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Vertical, Convective Spallation Target at SIN

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Abstract

A new version of a spallation target for the SIN neutron source is presented. It consists of a vertical container filled with a eutectic mixture of Pb and Bi (LBE). The proton beam enters from the bottom through a window. The heat of 1 MW deposited by the beam is carried to a heat exchanger inside the LBE target by natural convection. Calculations for start-up and stationary flow of the LBE show stable thermodynamic behaviour with maximal temperatures well below 500° C. Problems of window materials and operational aspects are also discussed.

VERTICAL, CONVECTIVE SPALLATION TARGET AT SIN

1. Layout

The latest layout version for the spallation neutron source at SIN as mentioned in the survey talk is shown in figs. 1a and 1b. The proton beam is bent down into a ditch and subsequently deflected vertically upwards into a vertical, cylindrical target filled with a liquid entectic of lead and bismuth (LBE). The physical advantages of such an arrangement are a 360°-access to the source for the neutron users and optimal coupling of high-flux rectangular neutron tubes to the source. The technical advantages are a simple, highly symmetric structure of the entire source (modular shielding etc.) and the introduction of a simple target cooled by natural internal convection eliminating the need for expensive external cooling system carrying highly radioactive fluid.

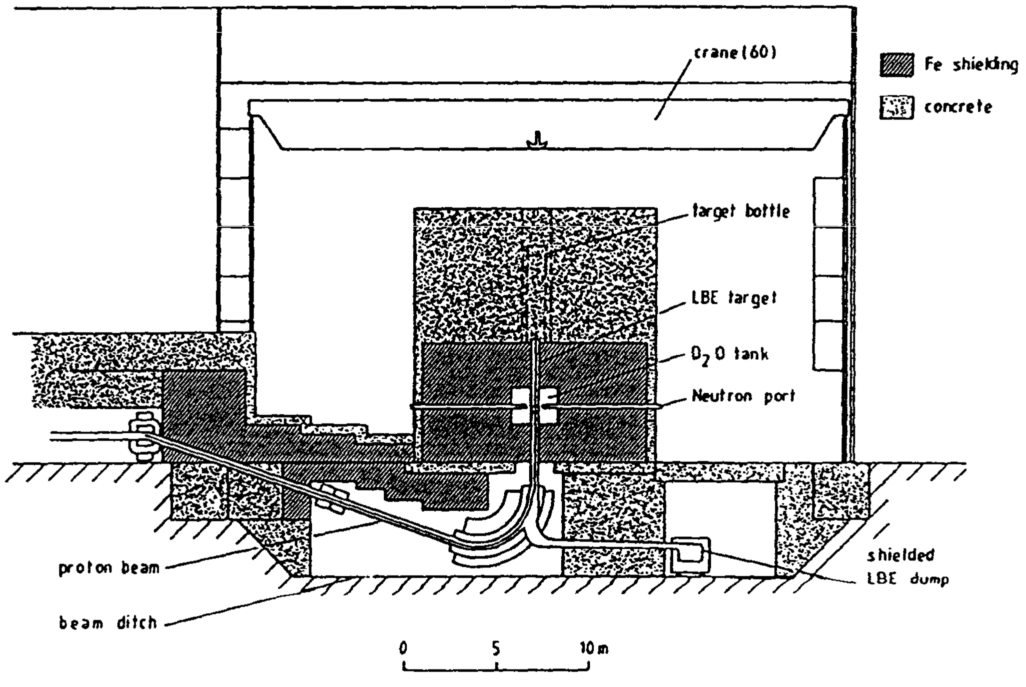

Fig. 1a

SIN neutron source: vertical cross section

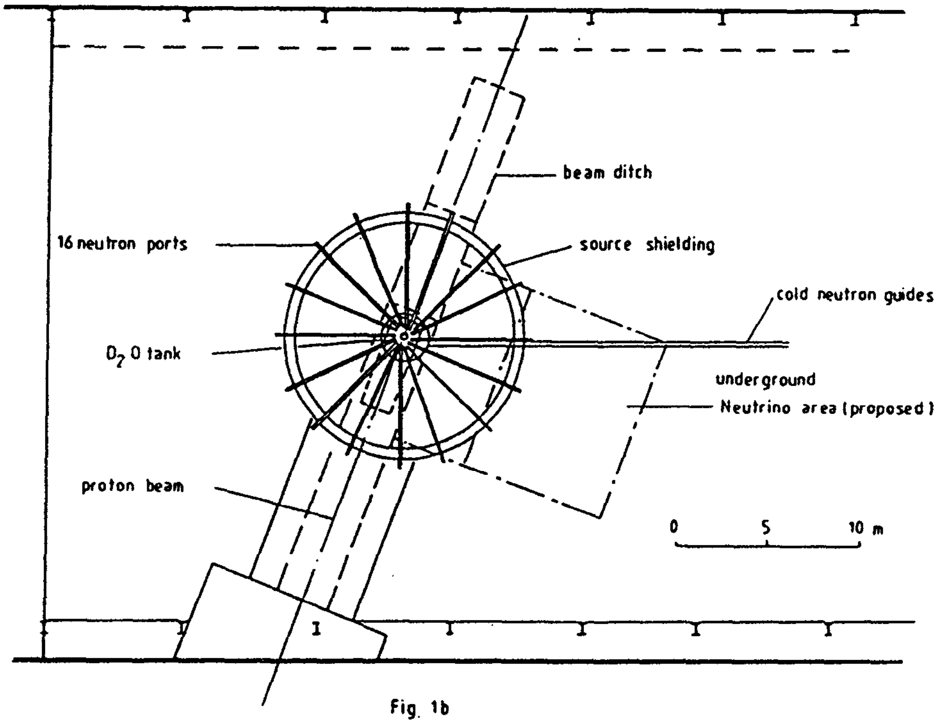

Fig. 1b

SIN neutron source: horizontal cross section

2. Convective Pb-Bi target

2.1 Description

The spallation target consists of a vertical, cylindrical vessel of about 20 cm diameter and a height of 3.5 m (fig. 2). The bottom end is closed off by a conical beam entrance window. The top is covered by flange carrying an array of cooling pipes which extend down by about 2 meters into the target vessel filled with liquid LBE. The proton beam entering the target deposits its energy near the entrance window. The hot LBE rises to the top where it is cooled on the cooling pipes and flows back along the wall of the target vessel. An internal coaxial guiding tube separates the hot and cold convective currents thereby preventing formation of "back water" pockets near the window and optimising the flow through the heat exchanger.

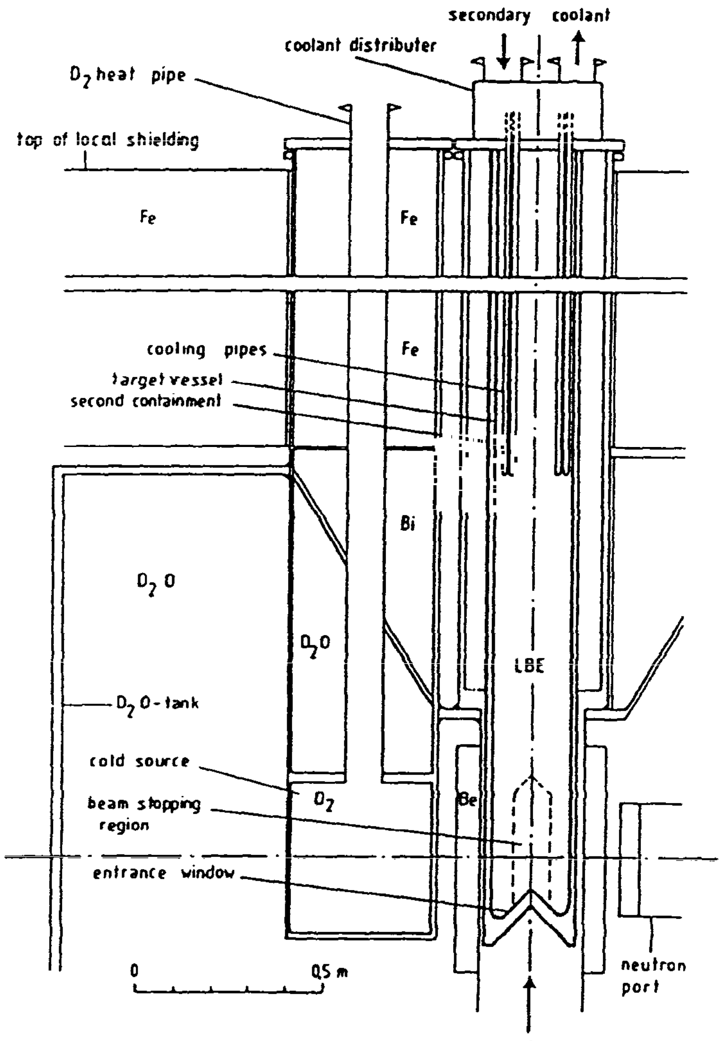

Fig 2

Spallation target region: vertical cross section

The inner target vessel is enclosed by a concentric outer vessel acting as a second containment fitted with a similar conical window cooled by radiation. Both vessels form an integrated target unit which is exchanged from the top in case of failure. The height of the target is designed such that the radiation level at the top flange allows simple manual coupling and decoupling of the target from the secondary cooling circuit and auxiliary connections.

2.2 Flow calculations

Calculations have been made of the convective flow of LBE in a vertical target . The stationary case can be described rather simply if we make the plausible assumption that the stationary flow can be represented as a sum of infinitesimal closed flow loops of volume flux $d\dot{V}$ which is constant over the loop, where the flow loops follow the direction of the flow velocity. Equilibrium between the buoyancy and the net frictional pressure drop Δp about each loop is expressed by the relation

$$\int_L d\dot{V} \cdot \Delta p = \int_L d\dot{V} \oint dz \cdot g \cdot \Delta\rho = \rho g \beta \int_L d\dot{V} \oint dz \cdot T$$

where

$\int_L$ = sum over all flow loops

$\oint\cdot$ = line integral over an individual loop

$\Delta\rho$ = change of density of LBE by heating

g = acceleration of gravity (= 981 cm/s^2)

β = volumeric thermal expansion coefficient of LBE

z = vertical coordinate

T = relative temperature of LBE

ρ = density of LBE at T = 0 (= 10 g/cm^3)

If the net rise of temperature in each flow loop by beam heating is ΔT, then the total beam power P is

$$P = c_\rho \int_L d\dot{V} \cdot \Delta T$$

where c_p is the heat capacity of LBE (=1.46 Ws/cm^3 K). We now define the mean difference of height between the area of heating and of cooling of the LBE as

$$\bar{h} = \frac{\int_L d\dot{V} \oint dz\, T}{\int_L d\dot{V} \cdot \Delta T} = \frac{\int_L d\dot{V} \oint dz\, T}{P/c_p}$$

As a final simplification we assume the mean pressure drop $\overline{\Delta p}$ over the flow loops to depend quadratically on the total volume flux $\dot{V}$:

$$\overline{\Delta p} \equiv \frac{1}{\dot{V}} \int_L d\dot{V}\,\Delta p = k \cdot \dot{V}^2$$

where $\dot{V} \equiv \int_L d\dot{V}$ and k is the constant of flow resistance.

Thus

$$k\dot{V}^3 = \rho g \beta \bar{h}\, P/c_p$$

or

$$\boxed{\dot{V} = \left[\frac{P \cdot \bar{h}}{k} \cdot \frac{\rho g \beta}{c_p}\right]^{1/3}} \qquad (1)$$

The mean temperature rise $\overline{\Delta T}$, defined as

$$\overline{\Delta T} \equiv \frac{1}{\dot{V}} \int_L d\dot{V} \cdot \Delta T = \frac{P}{c_p \dot{V}}$$

is then given by

$$\boxed{\overline{\Delta T} = \left[\frac{P^2 k}{\bar{h}} \cdot \frac{1}{\rho g \beta c_p^2}\right]^{1/3}} \qquad (2)$$

Two examples for convective LBE targets for proton beam powers of 1 MW and 10 MW resp. are shown schematically in fig. 3a and 3b. Both targets are cooled by an array of water pipes of 16 mm outer

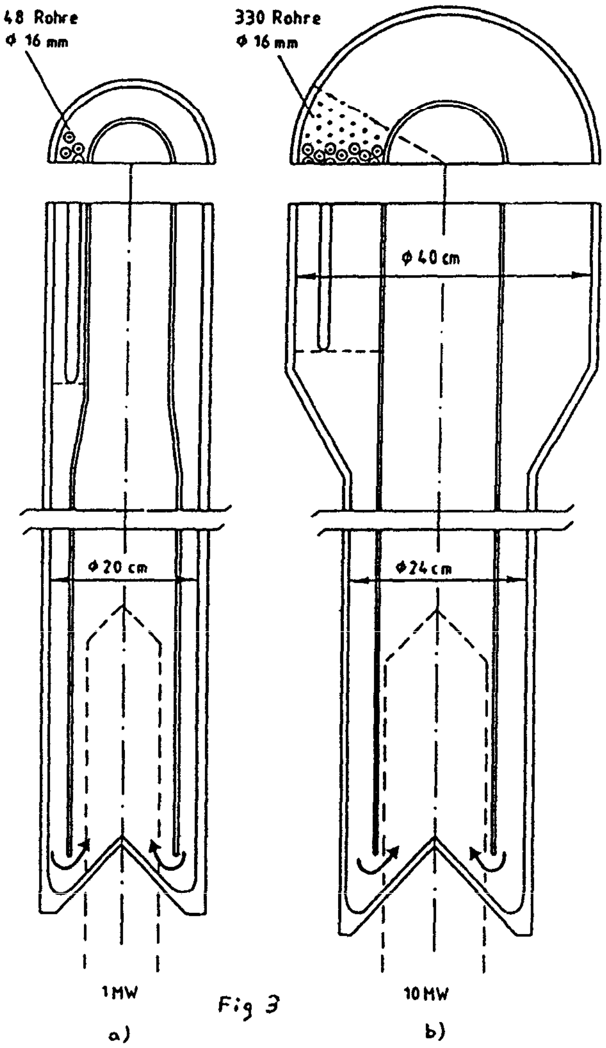

Fig 3

Convective spallation targets: conceptual layouts

diameter and 2 m length. The dimensions of these systems and the resulting characteristics of the stationary flow are shown in table 1:

Table 1

Target		I	II
Beam power	P	= 1	10 MW
Height of target	H	= 3.5	4.5 m
Effective convective height	$\bar{h}$	= 2	3 m

Number of cooling pipes	n =	48	330
Flow surface at heat exchanger	F_s =	100	400 cm^2
Total heat exchanger surface	F_k =	4.8	33 m^2
Water velocity	w =	2	3 m/s
Water flux	$\dot{V}_w$ =	4.8	54 l/s
Total heat transfer number water-LBE	α =	0.3	0.3 $W/cm^2 K$
Theoretical flow resistance	k =	$2.3 \cdot 10^{-3}$	$2.3 \cdot 10^{-4}$ $bar/(l/s)^2$
Effective flow resistance	k_{eff} =	$3.4 \cdot 10^{-3}$	$3.4 \cdot 10^{-4}$ $bar/((l/s))^2$
LBE flux	$\dot{V}_p$ =	3.4	18 l/s
Mean frictional pressure drop	$\overline{\Delta p}$ =	40	110 mbar
Mean LBE temperature rise	$\overline{\Delta T}$ =	200	380 °C
Water inlet temperature	T_{0w} =	100	100 °C
Water outlet	T_{1w} =	150	145 °C
LBE inlet temperature	T_{0p} =	375	540 °C
LBE outlet temperature	T_{1p} =	155	160 °C

The temperatures reached by the LBE even for the 10 MW example are still very manageable, especially since the only surfaces which are in contact with the LBE and which cannot be kept at low temperature are the window and the inner guiding tube which therefore have to be made of corrosion resistant materials e.g. graphite. The outer wall and the cooling pipes can probably be made of regular stainless steel since their temperature can be kept below 200 °C. Since the temperature rise ΔT calculated in these examples is proportional to only the power of 1/3 of the geometry factors h and k, the system temperatures will not vary much even if actual geometries turn out somewhat different from the simple-minded model described here.

In the start-up phase of the convective flow after the proton beam has been switched on, the LBE, initially at rest, has to be accelerated until the final stationary flow is achieved. In this phase the convective flow pattern is expected to change rapidly and local overheating of the LBE will occur.

In order to evaluate the behaviour of the system realistically, a computer programme for two-dimensional (cylindrical coordinates r, z), time dependent convective flow was written and used to compute the start-up phase of an LBE flow in a vertical cylindrical vessel in which the upper part of the side walls were held at constant temperature to simulate the heat exchanger and the lower part around the beam stopping region was insulated. For simplicity the frictional flow resistance in a realistic heat exchanger was neglected since in the start-up phase inertial forces in the LBE dominate. The basic Navier-Stokes equations were integrated using several suitable approximations especially that of constant density (exept for the buoyancy terms) and of low viscosity.

The temperature profiles in the flow at several heights z and times t after start-up are shown in fig.4. The cylindrical target vessel has a diameter of 20 cm and the r.m.s. diameter of the 600 MeV proton beam of power P is 5 cm and 10 cm resp. The target vessel is insulated over a height of 60 cm.

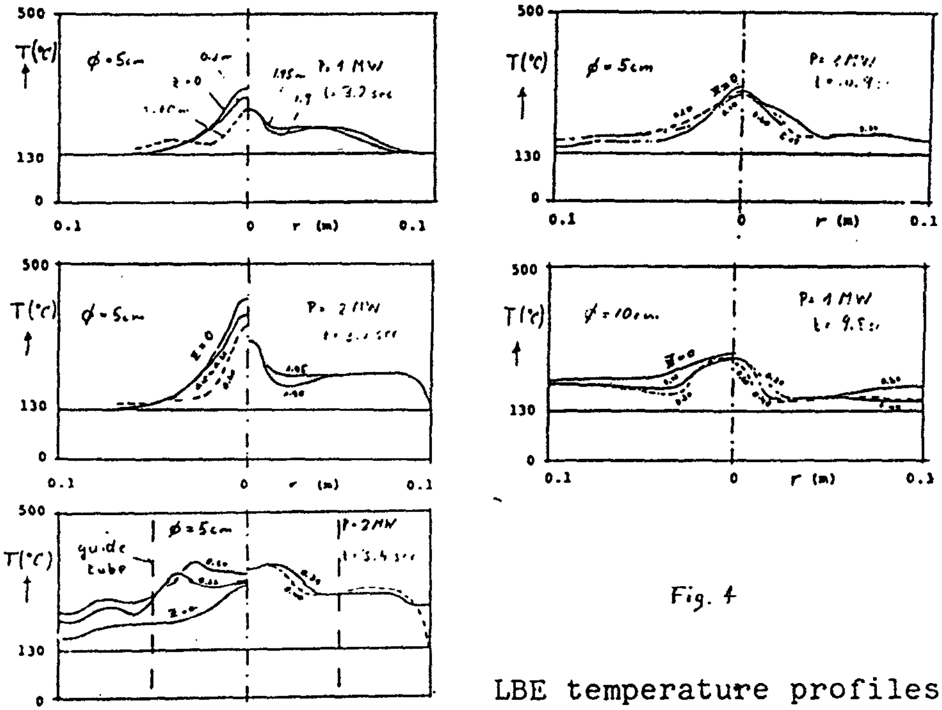

Fig. 4

LBE temperature profiles at start-up

In contrast to some earlier calculations for a target vessel and beam inclined at 20° to the horizontal, overheating in the vertical geometry is almost negligeable and the flow shows very stable behavior, especially if a concentric guiding tube is inserted into the heating region. The only condition for safe start-up is that the LBE be completely molten before the beam is switched on. However, the time structure and, within rather wide limits, also the diameter and shape of the proton beam does not critically affect the flow. Furthermore, an extension to higher beam power is easily possible by essentially beefing up the heat exchanger.

2.3 Beam window

The beam entrance window is obviously a crucial element since the entire lay out and target concept depends on its functioning. Besides questions of thermal and mechanical stress, the main uncertainty of window performance is still radiation damage by the proton beam. In order to minimize this problem, the design philosophy for the SIN spallation target calls for a proton beam as wide as possible even if it leads to a slightly larger source diameter. For beam powers above about 1 MW even tayloring of the beam profile to produce sharper edges and lower density at the centre for given source diameter would be considered. Widening of the beam in a given source will if anything in crease the neutron flux density at the neutron tube as long as the entire beam is still hitting the target. Flux calculations indicate that the flux reduction by going from a minimal source diameter of about 10 cm to about 20 cm is in the order of 10 %, a value which is probably reduced by reduced mutual flux depression through wider spacing of any given number of neutron ports. A further advantage of a larger source is the reduction of gamma heating in the surrounding structures and especially in a cold source. In view of these considerations, an r.m.s. beam diameter of 10 cm for a 1 MW beam (1.7 mA at 600 MeV; centre beam density = 20 A/cm2) and a LBE source diameter of 20 cm resulting in an inner D_2O tank diamter of 28 cm seemed quite acceptable.

In a radiation damage test at SIN, a disk of reactor graphite of 3 mm thickness and 3 cm diameter was exposed to the primary beam of 100 μA of 600 MeV protons for 200 hours. The beam spot area was 0.3 cm^2 resulting in sample temperatures between 1100 and 1300 °C. After irradiation the disk showed no measurable swelling or visible cracks. A graphite window for the proposed neutron source with a peak load of 20μA/cm^2 can therefore be expected live for several thousand hours or many months before radiation damage causes failure. In the case of a 10 MW source shown in fig. 3b assuming an r.m.s. beam diameter of 14 cm and a central beam density of 100μA/cm^2, a window life time of several weeks can still be expected.

Three further examples of high intensity proton irradiations of target and win dow materials have been reported from LAMPF and TRIUMF and are listed below together with the SIN sample:

	LAMPF	LAMPF	SIN	TRIUMF	
sample material dimensions	pyro-graphite (A5 target)	inconel (A6 window)	reactor graphite	stainless steel	
	5 mm thick	3 mm thick	3 mm x 25 mm	3 mm thick	
beam energy	800	800	600	500	MeV
beam current	400	400	100	100	μA
spot size	< 0.5	10	0.3	10	cm^2
irrad. time	1000	10^4	200	5000	h
sample temp.	~ 1000	~ 500	~ 1200	~ 500	°C
equivalent dose	800	~ 400	60	50	mAh/cm^2

None of these samples showed any macroscopic damage but microscopic analysis is yet to be carried out. The evidence, however, points to possible life spans of several hundred mAh/cm^2 for some window materials.

Approximate calculations were made for the thermal strain χ and the compressive stress σ from the LBE pressure p on conical windows shown in fig. 3a and 3b.

The windows, made from reactor graphite (density 1.75 g /cm , minimal heat conductivity of 0.5 W/cm K, a thermal expansion coefficient of 3 ppm/K and a proton energy absorbtion of 6 MeV/cm), have a half opening angle of 45°, a thickness of 0.5 cm at the vertex and 1 cm at the base. For exponential beam profiles, the largest thermal strain ε_{max} occurs at about half the r.m.s. beam radius R. The largest compressive stress σ_{max} is found at the base. The calculated values for ε_{max} and σ_{max} and their relation to the limiting values break and break for graphite are shown in table 2:

Table 2

P	1	10	MW
$r_{r.m.s.}$	5	7	cm
ε_{max}	$1.4 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	
$\varepsilon_{max}/\varepsilon_{break.}$	7 %	40 %	
σ_{max}/p	16	20	
σ_{max}	56	80	bar
$\sigma_{max}/\sigma_{break}$	11 %	15 %	

The radiation cooled window on the second containment of the same shape and material would develop smaller thermal strains than the main window. In a 1 MW beam of 10 cm r.m.s. diameter it would heat up to about 1500 °C which is an acceptable operating temperature for graphite and still below the boiling point of LBE so that evaporation in the case of an LBE leak would be moderate. For a 10 MW beam at 14 cm r.m.s. diameter, however, temperatures of 2300 °C would be reached, therefore a thinner window may be a safer solution in this case.

2.4 Operation and safety

Flow calculations have shown that neither the time structure of the beam intensity nor the beam profile have a serious effect on the safe behaviour of the convective LBE flow and its temperature, provided the LBE is kept liquid at all times. Apart from considerations of life-time the same is true for the window performance within rather wide margins of beam variations.

If the exit temperature of the secondary coolant is kept at about 150 °C, the heating of the LBE by residual radioactivity will normally maintain a minimal convective current and prevent the LBE from freezing during stand-by. An electrical heating element of a few kW power inserted into the centre of the target near the top would have the same effect even in a fresh, non-activated LBE target. Should the LBE freeze accidentally or during a long shutdown, it could be melted by circulating hot gas between the target and secondary containment.

During normal operation, the space between target and second containment would be kept filled with helium at low pressure and monitored continuously for leaks from the the target. Gauges on the beam vacuum system would indicate any leaks form the secondary confinement.

The LBE target itself will have to be vented through an appropriate filtering system to prevent a major build up of gaseous spallation products in particular H_2 and He.

Leaks from the target would normally be contained within the target unit (second containment) which can be exchanged routinely. Should the windows of both containments break simultaneously, The LBE content would fall into a duct directly below the target at the "back" of the beam bending magnet where it will be slowed down and allowed to empty into a shielded dump at the end of the beam ditch. A fast closing vacuum valve placed suitably upstream in the proton beam line would localize contaminaton of the beam vacuum.

In case of stoppage or loss of secondary coolant the convective LBE current will continue automatically with the average temperature rising at about 450 °C /min allowing ample time to switch off the beam. The heat produced by the residual radioactivity (~ 1 % of beam power) can be radiated off through the target and vacuum vessels into the shielding. If the total emissivities of the vessel walls are above 0.5, the LBE temperature will stay below 800 °C.

3. Uranium target cooled be LBE convection

In order to boost the thermal neutron flux, concepts for a second generation target of uranium were studied. A simple proposal involves insertion of a bundle of cylindrical fuel rods filled with uranium carbide into a convective LBE target of the same dimensions as the one in fig. 3a exept that the heat exchanger would be enlarged to handle the power increase of a factor of 2 expected from a UC-target (see fig.5). The fuel rods would carry conical caps at both ends to reduce flow resistance and would be held by an appropriate matrix to allow the LBE to enter into the bundle from below and to ensure proper spacing of the rods.

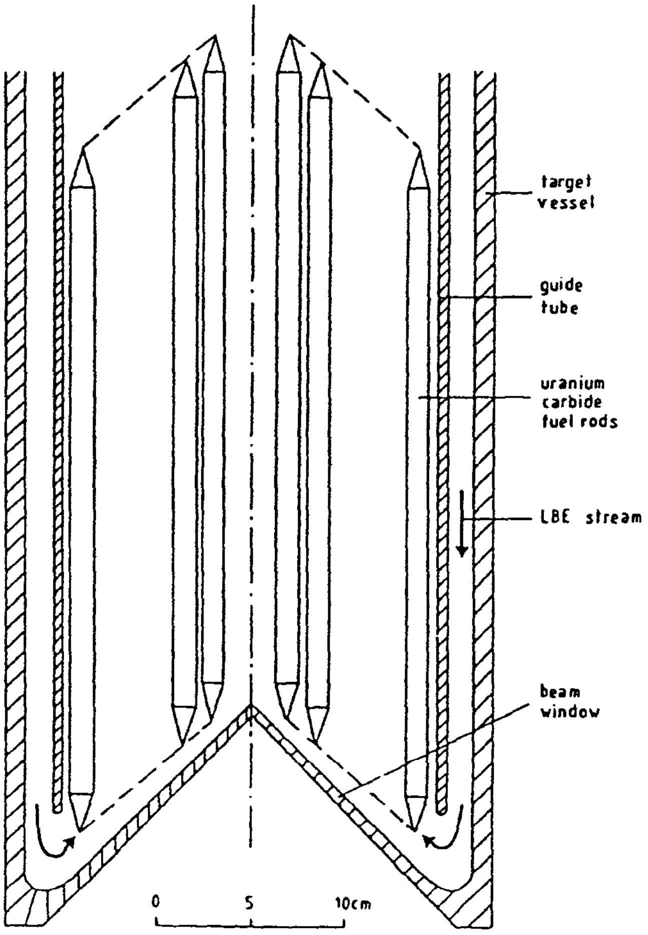

Fig 5

LBE target boosted by UC fuel rods

First approximate calculations for the stationary LBE flow through a bundle of fuel rods of 1.2 cm diameter and 35 cm length (beam stopping characteristics of a UC fuel rod with 80 % filling factor is about equal to that of LBE) have shown that by an appropriate spacing of the rods the maximum cladding temperature which is the critical temperature in view of the high melting point of UC (2300 °C) can be kept uniformly low for gaussian beams of r.m.s. diameter between 4 cm and 16 cm. The corresponding design figures and resulting thermodynamic flow values are shown in table 3. For simplicity the LBE flow resistance is assumed to be determined only by the flow resistance in the UC-bundle.

Table 3
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beam current	1.7 mA
beam r.m.s. diameter	10 cm
fuel rod diameter	$d = 1.2$ cm
beam power deposited	$P = 1.5$ MW
flow resistence through bundle	$k = 7.5 \cdot 10^{-4} \frac{\text{bar}}{(l/s)^2}$
flow rate	$\dot{V} = 6.5$ l/s
pressure drop	$\overline{\Delta p} = 32$ mbar
max. local temperature rise of LBE (same for beam diameters from 4 cm to 16 cm)	$\overline{\Delta T} = 260$ °C
effective relative density of UC	56 %
relative source strength compared to LBE (pure UC = 2.8)	2.0

If further flow resistences e.g. of the heat exchanger are significant, the flow rate $\dot{V}$ would be reduced by a factor of $(\text{ktotal}/k)^{1/3}$ and the LBE temperature rises increased by the same factor.

For the start-up phase of the flow through a UC-bundle computer calculations are in progress.