Karlsruhe Institute of Technology

EUROfusion

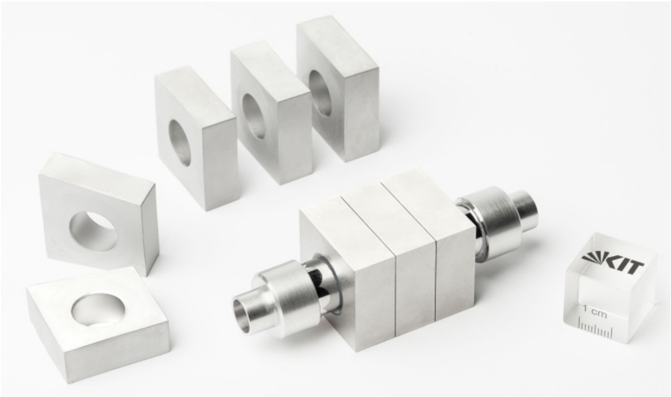
WPMAT

CIMTEC 2018, Forum on New Materials, June 10th – 14th, Perugia, Italy

Tungsten Powder Injection Molding @ KIT: Achievements and Trends

Steffen Antusch*, Jan Hoffmann, Peter Holzer, Alexander Klein, Dorit Noetzel, Kilian Pursche, Michael Rieth, Heinz Walter, Tobias Weingaertner

INSTITUTE FOR APPLIED MATERIALS



Outline

- **Powder Injection Molding @ KIT**
- **Mass fabrication of tungsten parts**
- **Development of new materials**
- **Summary**

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Powder Injection Molding @

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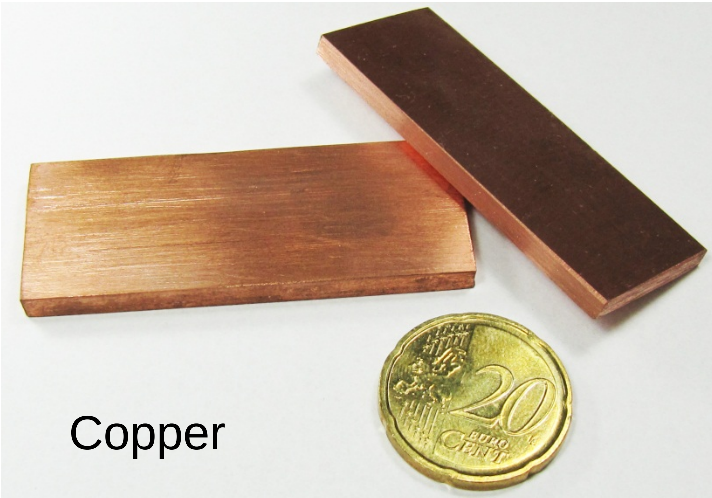
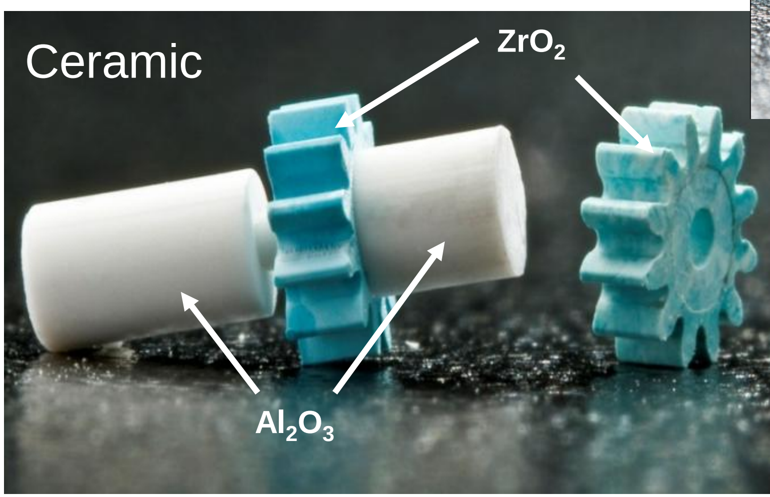
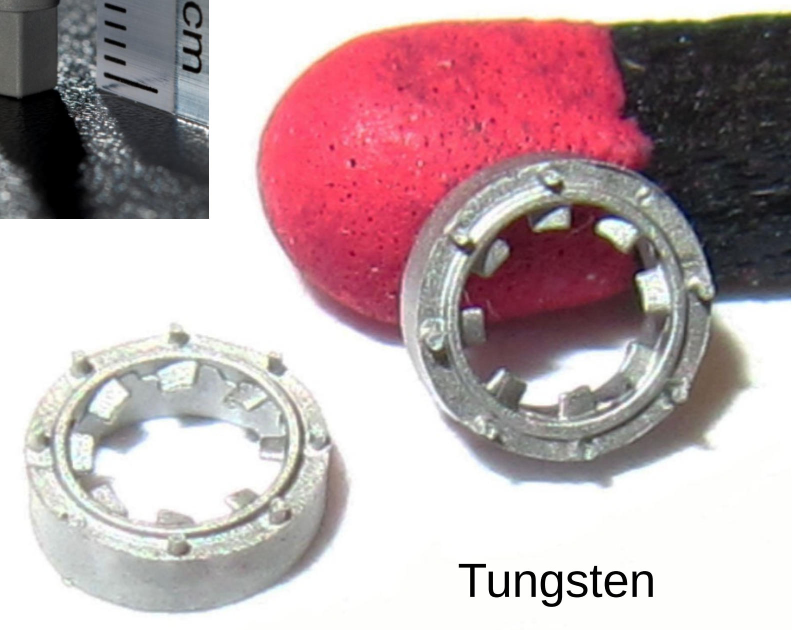




Smallest ZrO_2 gear wheel of the world:
outer-∅ 275 µm



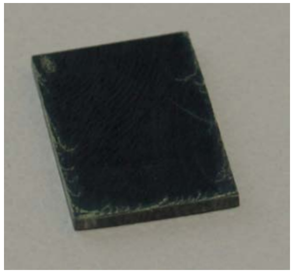
Powder Injection Molding @ KIT

… Tungsten: Properties …

Atomic number	74
Atomic mass	183.84
Atomic volume	0.0159 [nm^3]
Lattice structure	Body-centered
Lattice constant	0.3165 [nm]
Incidence into earth crust	1.25 [g/t]

+ Highest melting temperature of pure metals (3400 °C)
+ Density (19.25 g/cm^3)
+ Hardness (Mohs 7,5)
+ Heat conductivity (170 W/(mK))
+ Corrosion resistance
+ Electric conductivity (18.52*10^6 A/(Vm))

- Low ductility and fracture toughness @ RT
- Low oxidation resistance



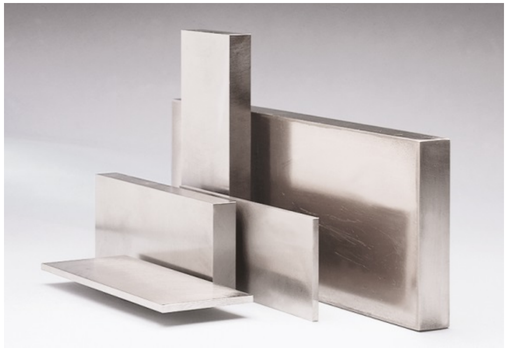
Original state

After 48 hours @ 600 °C oxygen atmosphere

Powder Injection Molding @ KIT

… Tungsten: Industrial Production and Application …

- Industrial production of semi-finished products (rods, plates) via Powdermetallurgy (powder compaction, sintering, rolling, forging)
- High density, large quantity



- The subsequent mechanical machining is time and cost intensive!

- ✓ Cutting tools
- ✓ Welding electrodes
- ✓ Rocket nozzles and heat shields for aerospace industry
- ✓ Heater for high-temperature furnace
- ✓ Screws, blanks, screw nuts
- ✓ X-ray equipment (anode)
- ✓ Sputtering targets

Source: PLANSEE GROUP

Tungsten Powder Injection Molding @ KIT

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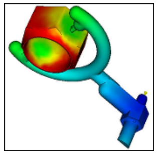
Powder

+

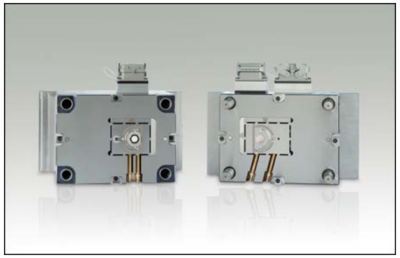
Binder

=

Feedstock



Simulation

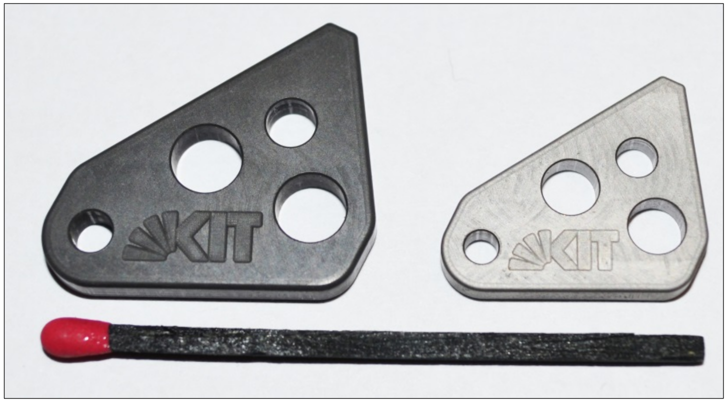


PIM-Tool

Fabrication of green parts

Heat-treatment

~ 2000 °C



Green part vs. Final part

Powder Injection Molding @ KIT

… Tolerances …

Materials	min. lat. Dimension [µm]	min. Detail [µm]	Aspect Ratio [isolated walls]	Tolerance [%]	Roughness ** R_{max} / R_a [µm]	Materials tested
Plastics	10	≤0.08	>20 (200*)	± 0.05	0.05 / <0.05	Thermoplastics, TPE
Metals	50	10	>10	< ± 0.5	7 / 0.8	17-4PH, 316L, Cu, W, W-alloys
Ceramics	<10	<3	<15	(± 0.1) ± 0.3	2 / <0.3	ZrO_2, Al_20_3, ZTA, Al_2O_3/TiN, Si_3N_4

* flow length to wall thickness ratio   ** depending on mold insert

Tungsten Powder Injection Molding @ KIT

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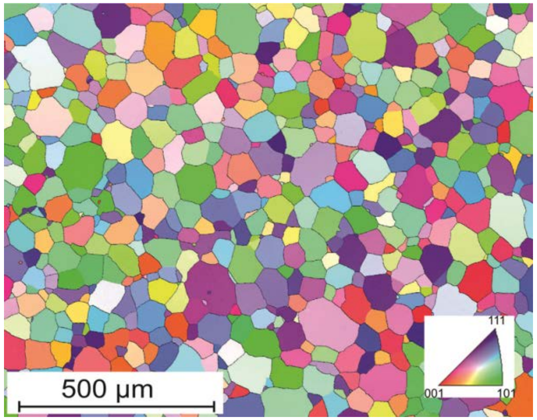
Mass production of components

Time & cost effective
near-net-shape forming process

Shape complexity & high final density

Material development



Tailoring new materials
&
Investigation of properties

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- **Mass fabrication of tungsten parts**
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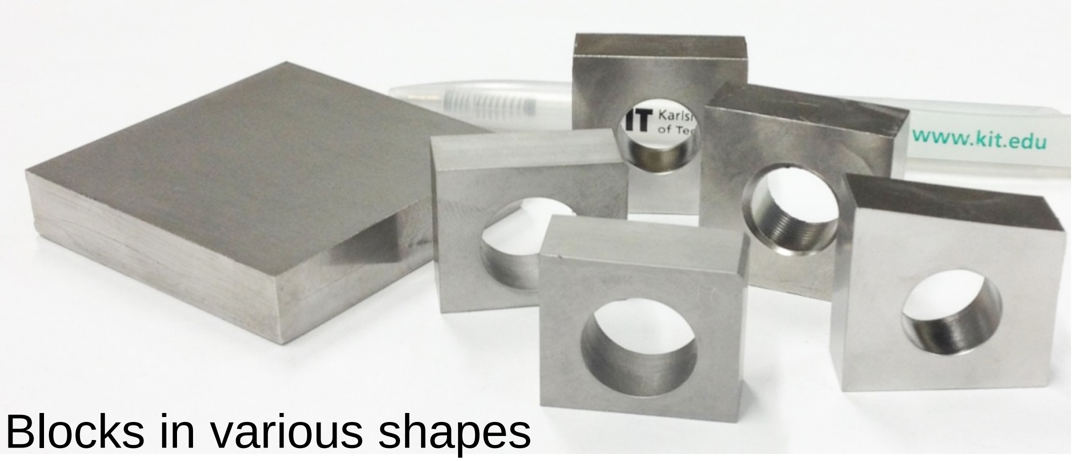
Mass fabrication of tungsten parts



Blocks in various shapes

Samples for ASDEX Upgrade

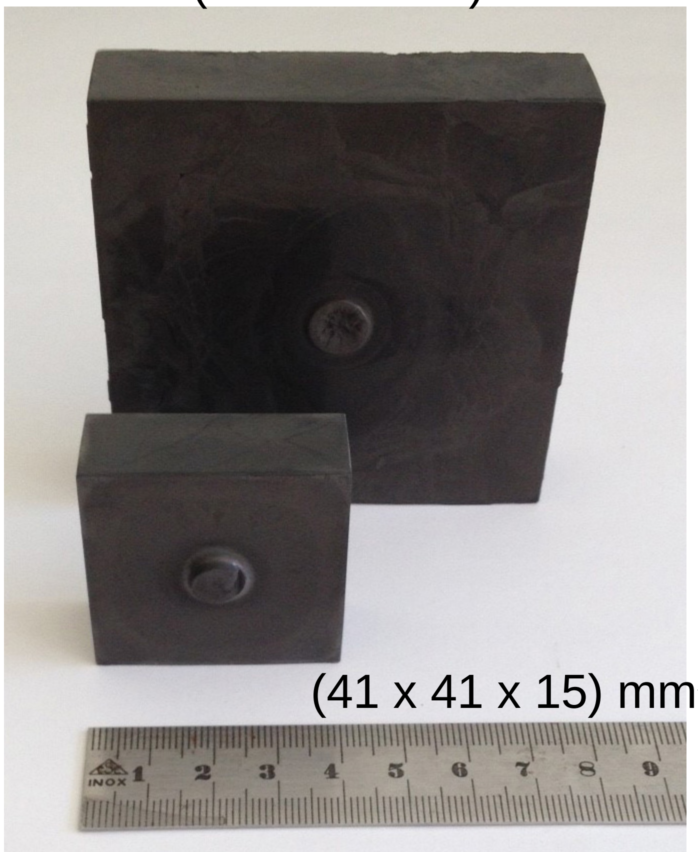
Mock-up`s for HHF testing

Langmuir probes for WEST

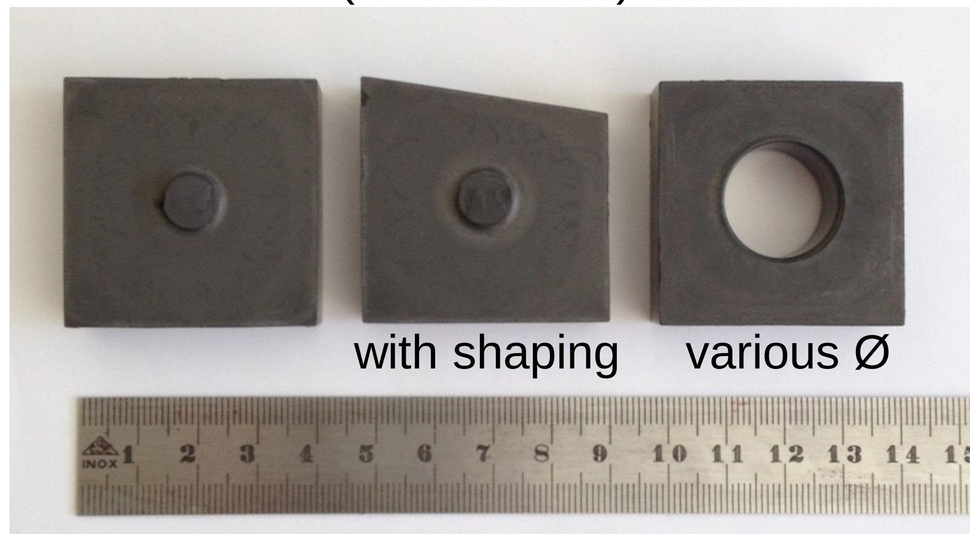
Mass fabrication of tungsten parts

… Dimension of **green-parts** …

(77 x 77 x 25) mm³



(41 x 41 x 15) mm³



Dimension & Quantity

(77 x 77 x 25) mm³	(~1.4 kg):	4 parts/hour
(41 x 41 x 15) mm³	(~0.25 kg):	15 parts/hour
(34 x 41 x 15) mm³	(~0.24 kg):	27 parts/hour

Mass fabrication of tungsten parts

… Dimension of **finished parts** …

(60 x 60 x 20) mm^3

(32 x 32 x 12) mm^3

(32 x 32 x 12) mm^3 with shaping

(26 x 32 x 12) mm^3

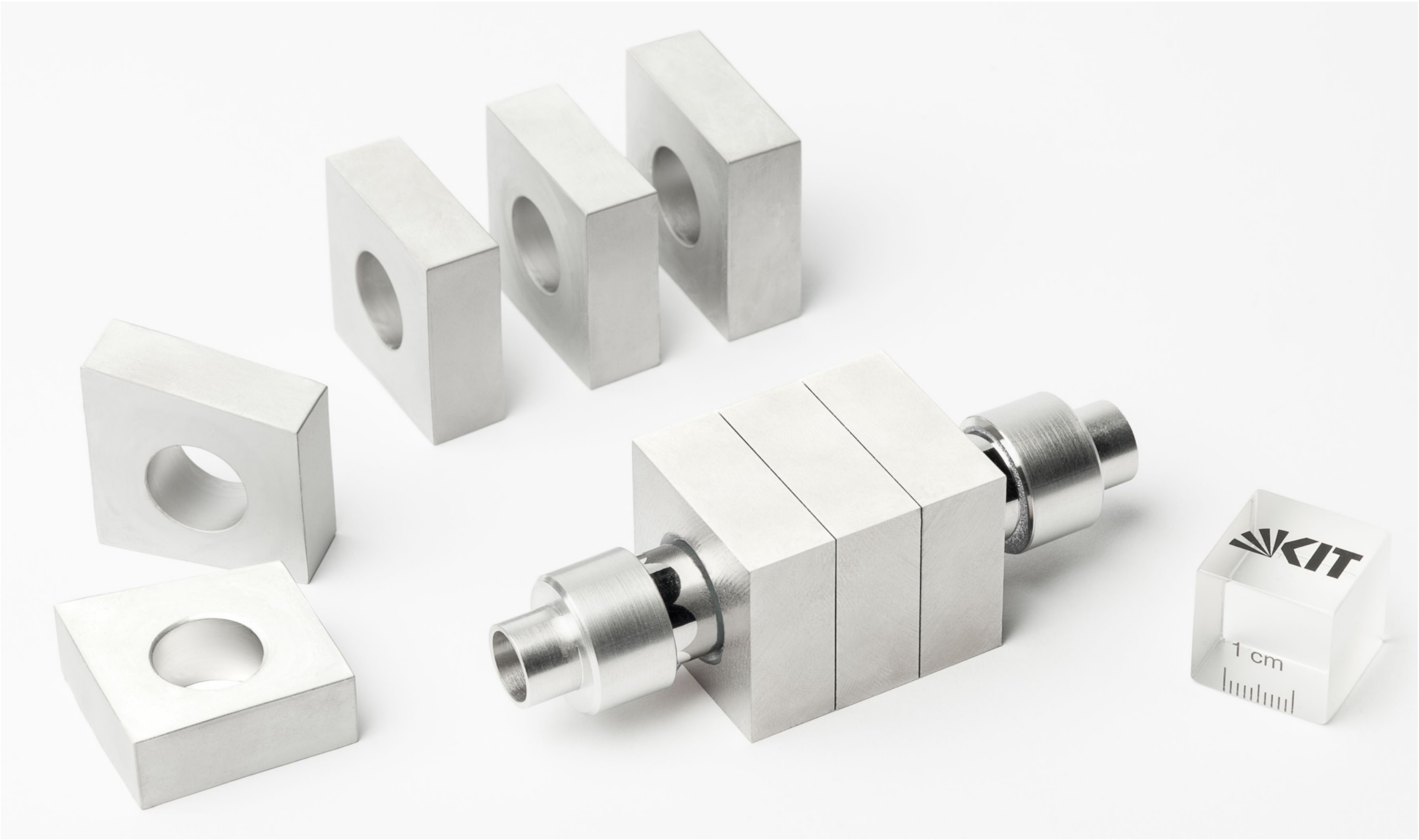
(26 x 26 x 12) mm^3

(24 x 22 x 4) mm^3

...+ various Ø and position of the bore…

Mass fabrication of tungsten parts

… W monoblocks – various size and shape – assembly to a component …



Mass fabrication of tungsten parts

… Qualification via high heat flux testing …

W-PIM monoblocks produced by KIT (collaboration with RKT and PLANSEE)

Assembly to a Mock-up via Hot Radial Pressing by ENEA

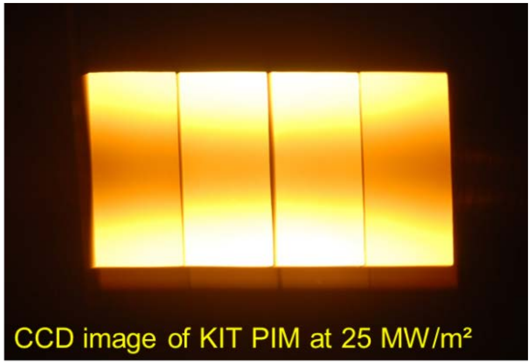
Courtesy of H. Greuner, B. Boeswirth (IPP Garching), G. Pintsuk (FZJ), E. Visca (ENEA)

HHF testing in GLADIS (IPP) **Hydrogen ion sorce**

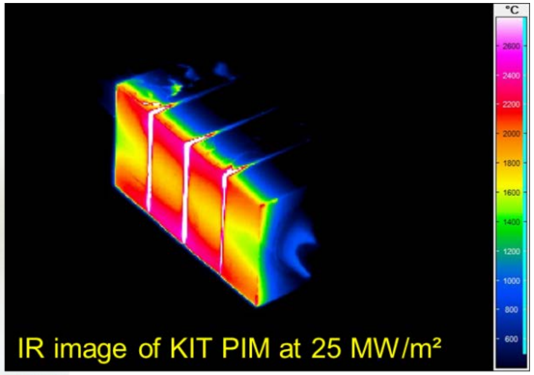
1) Screening till 25 MW/m²
2) 200 cycles @ 20 MW/m², 10 s, 20 °C
3) 100 cycles @ 20 MW/m², 10 s, 130 °C, 4 MPa

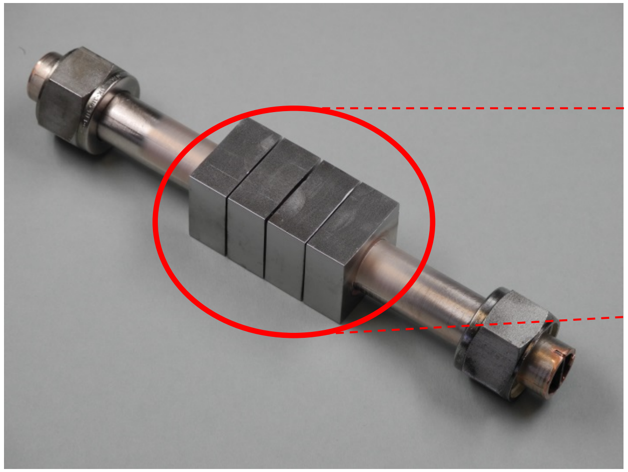
HHF testing in JUDITH (FZJ) **Electron beam testing**

4) 100 cycles @ 10 MW/m²
5) 1000 cycles @ 20 MW/m²

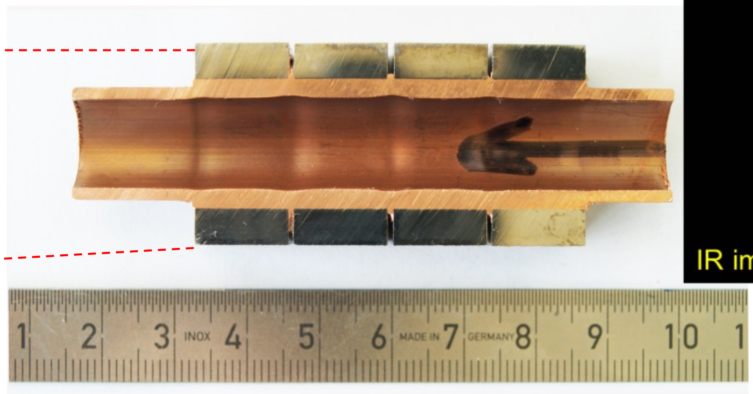


Total: 1400 cycles





W-PIM mock-up



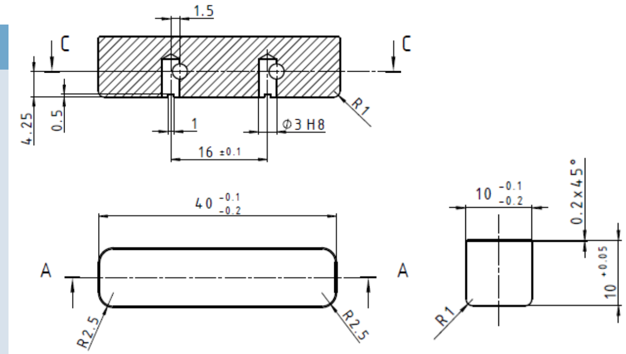
Mock-up (cross section) after HHF test

Mass fabrication of tungsten parts

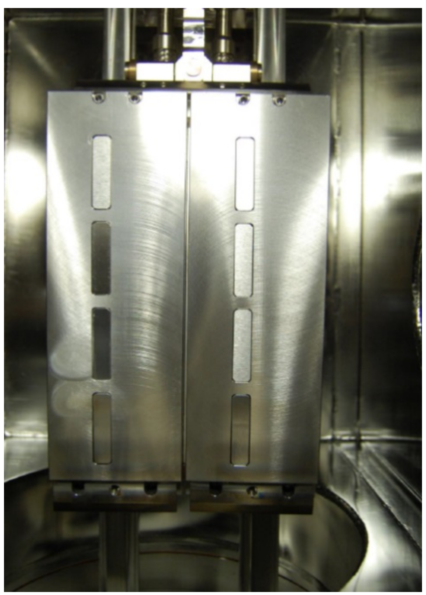
… Samples for ASDEX Upgrade
(Axialsymmetrisches Divertor-Experiment) …

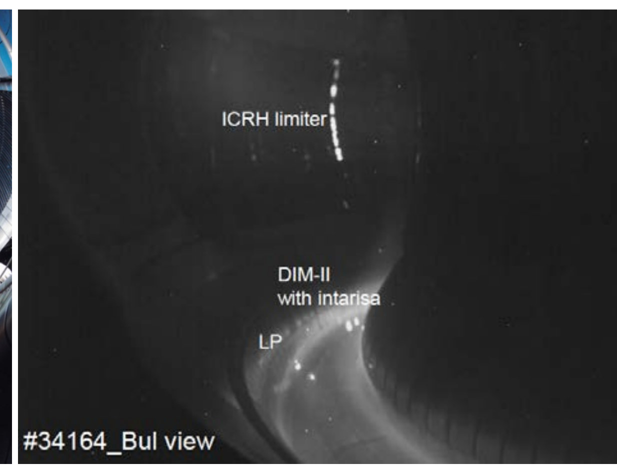
Courtesy of A. Herrmann (IPP Garching)

Technical data:	
Total height of the device	9 metres
Major plasma radius	1.6 metres
Minor plasma radii	0.5 / 0.8 metres
Magnetic field	3.9 tesla
Plasma current	2 megaamperes
Pulse lenght	10 seconds
Plasma heating	27 megawatts
Plasma volume	13 cubic metres
Plasma quantity	3 milligrams
Plasma mixture	hydrogen, deuterium
Plasma density	2 x 10^{20} particles per m^3
Plasma temperature	100 million degrees



75 plasma shots up to 20 MW w/o vissible damages of the probes





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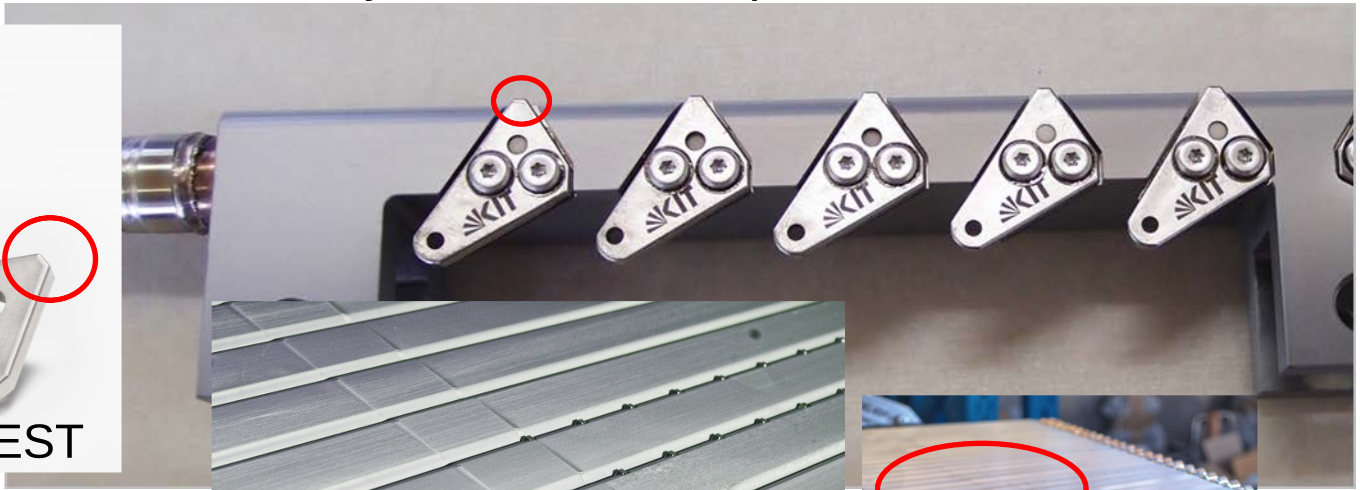
Mass fabrication of tungsten parts

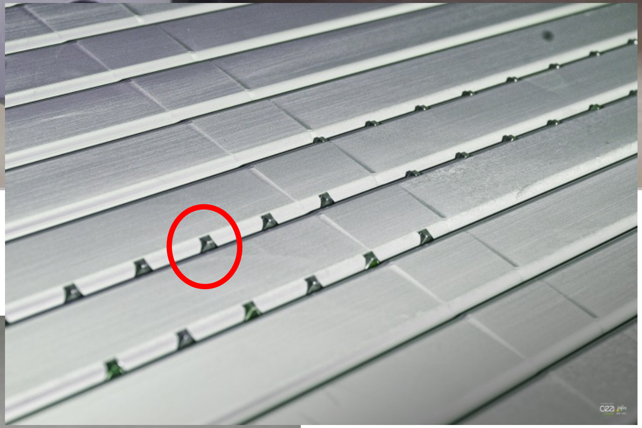
… Samples for WEST

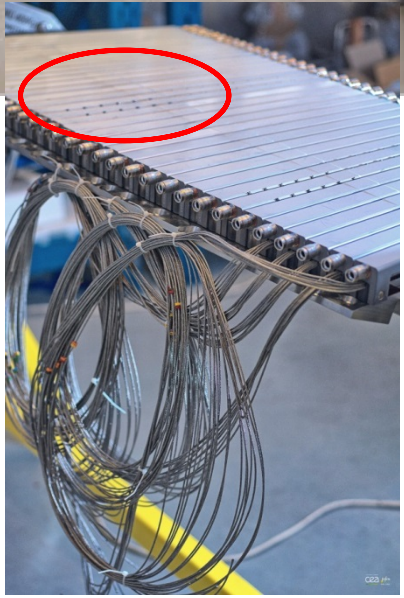
(Tungsten (W) Environment in Steady-state Tokomak) …

Courtesy of J. Gunn (CEA)

Langmuir probes for WEST

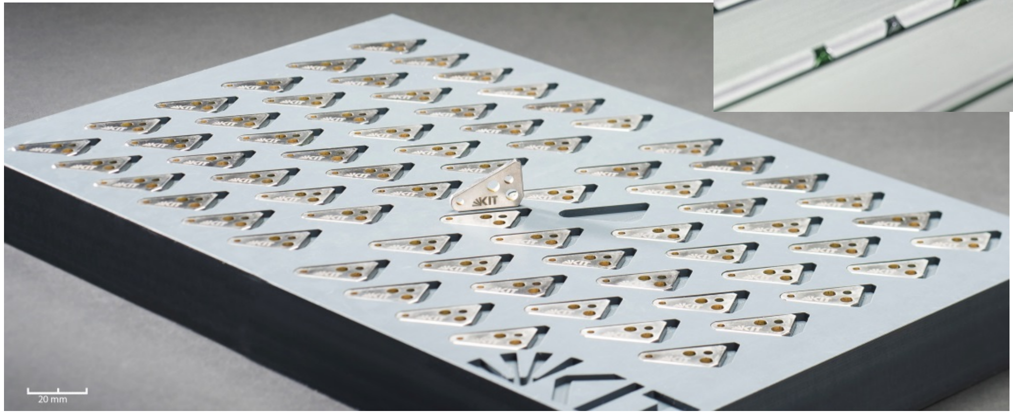






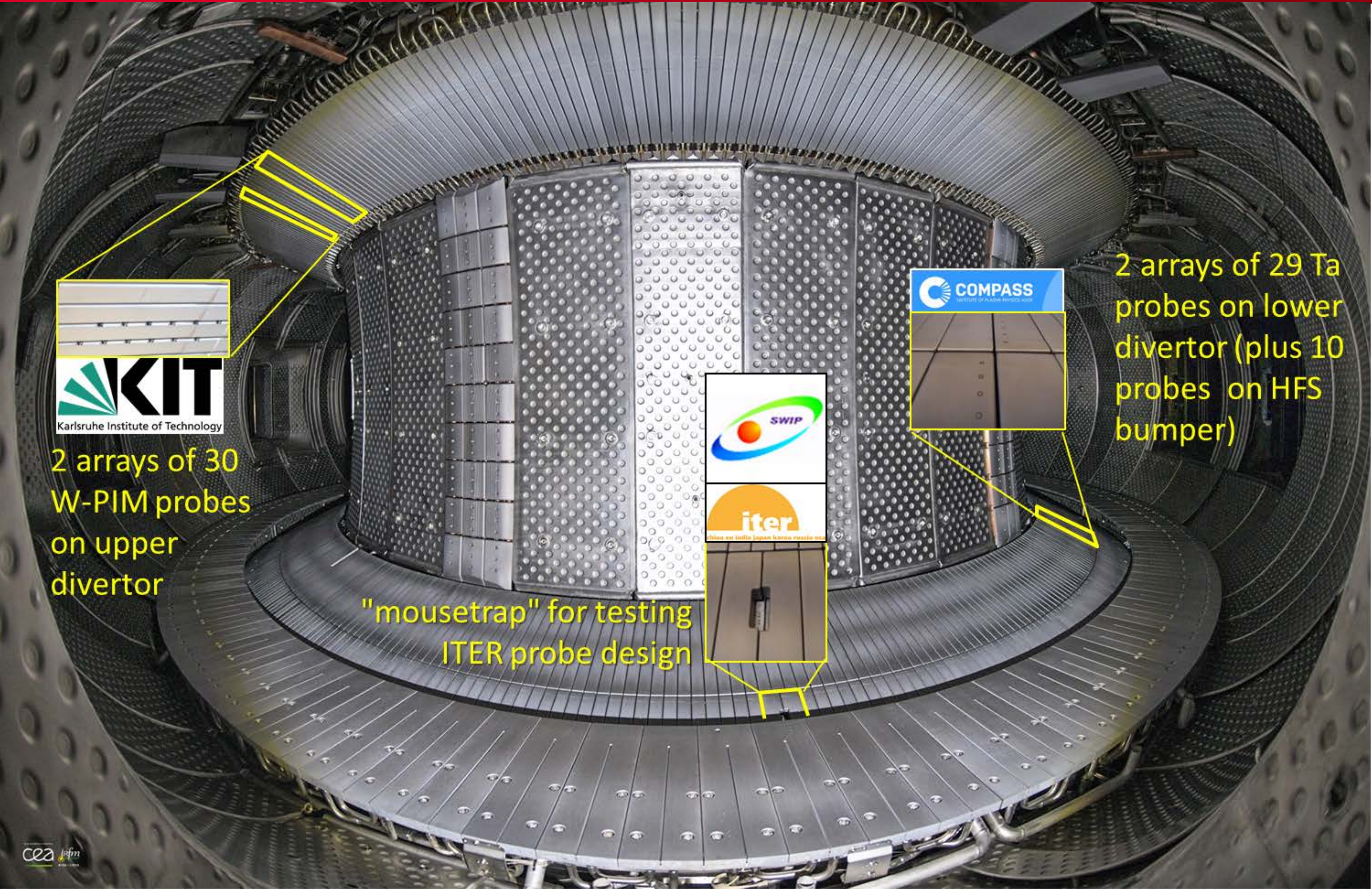
Watercooled CuCrZr PFU

Device to determine the electron temperature, electron density, and electric potential of a plasma.



Fabrication of a series of 60 Langmuir probes via W-PIM @ KIT.

THANK YOU! NOW WE'RE READY TO HAVE FUN



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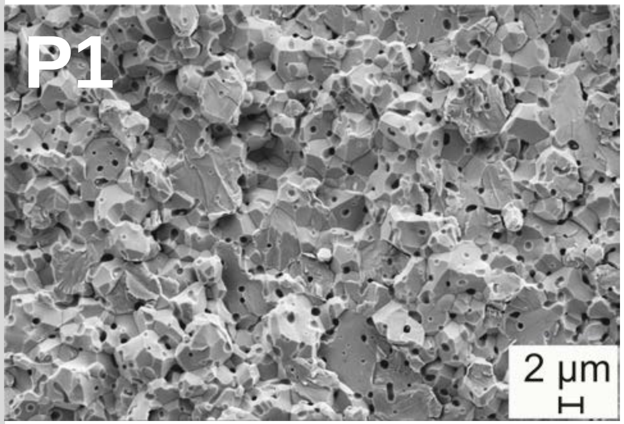
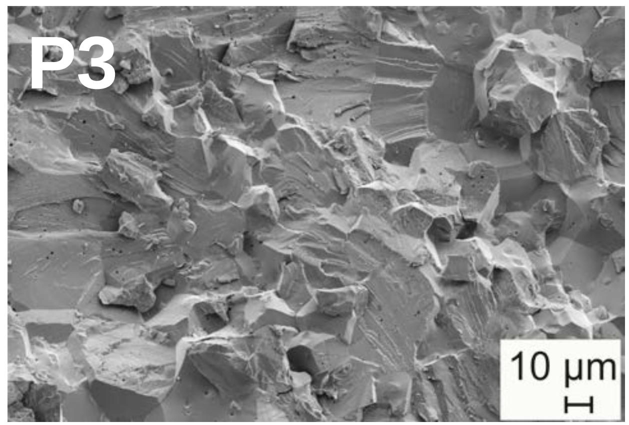
Development of new materials

… Sintering temperature vs. grain growth …

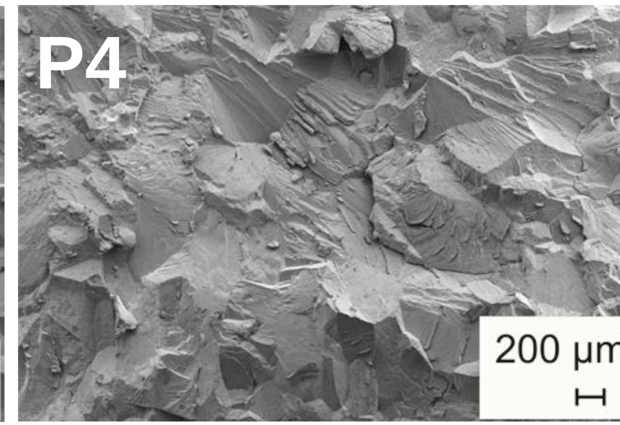
Pure Tungsten



T_{sint} 1800 °C
Density: 95 – 96% T.D.
Grain size ~ 10 - 20 µm



T_{sint} 2400 °C
Density: 98.8% T.D.
Grain size ~ 50 -100 µm



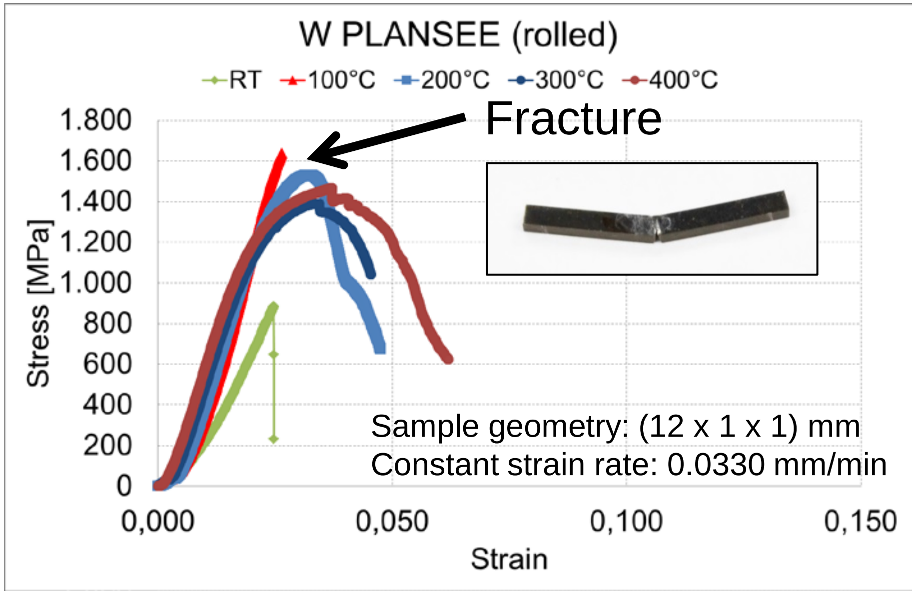
T_{sint} 2600 °C
Density: 99% T.D.
Grain size ~ 200 - 400 µm

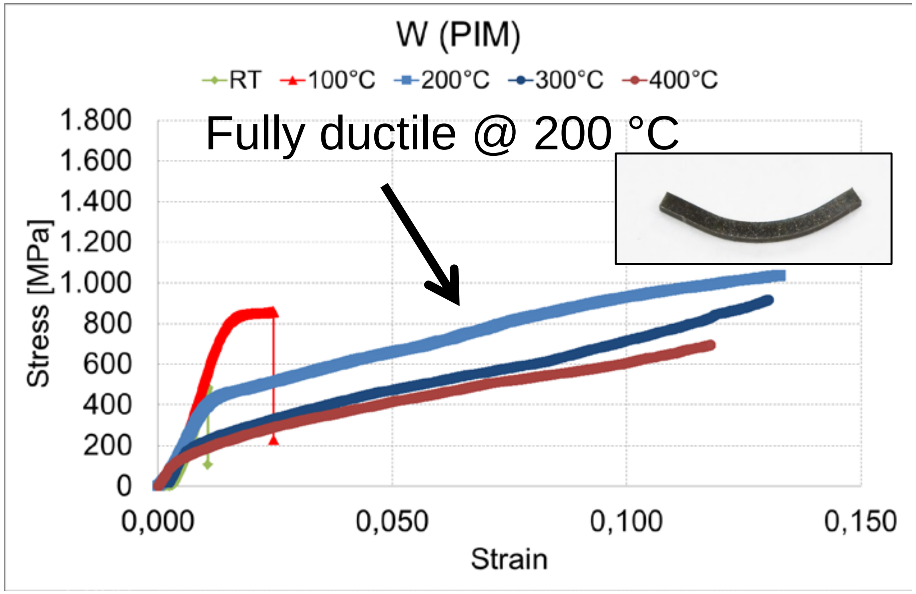
Grain growth

Sintering temperature

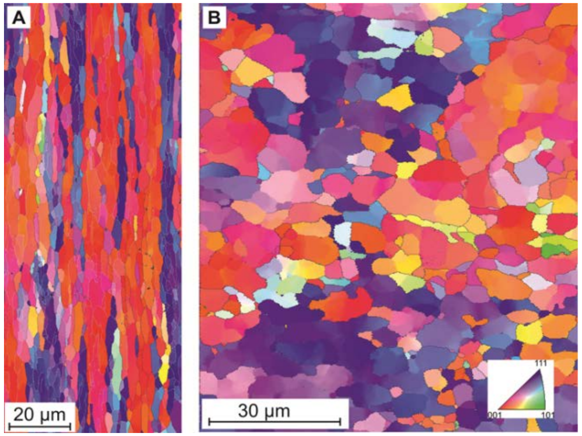
Development of new materials

… Mecanical testing via 4-PB tests from 20 °C to 400 °C …

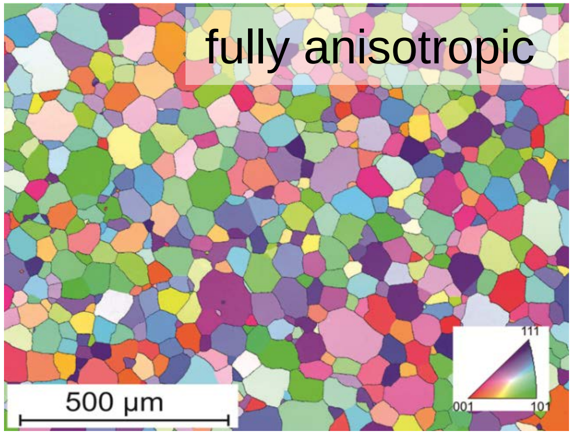




High strength in rolling direction (A)



Same strength in all directions

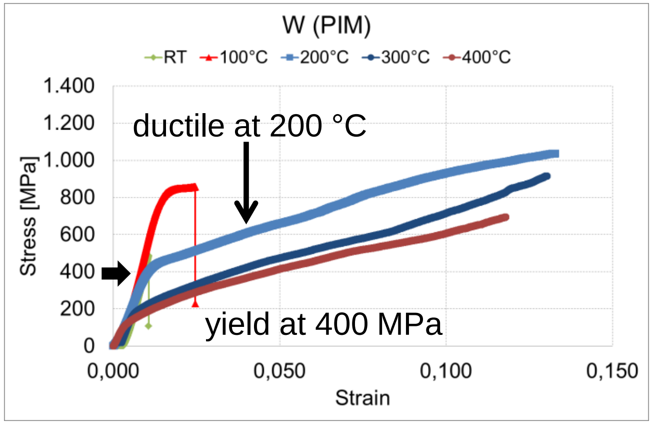


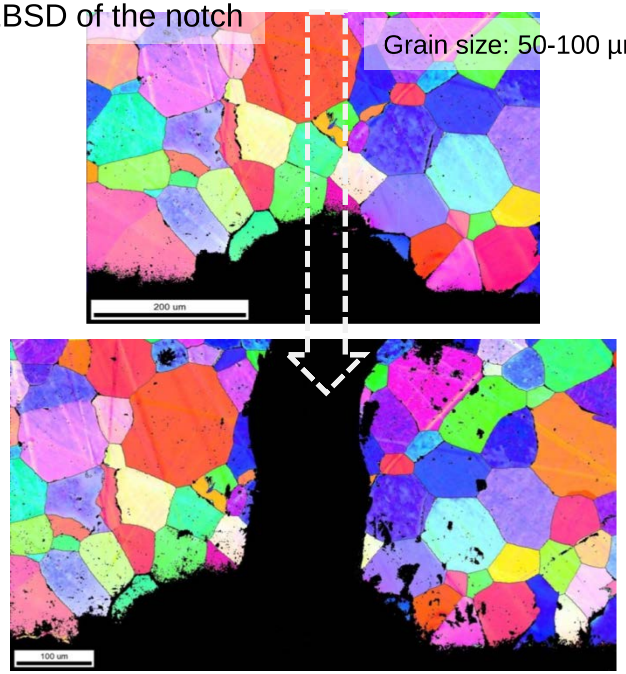
S. Antusch et al., Nuclear Materials and Energy 3-4 (2015), 22-31

Development of new materials

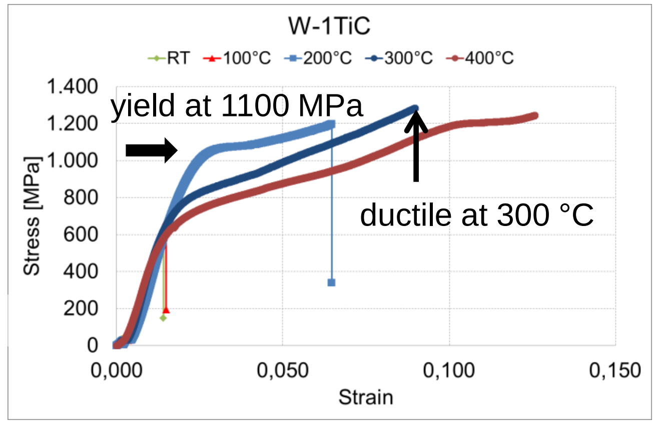
… Mecanical testing via 4-PB tests from 20 °C to 400 °C …

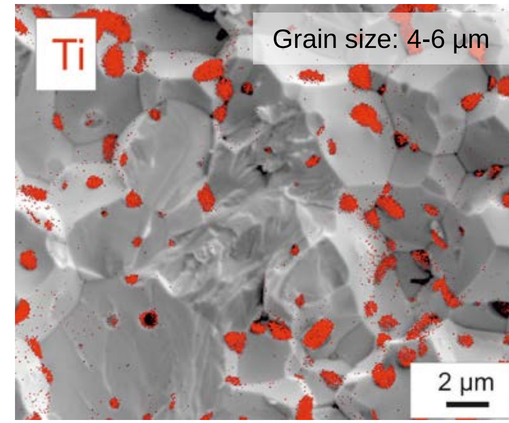
Sample geometry: (12 x 1 x 1) mm
Constant strain rate: 0.0330 mm/min

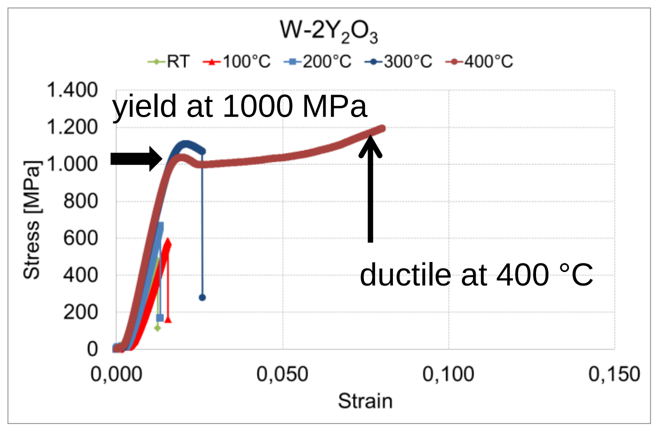


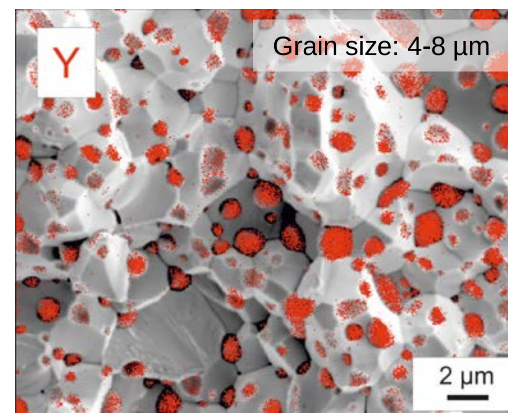


Transgranular crack @ RT









AES: Microstructure & element allocation

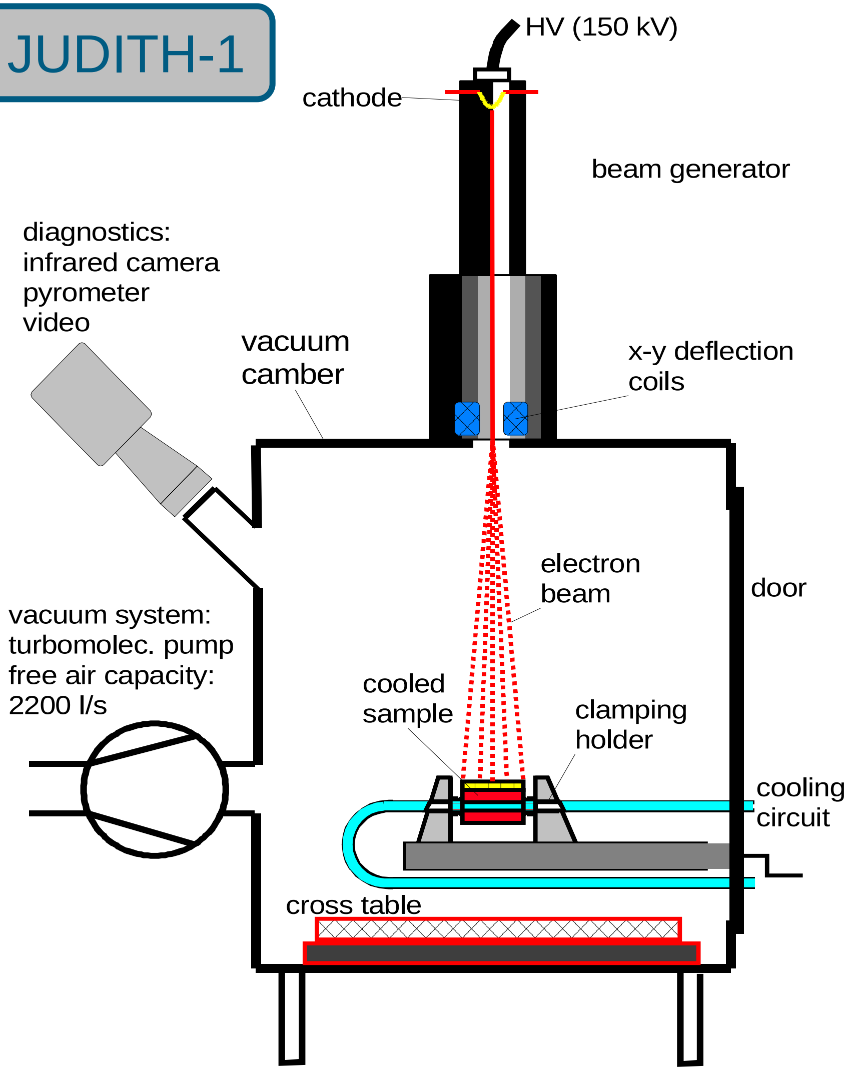
S. Antusch et al. Nuclear Materials and Energy (accepted)

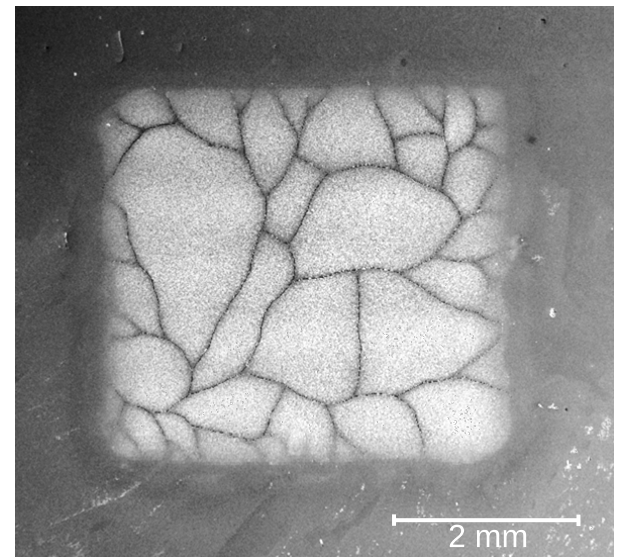
Development of new materials

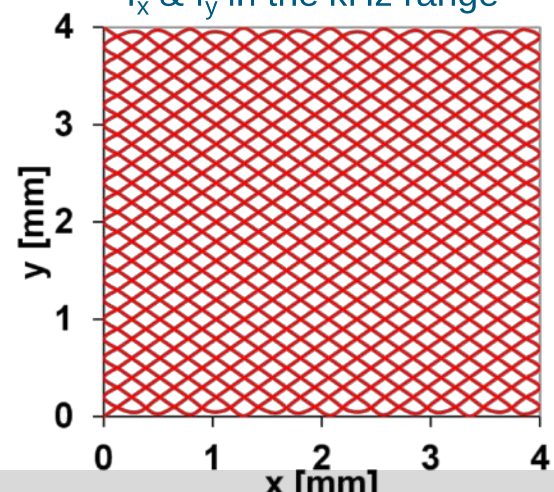
… Thermal shock testing with e-beam in JUDITH-1 …

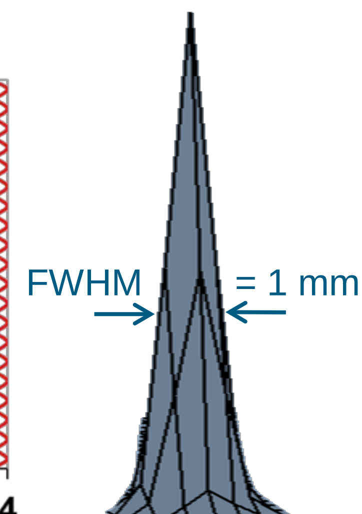
Courtesy of G. Pintsuk (FZJ)

JUDITH-1









Total power:	60 kW
Acceleration voltage:	120 kV

Development of new materials

… Thermal shock tests via e-beam @ JUDITH-1 …

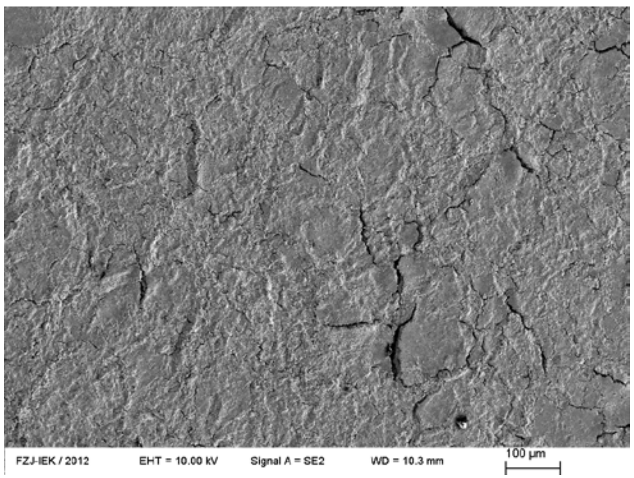
JÜLICH FORSCHUNGSZENTRUM — KIT Karlsruhe Institute of Technology

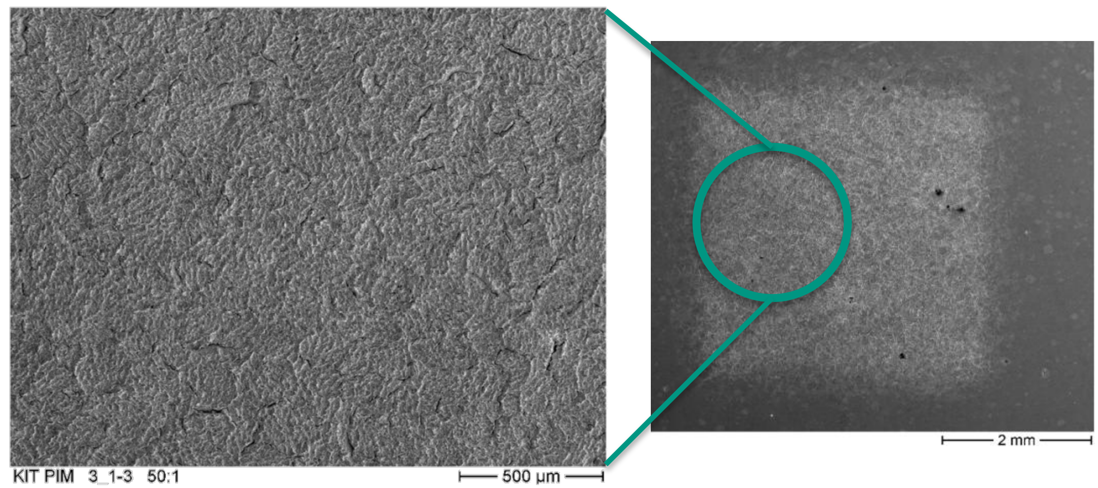
Courtesy of G. Pintsuk (FZJ)

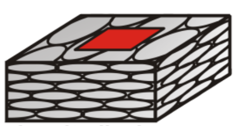
#	T [°C]	P_{abs} [GW/m^2]	Δt [ms]	E_{abs} [MJ/m^2]	FHF [MW/m^2*s$^{1/2}$]	# shots
C	1000	0.38	1	0.38	12	1000

W PLANSEE (single forged)

W (PIM)







Note the different scale markers !

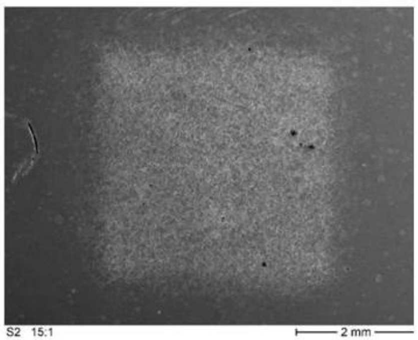
Development of new materials

… Thermal shock tests via e-beam @ JUDITH-1 …

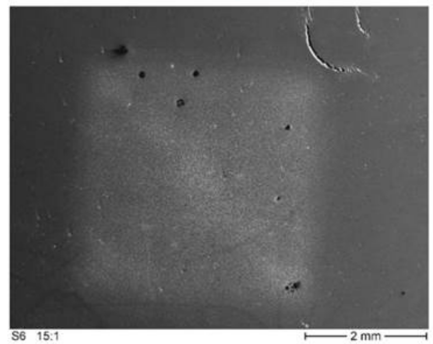
Courtesy of G. Pintsuk (FZJ)

T [°C]	P_{abs} [GW/m²]	Δt [ms]	E_{abs} [MJ/m²]	F_{HF} [$MW/m^2 {*} s^{1/2}$]	# shots
1000	0.38	1	0.38	12	1000

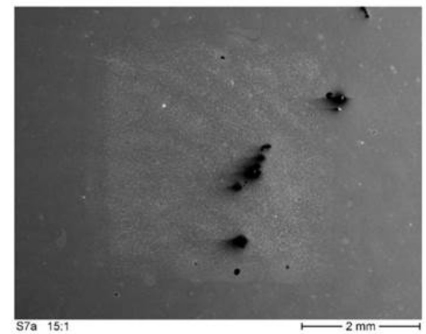
W

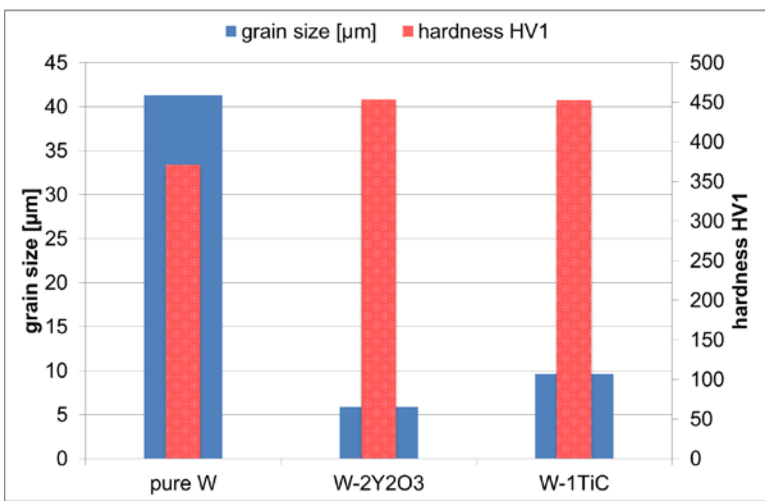


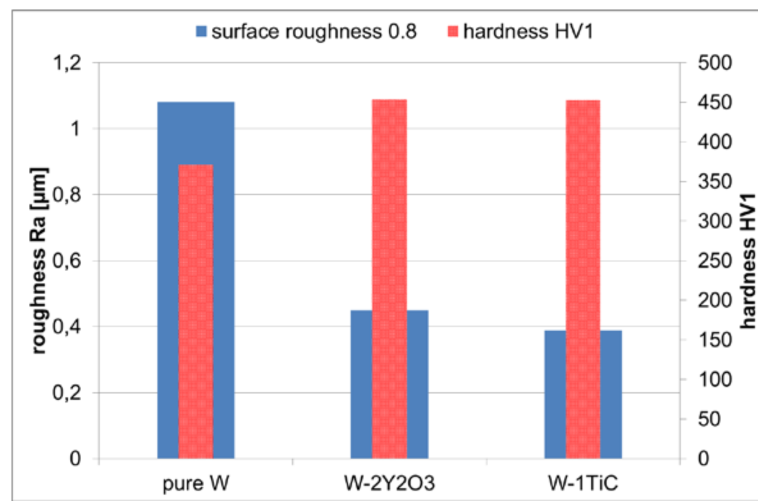
$W\text{-}2Y_2O_3$



W-1TiC







Development of new materials

… Urgend need of irradiation data …

Fabrication of parts for an irradiation campaign organized by EUROfusion

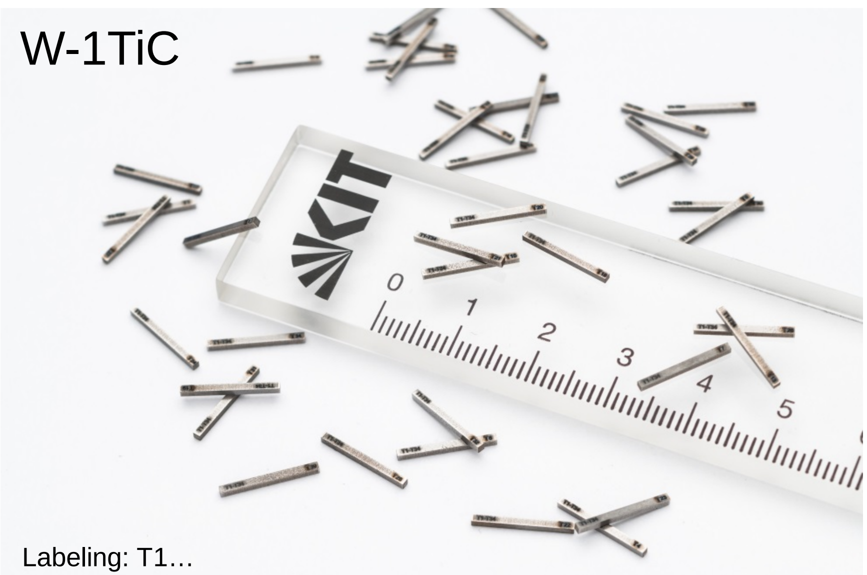
W-2Y_2O_3 and **W-1TiC**

Mini 4P bend bars (12 mm x 1 mm x 1 mm): 40 samples / material

Irradiation dose: 0.7 – 0.8 dpa

Irradiation temperatures: 600, 1000, 1100 °C

→Time schedule by SCK-CEN, Belgium: June 2018 – May 2019

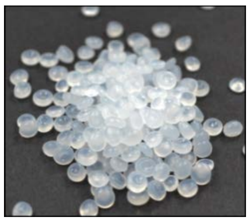


Development of new materials

… 3D printing of Tungsten …

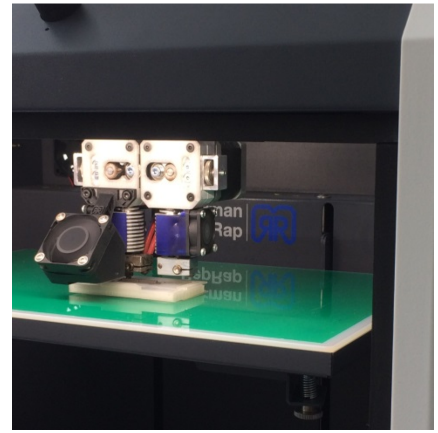
Fused Filament Fabrication (FFF) /
Fused Deposition Modelling (FDM)

Karlsruhe Institute of Technology



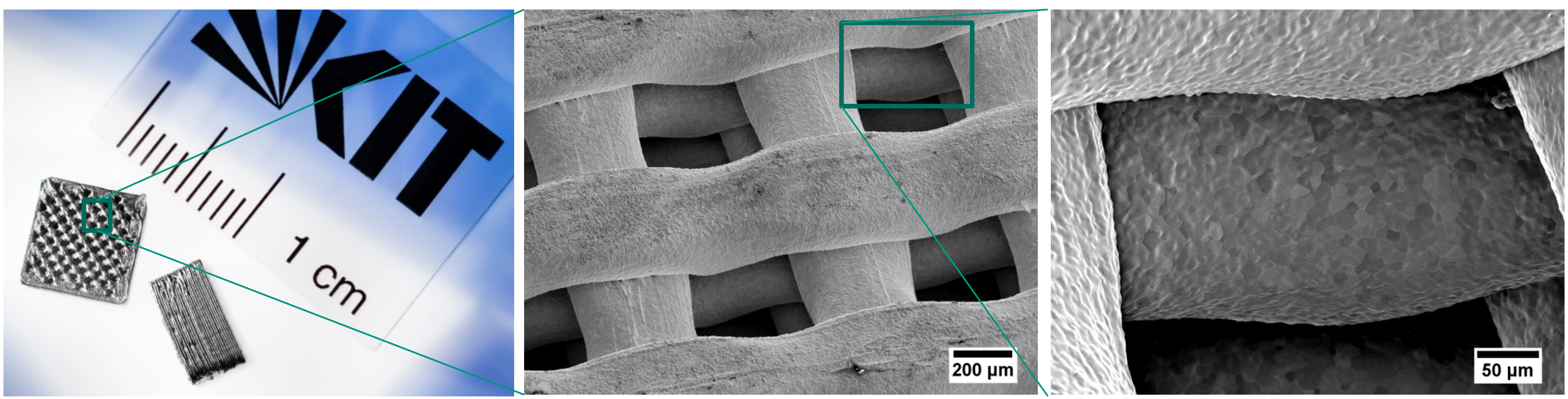
Powder + Binder

Filament fabrication



3D printing of green parts

Heat-treatment



S. Antusch : Need a tricky tungsten piece ? Print it ! Fusion in Europe 1/2018 (2018)

Outline

- Powder Injection Molding @ KIT
- Mass fabrication of tungsten parts
- Development of new materials
- **Summary**

Summary

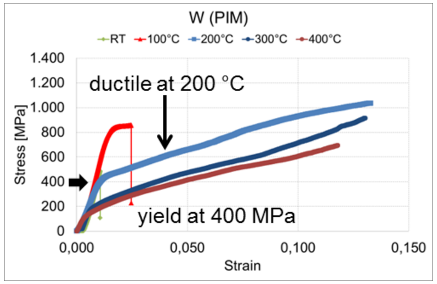
Tungsten Powder Injection Molding @ Karlsruhe Institute of Technology

Mass production of components

Time & cost effective
near-net-shape forming process

Shape complexity &
high final density

Properties



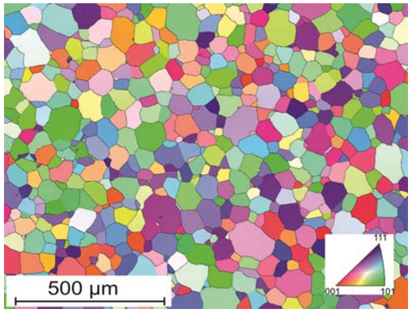
Brittle to ductil transition at 200 °C

No recrystallisation

High thermal shock resistance

Fully anisotropic

Rapid material development



Create new materials
&
Investigation of properties

3D printing of Tungsten: new method for papid prototyping

Max-Planck-Institut für Plasmaphysik

THANK YOU VERY MUCH!

PL FUSION