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DESIGN CONSIDERATIONS FOR THE SINQ TARGET WINDOW

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ABSTRACT

Since the proton-beam enters the SINQ liquid lead-bismuth target from below, a special window design is needed to attain safe operation for at least one year. The present design consist of a double-walled water cooled entrance-window and a third wall cooled by lead-bismuth. The intermediate volume contains circulating helium in order to detect any leaks in the 2nd or 3rd wall at an early stage. Several investigations have been made in the fields of radiation-damage, thermohydraulics and stress analysis.

I INTRODUCTION

This report presents an overview of the factors being taken into account in the design for the beam-window of the SINQ target.

SINQ will use the part of the proton beam left-over after passing through Target-E, the second of two meson targets here at PSI. The non-interacting part of the proton beam will be collected beyond Target-E, deflected downwards to pass under the experimental area to the centre of the source and finally pitched upwards to strike the SINQ-target from below. The spot on the target has normally a peak density of about 25 $\mu A/cm^2$ at the SINQ design current of 1500 μA.

The target consists of liquid Pb-Bi eutectic in a closed chrome-steel bottle (Fig. 1). Cooling is achieved by natural convection in the Pb-Bi transporting the heat from the neutron-production region at the bottom of the target to a heat-exchanger at the top.

The beam-window not only has to allow the protons to pass from the beam-line vacuum to the Pb-Bi but also completes the containment and supports the pressure of the liquid.

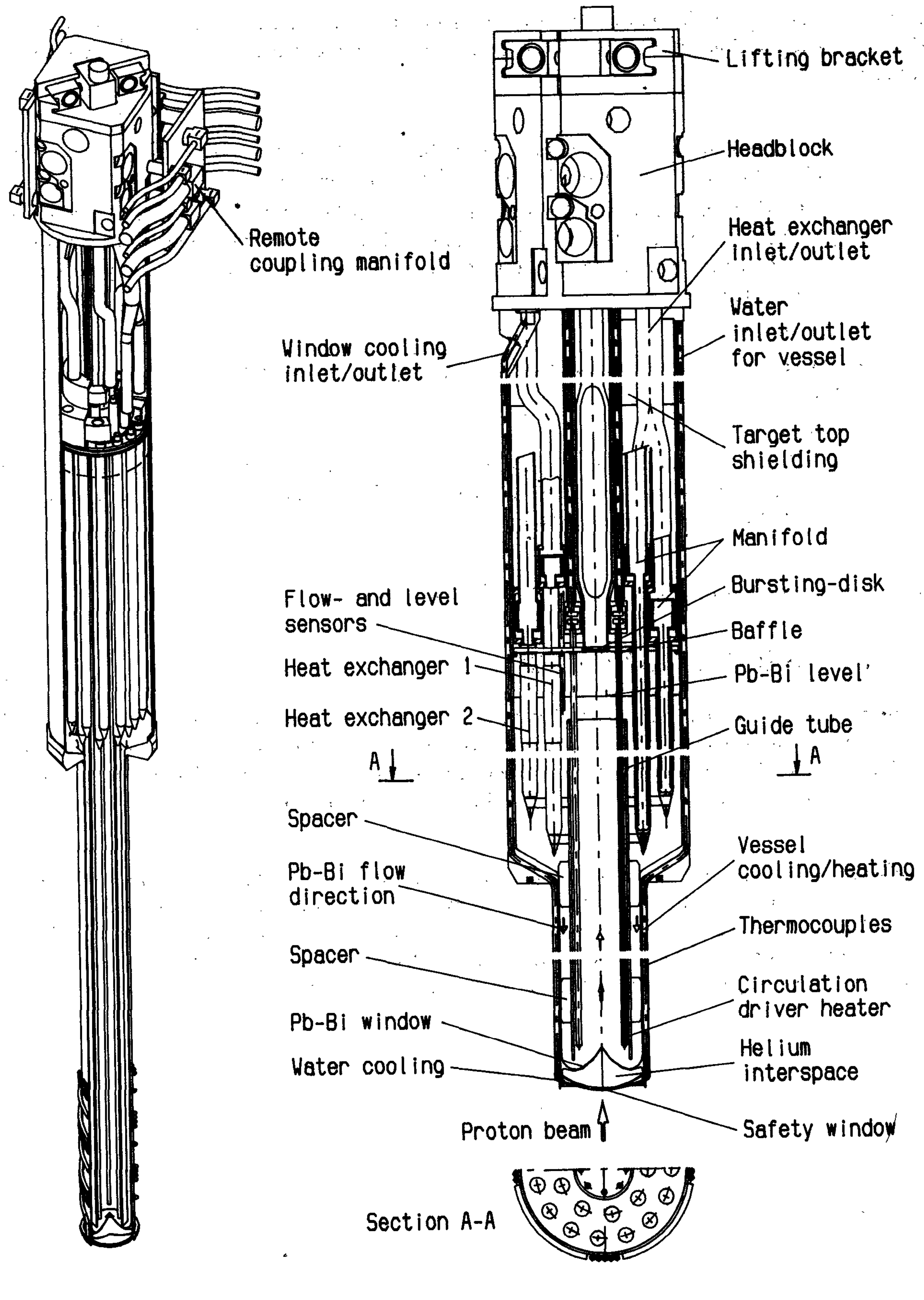


Fig. 1 Layout of the SINQ target.

The target window material will be subjected to high loading and has, as design goal, a guaranteed safe operational life-time of at least 1 mA · year. The following considerations have to be taken into account:

- The main loading comes from the stress induced by the heating caused by the proton beam. This will depend directly on the current density in the beam spot.
- Parts of the proton beam that miss Target-E will be better focused producing a higher peak to average current density. The window should be able to operate normally with up to 30 % of the beam by-passing Target-E and withstand a beam that totally misses it for a short time.
- Pressure loadings.
- Material property and geometry changes ("swelling") from radiation damage and temperature.
- Corrosion.
- Cyclic stresses from beam interruptions (at present these average at about 4 per hour and it is not unlikely that this rate will increase at least temporarily when the accelerator is operated at higher current levels).

The design study requires a combination of experiment, calculation and testing.

II TECHNICAL CONCEPT

The present window design has envolved from of an earlier water-cooled two-element concept. The high current density from the beam by-passing Target-E meant that the windows could only be cooled by using unacceptably high water pressures leading to straightforward mechanical problems and also to concern over safety: only a single mechanical barrier preventing leakage of water into the hot liquid Pb-Bi.

The overall window assembly is now in two parts (Fig. 2) and gives three material barriers between the proton-beam vacuum and the Pb-Bi: the first (safety window) consists of a water-cooled "sandwich" of two elements and the second, a single element in contact with and cooled by the Pb-Bi. The interspace contains a flowing helium atmosphere (for detection of leaks in the window assembly) at a pressure somewhat higher than that of the Pb-Bi on the inner window.

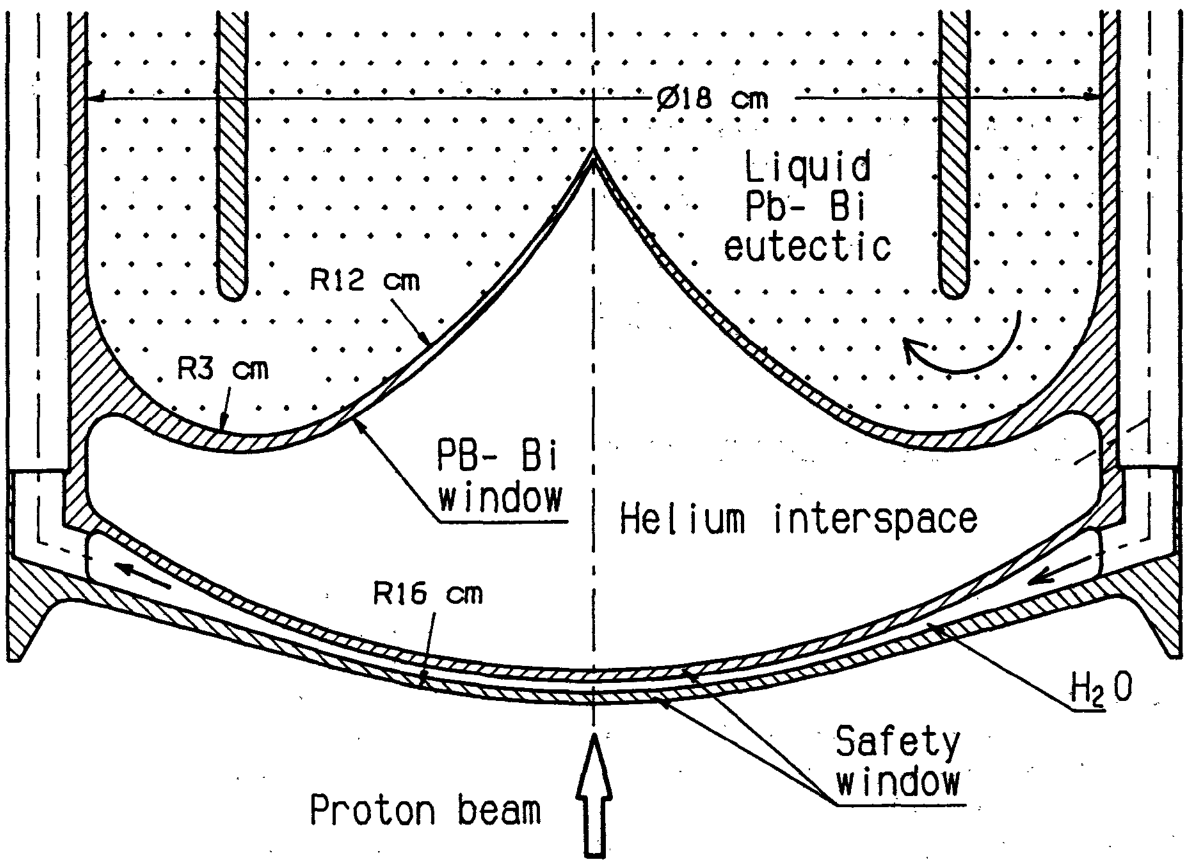


Fig. 2 SINQ-target window assembly.

Technical data and parameters for the window are given in Table 1.

The shape of the Pb-Bi window is determined by thermohydraulic considerations to give:

- good heat-transfer in the central (beam-heated) region of the window
- low pressure loss in diverting the flow of the Pb-Bi upwards into the guide-tube.

The selection of the window element thicknesses and thickness-profile depends on:

- the maximum stress (because of the three-dimensional loading, this is based on the von Mises stress) compared with the yield stress under the various operating conditions, bearing in mind all temperature gradients.
- Pressure differentials.

The safety window is cooled by a transverse flow which enters through a series of holes at the rim.

A uniform flow distribution across the full diameter of the window is achieved by suitably shaped guides (see section III.2).

The present material choice for the window complex is type X 20 CrMoV 12 1 chrome steel (similar to type HT9): this has good mechanical properties at high temperatures and is compatible with hot liquid Pb-Bi under radiation conditions. In the event that future studies show problems with this steel, an alternative is Inconel for the safety window and possibly a ceramic material for the Pb-Bi window.

Table 1

Technical data for the SINQ target window

Proton Beam Energy	570 MeV
Design Current	1500 μA
Diameter	18 cm
Thickness at Centre	0.1 - 0.2 cm
Power Deposition in Steel per cm of Window Material	30 kW
Maximum Power Density (30 % of beam by-passing Target-E)	ca. 1900 W/cm^3
Static Pressure on Pb-Bi Window	
(including 0 to 0.9 bar pressure above Pb-Bi surface)	3.3 - 4.2 bar
Helium Pressure in Interspace	4.5 bar
Water Pressure for Safety Window	10 bar

III EXPERIMENTAL TESTS

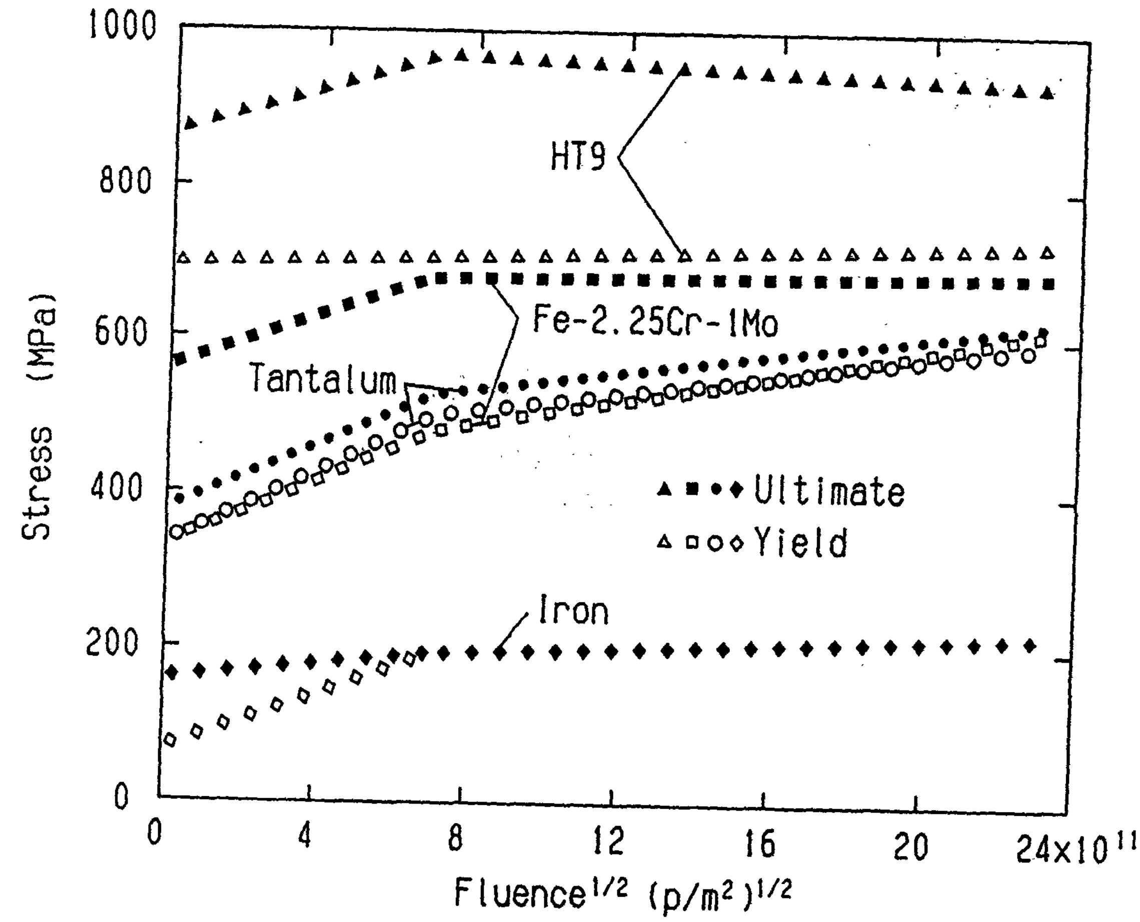
As part of the overall design study, a series of experimental tests looking at various aspects of the window, have been undertaken. These are described in the following sub-sections.

III.1 RADIATION DAMAGE

The life limit for the window will most likely be determined by radiation damage. Two experiments have been mounted at the LAMPF (Los-Alamos) radiation effects facility.

In the first, the mechanical properties of various sample materials (iron, tantalum, Fe-2.25Cr-1Mo and Fe-12Cr-1Mo) irradiated in contact with Pb-Bi were measured [1]. The materials were irradiated with 800 MeV protons to a fluence of about 5.4 x 10^{24}/m^2 which corresponds to about 1.6 dpa in steel. The HT9 (Fe-12Cr-1Mo) gave the best results (Fig. 3)

The second test is a long-term irradiation of a prototype water-cooled window (Fig. 4). Two windows have been constructed from 10.5 % Chrome-steel (X 20 CrMoV 12 1 was not obtainable within the time schedule for the experiment) and mounted at the LAMPF proton-beamline. Technical data for these windows is given in Table-II. So far the windows have been irradiated for two beam-periods (about 2000 mA hours beam current) and have received damage corresponding to about 7 dpa. The higher current densities to be handled by the SINQ-target due to the 30 % beam by-passing Target-E are estimated to correspond to a yearly damage accumulation of 40 dpa. It is hoped that the experiment can be run for some more beam-periods.



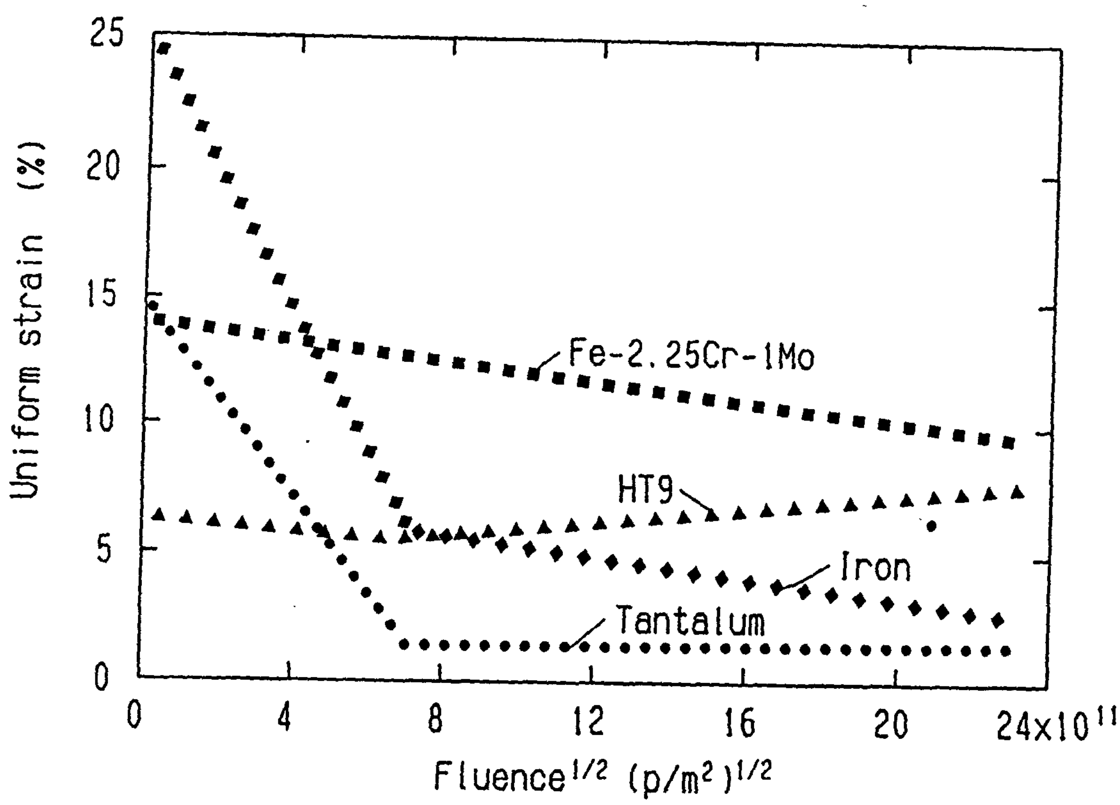


Fig. 3 Effect of irradiation with 800 MeV protons at a temperature of 400 °C for different materials.
Top: yield stress and ultimate tensile strength, bottom: uniform strain. Both are plotted as a function of the square-root of proton fluence.

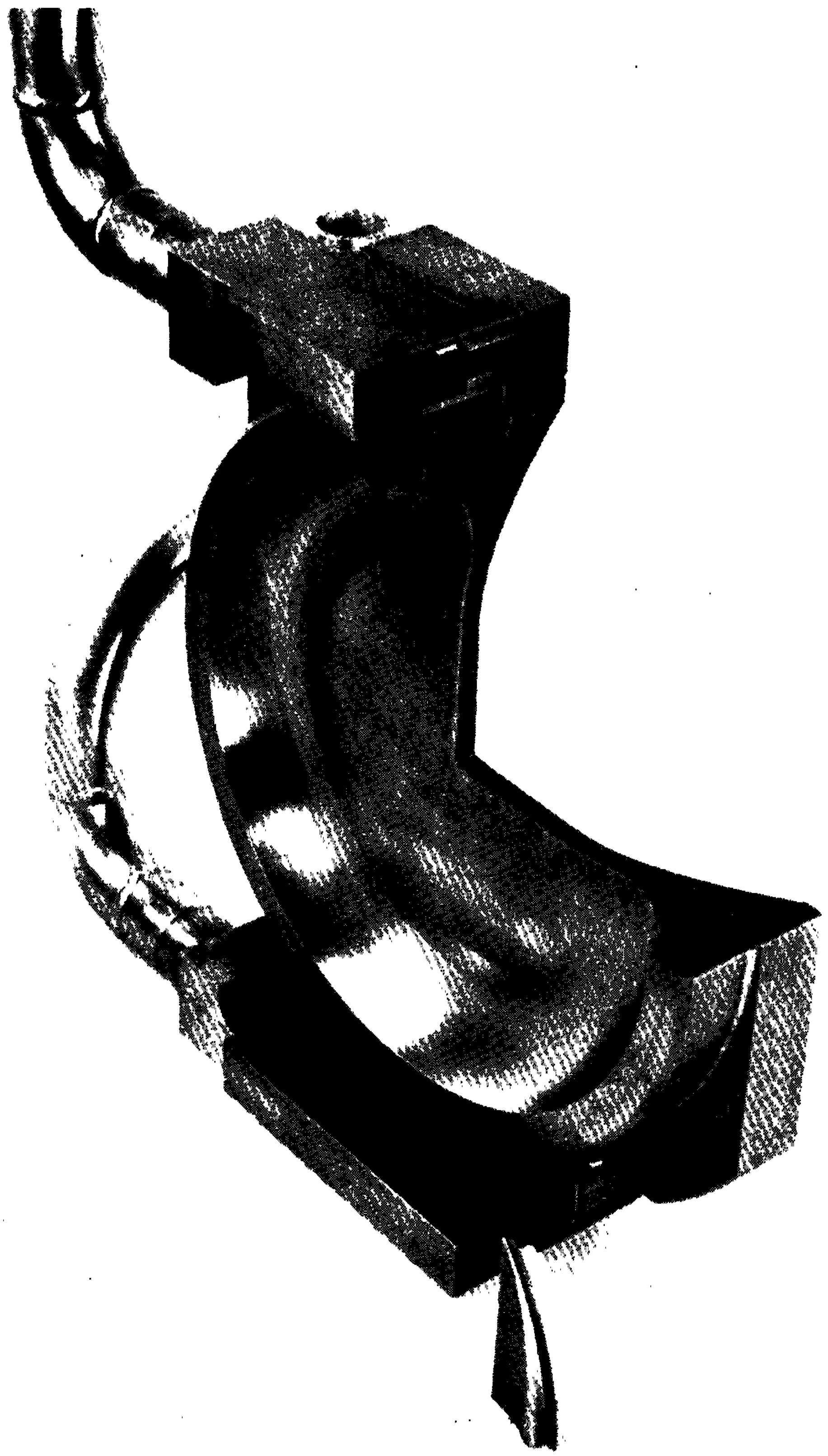


Fig. 4 Photograph of a cut-away model of the lifetime-test window mounted at LAMPF radiation effects facility. The small item standing beside the window is part of the wedge-shaped flow guide.

The fabrication of these windows has brought much valuable experience in machining and welding techniques: in particular, the importance of correct heat treatment before and after electron-beam welding (Fig. 5).

Table 2

Technical data for the Los-Alamos test windows

Proton Beam Energy	750 MeV
Average Current	700 μA
Window Diameter	18 cm
Window Material Thickness	2 x 0.2 cm
Water Channel Width	0.2 cm
Maximum Proton Beam Current Density	40 $\mu A/cm^2$
Maximum Power Density	650 W/cm^3
Water Temperature at Entrance	40 °C
Maximum Measured Window Temperature	182 °C

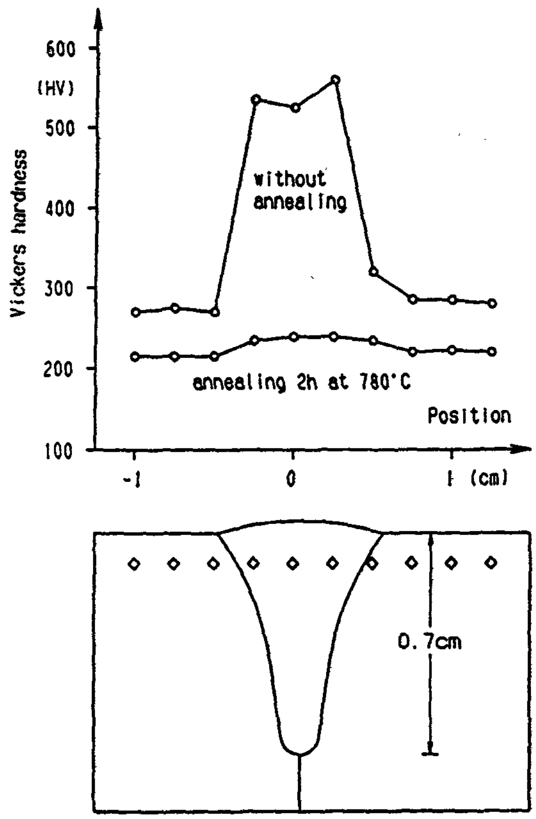


Fig. 5 Results from a test of the Vickers-hardness of a sample weld for the LAMPF irradiation-test window (Electron-beam welding at 350 °C of 10.5 % chrome-steel).
Upper: Hardness-profile of weld before and after annealing.
Lower: Profile of welding seam showing the measurement positions.

III.2 WATER FLOW IN THE SAFETY WINDOW

The window is to be constructed from a pair of dome-shaped caps and the water flow is to be across the gap from an entrance to an exit manifold. The major part of the window heating is in a small region at the centre: the water flow must be adjusted to obtain proper cooling over the whole surface with particular emphasis on the central region.

A plexiglass model of the window has been built and the flow patterns examined by injecting air bubbles. A good flow distribution was obtained by mounting wedge shaped guide-pieces at the edges of the window (Fig. 6).

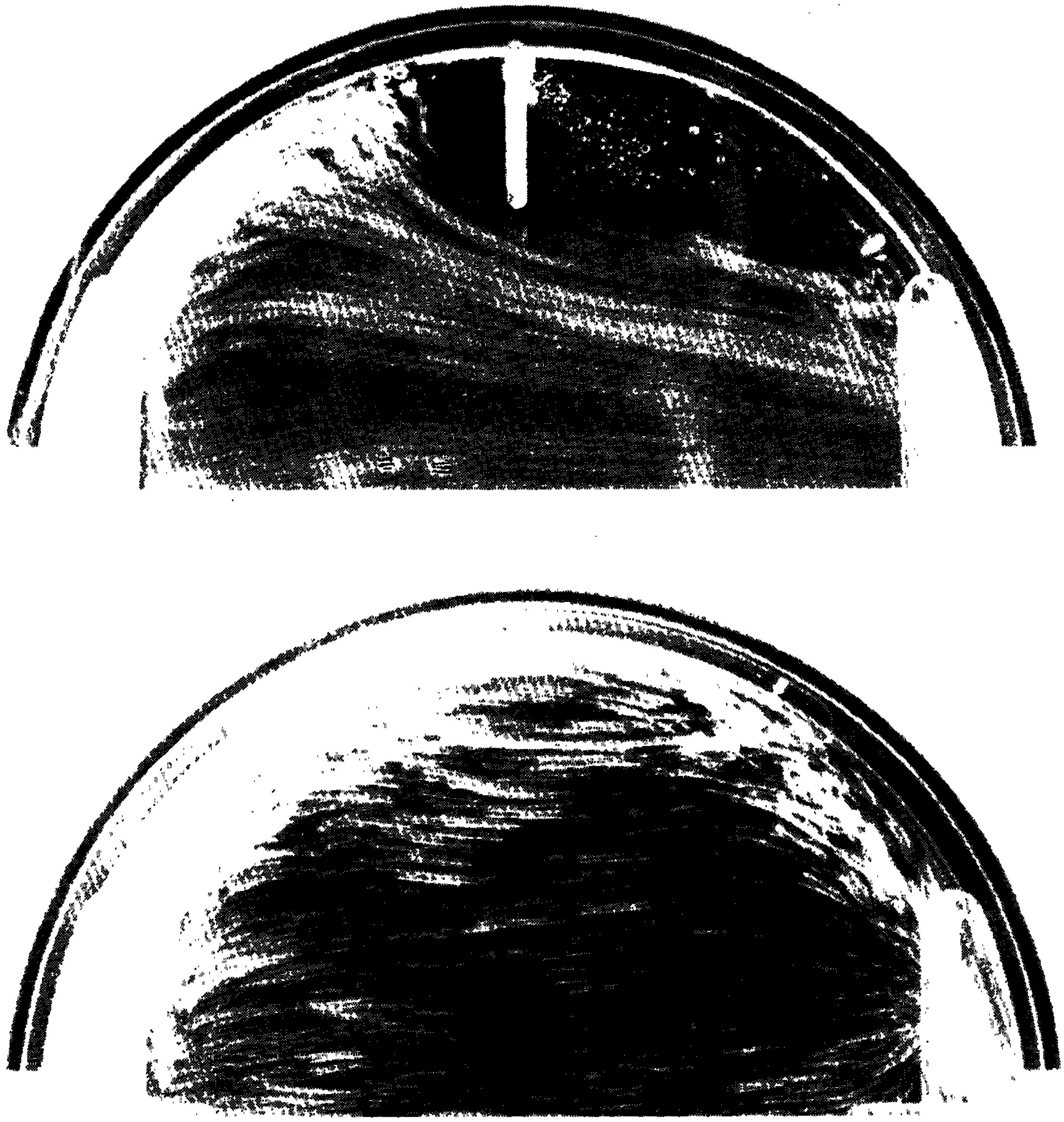


Fig. 6 Photograph of the flow in the Plexi-glass model window. The upper picture shows the effect of a simple baffle and the lower, of the wedge shaped flow-guide (see Figure 4).

III.3 EXPERIMENTS WITH Pb-Bi

A set of experiments have been made or are in progress to investigate various aspects of Pb-Bi relevant to the window design.

The temperature distribution (and hence stresses) in the inner window will depend on the flow of Pb-Bi in the neighbourhood of the window. This is complicated and has been studied by Y. Takeda [2], using a water-model. Flow conditions for various velocities and guide-tube positions have been examined.

Pb-Bi is known to corrode several materials (aluminium, nickel containing steel etc.). Samples of possible compatible steels have been mounted in an electrically heated, water cooled Pb-Bi test circuit. So far, this experiment has only run for six months and no probes have been extracted yet.

A second similar Pb-Bi test circuit is being built. There are two main aims:

- direct measurement of the heat transfer coefficient by Pb-Bi from steel
- measurements of the characteristics of a naturally circulating liquid-metal circuit [2].

A Pb-Bi eutectic mixture has the undesirable property of a delayed swelling after freezing.

A simple test to measure the size of the effect has been made: a 6.55 cm O.D. cylinder constructed from 0.175 cm thick chrome-steel was filled with molten Pb-Bi and then allowed to solidify. The diameter increased by a maximum of 0.35 % over a period of about 6 months: no measurable change of diameter occurred at later times. The consequence of this is that the Pb-Bi should be kept molten as long as the target is to be operated.

IV CALCULATIONS

The basic information required for both thermohydraulic and stress analysis is the heating rate. The major part comes from the proton beam and there is a small contribution from backscattered particles from the target. The current distribution at the beam-window for both the "normal" and the "by-pass" components of the beam comes from beam-transport calculations.

As experiments using surface-muons are to be mounted at Target-E (these require a high proton flux at the surface of Target-E), the rather high value of 30 % of the proton beam by-passing Target-E has been taken as a reference value for calculations (Fig. 7).

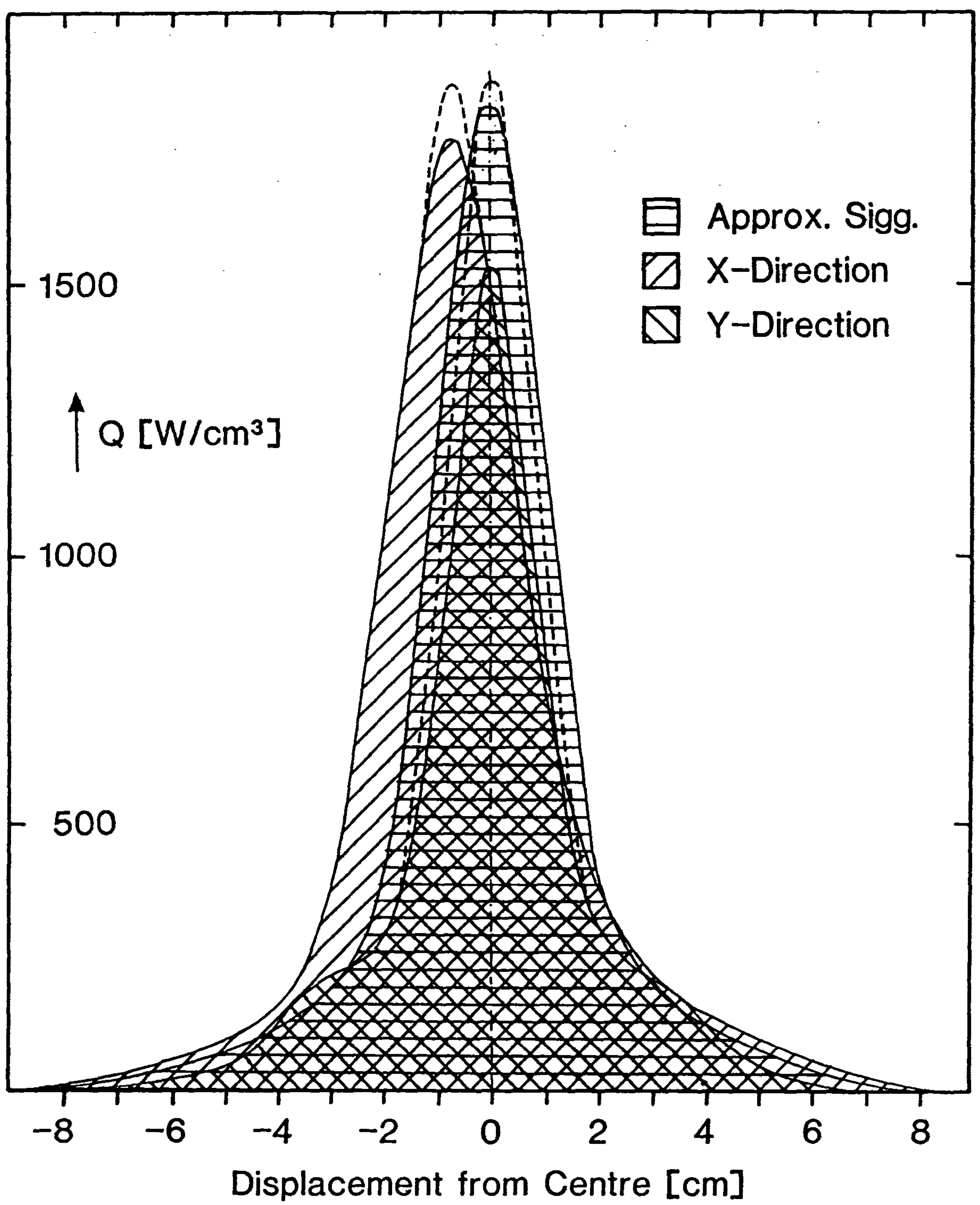


Fig. 7 Calculated profiles of power density in steel of SINQ-target window, for condition where 30 % beam by-passes Target-E, in the X- (bending plane) and Y-planes. Solid lines show the profiles on the target axes and dashed lines, through the peak of the beam. Also shown is the symmetric approximation as used by Sigg et al. [3] and Heidenreich [4].

The latest thermohydraulic calculations are presented in the report of B. Sigg et al. [3] and results of a thermal and mechanical analysis of the current window design given in the report of G. Heidenreich [4].

Both sets of calculations mainly discuss the steady state condition and also assume a radially symmetric beam exactly on the centre of the beam window. The next calculations will look at transient conditions: these will come from beam interruptions and also from the current-ramp at beam switch-on (Fig. 8).

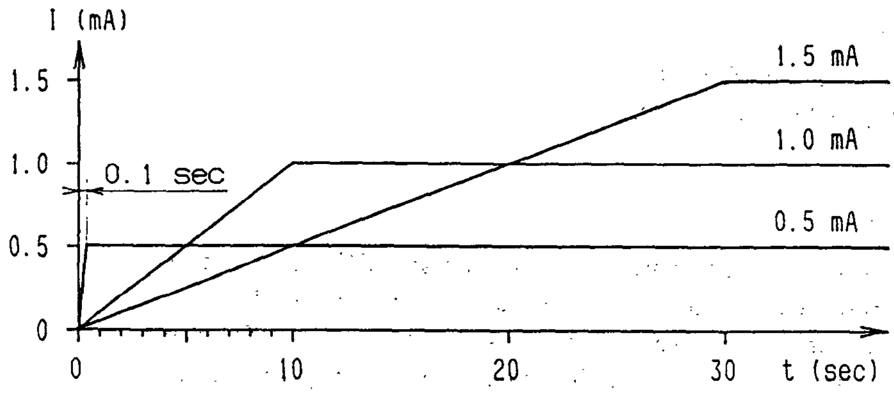


Fig. 8 Proposed accelerator start-up current ramps to different proton-beam current levels.

Future studies will need to include the effect of asymmetric loading. These will require the use of very elaborate modelling calculations and can only be justified when the design of the window is more firmly established.

REFERENCES

[1] Brown, R.D., Wechsler, M.S., and Tschalär, C., 1988, 13th Int. Symp. on "Effects of Radiation on Matter", June 23/25, Seattle.

[2] Y. Takeda, W.E. Fischer, "Thermofluid Dynamics of the Liquid Metal Target of SINQ", ICANS-XI, Japan 1990.

[3] B. Sigg et al., "Thermal-hydraulics Investigation for the Liquid Lead-Bismuth Target of the SINQ Spallation Source", ICANS-Xi, Japan 1990.

[4] G. Heidenreich, "Preliminary Thermal and Stress Analysis of the SINQ Window", ICANS-XI, Japan 1990.