First experience with the focusing neutron guide on IN10C

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1. INTRODUCTION

Neutron backscattering has been invented just about 25 years ago[1,2]. It is based on the fact, that the precision of the wavelength $\Delta\lambda/\lambda$ of a neutron beam after reflection from a crystal improves with increasing Bragg angle θ. In fact, $\Delta\lambda/\lambda$ becomes infinitely small for $\theta = 90°$ in the usual first order approach in kinematical theory. Closer inspection involving dynamical scattering theory reveals that the wavelength spread is given by[2]

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\tau}{\tau} + \frac{1}{8}\alpha^2 \tag{1}$$

$\Delta\tau/\tau$ is the extinction-limited extension of the Bragg peak in reciprocal space[3] and α is the divergence (full width) of the beam. In numbers, we obtain $\Delta\tau/\tau = 1.86 \bullet 10^{-5}$ for the 111 reflection of Si. Thus, a beam divergence of .70° would balance both terms in eq. 1. The neutron flux for such a highly monochromatic beam is very low. Consequently, backscattering spectrometers can only be operated at high flux reactors, and indeed the backscattering spectrometer IN10 at the ILL has been the only widely used crystal spectrometer with sub-µeV resolution. In most cases only strong scattering samples containing H could be measured in spite of this favorable implementation.

Recently the question arose whether a backscattering spectrometer could be designed which would offer improved performance. A higher count rate should result from an extensive use of focusing neutron optical elements throughout the instrument, while it was considered mandatory to maintain the unique energy resolution of IN10. (The measured resolution on IN10 is $\Delta E = 0.3\mu eV$, i.e., $\Delta\lambda/\lambda = 7.2 \bullet 10^{-5}$. This indicates that the resolution is dominated by the beam divergence).

The next chapter compares the design concepts of the new spectrometer IN10C with that of IN10. It will be shown that a focusing neutron guide with supermirror coating is a most crucial component in the novel layout of the primary spectrometer. In chapter 3 the real performance of the instrument will be compared with computer simulations pointing out again the paramount importance of focusing devices. We will conclude this paper in chapter 4 with an outlook into future possibilities for high resolution crystal spectrometers which will require next generation focusing devices.

2. BEAM OPTICS OF THE PRIMARY SPECTROMETER

2.1 The basic concept

The layout of IN10 is shown in fig. 1a. The primary guide with dimensions 30x50mm^2 (width x height) is cut at a position indicated D. Following a gap of about 200mm another straight guide with a section of 30x80mm brings the neutrons to the monochromator at a distance of 6m. A narrow wavelength band is backreflected into the same guide by a perfect Si[111] crystal. A graphite crystal at D just above the primary beam deflects the upper $^3/_8$ of the highly monochromator beam away from the primary guide with high radiation background. A further guide with a cross section of 30x30mm^2 and a length of 4.25m brings the beam towards the sample

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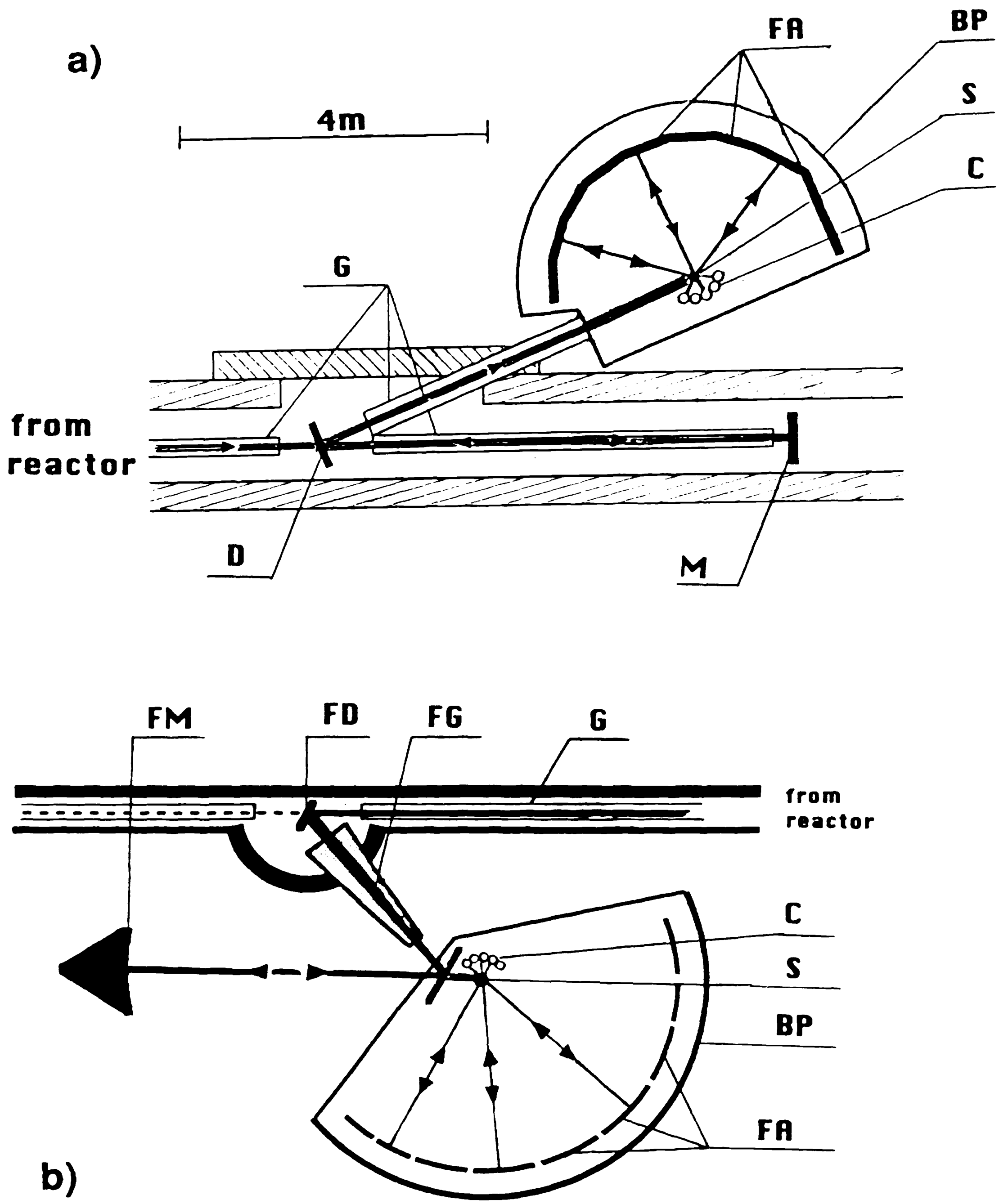

Fig. 1 The layout of the primary spectrometer of IN10 (a) and of IN10C (b). G is for neutron guides, D is the deflector, S is the sample position, M is the monochromator,C is the detectors of the counting unit, A is the analysers and BP represents structures for background protection. F is added whenever the element has focusing properties.

position. No beam focusing is attempted in this design. Very large solid angles of typically 0.10 sterad are used at the detectors to compensate for the low flux. This needs to be compared with the solid angle employed in the primary spectrometer. It is given by the critical angle of the Ni-coated primary guide γ^{Ni} for a wavelength of 6.3Å, with $\gamma^{Ni} = 0.60°$ (nat. Ni). Thus the solid angle at the monochromator amounts to $2.8 \bullet 10^{-4}$sterad which is about a factor of 350 smaller than the solid angle used in the secondary spectrometer.

The novel concept of IN10C (fig. 1b) aims to reduce this imbalance by a redesigned primary spectrometer. The idea is to start with a neutron beam with a large cross section and to focus it down to a smaller area. This creates a high intensity spot with high beam divergence. It will be regarded as the source point for the instrument and all further optical elements are designed to project its image into the detector.

The size of this spot is an essential parameter for the beam divergence α in eq. 1 and hence it determines the energy resolution of the instrument. As explained in detail elsewhere[4] its real size should be $27x27mm^2$. The biggest neutron guide available at the cold source of the ILL is of dimension $60x120mm^2$. The task is to reduce the vertical dimension of this beam by a factor of 4.4 and its horizontal dimension by a factor of 2.2 with a minimum of losses.

It seems difficult to achieve this goal with only one optical element. Consequently, IN10C features a vertically focusing graphite deflector followed by a conically shaped guide. Their combined action is expected to perform the necessary beam compression. Their main characteristics will be described in the following two sections and their performance is estimated at this stage by simple arguments which are well suited to guide the layout of an instrument.

2.2 The focusing graphite deflector

High quality pyrolytic graphite (PG) is used to bend the beam away from the primary guide. The crystals should best be flat in the (horizontal) scattering plane for a deflection of a homogenous beam delivered by a guide. Their horizontal mosaicity η^h should correspond to the beam divergence α, which is 1.2° in the present case. The in-plane beam divergence is maintained for a strictly monochromatic deflection (Note, that this is no more valid when a large bandwidth is considered as it is usually the case).

An isotropic mosaicity of the deflection of 1.2° can have disasterous consequences for the beam characteristics after the deflection. This holds in particular when further focusing elements will follow. The vertical beam divergence α^V will increase related to the vertical crystal mosaicity η^V according to

$$\alpha^V = 2\,\eta^V \bullet \sin\theta \tag{2}$$

For the present case of Si[111] we obtain with $\theta = 69.3°$ a value of $\alpha^V = 2.25°$. This largely exceeds the primary divergence!

To overcome this problem a PG deflector with anisotropic mosaicity was assembled. Starting from graphite crystals with $\eta = 0.4°$, three of these plates were assembled slightly misaligned in-plane, such that the total width for $\eta^h = 1.2°$, whereas the out-of-plane value remains at $\eta^V = 0.4°$. Nine assemblies of such three-crystal packages with individual heights of 14mm and mounted on a vertically focusing mechanics make up the deflector. The in-plane mosaic structure obtained provides full reflectivity, while the increase of the vertical divergence due to the mosaicity of the deflector according to eq. 2 remains limited to $\alpha^V = 0.75°$. This is now of less importance than the primary divergence. If we consider the contribution to the beam blurring from the primary divergence and from the crystal mosaicity by quadratic summation while neglecting other sources like the finite height of the PG crystals,we obtain a vertical spot size of 50mm, at a distance of 2m. This is about double the value of the envisaged spot size!

2.3 The focusing guide

From the above it is evidence that a large fraction of the compression of the beam size down to $27x27mm^2$ must be achieved by the focusing guide. This holds equally well for the horizontal and the vertical dimensions The beam characteristics at the exit of the guide determine also the design of subsequent components like a novel chopper-deflector unit and a large size focusing Si monochromator.

The conical guide must have a higher critical angle of reflection than the divergence of the incoming beam. We opted for a now classical multilayer structure with 80 Ni/Ti depositions with a cut off angle twice the critical angle γ^{Ni}. An example for the reflection profile of an assembled side wall piece is shown in fig. 2.

The change of beam properties in response to various optical elements can be visualized very elegantly by phase-space presentations.[5] However, we preferred a computer simulation to describe the entire spectrometer and to optimize the various components. This is suggested by the complexity of the primary spectrometer and by the possibility to implement from the beginning realistic reflection curves and mosaic structures. We shall concentrate here on results related to the guide. For a more complete description we refer to ref. 4.

The important input parameters are the geometry and the beam divergence of the primary guide, and the geometry, the vertical focusing and the anisotropic reflection profile of the graphite deflector. The geometry of the guide (length, entrance and exit dimensions, straight or curved walls) was optimized to create a high intensity spot with a size of $27x27mm^2$. It was found that the exit of the guide itself was the best choice for a high intensity spot when an appropriate focusing of the graphite deflector was considered. Therefore, the end window of the guide was fixed to the requested dimension.

Special attention was given to find the optimum shape of the walls. Bent profiles may give superior transmissions if parallel beams are considered. However, divergent beams reduce this advantage to a marginal level which is set off by a more complex realization of the guide. Consequently, we have adopted for simple straight walls. The optimum dimensions of the guide were a length of 1.60m and entrance and exit windows of $60x120mm^2$ and $27x27mm^2$, respectively.

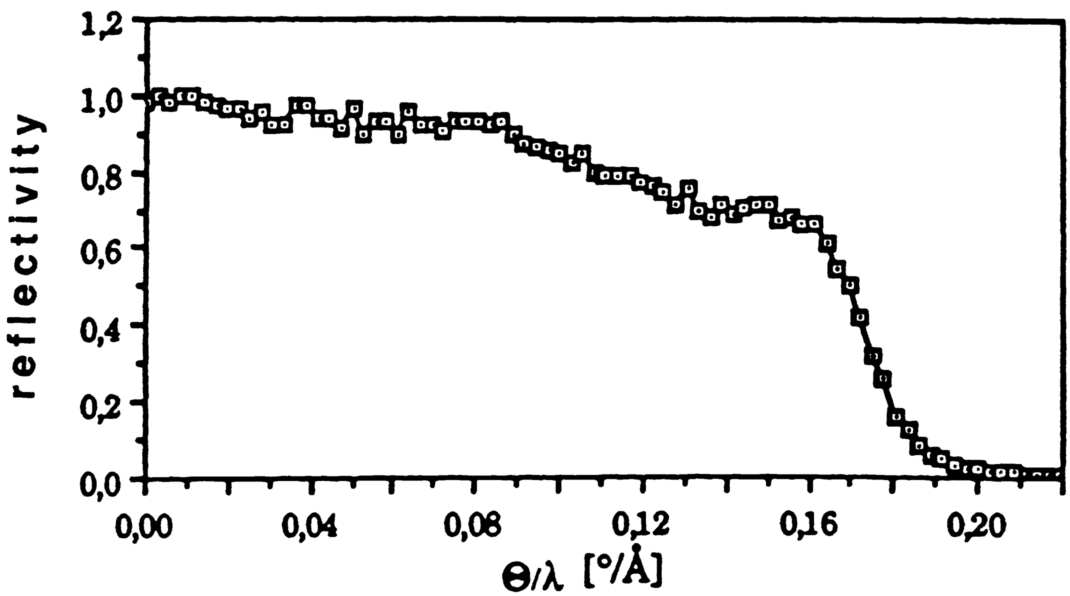

Fig. 2 Reflectivity profile of an assembled side wall piece of the focusing guide.

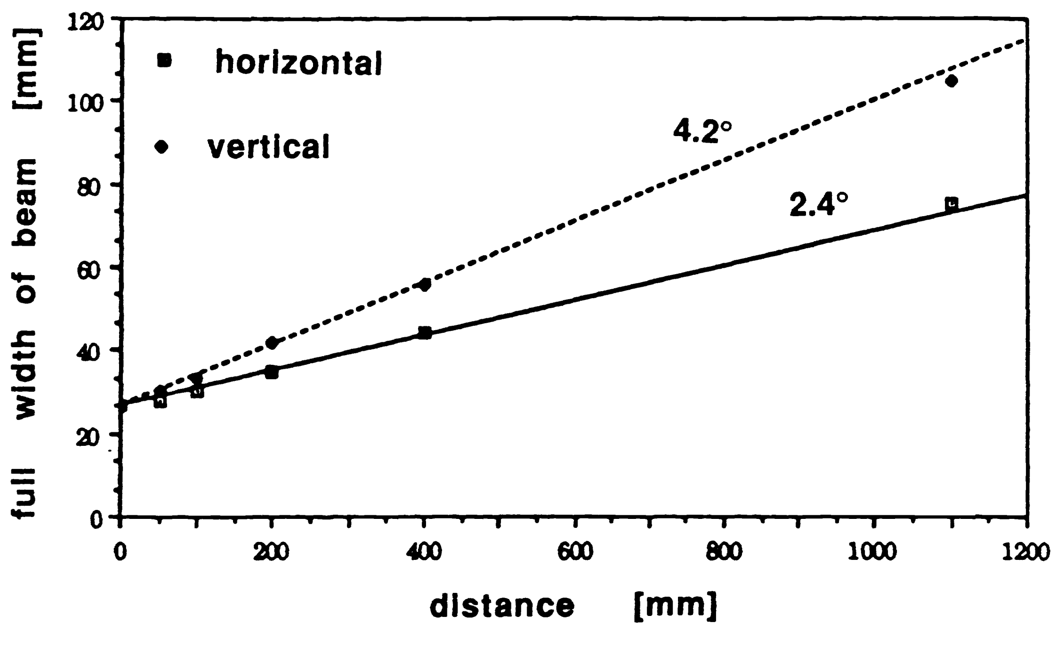

Fig. 3 Beam width at various positions behind the focusing guide

3. RESULTS AND DISCUSSION

Let us first consider the evolution of the beam size behind the focusing guide. This has been evaluated experimentally by scanning the beam profile with a small neutron counter at various positions. The data shown in fig. 3 reveal a horizontal and a vertical divergence of 2.4° and 4.2°, respectively. Thus, the large discrepancy between the solid angles of the primary and the secondary spectrometers on IN10 (see chapter 1) has been reduced by a factor of 7. However, the computer simulations for the same quantity gave slightly higher values of 3.0° and 5.5° for the horizontal and vertical divergence. We attribute this to the fact, that the reflectivity of our supermirror coating for high incident angles is not sufficient.

The profile of the beam divergence was obtained from a second measurement. Although related to the beam size, it has to be considered independently. The divergence has been obtained from the reflection curve of a high quality Ge(111) crystal rotated in the beam. The spectrum shown in fig. 4a reveals a narrow central peak and two symmetrical side peaks. The central structure relates to neutrons which have passed through the guide without reflection. It appears narrow and high because it has been measured in a focusing diffraction geometry. The two side peaks originate from neutrons having experienced one reflection at a side wall. Thus the angular-wavelength dispersion from the reflection at the detector is reversed and the peaks are measured in a defocused condition with a large width. The measured profile in fig 4a is in good agreement with the simulation in fig. 4b which shows a similar three-peak structure with the same separation between the peaks.

Related to high radiation and background levels at the position of the graphite deflector and due to higher order contaminations at this point it is difficult to determine a reliable value for the flux increase by the conical guide by direct measurement. Alternatively, the monochromatic flux at the sample positions of IN10 and IN10C can be compared. So far, an increase by a factor of 5.5 has been found experimentally, which will go up to 7 when evacuated flight paths will be installed on IN10. This observed increase compares well with the augmented solid angle after the focusing guide.

4. OUTLOOK

This paper has demonstrated with IN10C as an example how neutron instrumentation can be improved by properly incorporating focusing elements in their design . Nevertheless, it seems that the performance of IN10C could be improved already now by using a state-of-the-art coating with higher reflectivity out to 2 γ^{Ni}.

Actually, IN10C is located at a primary guide with a ^{58}Ni coating, giving a 40% flux increase compared to natural Ni. Our simulations have shown, that IN10C hardly benefits from this increase. The additional neutrons have a high divergence, and they are the first ones lost in the focusing guide. To take advantage of the ^{58}Ni coating a high performance supermirror with a critical angle of 2.5 γ^{Ni} would be needed.

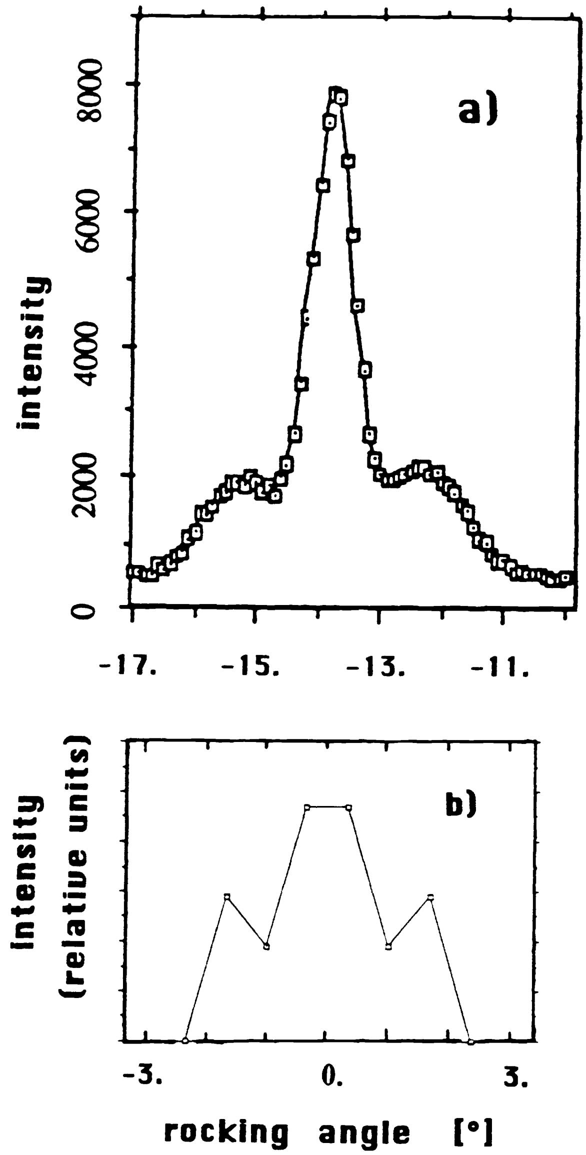

Fig. 4 Measured (a) and calculated (b) profile of the beam divergence at the exit of the focusing guide.

Recently, the idea has been put forward to build a backscattering instrument with even finer energy resolution. To this end both the extinction limited crystal term and the divergence term must be reduced according to eq.1. GaAs[200] would be a favorable candidate, and indeed an energy resolution of $\Delta E = 0.043\mu eV$ has already been measured in a dispersion-free setup.[6] Note, that this is 7 times better than the best resolution presently available. To reduce the divergence term accordingly requires, that the primary beam must be focused into a source spot of about $10x10mm^2$, a challenging task for next generation optical elements.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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