Academia Meets Industry on Cryogenics

HEPTech

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Dynamic simulations:
a useful tool for cryogenic installations

Benjamin Bradu

Process Control Section

Industrial Controls & Safety Systems

CERN

Contents

What is dynamic process simulation ?

- **Simulation** = mimic the reality in a computer
  - Need to model your system first !

- **Dynamic** = evolution over time

- Applied on cryogenic **processes**:
  - Macroscopic modelling from a process point of view (0D/1D)

  - Use of an object-oriented modelling approach
    - Active equipment: valves, heaters, turbines, etc.
    - Passive equipment: pipes, HX, phase separators, etc.

  - Simulate all pressures, temperatures, mass flows over a cryogenic installation

➔ ≠ CFD simulation (different objectives, different techniques)

Why using it for cryogenics ?

- Dynamic simulation is a great tool to:
  - **Train operators**
    - ✓ Safe training with no risk on the process
    - ➢ Simulate failure scenarios (e.g turbine or compressor trips)
    - ➢ Simulate occasional events (e.g. cooldown phases)
  - **Validate new control strategies**
    - ✓ No disturbance on the process
    - ✓ Fair comparison between strategies
    - ✓ Time saving
  - **Perform virtual commissioning**
    - ✓ Debug safely the control programs
    - ✓ Fast validation of complex starting/stopping sequences
    - ✓ Commissioning control systems offline
    - ✓ Reduce commissioning time with the real plant

How does it works ?

Model each cryo component individually + fluid properties

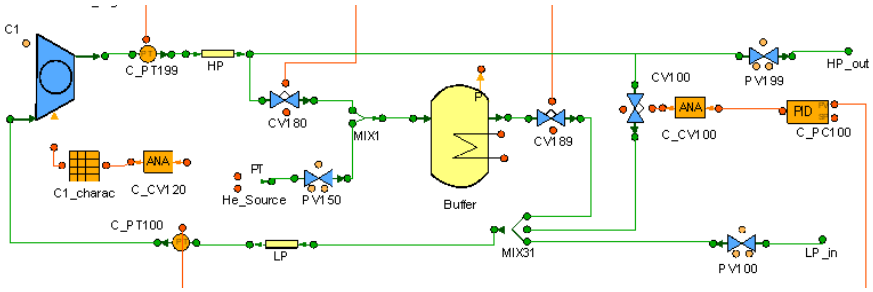
Build your complete model by assembling elementary components
+ Parametrize each component with your specifications (pipe diameter, valve size, etc.)

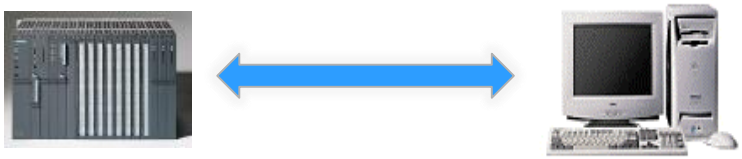
Include basic control in model
OR: couple it to real control system

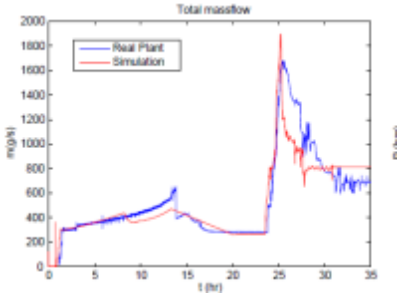
Define boundary conditions over time

Simulate

```
--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)
```







Main existing tools

- Full commercial solutions for cryogenics
  - **HYSIS Dynamics** (AspenTech, USA)
    - ✓ Air-Liquide, CAS, IIT
  - **EcosimPro + CRYOLIB** (EA international, Spain)
    - ✓ CERN, CEA, ITER, KEK, CAS

- Homemade libraries/software
  - **C-PREST**
    - ✓ NIFS
  - **Matlab/Simscape**
    - ✓ CEA
  - **Dymola** (Modelica)
    - ✓ University of Torino

Some examples

Some labs in the world doing dynamic simulations for cryogenic processes:
➔ NIFS, CERN, CEA, ITER, KEK

This is obviously not an exhaustive list…

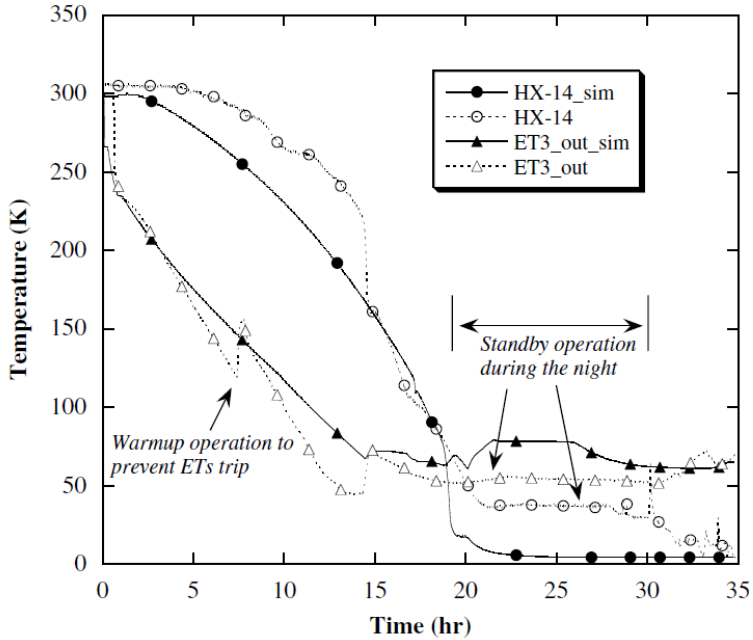
The number of publications using dynamic process simulation is increasing significantly…

ICEC conference
ICEC 2006 (Prague): 2/422 papers
ICEC 2016 (New-Delhi): 8/378 papers

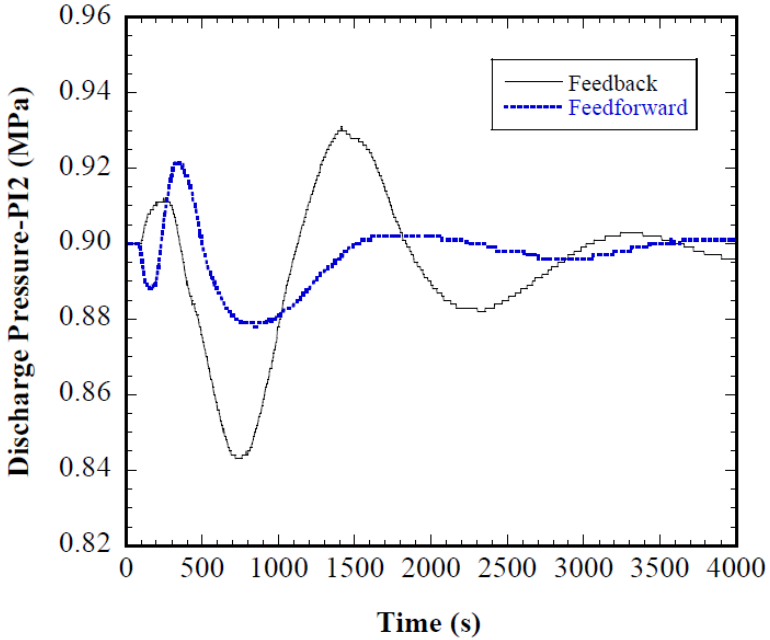
Elsevier Cryogenics journal
2005: 1
2010: 1
2013: 5
2014: 5
2015: 4
2016 (Jan-May): 4

NIFS

- LHD = Large Helical Device, Stellerator for fusion research in Japan
- 10 kW helium cryoplant
- First large-scale cryoplant dynamic simulation
- Used to improve some regulations



Comparison between simulation and experimental data during a cooldown of the coldbox (R. Maekawa, Cryogenics, 2005)



Comparison between different control techniques for the discharge pressure control after a heat pulse (R. Maekawa, ICEC, 2008)

CERN: Operator training platform

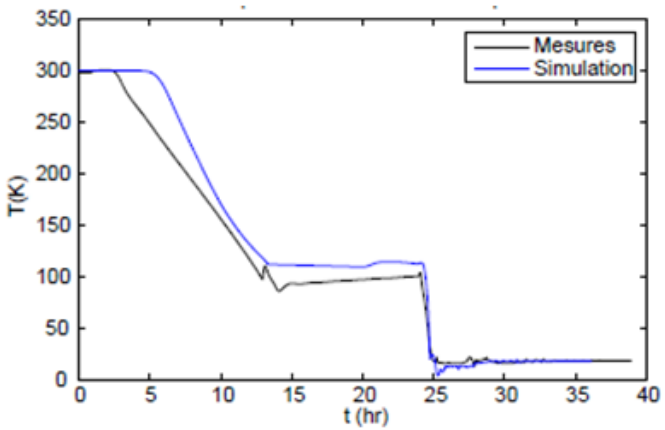
Linde 4.5 K refrigerator for LHC
(18 kW@4.5 K)

- 6100 Algebraic equations
- 500 Differential Equations
- Simulation speed: x3

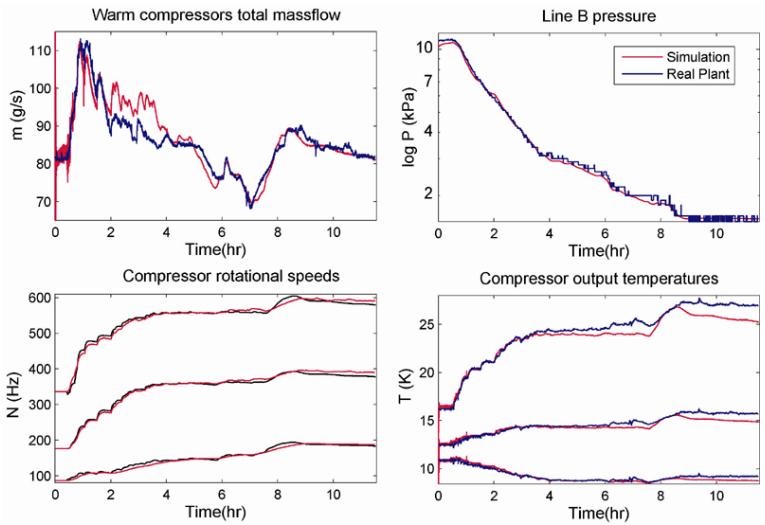
Air-Liquide 1.8 K refrigeration unit
for LHC (2.4 kW@1.8 K)

- 3500 Algebraic equations
- 320 Differential equations
- Simulation speed : x80

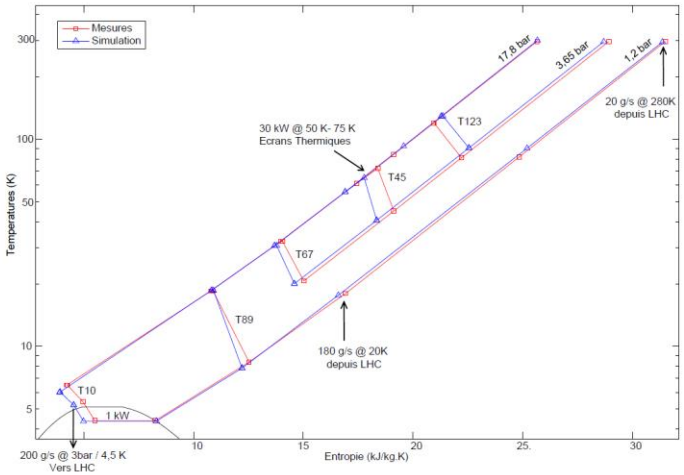
CERN: Simulation results



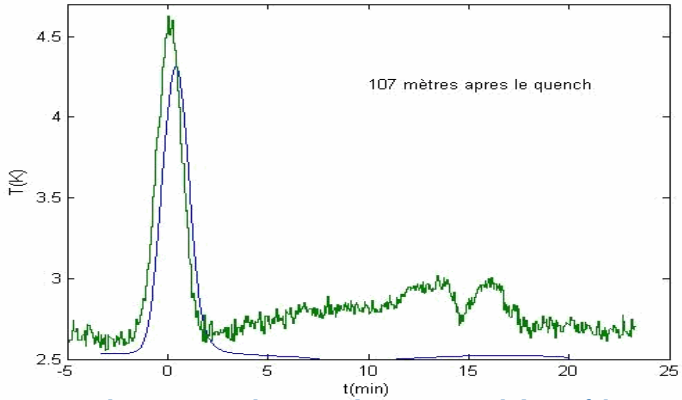
Comparison between simulation and experimental during a LHC 18kW refrigerator cooldown (B. Bradu, PhD, 2010)



Comparison between simulation and experimental data during the LHC final cooldown with cold-compressor in sector 5-6 (B. Bradu, ICEC, 2008)



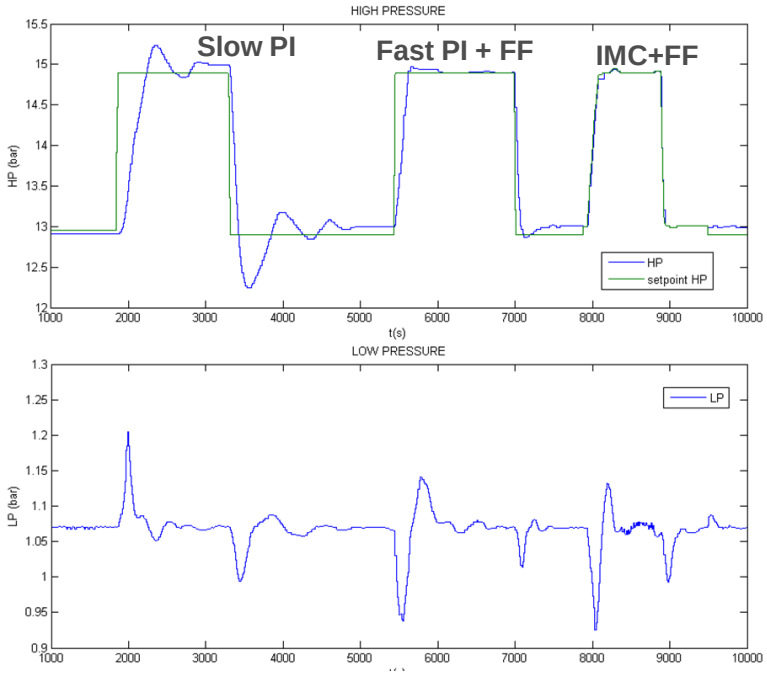
Comparison between simulated and experimental TS diagram of a LHC 18kW refrigerator after cooldown (B. Bradu, PhD, 2010)



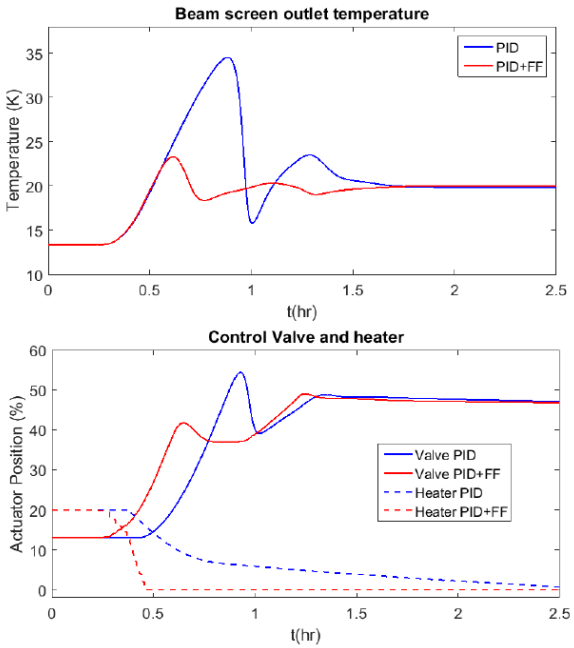
Comparison between simulation and experimental data of the LHC cryogenic pumping line temperature after a quench (B. Bradu, Cryogenics, 2010)

CERN: Control improvements

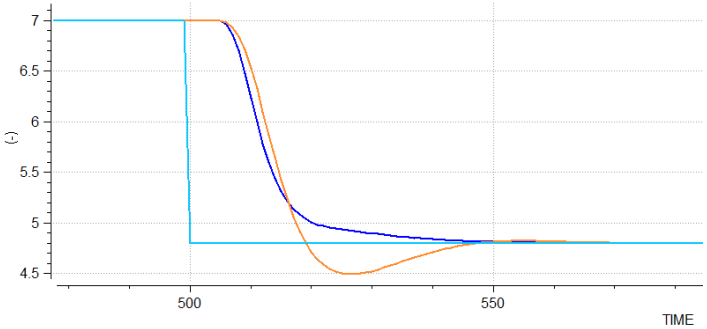
- Control improvements using simulations
  - Cold-compressor speed management
  - HP and LP control
  - Beam screen temperature regulation
  - PID tuning for GreC experiment in SM18



Comparison of different control techniques for the LHC P6 warm compression station pressures (B. Bradu, Aussois 2012)



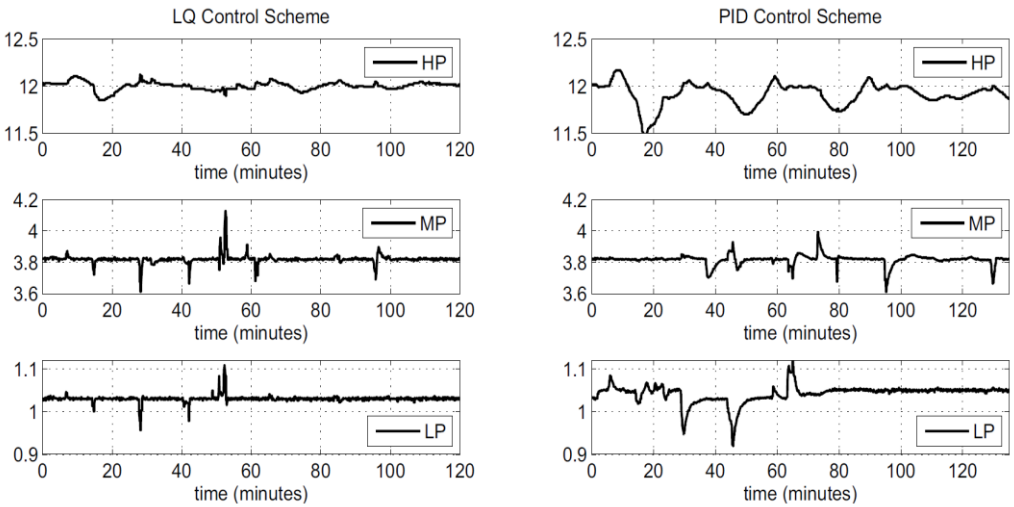
Comparison of different control techniques for the LHC beam screen temperature control during beam injection (B. Bradu, ICEC, 2016)



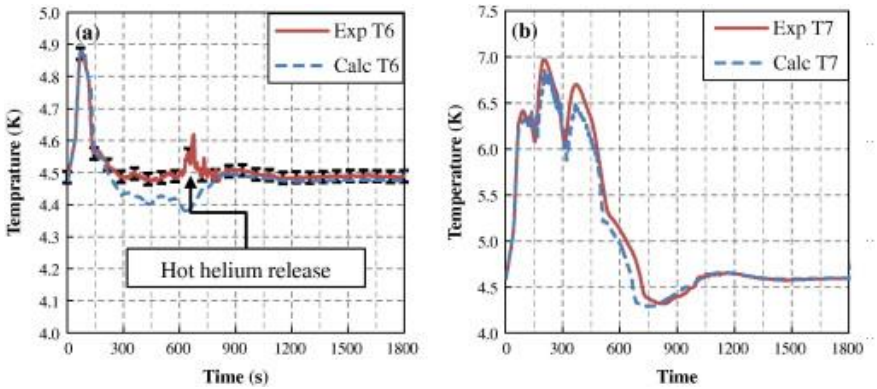
Comparison of different PID tunings for the output temperature regulation of GreC

CEA

- Many dynamic simulations performed at CEA-Grenoble
  - Develop multivariable model-based control techniques (LQ, MPC, etc.)
  - Control improvements to compensate the fast heat load variations
  - Control improvements to minimize energy consumption
  - CRYOGREEN project between CEA, UJF and CERN
  - Many studies/simulation on HELIOS for heat pulse compensation of JT60-SA



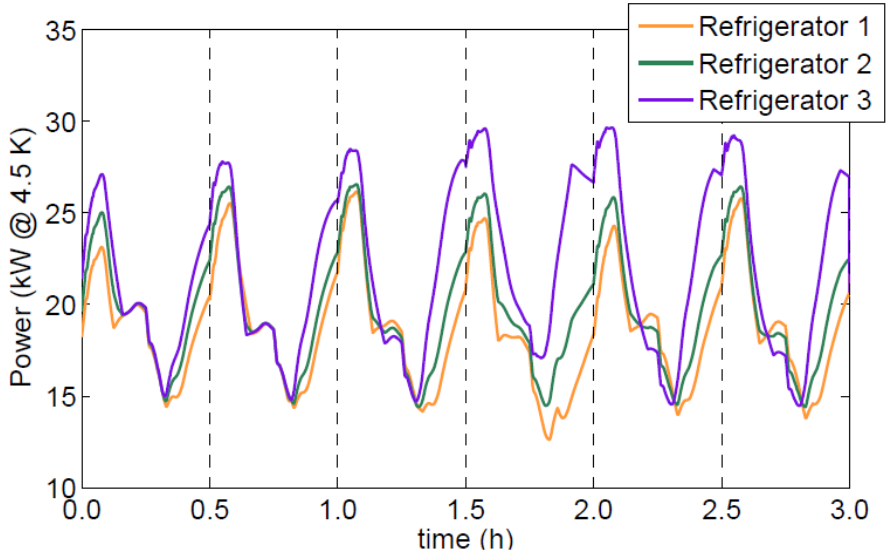
Comparison of different control techniques for LHC 18 kW cryoplant. (F . Bonne, CEC, 2013)



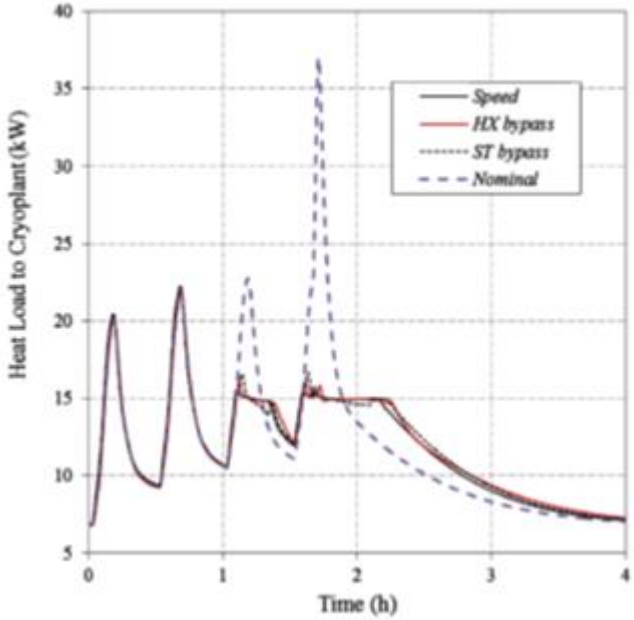
Comparison between simulation and experimental data during a heat pulse in HELIOS (B. Lagier, Cryogenics, 2014)

ITER

- Different dynamic simulations performed for ITER cryogenics
  - Cryoplants + Distribution with EcosimPro (ITER/CERN)
    - ✓ Cryoplant validation under pulsed heat loads
    - ✓ Study on the parallel cryoplants management
  - Auxiliary cold-boxes with internal loops with C-PREST (ITER/NIFS)
    - ✓ Study and validation of different mitigation techniques at ACB level



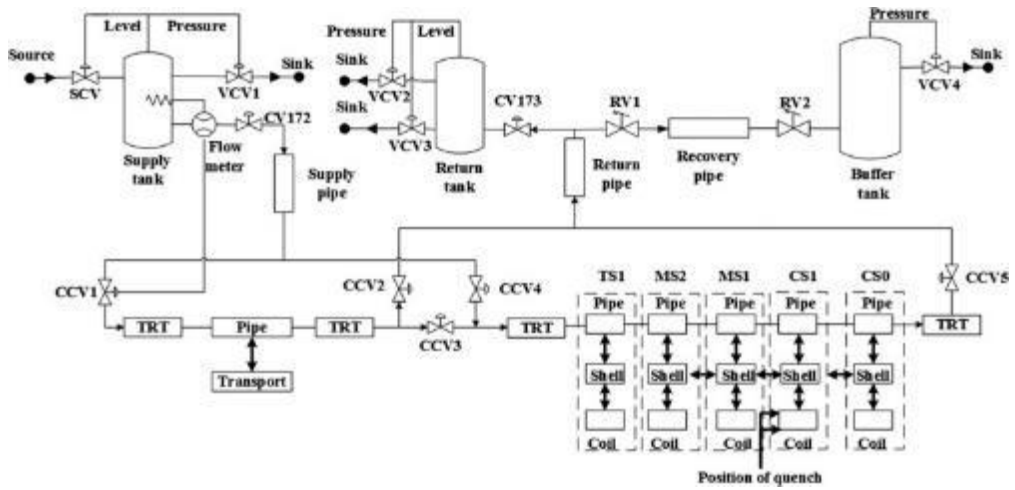
Evolution of the refrigeration power provided by the three refrigerators (L. Gomez, ICEC, 2014)

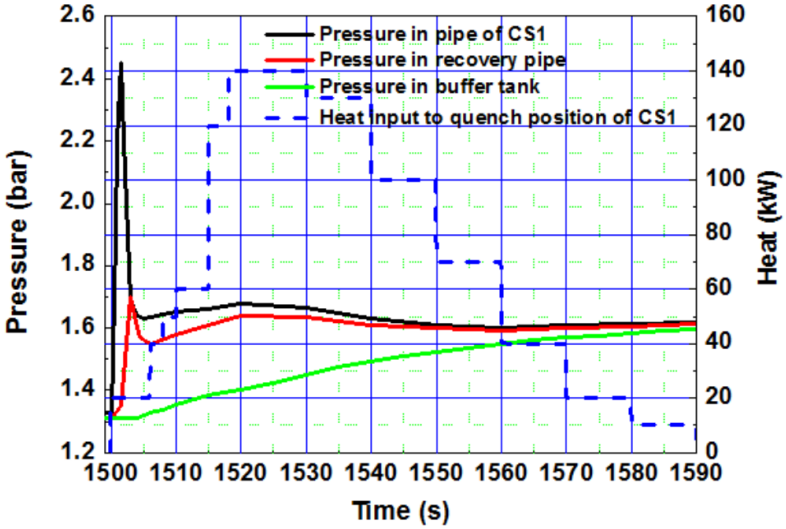


Variation of heat load to Cryoplant in the case of plasma disruption (R . Maekawa, Cryogenics, 2014)

KEK

- COMET: Future experiment in J-PARC to produce a muon beam line (Japan)
- Use of dynamic simulations with EcosimPro
  - Quench simulation is performed to check the maximum pressure in the cooling pipe





Pressure and heat curves during a quench. (T .Ki, Cryogenics, 2016).

Other potential future projects

- GANIL (France)
  - RF cavities cooldown scenario validation
- FAIR (Germany)
  - Operation of cryogenic plants in parallel
  - Validation of control system
- HL-LHC (Switzerland)
  - Beam screen dynamics
- FCC (Switzerland)
  - Cooldown scenario studies
- All projects having significant variable heat loads where dynamics play an important role

Summary

- Dynamic simulations are really helpful along projects
  - During the **design** phase
    - ✓ Validation of dynamic behaviour
    - ✓ Setup of control schemes
  - During the **commissioning** phase
    - ✓ Virtual commissioning
    - ✓ Tuning of control loops
  - During the **operation** phase
    - ✓ Operator training
    - ✓ Control improvements
    - ✓ Cryoplant optimization

CERN