... and other neutron imaging facilities

Michael Schulz
Outline

- Neutron production & interaction
- ANTARES: neutron imaging at a reactor
  - Beam line overview
  - Basic components
  - Advanced setups
- ODIN: neutron imaging at a spallation source
Modern reactor design:
Tangential beam tubes at the FRM II reactor (First introduced 1967 at the ILL Reactor)

- Cold neutrons (Radiography)
- Fast neutrons
- Thermal neutrons
- Ultra cold neutrons
- Positrons

Beam tubes look into cloud of moderated neutrons around the core-no direct view to core, Less shielding required at experiment. Fast neutrons can still enter beam tubes by one single scatter process.
Neutron spectrum

- Cold, thermal, hot, (fission) sources
- General 1/ν law
- Plus Bragg edges
- Beam Hardening effects

\[ \lambda = 2d/n \sin\Theta \]

\[ \sigma \text{ [barn]} \]

Energy \( E \) vs. Neutron wavelength \( \lambda \)

\[ \Phi(\lambda) = 4\pi \frac{1}{1/cm^2A} \]

Absorption range for different materials: Fe, Cu, Pb, Zr, Al, Ni.
ANTARES beamline
ANTARES Beam Line Concept

- 3 chambers
- Beam fully accessible along flight path
- High flexibility
- New & light shielding material (only 500t)
- Plenty of space available for experiments & sample environment
Main Components of ANTARES

- Shutter(s)
- Flight Tubes
- Beam Limiters
- Motorized Stages
- Detector(s)
- Shielding
- Collimator(s)

optional:
- Beam Filters
- Monochromator / Selector

plus:
- Access Control
- Media Supply (electricity, gas, water, ...)
- IT (network, storage, servers, software, ...)
Shutters

- Stop full beam for access of cave
- One shutter must be fail-safe!
- Additional fast shutter (B$_4$C) to reduce sample activation (closed after each image)
Collimators

- Massive for beam tube instruments to stop background
- Material with low activation (i.e. borated steel)
- Machined by spark erosion
- Pinhole sizes: 2, 4.5, 9, 18, 36, 71mm
Detectors – Camera Based Systems

- General principle: scintillator – camera – mirror
- Cooled scientific CCD / CMOS for reduced / negligible dark current
- Surface mirror with > 99% reflectivity
- High end optics: SLR or custom made
High resolution detector

- Adjustable FOV (14mm ... 60mm)
- Smallest pixel size 6.5µm
- One or two mirror configuration

- 10/20µm Gd$_2$O$_2$S scintillator
- Camera shielded with 5cm Pb
- Autofocus
Flight Tubes

- Intensity loss in air ~8% per m (depends on moisture)
- Flight Tubes with thin Al windows
- Penumbra must not touch the tubes
- He filled or evacuated (danger!)
- Flexible arrangement desired
Beam Limiters

- Absorb most of the unused beam area before the sample position
- Reduced background at sample position
- Neutron absorber: BorAl, BN or $B_4C$ (B: low gamma energy ~500keV)
Motorized Stages

- High precision / high load capacity
- X,y,phi, (+ optional goniometers)

10kg

500kg
Additional things…

- A place to work
Additional things…

- Racks for electronics
- Safety access control
- IT: (File server, Computers for reconstruction / visualization / Instrument control)
Monochromatization

Astrium Neutron Velocity Selector

- 144 lamellae
- $\lambda_{\text{min}} = 2.95\text{Å}$
- $\Delta\lambda/\lambda = 10\%$
- Peak Transmission > 80%
- FOV ~ 20 x 20 cm

Double Crystal Monochromator

- Pyrolytic graphite (002) crystals
- Mosaicity 0.7°
- $\Delta\lambda/\lambda = 1\% \ldots 3\%$
- Wavelength band: 1.4 ... 6.0Å

Applications:
- Bragg Edges
- Texture
Setup for Depolarization Imaging
$Pd_{1-x}Ni_x$

depolarization

increasing $T$

$T = 8K$

$T_c(K)$

Para

Ferro

M. Schulz, et.al.
Neutron grating interferometer at ANTARES

Absorption grating \( p_0 = 1.6 \text{ mm} \)

Phase grating \( p_1 = 7.98 \mu\text{m} \)

Analyzer grating \( p_2 = 4.0 \mu\text{m} \)
The nGI setup

• Setup generates neutron interference pattern at detector:
  
  \[
  DFI = \frac{a^s_1 a^f_0}{a^f_1 a^s_0}
  \]

• Scattering at μm structures locally degrades interference pattern
• Degradation of interference pattern mapped in the DFI

→ DFI = spatially resolved USANS scattering map
Applications:

- Material differentiation and testing for µm inhomogeneities
- Investigation of µm domain structures and nucleation in ferromagnets, superconductors, multiferroics, etc.

Examples:

Domain expulsion in the IMS of superconducting Nb in increasing field after FC to 4 K. In the white regions islands of flux line lattice coexist with field free Meissner phase.

Under development:

Probing for micrometer anisotropies

Direction and magnitude of anisotropy in a µm neutron absorption grating, a brass rod and a glass fiber mat (from left to right)
Electric steel

- Transmission image (TI) and dark field image (DFI)
- DFI visualizes domain walls inside the material
- Investigate how machining affects magnetic properties

TI and DFI of a grain oriented electric steel (t = 300 µm)  
B. Betz et al., Physics Procedia 69, 399-403 (2015)

DFI and DFI-profiles of several not oriented electric steels  
Betz et al., Physics Procedia 69, 399-403 (2015)
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- 5 MW accelerator (3GeV protons)
- Cost Book construction cost of 1.843 B€ (2013)
- Cost Book annual operations cost target of 140 M€ (2013)
- 22 “public” instruments (15 included in the construction budget)
Civil Construction
Imaging at ESS

- **standard neutron imaging**
- **depolarization imaging**
- **dark field and phase imaging**
- **quantitative magnetic imaging**
- **stress and strain imaging**

**Δλ/λ** not required

10 %

10 %

1 %

0.5 %

✓ Can be realized with sophisticated Chopper System
ODIN Overview

• **Optical and Diffraction Imaging with Neutrons**: Neutron radiography and ToF imaging with variable wavelength resolution

• ODIN will be the only imaging instrument installed during the first round

• It will be a “day-1” instrument: first neutrons planned for 2021

• Joint project of PSI and TUM (lead institution)

• Budget 11.6M€.
Thank You!