CHATS on Applied Superconductivity 2011

Modeling and simulation of cryogenic processes using EcosimPro

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Contents

Introduction

- Cryogenic process simulation
  - ✓ Applied to cryogenic plants (large or small scale)
  - ✓ Macroscopic simulation (0D or 1D)

- Dynamic process simulations embed:
  - ✓ Actuators (valves, turbines, compressors…)
  - ✓ Passive components (HX, pipes, cold mass…)
  - ✓ Simulation of main process variables (P,T,m,x)

Why cryogenic process simulation ?

- **Interest on dynamic simulations on cryogenic processes increased a lot**
  - More than 20 papers published in the 5 last years (almost 0 before)
  - Computation power available with sophisticated tools
  - Pulsed load on superconducting tokamaks (EAST, ITER, JT60SA, KSTAR)
  - Energetic costs of very large cryoplants

- **Dynamic cryogenic process simulations are a good tool for :**
  - Validate/check process behaviors during transients
    - Anticipate transient responses
  - Test new control strategies without disturbing real operation
    - Improve stability and energy consumption
  - Train operators safely and in degraded conditions
    - Improve long-term operation
  - Virtual Commissioning: Validate control and supervision systems in simulation
    - Improve installation time and minimize commissioning risks

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- Example of component modeling: Super critical helium flow
  - LHC beam screens
- Example of large-scale modeling: LHC cryoplant
  - 4.5 K refrigerator
- Conclusion

EcosimPro

- **EcosimPro**: Commercial modeling & Simulation software
  - ✓ Modeling with a non causal object-oriented language (EL language)
  - ✓ Convivial GUI to build complex systems

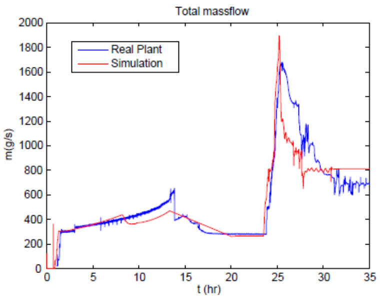
- Modeling of 0D / 1D multidisciplinary continuous-discreet systems
  - ✓ Steady-State computations
  - ✓ Parametrical studies
  - ✓ Dynamic simulations

- Based on Differential Algebraic Equations (DAE)
  - ✓ 0D Thermo-hydraulic systems well described with DAE
  - ✓ Need spatial discretization for 1D systems

- Numerical Solvers
  - ✓ Linear systems with constant coefficients
  - ✓ Linear algebraic sub-systems
  - ✓ Non-Linear algebraic sub-systems (iterative tearing technique)
  - ✓ DAE systems: DASSL Solver (finite difference + NR)

From Modeling to Simulation

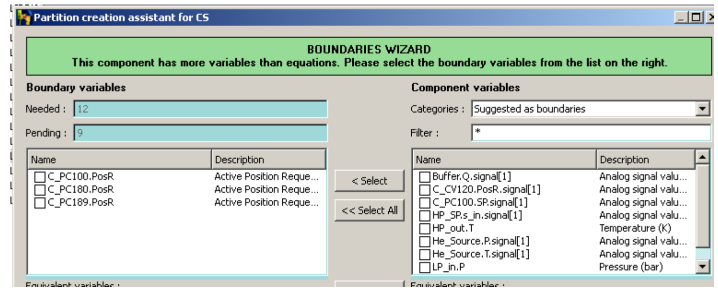
Simulations



Experiment definition

```
BOUNDS

  Circuit1.RFQ_PC0002.SP.signal[1] = 0.2 + 0.1*step(TIME,1000)
  Circuit1.RFQ_TC0002.SP.signal[1] = 25
  Circuit1.RFQ_TC0003.SP.signal[1] = 25.5

BODY

--Circuit1
Circuit1.RFQ_P0001DO.s_in.signal[1] = TRUE AFTER TSTART
Circuit1.RFQ_PC0002.TR_S = FALSE AFTER TSTART
Circuit1.RFQ_TC0002.TR_S = FALSE AFTER TSTART+100
Circuit1.RFQ_TC0003.TR_S = FALSE AFTER TSTART+100
Circuit1.RFQ_VMA0002DO.s_in.signal[1] = TRUE AFTER TSTART+10
Circuit1.RFQ_VMA0002DO.s_in.signal[1] = FALSE AFTER TSTART+50
```

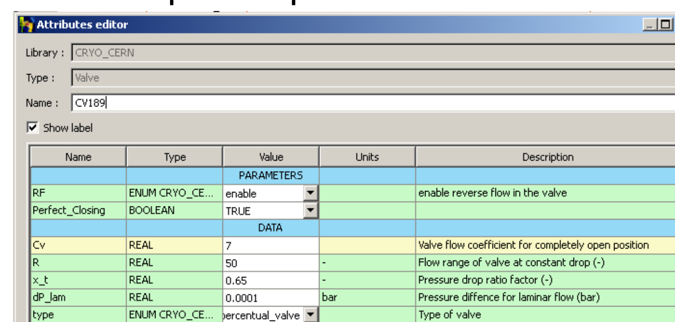
Boundary conditions



Component Modeling

```
Cpw = Cp_vs_mat_T(mat,Tw)
row = ro_vs_mat(mat)

--Mass Balance
M' = f_in.m - f_out.m

-- Energy Balance
M*u'+u*M' = f_in.m*f_in.h - f_out.m*f_out.h + hc*Sw*(Tw-T) + Qrad

--radiation losses
Qrad = C*(T_amb**4 - Tw**4)

--Wall energy balance
Mw*Cpw*Tw' = -hc*Sw*(Tw-T)
```

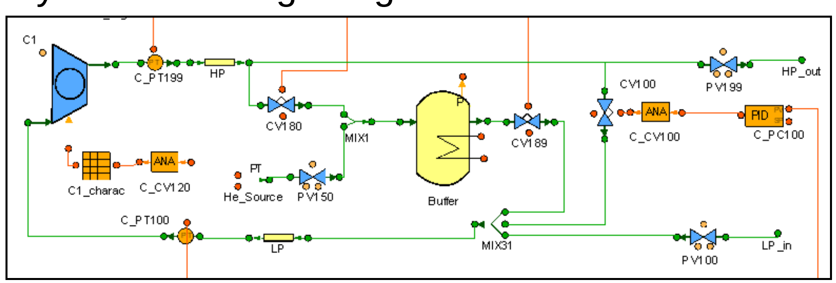
Component parameterization



Schematic creation

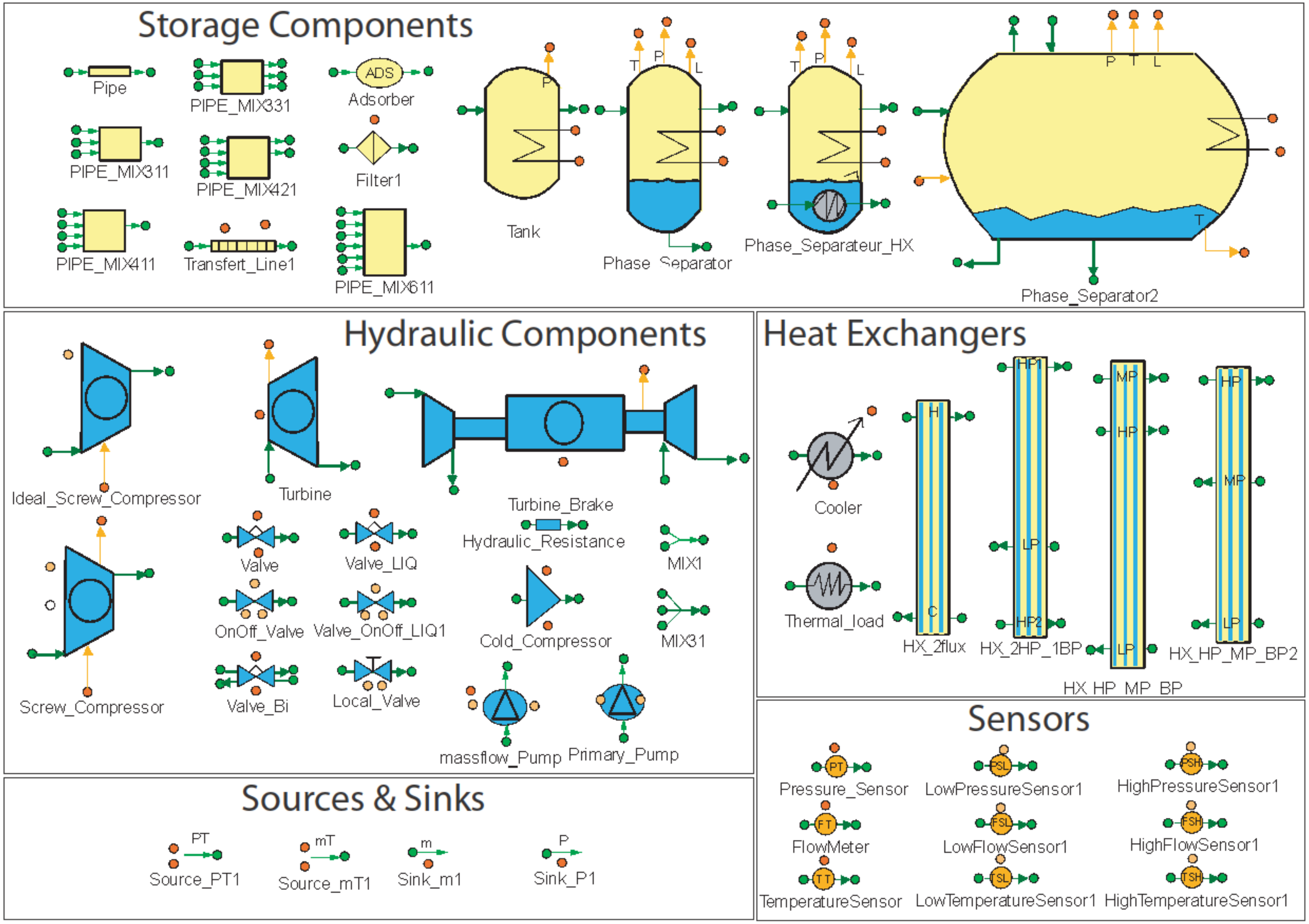
Pipe

System Modeling using libraries



All libraries are entirely opened ant it is very to see which equations are used to modify them if necessary

CERN Cryogenic library



Equations or materials can be easily added to the library according to user requirements

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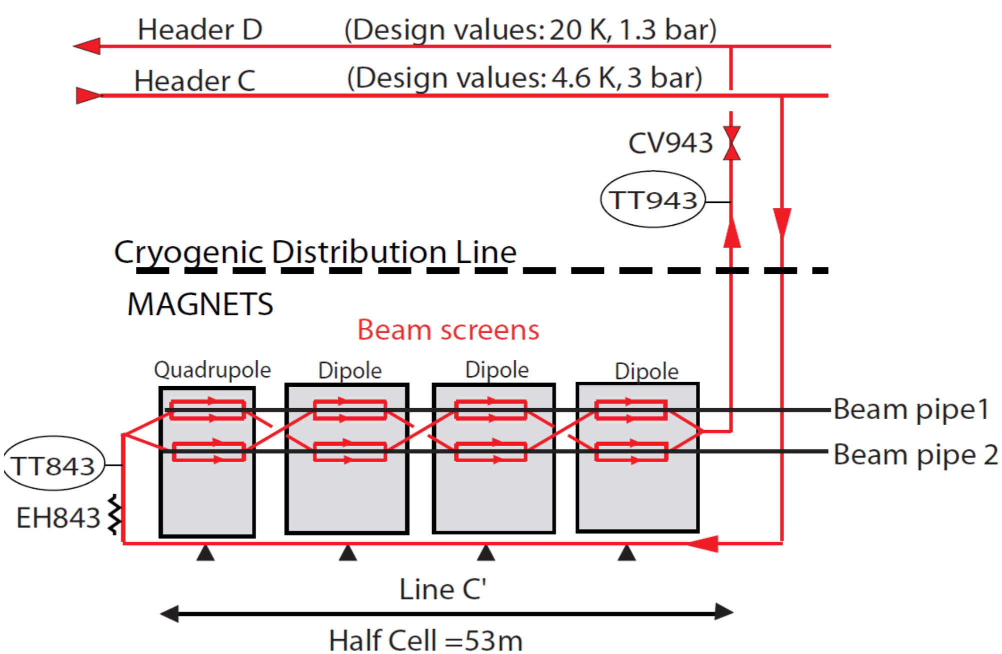
Modeling Example: LHC Beam Screens

- LHC beam screens
  - ✓ Minimize heat loads, remove resistive wall power losses and intercept synchrotron radiation/molecules
  - ✓ Supercritical helium flow at 3 bar from 4.6K to 20K
  - ✓ 2 cooling tubes of 53m long / 3.7mm diameter

- Modeling based on 1D Euler equations (3 PDE)



$$\frac{\partial \rho}{\partial t} + \frac{\partial M}{\partial x} = 0$$

$$\frac{\partial M}{\partial t} + \frac{\partial P}{\partial x} + \frac{fr}{2D\rho} \cdot M^2 - \frac{\rho g z}{100} = 0$$

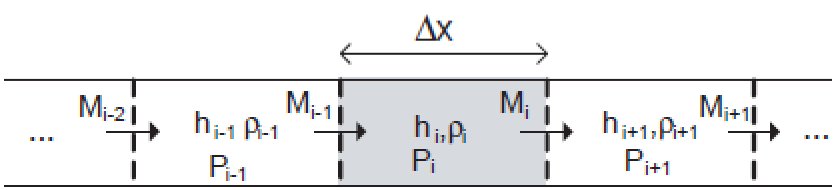
$$\rho \cdot \frac{\partial h}{\partial t} + M \cdot \frac{\partial h}{\partial x} = \frac{q}{V}$$

Modeling of supercritical helium flow

- Simulation for general cooling behavior
  - Neglect momentum fast dynamics: friction term (Haaland) + gravity

$$M = \sqrt{\left(\frac{\partial P}{\partial x} - \frac{\rho g z}{100}\right) \cdot \frac{2D\rho}{fr}} \qquad fr = \frac{1}{\left[1.8 \cdot \log_{10}\left(\left(\frac{\epsilon}{3.7D}\right)^{0.11} + \frac{6.9}{Re}\right)\right]^2}$$

- Spatial discretization in *N* nodes (1st order finite difference)
  - ✓ Obtain *3*N* DAEs directly integrated in EcosimPro



$$\rho_i' + \frac{\Delta M_i}{\Delta x} = 0$$

$$M_i = \sqrt{\left(\frac{\Delta P_i}{\Delta x} - \frac{\rho_i g z_i}{100}\right) \cdot \frac{2D\rho_i}{fr_i}}$$

$$\rho_i \cdot h_i' + M_i \cdot \frac{\Delta h_i}{\Delta x} = \frac{q_i}{V_i}$$

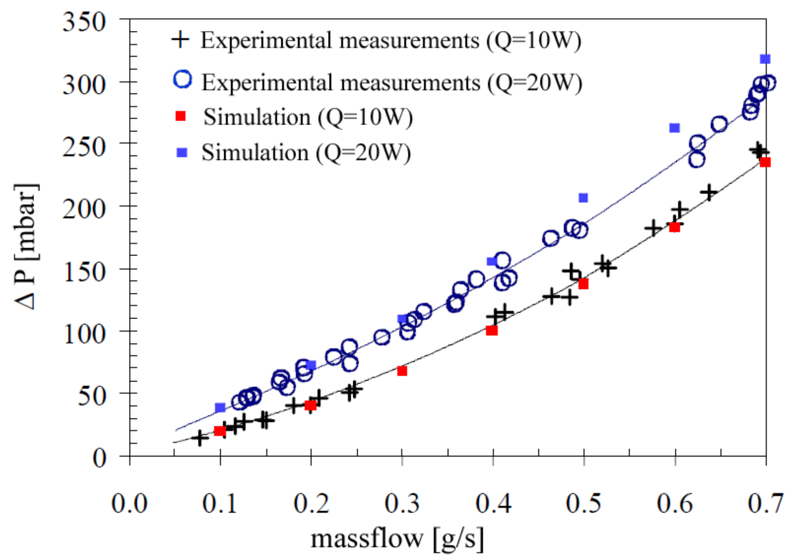
- Thermodynamic and material properties computed from cryogenic library (HEPAK for helium)
  - k_i, P_i, Pr_i, T_i, μ_i of helium from ρ_i and h_i
  - Cpw_i of stainless steel 304L from temperature

Modeling of Heat Transfer

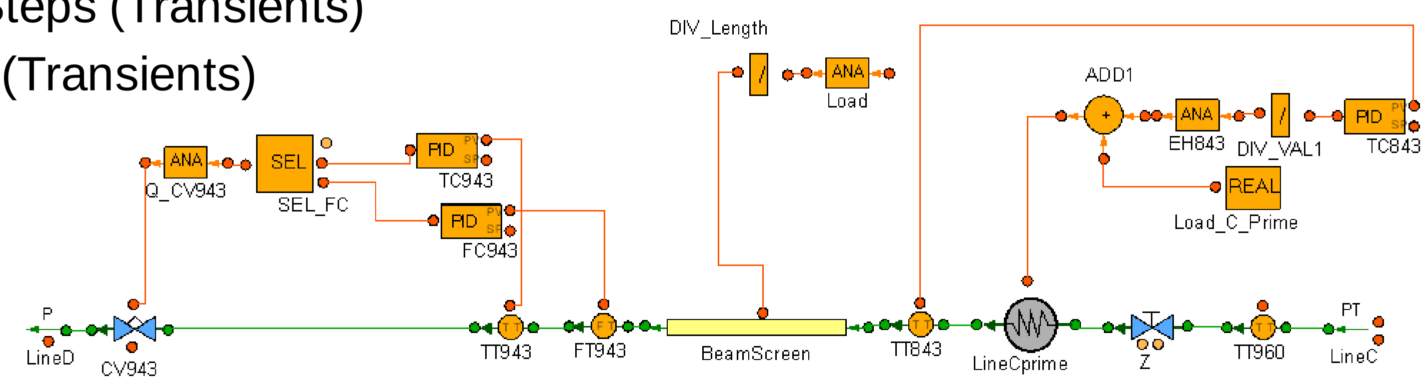
- Total heat applied to the fluid
  - ✓ *N* algebraic equations $q_i = hc_i \cdot Sw_i \cdot (Tw_i - T_i) + Q_{lin} \cdot \Delta x$
- Energy balance between fluid and beam screen
  - ✓ *N* DAEs $(Mw_i + Mc_i) \cdot Cpw_i \cdot Tw_i' = -hc_i \cdot Sw_i \cdot (Tw_i - T_i)$
- Heat transfer coefficient from Colburn equation
  - ✓ *2*N* algebraic equations $hc_i = Nu_i \cdot \frac{k_i}{D}$ $Nu_i = 0.023 \cdot Pr_i^{1/3} \cdot Re^{0.8}$
- In Total : 3*N DAEs + 5*N algebraic equations
- Boundary conditions
  - ✓ Inlet enthalpy, density, Momentum: h_0 ρ_0 M_0
  - ✓ Outlet momentum: M_N
  - ✓ Lineal heat load: Q_{lin}

LHC Beam screens in EcosimPro

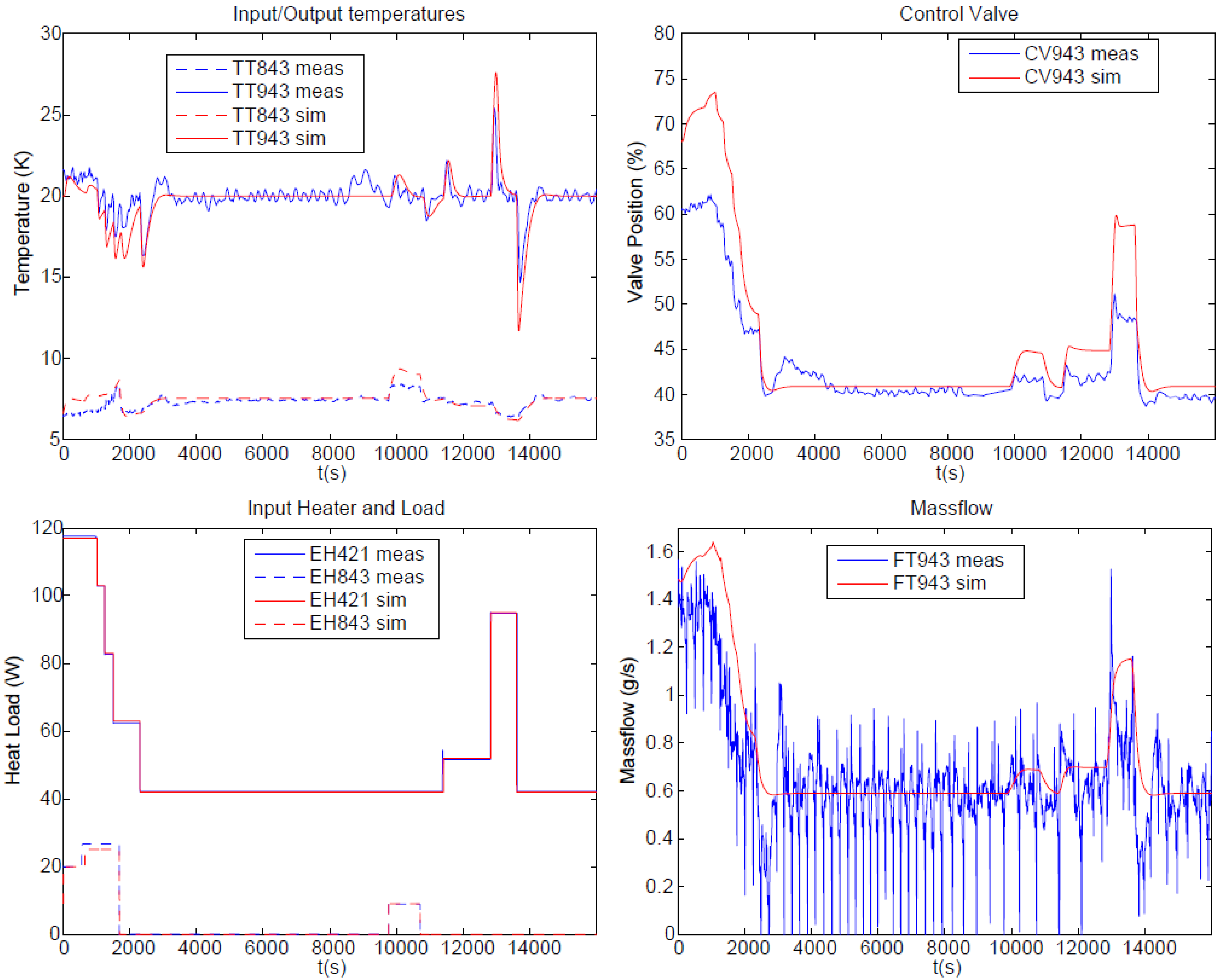
- Integration of the supercritical helium line inside a schematic with other existing components



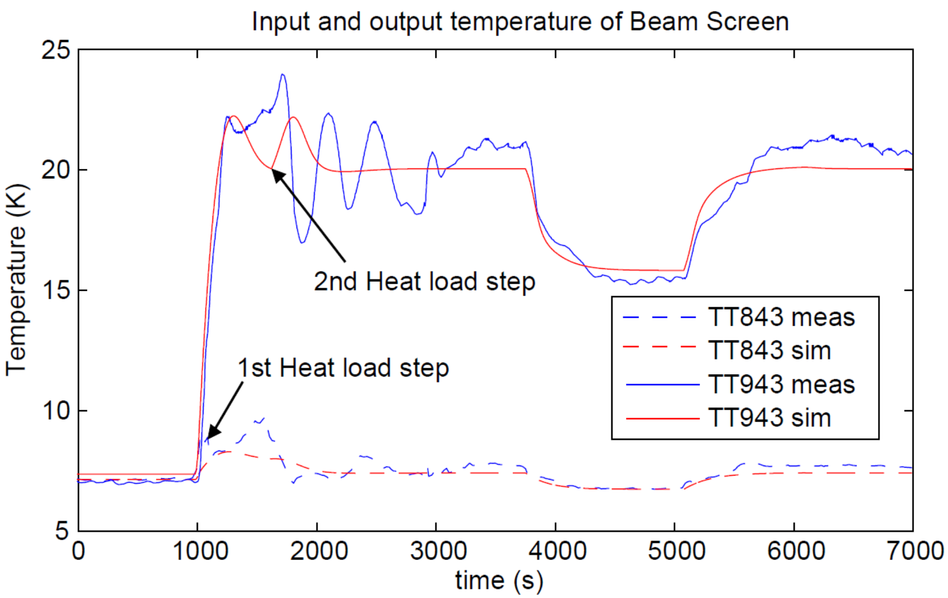
- Boundary conditions
  - ✓ Line C : 3 bar / 5.6 K
  - ✓ Line D : 1.2 bar
  - ✓ Heat load varying
- Simulation Vs Measurements on LHC String2 (2002)
  - ✓ Pressure Drop (Steady-Sate)
  - ✓ Heat Load Steps (Transients)
  - ✓ Valve steps (Transients)

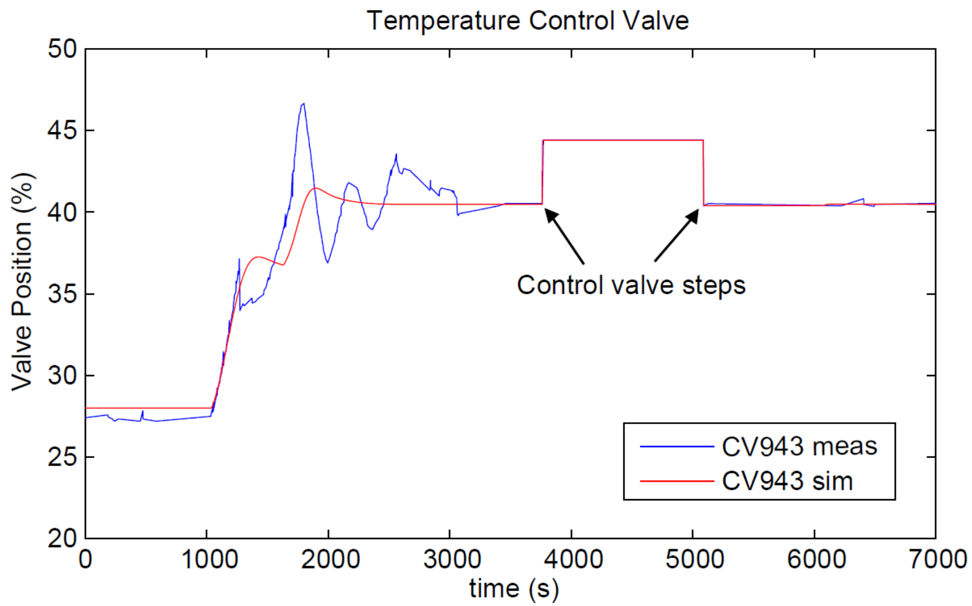


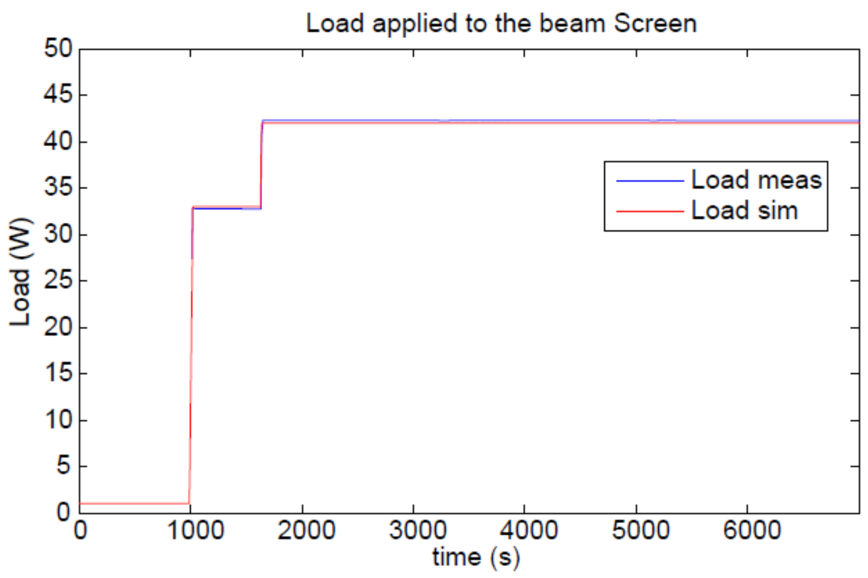
Simulation Results(1/2)

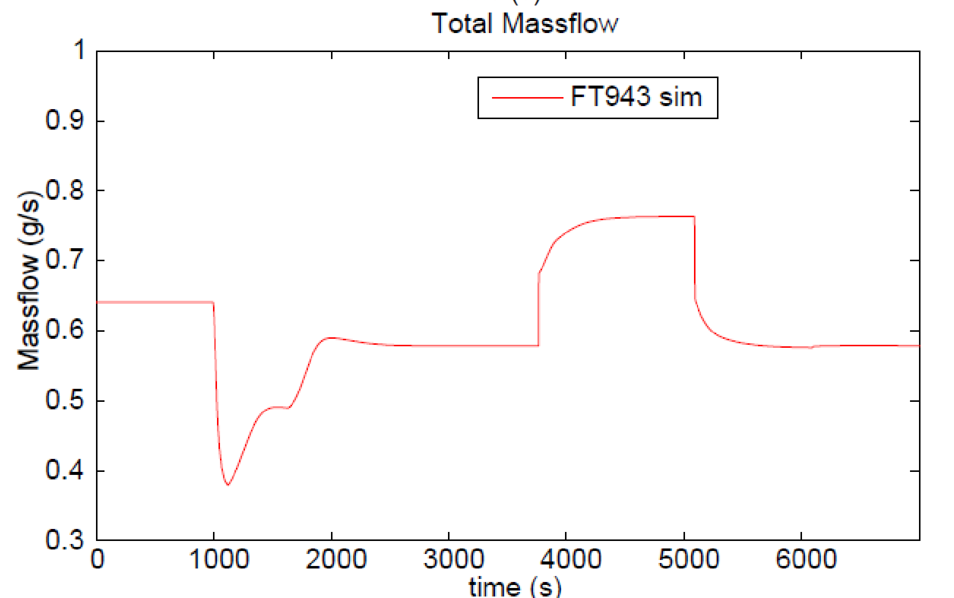


Simulation Results (2/2)









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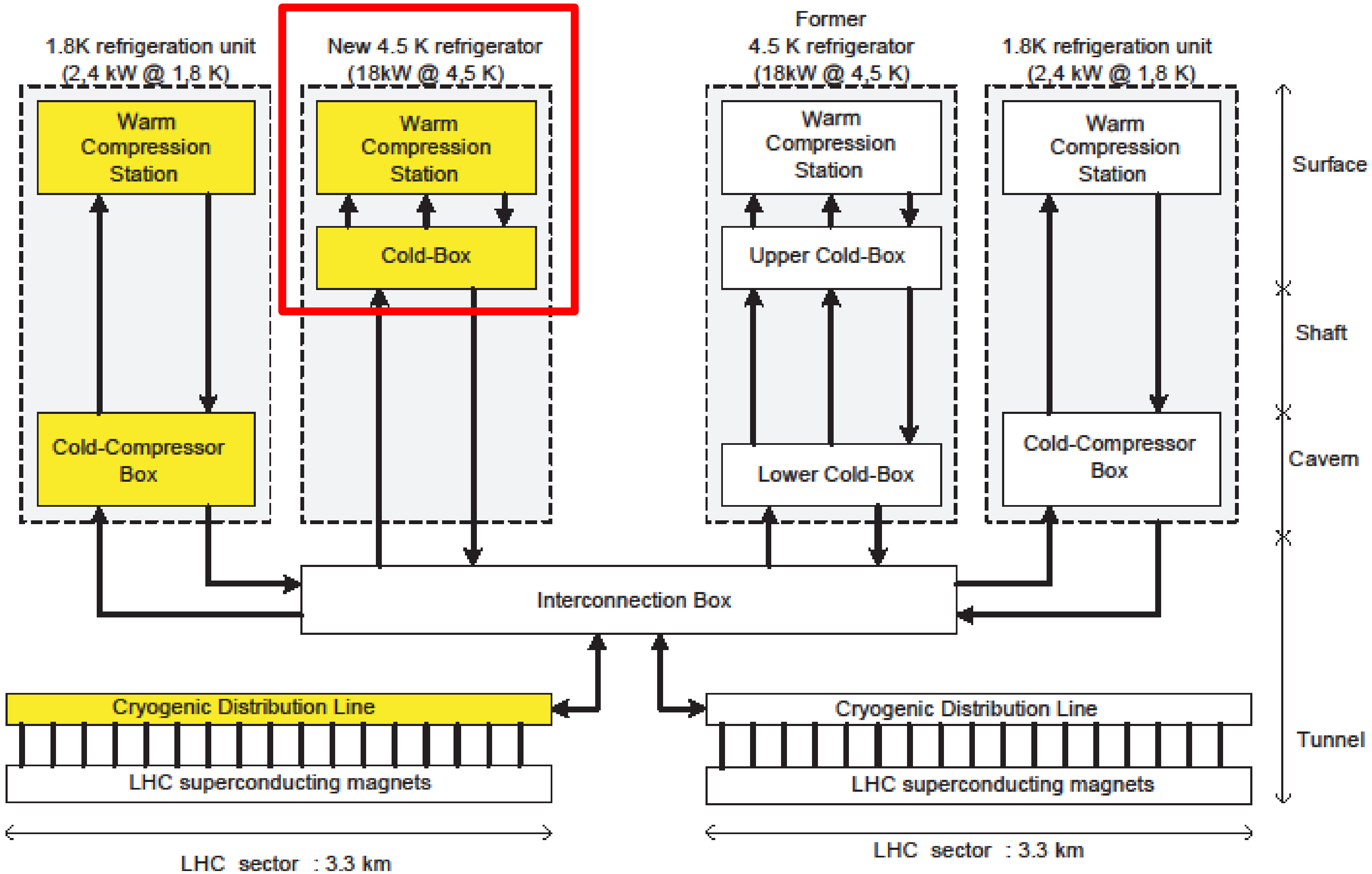
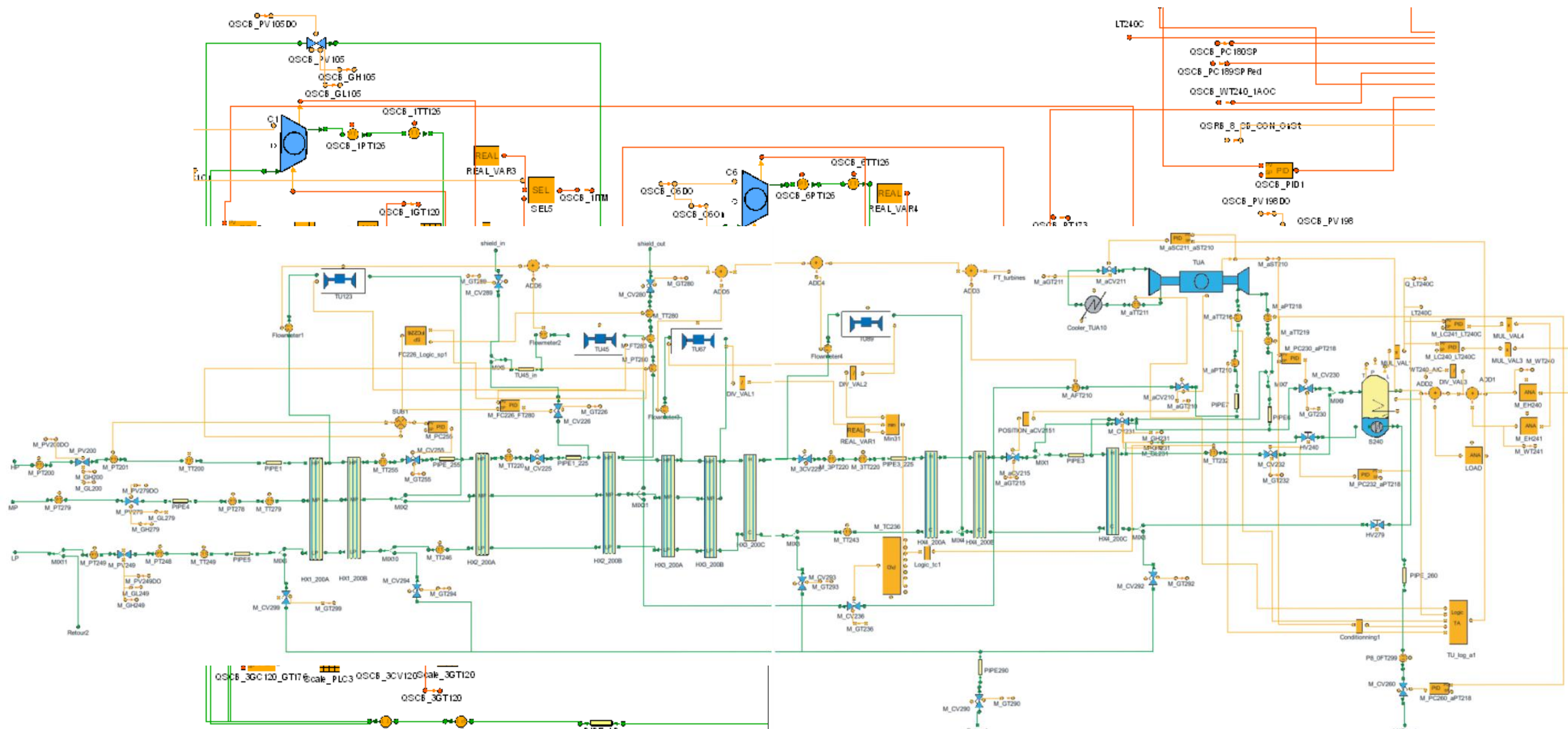
LHC Cryoplant

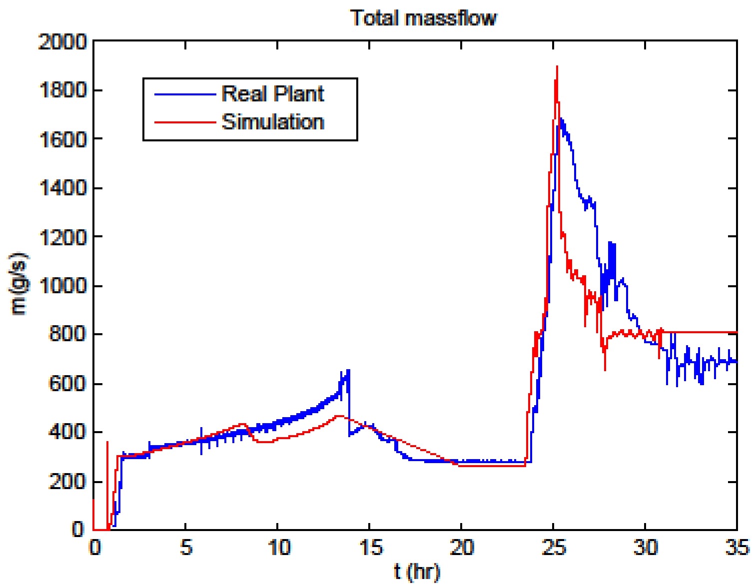


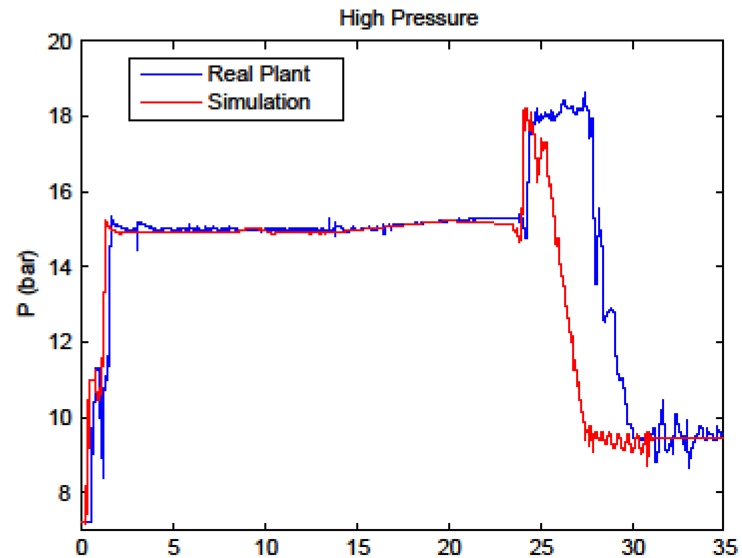
4.5 K refrigerator

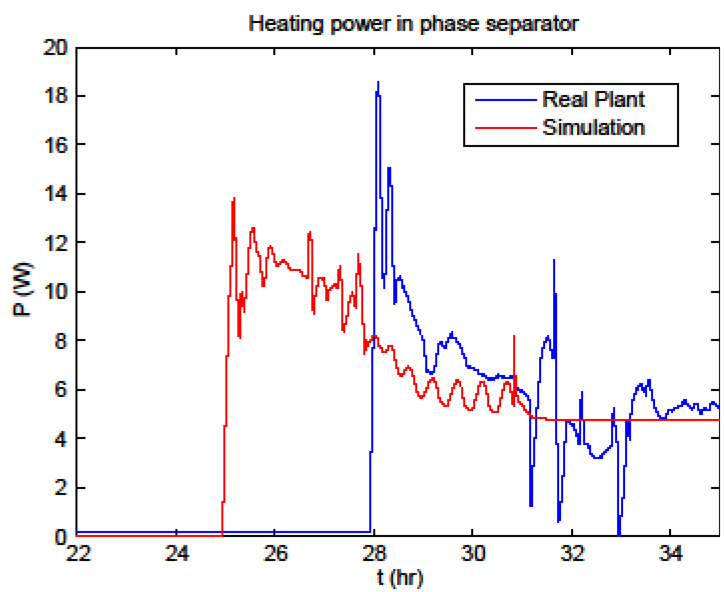
- 5 compressors, 10 HX, 10 Turbines, 1 phase separator, 75 valves, 50 PID loops
  - ✓ 5800 algebraic equations / 530 DAE
  - ✓ Simulation 5x real time

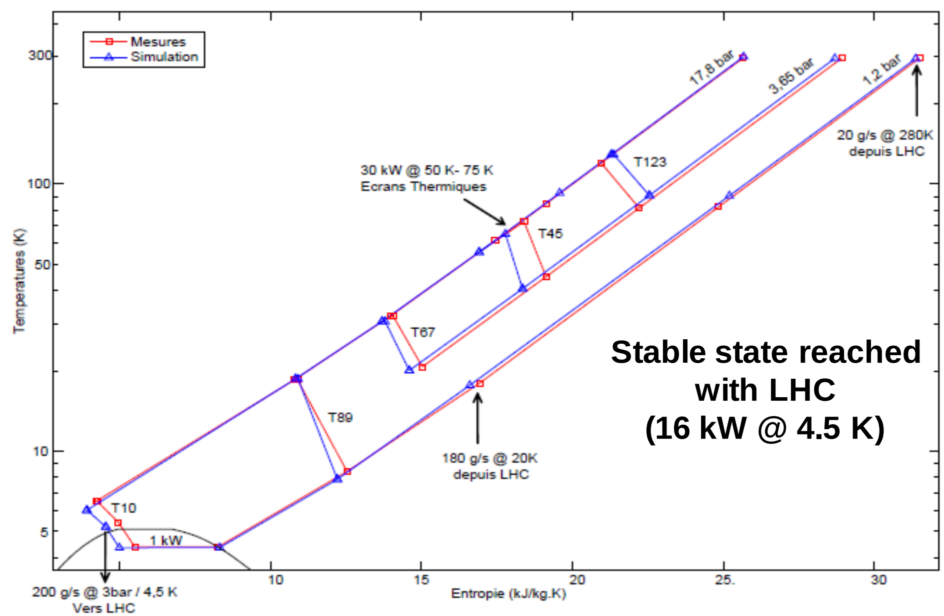


4.5 K refrigerator









Real-Time simulator

- **A dynamic simulator for CERN cryogenic plants**
  - « *Cryo Simulation Lab* » available at CERN for operators (building 36)

Conclusion

- EcosimPro: Flexible tool to model 0D/1D from DAE

- A cryogenic library has been developed at CERN
  - ✓ Allow users to build classical cryogenic systems
  - ✓ Has been tested on main CERN cryogenic plants
  - ✓ Can be enlarged easily to fit user requirements

- Dynamic simulations can help cryogenics
  - ✓ **Process engineers**: check behavior during transients
  - ✓ **Control engineers**: improve control / virtual commissioning
  - ✓ **Operation teams**: operator training platform

Thank you for your attention