Simulation of the Operation of the ITER Coils using a Domain Decomposition Method

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the way to new energy

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HORIZON TECHNOLOGIES

Outline

- A domain decomposition ?
- Practical implementation
- The ITER CS coil – a test problem
- Other results and further work
    - ITER PF coils
    - ITER TF coils
- Summary and perspective

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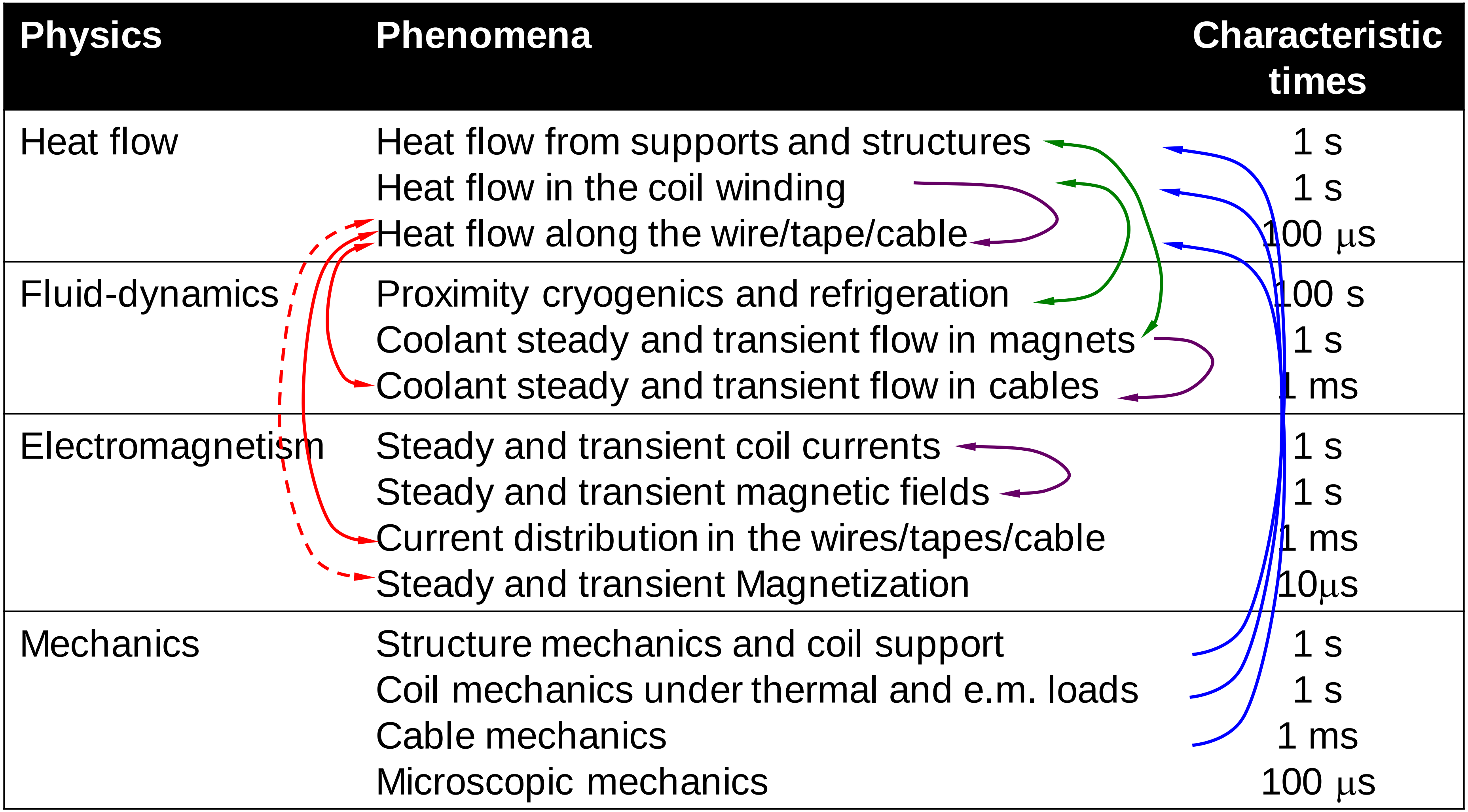
http://en.wikipedia.org/wiki/Domain_decomposition_methods

Sigh…

Domain Decomposition

- […] domain decomposition methods solve a boundary value problem **by splitting it into smaller boundary value problems** on subdomains and **iterating to coordinate the solution** between adjacent subdomains […] which makes domain decomposition methods **suitable for parallel computing**

The physics domains



Physics	Phenomena	Characteristic times
Heat flow	Heat flow from supports and structures	1 s
	Heat flow in the coil winding	1 s
	Heat flow along the wire/tape/cable	100 μs
Fluid-dynamics	Proximity cryogenics and refrigeration	100 s
	Coolant steady and transient flow in magnets	1 s
	Coolant steady and transient flow in cables	1 ms
Electromagnetism	Steady and transient coil currents	1 s
	Steady and transient magnetic fields	1 s
	Current distribution in the wires/tapes/cable	1 ms
	Steady and transient Magnetization	10μs
Mechanics	Structure mechanics and coil support	1 s
	Coil mechanics under thermal and e.m. loads	1 s
	Cable mechanics	1 ms
	Microscopic mechanics	100 μs

Which decomposition ?

- Different **physics domains** are strongly coupled on comparable time scales
- Geometric proximity (**space domains**) and difference of characteristic times (**time scale domain**) are more suitable for a domain decomposition
- The *building bricks* are attacking different sets of combined physics on physically coherent objects

The physics domains

Physics	Phenomena	Characteristic times
Heat flow	Heat flow from supports and structures HEATER	1 s
	Heat flow in the coil winding	1 s
	Heat flow along the wire/tape/cable	100 μs
Fluid-dynamics	Proximity cryogenics and refrigeration	100 s
FLOWER	Coolant steady and transient flow in magnets	1 s
	Coolant steady and transient flow in cables	1 ms
Electromagnetism	Steady and transient coil currents POWER	1 s
	Steady and transient magnetic fields	1 s
THEA	Current distribution in the wires/tapes/cable	1 ms
	Steady and transient Magnetization M’C	10μs
Mechanics	Structure mechanics and coil support	1 s
	Coil mechanics under thermal and e.m. loads	1 s
	Cable mechanics	1 ms
	Microscopic mechanics	100 μs

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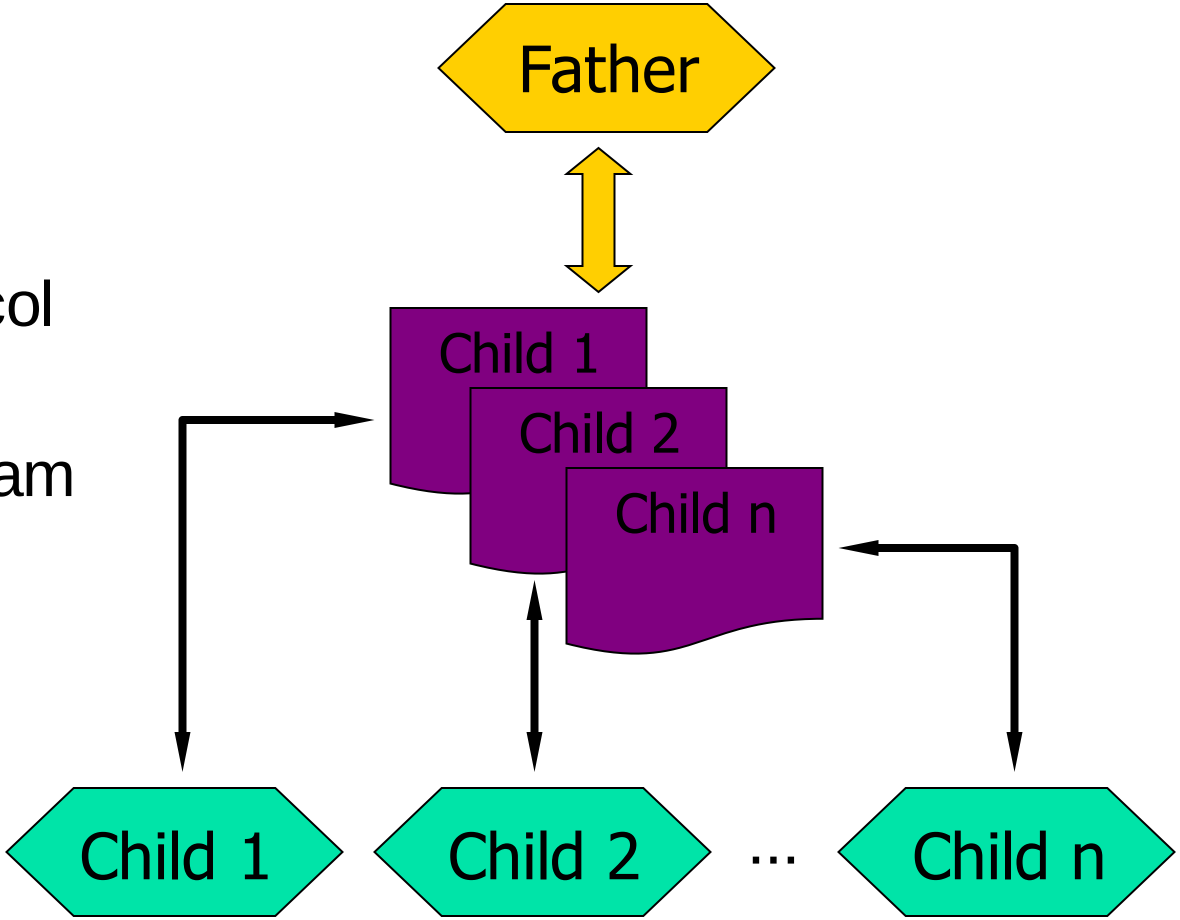
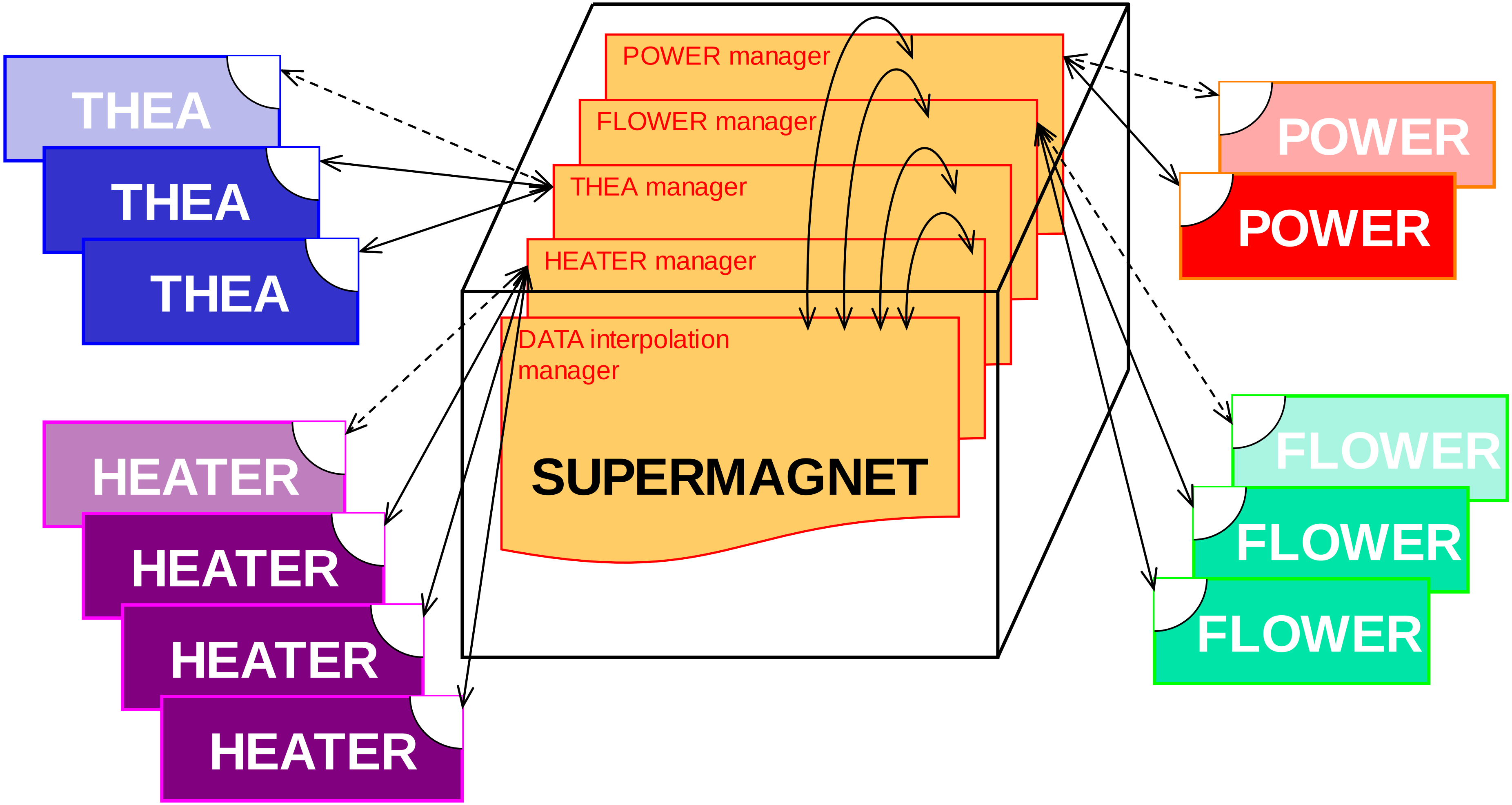
Implementation

- Link independent simulation processes (children) through a communication protocol for data exchange
- A single master program (father) manages generation of each process, synchronization, and communication



Father **and** ***Child*** **processes is a concept borrowed from unix**

Overall structure



THEA

THEA

THEA

HEATER

HEATER

HEATER

HEATER

POWER manager

FLOWER manager

THEA manager

HEATER manager

DATA interpolation manager

SUPERMAGNET

POWER

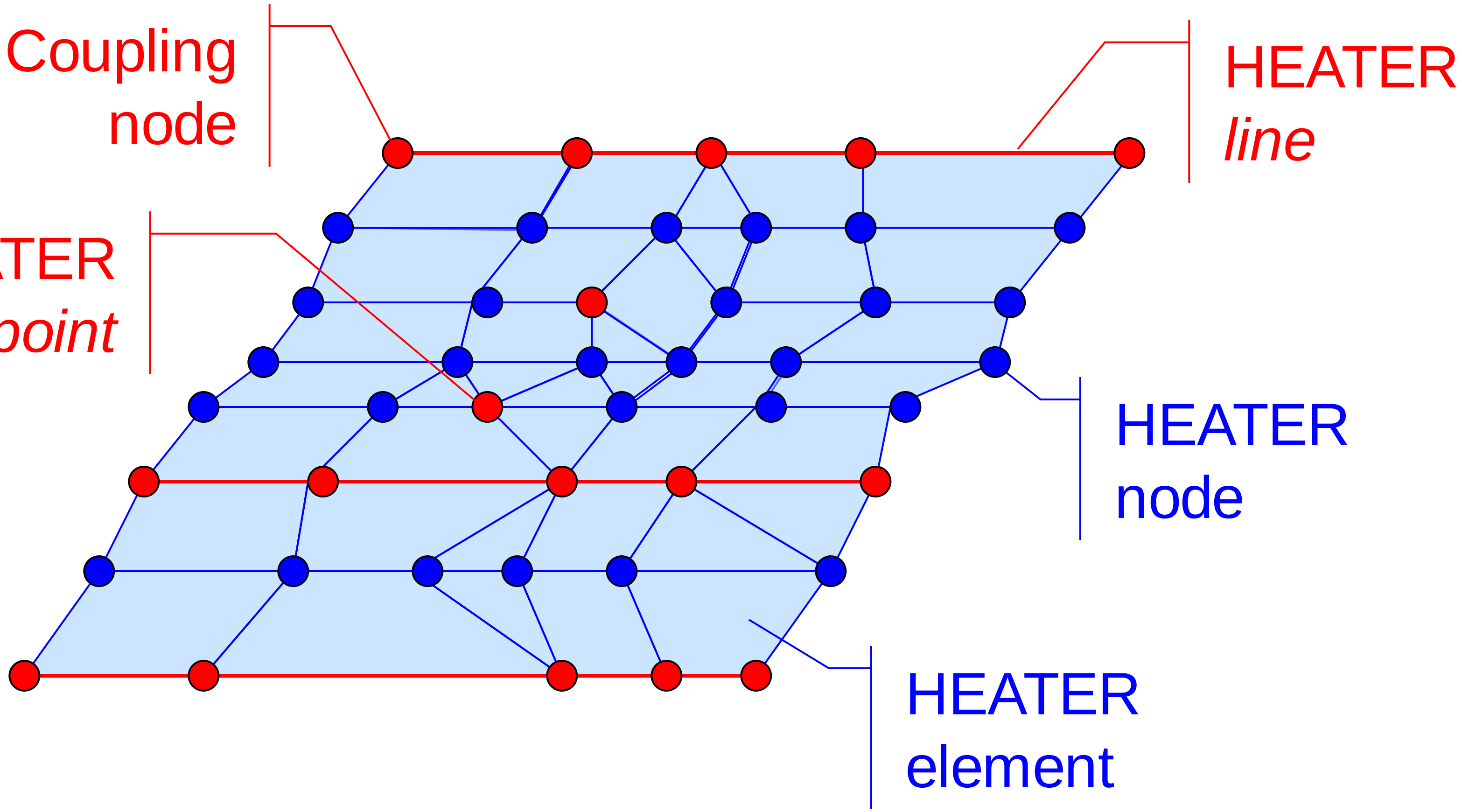
POWER

FLOWER

FLOWER

FLOWER

Sample coupling – 1/2



Coupling node

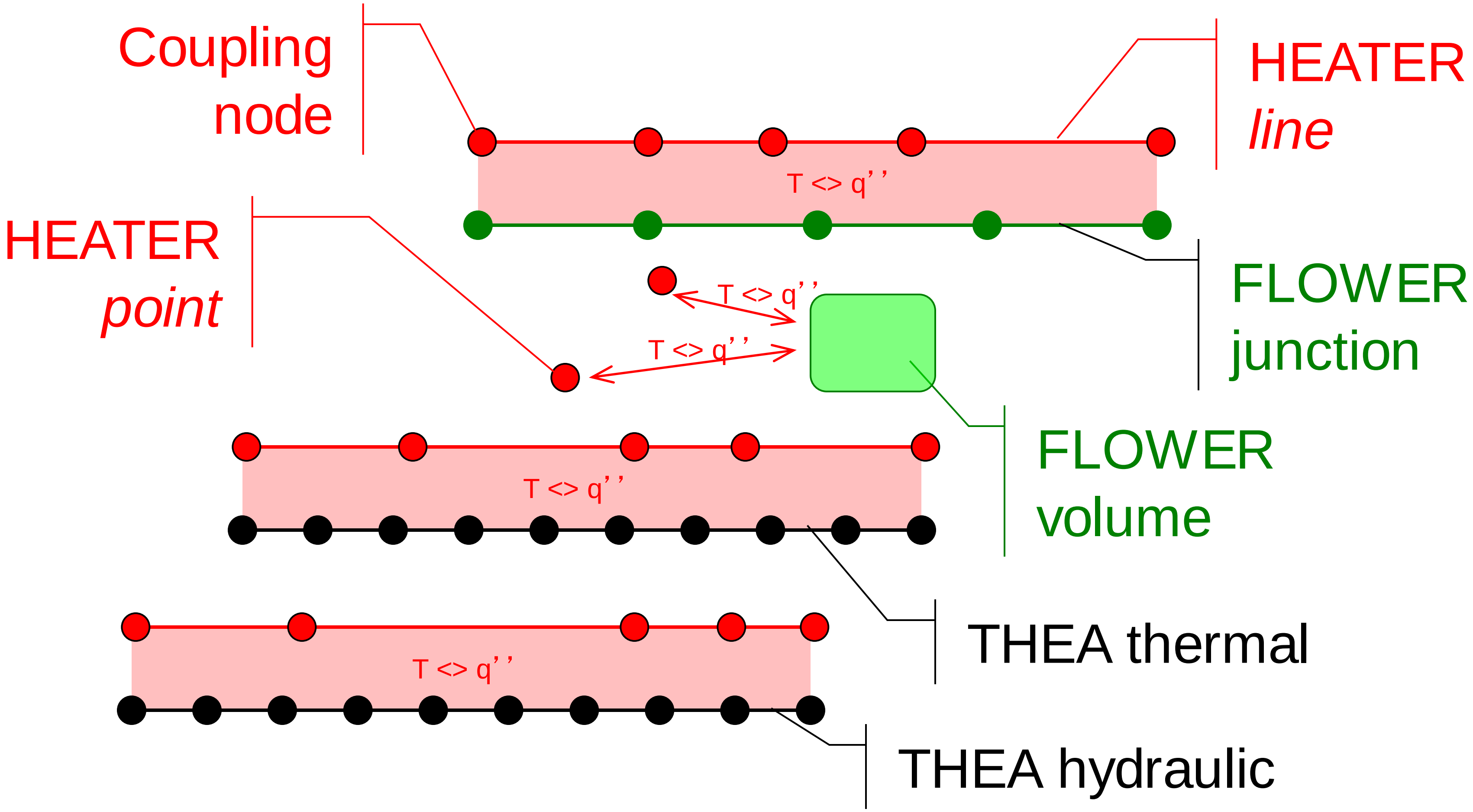
HEATER *line*

HEATER *point*

HEATER node

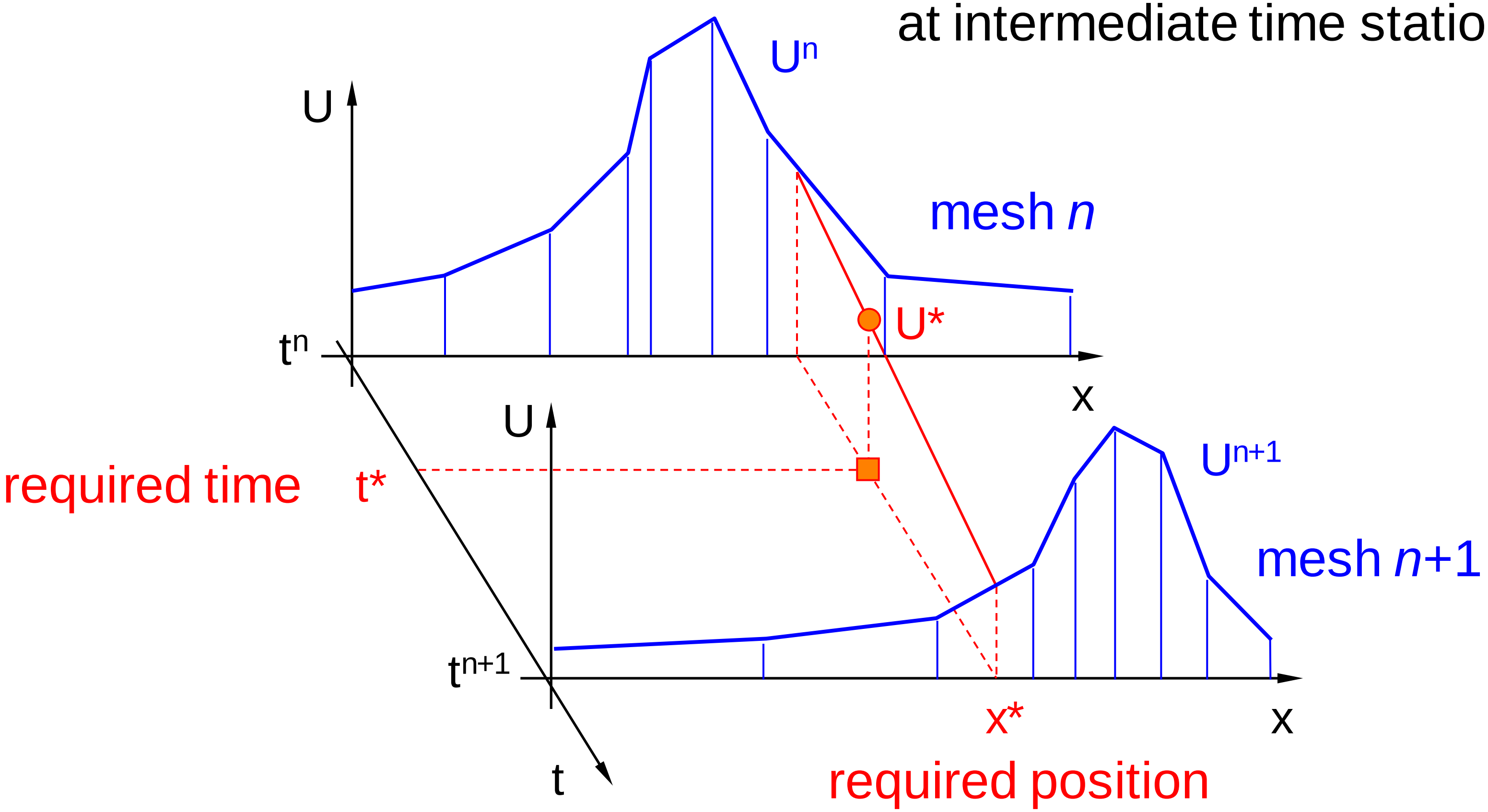
HEATER element

Sample coupling – 2/2



Data interpolation

- Linear interpolation of *point* results in time to exchange data at intermediate time stations
- Bi-linear interpolation of *line* results in space **and** time to exchange data between different meshes and at intermediate time stations



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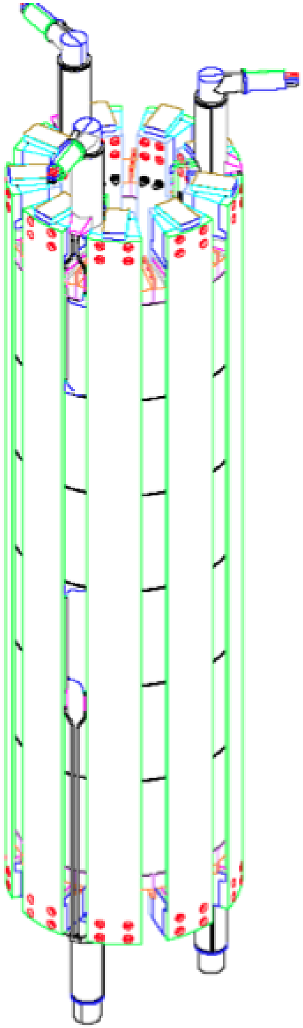
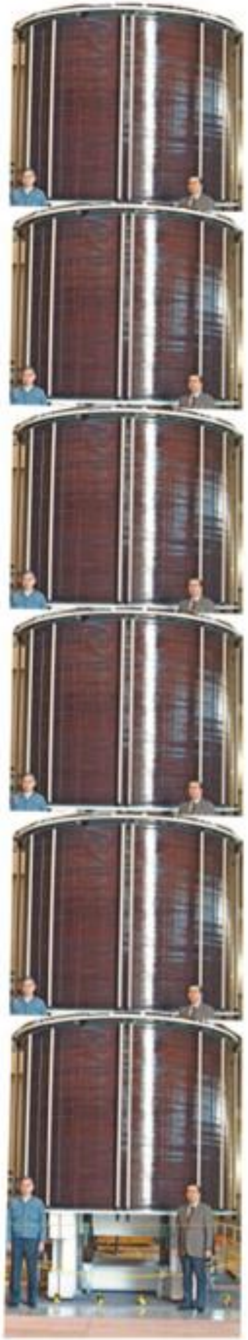
The ITER CS

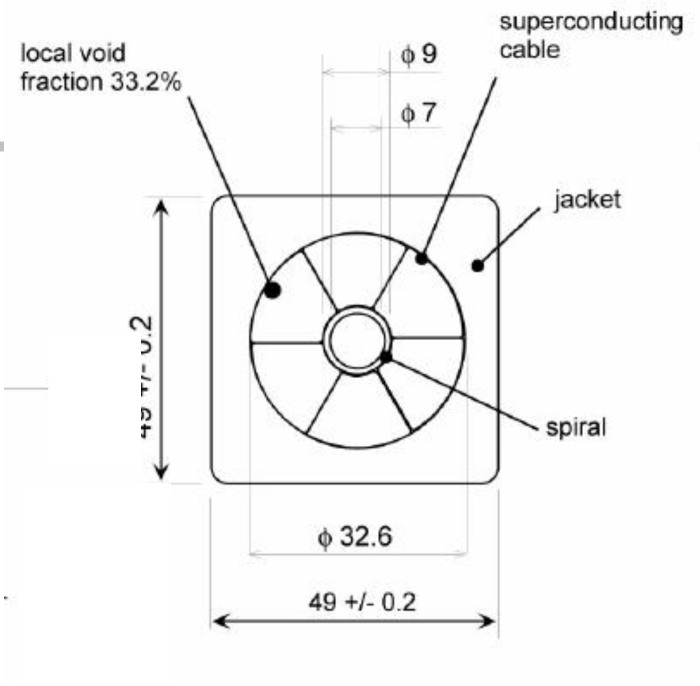
- Winding pack (WP) consisting of 240 pancakes
- cold mass: 700 t
- cooling path (one pancake): 150m
- supply/return feeders from CTB to WP: 53m
- 4 main cryolines CTB to ACB: 40m, 95m
- Circulator (pump): 2 kg/s
- Heat exchanger: 4.2K





CS conductor

Cable Pattern	(2sc+1cu)x3x4 x4x6
Central spiral	9 x 7 mm
Petal SS wrap	0.05 mm thick, 70% cover
Cable SS wrap	0.08 mm thick, 40% overlap
Strand Diameter (mm)	0.83
Sc strand Cu:nonCu Ratio	1.0
Number of SC Strands	576
Void Fraction (%) in Annulus	33.2
Cable diameter (mm)	32.6
Jacket dimension (mm)	Circle in square 49.0 x 49.0

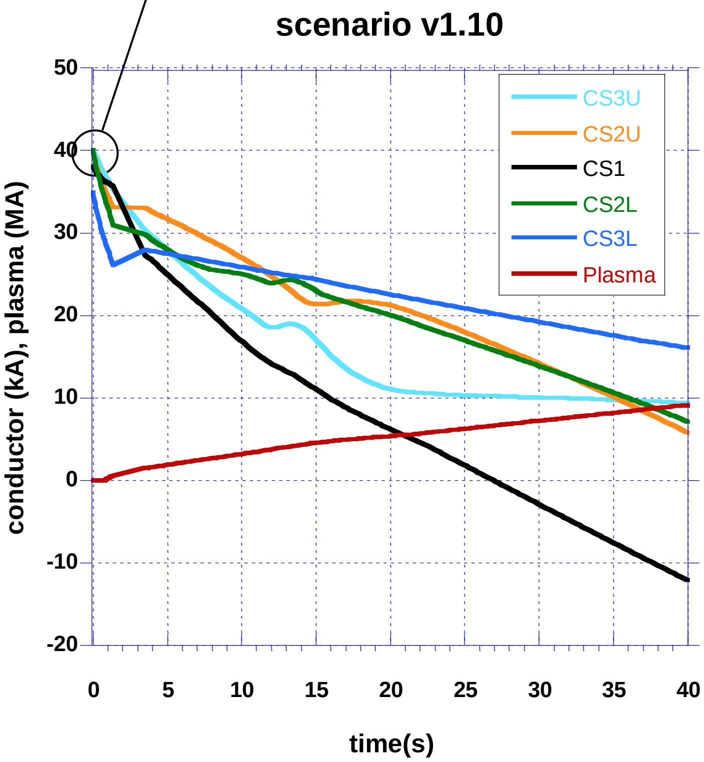


CS CICC originally designed for operating at 40 kA, 13T, 4.5K with a T margin higher (or equal) to 0.7K

Copper content sufficient to limit the hot spot temperature below 150K in case of fast discharge of 7.5 s time constant triggered by a quench

15 MA Scenario v1.10
Conductor current

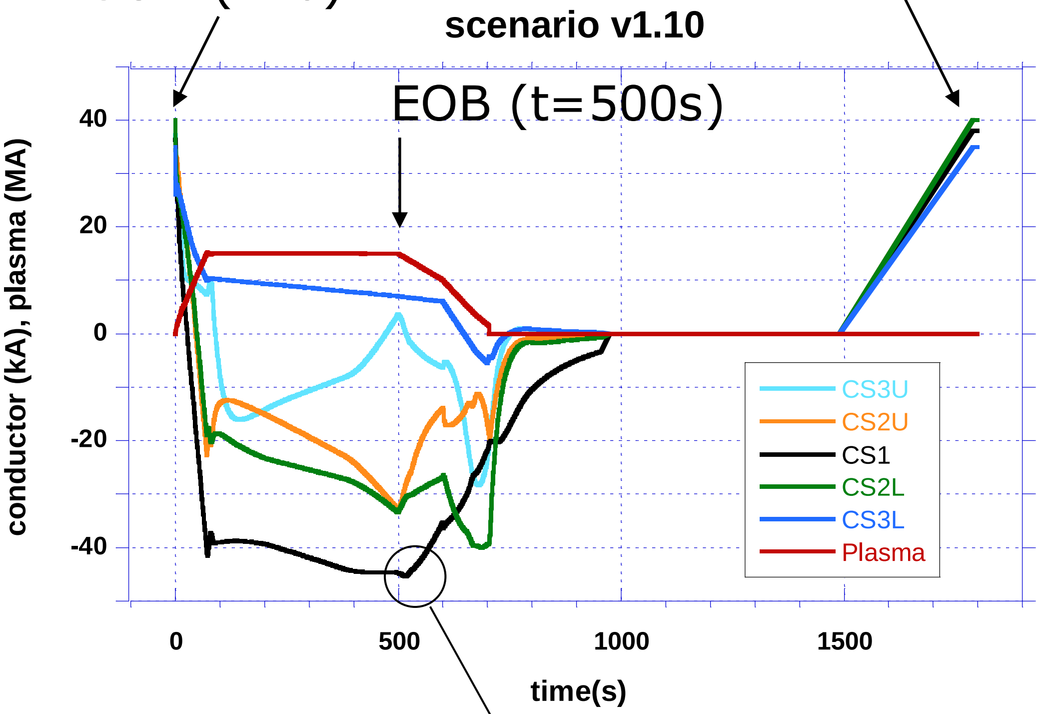
40.0 kA at SOD



End of Rebias (t=1790s)

SOD (t=0)

EOB (t=500s)



45.4 kA at 516s

15 MA Scenario v1.10

Magnetic field and strain

B map and Strain map are established from the conductor current and the coil layout. Peak values of I, dI/dt, B, dB/dt are generally not coincident in time, space

I, B operating window

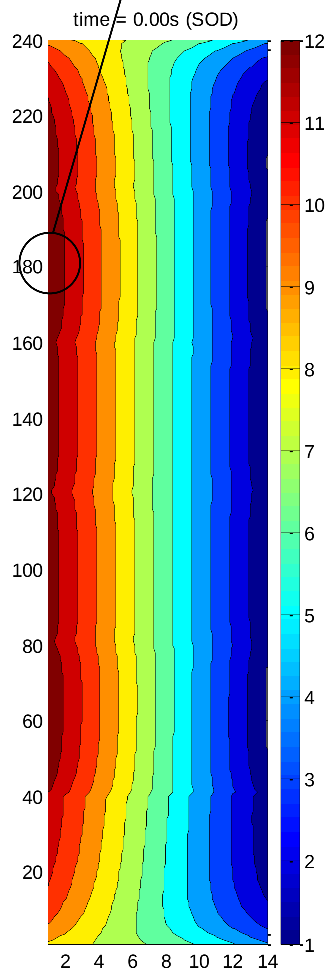
	CS3U	CS2U	CS1U	CS1L	CS2L	CS3L
Imax (kA)	40.00	40.00	38.05	38.05	40.00	34.85
Imin (kA)	-28.33	-32.90	-45.41	-45.41	-40.01	-5.52
dI/dtmax (kA/s)	0.87	0.59	0.30	0.30	1.52	0.86
dI/dtmin (kA/s)	-3.79	-6.78	-3.89	-3.89	-8.08	-8.04
Bpeak (T)	12.59	12.96	12.62	12.61	12.87	11.77
dB/dtmax (T/s)	0.14	0.26	0.27	0.37	0.37	0.21
db/dtmin (T/s)	-1.50	-1.73	-1.29	-1.45	-2.13	-2.11

Local Strain IxB dependence is included (derived from TFJA4 test at 1000 cycles)

ε (%) = -0.74 – 1.3 e-4 BI with I (kA), B(T)

Potential benefit of the hoop strain not included

40 kA, 12.96 T



Contour plot of Bpeak a SOD

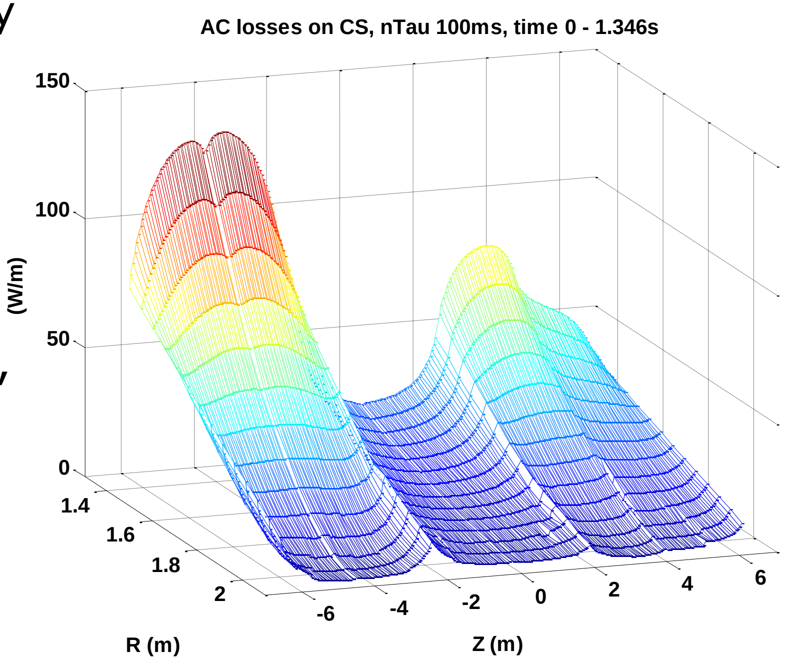
15 MA Scenario v1.10
AC loss

Consider (Jc, Qhyst) of strands selected for the CS conductor (e.g. Hitachi)

Two approaches for coupling losses: models by E. Zapretilina https://user.iter.org/?uid=2FVJB7

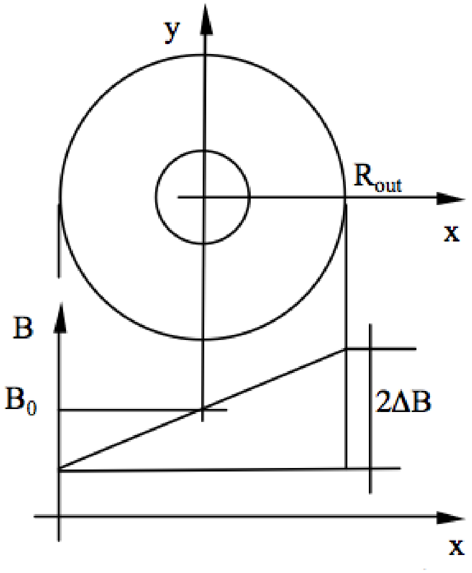
- Single time constant model (conservative), nTau = 100ms, Qcoupl 60%, Qhyst 40% - **8.1 MJ** total losses

- Varying time constant model (most realistic), saturation completed at cycle nr 10,000 Qcoupl 40%, Qhyst 60% - **6.4 MJ** total losses



Self field effect

$$E(x,y) = E_0\left(\frac{J_{op}}{J_C\left(B(x,y),T,\varepsilon\right)}\right)^n \qquad B(x,y) = B_0 + \frac{\Delta B}{R_{out}}x$$



$$\bar{E} = \frac{1}{A}\int_A E(x,y)\,dA = \frac{1}{A}\int_A E_0\left(\frac{J_{op}}{J_C\left(B(x,y),T,\varepsilon\right)}\right)^n dA$$

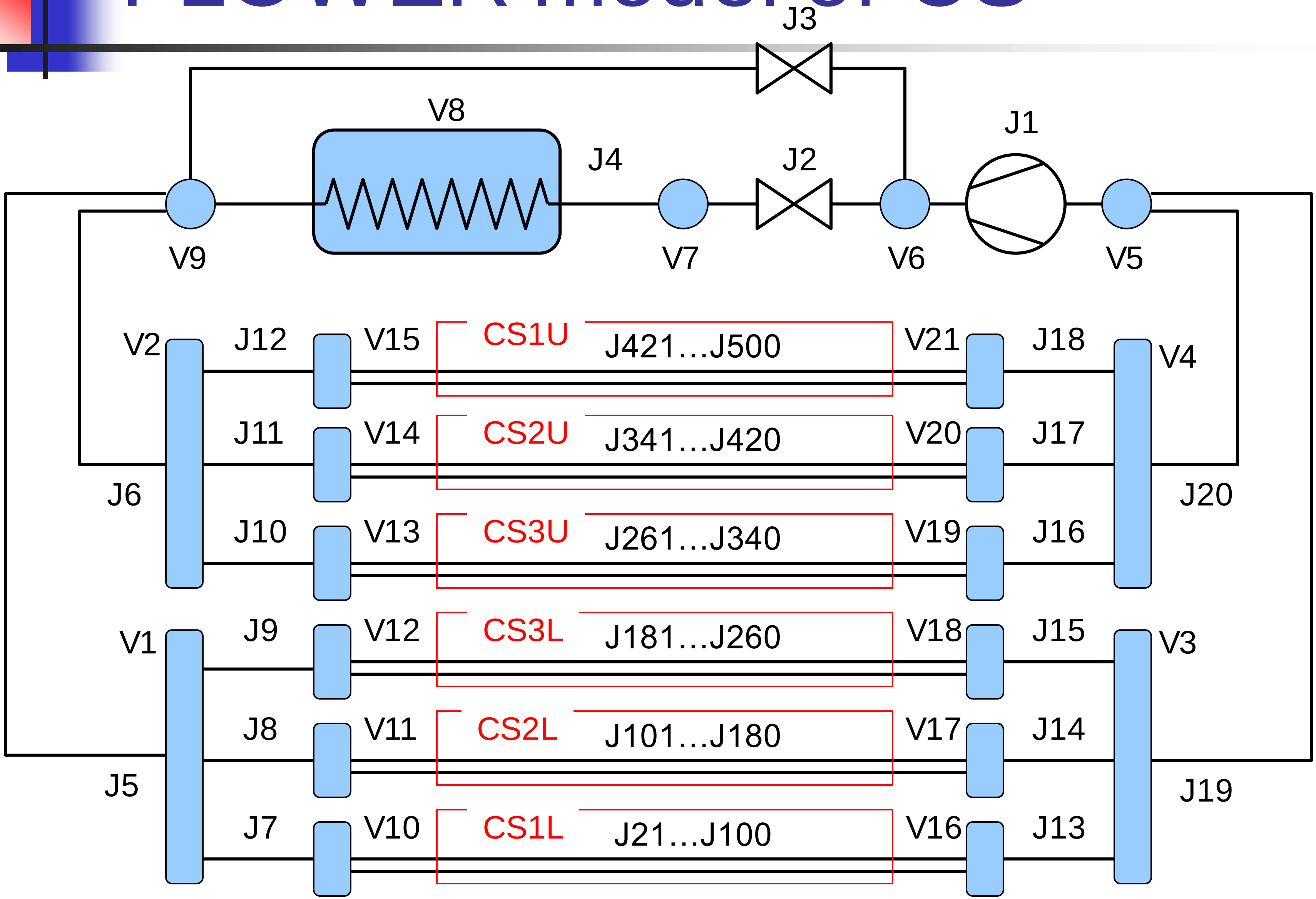
Definition of B_{eff}

$$E_0\left(\frac{J_{op}}{J_C\left(B_{eff},T,\varepsilon\right)}\right)^n = \bar{E}$$

1. compute: $\bar{J}_C = \dfrac{J_{op}}{\left(\dfrac{\bar{E}}{E_0}\right)^{1/n}}$

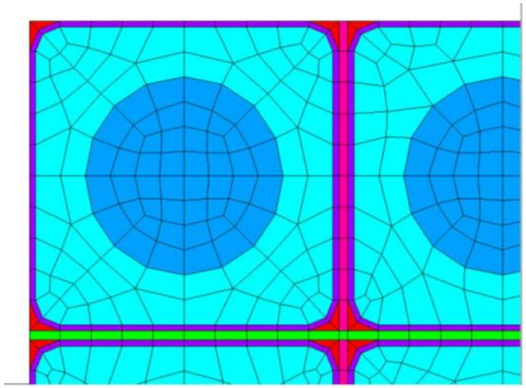
2. solve iteratively: $J_C\left(B_{eff},T,\varepsilon\right) = \bar{J}_C$

FLOWER model of CS

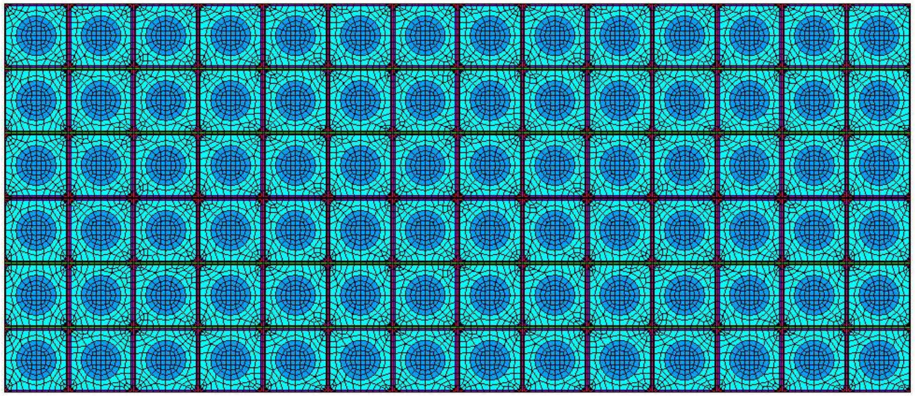


Thermal meshing issues

- The typical “mechanical” mesh requires a relatively fine level of detail (mm) to capture large gradients in stress/strain

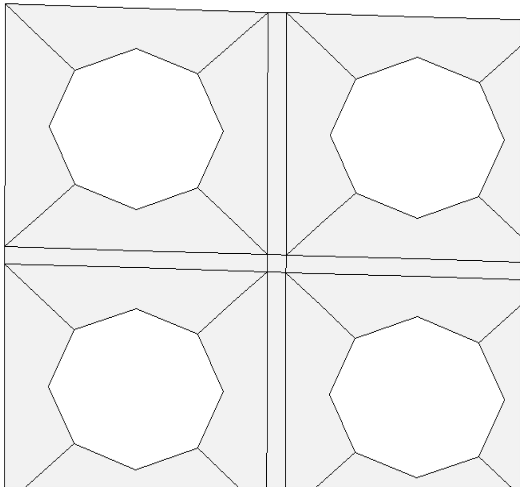


- This level of detail (about 10000 elements per x-section !) is not practical for the thermal analysis

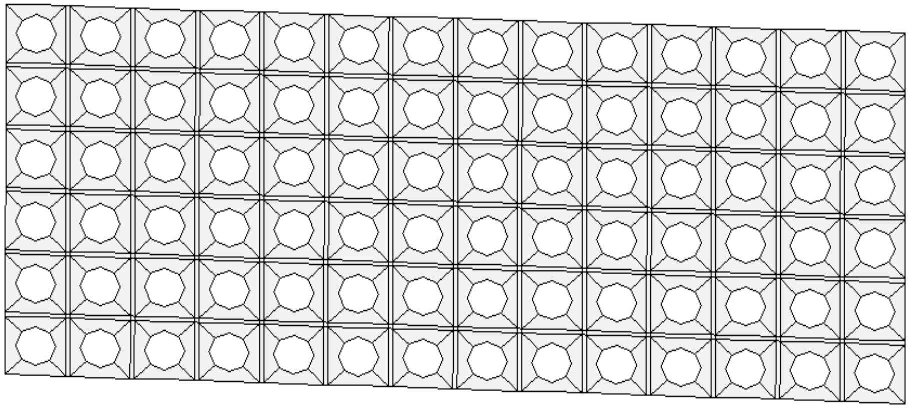


Typical *maximal* mesh

- The “thermal” mesh required is much coarser for the type of system-scale analysis targeted

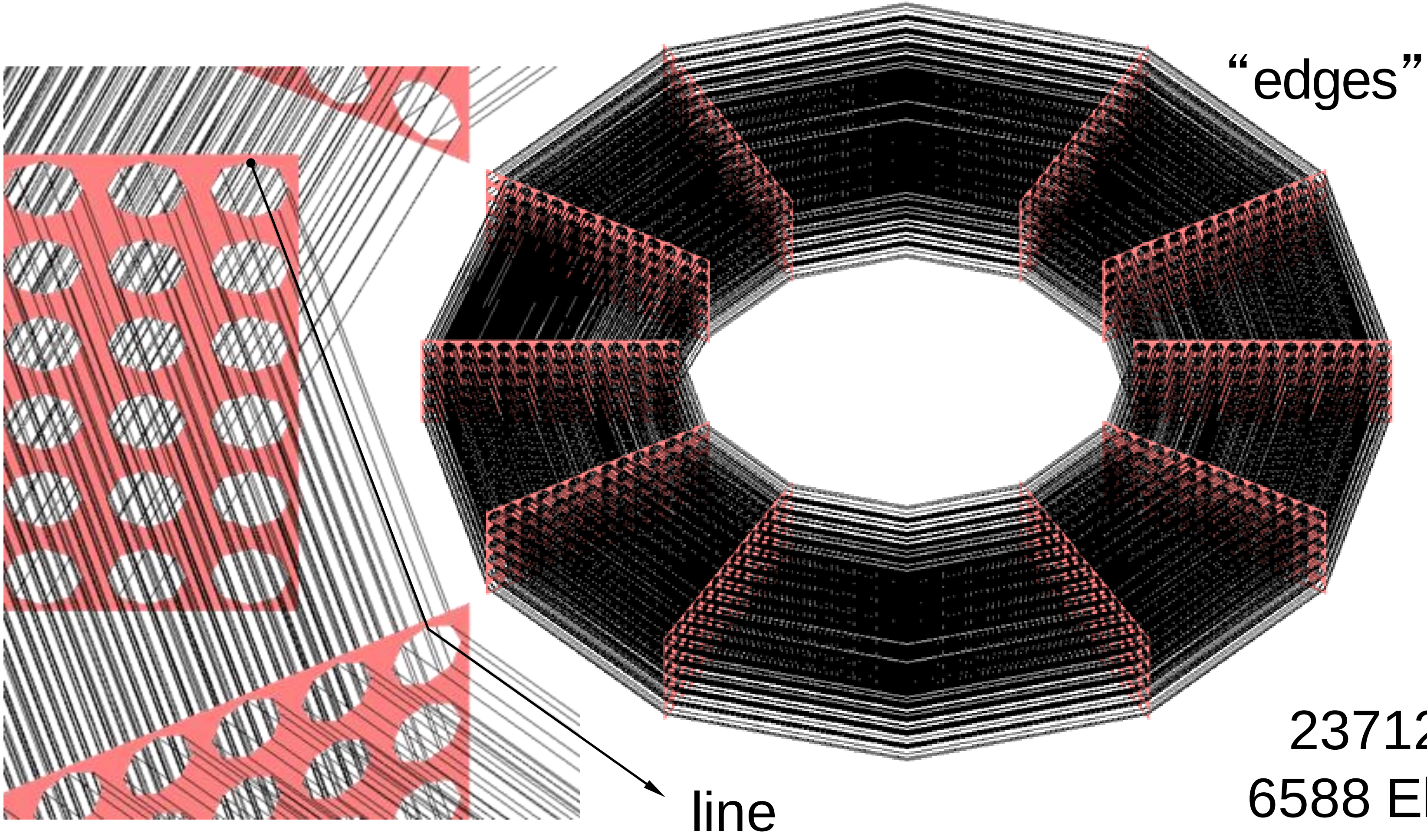


- This is the maximum level of detail recommended (about 500 elements per x-section)



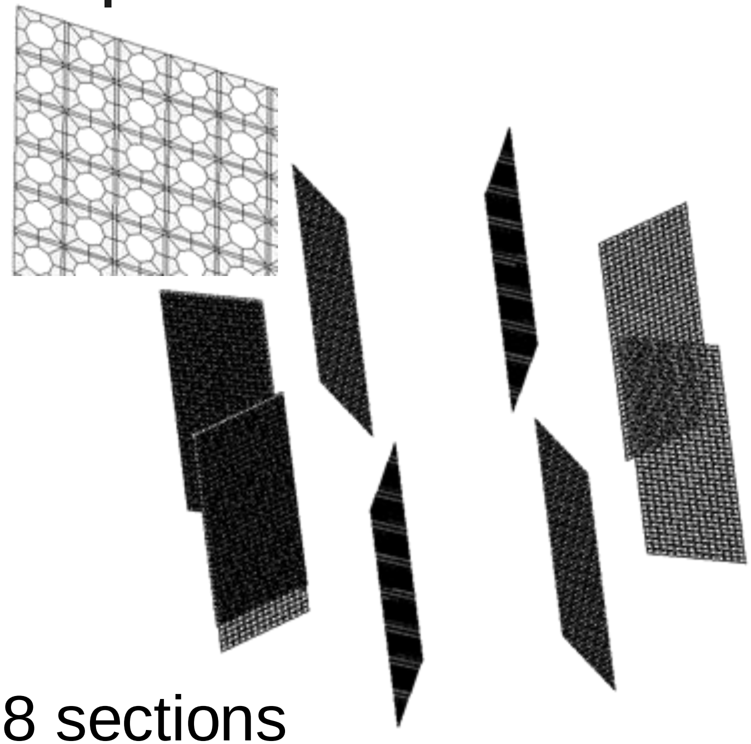
Parabolic, 8-nodes, iso-parametric elements

Example of CS Hexa-pancake geometry - edges and lines



23712 Nodes
6588 Elements
8016 Edges

Model of CS module



2 fluid channels
1 conductor component
200 nodes per channel
240 THEA processes

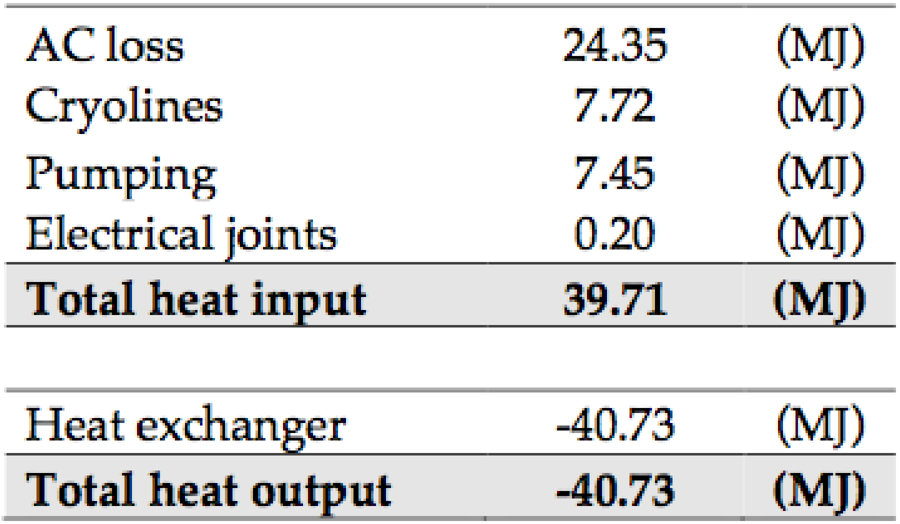
Approximately 1 MDOFs
24 hrs execution time for 1800 s

8 sections
106656 nodes
30504 quad elements
35520 line edges
6 HEATER processes

21 volumes
500 junctions
1 FLOWER process

CS simulation heat balance

- Approximate calculation of the total energy in- and outflow (pump work, enthalpy difference, neglect energy stored in heat capacity)
- estimated 2.5 % “discrepancy” on the overall balance – quite good



AC loss	24.35	(MJ)
Cryolines	7.72	(MJ)
Pumping	7.45	(MJ)
Electrical joints	0.20	(MJ)
Total heat input	**39.71**	**(MJ)**

Heat exchanger	-40.73	(MJ)
Total heat output	**-40.73**	**(MJ)**

HX temperatures

HX inlet

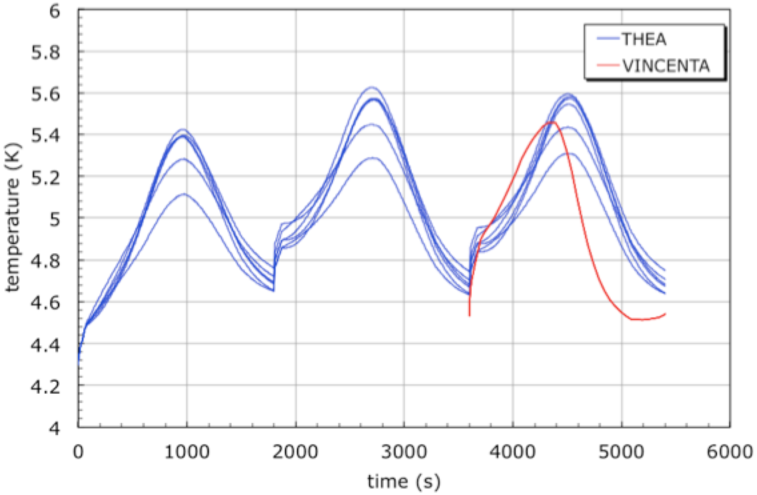


Figure 3.9. Outlet temperature at the CS manifolds during three subsequent plasma pulses.

HX outlet

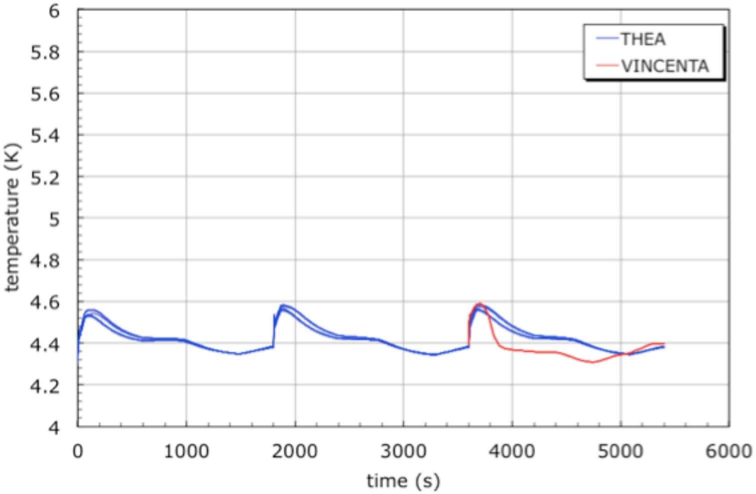


Figure 3.8. Inlet temperature at the CS manifolds during three subsequent plasma pulses.

- Heat transfer coefficient taken as constant (500 W/m^2K)
- Inner surface 2 m^2
- Outer surface 6 m^2

Pressure *bumps* during operation

HX inlet

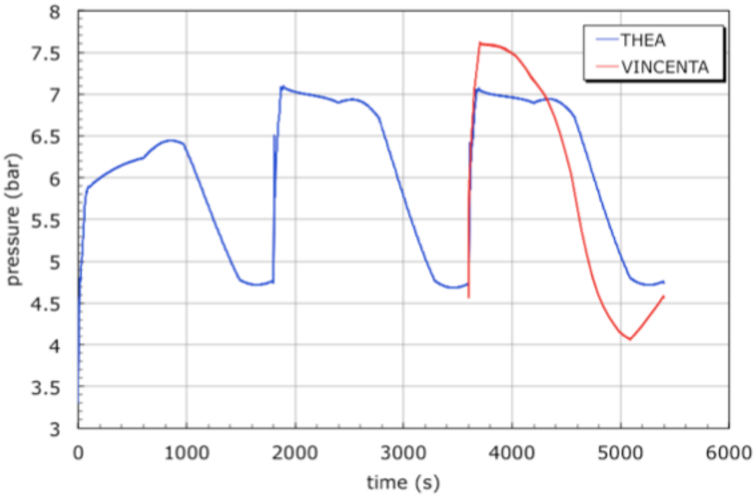


Figure 3.6. Inlet pressure at the CS manifolds during three subsequent plasma pulses.

HX outlet

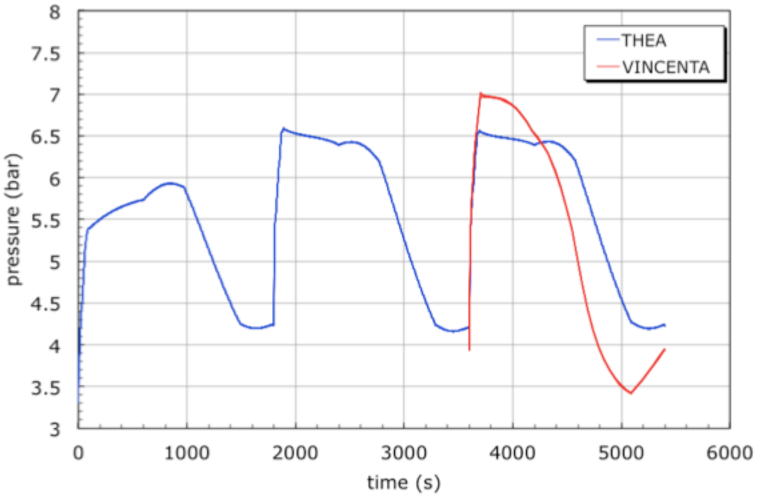


Figure 3.7. Outlet pressure at the CS manifolds during three subsequent plasma pulses.

- Pressure flexes correspond to changes in heating power
- Relatively large pressure excursions and heating induced backflow

Temperature increases – 1/2

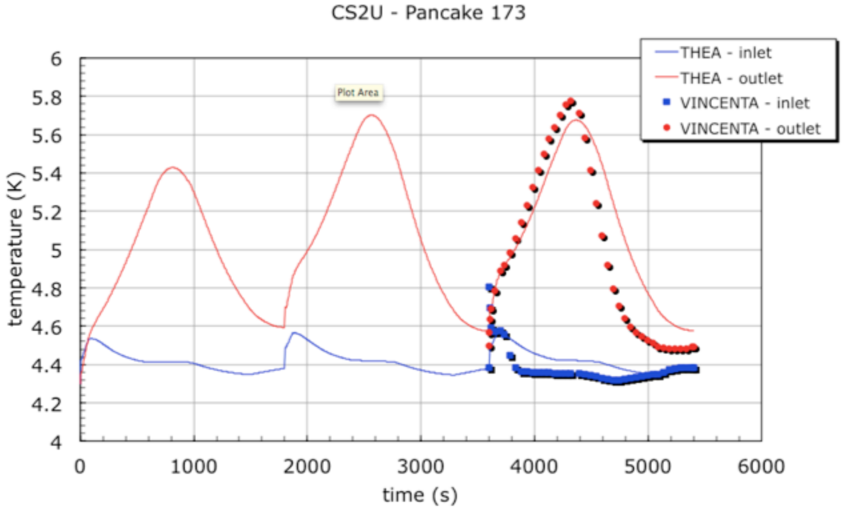


Figure 3.21. Inlet and outlet temperature at the selected pancake 173 in CS module 2U during three subsequent plasma pulses.

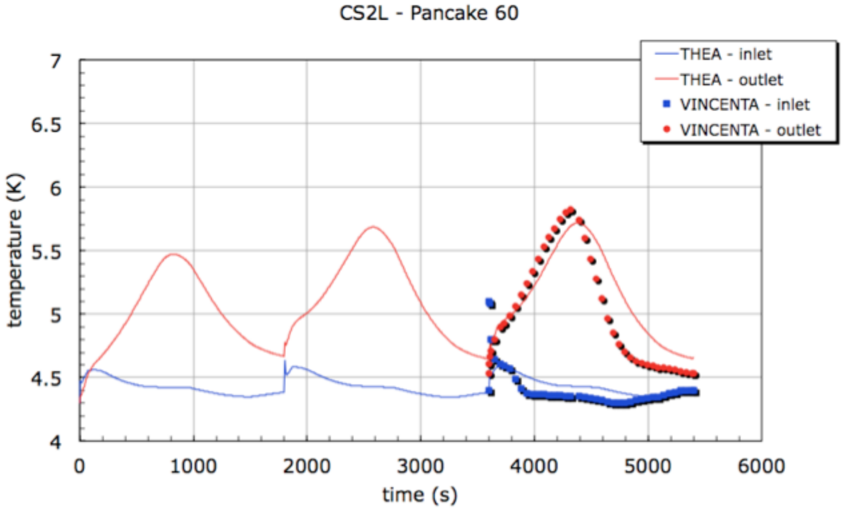


Figure 3.18. Inlet and outlet temperature at the selected pancake 60 in CS module 2L during three subsequent plasma pulses.

Temperature increases – 2/2

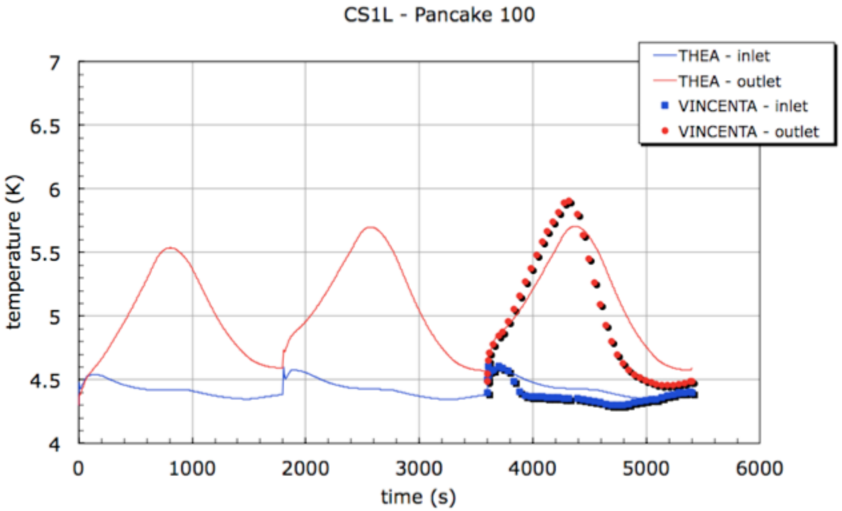


Figure 3.19. Inlet and outlet temperature at the selected pancake 100 in CS module 1L during three subsequent plasma pulses.

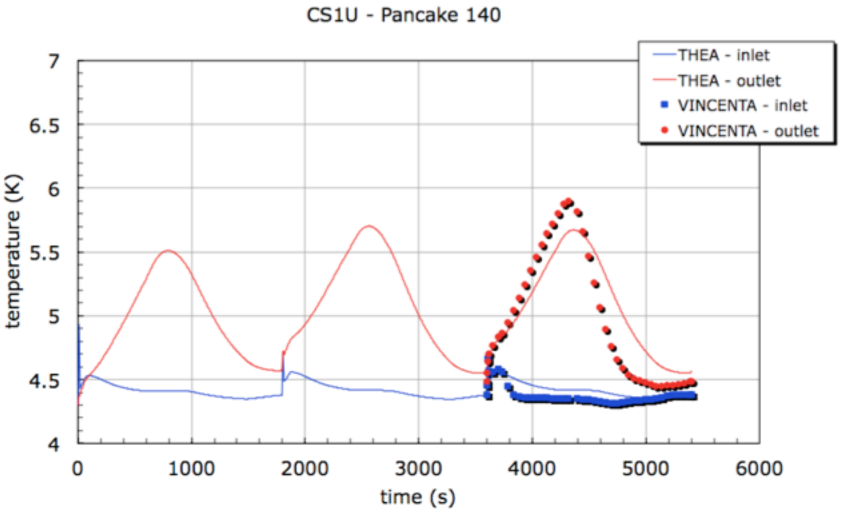
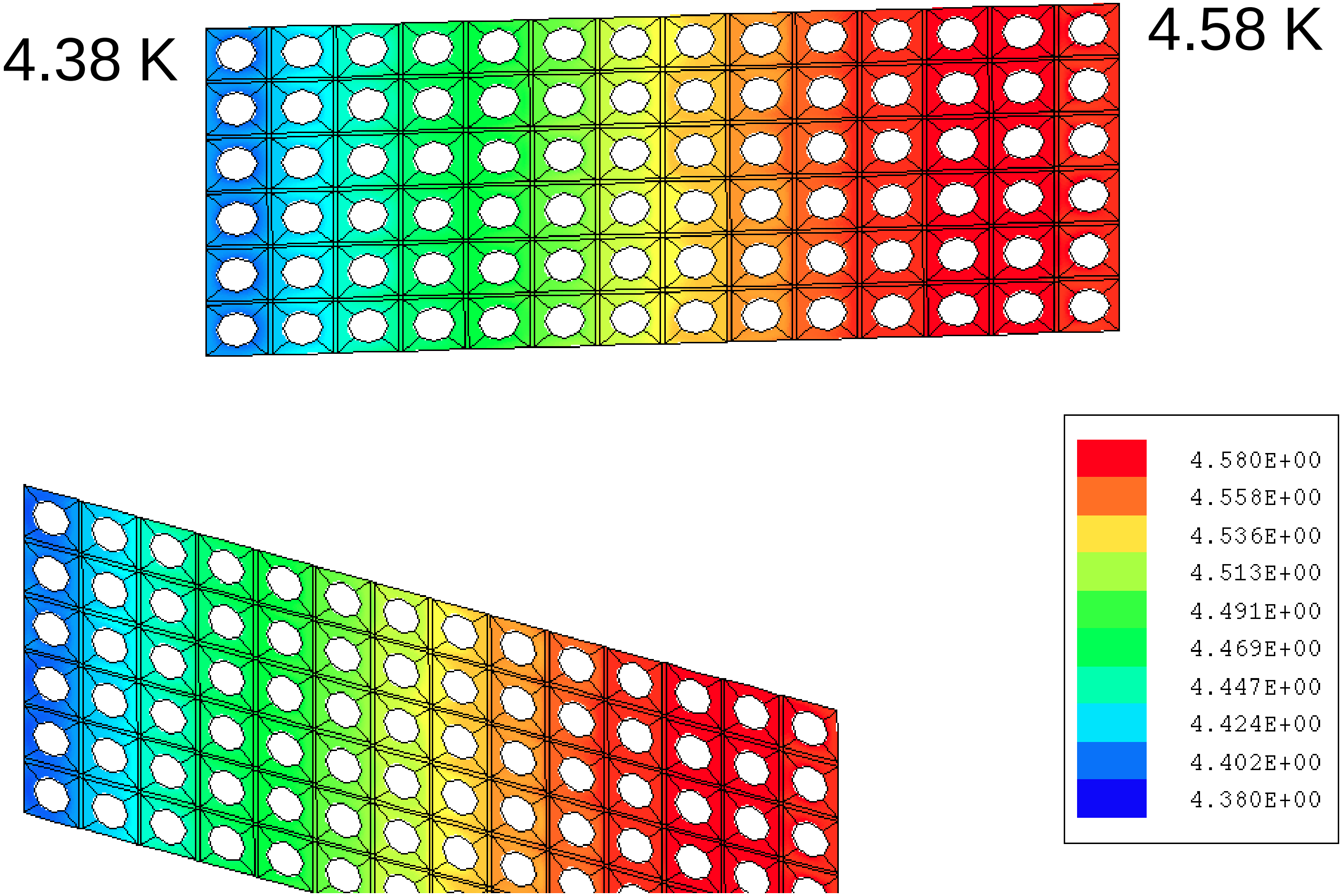
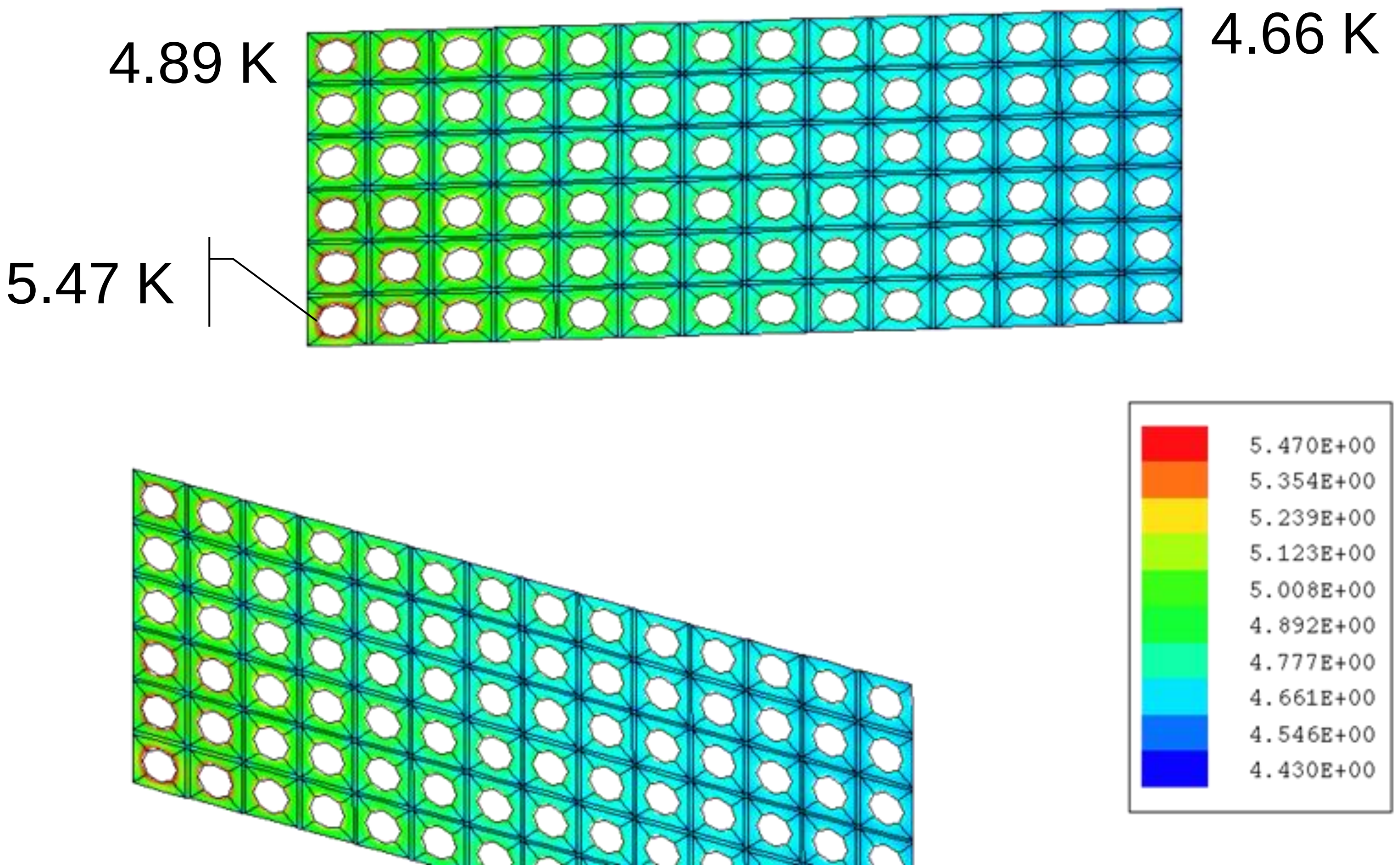


Figure 3.20. Inlet and outlet temperature at the selected pancake 135 in CS module 1U during three subsequent plasma pulses.

3-D maps at 3600 s



3-D maps at 3610 s

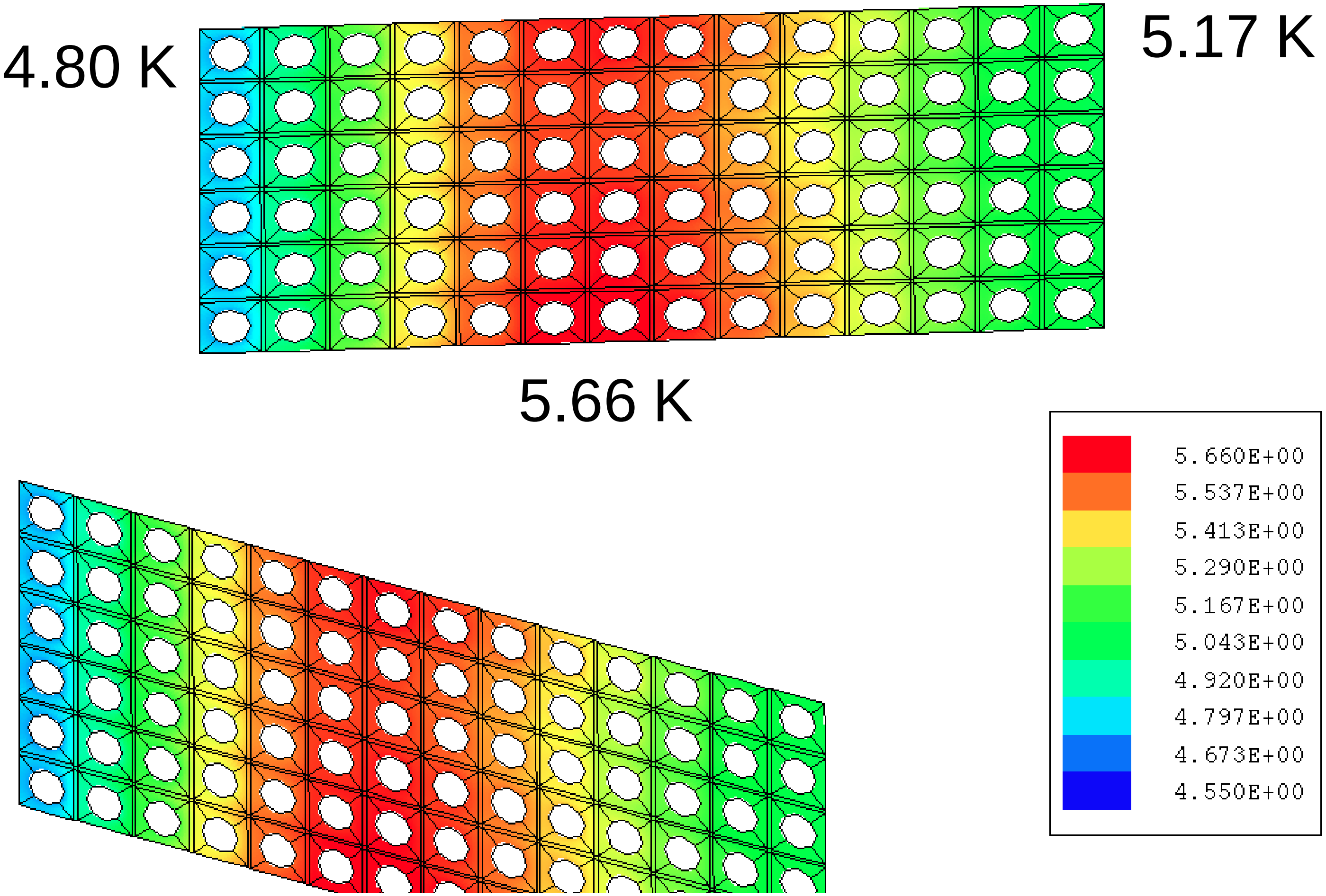


4.89 K

4.66 K

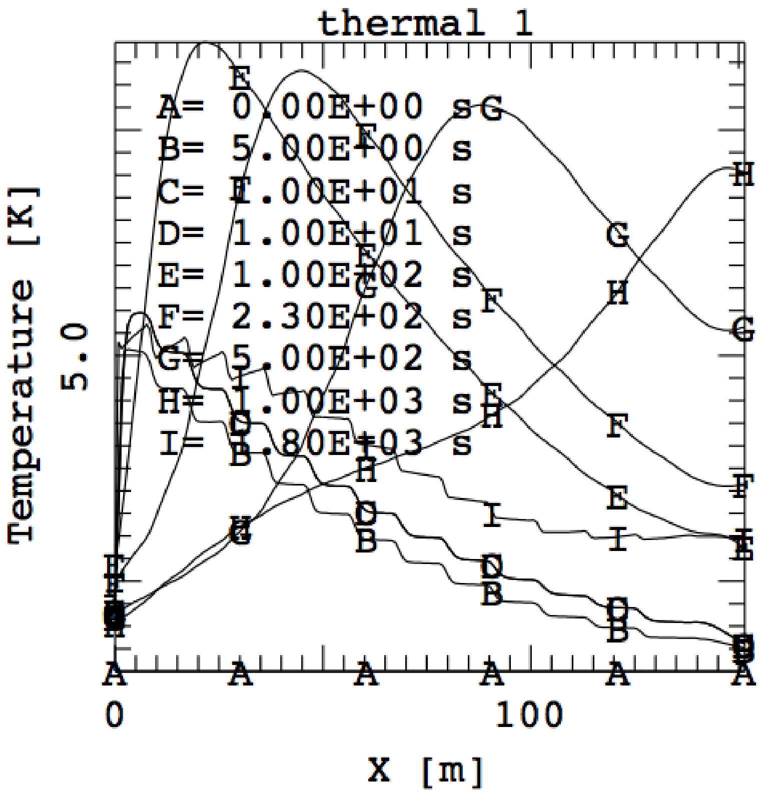
5.47 K

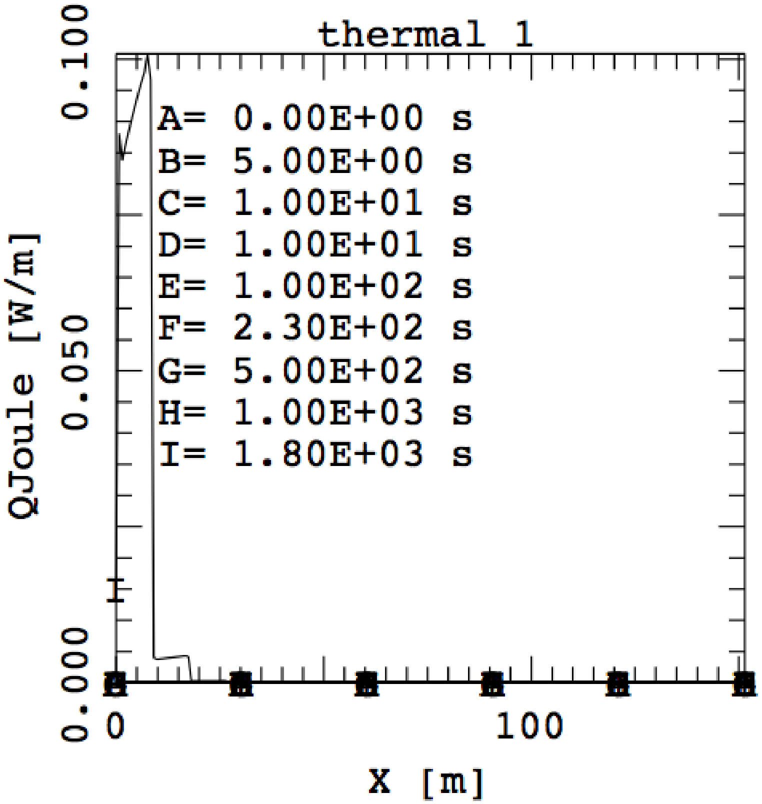
3-D maps at 3700 s



CS results – first cycle

CS2U Pancake 173

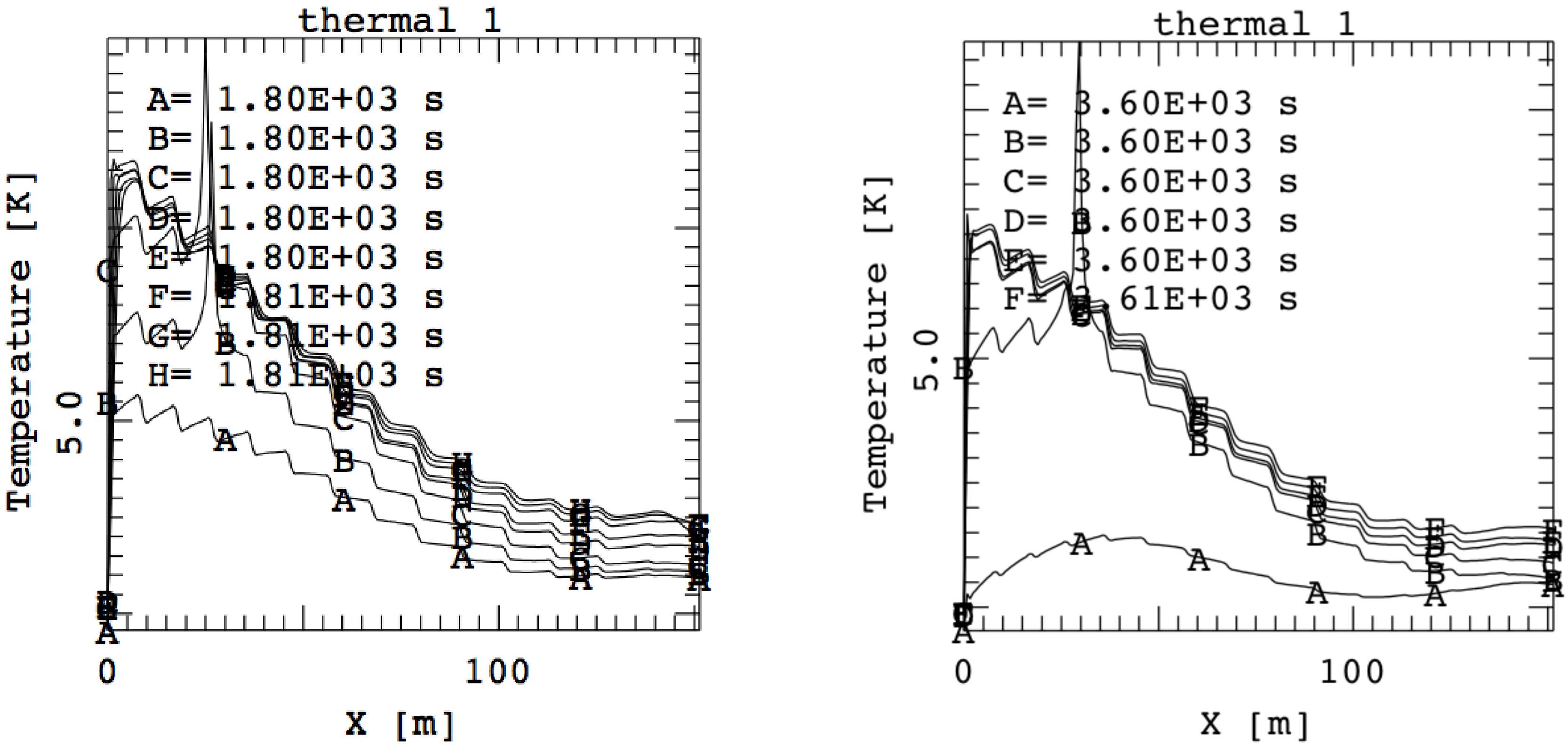




Restarted 4 times during the 1800 s of simulation

CS results – following cycles

CS2U Pancake 173



Detail of the first 10 s of simulation

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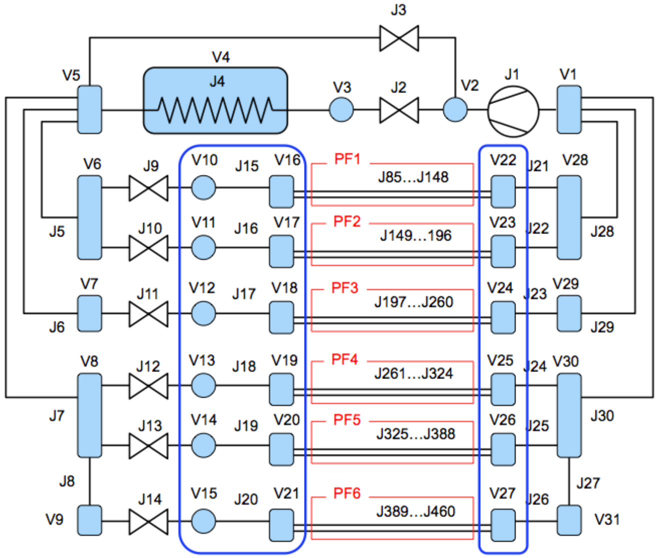
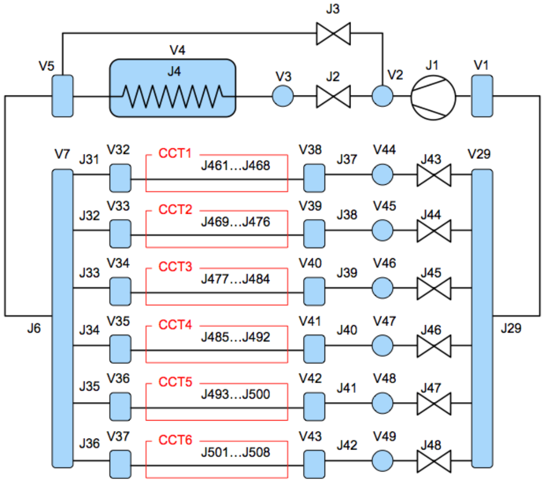
FLOWER model of PF coils

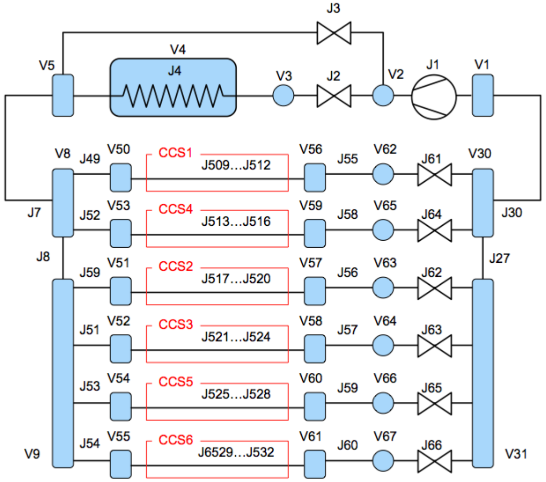
85 volumes
580 junctions



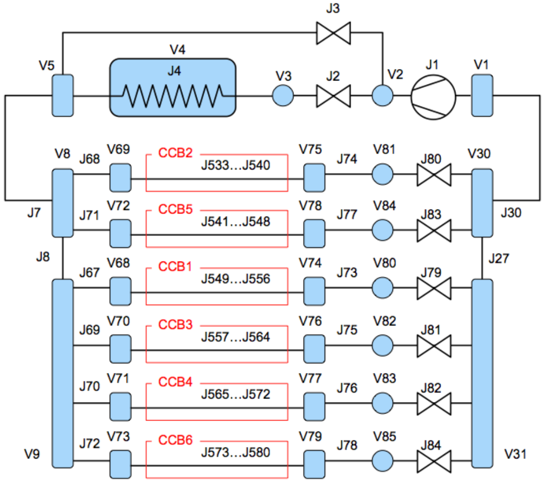
PF windings



CCT



CCS

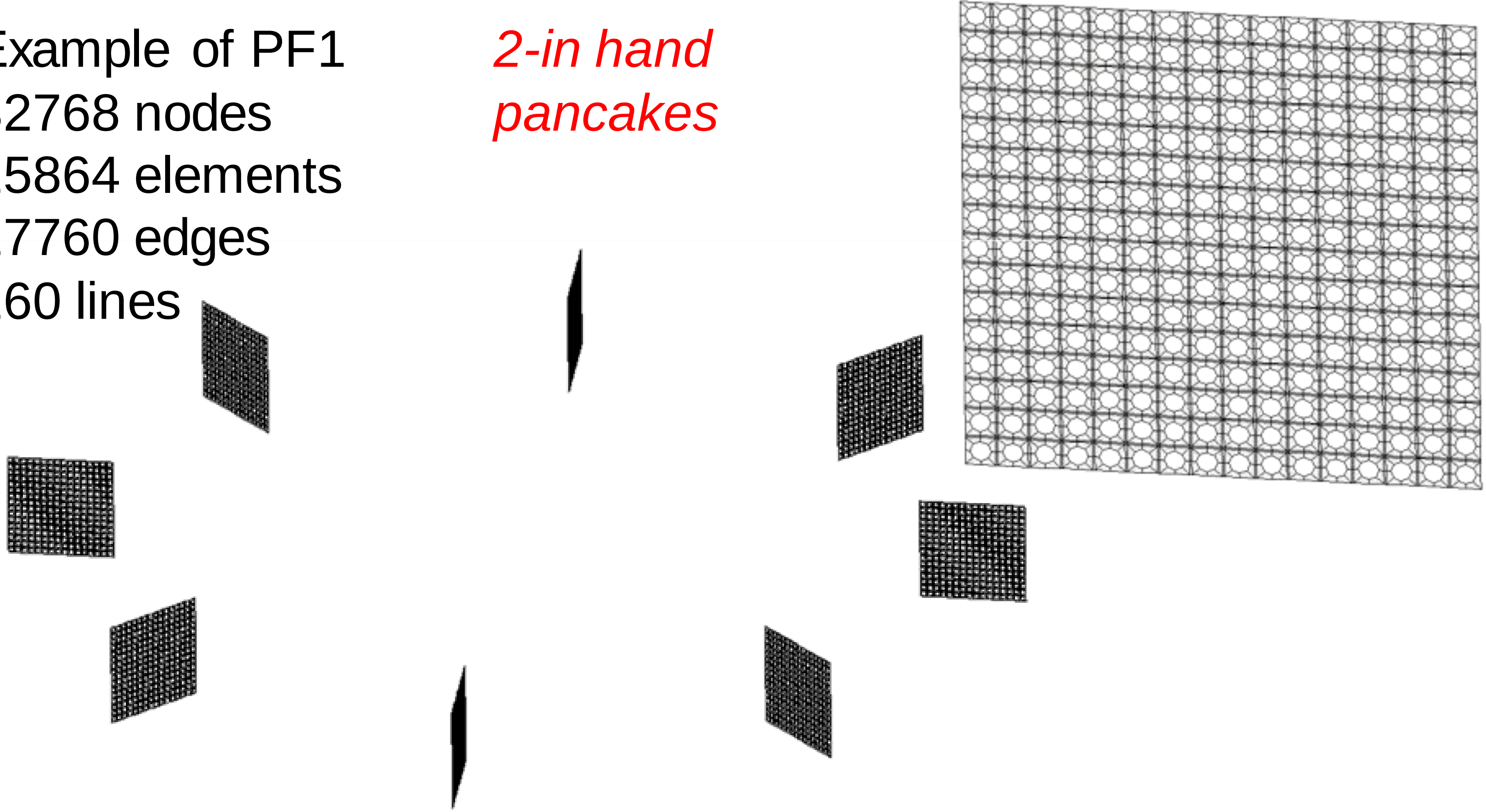


CCB

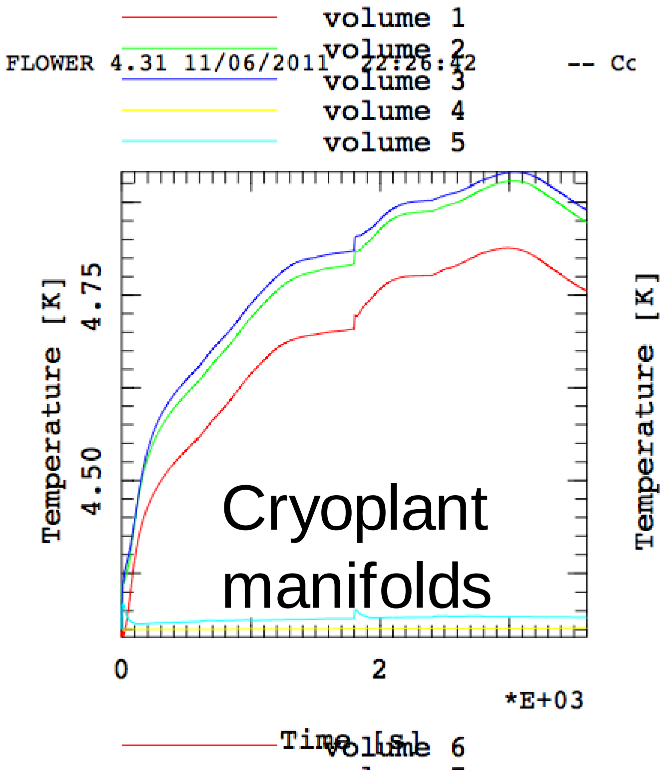
HEATER models of PF

Example of PF1
32768 nodes
25864 elements
17760 edges
160 lines

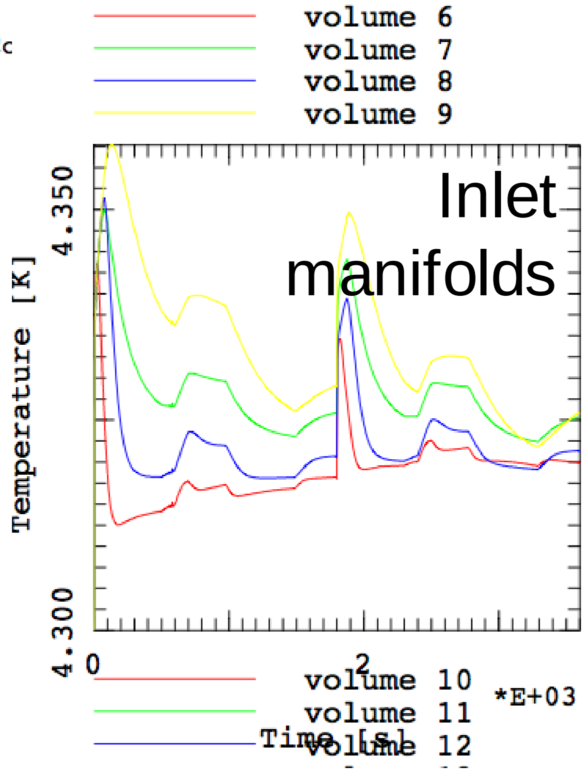
2-in hand pancakes



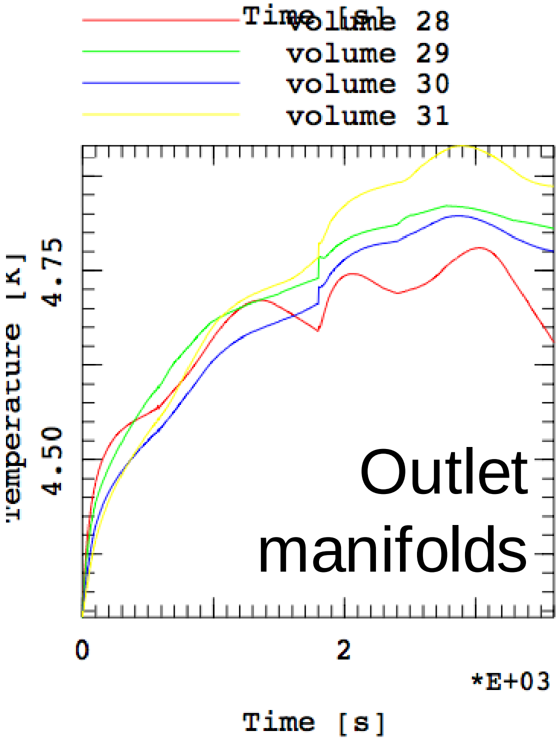
PF Manifolds temperatures



Cryoplant manifolds

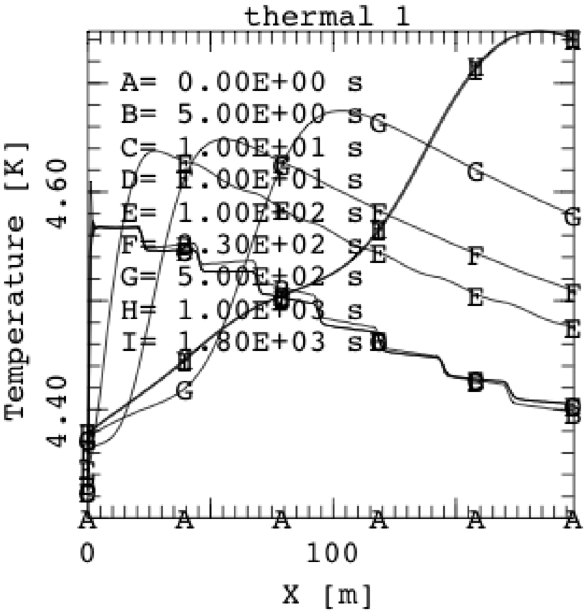


Inlet manifolds

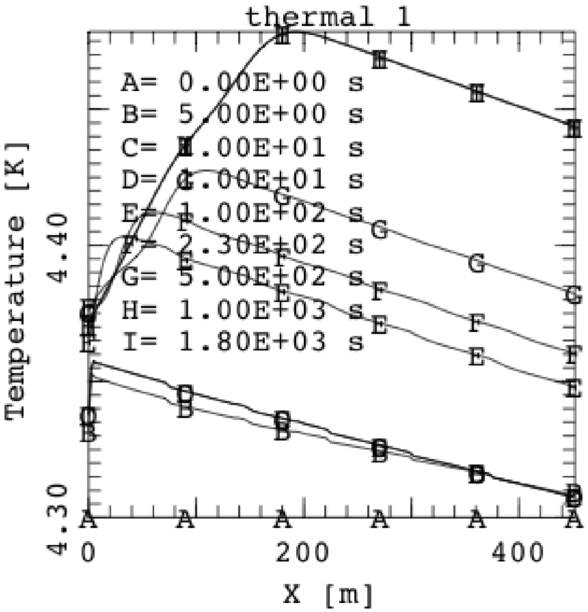


Outlet manifolds

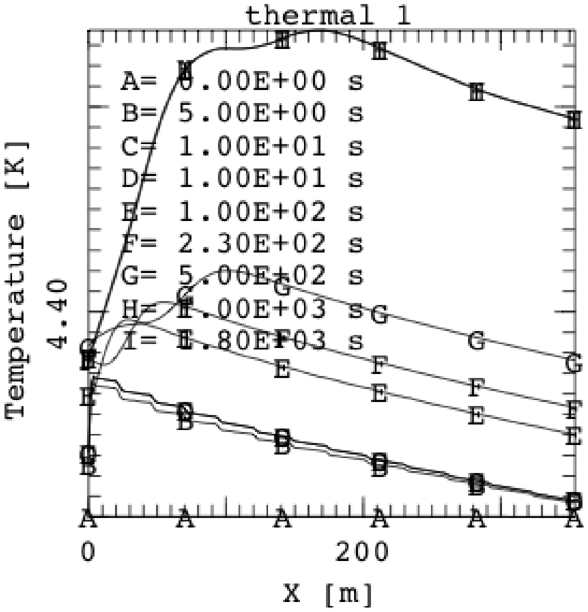
PF coil temperatures



PF1
Pancake 1
1st in hand



PF3
Pancake 1
1st in hand

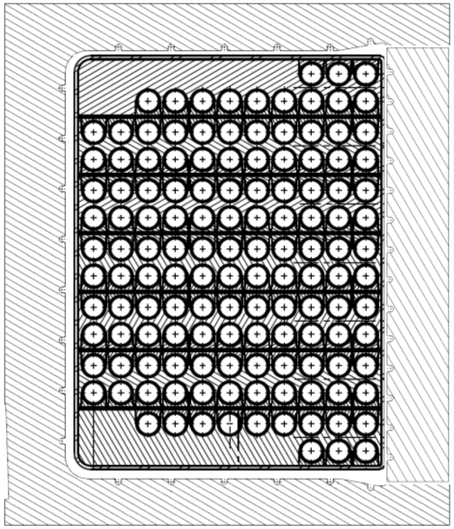


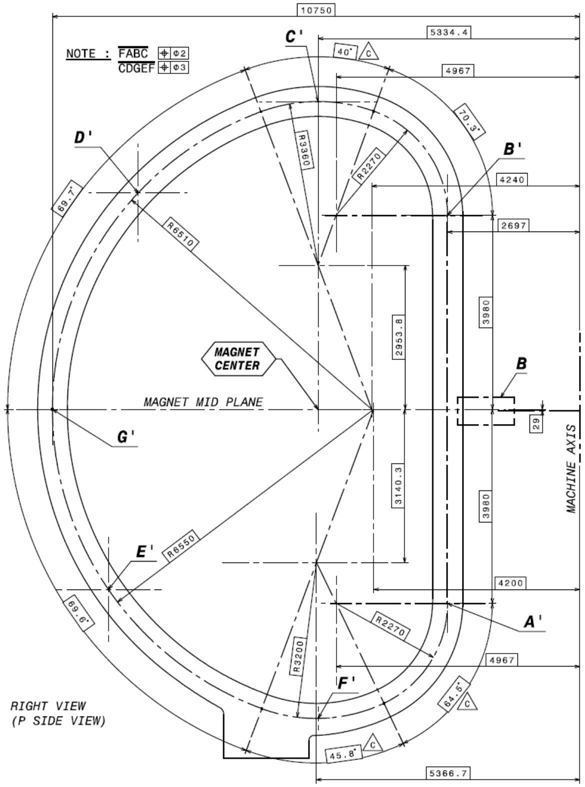
PF6
Pancake 1
1st in hand

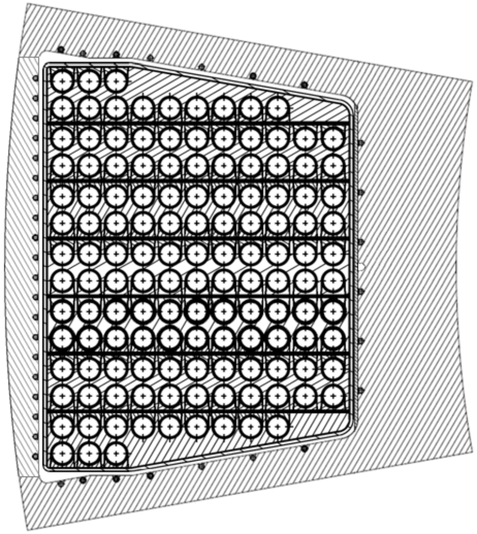
Outline

- A domain decomposition ?
- Practical implementation
- The ITER CS – a test problem
- Other results and further work
  - PF coils
  - TF coils
- Summary and perspective

TF coil geometry

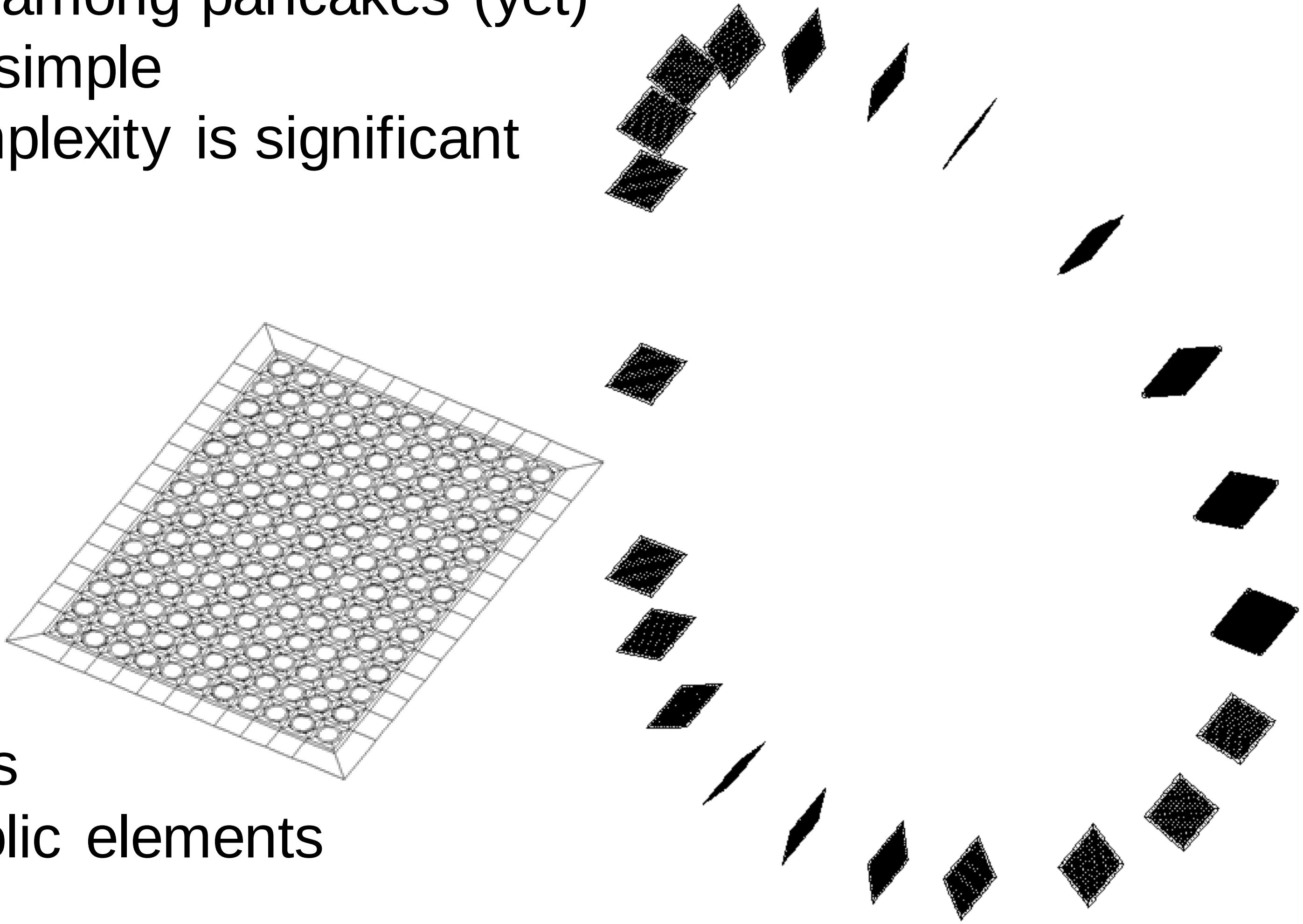






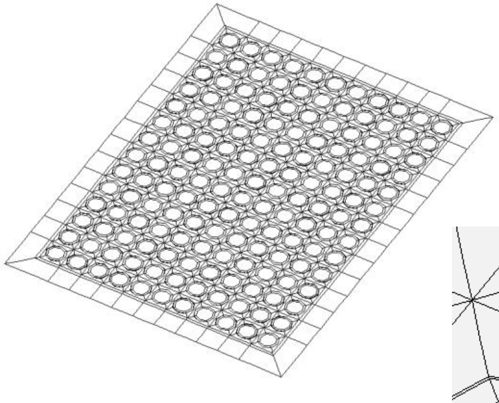
TF mesh example

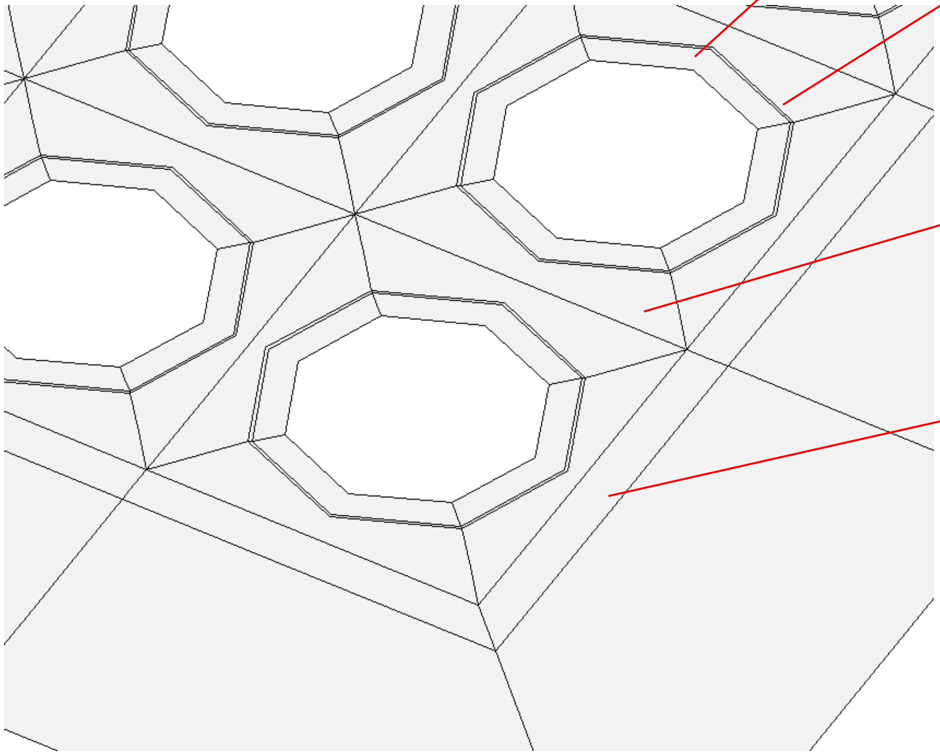
No difference among pancakes (yet)
Conceptually simple
However, complexity is significant



139854 nodes
42856 parabolic elements
26992 edges

TF mesh details





Jacket

Conductor insulation

Plate

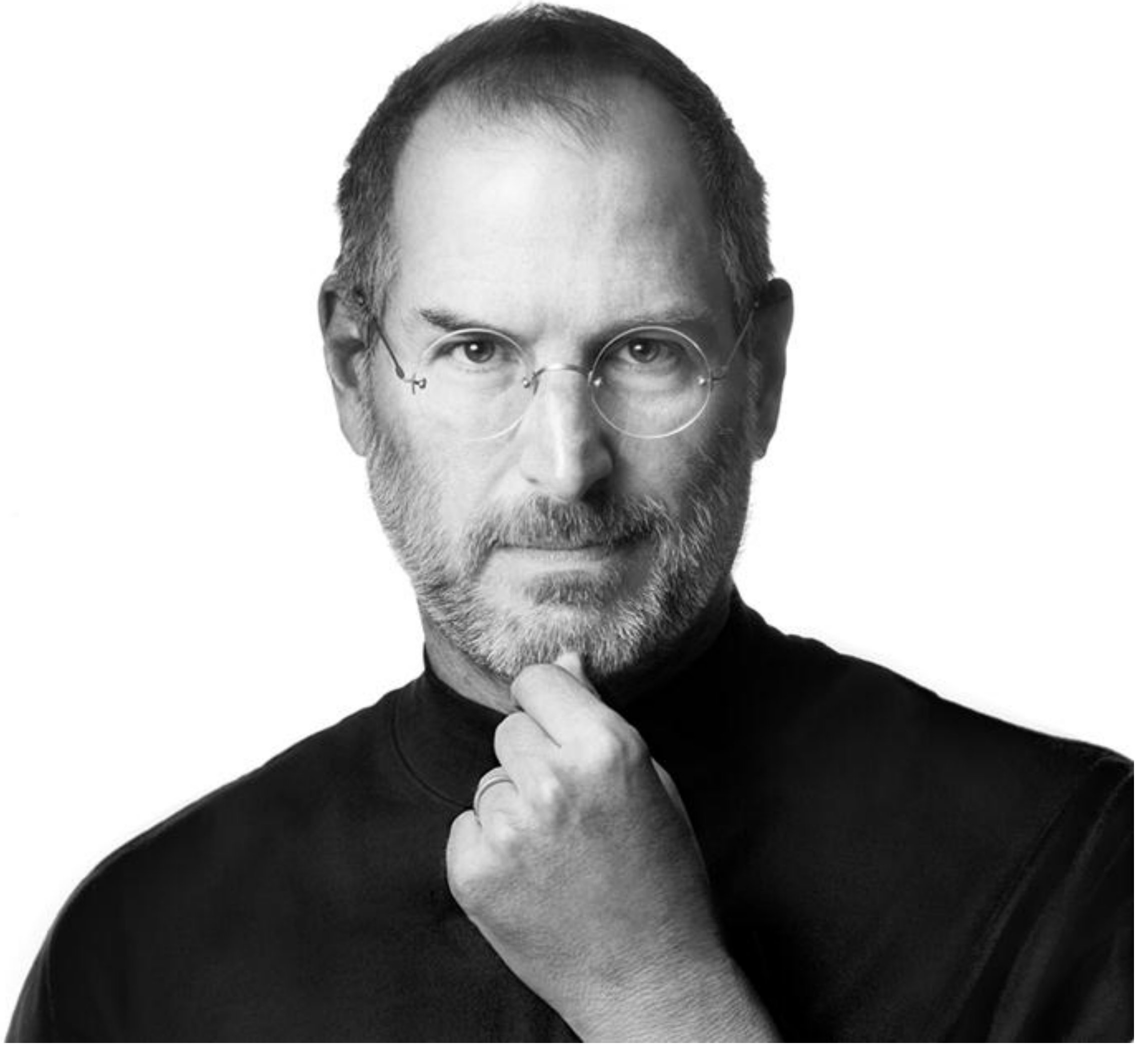
Ground insulation

Summary

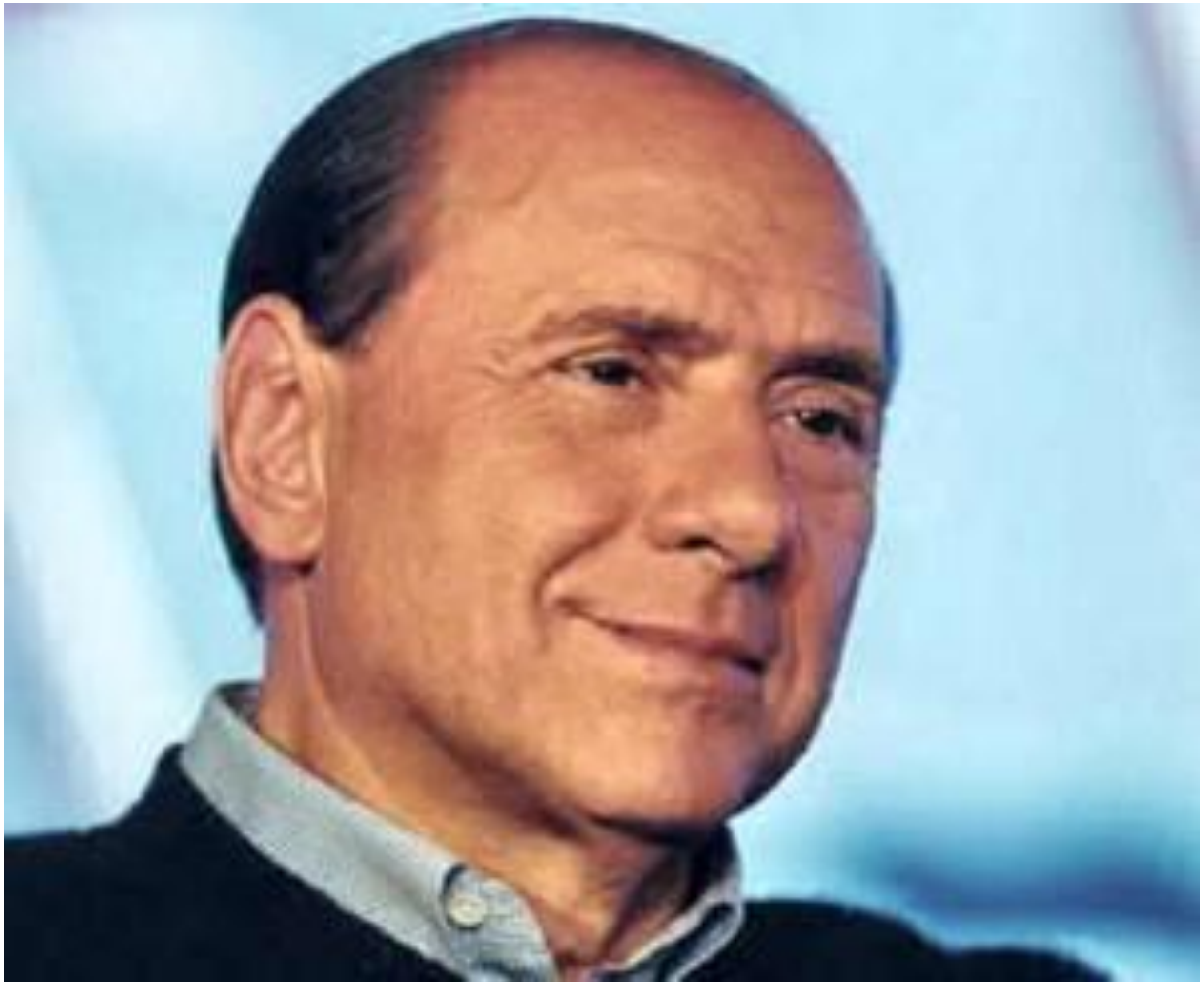
- Displace on the user's side the parameterization of the system analyzed
  - PRO: generic code(s), e.g. number of strands in the cable, topology of the coil, cooling mode, field and AC loss dependence on lengthand time, without the need to "recompile"
  - CON: logistics of a large size system becomes heavy, easy to get lost
- Big is out, small and modular is in
  - PRO: The good *Father* directs many *Children*, and finds its reward in the details the work of every single one
  - CON: The control-freak *Manager* spends most of his time dealing with the details of every *Slave* process (also called micro-management, watch-out for a "Banker's Bonus")
- Lots can be done, *do we really need it* ?
- Ah, by the way, why "SuperMagnet" ?

MyMagnet v8.0

iMagnet

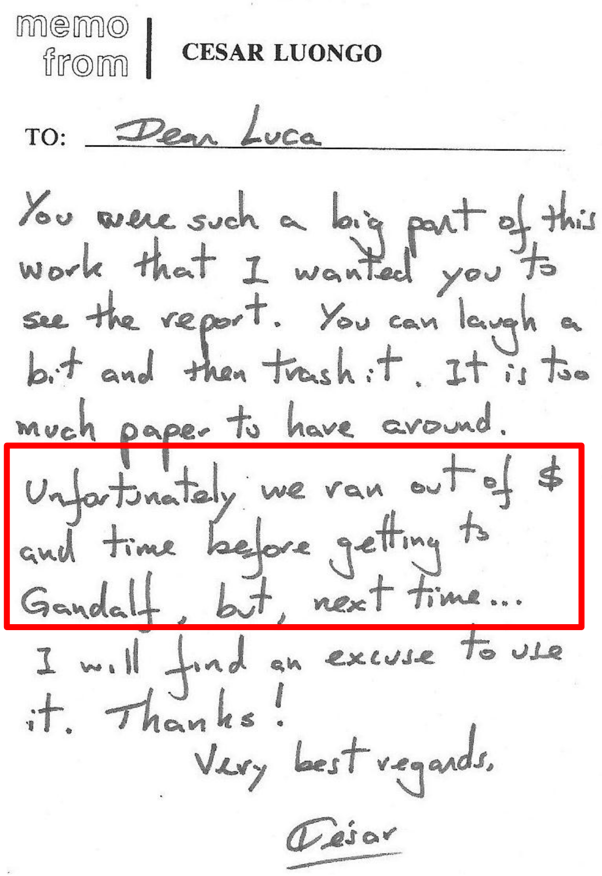


Bunga-BungaMagnet



SuperMagnet

- 1987 – C. Marinucci at SIN computes B, AC loss, temperatures in a plasma burn scenario using a code sequence named “Phase1, Phase2, Phase3,…”: the first *power user* of the codes is born
- 1989-1995 – monolithic analysis codes (SARUMAN, GANDALF) and first attempts to couple domains
- 1995 – V. Arp at Cryodata distributes CryoSoft codes under the package name of *Supermagnetpak* (akin to Hepak, Gaspak, Metalpak, Expak, Cppak). I admit I did not like the name
- 1997 – C. Luongo and B. Parsons (Bechtel) perform design and analysis of a superconducting system using codes operated in sequence (M’C, OPTICON, ZERODEE) and advocate the need for an integrated system of codes for SC magnet design and analysis
- 2001 – THEA
- 2008 – HEATER
- Challenge launched in 2008 by the ITER magnet project leader (“you will not manage to simulate the ITER system”) vs. a bottle of *good French Wine*. SuperMagnet is born



memo from | **CESAR LUONGO**

TO: Dear Luca

You were such a big part of this work that I wanted you to see the report. You can laugh a bit and then trash it. It is too much paper to have around. Unfortunately we ran out of $ and time before getting to Gandalf, but, next time... I will find an excuse to use it. Thanks!

Very best regards,

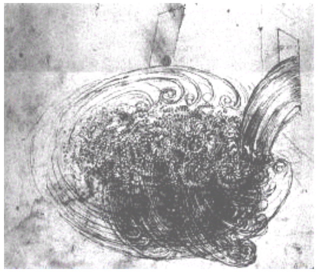
Cesar

Just in case…

THEA

- THEA performs stationary and non-stationary Thermal, Hydraulic and Electric Analysis of a generic cable
- Based on a arbitrary set of parallel, 1-D components
- Models:
  - heat generation and diffusion along the cable
  - mass, momentum and energy transport (He-I and He-II) along the coolant flow
  - current diffusion and distribution along the cable

FLOWER



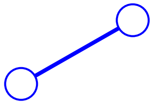
- Transient and steady state response of a proximity cryogenic system
- Modeling is based on an assembly of active and passive components forming an hydraulic network:
  - Volumes
  - Interconnected pipes where the flow can be steady state or transient
  - Valves
  - Pumps
  - Turbines
  - Heat exchangers

POWER

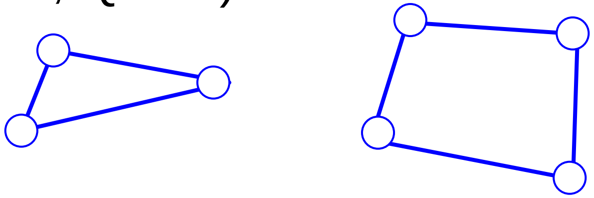
- Simulation of an electrical circuit powering a coil, modeled as an arbitrary network formed by
  - Resistances, constant or variable, e.g. the non-linear value from a quenching cable
  - Inductances
  - voltage or current sources, possibly non-linear

HEATER – 1/2

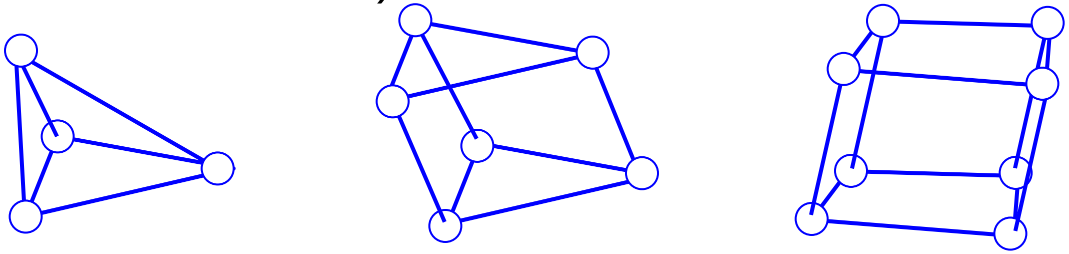
- A3-D solver developed to model heat conduction in solid structures of arbitrary shape
    - Large iso-parametric element library available:
        - 1-D (LINE)



        - 2-D (TRIA, QUAD)



        - 3-D (TETR, PYRA, HEXA)

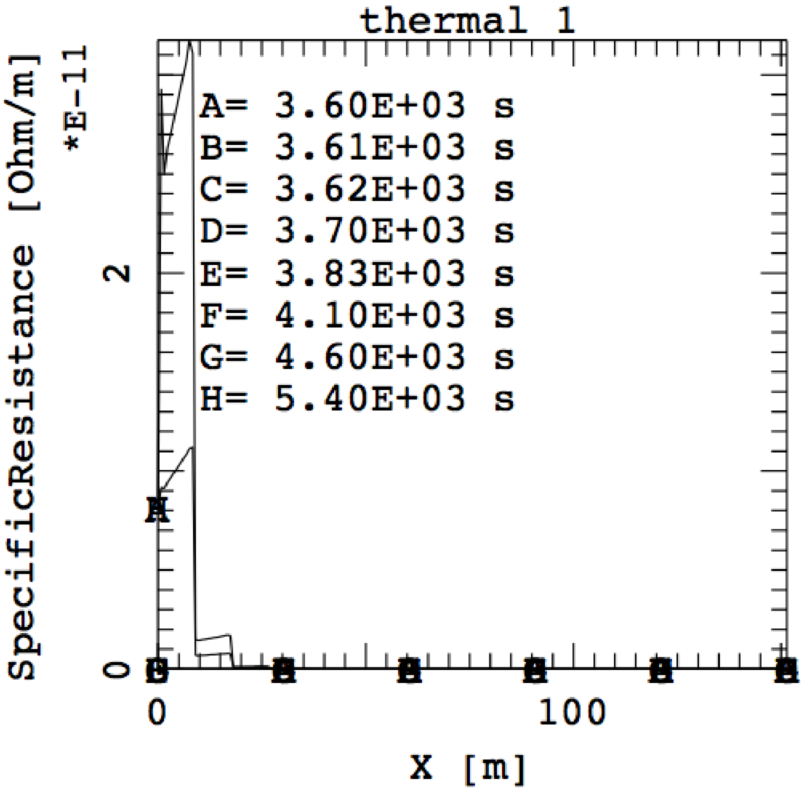


HEATER – 2/2

- Standard features introduced for ease of use:
  - Standard access to the database of thermo-physical properties for cryogenic materials
  - Possibility to customize the code through usual mechanisms (user's routines compiled with main code) for:
    - User's defined materials
    - Heating distributions and waveforms other than the simple models available
  - Input (mesh, source terms, boundary conditions, simulation parameters) through command file, parsed at runtime. Syntax similar to that used by the other programs of the SuperMagnet suite
  - Storage of calculation results for later post-processing
  - Does not require licenses and libraries other than a standard installation (source code)

Effect of self field

Pancake 173
Beff=Baverage



Pancake 173
Beff from E-field