CARBON and BERYLLIUM TARGETS

and

BEAM WINDOWS

at PSI

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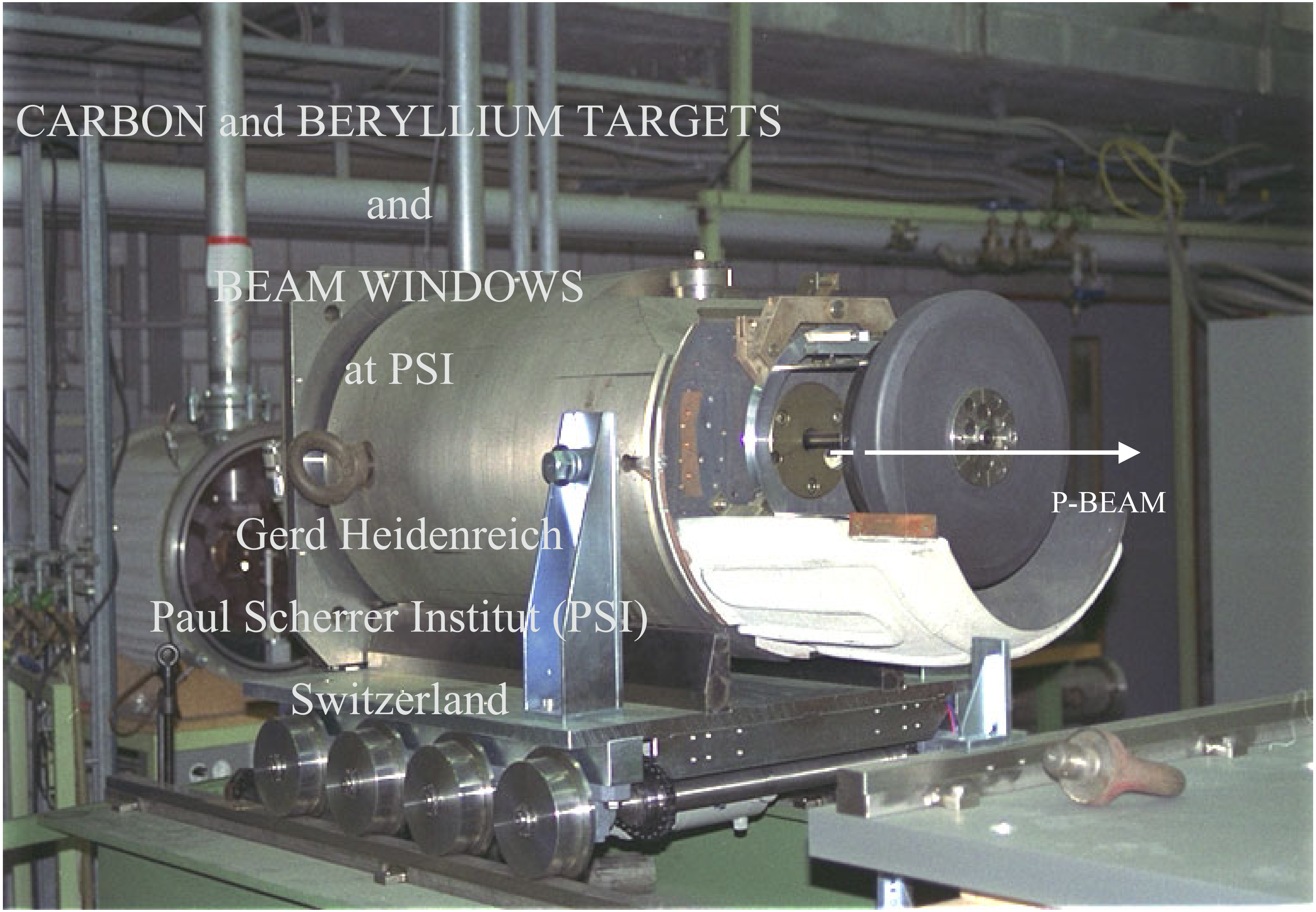


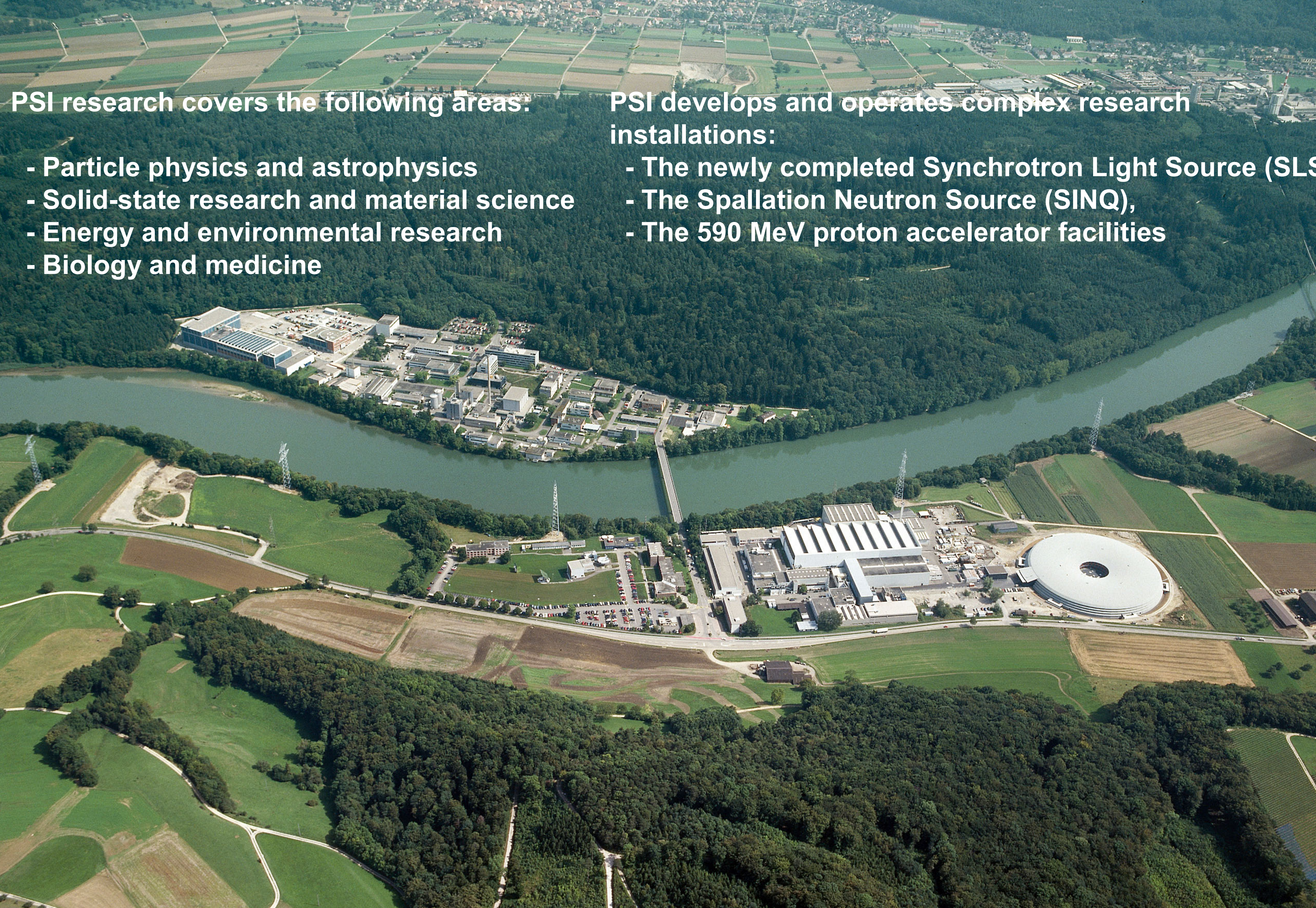
Abstract

The Paul Scherrer Institut (PSI) operates a cyclotron facility for the production of a high intensity proton beam at an energy of 590 MeV. The majority of the beam is delivered to the two target stations M and E, mounted in series, to generate intense pion and muon beams for research in particle physics and muon-spin-resonance applications. Both targets consist of rotating wheels of polycrystalline graphite cooled by thermal radiation. About 40% of the proton beam is lost at the target-E station; the remainder of the beam is transported to the spallation neutron source SINQ or to a beam dump. Since the upgrade to the cyclotron, the target facilities have had to handle significantly higher beam current; both target stations were completely rebuilt (M in 1985 and E in 1990) to handle 2 mA. An overview of target station E will be presented, concentrating on design, operational limits and failures of the targets used at PSI. In addition, the design and operational limits of the beam window for the SINQ spallation target will be discussed.

The first picture shows the meson production target M:

This target consists of a rotating wheel of polycrystalline graphite cooled by thermal radiation. The main difficulties for the design of a reliable mechanical system are i) the high radiation levels around the target and ii) it is inside a vacuum system. Our solution at PSI is to have the rotation of the target made using a long drive shaft equipped with a pair of commercially available ball bearings, the balls and rings of which are silver coated to achieve lubrication hence to prevent adhesive wear in vacuum. The drive-motor is mounted outside the vacuum with the torque to the drive shaft transmitted by a permanent-magnet clutch.

The present target-M unit has operated without failure for more than 50’000 hours since installation in 1991. The graphite of the target has been irradiated with a total integrated beam current of 44 amp hours (Ah), which corresponds to a radiation damage level of about 4 dpa.


PSI research covers the following areas:
- Particle physics and astrophysics
- Solid-state research and material science
- Energy and environmental research
- Biology and medicine
PSI develops and operates complex research installations:
- The newly completed Synchrotron Light Source (SLS
- The Spallation Neutron Source (SINQ),
- The 590 MeV proton accelerator facilities

Accelerator facilities of PSI

The circa 2 mA proton beam from the 590 MeV cyclotron is delivered to two meson production targets, "M" and "E", mounted in series, which generate intense pion and muon beams for research in particle physics and for muon spin-resonance applications. These targets consist of rotating wheels of polycrystalline graphite, cooled by thermal radiation.

Target-M feeds two meson beam-lines, π-M1 a high resolution pion beam and π-M3, which is dedicated to μSR applications. Both beams are extracted in the forward direction at a production angle of 22.5^o.

The target-E complex provides five high intensity meson beam-lines; π-E1, π-E3 and π-E5 for pions; μ-E1 and μ-E4 for muons.

- π-E1 and μ-E1 are extracted by half-quadrupoles in the forward direction at 8 degree.
- π-E3 and μ-E4 at 90 degree.
- π-E5, a high acceptance low energy beam line, extracted in the backward direction at 168 degree.

After target E, the remaining proton beam (60% of typically 1.8 mA) is either delivered to the spallation neutron source SINQ or defocused and stopped in a high power beam dump.

Before the meson production targets, there is an electrostatic splitter, which allows between 100 nA and 20 μA to be split from the main beam for use in the NA-Hall. This low intensity proton beam is for use by PIF (proton irradiation facility) and Gantry (proton therapy facility). A degrader is available to reduce the energy of the proton beam to a few hundred MeV and an intensity of a few nA.

Two new projects are planned in the NA - Hall:

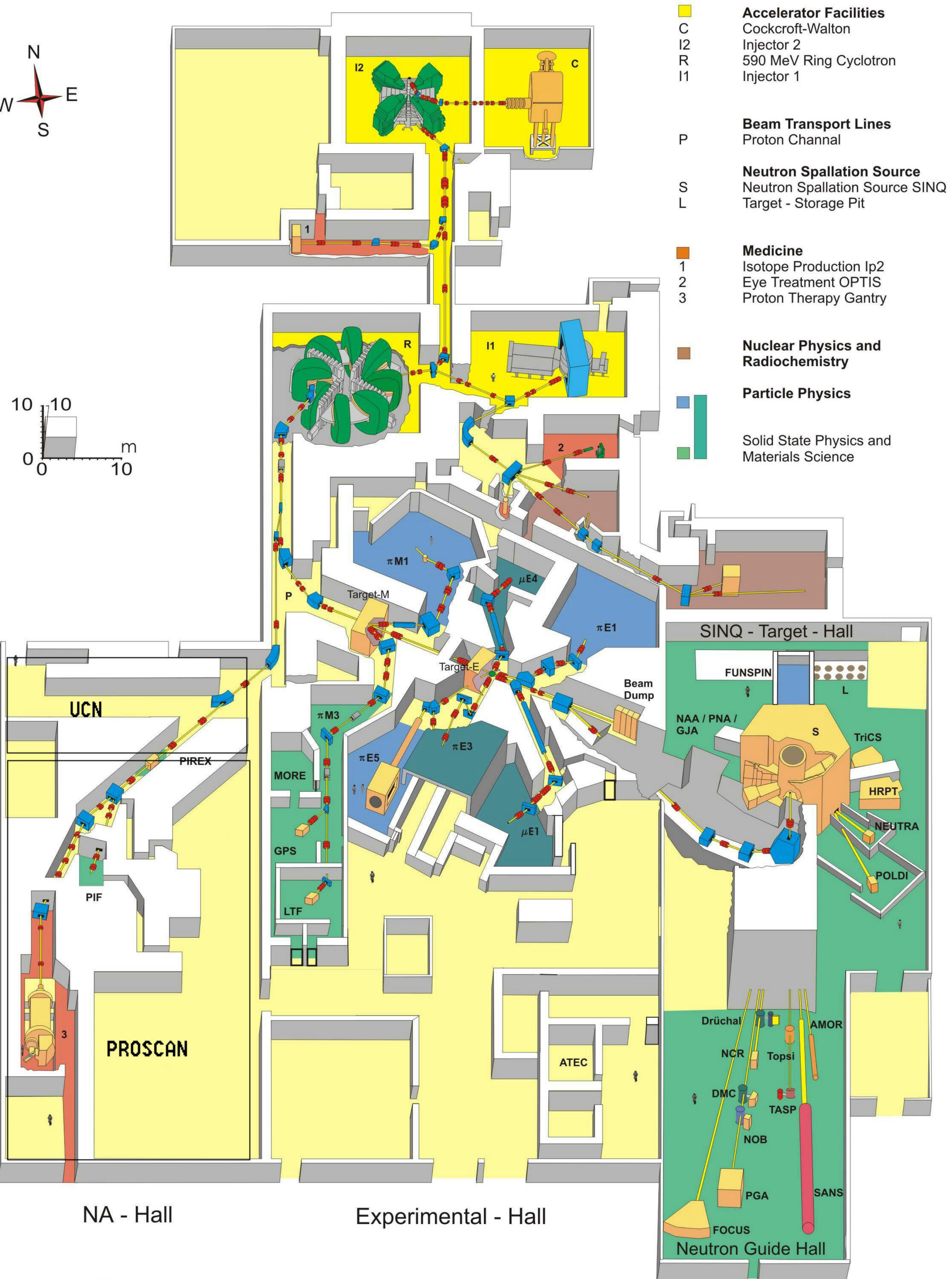
- The project PROSCAN. This is a dedicated 250 MeV cyclotron for proton therapy feeding two treatment rooms and one experimental area.

- The construction of an ultra cold neutron source (UCN), based on the spallation process. With the help of a fast kicker the whole beam (2 mA) will be directed for a few seconds every 10 minutes onto the UCN spallation target. This should produce a UCN density of 4000/cm^3 (orders of magnitude higher than any other UCN source in the world).

The beam losses in the targets and collimators produce highly activated components. These can be removed using a dedicated remote handling system and transported in a shielded flask to the hot cell area (ATEC) for maintenance.

AUL SCHERRER INSTITUT

Accelerator Facilities of PSI

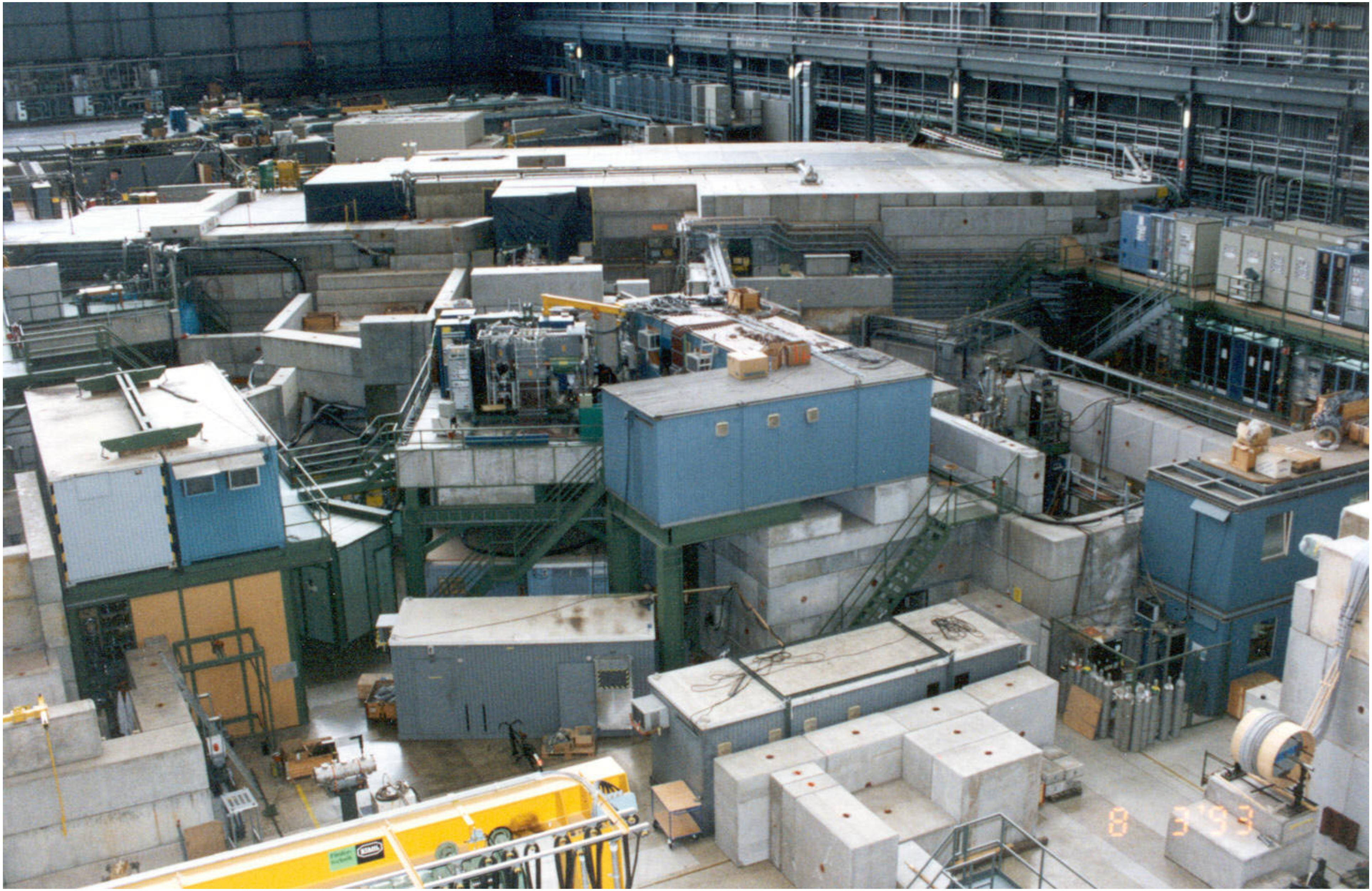


View of the proton channel and the experimental facilities in the Experimental Hall

- I In the foreground are the experimental areas μ-E1, π-E3 and π-E5

- In the middle the concrete shielding of the proton channel

- In the background the tops of the Injector 1 and the 590 MeV cyclotron shielding bunkers.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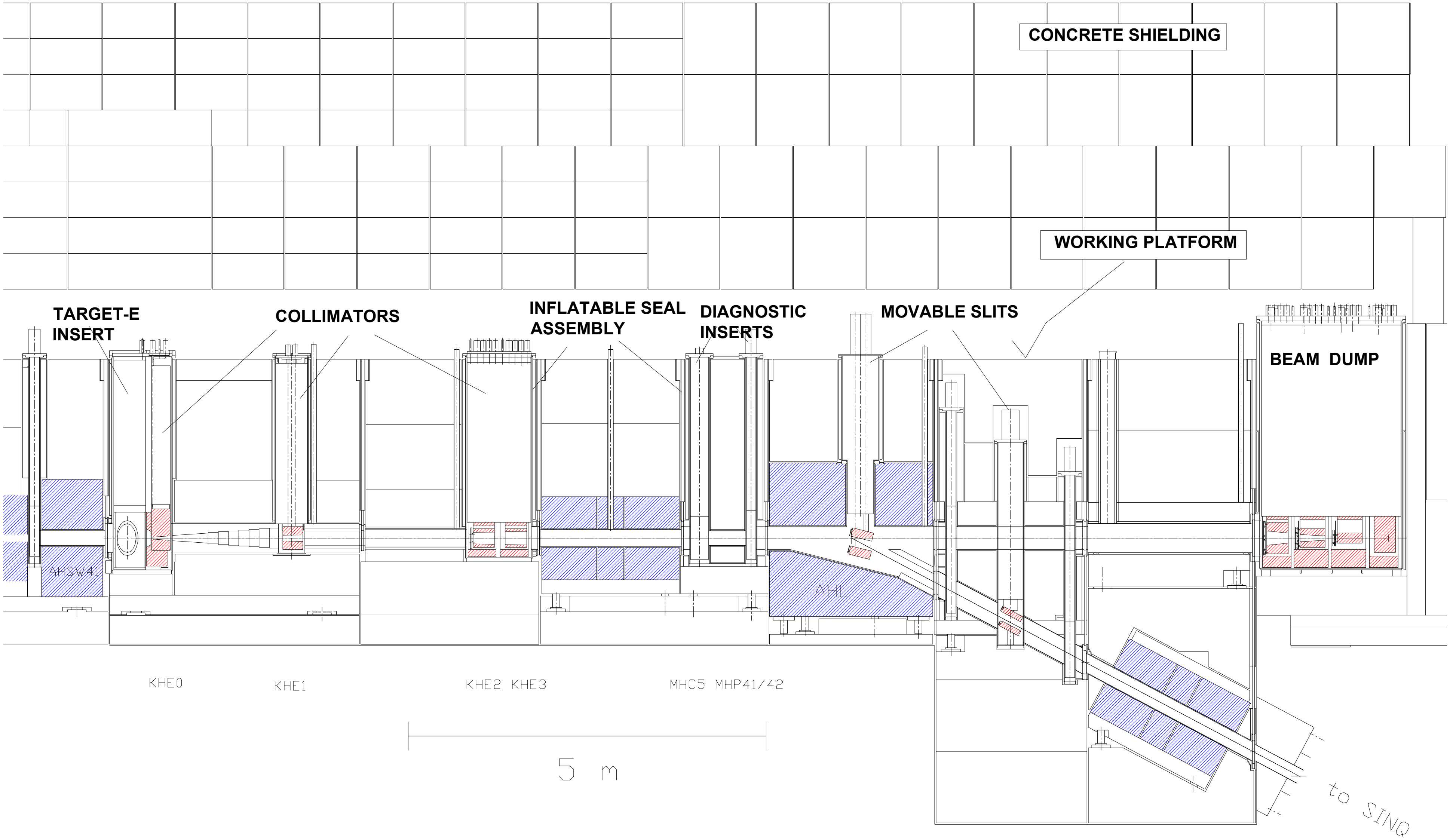
Design of the proton channel between target E and the beam dump

- All the beam line elements, the rotating carbon target, beam monitors, beam collimators, the elements of the beam dump and their local shielding are mounted on support stands, which are precisely positioned on ground plates, allowing a self-centring installation of the elements without any fastenings. All elements can thus be installed and removed exclusively in the vertical direction with the crane. There is no need for local mechanical work on the highly activated components.

- The connection between beam pipes and vacuum chambers are made by means of inflatable all-metal seals which do not require any clamping.

- All the power-, cooling- and signal connections are brought through the local shielding to a working platform 2.5 m above the proton beam axis, where the dose rate (with the beam off) is low enough to allow hands-on maintenance.

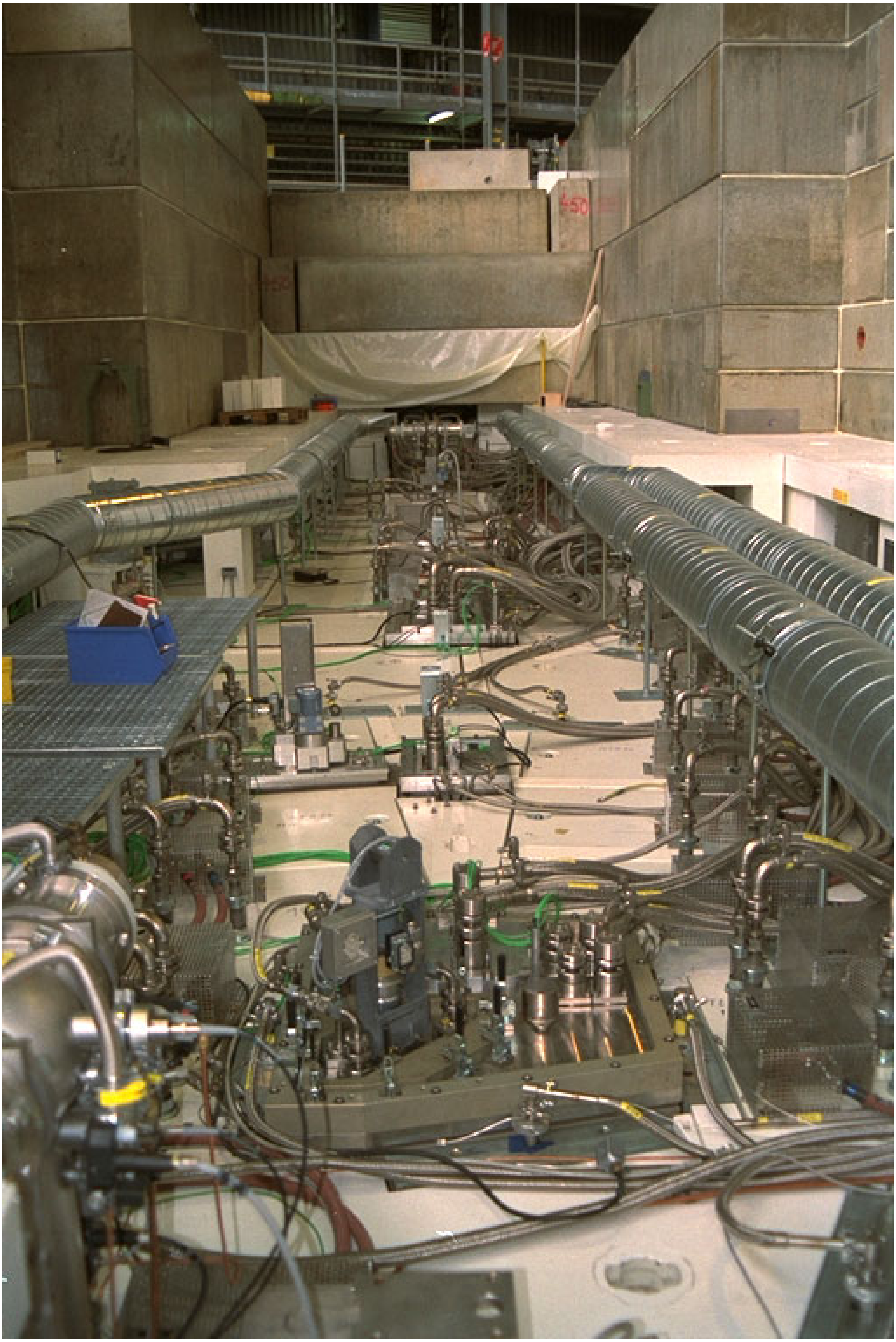
DESIGN OF THE PROTON CHANNEL BETWEEN TARGET-E AND THE BEAM DUMP



View of the working platform

- In the foreground is the top of the Target-E chamber, in the middle the vacuum chambers of the collimators KHE1, KHE2 & KHE3 and in the background the beam dump region.

- With the proton beam off and a cooling time of a few weeks the dose rate at the working platform is in the region of 200 μSv/hour



Operation of the remotely controlled shielded flask

The target station component-inserts can be removed into a remotely controlled shielded flask and transported by crane to the hot cell for maintenance. The same shielded flask can be used for all collimator and beam monitor assemblies and also for the target-E unit.


ACHTUNG
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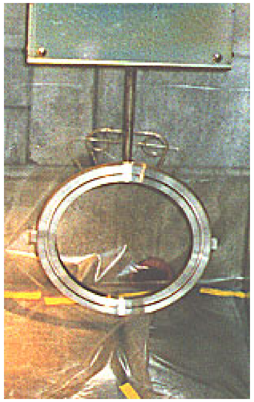
Thermal and mechanical design aspects of target station E

The mesons are produced by a carbon target, which consists of a rotating truncated cone of polycrystalline graphite, cooled by thermal radiation. The length of the target in the beam direction is 60 mm (10.7 g/cm^2). The coulomb scattering in the target increases the angular divergence of the proton beam, which requires the shaping collimators KHE2 & KHE3 to match the emittance of the proton beam with the acceptance of the beam line to SINQ.

This brings the average beam loss rate to the order of 1 nA/m, which is the typical value for the whole complex. About 60% of the proton beam reaches the SINQ target.

Because of the high beam loss, a considerable part of the surrounding shielding etc. requires water cooling (about 450 kW deposited power for a 2 mA beam). Because of this, the structure is strictly separated into two parts, an inner part optimised to handle the thermal problems and so protect the outer, mechanical part from heat.

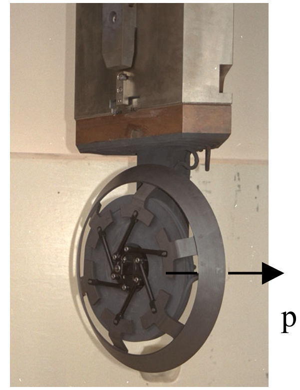
The inner part consists of a set of shielding collimators and local shields, all water cooled and generally made of copper. All sensitive mechanical parts, such as vacuum chambers & seals and the support structure for the inserts, are mounted outside these heat shields to reduce thermal stresses



INFLATABLE
ALL-METAL SEAL

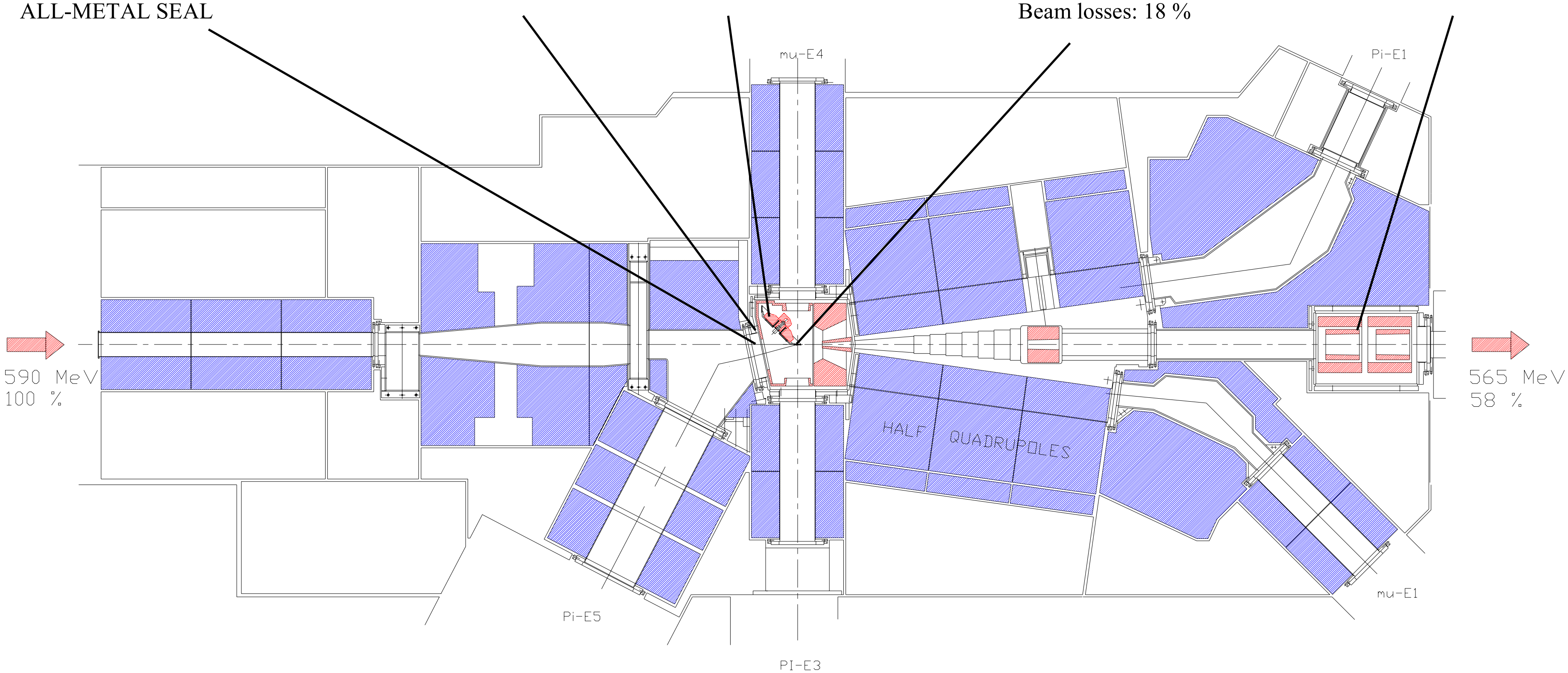
BACKWARD SHIELDING

TARGET CHAMBER



TARGET E
Beam losses: 18 %

COLLIMATOR KHE2
Beam losses: 29 %



Design of beam collimators and beam dump elements

The beam collimators and beam dump elements have to handle a total power of up to 250 KW and a peak power density of 350 W/cm^3. The copper of collimator KHE2 has been irradiated with a total integrated beam current of 50 Ah, which corresponds to a peak radiation damage level of about 35 dpa.

Each collimator and beam dump element is 30 cm long and made up from six copper disks with a thickness of 50 mm connected together with four bolts. Stainless steel tubes brazed onto the copper disks provide the cooling.

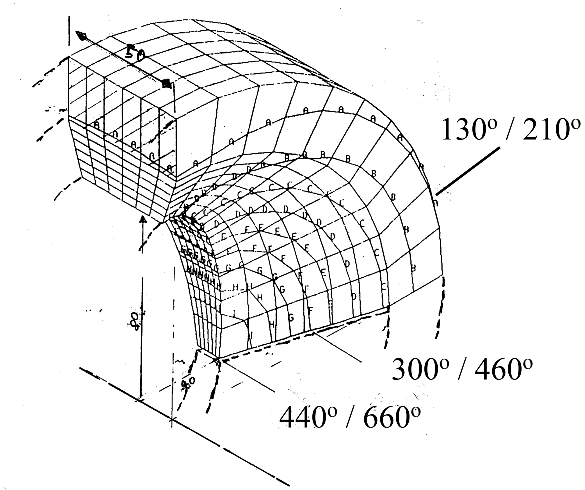
The tapered shape of the disks within the beam region is to give a better distribution of power load and hence reduced temperatures.

Due to beam trips, the collimators are subjected to more than 20’000 cycles per year. Therefore each disk is divided into four segments by means of gaps. These gaps allow free thermal expansion of each segment, which avoids problems from cyclic fatigue.

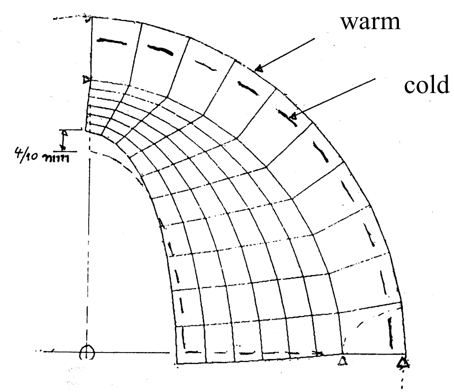
DESIGN OF BEAM COLLIMATORS AND BEAM DUMP ELEMENTS

Each collimator consists of a set of disks, made from copper (OFHC)

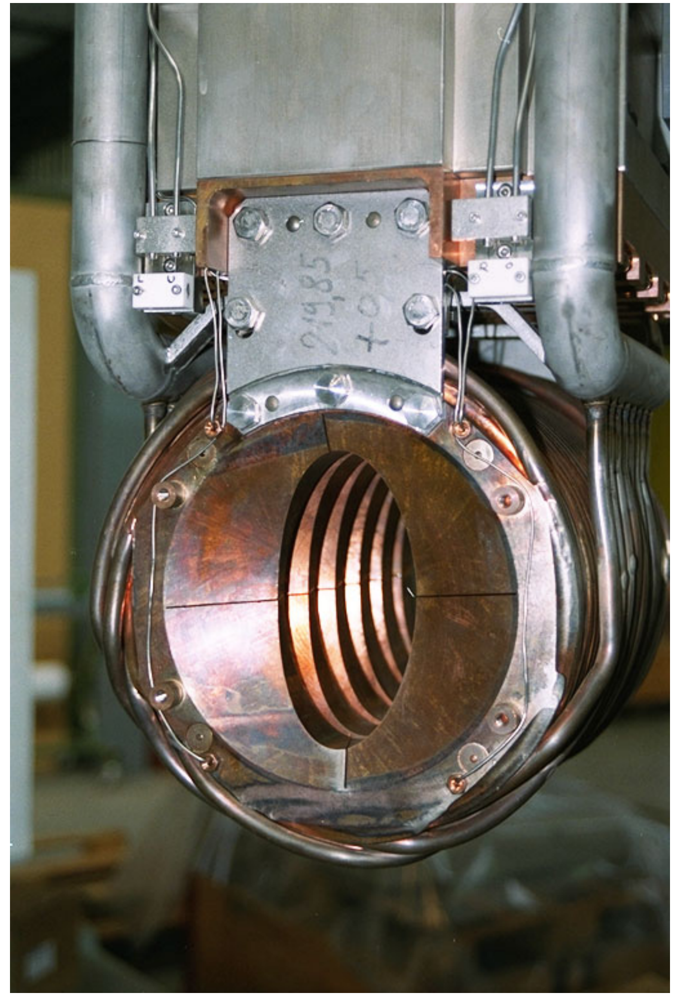
The tapered shape of each disk give a better distribution of the power load and hence reduced temperatures (^{o}C, 1st no. with tapered design, 2nd for an uniform thickness)



The gaps in each disk allow free thermal expansion of each segment which prevent the copper from cyclic fatigue.



Displacements



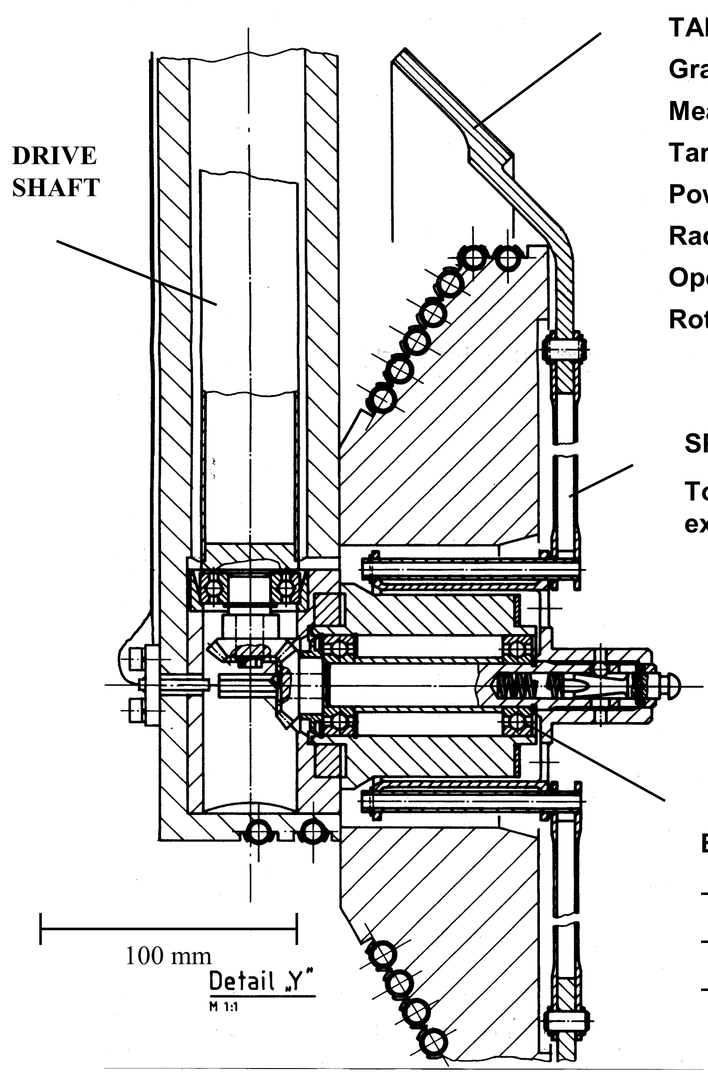
COLLIMATOR KHE2 (200 kW)

Design of Target-E

The target is driven by a long vertically mounted drive shaft, so that the electric motor is mounted in a low radiation field region. The bearings contain silicon nitride balls; the rings and the cage are silver coated to act as lubricant. The lifetime of the bearings is about 3000 hours presently and causes up to three replacements of the target insert per operational year.

The target consists of a rotating cone of polycrystalline graphite, cooled by thermal radiation. The cone is attached to the wheel hub by six spokes. This design allows dimensional changes, such as thermal expansion during heating, to be taken up, but constrains the irradiation-induced anisotropic shrinkage of the polycrystalline graphite, which causes deformation of the shape and hence leads to a radial wobble.

TARGET - E



TARGET CONE

Graphite density:	**1.8 g/cm^3**
Mean Diameter:	**450 mm**
Target length:	**60 mm**
Power deposition:	**60 kW**
Radiation damage rate:	**0.1 dpa/Ah**
Operating temperature:	**1700 K**
Rotation speed:	**1 turn/s**

SPOKES

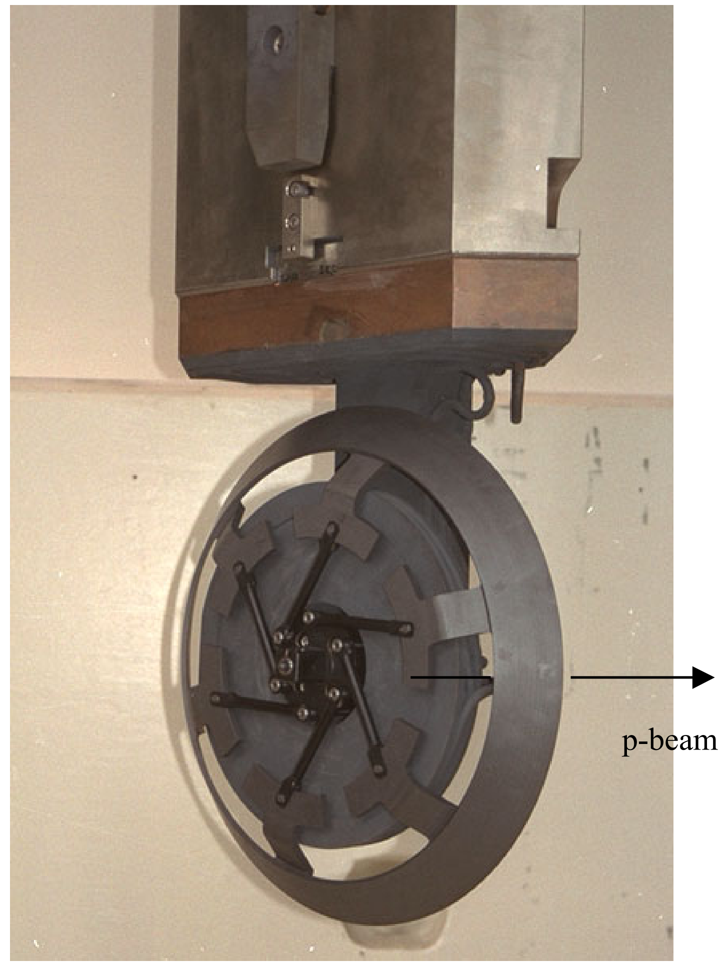
To enable the thermal expansion of the target cone

BALL BEARINGS

-Rings and cage silver coated

-Silicon nitride balls

-Lifetime ~3000 h



Lifetime of the polycrystalline graphite target cones

Radiation-induced anisotropic shrinkage of the polycrystalline graphite causes deformation of the shape and hence leads to a radial wobble of the target cone. The radial displacement amplitude must be less then 2 mm for the operation of the target in the proton beam. The figure shows the measured radial displacement rate [mm/Ah] for the targets made from the graphite grades R6300P and R6400P [1].

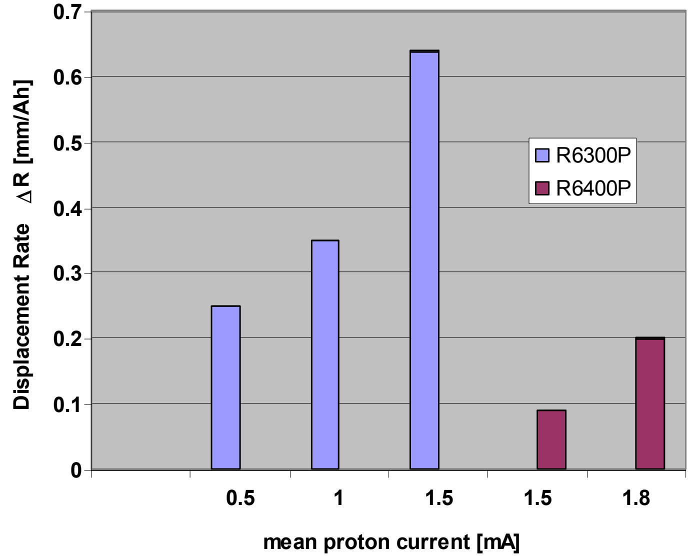
Since 1997 the targets were made from R6400P, which is a more isotropic form of graphite. This has resulted in a significant improvement of the lifetime, which presently reaches 10 Ah (one operational year).

In order to increase the operational lifetime, a new design of graphite wheel, as shown in the figure, has been developed. The target cone is subdivided into 12 segments separated by gaps of 1 mm at an angle of 45º to the beam direction: This allows unconstrained dimensional changes of the irradiated part of the graphite. At the normal operating temperature the width of the gaps in the beam direction will close to about 0.5 mm, which will lead to an intensity modulation of the proton beam in the order of 0.4 %. This target design will be tested this year.

[1] SGL Carbon, Bonn, Germany

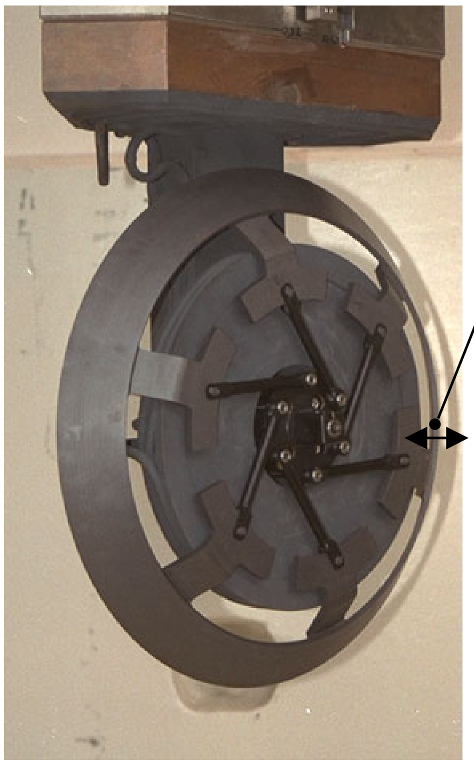
LIFETIME OF THE ROTATING POLYCRYSTALLINE GRAPHITE TARGET CONES

Radiation-induced anisotropic shrinkage of polycrystalline graphite causes deformation of the shape and hence leads to a radial wobble. The radial displacement amplitude ΔR must be ≤ 2mm for the operation of the target.



Measured radial displacement rates for the targets made from the graphite grades R6300P and R6400P *)

*) SGL Carbon, D-53170 Bonn, Germany



Beam axis

ΔR ≤ 2 mm

A new design of graphite wheel. The target cone is subdivided into 12 segments separated by gaps of 1mm at an angle of 45° to the beam direction: This allows unconstrained dimensional changes of the irradiated part of the graphite.

Operational limits of the rotating carbon and beryllium target cones

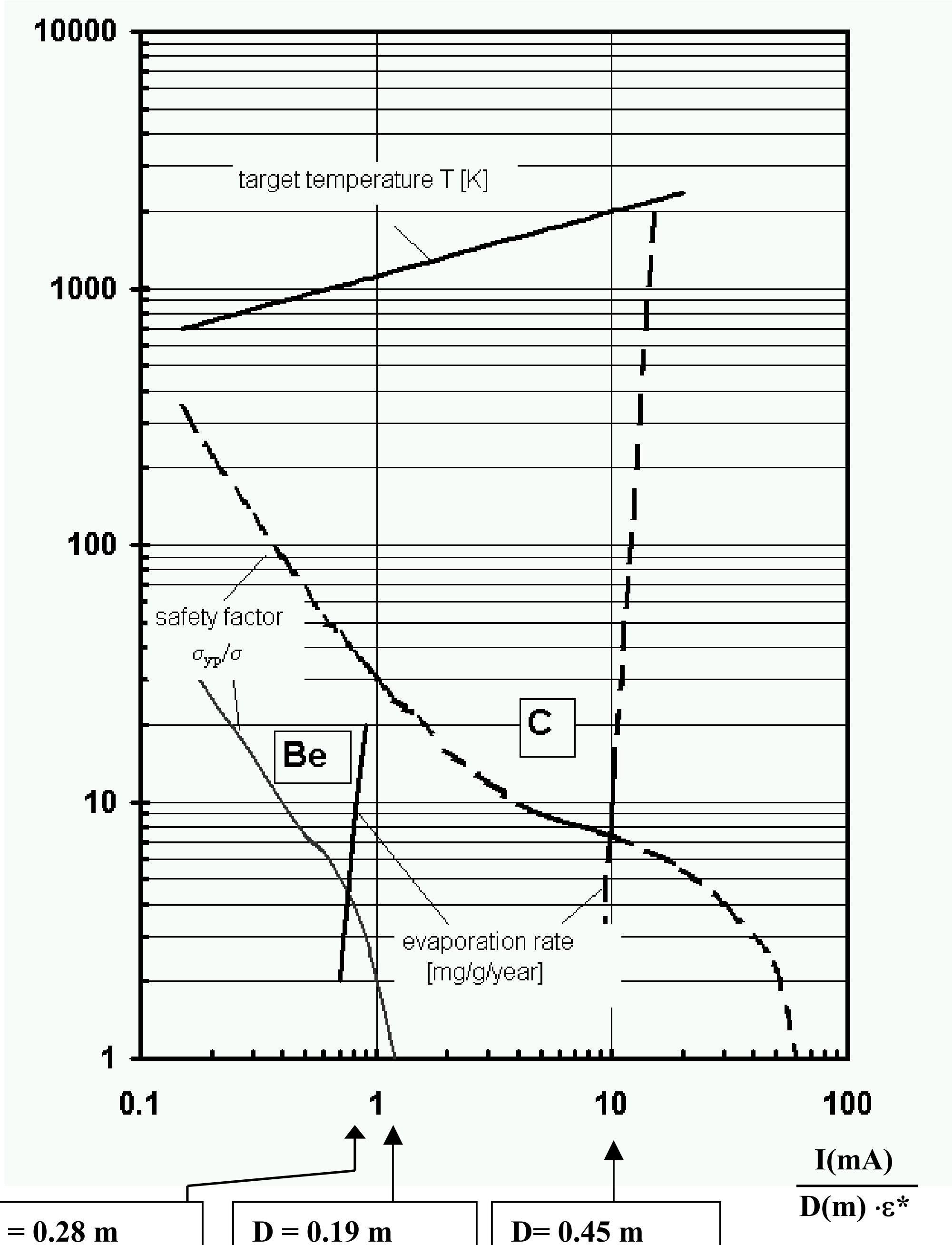
The important operational concerns are mechanical reliability, mainly caused by thermal induced stresses, which can cause cracking of the target cone and spread of radioactivity from evaporation of the target material because of the high temperatures.

The figure shows the variation of the critical operational parameters (the temperature, the safety factor and the evaporation rate) for the beryllium and carbon targets as a function of $I/D \cdot \varepsilon^*$, which is the proton current I(mA), divided by the target diameter D(m) multiplied by the effective emissivity ε^* of the radiating surfaces. The current design for the graphite targets have a diameter of D=0.45 m, which gives acceptable operational parameters for proton currents up to 3 mA.

In the case of a beryllium target, a diameter ten times larger would be necessary. (e.g. for 3 mA 4.5 m diameter)

In the early days of operation, beryllium targets were used with beam currents up to 150 μA. The targets with a diameter of 0.19 m failed at operating currents of 120 μA due to cracks of the target cone; with a diameter of 0.28 m they operated successfully at up to 150 μA.

OPERATIONAL LIMITS OF THE ROTATING CARBON & BERYLLIUM TARGET CONES



D = 0.28 m	D = 0.19 m	D= 0.45 m
I = 0.15 mA	I = 0.12 mA	I = 3 mA
ε^* = 0.6	ε^* = 0.6	ε^* = 0.75

I : Proton current (mA)

D : Mean target diameter (m)

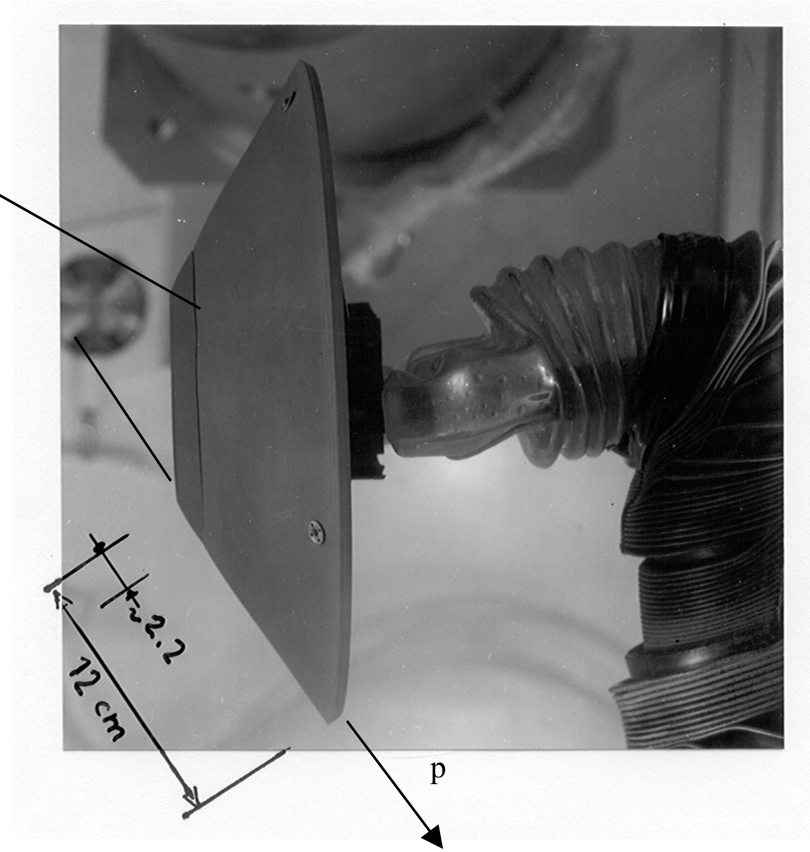
ε^* : effective emissivity = F (emissivity, view factors and areas of the radiating surfaces)

Failure of the rotating beryllium target cones

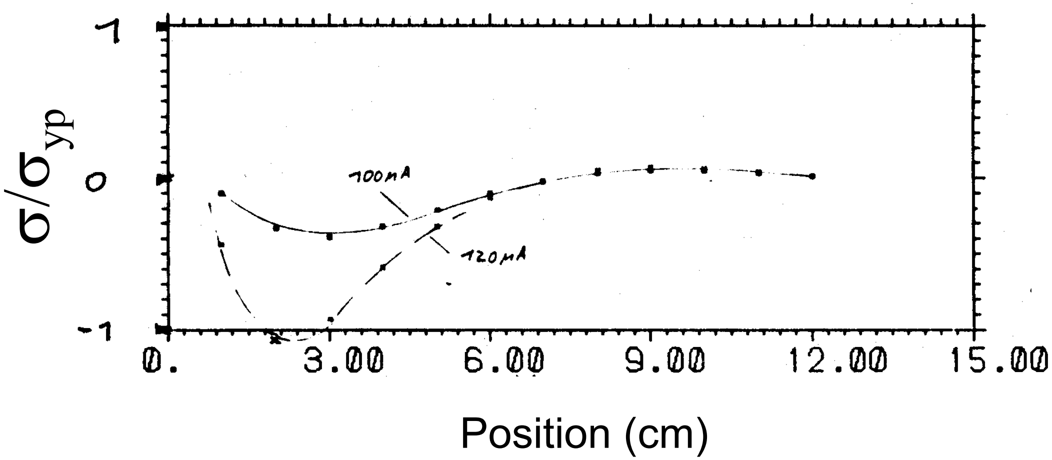
The picture shows a crack in a beryllium target cone which was operated above 120 μA. The calculated bending stress has a maximum value exactly at the position of the crack.

FAILURE OF THE ROTATING BERYLLIUM TARGET CONES

Crack after operation above 120 μA



Calculated bending stress / yield strength



The beam window for SINQ

The present SINQ target consists of an array of stainless steel tubes filled with lead and cooled by D_2O; it replaced an earlier design consisting of solid zircaloy rods in an identical geometric arrangement. Originally it was planned to replace the zircaloy rods by lead-filled aluminium tubes, which will double the neutron yield.

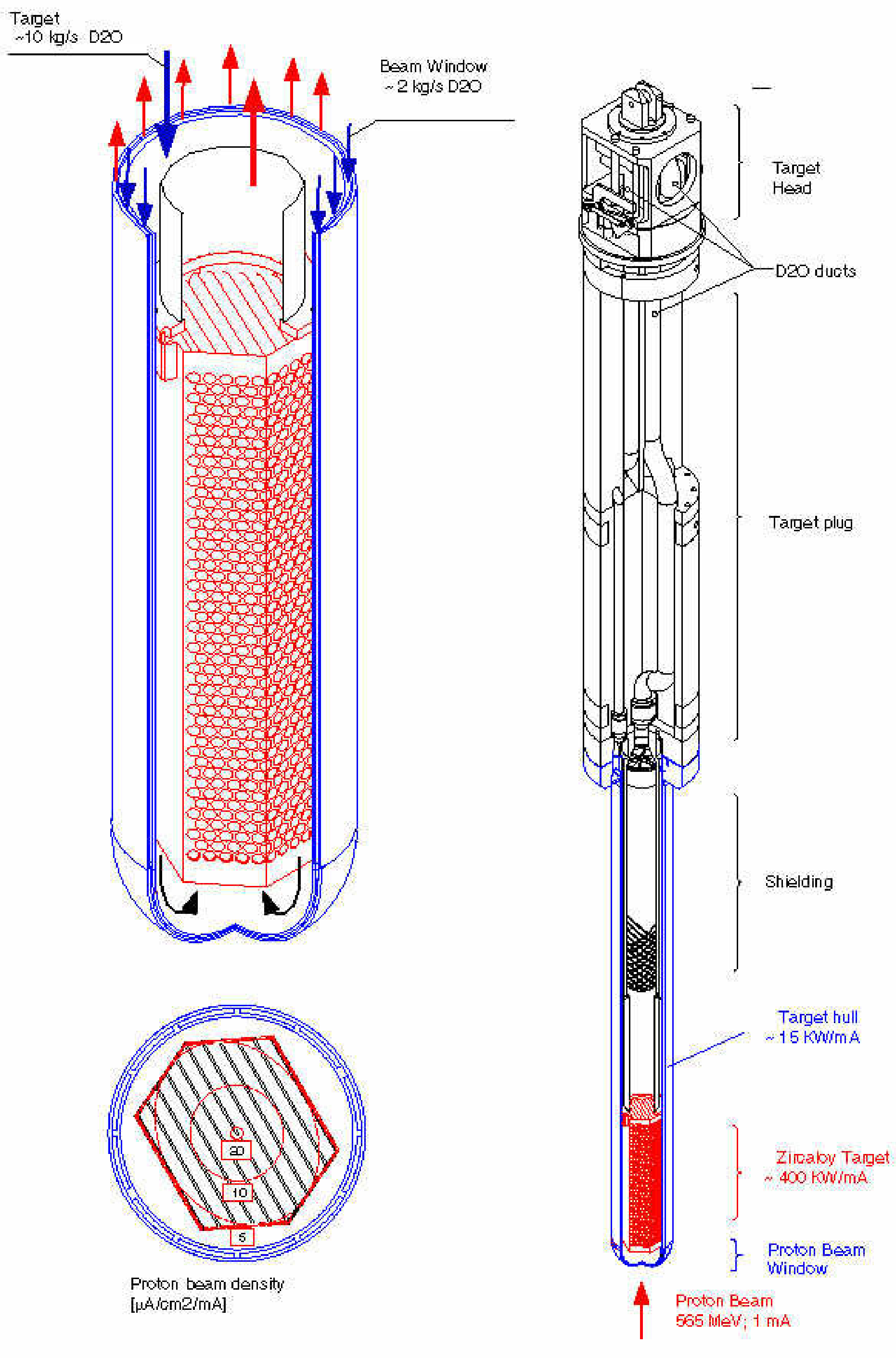
The beam window, which is a part of the target hull, consists of two concentric aluminum shells with D_2O flowing between. This design allows a completely cooling of the whole assembly. A mass flow of ~2 kg/s D_2O is necessary to cool the window and the target hull.

The window operates at a peak proton current density of 20 μA/cm² for a proton current of 2 mA onto a 60 mm long target-E. In the case of a 40 mm long target-E the peak current density at the window will be 40 μA/cm².

Thermal neutron flux in the SINQ D_2O-moderator at a radius of 25 cm in units of neutrons/cm²/sec/mA proton current onto the target *):

Target	**Flux (n/cm²/s/mA)**
Zircaloy rods	$0.52 \cdot 10^{14}$
Tungsten plates	$0.60 \cdot 10^{14}$
Lead-filled stainless steel tubes	$0.70 \cdot 10^{14}$
Liquid Pb-Bi with Steel container	$0.85 \cdot 10^{14}$
Lead-filled aluminium tubes	$1.00 \cdot 10^{14}$
"Ideal/Best" Pb target	$1.30 \cdot 10^{14}$

*) F. Atchison, Proceedings of the Specialists' Meeting on Accelerator-Based Transmutation, PSI-Proceedings 92-02 (1992) ISSN 1019-6447


Target
~10 kg/s D2O
Beam Window
~ 2 kg/s D2O
Target
Head
D2O ducts
Target plug
Shielding
Target hull
~ 15 KW/mA
Zircaloy Target
~ 400 KW/mA
Proton Beam
Window
Proton Beam
565 MeV; 1 mA
20
10
5
Proton beam density
[µA/cm2/mA]

Picture of the beam window

The photograph shows the beam window before welding. The target hull consists of two concentric shells, which are connected in the cylindrical section by bars. The spherical section forms the beam window. The mean diameter of the target hull and the spherical window is 200 mm. The thickness of each window is 2mm at the beam center and 4 mm at the edge. The gap between the two windows has a uniform width of 2 mm. Two flow guides at the inner window direct the flow to the center, where the power density is highest.

BEAM WINDOW FOR THE SINQ-TARGET

Beam window design

A CFD-analysis can be performed to calculate the thermo-hydraulic parameters. The fluid velocity in the beam region is approximately 6 m/s for a total mass flow of 2 kg/s of D_2O. In the figure the surface temperature of the window is plotted as a function of the heat flux. For a fluid velocity of 6 m/s and a saturation temperature of T_{sat} = 150 ^oC, the forced convection regime allows a heat flux of up to 4 MW/m^2, which corresponds in the case of a 2 mm thick aluminium window, to a peak current density of 280 $\mu A/cm^2$. Above this value subcooled boiling occurs [1], which enhance the heat transfer, The critical heat flux (burn out) [2] is expected at 10 MW/m^2, which corresponds to a peak current density of 700 $\mu A/cm^2$.

A FE-analysis can be performed to calculate the temperature and stress distribution within the window material.

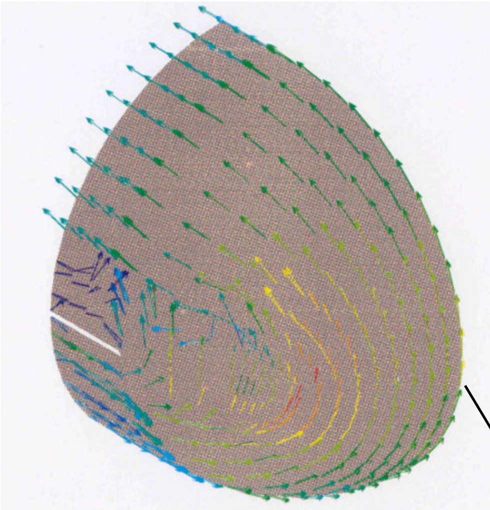
The figure shows the temperature distribution for a 3 mm thick window in the case of a fluid velocity of 4 m/s and a gaussian shape of the beam with a peak current density of 175 $\mu A/cm^2$. Subcooled boiling occurs at the beam window center.

The window material is subjected to a primary and a secondary stress component. The primary component is a static stress, which comes from the pressure load of the coolant. The secondary component is due to the cyclic heating by the proton beam. For a spherical window the primary stress is a pure membrane stress, which depends on the radius R and the thickness t of the window and the coolant pressure P. The secondary stress is a pure bending stress, which depends on the thermal gradients and on the properties of the window material.

[1] M.M. Shah, Generalized Prediction of Heat Transfer during Subcooled Boiling in Annuli, Heat Transfer Eng., Vol 4, no.1, 1983

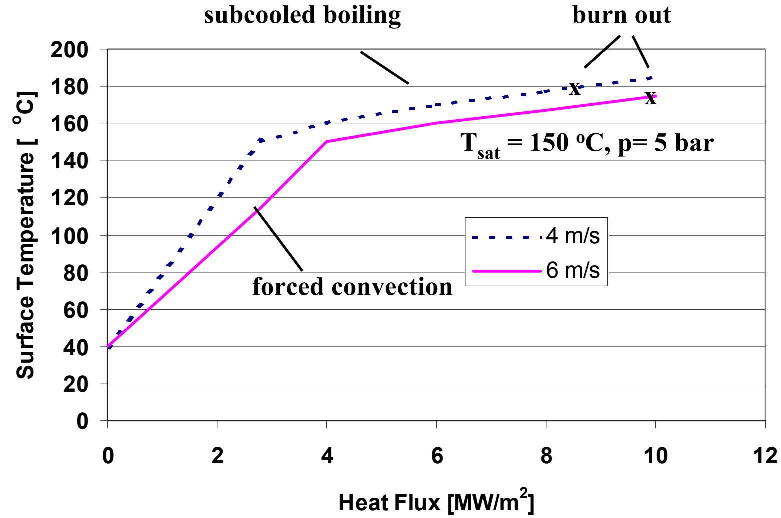
[2] S. Mirshak et al., Heat Flux at Burn-out, Du Pont de Namours, Savannah River, DP-355, 1959

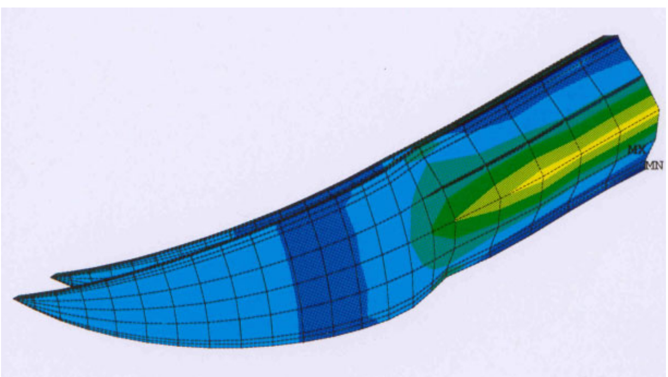
BEAM WINDOW DESIGN



CFD – ANALYSIS

- Fluid velocity
- Pressure loss
- Heat transfer





FE – ANALYSIS

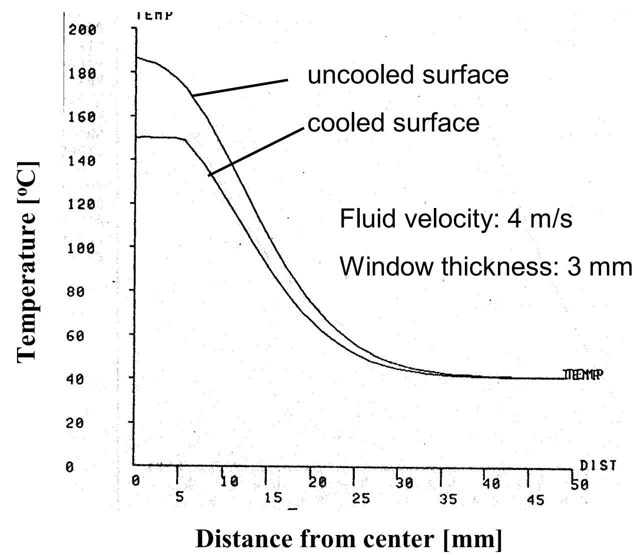
- Temperature distribution T(x)
- Primary stress :

  σ_p= PR/2t

-Secondary stress :

  σ_s= F(T(x),mech. properties)

Temperature distribution for a peak current density of 175 μA/cm^2



Strain limits of the beam window using elastic analysis

The results from the elastic analysis can be used to evaluate the strain limits of the window.

In the diagram the dimensionless stress parameters X and Y, the stress components normalized to the yield strength σ_{yp}, can be used to define four stress regimes [1].

Failure due to ratcheting occurs if the normalized stress lies in the region R, while plastic cycling occurs in the region P. Shakedown occurs after the first cycle in the stress regime S and purely elastic behavior is experienced in the stress regime E.

The dotted line shows the stress parameter for the present 2 mm thick window and a coolant pressure of 1 Mpa for various proton beam current densities. The behavior of the window material is purely elastic up to 100 $\mu A/cm^2$. In the stress regime S, up to 250 $\mu A/cm^2$, the window material yields, bu+t stress relaxation occurs after the first cycle. In the plastic cycling regime P, the window material is subjected to cyclic fatigue. The number of cycles to failure can be estimated from strain versus life curves. Above 350 $\mu A/cm^2$ failure is expected due to ratcheting.

[1] J. Bree, Journal of Strain Analysis, Vol.2, No.3, (1967), p.226

Operational limits of the 2 mm SINQ window:

Thermal limits:	**Peak current densities ($\mu A/cm^2$)**
Forced convection regime	$\leq$ 280
Subcooled boiling regime	280 $\leq$ 700
Critical heat flux (burn out)	700

Mechanical limits:	
Elastic cycling	$\leq$ 100
Plastic cycling ($\Delta\varepsilon_t \cong 0.4$ %)	
$\Rightarrow$ Nf $\cong 10^5$ cycles	250 $\leq$ 350
Ratcheting	> 350

STRAIN LIMITS USING ELASTIC ANALYSIS *)

R: Ratcheting regime:

- failure due to ratcheting

P: Plastic cycling regime:

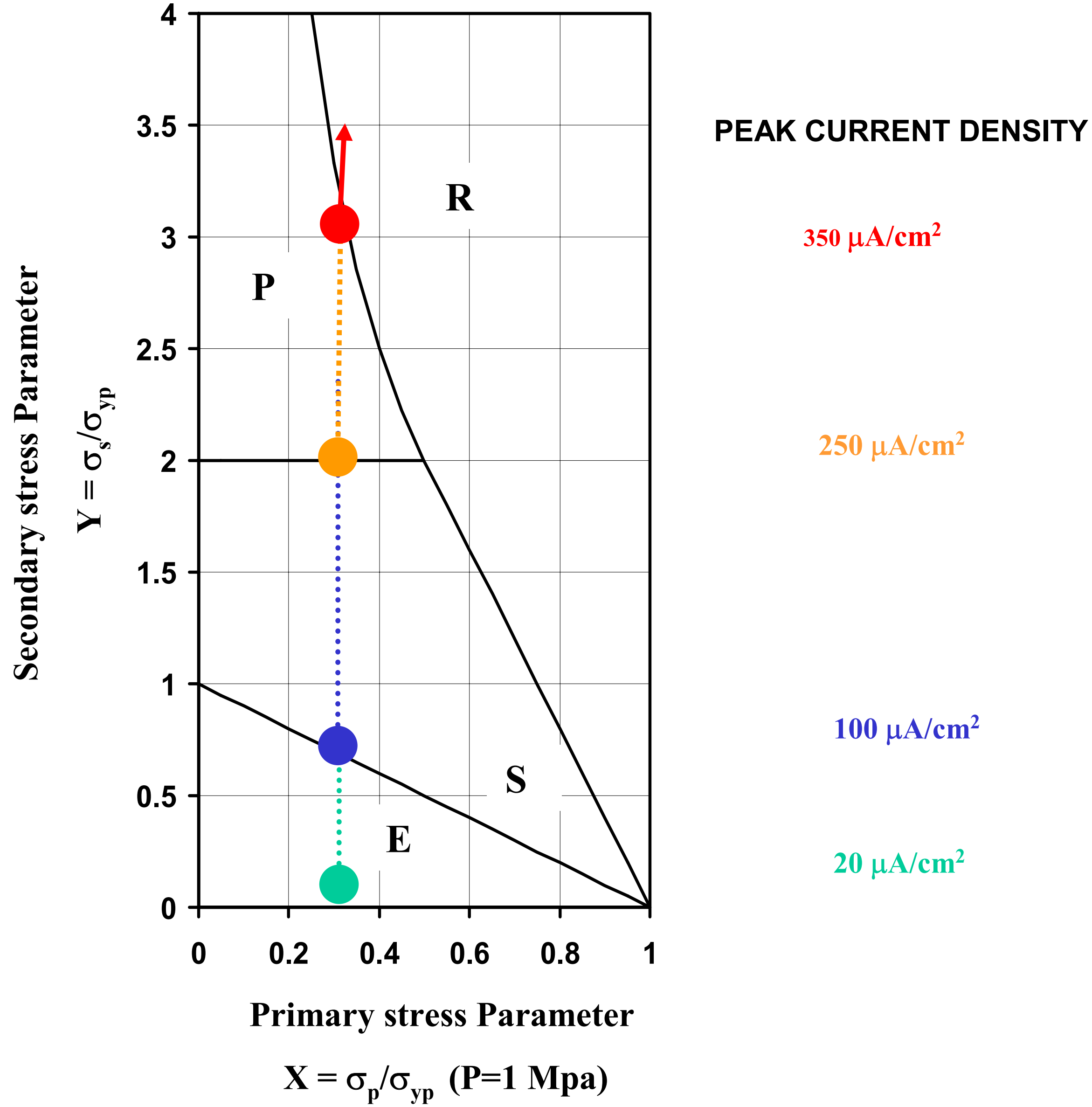
- cyclic fatigue from strain versus life curves

S: Shakedown regime:

- stress relaxation after first cycle

E: Elastic regime:

- purely elastic behavior



*) J. Bree, Journal of Strain Analysis, Vol.2, No.3, (1967), p.226