The Abdus Salam
International Centre for Theoretical Physics

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Energy Agency

Workshop on
"Technology and Applications of Accelerator Driven Systems (ADS)"

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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

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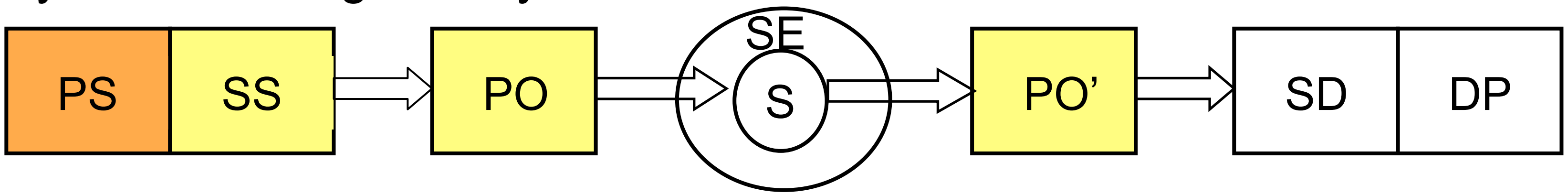
Neutron Sources for Neutron Scattering

- The essence of a neutron scattering experiment is to learn about the structure and dynamics of matter by measuring the momentum and energy transfer the neutrons experience when interacting with matter.
- Neutron scattering instruments can be designed to work in continuous mode or in time of flight mode.
- There is no one instrument that can cover most of the $\underline{Q}$-ω space with sufficient resolution and flexibility.
- Instruments have varying requirements with respect to spectral properties and time structure.
- This is why instrument and source designers have come to interact ever more closely in conceiving new systems.



- Spallation neutron sources offer a high degree of flexibility in this respect, but have their difficulties, too.

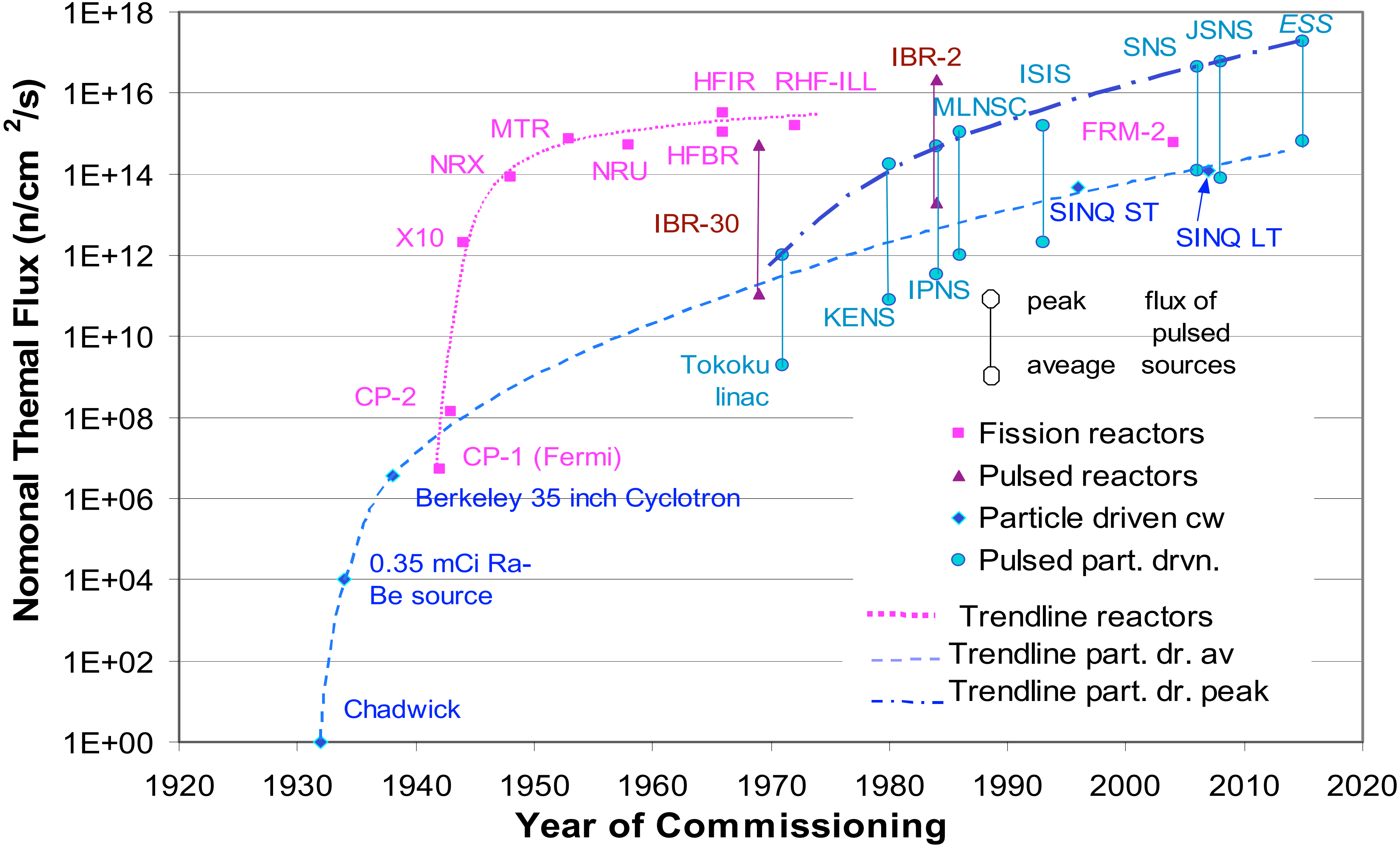
Spallation Neutron Sources

Arguments used in their favour

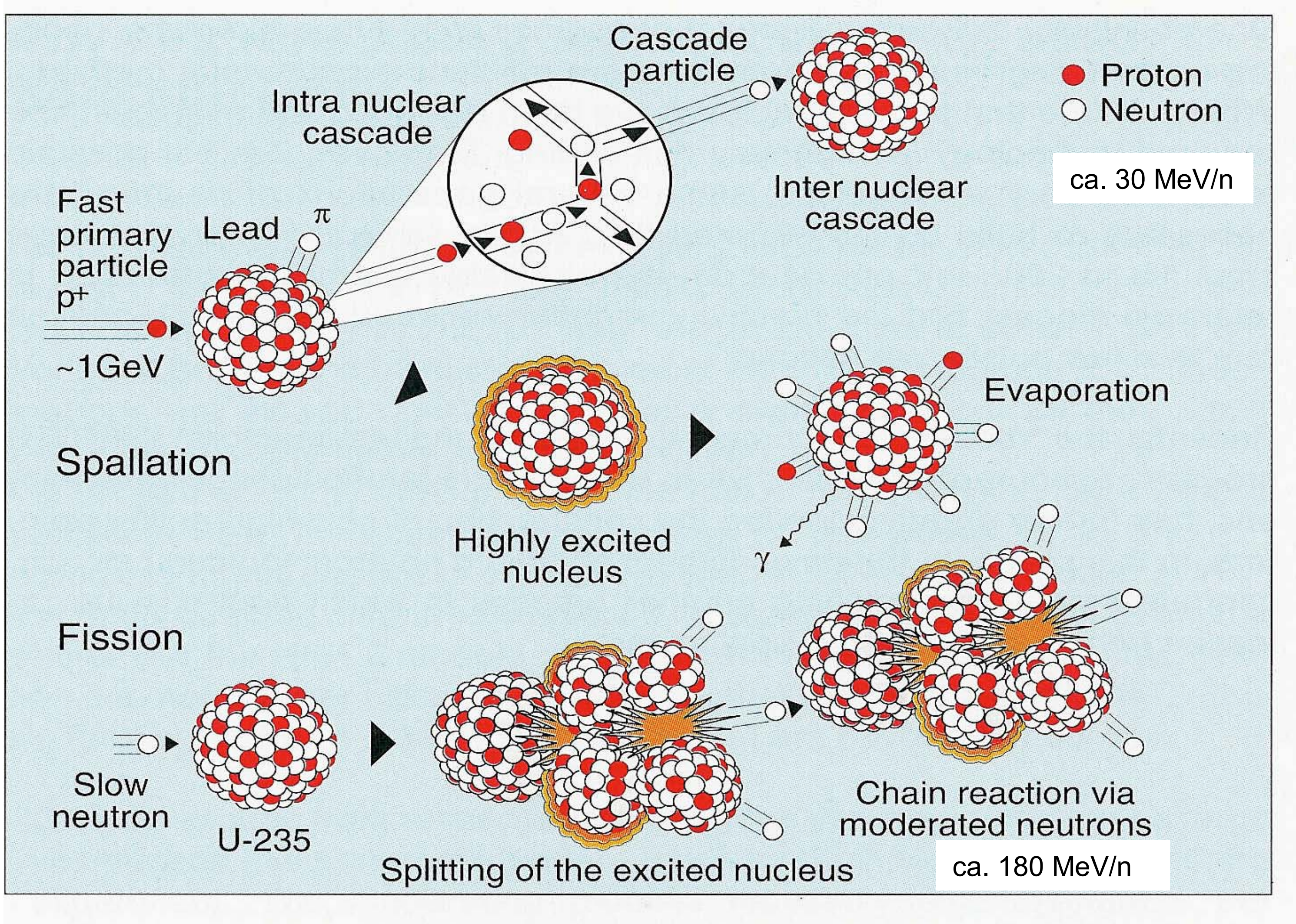
- No criticality issues
- No actinide waste
- Proliferation safe
- Advantage by exploiting time structure
- Less heat per neutron than other nuclear processes
- High degree of design flexibility (accelerator and target system)

- **But**
- Demanding shielding issues
- Extra complexity by need for accelerator
- More distributed radioactivity (e.g. in cooling loops and shielding)

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



Visualisation of the Spallation and Fission Processes

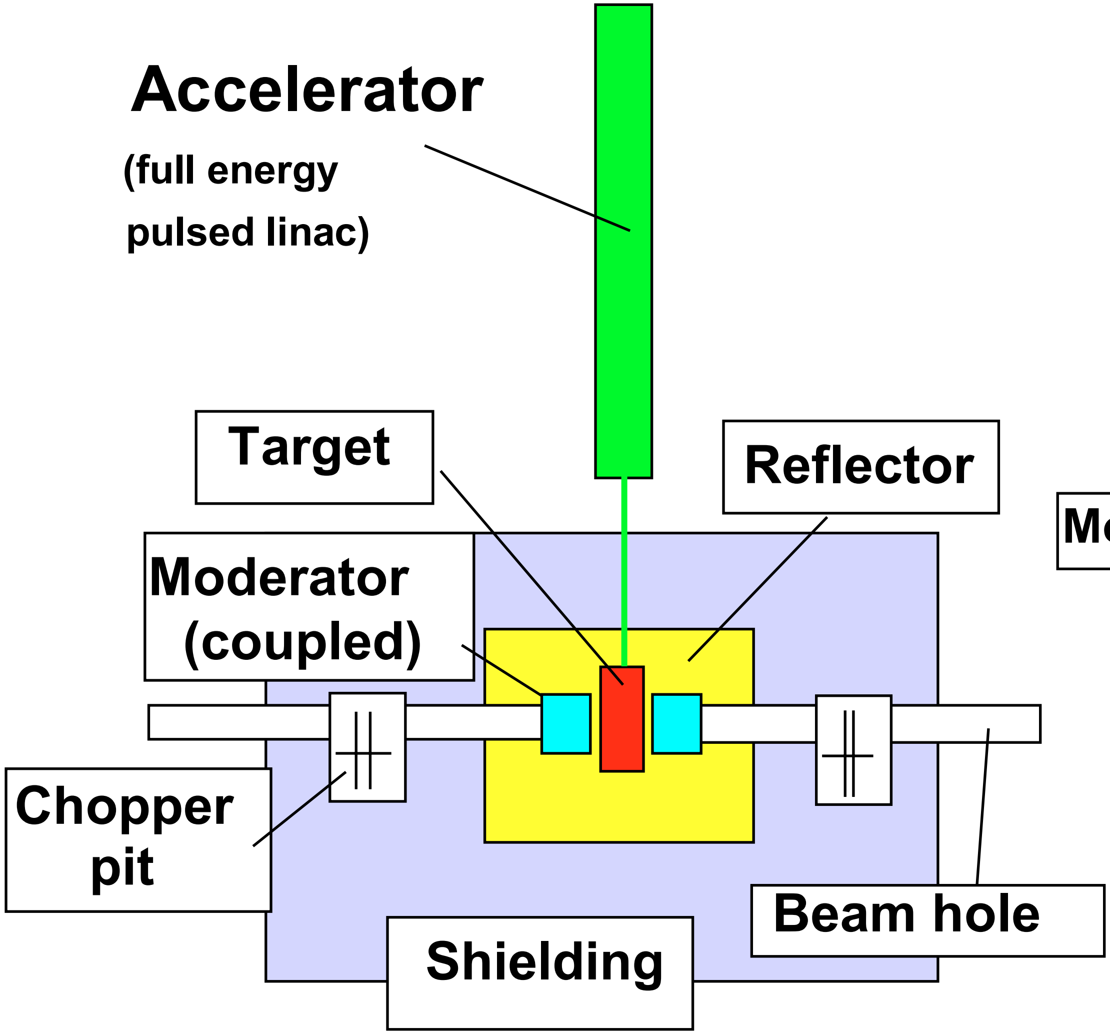


Cascade particles have energies up to the incident proton energy and can cause evaporation reactions in other nuclei

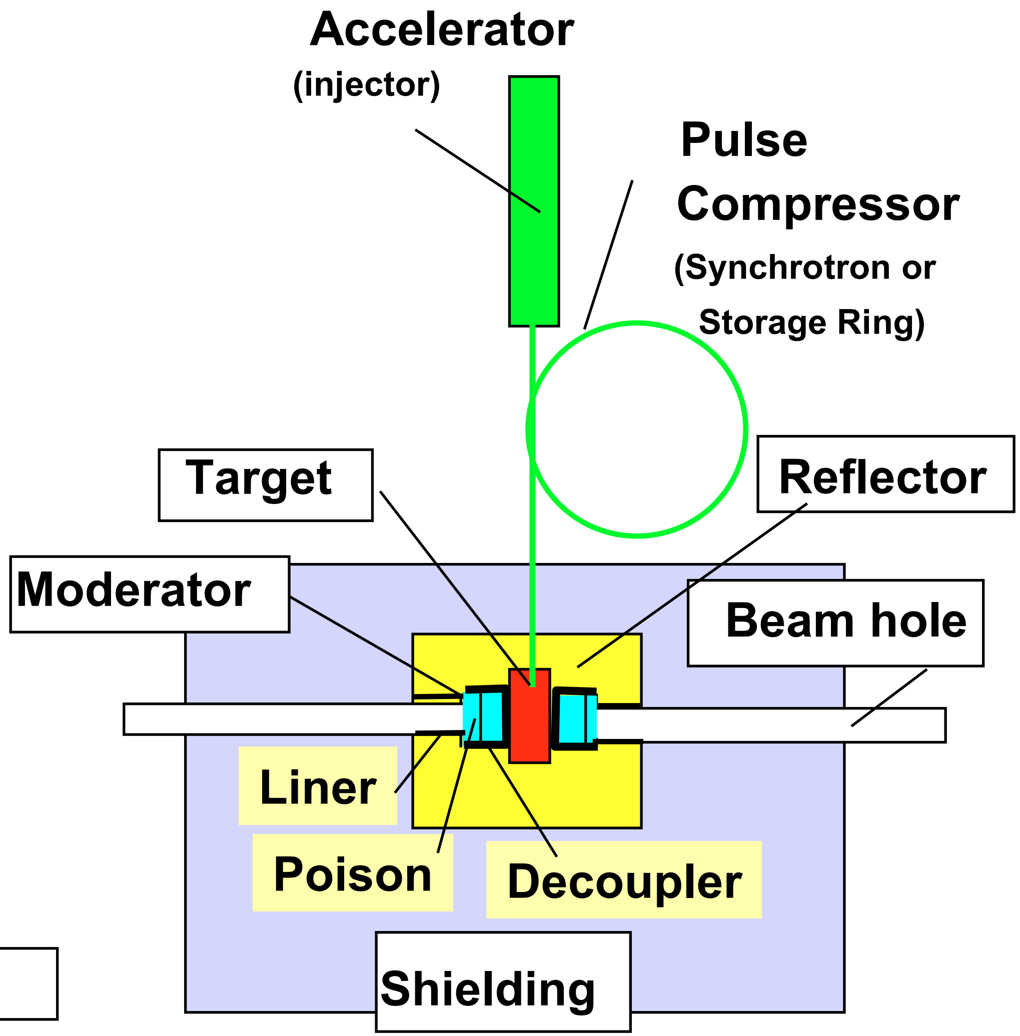
In contrast to fission, spallation cannot be self sustaining!

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

Spallation Neutron Source

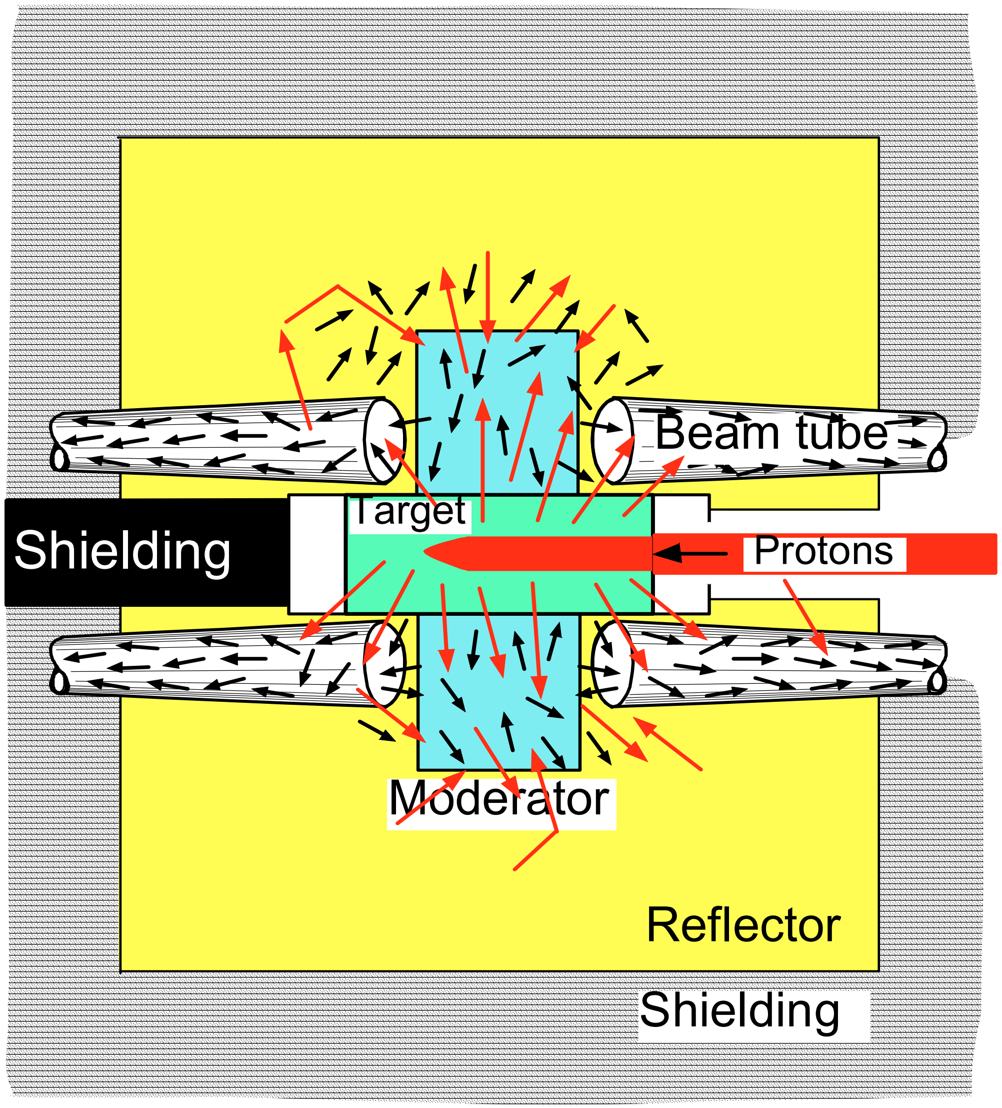


Long pulse source



Short pulse source

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 thr 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

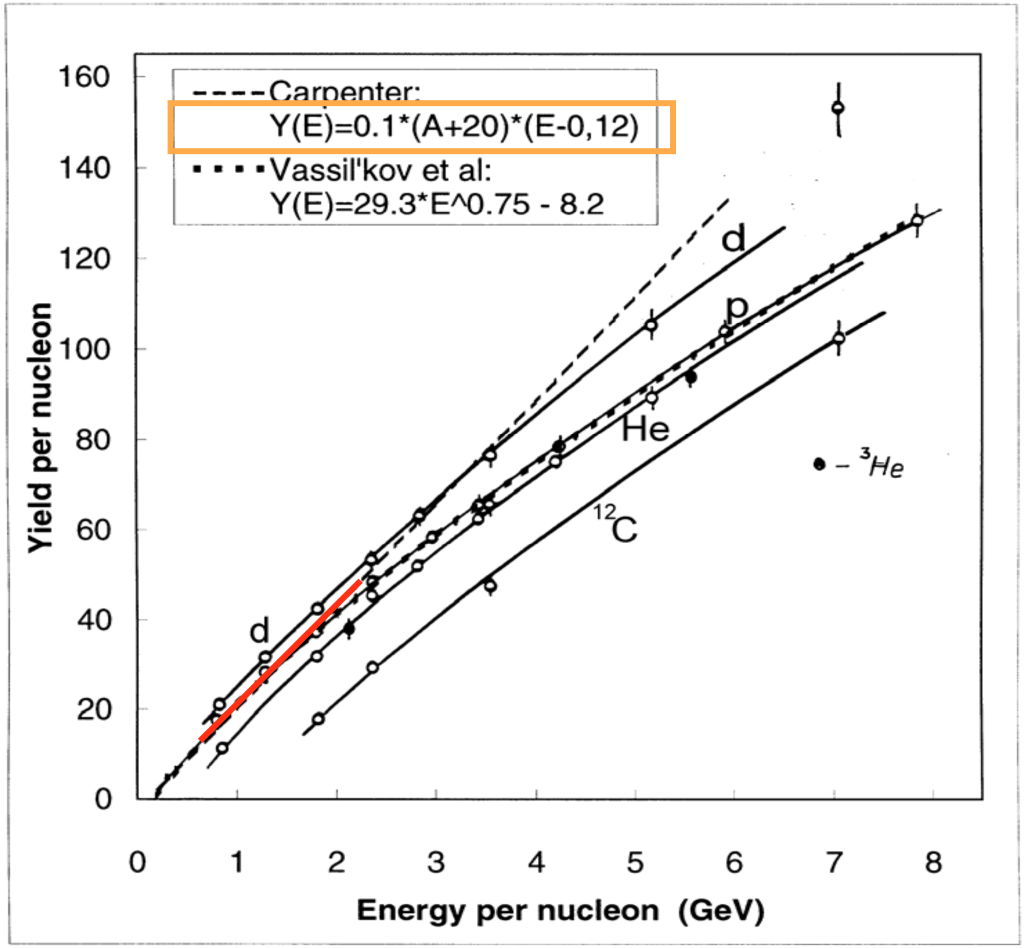
Spallation Neutron Sources with P_b>100kW

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.	0.85	solid, Pb rods liquid, PbBi	$6x10^{13}$ $1x10^{14}$	$6x10^{13}$ $1x10^{14}$	operating in preparation
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	5	liquid metal (Hg)	$2x10^{17}$	$2.5x10^{14}$	deferred
SNS, USA	linac plus compressor	1	60	1,4	liquid metal (Hg)	$2x10^{16}$	$8x10^{13}$	under construction
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 construction
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

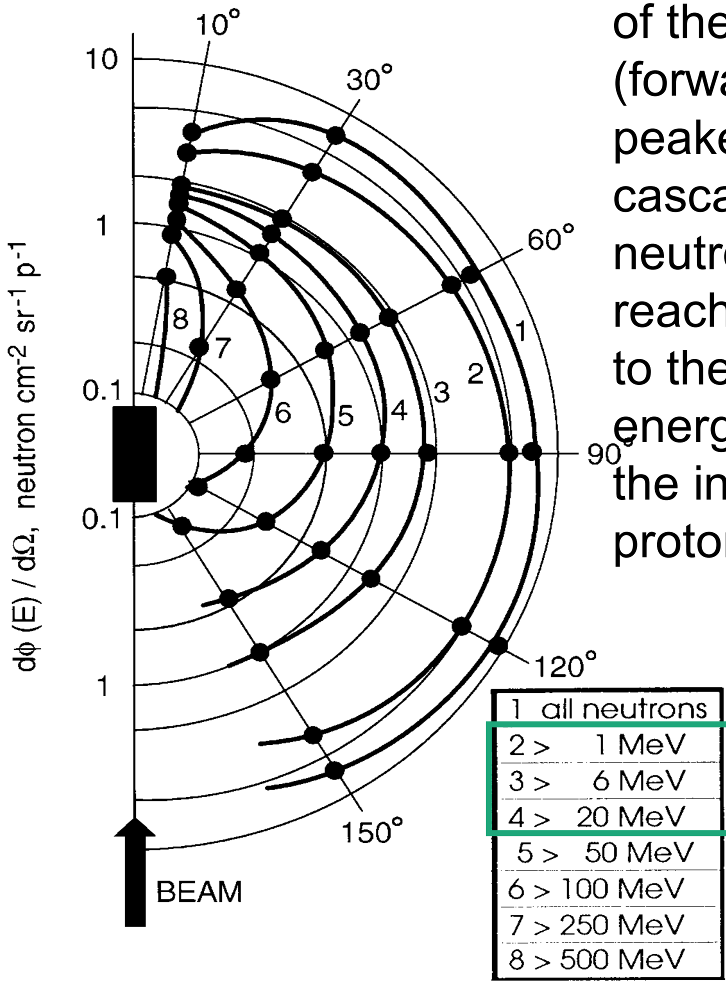
* *typical maximum values; precise figures vary, depending on type of moderator*

Spallation Neutron Sources – General Aspects (1)

Spallation Neutron Yield and Angular Distribution

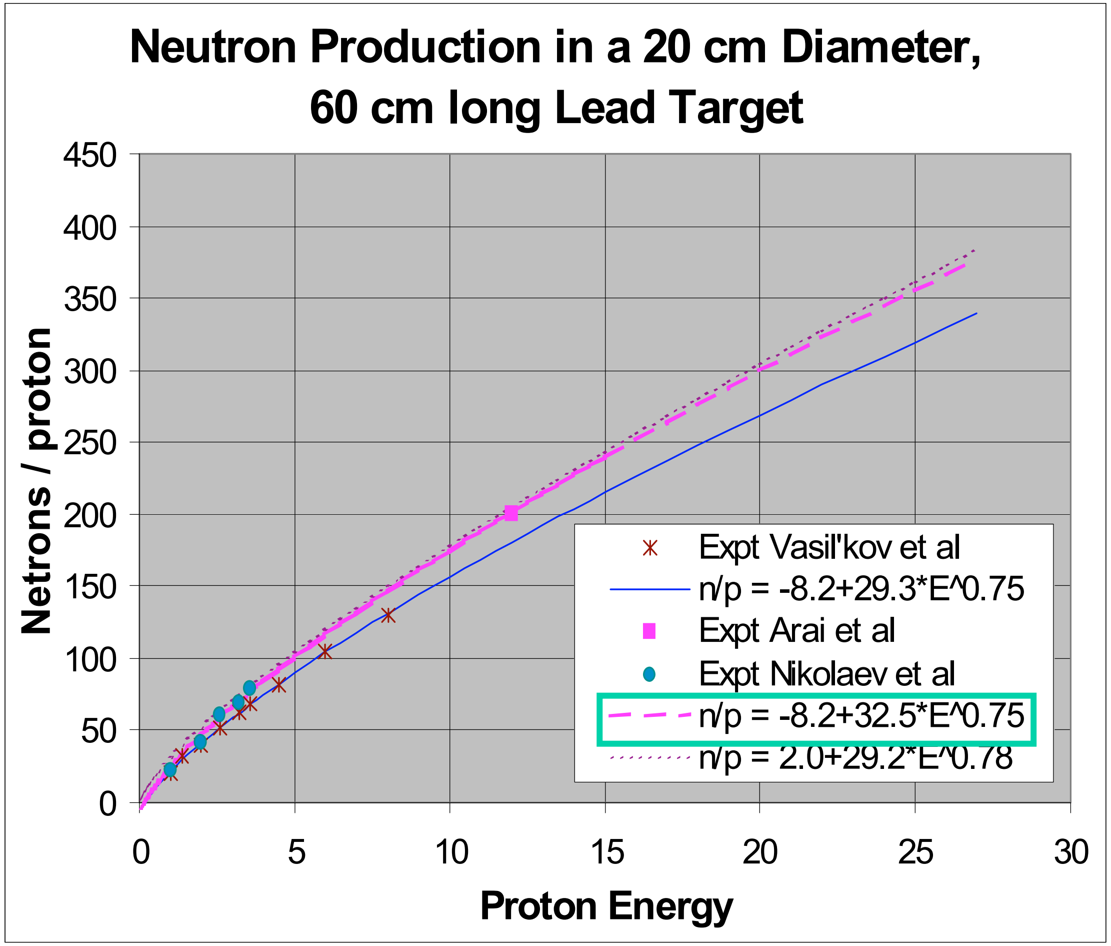


Measured neuron yield from thick lead targets



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

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

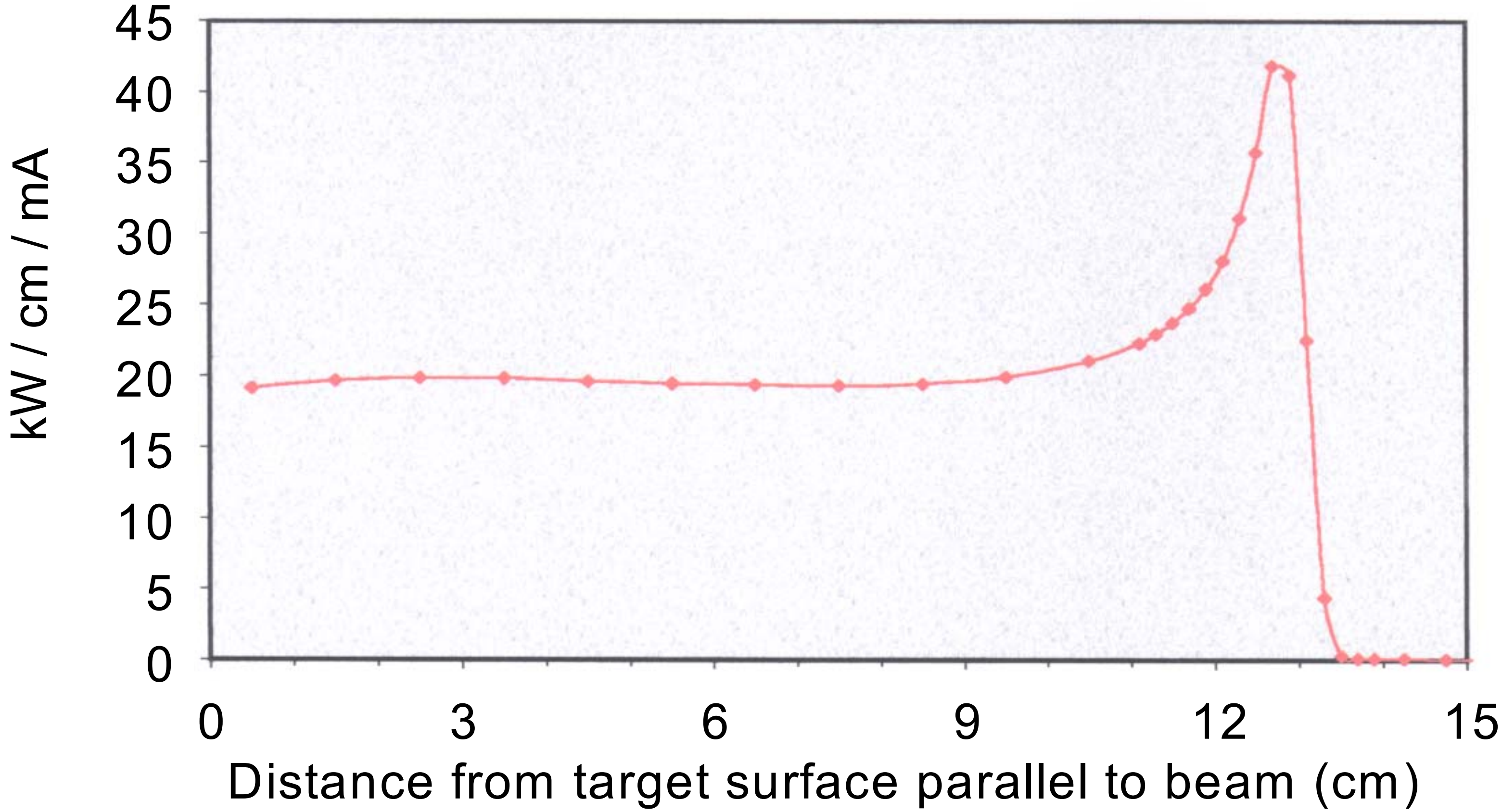


Neutron Production in a 20 cm Diameter,
60 cm long Lead Target
Netrons / proton
Proton Energy
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
Expt Vasil'kov et al
n/p = -8.2+29.3*E^0.75
Expt Arai et al
Expt Nikolaev et al
n/p = -8.2+32.5*E^0.75
n/p = 2.0+29.2*E^0.78

Axial Distribution of Power in a Spallation Target

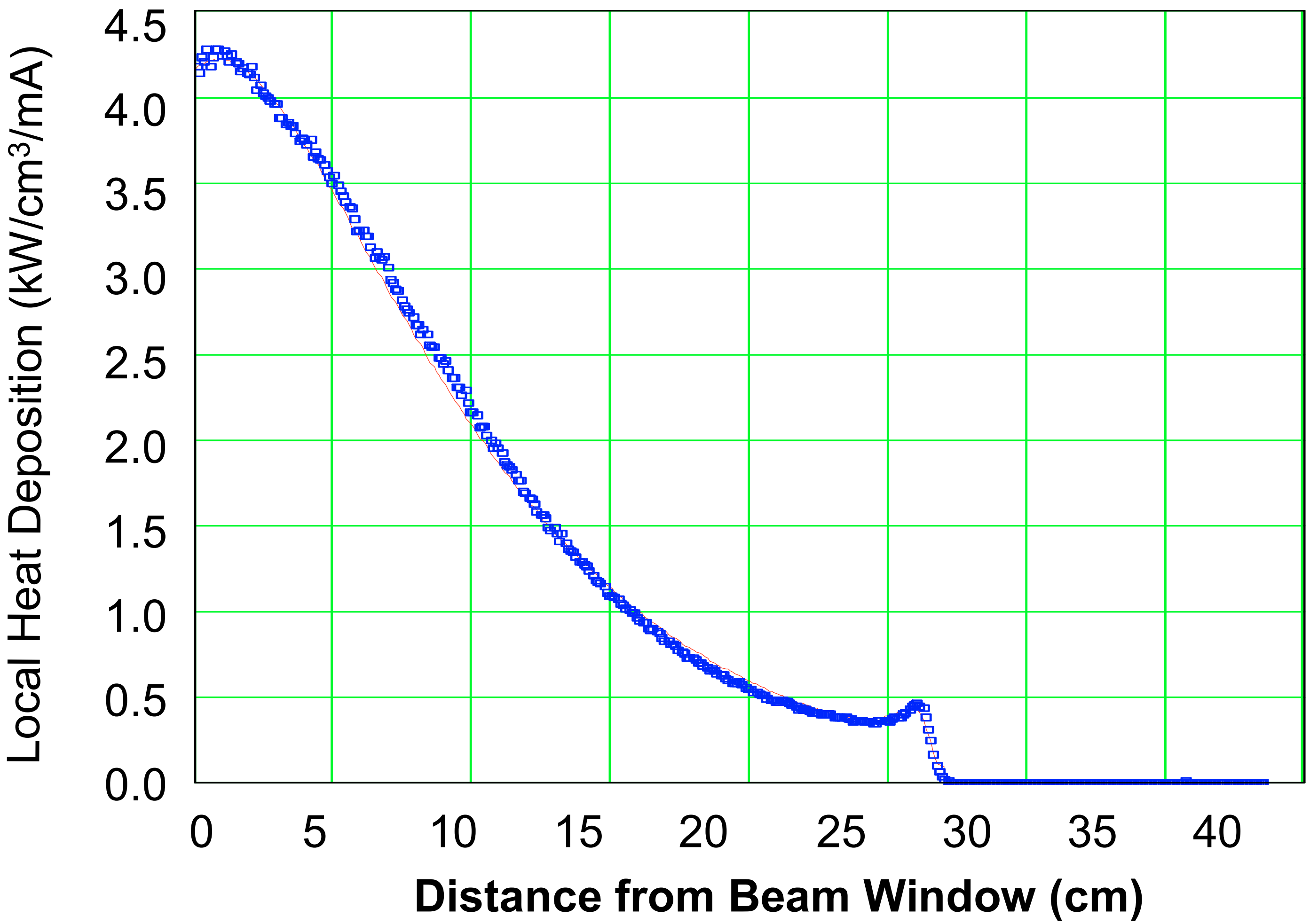
Power deposition by 450 MeV Protons in PbBi
(MYRRAH, integral over beam cross section)

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



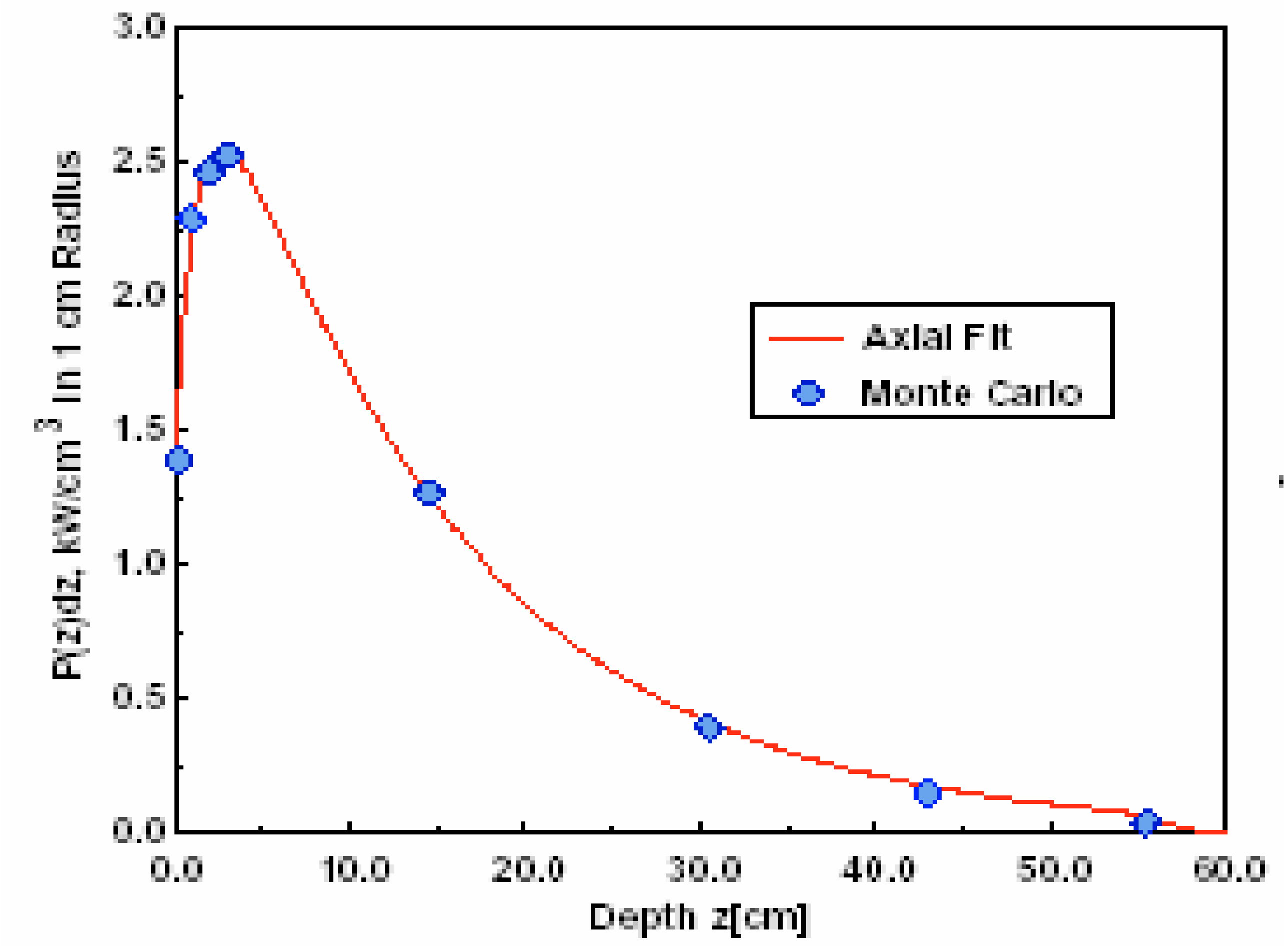
Axial Distribution of Power in a Spallation Target

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



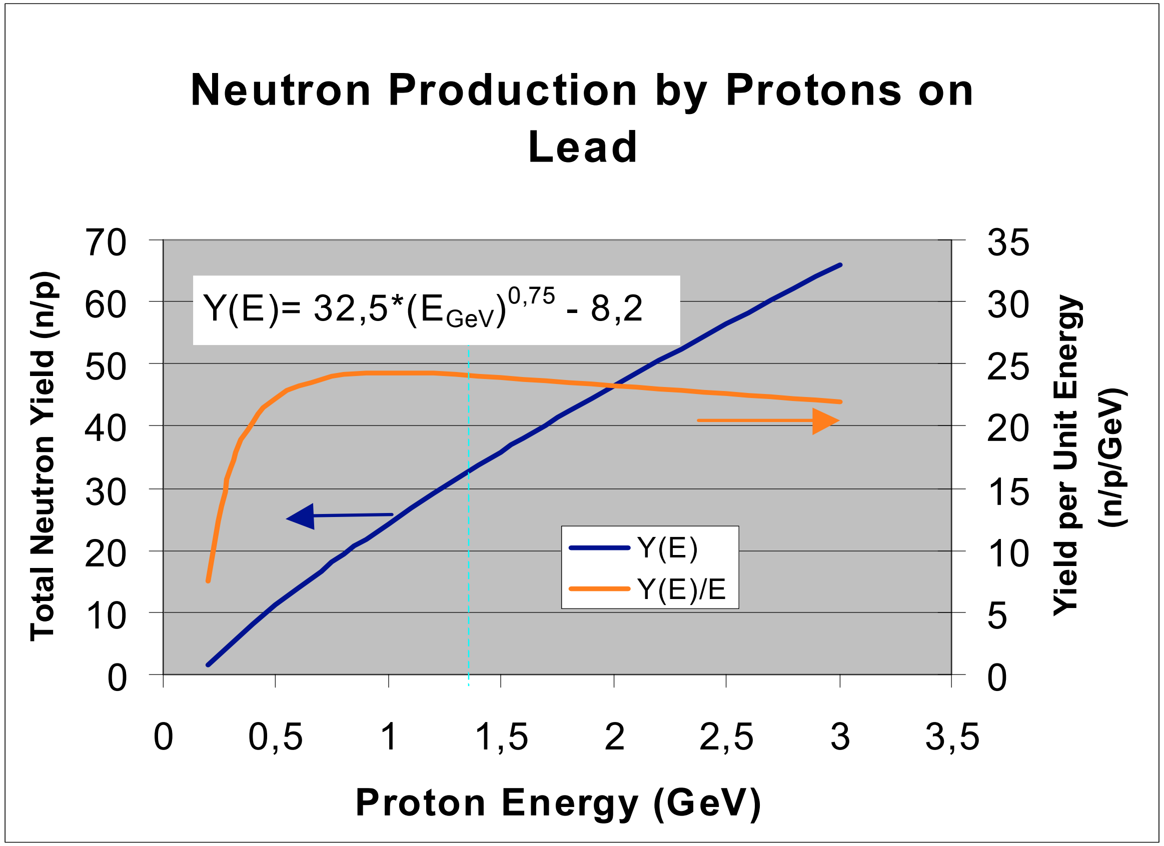
Axial Distribution of Power in a Spallation Target

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 Neutron Sources – General Aspects (2)

Choice of proton energy



Arguments for higher proton energy:

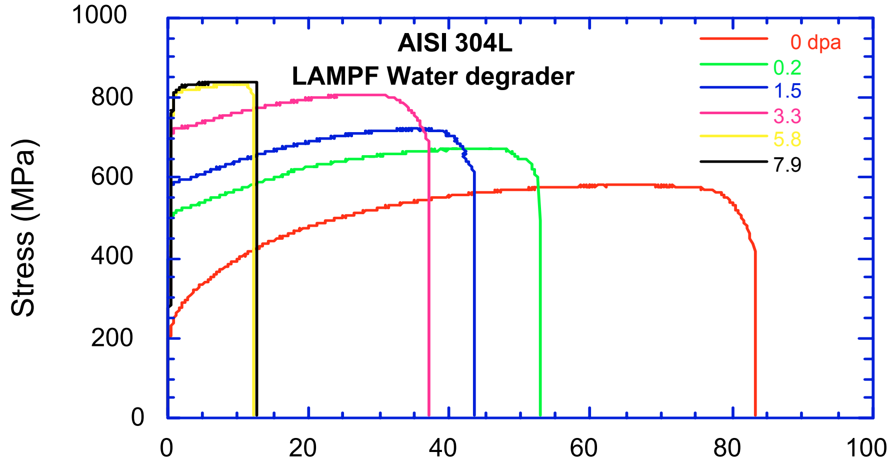
Easier to accelerate to higher energy than to increase current (in particular with circular accelerators)

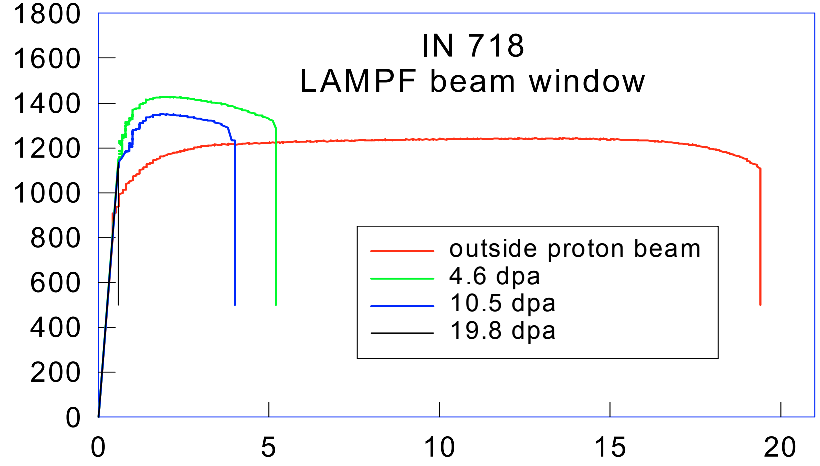
Radiation damage in target and window materials scales roughly with number of protons, not with beam power

Radiation Damage in Target Window Materials (1)

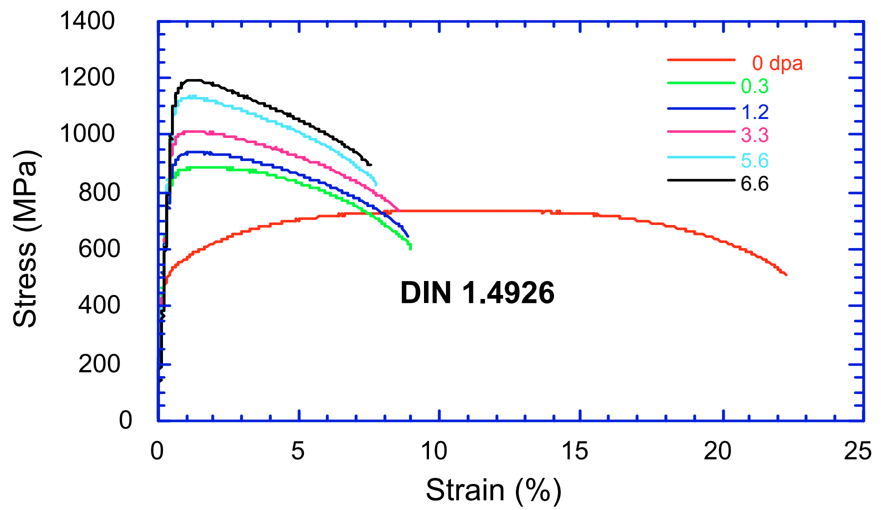
Stress-strain curves for different spallation structural materials after irradiation

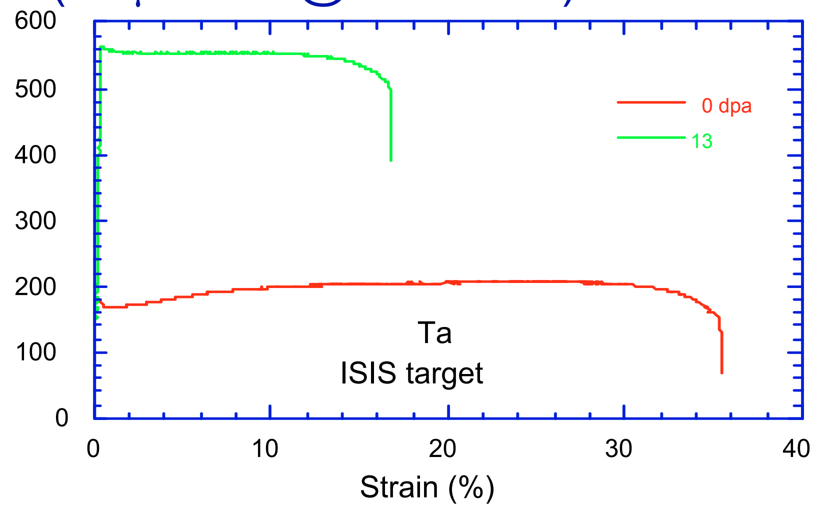
J. Chen, FZJ-IFF





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

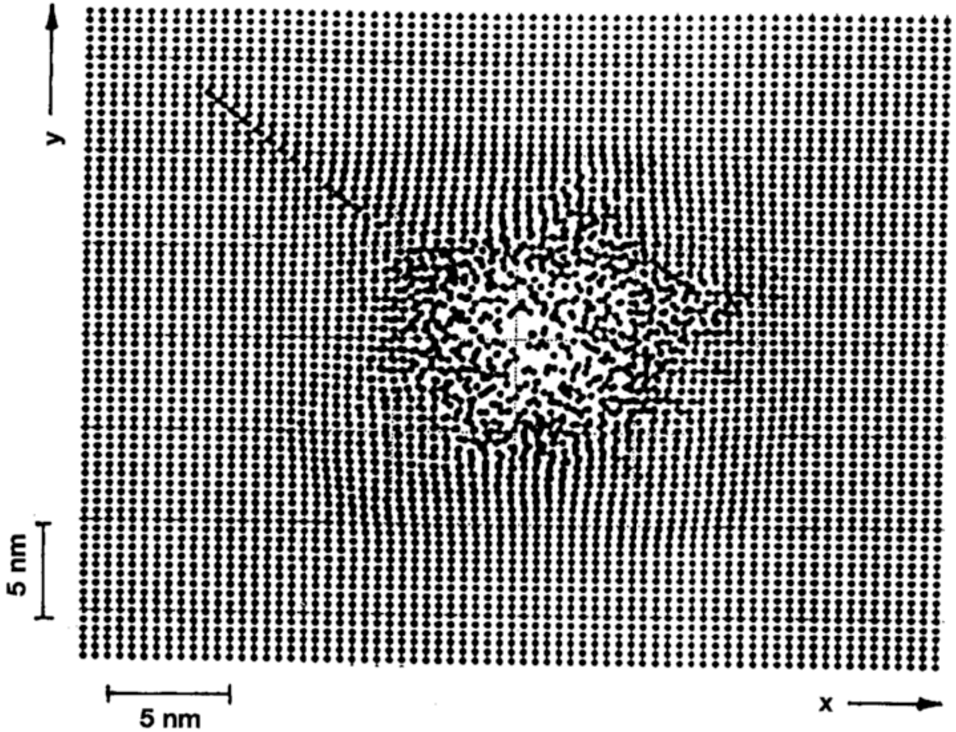




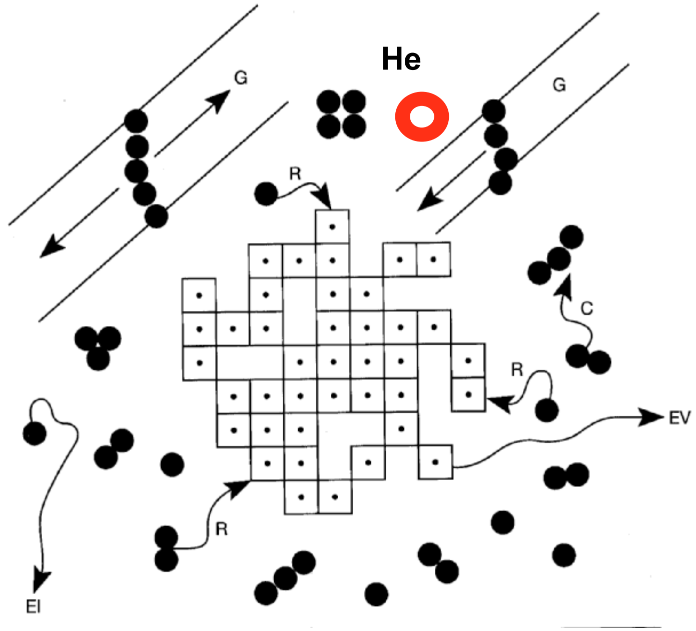
Radiation Damage in Target Window Materials (2)

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 (foreign elements „appm“)



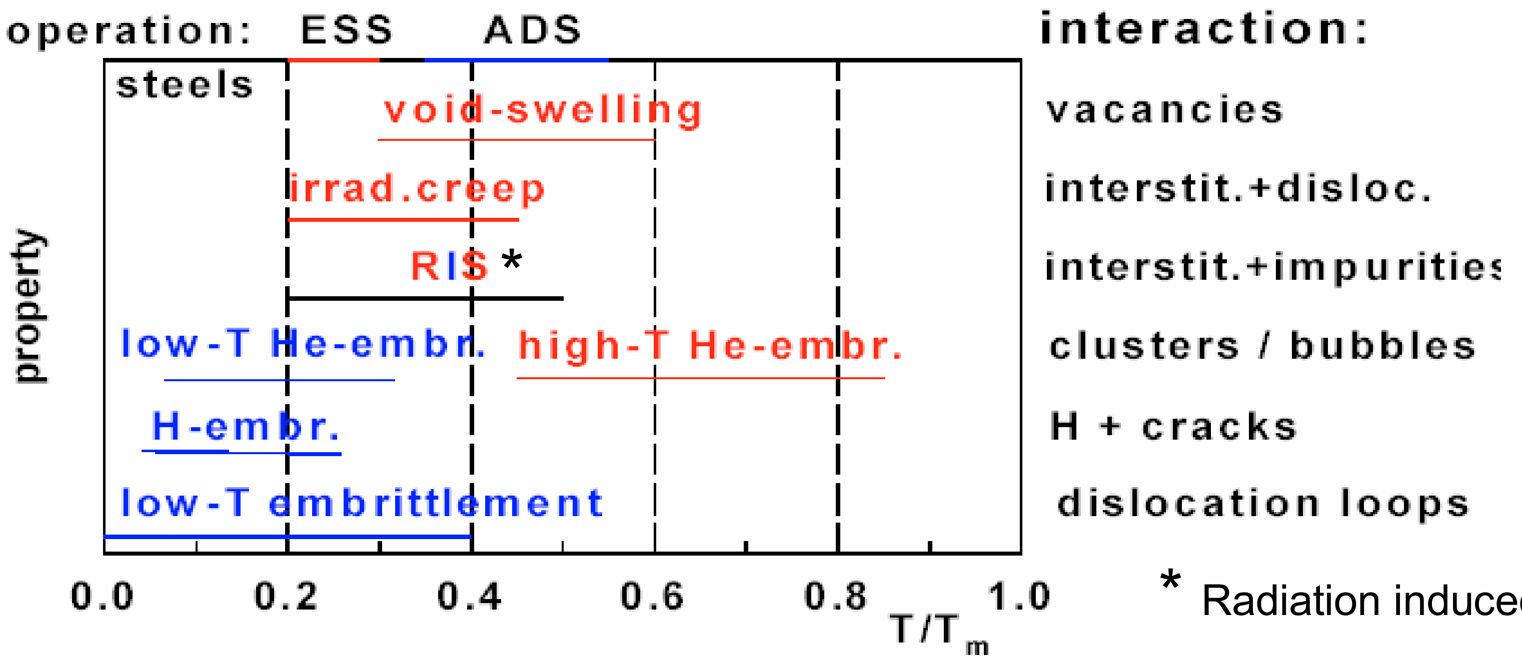
Molecular dynamics simulation of a displacement cascade produced by a 10 keV primary knock-on event in an fcc lattice (Ghaly and Averback).



Schematic representation of the defect arrangement in a displacement cascade

Radiation Damage in Target Window Materials (3)

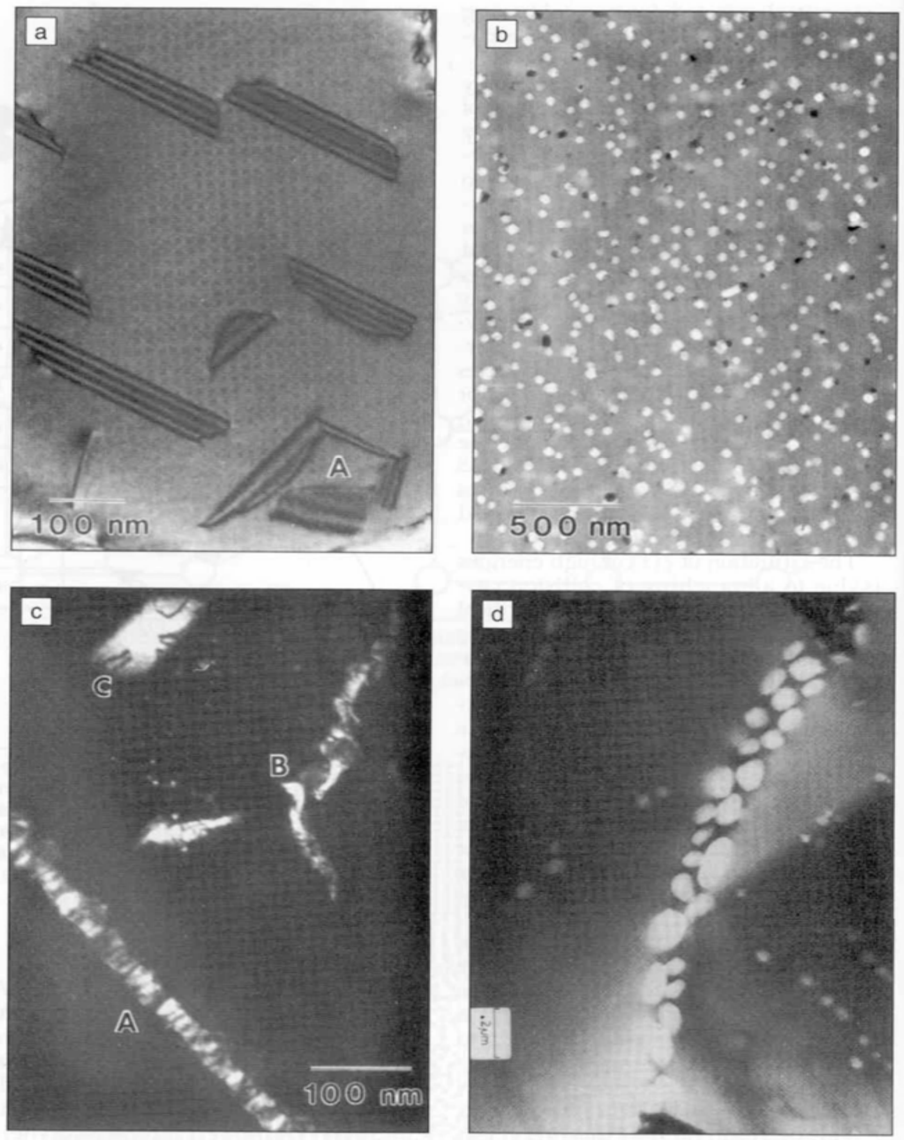
Red / blue: most prominent in austenitic / ferritic-martensitic steel



* Radiation induced segregation

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.

Radiation Damage in Target Window Materials (4)



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

a) Dislocation loops

b) Voids

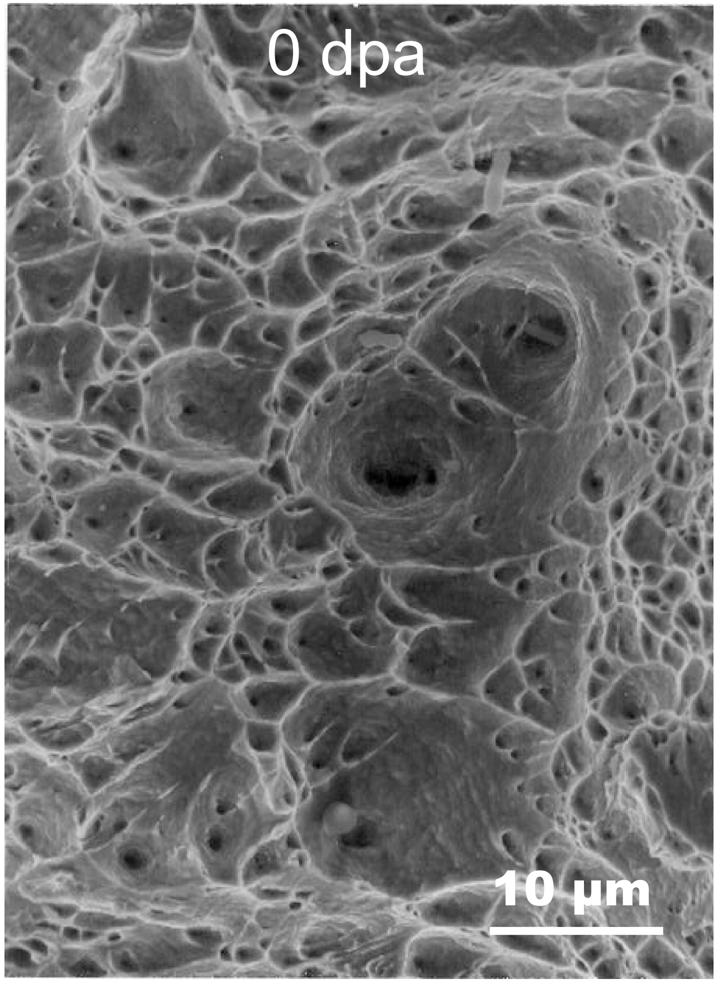
c) Precipitates

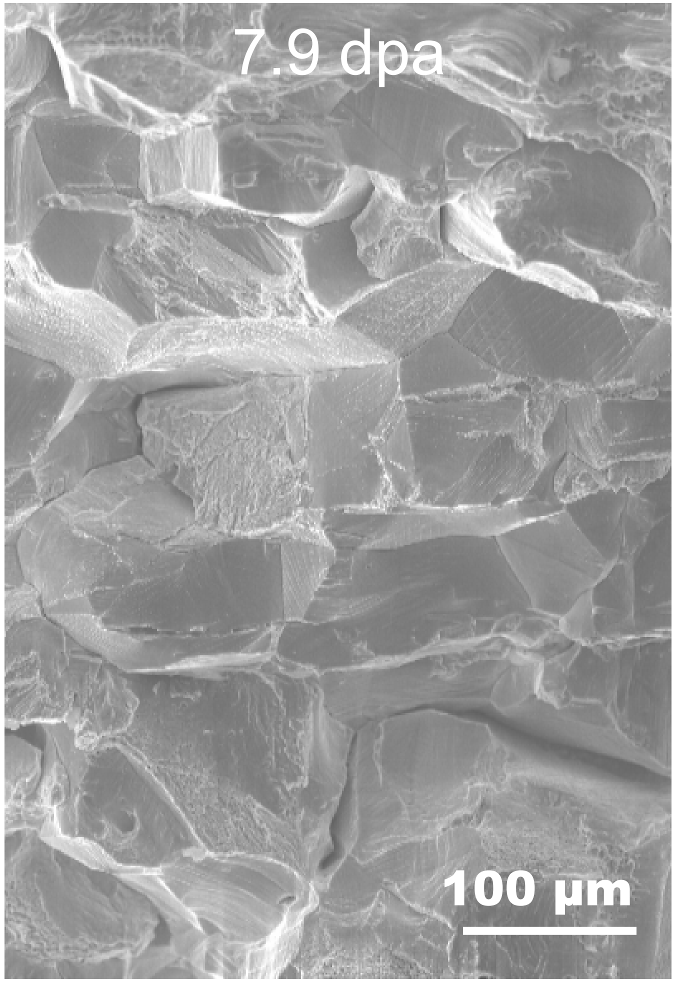
d) Helium bubbles

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

Radiation Damage in Target Window Materials (5)

Fracture surface of 304L after tensile test at RT

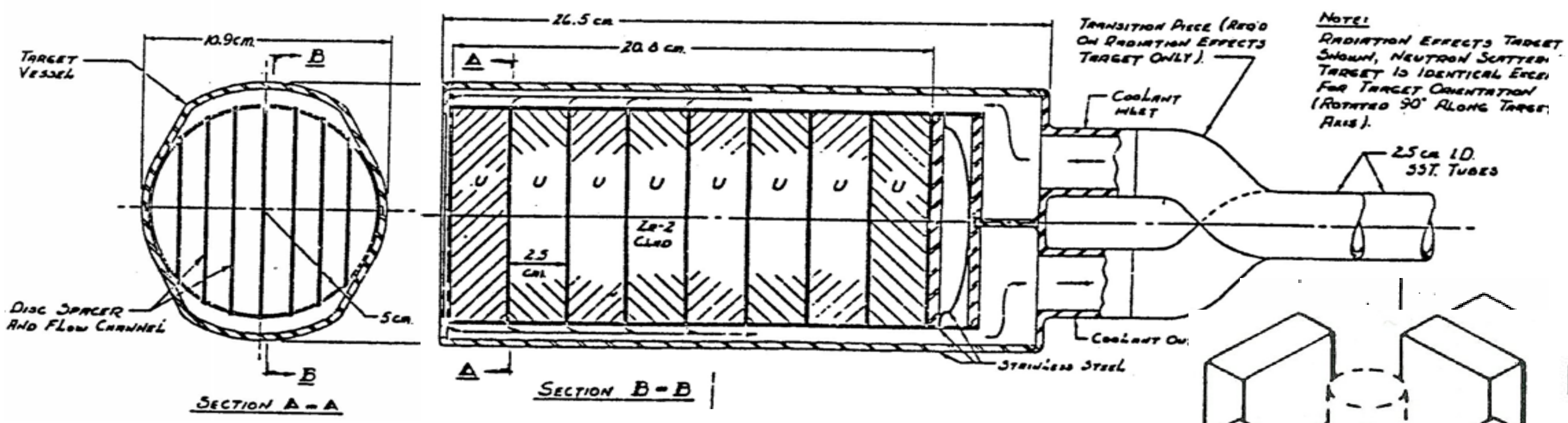




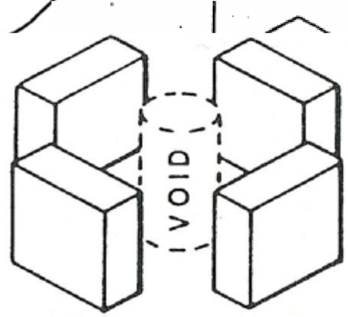
Spallation Targets : Beam Energy and Distribution

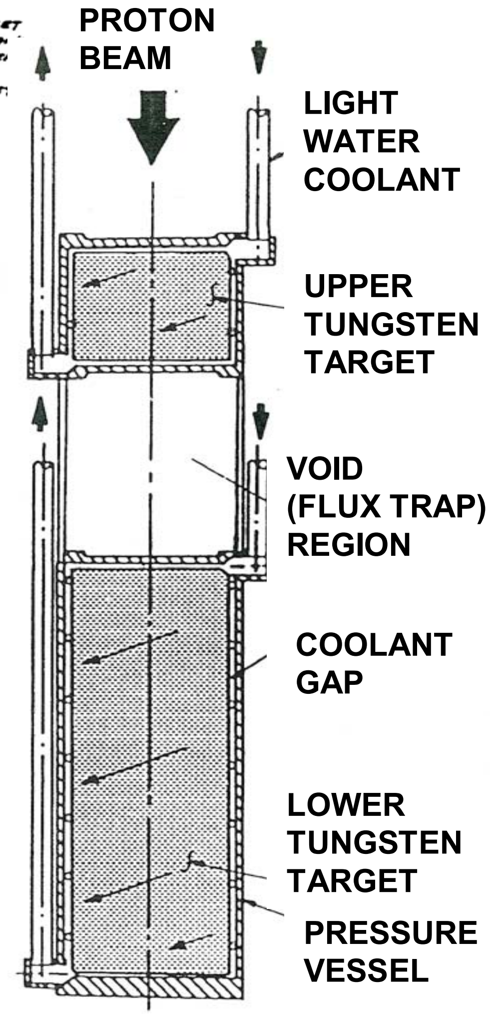
- At low E (<3 GeV), yield increases approximately linear with energy. At constant power a higher energy allows a lower current, resp. current density.
- A current density of 100 $\mu A/cm^2$ is presently considered an upper allowable limit in terms of heat deposition and stress, but may be high.
- For 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.

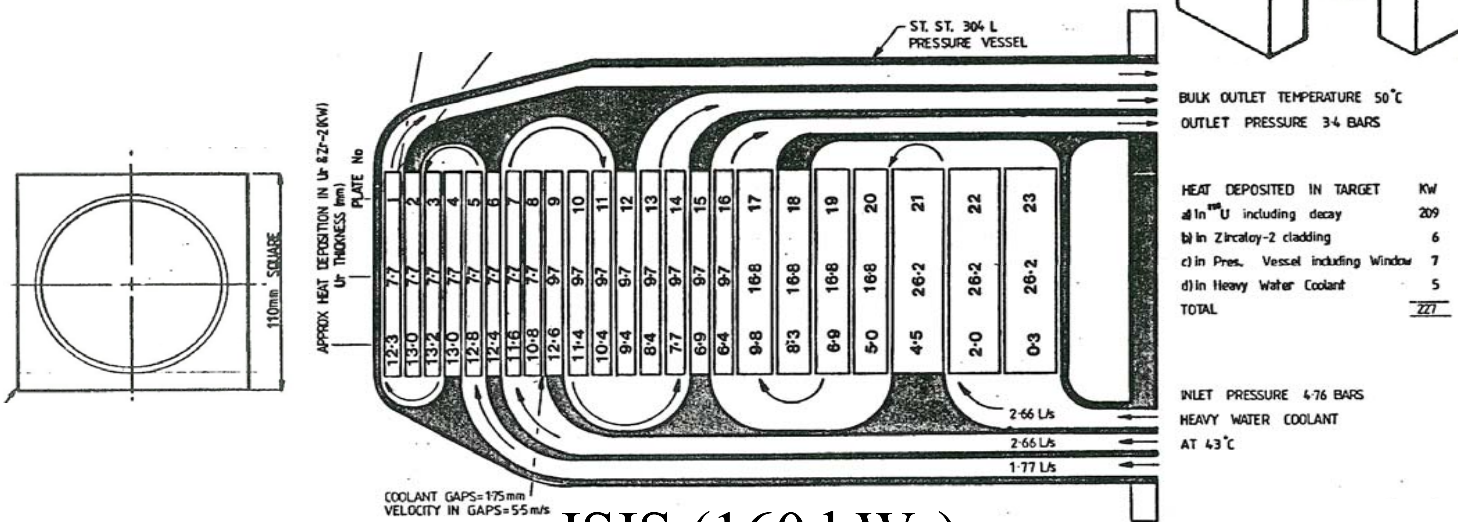
Target Concepts of Existing Pulsed Spallation Sources



IPNS-1 (7 kW_b)







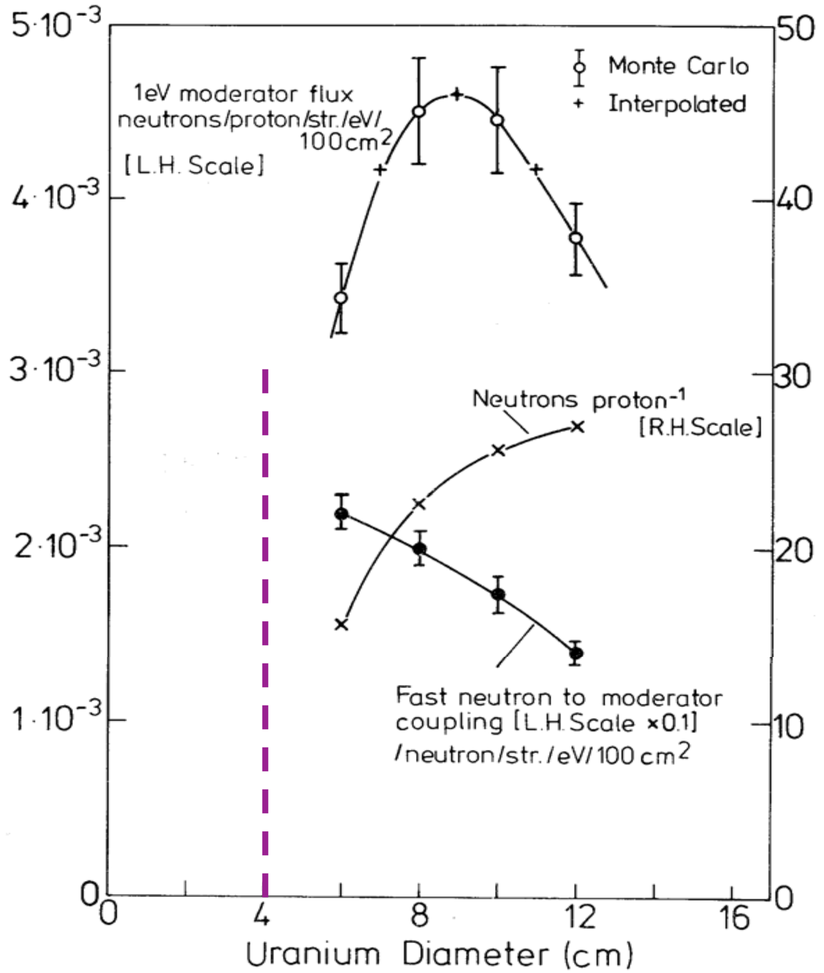
ISIS (160 kW_b)

designed for 300 kW_{th}

WNR (LANSCE), 80 kW_b

Optimization of the ISIS Target Diameter

Proton beam intensity distribution:
parabolic with 4 cm FWHM



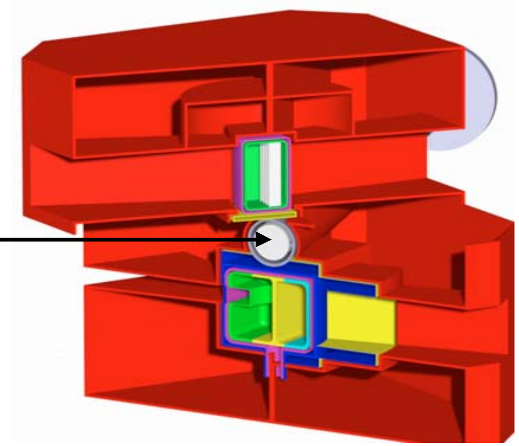
F. Atchison, 1979

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.

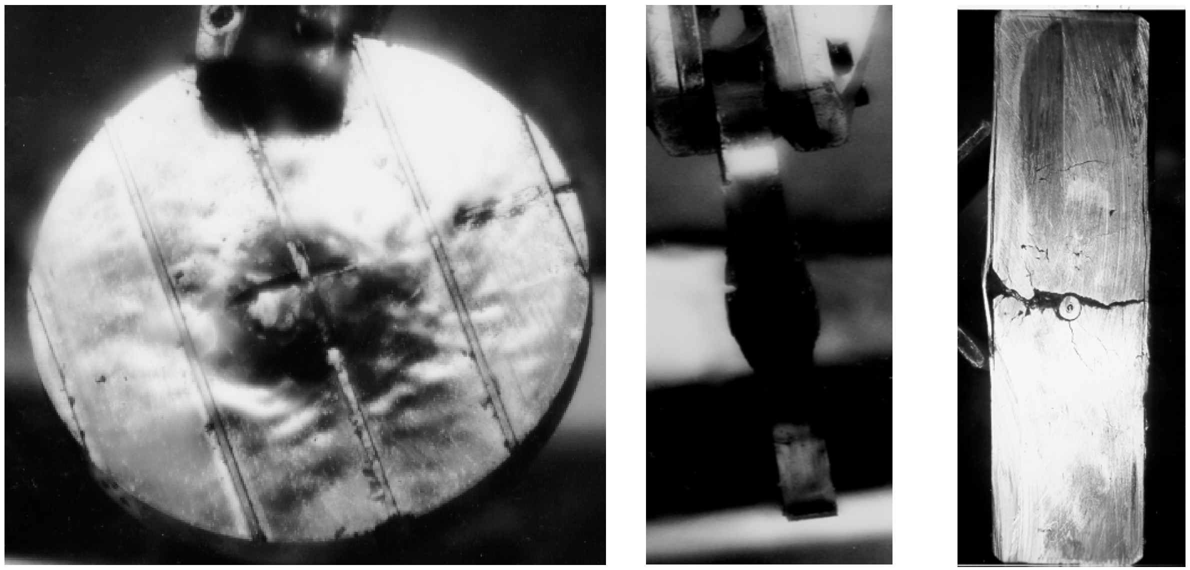
For the ISIS-2 target station a Ta-clad tungsten target of 6 cm diameter has been selected.

6 cm diameter
Ta-clad W-target



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 (T.A. Broome) and IPNS (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

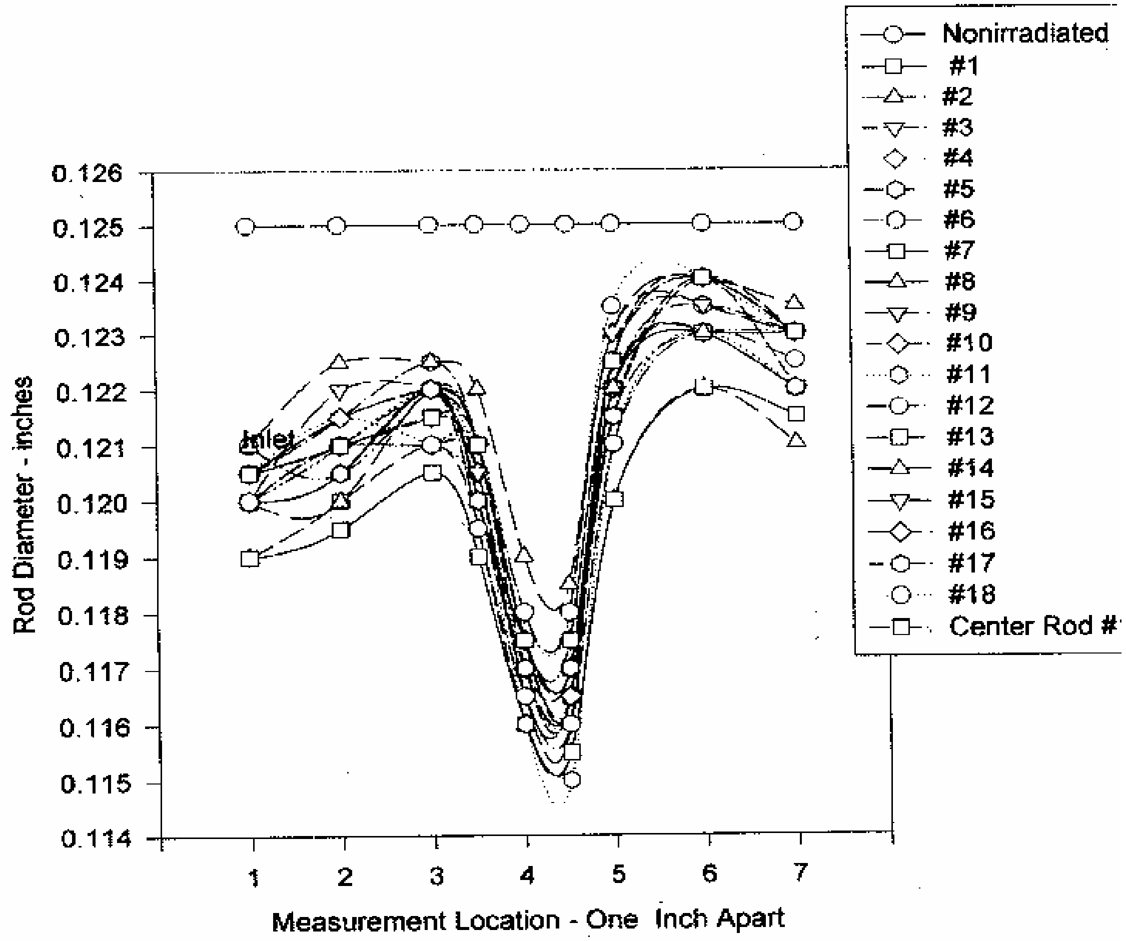
- Gamma-stabilised U-10%Mo was examined in the RERTR-program up to 70% burn-up with the material remaining stable.
- Expected to yield 1.7x more neutrons as a spallation target than best lower Z materials.
- Studied as a target material for the German SNQ project (early 1980ies).
- Proposed for closer examination within the Long Wavelength Target Station studies in the US SNS project.
- 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).
- 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.

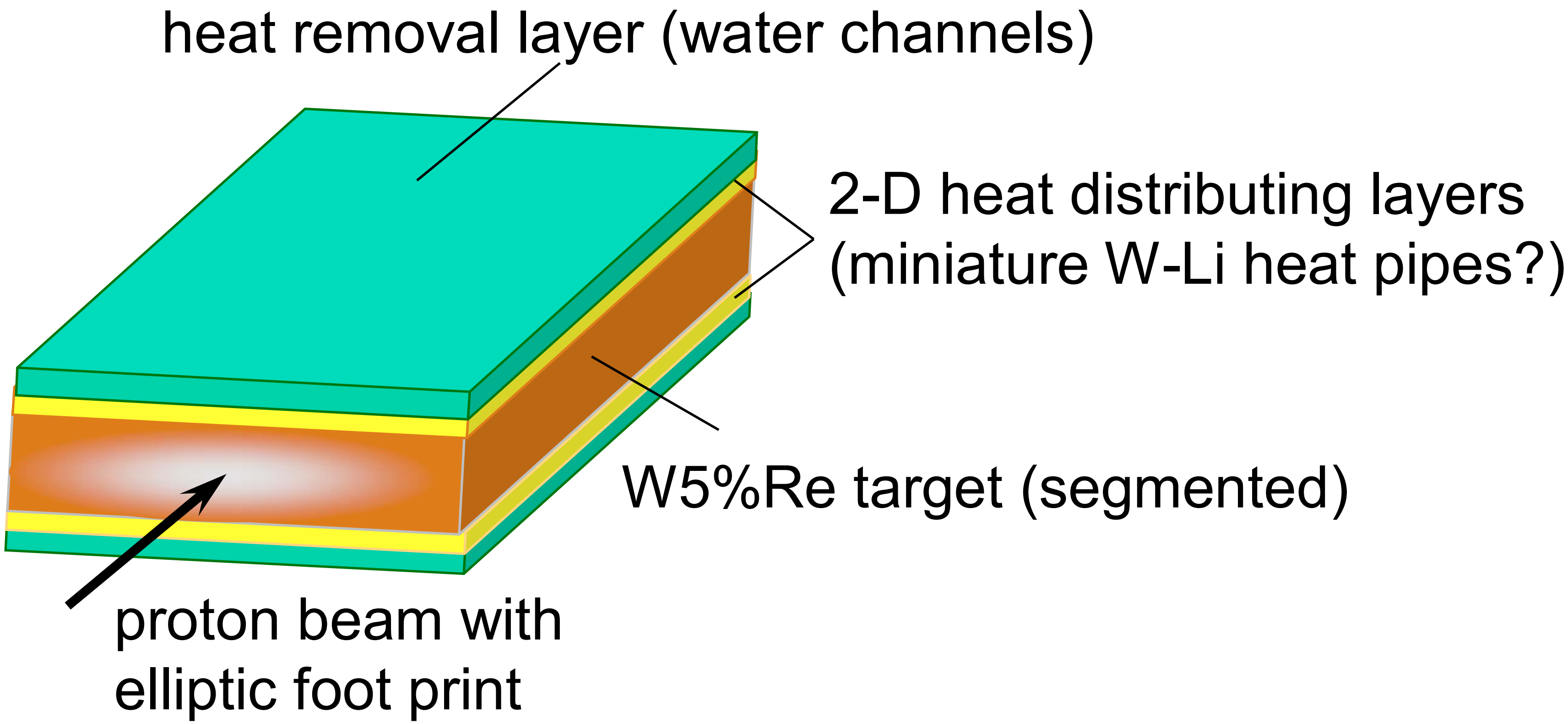
(W. Sommer, 1997)

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°C
- 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.

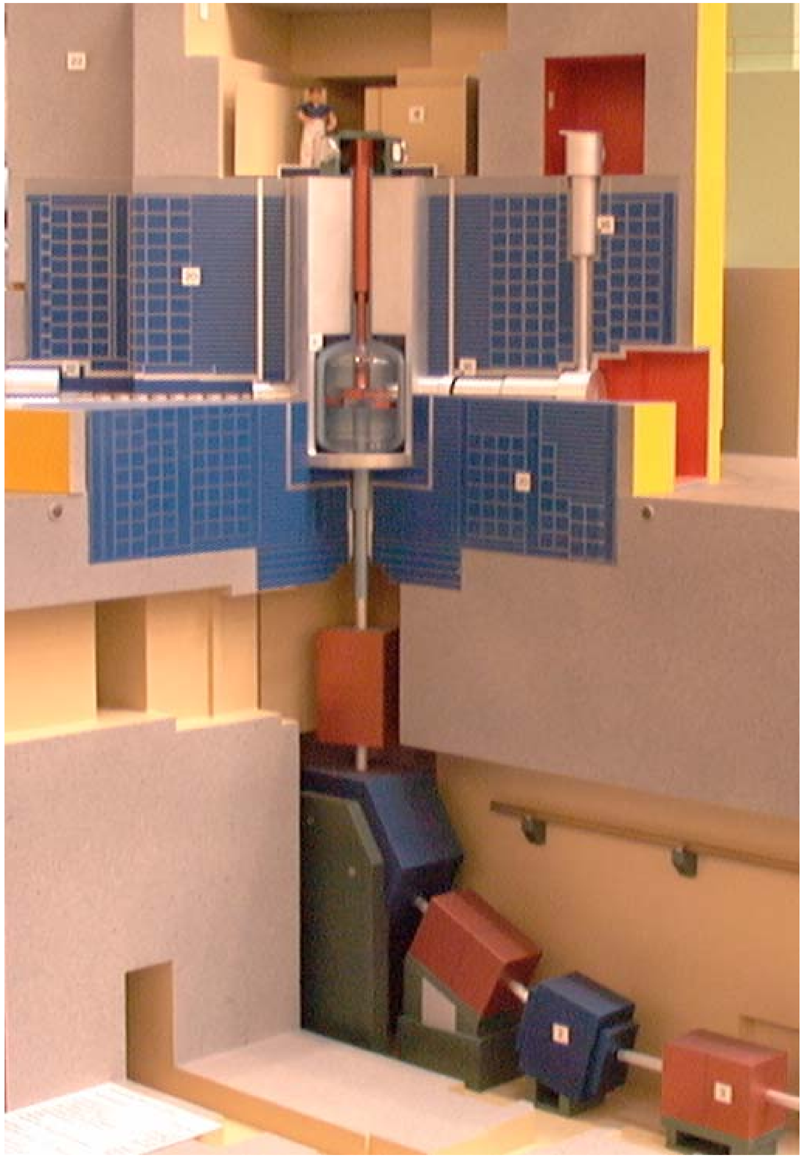
Spallation Target Materials: Solid Bismuth

- Z =83 , A=209, d= 9.75 g/cm³, T_m=271.3°C
- Very low neutron absorption (0.034 barn)
- ^{210}Po 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

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).

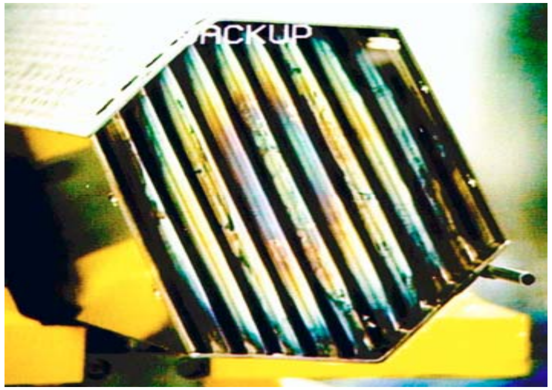
Beam injection into the target is from underneath.

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

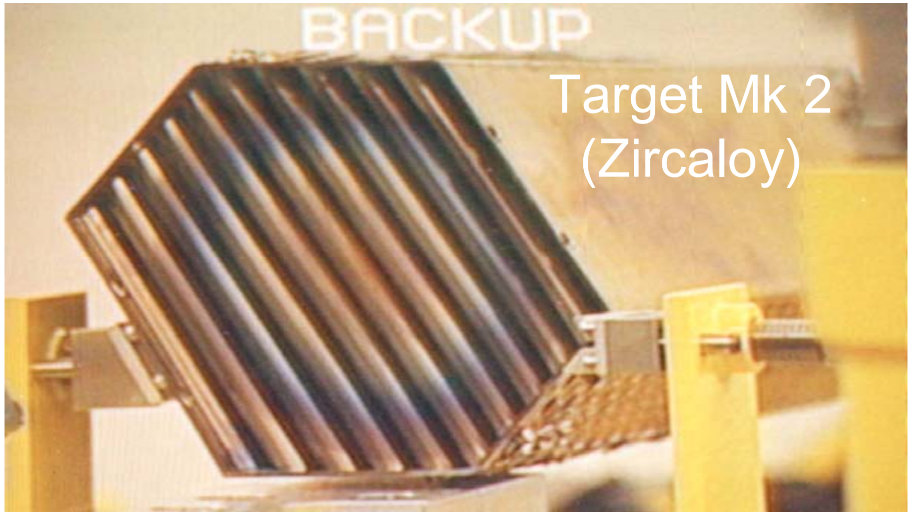
The solid metal targets used are of the rod-type and are cooled by heavy water flowing upwards between the rods.

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

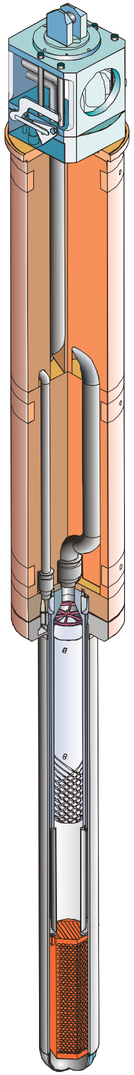
Solid Metal Targets: The SINQ Rod Target (2)



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

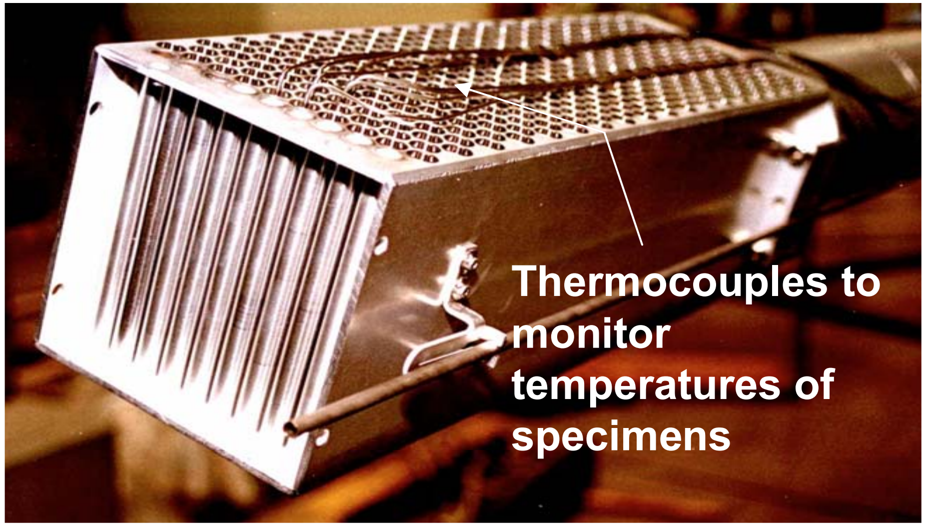


Removed after 6.8 Ah of beam (water purification on)

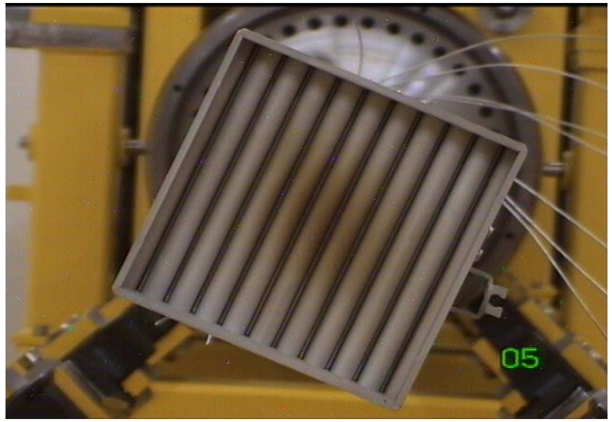


Incident proton beam

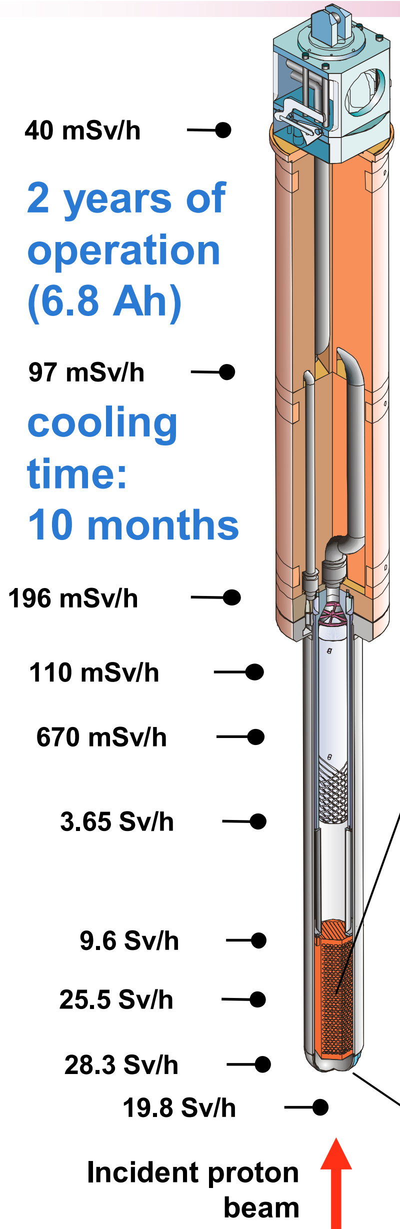
Target Mk 3
(lead rods in SS-tubes,
bottom row empty Al-tubes)



Exposed
to 10 Ah
of beam;



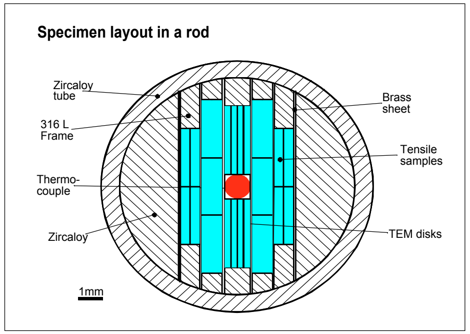
Radiation Effects Research with SINQ (1)

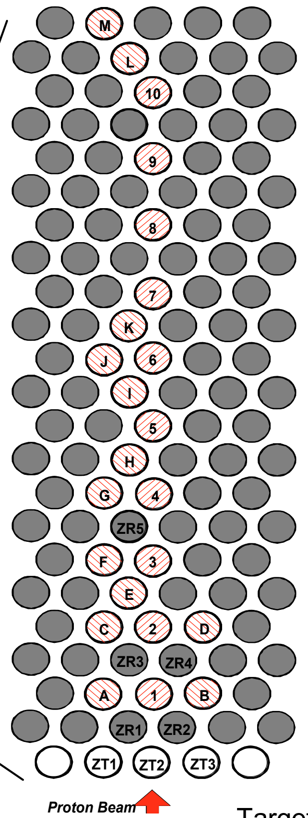


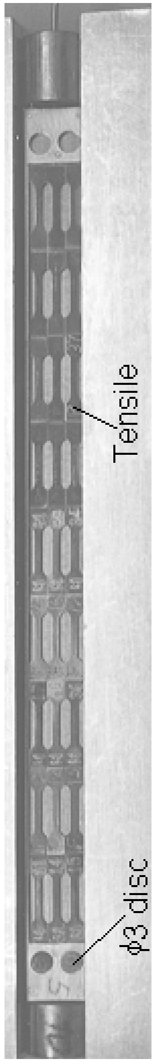
2 years of operation (6.8 Ah)

cooling time: 10 months

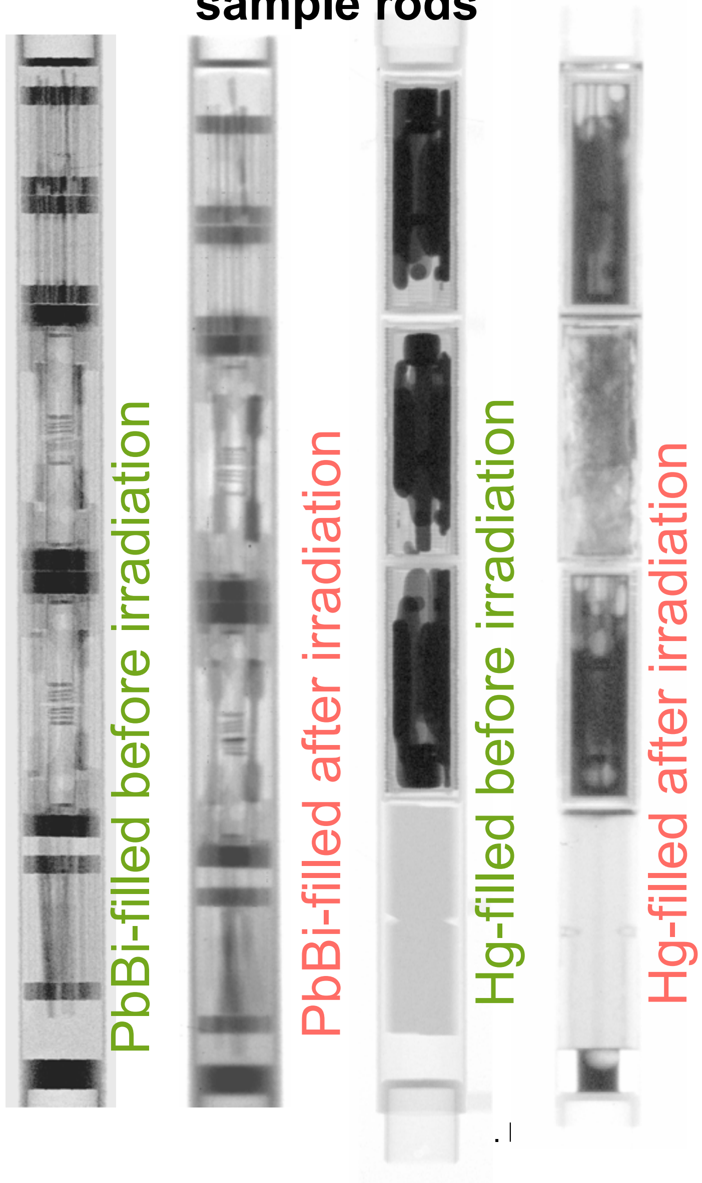
Rod with test specimens







Neutron radiographs of sample rods

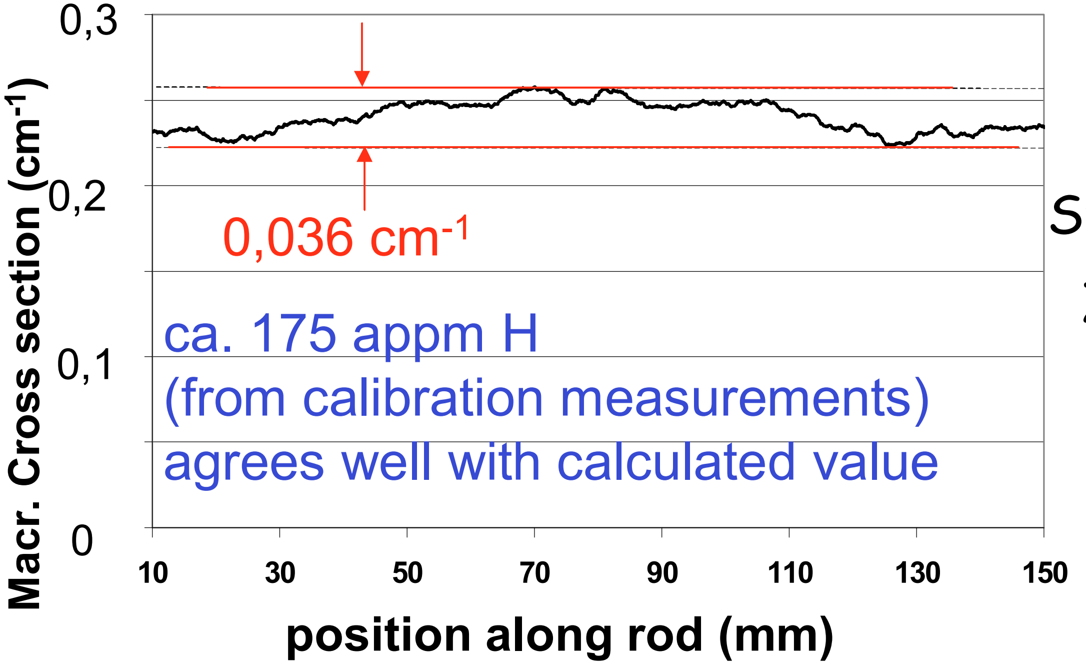


Radiation Effects Research with SINQ (2)

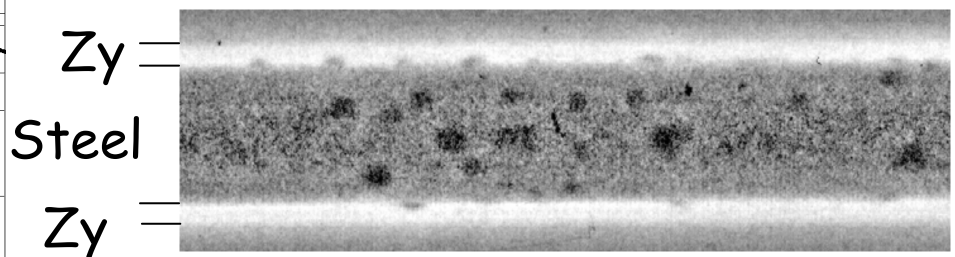
Hydrogen Retention in Zircaloy

Neutron radiography on highly radioactive rods irradiated in SINQ !

Zircaloy rod ZR5, Target Mk 2



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

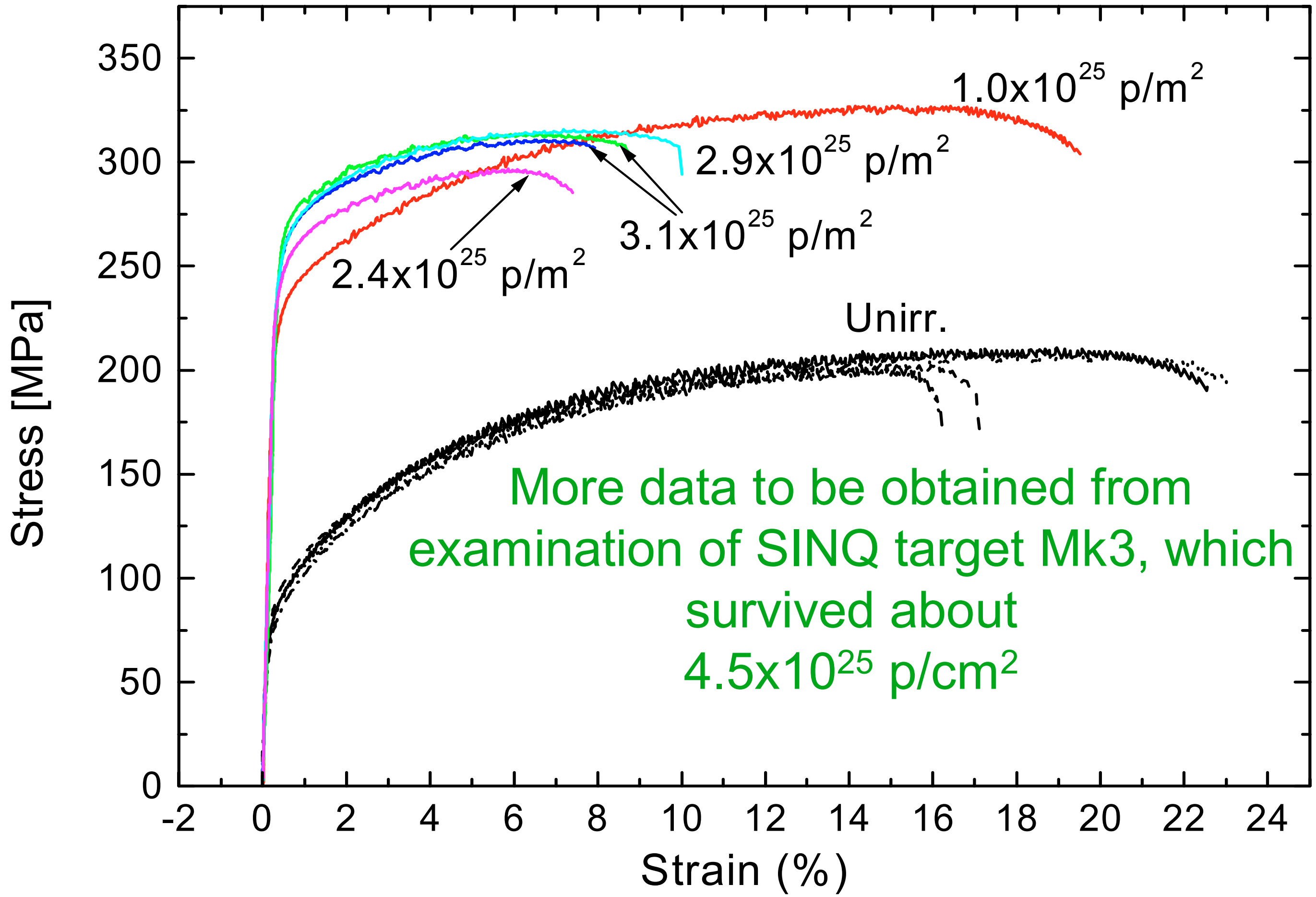


The high hydrogen production rate in higher Z spallation materials might make Zircaloy a difficult cladding material

The next solid SINQ target will have Zy-clad Pb-rods in zones of lower beam lod!

Radiation Effects Research with SINQ (3)

PIE on Irradiated Hull (AlMg3) of SINQ Target Mk2



4.5×10^{25} p/m² correspond to ca 2000 hours (ca 83 days) of operation at 100 µA/cm²

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.

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.
- 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 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.

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?)
- Largely unexplored and potentially more difficult technology.
- Beam entrance window is the most highly loaded component in the system.
- Completely new safety case.

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

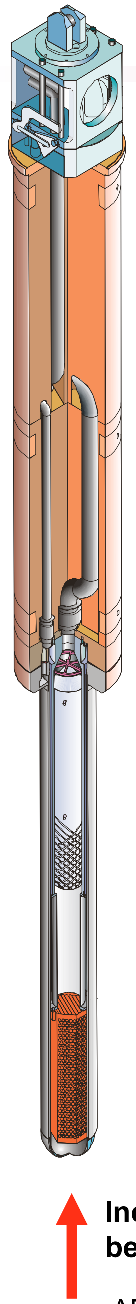
** Lead magnesium eutectic ** Lead bismuth etectic*

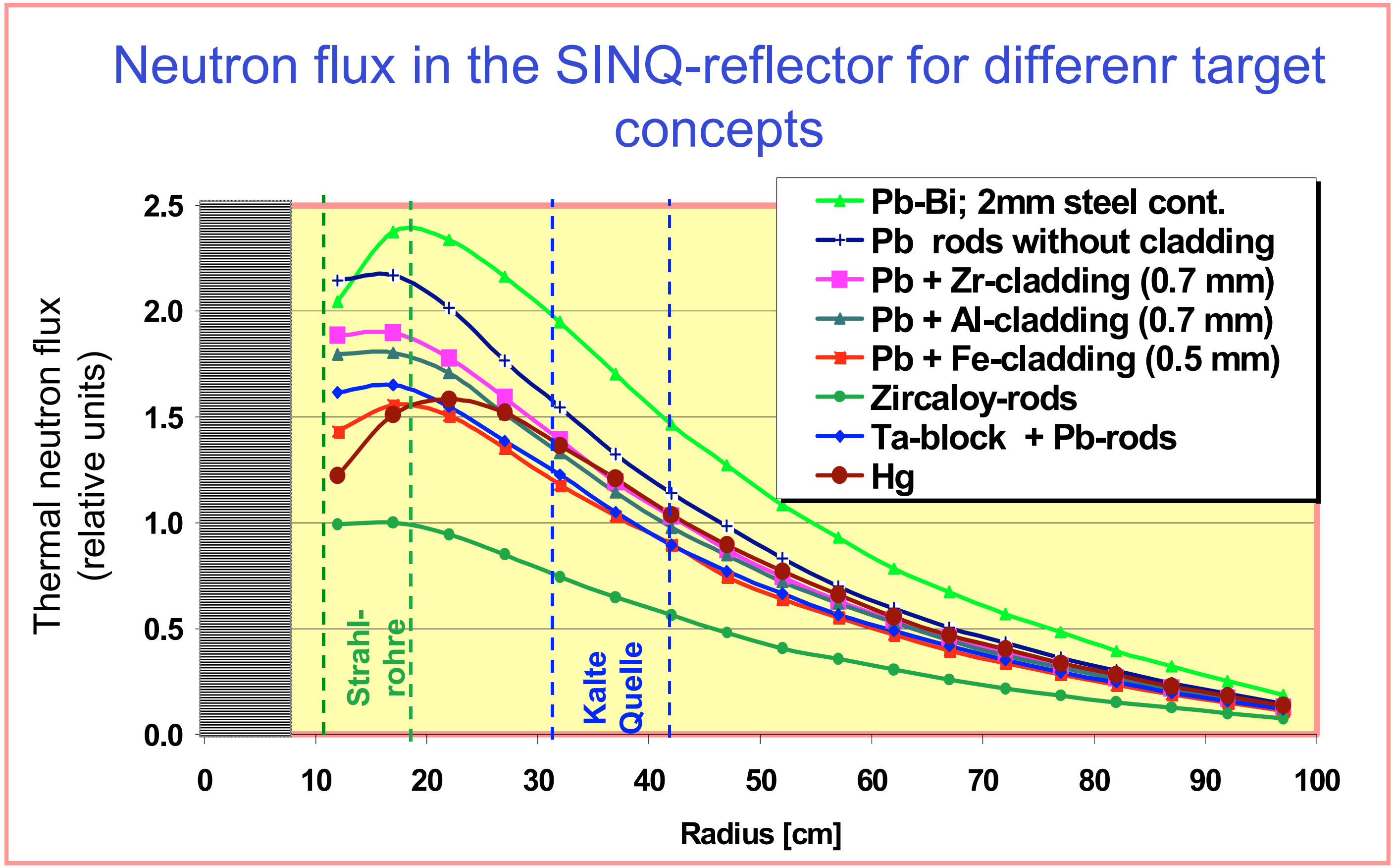
* Lead magnesium eutectic ** Lead bismuth eutectic

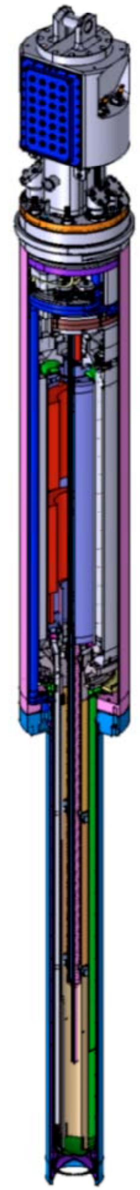
Liquid Metal Targets: Pb, Bi

- 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

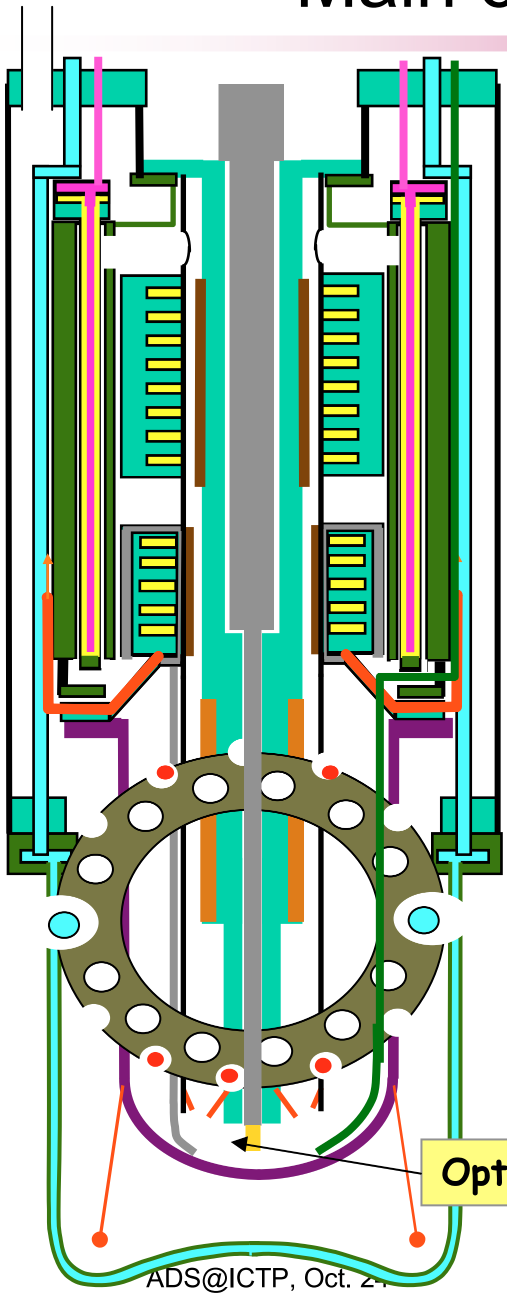






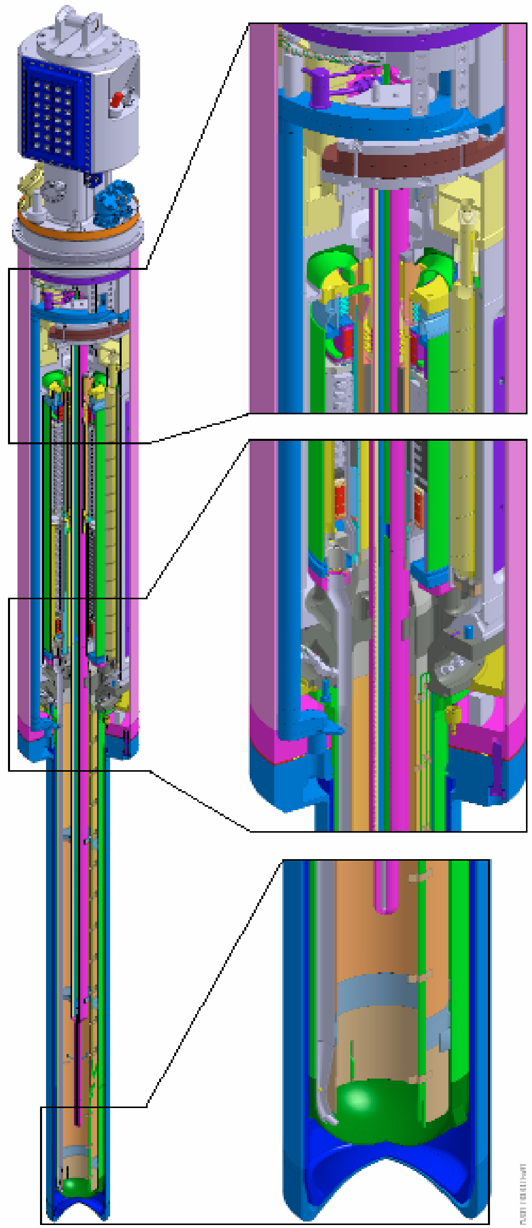
- Higher neutron yield (flux in the reflector)
- Less radiolytic effects in the cooling water
- Reduced radiation levels in the cooling plant room
- New technology for next generation neutron sources (ADS)

Main components of the MEGAPIE Target

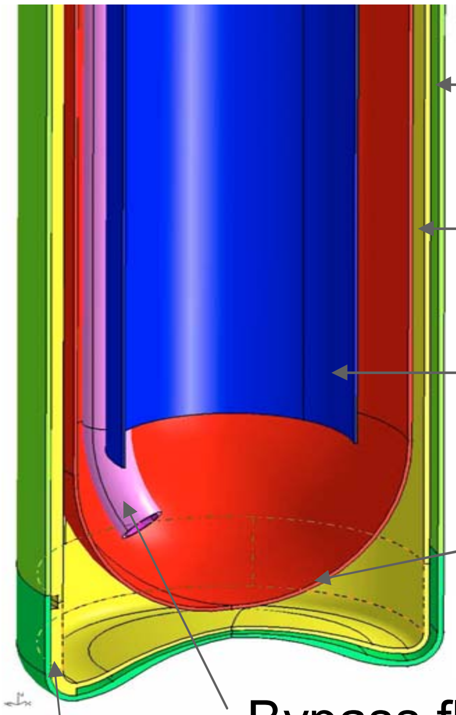


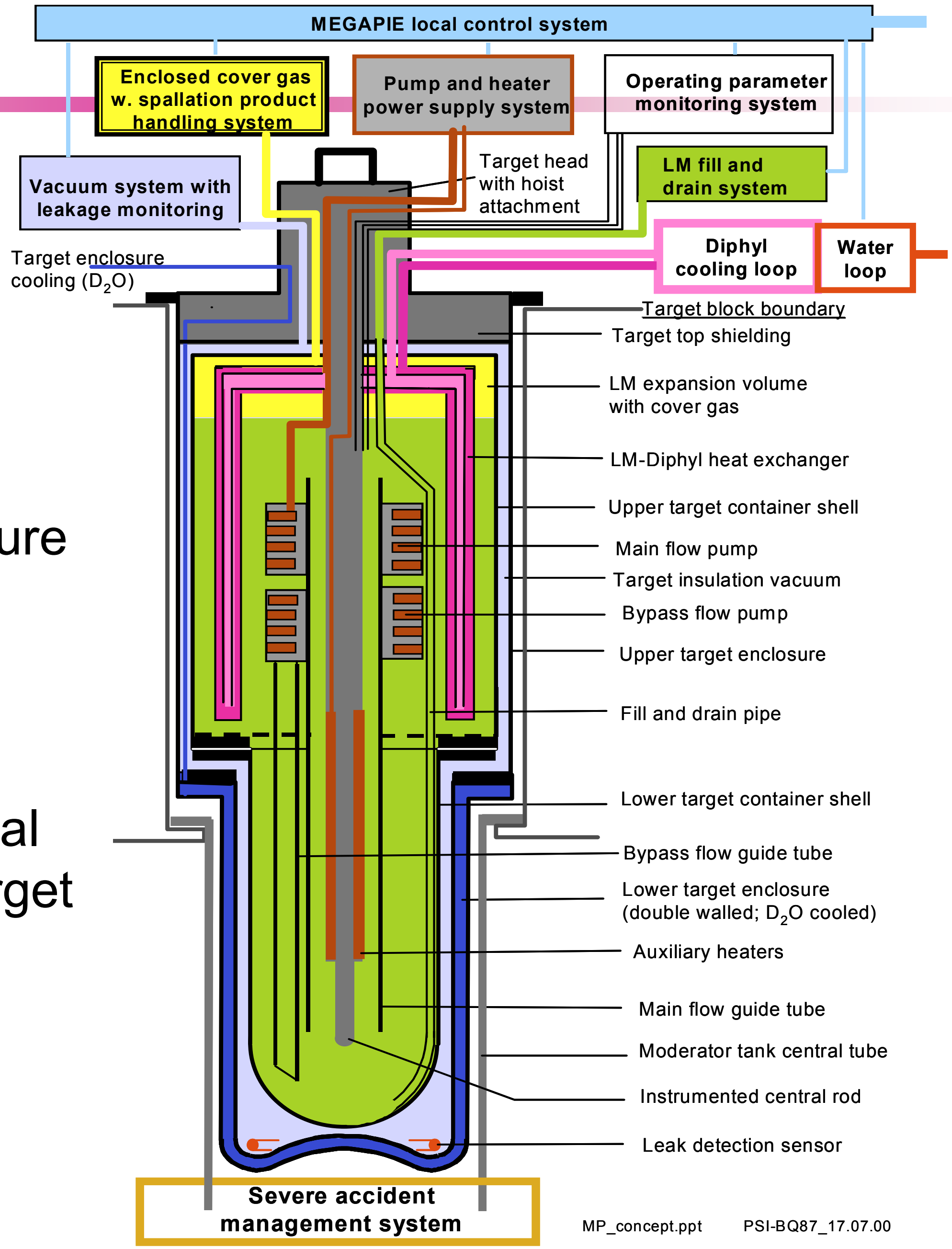
1. Upper liquid metal container and displacement body
2. Heat exchanger
3. Pump unit and lower flow guide
4. Central rod with auxilliary heating
5. Fill-and drain tube
6. Lower liquid metal container with leak sensors
7. Upper flange with feed-throughs
8. Upper vacuum chamber with outer enclosure
9.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

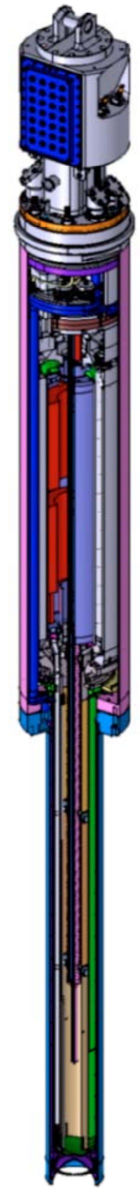
Option for materials test samples (not realised)



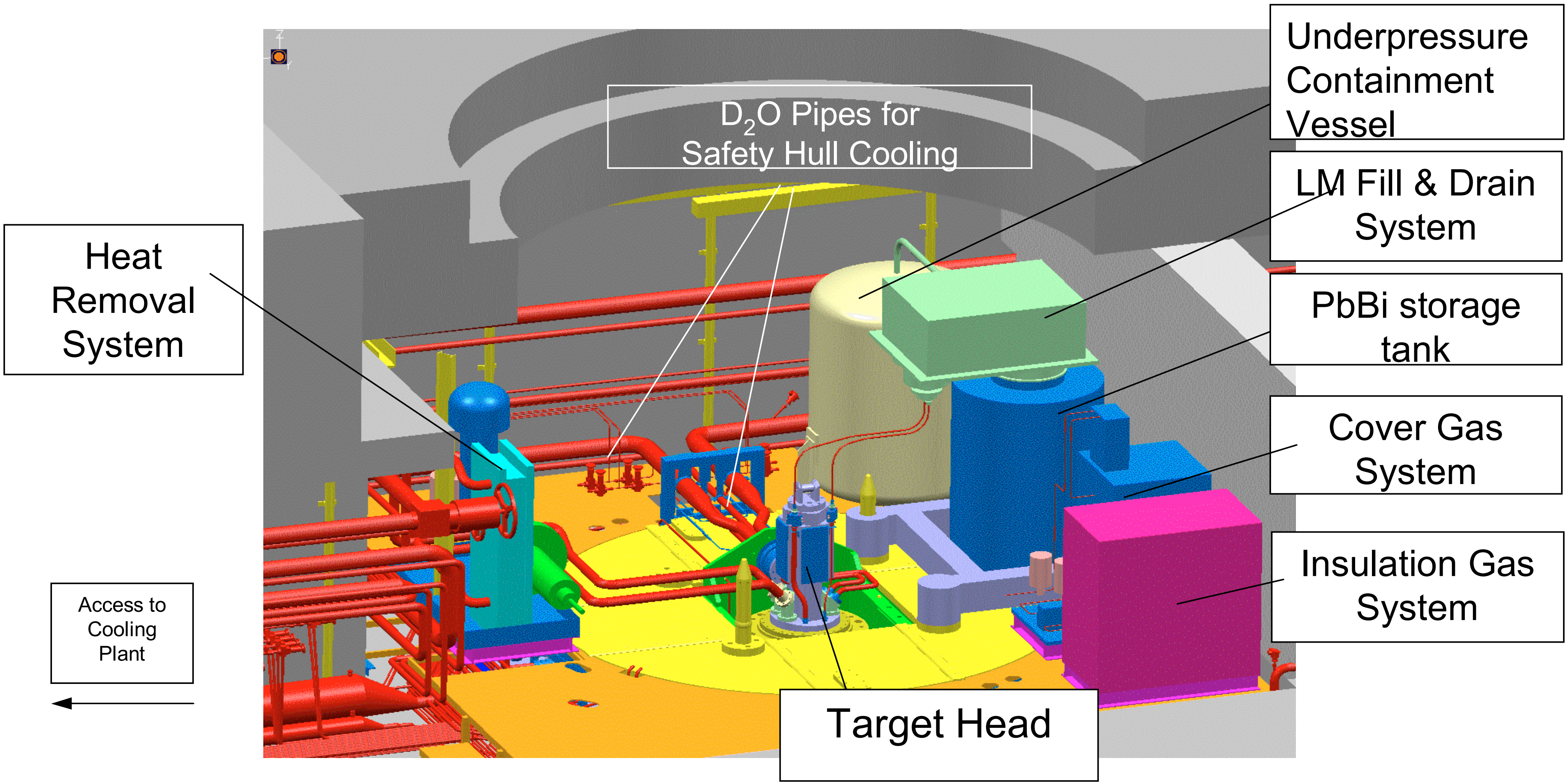
The SINQ PbBi MEGAPIE Target







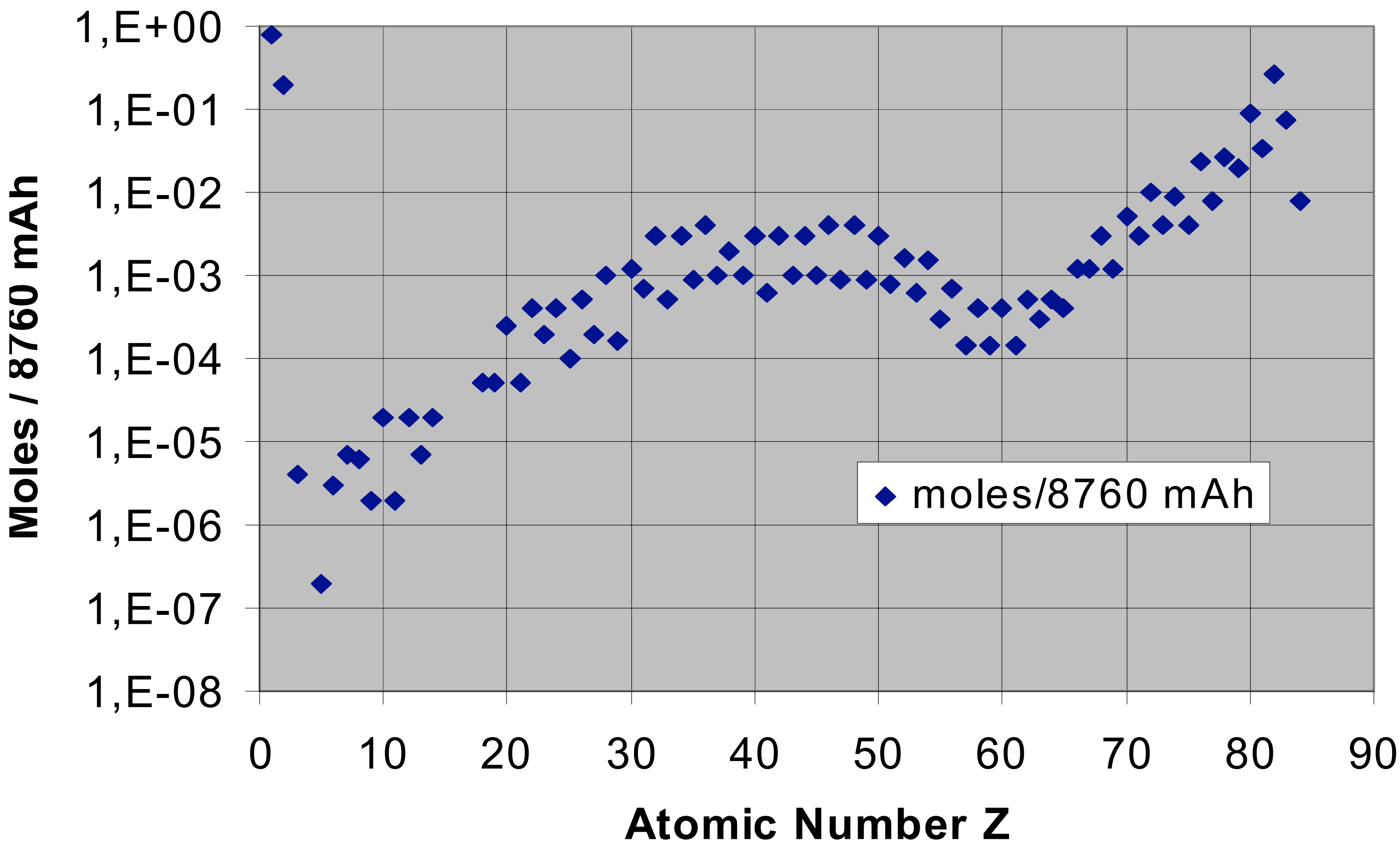
The MEGAPIE-Auxiliary Systems



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)

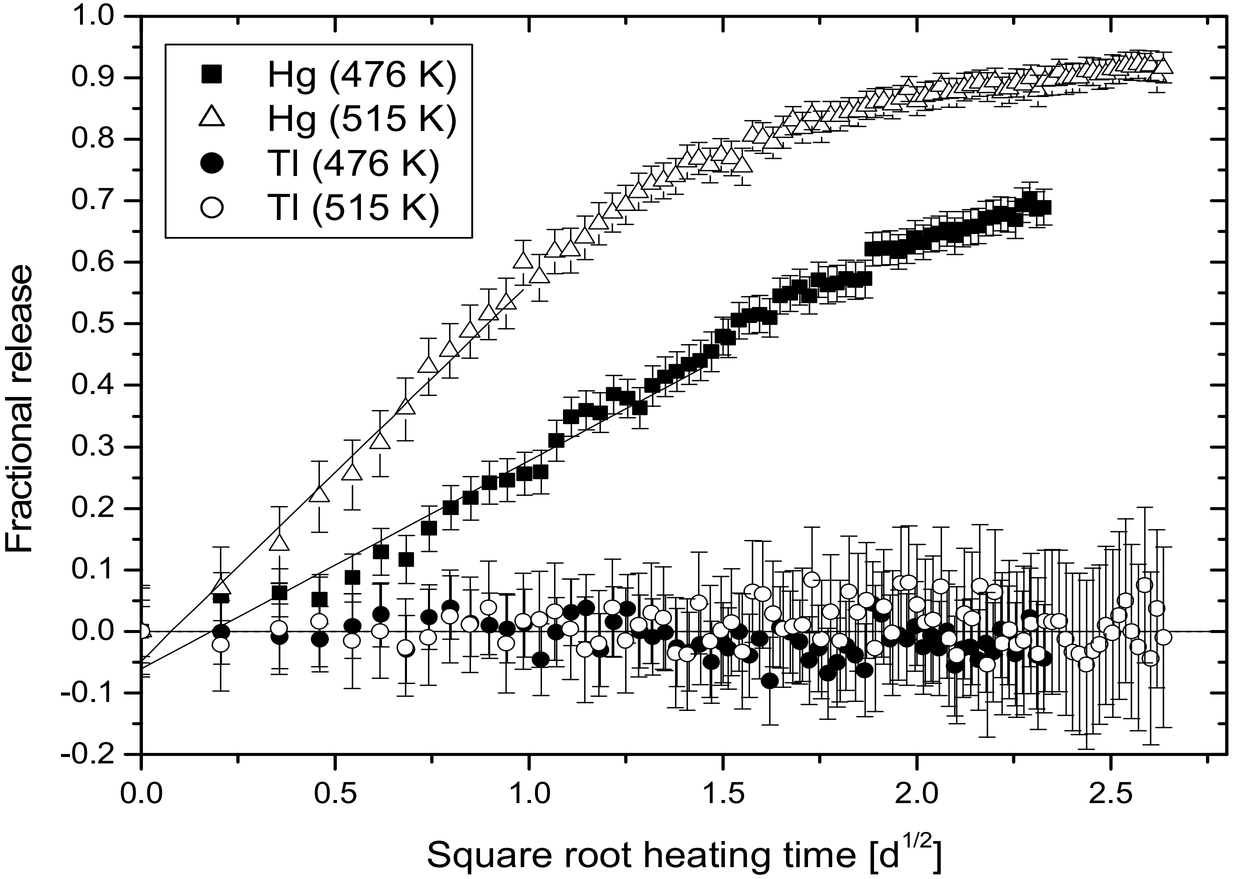
Gaseous spallation products

- 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 the required frequency of depressurization is difficult to predict.
- 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 requires 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)



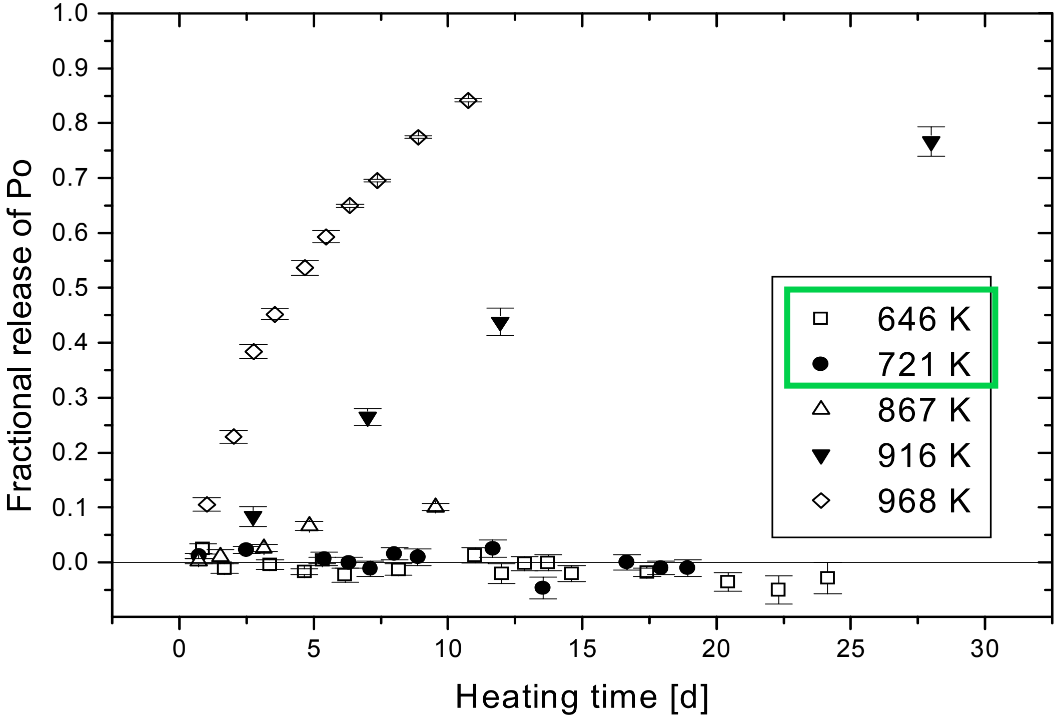
Hg vapors are trapped in an annex vessel to the expansion tank which is cooled to < 120 °C and is filled with a coil of 100 g of Pd wire of 100 µm diameter.

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.



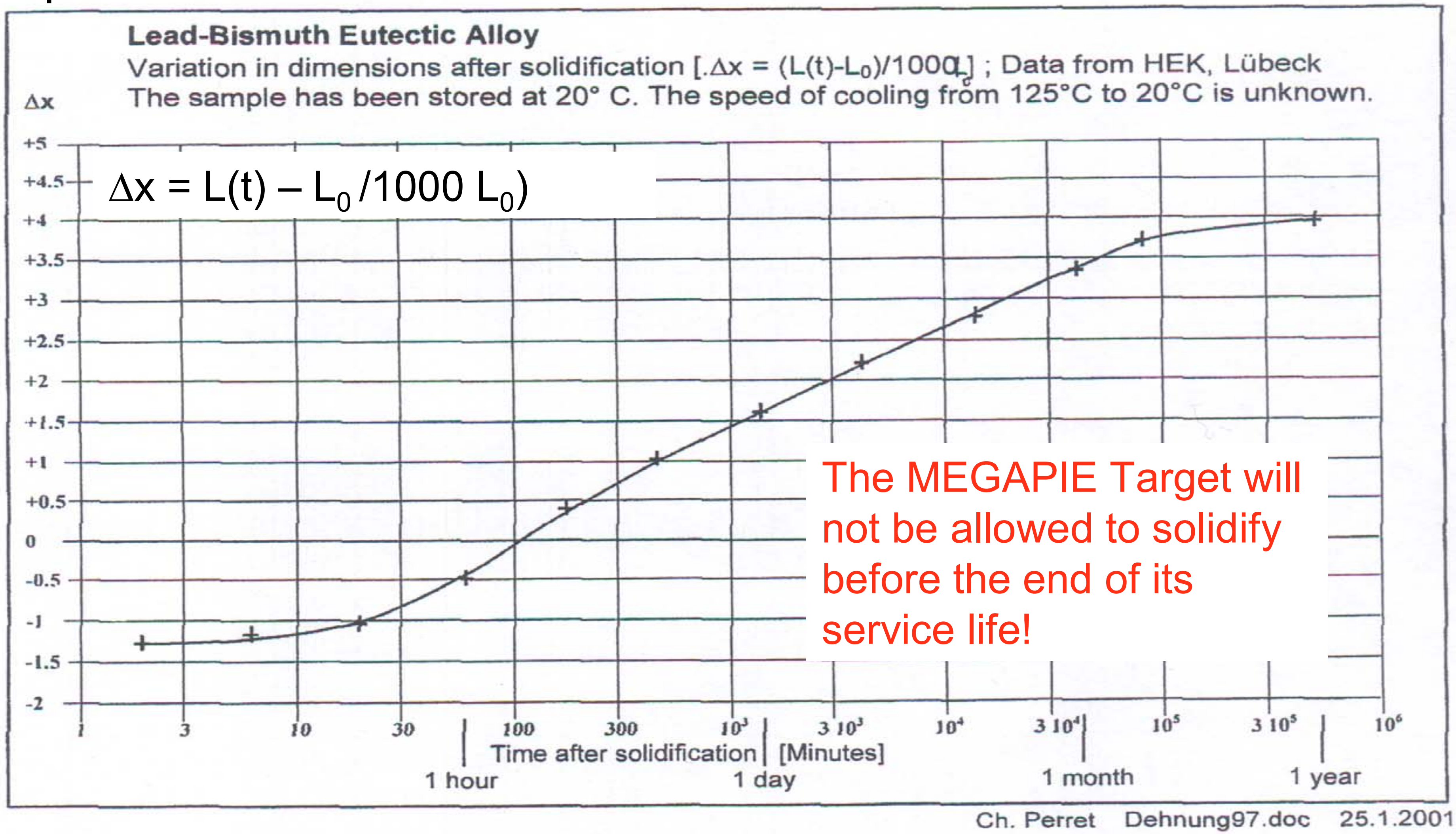
Po is not expected to be released in noticeable quantities from PbBi at 340°C (613 K)

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

Expansion of PbBi after Solidification



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

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

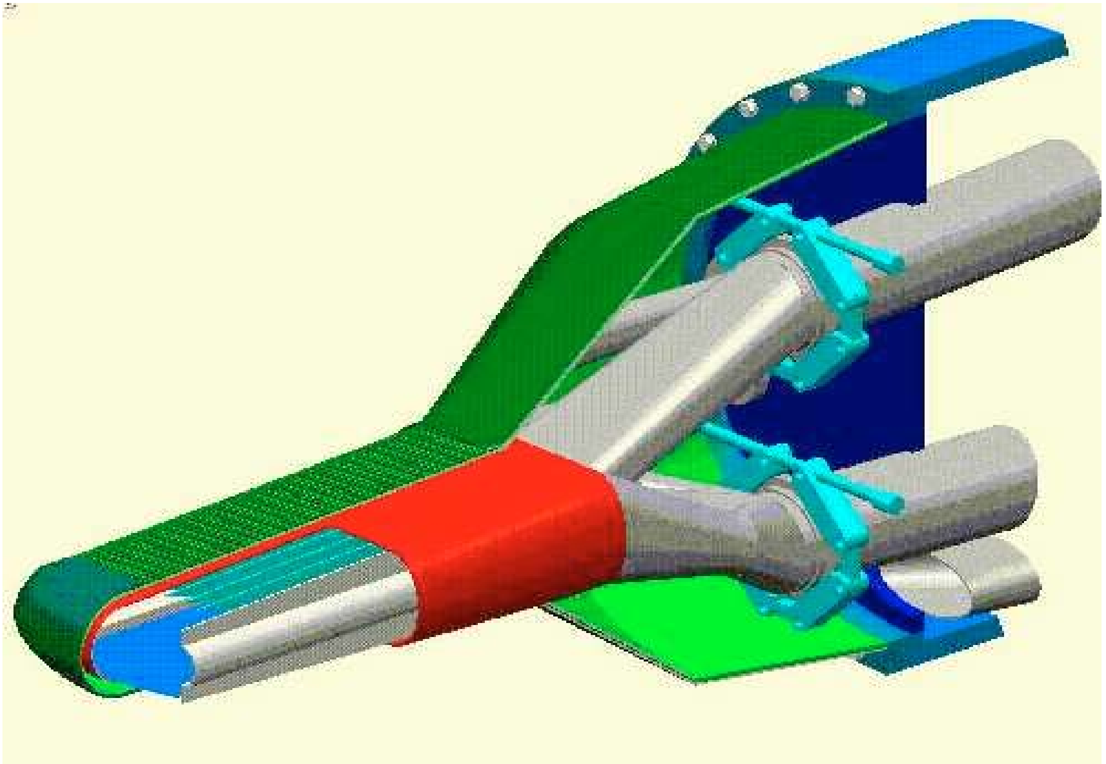
Status of the MEGAPIE Project

- The target has been built and delivered to PSI.
- Almost all auxiliary systems are in place at the test stand.
- Off-beam commissioning is under way.
- Flanking measures in the SINQ installation to allow operation of a liquid metal target have been completed.
- Supporting R&D has provided results on LM-corrosion, spallation product release and other safety-relevant issues that support the view that the target can be operated safely for at least half a year at 1 MW.
- Licensing process is ongoing (stepwise).
- Installation of the target planned for summer 2006.

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, JNP-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)

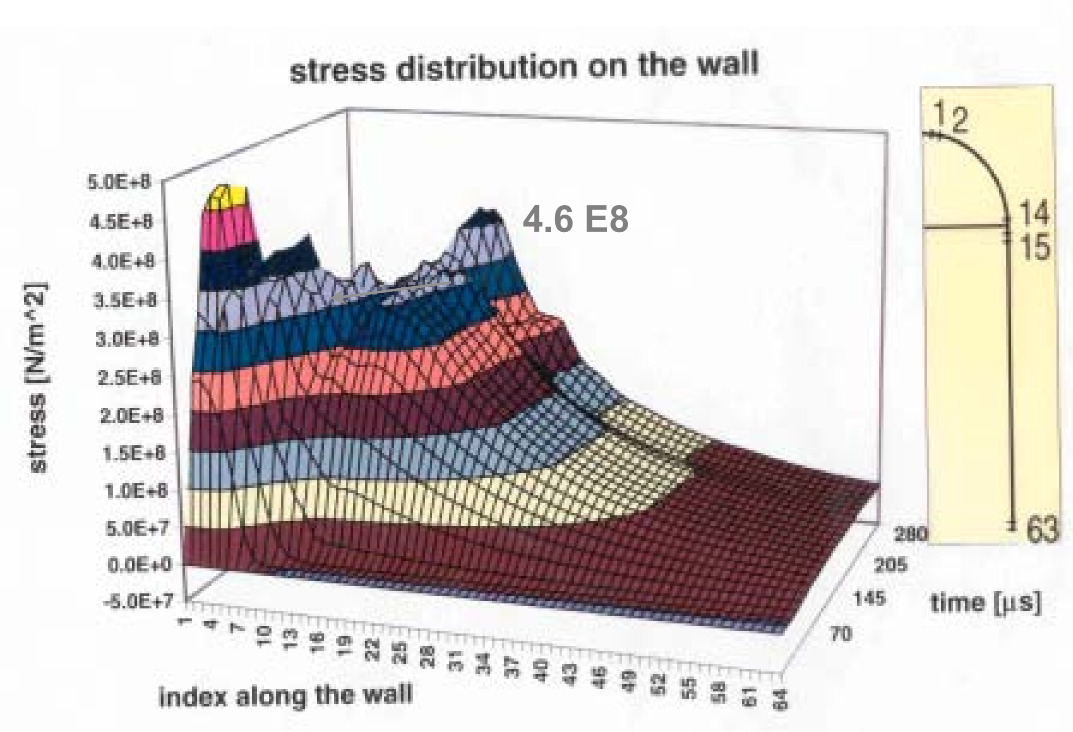
- The case of a window failure and easy exchange of the window will have to be design requirements. This favours horizontal beam injection (outer shroud with leakage monitoring of the interspace).
- In order to avoid dangerously high temperatures in the window, the bulk liquid metal flow should be directed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

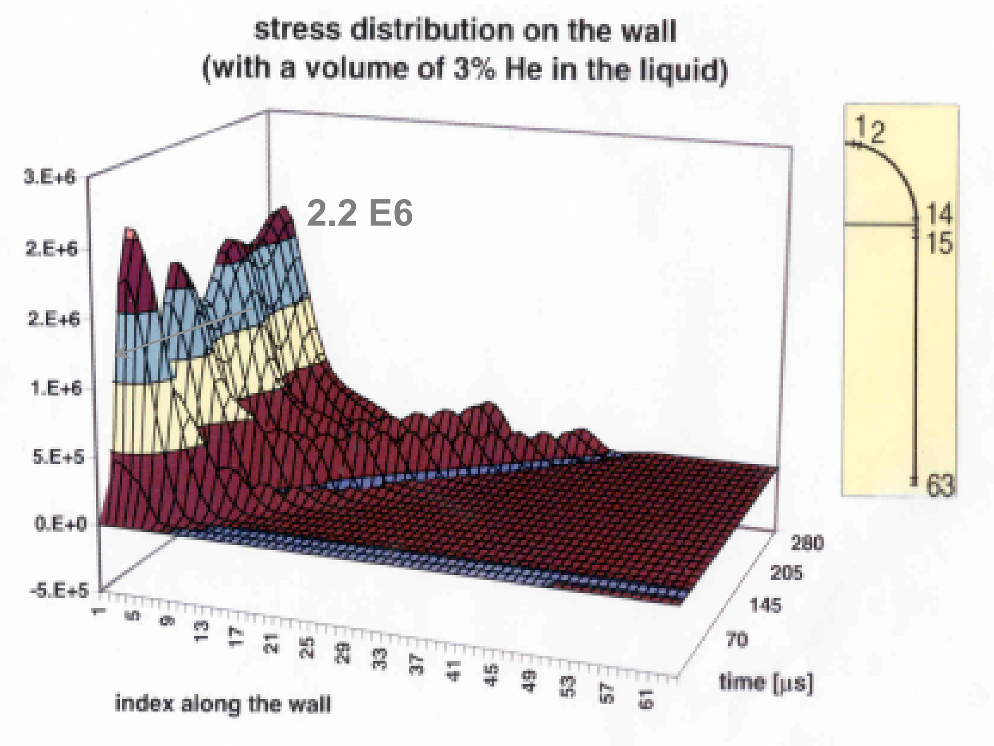
Liquid Metal Targets: The Pressure Wave Problem (1)

- 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)

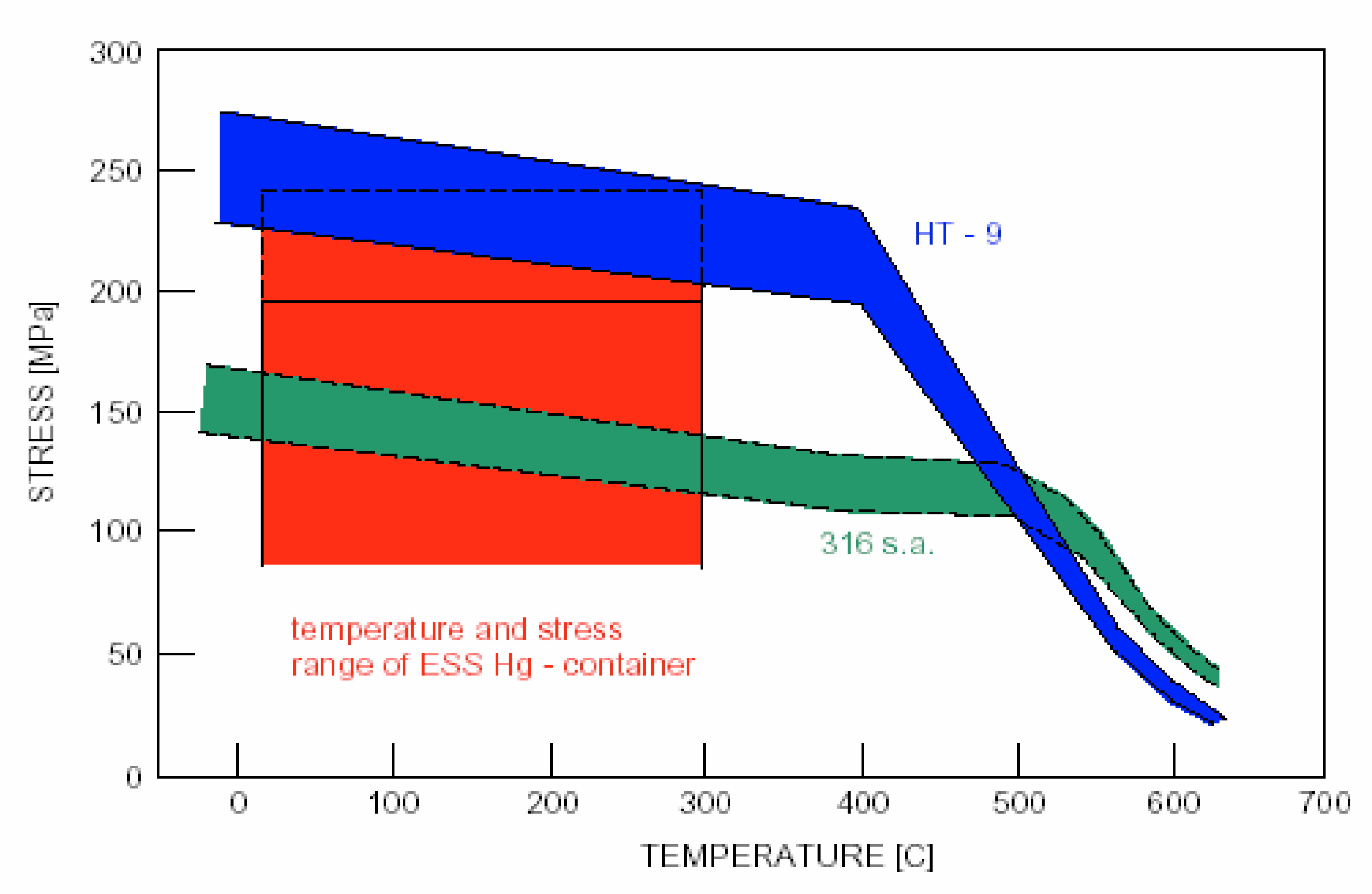




In theory, 3 vol% of helium in the mercury can reduce the stress on the walls by 2 orders of magnitude:
Experimental proof and technical concept are still missing!

Liquid Metal Targets: The Pressure Wave Problem (3)

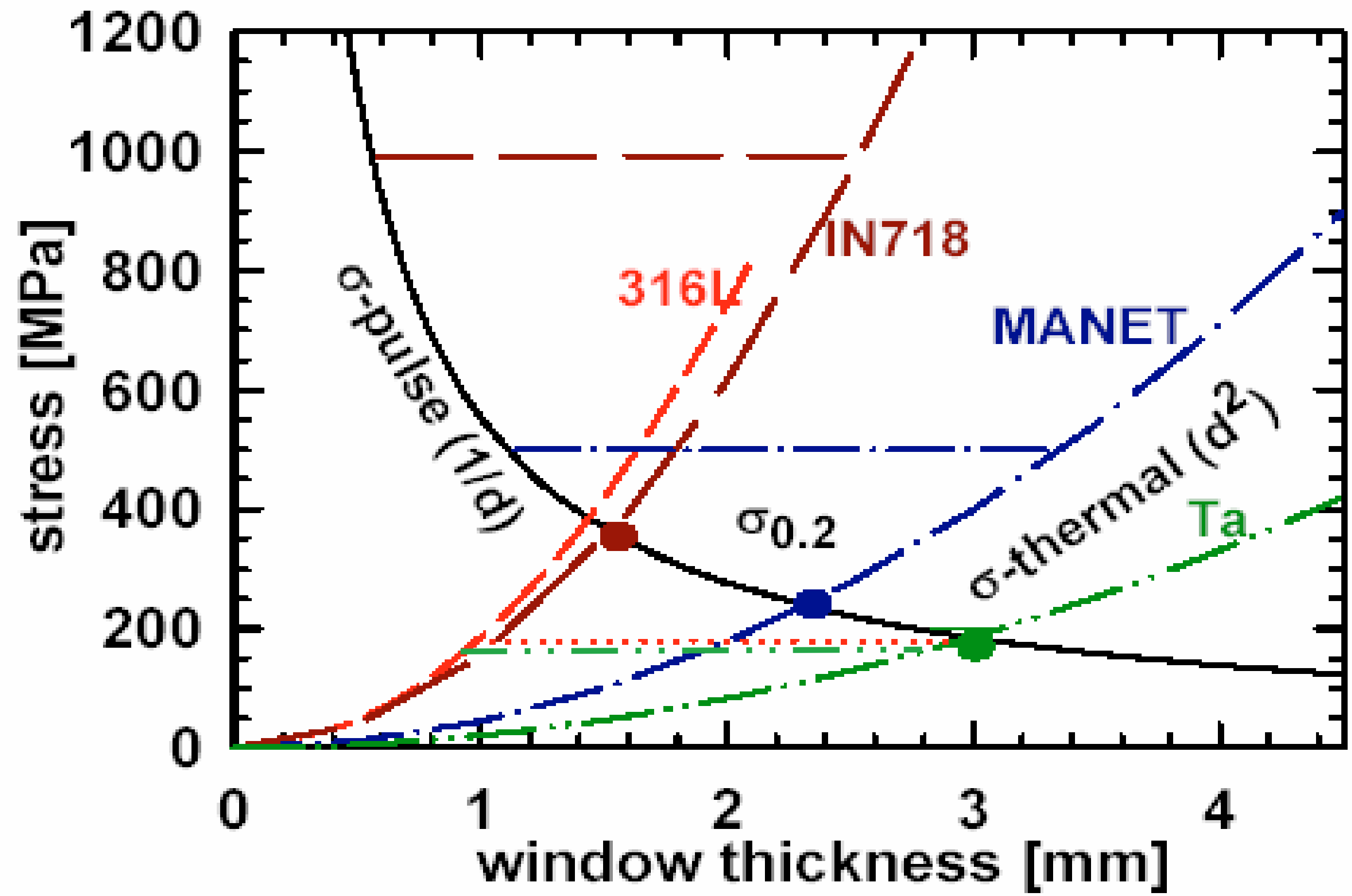
Recommended design stress (for the fusion reactor first wall) as a function of temperature.



In order for the martensitic steel HT9 to fulfil the design criteria for the ESS target operating conditions the effect of pressure waves due to pulsed operation must be mitigated as predicted,

Liquid Metal Targets: The Pressure Wave Problem (4)

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



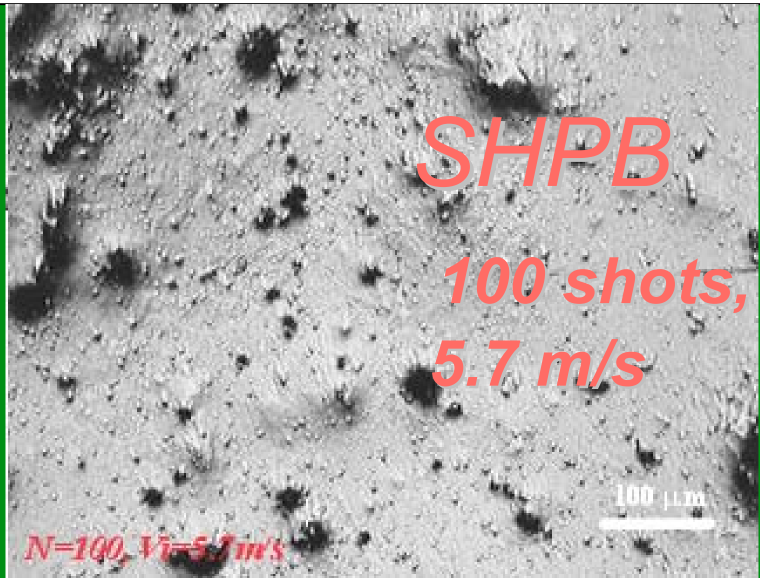
Horizontal lines: yield stress for the respective materials (colour coded, unirradiated)

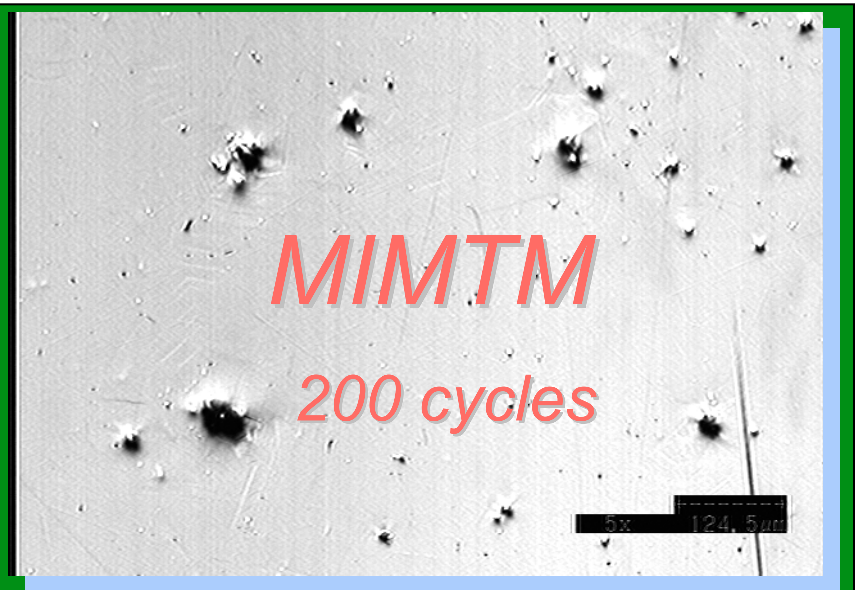
Liquid Metal Targets: The Cavitation Issue

- 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.

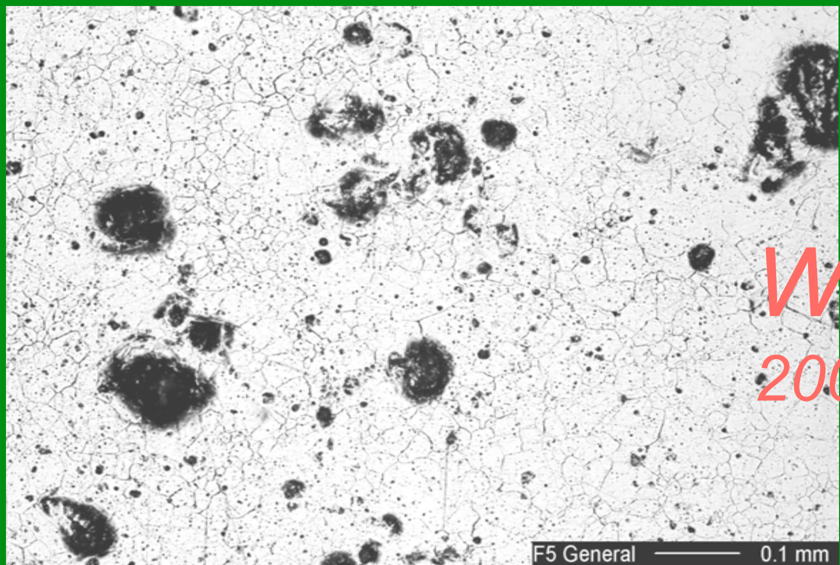
Cavitation-Erosion („Pitting“) by Pressure Pulses (1)

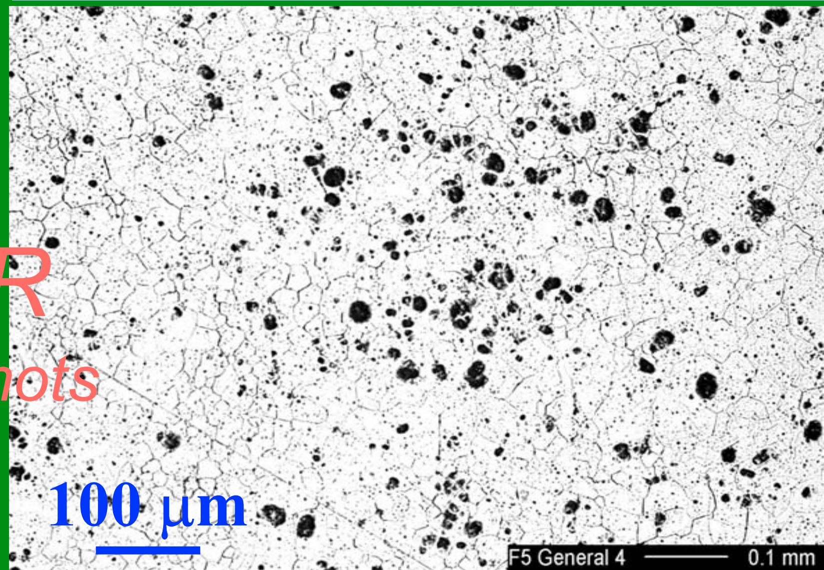
Out of beam





800 MeV prot. beam

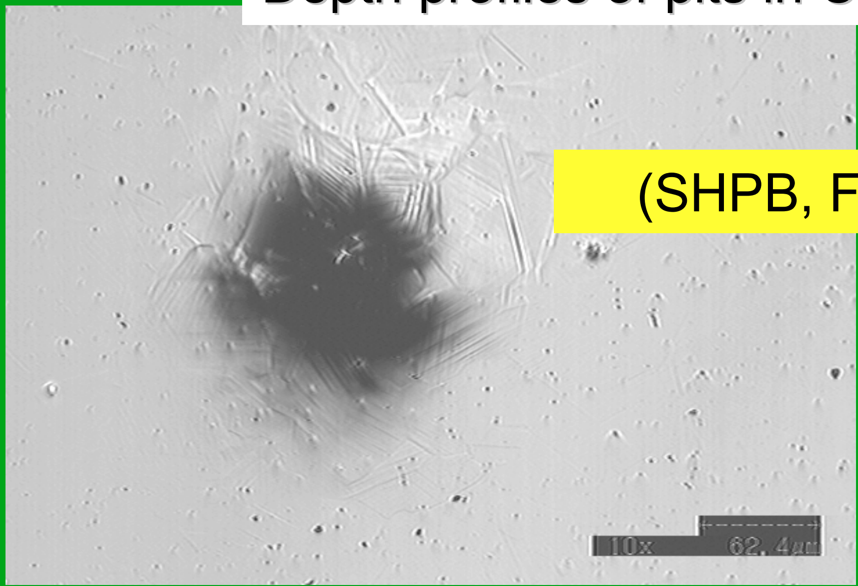


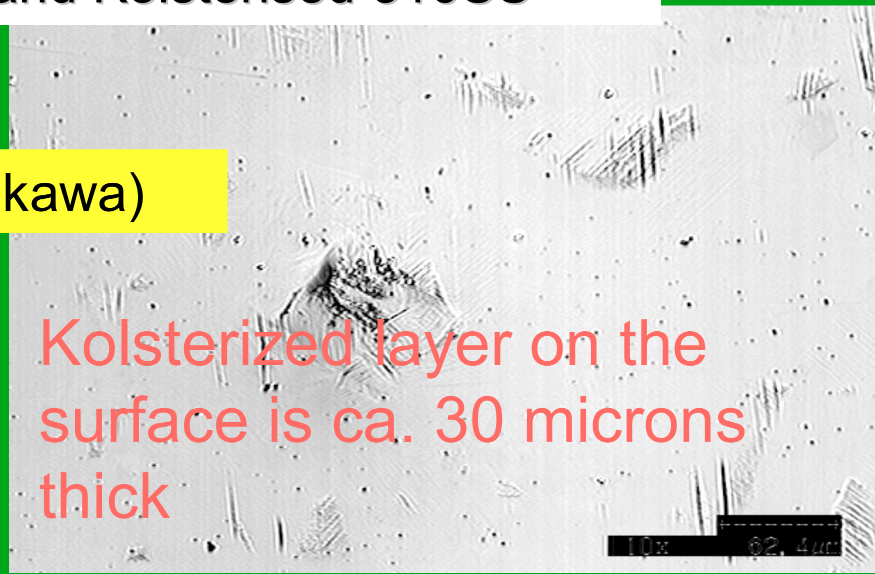


Cavitation-Erosion („Pitting“) by Pressure Pulses (2)

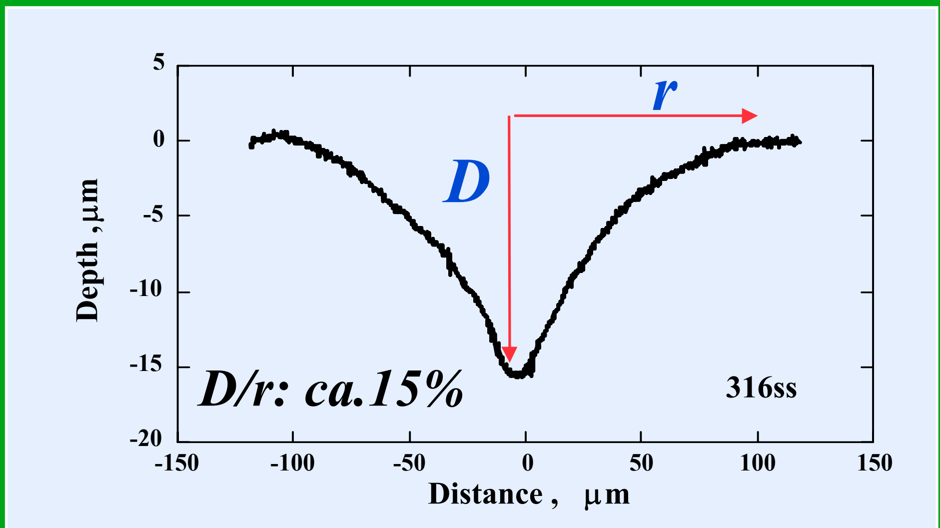
Depth profiles of pits in CW and Kolsterised 316SS

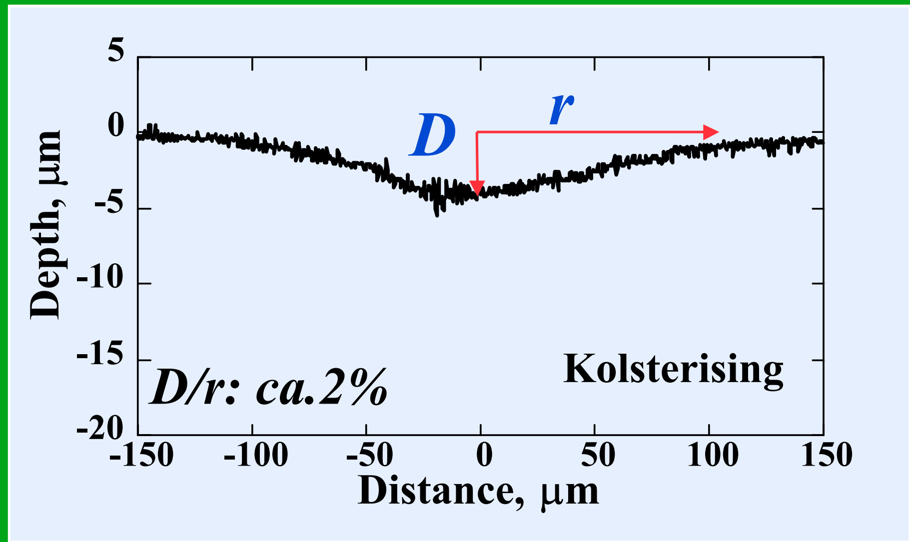
(SHPB, Futakawa)





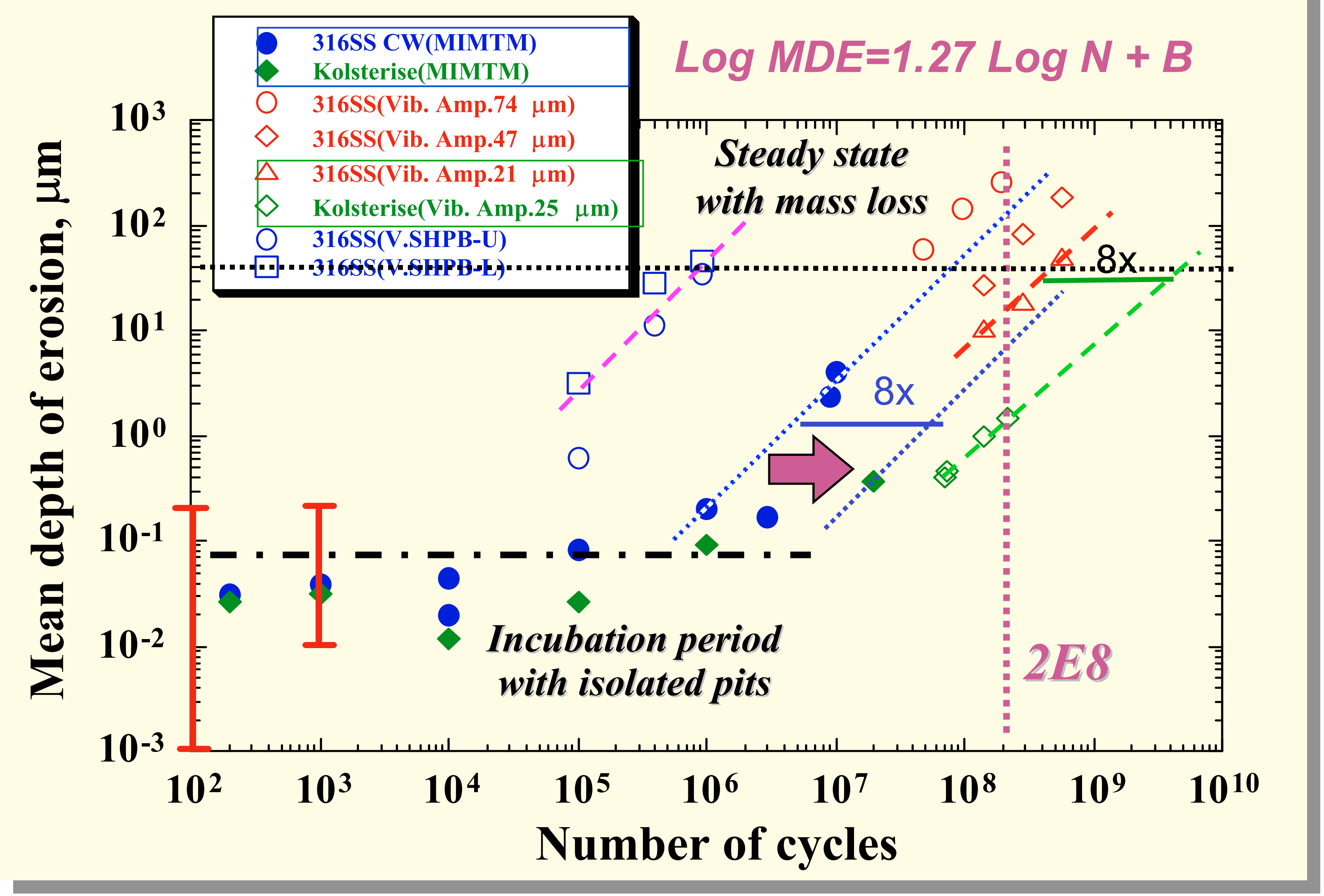
Kolsterized layer on the surface is ca. 30 microns thick





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

Summary Diagram of Pitting Results



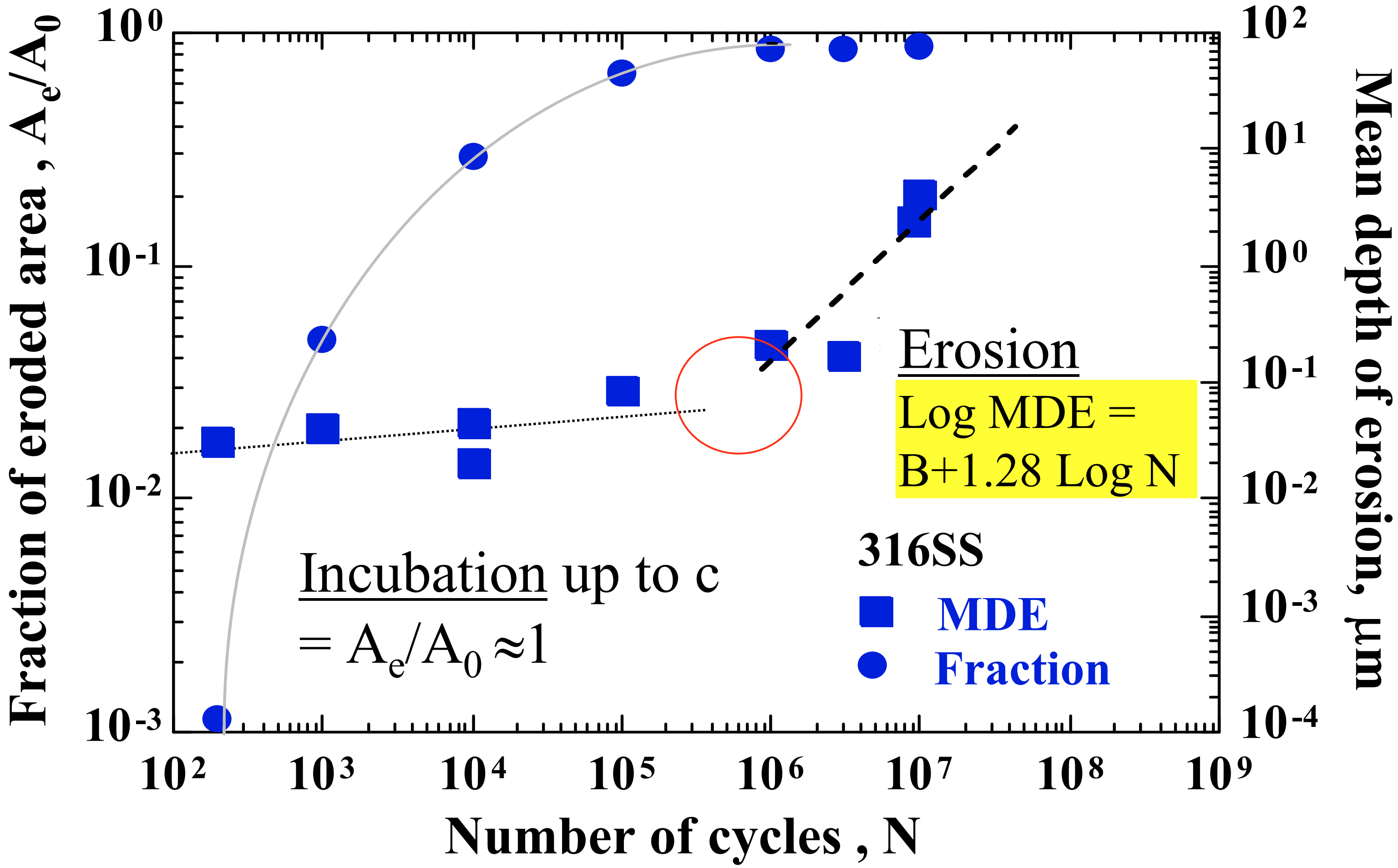
M. Futakawa, JAERI

Kolsterising can expand incubation period

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

Cavitation-Erosion („Pitting“) by Pressure Pulses (4)

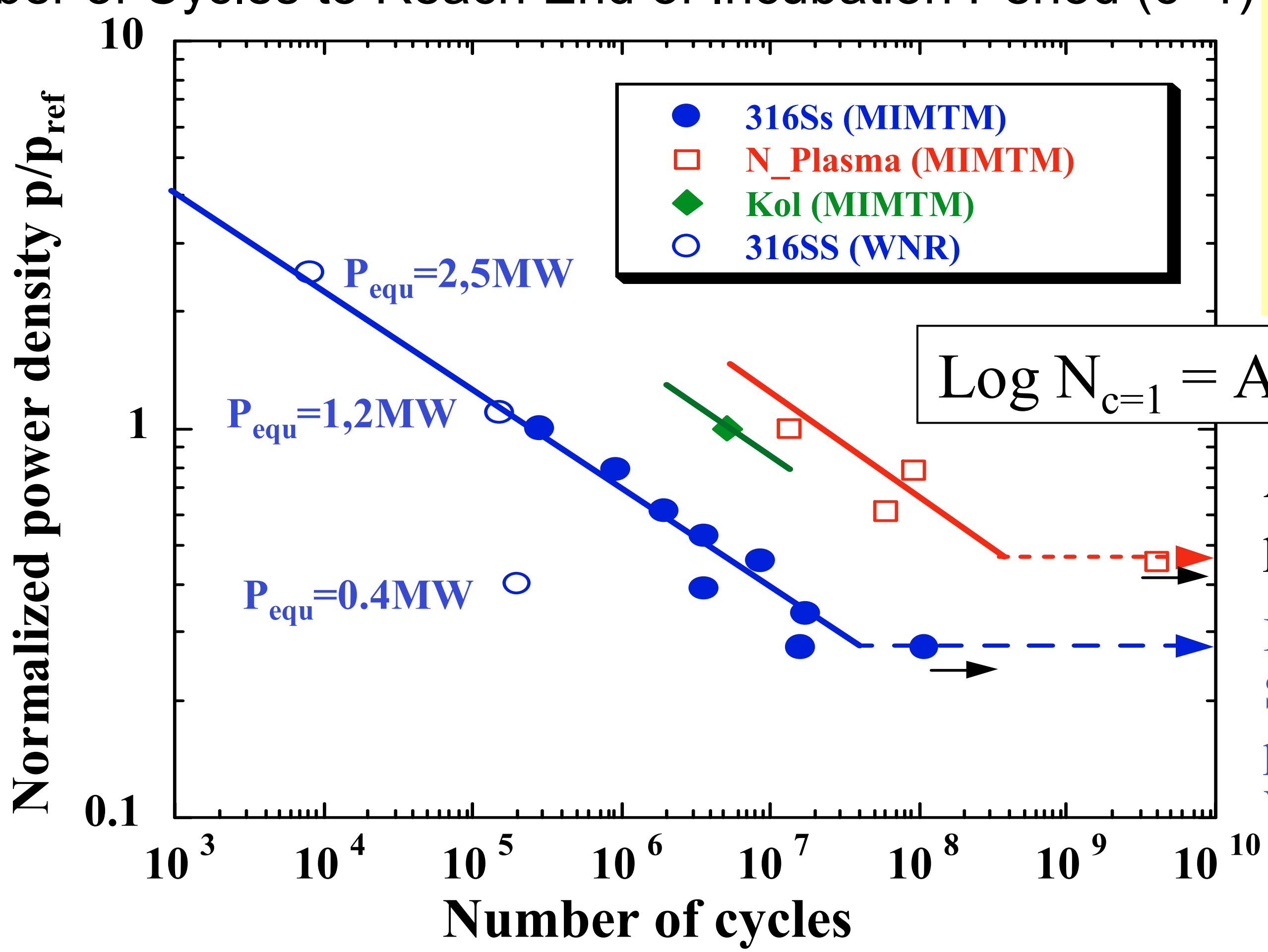
Correlation Between Area Covered with Pits and Mean Depth of Erosion



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

Cavitation-Erosion („Pitting") by Pressure Pulses (5)

Number of Cycles to Reach End of Incubation Period (c≈1)



Pitting damage increases with the 4^{th} 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

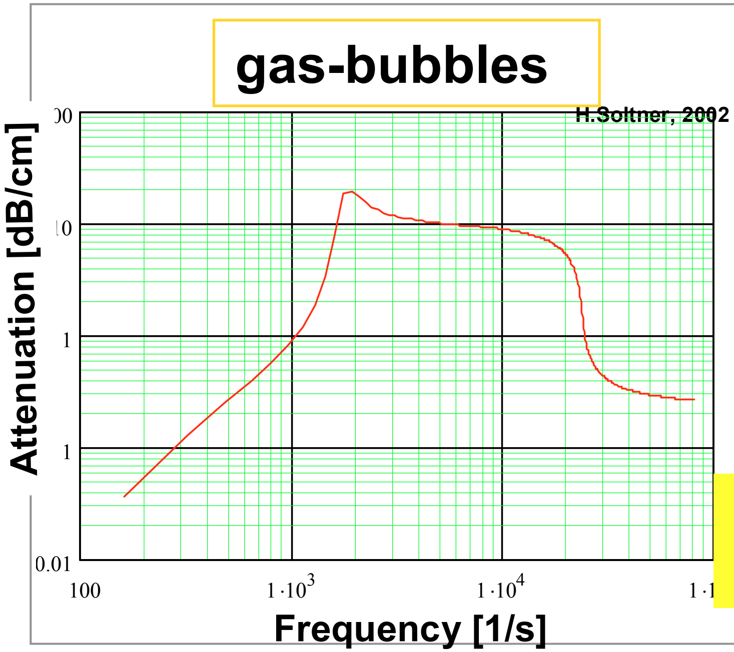
M. Futakawa, T. Naoe, C.C. Tsai, H. Kogawa, S. Ishikura, Y. Ikeda, H. Soyama, H. Date
"Cavitation Erosion in Mercury Target of Spallation Neutron Source" paper GS-11-006
5^{th} International Symposium on Cavitation, Osaka, Japan, Nov. 1-4, 2003

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**

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

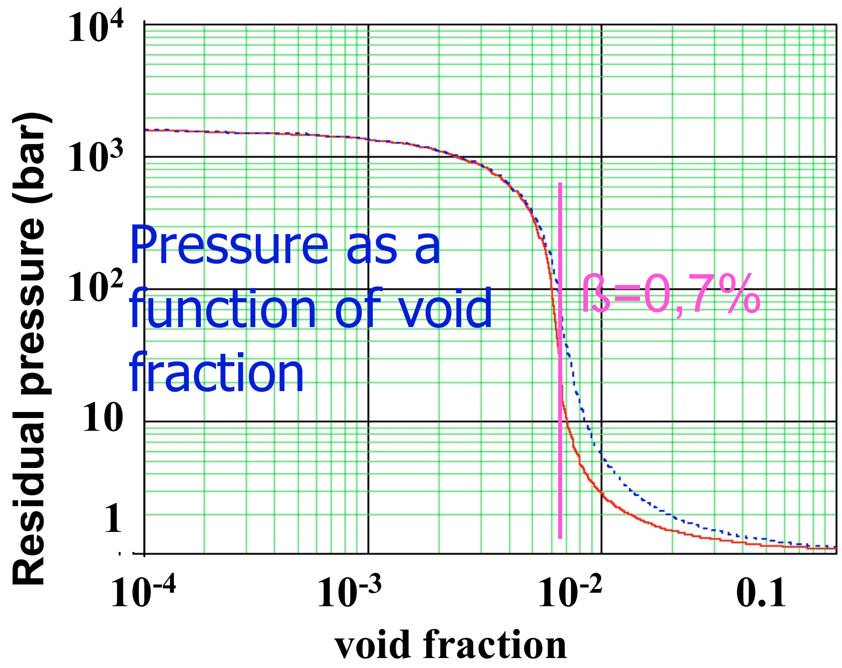
Pressure wave mitigation by gas bubbles



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

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

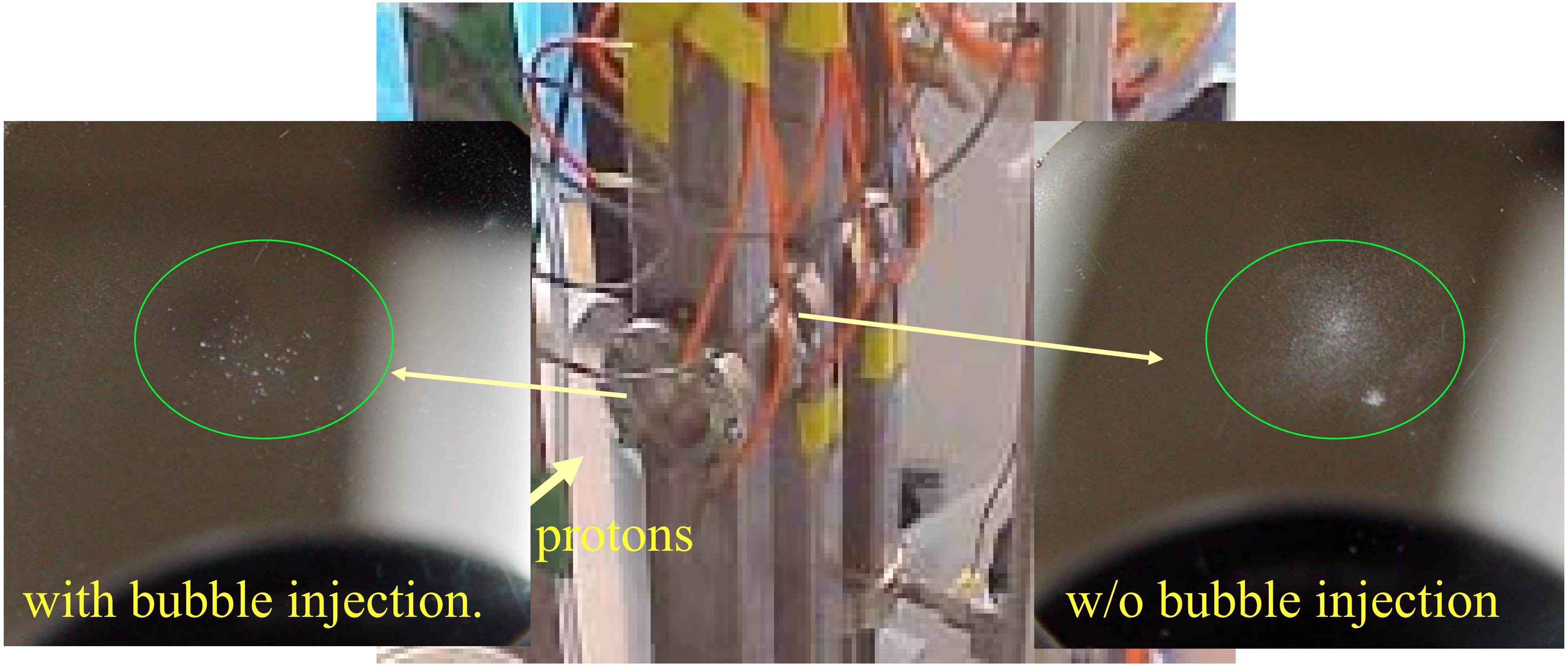
10 kHz→ 0.4mm



- 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

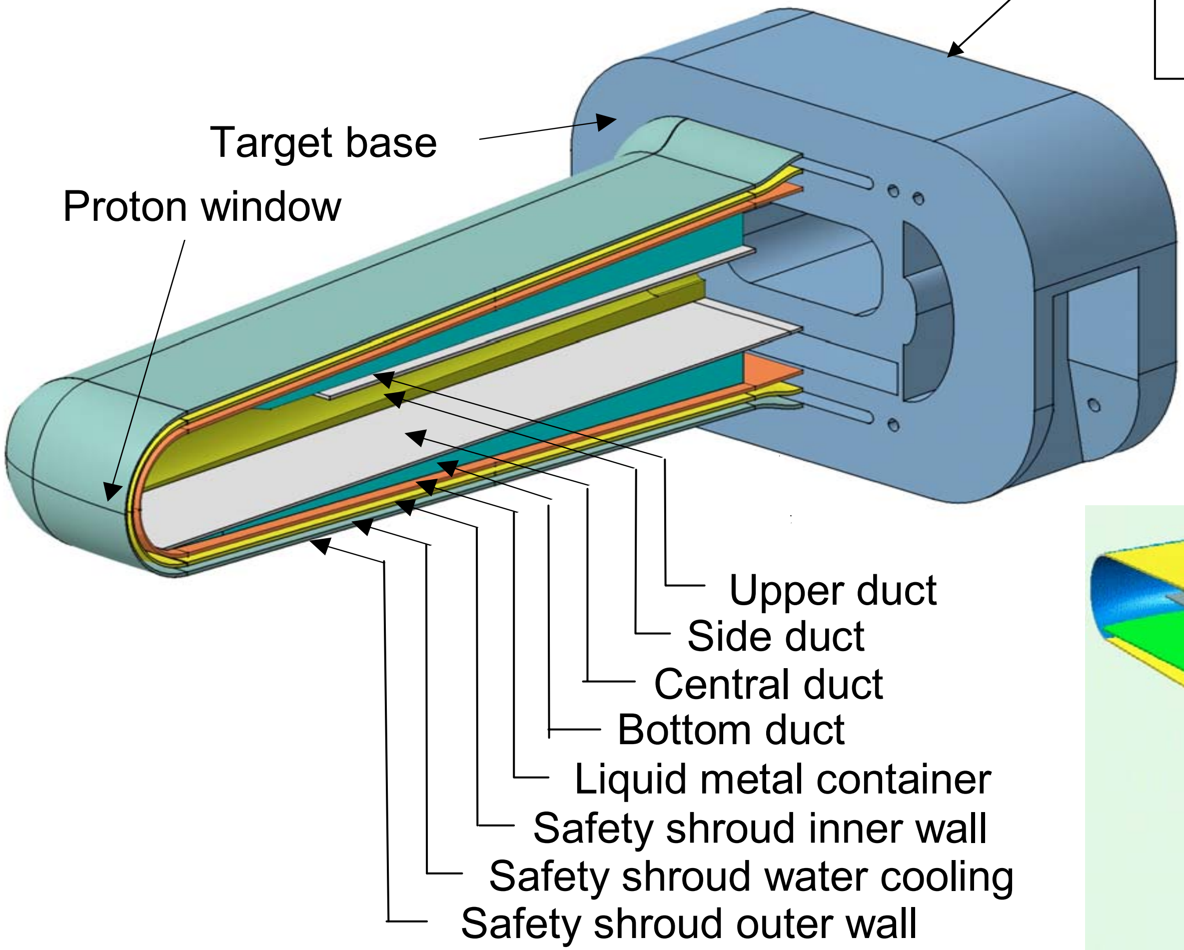
⇒ Find significantly less

Next series of tests at WNR under evaluation

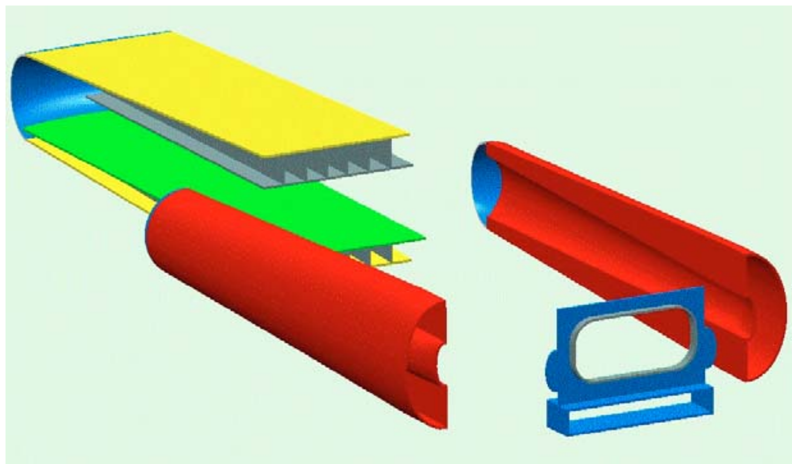
Liquid Metal Targets: Design example – ESS (1)

ESS target with quick disconnect flange for rapid exchange

Some connections may have to be made separately



Components of the liquid metal container

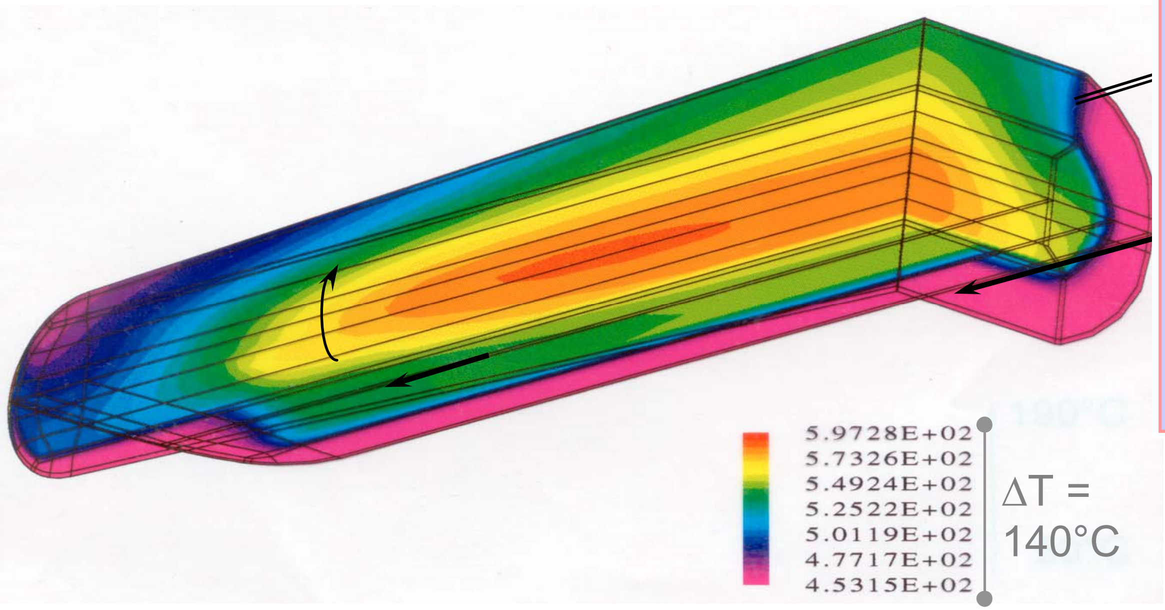


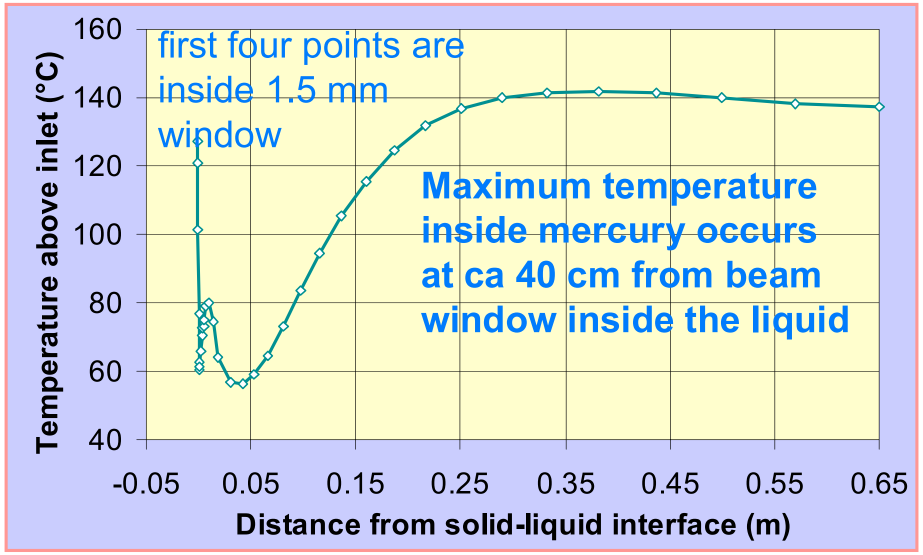
Liquid Metal Targets: Design example – ESS (2)

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).

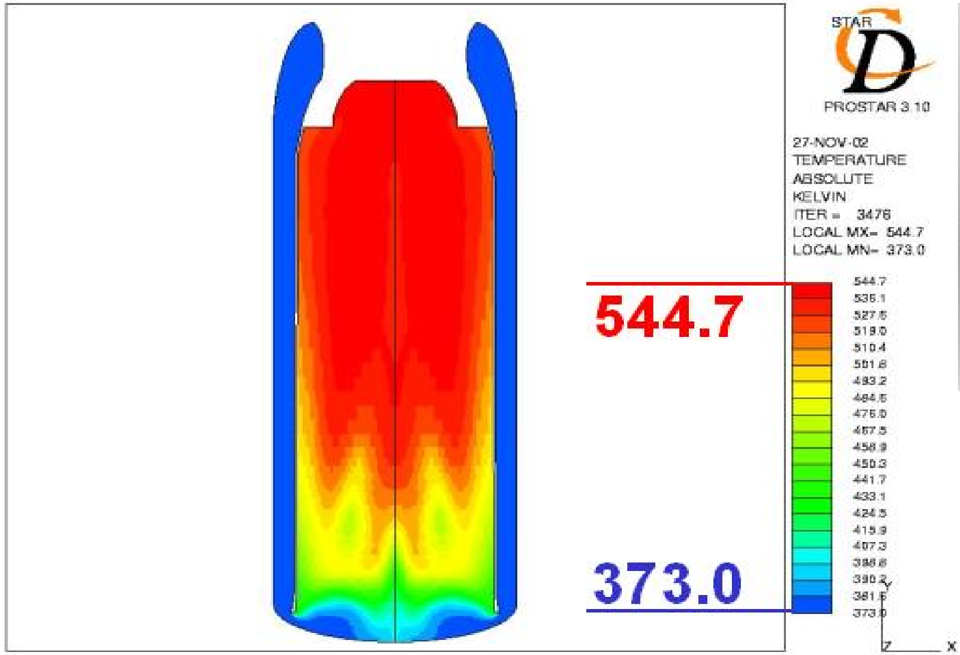
Bulk flow is away from the window!



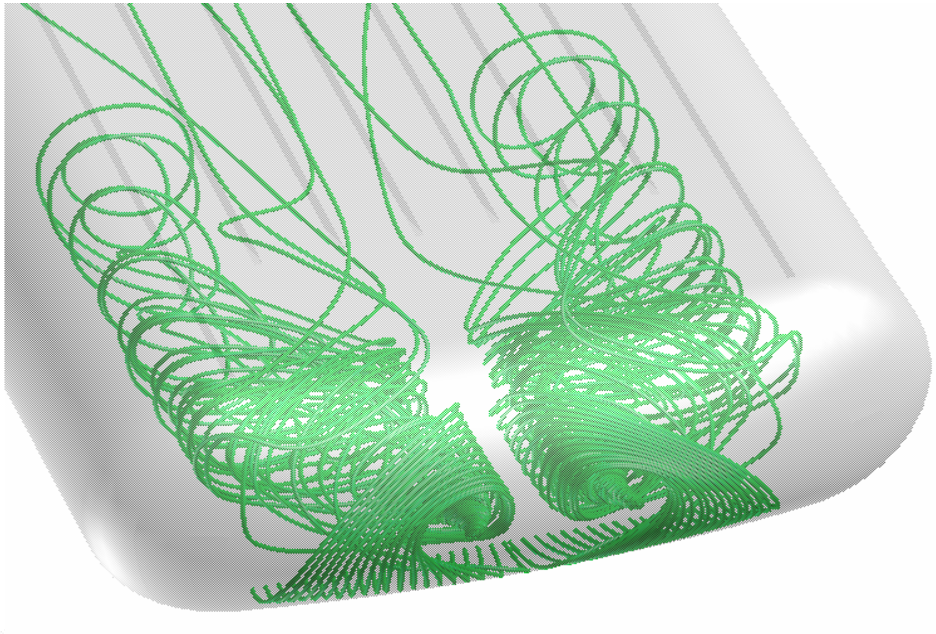


Liquid Metal Targets: Design example – ESS (3)

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]

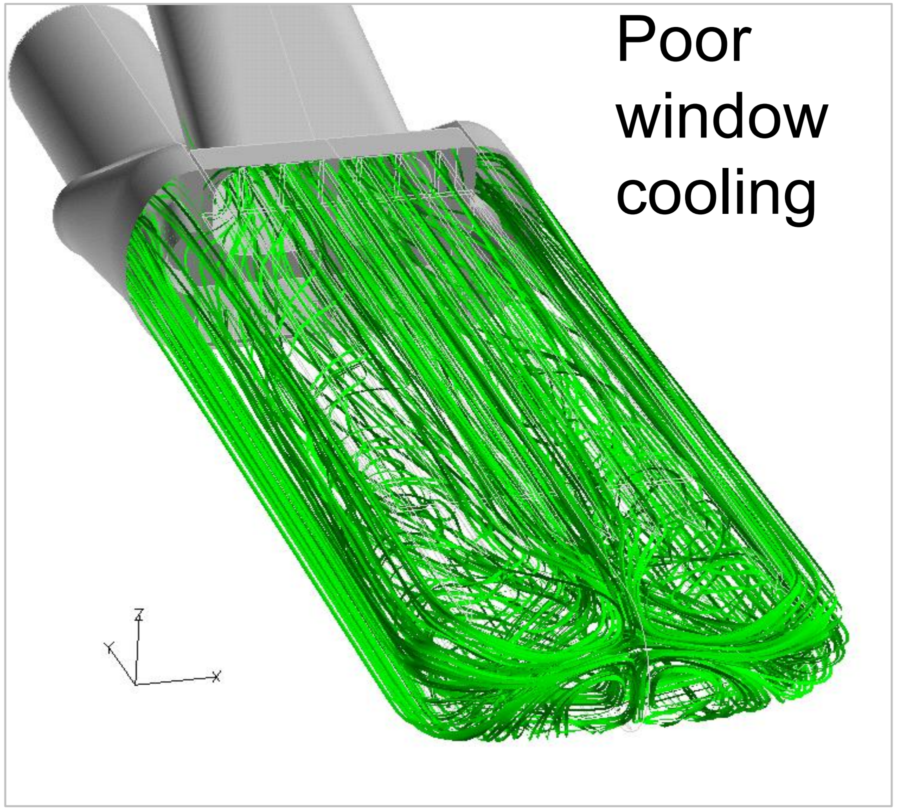
More work is clearly needed!

Liquid Metal Targets: Design example – ESS (4)

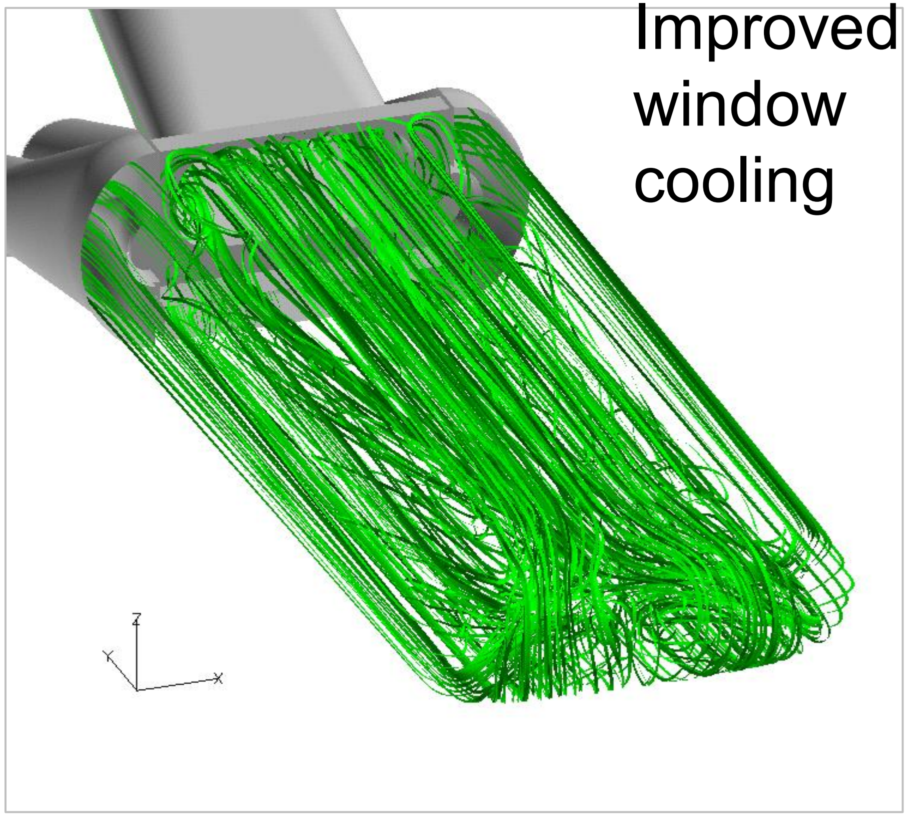
Optimizing the ESS target geometry

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

39% / 22% / 39%

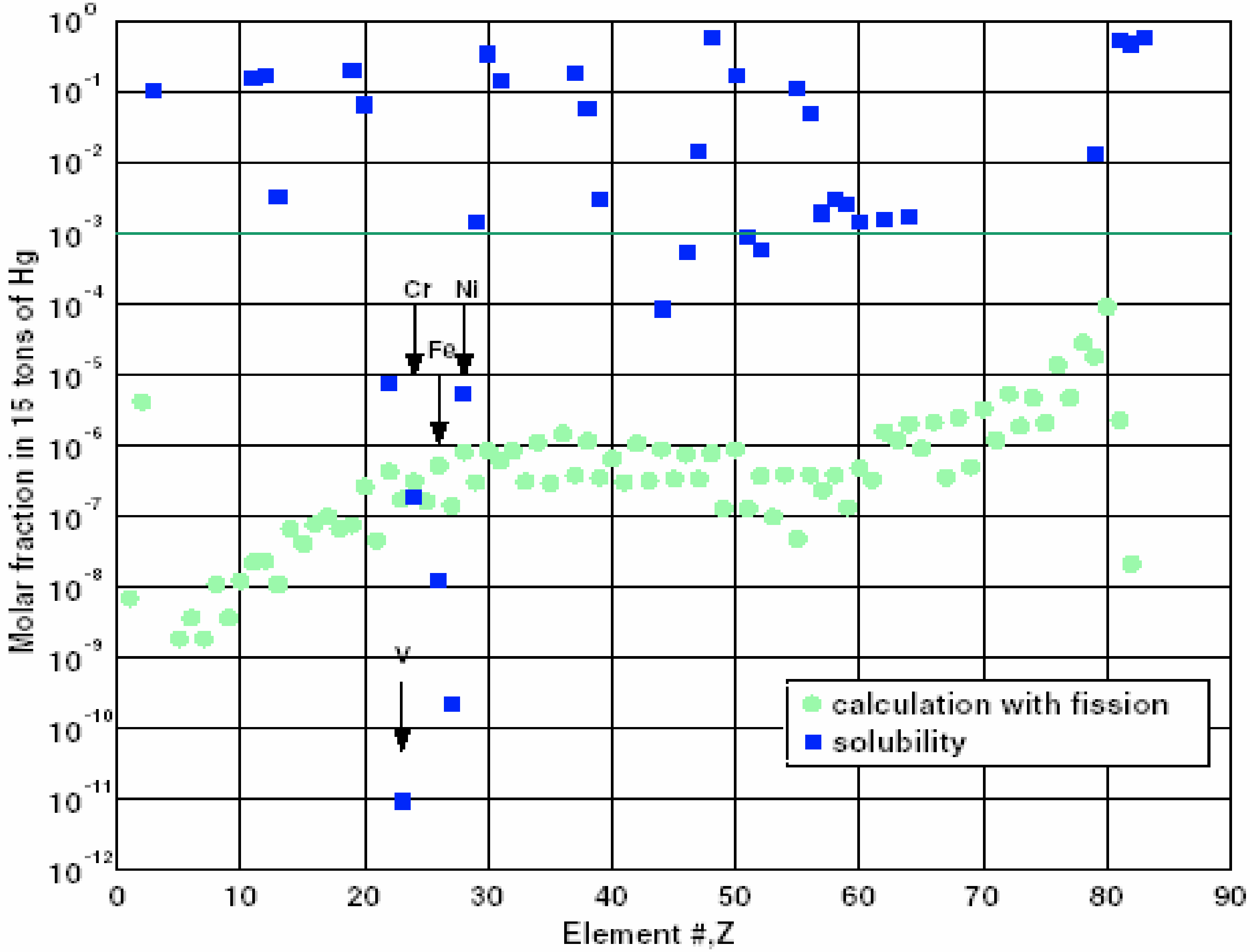


30% / 40% / 30%



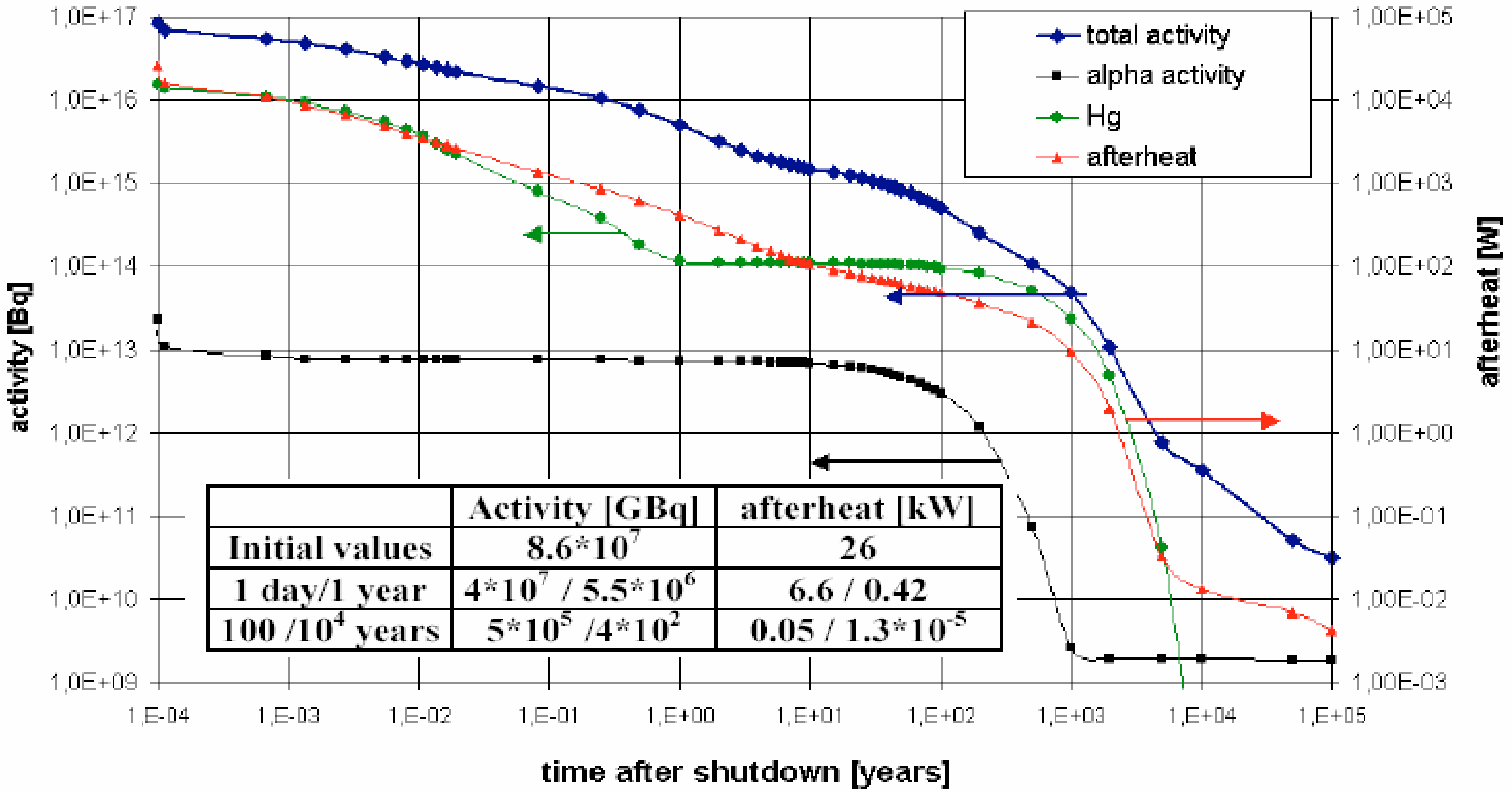
Mercury target: Radiation effects (1)

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



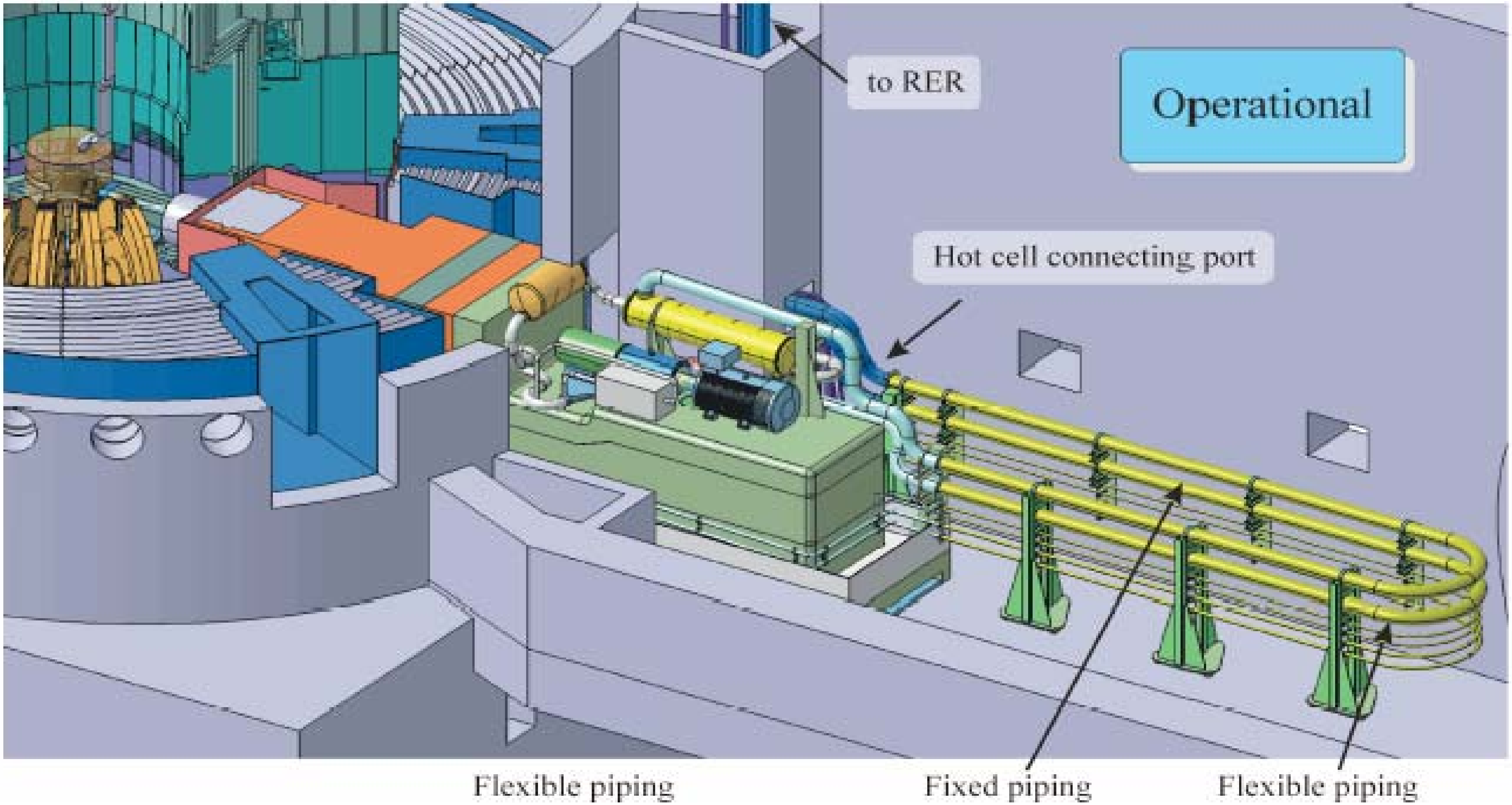
Mercury target: Radiation effects (2)

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



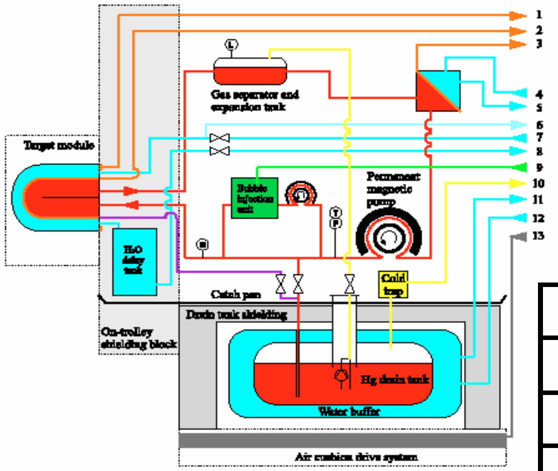
	Activity [GBq]	afterheat [kW]
Initial values	$8.6*10^7$	26
1 day/1 year	$4*10^7$ / $5.5*10^6$	6.6 / 0.42
100 /10^4 years	$5*10^5$ /$4*10^2$	0.05 / $1.3*10^{-5}$

Mercury Target Loop Design (1)



Mercury Target Loop Design (2)

Thermal hydraulics design parameters of the ESS primary target loop



Thermal power (design criterion)	2800	kW
Hg flow rate	220	kg/s
Hg flow rate (low flow shut down criterion)	175	kg/s
Hg temperature at target inlet (nominal)	60	°C
Hg temperature at target outlet (nominal)	152	°C
Hg temperature at target inlet (maximum)	80	°C
Hg temp. at target outlet (max. at low flow)	195	°C
Target Hg frictional pressure drop (nom. flow)	2.5	bar
Hg pressure at target inlet	5	bar
Loop Hg frictional pressure drop (nom. flow)	5-7	bar
Estimated Hg inventory including permanent sump in drain tank	20	t

Mercury Target Loop Design (4)

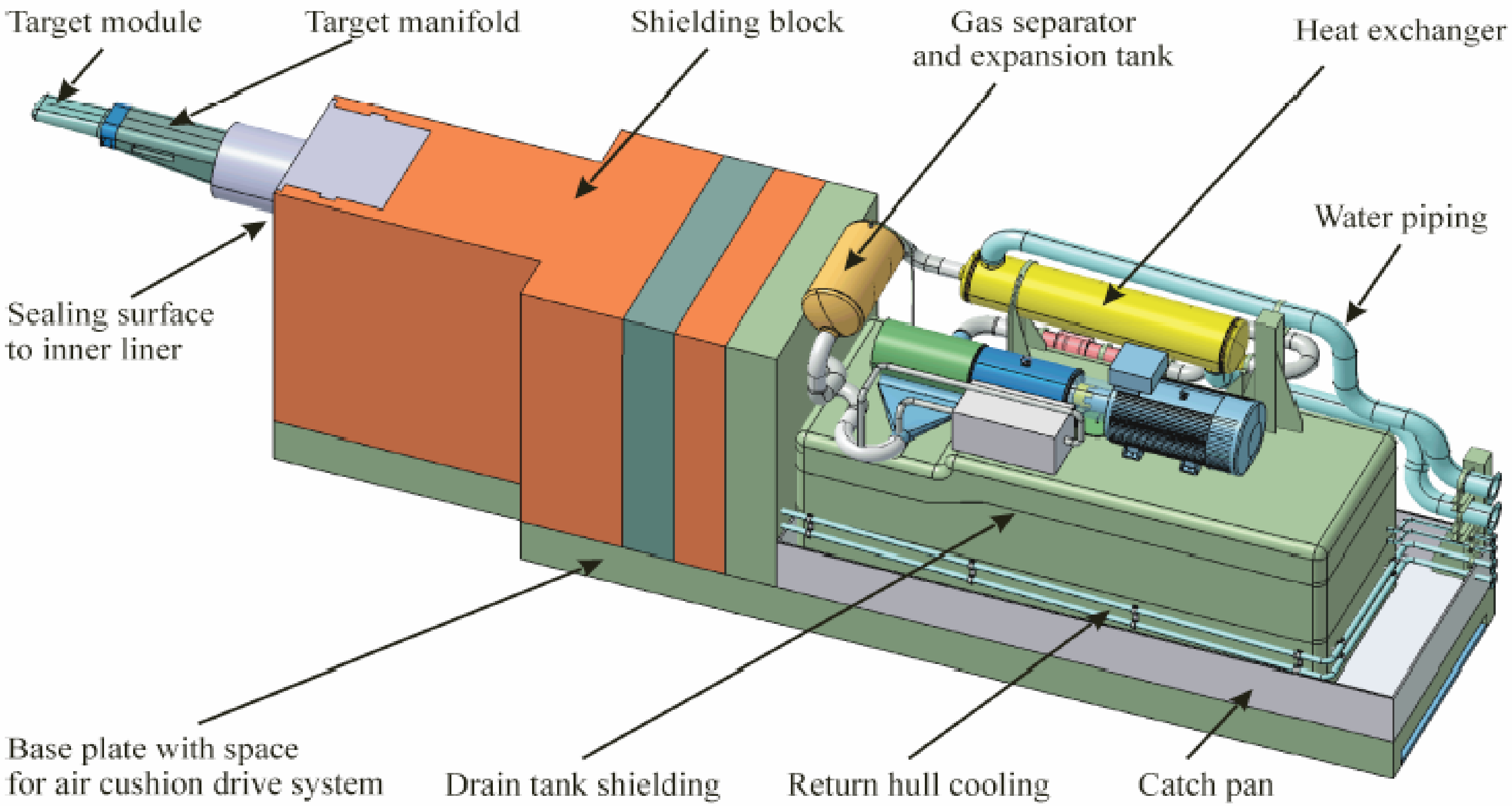
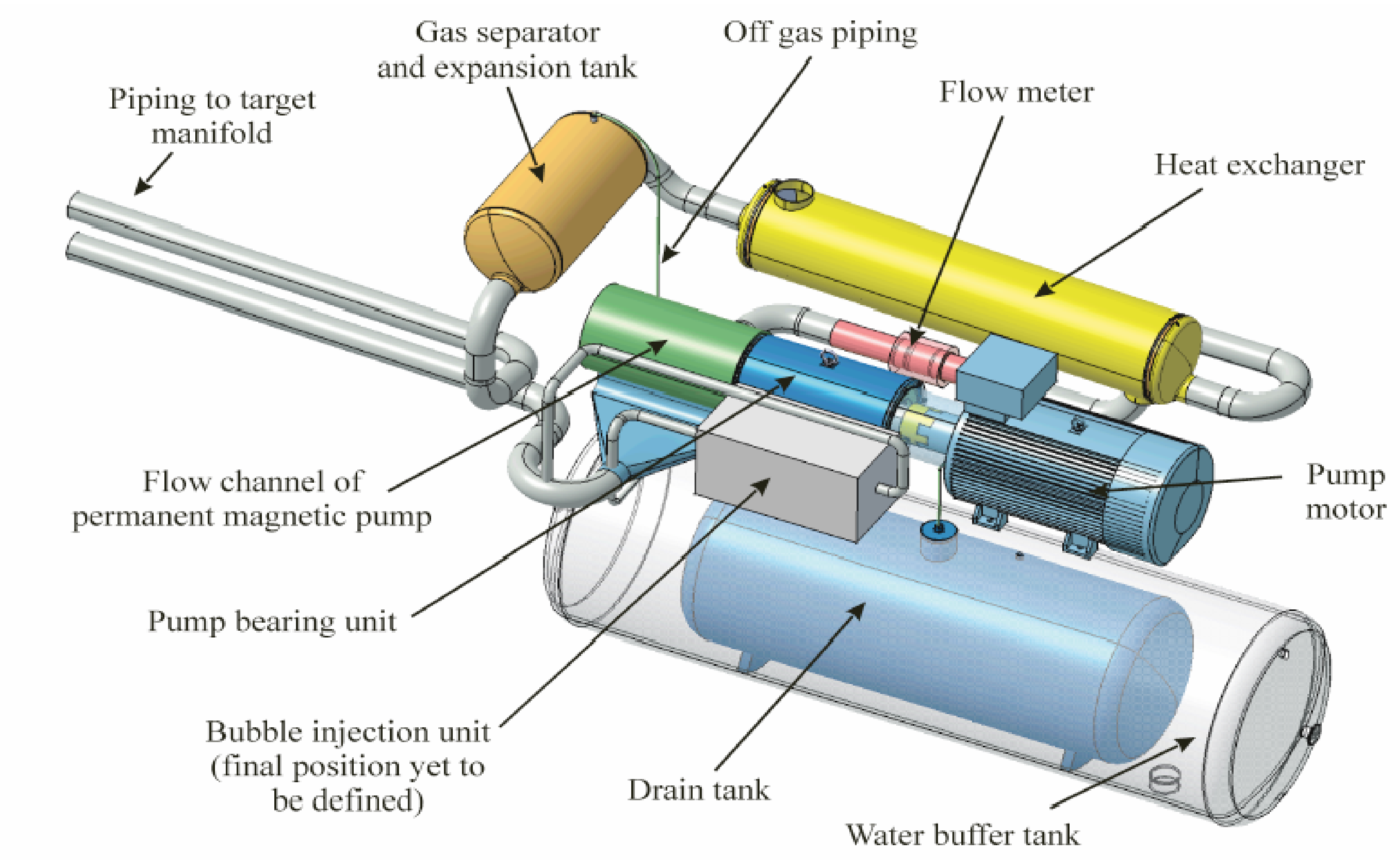


Figure 4.3.5.1: Trolley system (local shielding of components not shown)

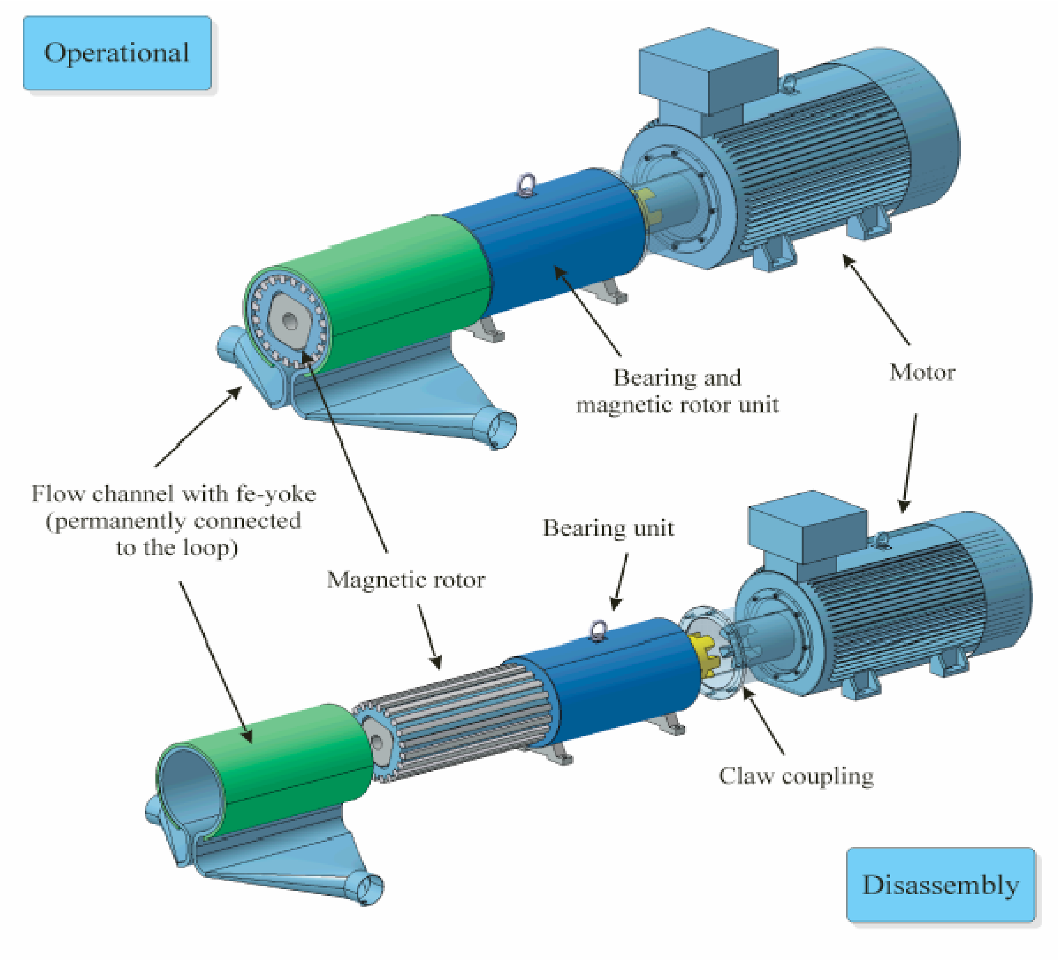
Mercury Target Loop Design (5)

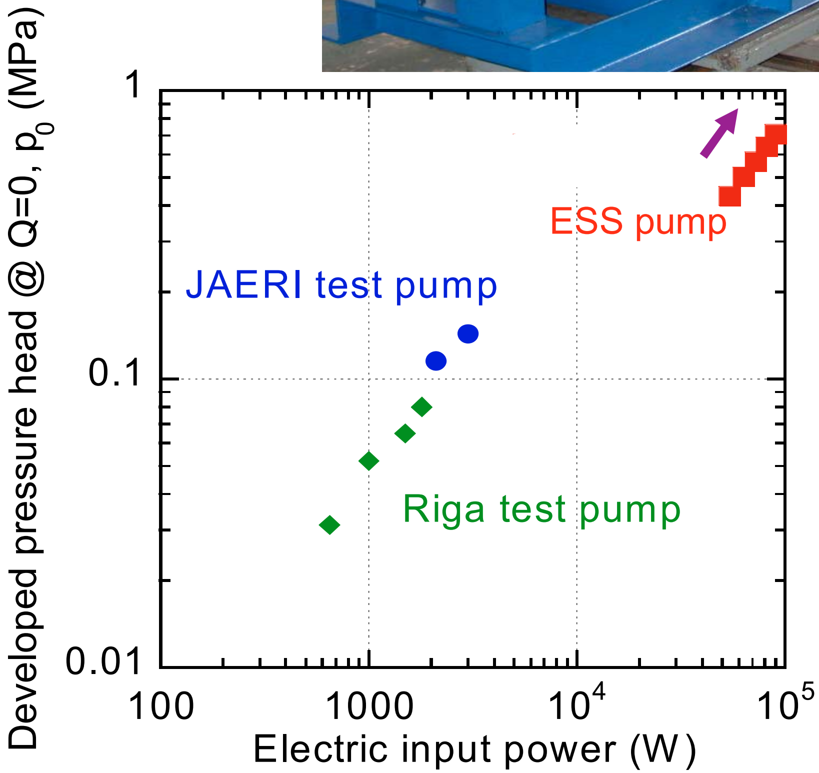
Arrangement of the ESS mercury loop components



Mercury Target Loop Design (6)

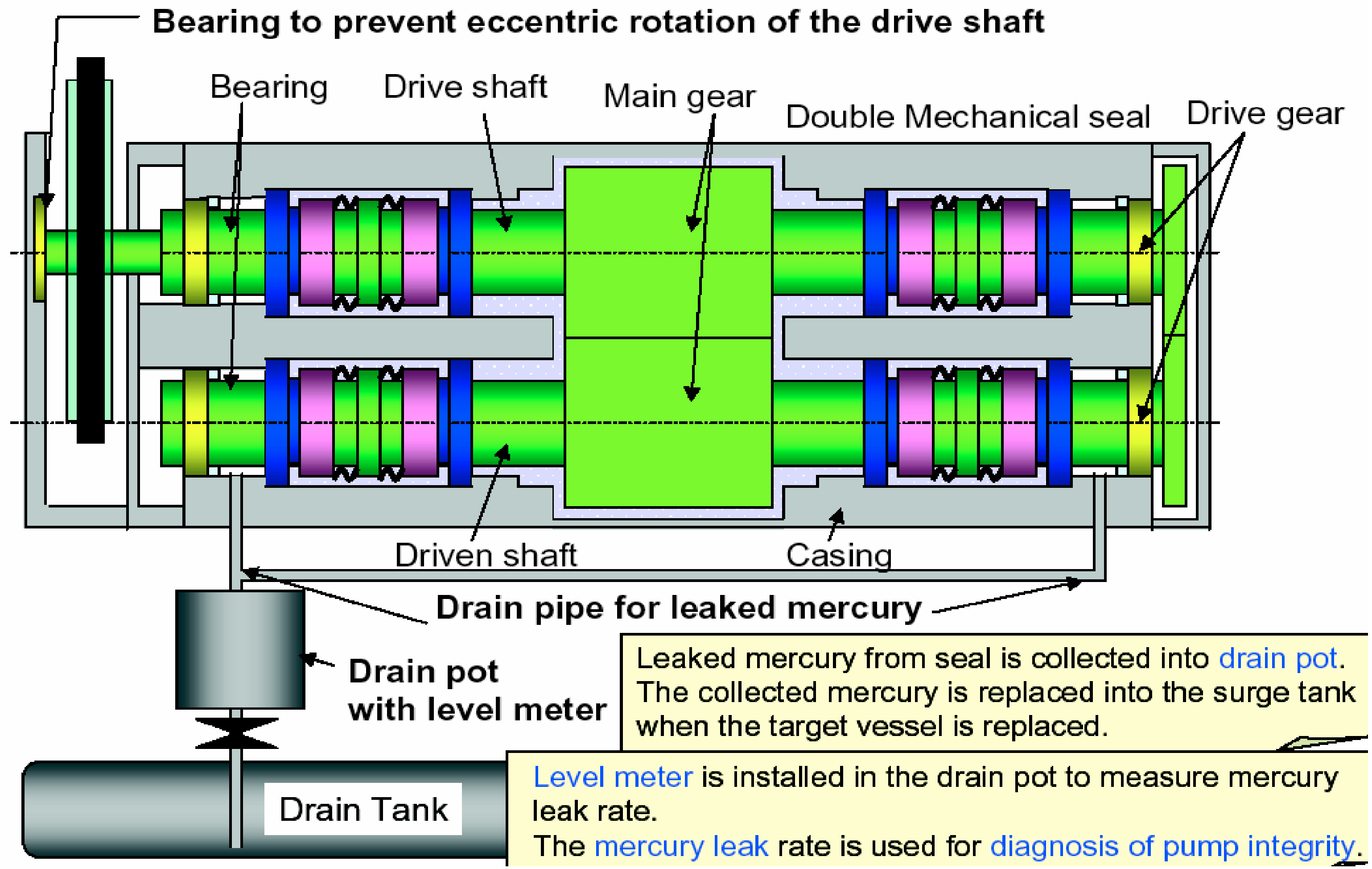
The ESS rotating magnets EM-pump



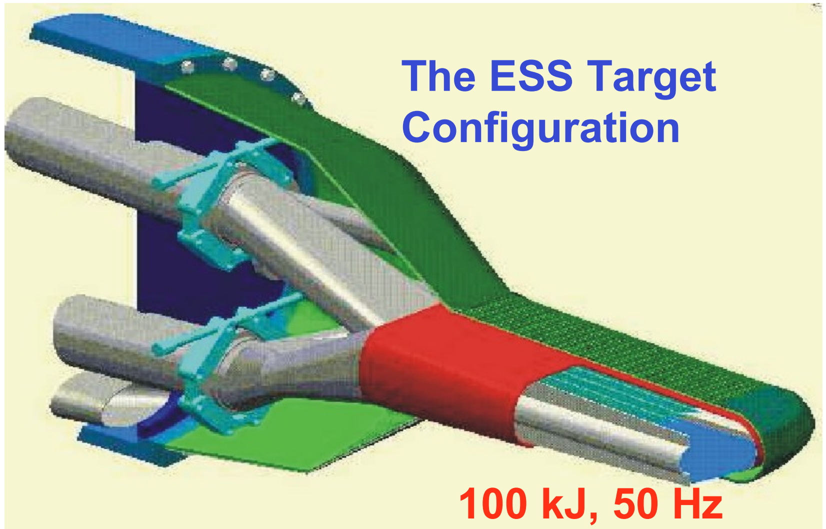


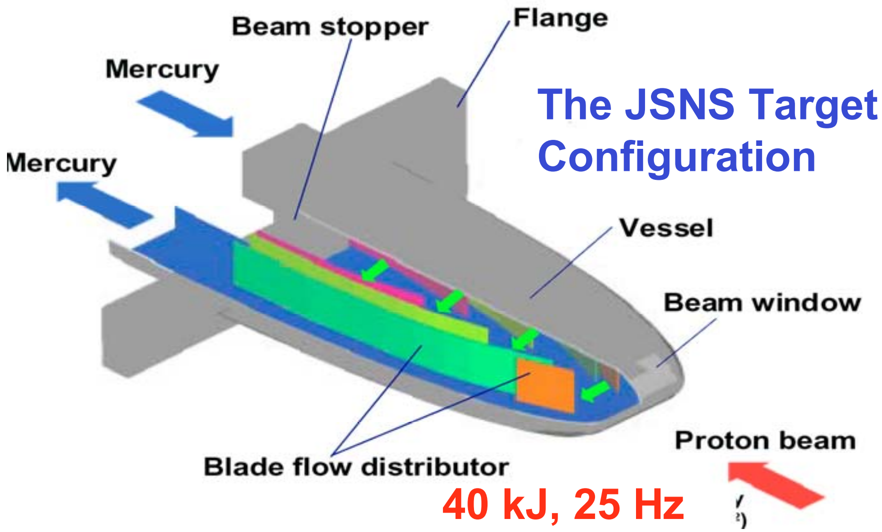
Mercury Target Loop Design (7)

Gear pump discussed in the JSNS Project

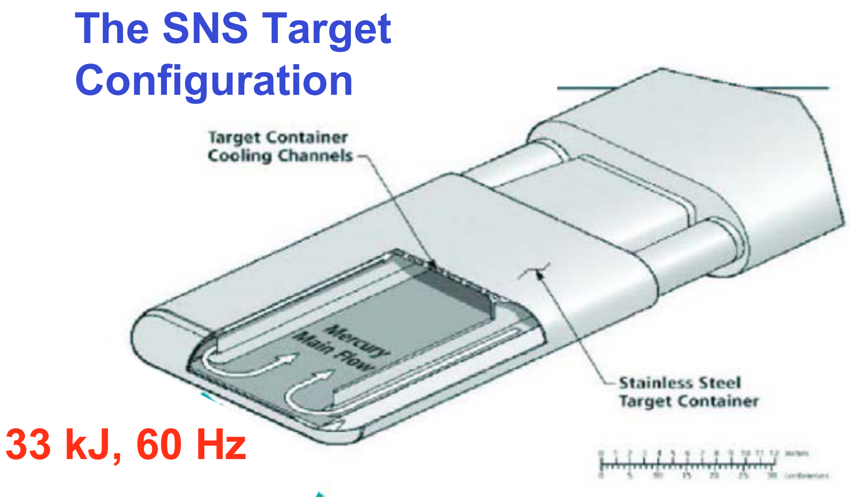


The ESS-SNS-JSNS Hg Target Concepts

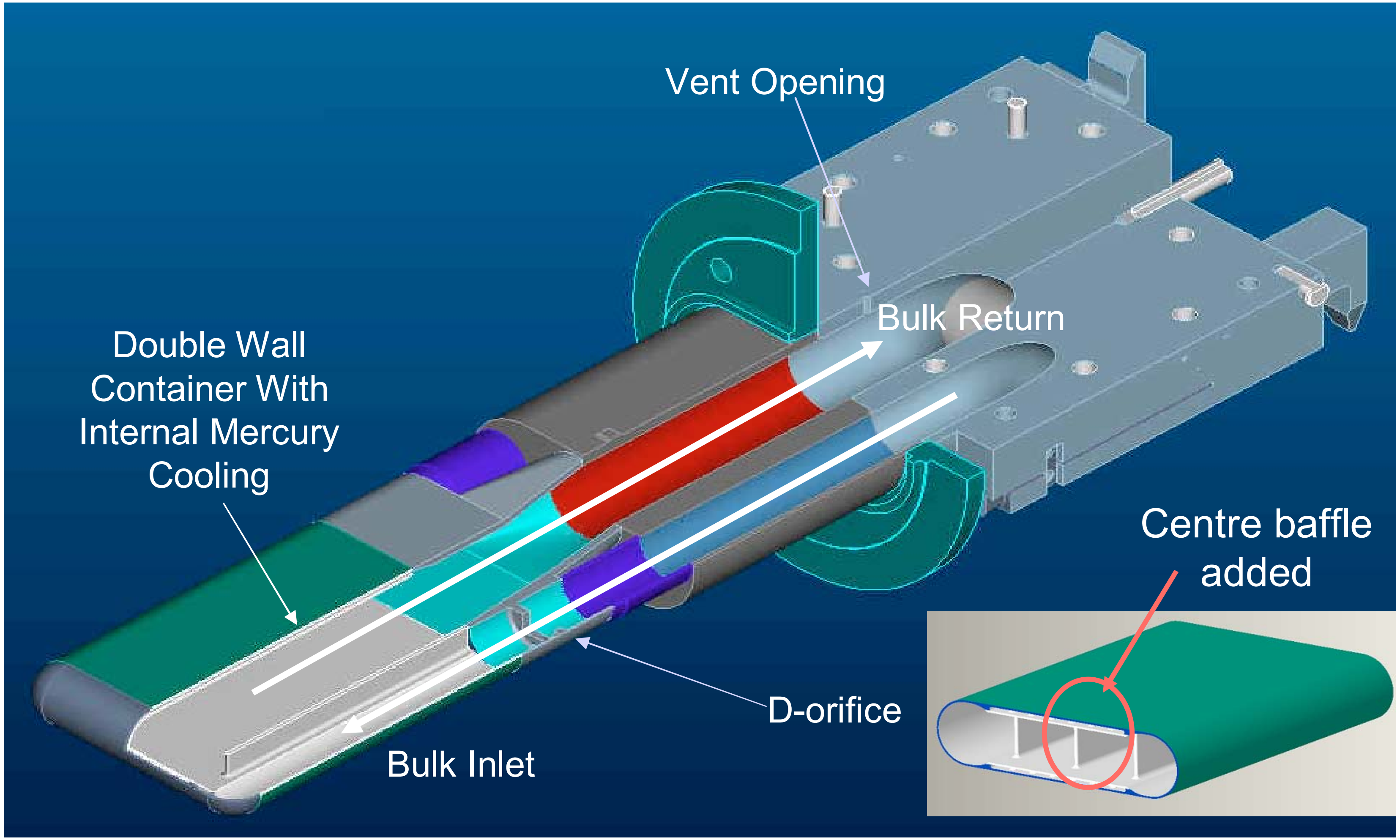




ESS (5 MW), SNS (2 MW) and JSNS (1 MW) use liquid mercury targets enclosed in steel shells, albeit with different internal flow distributions.



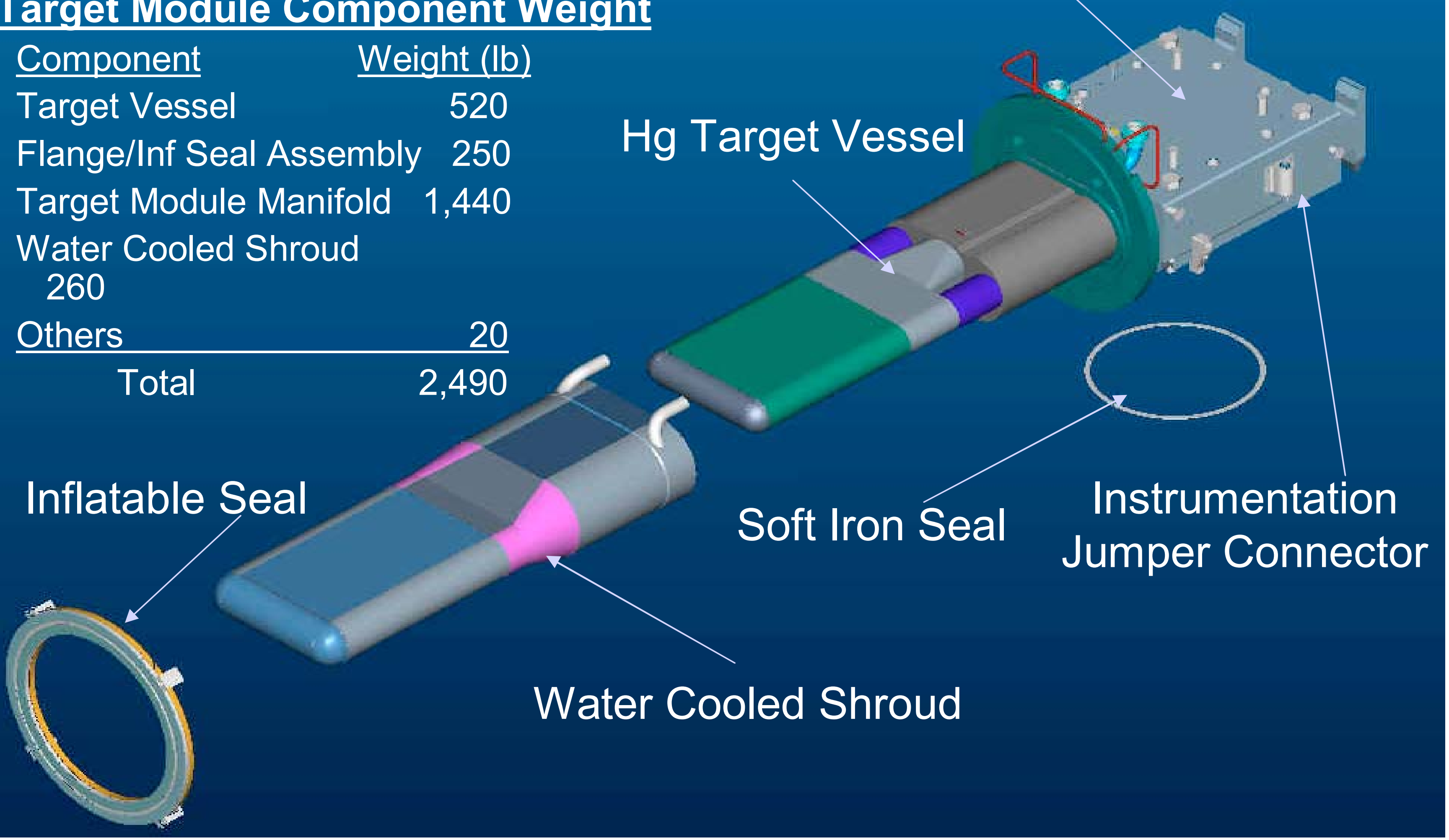
SNS - Hg Target Vessel Design



SNS - Hg Target Module

Target Module Component Weight

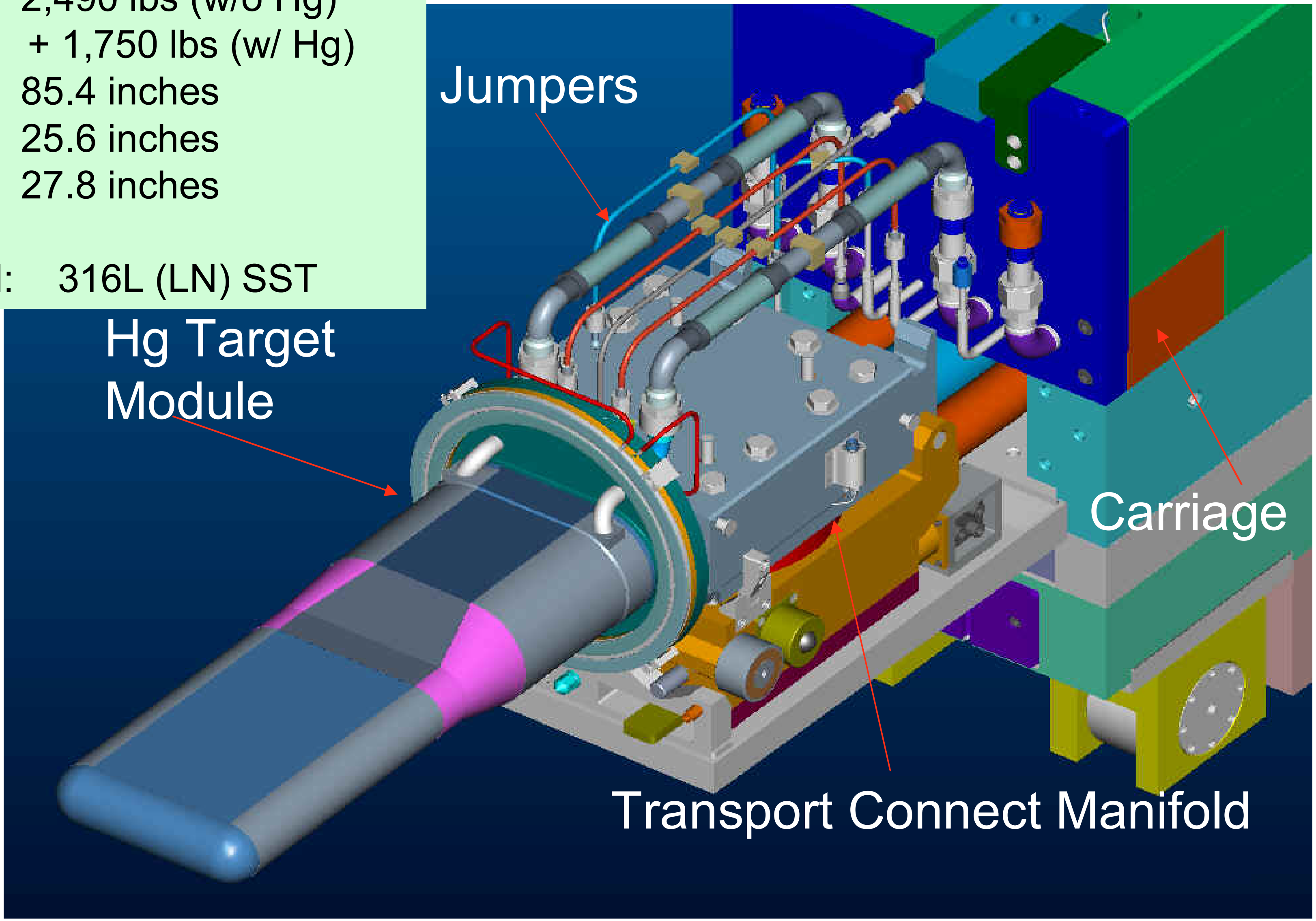
Component	Weight (lb)
Target Vessel	520
Flange/Inf Seal Assembly	250
Target Module Manifold	1,440
Water Cooled Shroud	260
Others	20
Total	2,490



SNS - Hg Target Module

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 experience with liquid metal targets!
- A pilot experiment is under preparation at PSI (MEGAPIE), albeit without beam compression (pulsing).
- In the context of this experiment the possible embrittlement of the wall by PbBi under irradiation and stress is investigated (LiSoR).
- SNS and JSNS will need to continue improving theit 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!

What - If?

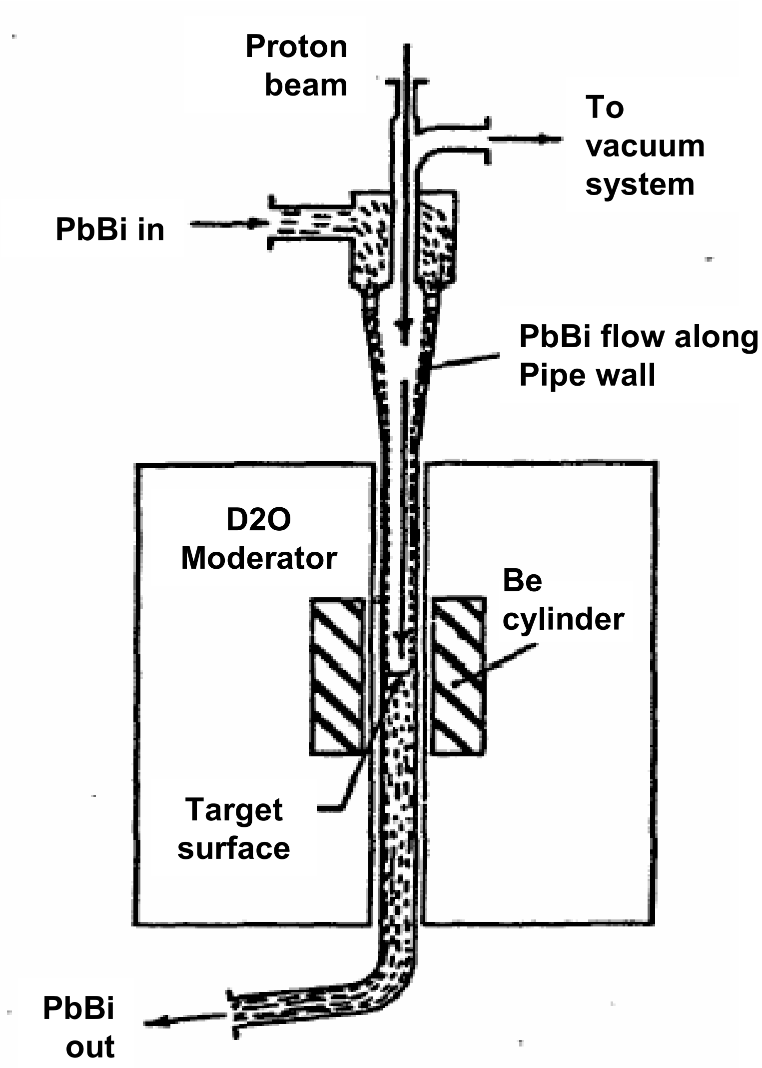
Although there exists a reasonable basis for the assumption that the pressure wave problem can be mitigated to a degree which allows an acceptably long service life for the targets of the 1 MW class pulsed Spallation neutron sources presently under construction (SNS and JSNS), the question remains as to whether this technology can be extended to 5MW class facilities or beyond.

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

A window-less liquid metal target??

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

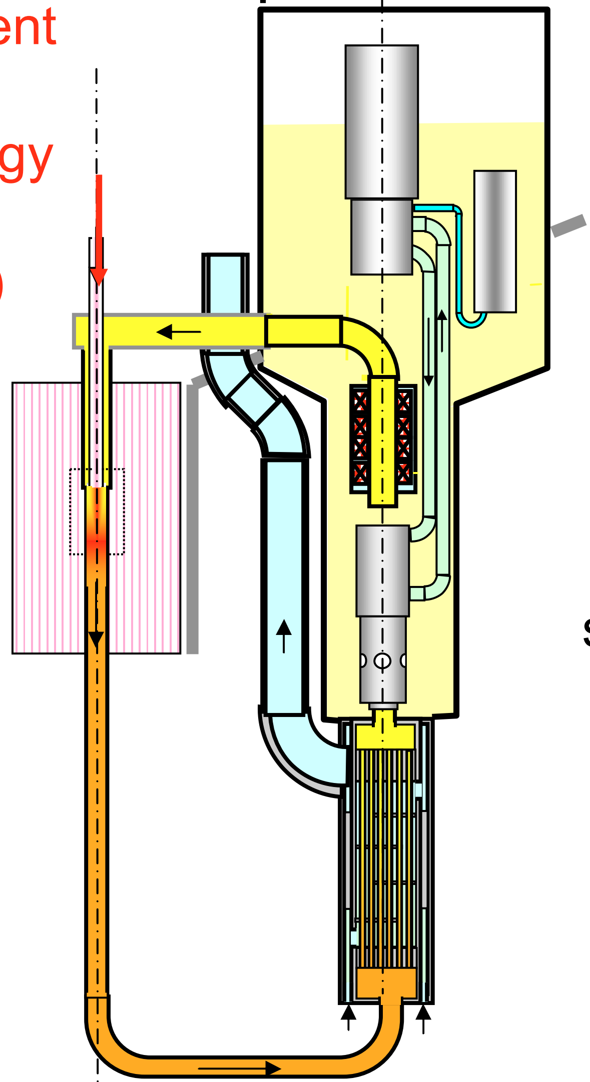


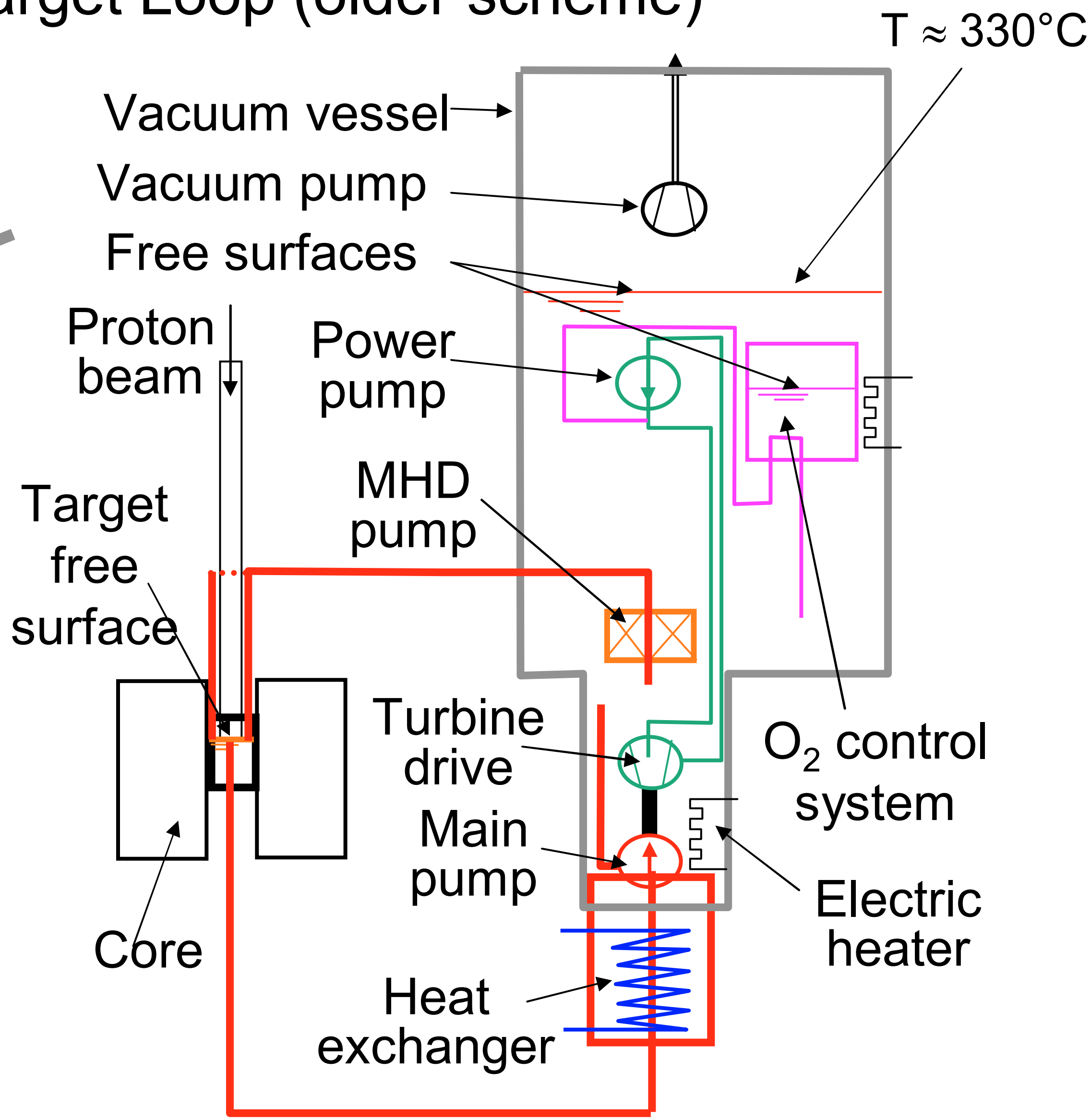
G.A. Bartholomew and
P.R. Tunnicliffe (eds),
"The AECL-Study for an
Intense Neutron Generator";
rep. AECL-2600 (1966)

Windowless Liquid Metal Targets (2)

The MYRRHA Spallation Target Loop (older scheme)

Beam current
5 mA
Beam energy
450 MeV
(2.25 MW_b)



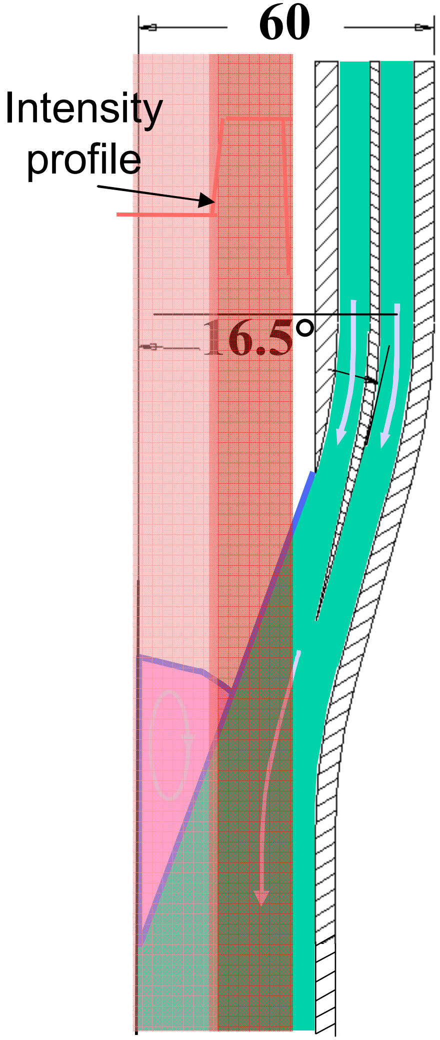


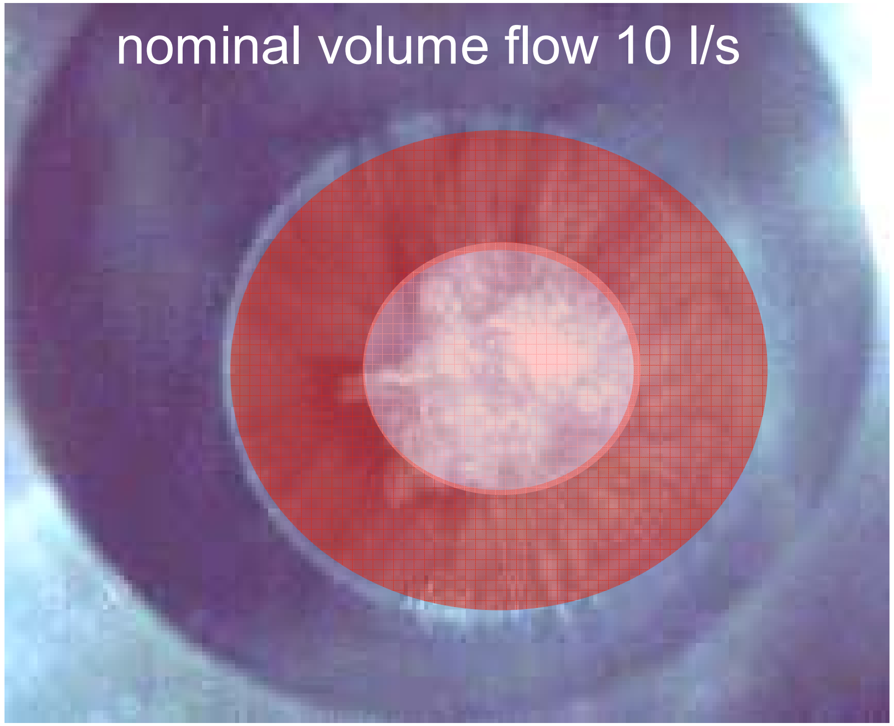
Windowless Liquid Metal Targets (4)

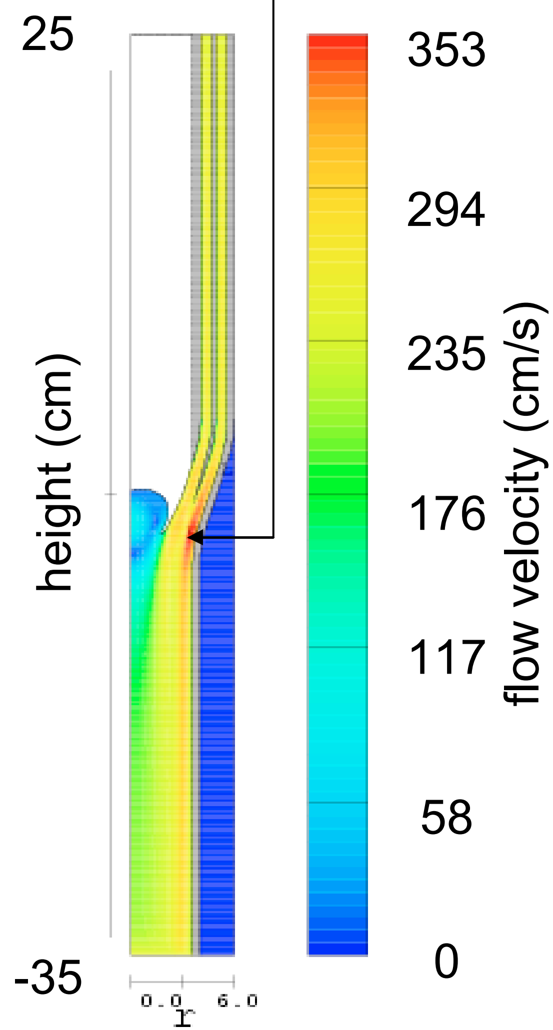
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

MYRRHA Spallation Target
Flow Experiment with Mercury

Risk of cavitation?





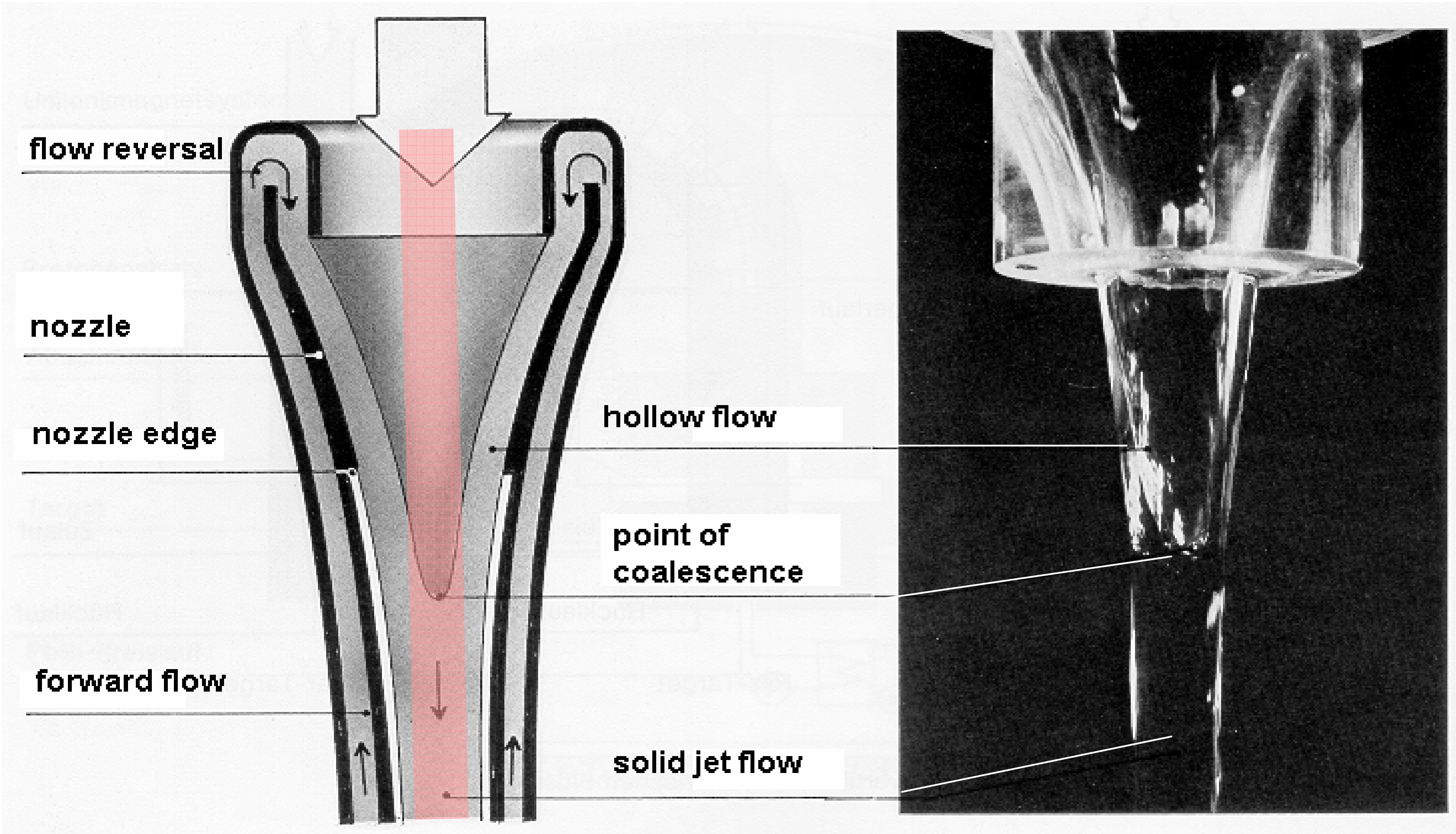


Close to desired configuration !

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

Windowless Liquid Metal Targets (5)

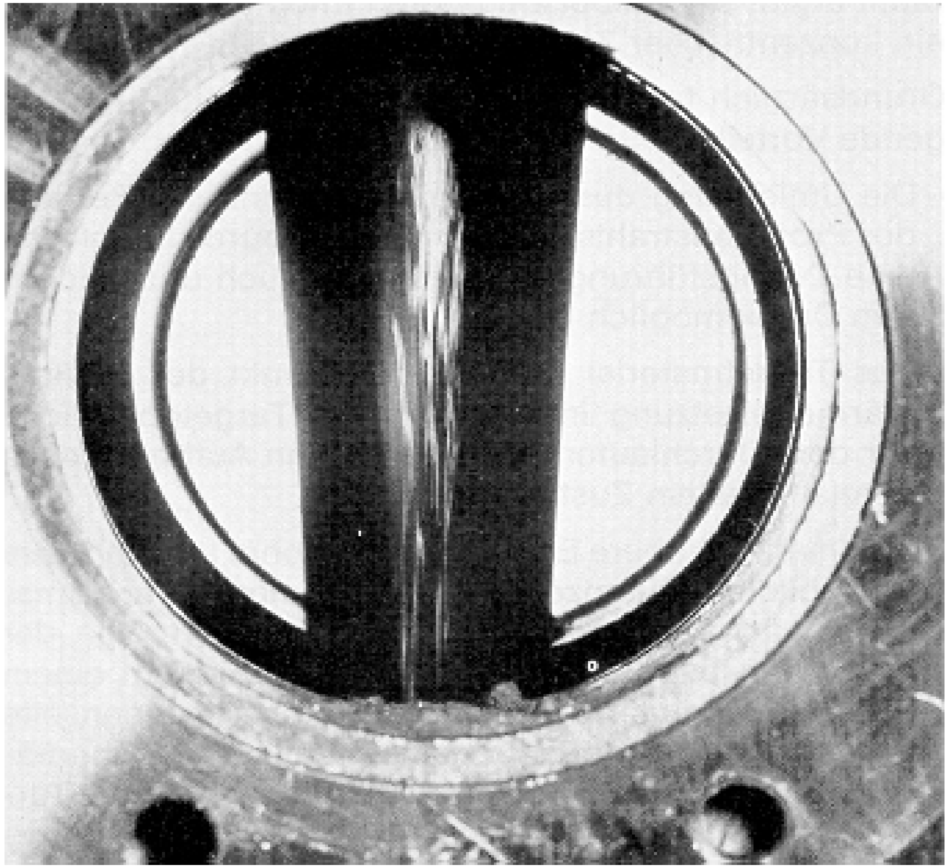
The SNQ Study: *“Free Falling Jet”*



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

Windowless Liquid Metal Targets (6)

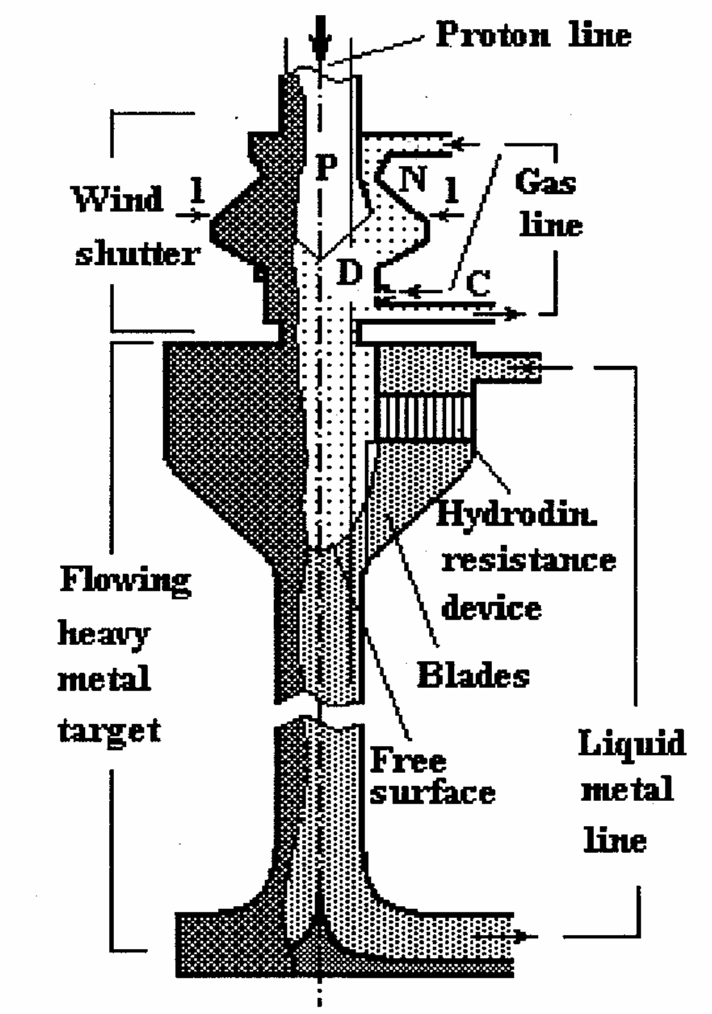
The SNQ Study: Small scale PbBi jet experiment at KfK



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.

Windowless Liquid Metal Targets (7)

ISTC-17 Study*



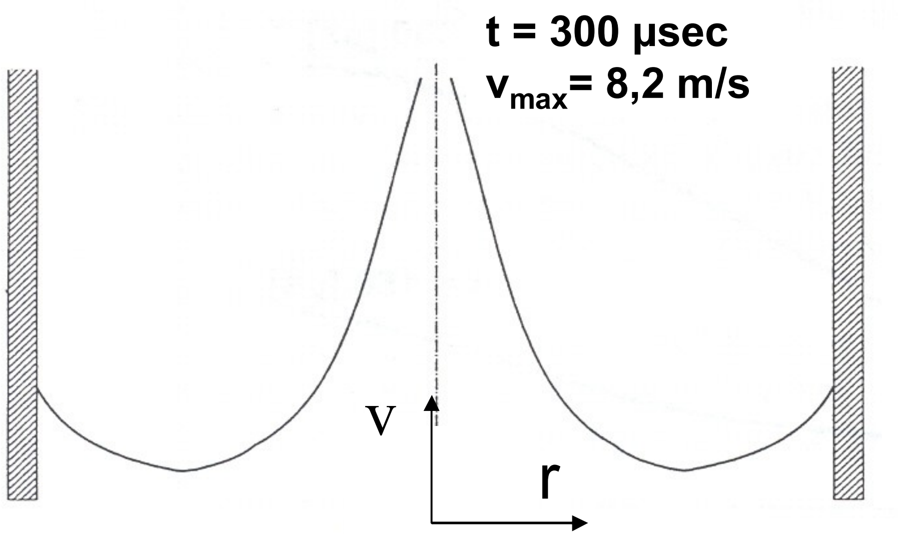
- Design goal: 20 MW_b
- Flow guided on outside
- Gas pressure above free surface found necessary to prevent cavitation; supersonic gas jet proposed
- Forced coalescence point; risk of re-circulating zone; “swirl" (angular momentum) imposed by blades was found not to solve this problem.

**Belyakov-Bodin et al. Kalmar 1996*

Windowless Liquid Metal Targets (8)

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*

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

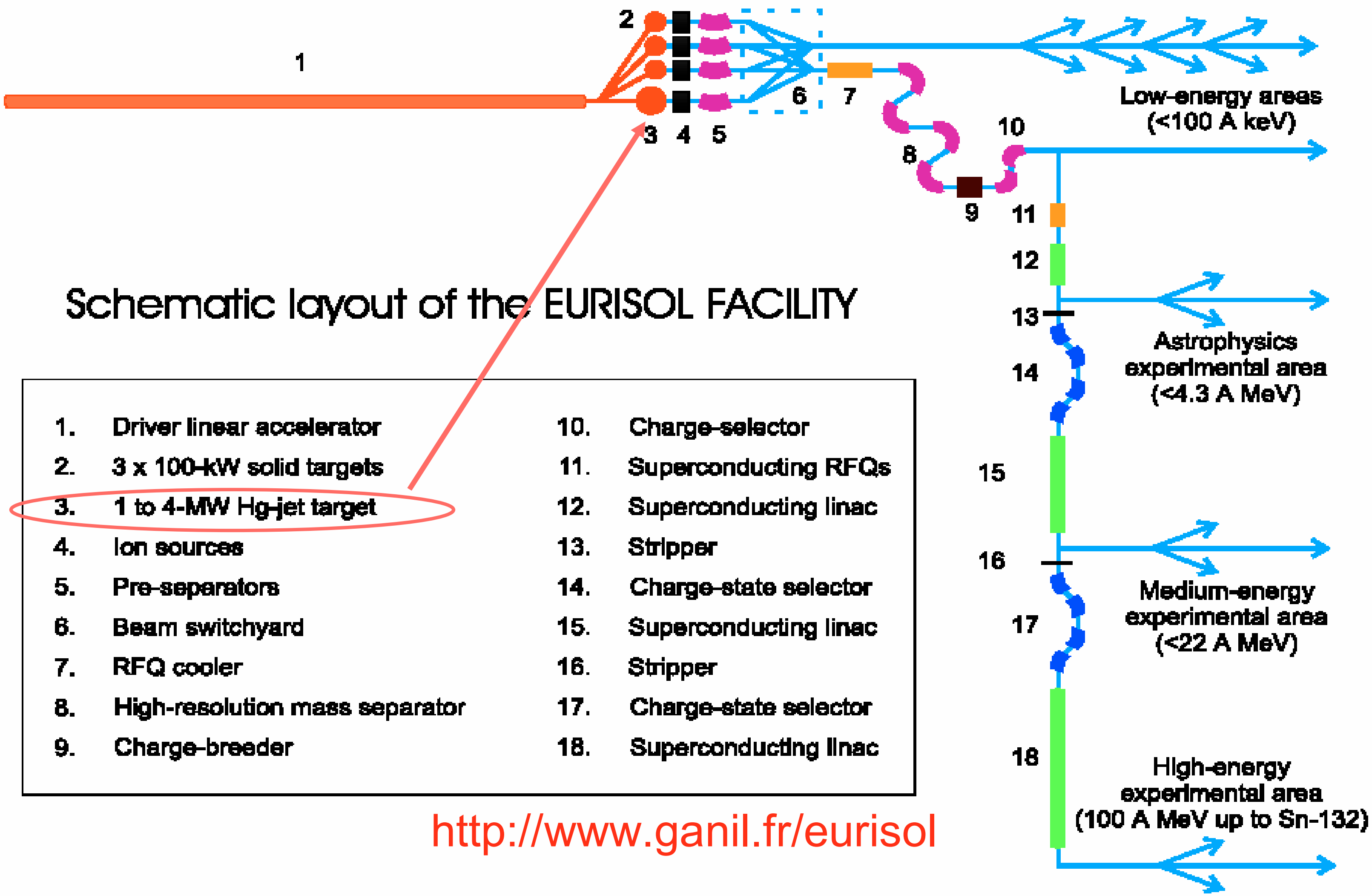
*K. Skala and G.S. Bauer, Proc ICANS XII, pp. 559-571 (1995)

So, What now?

What can we learn by
looking over the fence?

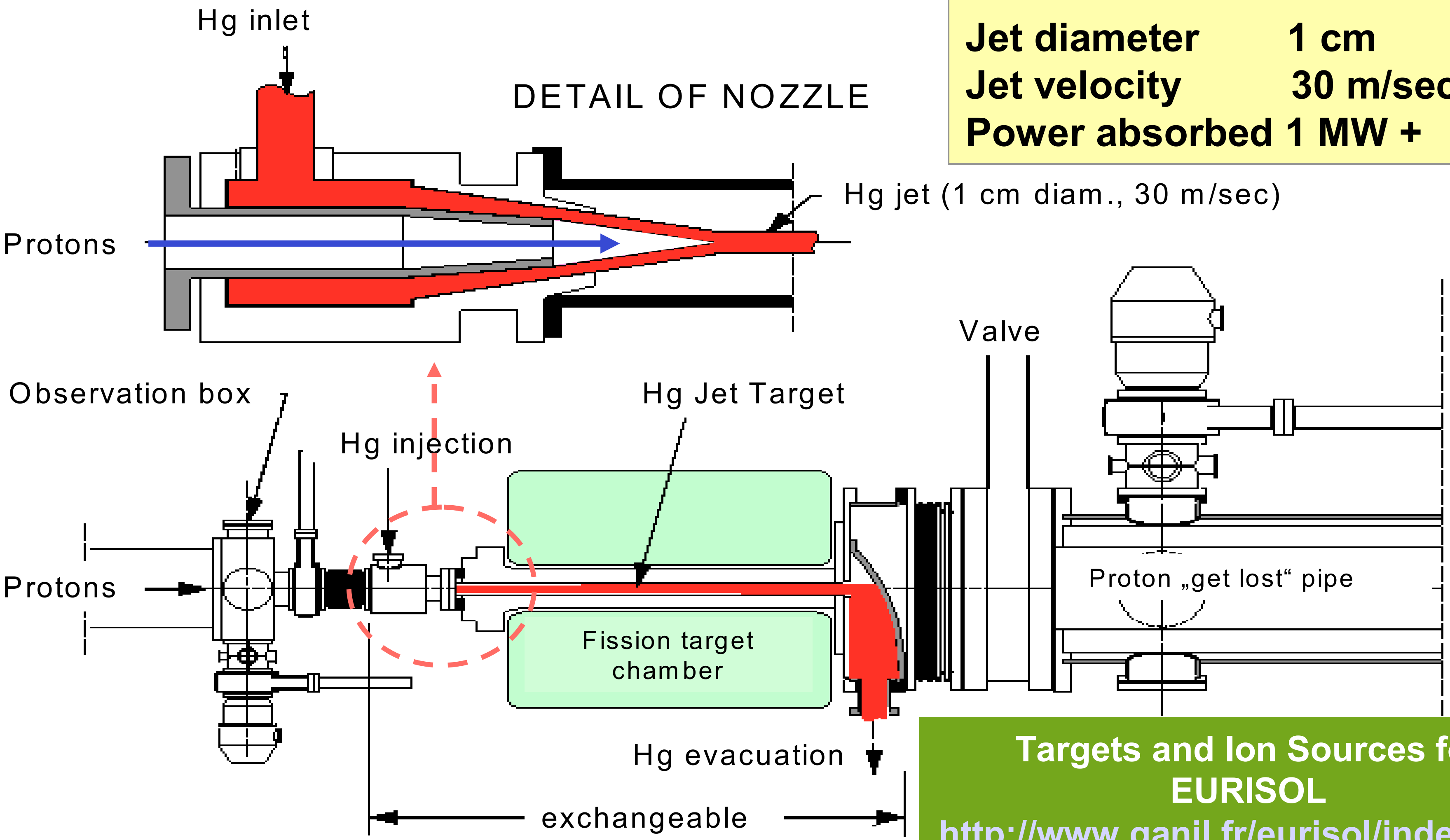
A Free Jet Target for EURISOL

EURISOL European Isotope Separation On-Line Radioactive Nuclear Beam Facility



http://www.ganil.fr/eurisol

The EURISOL Hg Jet Target Concept



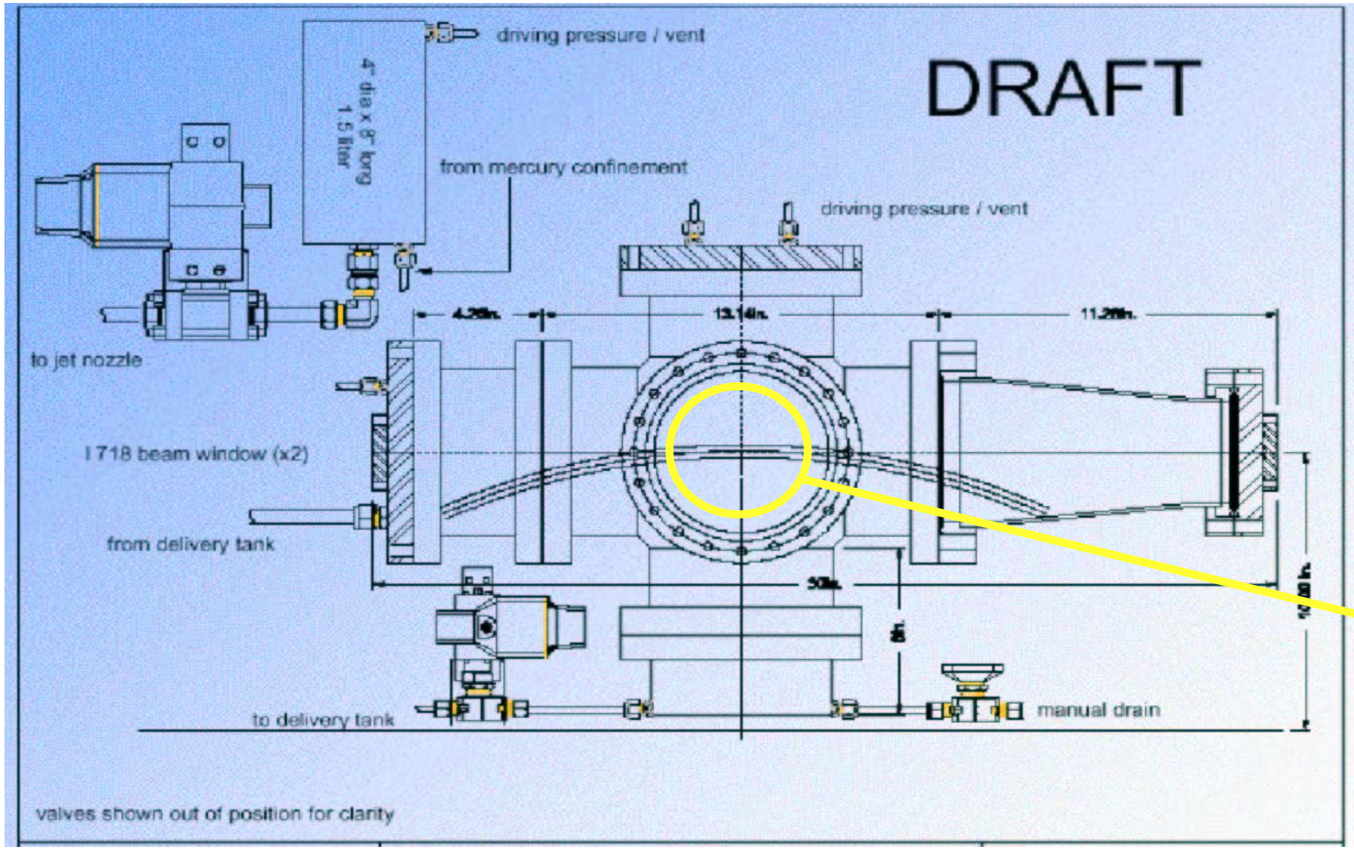
Target Parmeters:

Jet diameter 1 cm
Jet velocity 30 m/sec
Power absorbed 1 MW +

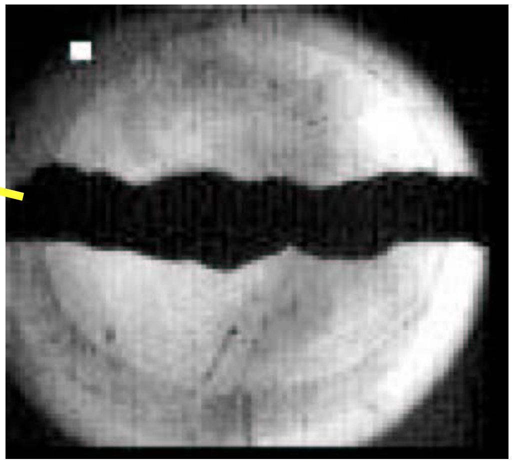
Targets and Ion Sources for EURISOL
http://www.ganil.fr/eurisol/index.html

The NuFact Hg Jet Target Experiment with Pulsed Beam

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



POP-Test at 1/100 of ultimate power density and 1/10 of required jet speed



The NuFact Hg Jet Target Experiment with Pulsed Beam

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

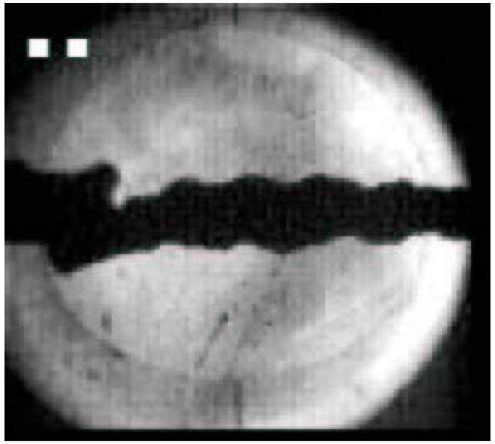
Event #11, April 25, 2001

Hg-Jet:

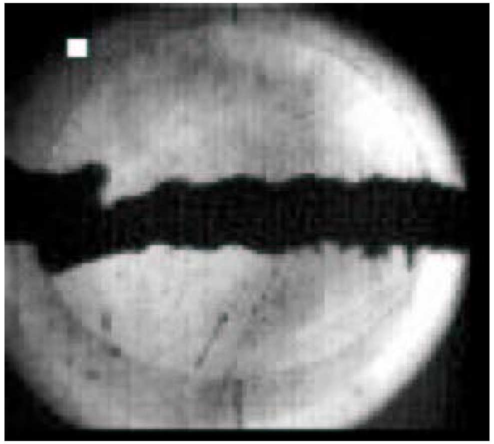
diameter 1.2 cm

velocity 2.5 m/s

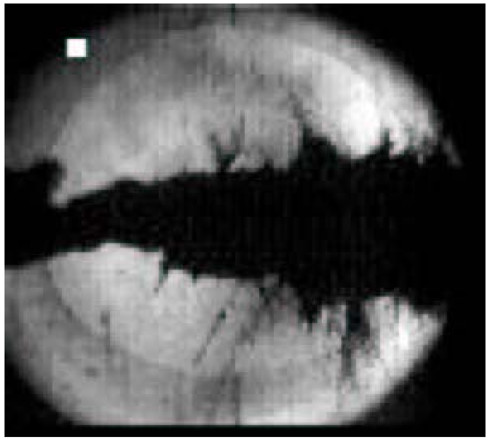
perp. velocity: ca 5m/s



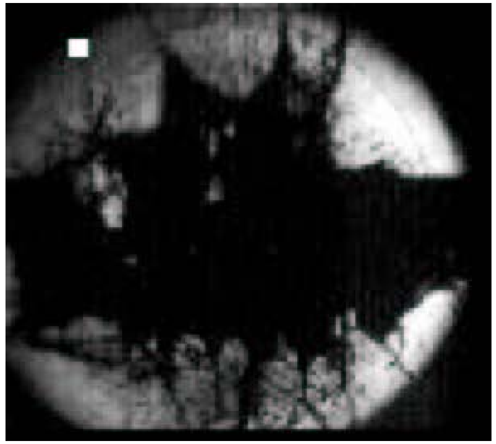
0.00 ms



0.75 ms



4.50 ms



13.00 ms

$2{,}7\text{x}10^{12}$ protons

100 nsec

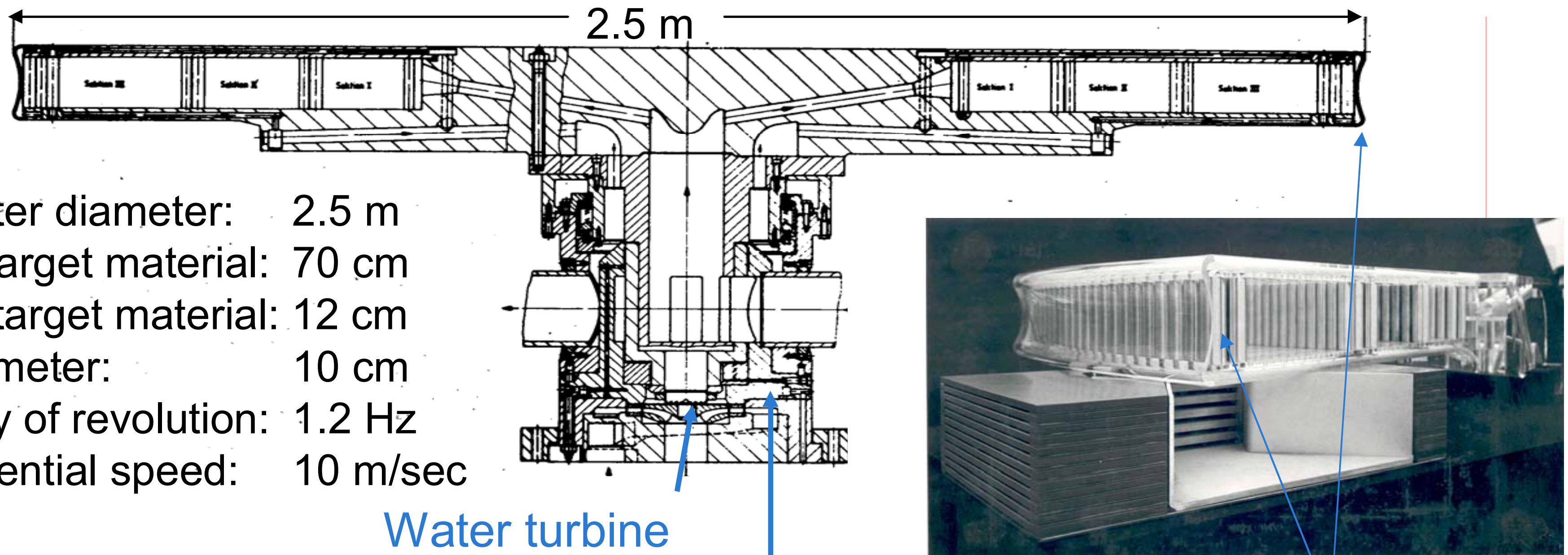
t_0 ca. 0,45 ms

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.
- In any case, the experience that accrues from designing and operating research spallation neutron sources will be of great value for ADS facilities.

Thank you for your patience!

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

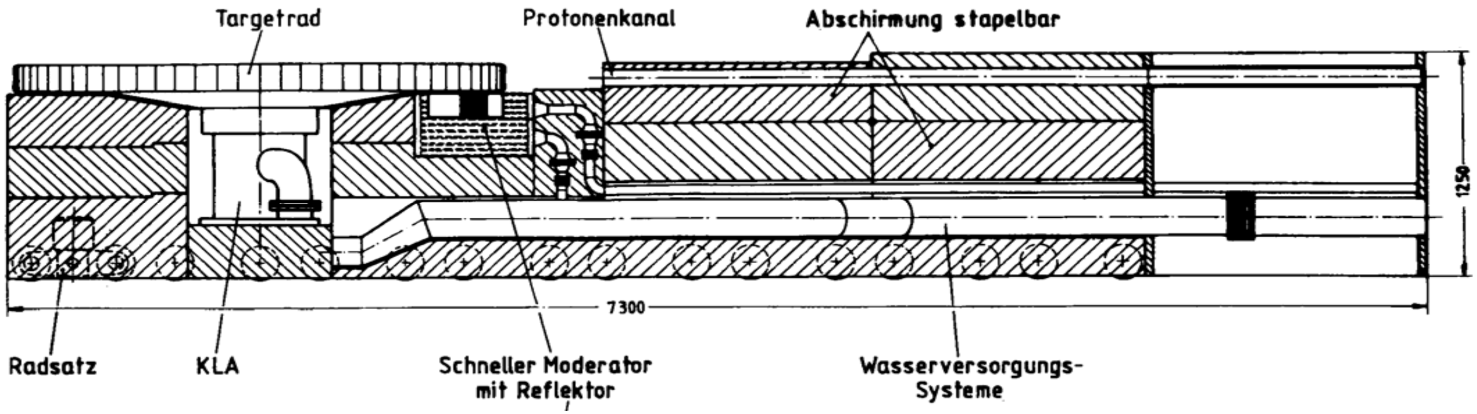


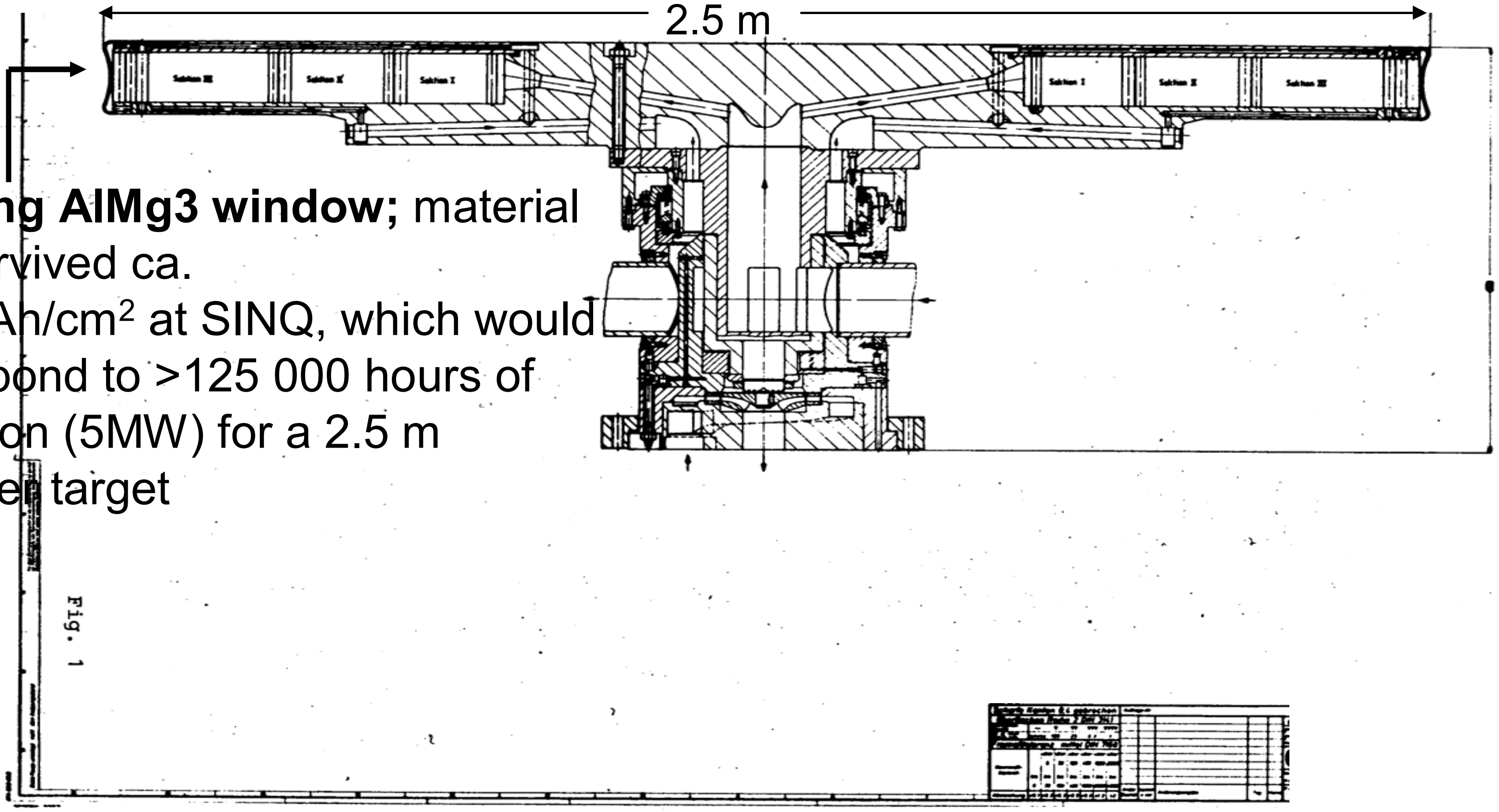
Target outer diameter: 2.5 m
Depth of target material: 70 cm
Height of target material: 12 cm
Beam diameter: 10 cm
Frequency of revolution: 1.2 Hz
Circumferential speed: 10 m/sec

Water turbine

Hydraulic bearings

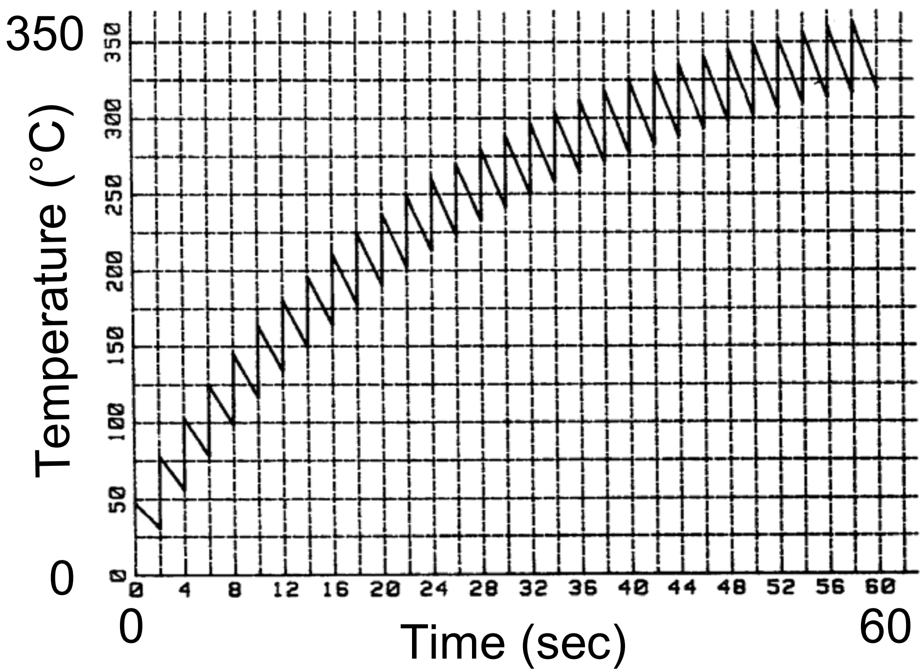
Target rods:
Pb in Al tubes,
surface cooled



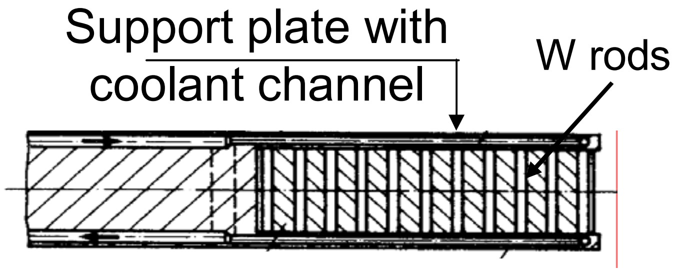


Rotating AlMg3 window; material has survived ca. 200 mAh/cm^2 at SINQ, which would correspond to >125 000 hours of operation (5MW) for a 2.5 m diameter target

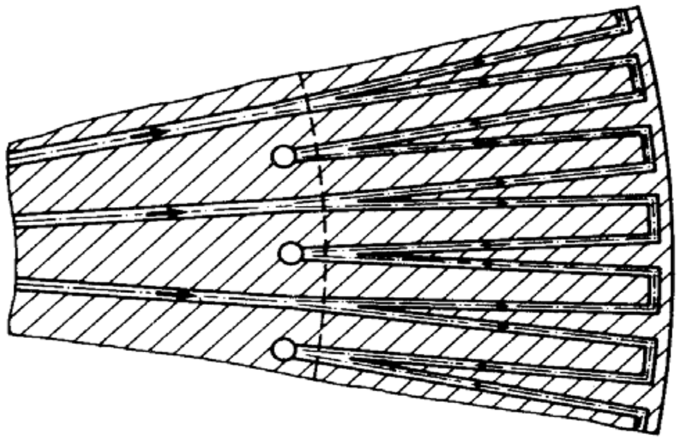
The SNQ W-Target Version (edge cooled)



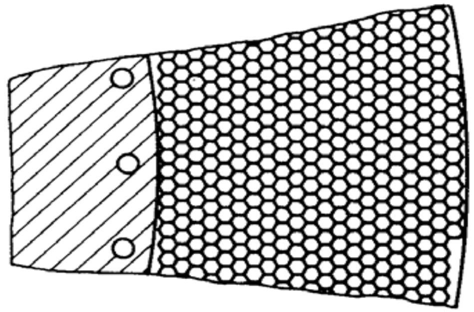
Calculated Temperature evolution at the target hot spot after start up at full beam power (5.5 MW)



Vertical cut through target zone



Horizontal cut through support plate



Horizontal cut through target rod array