A Physics-Based Simplified Model for the ITER Cooling Loops

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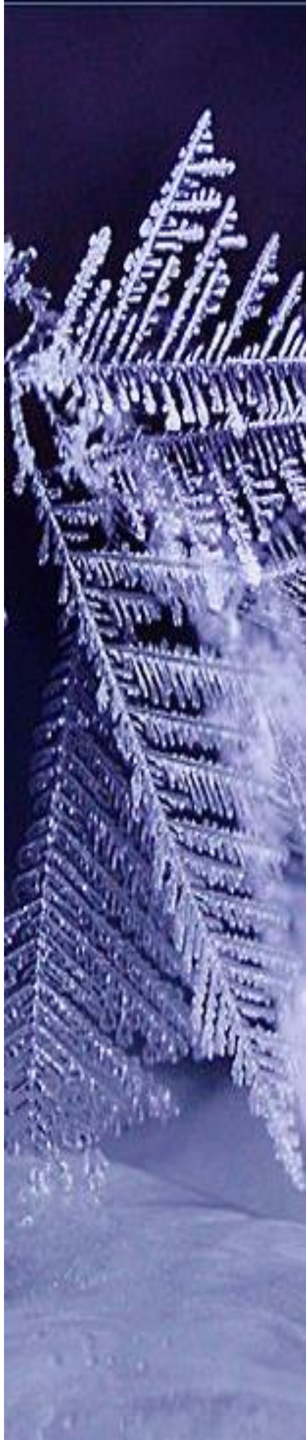
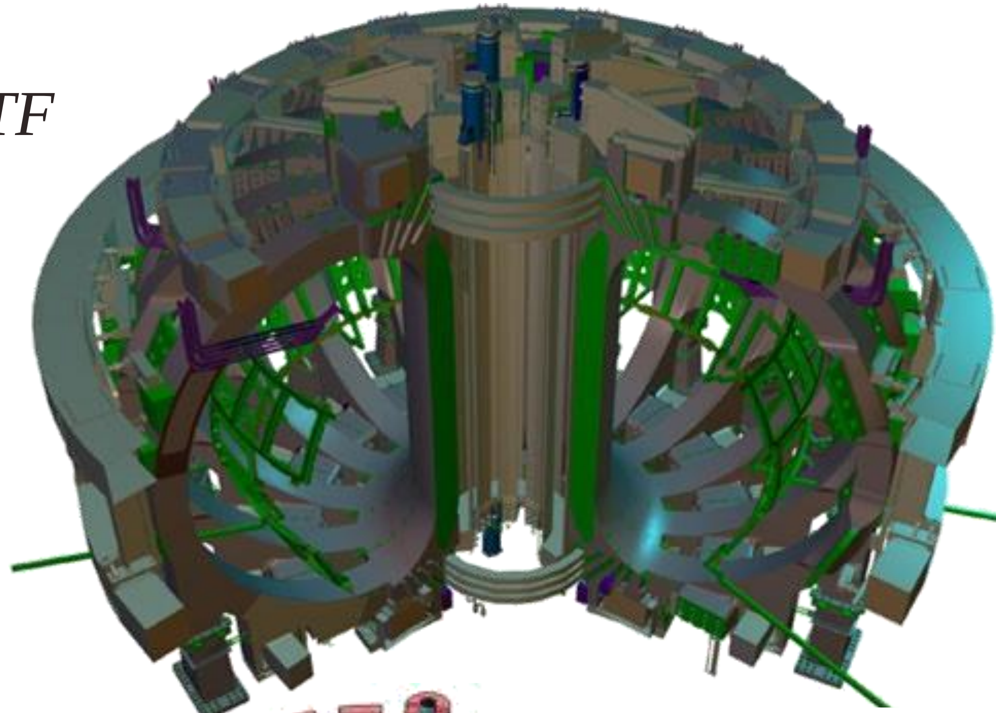


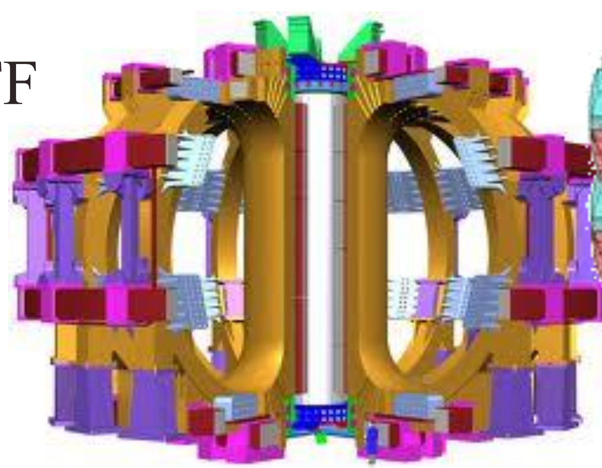
CHATS-AS Workshop
Bologna, September 14th-16th, 2015

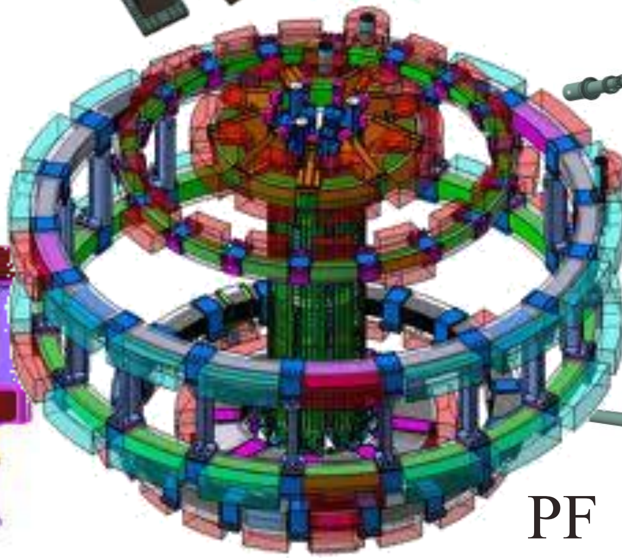
Analysis of ITER coils

- *ITER CS, PF, and TF* ***can be analyzed*** *through nominal plasma pulses, as well as off-normal conditions such as fast discharge and quench*

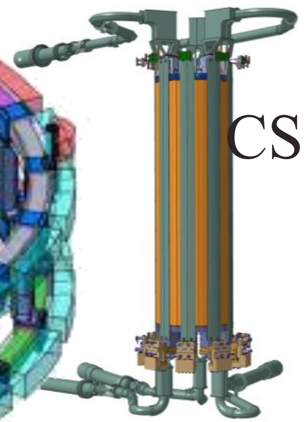


TF

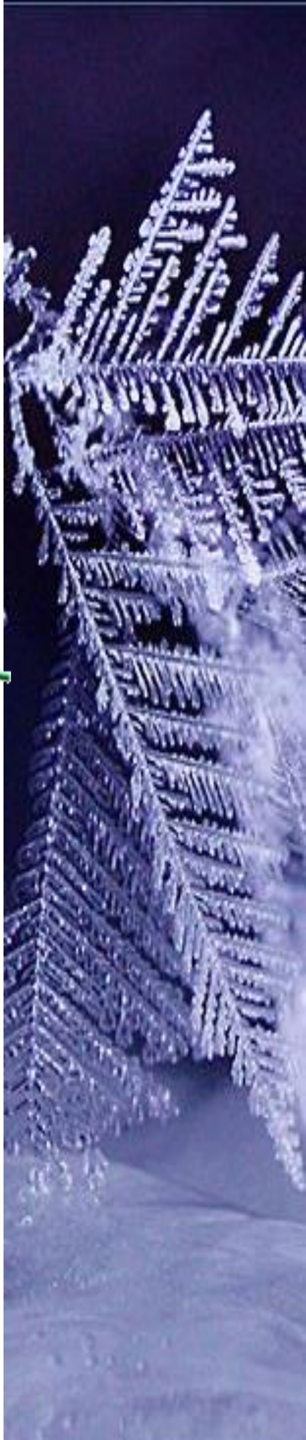




PF



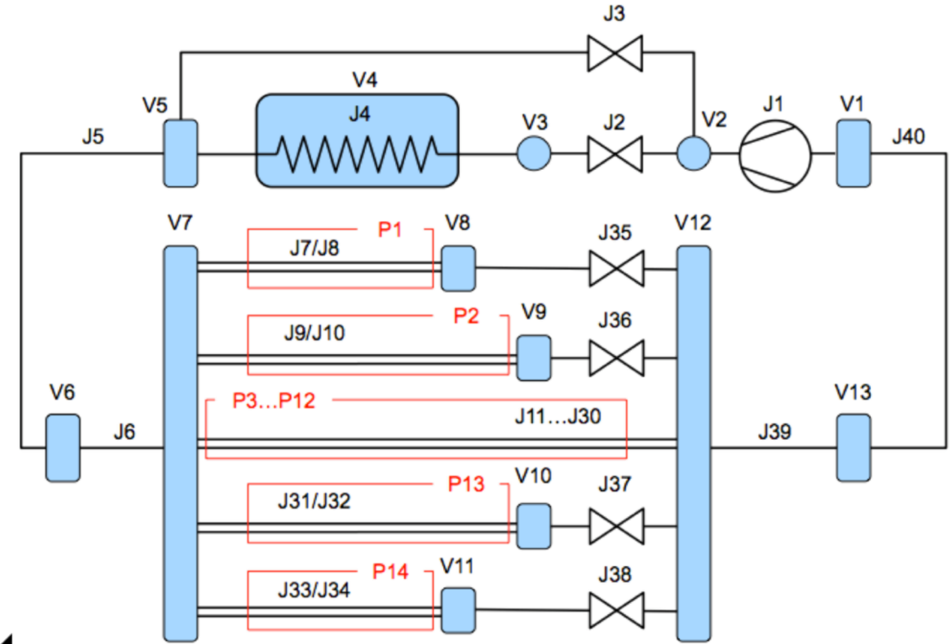
CS

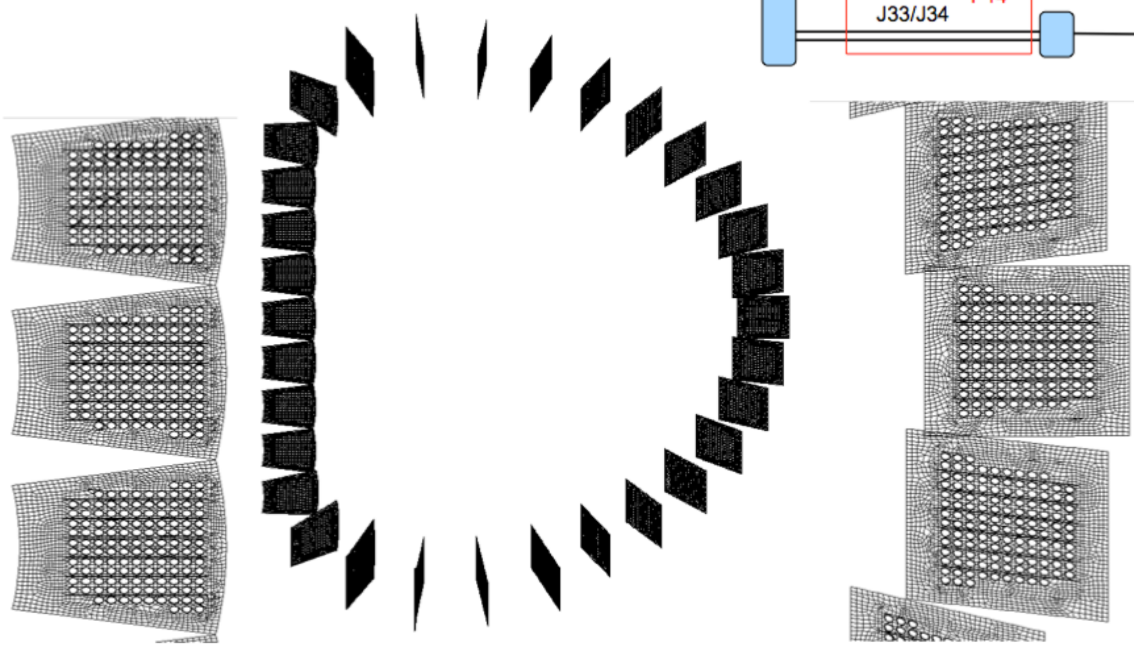


SuperMagnet model of TF

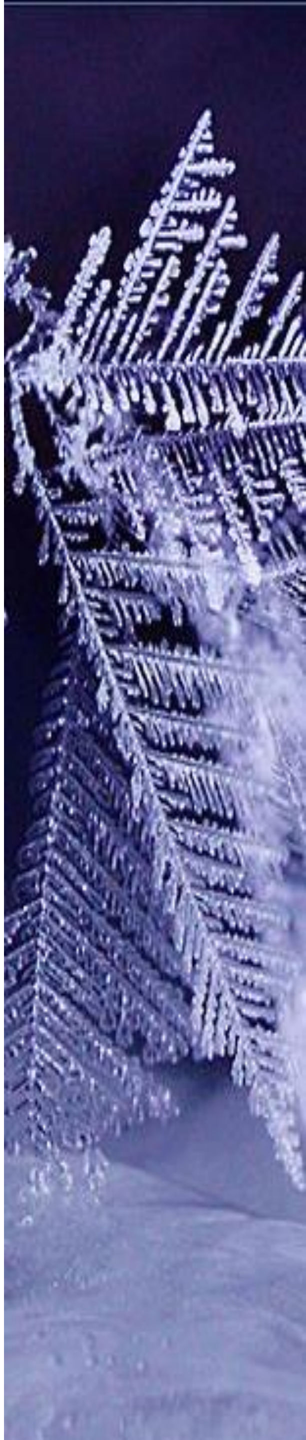
132 junctions
25 volumes

163706 nodes
151268 elements
38544 edges
32 sections



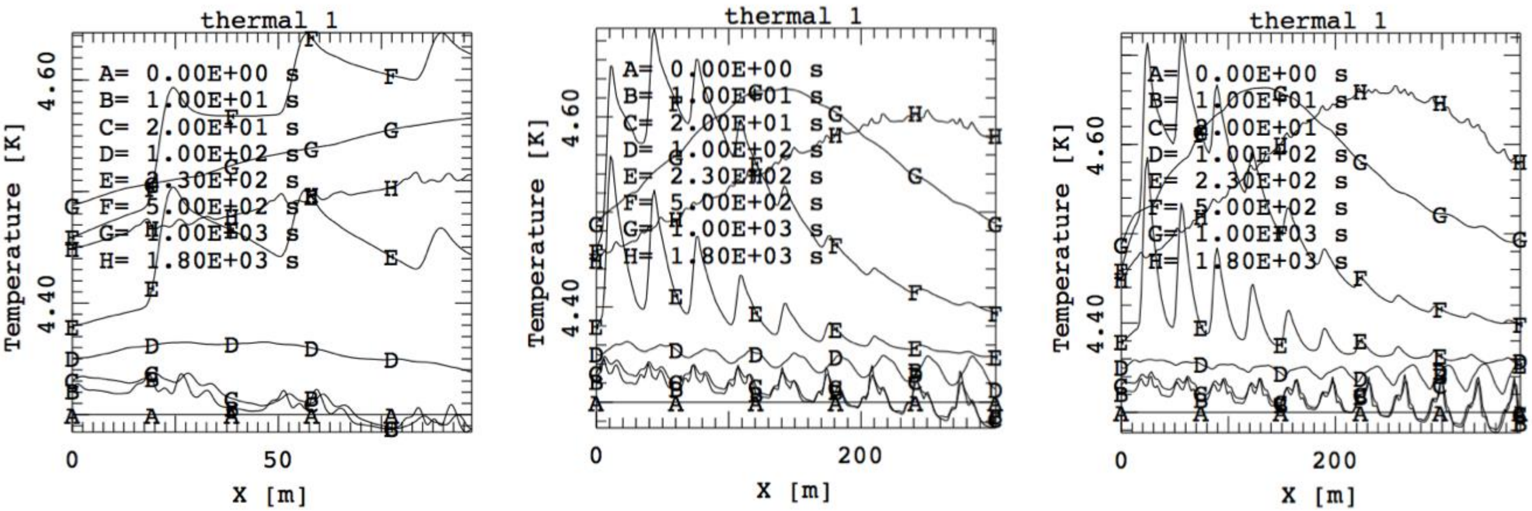


mesh generated with ANSYS by F. Gauthier (ITER-IO)

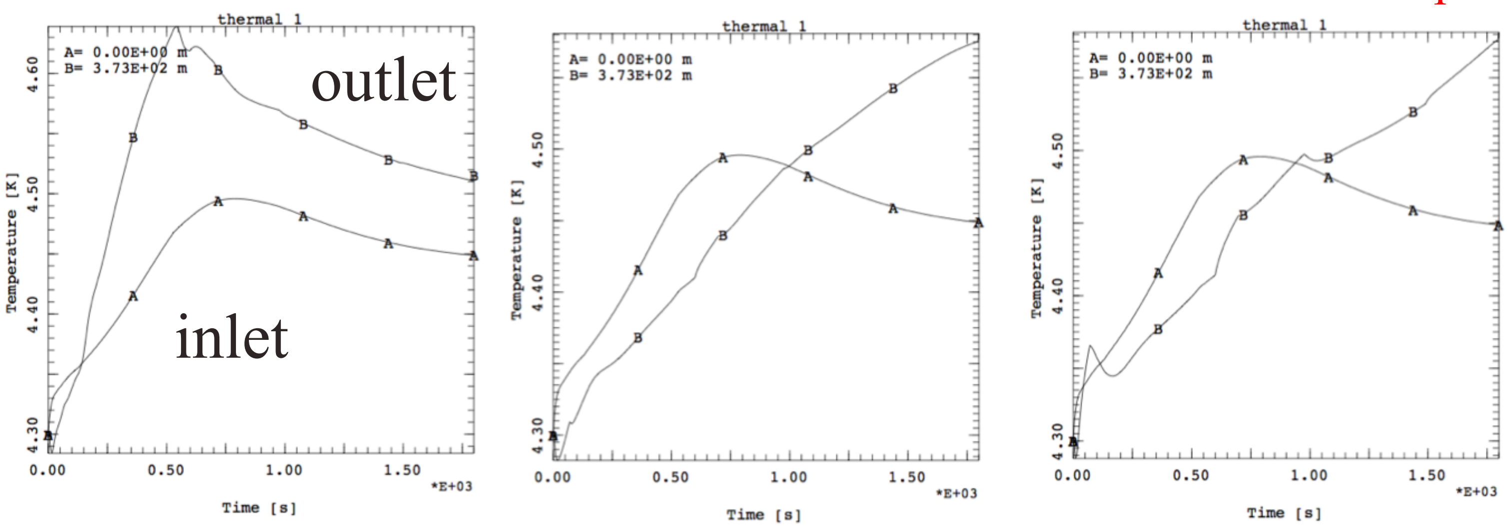


TF temperatures

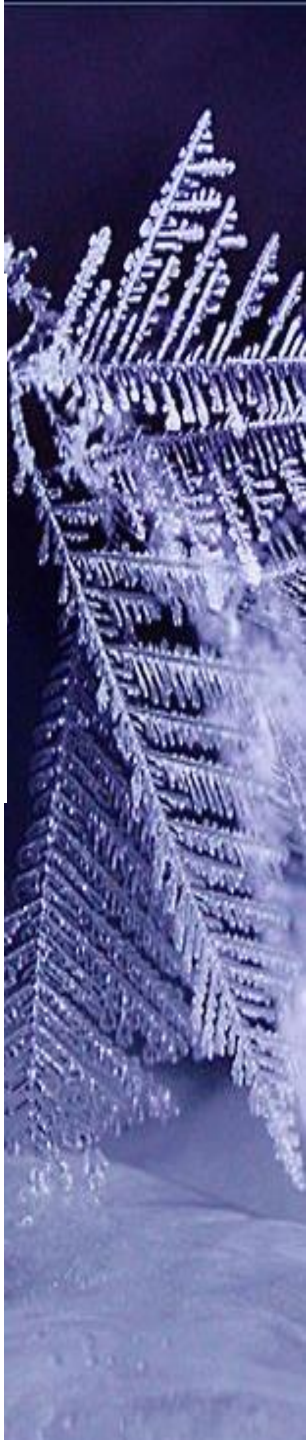
Pancake 1 | Pancake 2 | Pancake 7



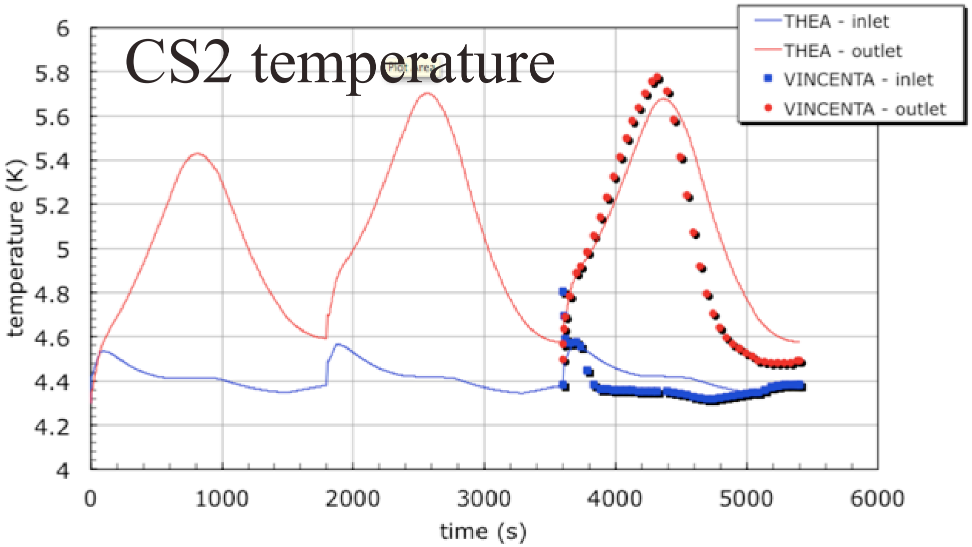
Periodic structure of heat input



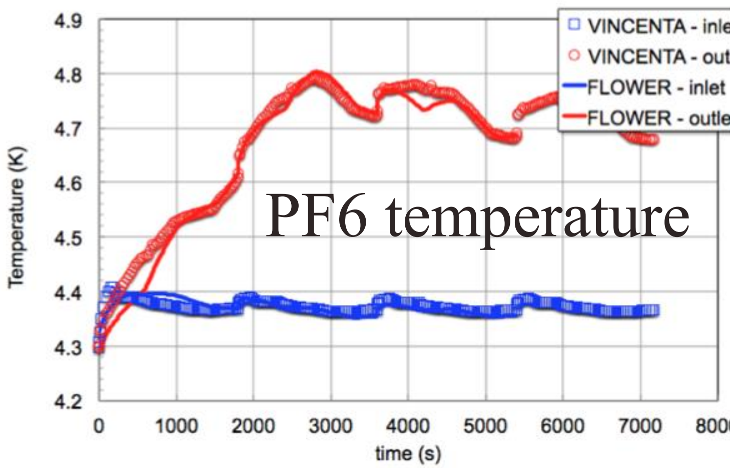
Difference in residence times

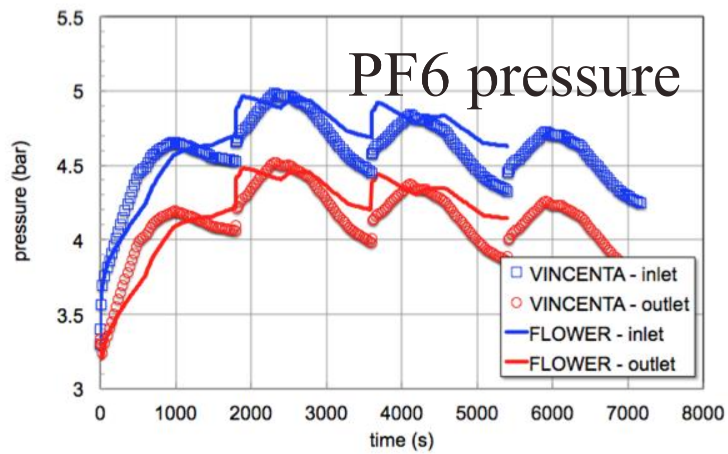


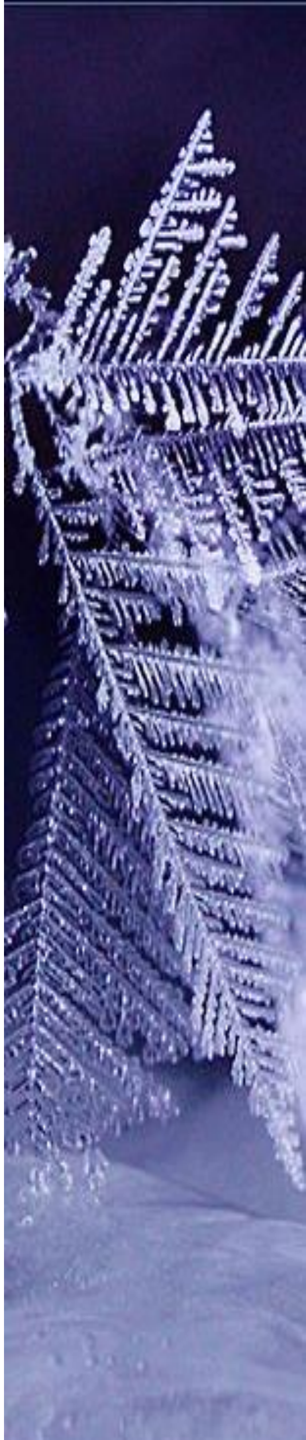
Comparison to other simulators



Direct comparison to VINCENTA provides a satisfactory match: the models make sense



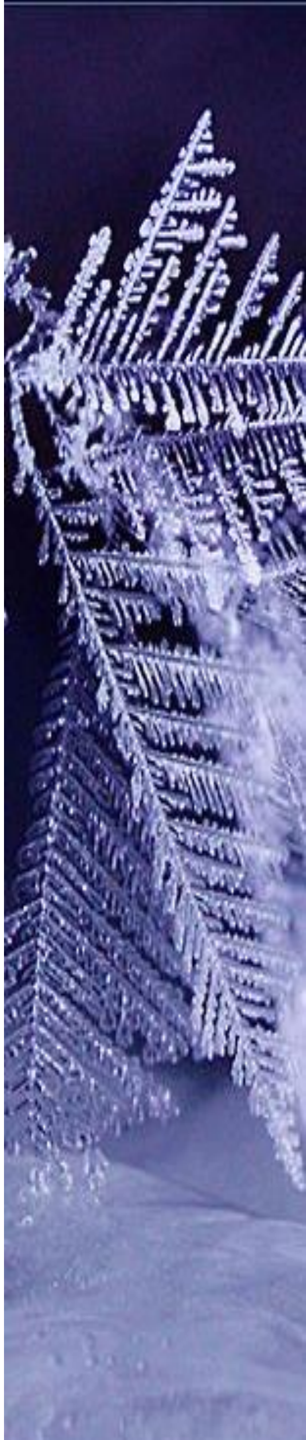




Temperature margins well within allowables

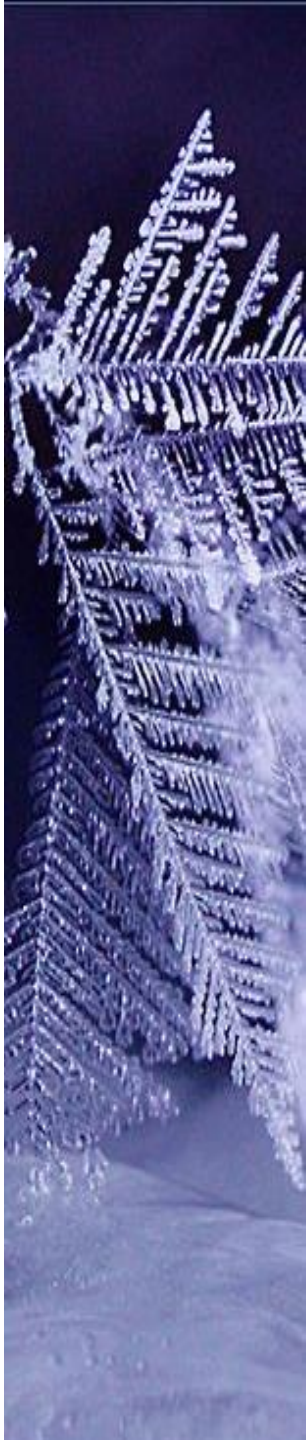
The snag…

The simulation of three plasma burns takes 32.6 hours



Possible solutions

- *Patience*
- *Get a faster computer*
- *Simplify the model*
  - *Computational (Furci, Luongo at CHATS-2013)*
  - *Process simulation (R. Maekawa, C-PREST; B. Bradu, ECOSIMPRO)*
  - *Analytical (Rousset, Hoa, Lagier, Vallcorba at CHATS-2011)*
- *Neural networks (fuzzy logic) (Savoldi, Zanino, CHATS-2013)*
- *Control approach*
  - *Classical control theory (Gayet @ LHC)*
  - *Adaptive controls, model identification, etc.*



Physical model

FLOWER v4.2

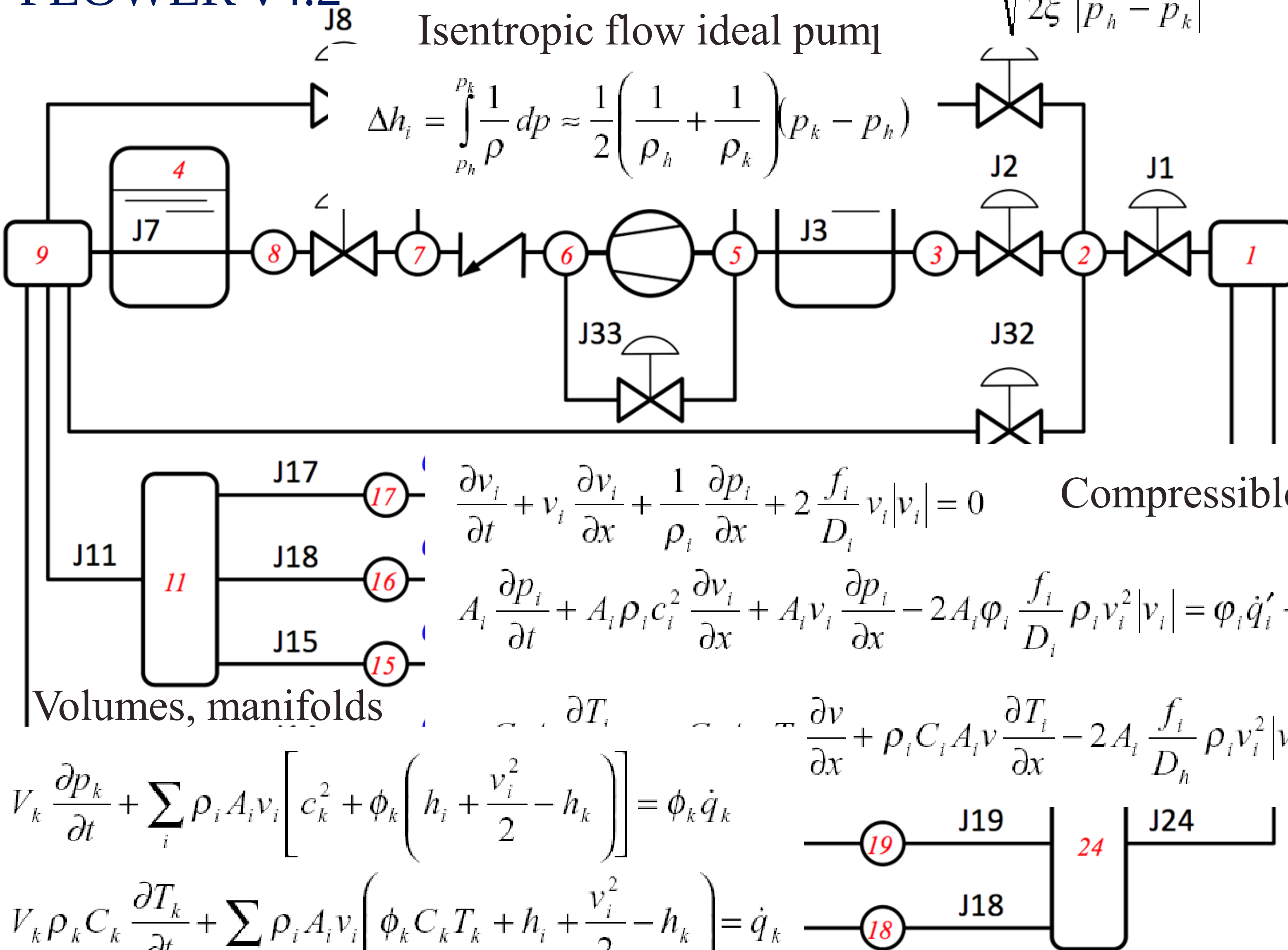
Valves

$$\dot m_i = \alpha (p_k - p_h)$$

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

Isentropic flow ideal pump

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



Compressible flow pipes

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

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

$$\ldots \frac{\partial T_i}{\ldots} \ldots \frac{\partial v}{\partial x} + \rho_i C_i A_i v \frac{\partial T_i}{\partial x} - 2 A_i \frac{f_i}{D_h} \rho_i v_i^2 |v_i|_i = \dot q_i' + \dot q_{cf,i}'$$

Volumes, manifolds

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

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

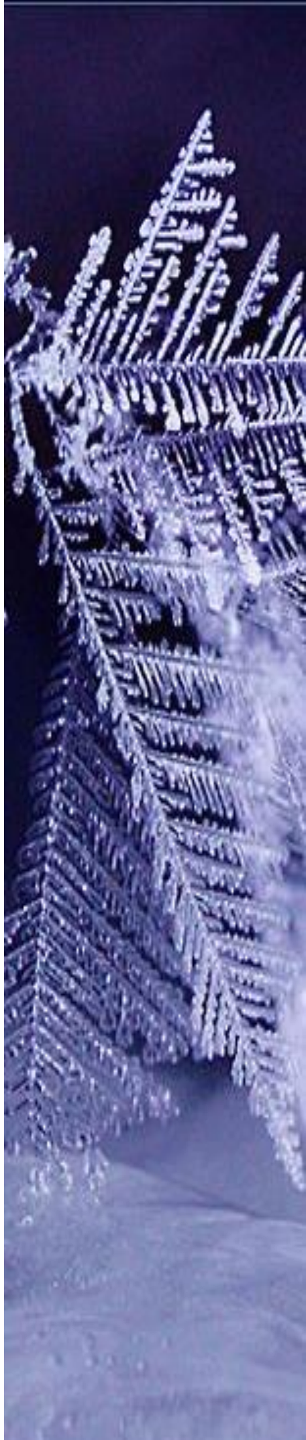
Model reduction

- *Consider (equal) parallel channels as a single unit (possible for non-equal channels too by weighted averages)*
- *Conserve the physical lengths and hydraulic diameter*
  - *Identical pressure drop and residence time*
- *Cumulate cross sections and heat loads*
  - *Identical enthalpy and temperature profile*

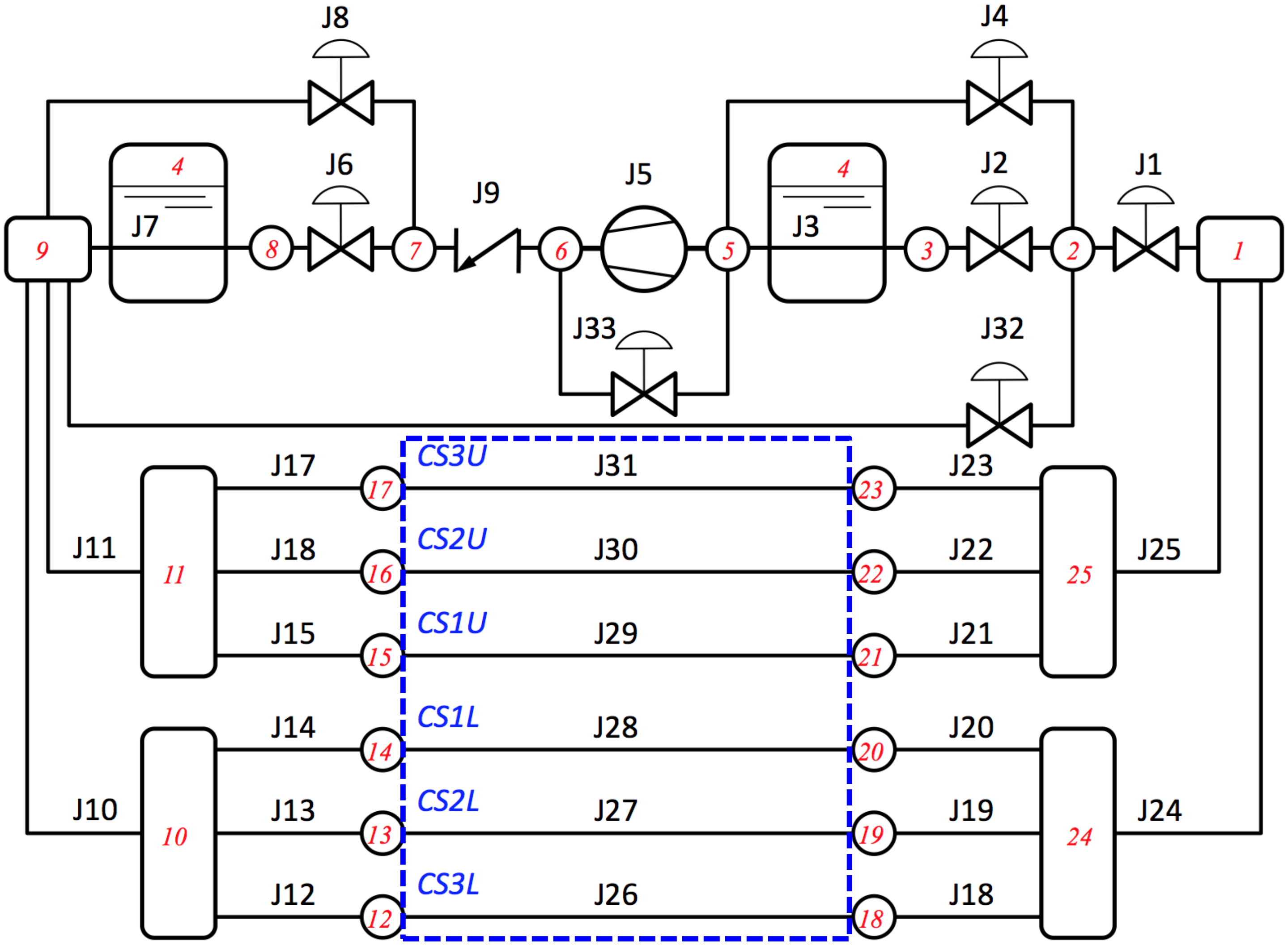
$$v_i = dm_i/dt \,/\, (A_i\rho) \qquad v_{eq} = dm_{tot}/dt \,/\, (A_{tot}\rho)$$

$$dp_i/dx = 2f/D_h \; \rho v_i^2 \qquad dp_{eq}/dx = 2f/D_h \; \rho v_{eq}^2$$

$$\Delta h_i = dq_i/dt \,/\, dm_i/dt \qquad \Delta h_{eq} = dq_{tot}/dt \,/\, dm_{tot}/dt$$

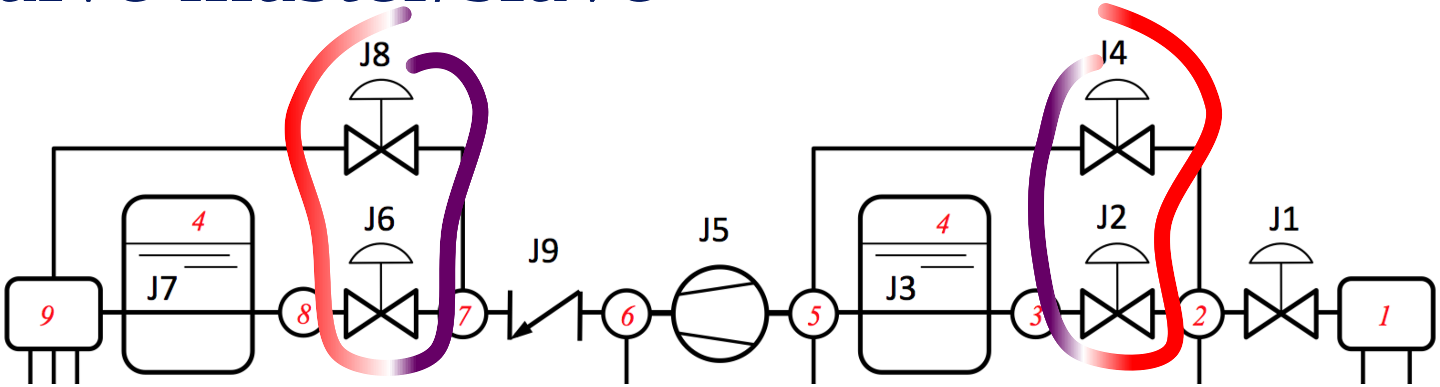


Simplified CS model



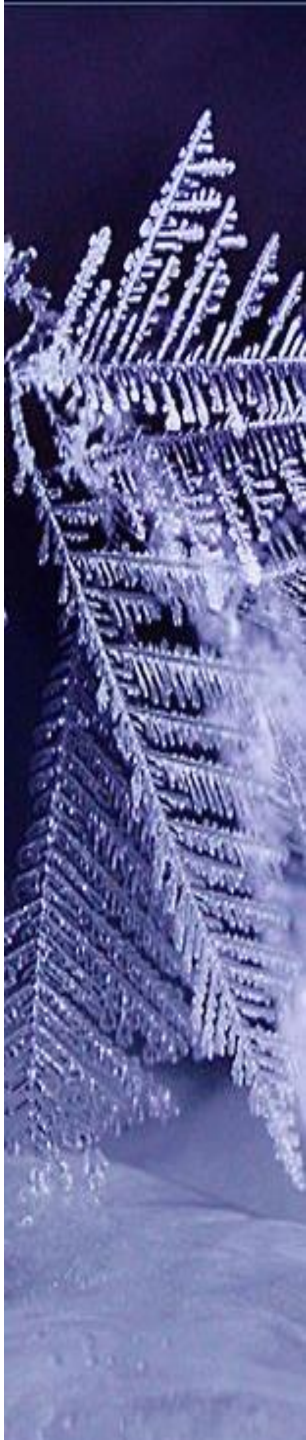
Each pipe represents 40 dual flow channels

Valve master/slave



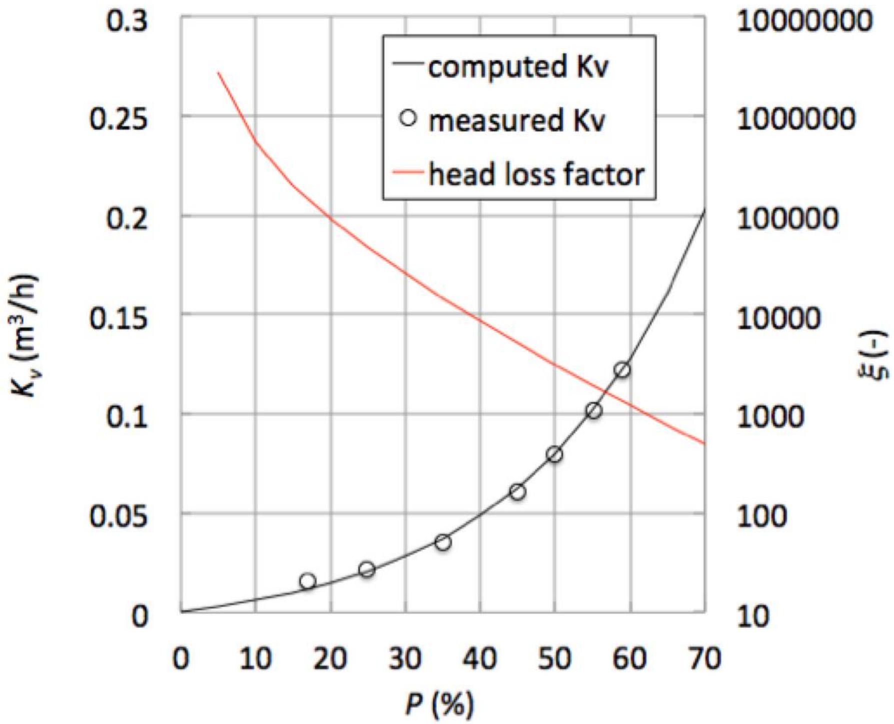
- *Two valves are used in tandem of* ***master*** *and* ***slave*** *when using a flow by-pass*
- *The impedance seen by the pump is (approximately) constant by acting on the two valves in tandem:*

$$K_v = K_{v,master} + K_{v,slave}$$



Control valve model

Example of control valve in HELIOS



- *Valve pressure drop (FLOWER)*

$$p_{in} - p_{out} = \frac{2\xi}{A^2}\frac{\dot{m}^2}{\rho}$$

- *Relation between ξ and K_v*

$$\xi \approx 6.48\ 10^8 \left(\frac{A}{K_v}\right)^2$$

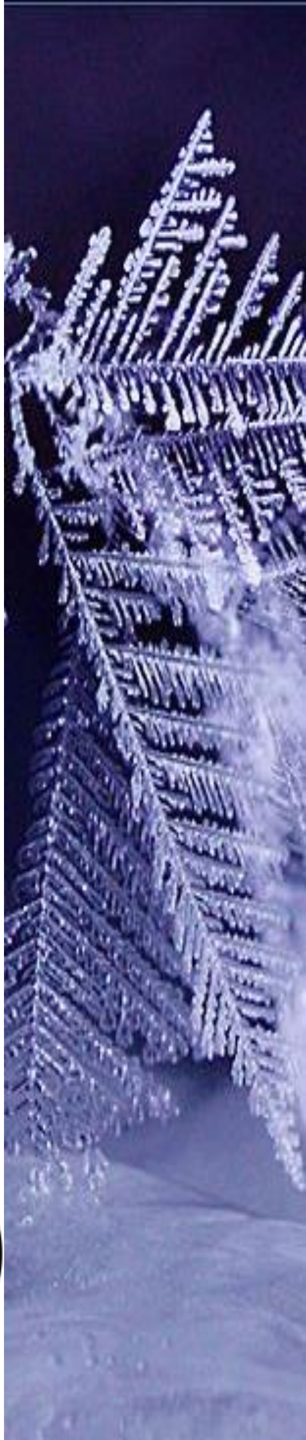
- *Effect of opening in a typical control valve*

DN15

Nominal $K_v = 0.48$, $R = 100$

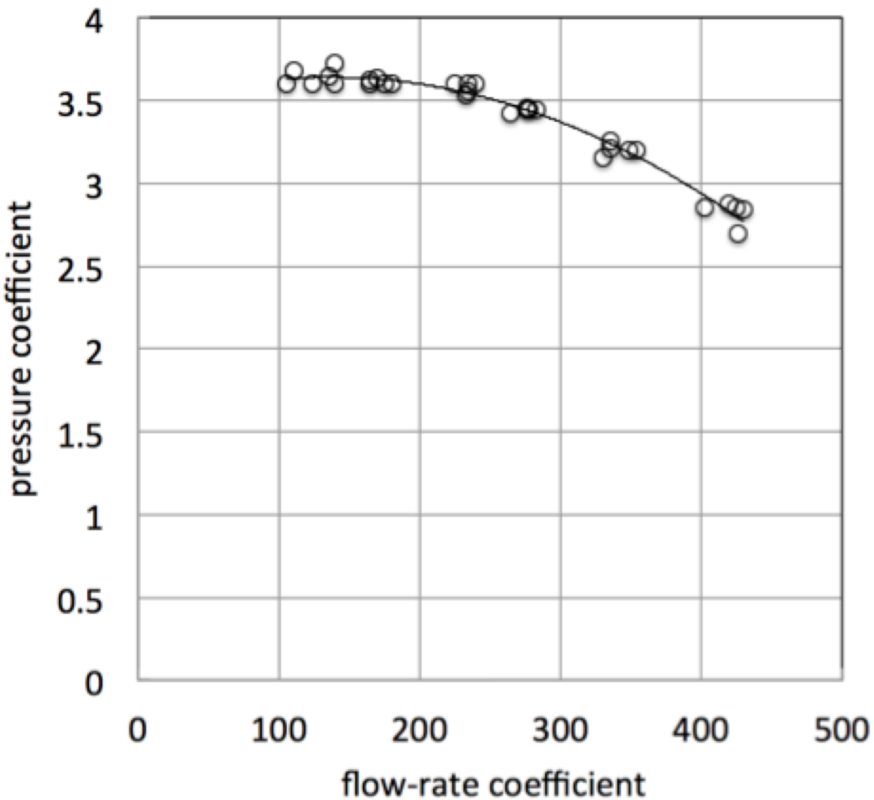
Calibrated $K_v = 0.79$, $R = 87$

$$K_v \approx \frac{K_v^{max}}{R}\left(e^{\frac{P}{100}ln(R)} - \left(1 - \frac{P}{100}\right)\right)$$



Pump (cold circulator)

Example of TFMC pump at KIT



$$\psi' = -10^{-5}\,\varphi'^2 + 0.0027\varphi' + 3.4571$$

- *Pump characteristic*

$$\psi = a\varphi^2 + b\varphi + c$$

$$\psi' = \frac{\Delta p}{N^2} \qquad \varphi' = \frac{\dot{m}}{N}$$

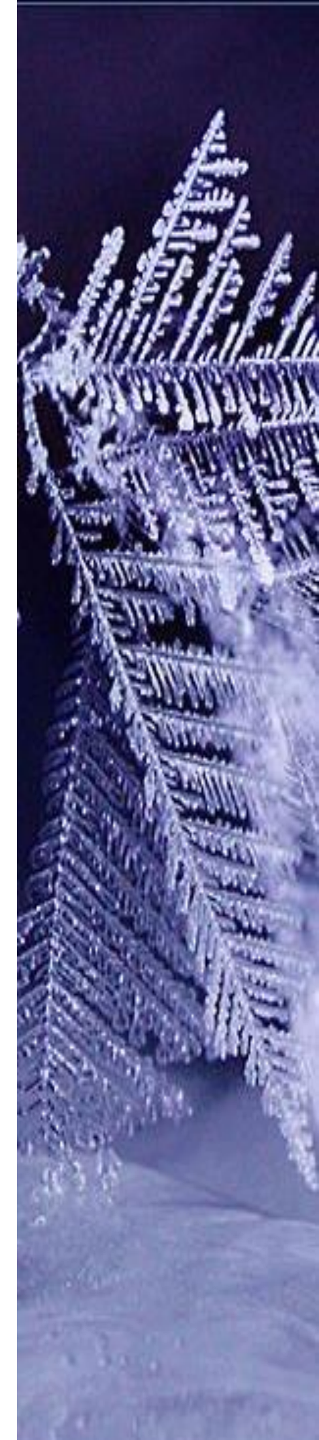
- *Range of validity*

$$\varphi_{surge} \leq \varphi \leq \varphi_{choke}$$

- *Isentropic efficiency*

$$\eta = C\,\dot{m}^m\,\Delta p^p\left(\frac{N}{N_{max}}\right)^n$$

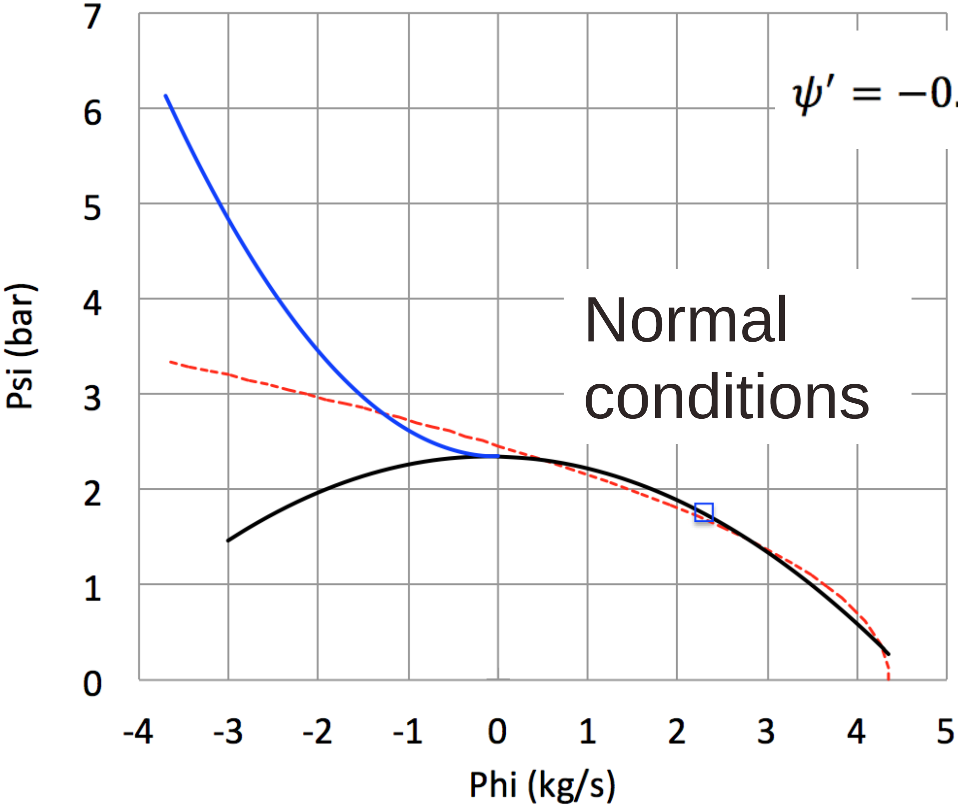
Not used at present



Pump (cold circulator)

normal conditions (dm/dt > surge)

ITER CS circulator



- *Pump characteristic*

$$\psi' = -0.1044\,\varphi'^2 - 0.0209\,\varphi' + 2.3452$$

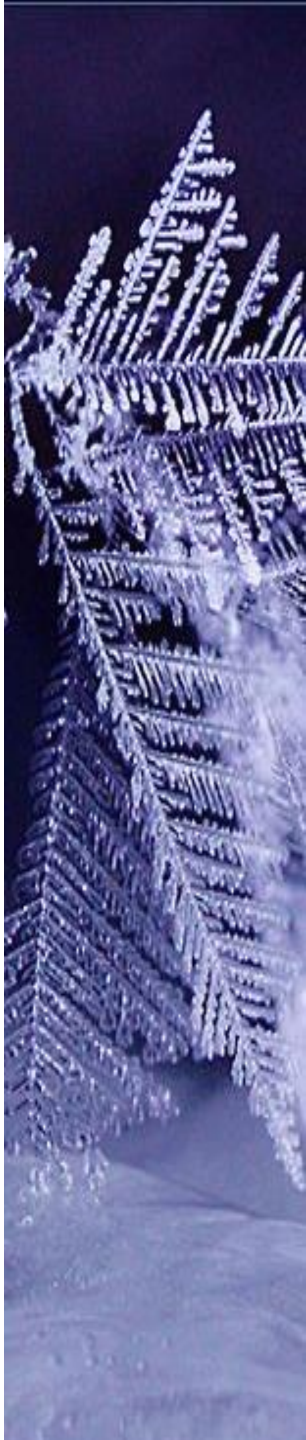
$$\psi' = \frac{\Delta p}{N^2} \qquad \varphi' = \frac{\dot{m}}{N}$$

- *Range of validity*

$$\varphi_{surge} \le \varphi \le \varphi_{choke}$$

$$\varphi'_{surge} = -\frac{b}{2a}$$

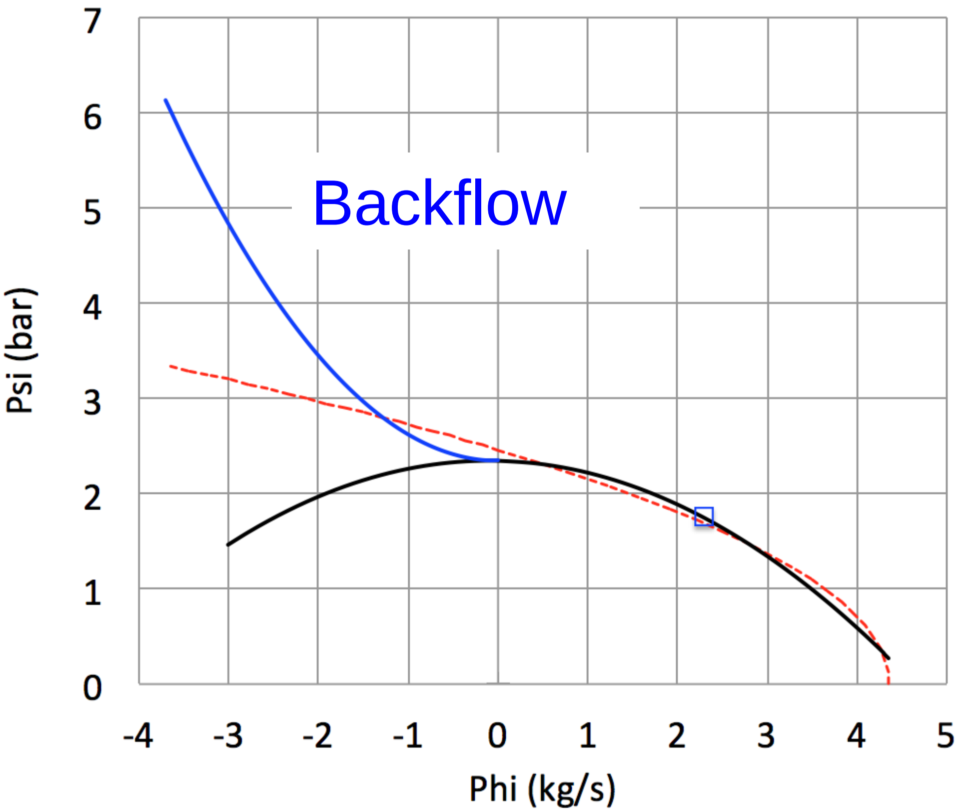
$$\psi'_{surge} = c - \frac{b^2}{4a}$$



Pump (cold circulator)

backflow (dm/dt < surge)

ITER CS circulator



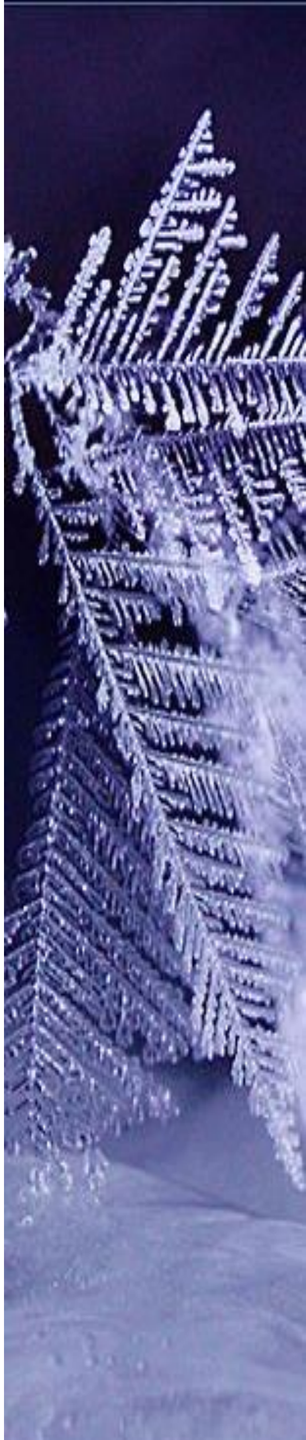
- *Flow model*

$$\psi' - \psi'_0 = \frac{2\xi}{A^2\rho}\,\varphi'^2$$

$$\psi' = \frac{\Delta p}{N^2} \qquad \varphi' = \frac{\dot{m}}{N}$$

- *Massflow calculation*

$$\varphi' = -A\sqrt{\frac{\rho}{2\xi}\left(\psi' - \psi'_0\right)}$$

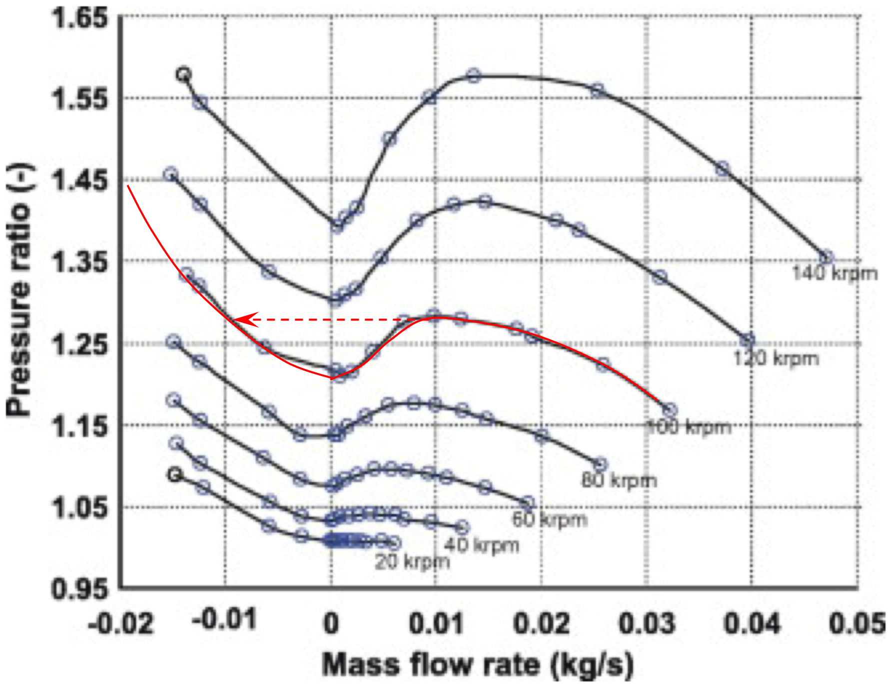


On the pump model

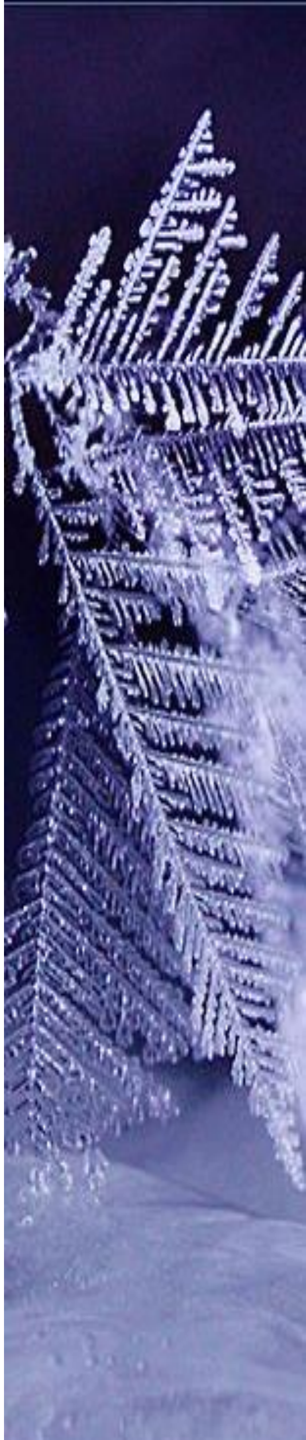
Experimental Thermal and Fluid Science
Volume 32, Issue 3, January 2008, Pages 818–826

Experiments and modelling of surge in small centrifugal compressor for automotive engines

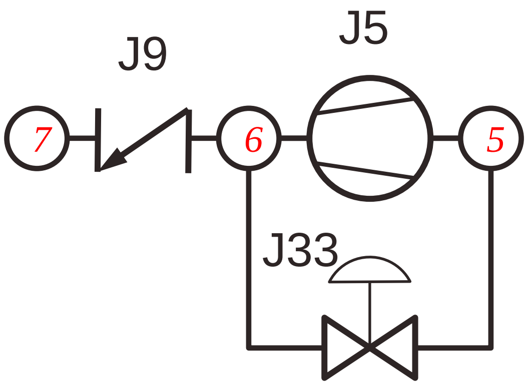
J. Galindo, J.R. Serrano, H. Climent, A. Tiseira

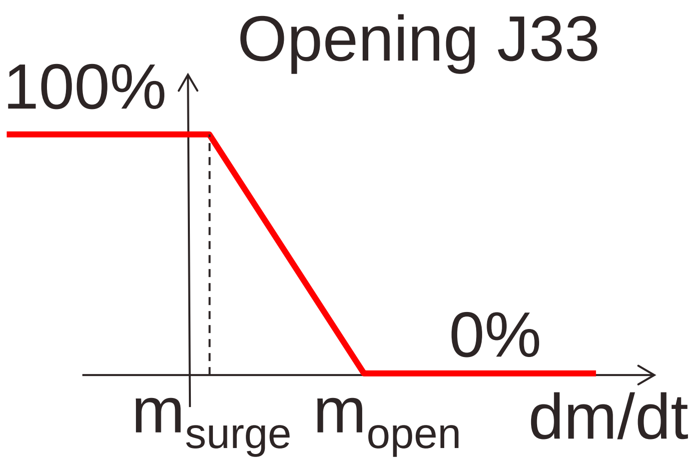


- *Measured characteristic is close to the approximation used for the forward and backflow*
- *The model does not take hysteresis (surge) into account*



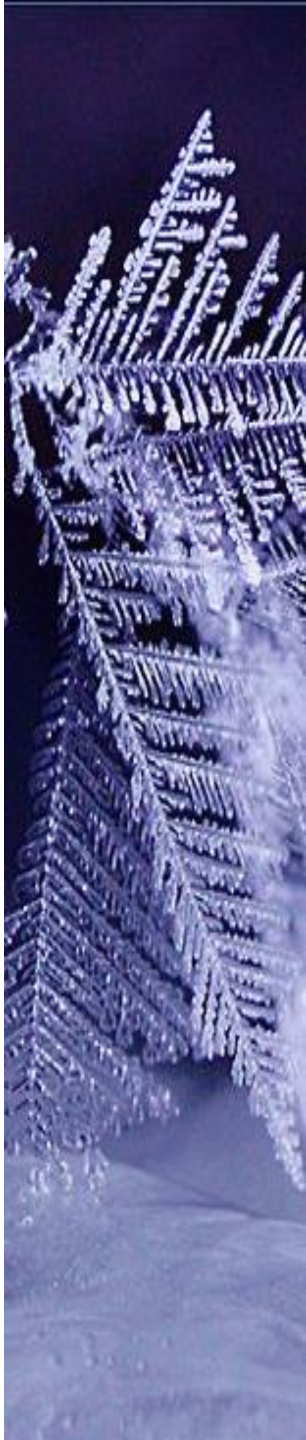
Pump protection





PID used as an alternative

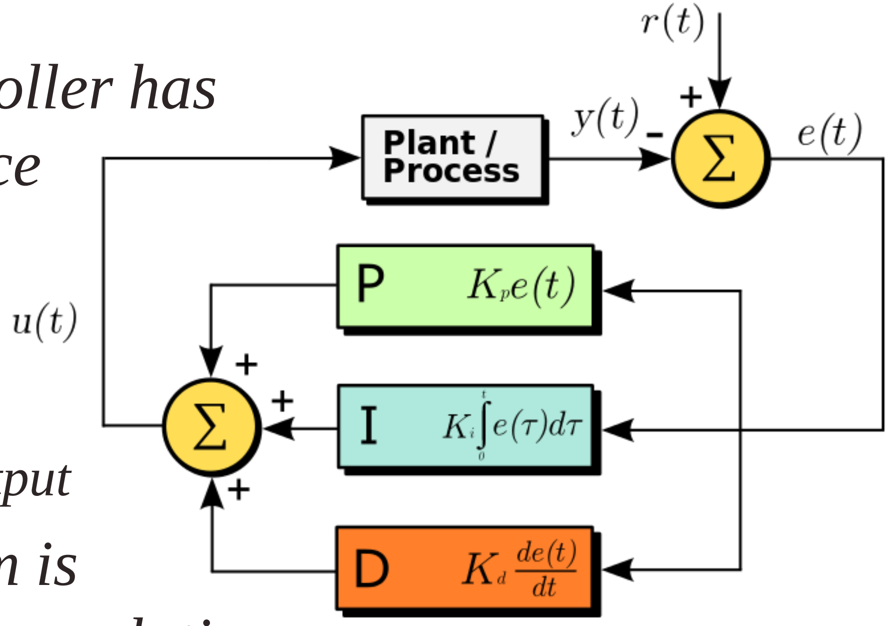
- *Compressor protection is mandatory to avoid surge and backflow, and potential damage to the blades*
- *Protection can be achieved by the combination of*
  - *Check valve on the discharge line (avoid backflow)*
  - *Surge control recirculation valve, driven by the measured compressor flow*

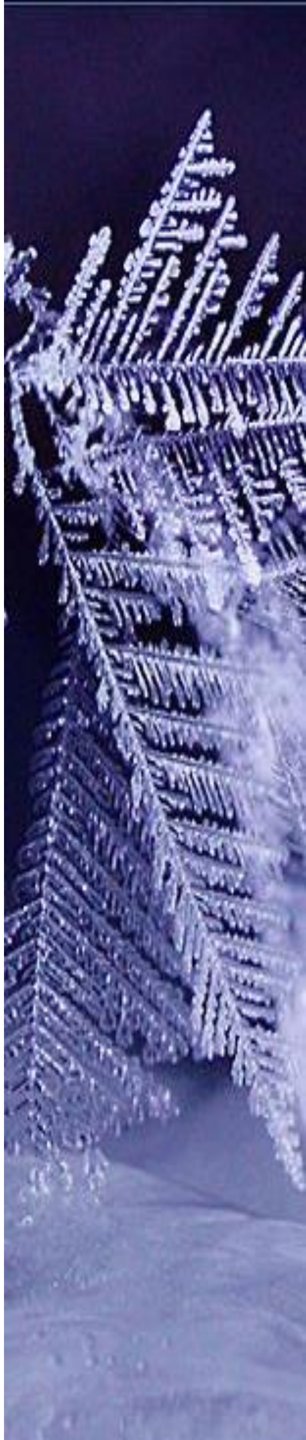


PID controller

$$u(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$

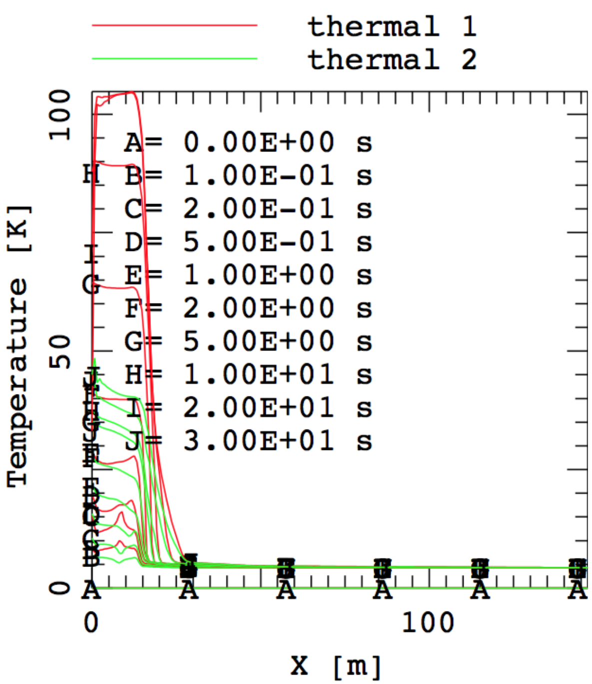
- *A standard PID controller has been taken as reference*
  - *PV: process variable*
  - *SP: set point*
  - *e(t) = SP-PV: error*
  - *u(t) = MV: control output*
- *Anti-windup algorithm is necessary to avoid accumulating errors when at the saturation of an actuator (e.g. completely opened valve)*
- *Discrete form programmed in FLOWER (user routine)*

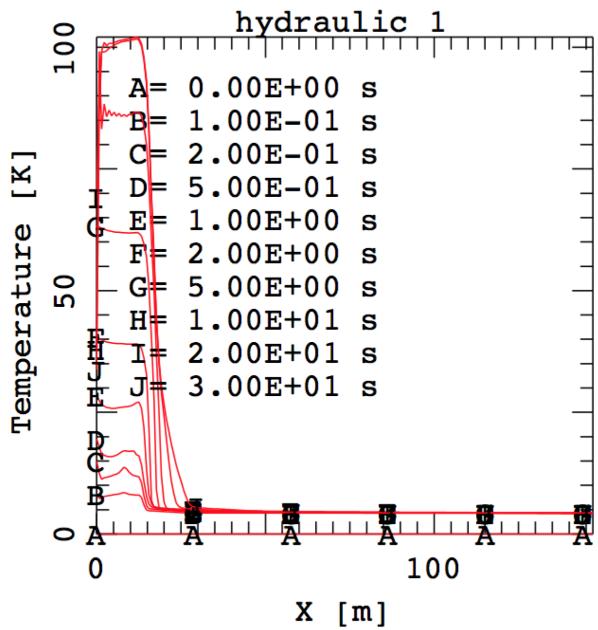




Quench heat load

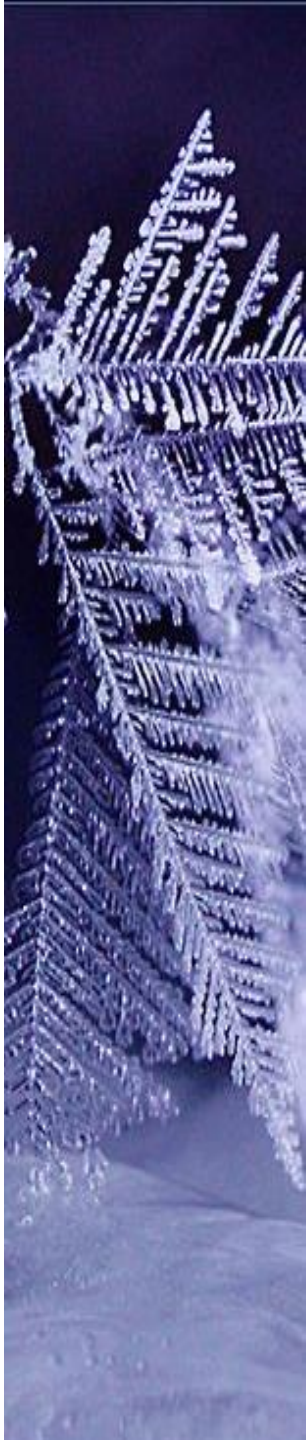
- *To simplify analysis, a "typical" quench was computed using THEA:*
  - *Single CS pancake (147 m)*
  - *Nominal current (40 kA), detection 2 s, dump 10 s*
  - *14 m initial normal zone (5 kW/m, 200 ms)*
  - *Constant pressure at the ends*



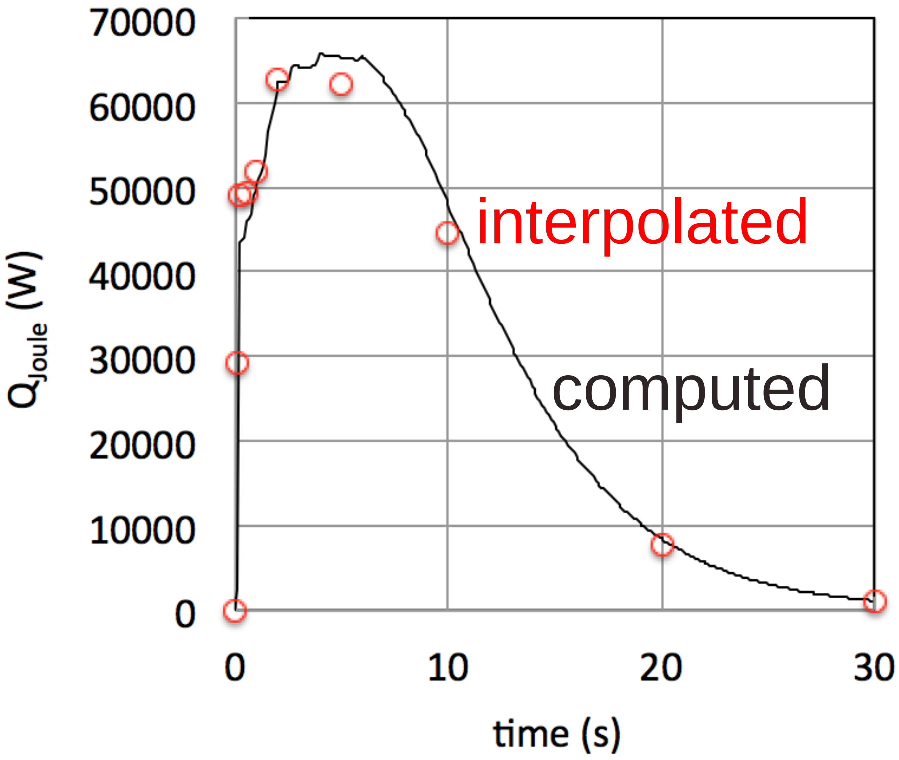


Hot-spot temperature approximately 100 K

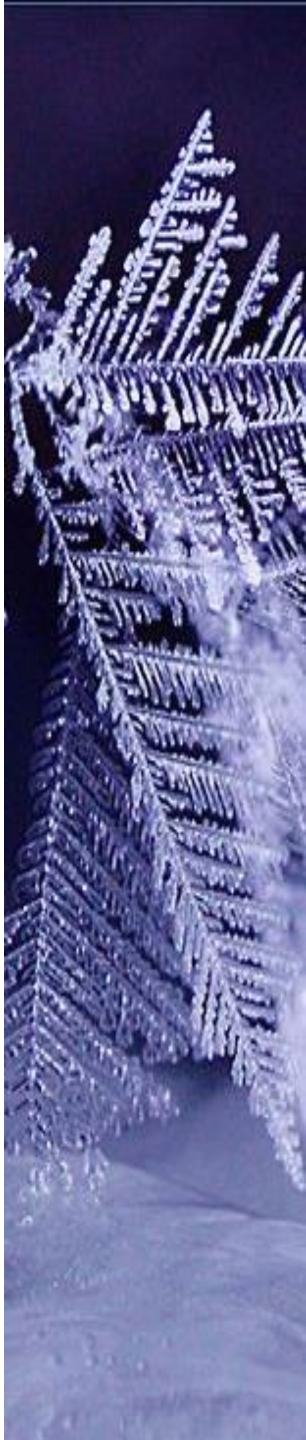
Minimal propagation of the normal zone



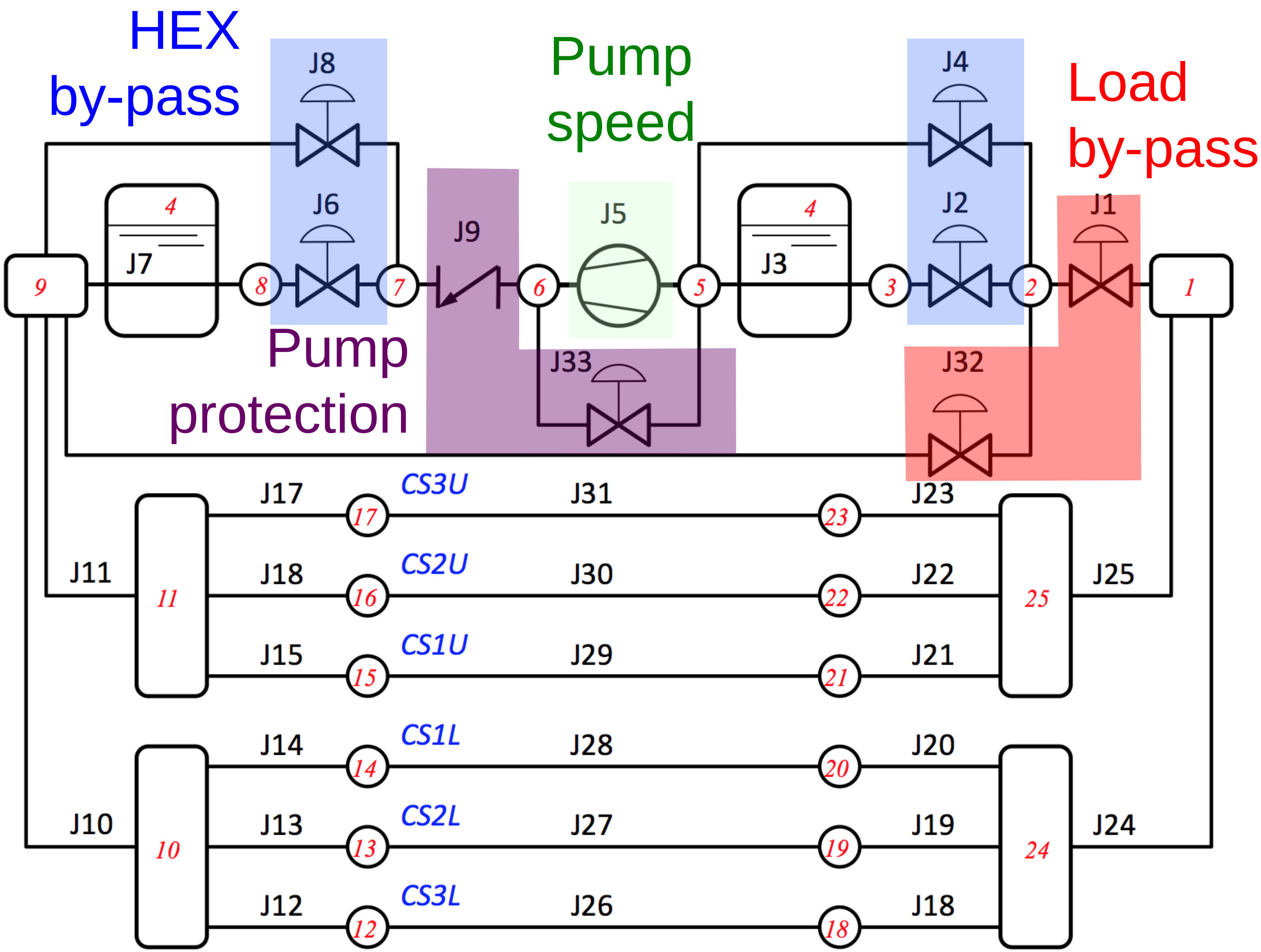
Quench heating

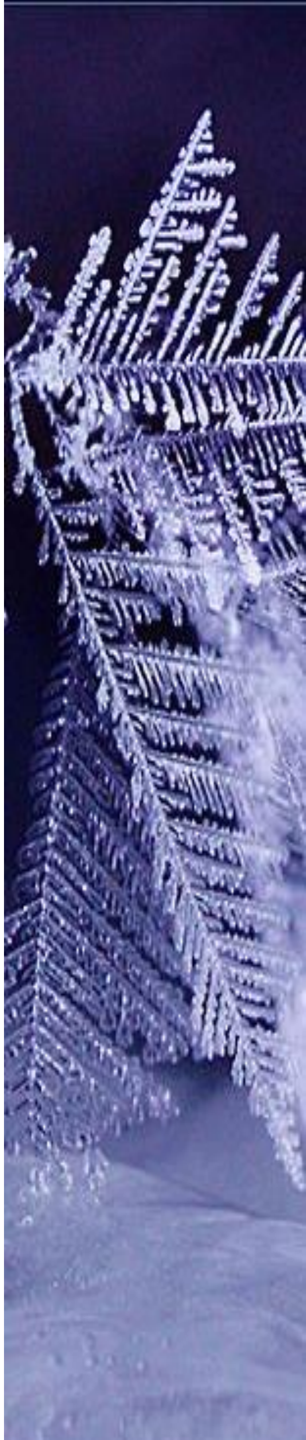


- *A "single pancake" quench heat function has been computed from the Joule heating profile obtained from the THEA simulation*
  - *constant function in space over the normal zone (0-14 m)*
  - *linear interpolation in time over the computed domain (30 s)*



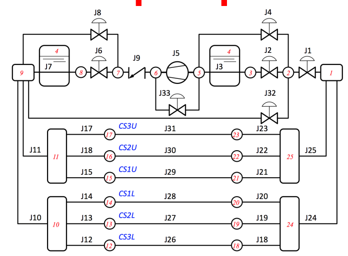
Mitigation scenarios



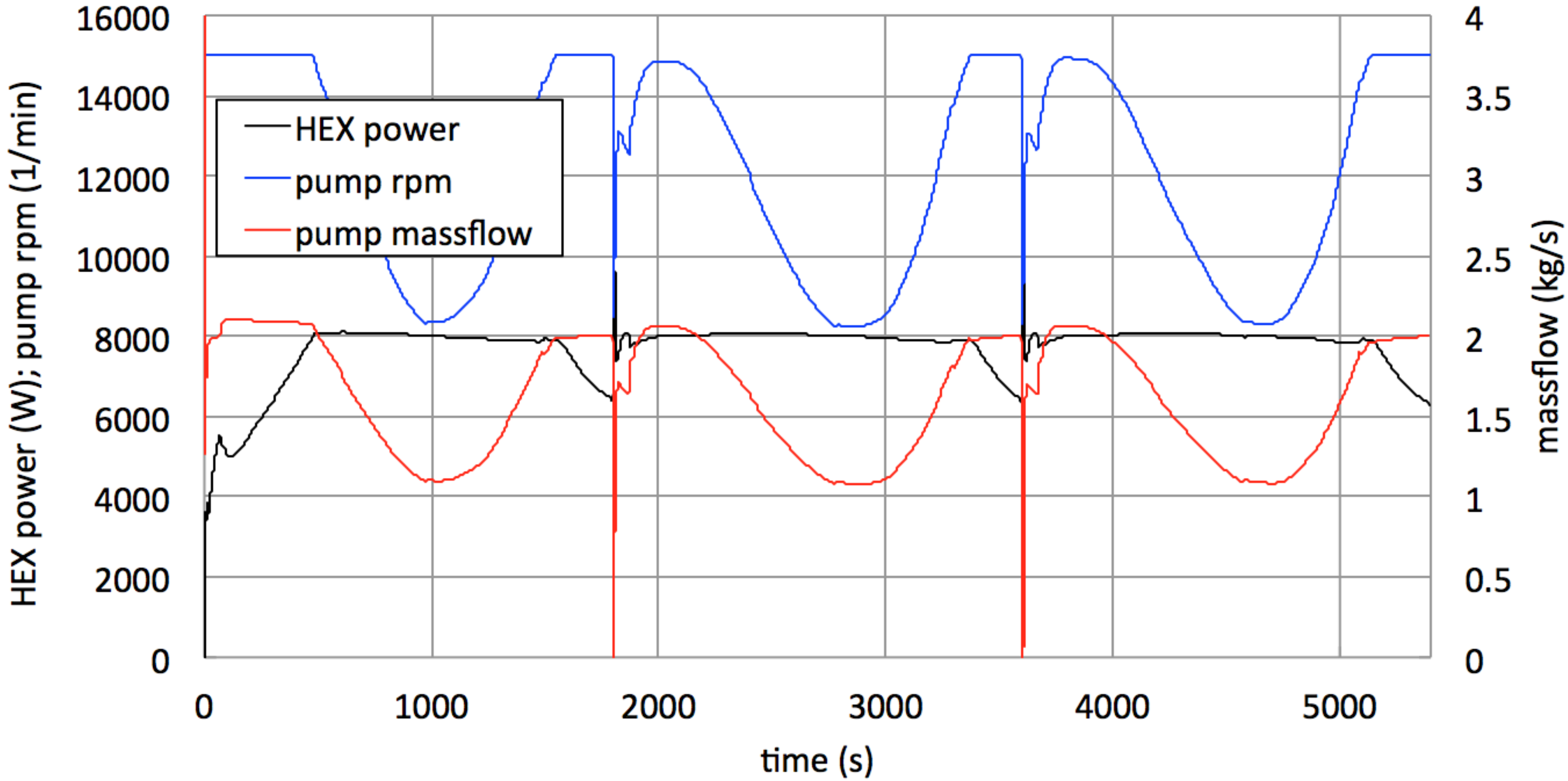


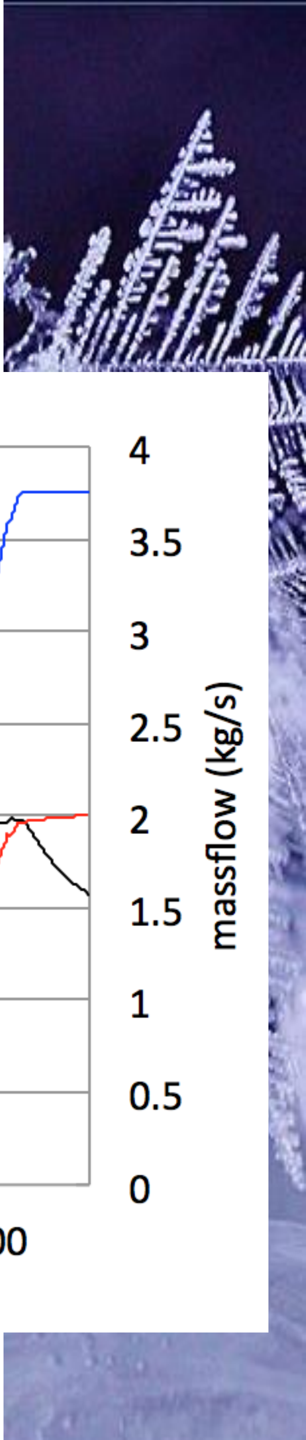
PID setting run – 10 kW (PI)

Pump speed



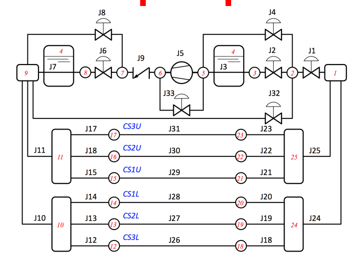
Kp=9.0e-5; Ki=1.2e-5 Kd=0.0

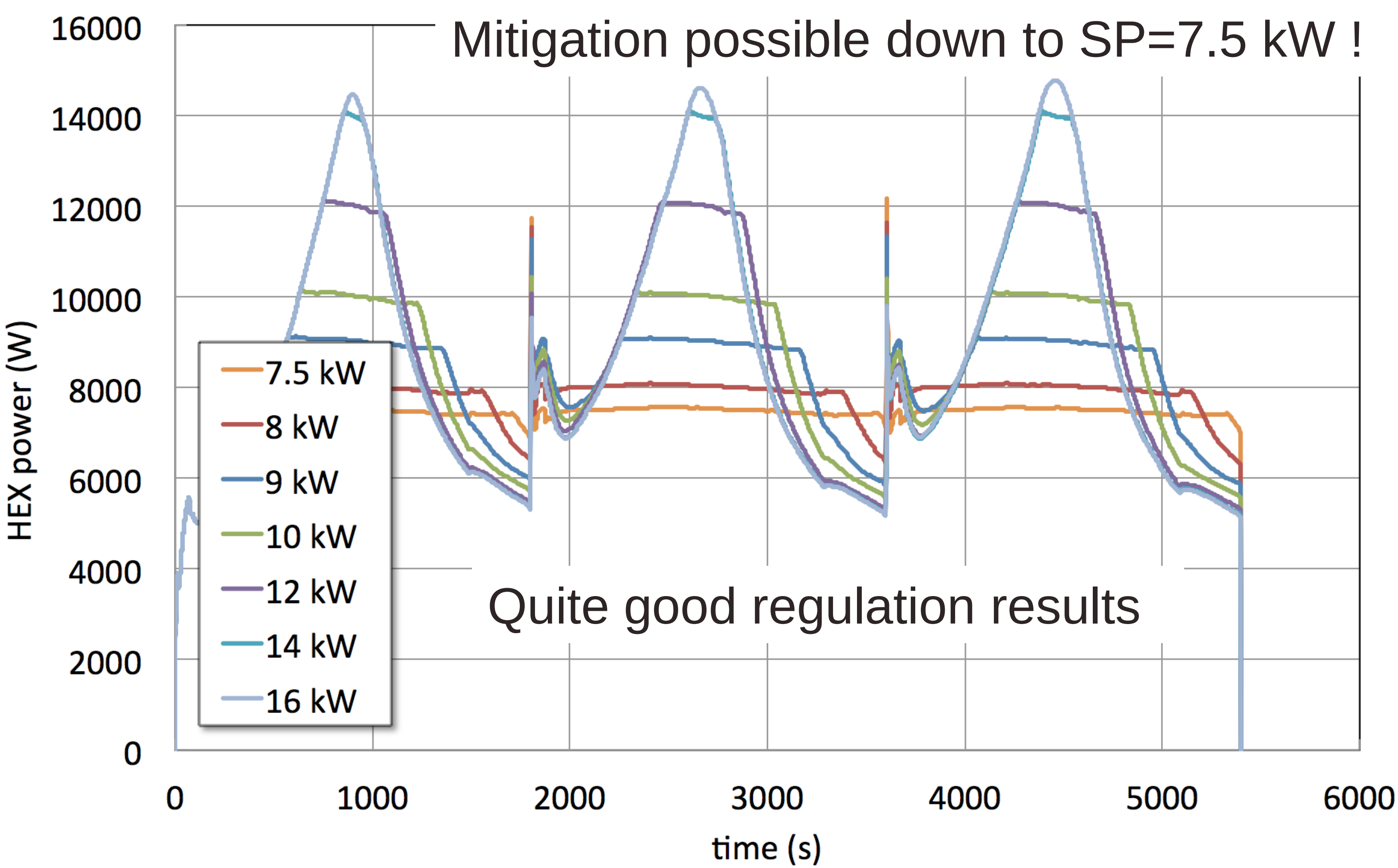




HEX heat load

Pump speed



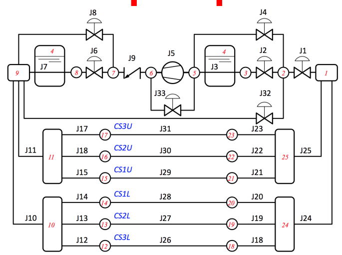


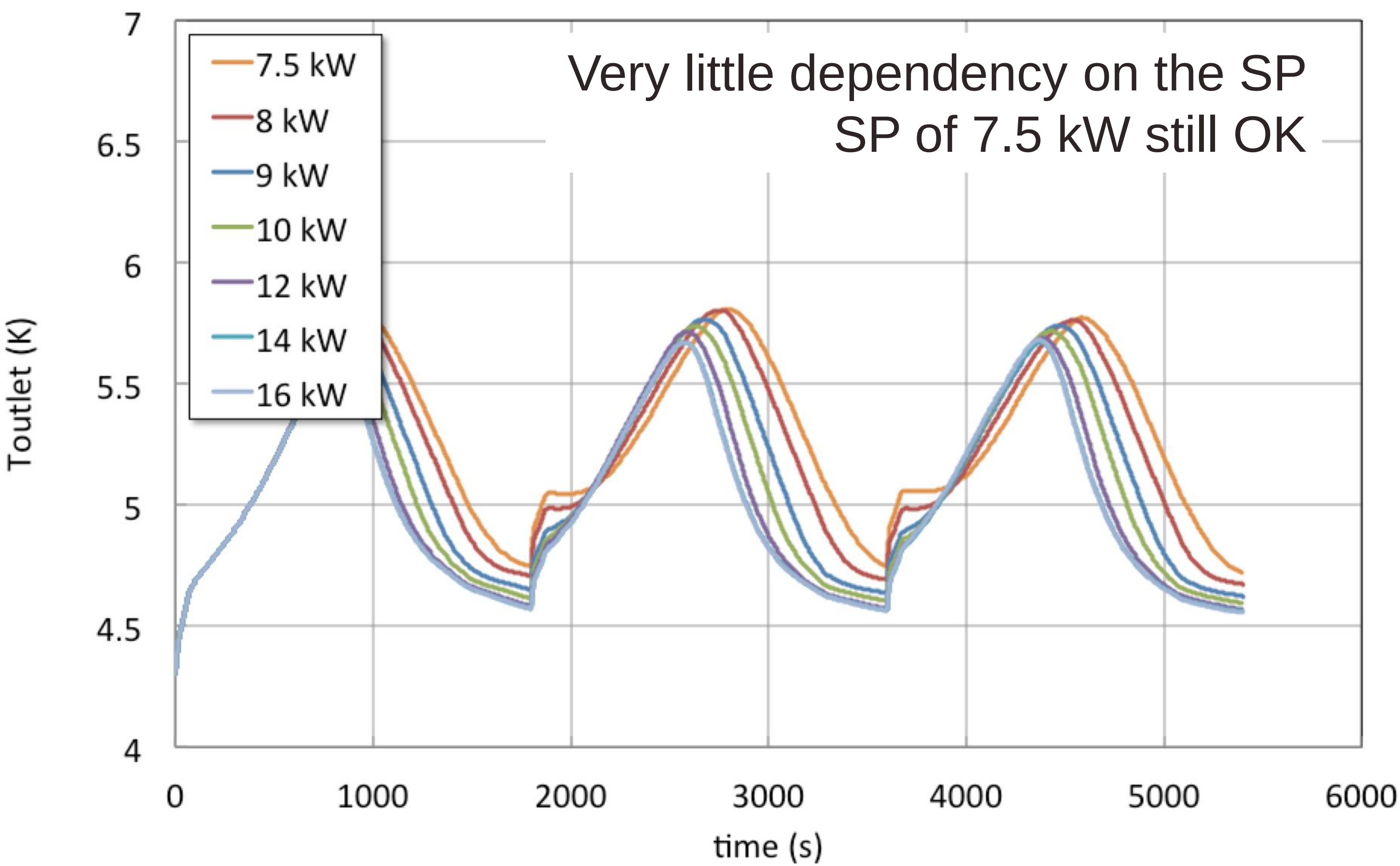
Mitigation possible down to SP=7.5 kW !

Quite good regulation results

CS outlet temperature

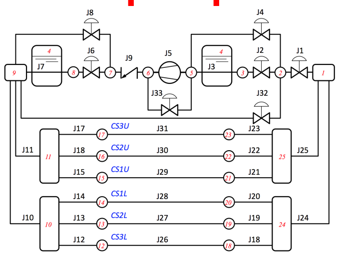
Pump speed

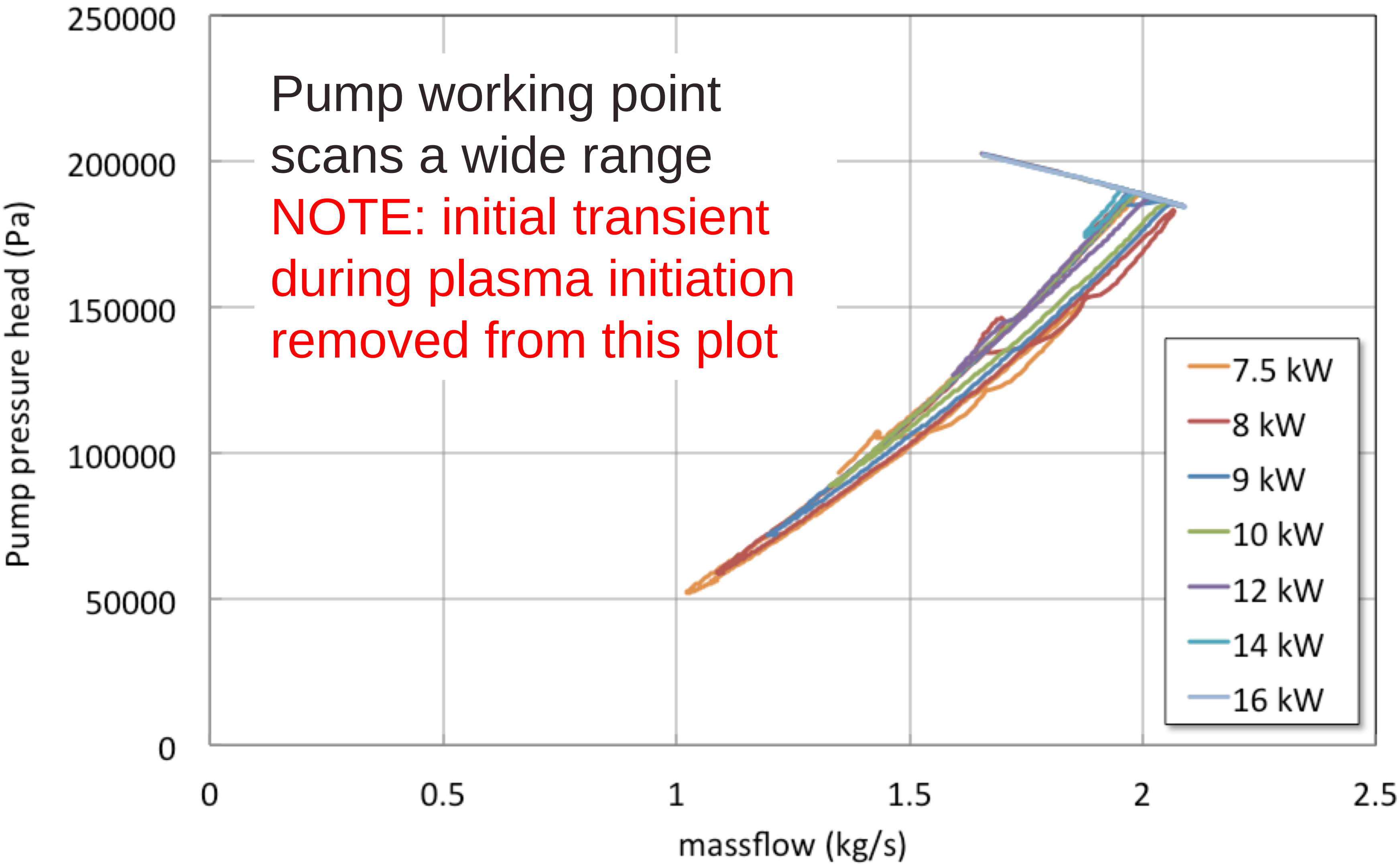




Pump working point

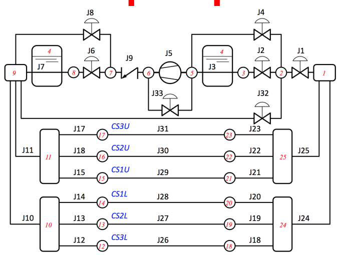
Pump speed



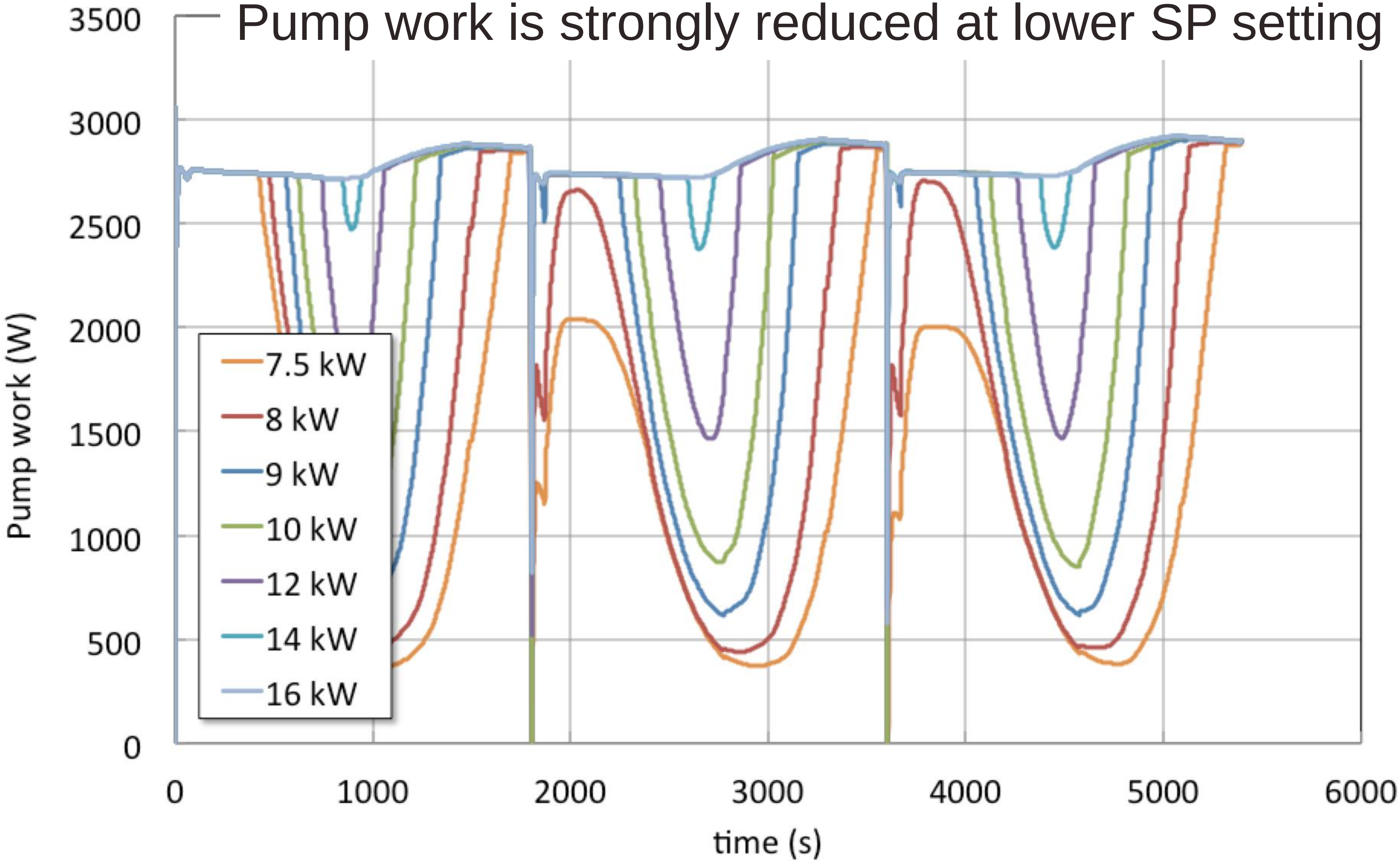


Pump work

Pump speed

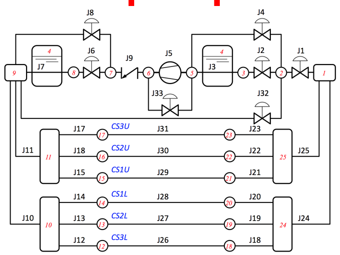


Pump work is strongly reduced at lower SP setting

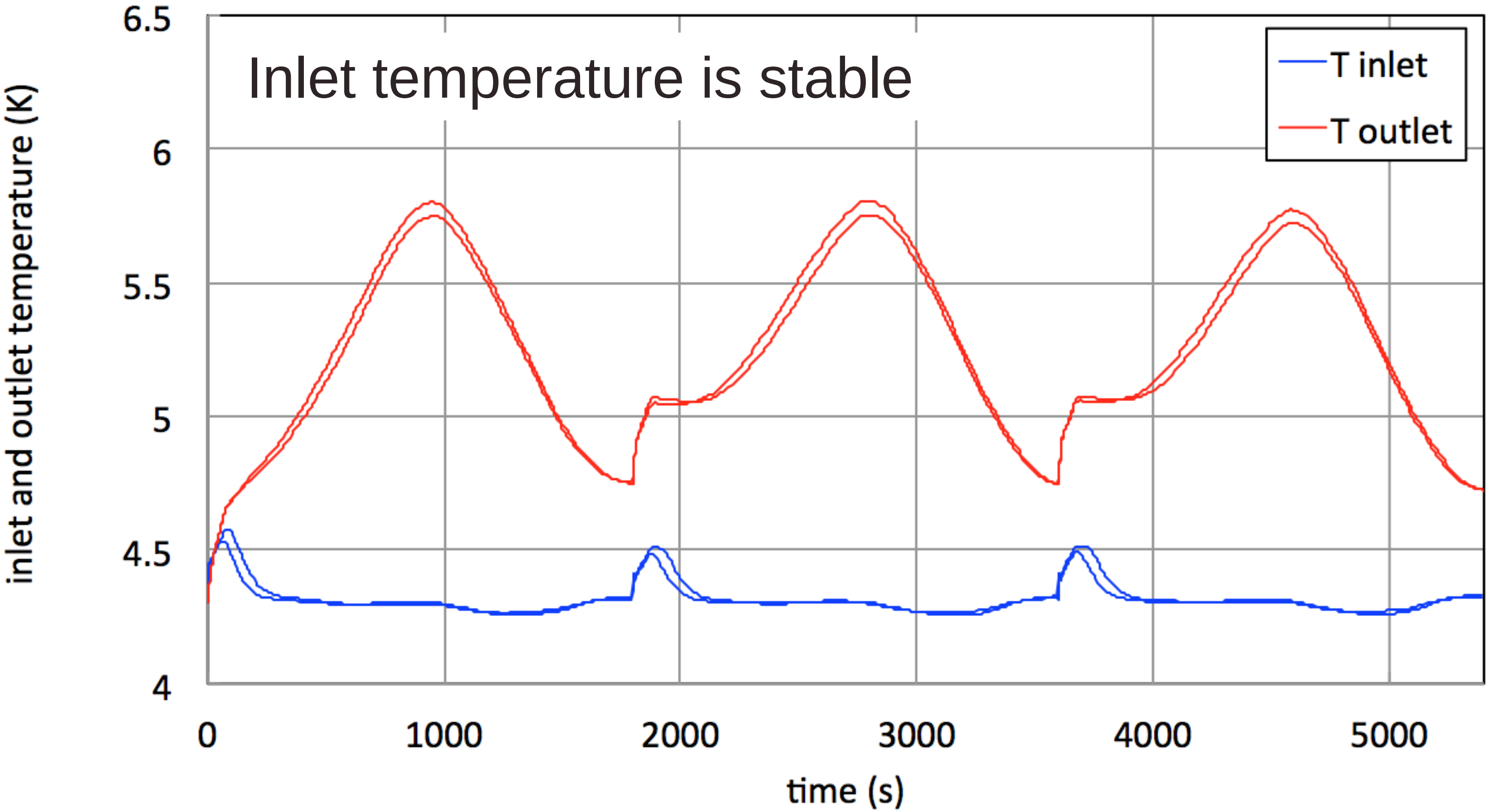


Inlet and outlet temperatures

Pump speed



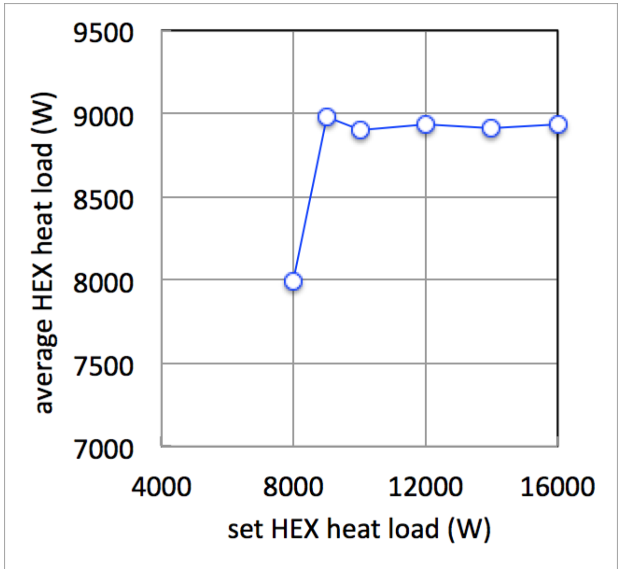
SP=8 kW



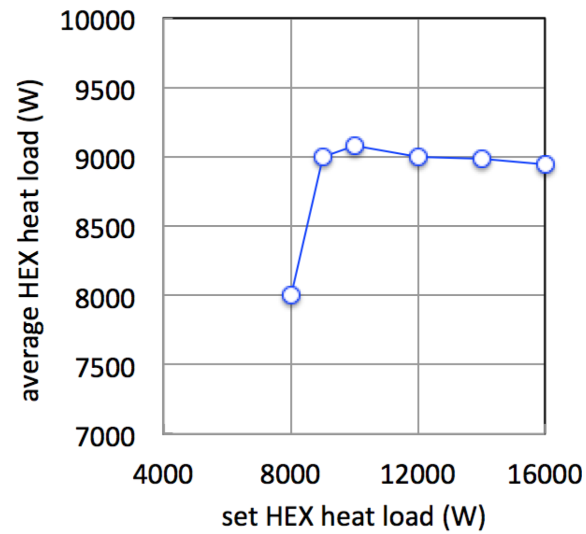
Comparison of scenarios

Average heat load at the HEX

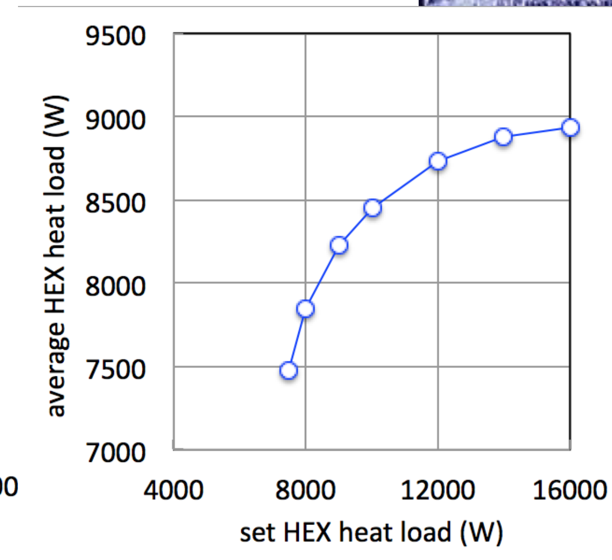
Load by-pass



HEX by-pass



Pump speed

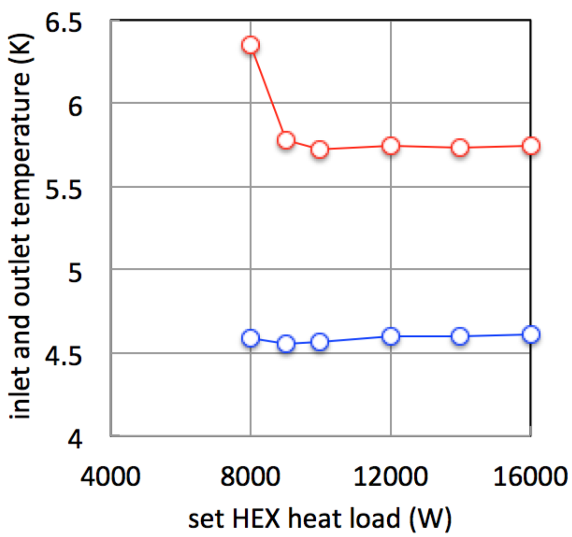


- *The HEX heat load is constant at 9 kW average in case of by-pass mitigation, and decreases in case of pump-speed mitigation*
- *Lower mitigation limit is 9 kW for by-pass scenarios, 7.5 kW for pump speed scenario*

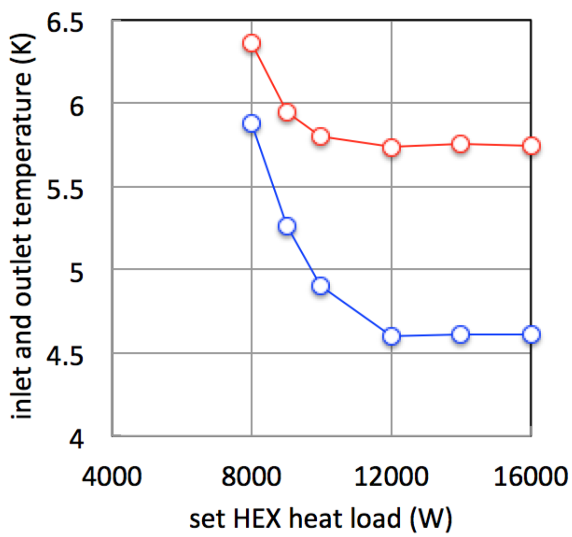
Comparison of scenarios

Inlet and outlet temperatures

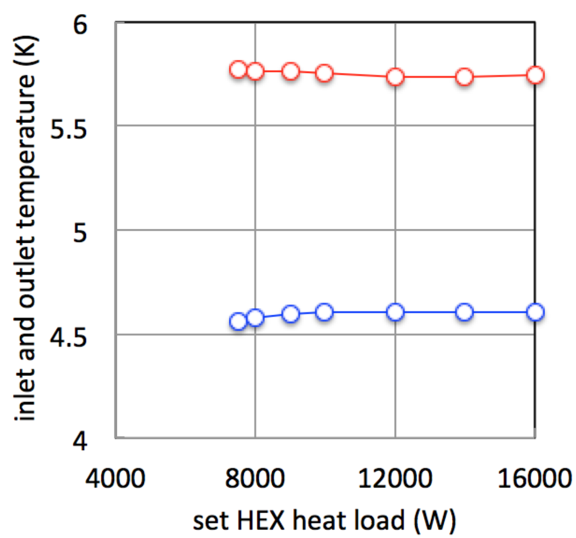
Load by-pass



HEX by-pass



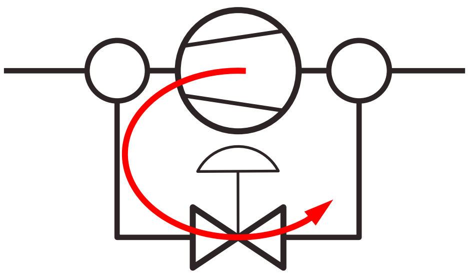
Pump speed

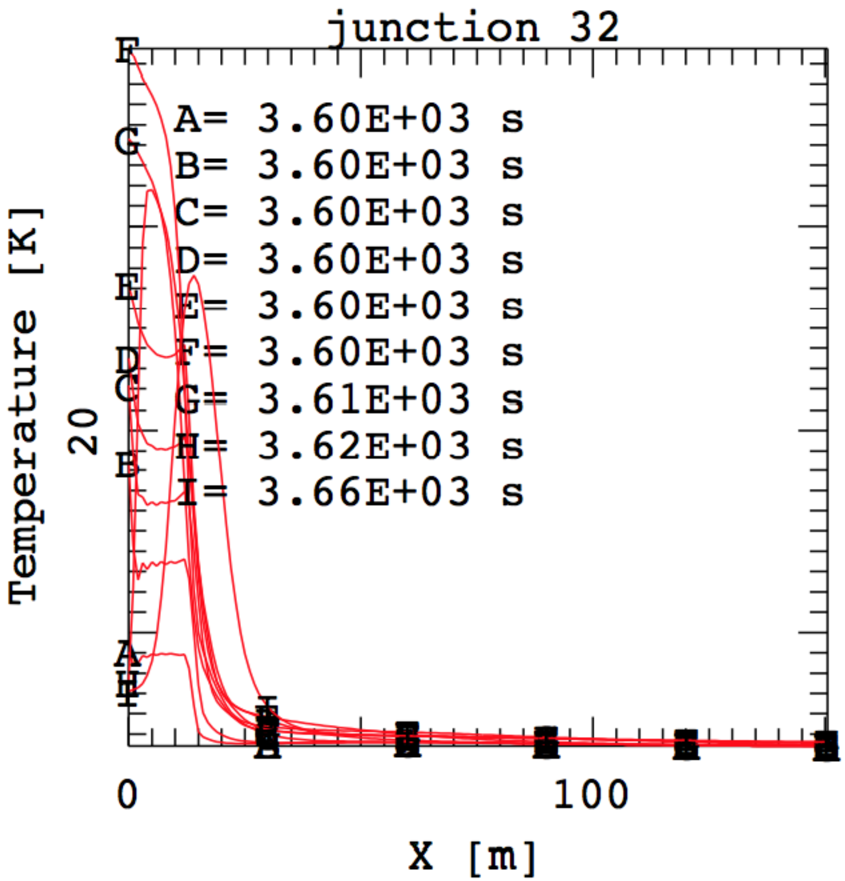


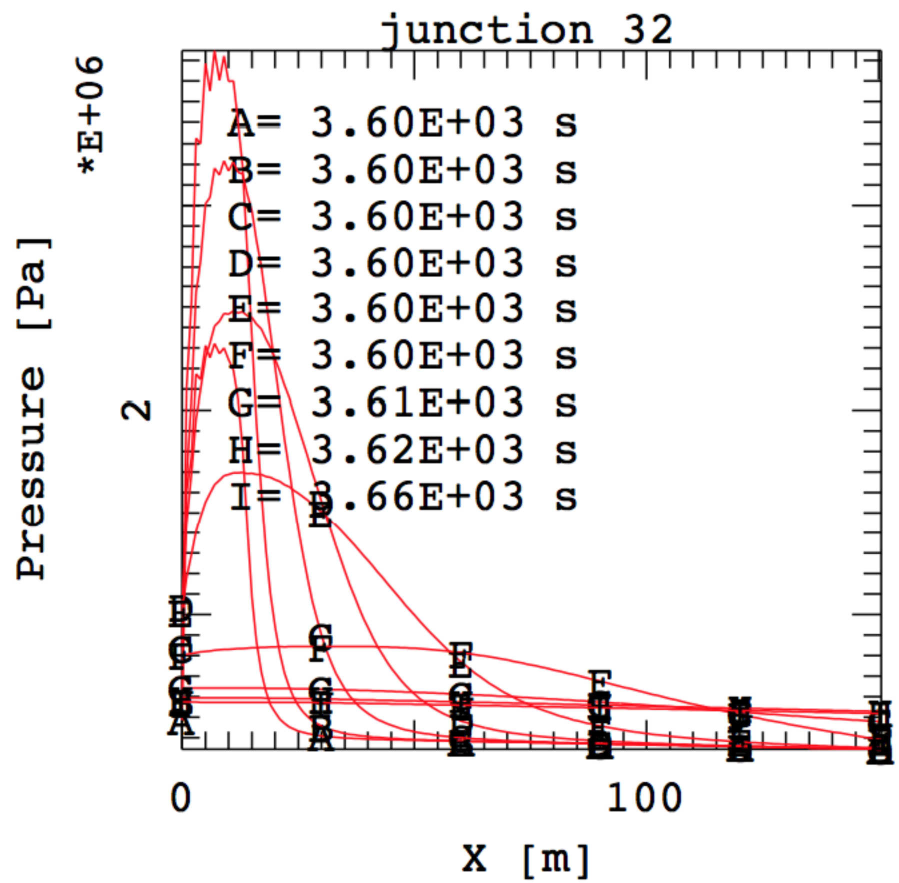
- *Inlet/outlet temperature increases in the case of HEX by-pass (temperature bump by-passes the HEX)*
- *No significant change of inlet and outlet temperature for the load by-pass and pump-speed scenarios, when in mitigation range (SP>9 kW for by-pass, SP>7.5 kW for pump speed)*

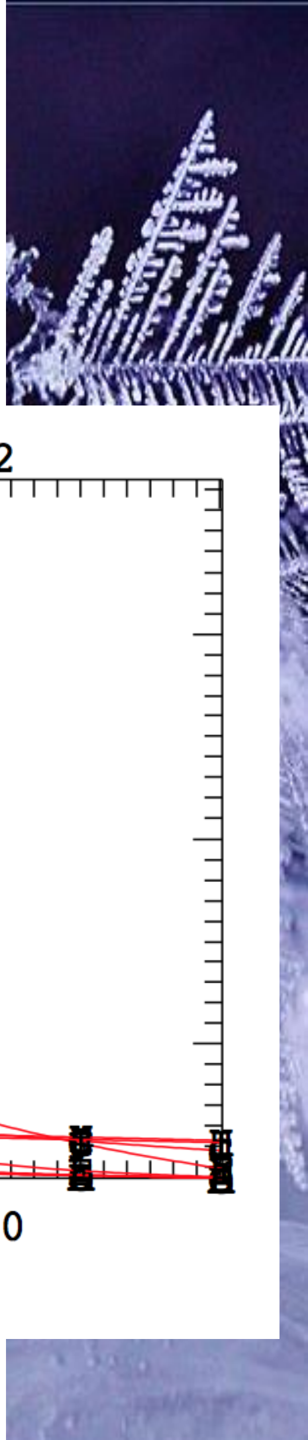
Quench of CS2U
40 pancakes

Pump protection





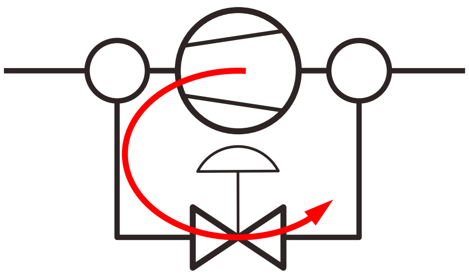


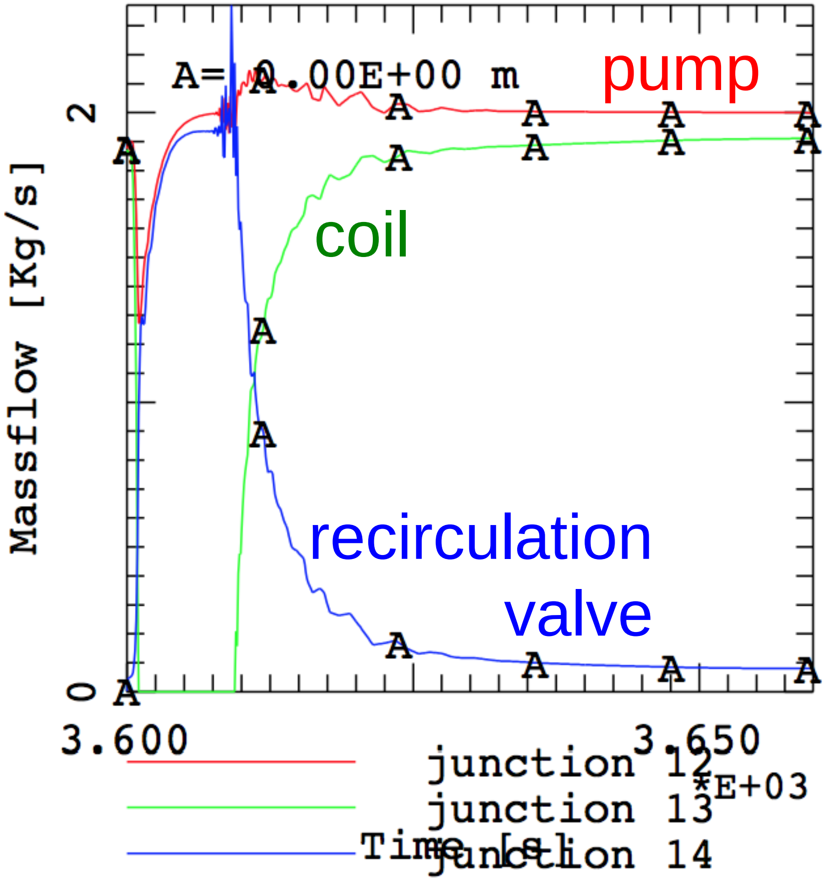


Good approximation of a real quench

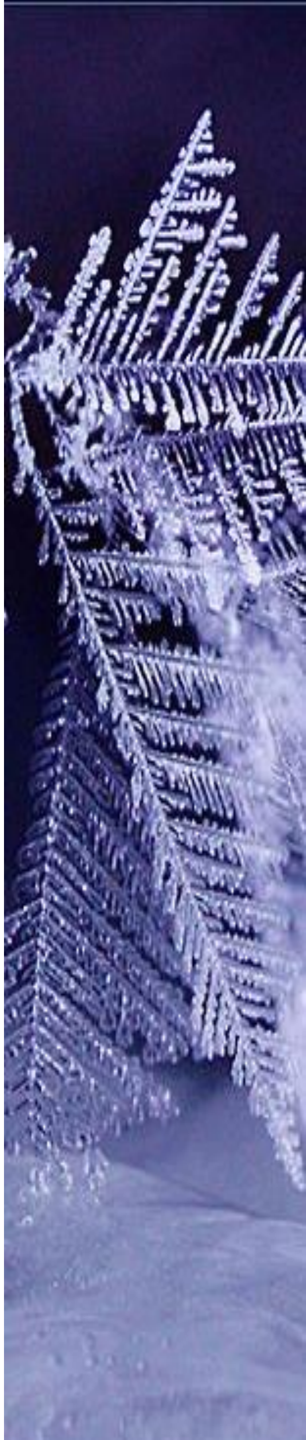
Quench of 40 pcks CS2U

Pump protection



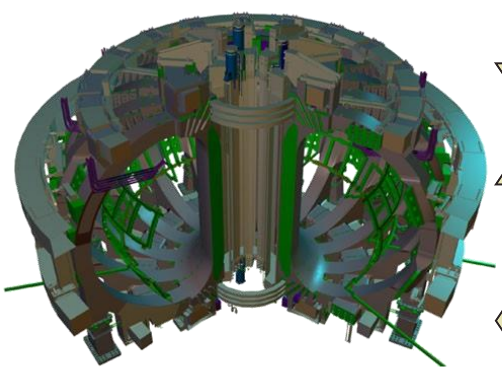


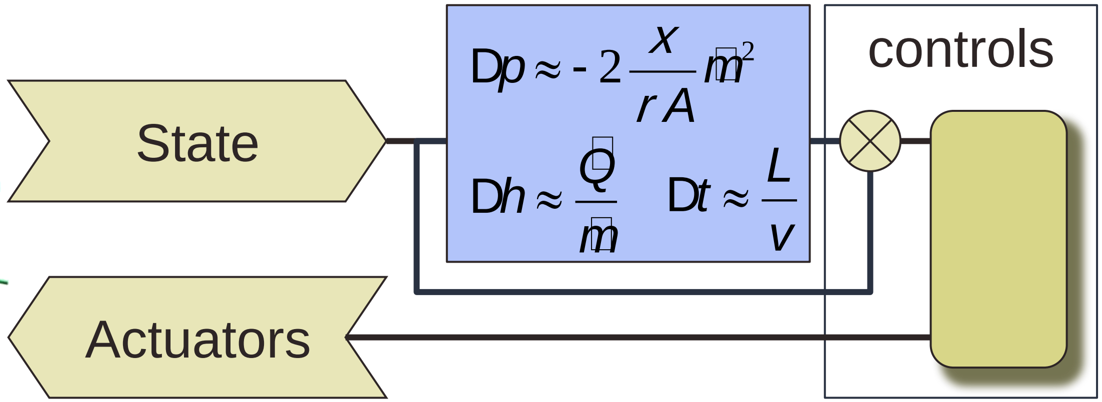
- *Minimum pump flow is 1.3 kg/s*
- *Recirculation valve takes full flow in 1 s, at which time the flow in the coil is zero*
- *Flow in the coil could be re-initiated already after 10 s, and fully re-established in 25 s*
- *Relatively stable PID response*

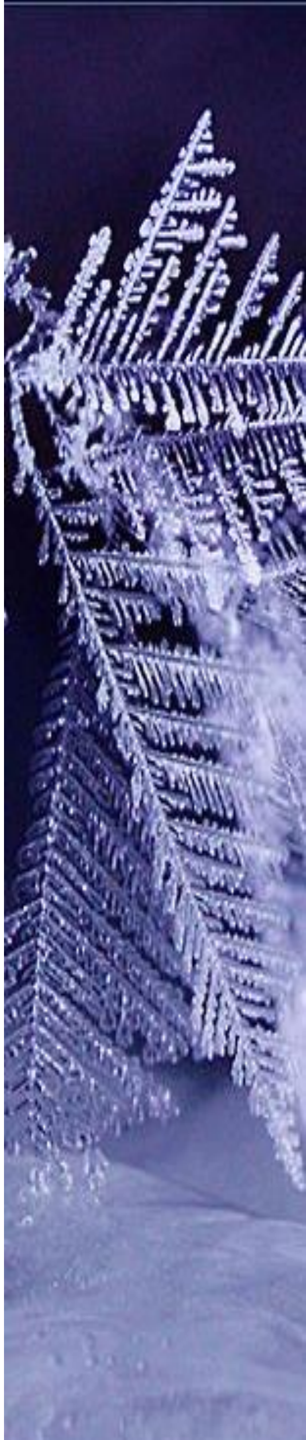


Conclusions and perspective

- *A simplified physical model can provide a good level of approximation for the parametric study of operation scenarios in a large scale superconducting magnet system*
- *It runs fast (typically twice "real time" for the examples shown)*
- *It can be further simplified and provide guidelines for a fully-analytical model core that could be implemented in the ITER operation control system (cf. LHC FiDeL)*
  - *Main physical drivers for the evolution (Rousset-2011)*
    - *Pressure drop and flow*
    - *Enthalpy balances*
    - *Propagation delays*
  - *Mix and match in a simulation tin-box for the ITER control system*

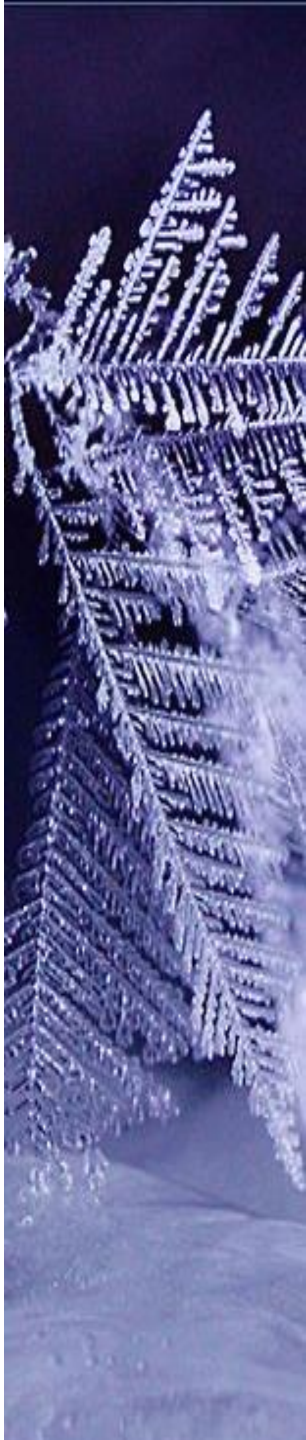






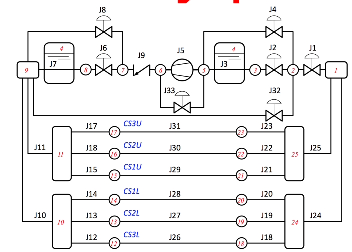
Abstract

- *The pulsed nature of the heat loads on the ITER magnets is a challenge for the operation of the inherently stead-state refrigerator loop. Here we present a model which is based on a simplified physics description of the loop, as readily implemented in a hydraulic network simulator, and can be used to explore parametrically the effect of pulsed heat loads, non-linear response of the main regulating components, and PID control actions. The model runs significantly faster than "real-time", and, being based on physics, can be used to identify the leading mechanisms, and thus provide directions for further scale reduction and simplification as would be required to include it in the real-time control system.*

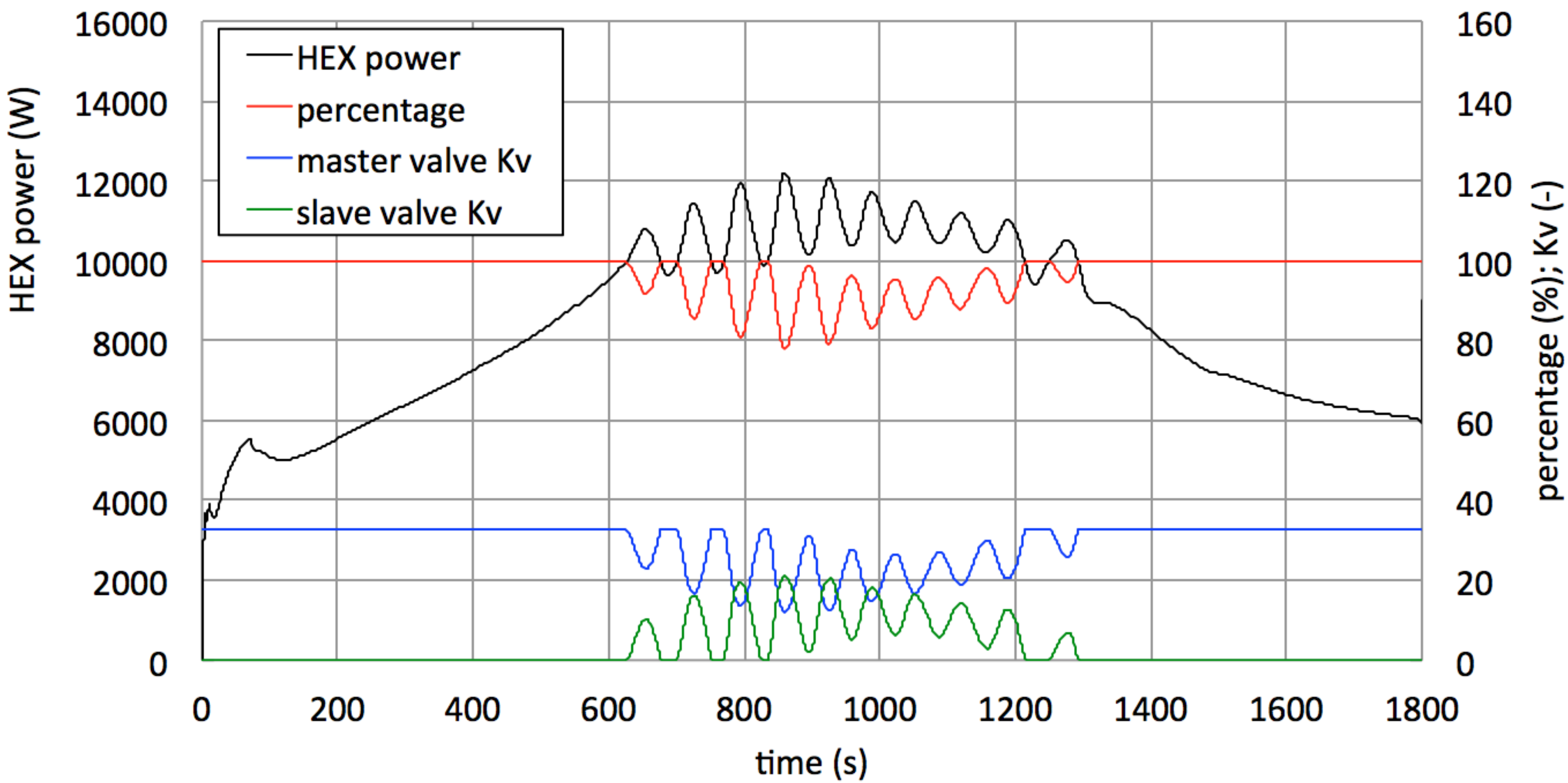


PID setting run – 10 kW (P)

Load by-pass

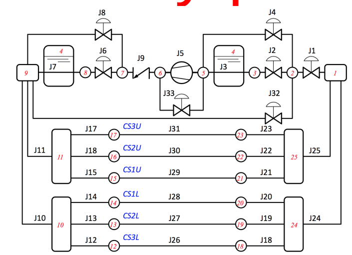


Kp=1.0e-2; Ki=0.0 Kd=0.0

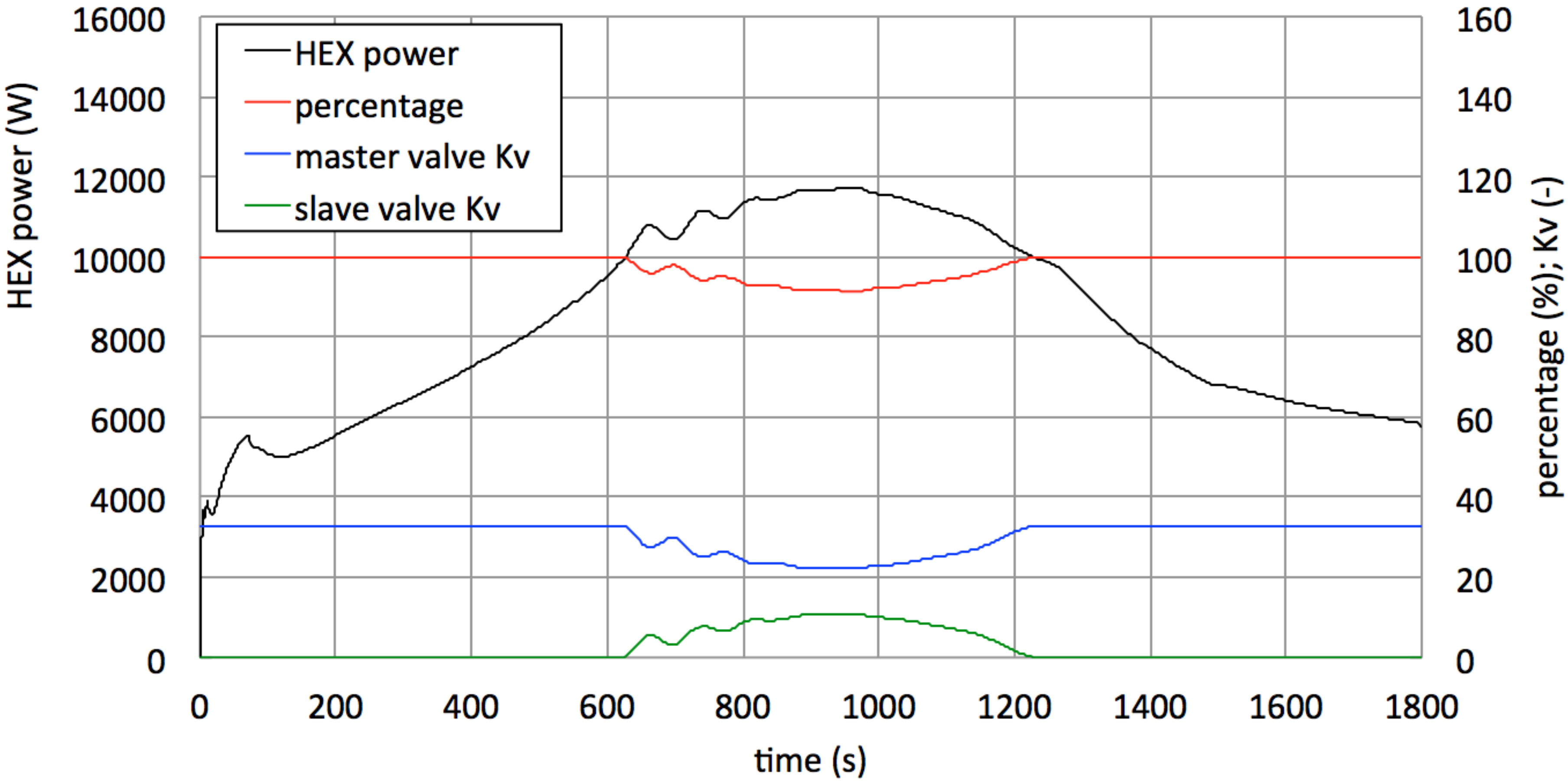


PID setting run – 10 kW (P)

Load by-pass

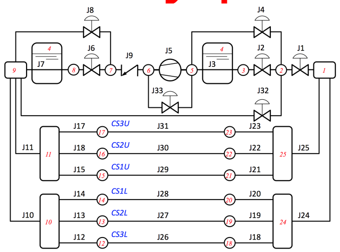


Kp=5.0e-3; Ki=0.0 Kd=0.0



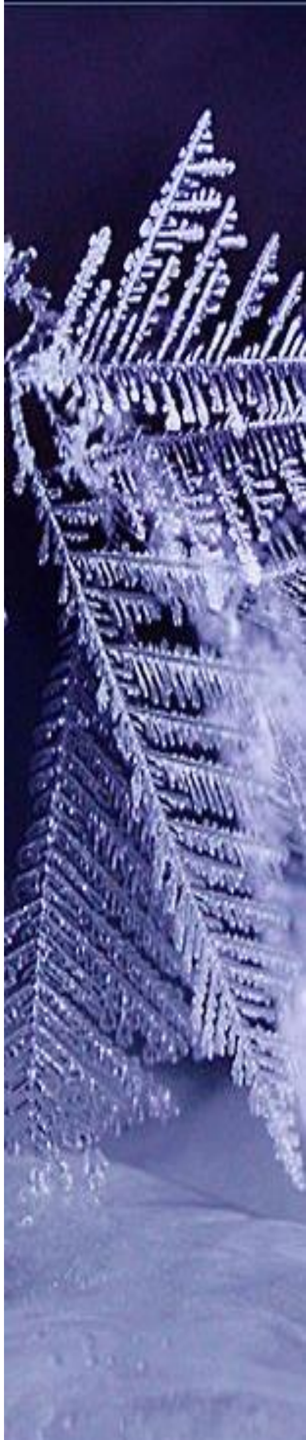
Optimal PID parameters

Load by-pass



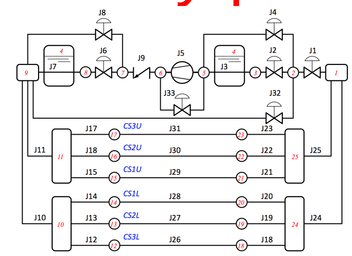
- *Use the Ziegler-Nichols rule:*

Ziegler Nichols method				
	Ku	1.00E-02		
	Pu	66.667		
		Kp	Ki	Kd
	P	5.00E-03		
	PI	4.50E-03	8.10E-05	
	PID	6.00E-03	1.80E-04	5.00E-02

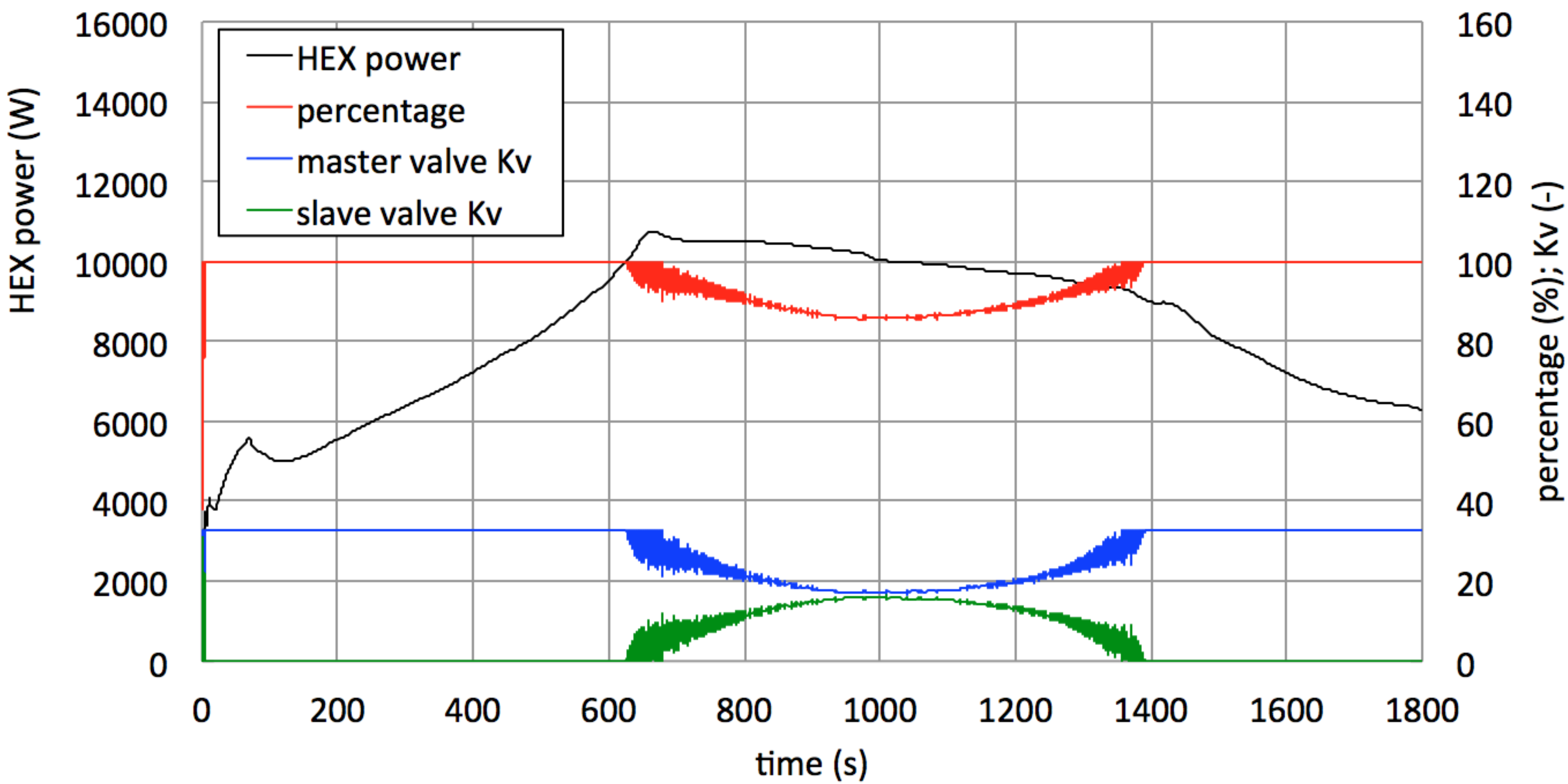


PID setting run – 10 kW (PID)

Load by-pass

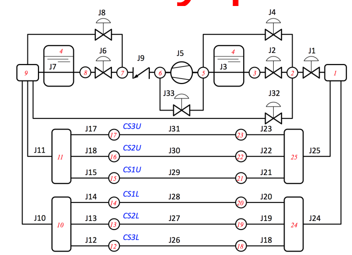


Kp=4.0e-3; Ki=9.0e-5 Kd=2.5e-2



PID setting run – 10 kW (PI)

Load by-pass



Kp=4.5e-3; Ki=8.1e-5 Kd=0.0