Flower, a Model for the Analysis of Hydraulic Networks and Processes

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Overview

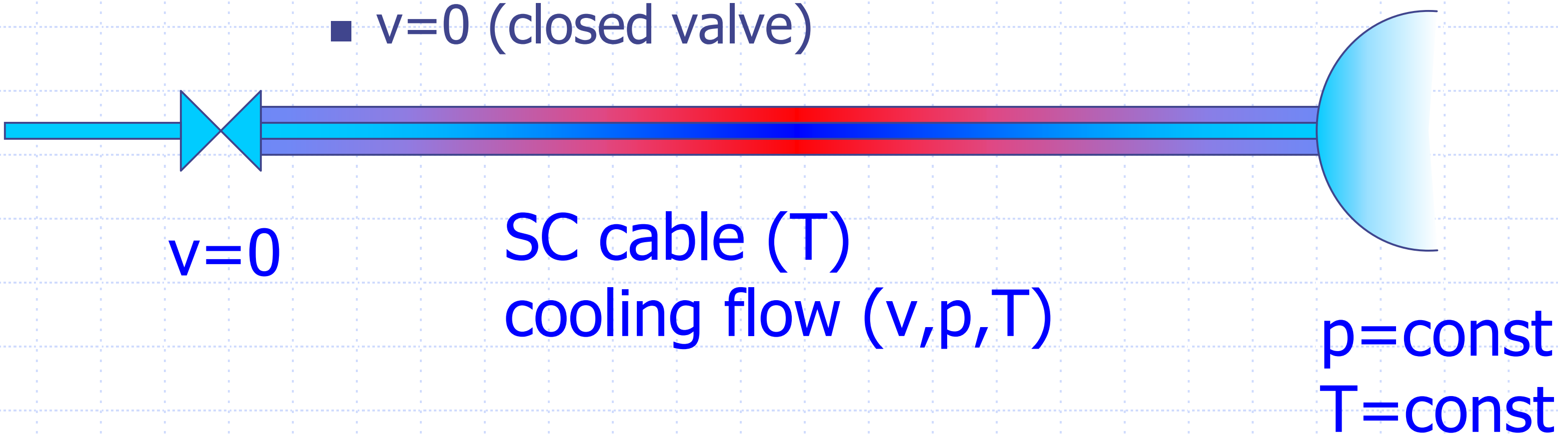
- A bit of history
- What is *Flower* today ?
  - preliminaries on state equation and variable choice
  - bits and pieces…
  - … of a circuit   the painful bit… Lots of equations !
- What is it good for ?
- Perspective

A bit of history (the 70's)

- Quench analysis for fusion magnets (70's)
  - large stored energy (16 coils, ≈100 GJ)
  - force-flow cooled cables (CICC's)
  - issues:
    - pressure increase (typically > 150 bar)
    - temperature increase (typically <150 K)
    - helium massflow (typically 1 to 10 Kg/s per coil)
  - safety is critical
    - radioactive release in case of structural faults

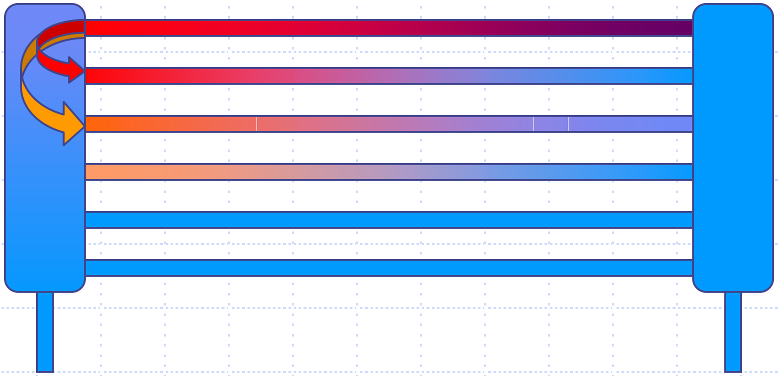
A bit of history (the 80's)

- 1-D (pipe) model of flow and temperature
  - simple boundary conditions
    - p=const, T=const (infinite reservoir)
    - v=0 (closed valve)



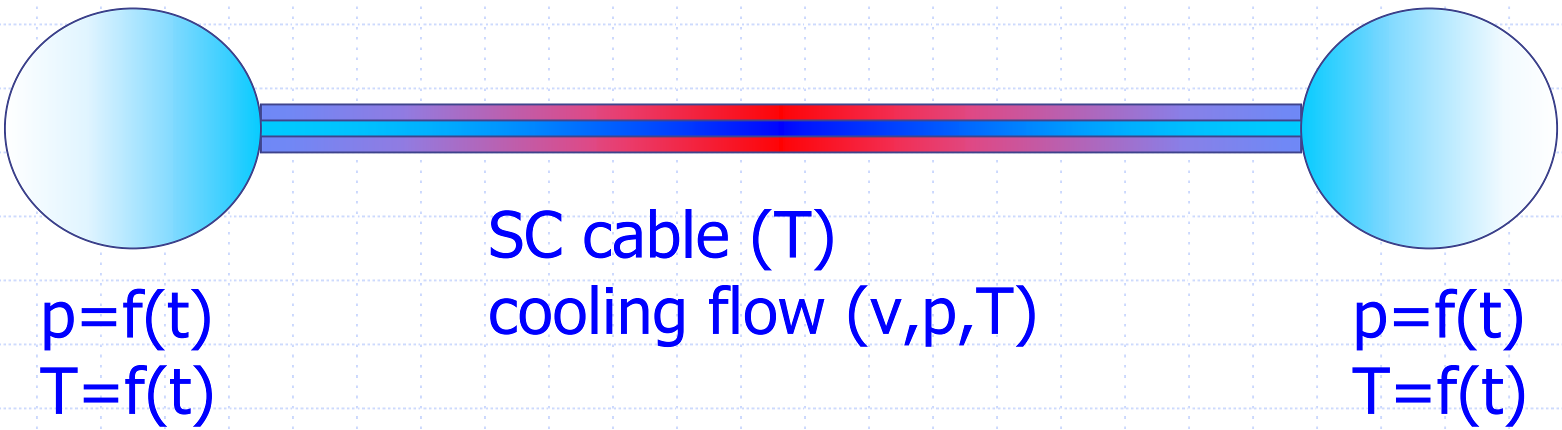
A bit of history (the 90's)

- Manifolds
  - direct interconnection between quenching cables
  - can propagate hydraulically the quench
    - IEEE Trans. Appl. Sup., 3 (1), 606-609, 1993
    - see also LHC-String-1 experimental program
  - must be considered for time scales ≈ 10 s



A bit of history (80's to 90's)

- First level of improvement
  - simple model for finite inlet/outlet volumes



$$V\frac{\partial \rho}{\partial t}+\sum \dot{m}_i=0$$

mass conservation

$$V\frac{\partial \rho i}{\partial t}+\sum \dot{m}_i\left(h_i+\frac{v_i^2}{2}\right)=\dot{q}$$

energy conservation

A bit of history (90's to 00's)

- Second level of improvement
  - describe the external piping circuit, focus on:
    - buffers/volumes (damp pressure transients)
    - valves (choke the flow, relief lines)
    - pipes (delay lines)
    - heat exchangers (temperature control)
    - pumps/compressors (flow, pressure control)
  - adopt drastic simplifications in the model

Flower versions 1, 2 and 3

A bit of history (2002, today)

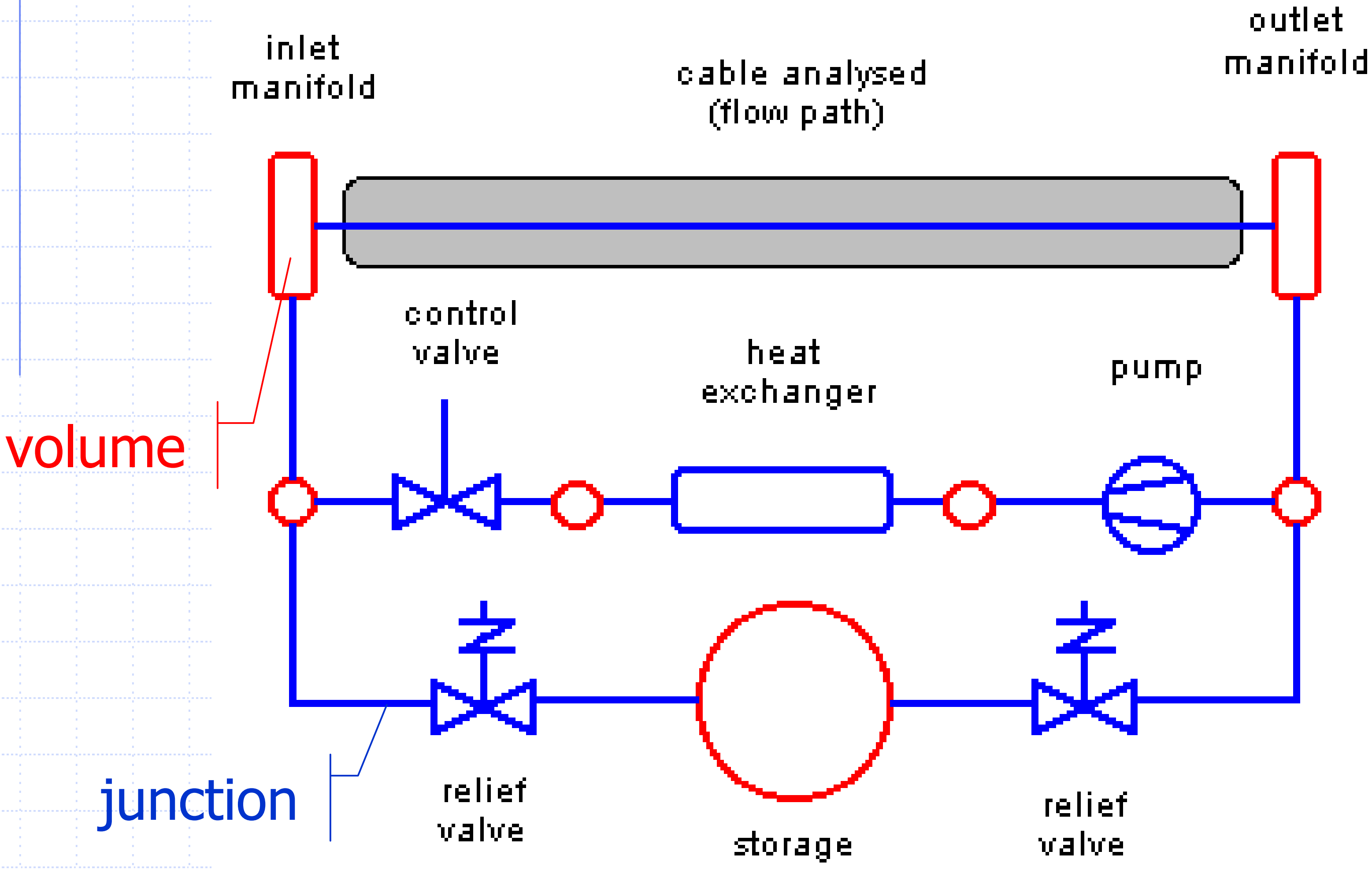
- Evolution
  - add new modeling elements:
    - heat exchangers
    - turbines
  - sparse matrix storage technique
  - GMRES iterative solution

Flower version 4

What is *Flower* version 4.0?

- Objective of the code:
  - a simplified model of the hydraulic (helium) network that feeds a SC magnet …
  - … reproducing key features of the (cryogenic) system response …
  - … allowing consistent simulation of both transient and steady state.

Vocabulary for an *hydraulic network*



Bits and pieces - Preliminaries

- pressure *p* and temperature *T* as state variables (V. Arp, 1980):

Gruneisen parameter
$\phi=\gamma-1$ for perfect gas

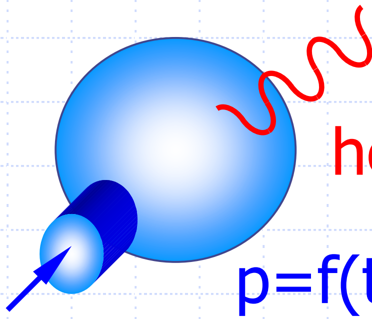
$$d\rho = \frac{1+\phi}{c^2}dp - \frac{\phi\rho}{c^2}dh \qquad di = \frac{1}{\rho}\left(\frac{p}{\rho} - \phi C_v T\right)d\rho - C_v dT$$

- velocity *v* for flow

vast improvement of numerical stability for the flow calculation

Bits and pieces - 1

- Volumes, buffers, manifolds



$$V_k \frac{\partial \rho_k}{\partial t} + \sum \dot{m}_i = 0$$

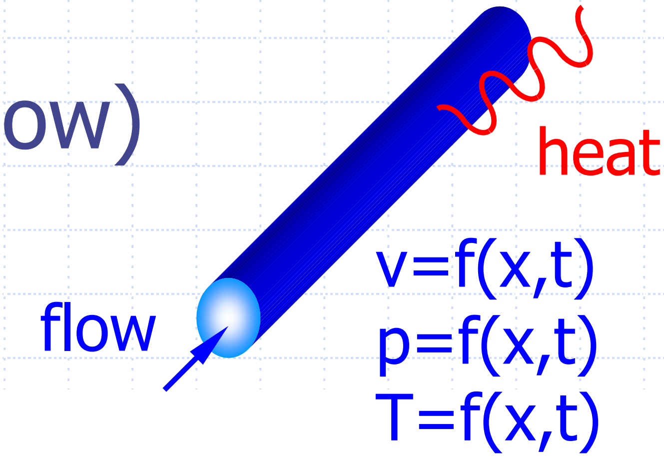
$$V_k \frac{\partial \rho_k i_k}{\partial t} + \sum \dot{m}_i \left(h_i + \frac{v_i^2}{2} \right) = \dot{q}_k$$

$$V_k \frac{\partial p_k}{\partial t} + \sum_i \rho_i A_i v_i \left[c_k^2 + \phi_k \left(h_i + \frac{v_i^2}{2} - h_k \right) \right] = \phi_k \dot{q}_k$$

$$V_k \rho_k C_k \frac{\partial T_k}{\partial t} + \sum_i \rho_i A_i v_i \left(\phi_k C_k T_k + h_i + \frac{v_i^2}{2} - h_k \right) = \dot{q}_k$$

Bits and pieces - 2

- Pipes (compressible flow)



$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial x} + \frac{1}{\rho_i}\frac{\partial p_i}{\partial x} + 2\frac{f_i}{D_i} v_i |v_i| = 0$$

$$A_i \frac{\partial p_i}{\partial t} + A_i \rho_i c_i^2 \frac{\partial v_i}{\partial x} + A_i v_i \frac{\partial p_i}{\partial x} - 2 A_i \varphi_i \frac{f_i}{D_i} \rho_i v_i^2 |v_i| = \varphi_i \dot{q}_i' + \varphi_i \dot{q}_{cf,i}'$$

$$\rho_i C_i A_i \frac{\partial T_i}{\partial t} + \rho_i C_i A_i \varphi T_i \frac{\partial v}{\partial x} + \rho_i C_i A_i v \frac{\partial T_i}{\partial x} - 2 A_i \frac{f_i}{D_h} \rho_i v_i^2 |v_i|_i = \dot{q}_i' + \dot{q}_{cf,i}'$$

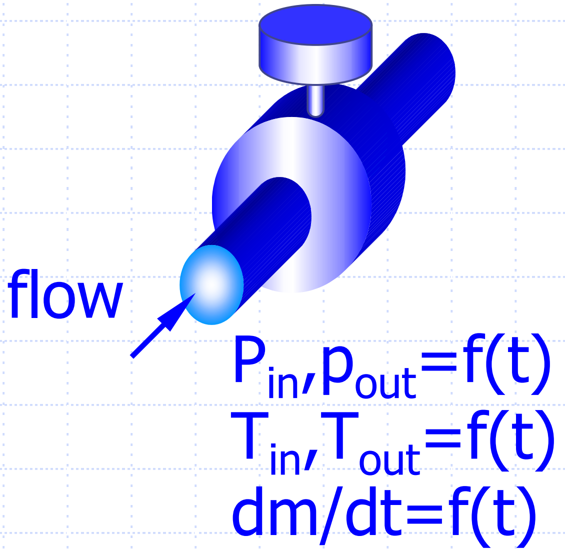
Bits and pieces - 3

- Valves
  - as steady state pipes but:
    - no heat input
    - variable head loss factor ξ:

$$\Delta p \approx -2\xi\rho v|v|$$

$$\dot{m}_i = \alpha(p_k - p_h)$$

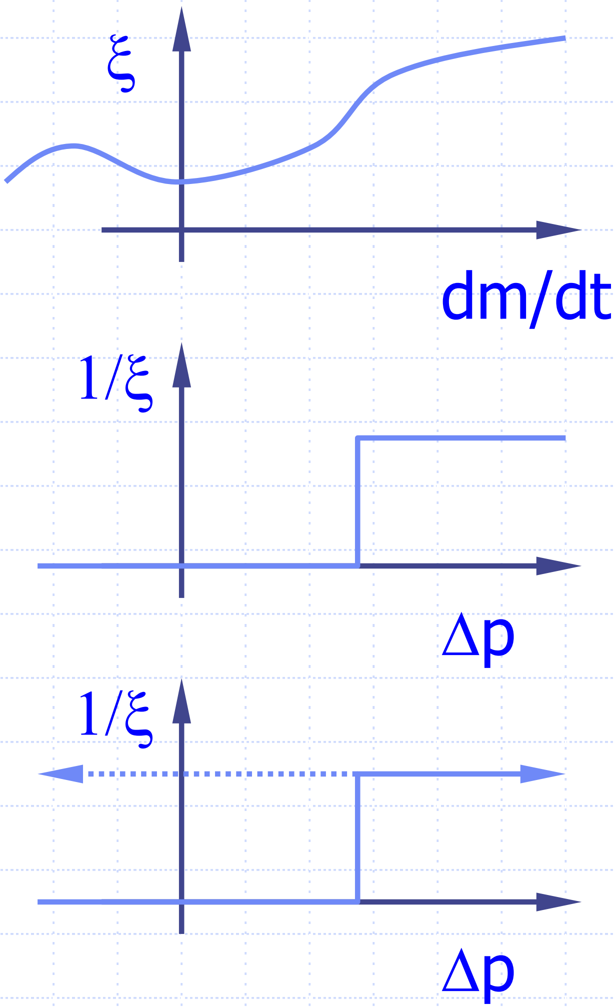
$$\alpha = A\sqrt{\frac{1}{2\xi}\frac{\bar{\rho}}{|p_h - p_k|}}$$



$$\xi \approx 6.5\times10^8\left(\frac{A}{K_v}\right)^2$$

Bits and pieces - 4

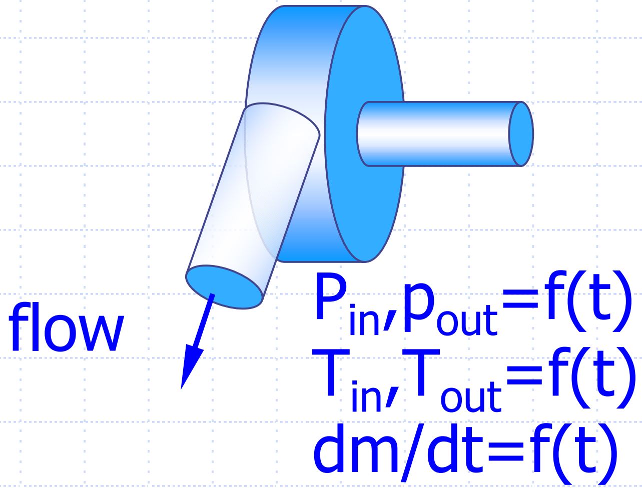
- Control valves
  - $\xi = f(t, dm/dt, \Delta p)$
- Relief valves
  - $\xi = f(\Delta p)$
- Burst disks
  - $\xi = f(\Delta p(t))$



Bits and pieces - 5

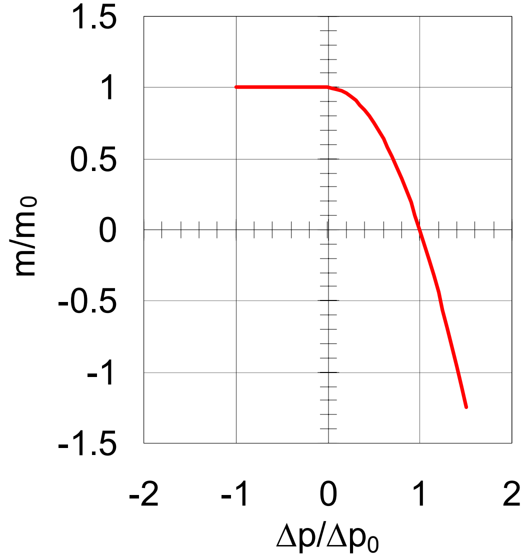
- Volumetric pumps:

$$\dot{m}_i = \dot{m}_0$$



- Compressors:

$$\dot{m}_i = \begin{cases} \dot{m}_0 \left(1 - \left(\frac{p_k - p_h}{\Delta p_0} \right)^2 \right) & for\ p_k \geq p_h \\ \dot{m}_0 & for\ p_k < p_h \end{cases}$$



Bits and pieces - 6

- Isentropic flow (ideal pump):

dS=0

$$dh = TdS + \frac{1}{\rho} dp$$

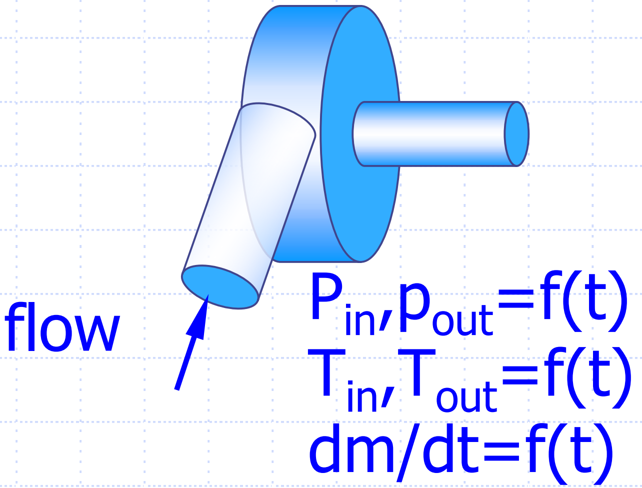
$$\Downarrow$$

$$\Delta h_i = \int_{p_h}^{p_k} \frac{1}{\rho} dp \approx \frac{1}{2}\left(\frac{1}{\rho_h} + \frac{1}{\rho_k}\right)(p_k - p_h)$$

Bits and pieces - 7

- Turbines

$$\Delta p \approx -2\xi_T \rho v|v|$$



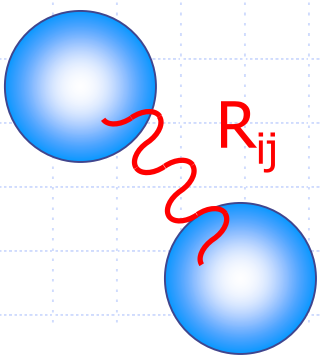
- Isentropic flow (as for ideal pump):

$$\Delta h_i = \int_{p_h}^{p_k} \frac{1}{\rho} dp \approx \frac{1}{2}\left(\frac{1}{\rho_h} + \frac{1}{\rho_k}\right)(p_k - p_h)$$

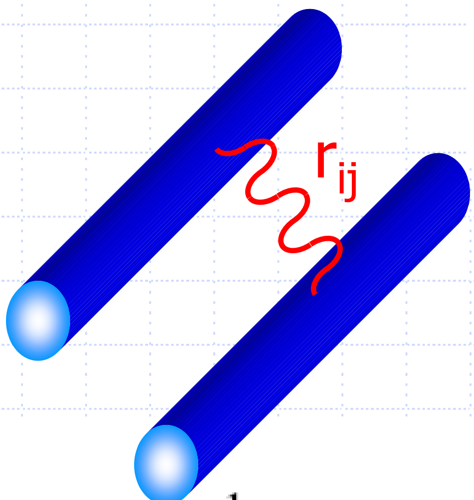
Bits and pieces - 8

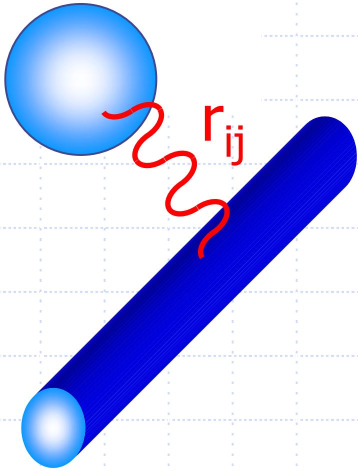
- Heat exchange

$$\dot{q}'_{ki} = \frac{1}{r_{ji} + \frac{1}{w_i \eta_i}} \left(T_k - T_i\right)$$



$$\dot{q}_{ik} = \int_L \frac{1}{r_{ji} + \frac{1}{w_i \eta_i}} \left(T_k - T_i\right) dx$$





$$\dot{q}_{hk} = \frac{1}{R_{hk}} \left(T_h - T_k\right)$$

$$\dot{q}'_{ji} = \frac{1}{\frac{1}{w_j \eta_j} + r_{ji} + \frac{1}{w_i \eta_i}} \left(T_j - T_i\right)$$

Bits and pieces - Summary

- Model is an assembly of:
  - volumes, manifolds, buffers…
  - …1-D flow pipes…
  - …control and check valves…
  - …burst disks…
  - ….ideal volumetric pumps and compressors…
  - …turbines…
  - …with (possible) heat exchange among volumes and pipes (HEX)

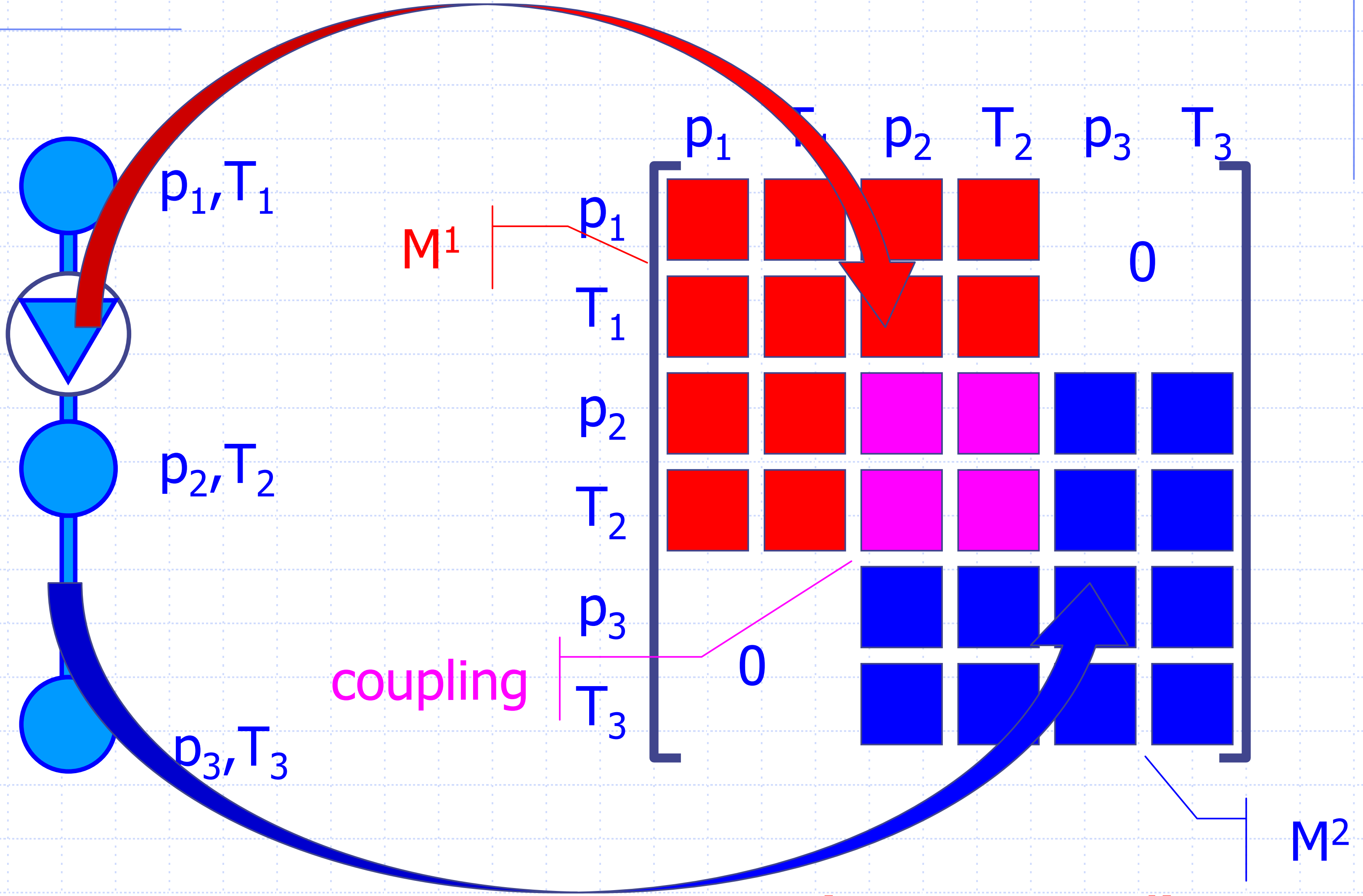
Equations as matrices

- all equations are in the general form:

$$\mathbf{M}^{el}\frac{\partial \mathbf{U}^{el}}{\partial t}+\left(\mathbf{A}^{el}+\mathbf{S}^{el}\right)\mathbf{U}^{el}=\mathbf{Q}^{el}$$

- non-linear system of ODE’s for each element

The circuit matrices



Sparse matrix storage (SLAP triad)

System solution

- Solution technique

$$\mathbf{M}\frac{\partial \mathbf{U}}{\partial t}+(\mathbf{A}+\mathbf{S})\mathbf{U}=\mathbf{Q}$$

⇓

$$\mathbf{M}\left(\mathbf{U}^{n+1}\right)\frac{\mathbf{U}^{n+1}-\mathbf{U}^{n}}{\Delta t}+\left(\mathbf{A}\left(\mathbf{U}^{n+1}\right)+\mathbf{S}\left(\mathbf{U}^{n+1}\right)\right)\mathbf{U}^{n+1}=\mathbf{Q}\left(\mathbf{U}^{n+1}\right)$$

Iterative solution of algebraic system
incomplete preconditioning GMRES algorithm

What is it good for ?

- Results in the QUELL experiment
- Response of a heated helium loop such as the LHC Beam screen
- A string of LHC magnets

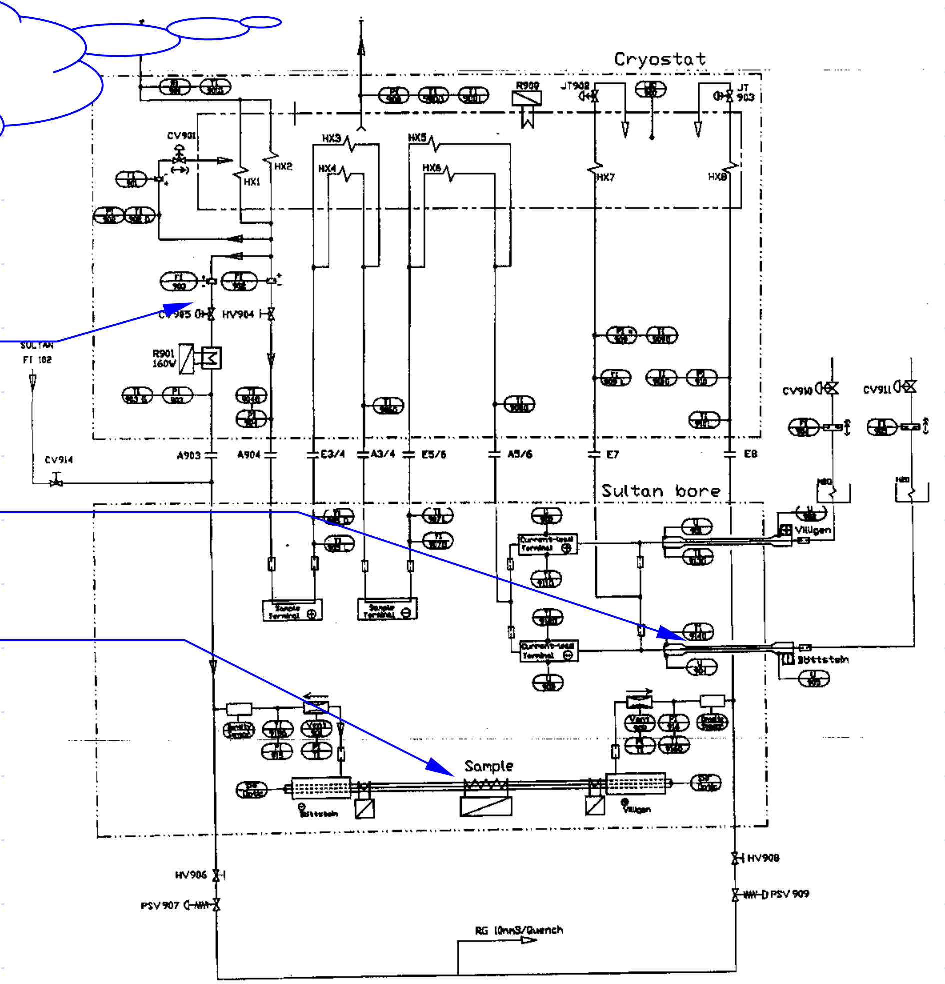
QUEnch on Long Length

Cryogenic plant

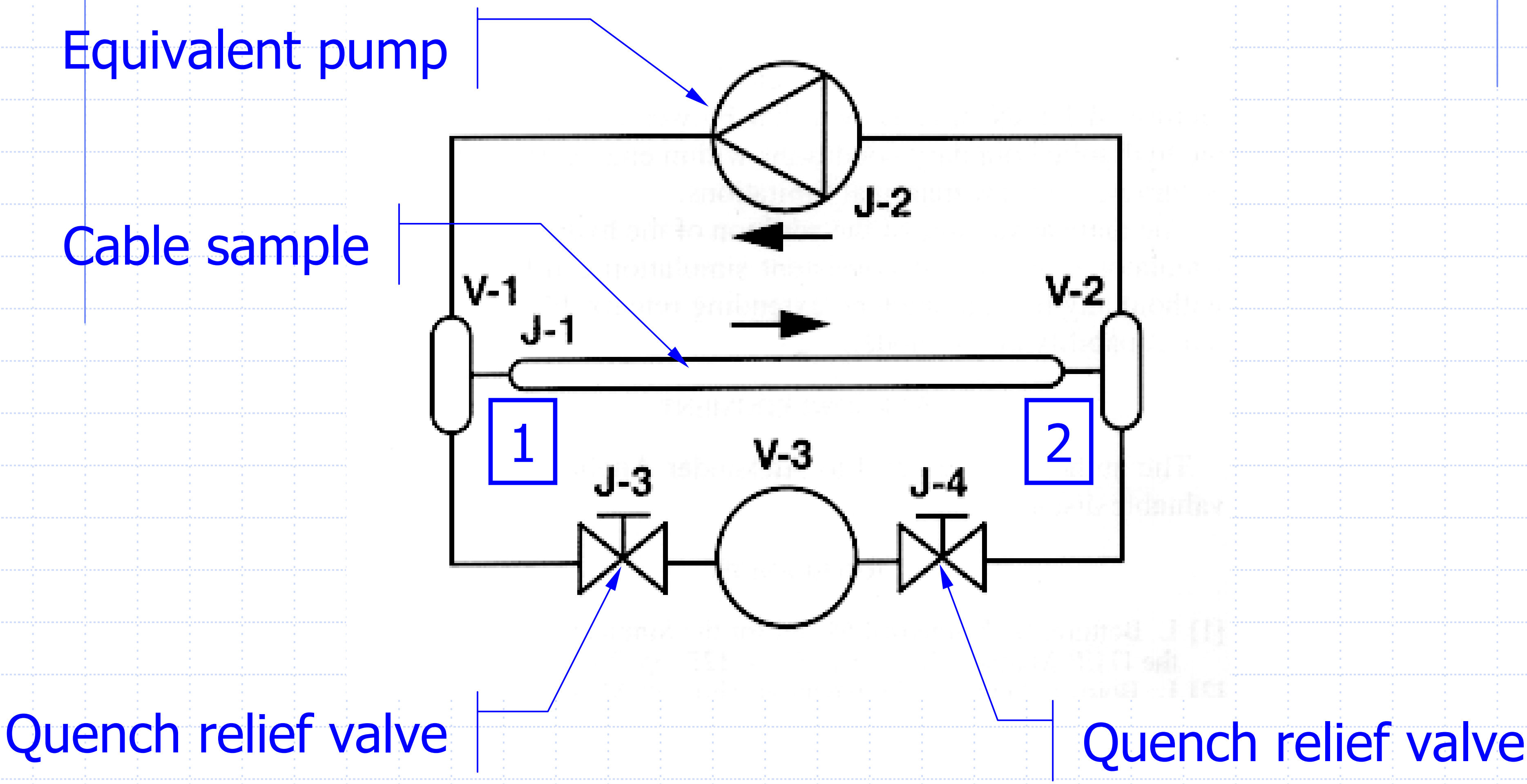
Flow regulation

Current lead

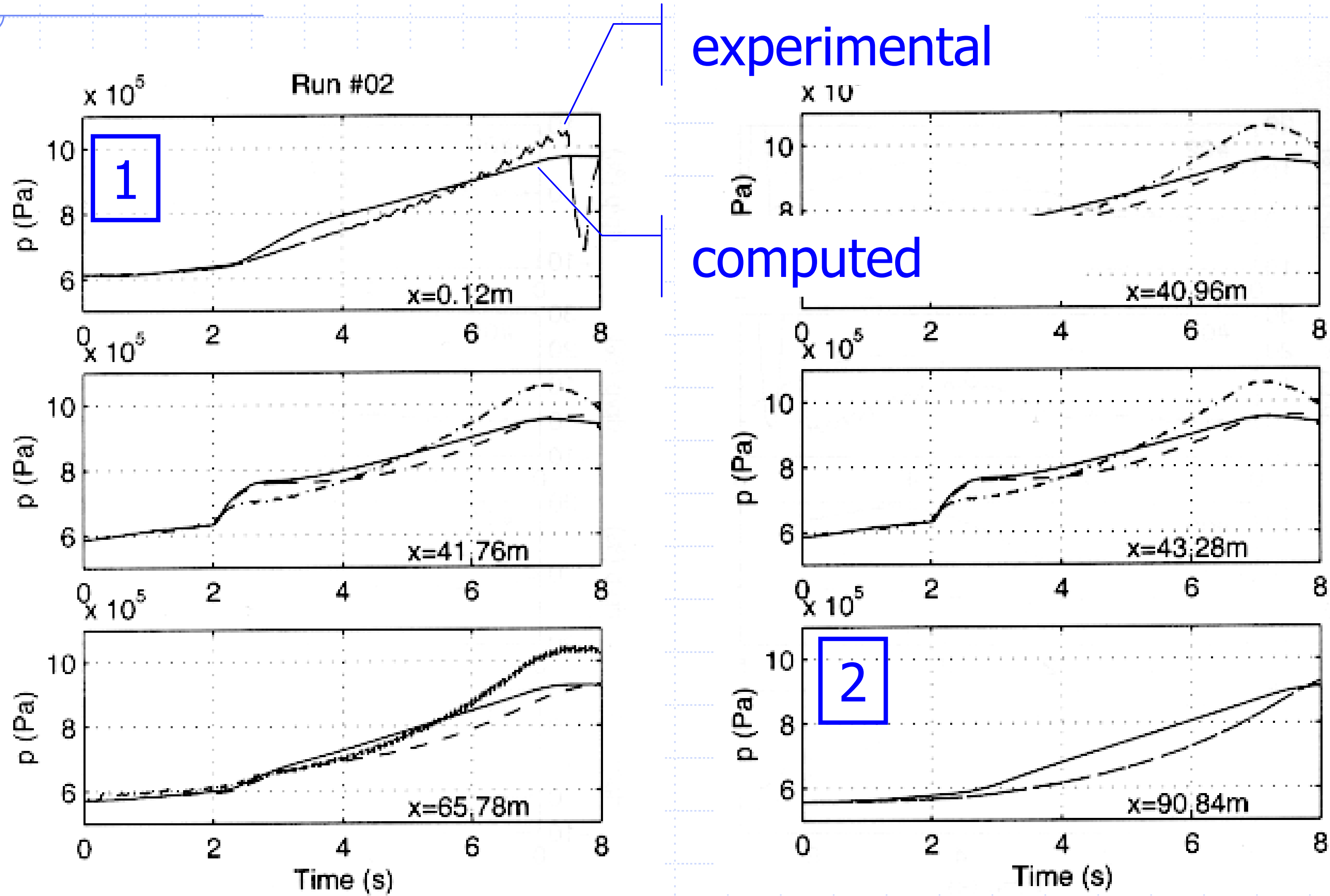
Cable sample



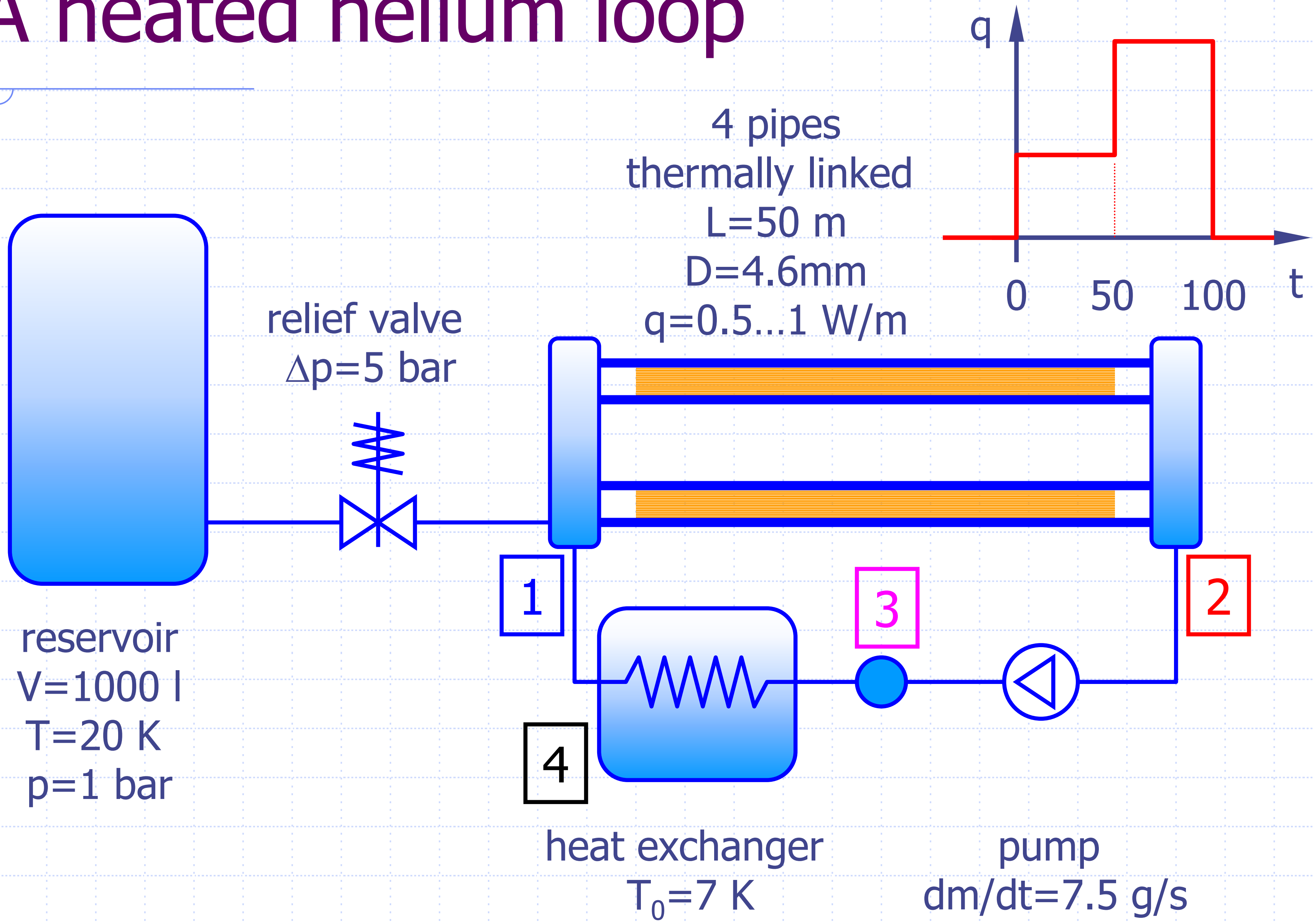
QUEnch on Long Length



QUEnch on Long Length

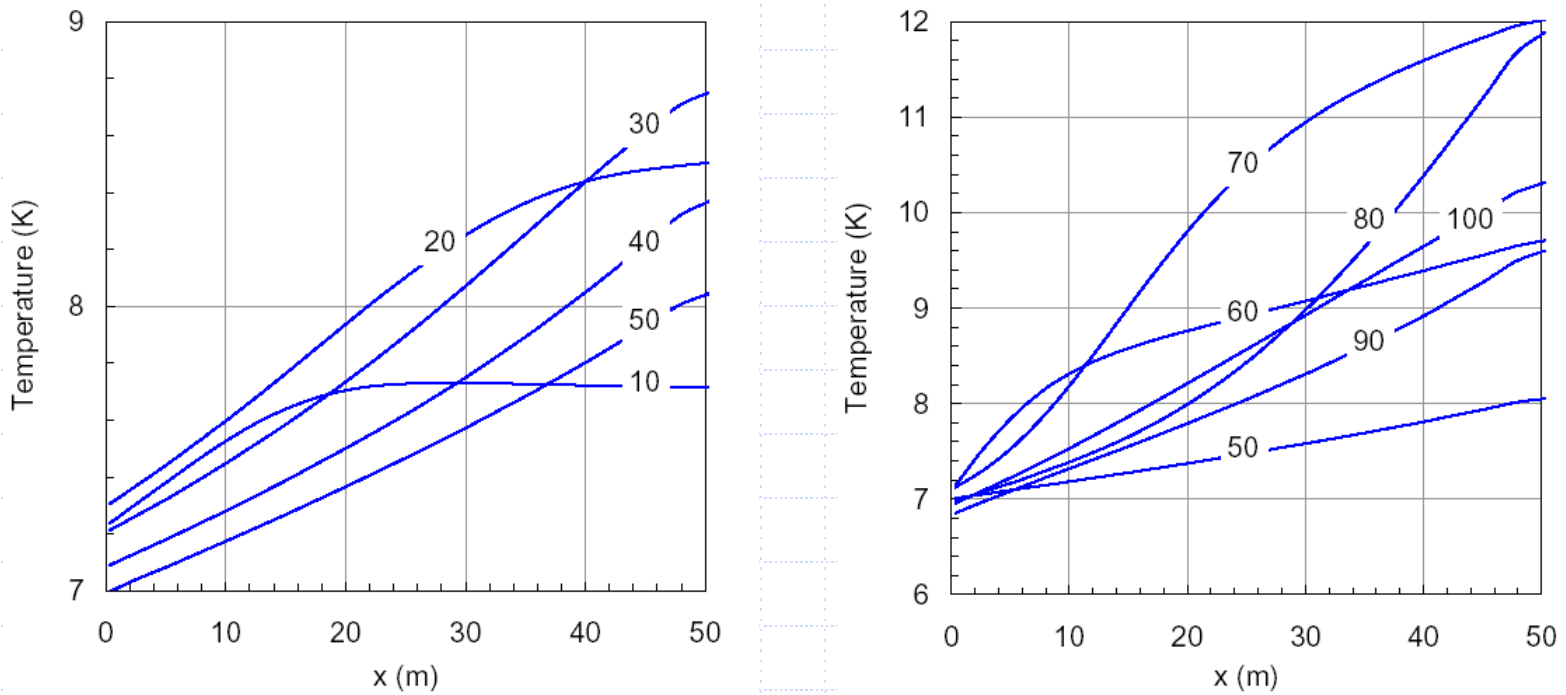


A heated helium loop



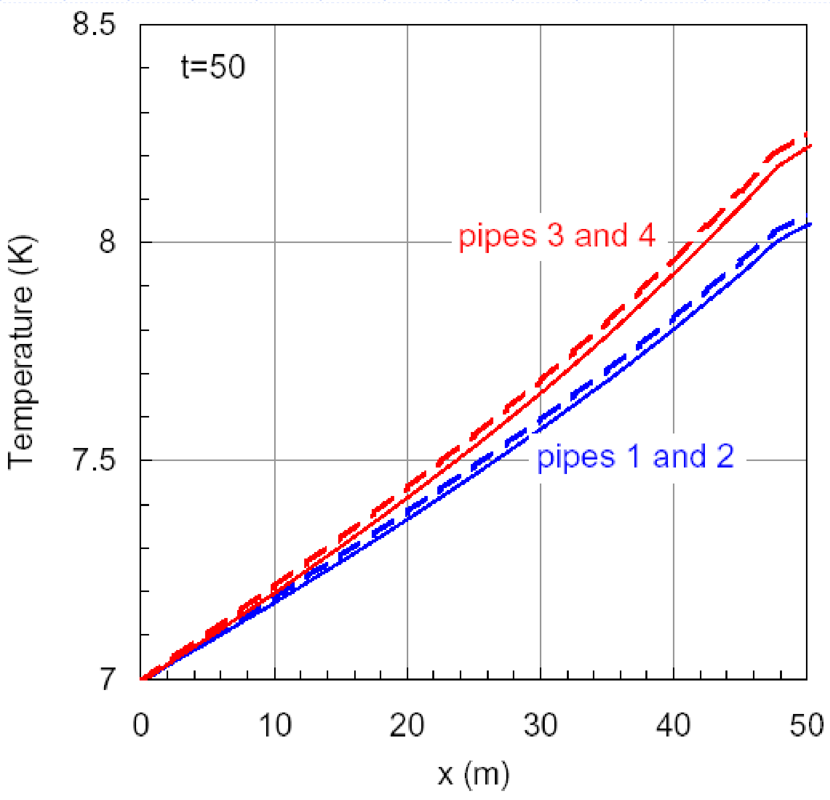
A heated helium loop

Temperature along the pipe



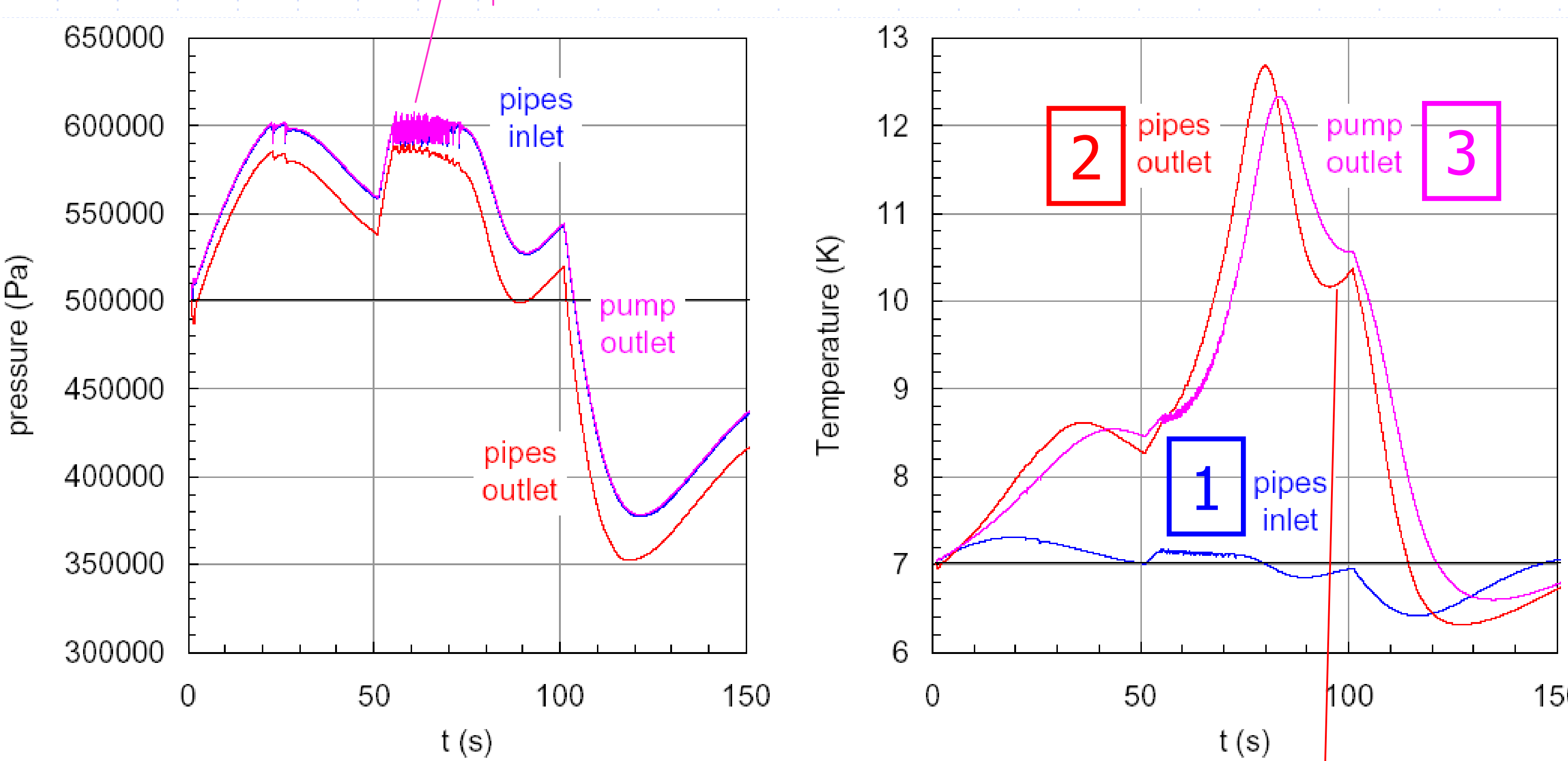
A heated helium loop

Temperature distribution among the pipes
differences in friction factor +/- 15 %



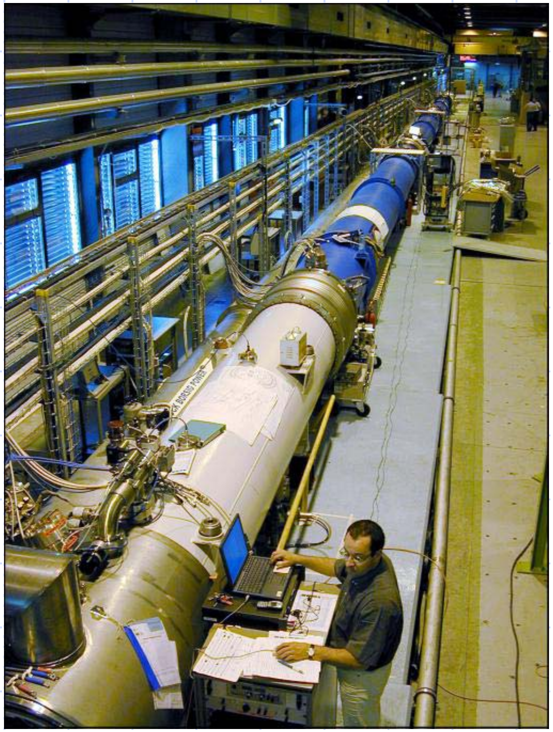
A heated helium loop

oscillations induced by the relief valve

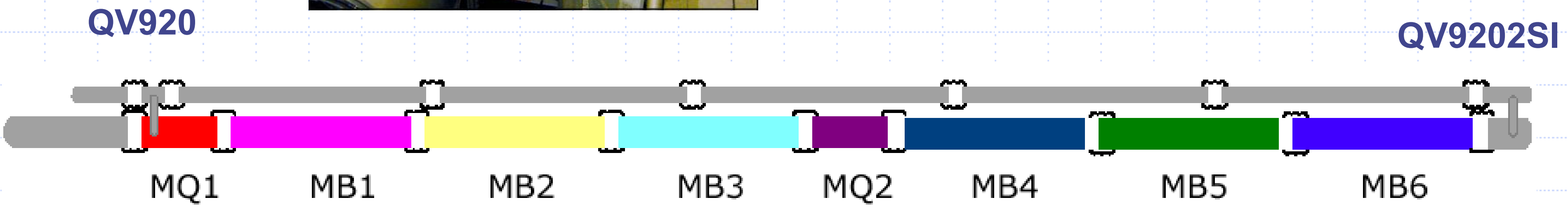


oscillations due to the response of the system

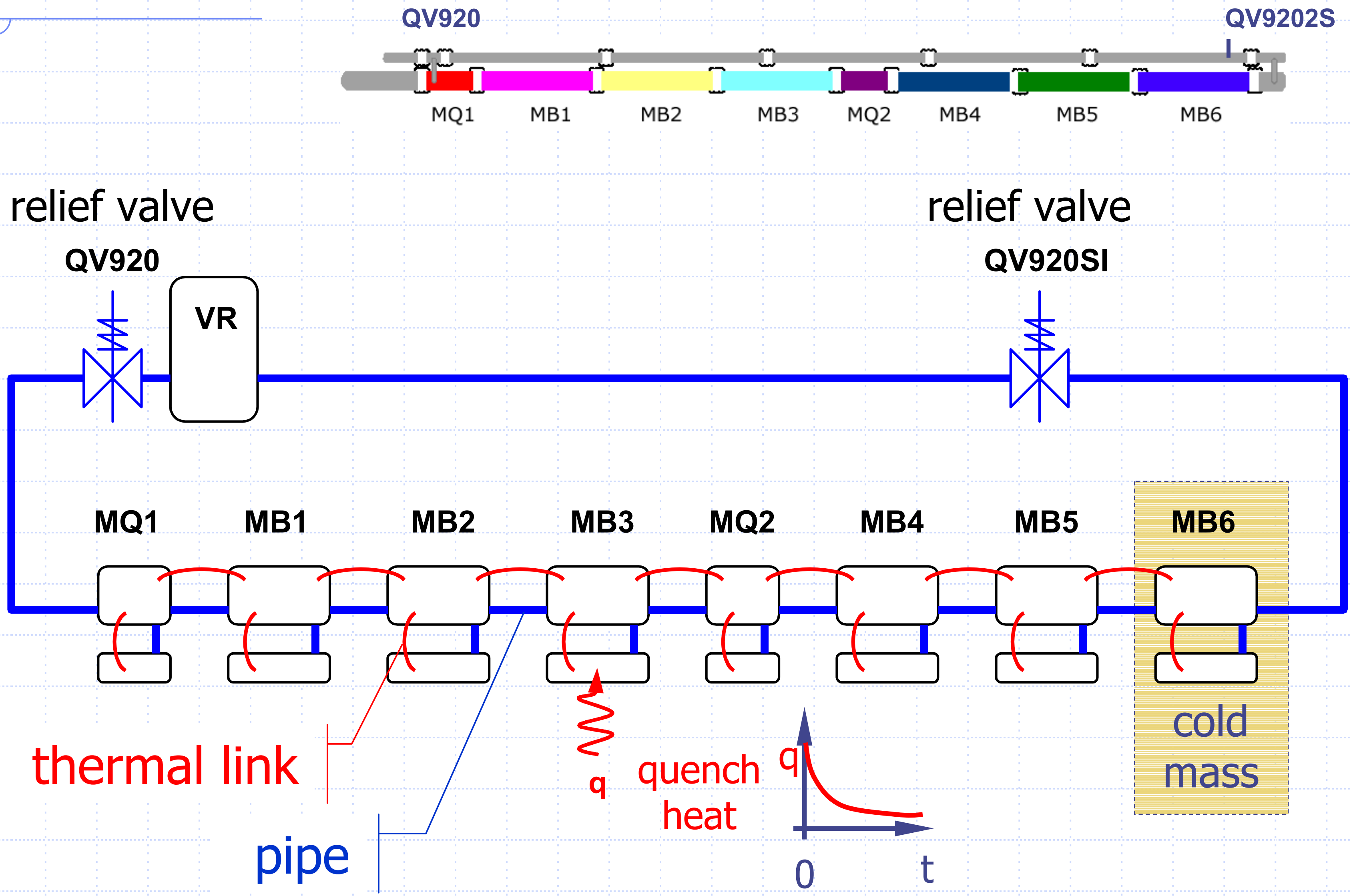
A *string* of LHC magnets



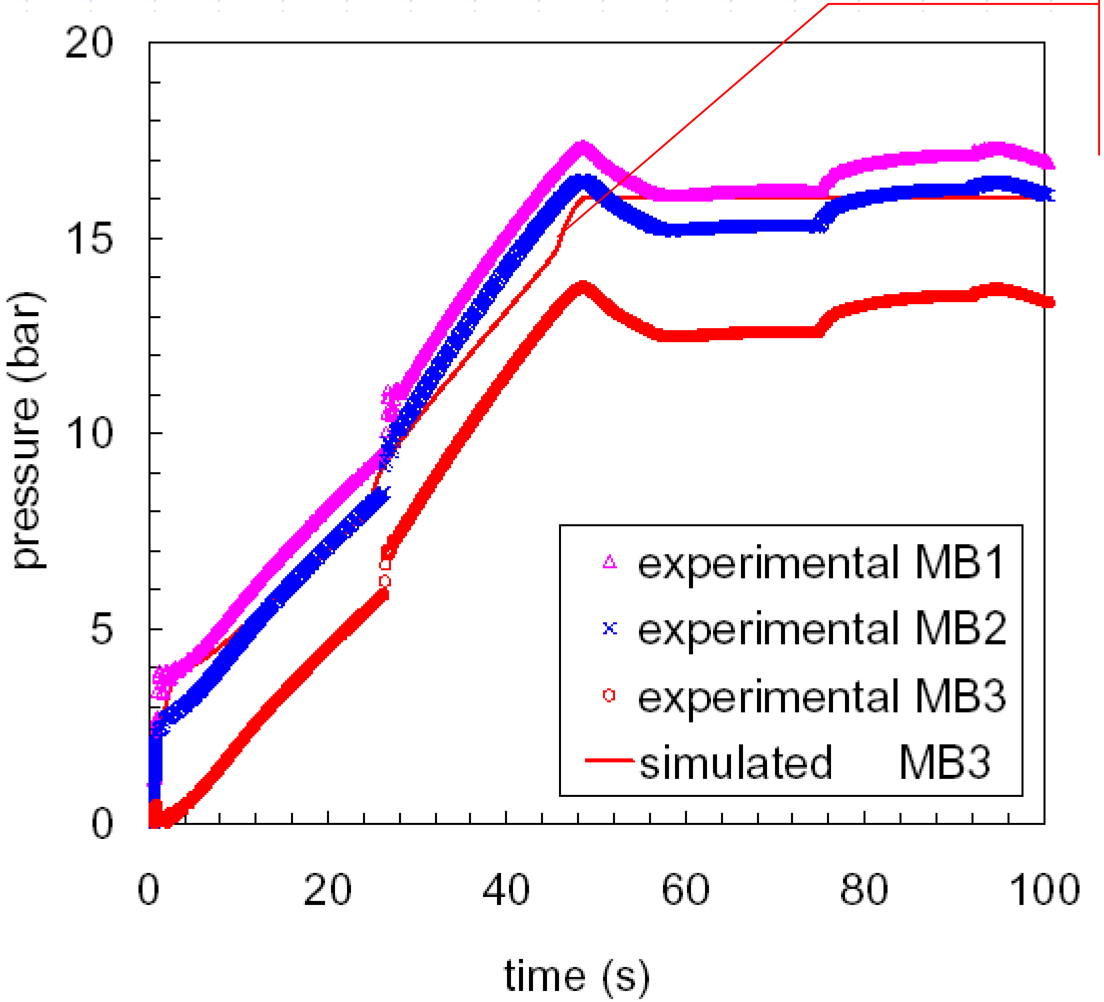
- model of the regular LHC cell:
  - D quadrupole and lattice correctors
  - 3 dipoles
  - F quadrupole and lattice correctors
  - 3 dipoles



A *string* of LHC magnets



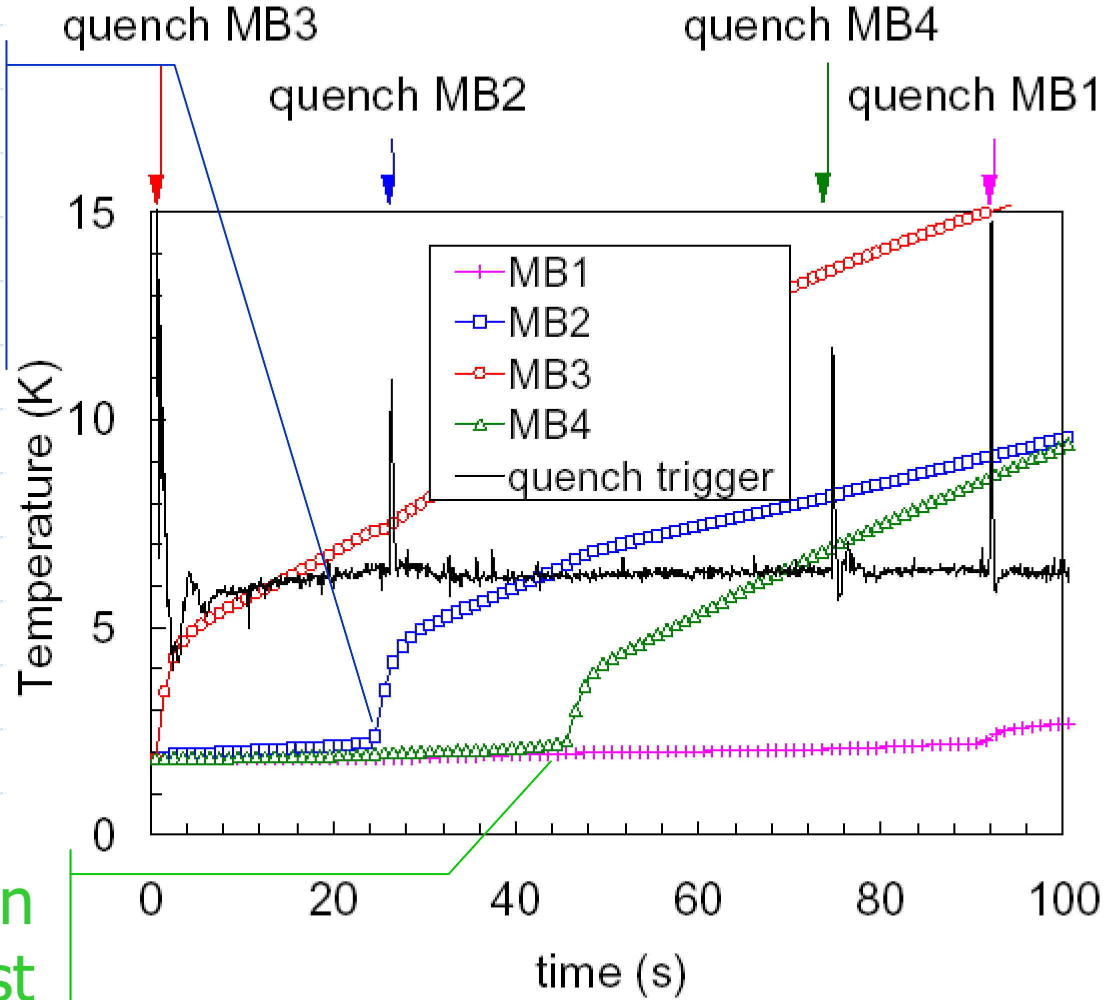
Pressure evolution



computed pressure OK

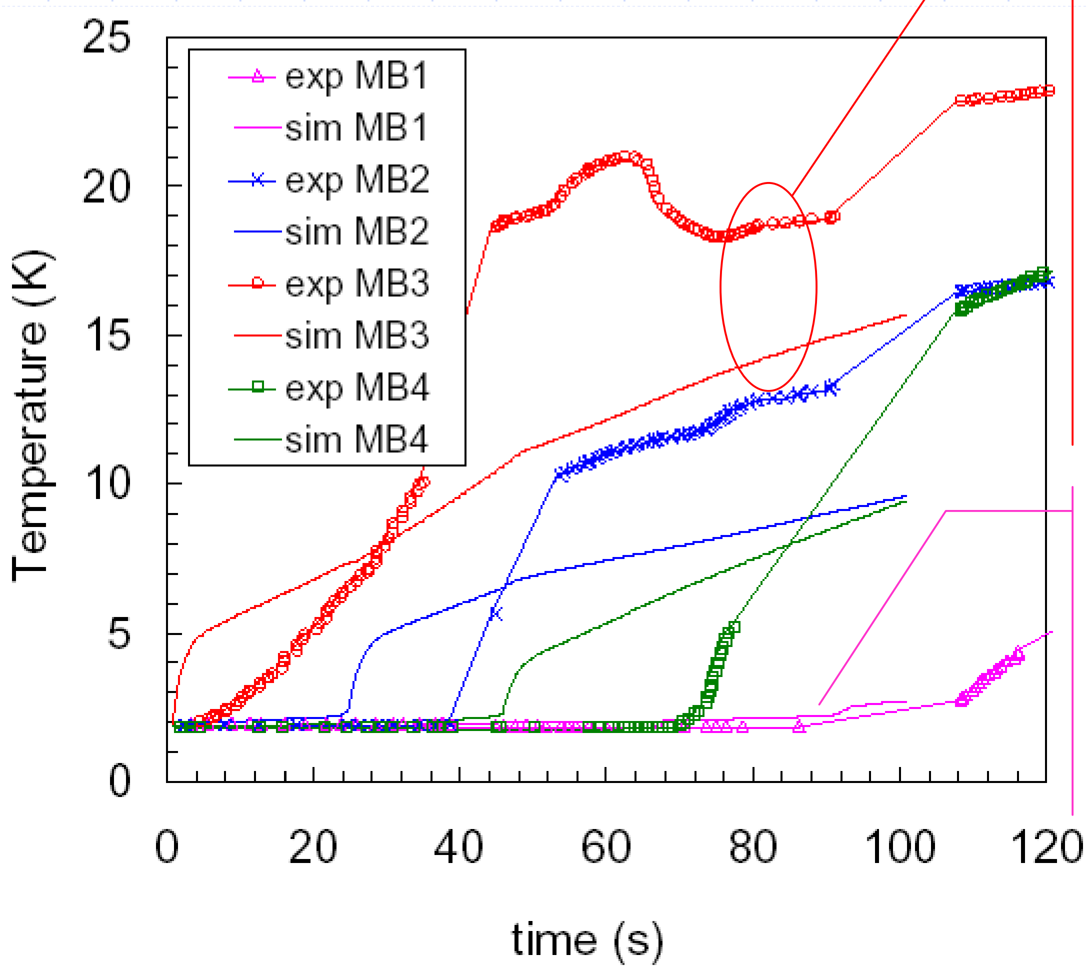
Quench propagation

reasonable match of quench propagation MB3-MB2-MB1



quench propagation MB3-MB4 too fast

Temperature evolution



computed temperature corresponds to *time averaged* measured value (no spatial detail)

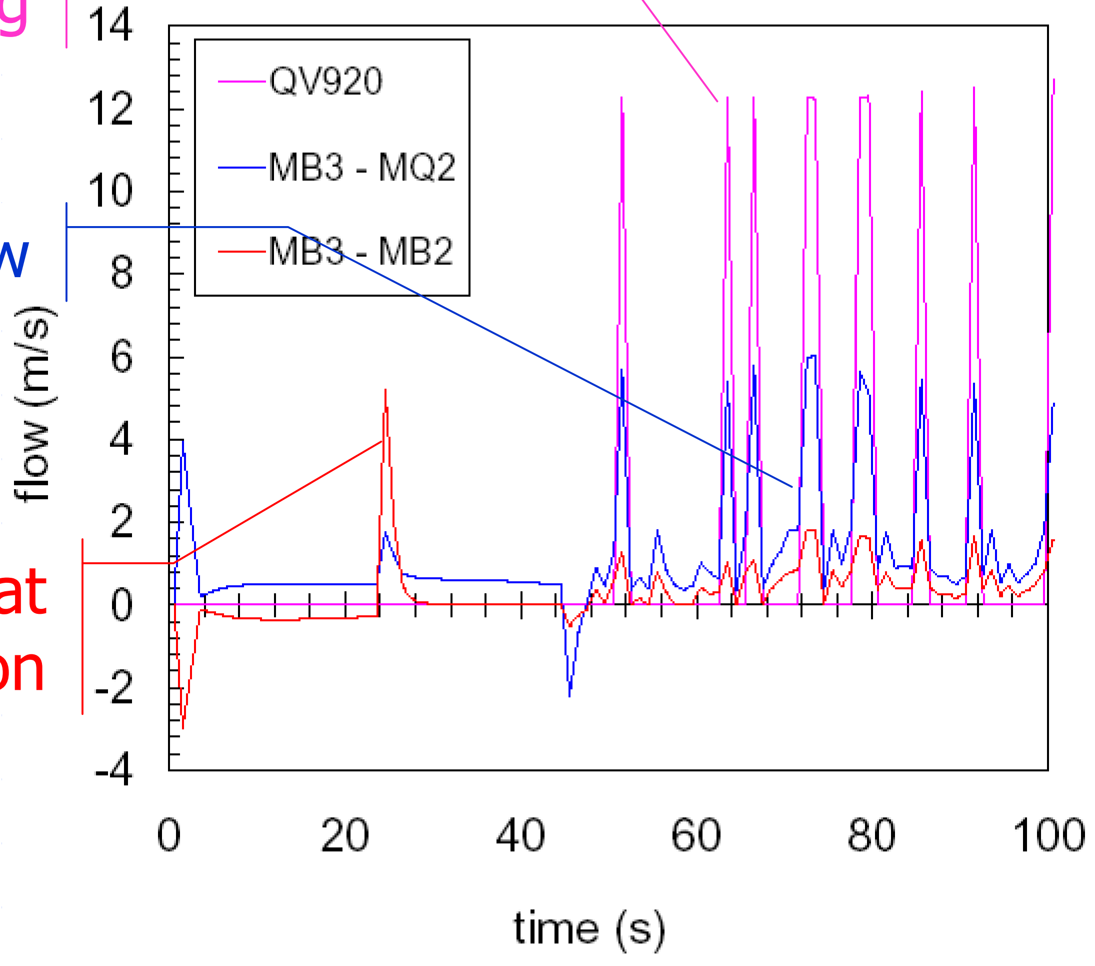
by the way... superfluid heat transport is included

Induced flow and discharge

valve opening

discharge flow

short flow bursts at quench initiation



Summary…

The model in Flower v4.0 has improved:

- include new features
  - turbines
  - heat exchangers
- take advantage of matrix sparseness
  - reduce memory requirements
  - decrease CPU time

allow solution of larger, more complex systems

… and perspectives

Towards *system solution*

- avoid need for coupling different codes, describing the assembly of:
  - cryogenic plant
  - proximity cryogenics
  - end-user(s)
- a significant improvement is necessary for the next step:
  - single models (turbine, pumps)
  - two-phase thermodynamics and flow