Development of reusable liquid propulsion units based on transpiration cooled, ceramic thrust chambers and turbo pumps for launch and in space applications

15th Reinventing Space Conference

(Glasgow, 24 – 26/10/2017)

Dr.-Ing. Peter H. Weuta (WEPA-Technologies GmbH (Germany))
Dipl.-Ing. Markus Ortelt (German Aerospace Center / DLR)
Dipl.-Ing. Thoralf Hofmann (WEPA-Technologies GmbH (Germany))

Introduction: WEPA-Technologies GmbH

1 Introduction: WEPA-Technologies GmbH

- **Business activities: Mechanical Engineering, General Automation and Rocket Technology**

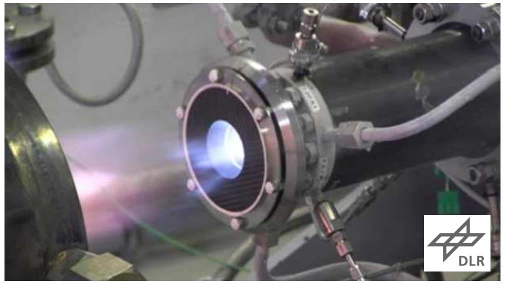
- **R&D focussed engineering office and manufacturing company**
  - **<u>Planning, development and realization of non-standard solutions</u>**

- **Manufacturing of prototypes and small lots**
  - **company owned 750 m^2 workshop**
  - **broad range of manufacturing technologies (CNC- and conventional machining)**

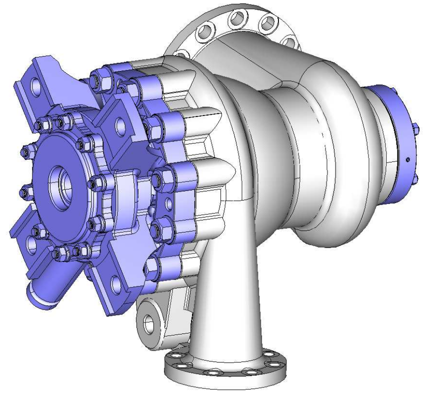
Development Activities

Technologies

2 Development Activities (Rocket Propulsion Technology)



- **Liquid propellant rocket engines (LPRE)**
- **Turbo pumps (LPRE or hybrid engines)**
- **H_2O_2 - concentration plants**
  - **Automatic operation (24 / 7)**
  - **50 – 1500 kg / day**
  - **88 - 98 % product concentration**



- **Solid rocket motors (SRM) (Chlorine free)**

- **Public references include…**
  - **CASSIDIAN GmbH (Airbus Defence & Space)**
  - **Dynamit Nobel Defence GmbH**
  - **EU-customer (H_2O_2 - concentration plant)**

2 Development Activities (Rocket Propulsion Technology)

- General philosophy: offer solutions tailored to customer requirements
  - Expendable and re-usable systems
  - Oxidizers: LOX, H_2O_2
  - Fuels: Kerosene, Methane (LCH_4), Ethanol (Alcohol)

- Common propellant combinations requested

- LOX / LCH_4	(preferred system for reusable LPRE !)
- LOX / Kerosene	(traditional combination; also SMILE-project / H2020)
- H_2O_2	(hybrid propulsion; also SMILE-project / H2020)
- H_2O_2 / Kerosene	(all-storable-propellants)
- LOX / Ethanol	(no environmental constrains)

- Expendable and re-usable systems under development

Development of Reusable Liquid Propellant Engines
- General overview -

Development of reusable, liquid propulsion units based on transpiration cooled, ceramic thrust chambers and turbo pumps for launch and in space applications

Dr.-Ing. P. Weuta, Dipl.-Ing. M. Ortelt, Dipl.-Ing. Th. Hofmann

DLR

WEPA Technologies

3 Development of LPRE – overview

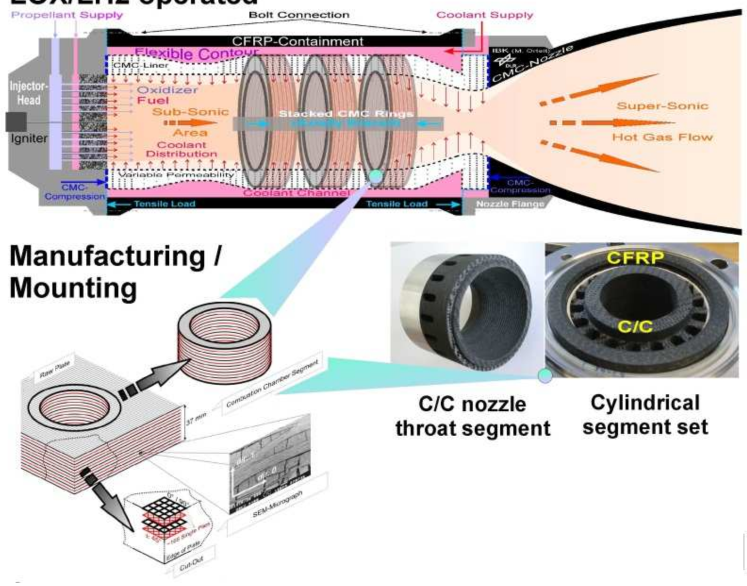
- Why re-usable rocket engines ?
  - worldwide increase of activities to develop re-usable launch systems (cost reduction and / or increase of launch rate)
  - Propulsion system one of main issues to be solved
- Typical drawbacks of traditional, metallic structures include…
  - Expensive and slow production process (=> when using electrodeposition procedure)
  - Heavy weight structure
  - High temperature gradient across inner chamber wall + high thermal expansion coefficient
    - Low cycle fatigue phenomena => limited number of cycles

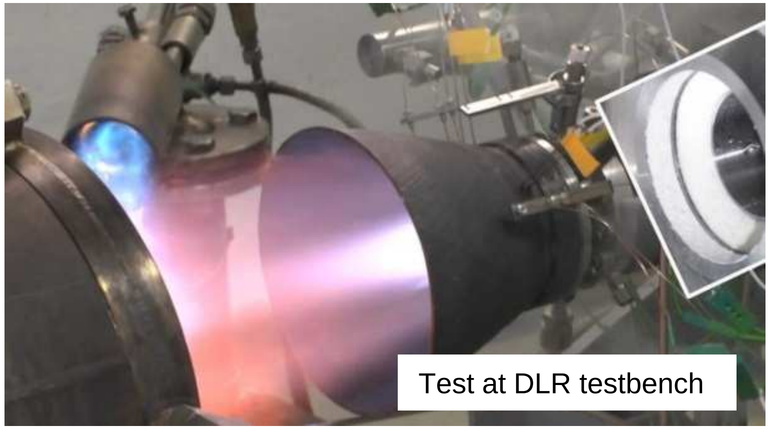
  => only limited applicability in re-usable launch or in-space applications
- Focus on ceramic thrust chamber technology
  - Active (transpiration) cooling !

3 Development of LPRE – thrust chamber - 1 -

- Use of ceramic thrust chamber technology developed by German Aerospace Center (DLR) since mid-1990’s
  - License agreement finalized in 12/2016
  - WEPA – DLR joint marketing of technology in progress
- <u>long term experience with ceramic thrust chambers (DLR)</u>
  - Multiple successful tests with LOX / LH_2 (GH_2)
  - Chamber pressures up to 100 bar / huge upside potential
- Use of non-oxide and oxide ceramic matrix material (ceramic matrix composites / CMCs)

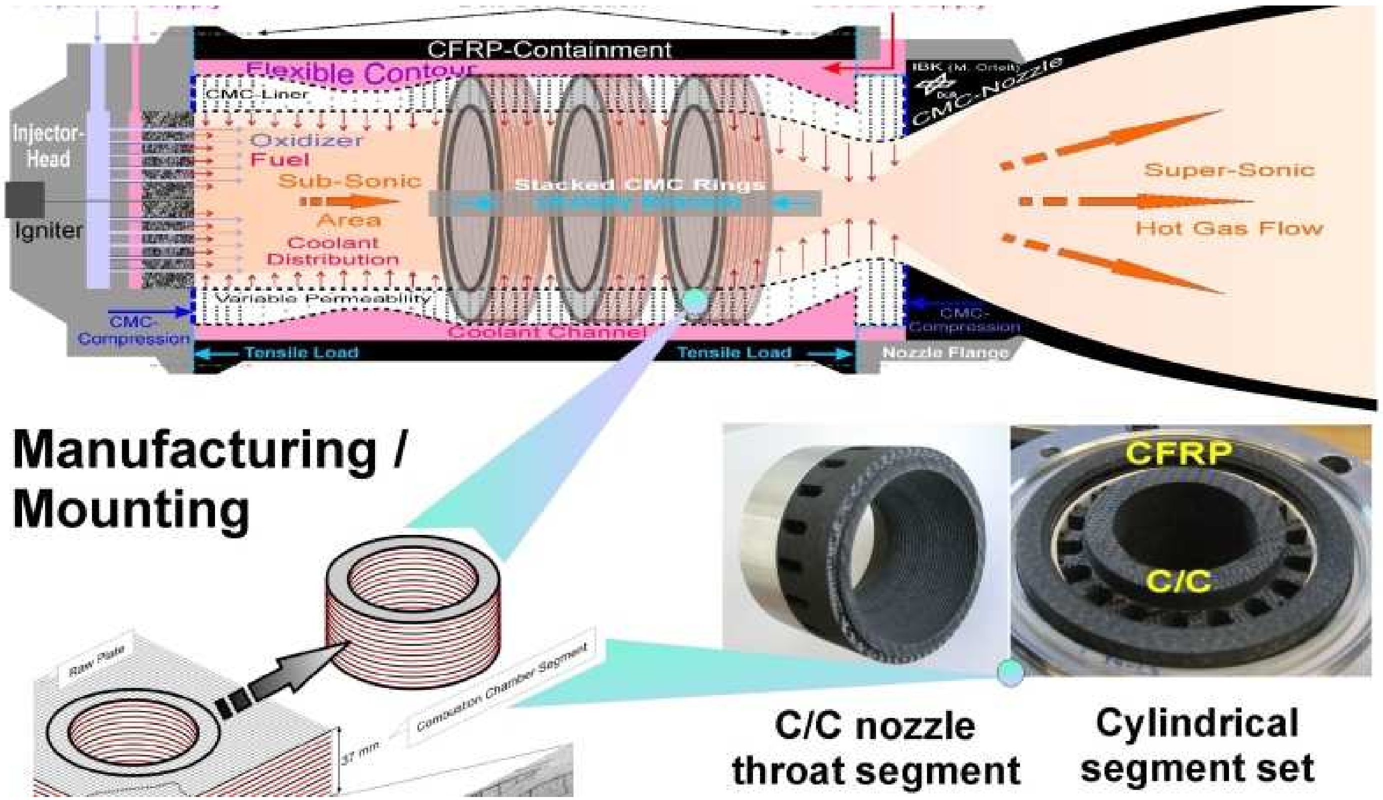
Cryogenic composite rocket thrust chamber
Transpiration cooled design principle
LOX/LH2 operated



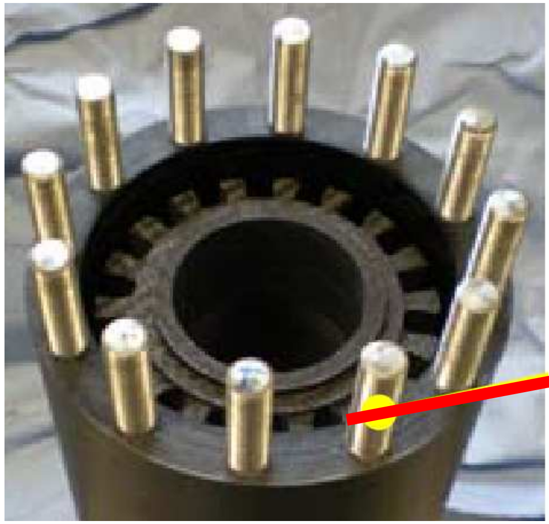

Test at DLR testbench

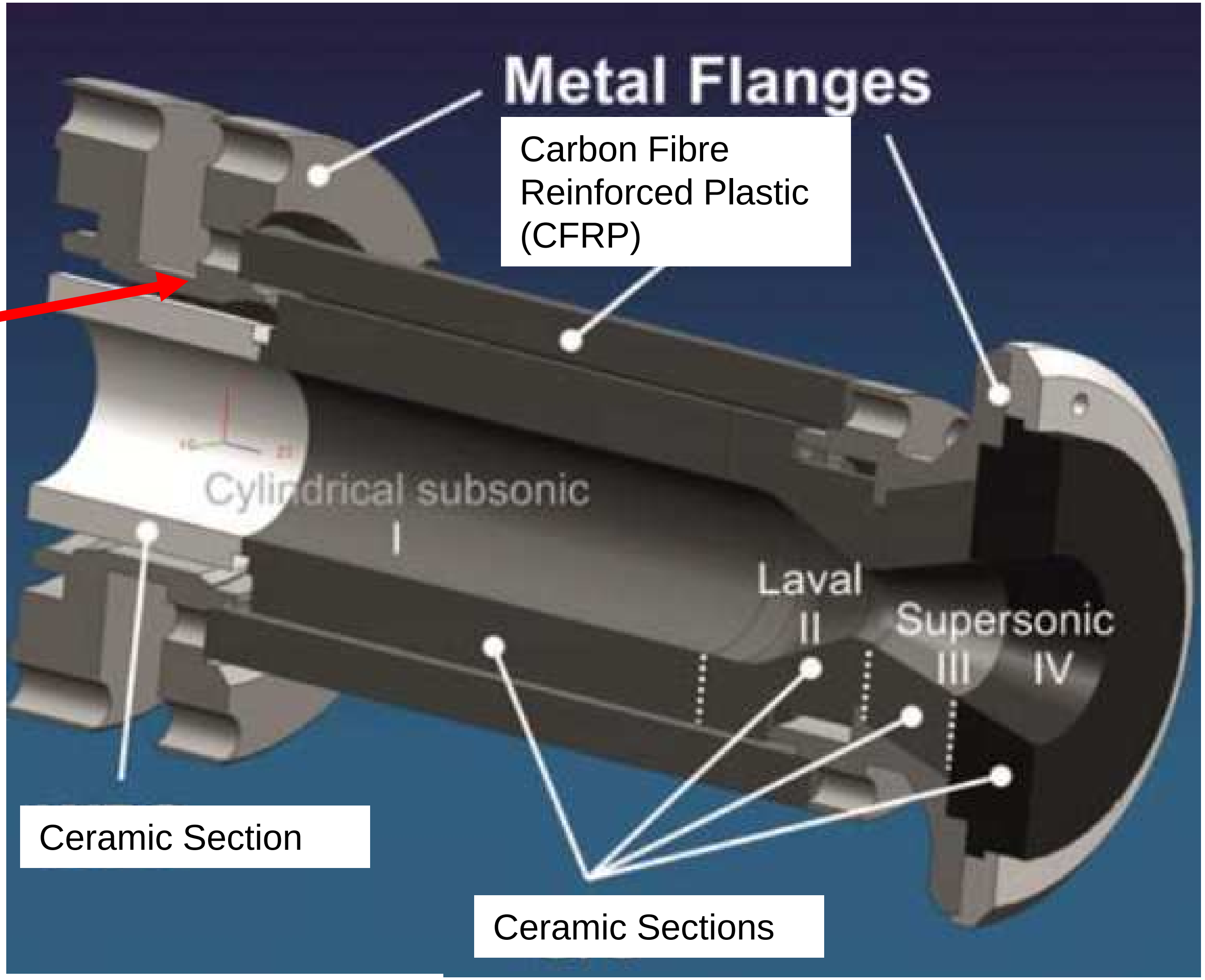
DLR
WEPA Technologies

- Transpiration cooled, ceramic thrust chamber
  - Mechanically decoupled design principle
  - Clamped assembly of all components / no permanent joints by brazing, galvanizing or welding
  - Straight forward variation and combination of different materials feasable
  - Light weight carbon fiber composite casing
  - Interface technologies to join injector, nozzle and thrust chamber are qualified

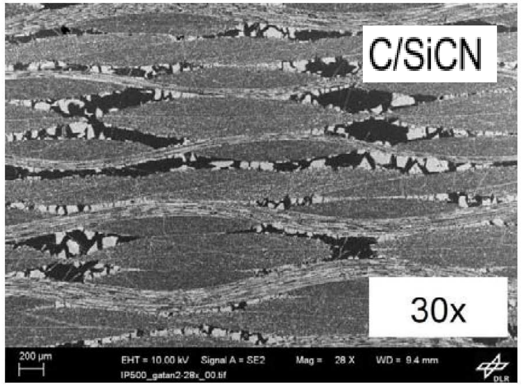


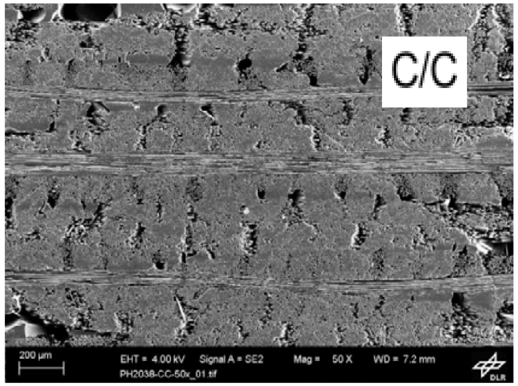
Transpiration cooled, ceramic thrust chamber – mechanical design





- Ceramic thrust chambers are very promising candidates for multiple reusability
  - Low thermal expansion → no fatigue effects caused by thermal cycling
  - System simplification → cost reduction, high reliability
  - High specific strength at elevated temperatures / lower weight
  - Oxidation resistance
  - Improved lifetime
    - Thermo-shock resistance
    - Thermal cycling ability

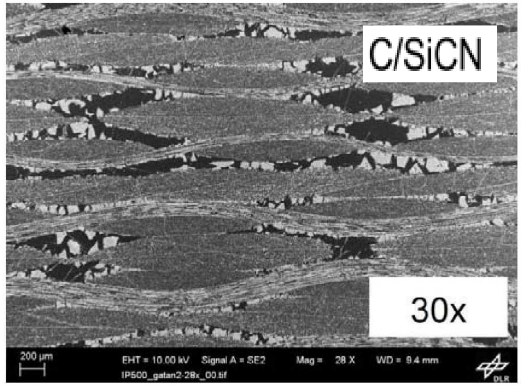


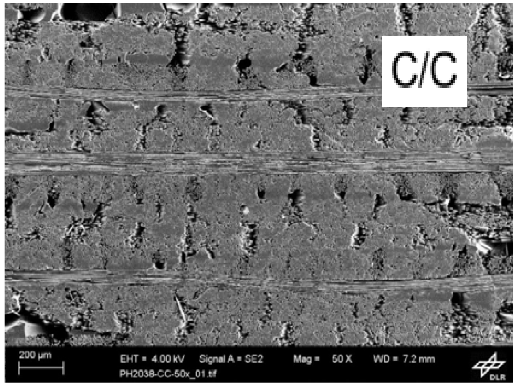


3 Development of LPRE – CMC material

- Material properties can be tailored to requirements
  - Morphology and permeability
  - Oxidation resistance
  - Thermal expansion coefficient
  - Multiple zones within thrust chamber can be integrated

  => Development / manufacturing in-house by DLR





Oxipol | AvA-Z-ISC | C/SiCN | C/C (CVI)

Development of Re-usable Liquid Propellant Engines
- Technology Demonstrator Unit -

Development of reusable, liquid propulsion units based on transpiration cooled, ceramic thrust chambers and turbo pumps for launch and in space applications

Dr.-Ing. P. Weuta, Dipl.-Ing. M. Ortelt, Dipl.-Ing. Th. Hofmann

15th Re-Inventing Space Conference / Glasgow, 10/2017

DLR

WEPA Technologies

4 Development of LPRE - Technology Demonstrator - 1-

- Current project – 35 kN technology demonstrator
  - Joint project of WEPA and DLR Stuttgart
- Design overview
  - Use of highly effective transpiration cooled thrust chamber
    - LOX + LCH_4 (alternative fuels: Kerosene or Ethanol)
  - Injector
    - "Cone" type: DLR development (deeply throttleable !)
    - Classic designs: coaxial type
  - Chamber pressure: 7.5 MPa
  - Propellant feed rate: 12 kg / s
  - Turbo pump fed, open gas generator cycle (**WEPA** in collaboration with DLR; University of Technology Kaiserslautern; University of Technology Dresden)

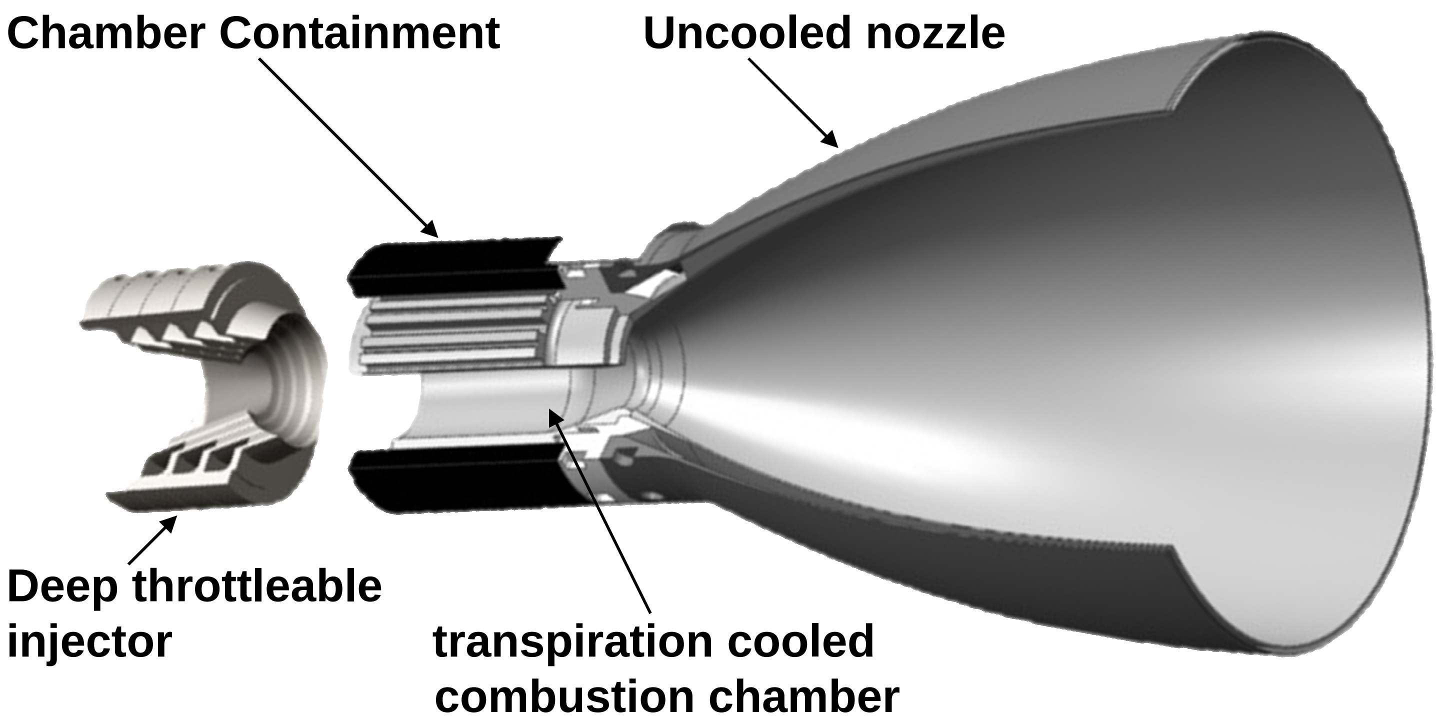
- Subsystems already qualified by DLR
- Adaption to propellants and scale up to 35 kN necessary

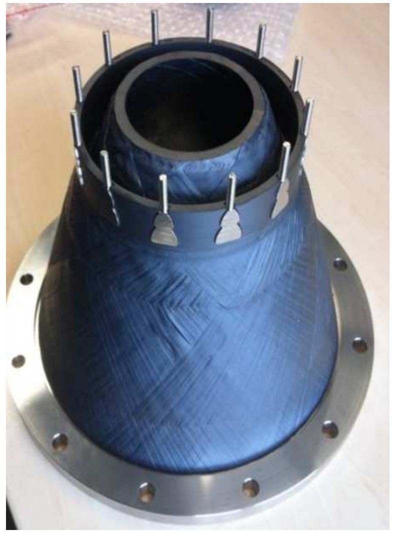
- Design rationale to select 35 kN class: potential uses in micro satellite launch systems (50 – 100 kg to LEO / 3 stage launch system)
  - 4 x 35 kN cluster => 1. stage propulsion
  - 1 x 35 kN engine => 2. stage propulsion

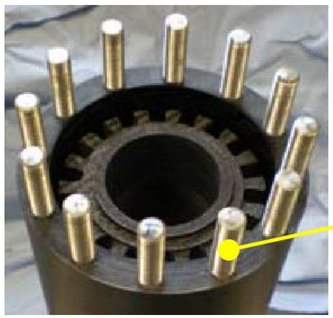
4 Development of LPRE – Technology Demonstrator - 2 -

- 35 kN demonstrator engine is designed using all ceramic components
  - Thrust chamber (transpiration cooled)
  - Injector
  - Nozzle extension

  => all sub-systems already principally qualified by DLR. Scale-up to 35 kN in progress.

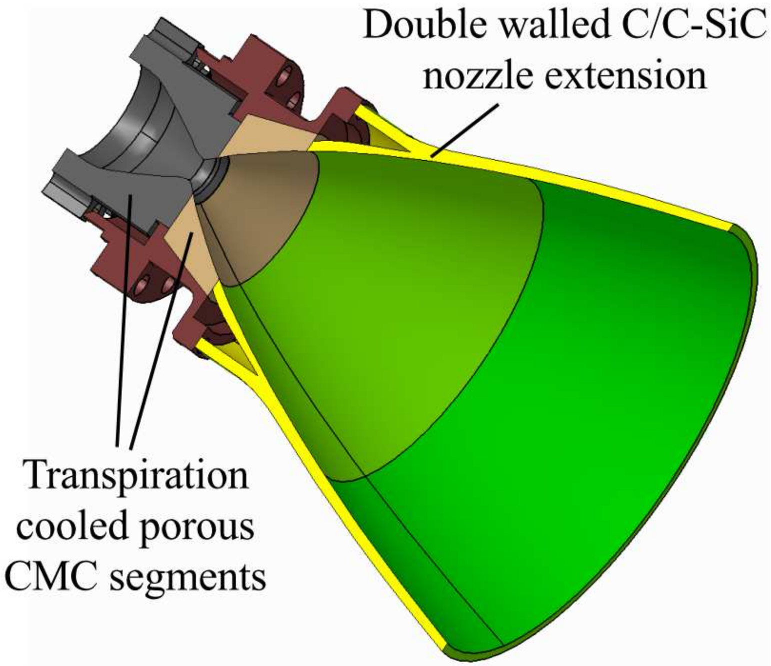


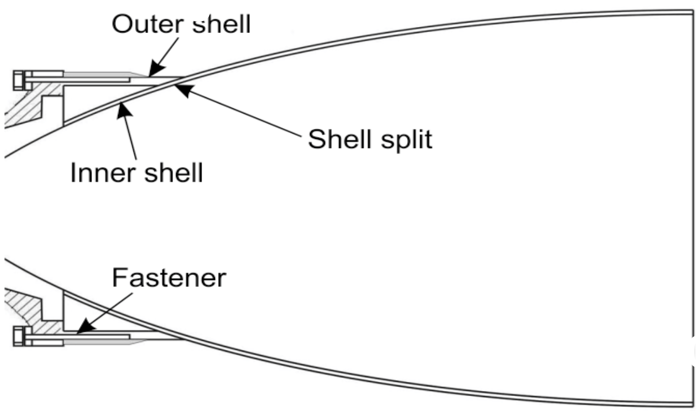


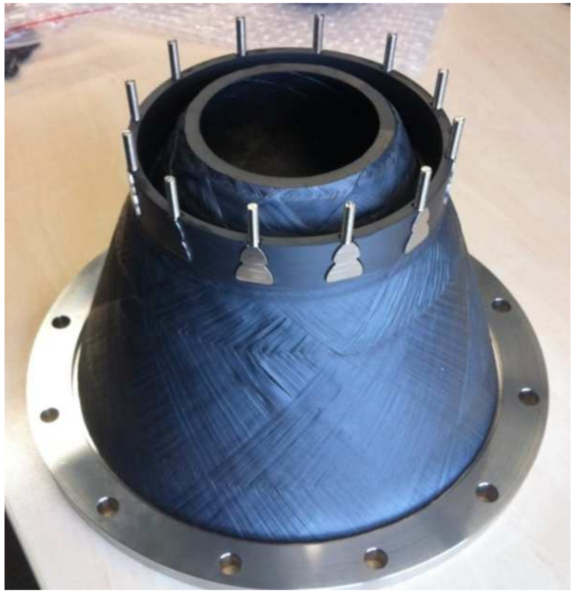


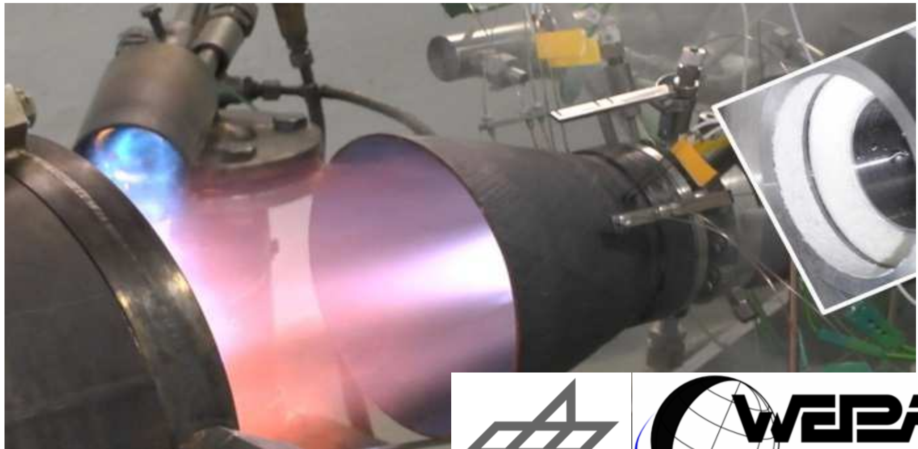
4 Development of LPRE – CMC Nozzle extension

- Non-cooled CMC nozzle extension bolted onto thrust chamber
- Double shell design choosen (thermal and mechanical load decoupling)









DLR

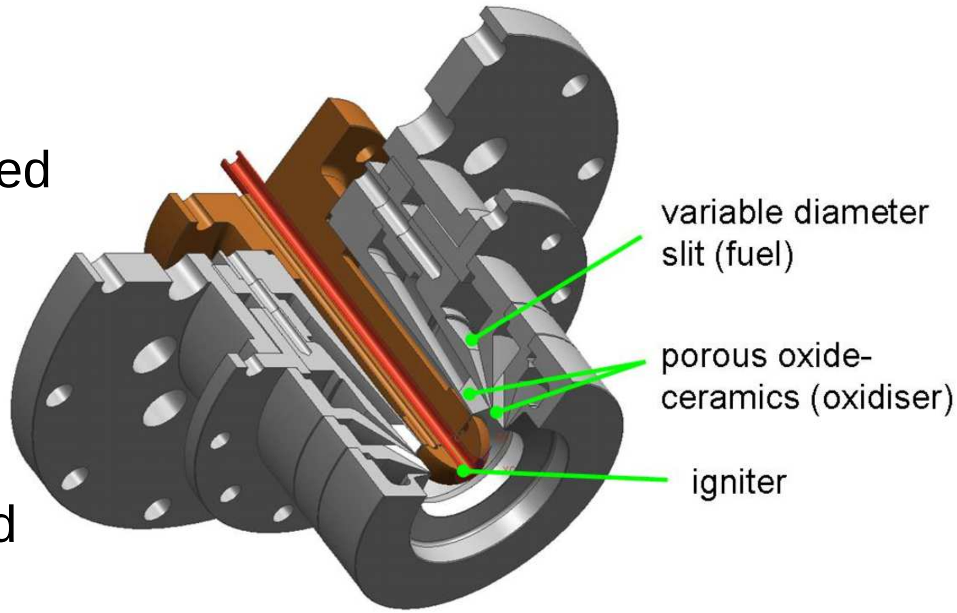
WEPA Technologies

4 Development of LPRE – CMC injector

- Innovative injector design promising stable operation (cryogenic and staged combustion conditions)
  - Hollow conical CMC segments stacked together ontop / separation by conical segment holders
  - Alternating gaps fed with different propellants to assure efficient mixing
  - Simple implementation of channel geometries and advanced injection patterns / reduced manufacturing effort vs. traditional systems

- Deep throttling capability feasable
  - Distance between segments could be adjusted
  - Partial feed of limited number of segments

- Very fine atomization of propellants
  - Stabilization of combustion process expected
  - High combustion efficiency



DLR

WEPA Technologies

4 Development of LPRE – system analysis - 1 -

- Overall system performance estimation
  - losses due to transpiration cooling
- Analysis / scaling based on demonstration runs using 50 mm chamber
  - LOX / LH_2
  - contraction ratio 6.25
  - l* = 1.84m
  - 7% coolant ratio => damage free operation
  - Porous injector (API)
  - C/C liner
- Amount of coolant required depends on
  - Thermochemical resistance of ceramic liner
  - Hotgas conditions
  - Contraction ratio and chamber length

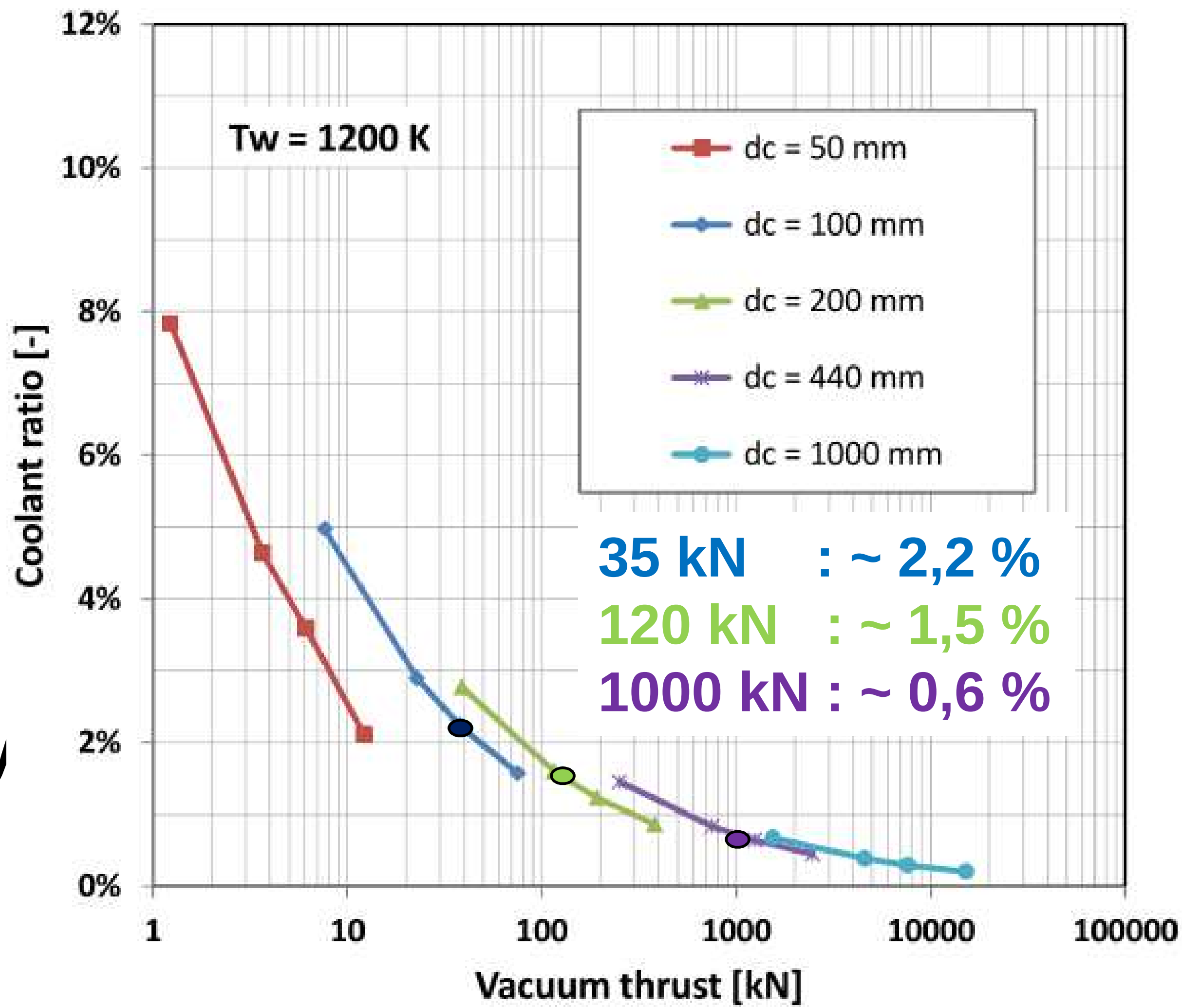
-> 7 % coolant ratio could not be decreased (50 mm TC)

- Liner system was very sensitive towards thermo-chemical degradation !
- Advanced ceramic materials accept higher operating temperatures / lower coolant ratio

-> Larger diameter engines / higher pressure operation = reduction of coolant ratio !

-> High operational efficiency predicted !

Estimation of coolant mass flow rate



Turbo Pump Units

5 Development of Turbo Pump Units – overview

- General philosophy: provide pumps meeting majority of customer requirements

- Common propellant combinations used
  - LOX / LCH_4 (preferred system for reusable LPRE)
  - LOX / Kerosene (traditional combination; also SMILE-project / H2020)
  - LOX / Ethanol (no environmental constrains)

  - H_2O_2 (hybrid propulsion; also SMILE-project / H2020)
  - H_2O_2 / Kerosene (all-storable-propellants)

- TPU under development for multiple propellants
  - Oxidizers: LOX, H_2O_2
  - Fuels: Kerosene, Methane (LCH_4), Ethanol (Alcohol)
  - Focus on open gas generator cycle (staged combustion cycle under consideration)

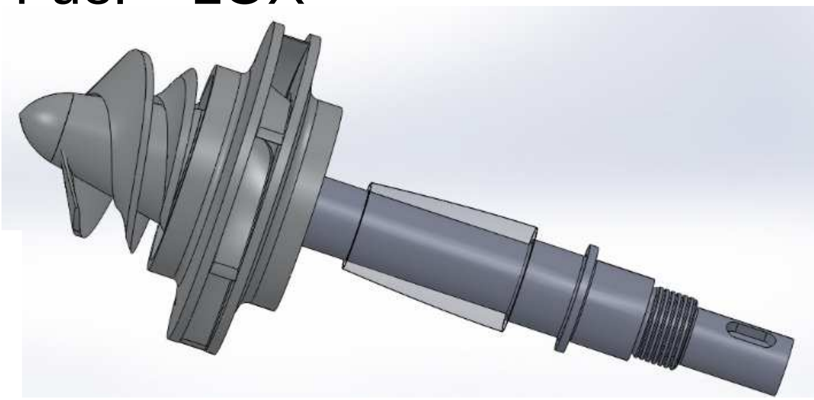
- Expendable and re-usable systems under development

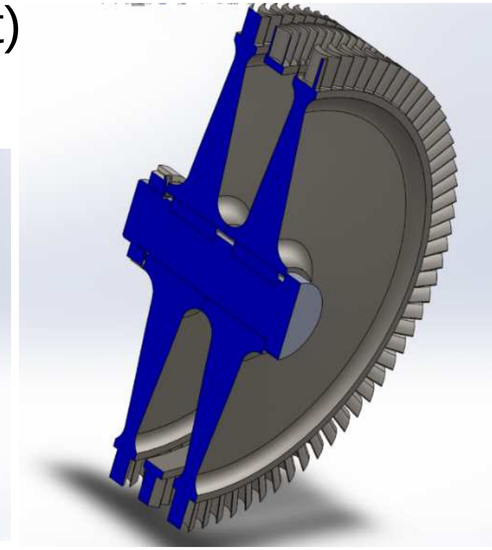
TECHNISCHE UNIVERSITÄT DRESDEN

WEPA Technologies

5 Development of Turbo Pump Units
Technology demonstrator (LOX / LCH_4)

- LOX / LCH_4-TPU to feed 35 kN reusable engine demonstrator (DLR / WEPA)
- Rationale: minimize engineering, testing and manufacturing effort by low level operational parameter
  - Exit pressure: max. 100 bar
  - Operating points: max. 30,000 RPM
  - Open gas generator cycle (LOX / LCH_4)
- Mass flow rate: ~ 12 kg/s LOX / LCH_4 (35 kN engine)
- Weight: max. 30 kg (incl. gas generator + control unit)
- Arrangement: Turbine – Fuel – LOX





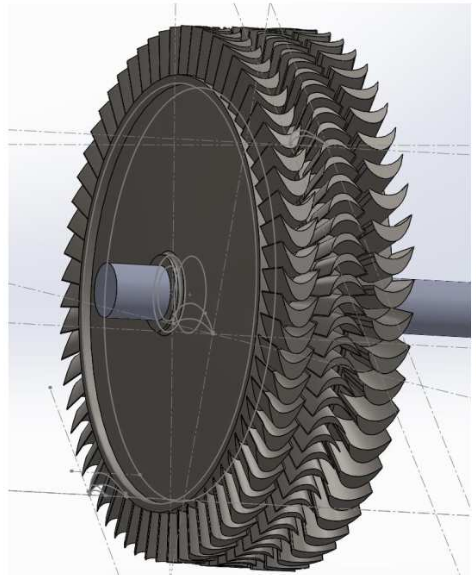
credit:
H. Zetschke (2014)
H. Wiessner (2016)

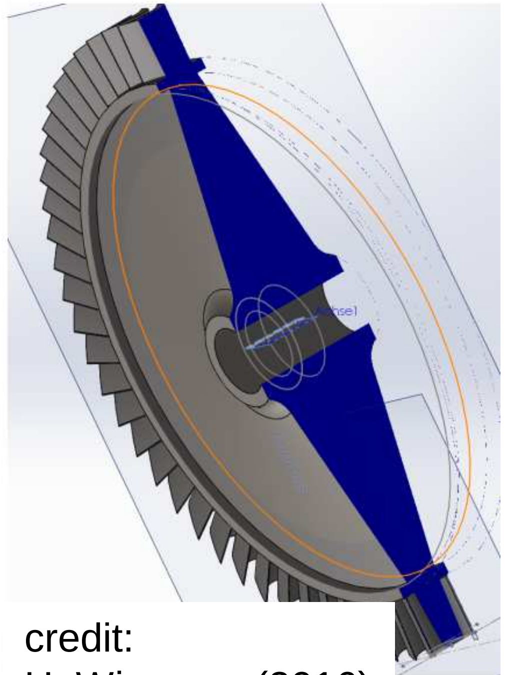
5 Development of Turbo Pump Units

Technology demonstrator (LOX / LCH_4)

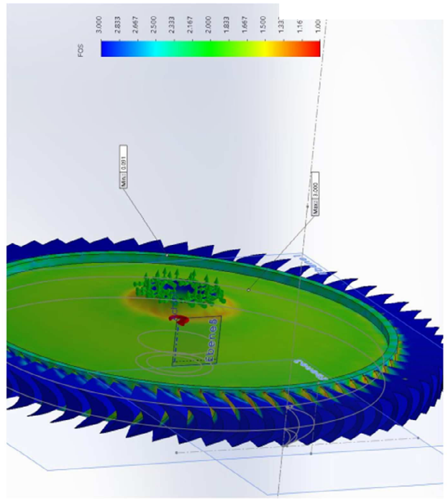
- Turbine
  - single or double axial stage, impulse type
  - partial admission of drive gas
  - inlet temperature: < 850 K
- Pump
  - single or double radial stage
- Seals (impeller / shaft) : dynamic type
- Optimization of geometries (inducer, impeller, volute, turbine): collaboration with TU Kaiserslautern; TU Dresden
- Bearings
  - ceramic material based
    - ball bearings
    - journal type – transpiration lubrication

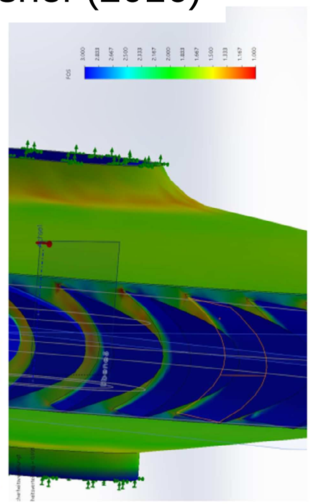
    (collaboration with DLR and TU Kaiserslautern)





credit:
H. Wiessner (2016)





TECHNISCHE UNIVERSITÄT DRESDEN

WEPA Technologies

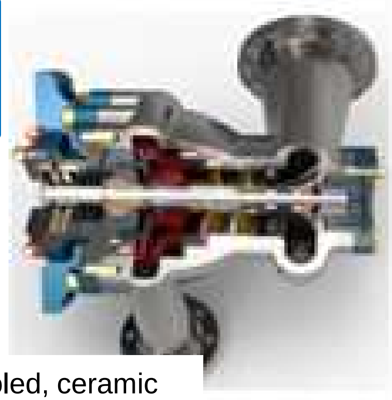
5 Development of Turbo Pump Units
Development of re-usable systems

- Re-usable propulsion systems also require re-usable feed devices !
  - Development of demonstrator unit feeding 35 kN LOX / LCH_4 LPRE
- Focus on innovation in bearing technology !
- Well proven technology: ball bearings
  - f. ex. metal / ceramic hydrid bearings (Si_3N_4) => used in SSME TPU !
  - No ‚commercial of the shelf' availability (COTS) – custom manufacturing is necessary
  - Speed limitations (2,0 Mio DN x n)
- Hydrodynamic / hydrostatic journal bearings in principle should outperform ball bearings (speed; lifetime)
  - very low viscosity of storable and cryogenic propellants presents significant challenges

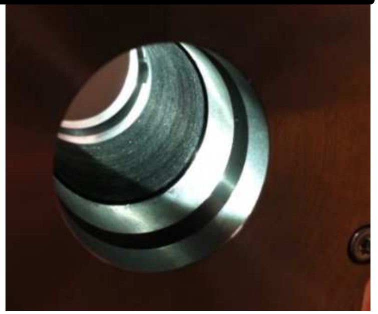
5 Development of Turbo Pump Units
Development of re-usable systems

- Collaboration of WEPA, DLR, University of Technology Kaiserslautern
  - Development, Integration and experimental qualification of journal bearings in turbo pumps
- Approach: Ceramic matrix composites to be used as journal bearing
  - Radial and axial porous liquid bearing design (C/C; C/SiC(N) material)
  - Very homogeneous supply of LOX / LCH_4 („lubricant“) due to porous structure
  - Expected to be very advantageous resp. load capacity and allowable max. speed
  - High margin towards wear during dry runs (start-up transients)
  - Pretesting of gas-lubricated bearings at Kaiserslautern University of Technology very promising

Mechanical Design WEPA-LOX-TPU (Application: 35kN LOX / LCH_4-LPRE)



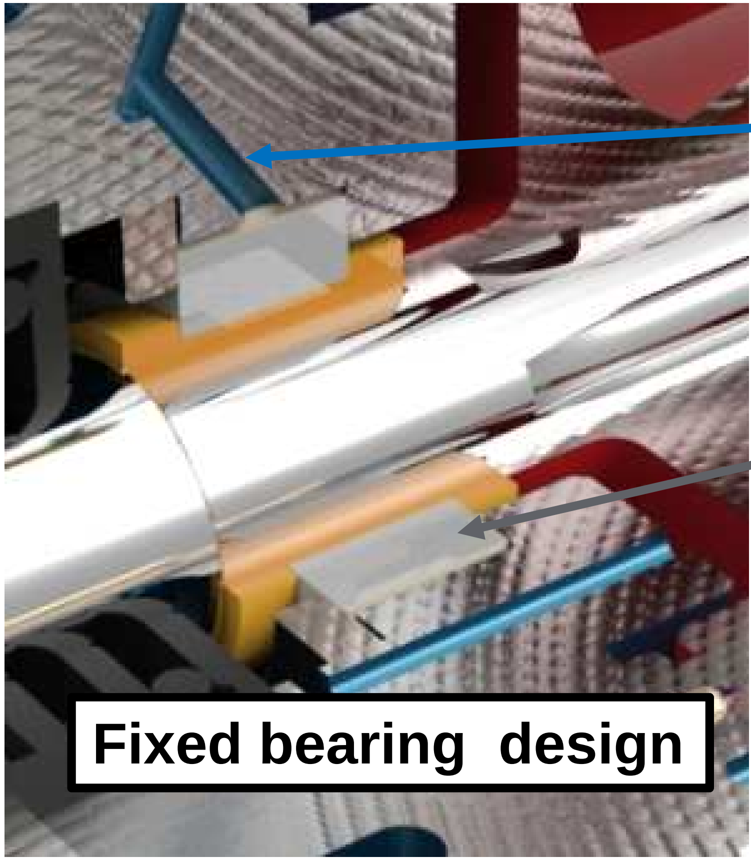
Test bearing of Kaiserslautern University of Technology

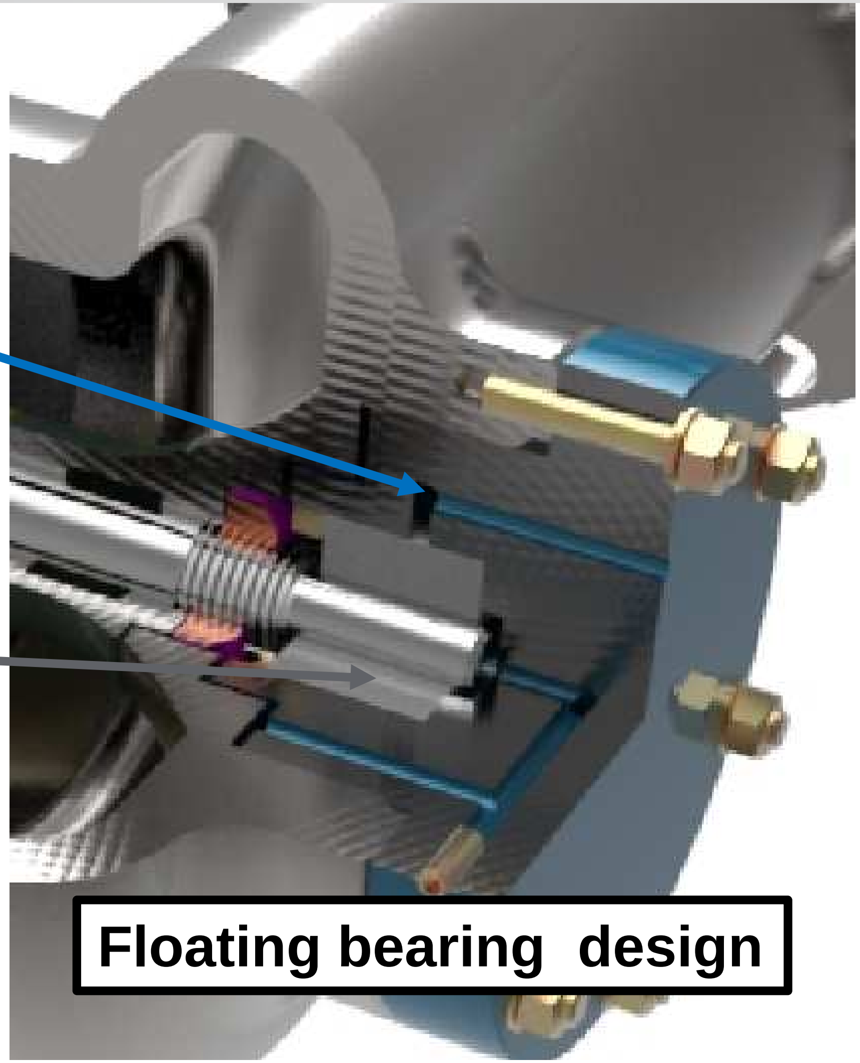


5 Development of Turbo Pump Units

Development of re-usable systems

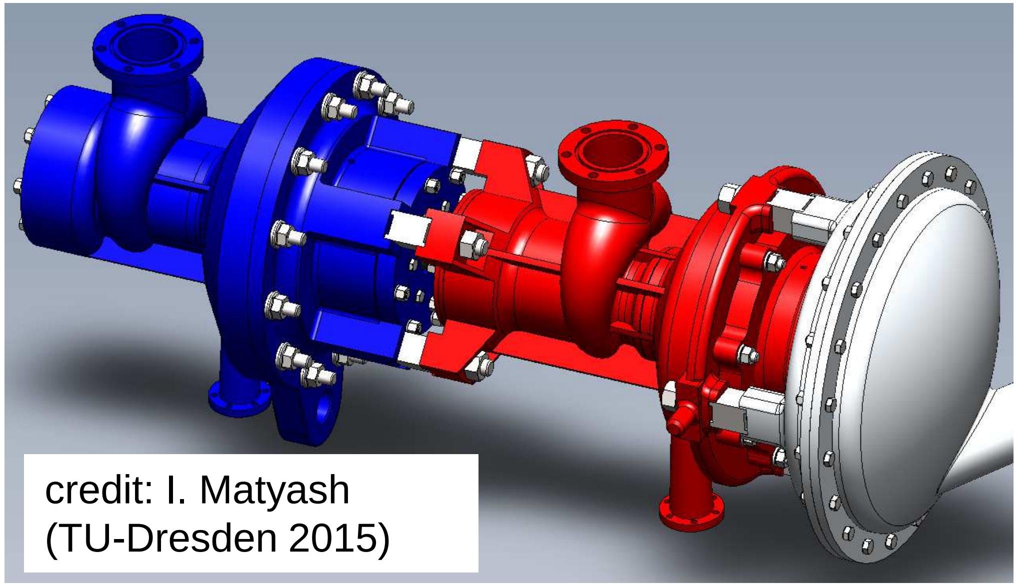
Mechanical Design WEPA-LOX-TPU
(Application: 35kN LOX / LCH_4-LPRE)

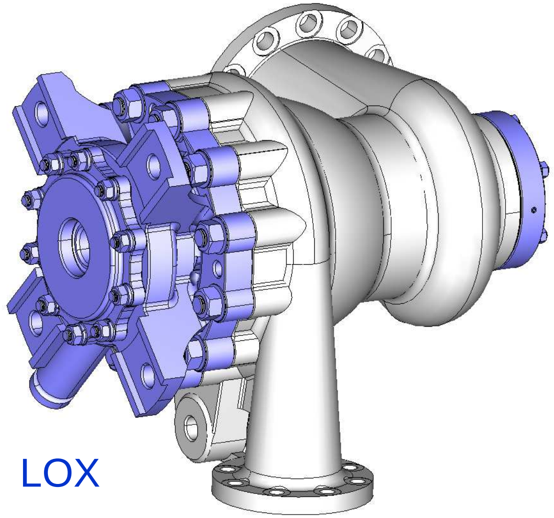


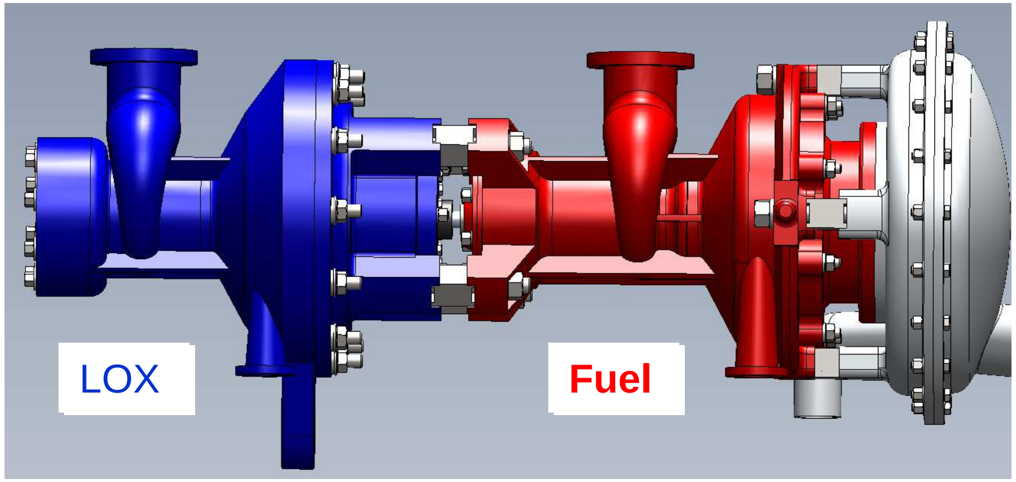


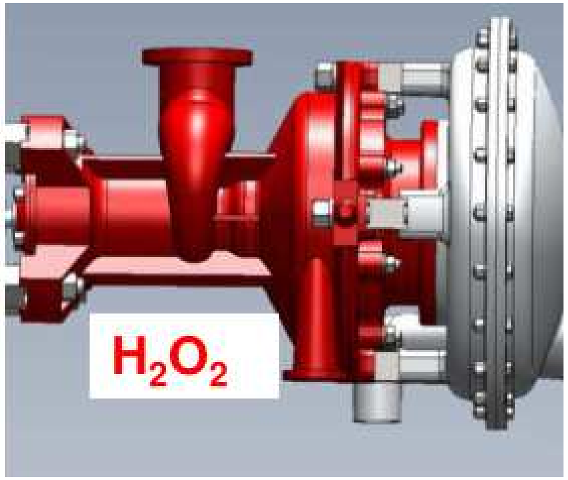
- Collaboration of WEPA. DLR. Kaiserslautern University of Technology

5 Development of Turbo Pump Units – overview









Examples of TPU design: bipropellant and hybrid engine applications
(H2020 / SMILE- project in progress (**S**mall **I**nnovative **L**auncher for **E**urope)

TECHNISCHE UNIVERSITÄT DRESDEN

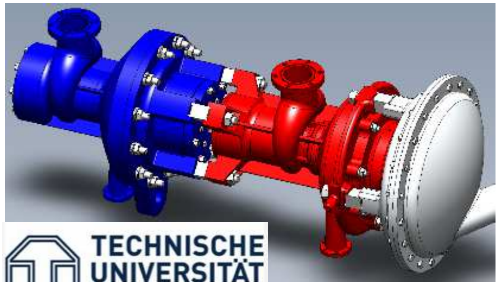
WEPA Technologies

Summary

6. Summary: development activities at WEPA-Technologies

- Development of Re-usable LPRE (Technology demonstrator: LOX / LCH_4)
  - 35 kN technology demonstrator motor under development by WEPA and DLR
  - Technological base: CMC material research and testing conducted since mid 1990's by DLR
  - Transpiration cooled CMC thrust chamber design: very promising base (multiple demonstration already achieved)
  - All required components generally qualified by trials using LOX / LH_2 propellant: adaptation and scale-up required
  - Alternative propellants under consideration

    LOX + Ethanol, LOX + Kerosene; H_2O_2 + Kerosene



TECHNISCHE UNIVERSITÄT DRESDEN

- Development of Re-usable turbo pumps (LOX / LCH_4)
  - Focus on CMC bearing technology under development by WEPA,

    DLR and TU-Kaiserslautern
  - CMC materials expected to be very advantageous resp. load capacity and

    max. speed
  - Pretesting with gas lubrication very promising

DLR

WEPA Technologies

Thank you for your attention !

peter.weuta@wepa-technologies.de
markus.ortelt@dlr.de

Back up

WEPA Technologies

H_2O_2-Concentration Technology

7 Supply of H_2O_2 (88 - 98 %): Motivation

- Advantages of H_2O_2-based propulsion systems
  - Storability / no evaporative losses during pre-operation time
  - Simplified, non cryogenic feed system (turbo pump and pressure feeding)
  - No chill down of system prior to ignition required
  - Reliable, “hypergolic” ignition process (catalytic decomposition)
  - Multiple burns possible
  - No safety / toxicity issues compared to N_2O_4 / UDMH
  - Reduced system complexity => increased operational reliability !

- Use in many different propulsion systems possible
  - launchers, upper stages, sounding rockets, space planes, RCS

- Very high strength H_2O_2 required for high performance systems
  - H_2O_2 (95 %) / Kerosene does show comparable overall system performance with respect to LOX / Kerosene (=> higher density impulse of H_2O_2 system)

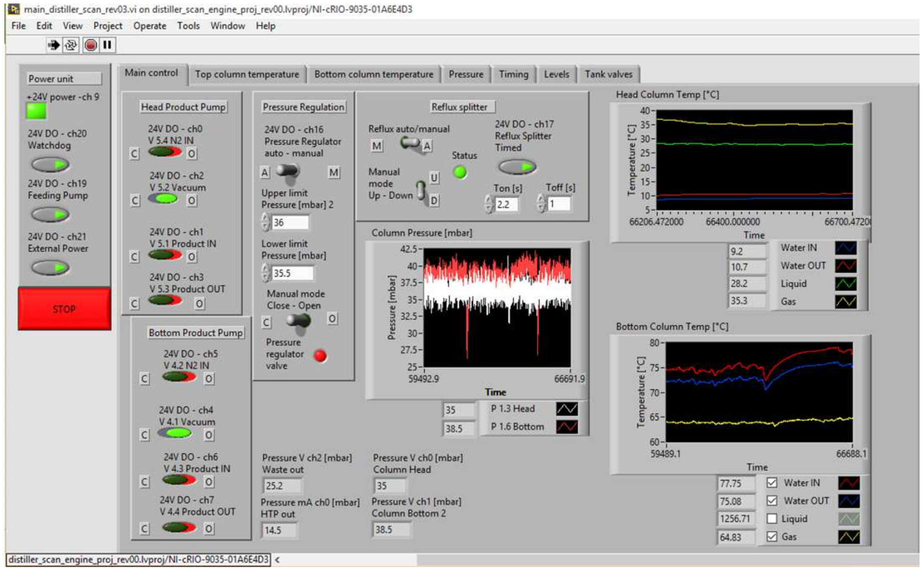
- Limited commercial availability / high costs, even though one large company entered pilot production of 98 % - grade in late 2015

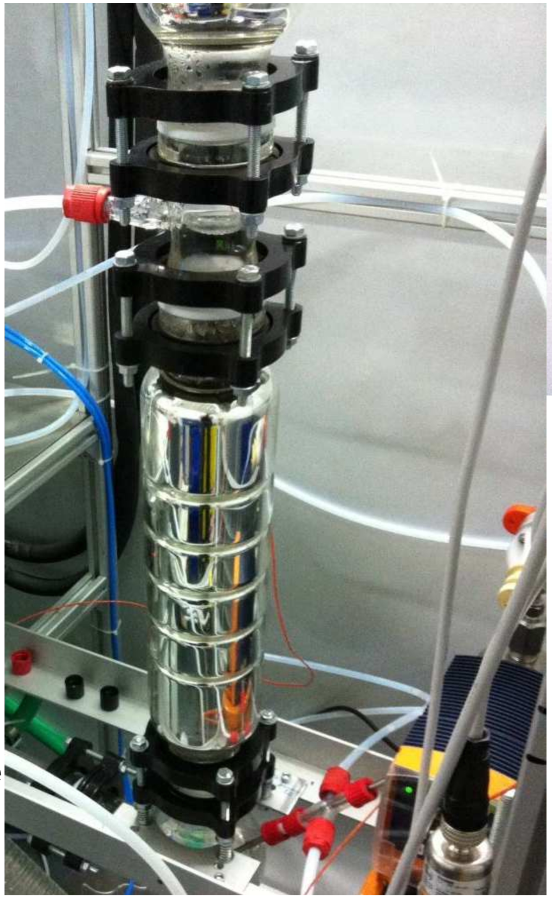
7 Supply of H_2O_2 (88 - 98 %)

- **H_2O_2 concentration plant developed by WEPA-Technologies (EU-customer / 2015)**
  - **Capacity: up to ~ 50 kg / d (91 %)**
  - **Feed: 50 % - 70 % H_2O_2**
  - **Fully automatic, 24 / 7 operability implementable**
  - **Working packages supplied by WEPA-Technologies**
    - **Conceptional process design incl. safety concept**
    - **Detail engineering (process-, control- and electrical diagrams)**
    - **Equipment purchase**
    - **Erection and commissioning**
    - **Trouble shooting**

- **Very safe production process up to 98 % concentration available (~ 50 kg / day)**
  - **Scale-up to 1500 kg H_2O_2 / day possible (set-up in 20 – 40 ft container)**

7 Supply of H_2O_2 (91 %) : Plant





=> general commercialisation of H_2O_2 concentration (88 – 98 %)

=> customer requests welcome !

Control by PLC:
LabVIEW RT
(alternative: TWINCAT)

Development history of CMC material @ DLR

4.4 Development of Liquid Propellant Engines

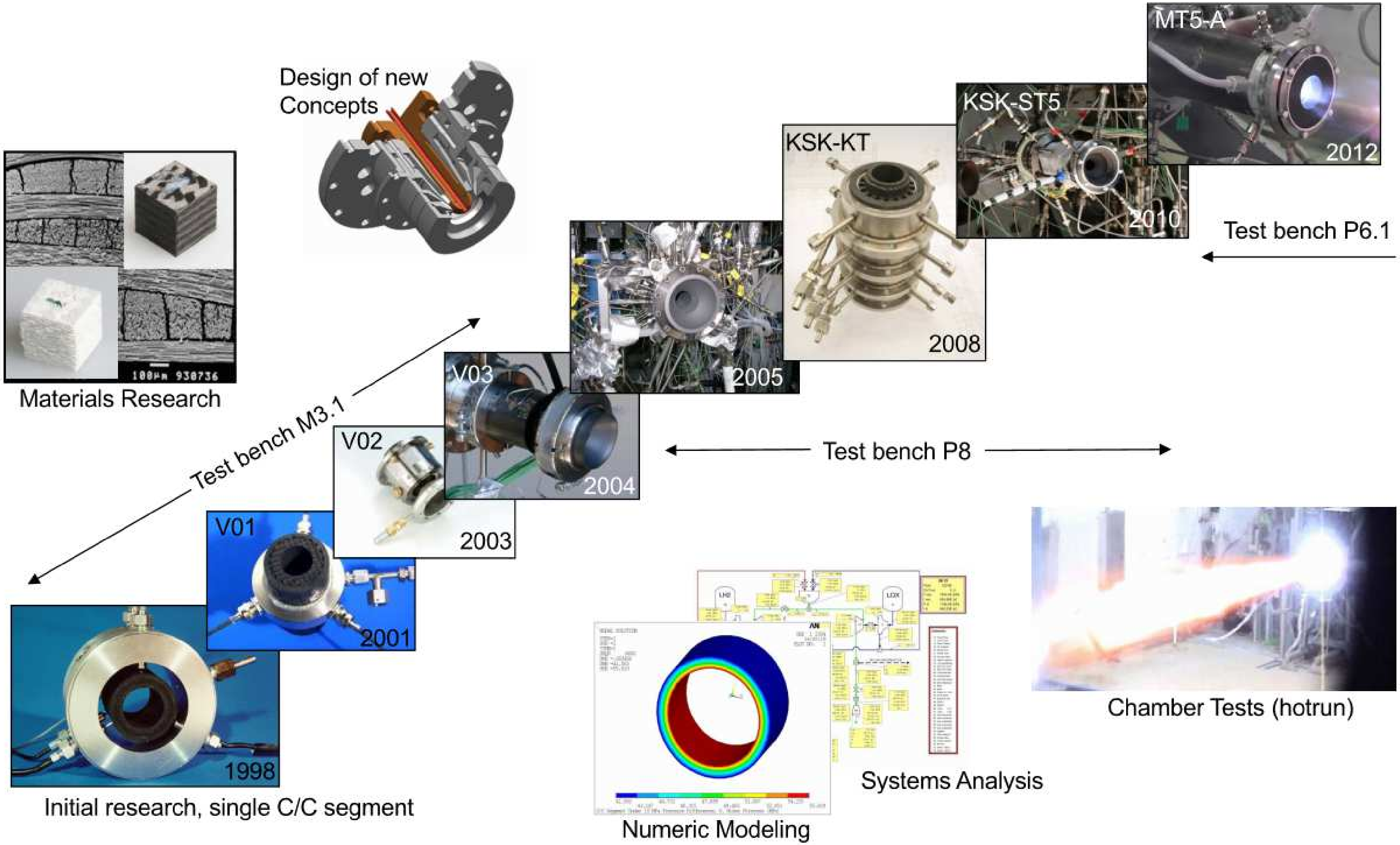


Figure 1: Development history of the ceramic combustion chamber at the DLR.

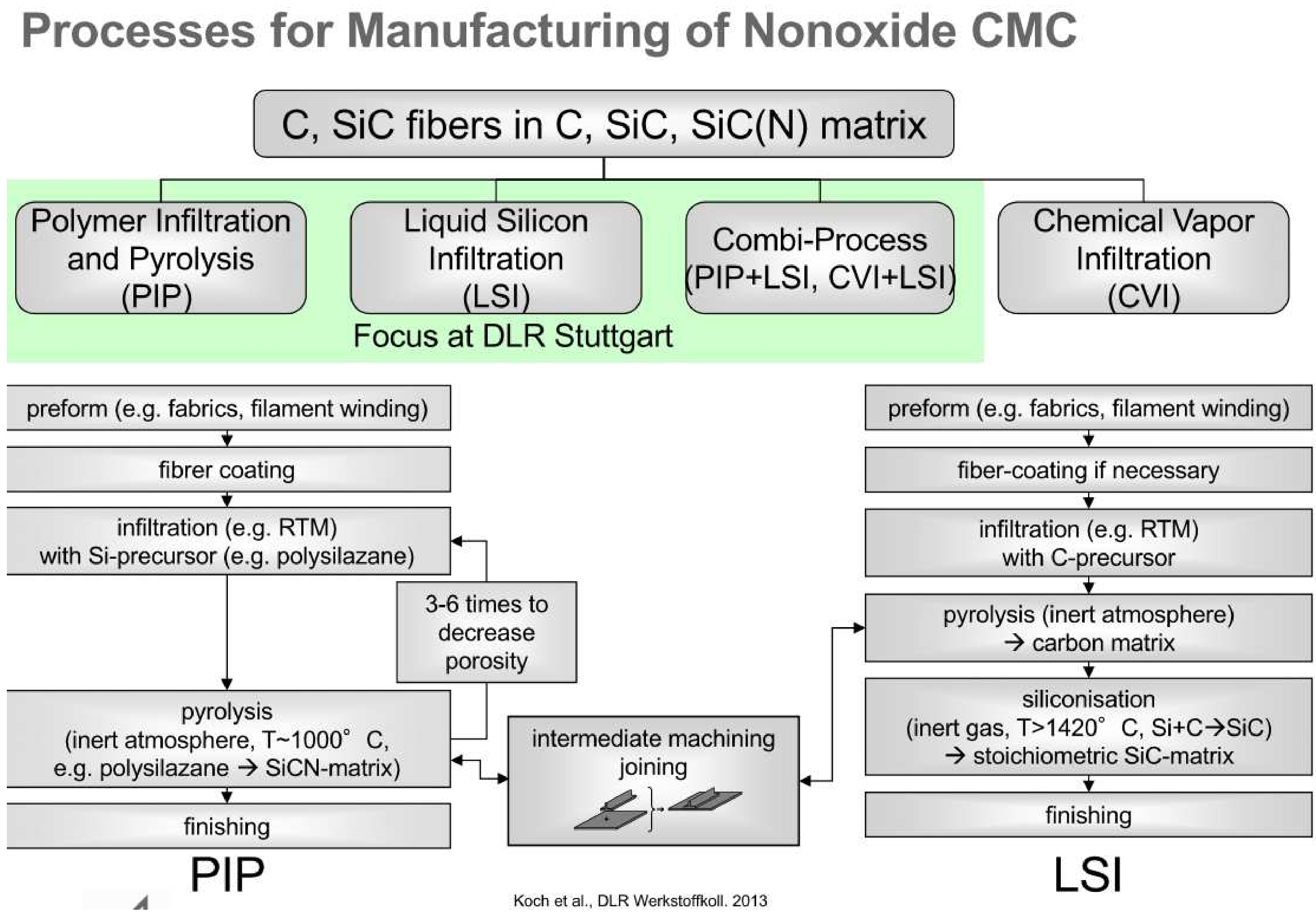
credit: DLR (M. Ortelt)

5. Effusion cooled CMC rocket thrust chamber.
56th International Astronautical Congress, Fukuoka, Japan.

WEPA Technologies

Production of CMC material

4.4 Development of Liquid Propellant Engines



Development of reusable, liquid propulsion units based on transpiration cooled, ceramic thrust chambers and turbo pumps for launch and in space applications

Dr.-Ing. P. Weuta, Dipl.-Ing. M. Ortelt, Dipl.-Ing. Th. Hofmann

15th Re-Inventing Space Conference / Glasgow, 10/2017

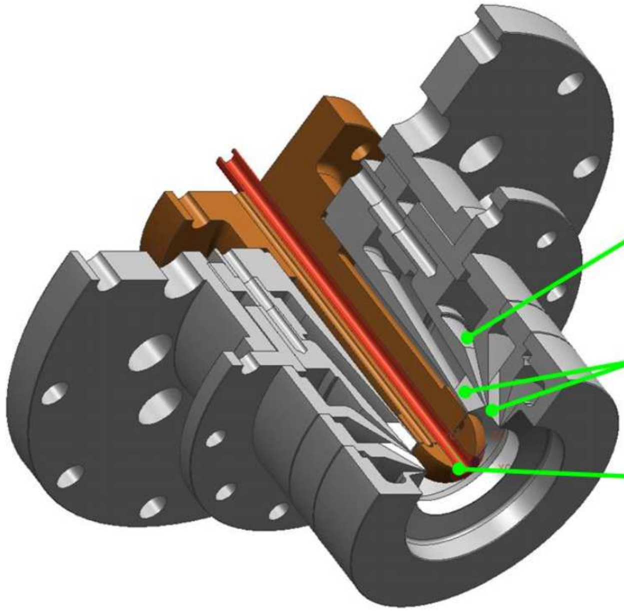
credit: DLR (M. Ortelt)

5. Effusion cooled CMC rocket thrust chamber. 56th International Astronautical Congress, Fukuoka, Japan.

CMC cone injector

3 Development of LPRE – CMC injector - 1 -

- Innovative injector design promising stable operation (cryogenic and staged combustion conditions)
  - Hollow conical CMC segments stacked together ontop / separation by conical segment holders
  - Alternating gaps fed with different propellants to assure efficient mixing
  - Simple implementation of channel geometries and advanced injection patterns / reduced manufacturing effort compared to traditional systems

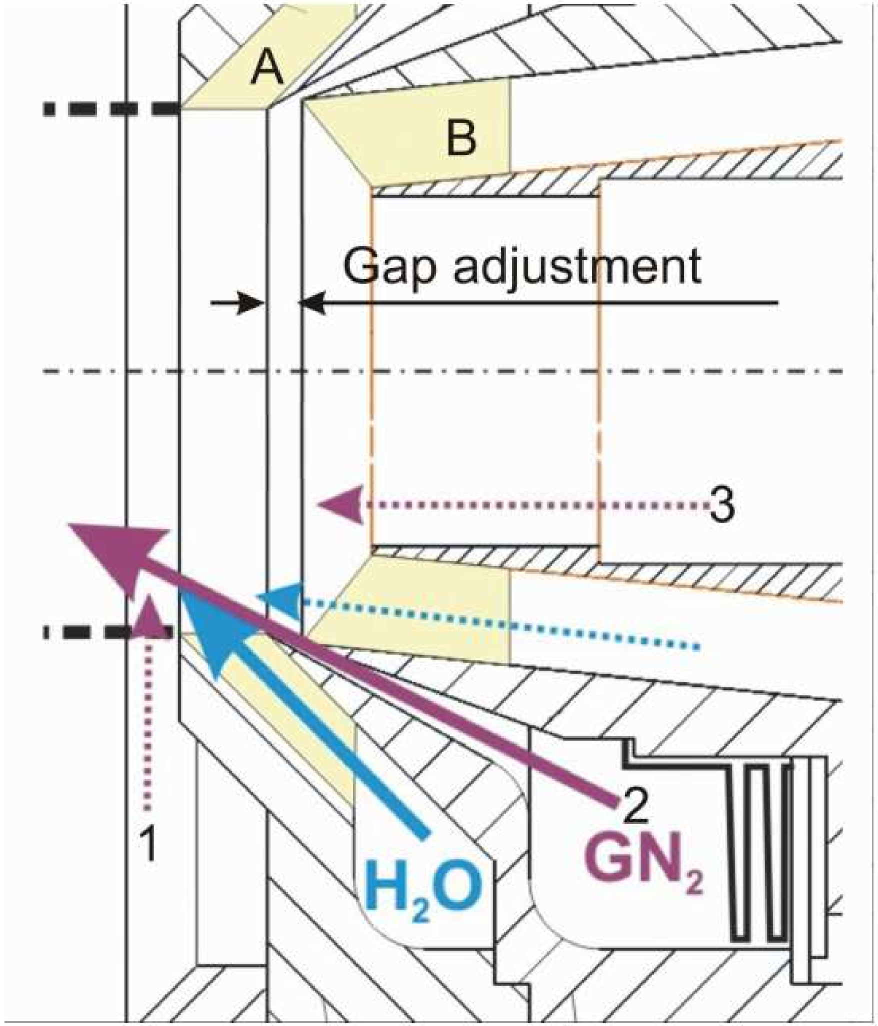


credit: DLR (M.

3 Development of LPRE – CMC injector - 2 -

- Deep throttling capability feasable
  - Distance between segments can be adjusted
  - Partial feed of limited number of segments
- Very fine atomization of propellants
  - stabilization of combustion process expected
  - High combustion efficiency expected

GN_2 / H_2O pretest



credit: DLR (M.

. Effusion cooled CMC rocket thrus
›nal Astronautical Congress, Fukuc