Development of an Additive Manufactured Ultra Micro Turbine

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MICRO TURBINE ENERGY DENSITY

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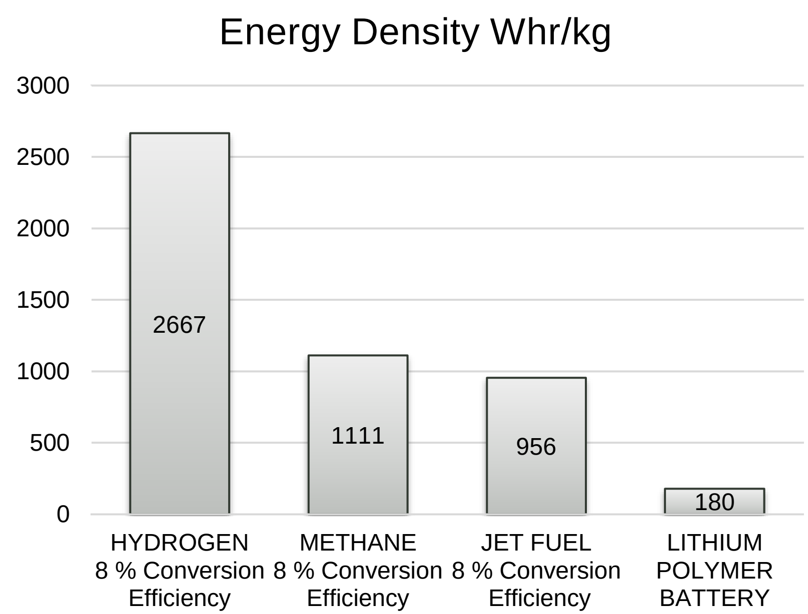
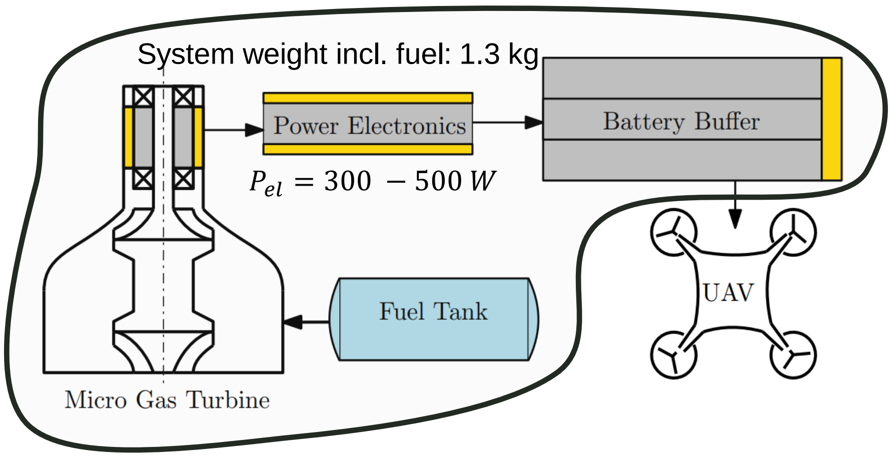
Hydrocarbons: 12-14 kWhr/kg

Lithium polymer batteries (UAV standard): 0.135-0.180[1] kWhr/kg



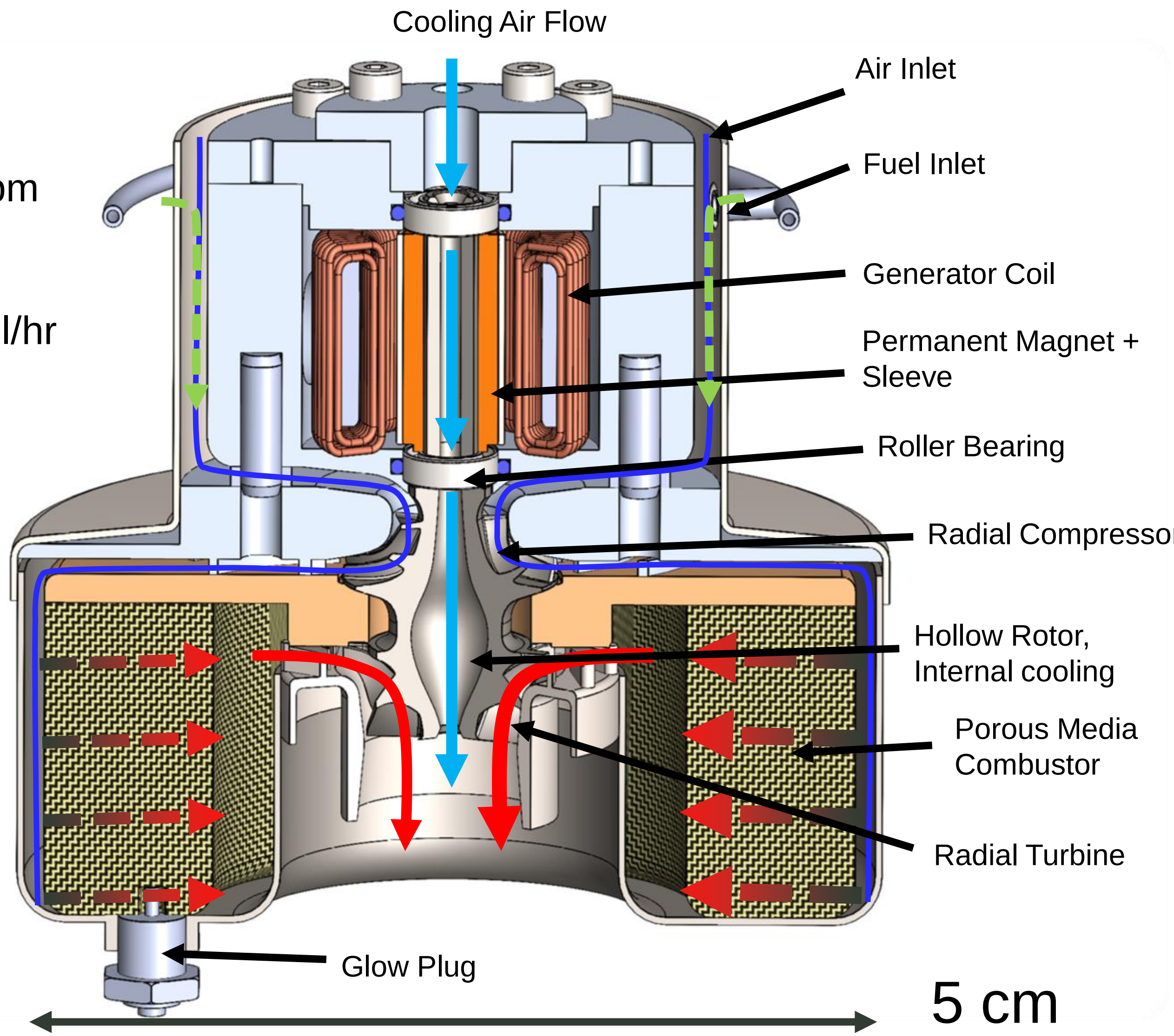


- ✓ **Jet fuel** performance improvement factor: **5.3**
- ✓ **Hydrogen** performance improvement factor: **14.8**

[1]Budde-Meiwes et al.: A review of current automotive battery technology and future prospects, *Journal of Automobile Engineering, p.761-765.* ***2013***

ENGINE LAYOUT

Electric Power: 300 W
Weight (incl. fuel): 1.3 kg
Rotational Speed: 500 krpm
Pressure ratio: 2.5
TIT: 970° C
Fuel consumption: 400 ml/hr
Cycle efficiency: 8%
BSFC: 1040 g/(kW hr)



DEVELOPING A MICRO TURBINE FROM SCRATCH

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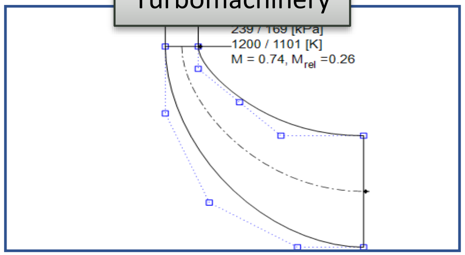
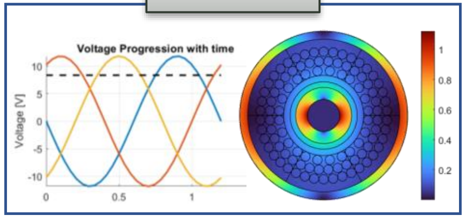
Reduced Order Models

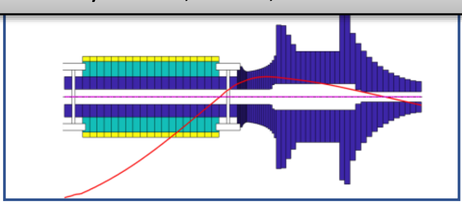
Turbomachinery



Generator

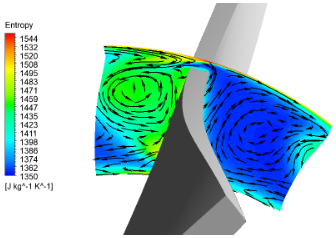


Rotordynamics, Stress, Heat Transfer



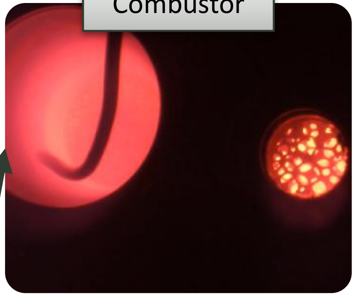
Interdisciplinary Engine Optimization

High Fidelity Optimization

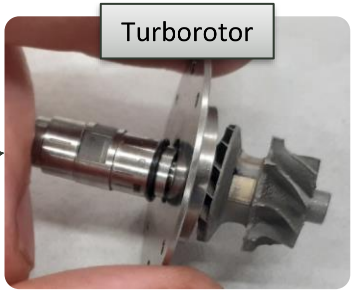


Component Manufacturing and Testing

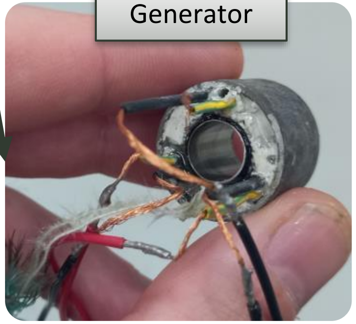
Combustor



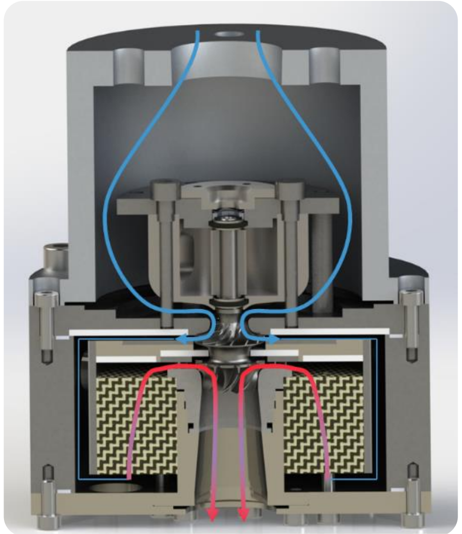
Turborotor



Generator

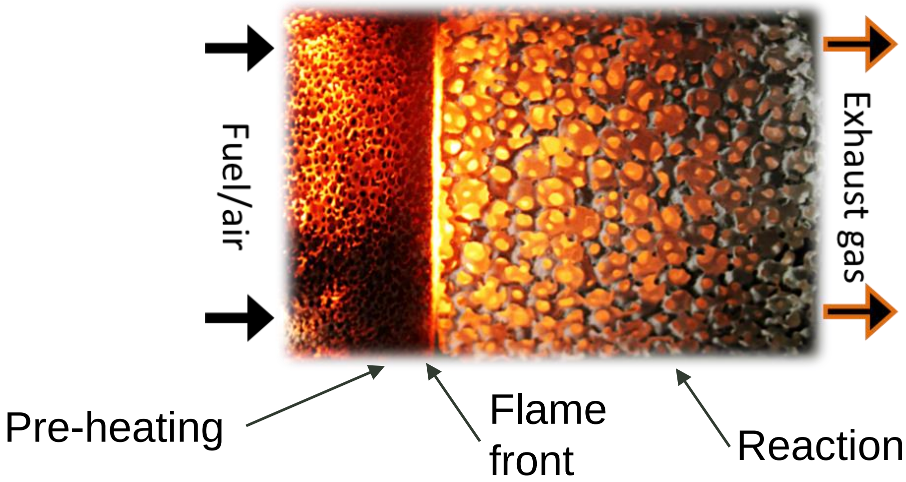


Prototype Design and System Level Testing



POROUS MEDIA COMBSTION

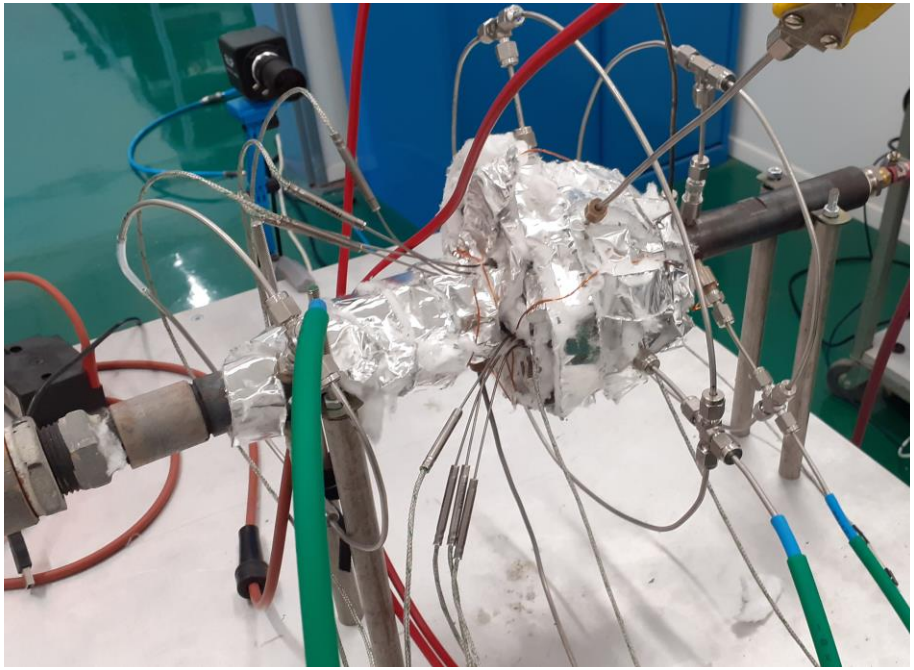
- **Efficient pre-mixed combustion**
  - Every ‘cell’ acts like a flame holder
  - No dilution necessary
  - Very compact combustor
- **Low equivalence ratios achievable**
  - Radiation and conduction upstream of flame front
  - Mixture temperature increases upstream of the flame front
  - Laminar flame speed increases

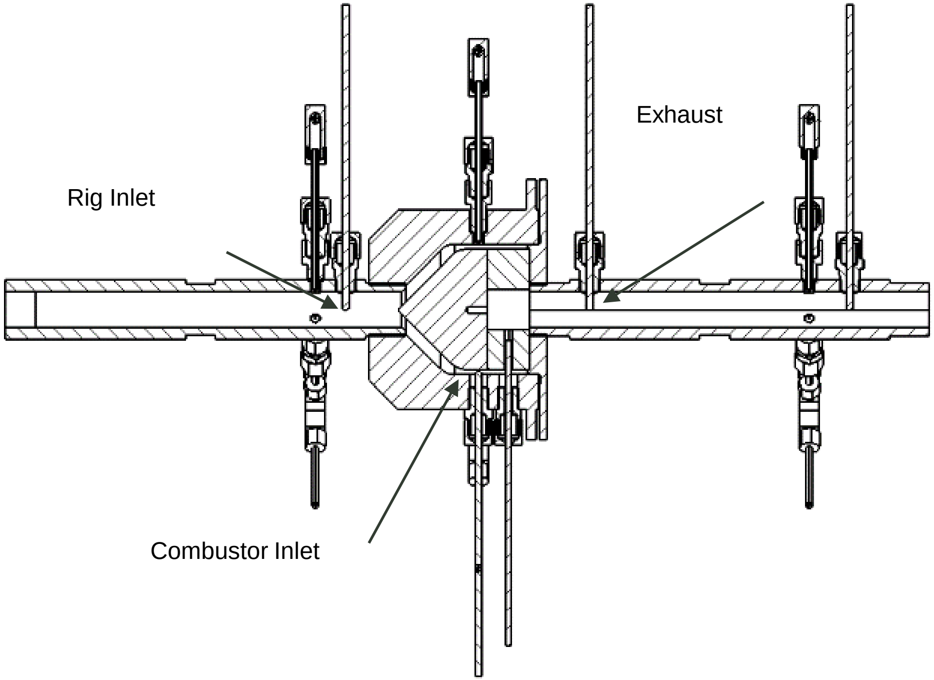


Porous combustion picture taken from: Fx Lab Stanford Engineering, https://web.stanford.edu/

COMBUSTOR TEST RIG

- **Porous media combustor test rig**
  - Measurement of various foam geometries
  - Measurement of pressure drop
  - Insulated combustion chamber
  - Pressurized combustion





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COMBUSTOR TEST RESULTS (PROPANE)

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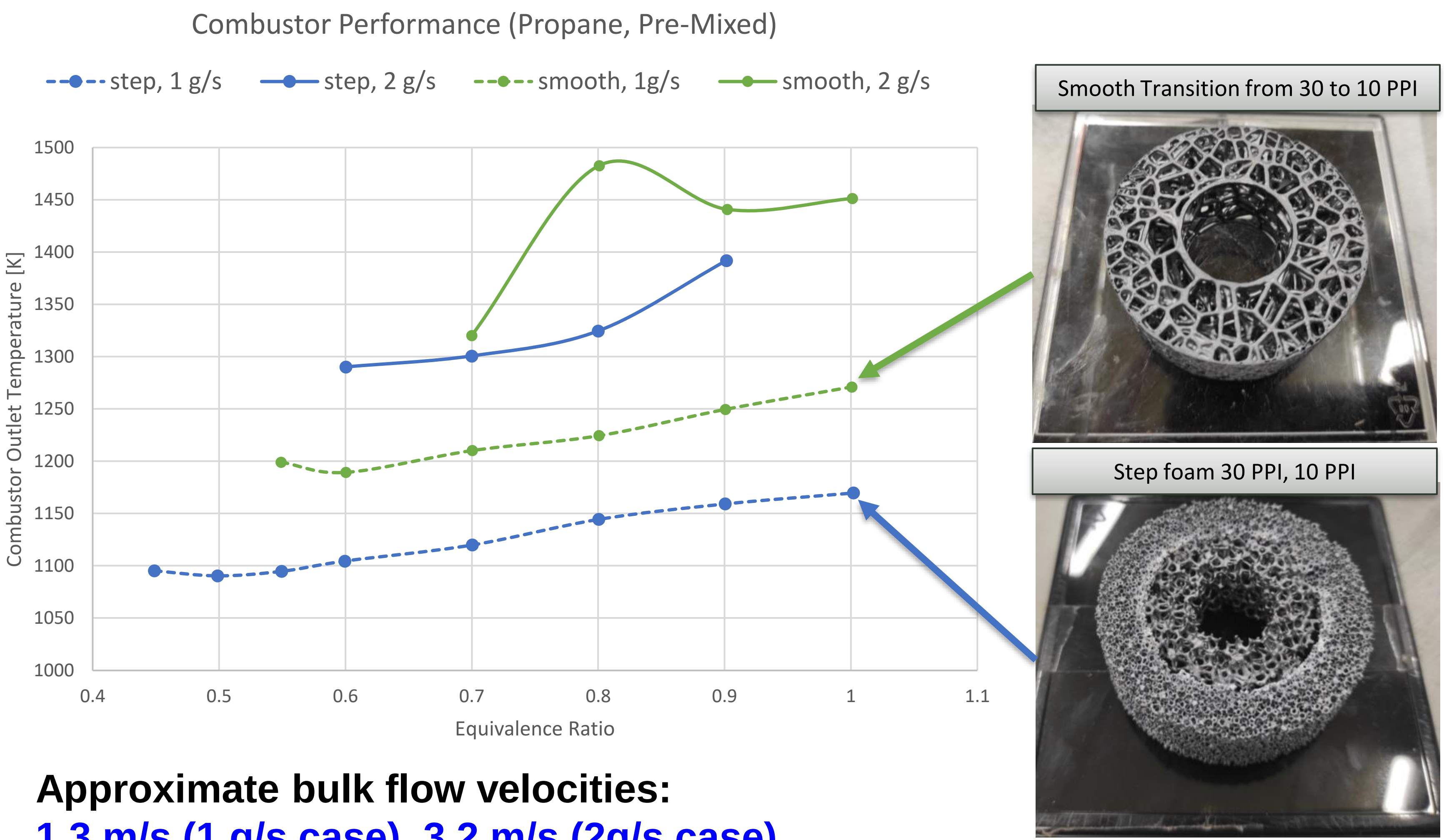


Approximate bulk flow velocities:

1.3 m/s (1 g/s case), 3.2 m/s (2g/s case)

COMBUSTOR TAKEAWAY

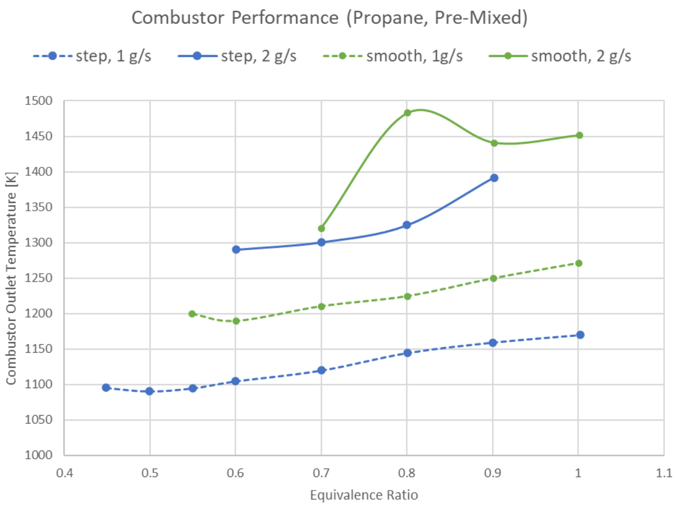
- **As expected, outlet temperature generally rises with rising equivalence ratio**

- **Minimum equivalence ratio limited by bulk flow velocity**
  - 1.3 m/s: $\phi_{min} = 0.45$
    3.2 m/s: $\phi_{min} = 0.6$

- **Pore size distribution needs to be optimized**
  - Stepped foam: lower equivalence ratio but also lower efficiency

- **Heat losses considerable -> low efficiency**
  - Volume to surface effects must be taken into account during design

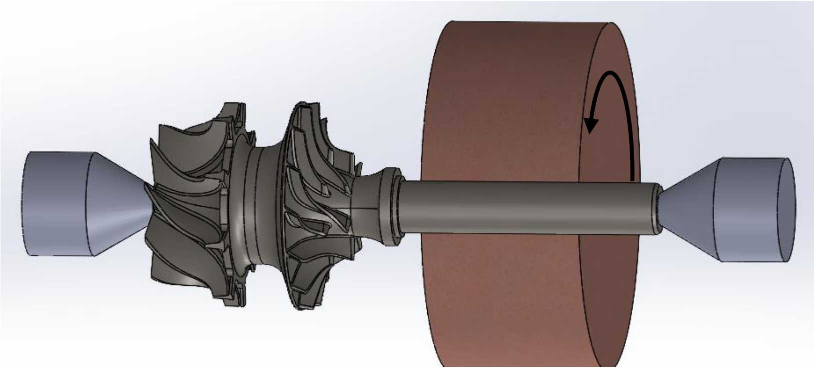
- **Switch to liquid fuel**

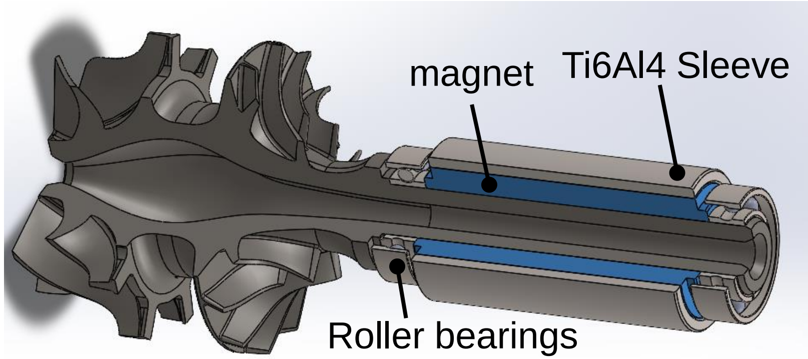


ROTOR MANUFACTURING

- **Monolithic Rotor Geometry**
  - Compressor diameter: 16mm
  - Overall length: 40 mm

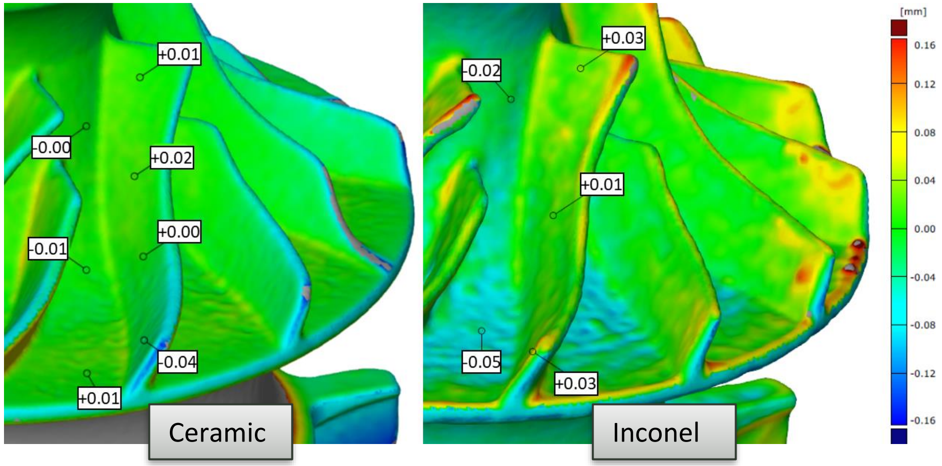
- **Ceramic rotors (Alumina, Zirconia, Silicon Nitride)**
  - Lithography based additive manufacturing
- **Inconel 718 rotors**
  - Selective Laser Melting
- **Grinding and rotor assembly**
  - Grinding between tips, bearing seat dimensional tolerances $5\mu m$
  - Press fitting bearing, magnet and sleeve

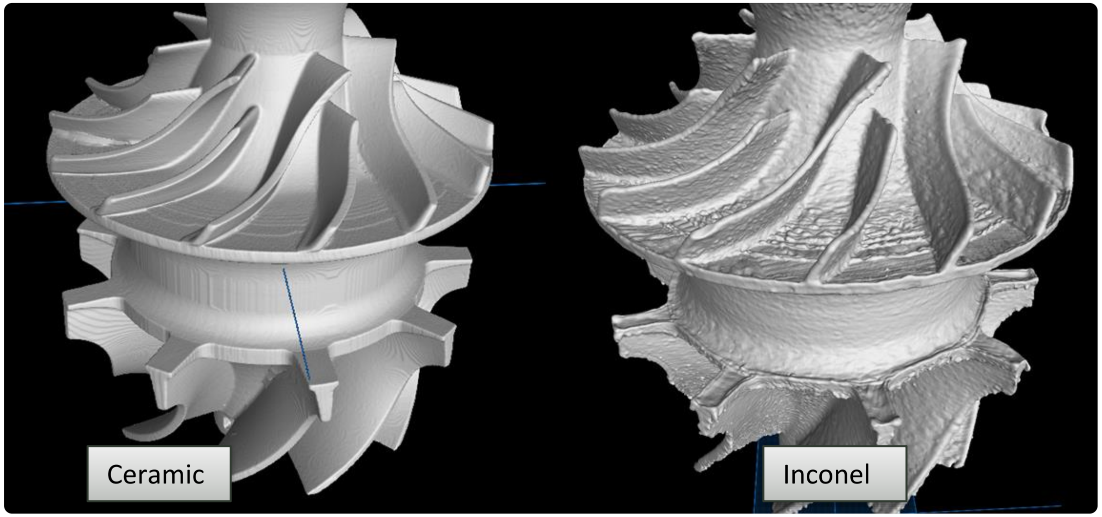


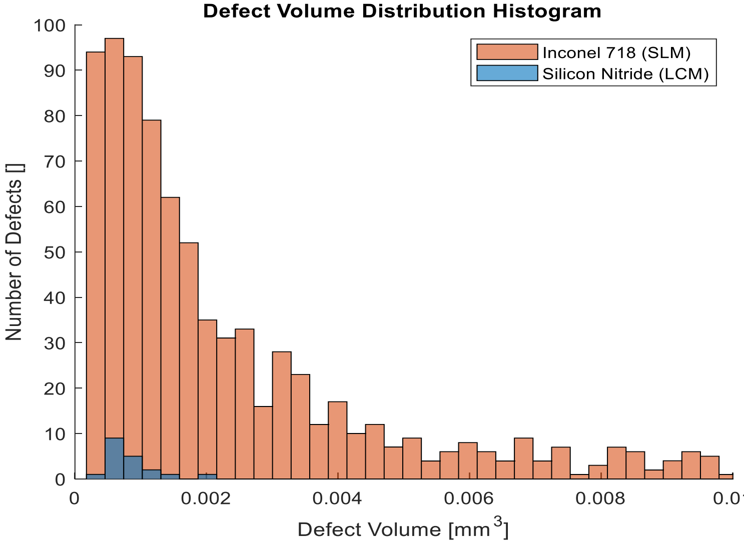


PRINT QUALITY COMPARISON

- **Dimensional accuracy**
  - Maximum deviation 40 μm, average around 20 μm
- **Surface roughness**
  - Ceramic rotors: 2-3 μm Ra, 13 μm Rz
  - Inconel 718: 8-11 μm Ra
- **Defects and artefacts**
  - Inconel geometry very “fuzzy”, many defects and artefacts







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MICRO ROTOR TESTING: CHALLENGES

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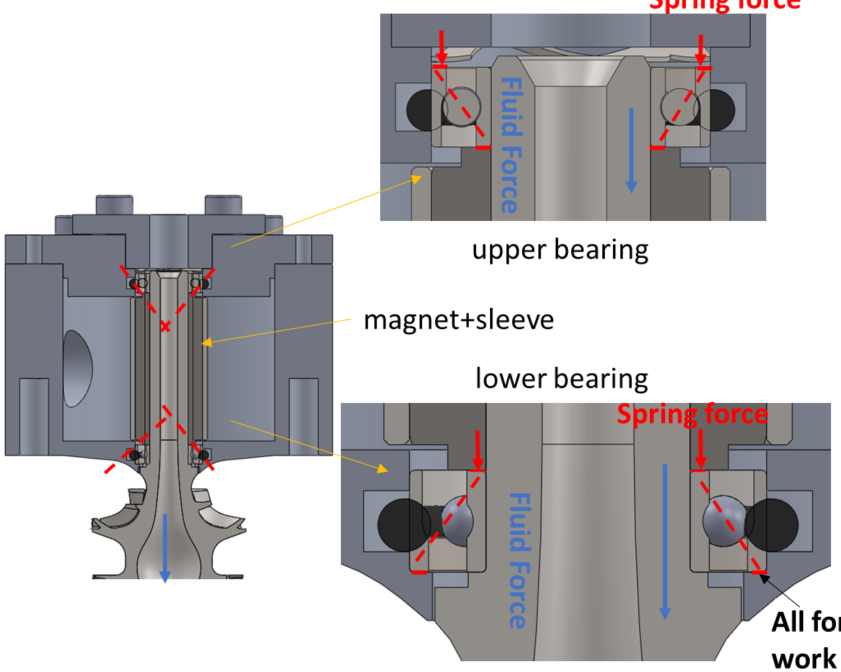
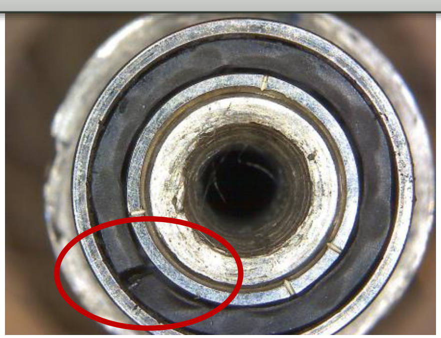
- **Stable bearing operation at speeds up to 500 krpm**
  - Elastic bearing suspension
  - Avoid overheating
  - “perfect” balancing
  - **Angular contact bearings in X-configuration:**
    Rotor must be loaded in the right direction always (balance piston)!



Broken bearing cage due to vibrations



Cage wear
(insufficient lubrication)

Load direction reversed

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AERODYNAMIC ROTOR TESTING

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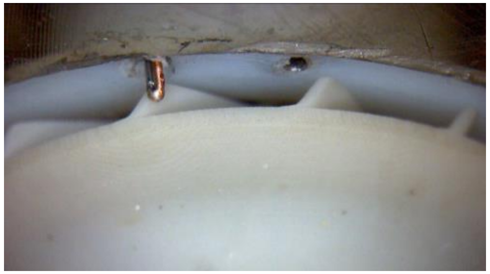
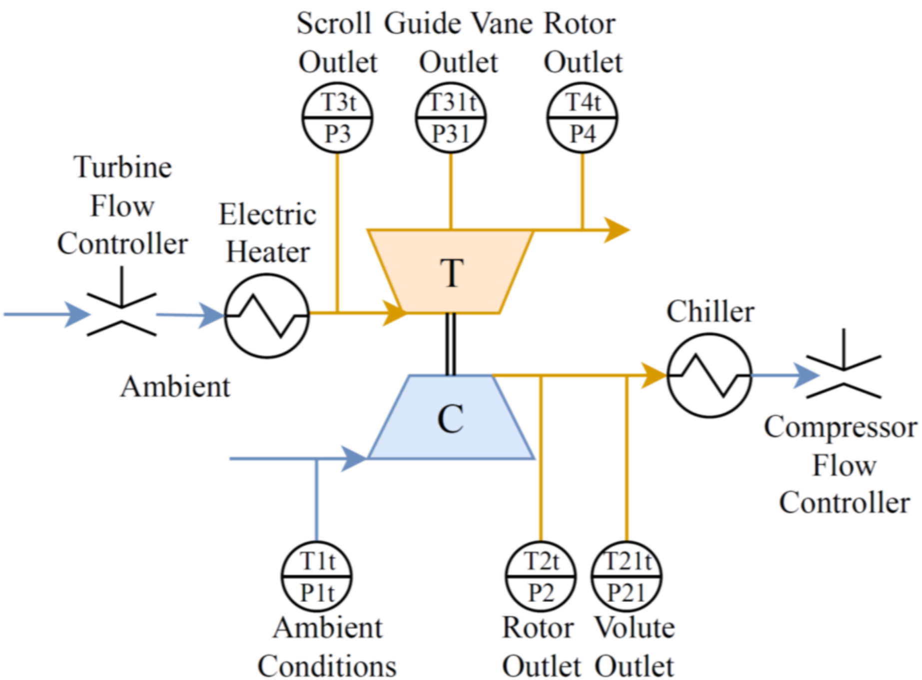
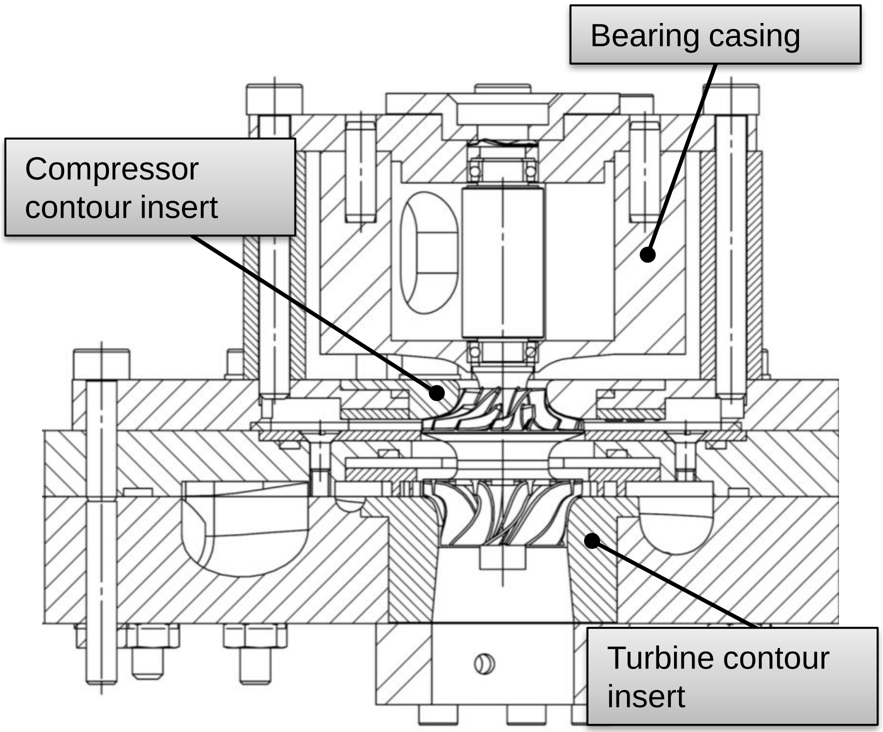
- **Modular test rig development**
  - "turbocharger" test rig (turbine drives compressor)
  - Turbine inlet air can be heated (max. 500 C)
  - Measurement of rotor outlet conditions
  - Adjustment of tip clearance possible

Rotor tip measurement stations (3x)

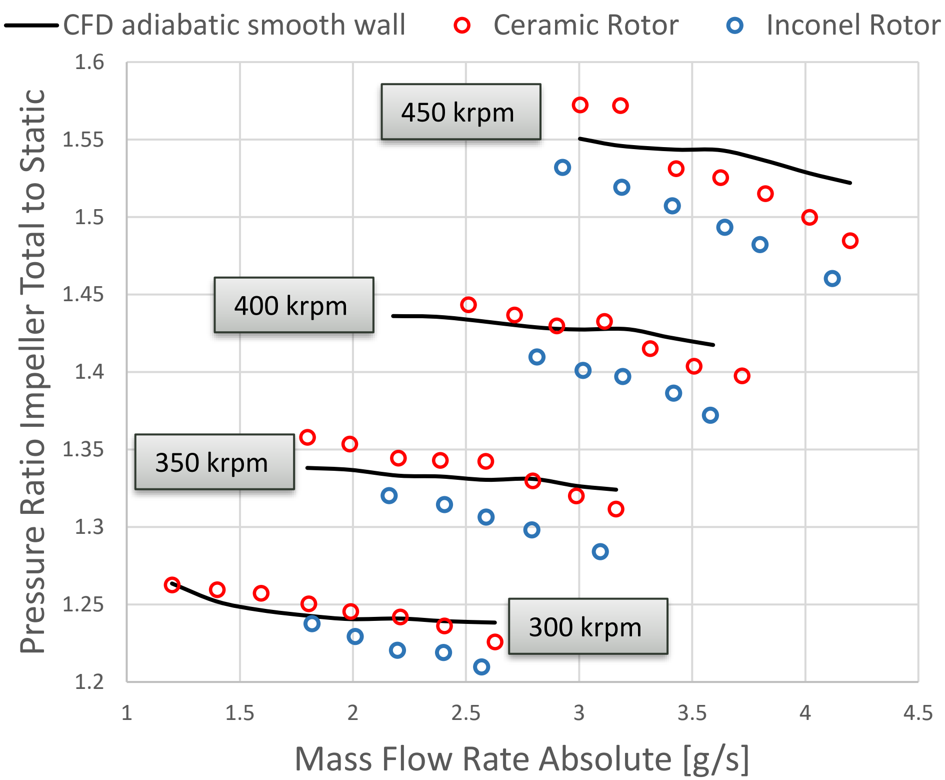


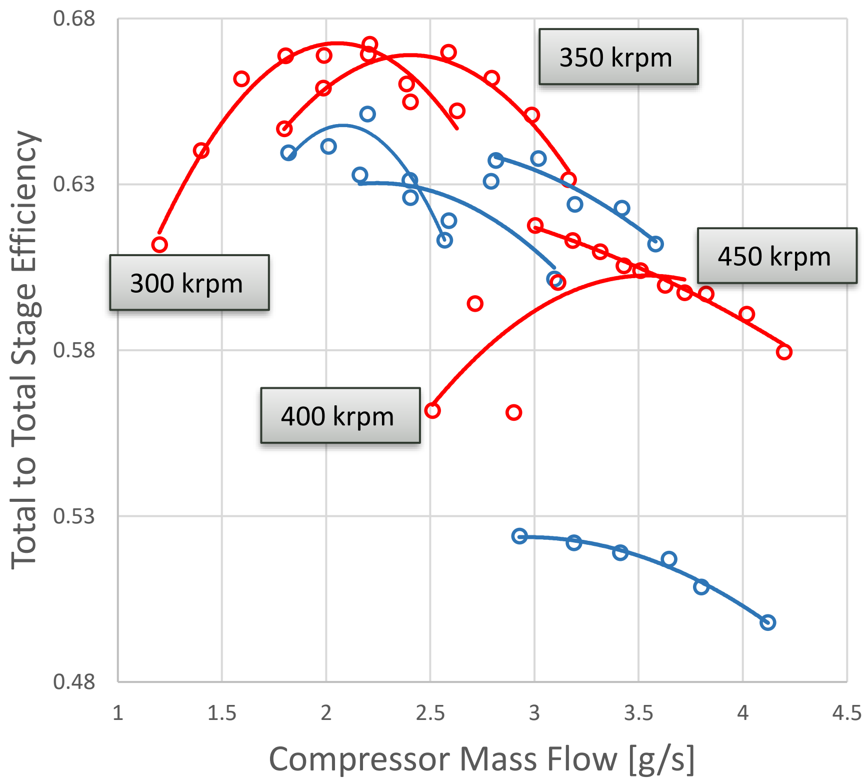




PRELIMINARY RESULTS: COMPARISON INCONEL VS CERAMIC

- Static pressure measurements match RANS CFD results (rotor)
- Acceptable stage efficiency can be reached
- Diffuser CFD doesn't match measured values (flow separation difficult to predict)
- Ceramic rotor outperforms Inconel rotor





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PROTOTYPE ENGINE LAYOUT

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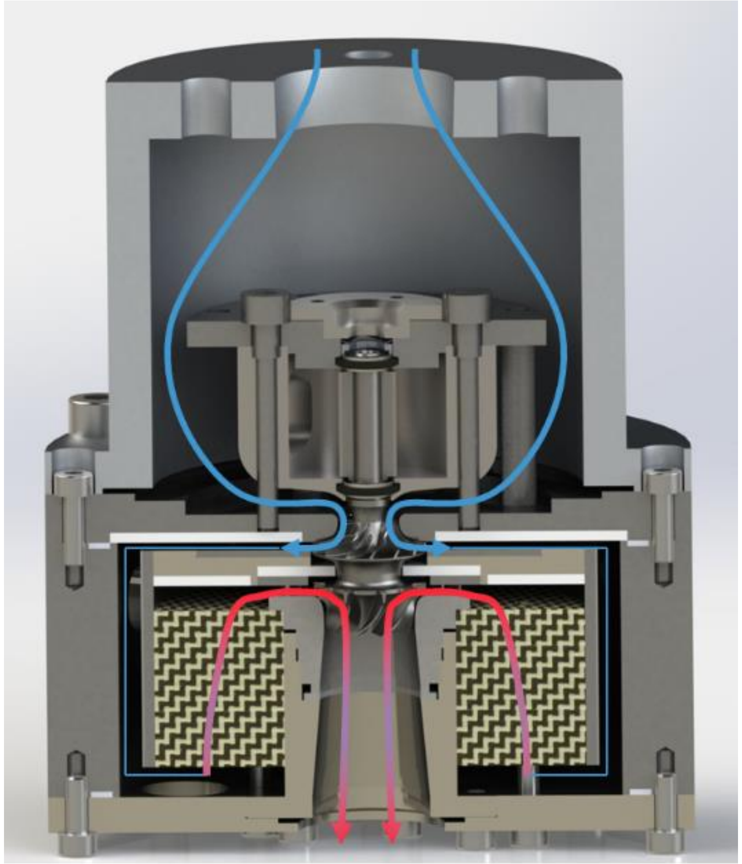
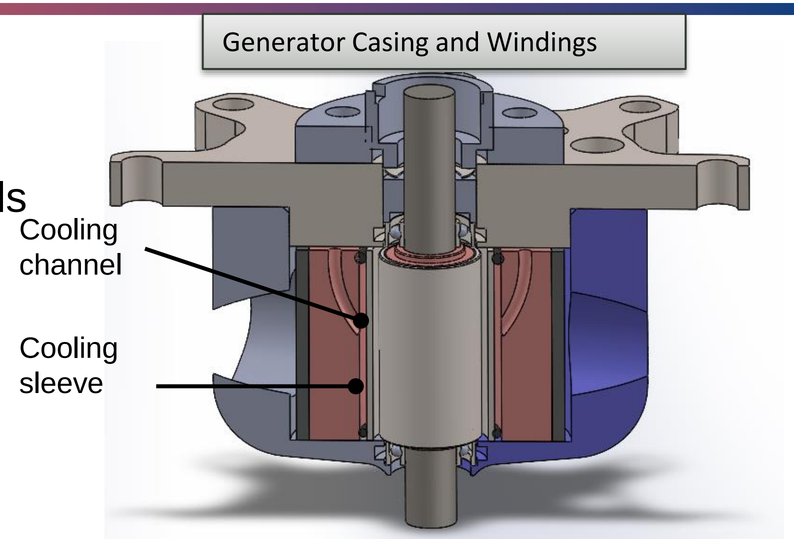
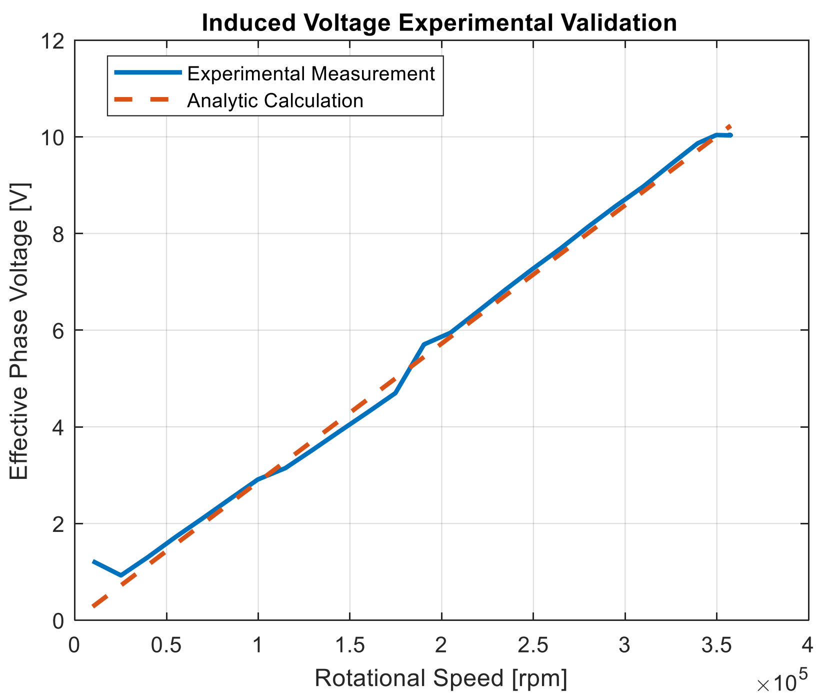
- **System Level Prototype Manufacturing and Testing**
  - Reverse flow combustor
  - 20 PPI and 30 PPI foam in series
  - Prototype parts are ready…

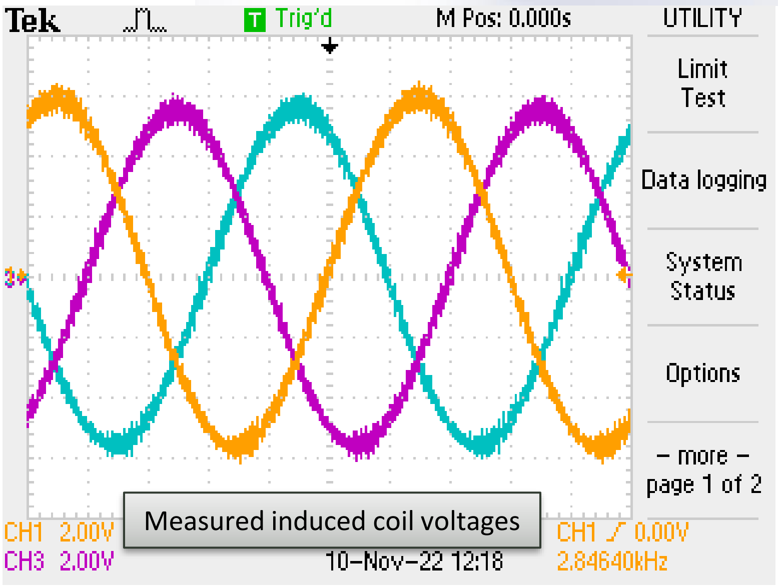


GENERATOR DEVELOPMENT

- **High-speed generator design**
  - Slotless design for lower iron losses
  - In-house code development including loss-models
- **Coil manufacturing in-house**
  - Winding of air coils with self-developed tools
  - Including water cooling channels







TURBOMACHINERY TAKEAWAY

- **Manufacturing**
  - Inconel (SLM) is easier to post-process
  - ceramic (LCM) has higher quality
- **Bearing system requires well thought out design**
  - Heat transfer management
  - Elastic suspension
  - Correct load force direction
- **Achieved polytropic compressor efficiency: 55-65 %**

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Questions?

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