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SINQ

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G.S. Bauer
for the SINQ project team
PAUL SCHERRER INSTITUTE
CH-5232 Villigen-PSI, Switzerland

ABSTRACT

After a lengthy period of "digging-work" which started on 8-8-88 to build the 11 m deep proton transport tunnel, most of the concrete work is now complete and the steel structure for the target and neutron guide halls has been erected. Design work on the target- and supplies system is progressing well and a basis for the safety analysis report has been established. Besides investigations towards protection against air-plane crash and earthquake this also includes research to determine the retention factor of lead-bismuth for polonium and mercury. Studies on the lead bismuth thermal hydraulics and on the D_2-cold moderator system have so far confirmed our expectations and are still in progress. Also in progress is an irradiation endurance test on the target window material at Los Alamos. In addition to intensive development work on the liquid metal target, research on a lead pebble bed target has been initiated.

I THE SOURCE CONCEPT

The final decision to add a spallation target and neutron scattering facility to the meson factory of the then Swiss Institute for Nuclear research (SIN) was made in 1987, when funding from the Swiss government was obtained.

Following this milestone, the work done in preparation of the funding request was reviewed, a formal project was established and a technical baseline was fixed.

This technical baseline took into account various boundary conditions:

- the fact that the accelerator available was a cyclotron with no macro-pulse structure on the proton beam;
- an anticipated proton current around 1.5 mA after an accelerator upgrade and a rebuild of the main meson production target;

- space limitations resulting from the fact that the proton beam line was pointing towards the steep shore of the river Aare and could only be extended by some 30 m beyond the last meson production target without violating the public requirements about distance of a building from high growing trees;
- the need of a straight-through beam line to a beam stop behind the meson production target and its associated shielding in case the spallation target was not ready for operation.

The spatial limitations can be seen from Fig. 1, which shows the PSI-West experimental complex as it is planned for future operation.

The most important feature, which is shown on Fig. 2, is the bending-down of the proton beam between the meson production target (E) and its beam dump to an inclined drift section which passes under the foundations of the Experimental Hall and the adjacent Neutron Target Hall into an 11 m deep tunnel. This tunnel will house the beam-optical devices necessary to guide the beam with very little losses and to direct it upwards again to the neutron production target.

The target concept selected for further development was close to the theoretical best, given the fact that, as a continuous source, SINQ was to ressemble very much a beamhole reactor in terms of utilization. This means that a time average thermal neutron flux as high as possible had to be achieved. The proven ways to do this are a large D_2O-moderator, high fast neutron production density and little absorption in the slowing-down regime as well as for thermal neutron.

The liquid lead bismuth target shown in Fig. 3 seemed to be almost ideal:

- the low melting point of the eutectic mixture (125 °C) allows operation at a moderate temperature level around 200 °C
- heat removal from the interaction zone by natural convection results in the highest possible material density with no cooling gaps in the reaction zone
- lead and bismuth both show good neutron yield and very little absorption
- the cylindrical geometry with a vertical axis is best for horizontal beam extraction in all directions
- the large target mass results in good high energy radiation shielding in the forward direction of the proton beam (Fig. 4) and in a low enough specific activation to make emergency removal of decay heat possible by radiation through the surface alone.

It was planned from the very beginning, to have two cold moderators at SINQ, one operating on liquid deuterium and feeding a set of neutron guides as well as a pair of beam tubes. The second cold moderator was planned to operate on liquid H_2 and to feed two pairs of beam holes. Two further pairs of beam holes were foreseen for extraction of thermal neutrons from the moderator.
For financial reasons as well as in view of the lack of experience in carrying out experiments on a non-pulsed and high power spallation source, we decided to postpone the construction of the H_2-moderator and of four of the five beamhole inserts shown on Fig. 5. In this way we expect to be able to optimize the layout on the basis of what we learn when working on the first instrument. On the other hand, four neutron guides will be available from the very beginning, with an option of a fifth one for later installation.

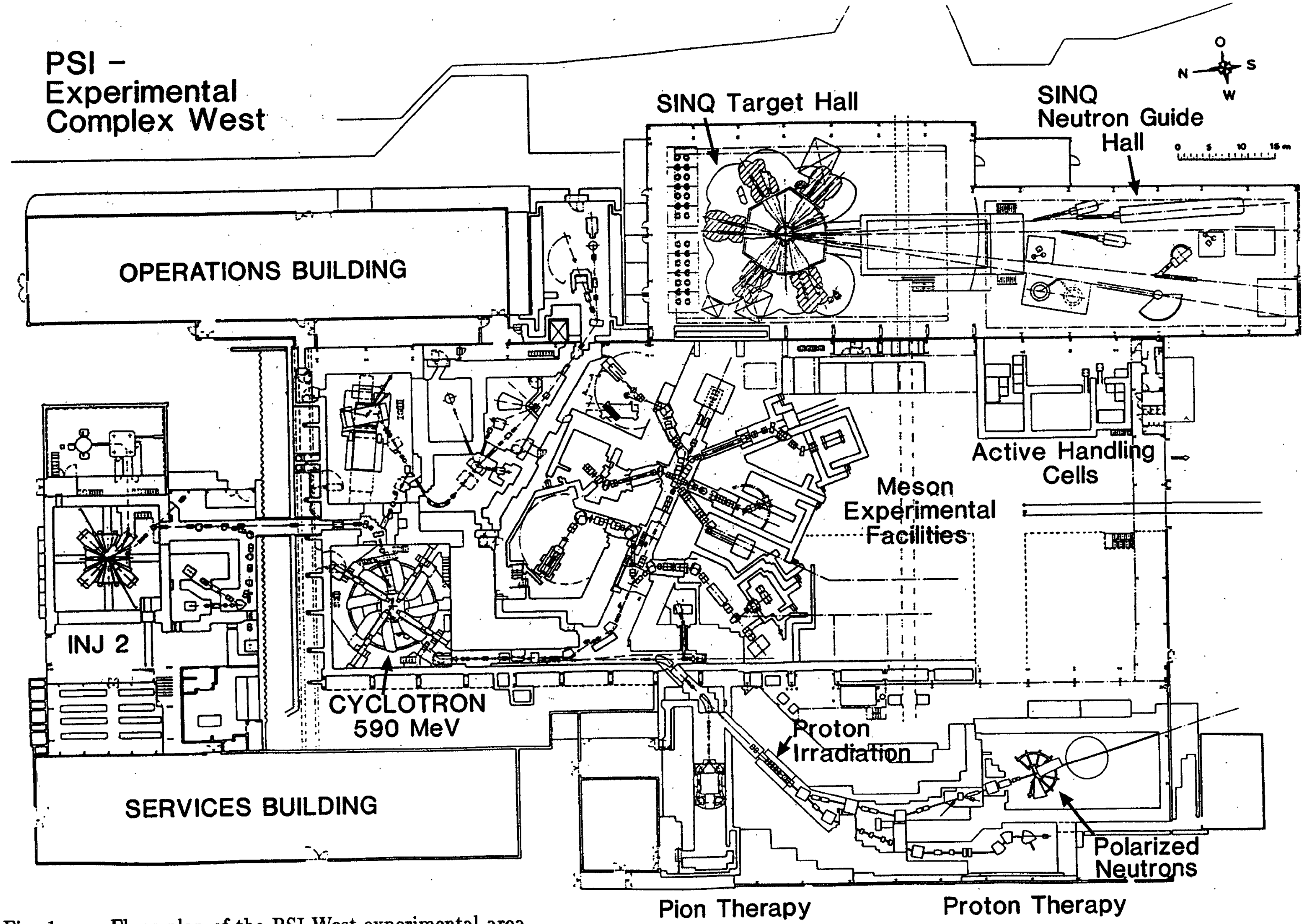

Fig. 1 Floor plan of the PSI-West experimental area as planned for operation in the mid 90's

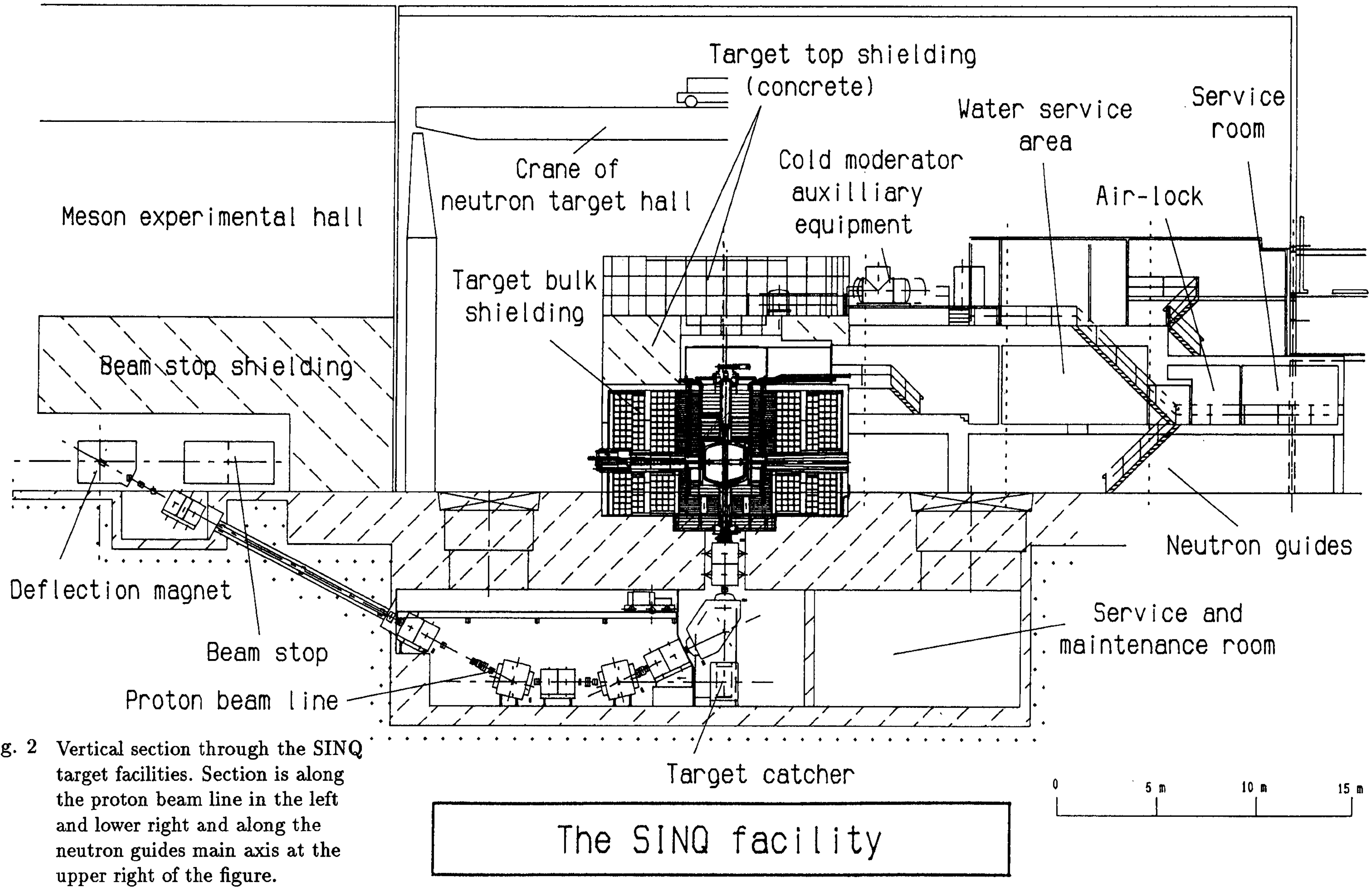

Fig. 2 Vertical section through the SINQ target facilities. Section is along the proton beam line in the left and lower right and along the neutron guides main axis at the upper right of the figure.

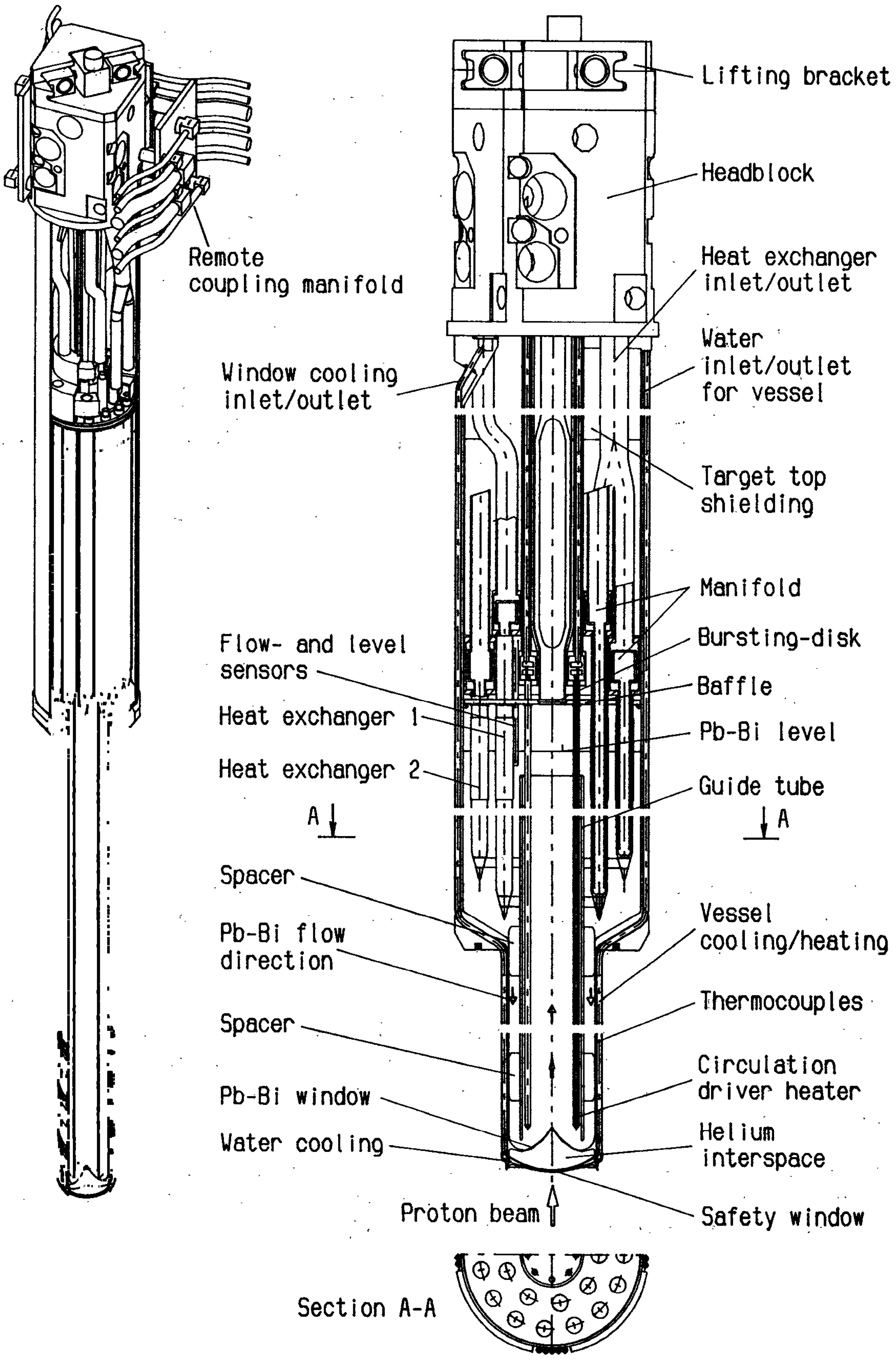

Fig. 3 Vertical section (right) and cut away view (left) of the liquid Pb-Bi target for SINQ. All connections to the target are made via four connector plates at the target head.

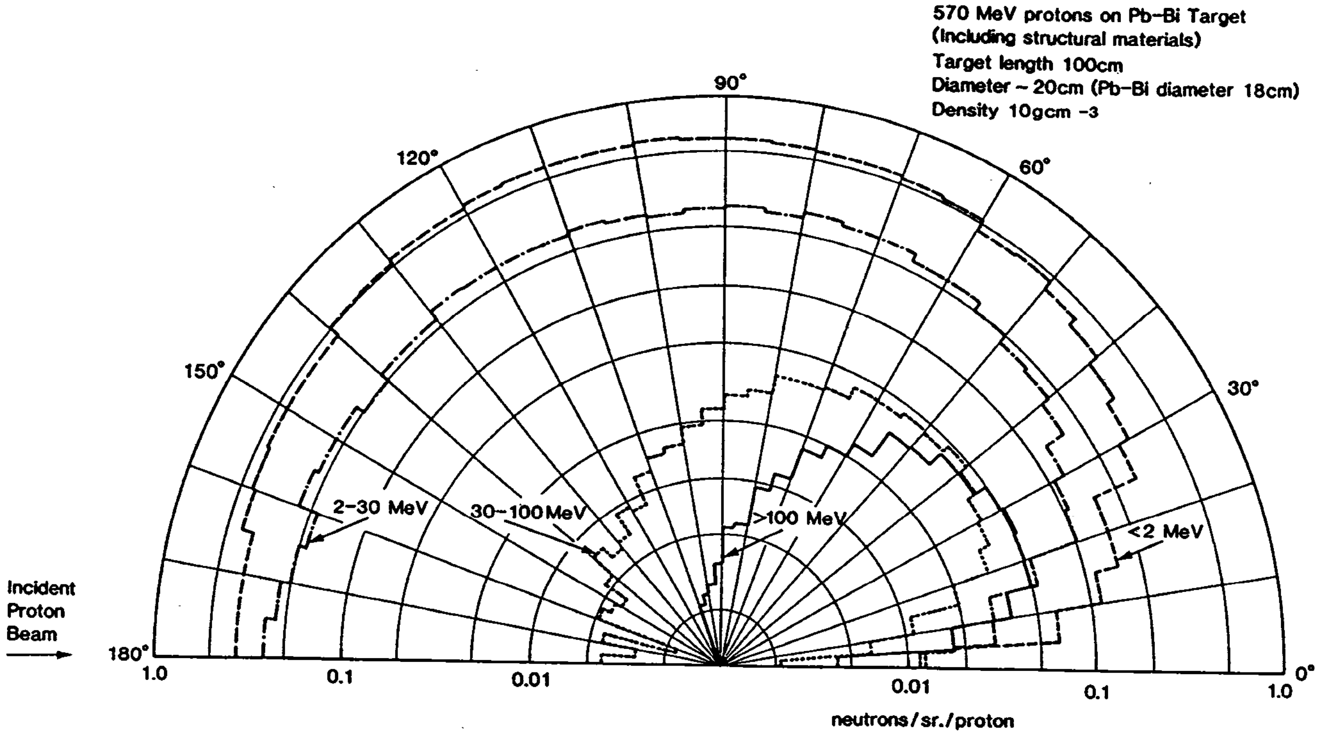

Fig. 4 Angular distribution of leakage neutrons from the liquid Pb-Bi target for SINQ. Note the self-shielding effect in forward direction for high energy neutrons.

Thus, most of the instruments scheduled for early operation on SINQ will be in the neutron guide hall. This has the additional advantage that the large access shafts to the proton channel, which are located in the neutron target hall and which will ultimately be covered with a "tanzboden" for neutron spectrometers need only be blocked after the proton beam line has been in operation for some time.

The neutron guides will have a shutter system adjacent to the main target block shielding which will be accessible by removing the heavy concrete blocks used for shielding. Following this stacked shielding there will be a cast concrete cavern extending all the way to the neutron guide hall. Above this cavern the service area will be located as shown in Fig. 6, thus forming a big service building inside the main neutron target hall.

The cold box and control system for the D_2-cold moderator will sit on top of the tunnel connecting the service building to the target block, with the D_2-ballast tank sitting on the roof of the access building for heavy equipment next to the neutron guide hall (see Fig. 1).

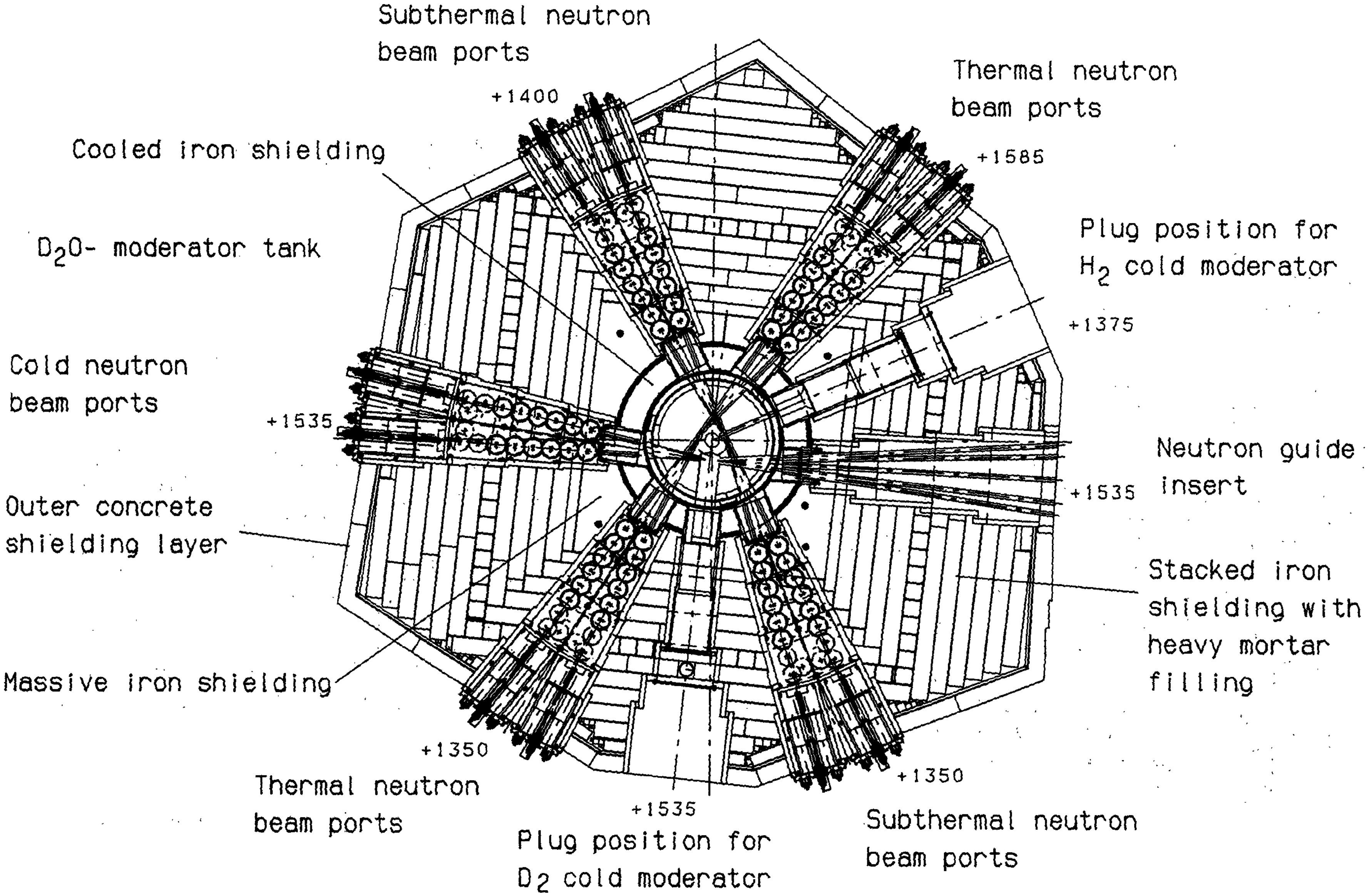

Fig. 5 **Horizontal section through the SINQ target block showing the ports for beam extraction and cold moderator insertion. Beam ports viewing cold moderators are directly connected to the moderator thimbles to avoid windows and rethermalizing layers of D_2O.**

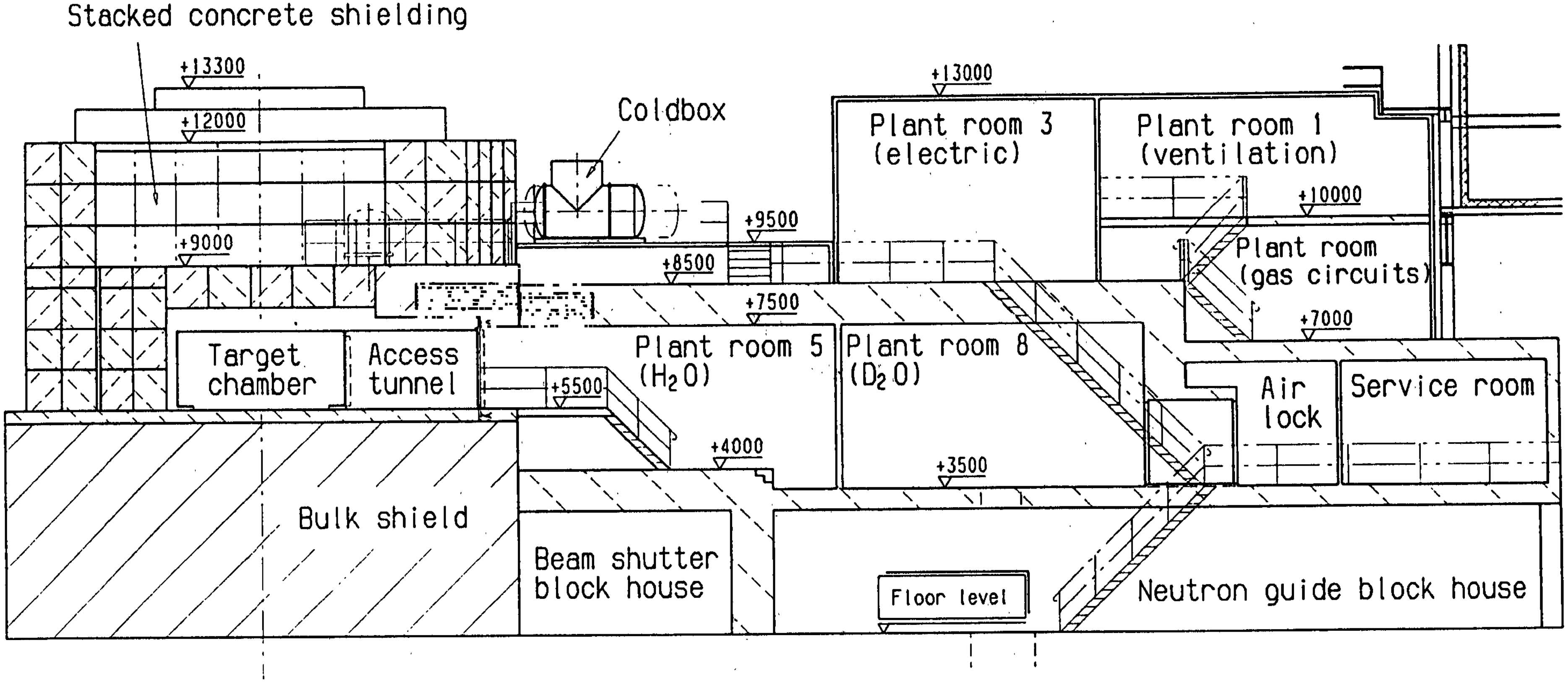

Fig. 6 Overview of the SINQ plant facilities located on top of the neutron guide block house adjacent to the target block.

II SAFETY AND LICENSING

Although not considered as a "nuclear installation" in the sense of the nuclear legislation, SINQ will require a licence from the Swiss Nuclear Safety Authorities for construction as well as for operation. This is due to the hazard potential associated with the production of polonium by neutron capture in the bismuth of the target. An estimated 9 kCi of long lived α-emitters, mainly Po, are produced during one year of target operation at 1.5 mA proton current. In an accident scenario which would destroy all protective barriers and would set free 100 % of the noble gases, 10 % of other easily volatile species including Po and Hg, 1 % of the medium volatile nuclides and 0.1 % of the less volatile spallation products it was found that 95 % of the risk potential come from the Po-isotopes. This would make emergency planning for the general public necessary. In order to avoid this, it was requested that the radioactivity in the SINQ target must remain contained in the case of

- an airplane crash with resulting kerosene fire,
- an earthquake as assumed for nuclear power stations,
- the target transport container dropping off the crane hook during target exchange.

Since the SINQ buildings will not be able to contain radioactivity over an extended period of time or withstand the crash of a (military) airplane, the safety features to meet the first two requirements will have to be built into the target shielding block and the storage holes for used targets. As a result of an analysis carried out for both kinds of events it was found that the impact of a military airplane was the more serious one. The following main measures were requested:

- the heads of the used targets in storage must be secured by 20 cm thick steel housings bolted to the concrete structure in addition to the 80 cm thick concrete covers
- the target block must have a 5 cm thick outer steel liner capable of withstanding a torque of 20 MNm and an average azimuthal stress of 70 N/mm^2 with only moderate plastic deformation
- unused beam ports must be secured by reinforced concrete or steel beams positioned in such a way that the impact force is transferred to the shielding block and not to the beam hole plug.
- the stack of iron bars inside the main target shield has to be arranged such that the impact force is distributed over the full height of the stack to avoid "spallation" of the whole shield under an impact.

These requirements will be met by the present design of the target block and target storage area.

The question, how release of radioactivity can be safely prevented in the event of a catastrophic crane failure during target transport is still under examination. Generally the risk of activity release is very small, since the radioactive nuclides will be contained by three barriers:

- the transport cask will be tightly sealed to form the outermost containment;
- the second containment is formed by the target vessel;

- thirdly, the target will be in a solid state when transported.

In order to make sure that the solid state of the target can in fact be counted as a containment of the radioactive nuclides present during transport, it is foreseen to vent and evacuate the space above the target while the target material is still liquid and thus remove practically all volatile substances from the target before transport. If necessary, the space can afterwards be filled with lead before the target is removed from its operating position. Our preliminary investigations indicate that, once the target is in a solid state and cooled down to some 50 °C for a few days, decay heat can be removed through the target surface by a contact gas. It remains to be studied, whether the shielding of the transport cask in the absence of active cooling would warm up sufficiently high to bring the target temperature back up to the melting point. At present it is our feeling, that this is rather unlikely. Detailed studies will be started soon.

Unfortunately we have some uncertainty on the radiation load in our anticipated mode of operation since we rely on the beam scattering and energy loss when the protons traverse the meson production target. It is, however, possible and even likely that a certain fraction of the beam will go past this target unscattered. This fraction may be as high as 30 % under certain operating conditions.

Partly for this reason we have not been able to quantify with a good level of confidence the life expectancy of the beam entry window at the bottom of the target. Test windows under irradiation at the LAMPF accelerator have so far stood up to 80 mAh/cm^2, which corresponds to 1200 hours of operation at 1 mA beam in our 30 % bypass situation. We hope to continue these tests.

Since the fraction of unscattered beam is very hard to monitor, we have adopted a window design in which we count on being able to detect a failure before any severe consequences develop. The idea is to have three windows at different operating conditions (pressure difference, temperature, stress situation) and to monitor the spaces between them. The first window, as can be seen in Fig. 3, is the cusp-shaped operating window cooled by the liquid lead bismuth itself and hence operating at the highest temperature. Underneath this window there will be two dome-shaped safety windows with cooling water flowing between them and with gas circulation between the operating window and the upper safety window. By suitable choice of the gas and water pressure, we can establish different load and stress situations on the three windows. If a pressure change or contamination is detected in either the gas or the water, interruption of the proton beam and closure of two safety valves in the beam line will be triggered.

These problems will be dealt with in substantial detail in the safety analysis report which we have to prepare to apply for permission from our licensing authorities for construction and operation of the source. We hope to obtain this permission by late 1991 or early 1992. It is only then that we can start building the target block and its auxiliary systems.

III SITE CONSTRUCTION AND RELATED WORK

Due to the fact that no containment functions are necessary for the neutron target and neutron guide halls, we were able to start their construction on 8-8-88. Excavations for a waste-water storage tank cavern and the 12 m deep hole of the beam transport tunnel progressed well and during the year of 1989 thousands of tons of concrete were brought to the site to form the plinth and heavy load floor (60 t/m^2) requested for the target block and target hall.

The steel structure of the neutron target and guide halls went up this summer and the halls will have walls and roofs before winter starts.

In parallel with setting up the steel structure, an 80 cm diameter inclined hole lined with concrete pipes was bored from the proton tunnel under the foundations of the existing experiment hall. It ends in a pit which had been opened in the 50 cm thick and heavily reinforced floor by cutting and lifting out a suitably large section of the concrete floor.

Although not strictly part of the SINQ project but carried out as projects of their own, it is important to note that the rebuilding of the thick meson production target and the upgrade of the cyclotron to 1.5 mA proton current are progressing well. This work was started on Jan. 3, 1990. By now, all shielding of the relevant section of the proton beam line has been dismantled. The old beam catcher and the old meson production target had to be removed with extreme precautions due to their high level of radioactivity. The new target station has been assembled and will be put in place soon. The same is true for the new beam catcher, which is ready for installation and which will be mounted as soon as the temporary concrete block house, which was set up for the construction of the inclined drift tunnel in the experimental hall, has been removed. We count on having beam again by the middle of 1991, quite a while before SINQ will be ready to accept it. This will allow the accelerator crew to do their start-up work and beam line tuning without the extra complication of the SINQ beam line section. It is planned to work up to 650 μA rather quickly after the end of the shut down period and then gradually increase the beam current by adding more rf-power to the accelerator in steps over another year or more.

IV ONGOING DEVELOPMENT AND DESIGN WORK

Although we do not anticipate to start procurement of the target station and its auxiliaries before the end of 1991, there are intense planning, design and development activities going on. In the following, only part of this work can be highlighted.

IV.1 Liquid Metal Target Development

Research and development work for the liquid metal target and its containment including the beam entry window is a major topic of research.

In this context it is important to be certain about the degree of retention of polonium and mercury in the lead-bismuth mixture. Literature data are very scarce and not convincingly consistent. For this reason we have started our own experimental investigation where we measure the amount of polonium and mercury coming off the surface of small reactor-irradiated Pb-Bi samples.

- Further experimental work in progress includes fluid dynamics investigations in a scaled-down mockup including ultrasonic velocity measurements and flow visualization by different means /1/
- theoretical thermal-hydraulics studies of the flow distribution and heat transfer problems including a suitable benchmark experiment /2/
- liquid metal corrosion tests of various materials
- measurements of the post-solidification expansion of the lead-bismuth to determine stresses in the target vessel in the event of a target solidification /3/
- flow optimization of the cooling water in the target safety window /3/
- irradiation tests of a safety window at LAMPF /3/
- detailed stress analysis for shape optimization of the target window (operating window plus safety windows) /4/

IV.2 Alternative Target Studies

Although an optimized Pb-Bi liquid metal target would be the best possible solution for SINQ from a neutronics point of view /5/, practical considerations such as the polonium problem on the one hand and materials and beam size restrictions on the other have prompted us to look into alternative solutions using solid target materials. A series of theoretical calculations on the expected neutronic performance showed that, when comparing "realistic" design of the Pb-Bi liquid metal target, to directly D_2O-cooled plate targets of Ta or W and a pebble bed target of lead shot, the unperturbed maximum thermal flux ratios at 25 cm from the centre line are /5/:

Pb-Bi : W : Ta : Pb Shot = 1 : 0.7 : 0.53 : 1.17

The reference value of 1 for the Pb-Bi is not the theoretical optimum but what one could expect to achieve under the existing boundary conditions. The relatively poor performance of Ta and W in our case is due to absorption of thermal as well as epithermal neutrons in these materials.

In view of the relatively good performance expectancy of the Pb-shot target, this alternative is now being studied in more detail /6/. One consequence of a transition to a D_2O-cooled target would be that a much more complicated D_2O-circuit with purification and recombination facilities would have to be provided at probably higher costs than for the H_2O-cooling circuit which does not intercept the beam. Also, the high local activation and after heat density of a stationary target is of some concern especially during the target exchange process. Nevertheless, a successful development of a solid target would be of substantial practical advantage. It will be actively pursued in particular for a day-one option. In this way the concept of the double safety window can be practice-tested without the risk potential of the liquid lead bismuth.

IV.3 Target Block And Moderator Tank

Detailed layout of the relatively complicated moderator tank with its double wall and its T-shaped penetrations for the beam tubes and cold moderators (Fig. 5) is in progress with stress analysis for temperature and mechanical load effects. One consequence of this analysis is that the target will now not be suspended from the moderator tank as originally planned but from the shielding block itself.

The outer part of the target shielding block will be built of existing iron rods, 30 x 30 cm^2 in cross section. Due to the relatively complicated shape of the shielding block many rods will have to be cut to size. A suitable machine has been purchased and a computer code is being developed now to minimize the number of cuts and to optimize the useage of the existing material. Tests are under way to develop a method to fill the gaps between the rods with heavy mortar. Generally the rods will be put down horizontally but as a result of the plane-crash analysis mentioned earlier there will be one "wall" of standing rods for load distribution. The rods will be contained in a 5 cm thick steel liner which will have 30 cm of boron loaded concrete to reduce the dose from the keV neutrons.

For the inner part of the shielding inside the N_2- and He-containments the possibility is under investigation of using slightly activated reprocessed scrap steel from dismantled nuclear installations.

IV.4 Cold D_2-Moderator And Neutron Guides

Design work on the cold D_2-moderator, which will be an important feature of SINQ from the first day on is well advanced /7/. The concept is based on isothermal natural circulation of a liquid-gas mixture from the moderator vessel to the heat exchanger and of liquid in the other direction through concentric tubes. The thermodynamic properties of the system are now quite well understood and calculations pertaining to accident situations such as loss of insulating vacuum have shown that no damage will result from such situations /8/.

Four neutron guides will view the cold moderator. The guides will start at 1.5 m from the moderator surface requiring a target block insert which allows precise alignment on the one hand and minimizes parasitic radiation on the other. A system of two shutters rotating about a horizontal axis perpendicular to the guides will be installed at the outside of the target block behind heavy shielding. When open, the shutters will bridge the gaps between the inner and outer guides by neutron reflecting channels which, again, require precise alignment and a high degree of reproducibility /9/.

For the coating of the neutron guides we hope to use high performance multilayer mirrors. Development work in this direction is in progress /10/.

IV.5 Beam Port Inserts

The standard beam extraction ports in the target block will be twin ports with a separation angle of 10° between the two beam axes (Fig. 5). In view of the long distance from the target to the outside of the shielding block, an attempt was made to incorporate as many of the functions necessary for beam tube operation into the beam port inserts. These include:

- beam shutters
- filters
- exchangeable collimators

A design has been worked out which, as shown in Fig. 7, allows the port inserts to be installed for each extraction channel separately and which subdivides the whole insert into different functional units which can be handled independently. The units are: an inner shielding block, three shutter blocks, a shutter drive base and a user specific filter and collimator insert. The exploded view in Fig. 7 shows, how these parts can be mounted as separate units.

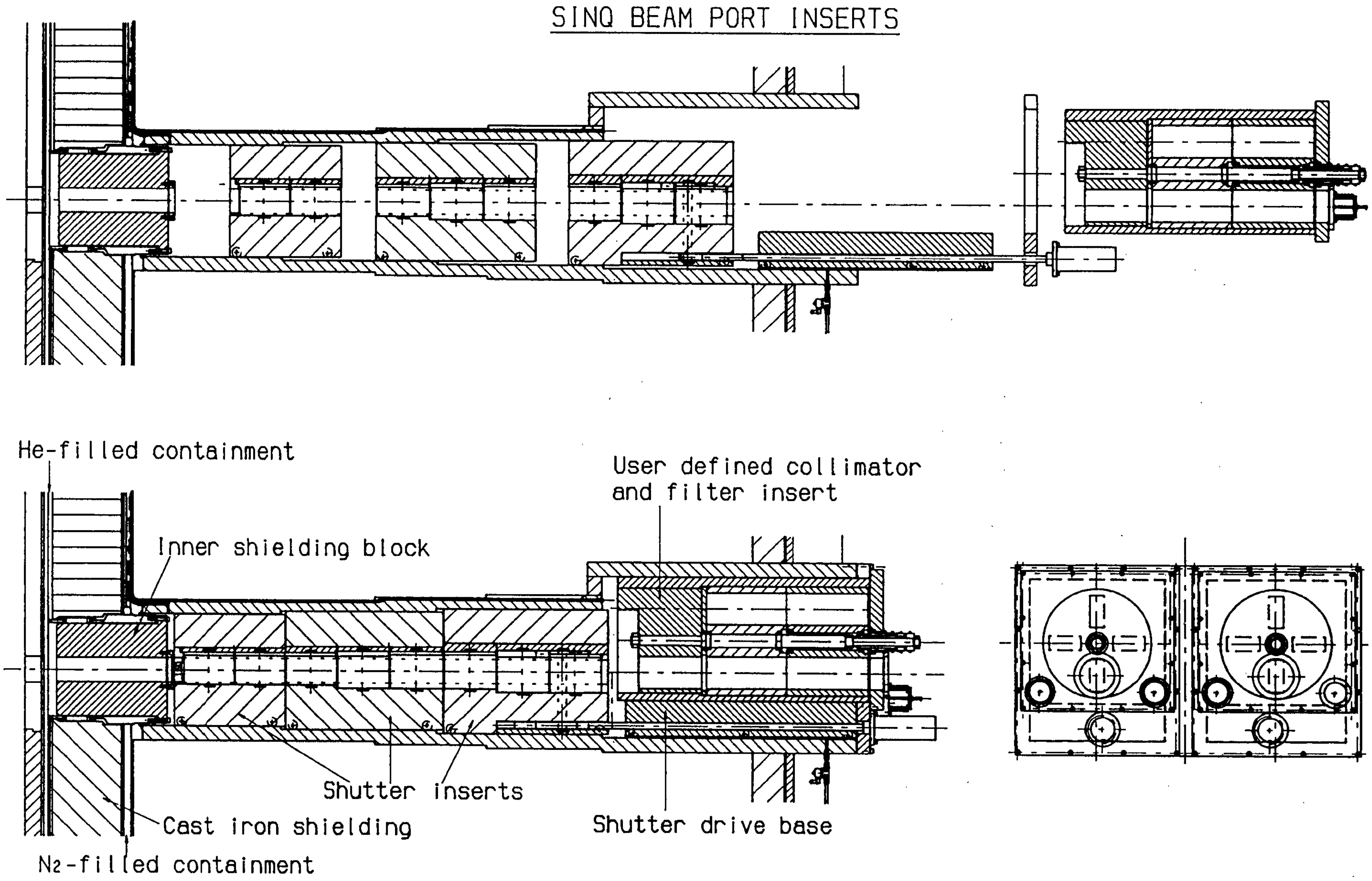

Fig. 7 Vertical section through a SINQ beam port insert. The exploded view at the top shows the units which can be removed separately. A front view of the twin channel is shown at the lower right.

V INSTRUMENT PLANNING

Based on the reference value of 1 mA beam on target and the lead-bismuth target as presently under development, we expect the neutronic performance of SINQ to be as given in Fig. 8. This shows that, in terms of time average thermal and cold neutron flux, SINQ will compare favourably with most of the medium flux reactors, such as the various DIDO-variants, that have been successfully used for neutron scattering work throughout the world during the past 3 decades.

A certain disadvantage may result from the high energy neutrons which are produced in the spallation process. Great care has been taken in the design of the bulk shield to keep them from reaching the surface of the target block. The resulting distance from the thermal flux maximum to the shield surface is 6 m. As mentioned before, part of this distance will be used to house beam shutters as well as interchangeable filter and collimator inserts.

While the shutters will be standard, filters and collimators are instrument specific and will be devised in conjunction with the respective instrument design. Controlling the high energy background contribution from the beam holes will not be an easy task. This is the main reason, why only one pair of beam holes is planned to be equipped for day one operation. The instruments selected are a high resolution powder diffractometer and a four circle diffractometer. They will use a common monochromator shielding block as shown in Fig. 9.

In this block two different concepts for variable incident energy are combined: While the HRPD will have a monochromator that can be moved to different positions to deflect neutrons of different energies to the fixed position of the instrument, the 4-circle diffractometer will be rotated around the monochromator axis as the incident energy is varied. These two concepts have been selected also in view of the need to gain experience working on a continuous spallation neutron source before further instruments are designed.

In terms of cold neutron flux, we expect SINQ to rank among the best in the world. This is due to the optimized flux position of the cold moderator and the care that was taken to minimize rethermalization of the cold neutrons by warm Al-windows or D_2O-layers /11/. It is therefore justified to put most of the emphasis in the instrumentation for day one on the cold neutron side.

The following instruments to be built on the neutron guides have been given first priority:

- Low energy transfer triple axis spectrometer
- Very high resolution time-of-flight spectrometer
- Small angle neutron scattering facility
- Polarized neutrons triple axis spectrometer
- Neutron-optical bench for ultra high precision measurements
- Diffuse-elastic neutron scattering spectrometer

The last two instruments are included on specific user's request and will be mainly under users' responsibility. Table 1 gives a summary of the main characteristics of the instruments planned for SINQ. The floor plan of the facility is shown in Fig. 10.

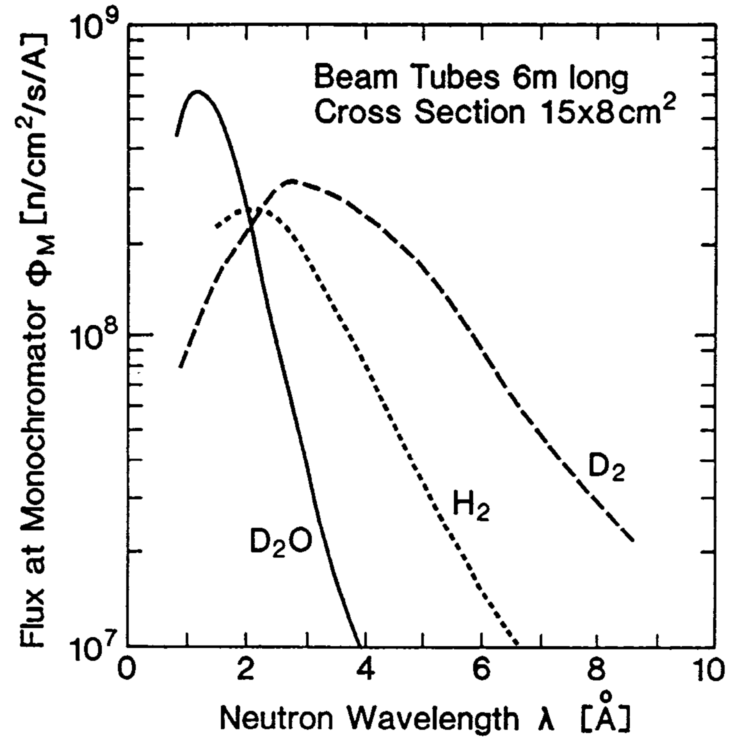

Fig. 8 Expected spectral flux distribution at 6 m from the various SINQ moderators at 1 mA proton current on target. For the D_2 moderator no effect of neutron guides has been taken into account.

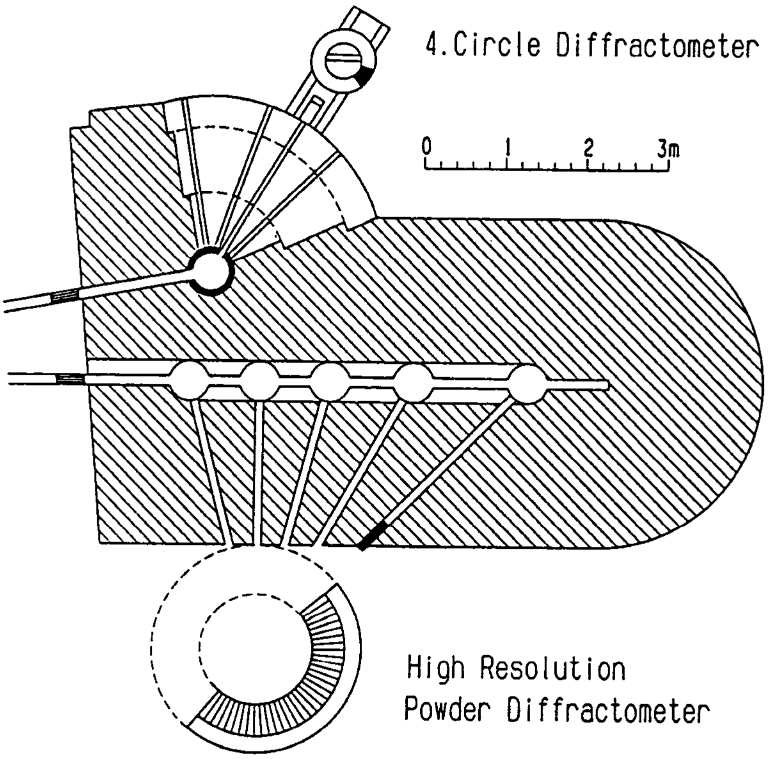

Fig. 9 Example of monochromator shielding for SINQ. Shown is the shielding block as planned for the two day one thermal neutron instruments, the HRPD and a four circle diffractometer.

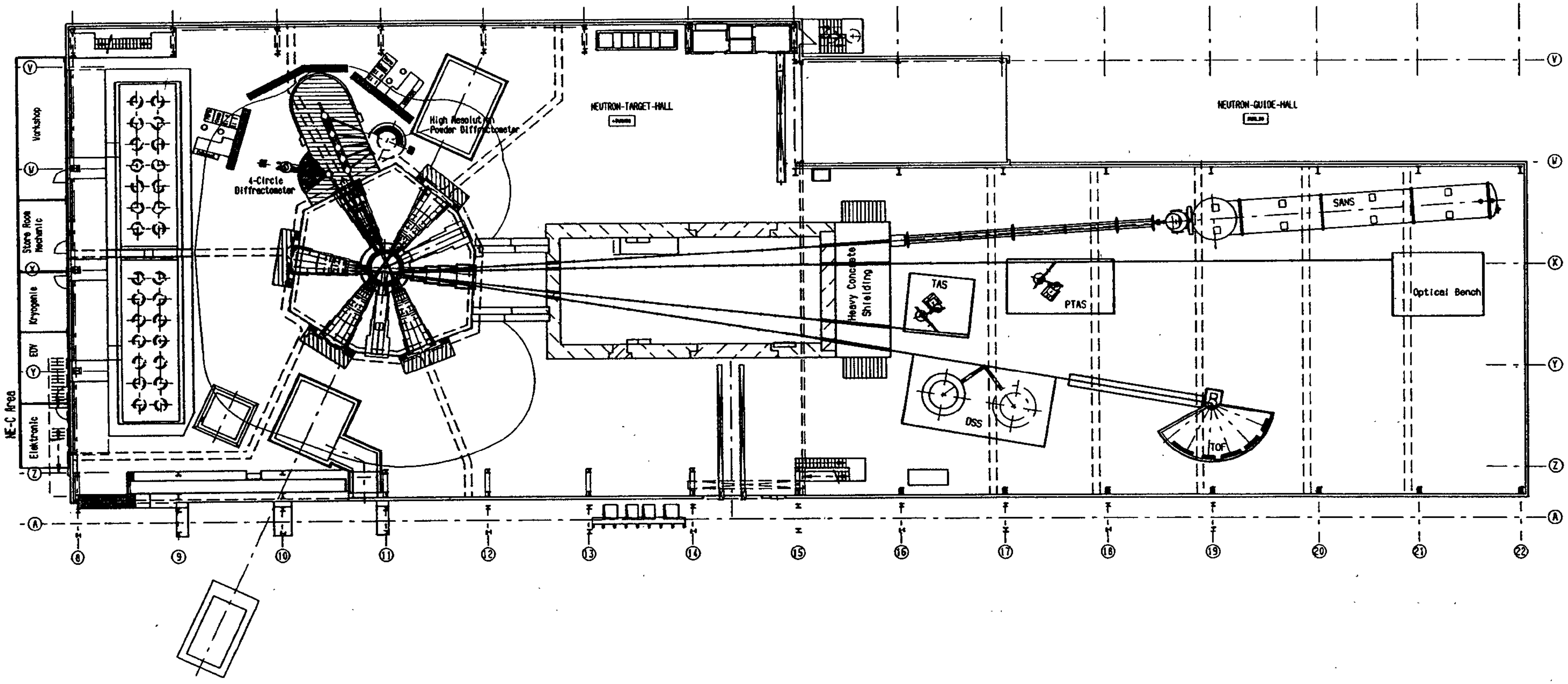

Fig. 10 Floor plan of the SINQ target and neutron guide halls showing instruments planned for early operation.

Instrument	High resolution powder diffractometer	Four circle diffractometer	High resolation triple axis	Polarized neutrons triple axis	High resoluting Time-of-flight spectrometer	Small angle scattering instrument
location	thermal neutron beam port	thermal neutron beam port	cold neutron guide	cold neutron guide	cold neutron guide	cold neutron guide
monochromator	Ge (hkl)	PG (002), Cu (220)	PG (002), Be (002)	Heusler (111) PG (002)	chopper 3-12 Å	mech. velocity selector
2 θ_{mon}	75 - 135 deg	15 - 90 deg	30 - 145 deg	30 - 145 deg	–	–
detectors	64 He-3 or linear scintillation	2 dim, He-3 210 x 185 mm^2	He-3	He-3	He-3 detector array	2 dim, 128 x 128 cells 960 x 960 mm^2
resolution/range	$\Delta d/d = 4 \cdot 10^{-4}$		$\geq 7\ \mu eV$	$\geq 7\ \mu eV$	0.005 ÷ 0.5 meV	$3 \cdot 10^{-3}\ nm^{-1} \leq Q \leq 10\ nm^{-1}$
special features/ remarks	option: position - sensitive detector; vertically focussing monochromator; GdO-mylar sollers in front of detectors	dilution cryostat; closed cycle cryostat;			counter-rotating disc choppers 100 ÷ 400 Hz; detector angular range 10 - 135 °; converging super mirror	polarization (option) specimen changer cryostat; furnarce; electromagnet;

Table 1 First generation instruments planned for SINQ under PSI-responisibility

VI CONCLUSIONS AND SUMMARY

As a continuous high power spallation neutron source, SINQ will be the first of its kind. It is expected to come on line at a time when operational research reactors in Western Europe continue to decrease in number due to the fact that most of them have been build some 30 years ago. It will not only be a test facility for a new source concept but will also help to fill a gap which would otherwise be wide open. There may be a question as to what extent neutrons will be needed in the future to solve specific scientific problems, but there is no question that they will be necessary.

The rate of progress in the construction of the buildings for SINQ since it was started in August 1988 has been impressive, considering the huge amount of concrete work that was necessary. Its future progress will depend on the licensing procedure that lies ahead of us, but we are confident that construction of the "systems" part can start in early 1992. In this case we expect to produce useful neutrons in 1995. Together with the rebuild of the proton beam line and the upgrade of the cyclotron to deliver 1.5 mA this is a major undertaking for the Paul Scherrer Institute and will not only require a substantial effort from our own project team but also active support from outside, in particular from potential future users.

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/3/ M. Dubs and J. Ulrich
"Design considerations of the target window"
This conference

/4/ G. Heidenreich
"Preliminary thermal and stress analysis of the SINQ window"
This conference

/5/ F. Atchison
"The neutronic performance of solid-target alternatives for SINQ"
This conference

/6/ F. Atchison and G. Heidenreich
"A solid target for SINQ based on a Pb-shot pebble-bed"
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"Technical concept of the liquid D_2-cold moderator for SINQ"
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This conference

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This conference

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