Industrial Controls
Engineering Department

*Advanced Control Engineering:*
*Academia - Industry*

# Control and simulation of cryogenic plants at CERN


***Benjamin Bradu,***
***CERN, EN-ICE***

# Contents

- **Introduction**
  - Motivation

- **Dynamic simulator for cryogenic systems**
  - Control and simulation architecture for cryogenics
  - Cryogenic Modeling

- **Advanced control applications in the LHC cryogenics**
  - Beam screens cooling: PID tuning
  - 1.8 K refrigeration units: Cold compressors control
  - Warm compressor stations: High Pressure control
  - Warm compressor stations: Energy optimization

- **Conclusion & Perspectives**

# Contents

- **Introduction**
  - Motivation

- **Dynamic simulator for cryogenic systems**
  - Control and simulation architecture for cryogenics
  - Cryogenic Modeling

- **Advanced control applications in the LHC cryogenics**
  - Beam screens cooling: PID tuning
  - 1.8 K refrigeration units: Cold compressors control
  - Warm compressor stations: High Pressure control
  - Warm compressor stations: Energy optimization

- **Conclusion & Perspectives**

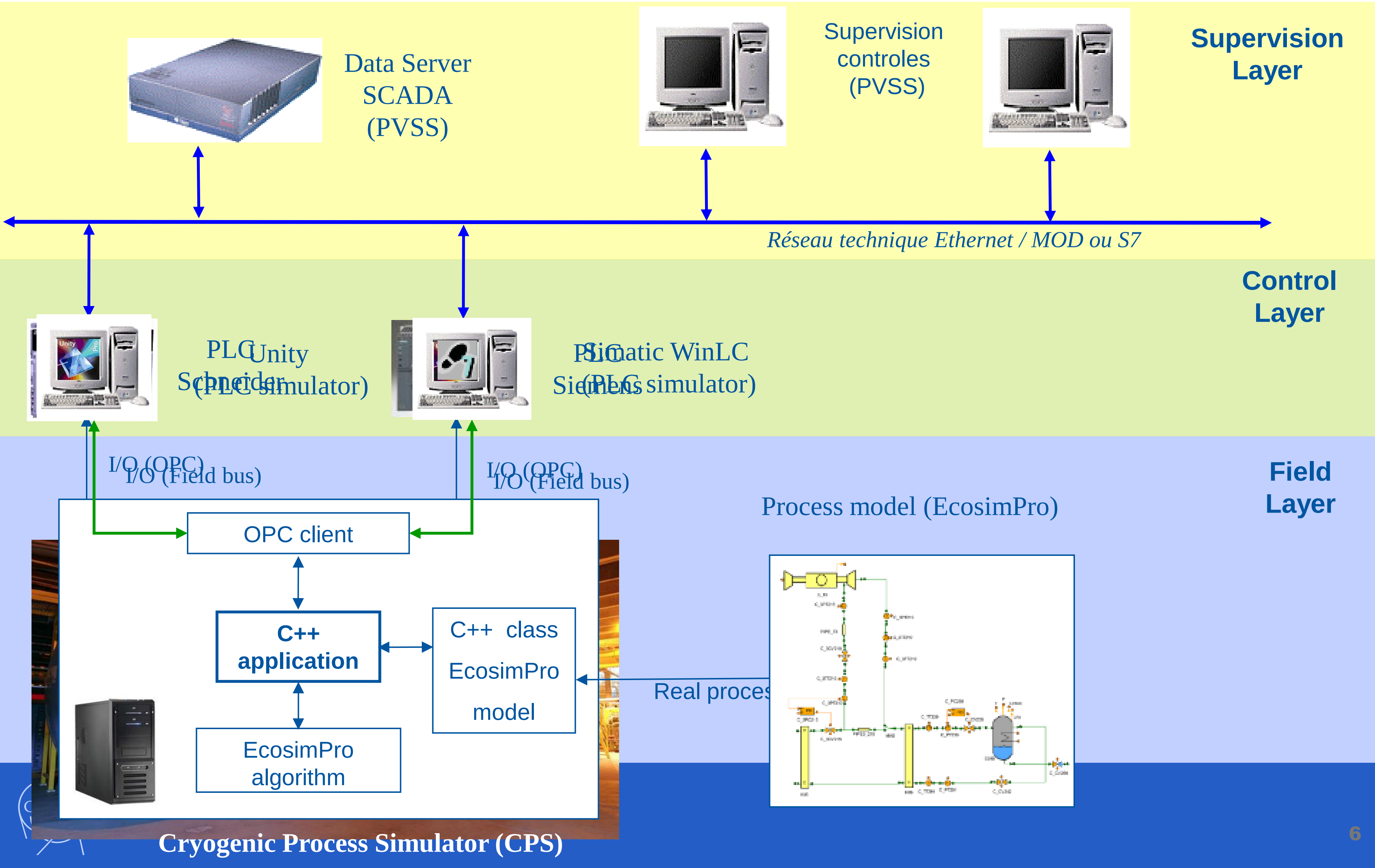
# Motivation

**Develop a dynamic simulator for CERN cryogenic systems**
**➔ Model Large-Scale helium refrigerators**

- CERN cryogenic systems: **large scale complex** systems
  - ✓ Similar to other large industrial systems (Petroleum refineries, food industry...)
  - ✓ LHC cryogenics : *42 000 I/O & 5 000 control loops*
- **Non-linearity** of helium properties (wide operation ranges)
  - ✓ Temperature : 1.8 K to 300 K
  - ✓ Pressure : 14 mbar to 20 bar
- **Unique** systems
  - ✓ Built to be operated at nominal conditions
  - ✓ Poor insight about transients and out of operation points predefined
- **Dynamic simulation** is a great tool for :
  - ✓ *Train operators safely and in degraded conditions*
  - ✓ *Test new control strategies without disturbing real operation*
  - ✓ Validate control and supervision systems in simulation : « *Virtual Commissioning* »

# Contents

# Control and simulation architecture for cryogenics

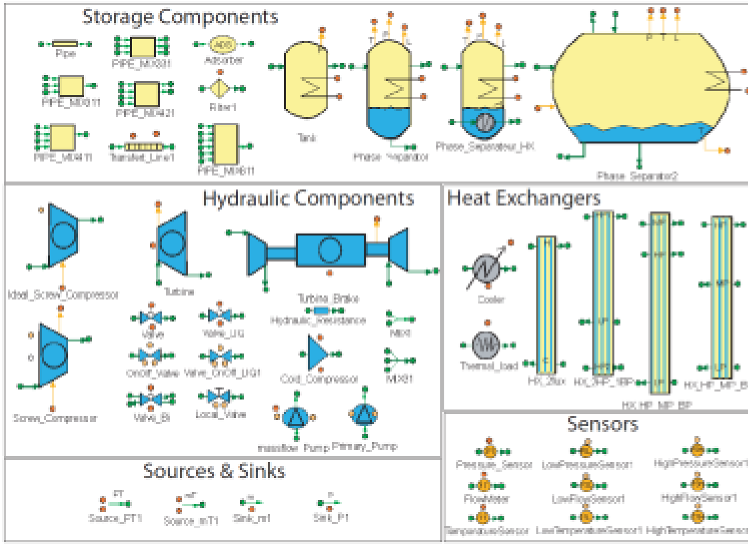


# Cryogenic modelling

- **Macroscopic** modelling in 0D/1D
  - ✓ Knowledge model based on physics
    - ✓ Thermodynamic
    - ✓ Fluid mechanics
    - ✓ ...

EcosimPro
Modelling and Simulation Software

- Use of a commercial software: **EcosimPro**
  - ✓ Object oriented modelling approach (1 component= 1 process equipment)
    - ✓ Modelling of fluids (water, helium…)
    - ✓ Modelling of actuators (valves, pumps, compressors…)
    - ✓ Modelling of passive equipment (pipes, vessels,…)
    - ✓ Modelling of sensors (temperature, pressure, massflow…)
  - ✓ Non-causal modelling
  - ✓ Differential Algebraic Equations (DAE)
  - ✓ Manual spatial discretisation for 1D components
  - ✓ Nice Graphical User Interface



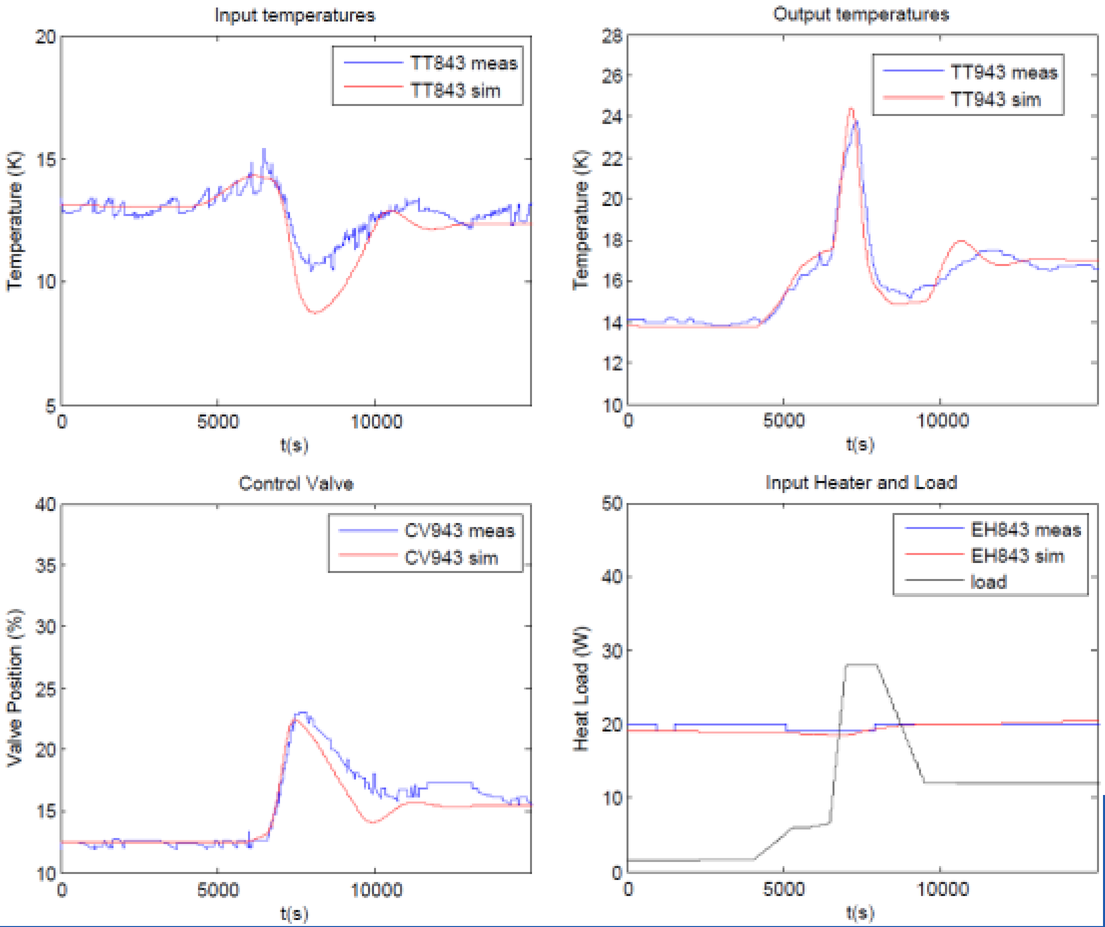

- Use of a cryogenic library (**CRYOLIB**)
  - ✓ Developed at CERN
  - ✓ Technology transferred and commercialized by EcosimPro

# Contents

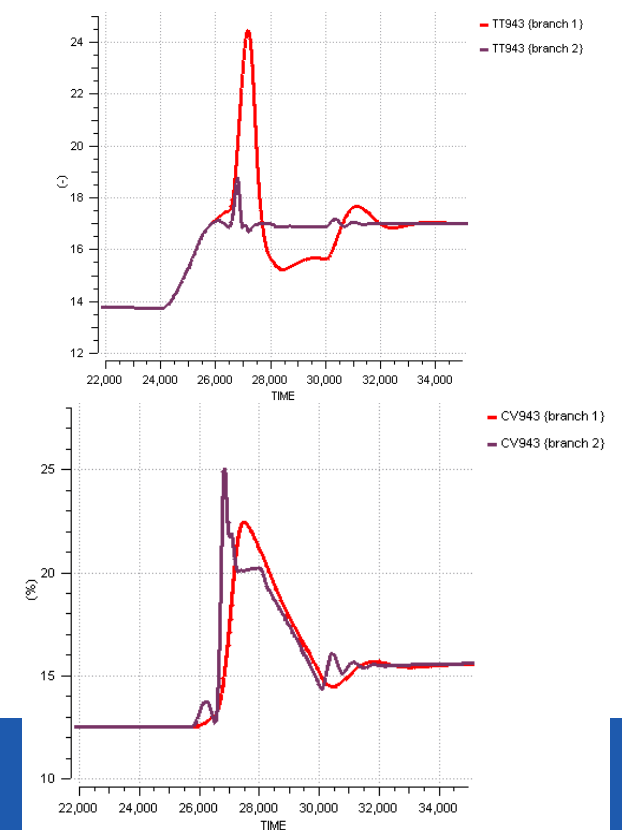
# Beam screens cooling: PID tuning

- Output temperature of beam screens must be below 20 K to ensure ultra high vacuum in LHC
- Heat peak is induced during the beam injection in LHC. Temperature was sometimes rising up to 20 K
- Reproduction in simulation and tuning of controller to reduce the peak

Model validation with experimental data

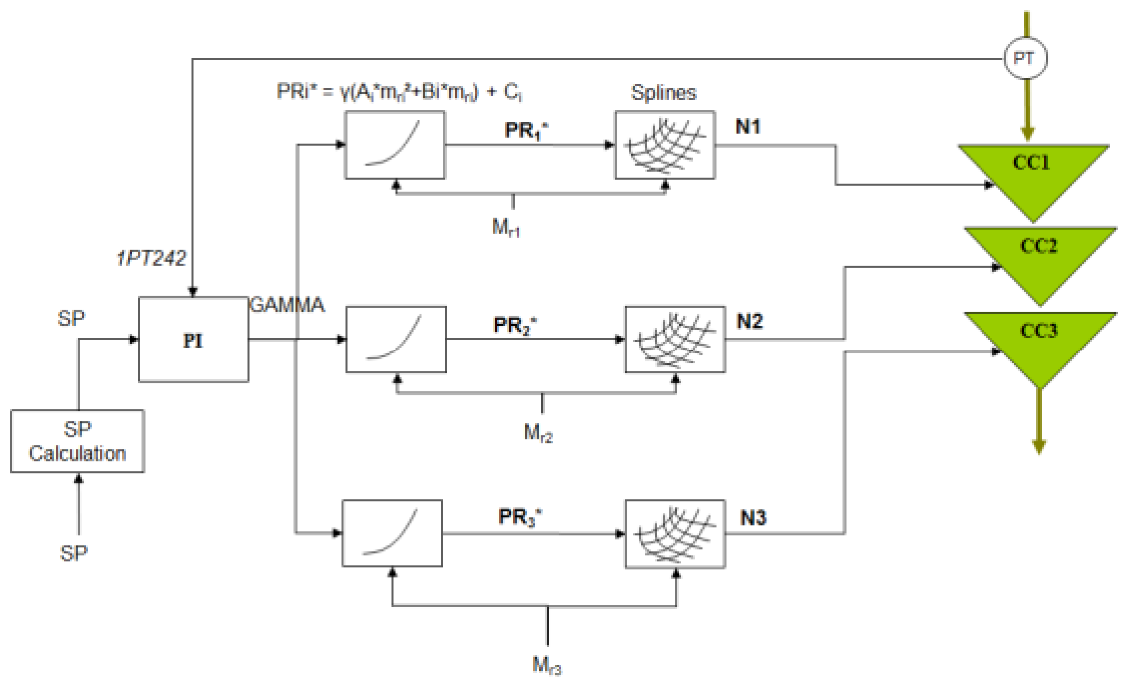



Simulation with new PID including some data filtering



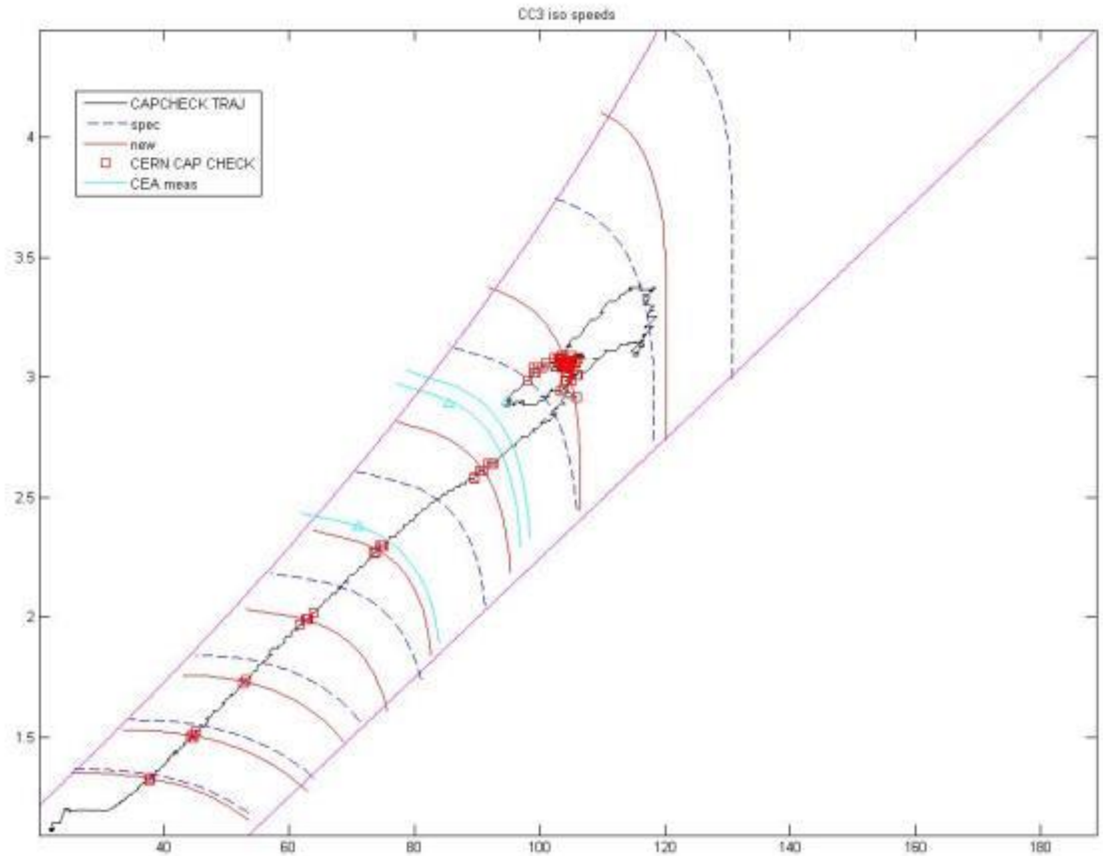
# Cold compressor control (1/2)

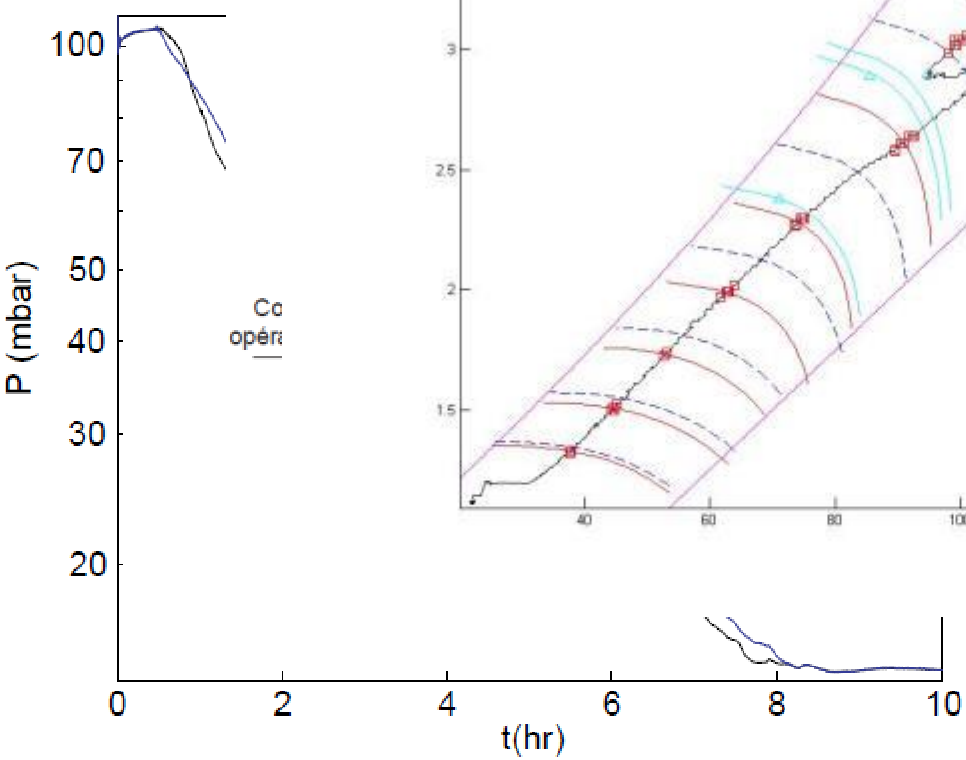
- Cold compressors are complex hydrodynamic machines
  - ✓ Allow to pump helium at 16 mbar at 3 K to reach 1.8 K in LHC magnets
  - ✓ A narrow pressure field has to be respected
- Original control was too slow or too “brutal” during pumping sequence

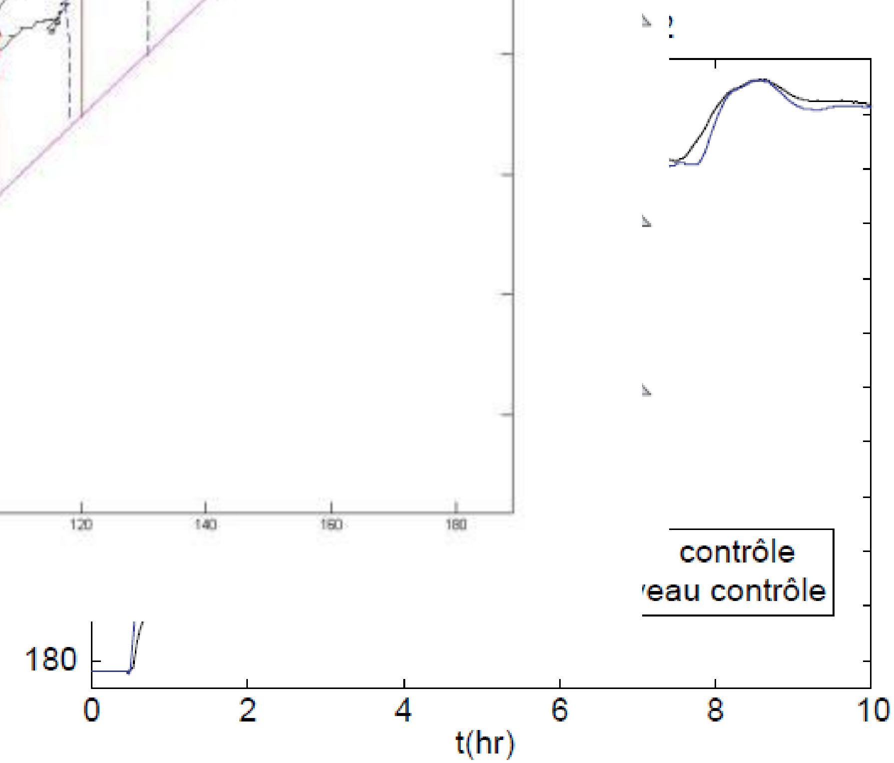



# Cold compressor control (2/2)

- Modeling and identification of pressure fields using optimization techniques
- Design o e trajectory
- Pumping
  - No n
  - S
  - E

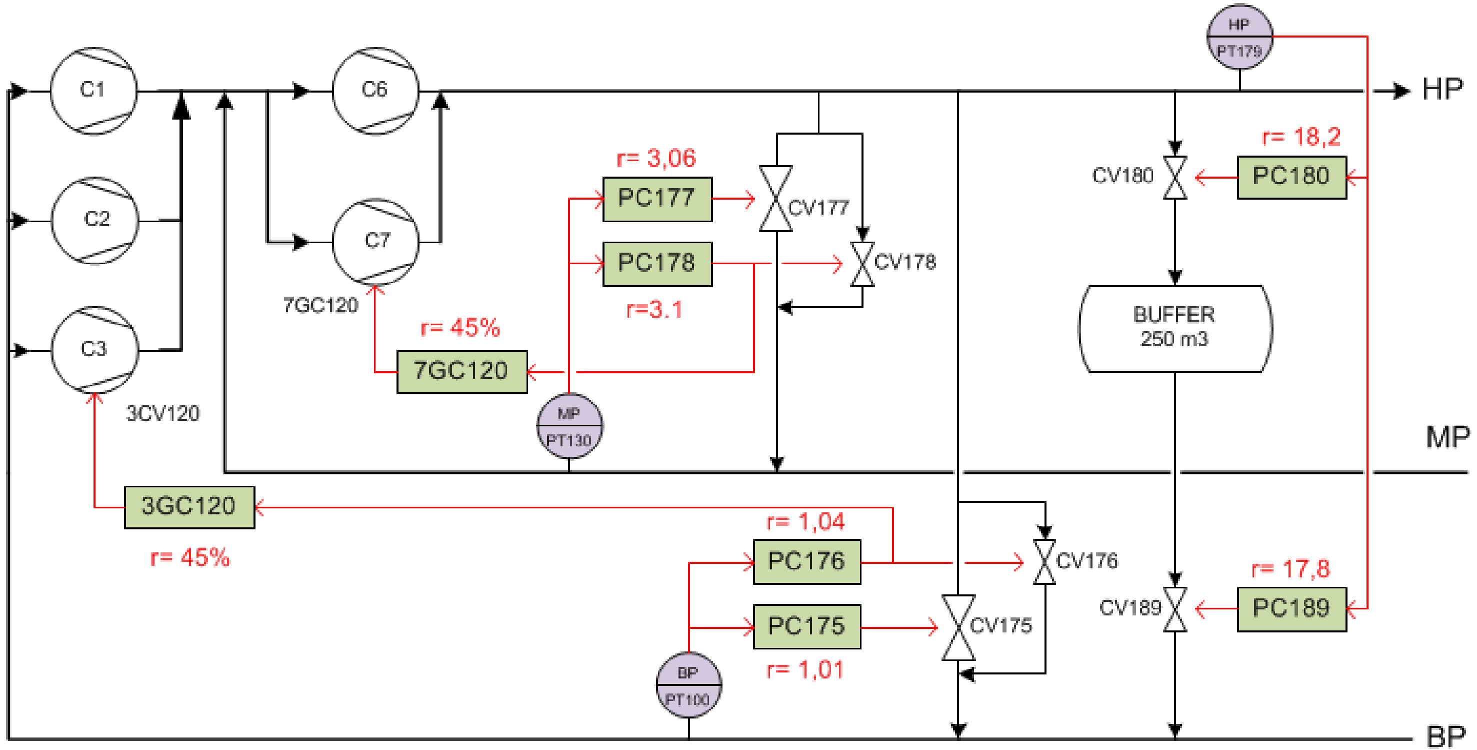


# Warm Compression Station Control (1/3)

- Compress 1.6 kg/s of warm helium from 1 bar to 18 bar
- Electrical consumption : 4.5 MW ➔ x8 = 36 MW
- 5 compressors + 6 valves + buffer tank + piping
- Objective = maintain constant pressures
  - ✓ High Pressure, Low Pressure, Medium Pressure
- ➢ Usually controlled by 8 PID controllers



# Warm Compression Station Control (2/3)

**IMC Control:** *Internal Model Control*

- Linear Model Synthesis from physics

$$\frac{dP}{dt} = \frac{d\rho}{dt} \cdot \bar{R} \cdot T = \frac{dM}{dt} \cdot \frac{\bar{R} \cdot T}{V}$$

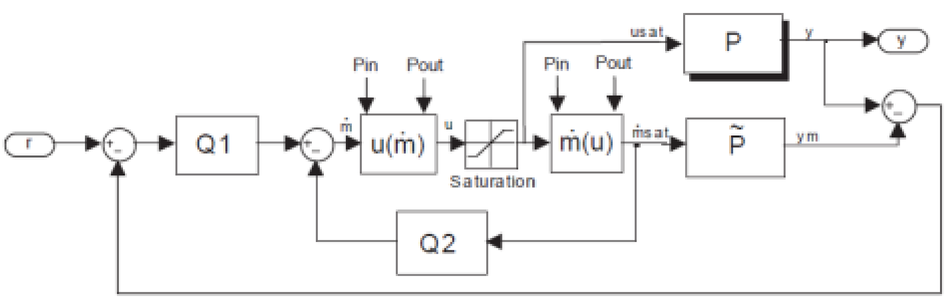
- Model uncertainties evaluations

$$lm(j\omega) = \frac{P(j\omega) - \tilde{P}(j\omega)}{\tilde{P}(j\omega)}$$

- Synthesis of the controller Q using a robust tuning

$$\min_{Q} \sup_{\omega} (|\eta \bar{l}m| + |\epsilon w|) \qquad \forall \omega \in \Re_{+}$$

- Guarantee stability for the worst case
- Adapt model in real-time (according to current state)
- Take into account saturation of valves (« *anti-windup* »)




**Optimal LQ Control:** *Linear Quadratic Control*

- Linear Model Synthesis from physics

$$\frac{dP}{dt} = \frac{d\rho}{dt} \cdot \bar{R} \cdot T = \frac{dM}{dt} \cdot \frac{\bar{R} \cdot T}{V}$$

- Calculation of the error regarding set-point

$$x_{\epsilon} = x - x_{sp}$$

- Integrate the error

$$x_{I_{\epsilon}} = x_{I_{\epsilon}} + x_{\epsilon}$$

- Compute the virtual control effort

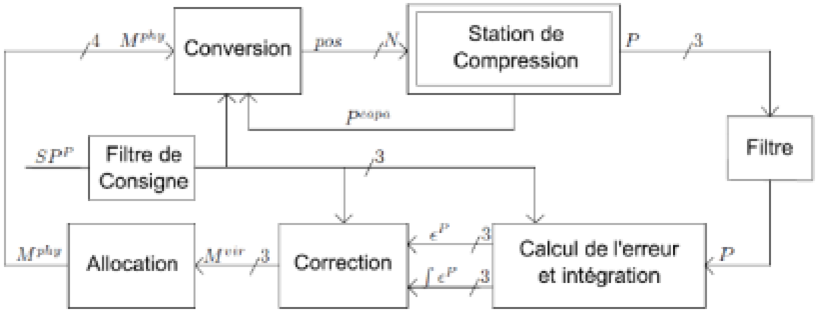
$$u_{vir} = K \cdot [x_{\epsilon} x_{I_{\epsilon}}]$$

- Project on the admissible space

$$u_{phy} = \mathcal{P}(u_{vir})$$

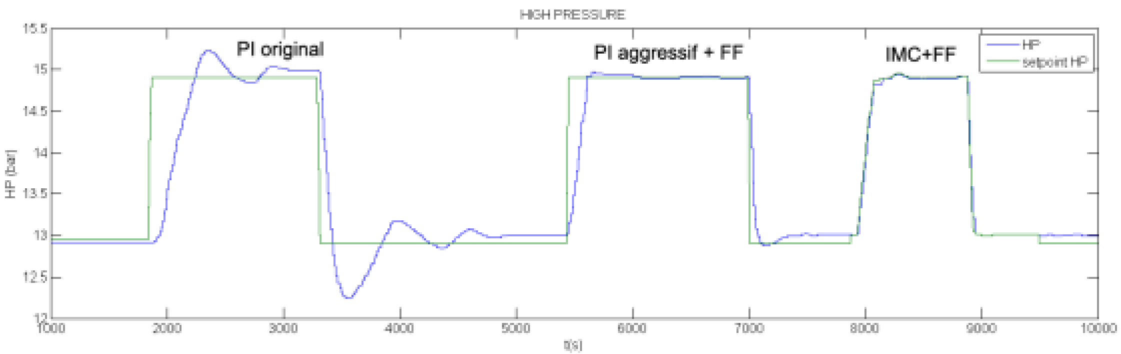
- Transformation from flowrate to actual control effort

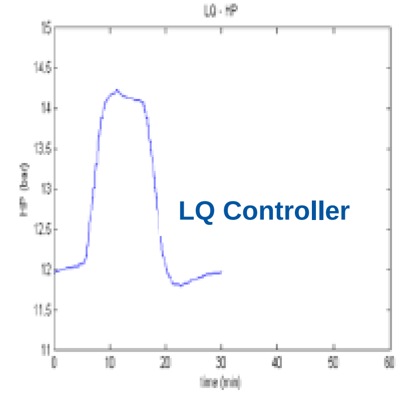
$$u_{phy} \rightarrow u$$

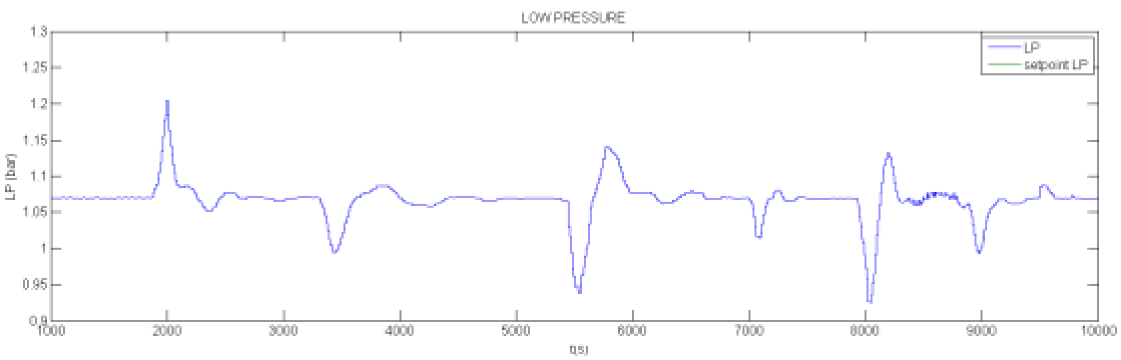


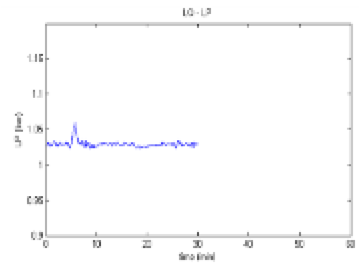
# Warm Compression Station Control (3/3)

- Comparison of different regulation techniques (sim + real)
  - ✓ Original PI controllers
  - ✓ Aggressive PI controllers + Feed-Forward
  - ✓ IMC + Feed-Forward
  - ✓ Optimal Multivariable LQ controller



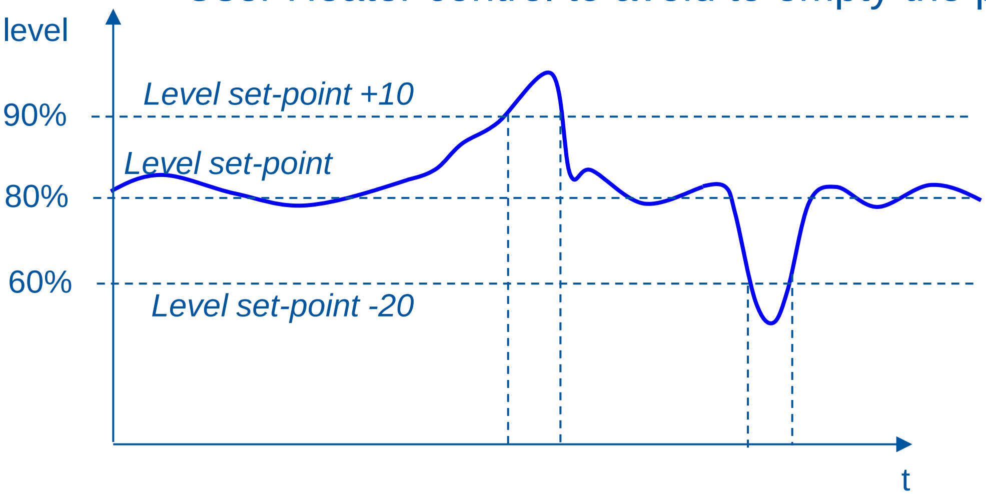



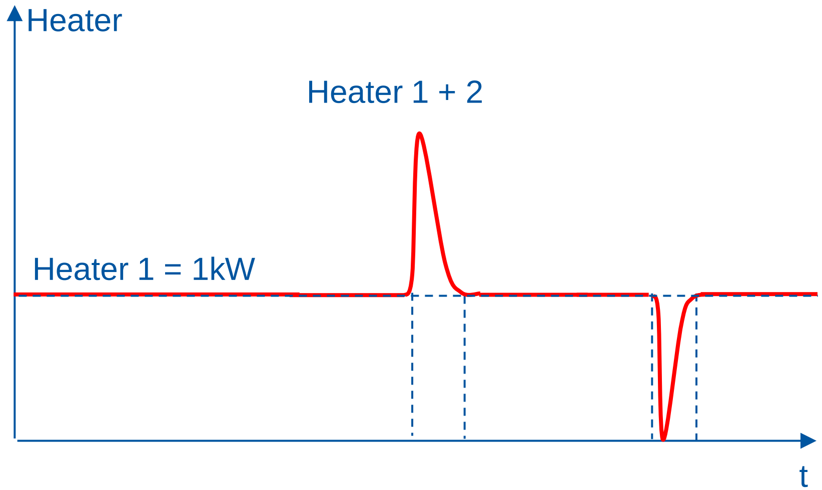



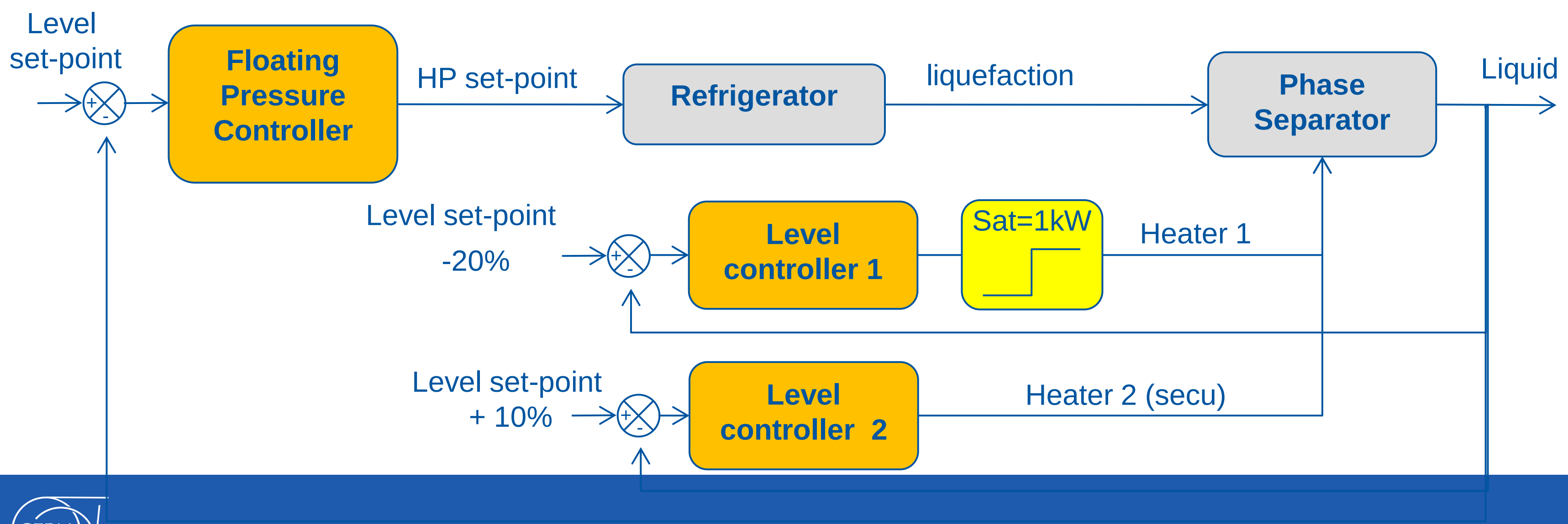



# Energy Optimization (1/2)

- Include a new control loop to optimize energy consumption (cascade)
- User Heater control to avoid to empty the phase separator or to have an overflow

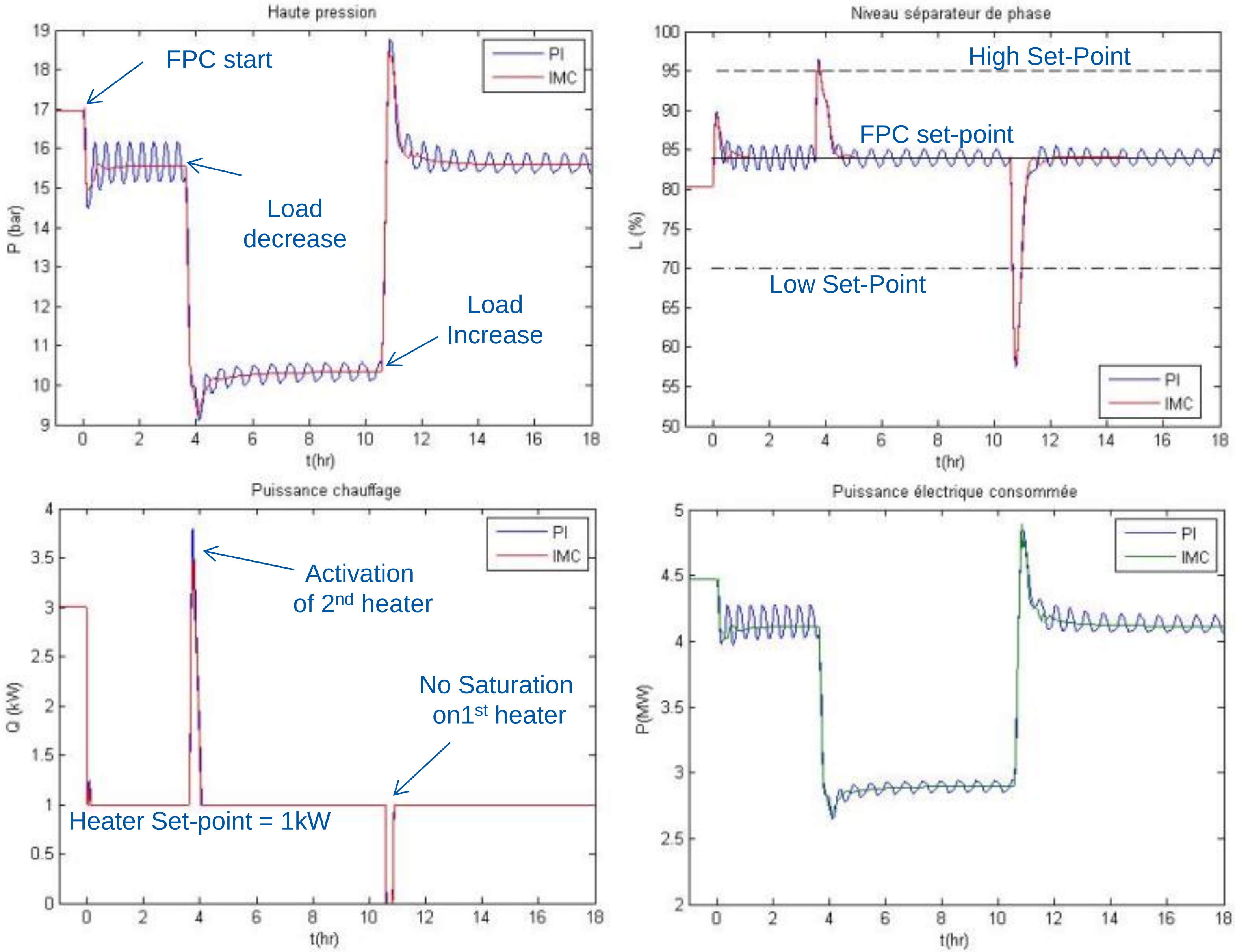


# Energy Optimization (2/2)

Simulations:



# Contents

# Conclusion & Perspectives

- Cryogenics are very complex processes
  - ✓ Large-Scale
  - ✓ Multivariable
  - ✓ Non-Linear

- Dynamic simulation is an adequate tool to validate new control schemes

- Cryogenics (as other processes) is using mainly PI controllers

- Cryogenics begins to use advanced control to optimize controls

CERN