Proceedings of International Collaboration on Advanced Neutron Sources (ICANS-VII), 1983 September 13-16
Atomic Energy of Canada Limited, Report AECL-8488

The SNQ-Project

Status report as of August 1983

G. S. Bauer
Projektleitung Spallations-Neutronenquelle
KFA Jülich, D-5170 Jülich, FRG

1. Development of the SNQ-concept

The SNQ-project, with SNQ standing for the German term "Spallations-Neutronen-Quelle" (spallation neutron source) went through a fairly lengthy analysis phase during the years 1979 through 1982. During this period the goal was defined to substitute a new high flux neutron source for the slowly aging German low to medium flux research reactors, most of which were more than 20 years old and could no more be considered as meeting modern research needs in a satisfactory and economic way. A feasibility analysis was carried out jointly by the two national research centres at Karlsruhe (KfK) and at Jülich (KFA), demonstrating that with present day technology and some additional development work a spallation neutron source could be built whose effective time average thermal neutron flux is equivalent to that of an advanced thermal high flux reactor (i.e. of the order of 10^{15} $cm^{-2}s^{-1}$), but which, by virtue of a pronounced time structure and a broader range of scientific use , has a much higher performance potential. The concept included a proton linac with 5 mA time average current operating at 100 Hz repetition rate and a target station with one H_2O-moderator for thermal neutrons with good time structure and a D_2O-tank to provide good conditions for a cold neutron source and for irradiation facilities. It was described at previous ICANS-meetings and in a formal study report (Bauer et al, 1981; Vetter, 1981) as well as in several papers (e.g. Bauer and Vetter, 1983; Bauer, 1982). In order to make possible much shorter proton pulses at high intensity than can be obtained from an rf-linac, the addition of a proton pulse compressor was studied (e.g. Schaffer, 1981).

Two alternative concepts for a stepwise realization of the project were subsequently considered:

Concept 1 aimed at providing short high energy proton pulses at the earliest possible stage to establish good experimental conditions not only for neutron scattering but also for other uses of the facility such as neutrino research and µSR. For this goal a 0.5 mA time average rapid cycling synchrotron with 200 MeV injection energy which could later on be converted into a proton pulse compressor at a much higher injection energy (1100 MeV) and 5 mA time average current was studied by a joint ANL-KFA working group (1983). It was shown that, although at the limit of technical feasibility, such a machine could be built with a reasonable level of confidence but at relatively high cost. However, only a small fraction of the capital investment would be lost, if, in stage II, a high current linac was added and the synchrotron operated in a non - or only slightly - accelerating mode for pulse compression.

Concept 2 was to start with the high current linac from the very beginning but to equip it with the (costly) rf-power generation system only for some intermediate proton energy (350 MeV or above) in stage I. Stage II would then complete the linac for 1100 MeV and add a proton pulse compressor. This concept was studied by a newly established team at KFA Jülich. With respect to the original reference accelerator concept, a number of changes were made to facilitate achieving the above goal by providing added flexibility and making the design parameters more attractive for the proposed use . **The most important change in this latter respect was the increase of the pulse current from 100 to 200 mA with a simultaneous shortening of the pulse length from 500 to 250 µs.**

A meeting of the SNQ-scientific advisory board was held in February 1983 to discuss the two concepts and to the end the analysis phase of the project by a decision, which way to follow.

Since the scientific merits of both concepts seemed to balance out in stage I, it was decided to go the apparently more direct and probably cheaper way of starting with the high current linac in stage I (concept 2).

2. The neutron source DIANE

With the new linac parameters, the design goals of the SNQ (without pulse compressor) are now as follows:

Accelerator

Time average proton current	5 mA
Pulse current	200 mA
Pulse repetition rate	100 Hz
Pulse duration	250 µs
Final proton energy	1.1 GeV

Target station DIANE

Target material	depleted U
Target coolant	H_2O
Power dissipation in target	10-12 MW
Moderators	H_2O and D_2O
Time average thermal neutron flux in moderators	$1.2 \cdot 10^{15} cm^{-2} s^{-1}$
Peak thermal neutron flux (H_2O-moderator)	$5 \cdot 10^{16} cm^{-2} s^{-1}$

It is planned to operate the target station DIANE of the SNQ as an intensity modulated source with both, high peak and high time average flux, i.e. without poisoning or decoupling the moderator. This philosophy has been discussed at various ICANS-meetings and a summary may be found in a recent paper (Bauer, 1983). Nevertheless, the changes in accelerator concept and the decision to develop a uranium target let us expect considerable improvements in the overall performance of the neutron source.

Relative to the data in the reference study, the goals in neutron flux have changed significantly:
The effective time average flux is up by almost a factor of 2, which results from the use of depleted uranium rather than lead in the target. With respect to the effective peak flux in the pulse, the increase is almost fourfold, resulting from the combined effects of the use of uranium and the shortening of the proton pulse. The effect of the duration of the proton pulse on peak flux and thermal neutron pulse shape is shown in Fig. 1.

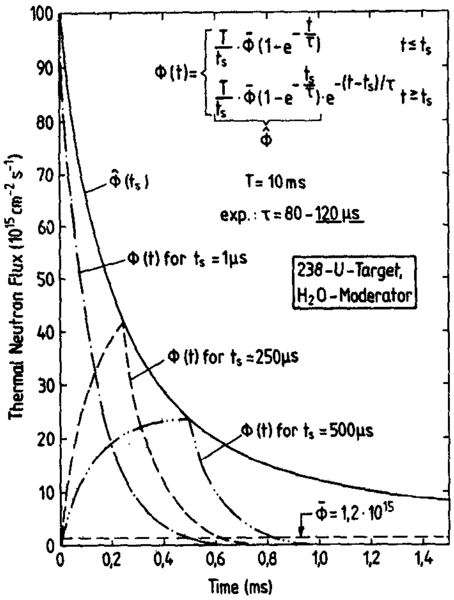

Fig. 1 Dependency of the thermal neutron peak flux in the H_2O-moderator of DIANE on the duration of the source pulse t_s at constant neutron production. Also shown is the shape of the pulses for source pulses of t_s = 1, 250 and 500 µs.

In this figure, one single decay constant τ=120 µs has been assumed as a result of experimental investigations with a fairly realistic mock-up at the SIN cyclotron as reported at the previous ICANS meeting (Bauer et al, 1983a). Earlier estimates had been based on τ=200 µs. No new data for the time constants in the D_2O have been measured. Using the ones reported at ICANS-V (Bauer et al, 1981) for a U-target (τ_1=440 µs, τ_2=5000 µs, Φ_1=97%, Φ_2=3%) we obtain the pulse shape shown in Fig. 2 for the D_2O-case in comparison to the one in the H_2O-moderator.

The peak-to-average flux ratio in the (unperturbed) D_2O-tank follows as 13.3, as compared to 7.9 which was expected for a Pb-target. This is attributed to the strong absorption of thermal neutrons by the large U-target.

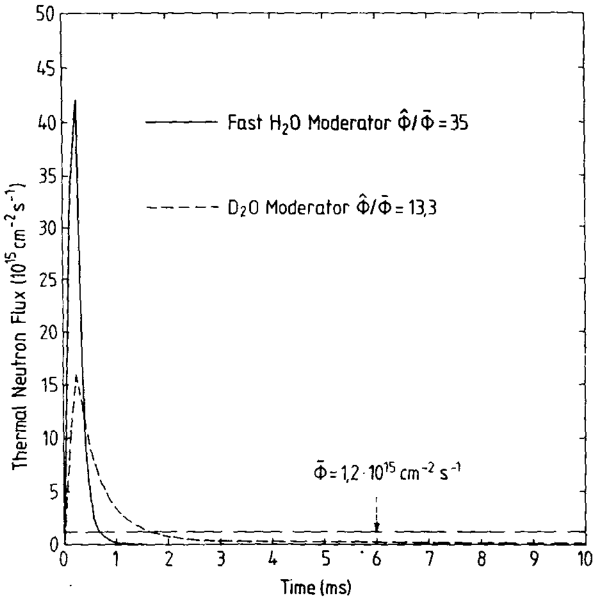

Fig. 2 Expected pulse shapes in the H_2O- and D_2O-moderators of DIANE with U-238 target.

As a result of measurements carried out at the SATURNE-accelerator in Saclay, France, with variable proton energy (Bauer et al, 1983b), we anticipate a 4.25-fold reduction in neutron flux when working with 350 MeV proton energy instead of 1100 MeV, with no changes in pulse shape or peak-to-average ratio.

3. Target related research and development work

Since this topic will be the subject of various presentations at this meeting, only a brief survey shall be given here:
The decisions to (a) start with a proton energy as low as 350 MeV and (b) develop a uranium-target were of considerable impact on the R+D-work related to the target. New calculations on production of radioactivity and heat deposition and on the resulting stress distribution had to be initiated. As will be shown in a separate paper (Filges et al, 1983) the low proton energy produces a strong peak in heat deposition at the end of the proton range. The consequences of the SNQ staging programme on the target design will be discussed by H. Stechemesser (1983). Since there are considerably more radioactive isotopes produced in a U-target than in Pb, handling and safety aspects had to be reconsidered (Thamm, 1983).

The high pulse power in the SNQ proton beam has the inevitable consequence of high heat density and hence a noticeable temperature increase during each pulse in the target. Although the number of cycles per unit time and the resulting mean operating temperature are strongly reduced by the target rotation, the effect of this thermal cycling on the structural integrity of the target material is a matter of concern. W. Lohmann (1983) is going to report on work which we have initiated to obtain more information on this problem and to develop a clad target element which can stand the thermomechanical and radiation load for at least two years of operation.

Another problem to which we devoted considerable theoretical effort was the question of appropriate target shielding and the effect of penetrations through the shield. The implementation of an appropriately coupled code system for this purpose will be discussed by Cloth et al. (1983) in this meeting.

4. The SNQ accelerator

Although a more detailed report on the new SNQ accelerator is given in a later paper at this meeting (Schelten and Zettler, 1983), it shall be described here briefly:
The concept is shown schematically in Fig. 3.

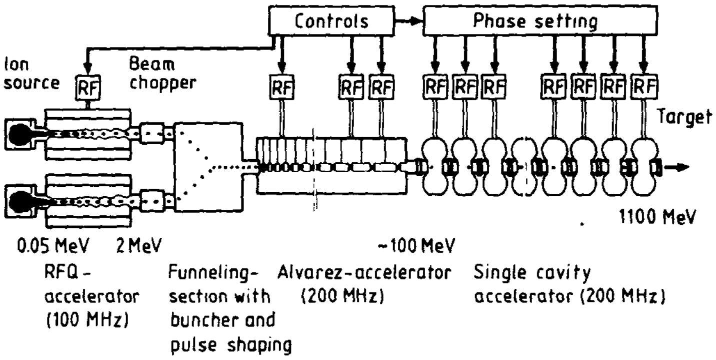

Fig. 3 Schematic illustration of the SNQ rf-accelerator.

Two ion sources operating in parallel with an extraction voltage of 50 keV inject into **two RFQ-structures** which run on 100 MHz rf-frequency with a relative phase shift of 180 degrees and accelerate the beams to an energy of 2 MeV. In a **funneling section** which includes devices for bunching and pulse shaping, the two beams are merged together according to the "zipper principle", which results in a pulse sequence of 200 MHz. This is exactly the frequency on which the subsequent **Alvarez structure** operates, which means that each of its rf-buckets is filled for optimal accelerating efficiency. At an energy around 100 MeV the Alvarez-structure becomes rather inefficient and a different accelerating structure is used. A **single cavity structure** with a separate rf-amplifier for each cell is under study for the SNQ linac. Some reasons for this choice will be given below. It is intended to install only part of the accelerating structure initially to limit the overall cost until the first neutron producing stage can be reached and to gain experience in operating the facility at reduced power and beam energy. While incorporating essential new parts such as the low energy end and the funneling section, this allows further studies concerning the optimisation of the high energy structure (e.g. superconducting cavities).

The RFQ, which has been selected for the low energy end is generally considered a major improvement in accelerator technology. Since it uses electrostatic rather than magnetic focusing, it can handle beams of very low velocity. Due to a peculiar shaping of the edges of the four vanes which constitute the electric quadrupole, the structure is able to trap slow protons at low velocities with high efficiency, focus the beam, bunch it, and accelerate it to energies much higher than what can be achieved with dc-preacceleration at high currents. Although under development at various laboratories, this structure is still very new and no experience on its reliability and operating performance is yet available.

The funneling section, whose overall length will be about 11 m will contain beam chopping devices and several bunchers and rebunchers to maintain the micropulse structure of the beam over the whole distance. Merging of the two beams is achieved by a series of bending and septum magnets and an rf-deflector. The latter operates at 100 MHz and will give a kick in opposite directions to the microbunches arriving at 180 degrees phase intervals. So far, funneling has not been used on existing accelerators.

Alvarez accelerators of 200 MHz have been operating successfully and reliably at various laboratories over many years now and even pulse currents of 300 mA have been achieved, although for a pulse duration short enough to allow running off the stored energy in the cavities. This will not be possible in the SNQ-Alvarez. This is why well controlled distributed power feeding into the structure during the macropulses will be required, together with the usual measures to achieve a finite group (i.e. energy flow) velocity along the accelerator by two overlapping pass bands.

A single cavity structure with separate rf-feeding into each cell has been chosen for the high energy part of the accelerator for a variety of reasons:

With a coupled cavity structure, the mechanical dimensions of the cavities have to be matched to the velocity of the particles (as in the Alvarez structure). This is because a whole set of cavities is resonating with fixed rf-phase from one common feeder line. As a consequence the energy of the beam is predetermined at each point of the accelerator and no variation is possible (fixed β-structure; β is the ratio between the velocity of the particles and the velocity of light). Hence, if at any position the energy gain is significantly less than the design value, the beam will be out of phase with the rf in the rest of the accelerator, which means that operation cannot continue. In contrast to this, with a single cell structure (**variable β-structure**) the relative rf-phase between cavities is controlled by electronic means and can be changed very rapidly.

With respect to the rf-supply to the accelerating gap, the optimally distributed feeding points with the single cell structure offer the important advantage that no energy flow along the accelerating structure is necessary.

The rf-amplifiers are relatively low-power units but large in number. Thus, if one or a few of them fail, the phase in the following cavities can be readjusted to the new local beam velocity and operation can continue with virtually no interruption. Suitable provisions for automatic exchange of rf-amplifiers with the accelerator in operation will be made. In order to avoid high induced voltage by the beam accross the gap of those cavities, whose rf-feeding has failed, electronic detuning of the cavity is studied. In this way it becomes possible to continue with the operation of the linac even if one or several rf-systems do not work. Rapid exchange of units and off-line repair will contribute to this.

Apart from the prospect for a high availability of the accelerator, the fact that the single cell structure can accelerate the beam with a **variable output energy** constitutes important advantages for the SNQ-accelerator:

- By reducing the voltage accross the accelerator gaps, more economic operation of the accelerator becomes possible, although at lower output energy. Since the losses in the accelerator are proportional to the square of the electric field whereas the output energy (and the neutron production) depends linearly on it, optimization of the operating parameters is possible. This is of particular interest, if a post-accelerating proton pulse compressor (e.g. an FFAG, see below) becomes available.

- With only part of the accelerating structure installed in stage one (say for a final energy of 350 MeV at 5 mA beam current), it is still possible to produce a higher output energy at a reduced current mainly by readjusting the rf-voltage accross the accelerating gap (increasing the accelerating gradient). Since this means an increase in the losses in the cavities, the current that can be accelerated goes down, as shown in Fig. 4. Of course, as shown by the dashed curve, also the neutron yield in the target will be reduced. Nevertheless, this option is an important feature to study the next step in a staged development program at reduced intensity.

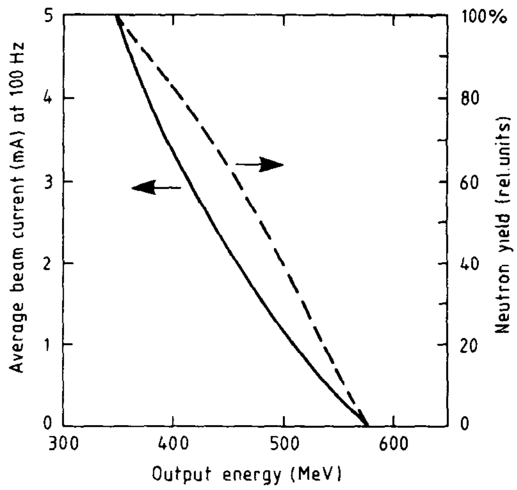

Fig. 4 Dependency of the current, that can be accelerated, on the output energy in stage I of the SNQ-accelerator. The dashed curve shows the resulting decrease of neutron yield in the target.

- Some of the non-neutron users (e.g. nuclear physics experiments, cross section measurements etc.) may want to work with an energy that is variable over a certain range. This is much more difficult with a coupled cavity structure.

- In some cases very short pulses, of the order of individual bunches, are desired for special purposes. Rather than cutting out just one bunch at a time, a method is studied to increase this intensity by time-focussing several of them by letting them pass through some low frequency (e.g. 20 MHz) cavities which are phased in such a way that the first half of the series is decelerated, the other half accelerated in proportion to their distance from the centre of the sequence. After passing a certain drift space (inactive cavities), the microbunches can thus catch up with one another and combine to one short pulse of correspondingly higher intensity, which can be further accelerated in the following cells.

Last not least, the accelerating cavities (and rf-amplifiers) can be manufactured in relatively large series rather than individually as in the case of a fixed ß-structure.

Tetrodes are presently considered as the most economic solution for the rf-amplifiers, but their life time is limited and some development in the field of rf-amplifiers is highly desirable. This is also true with respect to power losses, because the largest fractional losses occur in the rf-generation system as can be seen from the diagram of anticipated power flow shown in Fig. 5.

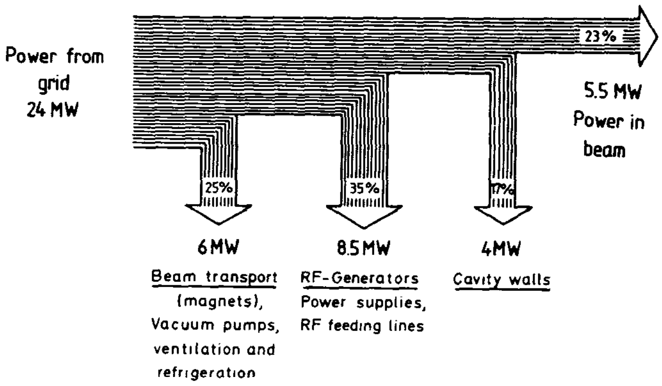

Fig. 5 Approximate energy flow scheme for the SNQ-accelerator.

5. The proton pulse compressor

While the concept of DIANE aimes at improving experimental conditions for all sorts of neutron scattering techniques over those at a high flux reactor, i.e. also for non-time of flight techniques, most other spallation neutron sources have been designed as pulsed sources, utilizing the source pulse as the first resolution element in time-of-flight techniques. This has several attractive advantages, in particular if neutrons in the epithermal energy range are to be used. It is mainly for this reason, that a concept for an isochronouns compressor ring (IKOR) had been worked out in the first SNQ-study. Since the slowing-down time even to energies of several eV is of the order of several microseconds, there seemed to be little incentive to go to much less than one microsecond in the duration of the proton pulses. During the study work it became more and more obvious, however, that other scientific disciplines such as µSR and neutrino physics utilizing the beam stop neutrinos could benefit considerably from even shorter pulses. Therefore the goal was set to 200 ns for the synchrotron - which would act as proton pulse compressor later on - studied by the ANL-KFA working group (1983). This study showed, that such short pulses could probably be produced but would require a compressor ring equipped with an rf-system (which was not the case at IKOR). At a workshop held at KFA in Feb. 83 (Martin and Wüstefeld, 1983) it became obvious that the concept of a fixed field alternating gradient synchrotron which was under study at Argonne National Laboratory had a potential to serve the same purpose at probably lower cost and with added flexibility. For the SNQ-project this scheme looked particularly promising because, by going to a lower accelerating gradient in the SNQ linac, i.e. to an injection energy into the FFAG somewhere between 400 and 600 MeV, the linac can operate much more economically than at the full design gradient of 3 MeV/m. Thus, if the FFAG could be designed to handle more or less the full linac current by choosing a suitable injection energy and using it as a post-accelerator to a final energy which might even be higher than 1.1 GeV, say 1.5 to 1.6 GeV, the system looks very attractive, especially also in view of the rapidly increasing pion (and hence muon and neutrino) production rate at this energy, even if the current is reduced in such a way, that the neutron flux remains constant.

These considerations lead us to form a study group, who, as a first step, examine the possibilty of scaling the ANL - FFAG design to our parameters and determine the conditions, under which such a machine could operate. The results obtained so far seem quite encouraging. However, much more work including nonlinear calculations is needed before a technical design can be tackled.

From Fig. 1 it can be seen that even with very short source pulses, and under the assumption that a U-target can still be used, the thermal neutron peak flux can increase only by about a factor of two relative to the one for a 250 µs-pulse. At the same time it becomes slightly more difficult to phase the choppers needed for time-of-flight experiments. However, since - in contrast to choppers at pulsed sources - these choppers will not serve as time-of-flight monochromators but rather as pulse shapers for a monochromatic beam, the phasing problem is much less serious. Only the intensity of the pulse may vary slightly.

On the other hand it might become desirable to equip the SNQ-facility with a pulsed source at some date. This could either be achieved by building a second target station with poisoned and decoupled moderators or by replacing the DIANE H_2O-moderator by a differently designed one.

6. Near term outlook

With the analysis phase of the project terminated in Feb. 1983 by the decision, which staging concept to follow, the project is now in its system definition phase, in which more detailed studies of system components are carried out and preliminary designs and specifications are developed. An R+D-program is defined and preliminary manufacturing and test requirements are assessed. This phase is due to end in December 1983 at which time a report will be produced,describing a specific concept for further detailed design, preliminary specifications and preliminary schedule, resource- and management-plans. The design phase, during which the project design and specifications including manufacture, test and operating plans have to be established as well as a construction schedule with a detailed work break down structure will essentially end in spring 1985. This date was set by a recent letter from our Minister for Research and Technology which also contained the statement that the SNQ was to be part of the ministry's medium term financial planning. A final decision on the construction of the facility was announced for summer 1985. In preparation of this decision a final project plan which should also contain realistic cost estimates was requested.

References

ANL-KFA Study Group (1983)
"Conceptual Design of a Rapid Cycling Synchrotron for the KFA-Jülich Spallation Neutron Source"
report ANL-83-13, Argonne National Laboratory

Bauer, G.S. (1982)
"The General Concept for a Spallation Neutron Source in the Federal Republic of Germany"
Atomkernenergie/Kerntechnik 41 (1982), p. 234-242

Bauer, G.S. (1983)
"DIANE - A Project for a New High Performance Neutron Source in the Federal Republic of Germany"
Proc. IV Int. School on Neutron Physics, Joint Institute for Nuclear Research, Dubna 1982, D3,4-82-704
and unpublished report SNQ 0Y/CV 24 08 83, KFA Jülich (revised version)

Bauer, G.S.; Conrad, H.M.; Grünhagen, K.; Spitzer, H.; Gompf, F.; Reichardt, W. and Fischer, W.E. (1983a)
"Time-Structure of Thermal Neutron Leakage from fast and slow Moderators for Spallation Neutron Sources"
Proc. ICANS-VI, report ANL-82-80, Argonne National Laboratory

Bauer, G.S.; Conrad, H.M.; Grünhagen, K.; Spitzer, H. and Milleret, G. (1983b)
"How much Thermal Neutron Flux is Gained Using; Deuterons instead of Protons?"
Proc. ICANS-VI, report ANL-82-80, Argonne National Laboratory

Bauer, G.S.; Fischer, W.E.; Gompf, F.; Küchle, M.; Reichardt, W. and Spitzer, H. (1981)
"Thermal Neutron Leakage and Time Structure Measured for Various Target-Moderator-Reflector Configurations for a Spallation Neutron Source"
Proc. ICANS-V, Jül-Conf-45, G.S. Bauer and D. Filges, eds., Kernforschungsanlage Jülich

Bauer, G.S.; Sebening, H.; Vetter, J.-E. and Willax, H. (eds.) (1981)
"Realisierungsstudie zur Spallations-Neutronenquelle, part I"
report Jül-Spez-113/KfK 3175, Jülich and Karlsruhe

Bauer, G.S. and Vetter, J.-E. (1983)
"The FRG-Project for a High-Power Spallation Neutron Source for Fundamental Research"
in "Nuclear Technologies in a Sustainable Energy System", G.S. Bauer and A. McDonald eds., IIASA - Springer, Berlin 1983

Cloth, P.; Armstrong, T.; Filges, D. and Schaal, H. (1983)
"Calculational Methods and High Energy Cross Sections for Spallation Source Shielding"
Proc. ICANS-VII, this volume

Filges, D.; Cloth, P.; Neef, R. and Schaal, H. (1983)
"Recent Target Design Calculations at KFA"
Proc. ICANS-VII, this volume

Lohmann, W. and Krautwasser, P. (1983)
"Progress in Materials Investigation for the SNQ-Target"
Proc. ICANS-VII, this volume

Martin, S. and Wüstefeld, G. (eds.)
"Informal Collection of Talks Held in the Seminar on FFAG"
unpublished report SNQ 2 MZ/BS 001

Schaffer, G. (ed.) (1981)
"IKOR - An Isochronous Pulse Compressor Ring for Proton Beams"
report Jül-Spez-114, KFA Jülich

Schelten, J. and Zettler, C.
"Present Design of the Linac of the SNQ-Project"
Proc. ICANS-VII, this volume

Stechemesser, H. and Thamm, G. (1983)
"Target Design for Stepwise Development of the SNQ"
Proc. ICANS-VII, this volume

Thamm, G.; Buttgereit, H.; Stechemesser, H. and Wolters, J. (1983)
"Operational, Handling and Safetly Aspects of the SNQ-Target Station"
Proc. ICANS-VII, this volume

Vetter, J.-E. (ed.) (1981)
"The Basic Concept of the SNQ Linear Accelerator"
report KfK 3180 B