Cryo-Magnetic Cost Optimization
The importance of integrated simulation

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Overview

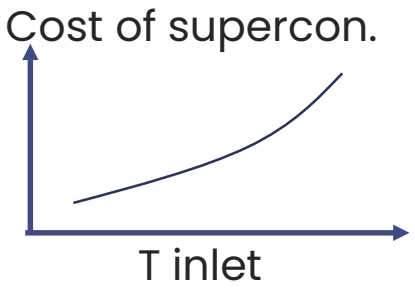
I. Introduction
II. Simcryogenics : our simulation software
III. Lets start easy with TF optimization
IV. Exploration around the CS cryogenics
V. First cost exploration
VI. Conclusion

3 messages in this presentation:

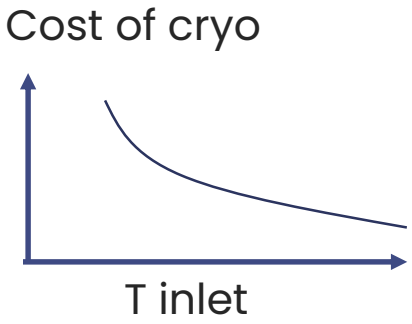
- Cryogenics plays a large role in the cost of magnet : **lets take advantage of this**
- Geometry and controls of the loop matter (a lot) and change the margin of a magnet
- DeltaP 1 bar – Tin 4,5 K to cool down magnets are not necessarily the best options (from the cost point of view)

I. Introduction

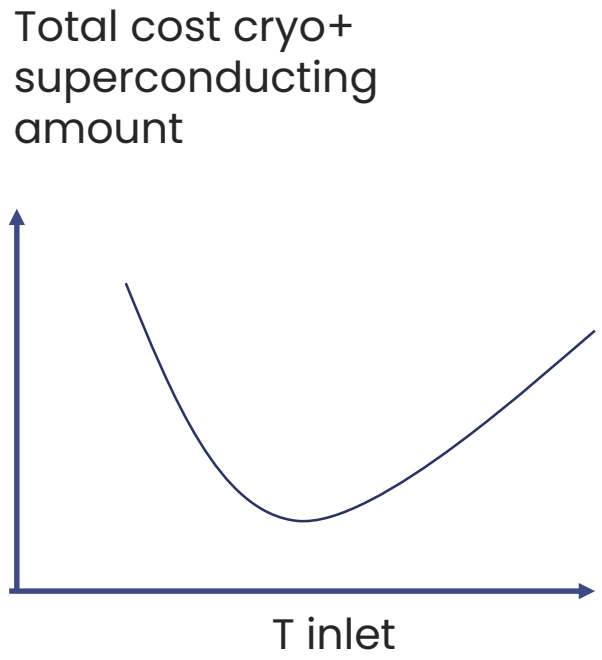
The amount (cost!) of superconducting material goes down with inlet temperature



Cryogenics is less expensive (but still!) but varies in the opposite direction



Cost of superconducting material and cost of cryogenic both varies w.r.t. the inlet temperature … **in opposite directions**!



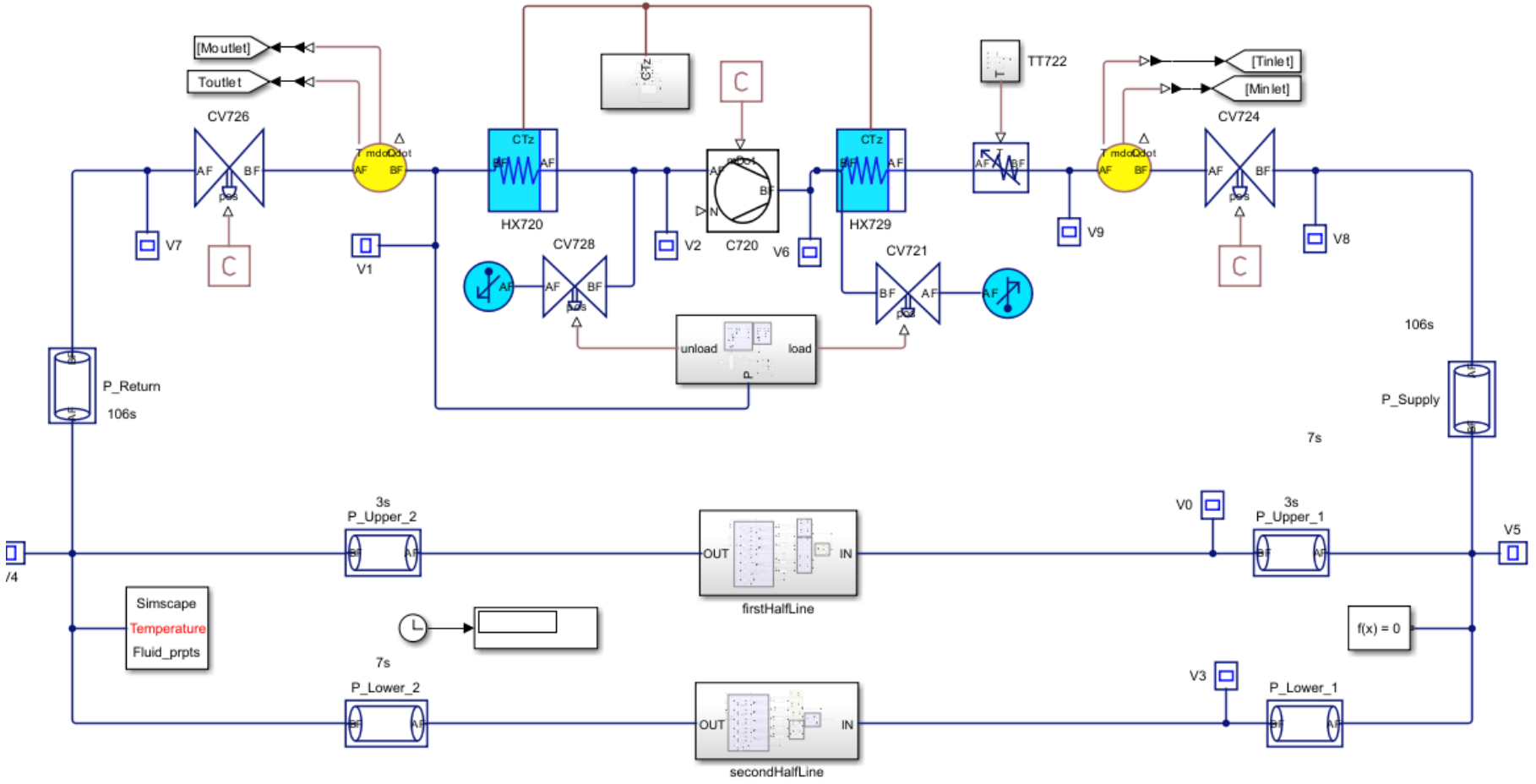
Dynamics can Let's explore that !

II. Simcryogenics : our simulation software

Simcryogenics : our simulation software

What Simcryogenics looks look like

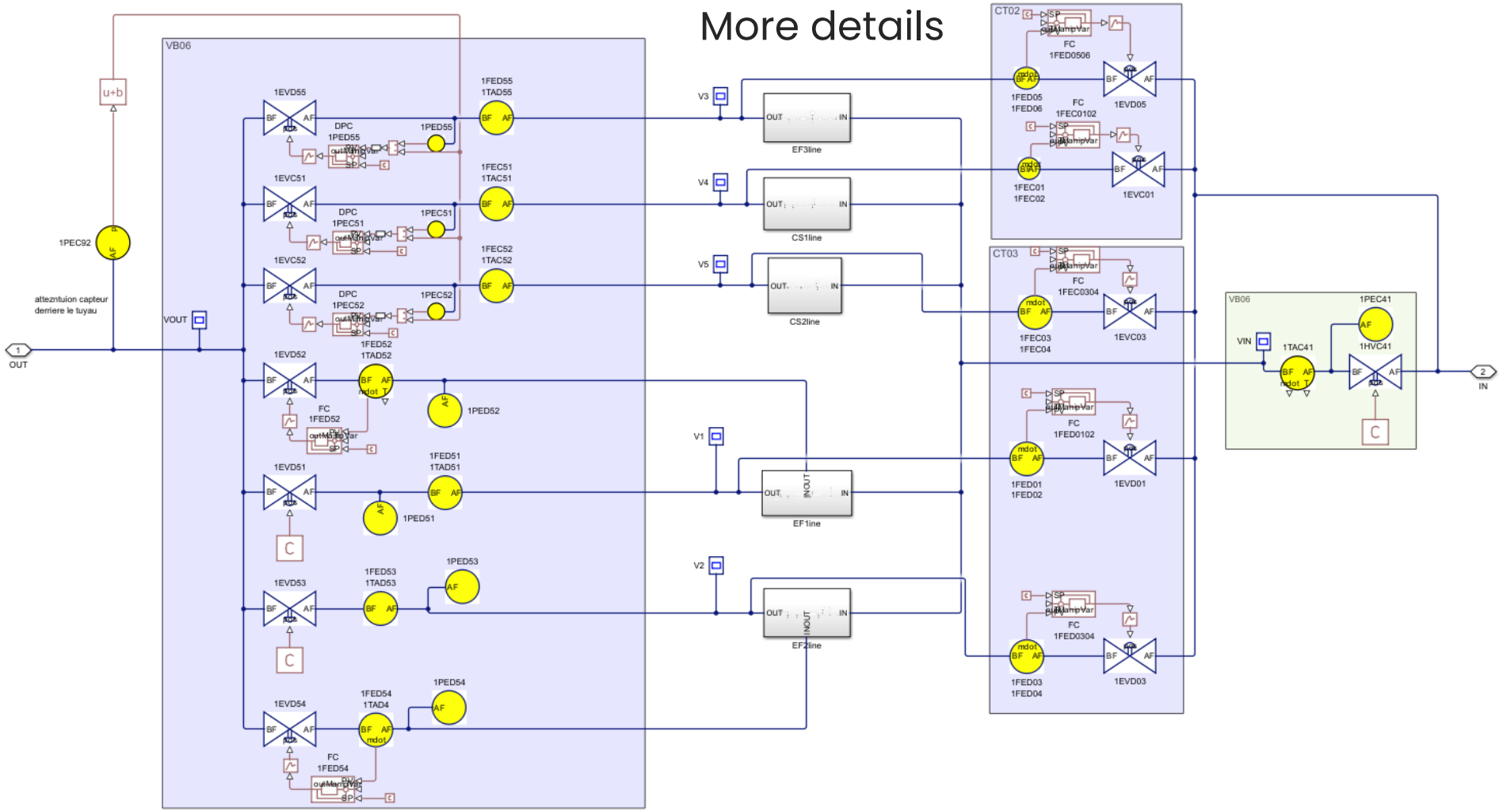
Distribution part



Simcryogenics : our simulation software

What Simcryogenics looks look like

More details

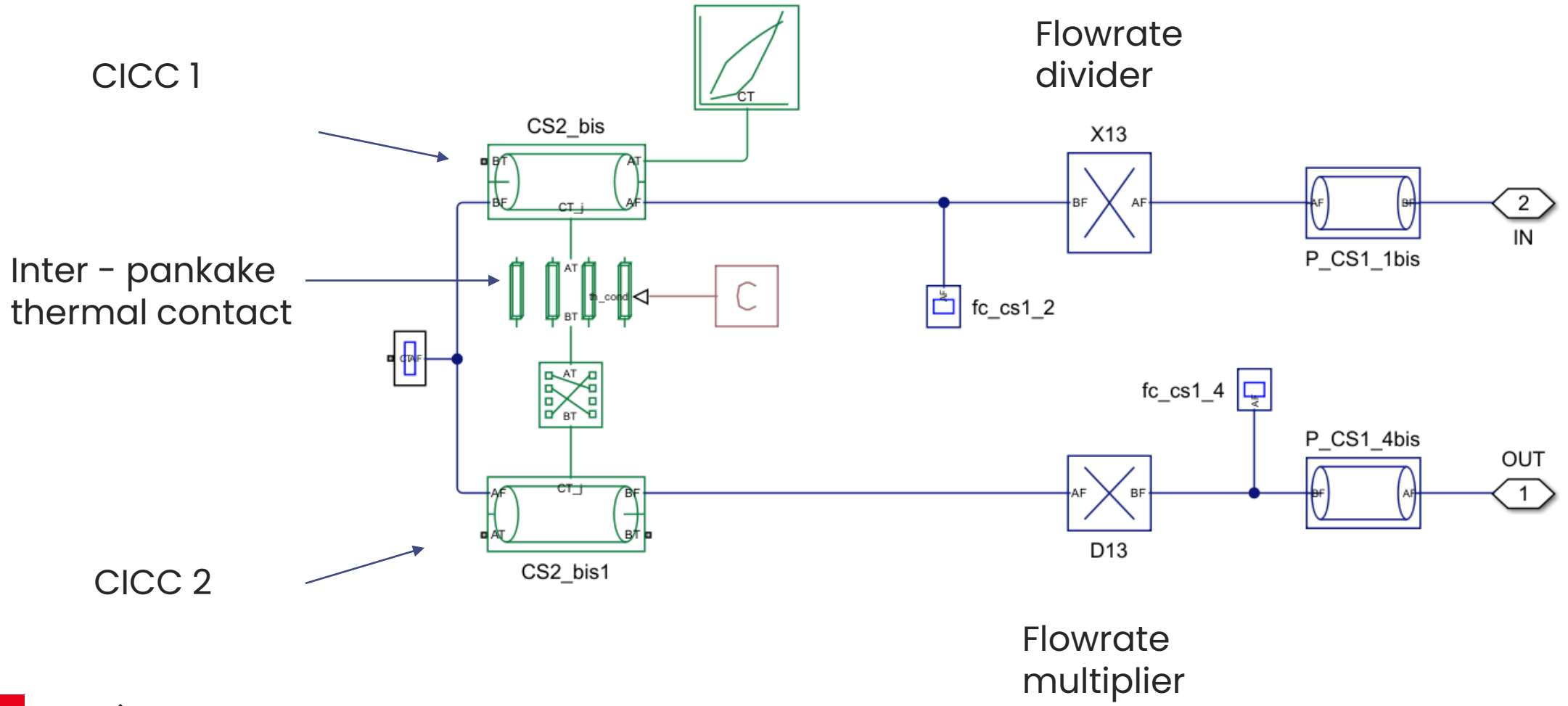


Upper part (same for lower part) Valves, 1D pipes and CICCs has been used to model the loop 2

Simcryogenics : our simulation software

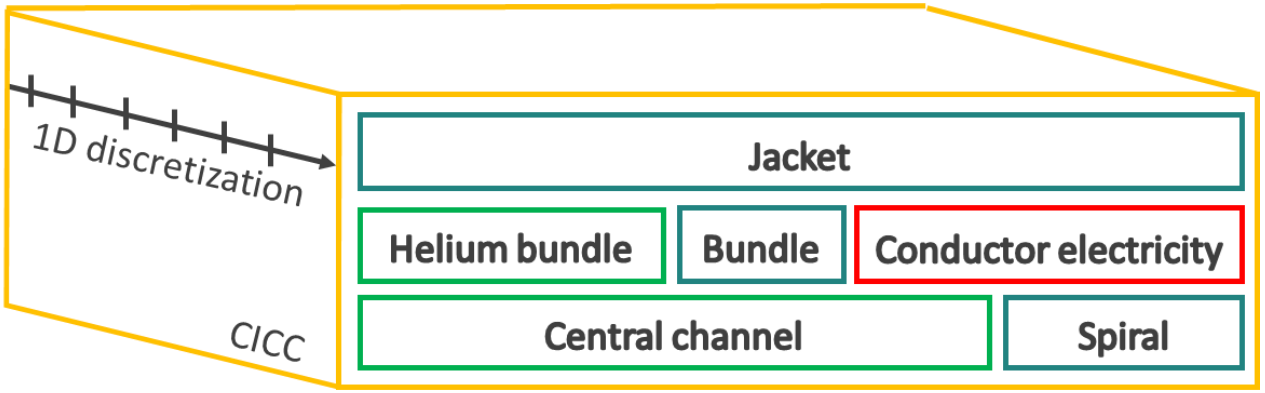
What Simcryogenics looks look like

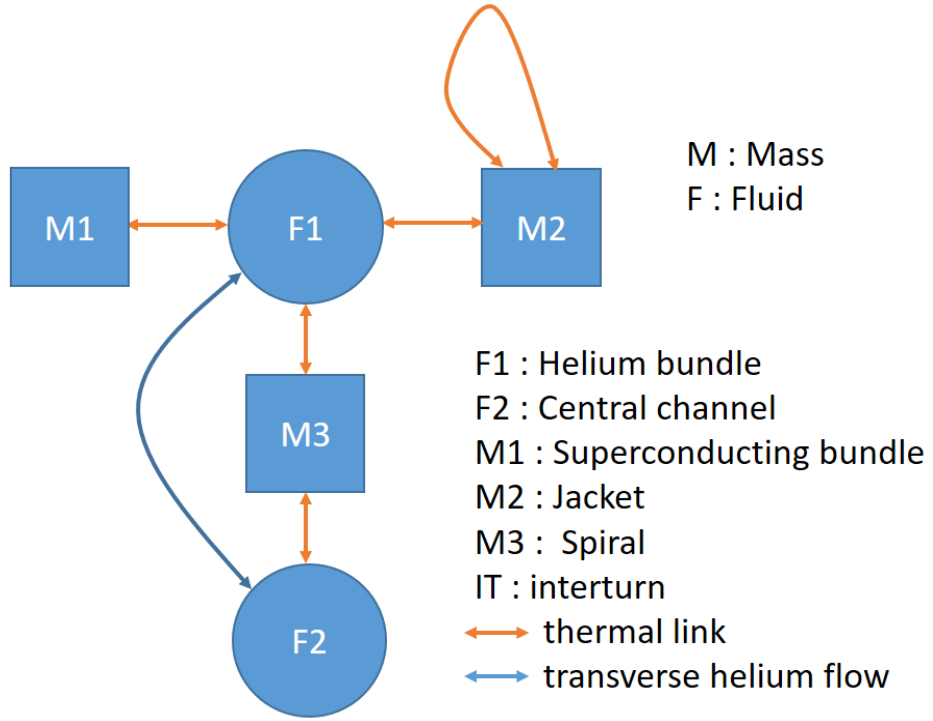
Even more details down to the CS



Simcryogenics : our simulation software

The CICC is modelled from the thermal-hydraulical point of view, in 1D





The CD and EF are modeled in 1D, with 3 fluids and 3 masses according to the illustration above

Simcryogenics Support to every steps of a cryogenic project

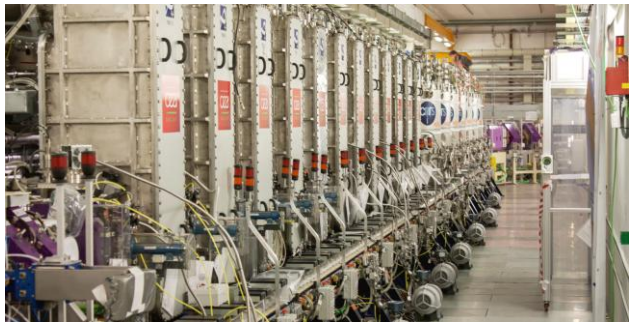
Studies	Control	Commissioning	Exploitation
▪ Parametric optimization ▪ Behaviour studies	▪ Check PLC code and control strategies ▪ Model-based control	▪ Saving time with control tunning ▪ Real-time simulation	▪ Increase availability ▪ Operator training

Minerva cryoplant conceptual design



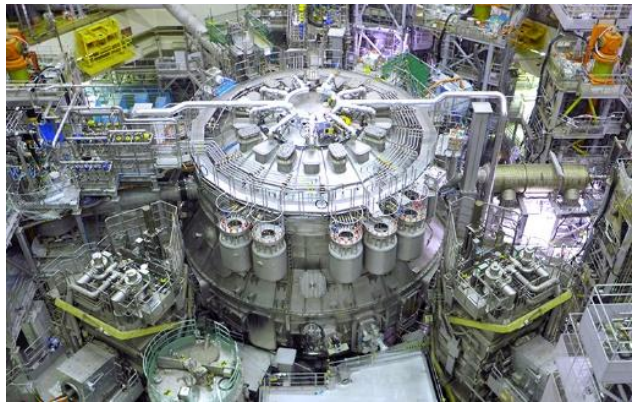
MYRRHA

Control of Cavities of GANIL



GANIL spiral2
laboratoire commun CEA/DRF CNRS/IN2P3

On site pressure prediction at JT60



JT-60SA
Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

Control of the 400 W Station



SBT

TF optimization (DEMO EXAMPLE)

Lets start easy with TF optimization

In the past year, we have performed cost exploration for the DEMO TF system

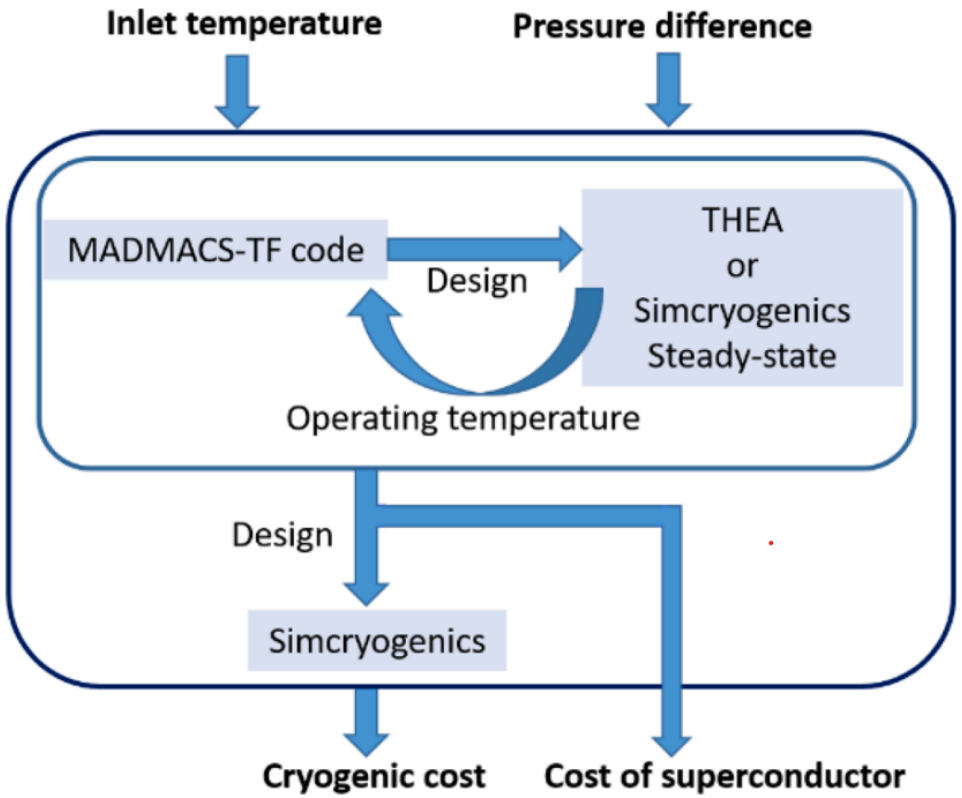
The main hypothesis were :

- Cost of superconducting material : 8 M€ / m^3
- Cost of cryogenics : CAPEX (Green formula) + 20 years of electricity at 100 € / MWh
- Design is varying to ensure 1,5 K margin regarding the Tcs

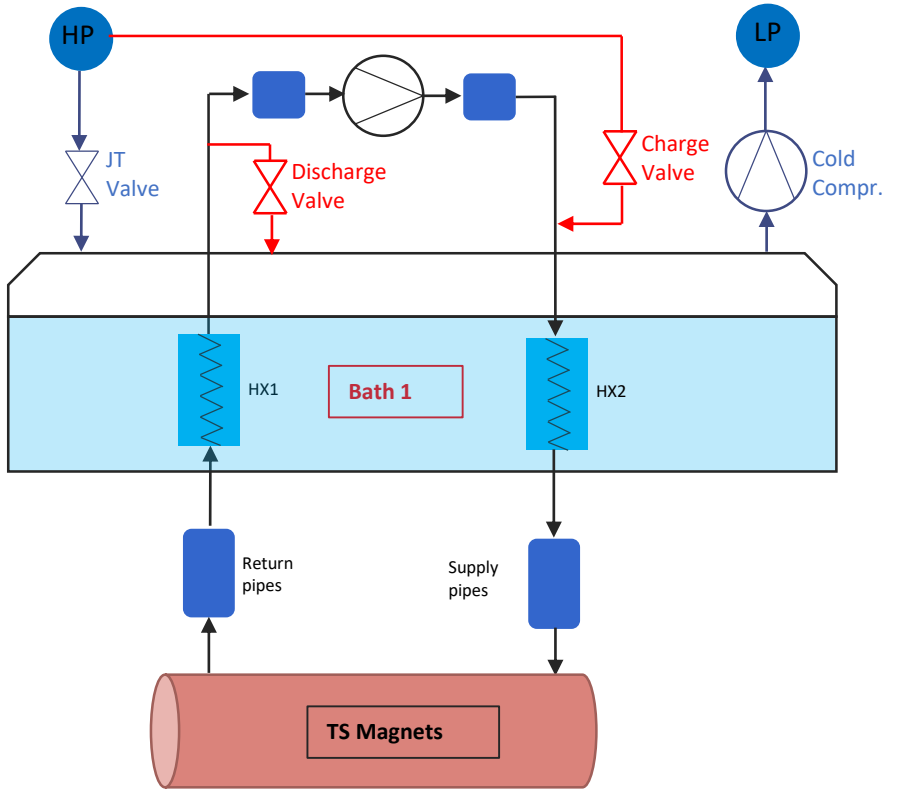
Ajout publication référence

Lets start easy with TF optimization

Workflow

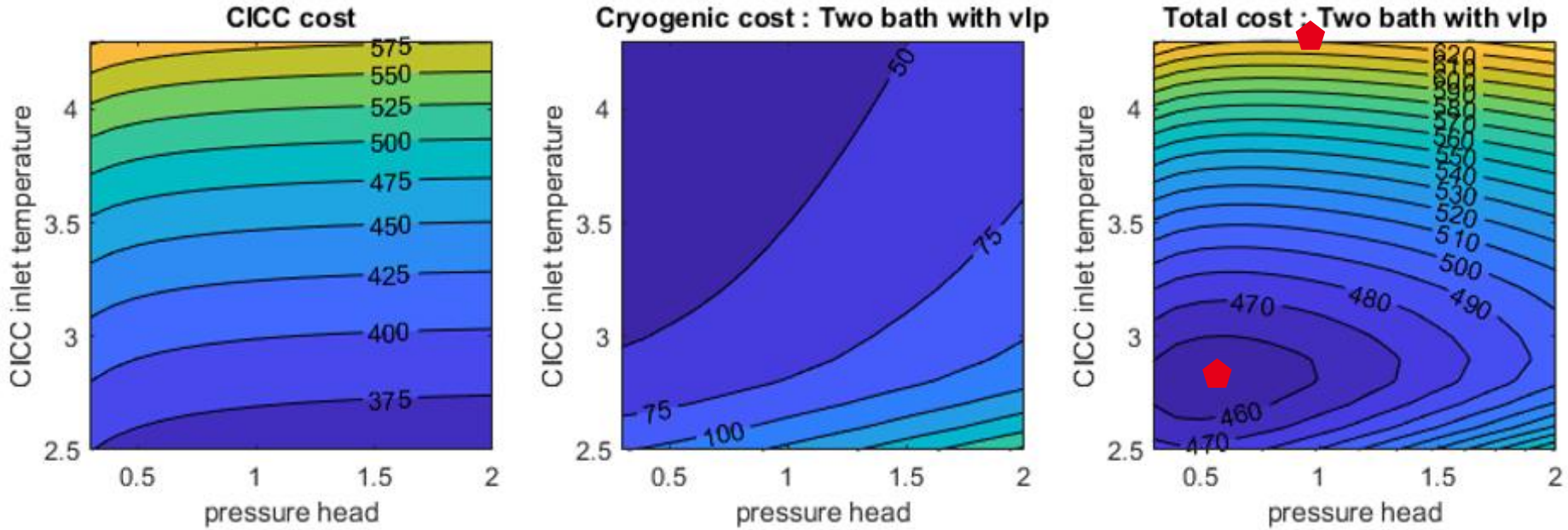


Cryogenic cold end + distribution



Lets start easy with TF optimization

Cost results (M€) : Magnet and cryo cost as a function of the **Tin** and **ΔP** of the magnet



The total cost is lowered by 25 % using **Tin = 2,8 K and ΔP 0,6 bar** instead of the usual 4,5 K / 1 bar

Warning : This is obviously not the final cost estimation of TF cryo-magnetic system, just an illustration that total cost is driven by cryogenic parameters

Lets start easy with TF optimization

Conclusion

Once the parameters of the magnets have been chosen (magnetic field to produce, NI, …), cost of cryo-magnetic system can be **driven by the cryogenic parameters**

In this TF example, the cost can be lowered by **25 %** by working at lower **Tin** and, lower **ΔP**.

The superconducting amount is also lowered, leading to smaller magnets

Exploration around the CS cryogenics (DEMO EXAMPLE)

Exploration around the CS cryogenics

Objective of the study : explore different “cryogenic” ways to achieve the 1,5 K margin at constant CS design

- **One bath**

  → Classical approach, we will play on the bath temperature

- **Two bath**

  → We will play on the second bath temperature (and subcooling duration)

- **One bath with depressurization**

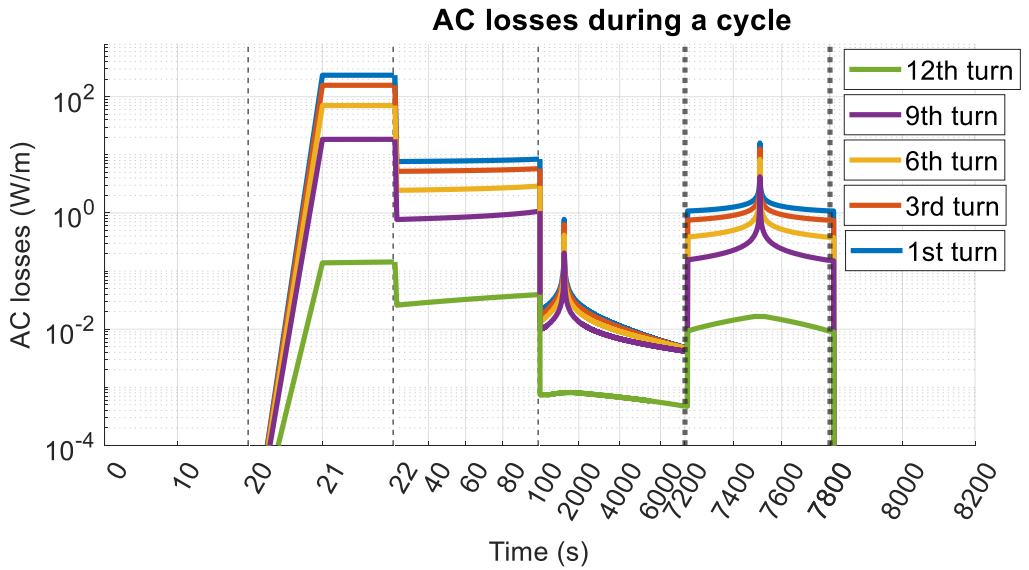
  → Variable pressure in the loop, to create instantaneous cool down effect

Exploration around the CS cryogenics

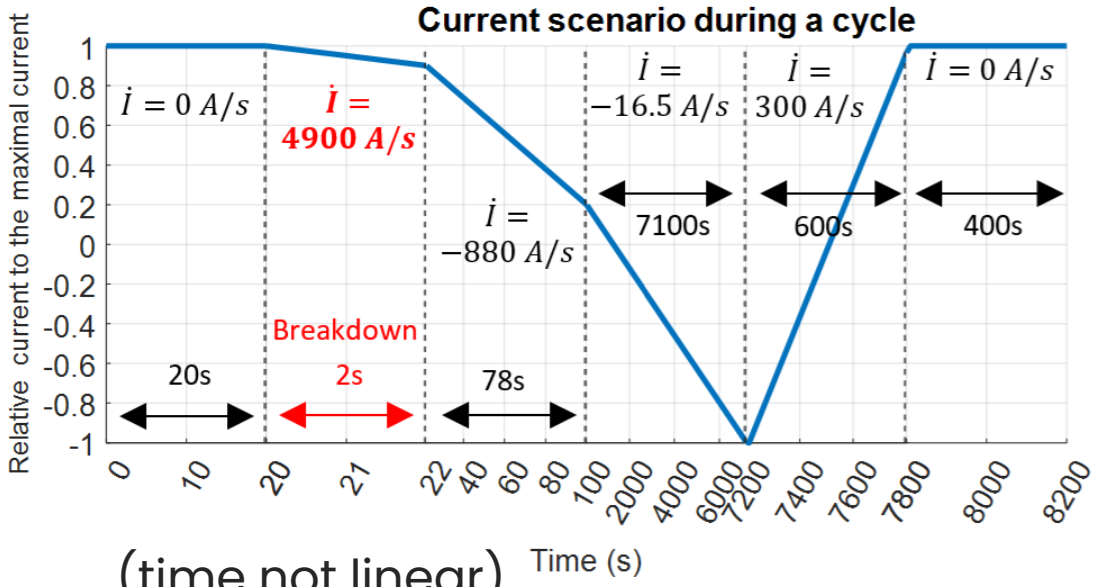
The 2022 CEA CS design is used in this study

The same current scenario is applied since 2022 to help with comparisons.

The CS design has not changed/ being update for the same reason



(time not linear)



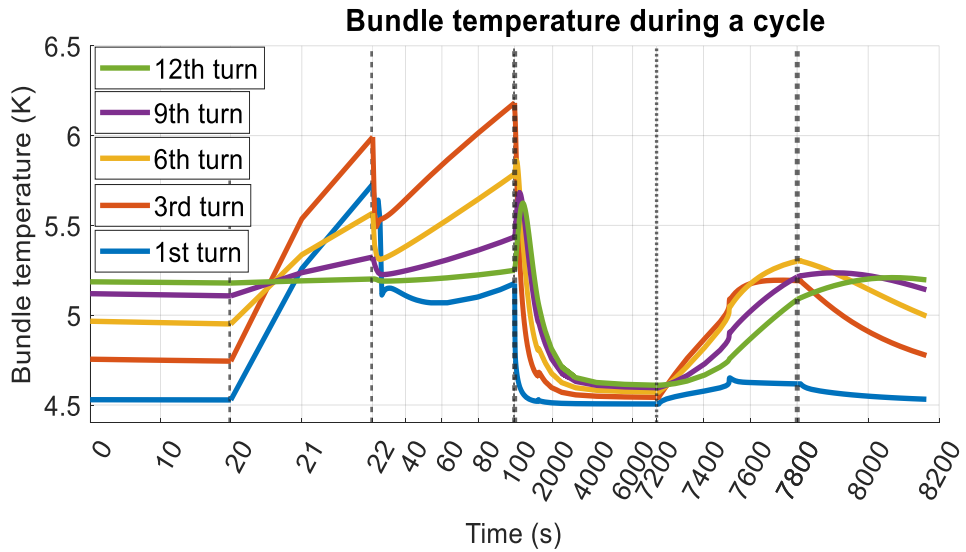
(time not linear)

Exploration around the CS cryogenics

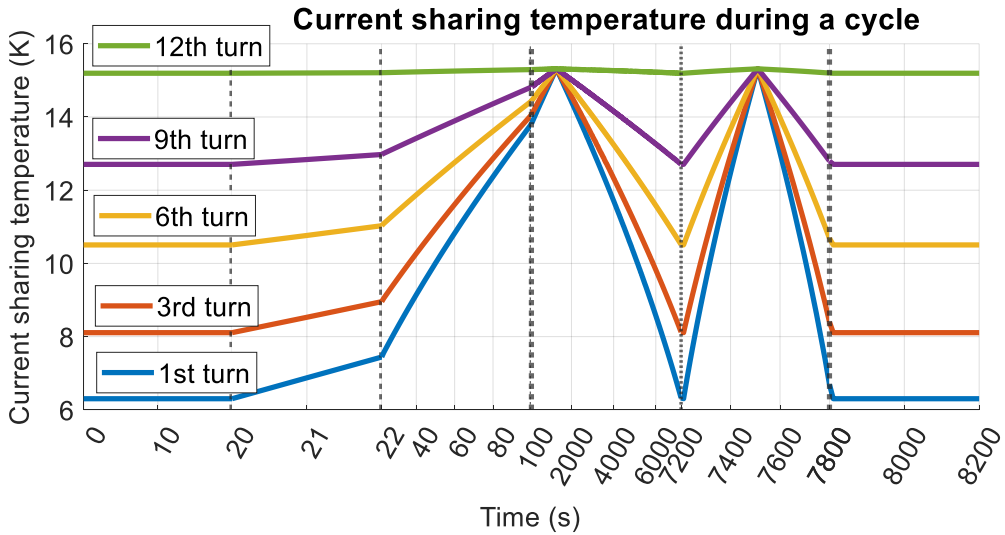
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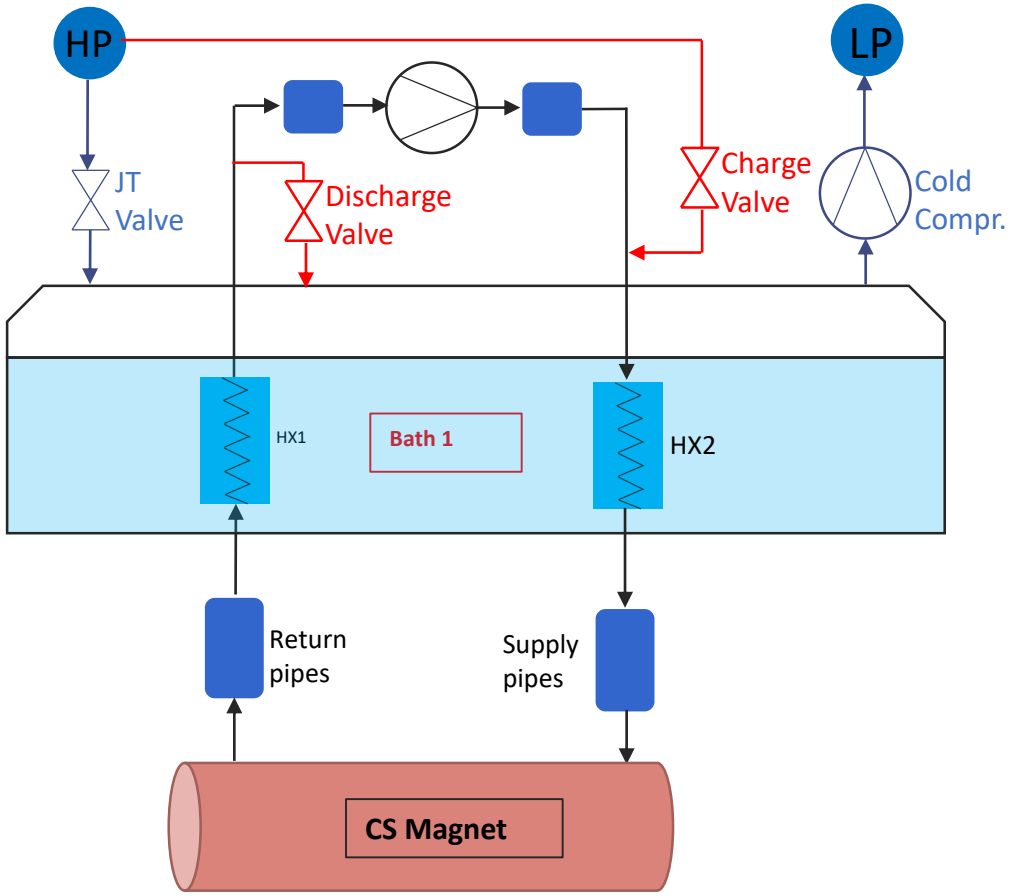


(time not linear)



(time not linear)

Exploration around the CS cryogenics



One bath

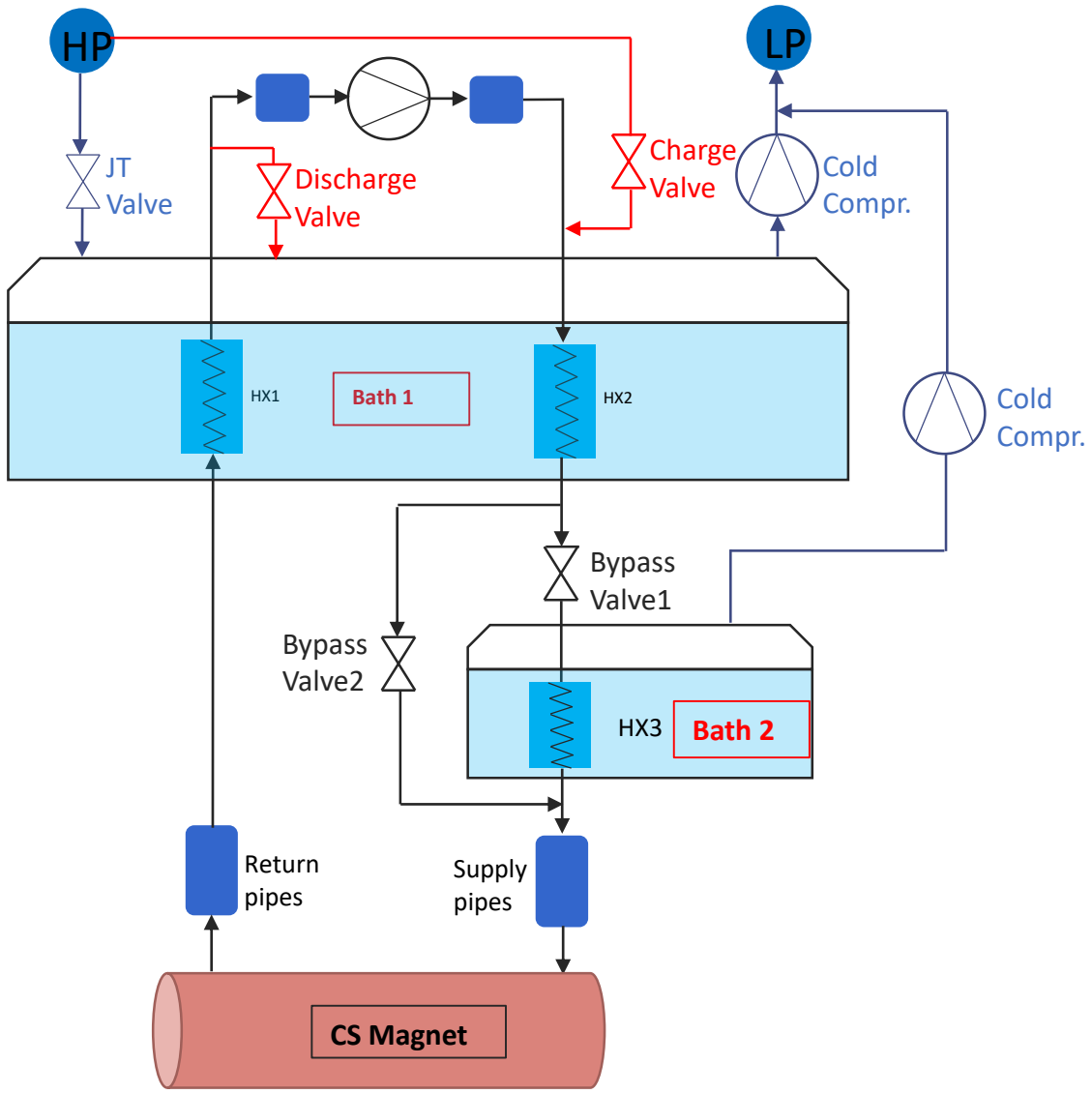
→ Classical approach, play on the bath temperature

With all the geometrical parameters being fixed, CS margin is mostly driven by the **bath temperature**

Bath temperature = 3,43 K

➔ **Margin 1,5 K**

Exploration around the CS cryogenics



Two bath -> temporary subcooling prior to break down

→ Play on the second bath temperature (and subcooling duration)

With all the geometrical parameters being fixed, CS margin is mostly driven by the **bath 2 temperature**

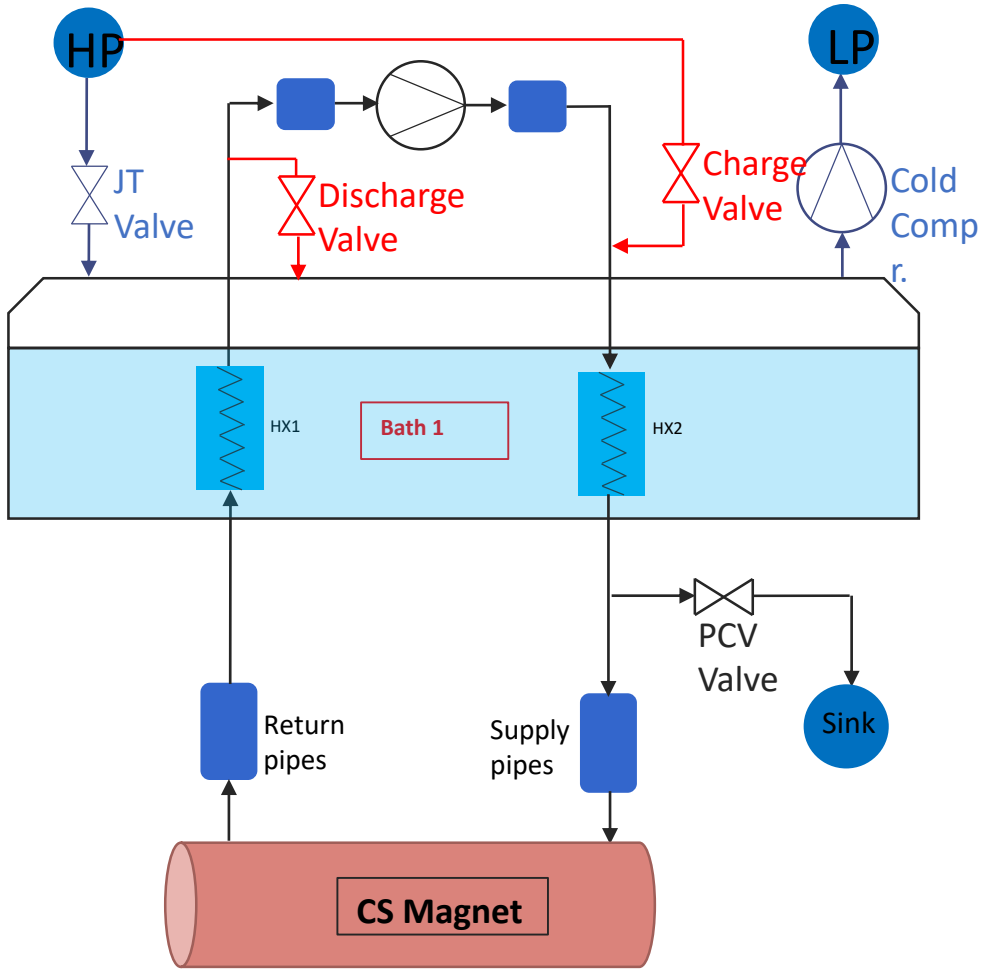
Bath 1 temperature = 4,2 K

Bath 2 temperature = 3,3 K

Precooling time prior to cool down= 500 s

➔ Margin 1,5 K

Exploration around the CS cryogenics



Depressurization

→ Variable pressure in the loop, to create instantaneous cooling effect **prior to break down**

With all the geometrical parameters being fixed, CS margin is mostly driven by the **bath temperature and the lost pressure**

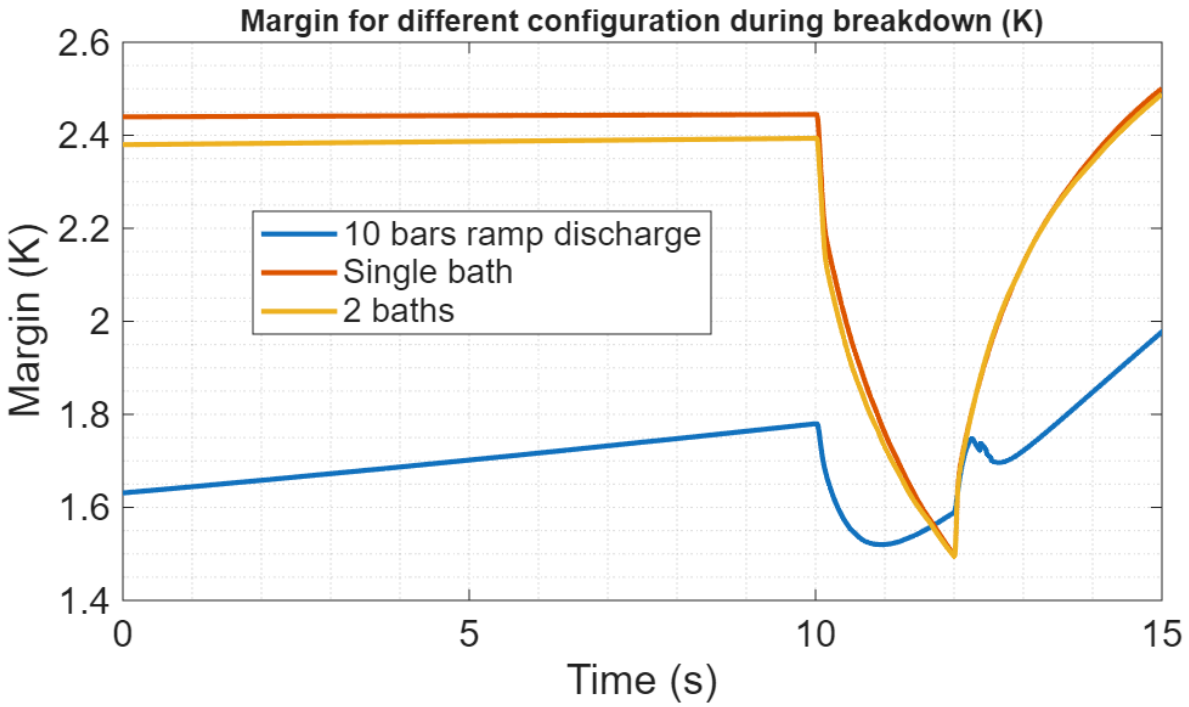
Temperature of the bath = 4,2 K

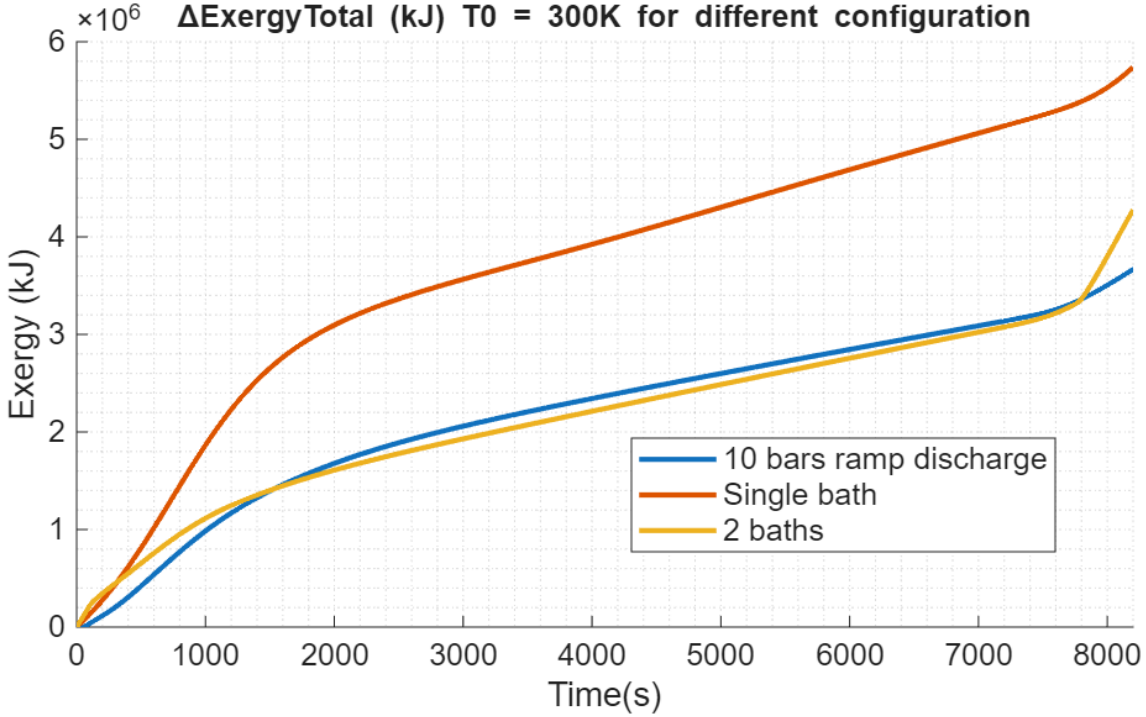
Pressure lost during the 20 seconds depressurization = 10 bars

→ **Margin 1,5 K**

Exploration around the CS cryogenics

- **Comparison of the 3 strategies**





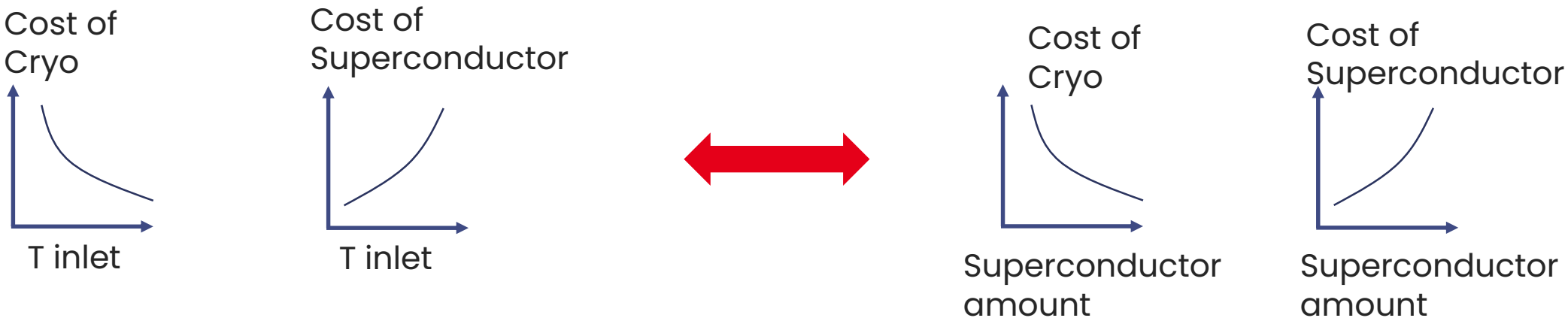
For the same margin obtained, the cost in term of energy consumption can be very different

First cost exploration

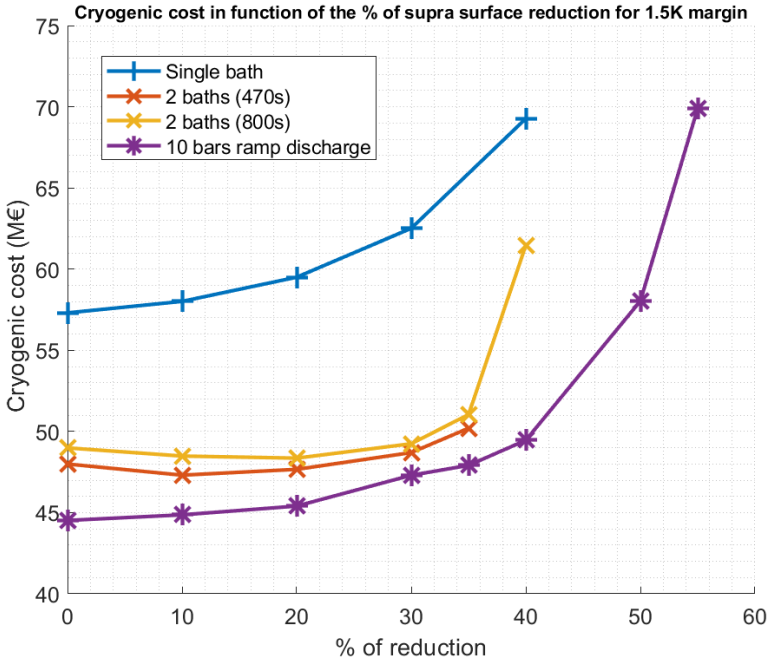
First cost exploration

Lets apply our models with a changing CS conductor

- Simply proportionality ratios
  - Bundle section → Nominal bundle section * (1-coef)
    - Tcs, AC losses, … calculated accordingly
  - Central channel → Nominal
- Cost of supraconducting material = 8 M€ / m^3
- Cost of cryo : OPEX 20 years electricity + CAPEX Green formula multiplied by 3



First cost exploration



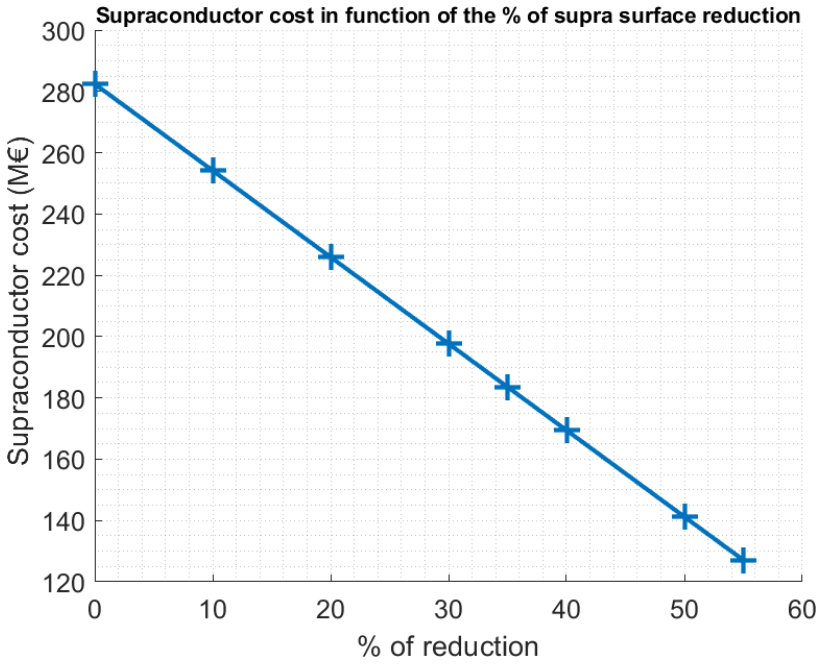
$$P_{eq4,5K} = \left(\frac{Exergy_{300K}(J)}{time_{cycle}}\right) \times \left(\frac{4,5}{(300-4,5)}\right)$$

$$CAPEX(M€) = 2,9 \times P_{eq_{4,5K}}^{0,63}[kW] \times 3$$

$$OPEX(M€) = Elec_{cost}(M€) =$$

$$250 \left[\frac{W_{elec}}{W_{4,5K}}\right] \times P_{eq\,4,5K}[MW] \times 20years \times \frac{50\left[\frac{€}{MWh}\right]}{1000000}$$

$$Cryogenic\ cost = CAPEX + OPEX$$

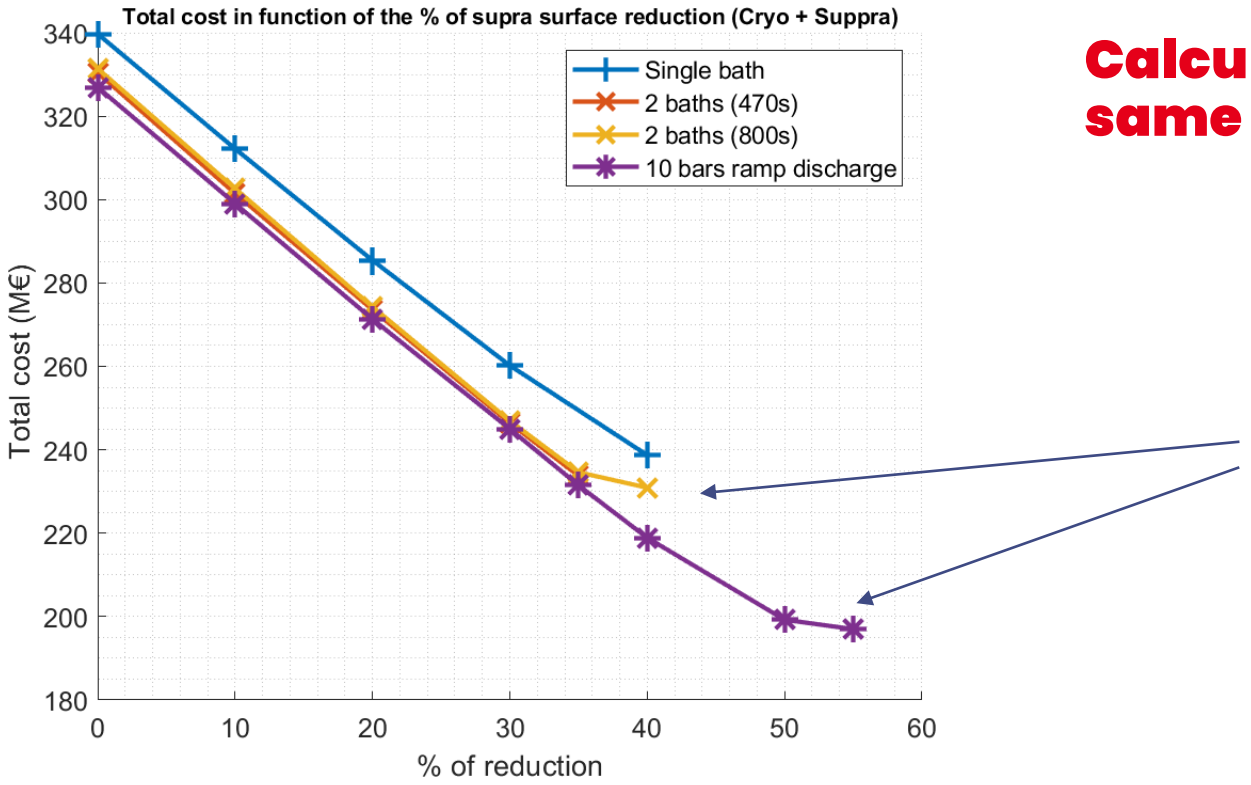


$$Cost_{supraconductor} = V_{168CICC}[m^3] \times 8\left[\frac{M€}{m^3}\right]$$

i.e. volume superconducting material of 168 CICC for the CS

Calculation has been performed with the same current scenario, with a 1,5 K margin on the CS

First cost exploration



Calculation has been performed with the same current scenario, with a 1,5 K margin

Points which cryogenic cost starts increase to be higher than superconductor cost diminution.

Any configurations allows to save (up to 120 M€) by reducing amount of superconductor

Warning : This is **obviously** not the final cost estimation of CS cryo-magnetic system, just an illustration that total cost is driven by cryogenic parameters

Conclusion

Cryogenics has a role to play in the magnet design

- When design of a magnet is done, cryogenics is key to ensure margin
  - Beware of the loop geometry and controls (pressure rise eats up margin)
  - **ΔP** and **Tin** obviously can increase or decrease margin

- During design, cryogenics must be included to ensure cryo-magnetic optimum
  - Loop depressurization of lower Tin leads to less superconducting amount
  - Several 10% can be saved by doing cost exploration at constant margin