Validation of the 4C code cryogenic circuit model against data from the Helios/JT60SA loop at CEA Grenoble

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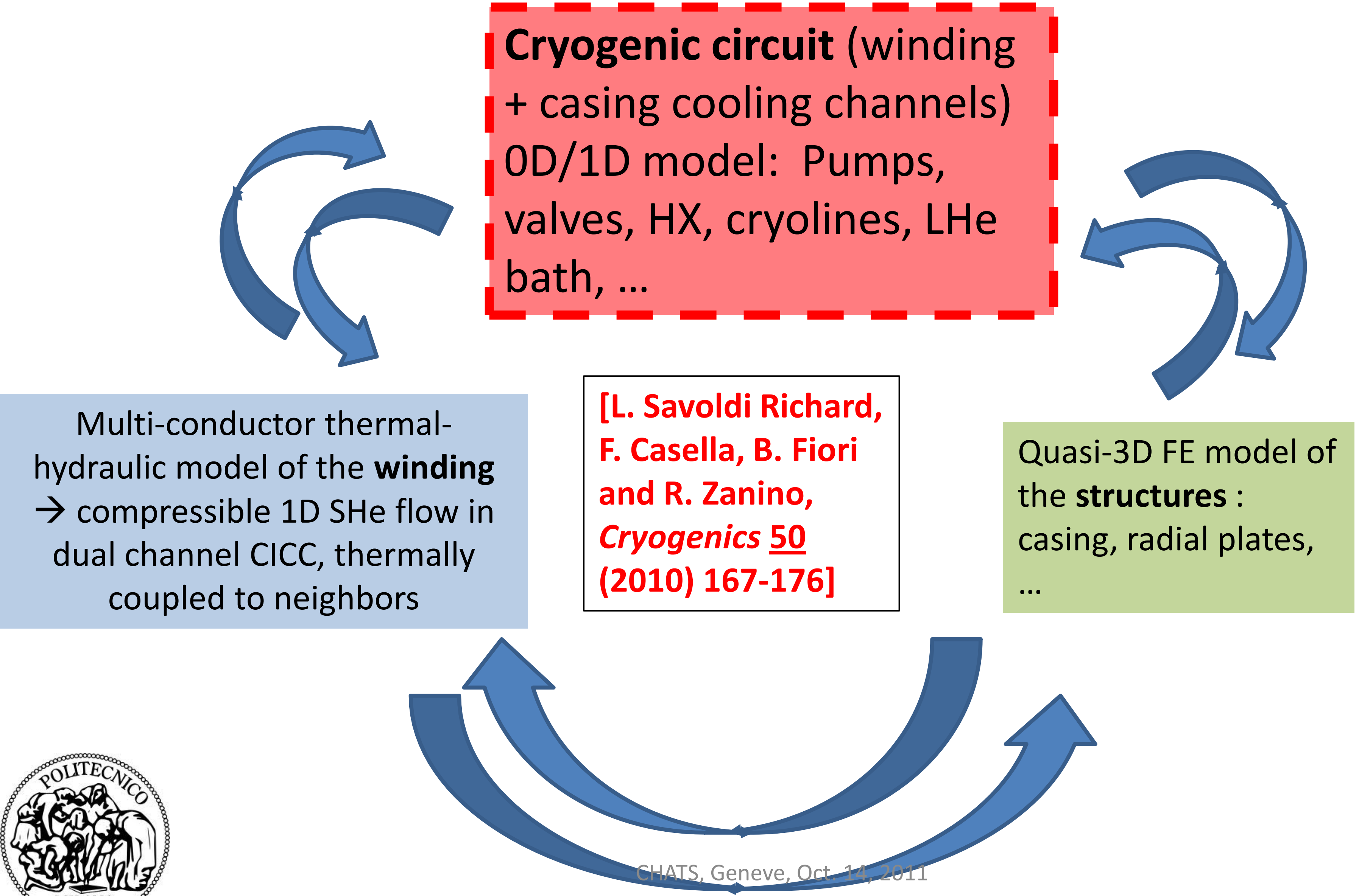
ACKNOWLEDGMENTS: C. Hoa, CEA Grenoble, France

Outline

- Introduction: the 4C code
- Experimental setup
- Model of the scenario
- Simulation results and comparison with experimental data
- Conclusions and perspective

Intro: The 4C code



Cryogenic circuit (winding + casing cooling channels) 0D/1D model: Pumps, valves, HX, cryolines, LHe bath, …

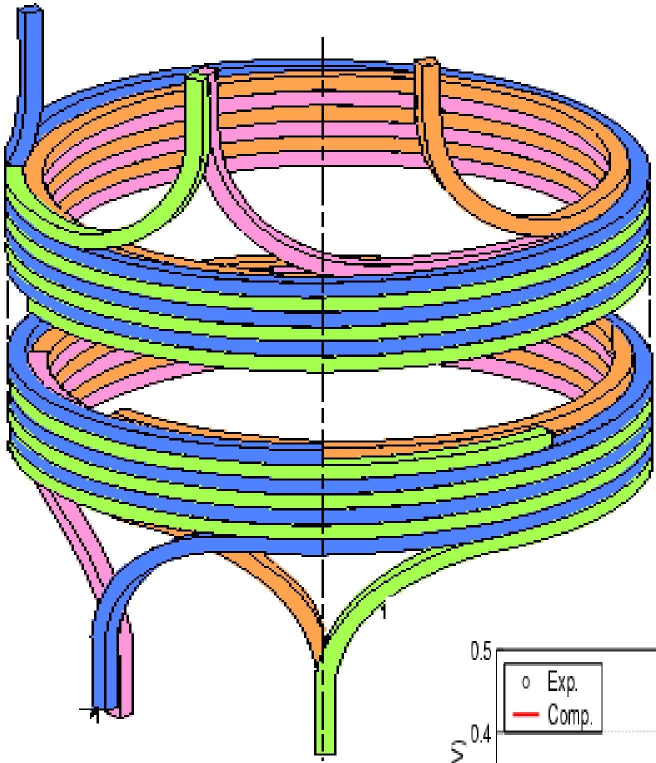
Multi-conductor thermal-hydraulic model of the **winding** → compressible 1D SHe flow in dual channel CICC, thermally coupled to neighbors

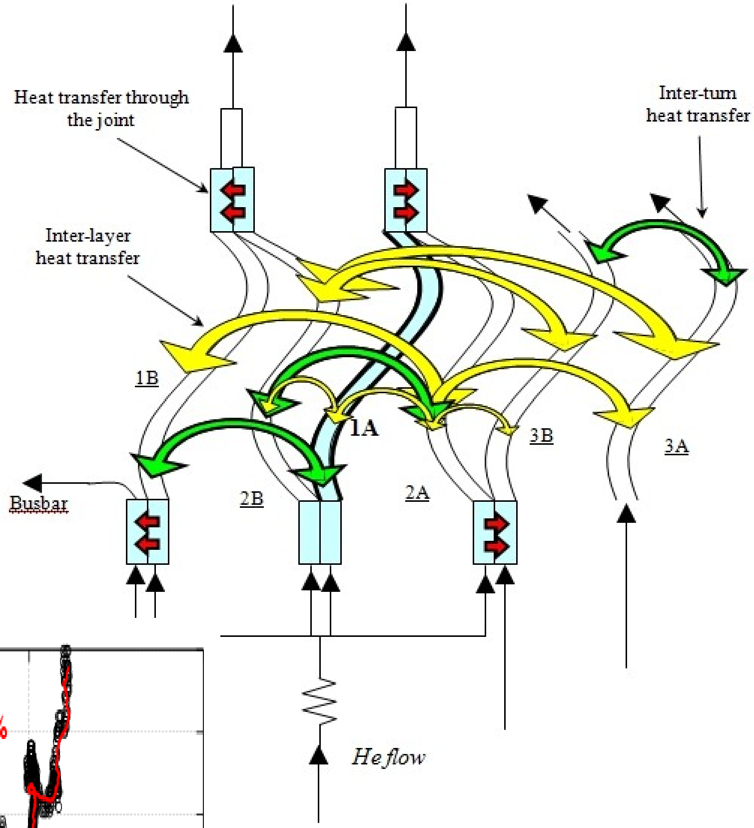
[L. Savoldi Richard, F. Casella, B. Fiori and R. Zanino, *Cryogenics* 50 (2010) 167-176]

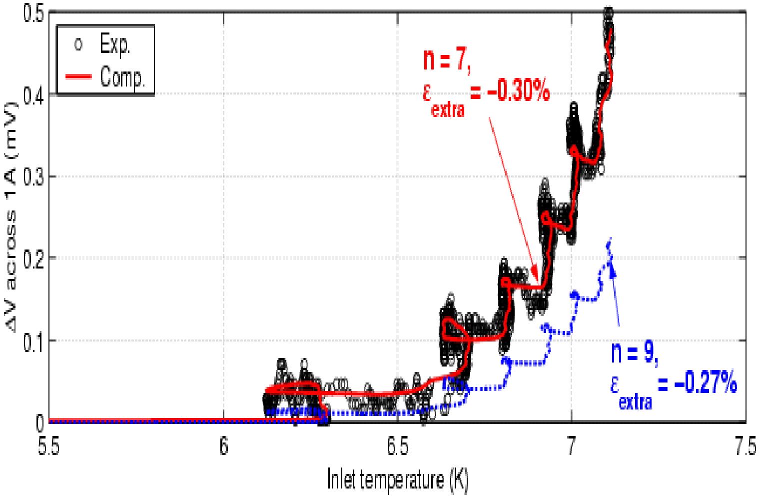
Quasi-3D FE model of the **structures** : casing, radial plates, …

Intro: The 4C winding model

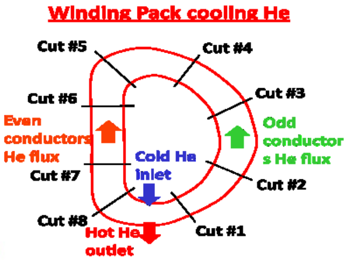
[L. Savoldi et al., *Cryogenics* 40 (2000) 179-189]
[R. Zanino et al., *Cryogenics* 43 (2003) 179-197]

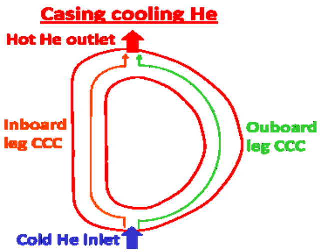


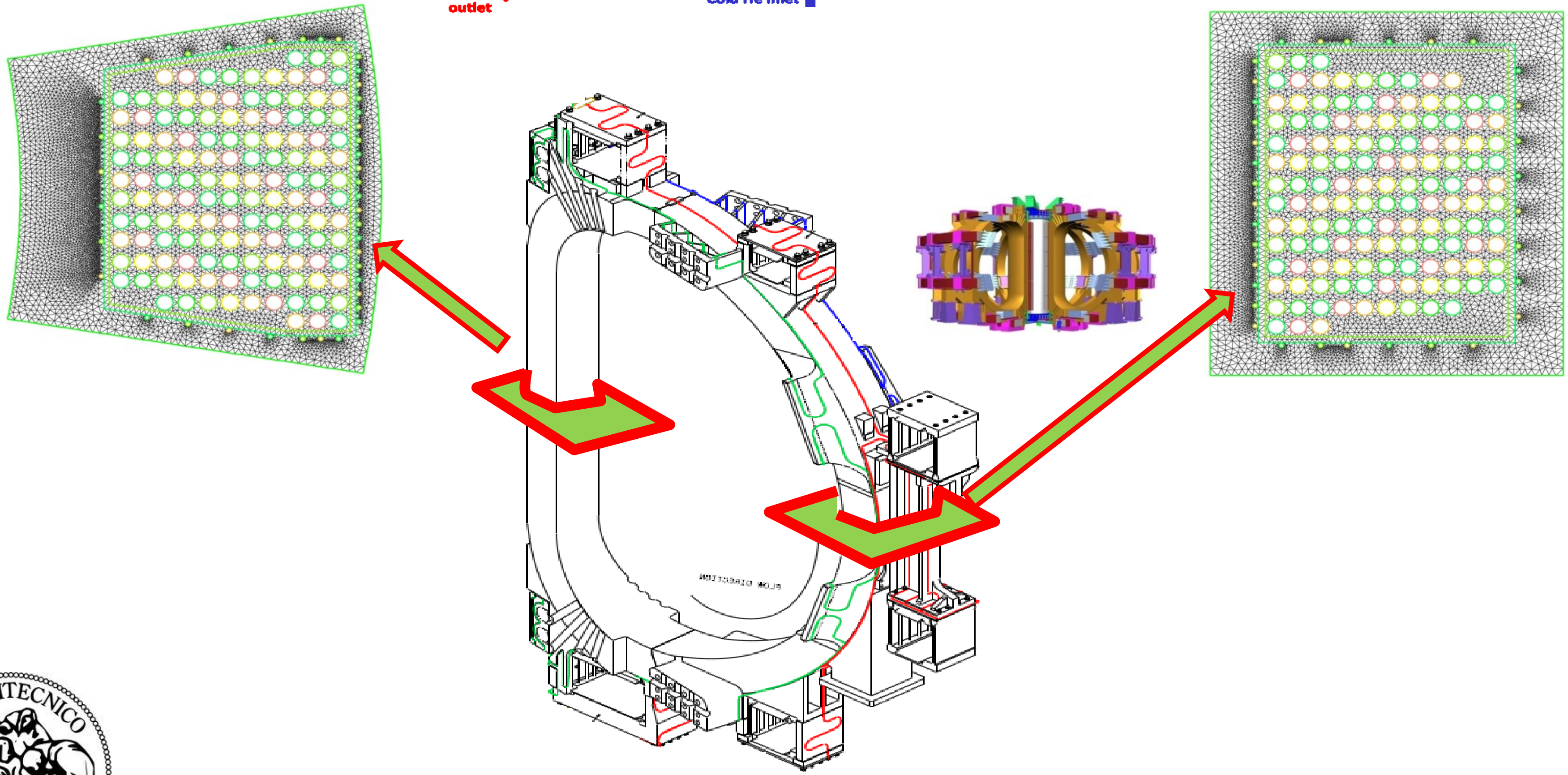




Intro: The 4C structures model

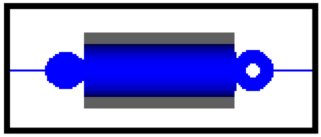




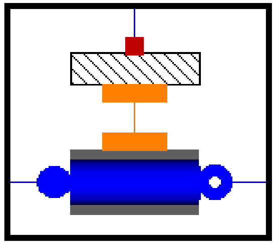


Intro: The 4C circuit model

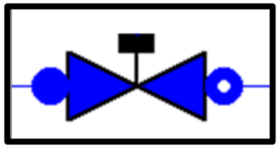
(Cryogenics Modelica library)



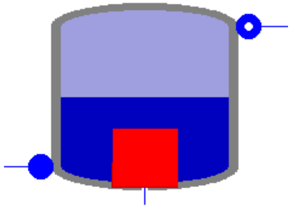
- The **Modelica** language is a non-proprietary standard language that allows describing the basic components of a circuit and the related physical phenomena.



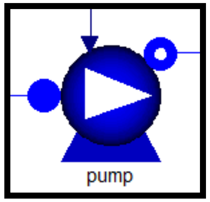
- Components are described in terms of **differential-algebraic equations**, relating the internal variables with each other and with the variables of the ports, which define the physical boundary of each component.
- The port interfaces are **a-causal**: no inputs or outputs are defined a priori and the Modelica compiler automatically determines the causality (i.e., how to solve the equations) at the overall system level.



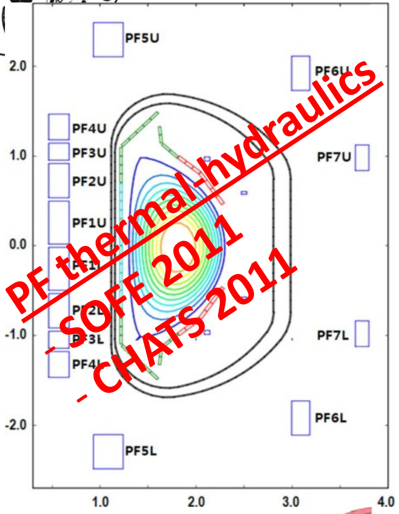
- These **components** can then be connected hierarchically to build arbitrarily complex system models, in a way that can be represented graphically in terms of **object diagrams**.



- A new Modelica **"Cryogenics" library** has been developed for the modeling of cryogenic circuits using He as a working fluid (NIST RefProp properties). The library contains all the relevant circuit components.



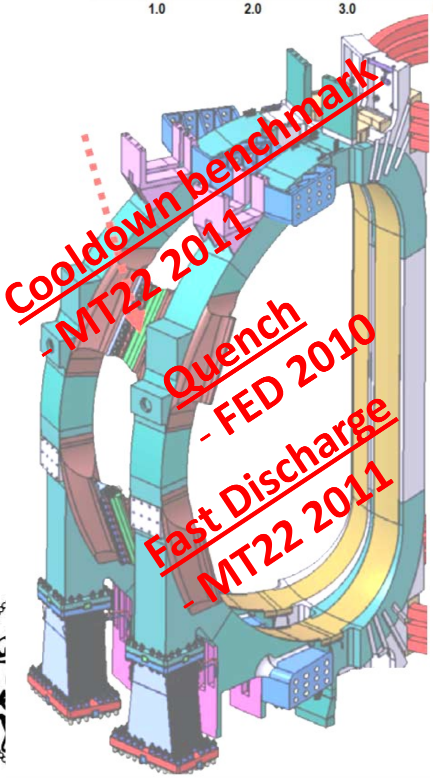
Intro: 4C validation and benchmark



PF thermal-hydraulics
- SOFE 2011
- CHATS 2011

FD validation
- IEEE TAS 2011
- SOFE 2011

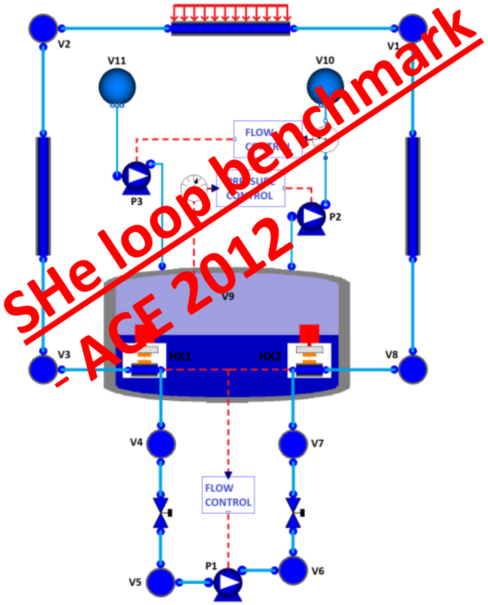
Cooldown validation
- FED 2011



Cooldown benchmark
- MT22 2011

Quench
- FED 2010

Fast Discharge
- MT22 2011



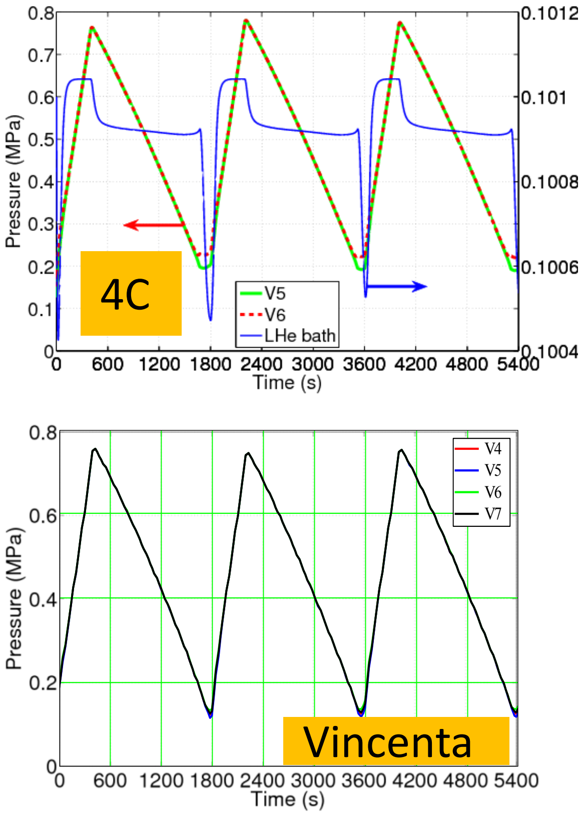
SHe loop benchmark
- ACE 2012

Temperature margin
- FED 2011

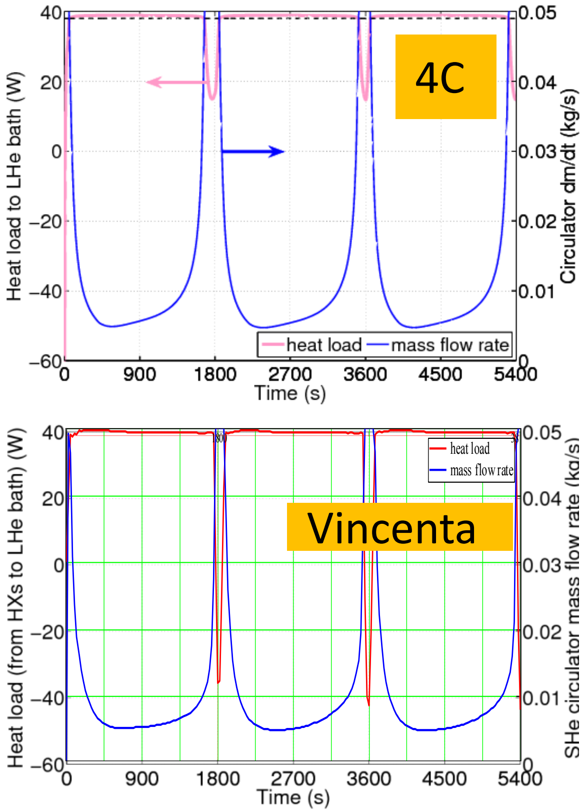
SHe loop validation HERE!

Intro: 4C circuit model benchmark

Loop pressure



Loop dm/dt control



4C results in very good qualitative agreement with Vincenta results

[R. Bonifetto, F. Casella, L. Savoldi Richard, and R. Zanino, *Adv. Cryo. Eng.* (2012)]

Experimental setup (I)

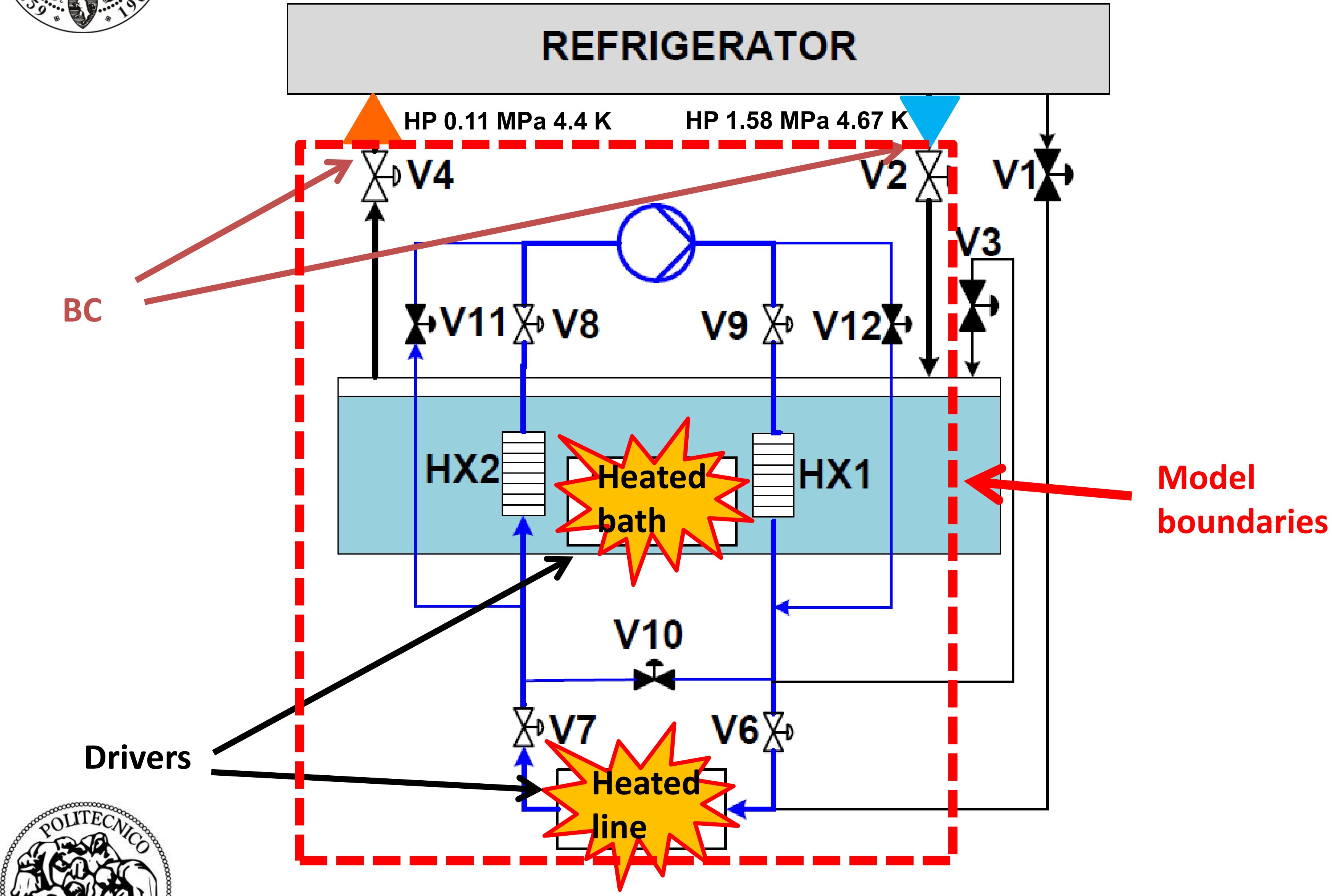
HELIOS (HElium Loop for hIgh lOads Smoothing) @ CEA Grenoble

- Test and assess pulsed load smoothing methods
- Plasma pulse heat loads on JT60-SA magnet system (1/20 ratio)

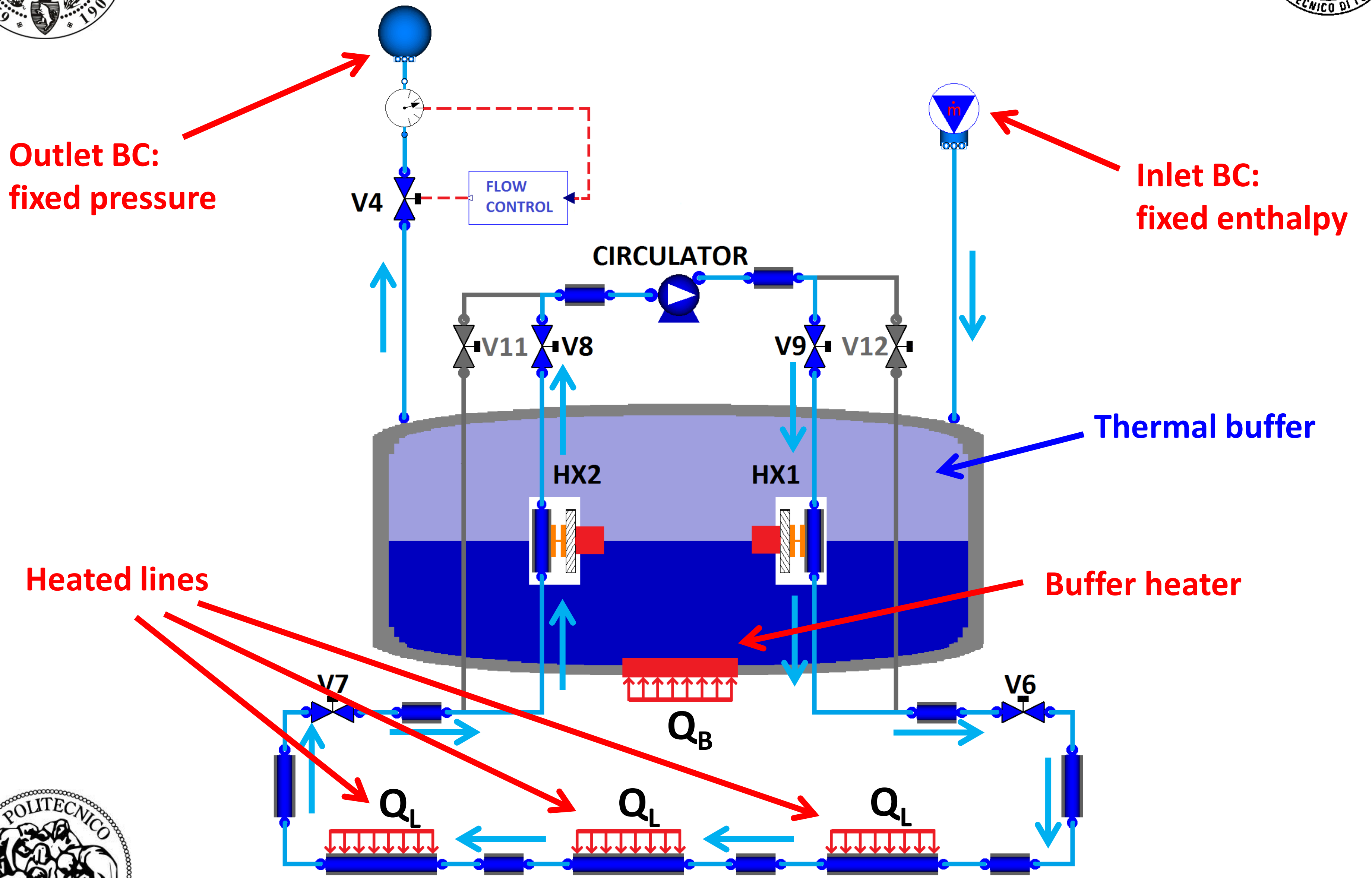
[C. Hoa, et al., *Proceedings of ICEC 23* (2010)]

[C. Hoa, et al., *Adv. Cryo. Eng.* (2012)]

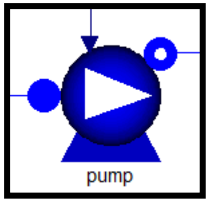
Experimental setup (II)



Circuit model



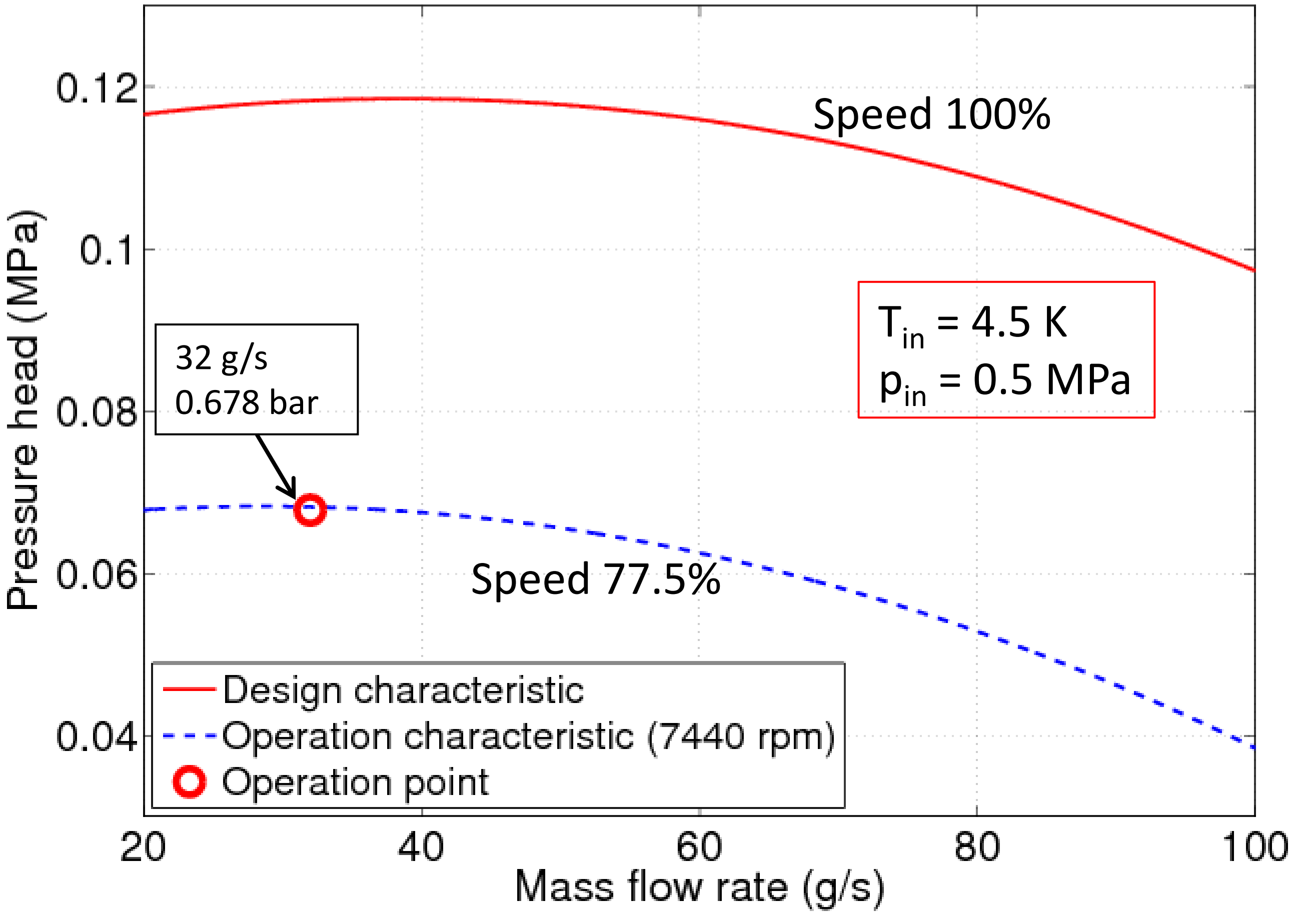
SHe circulator model



Use nominal (parabolic) characteristic of the centrifugal pump at full speed

Rescale to operation point → $\Delta p = \Delta p_0 \times (n/n_0)^2$

Pump efficiency = 21% @ operation point



32 g/s
0.678 bar

T_{in} = 4.5 K
p_{in} = 0.5 MPa

Model assumptions

SHe loop

- Static load split among all pipes, proportionally to lengths
- Adiabatic valves
- V7 (control) valve characteristic: equal percentage

Fraction of valve opening

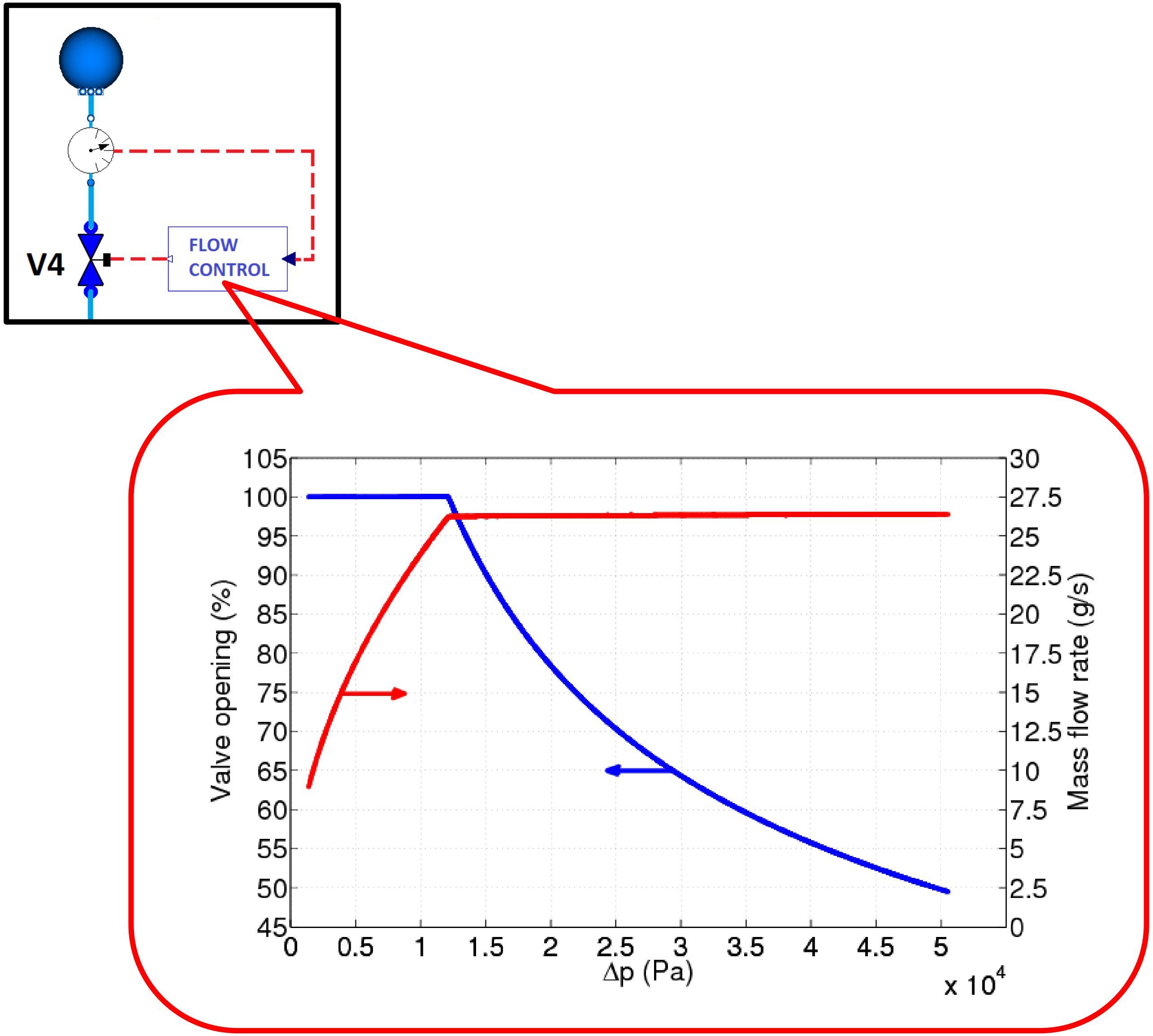
$$Q = C_v \cdot \sqrt{\frac{\Delta p}{\rho}} \cdot R^{x-}$$

Specific gravity

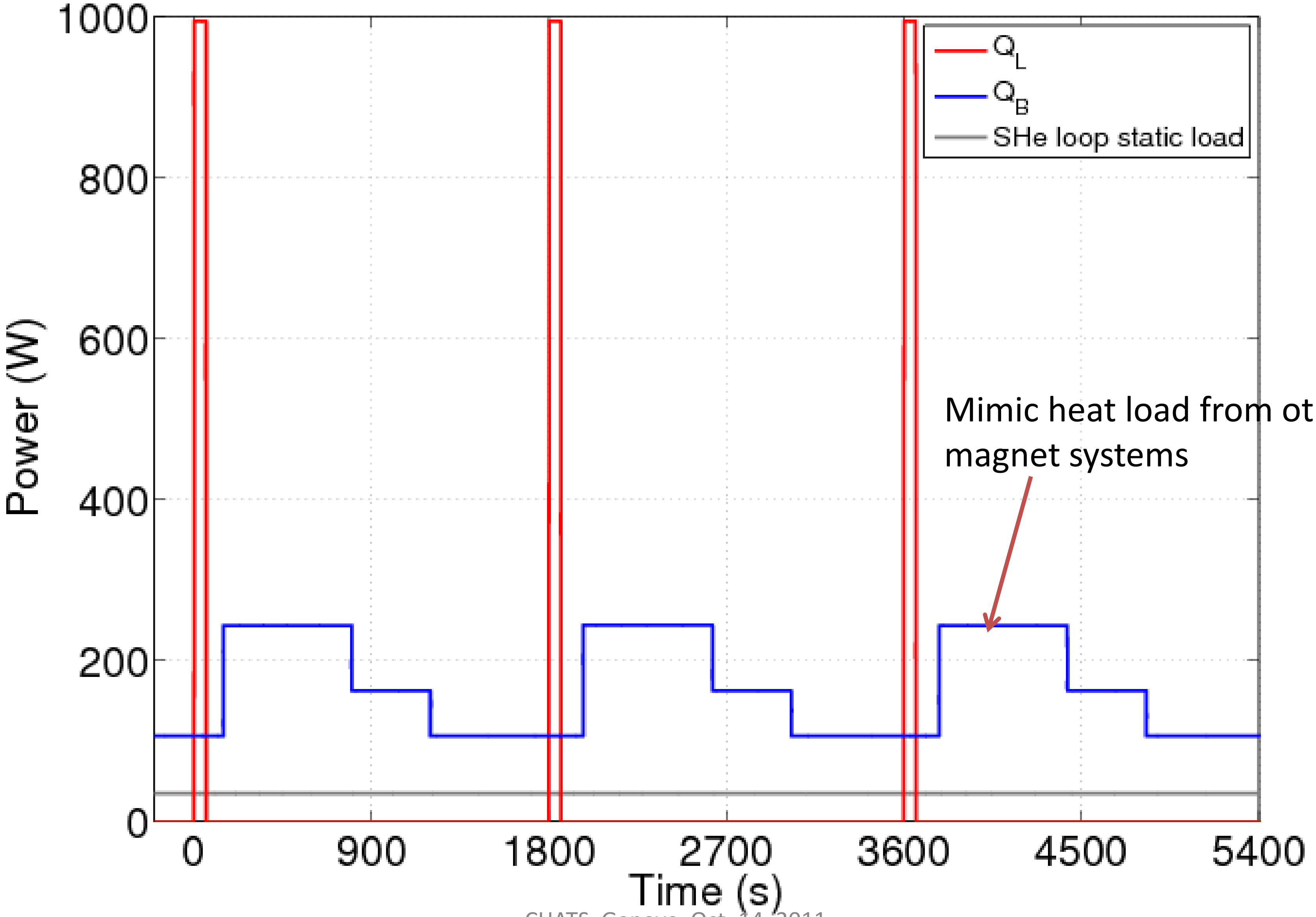
LHe bath

- *inlet*: enthalpy source (h = $h_{\text{refrigerator,outlet}}$)
- dm/dt_{in} = 26 g/s
- *outlet*: reservoir (p = $p_{\text{refrigerator,inlet}}$)
- CONTROL → $dm/dt_{out} \leq$ 26.5 g/s (uncertainty in exp value ...)

Buffer control strategy

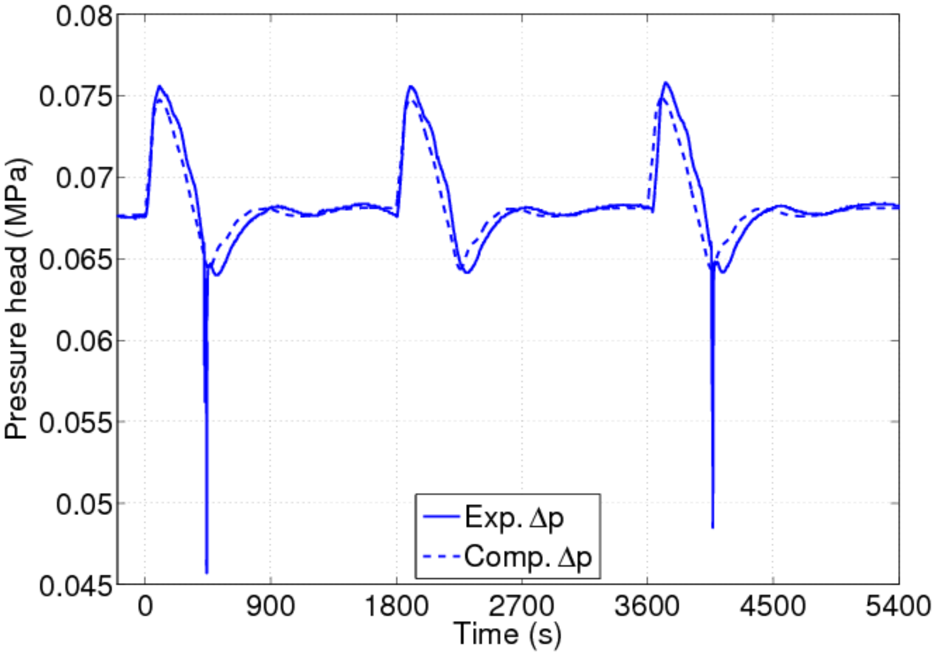


Drivers



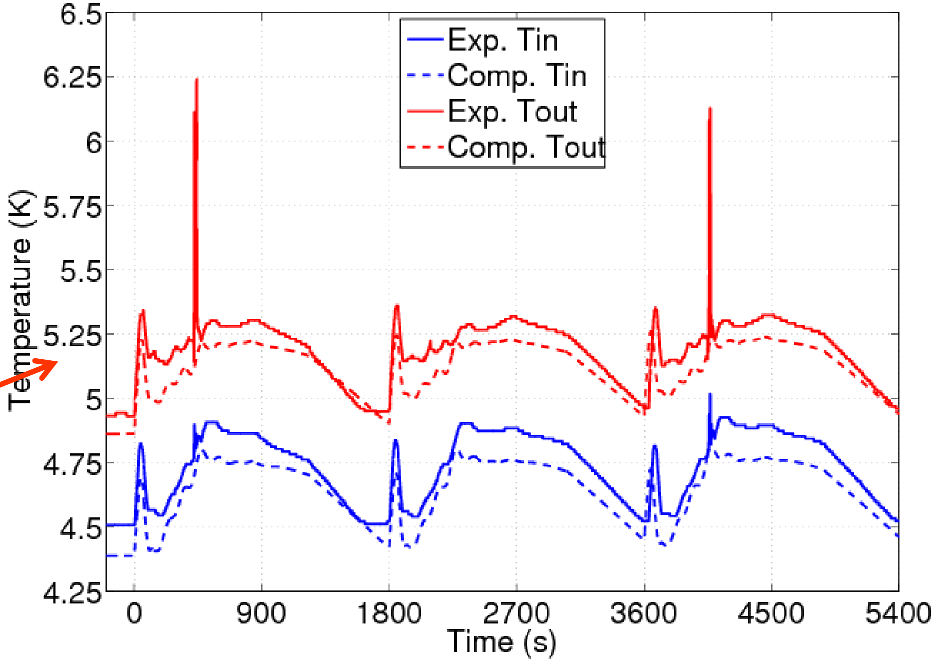
Mimic heat load from other magnet systems

Results: SHe circulator



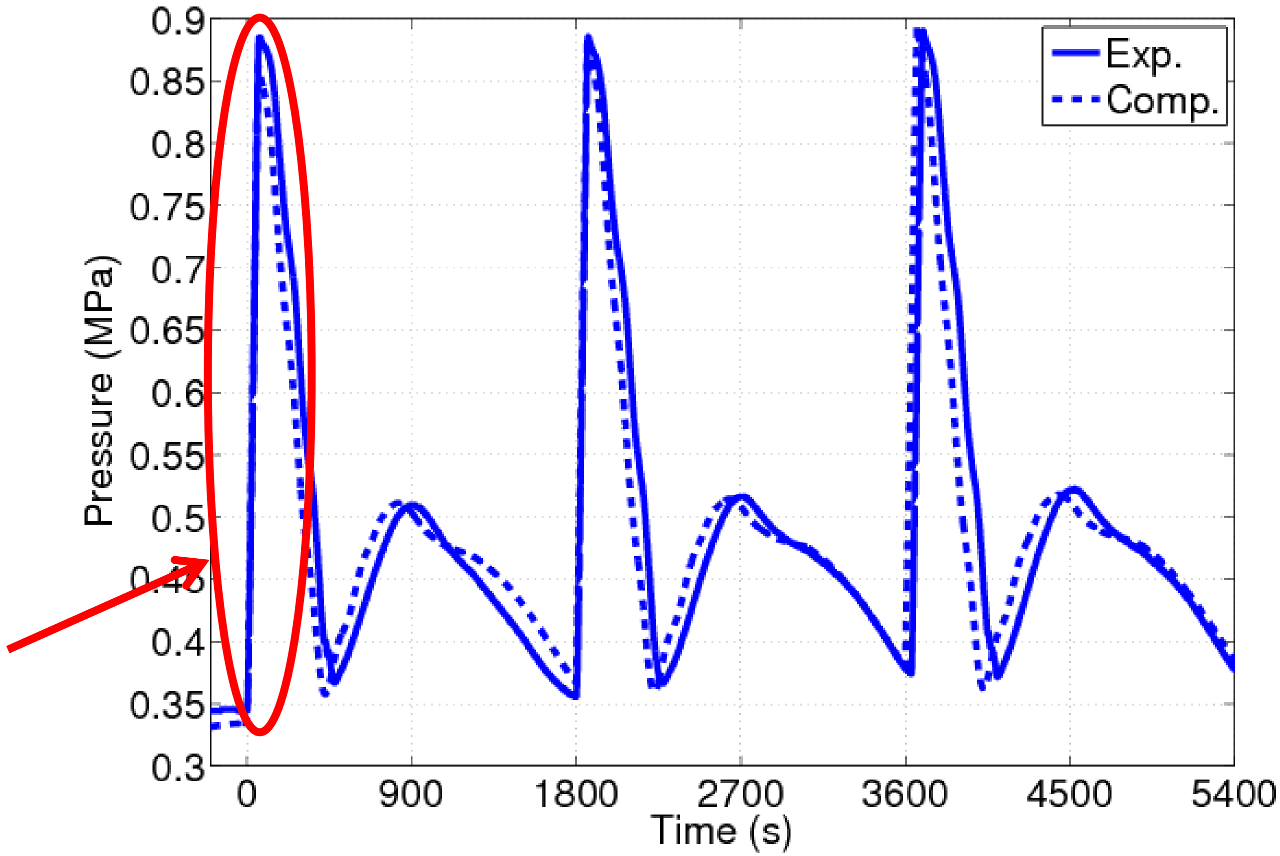
- Very good agreement in pressure head
- Measured spikes (under investigation at CEA) not seen in simulations

Small offset in inlet /outlet temperature



Results: SHe loop pressurization

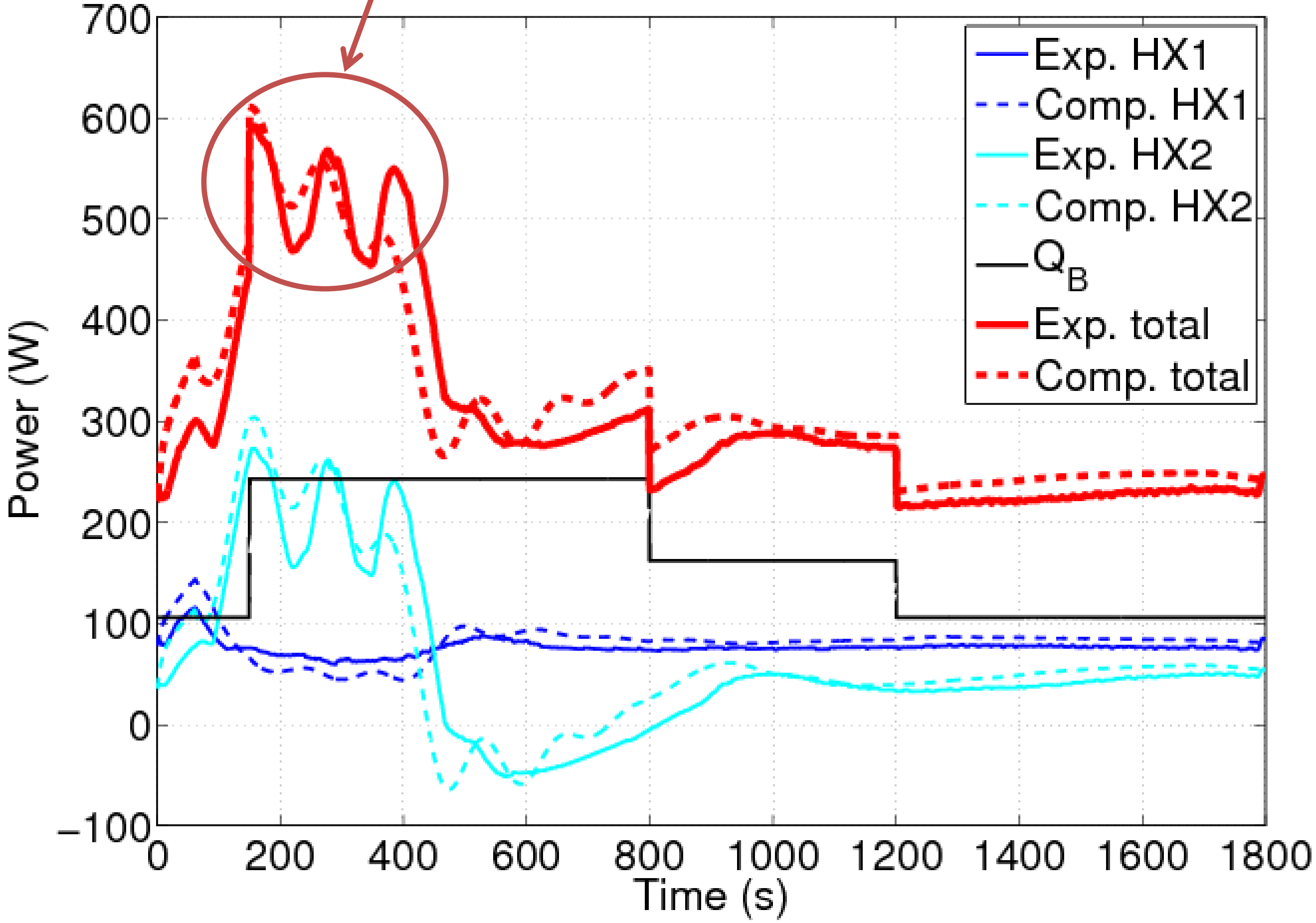
Very good agreement between computed and experimental pressure at the outlet of the heated line



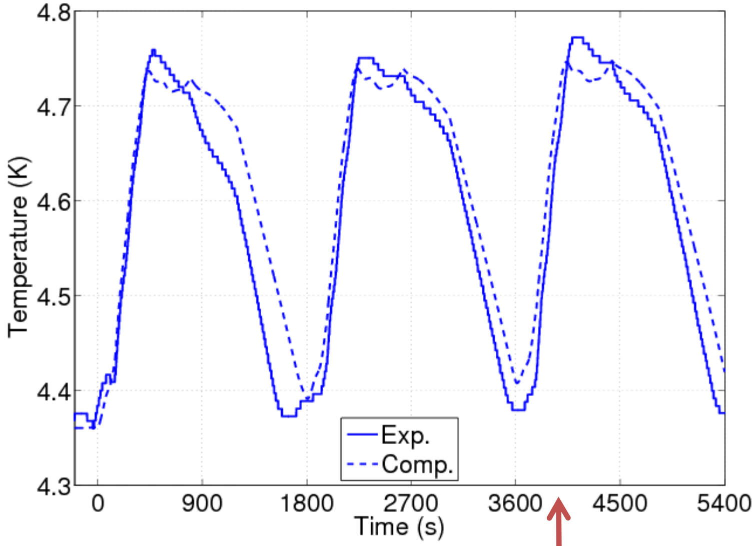
Loop pressurization on the timescale of Q_L heat deposition.

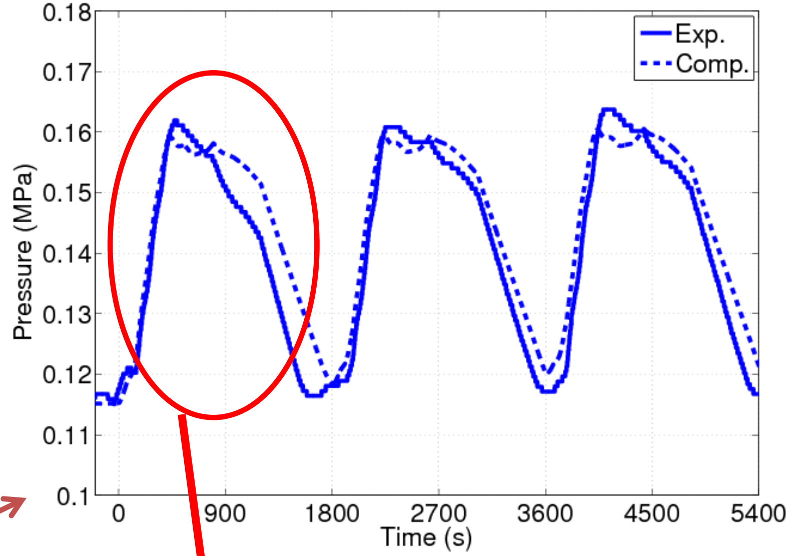
Results: Load on thermal buffer

Three peaks due to three heated sectors

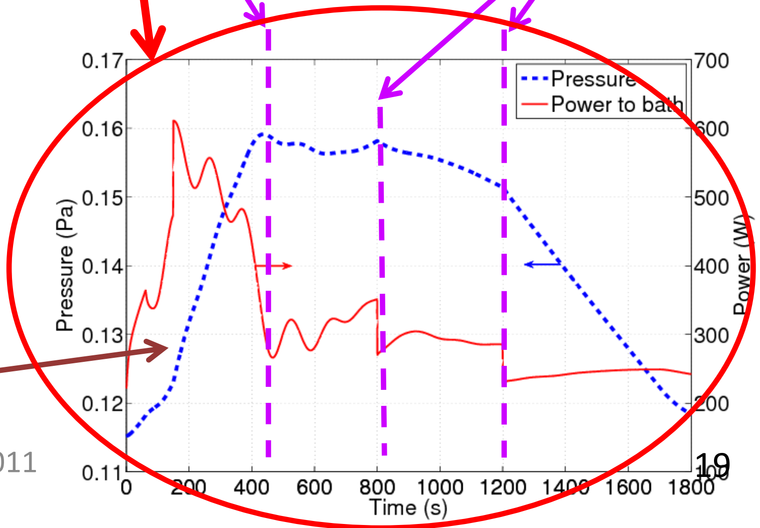


Results: Thermal buffer response





Good approximation of bath T and p evolution, with some lag



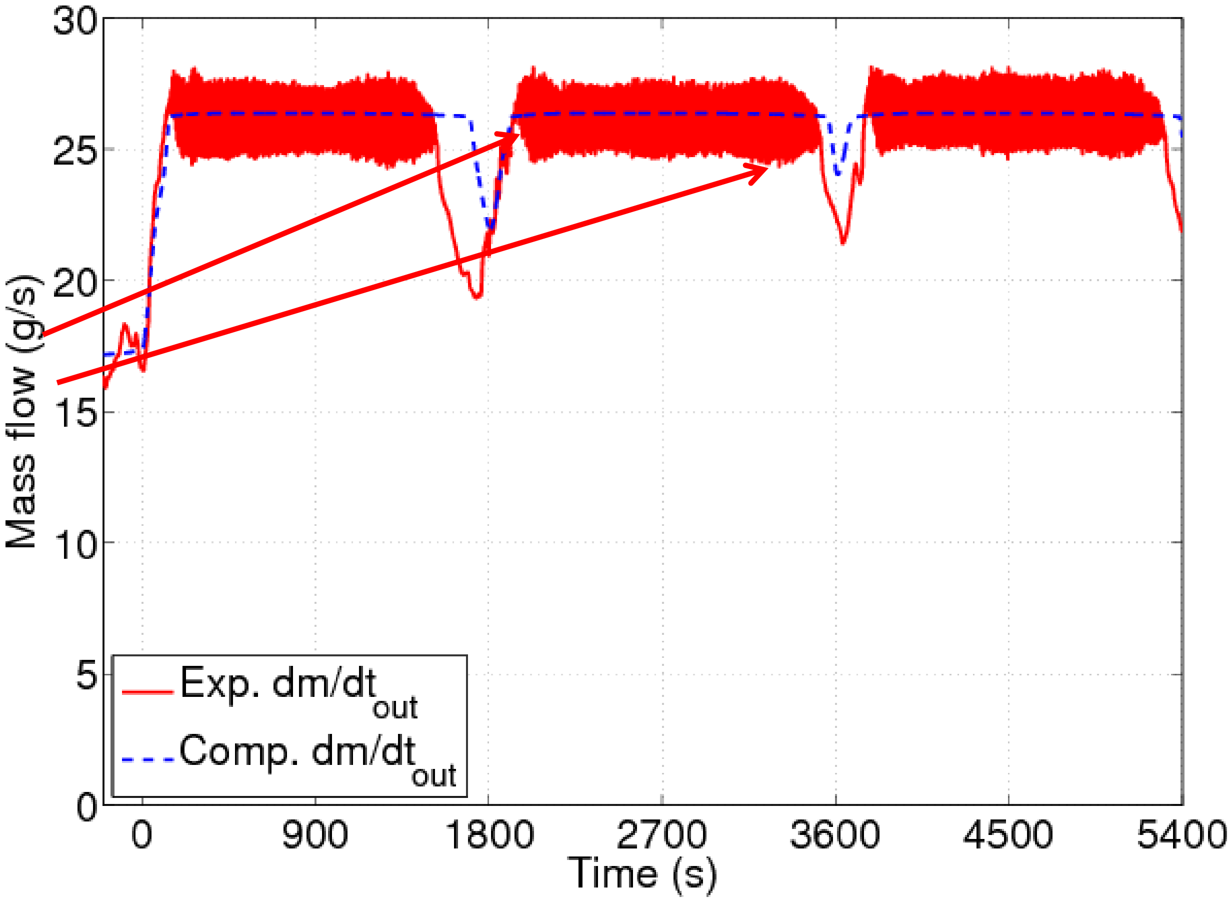
Transit time from heated line to HX2

Steps in Q_B

Slope changes synchronized with changes in power input to bath

Results: Thermal buffer control

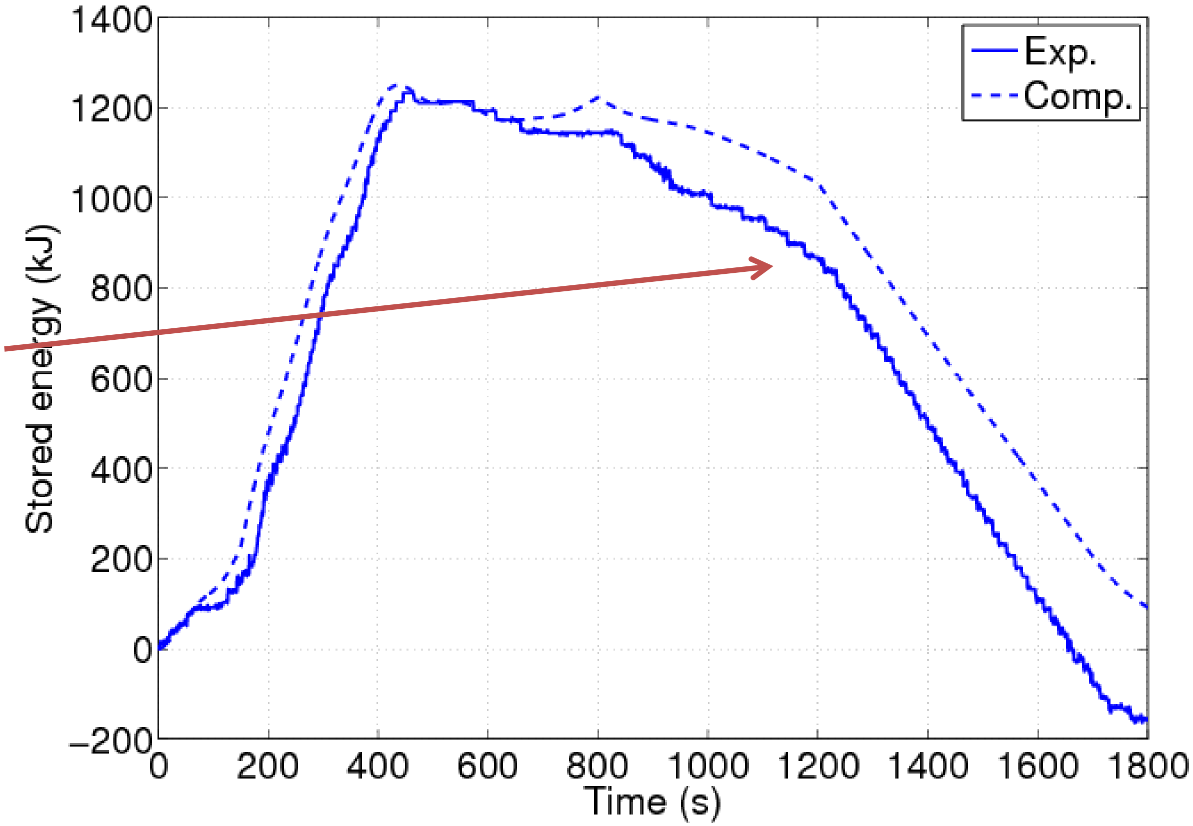
Computed *dm/dt* @ outlet of thermal buffer lags behind exp ← lagging of simulated *p_bath* ← uncertainty of exp *dm/dt* corresponding to V4 setting point



Results: Thermal buffer stored energy

Computed stored energy = $U(p(T_{sat},t)) - U(p(T_{sat},0))$

Small overestimation of stored energy ← slightly different behavior of thermal buffer pressure



Conclusions and perspective

- The circuit model implemented in 4C was successfully validated against experimental results from the HELIOS/JT60-SA facility @ CEA Grenoble, for a multiple heat pulse scenario
- Good quantitative agreement between simulation and measurements was shown over the whole transient, <u>without fitting parameters</u>, for T(t), p(t) dm/dt(t) in both SHe closed loop and saturated helium bath
- We plan to apply the tool to more comprehensive studies in the next future