Sector Temperature Control

(Preliminary Analysis)

LHC CP Workshop

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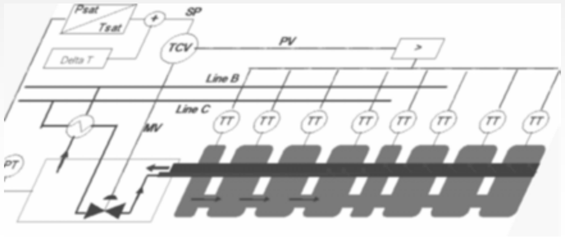

Outline

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   3. Challenges: process dynamics
2. Automation solutions: feedback control
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   2. Advanced control: experience at CERN
3. Sector Temperature Control
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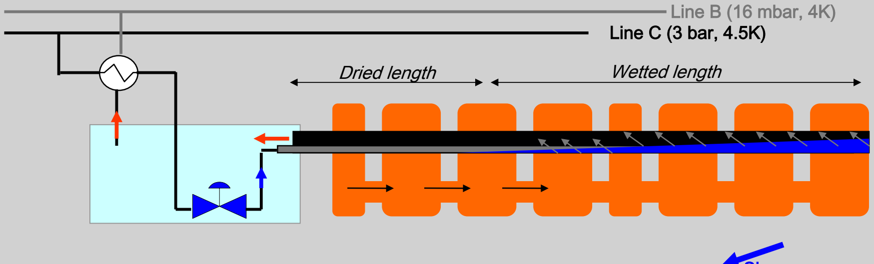
   3. Major technical choices
   4. Infrastructure & planning

1.- LHC cell magnet temperature control

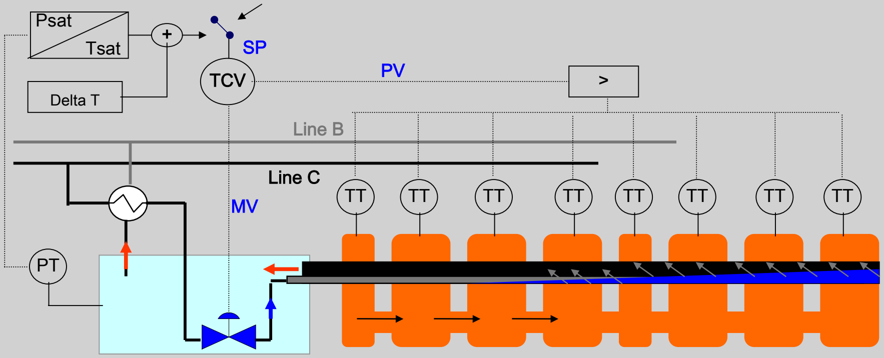
- The LHC superconducting magnets are cooled below 1.9 K.
  - ✓ Deposited heat is extracted by conduction to a HX tube
  - ✓ Saturated superfluid helium flows through a HX located along the magnets and absorbs the heat load by gradual vaporization



LHC cell archictecture

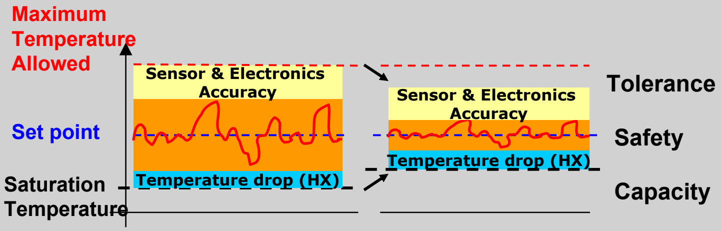
1.2.- Control Architecture

- ✓ Process variable (PV): temperatures measured at each magnet
- ✓ Temperature setpoint (SP): obtained dynamically adding a deltaT, typically 30 mK, to the saturation temperature, or absolute desired temperature
- ✓ Manipulated variable (MV): Joule-Thomson valve
- ✓ Disturbances: Heat loads, LHe inlet flow (g/s, T, P), back pressure



1.3.- Regulation requirements

- ✓ Regulation goal: to keep the temperature as constant as possible within strict operating constraints imposed by:
  - Allowed maximum temperature for the magnets (1.9 K)
  - Cooling capacity of the cryogenic system (pumping requirements)
  - Disturbances: Dynamic heat loads
  - Instrumentation accuracy (radiation)
- ✓ Motivation for optimizing the regulation



Maximum Temperature Allowed

Set point

Saturation Temperature

Sensor & Electronics Accuracy

Temperature drop (HX)

Sensor & Electronics Accuracy

Temperature drop (HX)

Tolerance

Safety

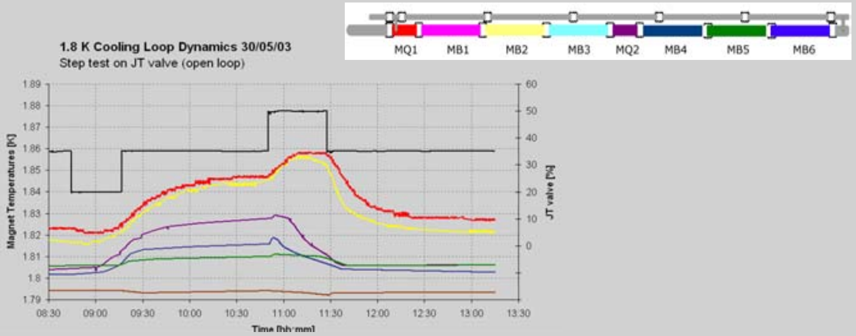
Capacity

1.4.- Challenges: Process dynamics

- Dynamics
  - ✓ Highly **nonlinear** on physical parameters
  - ✓ Non-self regulating process (integrating)
  - ✓ Exhibits inverse response
  - ✓ Variable Dead-time (transportation lag)
  - ✓ Coupling between action and feedback

~ 0.3 W/m	~ 0.4 W/m	~ 0.6 W/m
12 mK 50 minutes	13 mK 30 minutes	19 mK 22 minutes

Inverse response: amplitude & duration



2.- Automation solutions: feedback control

- PID control

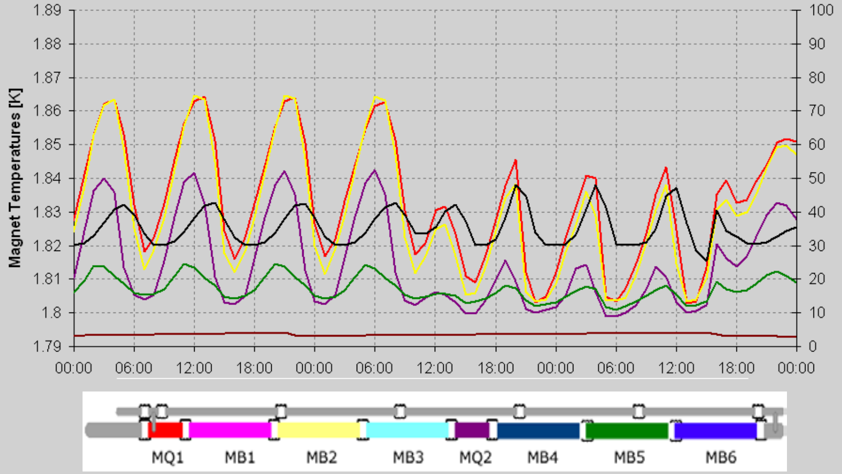
$$u(t) = K_p[e(t) + \frac{1}{\mathrm{T_i}}\int e(t)dt + T_d\frac{de(t)}{dt}]$$

- ✓ Tuning based on multiple methods showed poor performance as far as transportation lag and inverse response were accentuated
- ✓ STRING2: (LHC cell) From phase to phase [1..3]
  - Increase the DeltaT to 50mK to have margin and not overflow
  - Regulate with oscillations up to 40 mK peak to peak
  - New parameters have to be found to stabilize the control loop
- ✓ Parameters selected in a compromise: stability + heat load cancellation
- ✓ No single set of parameters for the whole sector and the bad choice of them could cause oscillations driving to INSTABILITY.
- ✓ The only solution is try to identify the sluggish case (longest dead time) and tune for that situation (a PID controller that is tuned too conservatively may not be able to eliminate one error before the next one appears !)

2.1.- PID performance (String2, phase3)

1.8 K Cooling Loop Dynamics [17-20/05/03]

PID regulation [DeltaT=50mK (~1.843 K)]

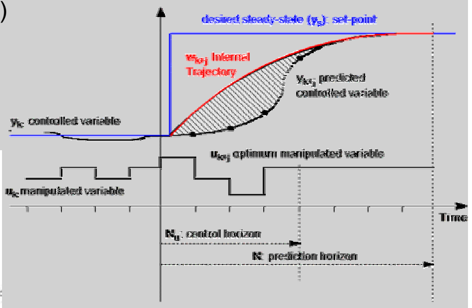


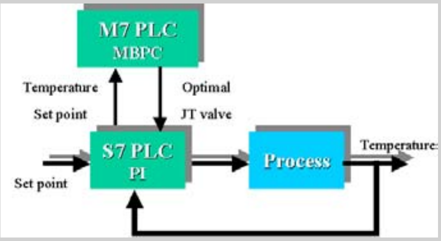
2.2.- Advanced control experience at CERN

- The most used technique in industry is **model-based predictive control (MBPC)**. Having a good model of the plant, the controller can predict the future behavior of the process and then propose the optimal control actions.
- Several strategies have been fully tested along the different setup experiments mounted at CERN (STRING1, Inner Triplet, STRING2).
- There is not a magic controller plug & play.

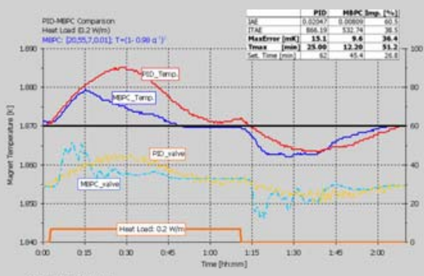
  (few nonlinear commercial applications)

$$I = \sum_{j=N1}^{N2} [w(t+j) - \hat{y}(t+j)]^2 + \beta \sum_{j=0}^{Nu} [\Delta u(t+j)]^2$$

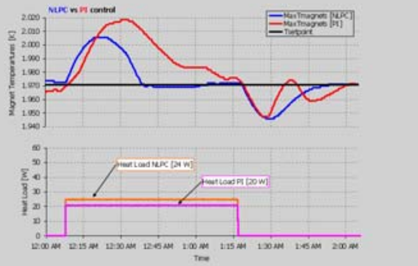


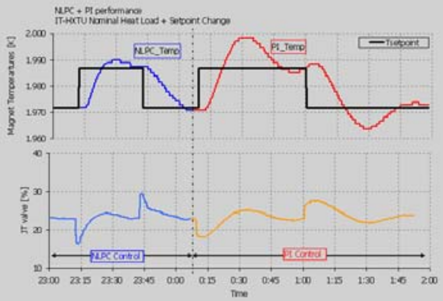


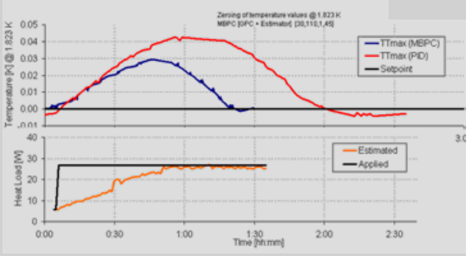
2.2.- MBPC performance



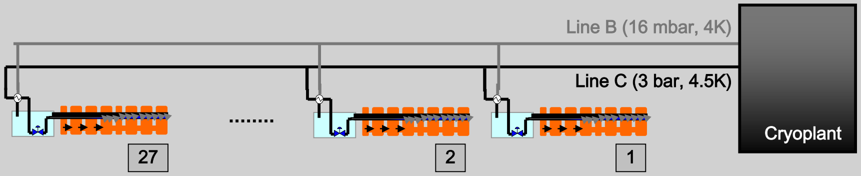
	PID	MBPC	Imp. [%]
IAE	0.02047	0.00809	60.5
ITAE	866.19	532.74	38.5
MaxError [mK]	**15.1**	**9.6**	**36.4**
Tmax [min]	**25.00**	**12.20**	**51.2**
Set. Time [min]	62	45.4	26.8







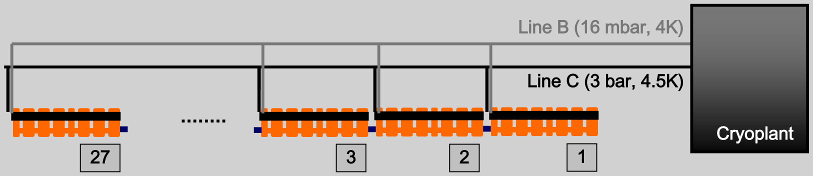
3.- Sector Temperature Control



What changes from a single cell (String2):

- Multiple clients (cells) for line C
  - ✓ Line C provides liquid He within the limits of T [4.6,..,5.2 K], P[2.4,..,3 bar]
- Back pressure is shared among all the cells (line B)
  - ✓ Pumping capacity will be fixed at the cryoplant (~15 mbar)
- Hydraulic plugs between some cells
  - ✓ Additional heat conduction to the cells

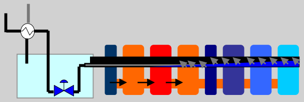
3.1.- Outstanding issues



1. Line C
   - ✓ Variations in temperature or pressure of line C will provoke changes in the JT valve flash and the quantity of inlet flow causing control movements
2. Line B
   - ✓ Line pressure drop provokes the farthest cells to be close to the limits and perturbation in this line will affect to temperature control.
   - ✓ Changes in pressure will modify the inlet JT temperature -> flash.

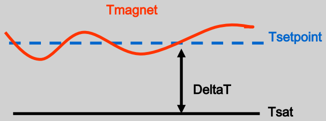
LHC

3. Hydraulic plugs between cells
   - ✓ Cell cooling/heating will be provided non only by its JT valve but also but the adjacent cells (increase cell coupling)



3.2 What is really required?

- On top of the mentioned requirement of maximum allowed temperature it must be considered:
  - ✓ Avoiding HX LHe flow going to overflow pot (waste of money)
  - ✓ As much decoupling as possible between cells
  - ✓ Allowing powering of the machine while ensuring stability
  - ✓ No need of single cells tuning
- Regulation strategy: Absolute temperature vs. DeltaT
  - ✓ Overflow risk
  - ✓ Dynamics: Tuning
  - ✓ Operator usability
  - ✓ Instrumentation confidence: pressure



3.3.- Major technical choices

PID

Experience:

- Poor performance with dead-time
- Not a single tuning for all LHC cells
- Could cause instabilities

Pro's:

- Easy implementation

Con's:

- Conservative tuning
- Degraded performance
- Complex decoupling methods
- No *feedforward* during powering

MBPC: PREDICTIVE CONTROL

Experience:

- Improved performance
- Easy tuning
- Increase robustness

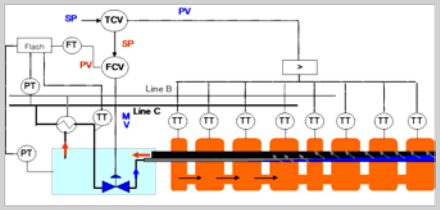
Pro's:

- Optimal method under constraints
- Gives additional process knowledge
- Multivariable capabilities (sector)
- *Feedforward* by nature
- Adaptation capabilities (no tuning)

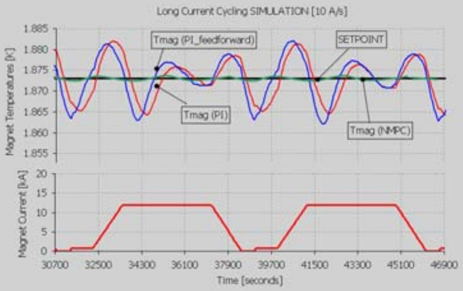
Con's:

- Modeling effort
- Elaborated development and implementation
- Simulation work until sector ready

3.3.- Other control issues

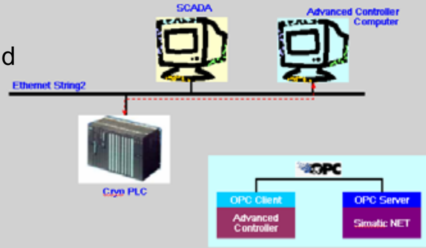


- Overcoming the flash effect
  Inferential + cascade control
- Magnets powering
  Feedforward control
- Fault detection techniques
  Instrumentation malfunctioning

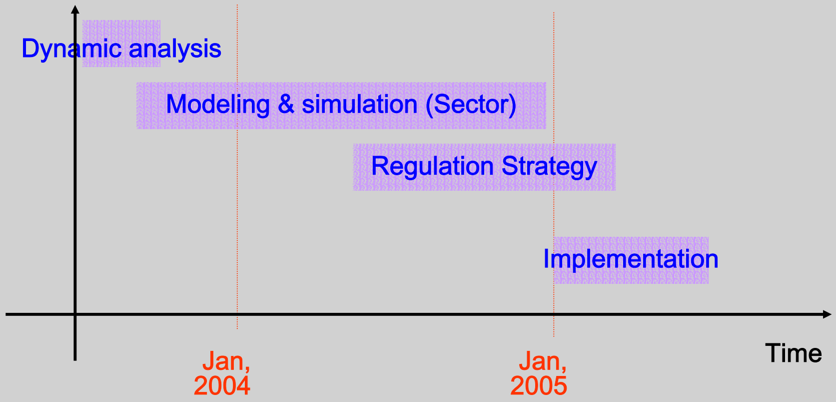


3.4.- Infrastructure required

- Hardware
  - ✓ PID : use the existing PLC equipments
  - ✓ MBPC: dedicated machine
    - 1 – Industrial PC running a real time operating system at PLC level
    - 2 – Classical PC running windows at supervision level (OPC comms through Ethernet).
- Software
  - ✓ Intensive use of optimization and numerical integration solving libraries.



3.4 Some preliminary planning



Dynamic analysis

Modeling & simulation (Sector)

Regulation Strategy

Implementation

A.- Temperature profiles along the LHC

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