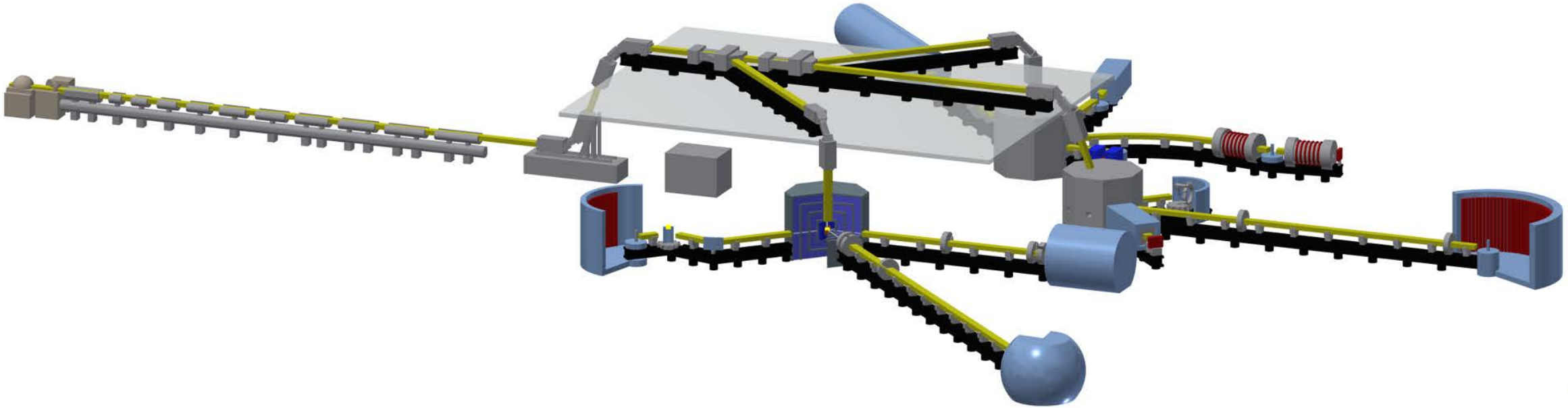


HIGH POWER TARGET FOR HBS

Concepts for cooling a 100 kW target

09/18/2019 I PAUL-EMMANUEL DOEGE

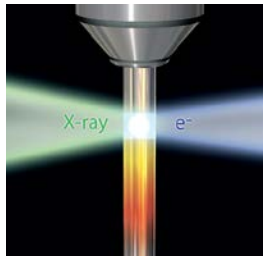
MOTIVATION

a scalable neutron source

X-RAY



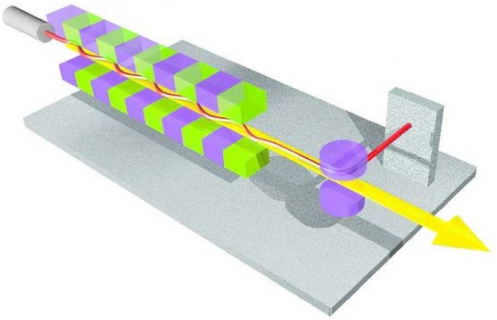
X-Ray Tube



Metal-Jet
GALAXI (BRUKER)



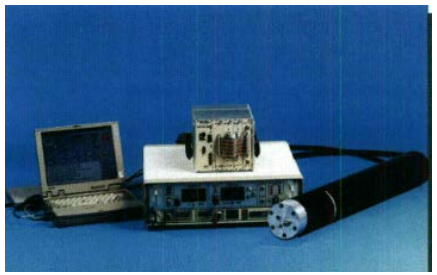
Synchrotron
SOLEIL



Free Electron Laser
European XFEL

FLUX → SIZE → INVEST

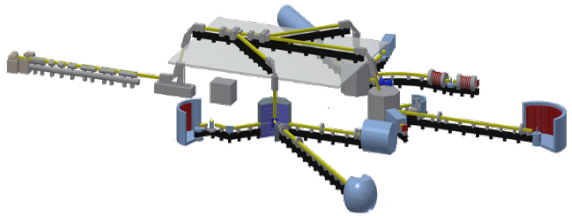
NEUTRON



Neutron Generator
SODERN



CANS
NOVA ERA



high power CANS
HBS



Spallation Source
ESS

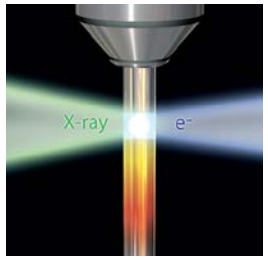
MOTIVATION

a scalable neutron source

X-RAY



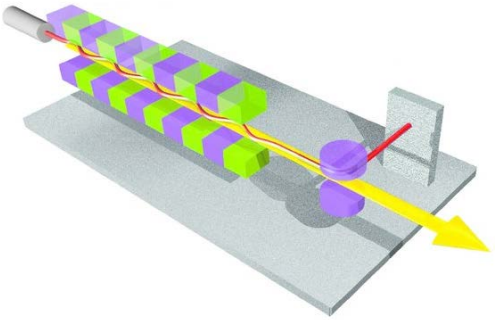
X-Ray Tube



Metal-Jet
GALAXI (BRUKER)



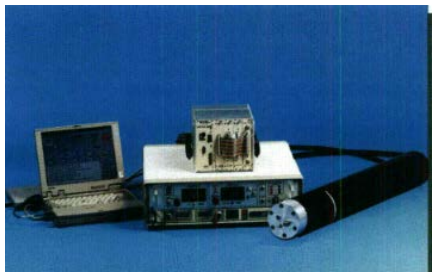
Synchrotron
SOLEIL



Free Electron Laser
European XFEL

FLUX → SIZE → INVEST

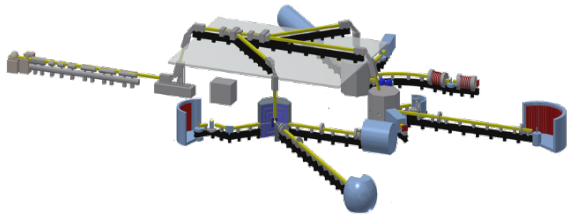
NEUTRON



Neutron Generator
SODERN



CANS
NOVA ERA



high power CANS
HBS



Spallation Source
ESS

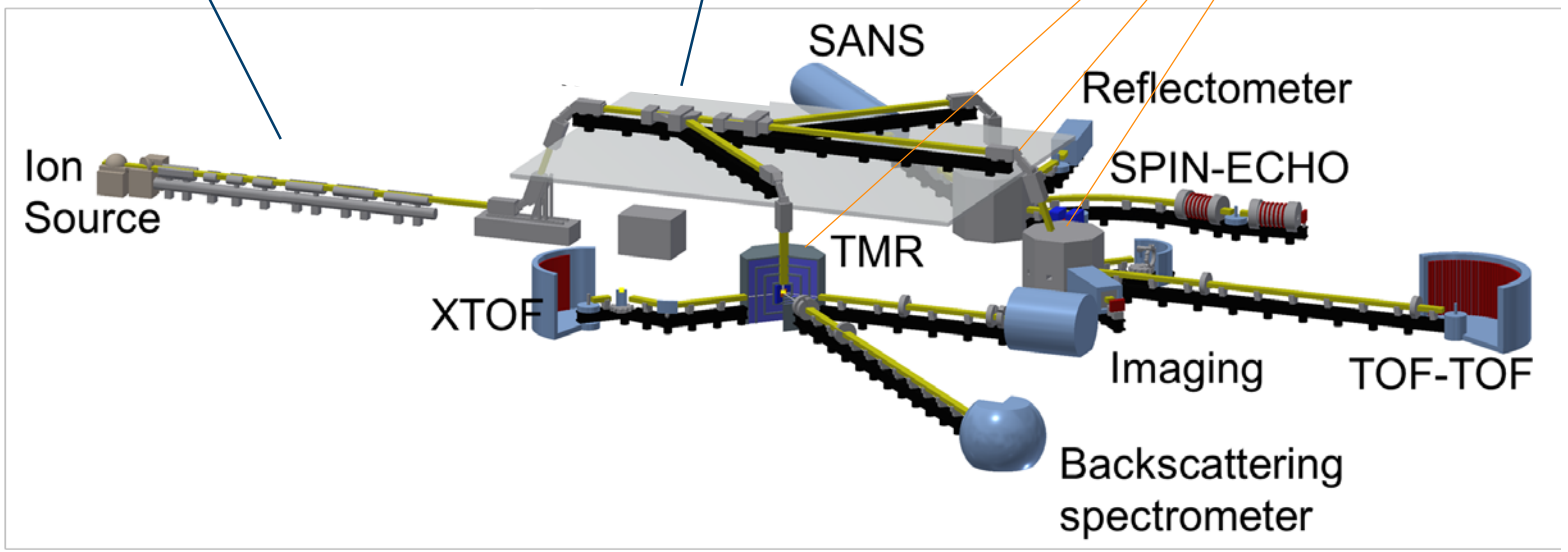
HIGH BRILLIANCE NEUTRON SOURCE

Facility Concept Overview

LINAC
- 70 MeV protons
- 100 mA peak
- < 6% duty factor

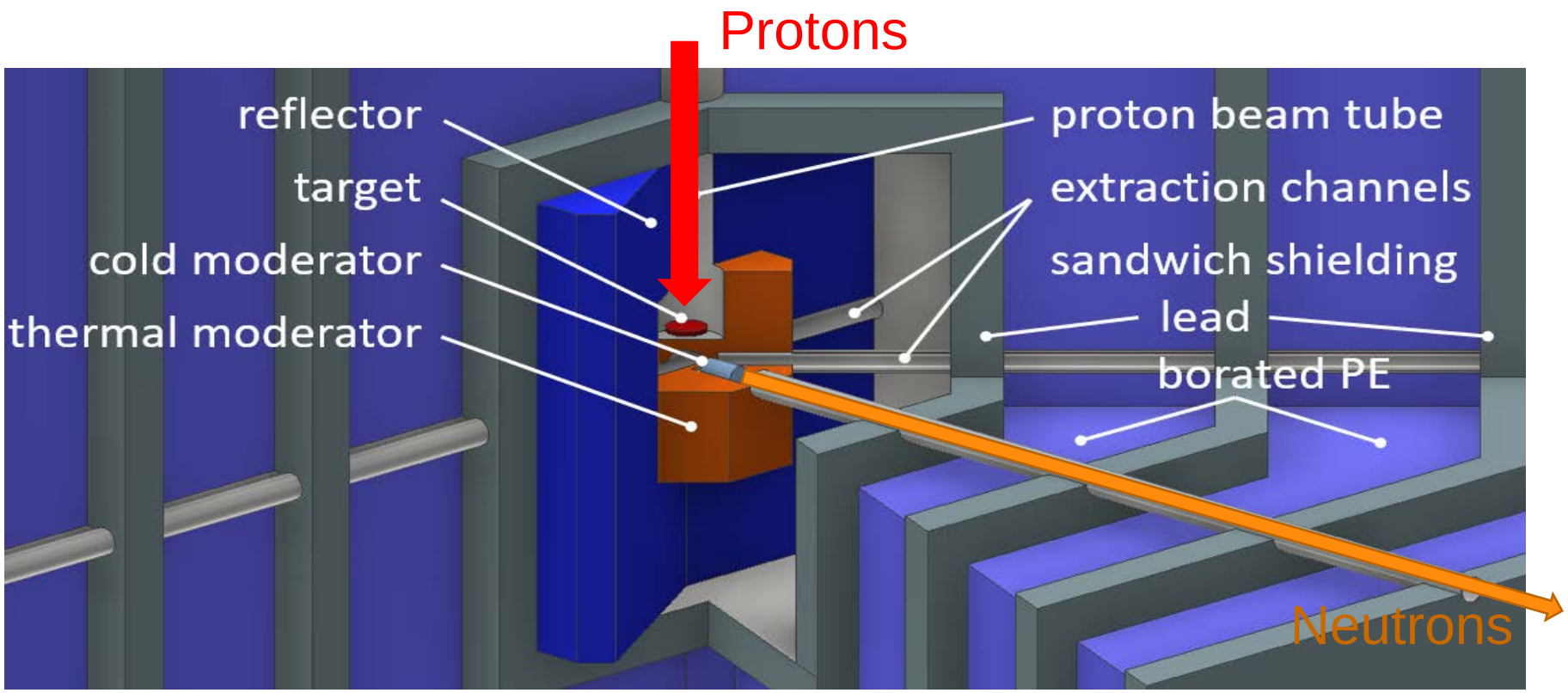
Beam Multiplexer (2nd floor)
- Pulse Distribution to TMRs
- 24 Hz, 96 Hz, 384 Hz
- 833 µs, 208 µs, 52 µs

Target Moderator Reflector
3 Stations with each:
- 100 kW average
- 100 mA peak
- < 2% duty factor



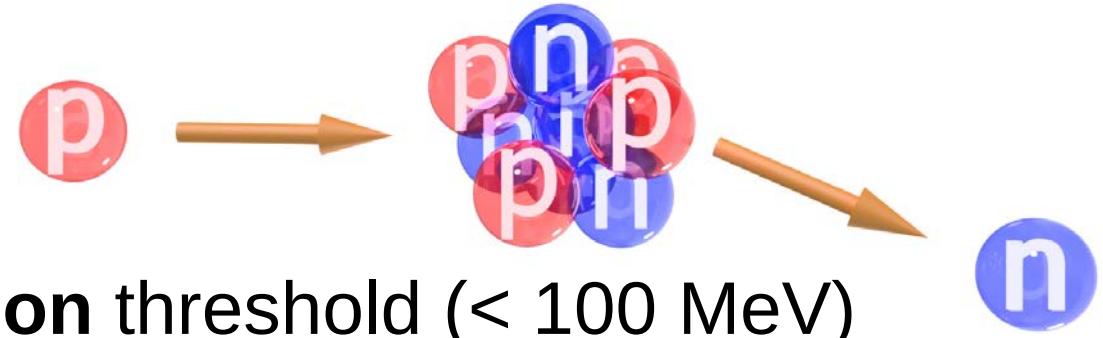
HIGH BRILLIANCE NEUTRON SOURCE

Target Moderator Reflector (TMR) Concept Overview



TARGETS FOR CANS

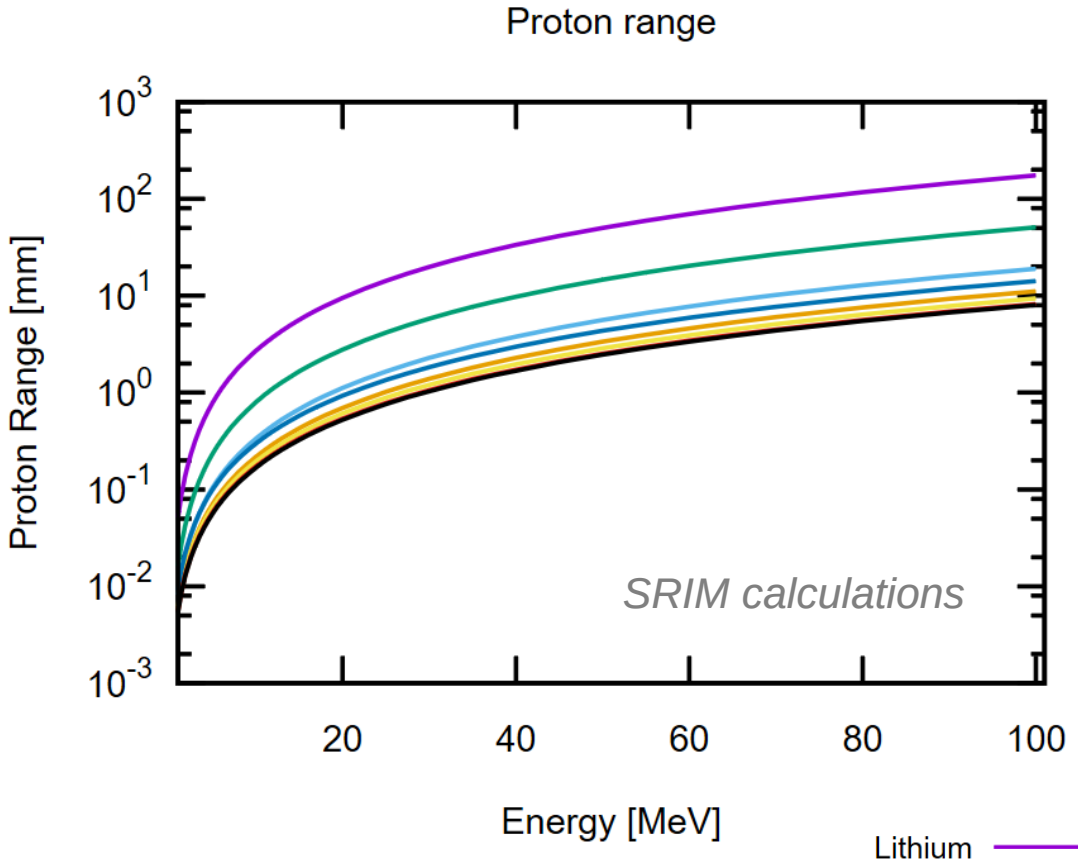
General Requirements to Target

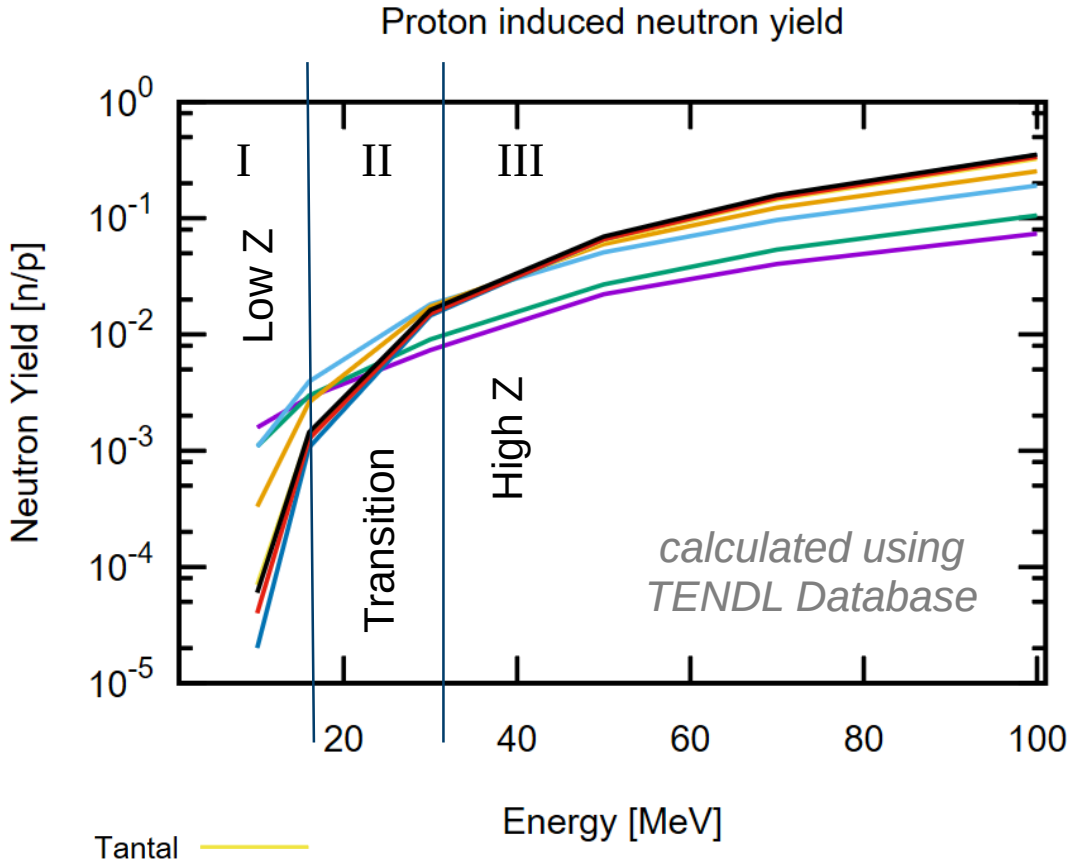


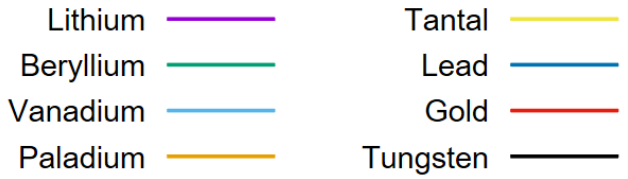
- incident proton energy **below spallation** threshold (< 100 MeV)
  - ➢ beam windows decelerate the beam significantly
- neutrons are produced via nuclear reactions
  - ➢ **1% to 10%** of the incident **protons** produce a **neutron**
- the **range** of the protons inside the target is in the order of **mm**
  - ➢ thin targets to **avoid proton accumulation** inside target
  - ➢ disc shaped targets

CHOICE OF MATERIAL

depending on incident proton energy







HIGH POWER TARGETS

Target for 100 kW HBS pulsed proton beam

- **Current state of the art purchasable accelerators are limited to 100 mA**
- **For higher power need to increase proton energy**

High Z materials

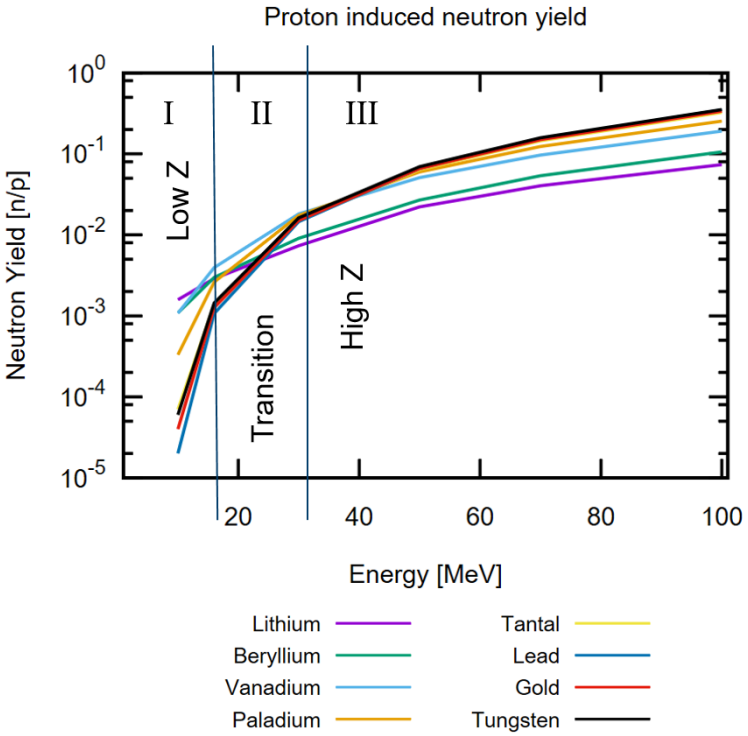
- High neutron yield at increased ion energies
- Low range of neutrons

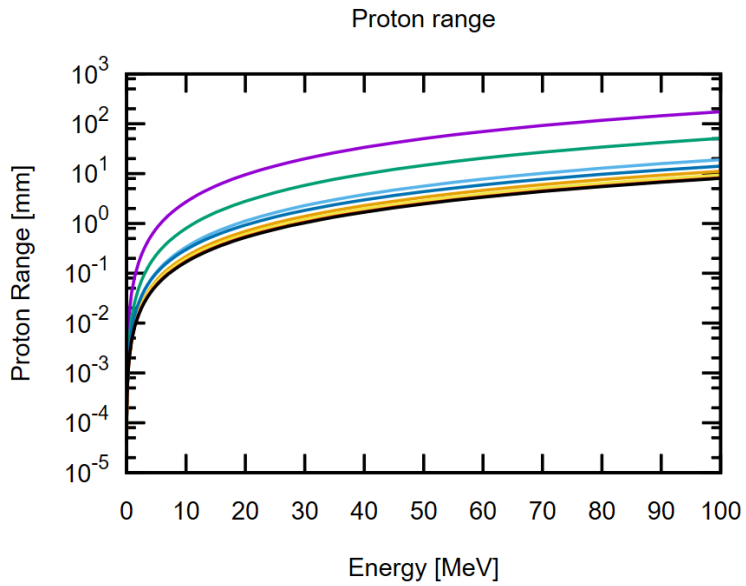
Refractory Metals

- Good general thermo-mechanical properties at high temperatures
- Good corrosion resistance
- Nb, Mo, Ta, W, Re

Tantalum

- High blistering threshold
- Ductile material
- Structural material
- Good workability

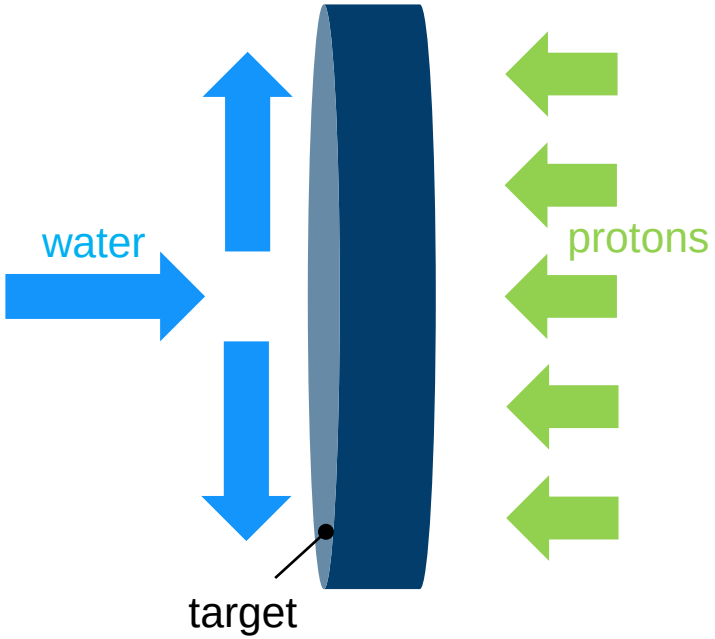




CONSIDERED TARGET COOLING METHODS

Jet cooling

method	coolant	heat transfer coefficient $W\,m^{-2}\,K^{-1}$	achievable power density $kW\,cm^{-2}$
jet cooling	water liquid metals	4000 – 16000	0.13 0.26



water:

α_{water} = 4000 – 16000 W m^{-2} K^{-1}

$T_{wall,max}$ approx. 100 °C (prevent boiling)

→ $\dot{p}_{max} \approx 130\ {}^{W}/_{cm^2}$

- used at LENS (USA)
- will be used for NOVA ERA
- Suitable for 1 to 2 kW
- protons dumped in water

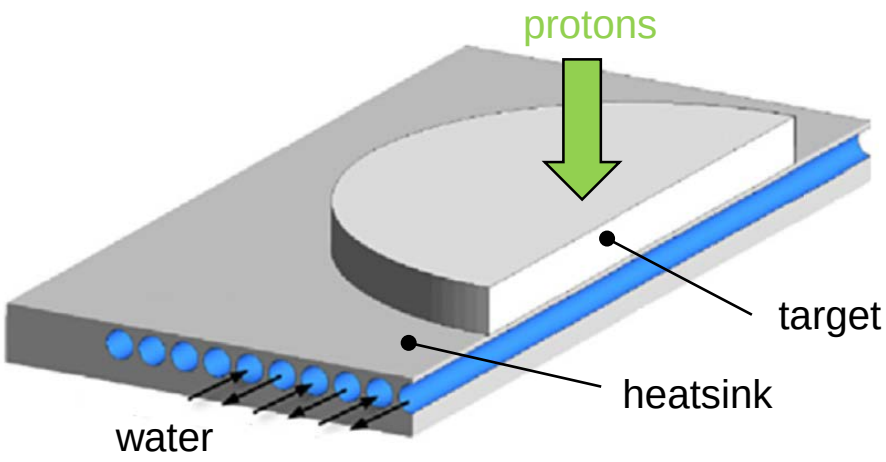
- thin disc subjected to water pressure
- target disc is structural barrier between water and vacuum

CONSIDERED TARGET COOLING METHODS

Bonded heat sink

method	coolant	heat transfer coefficient $W\,m^{-2}\,K^{-1}$	achievable power density $kW\,cm^{-2}$
jet cooling	water liquid metals	4000 – 16000	0.13 0.26
heat sink	water liquid metals	4000 – 16000	0.3 – 0.4 0.4 – 0.8

- **higher water pressure possible**
- **larger thermal exchange surface**
- **target is not structural barrier**



water:

α_{water} = 4000 – 4700 W m^{-2} K^{-1}

T_{wall} > 100 °C possible

→ $\dot{p}_{max} \approx 200 - 400\ {}^{W}/_{cm^2}$

- **different thermal expansion of materials**
- **dumping of protons in heat sink**
- **thermal resistance (additional material)**

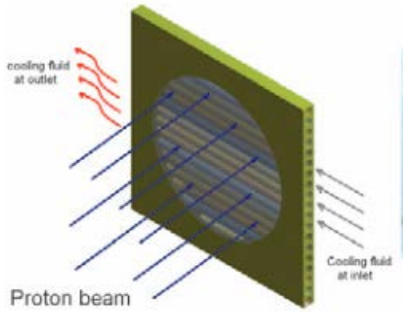
CONSIDERED TARGET COOLING METHODS

Micro channel cooling

method	coolant	heat transfer coefficient $W\,m^{-2}\,K^{-1}$	achievable power density $kW\,cm^{-2}$
forced cooling	water liquid metals	4000 – 16000	0.13 0.26
heat sink	water liquid metals	4000 – 16000	0.3 – 0.4 0.4 – 0.8
micro channel cooling	water (1-phase) water (2-phase) liquid metal	3000 80000 80000	1.2 – 4.5 10 – 22.8 1.0 – 3.5

- **very high water pressure possible**
- **larger thermal exchange surface**
- **optimum for high power densities**

- **difficult to fabricate**



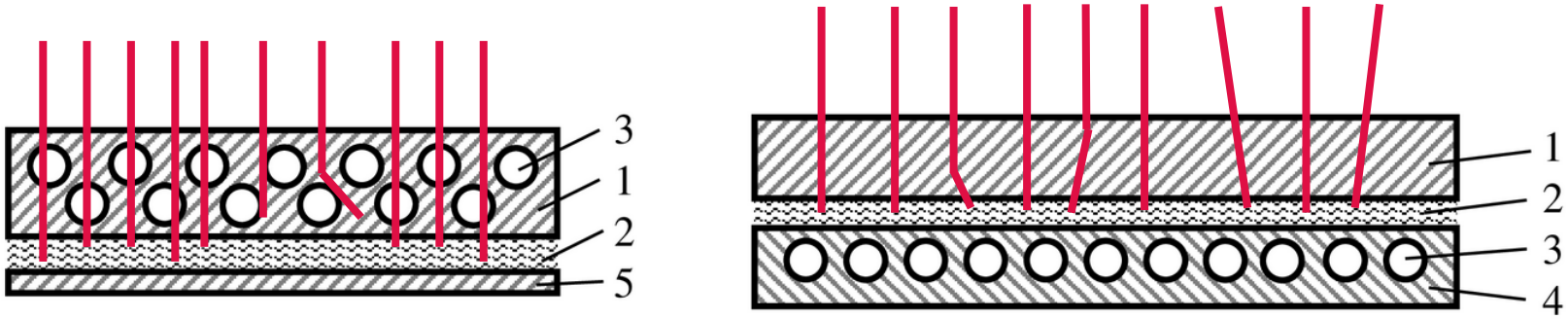
[6] P. Mastinu et.al Status of the Legnaro neutron Source facility, 2012



TWO OPTIONS FOR HIGH POWER TARGET

Internally and externally micro channel cooled target

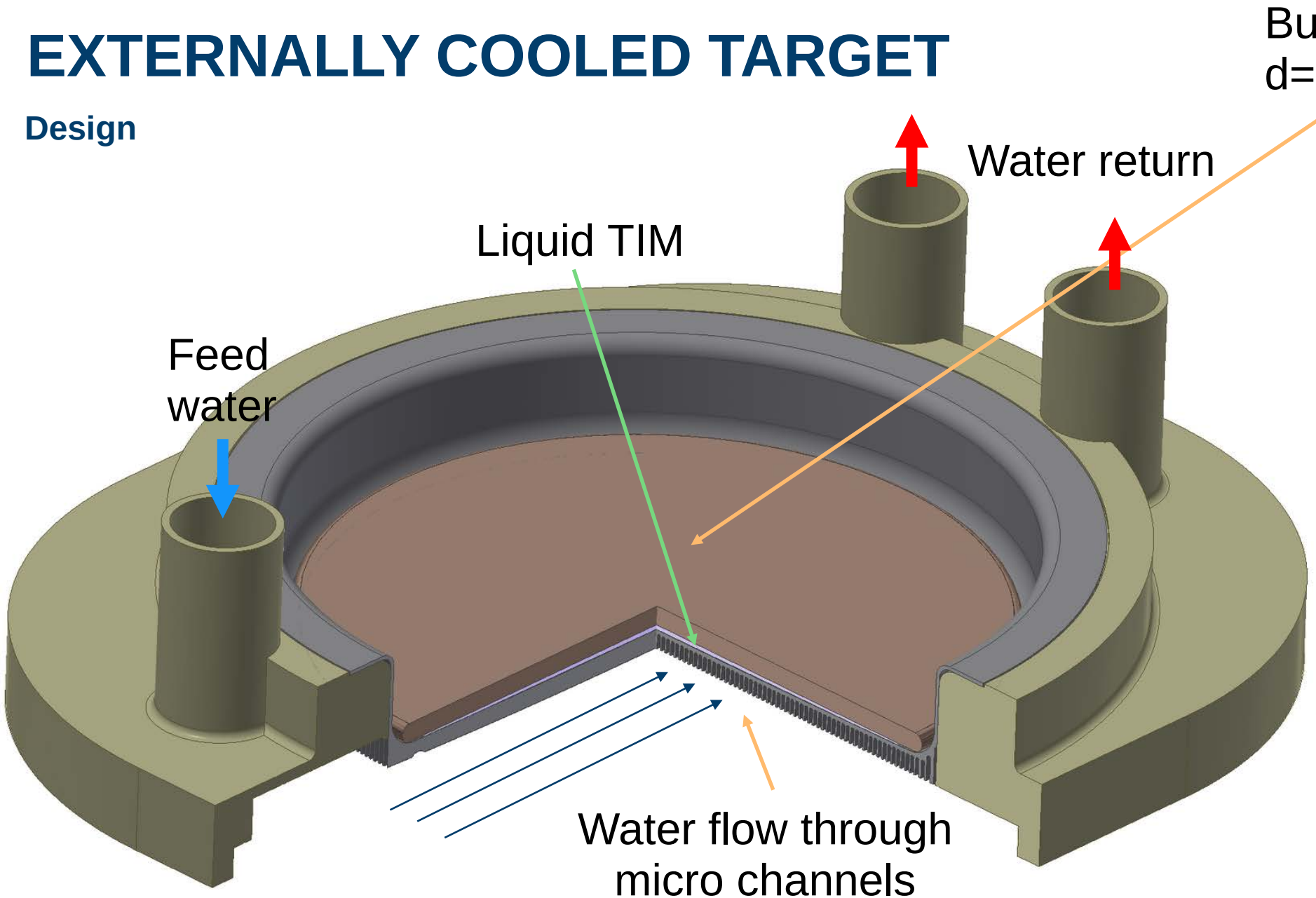
- High heat load requires micro-channel cooling (MC)
- Idea: Protons should travel always the same path length in tantalum
- Deposition of protons in a dumping layer
- Protons are coming from the top in order to be able to extract neutrons in 360°



1 target, 2 dumping layer, 3 MC, 4 heat sink, 5 structural material

EXTERNALLY COOLED TARGET

Design



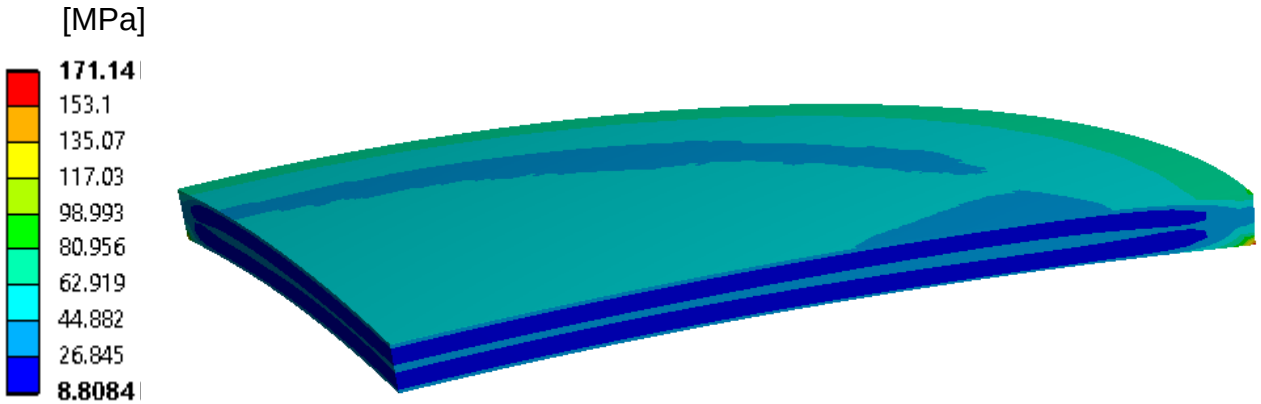
Liquid Thermal Interface Material (TIM)

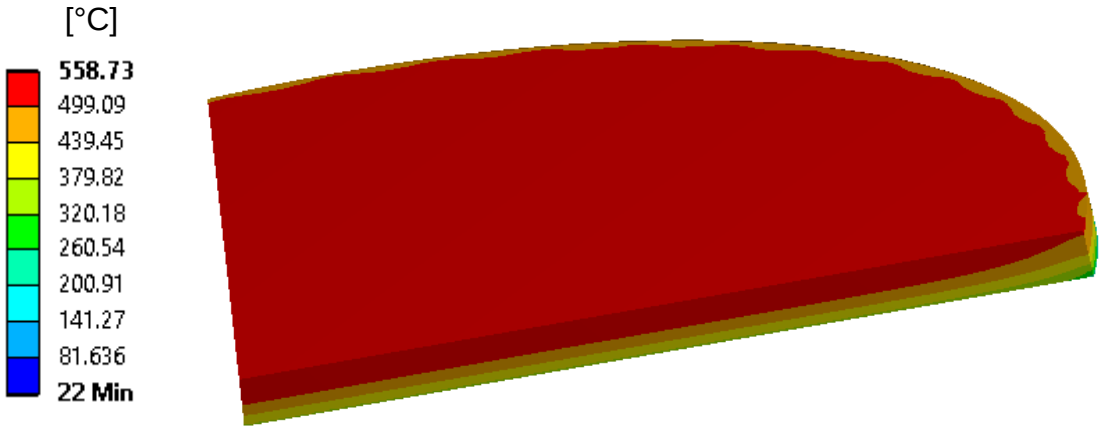
Gallium:

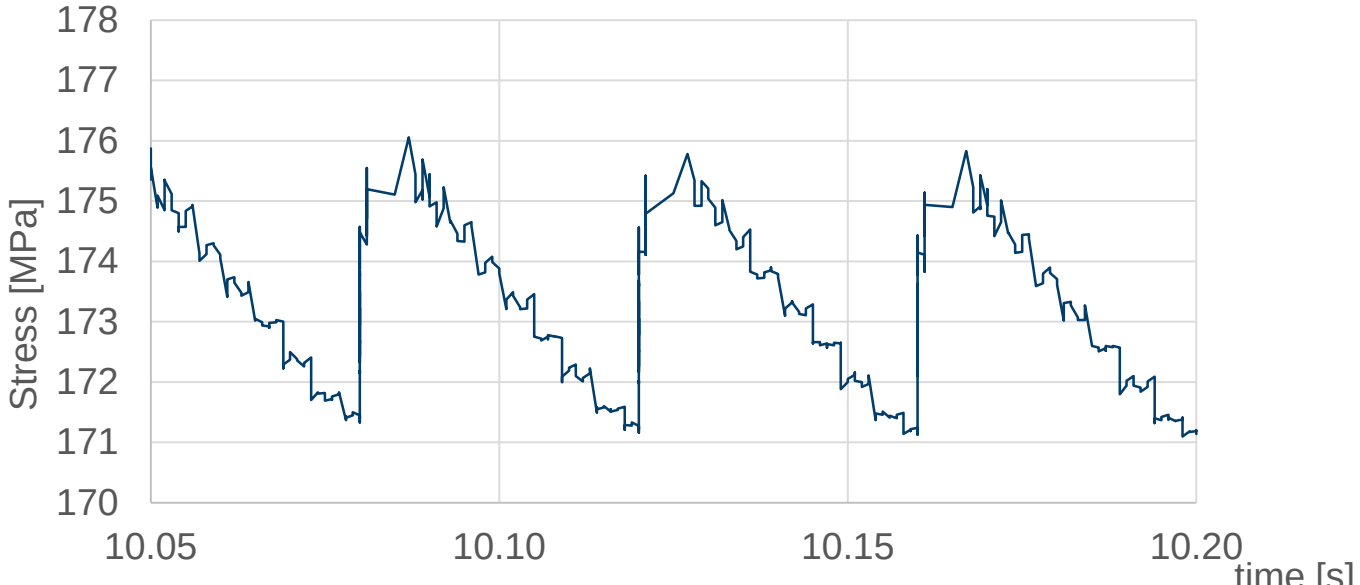
- $\lambda = 30\ W\ m^{-1}\ K^{-1}$
- Low vapor pressure
- Good wetting of Tantalum
- No reactions with Tantalum

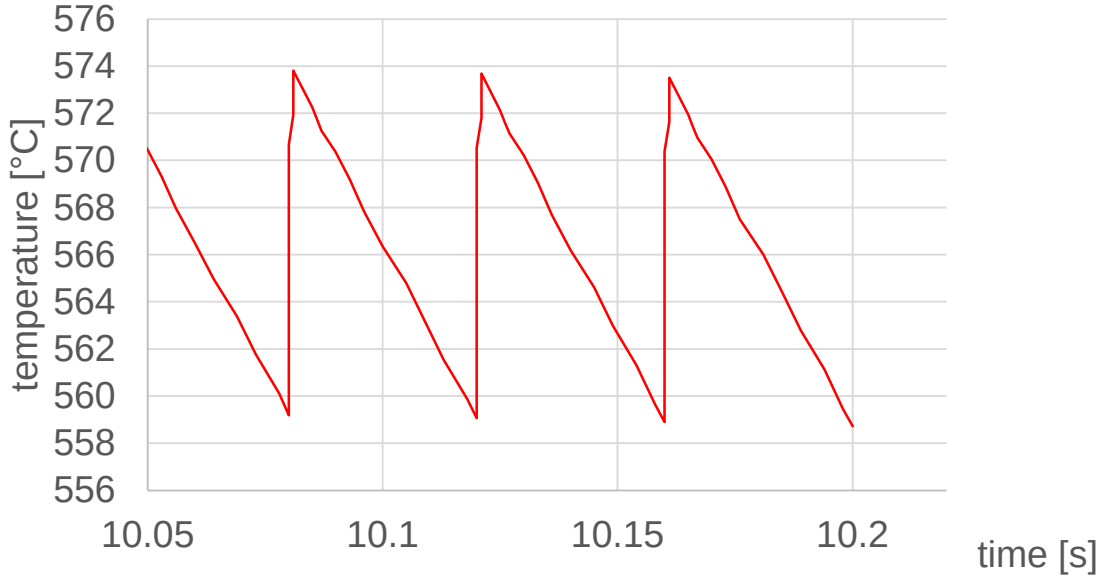
STRESS AND TEMPERATURE

Pulsed proton beam 100 kW at 24 Hz



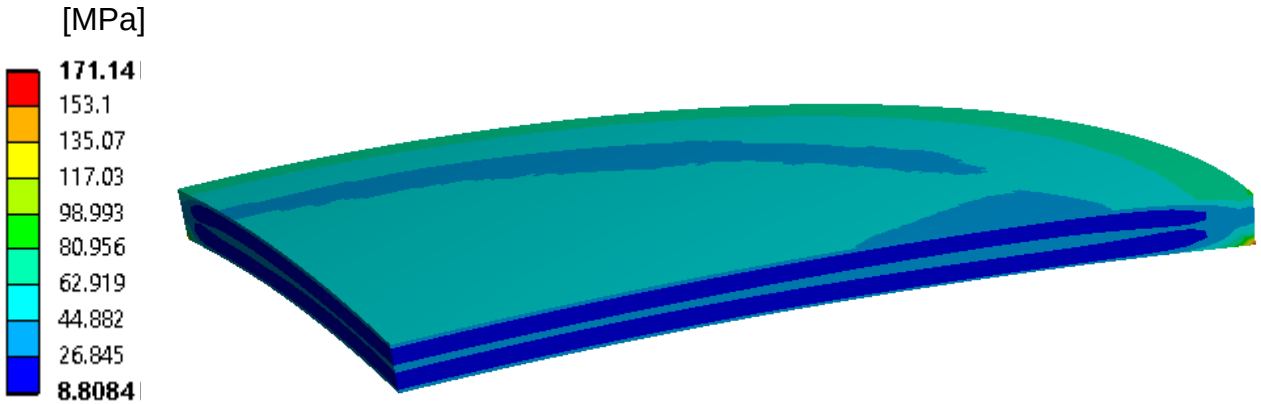


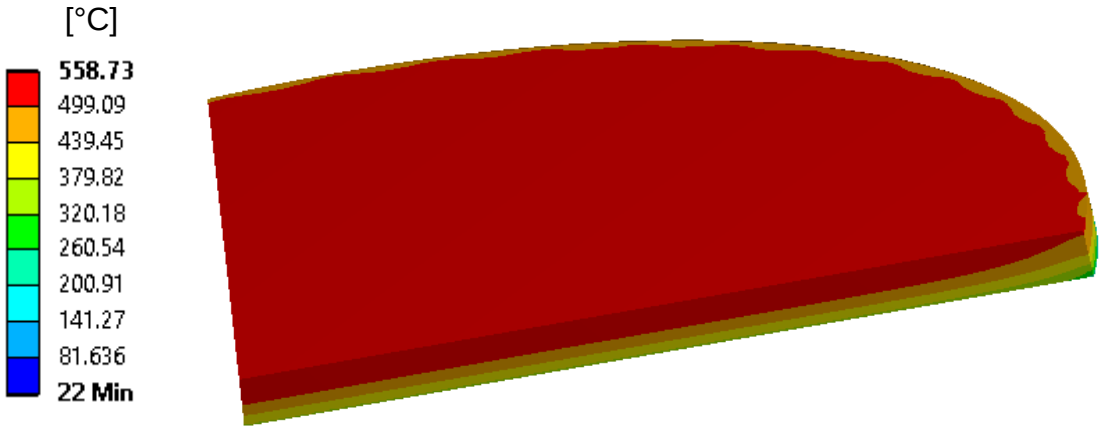


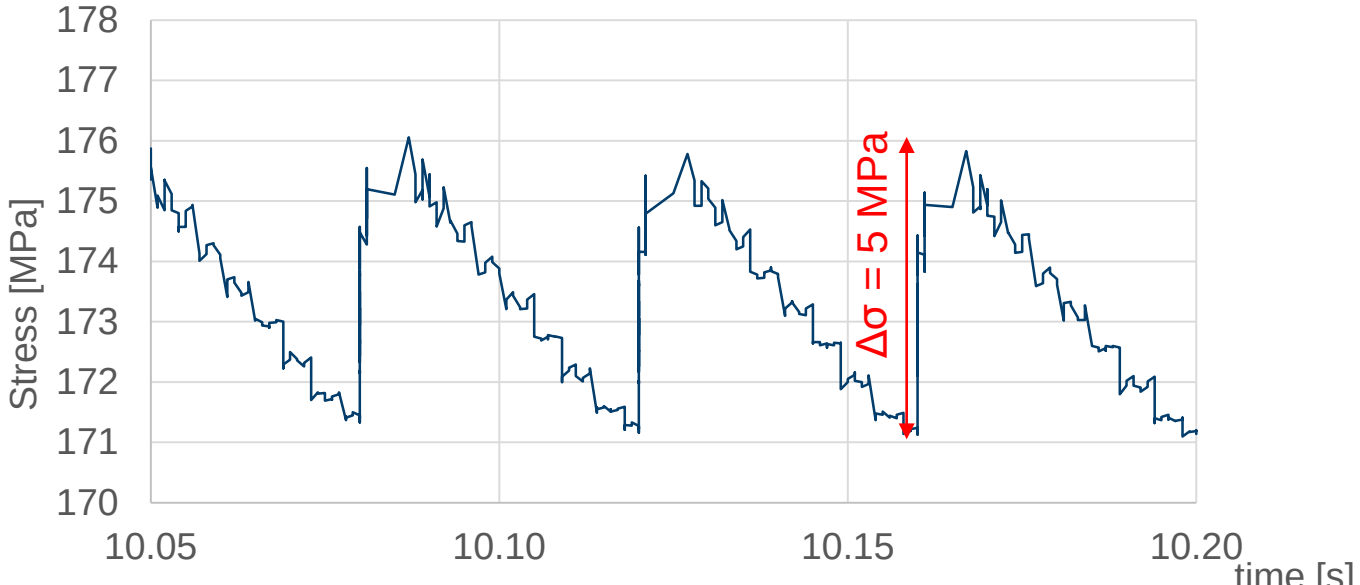


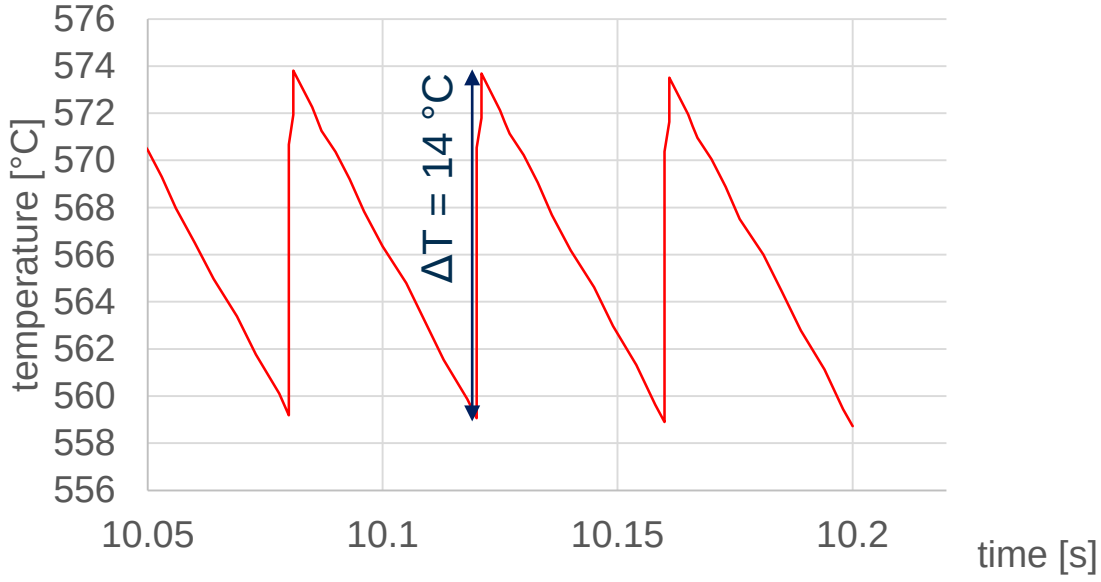
STRESS AND TEMPERATURE

Pulsed proton beam 100 kW at 24 Hz



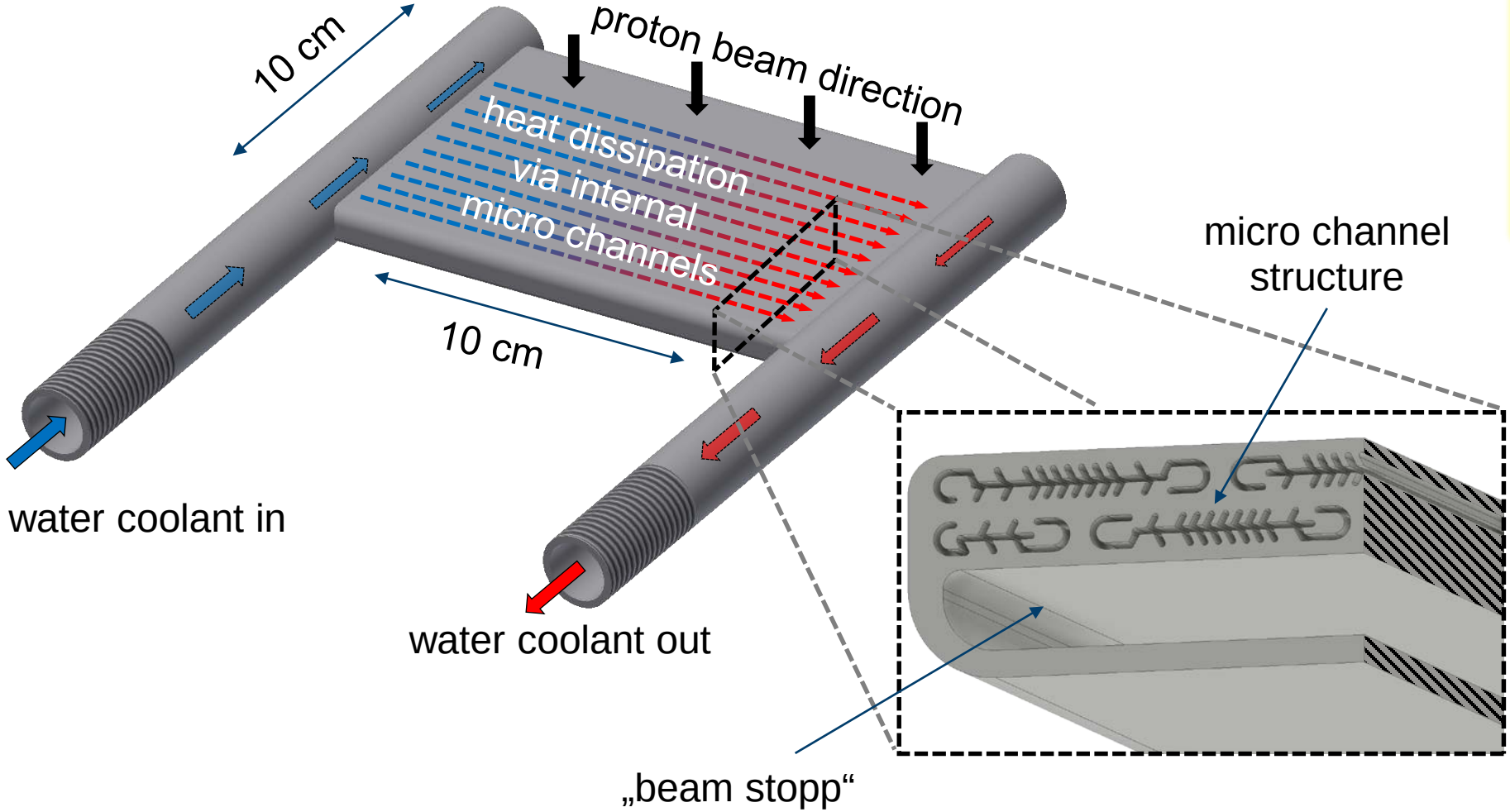






INTERNALLY COOLED TARGET

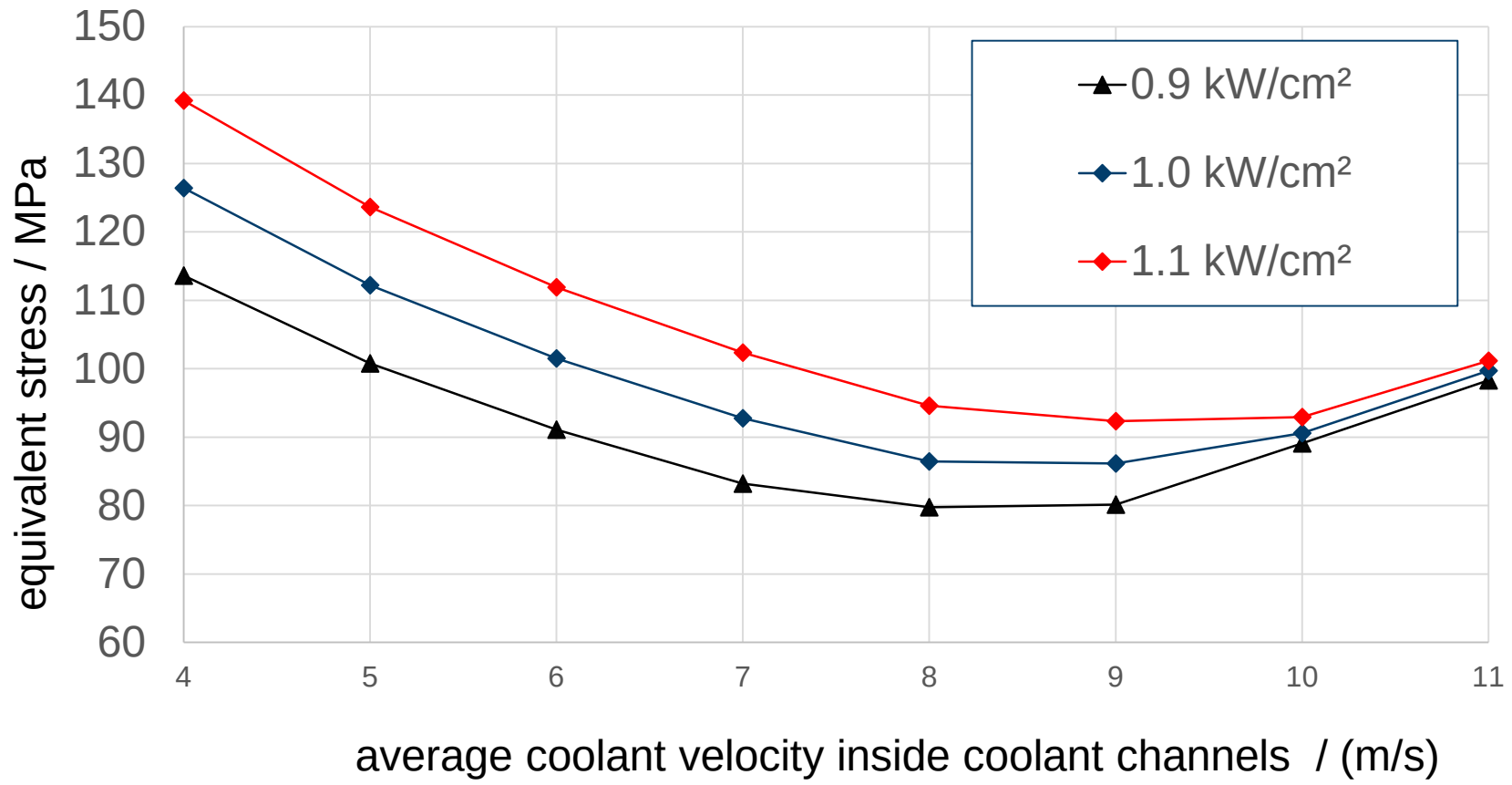
Design



Fish bone structure allows manufacturing by wire-cut electrical discharge machining (EDM) with only few paths

STEADY STATE STRUCTURAL SIMULATION

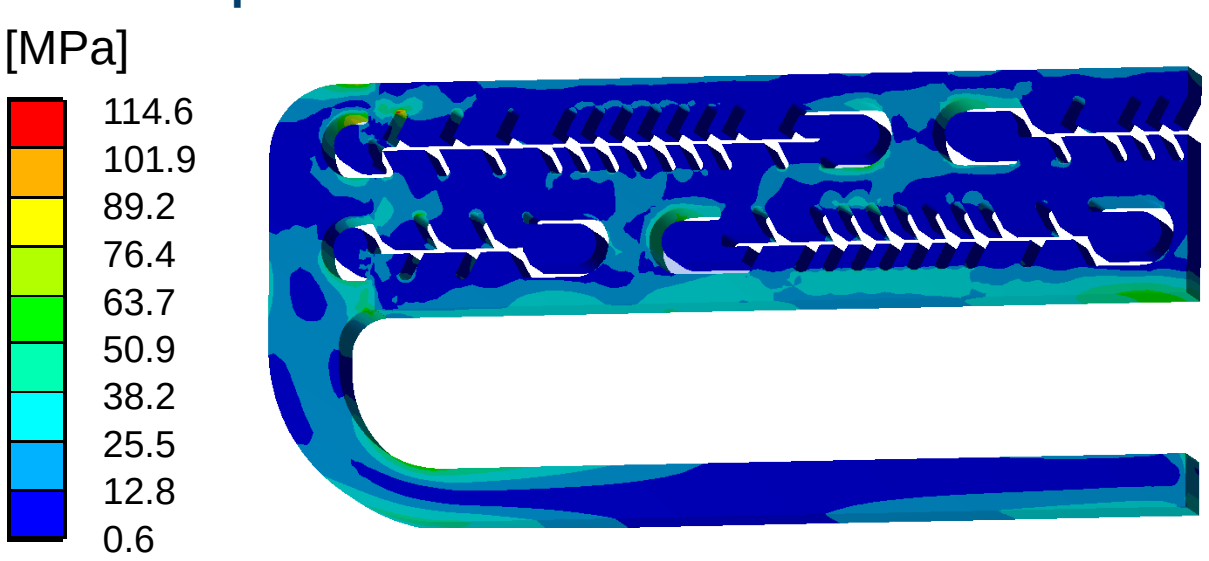
Coolant pressure vs. thermal stress

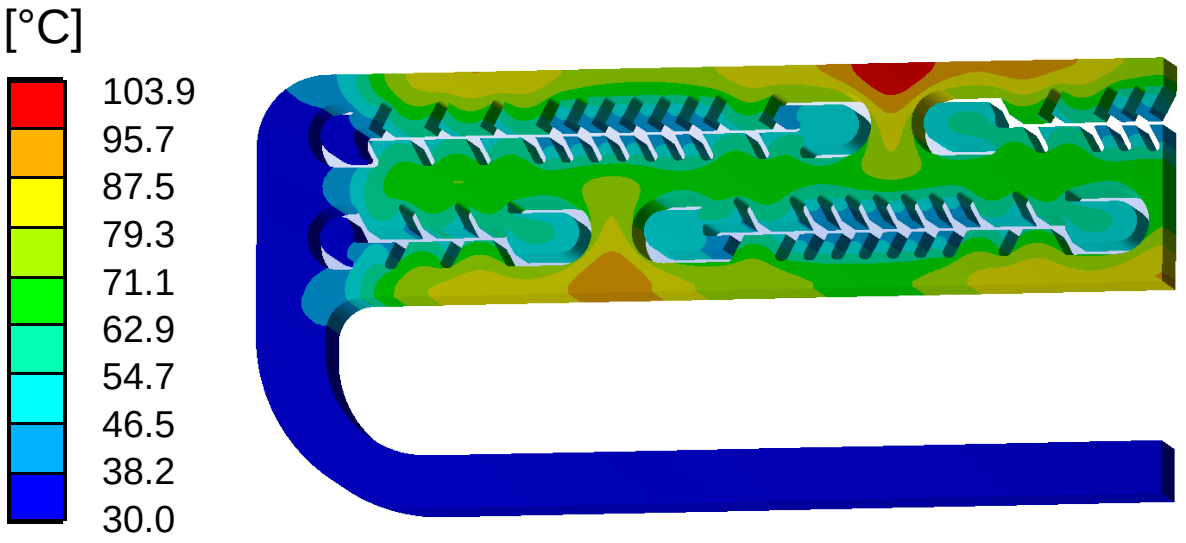


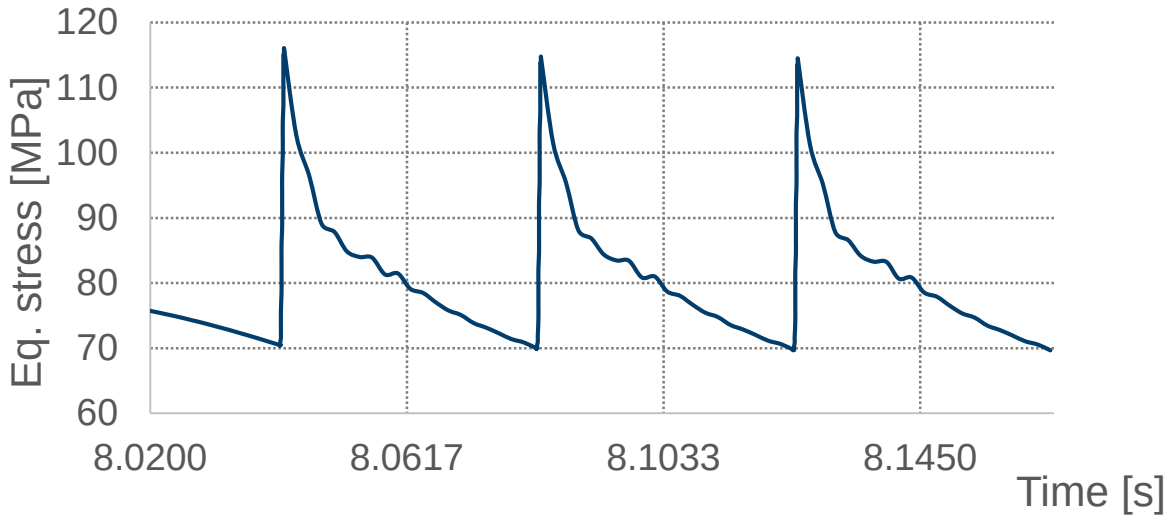
yield strength of tantalum is between 180 MPa and 380 MPa, depending on grade

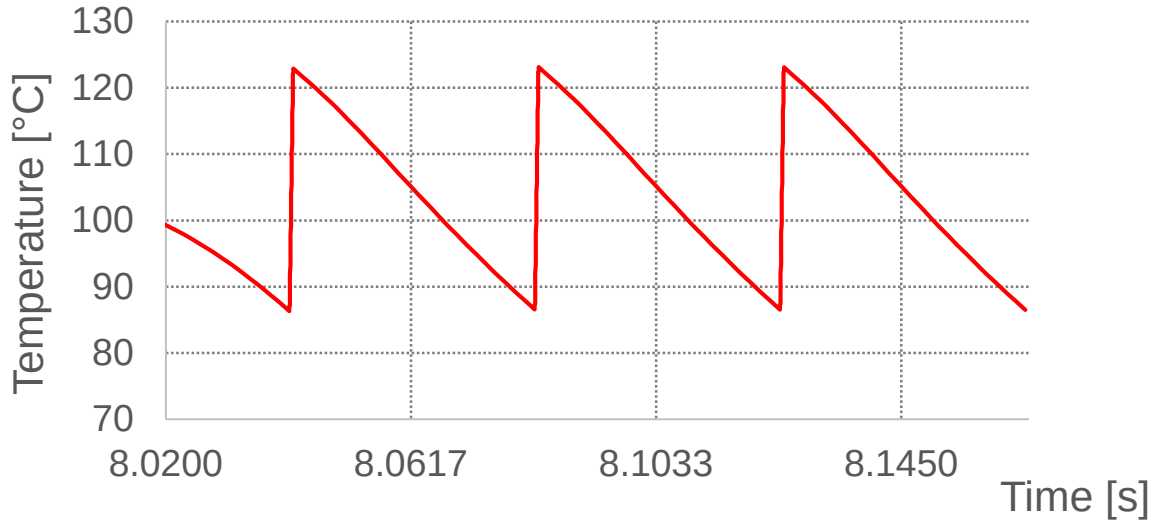
STRESS AND TEMPERATURE

Pulsed proton beam 100 kW at 24 Hz



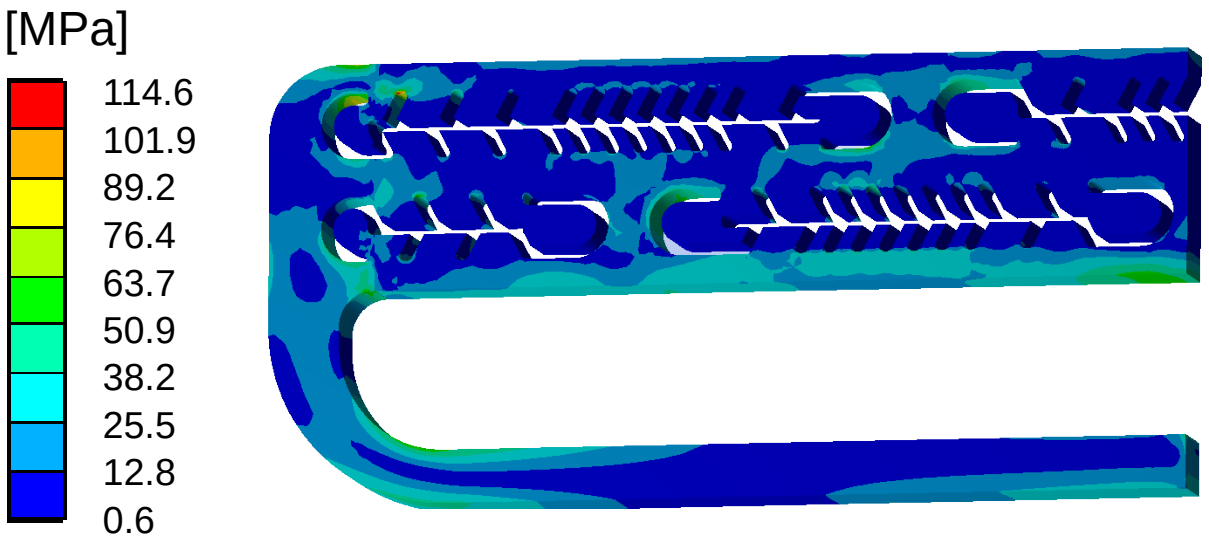


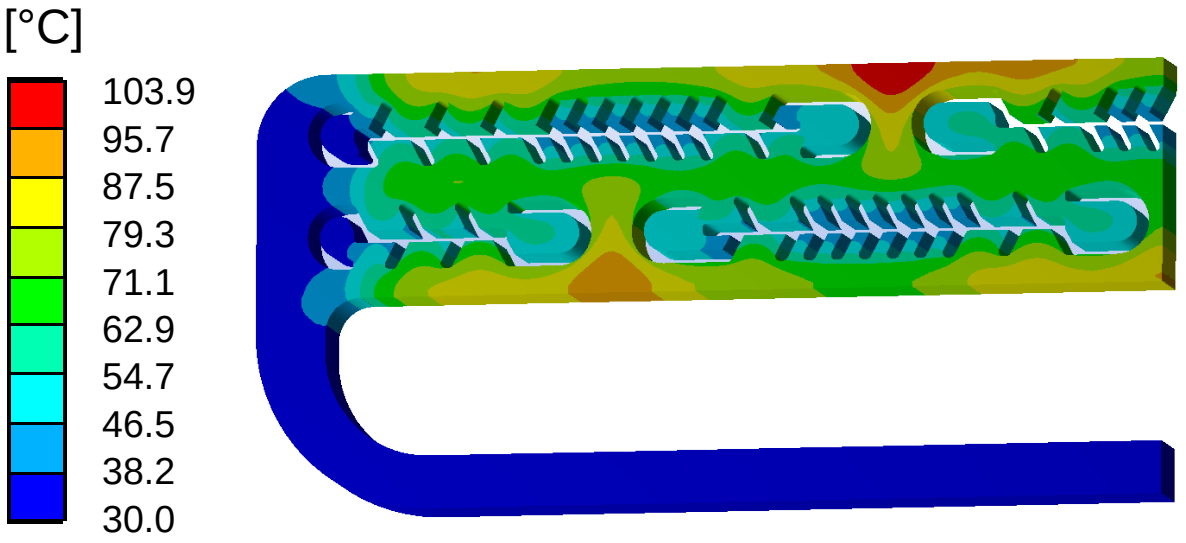


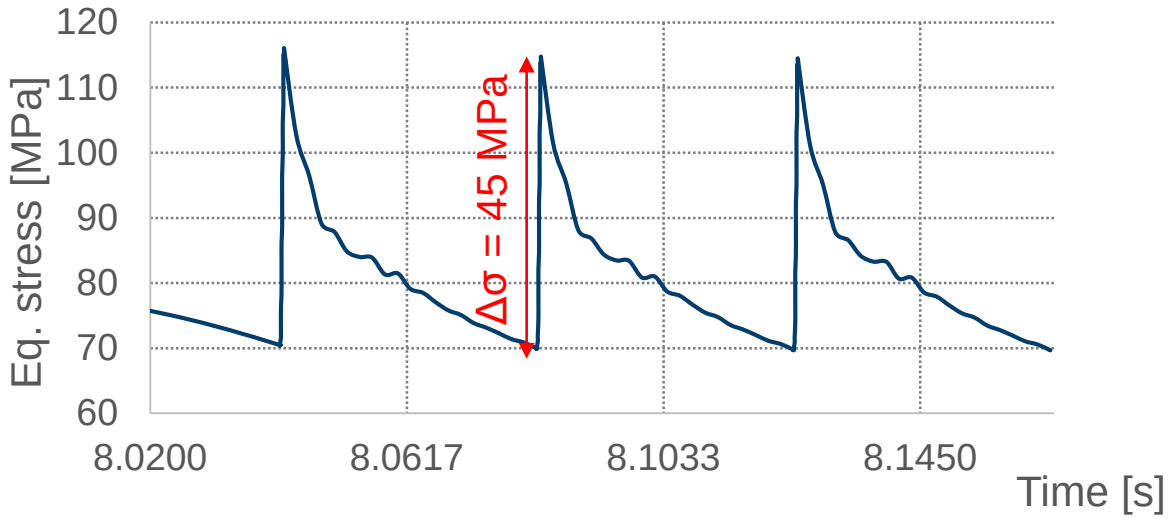


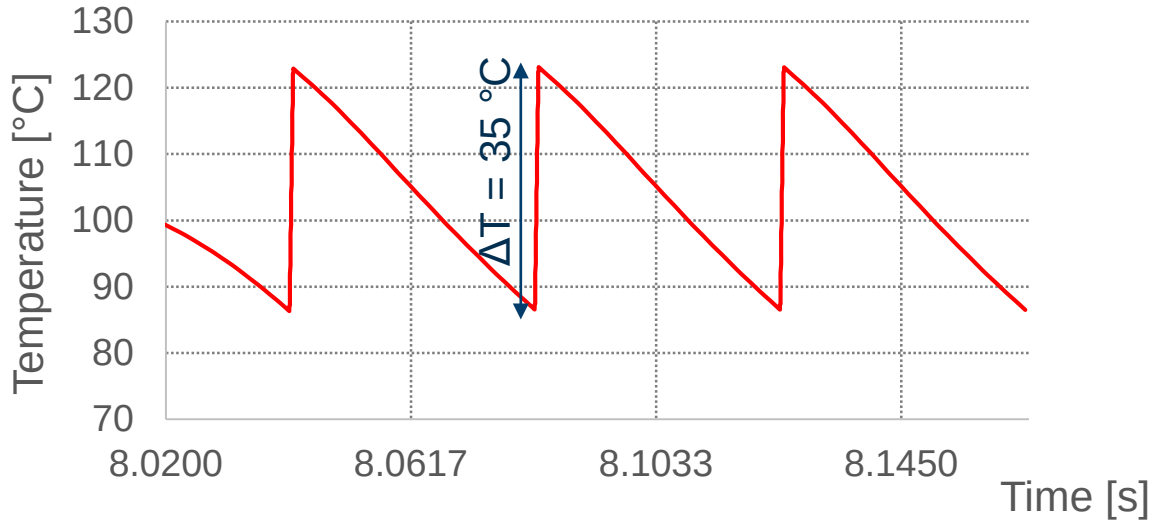
STRESS AND TEMPERATURE

Pulsed proton beam 100 kW at 24 Hz





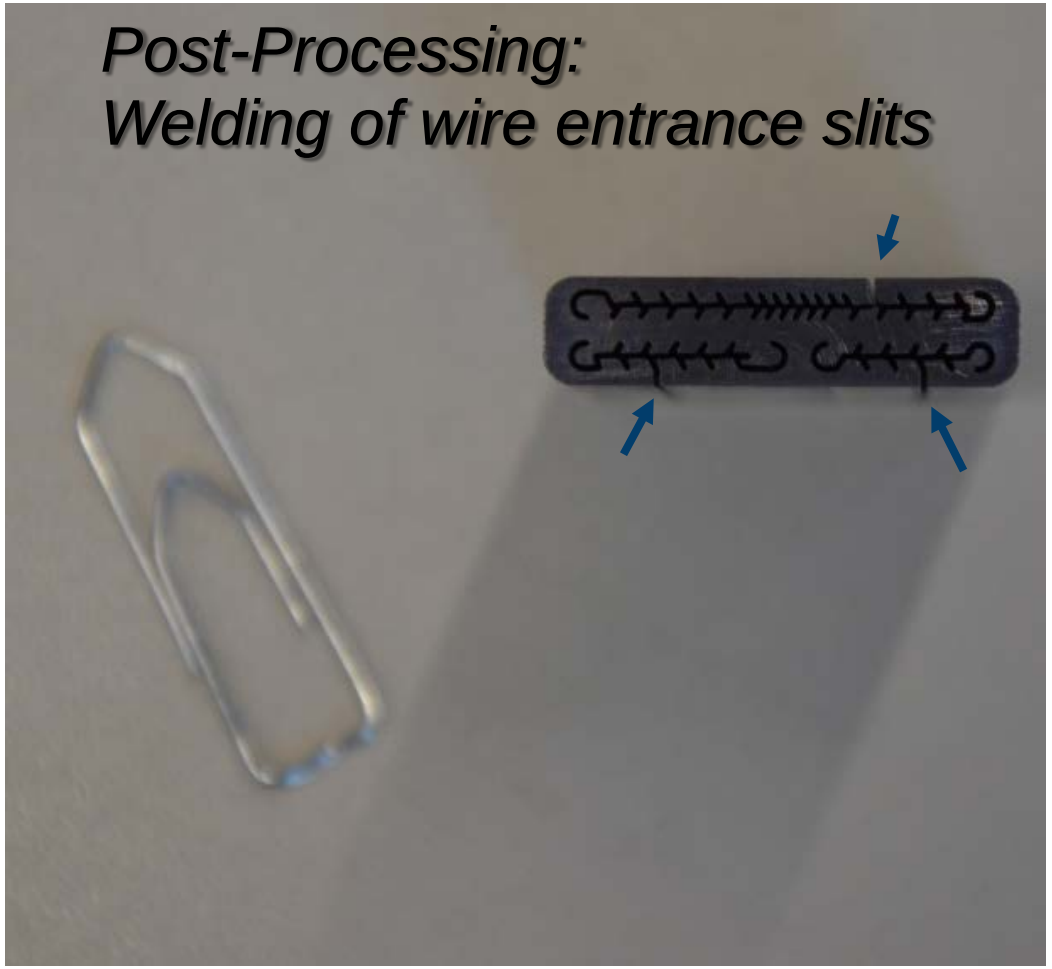




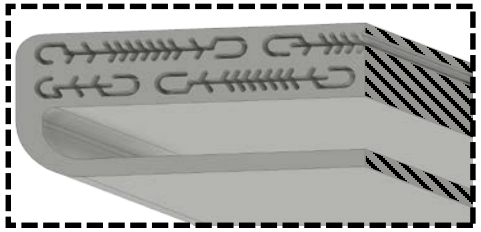
MANUFACTURING

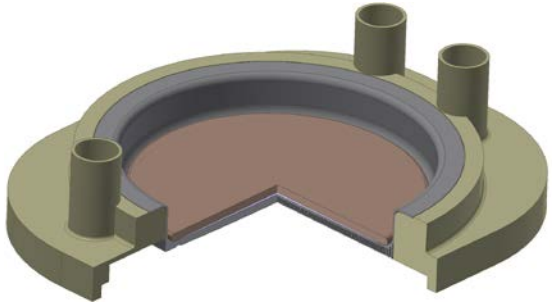
Wire-cut EDM of internally cooled Target





CONCLUSION





Internally cooled target	Externally cooled target
Low temperature	High temperature
Higher beam concentration possible (smaller target)	Lower beam concentration (larger target)
Target is structural	Target and dump layer are not structural
Absolute stress is lower	Absolut stress is higher
Cycling (24 Hz): High stress and temperature amplitude	Cycling (24 Hz): Low stress and temperature amplitude
Damage critical for other components	Damage not critical
Deposition of protons less predictable	Deposition of protons more predictable
Is already manufactured	Is not yet manufactured
Less material	Additional potentially activated material

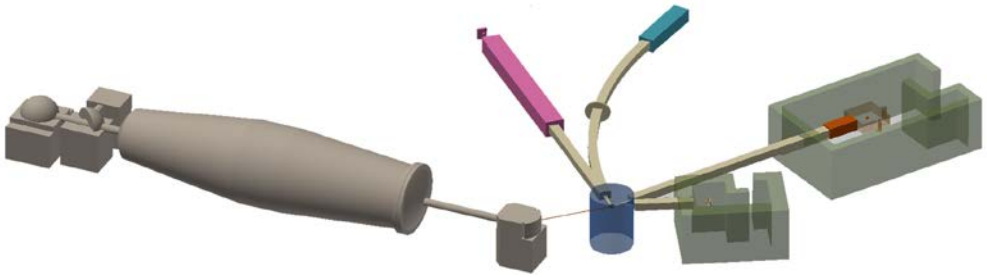
OUTLOOK

- Manufacturing of externally cooled Target



- Testing of both targets (first e-beam heating)

- The externally cooled target design might be an option for low power CANS with very thin targets (e.g. Beryllium around 10 MeV)



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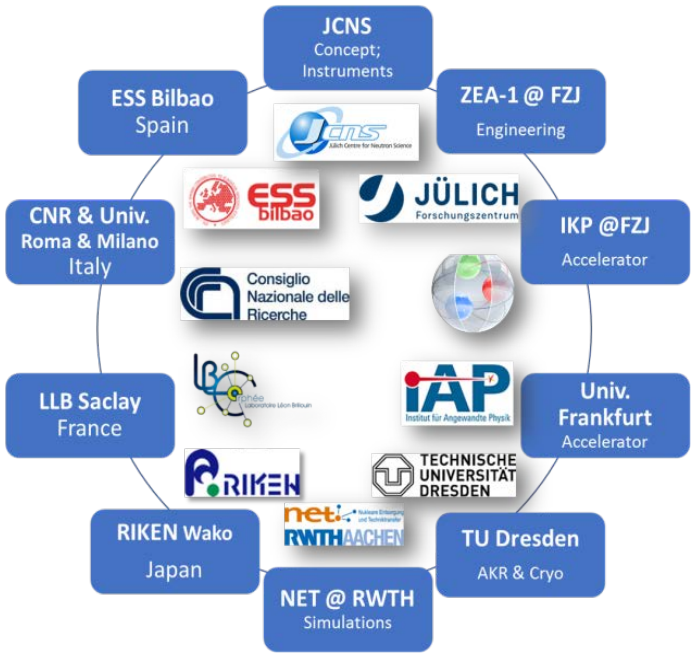

HIGH BRILLIANCE SOURCE

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IKP-4:
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D. Prasuhn
- Nuclear Physics

GSI / HIM
M. Bai
W. Barth
- Accelerator

S. Böhm
J.P. Dabruck
R. Nabbi
- Nuclear simul.

TECHNISCHE UNIVERSITÄT DRESDEN
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Ch. Haberstroh
M. Klaus
S. Eisenhut
- AKR-2, liquid H_2

IAP Institut für Angewandte Physik
H. Podlech
O. Meusel
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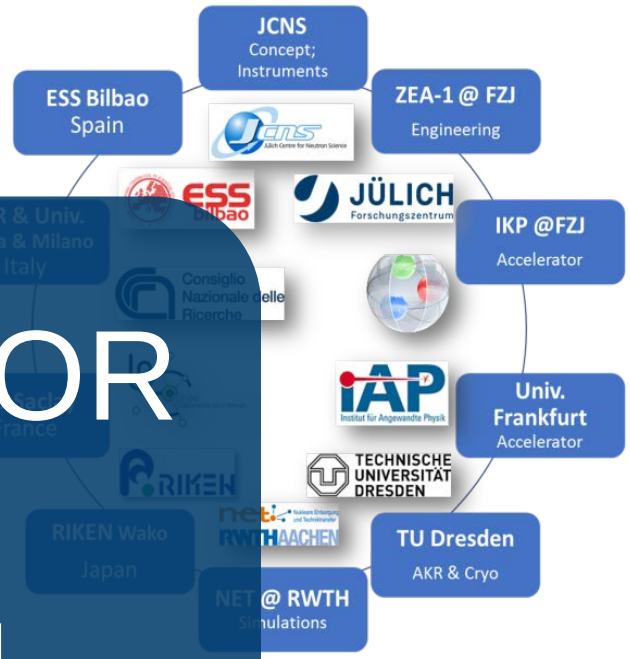


THANK YOU FOR YOUR ATTENTION

HIGH BRILLIANCE SOURCE

NEUTRON PRODUCTION

Sub-spallation, nuclear reaction based neutron production

COMMON POINTS

- Accelerator based
- Proton induced

Nuclear Reactions

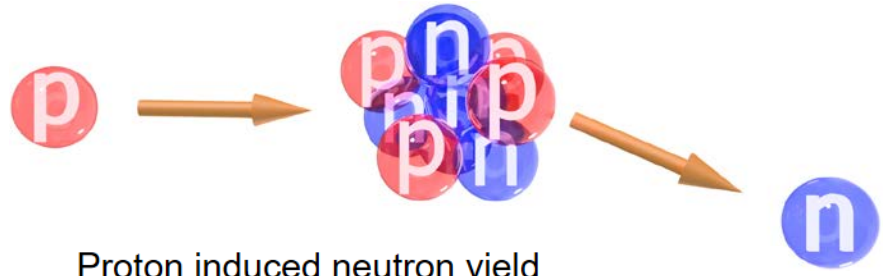
- Energies < 100 MeV
- Less expensive accelerator
- 0.01 to 0.1 n/proton
- Thin targets (low p range)
- Low activation
- Less shielding required

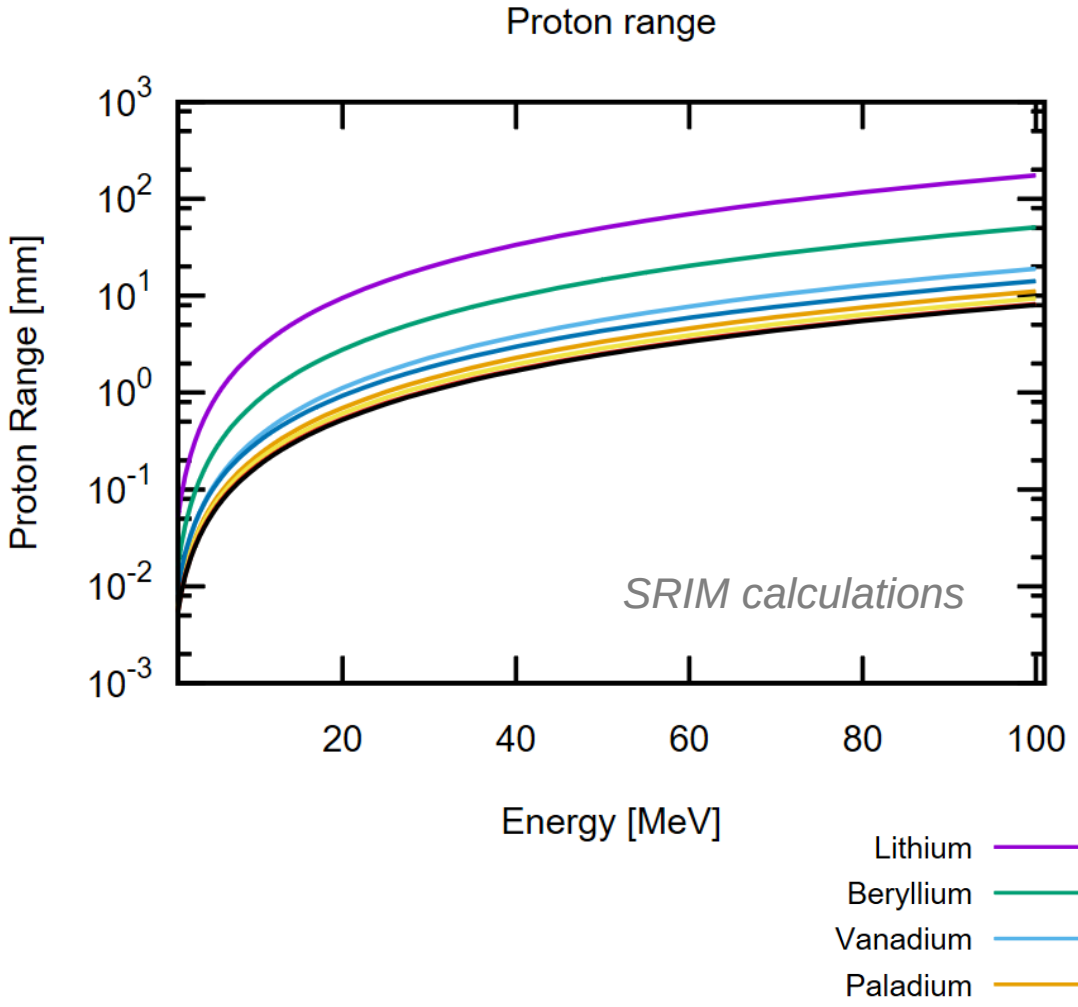
Spallation

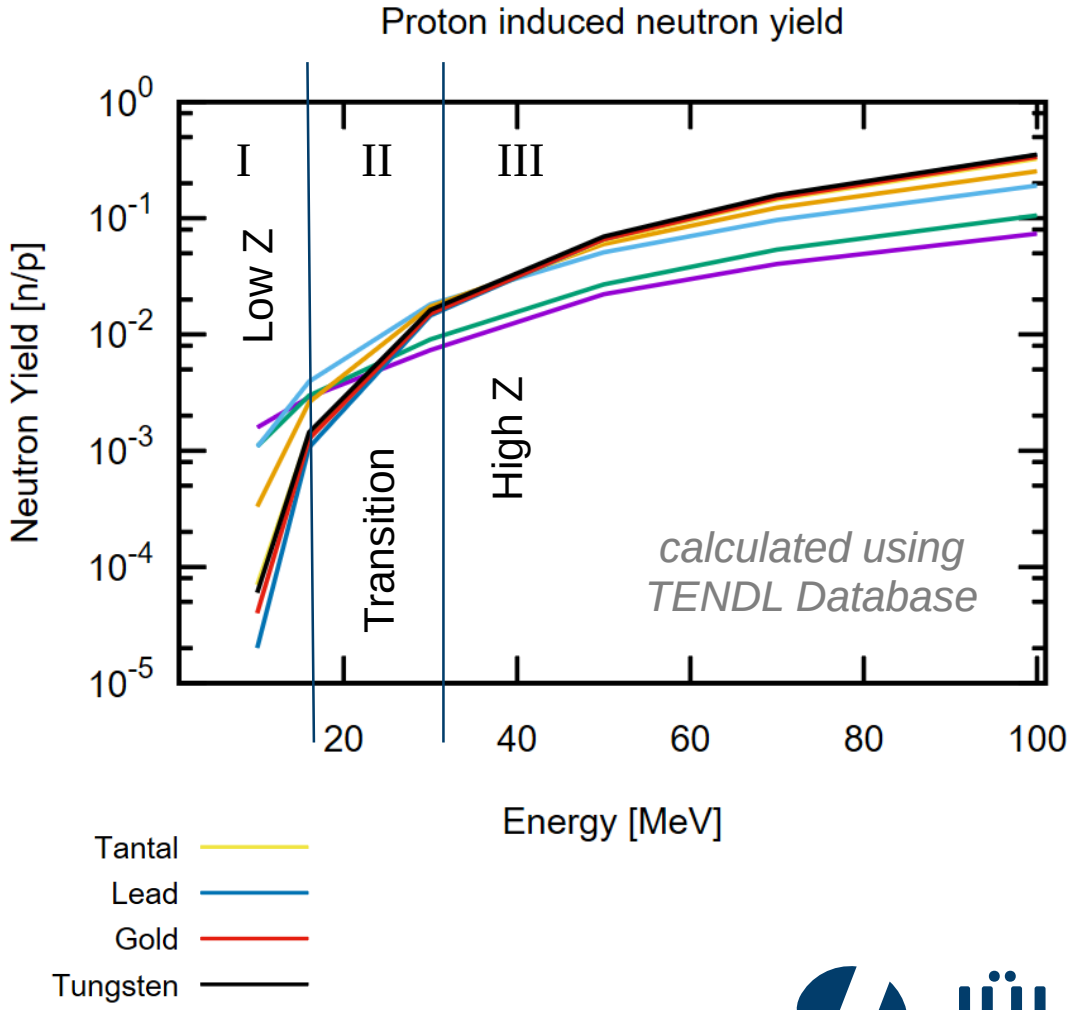
- Energies >> 100 MeV up to 1-2 GeV
- Expensive Accelerator
- Several n/p (+ 2^{nd}ary neutrons)
- Long target (high proton range)
- Highly activated components
- Massive shielding required

ENERGY RANGES

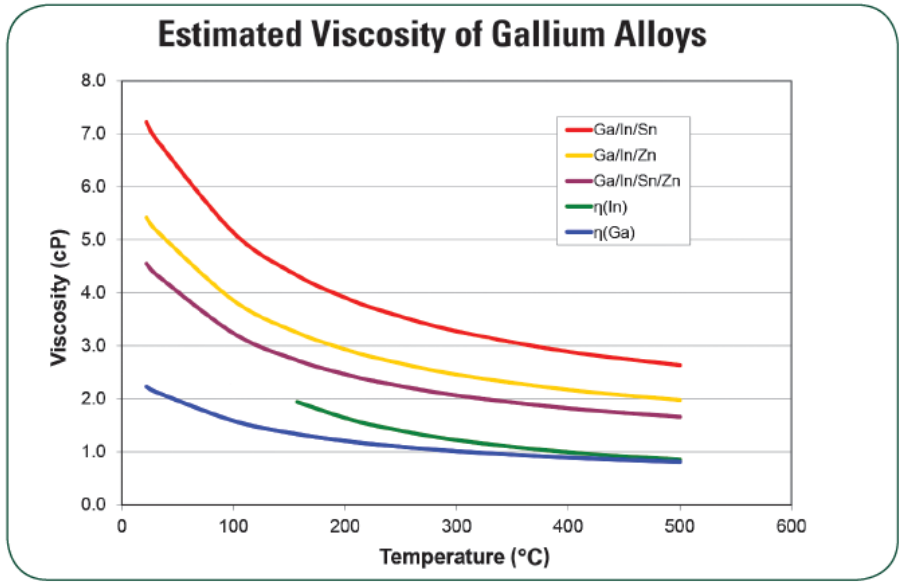
Sub-spallation, nuclear reaction based neutron production

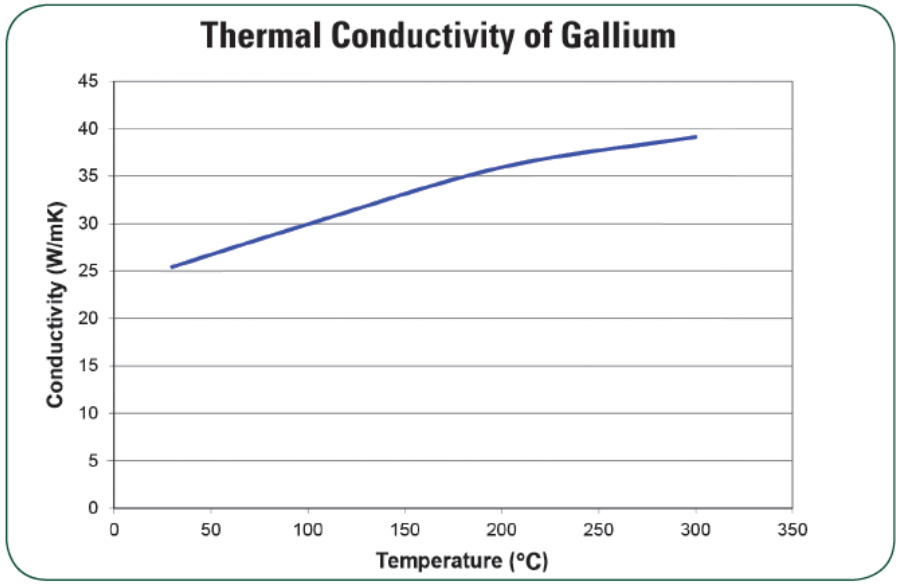


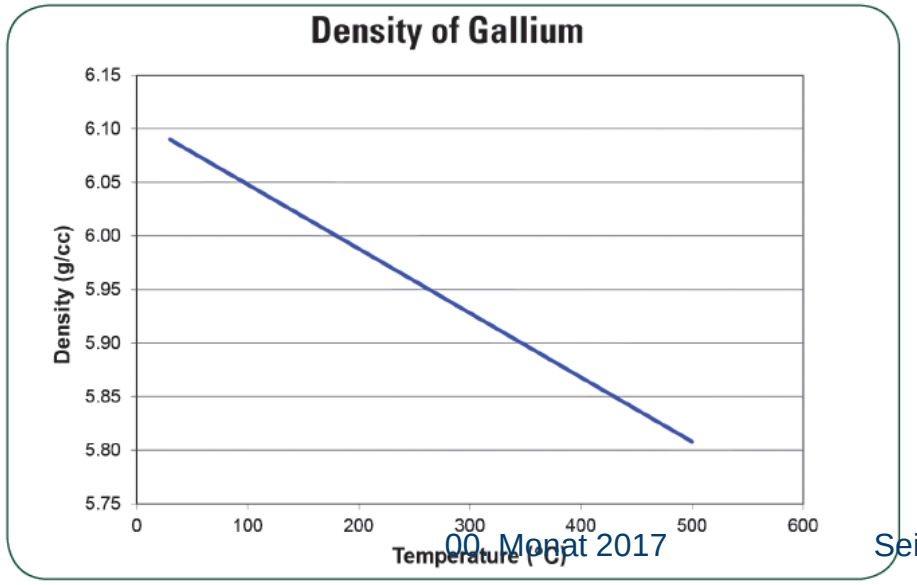


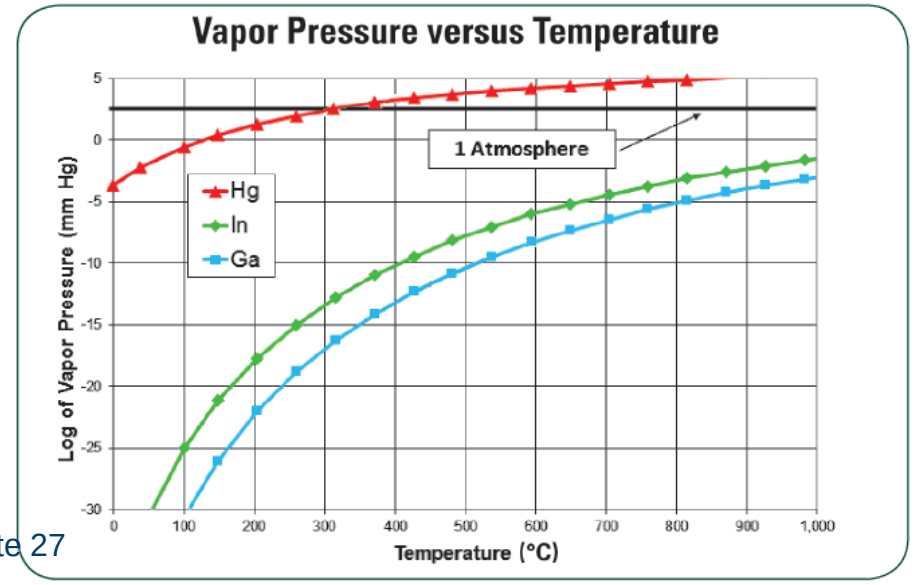


GALLIUM PROPERTIES









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GALLIUM PROPERTIES

Indalloy® Number	Liquidus (°C)	Solidus (°C)	Composition	Specific Gravity (gm/cm^3)	Thermal Conductivity (W/mK)	Electrical Resistivity (10^8 Ω-m)
46L	7.6	6.5	61.0Ga/25.0In/13.0Sn/1.0Zn	6.37	15*	33*
51E	11	11	66.5Ga/20.5In/13.0Sn	6.32	16.5[1]	28.9[1]
51	17	11	62.5Ga/21.5In/16.0Sn	6.50	16.5[1]	28.9[1]
60	15.7	15.7	75.5Ga/24.5In	6.35	20*	29.4[2]
77	25.0	15.7	95Ga/5In	6.15	25*	20*
14	29.8	29.8	100Ga	5.90	28.1[3]	14.85[4]

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TANTALUM PROPERTIES

Table 4.79. Physical properties of selected tantalum alloys

Common and trade name	UNS	Average chemical composition (x/ wt.%)	Density (ρ/kg.m^{-3})	Young's modulus (E/GPa)	Yield strength 0.2% proof (σ_y/MPa)	Ultimate tensile strength (σ_{uts}/MPa)	Elongation (Z/%)	Micro-Vickers hardness (HV)	Melting or liquidus temperature (T/°C)	Thermal conductivity (k/W.m^{-1}.K^{-1})	Specific heat capacity (c_p/J.kg^{-1}.K^{-1})	Coefficient linear thermal expansion (α/10^{-6}K^{-1})	Electrical resistivity (ρ/μΩ.cm)
Ta (unalloyed, EB cast)	R05200	99.98 wt.% (electron-beam melted, cold rolled, and annealed at 1200°C)	16,656	179–185	165–180	205–276	35–50	70–80	2996	57.55	142	6.5	12.5
Tantalum (soft)		99.95 wt.% (recrystallized)	16,656	179	310–380	310–485	25–40	90	2996	57.55	142	6.5	n.a.
Tantalum (hard)		99.95 wt.% (cold worked)	16,656	185	705	760	3	200	2996	57.55	142	6.5	n.a.
Ta (sintered, cast)	R05210	Sintered unalloyed	16,656	185	220	310	30	120	2996	57.55	139	6.5	12.5
Ta (sintered, cast)	R05400	Sintered unalloyed tantalum	16,656	185	220	310	30	120	2996	57.5	139	6.5	12.5
KBI®2, Tantaloy® 63	R05252	Ta-2.5W (electron-beam cast)	16,700	179–195	230–241	345–379	40	130	3005	n.a.	n.a.	n.a.	n.a.
KBI®6	n.a.	Ta-6W											n.a.
KBI®10, Tantaloy® 60, Cabot 10	R05255	Ta-10W (electron-beam cast)	16,900	205–207	460–482	550–620	30	245	3030	n.a.	n.a.	n.a.	17.6
KBI®40	R05240	Ta-40Nb (electron-beam cast)	12,100	152	193–207	275–310	25–40	n.a.	2705	n.a.	n.a.	n.a.	n.a.
Tantaloy 61 (P/M)	n.a.	Ta-7.5W (sintered)	16,800	200	875	1165	7	400	3025	n.a.	n.a.	n.a.	n.a.
T-111®	n.a.	Ta-8W-2Hf-0.02C											
T-222®	n.a.	Ta-10W-10Hf -0.01C											

TANTALUM PROPERTIES

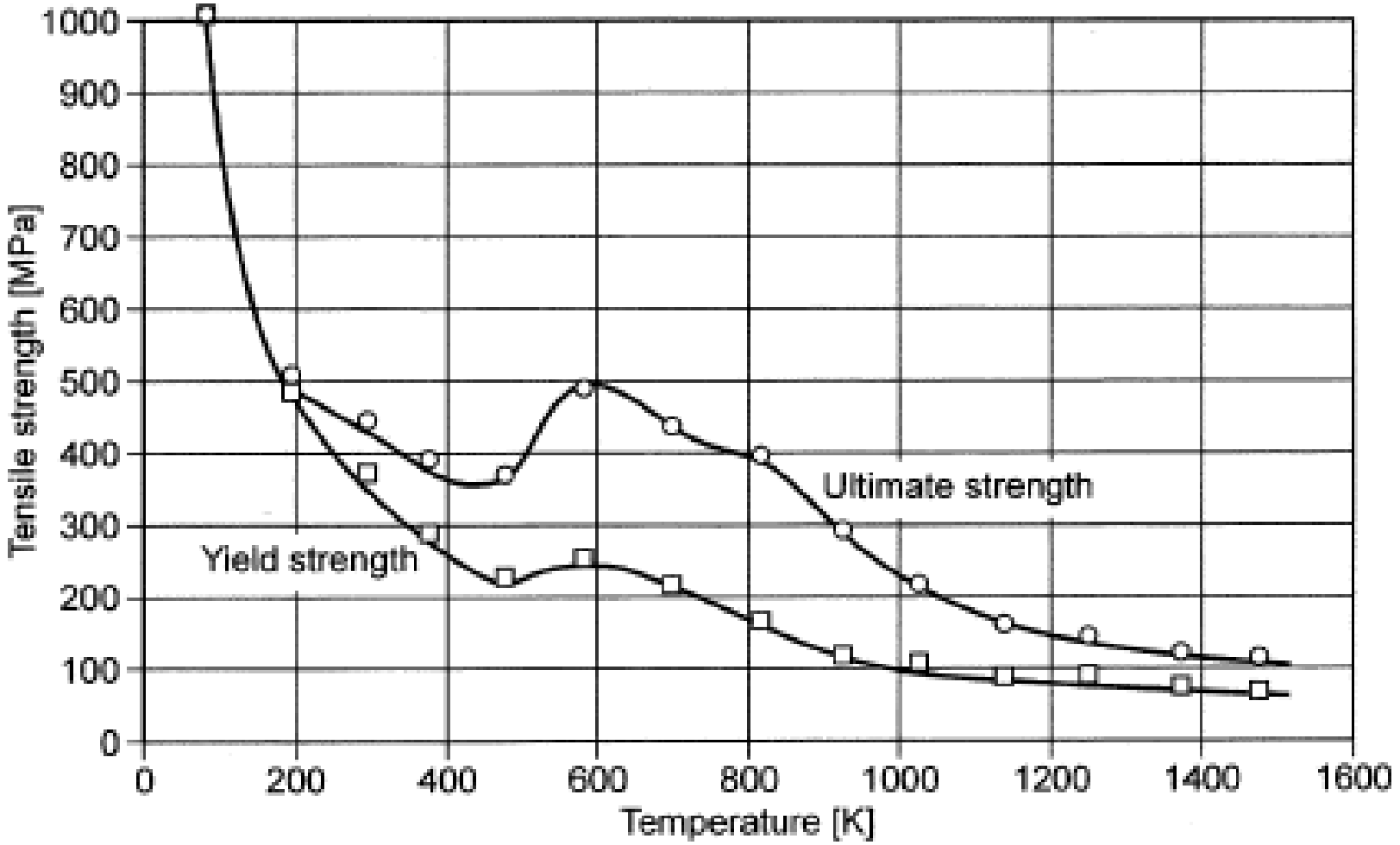


Fig. 21-35: Temperature dependence of yield stress and ultimate tensile strength of impure Ta [7].

JÜLICH Forschungszentrum

TANTALUM PROPERTIES

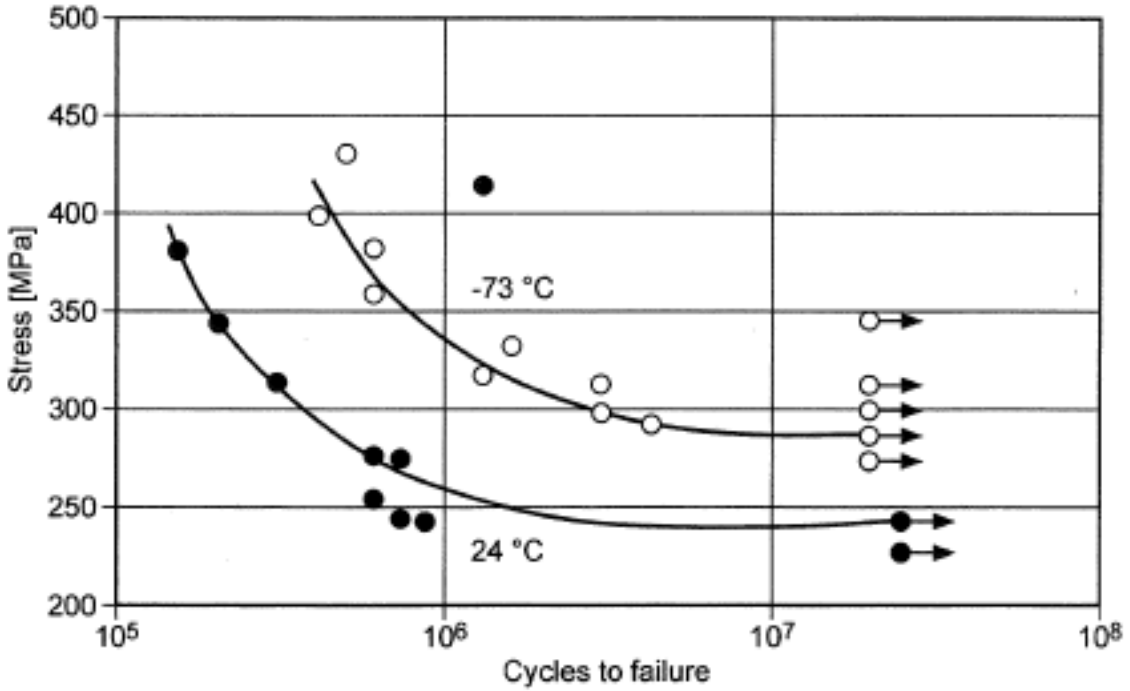


Fig. 21-55: Fatigue characteristics of 1 mm thick Ta sheets rolled to 33% reduction in area and annealed at 1400°C for 1 hour before testing at 25 and –73°C, respectively (after Ref. [1] using data by A. Bornemann).

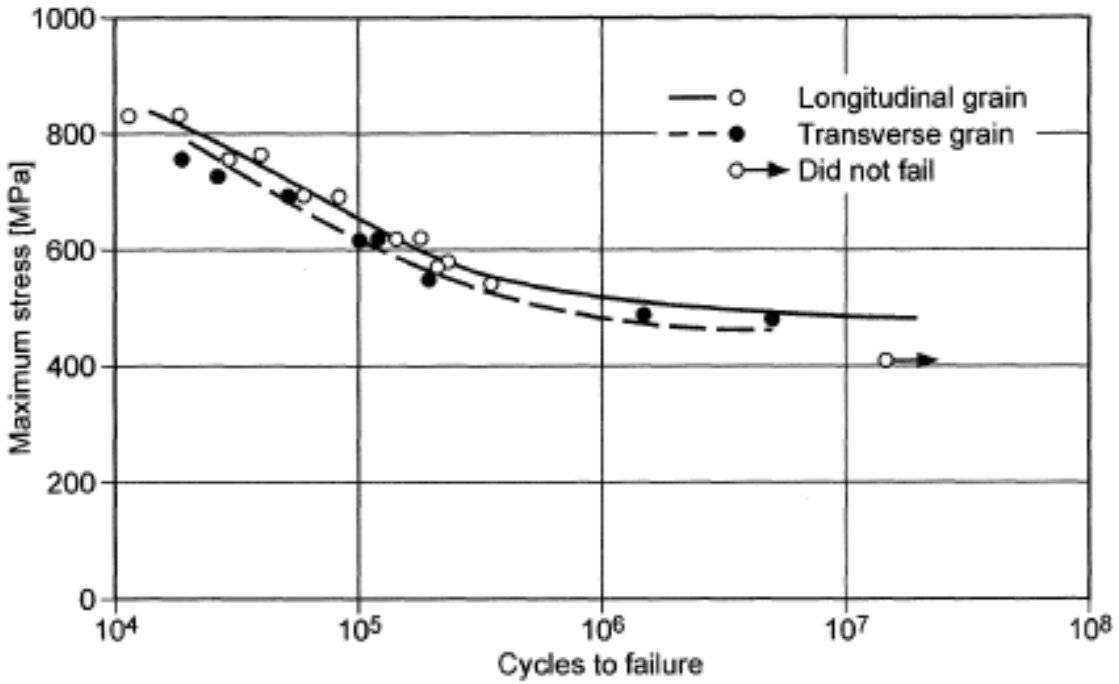


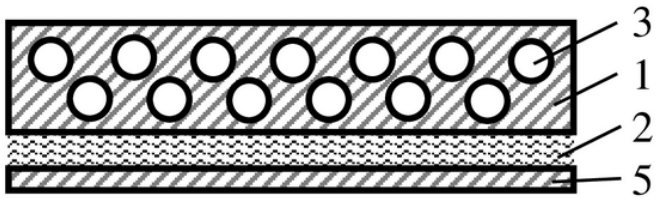
Fig. 21-57: Reversed bending fatigue properties of cold-rolled, 0.64 mm thick Ta-10%W sheets at 25°C [2].

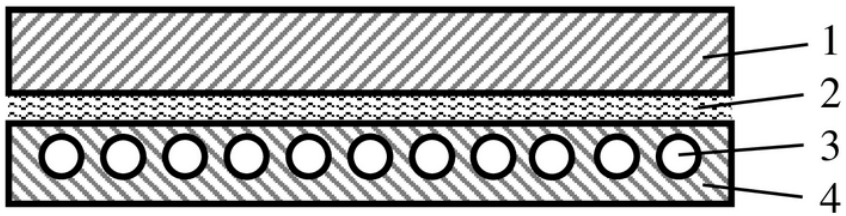
Fatigue data for tantalum and its alloys are scarce. The results found in the literature are given in *Figs. 21-55* to *21-57*. They indicate that Ta exhibits a fatigue limit which is around 240 MPa for the annealed pure material and somewhat higher for the stronger Ta-10%W alloy at 25°C. No information on fatigue properties at elevated temperatures or of irradiated material is available.

TWO OPTIONS FOR HIGH POWER TARGET

Internally and externally micro channel cooled target

Internally cooled target	Externally cooled target
Low temperature	High temperature
Higher beam concentration possible (smaller target)	Lower beam concentration (larger target)
Target is structural	Target and dump layer are not structural
Damage critical for other components	Damage not critical
Deposition of protons less predictable	Deposition of protons more predictable





1 target, 2 dumping layer, 3 MC, 4 heat sink, 5 structural material