HYDROGEN PRODUCTION VIA THERMOCHEMICAL CYCLES USING SOLAR PARTICLE REACTORS

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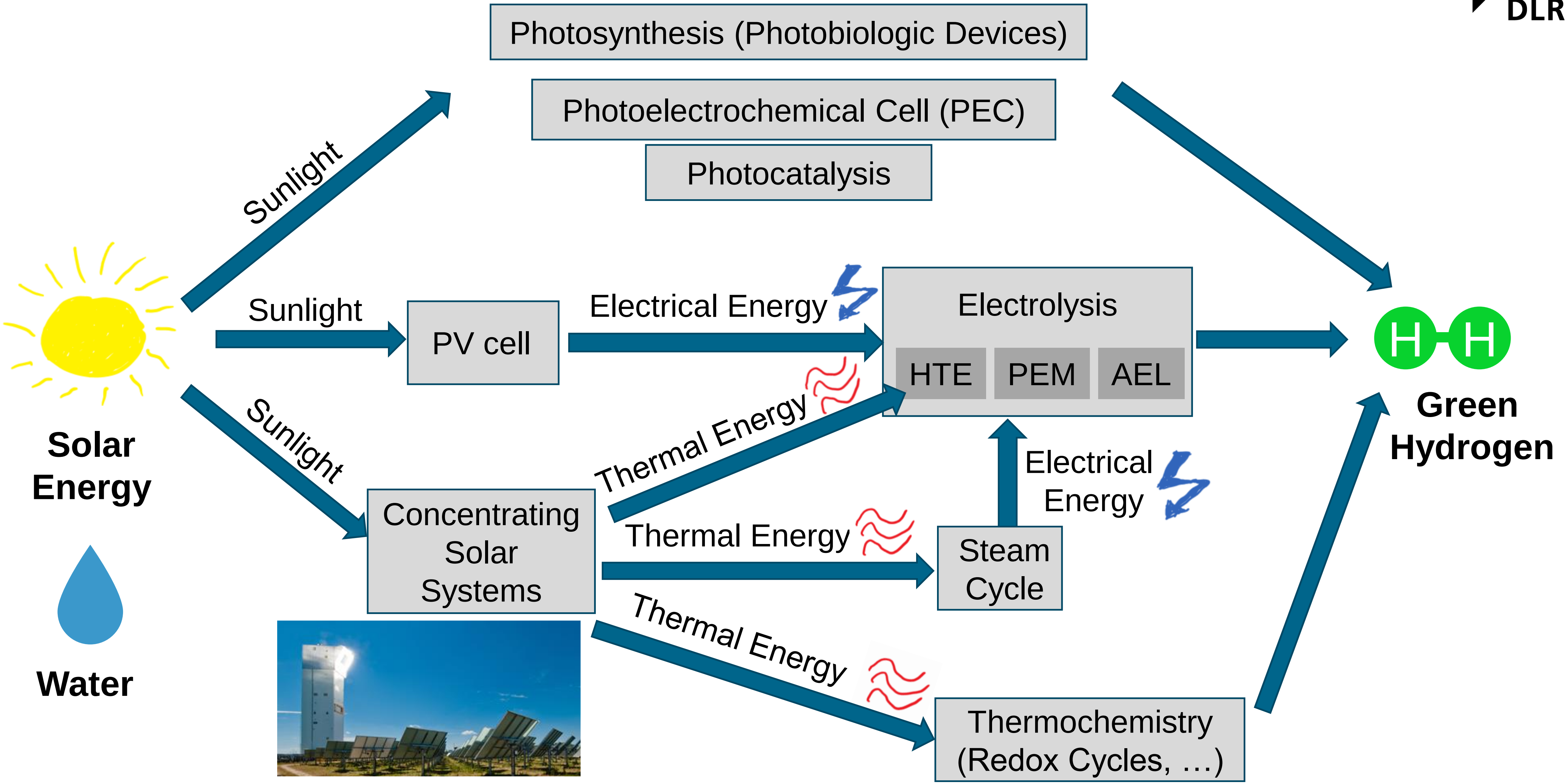
DLR

Green Hydrogen from Water Splitting by Solar Energy



Solar Thermochemical Redox Cycle

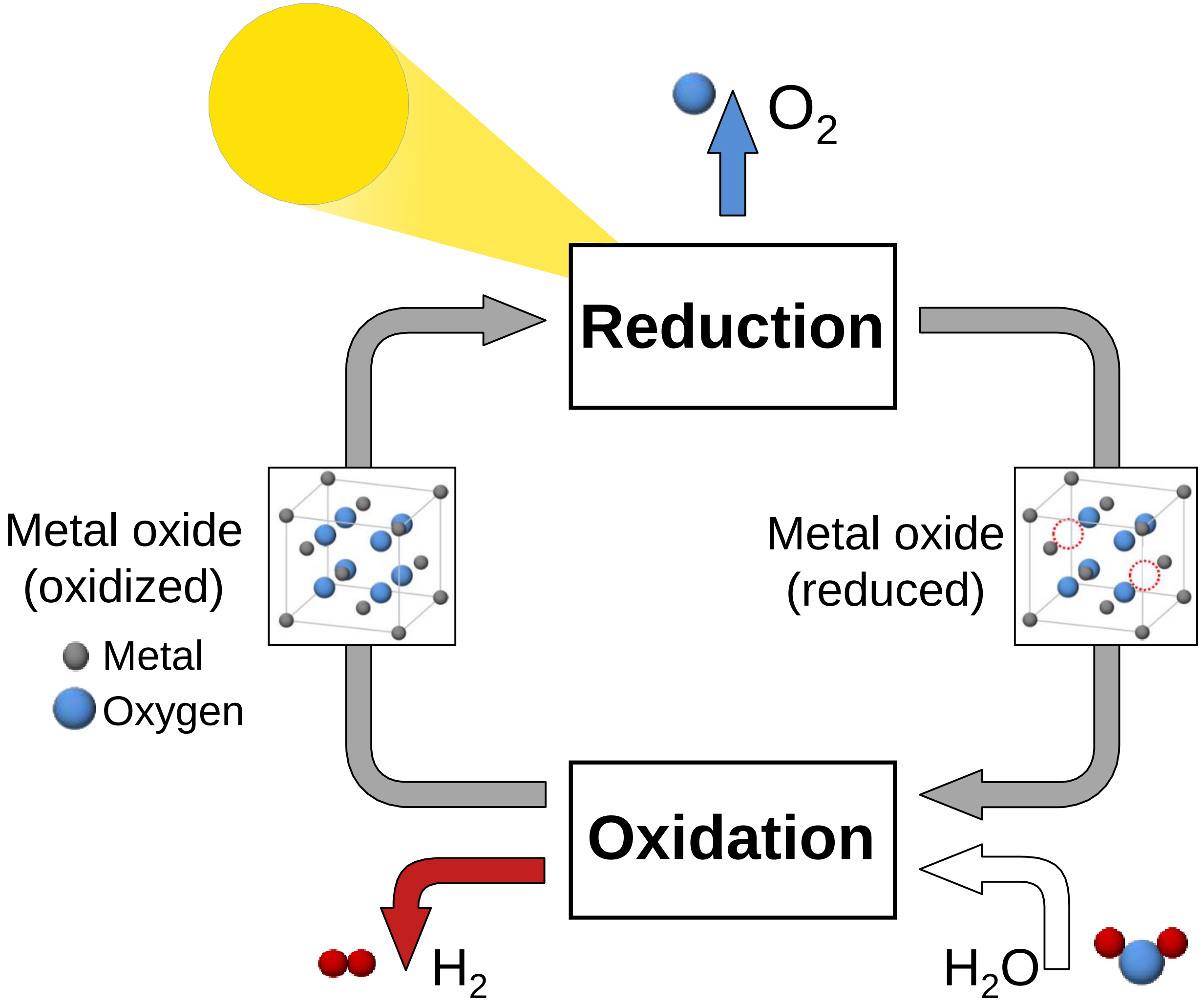


image adapted from [Richter2017]

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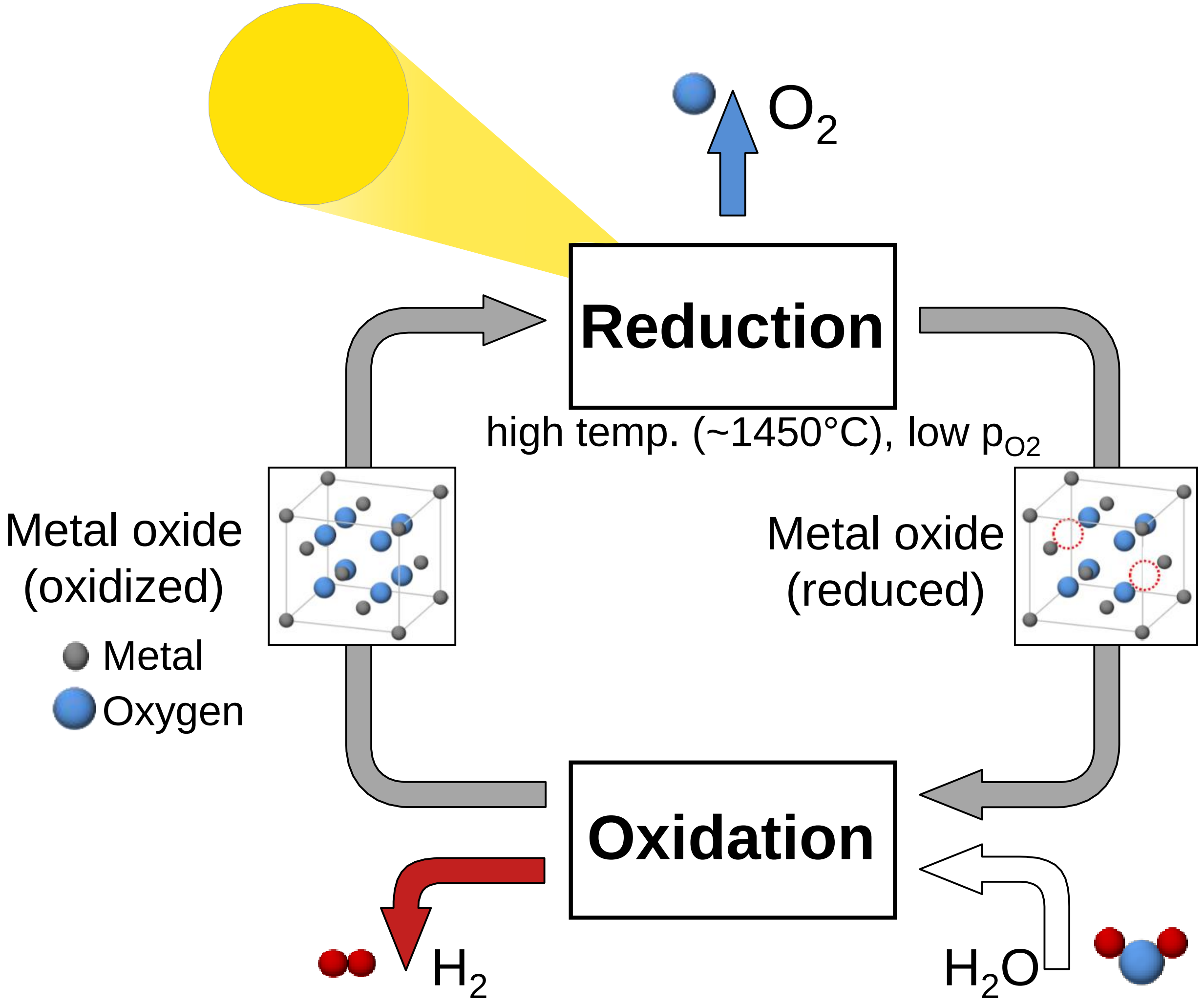
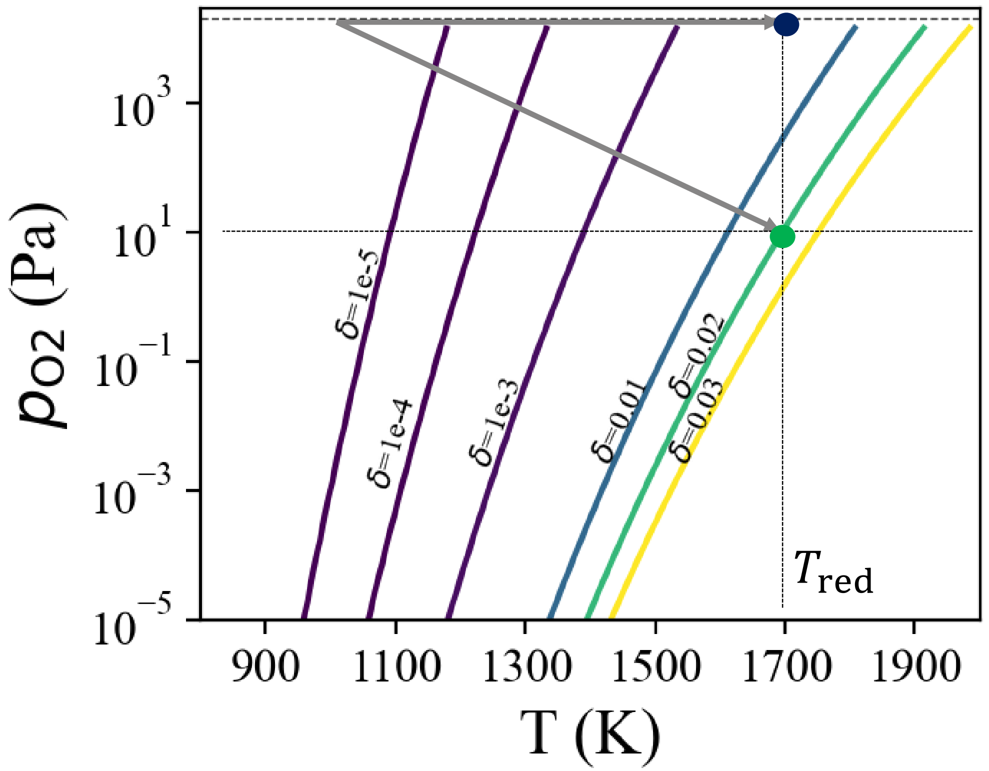


image adapted from [Richter2017]

Reduction $$CeO_2 \longrightarrow CeO_{2-\delta} + \frac{\delta}{2} O_2$$



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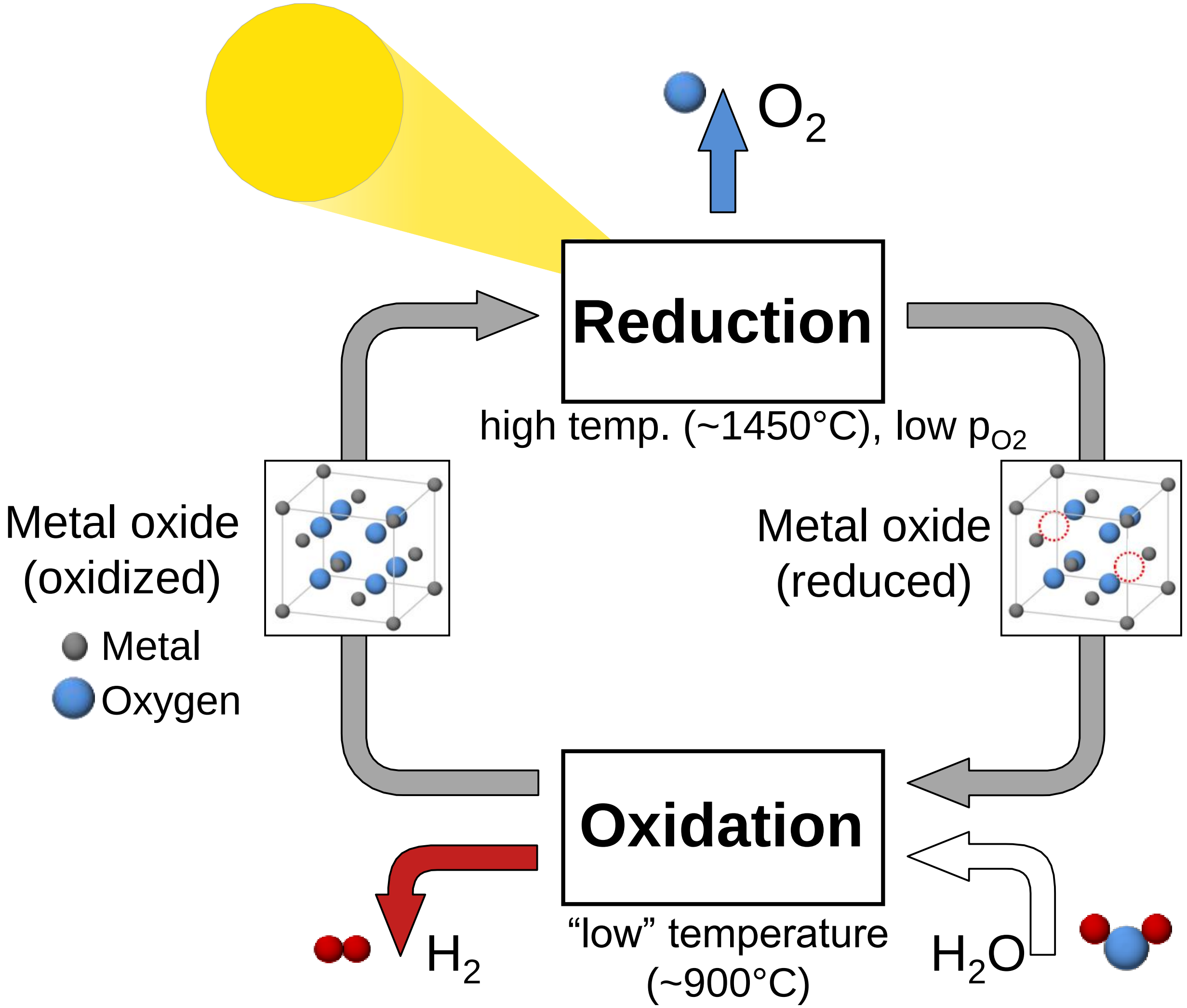
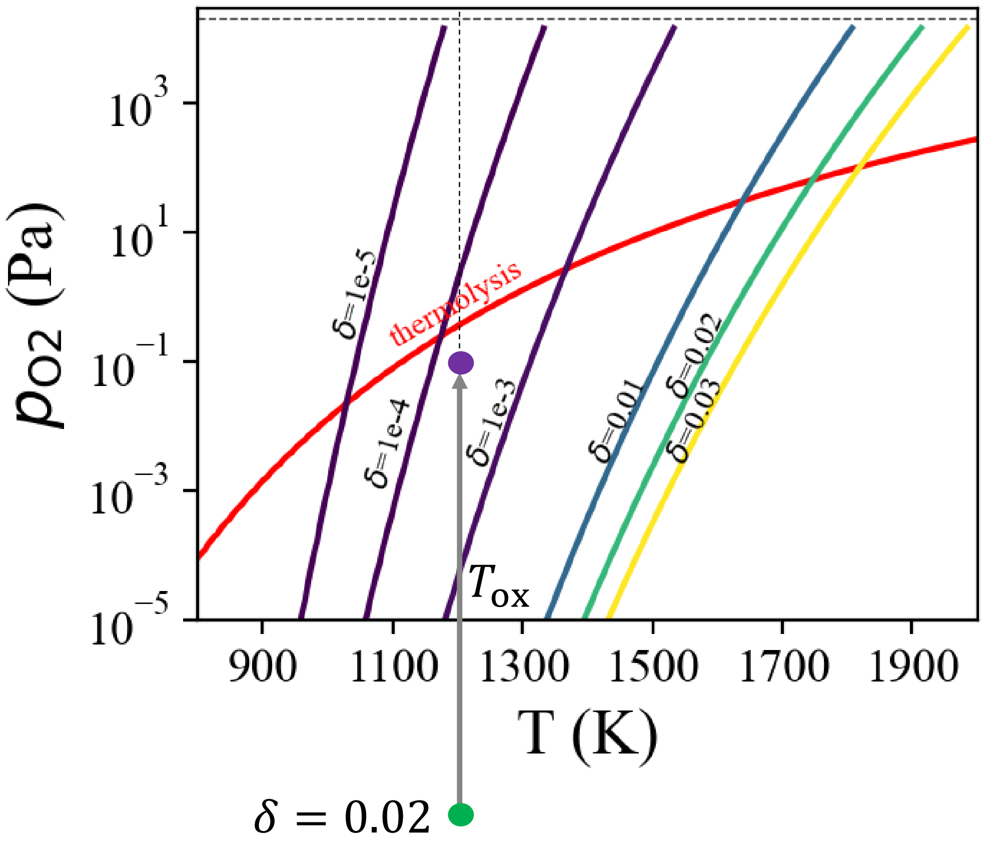


image adapted from [Richter2017]

Oxidation

$$H_2O \leftrightarrow H_2 + \frac{1}{2} O_2$$

$$CeO_{2-\delta} + \frac{\delta}{2}\ O_2 \rightarrow CeO_2$$

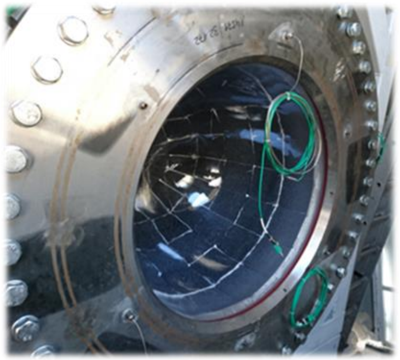


Reactor and System Design Concepts

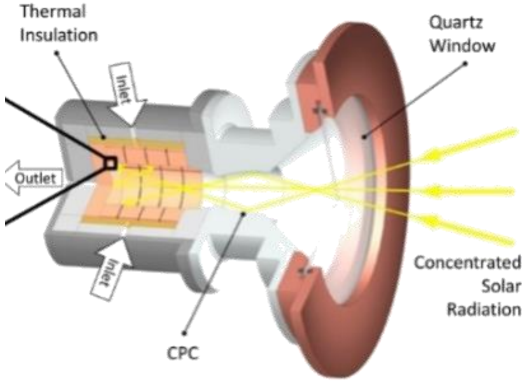
- Redox material must be cycled between
  1. High (1450°C) and low (900°C) temperatures → heat recovery required
  2. Atmospheres with low oxygen partial pressures and steam atmospheres
     - either purge gas or vacuum for low p_{O2}
     - heat/power demand for steam / purge gas / vacuum generation important
- Move the material or change its surrounding conditions?

<u>Fixed Redox Monoliths</u>

Only Purge Gas

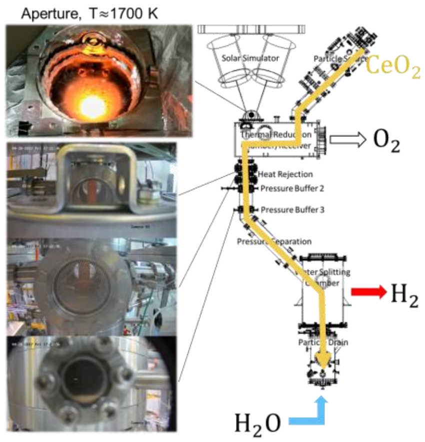


Purge Gas & Vacuum

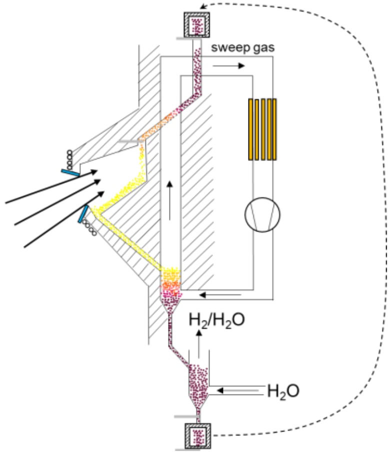


<u>Moving Redox Particles</u>

Vacuum (& Purge Gas)



Only Purge Gas



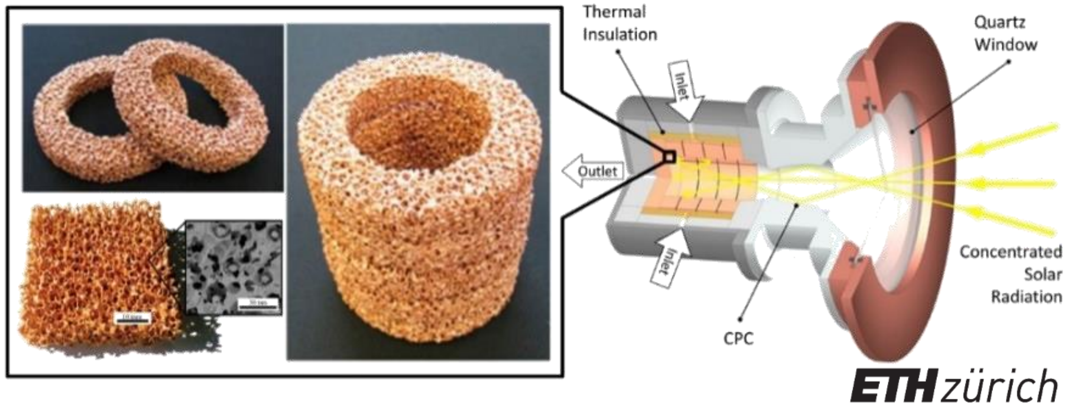
Solar Thermochemical Hydrogen Production

State of the Art: Batch Reactors with Fixed, Porous Monoliths of Redox Material

Source: Plataforma Solar de Almeria (Owned by the Spanish research centre CIEMAT)

Source: DLR

Source: IMDEA / SUN-to-LIQUID project



Solar Thermochemical Hydrogen Production

State of the Art: Batch Reactors with Fixed, Porous Monoliths of Redox Material

Source: Plat
(Owned by t
centre CIEM

1st step: **Reduction**

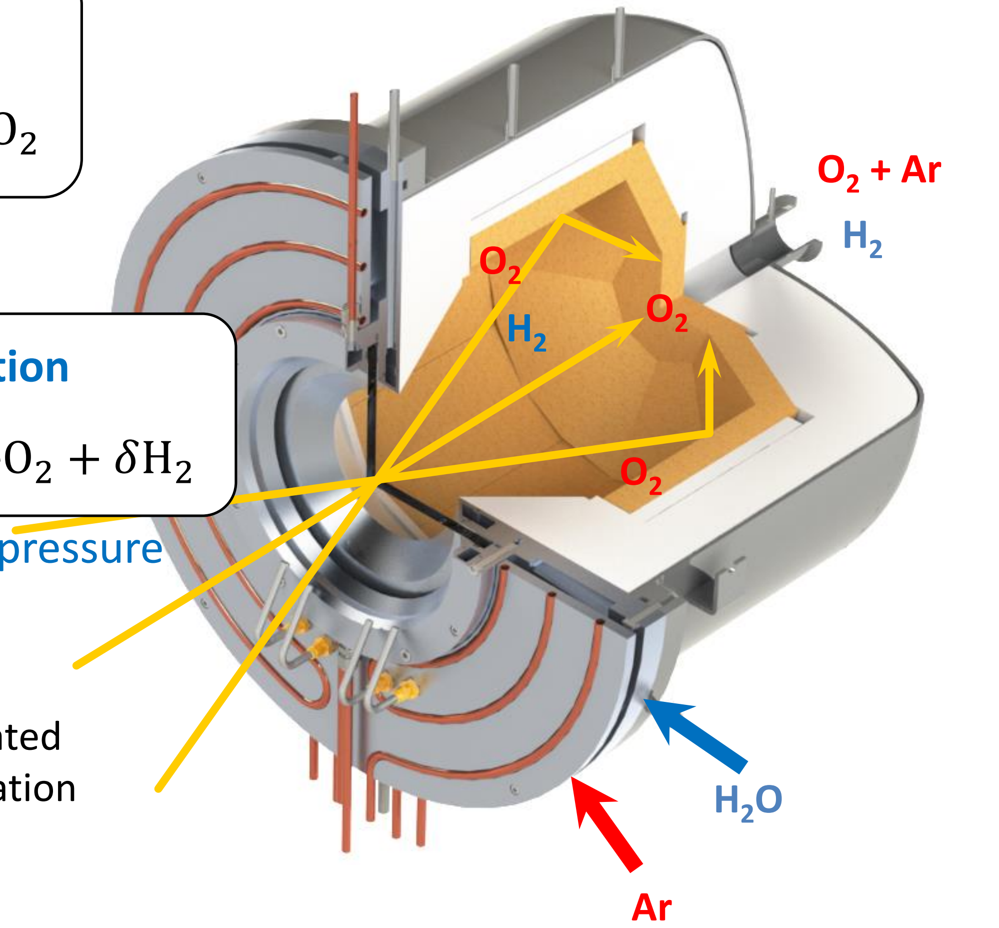
$$CeO_2 \rightarrow CeO_{2-\delta} + \frac{\delta}{2} O_2$$

1500 °C, vacuum

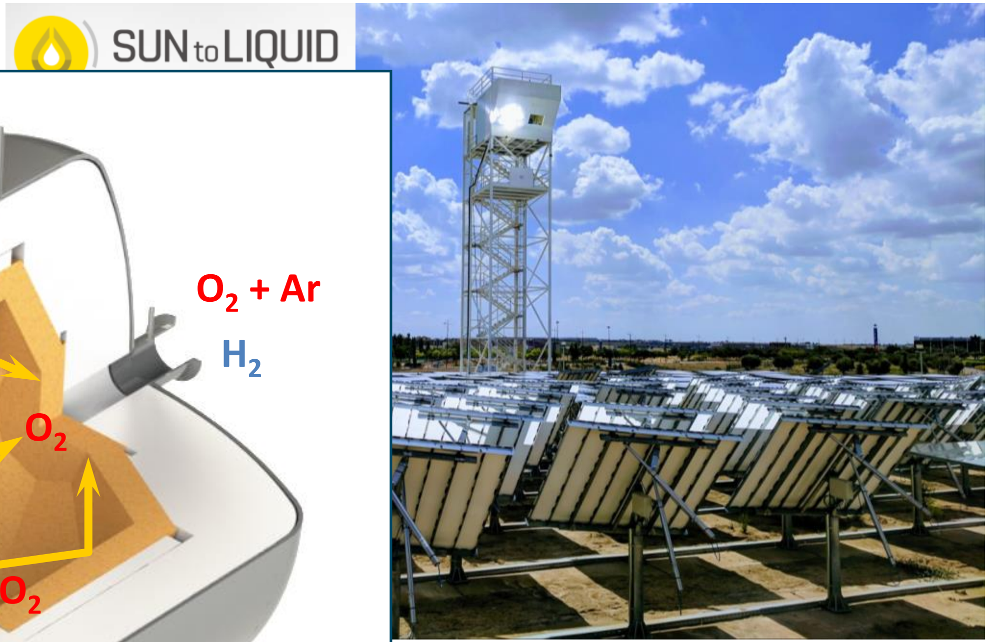
2nd step: **Oxidation**

$$CeO_{2-\delta} + \delta H_2O \rightarrow CeO_2 + \delta H_2$$

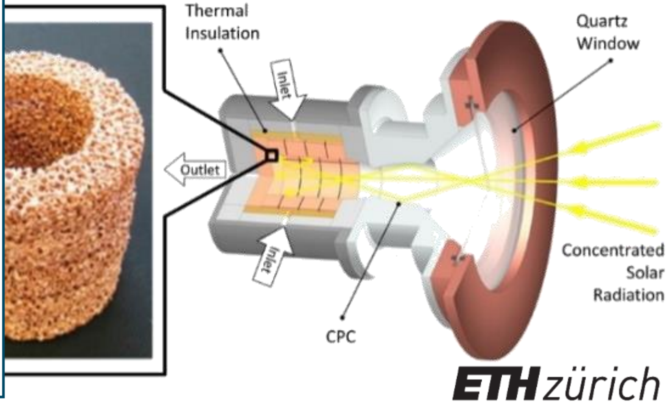
900 °C, atmospheric pressure



Source: adapted from ETH Sun2Liquid schematics



o-LIQUID project



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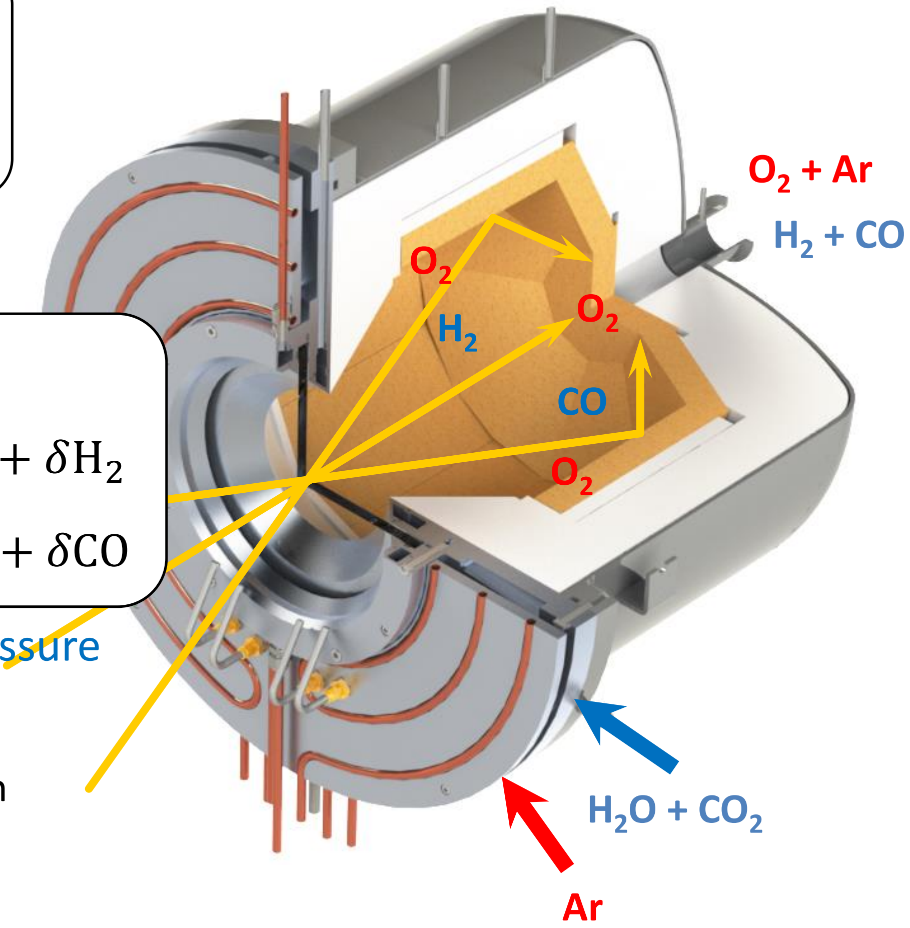
$$CeO_{2-\delta} + \delta H_2O \rightarrow CeO_2 + \delta H_2$$

$$CeO_{2-\delta} + \delta CO_2 \rightarrow CeO_2 + \delta CO$$

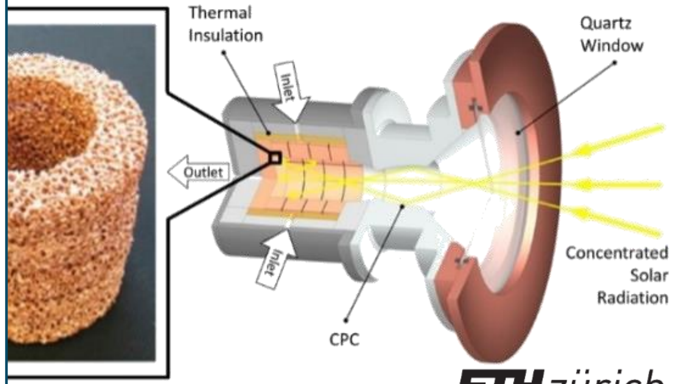
900 °C, atmospheric pressure



Source: adapted from ETH Sun2Liquid schematics

SUN to LIQUID

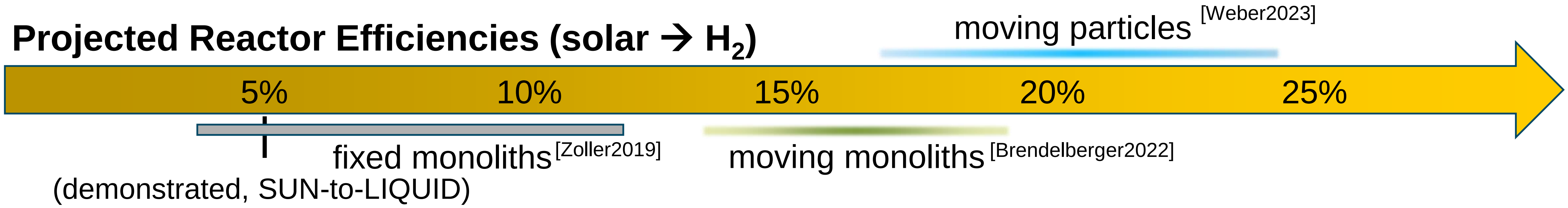
o-LIQUID project



Advantages of Moving Particle Reactor Systems

- Continuous and more flexible operation
- Less sensible heat losses, less thermal stresses
- Easy replacement of redox material
- Better heat transfer & better heat recovery

Projected Reactor Efficiencies (solar → H_2)



DOE-STCH Project (2015-2017)
Vacuum Reactors with Moving Ceria Particles

initial concept

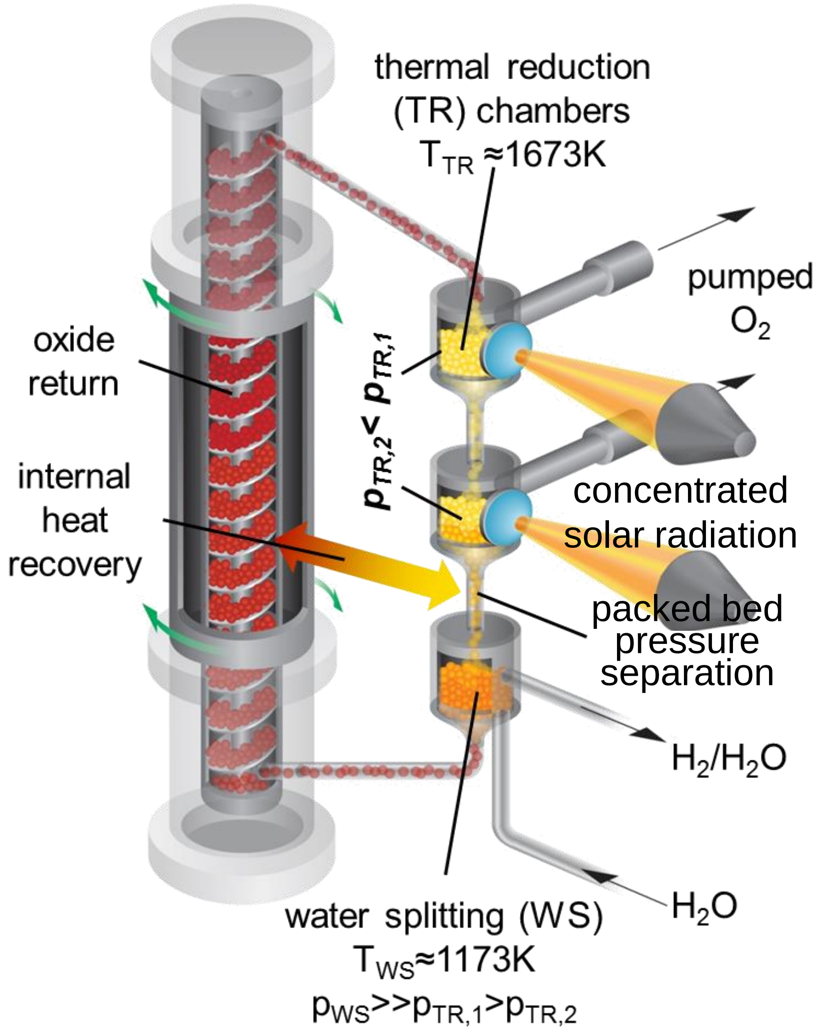


image: Ermanoski2016

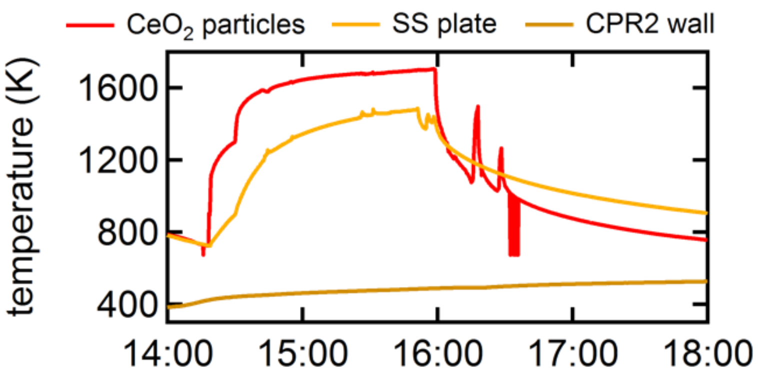
image: Grobbel2017

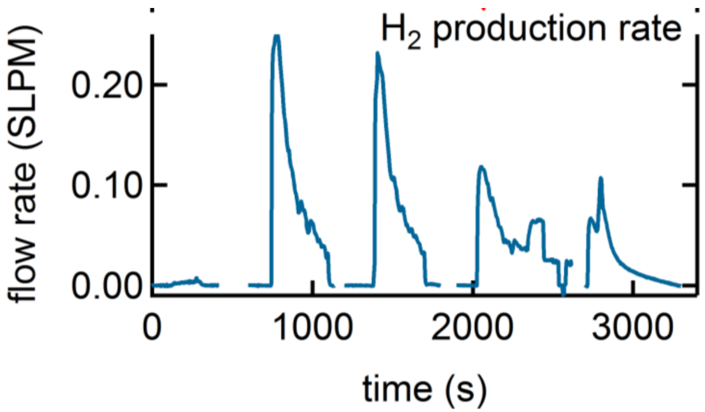
Ceria (CeO_2) Particles

- Sauter diameter 277 µm
- Density 6.6 g/cm³

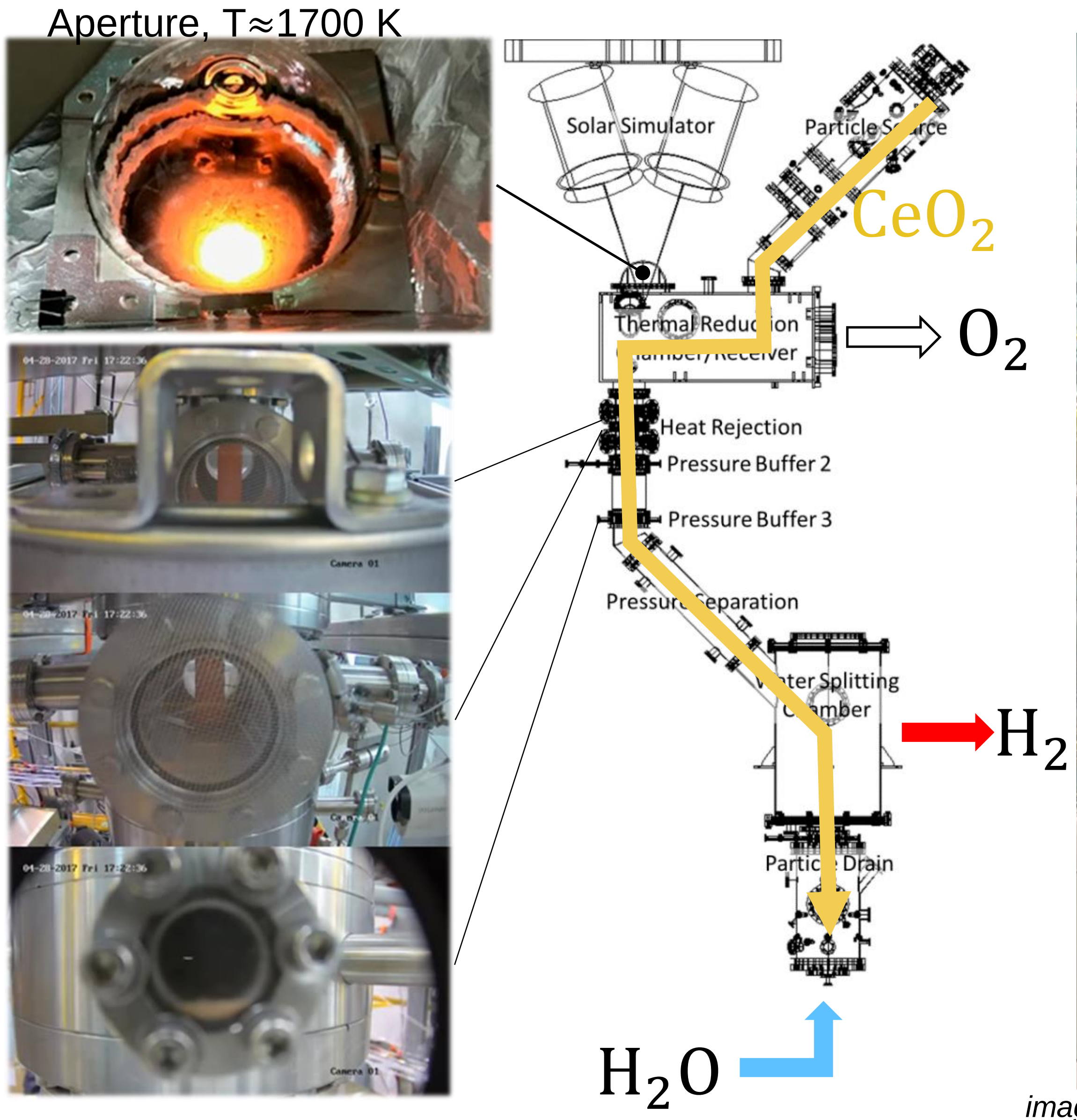
DOE-STCH Project (2015-2017)

Vacuum Reactors with Moving Ceria Particles





- Particles heated to 1700 K
- 0.25 SLPM peak H_2 rate

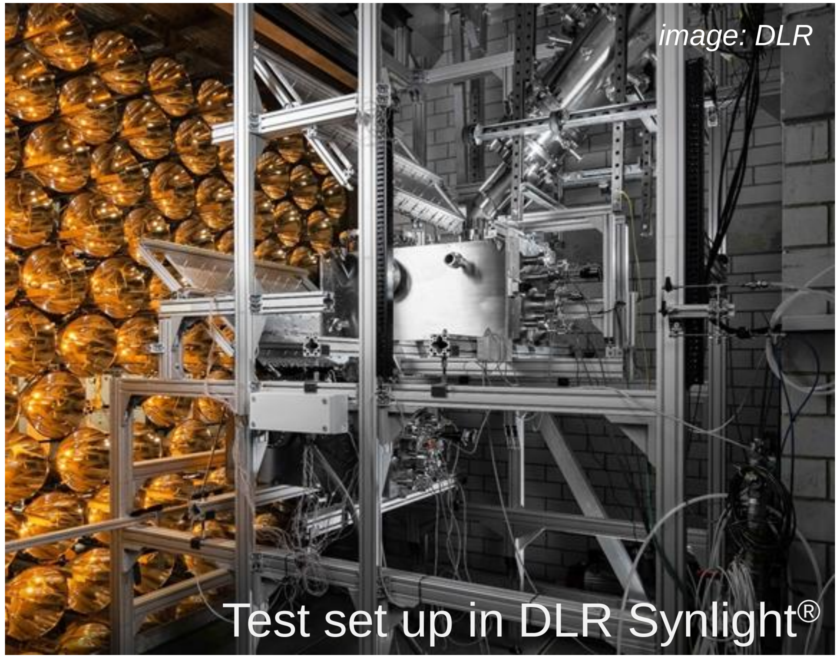


images: adapted from SANDIA

Ongoing Work of Sandia and DLR

Main goals:

- Improve vacuum receiver-reactors
- Prove pressure separation by packed bed between two receivers
- Collect more operational data in DLR Synlight®



Test set up in DLR Synlight®

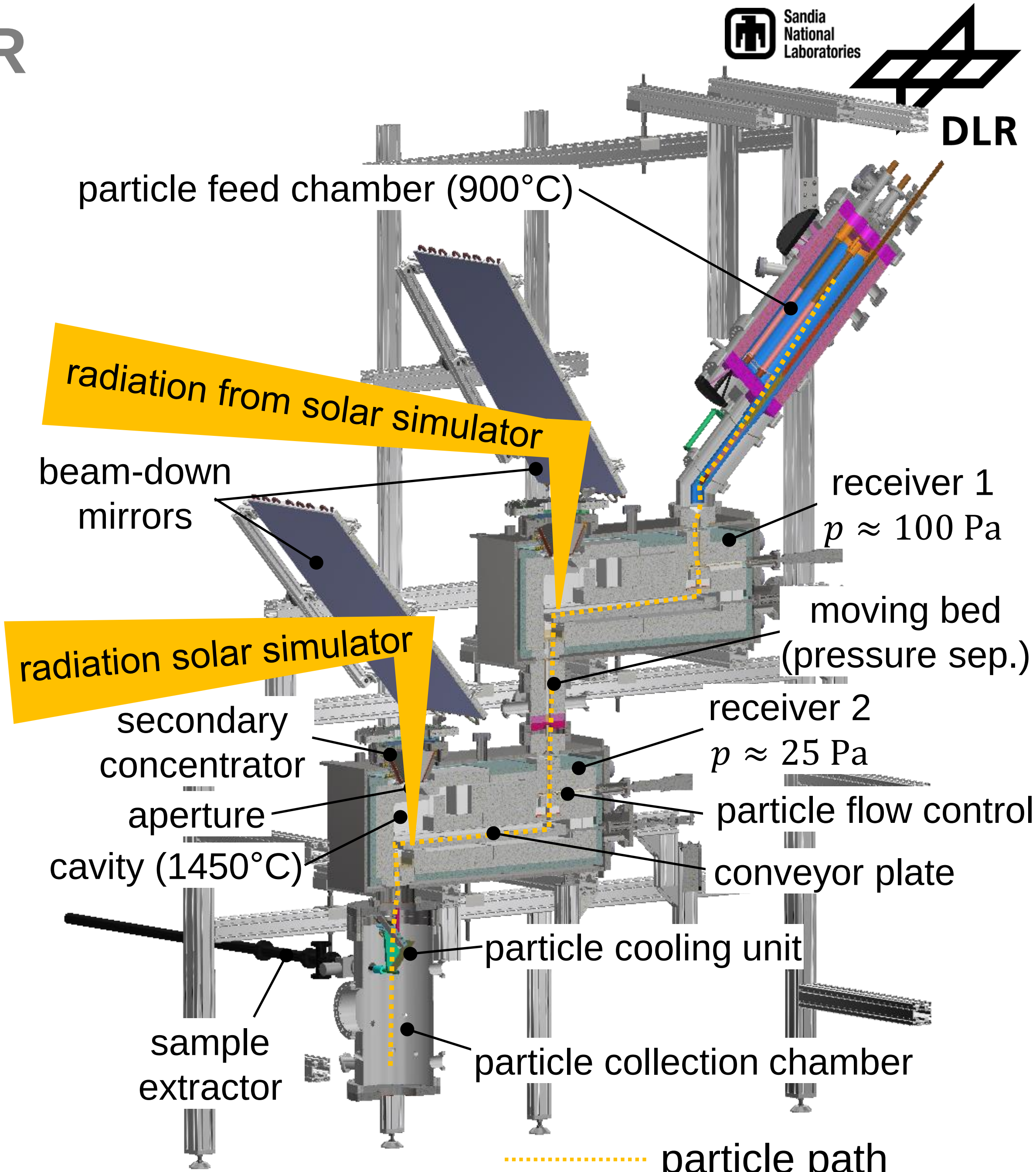


image: Grobbel2022

SOMPIHR

Sweep (gas) & open moving particle receiver with heat recovery

- Lessons Learned
  → New concept
- Advantages:
  - Continuous operation
  - good part load behavior through particle flow control
  - No window
  - No high-temperature valves
  - purge gas for efficient heat recovery
  - high-temperature purge gas cleaning → lower parasitic losses
- Patent pending

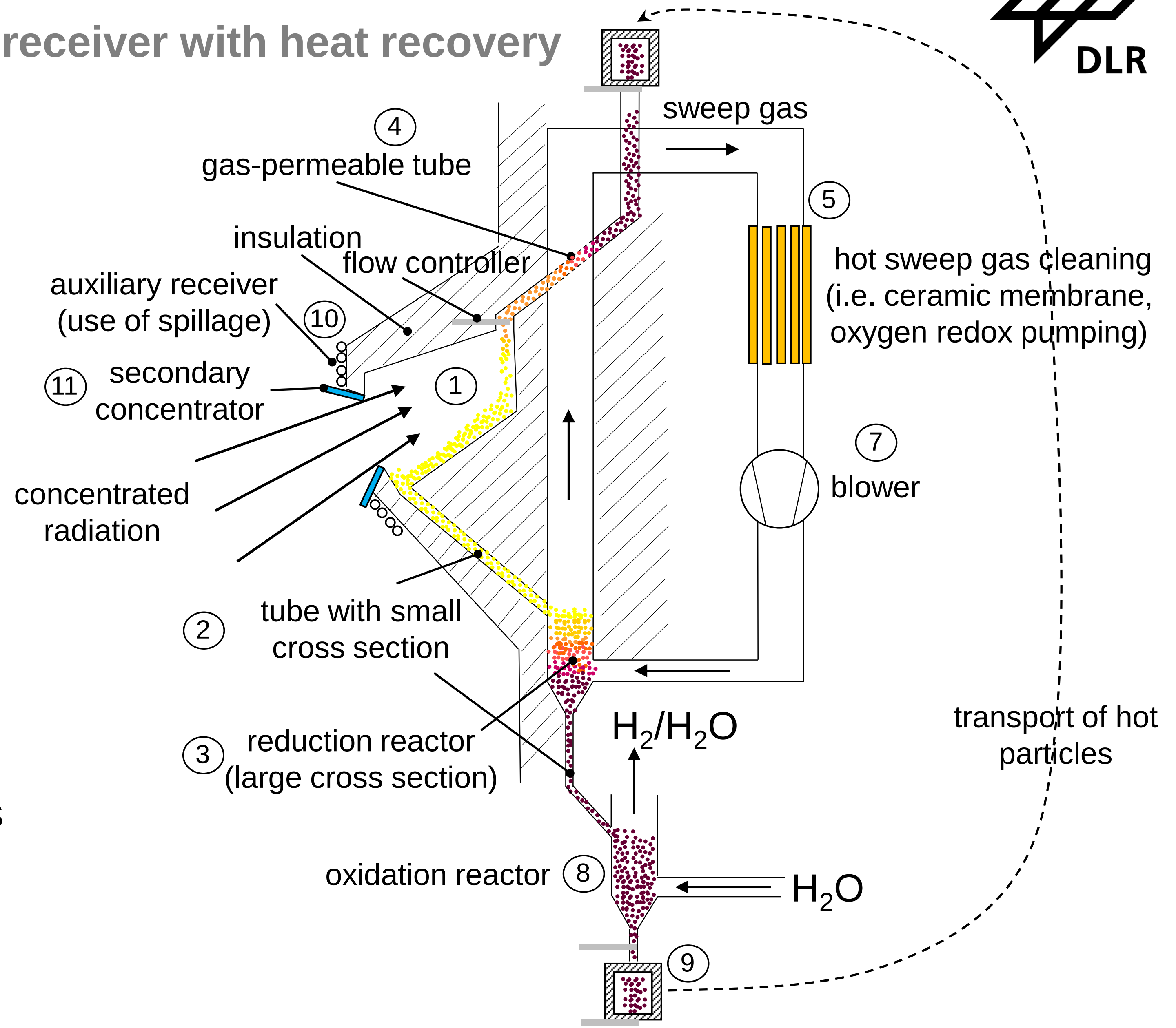
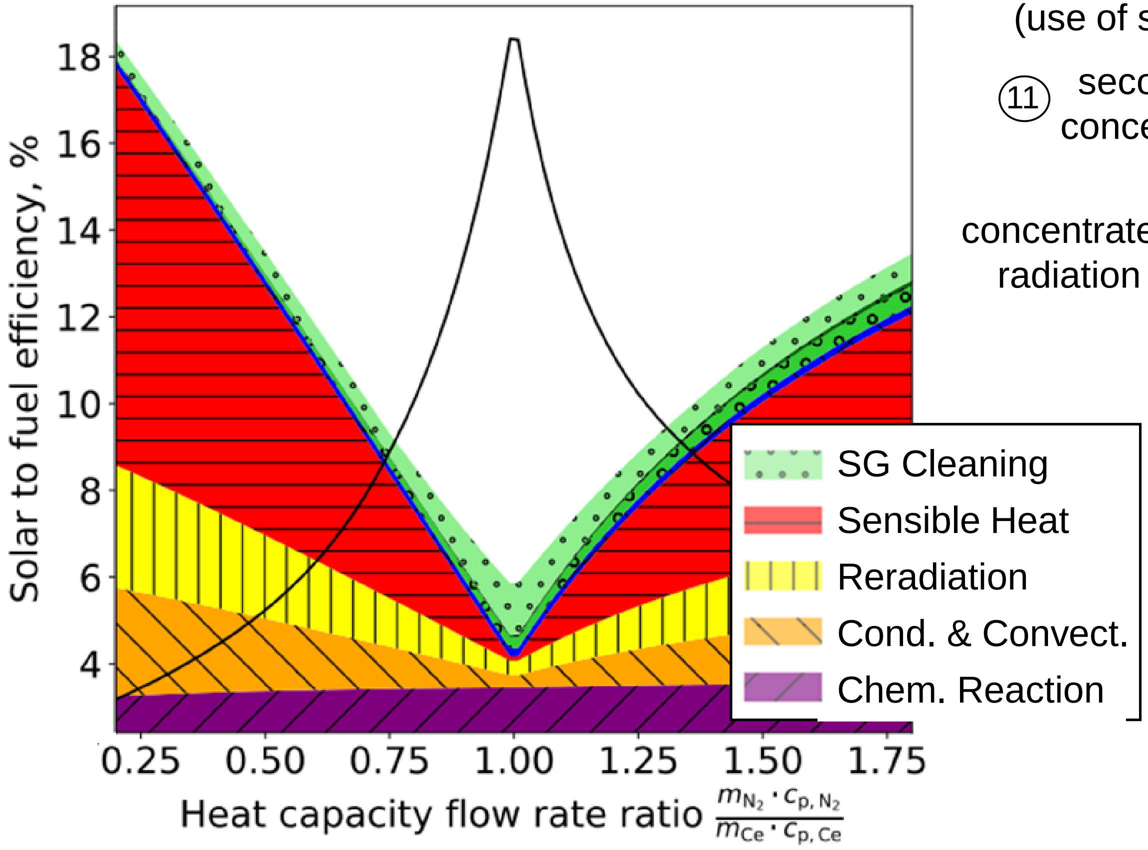


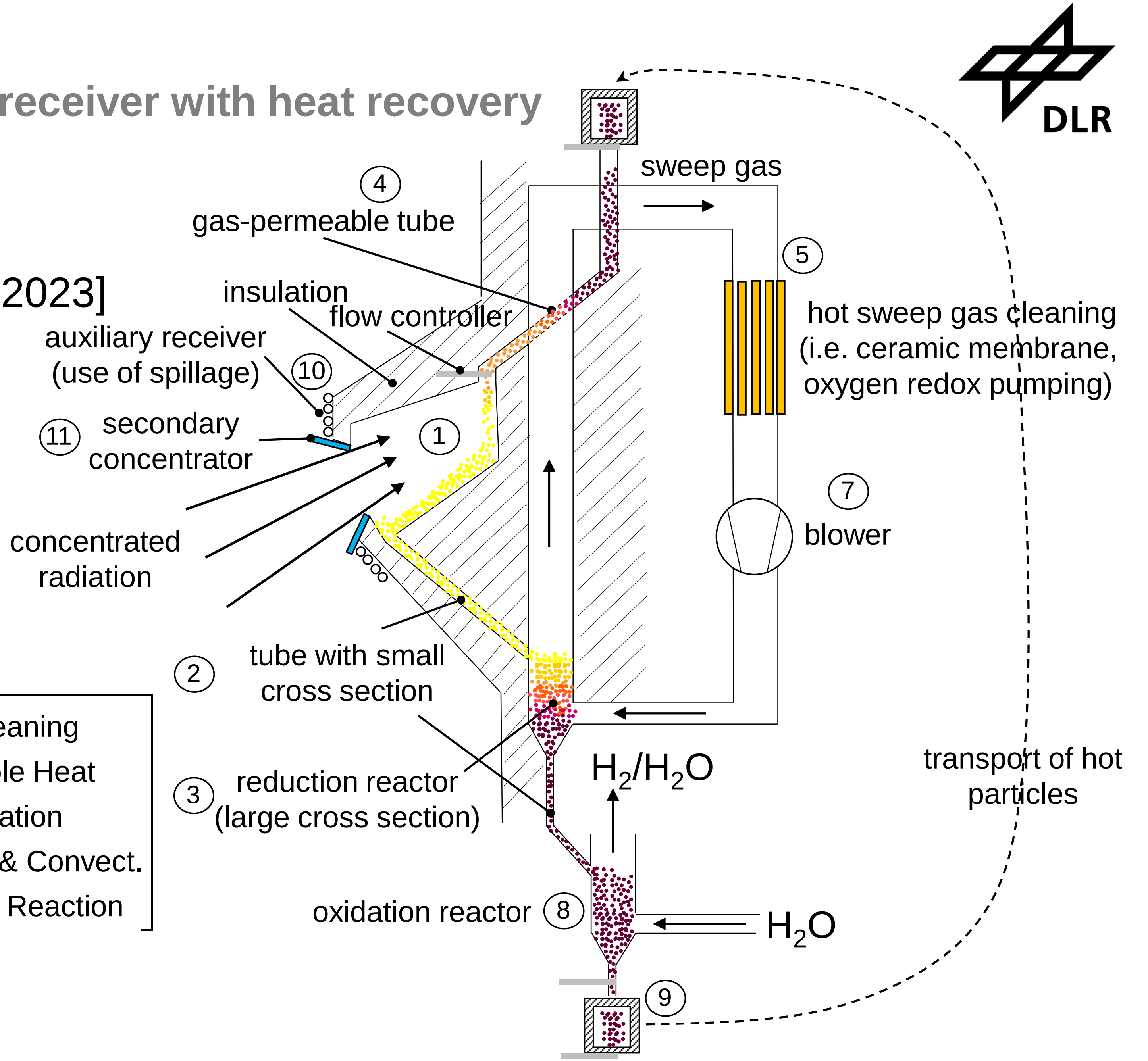
image: DLR

SOMPIHR

Sweep (gas) & open moving particle receiver with heat recovery

- Projected solar to H2 efficiency for prototype scale (2 kW): ~18% [Weber2023]

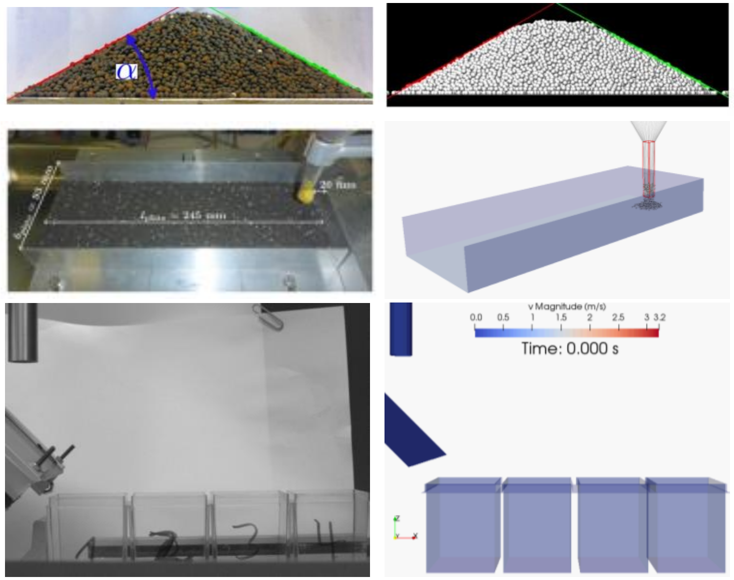




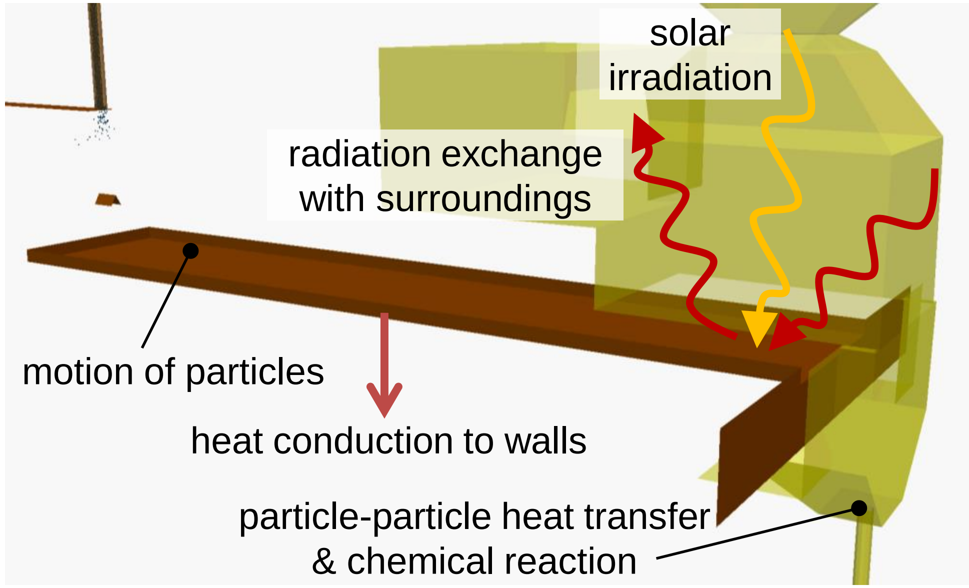
images: DLR

Modeling Solar Particle Receivers

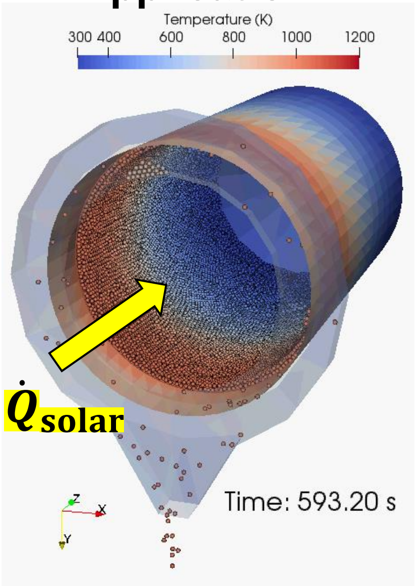
Calibration of contact models



Heat transfer models



Application



Discrete Element Method (DEM) coupled to CFD

- Particle motion
- Heat transfer
- Reactions

Challenges and Outlook

Challenges (some of them):

- Moving particles at very high temperatures (1500°C)
- Wear on particles and components
- Gas flow control through particle beds (uniformity, pressure drop, …)

Outlook:

- Prototype testing of vacuum reactor system in DLR Synlight
- Modeling of new SOMPIHR concept (i.e. CFD-DEM models)
- Prototype design and construction

Summary

- Concentrated solar energy can drive high-temperature chemical redox reactions to produce hydrogen or syngas (w/o producing electricity first)
- Reactor efficiencies can be increased significantly by moving the redox material instead of changing its surrounding conditions (temp. / p_{O2})

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