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Status of the neutron imaging and diffraction instrument IMAT

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Abstract

A cold neutron imaging and diffraction instrument, IMAT, is currently being constructed at the ISIS second target station. IMAT will capitalize on time-of-flight transmission and diffraction techniques available at a pulsed neutron source. Analytical techniques will include neutron radiography, neutron tomography, energy-selective neutron imaging, and spatially resolved diffraction scans for residual strain and texture determination. Commissioning of the instrument will start in 2015, with time-resolving imaging detectors and two diffraction detector prototype modules. IMAT will be operated as a user facility for material science applications and will be open for developments of time-of-flight imaging methods.

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1. Introduction

The case for the imaging instrument IMAT (Imaging and MATerials science) at the pulsed neutron spallation source ISIS was motivated to a large extent by the need for neutron radiography and tomography analysis for many of the user projects on the engineering instrument ENGIN-X at ISIS. Bragg edge transmission analysis which is

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performed in a radiography-type set-up was developed at ISIS in the late 1990s. A Bragg edge detector of 10x10 pixels complements the diffraction strain analysis set-up on ENGIN-X (Santisteban et al., 2001; 2006). The spatial resolution of the transmission detector is limited to 2 mm, however the neutron detection efficiency and spectral resolution of each pixel is high and sufficient for precise determinations of Bragg edge positions, lattice parameters and strains, for a quantitative phase analysis as well as for texture analysis (Santisteban et al., 2002; 2006). The need for higher spatial resolution for transmission analysis necessitated the design of a new neutron instrument and the use of high-resolution neutron imaging cameras with timing capabilities. An energy-selective imaging approach with a gated CCD on ENGIN-X showed that structural information can be visualized (Kockelmann et al, 2007), a pilot project which helped to make the case for a new neutron imaging instrument. Moreover, the development of a system based on microchannel plates and a Timepix readout has shown potential for high resolution mapping of microstructure properties (Tremsin et al., 2009). IMAT is currently under construction at the second target station (TS-2) of ISIS and will offer a combination of imaging and spatially resolved diffraction modes such as neutron radiography, neutron tomography, energy-selective imaging, neutron strain scanning, crystallographic structure, phase, and texture analysis. Of particular importance for IMAT will be Bragg edge transmission analysis for strain and crystallographic texture mapping (Kockelmann et al, 2007; Tremsin et al., 2009; Sato et al., 2010). In this paper we introduce the basic design and instrument parameters of IMAT, report on the current installation status, and provide an overview of the envisaged detection systems for IMAT.

2. Outline design of the instrument

2.1. Basic components of a combined TOF imaging and diffraction instrument

IMAT will enable both imaging and diffraction applications by making use of time-of-flight (TOF) techniques. On a TOF instrument the wavelengths of the neutrons are determined by timing their flight over the length of instrument. The instrument parameters are determined by the source characteristics (e.g. energy dependent pulse widths) and the geometry (e.g. path lengths) which determine the energy resolution and the bandwidth, to mention two of the most important characteristics of such an instrument. It is important to operate not only the neutron cameras and diffraction detectors in TOF mode but also synchronise other components such as filters and monitors with the pulsed source.

Fig. 1 gives a schematic overview of components and measured data on a combined imaging and diffraction instrument. The source produces pulses of polychromatic neutrons which are transported down the instrument in evacuated flight tubes or evacuated neutron guide systems. Such an instrument will be operated either in imaging
or diffraction mode. For imaging a pinhole is inserted to achieve a given local collimation of the beam at the sample position. For diffraction, the pinhole is removed and a series of slits (not shown) are used to collimate the beam down to a few square millimetres at the sample position. On a short-pulse source the instrument can be installed on a short flight path without a neutron guide. On a broad-pulse source the instrument needs to be on a long flight path to achieve a good energy resolution which necessitates a neutron guide. On a pulsed source choppers can be effectively used for gamma and fast neutron background filtering, as well as for flexible bandwidth selection. TOF beam monitors are crucial for the operation of a TOF imaging instrument to measure incident beam spectra for diagnostics and normalization purposes. The incident beam divergence and the pinhole geometry determine the collimation ratio which can be expressed as L/D. Each pixel of the imaging and the diffraction detector measures a neutron TOF spectrum, hence achieving a (spatial and angular) mapping of Bragg edges and Bragg peaks, respectively. One important consequence for the imaging set-up is that energy-selective radiography can be carried out for the full field of view with a spatial resolution in the tens of microns. By using diffraction detector arrays composed of many detector elements at different scattering angles, different strain components and grain orientations (texture) in a millimetre-sized gauge volume of a polycrystalline sample can be measured. The Bragg edges in a transmission detector pixel correspond to Bragg peaks in diffraction pattern pixel when plotted on a d-spacing scale. With an imaging set-up structure properties are measured with high spatial resolution, however with reduced sensitivity with regards to phase and structure and with reduced information contents with regards to the strain tensors and grain orientation distributions compared to the diffraction set-up.

2.2. Engineering outline design and instrument parameters

IMAT is installed on a ‘broad pulse’ coupled, cold (20 K) liquid hydrogen moderator on the W5 (“West” 5) beam port on TS-2, a low-power pulsed source of about 40 kW. The moderator receives neutron pulses from the tungsten target and Be reflector assembly, slows them down, and then delivers polychromatic pulses of neutrons to the beamline with a repetition rate of 10 Hz. This means, in the time of 0.1 s between two pulses (‘frame’) neutrons of one pulse travel down the instrument and, if the interaction with the sample sends them in the right direction, are registered in the imaging camera or in the diffraction detector. A long flight path of 56 m to the sample position ensures good time-of-flight resolution while retaining a large neutron energy bandwidth. Fig. 2 shows an outline of the instrument on the ISIS TS-2 target station. The instrument parameters in Table 1 are based on a number of design considerations (Kockelmann et al., 2013) and on McStas simulations (Burca et al., 2013).

![Outline design of the IMAT instrument with the sample position at 56 m from the neutron source.](image-url)
A two meter long shutter in the target station monolith is lowered into and blocks the neutron beam if entrance to the experimental area is required. A square, straight, evacuated 44m long neutron guide starting at the upstream end of the shutter transports the neutrons to a pinhole selector at 46 m from where they are guided in evacuated ‘flight tubes’ to the sample position. There are a total of five 0.5mm thick aluminium vacuum windows: two in the shutter section, two for the length of the beamline, and a safety window in the experimental area. This means that there is a continuous vacuum system from the shutter to the sample area thus minimizing Bragg edge contamination in the beam which in turn benefits the image analysis and diffraction data normalisation. A 20Hz T0 chopper with inconnel as main absorbing material serves as fast neutron and gamma filter. Two 10Hz double-disk choppers (with blades made of B₄C-containing ‘s-dough’) are used to define wide (e.g. 6 Å) or narrow (e.g. 0.5 Å) wavelength bands but also to prevent frame-overlap of neutrons between successive time frames. The choppers can be run at half-frequency to access the second frame, thereby doubling the neutron wavelength bandwidth to 12 Å. The two disks of one chopper can be operated independently to facilitate energy scans. Three TOF monitors are installed in the guide section up- and downstream of the choppers for beam diagnostics purposes. Between the end of the neutron guide at 45.7 m and the pinhole selector at 46 m a filter section is available to accommodate a diffuser in the beam path if necessary. The pinhole selector (of rotating wheel design) offers a choice of five circular apertures for the imaging mode, to define a choice of five circular apertures for the imaging mode, to define five different L/D ratios (Table 1), and one large square aperture of the size of the neutron guide (95×95 mm²) for the beam to pass through for diffraction experiments. The selector uses a system of changeable cartridges into which neutron-absorbing apertures (typically consisting of sheets of boron based materials) are inserted. Access to the pinhole selector area is via door-access and does not need shielding to be dismantled. The neutron beam travels in evacuated flight tubes from the pinhole selector to the sample area thus reducing air scattering. Downstream from the sample and camera position the beam enters a large-diameter evacuated flight tube and a ‘beamstop’ where the neutron beam is absorbed by a combination of B₄C materials, steel and borated wax.

| Table 1. Main IMAT instrument parameters |
|-----------------------------------------|
| General                | Single frame bandwidth | 1 - 7 Å; maximum of flux at 3 Å |
|                        | Flight path to sample  | 56 m |
| Imaging                |                         |      |
| L: Distance pinhole – sample |                      | 10 m |
| D: Aperture diameter   | 5, 10, 20, 40, 80 mm   |
| L/D                    | 2000, 1000, 500, 250, 125 |
| Best spatial resolution| 50 µm                   |
| Max Field of View      | 200x200 mm²             |
| Wavelength resolution  | Δλ/λ = 0.7 % (at 3 Å)   |
| Time-integrated neutron flux | 4 x 10¹⁷ n/cm²/sec (for L/D: 250) |
| Diffraction at 90⁰     |                         | 2.0 m |
| Secondary flight path  |                         |      |
| Detector coverage (each of the two arrays) | 30x60 degrees (horizontal × vertical) |
| Diffraction resolution | Δd/d =0.7 % (at 3 Å)   |
| Minimum gauge volume   | 1x1x1 mm³               |

A large experimental area of more than 50 m² provides ample space for instrument equipment, samples and sample environment equipment. Crane access through the blockhouse roof shielding is available to lift samples and equipment into the experimental area. Beamline components in the experimental area are easily accessible; they include (Fig. 3):

- Heavy-duty Sample Positioning System (maximum weight: 1.5 tonnes) with a tomography rotation stage;
- Fast acting attenuator to minimize activation of the sample when no data are collected;
- Retractable TOF neutron beam monitor on a remote-controlled translator; the monitor provides an incident beam spectrum for normalisation of diffraction data;
- Sets of five beamline ‘jaws’ (beam delimiters), each set with four 10 mm thick sintered B₄C blades;
- Retractable sample slits made of four 3mm thick, sintered B-10 blades, for the beam size in front of the sample to be adjusted from 50x50 mm² to 1x1 mm²;
• Imaging cameras and diffraction detector (see below), detector frames and a camera positioning system (the latter is not shown in Fig. 3);
• Optional second sample position at 5 m downstream from the pinhole selector (see upstream camera in Fig. 3).

In order to swap from imaging to diffraction mode, the pinhole selector is moved to the open position, and the beam jaws are adjusted to the desired sampling size.

Fig. 3. Outline design of the IMAT sample area: imaging camera box (of 85cm height) at the sample position at 10 m from the pinhole selector; a sample positioning system; diffraction detectors at 90 degrees. Radial collimators in front of the 90-degree diffraction detectors are not shown. The camera shown at the second sample position at 5 m from the pinhole will be removed if the downstream sample position is used.

2.3. Installation status

Fig. 4 shows some of the installed infrastructure and components of the beamline. The neutron guide and the associated vacuum system with separating gate valves, monitor housings, and gaps for the neutron choppers have been installed (Fig. 4a). The front end of the beamline has been constructed and installed, including the shutter and the shielding insert tube with a supermirror guide in the target (steel) monolith. Fig. 4a shows the shielding construction starting at the target shielding wall, 6 m from the neutron source. The neutron guide is surrounded by a combination of steel and borated wax shielding which will provide a low radiation background on the outside of the order $<2 \mu$Sv/h. The chopper pits (with steel and wax shielding) have been erected whilst the double disk choppers and T0 choppers are being build and tested. Further downstream, 28.5 m from the source light-concrete shielding is used (instead of steel and wax) around the neutron guide up to the pinhole selector bunker (not shown in Fig. 4). The pinhole area is again shielded with steel and borated wax. The extension building and a sample environment services shed (orange) were constructed and the breakthrough into the main TS-2 hall was made (Fig. 4b). Construction of the shielding around the experimental area inside the extension building has started (Fig. 4c); the shielding walls are made of steel containers filled with borated wax. The large opening in the shielding in Fig. 4c is for the installation of the beam stop.
3. IMAT Imaging Detectors

Neutron cameras will take advantage of the time-of-flight information for energy resolved imaging where possible. Three detector systems that are envisaged and developed for use on IMAT will be interchangeable. The parameters are summarized in Table 2 and photos of two of the cameras systems are shown in Fig. 5. IMAT will have a camera box, with a Li-6 or Gd scintillator screen, 45 degree mirror and lens system for measurement with a field-of-view (FOV) of 200×200 mm$^2$, for white beam imaging with an integrating CCD/CMOS or for energy scans with a CCD coupled to an image intensifier which enables fast gating. The achievable spatial resolution is limited by the expected neutron flux rather than by the capabilities of the camera box itself. The field of view and the spatial resolution can be adapted by using a corresponding lens. With a 1k×1k pixel camera the best spatial resolution will be achieved for a FOV of 50×50 mm$^2$. It is worth mentioning that the camera has a built-in optical autofocus system (Finocchiaro et al., 2013). The system will be used for white-beam radiography and tomography measurements as well as for energy-selective applications for contrast enhancement and contrast variation, and for large-field-of-view Bragg edge mapping. A microchannel plate system (MCP) utilizes neutron absorption by $^{10}$B atoms impregnated into the MCP glass followed by the generation of secondary electrons and signal amplification within the pores of the MCP localized to a ~10 μm area (Tremsin et al., 2015). The field of view is 28×28 mm$^2$ and the detector is capable of providing a time-of-flight spectrum for each pixel (512×512 pixels, each 55×55 μm$^2$). The camera is placed directly in the neutron beam. The spatial resolution limit of 55 micron is given by the Timepix readout chip, but it has been shown that the resolution can be improved by event centroiding (Tremsin et al., 2012). The achievable resolution for tomography will be limited by the flux rather than by the system itself. A third option for IMAT is an active pixel sensor (GP2) which uses the PImMS-2 CMOS and is currently under development (Vallance et al., 2014). A gadolinium sheet is used for converting neutrons to electrons which are then counted by a CMOS sensor with a pixel size of 70 μm. A number of up to 4096 times slices can be used and the timing resolution is better than 12 ns. Additionally, PImMS has four 12-bit registers per pixel.
Limiting factors for the spatial and the timing resolutions for the CCD and CMOS systems are the thickness of the scintillation screen (related to a blurring of the event determination) and the afterglow (limiting the time-of-flight determination to tens of microseconds). For IMAT a timing resolution of at least 10 microseconds is required for time of flight applications utilizing thermal and cold neutrons. Some applications that will use the MCP or the GP2 pixel detector are limited by the relatively small active areas. Both pixel detectors have potential for the active areas to be increased by tiling, i.e. by placing readout chips side by side. For instance, the current generation of the Timepix chip is three-side buttable allowing 28×N mm configurations. Future chips will be four-side buttable by implementation of through-silicon vias.

Table 2. IMAT imaging detectors

|                      | CCD/CMOS | MCP   | GP2   |
|----------------------|----------|-------|-------|
| Sensitive area [mm²] | 200×200  | 28×28 | 22×22 |
| Number of pixel (row)| 1024 / 2048 | 512 | 324 |
| Spatial resolution [µm] | 50       | 55    | 70    |
| Timing resolution [ns] | -        | ~10   | ~12.5 |
| Time slices per pulse | 1 / 0   | 3000  | n/a   |
| Outer dimensions width x depth x height [cm] | 45×50×85 | 25×40×20 | 20×10×20 |
| R&D                  | CNR Messina, Italy | University of California at Berkeley, USA | Oxford University, STFC, UK |
| Reference            | Finocchiaro et al. (2013) | Tremsin et al. (2015) | Vallance et al. (2014) |

Diffraction detectors will be installed on IMAT in several stages. For the day-one operation, two prototype diffraction detector modules left and right of the incoming beam at scattering angles around 90 degrees will be available to test the diffraction capabilities of the beamline. In the second stage more diffraction detectors at 90 degrees will be added as illustrated in Fig. 3. Each of the prototype detectors is composed of 50 ZnS/LiF scintillator strips (pixels) of size of 4×100 mm² which defines the position resolution. The readout will be realized with wavelength shifting fibre technology developed in-house at ISIS. Each 90-degree detector will be at a distance of 2 m from the nominal sample position. The two detector modules, left and right of the incident beam, have a particular relevance for strain analysis, i.e. for simultaneously measuring two orthogonal strain components following the ENGIN-X model (Santisteban et al., 2006). A radial collimator each will be installed in front of the 90-degree detector in order to define a diffracting (gauge) volume for a given beam size. Collimators with varying gauge sizes will be used which, however, will leave ample space for samples and diffraction scans. For example,
the available space between the collimator faces for a ‘2 mm gauge’ collimator will be about 1 m. The final stage of the construction of IMAT will be the installation of further diffraction detectors at forward and backscattering angles, bringing the detector coverage to a total of 4 sr. This will enable in-situ texture studies in combination with phase, strain, and imaging analyses at non-ambient sample conditions. The additional detectors will significantly extend the d-spacing range to 0.35-20 Å. Also, the extra angular coverage will permit in-situ texture analyses during tensile testing and/or temperature treatment for a single sample orientation.

4. Conclusions and outlook

IMAT will enhance the existing engineering materials analysis facilities at ISIS by adding neutron radiography and neutron tomography options to the ISIS user programme. The residual strains, stresses and structures inside large engineering samples can be more effectively analysed if the diffraction scans are guided by radiographic data. Vice versa, diffraction analysis may be indispensable for a quantitative analysis and physical interpretation of the attenuation features observed in the energy-dependent radiography data. An important feature of IMAT will be ‘tomography-driven’ diffraction and instrument control which will enable a user-friendly operation of the instrument to study structurally and geometrically complex samples. The instrument will be built to be as versatile and flexible as possible to enable swift interchanges between the measurement modes and to allow for future upgrades of neutron imaging technology. With the location of IMAT in its own building and with a large experimental area inside the blockhouse there is sufficient flexibility for future upgrades, for example with additional diffraction detectors, installation of a second sample position, and for future sample environment equipment. Ample equipment storage, sample preparation and off-line testing areas will be available, as well as secure storage areas for activated large and bulky engineering and cultural heritage samples. IMAT will, from the start, support user projects that require mechanical loading rigs.

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