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Target Design and Technology for Research Spallation Neutron Sources

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Target Design and Technology for Research Spallation Neutron Sources

- A Sidestep into Reality -

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Target Design and Technology for Research Spallation Neutron Sources

Part 1: Solid Spallation Targets
Part 2: Liquid Metal Targets

Structure of Part 1

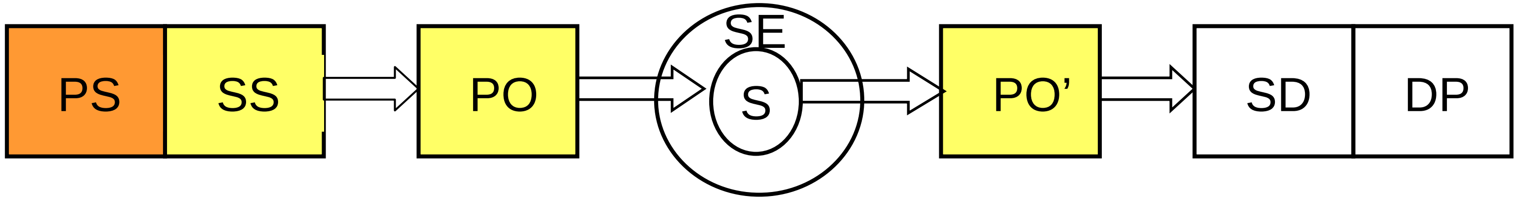
- General Introduction, Summary of Design Issues and Examples for Spallation Targets
- Radiation Damage in Target and Structural Materials
- Choice of Proton Energy, Power Deposition and Heat Removal from Solid Targets
- Some Candidate Target Materials
- Solid Spallation Target R&D at SINQ, PSI, Switzerland
- Summary on Solid Metal Targets Issues

General Introduction,
Summary of Design Issues
and Examples for Spallation Targets

Spallation Target for an ADS

- The spallation target will be a crucial component in all potential future ADS Systems.
- It has to withstand the highest thermal and radiation load density of all subsystems.
- Currently there is no proven design of a spallation target that would meet all requirements for an ADS in a satisfactory way.
- The only spallation targets so far realized are for *research spallation neutron sources* designed for neutron extraction through beam holes.
- Experience obtained with these systems should be highly relevant for ADS spallation targets.

What is a Research Spallation Neutron Source?

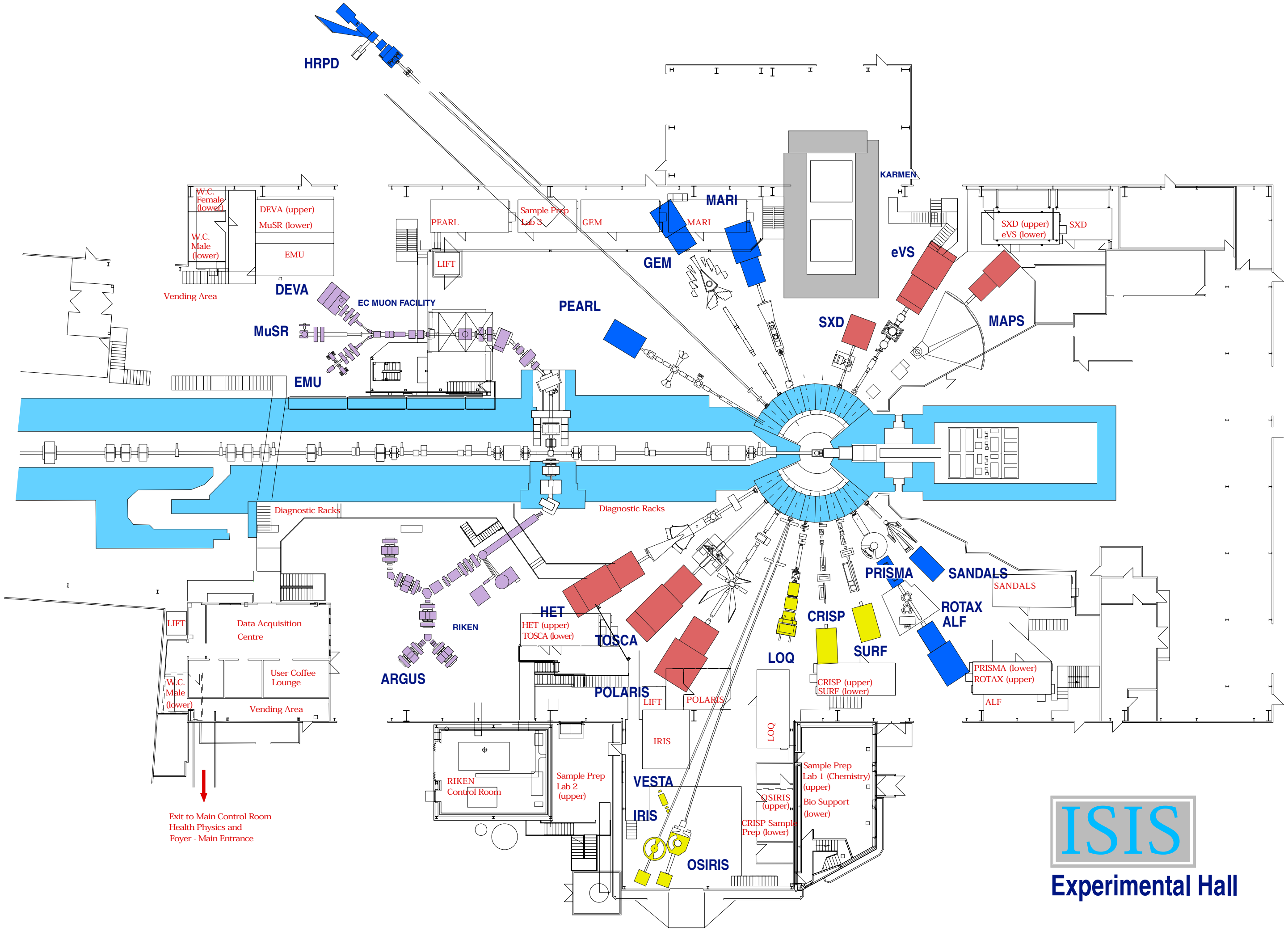


PS:Primary Source; SS: Secondary Source (Moderator); PO: Phase space operator; S: Sample; SE: Sample environment; SD: Signal detector; DP: Data processing

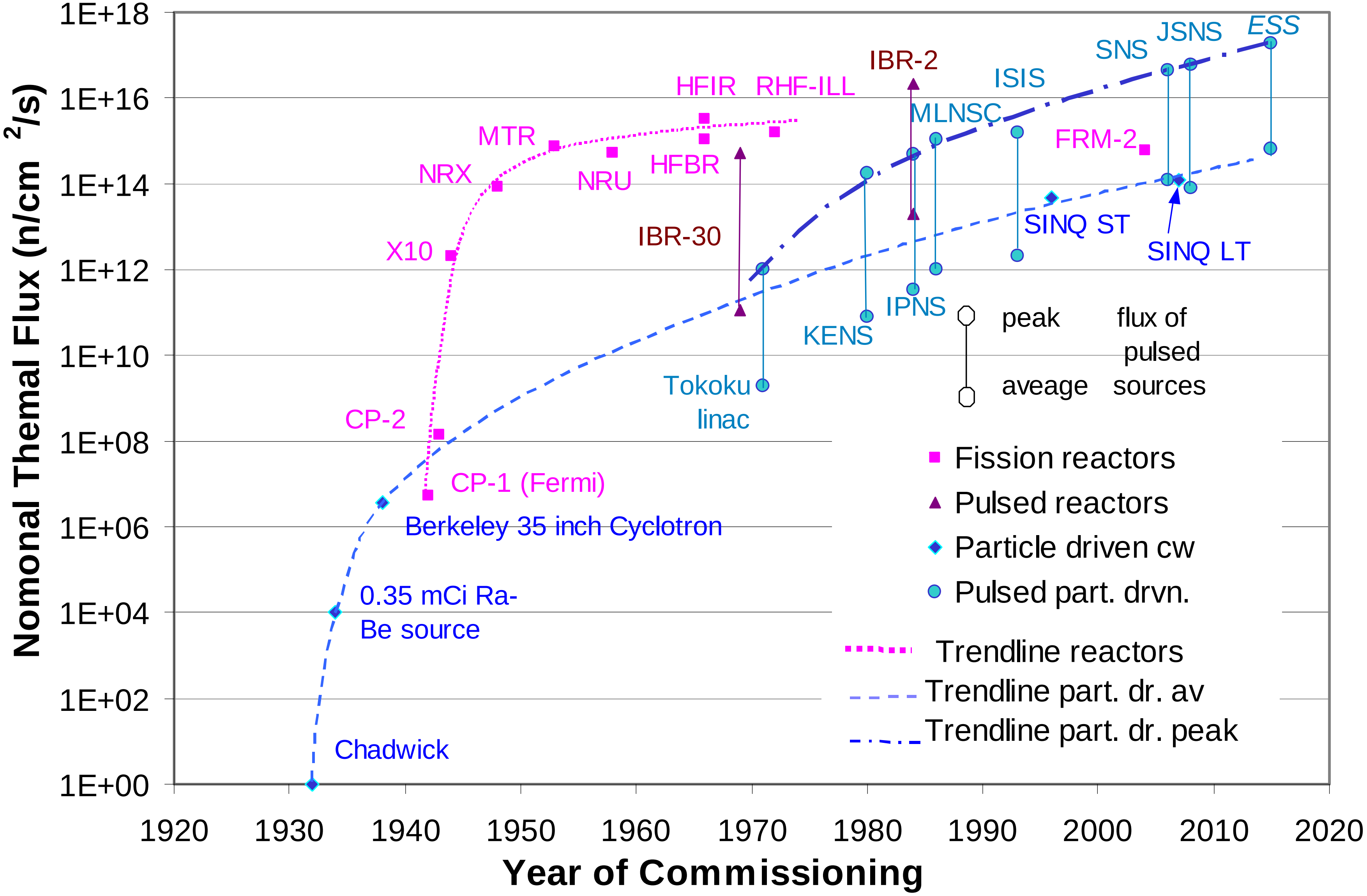
- A research spallation neutron source is essentially a replacement for a (beam hole) research reactor, optimized for neutron scattering experiments with slow (thermal or cold) neutrons.
- For many experiments the option of running a spallation neutron source in a pulsed mode offers significant advantages, which is one of the reasons why most recent research neutron sources are spallation sources.
- A certain flexibility exists to match the design of a spallation neutron source to the needs of the various types of neutron scattering experiments.

Footprint of the ISIS Experimental Hall (UK)

- an example for a research spallation neutron source -



Development of Neutron Sources ("Top of the Line")



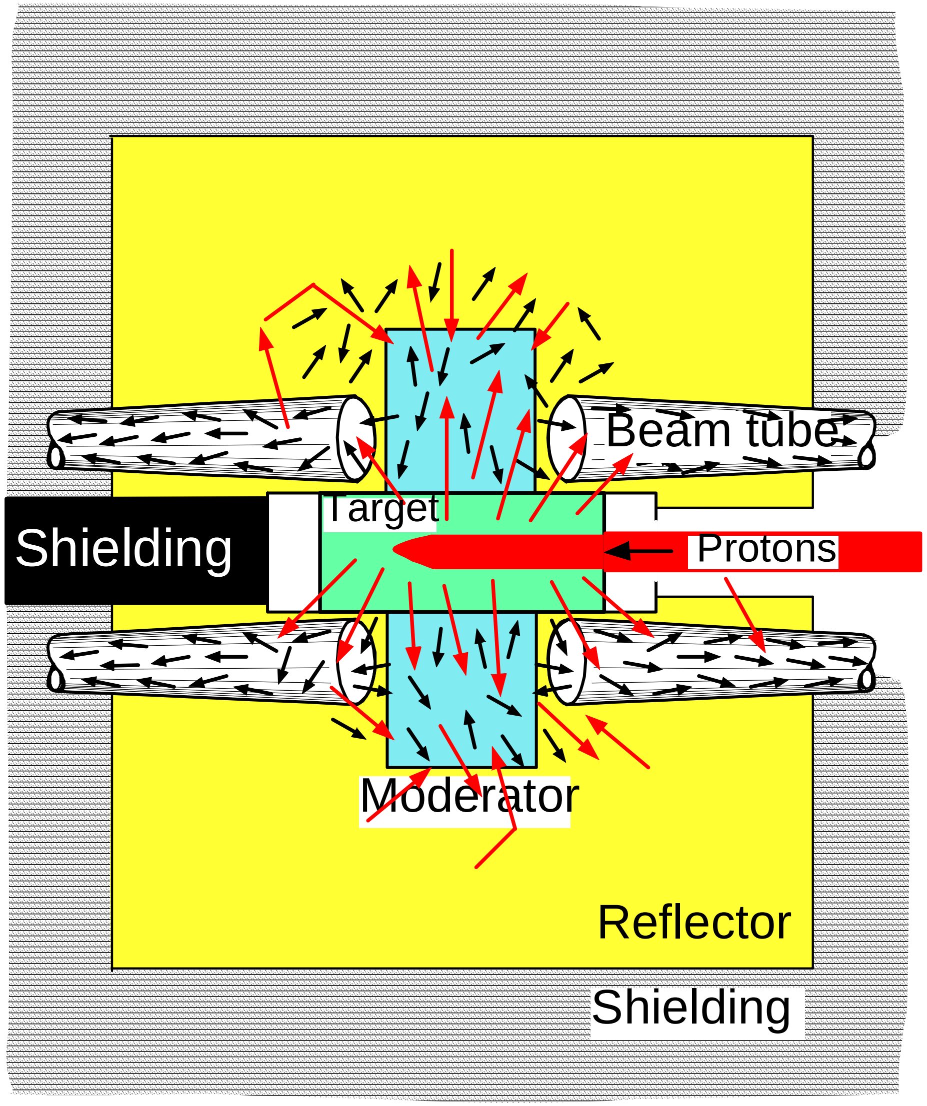
Spallation Neutron Sources

Arguments used in their favour

- No criticality issues
- No actinide waste
- Proliferation safe
- Advantage by exploiting time structure
- High degree of design flexibility (accelerator and target system)
- Less heat per neutron than other nuclear processes

- **But**
- Demanding shielding issues
- Extra complexity by need for an accelerator
- More distributed radioactivity (e.g. in cooling loops and shielding)
- Peak power density very high in the target!

The Main Components of a Research Spallation Neutron Source



The **target** should be optimised for neutron generation and coupling into the moderators

The **moderators** are designed according to users' needs for best output intensity at the desired neutron energy and time structure

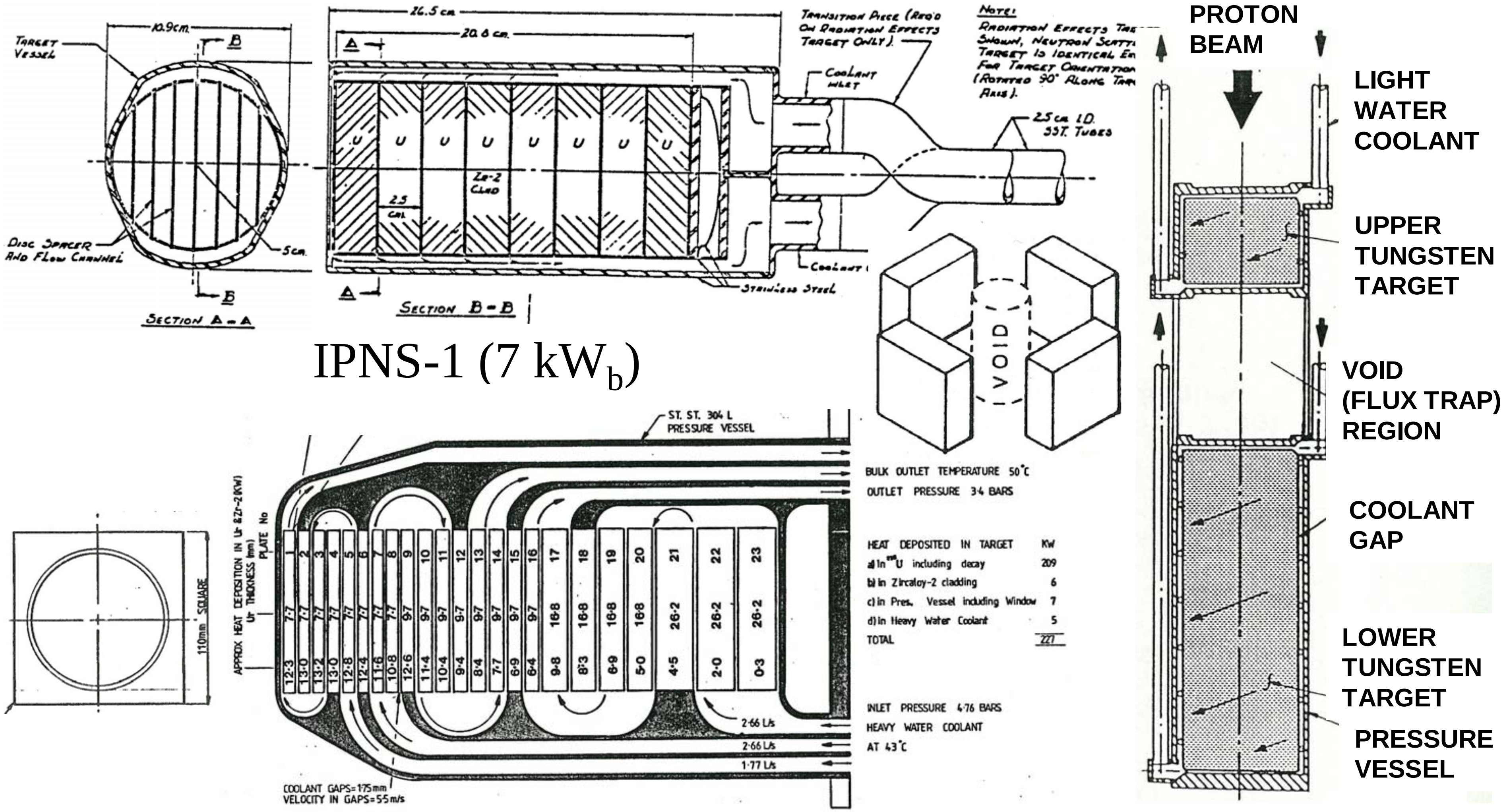
The **reflector** serves to enhance the neutron output from the moderator at minimum adverse effect on time structure

The **beam tubes** are arranged such as to avoid direct view on the target to minimize high energy neutron and γ-contamination

A Glance at History

Period	**Project**	**Beam power**	**Target concept**	**Satus**
1960ies	ING, Can.	60 MW	Flowing windowless LBE	cancelled
Late1970ies	KENS, Jap. IPNS, USA	3 kW 7 kW	Solid, W Solid U	EoL 2005 EoL 2008 (?)
	WNR, USA	80 kW	Solid W	operating
Early 1980ies	SNQ, Ger	5 MW	Solid Pb (U) Flowing windowless LBE	cancelled
	ISIS, UK	160 kW	Solid (U), (Ta), W	operating
1997 2006	SINQ, CH MEGAPIE	600 kW	Solid, Pb Flowing liquid, LBE	operating finished
Early 2000s	ESS	5 MW		deferred
	SNS, USA J-SNS, Jap	1.4 MW 1 MW	Flowing liquid, Hg	commissioning commissioning

Target Concepts of Existing Pulsed Spallation Sources



PROTON BEAM

LIGHT WATER COOLANT

UPPER TUNGSTEN TARGET

VOID (FLUX TRAP) REGION

COOLANT GAP

LOWER TUNGSTEN TARGET

PRESSURE VESSEL

IPNS-1 (7 kW$_b$)

ISIS (160 kW$_b$)
designed for 300 kW$_{th}$

WNR (LANSCE), 80 kW$_b$

Main Issues in Spallation Target Design

- The main purpose of a spallation target is neutron production
  - In the required quantity to serve the foreseen purpose
  - In the most suitable spatial distribution (point source, line source, etc.)
- The biggest design issues are heat removal and safety of operation, which mainly affect
  - The overall concept chosen (surface or volume cooled solid, liquid)
  - The amount of structural material required (e.g. afterheat removal)
  - The distribution of radioactivity in the system
- Another important aspect is source availability and cost of operation, which is affected by
  - Service life of the target (radiation effects, fatigue, other damage)
  - Time and effort required for target exchange

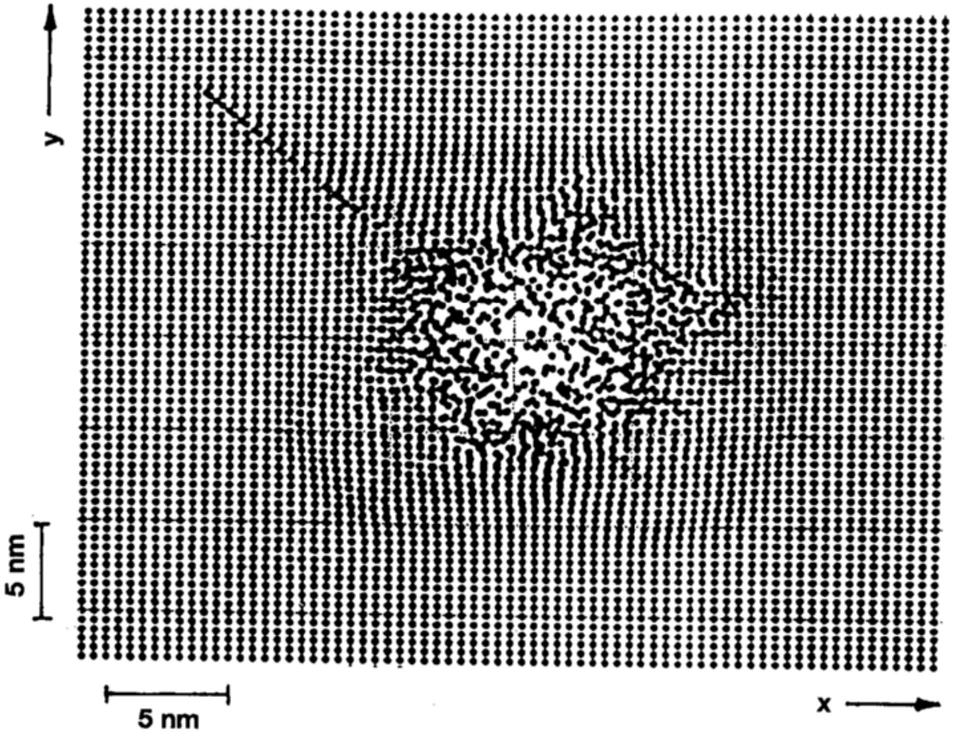
Finding an optimum solution for all this is a real challenge!

Radiation Effects in Target and Structural Materials

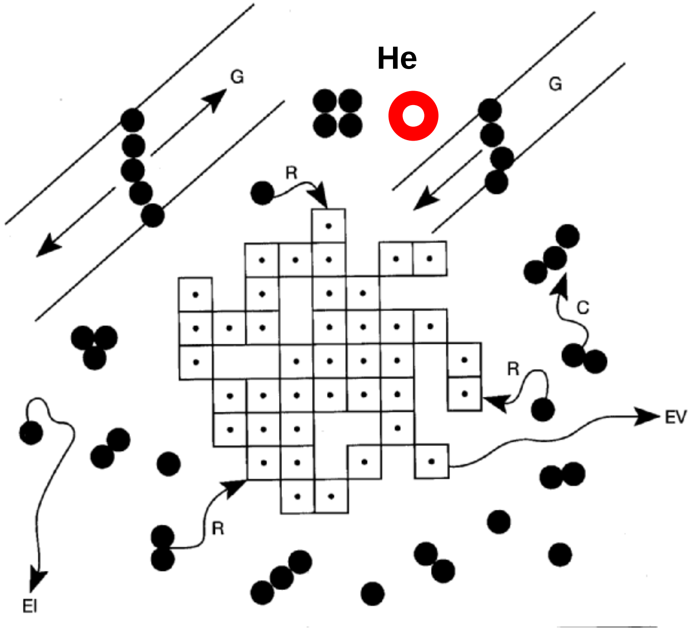
Radiation Damage in Target and Window Materials (1)

Radiation damage effects are caused by 2 elementary interactions of the irradiating particles with the atoms of the solid:

Atomic displacements („dpa“) and nuclear reactions (n,p; n,α; spallation → foreign elements „appm“)

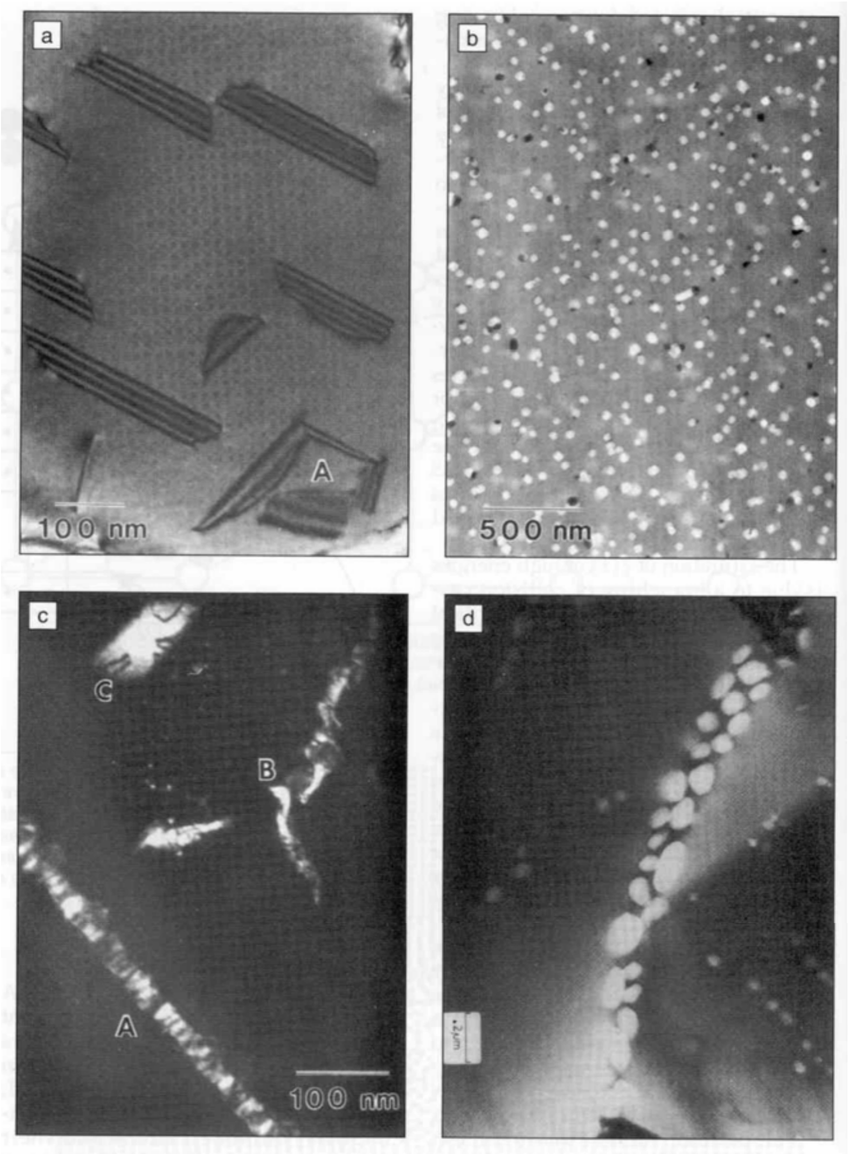


Molecular dynamics simulation of a displacement cascade produced by a 10 keV primary knock-on event in an fcc lattice (Ghaly and Averback).



Schematic representation of the defect arrangement in a displacement cascade

Radiation Damage in Target and Window Materials (2)



Transmission electron-microscopy micrographs of typical radiation-induced secondary defects in metals:

a) Dislocation loops

b) Voids

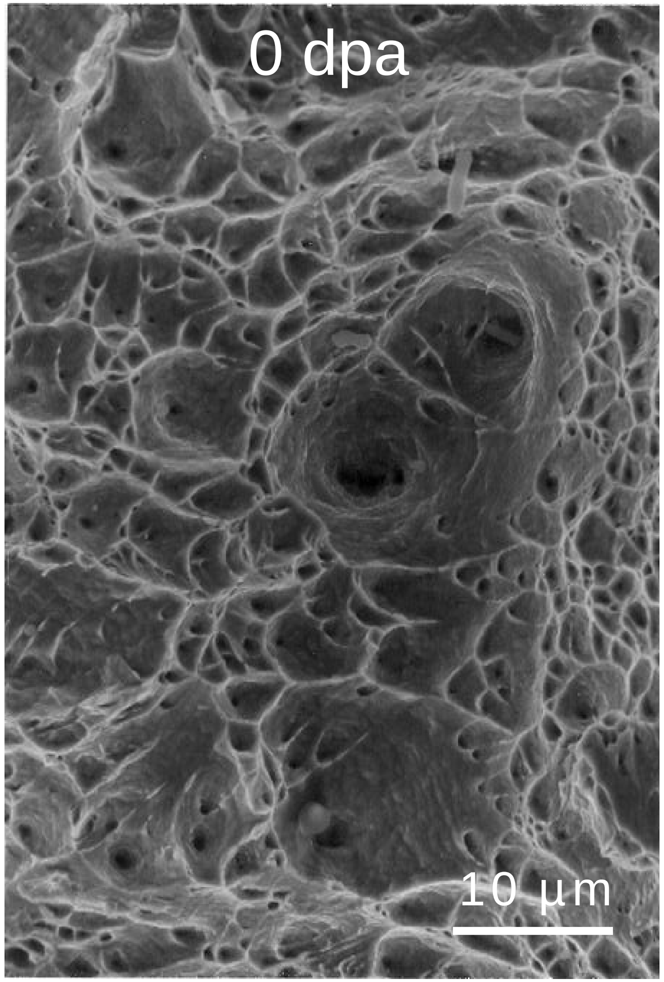
c) Precipitates

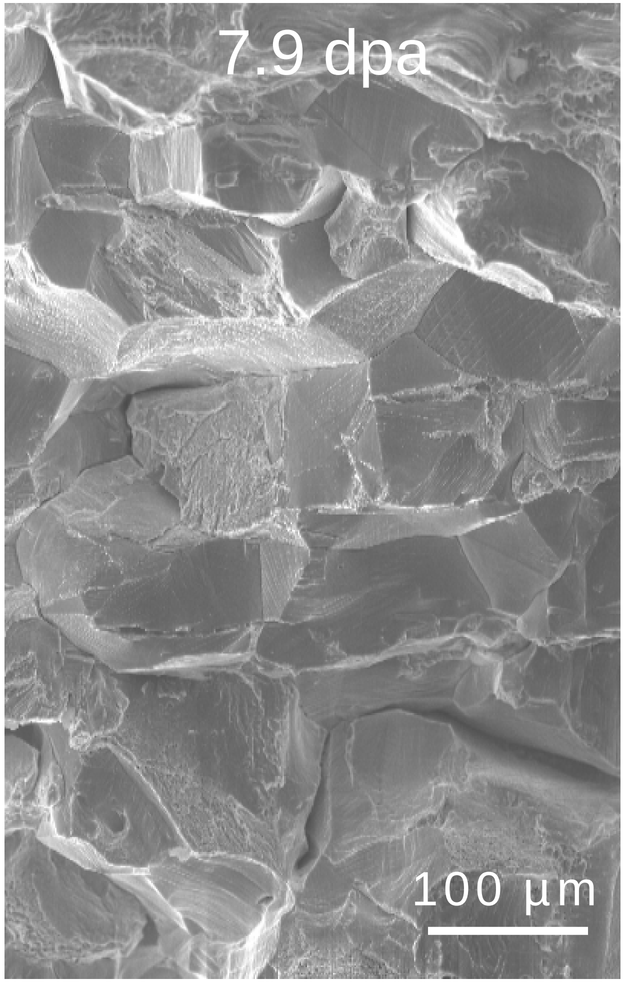
d) Helium bubbles

All these effect lead to hardening and/or embrittlement of the material

Radiation Damage in Target and Window Materials (3)

Fracture surface of 304L after tensile test at RT

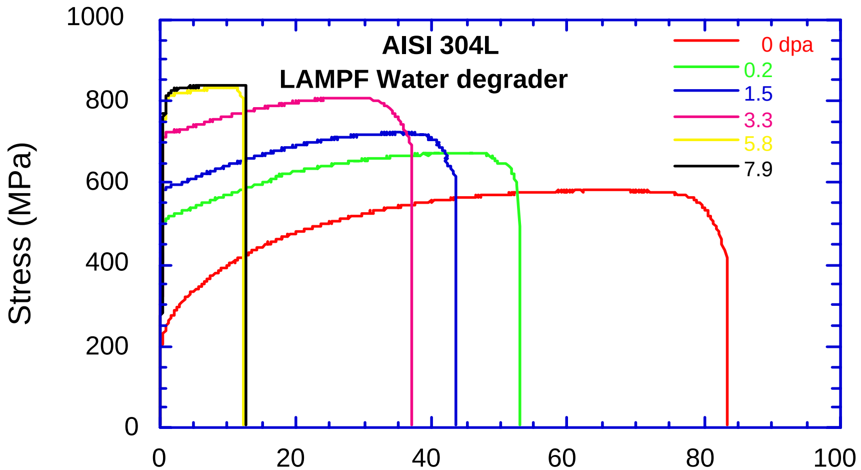


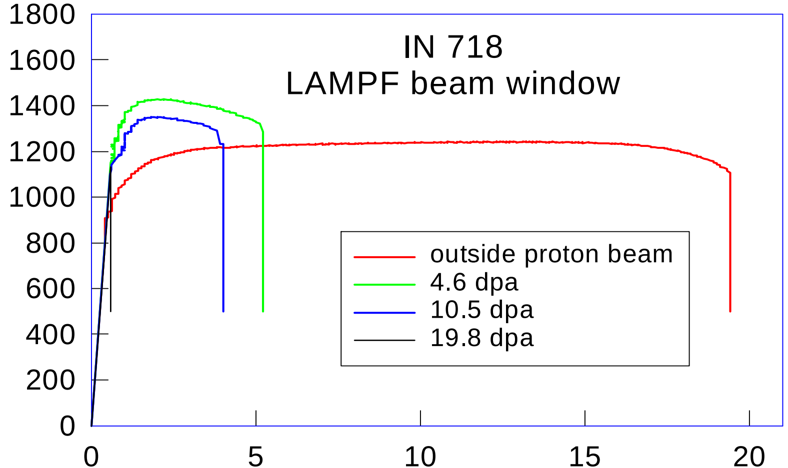


Radiation Damage in Target and Window Materials (4)

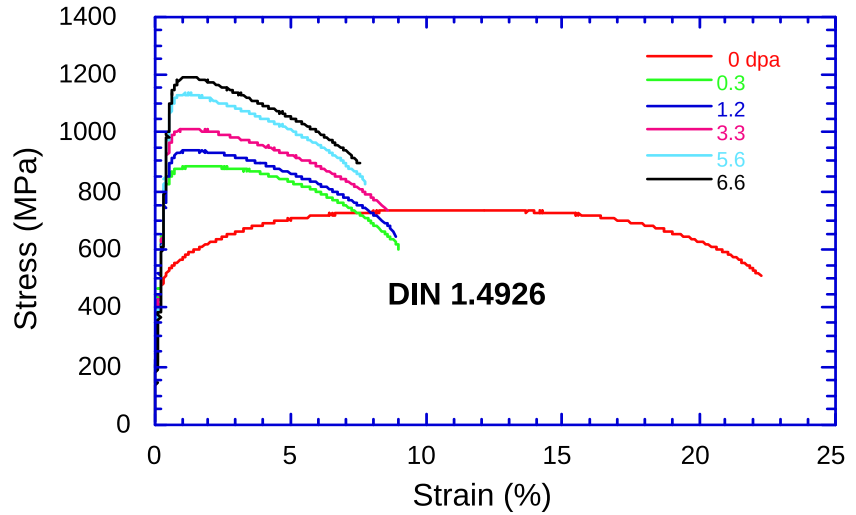
Stress-strain curves for different spallation structural materials after irradiation

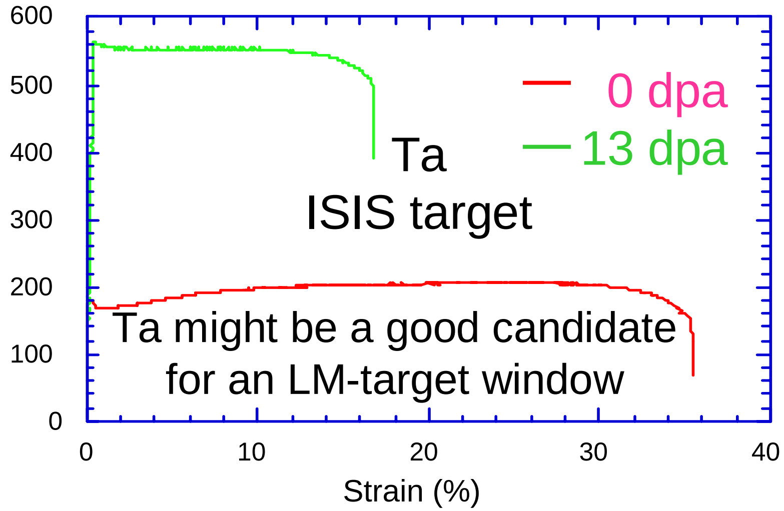
J. Chen, FZJ-IFF





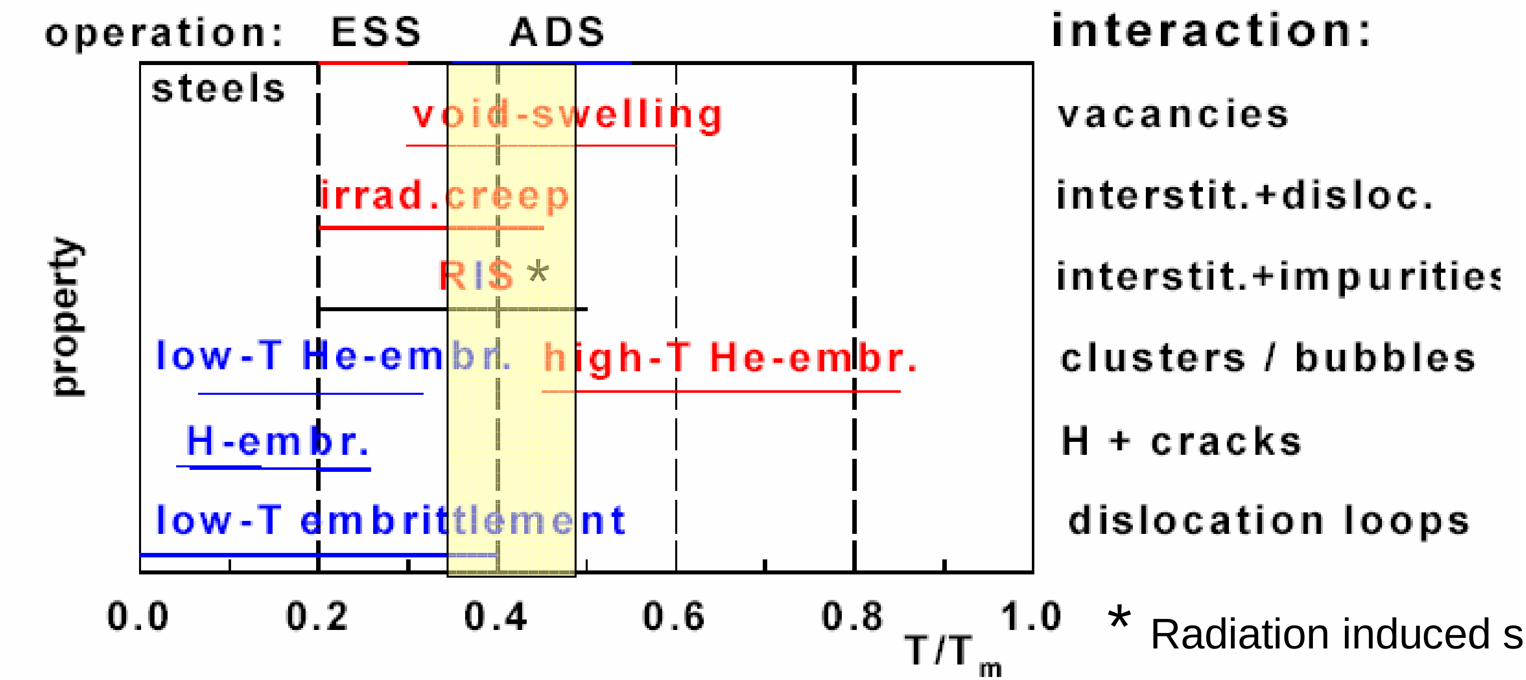
ESS-beam window: 0,16 dpa/d in steel (80 μA/cm^2 @ 1.33 GeV)





Ta might be a good candidate for an LM-target window

Radiation Damage in Target and Window Materials (5)



T_M(a) ca 1700K
T_M(f) ca 1800K

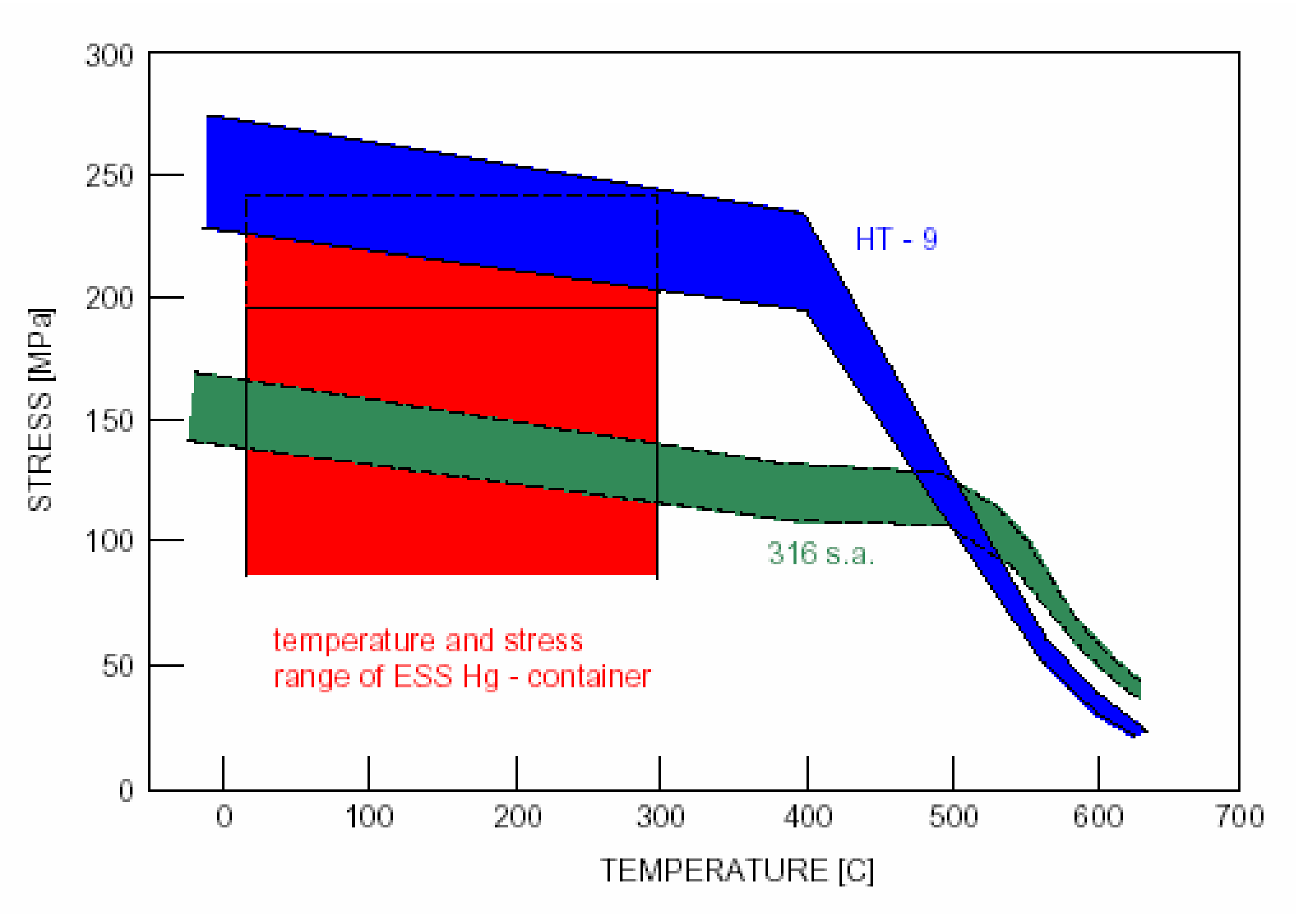
* Radiation induced segregation

Red / blue: most prominent in austenitic / ferritic-martensitic steel

At the operating temperatures of target components, most irradiation-induced defects or defect clusters are mobile and can react with one another. Such defect reactions lead to changes in the microstructure, which in turn cause (mostly detrimental) changes of the properties of the material. They occur in ranges of homologuous temperature (T divided by the melting temperature T_m), which are rather independent of the material.

Target Structural Materials: Allowable Stress

Recommended design stress (for the fusion reactor first wall) as a function of temperature.

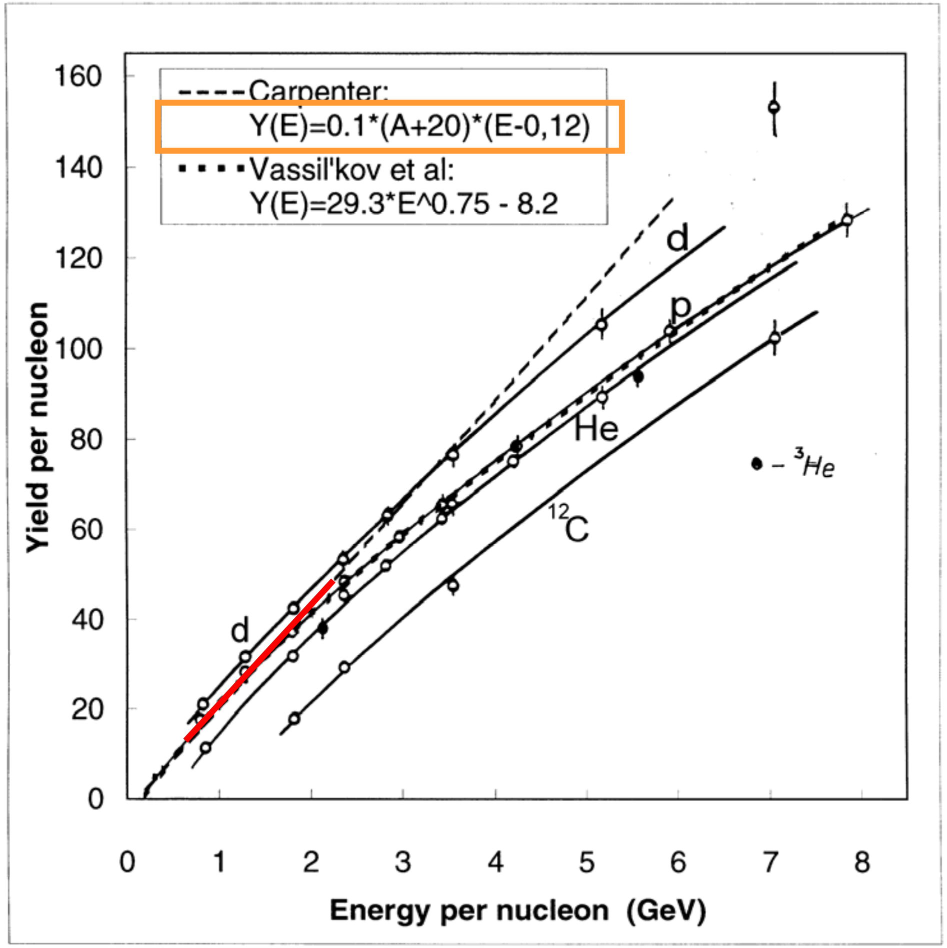


The strength of martensitic steel HT9 (and also of austenitic 316) decreases rapidly above 400 (500)°C (670-770K).
This is about 0.3 (0.5) T_M

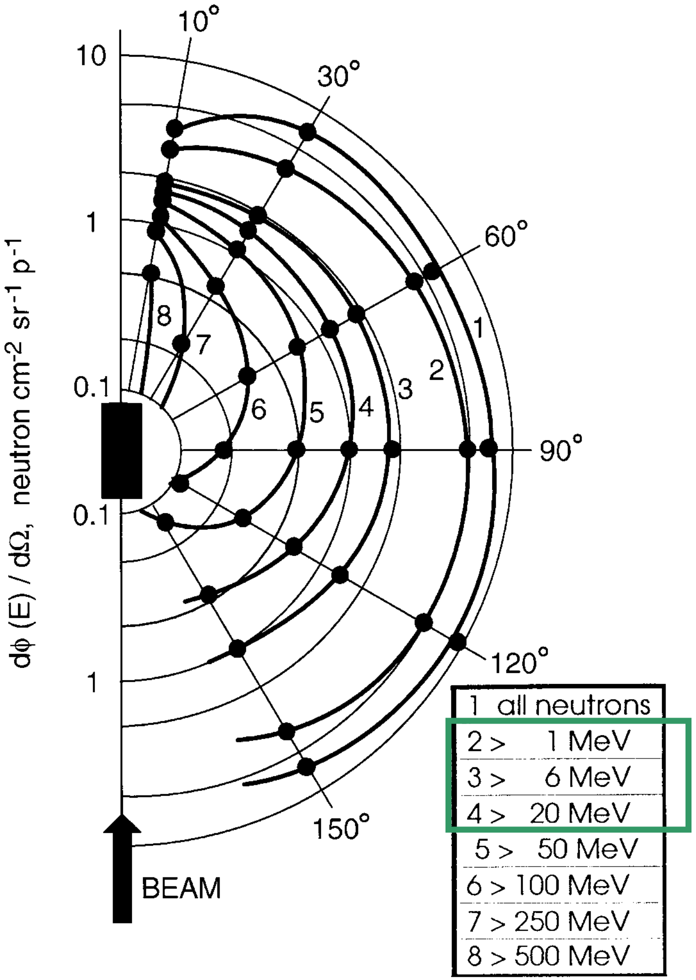
Radiation damage is most prominent at low temperatures

Choice of Proton Energy,
Power Deposition
and Heat Removal from Solid Targets

Spallation Neutron Yield and Angular Distribution

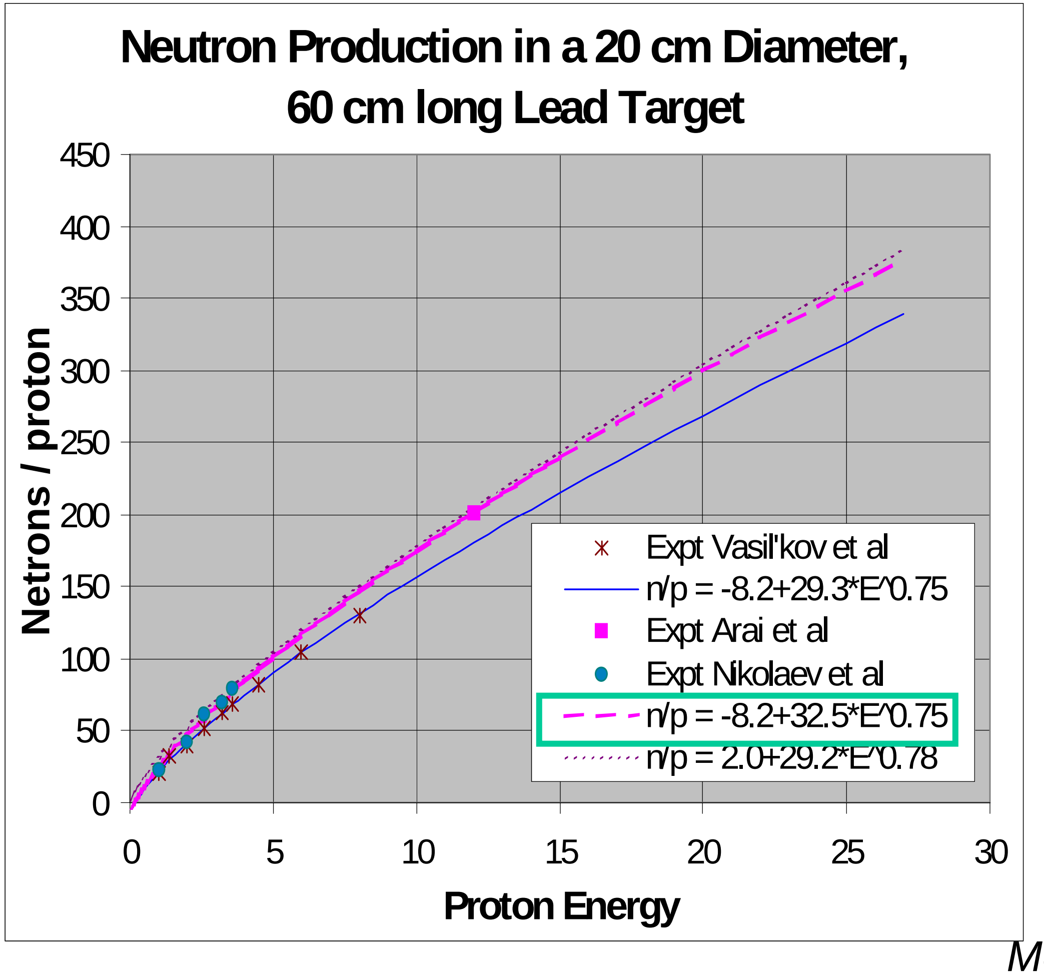


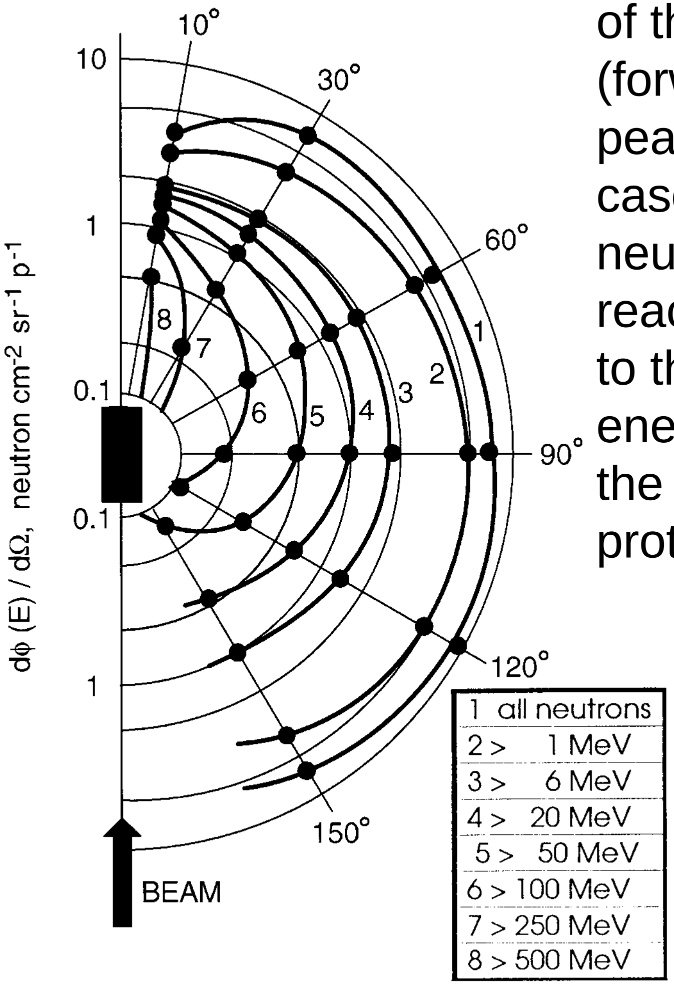
Measured neuron yield from thick lead targets



Measured angular distribution of neutrons in different energy groups for a 20 cm diameter lead target bombarded by protons of 2 GeV

Spallation Neutron Yield and Angular Distribution

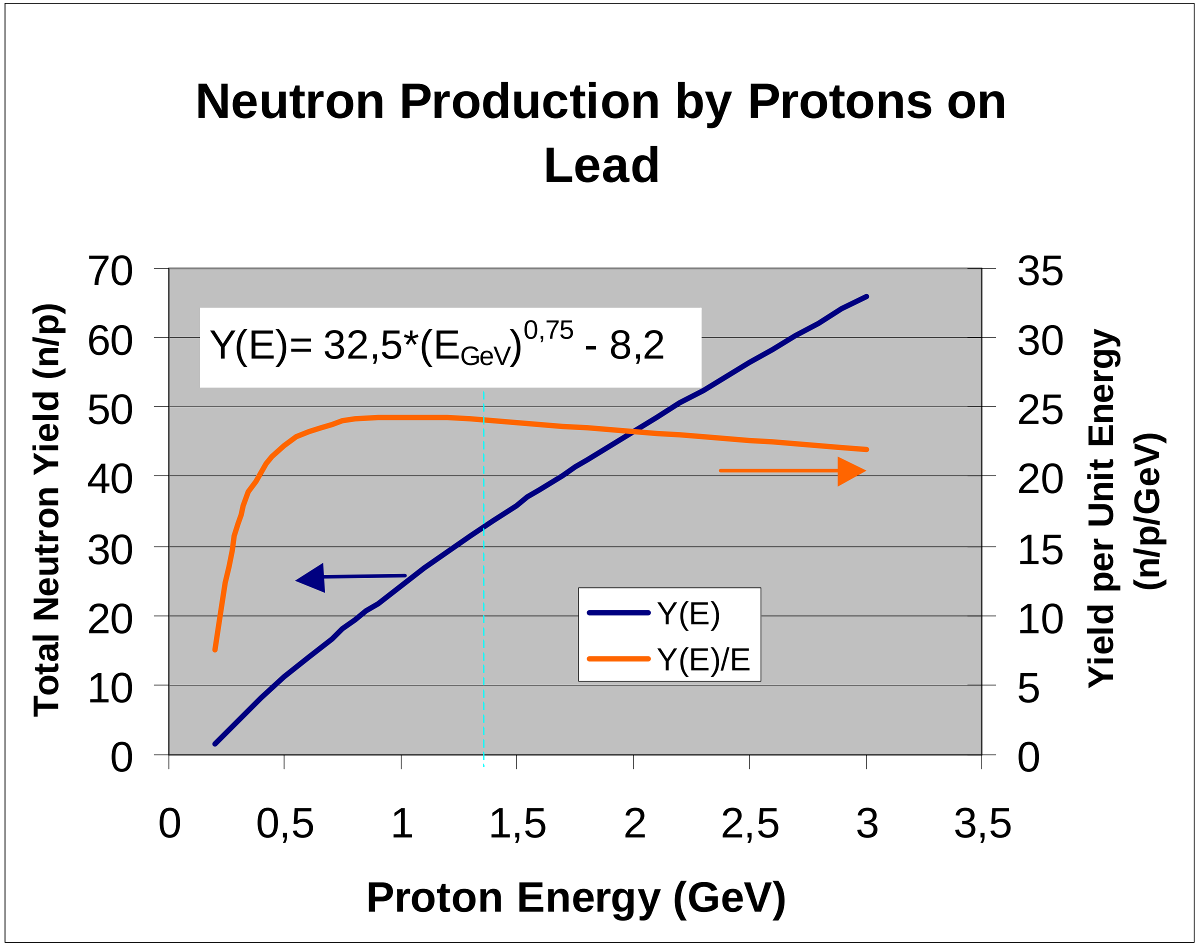




The energy of the (forward peaked) cascade neutrons reaches up to the energy of the incident protons!

Measured angular distribution of neutrons in different energy groups for a 20 cm diameter lead target bombarded by protons of 2 GeV

Choice of proton energy



Arguments for higher proton energy:

Easier to accelerate to higher energy than to increase current (in particular with circular accelerators)

Radiation damage in target window scales roughly with number of protons, not with beam power.

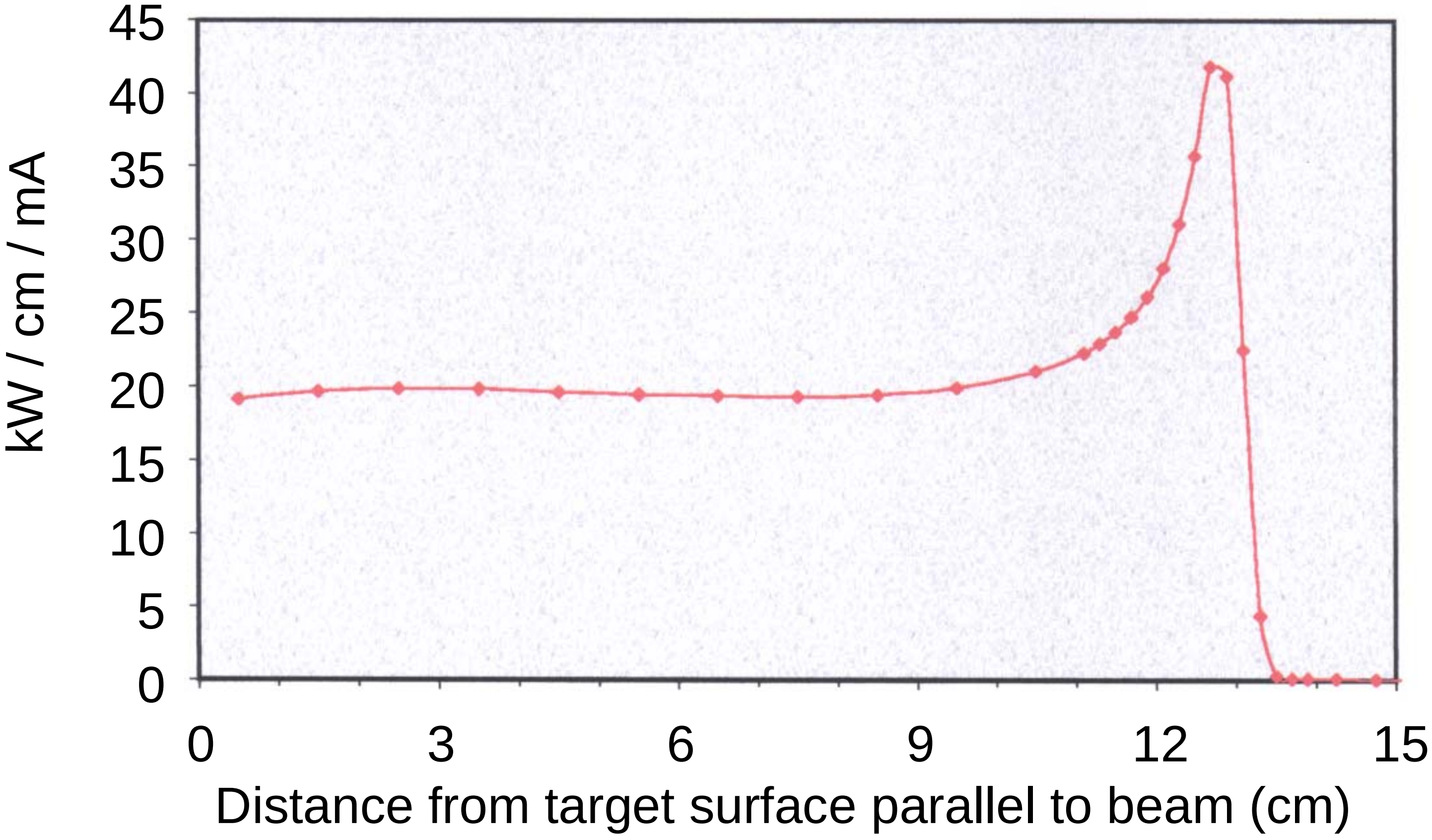
No “Bragg” peak above 600 MeV

Heat dissipation in the Spallation Target

- The attenuation of the beam in the target is governed by cross sections. This results in an essentially exponential decrease of intensity along the target axis, with a high peak load near the target head (heat deposited by recoil nuclei).
- Other sources of heat deposition (absorption of γ–radiation, pion-decay etc.) may be distributed differently throughout the target volume.
- Ionization losses due to the proton charge are inversely proportional to the proton energy and are most important for low beam energies (a few hundred MeV → “Bragg”-peak at the end of range).

Axial Distribution of Power in a Spallation Target

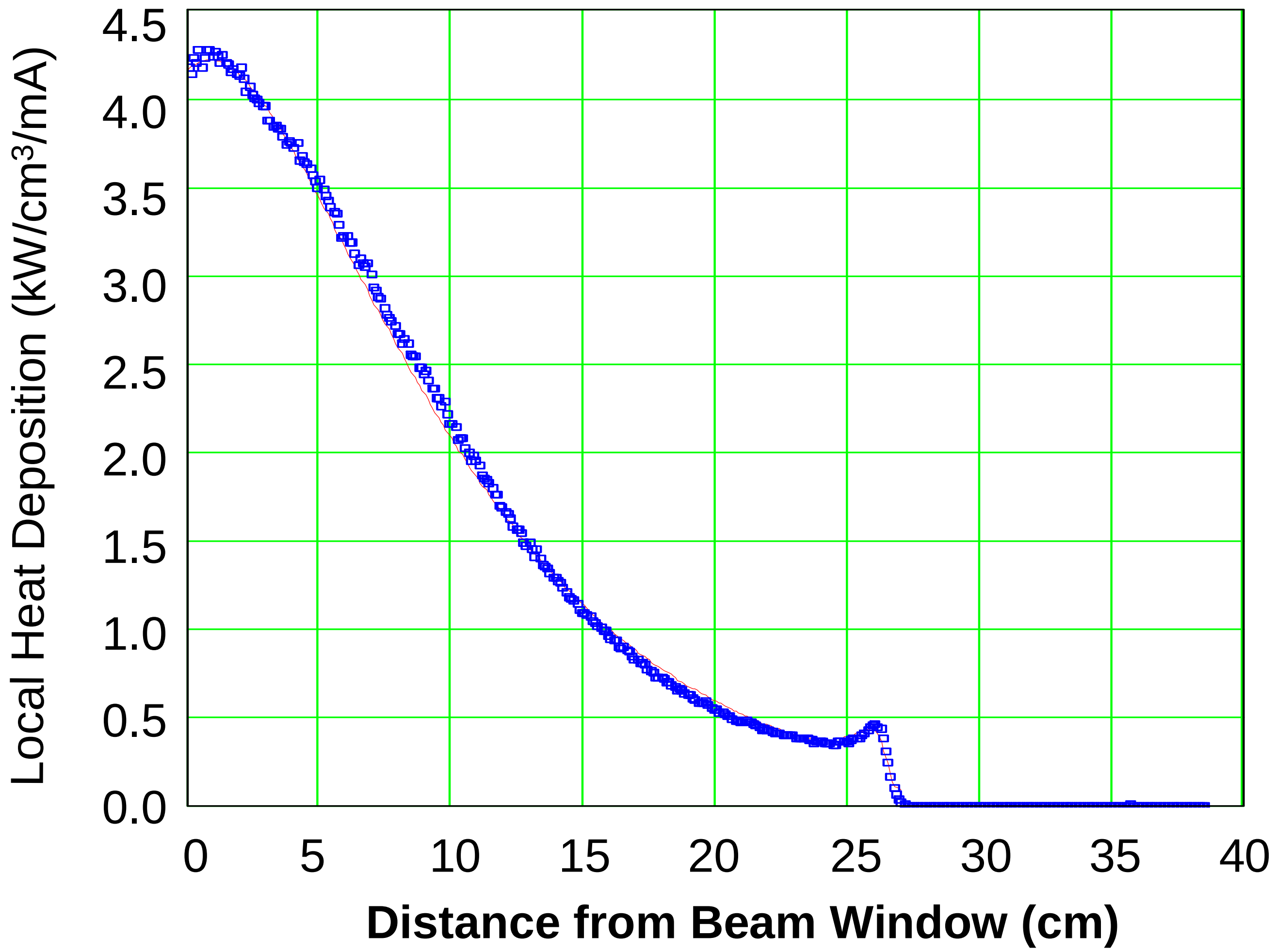
Power deposition by 450 MeV Protons in PbBi
(MYRRAH, integral over beam cross section)



$$\frac{\mathrm{kW/cm^3}}{\mathrm{mA/cm^2}}$$

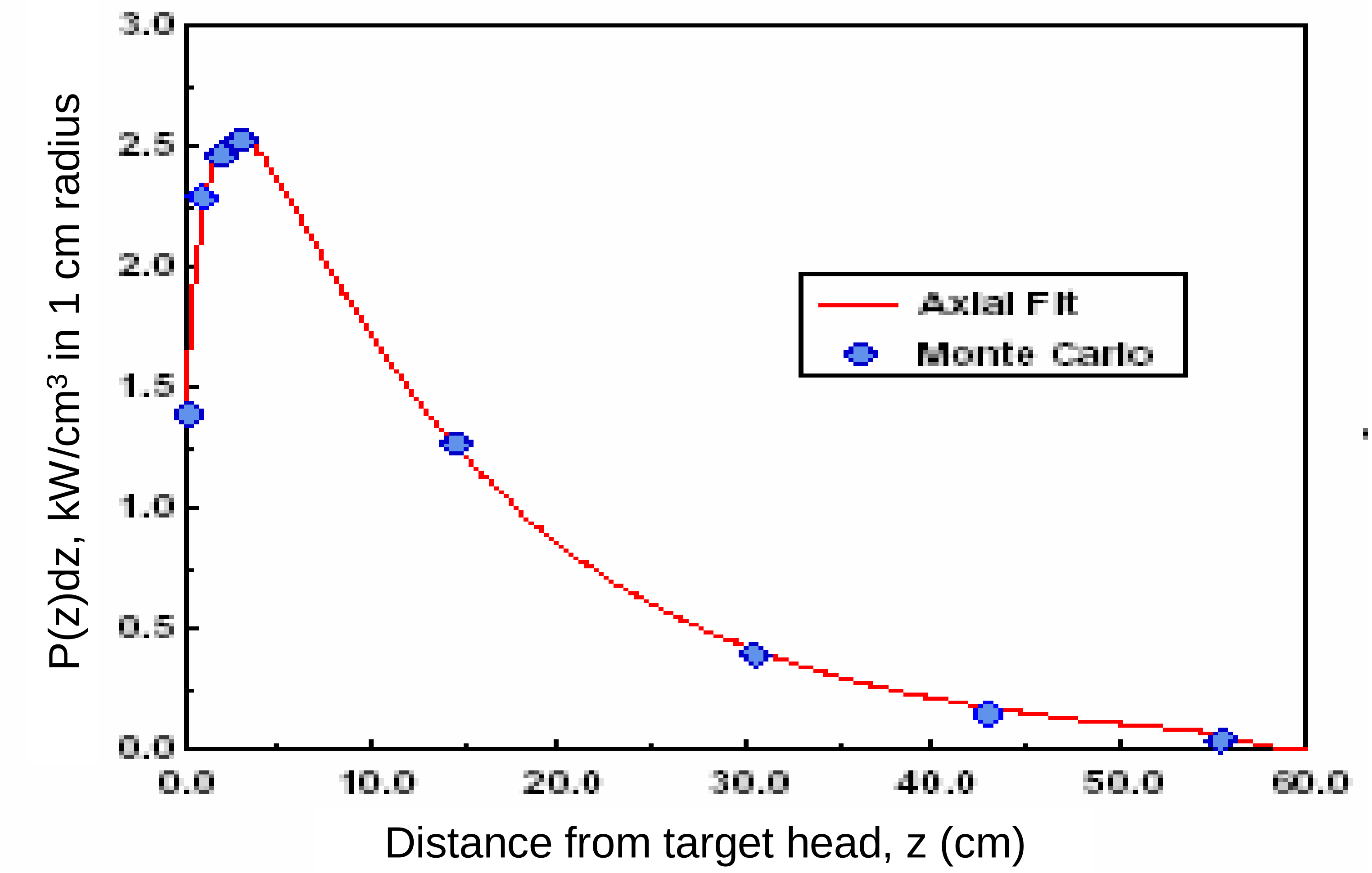
Axial Distribution of Power in a Spallation Target

Power deposition along the axis of the MEGAPIE Target (575 MeV protons)



Axial Distribution of Power in a Spallation Target

Power density in the central cylinder of 1 cm radius along the proton beam in a 5 MW_b spallation target (ESS, E=1.3 GeV)

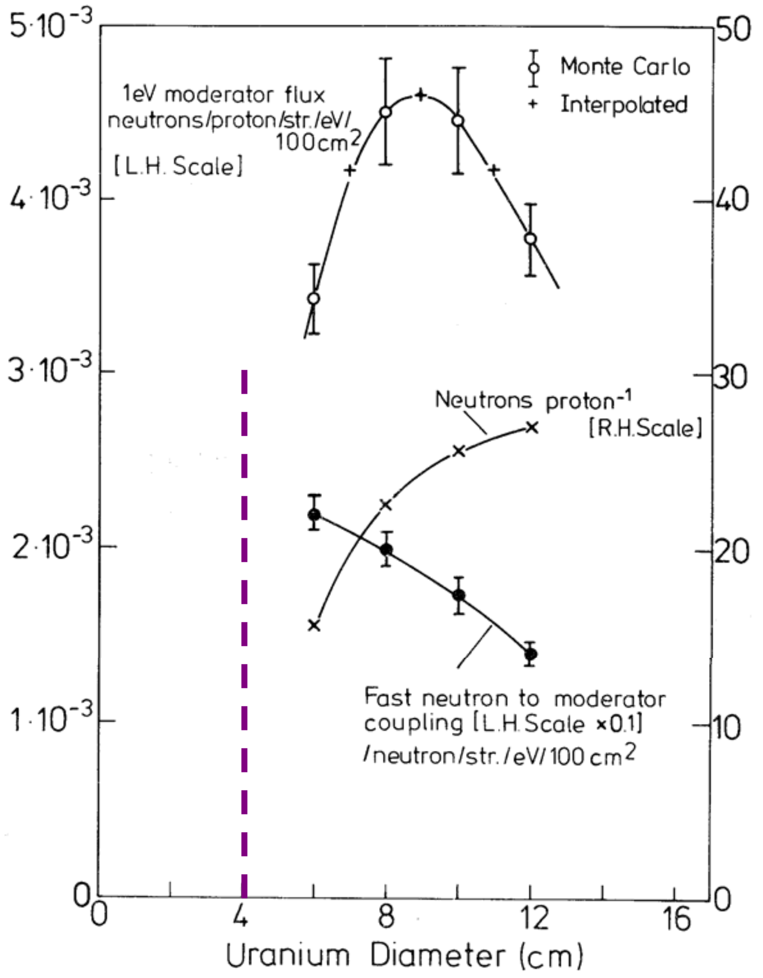


Spallation Targets : Beam Energy and Distribution

- At low E (<3 GeV), yield increases approximately linear with energy. At constant power a higher energy allows a lower current, resp. current density.
- A current density of 100 μA/cm^2 is presently considered an upper allowable limit in terms of heat deposition and stress in Al-alloys, but may be high for heavier materials.
- Target geometry (diameter relative to beam diameter) is important; there exists an optimum with respect to neutron leakage current density from the target surface.
- For reasons of power density, relatively large beam cross sections become necessary in high power targets. In this case slab targets with an elliptic beam footprint are the preferred option.

Optimization of the ISIS Target Diameter

Proton beam intensity distribution: parabolic with 4 cm FWHM

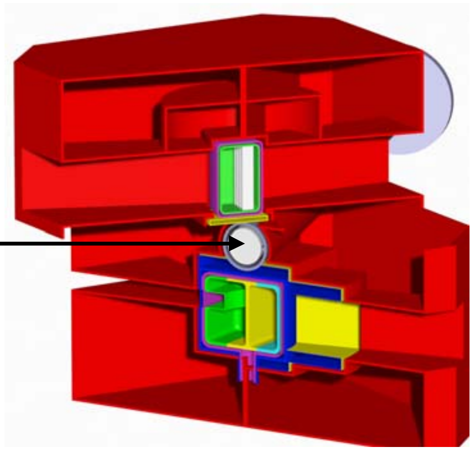


F. Atchison, 1979

The diameter of the ISIS-1 target is optimised for a U-Target (300 kW), which yields fission reactions throughout the target volume.

Secondary reactions by cascade particles in non-fissile materials occur mainly in the forward direction.Every target-moderator system must be optimized individually.

For the ISIS-2 target station (60 kW) a Ta-clad tungsten target of 6 cm diameter has been selected.

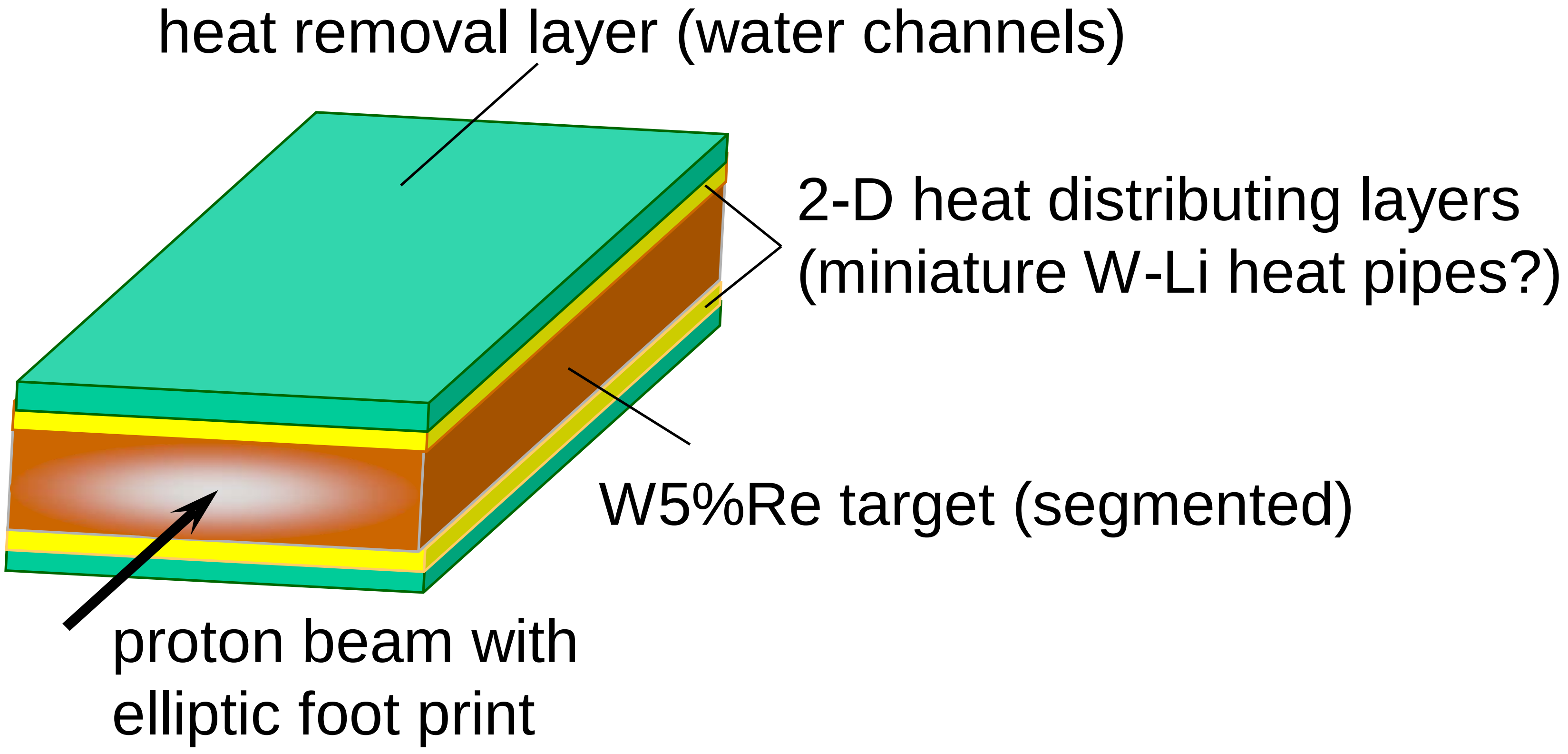


6 cm diameter
Ta-clad W-target

The AUSTRON Target Concept

High temperature *segmented* massive target for 500 kW_b

An elliptic footprint is chosen for maximum neutron leakage through the target top and bottom surface at a manageable peak beam current density


heat removal layer (water channels)

2-D heat distributing layers (miniature W-Li heat pipes?)

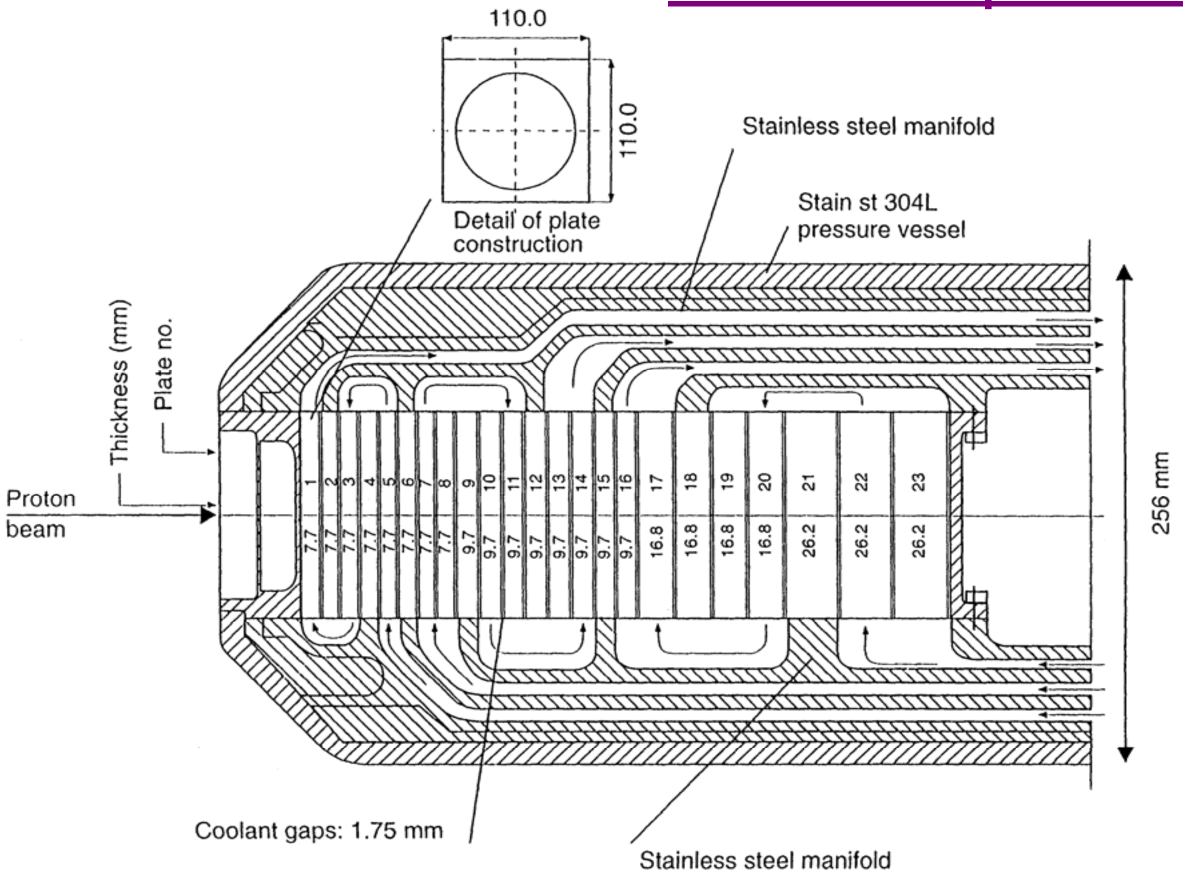
W5%Re target (segmented)

proton beam with elliptic foot print

Heat Removal From Plate Type Targets

Plate targets are in use at ISIS (160 kW_b) and IPNS (7 kW_b)

The ISIS plate target



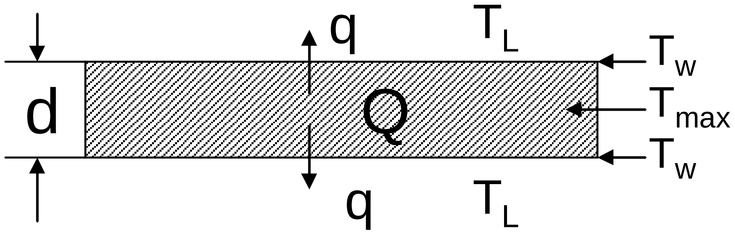
In order to minimize coolant content in the target volume plates have graded thickness along the proton beam as the power deposition decreases

Heat Removal From Plate Type Targets

In a 1-D approximation (heat flux perpendicular to the target surface only) the heat flux on the surface is

$$q = \underline{Q \cdot d}/2 = h \cdot (T_w - T_L).$$

T_w and T_L wall and coolant temperatures
h heat transfer coefficient
d plate thickness



Approximating the mean distance of heat transport by half of the heated region (d/4) the temperature drop from the plate center to the surface becomes

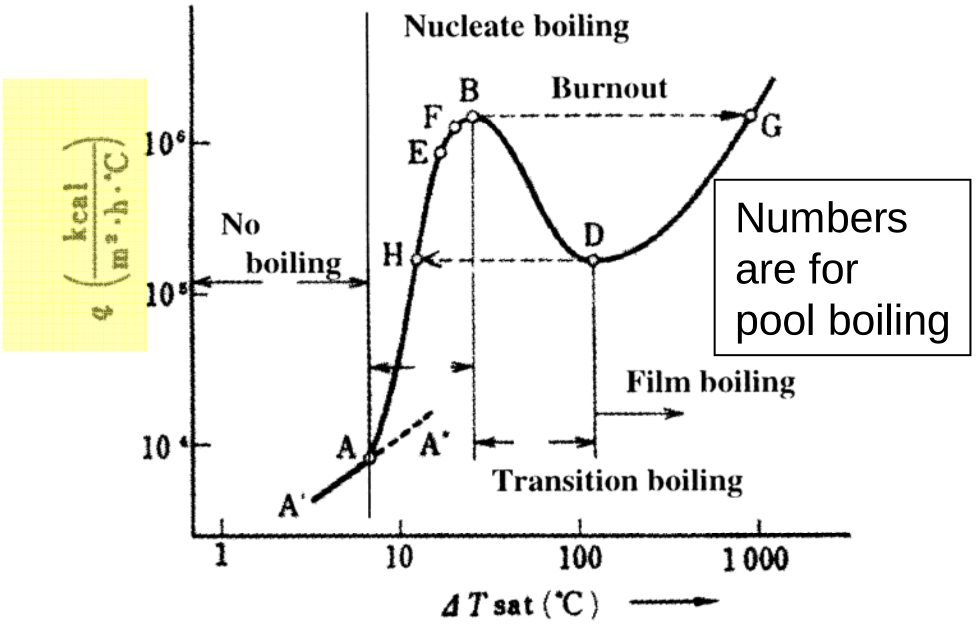
$$T_{\max} - T_w = \frac{1}{8\lambda_s} \cdot \underline{Q \cdot d^2}$$

λ_s thermal conductivity.

Stress in plate surface is proportional to T_{max}-T_w!

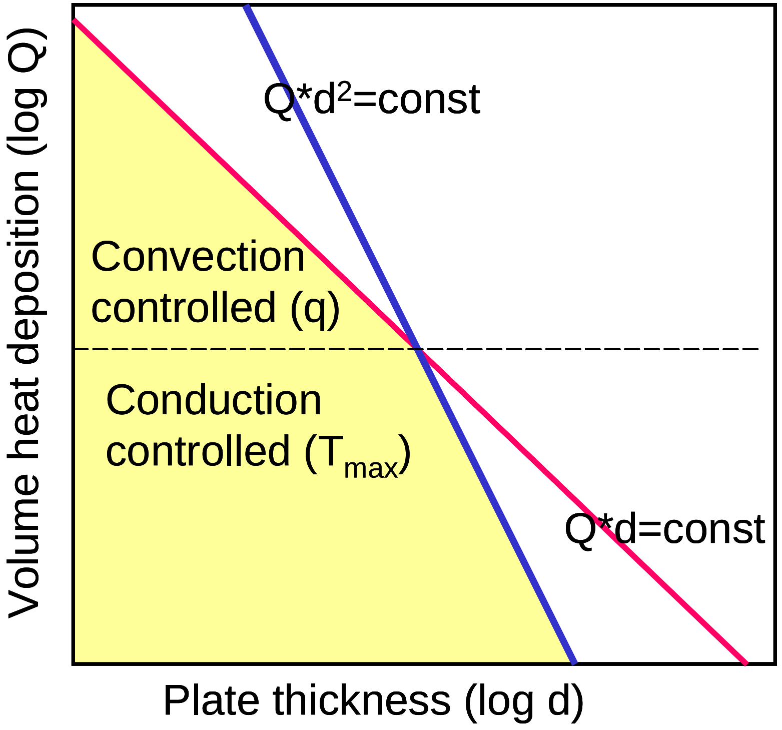
Heat Removal From Plate Type Targets

Depending on whether heat flux density (protection against burnout) or maximum centre line temperature (surface stress, materials properties) is the limiting condition, we have $Q \bullet d = const.$ or $Q \bullet d^2 = const.$



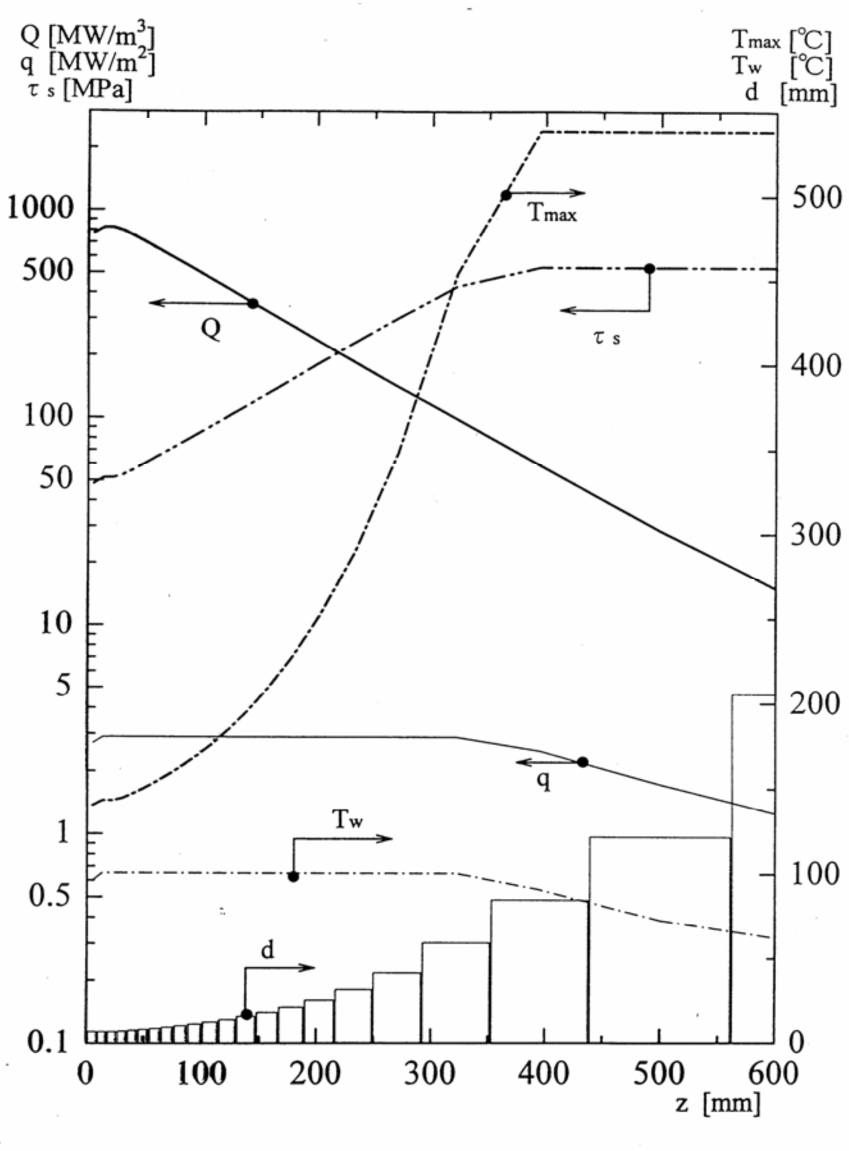
Numbers are for pool boiling

The boiling curve: A: onset of nucleate boiling; E: departure from nucleate boiling; B: burnout point; Conventional design stays below point A.



The heat transfer limitations in plate target design.

Heat Removal From Plate Type Targets



1D-design of a 600 kW, 3 GeV plate target [*]. Flow velocity in the cooling channels 10 m/s; wall temperature 100°C, max. allowed center temperature 538°C; allowed heat flux density 300 MW/m^2. Up to the transition from convection limited to conduction limited the surface heat flux is constant, above the transition T_{max} is constant.

* N. Takenaka, KEK Proceedings 98-5 III (1998) pp 37-40

Some Candidate Target Materials

Spallation Neutron Yield

Based on available experimental data the following formula has proposed for the neutron yield Y as a function of proton energy and target material in the energy range between 0.5 and 2 GeV (Carpenter, 1975):

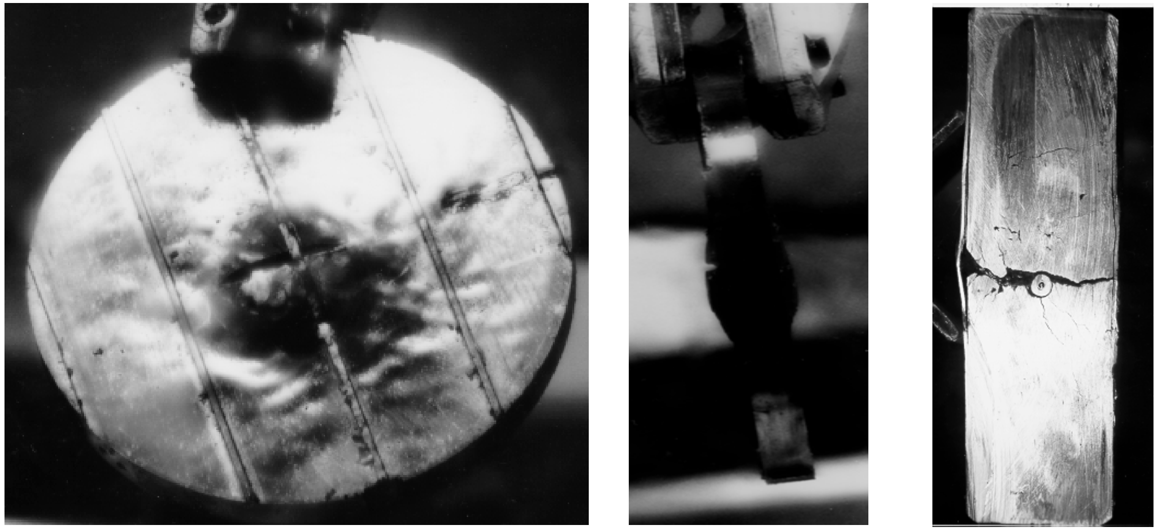
$$Y(E,A) = a*(E_{GeV} - 0.12)*\boxed{(A+20)}\ n/p$$

$$\text{with } a = \begin{cases} 0.18 \text{ for } {}^{238}U \\ 0.1 \text{ for } Z \leq 90 \end{cases}$$

Although ${}^{238}U$ has a higher neutron yield than lower Z materials it is difficult to use as a spallation target due to its high heat generation (from fast fission) and because of metallurgical problems

Experience with U-Targets at IPNS and ISIS

- Uranium (depl.) has about 2x higher neutron yield than other heavy metal **but:** much higher energy dissipation due to fission and formation of actinides.
- U-Targets have so far been used in low power spallation neutron sources only (KENS, P_b = 3kW, IPNS, P_b = 7kW, ISIS, P_b = 160 kW)
- Experience is poor, *all targets failed after less than 250 mAh of beam loading* . Reason is not clear (thermal cycling?, H-production? other causes?)



Failed Uranium Target Disks from ISIS and IPNS

(T.A. Broome) (J.M. Carpenter)

Spallation Target Materials: ^{238}U-10%Mo

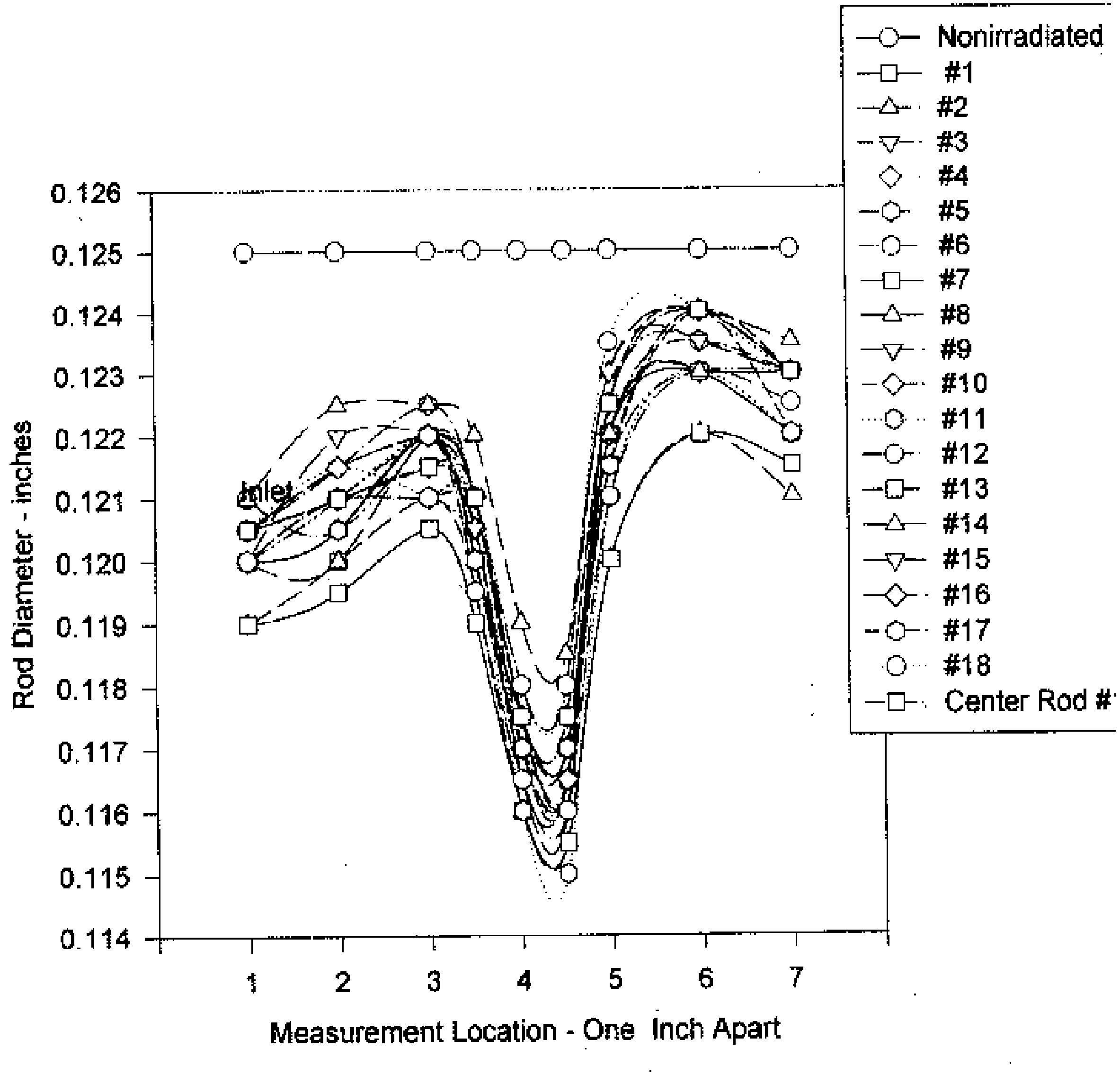
- Gamma-stabilised U-10%Mo was examined in the RERTR-program up to 70% burn-up with the material remaining stable.
- Expected to yield 1.7x more neutrons as a spallation target than best lower Z materials.
- Studied as a target material for the German SNQ project (early 1980ies).
- Proposed for closer examination within the Long Wavelength Target Station studies in the US SNS proposal.
- If found a suitable target material, this might be a candidate in high power applications in connection with a heavy liquid metal coolant to avoid neutron slowing-down in the target.
  (speculative! - combining the worst of both worlds?).

Another issue with ^{238}U-targets is the production of actinides by neutron capture (different licensing regime than lower Z materials!).

Spallation Target Materials: Tungsten

- Z = 74, A=183.84, d =19.3 g/cm³, T_m=3410°C
- Tungsten targets (surface cooled block) have been in use at KENS and MLNSC (LANSCE).
- Gives the brightest neutron source of all non-fissile materials due to its high density
- Reduction of thermal conductivity under irradiation
- Between 800 and 1500°C, W reacts with water forming hydrogen and a volatile aerosol: $W\ (s) + 4H_2O\ (v) \Rightarrow WO_2(OH)_2\ (g) + 3H_2\ (g)$.
- Experience at MLNSC shows that W corrodes strongly when irradiated in contact with water.

Spallation Target Materials: Tungsten



3 mm diameter W-rods irradiated at the LANCE radiation effects facility to a maximum fluence of 2x10^{21} p/cm^{2} in cooling water flowing from left to right. Tungsten concentration in the cooling water increased to 35 mg/l over the 24 days irradiation period.

(W. Sommer, 1997)

Spallation Target Materials: W5%Re

- Z = (74), A=(184), d=19.4 g/cm³, T_m=3300°C
- Proposed for the AUSTRON target
- Expected to retain good thermal conductivity under irradiation (in contrast to pure W, in which spallation products have a negative effect).
- Little experience on irradiation behaviour, preliminary results seem to indicate severe embrittlement (W-10%Re).
- Specimens have been irradiated in the SINQ target (STIP-program)

Spallation Target Materials: Tantalum

- $Z = 73$, $A=180.95$, $d=16.6\ g/cm^3$, $T_m=3000°C$
- Ta was used as a target material at ISIS (plate).
- Ta is very resistant to corrosion, also against liquid metals, and is relatively easy to machine and EB-weld.
- Embrittlement of Ta in a spallation spectrum is not clear (pure Ta from used ISIS target was still very ductile after 13 dpa).
- High absorption cross section (thermal and resonance) reduces effective yield and makes used targets very radioactive (afterheat!).
- Ta cladding for W targets developed at KENS and ISIS.

Spallation Target Materials: Solid Bismuth

- Z =83 , A=209, d= 9.75 g/cm³, T_m=271.3°C
- Very low neutron absorption (0.034 barn)
- α-active ^{210}Po is created from two neutron captures
- Contracts upon melting (d_{liqu}=10.07 g/cm³)
- Rather corrosive when molten, very brittle when solid
- Has never been proposed as spallation target material in elemental form
- Neutronically, Bi in Zircaloy-cladding with D_2O cooling might be the ultimate solid target for continuous or long pulse spallation sources up to a few MW_b

(Zy is now being tested as cladding for Pb in the SINQ-target)

Spallation Target Materials: Solid Lead

- Z =82 , A=207.2, d= 11.3 g/cm^3, T_m=327.5°C
- Low neutron absorption (0.17 barn)
- Some ^{209}Po created in spallation process.
- Low mechanical stability, can only be used with supporting structure.
- Used in the present SINQ target
  (10.5 mm lead rods in 0.5 mm wall steel tubes, heavy water cooled); suitable up to a few MW, if local melting is allowed.

Solid Spallation Target R&D at SINQ, PSI, Switzerland

The SINQ Spallation Facility at PSI

SINQ (PSI,CH) is a ***continuous*** spallation neutron source of the 1 MW_b class (590 MeV, 1.4 mA).

Beam injection into the target is from underneath, making available 360°around the target block for instruments.

There is no hot cell directly attached to SINQ

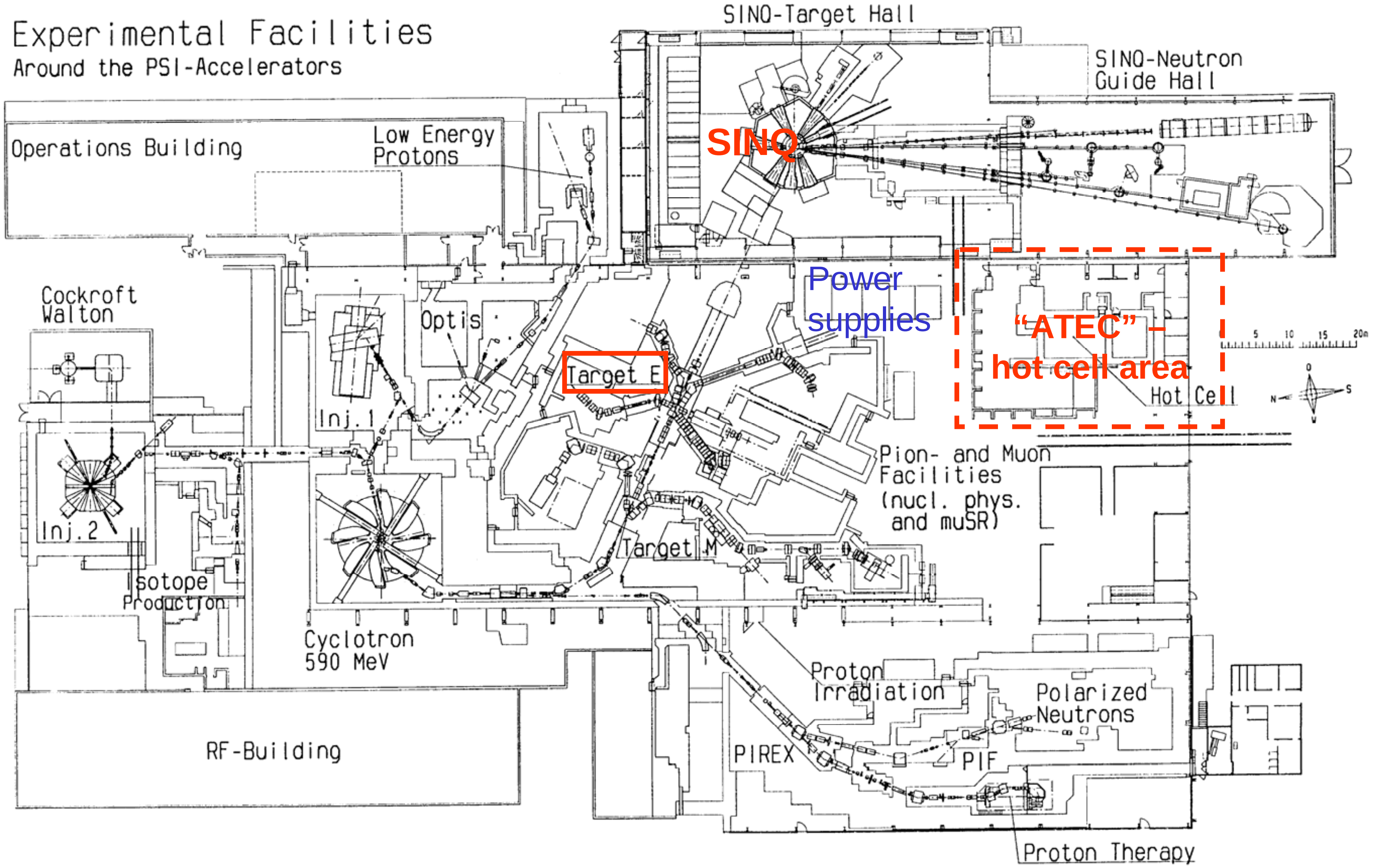
For high thermal moderator flux its target is surrounded by a 2m diameter heavy water tank, from which the beam tubes originate.

The solid metal targets used are of the rod-type and are cooled by heavy water flowing upwards between the rods.

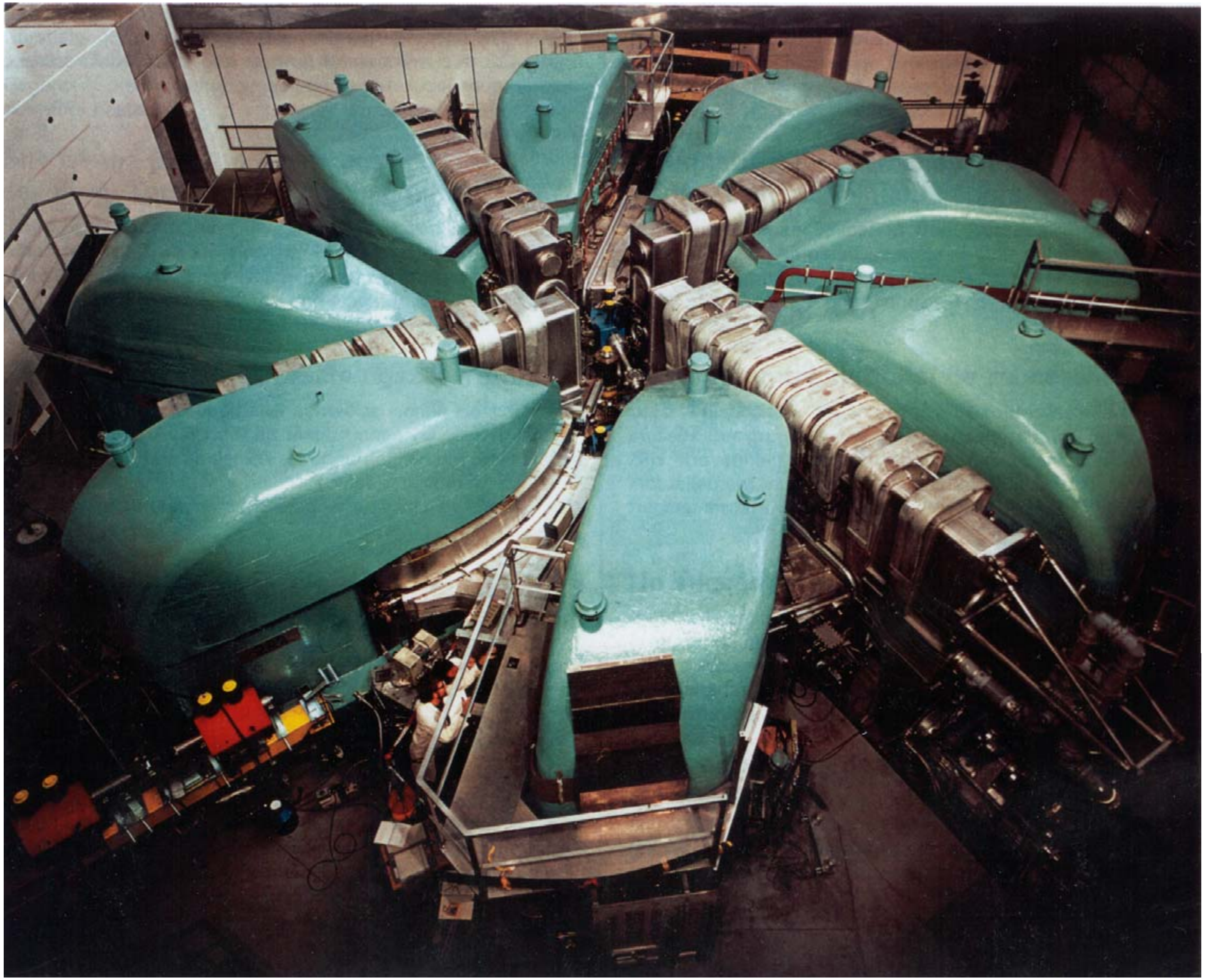
The upper 3m of the 4m long target insert are filled with shielding material.

The PSI Proton Facilities (2000)

Beam power >1MW at 590 MeV

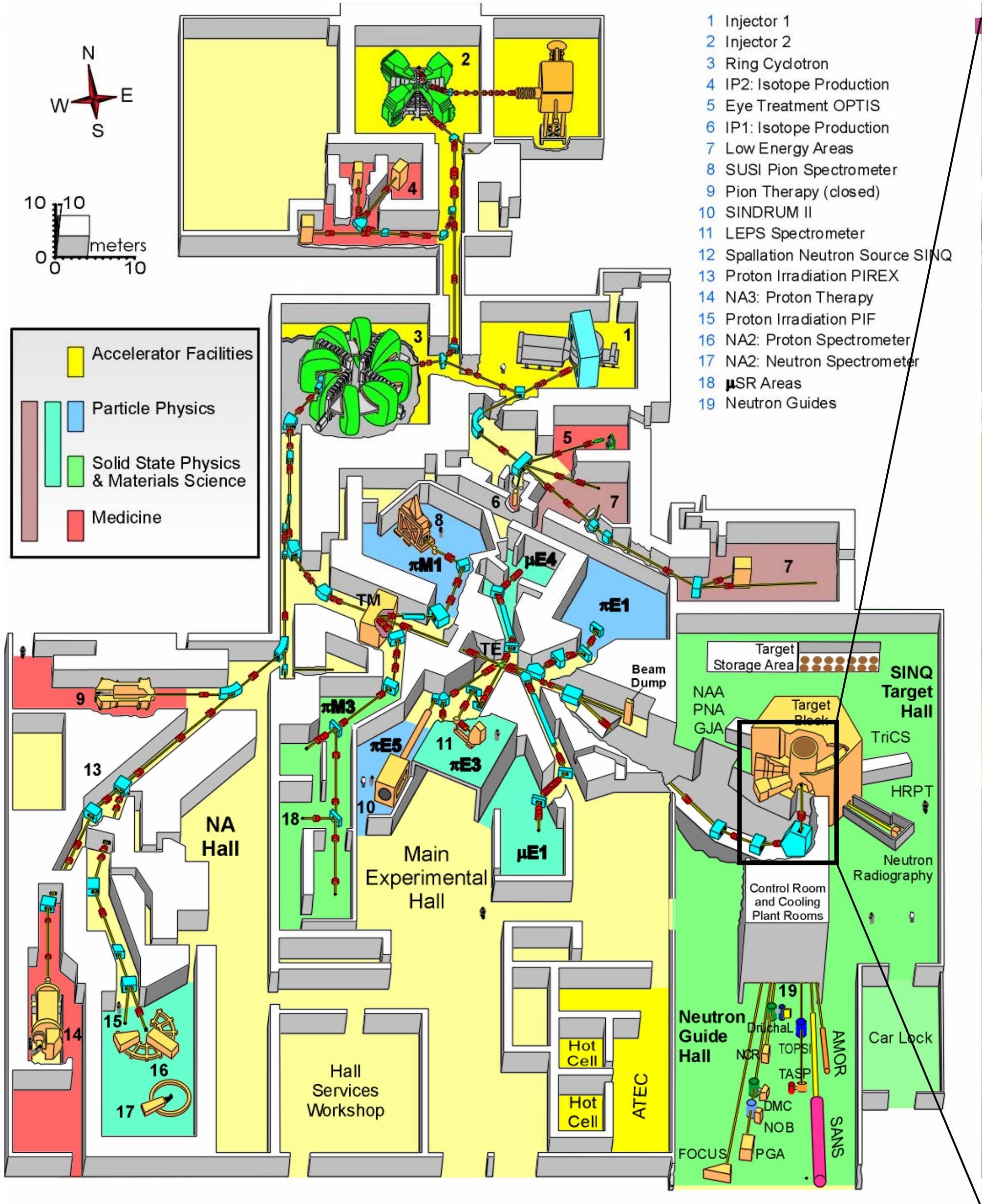


The PSI 590 MeV-Ring Cyclotron



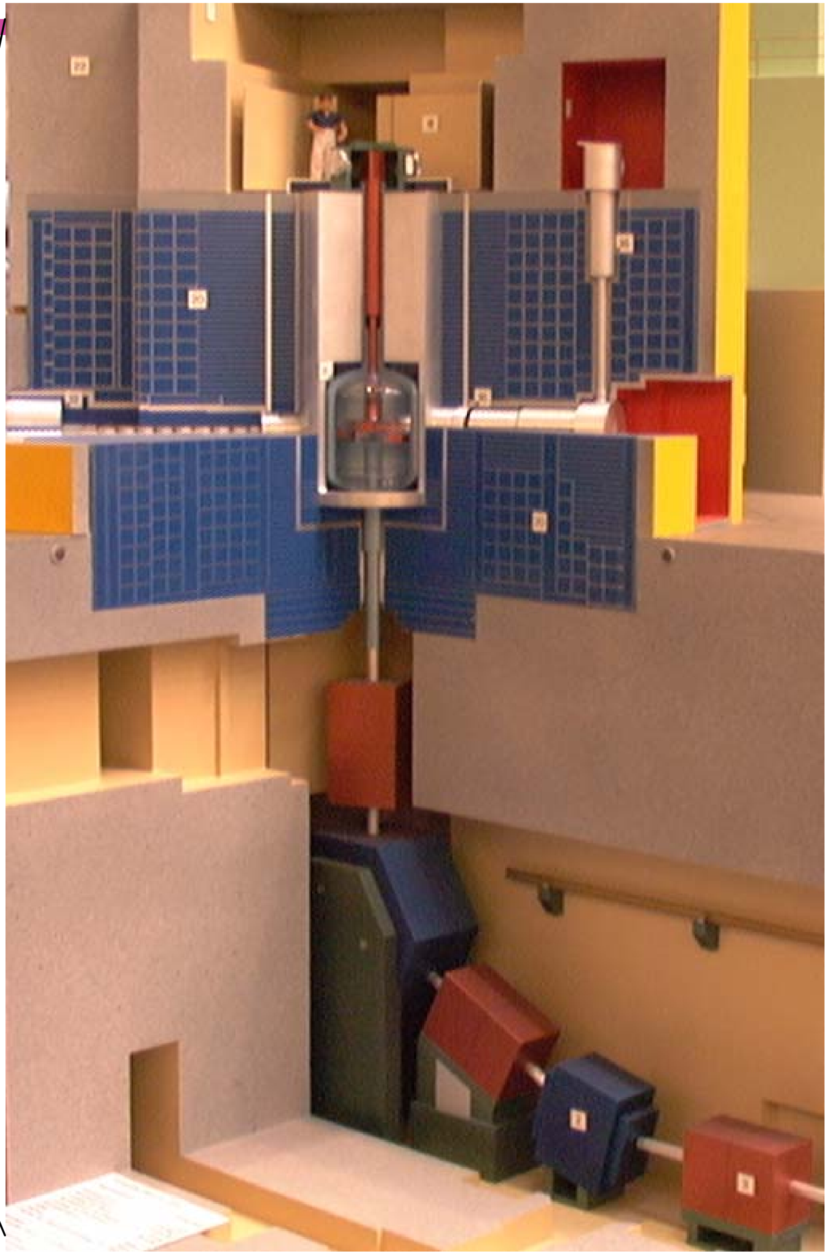
PSI Accelerator Facilities

Model of the SINQ Target Block

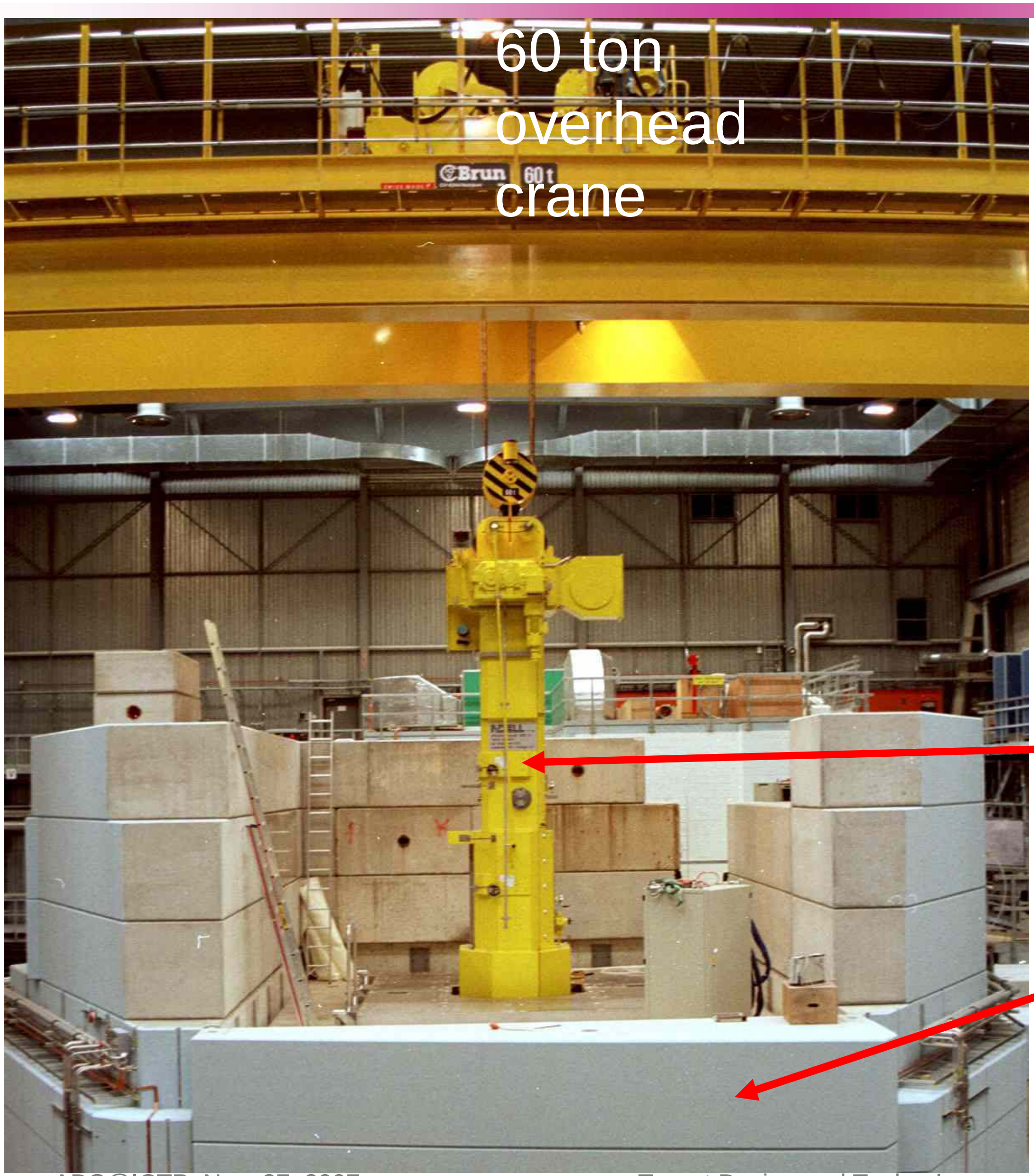


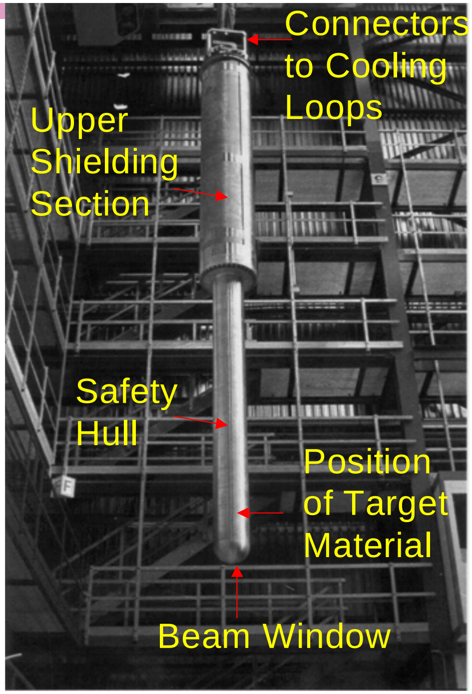
1 Injector 1
2 Injector 2
3 Ring Cyclotron
4 IP2: Isotope Production
5 Eye Treatment OPTIS
6 IP1: Isotope Production
7 Low Energy Areas
8 SUSI Pion Spectrometer
9 Pion Therapy (closed)
10 SINDRUM II
11 LEPS Spectrometer
12 Spallation Neutron Source SINQ
13 Proton Irradiation PIREX
14 NA3: Proton Therapy
15 Proton Irradiation PIF
16 NA2: Proton Spectrometer
17 NA2: Neutron Spectrometer
18 μSR Areas
19 Neutron Guides

Walter/Heyck - Jan. 1998 -Hallenplan



The SINQ-Target Exchange

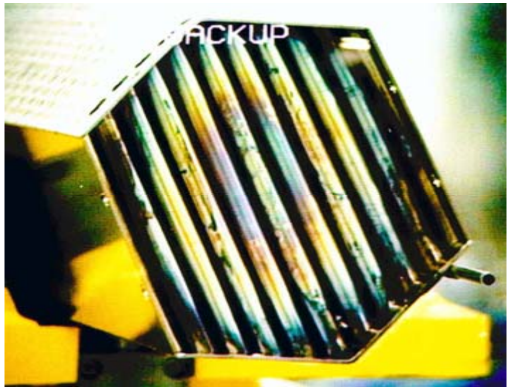




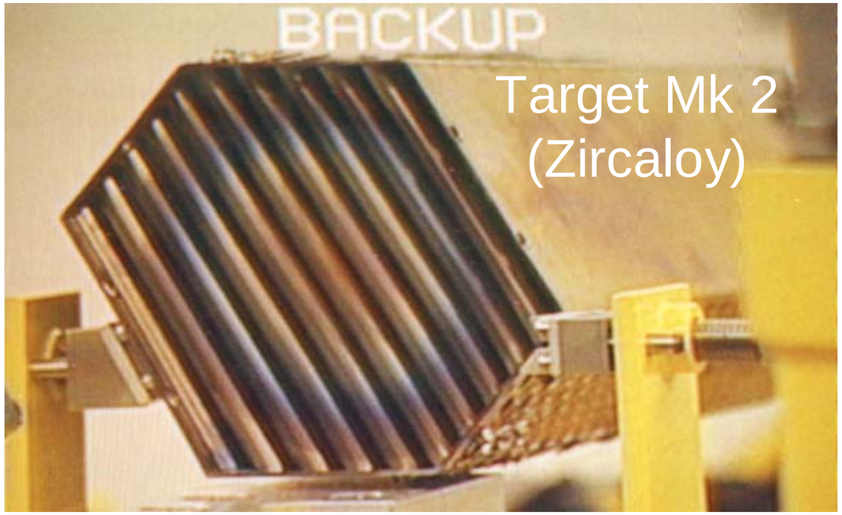
Target exchange flask in position above target head

Bulk shielding of target block (top part removed)

The SINQ Rod Target

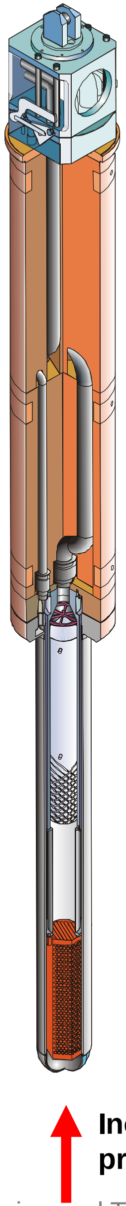


Target Mk 1
(Zircaloy)
after 0.5 Ah
water
purification off



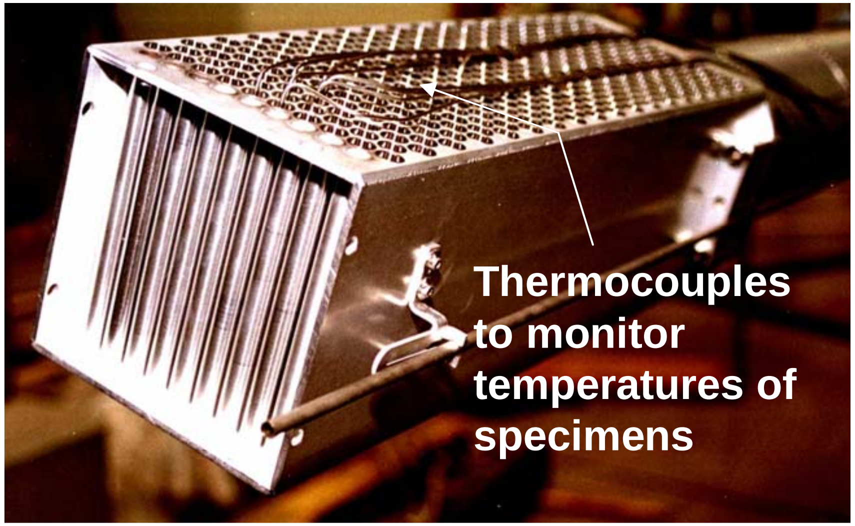
Target Mk 2
(Zircaloy)

Removed after 6.8 Ah of beam
(water purification on)



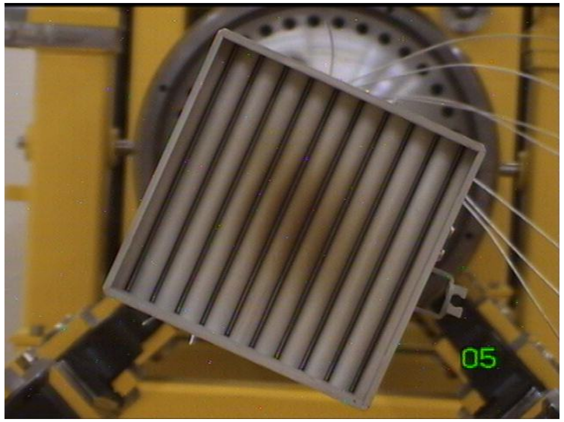
Incident proton beam

Target Mk 3
(lead rods in SS-tubes,
bottom row empty Al-tubes)

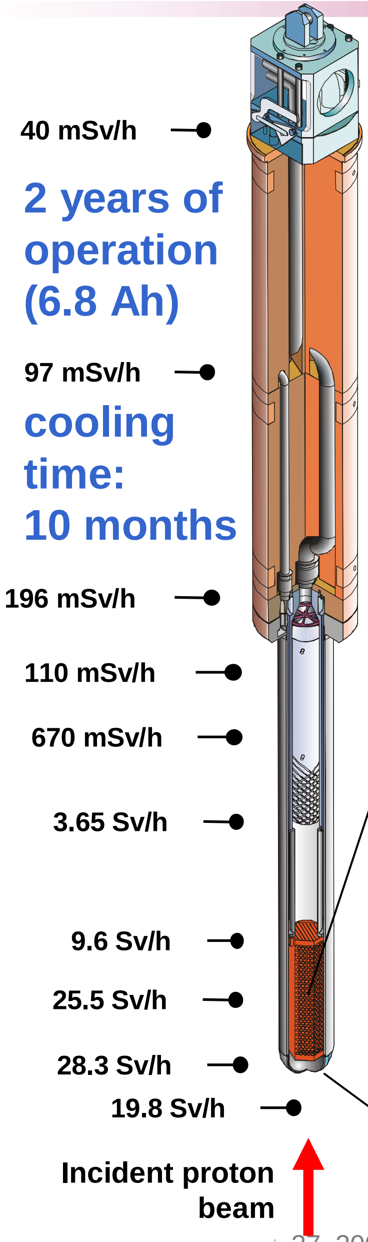


Thermocouples to monitor temperatures of specimens

Exposed
to 10 Ah
of beam;



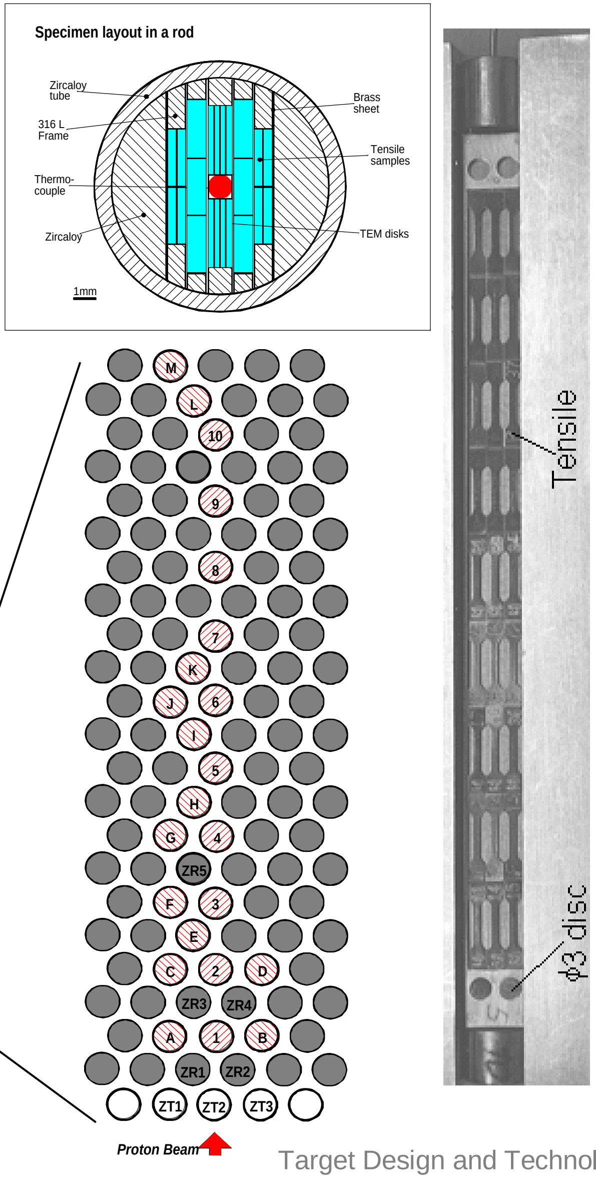
Radiation Effects Research with SINQ (1)



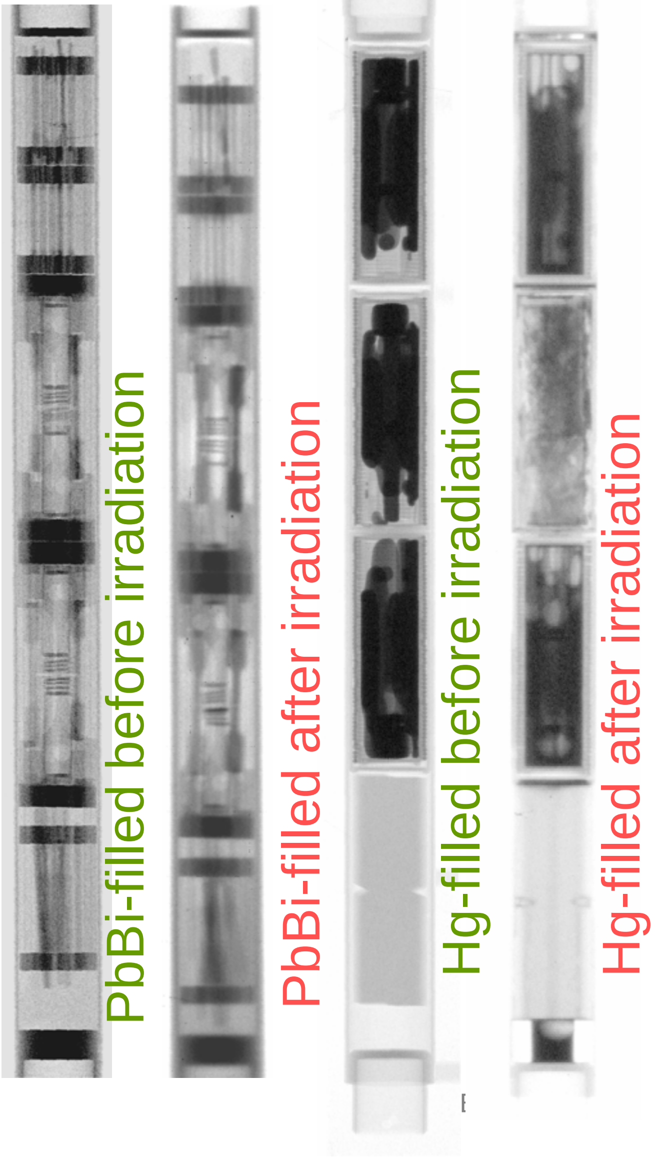
2 years of operation (6.8 Ah)

cooling time: 10 months

Rod with test specimens



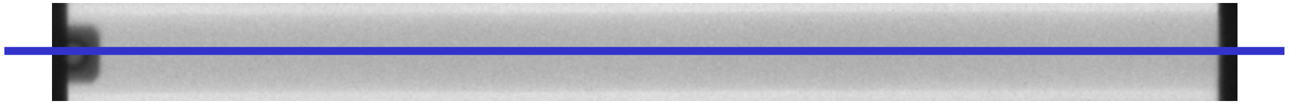
Neutron radiographs of sample rods



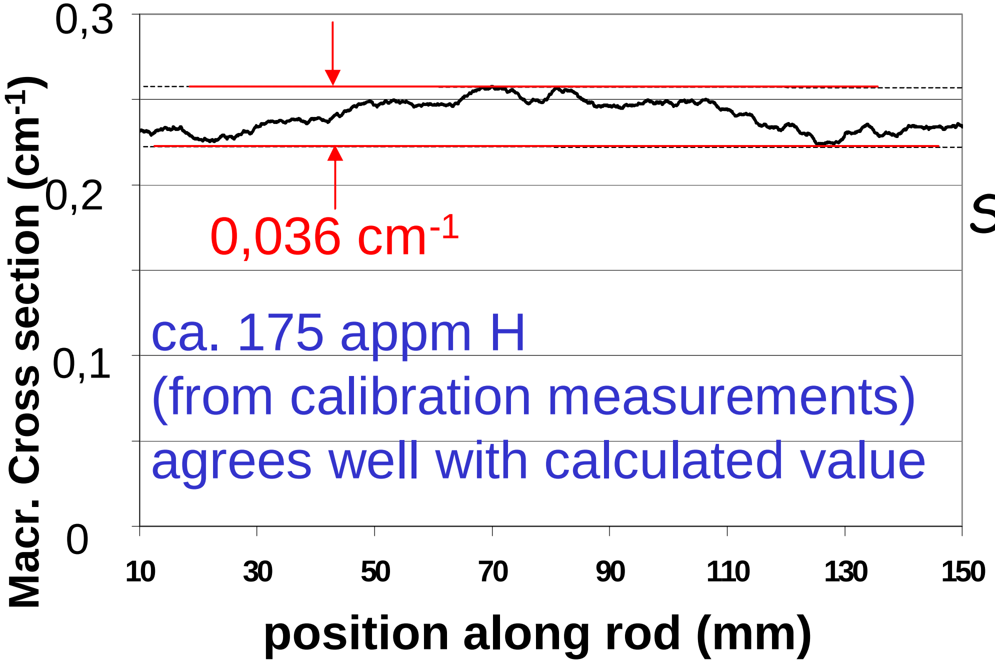
Radiation Effects Research with SINQ (2)

Hydrogen retention in Zircaloy

Neutron radiography on highly radioactive rods irradiated in SINQ !



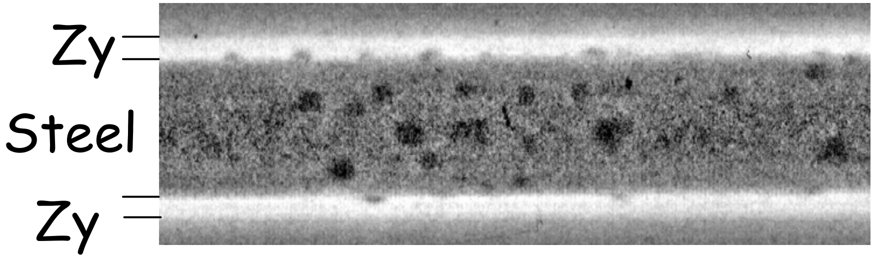
Zircaloy rod ZR5, Target Mk 2



0,036 cm^{-1}

ca. 175 appm H (from calibration measurements) agrees well with calculated value

Rod of martensitic steel with Zircaloy cladding irradiated in SINQ Target Mk2

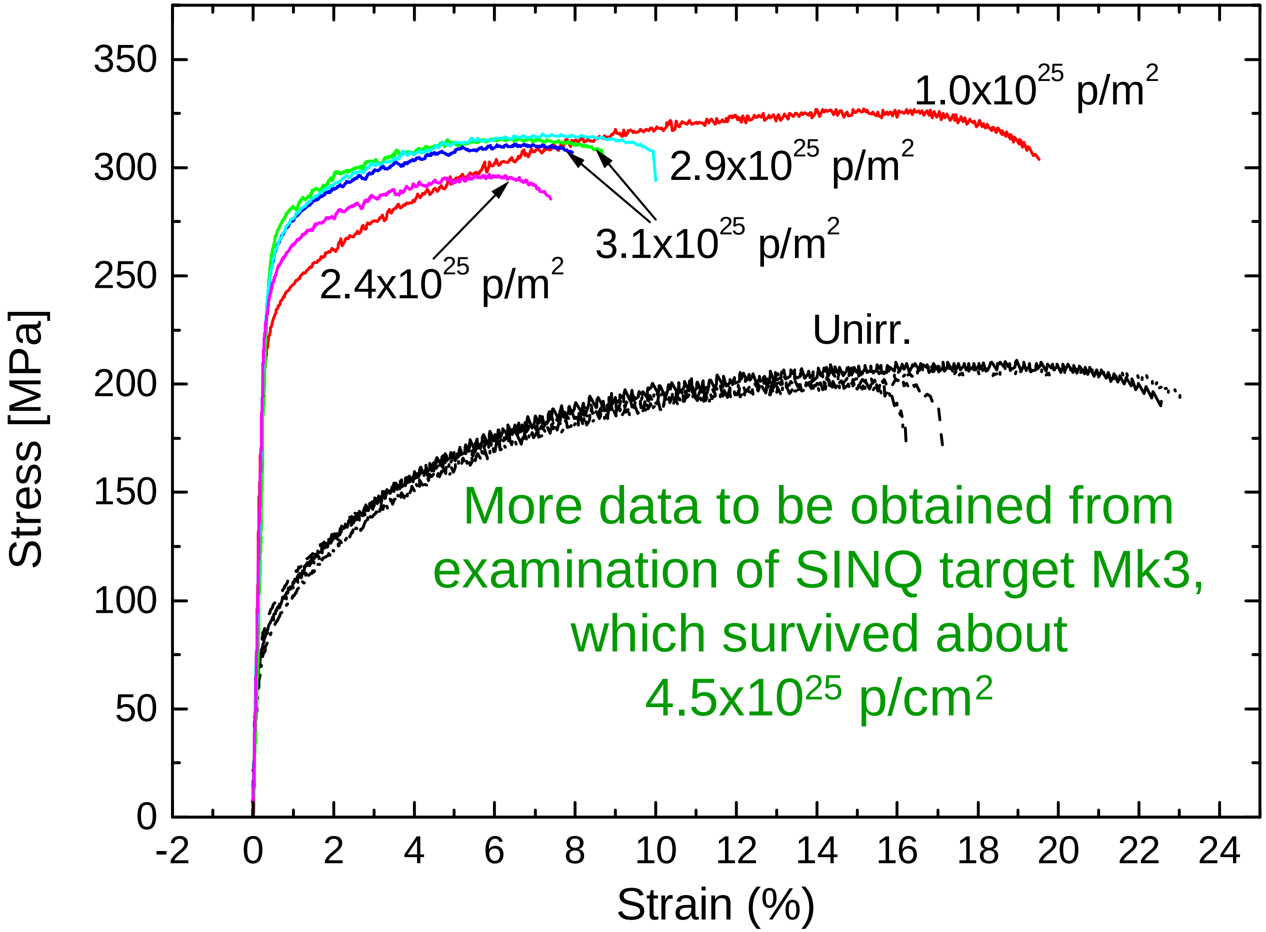


The high hydrogen production rate in higher Z spallation materials might make Zircaloy a difficult cladding material

Zy-clad Pb-rods have been successfully used in SINQ in zones of lower beam lod!

Radiation Effects Research with SINQ (3)

PIE on Irradiated Hull (AlMg3) of SINQ Target Mk2



More data to be obtained from examination of SINQ target Mk3, which survived about 4.5x10^{25} p/cm^2

4.5x10^{25}p/m^2 correspond to ca 2000 hours (ca 83 days) of operation at 100 µA/cm^2

Target Design and Technology for Research Spallation Neutron Sources

Summary on Solid Metal Targets
General Issues

Solid Metal Targets: General Issues (1)

- Heat produced in the volume must be conducted to the surface, which produces large axial thermal gradients and stress.
- Beam distribution causes radial temperature gradients and stress and may make curved plates necessary.
- Plate thickness is limited by heat flux density on the surface to avoid nucleate boiling and parallel flow instabilities (or use complicated flow guide system).
- Cooling water mass flow is determined by heat transfer requirements rather than by allowed temperature rise.
- At high power the need to use very thin plates results in dilution of the material and unwanted moderation.
- The SINQ concept of using tubes only 90% filled with Pb - which is allowed to melt – has proven a highly successful solution.

Solid Metal Targets: General Issues (2)

- ^{7}Be is produced as a spallation product of oxygen in water. It has an unpleasant half life of 53 days and tends to plate out on the walls of the cooling loop, generating an unpleasant dose level in the room. Purification is, however, effective in removing ^{7}Be from the water. *Minimizing the water content in the target volume helps to reduce coolant activity an improves neutron yield!*
- Short lived positron emitters (^{11}C, ^{11}N, ^{13}N, ^{15}O) are created in large quantities and produce intense 511 keV radiation, which leads to high doses on filters, ion exchangers and other sensitive components of the loop. (At SINQ up to 1.5 Sv/h/mA were measured along the target cooling loop during operation at 1 mA.)

Solid Metal Targets: Bottom Line

- Solid heavy metal targets are the only ones routinely used so far in spallation neutron sources.
- Experience exists up to 0,85 MW and 10 Ah (SINQ).
- Except for U targets and corrosion problems with unclad water cooled W targets no solid target has failed or caused serious problems; radioactivity in water pipe work is unpleasant, but not prohibitive up to 1 MW_b.
- If significantly higher beam power (current density) is considered, heat flux density might become too high for water cooling.
- Liquid metal cooling (Na or NaK) seems to make sense only if a target material containing U can be used; otherwise a liquid metal (Hg, PbBi) can be directly used as target material.

End of Part 1

Part 2: Liquid Metal Targets

- Some General Comments on Liquid Metal Targets
- A Liquid Metal Target for SINQ - The MEGAPIE Project –
- An Upcoming Generation of Liquid Metal Targets: Mercury Targets for Pulsed Spallation Neutron Sources
- Back to the Future - A window-less liquid metal target ?

Some General Comments on Liquid Metal Targets

Liquid Metal Targets

- No radiation damage in target volume
- Heat transport in the target by convection rather then conduction (higher ultimate capacity).
- No stress from thermal gradients inside the target.
- Larger target volume results in lower specific activity and afterheat (less γ-heating in the moderators?).
- Largely unexplored and more difficult technology.
- Beam entrance window is the most highly loaded component in the system.
- Completely new safety case.

Should be designed to tolerate a window failure!

Liquid Metal Targets: Design Issues (1)

- In order to prevent evaporation into the accelerator vacuum, particularly of spallation products, a beam window is usually considered necessary.
- Radiation damage will rapidly embrittle the window material; therefore a design allowing for a brittle window and easy exchange is desirable.
- This window will be cooled by the liquid metal from one side only , which makes good thermal contact (wetting?) desirable. This may be at variance with the need for a protective layer against corrosion and liquid metal embrittlement.

Liquid Metal Targets: Design Issues (2)

- The case of a window failure and easy exchange of the window will have to be design requirements. This favours horizontal beam injection (outer shroud with leakage monitoring of the interspace).
- In order to avoid dangerously high temperatures in the window, the bulk liquid metal flow should be directed away from the window, while ensuring sufficient flow across the window for proper cooling.
- Temperature is important because of the damage a window may suffer (radiation effects, corrosion) on the one hand and LM-embrittlement and strength on the other.

Liquid Metal Targets: Candidate Materials

Property		**Pb**	**Bi**	**LME ***	**LBE****	**Hg**
Composition		elem.	elem.	Pb 97.5% Mg 2.5%	Pb 45% Bi 55%	elem.
Atomic mass A (g/mole)		207.2	209	202.6	208.2	200.6
Linear coefficient of thermal expansion (10^{-5} K^{-1})	solid	2.91	1.75			
	liqu. (400°C)	4		4		6.1
Volume change upon solidification (%)		3.32	-3.35	3.3	0	
Melting point (°C)		327.5	271.3	250	125	-38.87
Boiling point at 1 atm (°C)		1740	1560			356.58
Specific heat (J/gK)		0.14	0.15	0.15	0.15	0.12
Th. neutron absorpt. (barn)		0.17	0.034	0.17	0.11	389

* Lead magnesium eutectic ** Lead bismuth eutectic

Liquid Metal Targets: Pb, Bi

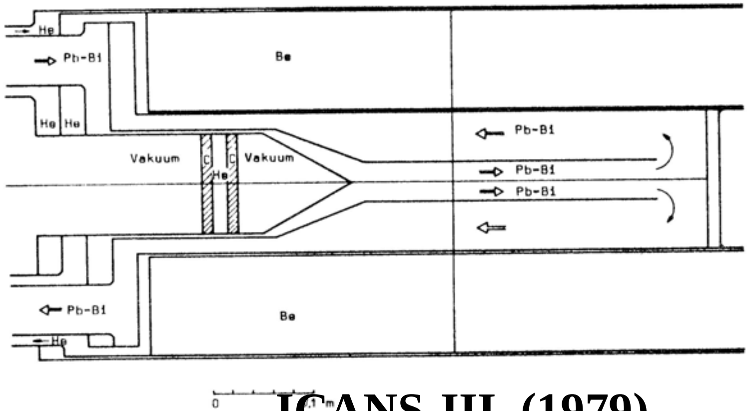
- PbBi is favoured in projects for cw-applications for its low melting point, high boiling point and low neutron absorption cross section.
- Potential problems with PbBi are the production of alpha-active isotopes (^{209}Po and ^{210}Po) by neutron capture and the corrosivity of Bi.
- Pb produces less Po, but requires high operating temperatures with the associated difficulties in finding strong enough structural materials. Also corrosion is increasing rapidly with higher temperatures.
- PbMg is similar to Pb but allows lower temperature; possible problem with narrow eutectic regime.

A Liquid Metal Target for SINQ
- The MEGAPIE Project -

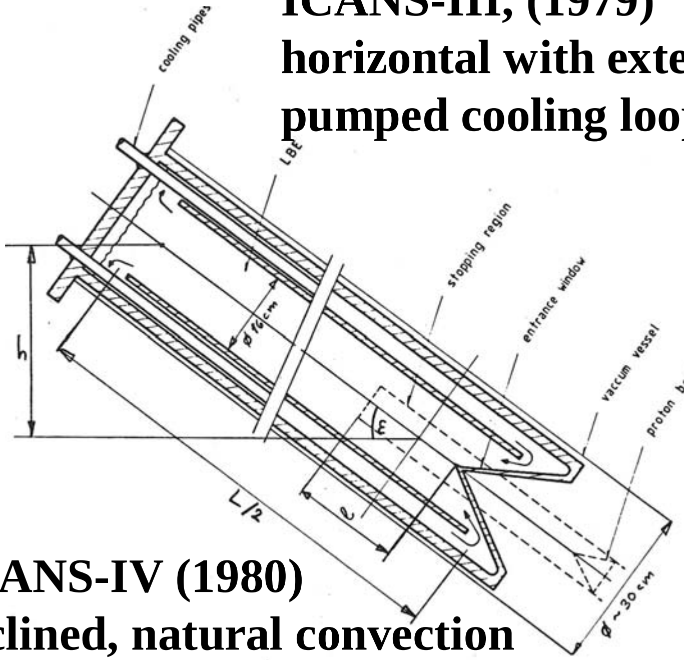
Evolution of the SINQ-Target Concept (1)

- The original concept for the SINQ target was to have a pumped liquid metal (PbBi) target with horizontal beam injection.
- In an attempt to “simplify” the design, natural convection became the preferred option, which looked perfectly feasible in an equilibrium state.
- In the course of more detailed study two problems became obvious:
  - The window would not be properly cooled during start up periods
  - A difficult licensing process would have to be envisaged
- For this reason it was decided in the early 90ies to postpone the liquid metal idea and embark on the design of a solid target
- It was only around 2000 that work on the liquid metal target was intensified again in an international partnership (MEGAPIE)

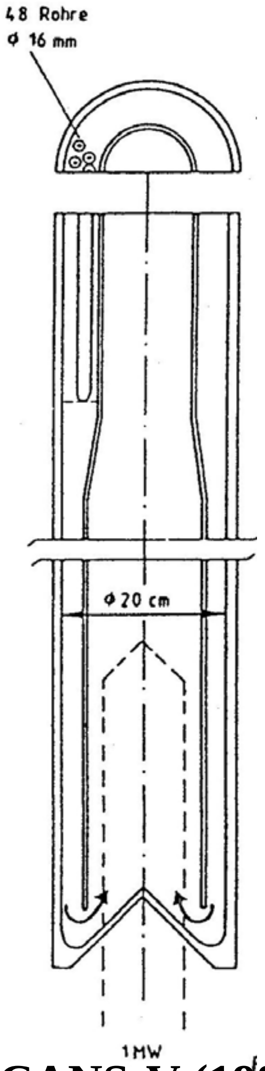
Evolution of the SINQ-Target Concept (2)



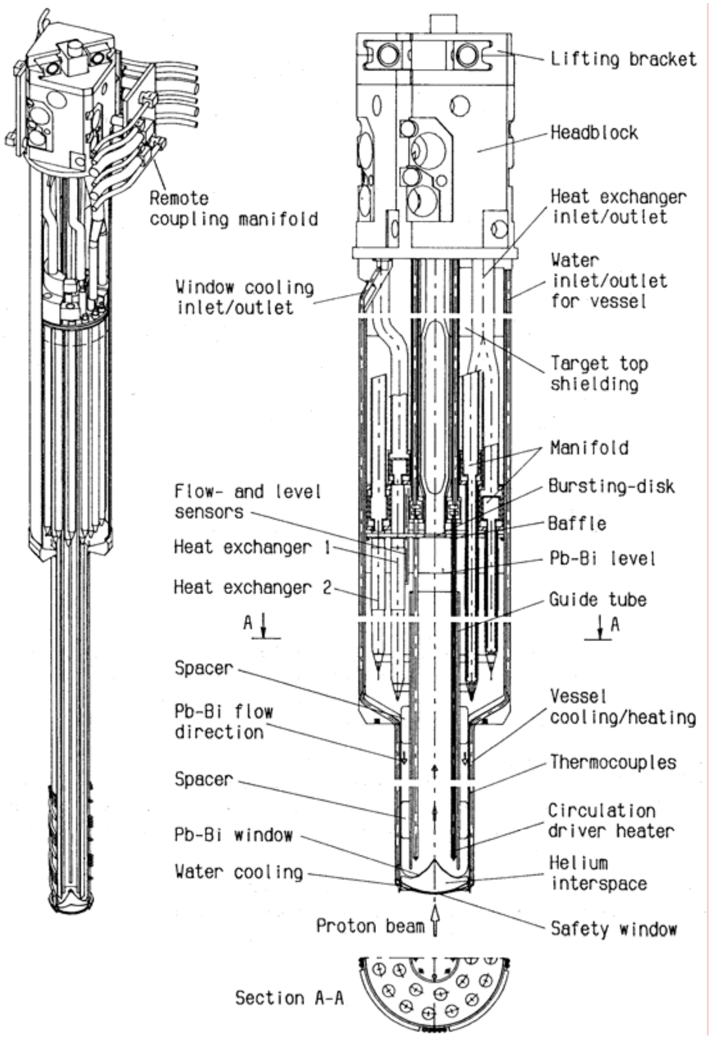
ICANS-III, (1979)
horizontal with external pumped cooling loop



ICANS-IV (1980)
inclined, natural convection



ICANS-V (1981)
vertical, nat. conv.



ICANS-XI (1990)

The MEGAPIE Partnership

PAUL SCHERRER INSTITUT

PSI

cea

COMMISSARIAT À L'ÉNERGIE ATOMIQUE

ENEA

CNRS

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

Department
of Energy

MEGAPIE

SCK•CEN

Japan Atomic Energy Research Institute

JAERI

한국원자력연구소

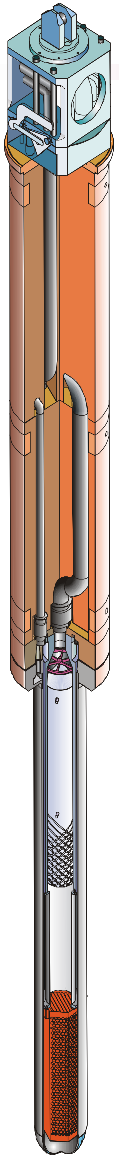
Korea Atomic Energy Research Institute

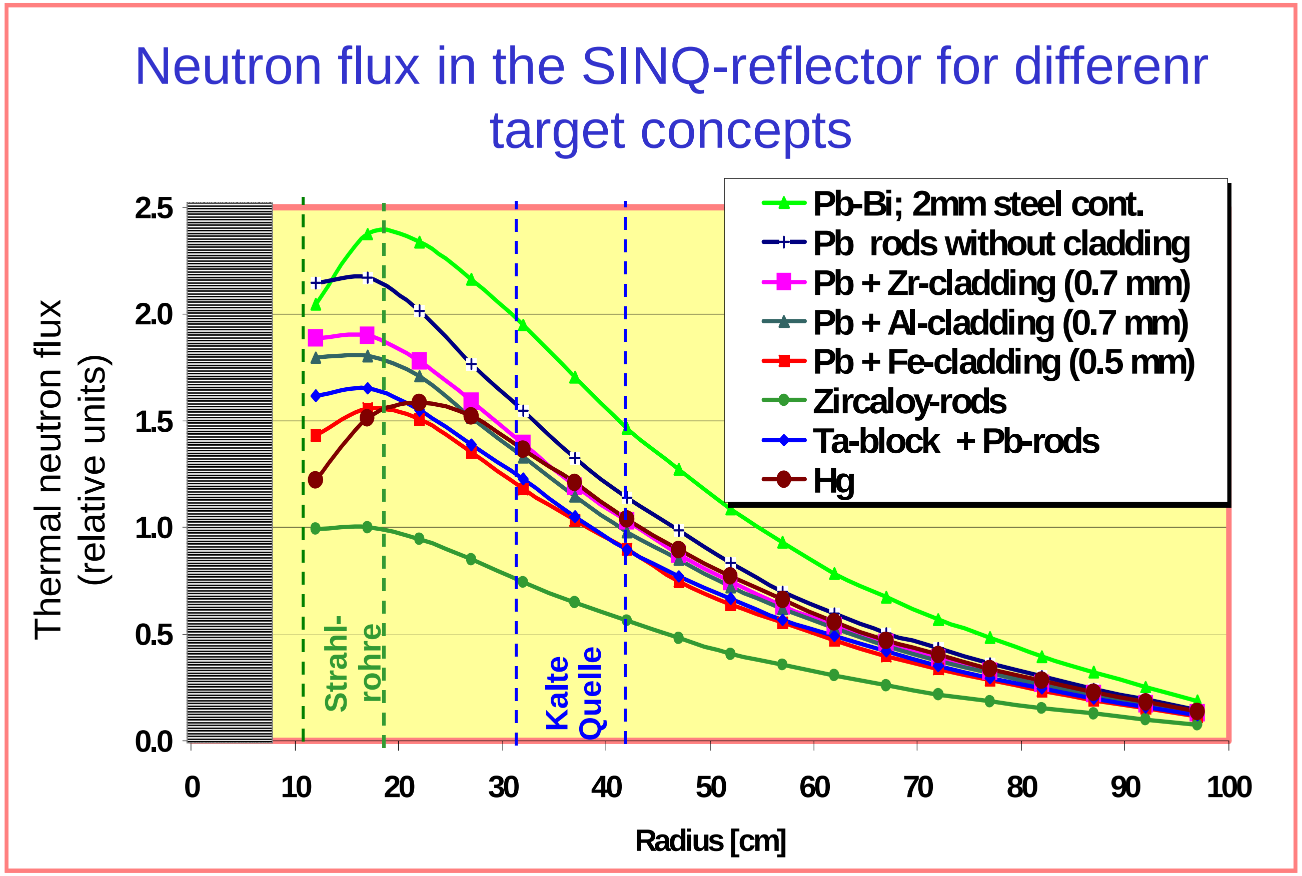
Forschungszentrum Karlsruhe
Technik und Umwelt

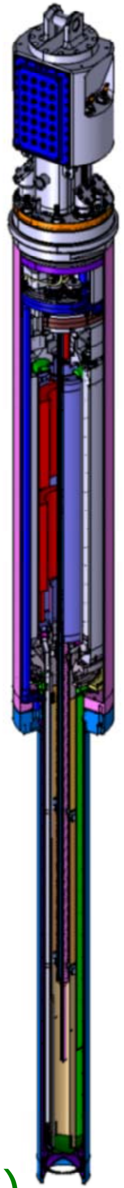
MEGAPIE-TEST

Ref: G.S. Bauer, M. Salvatores and G. Heusener "MEGAPIE, a 1 MW pilot experiment for a liquid metal spallation target" J. Nucl. Mat 296 (2001) 17-23

A Liquid Metal Target for SINQ:MEGAPIE



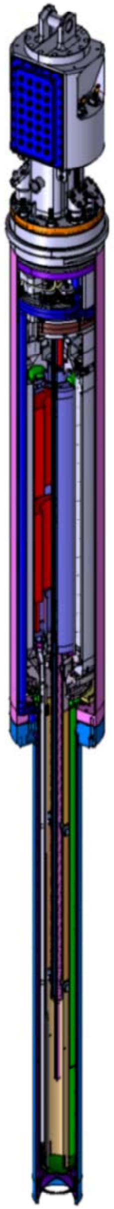




- Higher neutron yield (flux in the reflector)
- Less radiolytic effects in the cooling water
- Reduced radiation levels in the cooling plant room
- New technology for next generation neutron sources (ADS)

Incident proton beam

General Specifications of the MEGAPIE Target



Materials

Target	Lead Bismuth Eutectic (LBE)
Lower Liquid Metal Container:	T91 steel
Upper Container & Shielding:	316L steel
Lower Target Enclosure:	AlMg3

Dimensions

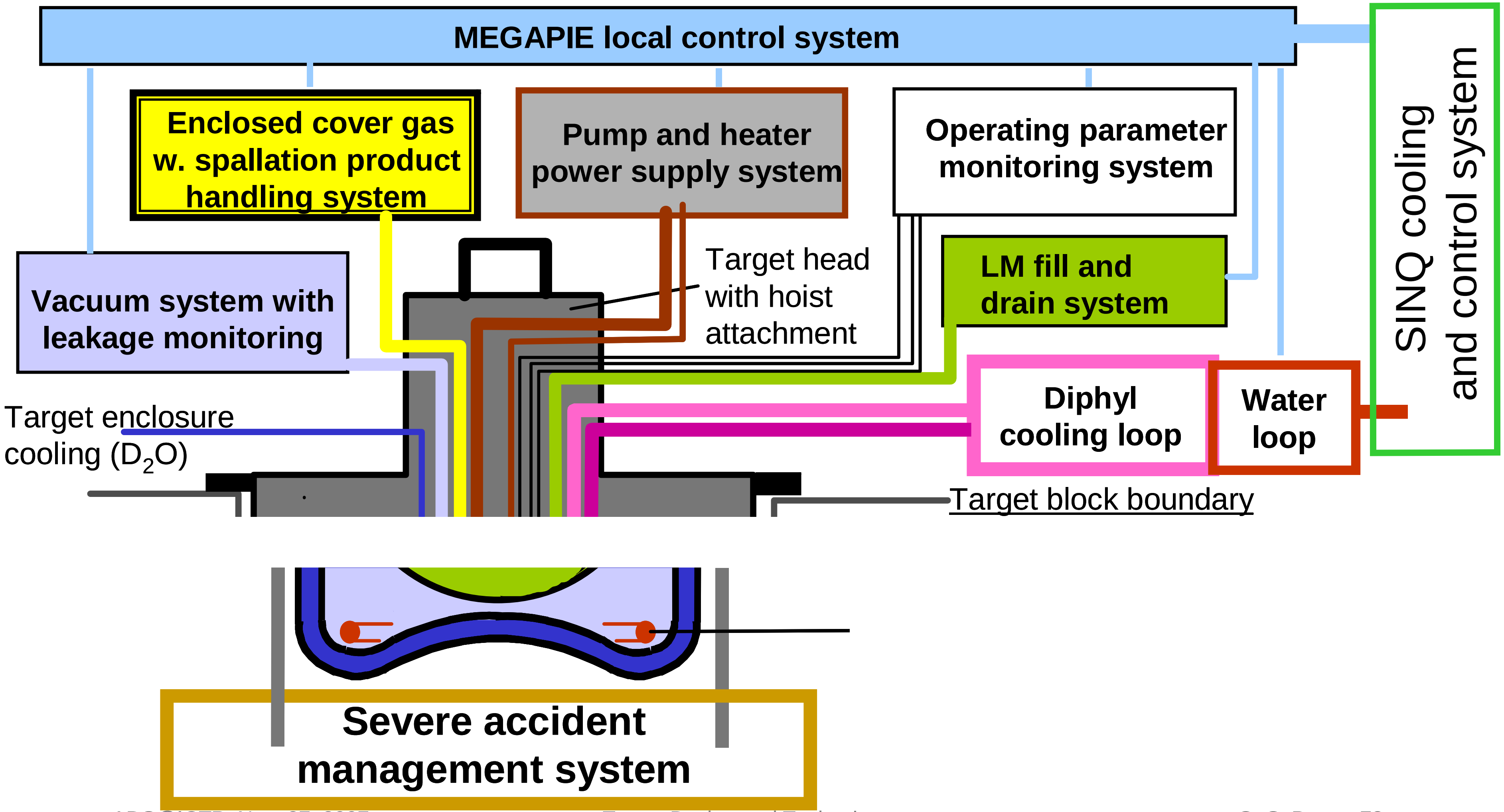
Length:	5.35.m	Weight:	1.5 t
LBE volume:	82 l	Gas Volume:	2 litres
Design pressure:	16 bar	Operating pressure:	0-3.2 bar
Design Temperature:	400ºC	Temperature range:	240-380°C
Max. flow velocity:	~1.2 m/s	Insulation Gas:	0.5 bar He

Heat Removal and Beam Window Cooling

Heat deposition :	650 kW (design value)
Heat transport:	Forced convection assisted by buoyancy
Main pump:	EM in-line pump (4 l/sec)
Bypass pump:	EM in-line pump (0.35 l/sec)
Heat removal:	12 pin heat exchanger with oil as secondary coolant

Auxiliary systems for the MEGAPIE target

A liquid metal target requires a significant amount of auxiliary systems not necessary for the solid target



MEGAPIE local control system

Enclosed cover gas w. spallation product handling system

Pump and heater power supply system

Operating parameter monitoring system

Vacuum system with leakage monitoring

Target head with hoist attachment

LM fill and drain system

SINQ cooling and control system

Target enclosure cooling (D_2O)

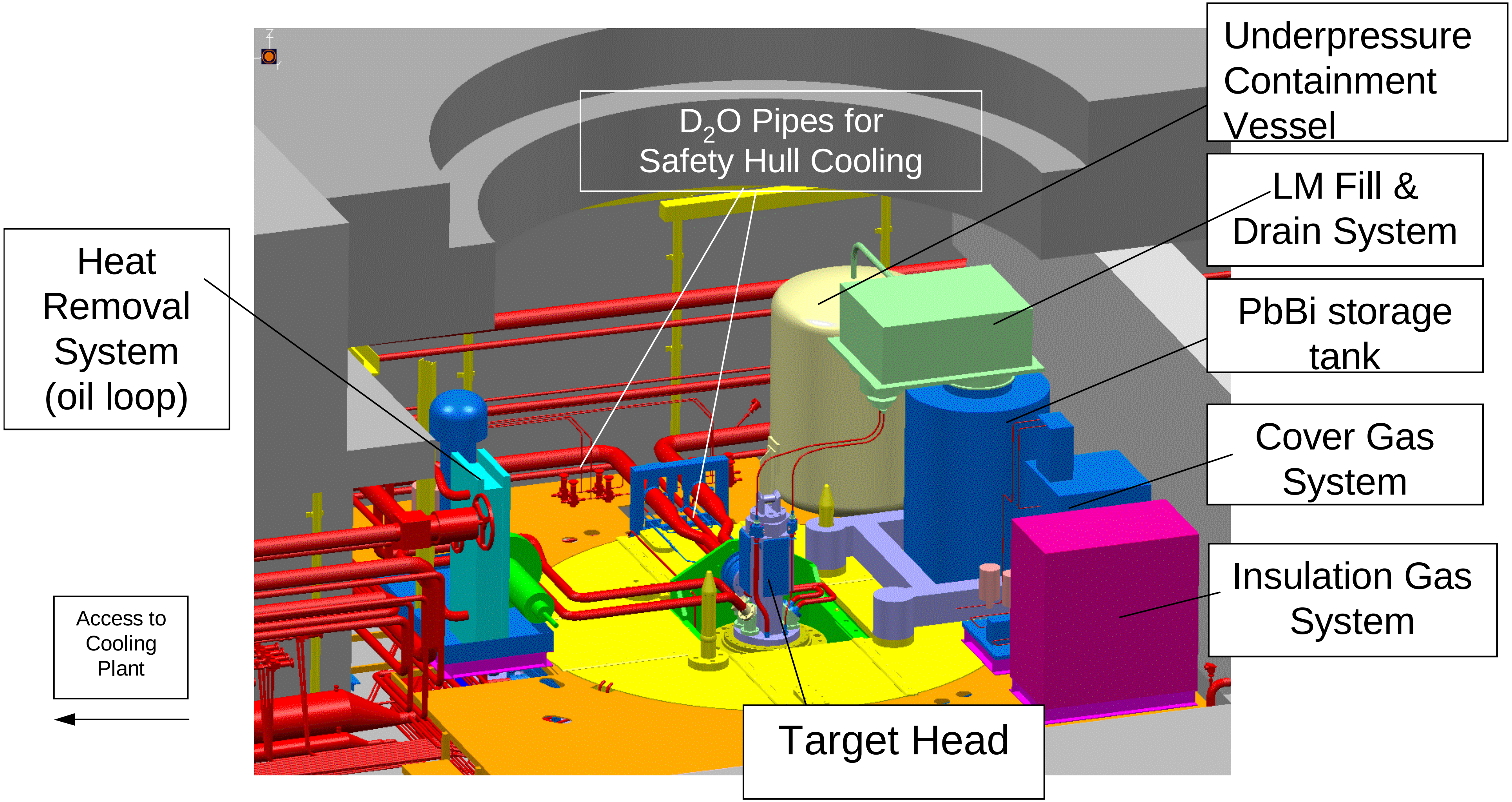
Diphyl cooling loop

Water loop

Target block boundary

Severe accident management system

The MEGAPIE-Auxiliary Systems

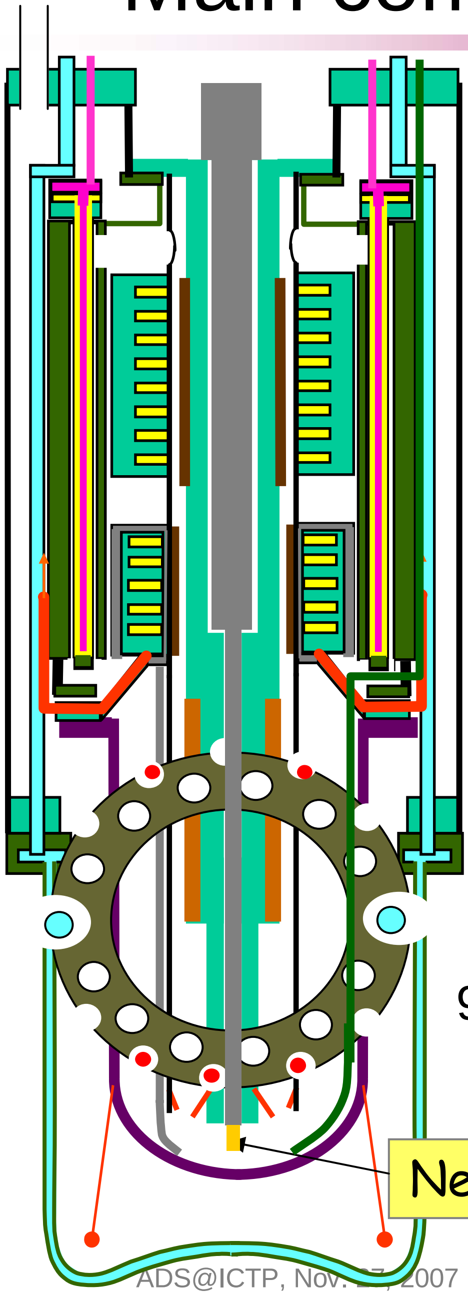


The MEGAPIE Target Head Room

The use of an oil intermediate cooling loop required an inert atmosphere in this room!

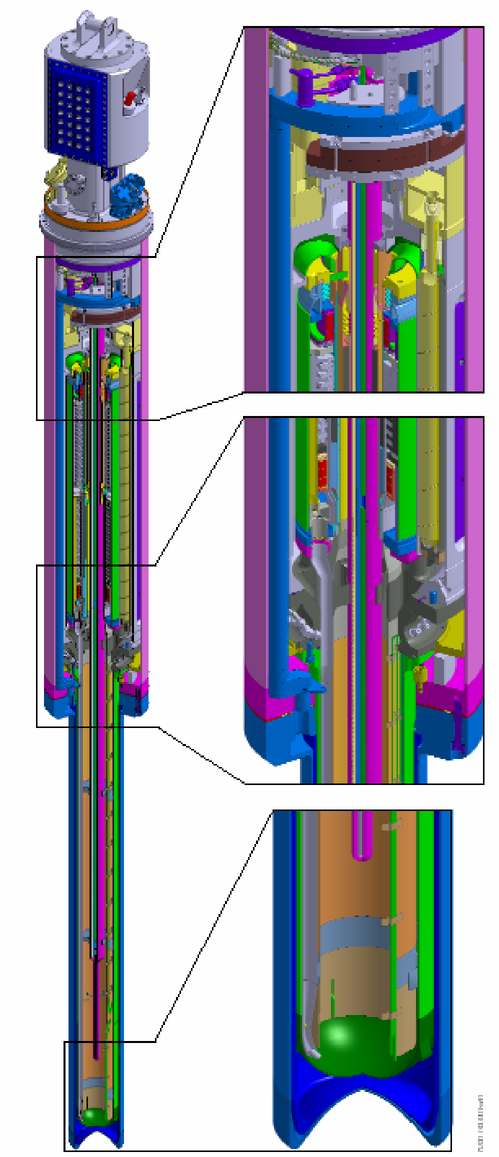
Wagner at al, proceedings IWSMT-8, JNM

Main components of the MEGAPIE Target



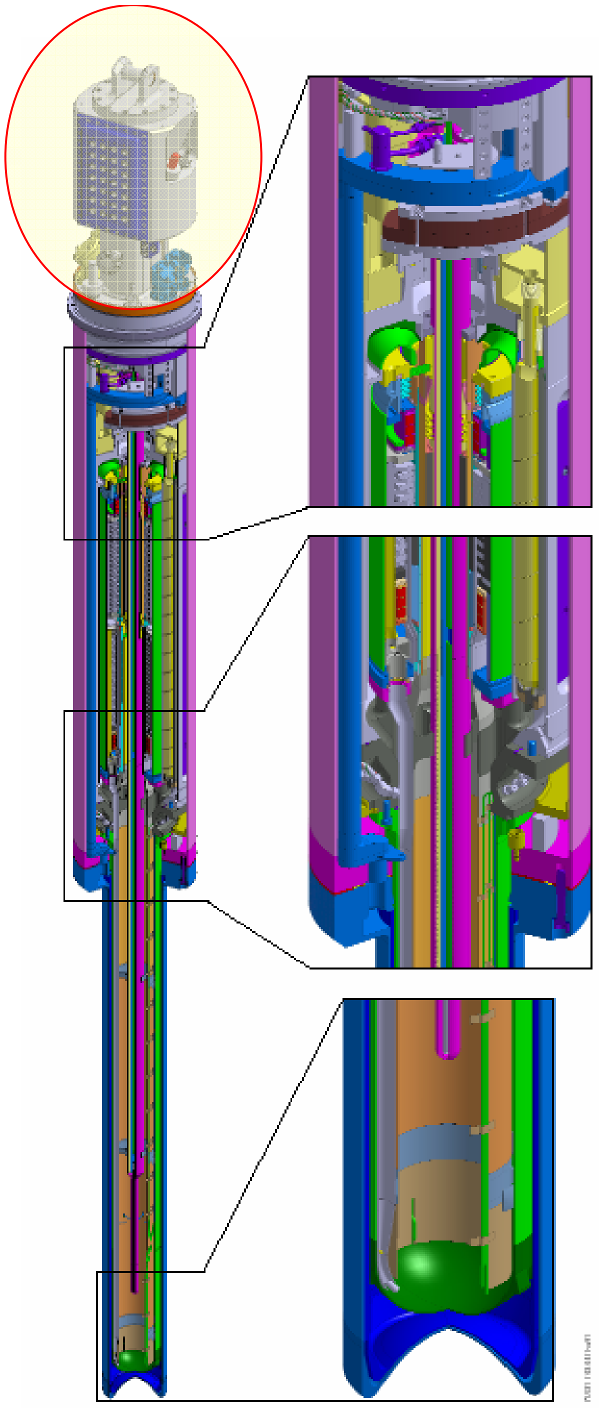
1. Upper liquid metal container and displacement body
2. Heat exchanger
3. Pump unit and lower flow guide
4. Central rod with auxilliary heating
5. Fill-and drain tube
6. Lower liquid metal container with leak sensors
7. Upper flange with feed-throughs
8. Upper vacuum chamber with outer enclosure
9. Water cooled lower enclosure

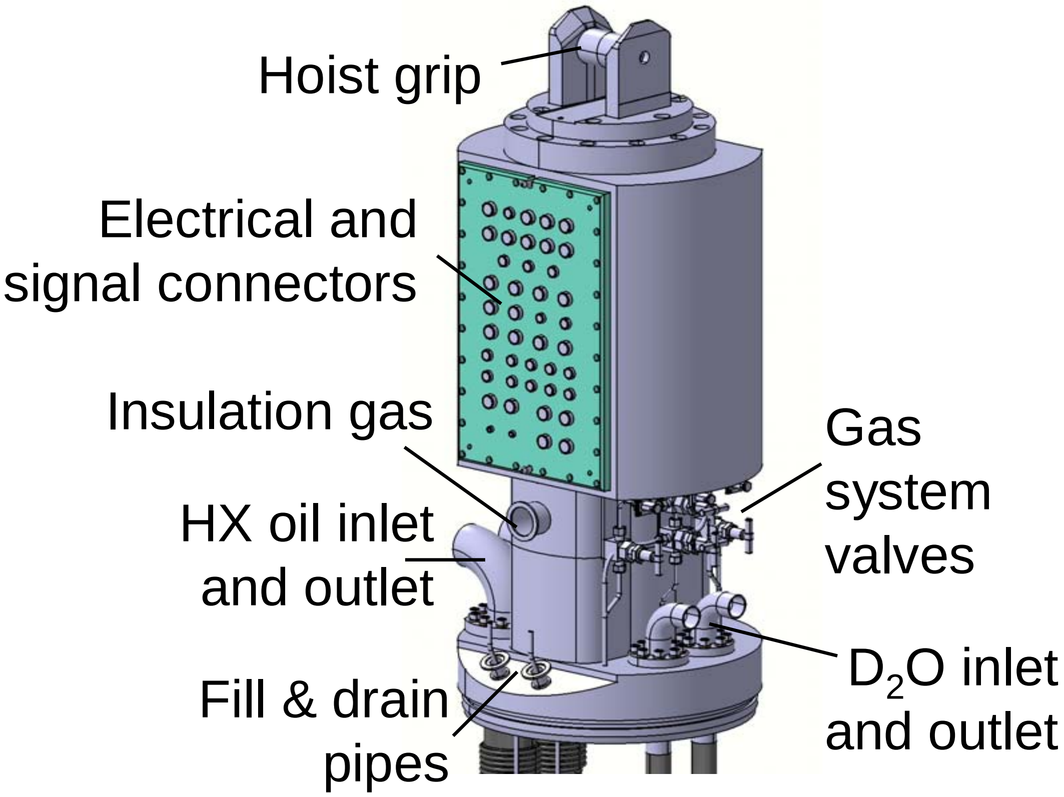
Neutron flux monitoring system

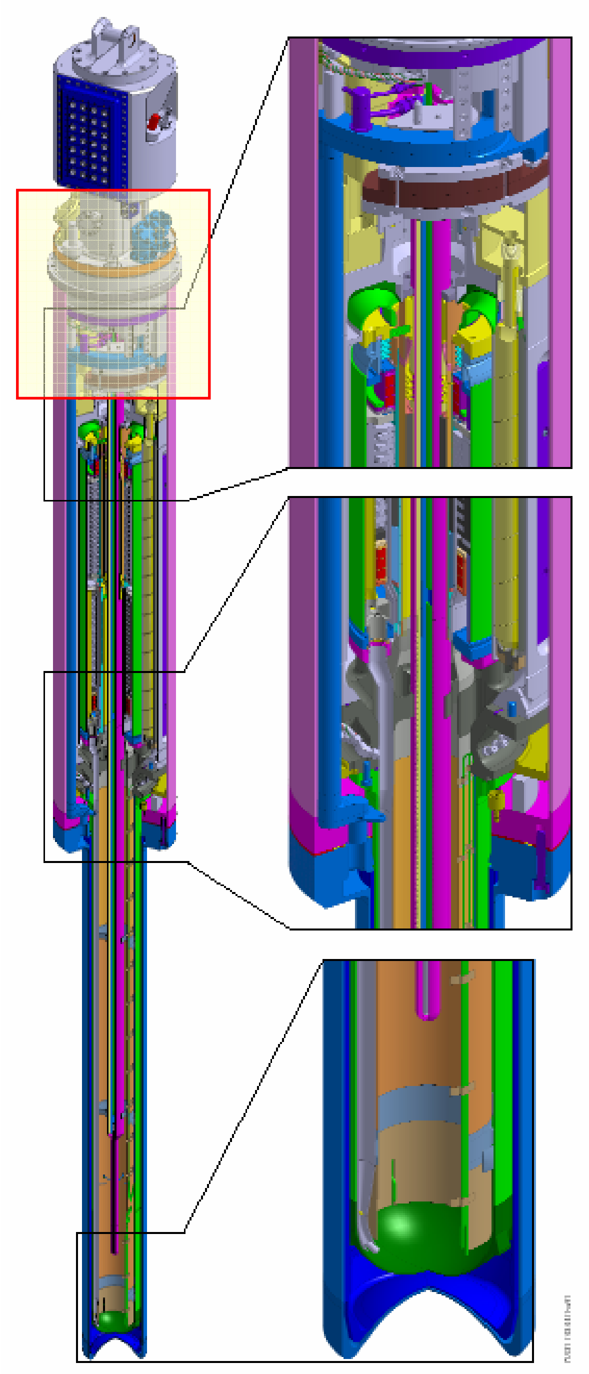


The MEGAPIE Target

- Target Head -

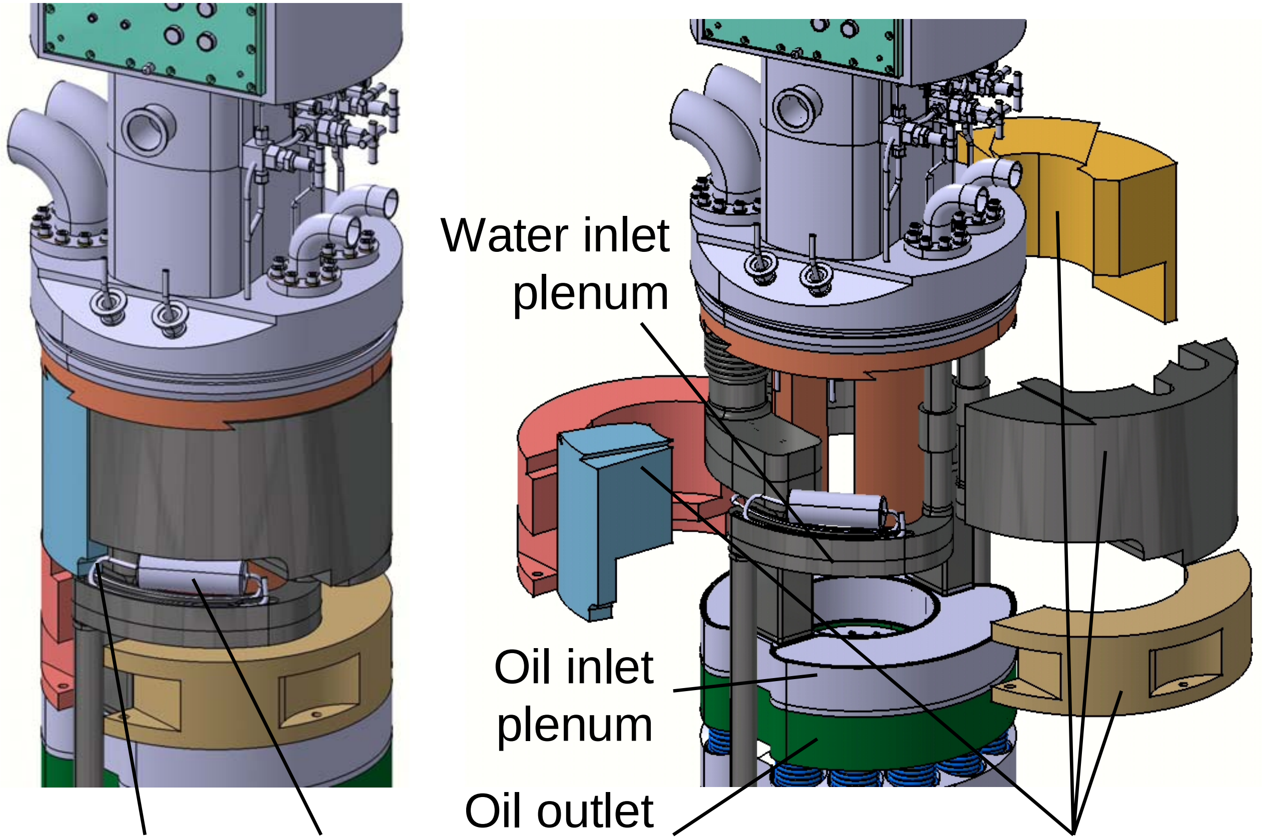






The MEGAPIE Target

- Upper Shielded Region -



Water inlet plenum

Oil inlet plenum

Oil outlet plenum

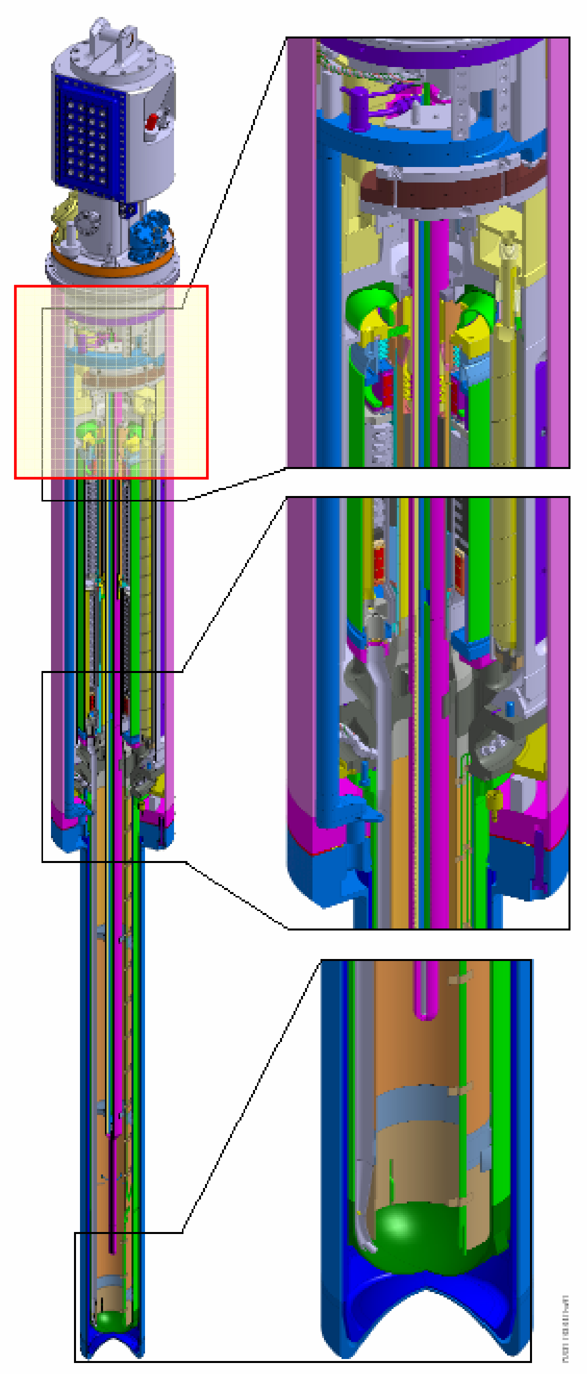
Gas condenser line

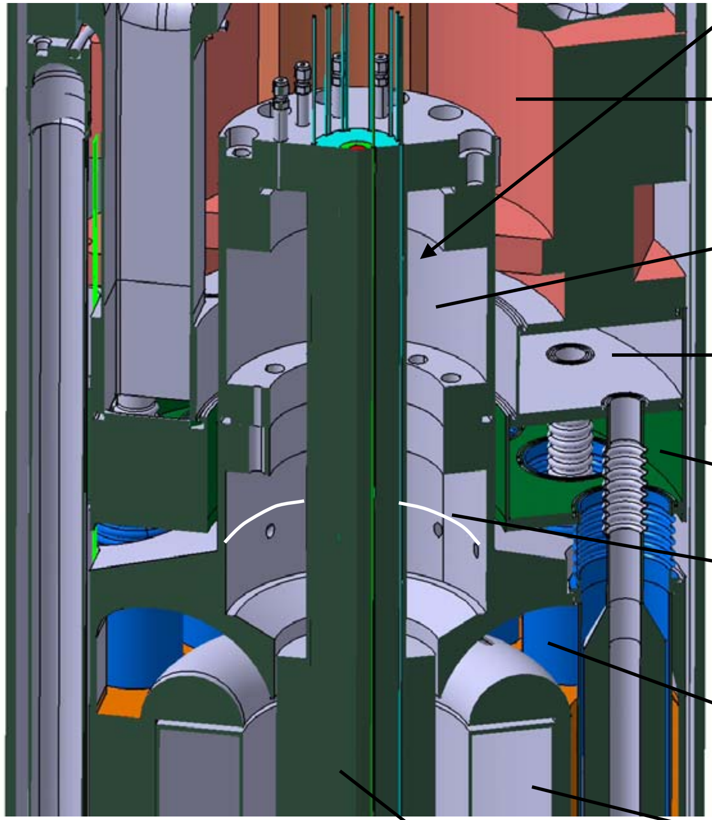
Hydrogen absorber (CuO+CaO)

Shielding blocks

The MEGAPIE Target

- Target Plena -





Location of proposed Hg-adsorber

Shielding block

Target expansion vessel

Oil inlet plenum

Oil outlet plenum

LBE level (monitored)

LBE flow path

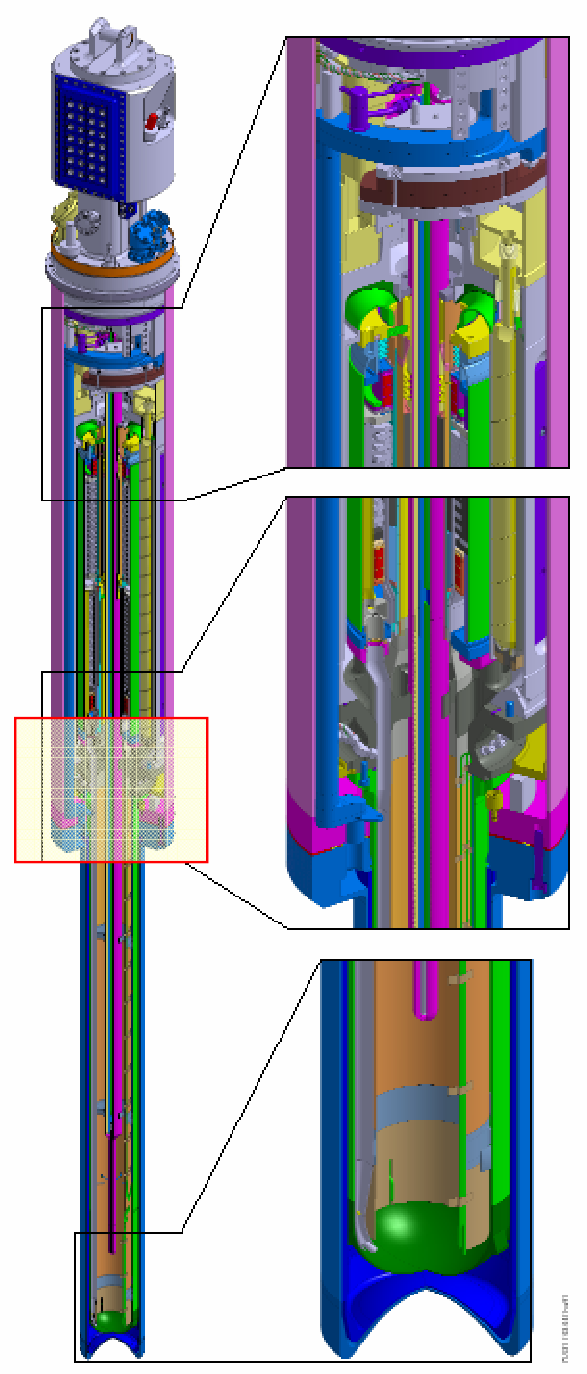
Main EM pump

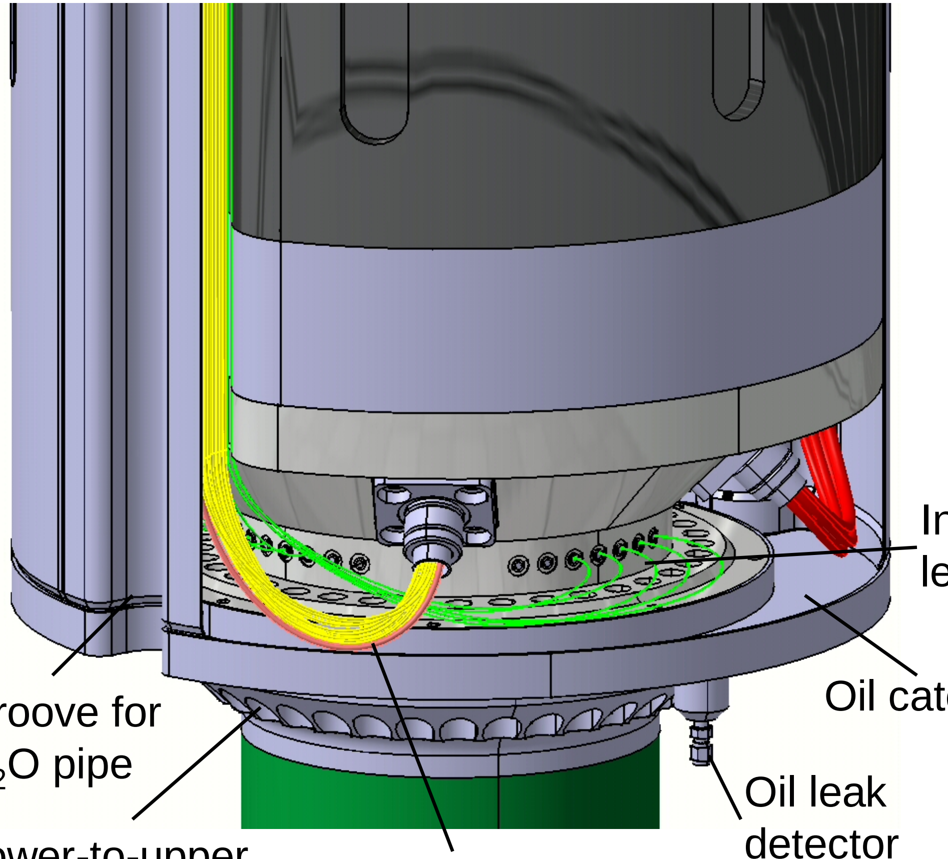
D_2O feed to LTE

Central rod

The MEGAPIE Target

- Transition Region -





Instrumentation leads

Groove for D_2O pipe

Oil catch pan

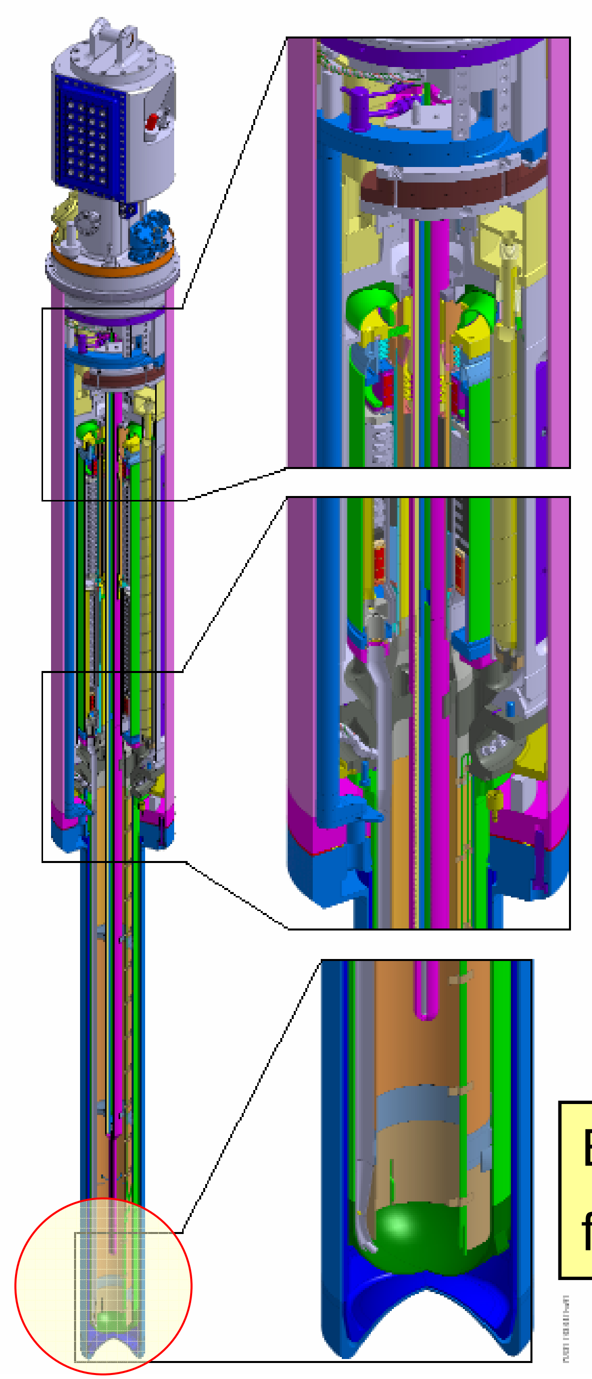
Oil leak detector

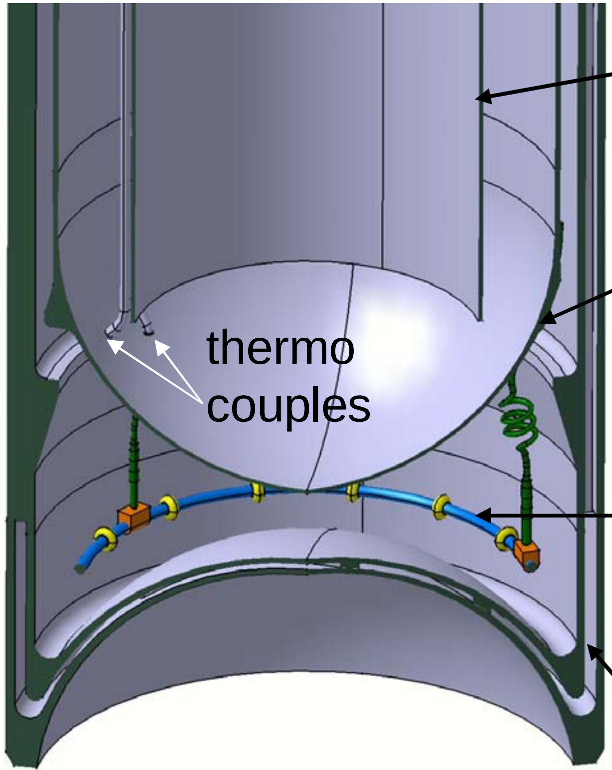
Lower-to-upper target container bolt connection

Power supply for EM-Pump

The MEGAPIE Target

-Target Window Region -





thermo couples

Inner flow guide tube

Liquid **M**etal **C**ontainer (LMC)

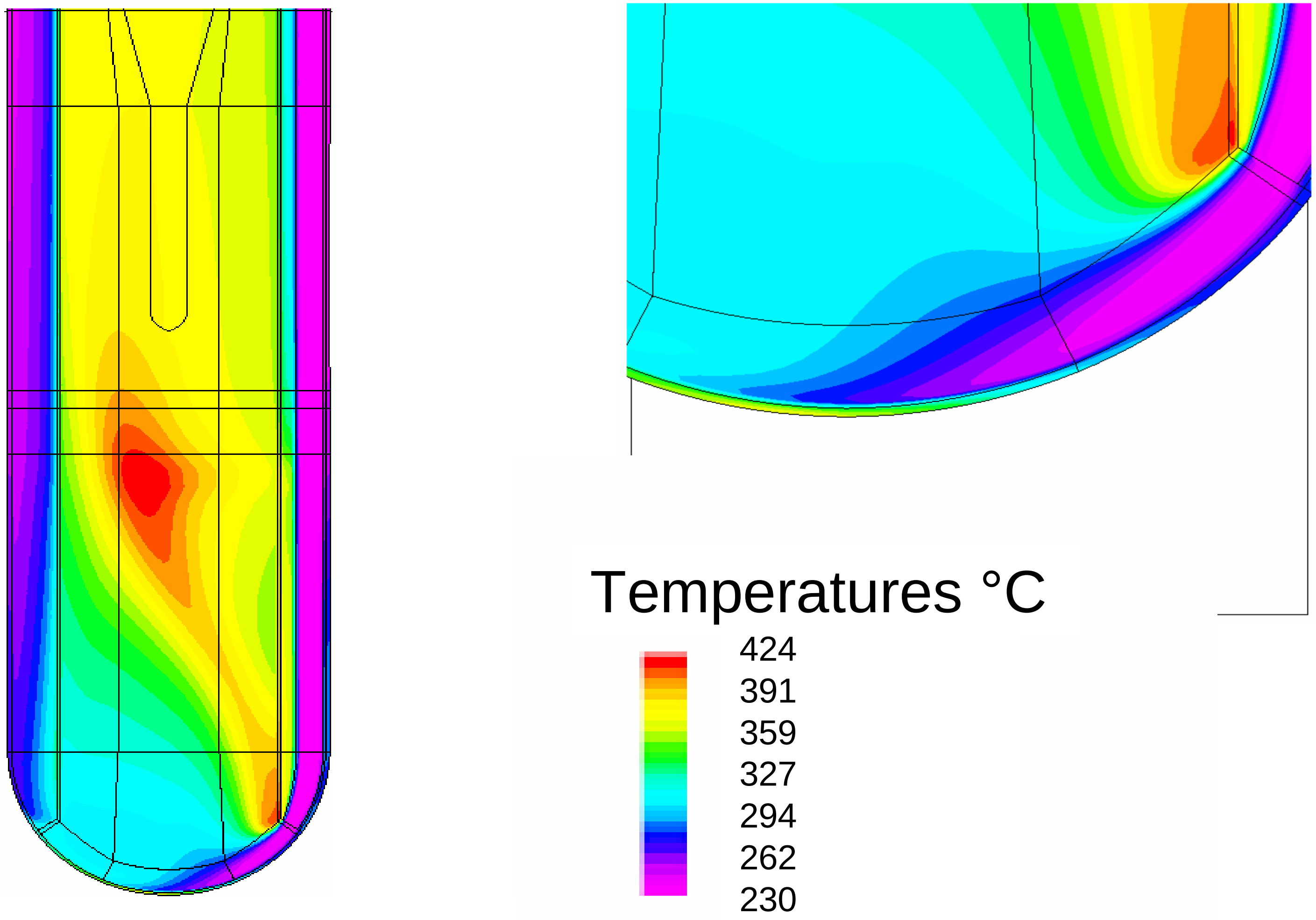
Liquid metal spill detector

Double walled D_2O cooled **L**ower **T**arget **E**nclosure (LTE)

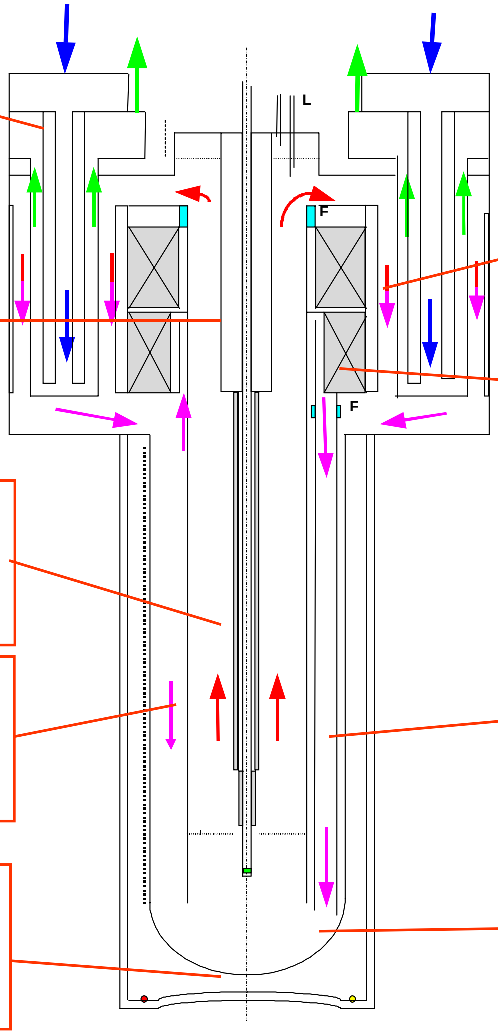
Bypass pump flow guide and fill and drain tube not shown!

Temperature Distribution in the Bottom Region

of the MEGAPIE Target - Reference Case



MEGAPIE Target Mass Flows and Temperatures



Heat Exchanger (Oil)
10 l/s, 5.5 m/s
140-175°C inside

Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

Beam Window
380°C outside
330°C inside

Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
380-230°C inside

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1m/s
230-240°C

Nozzle 1.2 m/s
Beam Window 1 m/s

→ Oil forward
→ Oil return
→ LBE forward
→ LBE return

Examples of Machined MEGAPIE Components

The 12-pin heat exchanger

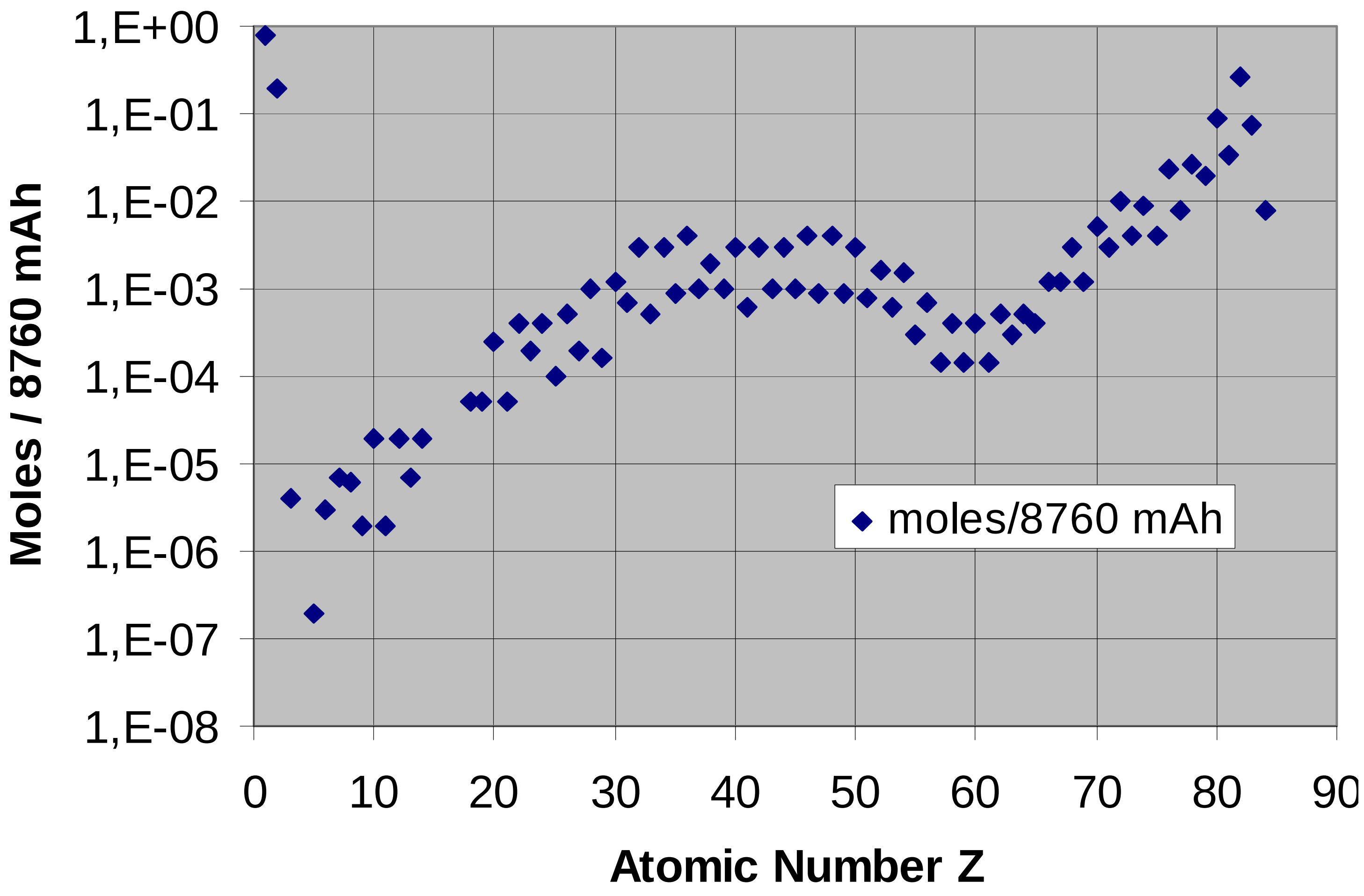
The central flow guide tube

Wagner at al, proceedings IWSMT-8, JNM

Some MEGAPIE Safety Aspects (1)

Spallation Products in PbBi

after 8760 h of irradiation by 1 mA of 575 MeV protons



Some MEGAPIE Safety Aspects (2)

Gaseous spallation products

	Production at 6000 mAh [l_{NTP}]	Partial pressure at beam off (2 l, 240 °C) [MPa]	Partial pressure at beam on (1.65 l, 340 °C) [MPa]
Hydrogen (diatomic), all isotopes: H, D, T	6.0	0.53	0.76
He, incl. ^{4}He ^{3}He	0.24 - 2.6	0.02 - 0.23	0.03 - 0.33
Ar	0.0026		
Kr	0.06	0.007	0.011
Xe	0.024		
Total	**6.3 - 8.7**	**0.56 - 0.77**	**0.81 - 1.1**
Ar, Kr, Xe total	0.086	0.007	0.011

Some MEGAPIE Safety Aspects (3)

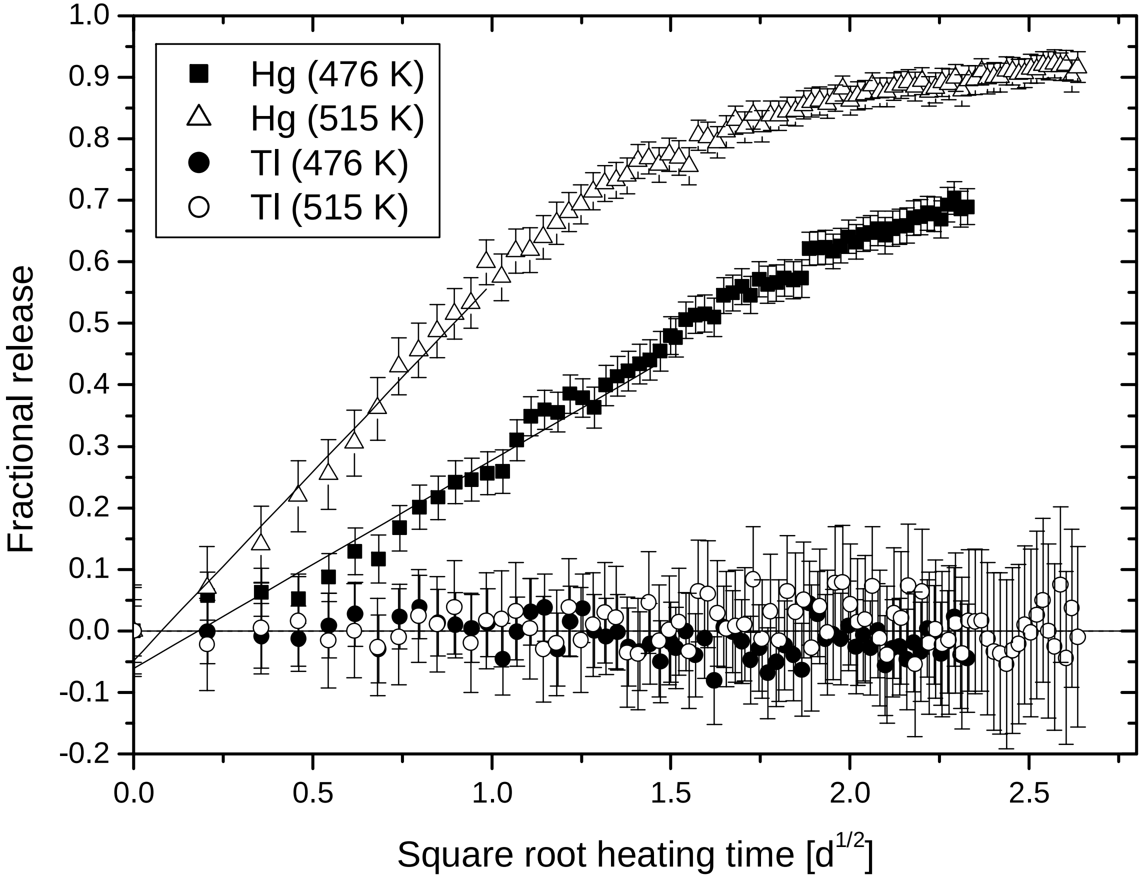
Gaseous spallation products

- The maximum permissible pressure rise in the MEGAPIE expansion tank prior to depressurization is 0.05 MPa.
- Given the high uncertainty in the calculated He-production frequent depressurization was carried out.
- The concentration of activity of the isotopes of the noble gases, Ar, Kr, Xe, of Tritium, (and of highly volatile radioactive substances) in the expansion tank required radiation protection measures to be taken for every venting step, especially for complete venting of the gases after the end of MEGAPIE operation.

Some MEGAPIE Safety Aspects (4)

Volatile spallation products

The most important volatile element in the MEGAPIE target is Hg. The calculated total quantity after 6000 mAh is approx. 12 g ≈ 60 mmol; most of it stable isotopes. Hg is expected to evaporate almost quantitatively from PbBi at 340°C (613K)



Hg vapors are trapped in an annex vessel to the expansion tank which is cooled to < 120 °C and is filled with a coil of 100 g of Pd wire of 100 µm diameter.

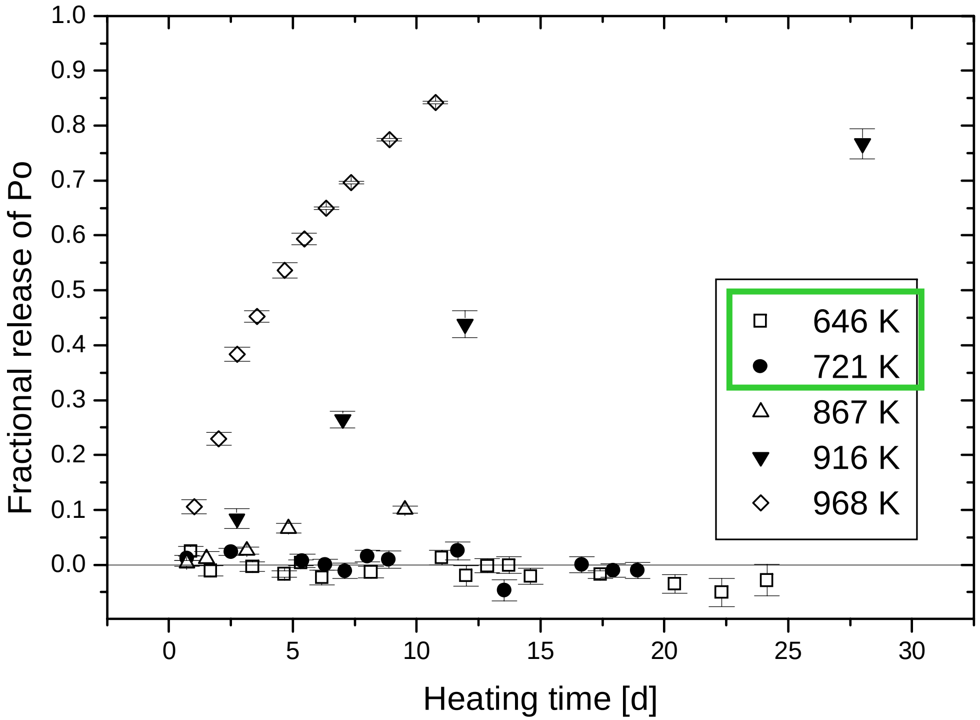
Long-term mercury and thallium release from LBE in an Ar/7%-H_2 atmosphere at different temperatures as a function of heating time

Some MEGAPIE Safety Aspects (5)

Polonium in the PbBi of MEGAPIE

- Ca. 10^{13} Bq of α-activity from all Po-isotopes (204-210) are produced by spallation in PbBi.

- Ca. 10^{14} Bq of α-activity from ^{210}Po are produced from thermal neutron capture in Bi due to the thermal neutron flux in the D_2O tank surrounding the MEGAPIE target.



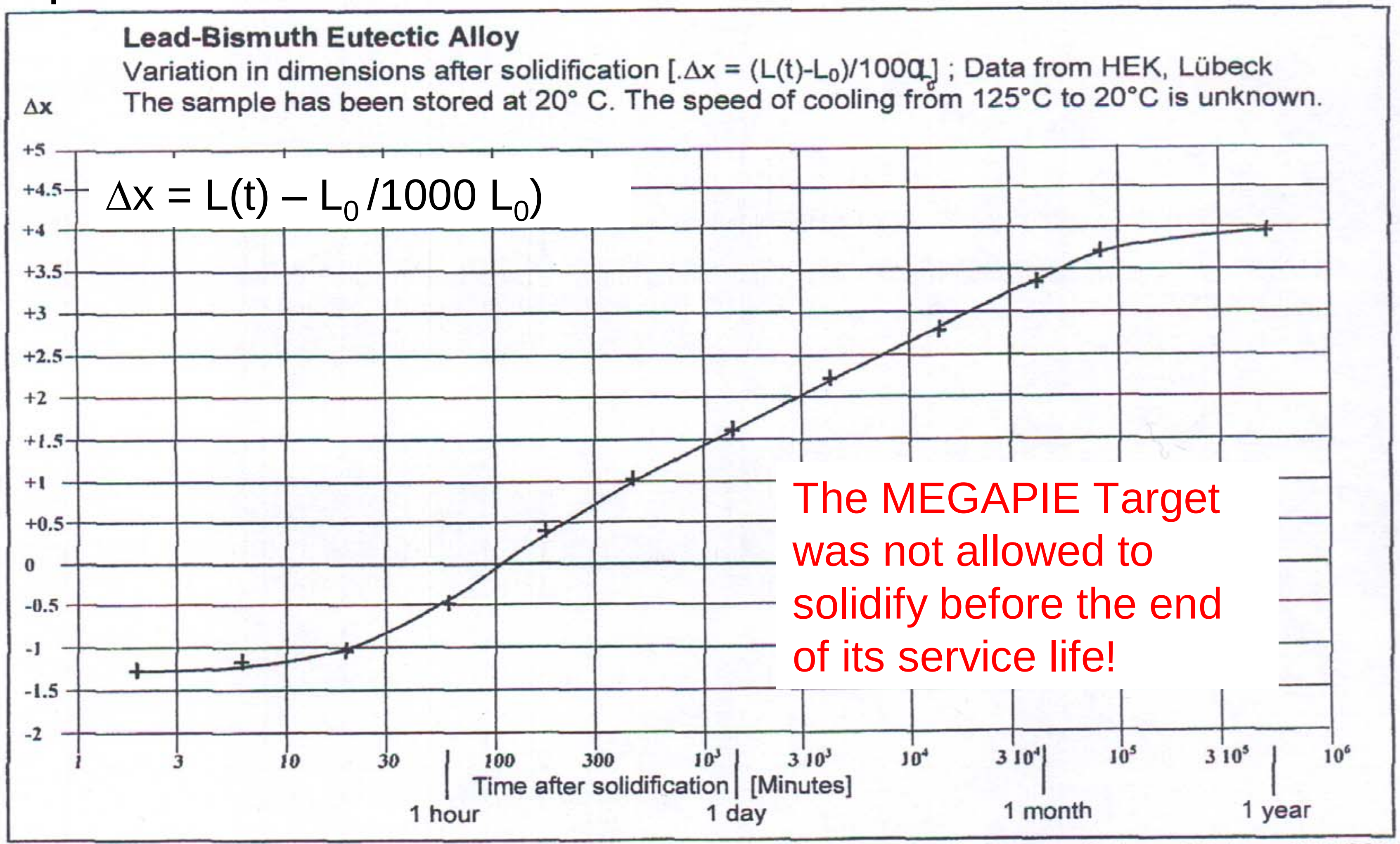
Po is not expected to be released in noticeable quantities from PbBi at 340°C (613 K)

Po release might be significant if the target material would be heated to 600°C or more in case of an accident!

Long-term polonium release from LBE in an Ar/7%-H_2 atmosphere at different temperatures as a function of heating time

Some MEGAPIE Safety Aspects (6)

Expansion of PbBi after Solidification



$\Delta x = L(t) - L_0 / 1000\ L_0)$

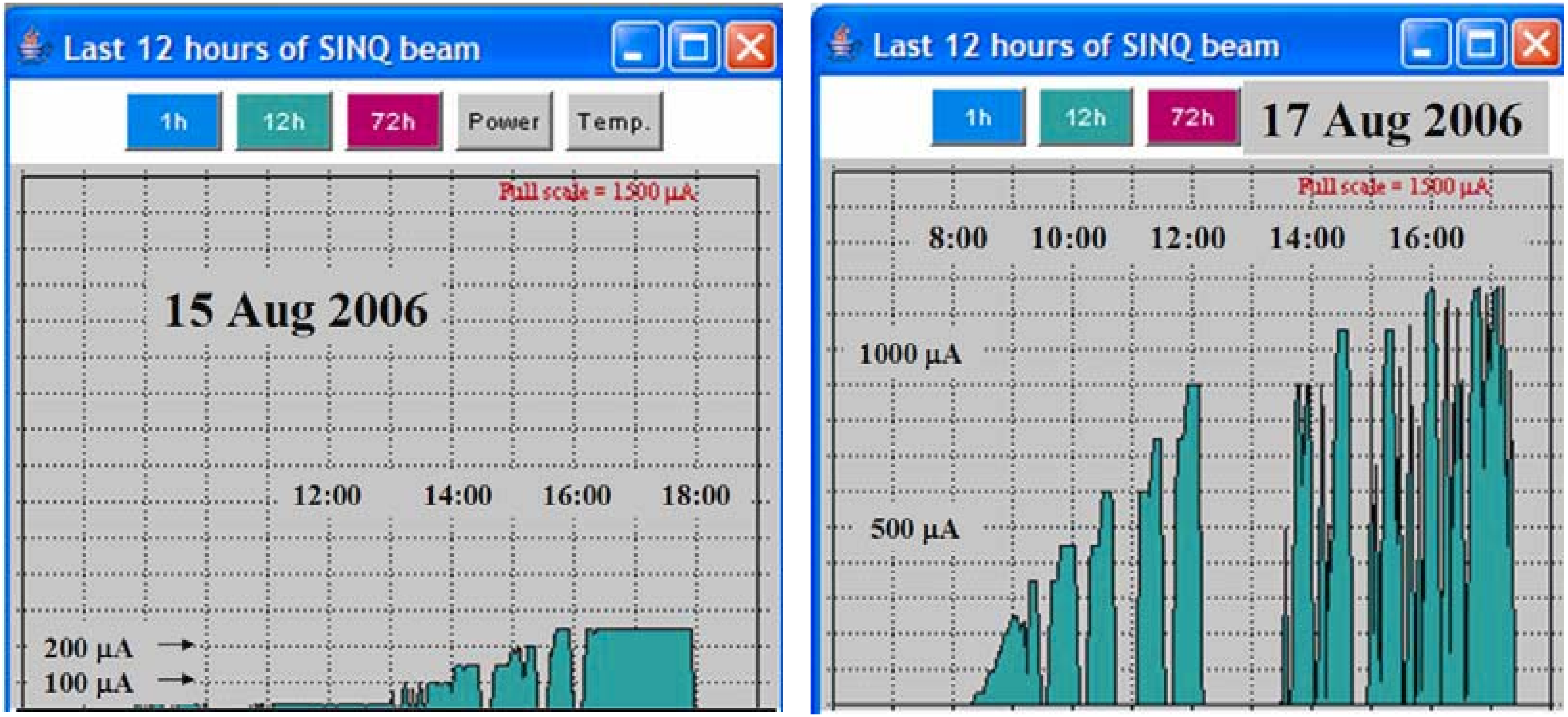
The MEGAPIE Target was not allowed to solidify before the end of its service life!

Ch. Perret Dehnung97.doc 25.1.2001

Status of the MEGAPIE Project

- The target has been built, tested, installed and run successfully in 2006 at PSI.
- All auxiliary systems and flanking measures in the SINQ installation worked fine after some initial hick-ups.
- Supporting R&D has provided numerous results on LM-corrosion, spallation product release and other safety-relevant issues that allowed to obtain an operating license under Swiss legislation.
- Target operation was stopped at the end of 2006 after 2.8 Ah at up to 800 kW (1.35 mA at 590 MeV).
- The anticipated neutronic performance has been fully reached (x 1.5 over solid Pb target)
- The target has been removed and transported to a large hot cell facility where it is being dismantled for PIE

Start Up of the MEGAPIE Target with Beam



Beam history during the start-up phase of the MEGAPIE target. On Aug. 15 the power was increased stepwise to 150 kW. On Aug. 17 the beam was ramped-up to full power. Most of the beam trips were introduced intentionally for transient studies

Wagner at al, proceedings IWSMT-8, JNM

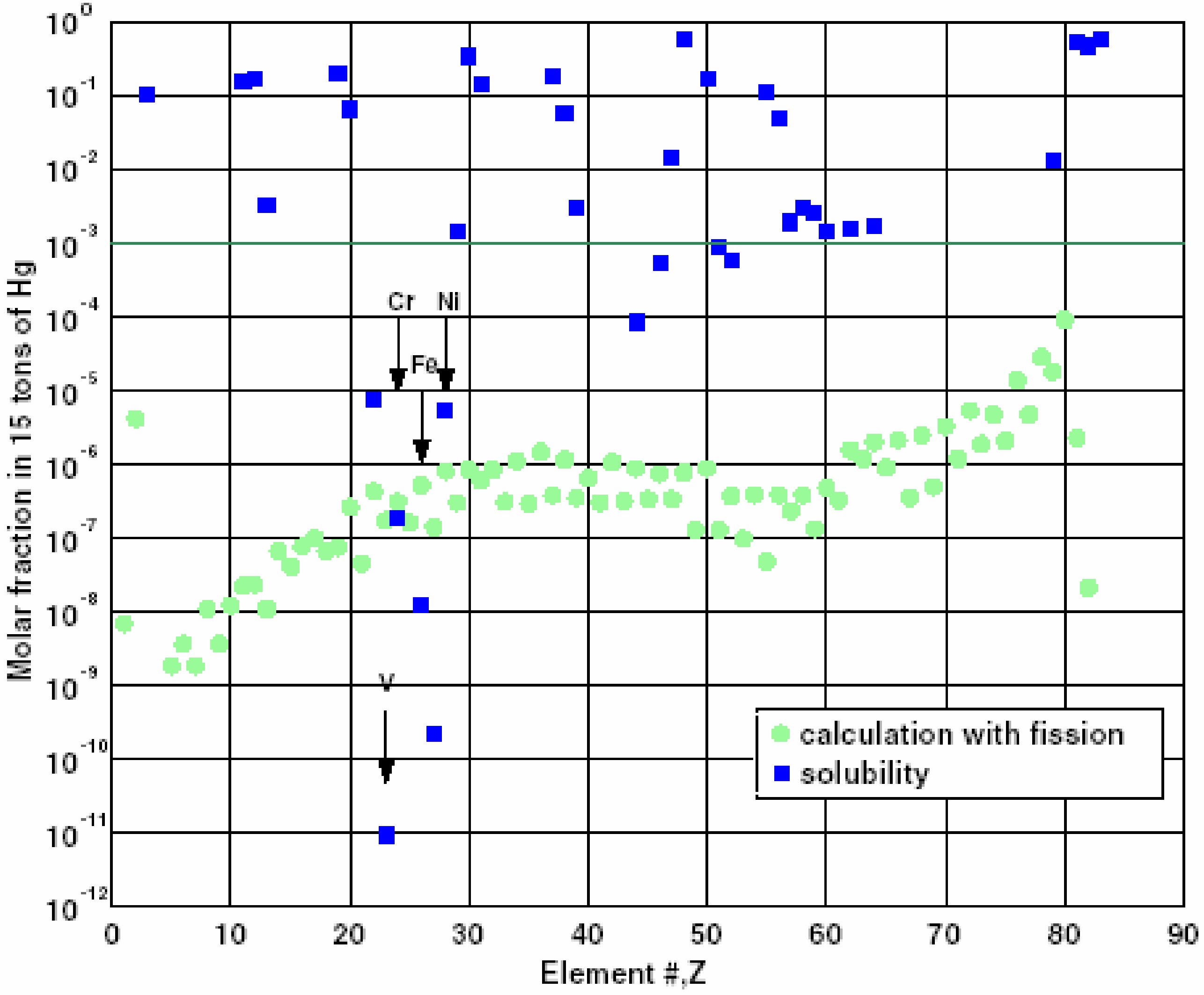
An Upcoming Generation of Liquid Metal Targets: Mercury Targets for Pulsed Spallation Sources

Mercury as a Target Material

- Mercury is liquid at room temperature and thus does not require auxiliary heating to prevent solidification.
- Mercury makes a brighter neutron source than PbBi due to a higher neutron yield and 30% more density.
- Mercury is easy to purify to a high degree, does not generate alpha-active products and has only one long lived radioactive isotope (^{194}Hg, 376a), which is a rare spallation product.
- The high thermal neutron absorption in Hg is a disadvantage in systems with well thermalised neutrons near the target, but not necessarily so, if a fast system is considered.
- For these reasons Hg was chosen as target material for all next generation high power pulsed research neutron sources (ESS 5 MW, J-SNS 1 MW, SNS 2 MW).

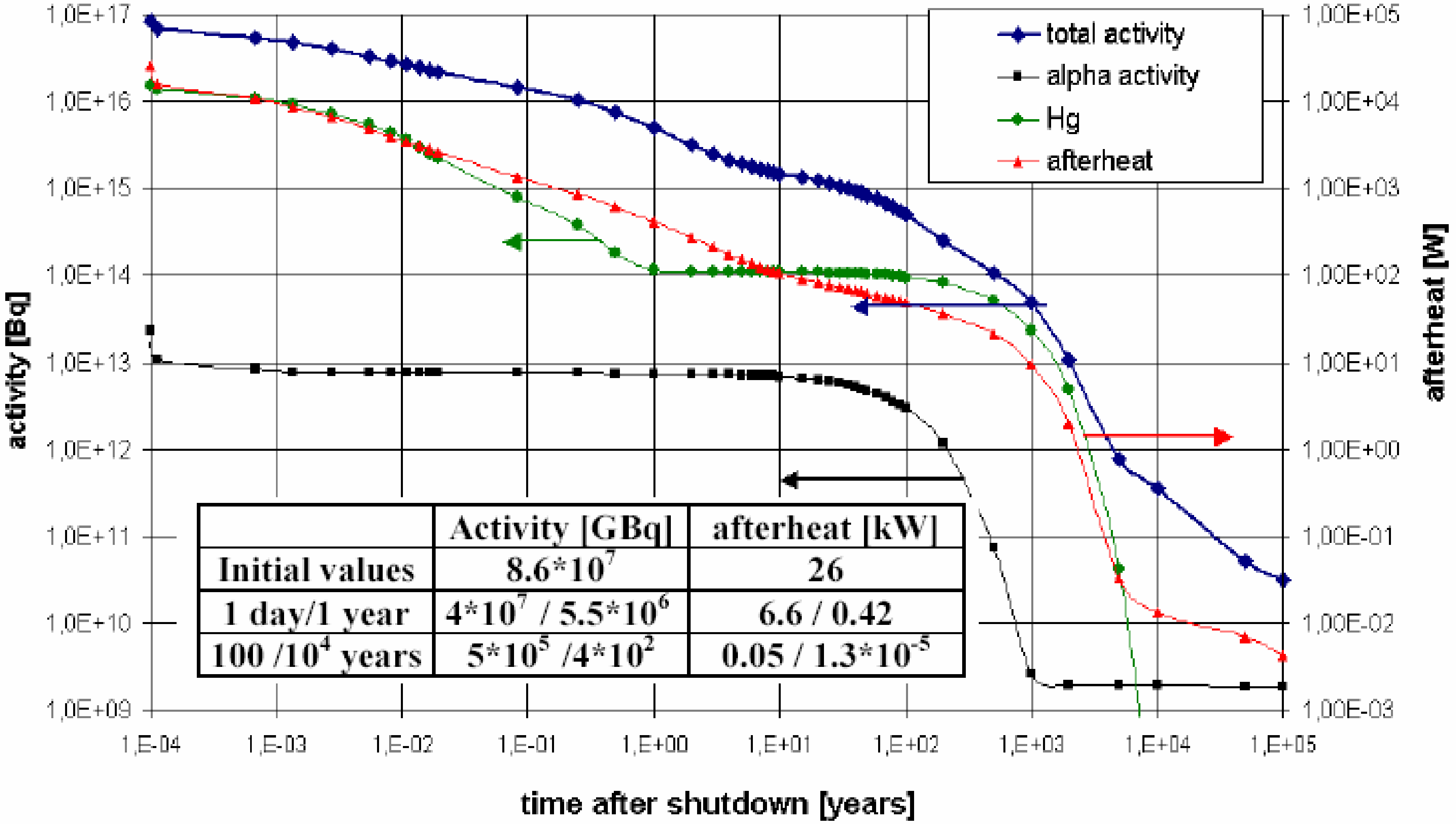
Mercury target: Radioactivity (1)

Spallation products generated in 15 t of Hg after 10 y of operation at 5 MW compared to their solubility limits



Mercury target: Radioactivity (2)

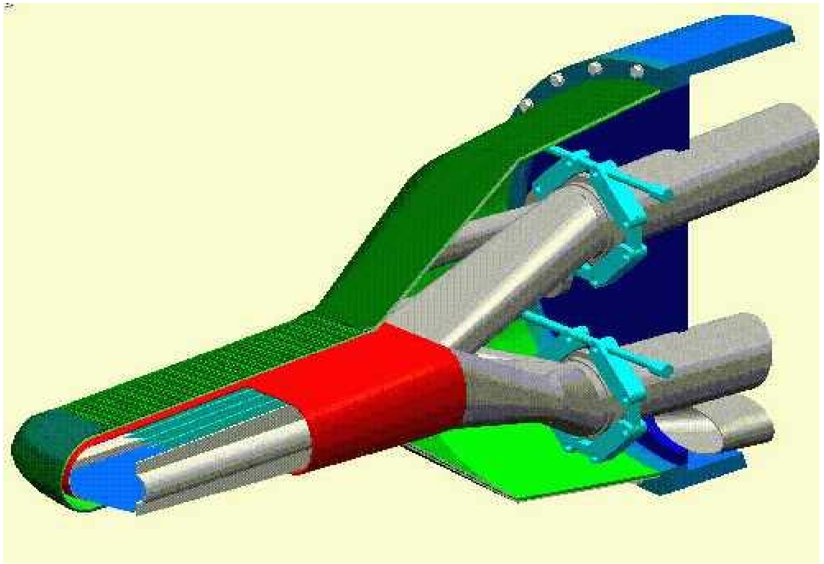
Activity and decay heat in the ESS mercury target after 30 y of operation



	Activity [GBq]	afterheat [kW]
Initial values	$8.6*10^7$	26
1 day/1 year	$4*10^7$ / $5.5*10^6$	6.6 / 0.42
100 /10^4 years	$5*10^5$ /$4*10^2$	0.05 / $1.3*10^{-5}$

Target Geometry: ESS Slab Target

Based on an evaluation by PSI, the ESS project decided in 1993 to adopt a mercury slab target for its reference concept.



The beam footprint on the target is elliptic with major and minor axes of 20 x 6 cm^2

A horizontal slab target lends itself to placement of moderators above and below the target.
(A vertical slab target provides for even illumination of slab moderators but bears the risk of high fast neutron and gamma contamination.)

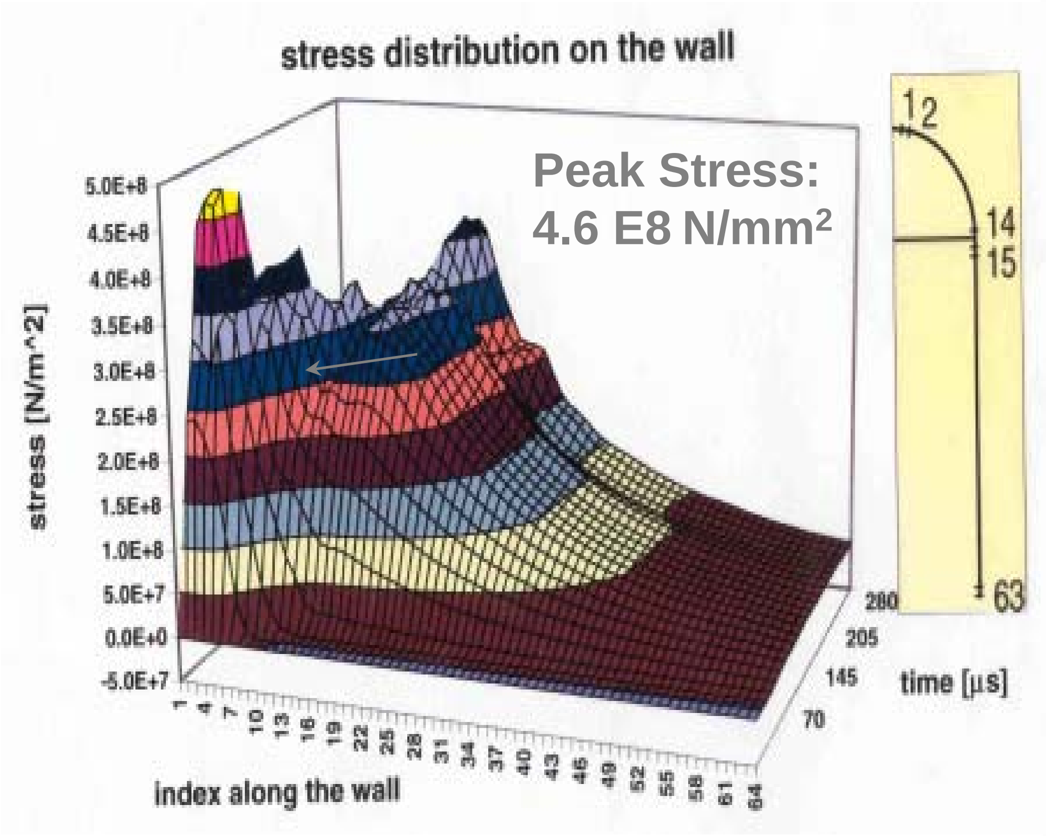
Similar geometries are used in the SNS (USA) and JSNS (Japan) projects

Liquid Metal Targets: The Pressure Wave Problem (1)

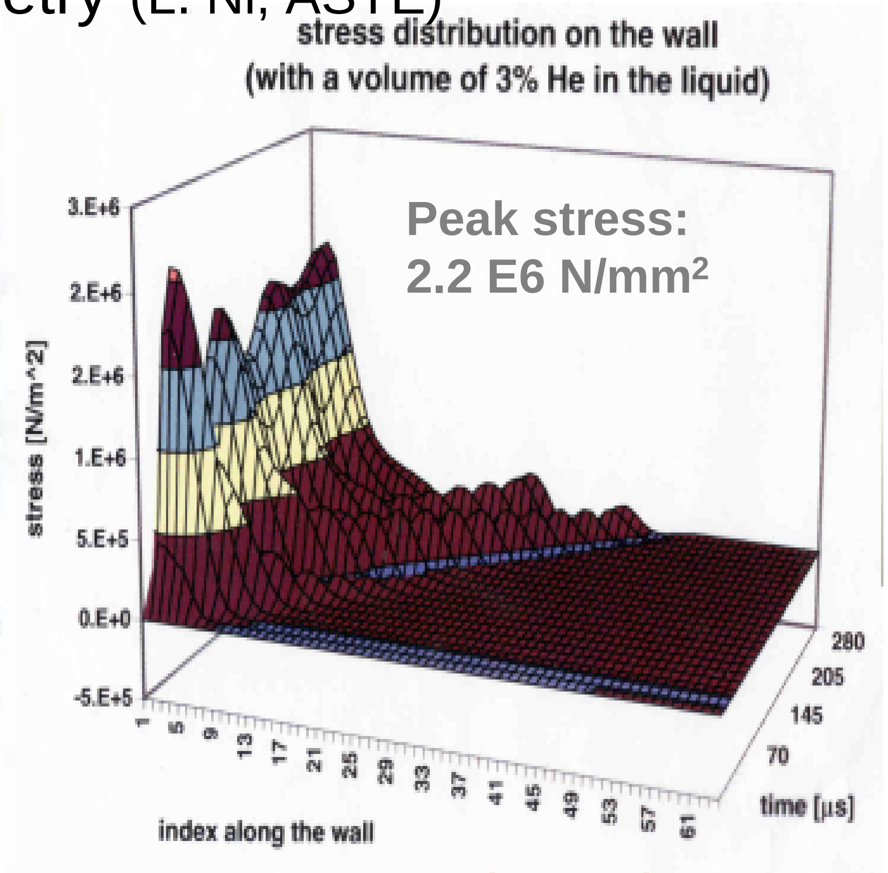
- In a 5 MW 50 Hz short pulse source some 60 kJ are deposited in a small volume within 1 microsecond.
- This leads to thermal expansion which cannot be accommodated by convection, conduction or displacement.
- The resulting pressure wave causes stress on the target container when it reaches the wall.
- This stress may be of the order of the endurance limit of the container material or higher and is generally superimposed on stress from other sources (thermal gradients, pressure etc.).

Liquid Metal Targets: The Pressure Wave Problem (2)

- Calculations for cylindrical geometry (L. Ni, ASTE)



Peak Stress:
4.6 E8 N/mm^2

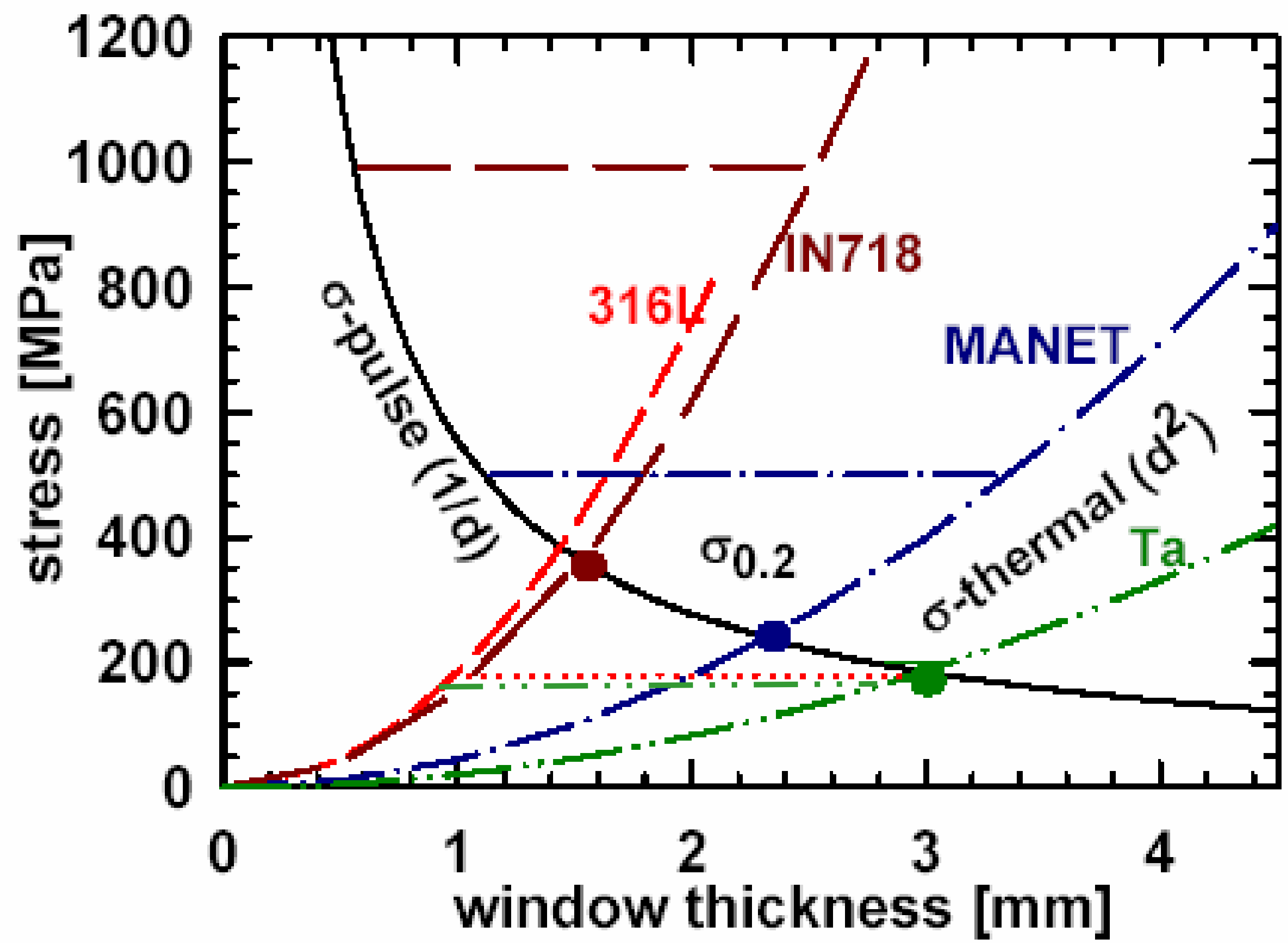


Peak stress:
2.2 E6 N/mm^2

In theory, 3 vol% of helium in the mercury can reduce the stress on the walls by 2 orders of magnitude:
Experimental proof and technical concept are still missing!

Liquid Metal Targets: The Pressure Wave Problem (3)

Induced *mechanical and thermal stress* in the centre of the target container window in pulsed operation at 5 MW



Horizontal lines:
yield stress for the respective materials (colour coded, unirradiated)

A high strength (low operating temperature) is essential!

Liquid Metal Targets: The Cavitation Issue

- During the rarefaction phase of the pressure wave the liquid metal goes into tension. This can lead to formation of cavities.
- Cavitation might also be the result of the extremely high power density in "thermal spikes" (energy deposition in the "damage cascade" by PKAs and recoil nuclei).
- Near the wall collapsing cavities have deleterious effects on the solid metal (pitting, erosion, destruction of the protective oxygen layer etc.).
- These problems are subject to intense research efforts.
- Injection of helium bubbles of suitable size and volume fraction is expected to remedy this problem at the same time as the wall stress.

Interim Summary on Cavitation Erosion

- Thanks to mainly the excellent research work done at JAERI, the mechanism of cavitation erosion is now rather well understood.
- Apart from mass removal (thinning of the wall), hardening and crack growth below the attacked surface is the main problem.
- This leads to a significant reduction of the fatigue life, which is particularly worrisome because the stress on the target wall is high during the pulse.
- **Pitting damage seems to increase with the 4th power of power density in the target!**
- Currently a service life of no more than two weeks can be expected for a mercury target container at 1 MW_b power in pulsed operation.

The Most Important Issue

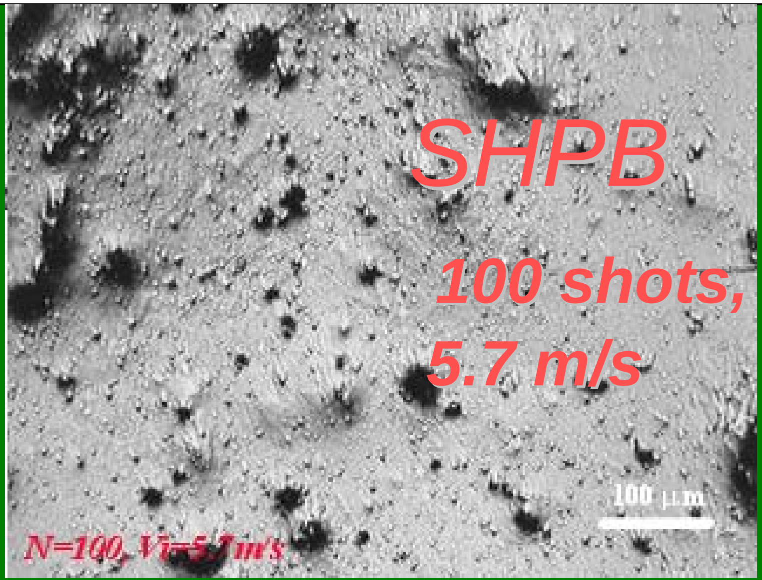
Mitigation of the pressure wave effect is a prime concern in the ongoing development of high power targets for pulsed sources.

Two methods are being pursued:

- surface hardening (not a real cure)
- gas injection in the volume and/or near the wall

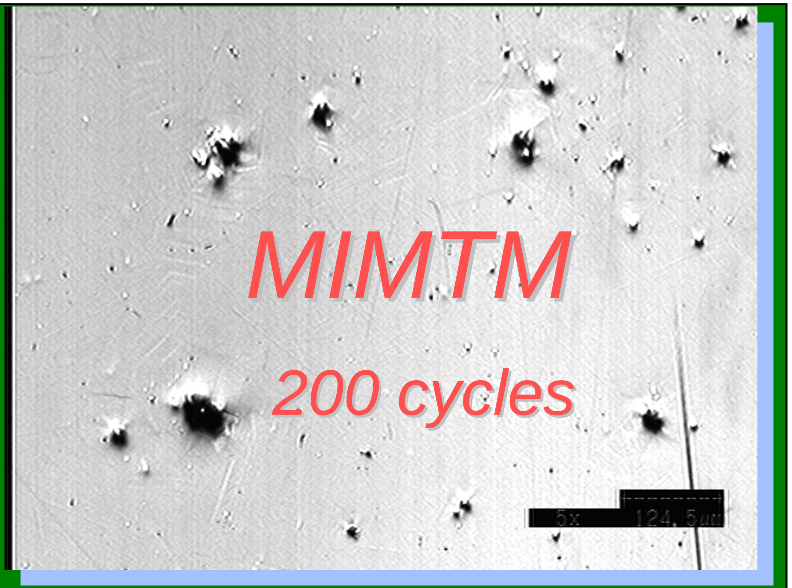
Cavitation-Erosion („Pitting“) by Pressure Pulses (1)

Out of beam



SHPB

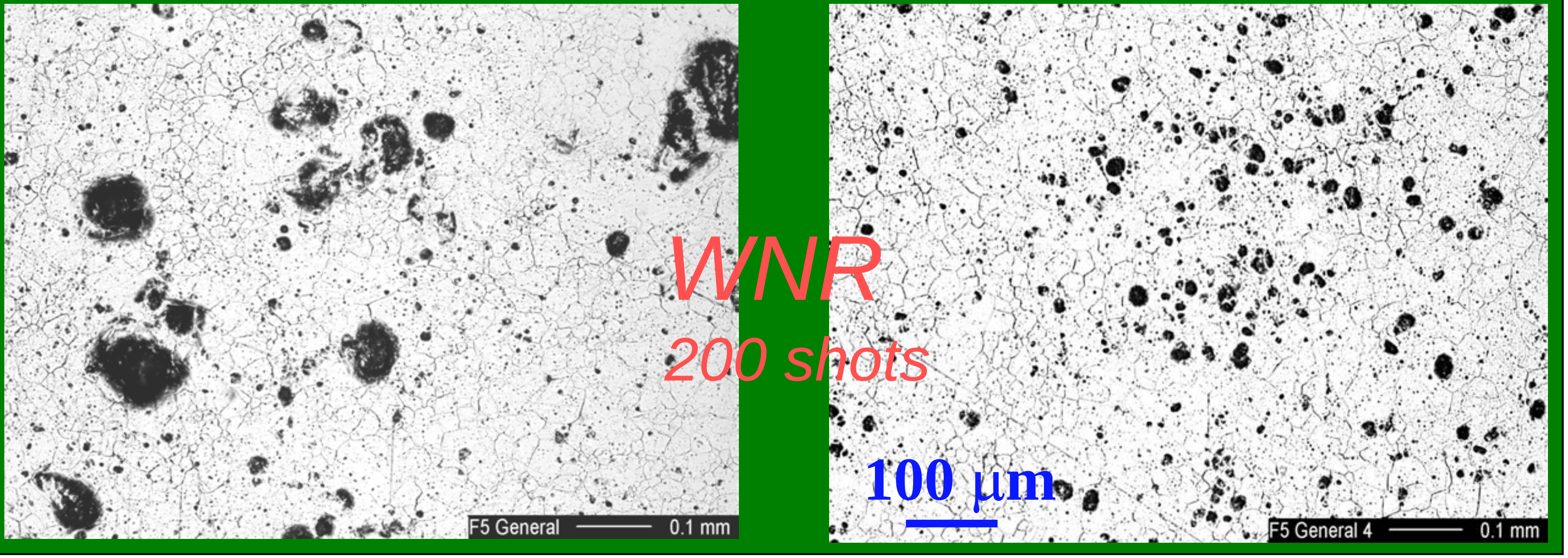
100 shots, 5.7 m/s



MIMTM

200 cycles

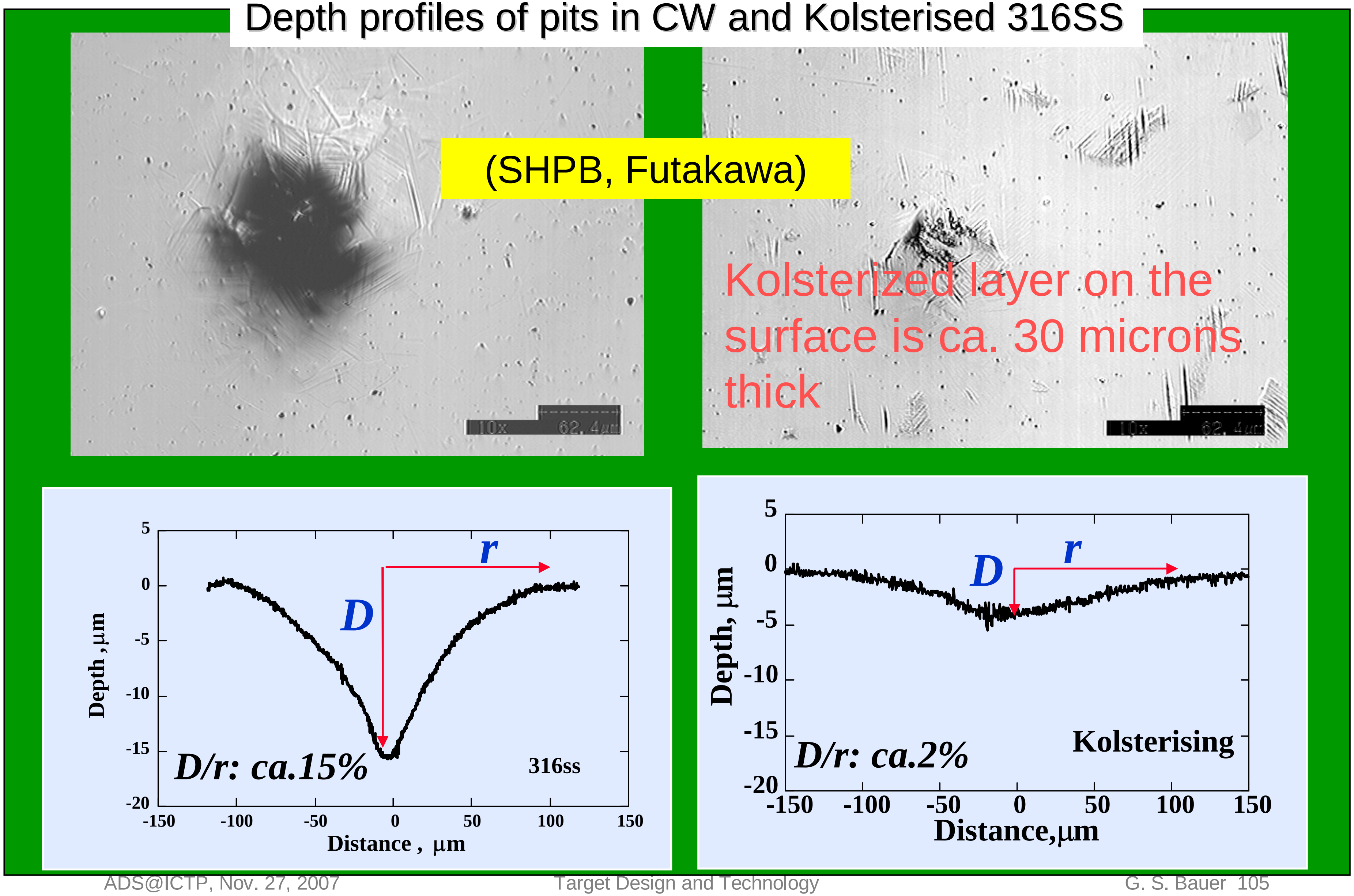
800 MeV prot. beam



WNR

200 shots

Cavitation-Erosion („Pitting“) by Pressure Pulses (2)



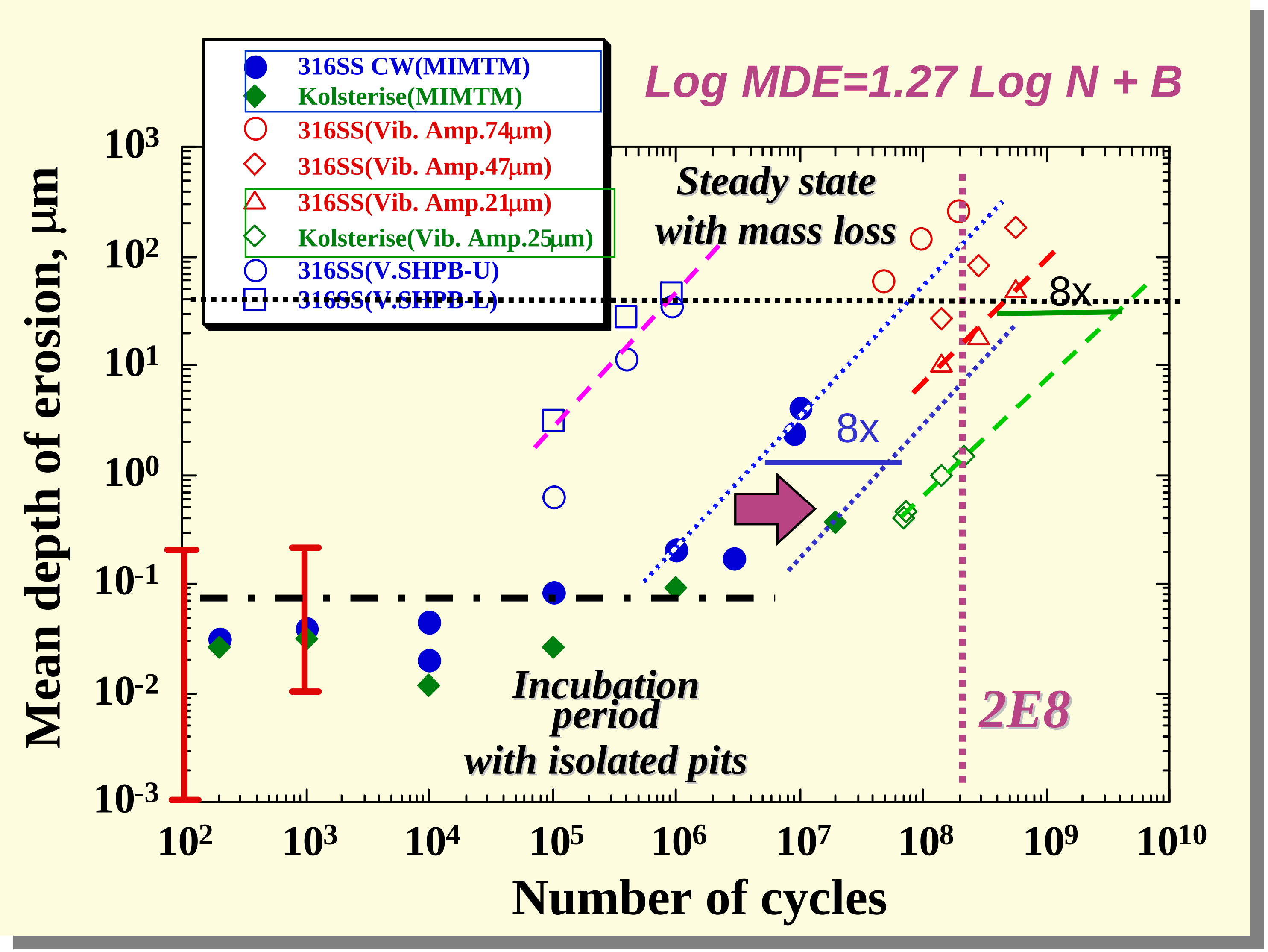
Depth profiles of pits in CW and Kolsterised 316SS

(SHPB, Futakawa)

Kolsterized layer on the surface is ca. 30 microns thick

Cavitation-Erosion („Pitting“) by Pressure Pulses (3)

Summary Diagram of Pitting Results



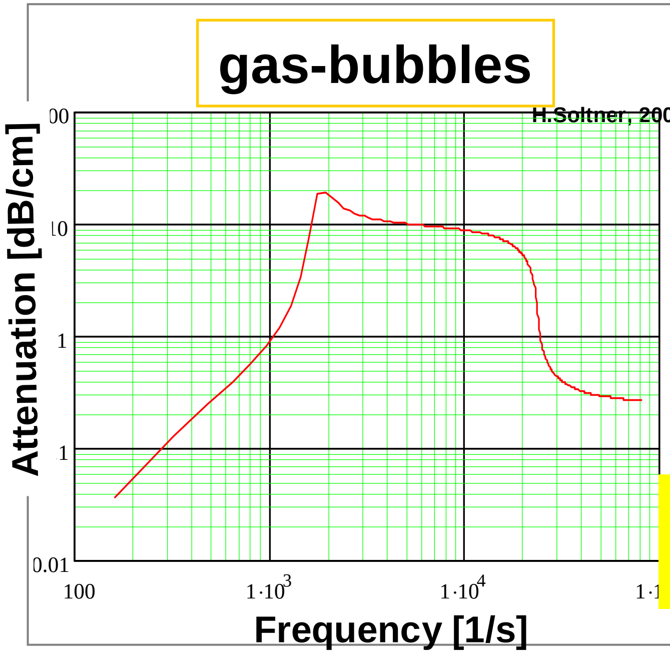
M. Futakawa, JAERI

Kolsterising can expand incubation period

Kolsterized layer on the surface is only ca. 30 microns thick!

Cavitation-Erosion („Pitting“) by Pressure Pulses (6)

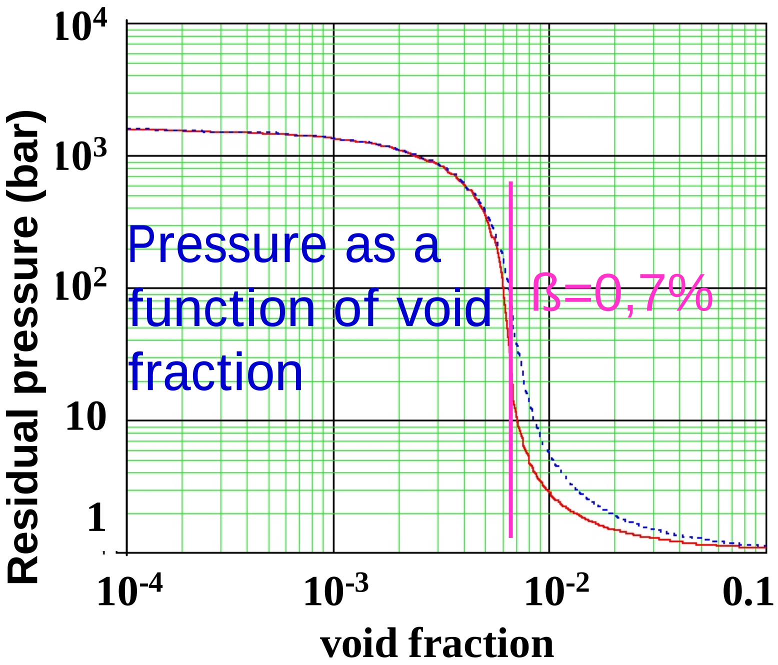
Pressure wave mitigation by gas bubbles



Attenuation of sound waves by helium bubbles (r = 1mm, ΔV/V=0.0377%) in mercury

$\omega=(3\gamma\, p/r^2\rho)^{1/2}$

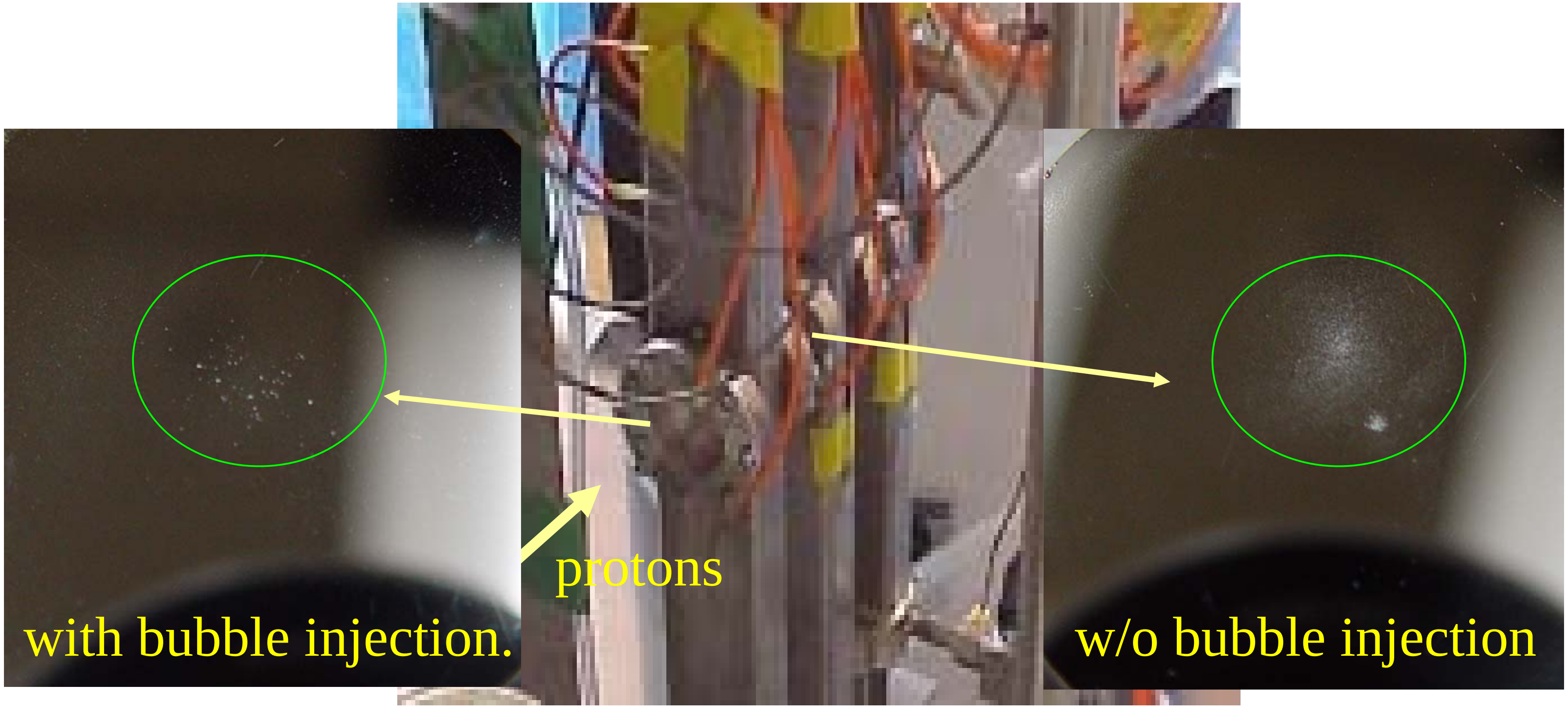
10 kHz→ 0.4mm



- A small amount of bubbles of the right size can attenuate a travelling pressure wave.
- A sufficiently large volume fraction of bubbles can substantially reduce the peak pressure.
- Bubble injection techniques are under development.

Cavitation-Erosion („Pitting“) by Pressure Pulses (7)

First PoP-test of bubble effect at WNR in June 2002



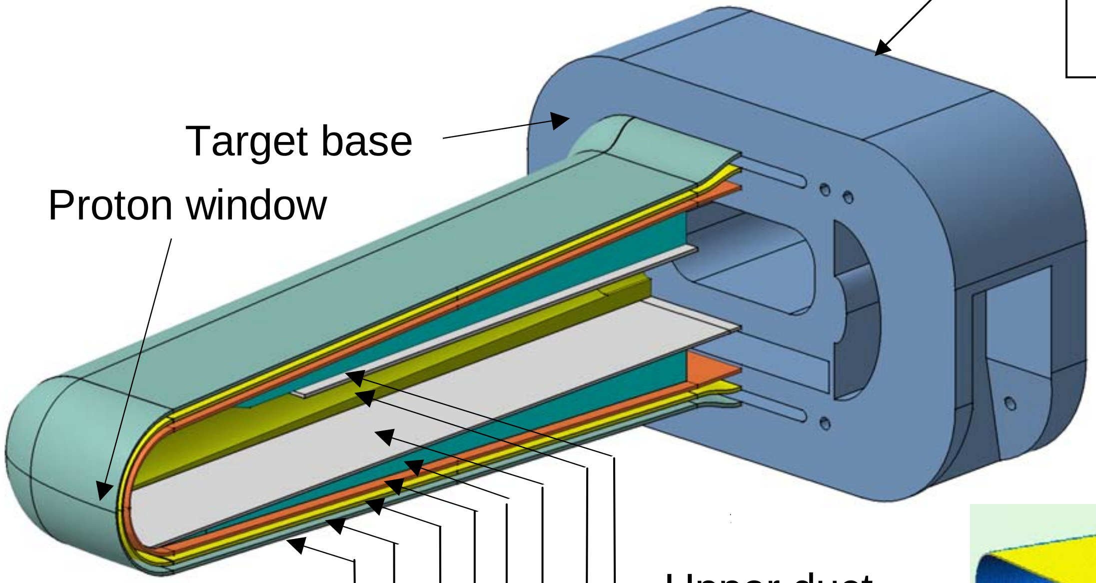
Maximum energy density in targets was 17.5 J/cc in bubble target and 14.4 J/cc in control target (p^4 = 93789 and 42998 respectively)

⇒ Would expect more than twice the damage in bubble target

⇒ Find significantly less   Next series of tests at WNR under evaluation

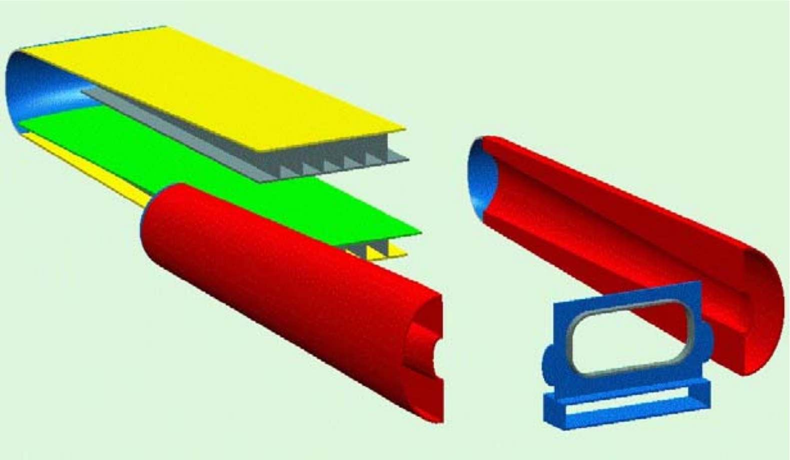
Liquid Metal Targets: Design example – ESS (1)

ESS target with quick disconnect flange for rapid exchange



Some connections may have to be made separately

Components of the liquid metal container

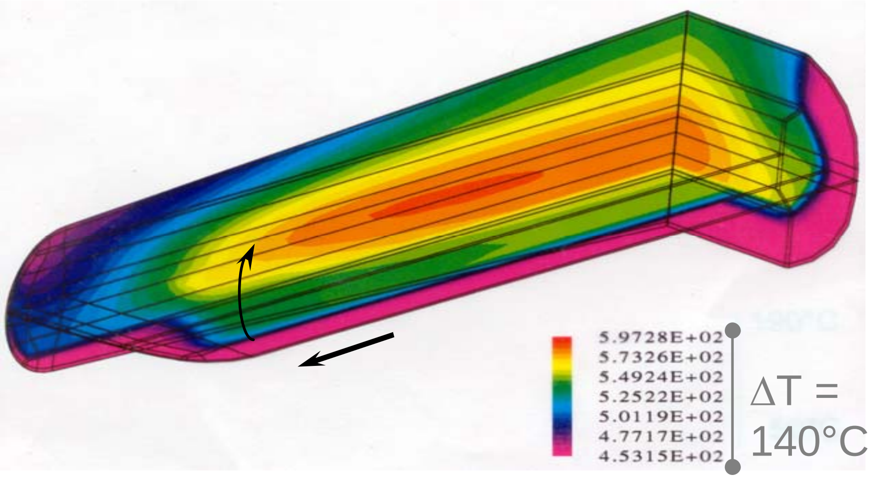


Liquid Metal Targets: Design example – ESS (2)

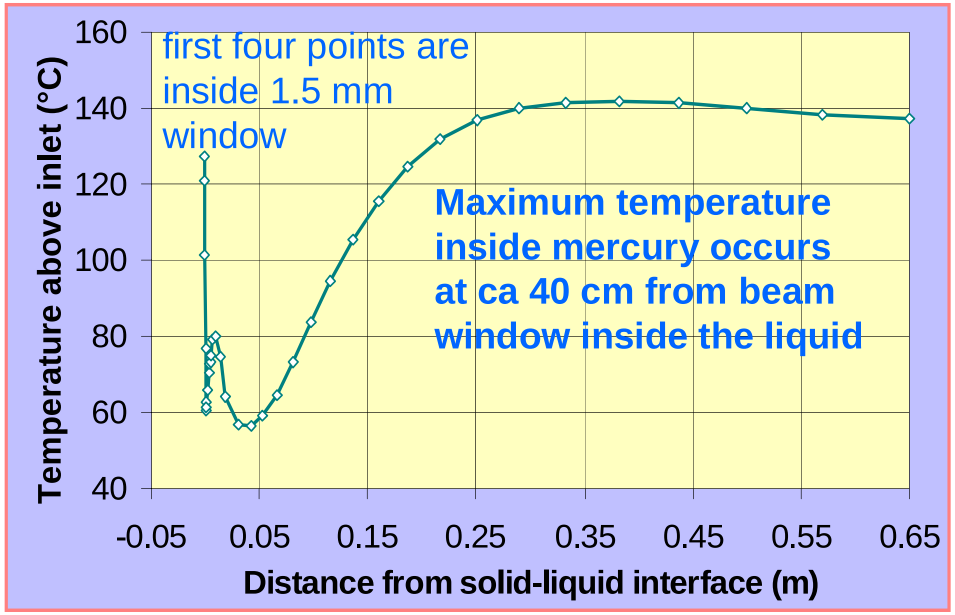
Peak current density: 80 μA/cm^2 of 1.33 GeV protons; window cooled in cross flow by 23% of total flow.

Calculated temperature distribution in 3 planes of the ESS target at 2.8 MW power dissipation and a mass flow of 175 kg/s (away from the beam window). Inlet velocities are 0.6 (bottom) and 1.78 m/s (sides).

Bulk flow is away from the window!



ΔT = 140°C

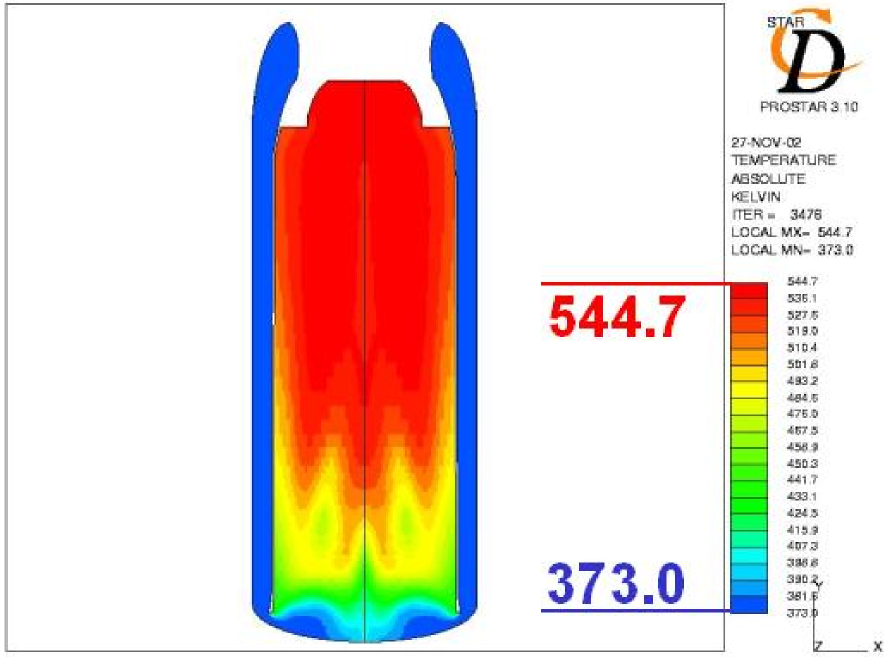


first four points are inside 1.5 mm window

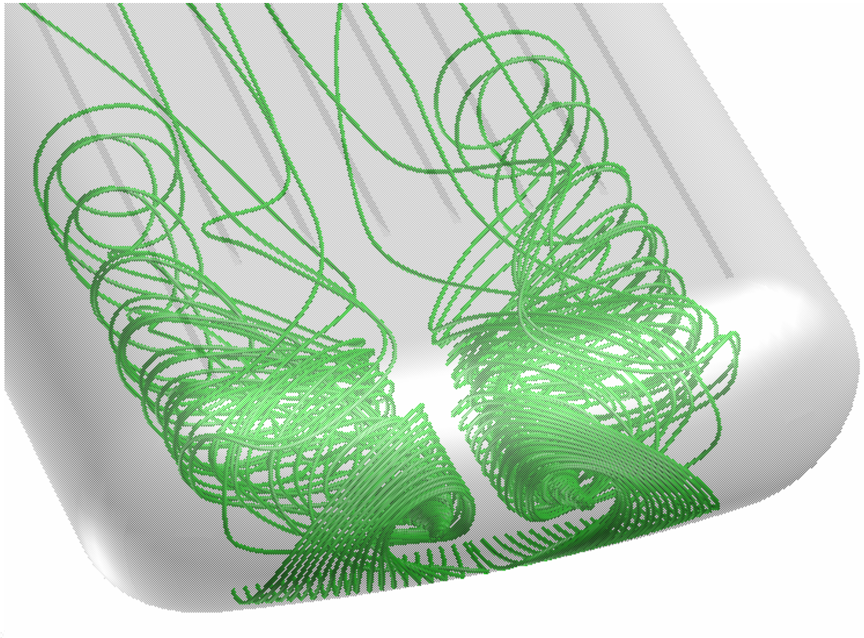
Maximum temperature inside mercury occurs at ca 40 cm from beam window inside the liquid

Liquid Metal Targets: Design example – ESS (3)

Flow optimization in the ESS-target



Computed liquid mercury temperature field in the horizontal mid-plane of the target for a flow distribution with 15% of the total mass flow through the bottom ducts [Komen, 2003b]



Computed trajectories of 0.1 mm diameter helium bubbles. The helium bubbles are injected from the bottom inlet duct [Komen, 2003]

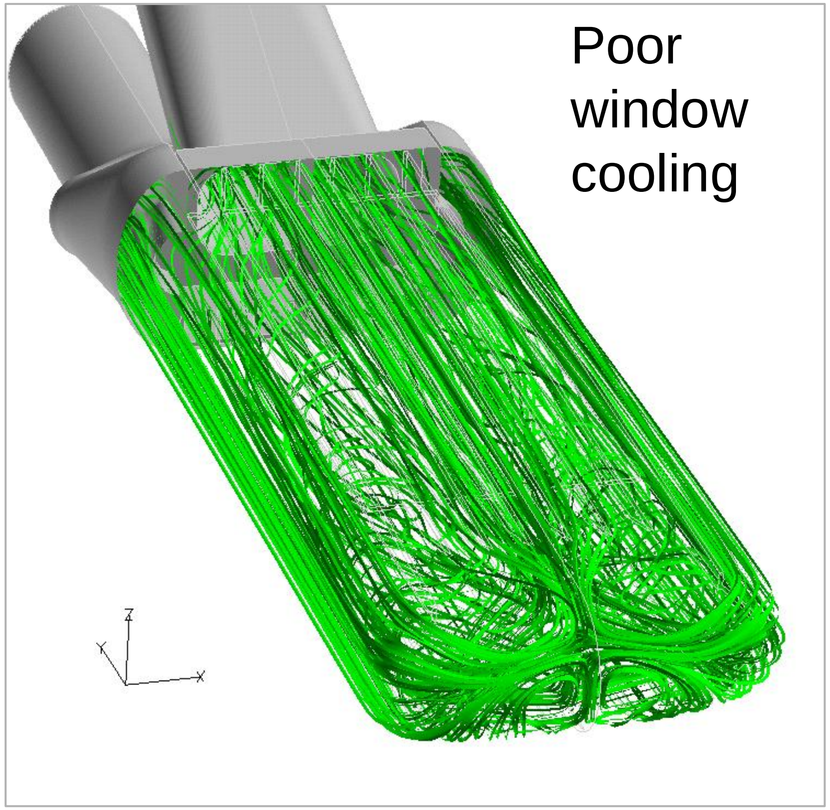
More work is clearly needed!

Liquid Metal Targets: Design example – ESS (4)

Optimizing the ESS target geometry

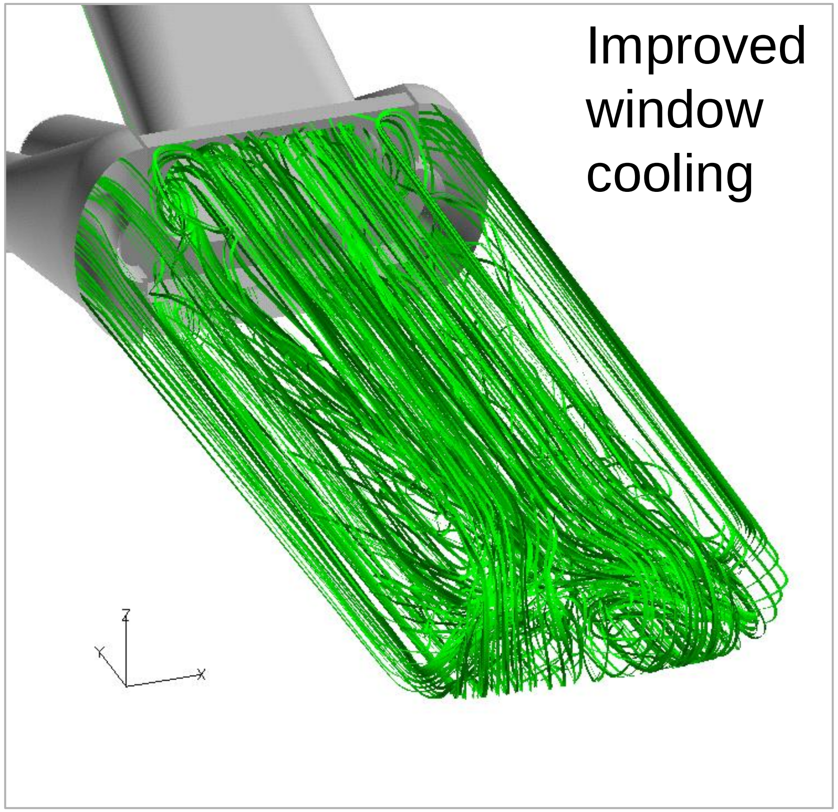
Flow line tracing for different inlet flow distributions
(side duct / bottom duct / side duct):

39% / 22% / 39%



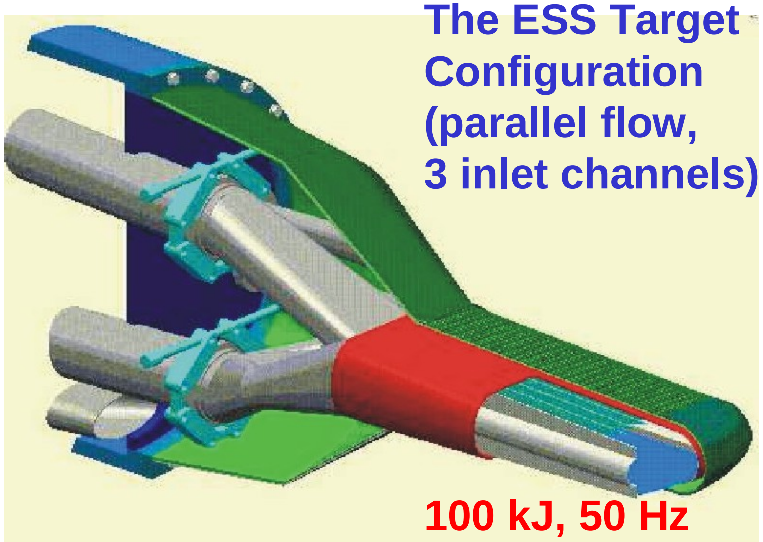
Poor window cooling

30% / 40% / 30%



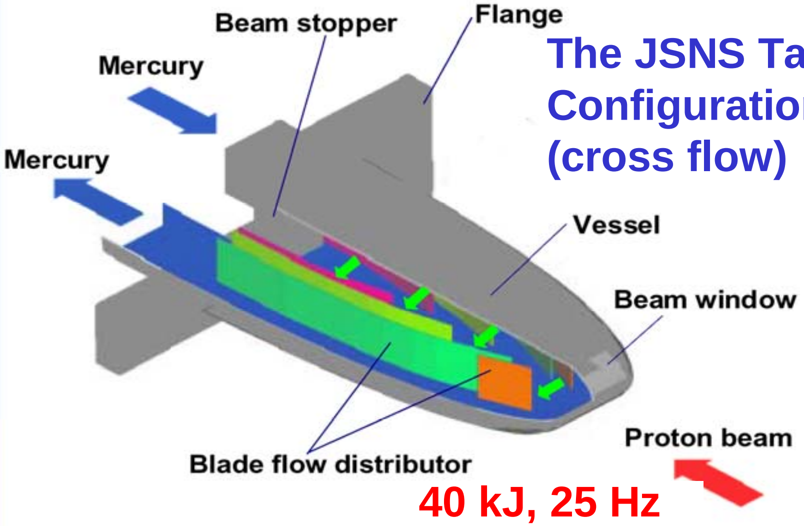
Improved window cooling

The ESS-SNS-JSNS Hg Target Concepts



The ESS Target Configuration (parallel flow, 3 inlet channels)

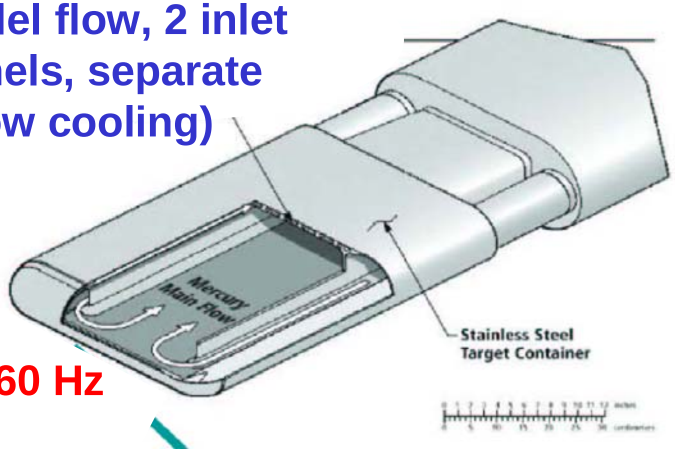
100 kJ, 50 Hz



The JSNS Target Configuration (cross flow)

40 kJ, 25 Hz

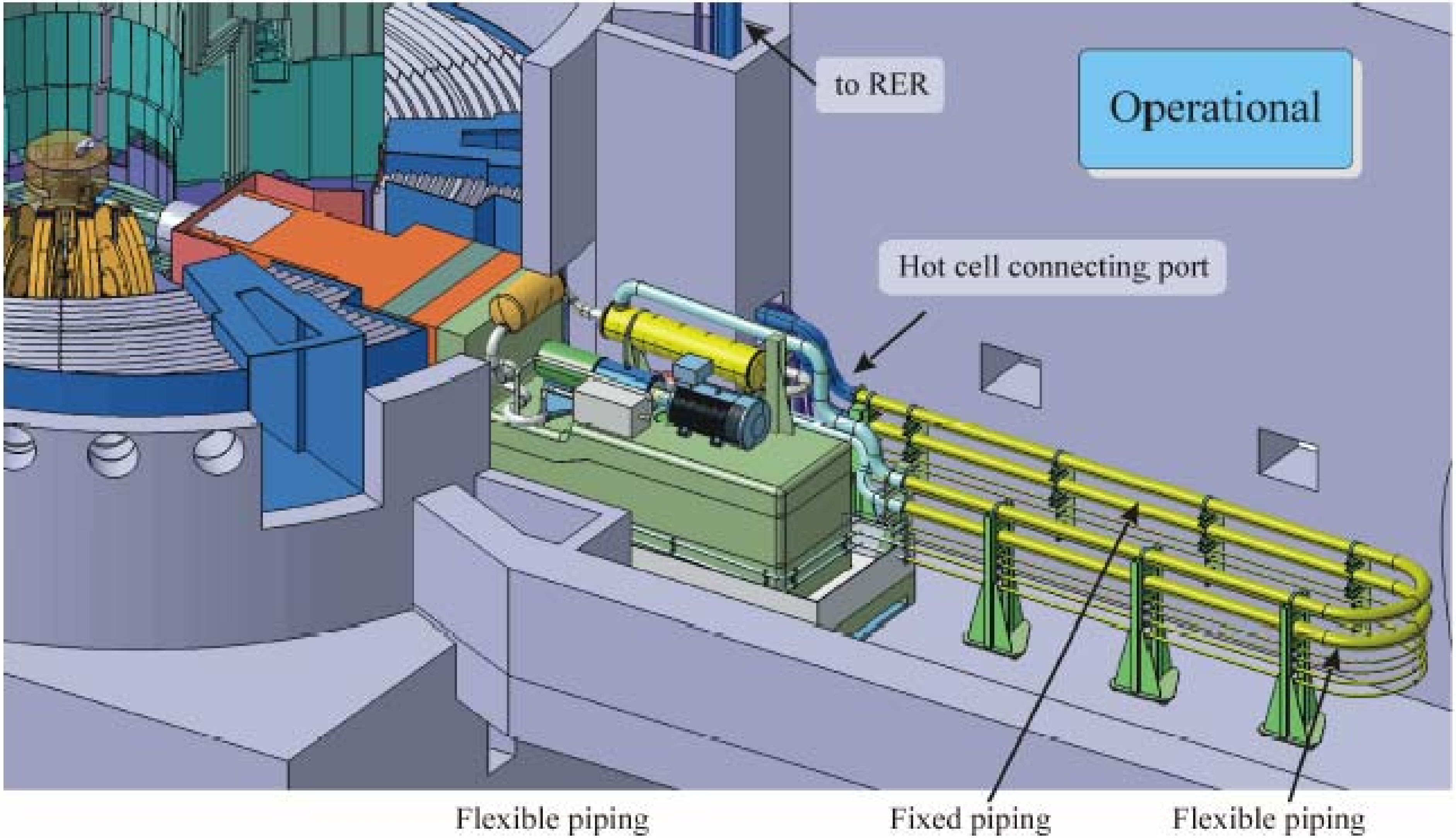
The SNS Target Configuration (parallel flow, 2 inlet channels, separate window cooling)



33 kJ, 60 Hz

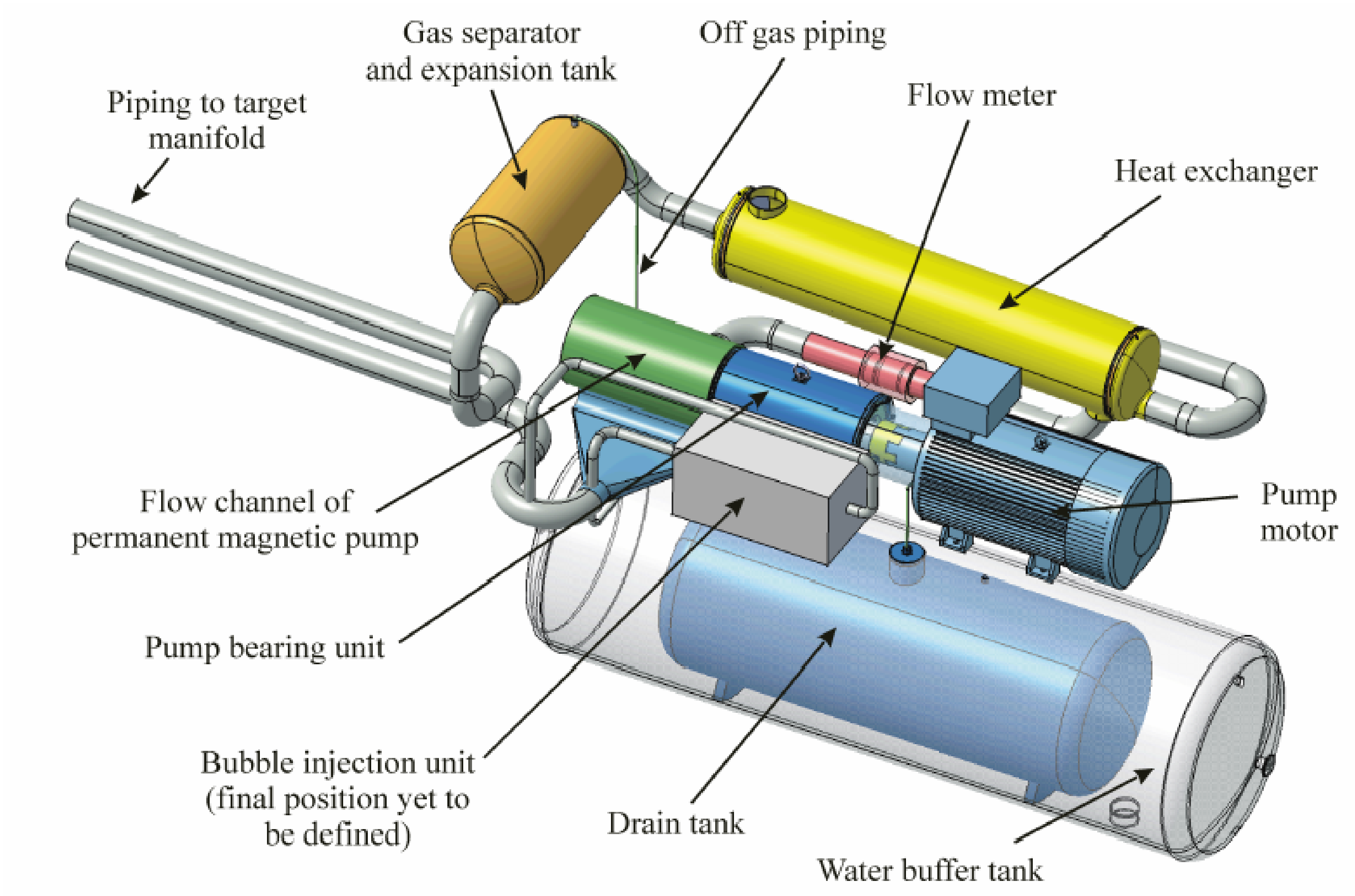
ESS (5 MW), SNS (2 MW) and JSNS (1 MW) use liquid mercury targets enclosed in steel shells, albeit with different internal flow distributions.

Mercury Target Loop Design (1)



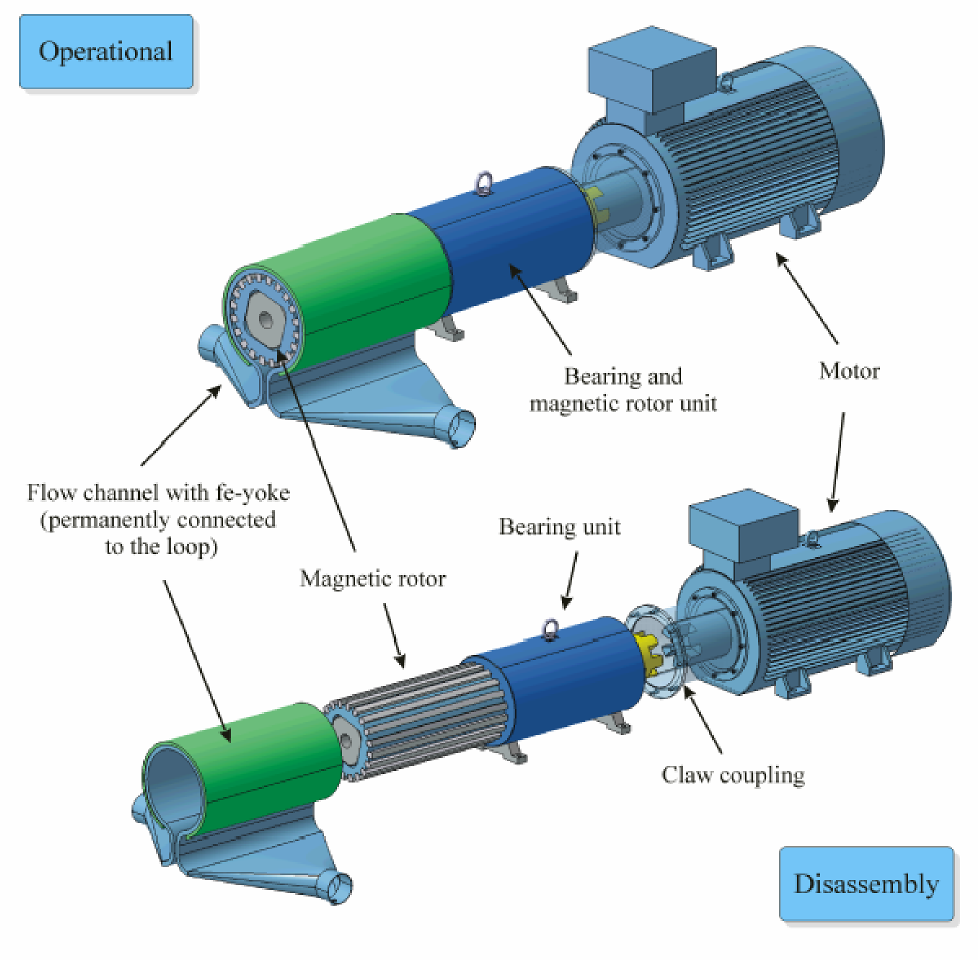
Mercury Target Loop Design (5)

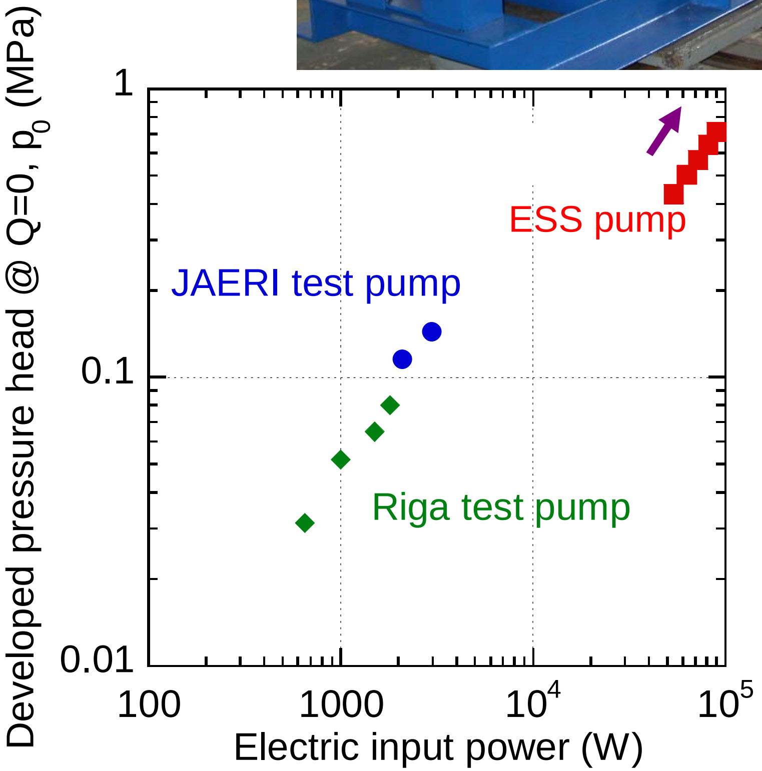
Arrangement of the ESS mercury loop components



Mercury Target Loop Design (6)

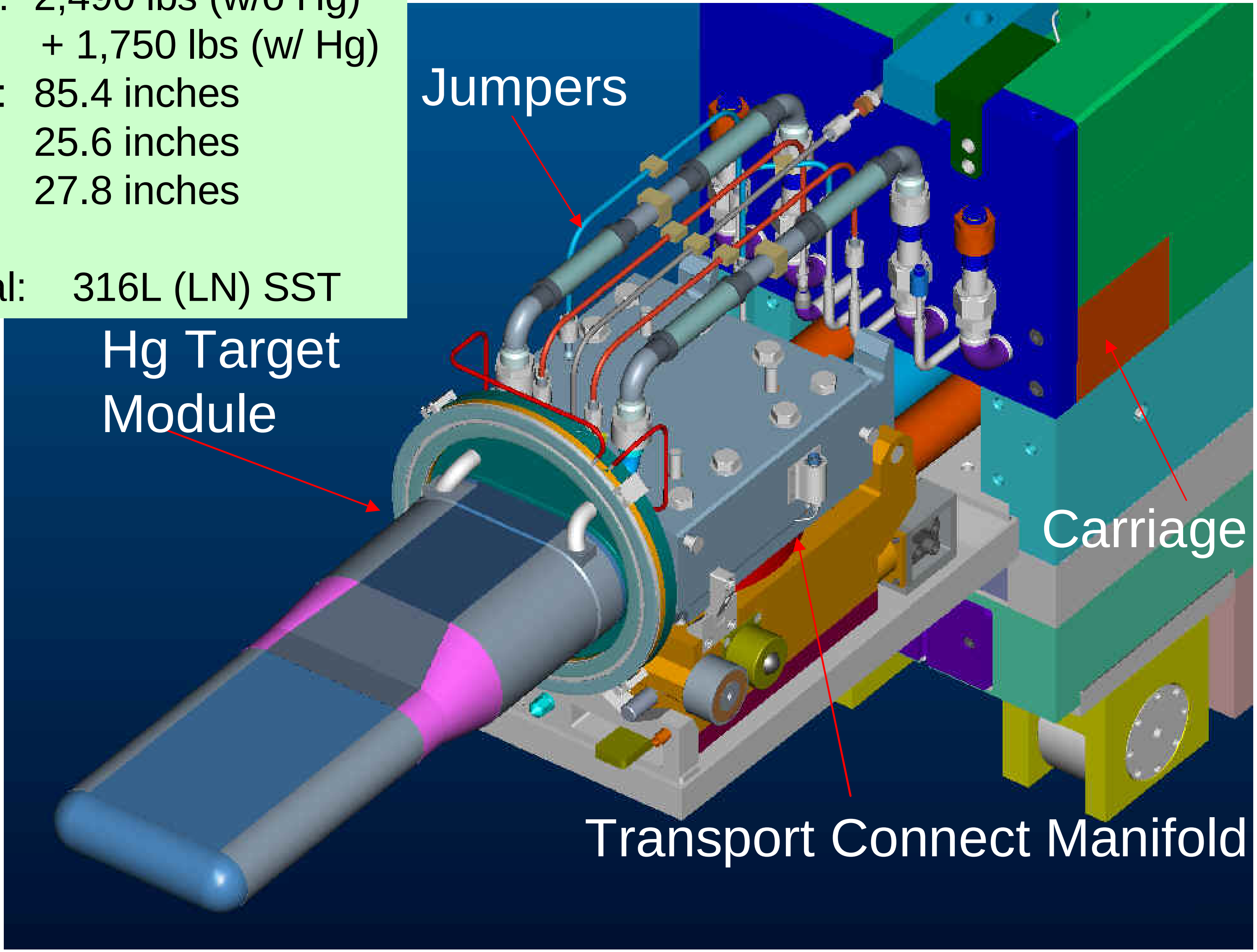
The ESS rotating magnets EM-pump





SNS - Hg Target Assembly

Weight:	2,490 lbs (w/o Hg) + 1,750 lbs (w/ Hg)
Length:	85.4 inches
Width:	25.6 inches
Height:	27.8 inches
Material:	316L (LN) SST



Common Features of Targets of the Current Projects

- Mercury has been selected as target material due to its superior neutronic performance and ease of heat removal.
- The primary liquid metal container suffers from intense radiation damage.
- Pulsed operation generates the risk of cavitation erosion to become the service time limiting factor by severely reducing the fatigue endurance.
- By design, failure of the liquid metal container is not an accident because the target material is safely contained in an outer enclosure.
- There may, however, be a need for frequent exchanges of the target container; therefore this procedure must be quick, which means fully remotely and well prepared.
- Fortunately the afterheat is low enough not to require cooling during the exchange process.

Enclosed Liquid Metal Targets: The Bottom Line

- There exists no long term experience with liquid metal targets!
- A pilot experiment at PSI (MEGAPIE), demonstrated their basic feasibility, albeit without beam compression (pulsing).
- In the context of this experiment the possible embrittlement of the wall by PbBi under irradiation and stress was investigated (LiSoR). This work still goes on.
- SNS and JSNS will need to continue improving their target systems based on initial operating experience (starting from low power).
- So far, the data base is not sufficient to confidently embark on the construction of a 5 MW short pulsed source!

Back to the Future

Although there exists a reasonable basis for the assumption that the pressure wave problem can be mitigated to allow an acceptably long service life for the targets of the 1 MW class pulsed spallation neutron sources presently under commissioning the question remains as to whether this technology can be extended to 5 MW class facilities or beyond.

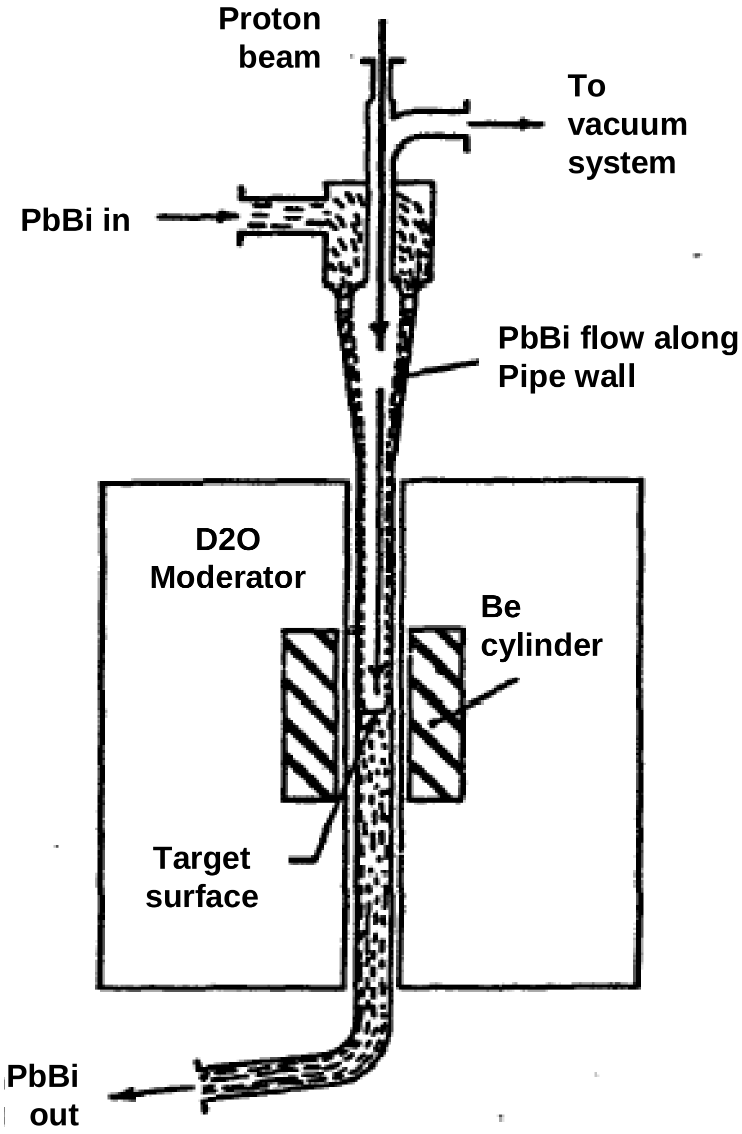
At the very minimum, the window will always be the limiting component of a fully contained spallation target.

This raises the question: Do we have an alternative to contained liquid metal targets at high beam power?

A window-less liquid metal target ??

Work on Windowless Liquid Metal Targets (1)

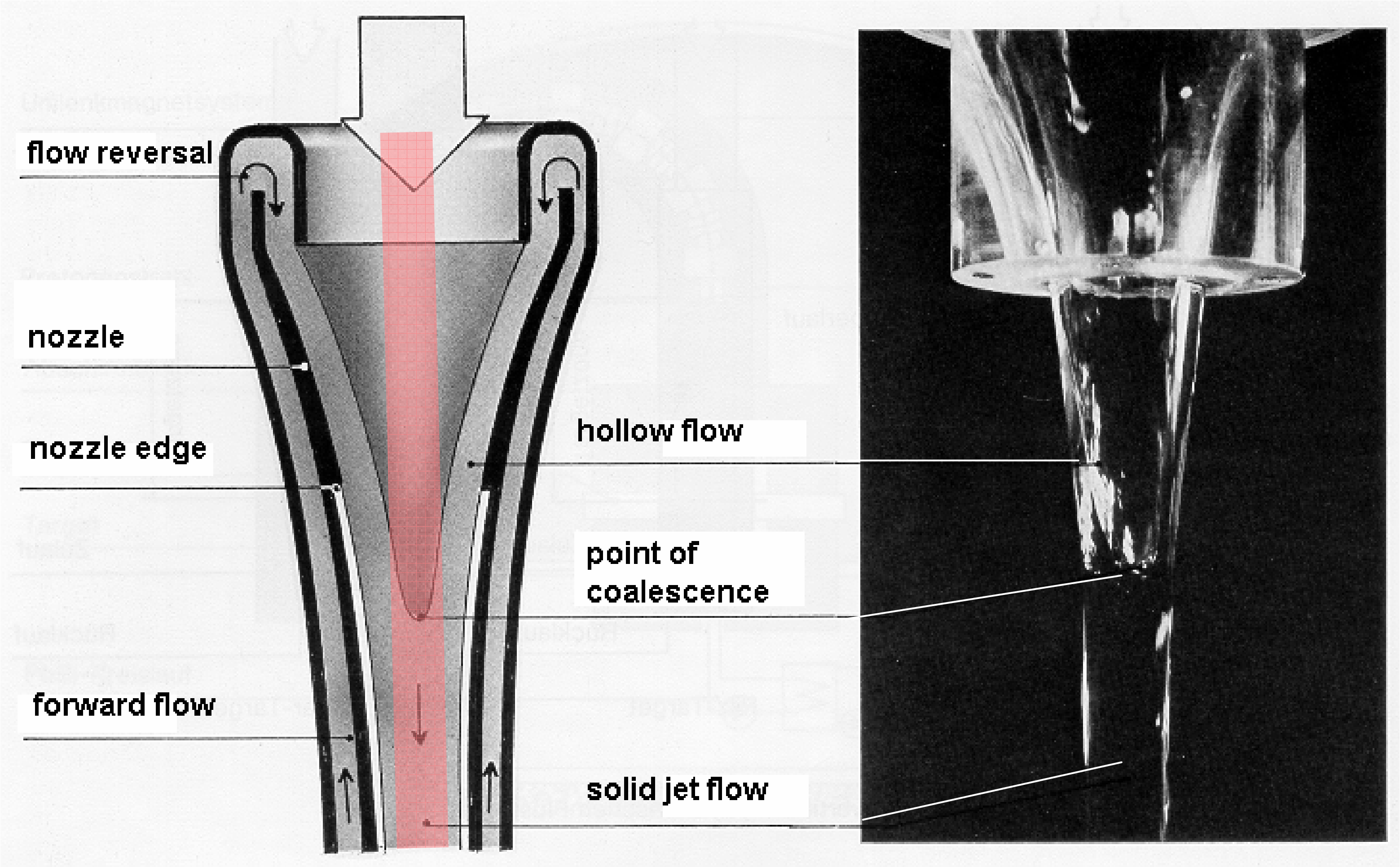
The first proposal:
Target for the Canadian ING
("Intense Neutron Generator")
Facility
60 MW_b at 1GeV protons cw;
thermal flux in the D_2O moderator
10^{16} n/cm^2/s



G.A. Bartholomew and
P.R. Tunnicliffe (eds),
"The AECL-Study for an
Intense Neutron Generator";
rep. AECL-2600 (1966)

Work on Windowless Liquid Metal Targets (2)

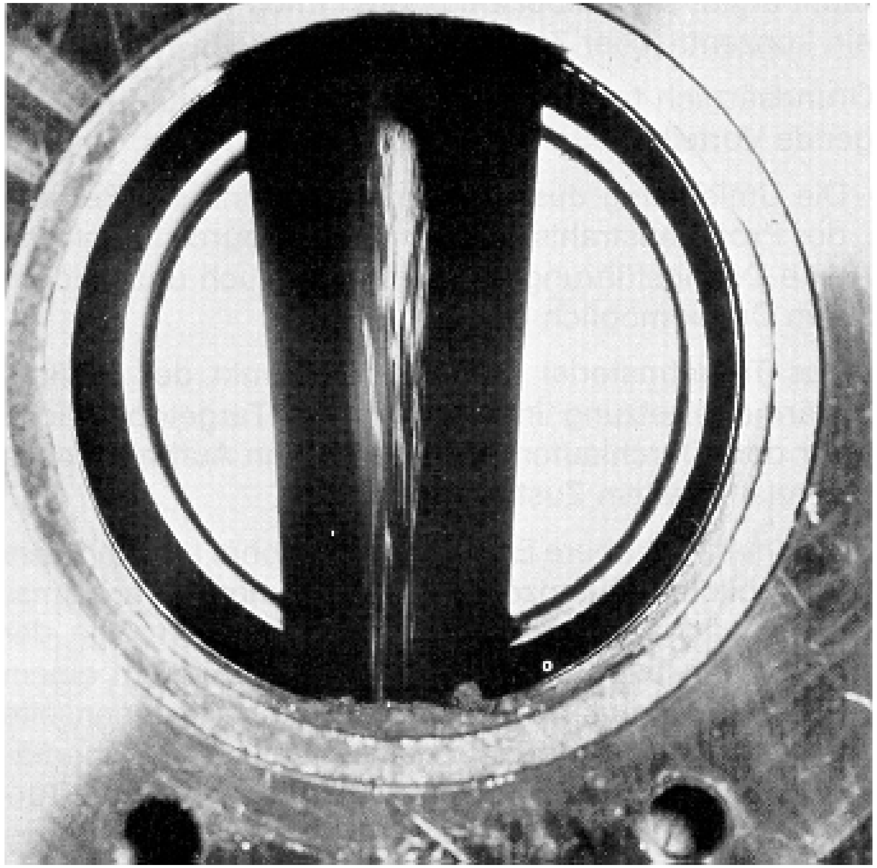
The SNQ Study: *“Free Falling Jet*”



Schematic and water model of a windowless target studied at KfK (FZK), 1981

Work on Windowless Liquid Metal Targets (3)

The SNQ Study: Small scale PbBi jet experiment at KfK

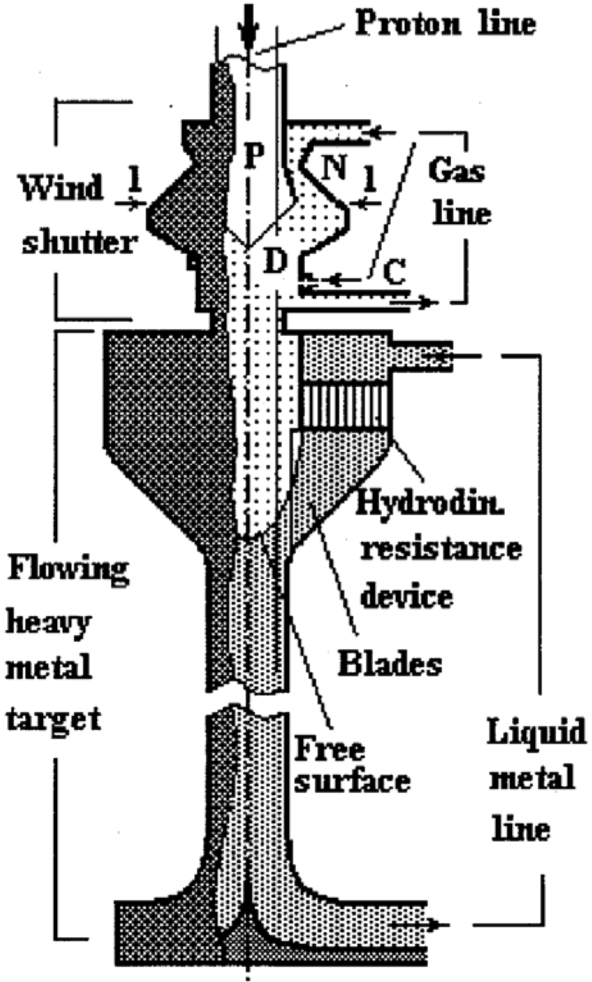


The position and stability of the point of coalescence is very sensitive to flow rate or perturbations of the flow upstream.

Without an outer guide tube all along the target jet it is difficult to imagine that a wide enough target cross section can be obtained at the point of coalescence.

Work on Windowless Liquid Metal Targets (4)

ISTC-17 Study*



Belyakov-Bodin et al. Kalmar 1996

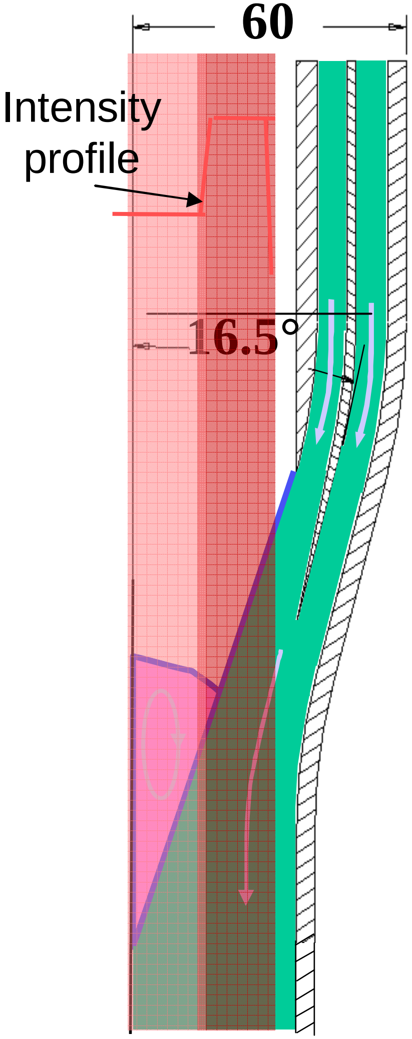
- Design goal: 20 MW_b
- Flow guided on outside
- Gas pressure above free surface found necessary to prevent cavitation; supersonic gas jet proposed
- Forced coalescence point; risk of re-circulating zone; “swirl" (angular momentum) imposed by blades was found not to solve this problem.

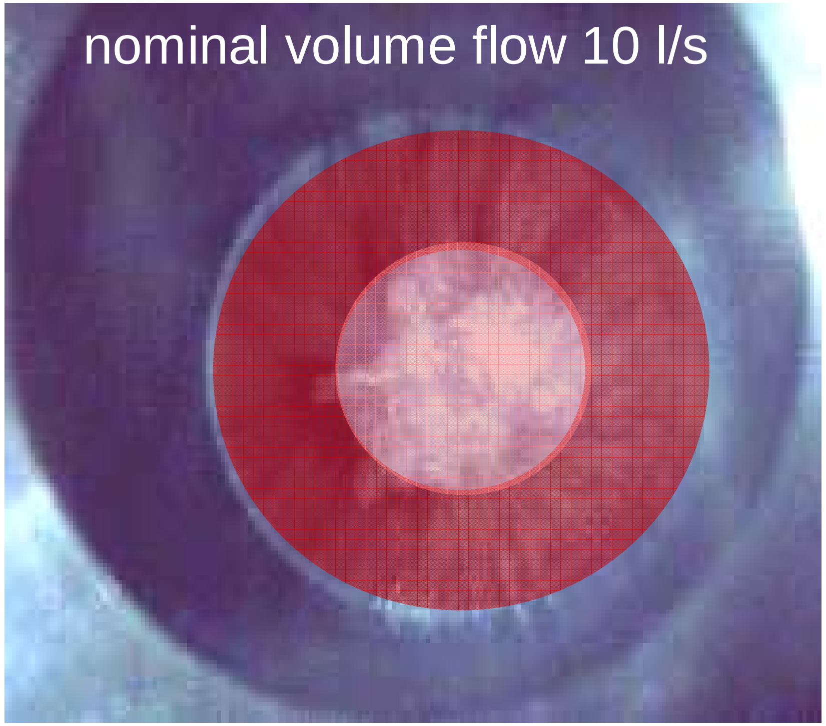
Work on Windowless Liquid Metal Targets (5)

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

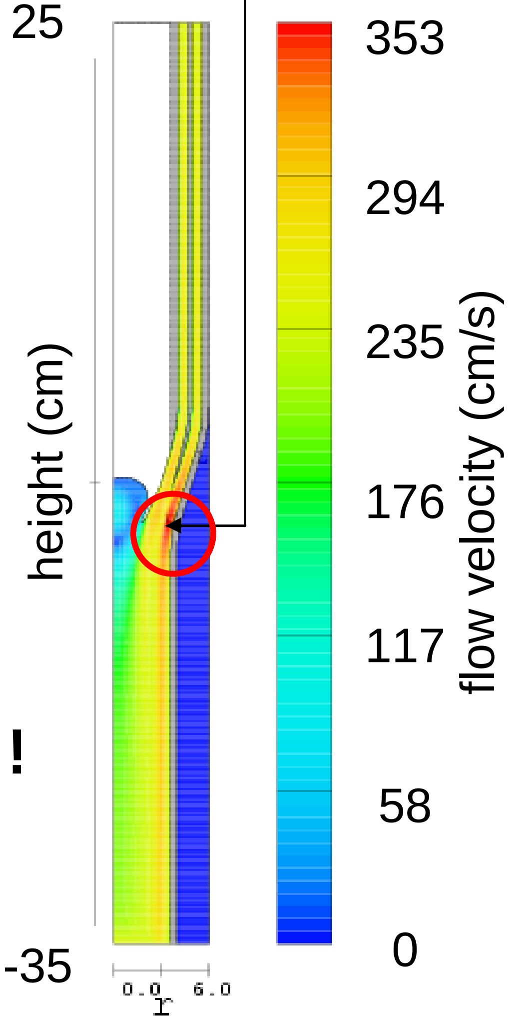
MYRRHA Spallation Target

Flow Experiment with Mercury




nominal volume flow 10 l/s

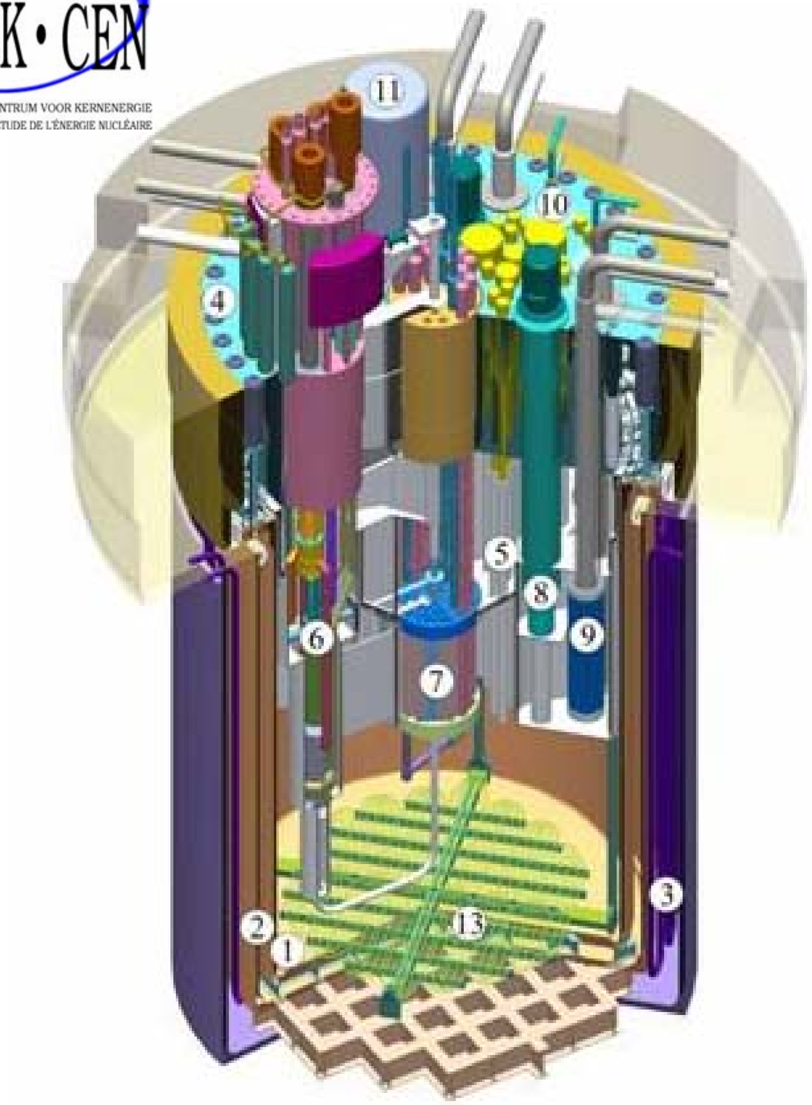
Risk of cavitation?



Close to desired configuration !

- intermediate lowering of level
- some spitting
- axial asymmetry
- **Use "hollow" beam ?**

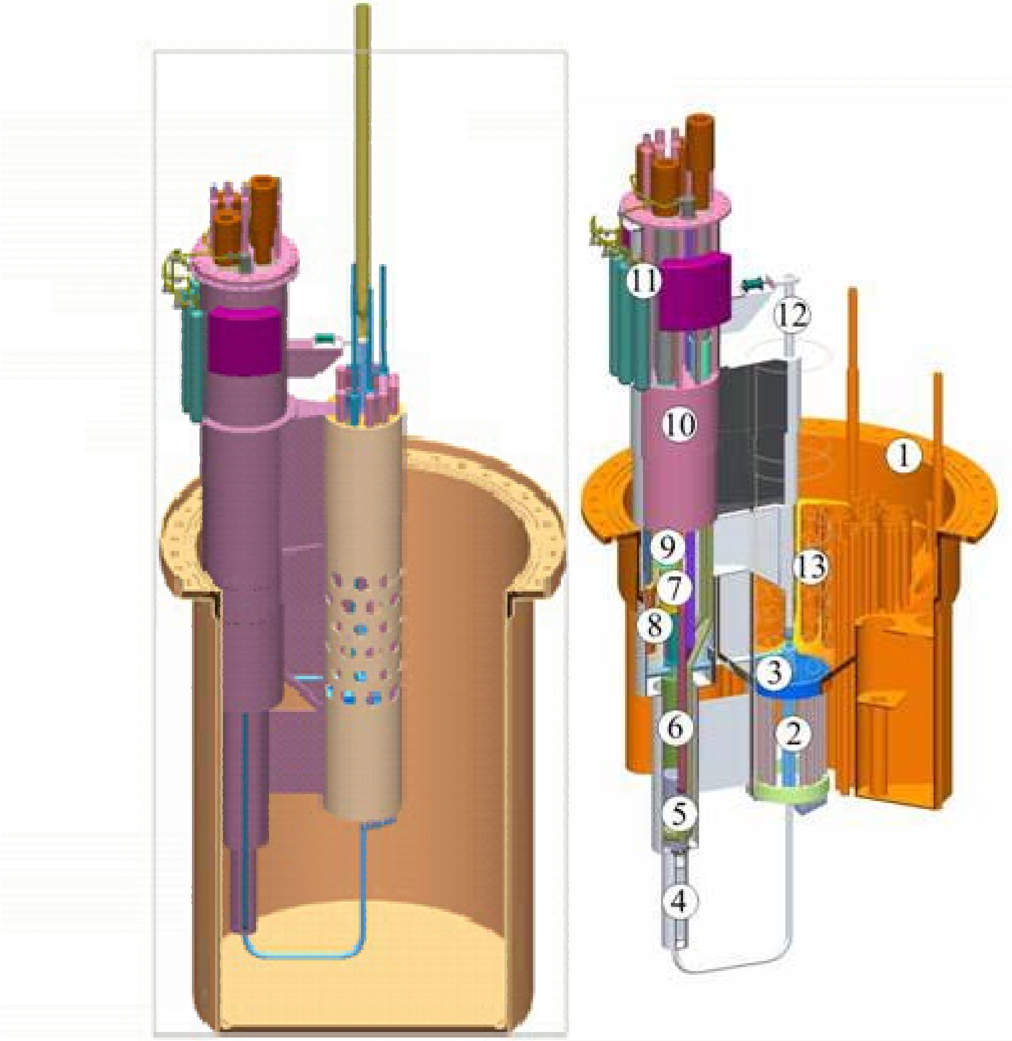
The MYRRHA Spallation Driven Fast Reactor



1. inner vessel
2. guard vessel
3. cooling tubes
4. cover
5. diaphragm
6. spallation loop
7. sub-critical core
8. primary pumps
9. primary heat exchangers
10. emergency heat exchangers
11. in-vessel fuel transfer machine
12. in-vessel fuel storage
13. coolant conditioning system

Didier de Bruyn

The Spallation Loop of the MYRRHA Facility

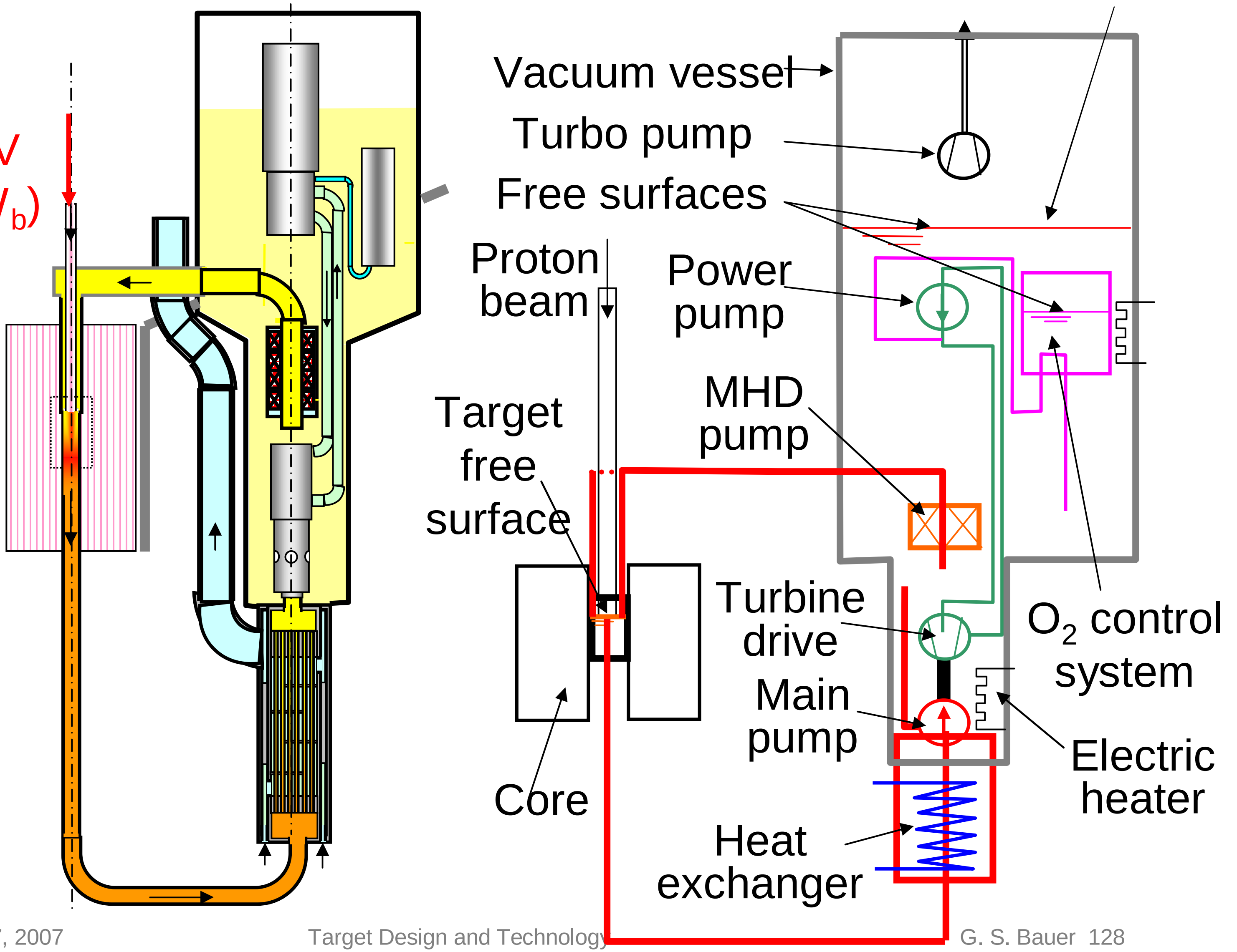


1. diaphragm
2. spallation target
3. core support plate slot
4. heat exchanger
5. turbine & pump
6. electromagnetic pump
7. hydraulic drive
8. Pb-Bi conditioning system
9. vacuum system with cryopumps
10. shielding bloc
11. regeneration circuit with absorber pumps
12. proton beam line
13. core barrel

Schematic of the MYRRHA Spallation Loop

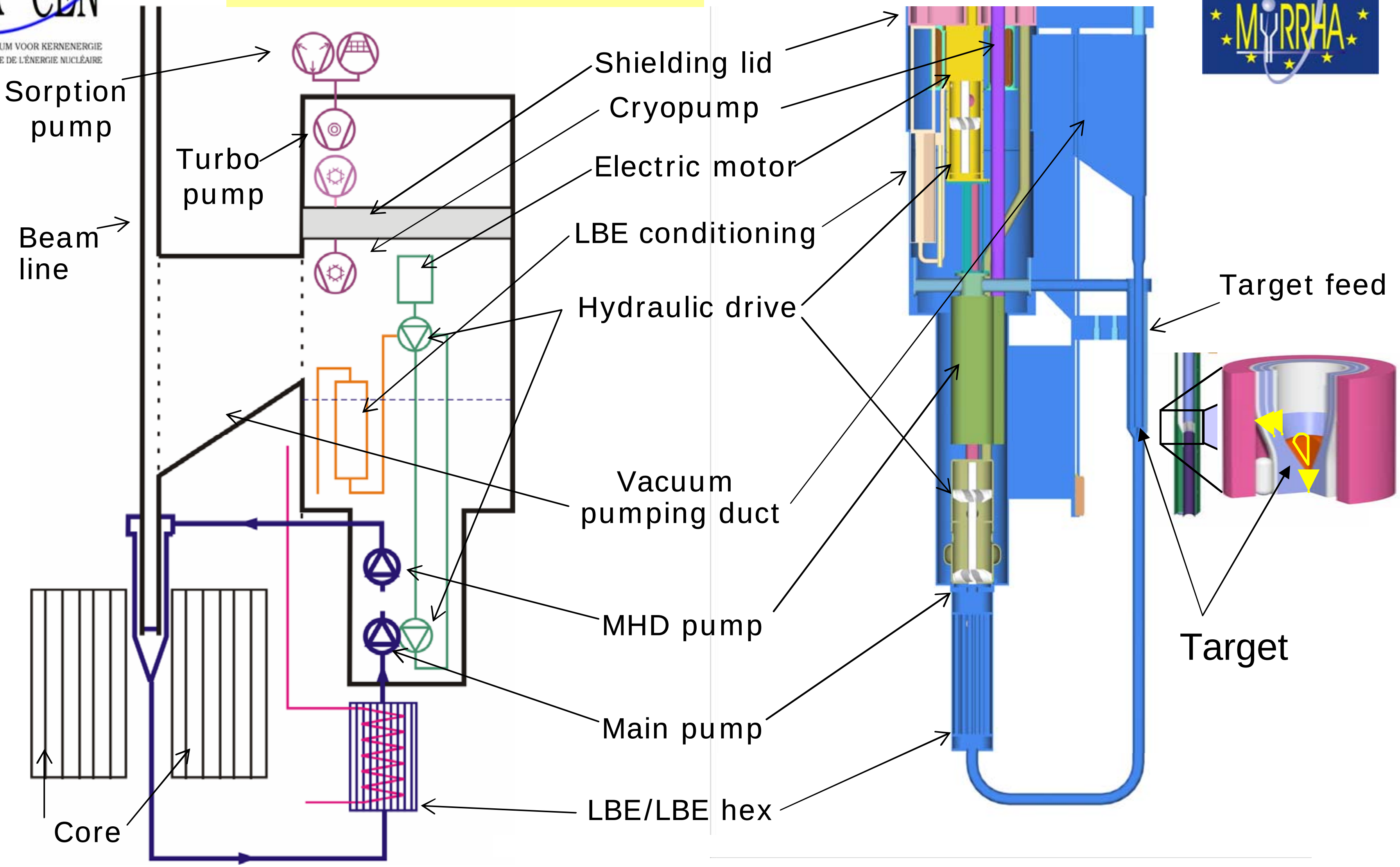
(older scheme)

Beam current
5 (2) mA)
Beam energy
450 (600) MeV
(2.25 (1.2) MW_b)



MYRRHA Target Module-Layout Schematics

P. Schuurmans et al, 2005



Sorption pump

Turbo pump

Beam line

Core

Shielding lid

Cryopump

Electric motor

LBE conditioning

Hydraulic drive

Vacuum pumping duct

MHD pump

Main pump

LBE/LBE hex

Target feed

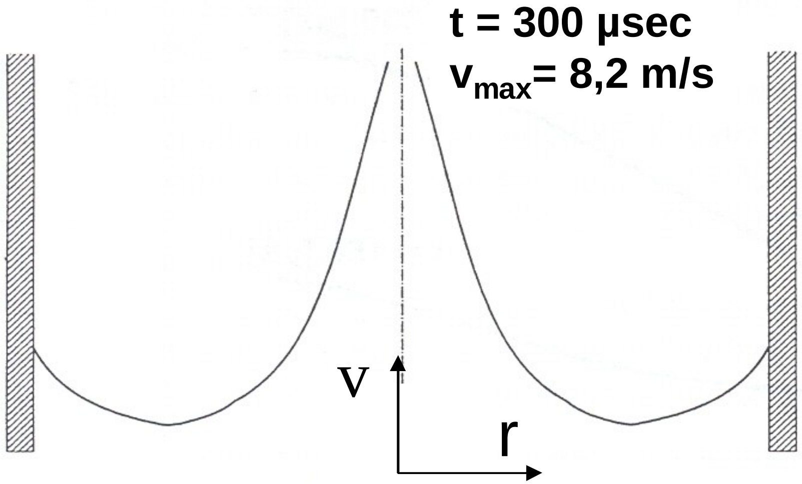
Target

A Word of Warning

A **laterally confined** windowless liquid metal target is not an option for a pulsed spallation neutron source

Free Surface Under Pulsed Beam Operation

Calculated result for a power deposition of 60 kJ in 1 µsec
in a 20 cm diameter target (beam diameter 10 cm, parabolic)



Velocity distribution on the (initially flat) surface of a laterally confined liquid PbBi target 300 µsec after pulsed power input *

- *Focusing effect!!*

- *Liquid would ultimately rise up to 3.4 m and return under the influence of gravity after 1.7 sec*

*K. Skala and G.S. Bauer, Proc ICANS XII, pp. 559-571 (1995)

Summary on Target Technology and Design Issues

- Stationary solid targets can be used up to a bam power level of 1-2 MW.
- Beyond this power level liquid metal targets are probably OK for cw operation.
- Their technology is presently explored and developed in several projects (MEGAPIE, PbBi; SNS, JSNS (ESS), Hg)
- For pulsed operation of liquid metal targets in the multi-megawatt regime more R&D work is needed.
- A fallback solution migt be a rotating solid target as explored for the 5 MW SNQ project in the 1980ies (most likely not for ADS).
- In any case, the experience that accrues from designing and operating research spallation neutron sources will be of great value for ADS facilities.

Target Design and Technology for Research Spallation Neutron Sources

End of the Lecture

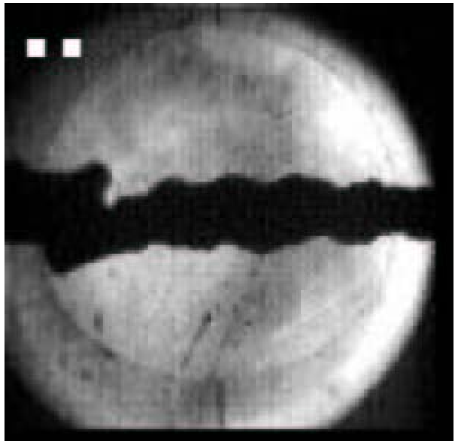
Thank you for your patience!

The NuFact Hg Jet Target Experiment with Pulsed Beam

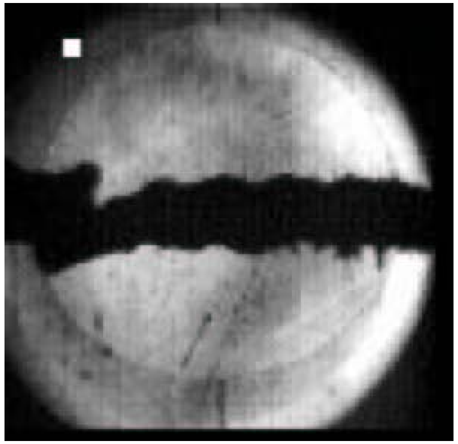
POP Test at BNL E-951, K. Mc Donald, H. Kirk, A. Fabich, J. Lettry

Event #11, April 25, 2001

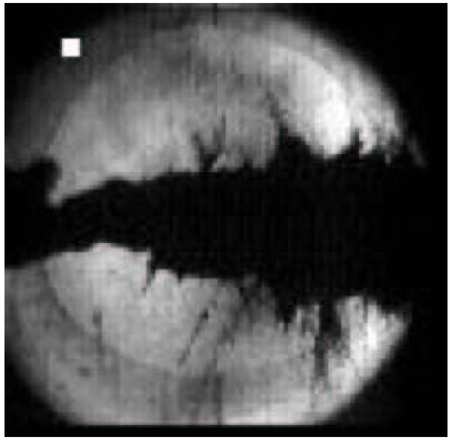
Hg-Jet:
diameter 1.2 cm
velocity 2.5 m/s
perp. velocity: ca 5m/s



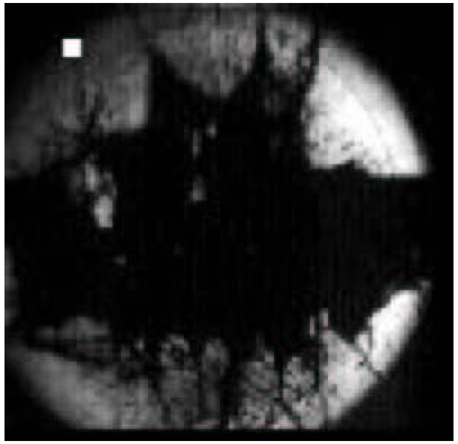
0.00 ms



0.75 ms



4.50 ms

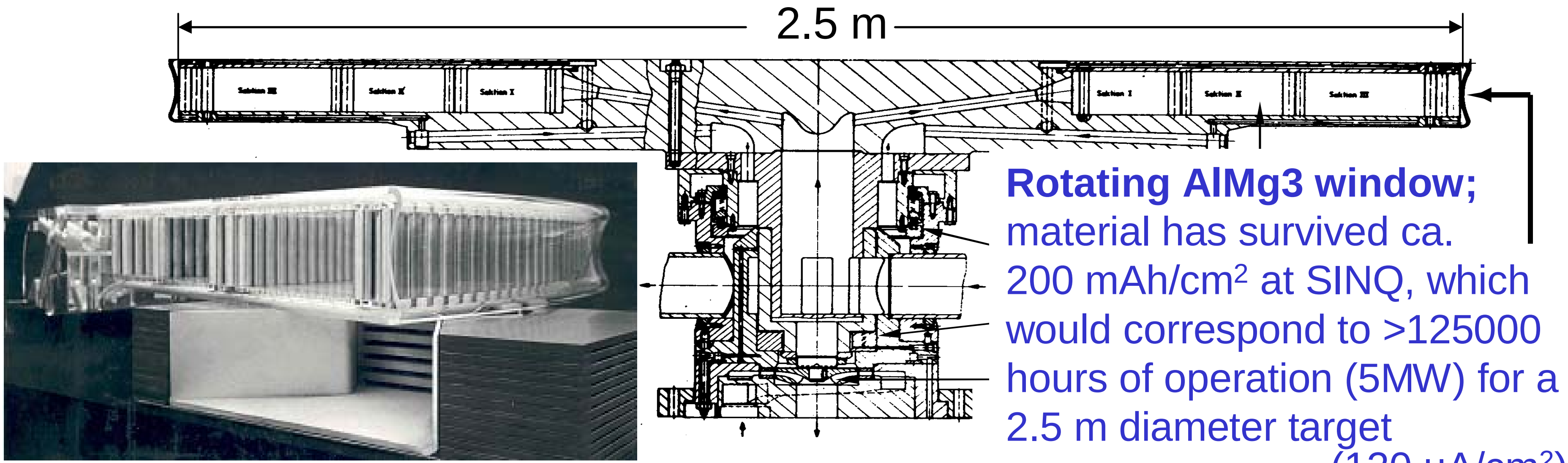


13.00 ms

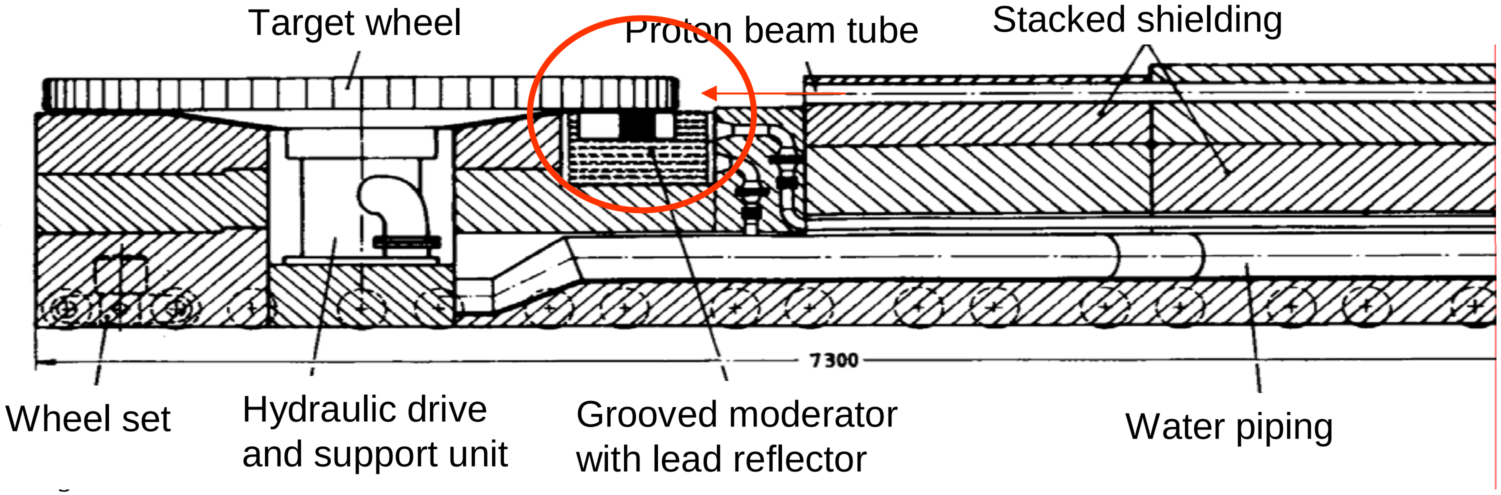
$2{,}7\times10^{12}$ protons
100 nsec
t_0 ca. 0,45 ms

The SNQ Rotating Target Concept

Jül-Spez-113 /
KfK 3175 (1981)

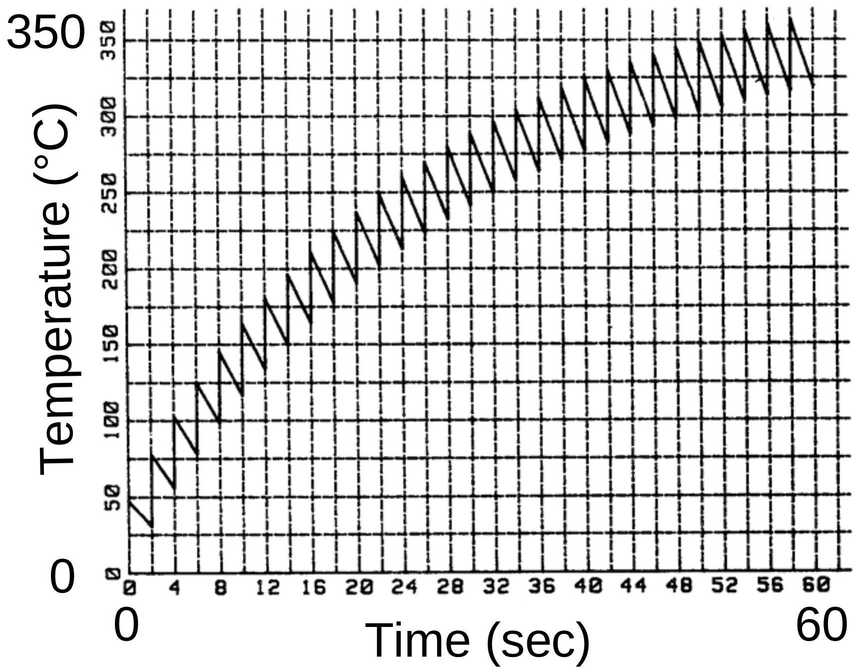


Rotating AlMg3 window; material has survived ca. 200 mAh/cm^2 at SINQ, which would correspond to >125000 hours of operation (5MW) for a 2.5 m diameter target (120 µA/cm^2)

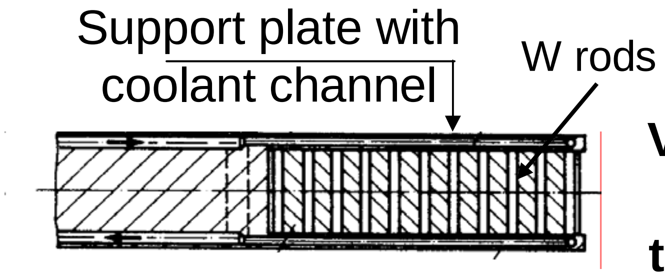


Note: The horizontal trolley was later replaced by one moving on an inclined trajectory

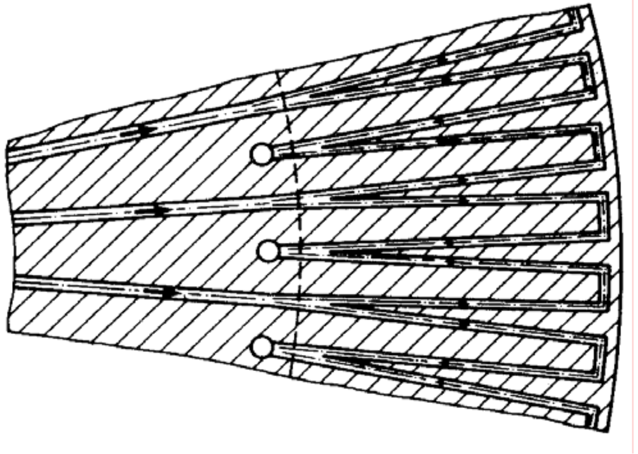
The SNQ W-Target Version (edge cooled)



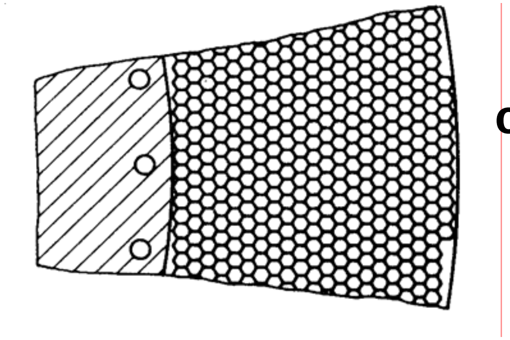
Calculated Temperature evolution at the target hot spot after start up at full beam power (5.5 MW)



Vertical cut through target zone

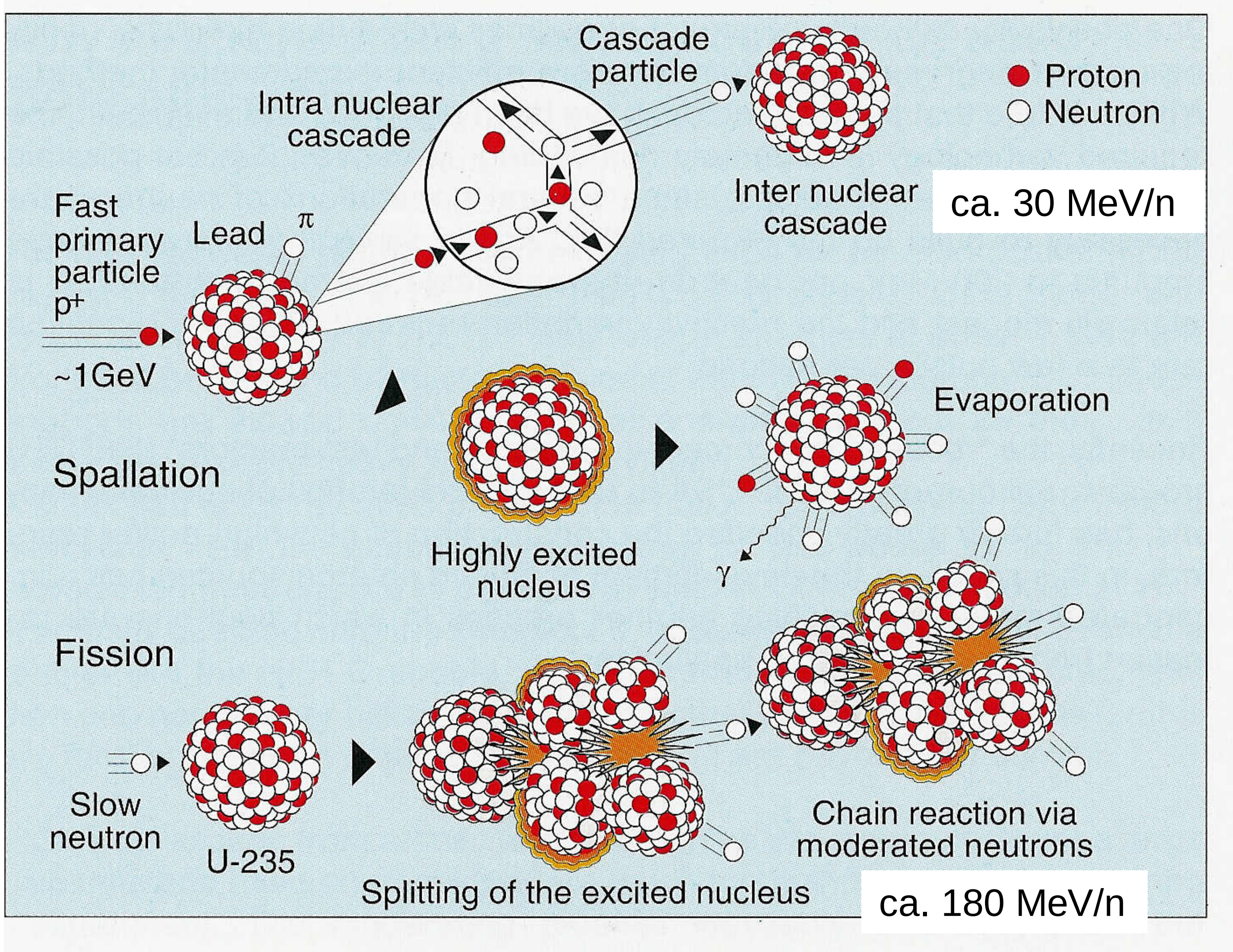


Horizontal cut through support plate



Horizontal cut through target rod array

Visualisation of the Spallation and Fission Processes



Cascade particles have energies up to the incident proton energy and can cause evaporation reactions in other nuclei

In contrast to fission, spallation cannot be self sustaining!

Fission neutrons must be moderated (slowed down to thermal energies) to cause fission in other nuclei