Beryllides as advanced materials for neutron multiplication

R. Gaisin[1], R. Rolli, V. Chakin, P. Vladimirov

[1] *Karlsruhe Institute of Technology, Institute for Applied Materials - Applied Materials Physics, 76344 Eggenstein-Leopoldshafen, Germany*

The neutron multiplier is an essential component of the blanket of future thermonuclear reactors, which should provide the tritium breeder with a sufficient amount of neutrons of a certain energy. Among all chemical elements, only beryllium and lead have an advantageous ratio of high neutron multiplication reaction at low neutron absorption rates. However, pure metals – beryllium and lead – for various reasons cannot be used in the harsh operating conditions of a fusion reactor blanket. Intermetallic compounds of beryllium – beryllides have a number of advantages over pure beryllium and are currently considered to be the reference neutron multiplication material for the Helium Cooled Pebble Bed (HCPB) breeding blanket concept of EU DEMO fusion reactor. Recently, a batch of full-size beryllide blocks has been manufactured on an industrial scale in cooperation with the Ulba Metallurgical Plant. The present work is devoted to the characterization and analysis of these beryllide blocks so that the material could be used for the manufacture of a blanket.

Titanium beryllide ($TiBe_{12}$) blocks are hexagonal prisms with an internal hole, while chromium beryllide ($CrBe_{12}$) blocks are solid prisms of complex shape. The resulting blocks have a single-phase structure of the corresponding beryllide with a small impurity in the form of beryllium oxide. One of the titanium beryllide blocks also has about 7% residual beryllium phase. Grains of titanium beryllide have an average size of about 7–8 µm, while grains of chromium beryllide are much larger and reach 40–50 µm. Mechanical compression and bending tests of beryllides showed their very high strength, which is maintained up to 1000°C. In terms of specific compressive strength, the single-phase $TiBe_{12}$ surpasses all materials, except diamond, in the 700–1000°C temperature range. Chromium beryllide and titanium beryllide with 7% of the beryllium phase have lower strength, but higher ductility. Corrosion tests were carried out in air and in He + 2% water vapor at 800–1200°C. Beryllides have high corrosion resistance similar to Ni-base superalloys and high temperature ceramics. Long-term thermal cycling tests with rapid heating and cooling, simulating operation in a fusion reactor, showed high resistance of beryllides to thermal shocks. The results obtained are also discussed from the point of view of the application of beryllides in other areas.

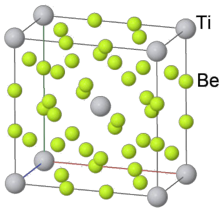
Corresponding Author:

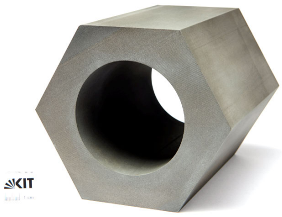
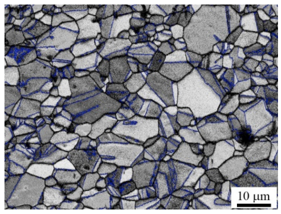
Dr. Ramil Gaisin
ramil.gaisin@kit.edu
Herrmann-von-Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen

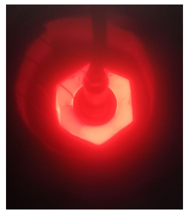
15th International Workshop on
Beryllium Technology, Karlsruhe

Beryllides as advanced materials for neutron multiplication

R. Gaisin, R. Rolli, V. Chakin, M. Dürrschnabel, P. Vladimirov
Institute for Applied Materials – Applied Materials Physics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
S. Udartsev, M. Kolmakov, E. Frantz
Ulba Metallurgical Plant, Ust-Kamenogorsk, Kazakhstan



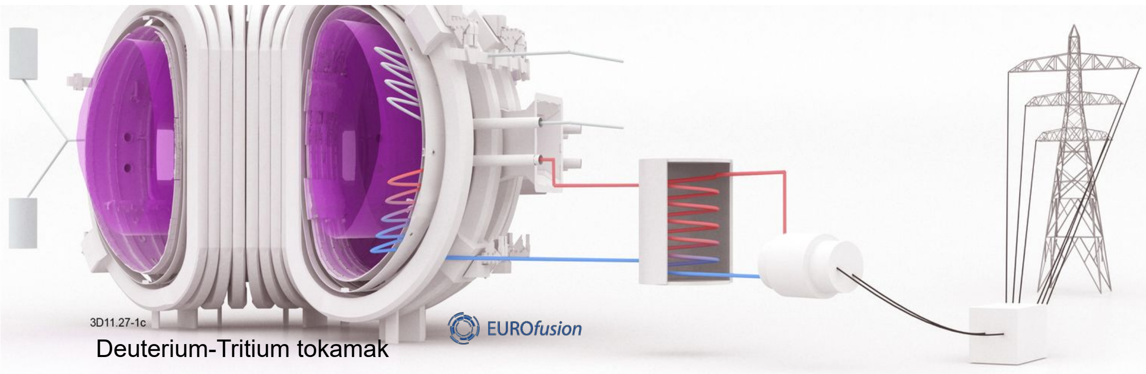


KIT – The Research University in the Helmholtz Association

www.kit.edu

Neutron multiplier materials for breeding blanket

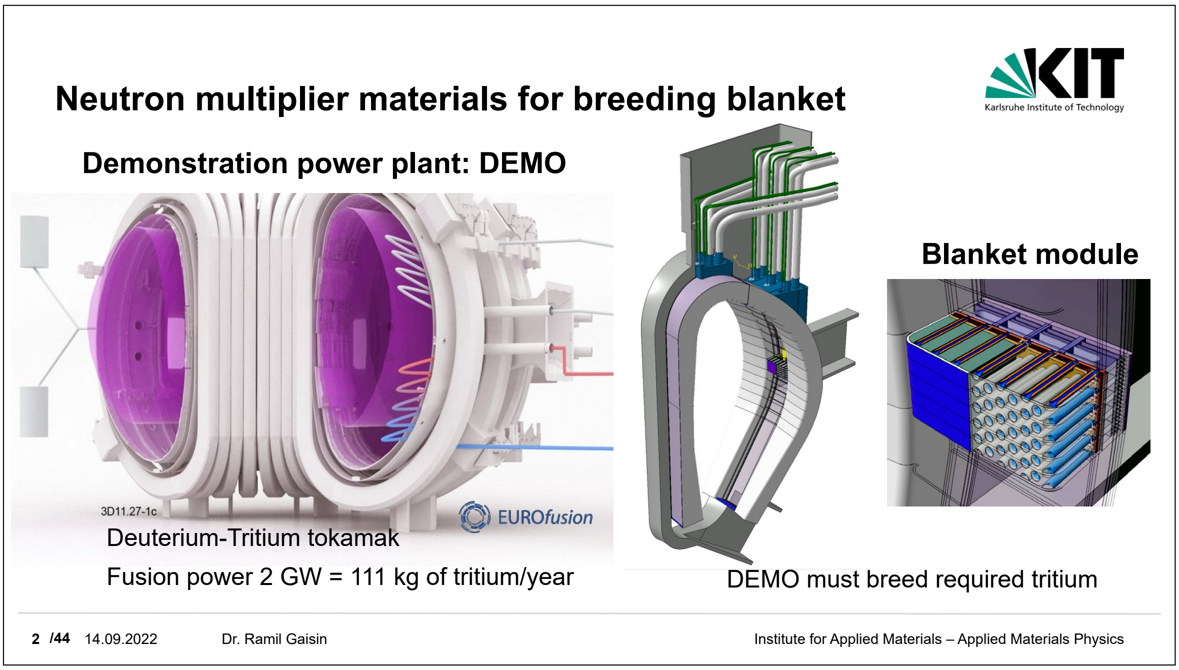
Demonstration power plant: DEMO

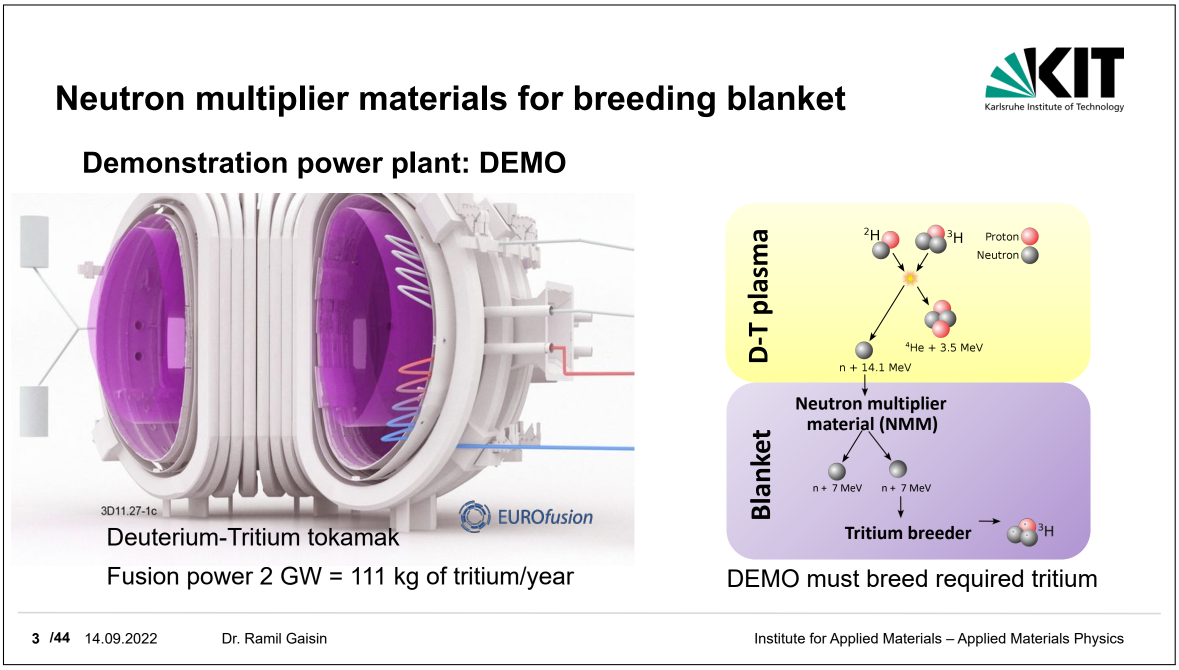


Deuterium-Tritium tokamak

Fusion power 2 GW = 111 kg of tritium/year

2 /44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

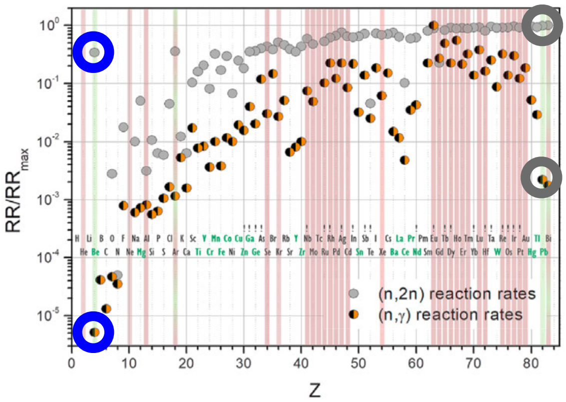

Neutron multiplier materials for breeding blanket
Karlsruhe Institute of Technology
Demonstration power plant: DEMO
3D11.27-1c
EUROfusion
Deuterium-Tritium tokamak
Fusion power 2 GW = 111 kg of tritium/year
Blanket module
DEMO must breed required tritium
2 /44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics


Neutron multiplier materials for breeding blanket
Karlsruhe Institute of Technology
Demonstration power plant: DEMO
3D11.27-1c
EUROfusion
Deuterium-Tritium tokamak
Fusion power 2 GW = 111 kg of tritium/year
D-T plasma
2H
3H
Proton
Neutron
4He + 3.5 MeV
n + 14.1 MeV
Blanket
Neutron multiplier material (NMM)
n + 7 MeV
n + 7 MeV
Tritium breeder
3H
DEMO must breed required tritium
3 /44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

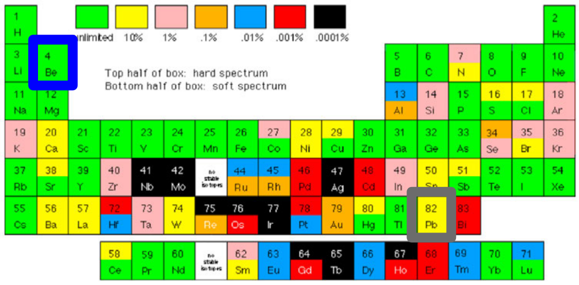
Selection of neutron multiplier material

Karlsruhe Institute of Technology

Relative reaction rates



Limits on the use of elements



NMM should have: - large (n,2n) cross-section
- low parasitic neutron absorption

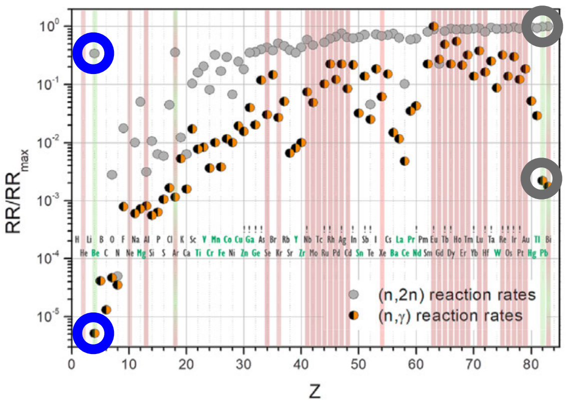
F.A. Hernández, P. Pereslavtsev FED 137 (2018) 243-256

4 /44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

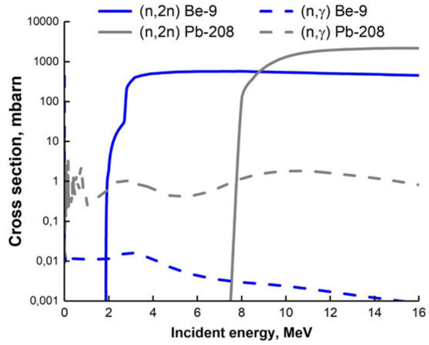
Selection of neutron multiplier material

Karlsruhe Institute of Technology

Relative reaction rates



Threshold energy



NMM should have: - large (n,2n) cross-section
- low parasitic neutron absorption

(n,2n) threshold energy for Be is much lower than for Pb

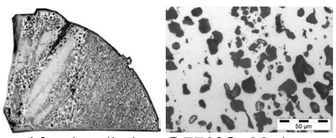
5 /44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Beryllium as NMM

ADVANTAGES:

+ The best neutron multiplier, dual function as multiplier and fair moderator
+ The most compact T-breeding blanket
+ Allows working with relatively low Li6 enrichment (≈60%)
+ Avoids problems of liquid metal blankets (corrosion, embrittlement, bubbles, magnetohydrodynamics)
+ Can operate above 400°C, thus avoiding irradiation embrittlement of steels

Before irradiation



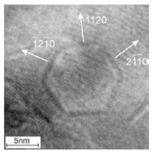
After irradiation @770°C, 38 dpa
*V*porosity = 24%

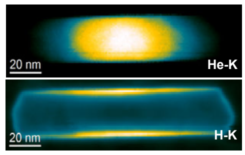
SHORTCOMINGS:

– High chemical reactivity with steam and air
– High swelling under neutron irradiation above 650°C
– High tritium retention

As received

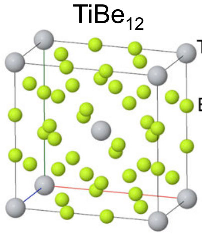
Corrosion in steam @800°C

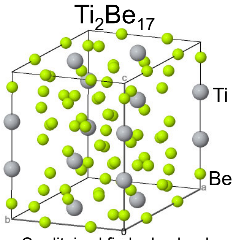




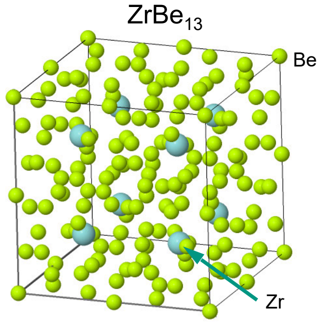
Solution - Beryllides

- Beryllium forms intermetallic compounds (beryllides) with almost all metals
- Typical compositions: MBe_{12}, MBe_{22}, MBe_{13}, M_2Be_{17}
- High corrosion resistance
- Low swelling and low tritium retention



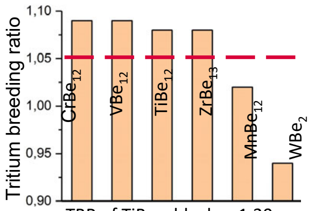


Credit: icsd.fiz-karlsruhe.de

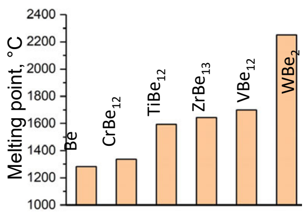


Selection of beryllides compositions

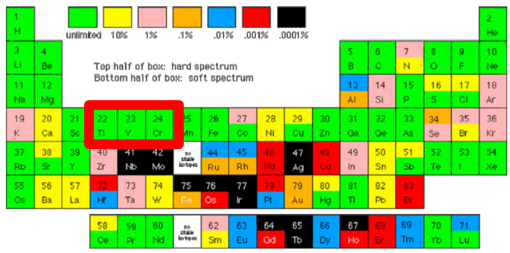
- Neutron performance – high Be content
- High melting point
- High corrosion resistance
- Reasonable strength
- Low radioactivation



TBR of $TiBe_{12}$ blocks - 1.20



Limits on the use of elements



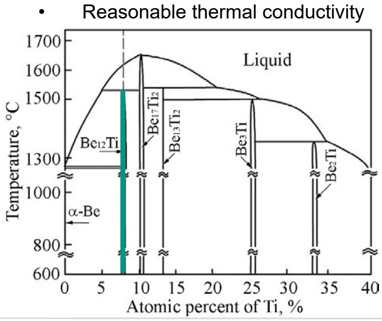
F.A. Hernández et al., FST 75 (2019) 352–364

F.A. Hernández, P. Pereslavtsev FED 137 (2018) 243-256

Titanium and chromium beryllides

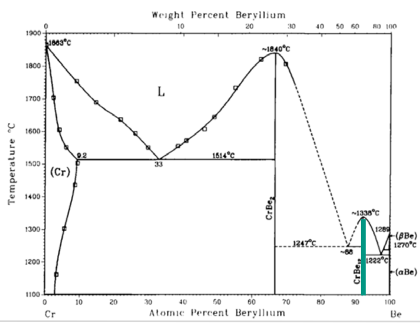
$TiBe_{12}$

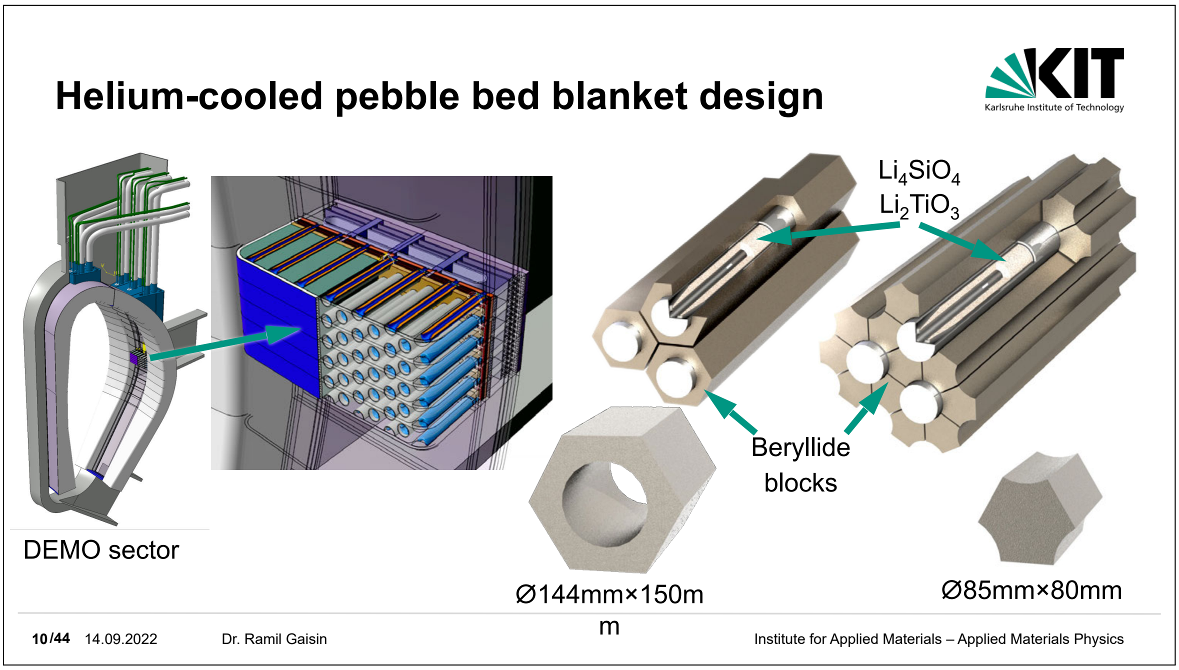
- Be-7.7at.%Ti or Be-30.8wt.%Ti
- T_m=1550°C
- ρ=2.28 g/cm³
- High corrosion resistance
- Reasonable thermal conductivity

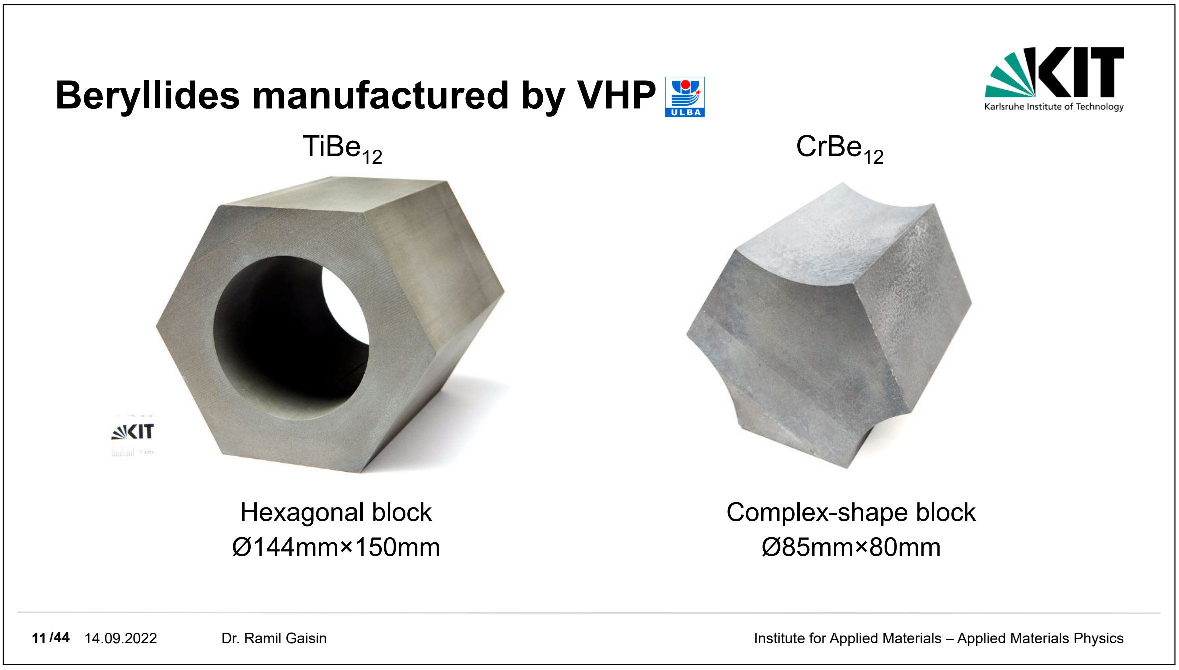


$CrBe_{12}$

- Be-7.7at.%Ti or Be-32.5wt.%Ti
- T_m=1340°C
- ρ=2.44 g/cm³
- Simple phase diagram, no peritectic reaction




Helium-cooled pebble bed blanket design
Karlsruhe Institute of Technology
Li_4SiO_4
Li_2TiO_3
Beryllide blocks
DEMO sector
Ø144mm×150mm
Ø85mm×80mm
10/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics

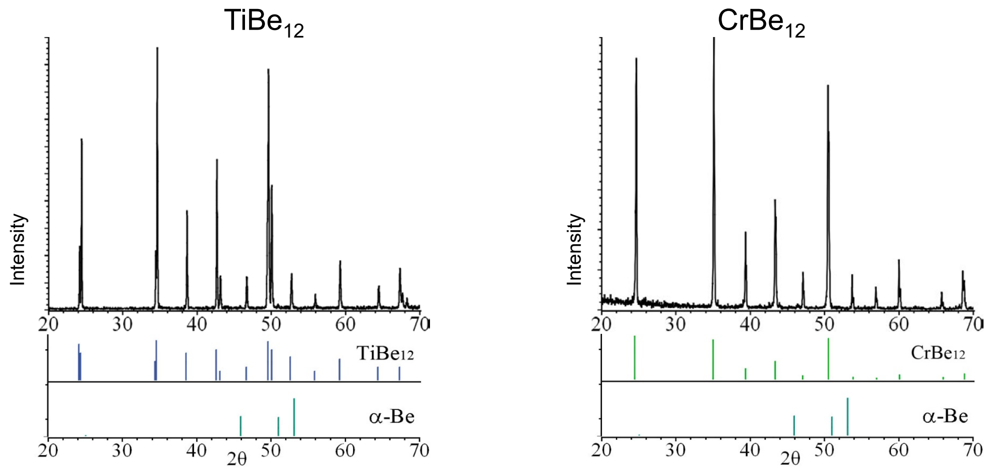

Beryllides manufactured by VHP
ULBA
Karlsruhe Institute of Technology
$TiBe_{12}$
$CrBe_{12}$
Hexagonal block
Ø144mm×150mm
Complex-shape block
Ø85mm×80mm
11/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics

Requirements for beryllides as neutron multiplier materials

- High tritium breeding ratio – maximum possible content of Be
- Minimum content of impurities that form long-lived isotopes under irradiation (e.g. Uranium)
- Fine grain structure for easy tritium release and reasonable mechanical properties
- Beryllide blocks must retain their shape and not fracture during operation
- Low corrosion in the air and purge gas atmosphere
- Low interaction with structural materials (e.g. EUROFER steel)
- No fracture or cracks during rapid heating/cooling due to pulsed operation of DEMO

12/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

$TiBe_{12}$ manufactured by VHP. XRD



13/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Requirements for beryllides as neutron multiplier materials

- High tritium breeding ratio – maximum possible content of Be
- Minimum content of impurities that form long-lived isotopes under irradiation (e.g. Uranium) – as low as possible activation
- Fine grain structure for easy tritium release and reasonable mechanical properties
- Beryllide blocks must retain their shape and not fracture during operation
- Low corrosion in the air and purge gas atmosphere
- Low interaction with structural materials (e.g. EUROFER steel)
- No fracture or cracks during rapid heating/cooling due to pulsed operation of DEMO

Chemical composition

Material	Ti	Cr	C	N	O	Mg	Al	Si	Ca	Fe	U, ppm	Be
$TiBe_{12}$ UMP	**29.6**	-	0.038	0.0801	0.597	<0.0002	0.0222	0.0213	0.01	0.124	0.51	Bal.
$TiBe_{12}$ + 7vol.% Be UMP	**27.8**	-	0.034	0.106	0.686	<0.00005	0.020	0.0162	0.015	0.118	0.395	Bal.
$CrBe_{12}$ UMP	-	30.8	0.0346	0.0177	0.555	<0.0002	0.0156	0.0237	0.0088	0.114	0.54	Bal.
$TiBe_{12}$ HIP (from Materion Be)	29.11	-	0.0774	0.0028	0.219	0.0355	0.037	0.0215	0.0018	0.102	19.3	Bal.

Almost no uranium in beryllides from UMP

Requirements for beryllides as neutron multiplier materials

KIT Karlsruhe Institute of Technology

- High tritium breeding ratio – maximum possible content of Be
- Minimum content of impurities that form long-lived isotopes under irradiation (e.g. Uranium)
- Fine grain structure for facilitated tritium release and reasonable mechanical properties
- Beryllide blocks must retain their shape and not fracture during operation
- Low corrosion in the air and purge gas atmosphere
- Low interaction with structural materials (e.g. EUROFER steel)
- No fracture or cracks during rapid heating/cooling due to pulsed operation of DEMO

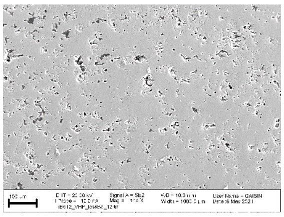
16/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Microstructure of $TiBe_{12}$

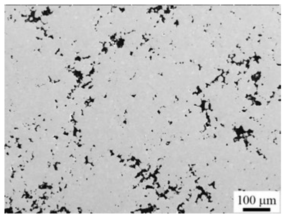
KIT Karlsruhe Institute of Technology

$TiBe_{12}$ | $TiBe_{12}$ + 7vol.% Be

Single phase $TiBe_{12}$ ρ=98.6%

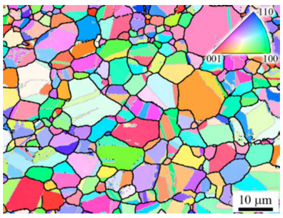


SEM

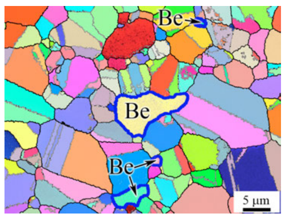


7 vol.% of Be phase (black) ρ=98.3%

D = 8±3.5 µm



EBSD



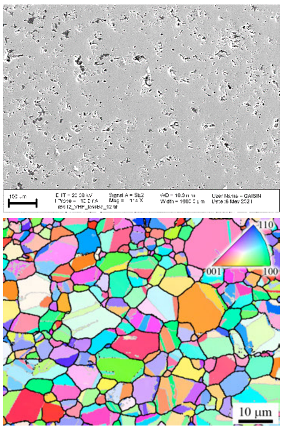
D = 7±3 µm

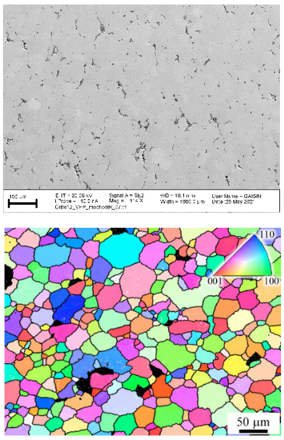
17/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Microstructure of Ti and Cr beryllides

KIT Karlsruhe Institute of Technology

	$TiBe_{12}$		$CrBe_{12}$	
Single phase $TiBe_{12}$ ρ=98.6%		SEM		Single phase $CrBe_{12}$ ρ=98.5%
D = 8±3.5 µm		EBSD		D = 42±18 µm





18/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

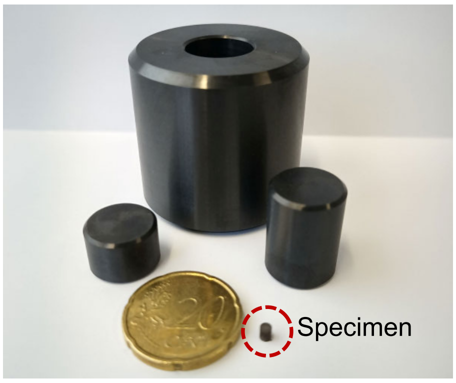
Requirements for beryllides as neutron multiplier materials

KIT Karlsruhe Institute of Technology

- High tritium breeding ratio – maximum possible content of Be
- Minimum content of impurities that form long-lived isotopes under irradiation (e.g. Uranium)
- Fine grain structure for easy tritium release and reasonable mechanical properties
- Beryllide blocks must retain their shape and not fracture during operation.
- Low corrosion in the air and purge gas atmosphere
- Low interaction with structural materials (e.g. EUROFER steel)
- No fracture or cracks during rapid heating/cooling due to pulsed operation of DEMO

19/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Compression tests



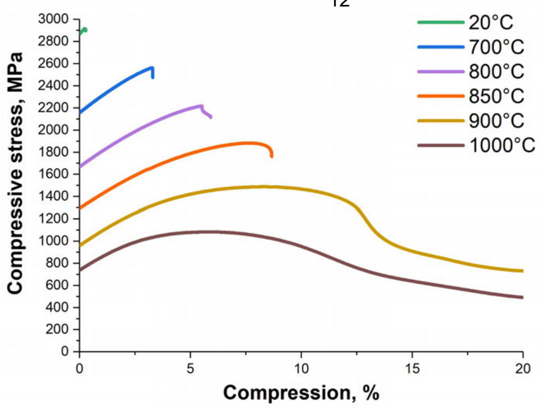
Cracked Si_3N_4 platens

Specimens from Ø2.2mm×2.6mm to Ø4mm×6mm

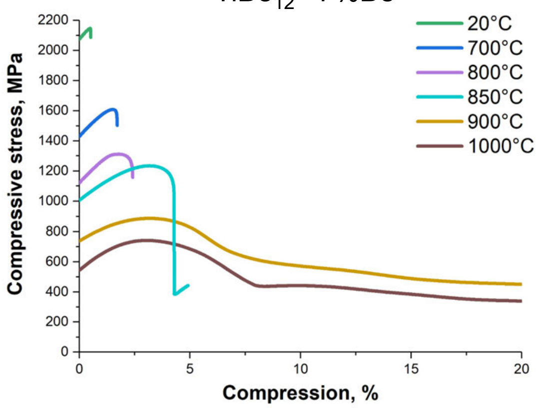
20/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Compressive properties of $TiBe_{12}$

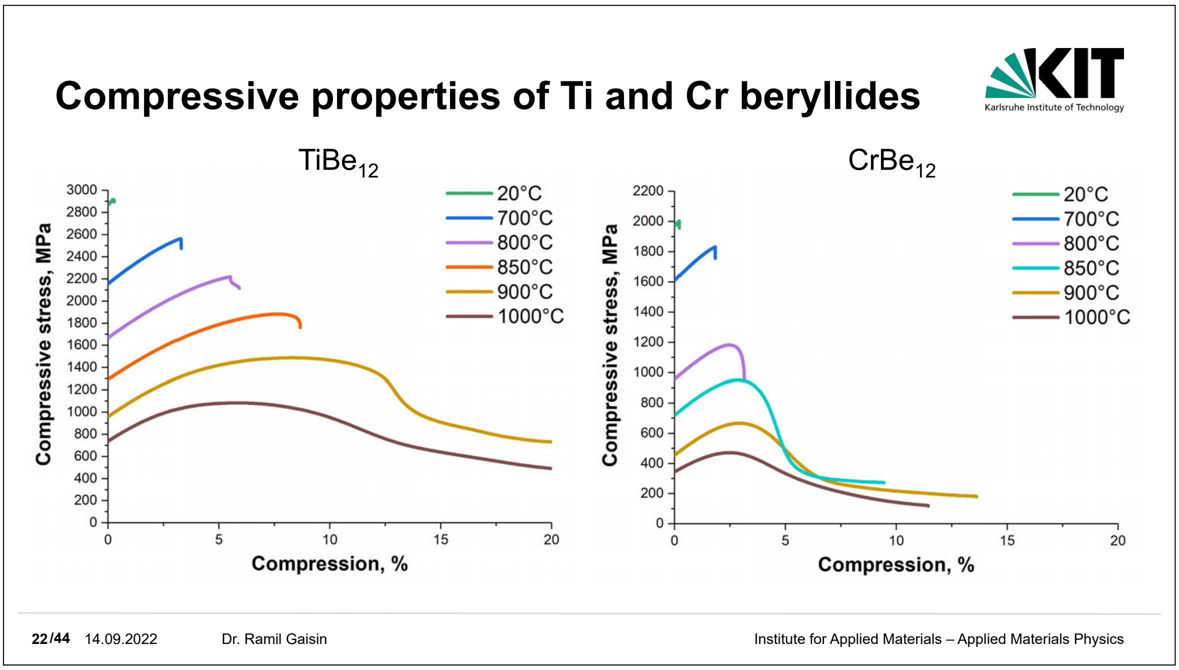
$TiBe_{12}$

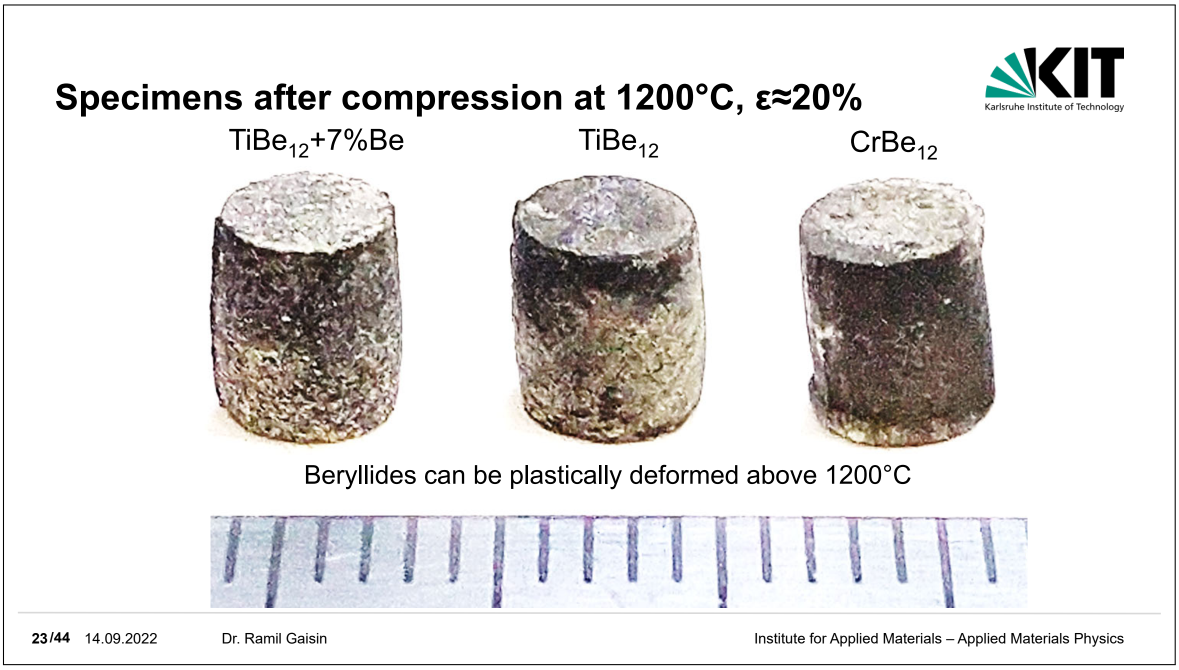


$TiBe_{12}$ +7%Be



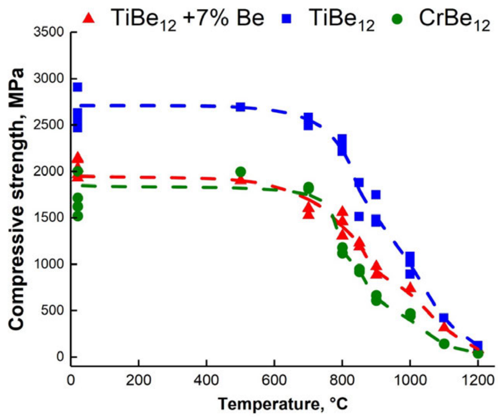
21/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

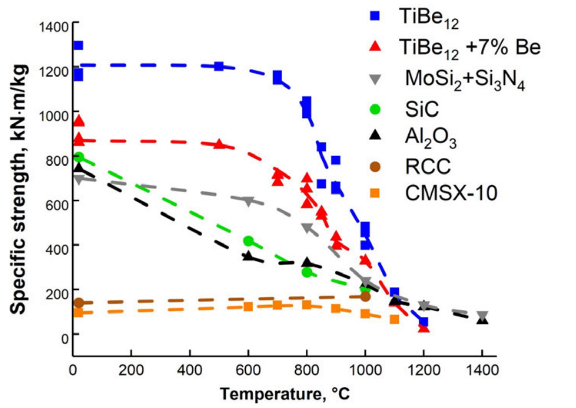

Compressive properties of Ti and Cr beryllides
KIT
Karlsruhe Institute of Technology
TiBe12
CrBe12
Compressive stress, MPa
Compression, %
20°C
700°C
800°C
850°C
900°C
1000°C
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
0
5
10
15
20
22/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics


Specimens after compression at 1200°C, ε≈20%
KIT
Karlsruhe Institute of Technology
TiBe12+7%Be
TiBe12
CrBe12
Beryllides can be plastically deformed above 1200°C
23/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics

Compressive strength of beryllides

Karlsruhe Institute of Technology



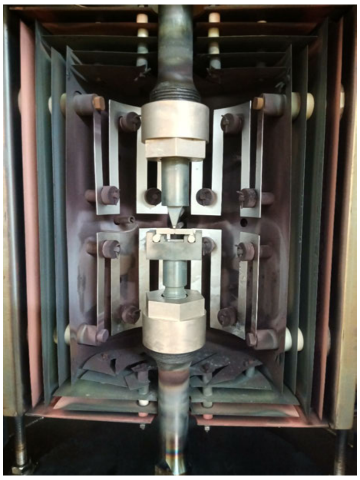


Shackelford, CRC Materials Science and Engineering Handbook, 2000
Hebsur, Handbook of Ceramic Composites, 2005
Reed, The Superalloys, 2006

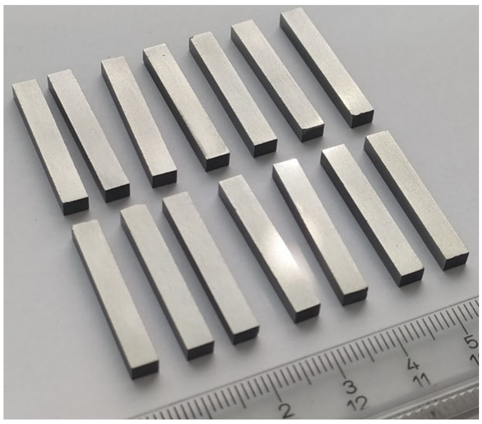
24/44   14.09.2022   Dr. Ramil Gaisin   Institute for Applied Materials – Applied Materials Physics

3 point bending tests

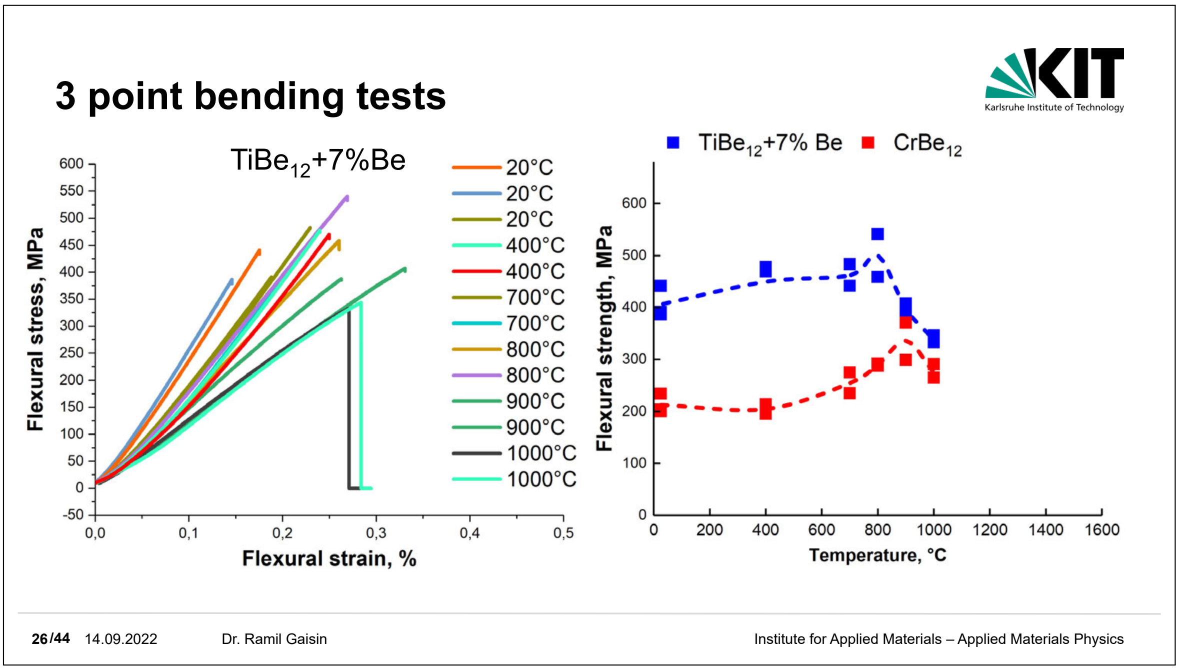
Karlsruhe Institute of Technology

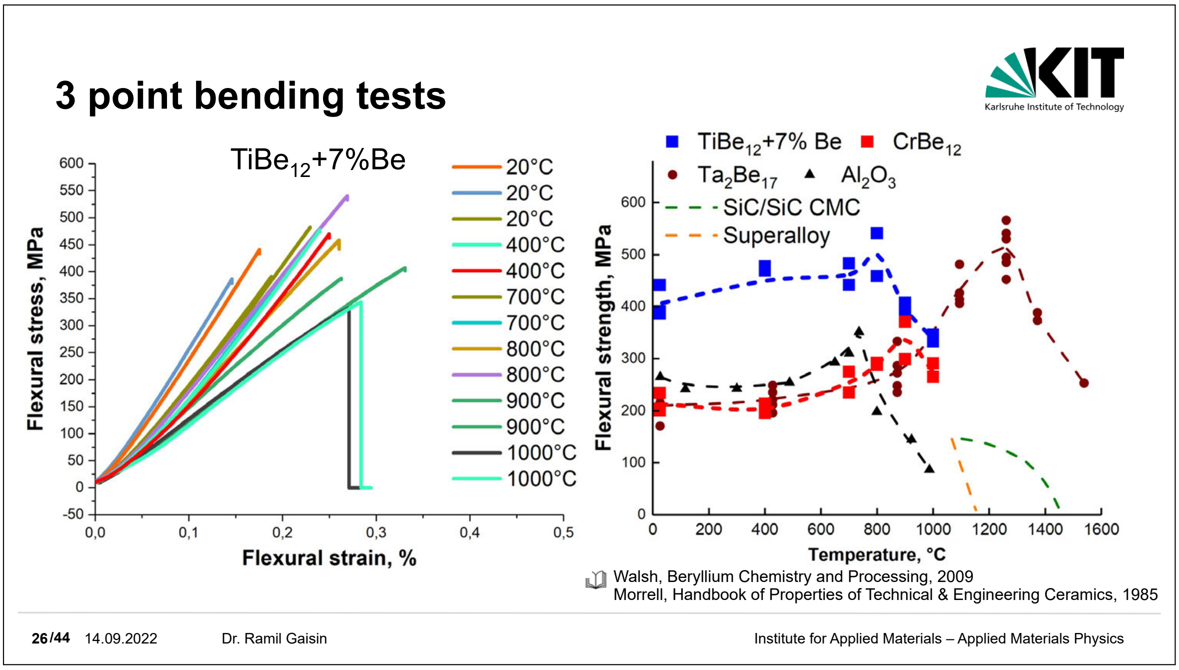


Specimens



25/44   14.09.2022   Dr. Ramil Gaisin   Institute for Applied Materials – Applied Materials Physics


3 point bending tests
KIT Karlsruhe Institute of Technology
TiBe12+7%Be
Flexural stress, MPa
Flexural strain, %
20°C
20°C
20°C
400°C
400°C
700°C
700°C
800°C
800°C
900°C
900°C
1000°C
1000°C
TiBe12+7% Be
CrBe12
Flexural strength, MPa
Temperature, °C
26/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics

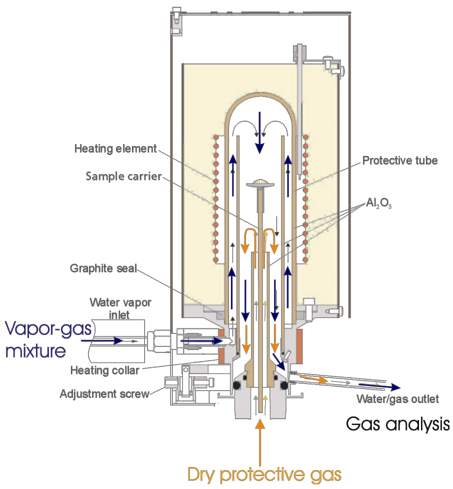

3 point bending tests
KIT Karlsruhe Institute of Technology
TiBe12+7%Be
Flexural stress, MPa
Flexural strain, %
20°C
20°C
20°C
400°C
400°C
700°C
700°C
800°C
800°C
900°C
900°C
1000°C
1000°C
TiBe12+7% Be
CrBe12
Ta2Be17
Al2O3
SiC/SiC CMC
Superalloy
Flexural strength, MPa
Temperature, °C
Walsh, Beryllium Chemistry and Processing, 2009
Morrell, Handbook of Properties of Technical & Engineering Ceramics, 1985
26/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics

Requirements for beryllides as neutron multiplier materials

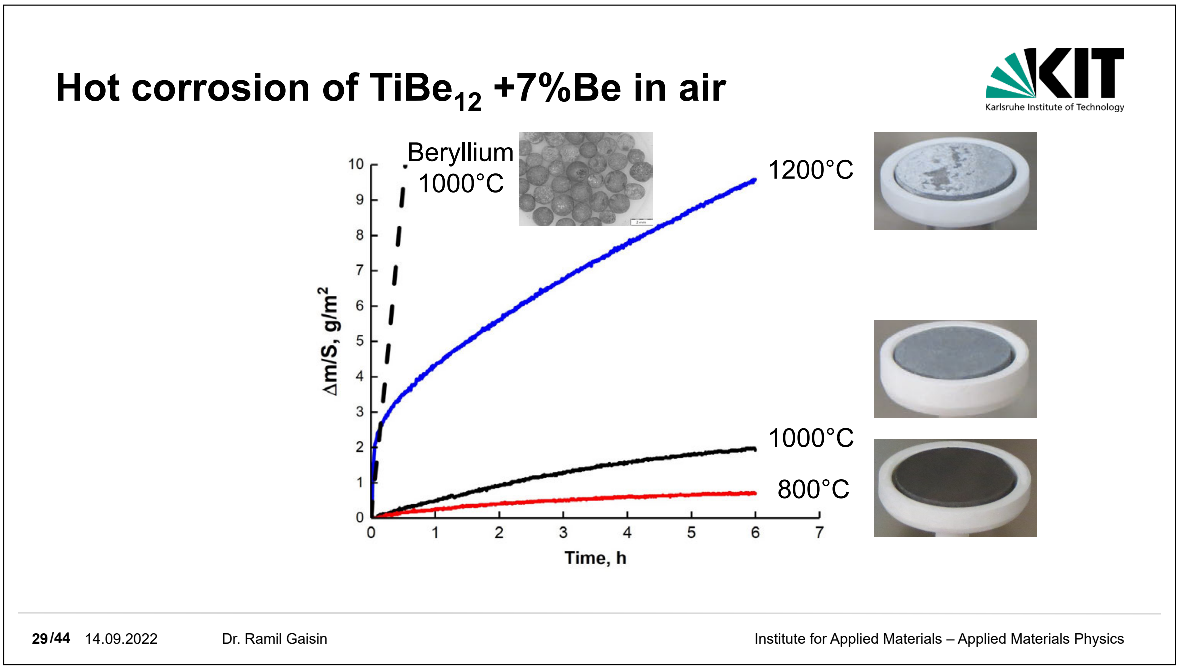
- High tritium breeding ratio – maximum possible content of Be
- Minimum content of impurities that form long-lived isotopes under irradiation (e.g. Uranium)
- Fine grain structure for easy tritium release and reasonable mechanical properties
- Beryllide blocks must retain their shape and not fracture during operation
- Low corrosion in the air and purge gas atmosphere
- Low interaction with structural materials (e.g. EUROFER steel)
- No fracture or cracks during rapid heating/cooling due to pulsed operation of DEMO

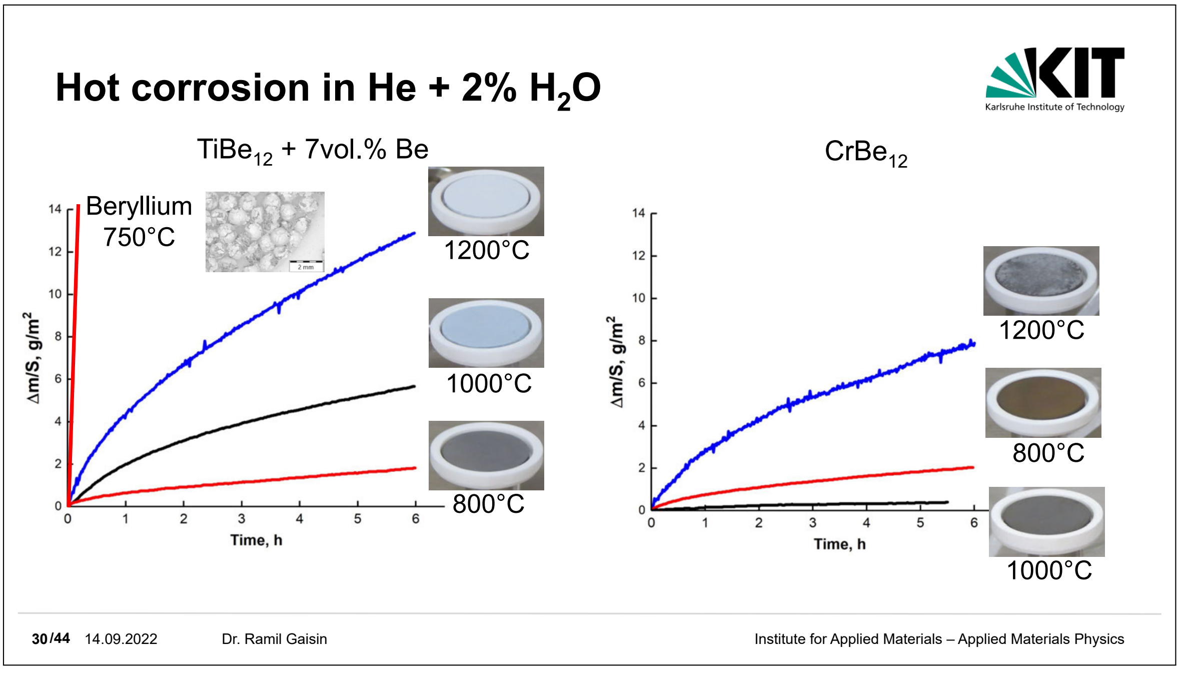
27/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Corrosion tests in air and He + 2% H_2O

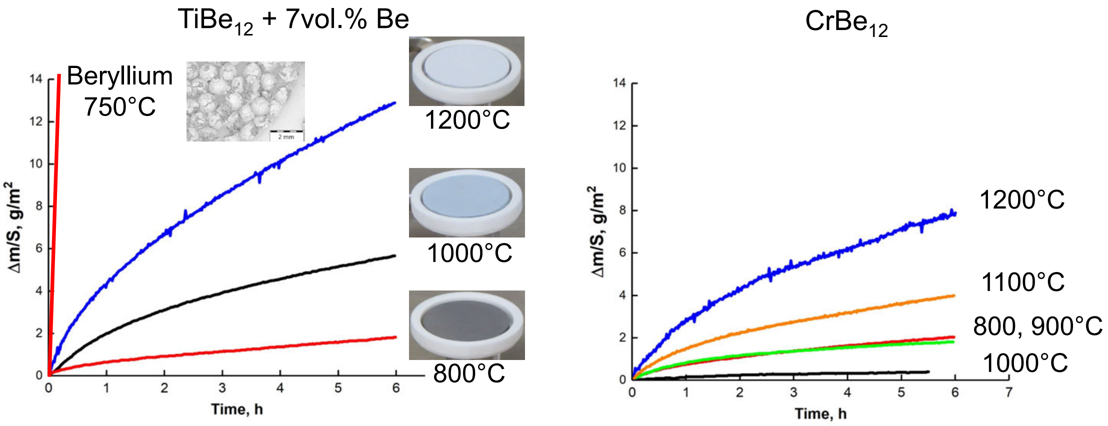


28/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics


Hot corrosion of TiBe12 +7%Be in air
KIT
Karlsruhe Institute of Technology
Beryllium
1000°C
1200°C
1000°C
800°C
Δm/S, g/m2
Time, h
29/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics


Hot corrosion in He + 2% H2O
KIT
Karlsruhe Institute of Technology
TiBe12 + 7vol.% Be
Beryllium
750°C
1200°C
1000°C
800°C
Δm/S, g/m2
Time, h
CrBe12
1200°C
800°C
1000°C
Δm/S, g/m2
Time, h
30/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics

Hot corrosion in He + 2% H_2O



31/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Requirements for beryllides as neutron multiplier materials

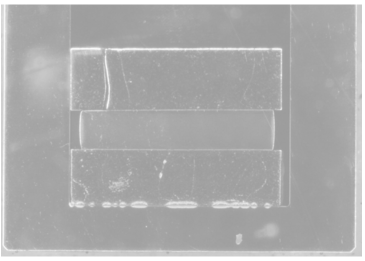
- High tritium breeding ratio – maximum possible content of Be
- Minimum content of impurities that form long-lived isotopes under irradiation (e.g. Uranium)
- Fine grain structure for easy tritium release and reasonable mechanical properties
- Beryllide blocks must retain their shape and not fracture during operation
- Low corrosion in the air and purge gas atmosphere
- Low interaction with structural materials (e.g. EUROFER steel)
- No fracture or cracks during rapid heating/cooling due to pulsed operation of DEMO

32/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Compatibility of Ti and Cr beryllides with EUROFER

KIT Karlsruhe Institute of Technology

$TiBe_{12}$+7%Be



900°C, 1000 N, 100 h

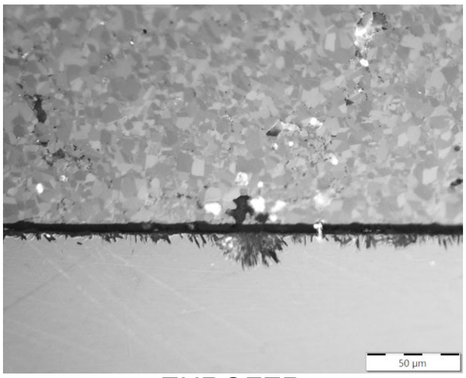
$CrBe_{12}$

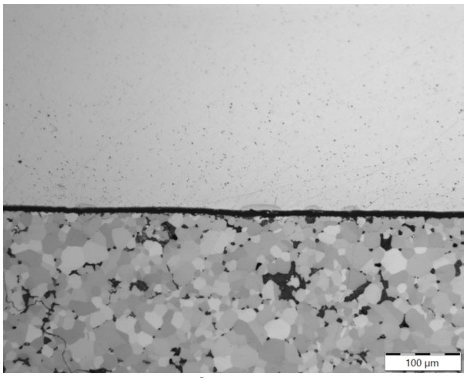
Compatibility of Ti and Cr beryllides with EUROFER

KIT Karlsruhe Institute of Technology

$TiBe_{12}$+7%Be

EUROFER





EUROFER

$CrBe_{12}$

Requirements for beryllides as neutron multiplier materials

Karlsruhe Institute of Technology

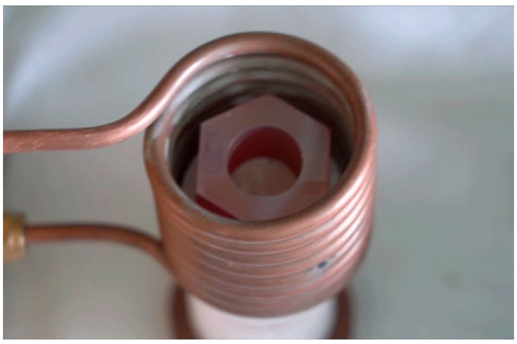
- High tritium breeding ratio – maximum possible content of Be
- Minimum content of impurities that form long-lived isotopes under irradiation (e.g. Uranium)
- Fine grain structure for easy tritium release and reasonable mechanical properties
- Beryllide blocks must retain their shape and not fracture during operation
- Low corrosion in the air and purge gas atmosphere
- Low interaction with structural materials (e.g. EUROFER steel)
- No fracture or cracks during rapid heating/cooling due to pulsed operation of DEMO

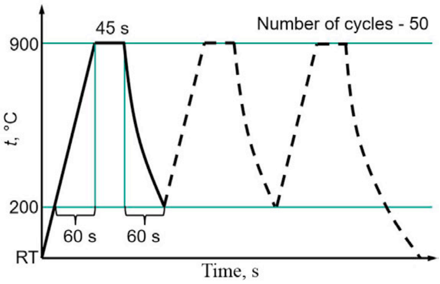
35/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Thermal cycling of test sample

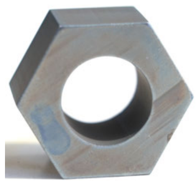
Karlsruhe Institute of Technology

$TiBe_{12}$ Ø40×20

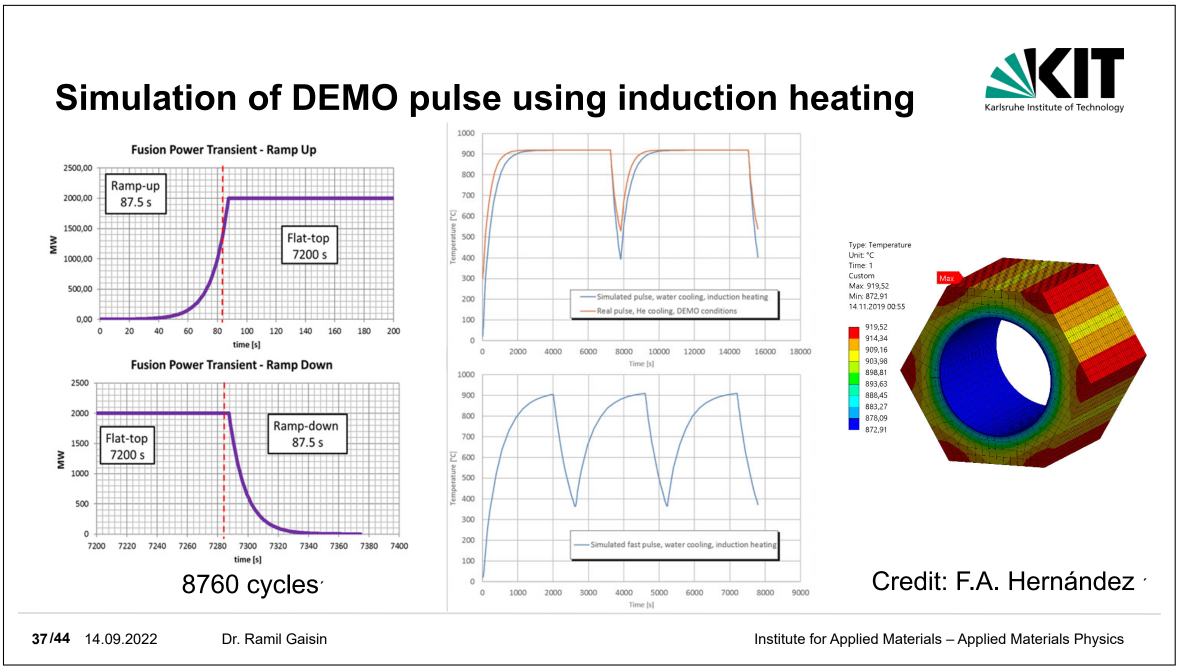


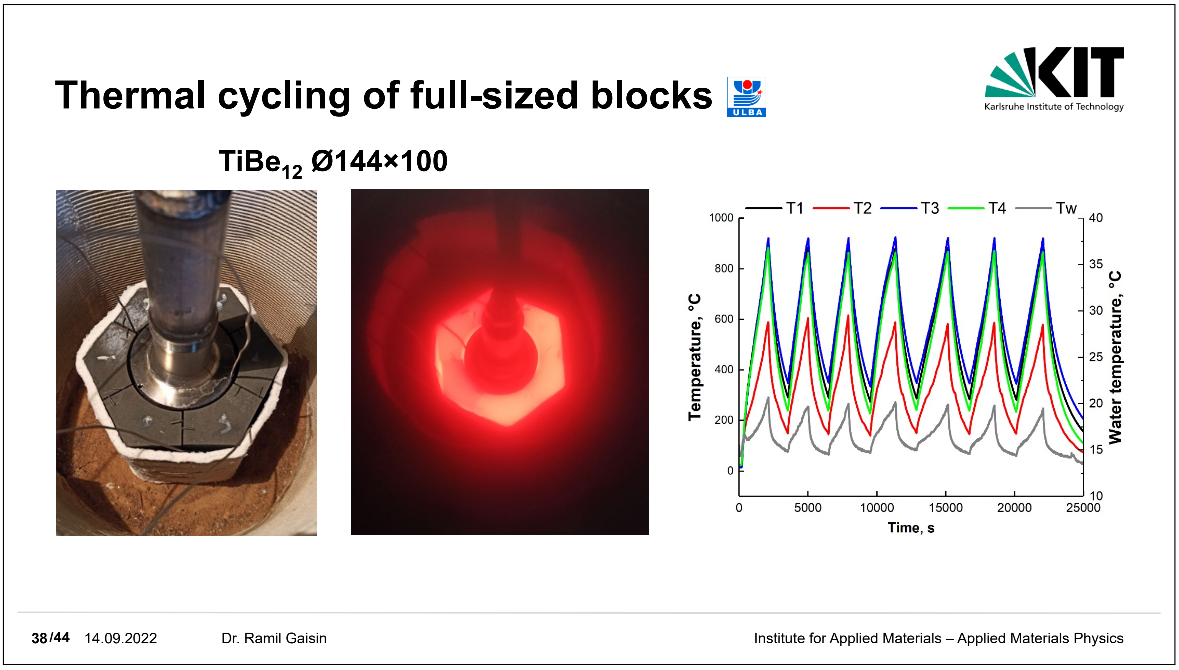


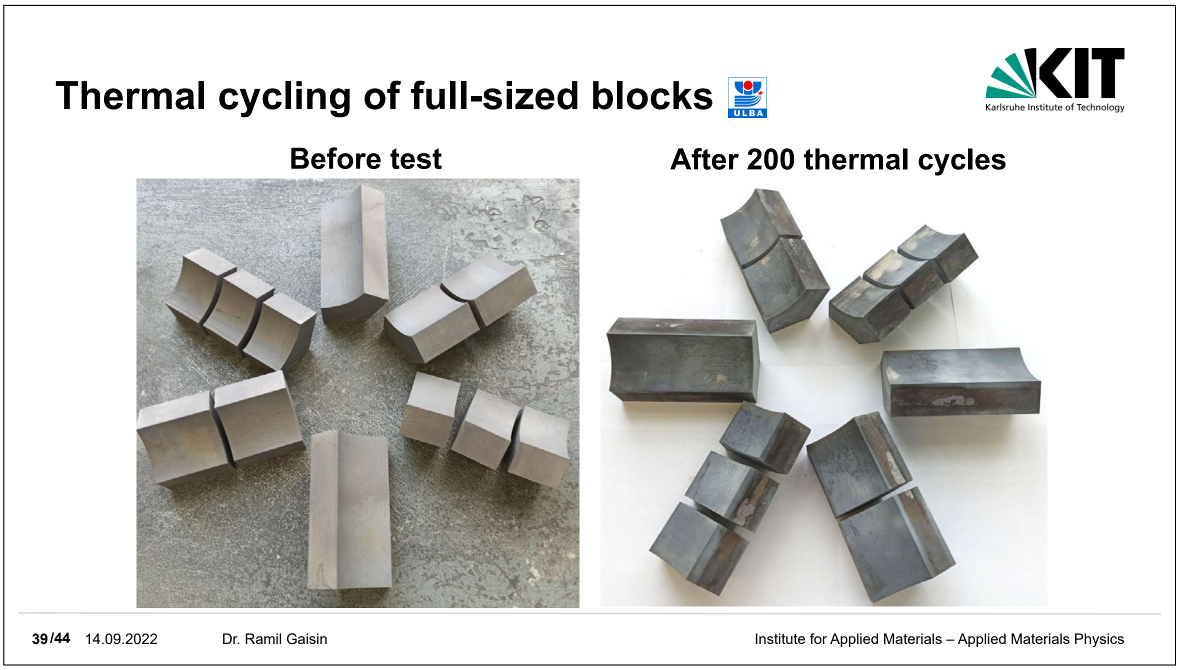
After thermal cycling

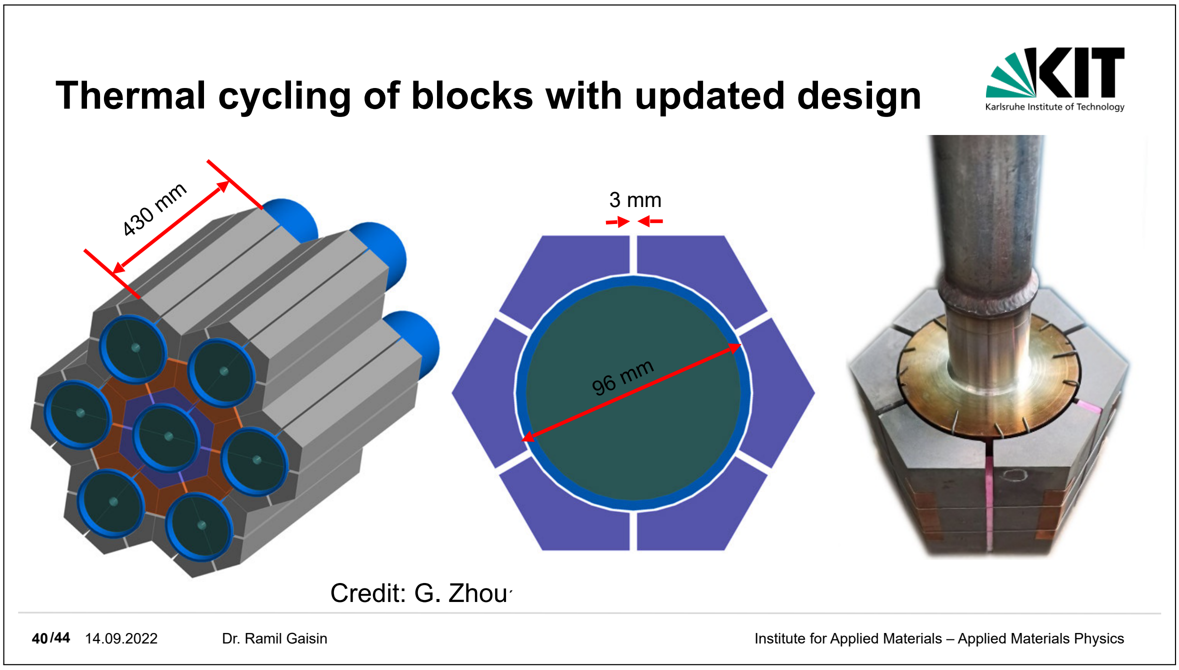


36/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics


Simulation of DEMO pulse using induction heating
KIT
Karlsruhe Institute of Technology
Fusion Power Transient - Ramp Up
Ramp-up
87.5 s
Flat-top
7200 s
MW
time [s]
Fusion Power Transient - Ramp Down
Flat-top
7200 s
Ramp-down
87.5 s
8760 cycles
Simulated pulse, water cooling, induction heating
Real pulse, He cooling, DEMO conditions
Simulated fast pulse, water cooling, induction heating
Credit: F.A. Hernández
37/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics


Thermal cycling of full-sized blocks
ULBA
KIT
Karlsruhe Institute of Technology
TiBe12 Ø144×100
T1 T2 T3 T4 Tw
Temperature, °C
Water temperature, °C
Time, s
38/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

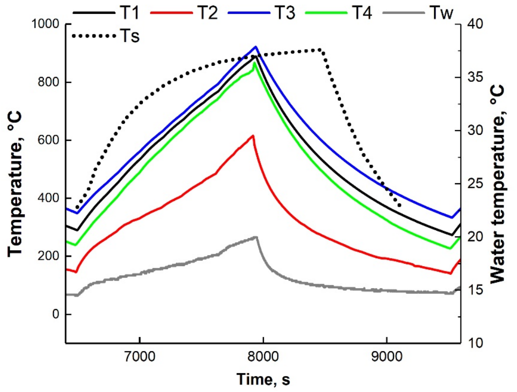

Thermal cycling of full-sized blocks
ULBA
KIT
Karlsruhe Institute of Technology
Before test
After 200 thermal cycles
39/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics


Thermal cycling of blocks with updated design
KIT
Karlsruhe Institute of Technology
430 mm
3 mm
96 mm
Credit: G. Zhou
40/44 14.09.2022
Dr. Ramil Gaisin
Institute for Applied Materials – Applied Materials Physics

Thermal cycling of beryllide blocks

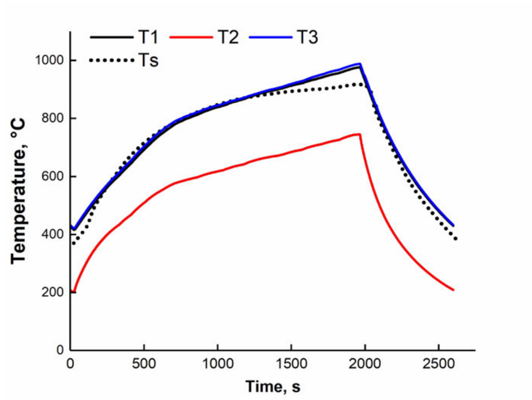
KIT Karlsruhe Institute of Technology

Thermal cycling in 2020-2021



360-930°C
200 cycles

Thermal cycling in 2022-2023



440-990°C
>500 of 1500 cycles

41/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Conclusions

KIT Karlsruhe Institute of Technology

- Single-phase $TiBe_{12}$ meets all the basic requirements for NMM.
- $CrBe_{12}$ is not yet well studied in terms of irradiation and thermal cycling, but may be a good alternative due to better corrosion resistance.
- The presence of a beryllium metal phase in beryllide increases ductility, but can cause accelerated corrosion or interaction with other materials.

Outlook

- New irradiation campaign up to 2-3 dpa and post irradiation examination

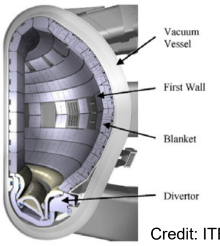
42/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Potential applications of beryllides in extreme environments

Karlsruhe Institute of Technology

Neutron multiplier material in fusion power plant blanket

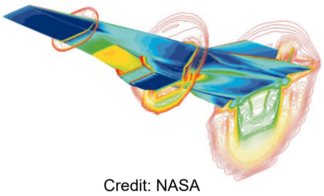
- High-dose irradiation (20-50 dpa) in high-energy neutrons
- High temperature up to 1000°C
- High heating/cooling rates
- Potentially corrosive atmosphere



Credit: ITER

Structural material for the skin of spacecraft and hypersonic vehicles

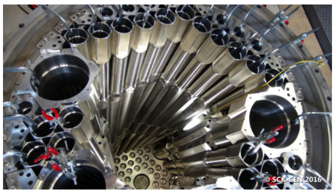
- High temperatures of 1000°C and above
- Thermal shocks
- Corrosive atmosphere
- High loads
- Collision with debris



Credit: NASA

Neutron reflector material in fission reactors

- High-dose irradiation in low-energy neutrons
- Low temperature (70-150°C) – cracking / swelling
- Water environment



Credit: Materion Corp.

43/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics

Karlsruhe Institute of Technology

Thank you for your attention!

44/44 14.09.2022 Dr. Ramil Gaisin Institute for Applied Materials – Applied Materials Physics