Design & operation of a bread board model of spirulina photobioreactor equipped with a harvesting system to support ISS On-Board Demonstrator development

Dominique CHAPUIS, Paolo DAINESI, Céline LAROCHE, David DUCHEZ, Baptiste JARRY, Gilles DUSSAP, Dries DEMEY, Marie VANDERMIES, Olivier GERBI, Chloe AUDAS, Christel **Paillé**

Contact: Dominique.Chapuis@beyondgravity.com

Outline

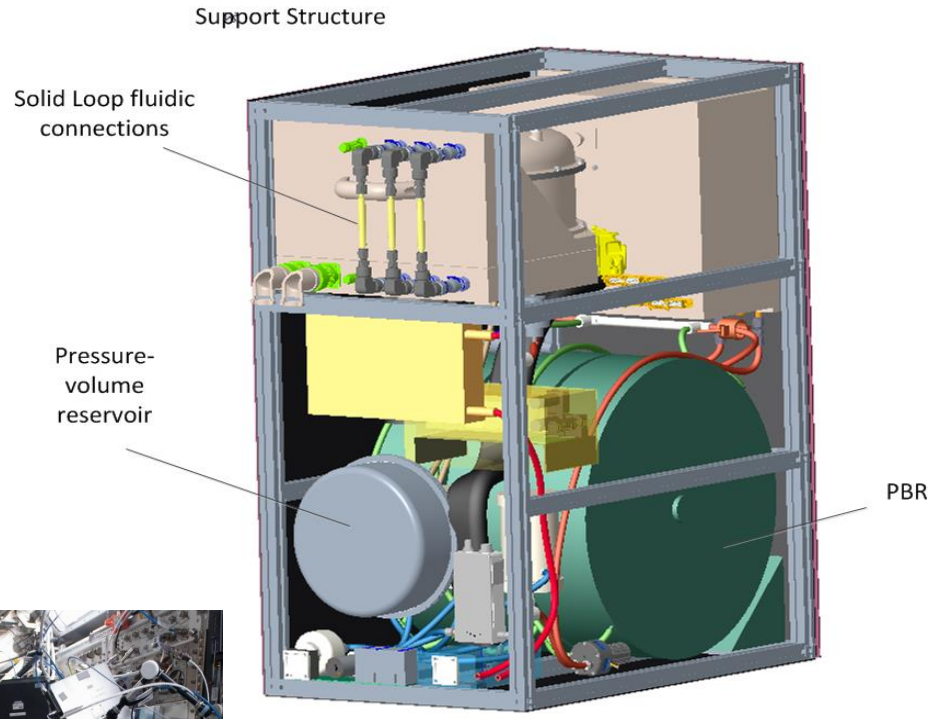
- Biorat-1 On-board Demonstrator
- Bread Board Model
  - Previous design
  - New functionalities
  - Life test results
- Conclusions & Way Forward

BIORAT-1 OBD Objectives

- **BRT1 On-board demonstrator (OBD)**
- **Objectives:**
  - **Demonstrate operation of Photoautotrophic Bacteria Compartment (IV4) in microgravity**
    - 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 **optimal 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 and controllability**

    (90 days demonstration sequence)
- **Accommodation**
  - ISS, European Drawer Rack 2 (EDR2)



BRT1 OBD Concept design

Installation of EDR2, source ESA

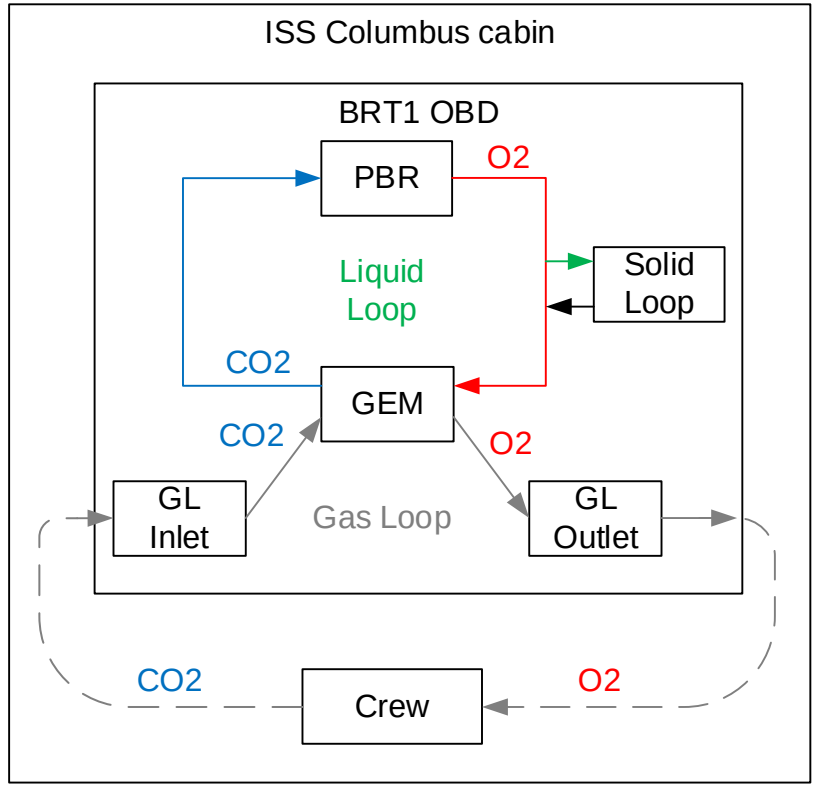
BIORAT-1 OBD Operation Principle

- Limnospira indica PCC 8005 oxygen production stoichiometry

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

Ref. Biorat, MELiSSA demonstration breadboard, Final Presentation 2000

- BRT-1 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):
    - Harvesting: Biomass concentration control,
    - Feeding: Nitrate supply in Zarrouk medium
- ***Life tests with Bread Board Models (BBM) to validate OBD design***

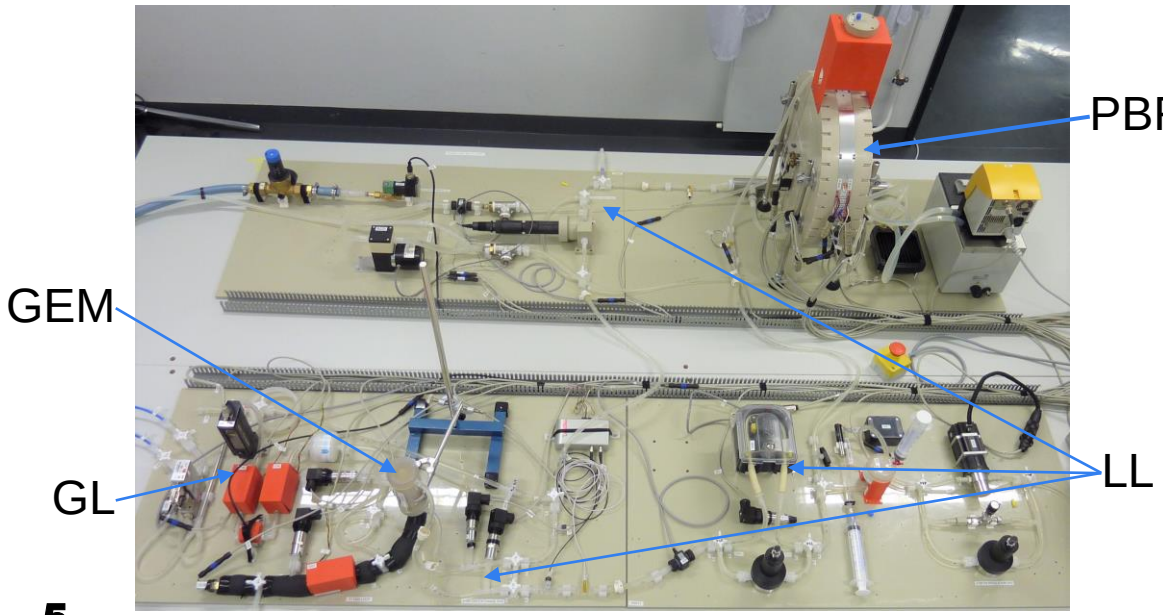


Biorat-1 BBM
Previous BBM design

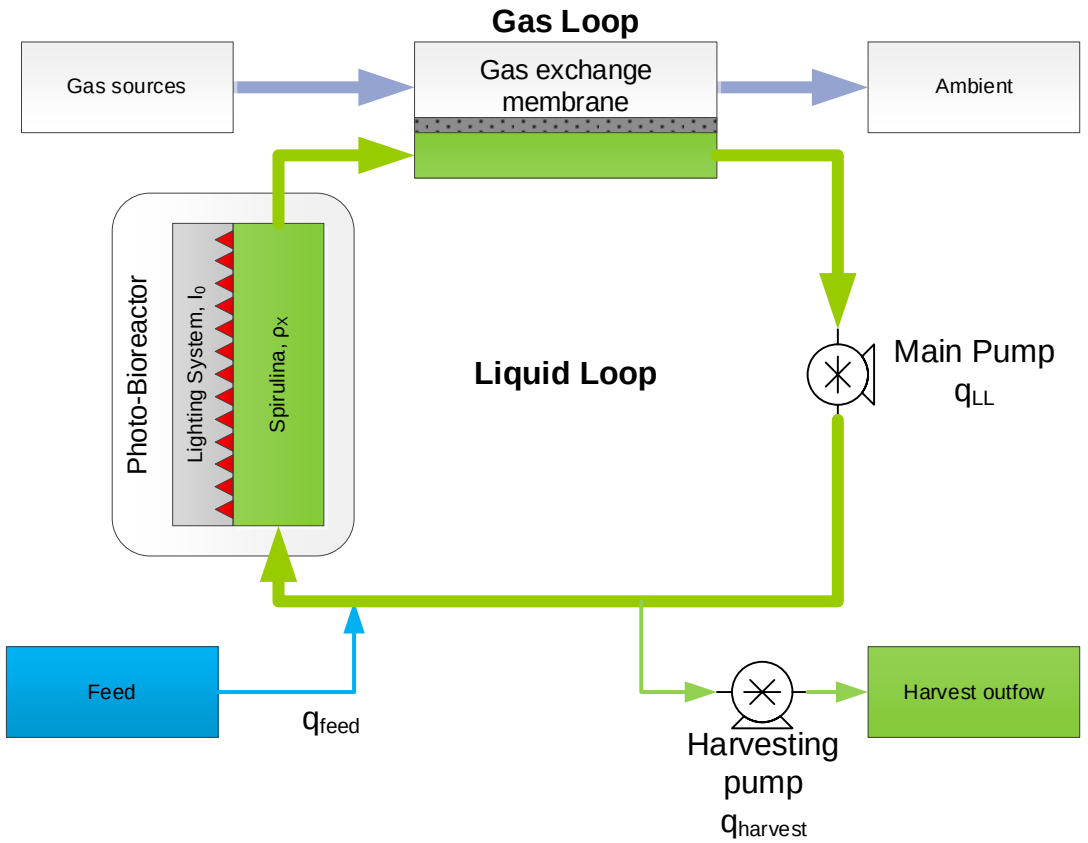
- 2019 BBM Life test, performed to validate Photobioreactor & Liquid Loop
  - PBR 2.6L, O2 production 6.8mmol/hr
  - Chemostat operation (no solid loop)

  ➔ high feed consumption
  - No process control

  ➔Light intensity, harvesting flow rate set manually



2019 BRT1 BBM

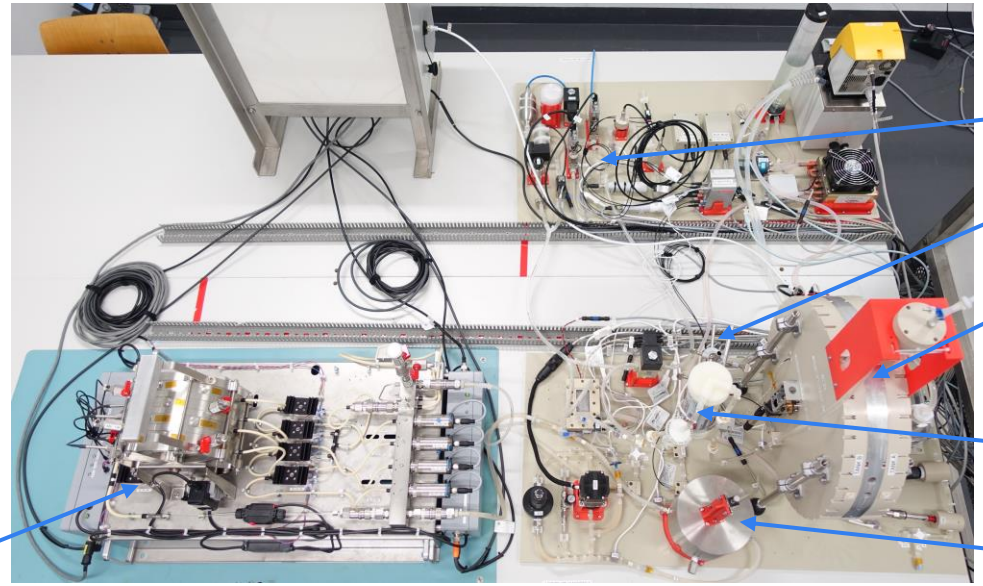


2019 BRT1 BBM P&ID

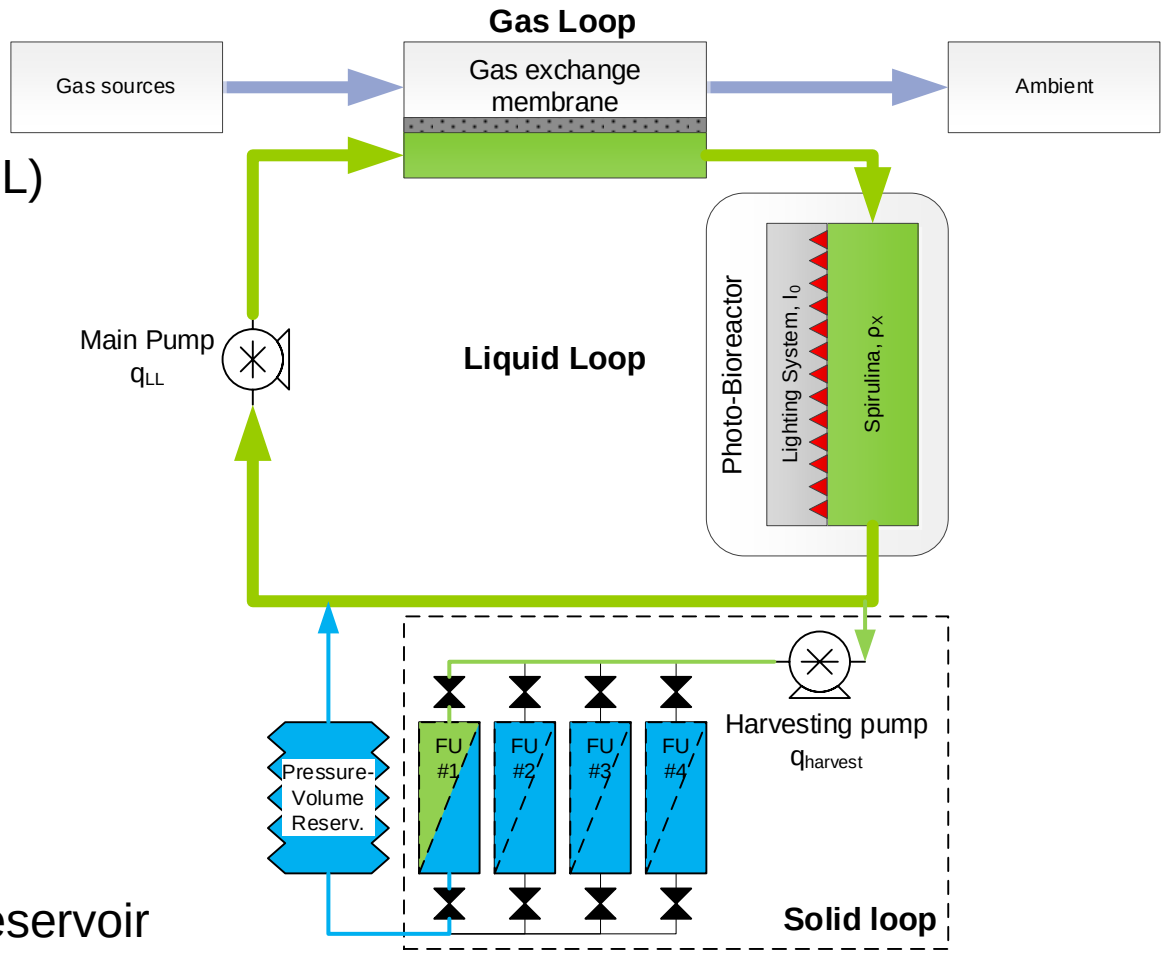
Biorat-1 BBM
2021 Life test objective

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

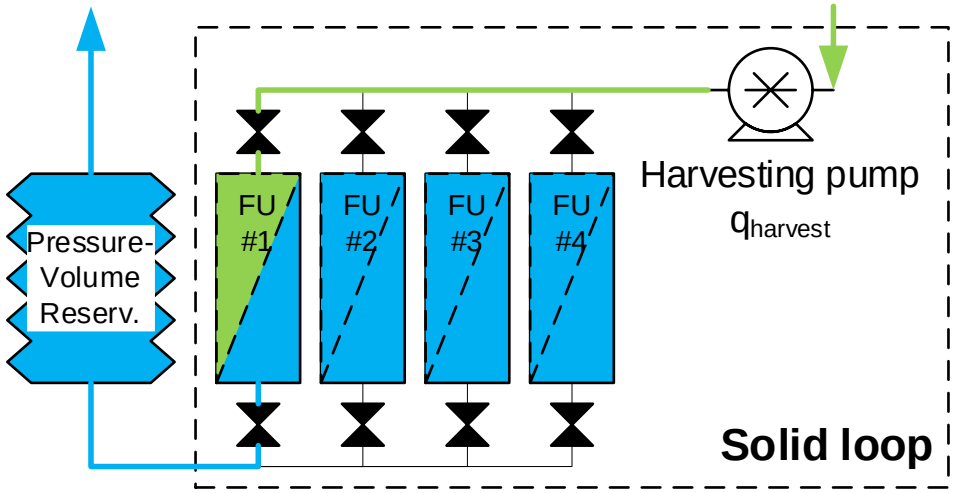


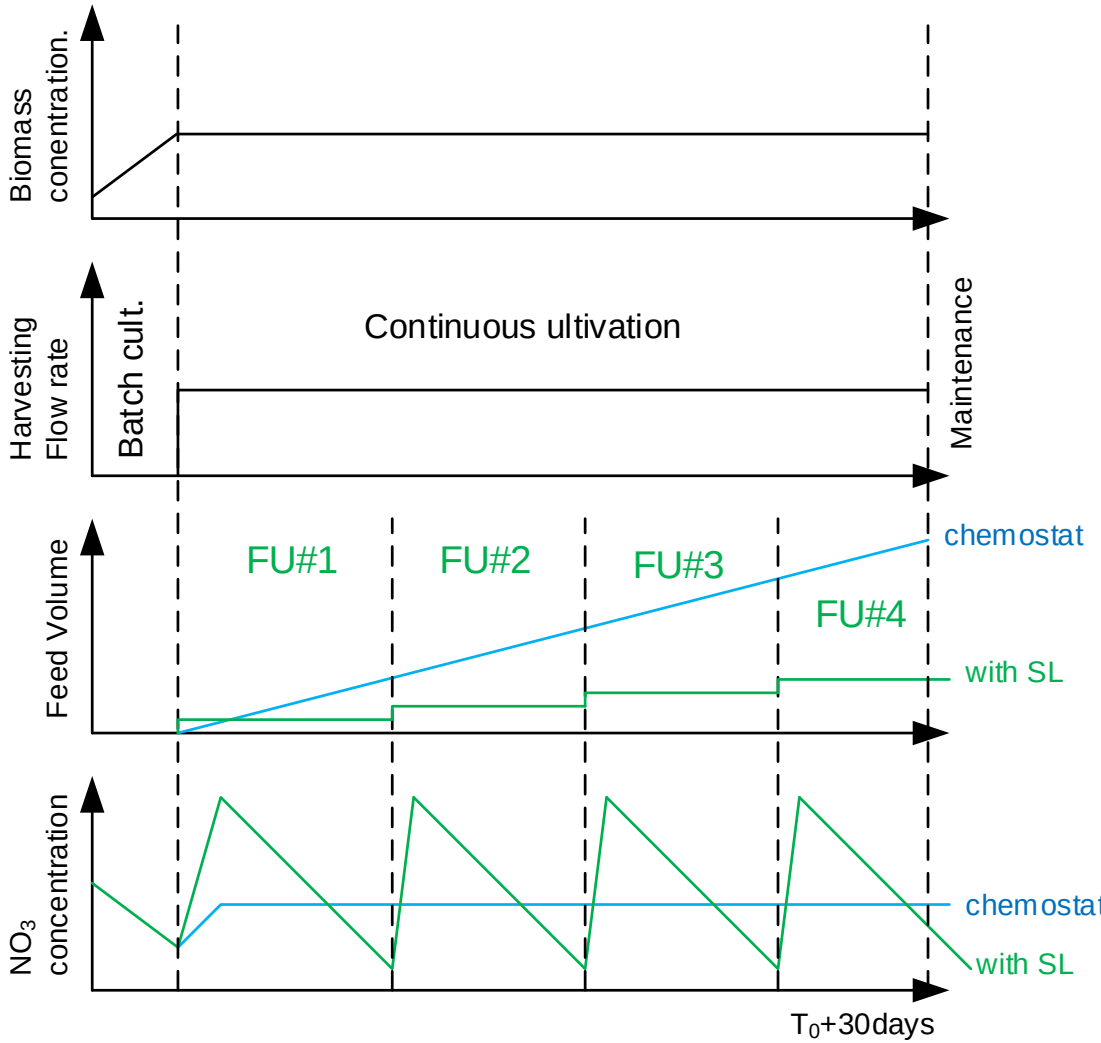
2021 BRT1 BBM



Biorat-1 BBM
Solid loop operation

- 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 activation
    - **Harvesting**: Biomass accumulated in the FU
    - **Feeding**: NO3 in Zarrouk medium released into LL
  - Sequential activation of the other FUs in function of NO3 concentration
- **Maintenance operation**: replacement of the FUs





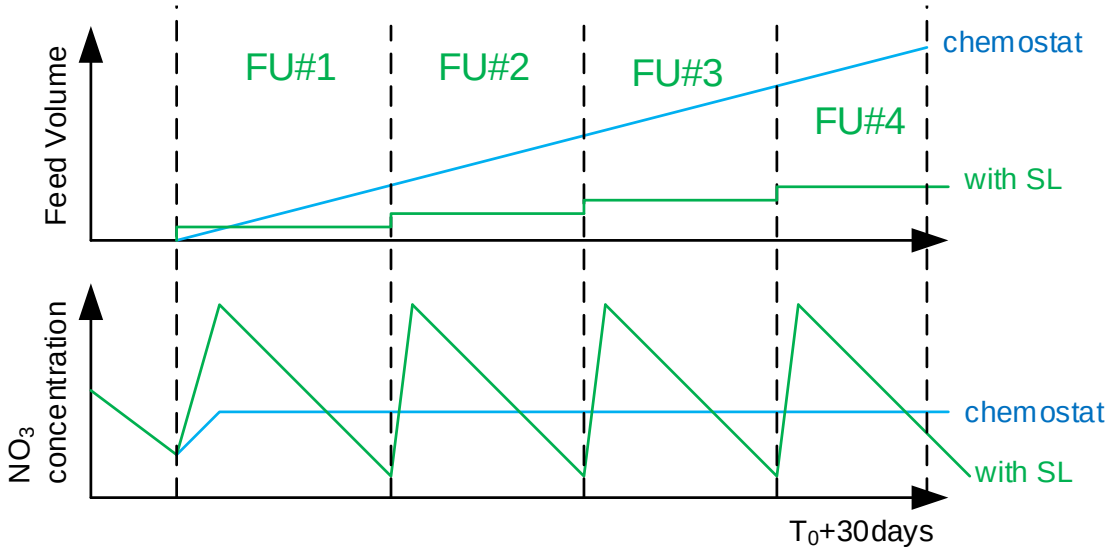
Biorat-1 BBM
Solid loop operation

Pros & cons of discrete/batch 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



Biorat-1 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 to correct NO3 estimator and O2 measurement.

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

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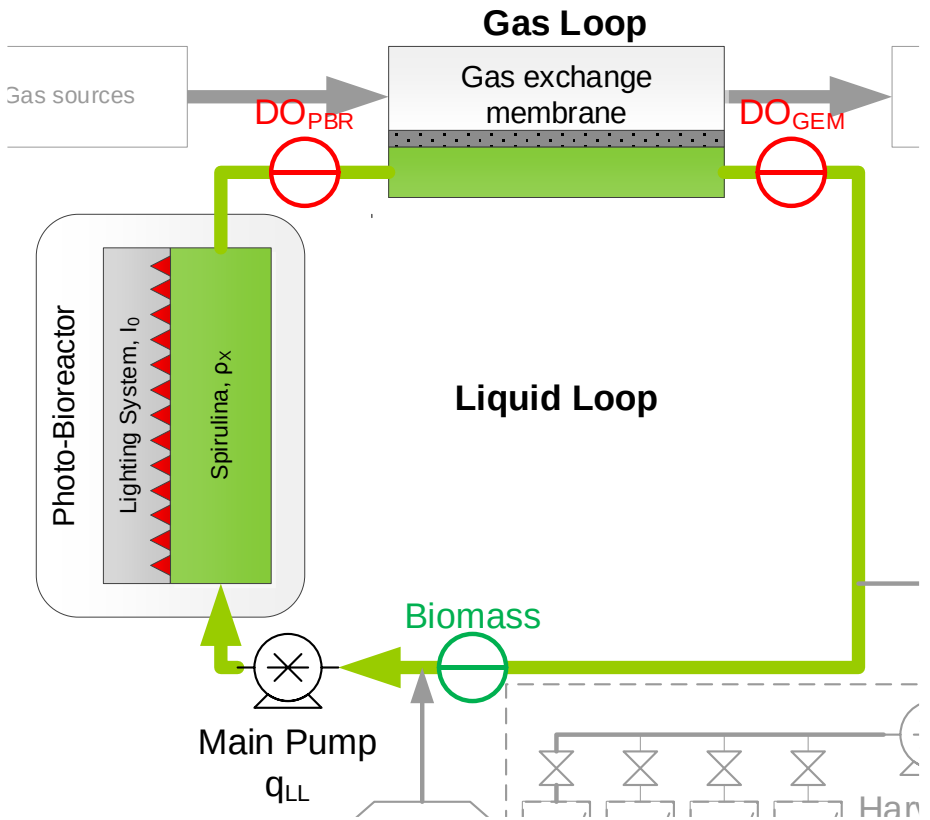
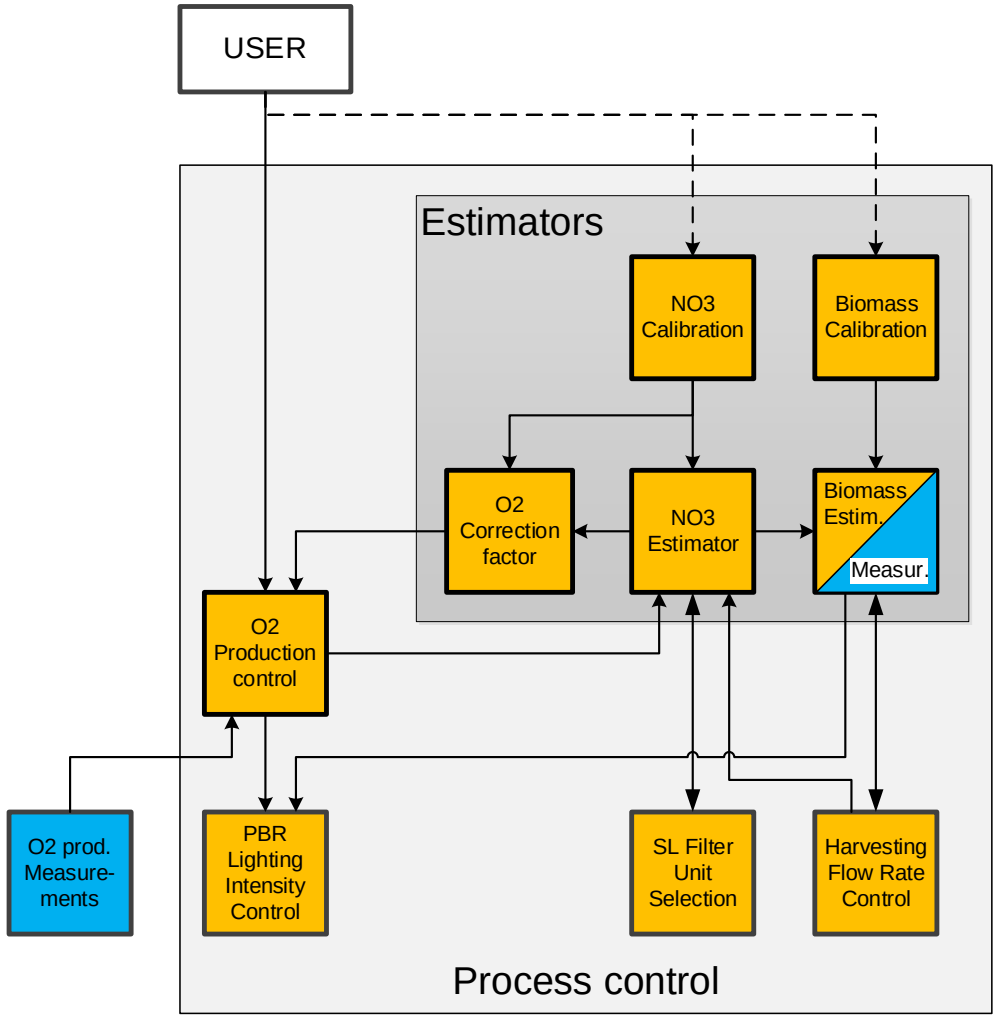


Biorat-1 BBM Process Control Software

- Existing Low level control loops:
  - LL flow rate & pressure, PBR Light intensity control, LL temperature control, Feed flow rate, GL flow rate, etc…
- Update:
  - Process control:
    - Estimators for NO3 & Biomass
    - Control of O2 production, SL Filter Unit selection and SL Harvesting flow rate
    - System Inputs:
      - O2 production measurement
      - LL NO3 concentration estimation
      - LL Biomass concentration estimation or measurement
      - Active FU's
    - User inputs:
      - O2 set point
      - When needed: NO3 or Biomass calibration value



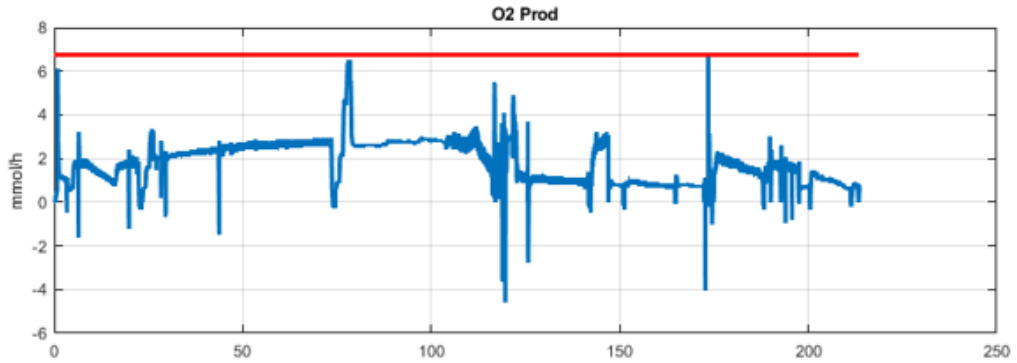
BBM Simplified process control

BRT1 BBM Life test Process Control Results

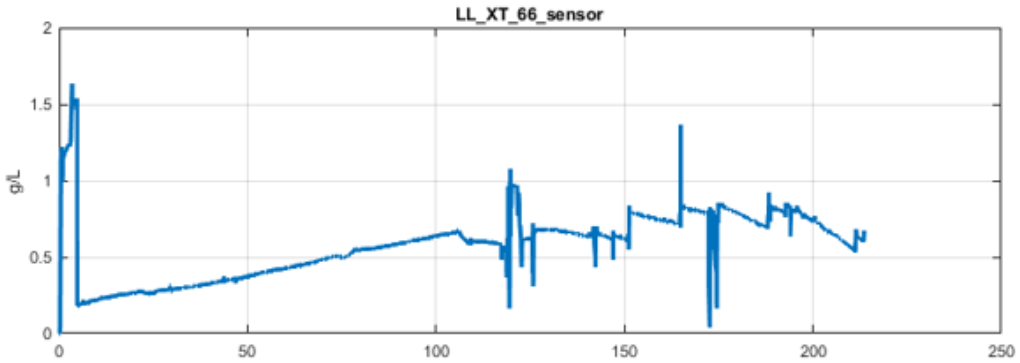
- Process control up to 5 days (99hr)
- GEM Clogging Issue @99hr

➔**Process control validated for batch cultivation mode**

O2 production

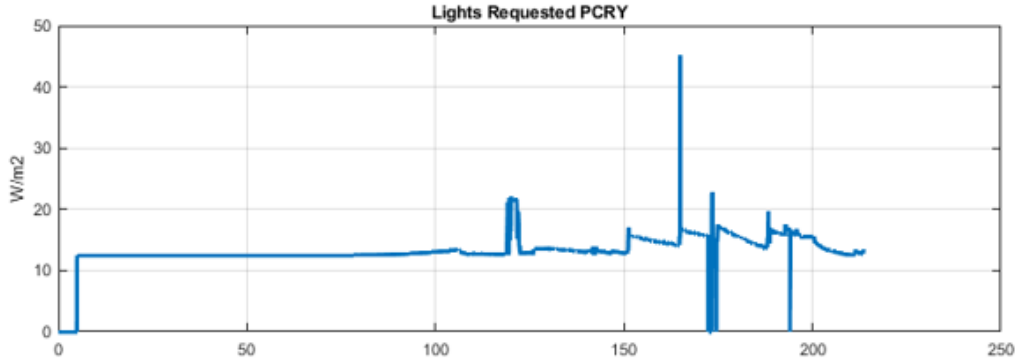


Biomass conc.

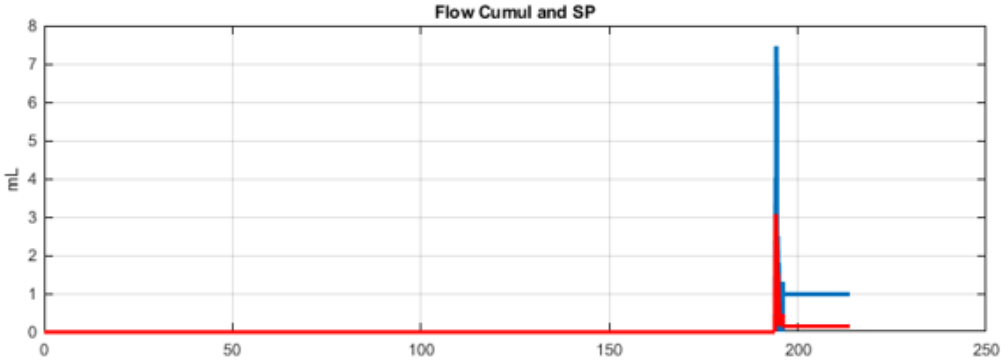


Process Control

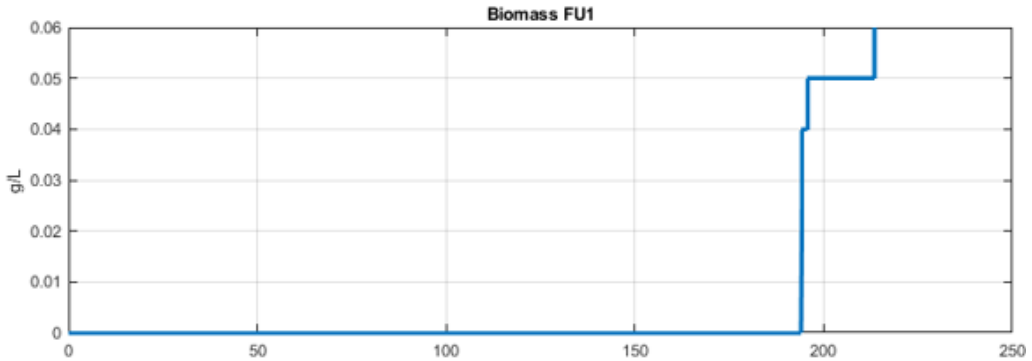
PBR Light int.



Harvesting SP



Filter Unit Load.



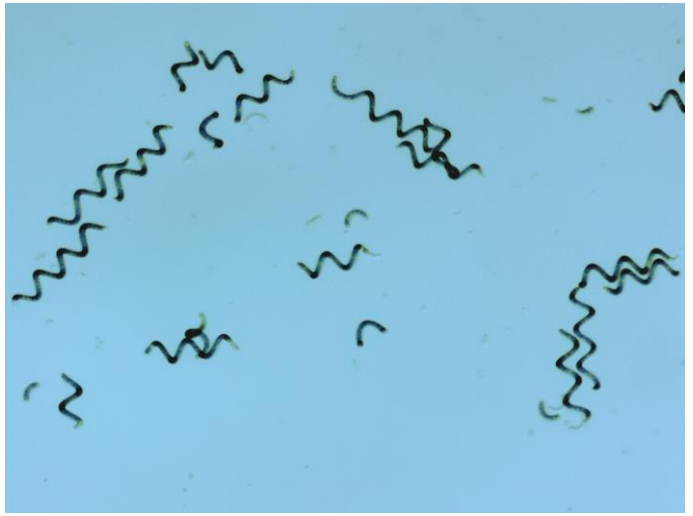
Time unit [hr] –Setpoint –Value (source SHERPA Eng.)

BRT1 BBM Life test
Spirulina morphology issue

beyond gravity

- GEM clogging anomaly
  - 2017 & 2019 life tests: Limnospira indica PCC 8005, with **straight morphology**➔Design & GEM validated
  - 2021 Life test: Limnospira indica PCC 8005 with **helix morphology**
    - GEM clogging anomaly at 0.65g/L
    - Hollow fiber diameter (200 µm) not compatible with helix shape (dia. 18-20 µm or trichomes clustering)
- Consequence: Life test sequence forced to be stopped during batch mode
- Lessons learned: Increase of GEM hollow fibers diameter in next BBM iteration

Straight morphology spirulina

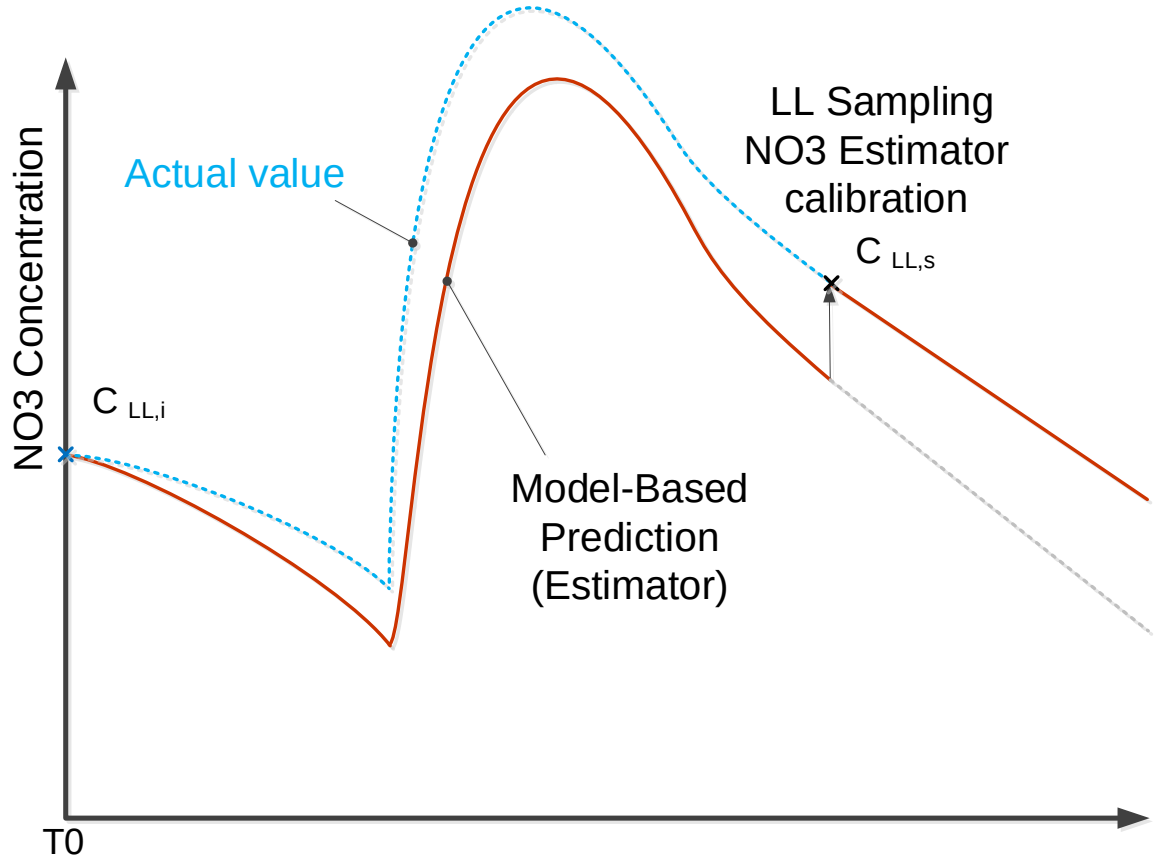


Helix morphology spirulina

BRT1 BBM Life test
Nitrate Estimator Calibration

beyond gravity

- Need of estimator calibration:
  - Low uncertainty: Stoichiometric coefficient
  - High uncertainty: O_2 production measurement
    - q_LL measured LL flow rate
    - H Henry coefficient of liquid
    - p_DO_GEM, P_DO_PBR measured dissolved oxygen
- Solution: NO_3 estimator calibration:
  - Input: Measured NO_3 value on a sample
  - Output:
    - Calculation of a O_2 production correction factor
    - Update of NO_3 estimator value
- NOTE: NO_3 titration not possible on-board of ISS

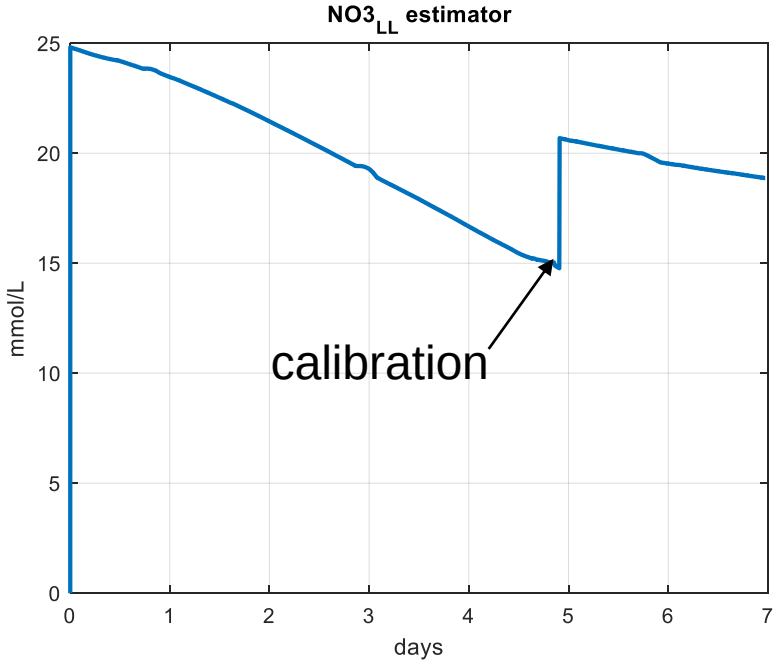


BRT1 BBM Life test
Nitrate Estimator Correlation

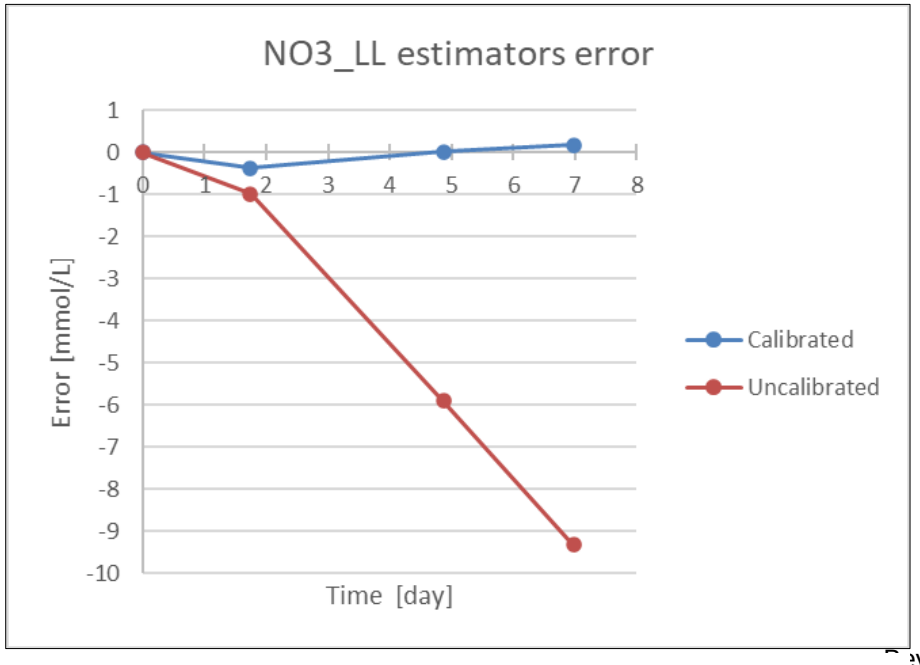
beyond gravity

- Sampling time: @day#0, #2, #5, #7
- Calibration time @**day #5**
- O_2 prod correction factor: 0.41 (Identified by the process control)
- After calibration: NO_3 estimator consumption better than **20% error**

➔ **NO_3 estimator & calibration validated**



NO3 estimator logging



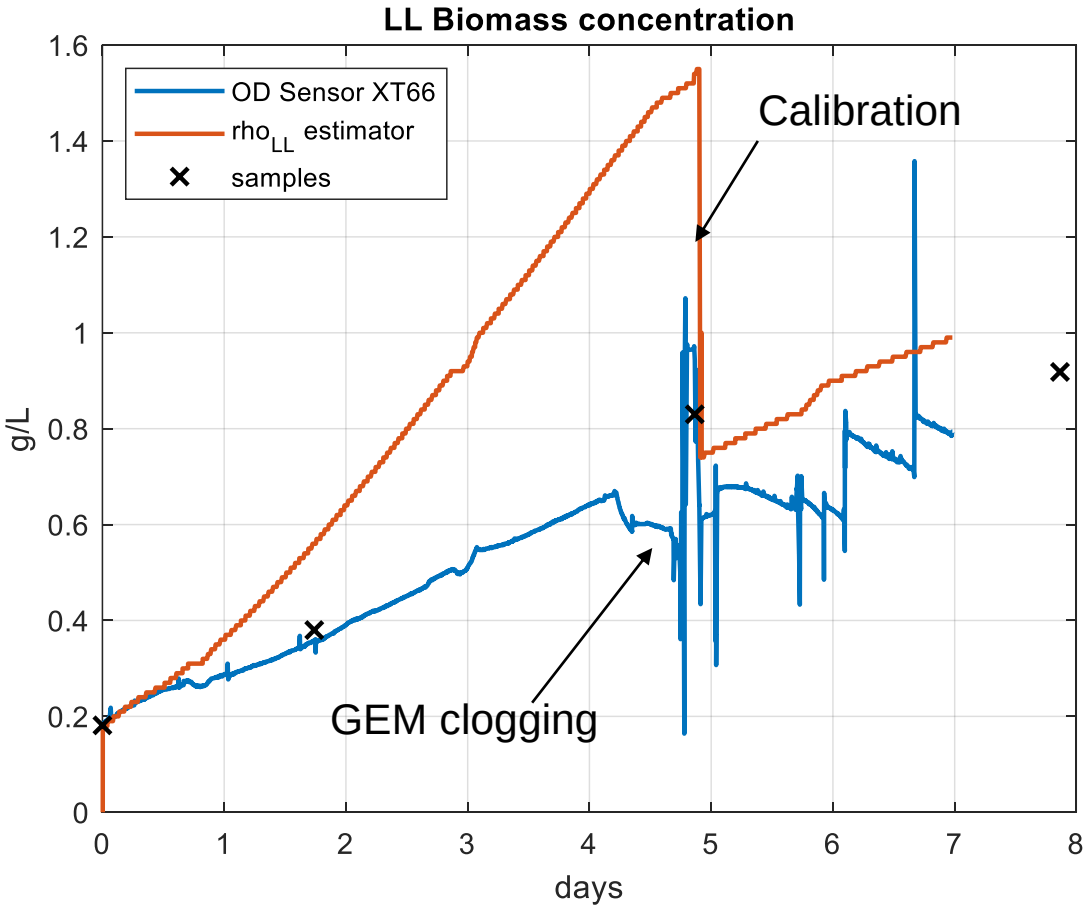
Post-processed errors with samples value

BRT1 BBM Life test
Biomass measurements comparison

beyond gravity

- Sampling performed in BBM activities
  - Samples @Day #0, #2, #5, #8
- Comparison of LL concentration:
  - Biomass estimator (model-based)
  - On-line Optical Density sensor (Hamilton Dencytee)
- Results:
  - Biomass estimator
    - divergence with actual value in case on anomaly
    - need calibration like NO_3 estimator
  - Optical density measurement
    + actual biomass concentration measurement

➔**OD sensor better than biomass estimator**



BRT1 BBM Life test
Optical Density-Biomass Correlation

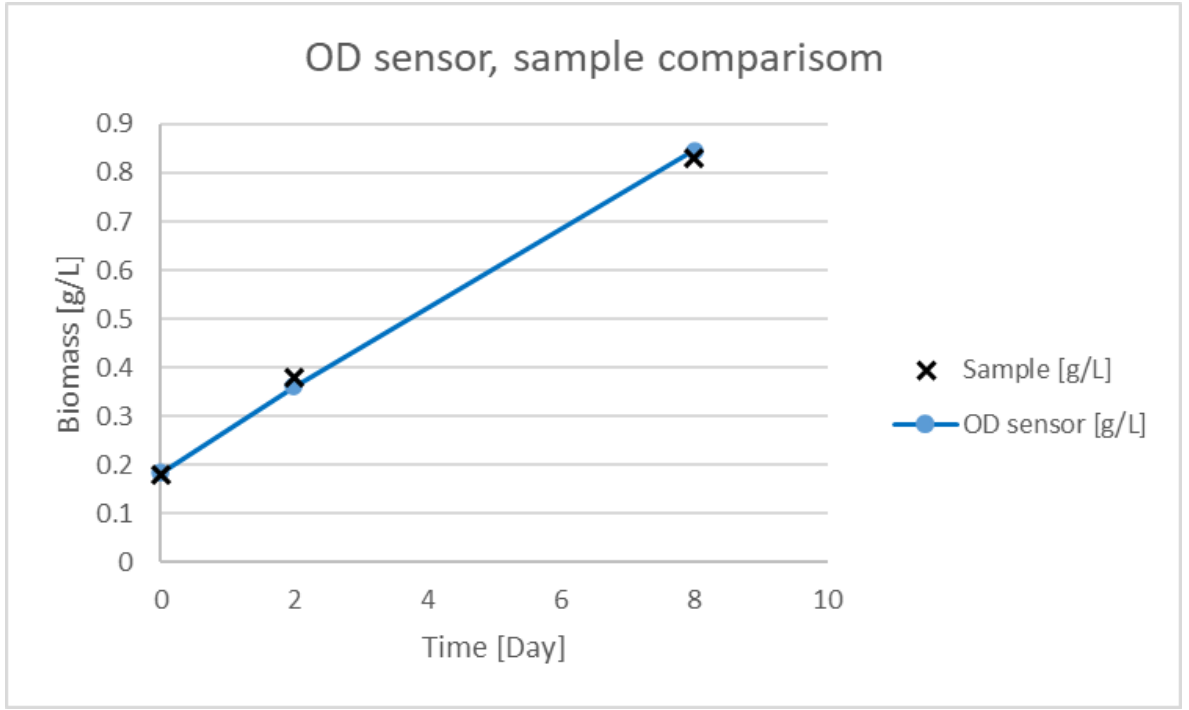
beyond gravity

- Optical density 2-points calibration with day#5 sample
- Errors after calibration (over a 0.2g/L to 0.8g/L range):
  - Maximum absolute error: 0.02[g/L]
  - Maximum relative error: 5%

  ➔OD sensor validated

- Correlation factor determination prior experiment:
  - Live calculation based on absorbance value prior & after inoculation

  - Recommended procedure: correlation with a laboratory spectrophotometer on the inoculum & scaling. **Higher accuracy**



Conclusion & Way Forward

beyond gravity

Conclusion

- Results validated over batch mode
  - Process control operation
  - NO_3 Estimator & Calibration function
  - Biomass OD sensor validated

- Lessons learned
  - GEM Design compatible with helix morphology spirulina needed.

Way Forward

- To be validated in next life test
  - Process control operation in continuous mode & during maintenance operations
  - SL operation in continuous mode
    - Harvesting
    - Feeding
- Upgrade for next BBM & OBD design
  - Robust NO_3 management compatible with ISS operation (without titration)
  - Axenic design

Acknowledgements

IN COOPERATION WITH

esa European Space Agency

MELISSA FOUNDATION

UNIVERSITÉ Clermont Auvergne

Life test performance
Spirulina expertise

QINETIQ

Control System Electronic & Software
Solid loop

SHERPA ENGINEERING

Control System Software
Control design & simulation