# Development of a multi-physic platform OLYMPE for fusion magnets design: progresses update and applications

DE LA RECHERCHE À L'INDUSTRIE

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# Outlines

- Introduction
- OLYMPE general presentation & status
- ElectroMagnetic-Design (EMD) bimodular loop
- ThermoHydraulic-Design (THD) bimodular loop
- ThermoHydraulic-Cryogenic-Design (THDC) trimodular loop
- Mechanical-Design (MECD) bimodular loop
- Conclusion-perspectives

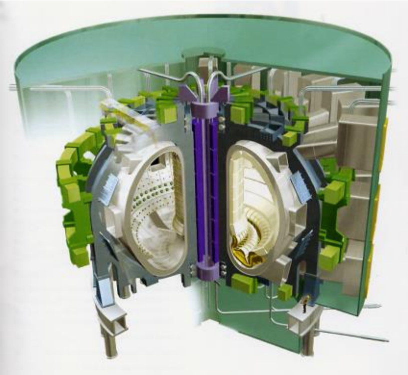
# Introduction



Tokamak **superconducting magnet** system design

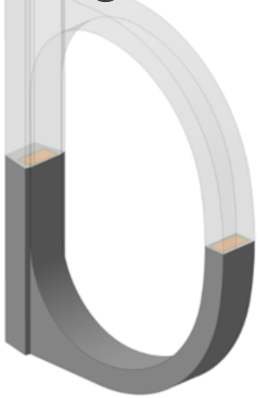
➔ multi-scale approach ➔ several stages of analyses detail

## 1- System scale



*downscale*

## 2- Magnet scale



*downscale*

## 3- Sub-magnet scale

- Perimeter = reactor
- components (magnets, VV…)
- **macroscopic models** for components

- Perimeter = magnet envelope
- Major sub-elements (conductor, structures)
- **macroscopic models** for sub-elements (mechanics, EM…)

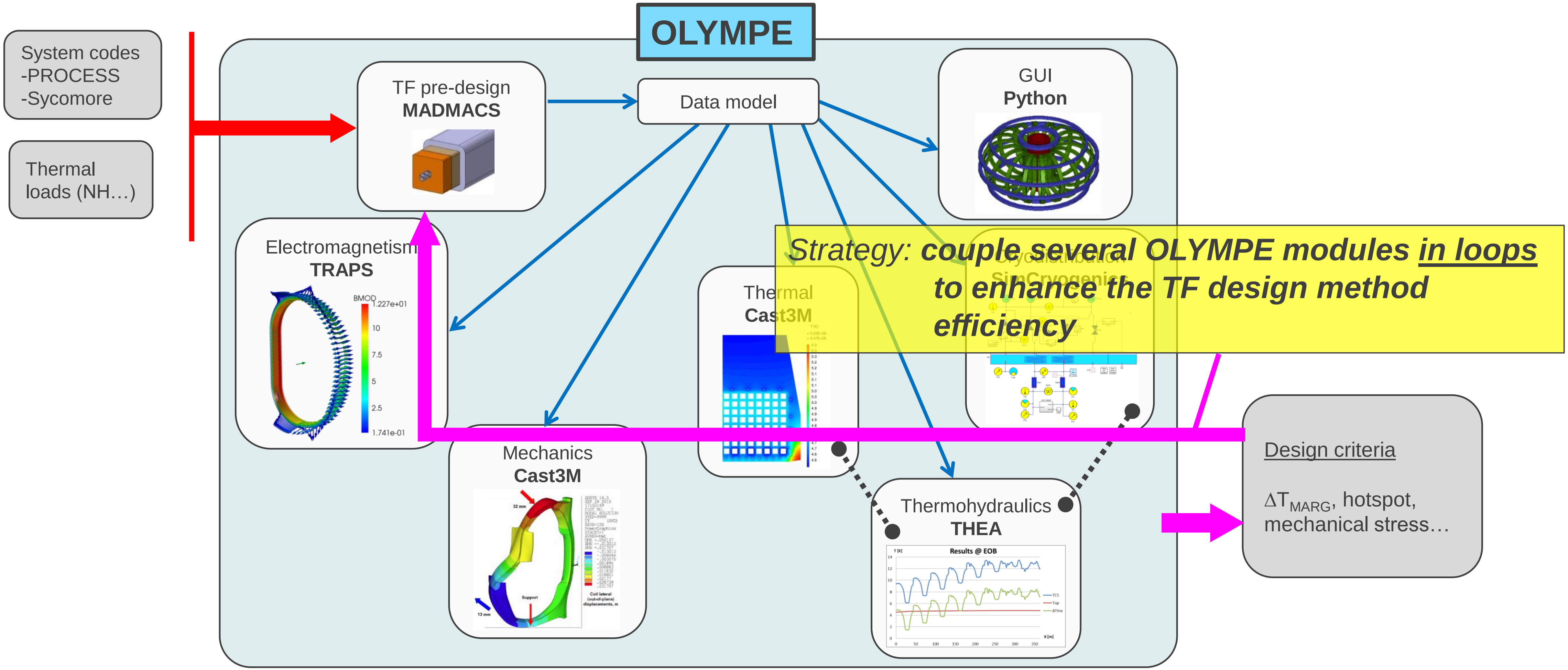
- Perimeter = subcomponent (conductor, insulation…)
- sub-elements details considered
- **Accurate models** of sub-elements (EM, thermohydraulic…),

**complexity ➚ when scale ➘ :** modelling & interfacing systems, calculation ressources…

# Workflow

CEA develops an **integrated tool** which holds **variants in scales, physics & fidelity**

The platform is named **OLYMPE** *(platefOrme muLtiphYsique pour aiMants suPraconductEurs)*

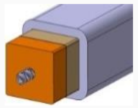


# EMD loop: principle

**EMD purpose :** issue a $B_{EFF}$-compliant TF design with regard to detailed analyses

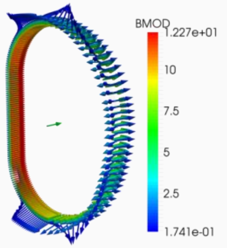
**ElectroMagnetic-Design** loop

TF pre-design
**MADMACS**



Data model

Electromagnetism
**TRAPS**




Logic flow

…

⇨ Step n : an effective field (**$B_{EFF}$**) is considered

⇨ The TF design is modified by this **$B_{EFF}$**

⇨ **MADMACS** output

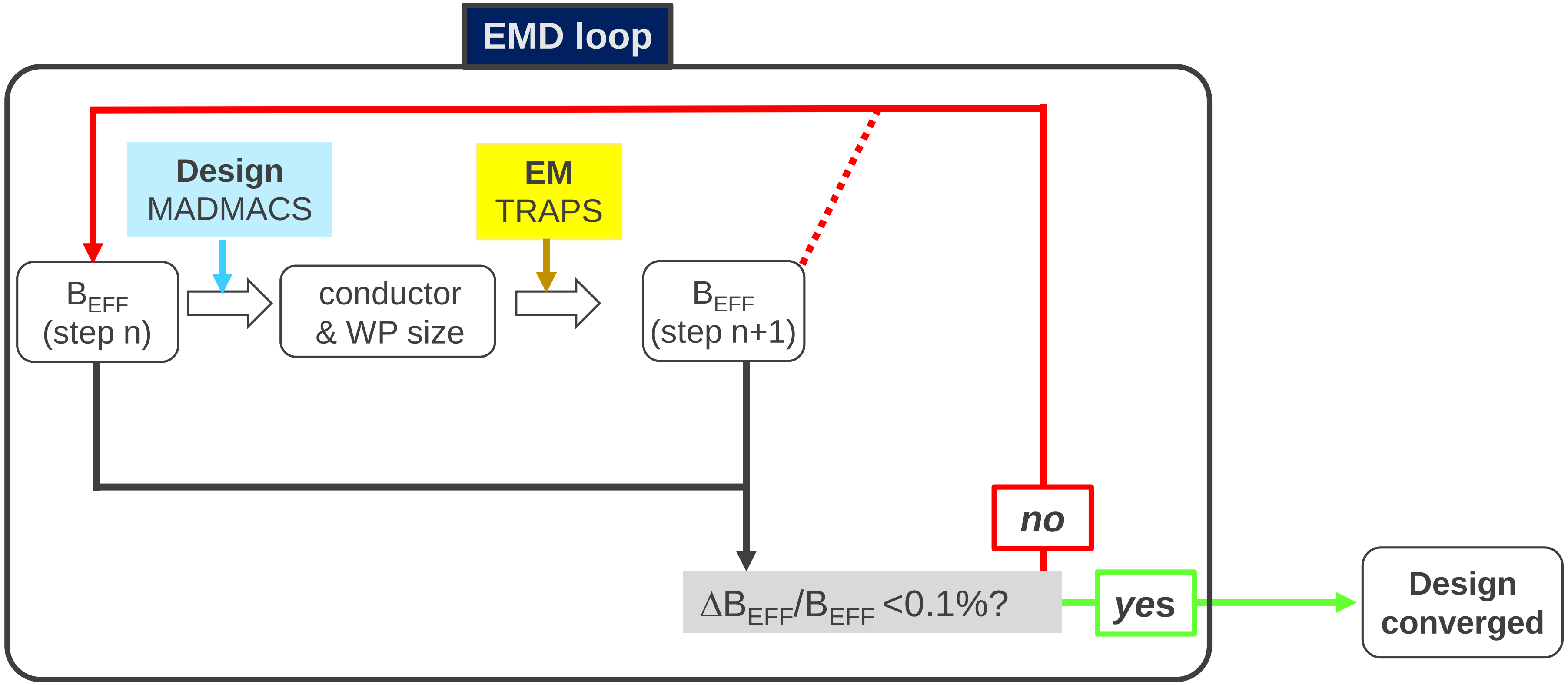
⇨ The TF design modifies **$B_{EFF}$** (current carriers toplogy)

⇨ **TRAPS** output

⇨ Step n+1 **:** a new **$B_{EFF}$** is considered

…

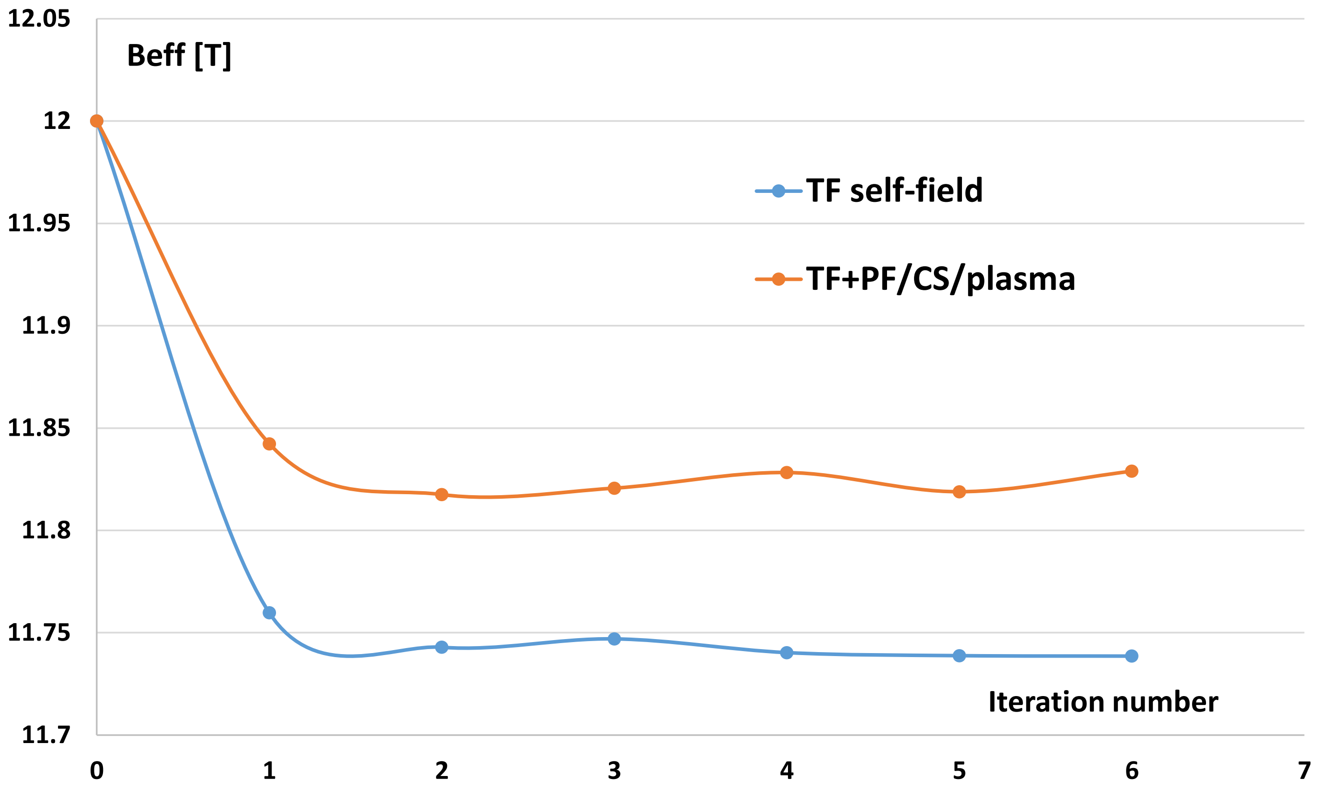
# EMD loop: principle




- TRAPS time consuming (~10 min per run)
- Not fully automatized

# EMD loop: application to DEMO

An application is conducted on the **DEMO 2018 WP#3** configuration (pancakes winding, no radial plates)
TRAPS calculates the B map with 3D model (separated individual conductors, D-shape)



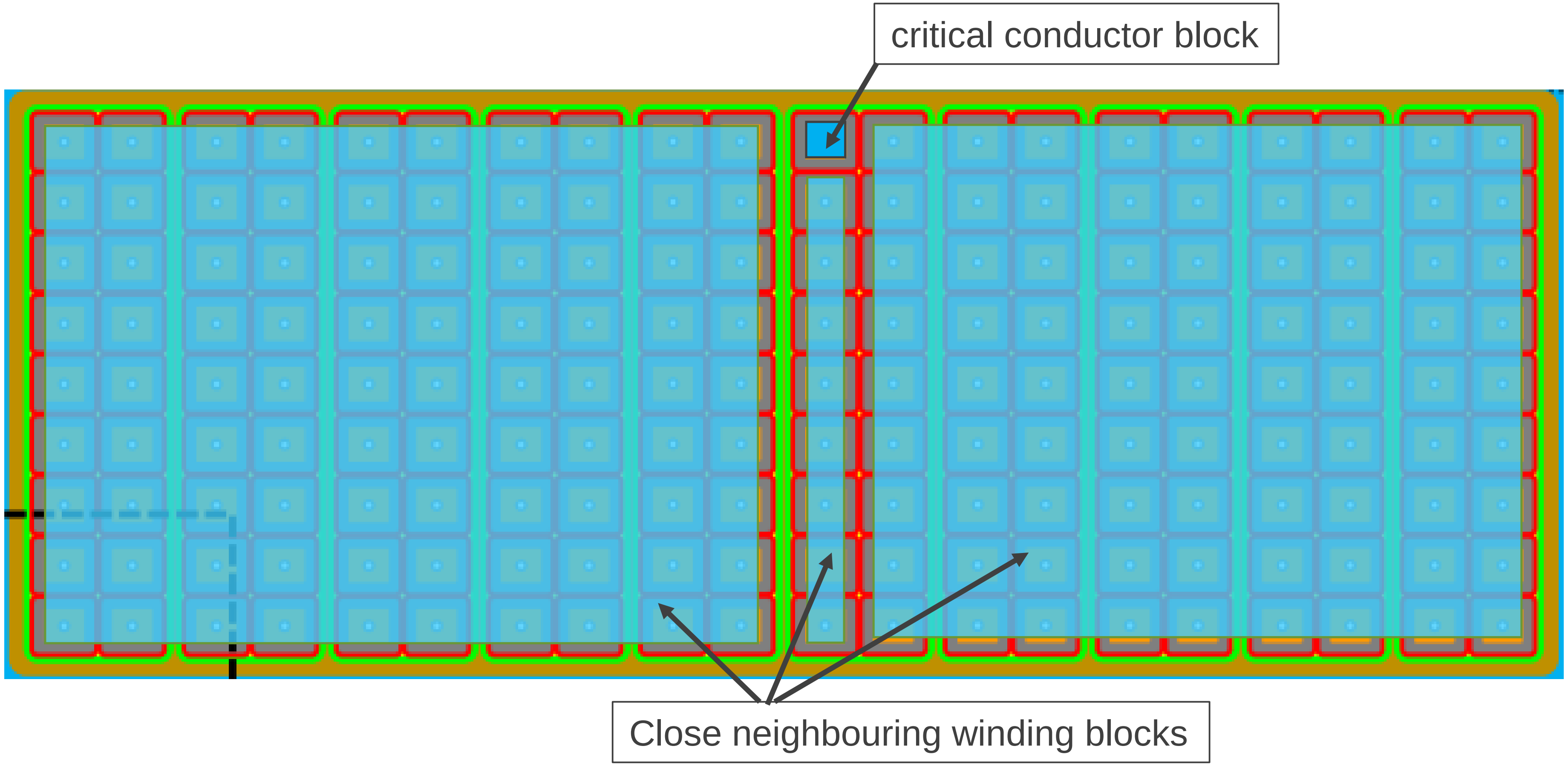

- Asymptotic behaviour after few iterations
- The TF self-induced configuration converges
- Independant B offset due to PF-CS creates small oscillations around close designs (1 strand difference)

➔ **EMD loop is reliable and outputs self-consistent TF designs**
➔ **The computing time remains important**
➔ **Owing the fact that other loops should be aggregated (e.g. TH module) efficiency is adressed**

# EMD loop: enhancement

B calculation efficiency is enhanced by considering **a full analytical approach**
B map is set with **infinite current carrier** having rectangular section (analytical formalism)

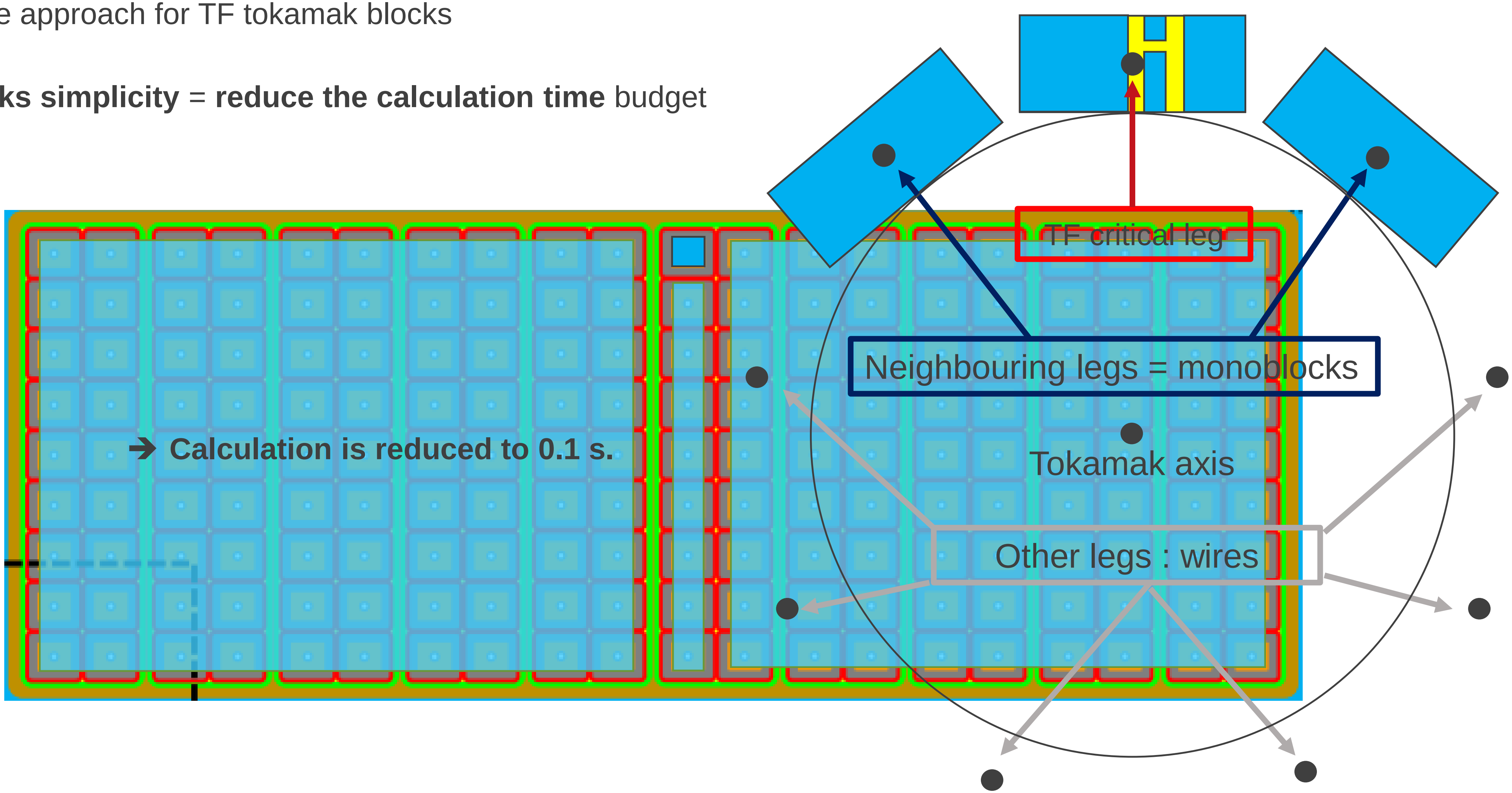
B in critical zone is represented by **contribution of section blocks** which size depend on distance from critical zone



# EMD loop: enhancement

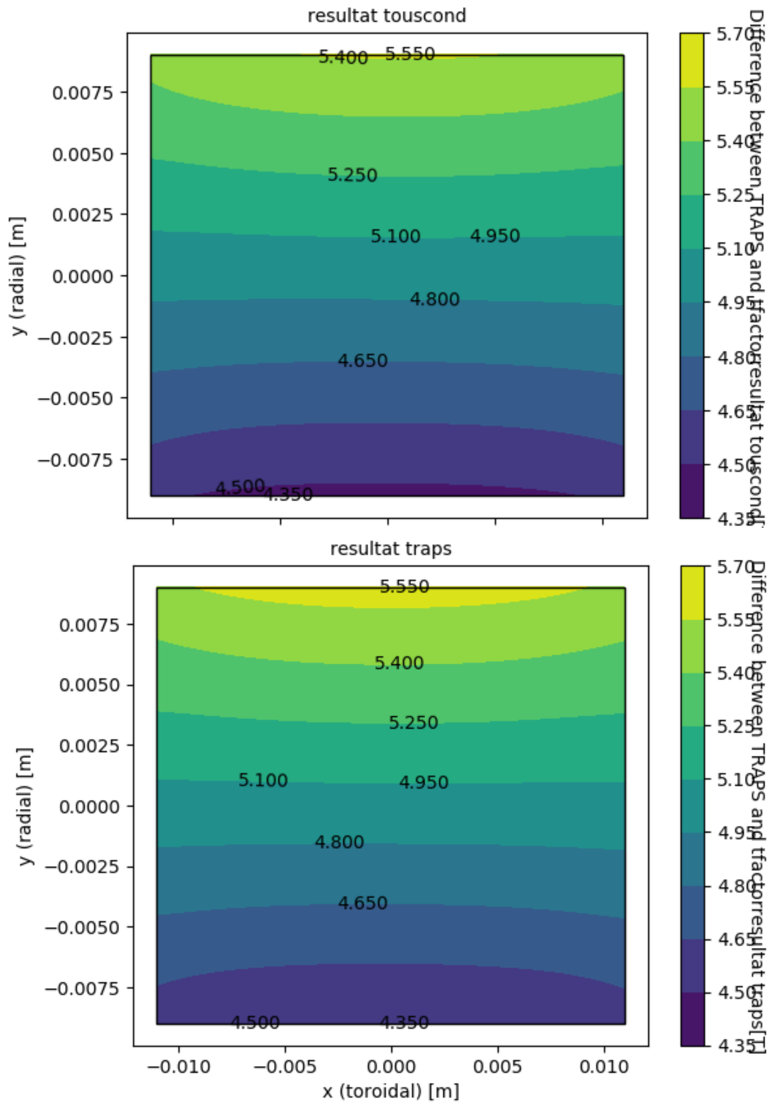
Same approach for TF tokamak blocks

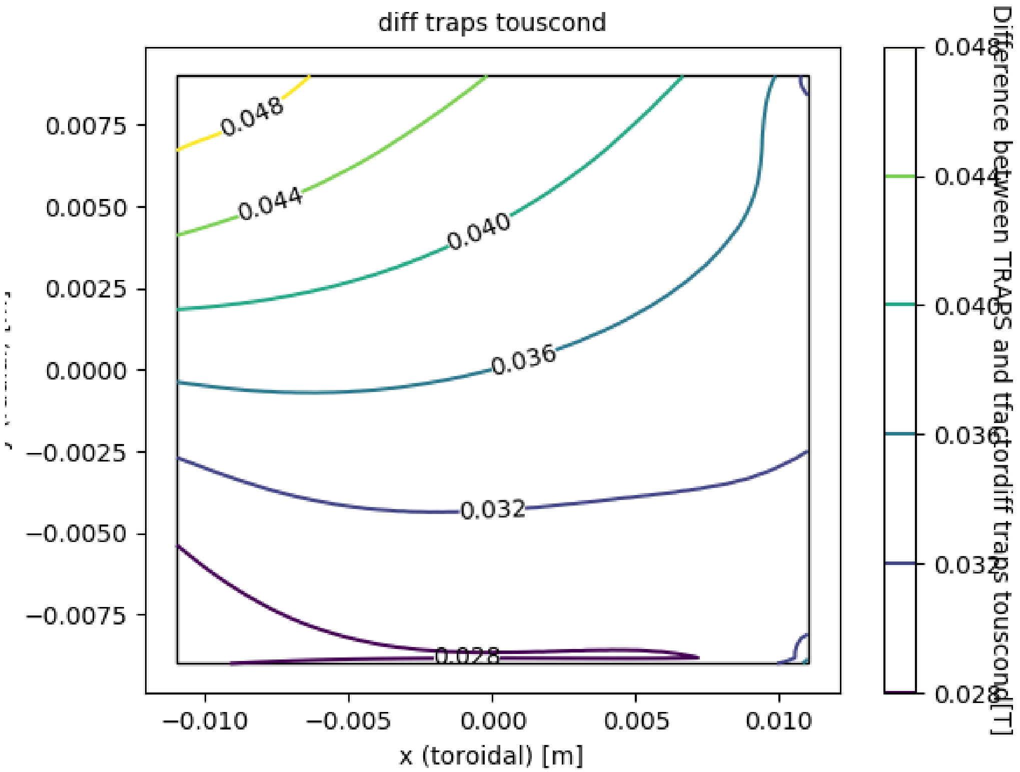
**Blocks simplicity** = **reduce the calculation time** budget



# EMD loop: enhancement

A benchmark of analytical approach (2D) with TRAPS (3D) was conducted on JT-60SA TF configuration

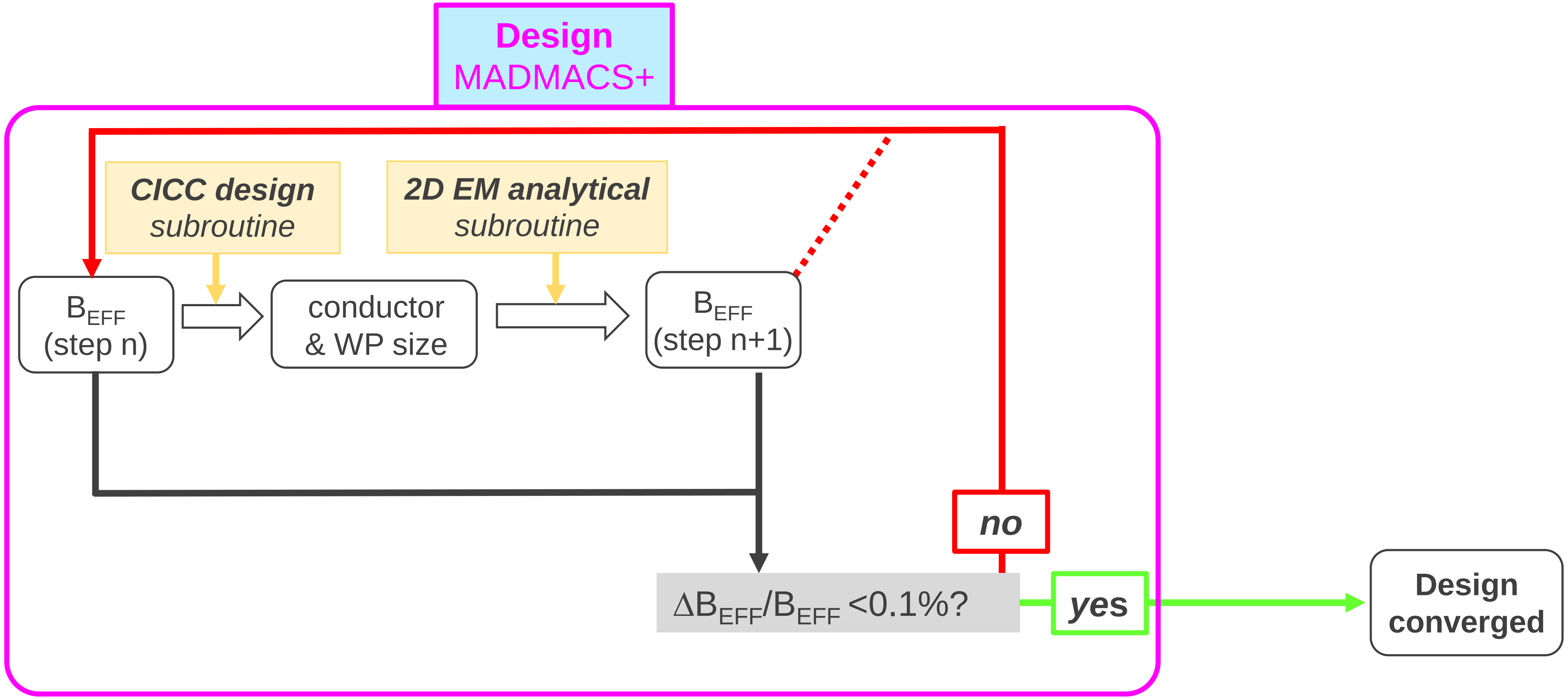



- ❑ **Difference between the two approaches is < 1%**
- ❑ **Sufficient for ensuring a convergence close to final state**

# EMD loop: enhancement

The 2D EM analytical script was **integrated into MADMACS structure** (enhanced MADMACS+)

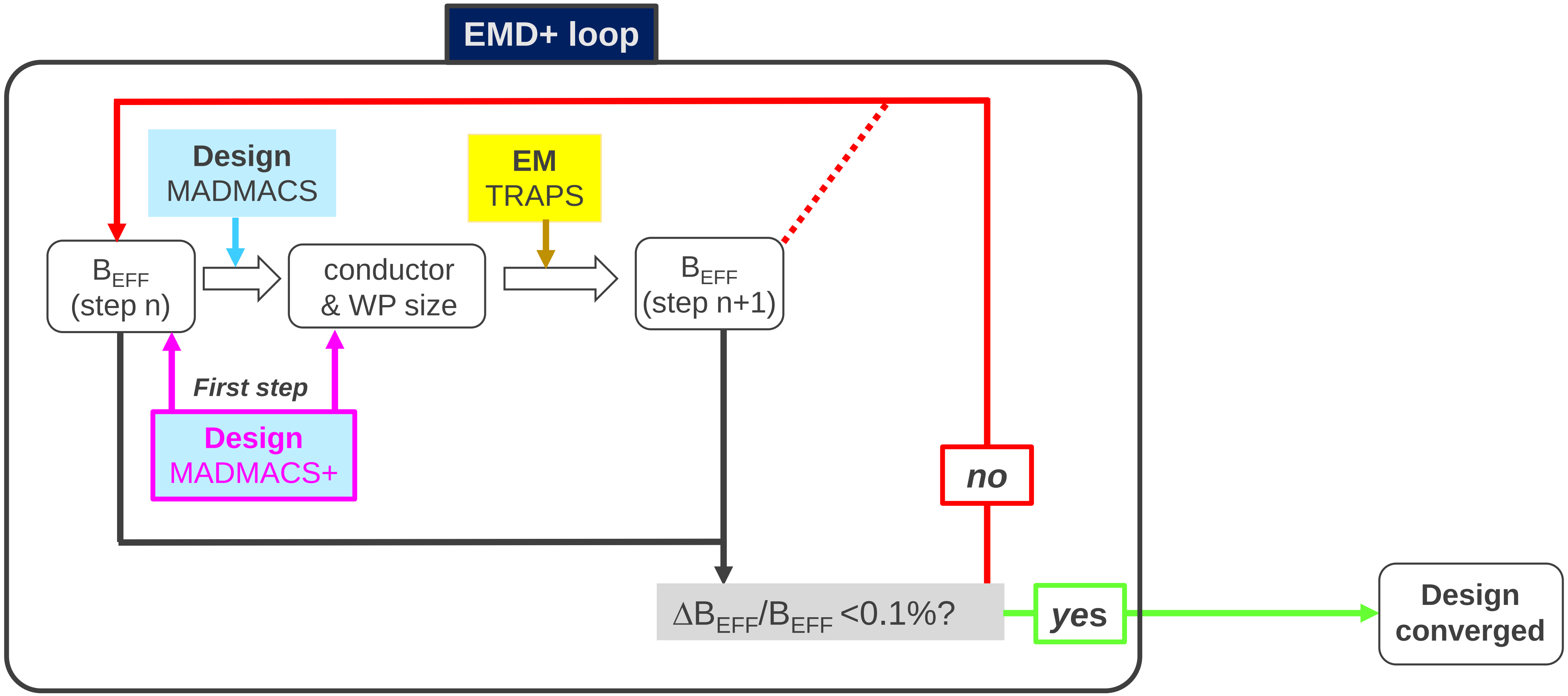



➔ **MADMACS+ calculation time < 1 second**

➔ **EDM+ loop: MADMACS+ convergence is placed before EMD loop (MADMACS & TRAPS)**

# EMD loop: enhancement






➔ **The EMD loop+ expected to run much less iterations with TRAPS (to be checked)**

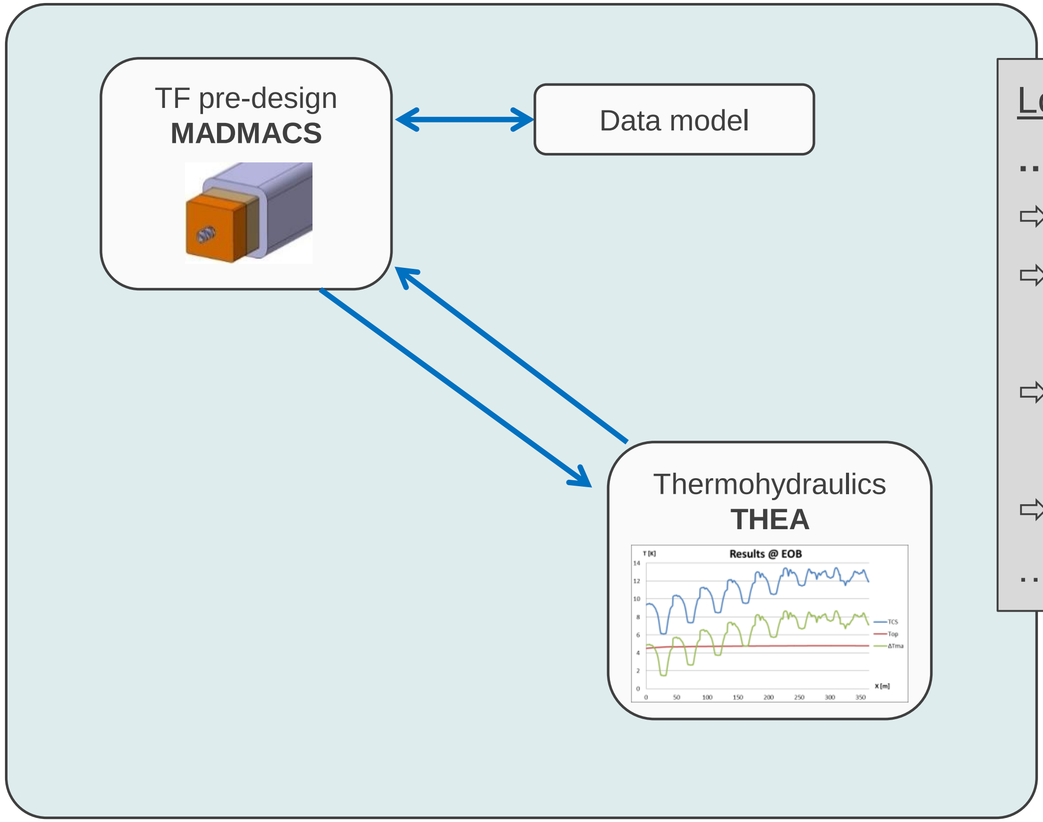
➔ **EMD loop+ full automatization to be carried out**

# THD loop: principle



**<u>THD purpose</u>:** issue a $\Delta T_{MARG}$-compliant TF design with regard to detailed analyses

**Thermo-Hydraulic Design** loop




Logic flow

…

⇨ Step n : an operation temperature ($T_{OP}$) is considered

⇨ a TF design is issued from this $T_{OP}$

⇨ MADMACS output

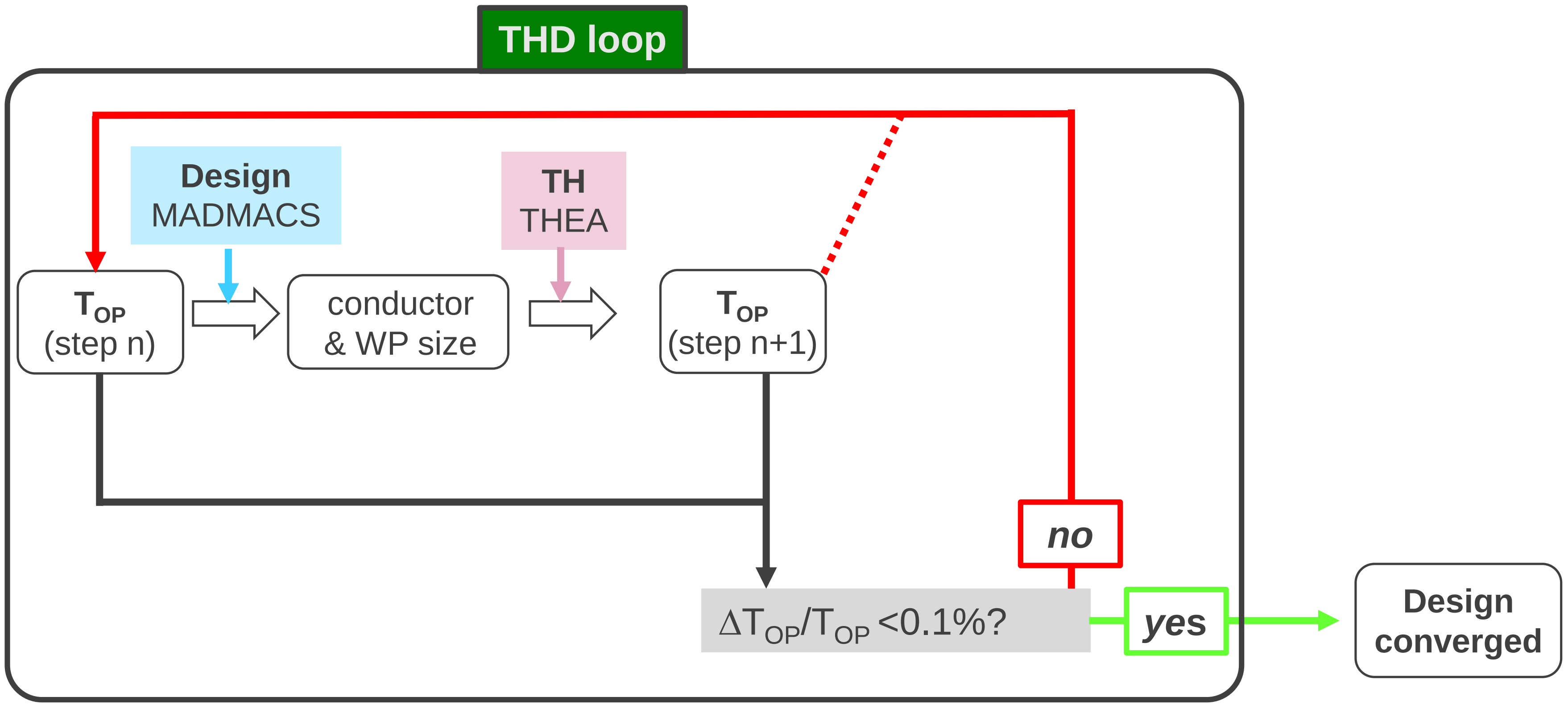
⇨ The TF design modifies the $T_{OP}$ (hydraulic properties)

⇨ TRAPS output

⇨ Step n+1 : a new $T_{OP}$ is considered

…

# THD loop: principle




- Fully automatized
- Run time is about 1 min per iteration ⇨ ~ 20 min usually for convergence
- EM considerations can be introduced with MADMACS+

*MADMACS+ output is a single $B_{EFF}$ value while THEA works with a 1D EM map B(x)*
*Initial B(x) is with TRAPS for first step, for next steps B(x) is shifted so that max(B(x))=$B_{EFF}$*

# THD loop: application on DEMO



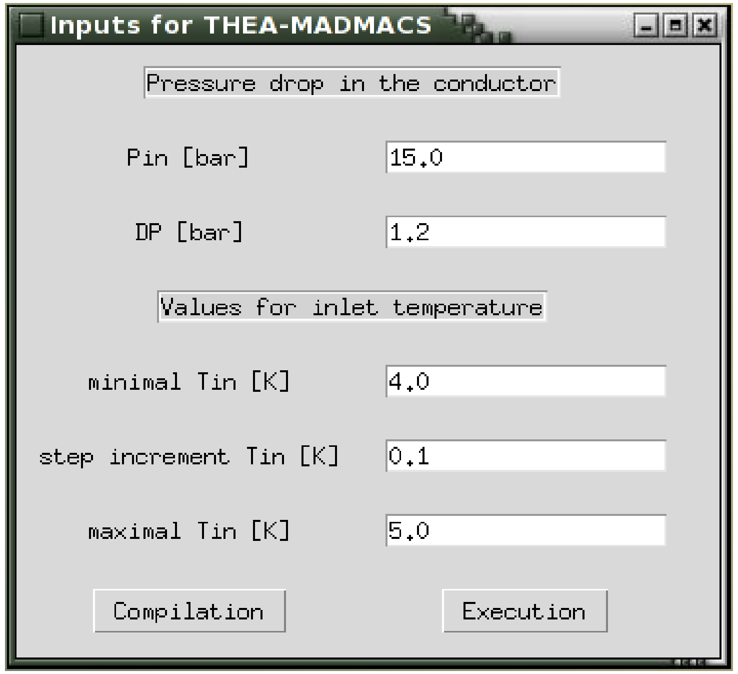
An **application** of the THD loop with MADMACS (original version) was initiated on DEMO 2018 TF WP#3 concept (pancake option without radial plates) : parametric exploration with different [$\Delta P$, $T_{IN}$] ➔ ref [1]

Present objective :

conduct similar parametric studies but

- With more realistic thermal load on conductor (i.e. considering the load from structures)
- across a broader [$\Delta P$, $T_{IN}$] range = [0.5 – 1.5 bar]*[2.5 – 4.5 K]
- MADMACS and MADMACS+ modules used to quote the effect of $B_{EFF}$ variation with design across the spanned zone

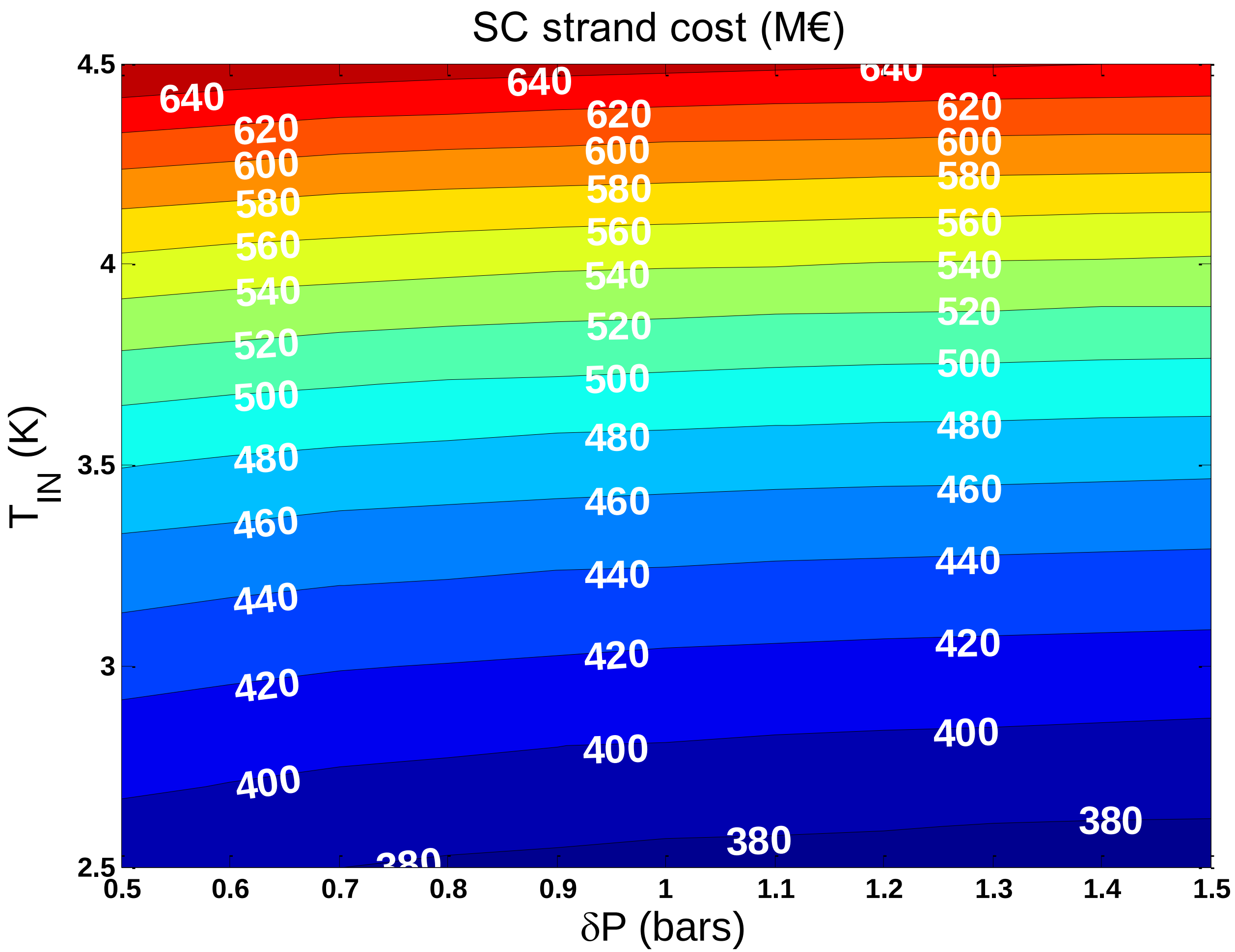
A dedicated GUI was developped (Python) for the THD loop

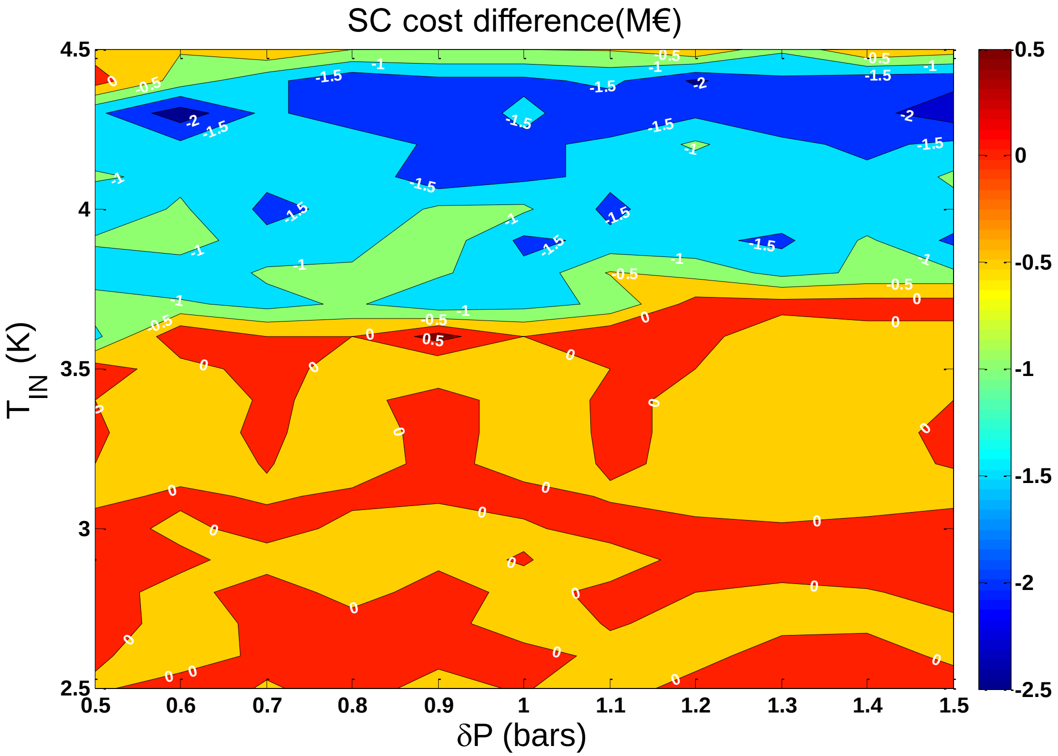



[1] Sandra Varin, François Bonne, Christine Hoa, Jean-Marc Poncet, Louis Zani, Benoît Lacroix, Quentin Le Coz, *Optimization of the overall Toroidal Field Coil cryomagnetic system at the pre-conceptual design phase of the European DEMO fusion reactor*, presented at SOFT 2020, to be published in Fusion Eng Design

# THD loop: application on DEMO

As result both cases look similar




Differences are marginal as **Δcost < 1 %**

This derives from the small difference in conductor size and then in $B_{EFF}$

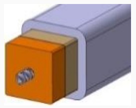
➔ **The $B_{EFF}$ calculation functionality does not change much the global dependance with ΔP and $T_{IN}$**

# THCD loop: principle

**Objective**: produce system-scale parametric studies considering magnet and cryoplant

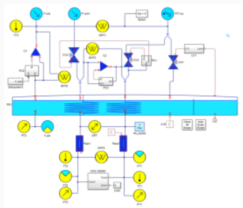
**Thermo-Hydraulic & Cryogenic Design** loop

TF pre-design
**MADMACS**

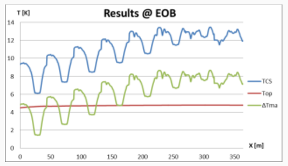


Data model

Cryodistribution
**SimCryogenics**



Thermohydraulics
**THEA**




Logic flow

- ⇨ THD loop is run across an operation domain
- ⇨ THD loop outputs defined factors of merit
- ⇨ THD loop data useful for cryogenic design are transferred to Simcryogenics
- ⇨ Simcryogenics is run across the same operation domain
- ⇨ Simcryogenics outputs factors of merits of same nature as for THD
- ⇨ Factors of merits are combined

# THCD loop: application to DEMO

In the logic of extension to coupled cryo-magnetic TF system similar as in ref [1] we carried out a parametric exploration with different [$\Delta P$, $T_{IN}$] with the same conditions as in THD loop example

The purpose is to combine the cost variations of the TF system and cryogenics systems across the [$\Delta P$, $T_{IN}$] range.

As per **TF magnet part** we retained the outputs obtained with MADMACS+ module (see previous)

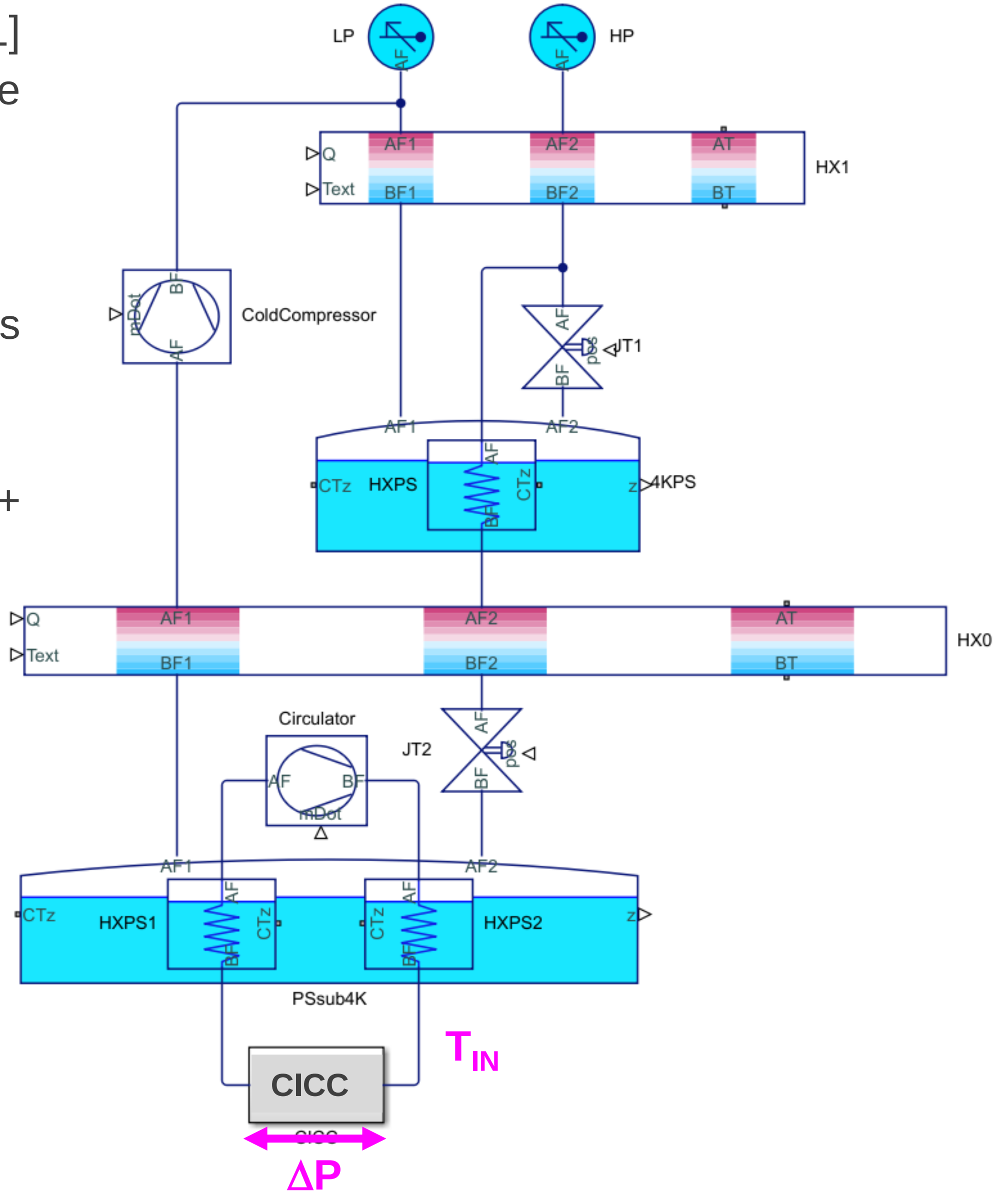
As per **TF cryogenic part** the configuration retained is a 2 bathes structured cold end with a 4.4 K bath that feeds a subcooler bath at Tin – 0.2 K .

→ The cost of the cryogenic part is divided in two :

- Investment cost estimated with the Green formula

$$\text{CAPEX} = \ 2.9 \times P_{eq,4.5K(kW)}^{0.63}$$

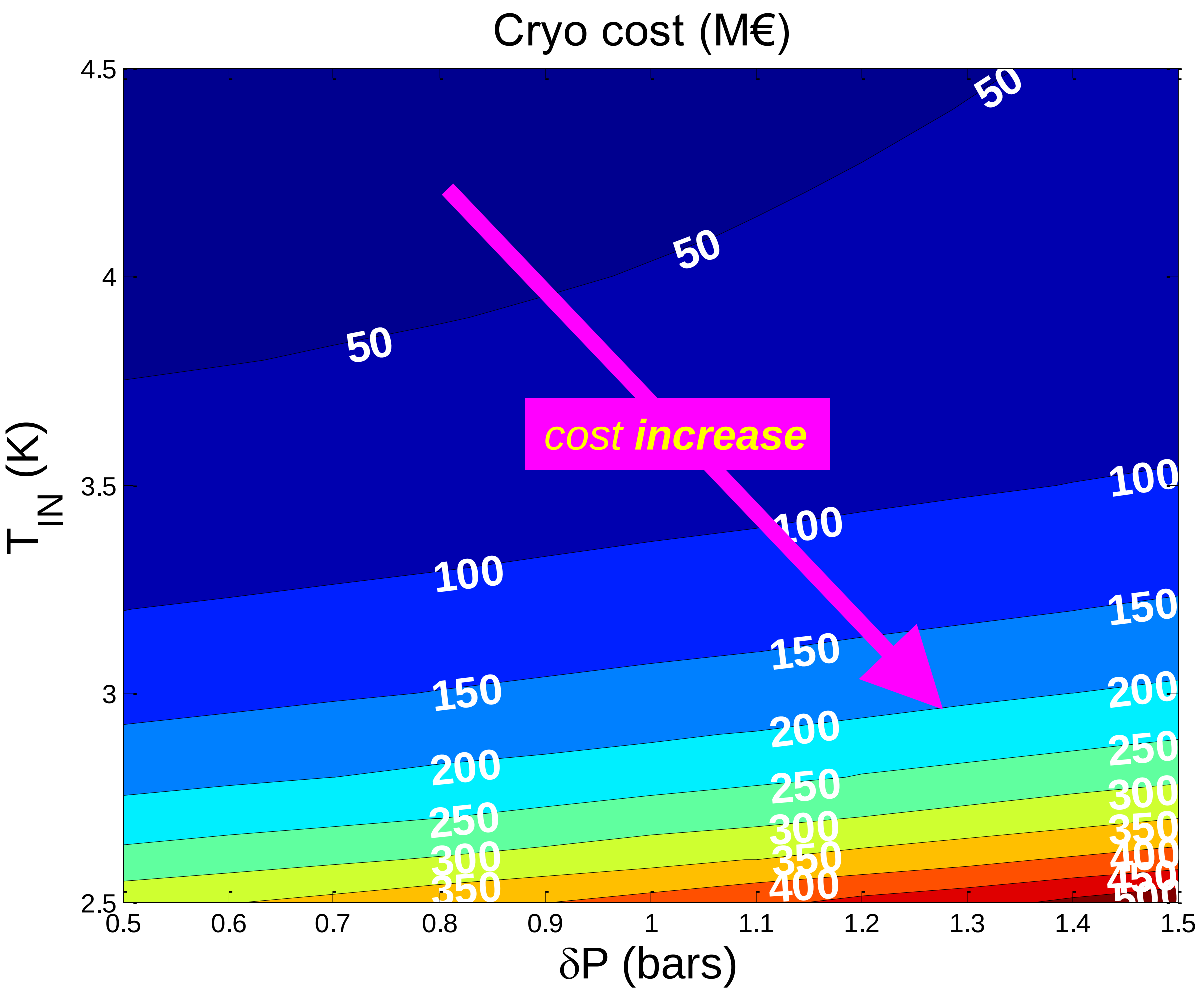
- Operational cost is estimated with the electricity cost over 20 year exploitation

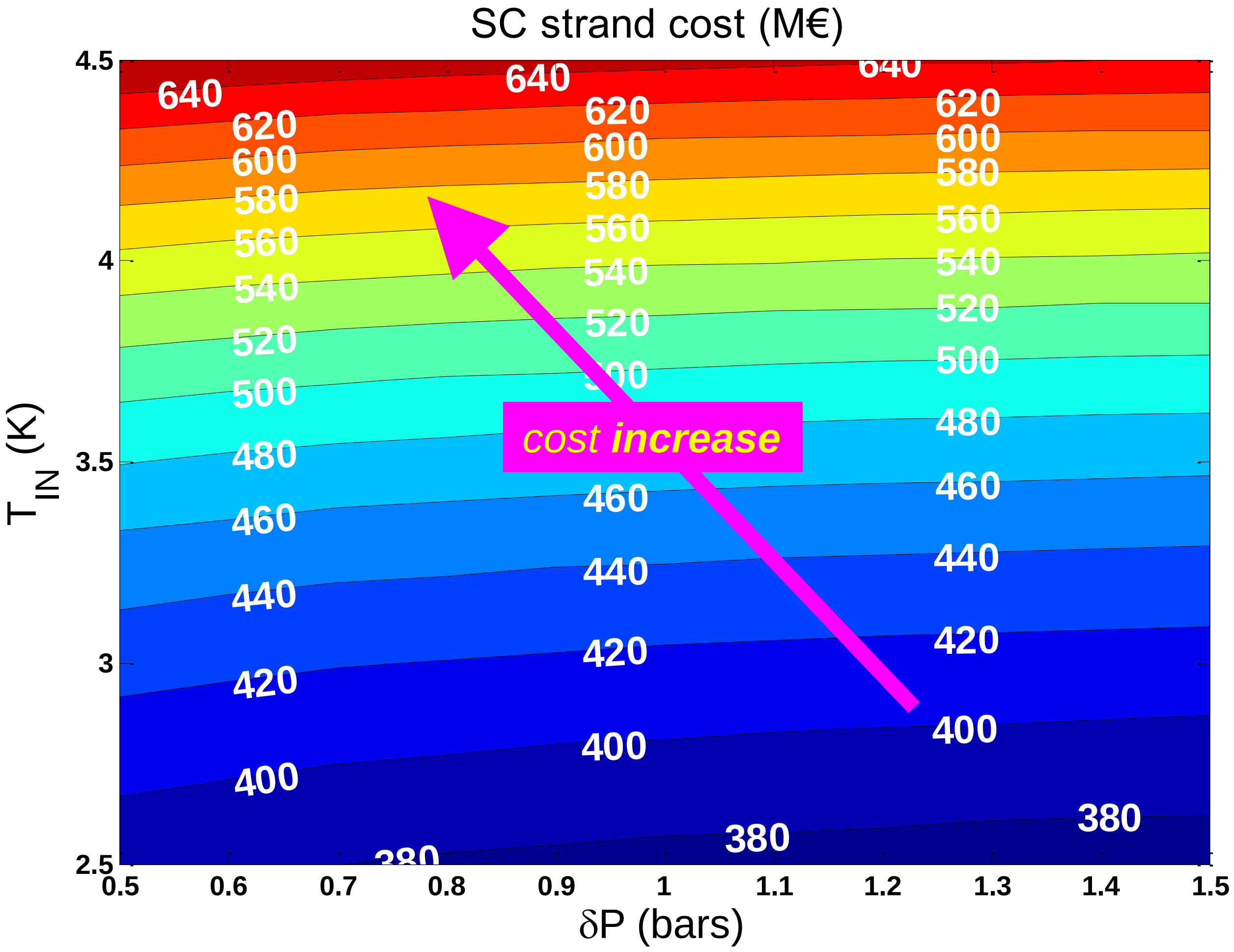


# THCD loop: application to DEMO



As result on the TF cryomagnetic system we obtain



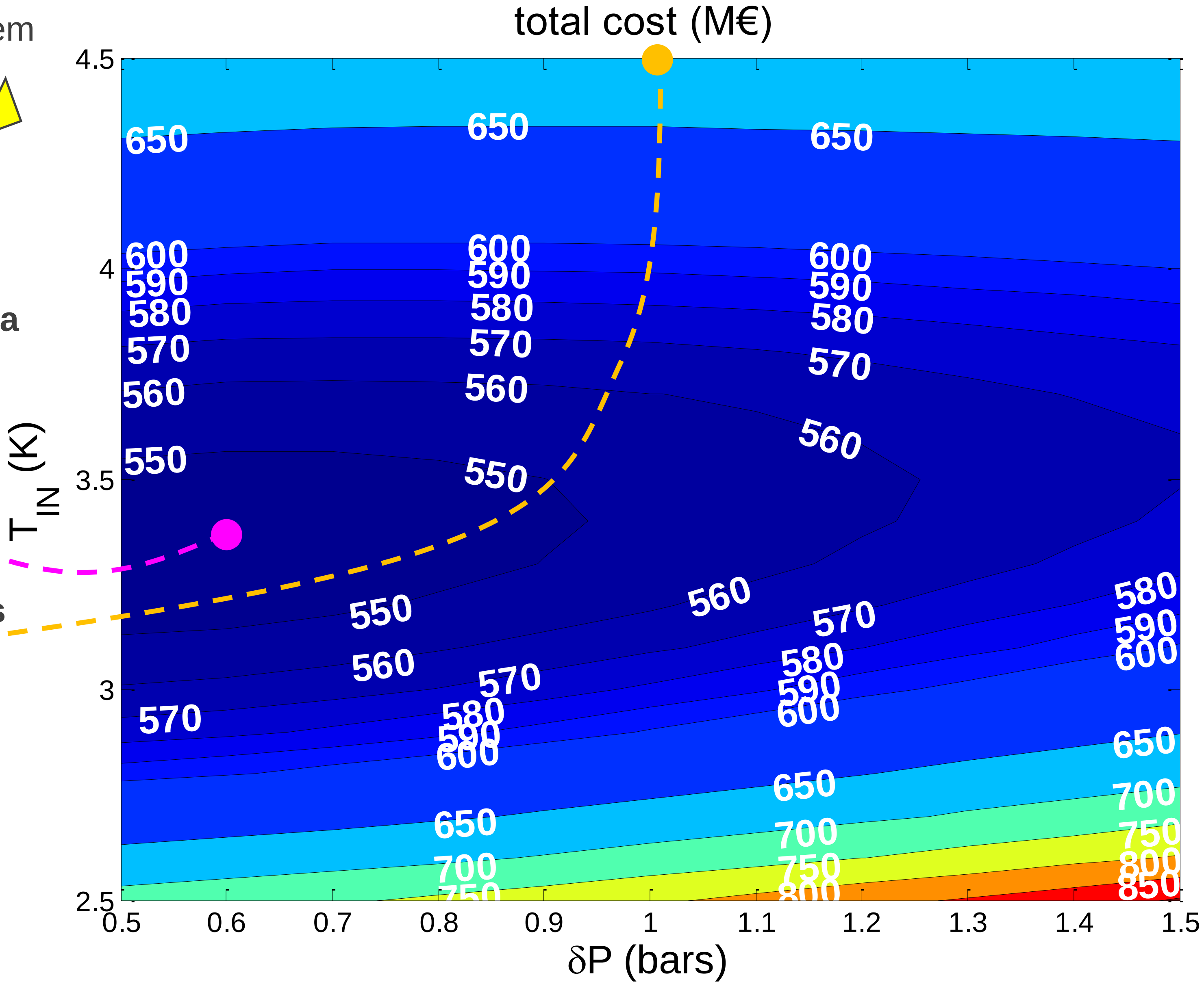




Cost combination claims for an optimum…

# THCD loop: application to DEMO



Result on the **overall cryomagnetic TF** system




➔ **The overall system cost spans across a broad range (545 ~ 900 M€)**

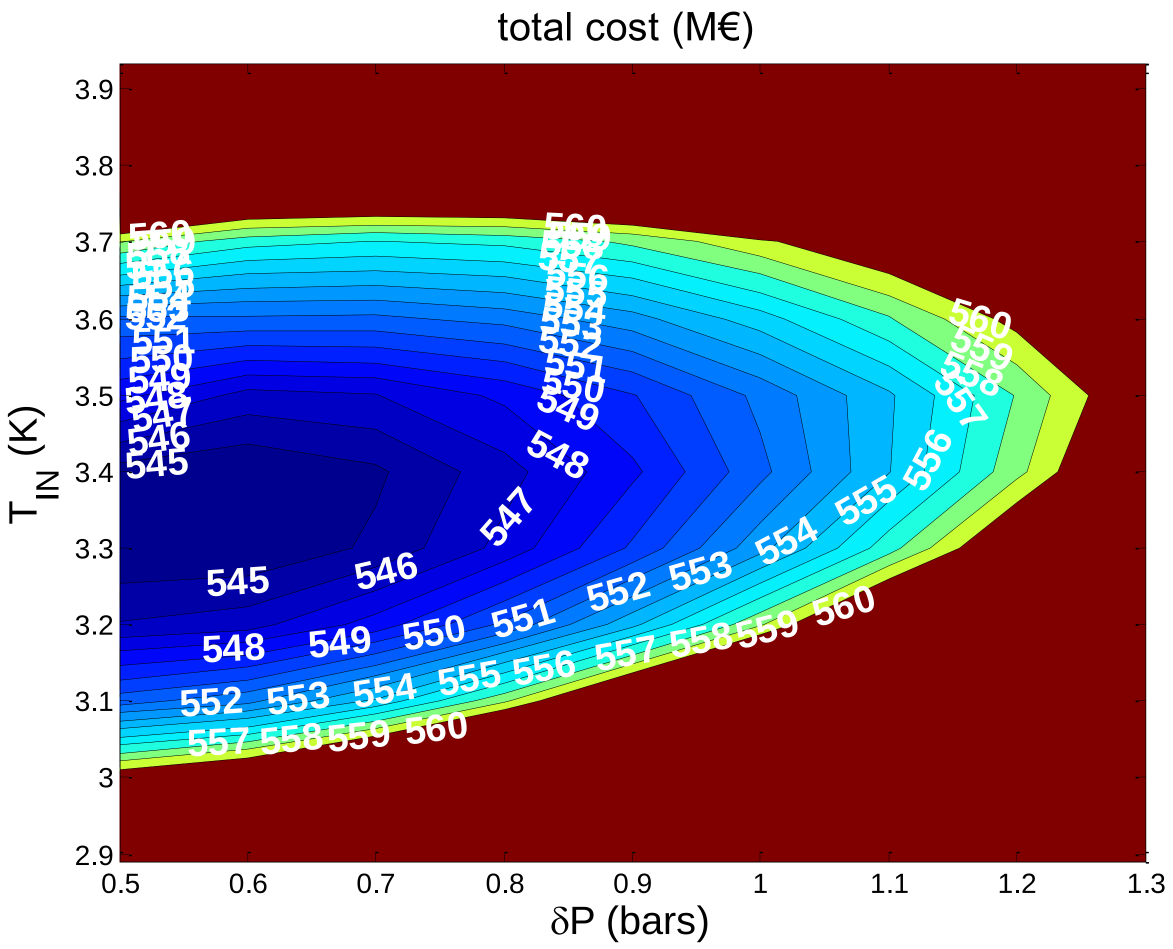
➔ **An absolute minimum is found at**
**~ [$T_{IN}$ = 3.4 K ΔP =0.6 bar]**
**minimum cost is ~ 545 M€**

➔ **Compared to DEMO nominal conditions**
**[$T_{IN}$ = 4.5 K ΔP = 1 bar]**
**cost difference is ~ 140 M€**

# THCD loop: application to DEMO

Discussion: is the minimum shallow or steep ?

A **3% decision flexibility margin** is considered to identify the boundaries of optimized operation domain




- On ΔP dimension, the minimum is rather shallow and any value of ΔP between 0.5 and 1.2 bar seem appropriate
- Conversly minimum is steeper across $T_{IN}$ dimension, claiming for a **$T_{IN}$ between 3 K and 3.7 K**

➔ **As per cost merits, the overall TF cryomagnetic system optimum pushes for <u>low temperature operation</u>**

## Perspectives

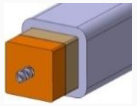
- Refine cost merit functions
- Consider technological choices (cryo…)
- Extend to the whole cryomagnet system (CS, PF)

# MECD loop: principle

**Objective:** issue a stress-compliant TF design with regard to **detailed mechanical** analysis

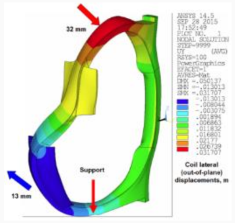
**MECanical Design** loop

TF pre-design
**MADMACS**



Data model

Mechanics
**Cast3M**



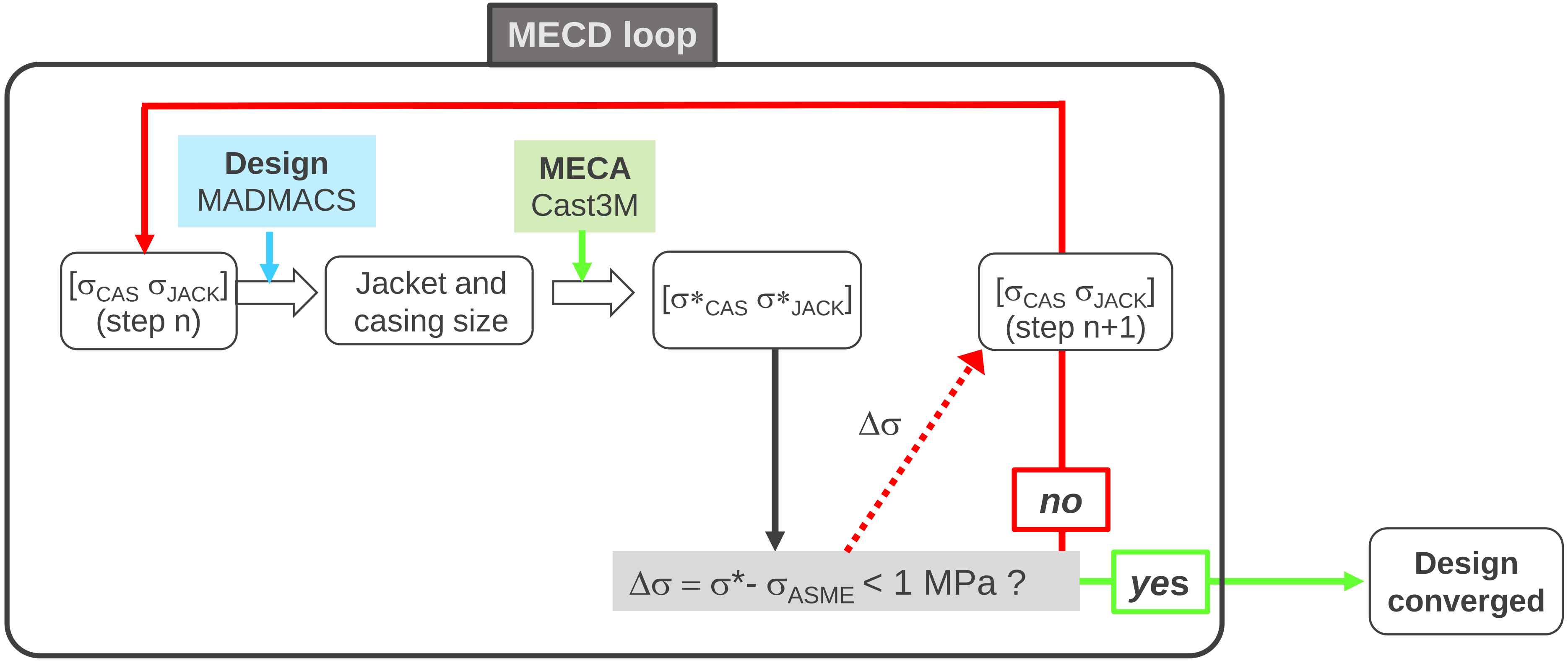
Logic flow

…

- Step n **:** a couple of stress values **(**$\sigma_{CASING}$ $\sigma_{JACKET}$**)** is considered
- a TF design is issued from this **(**$\sigma_C$ $\sigma_J$**) (macroscopic analysis)**
  - MADMACS output
- The TF design develops local **(**$\sigma^*_C$ $\sigma^*_J$**) (detailed analysis)**
  - CAst3M output
  - Comparison with ASME limits **(**$\Delta\sigma_C$ $\Delta\sigma_J$**) defined**
- Step n+1 **:** a new **(**$\sigma_C$ $\sigma_J$**)** is considered

…

# MECD loop: principle




- Cast3M time consuming (~2 hours per run)
  - *can be improved (friction considered, GPS method not optimized…)*
- Data exchanges in loop not yet automatized

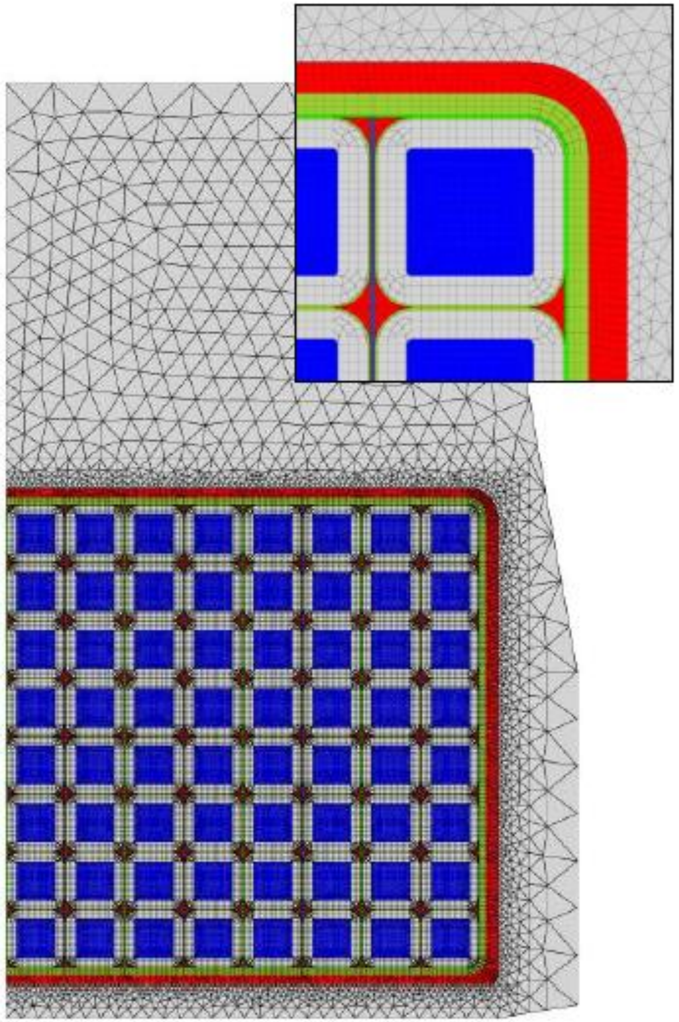
The first application attempt is conducted on **DEMO 2015 TF WP#3 concept**

**Design**
MADMACS

$\sigma_{CAS}$= 680 MPa
$\sigma_{JACK}$=622 MPa

| Feature | Value (mm) |
| --- | --- |
| Jacket thickness | 11 |
| Cable side | 48.3 |
| TF nose thickness | 511 |
| TF thickness | 1175 |

Cast3M model

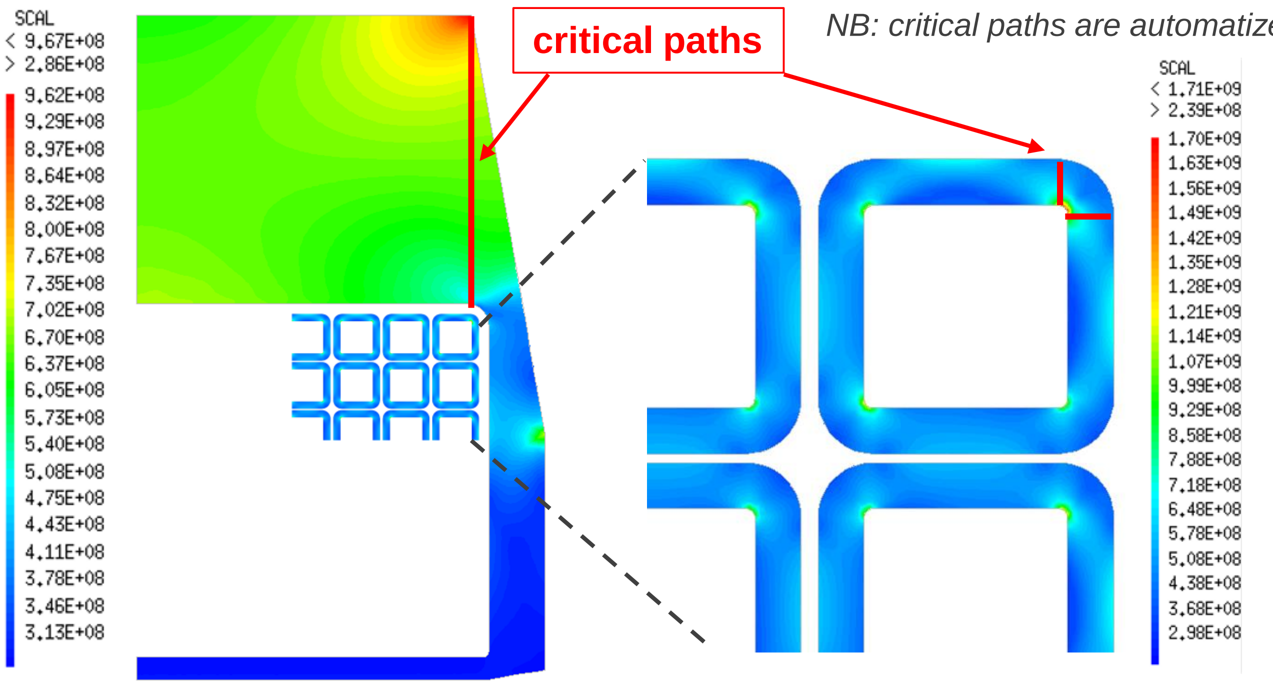


*NB: MADMACS Excel version is used for first attempt to ensure a stable optimisation with respect to both* $\sigma$

# MECD loop: application to DEMO

Detailed analysis of DEMO 2015 load case

*NB: critical paths are automatized*




**Casing stress map** — **Jacket stress map**

| Location | Membrane stress (MPa) | Margin to ASME (MPa) |
|---|---|---|
| Casing | 616 | **+ 50** |
| Jacket | 568 | **+ 100** |

$\sigma_{CAS}$= 680 **+ 50** = 730 MPa

$\sigma_{JACK}$=622 **+100** = 722 MPa

**Design**
MADMACS

| Feature | Value (mm) | Δ (mm) |
|---|---|---|
| Jacket thickness | 8.7 | **-2.3** |
| Cable side | 48.3 | 0% |
| TF nose thickness | 480 | **-31** |
| TF thickness | 1100 | **-75** |

- *Thinner jacket*
- *TF coil smaller radial buit*

- **new Cast3M run to be conducted**
- **MECD loop operationality to be assessed**
- **Consider membrane + bending criterion**

# Conclusion - Perspectives

- In the framework of **OLYMPE** development **several multi-physic design loops** were built using the different modules of the platform
- **Electromagnetic Design loop** was established with a two-stages approach
  - ✓ An integration ni MADMACS was carried out for analytical part (moderate fidelity)
  - ✓ An hybrid loop is combined with TRAPS (high fidelity)
- **Thermo-hydraulic Design loop** was established
  - ✓ A parametric study [$\Delta P$, $T_{IN}$] was conducted on DEMO configuration
  - ✓ In this application considering $B_{EFF}$ variation with design has margina impact on results
- **Thermo-hydraulic Cryogenic Design loop** was established
  - ✓ The parametric study [$\Delta P$, $T_{IN}$] was extended conducted on DEMO configuration
  - ✓ A global optimum for cryomagnetic system was found, claiming for low temperature operation
- **Mechanical Design loop** was established
  - ✓ A first try on DEMO 2015 was attempted to be consolidated

perspectives

→ Assess all loops convergence along their actual maturity (EMD, THCD, MECD…)
→ Develop data exchange automatization and GUIs
→ Run several application cases to establish their convergence stability
→ Improve time computation budget
→ Extend to all tokamak systems (CS, PF)

# Thank you for your attention

# Questions ?