BIORAT 1 Phase A/B1 Final Presentation

BIORAT 1 Development team

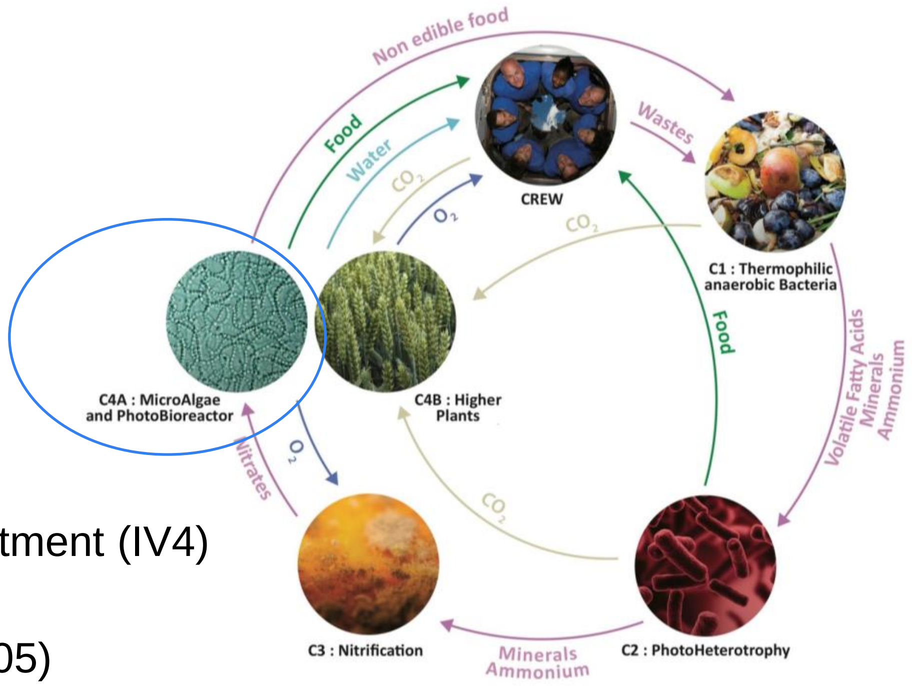
Agenda

beyond gravity

- 10:30 Presentation of participants
- Final Presentation
  - 10:40 Biorat1(BRT1) project framework
  - 10:45 Photobioreactor(PBR) & Liquid Loop(LL) subsystem Bread Board Model(BBM) life test
  - 10:50 System BBM Design
  - 11:00 System BBM life test
  - 11:15 Biorat1 On-Board Demonstrator(OBD)
  - 11:30 Conclusion & Future work
- 11:40 Questions & answers

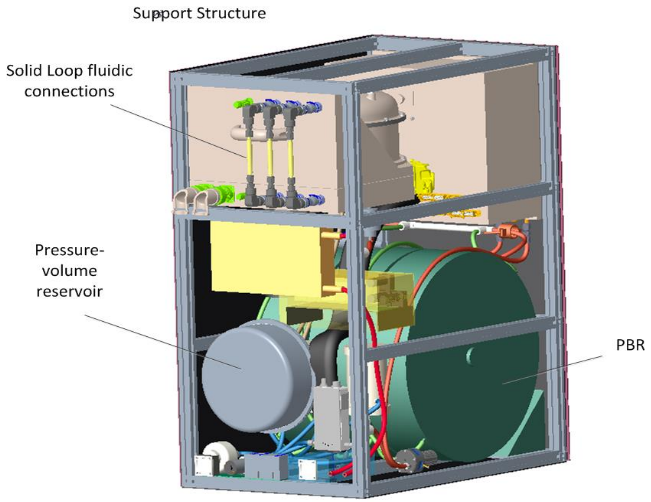
Project Framework
Biorat1 Objectives

- **Biorat 1 (BRT1) On-board demonstrator (OBD)**
  - International Space Station payload
  - Technological demonstrator
- **Objectives:**
  - To demonstrate the operation of the Photoautotrophic Bacteria Compartment (IV4)
    - Function: recycling of CO_2 directly from cabin into O_2
    - Principe: of a photobioreactor & spirulina (Limnospira indica PCC 8005)



MELiSSA loop,source Melissa Pilot Plant


International Space Station source NASA



BRT1 OBD Concept design

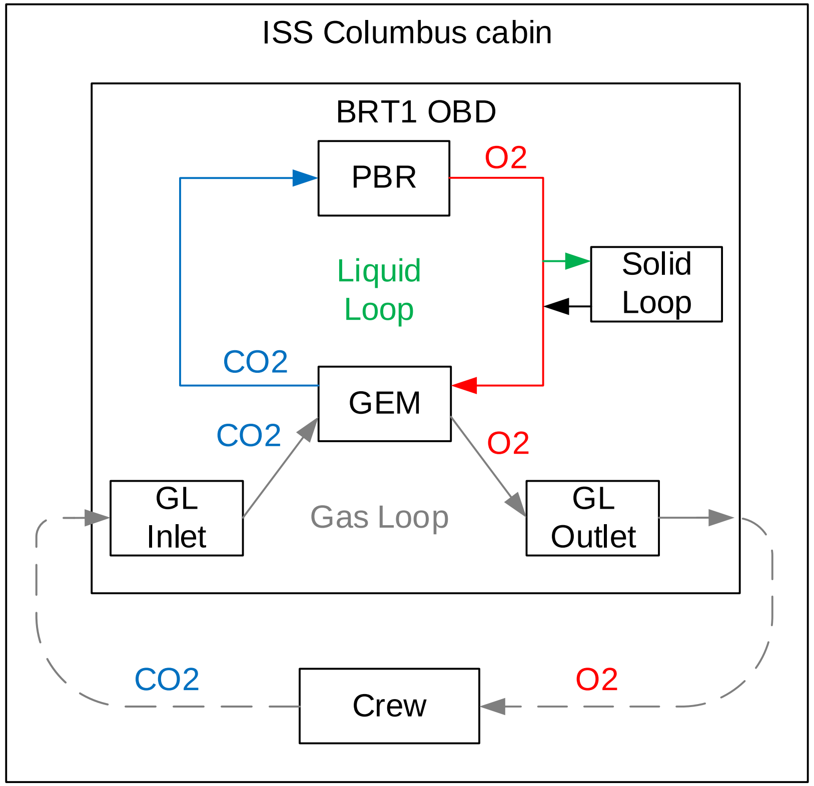
Project framework
Biorat1 Principle

beyond gravity

- Limnospira indica PCC 8005 oxygen production stoichiometry.
- **BRT1 OBD key components & functions**
  - **Liquid Loop (LL):** transfer of chemical species in liquid
    - **Photobioreactor (PBR)**: O2 & biomass production
    - Gas exchange membrane(GEM) : O2 & CO2 transfer between gas & liquid phase
  - **Gas Loop (GL):** Transfer of O2 to the LL & CO2 to the cabin
  - **Solid Loop (SL):**
    Biomass concentration control (harvesting),
    Nitrate supply with Zarrouk medium (feeding)
  - **Control System Electronic (CSE):**
    - Autonomous process control
    - Communication from/to ground

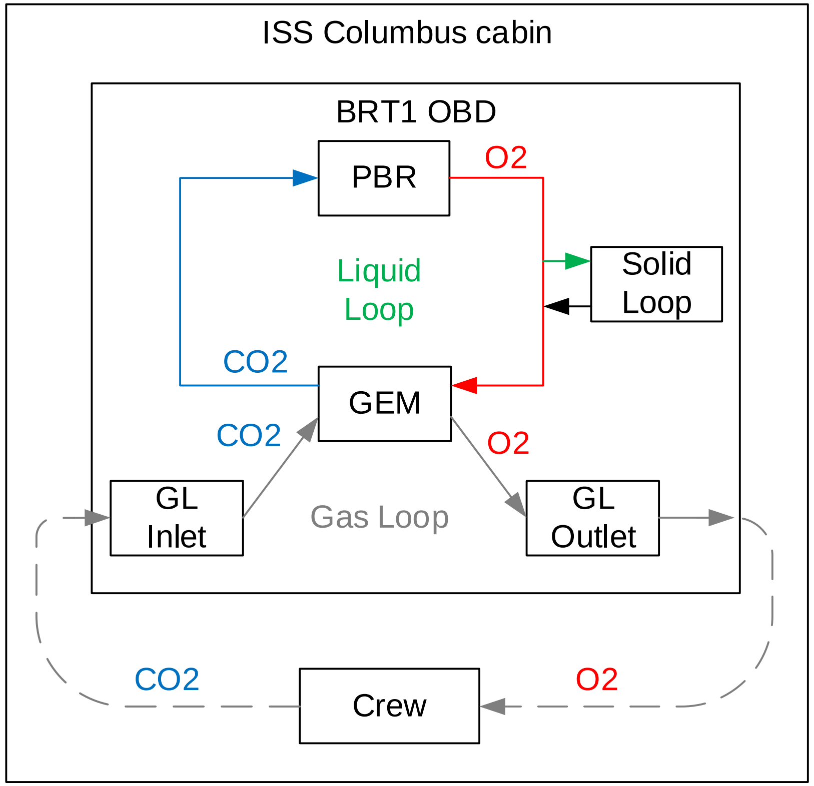
$$HCO_3^- + 0{,}70\ H_2O + 0{,}17\ NO_3^- + 0{,}007\ SO_4^{2-} + 0{,}006\ HPO_4^{2-} + 0{,}197\ H^+ \xrightarrow{<r_X>} CH_{1{,}58}O_{0{,}46}N_{0{,}17}S_{0{,}007}P_{0{,}006} + 1{,}39\ O_2 + OH^-$$

Ref. Biorat, MELiSSA demonstration breadboard, Final Presentation 2000



Project framework
Current phase objectives

- Current project phase: A/B1
- Mature OBD technologies:
  - through Breadboarding & Life Test (in laboratory)
    - Photobioreactor (PBR) & Liquid Loop (LL) subsystem
    - BBM at system level
- Define the BRT1 OBD Concept design
  - Inputs: BBM life test results
  - Objective: System Requirement Review



PBR & LL Subsystem BBM Design & Life test → System BBM Design & Life tes → OBD Concept Design

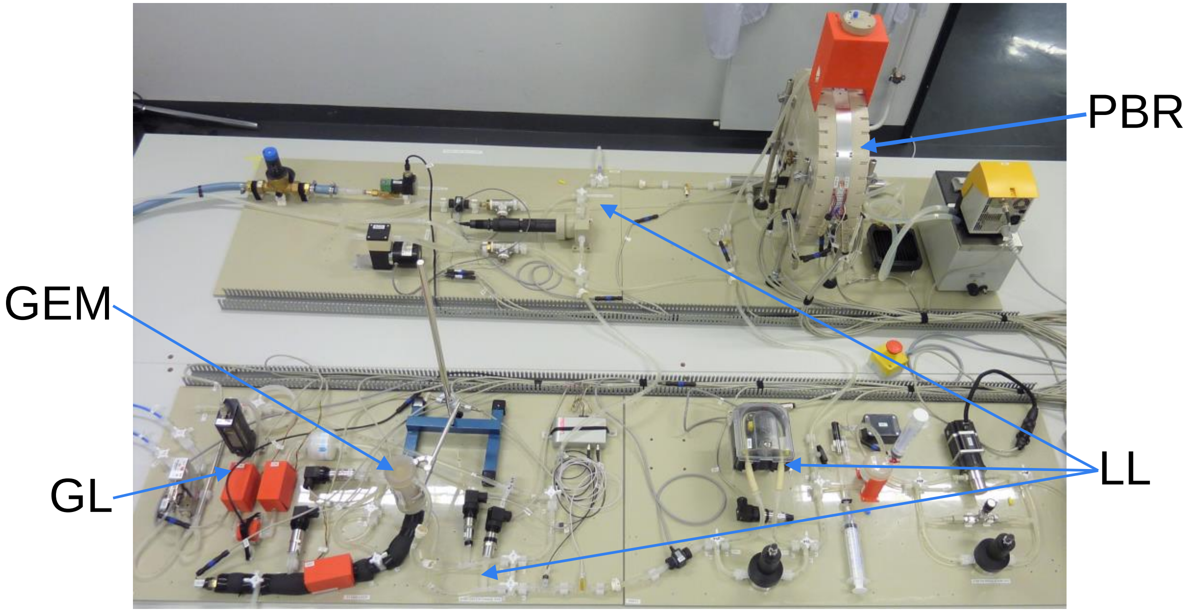
Project framework
BRT1 Development team

beyond gravity	REDWIRE	SHERPA engineering	uca
Beyond Gravity Slip Rings	**Redwire Space**	**SHERPA Engineering**	**Université Clermont Auvergne**
• System engineering, • Liquid Loop, • Gas Loop , • Thermal Control System	• Controls System Electronic (HW & SW) • Solid Loop	• Process modeling • Process control	• Biological expertise • Life test performance

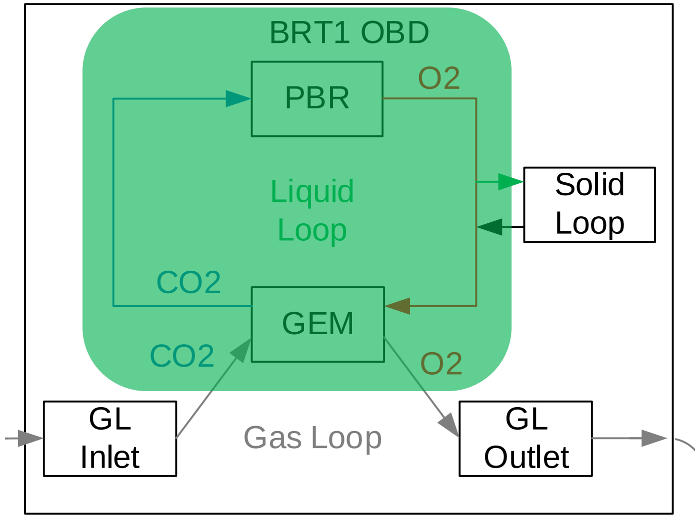
LL/PBR BBM

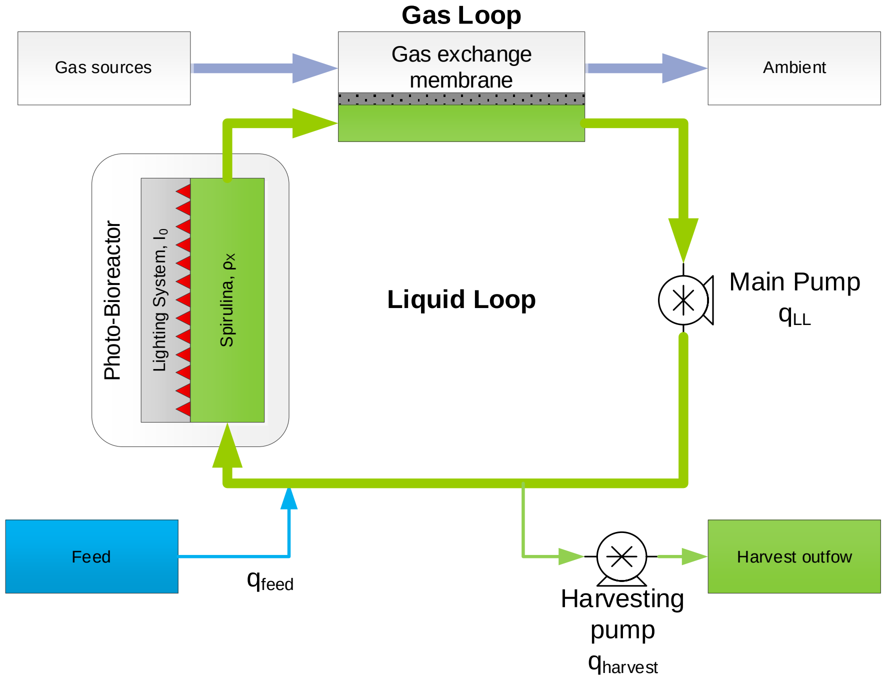
LL/PBR “growth model” life test

- 2019 BBM Life test
  - Performed to validate Photobioreactor & Liquid Loop concept design
  - Chemostat operation (no solid loop)
  - ➔ high volumetric feed consumption
  - No process control
  - ➔Manually setting of Light intensity, harvesting flow rate



2019 BRT1 BBM



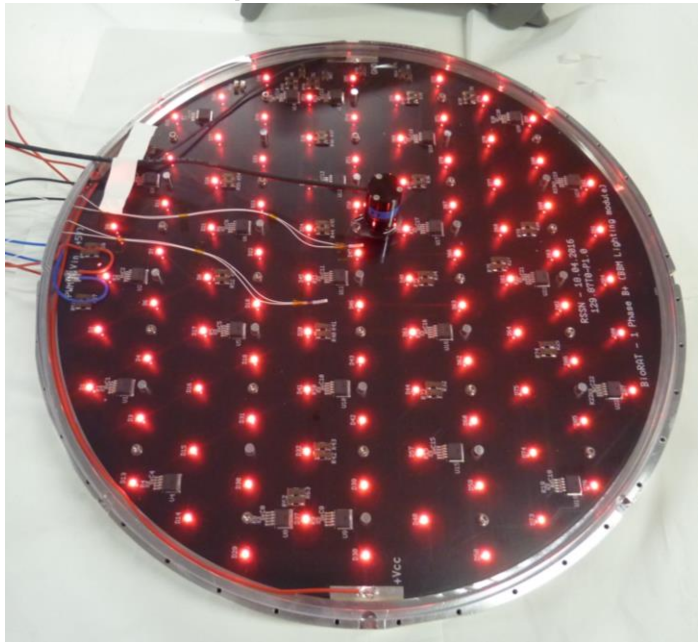


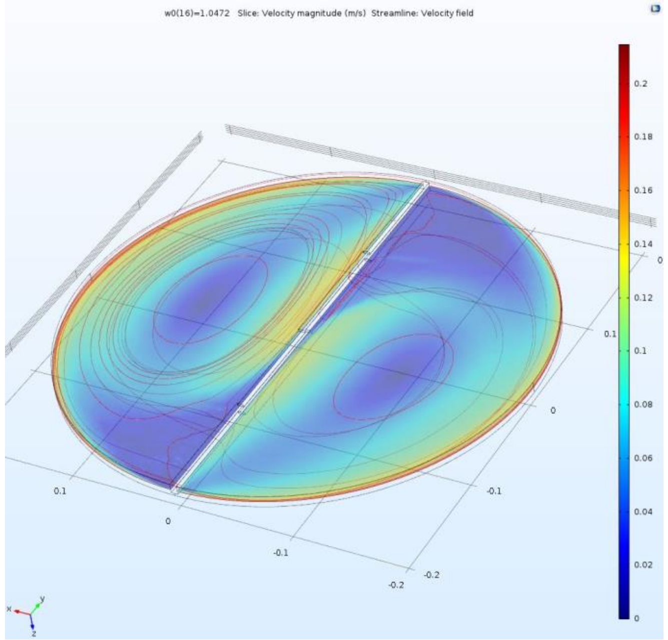
2019 BRT1 BBM P&ID

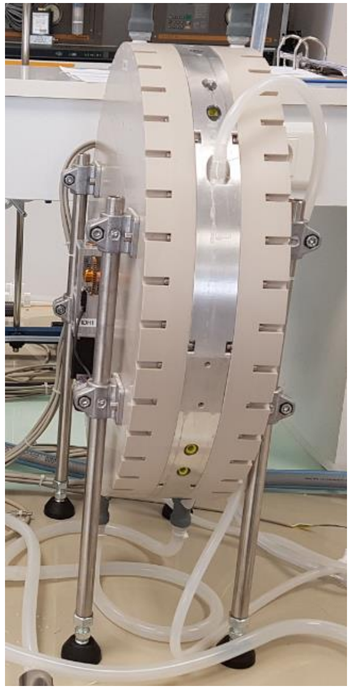
Beyond Gravity Slip Rings SA

LL/PBR BBM
Photobioreactor Design

- BBM Photobioreactor
  - Function: Produce O2 and biomass by photosynthesie from dissolved CO2
  - Flight representative design
  - Based on red LEDs panel
  - Mixing mechanism design supported by dissolved O2 simulation (COMSOL CFD & TDS)
  - Overal PBR liquid volume: 2.6L







LL/PBR BBM
Life test results

- LL/PBR BBM Life tests achievements:
  - 25 days of cultivation >1gr/L biomass concentration achieved
  - 5 days of cultivation >2gr/L biomass concentration
  - Continuous O2 production >6.75mmol/h PBR design point

➔PBR & LL design validated

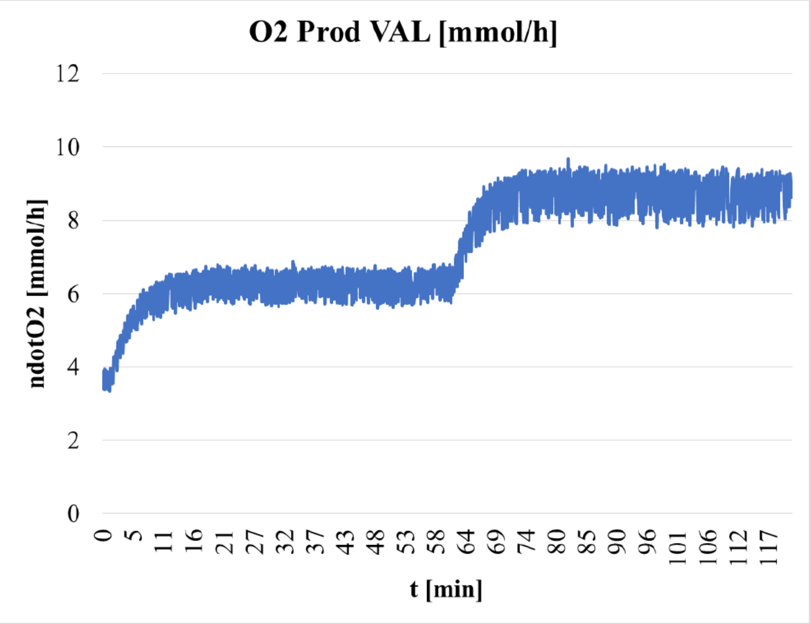


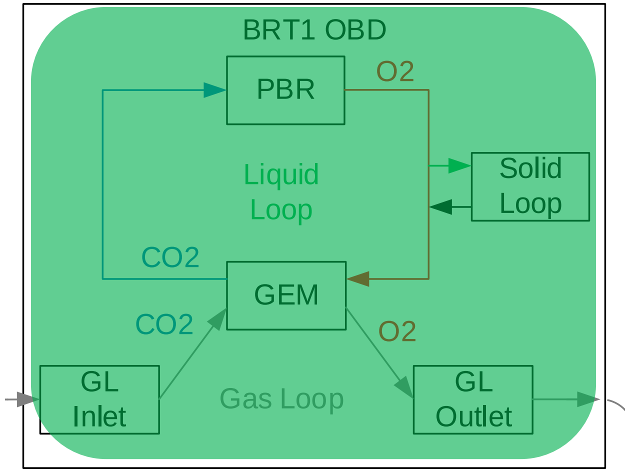
Figure 13 – Light step response to 35W/m2 & 50W/m2

Time	Average size [mm]	Concentration [g/L]
T0	166	0.24
T0+3d	247	1.17
T0+4d	229	1.3
T0+7d	227	1.53
T0+10d	213	1.56
T0+17d	288	1.37
T0+19d	271	2.03

Table 4 - Algae average size over time

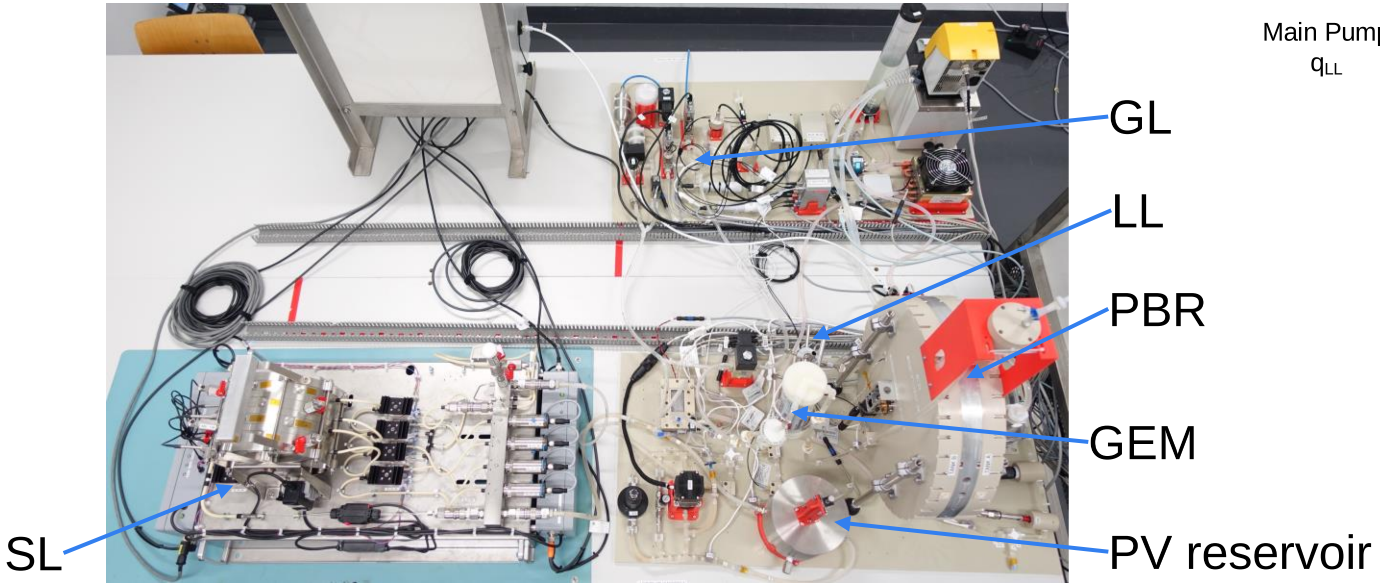
System BBM Design

Objectives & Key functions

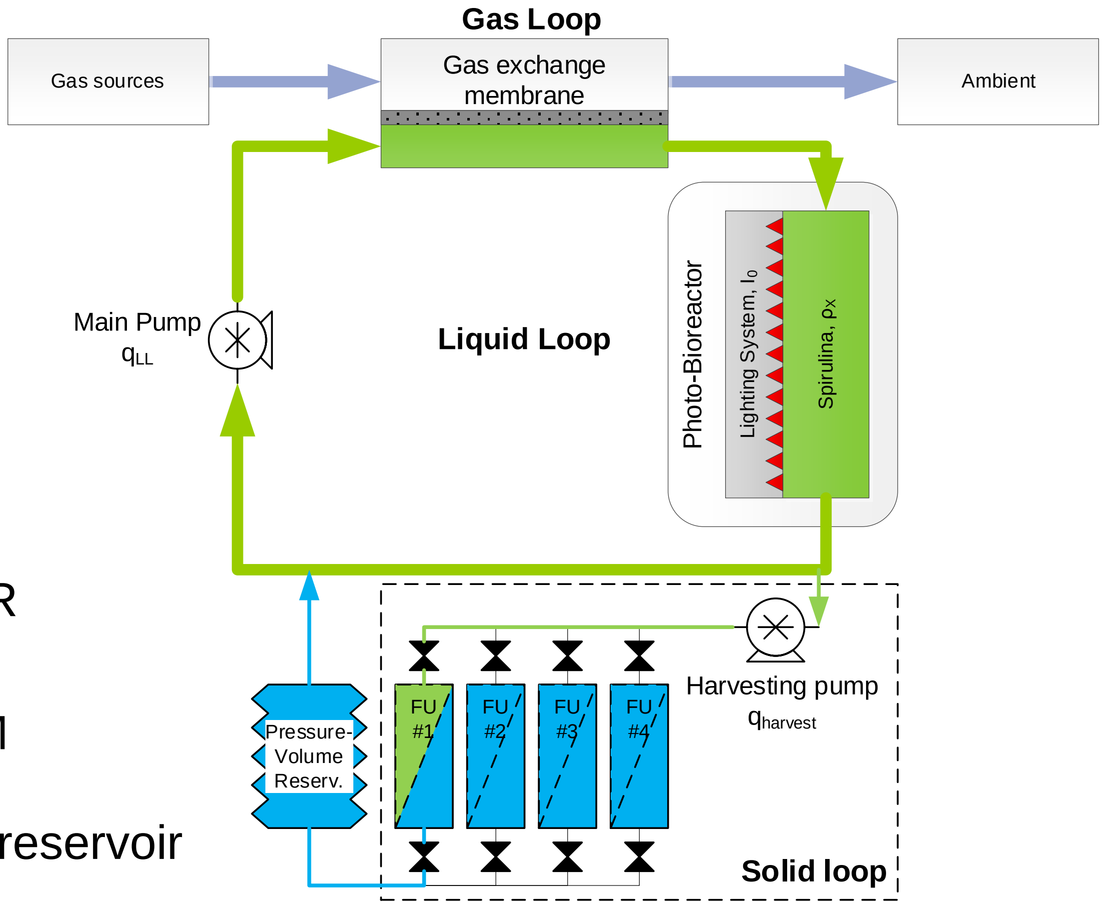


Perform sequence representative to OBD demonstration sequence

- Maintenance operation every 30 days
  ➔Medium consumption reduction with Solid Loop (SL)
- Autonomous operation
  ➔Process control to be implemented
- Aseptic cultivation condition
  ➔Hardware sterile design and aseptic operations



2021 BRT1 BBM



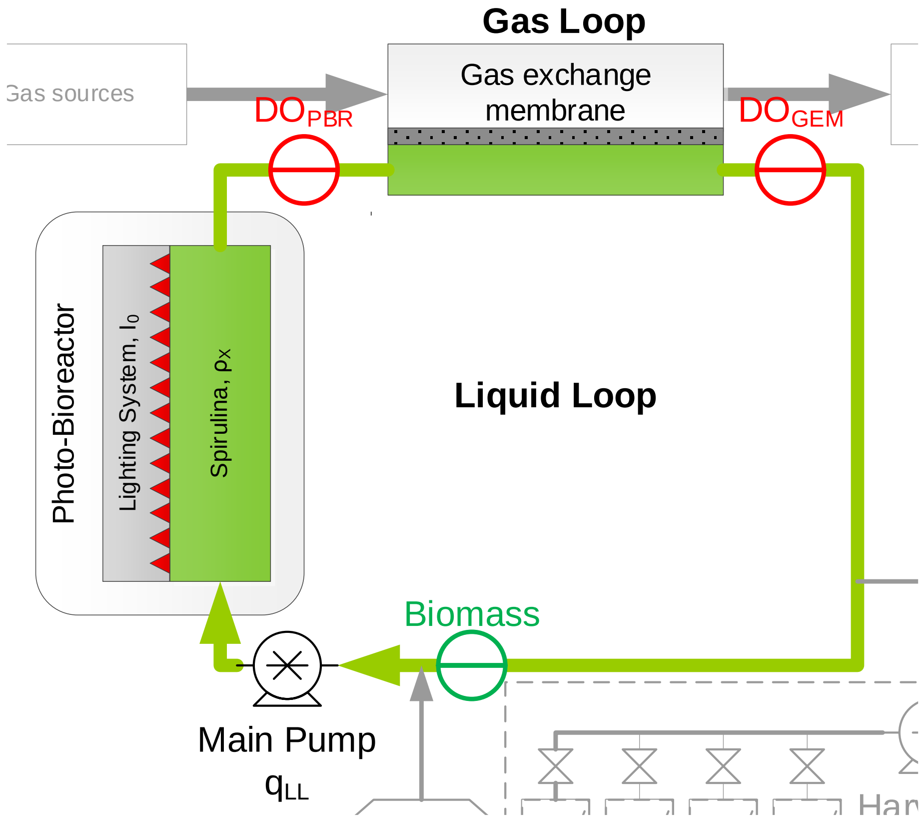
System BBM

Key process variables measurement

- Existing
  - **Oxygen** production measurement
    - Measurement: dissolved O2 mass balance before and after the GEM
      - Hardware: Pyroscience, Firesting O2 & OXROB3
- Upgrade
  - **Biomass**
    - Measurement: optical density sensor
      - Hardware: Hamilton, Dencytee
    - Alternative: software estimator based on O2 production measurement
  - **Nitrate**
    - No online sensor suitable
    - Software estimator based on O2 production measurement
    - NO3 Calibration function needed to correct NO3 estimator and O2 measurement.

$$HCO_3^- + 0{,}70\ H_2O + \boxed{0{,}17\ NO_3^-} + 0{,}007\ SO_4^{2-} + 0{,}006\ HPO_4^{2-} + 0{,}197\ H^+ \xrightarrow{<r_X>} \boxed{CH_{1,58}O_{0,46}N_{0,17}S_{0,007}P_{0,006}} + \boxed{1{,}39\ O_2} + OH^-$$

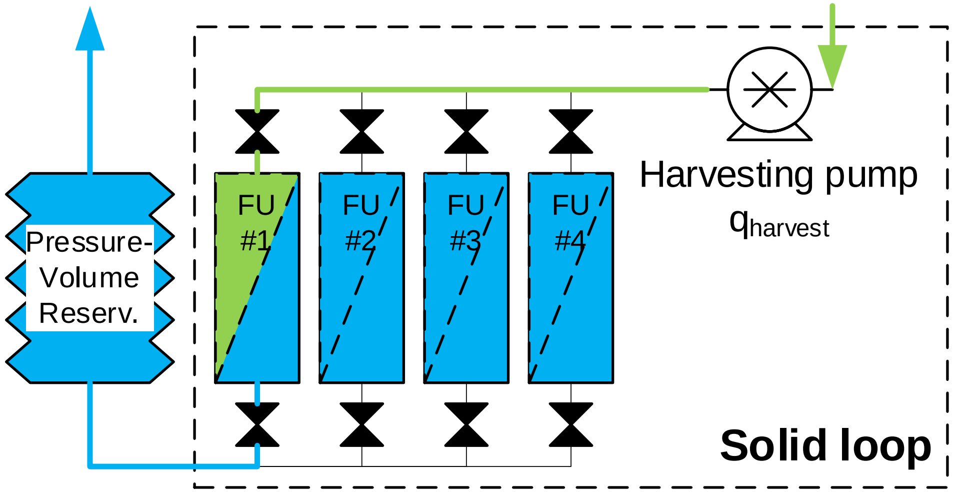
Ref. Biorat, MELiSSA demonstration breadboard, Final Presentation 2000

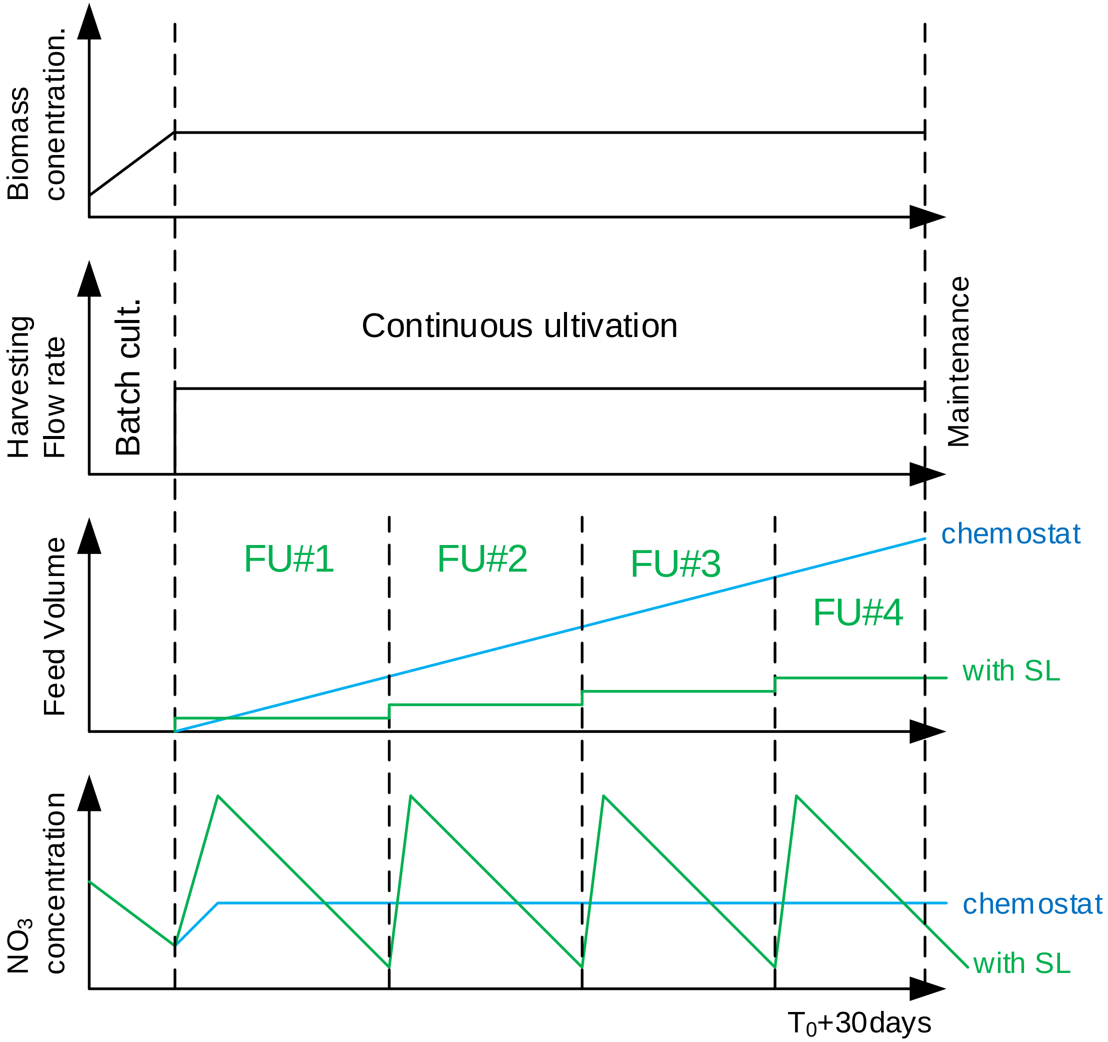


System BBM Design

Biomass & NO3 management concept

- LL operation at constant biomass concentration (1.5g/L)
- Batch cultivation: biomass increases, no harvesting
- Continuous cultivation: Harvesting flow rate enabled
  - Filter Unit (FU) #1 is activated
    - Biomass is accumulated in the FU
    - Concentrated Zarrouk medium is released in LL
  - The other FUs are activated sequentially before NO3 nitrate depletion
- Maintenance operation: replacement of the 4 FUs.





System BBM Design

NO3 management concept , Pros & Cons

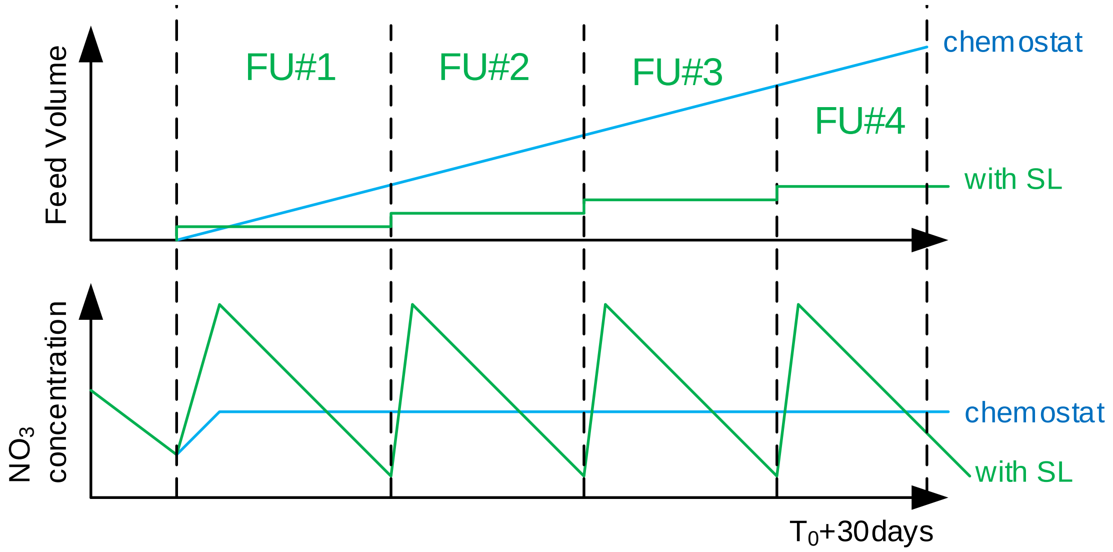
- Pros & cons of **discrete feeding**

  + Less volume medium needed from typically 1.8L/day to 0.11L/day by
    - decoupling between harvesting flow rate & feeding
    - concentrated Zarrouk up to (7.3x reference concentration) stored in FUs

  + Constant volume operation, fresh medium replaced by the harvested biomass in the FUs

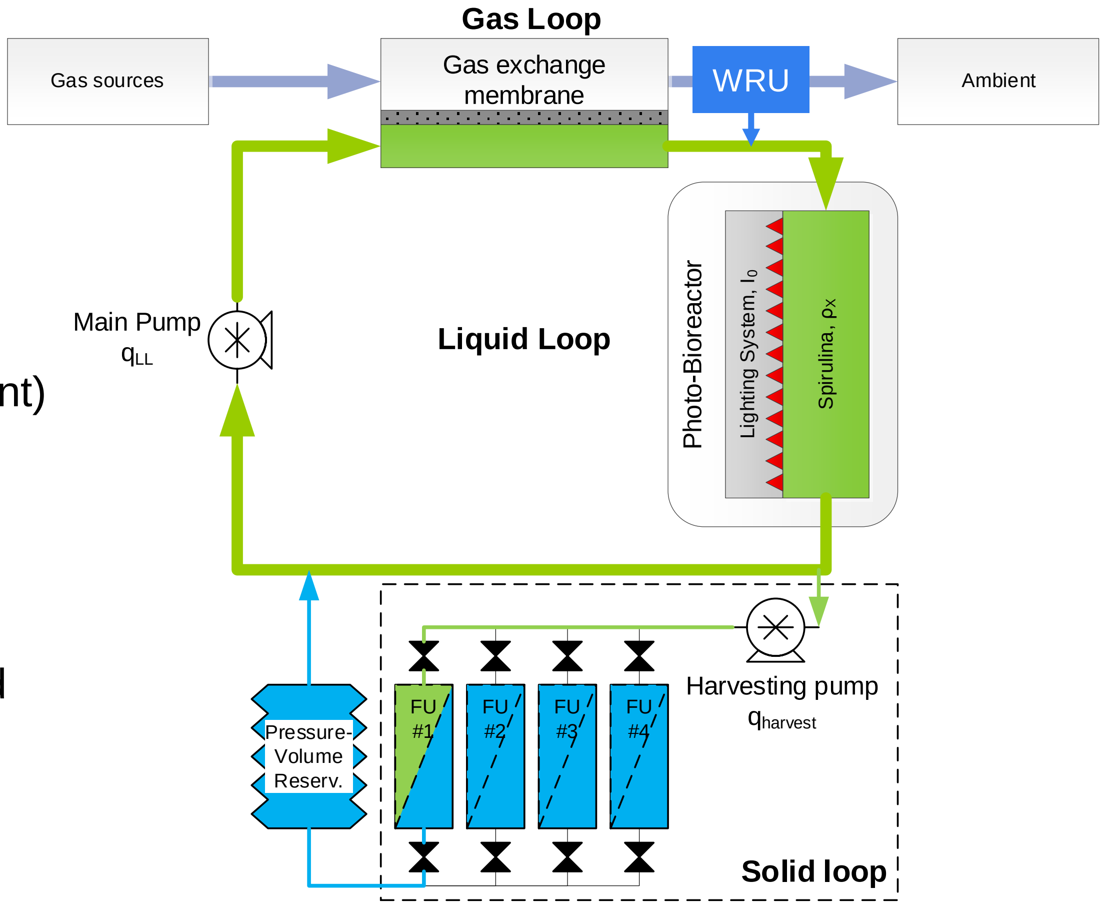
  + No dewatering needed for the harvested biomass

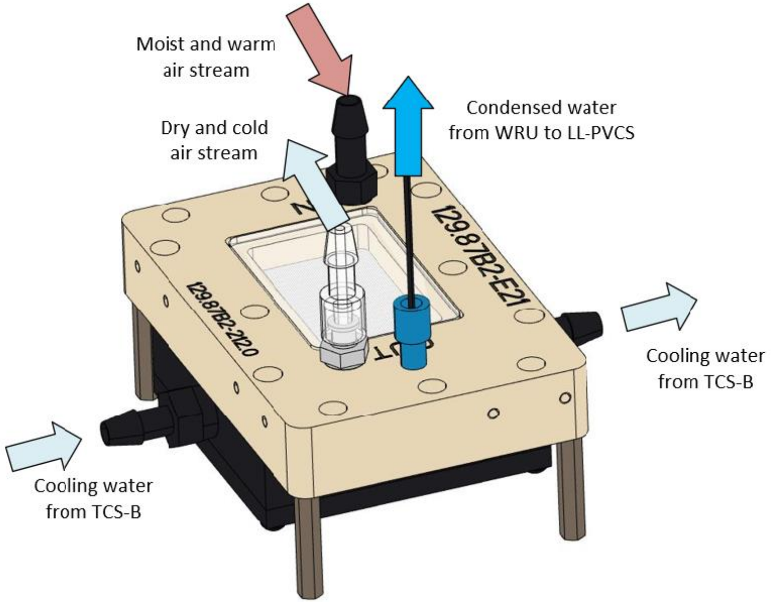
  -Variation of NO3 concentration in LL
  - Switching of FUs & maintenance operation must be performed at low NO_3 concentration to prevent overshoot
  - NO_3 concentration variable needed for process control



System BBM Design
GL Water Retrieval Unit

- High pervaporation of LL water through the GEM to the GL
- Need:
  - Reduce the humidity rejected in the cabin (Interface Requirement)
- Water retrieval unit is a condenser based on:
  - Peltier element for cooling
  - Capillary principle for water collection
- Benefits
  - Limit the amount of feed medium needed by reusing condensed water into the LL





System BBM Design (RW)
Solid Loop - Requirements

- Key requirements
  - Separate biomass and growth medium
  - Store the biomass in a safe way
  - Recycle the medium to the PBT
  - Resupply nutrients (nitrogen)

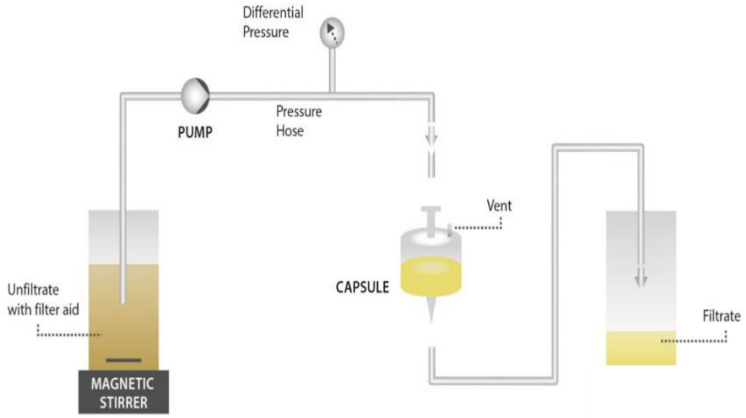
- Trade-off
  - Filtration principle : tangential / dead-end / deep-bed
  - Filtration modus : continuous or semi-continuous

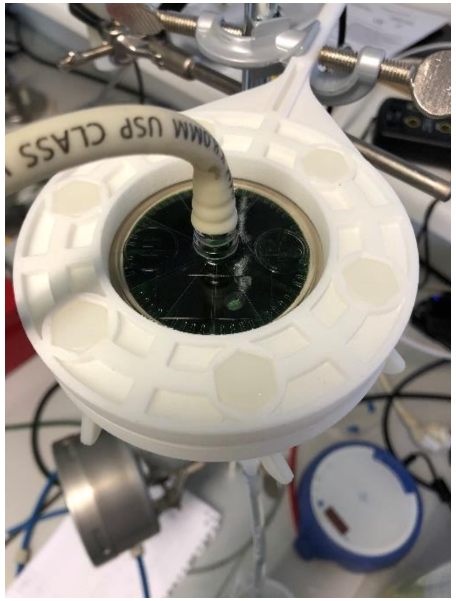
- Design parameters
  - Cut-off : pore size to separate the *Limnopira* (10-40 µm)
  - Flux : membrane can handle the desired filtrate flux (L/m^2.d)
  - Transmembrane pressure (mbar)
  - Holding capacity (g dry matter / m^2 filter surface)
  - Storage capacity (g dry matter / m^3 filter housing)

- Material selection
  - Compatibility with disinfection methods (chemical disinfection, thermal sterilization, steam sterilization,…)
  - Long term storage of filter material

System BBM Design (RW)
Solid Loop – Feasibility Tests

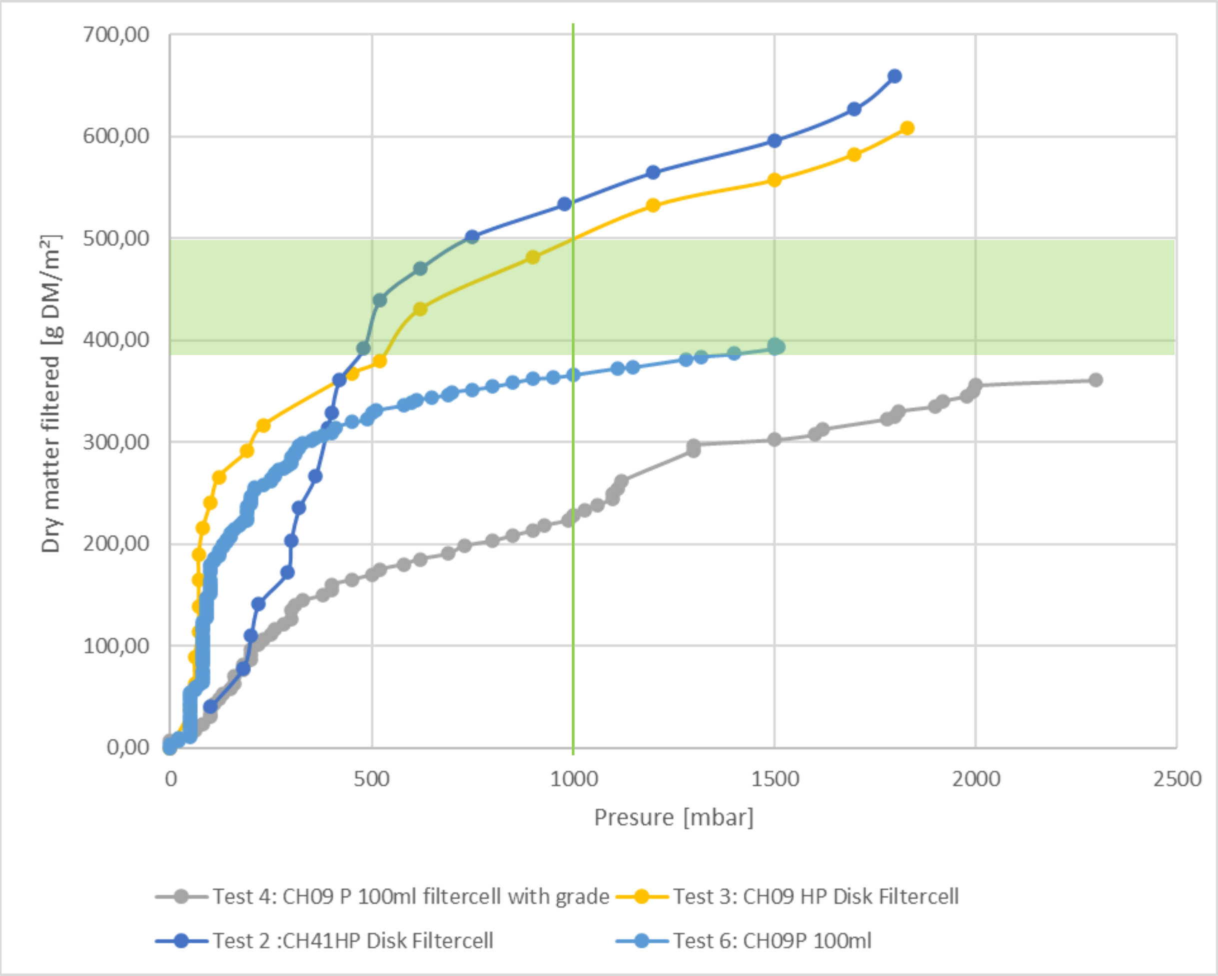
- Filtration medium tests – deep bed filter sheets Filtrox

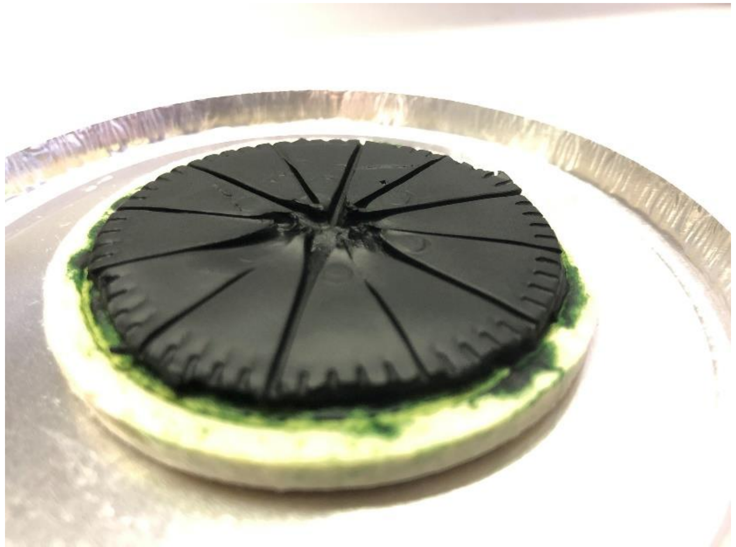




System BBM Design (RW)

Solid Loop – BBM Design

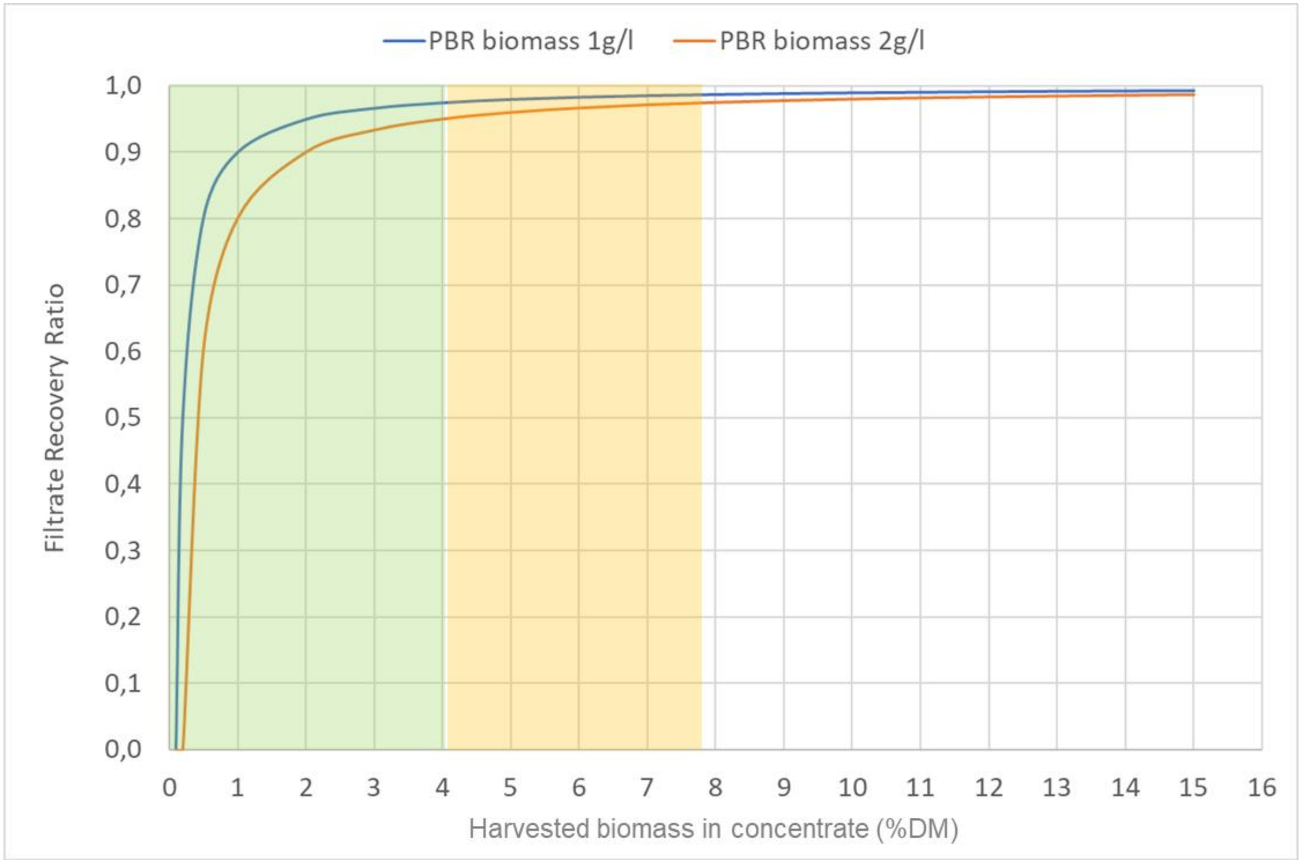


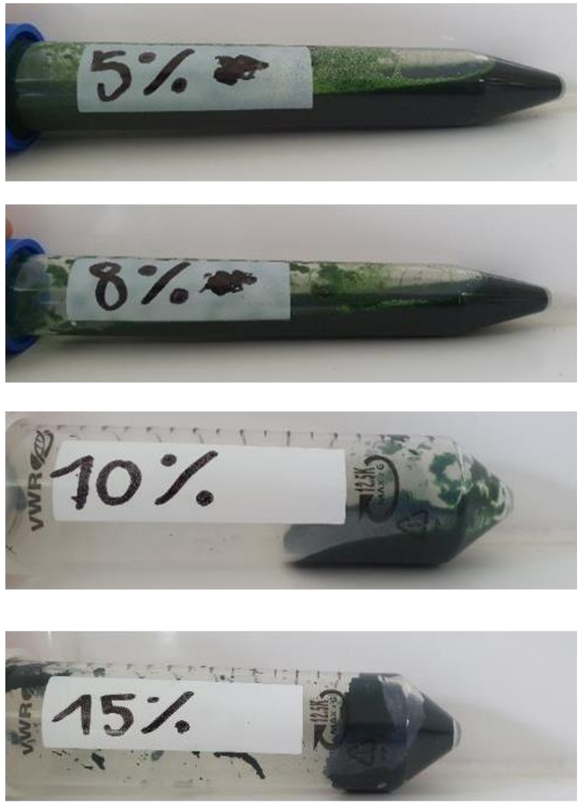


System BBM Design (RW)

Solid Loop – BBM Design

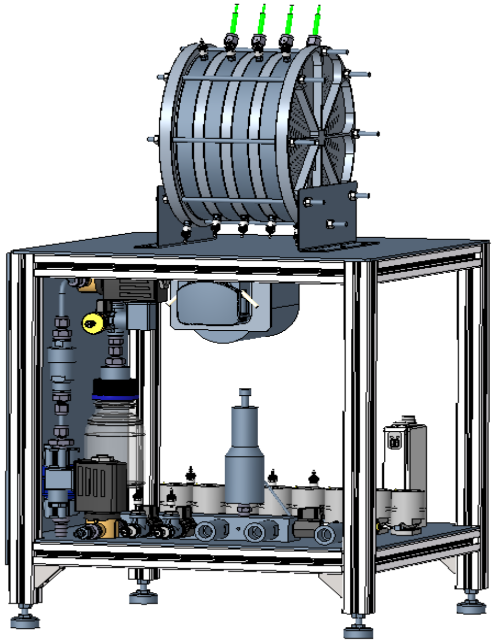
- Biomass surface load of the filter (B_A) : 500 g DM/m² -> 300 g DM/m² max
- Biomass holding capacity in filter house : >= 4 % DM

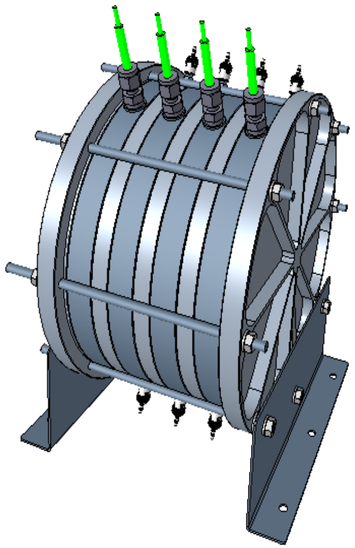


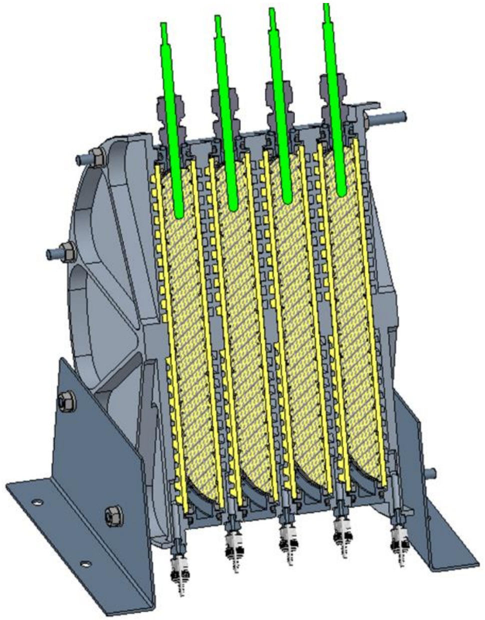


System BBM Design (RW)

Solid Loop – BBM Design



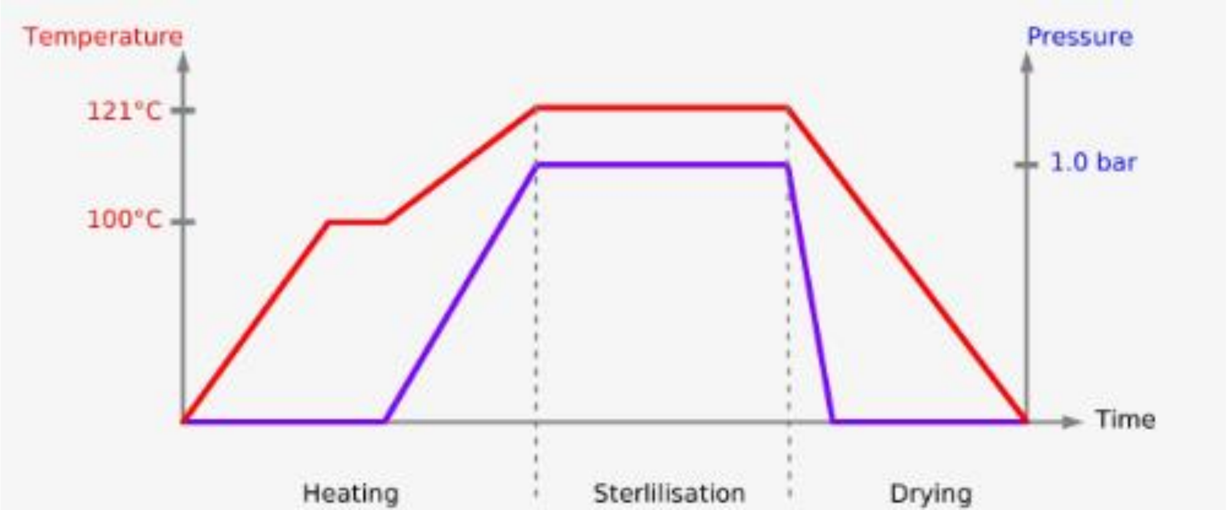




System BBM Design (RW)

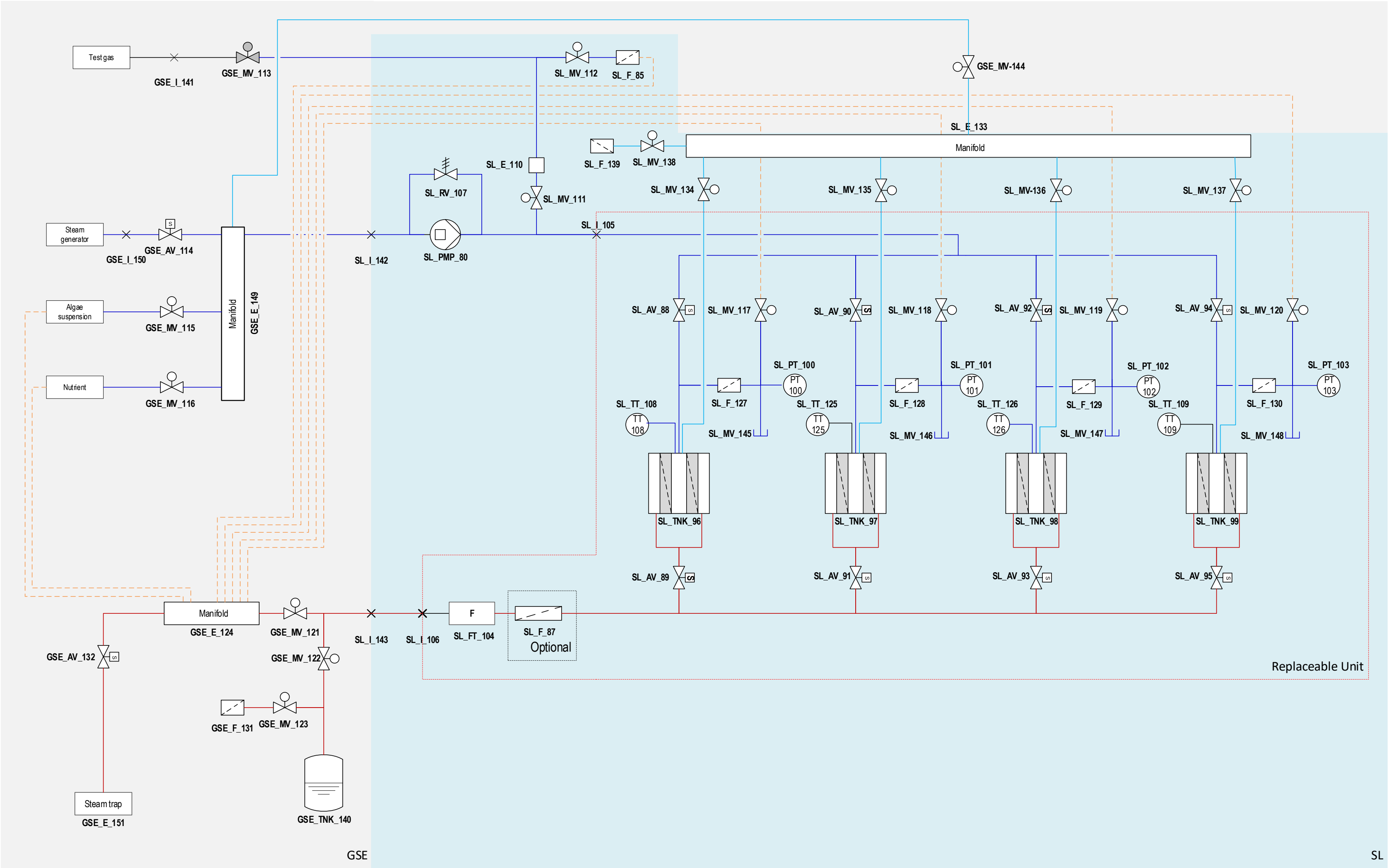
Solid Loop – Steam in place (SIP)

- Sterilisation
  - D value: time needed to kill 90% microorganism (reduction of 1 log) at a specified temperature
    z value: temperature difference causing a 10-fold variation of D-value, i.e., a variation of one logarithmic value of the sterilization time
  - Sterilization considered achieved when the microorganism population has endured a 10e6 decay (time = 6*D)
  - Typically: 121 °C during a period of 20 minutes or 135 °C during 10 minutes
  - $D_T = D_{121} * 10^{\frac{121-T}{z}}$, z= 10°C, *Geobacillus stearothermophilus* (used for steam sterilization validation)
    D_121 value of 2 min => 95.4 min at 112°C, 0.6 barg (cfr manufacturer)
- SIP: 3 phases



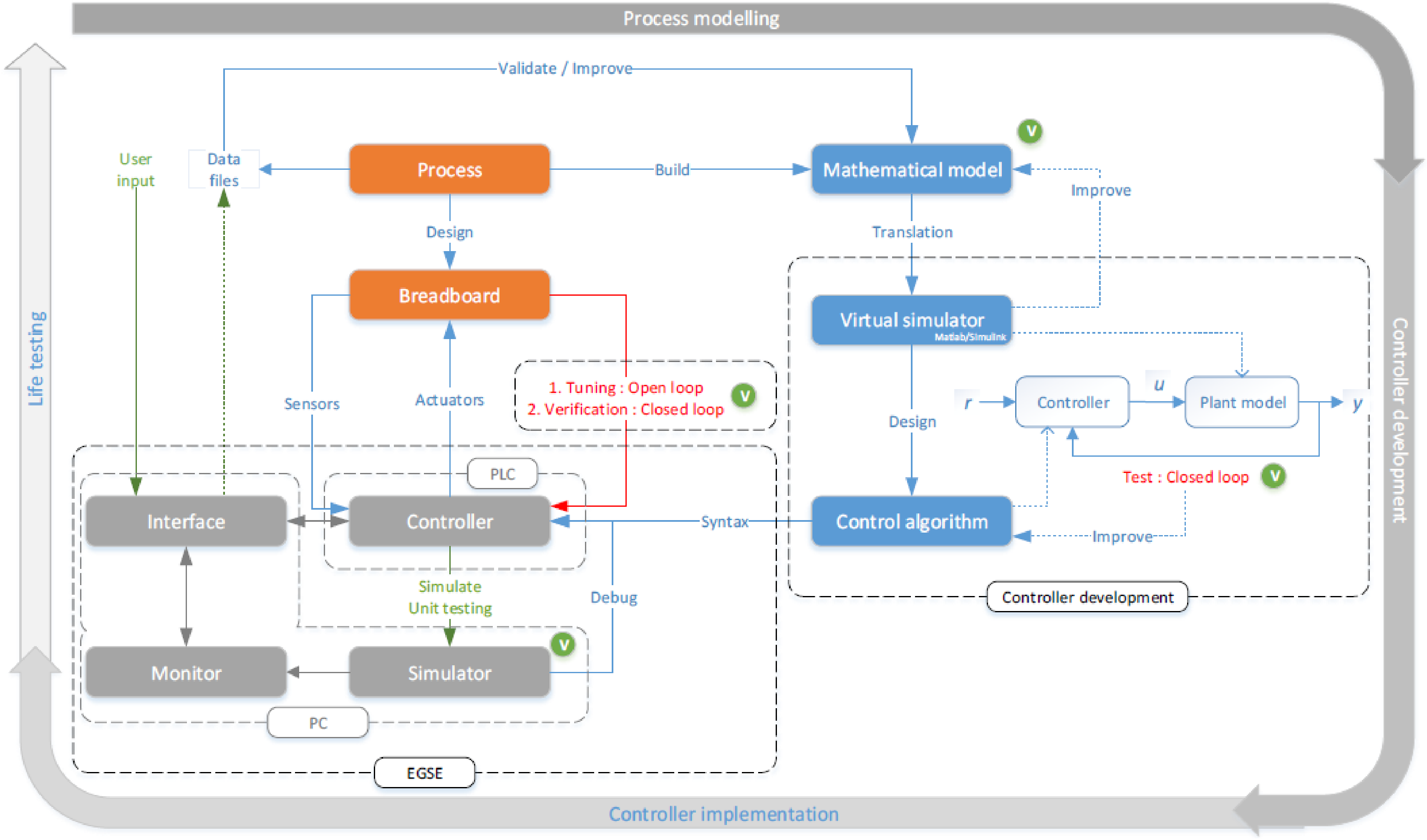
System BBM Design (RW)

Solid Loop – Steam in place (SIP)



System BBM Design (RW)

CSE Control System Electronic design



System BBM Design (RW)

CSE Control System Electronic integration

beyond gravity

Second Block : FUManagement

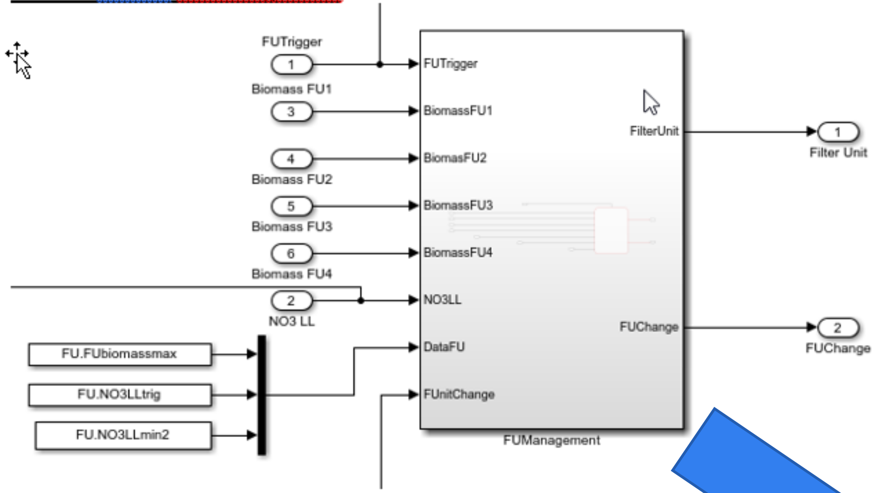
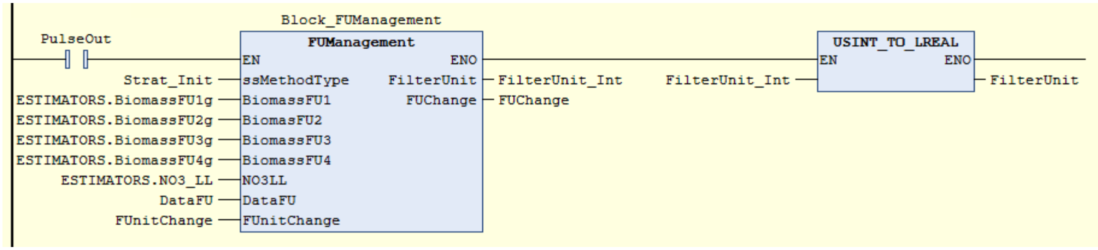


Figure 8: FU Management (Simulink)

Inputs are:

- Biomass in FU1 (g) from estimator output
- Biomass in FU2 (g) from estimator output
- Biomass in FU3 (g) from estimator output
- Biomass in FU1 (g) from estimator output
- NO3 LL(mol/m3) from estimator output
- Data FU (here are inputs but could be parameters)
  - *FUBiomassmax* (31.5 g)



System BBM Design (RW)

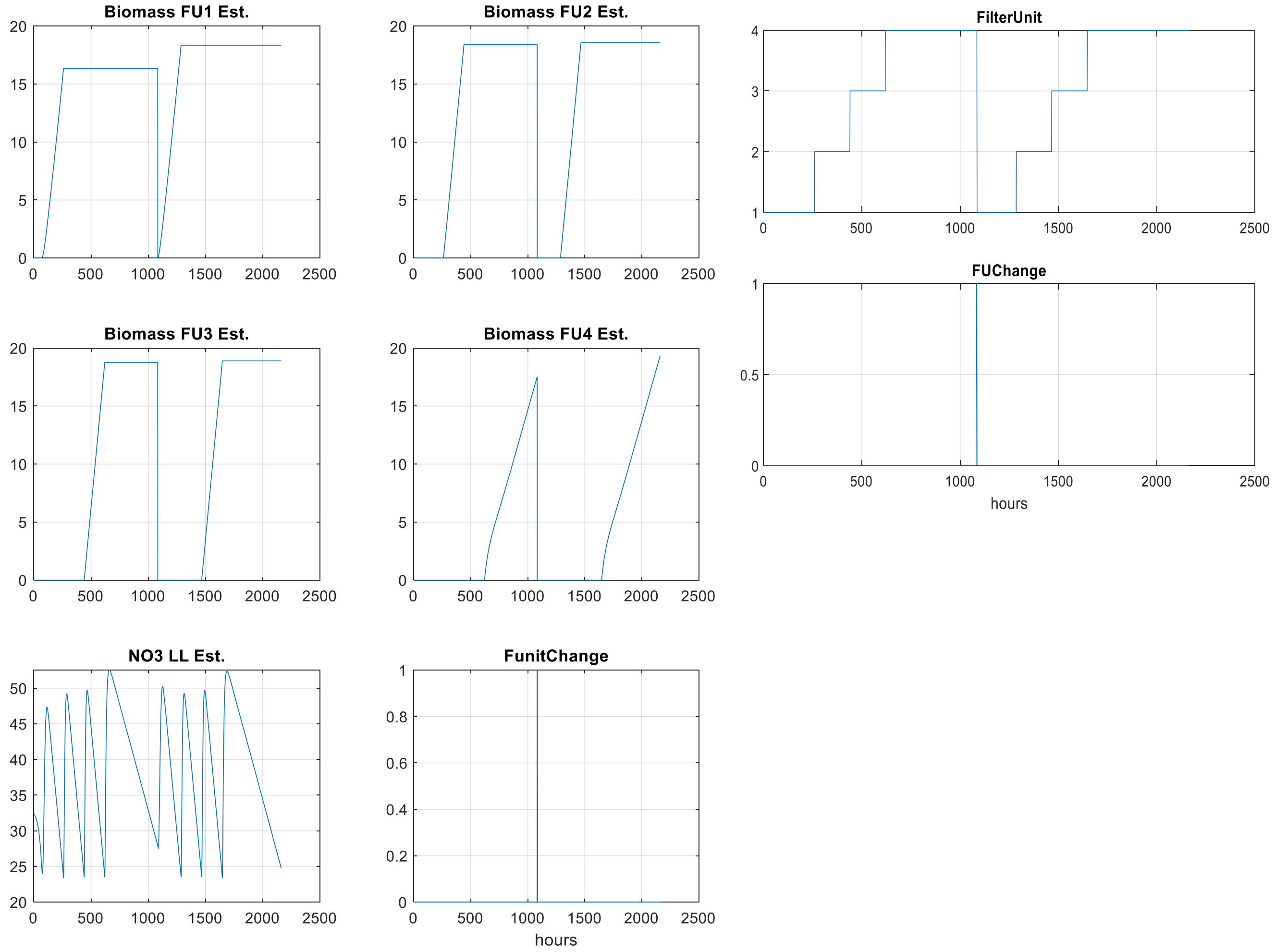
CSE Verification by Simulation

BiomassFU1	BiomassFU2	BiomassFU3	BiomassFU4	NO3LL	DataFU[1]	DataFU[2]	DataFU[3]	FUnitChange
0	0.00E+00	0	0	32.39104829	31.5	23.6	34.6	0
0	0	0	0	32.3714999	31.5	23.6	34.6	0
0	0	0	0	32.34393569	31.5	23.6	34.6	0
0	0	0	0	32.31543328	31.5	23.6	34.6	0
0	0	0	0	32.28596406	31.5	23.6	34.6	0
0	0	0	0	32.25549849	31.5	23.6	34.6	0
0	0	0	0	32.2240061	31.5	23.6	34.6	0
0	0	0	0	32.19145544	31.5	23.6	34.6	0

FUManagement_I | FUManagement_OSim | Units

FilterUnit	FUChange
1	0
1	0
1	0
1	0
1	0
1	0
1	0
1	0

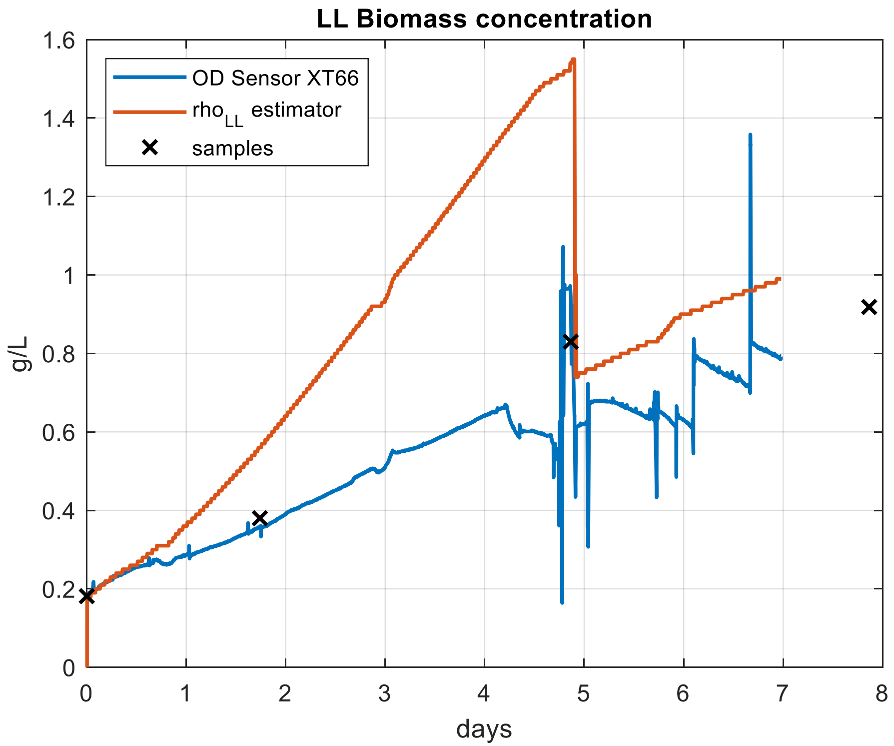
FUManagement_I | FUManagement_OSim | Units



System BBM Life Tests Results

Process results

- Achievement
  - biomass concentration 0.65g/L (Nominal 1.5g/L)
  - O2 production: short therm ~6.4mmol/hr (Nominal 6.75mmol/hr)
  - Autonomous operation: 5 days



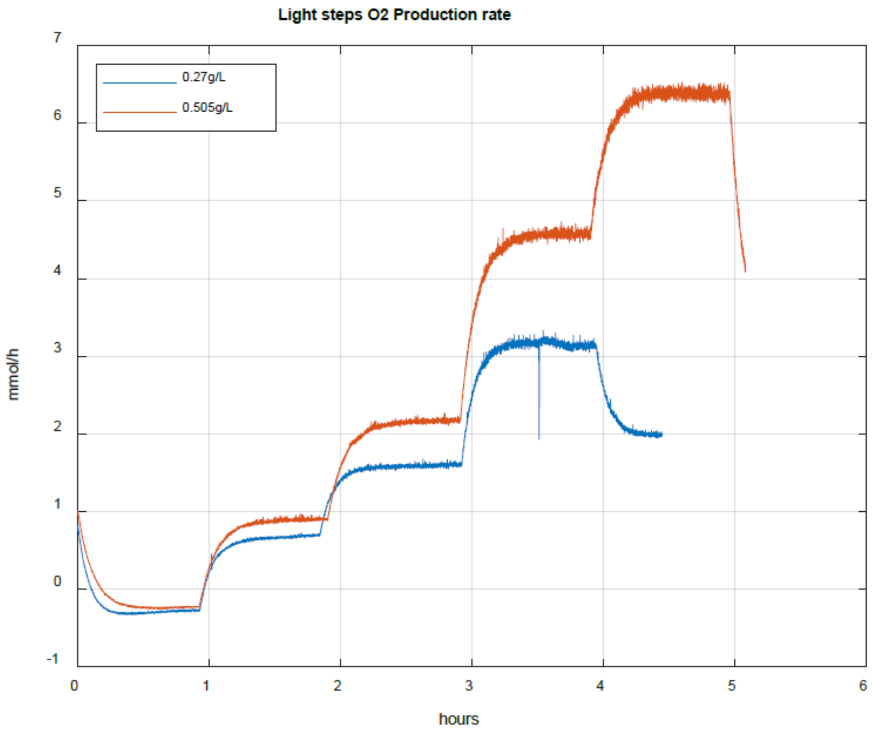
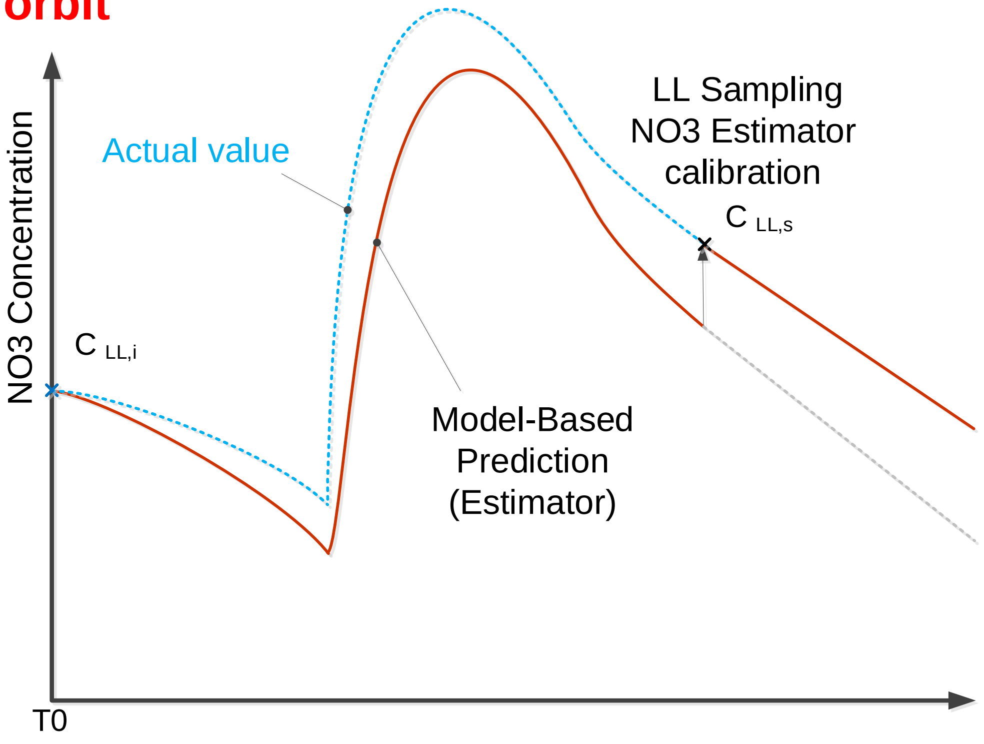


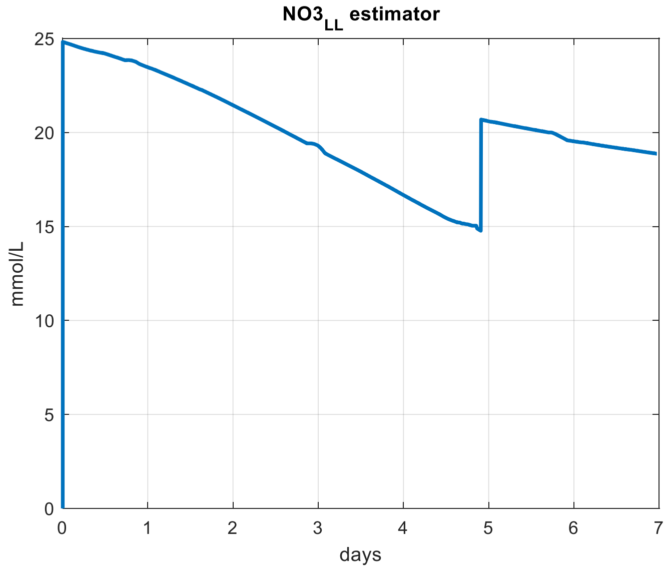
Figure 7 - Light intensity steps, O2 production rate

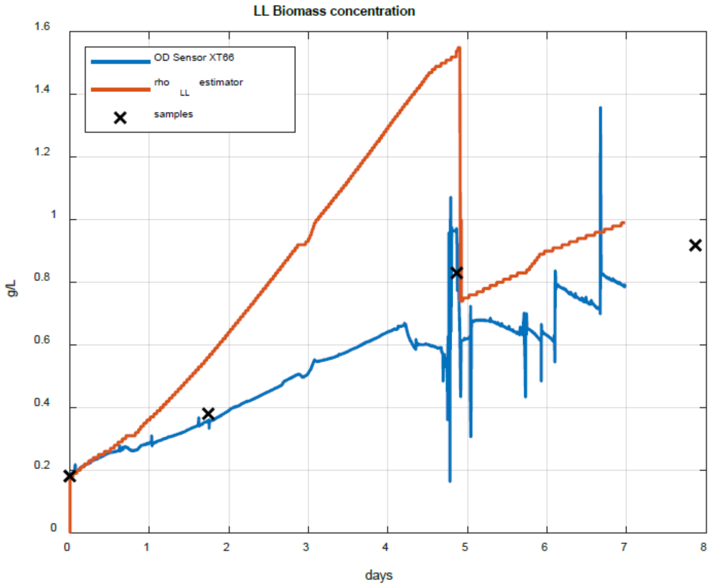
System BBM Life Tests Results

Process control results

- Autonomous process control:
  - **NO_3 estimation & live calibration**
    - **No NO_3 measurement in orbit**
  - **Biomass estimation**
  - Light intensity control
  - Harvesting fllow rate control (batch mode)
  - SL Filter unit selection
  - WRU temperature control







System BBM Life Tests Results

Sterility/Axenicity issue

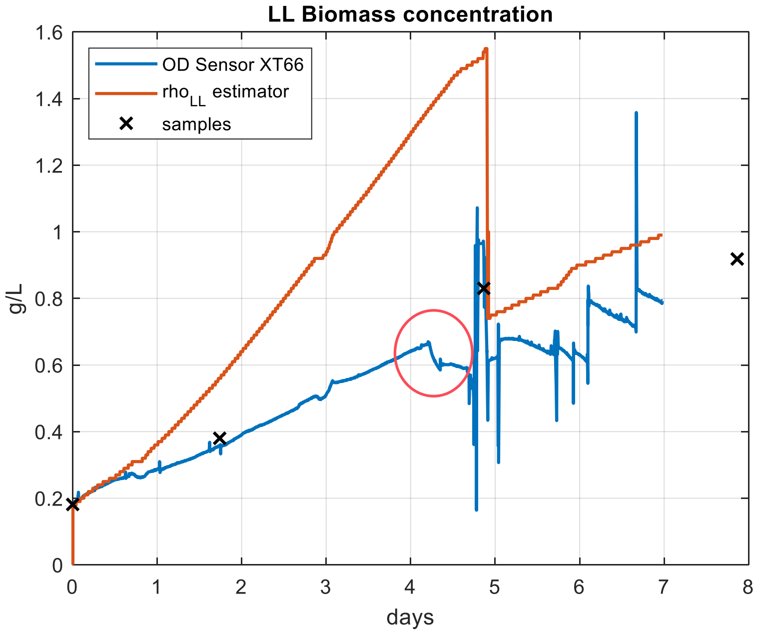
- Sterilitisation approach
  - LL subsystem➔Chemical sterilization with NaOH solution
  - SL subsystem➔SIP (Steaming In Place)
  - LL & SL sterile connection
- Results
  - Only Partial sterility achieved at subsystem system level
  - No sterility at system level/axenic cultivation achieved
- Non-conformance causes
  - Heat and alkali-resistant contamination: Bacillus pseudofirmus
  - LL intricate geometry and sliding sealing not reachable by NaOH solution
  - SL inhomogeneous heat and steam distribution in SIP
- Way-forward:
  - Lessons-learned for OBD concept design and next BBM iteration

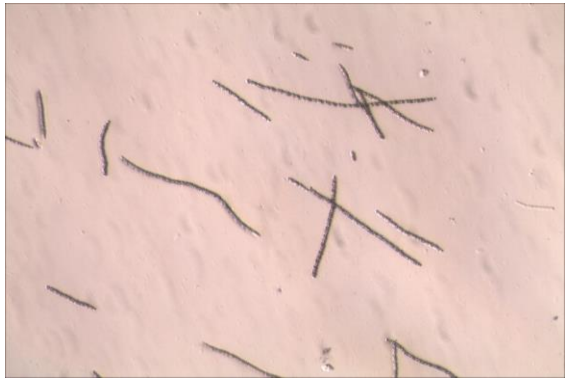
System BBM Life Tests Results

GEM Clogging anomaly

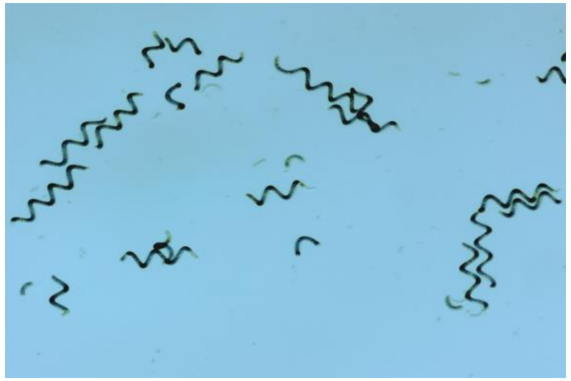
- BBM life test was shortened due the clogging of spirulina at entrance of the GEM
- Non-conformance cause:
  - System BBM life test: spirulina with **helix** morphology

  *(LL-PBR Sub-sys BBM life test: spirulina with **straight** morphology)*
- Way-forward
  - To procure straight morphology spirulina
  - Increase the GEM internal lumen diameter





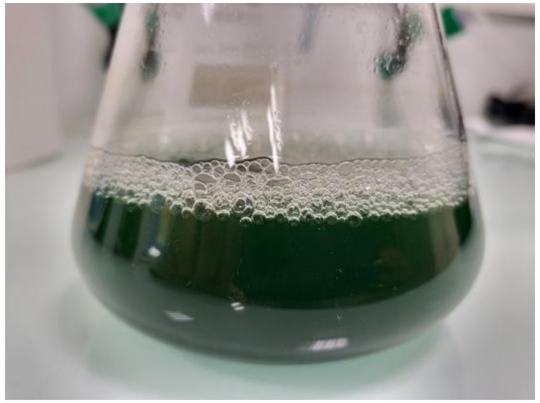
Straight morphology spirulina



Helix morphology spirulina

System BBM Life tests
Biological outcome (UCA)

- *Limnospira indica* PCC8005 is maintained by subcultures (no possibility to store it in freezer)
- Uncontrolled evolution of the strain (adaptation mechanisms):
  - Changes in morphology (helix/straight)
  - Light or temperature conditions (low/high tolerance)
  - …
- These changes can be reversible or not, and mechanisms are not elucidated
- Helix form increases risk of aggregates and clogging
- Strong impact on design



OBD concept design
Mission objectives and overview

- **Objectives:**
  - Demonstrate **recycling of CO_2 directly from ISS cabin into O_2** for crew by the mean of a photobioreactor & spirulina (Limnospira indica PCC 8005)
  - Demonstrate **autonomous process control**:
    - Precise regulation O_2 production on demand
    - Validation of model predictive strategy
  - Generate **edible biomass**

  (operate in axenic conditions, avoiding contamination)
  - Demonstrate **long term operation (90 days) and controllability**
- **Operations**:
  - Autonomous (process control)
  - Maintenance operation period 30 day
- **Accommodation**
  - ISS, European Drawer Rack 2 (EDR2)

International Space Station source NASA

Installation of EDR2, source ESA

OBD concept design

BRT1 OBD Feeding/NO3 management

Simplified feeding/NO3 management

- To address:
  - Maintenance operation timing constraint
  - In orbit, nitrate concentration measurement impossible

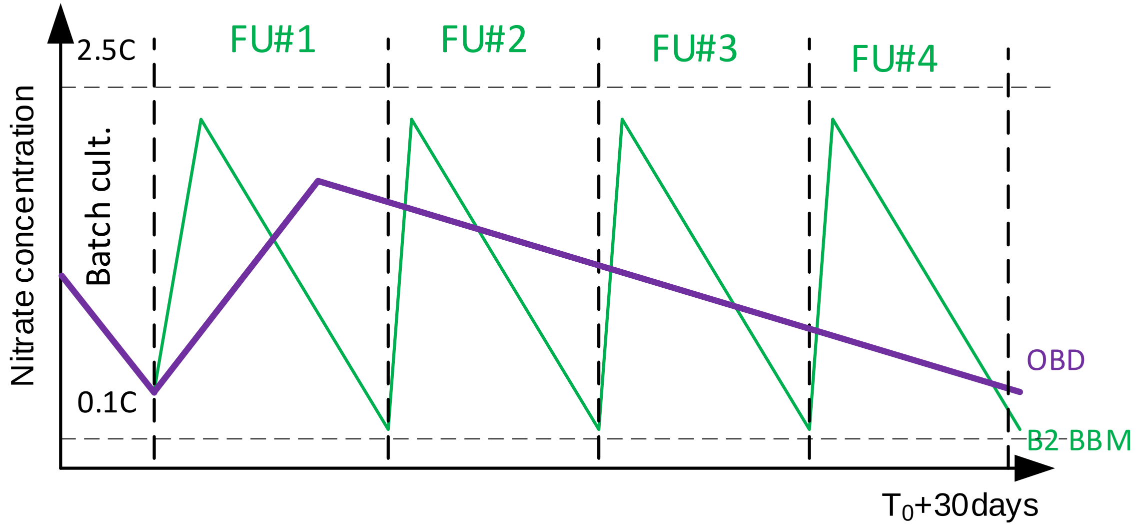
- OBD feeding concept:
  - moderate Zarrouk concentration 2.5C feeding (vs 10C in system BBM feeding)

+ **Intrinsically safe** for spirulina/no op constraint

+ **No need of NO3 measurement in orbit**

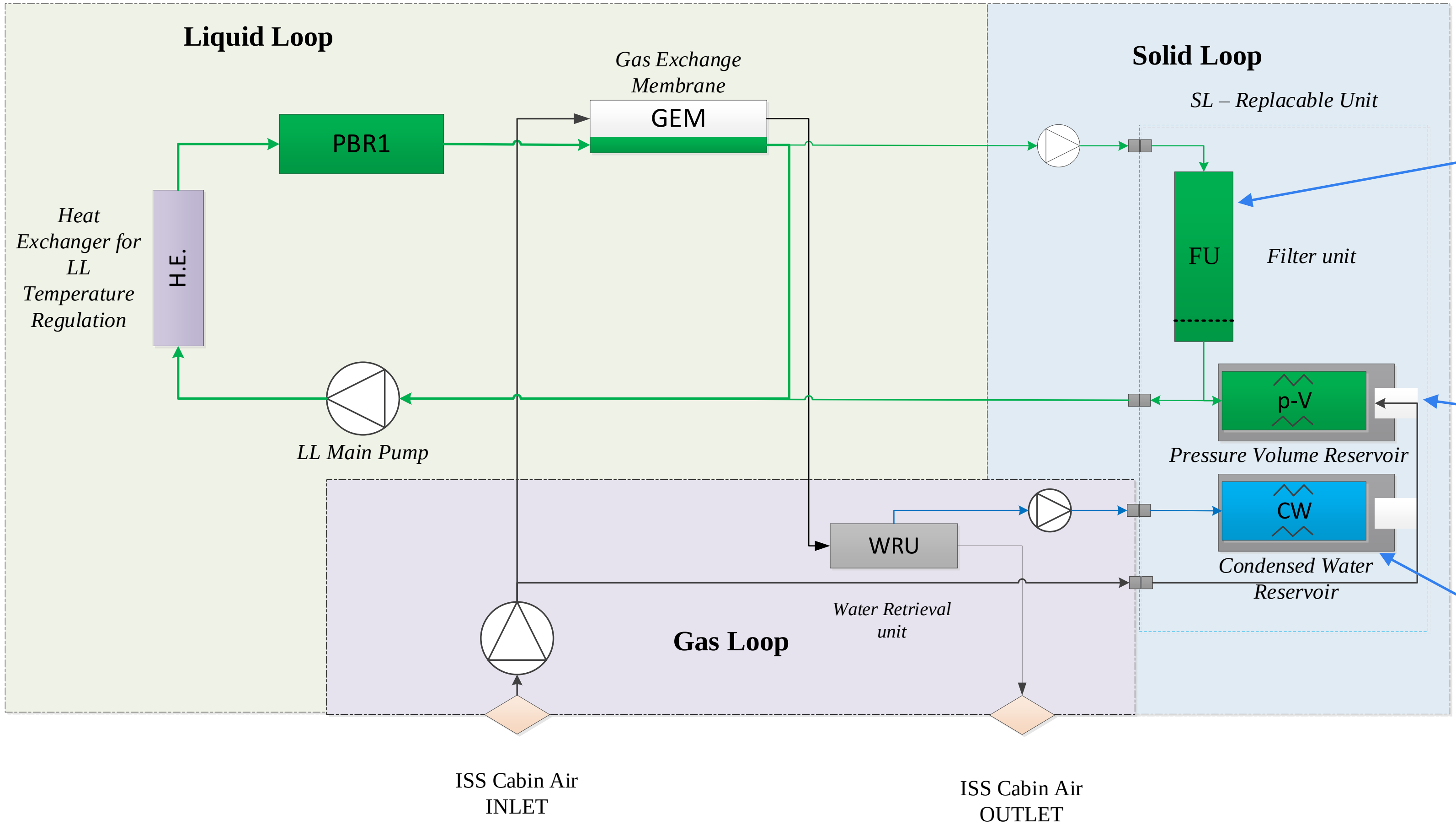
+ 1 Filter unit (instead of 4) per Replaceable Unit

- More Zarrouk volume medium needed



OBD concept design
BRT1 OBD design overview

- BBM to OBD evolution considering system BBM life test inputs



Single SL filter unit
Allowed by simplified NO3 management

LL Pressure control with Compressed air
To improve sterilization

WRU Condensed water
Not reused
To reduce contamination risk

OBD concept design
LL photobioreactor

- To address former Disk PBR:
  - wipers reliability
  - ➔convective mixing approach
  - structural strength against internal liquid pressure
  - ➔change to tubular geometry
  - sterilization issue
  - ➔PBR compatible with auto-clave

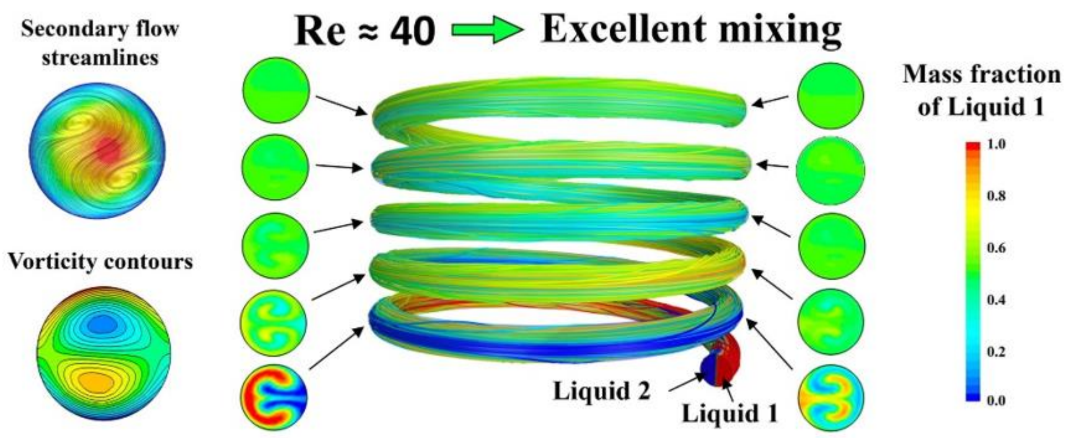
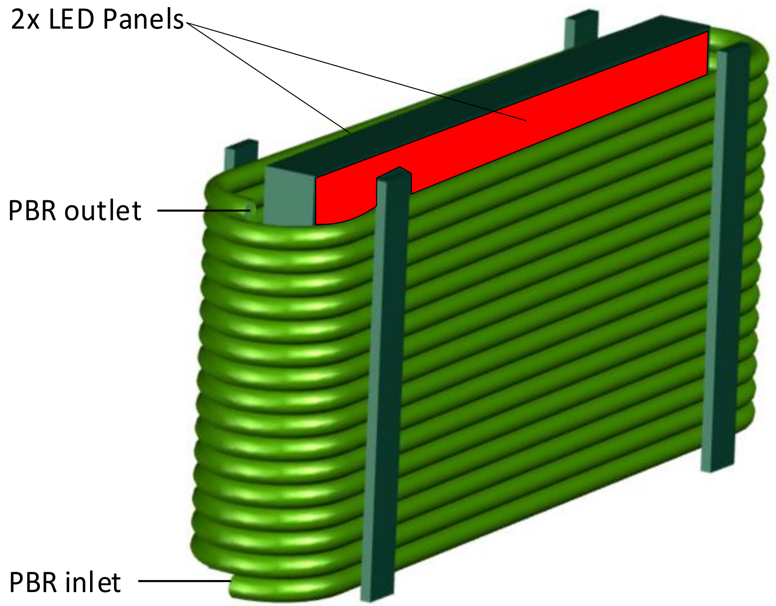


Figure 41 – Liquid mixing in a helical pipe reprinted from Mansoor et al. 2020



Tubular PBR

OBD concept design

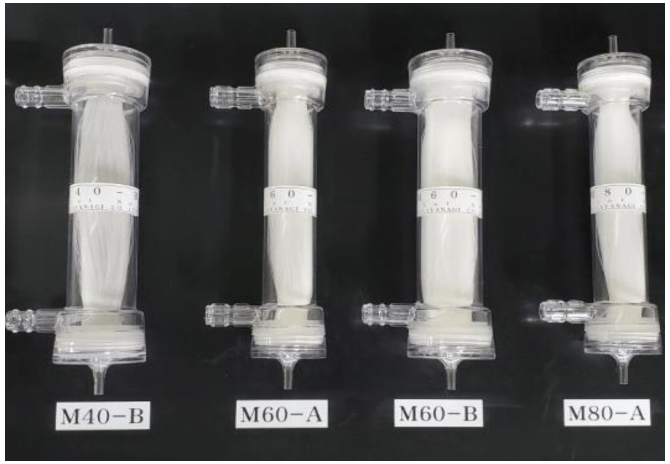
LL GEM & pump

Silicone GEM Membrane

- To address former membrane issue:
  - non-compatibility to steam sterilization
  - Contamination through membrane pores
  - Small membrane diameter: risk of clogging

Low pulsation pump

- Improved reliability no-wear components
- Autoclavable pump head
- Low flow pulsation pump

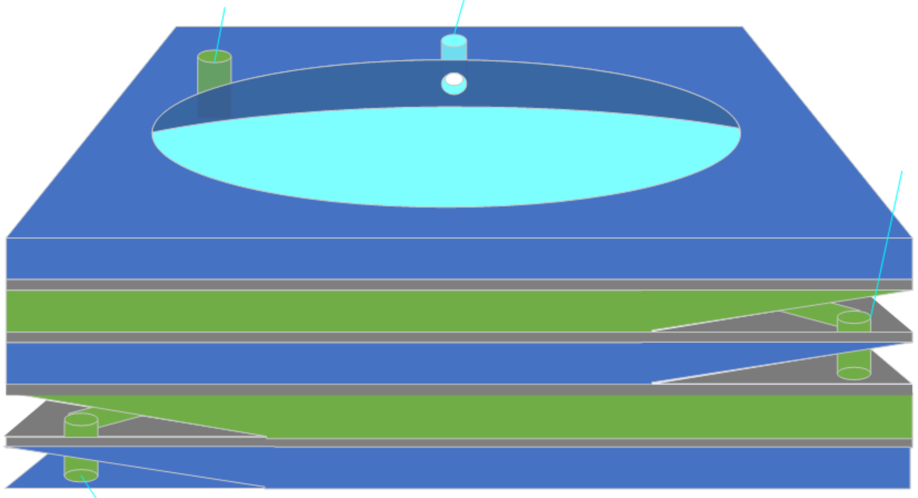


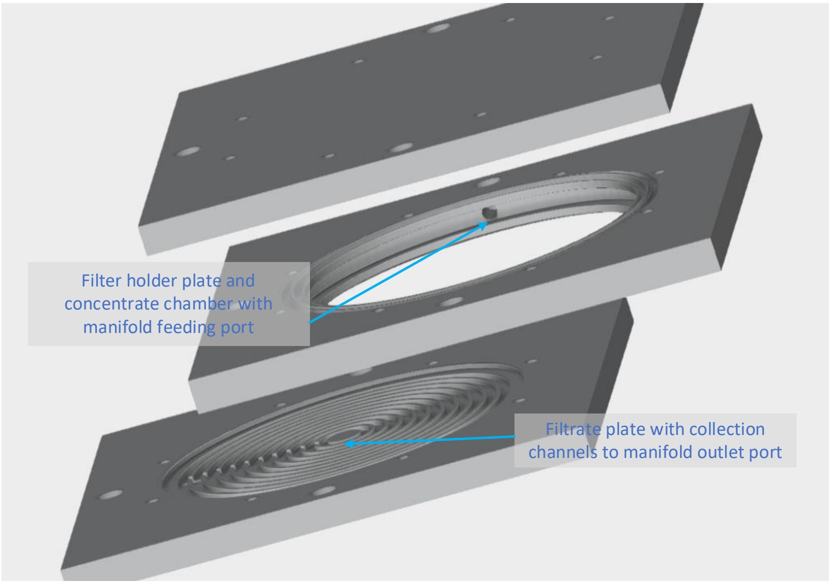
Example of Nagasep
silicone membrane module

Levitronix low-pulsation,
autoclavable pump

OBD concept design
SL Design

- Simplified Single Filter Unit Design
- Manifold design to improve:
  - Compactness
  - Temperature homogeneity during SIP



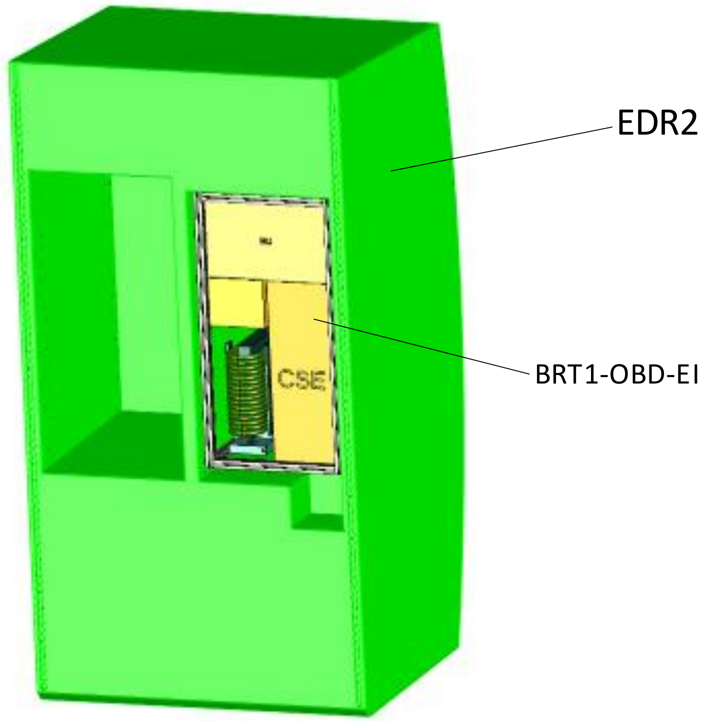


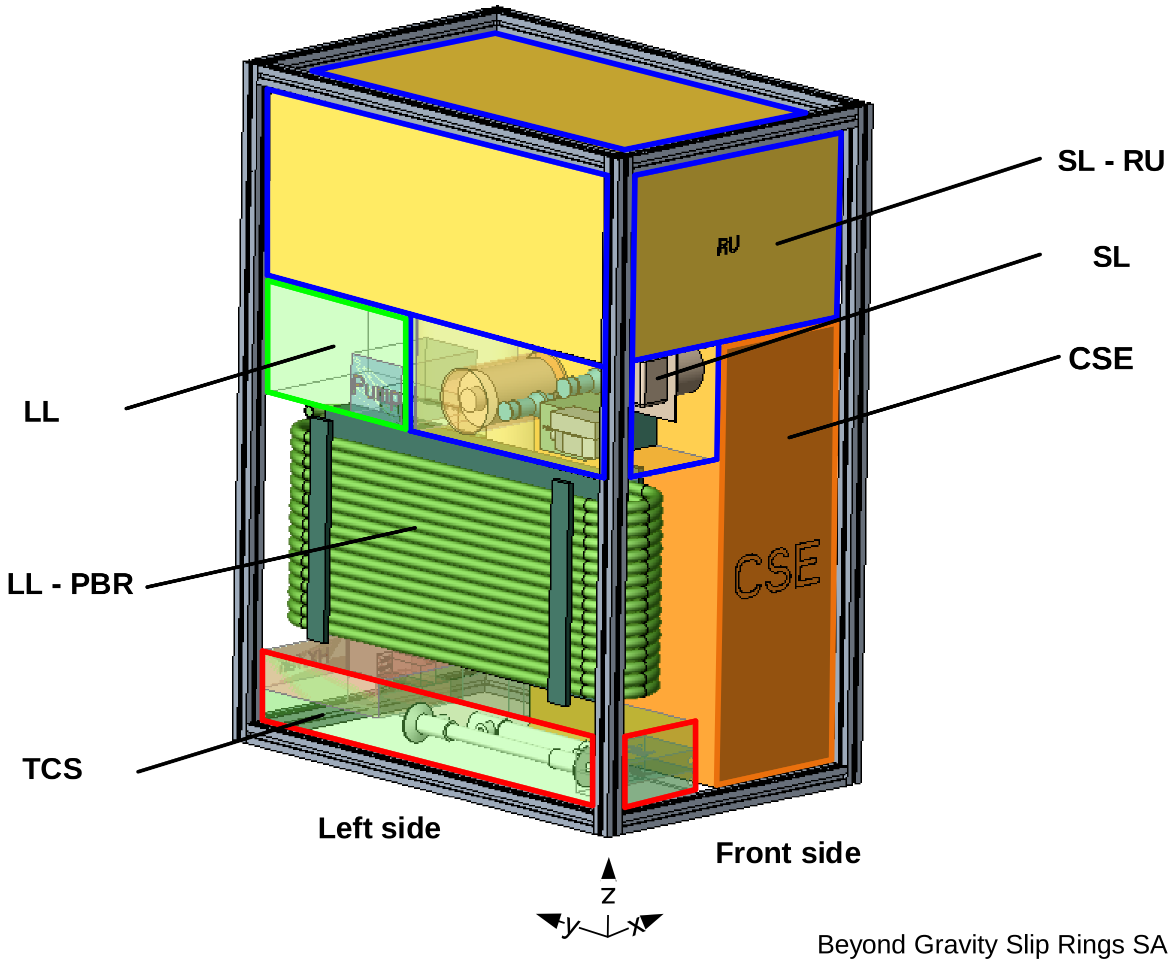
Manifold FU concept

OBD concept design

BRT1 OBD Accommodation

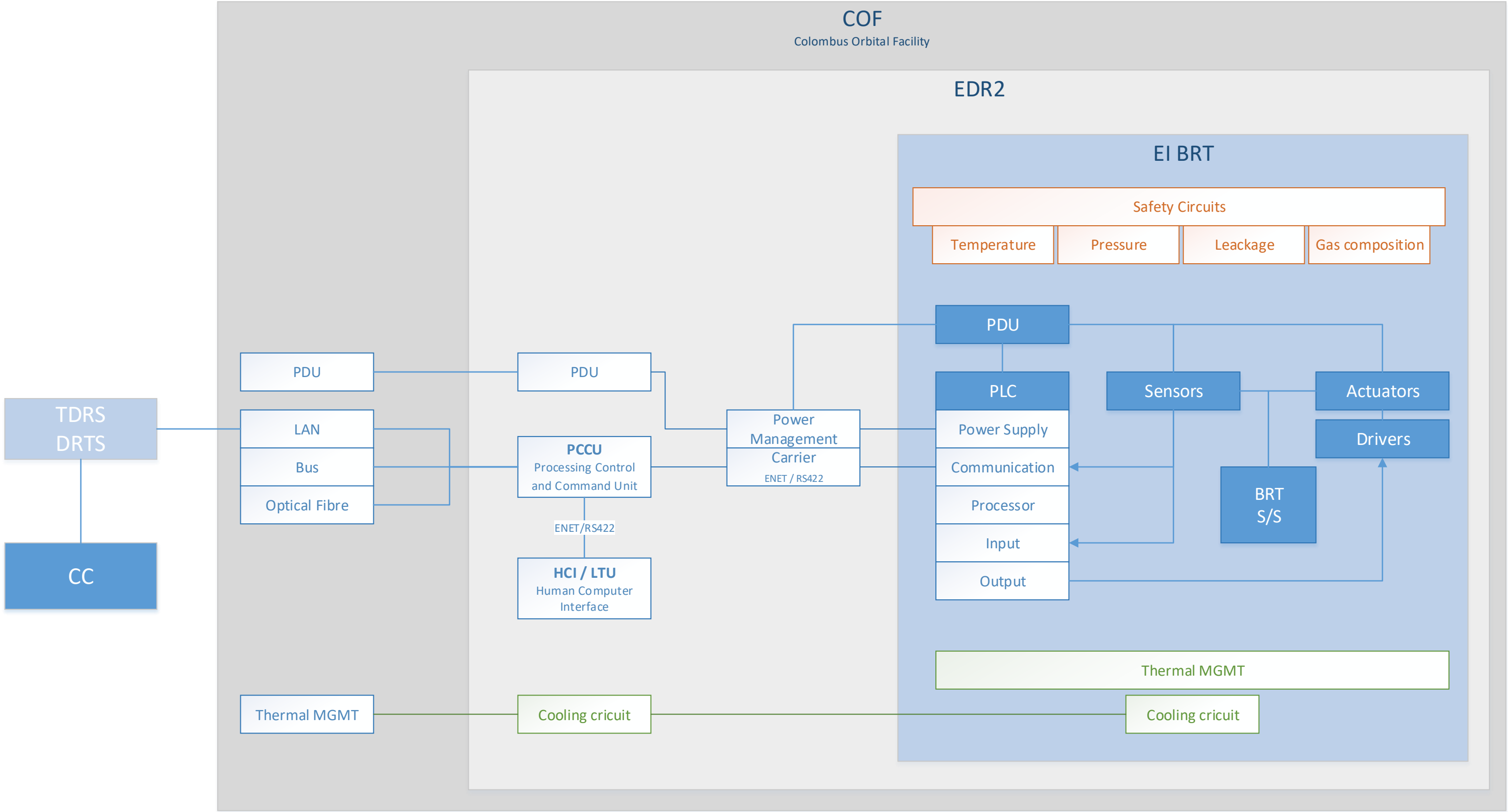
- An accommodation study performed with OBD concept design
  - Fitting one-side of EDR2 in term of:
    - Volume, Mass & Power budgets.
  - O2 production target adjusted to 4.5mmol/h





OBD concept design

CSE Architecture (RW Sherpa)



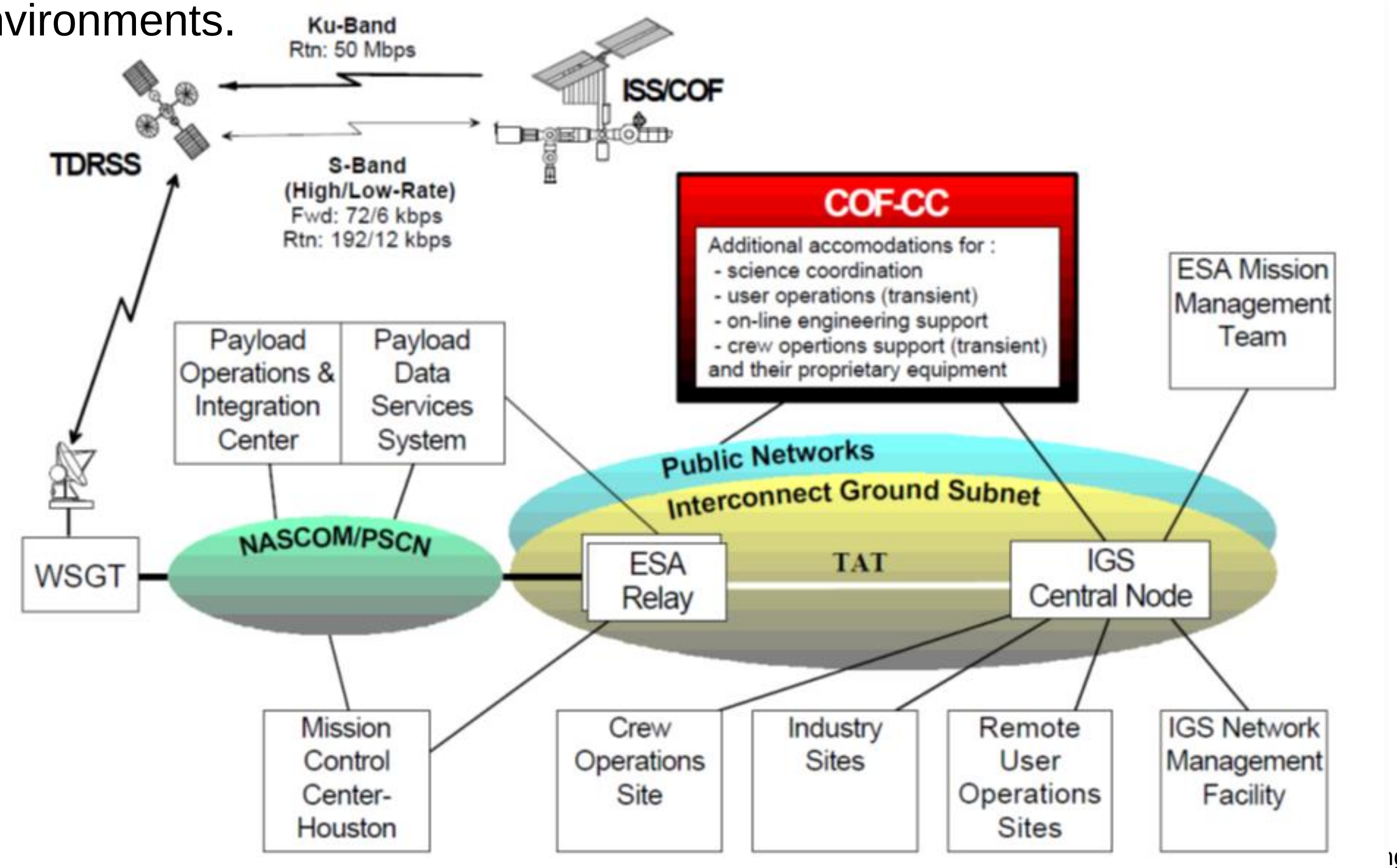
TDRSS: Tracking & Data Relay Satellite System (NASA)
DRTS: Data Relay & Test Satellite/Artemis systems (Japanese/ESA)
CC: control centres, for onward transmission to the users.
(Uplink command data from the ground is via only TDRSS.)

PDU: Power Distribution Unit

OBD concept design

Communication to ground (RW Sherpa)

- Columbus Orbital Facility - Control Centre (COF-CC)
- Maximize the use of commercial off-the-shelf hardware and software for both the computing and communications environments.



Conclusion
Hardware

- The LL/PBR subsystem BBM life test
  - In a chemostat operation
  - Non-axenic operation
  - Reached the O2 production and biomass concentration
  - ➔Validating the Photobioreactor & Liquid Loop Design
- The system BBM life test (representative to OBD operation)
  - Including an advanced biomass & NO3 management
  - Including CSE autonomous process control & NO3 and biomass estimator
  - **Results**
    - Sensorless-robust nitrate management needed for next iteration
    - Non-axenic operation due to sterilization issue➔Axenicity identified as design driver
    - Shortened life-test due to GEM clogging issue➔Spirulina interaction with GEM critical
- On Board Demonstrator concept design defined
  - BBMs life tests output
  - Successful System Requirement Review successful

Conclusion
CSE & Software (RW Sherpa)

- The design and development approach to integrate and validate advanced control laws developed in simulation environment (Matlab-Simulink) to a PLC (Programmable Logic Controller) using a standardized coding language is successful.
- CSE permits the system operations in an automated way
  - Basic control for maintaining the desired process operation (temperature, pressure, flows…) was validated during subsystem functional tests
  - Accurate O_2 production control based on Model Based Predictive Control was validated on system functional tests. To be confirmed for the Life Test campaign
- Estimators based on O2 production: nitrate and biomass give promising results. They will be reviewed and optimised in the next phase

Process control could be partially validated during the life test so that the BBM can operate in autonomous way between maintenance. This need to be confirmed.

Conclusion
Biology

- **Sterilization & axenicity**
  - Difficulties increase with the complexity of the hardware
  - Cleaning & decontamination is key to reuse the hardware

  ➔**Sterilization is a key criterion to prioritize in the hardware trade-off**
  - Heat & base resistant contamination

  ➔**Tyndalisation needed during the sterilization process**

- ***Limnospira indica* PCC8005 variability** (morphology, tolerance to light intensity, etc..)
  - Need of a better hardware/biology interaction repeatability

  ➔Approach with a better controlled strain (maintained) such as in ARTEMISS program

Future work

beyond gravity

- BBM testing:
  - Implement the design upgrades from the BRT1 OBD concept design
  - Perform BBM life test
    - Sequence representative to OBD demonstration sequence
      - 90 days of operation with 30 days of maintenance period
      - Autonomous operation with process control
      - Axenic cultivation

- Mature the OBD concept design to preliminary design
  - With next-phase BBM life test results
  - Pass the Preliminary Design Review
  - Perform the safety activity associated to the preliminary design
  - Pass the Safety Review 1

Acknowledgements

beyond gravity

This work was founded by:

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