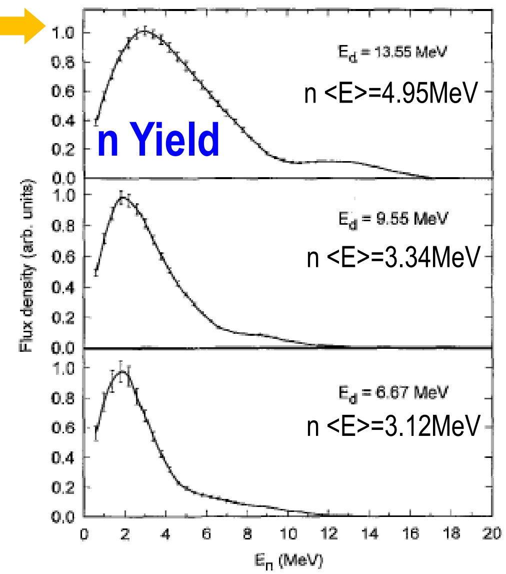
Alternative reactions to produce mono E fast neutrons:

- ${}^{1}_{1}H + {}^{3}_{1}T \rightarrow {}^{3}_{2}He$ + n(0.12-0.6MeV), Q=-0.76MeV, E_{th}=1.02MeV
- ${}^{1}_{1}H + {}^{7}_{3}Li \rightarrow {}^{7}_{4}Be$+ n(0.3-7.6MeV), Q=-1.64MeV, E_{th}=1.88MeV

Reactions producing white fast neutron spectra (thick target):

- ${}^{2}_{1}D + {}^{7}_{3}Li \rightarrow {}^{8}_{4}Be$ + n, Q=15.03MeV
- ${}^{2}_{1}D + {}^{9}_{4}Be \rightarrow {}^{10}_{5}B$ + n, Q=4.36MeV

large-scale infrastructure



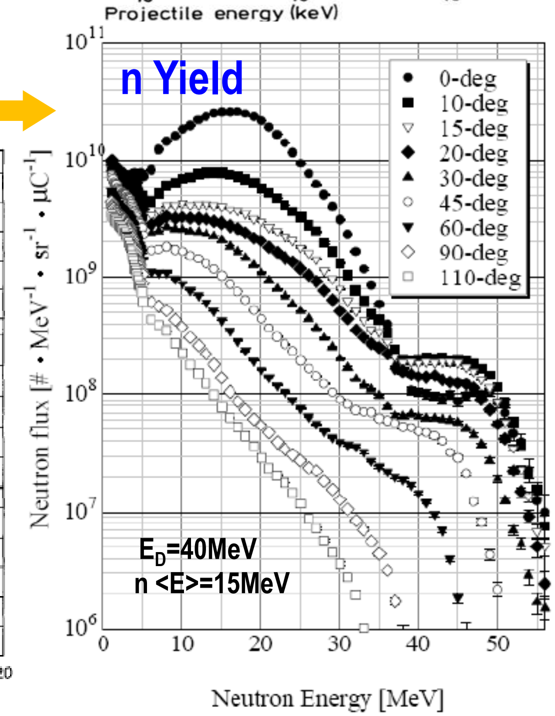


Photo neutron sources:

high E e- beam on Pb -> high E Xrays->(γ,n) reaction

Fission:

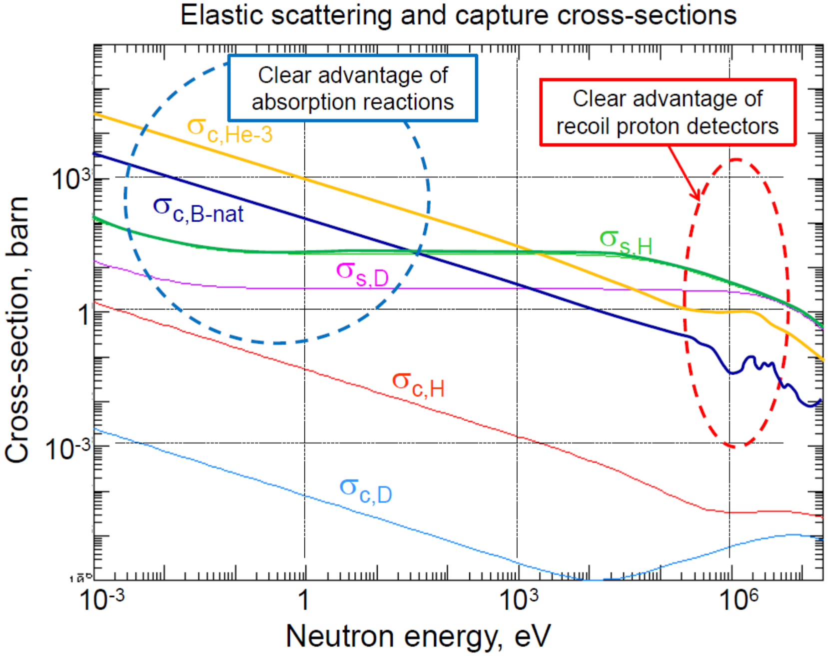
- ${}^{252}Cf$ spontaneous fission: <E>~2.1 MeV
- Fission chain reaction - nuclear reactor

Isotopic sources : ${}^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C$+n,Q=5.71MeV

- ${}^{239}Pu$-Be
- ${}^{241}Am$-Be

DETECTOR OPTIONS 1.

Proton recoil is the most efficient conversion mechanism for fast neutrons:



Hydrogen-rich, **plastic scintillators** are commonly utilized

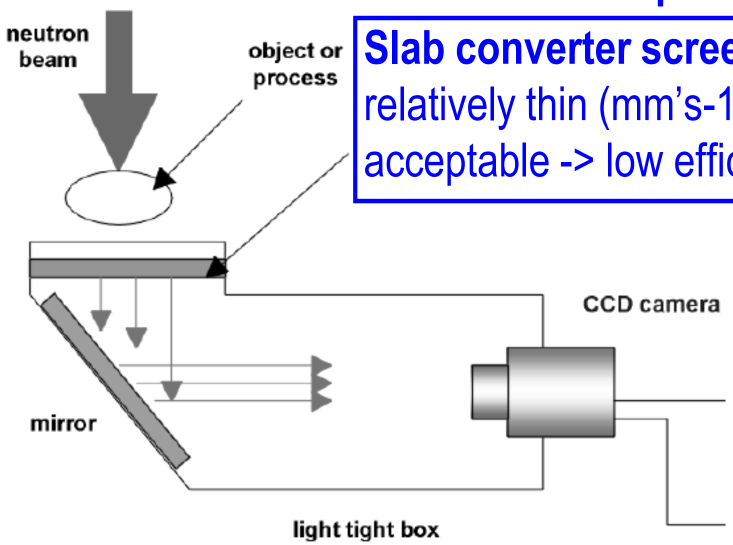
General remarks:

- Fast neutrons ->high penetration power -> deep, voluminous detectors (cm's) for efficiency-> inherent blur

Efficiency vs. Blur dilemma quiet pronounced

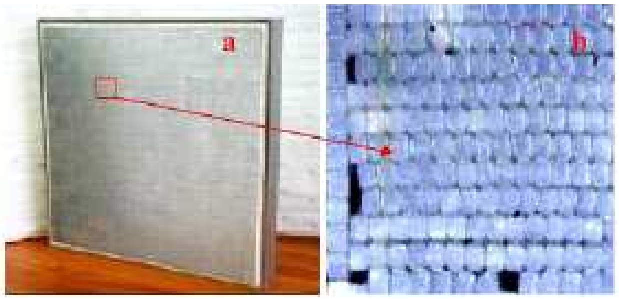
- resolution: besides detector properties depends on the full imaging arrangements, <1mm is difficult at reasonable det. efficiency!
- gamma sensitivity: issue enhanced by the volume/thickness of the detector

1. **Most common 2D detection concept:**



Slab converter screen must be relatively thin (mm's-1cm) to keep blur acceptable -> low efficiency (<1%)!

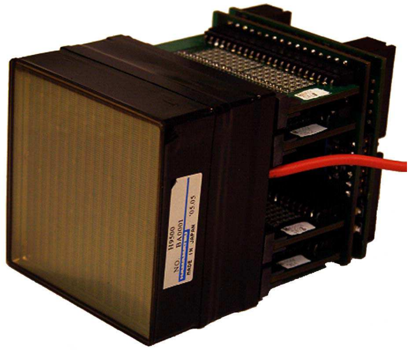
2. Similar to 1. but using plastic fiber scintillator screens: High 10-50mm thicknesses -> eff. up to 26% @ 6MeV, large areas ~ 200x200 mm^2 possible, clearly outperforms slab screens!



Mor et al., (2009)

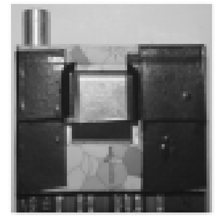
DETECTOR OPTIONS 2.

3. Plastic scintillator slab + multi anode, position sensitive PM tube:
4mm converter , 50x50mm^2 area (16x16 pads), good resolution ~0.5mm

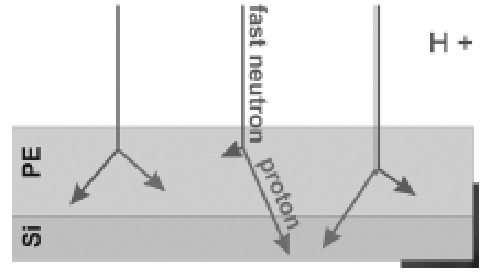


Popov et al., (2011)

4. PE converter+Si detector (Medipix 2), a more exotic approach:
1mm converter -> low eff. 0.1% @ 4MeV, only small area, but very high resolution 100um!

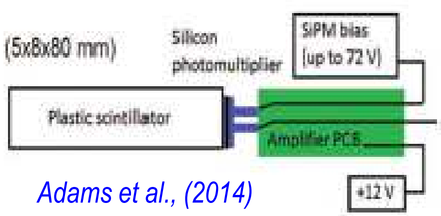


Uher et al., (2008)

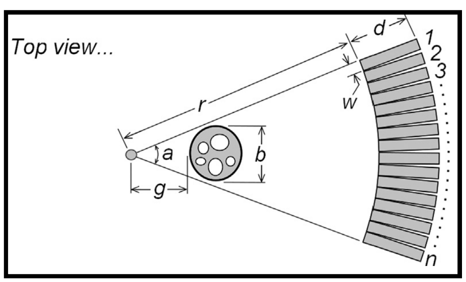


1D "line" detector concepts for cross sectional tomography:

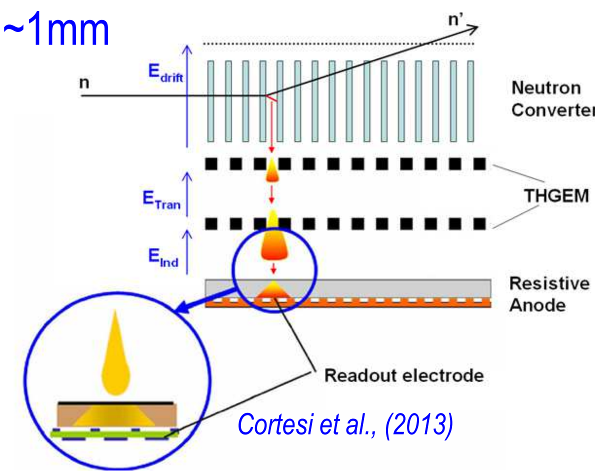
5. 1D detector arc of thick plastic scintillators + SIPMs:
80mm in beam direction -> eff. 33% @ 2.8MeV, ~100 detector elements, resolution ~1.5 mm



Adams et al., (2014)



6. PE multi-foil converter+ cascaded THGEM charge amplifier + 2D electrode pads readout:
100-200 thin converter foils (0.6mm) -> eff. up to 7% @ 2.8MeV, 2D detection capability is used for high eff. 1D detection, resolution ~1mm



Cortesi et al., (2013)

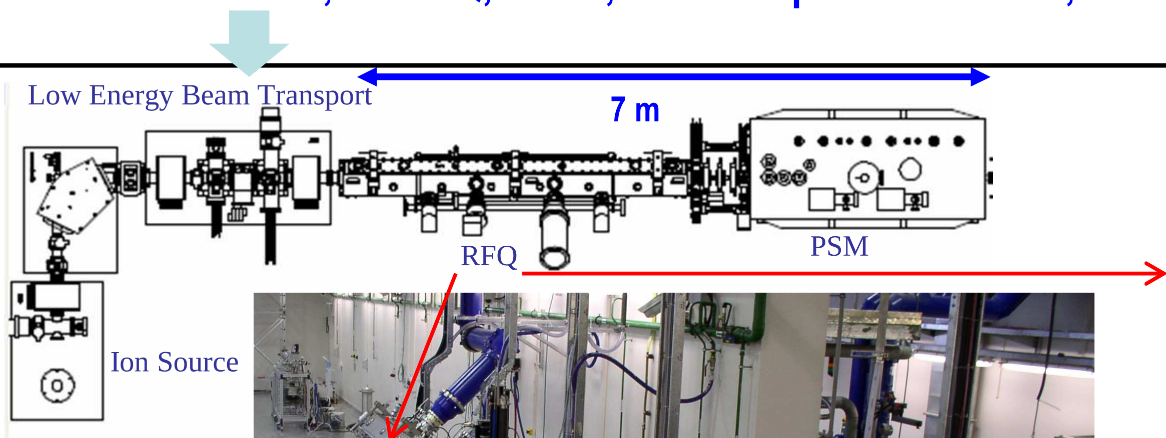
FAST NEUTRON IMAGING AT LARGE-SCALE SOURCES 1.

Nuclear reactor-based imaging facilities (examples):

- Beam line on YAYOI fast reactor, Tokyo University, JAPAN, 1e6-1e7n/cm^{2}s, <En>~1.3MeV *Fujine etal, (1999)*
- FMRII Reactor, Munich , Germany, NECTAR facility, ~1e8n/cm^{2}s, <En>~1.9 MeV *Bücherl et al (2011)*

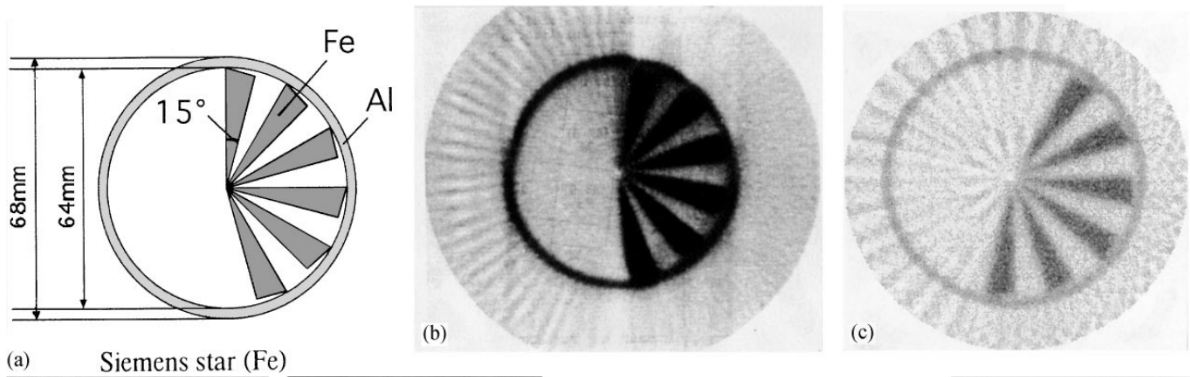
Large-scale accelerator-based facilities (examples):

- PTB Cyclotron, Braunschweig, Germany, 11.5MeV D beam, thick Be target, <En>~5.5MeV, ~1e7n/cm^{2}s @1m *Brede et al., (1989)*
- LLNL, USA, dual RFQ accelerator , 3bar D_2 gas target, E~7MeV *Hall & Rusnak (2006)*
- NECSA, South Africa, dual RFQ accelerator, 5MeV D beam, 3bar D_2 gas target, En=7-8MeV *Franklyn (2006)*
- SARAF accelerator, SOREQ, Israel, 5-40MeV p and D beams, D+Li, p+Li reactions, liquid Li target, <E>~15MeV



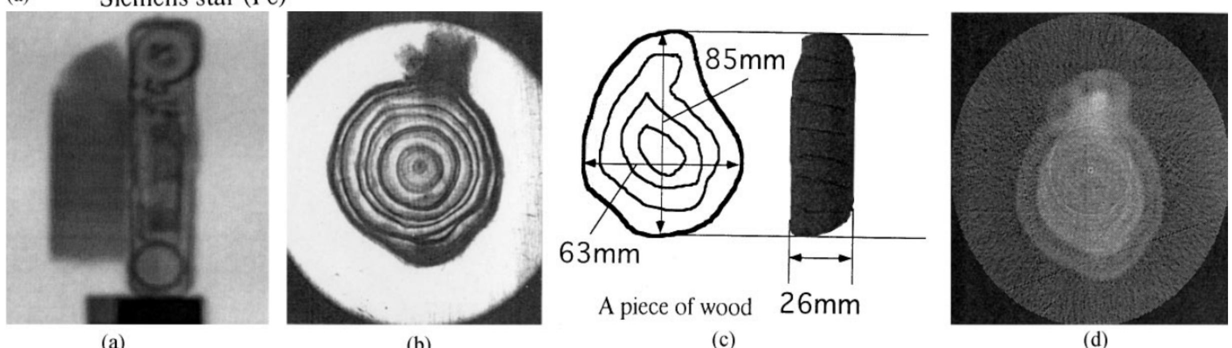
P.Fischer, 2007

FAST NEUTRON IMAGING AT LARGE-SCALE SOURCES 2.

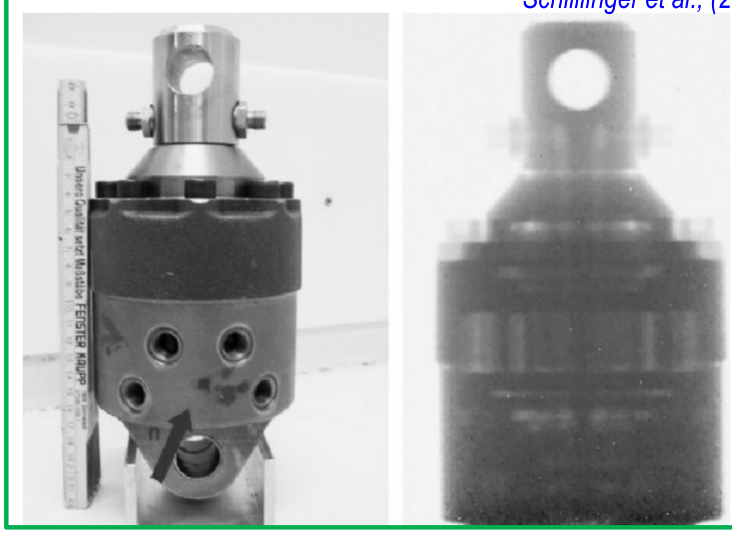


Fujine et al., (1999)

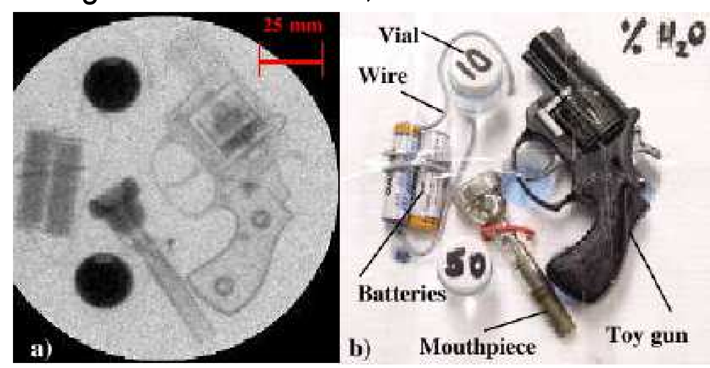
YAYOI reactor, CCD+PP screen mixed with ZnS(Ag) 2mm thick, res 1.5mm



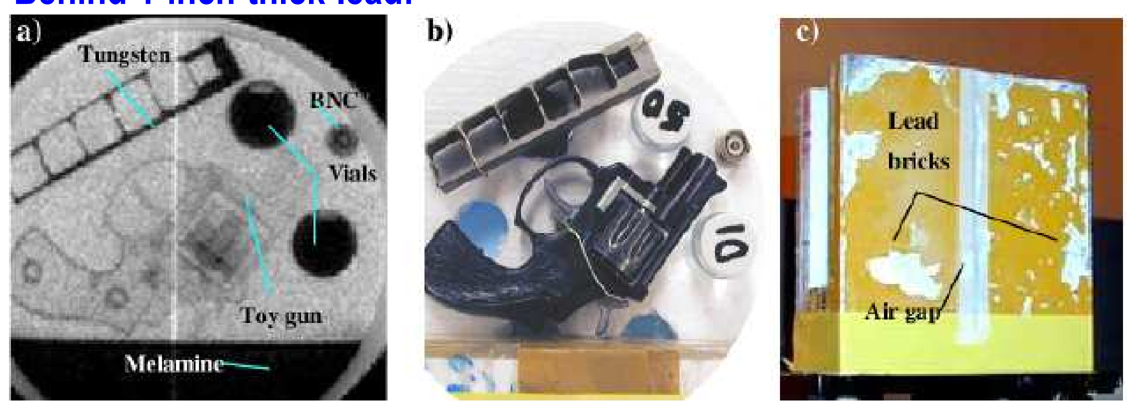
FRM II reactor, CCD+PP screen mixed with ZnS(Ag) 2.4mm thick, res. ~1mm *Schiillinger et al., (2008)*



PTB cyclotron, plastic scintillator fiber screen +image intensifier+CCD, res ~1mm



Behind 1-inch-thick lead:



Mor et al., (2009)

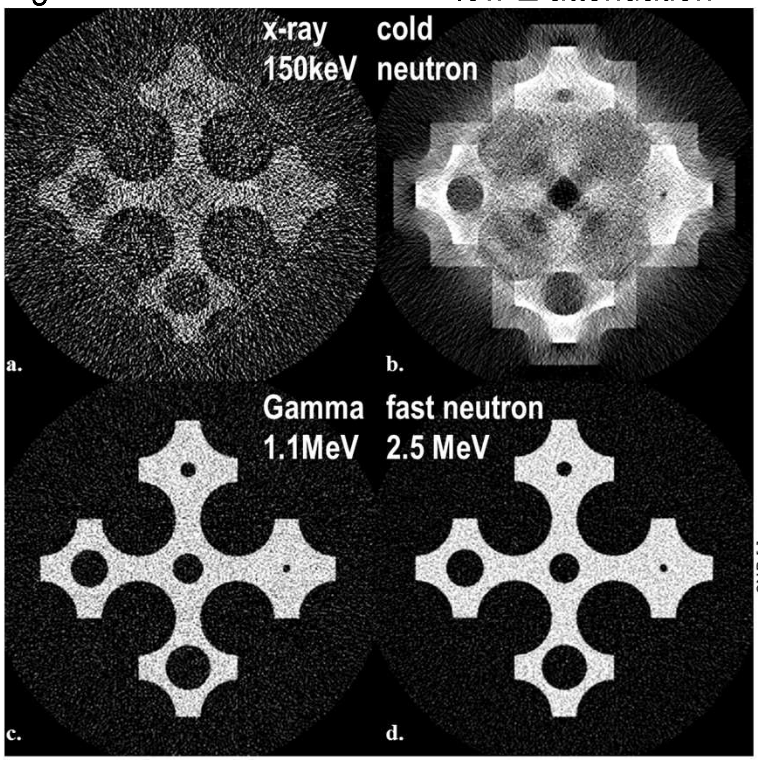
NI USING COMPACT FAST NEUTRON SOURCES AT PSI

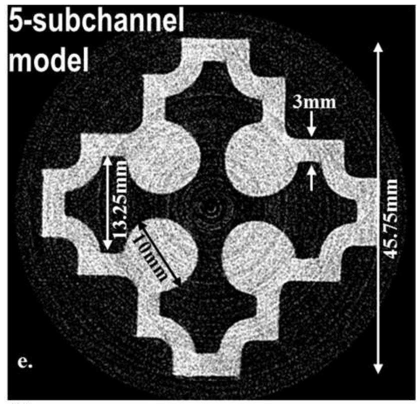
MOTIVATION: Instrumentation development for nuclear fuel bundle studies and optimization: two-phase flows in fuel bundles!

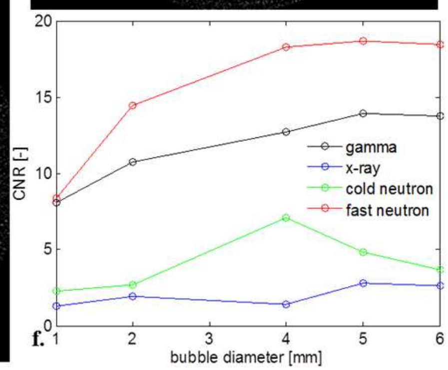
Tomography on a small partial bundle:

too much high-Z attenuation — too much low-Z attenuation

CNR: contrast-to-noise ratio air/water



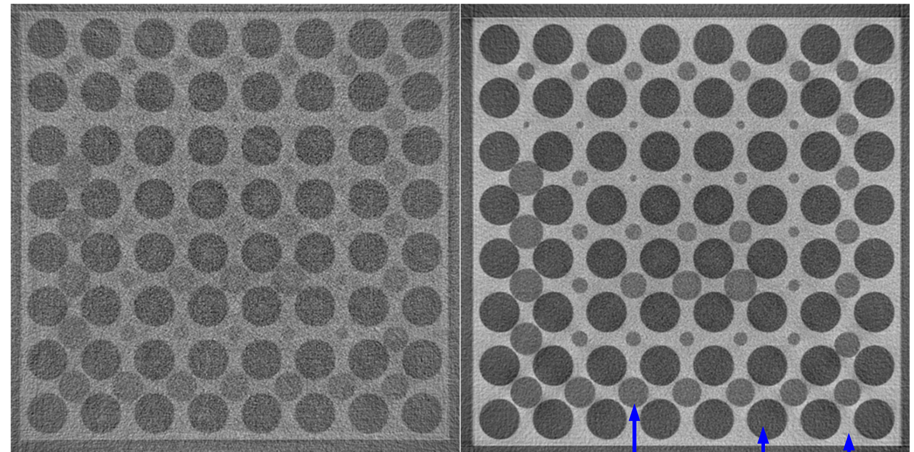


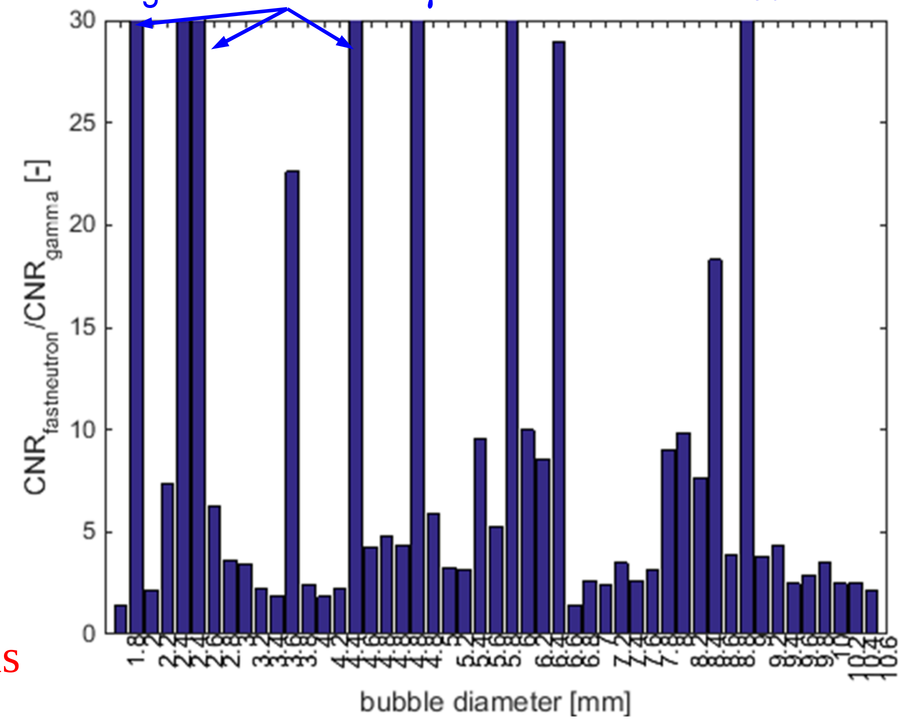


The same total fluence, but differing det. efficiencies for diff modalities.

Tomography on a full 8x8 bundle (MC Simulations):

Co-60 gamma — Fast neutron 1.98 MeV





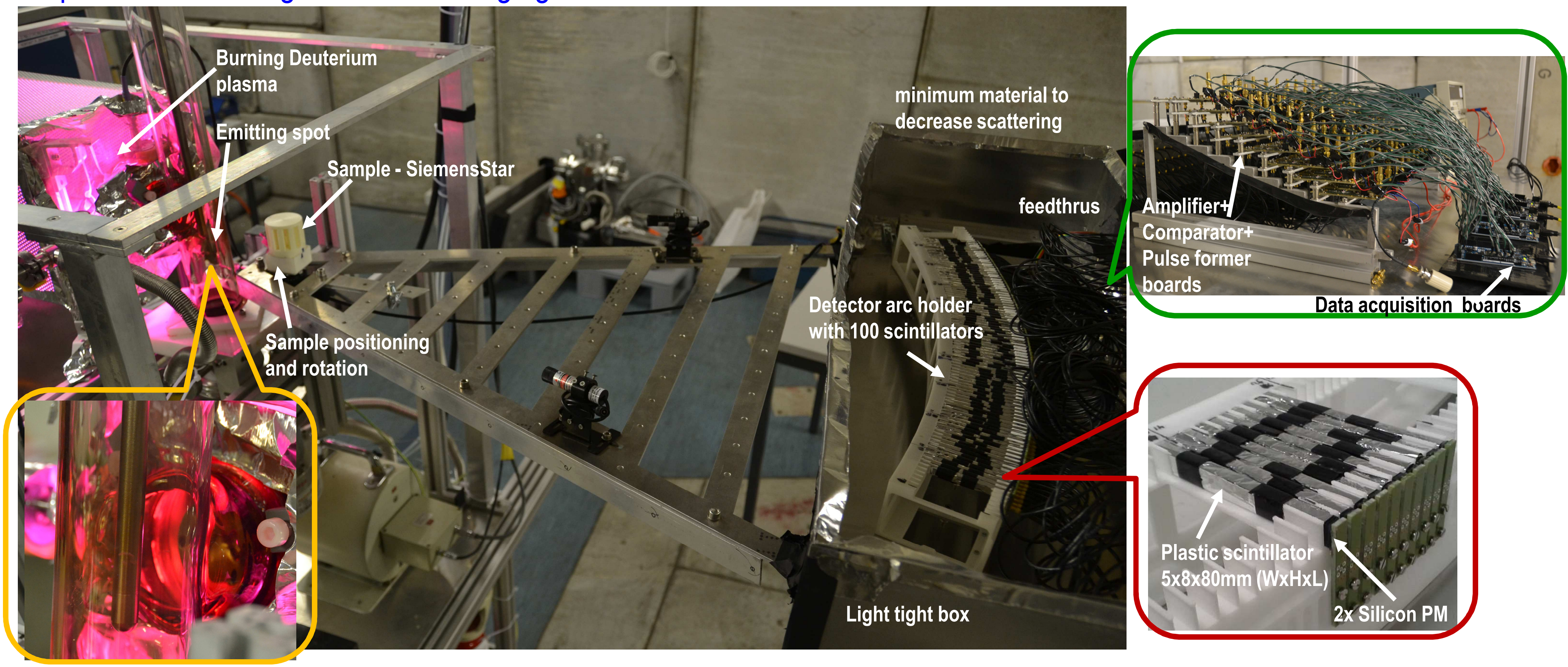
<u>Fast neutrons are superior for such applications</u>:

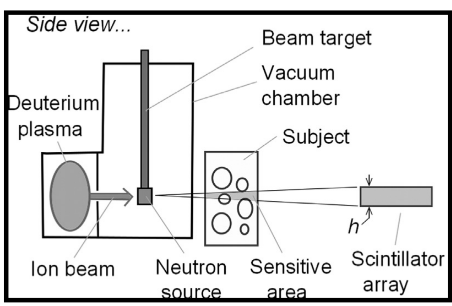
- high penetrating power
- good contrast for high amounts of both low-Z/high-Z materials

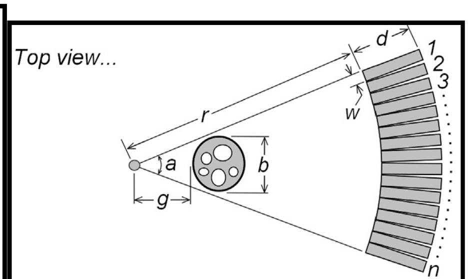
FAST NEUTRON IMAGING USING COMPACT SOURCES 1.

Deuterium-Deuterium fusion based (2.8MeV) compact fast neutron generator for imaging

1D detector arc for **cross-sectional tomography**



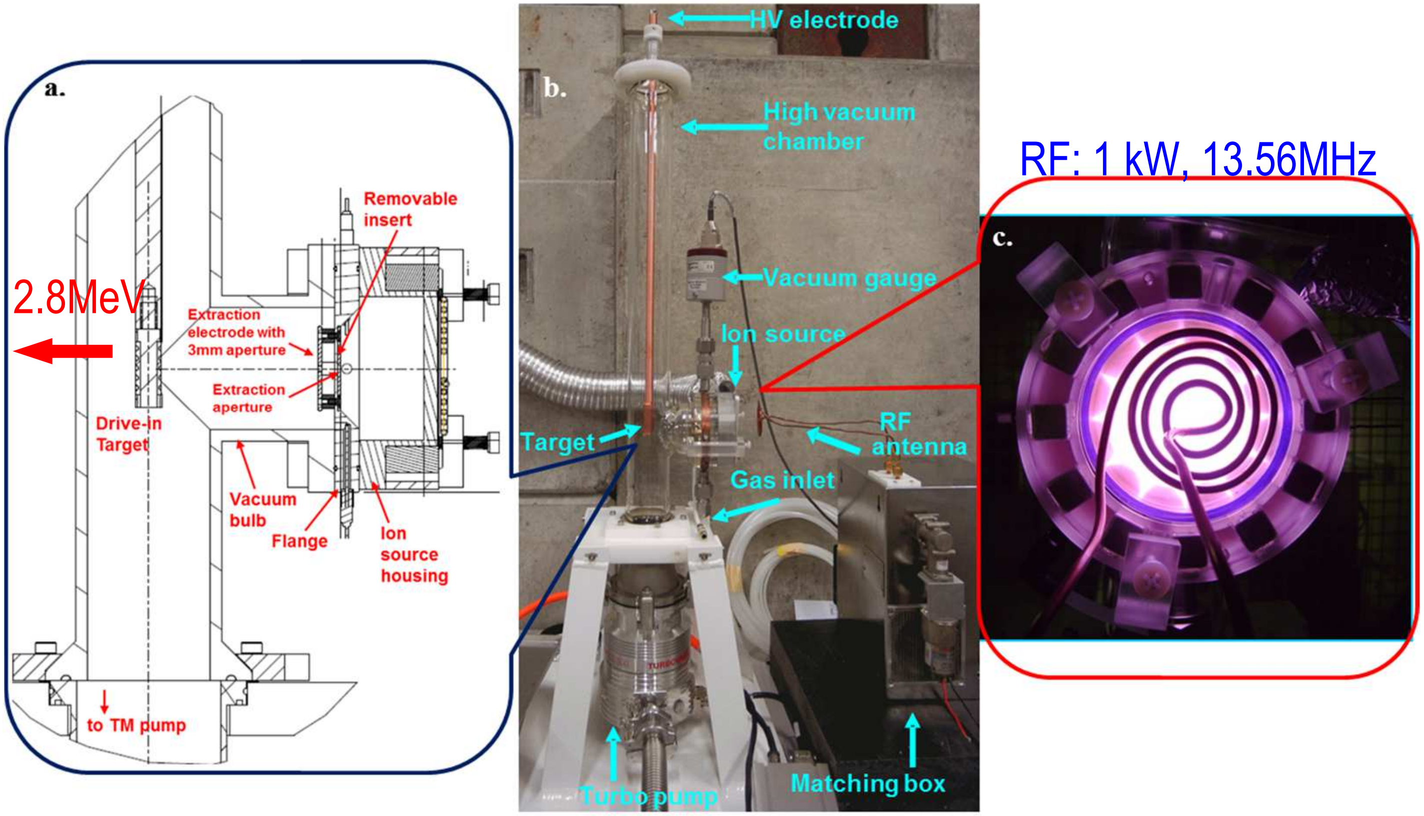




Boundary condition: small-scale, potentially portable device, so that eventually it could be setup next to large-scale, high-pressure, high-temperature nuclear bundle testing facilities!

FAST NEUTRON IMAGING USING COMPACT SOURCES 2.

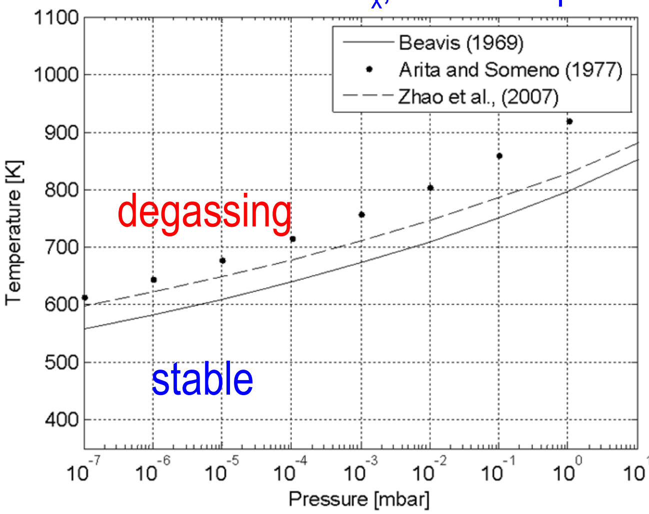
- Imaging in fan beam geometry from a quasi-point source (2mm) to minimize image blur! Commercial generators: much larger emitting volumes. Fan geometry -> magnification.
- Pulsed/CW operation: kHz range, pulse width down to 0.1us
- Source-detector distance: limited (1m) due to low intensity!
- Target perpendicular to beam -> object can be <10cm to source (high utilization of source neutrons),
- max. object size: 10cm at resolution of ~1.5 mm (design value)
- Output at present 1e7 n/s (at 110-120kV, 0.5mA)
- Target 0.5mm walled all-Ti tube internally cooled by deionized-water (without cooling: 1e6 n/s)



Target behavior:

Interstitial metal-hydride

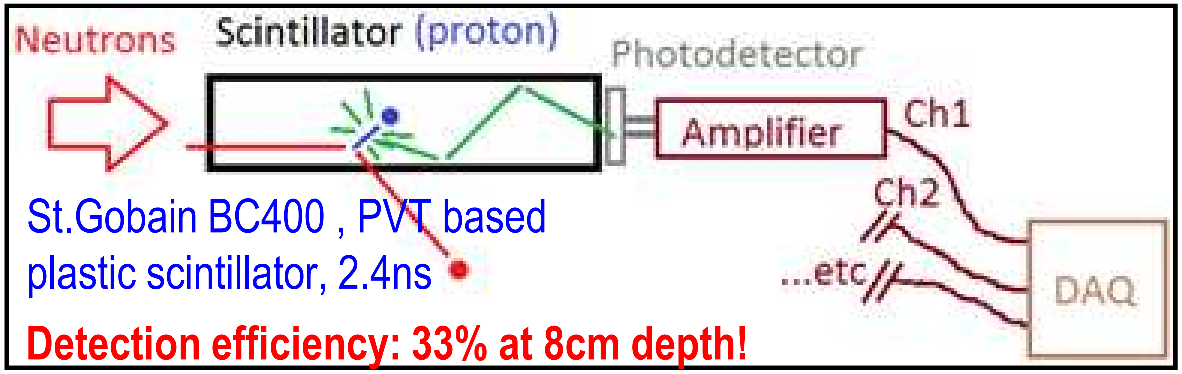
Thermal limit for TiD_x, x can be up to 2



Neutron production efficiency: ~10%

FAST NEUTRON IMAGING USING COMPACT SOURCES 3.

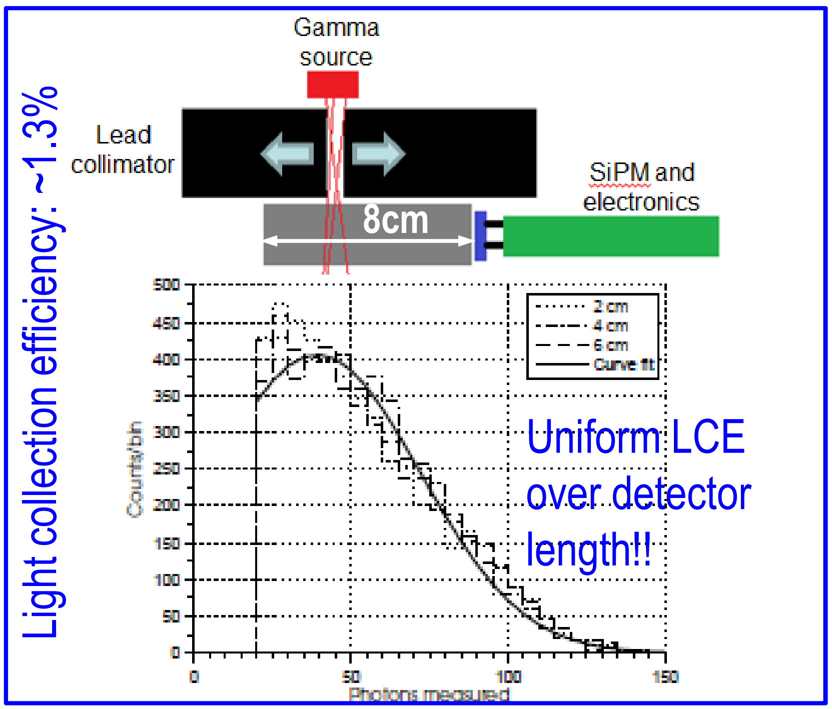
Detector concept:



St.Gobain BC400 , PVT based plastic scintillator, 2.4ns

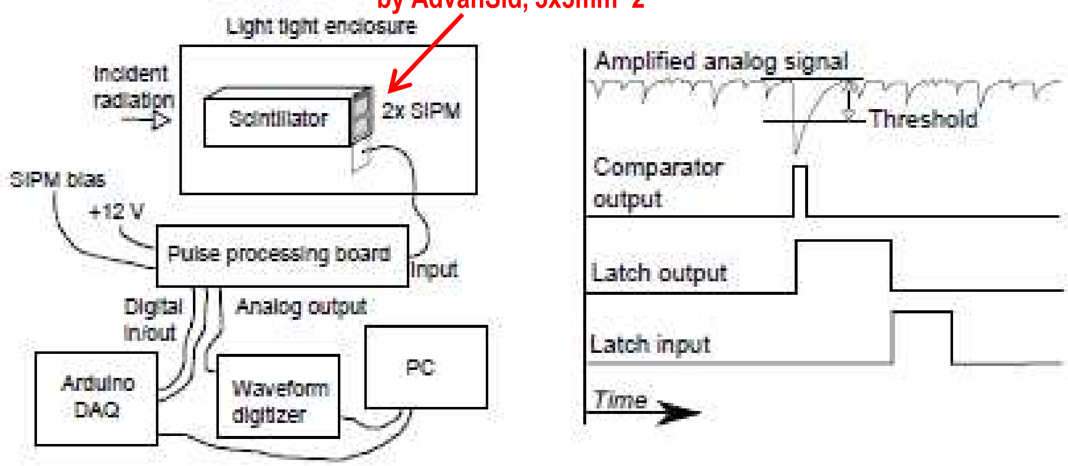
Detection efficiency: 33% at 8cm depth!

Size of scintillation detector elements and the arc optimized by MC simulations
Cost effective solution: ~100CHF/channel



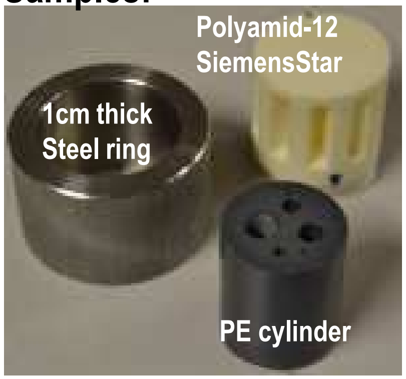
- PHD against X-rays from the generator at 0.12MeeV(~0.7MeV p) + to suppress scattered neutron contribution (~20-25% @ 1m)
- Fast signal (ns) enables minimizing X-ray pile up and facilitates PHD

by AdvanSid, 3x3mm^2

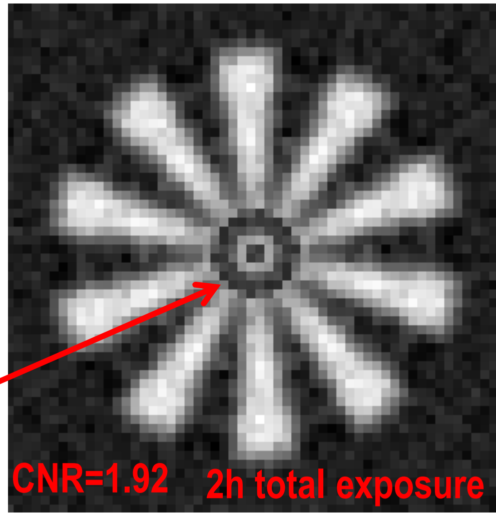


FAST NEUTRON IMAGING USING COMPACT SOURCES 4.

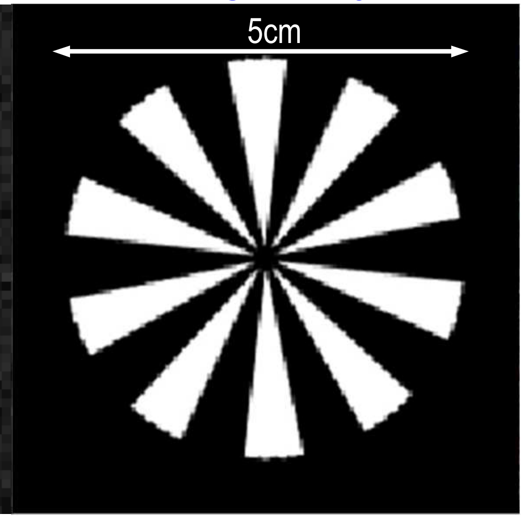
Samples:



Bare Siemens Star



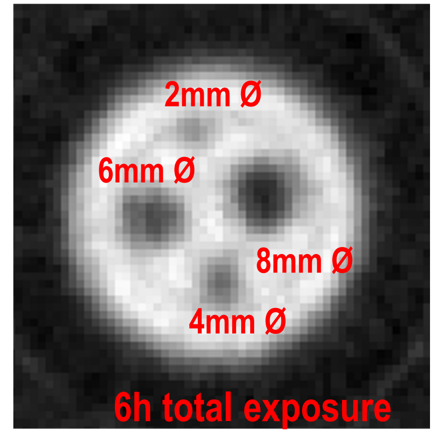
actual geometry



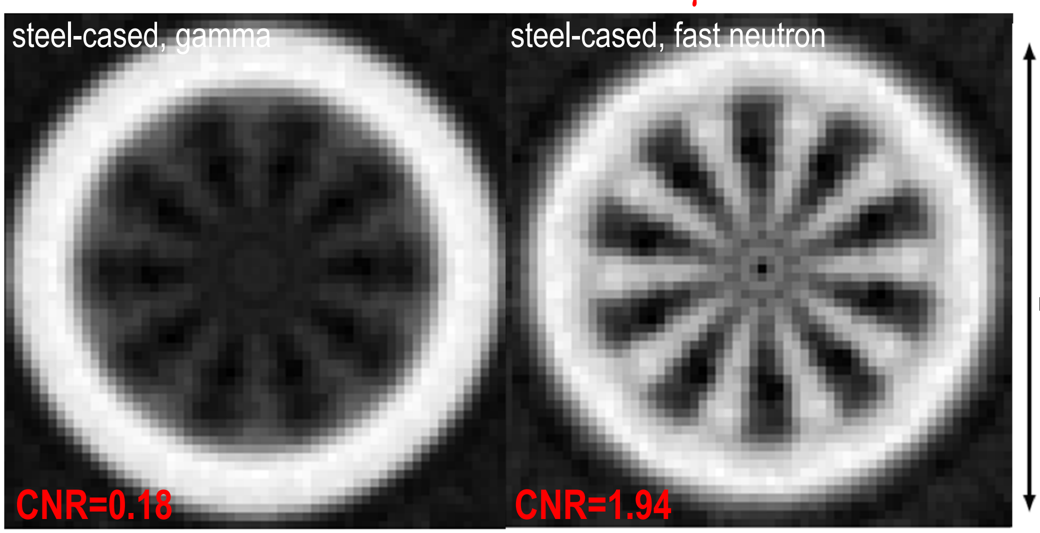
Resolution: ~2mm

CNR: contrast-to-noise ratio air/plastic

Non-symmetric object

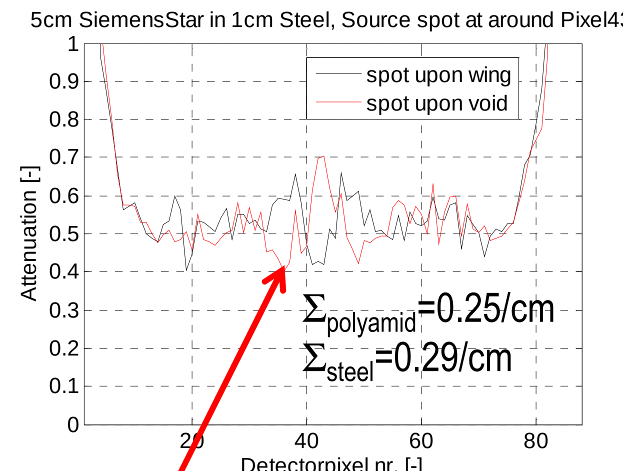


The advantage of use of fast neutrons to image low-Z material hidden in high-Z material: CNR_{FN} /CNR_{γ} ~11 (at similar flat cps)



Co-60 gamma source

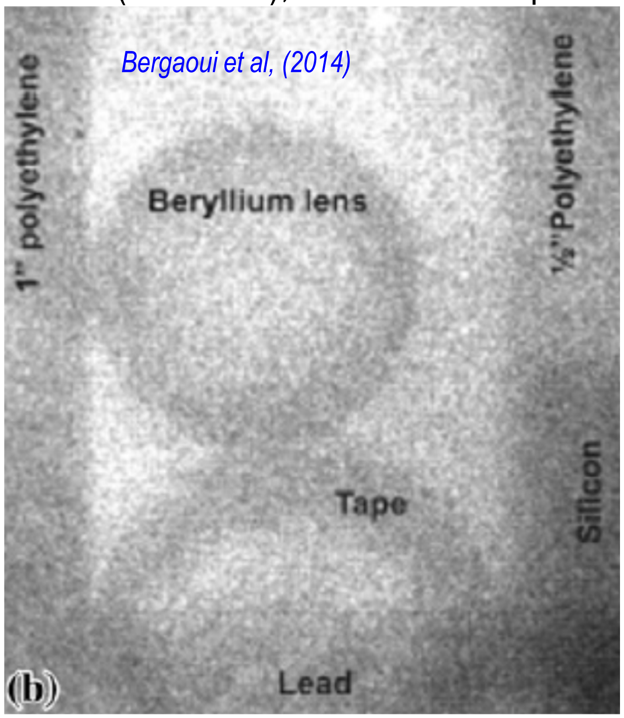
2h total exposure



Potential for larger object sizes up to 20-25cm!

FAST NEUTRON IMAGING USING COMPACT SOURCES 5.

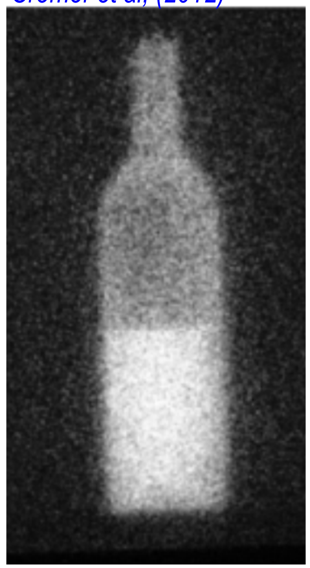
Compact DD generator, CCD+ plastic scintillator screen (4cm thick), over 67 min. exposure



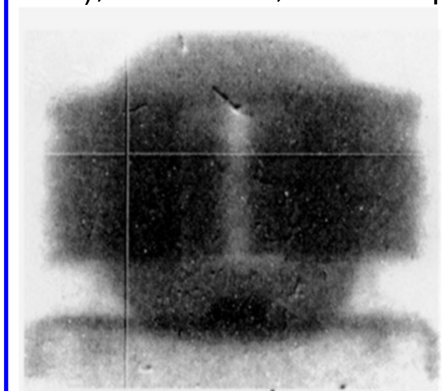
Bergaoui et al, (2014)

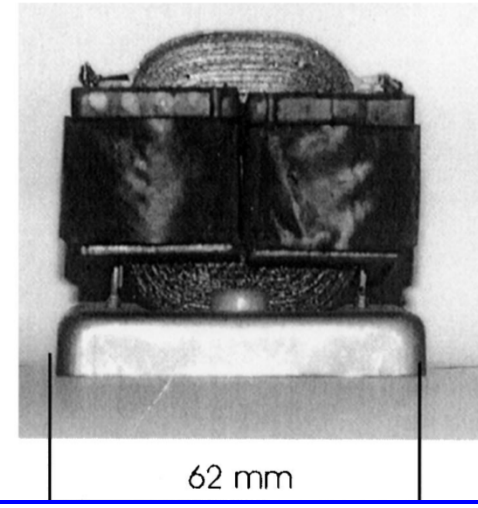
5.5 min. exposure

Cremer et al, (2012)

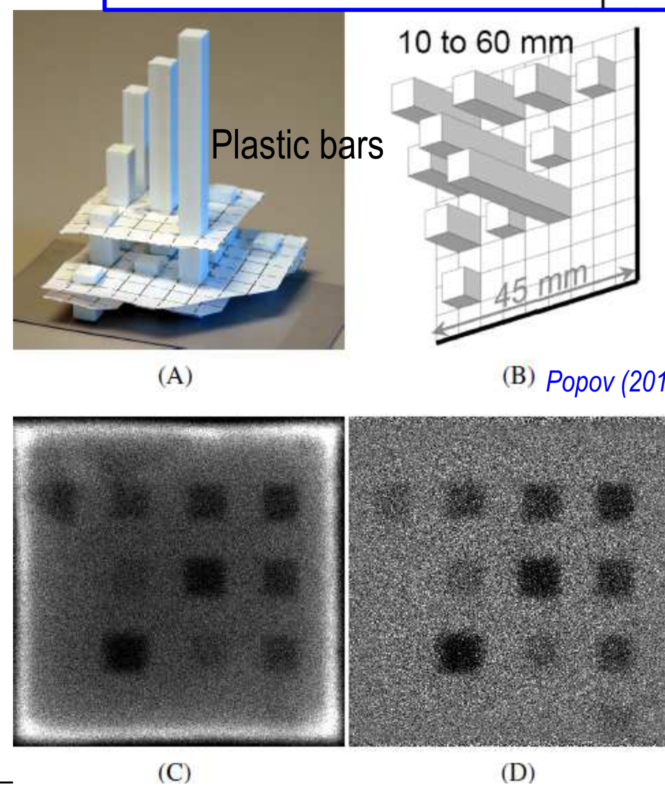


DD generator, CCD+ powder luminophor in plastic (1.6mm thick), res. ~1mm, 5 min. exposure





Mikerov&Wachowski (1999)

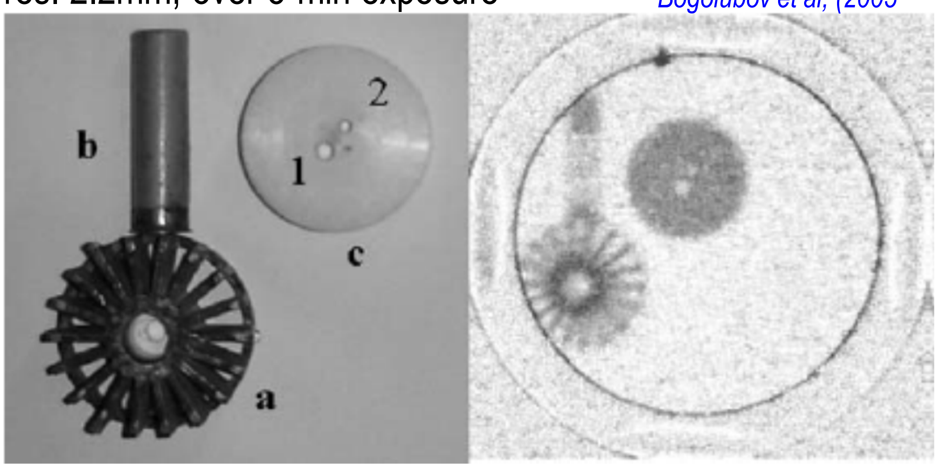


Popov (2011)

DD generator, multi-anode, position sensitive PM+ plastic scintillator screen (4mm thick), res. 0.5 mm

DT generator, CCD+ plastic scintillator screen (6cm thick), res. 2.2mm, over 5-min exposure

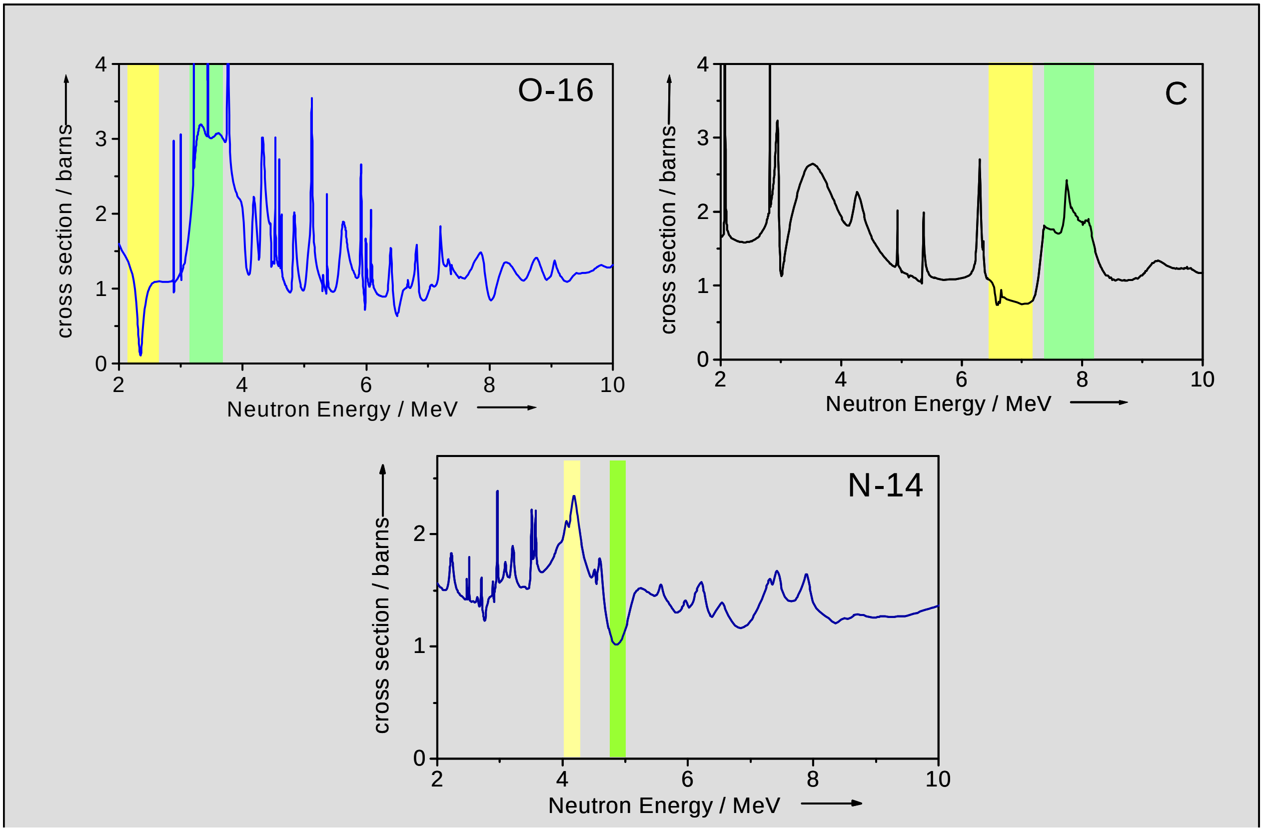
Bogolubov et al, (2005

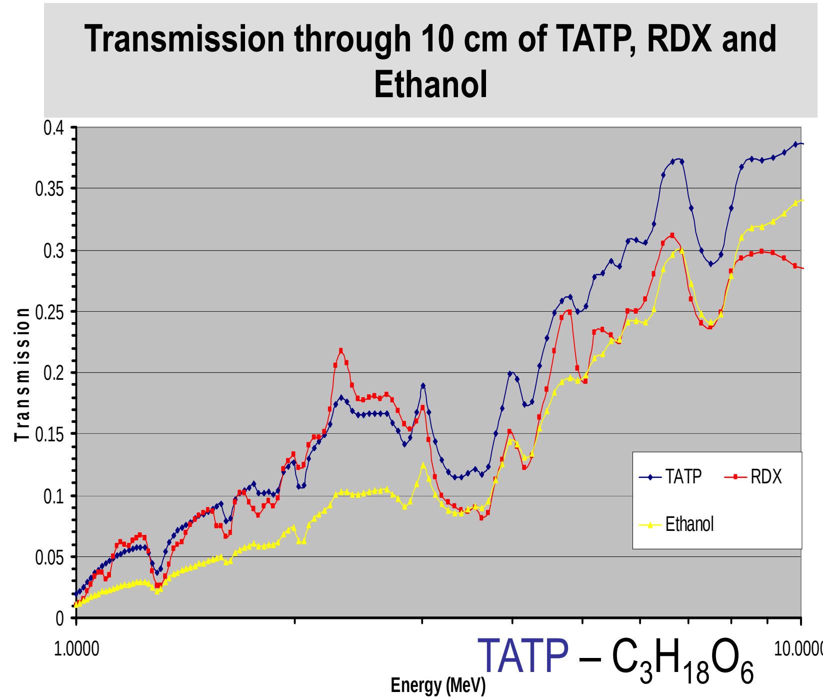


APPLICATIONS: FAST NEUTRON RESONANCE RADIOGRAPHY

FNRR exploits cross-section fluctuations to automatically detect specific elements within inspected items

Objective: Detection of standard and improvised explosives





TATP – $C_3H_{18}O_6$

RDX – $C_3H_6N_6O_6$

Ethanol – C_2H_6O

Pre-requisite for resonance imaging: determine/measure fast-neutron energies

1. Variable "Mono"-Energetic Neutron Source
2. Energy measurement by **Time-of-Flight** methods in a **Pulsed** Neutron Beam of **broad spectral** distribution (2 – 10 MeV)

FNRR ⇨ **PFNTS**: Pulsed Fast-Neutron Transmission Spectrometry

By courtesy of
V. Dengendorf, PTB, Braunschweig, Germany
I. Mor , Soreq, Israel

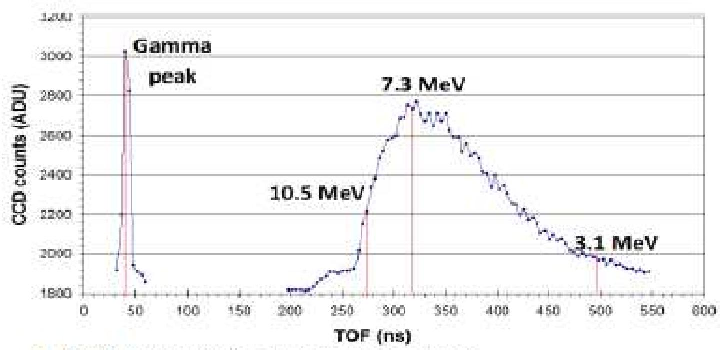
APPLICATIONS: FAST NEUTRON RESONANCE RADIOGRAPHY

a) Camera 0, gamma rays image

b) Camera 1, E_n = 10.5 MeV

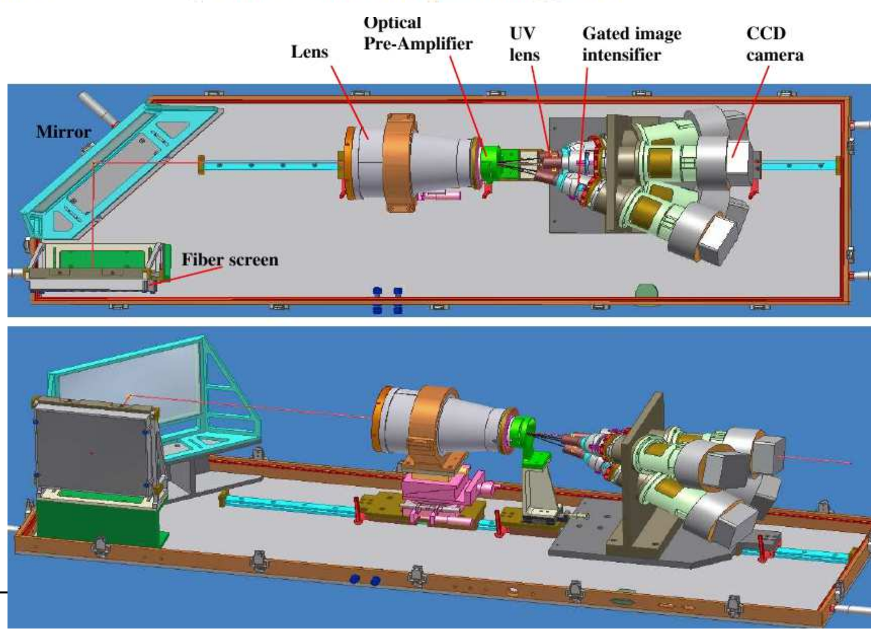
c) Camera 2, E_n = 7.3 MeV

d) Camera 3, E_n = 3.1 MeV

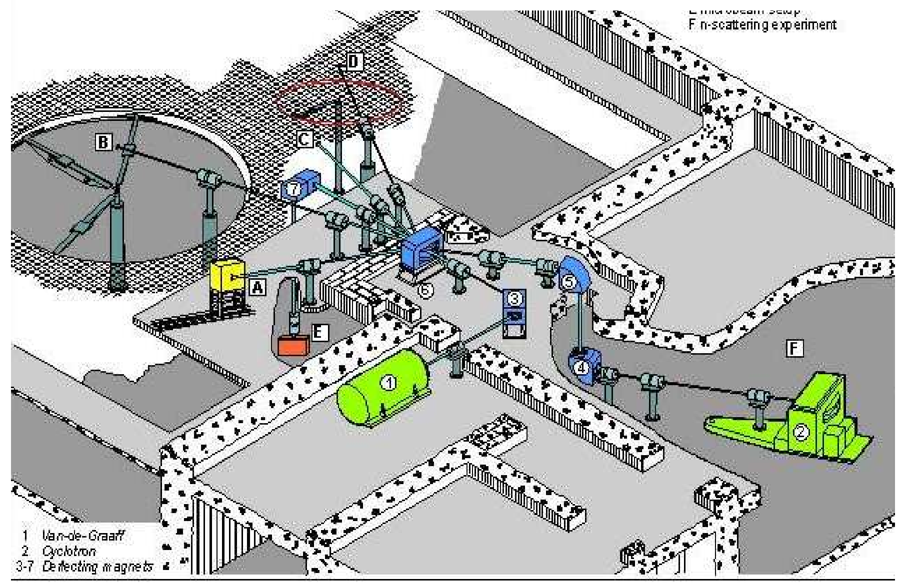


e) TOF transmission spectrum spectrum

TRION GEN II detector with 4 CCDs (3 neut eng's+γ)



Test Bench: PTB Cyclotron



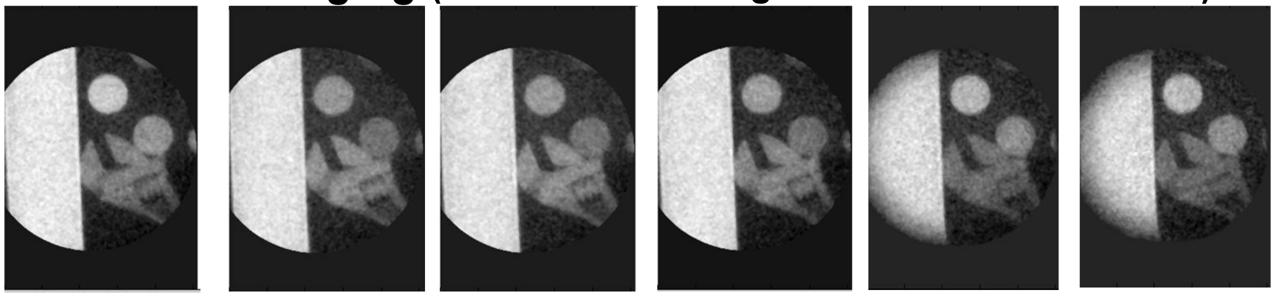
- Be (d,n) on thick Be target (3 mm)
- 1.5 ns pulse width, 500 ns rep rate
- E_d = 12 MeV
- I_d ca 2 uA (max)
- Detector distance from Target: 12 m
- prompt gamma burst
- n-Flux: **~ 2* 10^4 s^{-1} cm^{-2}**

More demanding requirements than for usual, non-TOF sources!

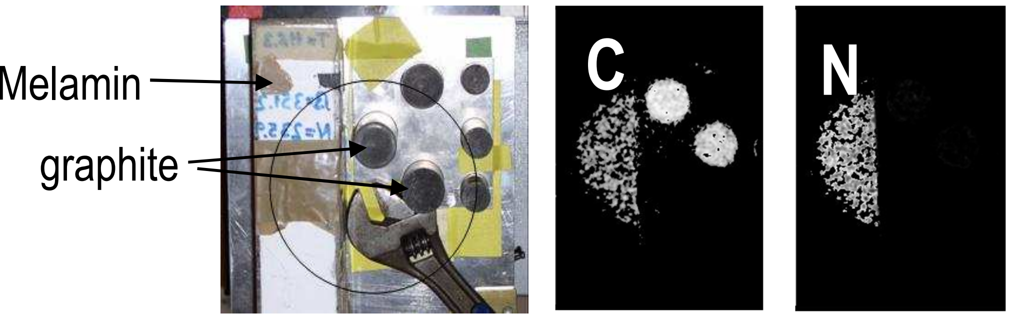
By courtesy of
V. Dengendorf, PTB, Braunschweig, Germany
I. Mor , Soreq, Israel

APPLICATIONS: FAST NEUTRON RESONANCE RADIOGRAPHY

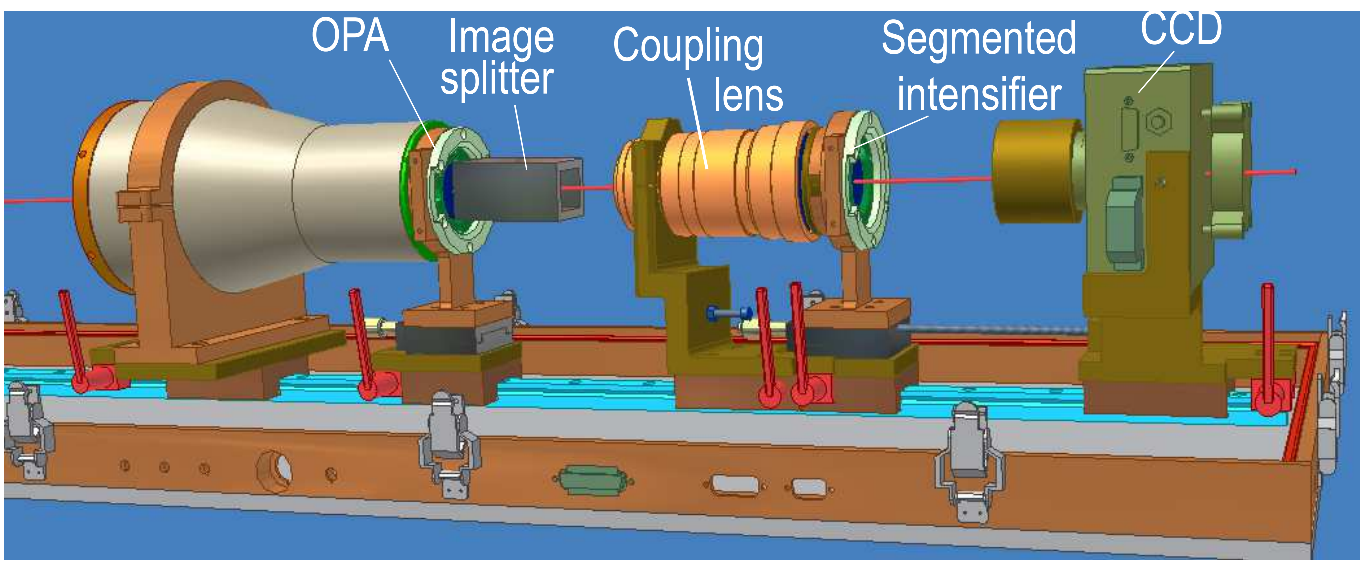
Elemental Imaging (from camera images in selected TOF bins)



180 ns 200 ns 210 ns 230 ns 320 ns 330 ns



Elemental ratios can be reconstructed with a good accuracy (<10%)



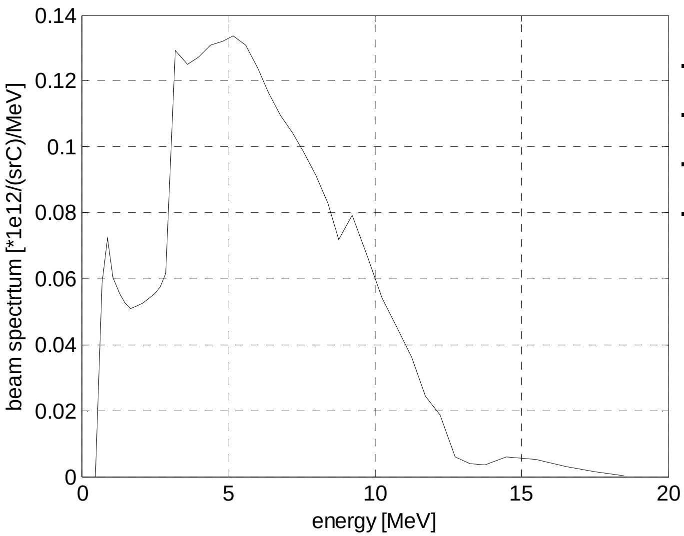
Newest detector generation: TRION GEN III with image splitter and image intensifier with 8-fold segmented photo cathode to increase measuring efficiency.

By courtesy of
V. Dengendorf, PTB, Braunschweig, Germany
I. Mor , Soreq, Israel

APPLICATIONS: TIME-RESOLVED IMAGING

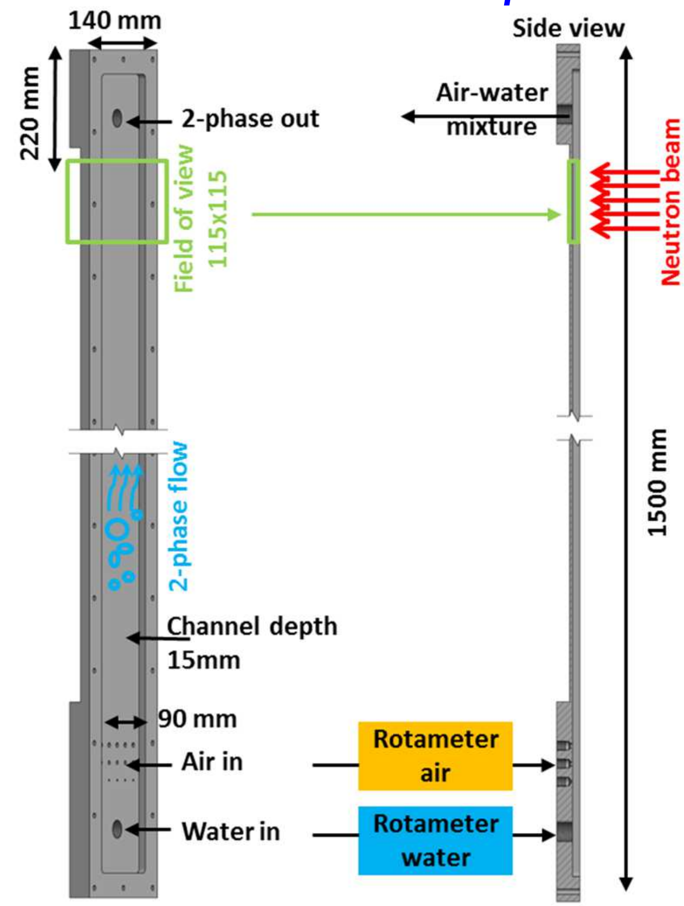
The high-intensity, broad-spectrum beam at PTB:

D (11.5 MeV) + Be -> n (<E>=5.5MeV)



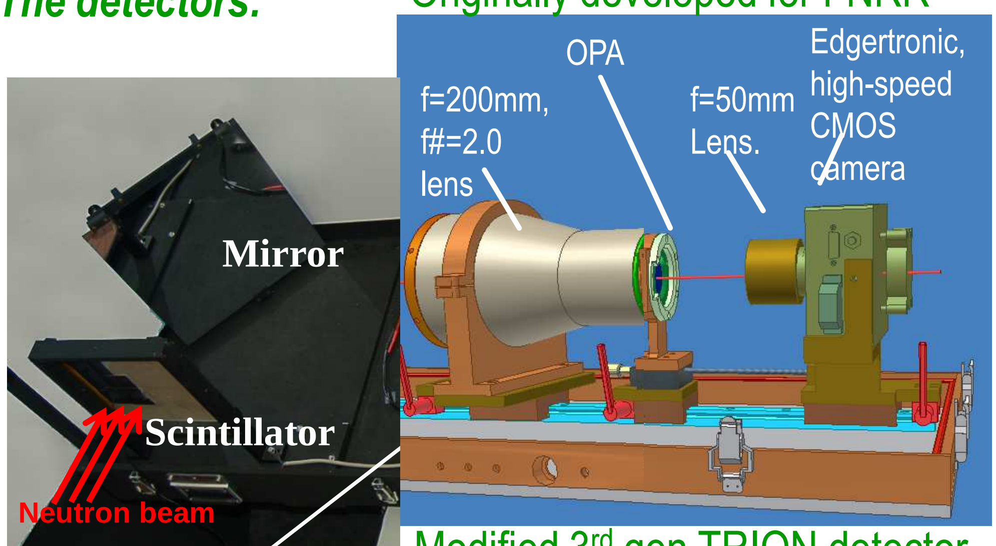
- thick, wobbling Be target
- pulsed D beam, 40uA
- emitting spot size ~5mm Ø
- Flux at sample: ~1.3e7n/cm^{2}s

Flat channel with adiabatic 2-phase flow:



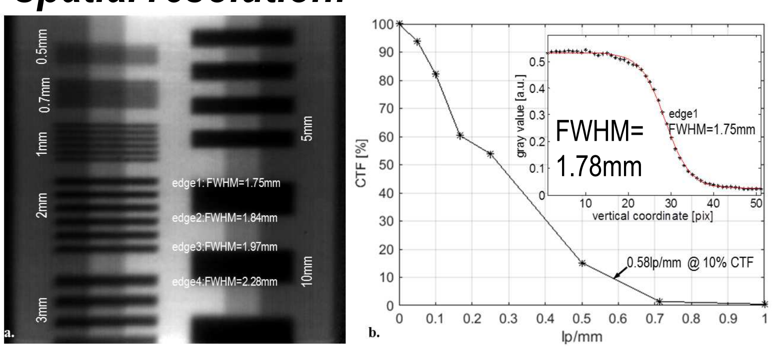
The detectors:

Originally developed for FNRR



Modified 3rd gen TRION detector

Spatial resolution:



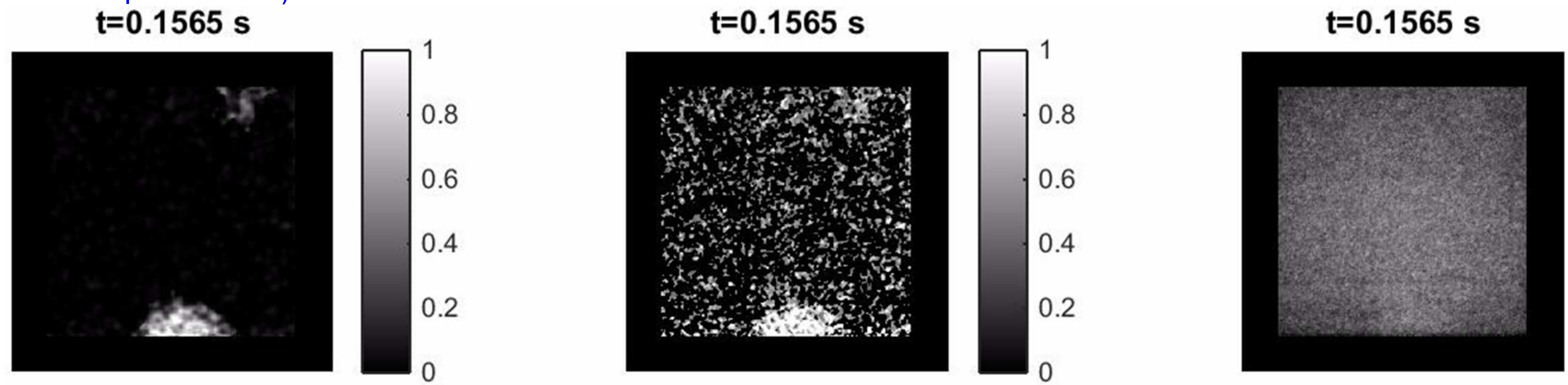
APPLICATIONS: TIME-RESOLVED IMAGING

Short exposures-> shot noise-> post processing

gas fraction, space (TH, median, anisotropic diffusion) - time filtered

gas fraction(flat field corrected)

raw image



Bubbly flow

Slug flow

Churn flow

t_{exp}=3.33ms

POTENTIAL APPLICATIONS

Home land/citizen security

Inspection/imaging of
- hazardous objects
- improvised explosives, explosive legacy etc.
- heavily shielded contra-band
- hidden nuclear materials (safeguards)
- …

Industrial metrology

In-field inspection of industrial specimen/critical components using a compact imager
- for defects/homogeneity
- to confirm dimensions/reliability

for quality insurance during production (automotive and aviation industry->bulky low-Z/ high-Z components)
to complement X-ray imaging

Applied science

- General NDA of large and dense (low-Z/high-Z) objects of interest
- Material science e.g. integrity of concrete/wood
- Mining: Carbon detection in minerals
- …

Goal: scanning of objects in a non-time-critical settings
with total exposure times: minutes, up ½-1 hour!
Yield/Flux is in generally not sufficient for higher timing requirements

CONCLUSIONS AND OUTLOOK

- **NI using fast neutrons covers a niche application within radiation imaging techniques, which is unfeasible for other modalities (mixed high-Z/low-Z, robust samples)**
- **It is a much less matured technique than thermal neutron imaging, not to mention X-ray imaging**
- **There are physical limitations due to fast neutron properties limiting performance in practical situation (detector resolution, source strength etc.)**
- **There are promising developments on-going (FNRR, compact systems)**
- **There is a steady interest for potential fast neutron applications: home land security, in-field industrial use of compact/portable setups etc.**

THANK YOU FOR YOUR ATTENTION!