DEVELOPMENT AND APPLICATION OF A SIMPLIFIED THERMAL MODEL OF THE ITER MAGNET SYSTEM

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Outline

Introduction
- Context of the work
- Magnets and Cooling System Description

General Approach to the Problem
- Motivation
- Brief model description

Modeling Features Evaluation & Results
- TF simplified scenario
- Influence of modeling features
  - conductor
  - central channel

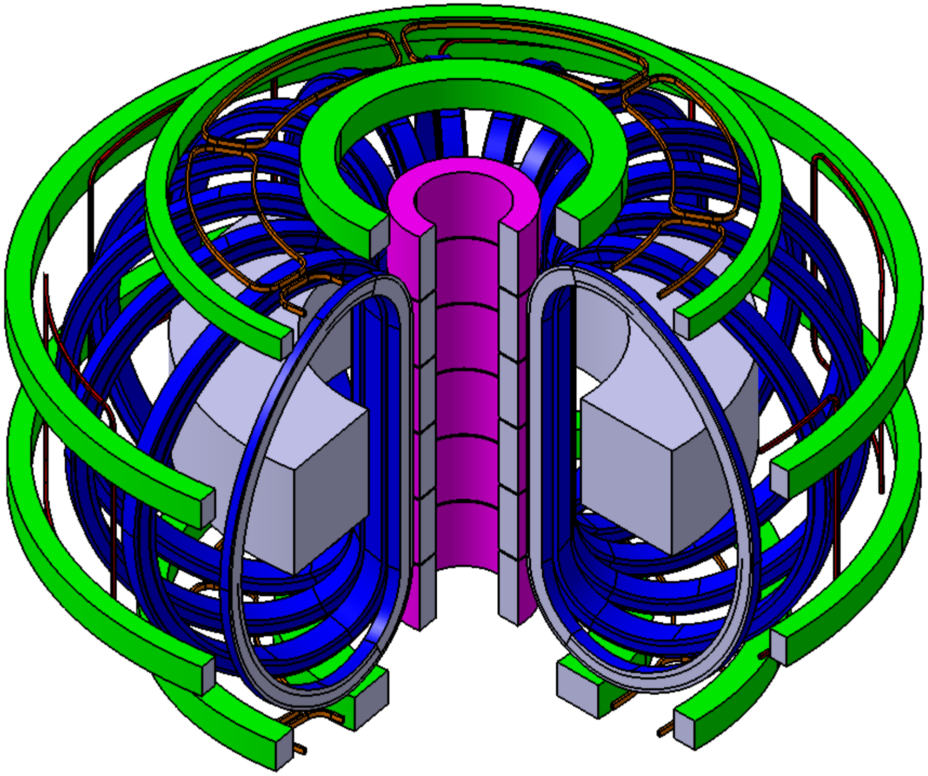
Benchmarking
- CS model
- Results

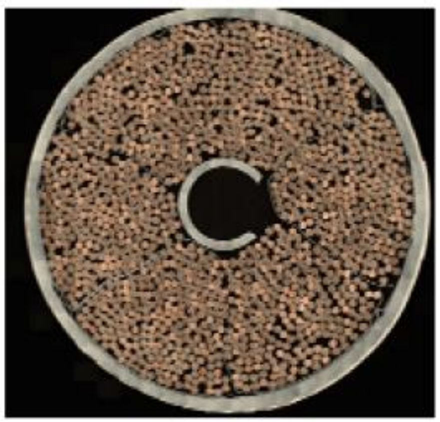
Conclusions
- Summary
- Conclusions

INTRODUCTION: ITER Magnets System

Toroidal Field Coils
Central Solenoid
Poloidal Field Coils
Correction Coils

Particle confinement and fusion plasma shaping, positioning and control

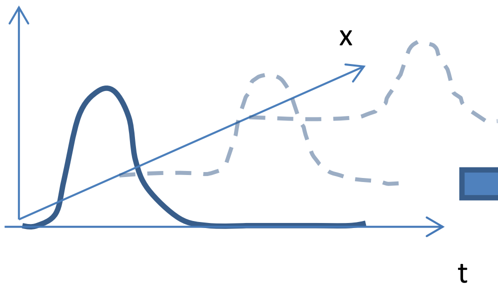




Cable in Conduit Conductors (CICC)
Superconducting strands immersed in SHe

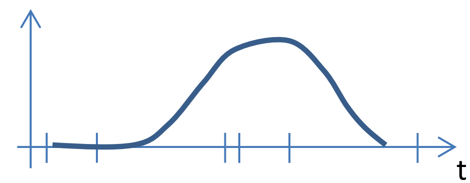
Magnets subject to transient heat loads (nuclear heating, AC losses) to be removed by cryoplant

INTRODUCTION: Problem Statement



Heat loads into magnets (radiation, AC losses, etc)
$q - in(\bar{x}, t)$

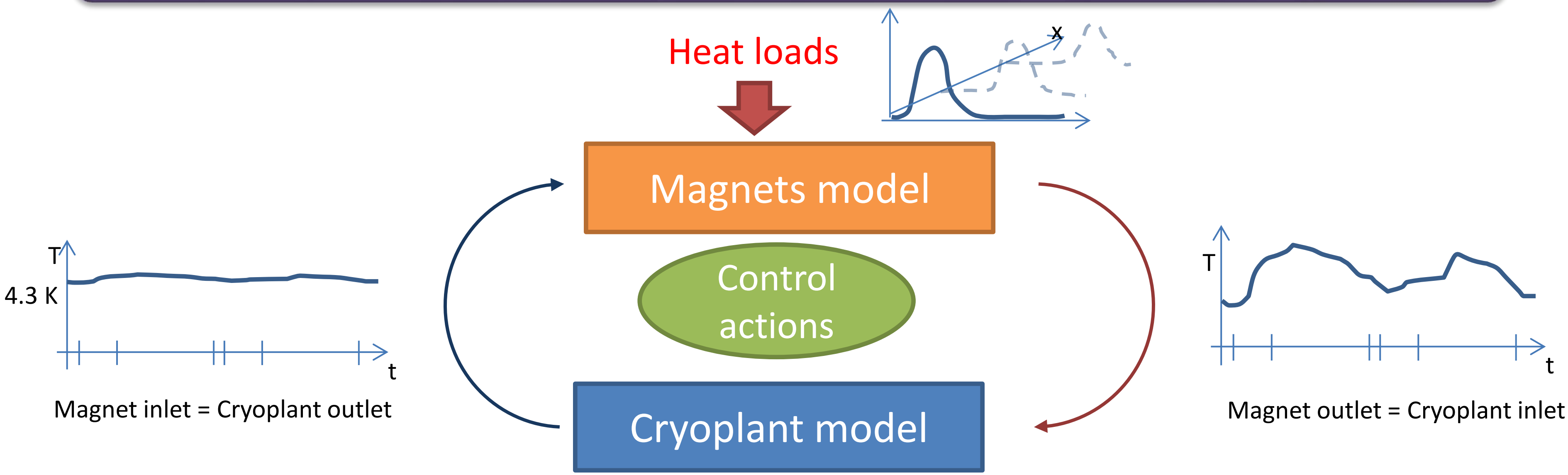
Heat Load Transfer Function (magnet thermal-hydraulic model)



Heat loads into cryoplant (magnet outlet enthalpy)
$q - out(t)$

- Magnet operates as a transfer function between the heat loads generated as a result of reactor operations, and what the cryoplant has to remove
- Currently the dynamic response of the magnet system is modeled with multi-dimensional thermo-hydraulic codes that are CPU-intensive, and provide sufficient accuracy to evaluate s/c thermal margin everywhere along the conductor
- What is needed is a simplified model/code that:
    - Captures the overall transient of the heat loads with sufficient accuracy to define the magnet/cryo interface, and for use in cryoplant control strategy simulations, without necessarily the fine detail of what happens everywhere along a conductor
    - Eventually can run simulations in real-time to be incorporated as a predictive control tool in cryoplant operation (feed-forward control of tokamak operations)

INTRODUCTION: Modeling Needs



Physics key issues

- Transit time in tubes
- Energy conservation
- Thermal inertia effects

Usability

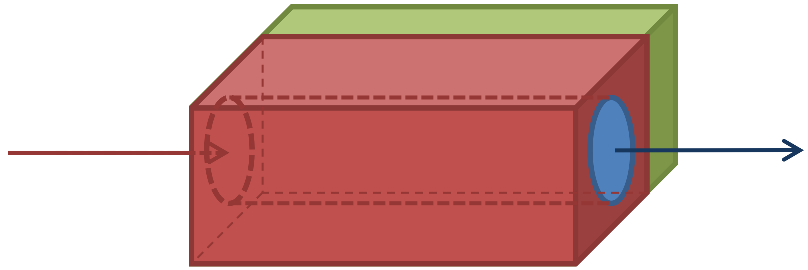
- Ability to customize distribution of heat loads in space and time
- Quick, light software ↔ level of detail must be reasonable

Development

- Part 1: Physical key feature identification using TF coils as platform
- Part2: benchmarking against other codes with CS Coils case

APPROACH: Mathematical Description of Physical Processes

In a MAGNET CROSS SECTION, normal to fluid flow, there are two types of elements



Solids

Temperature evolution

- lumped capacitance model
- $\frac{dT}{dt} = \frac{Q_{solid}}{M\,C_p}$

Heat Sources

- Heatloads (user specified)
- Interaction with fluid in tubes
  - Convection $Q = UA(T_{sol} - T_f)$
- Interaction with other solids
  - Conduction $Q = UA(T_{sol} - T_s)$

Tubes

Transit in tube volume

- $V = \int_{t-t_r(t)}^{t} \frac{\dot{m}(t\prime)}{\rho(t\prime)} dt'$ → def. of t_r

Heat Sources

- Heatloads (user specified)
- Interactions with the solid in contact

Transport of energy

- $h_{out}(t) = h_{in}(t - t_r) + \int_{t-t_r}^{t} \dot{q}\; dt + \int_{t-t_r}^{t} \frac{1}{\rho}\frac{dP}{dt}\; dt$

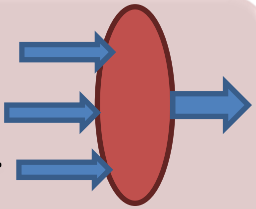
Temperature for convection

- $\frac{d(mu)}{dt} = \dot{Q}_i + \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$
- and Helium properties $T = T(P, u)$

APPROACH: Hydraulic network

Network connection elements of two types

- Instantaneous mixers without volume
- Mixers with volume (first-order time delay).



Assumptions applied to the loop

- Incompressible;
- Uniform density and mass flow rate;
- No friction head losses.

Pressure evolution

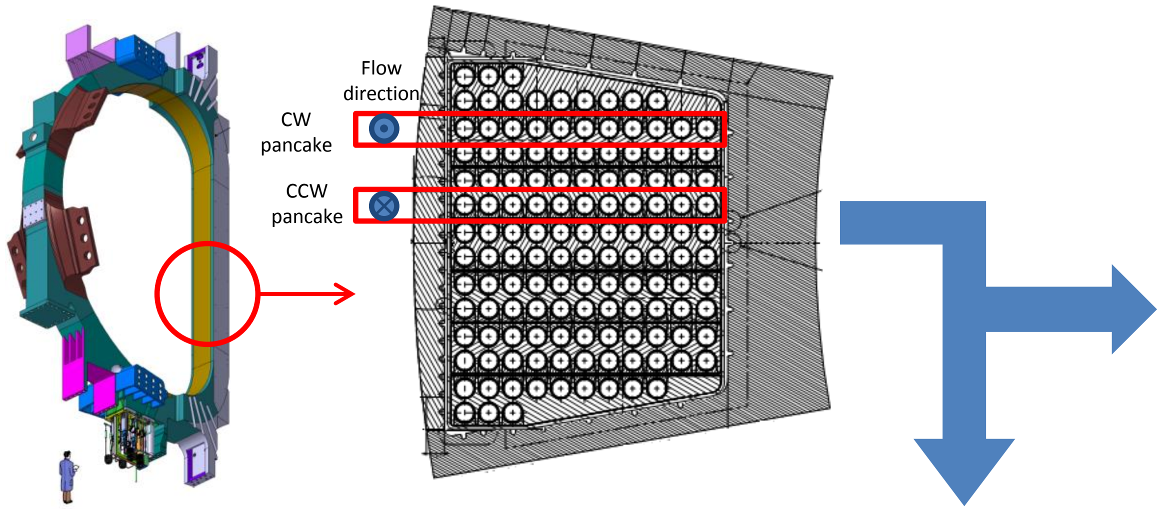
- In closed loop configuration, global pressure that evolves according to average internal energy.

$$\frac{dU}{dT} = \frac{\dot{Q}}{M}, \qquad P = P(U, \rho)$$

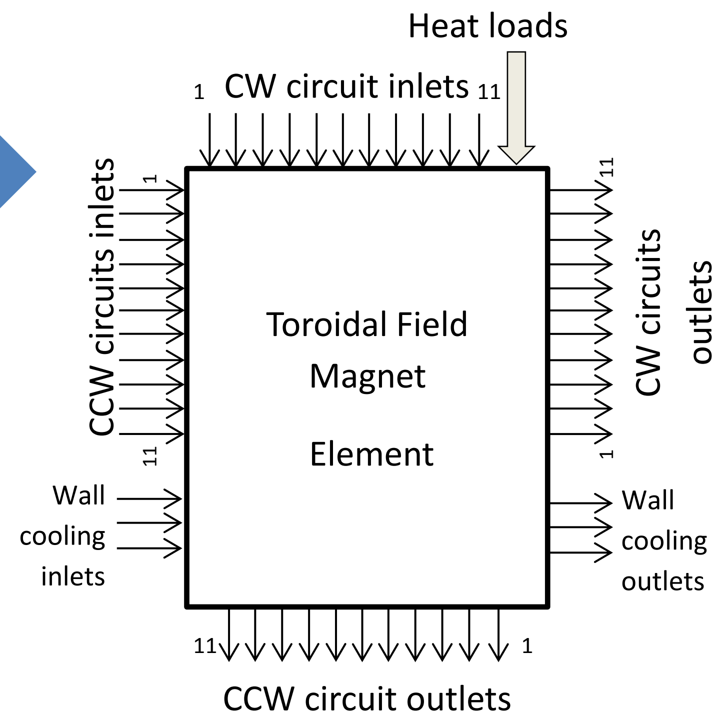
The model is programmed in C and the resulting code is called **STIMS**

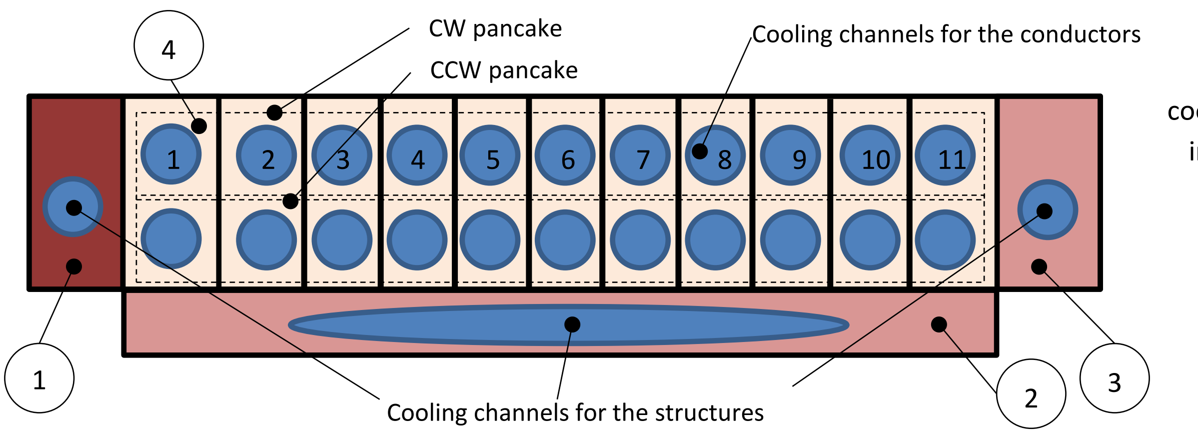
TF Coil Simplified Model

We want to test the modeling features in a somewhat realistic case: TF coils



The TF Coil Element as a black box, with inlet and outlet interfaces. There are 32 of these elements.



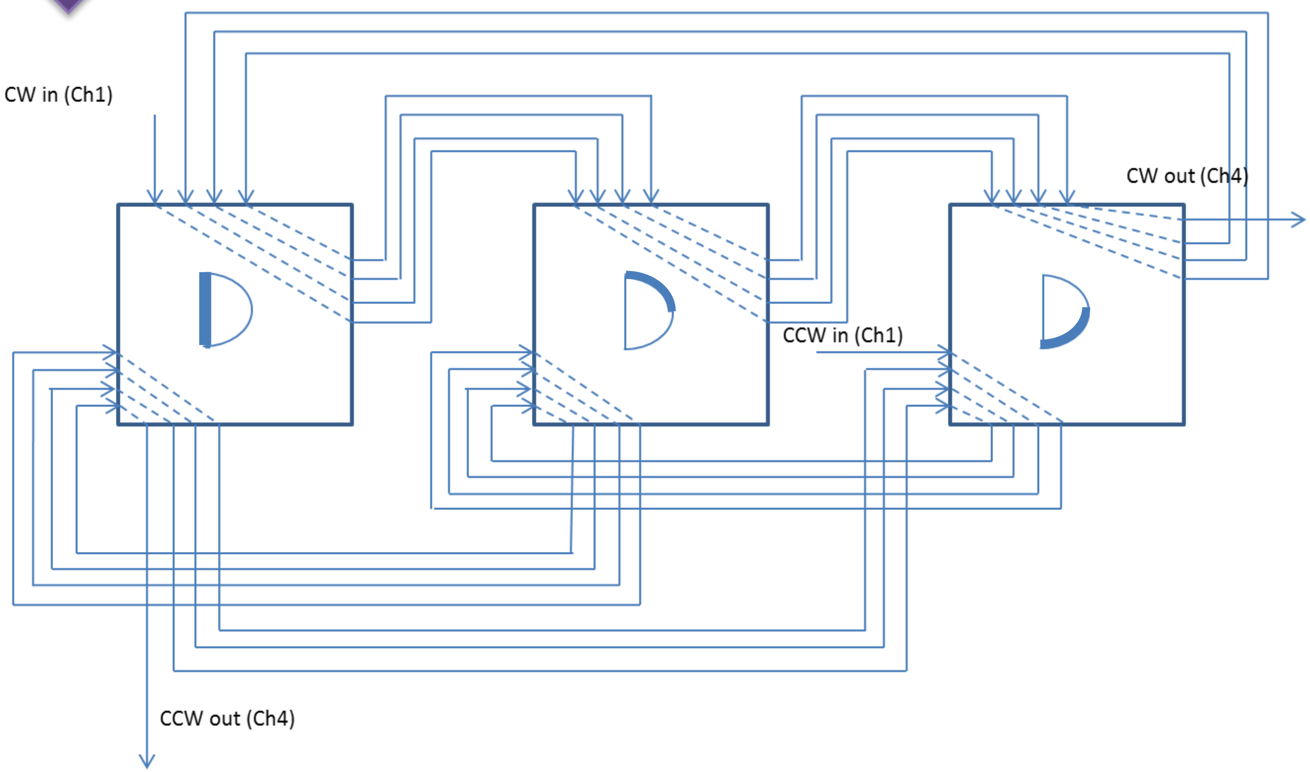


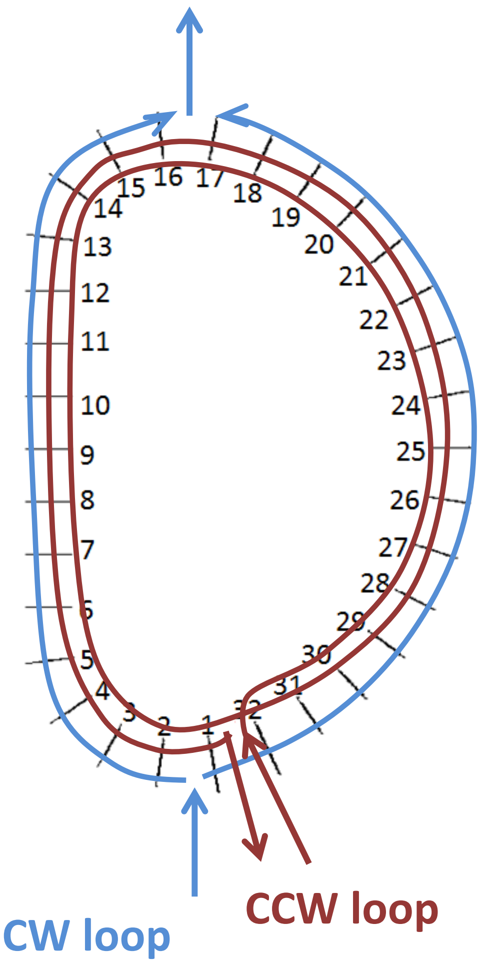
Cross section of the simplified model for TF coils. *References: 1. Casing plasma facing wall; 2. Casing side wall; 3. Casing external wall; 4. Radial plates.*

Thermal interactions between these parts will be modeled through **constant heat transfer coefficients**

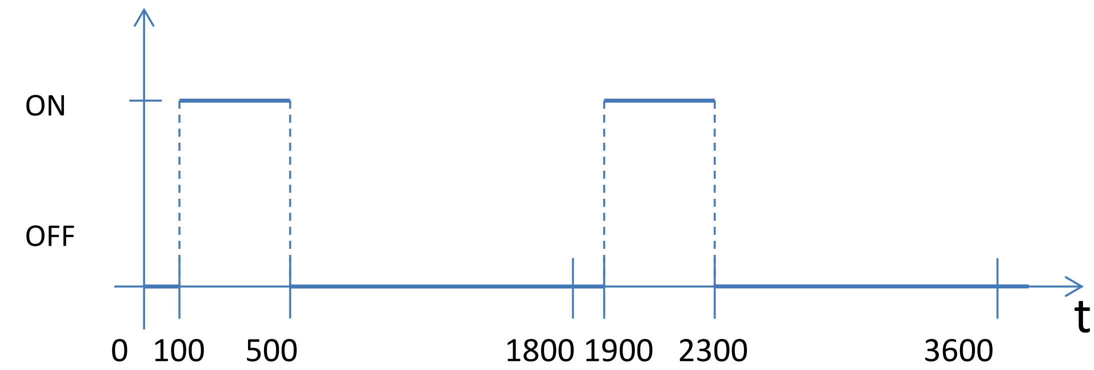
Magnet discretization and internal connection

- The TF Coil Assembly will be cut up into **several segments** with uniform properties and heat loads (as shown on the right), capturing the counterflow nature
- Segments will be as the ones just described and are connected as shown below.
- Different segments interact by means of tube connection, NO thermal conduction in flow direction.
- A simple heat exchanger with cold side at LHe temperature is connected to the model in order to close the loop.



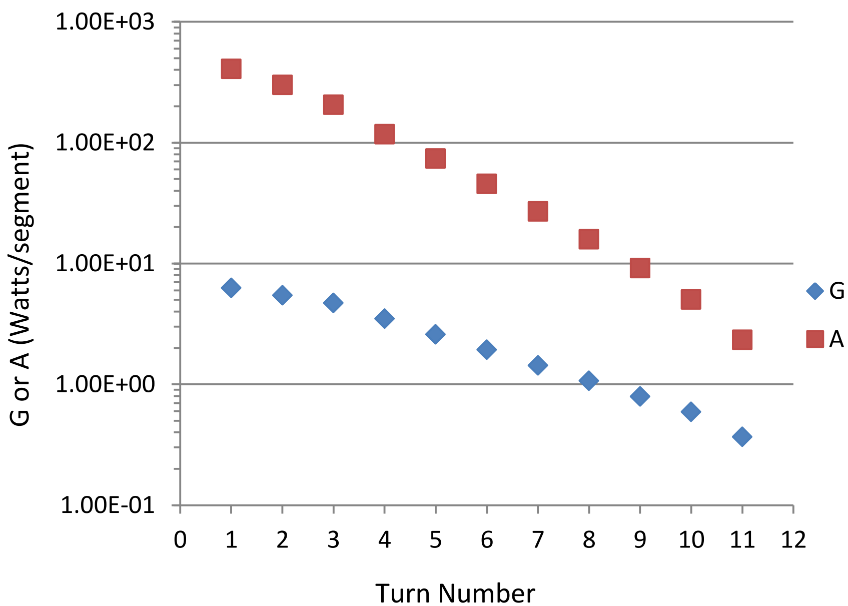


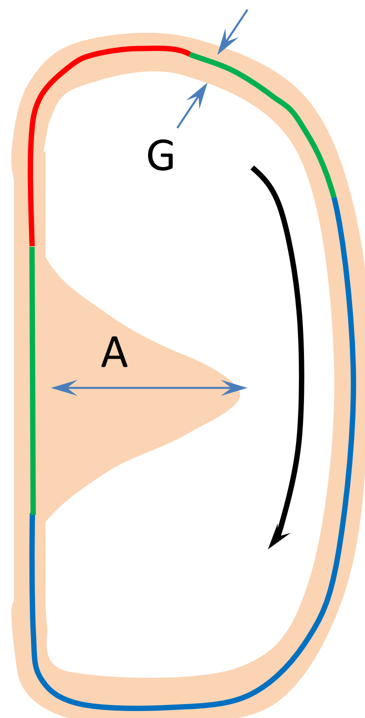
Nuclear Heat Load Scenario



Nuclear Heat Load (NHL) is constant in time during the ON intervals but not uniform in space

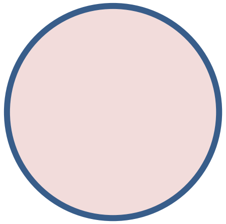
T r = 220 sec per turn
= 2420 sec in total

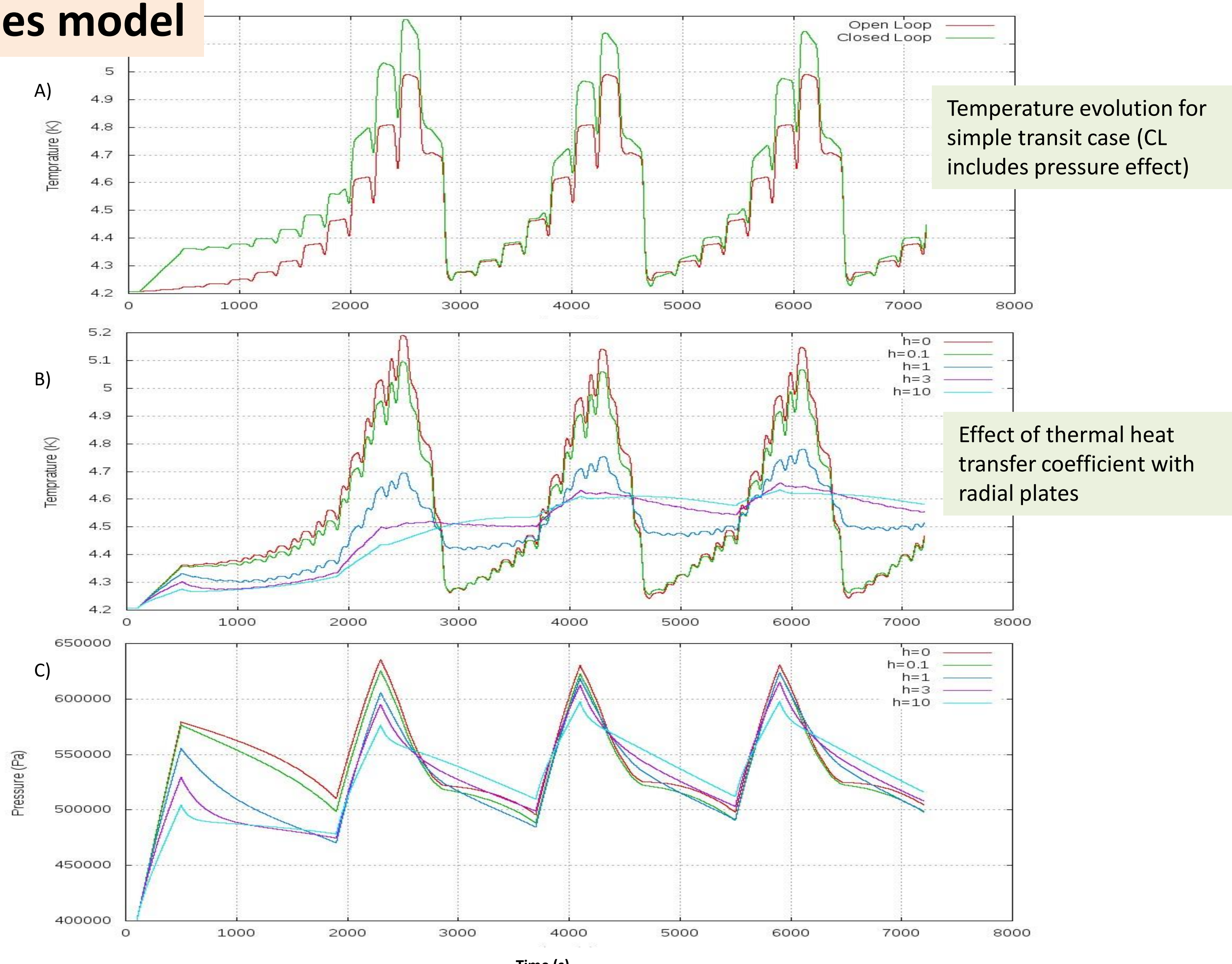




Number of NHL peaks a He particle will transit through during *NHL-ON interval* according to its *position at the moment when NHL turns ON.*

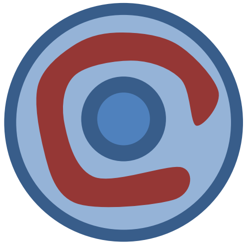
Plain Tubes model



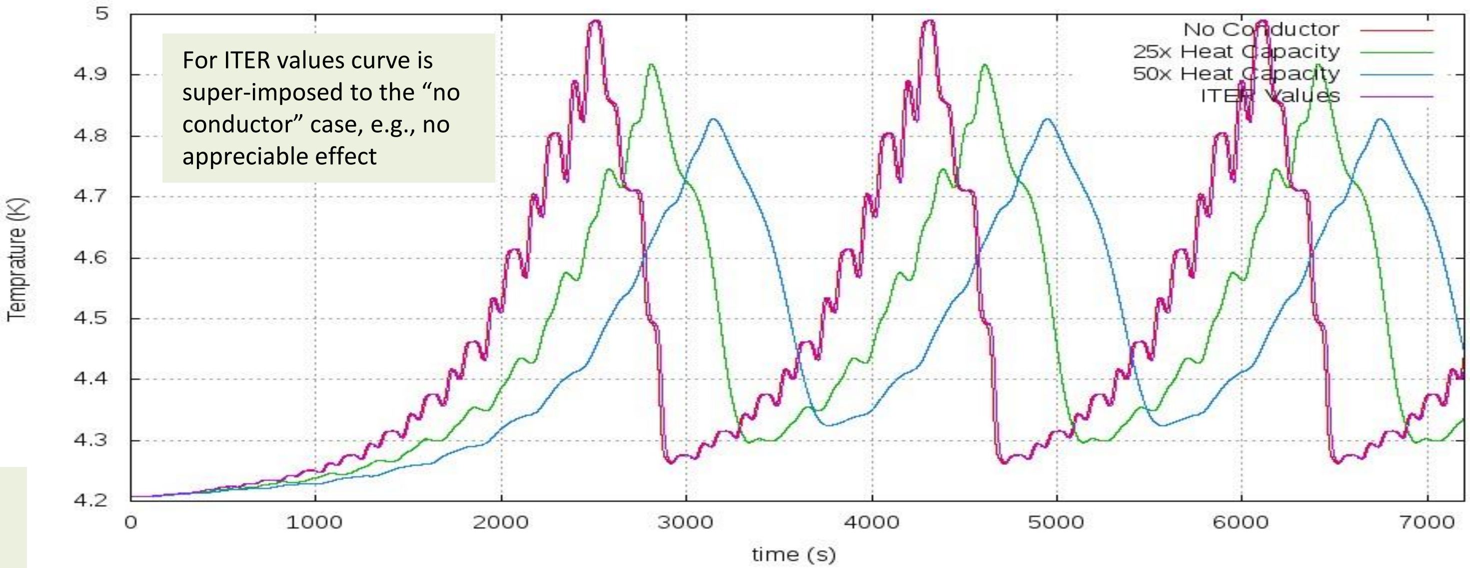


A) Outlet temperature of fluid in the CW winding *with no* heat transfer. B) Outlet temperature of WP collector *with* heat transfer to the radial plates *in closed loop*. C) Pressure evolution in the TF WP when the loop is closed for different values of heat transfer coefficient with RP.

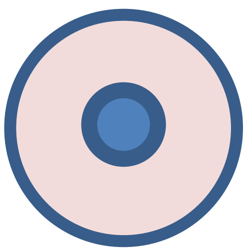
Detailed Tubes model (including segregated conductor)



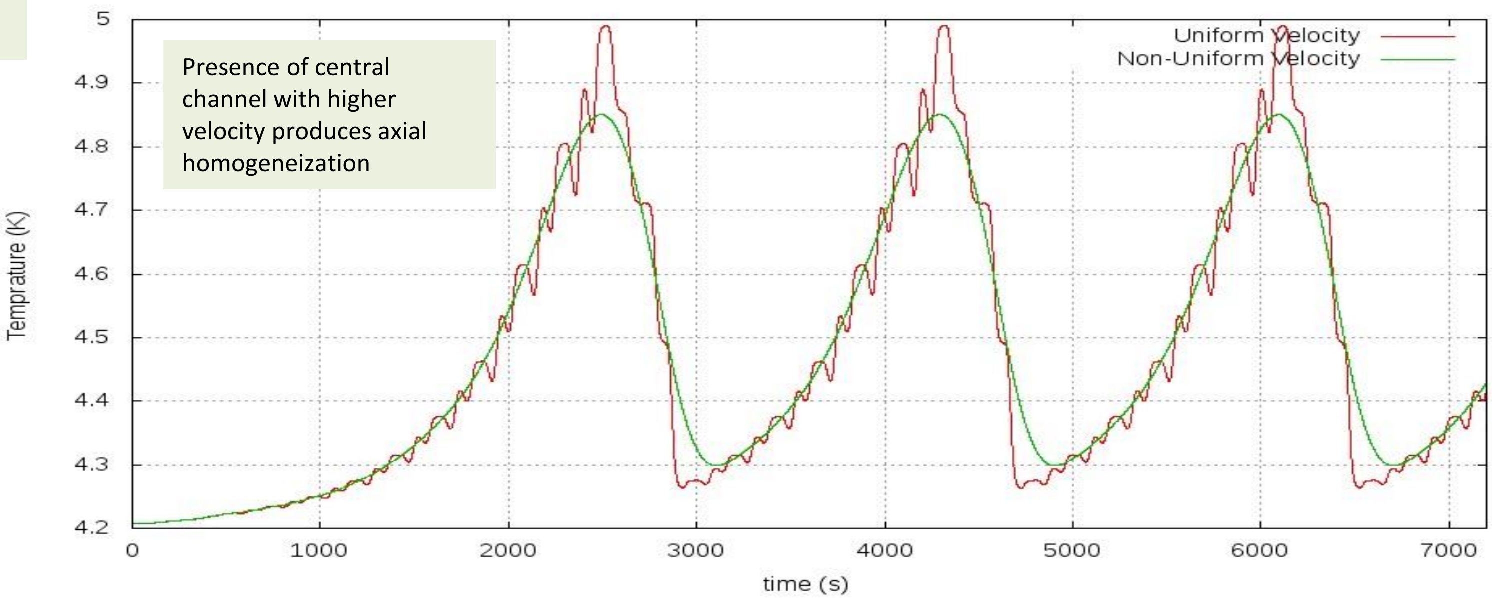
Effect of conductor heat capacity



Heat transfer coefficient with radial plates is 0.



Effect of the central channel with higher velocity

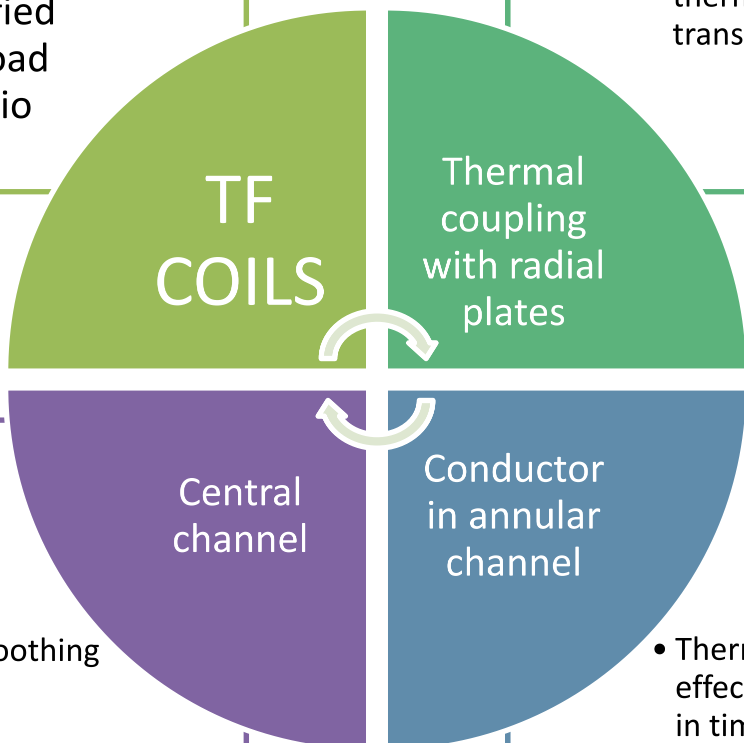


MODEL FEATURE CONCLUSIONS: Relevant features identified(*)

Simulations to identify which model features are sufficient to capture transient

- Analysis of a simplified heat load scenario

- smoothing and thermal inertia transients



- Axial smoothing effect

- Thermal inertia effects resulting in time delay (but NOT for ITER)

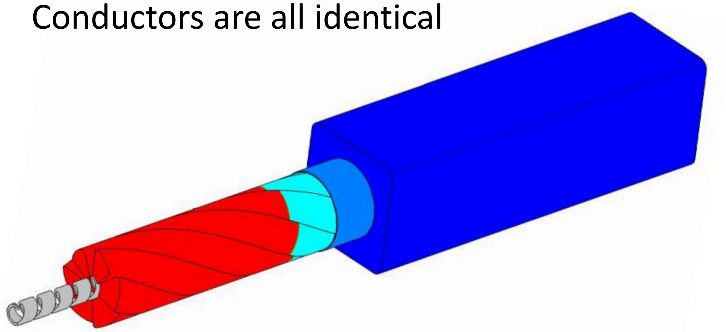
Recommended model for ITER Magnets

Central channel	• Yes • Relevant smoothing effect
Separate lumped element for the conductor	• No • Unstabilizing • Negligible effect
Heat load spatial detail	• Yes, but… • Just per turn

BENCHMARK: The CS Coil

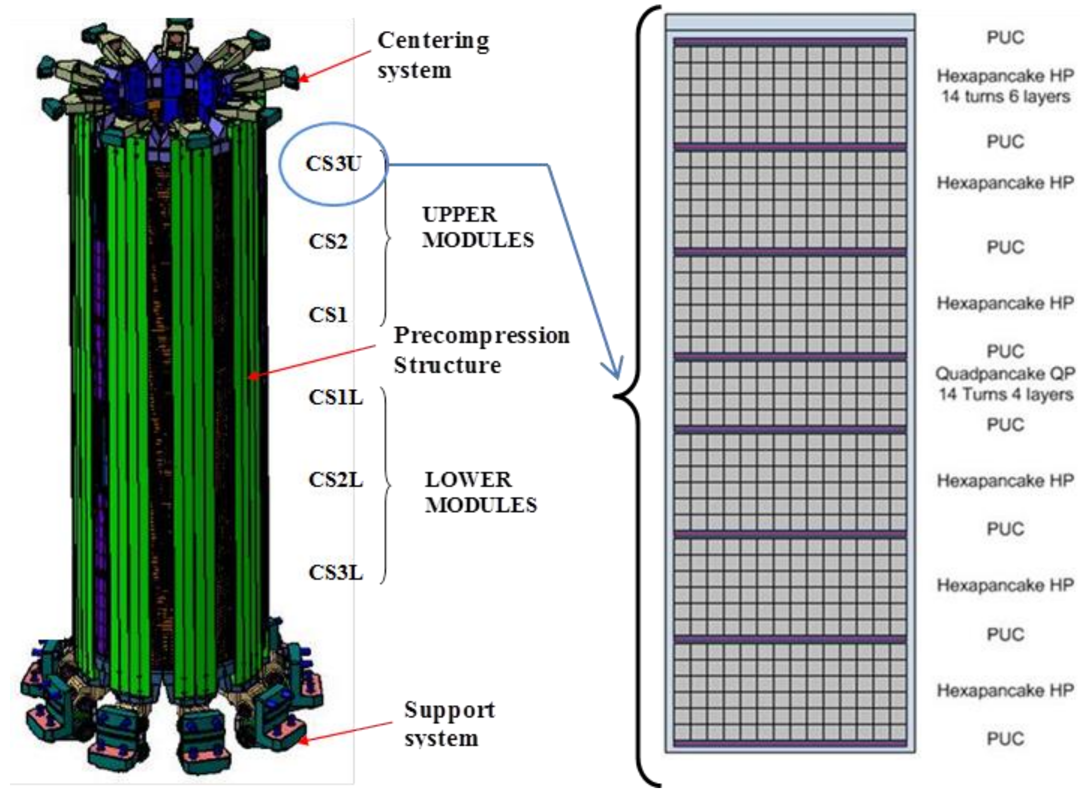
Hydraulically

- Alternate pancakes have alternate flow directions (CW and CCW).
- Fluid inlet is always at the innermost turn of each pancake.
- Each pancake has 14 turns.
- Conductors are all identical



Insulation

- 3.5 mm of insulation on jacket
- Thicker insulation between hexa and quadri-pancakes
- Modules can be considered thermally decoupled, other than just being in parallel fluid circuits

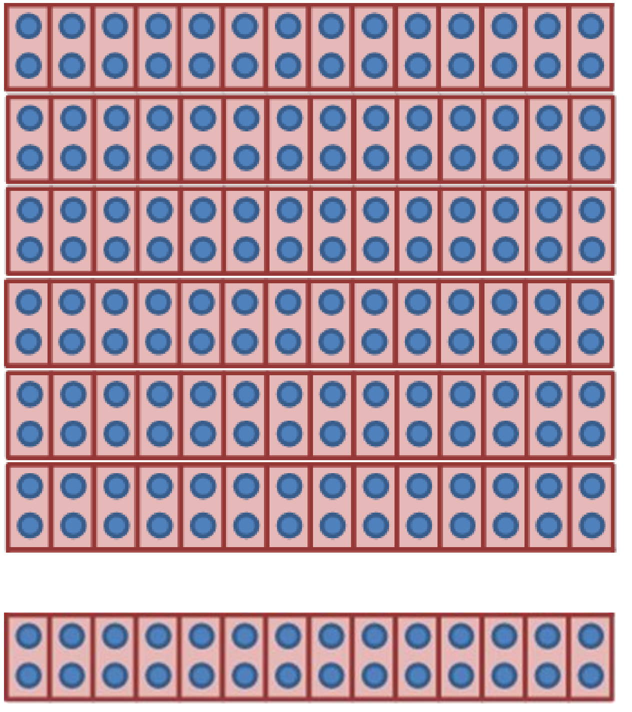


Heat loads on the CS total integrated values are

- **8115.1 kJ conductor AC loss** → Uniform in each turn, stepping in time
- 66.3 kJ ohmic heating in the joints;
- 1.8 kJ AC losses in the joints;
- **2572.3 kJ feeders and cryolines** → Uniform along pipes

Only the two most important sources will be accounted for.

BENCHMARK: The STIMS CS model compared to Vincenta/SuperMagnet



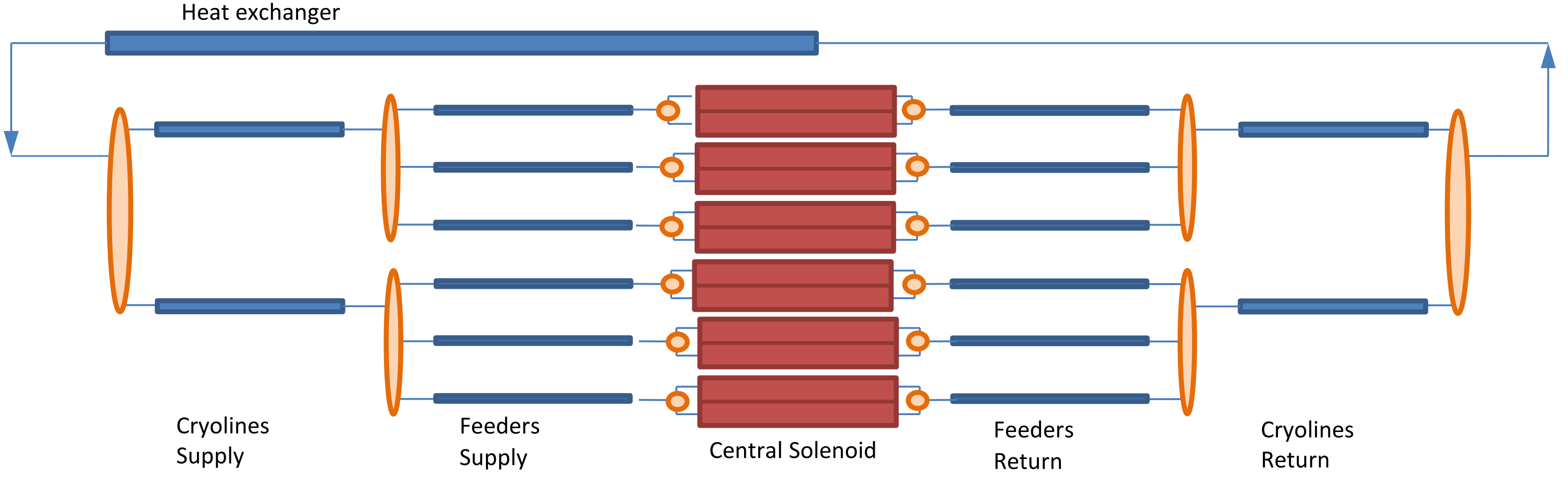
Different turn lengths are considered.
Magnet sliced into 20 elements ('pizza portions').
6-module-model:

- The 40 pancakes of a single module are condensed to only two pancakes, CW and CCW, keeping 6 independent modules.

1-module-model:

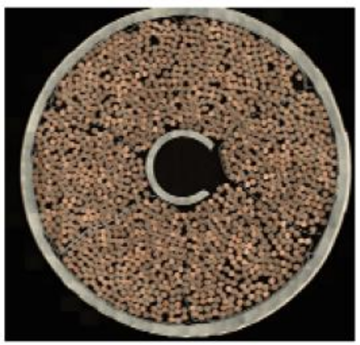
- The 240 pancakes of the 6 modules are condensed to just two pancakes, CW and CCW.

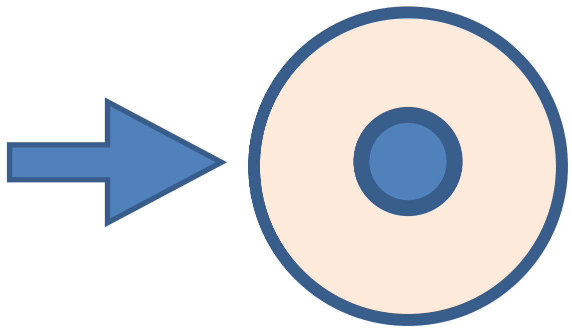
Each pancake has 14 turns, the inlet is at the innermost turn
Heat load time-space profiles condensed accordingly.
Hydraulic network the same as on Vincenta and SuperMagnet models (commercial codes for benchmark).



BENCHMARK: Simulations

- STIMS Mod6: CS with 6 modules
- STIMS Mod1: CS with 1 condensed module

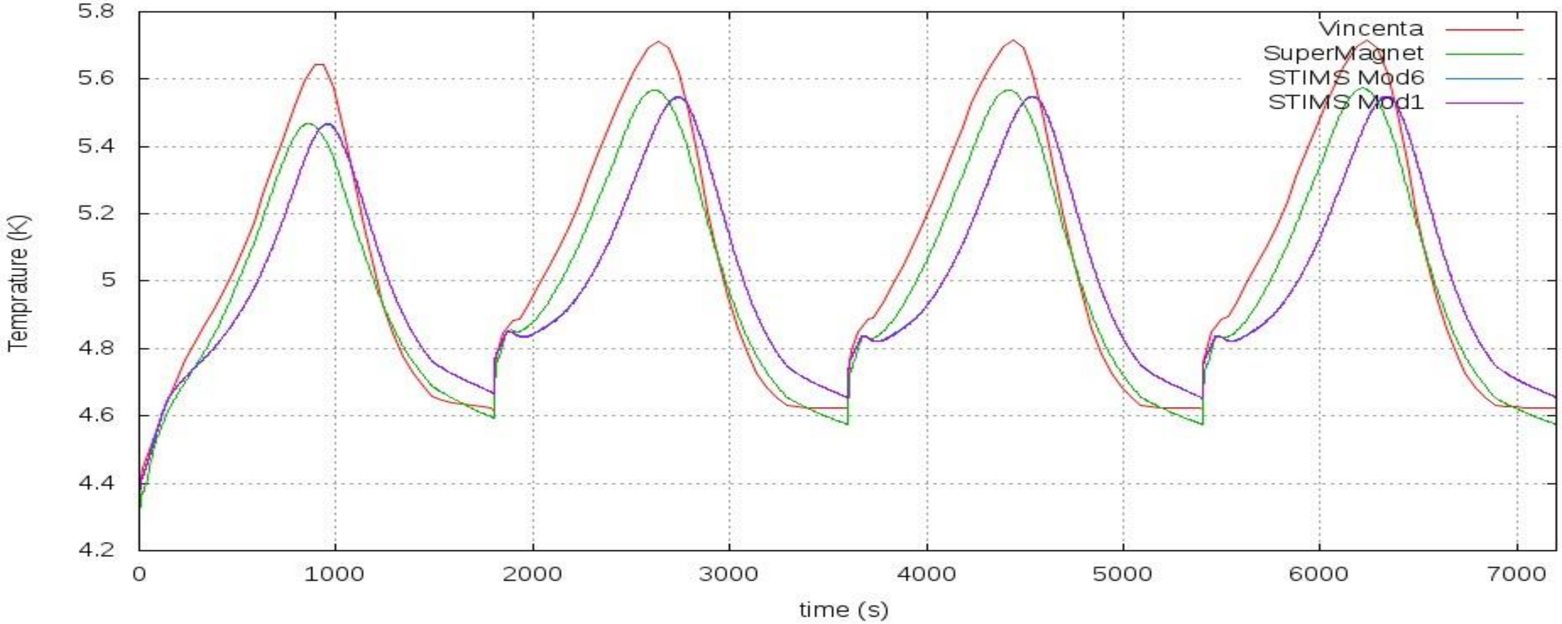




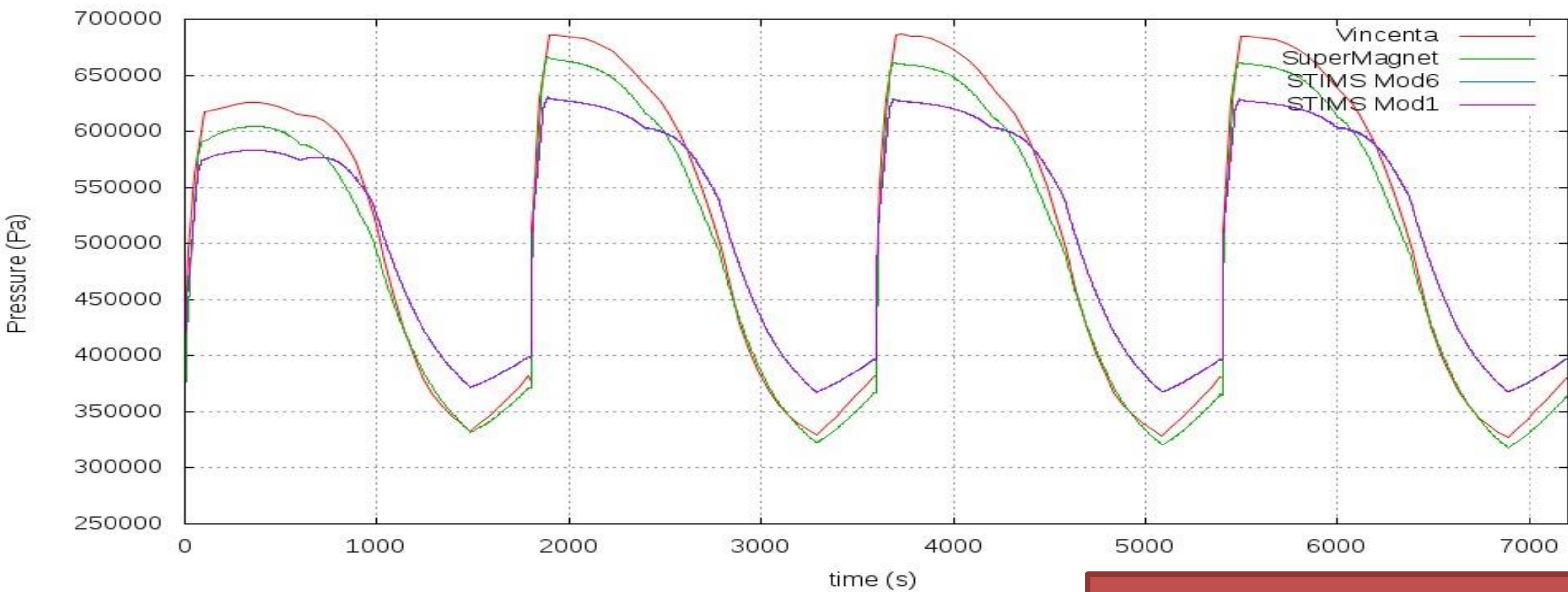
Conductor is represented with an annular space and a central channel. Heat load on the superconducting strands is directly applied on the helium of the annular channel (no metal conductor)

- Vincenta: Model with 240 pancakes and hydraulic network as previous slide.
- SuperMagnet: Model with 240 pancakes and hydraulic network as in previous slide.

Results: Temperature and Pressure



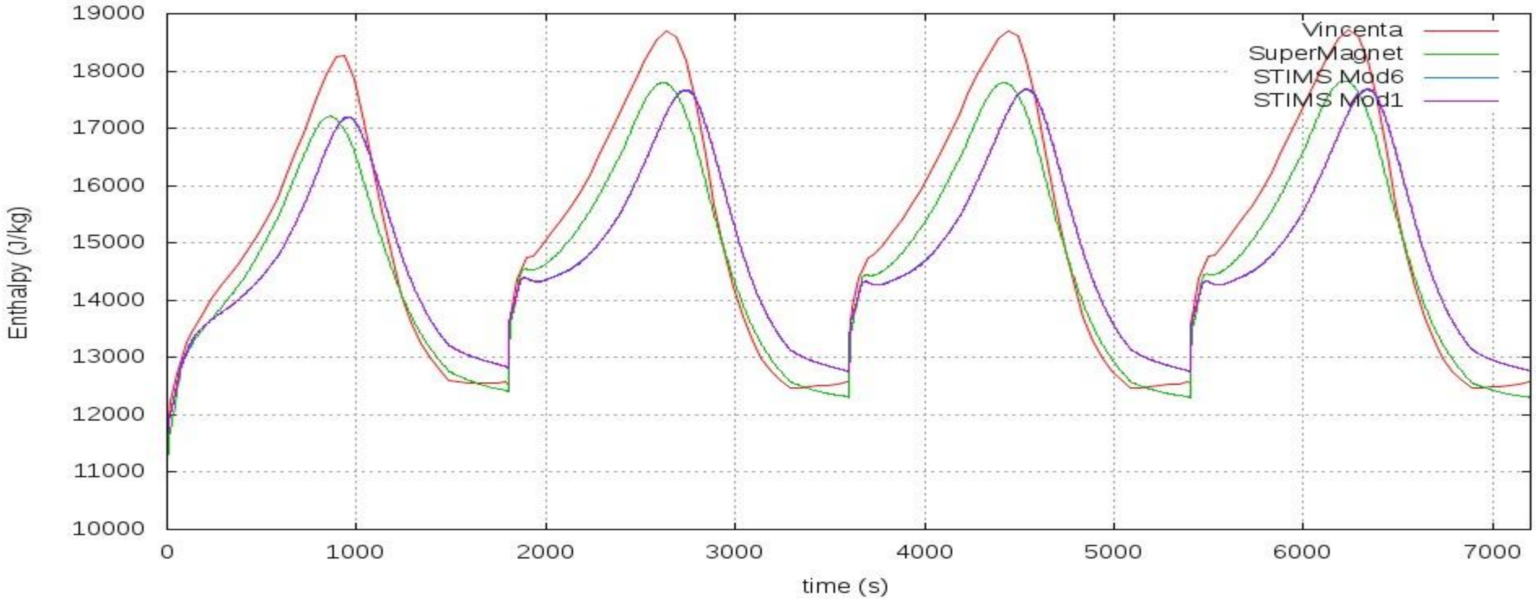
Temperature at the inlet of cryoplant, all models.



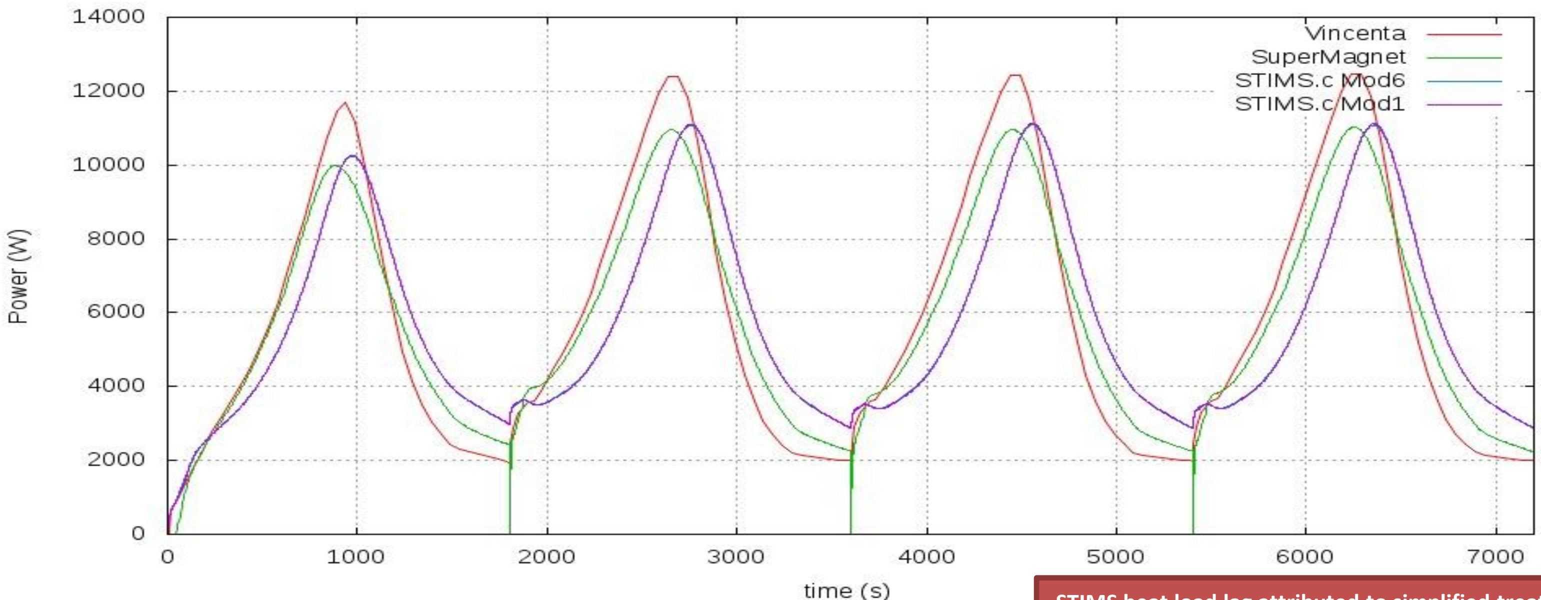
Pressure evolution, all models.

Mod1 and Mod6 are superimposed: Most extreme simplification is adequate (Success !)

Results: Enthalpy and Heat Load on Cryoplant



Enthalpy at the inlet of cryoplant, all models.



Power evacuated at the heat exchanger, all models.

STIMS heat load lag attributed to simplified treatment not capturing x-wise helium density changes, which in turn approximate transit time

BENCHMARK: Summary

- For the simulation of 4 plasma pulses in the CS coil system:

	Maximum Time (sec)			Maximum Value (Temperature K)			Heat evacuated in HX (MJ)		
	Vincenta	SuperMagnet	STIMS	Vincenta	SuperMagnet	STIMS	Vincenta	SuperMagnet	STIMS
Pulse 1	915	860	958	5.63	5.46	5.46	9.28	9.11	9.46
Pulse 2	2640	2615	2735	5.71	5.56	5.54	10.83	10.66	10.73
Pulse 3	4440	4415	4535	5.71	5.56	5.55	10.88	10.60	10.69
Pulse 4	6240	6225	6335	5.71	5.56	5.55	10.90	10.64	10.69

- STIMS obtains the cryoplant heat load to well within ~ 1% with respect to the more accurate models, the temperature peak to within 0.01K w.r.t. SuperMagnet and 0.15K w.r.t. Vincenta, with the peak lagging ~ 100 sec w.r.t. to the other models
- STIMS simulates these 4 pulses in ~ 2 minutes of CPU versus ~ 2 days runtime
- STIMS accomplishes the objective of accurately capturing the dynamics of heat loads/magnet response/cryoplant load without concern to magnet internal temperature distributions, and does it with 3 orders of magnitude less computational effort

Summary and conclusion

STIMS

- Model implemented and programmed in C
- Successive improvements
  - Physical representation, memory consumption, running time
  - Model uses minimal features to capture thermal-fluid transient rather than attempt to model every physical detail (e.g., parallelization of flow channels at the model level)

Physical key features study

- Implementation of TF Coils with nuclear heat load scenario.
- Influence of thermal coupling between elements
- Influence of detailed model for conductor tubes
  - Presence of conductor – not needed
  - Central channel - needed

Benchmarking

- CS Coil simulations with Vincenta and SuperMagnet detailed codes have shown that simplified models can reproduce the magnet thermal transient behavior (cryoplant load) with:
- ~ 1% accuracy in heat load, ~ 0.15K discrepancy in the worst case (0.01K w.r.t. SuperMagnet)
  - <100 seconds peaking time discrepancy, (in 1800 sec plasma pulse cycle)
  - Less than a thousandth of the computational effort (for a full plasma multi-pulse simulation CPU time cut from days to minutes)

Project objectives successfully met