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Development and test of a dynamic Modelica model of the He refrigerator for superconducting magnet systems

R. Bonifetto, P. Gaiotti

NEMO Nuclear Engineering MOdeling Group

Acknowledgements: K. Kawano
(National Institutes for Quantum and Radiological Science and Technology, Naka, Japan)

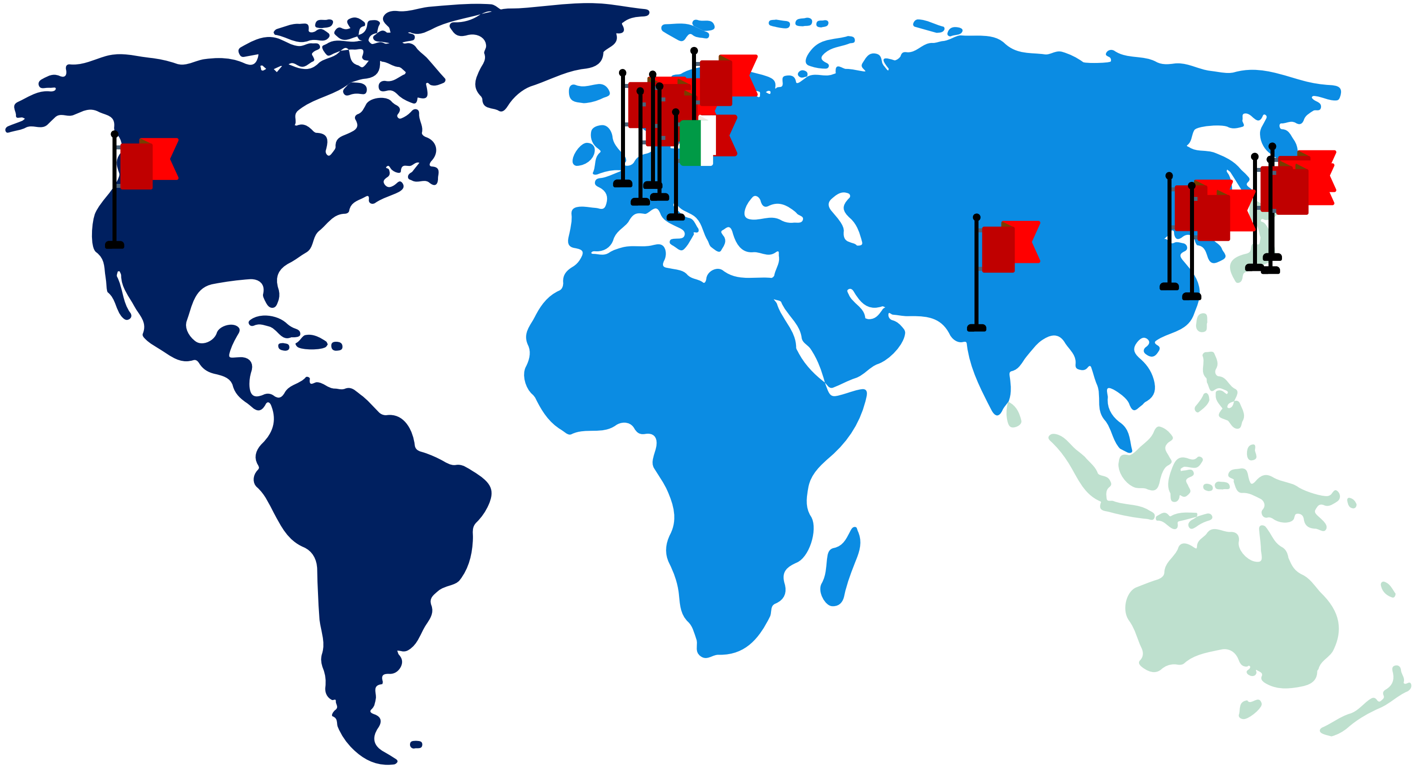
Politecnico di Torino 1859
energy

Outline

- Introduction and motivation
- Background and aim of the work
- The ITER CSMC He refrigerator
- Model description
- Model applications:
  - Normal operation
  - Accidental operation
- Conclusions and perspective

Existing (and future) refrigerators for fusion

Existing/future tokamak-type fusion reactors use superconducting magnets cooled by SHe to confine the plasma ➔ Cryoplant is needed



- ITER CS final test station (~1 kW)
- JT-60SA TF coils cold test facility (~10 kW)
- WEST
- HELIOS
- ITER (75 kW)
- W7-X
- DTT
- DTT cold test facility
- SST – 1 (~0.5 kW)
- EAST
- ITER CC test facility (~0.5 kW)
- ITER CSMC (~5 kW)
- LHD (~10 kW)
- JT-60SA (9 kW)

& others (EU DEMO, ...)

Normal operation regimes & need for modeling

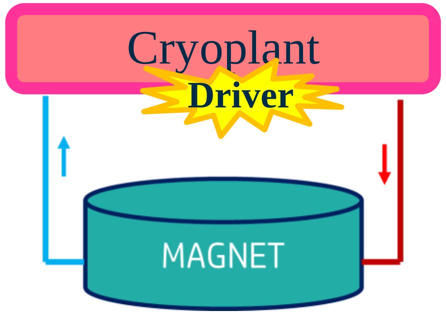
1) Cooldown

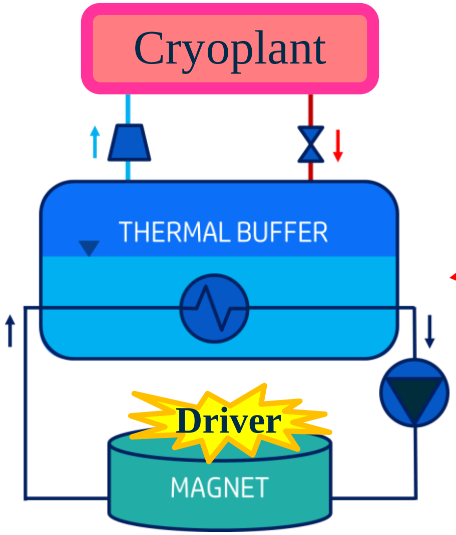
The refrigerator outlet is *directly* connected to the magnet

Transient *actively* driven by the refrigerator

→ coupling of the (refrigerator and magnet) models required to properly predict/optimize the controls to safely cool the magnet

→ refrigerator model for commissioning





2) Pulsed operation

Refrigerator connected to the magnets

– directly

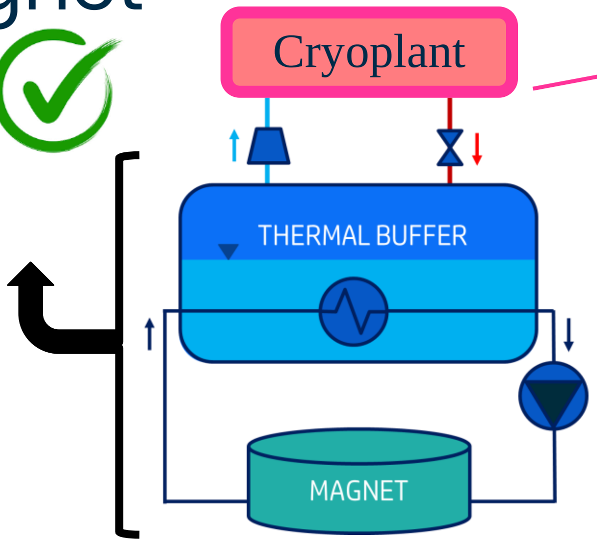
– through a *thermal buffer*

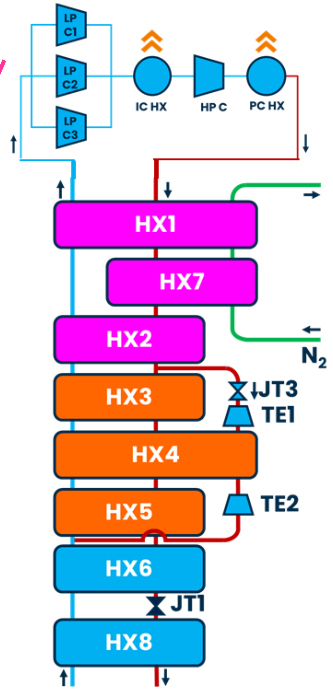
Transient driven by the pulsed heat load on the magnets, *passively* suffered by the refrigerator

→ coupling required to assess / optimize buffer action and effects on the refrigerator

Background

Detailed and reliable model of the cryodistribution (SHe loop [1],[2]) + magnet (e.g. 4C code [3]) already available





Preliminary, simplified model of the refrigerator developed [4] and validated [5] (cooldown to 80 K) **BUT** issues related to the dinamics at low T

[1] R. Bonifetto, et al., CEC 2011 (development and benchmark)

[2] R. Zanino, et al., CEC 2013 (predictive validation)

[3] L. Savoldi, et al., *Cryogenics* (2010)

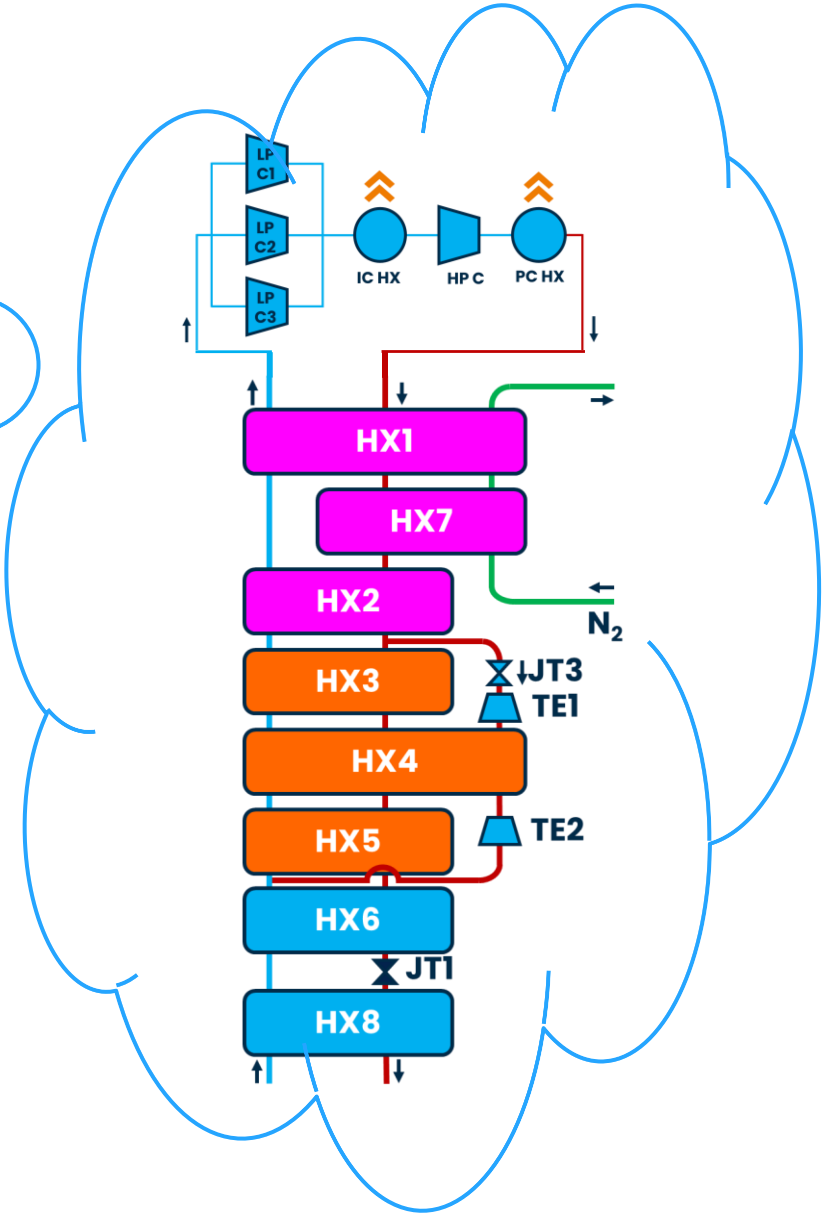
[4] R. Bonifetto, et al., presented at CHATS 2017

[5] R. Bonifetto, et al., Mat. Sci. Eng. (2019)

Aim of the work

Develop a model of the He refrigerator for fusion magnets

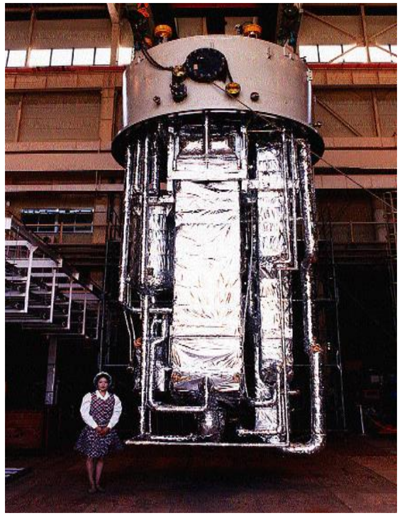
- complete
- *dynamic*
- reliable (validation will be the *next step*)
- capable to
  - run in standalone → support refrigerator commissioning / operator training
  - easily communicate with the 4C code detailed magnet model → support magnet system commissioning and normal / off-normal operation



CSMC refrigerator: thermodynamic reference cycle

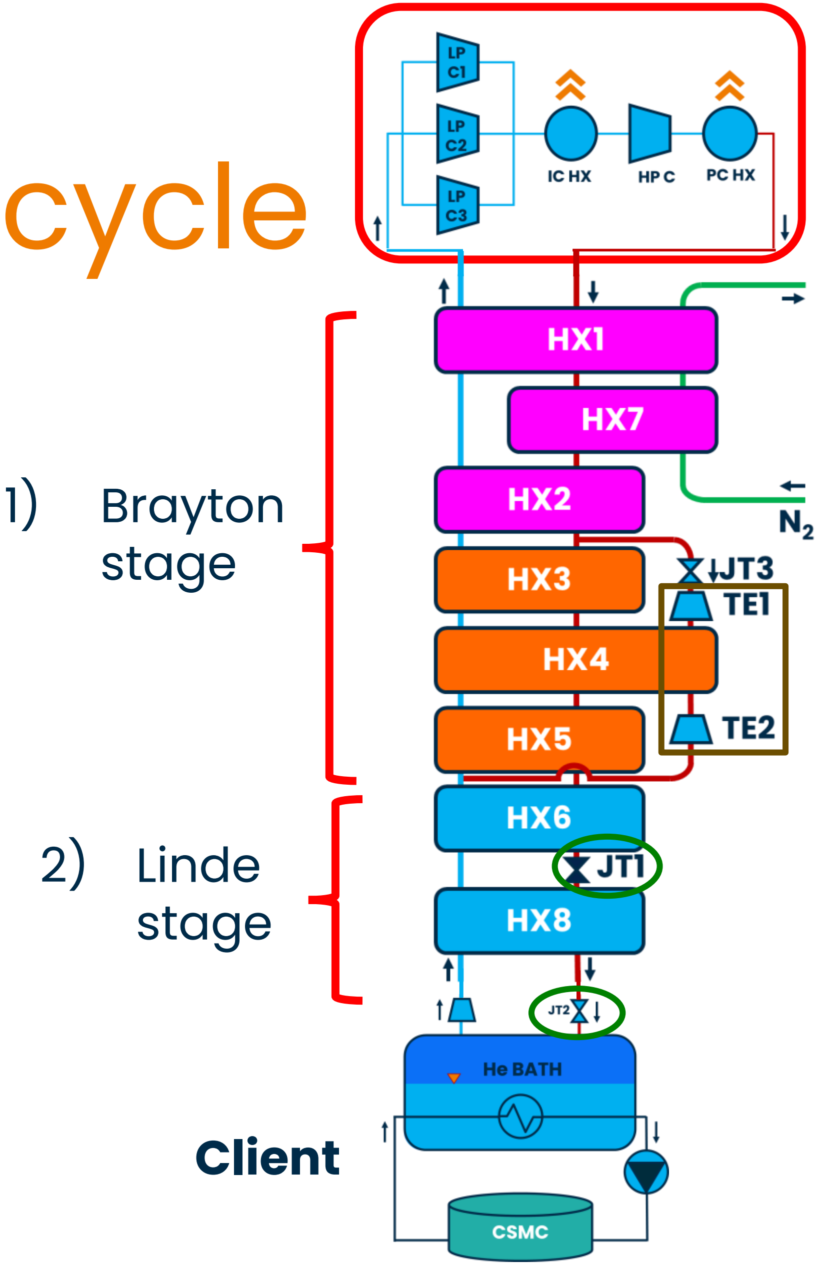
Collins cycle

Global configuration representative of several tokamak and SC test facility refrigerators

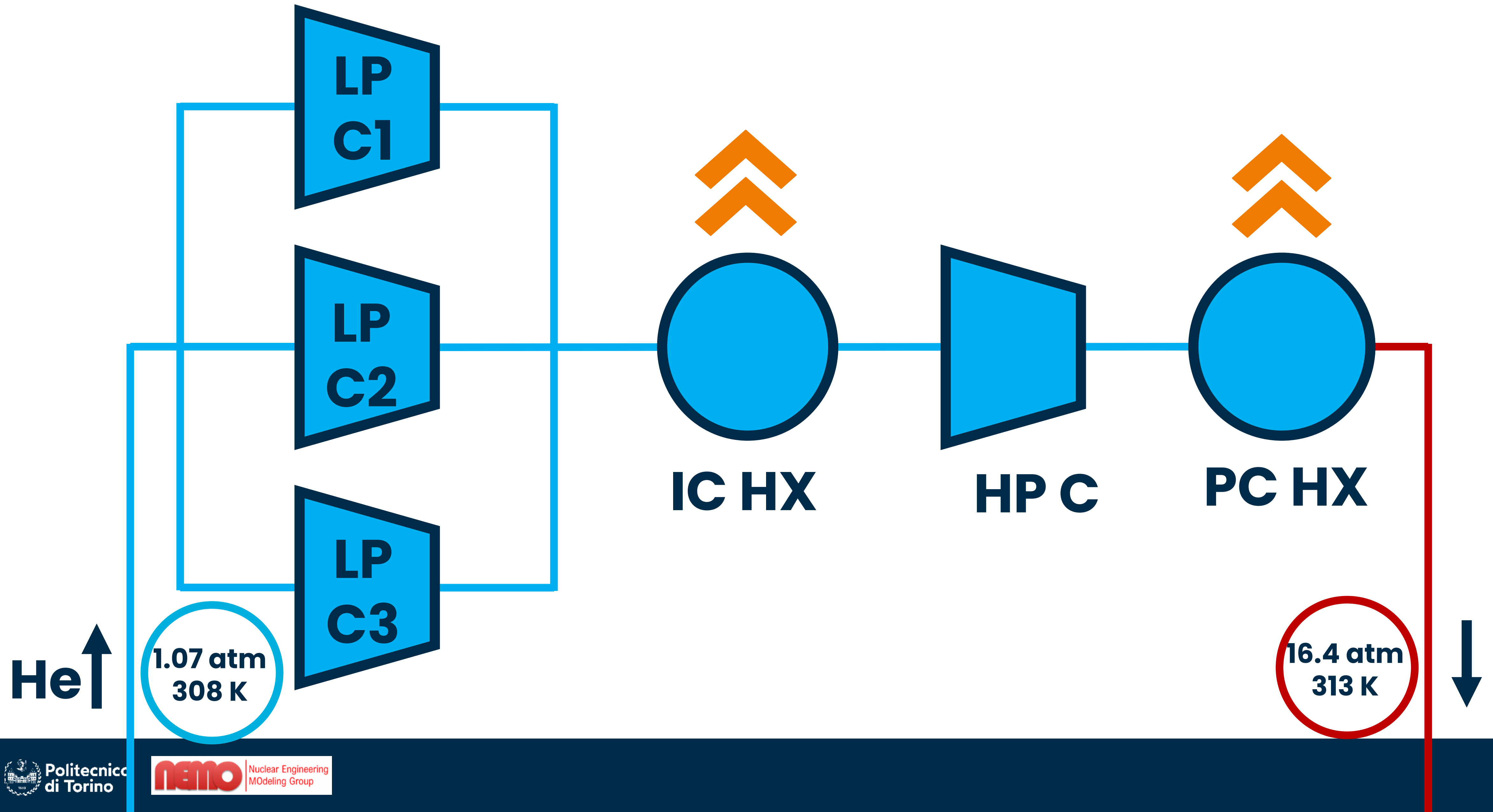


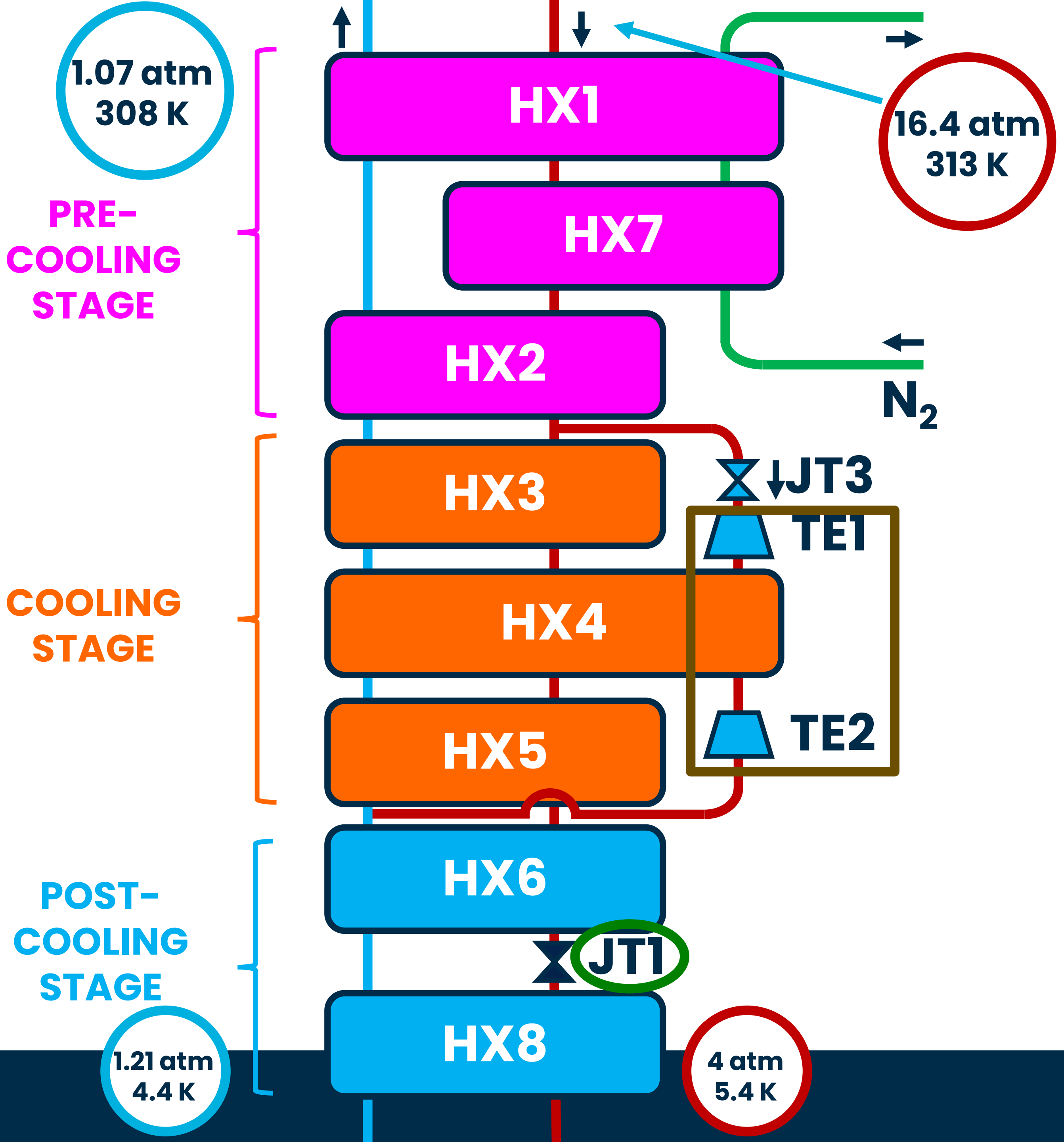
[T. Kato et al., Adv. Cryo. Eng., 1996]

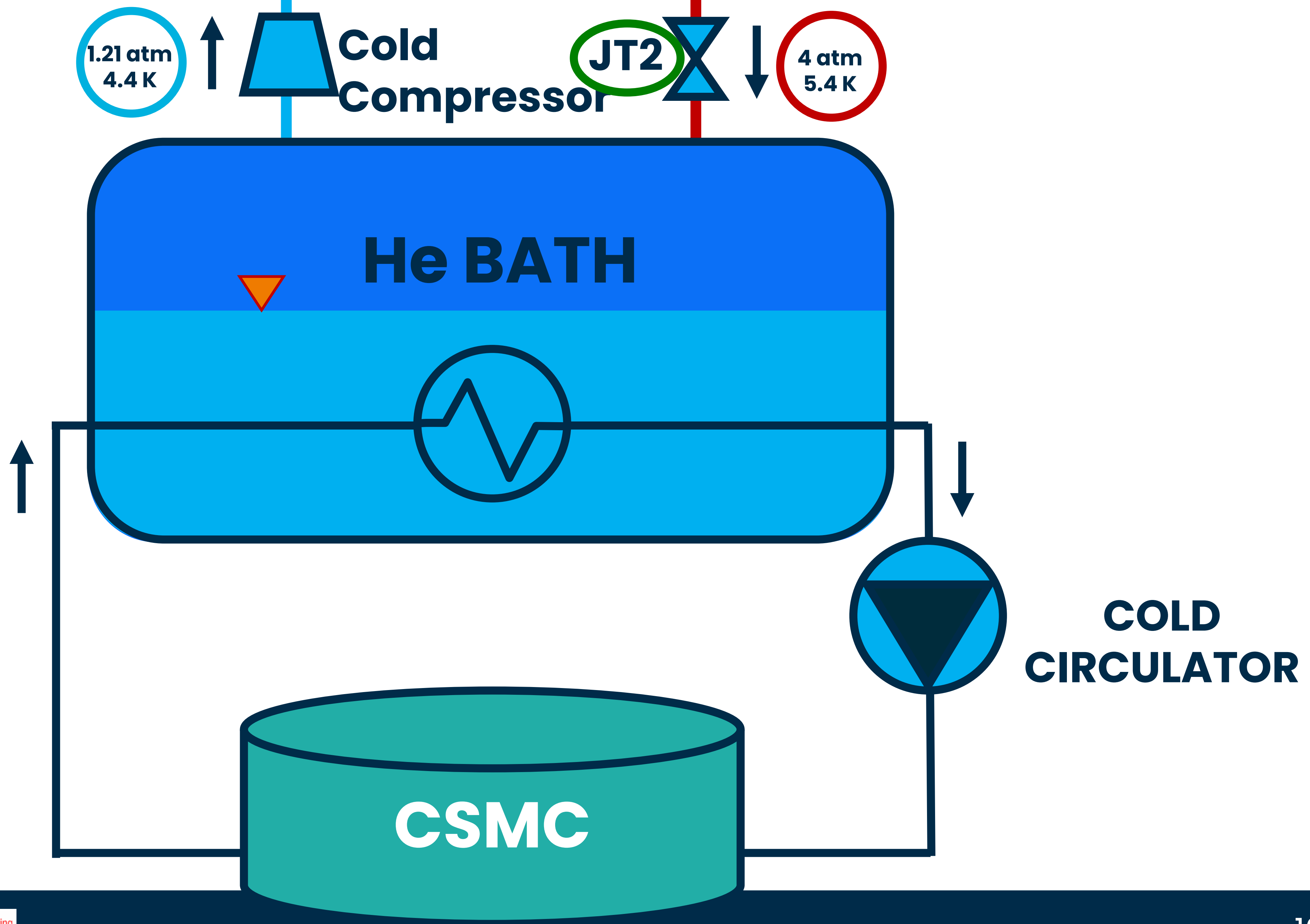
- 2 compression stages
- HXs:
  - 3 pre-cooling stages (including N_2 pre-cooling)
  - 3 cooling stages
  - 2 after-cooling stages
- 2 expansion stages:
  - 2 isentropic expansions
  - Adiabatic isenthalpic expansion



COMPRESSION UNIT




1.07 atm
308 K
PRE-
COOLING
STAGE
COOLING
STAGE
POST-
COOLING
STAGE
1.21 atm
4.4 K
HX1
HX7
HX2
HX3
HX4
HX5
HX6
JT1
HX8
16.4 atm
313 K
N2
JT3
TE1
TE2
4 atm
5.4 K


1.21 atm
4.4 K
Cold
Compressor
JT2
4 atm
5.4 K
He BATH
COLD
CIRCULATOR
CSMC

Structure of the refrigerator model

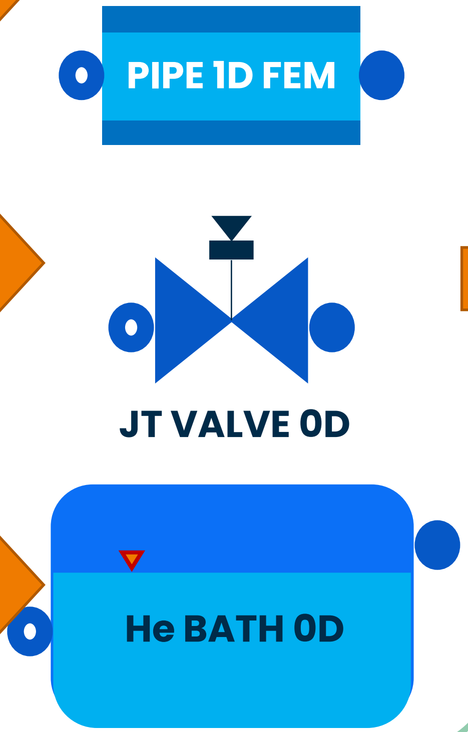
LIBRARIES

ExternalMedia
Interface to fluid property packages

ThermoPower
Components for power plants

CryoModelica
Components specific for cryogenic plants extending / replacing ThermoPower ones

COMPONENT MODELS



MODELICA (programming language)

- Object-oriented
- A-causal
- Equation-based

REFRIGERATOR MODEL

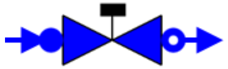
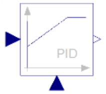
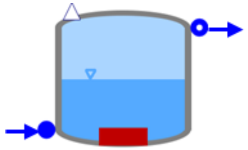
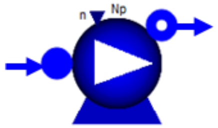
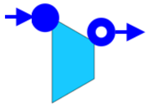
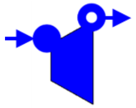
Same language of 4C circuit module model
→ easy coupling with detailed coil model

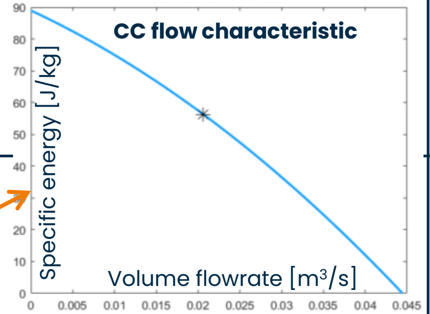
DYMOLA (simulation environment)

DIFFERENTIAL/ ALGEBRAIC SYSTEM SOLVER

Several solvers available with adaptive time-step

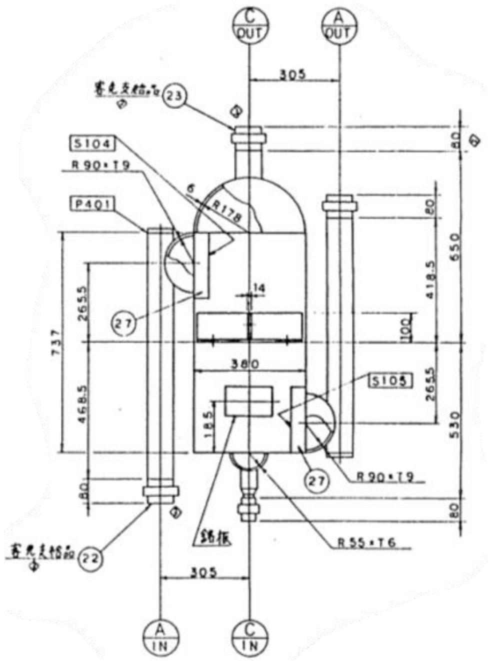
CryoModelica library main components

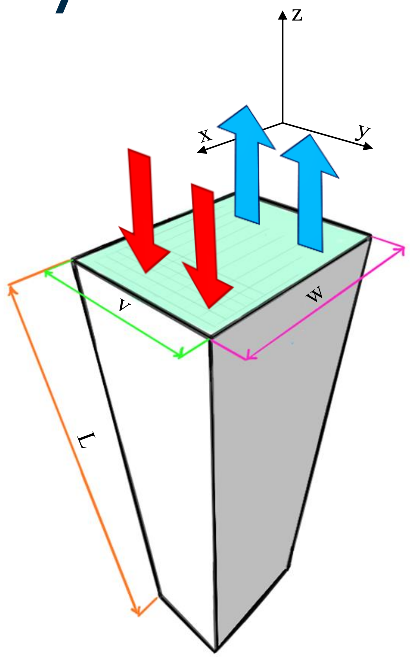
Component	Symbol	Assumptions	Input	Main eq.
Pipe / HX(1D)		1D	Geometry, Friction, HTC	Cons. mass/ momentum / energy
Valve		Volume is neglected	C_v, opening, characteristic type, rangeability	Cons. mass / energy, characteristic
Controller			PID parameters, set point, process variable signal	Manipulated variable
LHe bath		0D, only vapor is extracted	Volume	Cons. mass / energy for both phases
Pump		0D, η_{iso} constant Volume is neglected	$\Delta p(dm/dt)$ **characteristic**	Cons. mass / energy, characteristic
Compressor		0D, η_{iso} constant Volume is neglected	$dm/dt(p_{out}/p_{in})$ characteristic	Cons. mass / energy, characteristic
Turbine		0D, η_{iso} constant Volume is neglected	$dm/dt(p_{out}/p_{in})$ characteristic	Cons. mass / energy, characteristic

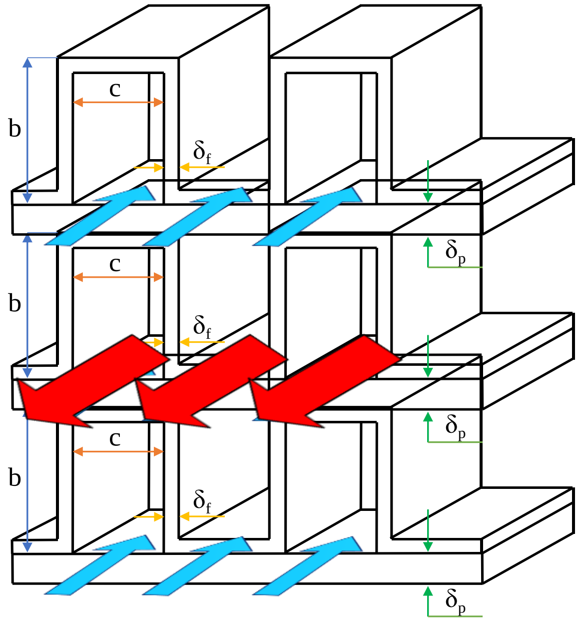


Two-fluid HX: the real object

- Plate-and-fin HX
- One fluid being cooled by the other fluid warming up







[K. Kawano, personal communication (2015)]

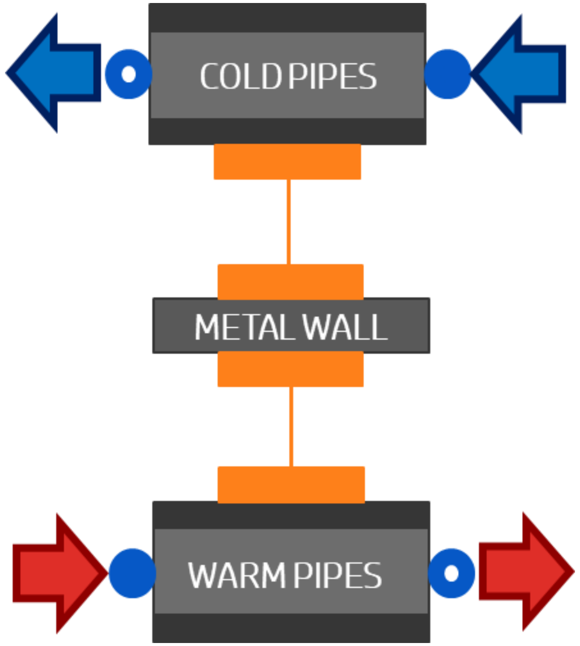
Important quantities to be preserved:

- Heat transfer area
- Solid and fluid cross sections for each passage
- Plate thickness

Two-fluid HX: the model

INPUT parameters

- Fin-and-plate geometry (plate thickness…)
- Heat transfer coefficient / correlation (and its multiplier β)
- Temperature-dependent material properties



PIPE 1D FEM

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \dfrac{\partial (\rho u)}{\partial z} = 0 \\ \dfrac{\partial (\rho u)}{\partial t} + \dfrac{\partial (\rho u u)}{\partial z} = -\dfrac{\partial p}{\partial z} - \rho g - \nabla \bar{\bar{\tau}} \\ \dfrac{\partial (\rho H)}{\partial t} + \dfrac{\partial (\rho u H)}{\partial z} = \nabla (k \nabla T) - \nabla \ddot{q}_r + \ddot{q} + \dfrac{D\rho}{Dt} + \phi \end{cases}$$

METAL WALL 0D FEM

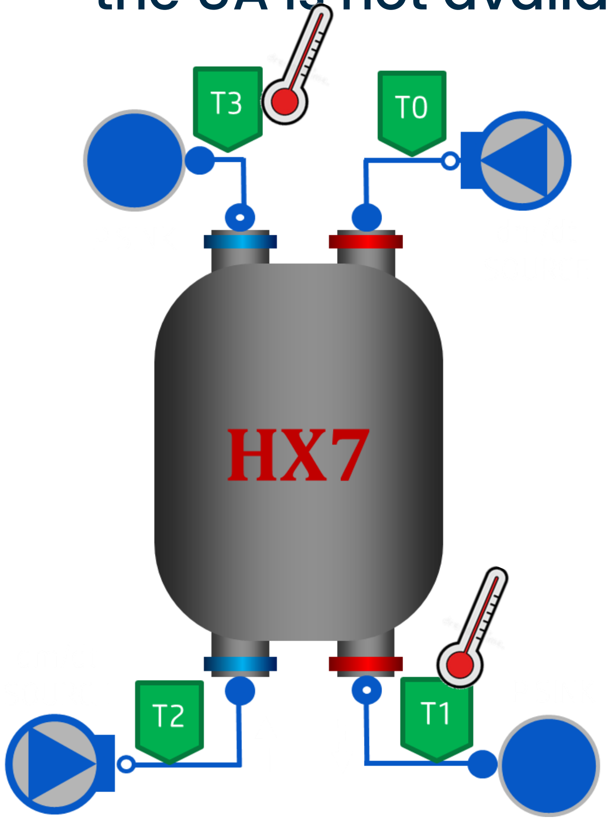
$$C_m \frac{\partial T}{\partial t} = S_{int}\phi + S_{ext}\phi$$

- Transient terms for the proper dynamic modeling

Two-fluid HX: calibration

The HTC needs to be calibrated (using measured T) because

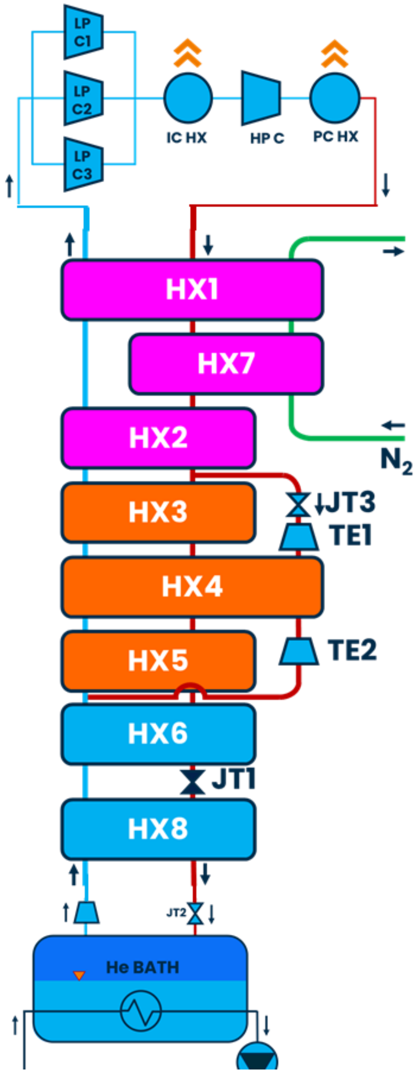
- the real operating condition may differ a lot from the testing one, where the overall heat transfer coefficient U was measured
- the refrigerator has been operated for ~20 years
- the UA is not available for all HXs



Result comparison 2-FLUID HX									
	β	T_{T2}[K]	T_{T3}[K]	$T_{T3,exp}$ [K]	err [%]	T_{T0} [K]	T_{T1} [K]	$T_{T1,exp}$ [K]	err [%]
HX8	2.04	4.433	5.12	5.06	1.186	5.89	5.36	5.366	0.112
HX6	2.35	5.06	12.01	11.9	0.924	12.24	5.75	5.8	0.862
HX5	2.33	11.9	17.33	17.23	0.580	18.6	12.242	12.24	0.016
HX3	2.27	28.08	33.75	33.57	0.536	36	28.48	28.59	0.385
HX2	2.15	33.57	83.39	83.52	0.156	85.03	35.92	36	0.222
HX7	1.5	77.42	77.4395	77.41	0.038	86.41	85.32	85	0.376

The HTC needs corrections between 1.5 and 2.5, depending on the HX, which is acceptable also in view of the approximations and uncertainties

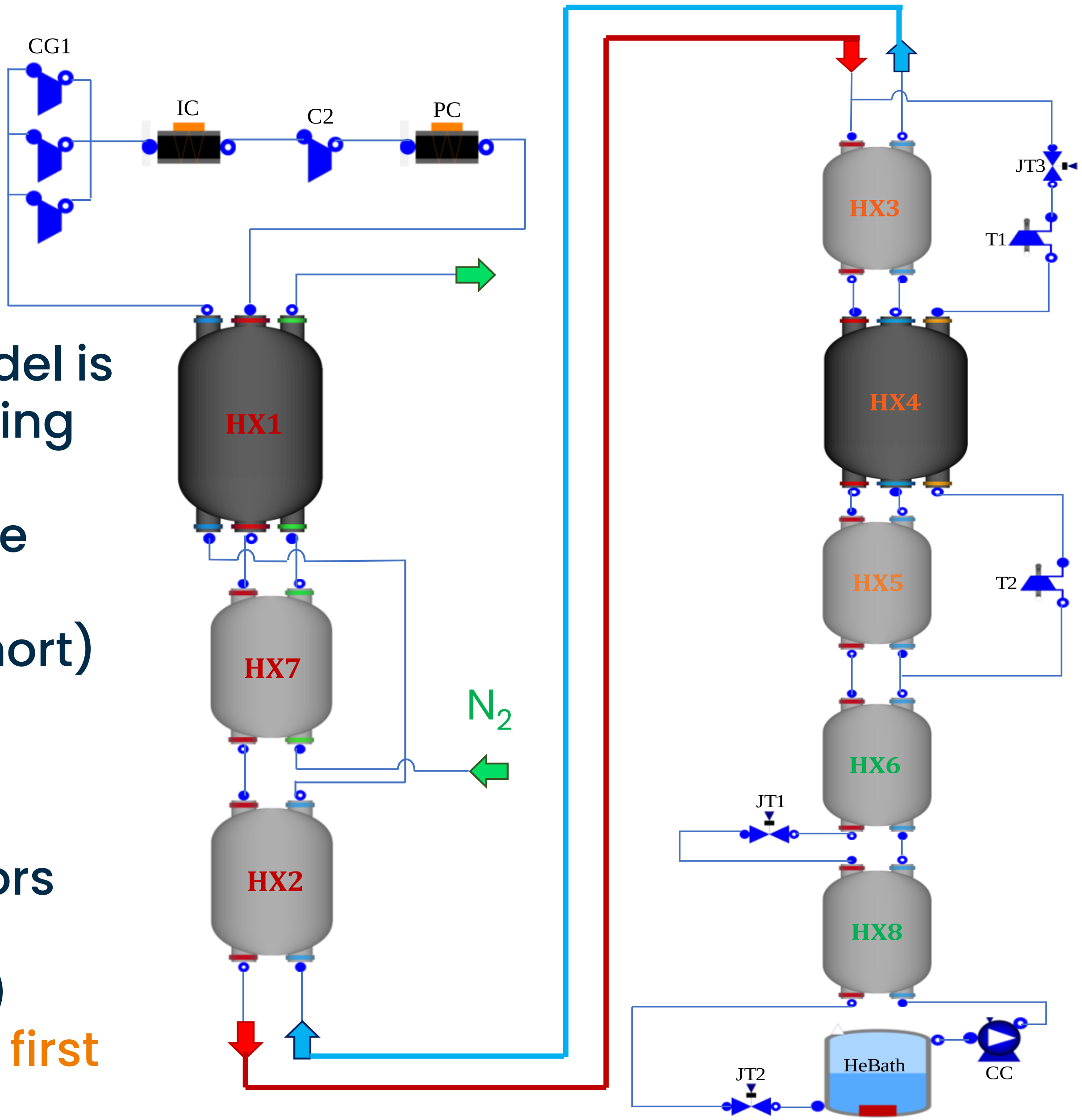
Refrigerator model



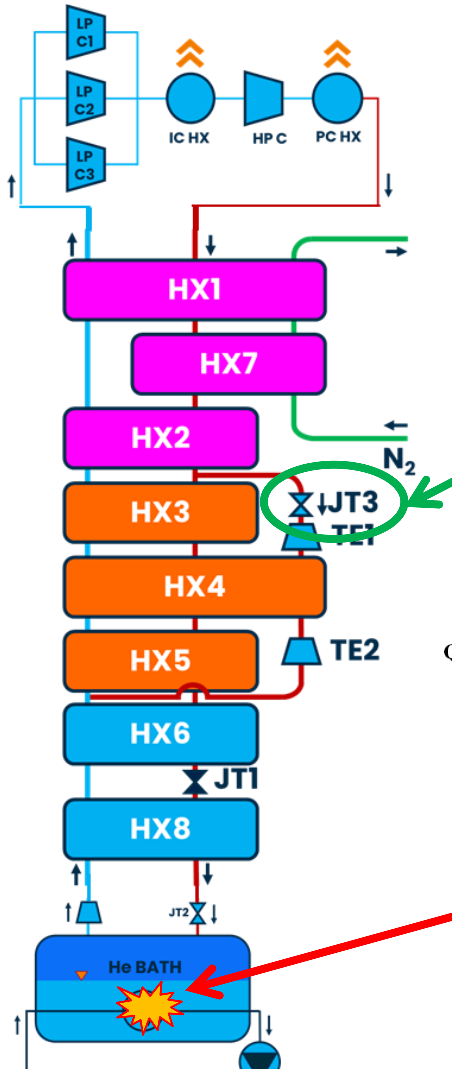
The entire refrigerator model is assembled with the following *assumptions*

- Client limited here to the LHe bath
- Pressure drop in the (short) pipes between the HX concentrated in the HX
- BCs:
  - Power to compressors
  - Room T reservoir
  - N2 dm/dt (@T=77K)

The model is ready for the first simulations!

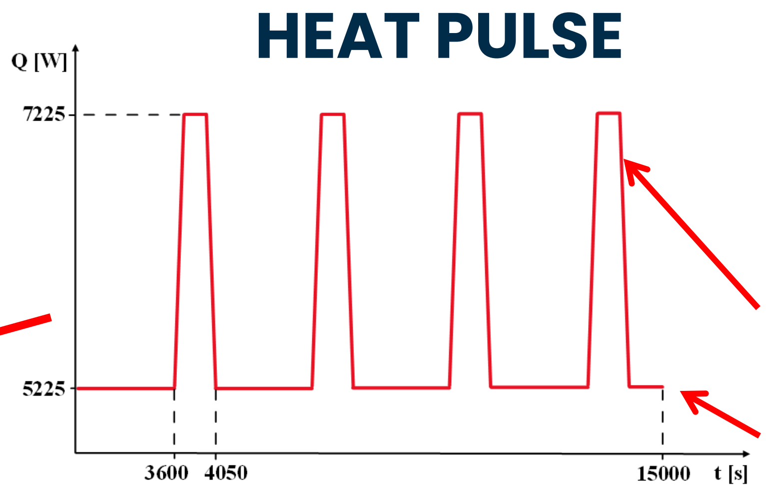


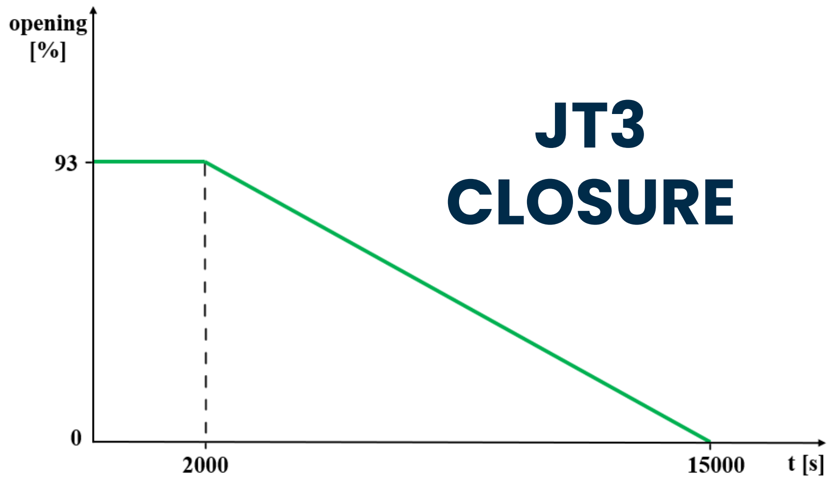
Simulation setup and drivers



PRELIMINARY CHECK:

- Simulate 4 power pulses to the LHe bath to mimic the pulsed tokamak operation
- Add an accidental condition: spurious closure of JT3 valve (turbine line supply)

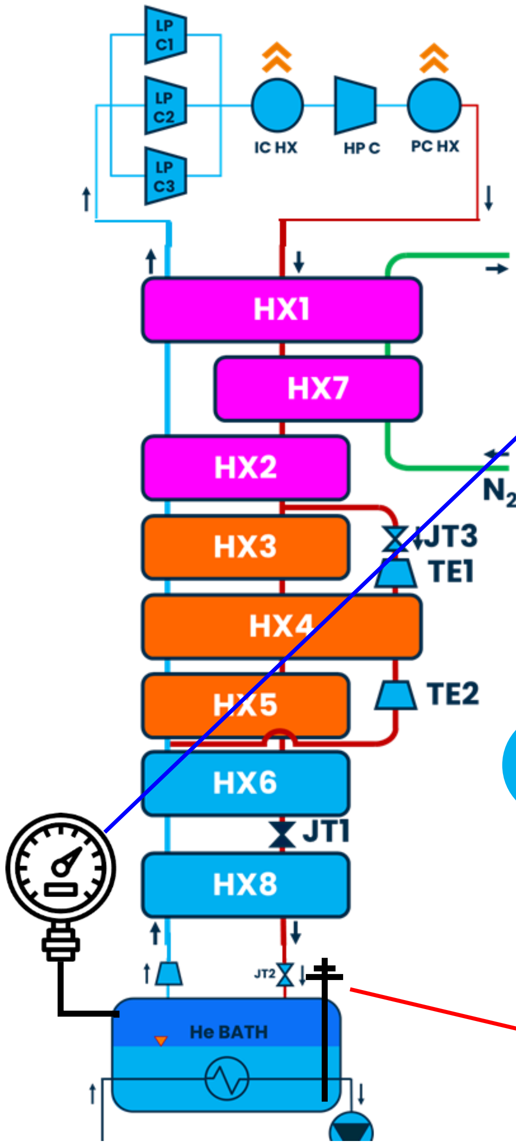


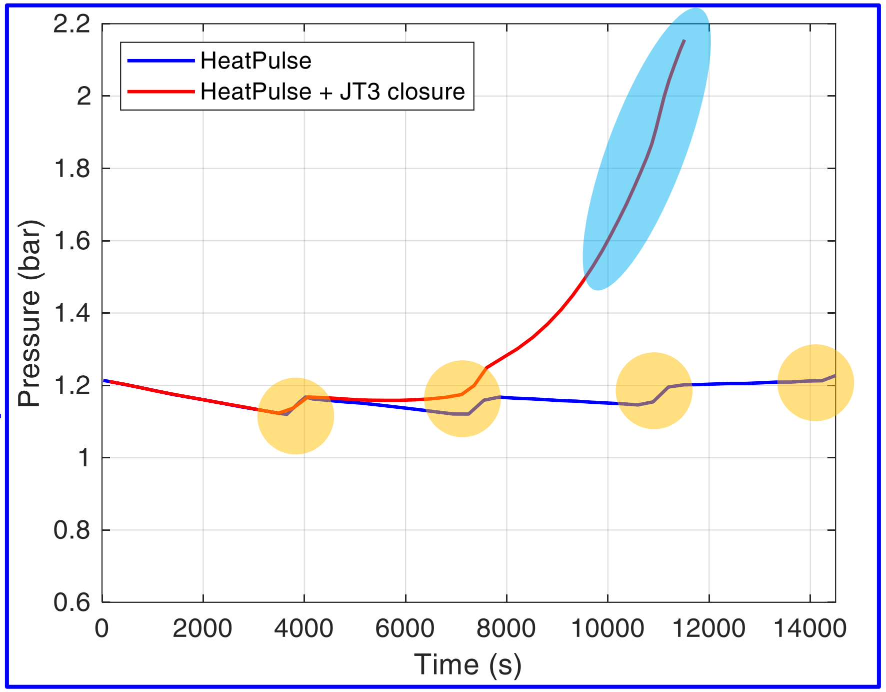


Peaks dimensioned to avoid liquid level drift (~ energy deposited during a CSMC fast current discharge)

Baseload due to static heat load

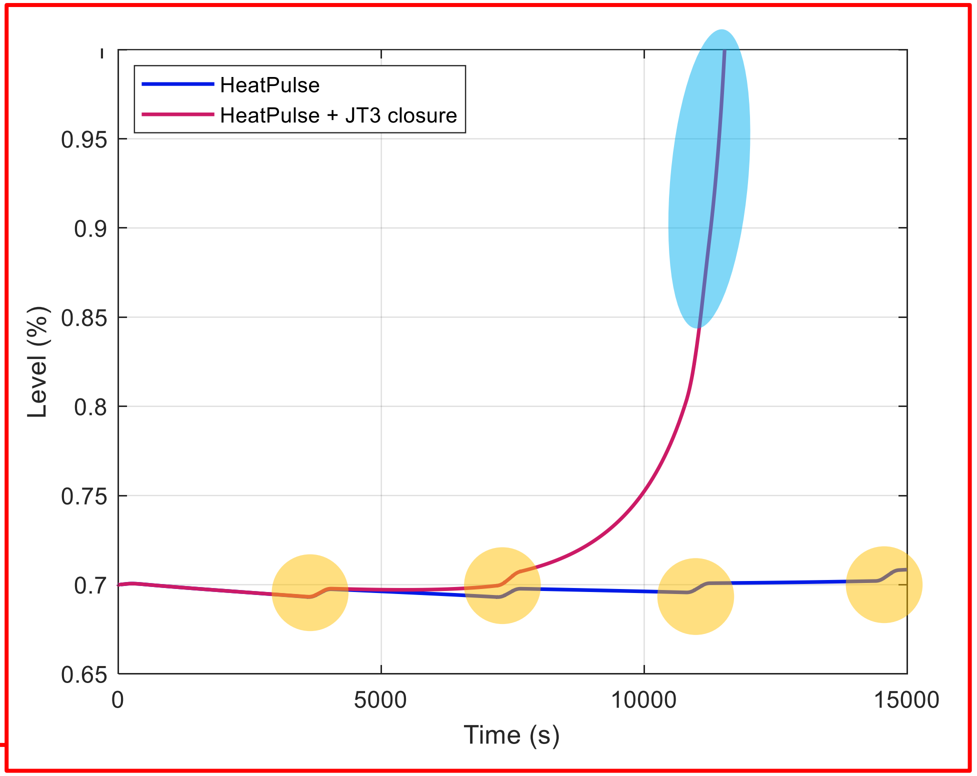
Results: liquid He bath



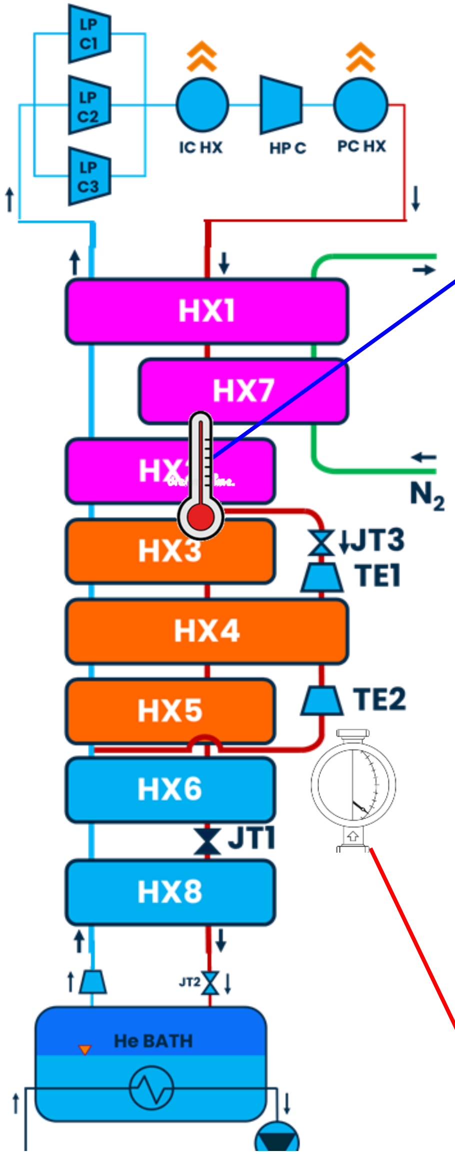


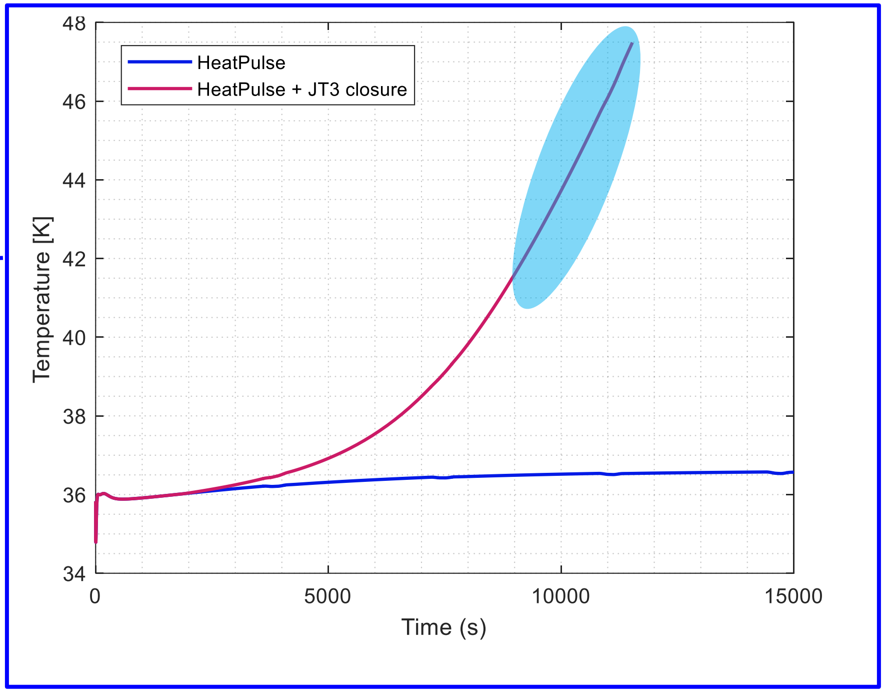
Liquid level increase due to power deposition (→ pressurization)

1) Pressure increases due to the progressive closure of the turbine line (less cooling + more mass flow to the LHe bath)
2) The He bath overfills



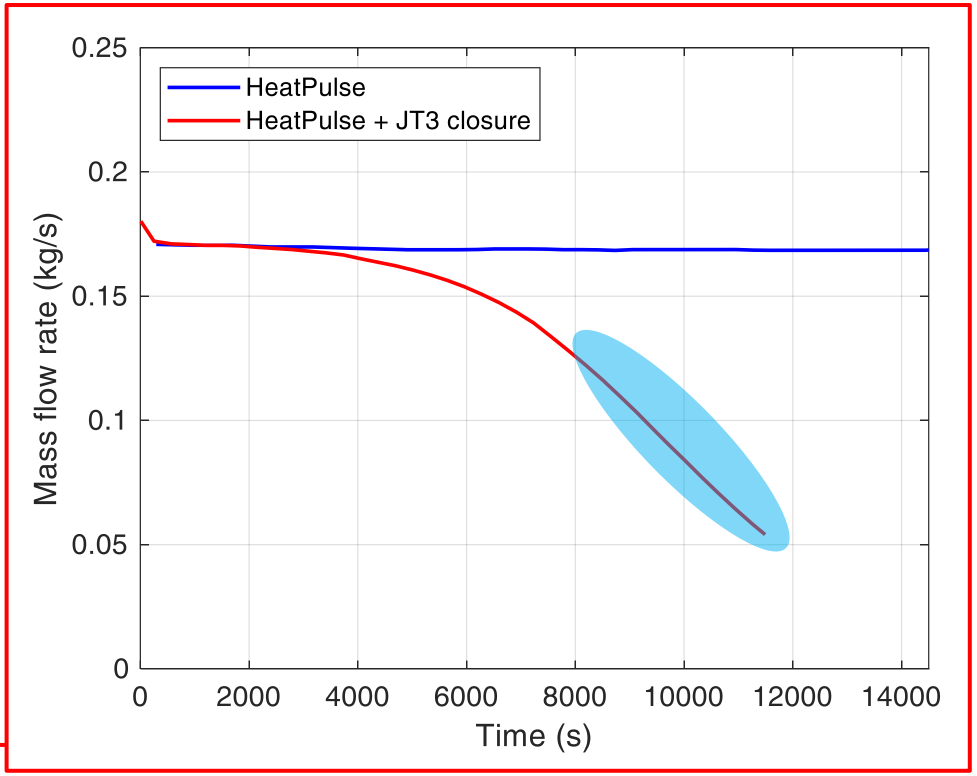
Results: turbine line





The periodic effect of the power deposition is negligible far from the LHe bath → **~steady operation**

1) As expected, dm/dt in the turbine line decreases due to the JT3 closure
2) The temperature in the cooling line increases due to reduced cooling



Conclusions

- The CSMC **He refrigerator *dynamic* model** has been developed in Modelica using the CryoModelica library
- Complex components (like HXs) have been built using existing base components → high flexibility of the CryoModelica library
- Suitable calibration performed
- Preliminary (fast!) simulations performed
  - refrigerator dynamics captured both in normal (steady) operation and during simple accidental transients
  - non-trivial information retrieved

Perspective

Support to the cryodistribution design

- Dimensioning of the thermal buffer / refrigerator
- Design of heat load smoothing strategies

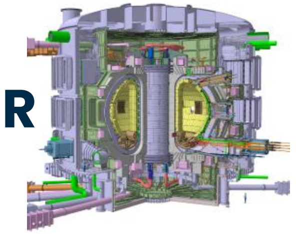
Development of the refrigerator model ✓

- **Coupling** of the refrigerator model with the magnet one
- **Validation** against CSMC and other data

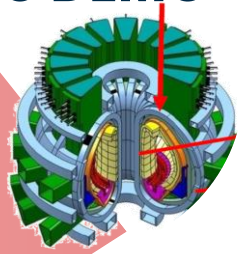
Support to

- **cooldown optimization**
  - Automatization and acceleration of the cooldown
  - Identification of hot spots / high thermal gradients
- **commissioning / training of operators**
- **operation of the DTT cold test facility**

ITER



EU DEMO



DTT

Thank you for your kind attention!

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