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Black Engine CMC Space Propulsion Technology

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DLR

Black Engine CMC Space Propulsion Technology
Outline

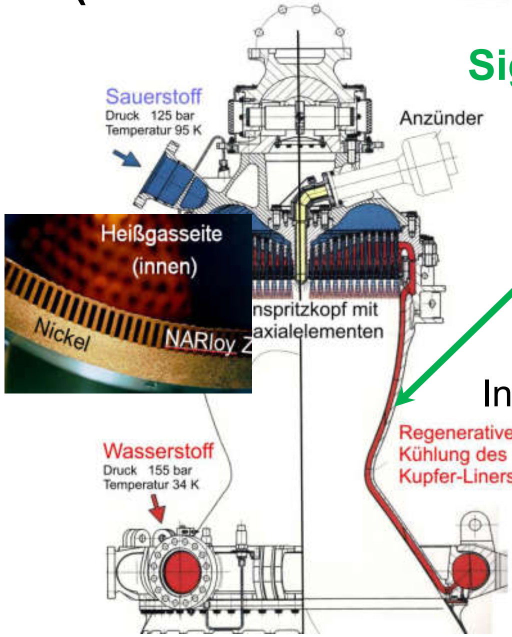
1. **Motivation, history and perspectives of ceramic rocket thrust chamber development at DLR**
2. **Conceptional apsects of the future competitive transpiration cooled CMC TCA**
    1. Design
    2. Materials
    3. Experimental investigations
3. **Further innovative technology approaches**
4. **Outlook & summary**

Transpiration Cooled CMC Rocket Thrust Chambers

1. Motivation / History / Perspectives

Europe's Existing High Performance Liquid Rocket Engines

1.1 Historically driven developments (metallic thrust chambers)



Significantly fatigue sensitive electroplating combustion chamber design

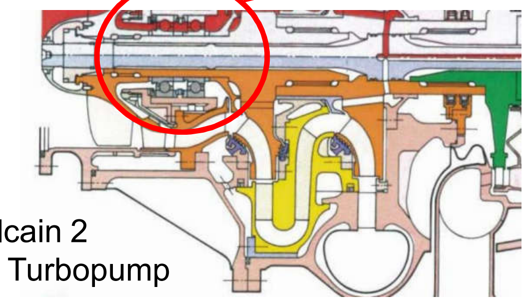
Narloy-Z Inner Liner

Nickel-Galvanic Housing

Vulcain 2 Main Stage Engine of Ariane 5

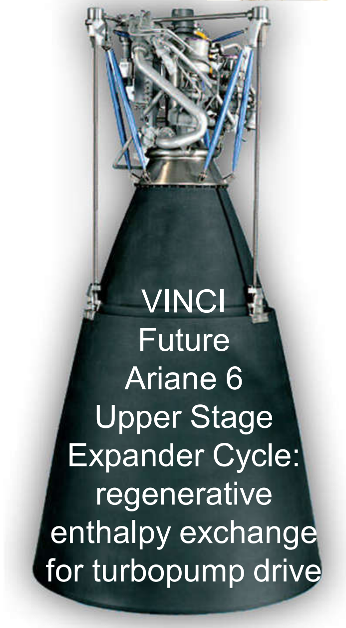
Ariane 5 Vulcain 2 Main Engine

Gas generator cycle
→ classical
Rocket Turbopump
Propellant feed system
(use of ball bearings)



Vulcain 2
H2 Turbopump

Highly sophisticated ball bearings in TPs



Ariane 5
HM7B
Upper Stage
Engine

Planned ‚Ariane 7'

Prometé Engine

1. Motivation / History / Perspectives

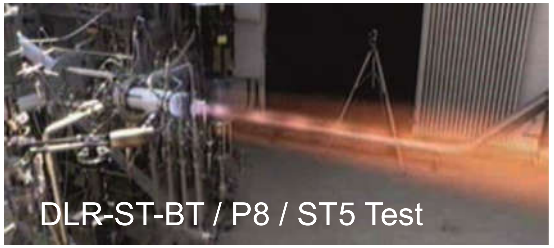
Innovative Approach for Transpiration Cooled CMC Rocket Thrust Chamber

1.2 Motivation / Perspectives

- The innovation for high performance rocket thrust chambers by the use of modern high temperature resistant Ceramic Matrix Composites (CMC), targets the …

    - Increase of
        - Efficiency
        - Lifetime
        - Reliability

    Reduction of
    - Cost
    - Weight



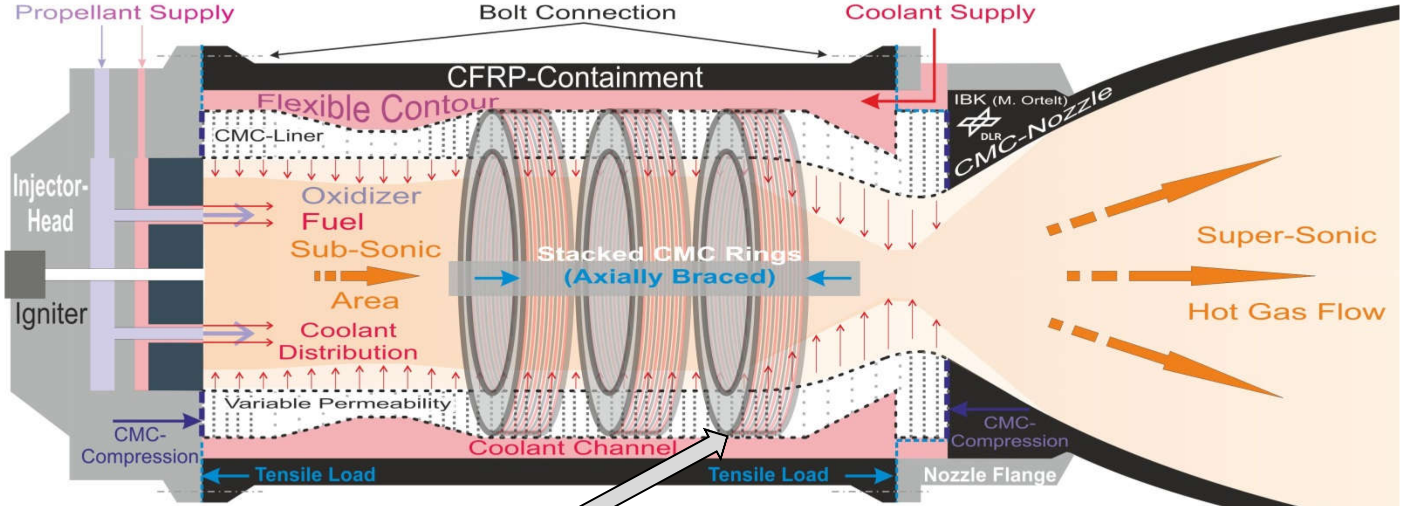
… considering additionally hybrid composite/metal (AM) structure design

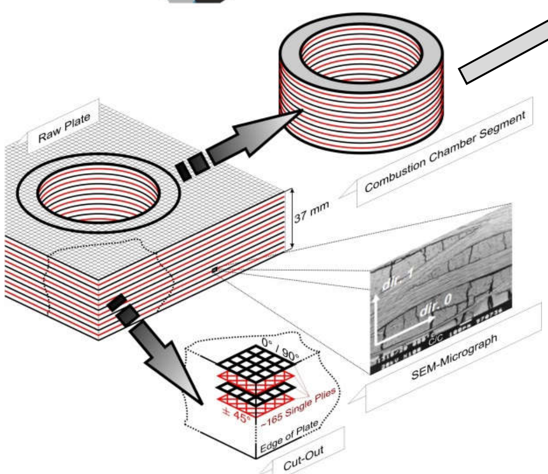
- Readiness for changing New Space activities by the development of future competitive technologies, e.g.
    - CMC thrust chamber components, like Combustion Chamber, Injector & Nozzle Extensions
    - Long-life transpiration lubricated CMC journal bearings for rocket turbo pumps
- Competitiveness is even expected compared to modern metallic additive manufactured TCAs (Thrust Chamber Assemblies)

2. Conceptional Aspects of the

Innovative Transpiration Cooled CMC Rocket Thrust Chamber Assembly (TCA)

2.1 Design → 2.1.1 Structure Components





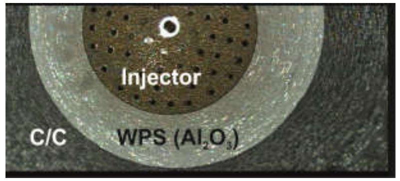
- **De-coupled design principle**
  - no components bonded
  - Easy material combination / variation
  - Easy manufacturing
  - Easy mounting → **Low fatigue!**
- **Light weight CFRP housing**
- **Suitable interface technologies**

Highly reproducible CMC ring segments → extracted from flat plates

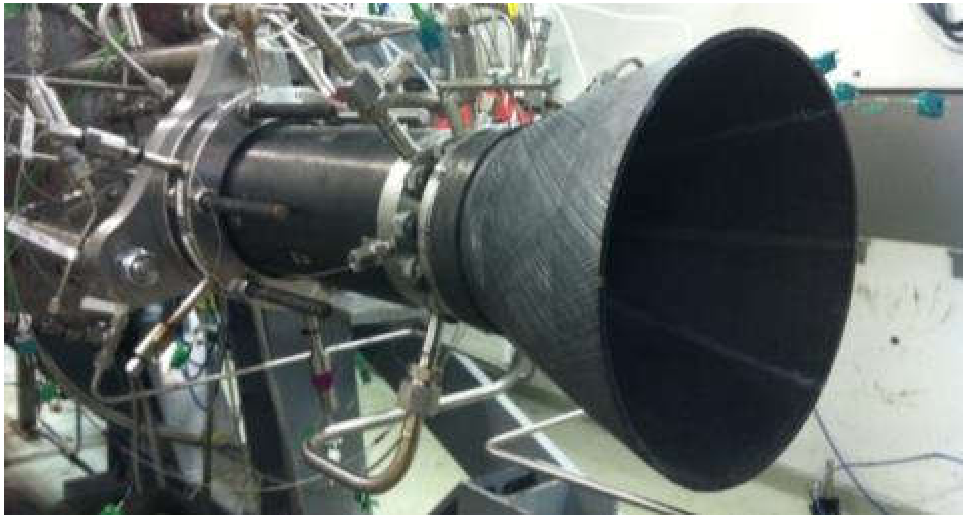
2. Conceptional Aspects of the

Innovative Transpiration Cooled CMC Rocket TCA

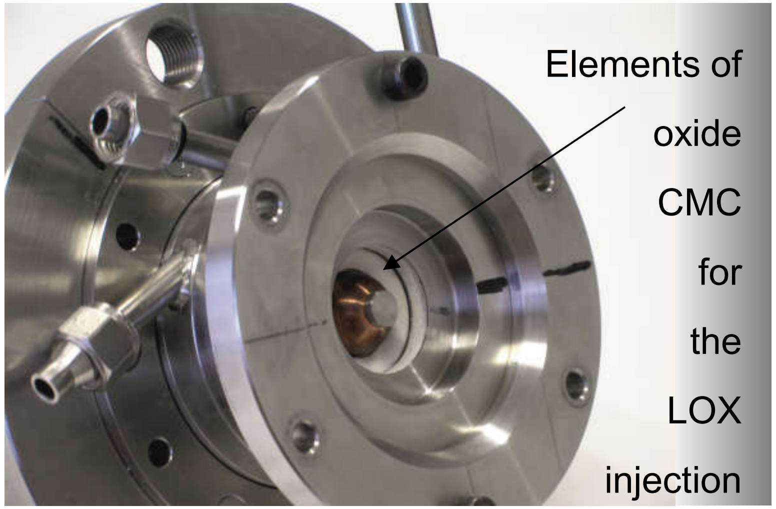
2.1 Design → 2.1.1 Structure Components



Porous metal injector



Integrated ‚BlackEngine' demonstrator, $\varnothing_{cyl.}$ 50 mm



Porous CMC injector

Inner liner segment

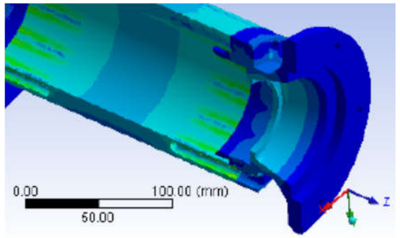
Applied injector systems for $\varnothing_{cyl.}$ 50 mm

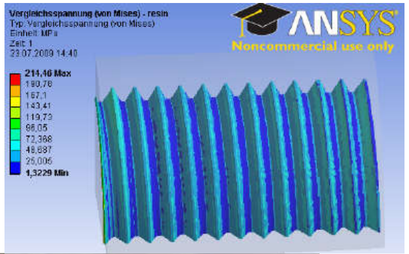
Co-axial injector

2. Conceptional Aspects of the

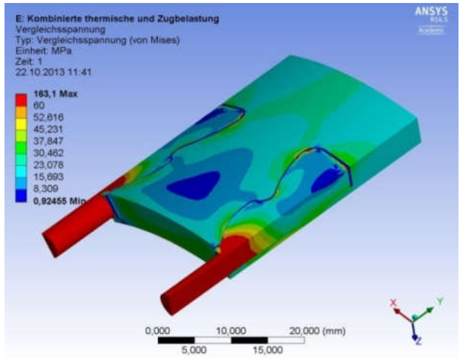
Innovative Transpiration Cooled CMC Rocket TCA

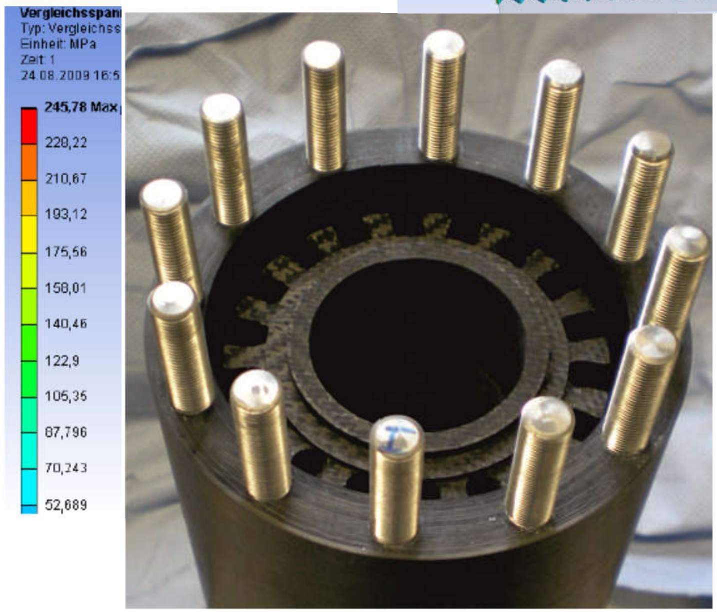
2.1 Design → 2.1.1 Structure Components





Specific Structure and Interface Technologies





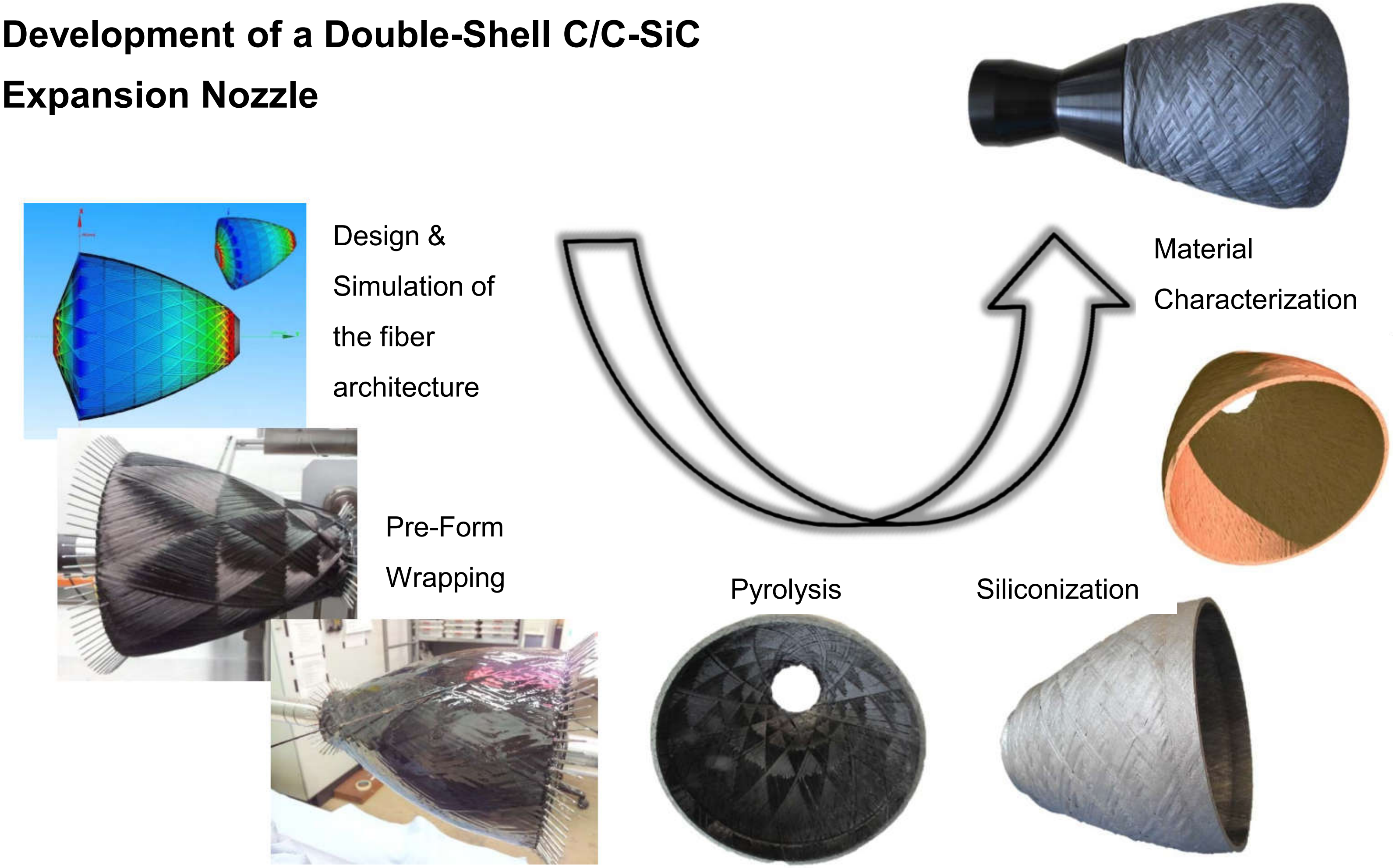
Bolt interface for CFRP-metal joining

Load-de-coupling double-shell nozzle extension with keyed joint elements for CMC-metal joining

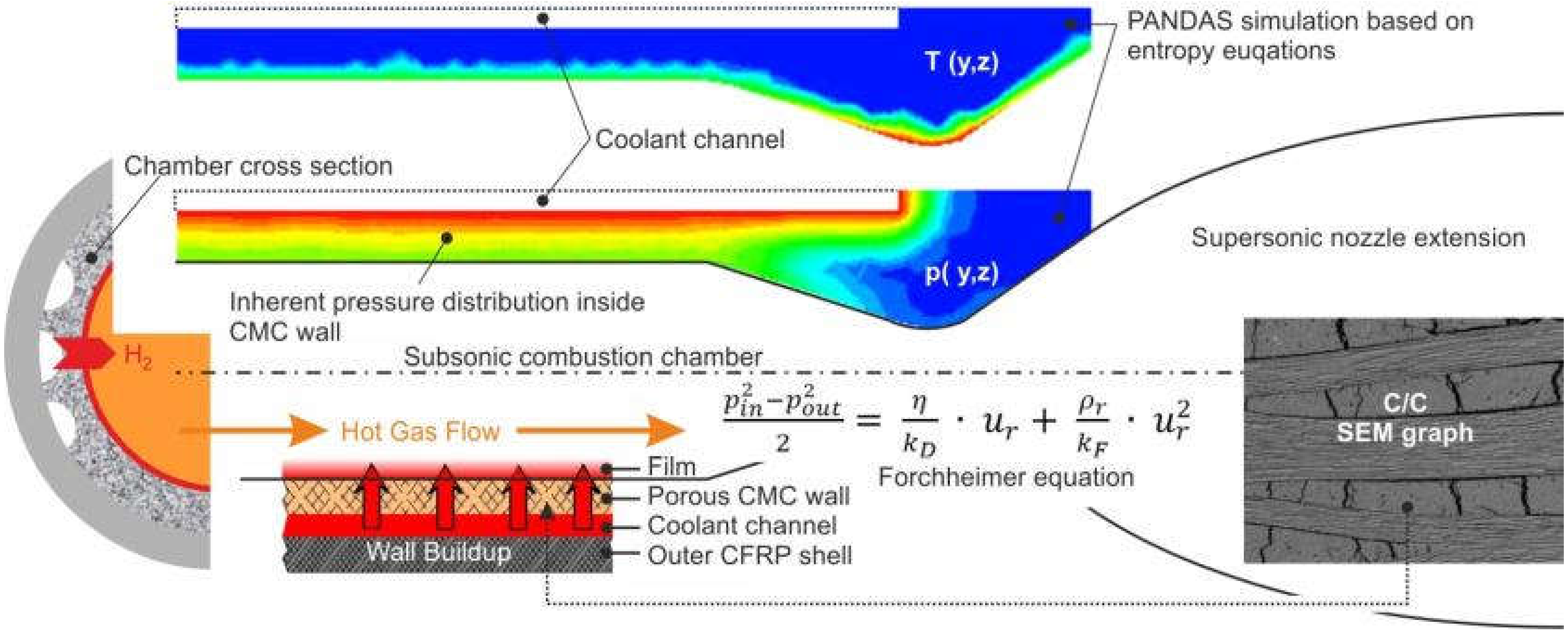
2. Conceptional Aspects of the
Innovative Transpiration Cooled CMC Rocket TCA
2.1 Design → 2.1.1 Structure Components

Development of a Double-Shell C/C-SiC

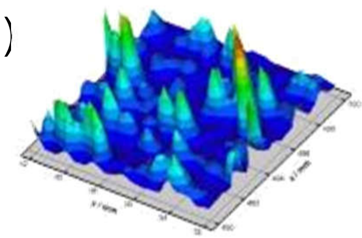
Expansion Nozzle



2. Conceptional Aspects of the
Innovative Transpiration Cooled CMC Rocket Thrust Chamber
2.1 Design → 2.1.2 Transpiration Cooling



- Standard CFD systems (FLUENT, CFX, …) are constructive (pure flow coupling)
- Ongoing tool-development for ‚structure-flow-coupling' (TAU, RCE)
- Investigations on materials out-flow homogeneity →



2. Conceptional Aspects of the

Innovative Transpiration Cooled CMC Rocket Thrust Chamber

2.1 Design → 2.1.3 System Efficiency (Scaling)

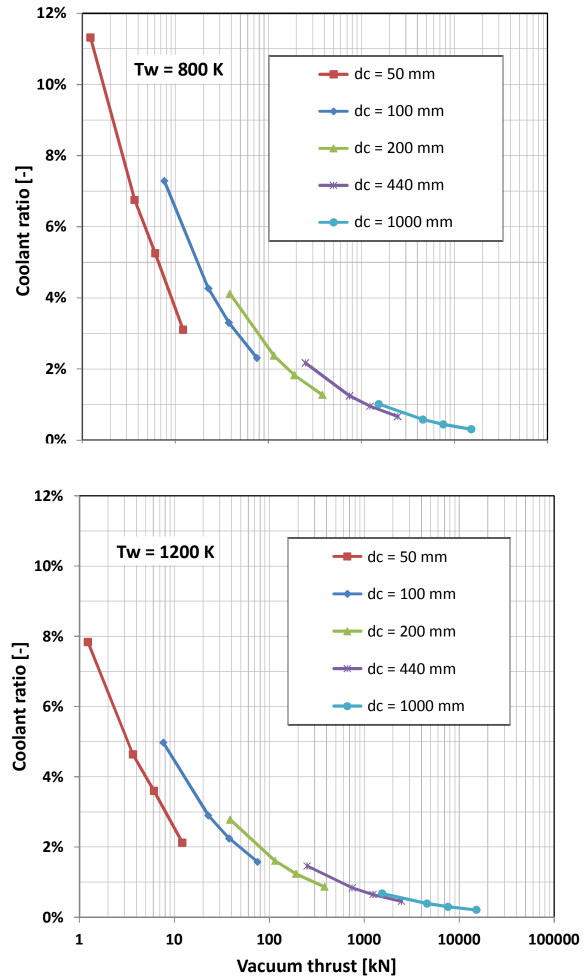
- **Comparison of chamber size (scaling)**
- **50 mm chamber demonstration**

  - O/F = 5.5 (injector)
  - Contraction ratio 6.25
  - Characteristic chamber length l*=1.84 m
  - 7 % coolant ratio
  - Damage free operation

  - Amount of coolant depends on
    - Hotgas conditions, A_S, T
    - D ↗ + p ↗ → required coolant ratio ↘

  - Further coolant ratio reduction potential
  - Chamber length can be shortened

→ **High operational efficiency predicted**



d = 200 mm → Vinci size / d = 440 mm → Vulcain size

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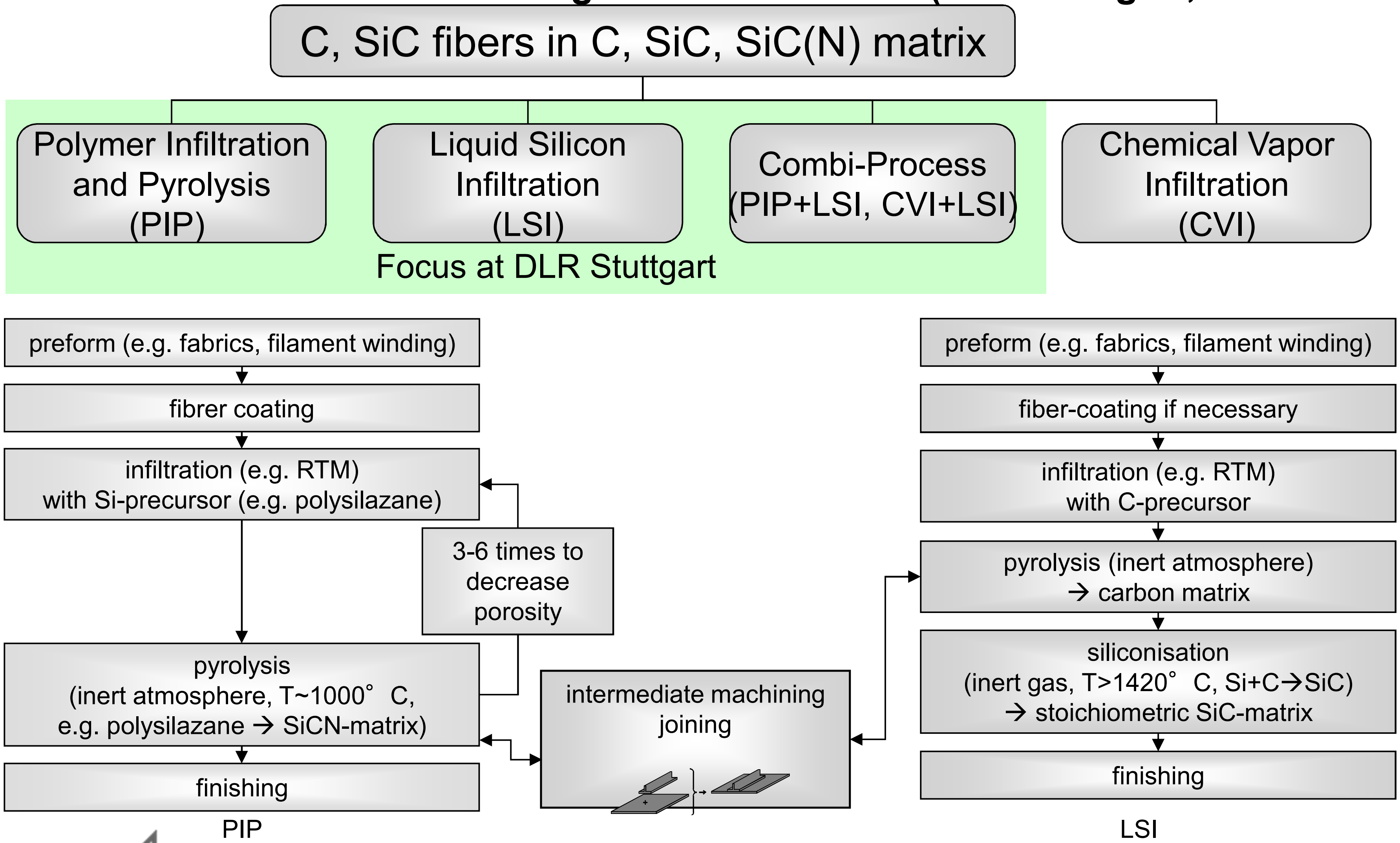
2.2 Potential Materials for the

Innovative Transpiration Cooled CMC Rocket Thrust Chamber

2.2.1 Process for Manufacturing of Nonoxide CMC (DLR Stuttgart, Institute BT)



Koch et al., DLR Werkstoffkoll. 2013

2.2 Potential Materials for the

Innovative Transpiration Cooled CMC Rocket Thrust Chamber

2.2.2 Processing of CMC (DLR ST, BT)

- Autoclave
  30 bar, 350 °C
- Warm Press 350° C
- RTM 300° C
- Pyrolysis, LSI, 2000° C
- Machining Center

2.2 Potential Materials for the

Innovative Transpiration Cooled CMC Rocket Thrust Chamber

2.2.3 Potential CMC Derivatives for CMC Thrust Chamber Application

Initial C/C model material LOX-sensitive!

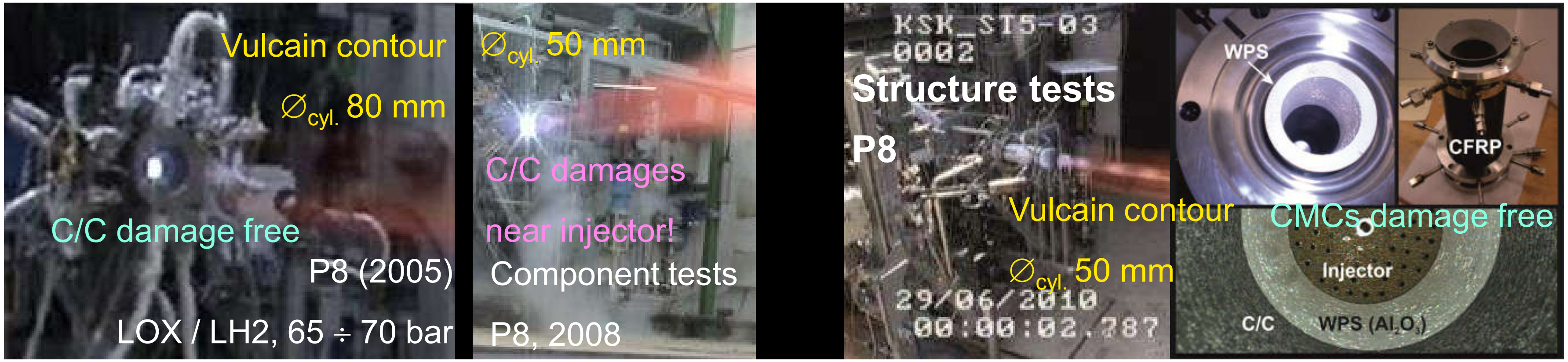
Other derivatives, after firing tests (→ damage free!):

Oxipol	AvA-Z-ISC	C/SiCN	C/C (CVI)
Open porosity ε [%] (porosity + permeability k_d / k_f adaptable by manufacturing process)			
10	**35**	**18**	**7**
Density kg/cm³			
2.3	**2.6**	**1.6**	**1.6**

2.3 Experimental Investigation of the

Innovative Transpiration Cooled CMC Rocket Thrust Chamber

2.3.1 Hot Gas Verification (LOX/LH2; LOX/GH2) European Techology Facilities



52 s, 5 ÷ 6 kg/s, τ = 4.2 % 90 bar tests 120 s, p_c = 55 bar, LOX / LH2 operation, τ = 15 %

20 s, p_c = 55 bar, LOX / GH2 (120 K), τ = 9 % Demonstration of the integrated CMC TCA

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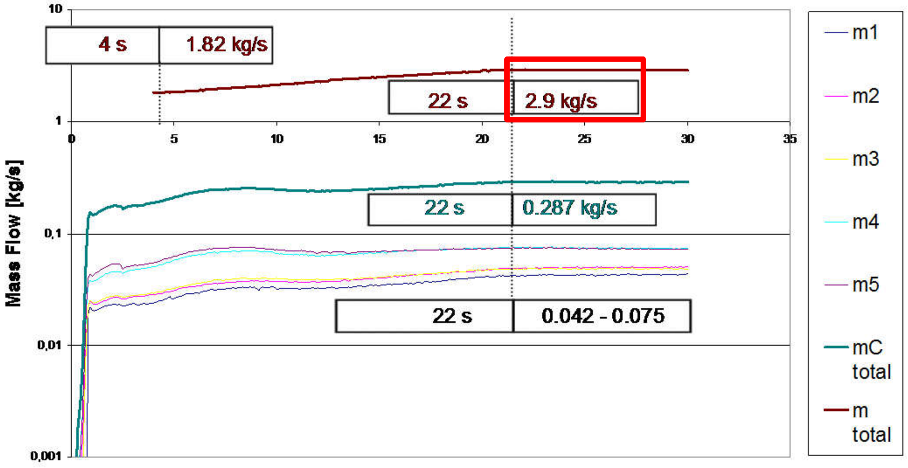
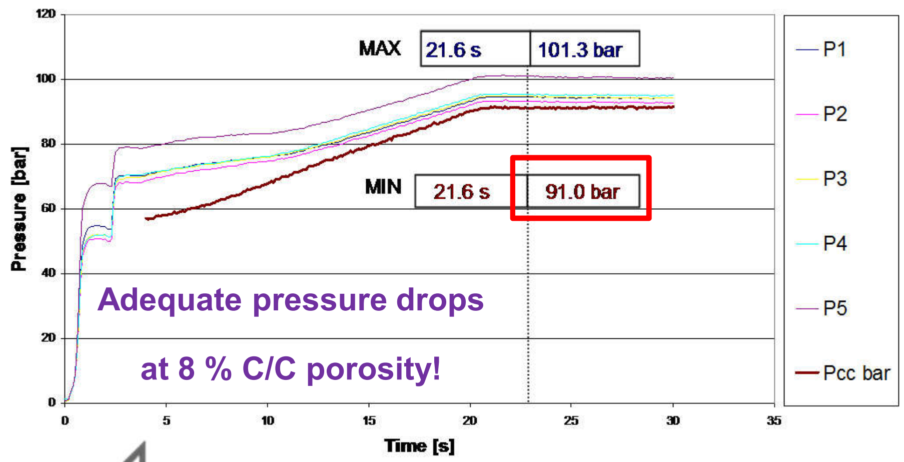
2.3 Experimental Investigation of the
Innovative Transpiration Cooled CMC Rocket Thrust Chamber
2.3.2 Pressure Measurement; European Techology Facilities

Propulsion 2010 - KSK-KT 50 mm Hardware - P8 2008

Hot Run 2 - *Mass Flows* Versus *Time*



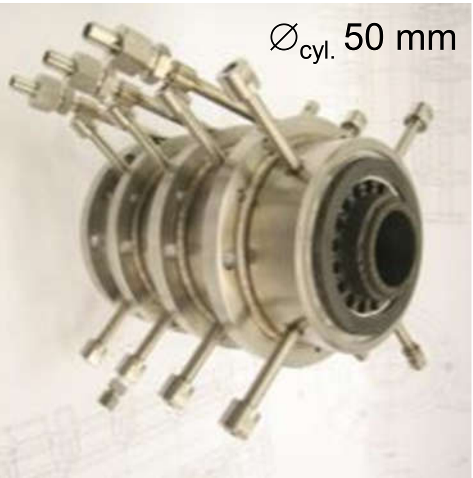
Hot Run 2 - *Coolant Manifold & Chamber Pressures* Versus *Time*



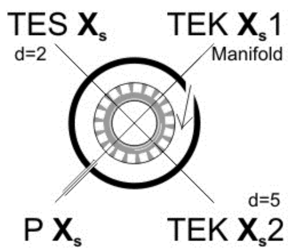
Inner liner:
Initial model material
C/C

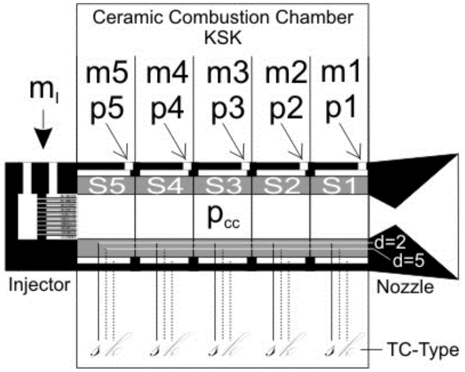
O/F = 5.5

Segmented chamber module



Circumferential Sensor Position





2.3 Experimental Investigation of the

Innovative Transpiration Cooled CMC Rocket Thrust Chamber

P6.1, 2012

2.3.3 Temperatures; European Techology Facilities

Nominal hotrun-sequence

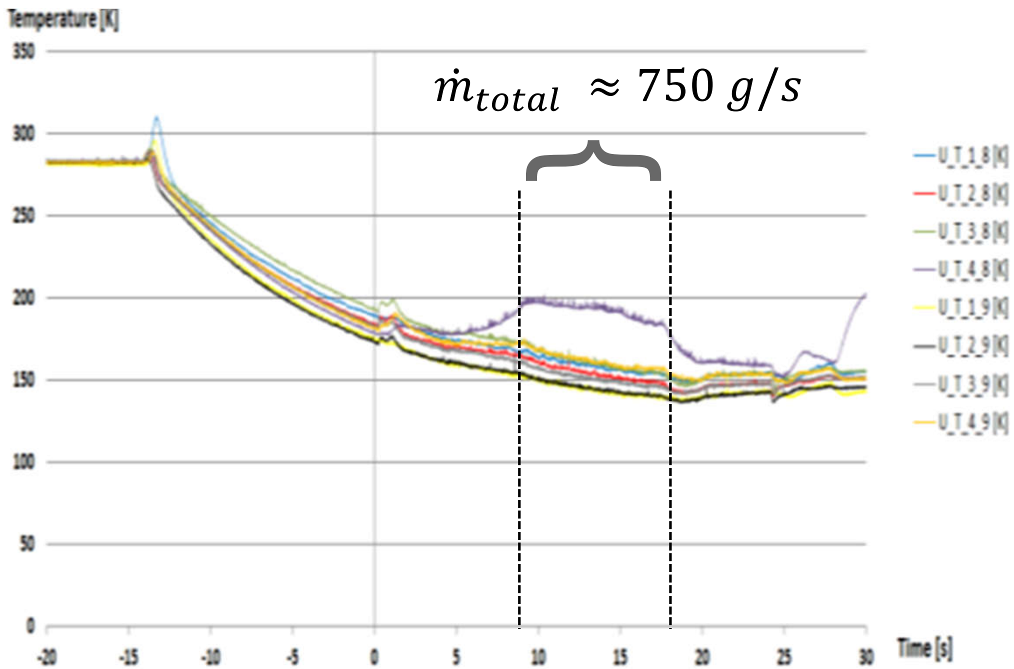
O/F = 5.5; τ = 6.72 %; $p_c \approx$ 55 bar

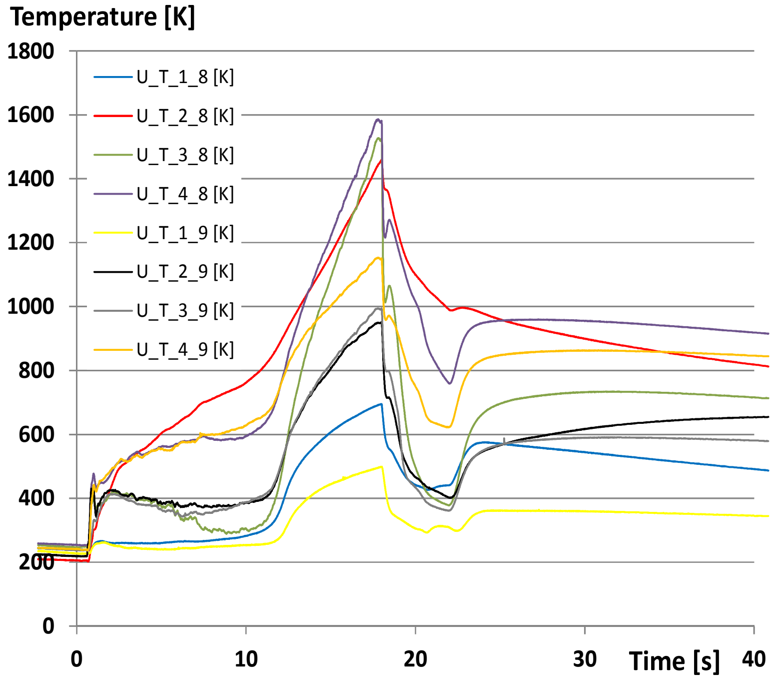
$\varnothing_{cyl.}$ 50 mm

Cooling turned off

O/F = 2.0

Max. $T_{surface} \cong$ 1800 K





Temperatures measured 1 mm behind hot gas surface

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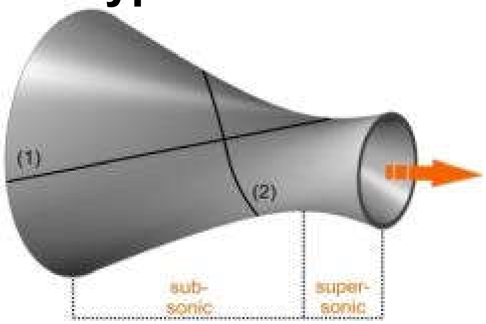
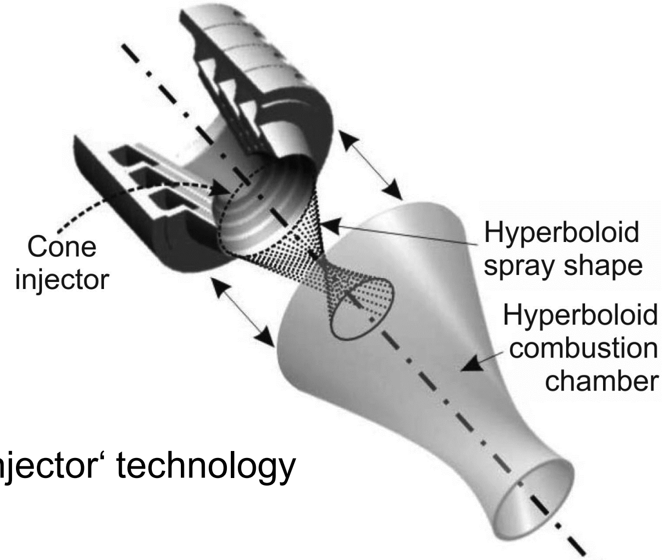
3 Further Innovations of the

Innovative Transpiration Cooled CMC Rocket TCA

3.1 Hyperboloid Subsonic Chamber Contour → 3.1.1 Orbital Propulsion





Hyperboloid chamber design

Perfectly combined with ‚cone injector' technology

Hyperboloid geometry

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{z^2}{c^2} = 1$$

Numerical comparison

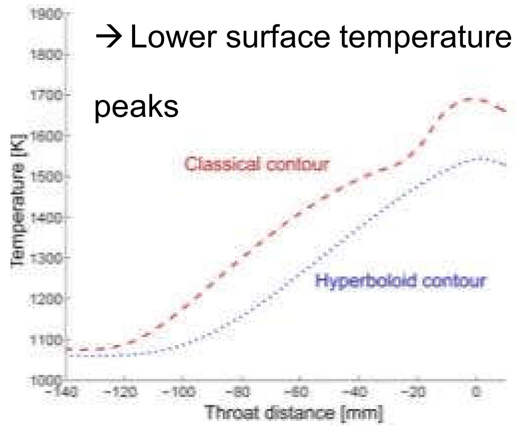
at similar performance

→ Lower surface temperature

peaks

Comparison referred to typical 500 N class

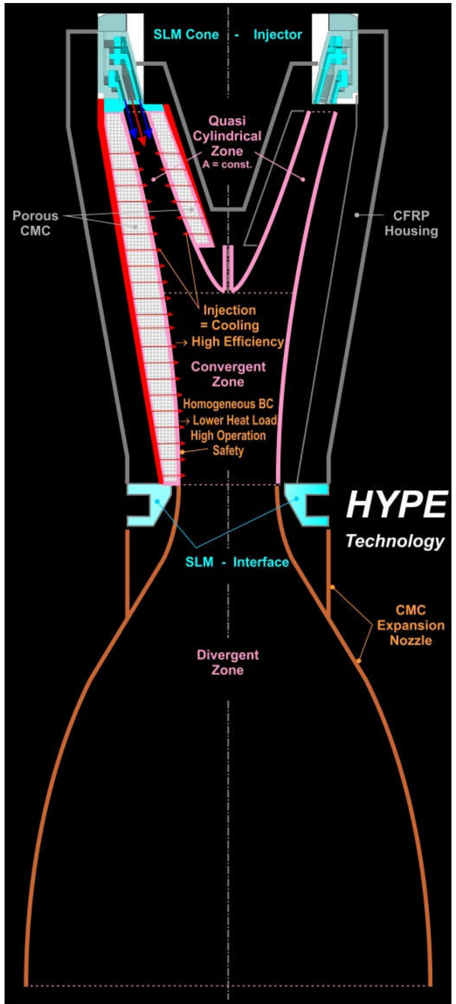
- Advantages for
    - film cooling
    - transpiration cooling
- Composite affine structure manufacturing (winding technique)

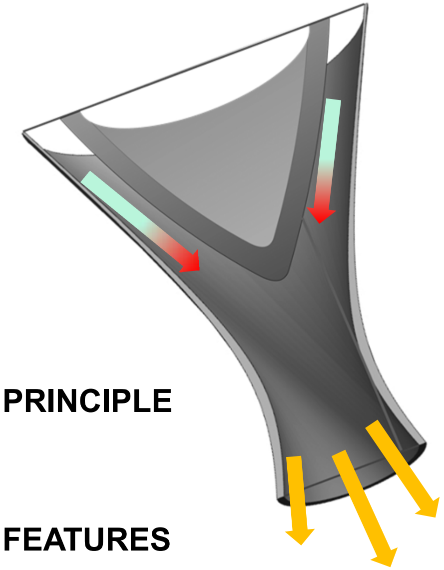


3 Further Innovations of the

Innovative Transpiration Cooled CMC Rocket TCA

3.1 Hyperboloid Subsonic Chamber Contour → 3.1.2 Stage Engines

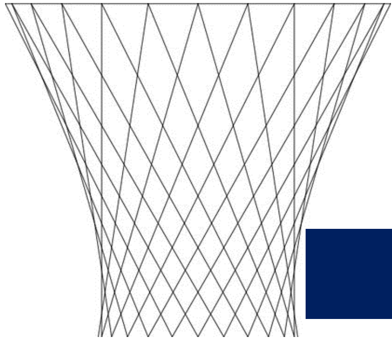




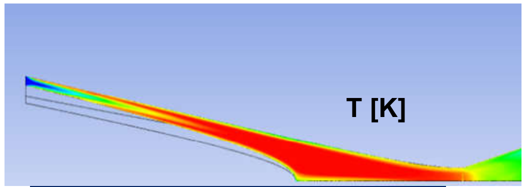
PRINCIPLE

FEATURES

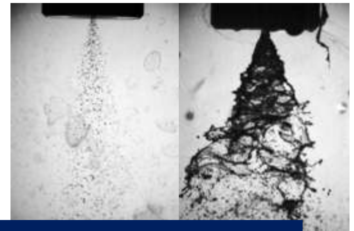
- → **LOW FATIGUE / LONG LIFE**
- → **HIGH REUSABILITY**
- → **HIGH RELIABILITY**
- → **HIGH EFFICIENCY**
- → **LOW WEIGHT**
- → **LOW COST**



Spray Forming

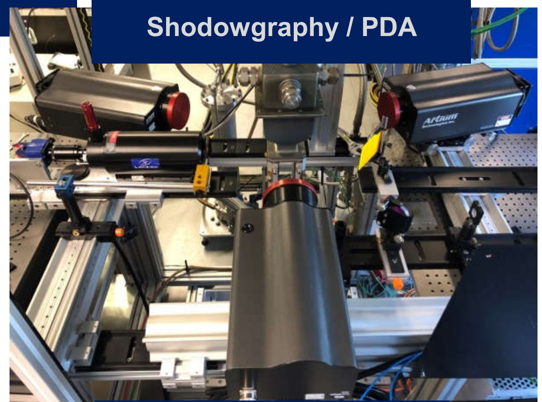


Numerical Analysis



Shodowgraphy / PDA

Subscale Hot Gas Verification



Spray Investigation

Short term development roadmap

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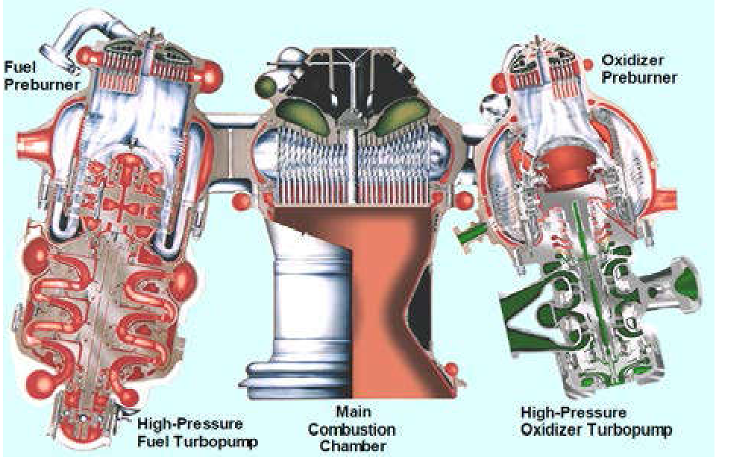
3 Further Innovations of the
Innovative Transpiration Cooled CMC TCA
3.2 Preburner Application

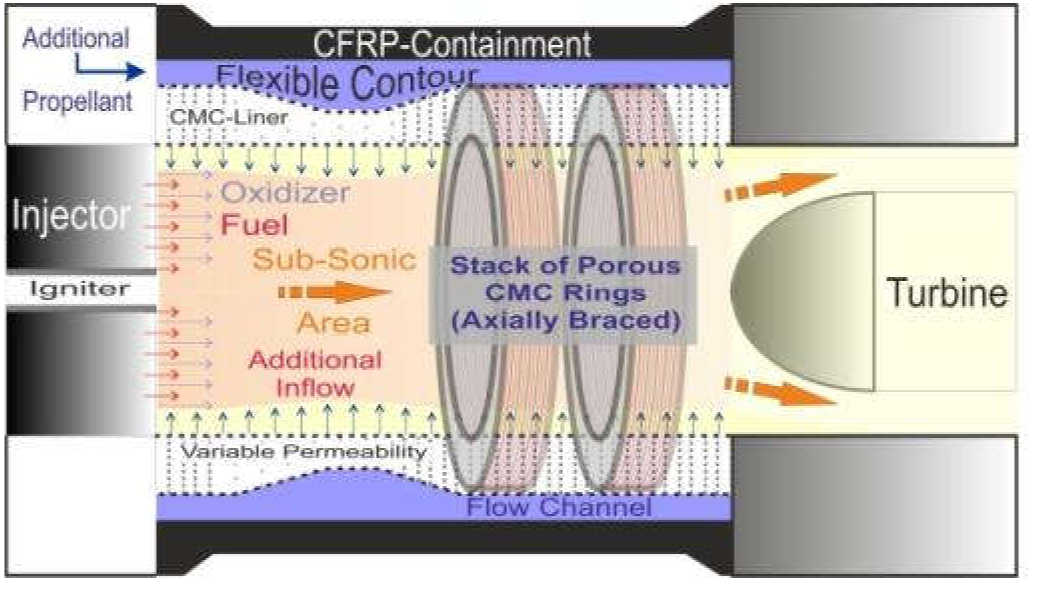


Features

- Standard injector technology concerning …
  - functional design
  - mixture ratio

- Propellant overhead injected through chamber wall

- Long life and light weight structures, similar to CMC thrust chamber design



Application principle

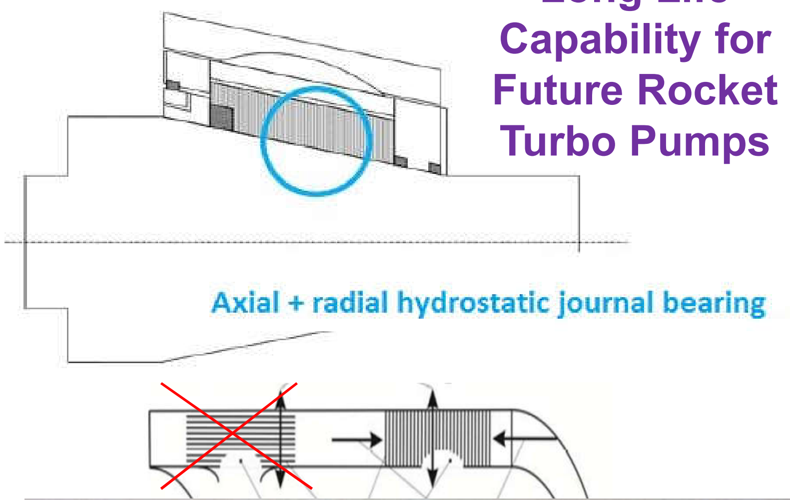
(oxide CMCs for ox-rich systems)

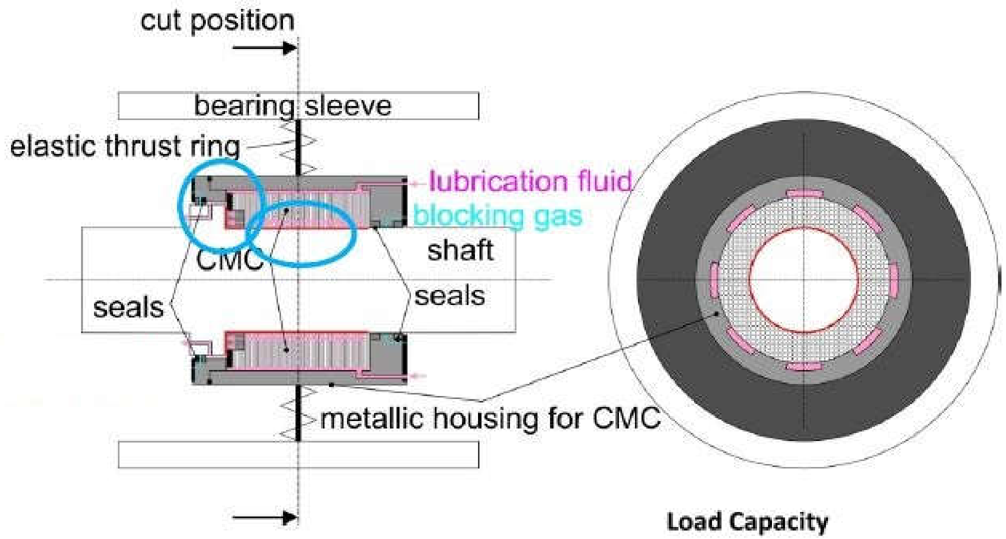
3 Further Innovations of the

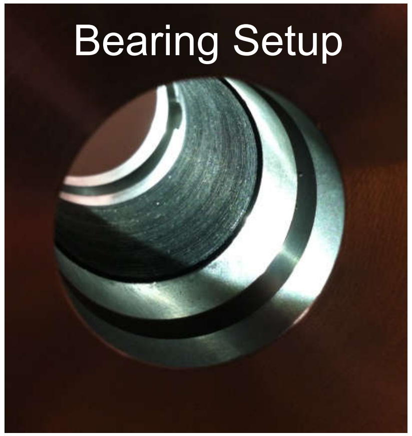
Innovative Transpiration Cooled CMC TCA

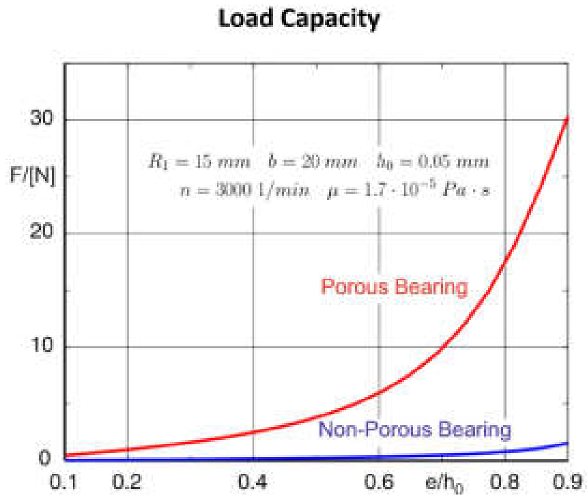
3.3 Transpiration Lubricated Micro-Porous CMC Journal Bearings

High Speed
Long Life
Capability for
Future Rocket
Turbo Pumps









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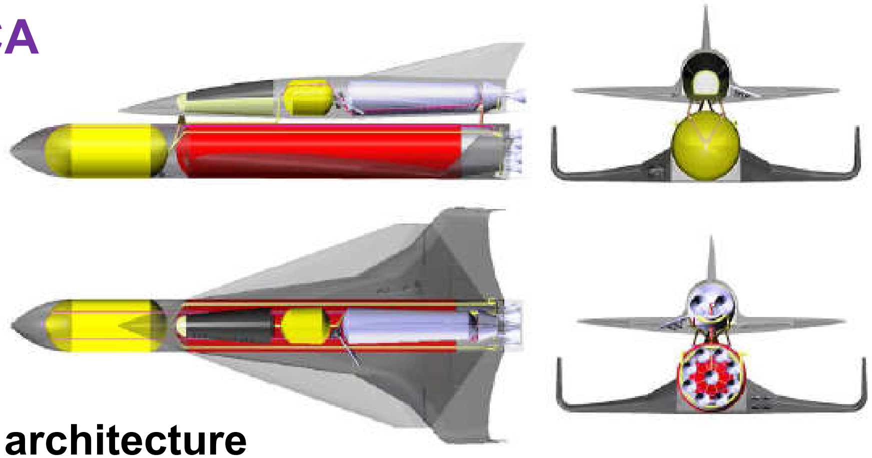
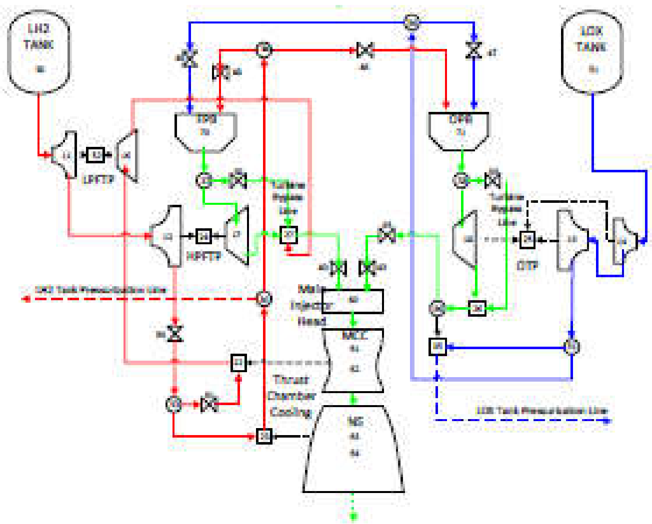
4 Outlook for the
Innovative Transpiration Cooled CMC TCA
4.1 RLV Applications



Space X
Falcon 9
Reusable
First Stages

CNES-DLR
Callisto
Reusable
Stage

System architecture of DLR *SpaceLiner*
For orbital and hypersonic flight

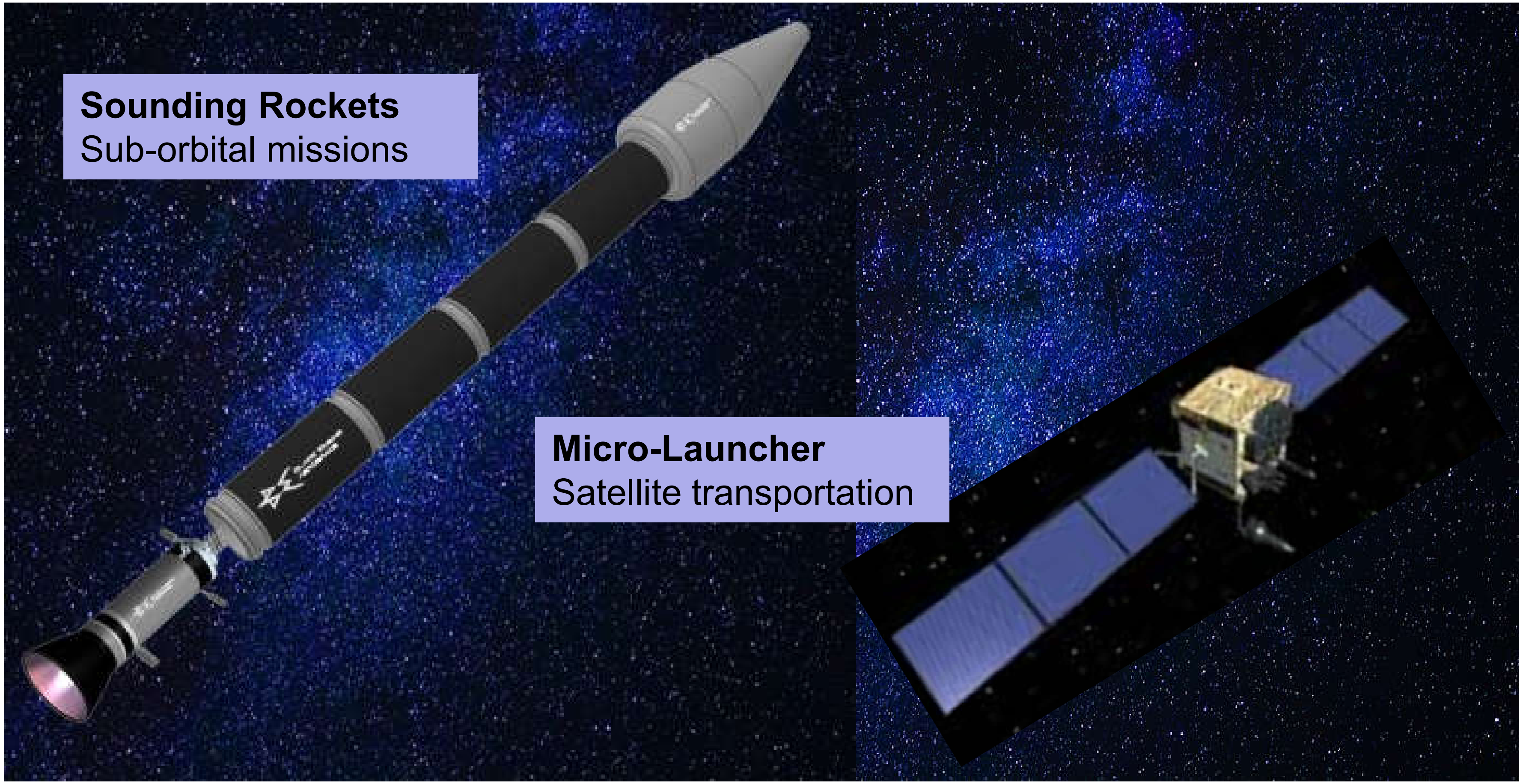


Engine Synoptic

4 Further Innovations of the

Innovative Transpiration Cooled CMC TCA

4.2 ELV Applications



4 Summary / Outlook

Summary

- DLR's development of the transpiratrion cooled CMC rocket TCA in the classical cylinder-laval design led to TRL 5 and promises high applicability in the growing New Space market.
- The CMC technology can be found in a variety of thrust chamber components, like combustion chambers,expansion nozzles and in potential pre-burners

Outlook

- Future impovements like the dual-shell hyperboloid combustion chamber design and the transpiration lubricated CMC journal bearing technology for long-life turbo pumps shall increase the future competitiveness of European high performance rocket engines

Thank you for your attention!