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Gain factors with the new supermirror guide system at the Budapest Neutron Centre

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Abstract. In parallel with the installation of a cold-neutron source (CNS) at the 10-MW Budapest Research Reactor, the neutron-guide system has been redesigned and replaced by state of art neutron optical elements. Monte Carlo calculations have been used to determine the optimal conditions for the guide parameters. For the three cold-neutron beams nearly 100 m of new guides were installed; a great part is made of supermirrors. The new in-pile guide system and the individual shutters enable minimal losses at the starting sections. The out-of-pile part was optimized for the experimental stations. The neutron-flux measurements were compared with the simulated values. The combined effect of the CNS and the guide system yields a gain factor in the flux as high as 30–60.

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In 1986–92 a full-scale reconstruction and upgrading of the Budapest Research Reactor (BRR) was performed. One of the tangential beam-tubes (channel no. 10) has been prepared to install there a cold-neutron source and a neutron-guide system. A $15 \times 27\,\mathrm{m}^2$ guide hall has also been constructed, housing three neutron guides with several instruments [1]. Although the installation of the cold-neutron source (CNS) was foreseen already in the reactor-refurbishment programme, the implementation was delayed, mainly because of financial difficulties at that period. In the years 1993–2000 the guide system [2] and five instruments in the guide hall were operated with thermal neutrons. Finally, the CNS project was completed in January 2001; since that time the liquid-hydrogen moderator is routinely operated.

Following the installation of the cold source the old guides have been replaced by a state-of-the-art supermirror guide system, with optical elements produced by MIRROTRON Co. (Hungary).

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1 Simulation of the neutron guides

The neutron optical features of the guide components were designed by using Monte Carlo (MC) optimisation; several compromises had to be made, however, because of the existing reactor and instrument geometry constraints.

During MC simulation of the guides, the system was modeled in the following way. The simulation code followed the traces of the neutrons along the different elements from the source through gaps and guide elements until the end position. The source was modeled with a flat surface of a given area emitting neutrons of different wavelengths according to the Maxwellian distribution of the temperature measured in the cold source. The randomly generated positions of the neutrons were distributed evenly along the surface. A uniform distribution was assumed for the directions of the emitted neutrons; any point of the surface radiated in a given solid angle isotropically. A large solid angle (the divergence) was chosen to cover all the possible reflections on the guide walls.

The reflections of the neutrons were followed through the guide elements; neutrons were reflected from the walls with a probability calculated from the reflectivity of the surface. In our model the walls of the guides are covered with $m = 1.5$ and 2 ($\theta_c = m \times \theta_c(^{nat}\!<\mathrm{Ni}))$ supermirrors (SMs) and with natural nickel. Flux data were calculated at the same positions where the measurements were performed.

2 Construction of the neutron-guide system

The guide construction is the following (Fig. 1): a bunch of three beam-lines is arranged in the horizontal channel no. 10; this assembly is incorporated in the cold-source plug with the cross point of the guide axis on the moderator cell. Three downstream sections of the beam-tubes are distinguished.

(i) The 2.7-m – long in-pile part starts at 1.65 m from the moderator chamber; the angles between the guide nos. 1–2 and 2–3 are 1.5 and 2 degrees, respectively. The neutron optical elements were provided as supermir-

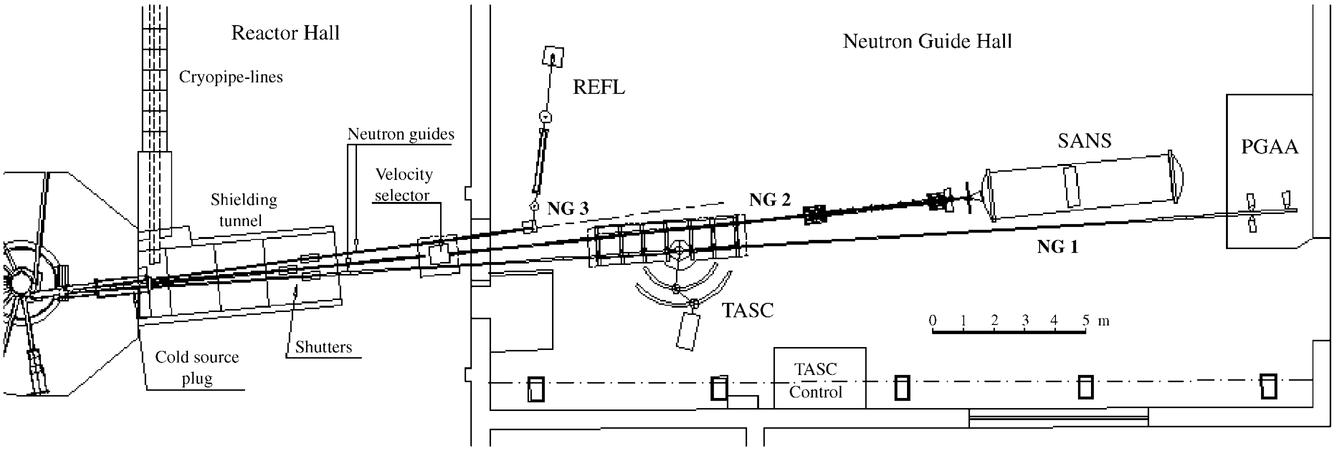

Fig. 1. Layout of the guide system

Table 1. The main characteristics of the guide system

Guide no.	Length (m)	Cross section $h \times w$ (cm^2)	Curvature R (m)	Coating m
NG1	22 + 17.5	10×2.5	5000	2, 1
NG2	22.5	10 and 4×4	1050	1, 1.5, 2
NG3	12 + 22.5	10×2.5	3000	2

rors. On a special, highly radiation-resistant ceramic substrate (labelled Sital or Zerodur) $m = 2$-type coatings of nickel/titanium multilayers were applied, with reflectivity $R \geq 0.85$. These mirrors were mechanically assembled in the steel block of the CNS plug.

(ii) The out-of-pile part starts with a ~ 6.5-m section included in a vacuum jacket. This part has a common vacuum with the previous section and at ~ 5 m from the reactor wall three shutters (each with a 0.5-m guide insertion) enable the individual closing of the beams. A biological-shielding tunnel, composed of heavy and normal concrete blocks as well as lead and polyethylene bricks, surrounds the guides.

(iii) The third part of the guide system extends from the reactor hall into the neutron-guide hall and transports neutrons directly to the experimental stations. These 'free-standing' guides are assembled of 1.5-m sections and the glass tubes have been sealed by silicone glue to ensure the ~ 0.05-mbar vacuum. For the out-of-pile guides a Borofloat® glass substrate was used; the other major characteristics are given in Table 1.

3 Flux measurements

Having completed the guide installation we carefully studied the neutron-flux values by gold-foil activation ($\sigma_0 = 98.65 \times 10^{-24}$ cm^2; ^{197}Au 2200-m/s cross section) measurements (Fig. 2) as well as the spectral distribution by time-of-flight (TOF) analysis. Gold foils irradiated directly and in cadmium shielding were used to determine the thermal and the epithermal neutron fluxes. In the curved guide sections the epithermal component disappears from the neutron spectrum,

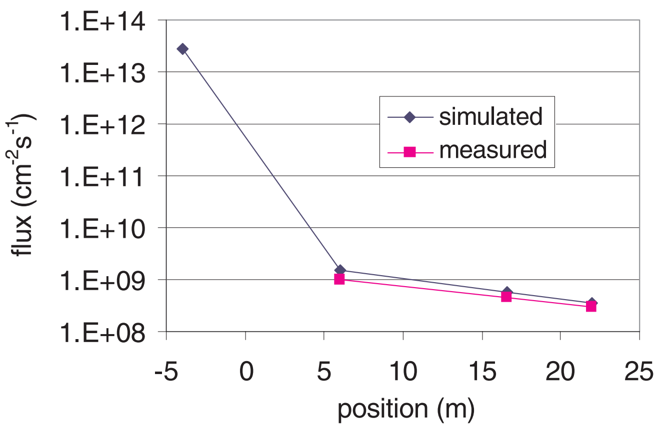

Fig. 2. Neutron fluxes measured and simulated on NG1. (Position 4 m from the reactor wall – cold source, 6 m – beam shutter, 17 m – triple-axis spectrometer, 22 m – temporary end of the guide)

but in the first sections – in the region of partial direct sight – a thermal/epithermal ratio of a few hundred is typical. 50-µm-thick gold foils were irradiated for 10 to 60 min. The activities were determined using a HPGe detector, whose counting efficiency was $5.33 \times 10^{-4} \pm 0.2\%$ at 411 keV. Gold foils were located near the concrete wall of the reactor, at the beam shutter and at the positions of the instruments. In the reactor hall (locations 1.5 to 9 m) epithermal fluxes were also determined. At the end of the beams the fluxes were measured at two different positions along the cross sections to verify the inhomogeneity of the flux profiles. Fluxes were measured with and without the cold source operating at different reactor powers.

Thermal fluxes at 10-MW reactor power in the first guide sections were $\sim 10^8$ n cm^{-2}s^{-1}, while the thermal-to-epithermal flux ratios were about 200. During the operation of the cold source the thermal flux rose to about 10^9 n cm^{-2}s^{-1}, while the thermal-to-epithermal ratio dropped to less than 1000. For example, on NG2 at the 6-m position 2.3×10^8 and 1.18×10^9 flux values were determined without and with CNS, whereas the respective thermal/epithermal ratios were 200 and 1460. The fluxes at the instruments were typically 2×10^8 to 6×10^8 n cm^{-2}s^{-1}. Flux values at different guide positions are shown in Fig. 3. The step for NG2 is due to the 1-m gap for the SANS velocity selector. The change in

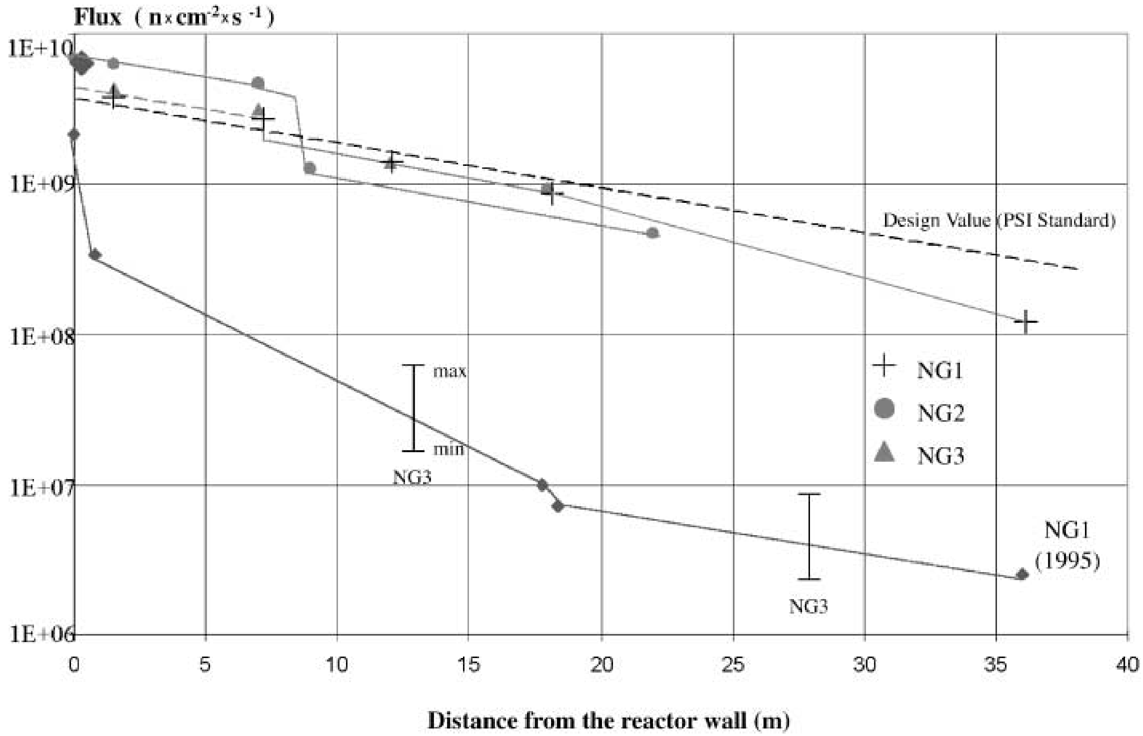

Fig. 3. Neutron flux gold foil measurement data at various guide positions. The *lower curve* relates to the old thermal guides with data from different periods

the slope at NG1 from the 22- to the 35.75-m position is explained by the fact that this part has not yet been replaced by SM-coated sections.

Following the expectations the Maxwellian peak has moved to ~ 4 Å. We consider that the neutron flux gain factor is composed as follows: a factor of 7–10 due to the cold source, a factor of 2 due to the elimination of losses replacing the old shutter (obsolete construction) and another factor of 2–3 due to the supermirrors.

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