The Abdus Salam International Centre for Theoretical Physics

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School on Pulsed Neutrons: Characterization of Materials

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Spallation Target Technology

Guenter Bauer

Forschungzentrum Julich GmbH
Julich
Germany

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

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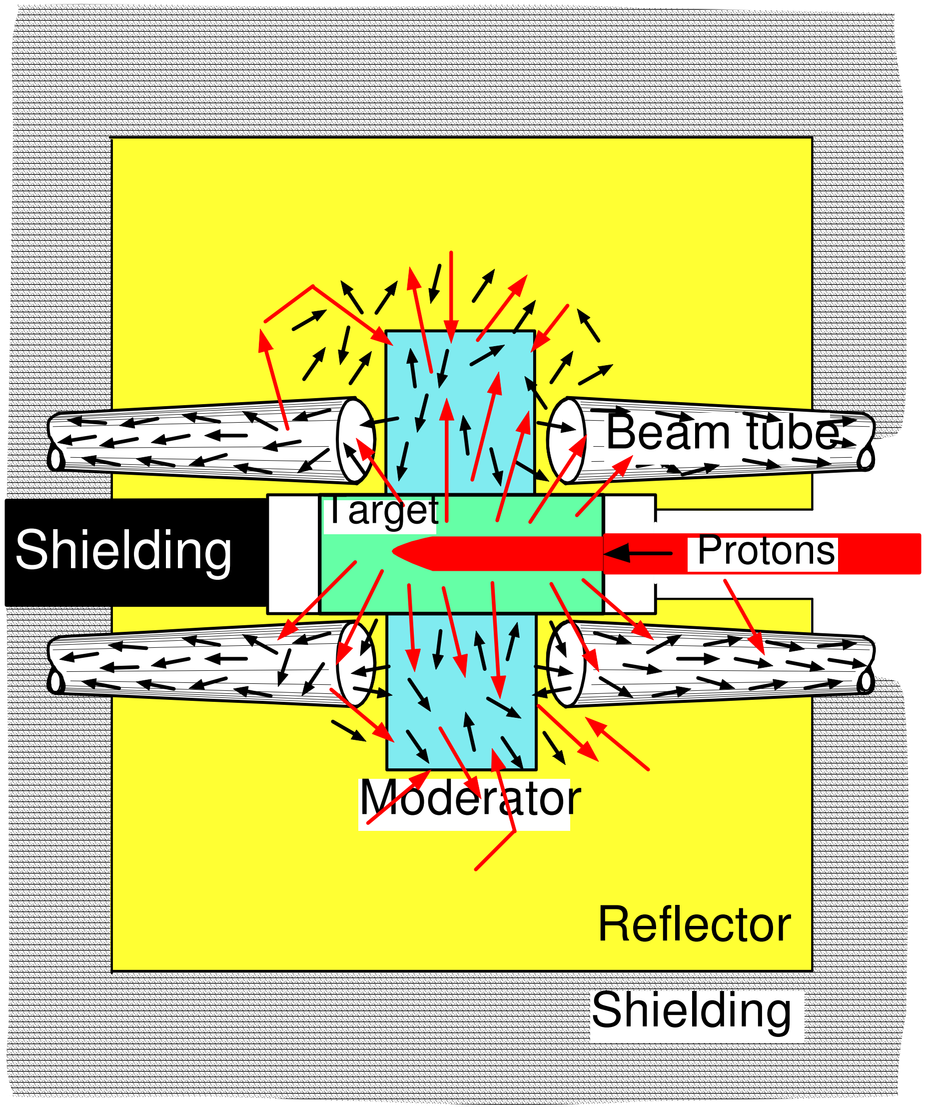
Target Design and Technology for Spallation Neutron Sources

Günter S. Bauer
Forschungszentrum Jülich
in der Helmholtz Gemeinschaft

guenter@bauer-wt.de

Principal Target-Moderator-Reflector Arrangement



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

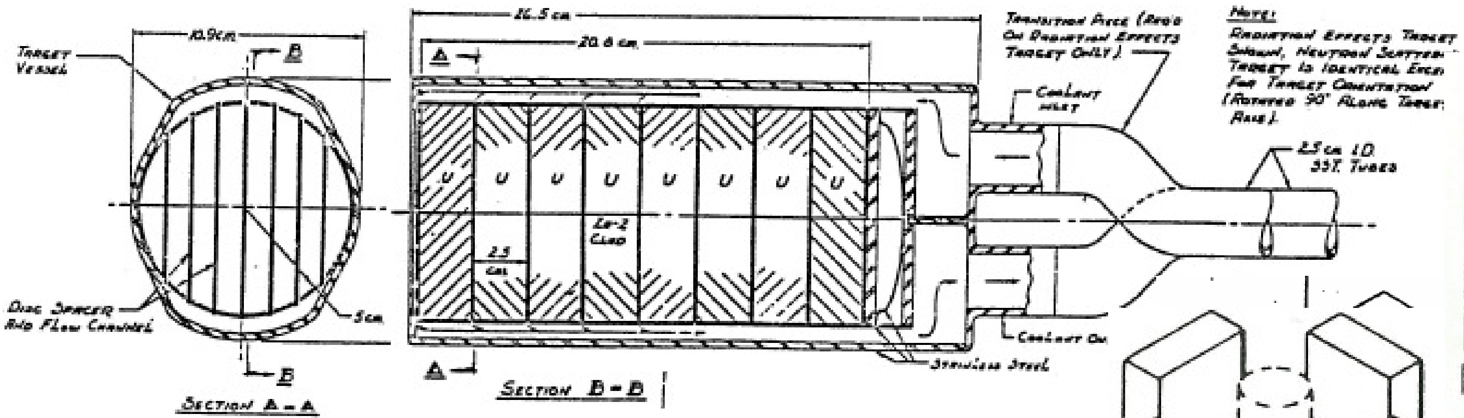
The **beam tubes** are arranged such as to avoid direct view on the target to minimize high energy neutron and γ contamination

Spallation Neutron Sources with P_b>100kW

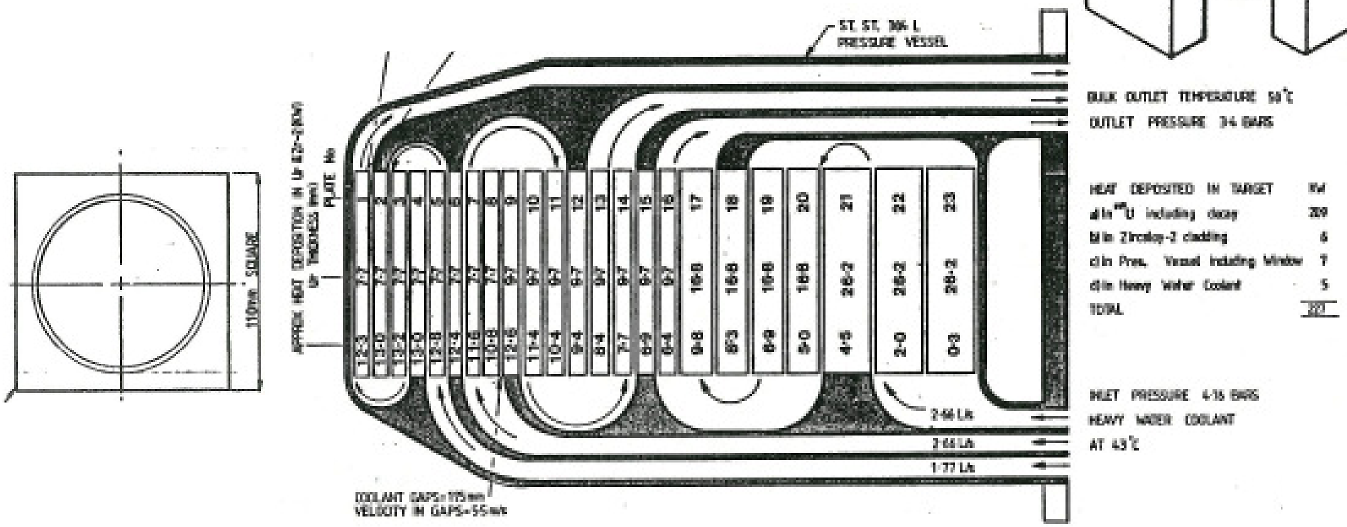
Source and location	Type of accelerator	Proton energy (Gev)	Pulse frequency (Hz)	Aver. beam power (MW)	Type of target	Peak thermal flux* ($cm^{-2}s^{-1}$)	Time av. thermal flux* ($cm^{-2}s^{-1}$)	Status
SINQ, CH	cyclotron	0.57	contin.	0.6	solid, Pb rods liquid, PbBi	$6x10^{13}$ $1x10^{14}$	$6x10^{13}$ $1\ 10^{14}$	operating demonstrated
ISIS, UK	synchrotron	0.8	50	0.16	solid, vol. cooled, Ta	$2.3x10^{15}$	$2x10^{12}$	operating
MLNSC, USA	linac plus PSR	0.8	20	0.08	solid, vol. cooled, W	$2.3x10^{15}$	$1x10^{12}$	operating
ESS, EU	linac ~~plus 2 compressors~~	1.33	~~50~~ 16 2/3	5	liquid metal (Hg)	~~$2x10^{17}$~~ $1x10^{16}$	~~$2.5x10^{14}$~~ $3x10^{14}$	deferred
SNS, USA	linac plus compressor	1	60	1,4	liquid metal (Hg)	$2x10^{16}$	$8x10^{13}$	under commissioning
AUSRTON Austria	synchrotron	1.6	10	0.5	solid, edge cooled W,	$4x10^{16}$	$6x10^{12}$	proposed
JSNS-1 Japan	synchrotron	3	25	1	liquid metal (Hg)	$1x10^{16}$	$8x10^{12}$	under commissioning
JSNS-2 Japan	2-ring synchrotron	3	50	5	liquid metal (Hg)	$2x10^{17}$	$2.5x10^{14}$	proposed
MMF RUS	linac (plus comp)	0.6		0.6	solid, vol. cooled W			commissioning (low power)

** typical maximum values; precise figures vary, depending on type of moderator*

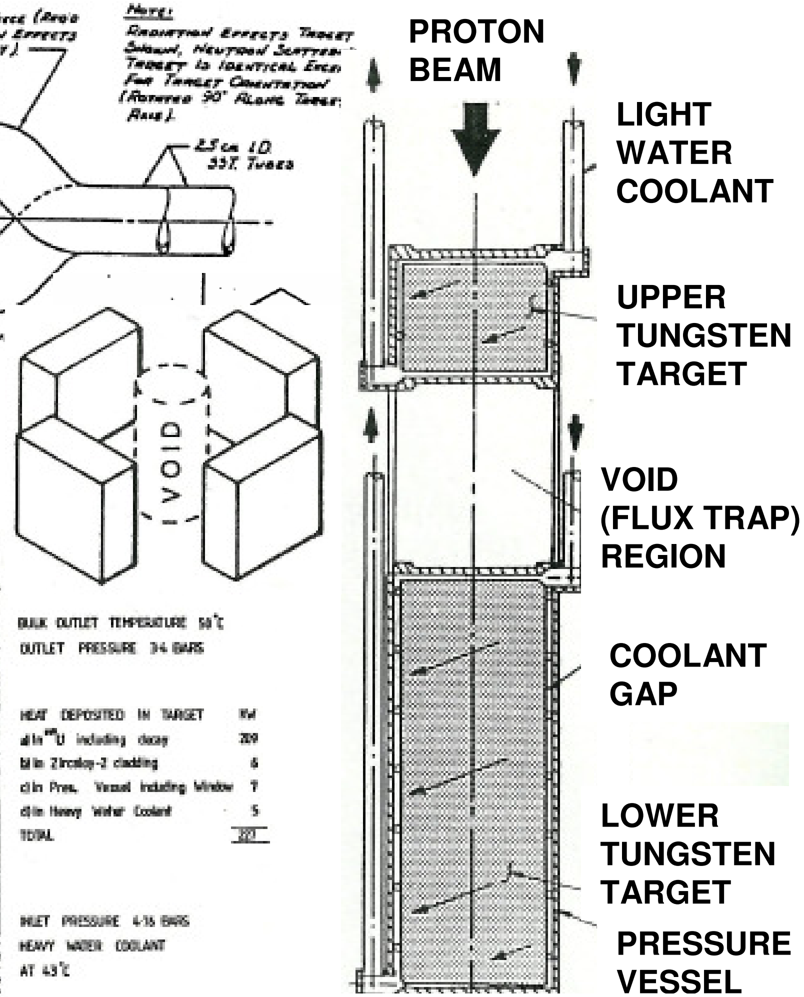
Target Concepts of Early Pulsed Spallation Sources



IPNS-1 (7 kW_b)



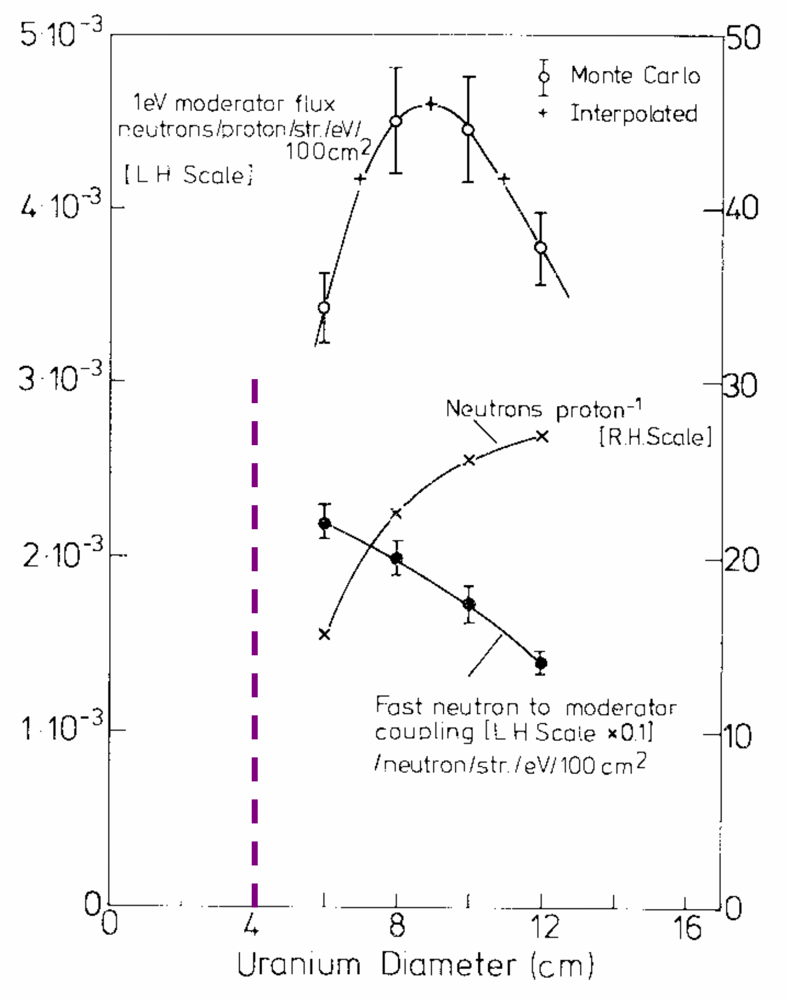
ISIS (160 kW_b)



MLNSC (LANSCE, 80 kW_b)

Optimization of the ISIS Target Diameter

Proton beam intensity distribution: parabolic with 4 cm FWHM

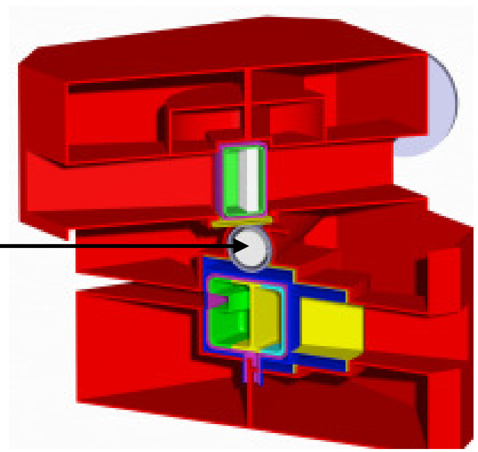


F. Atchison, 1979

The diameter of the ISIS-1 target is optimised for a U-Target, 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 a Ta-clad tungsten target of 6 cm diameter has been selected.



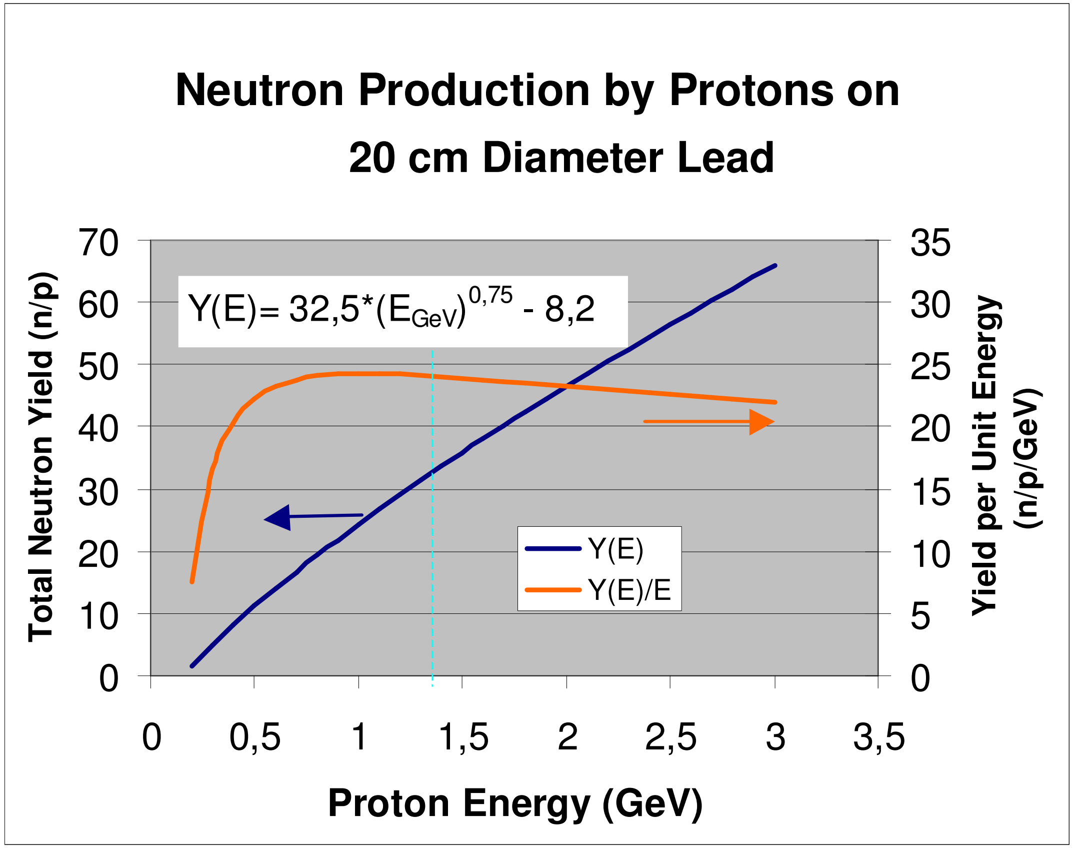
6 cm diameter Ta-clad W-target

Spallation Targets : Beam Energy and Distribution

- At low E (<3 GeV), yield increases approximately linear ($E^{0,75}$) 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, but may be high.
- For reasons of power density, relatively large beam cross sections become necessary in high power targets. In this case slab targets are the preferred option.
- Target geometry (diameter relative to beam diameter) is important; there exists an optimum with respect to neutron leakage from the target surface.

Spallation Neutron Sources – General Aspects (2)

Choice of proton energy



Arguments for higher proton energy:

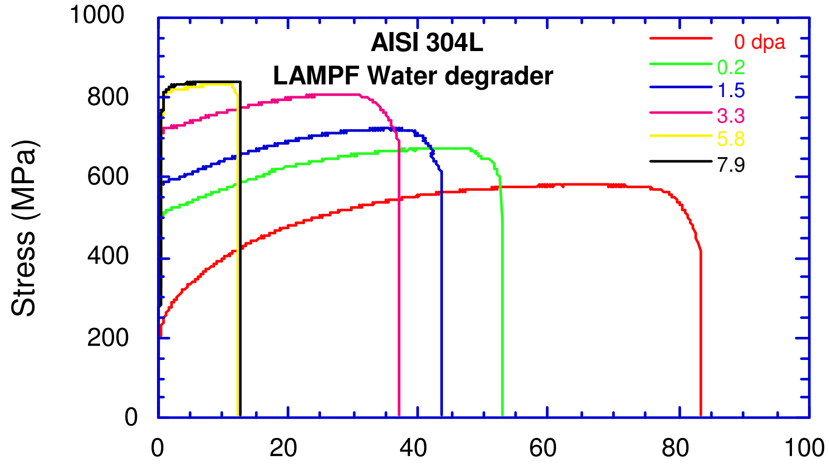
Easier to accelerate to higher energy than to increase current (in particular with circular accelerators)

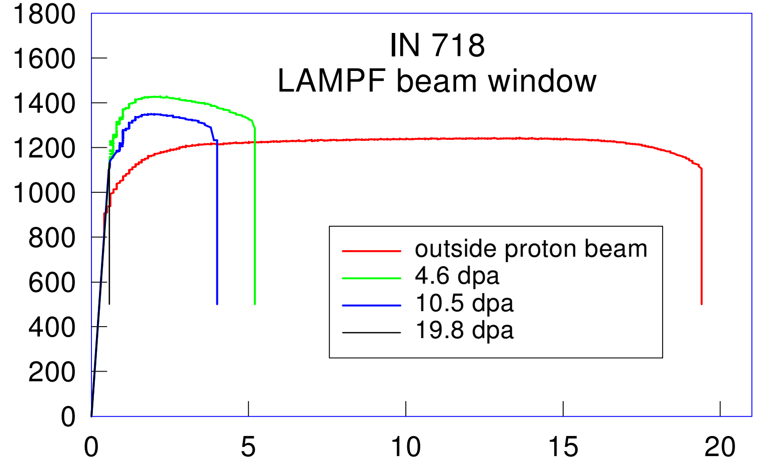
Radiation damage in target and window materials scales roughly with number of protons, not with beam power, hence fewer protons of higher energy are better

Radiation Damage in Target Window Materials

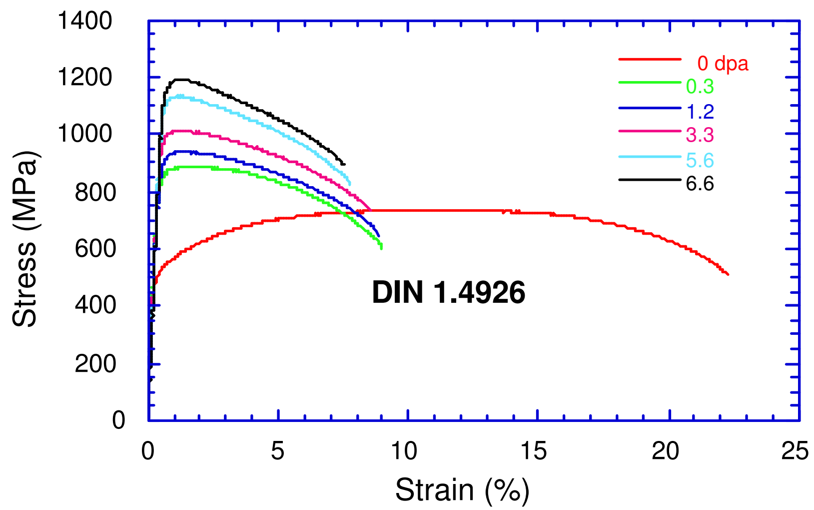
Stress-strain curves for different spallation structural materials after irradiation

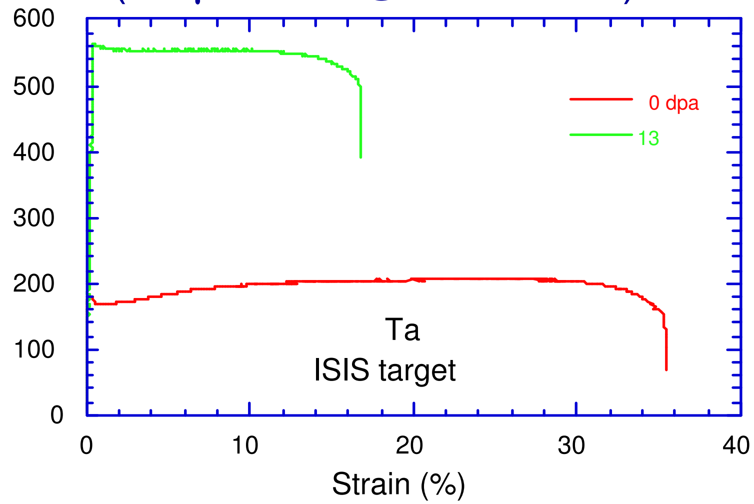
J. Chen, FZJ-IFF





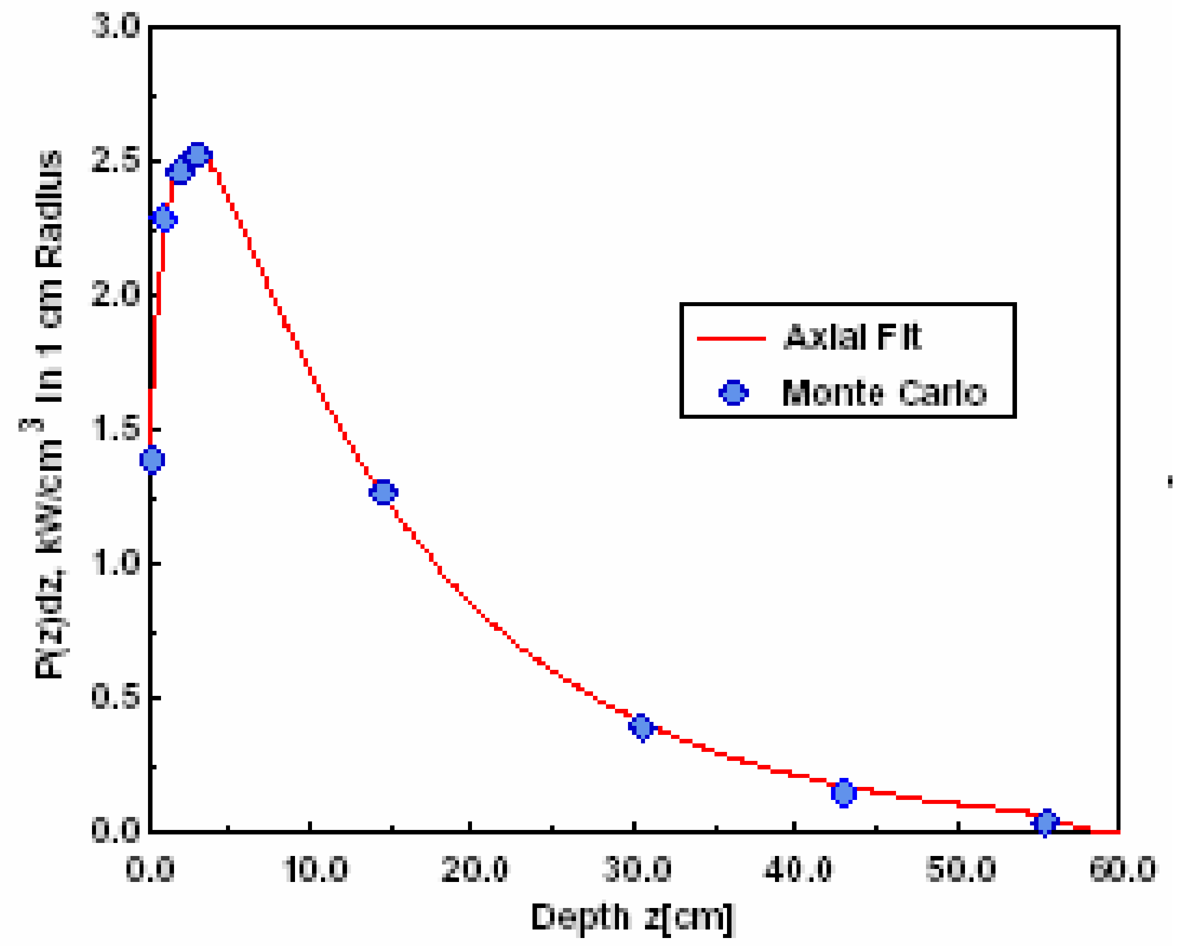
ESS-beam window: 0,16 dpa/d in steel (80 µA/cm² @ 1.33 GeV)





Axial Distribution of Power in a Spallation Target

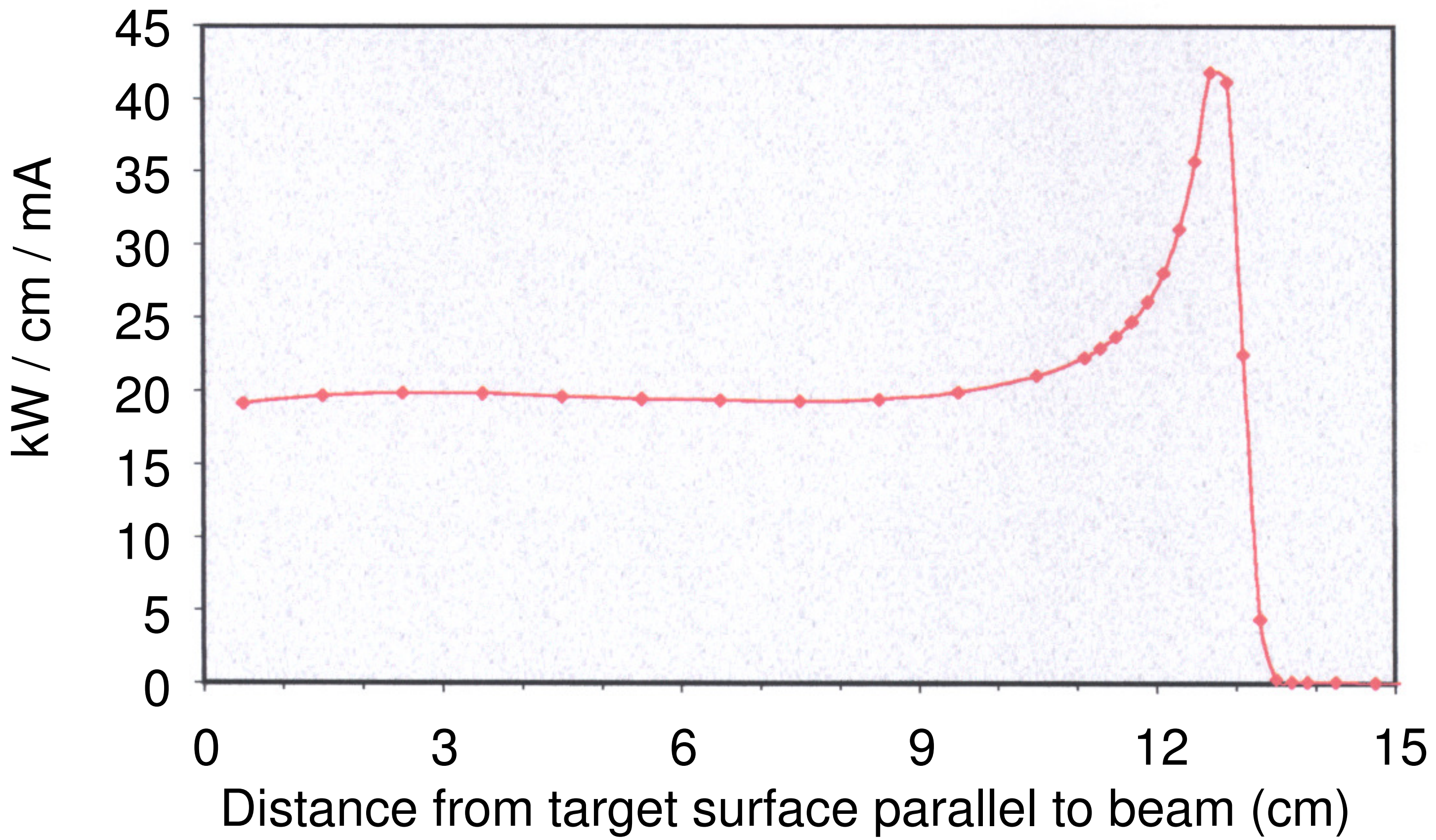
Power density in the central cylinder of 1 cm radius along the proton beam in a 5 MW_b spallation target (E=1.3 GeV)



Axial Distribution of Power in a Spallation Target

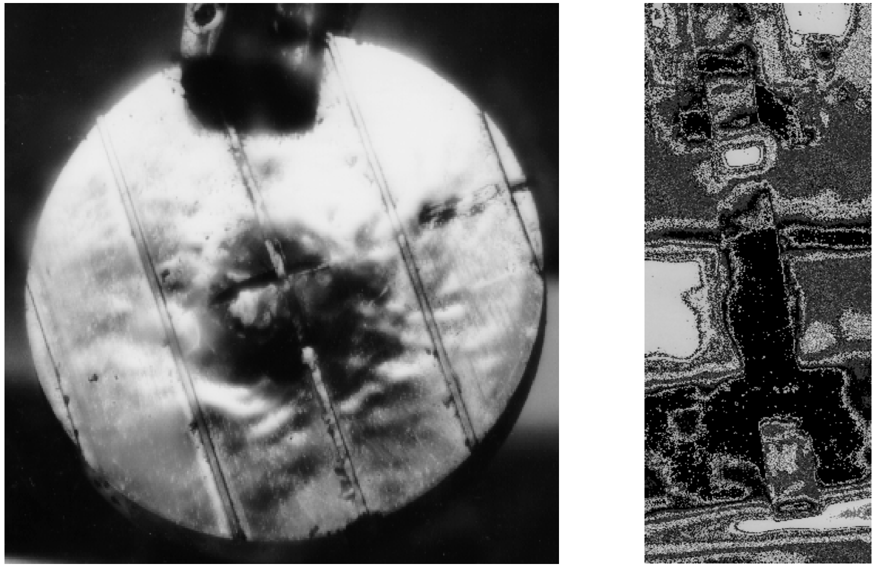
Power deposition by 450 MeV Protons in PbBi
(integral over beam cross section)

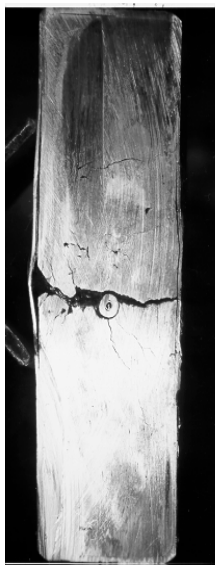
$$\frac{kW/cm^3}{mA/cm^2}$$



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)

- Note: U-10%Mo remained stable in reactor fuel tests up to 70% burn-up

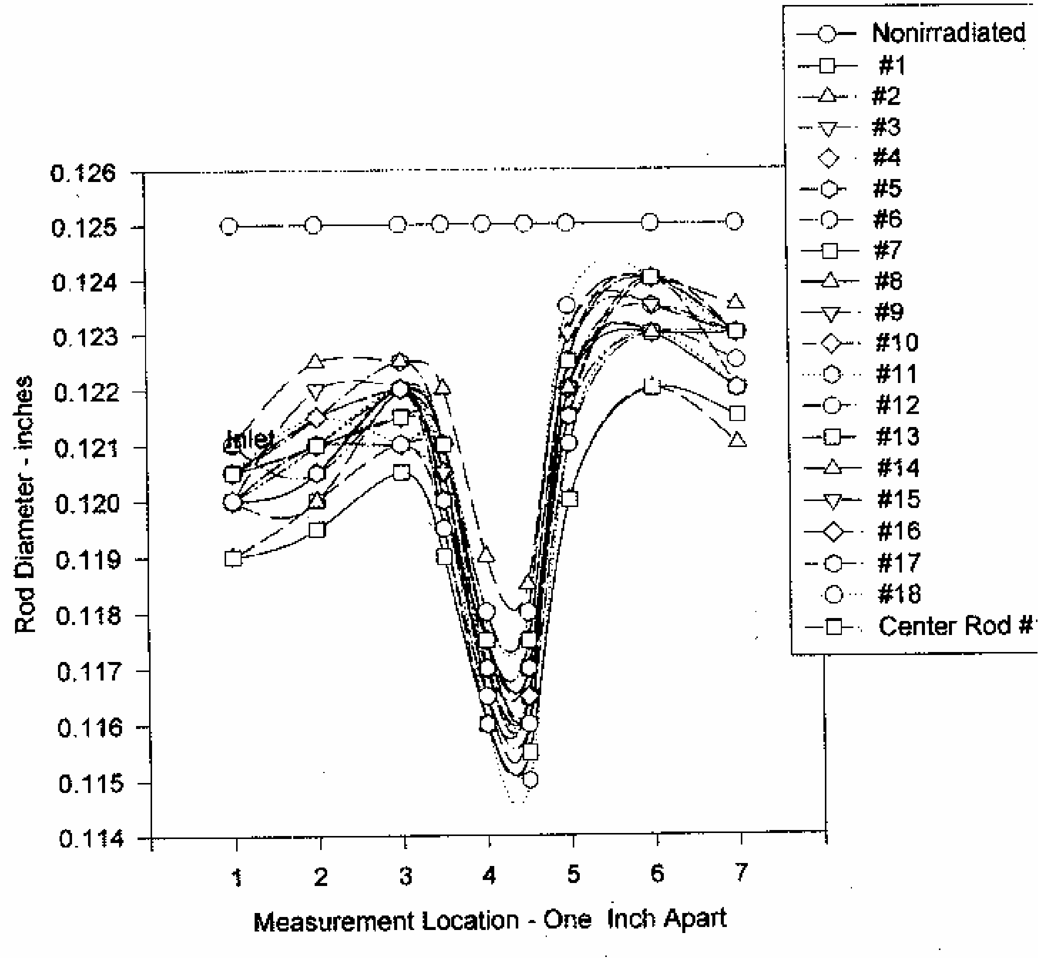
Spallation Target Materials: ^{238}U-10%Mo

- Gamma-stabilised U-10%Mo was examined in the RERTR-program up to 70% burnup with 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 project.
- If found a suitable target material, this might be a candidate in high power applications in connection with a heavy liquid metal coolant (speculative! - combining the worst of both worlds?).

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).
- 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



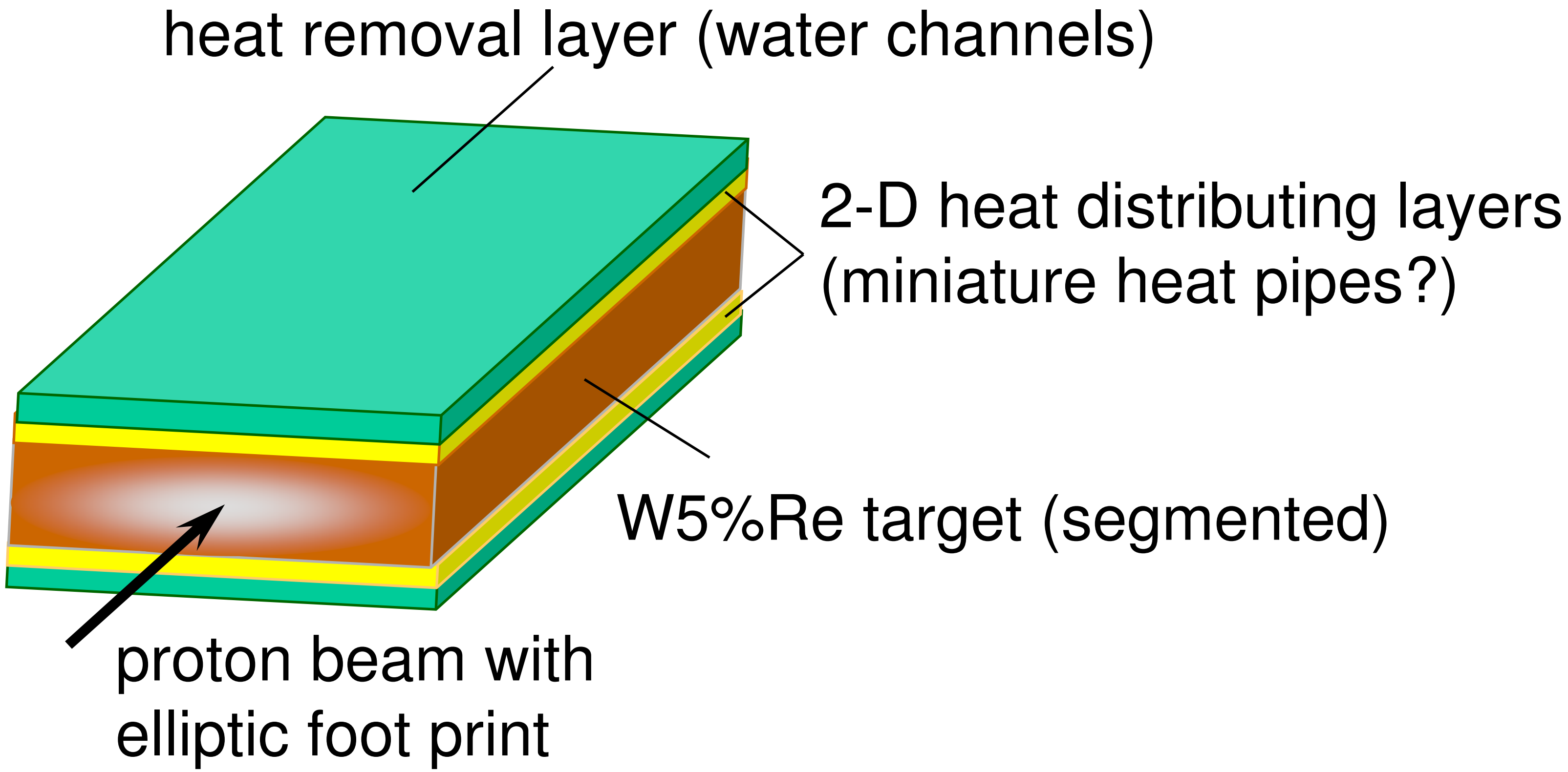
3 mm diameter W-rods irradiated at the LANCE radiation effects facility to a maximum fluence of $2x10^{21}$ p/cm^2 in cooling water flowing from left to right. Tungsten concentration in the cooling water increased to 35 mg/l over the 24 days irradiation period.
(W. Sommer, 1997)

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)

The AUSTRON Target Concept

High temperature segmented massive target for 500 kW_b



Spallation Target Materials: Tantalum

- Z = 73, A=180.95, d=16.6 g/cm³, T_m=3000℃
- Ta is 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 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.

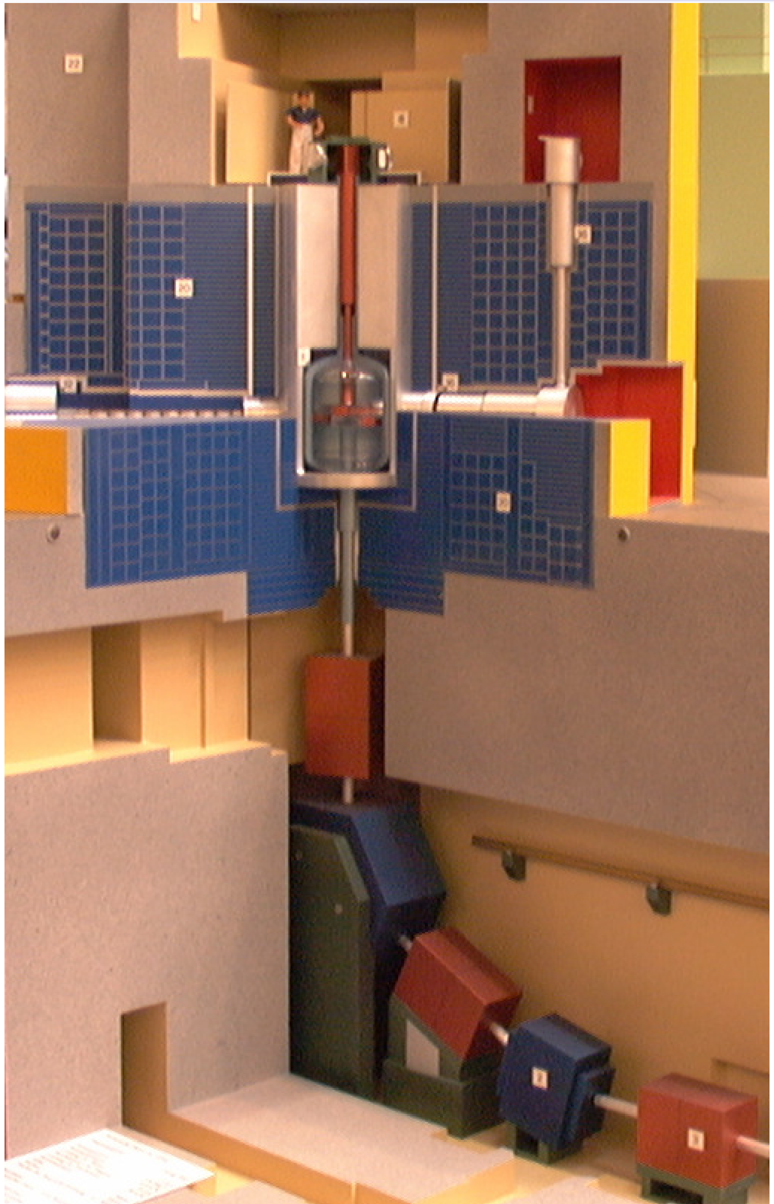
Spallation Target Materials: Solid Bismuth

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

Spallation Target Materials: Solid Lead

- Z =82 , A=207.2, d= 11.3 g/cm³, 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 Metal Targets: The SINQ Rod Target (1)



Model of the SINQ Target Block

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.

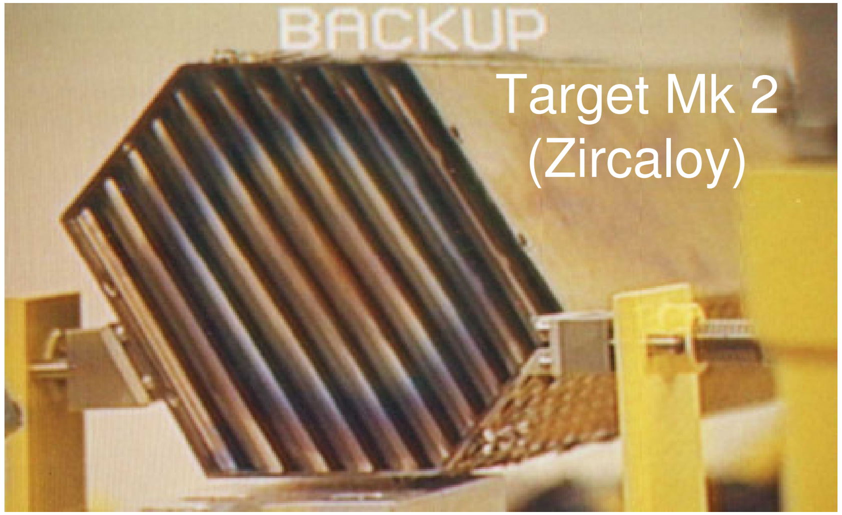
For high thermal moderator flux its target is surrounded by a 2m diameter heavy water tank, from which the bean tubes originate.

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

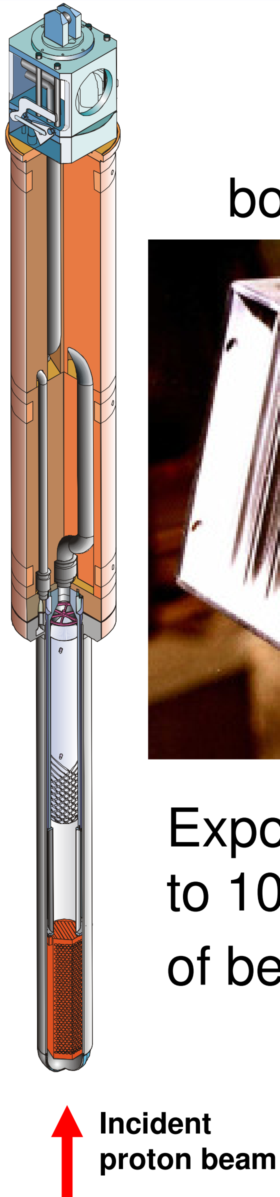
The upper 3m of the 4m long target insert are filled with shielding material.

Solid Metal Targets: The SINQ Rod Target (2)

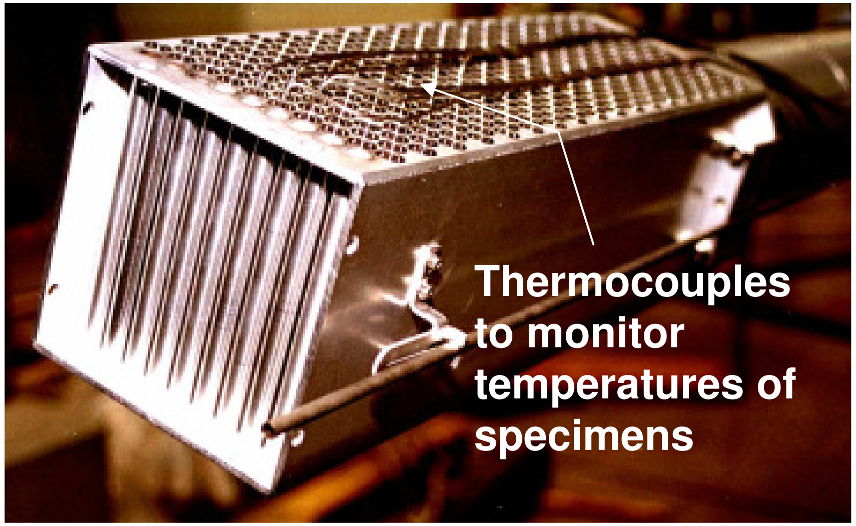
Target Mk 1
(Zircaloy)
after 0.5 Ah
water
purification off



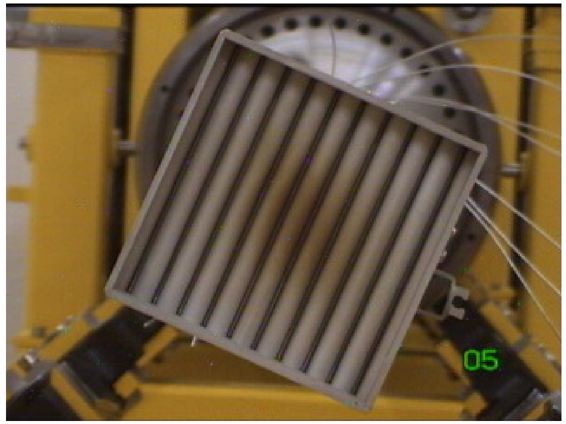
Removed after 6.8 Ah of beam
(water purification on)



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



Exposed
to 10 Ah
of beam;



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.
- 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.
- Beam distribution causes radial temperature gradients and stress and may make curved plates necessary.

Solid Metal Targets: General Issues (3)

- ^{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.
- 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

- Until recently solid heavy metal targets were the only ones used 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.

Liquid Metal Targets

- No radiation damage in target volume
- Heat transport in the target by convection rather than 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)
- More difficult technology, early experience just being collected (SNS, JSNS (Hg) and MEGAPIE (PbBi)
- Beam entrance window is the most highly loaded component in the system.
- Completely new safety case.
- Problem of cavitation erosion in pulsed source operation.

Liquid Metal Targets: Candidate Materials

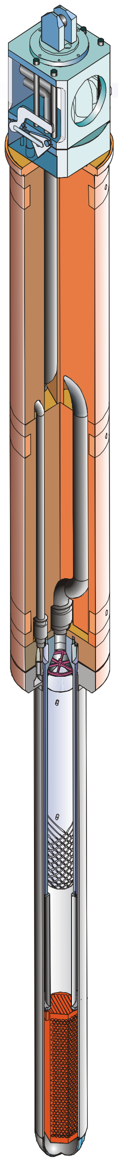
Property		Pb	Bi	LME *	LBE**	Hg
Composition		elem.	elem.	Pb 97.5% Mg 2.5%	Pb 45% Bi 55%	elem.
Atomic mass A (g/mole)		207.2	209	202.6	208.2	200.6
Linear coefficient of thermal expansion (10^{-5} K^{-1})	solid liqu. (400 °C)	2.91 4	1.75	4		6.1
Volume change upon solidification (%)		3.32	-3.35	3.3	0	
Melting 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

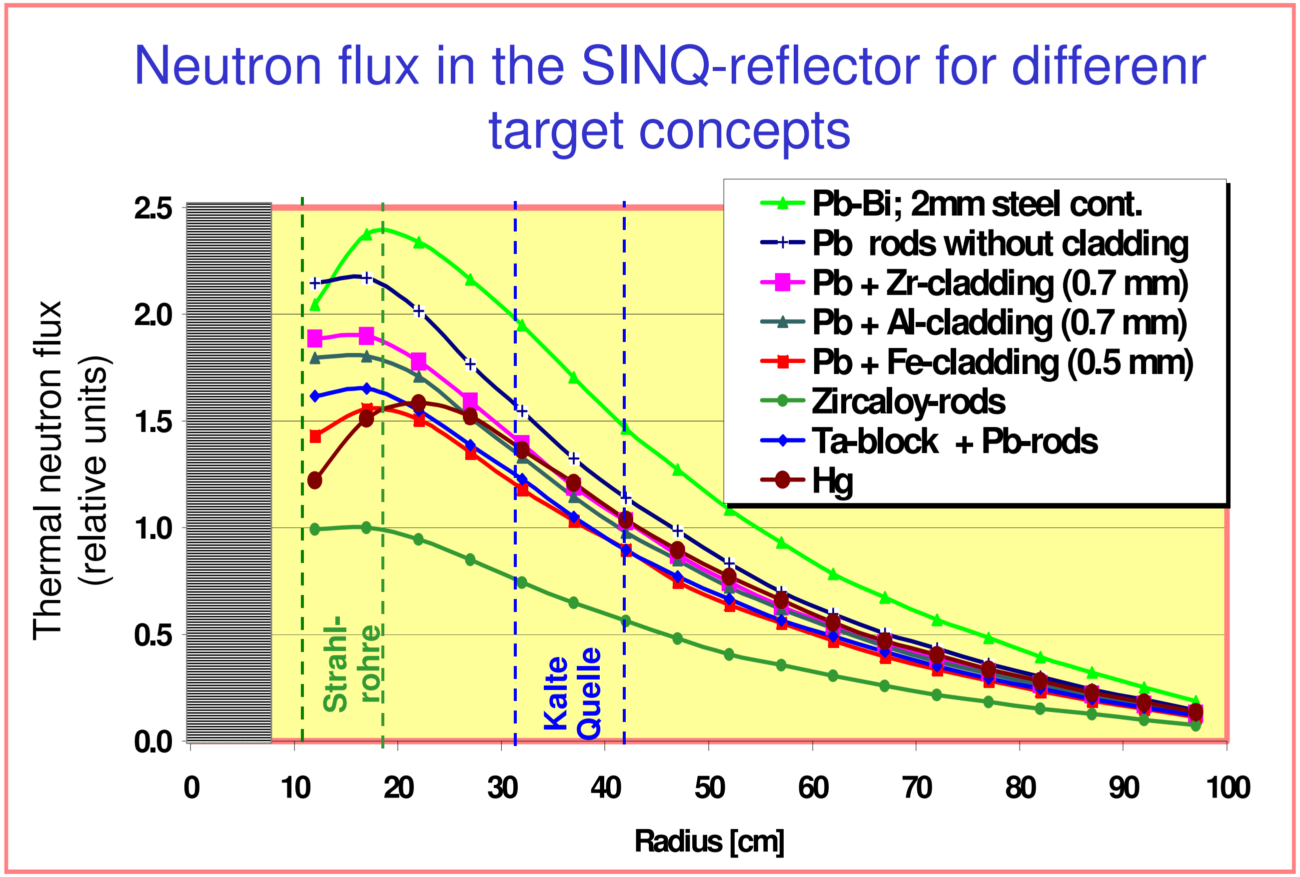
* Lead magnesium eutectic ** Lead bismuth eutectic

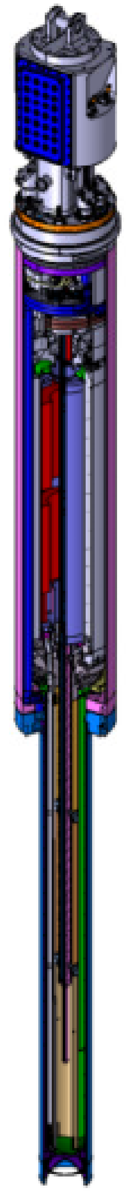
Liquid Metal Targets: Pb, Bi

- 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) 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:MEGAPIE



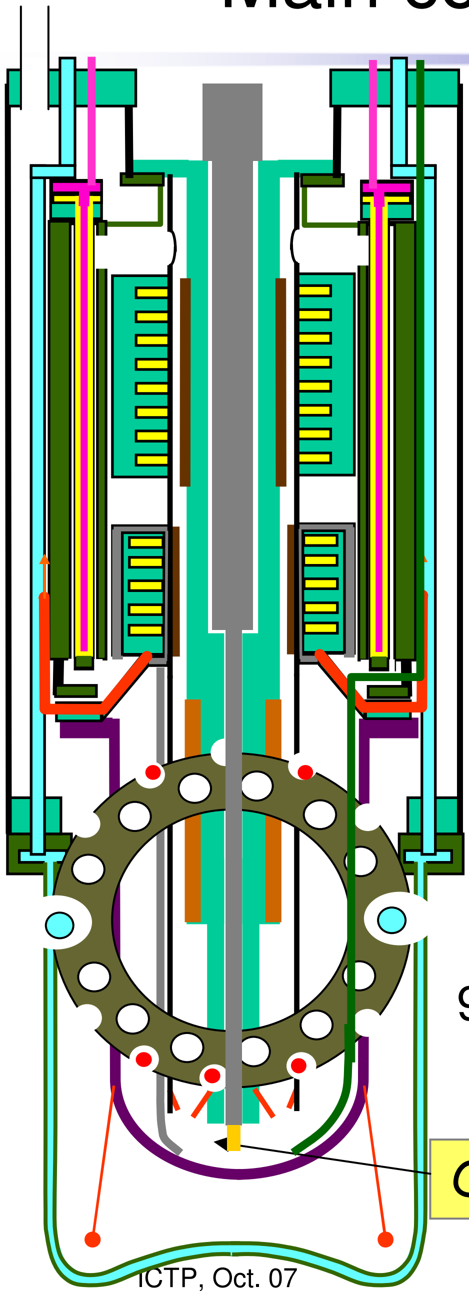




- Higher neutron yield (flux in the reflector)
- Less radiolytic effects in the cooling water
- Reduced radiation levels in the cooling plant room
- New technology for next generation neutron sources (ADS)

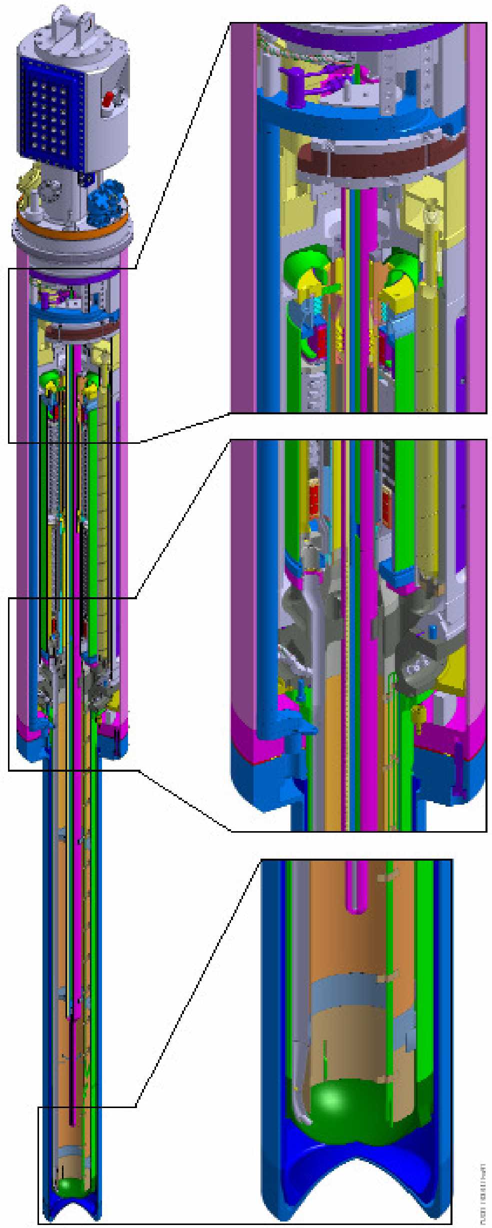
Incident proton beam

Main components of the MEGAPIE Target

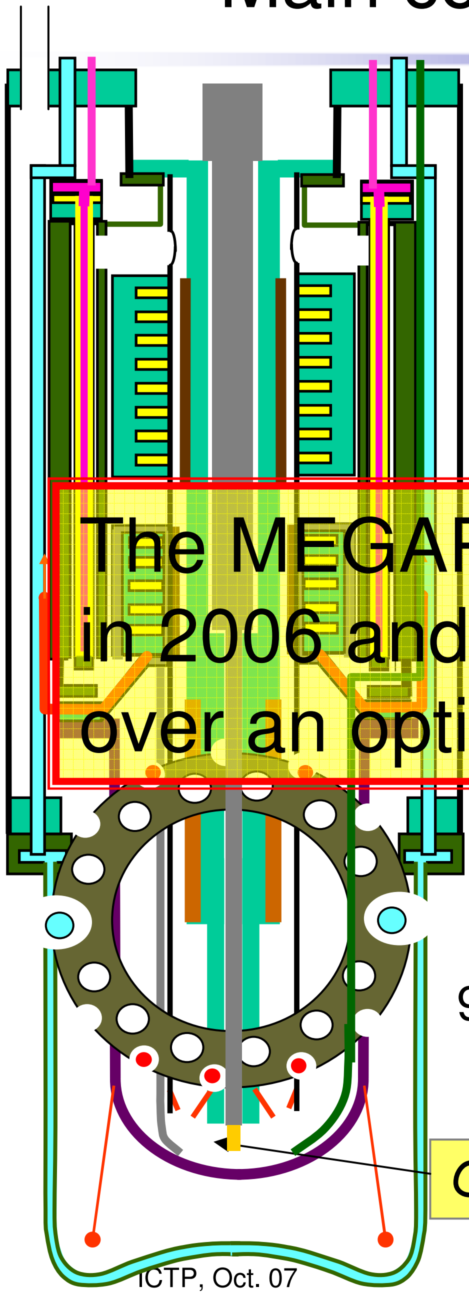


1. Upper liquid metal container and displacement body
2. Heat exchanger
3. Pump unit and lower flow guide
4. Central rod with auxilliary heating
5. Fill-and drain tube
6. Lower liquid metal container with leak sensors
7. Upper flange with feed-throughs
8. Upper vacuum chamber with outer enclosure
9.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

Option for materials test samples (not



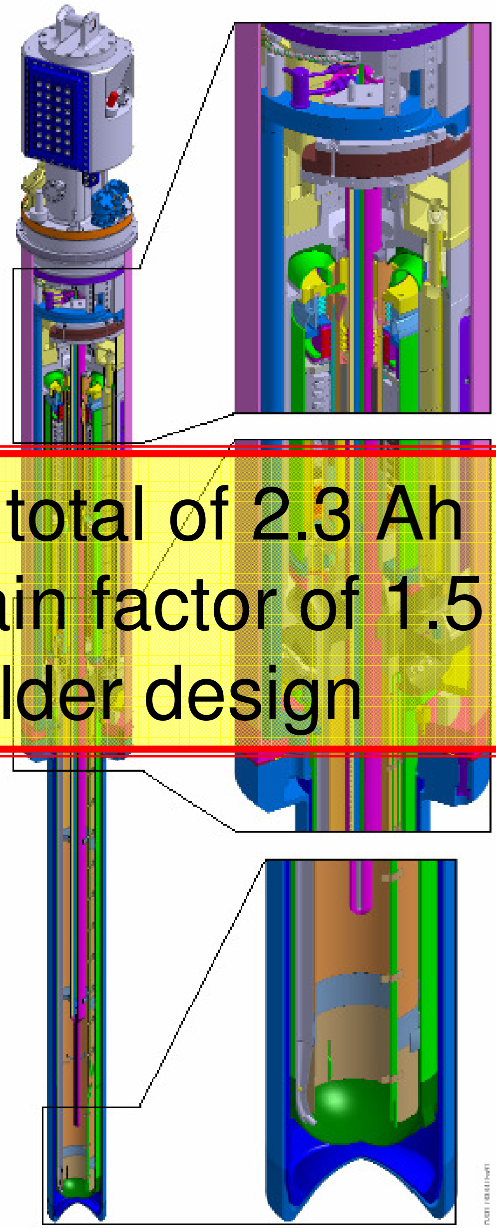
Main components of the MEGAPIE Target



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

The MEGAPIE target was run up to a total of 2.3 Ah in 2006 and yielded the anticipated gain factor of 1.5 over an optimized solid target of the older design

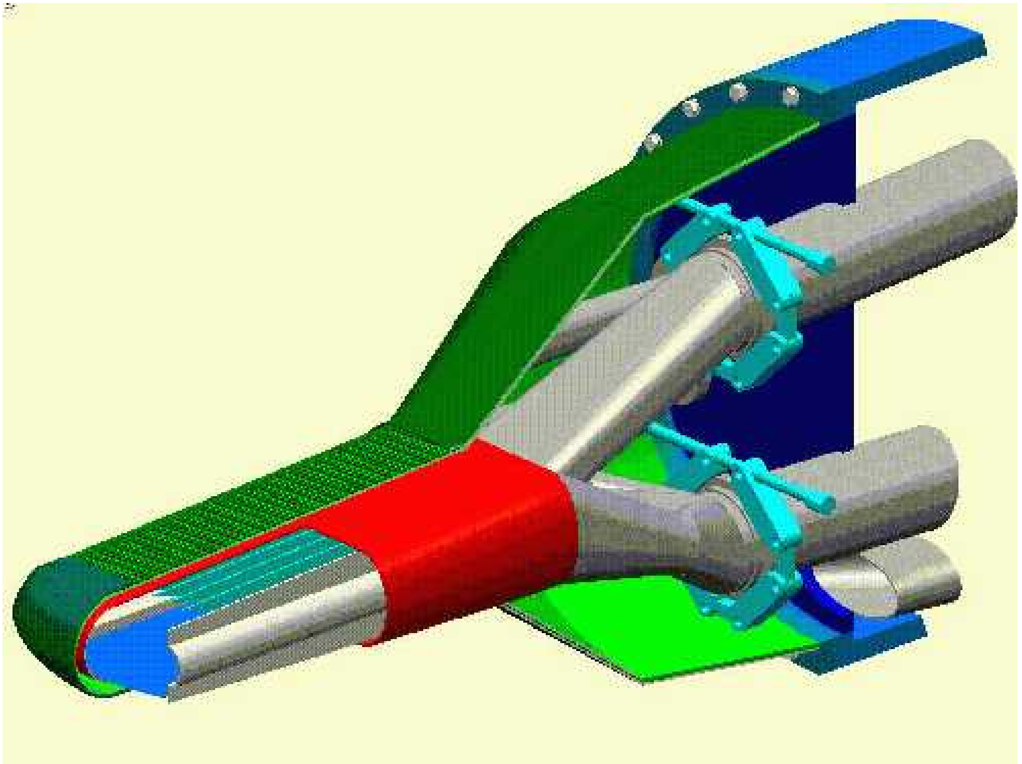
Option for materials test samples (not



Liquid Metal Targets: Hg

- 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 research neutron sources (ESS-5 MW, JSNS-1(5) MW, SNS-2 MW).

Target Geometry: ESS Slab Target



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: 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 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)

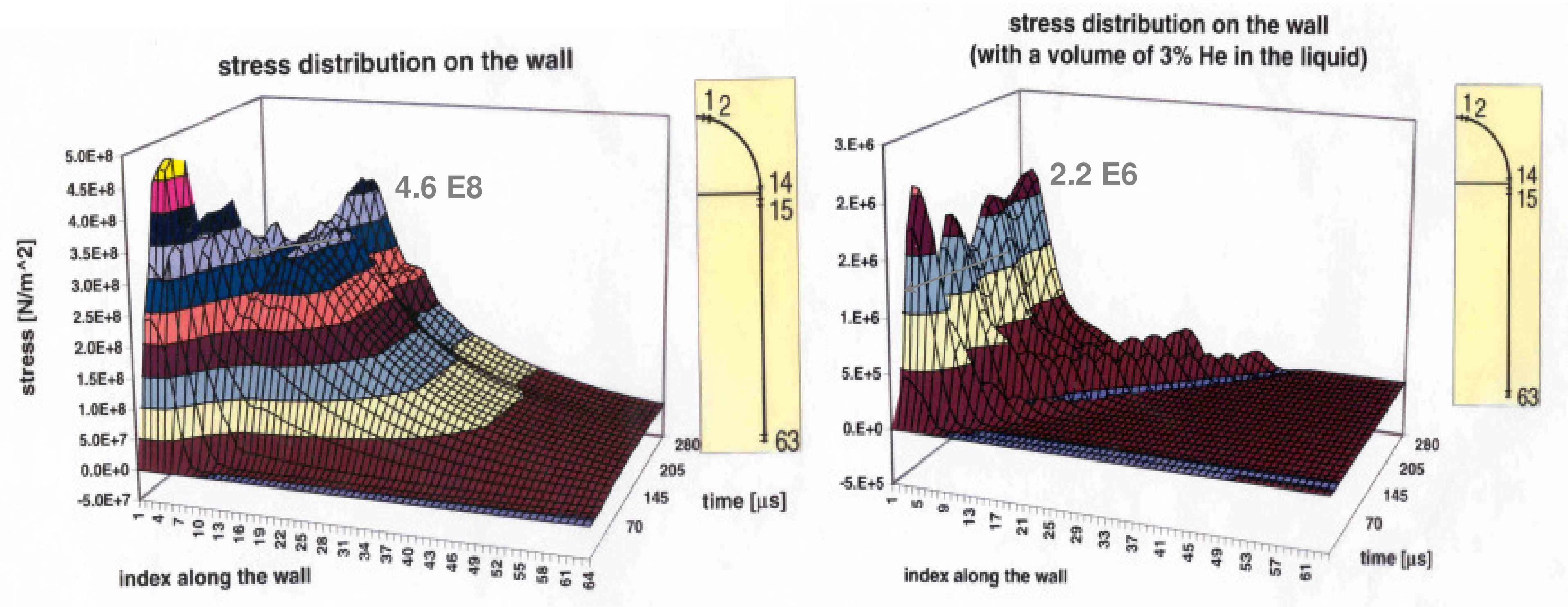
- The case of a window failure and easy exchange of the window will have to be design requirements. This favours horizontal beam injection (outer shroud with leakage monitoring of the interspace).
- In order to avoid dangerously high temperatures in the window, the liquid metal flow should be directed away from the window.
- Temperature also plays an important role in the damage a window may suffer (radiation effects, corrosion, embrittlement, strength).

Liquid Metal Targets: The Pressure Wave Problem

- 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

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



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!

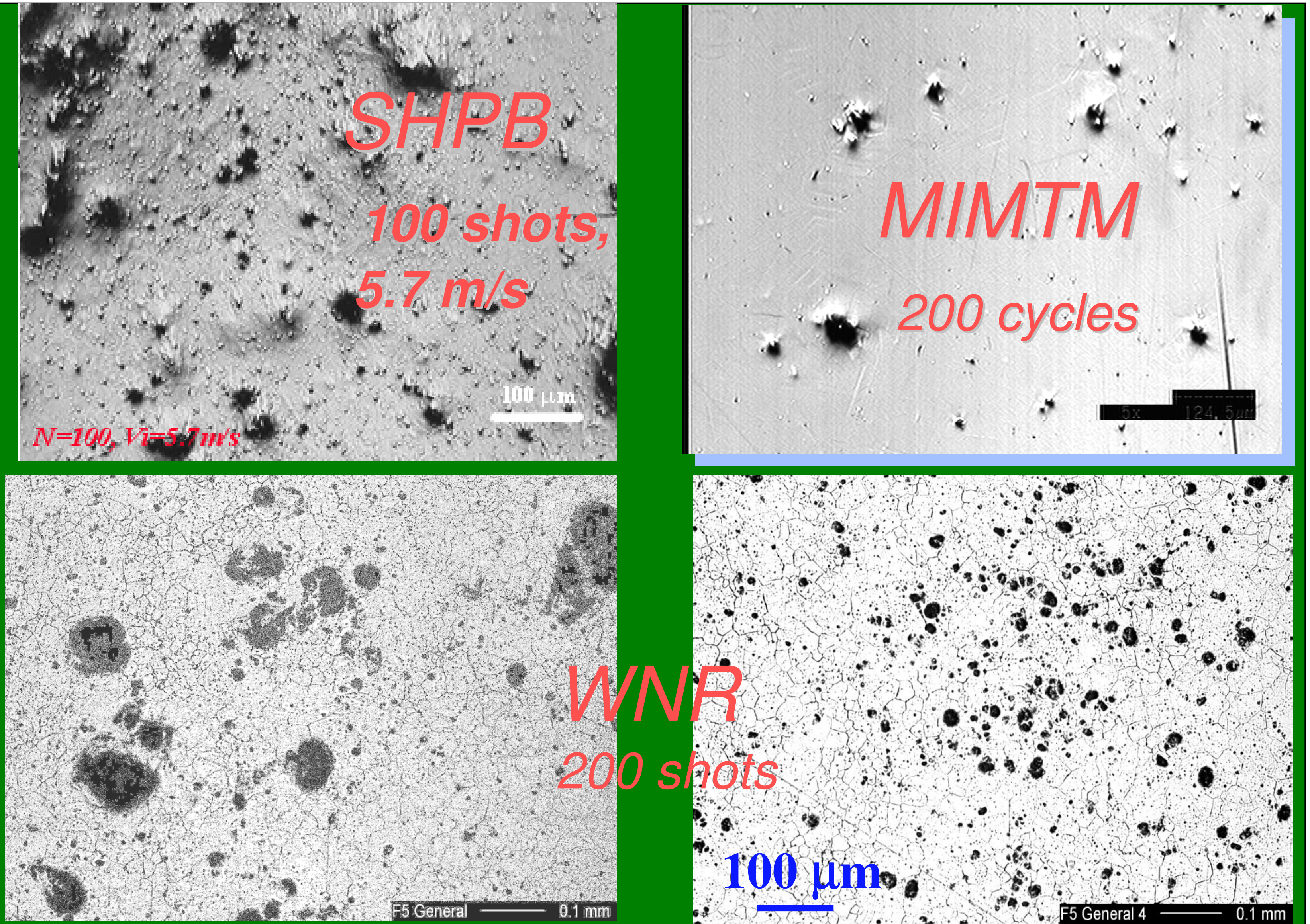
Liquid Metal Targets: The Cavitation Issue

- 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.

Cavitation-Erosion („Pitting“) by Pressure Pulses

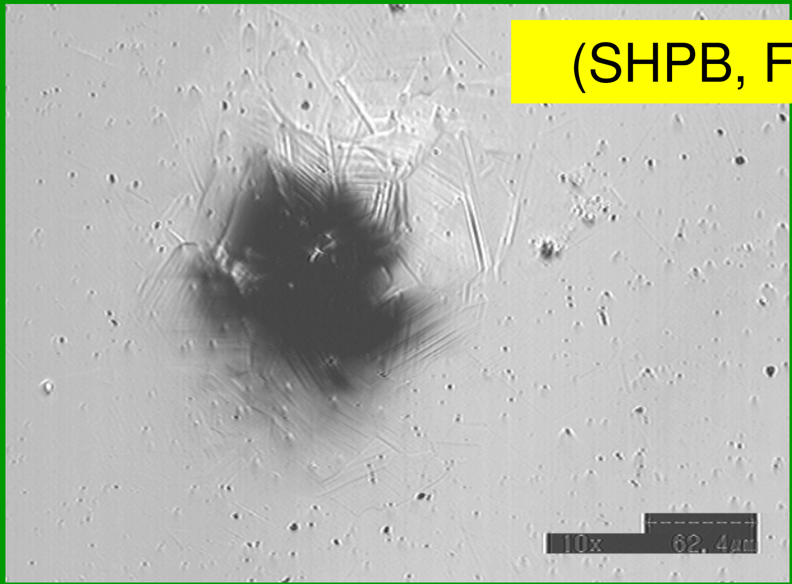
Out of beam

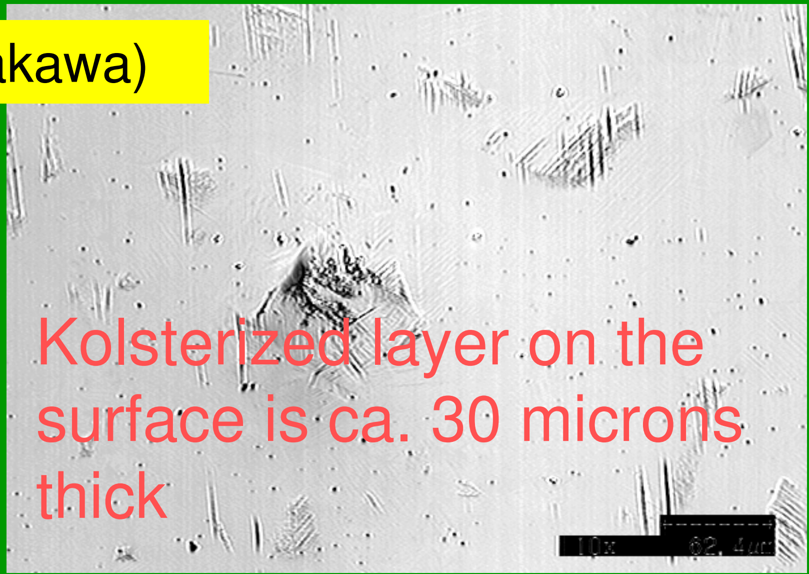
800 MeV prot. beam

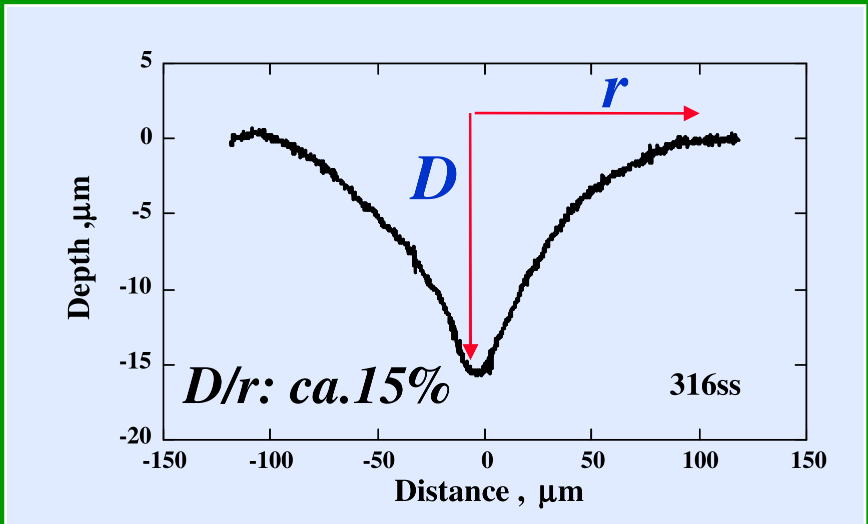


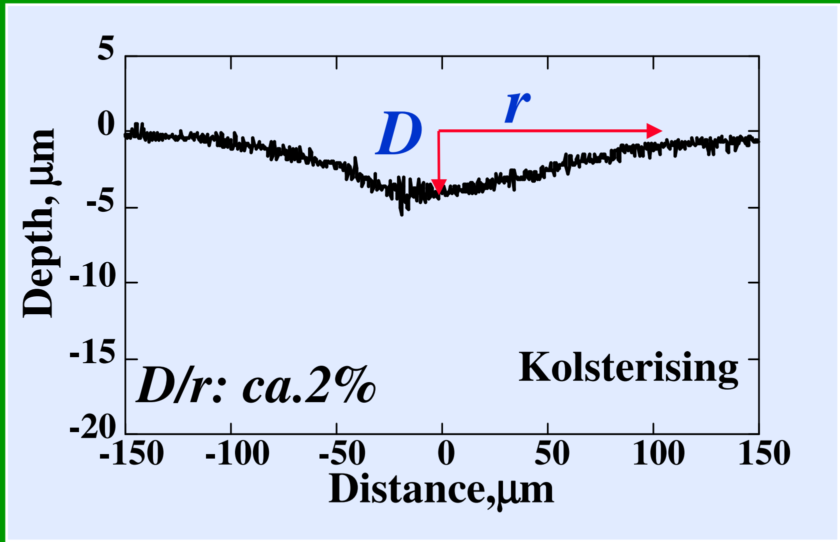
Depth profiles of pits in CW and Kolsterised 316SS

(SHPB, Futakawa)

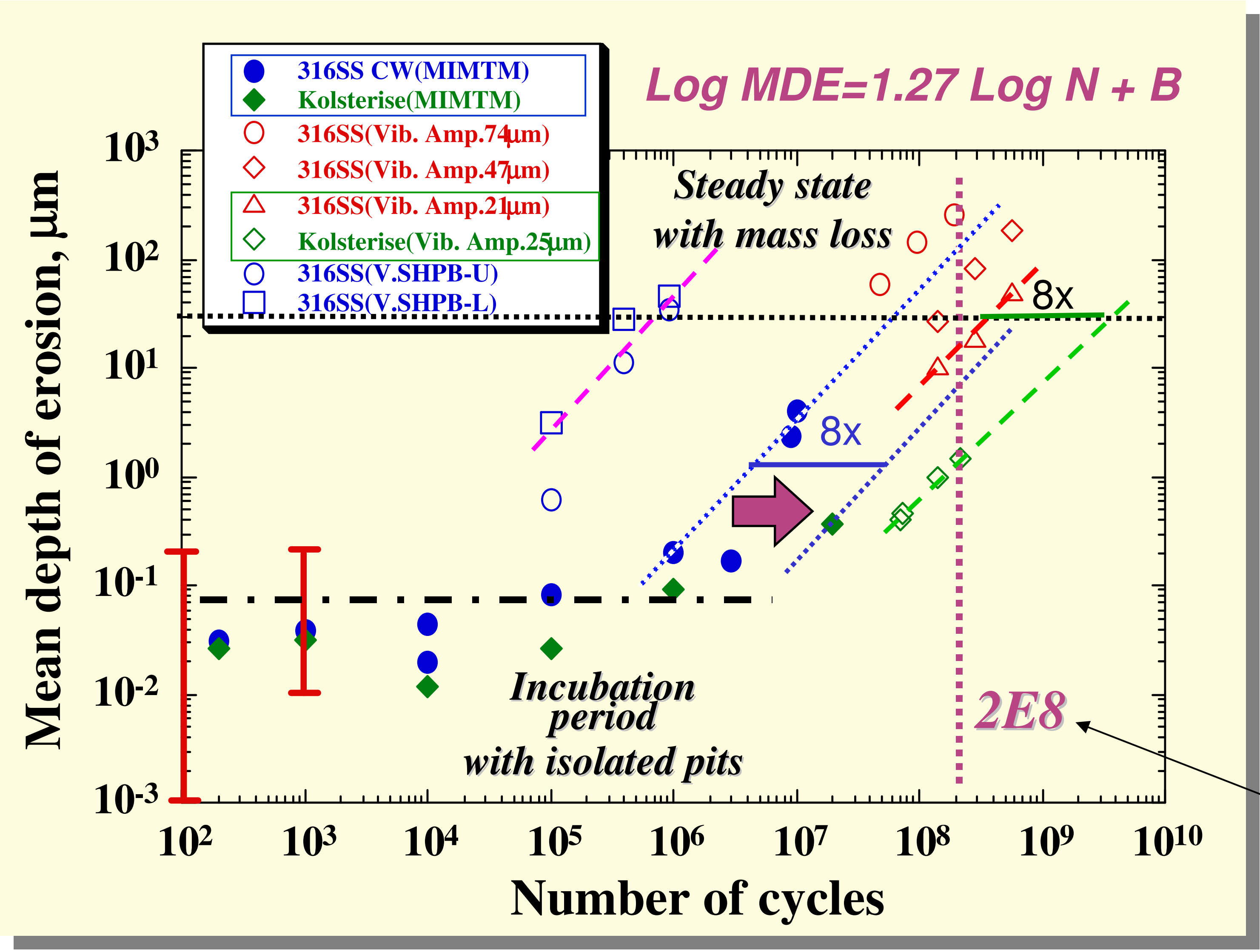








Summary Diagram of Pitting Results



M. Futakawa, JAERI

Kolsterising can expand incubation period

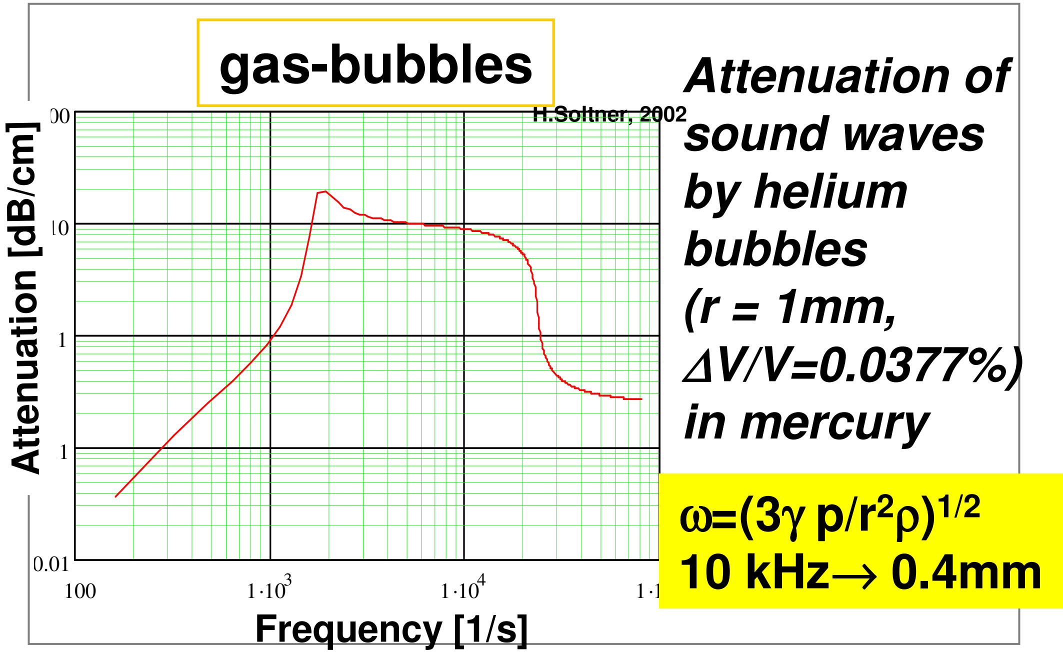
Kolsterized layer on the surface is only ca. 30 microns thick!

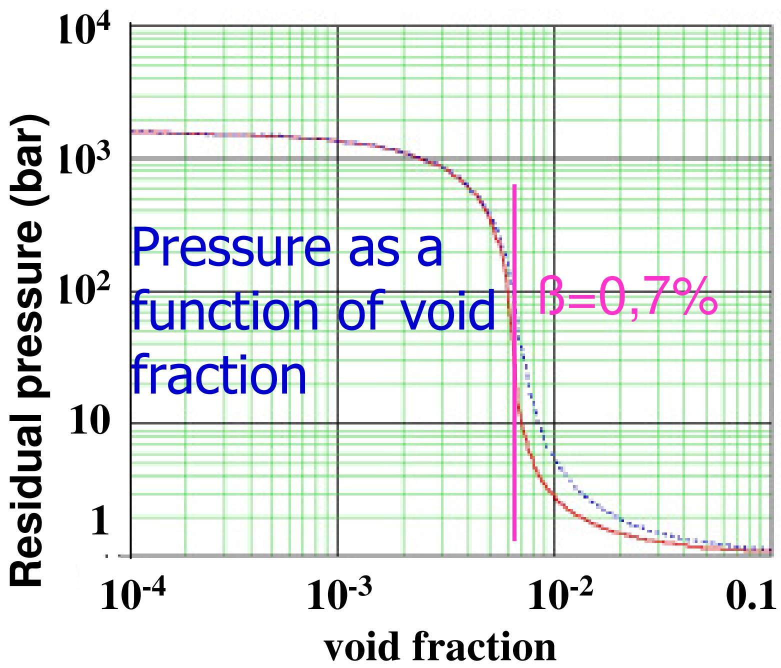
Ca 100 h at 60Hz

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

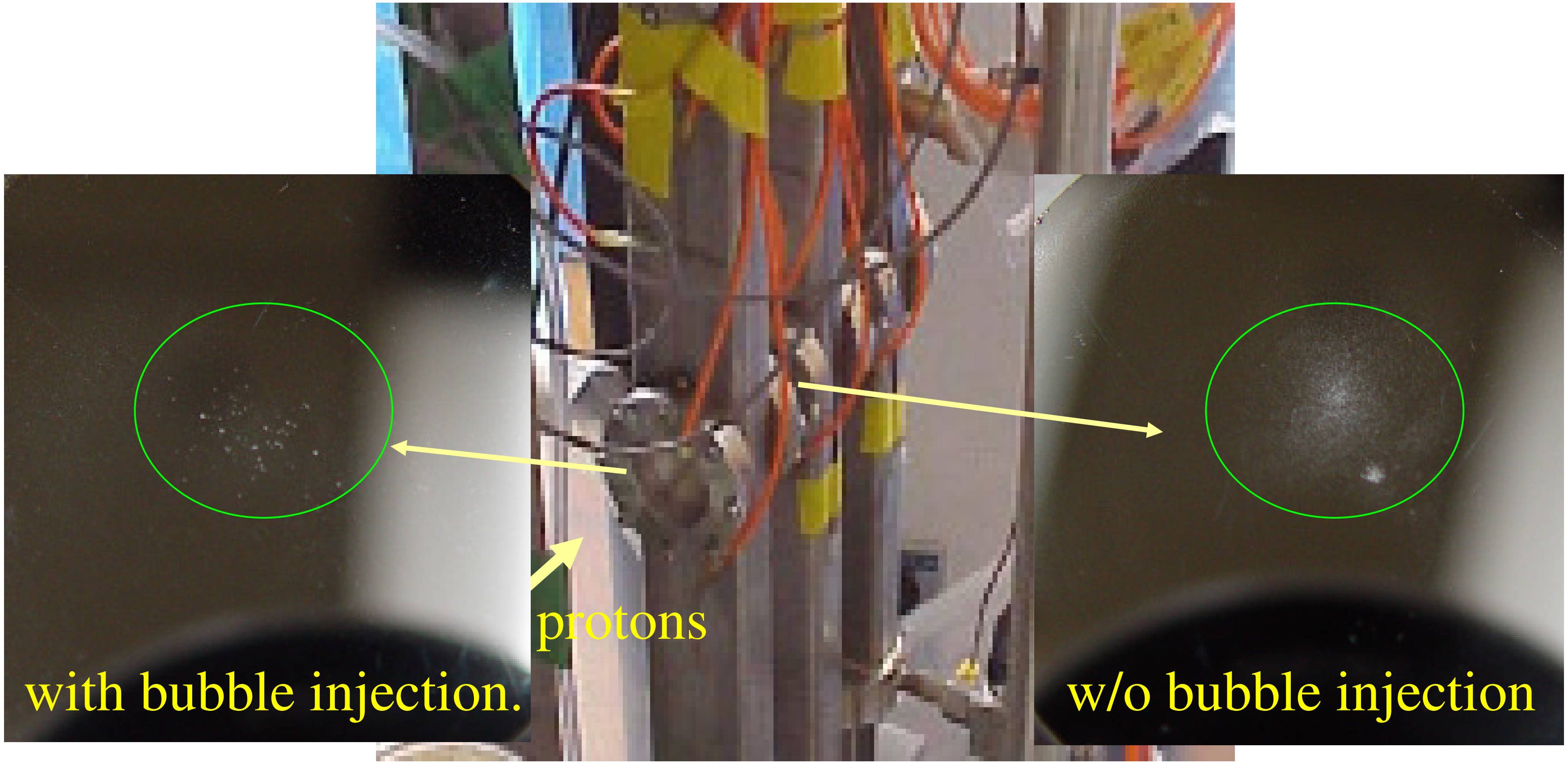
Pressure Wave Mitigation by Gas Bubbles





- 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.

First PoP-test of Bubble Effect at WNR in June 2002



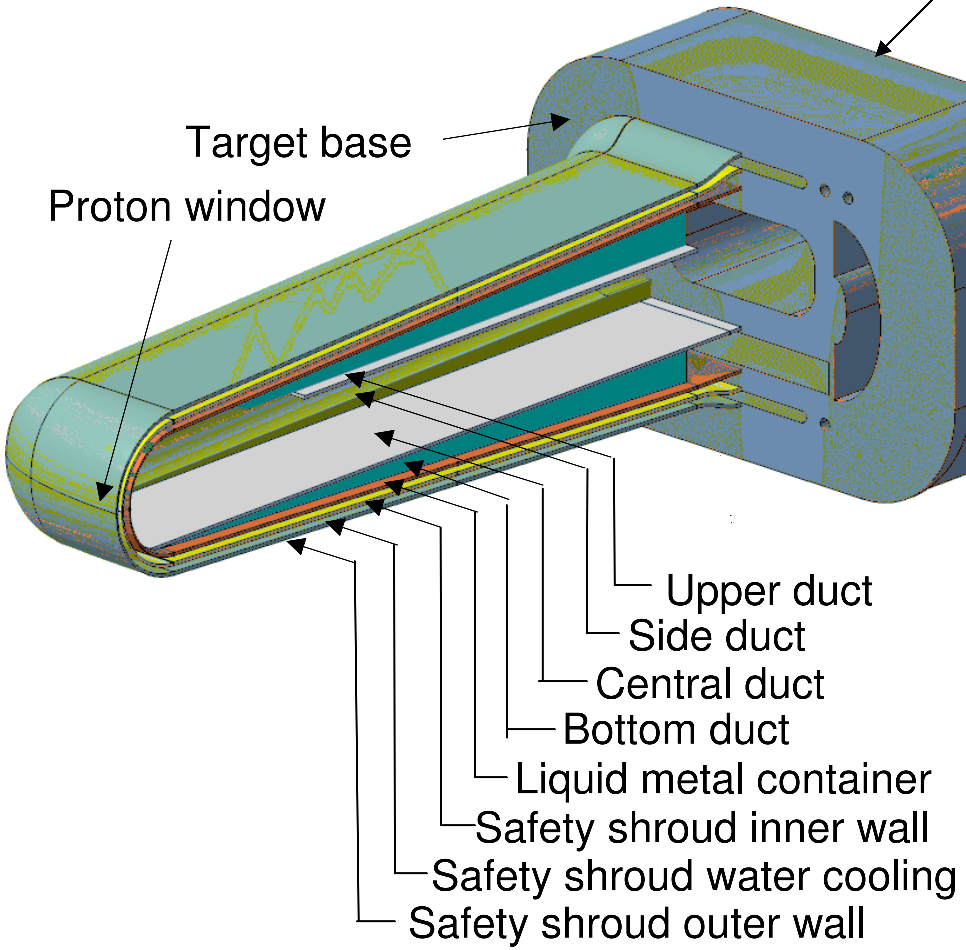
Maximum energy density in targets was 17.5 J/cc in bubble target and 14.4 J/cc in control target (p^4 = 93789 and 42998 respectively)

⇒ Would expect more than twice the damage in bubble target

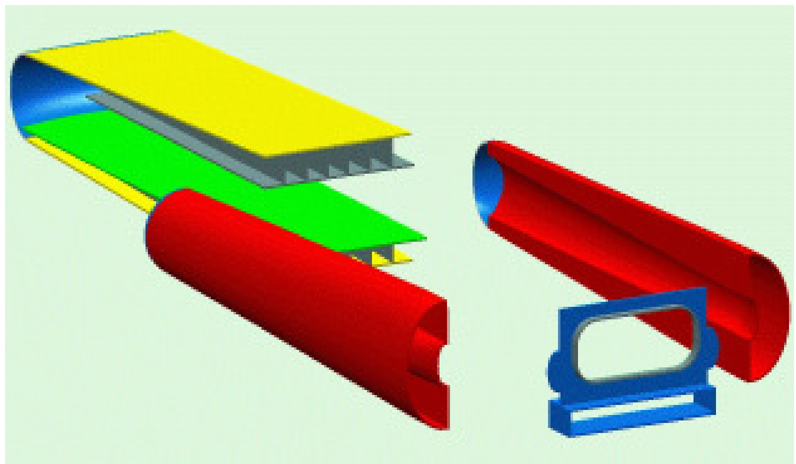
⇒ Find significantly less   Next series of tests at WNR under evaluation

Liquid Metal Targets: Design example – ESS (1)

ESS target with quick disconnect flange for rapid exchange



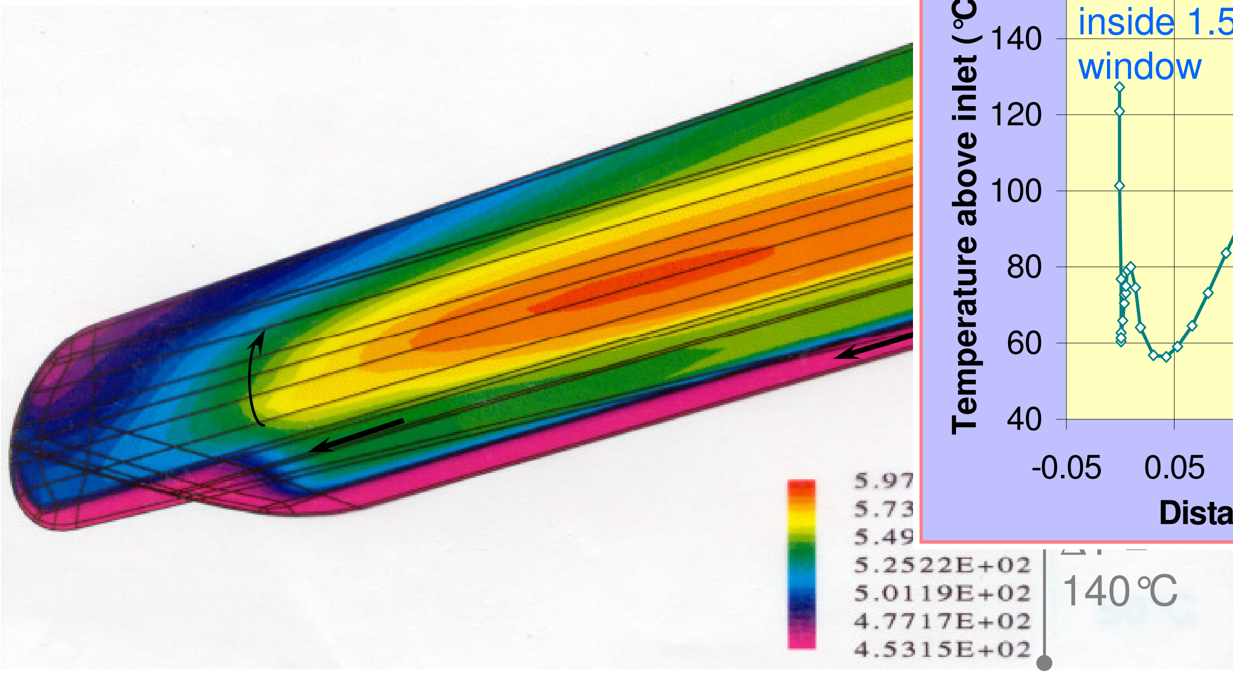
Components of the liquid metal container

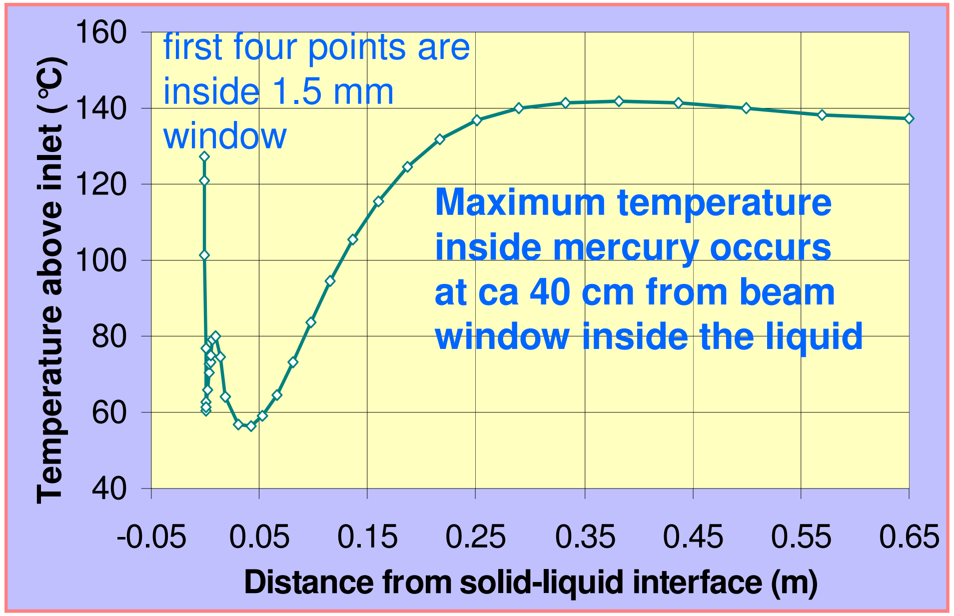


Liquid Metal Targets: Design example – ESS (2)

Peak current density: 80 µA/cm² of 1.33 GeV protons; window cooled in cross flow by 23% of total flow.

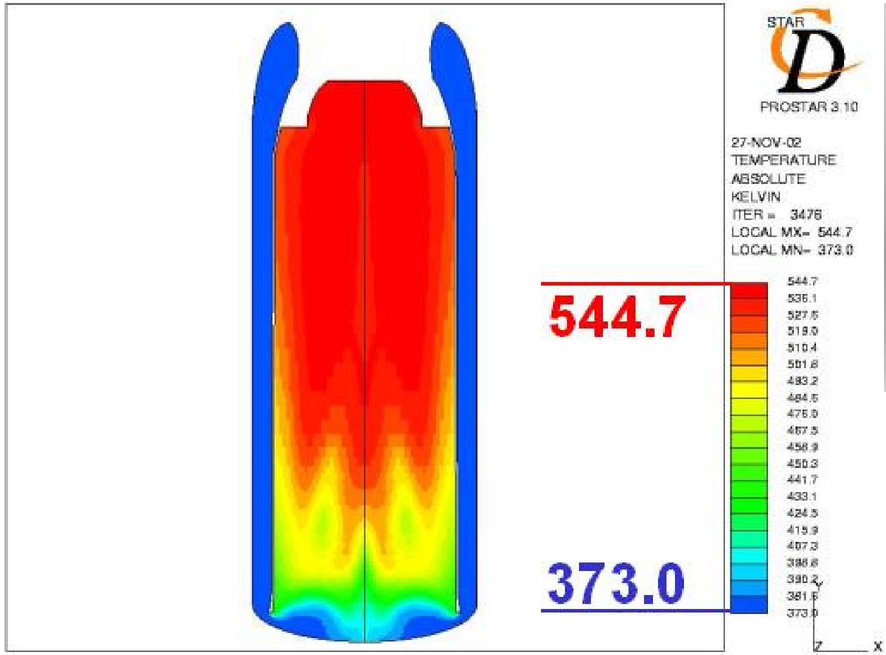
Calculated temperature distribution in 3 planes of the ESS target at 2.8 MW power dissipation and a mass flow of 175 kg/s (away from the beam window). Inlet velocities are 0.6 (bottom) and 1.78 m/s (sides).



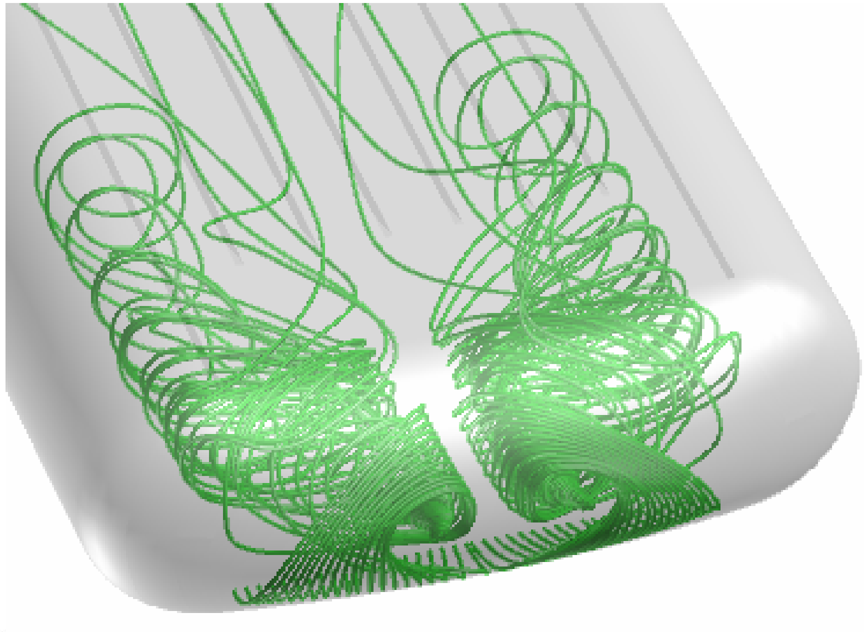


Liquid Metal Targets: Design example – ESS (3)

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]



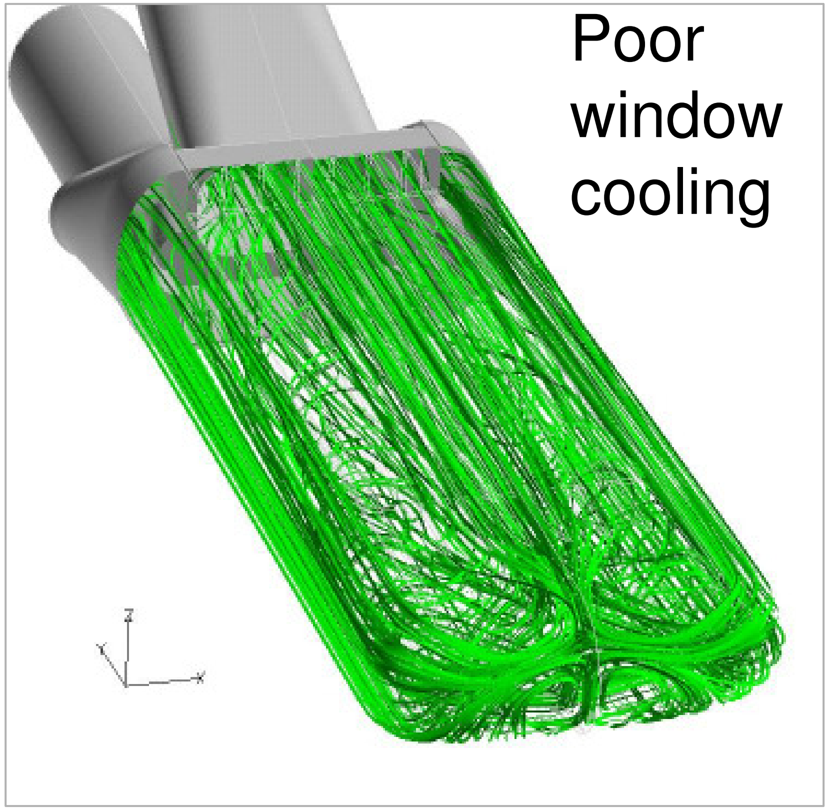
Computed trajectories of 0.1 mm diameter helium bubbles. The helium bubbles are injected from the bottom inlet duct [Komen, 2003]

More work is clearly needed!

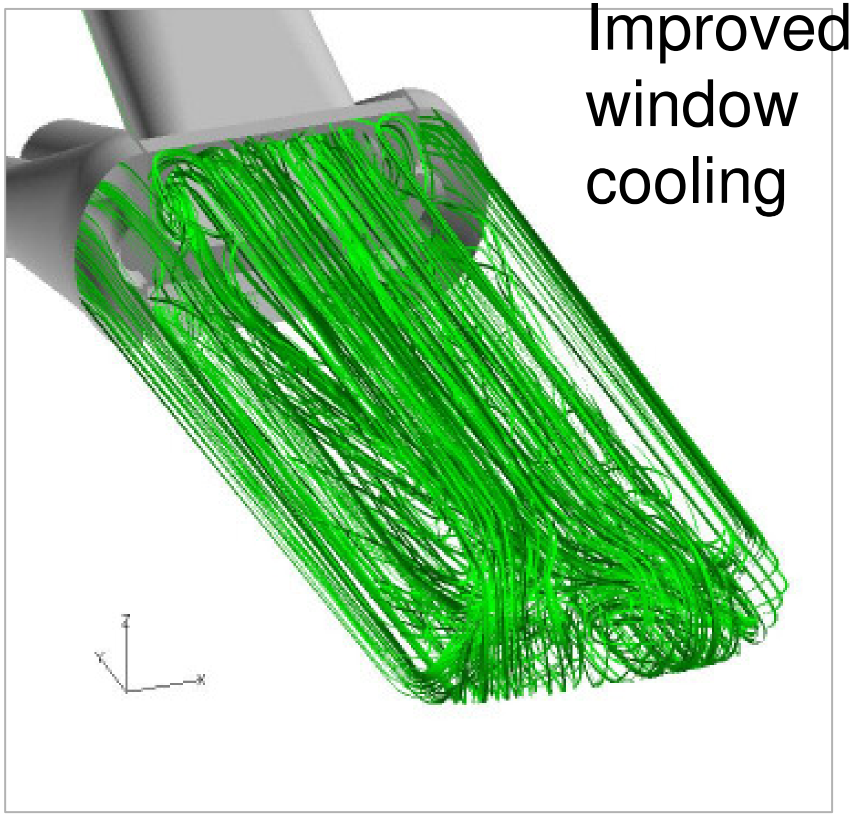
Optimizing the ESSTarget Geometry

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

39% / 22% / 39%



30% / 40% / 30%



Mercury Target Loop Design

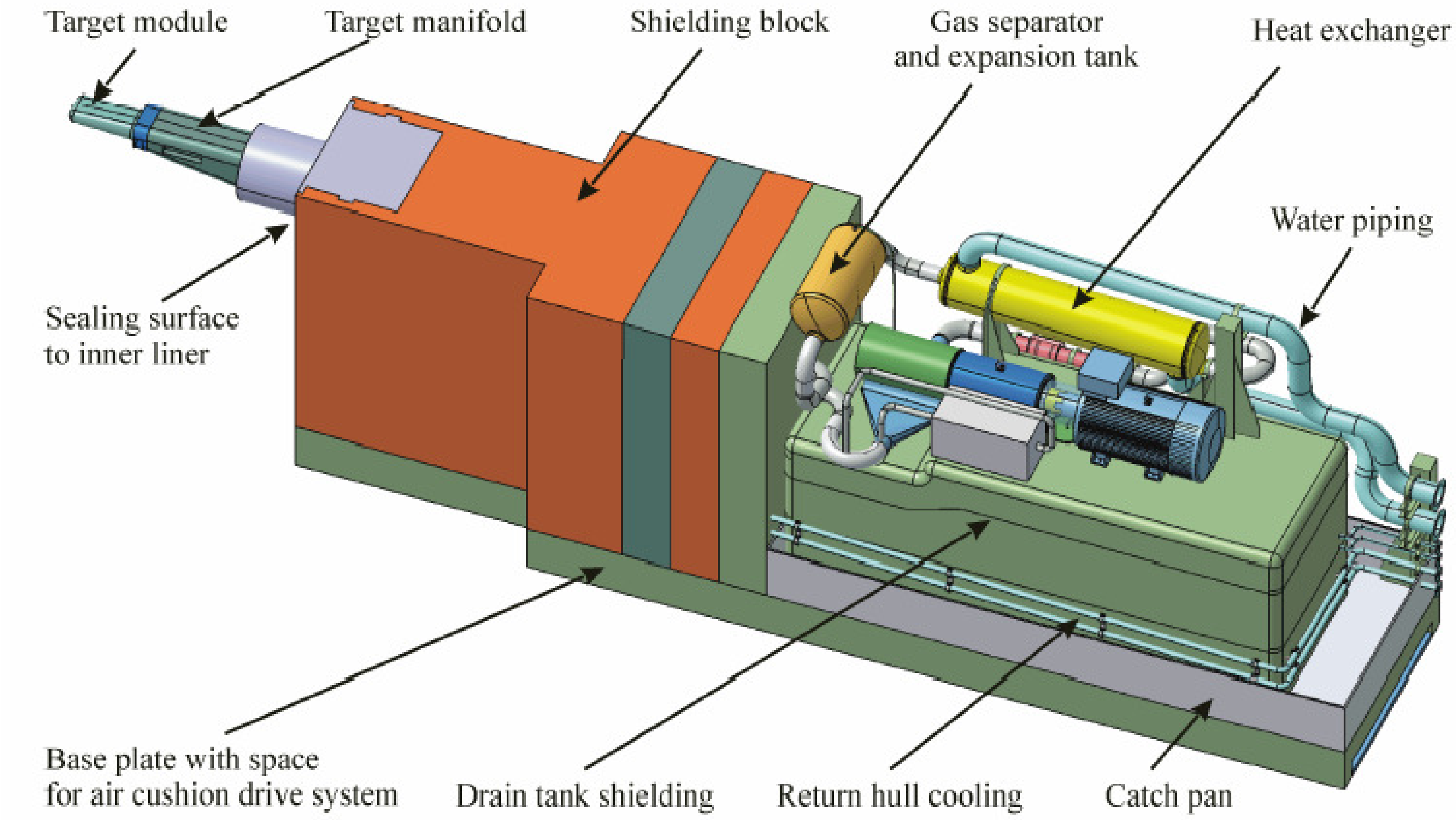
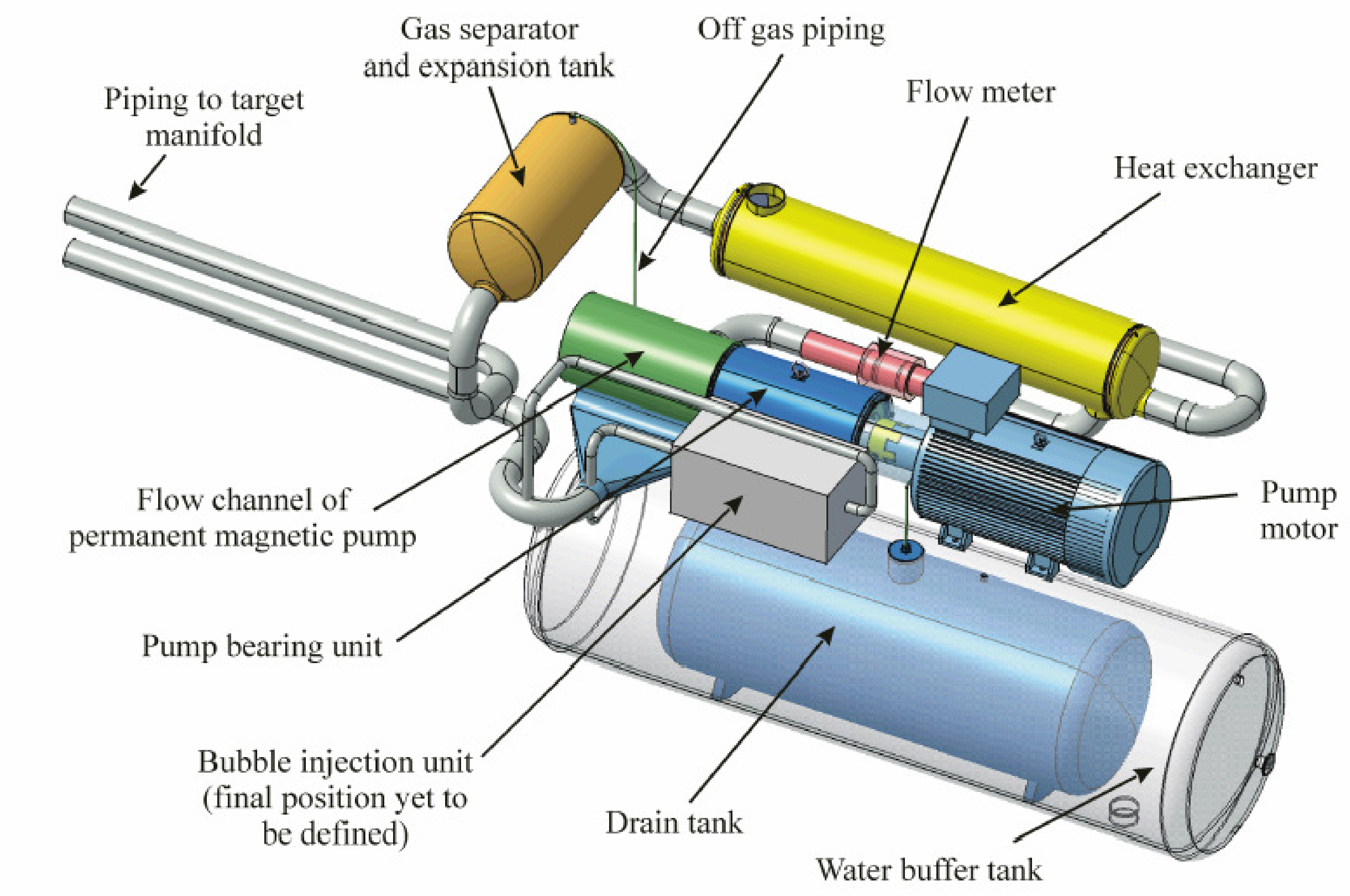


Figure 4.3.5.1: Trolley system (local shielding of components not shown)

The ESS Mercury Target Loop Design



Liquid Metal Targets: The Bottom Line

- There exists almost no experience with liquid metal targets!
- A pilot experiment at PSI (MEGAPIE) has been run successfully for ca 6 months (2.3 Ah), albeit without beam compression (cw-operation).
- In analysing this experiment the possible embrittlement of the wall by PbBi under irradiation and stress is investigated (LiSoR).
- A mercury target is under commissioning at SNS (up to 200 kW so far) and will soon be ramped up to higher power.
- So far, the data base is not sufficient to confidently embark on the construction of a 5 MW short pulsed source!

Summary on Target Technology and Design Issues

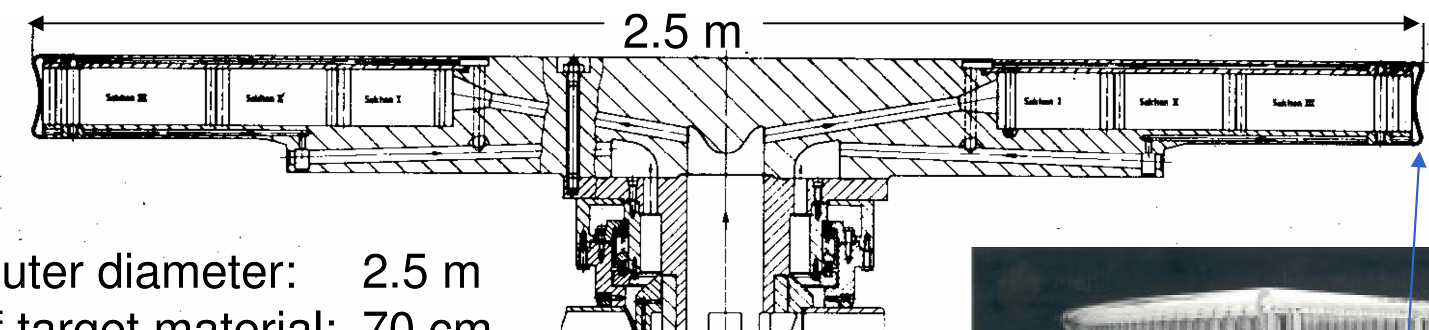
- Stationary solid targets can be used up to a beam power level of 1-2 MW.
- Beyond this power level liquid metal targets are probably OK for cw operation.
- Their technology is presently explored and developed in several projects (MEGAPIE, PbBi; SNS, JSNS (ESS), Hg)
- For pulsed operation of liquid metal targets in the multi-megawatt regime more R&D work is needed.

☹

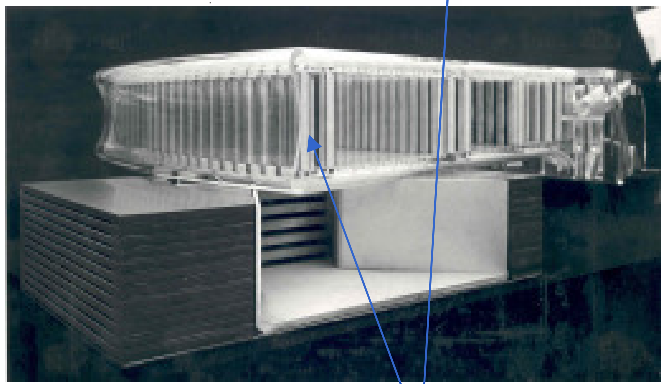
- A fallback solution might be a rotating solid target as explored for the 5 MW SNQ project in the 1980ies.

☺

The SNQ (5 MW) Rotating Target Concept (1980)



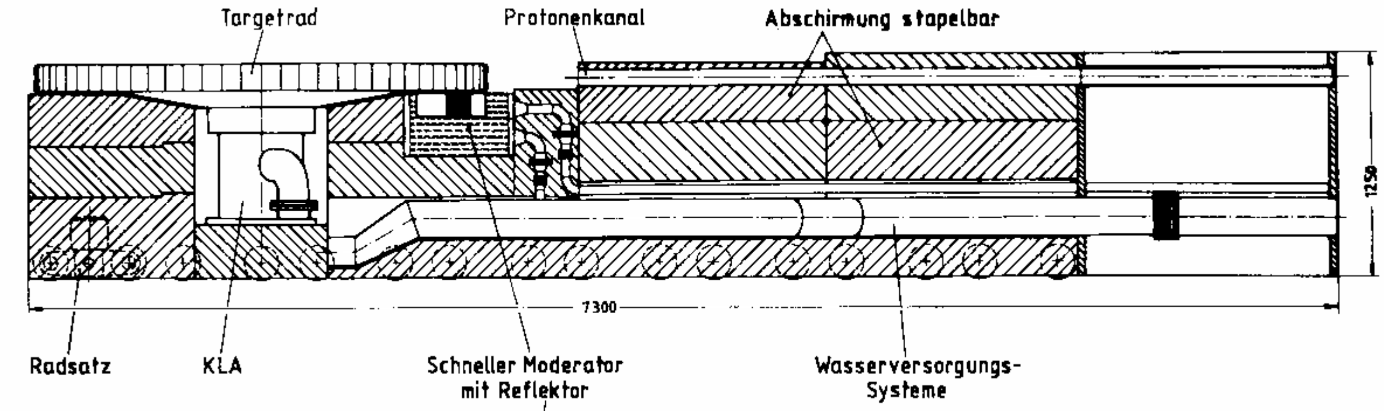
Target outer diameter: 2.5 m
Depth of target material: 70 cm
Height of target material: 12 cm
Beam diameter: 10 cm
Frequency of revolution: 1.2 Hz
Circumferential speed: 10 m/sec



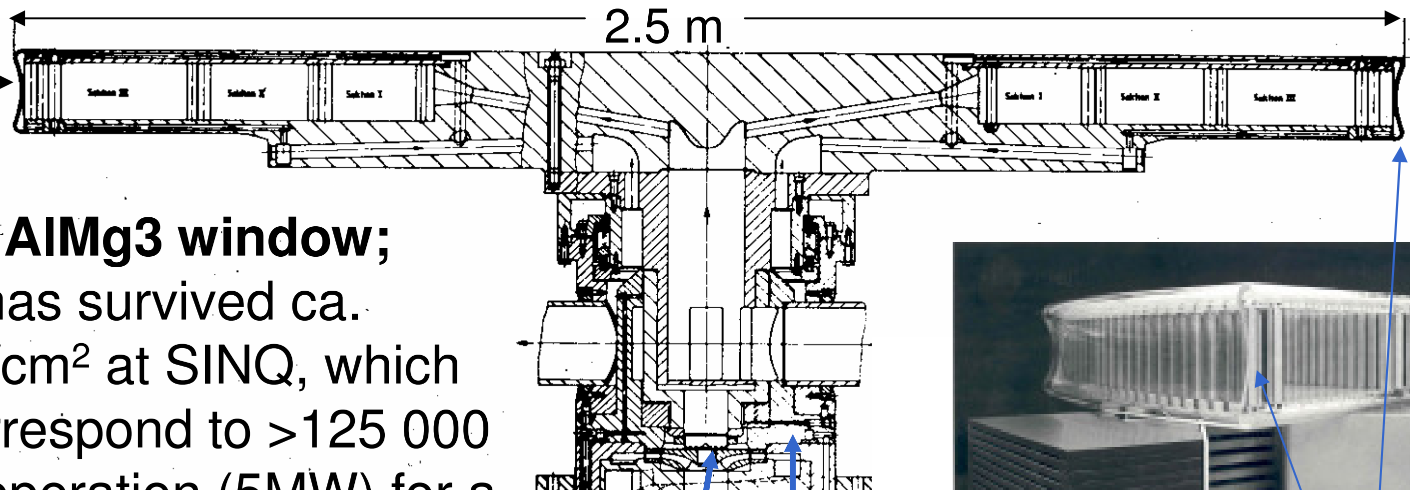
Water turbine

Hydraulic bearings

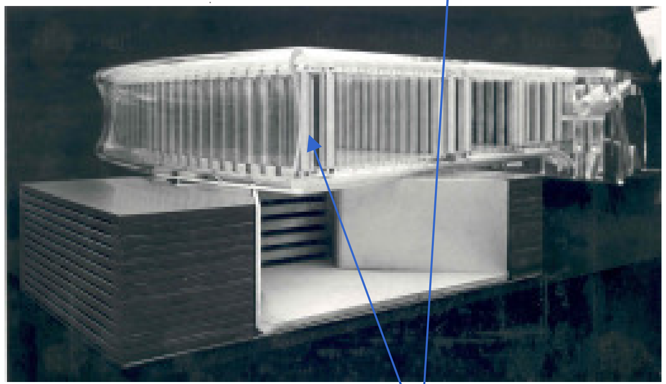
Target rods: Pb in Al tubes, surface cooled



The SNQ (5 MW) Rotating Target Concept (1980)

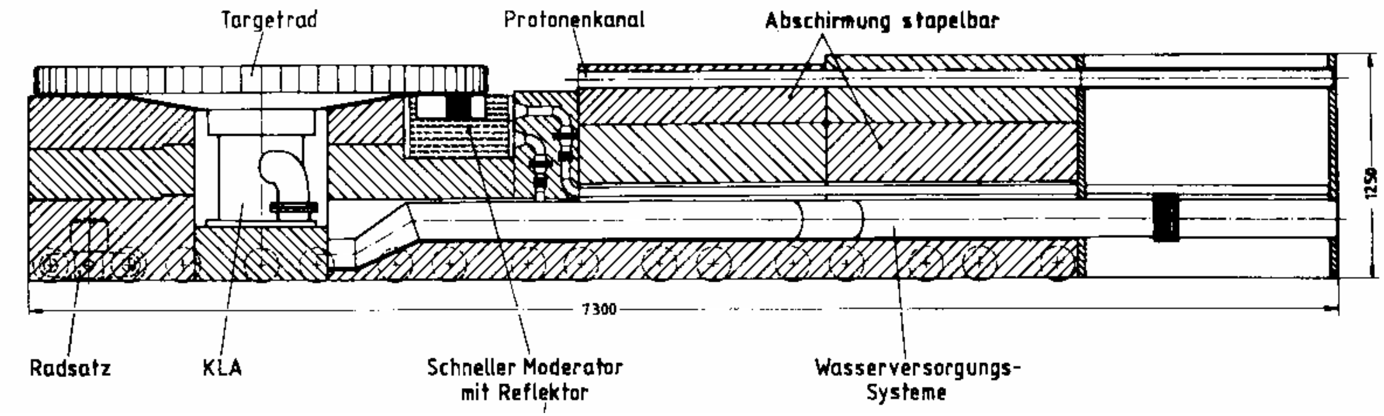


Rotating AlMg3 window; material has survived ca. 200 mAh/cm^2 at SINQ, which would correspond to >125 000 hours of operation (5MW) for a 2.5 m diameter target



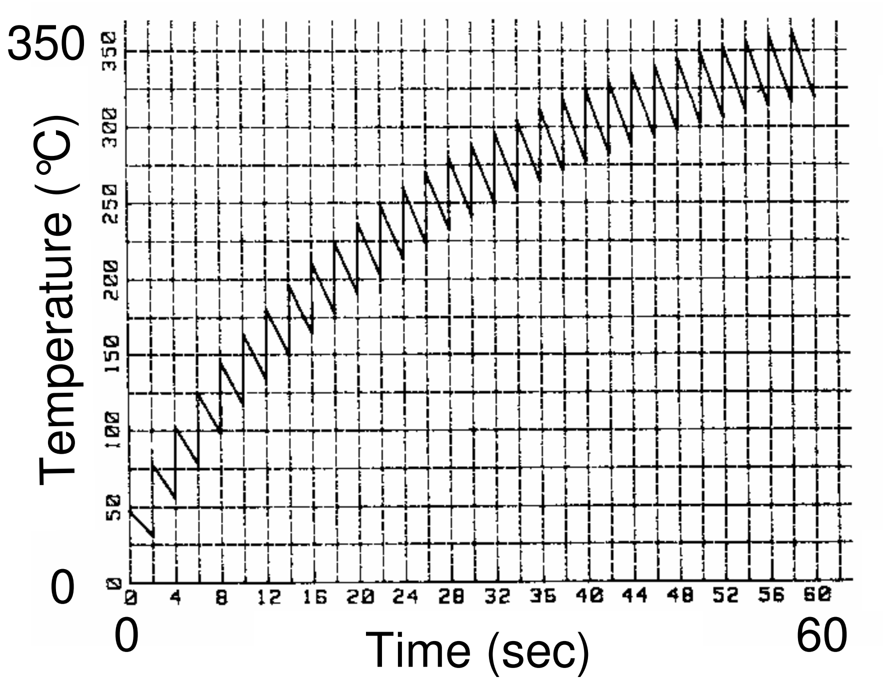
Water turbine

Hydraulic bearings

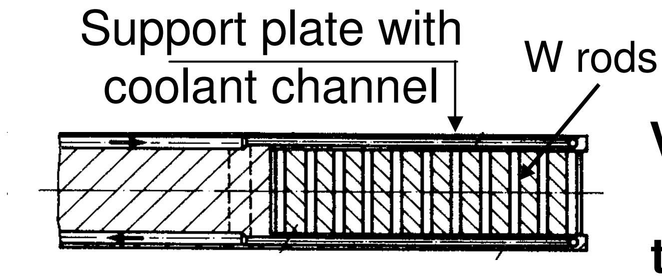


Target rods: Pb in Al tubes, surface cooled

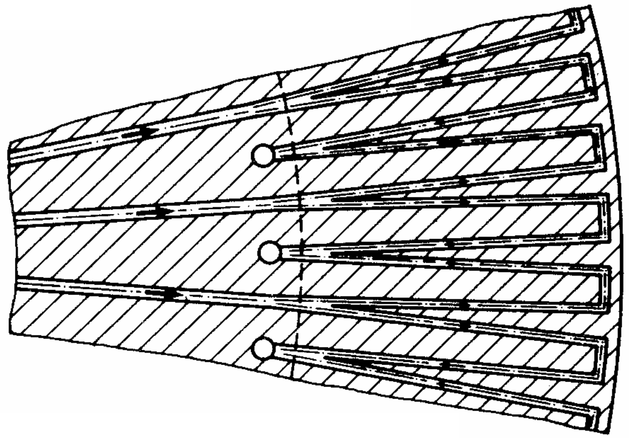
The SNQ W-Target Version (edge cooled)



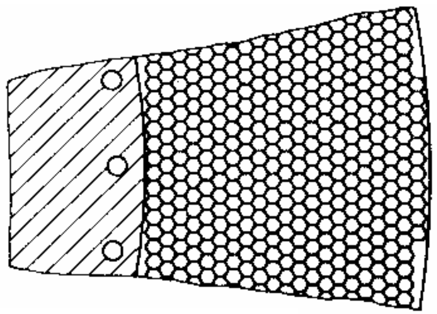
Calculated Temperature evolution at the target hot spot after start up at full beam power (5.5 MW)



Vertical cut through target zone

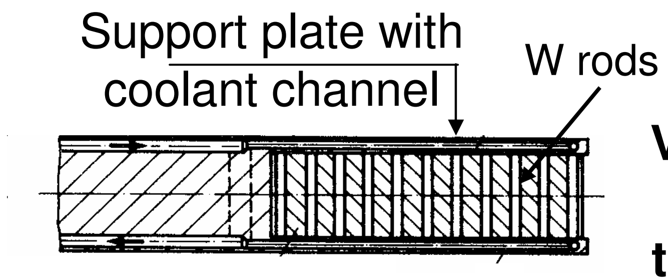


Horizontal cut through support plate

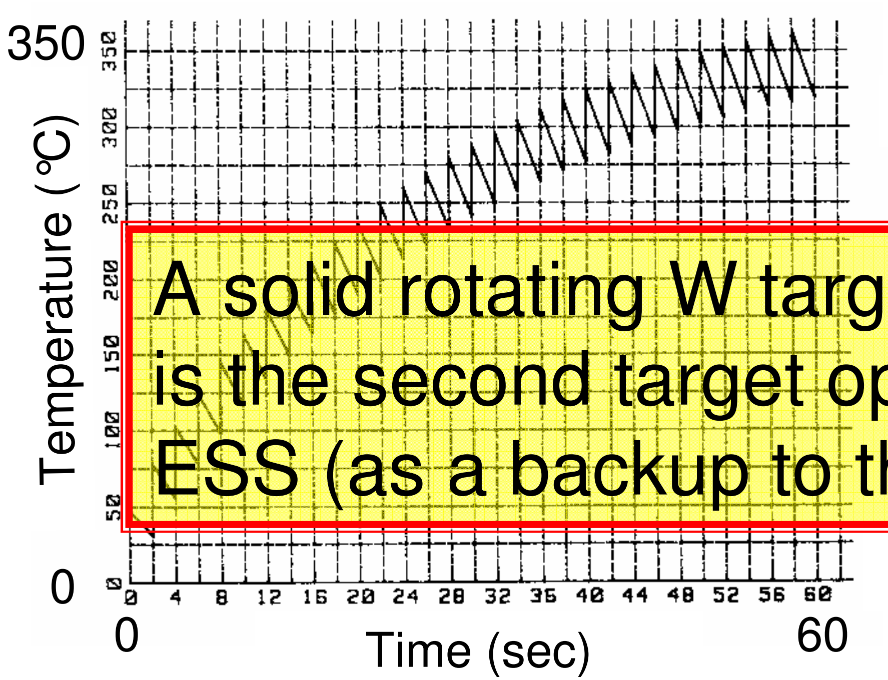


Horizontal cut through target rod array

The SNQ W-Target Version (edge cooled)

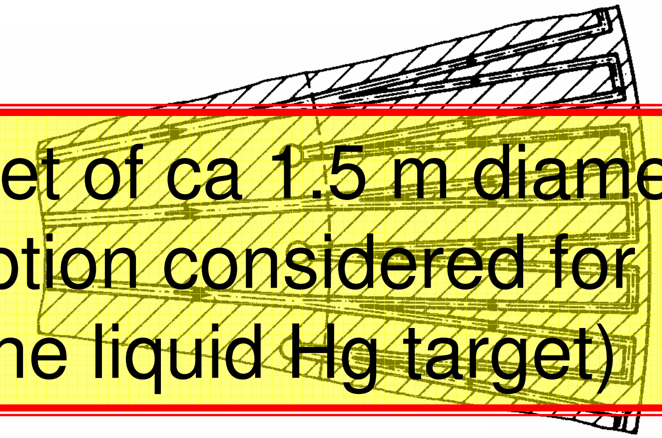


Vertical cut through target zone

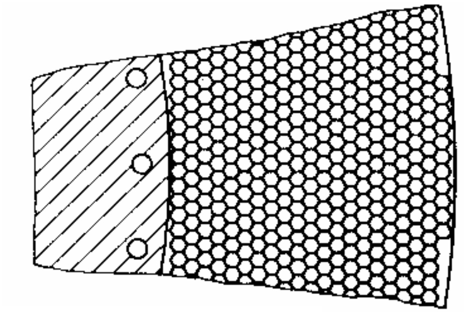


Calculated Temperature evolution at the target hot spot after start up at full beam power (5.5 MW)

A solid rotating W target of ca 1.5 m diameter is the second target option considered for ESS (as a backup to the liquid Hg target)

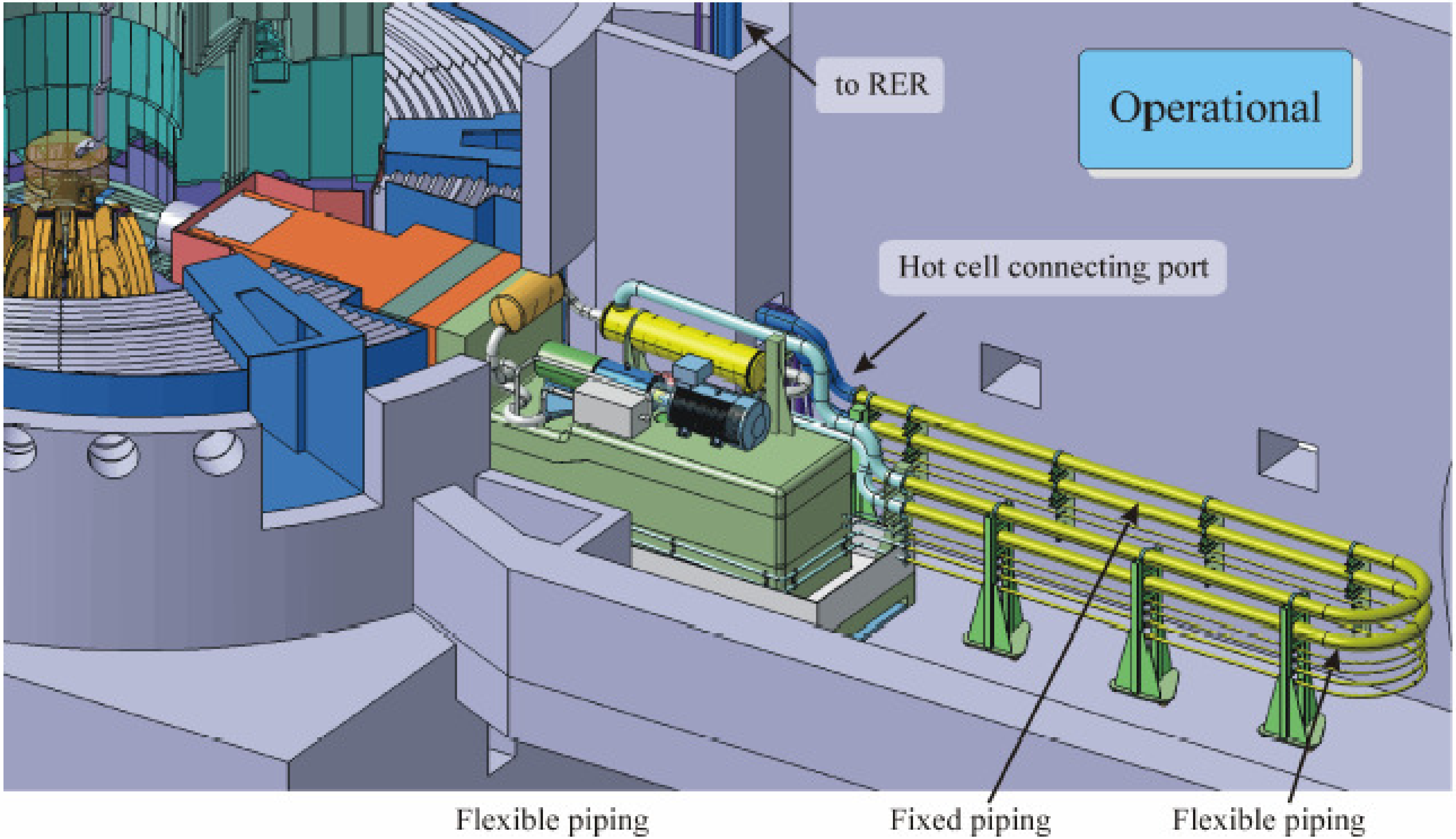


Horizontal cut through support plate



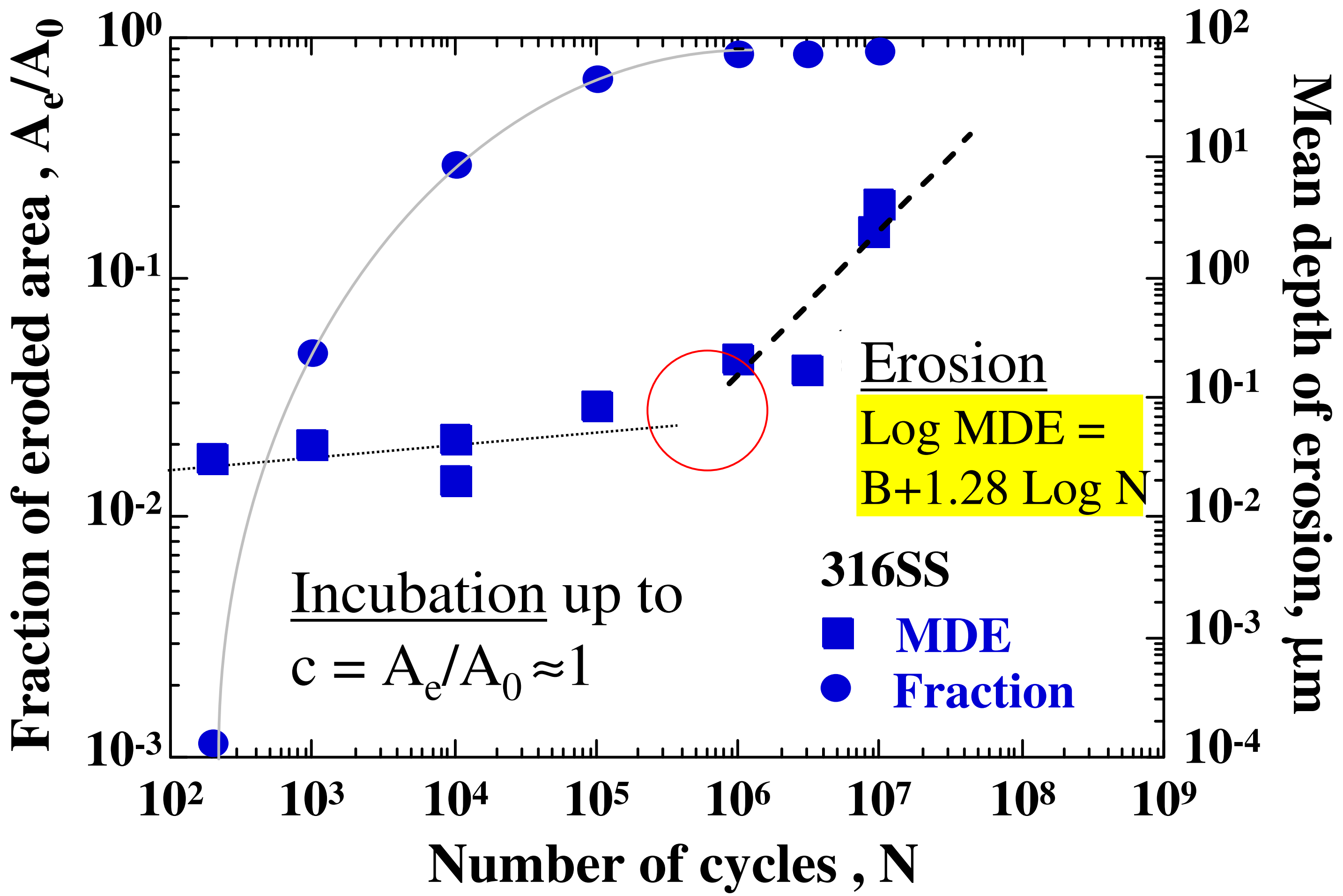
Horizontal cut through target rod array

The ESS Target Trolley



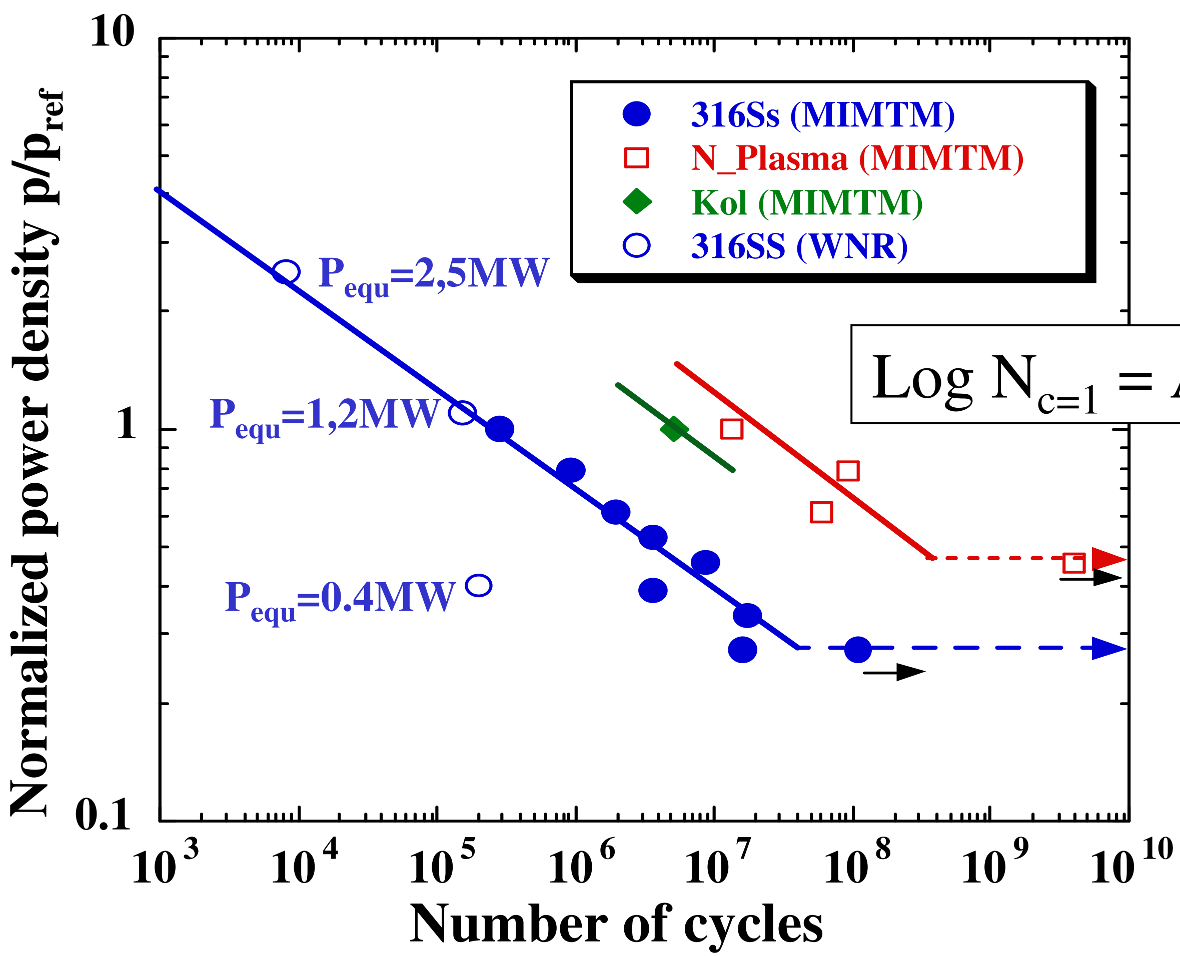
More on a
rotating target concept
this afternoon!

Correlation Between Area Covered with Pits and Mean Depth of Erosion



M. Futakawa, T. Naoe, C.C. Tsai, H. Kogawa, S. Ishikura, Y. Ikeda, H. Soyama, H. Date
"Cavitation Erosion in Mercury Target of Spallation Neutron Source" paper GS-11-006
5th International Symposium on Cavitation, Osaka, Japan, Nov. 1-4, 2003

Number of Cycles to Reach End of Incubation Period (c≈1) for Different Power Densities p and Different Surface Treatments



Pitting damage increases with the 4th power of power density!

$$\text{Log } N_{c=1} = A - 3{,}8 \text{ Log } p$$

A depends on material, pulse frequency etc.

P_{equ} is the power level in SNS that produces the power density used at WNR

M. Futakawa, T. Naoe, C.C. Tsai, H. Kogawa, S. Ishikura, Y. Ikeda, H. Soyama, H. Date
“Cavitation Erosion in Mercury Target of Spallation Neutron Source” paper GS-11-006
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