Target Station Development for Transportable Accelerator-driven Neutron Source

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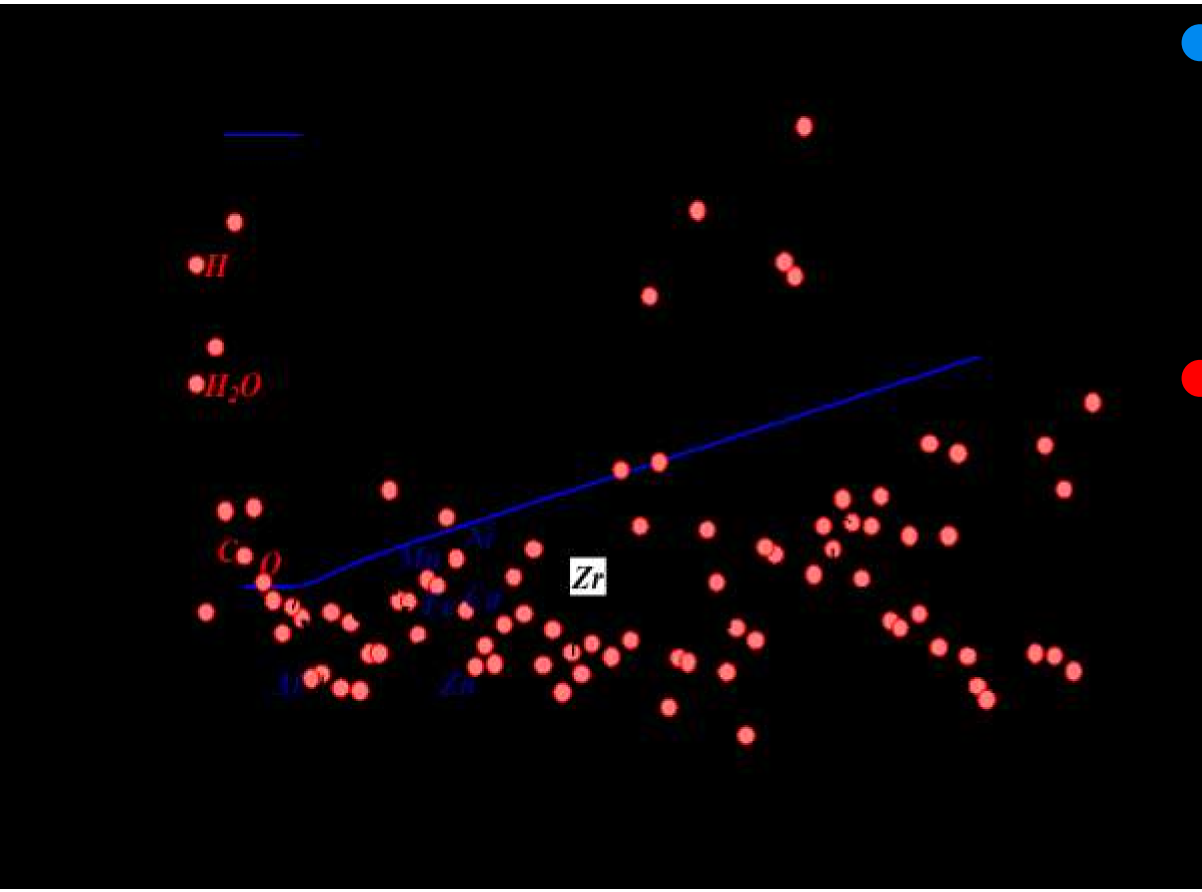
1.Transportable Accelerator-driven Neutron Source

1.Transportable Accelerator-driven Neutron Source

1.1 The advantages of neutron



- **X-ray interaction enhances with the atomic number increasing, which means it is easy to observe heavy material.**
- **Neutron interaction with different nucleus varies largely and for light material i gh valu**

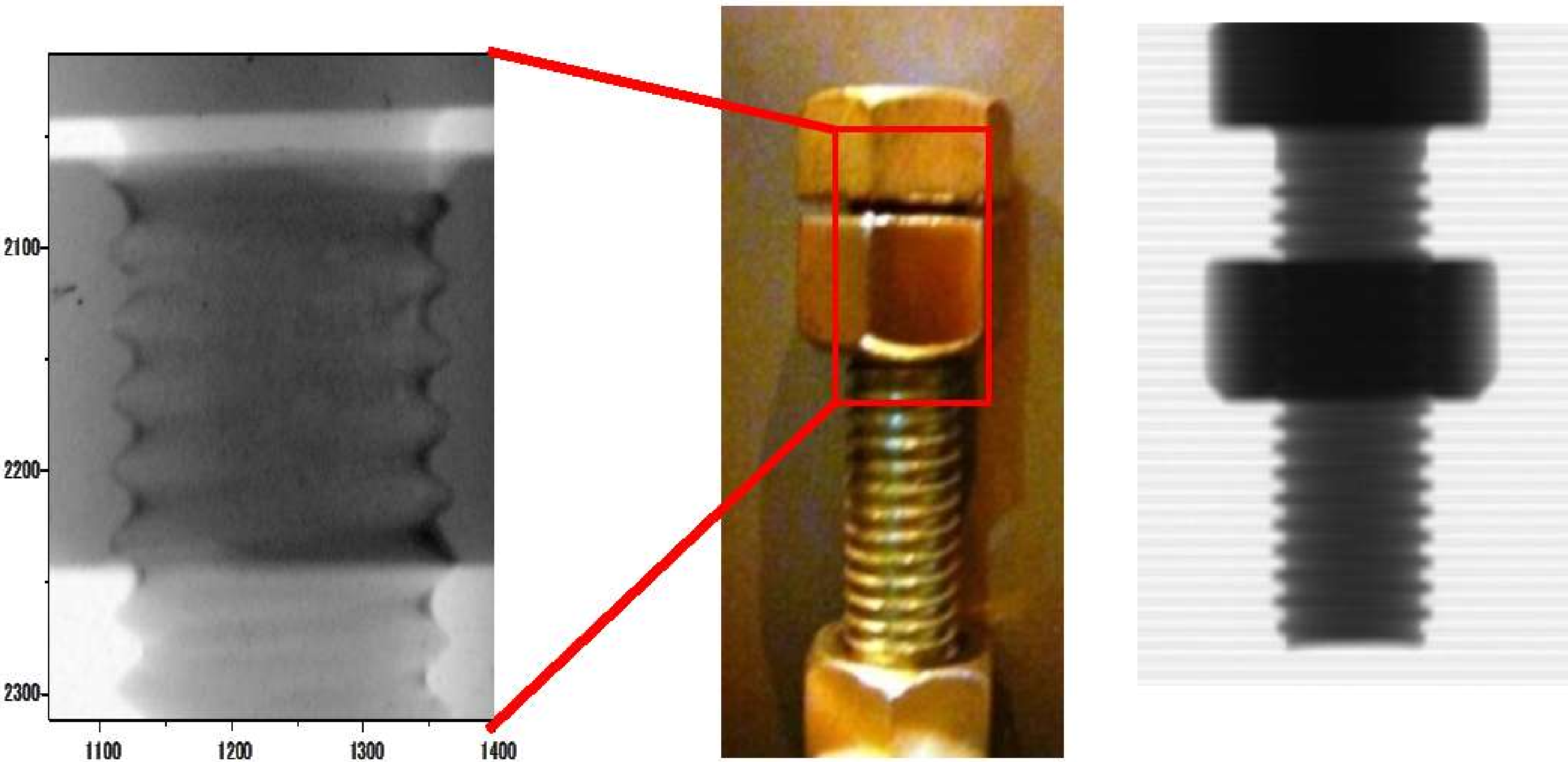
Electrically neutral

and

Deep penetration

1.Transportable Accelerator-driven Neutron Source

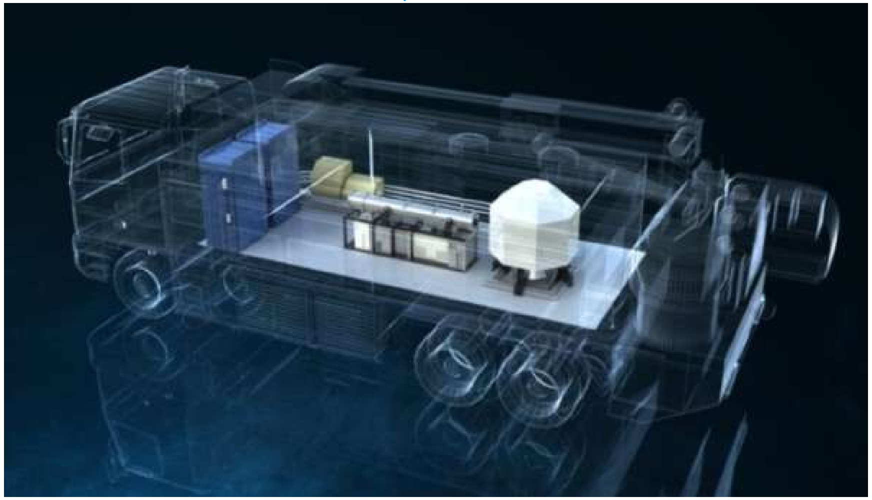
1.1 The advantages of neutron



1.Transportable Accelerator-driven Neutron Source

1.2 Neutron source

Further miniaturization



Transportable neutron source

1.Transportable Accelerator-driven Neutron Source

1.3 Specific application: NDT

Neutron Imaging

6 Tunnel

1 Pressure vessel

2 Oil-gas pipeline

5 Bridge

4 Rocket

3 A

1.Transportable Accelerator-driven Neutron Source

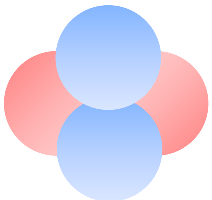
1.4 Transportable Accelerator-driven Neutron Source for NDT

A reliable and long-life target system

2.Development of Target System

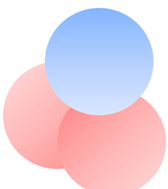
2.Development of Target System

2.1 Scheme to generate neutron



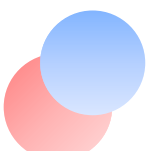
Heavy ion

Hard to be accelerated ✗



Tritium

Strong radioactivity ✗



Deuteron

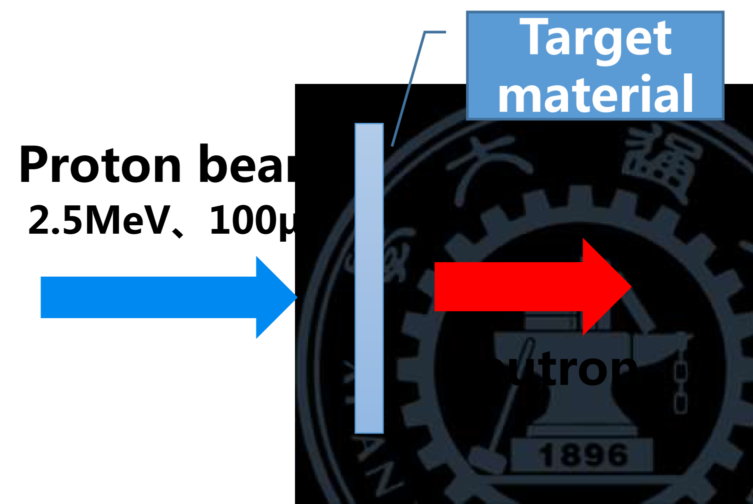
Low neutron yield ✗

Proton

Easy to be accelerated
High neutron generating efficiency ✓

Weight

Volume



2.Development of Target System

2.2 Choice of target material

Two main candidates for target material:

Be

Beryllium

Li

Lithium

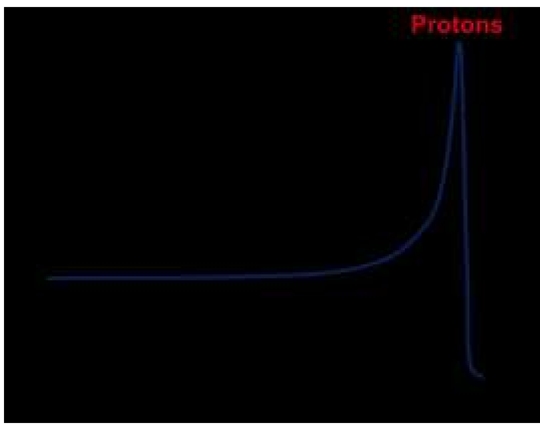
Thermodynamic Property Comparison: Be and Li

Material	Thermal conductivity (W/cm/K)	Specific Heat Capacity(J/gK)	Melting Point(℃)
Be	250	1.82	1278
Li	84.7	3.6	180.54

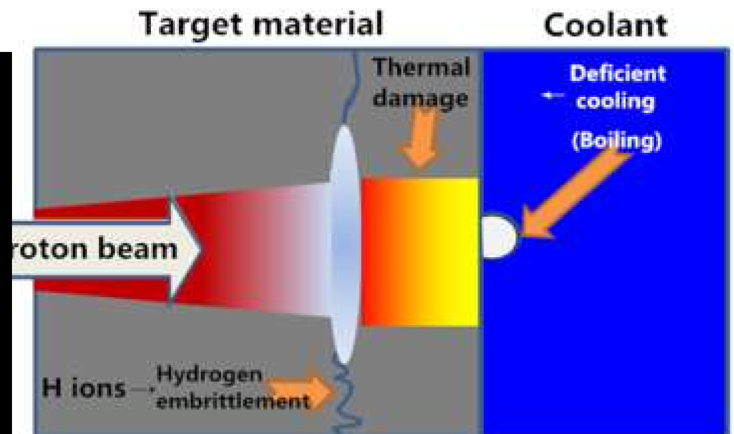
2.Development of Target System

2.2 Choice of target material

Hydrogen embrittlement of Beryllium



Bragg peak effect



Principle
of hydrogen embrittlement

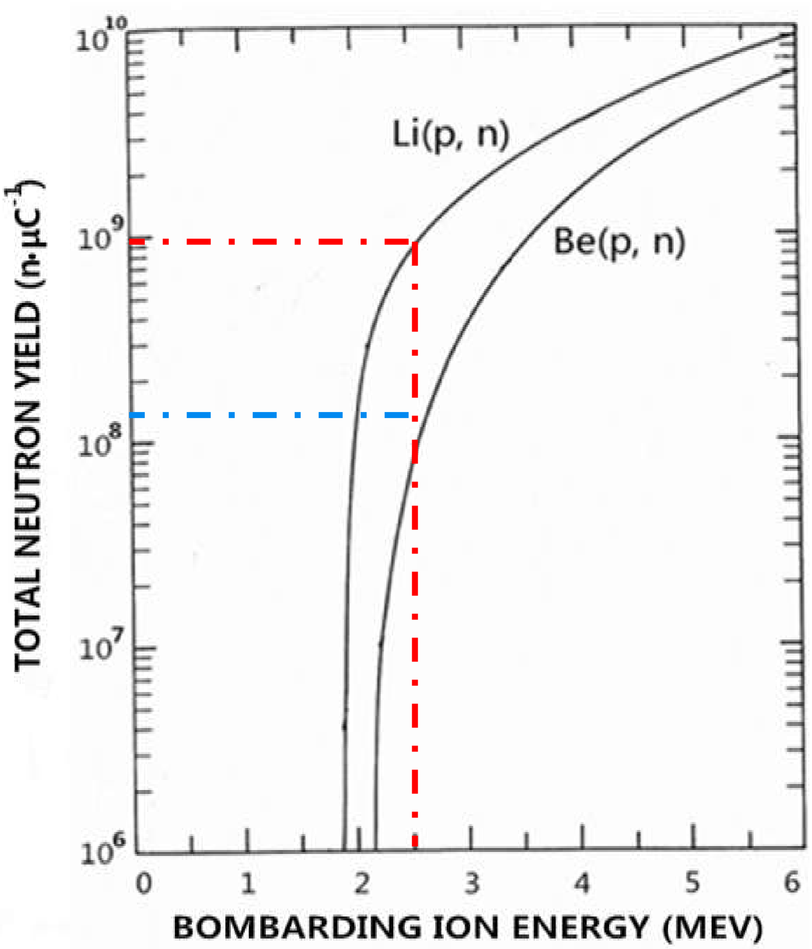
Hydrogen [redacted]

*Rinckel T, Baxter D V, Doskow J, et al. Target Performance at the Low Energy Neutron Source[J]. Physics Proc[redacted]

2.Development of Target System

2.2 Choice of target material

Reaction (p, n) neutron yield of Li and Be



Li target has higher neutron yield than Be target for low proton energy

M. R. Hawkesworth, Atomic Energy Review 15 2(1977), p. 169

2.Development of Target System

2.2 Choice of target material

Lithium compounds are also candidates:


Lithium oxide


Lithium nitride


Lithium carbonate

Comparison among lithium and its compounds

Material/ Property	Li	Li_2O	LiOH	Li_3N	LiH	Li_2CO_3	Li_2C_2
Atomicity, A	7	30	24	35	8	74	38
Density, ρ	0.534	2.013	1.46	1.3	0.82	2.11	1.65
Atom density	4.59×10^{22}	4.04×10^{22}	3.66×10^{22}	2.24×10^{22}	6.17×10^{22}	1.72×10^{22}	2.61×10^{22}
Li Atom density	4.59×10^{22}	8.08×10^{22}	3.66×10^{22}	6.72×10^{22}	6.17×10^{22}	3.44×10^{22}	5.22×10^{22}
Melting point	182℃	＞1700℃	471℃	845℃	689℃	618℃	＞550℃
Existence	Soft、Silver metal	White powder	White crystal powder or granules	Red brown or black grey crystals	Colorless crystals	Colorless crystals or white powder	White powder crystal

2.Development of Target System

2.2 Choice of target material

Material/ Property	Li	Li_2O	LiOH	Li_3N	LiH	Li_2CO_3	Li_2C_2
2.5 MeV range	231.5 um	64.14 um	82.27 um	99.23 um	121.92 um	61.60 um	74.85 um
1.88 MeV range	143.25 um	40.06 um	51.47 um	61.67 um	74.82 um	38.70 um	46.35 um
Target thickness	88.25 um	24.08 um	30.8 um	37.56 um	47.1 um	22.9 um	28.5 um
Atom density	4.59×10^{22}	8.08×10^{22}	3.66×10^{22}	6.72×10^{22}	6.17×10^{22}	3.44×10^{22}	5.22×10^{22}
Neutron yield Arb. Unit	1	0.48	0.278	0.623	0.718	0.195	0.367

2.Development of Target System

2.2 Choice of target material

Li

Melting point
180.5℃

Liquid lithium

Need to keep lithium liquid and prevent radioactivity diffusion, so heating system and additional shielding system are necessary.

Solid lithium

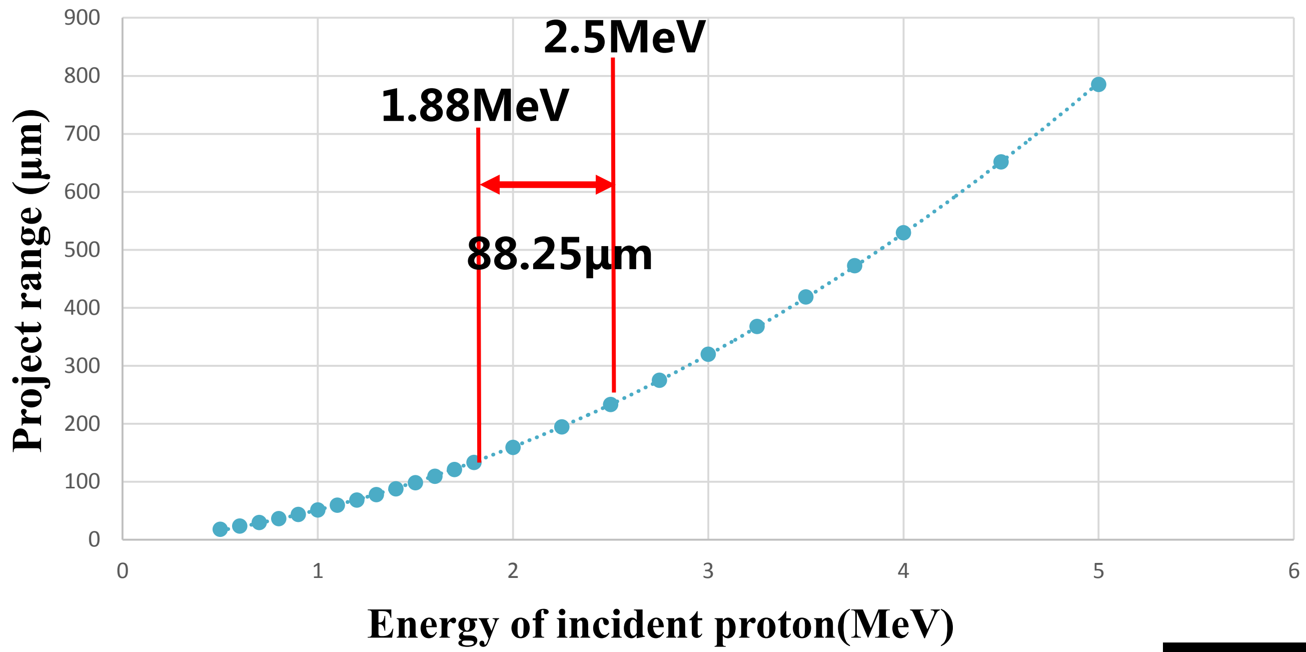
Easy to melt, so need effective cooling system.

If we achieve high cooling efficiency, solid lithium is the best!

2.Development of Target System

2.3 Thickness of solid lithium target

Project range of incident proton in lithium



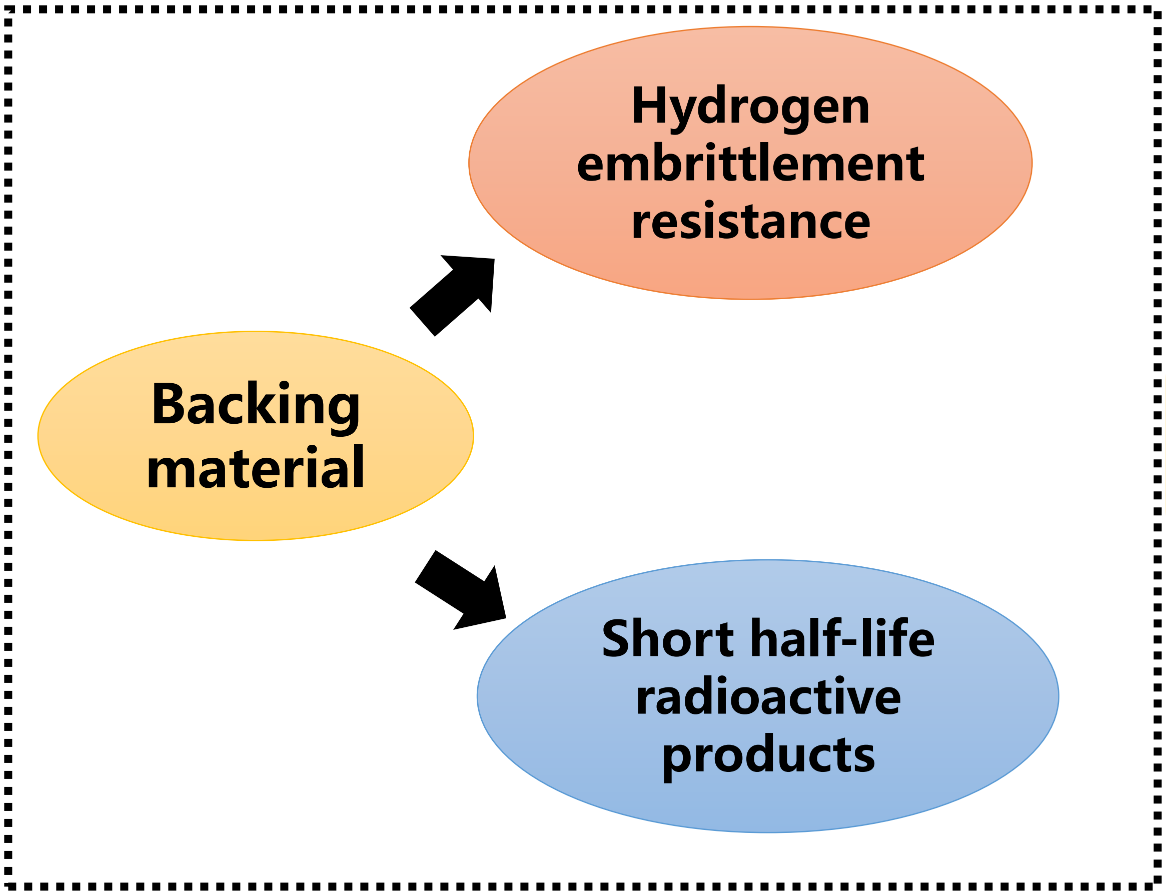
To avoid:

- **Additional influence on neutron yield and speed**
- **γ radiation**

*Calculated by SRIM

2.Development of Target System

2.4 Choice of backing material

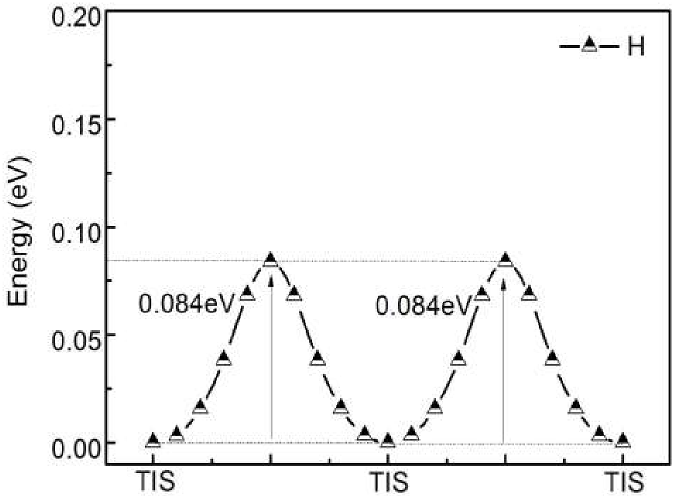


Backing material: Vanadium

2.Development of Target System

2.4 Choice of backing material

Hydrogen diffusion and solution in vanadium



Diffusion barrier of hydrogen in vanadium

Material	Diffusion activation energy (eV)	Dissolution (eV)
Vanadium	0.084	-0.3575
Copper	0.4	0.37
Tungsten	0.39	1.03

$$E_{sol} = E(metal + H) - E(metal) - \frac{1}{2}E(H_2)$$

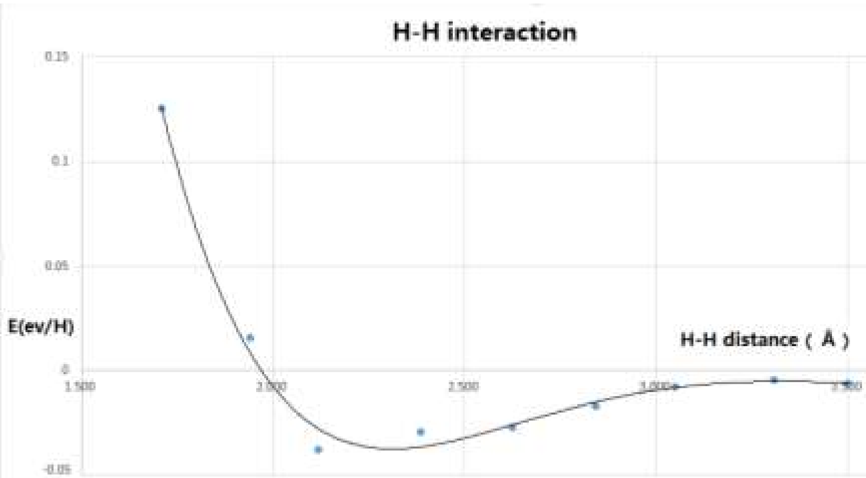
$$D(H) = D_0 \exp\left(\frac{-E_D}{k_B T}\right)$$

- Most important parameter that correlates with the blistering threshold is diffusion coefficient and dissolution energy.
- Vanadium has negative hydrogen dissolution energy, therefore, it can accumulate large amount of hydrogen. Hydrogen diffusion coefficient in vanadium is very high, therefore, hydrogen redistributes over the target deeper.

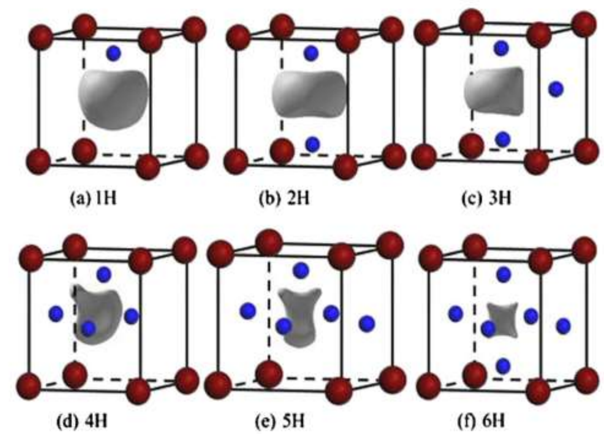
2.Development of Target System

2.4 Choice of backing material

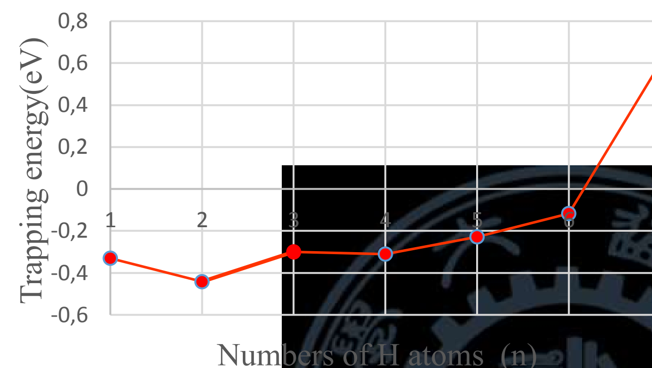
Interaction of H atoms with H and vacancy in vanadium



H-H interaction energies in vanadium vs H-H distance



Interaction of multi-H atoms with vacancy in vanadium

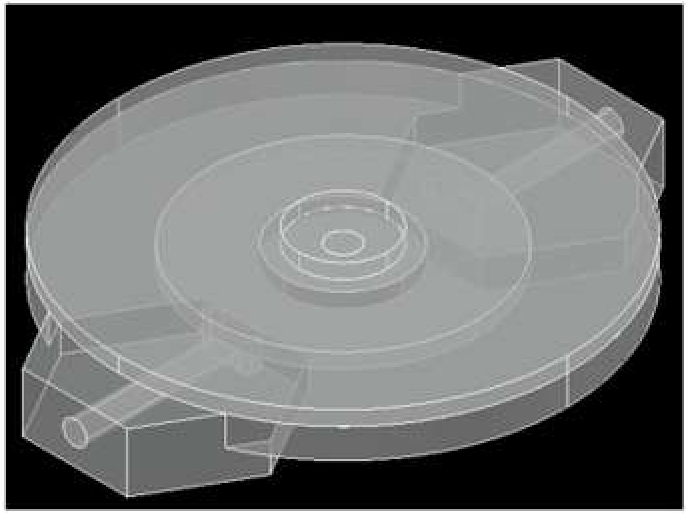


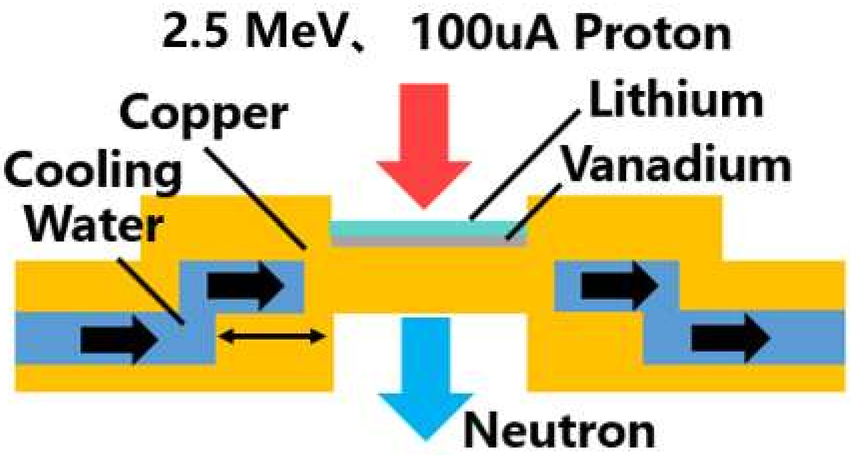
$E_H^{trap}(n) = \left[E_{vac+nH} - \ldots\right]$

- ➢Hydrogen embrittlement happens because of accumulation of large amount of H_2
- ✓ In perfect vanadium: To keep H-H distance smaller than than bond length of H_2 (0.75 A) needs extremely high energy, which implies that two H atoms is very difficult to bind together to directly form H_2 molecule.
- ✓For vanadium with vacancy: While six H atoms can be trapped in a vacancy, further trapping or formation of H_2 in a vacancy is suppressed owing to relatively stable H interstitials.
- ➢It is difficult to form H_2 in vanadium, so vanadium is a good anti hydrogen embrittlement mate

2.Development of Target System

2.5 Overall structure





Schematic diagram of the target

Lithium: Target material
Vanadium: Backing material
Water: Coolant
Copper: Cooling cavity material

2.Development of Target System

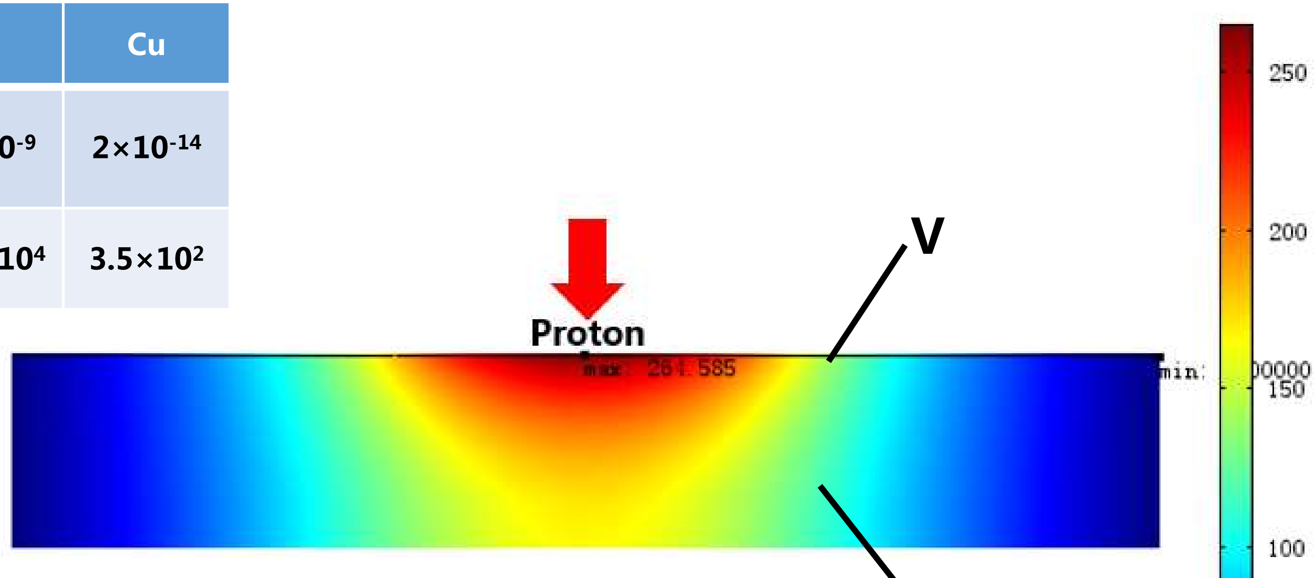
2.6 Resistance of Hydrogen Embrittlement

Hydrogen diffusion in the target system

Character of V and Cu☆

Material	V	Cu
Hydrogen diffusion coefficient (m^2/s) @25℃	5×10^{-9}	2×10^{-14}
Hydrogen embrittlement limit (mol/m^3)	1.4×10^{4}	3.5×10^{2}

*H/V = 0.3 at% H/Cu = 0.1



V=50um Max concentration: 264.585mol/m^3

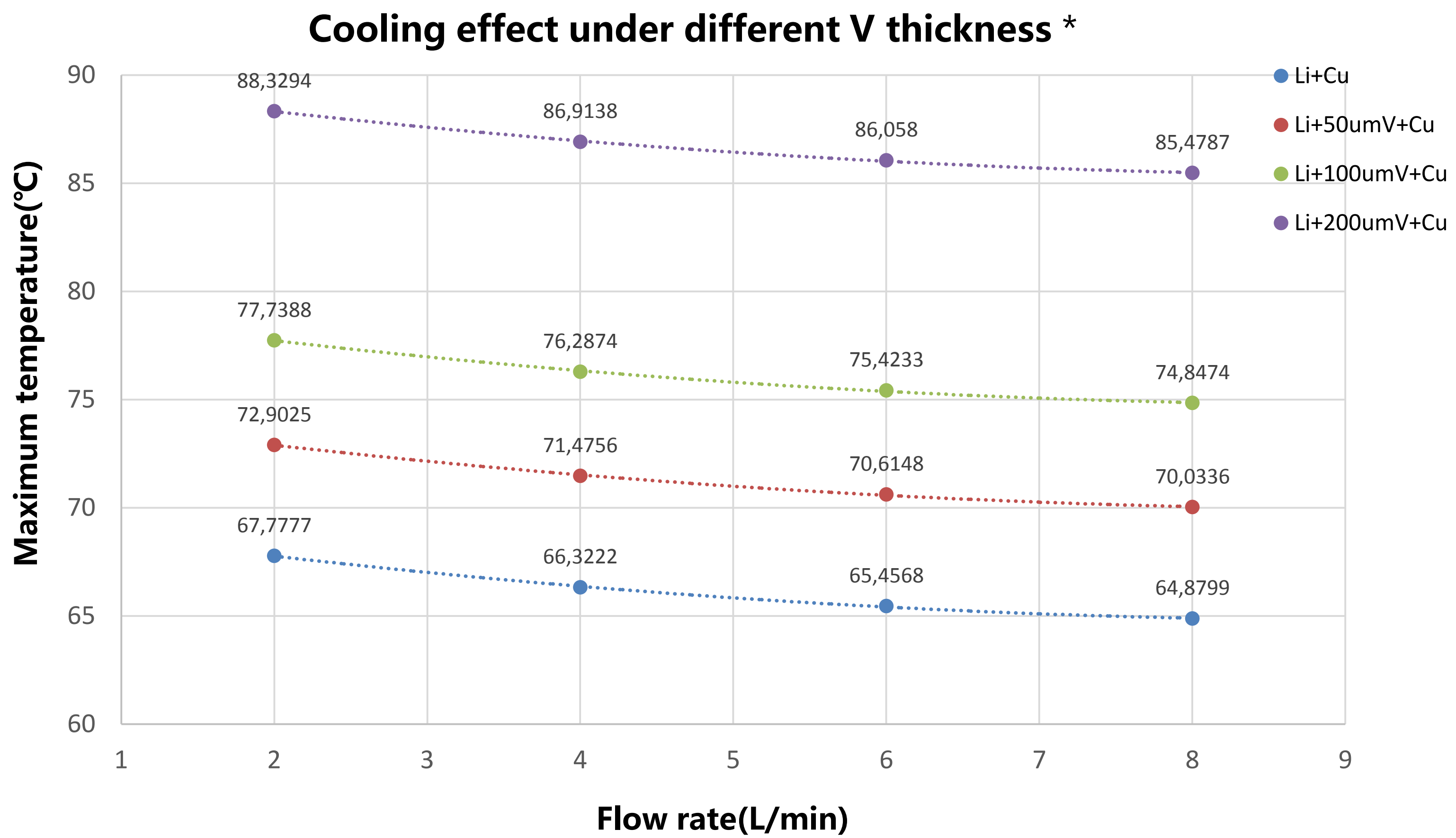
V=100um Max concentration: 132.418mol/m^3

V=200um Max concentration: 66.2921mol/m^3

☆Yamagata Y, Hirota K, Ju J, et al. Development of a neutron generating target for compact neutron sources using low energy proto[illegible] Journal of Radioanalytical & Nuclear Chemistry, 2015, 305(3):1-8.

2.Development of Target System

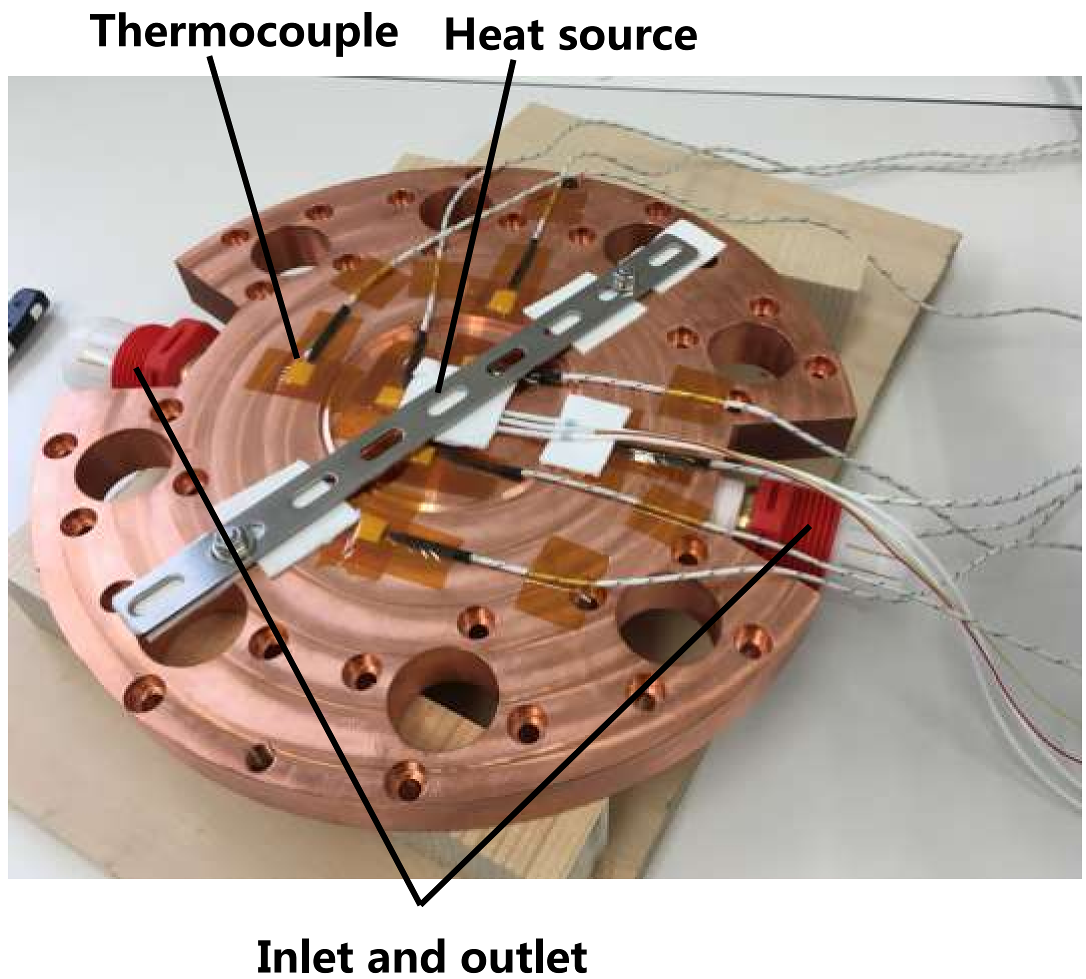
2.7 Cooling effect



*Calculated by COMSOL Multiphysics 5.1

2.Development of Target System

2.7 Cooling effect

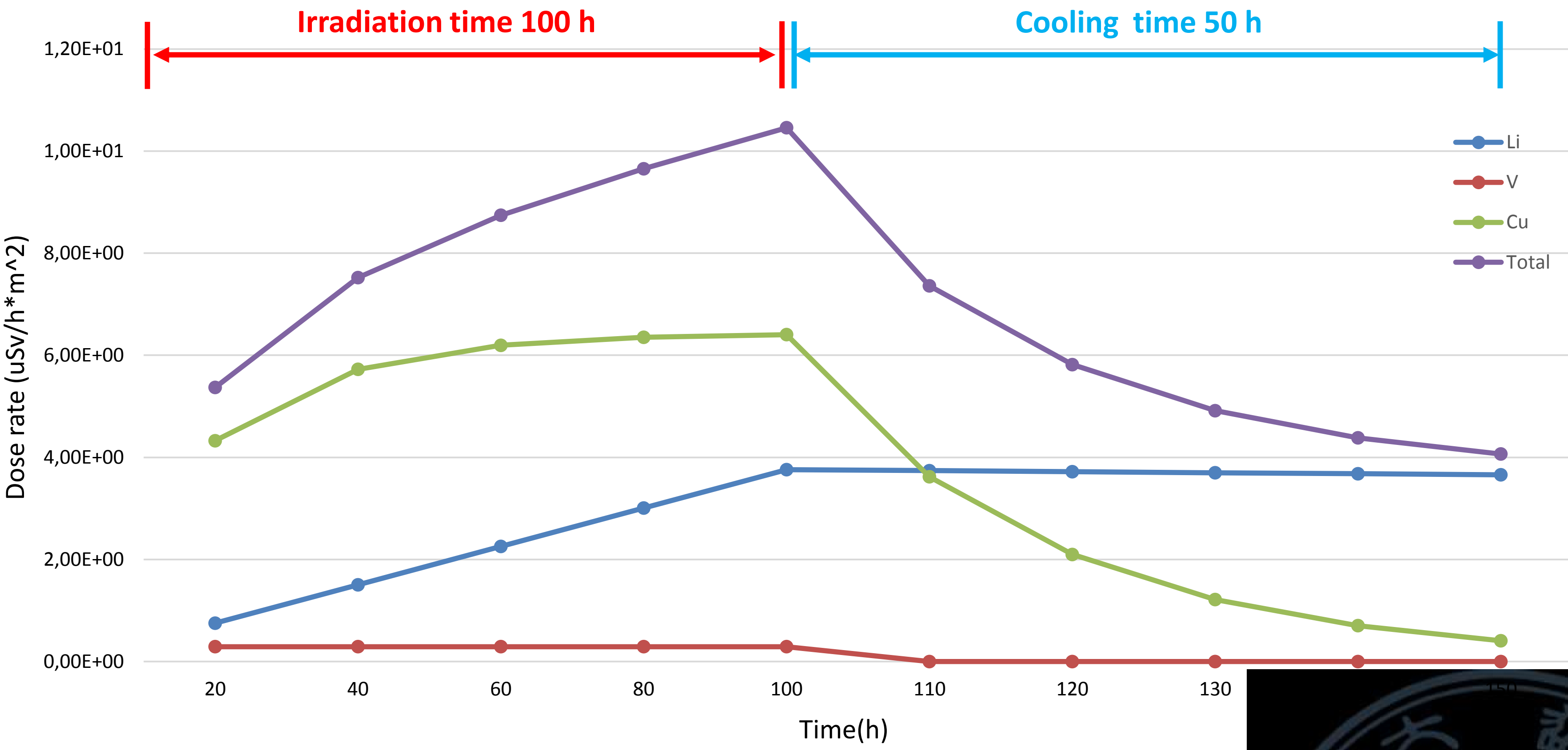


Cooling effect is under test

*Calculated by COMSOL Multiphysics 5.1

2.Development of Target System

2.8 Analysis of activation products radioactivity

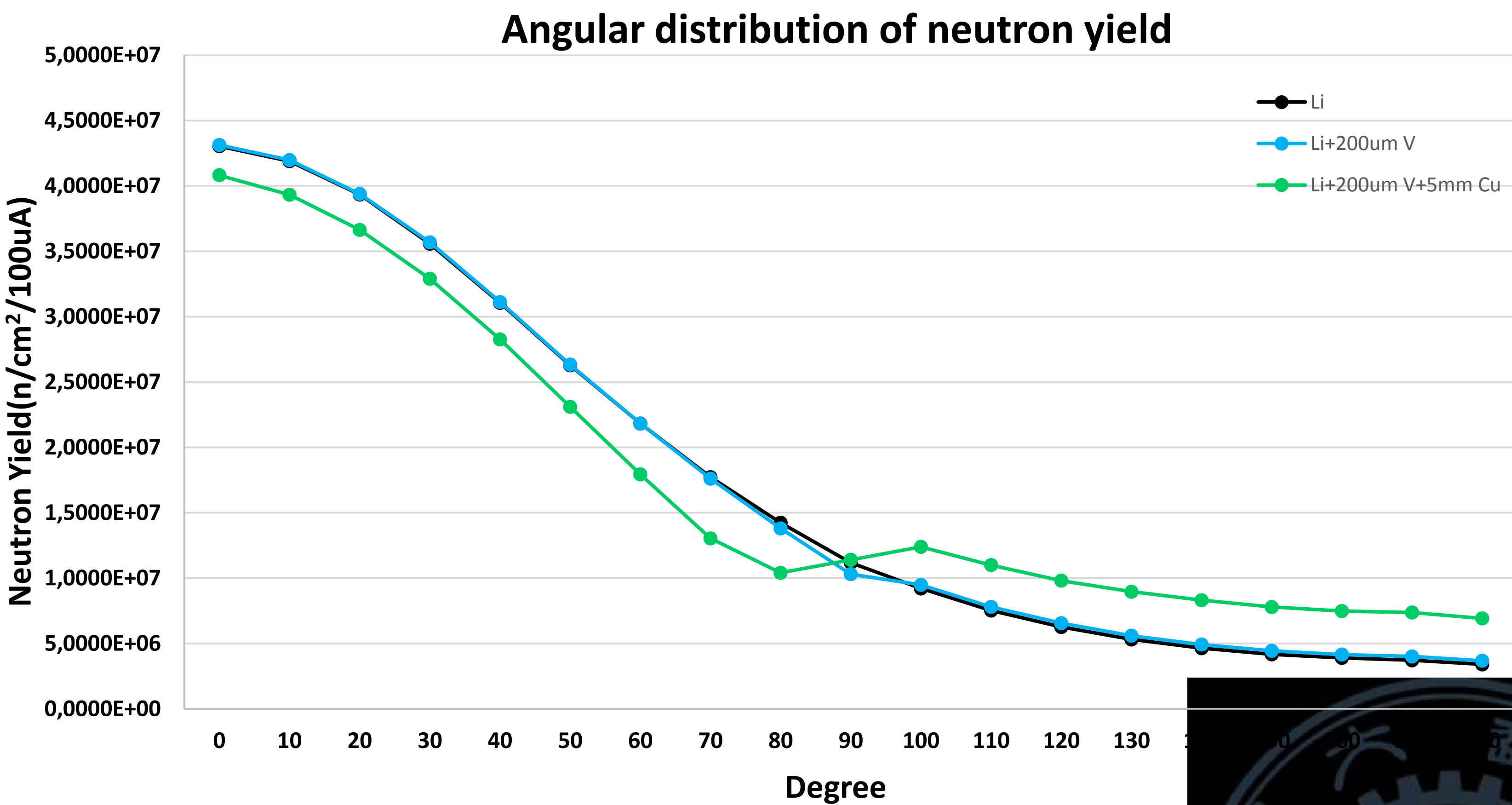


Generated radioactivity of different target materials

*Calculated by PHITS V2.88+DCHAIN-SP

2.Development of Target System

2.9 Neutron angular distribution



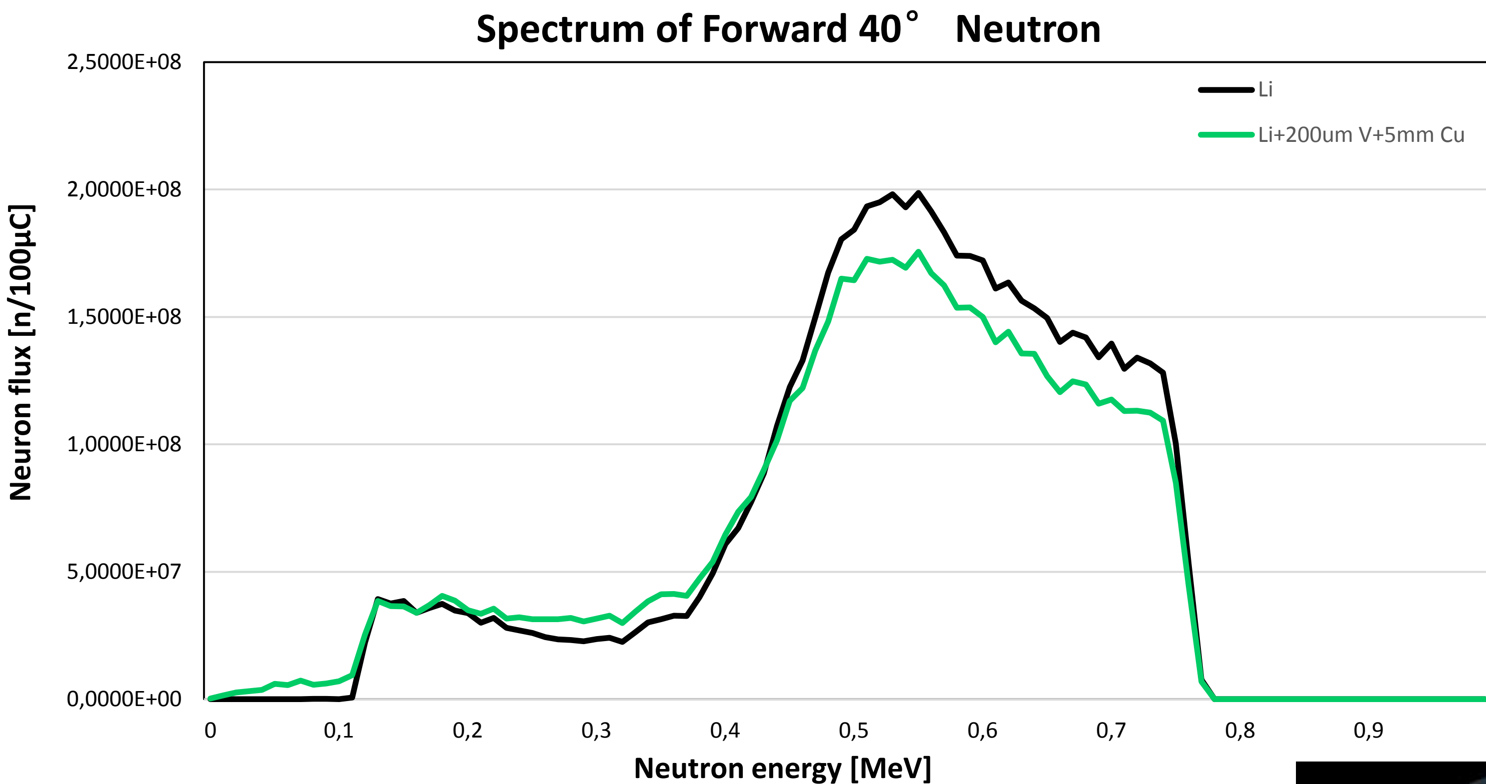
◆V is almost of no influence to angular distribution;

◆The existence of Cu decreases forward neutron and increases backward neutron.

*Calculated by PHITS V2.88

2.Development of Target System

2.10 Forward neutron spectrum



Forward neutron spectrum of 40°flare angle

- ◆**Neutron energy dominant at range 0.4-0.77 MeV, which can be used for bridge inspection;**
- ◆**Loss of total neutron yield is 6.44%;**
- ◆**Loss of neutron in range 0.4-0.77 MeV is 11.13%;**
- ◆**Sufficient to distinguish void with water or air gap in 30cm thick concrete wall with our fast neutron imaging technique.**

*Calculated by PHITS V2.88

3.Conclusions

3.Conclusion

Conclusion

1. Solid lithium is a prospective target for transportable accelerator-driven neutron source.

2. By using vanadium and cooper, the problems of lithium target could be solved properly.

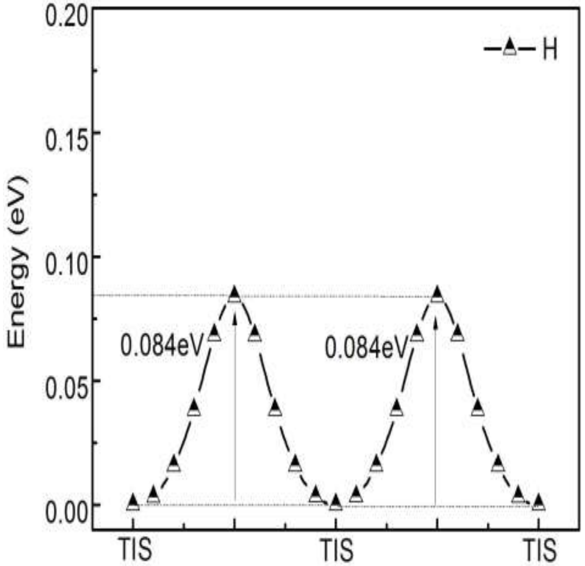
3. The yield and spectrum of forward neutron may fit the concrete imaging well.

Experiment verification is in progress!

WE ARE JUST ON THE WAY

THANK YOU FOR YOUR ATTENTION!

Hydrogen solution and diffusion in vanadium



The diffusion barrier of hydrogen in vanadium

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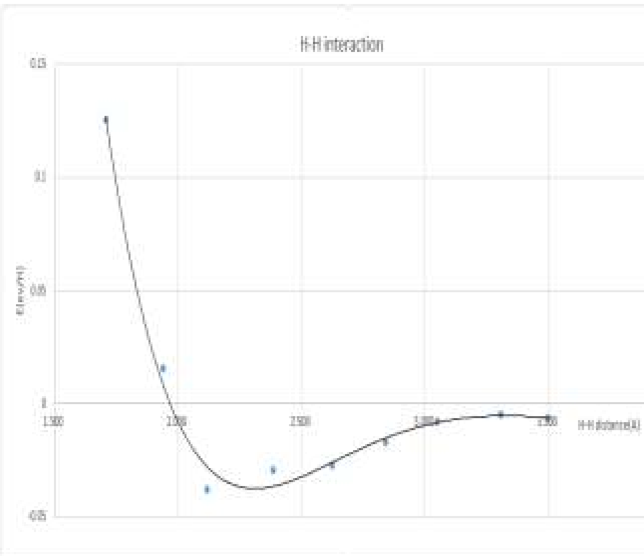
Vanadium	0.084	-0.3575
Copper	0.4	0.37
Tungsten	0.39	1.03

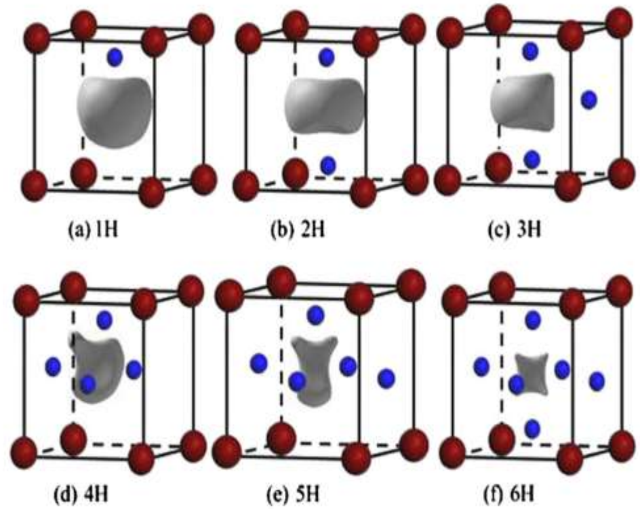
$$E_{sol} = E(metal + H) - E(metal) - \frac{1}{2}E(H_2)$$

$$D(H) = D_0 \exp\left(\frac{-E_D}{k_B T}\right)$$

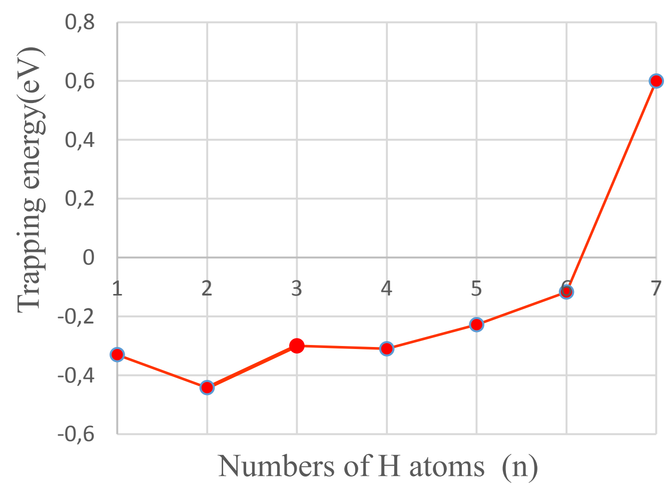
The most important parameter that correlates with the blistering threshold is the dissolution energy E_{sol} and diffusion coefficient D_H. Vanadium has negative hydrogen dissolution energy, therefore, it can accumulate large amount of hydrogen. Hydrogen diffusion rate in vanadium is very high, therefore, hydrogen redistributes over the target deeper.



Because this H-H distance is much larger than the bond length of H_2 (0.75 A).This implies that two H atoms cannot bind together to directly form an H_2 molecule in perfect vanadium.

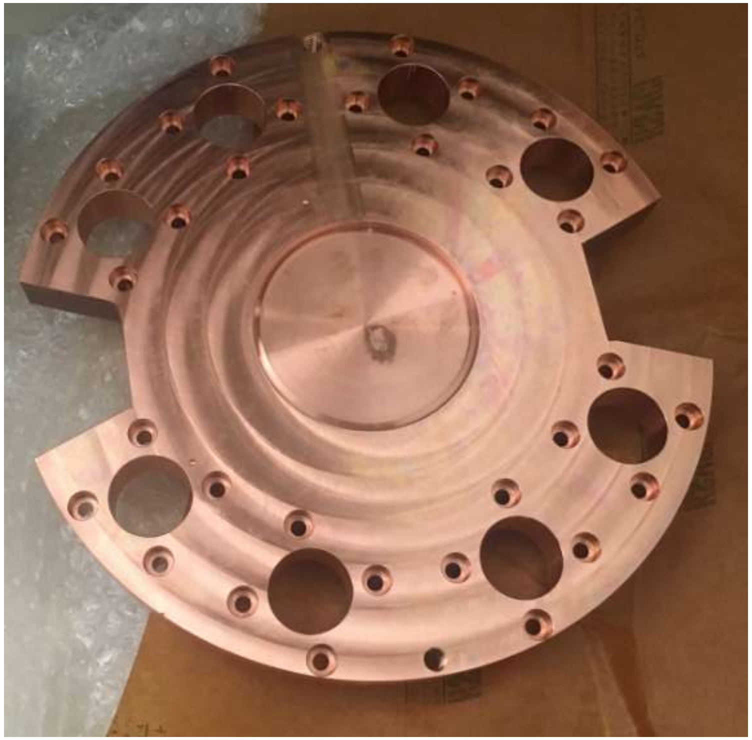


While six H atoms can be trapped in a vacancy, further trapping or formation of H_2 in a vacancy is suppressed owing to relatively stable H interstitials



$$E_H^{trap}(n) = \left[E_{vac+nH} - E_{vac+(n-1)H}\right] - \left[E_{V,H(T-site)} - E_V\right]$$

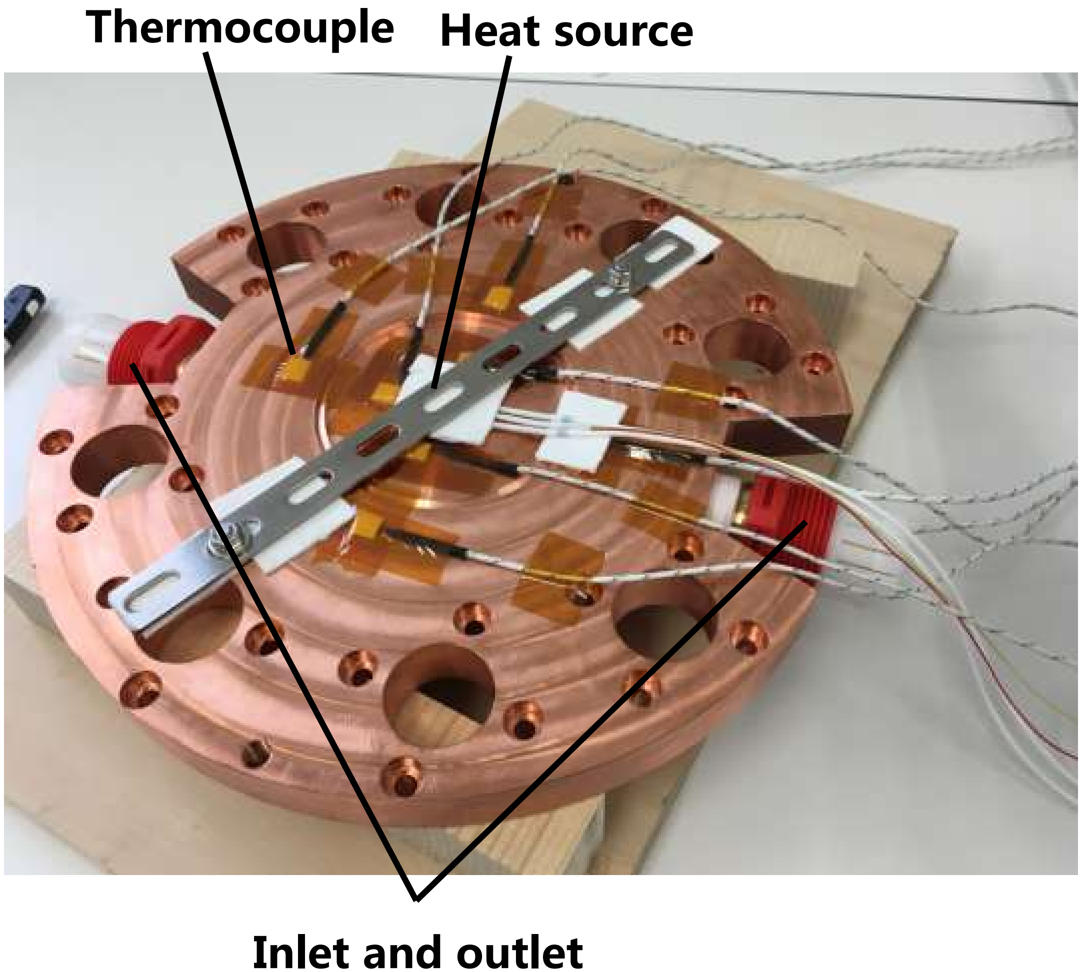
冷却实验



靶正面

靶背面

冷却实验



冷却实验

恒温热源

测温计