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MONTE CARLO MODELING OF NEUTRON IMAGING AT THE SINQ SPALLATION SOURCE

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Abstract

Modeling of the Swiss Spallation Neutron Source (SINQ) has been used to demonstrate the neutron radiography capability of the newly released MPI-version of the MCNPX Monte Carlo code. A detailed MCNPX model was developed of SINQ and its associated neutron transmission radiography (NEUTRA) facility. Preliminary validation of the model was performed by comparing the calculated and measured neutron fluxes in the NEUTRA beam line, and a simulated radiography image was generated for a sample consisting of steel tubes containing different materials. This paper describes the SINQ facility, provides details of the MCNPX model, and presents preliminary results of the neutron imaging.

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Introduction

Neutron imaging is increasingly used for the non-destructive testing of samples not readily probed with x-ray radiography, especially in the presence of hydrogen [1]. These include ceramics, organic materials, high-tech devices and thick metallic objects. Typical examples are archaeological objects, explosives, turbine blades, nuclear fuel and cladding, and automotive engines. Neutrons for imaging purposes are usually produced through fission in research reactors, but nuclear reactions in accelerator tubes or proton-driven spallation sources can also be used. In the Swiss Spallation Neutron Source (SINQ) at the Paul Scherrer Institute (PSI), neutrons are generated by bombarding a lead target with a 1.2 mA proton beam from a 590 MeV ring cyclotron. The high-energy spallation neutrons are thermalized in a heavy-water moderator and extracted by tangential beam tubes to experimental facilities [2]. The Neutron Transmission Radiography (NEUTRA) facility is located at thermal beam line 32 in SINQ [3].

Most neutron radiography experiments are performed by aiming a beam of neutrons at an object and detecting the transmitted neutrons with an imaging film or camera [1]. The object attenuates the incident beam, and the intensity of the transmitted neutrons I is related to the thickness of the sample via the following exponential law:

$$I = I_0 e^{-N s_{tot} d},$$

where I_0 is the incident neutron intensity, d is the thickness of the sample in the direction of the beam, and N and s_{tot} are the atom density and total microscopic cross-section of the material, respectively. Deviations from this simple formula occur because of secondary emissions from neutron absorptions and multiple scattering in the sample. These must be accounted for in the experimental set-up and the interpretation of the results. Unlike single-event counting in neutron scattering experiments, the radiography detector converts all transmitted neutrons to generate an adequate image of the sample.

Recent advances in parallel processing are facilitating the accurate modeling of neutron and gamma-ray imaging systems using the Monte Carlo method. MCNPX is a general-purpose Monte Carlo radiation transport code with a built-in radiography feature and a multi-tasking capability that can be used to reduce the time needed to obtain a sharp simulated image [4]. An accurate MCNPX model of SINQ has been prepared that includes a detailed representation of the NEUTRA flight-path collimator. The purpose of this paper is to describe this model and to present preliminary simulation results of neutron transmission imaging in the facility. The accuracy of the MCNPX model is further demonstrated by comparing the calculated thermal neutron flux with measured values obtained from gold activation experiments.

SINQ

SINQ consists of a neutron spallation target located in the middle of a large heavy-water moderator tank that contains a liquid-deuterium cold source, neutron activation stations and several tangential neutron beam tubes (Figure 1). The moderator vessel is approximately 2.25 m high with a 2 m outer diameter. Fast neutrons are produced via the spallation reaction by energetic protons impinging on the target from below. The existing (Mark 3) spallation target consists of an aluminum-magnesium alloy block with a hexagonal lattice of horizontally oriented steel-clad lead pins (Figure 2). The target itself is inserted from above and suspended from the upper edge of the target shielding block. This orientation of the proton beam facilitates the placement of experimental facilities around the target block. Heat deposited by the proton beam in the target is removed by a separate heavy-water

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cooling system, with additional light-water cooling of the outer safety hull. The facility is heavily shielded with iron and concrete to stop the highly penetrating radiation emitted from the source.

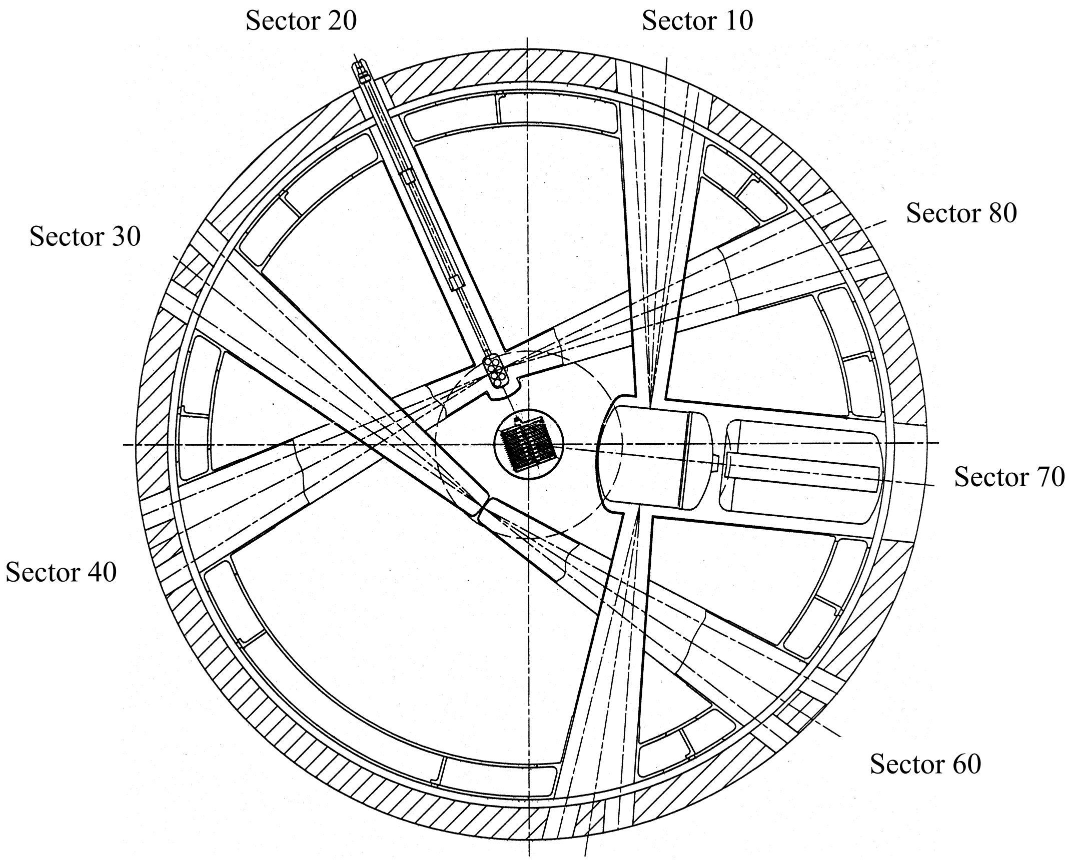

Figure 1: Top view of SINQ

The NEUTRA facility was commissioned in 1997 and rapidly proved to be one of the most power radiography stations in Europe. As shown in Figure 3, it consists of three main components added to the Sector 30 beam line: a 4.1-m-long inner collimator that resides inside the target block shielding and includes the main shutters; a 6.7-m-long evacuated divergent aluminum tube that serves as an outer collimator; and an associated experimental area with the sample station and detection systems inside concrete block shielding. The multiple-sectored inner collimator incorporates a bismuth filter to eliminate most of the gamma radiation, a 2-cm beam aperture surrounded with a boron-carbide absorber, and cadmium lining in the final section for shaping the thermal neutron beam. Radiography samples are located outside the outer collimator, the first position being approximately 10 cm past the exit. An imaging plate is typically placed 5 cm behind the sample.

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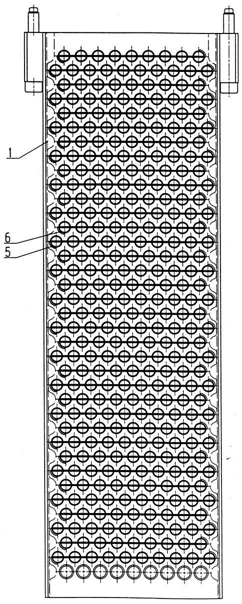

Figure 2: The Mark 3 steel-clad lead SINQ target

Since no provisions were made for nuclear instrumentation inside the moderator vessel in the original SINQ design, neutron and gamma flux measurements are currently possible only at the exits from the beam lines and in the two neutron activation stations. The NEUTRA beam line has a largely unperturbed view of the peak thermal flux radial position in the moderator tank. The beam distribution in the neutron radiography facility is affected only by the gamma filter and the beam aperture. Accurate spatial and spectral neutron flux measurements are available from gold-foil activations at various positions in the outer collimator tube.

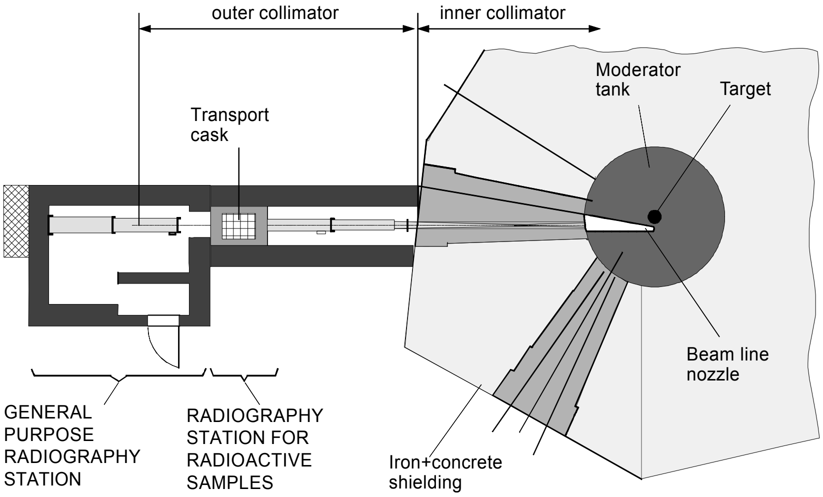

Figure 3:View of NEUTRA at thermal beam line 32 in SINQ

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MCNPX

MCNPX (MCNP eXtended) is a high-energy version of the general-purpose, Monte-Carlo radiation transport code MCNP (Monte Carlo N-Particle) [4, 5]. The code is capable of transporting 36 elementary particles at all energies, and its generalized geometry features and use of continuous-energy cross-sections can generate benchmark-quality results for a variety of nuclear applications.

The code provides a powerful capability for generating simulated radiography images for both pinhole and transmitted image projections. Although a variety of variance-reduction techniques are available for reducing the computer time needed to obtain precise results, a large number of neutron or photon histories is still required for sharp simulated images. Because Monte Carlo methods are inherently parallel in nature, a considerable calculational speedup is possible using a multiprocessor computing platform. A multi-tasking version of MCNP based on threading and message passing using the Parallel Virtual Machine (PVM) [6] has been available for some time, and extended more recently to high-energy transport in MCNPX version 2.4.0. However, the Message Passing Interface (MPI) [7] is increasingly replacing most other message-passing protocols for technical computing, and vendor-specific implementations are now available that utilize the lower latency and higher data rates of their networks. Accordingly, the latest beta release of MCNPX (Version 2.5.c) includes MPI support [8].

MCNPX Modeling of SINQ

A high-fidelity model of SINQ has been developed (Figure 4), which includes the proton beam, the Mark 3 solid-lead target (Figure 5), the moderator vessel, the liquid-deuterium cold neutron source, the neutron beam tube penetrations into the heavy-water moderator, and a very accurate representation of the NEUTRA beam line used for neutron radiography (Figure 6). The neutronic performance of the SINQ facility has been previously assessed using this MCNPX model [9]. Typical proton and neutron flux profiles are shown in Figure 7.

The propagation of neutrons along the NEUTRA collimator flight path is a difficult computational task, and non-analog Monte Carlo methods are used to preferentially select neutrons more likely to contribute to the radiography tally. The variance-reduction strategy adopted for modeling NEUTRA relies on a combination of the weight-window technique and deterministic transport [10]. The weight window is a space- and energy-dependent splitting and Russian roulette method, which kills neutrons moving away from the beam tube entrance while multiplying those that move towards it. In MCNPX 2.5.c, the weight window generator has been extended for use with both neutral and charged particles. A fine mesh was used to generate the optimum importance function for the neutron radiography tally. Figure 8 shows a horizontal view of the SINQ model in the plane of the NEUTRA beam line with the resulting colour-coded weight windows. Darker shades of blue represent regions of decreasing weight (hence increasing importance), clearly showing how neutrons are directed into the beam tube. The streaming of neutrons down the beam line was further enhanced by placing a DXTRAN sphere and forcing collisions within the Bi filter in the inner collimator. Collisions in the heavy-water moderator at the beam-tube entrance create special particles, which are deterministically scattered and transported toward the DXTRAN sphere using the weight windows to control their weight.

The radiography tally itself is based on a grid of point detectors in which pseudo-particles are directed to points on an imaging plane behind the sample [4]. For every forced scattering event in the Bi filter, a ray-trace contribution is made to each bin on the detector grid. This effectively eliminates statistical fluctuation across the grid and generates a transmitted image projection with relatively few neutrons.

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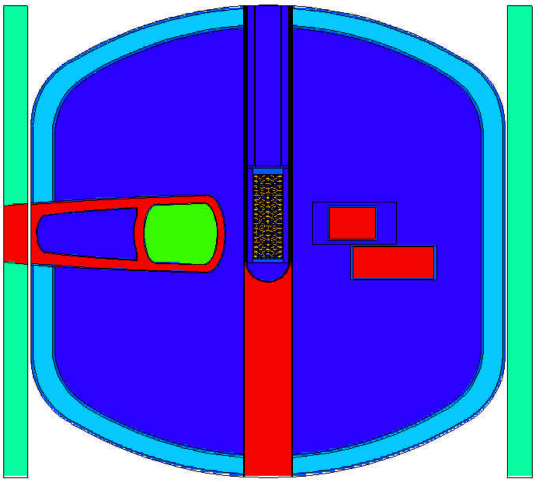

Figure 4: Vertical view of the SINQ model

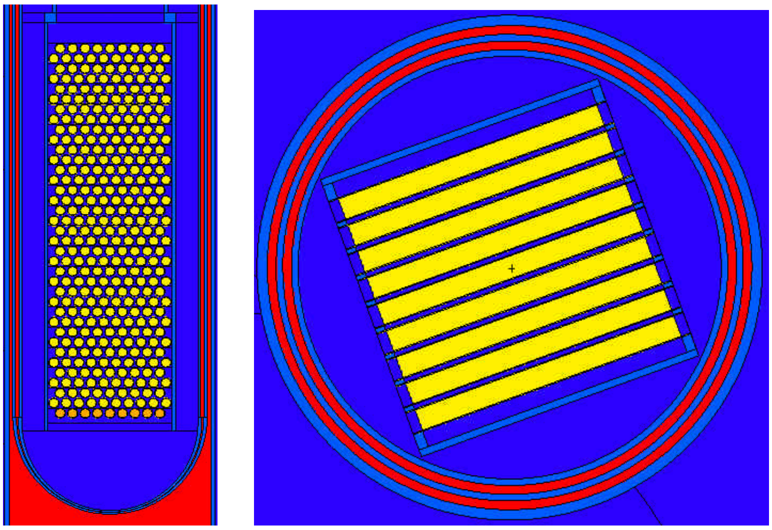

Figure 5: Vertical and horizontal views of the Mark 3 target model

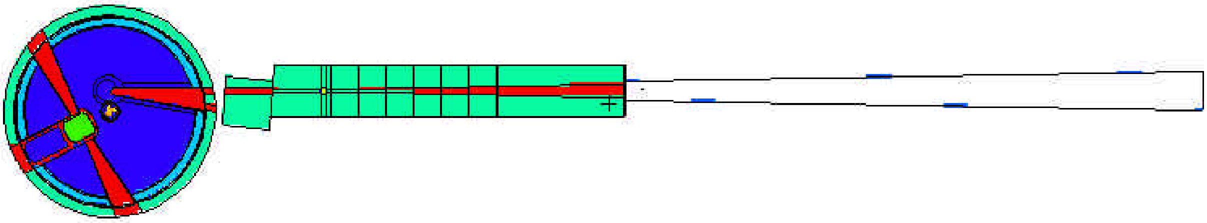

Figure 6: Horizontal view of the NEUTRA collimator model

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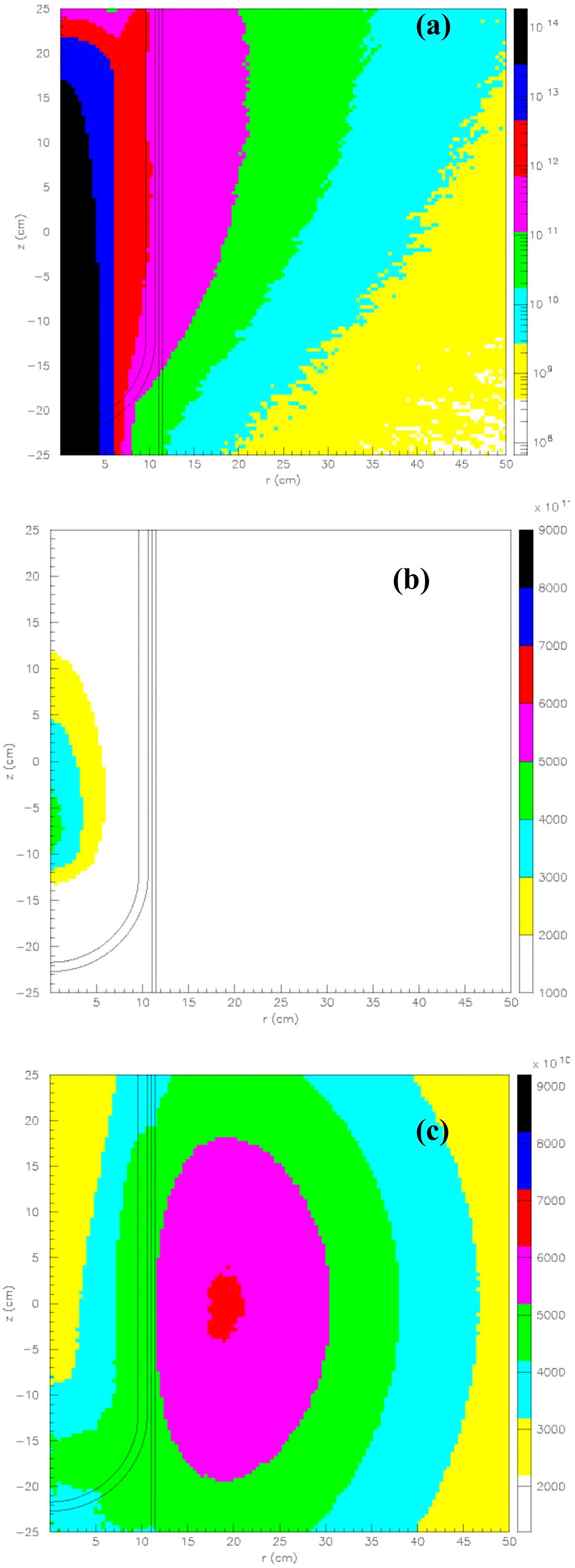

Figure 7: Profiles of (a) proton ,(b) total neutron and (c) thermal neutron fluxes in SINQ

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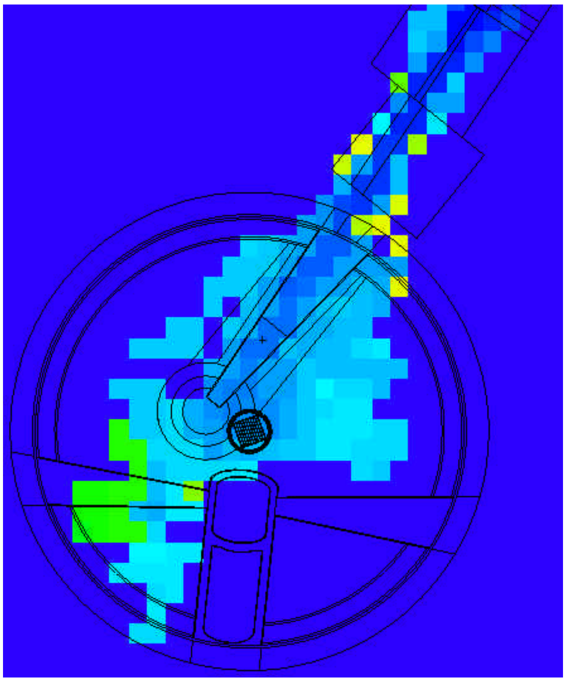

Figure 8: Weight windows used for variance reduction in SINQ model

Simulation Results

The MCNPX model of SINQ has been partially validated by comparing the calculated and measured neutron fluxes in the NEUTRA facility. The predicted total neutron flux of 2.70 × 10^7 (±1%) n·cm^{-2}·s^{-1} agrees well with an average value of 2.78 × 10^7 n·cm^{-2}·s^{-1} deduced from several gold-foil activations at the exit from the outer collimator [11]. The calculated neutron flux spectrum at the gold-foil activation position is shown in Figure 9.

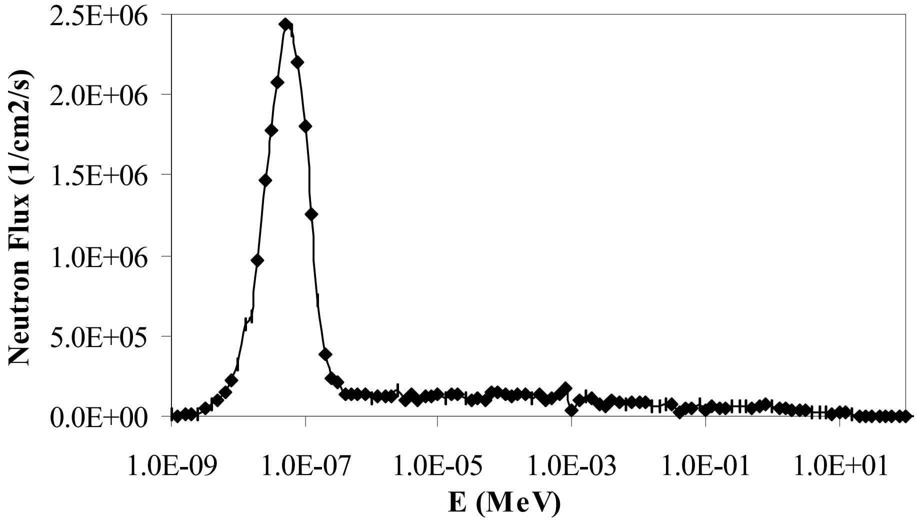

Figure 9: Calculated neutron flux spectrum in NEUTRA

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The neutron radiography capability of the model was tested using an assembly of three steel tubes containing different materials, but whose dimensions matched those of the Mark 3 spallation target pin. The MCNPX model of this radiography sample is shown in Figure 10 with water (blue), lead (yellow) and uranium (turquoise) fills. The simulated image, obtained with 100,000 source protons and a 0.4 mm × 0.4 mm resolution, appears in Figure 11. This may be compared in Figure 12 with an actual radiography image taken in NEUTRA of a Mark 3 test target pin, which contained metallic specimen embedded in a lead-bismuth alloy that is transparent to neutrons. The ability of neutron radiography to detect hydrogenous material is clearly visible.

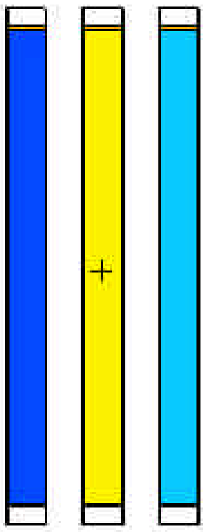

Figure 10: MCNPX model of the radiography sample

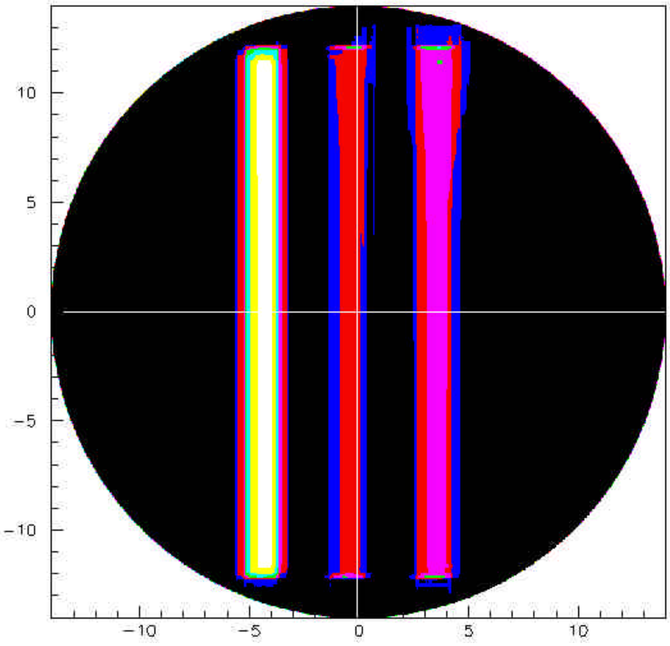

Figure 11: MCNPX generated neutron radiography image

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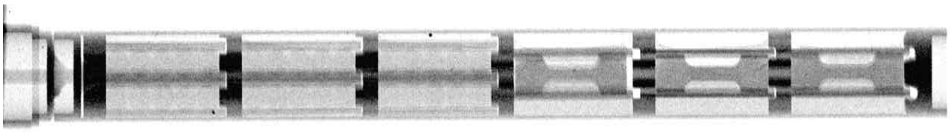

Figure 12: Actual neutron radiography image of a SINQ test target pin

The MCNPX calculations were performed on the Janus supercomputer at the Swiss Federal Institute of Technology in Lausanne (EPFL). The hardware platform is based on the Hewlett Packard SC (Scalable Computing) architecture and comprises a cluster of 24 nodes with four 1.25 GHz Alpha 21254C processors rated at 4 × 2.5 GFLOPS per node. Inter-node communication is provided by a high-bandwidth, ultra-low-latency Quadrics QMS 128 interconnect.

Concluding Remarks

The successful modeling of the Swiss Spallation Neutron Source and its associated neutron radiography facility using MCNPX is a clear demonstration of the code's state-of-the-art capabilities. While previous simulation of such imaging systems relied on specialized Monte Carlo codes [12], the present effort represents the first reported application of a general-purpose radiation transport code to the integral modeling of an accelerator driven system and its experimental facilities. This has been facilitated by recent advances in parallel processing that render such computationally intensive problems tractable. The MPI version of MCNPX has been developed in part to gain access to supercomputers that require support for this parallel processing protocol. The performance of MCNPX for neutron imaging on Janus and the SGI Origin 3800 at EPFL will be described separately elsewhere [13]. Apart from the on-going design and analysis of the MEGAPIE flowing liquid-metal target for SINQ [14], future applications of MCNPX at PSI will include the conceptual design of a new cold neutron radiography beam line and a more detailed characterization of the existing NEUTRA facility. These activities will serve to validate the physics models and nuclear data that underlie MCNPX, and to improve the performance of the experimental facilities in SINQ.

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