Materials Problems in Beam Windows
and Structural Components of the SNQ-Target

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1. Introduction

The materials performance of structural components must provide a reliable and economic operation of the SNQ target station. This means, that also critical parts should last for reasonably long times like two years, or have to be replaceable during shut-down periods easily. The load for these parts is strongly influenced by these LINAC reference data:

- E_p = 1.100 MeV
- $\bar{I}_p$ = 5 mA; $\hat{I}_p$ = 100 mA
- ν_p = 100 Hz
- FWHM = 4 cm

Apart from the lifetime question, there is another requirement: a change from the Pb- to a U-target with the connected higher thermal load has to be allowable. This implies a strength reserve of the material for higher temperatures as quoted for the reference design.

The information given in this paper is based on available irradiation, temperature-dependent strength and corrosion data. Results coming from the Fusion Reactor Materials R+D are of special importance. The considerations are valid for the present layout of a rotating target, being an essential part of the German high power spallation neutron source project (17, 18).

2. Thermal Load and Radiation Damage of Structural Material

The mean LINAC beam power of 5.5 MW will cause a high power density in parts hit by the proton beam. This is the case for the beam window, the cladding of the target rods and for the target material itself. Typical values of the mean power density

range from 2.7 $\frac{kW}{cm^3}$ for Mg up to 10.1 $\frac{kW}{cm^3}$ for Mo. Due to the heat deposition distribution, the highest temperatures are expected within the beam window on the centerline of the beam.

Further, these components suffer thermal fatigue out of different reasons, as treated in chapter 3 in more detail.

In addition to that, radiation damage is created by the high energetic protons, the produced neutrons and by secondary particles like spallation fragments. This leads e.g. to the following macroscopic effects, given in the order of decreasing importance:

- embrittlement, due to internal production of light gases or due to the shift of the ductile-brittle-transition temperature into the operations temperature range.
- swelling, due to voids or solid transmutation products.
- radiation enhanced diffusion, by which the release of undesirable spallation products is facilitated.
- sputtering, which could be a problem for thin foils (cf. 3.122)
- corrosion, e.g. by the radiolysis of the coolant and followed by an attack on the piping system.

The synergetic effects are of special importance and should be investigated carefully. So, fatigue under irradiation will have a strong influence on the lifetime, and the decrease of the thermal conductivity (irradiation leads to decohesion of the grain boundaries) should be taken into consideration.

The operations conditions are much less severe for material outside of the proton beam. They are similar to fission reactor conditions (Table 1). Therefore, mainly an analysis of the worst case is necessary. As an example, one can consider the beam window.

3. Problems of Beam Windows

One can define two different versions of a beam window:

a) A stationary window, separating the whole target station from the accelerator tube. It is necessary for the (back-up) liquid metal target design. Because of some advantages (avoidance of water leakage into the accelerator tube, further activity barrier), it is a desirable component for the rotating target, too.

b) The target wheel circumference is called the rotating window. It is an essential part of the target wheel (17).

3.1 Stationary Window

3.11 Operations Conditions

Operations conditions like the following are expected:

- pressure differential over the window of about 3 bar,
- high temperature, dependent on the choice of material, thickness and cooling mode,
- high cycle thermal fatigue, caused by the accelerator time structure.

The latter two points are illustrated in Fig. 1. For Mo, one has a mean temperature of about $800^{\circ}C$ with a ΔT of about $50^{\circ}C$ and a repetition frequency of 100 Hz.

- high damage rate, mainly determined by the protons,
- high gas production rate, for which also the protons are decisive.

One can calculate by Monte Carlo Methods (NMTC, HETC) (1) values for some metals (Table 2). The range for displacement damage spreads from 0.05 up to 3.10 dpa/day. The He-production rate lies between 15 and 125 appm/day, and the H-production rates show about seven times higher numbers. The main problems, based on these data, are considered to be strength at high temperatures, high temperature embrittlement as a result of the huge He-quantity, and fatigue under irradiation. There is a fairly limited choice of materials, which are able to withstand these conditions.

3.12 Possible Candidate Materials

3.121 Refractory Metals (RM)

The RM show good mechanical strength, also at higher temperatures. For this class of materials, there is a favourable combination of thermal expansion, Young's modulus and thermal conductivity, which keeps thermal stresses small. The high T_m will facilitate the cooling. From the high solubility of H in RM and the high H-diffusivity at higher temperatures one can

conclude, that the H-production should not be a problem here.

Looking at the irradiation properties, nearly only n-irradiation results are available. They indicate a very high resistance against void swelling, and a lot of adjustable parameters is known, too. For example, V-20 Ti shows no void swelling at all after 38 dpa at $650^{\circ}C$ (2).

The RM of goup VI (like Mo) show a strong shift of the ductile-brittle-transition temperature (DBTT) under irradiation. For a n-irradiation of Mo at 425-$1000^{\circ}C$ and 11 dpa, a DBTT up to $700^{\circ}C$ was found (3). As a further disadvantage, the effects of high He-concentrations are generally not known; due to the low thermal He-release, also for temperatures approaching T_m, severe detoriations are likely. By an appropriate choice of T/T_m, which can be kept small, unfavourable, thermally activated processes can perhaps be avoided.

3.122 Metallic Glasses (MG)

This new kind of materials offers several advantages, like very good strength/fatigue properties (4) and an excellent corrosion resistance, at least for Cr-containing MG (5).

As an unique feature due to the amorphous structure, a damage of dpa-type is not produced. Further, MG containing some crystalline phase may be reconverted to the glassy state under irradiation. This has been demonstrated e.g. for $Nb_{40}Ni_{60}$ (6).

Also the behaviour of He in MG might be different from crystalline metals. This is indicated by microhardness measurements (Fig. 2) (7), as well as by microstructure investigations (TEM) (8) of He-implanted samples. Further research within this field is under way in our institute.

Of course, there remain a lot of technological problems. The MG-production by methods like splat-cooling or roller-squeezing is connected with geometrical restrictions in diameter ($\sim$3 cm) respectively in width ($\lesssim$ 16 cm) and in thickness, which is about 50 μm typically. In principle, these limitations can be avoided by using the (very ambitious and expensive) high-rate sputtering method. To get bulky material, an explosive compaction technique has been shown to work for special MG (9). For the difficult task of welding and joining, only very few techniques like explosive or ultrasonic welding seem to be applicable at all.

Because of the metastable state of the MG, the operations temperature has to be kept below the glass temperature T_g. MG with a T_g up to 900°C have already be found. A further increase of T_g by an appropriate choice of constituents for RM-based MG seems to be possible, although difficult, because these components do not belong to the easy glass formers. Nevertheless, a potential for R+D can be seen.

3.2 Rotating Window

Here are relaxed operations conditions:

- pressure differential of ~ 3 bar will exist,
- low mean temperature (~ 50°C) because of rotation and efficient cooling (16),
- low cycle thermal fatigue due to the wheel rotation frequency of 0.5 Hz and a ΔT of 15°C. These values hold for a Al-window, 5 mm thick,
- radiation damage reduced by a factor of at least about 200, given by the ratio of beam width versus wheel circumference.

For aluminium, this gives about 3.4 dpa/year, a He-production of 130 appm/year including (n,α) and T-decay, a H-production 302 appm/year including (n,p) and a Si-production of about 0.15%/year (1 year = 6.000 operation hours).

Problems remaining here are the still fairly high thermal stresses and particularly the fatigue under irradiation. For the case of Al under p-irradiation and operations conditions similar to those quoted above, an effect on the microstructure (bubble-like inclusions at the grain boundaries) has been detected after ~0.1 dpa, giving ~10 appm He (10). A more detailed study of this synergetic effect is under way at the KFA.

3.21 Candidate Materials

First choice in this case is Al. It shows good thermomechanic properties, a favourable behaviour with regard to neutronics and induced activity and offers a manageable technology.

3.221 Al-Mg-Si Alloys

In order to keep relative changes in the Si-content small, it is proposed to use a Si-containing alloy from the very beginning. The material has an adequate strength for temperatures below ~ 150°C. Joining and welding can be practised by standard methods.

Being a reactor material, the n-irradiation response is fairly well known. Especially the alloys from the US-6000 Al series are very irradiation resistive; after 260 dpa at 328 K, a swelling of less than 1% was found (11). The ductility still remains acceptable (5-10%). Nearly no data are available for the fatigue under irradiation, so experiments are necessary.

3.222 SAP

The sintered aluminium product (SAP), consisting of an Al-matrix with Al_2O_3 as a second phase, presents good mechanical properties (strength, fatigue) also at higher temperatures (> 150°C), where conventional Al-alloys fail. These temperatures could occur, if one goes on from Pb to U as a target material.

On the other hand, the material is fairly brittle, and joining as well as welding is not well developped. But there seem some possibilities for materials preparation such, that a weldable border (Al) surrounds the rest of the component. This is under investigation in more detail.

A major advantage of SAP is the ability of allowing high amounts of light interstitial gases without drastic degradiation. This has been demonstrated for He/H-contents of up to 1700 appm each (12). The other radiation damage data are comparable with those of Al-alloys. Again, data for fatigue under irradiation are still missing.

4. Further Materials Problems

4.1 Cladding of the Target Rods

Apart from the lower heat production (wall thickness ~0.5 mm), the materials problems are equal to those of the rotating beam window. Therefore, Al is again the recommended material. A special point is the Hg-production by spallation events within the Pb-target. It is estimated to be 13o appm/year (13). Irradiation is known to enhance the thermal diffusion process, which is fortunately slow for Hg in Pb at the expected temperature. Hg, once in contact with the Al cladding, will destroy the oxide layer and possibly cause corrosion or liquid metal embrittlement. A detailed investigation remains to be done.

4.2 Sealings and Bearings of the Target Wheel (18)

Out of engineering considerations, special sinter materials (Triballoy) for the bearings and a combination of carbides together with cold-pressed carbon for the slide ring sealing of the target wheel are proposed. A special requirement is a low swelling of the bearings material in order to maintain the very narrow water flow gaps (~ 40 µm). Because data on the behaviour under irradiation are very scare for the cited materials, the feasibility of this and other properties should be investigated by a n-irradiation experiment; a calculation of the expected neutron fluxes is under way.

4.3 Radiolysis of Cooling Water

The proton beam, penetrating the cooling water, will lead to the formation of e.g. H_2 gas and H_2O_2. This causes corrosion of the surrounding structural material. For Al, the problem should be manageable by a purification and pH-control of the cooling water. These and other remedies are known from high energy accelerator experience (14).

5. Summary

For the most part of the structural material, the operations conditions are similar to nuclear reactor conditions. Nevertheless, there are some distinct weak points:

A stationary beam window, which is the worst case of a SNQ component, shows some analogies with the first wall of a fusion reactor. Promising materials are refractory metals and metallic glasses. The expected lifetime - at least for the metals - will not exceed several days.

For a rotating beam window, suitable materials are Al-Mg-Si alloys and SAP. A lifetime of more than two years seems to be feasable.

If not defeated by the Hg-corrosion, this holds for a target rod cladding, too, when Al-Mg-Si alloys are used.

For the bearing of the wheel, which requires a low swelling material, special sinter materials are envisaged. As in the case of the sealings (material: ceramics), a lifetime estimate cannot be given yet.

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Parameter	Fast Breeder	Fusion Reactor	SNQ
Number of thermal cycles [1/sec]	$3 \cdot 10^{-7}$	0.3 - 30 (inertially conf.)	0.5 rot. window 100 stat. window
Temperature [°C]	300 - 600	300-500 (steel) 500-1000 (refract.)	<100 structure rot. target >350 structure liquid metal target 800 stat. window
Average displacement damage [dpa/day]	0.1 - 0.2	0.02 - 0.1	<0.1 structure 0.05-3.1 stat. window
He-production [appm/day]	0.03	0.1 - 1.7	15-125 stat. window

Table 1: Comparison of important parameters for different nuclear facilities (15)

Material	Average displacement damage [dpa/day]	He-Production [appm/day]	H-production [appm/day]
Be	0.05	15	low
Al	0.15	45	190
316 SS	0.65	70	540
Cu	1.00	85	550
Mo	2.25	125	860
W	3.10	125	1100

Table 2: Expected values for radiation damage of a stationary window

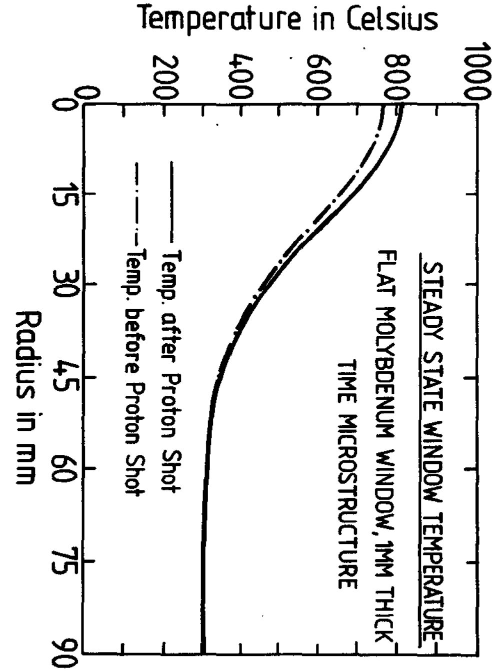

Fig. 1 Thermal operations conditions for a stationary, circular window. The proton shot has a length of 0.5 msec and a repetiton frequency of 100 Hz (16).

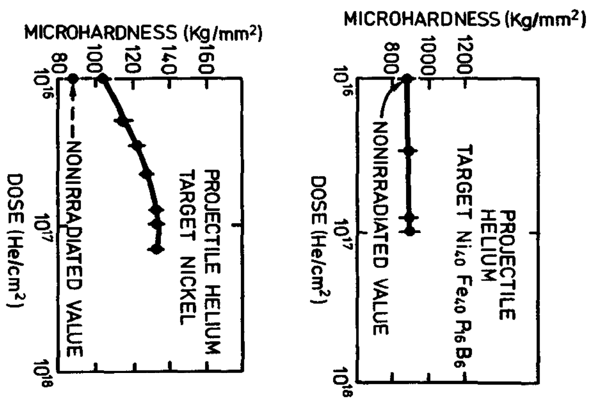

Fig. 2 Effect of He-implantation into a metallic glass and a metal (7).