Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO_2, syngas formation and Fischer-Tropsch synthesis

Power-to-X: On the development of a KEROGREEN reactor module for sustainable CO production and the challenges in CO_2 plasmolysis and gas separation

***S. Welzel*, A. Goede, M.C.M. van de Sanden, M. Tsampas**

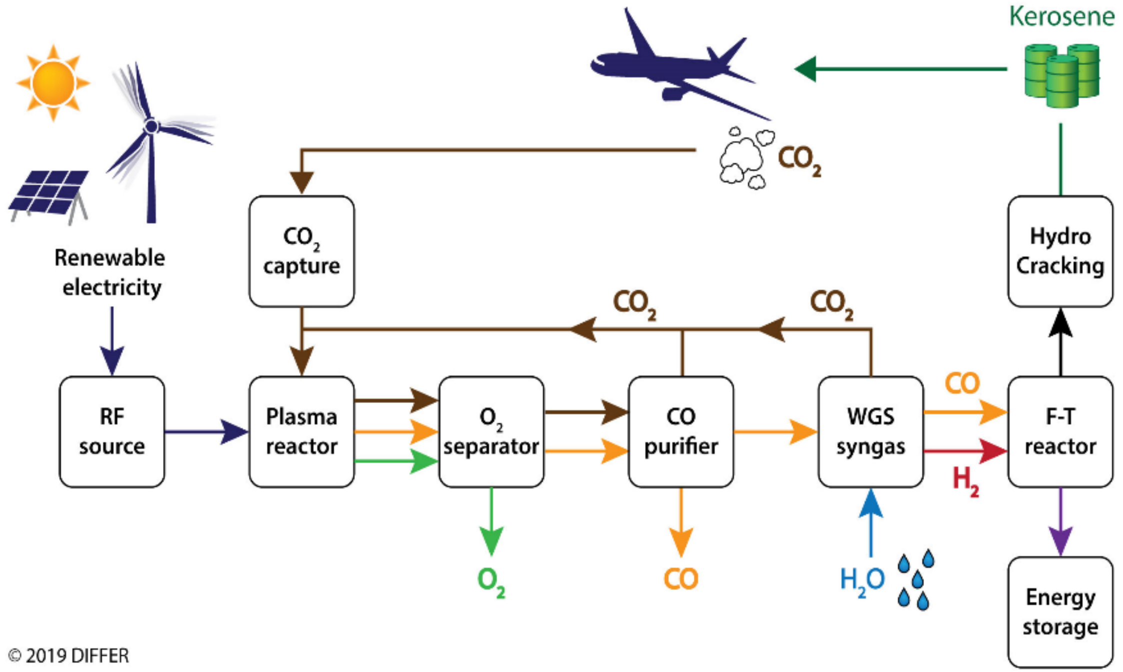
DUTCH INSTITUTE FOR FUNDAMENTAL ENERGY RESEARCH, EINDHOVEN, THE NETHERLANDS

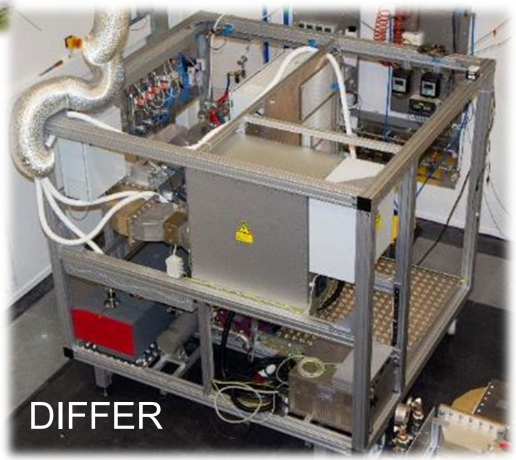
Trend workshop: "Plasma(-catalysis) in gas conversion processes"

18th International Conference on Plasma Surface Engineering
12/09/2022

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under GA-Nr. 763909

The KEROGREEN project





Kerogreen aim: Demonstation of the full chain process from renewable, electricity, CO_2 (captured) and H_2O to kerosene.

- Research and optimisation of individual process steps TRL (1-3) → 4
- Integration phase at Karlsruhe Institute of Technology → >1 L per day
- Duration 2018-2022

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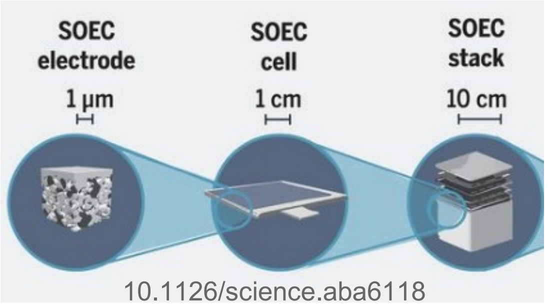
Outline

- The **KEROGREEN** project
- **Plasmolysis of CO_2**
  - Scientific insights of microwave plasma based processes
  - Engineering constraints during process chain integration
- **Oxygen separation**
  - Solid Oxide Electrochemical Cell (SOEC) based approach
  - Potential & Challenges
- Summary



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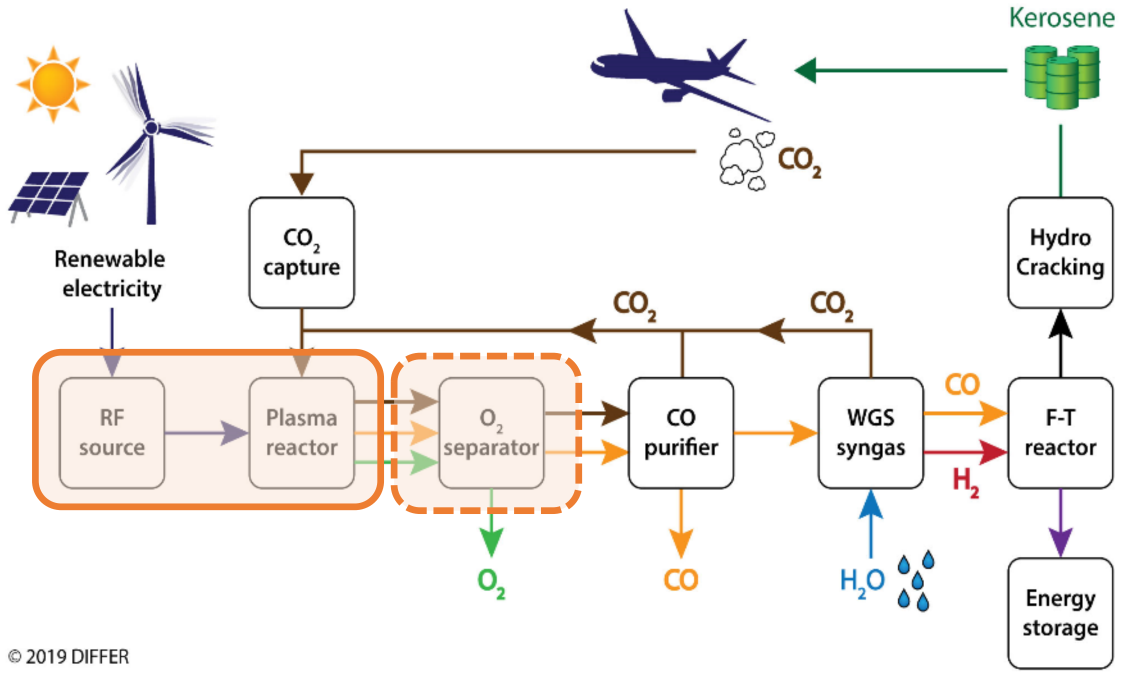
The KEROGREEN project



Main *project* challenges

- System integration of different technologies into one container sized assembly
- Oxygen separation after plasmolysis by SOEC
- Energy and carbon efficiency of the full chain

Main *upstream* (DIFFER) challenges

- Plasma modeling and optimisation
- Plasma upscaling 1 → 6 kW (2450 → 915 MHz)
- (Material) Requirements for using SOECs as oxygen separator
- SOEC upscaling from 1 W to 1500 W

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under GA-Nr. 763909

FINAL EVENT

27th September 2022 – 8:45-15:15 hrs
@ KIT, Karlsruhe + remote

Current challenges in Sustainable Aviation Fuel synthesis
Power-to-X enabling technology combined with Plasma Technology

Get an overview of the latest KEROGREEN results
Exchange ideas and discuss with invited speakers
On-site visit to KIT Energy Lab 2.0

>>> Registration: https://www.kerogreen.eu/249.php <<<

DIFFER | KIT Karlsruhe Institute of Technology | vito | Cerpotech | HYGEAR | INERATEC

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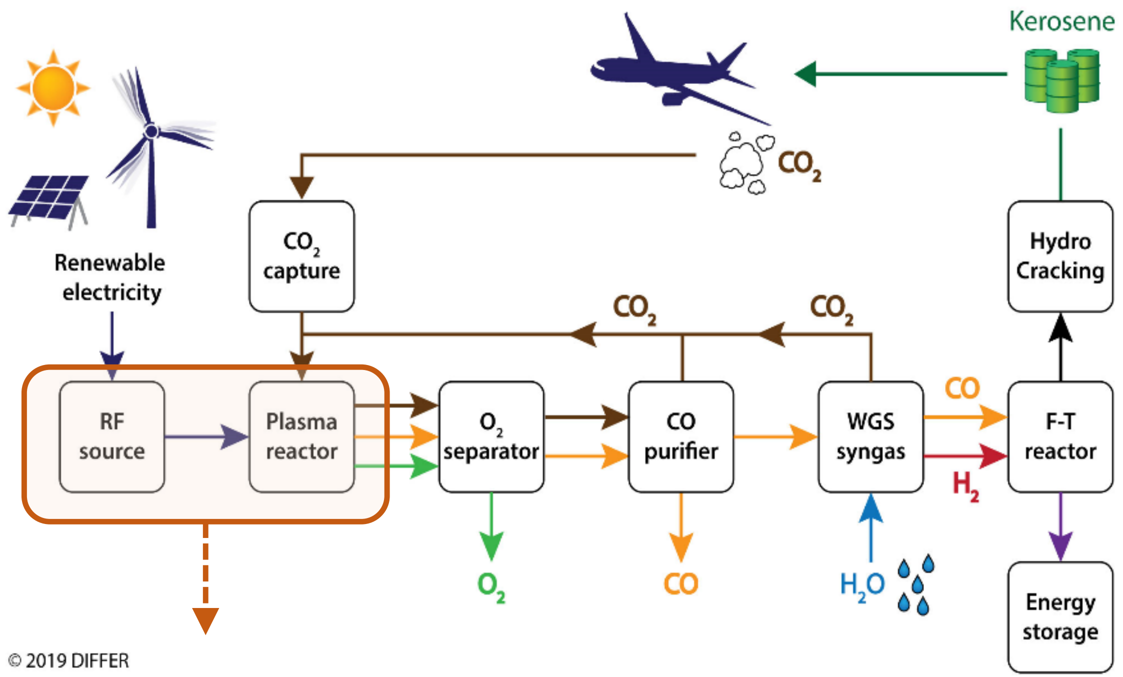
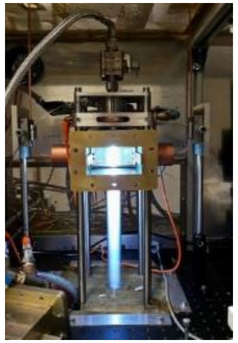
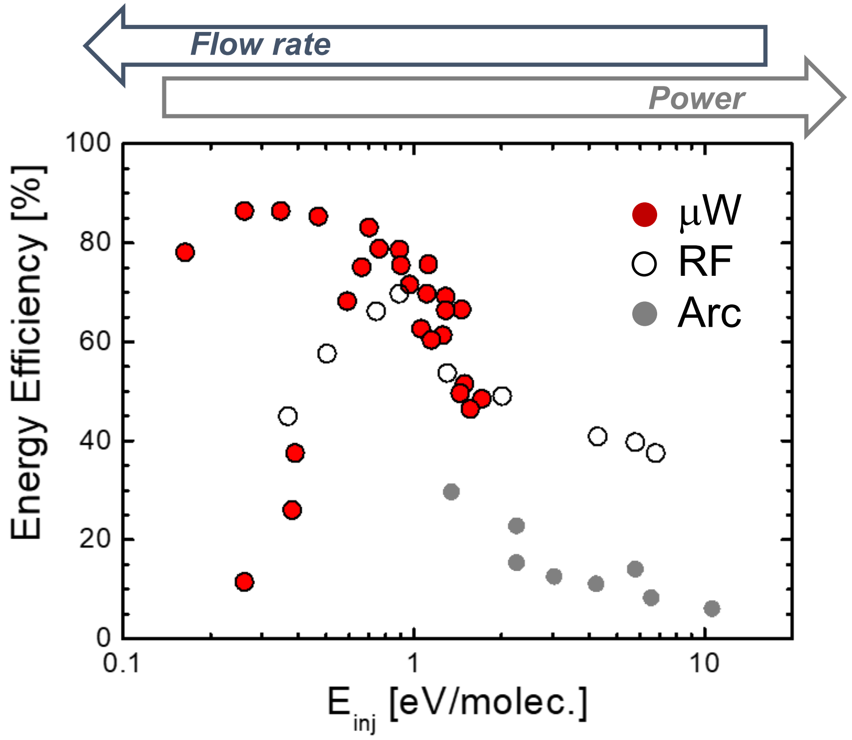
Why CO_2 plasmolysis?



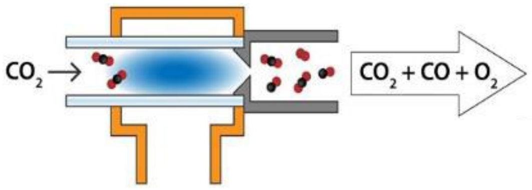




DOI: 10.1017/CBO9780511546075

CO_2 plasmolysis: $2CO_2 \rightarrow 2CO + O_2$

- Input: CO_2 + renewable electricity
- Output: CO_2, CO and O_2
- High efficiencies, …
- Main challenge downstream: O_2 separation



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CO_2 plasmolysis in literature

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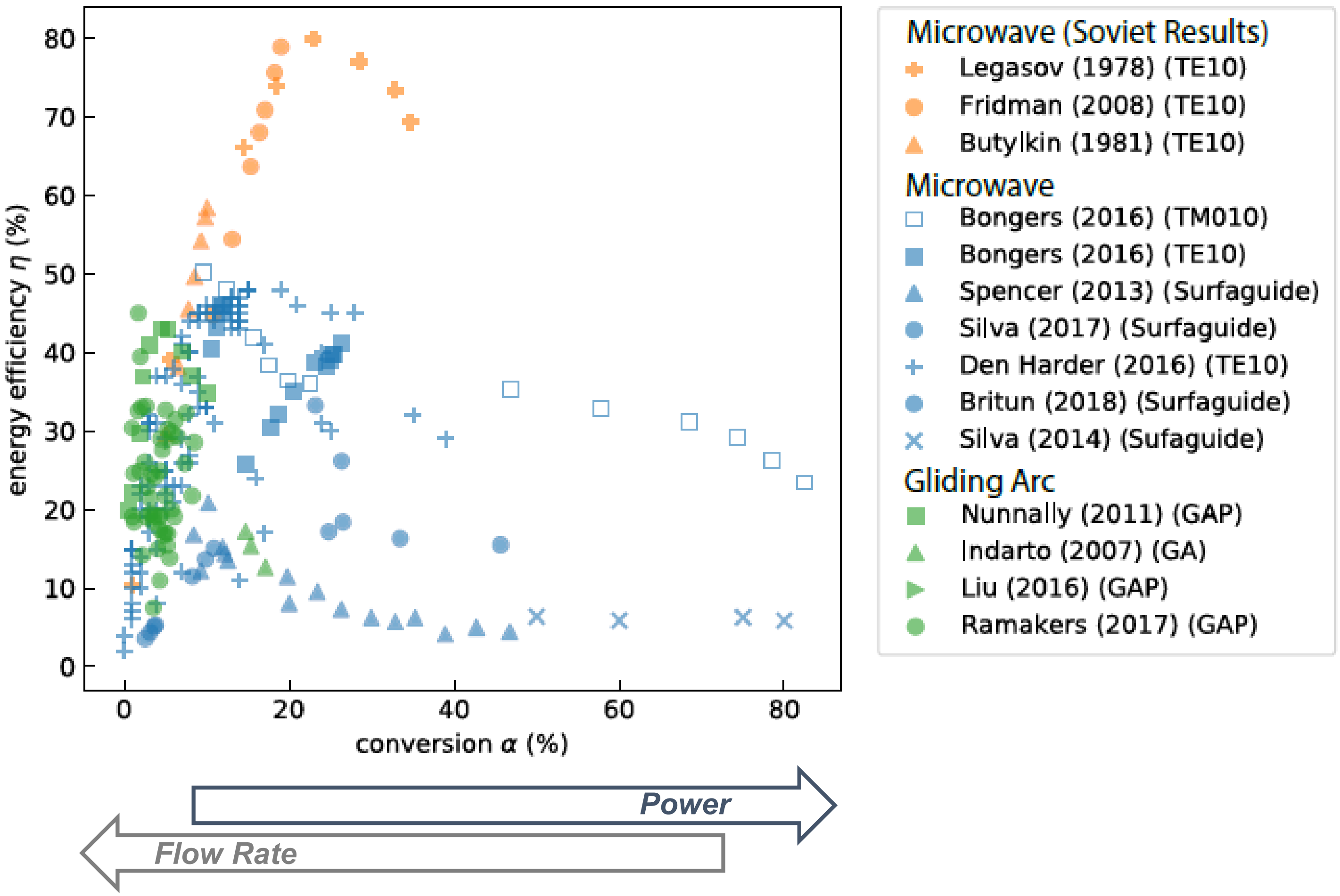

Specific Energy Input (SEI, E_{Spec})

$$E_{spec} = \frac{P_{RF}}{F_{CO2}} = \alpha \cdot E_{CO}$$

Conversion efficiency (α)
Energy efficiency (η)

$$\eta = \alpha \cdot \frac{H}{E_{spec}} = C \cdot \frac{F_{CO2}}{P_{RF}}$$

AJ Wolf PhD Thesis, Eindhoven Univ. Technology, 2021

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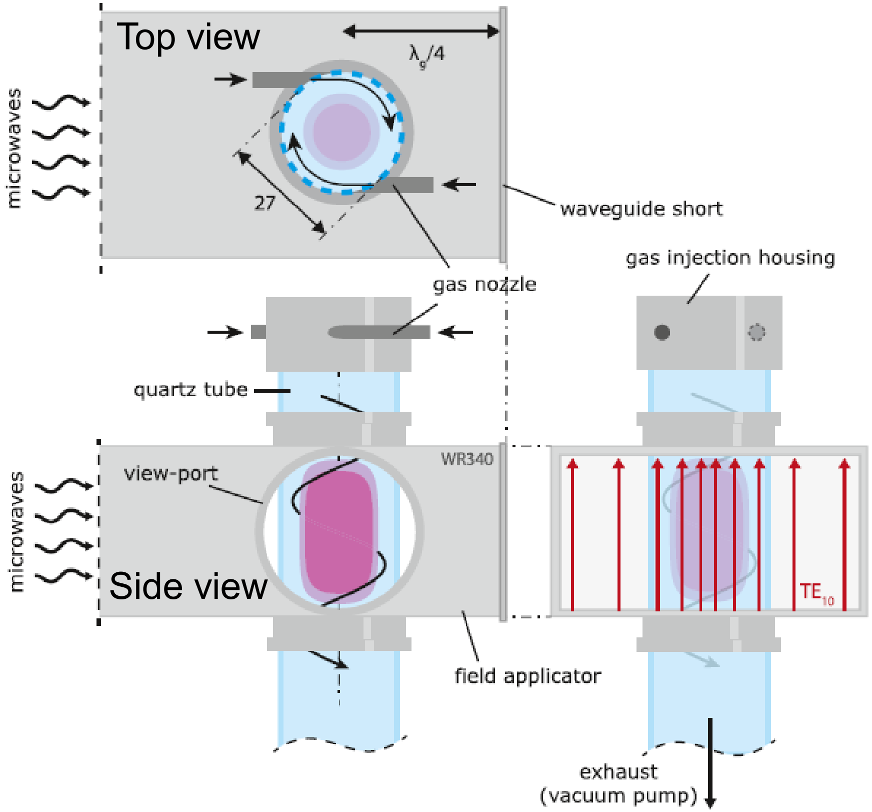
CO_2 plasmolysis: Experimental insights

DIFFER



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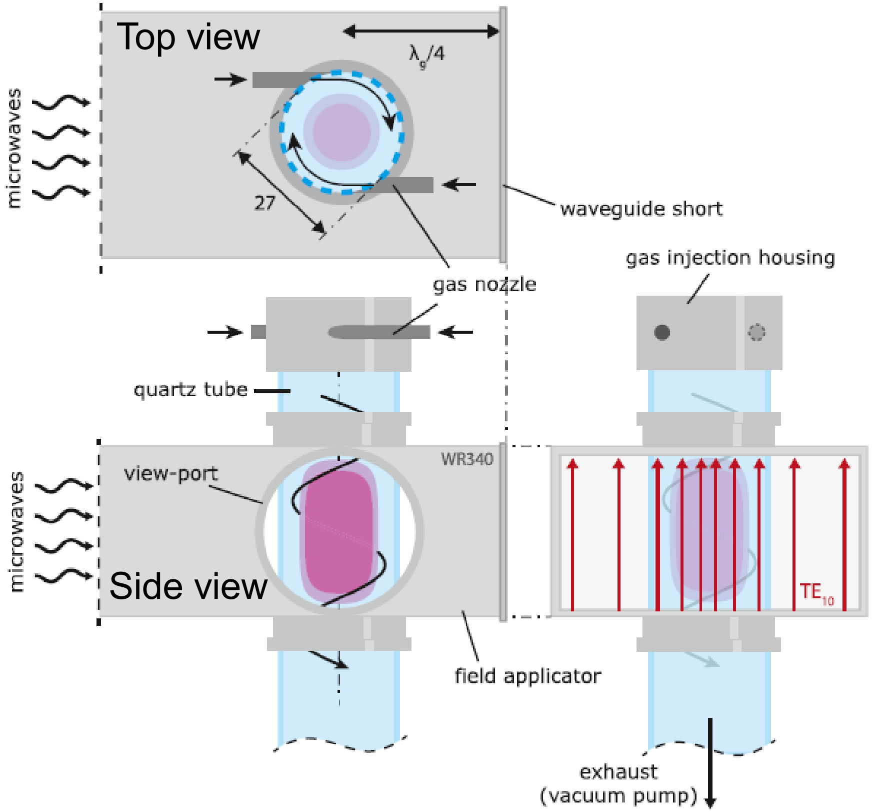

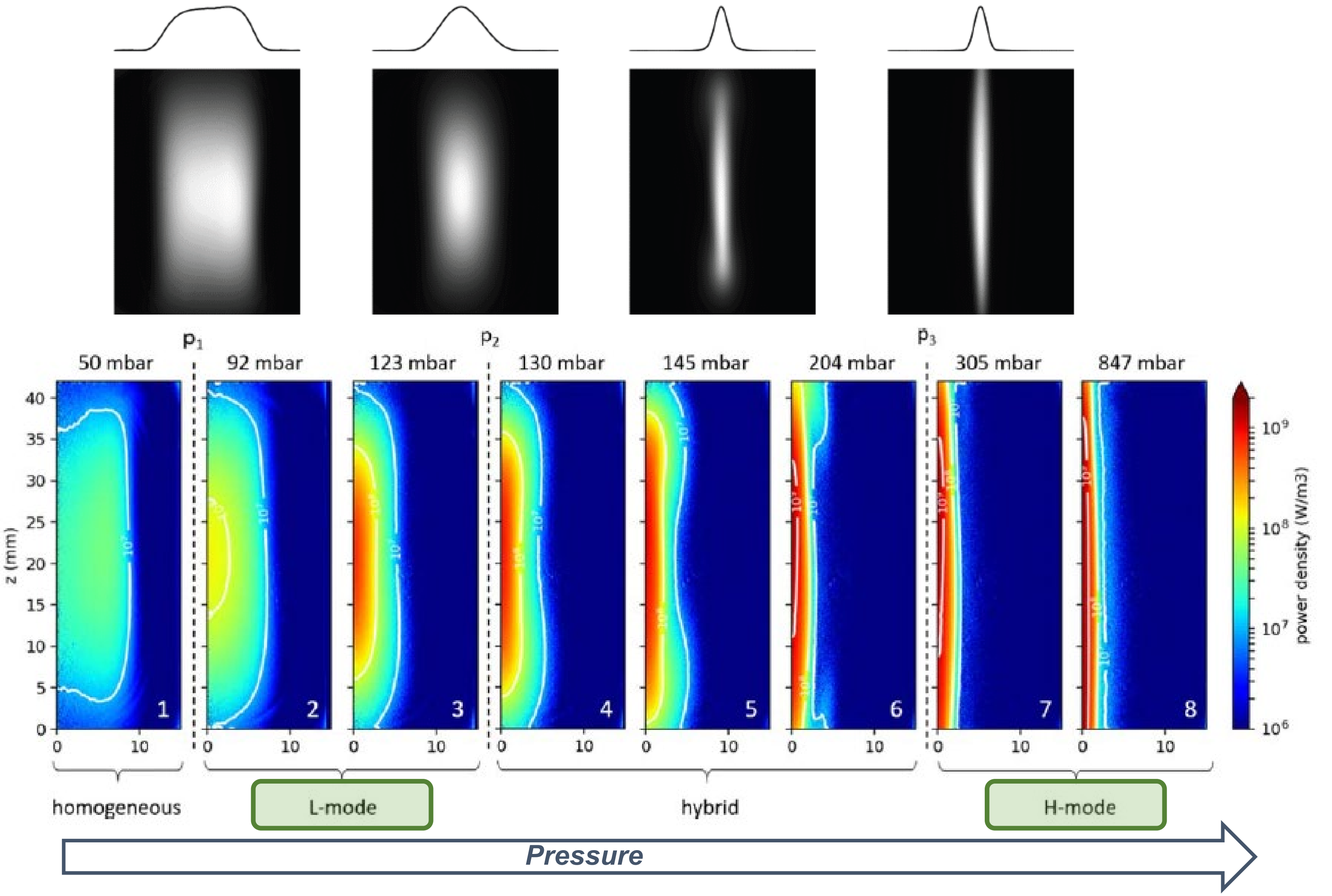

- Strong pressure dependence
- Low → High confinment modes

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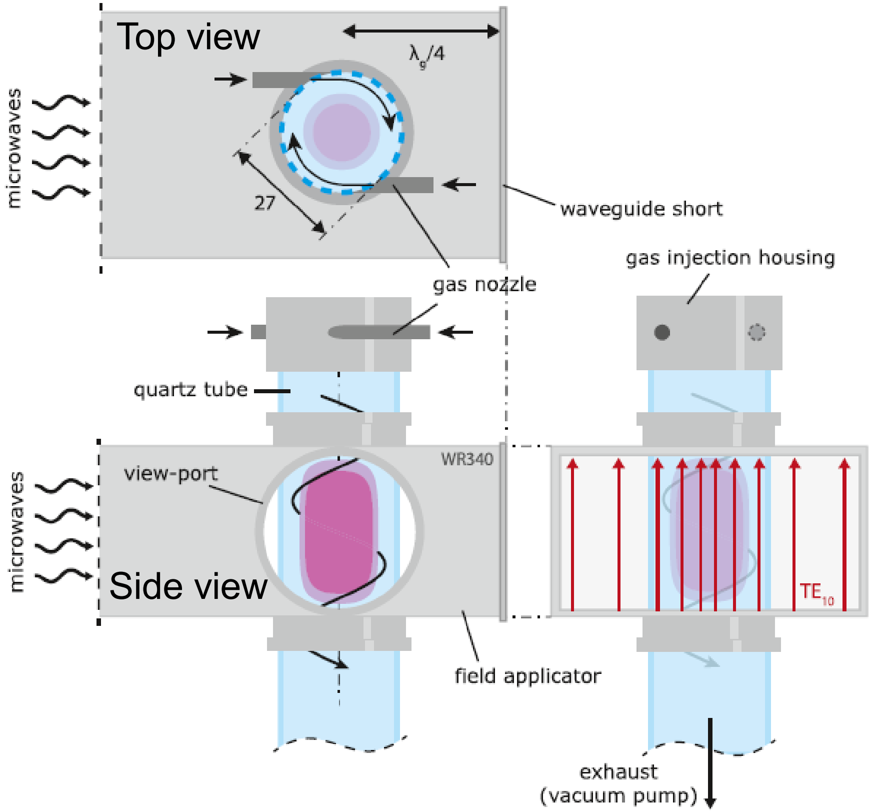

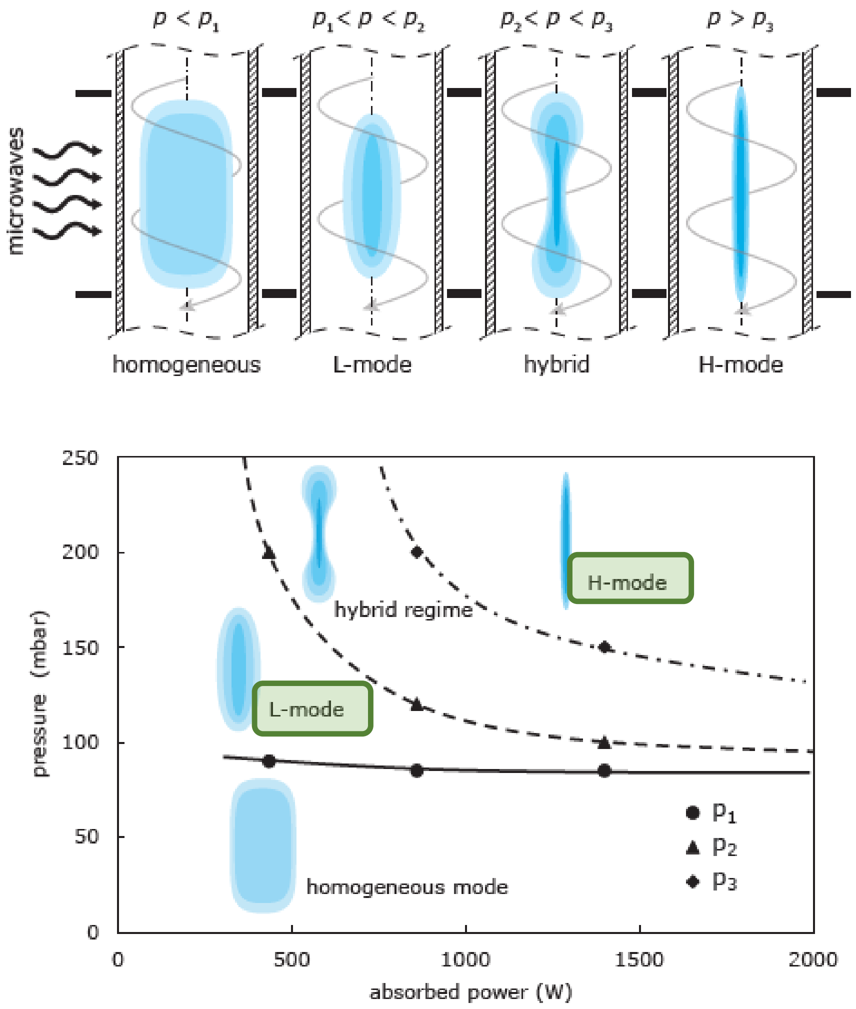

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AJ Wolf PhD Thesis, Eindhoven Univ. Technology, 2021
AJ Wolf et al. 2019 Plasma Sources Sci. Technol. **28** (2019) 115022

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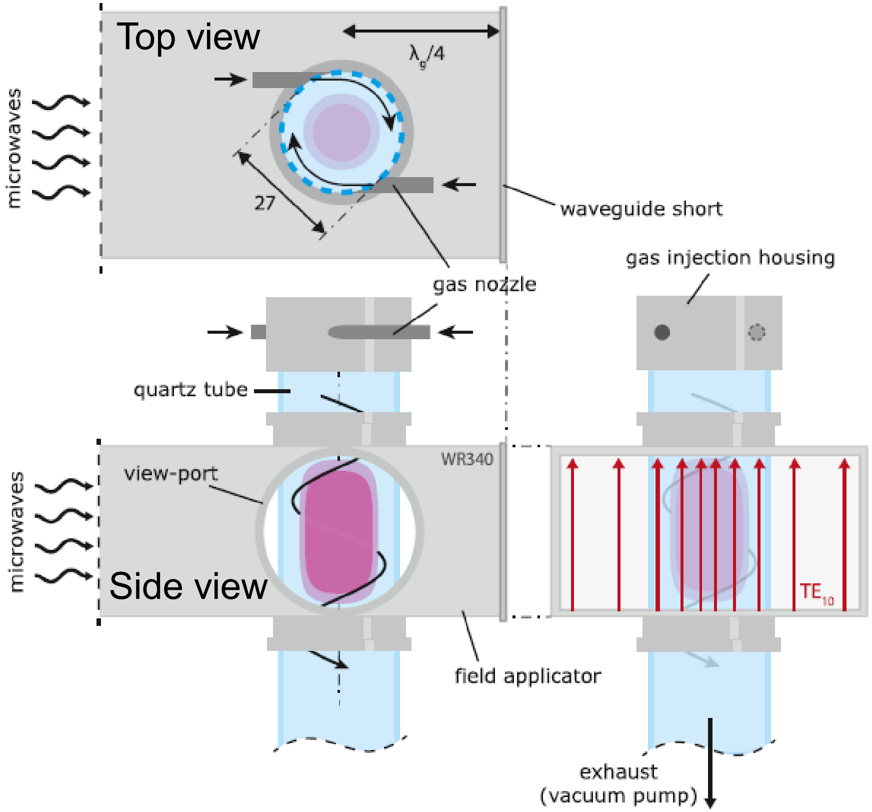
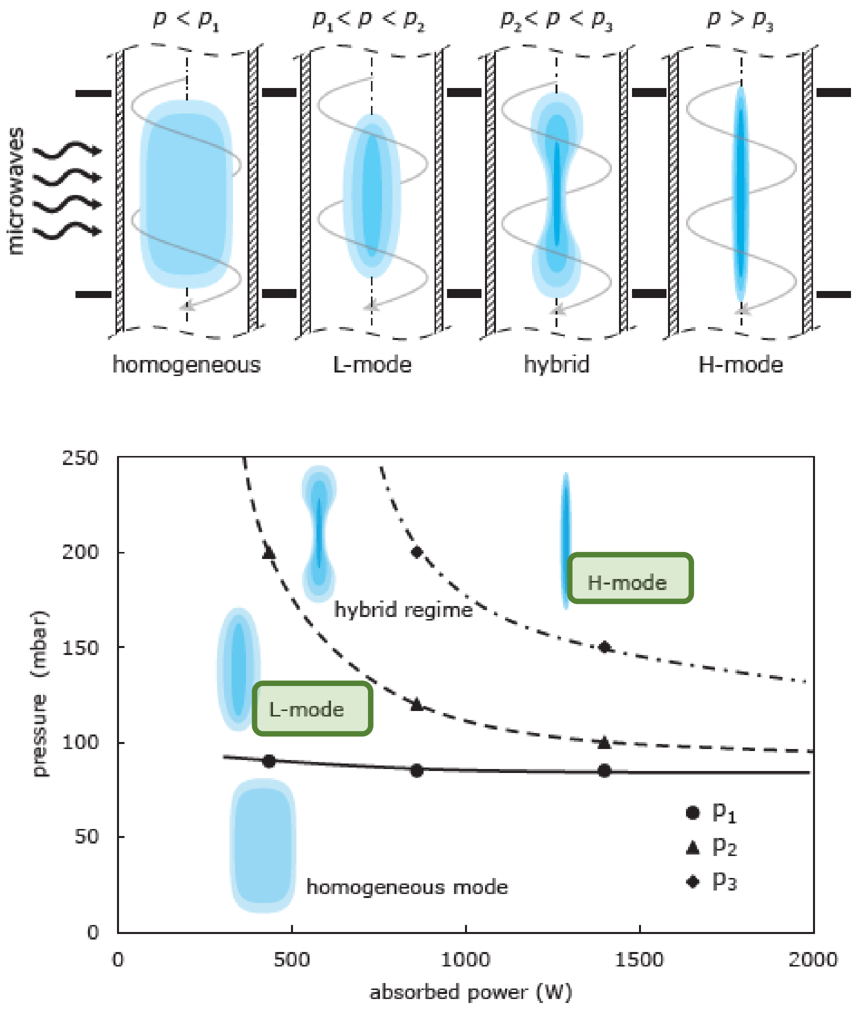
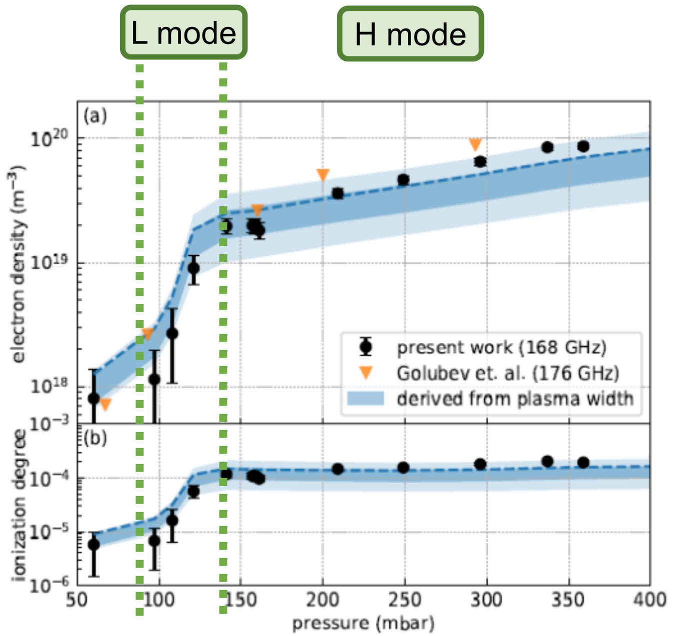
CO_2 plasmolysis: Experimental insights





Ionisation degree



- Mode transition reflected
  - in ionisation degree

AJ Wolf PhD Thesis, Eindhoven Univ. Technology, 2021
AJ Wolf et al. 2019 Plasma Sources Sci. Technol. **28** (2019) 115022

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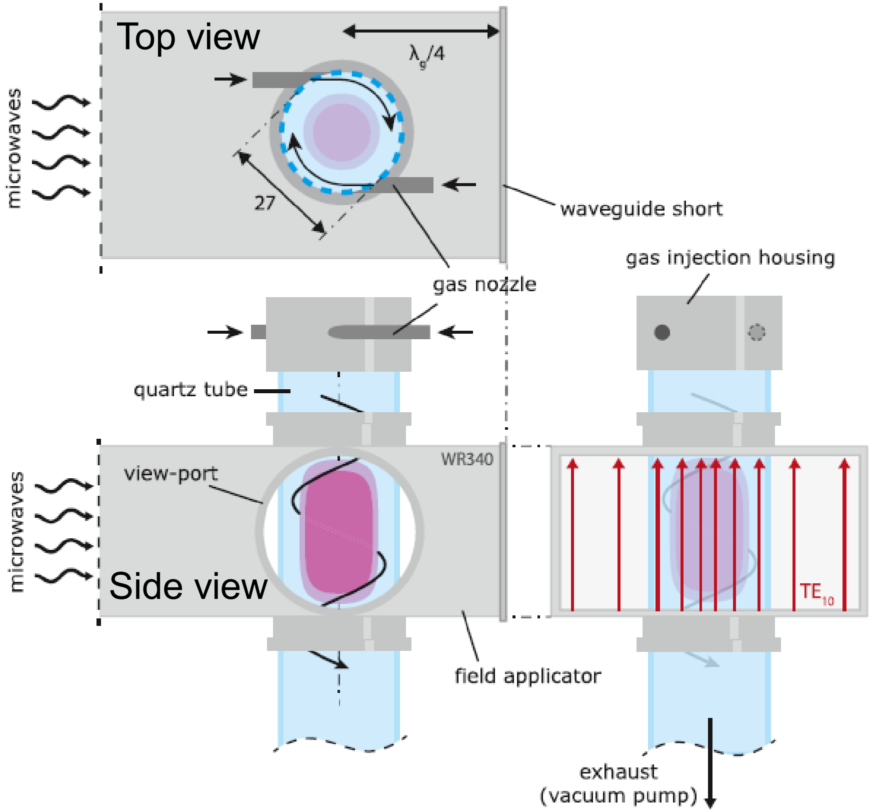
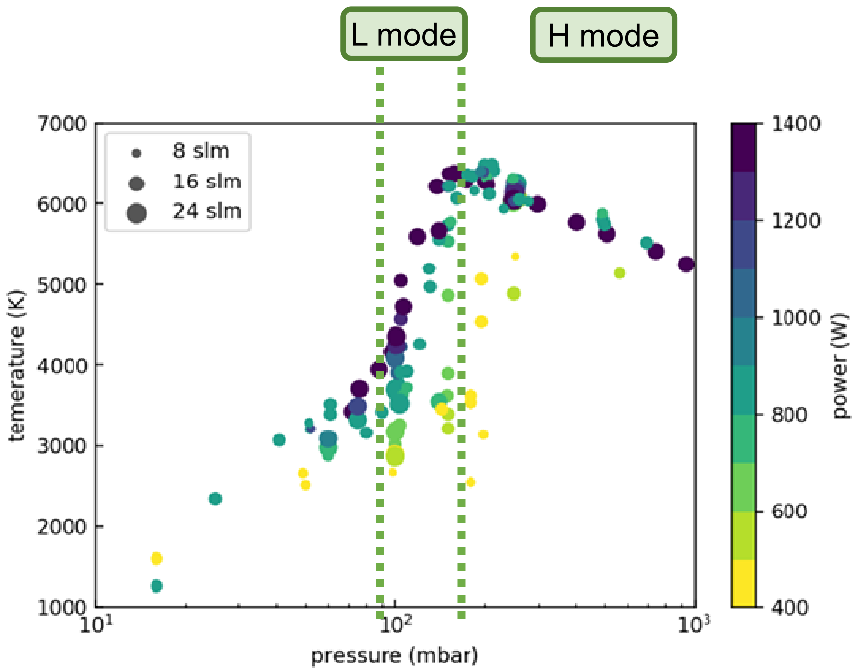
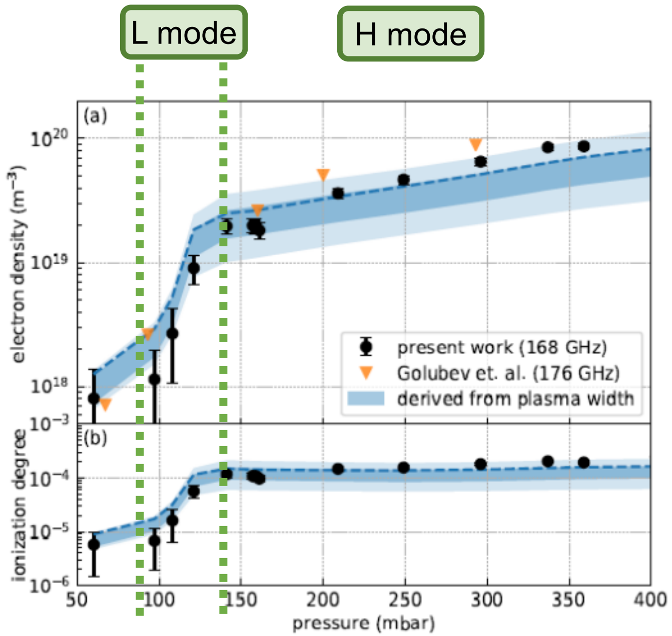
CO_2 plasmolysis: Experimental insights



Gas temperature



Ionisation degree



- Mode transition reflected:
  - in ionisation degree
  - in gas temperature (up to 6000 K)

AJ Wolf PhD Thesis, Eindhoven Univ. Technology, 2021
AJ Wolf et al. 2019 Plasma Sources Sci. Technol. **28** (2019) 115022

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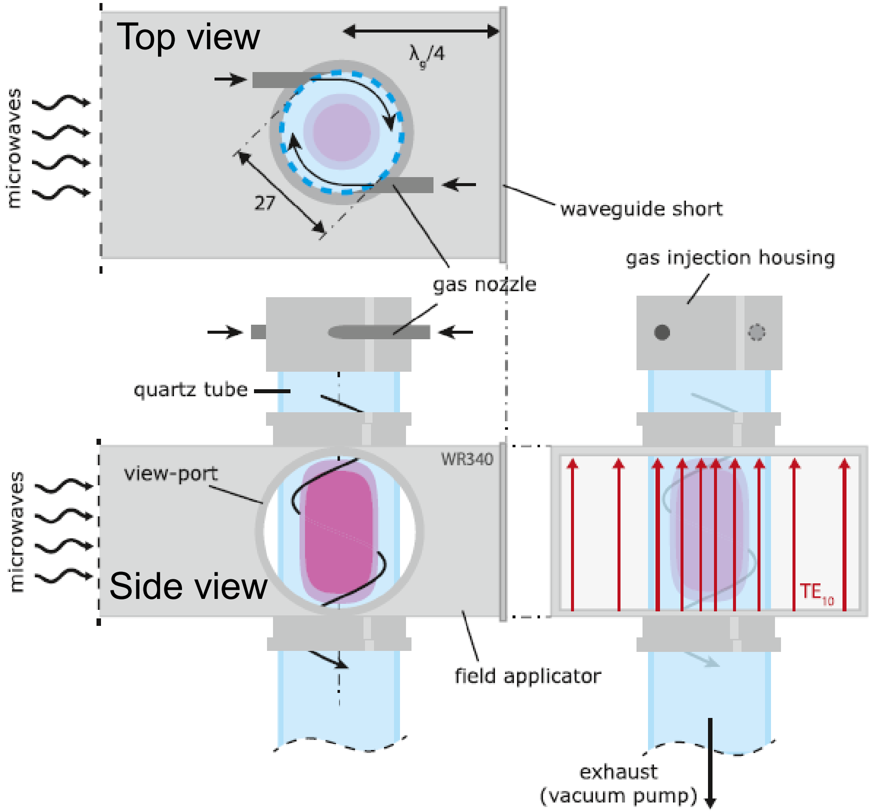
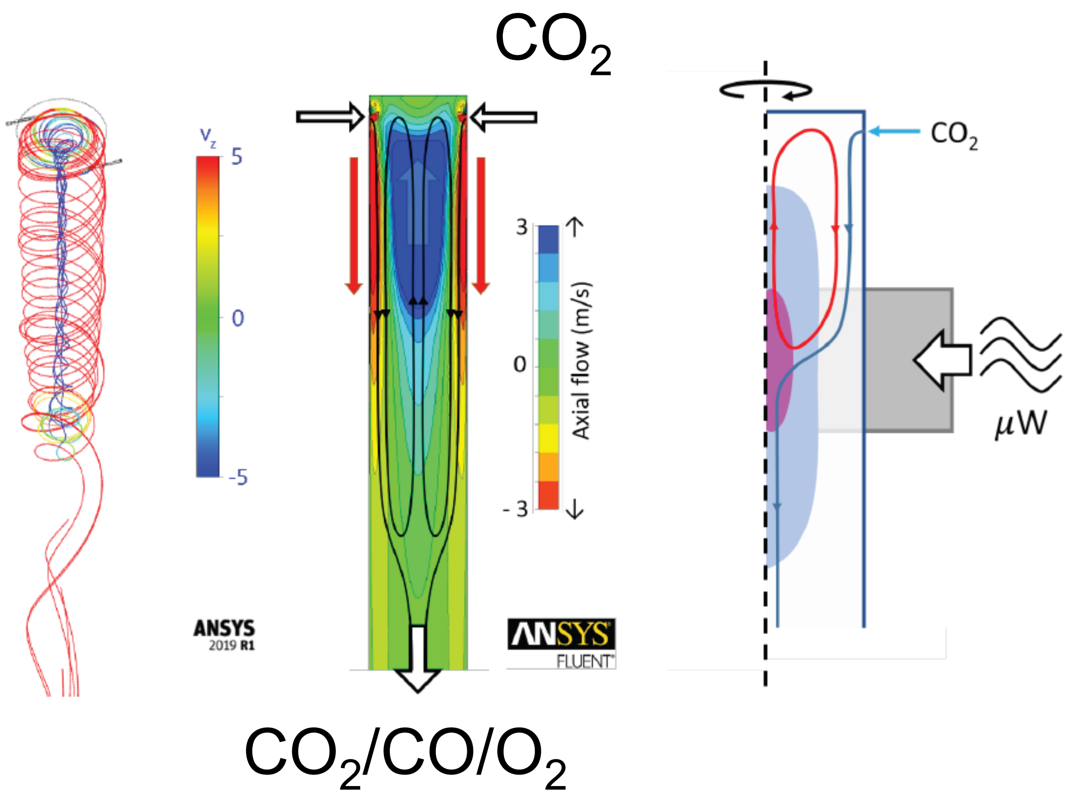
CO_2 plasmolysis: Flow pattern

DIFFER





- Strong pressure dependence
- Complex flow pattern

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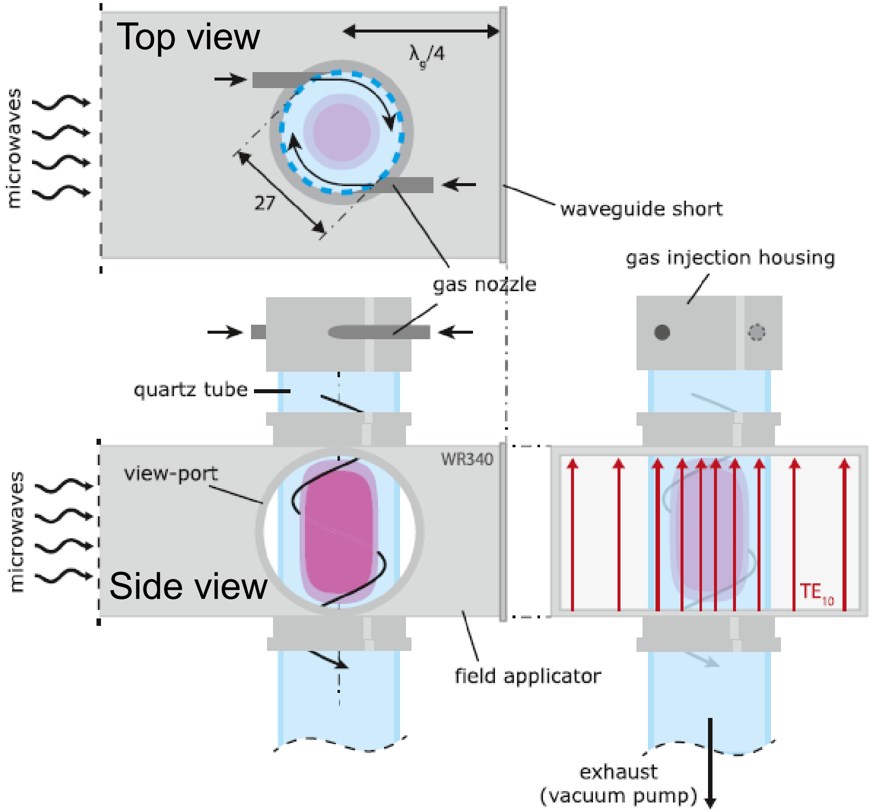
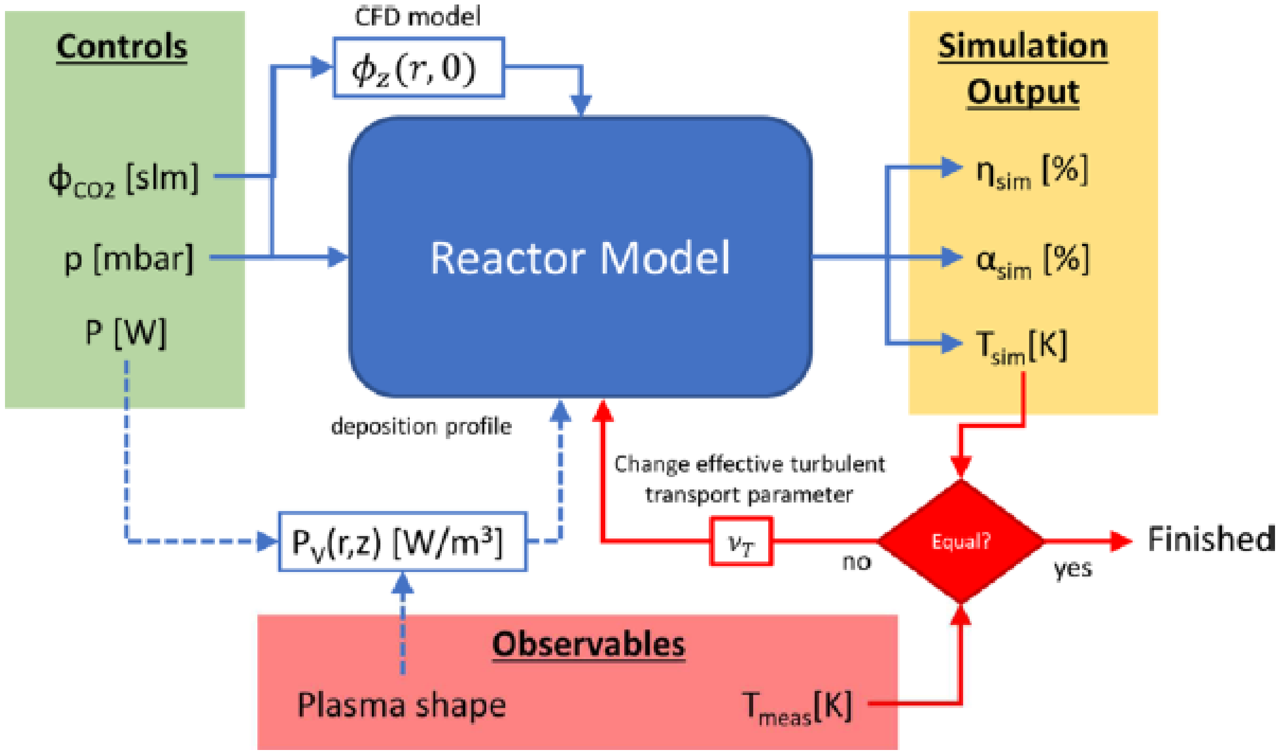
CO_2 plasmolysis: Reactor Model





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AJ Wolf PhD Thesis, Eindhoven Univ. Technology, 2021
AJ Wolf et al. J. Phys. Chem. C 2020, 124, 16806−16819

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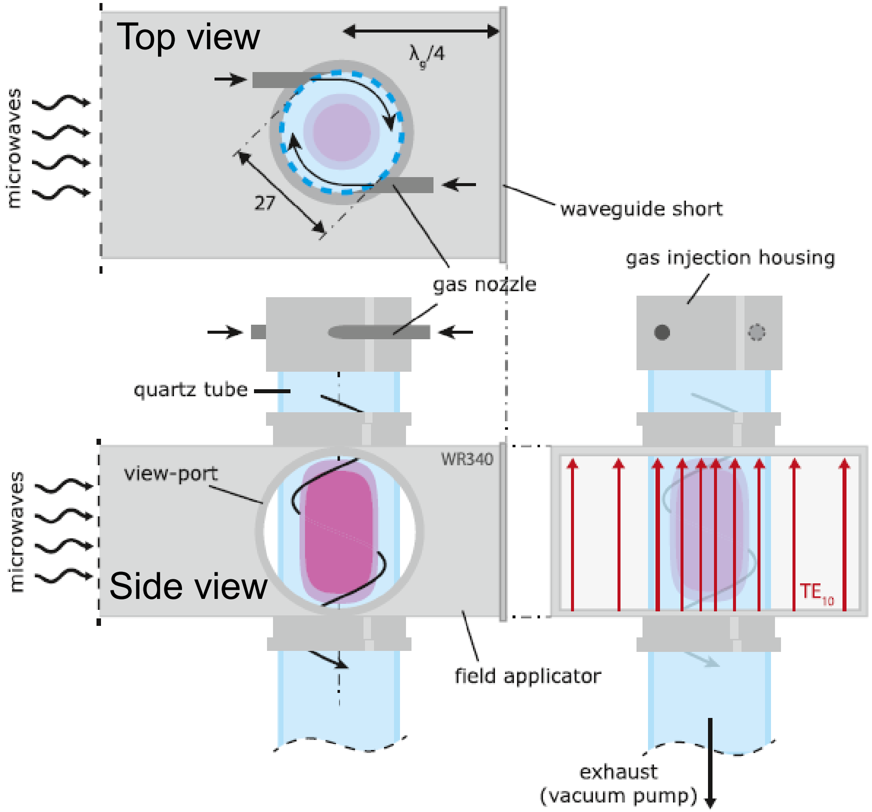
CO_2 plasmolysis: Reactor Model Results

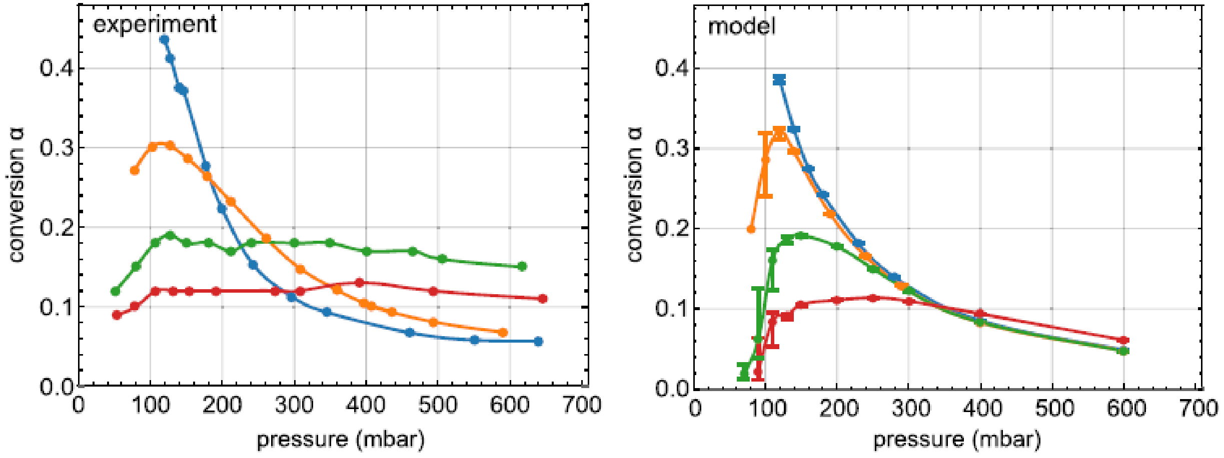


Experiment

Model

α

Conversion Eff.



- Mode transition reflected:
  - in conversion efficiency α
  - in energy efficiency η

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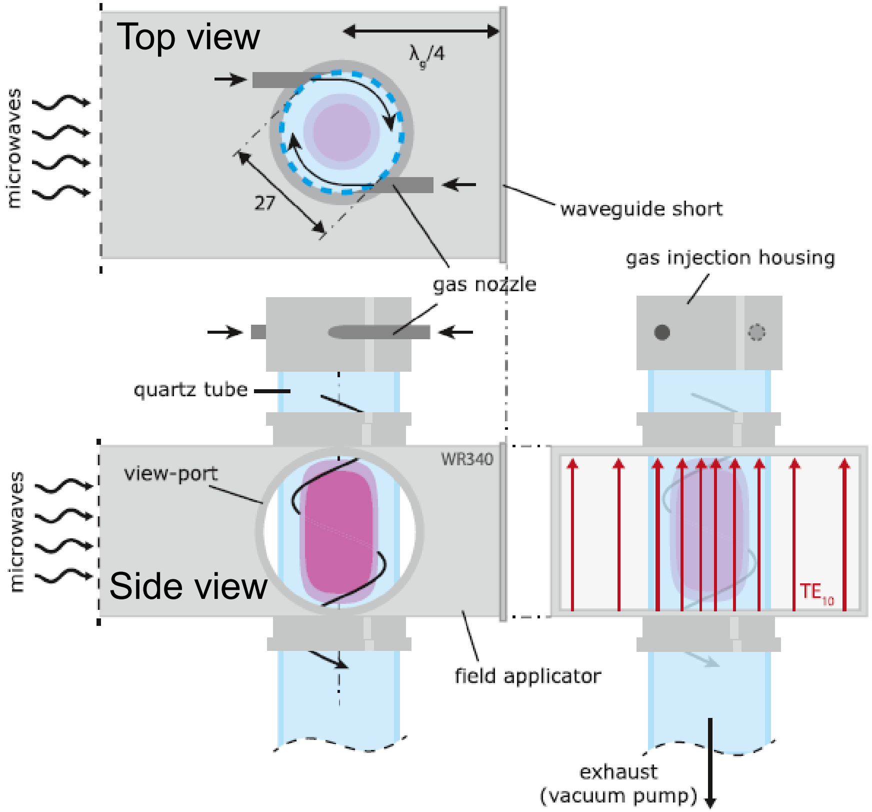
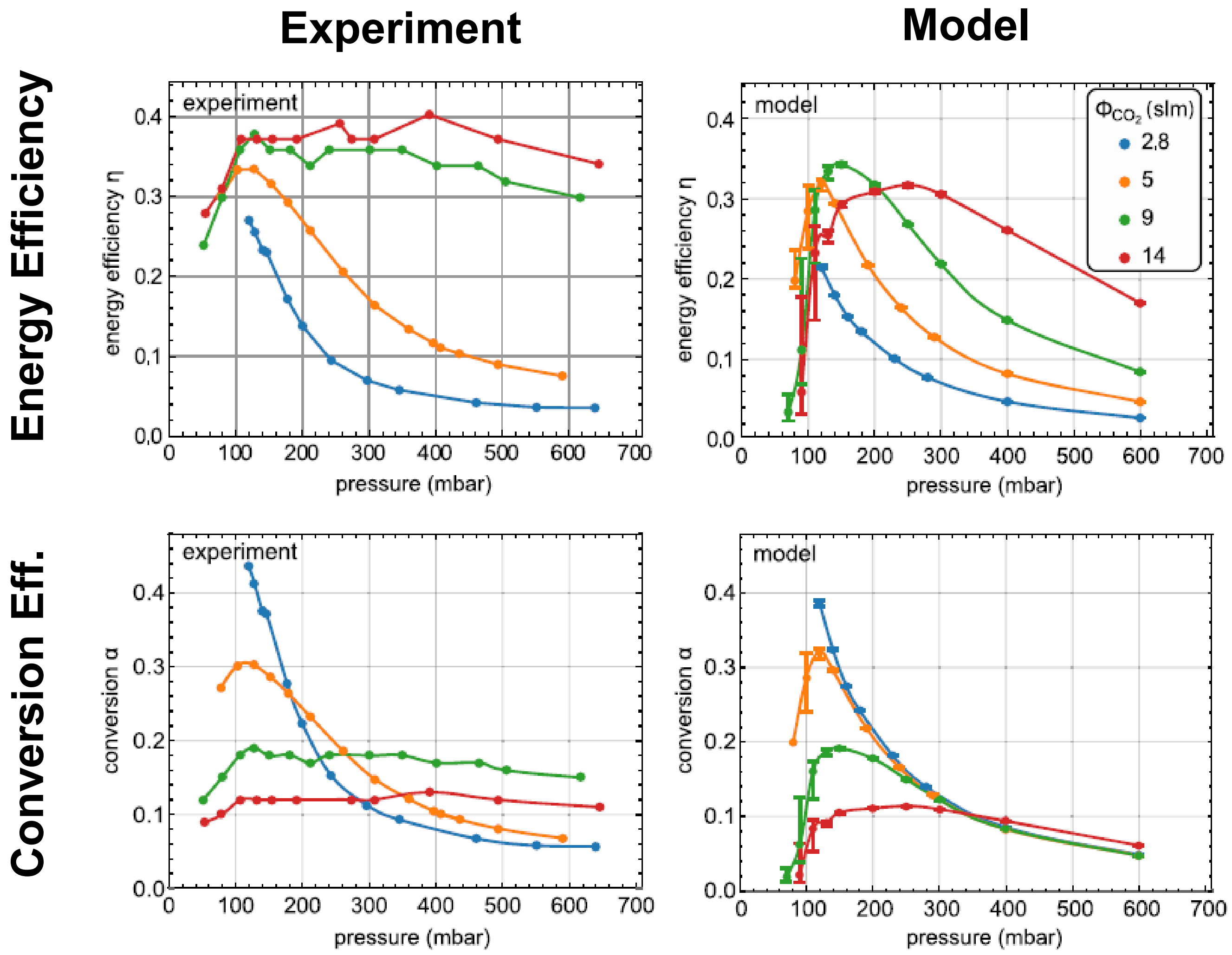


η

α



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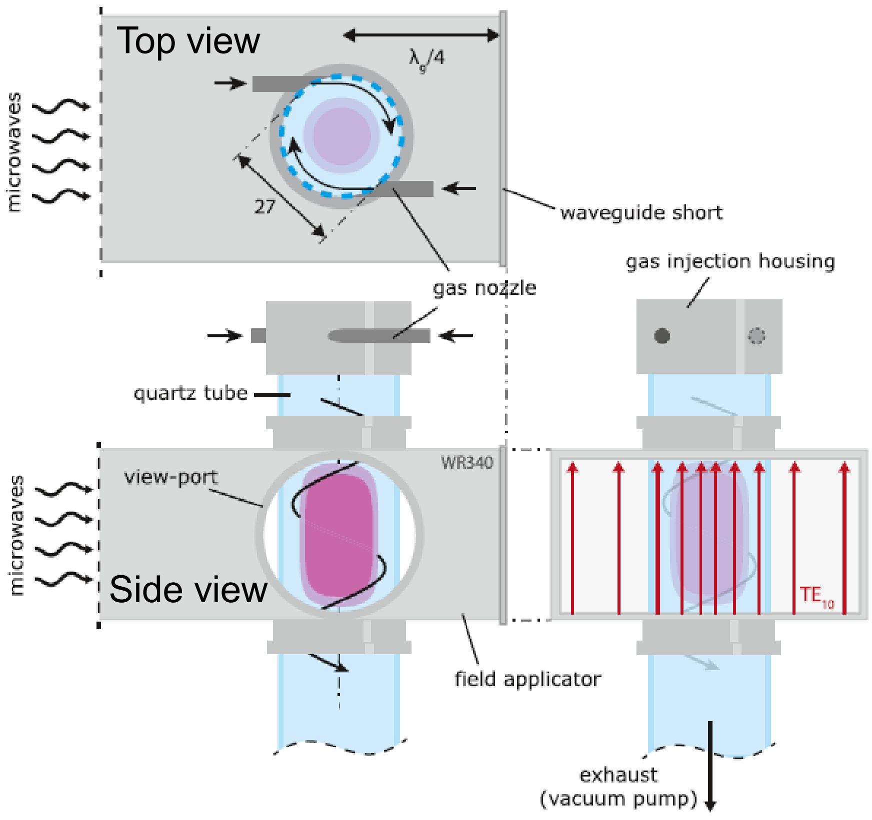
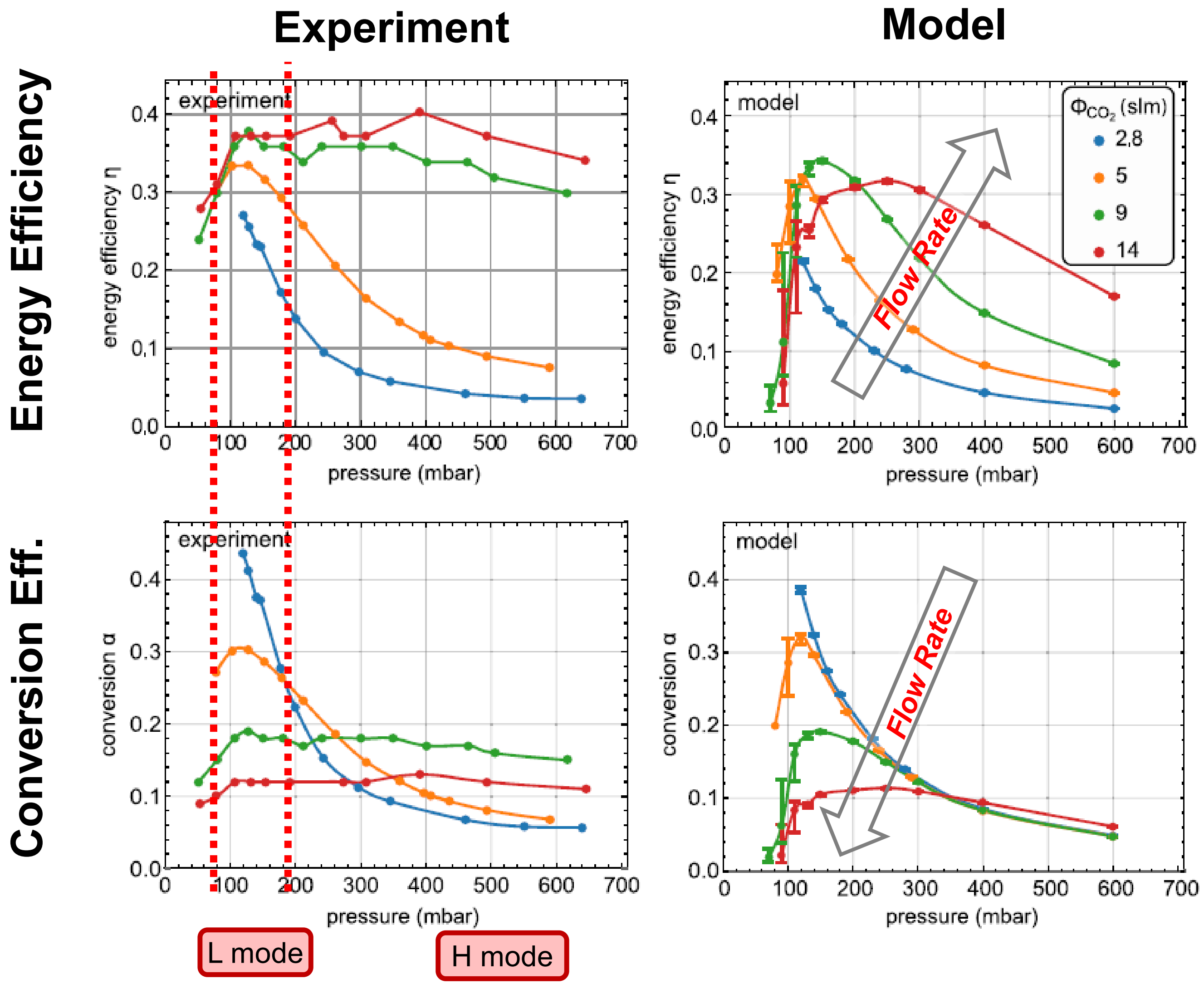


η

α



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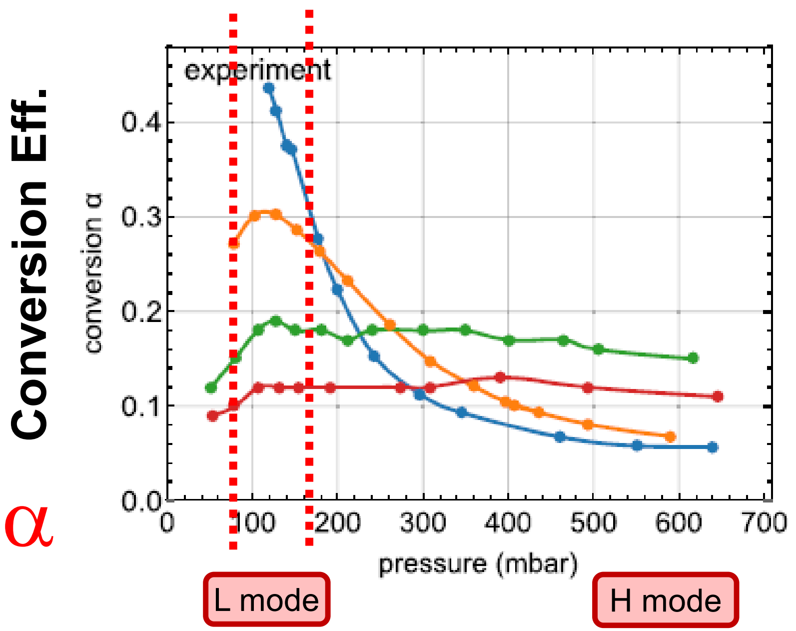
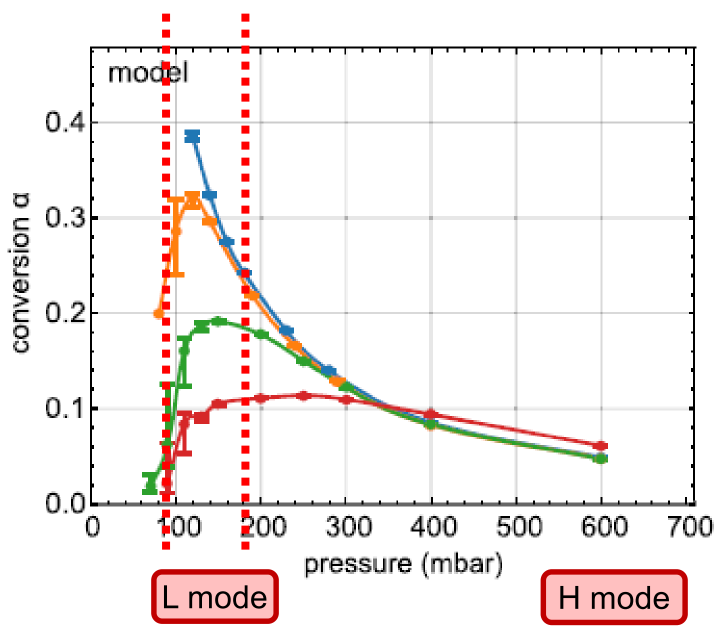
CO_2 plasmolysis: Reactor & Plasma Model Results

DIFFER

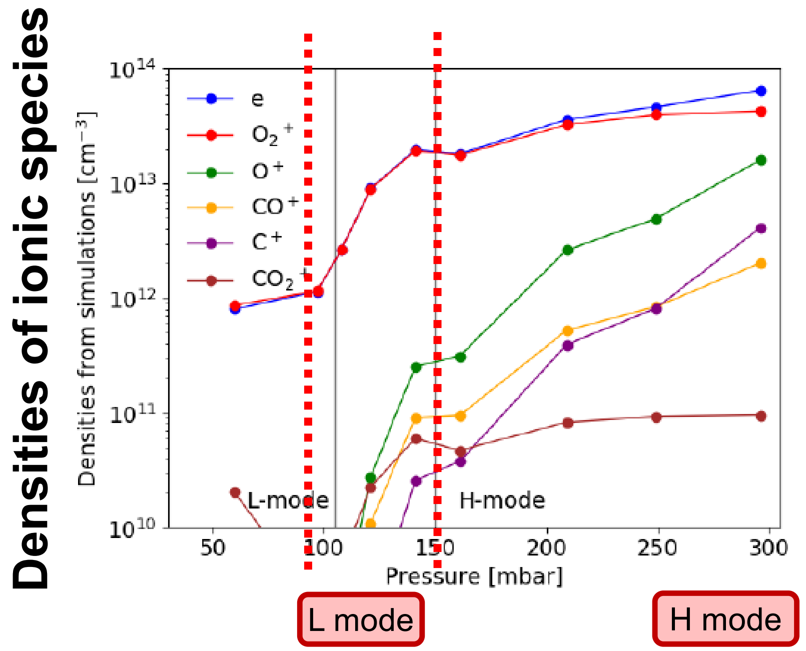
Experiment



Reactor Model



Plasma Model



- L-Mode (homogeneous): production limited, «low» gas temperatures, low ionisation degree
- H-Mode (constricted): «high» gas temperatures and ionisation degrees

AJ Wolf PhD Thesis, Eindhoven Univ. Technology, 2021
AJ Wolf et al. J. Phys. Chem. C 2020, 124, 16806−16819
P. Viegas et al. Plasma Sources Sci. Technol. 29, 2020, 105014

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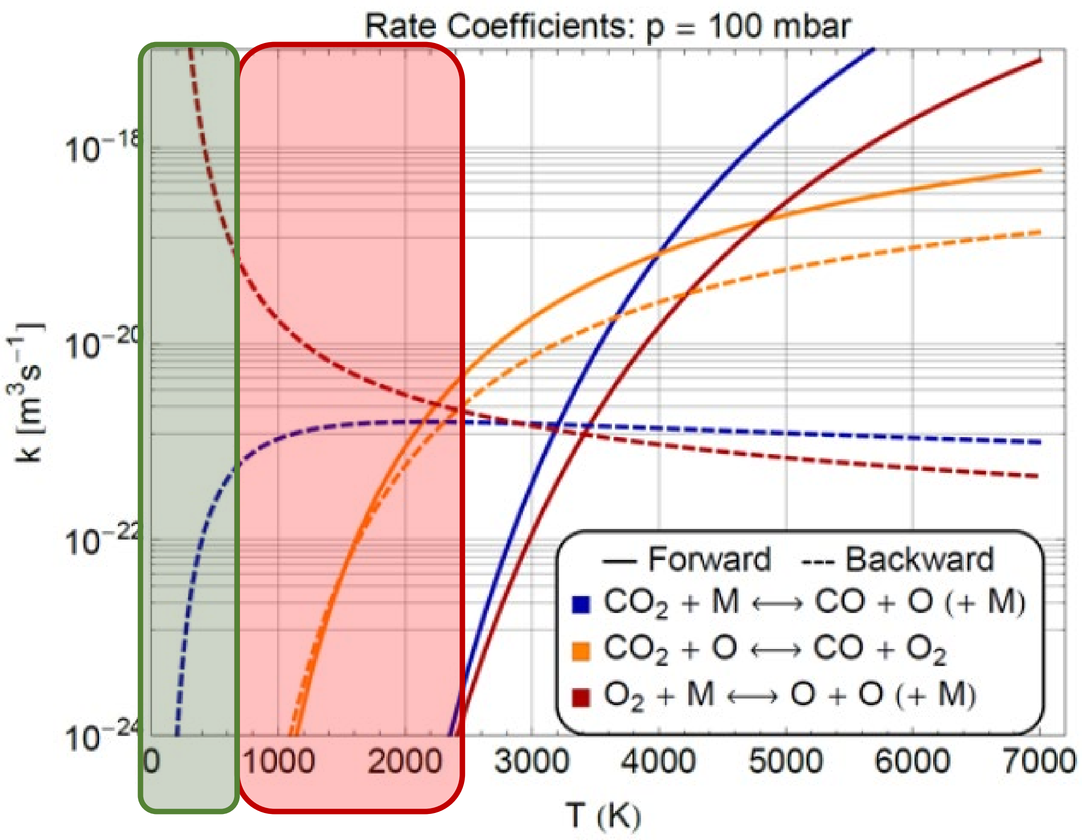
CO_2 plasmolysis: Temperature dependence

Rate coefficients



- At «intermediate» temperatures (~ 3000 K) atomic oxygen production inhibited
- At «low» temperatures (1000-2000 K) dominant CO recombination with re-heating of gas
- → Downstream active plasma-zone: efficient gas cooling and product dilution is desired

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CO_2 plasmolysis: Design criteria

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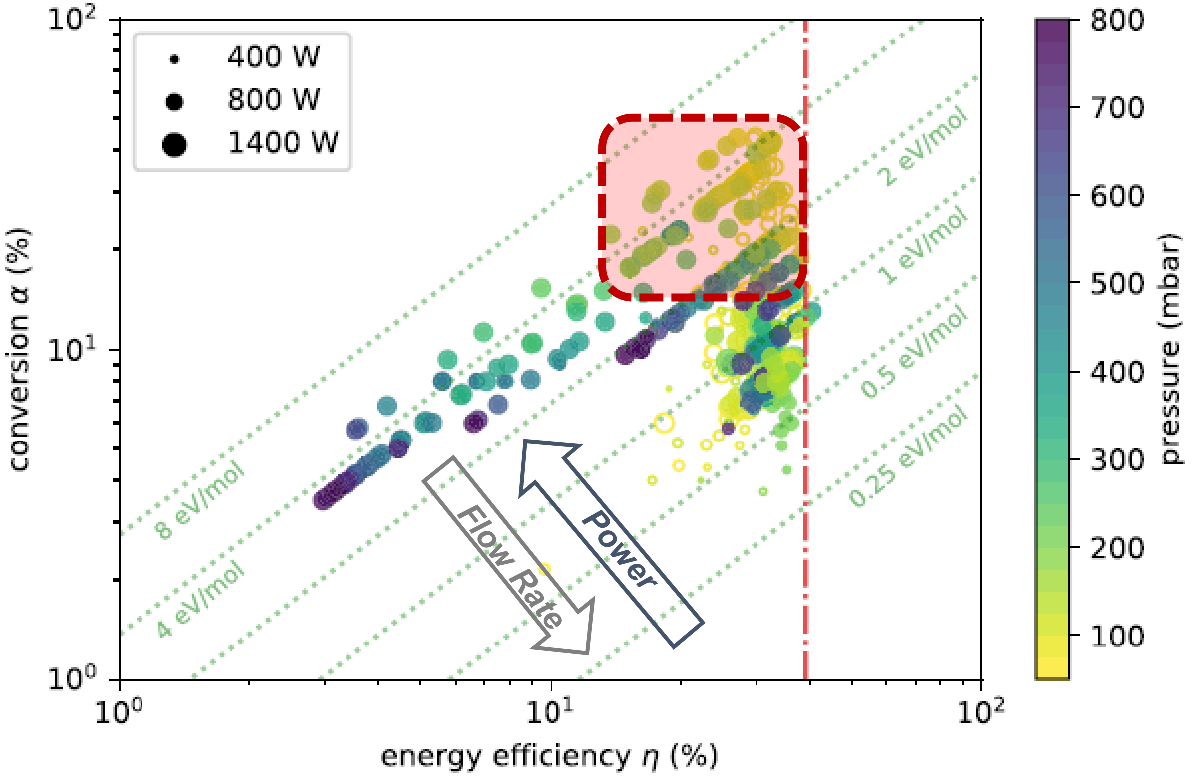

(Scientific) Design Criteria

... to maximise α & η (= indicated area)

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AJ Wolf et al. J. Phys. Chem. C 2020, 124, 16806−16819

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CO_2 plasmolysis: Design criteria

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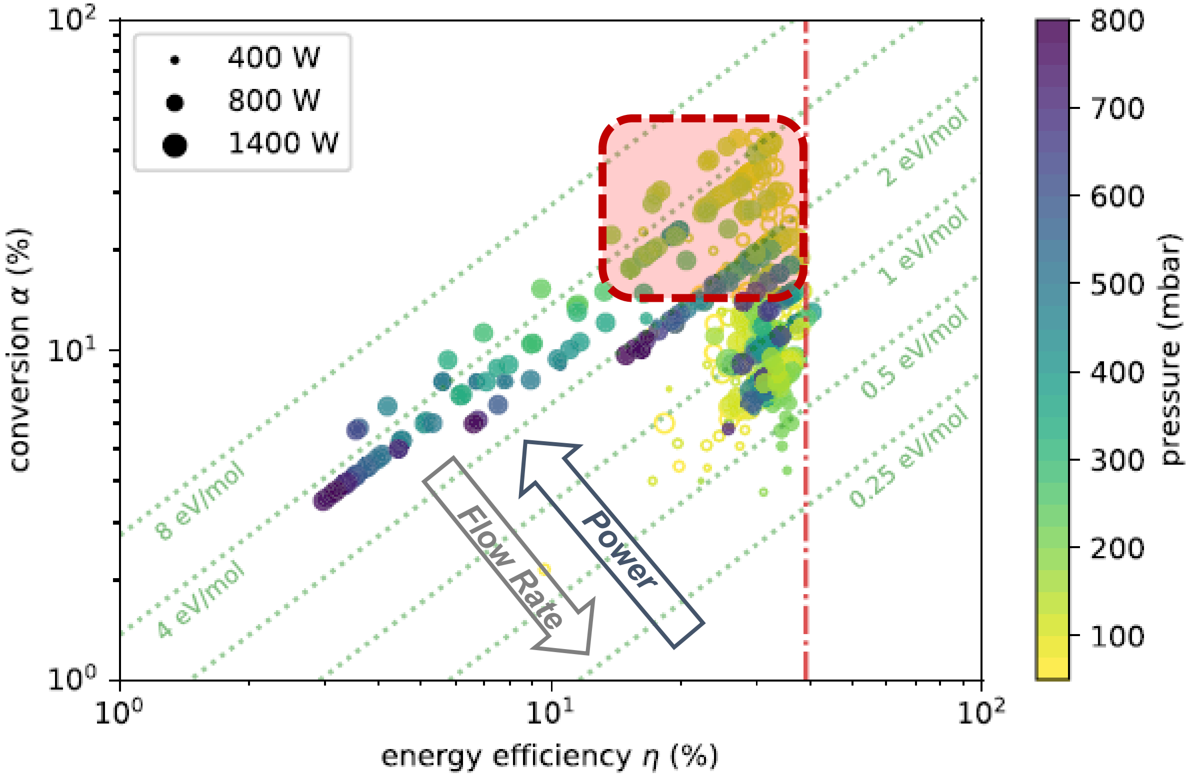

(Scientific) Design Criteria & Consequences

... to maximise α & η (= indicated area)

i. «low(er)» pressure regime: ~ 150 mbar

ii. efficient gas cooling downstream

iii. → Diluted gas stream

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AJ Wolf et al. J. Phys. Chem. C 2020, 124, 16806−16819

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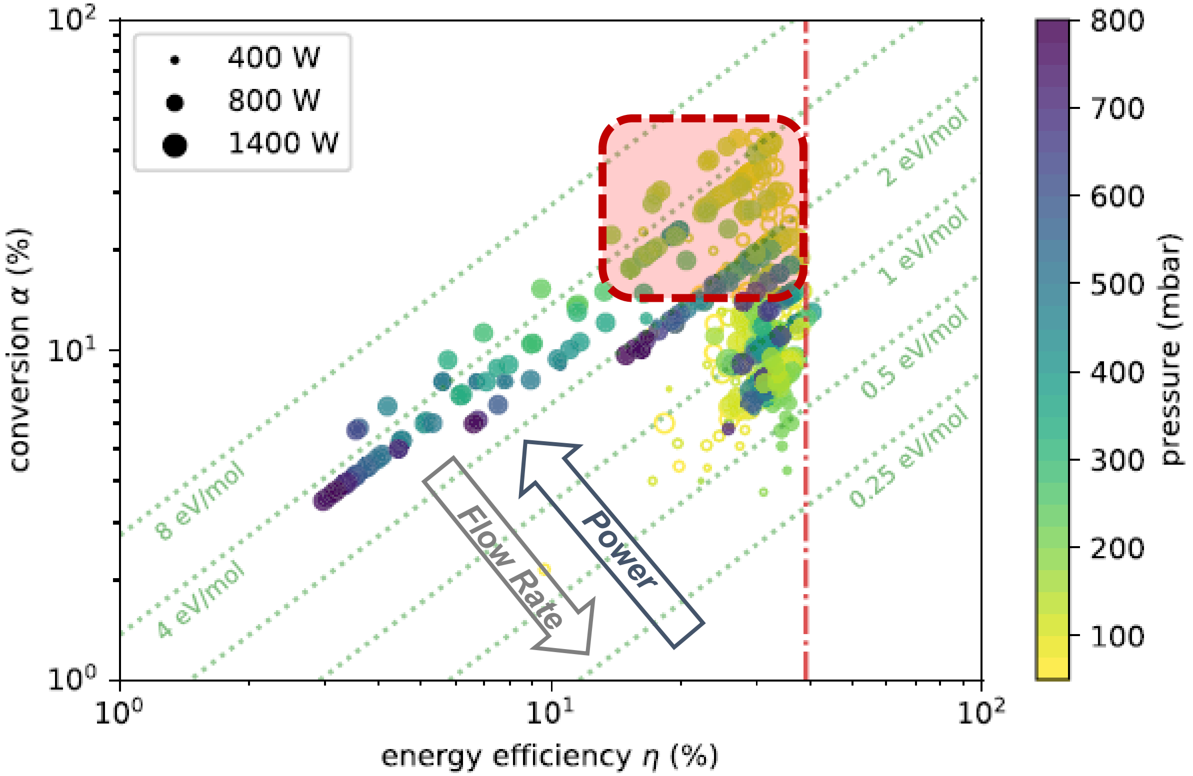
CO_2 plasmolysis: Design criteria



$$\eta = \alpha \cdot \frac{H}{E_{spec}} = C \cdot \frac{F_{CO2}}{P_{RF}}$$

(Scientific) Design Criteria & Consequences

... to maximise α & η (= indicated area)

i. «low(er)» pressure regime: ~ 150 mbar
   i. Vacuum pump (compression) required
   ii. ➔ Gas mixture (CO/O) is explosive → dilution needed
   iii. Dependence on (sharp) mode transitions
   iv. ➔ Control challenge

ii. efficient gas cooling downstream
   i. Achievable with
      i. High flow rates (and/or expansion)
      ii. High surface areas
   ii. ➔ High flow rates reduce conversion efficiency α
   iii. ➔ Material challenge: need to withstand >> 1000 K

iii. → Diluted gas stream
   i. (re-)circulation of «inert» gas and bigger size of all components

AJ Wolf PhD Thesis, Eindhoven Univ. Technology, 2021
AJ Wolf et al. J. Phys. Chem. C 2020, 124, 16806−16819

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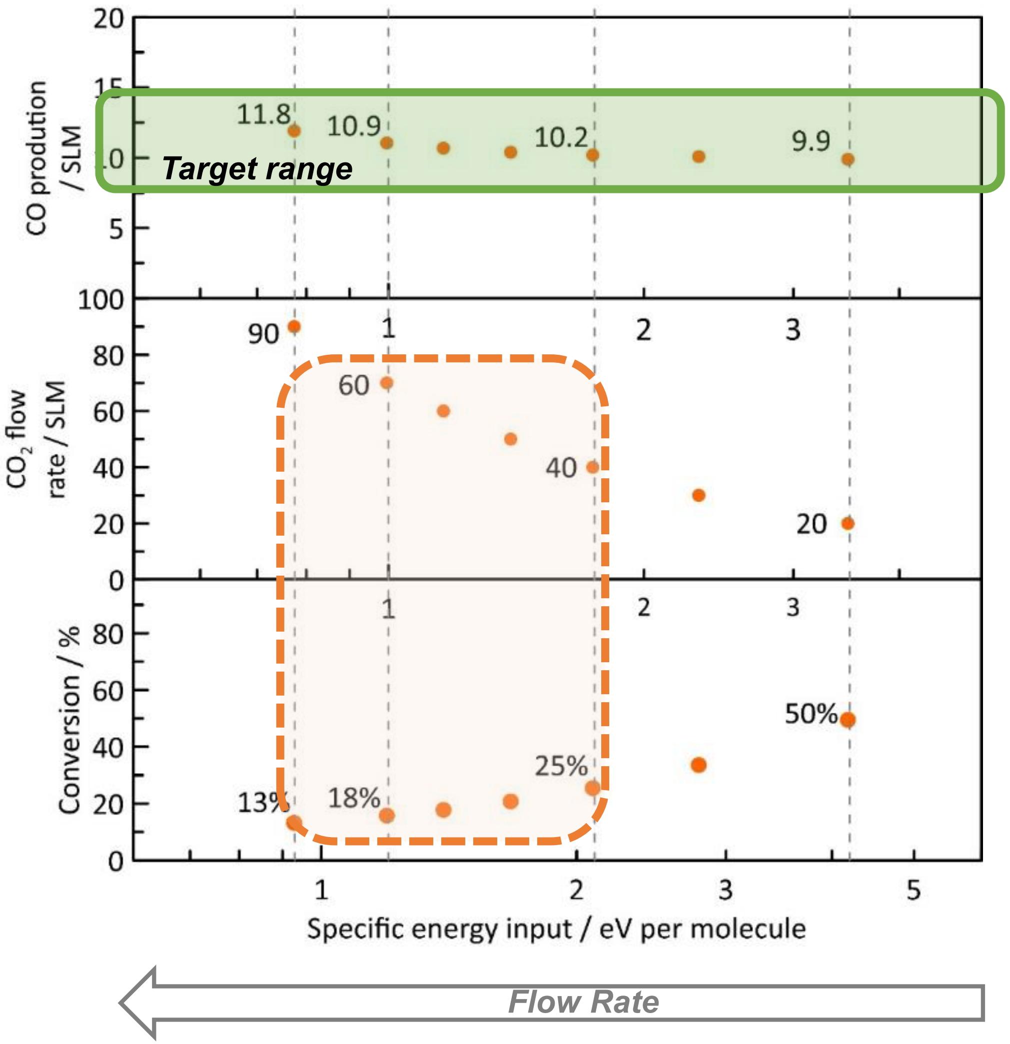
CO_2 plasmolysis: KEROGREEN implementation

DIFFER



(Scientific) Design Criteria & Consequences

i. «low(er)» pressure regime: ~ 150 mbar
   i. Vacuum pump (compression) required
   ii. ➔ Gas mixture (CO/O) is explosive → dilution needed
   iii. Dependence on (sharp) mode transitions
   iv. ➔ Control challenge («flattened» by higher flow rates)

ii. efficient gas cooling downstream
   i. Achievable with
      i. High flow rates (expansion)
      ii. High surface areas
   ii. ➔ High flow rates reduce conversion efficiency α
   iii. ➔ Material challenge: need to withstand >> 1000 K

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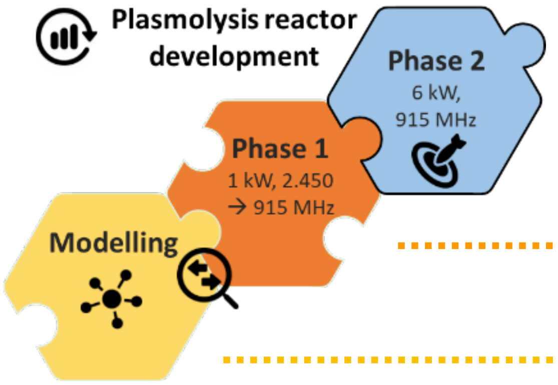
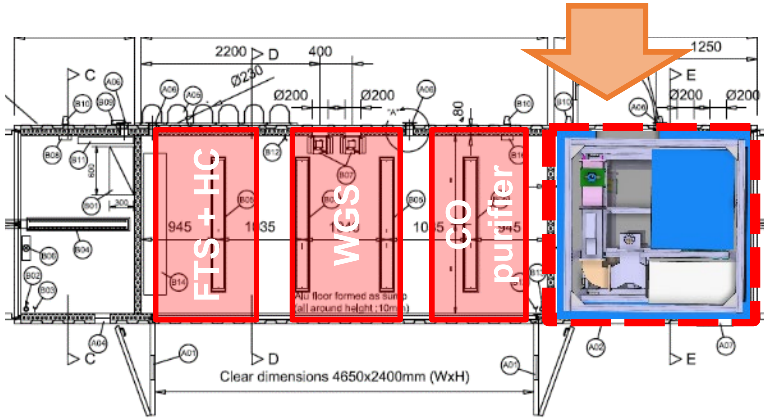
CO_2 plasmolysis: KEROGREEN implementation



	Power [kW]	Frequency [MHz]	Scale
Phase 2	6	915	Container/ Module
Phase 1	6	915	Lab
(InitSF)	1-2	2450	Lab



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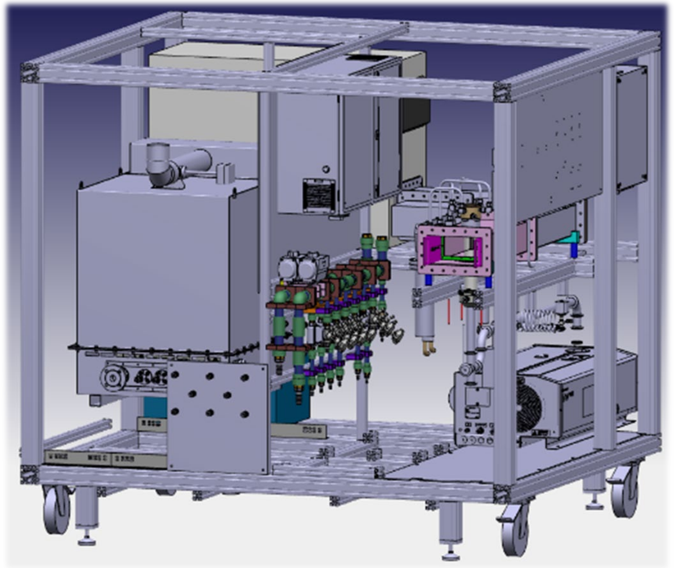
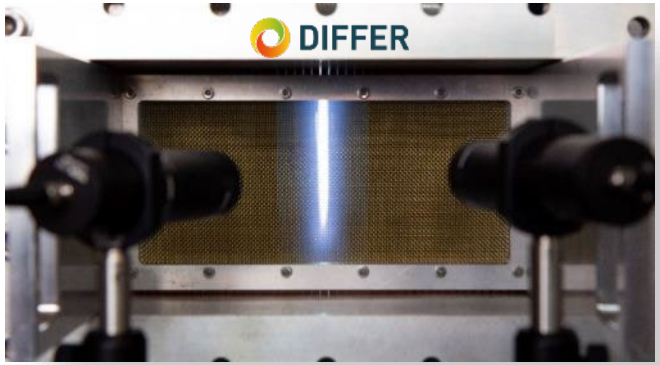
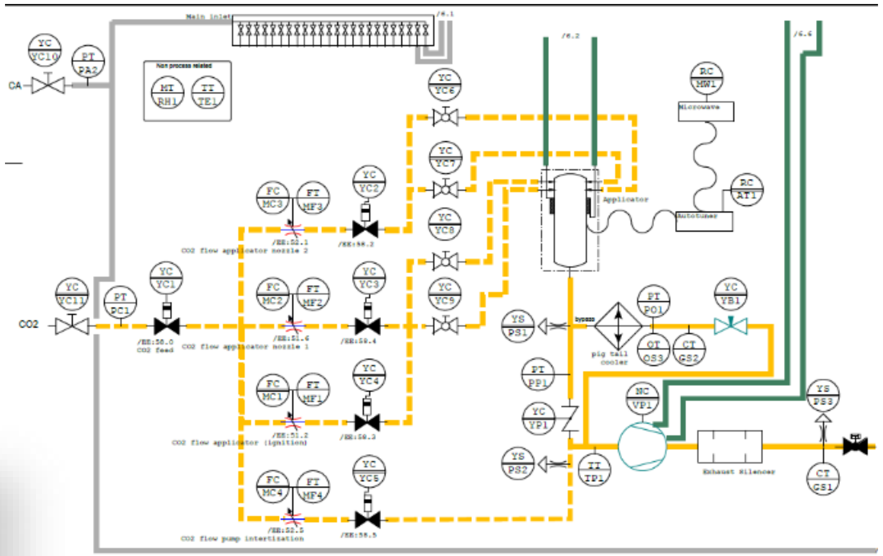
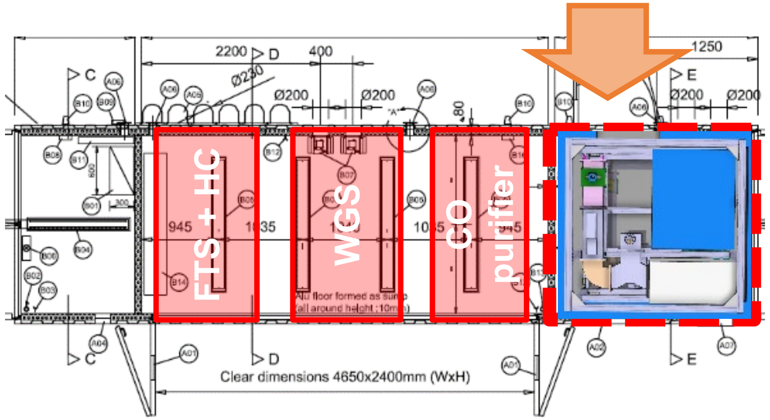
CO_2 plasmolysis: KEROGREEN implementation









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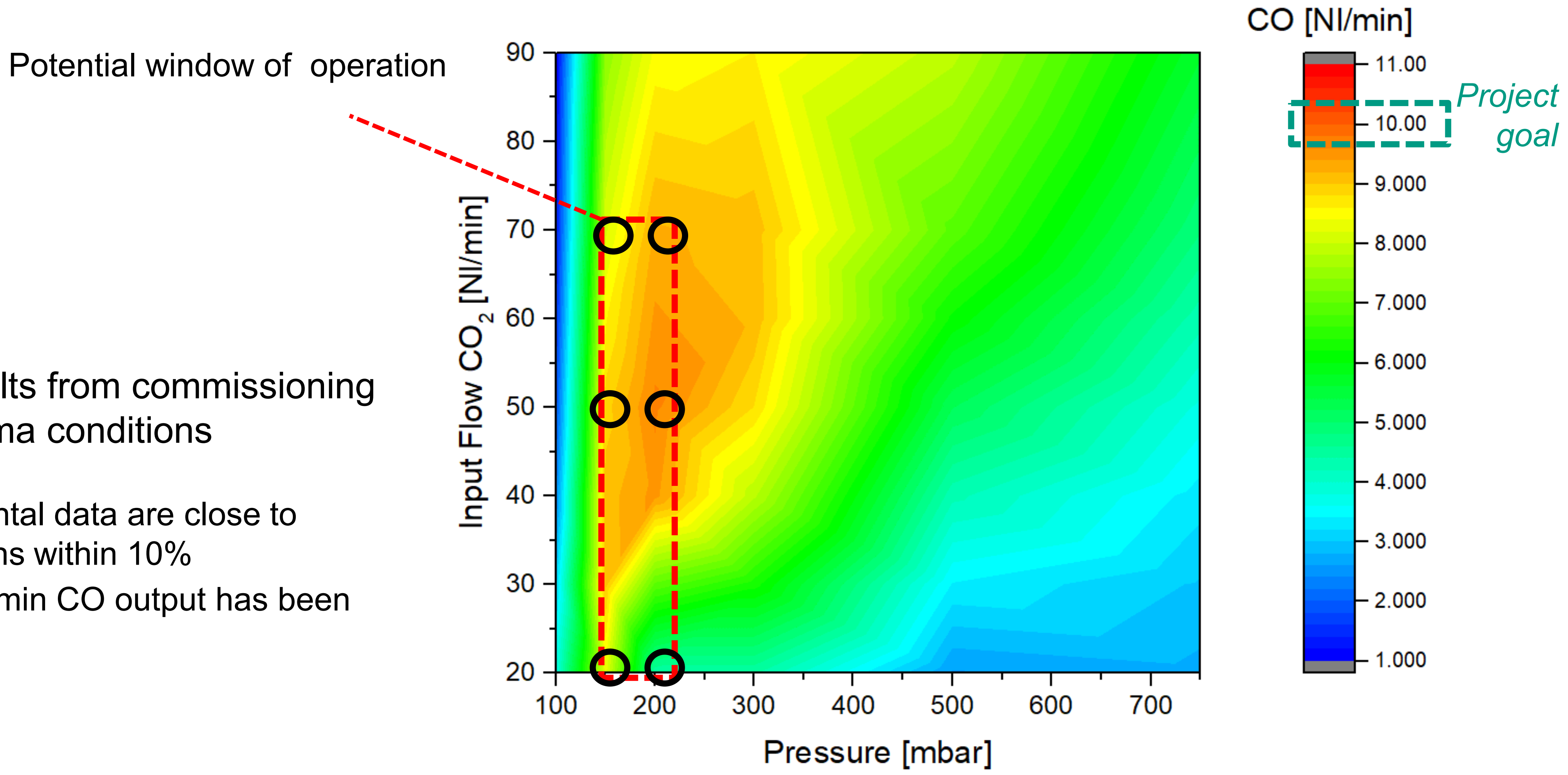
CO_2 plasmolysis: Reactor Model & Practise

DIFFER



Preliminary results from commissioning under CO_2 plasma conditions

- Experimental data are close to calculations within 10%
- 9 – 10 Nl/min CO output has been shown

Heat map = calculations for final applicator/reactor configuration with special thanks to F. Peeters, based on Wolf et al. J. Phys. Chem. C 2020, 124, 16806−16819

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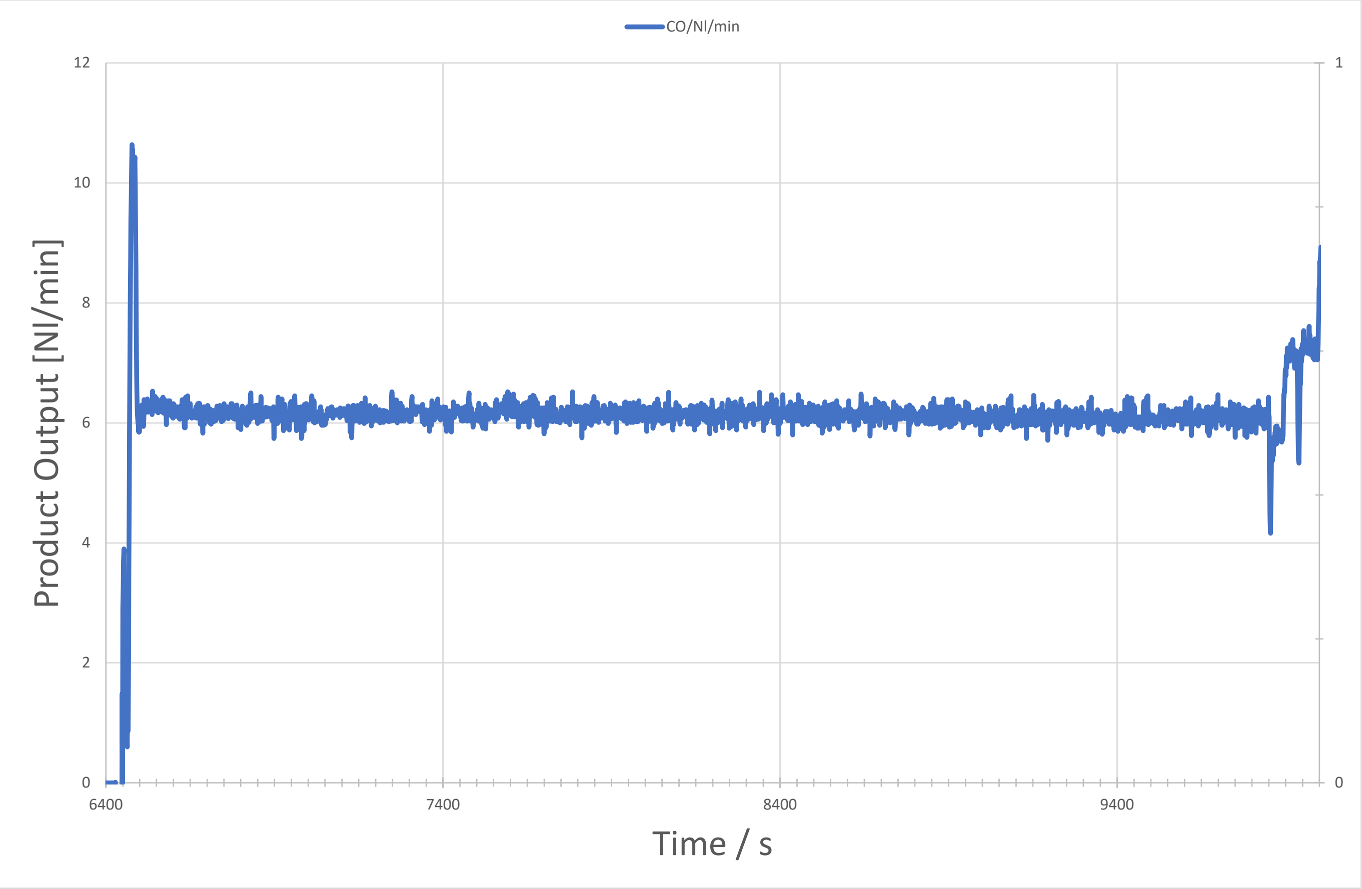
CO_2 plasmolysis: Reactor Model & Practise

DIFFER

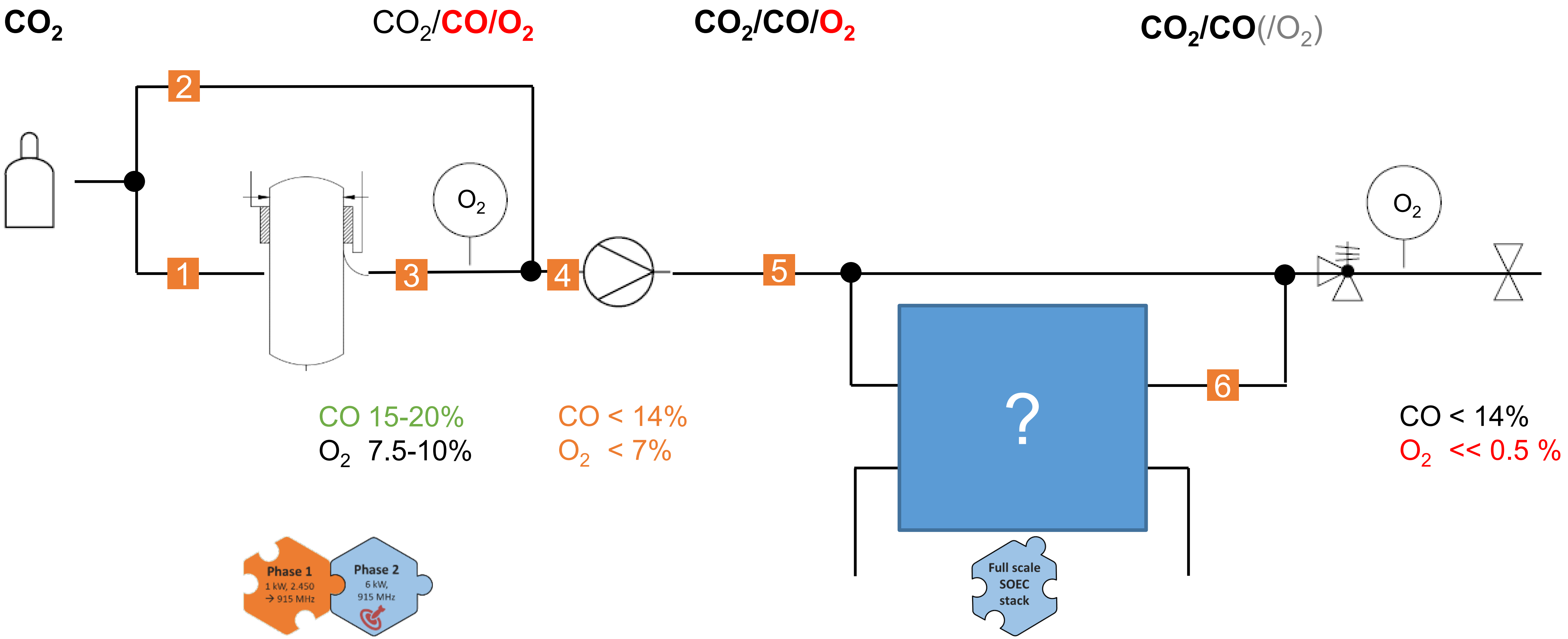
Preliminary results from commissioning under CO_2 plasma conditions

- Experimental data are close to calculations within 10%
- 9 – 10 Nl/min CO output has been shown
- Stability of operation > 1 hour
- “Operator”-free



This project has received funding from the European Union‘s Horizon 2020 Research and Innovation Programme under GA-Nr. 763909

Downstream Challenges: Dilution & Separation



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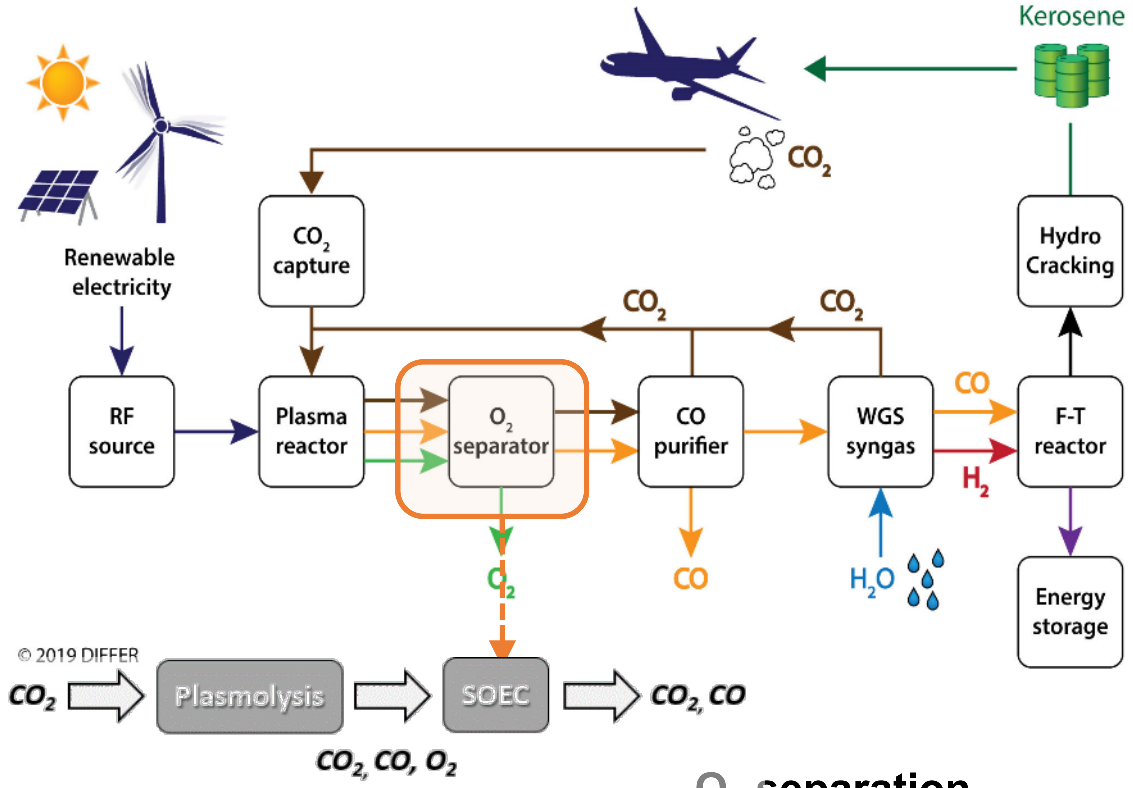
SOEC as oxygen separator: Concept



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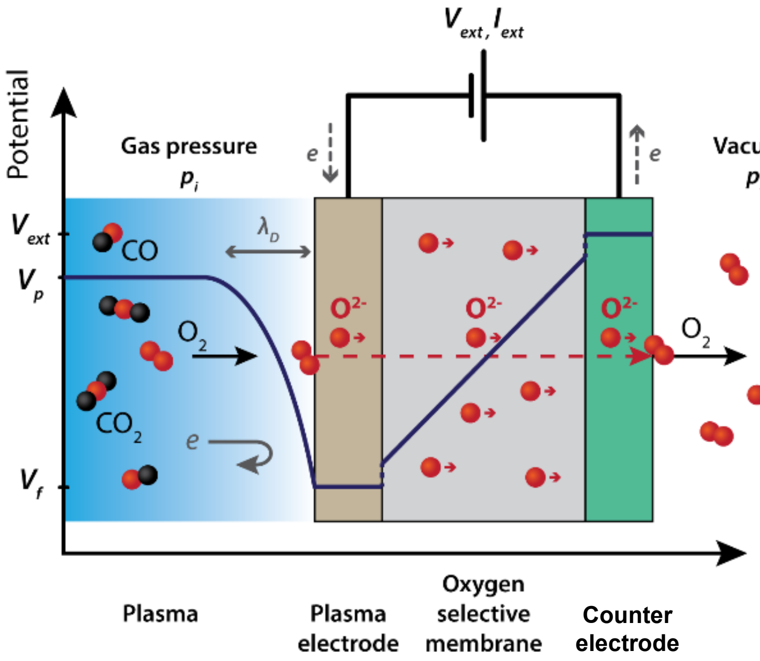

O_2 separation

- Difficult process
- Lack of literature
- SOEC: Electrochemical O_2 pumping

Plasma electrode reactions

- $O_2 + 4e^- \rightarrow 2O^{2-}$ (desired)
- $CO_2 + 2e^- \rightarrow CO + O^{2-}$ (neutral)
- $2CO + O_2 \rightarrow 2CO_2$ (unwanted)

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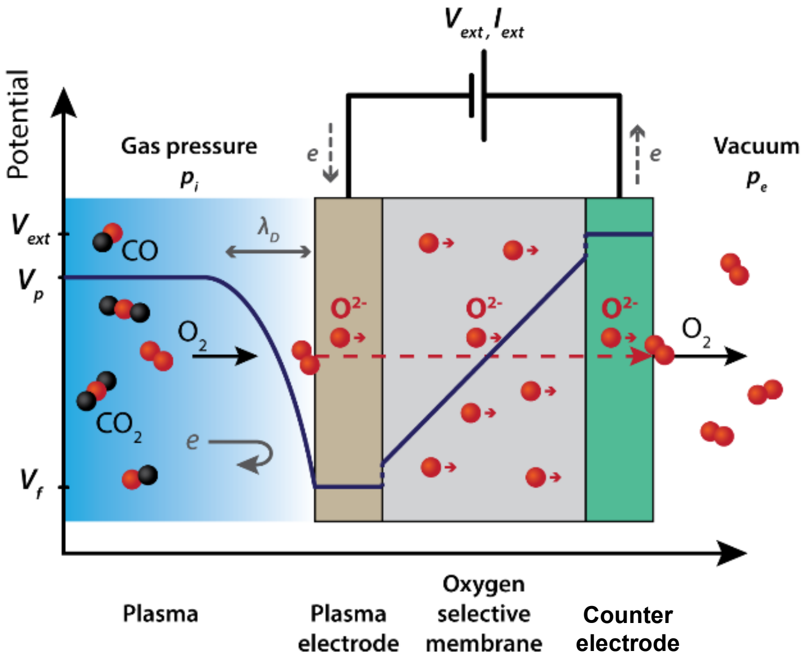
SOEC as oxygen separator: Complex requisites

Functionalities

- **Plasma electrode**
  Unconventional mixture (CO_2/CO/O_2)
  Poor CO activity
- **Electrolyte**
  Oxygen ion conductivity
  Low resistance → thin
- **For both electrodes:**
  Mixed electronic & ionic conductivity
  Low overpotential losses (gas composition, T)
- **Overall**
  High oxygen fluxes (increased T)
  Stability
  Reduced CO recombination (reduced T)



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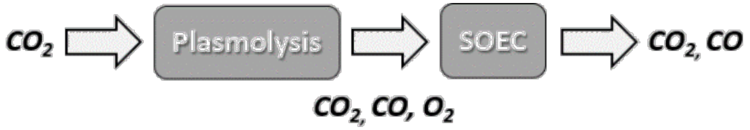
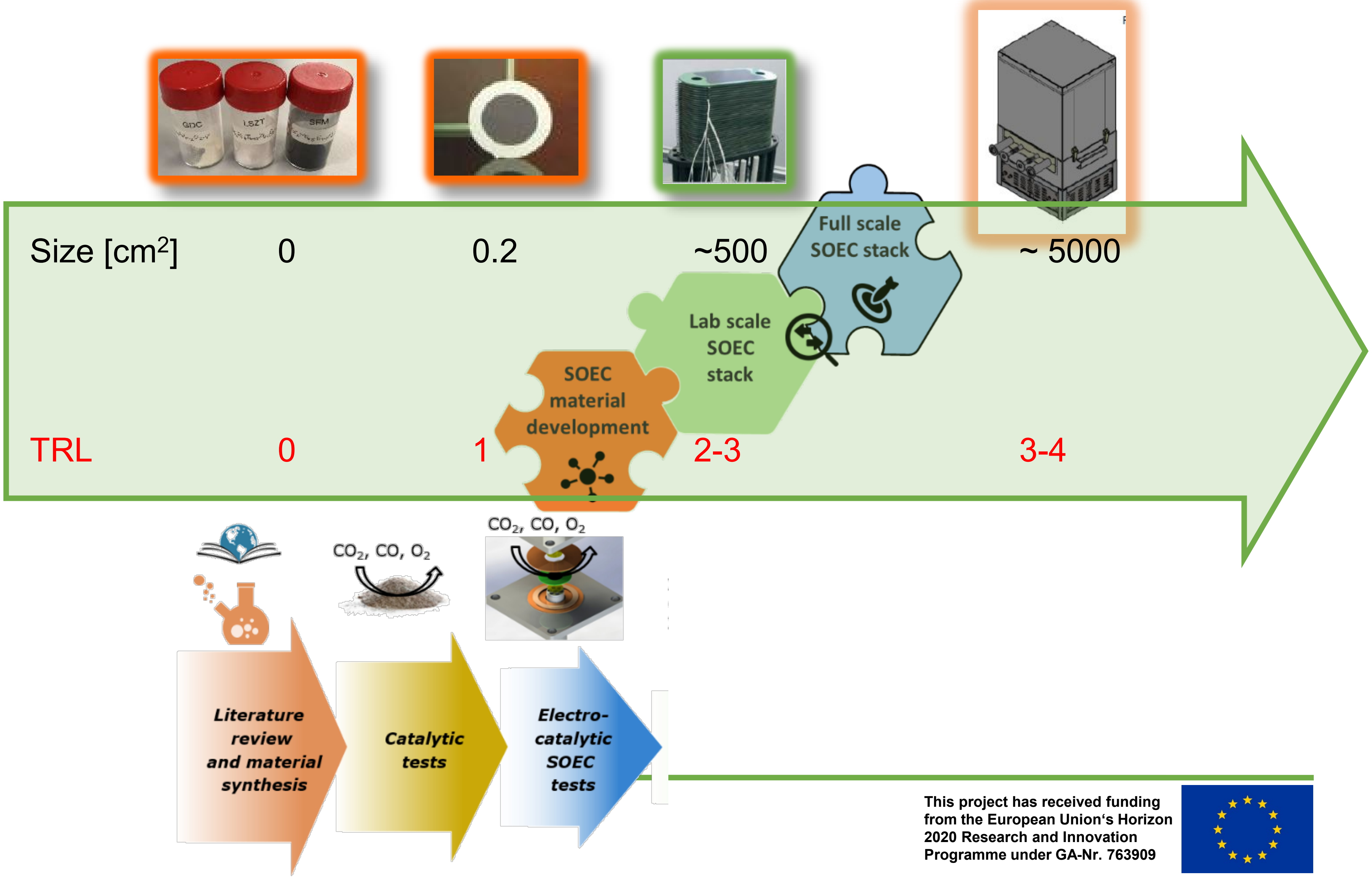
SOEC as oxygen separator: Steps





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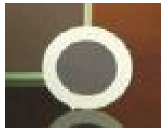
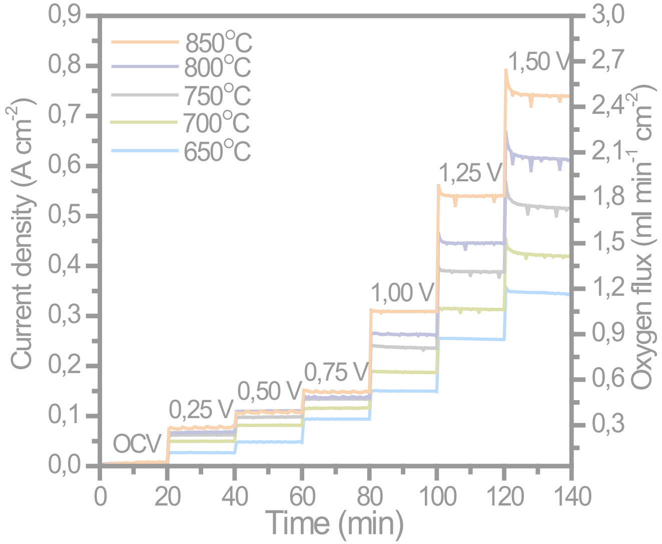
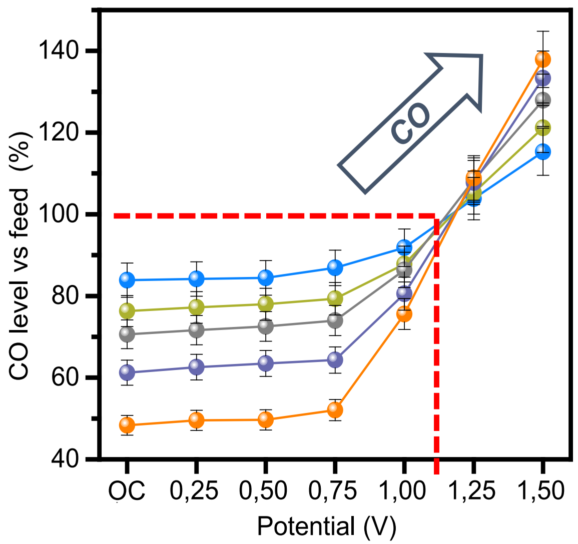
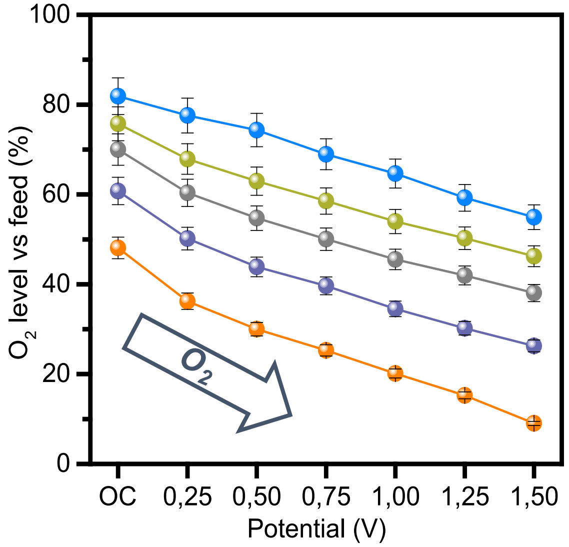
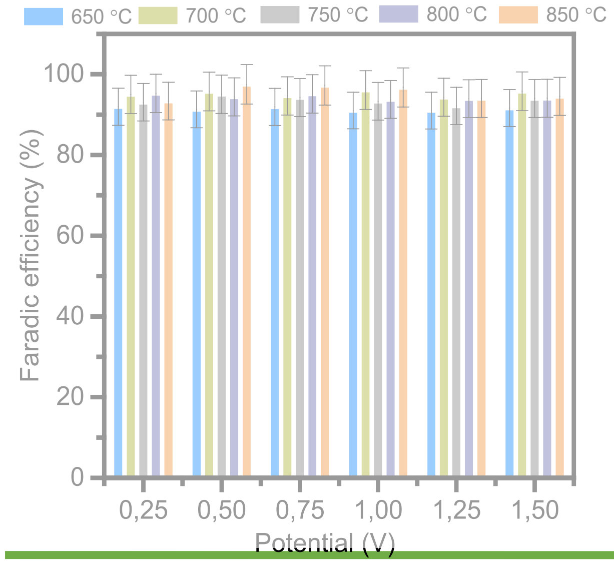
SOEC as oxygen separator: single cell level











Key findings

- OCV conditions
  - As the operation T is increased CO losses (via CO oxidation) are also increased
- Under polarization
  - Oxygen removal is favoured at high T due to higher current densities.
  - Increasing the applied potential is a knob to increase the amount of CO via CO_2 electrolysis.
  - Faradaic efficiency is high (> 90%)

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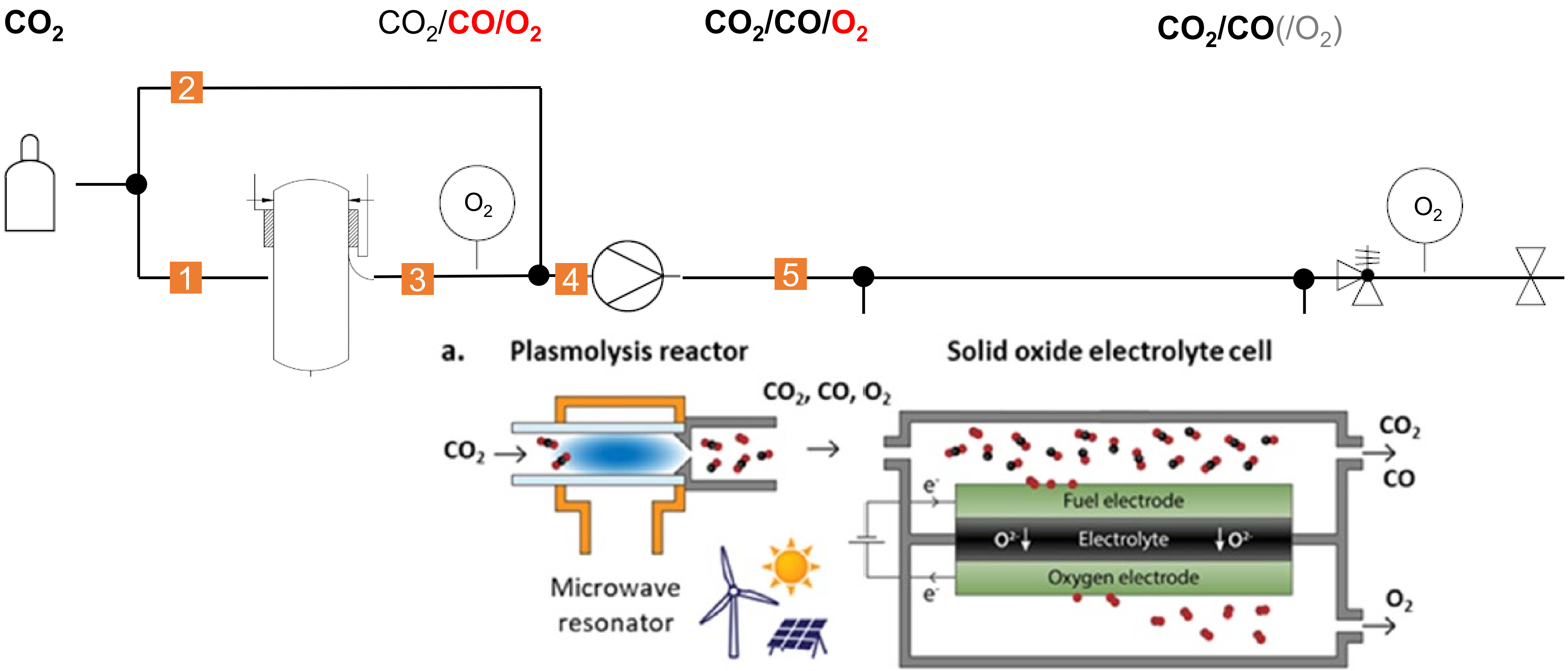
Downstream Challenges: Separation by SOEC



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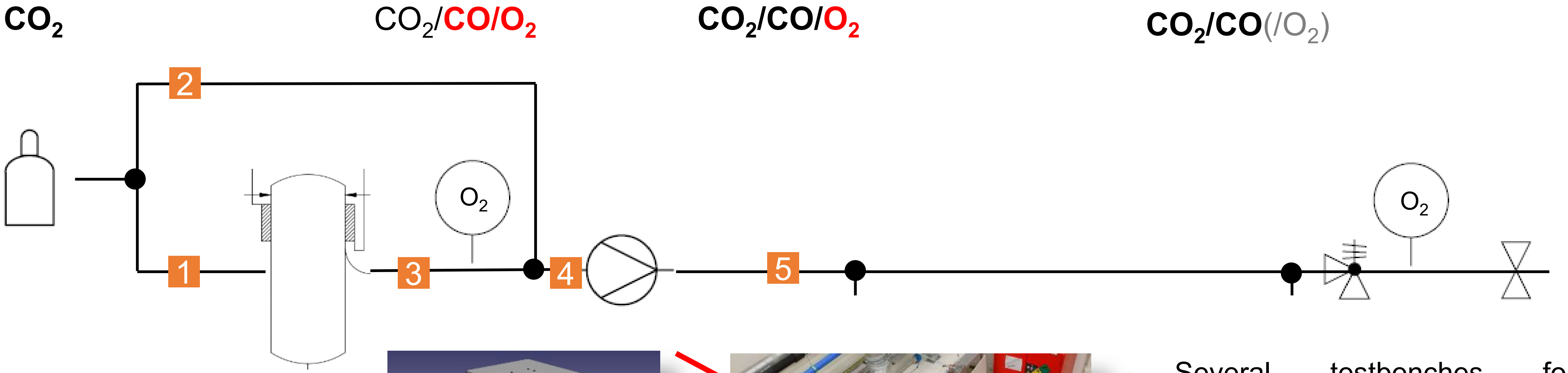

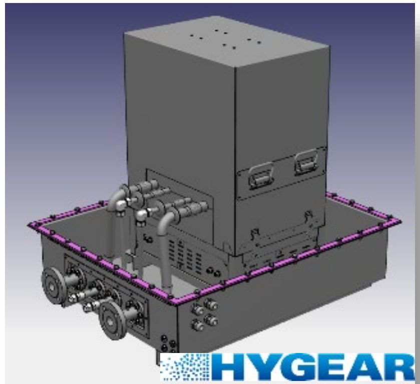

Modified (comm.) stack

Testbench for stack

- Several testbenches for performance test of cell-stacks
- Implementation (integration) with plasmolysis gas stream
- Performance of individual cells not reproduced

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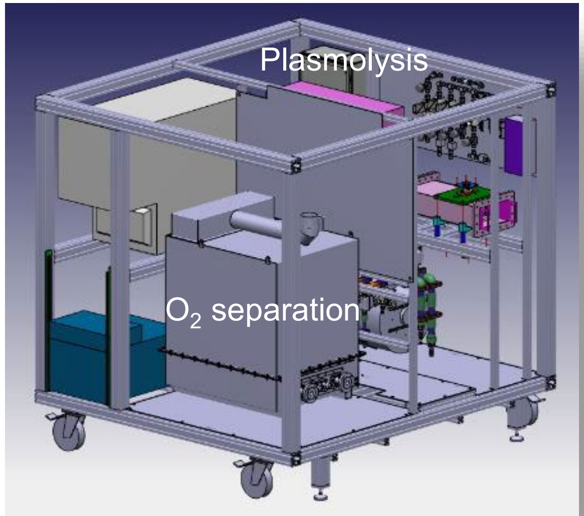
Summary / Take home messages

- **KEROGREEN** project
  - CO_2 & electricity ➔ Kerosene
  - Public event 27/09/2022
- **Plasmolysis of CO_2**
  - Conversion process dominated by strong and sharp gradients
  - Scientifically desired conditions form challenges for technical implementation
  - Standalone, operator-free, “plug-&-play” gas conversion module realised
  - Heat integration not (yet) considered
- **Oxygen separation**
  - SOEC approach promising on cell level
  - Testbenches realised for different scales
  - Upscaling and process integration seems to need radically new stack design



Plasmolysis applicator

Integrated plasma + separator module

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Any Questions ?

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