Engineering Department

A&T sector SEMINAR

Modeling, Simulation and Control of CERN cryogenic systems

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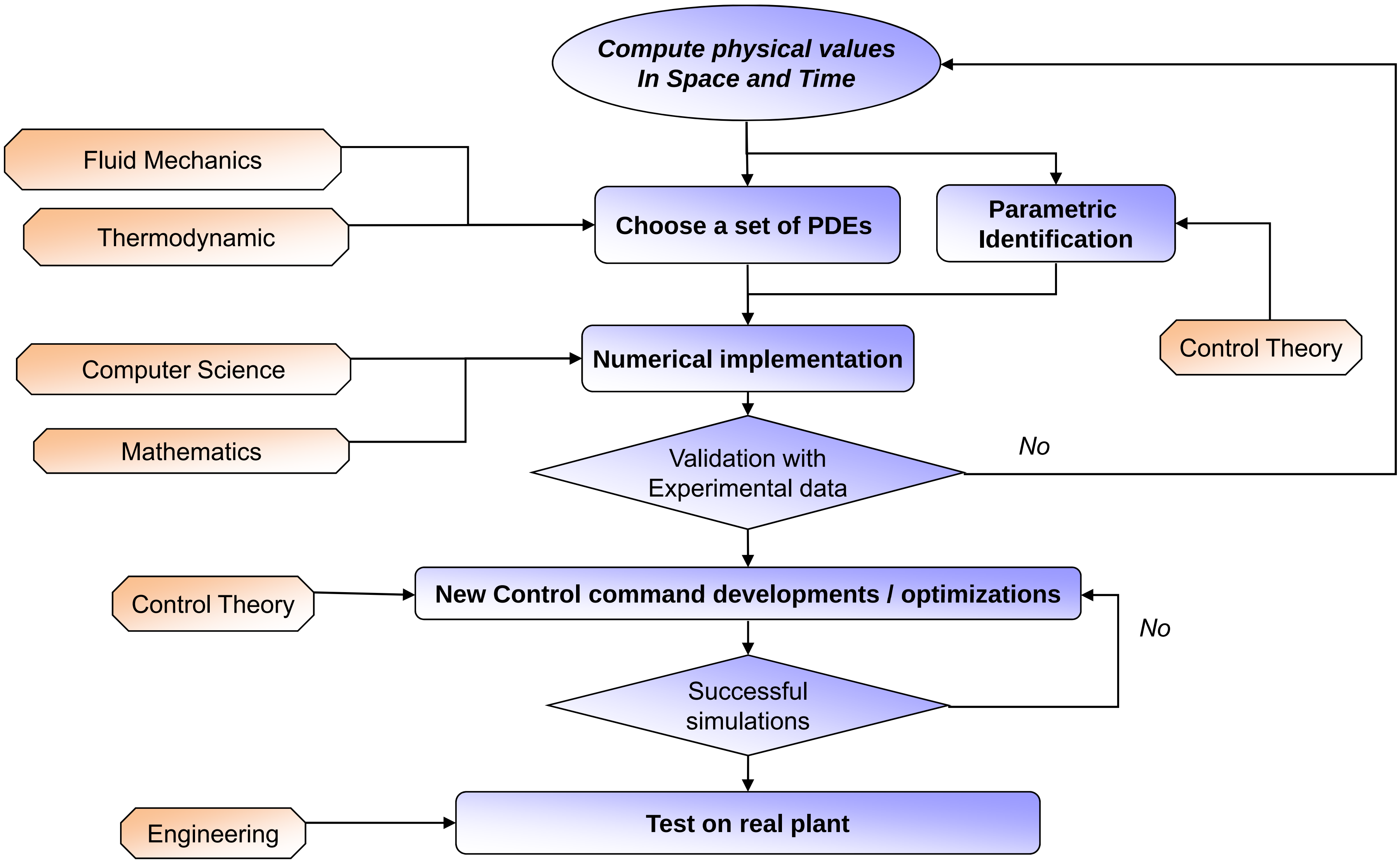
Motivations

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

- CERN cryogenic systems: **large scale complex** systems
  - ✓ Similar to large industrial systems (Petroleum refineries, food industry , etc.)
  - ✓ LHC cryogenics : *42 000 I/O & 5 000 control loops*
- **Non-linearity** of helium properties (wide operation ranges)
  - ✓ Temperature : 1.9 K to 300 K
  - ✓ Pressure : 14 mbar to 20 bar
- **Unique** systems
  - ✓ Built to be operated at nominal conditions
  - ✓ Few information about transients and out of predefined operation points
- **Dynamic simulation** is a good 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* »

Multidisciplinary Approach



State of art

Dynamic simulators of large-scale cryogenic systems

Team	Simulated Process	Process Modeling	Control Modeling	Optimization
R. Maekawa NIFS Japan	Commercial liquefier + LHD Refrigerator 10kW @ 4.5 K	Physics DAE* (cryo lib)	Partial	High Pressure control with feed-forward action
I.Butkevitch Kapitza insti. Russia	Commercial liquefier for university education	Mathematical Heuristic	No	No
H. Quack UT Dresden Germany	Commercial liquefier	Physics DAE* (cryo lib)	No	No
C. Deschildre CEA/AL/Gipsa France	800 W refrigerator + Commercial liquefier	Physics DAE* (standard lib)	No	Pulse management for future tokamaks

**Differential Algebraic Equations*

PROCOS : Process & Control Simulator

- **CERN processes :**
  - ✓ Commercial liquefier
  - ✓ Medium and very large helium refrigerators @ 4.5 K
  - ✓ Refrigeration units @ 1.8 K with cold-compressors

- **Modeling tasks**
  - ✓ Use of equations from physics
    - Differential Algebraic Equation (DAE) with EcosimPro
  - ✓ Identification techniques
    - Matlab

- **Constraint : Simulation of control systems**
  - ✓ Use of existing control programs
    - PLC Schneider & Siemens (*Programmable Logic Controller*)
  - ✓ Use of existing CERN supervision system
    - PVSS

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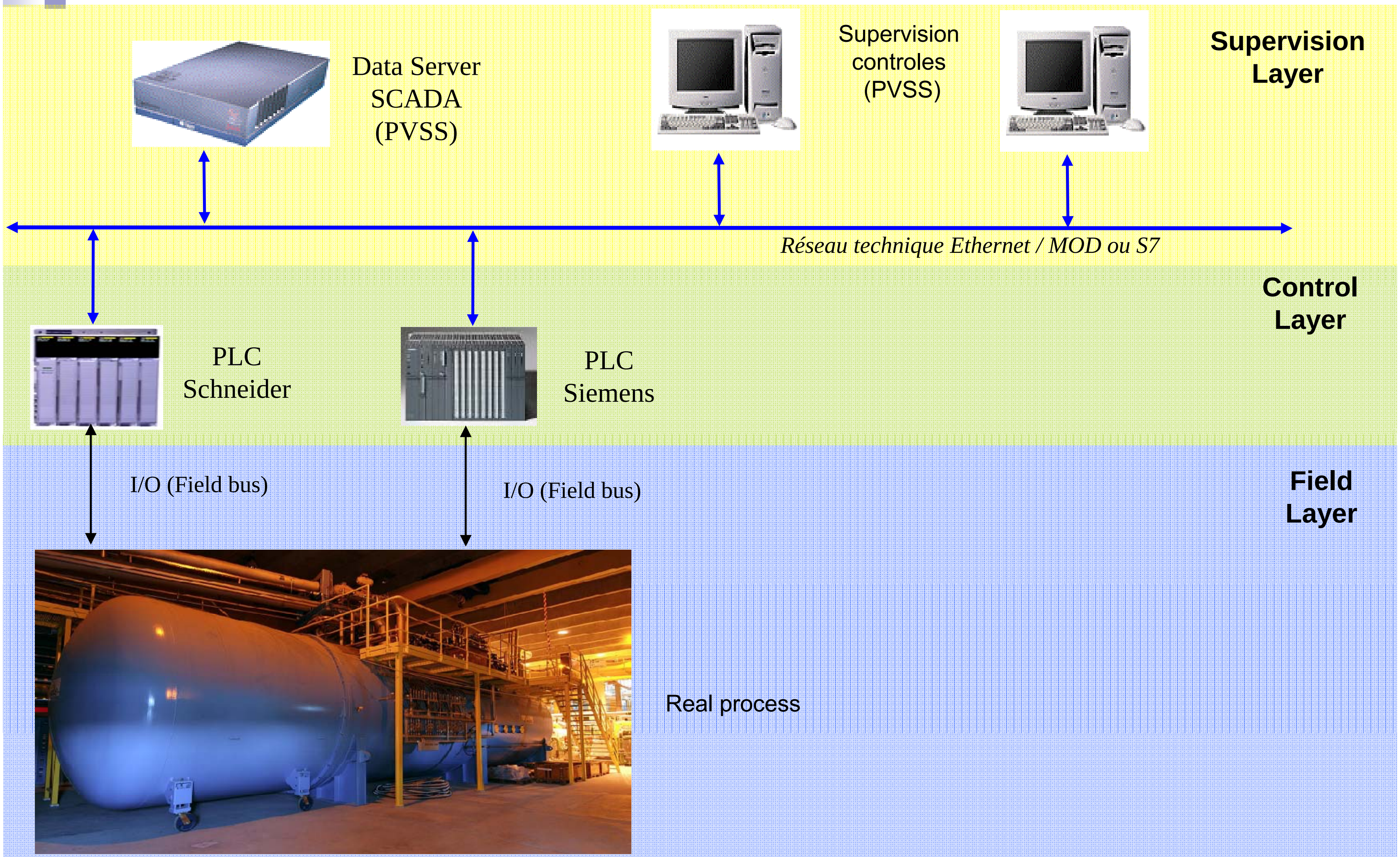
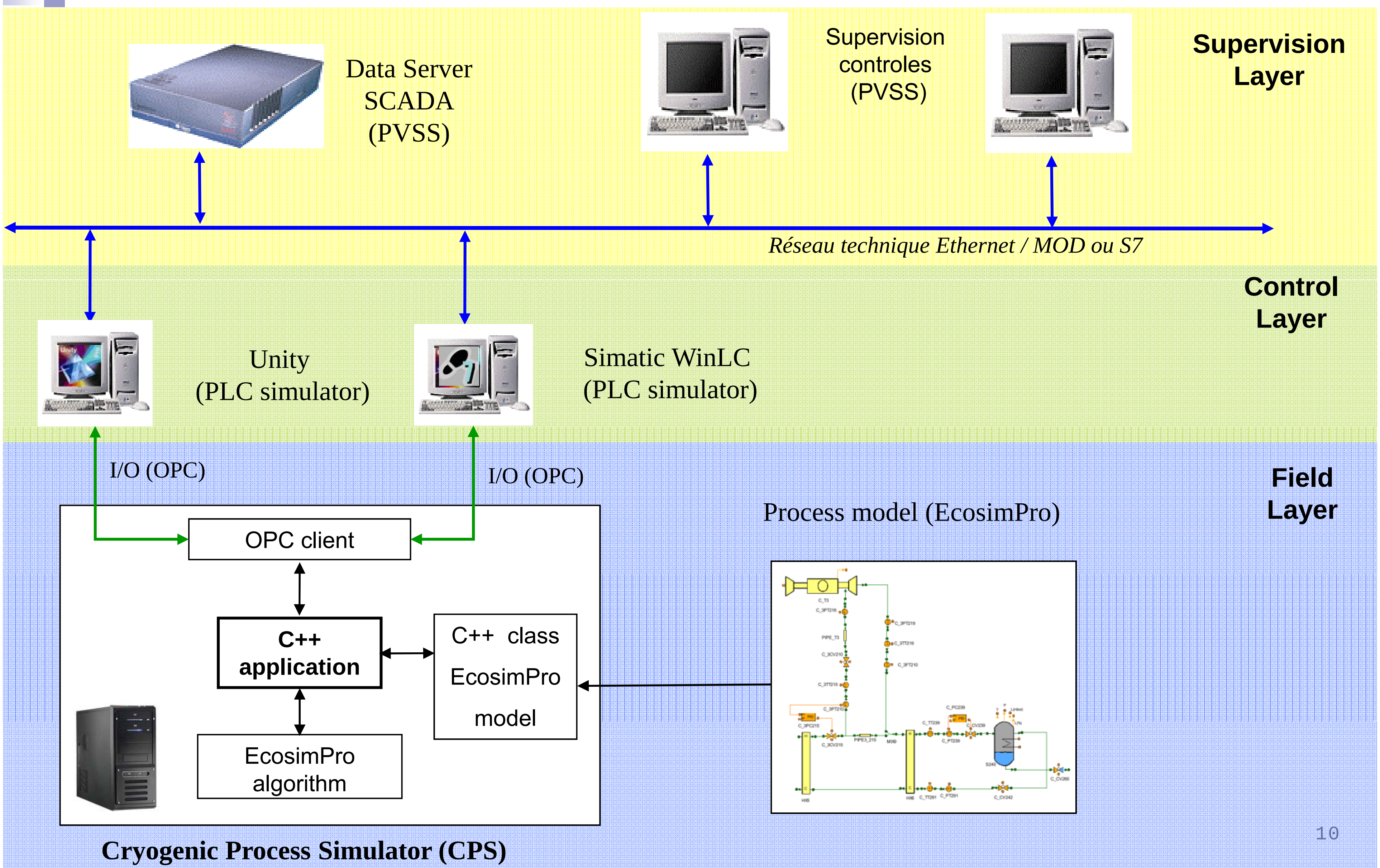
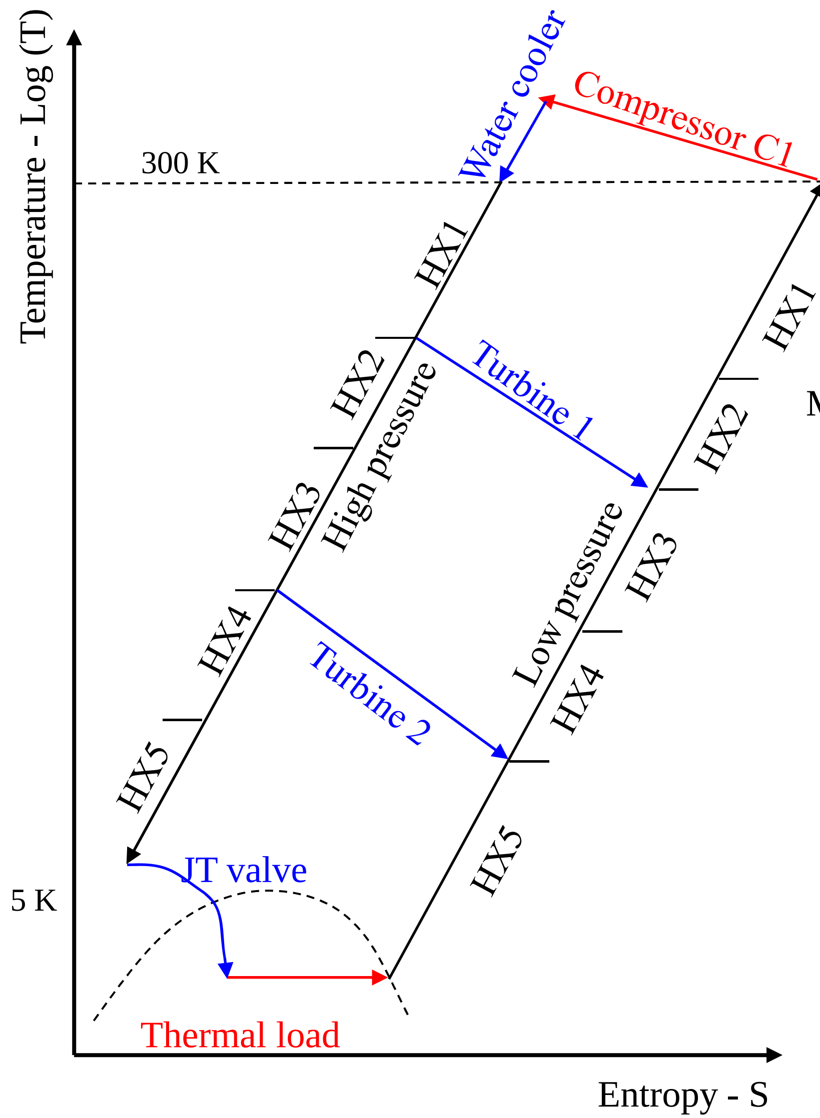
CERN control architecture for cryogenics

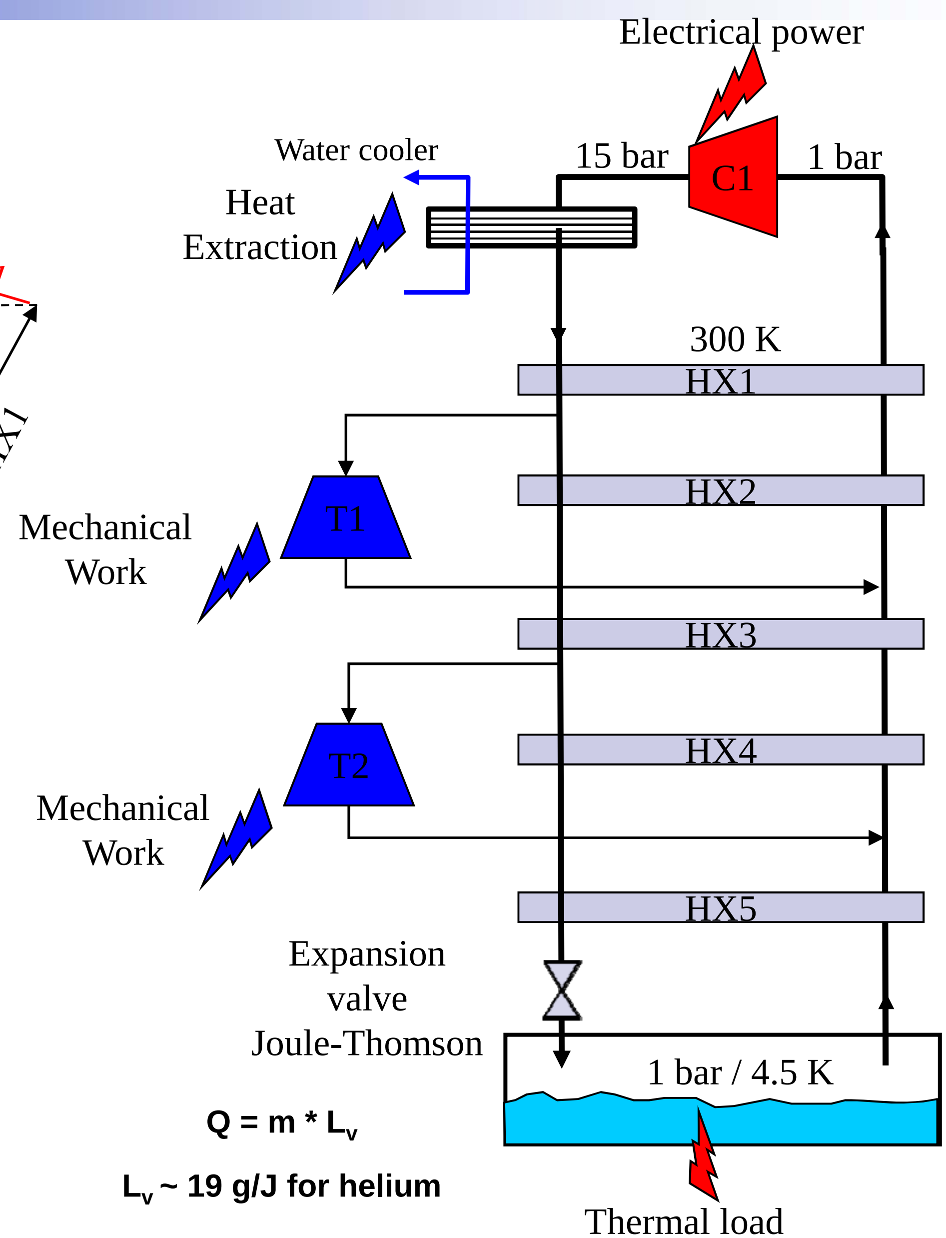


CERN control architecture for simulation



Refrigerator operation

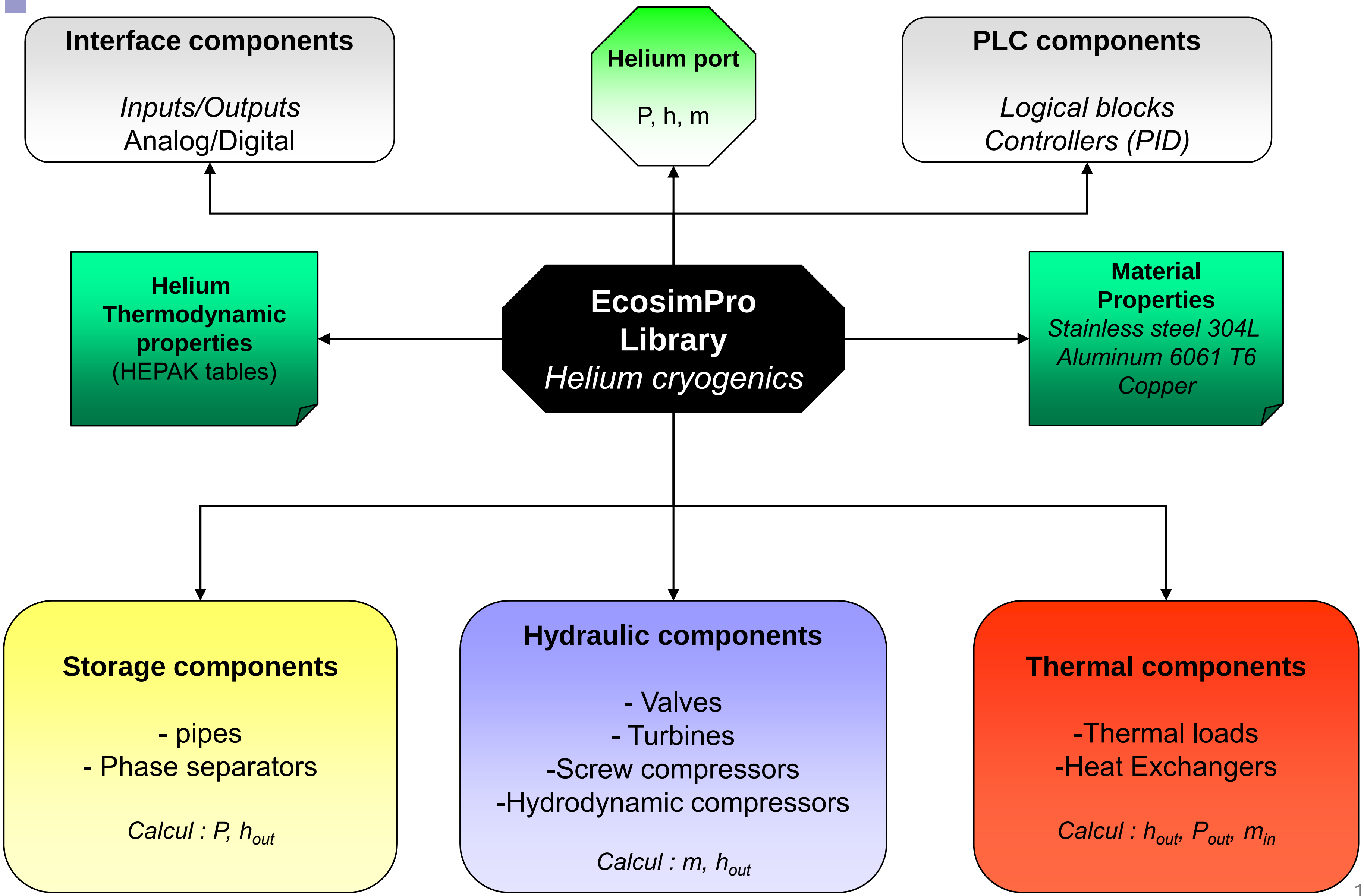




$Q = m * L_v$

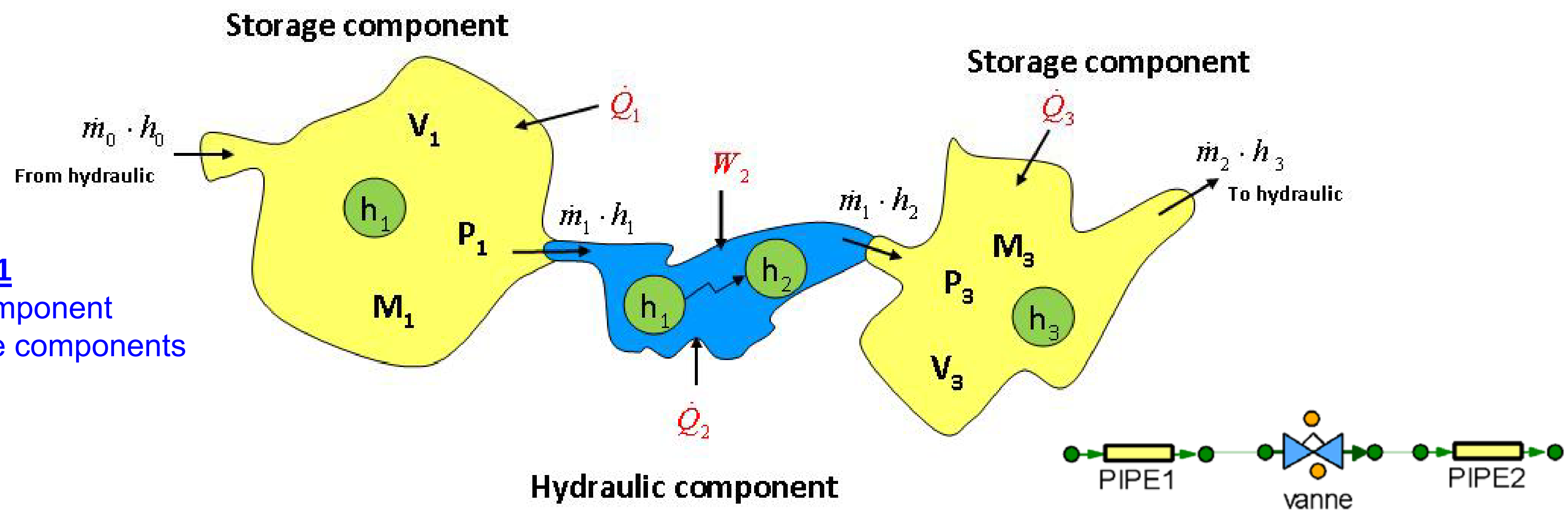
L_v ~ 19 g/J for helium

A component library for cryogenics

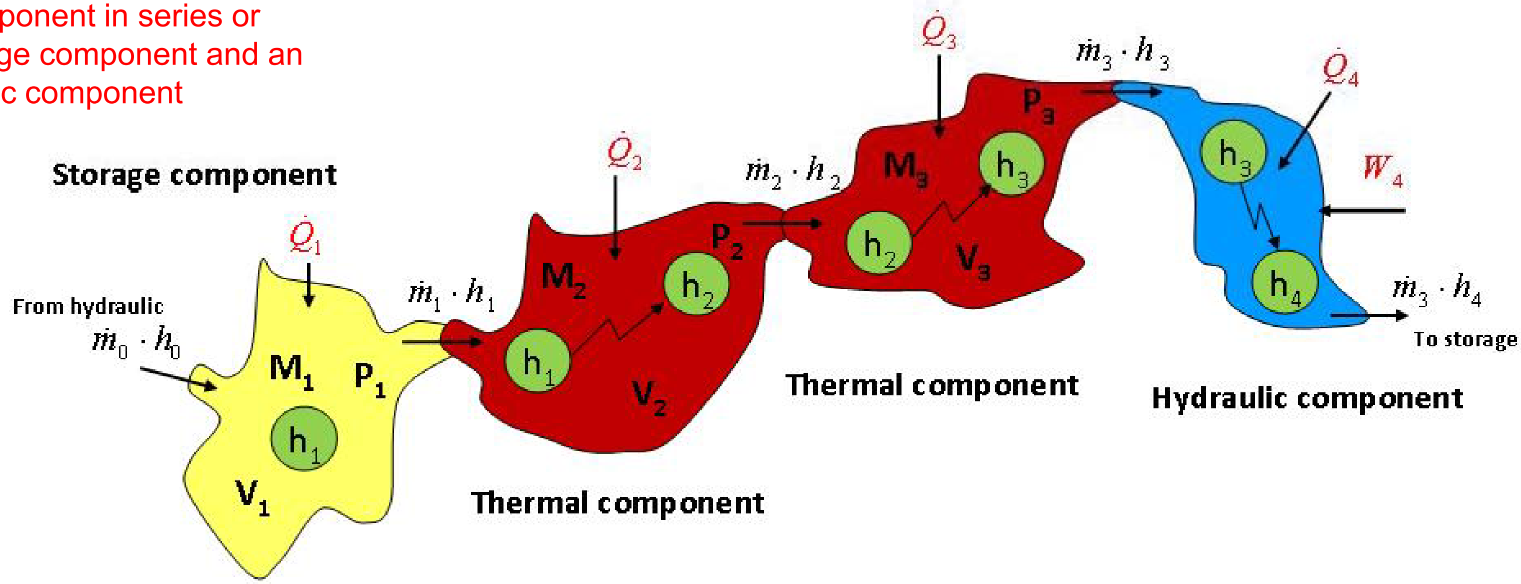


Interconnections between components

Rule 1
Hydraulic component
Between 2 storage components



Rule 2
Thermal component in series or
between a storage component and an
hydraulic component



Variational approach

- Some parameters are difficult to find in large cryogenic systems
  - Geometrical parameters (length, pipe shape, HX parameters, etc.)
  - Thermal parameters (insulation)
  - “Secret” parameters (turbines)

- Generally, manufacturers guarantee a nominal operation point :
  - Static calculations performed by manufacturers

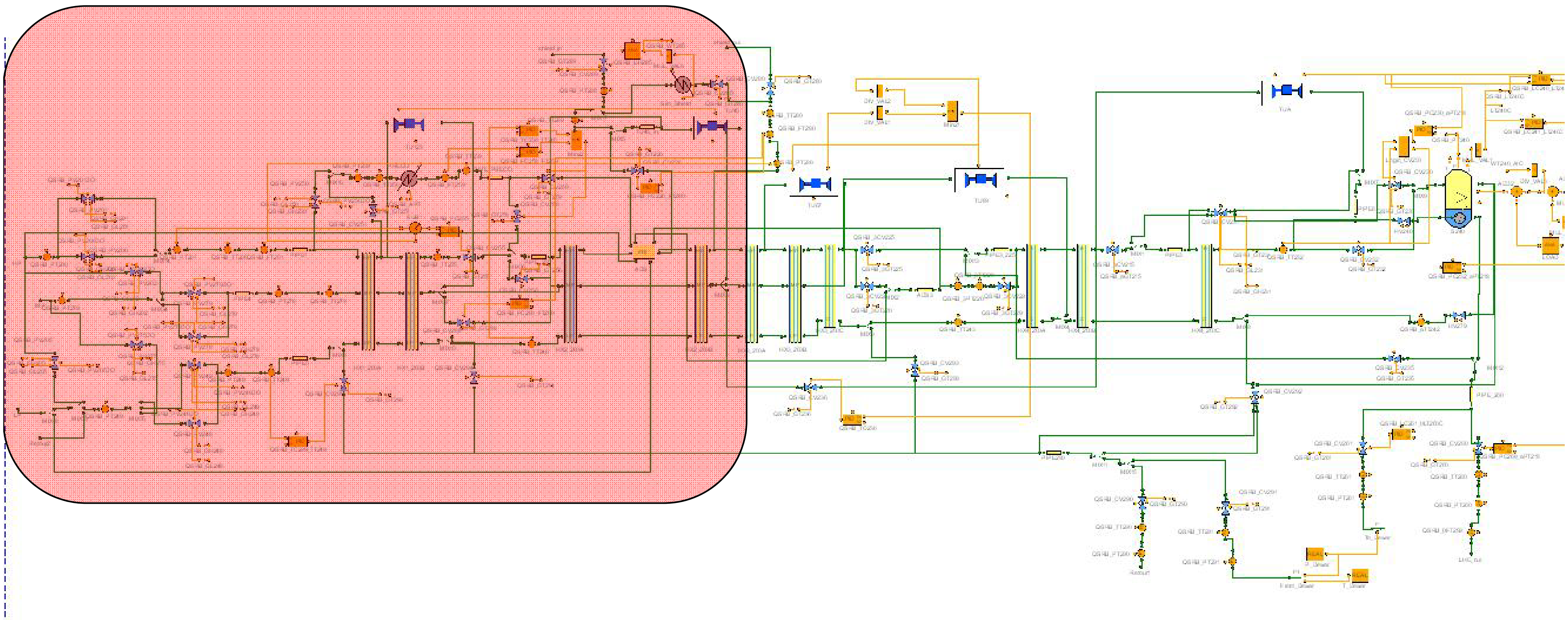
- If *X* depends on an unknown constant K1 : $X = K_1 \cdot f(P, T),$

- Known design point : $X_d = K_1 \cdot f(P_d, T_d).$

- Ratio between both: $X = X_d \cdot \frac{f(P, T)}{f(P_d, T_d)}.$

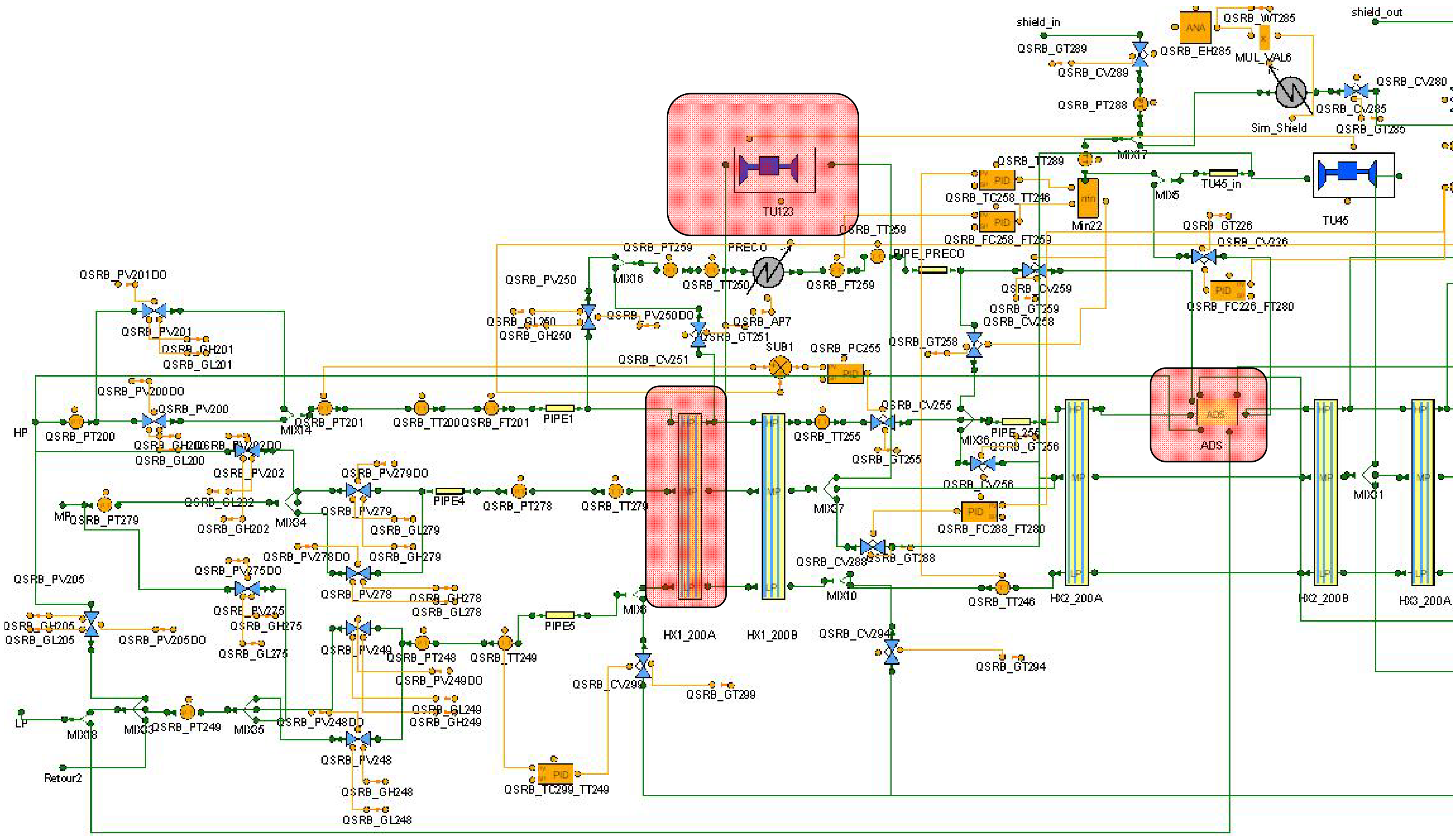
- Non-linearity of ‘f(P,T)’ are kept and unknown constants are removed

Example in EcosimPro



Example of a model in EcosimPro
Linde18kW cold-box for the LHC

Example in EcosimPro (Zoom)



Example in EcosimPro (HX parameters)

Attributes editor

Library : CRYO_CERN

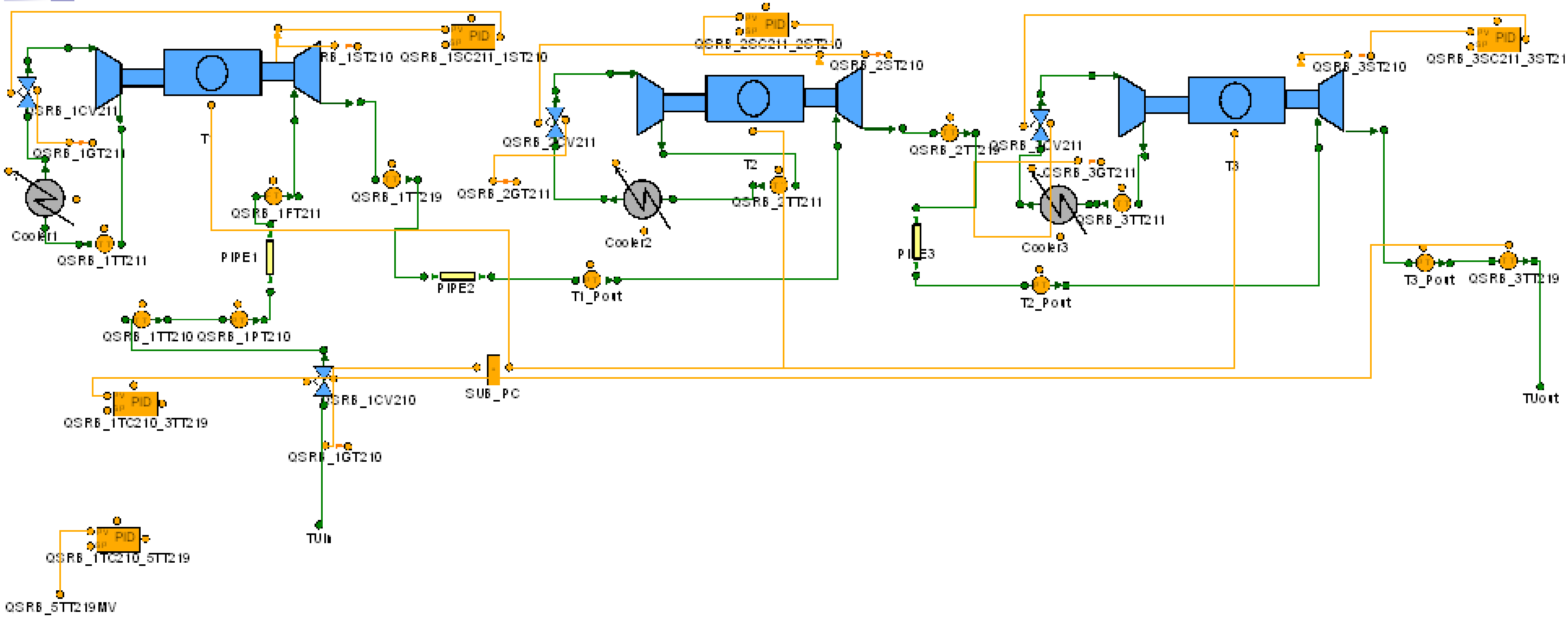
Type : Mhex_5

Name : HX1_200A

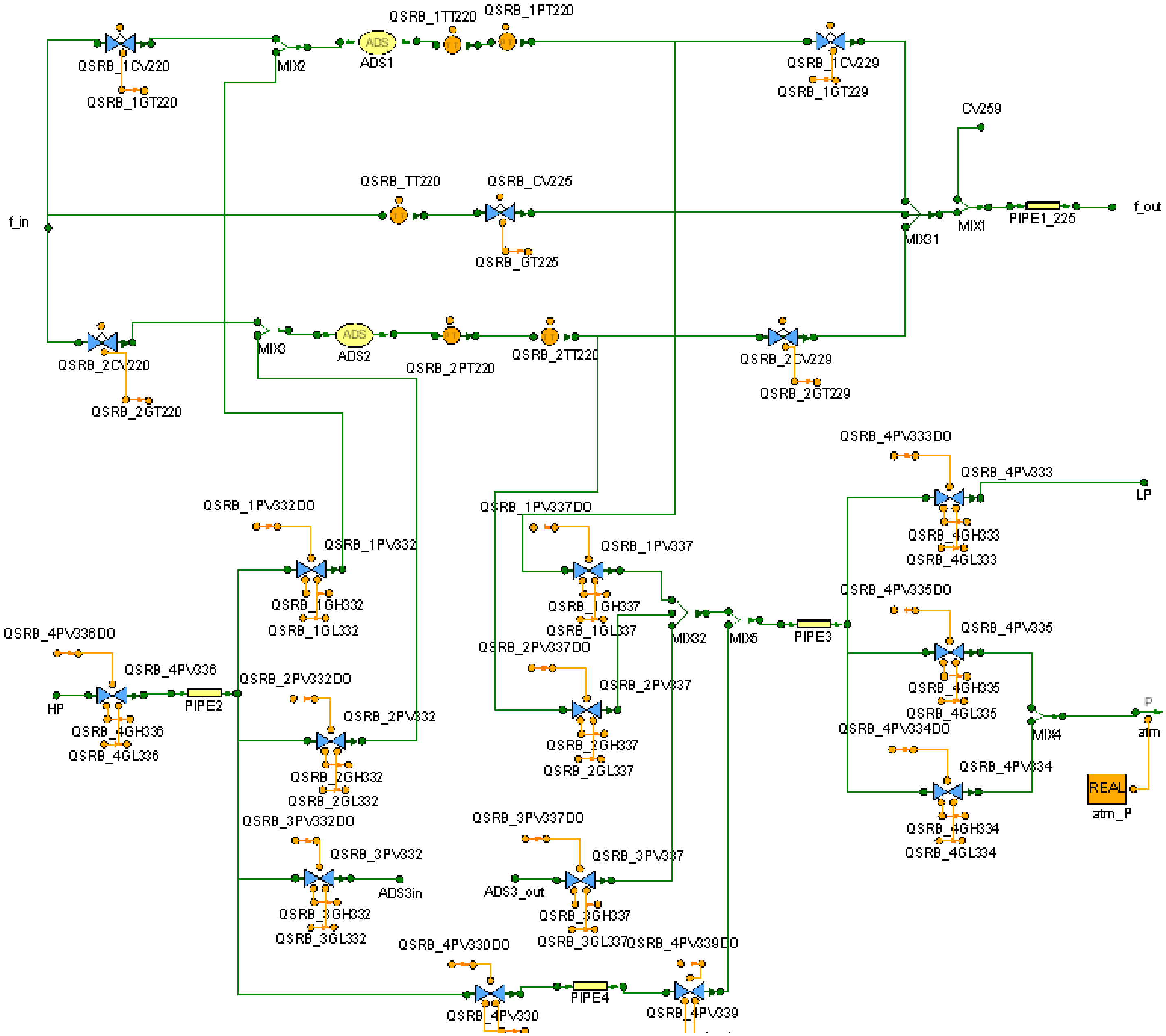
☑ Show label

Name	Type	Value	Units	Description
		PARAMETERS		
nodes	INTEGER	1		Number of nodes
type_hp	ENUM CRYO_CE...	esistive_Storage		Stream type
type_mp	ENUM CRYO_CE...	torage_Resistive		Stream type
type_lp	ENUM CRYO_CE...	torage_Resistive		Stream type
LMTD_Flag	BOOLEAN	TRUE		Logarithmic Mean Temperature Difference method
mat	ENUM CRYO_CE...	Alu_T6_6061		HX material
		DATA		
heat_leak	REAL	195	W	leak betweek the cold and the hot heat flux (W)
V_hp	REAL	0.935	m^3	Inner volume of the high pressure side (m^3)
V_mp	REAL	0.618	m^3	Inner volume of the medium pressure side (m^3)
V_lp	REAL	1.571	m^3	Inner volume of the low pressure side (m^3)
M_wall_hp	REAL	1374	kg	Metal mass of high pressure side (kg)
M_wall_mp	REAL	908	kg	Metal mass of medium pressure side (kg)
M_wall_lp	REAL	2311	kg	Metal mass of low pressure side (kg)
UA_d_hp	REAL	653619	W/K	Global heat transfer coefficient for high pressure side (W/K)
T_d_hp	REAL	302	K	Design temperature for high pressure side (K)
P_d_hp	REAL	18.52	bar	Design pressure for high pressure side (bar)
m_d_hp	REAL	1.597	kg/s	Design mass flow for the high pressure side (kg/s)
dP_d_hp	REAL	0.08	bar	Design pressure loss for the high pressure side (bar)
n_f_hp	REAL	-0.3	-	Constant for friction factor calculation in the hot side (-)
UA_d_mp	REAL	337382	W/K	Global heat transfer coefficient for medium pressure side (W/K)
T_d_mp	REAL	299.8	K	Design temperature for medium pressure side (K)
P_d_mp	REAL	4.07	bar	Design pressure for medium pressure side (bar)
m_d_mp	REAL	0.8018	kg/s	Design mass flow for the medium pressure side (kg/s)
dP_d_mp	REAL	0.02	bar	Design pressure loss for the medium pressure side (bar)
n_f_mp	REAL	-0.3	-	Constant for friction factor calculation in the medium pressure side (-)
UA_d_lp	REAL	316334	W/K	Global heat transfer coefficient for low pressure side (W/K)
T_d_lp	REAL	299.8	K	Design temperature for low pressure side (K)
P_d_lp	REAL	1.13	bar	Design pressure for low pressure side (bar)
m_d_lp	REAL	0.7518	kg/s	Design mass flow for the low pressure side (kg/s)
dP_d_lp	REAL	0.01	bar	Design pressure loss for the low pressure side (bar)
n_f_lp	REAL	-0.3	-	Constant for friction factor calculation in the cold side (-)
coefA_hp_lp	REAL	0.48		Ratio between the heat transfer area between the hp stream and the lp stream andthe total available heat transfer area of the hp stream ()
coefA_hp_mp	REAL	0.52		Ratio between the heat transfer area between the hp stream and the lp stream andthe total available heat transfer area of the hp stream ()
coefA_mp_hp	REAL	1		Ratio between the heat transfer area between the lp stream and the hp stream andthe total available heat transfer area of the mp stream
coefA_lp_hp	REAL	1		Ratio between the heat transfer area between the lp stream and the hp stream andthe total available heat transfer area of the lp stream
e	REAL	0.1	m	Thickness of HX for conduction (m)
S	REAL	0	m^2	Conduction surface of HX. Put 0 to neglect it (m^2)
Po_hp	REAL	1	bar	Initial pressure for the high pressure side (bar)

Example in EcosimPro (first turbines)



Example in EcosimPro (adsorbers)



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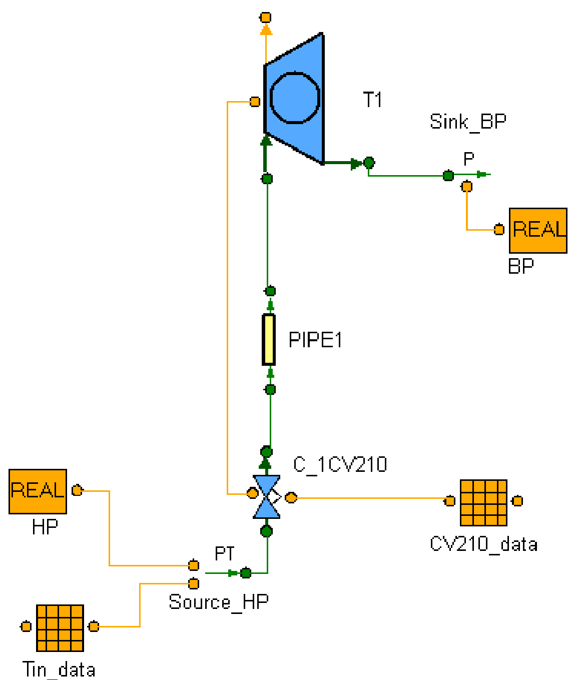
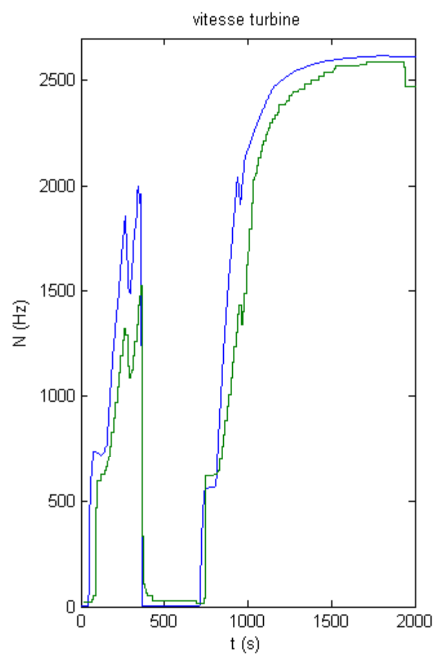
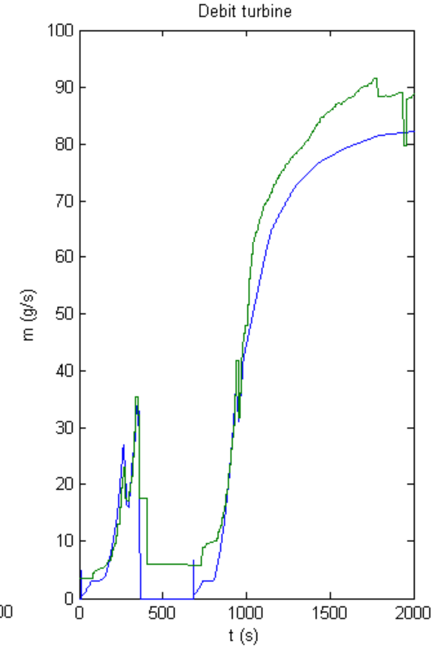
Component model validation

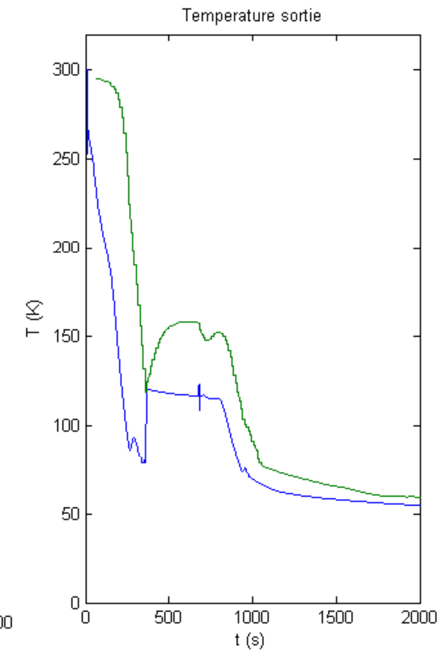
- Individual validation
  - ✓ Constant boundary conditions
  - ✓ Transient checking
  - ✓ Operation point checking

- Validation of a reduced set of components
  - ✓ Ex : Valve + pipe + turbine



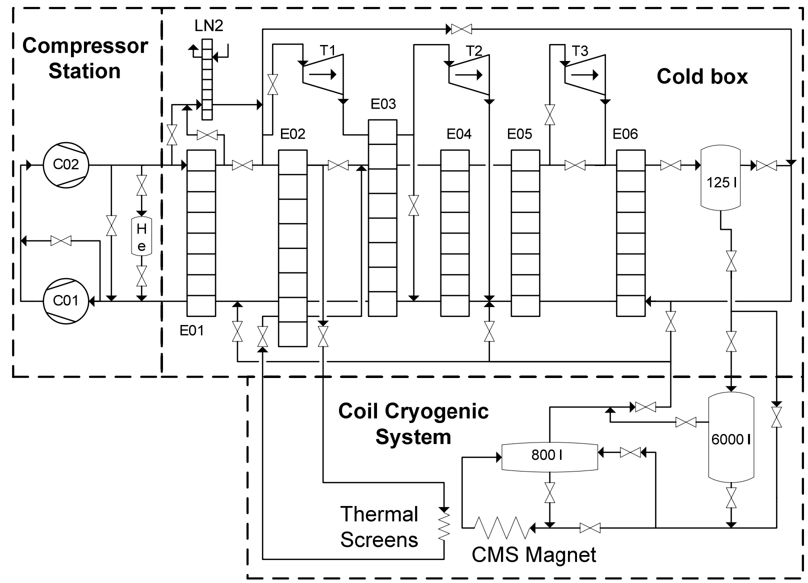


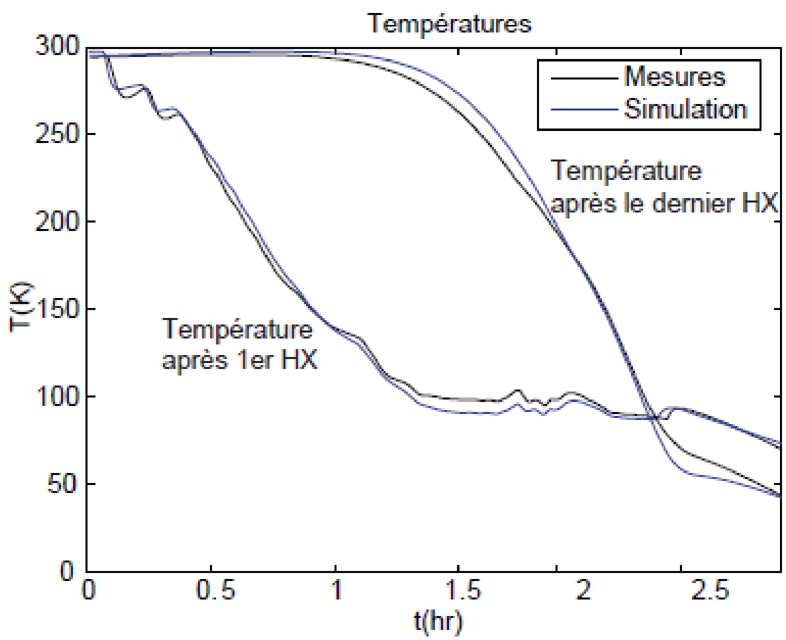


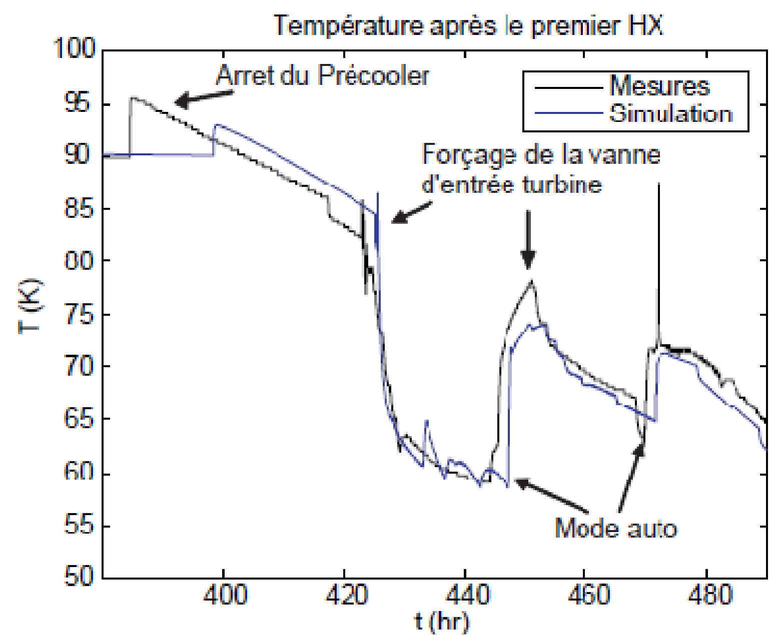


Multi-component model validation

- CMS cryoplant
  - ✓ Cooldown CMS magnet (225 tons)
  - ✓ Air Liquide – 1.5 kW @ 4.5 K
  - ✓ 3310 Algebraic equations
  - ✓ 244 Differential equations
  - ✓ Simulation speed during cool-down : x15
- Validation of a complete system
- Simulation architecture validation
- Operator training tool

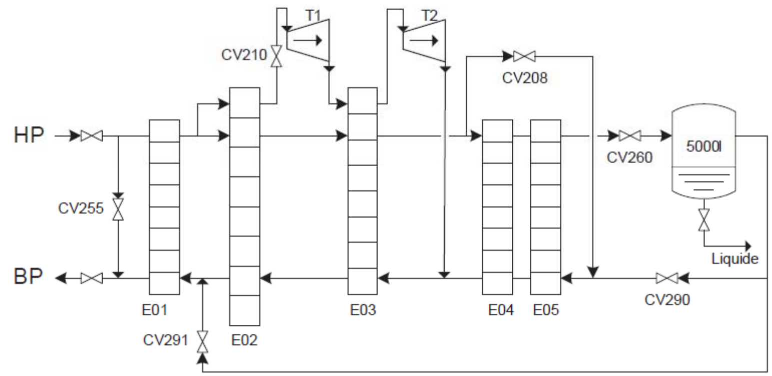




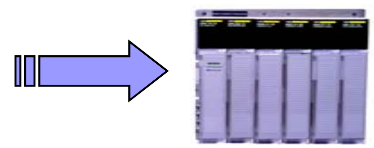


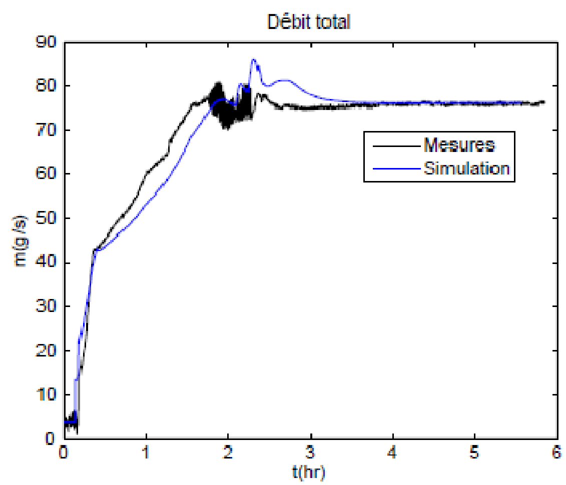
Virtual Commissioning

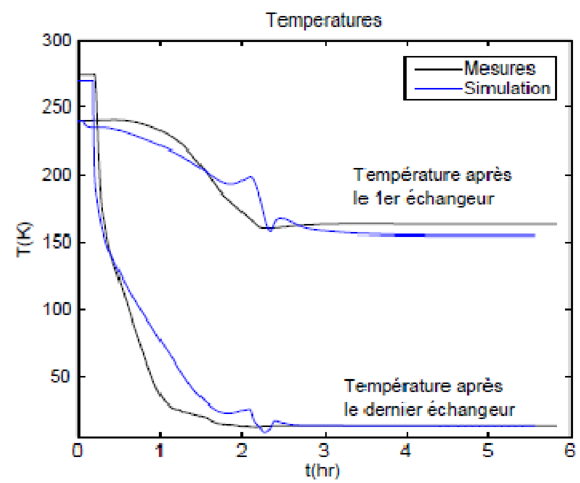
- CERN central helium liquefier (B165)
  - ✓ Provide liquid helium for small CERN experiments
  - ✓ Commercial Linde TCF 50 – 70 Lhe / hour
  - ✓ 2060 Algebraic equations
  - ✓ 170 Differential equations
  - ✓ Simulation speed during cool-down : x20
- Test and improve PLC code and supervision *(collaboration with TE-CRG-CE)*
  - ✓ Bad calibration of sensors
  - ✓ PLC-coding errors
  - ✓ Sequence errors (timers, threshold, etc.)
  - ✓ New turbine starting sequence
  - ✓ PI tuning



ABB

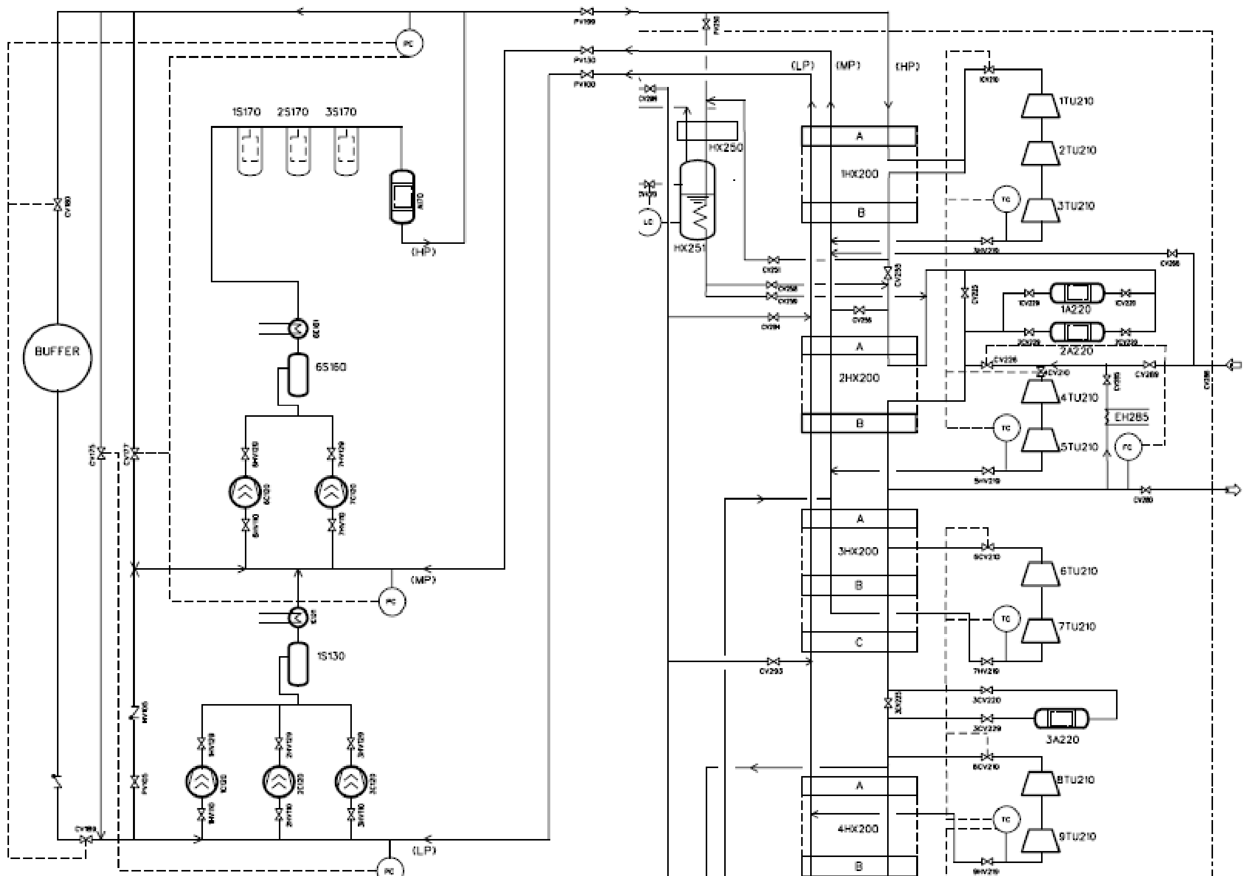






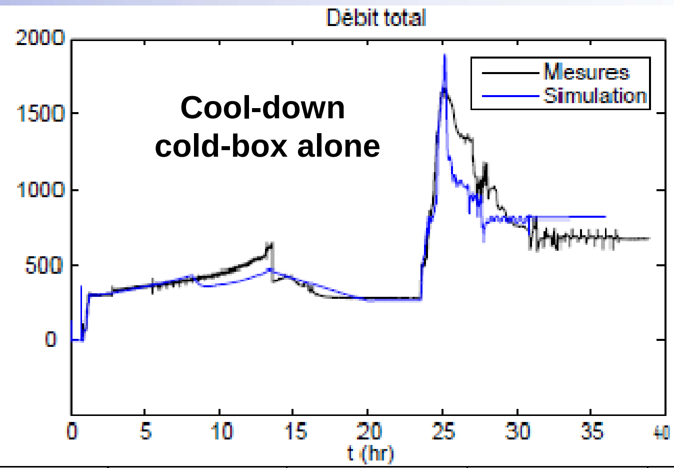
Large-Scale system simulation: LHC refrigerator

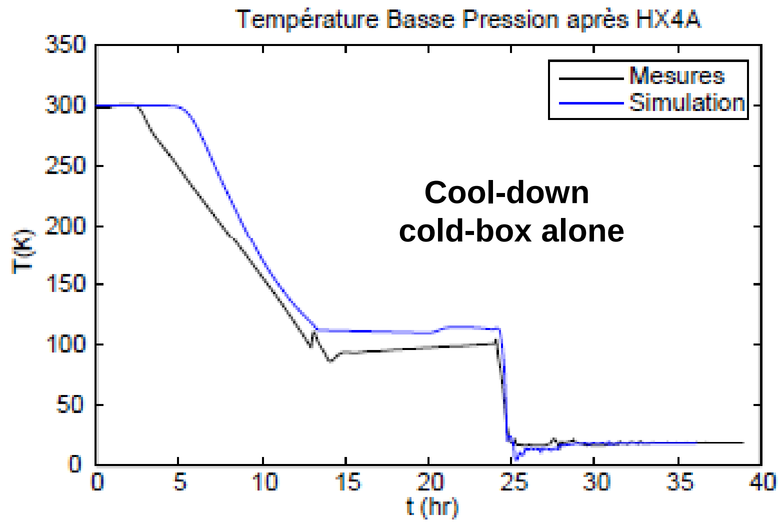
- 4.5 K LHC refrigerator
  - ✓ Linde 18 kW @ 4.5 K
  - ✓ 4600 Algebraic equations
  - ✓ 400 Differential Equations
  - ✓ Simulation speed: x3
- Operator training tool
- High Pressure control optimization (*IMC*)
- New control strategies to reduce operation costs (*floating pressure*)

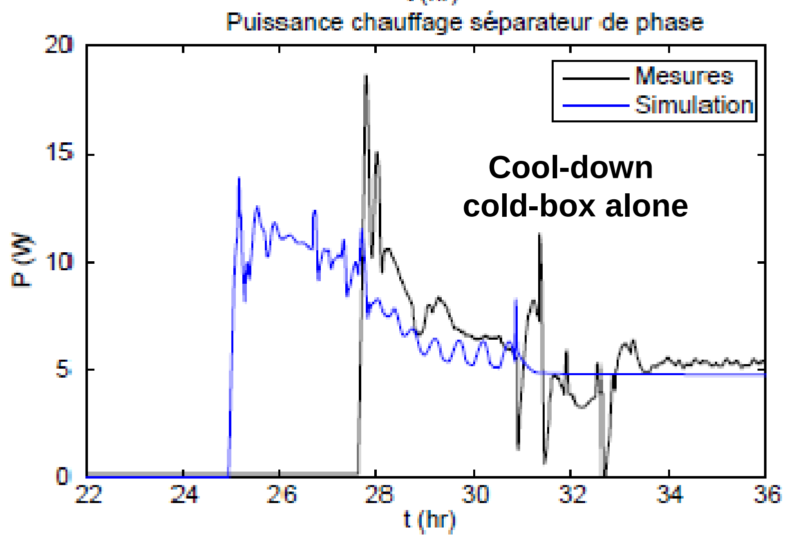


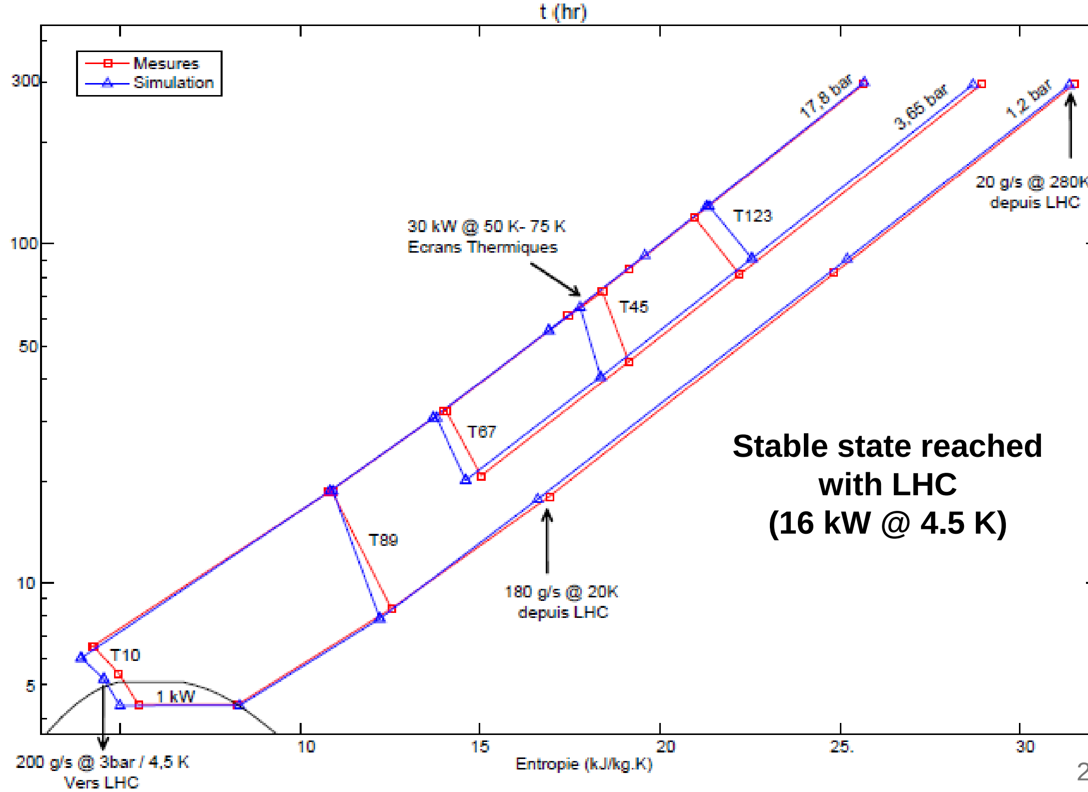
LHC refrigerator simulations

After model validation :
Optimization in simulation
(*real refrigerator in operation non available*)









High Pressure control optimization (IMC)

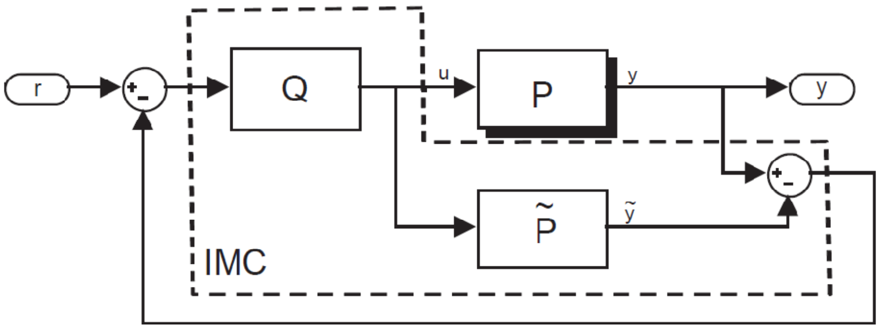
-IMC : « *Internal Model Control* »
-Model Synthesis
-Model uncertainties evaluations

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

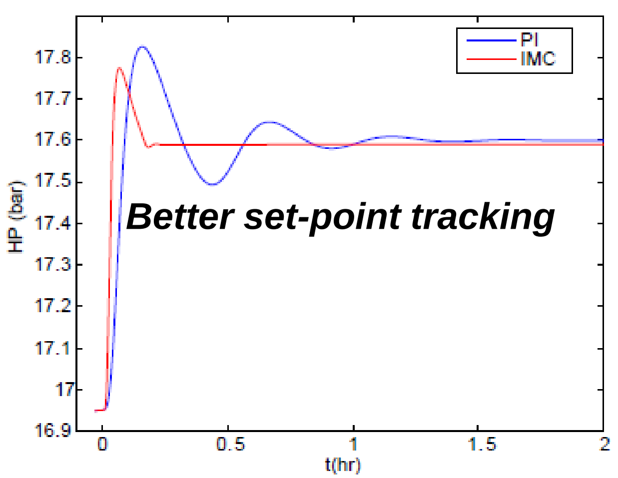
-Synthesis of the controller Q using a robust tunning

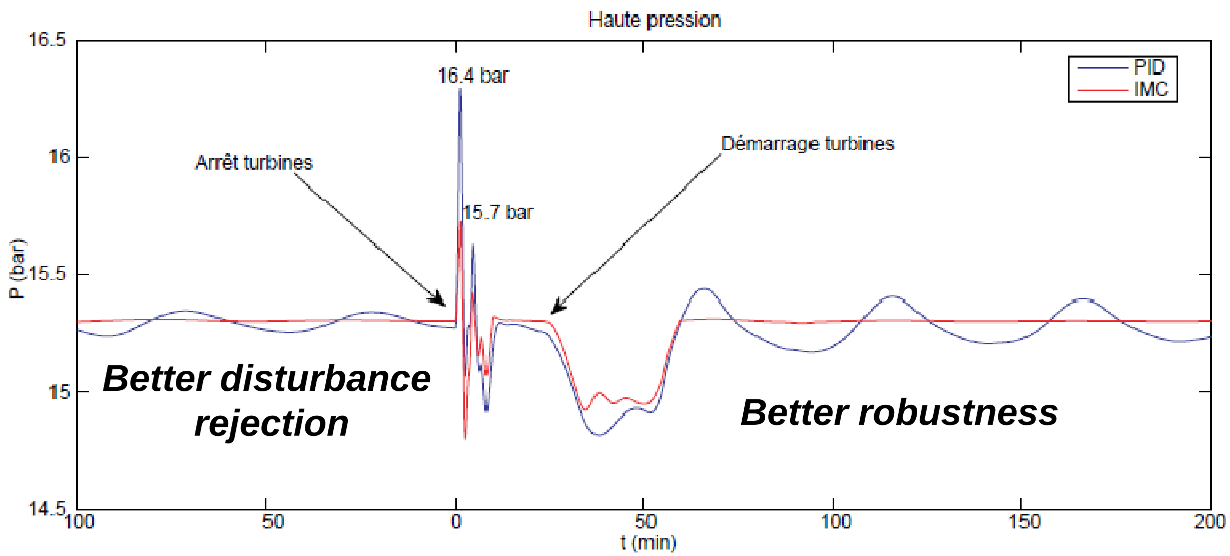
$$\min_{Q} \sup_{\omega} \left(|\eta \bar{l}m| + |\epsilon w| \right) \qquad \forall \omega \in \Re_{+}$$

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



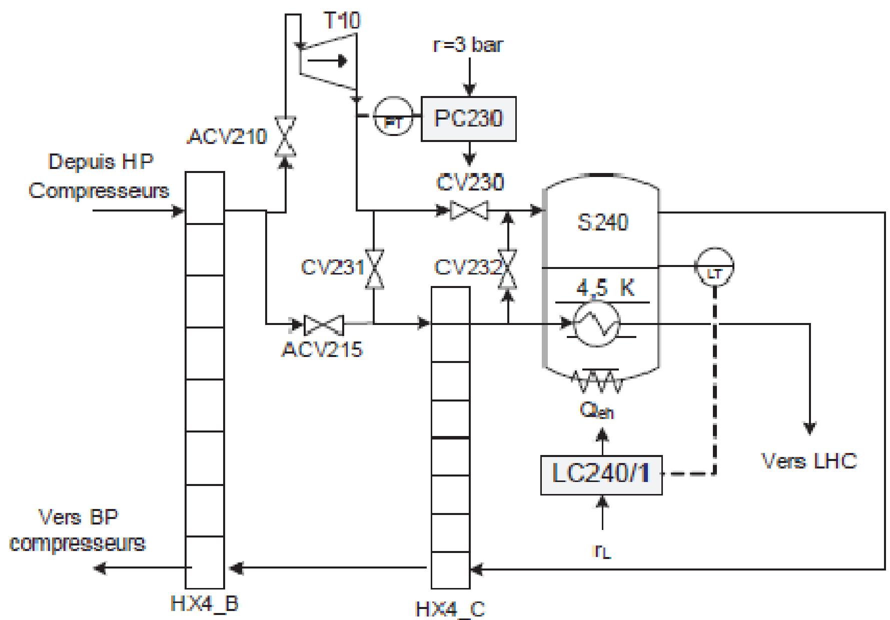
Simulation results:





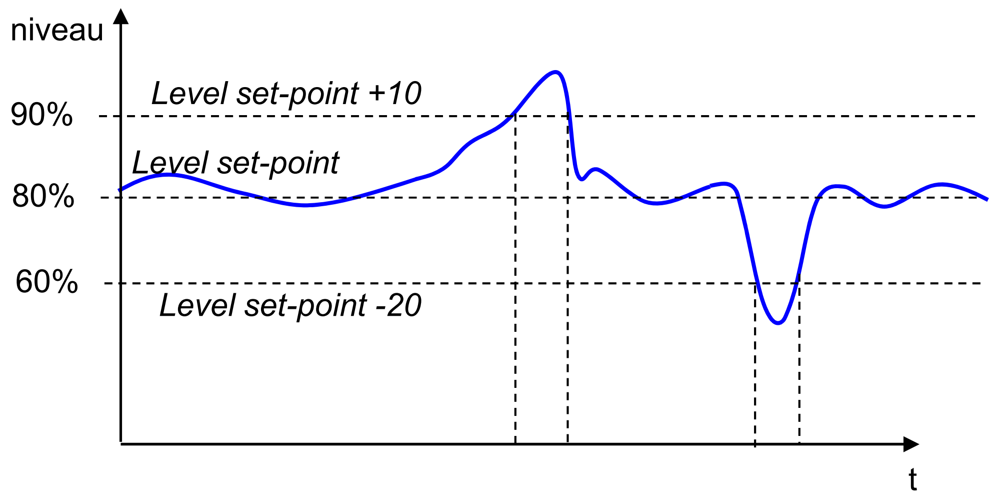
Floating pressure System

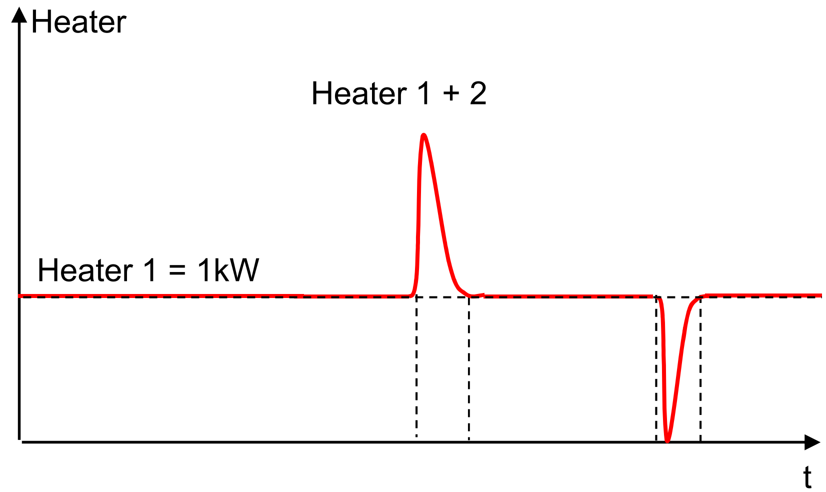
- High Pressure (HP) influences refrigeration power
  - ✓ Load adjusted with an electrical heater in the phase separator
- Floating Pressure system: Adaptation of HP and MP to loads applied to the refrigerator
  - ✓ Compressor flow rate decreases : Electrical consumption decreases
  - ✓ First tests in1994 on12kW @ 4.5 K refrigerators (LEP)
  - ✓ Manual or semi-automated management
- Automatic control system to fluctuate HP and MP
  - ✓ Objective : Stabilize the electrical heater at a desired value (ex : 1kW)

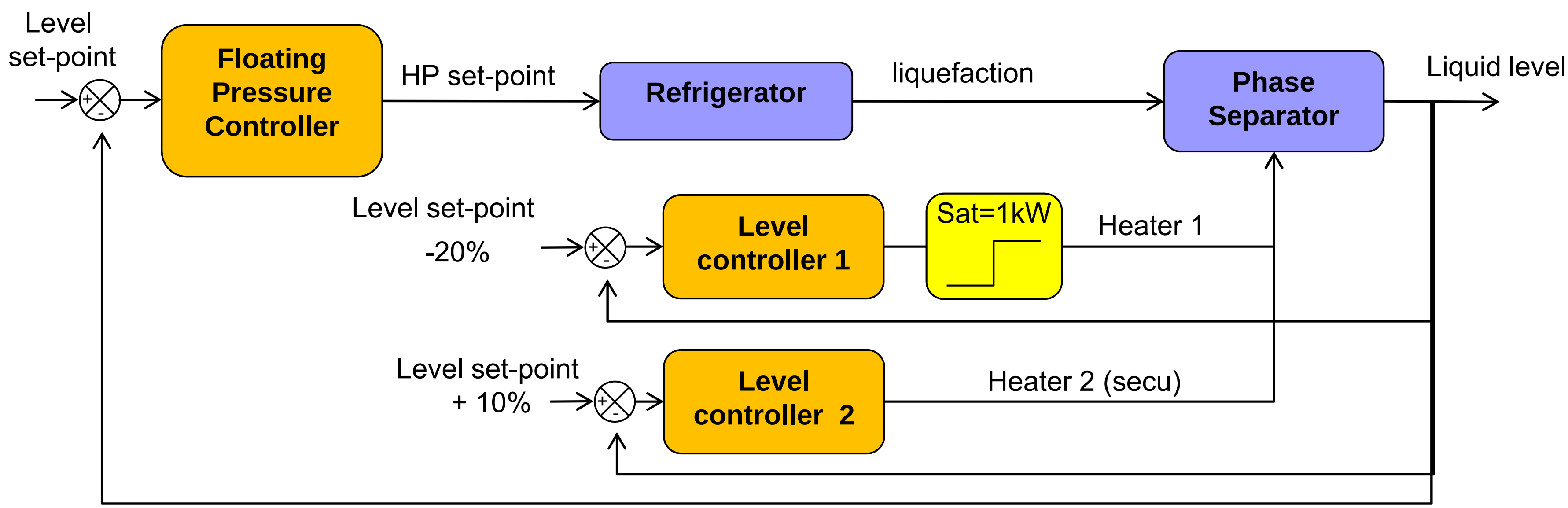


Floating Pressure approach

- Contrôle direct du niveau en pilotant la Haute Pression : Régulation Cascade



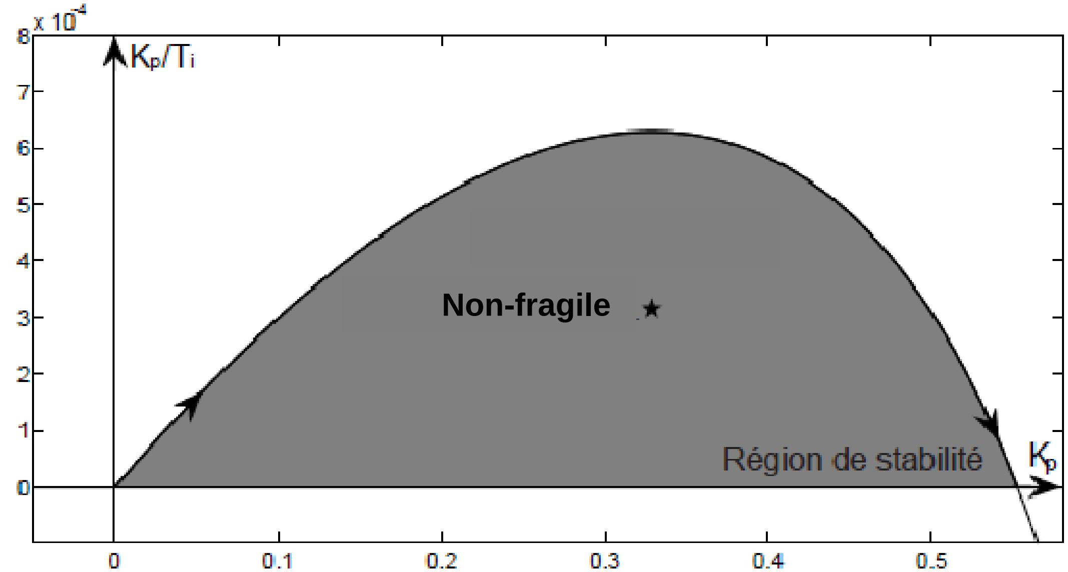




Non-Fragile PI tuning

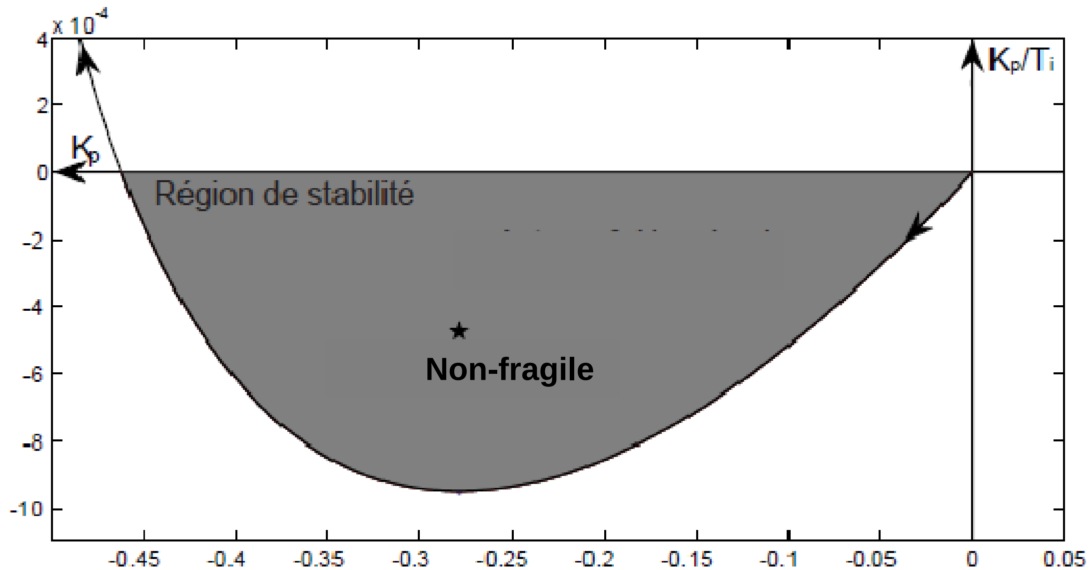
Floating Pressure controller (FPC)

$$G(s) = \frac{L}{r_{HP}} = \frac{0,01}{s(60s+1)} \cdot e^{-240s}$$

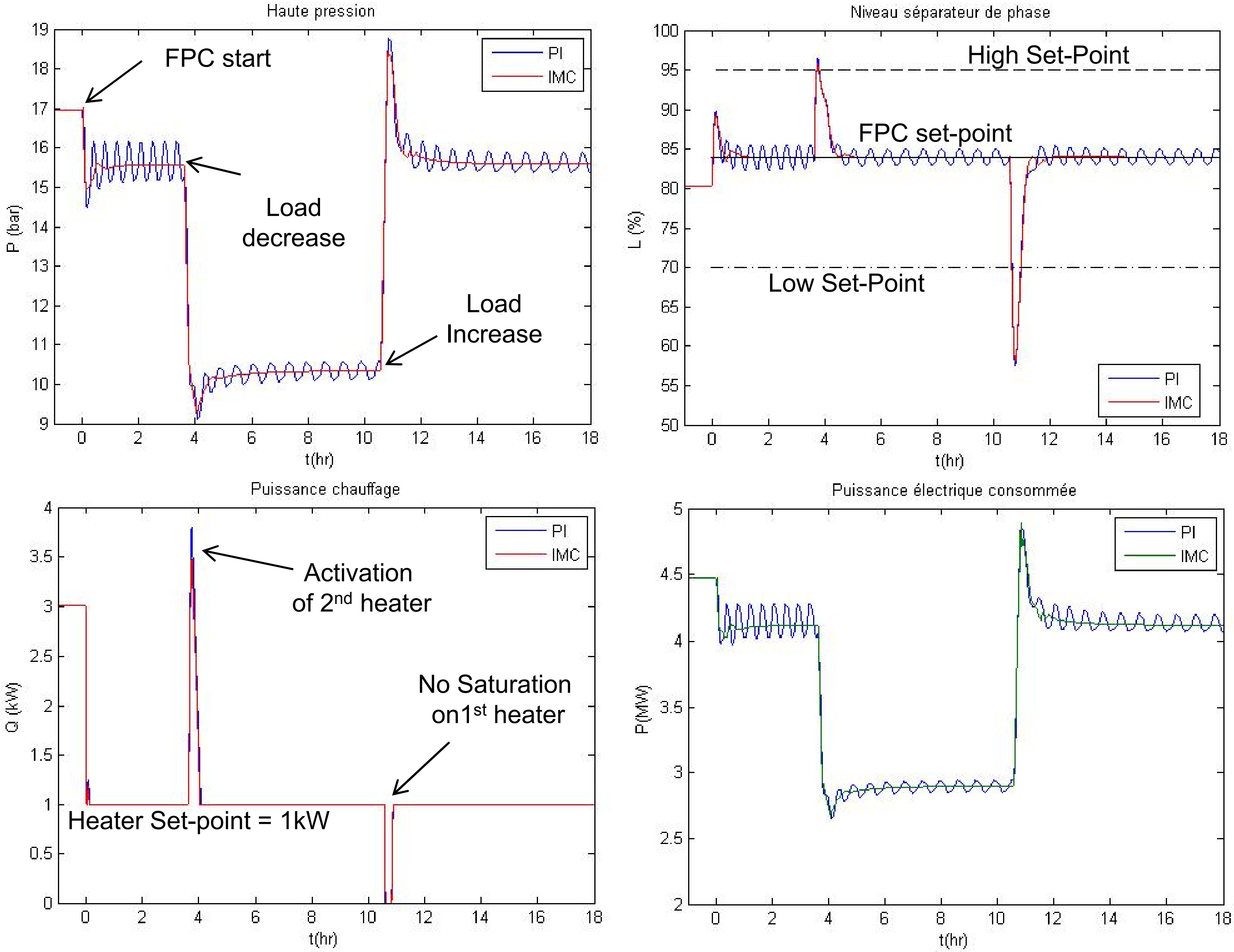


Level controllers (LC240/LC241)

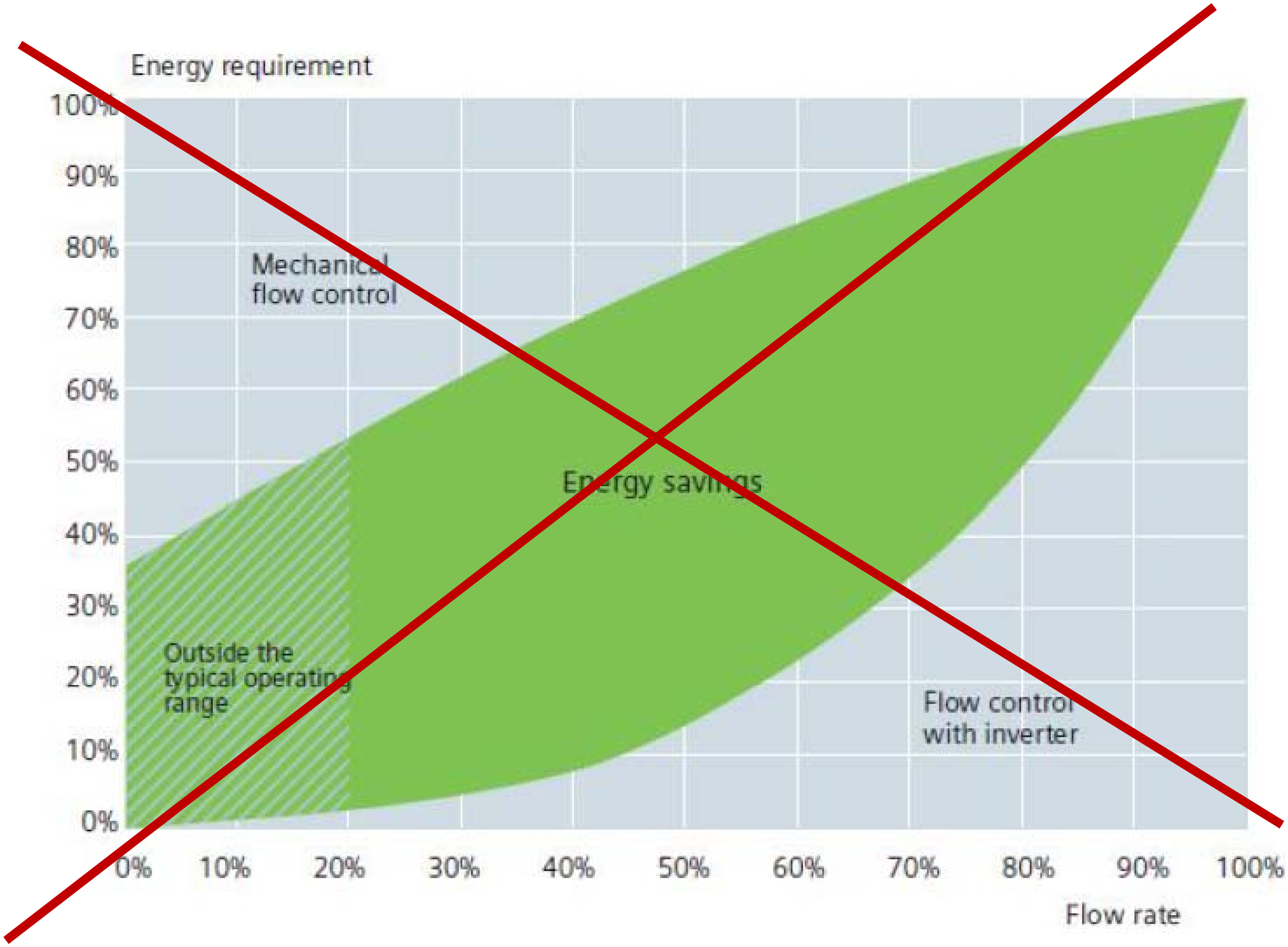
$$M(s) = \frac{L}{\dot{Q}_{eh}} = \frac{-0,022}{s} \cdot e^{-170s}$$



Simulation results



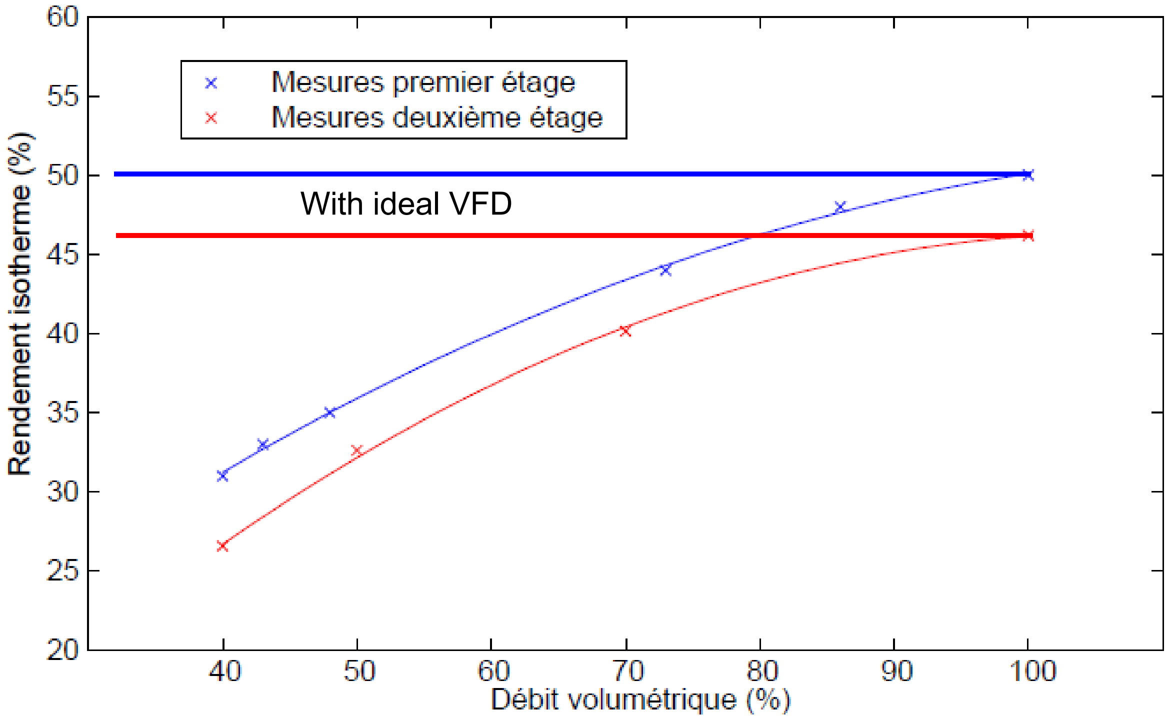
Variable-Frequency drive for compressors



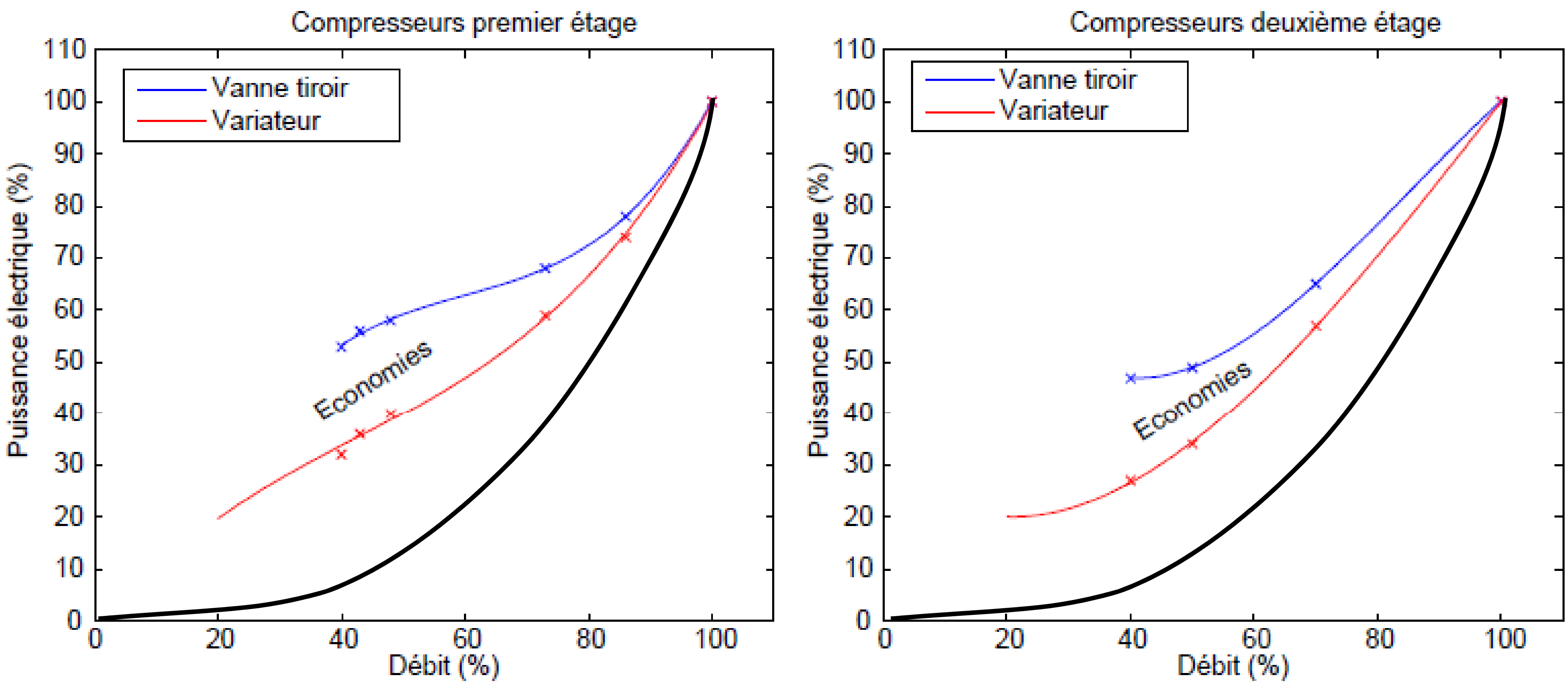
Variable-Frequency drive for compressors

$$P_{isoT} = \dot{m} \cdot \bar{R} \cdot T \cdot \ln\left(\frac{P_{out}}{P_{in}}\right)$$

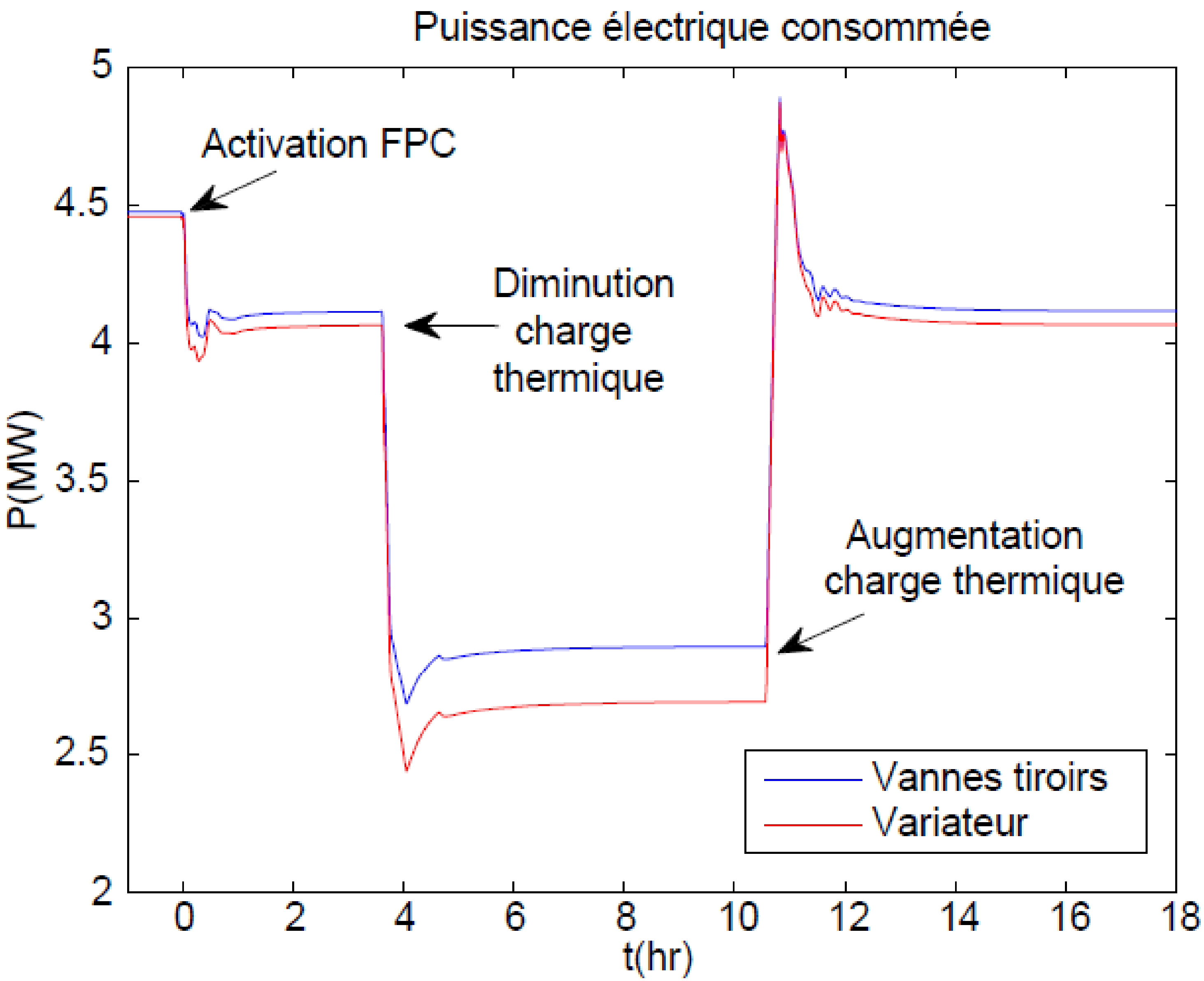
$$P = \frac{P_{isoT}}{\eta_{isoT}}$$



Variable-Frequency drive for compressors



VFD Vs slide valve during floating pressure



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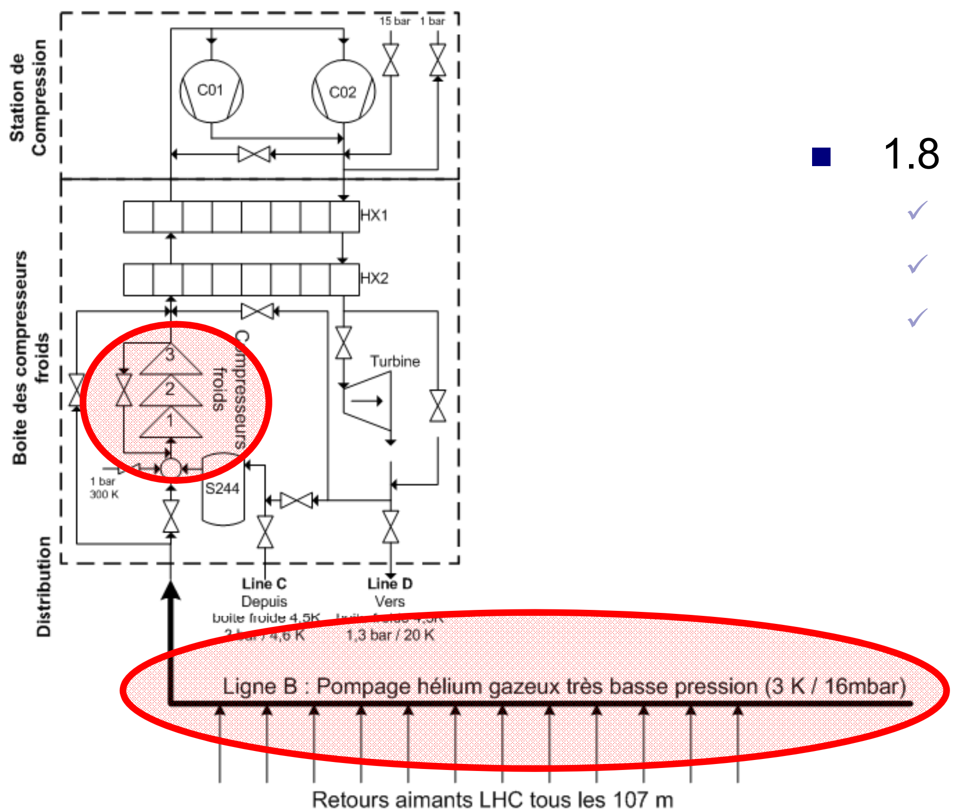
  - ✓ Cryogenic Distribution Line
- **Conclusion & Perspectives**

Large cryogenic systems at 1.8 K

- Cool-down dysphasic helium from 4.5 K to 1.8 K
  - ✓ Pumping on helium baths from 1 bar to 16 mbar

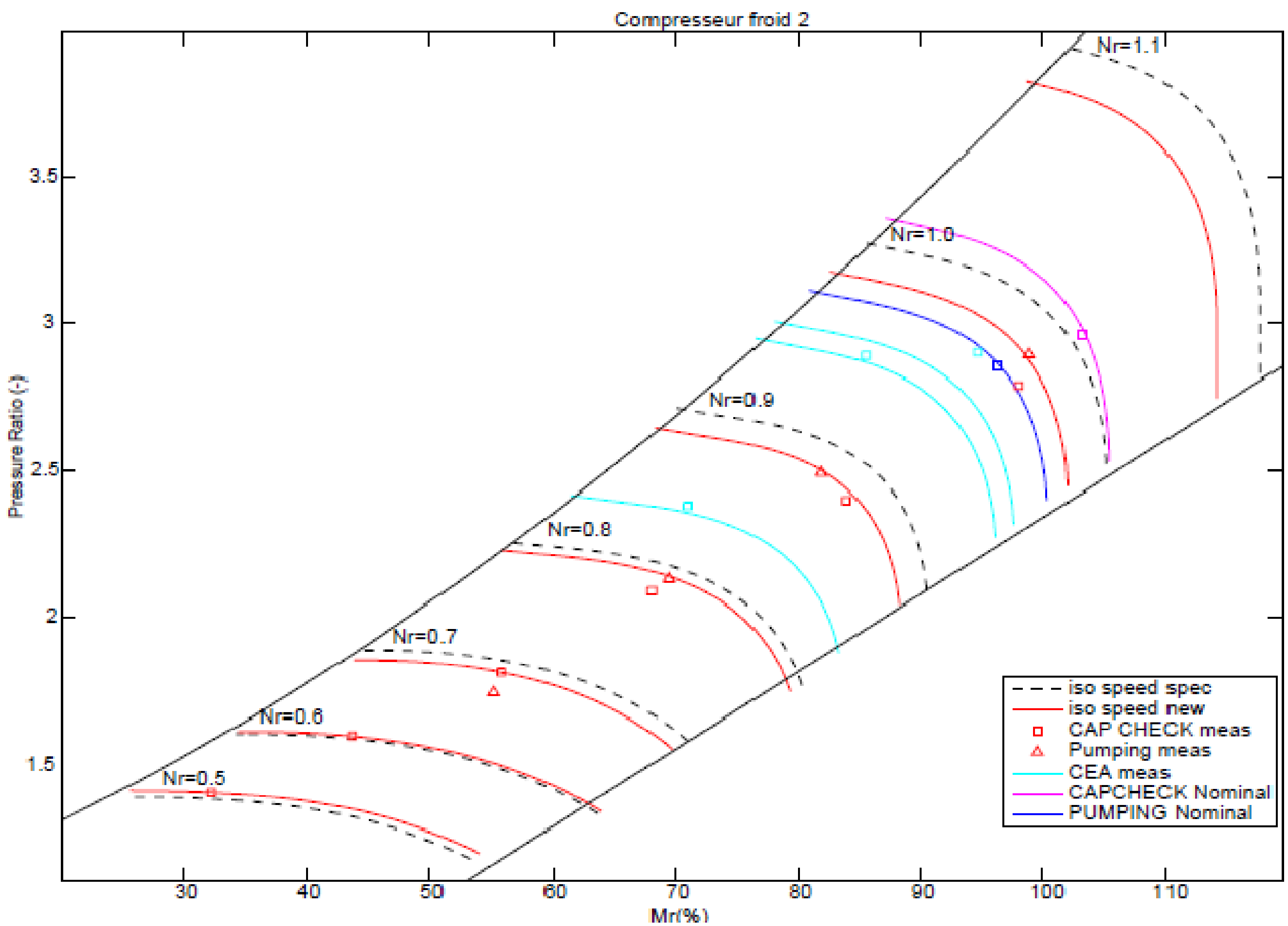
- Large cryogenic systems (pumping flow rate > 60 g/s for LHC)
  - ✓ Cold Compressors (helium at *4 K, compression ratio ~ 60*)
  - ✓ Pumping on long cryogenic lines (*3.3 km for the LHC*)



- 1.8 K refrigeration unit for the LHC
  - ✓ 2800 Algebraic equations
  - ✓ 210 Differential equations
  - ✓ Simulation speed during pumping : x80

Cold-Compressor : characteristic identification

- Cold compressor= hydraulic component
- Strict pressure field to respect: m = f(ratio pressure, speed)
- “Move” theoretical pressure field from measurements to fit real data



LHC cryogenic distribution line

- QRL : Transport cold helium along LHC
- Return Pumping Line (Line B)
  - ✓ Low pressure cold helium : 3 K /16 mbar

- Development of a dynamic model
  - ✓ Low pressure and temperature helium flow
  - ✓ Convection heat transfers
  - ✓ Interconnections every 107 m

- Euler equations:

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho \\ \vec{M} \\ E\end{bmatrix} + \vec{\nabla}\cdot\begin{bmatrix}\rho\cdot\vec{V} \\ \rho\cdot\vec{V}^T\otimes\vec{V} + P\cdot I \\ \rho\cdot\vec{V}\cdot\left(u+\frac{P}{\rho}\right)\end{bmatrix} = \begin{bmatrix}0 \\ 0 \\ \dot{q}\end{bmatrix}$$

- Simplification for QRL (PDE 1D) :

$$\frac{\partial X(x,t)}{\partial t} + F(X,t)\cdot\frac{\partial X(t)}{\partial x} = \dot{Q}(x,t)$$

with: $X = [\ \rho \quad M \quad E\ ]^T$

Jacobian calculation

Perfect GAZ

Equation of state:

$$u = Cv \cdot T$$

Pressure:

$$P = \rho \cdot R \cdot T = \rho \cdot u \cdot \frac{R}{Cv} = \rho \cdot u \cdot \hat{\gamma},$$

Sound speed:

$$c = \sqrt{\gamma R T} = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\gamma \hat{\gamma} (\frac{E}{\rho} - \frac{V^2}{2})}$$

Jacobian:

$$F = \begin{bmatrix} 0 & 1 & 0 \\ \frac{(\gamma-3)V^2}{2} & (3 \quad \gamma)V & \hat{\gamma} \\ \hat{\gamma}V^3 - \frac{\gamma V^3}{2} - \frac{c^2 V}{\hat{\gamma}} & \frac{\gamma V^2}{2} + \frac{c^2}{\hat{\gamma}} - \frac{3\hat{\gamma}V^2}{2} & \gamma V \end{bmatrix}$$

Eigen values:

$$\begin{cases} \lambda 1 = V + c \\ \lambda 2 = V \\ \lambda 3 - V - c. \end{cases}$$

Gaseous low pressure helium

Equation of state:

$$u = u_0 + Cv \cdot T$$

Pressure:

$$P = \rho \cdot \bar{R} \cdot T = \rho \cdot (u - u_0) \cdot \hat{\gamma}$$

Sound Speed:

$$c = \sqrt{\gamma \hat{\gamma} \left(\frac{E}{\rho} - \frac{V^2}{2} - u_0 \right)}$$

Jacobian:

$$F = \begin{bmatrix} 0 & 1 & 0 \\ \frac{(\gamma-3)V^2}{2} - u_0 \hat{\gamma} & (3 - \gamma)V & \hat{\gamma} \\ \hat{\gamma}V^3 - \frac{\gamma V^3}{2} - \gamma V u_0 - \frac{c^2 V}{\hat{\gamma}} & \frac{\gamma V^2}{2} + \gamma u_0 + \frac{c^2}{\hat{\gamma}} - \hat{\gamma}(\frac{3V^2}{2} + u_0) & \gamma V \end{bmatrix}$$

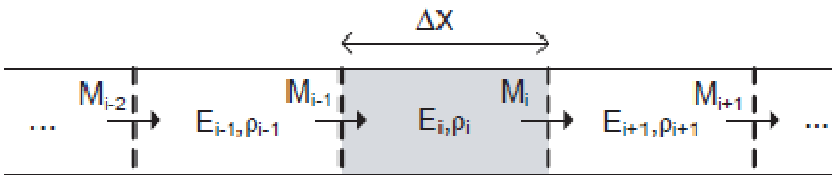
Eigen values :

$$\begin{cases} \lambda 1 = V + c \\ \lambda 2 = V \\ \lambda 3 - V - c. \end{cases}$$

Discretization

- Finite element method with an *upwind scheme*
  - ✓ Discretization according to the propagation direction
  - ✓ *Mass* and *energy* along the flow direction (transport)
  - ✓ *Momentum* on the **inverse** direction of the flow (pumping)

- Dirichlet boundary conditions:
  - ✓ Input density ρ(0,t)
  - ✓ Input energy E(0,t)
  - ✓ Output momentum M(L,t)



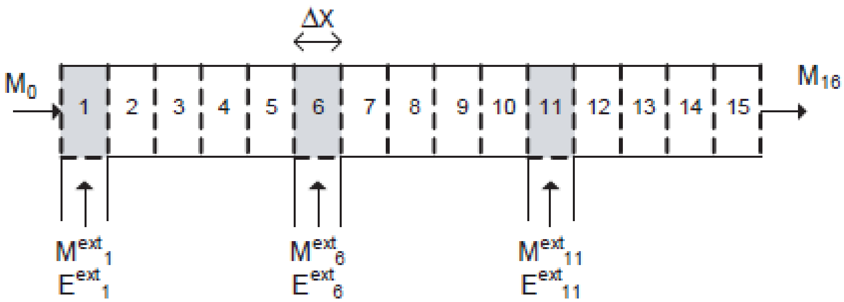
$$\dot{X}_i(t) + \frac{A_i(X_i)}{\Delta x} X_i(t) + \frac{B_i(X_i)}{\Delta x} X_{i-1}(t) + \frac{C_i(X_i)}{\Delta x} X_{i+1}(t) = Q_i(t)$$

- Implicit temporal discretization (backward Euler) :

$$\frac{\partial V_i}{\partial t} = \frac{V_i(t) - V_i(t-1)}{\Delta t}$$

Interconnections and heat transfers

- Interconnections every 107 m
  - ✓ Source term is augmented (mass, momentum and energy)

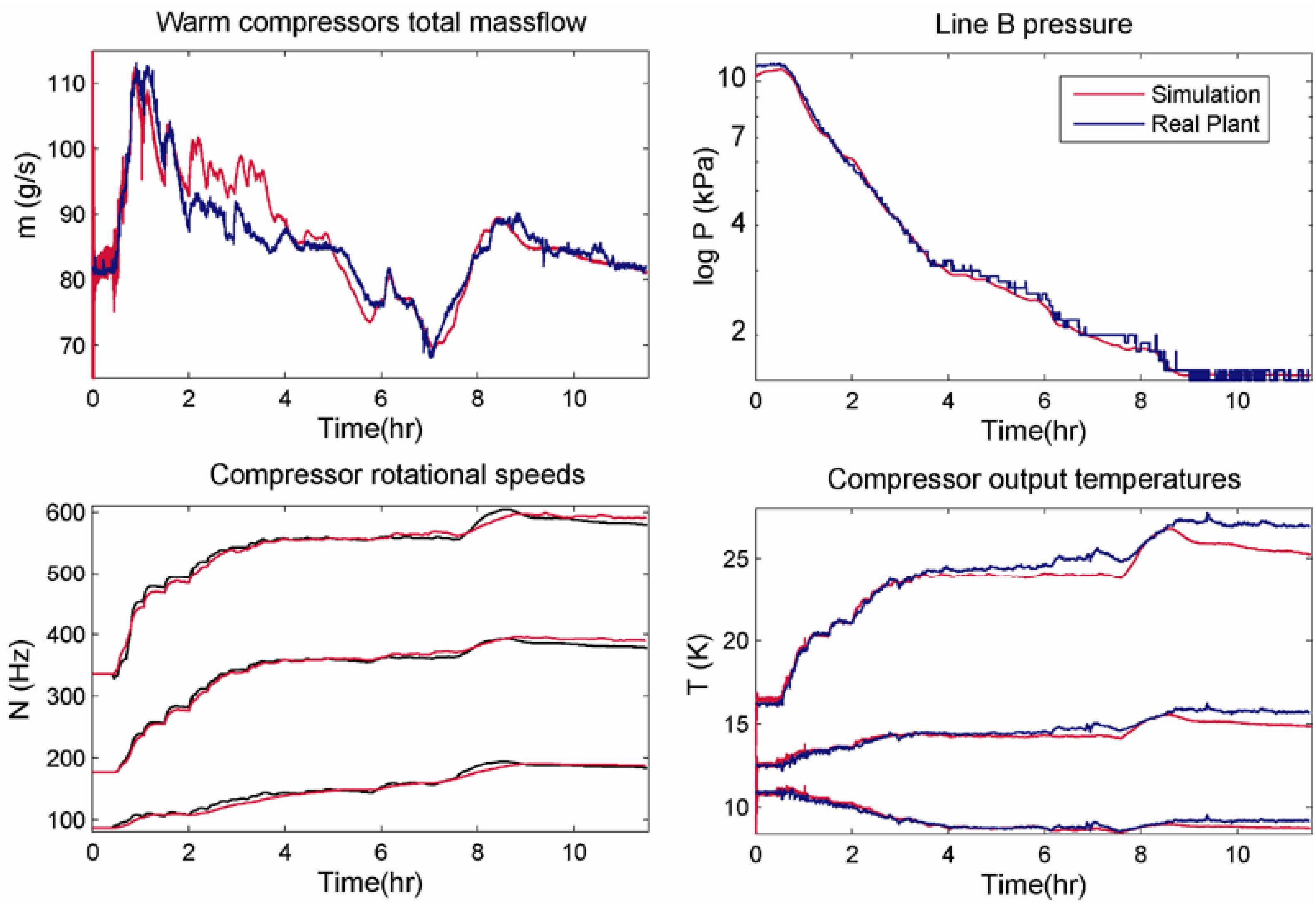


$$\dot{Q}_i = \begin{bmatrix} \frac{M_i^{ext}}{\Delta x} \\ (3-\gamma)V_i^{ext}\frac{M_i^{ext}}{\Delta x} \\ \dot{q}_i + \frac{\gamma E_i^{ext} M_i^{ext}}{\rho_i^{ext}.\Delta x} - (\gamma-1)(\frac{3V_i^{ext2}}{2} + u_0)\frac{M_i^{ext}}{\Delta x} \end{bmatrix}$$

- Heat transfers: $\dot{q} = \dot{q}_{const} + \dot{q}_{var}(t, \rho, M, E)$
  - ✓ Constant term (conduction, radiation) : 1,92 W/m^3 on line B
  - ✓ Variable term(convection) : $\dot{q}_{convi} = hc_i \cdot S_{wi} \cdot (T_{wi} - T_i) = M_{wi} \cdot Cp_{wi} \cdot \frac{dT_{wi}}{dt}$

Simulation of the final pumping

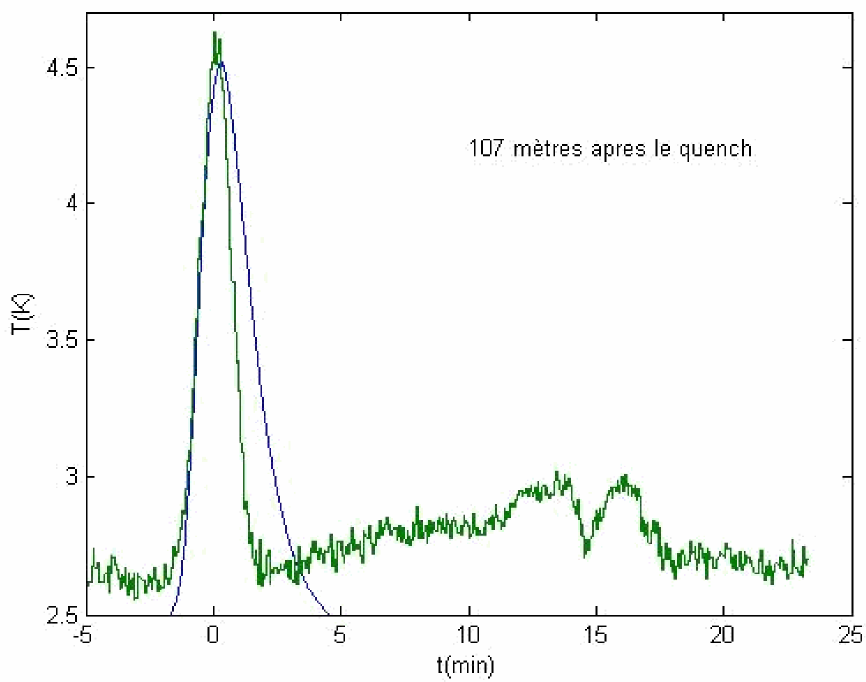
- Pumping between 100 mbar and16 mbar



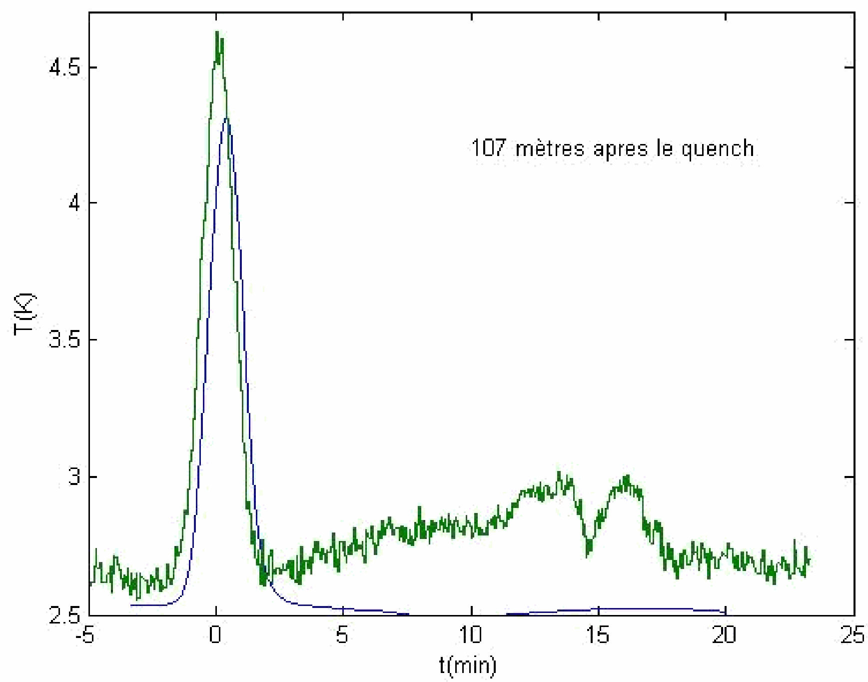
Simulation after a « *quench* »

- « *Quench* » : Resistive transition between the superconductor state and the resistive state:
  - ✓ Release a large amount of energy (heat)
- Simulation of the “heat wave” induced by a *quench* in the return pumping line
  - ✓ Comparison with a quench in the LHC sector 5-6 during hardware commissioning (May 2008)

Simulation with Δx=107m



Simulation with Δx=10,7m

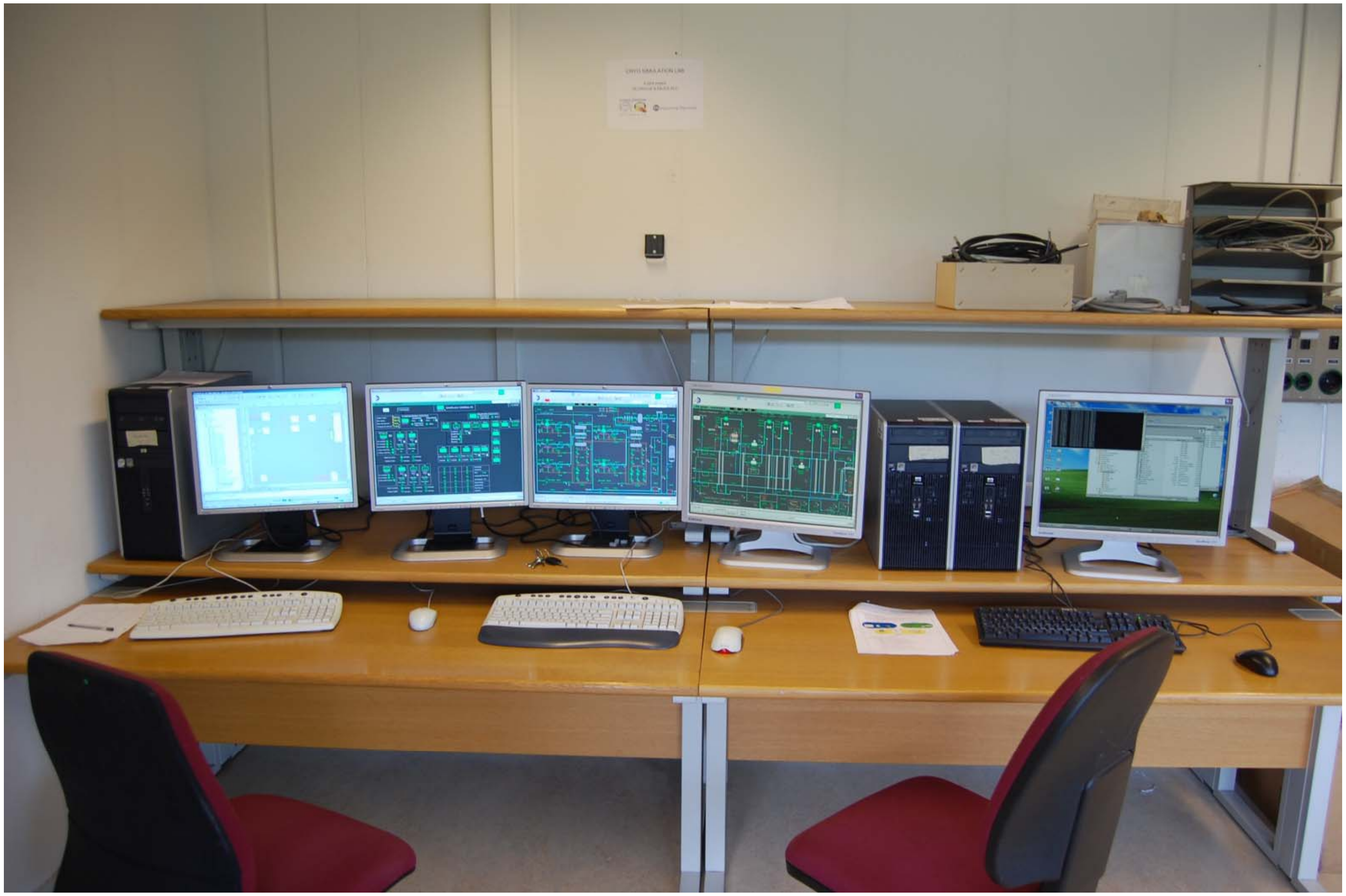


Contents

- **Introduction**
  - ✓ Motivations and state of art
- **Dynamic simulator for cryogenic systems**
  - ✓ Simulation and control architecture
  - ✓ Cryogenic Modeling
- **Simulations of cryogenic systems operating at 4.5 K**
  - ✓ CMS cryoplant
  - ✓ Central Helium Liquefier
  - ✓ LHC refrigerator
- **Simulation of LHC 1.8 K refrigeration units**
  - ✓ Cold compressors
  - ✓ Cryogenic Distribution Line
- **Conclusion & Perspectives**

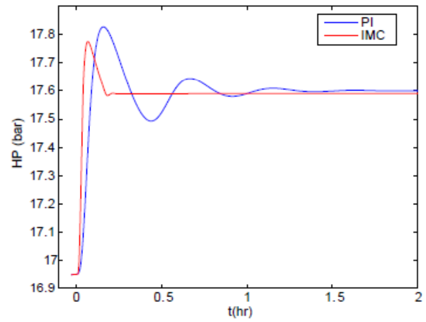
Main Contributions

- **A dynamic simulator for CERN cryogenic plants**
  - ✓ « *Cryo Simulation Lab* » available at CERN for TE-CRG (building 36)
  - ✓ « V*irtual commissioning » in collaboration with TE-CRG-CE (B163 & B165)*

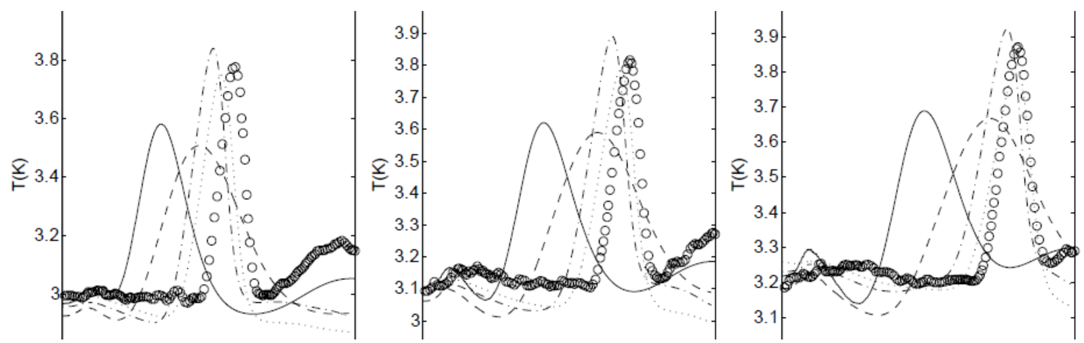


Main Contributions

- **Control Improvements**
  - ✓ Optimization of the High Pressure control on LHC refrigerators (IMC)
  - ✓ Development of a floating pressure control to reduce operational costs on LHC cryoplants



- **QRL model**
  - ✓ Dynamic model of low pressure helium flow in long pumping lines



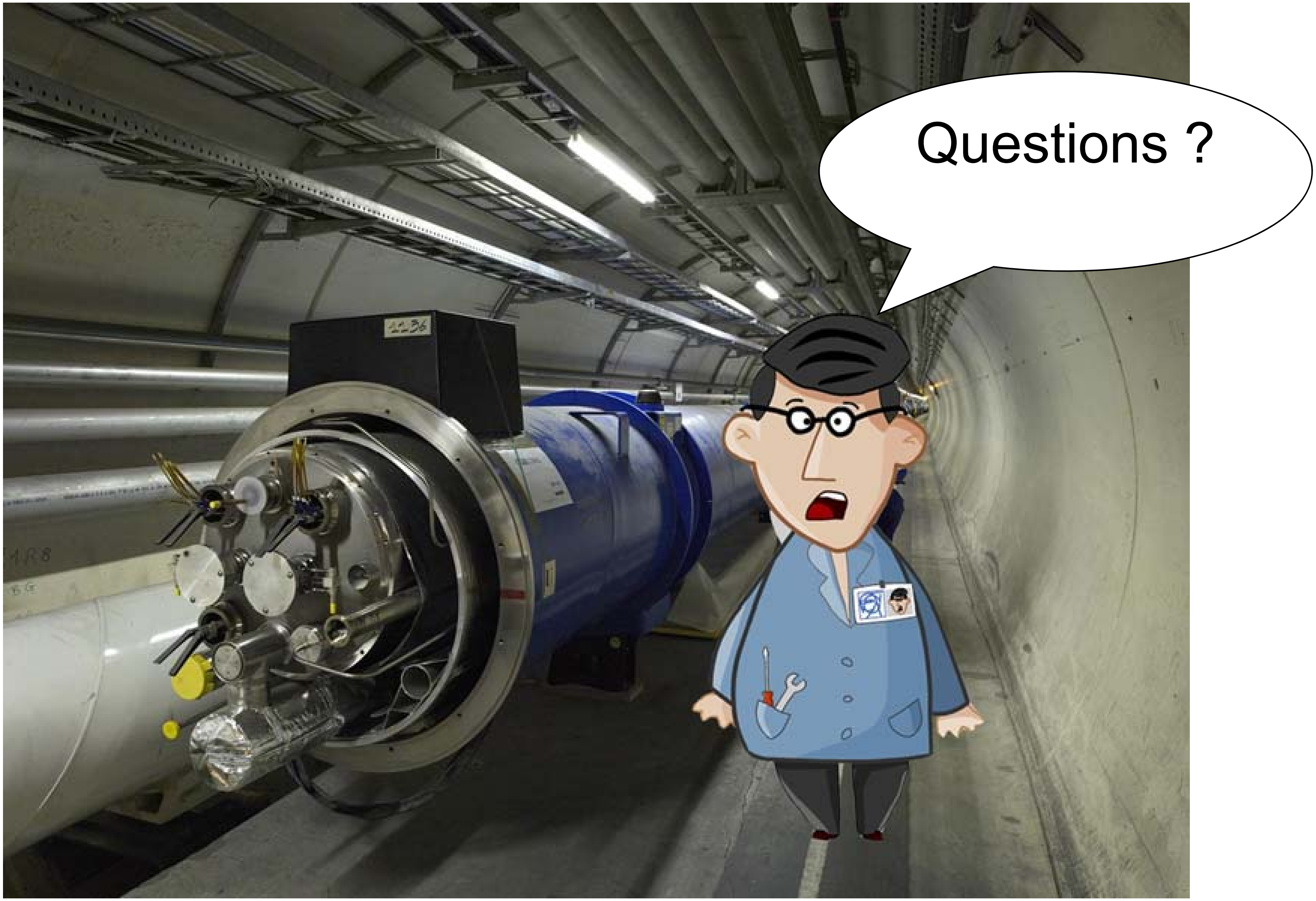
Perspectives

- Export simulator to other large cryogenic plants
  - ✓ Helium refrigerator @ 2 K for the XFEL project at DESY (*in discussion*)
  - ✓ Dynamic behavior during pulsed heat loads for tokamaks (ITER *?)*

- IMC and floating pressure control test on real LHC refrigerators
  - ✓ Possible windows in may/june 2010 ?
  - ✓ Speed variator study (*in discussion*)

- Extension of the « cryo » library to other industrial processes
  - ✓ Water cooling (*already done for STP18*)
  - ✓ Electronic cooling for detectors ($C0_2$, C_6F_{14} …)
  - ✓ LHC ventilation systems

Thank you for your attention



Cryo Simulation Lab