Surrogate Modelling for Optimal Design of a HTS Insert for Solenoid Magnets

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ENEA

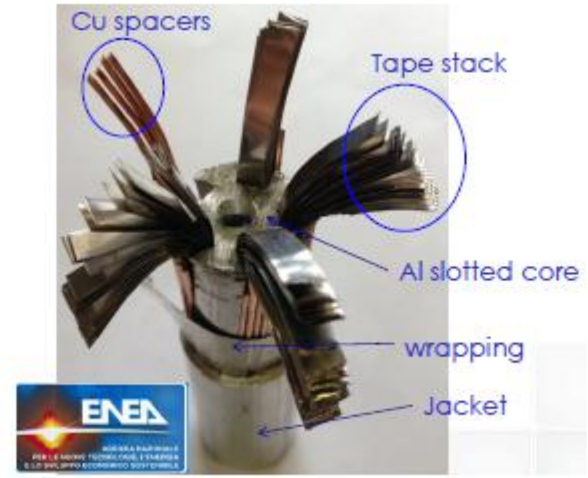
Outline

- Introduction & Scope
- The ENEA HTS CICC
- Finite Element Model
- *Direct* Optimization
- *Surrogate* Optimization
- Results & Conclusions

Introduction

- Recently, a HTS CICC cable comprised of 2[nd] generation ReBaCuO coated conductors has been designed and manufactured by ENEA

- With the availability of 2G HTS, high field magnets are now being considered



Slotted core HTS CIC conductor

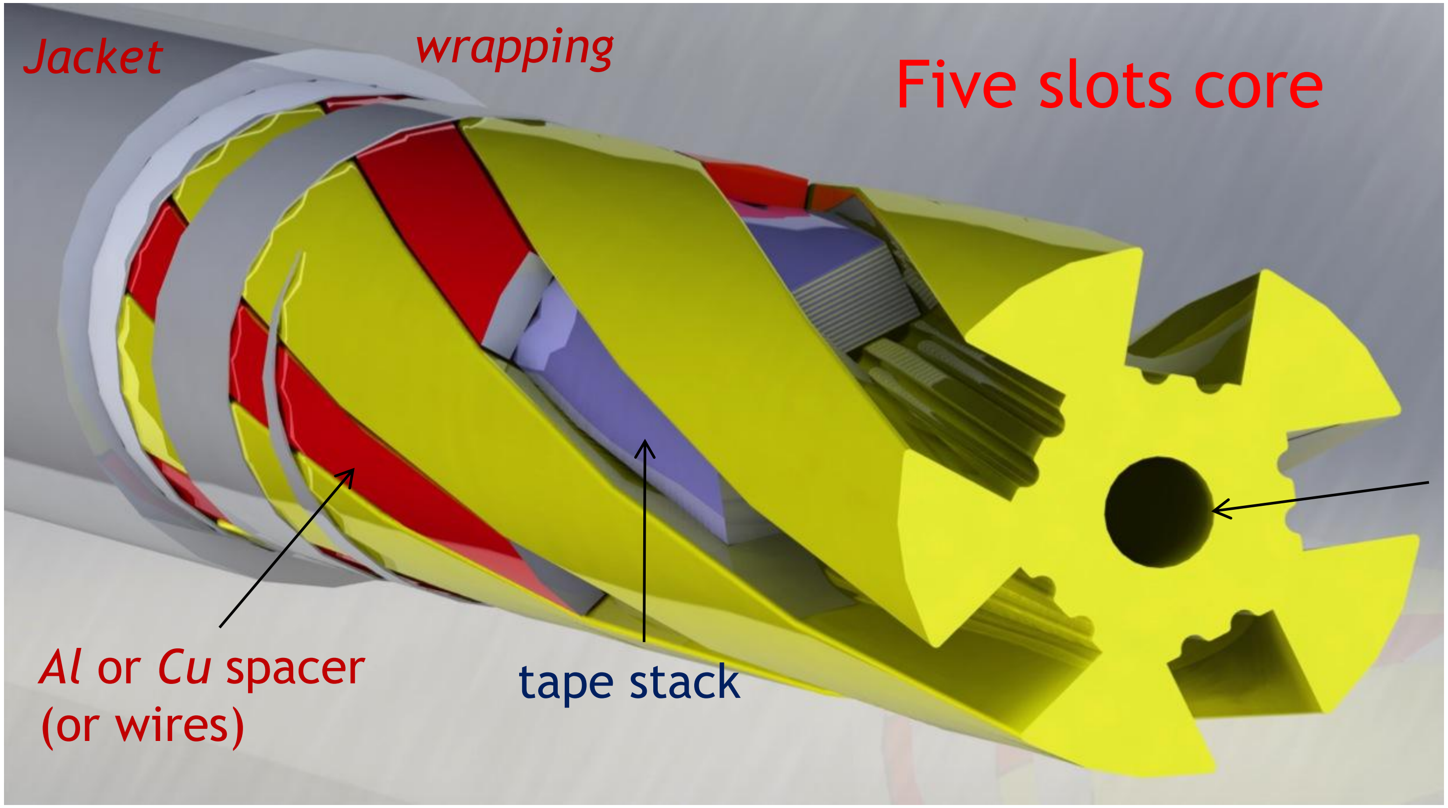
The ENEA HTS conductor is considered to be inserted into the bore of an existing high field magnet

Scope of this work

- to minimize total conductor length needed for an HTS insert magnet to reach a peak magnetic field (based on a background field), guaranteeing structural integrity
- length minimization means costs minimization

The ENEA slotted core CICC

10 kA – class cable: 150 2G-wires (5 stacks x 30 wires)

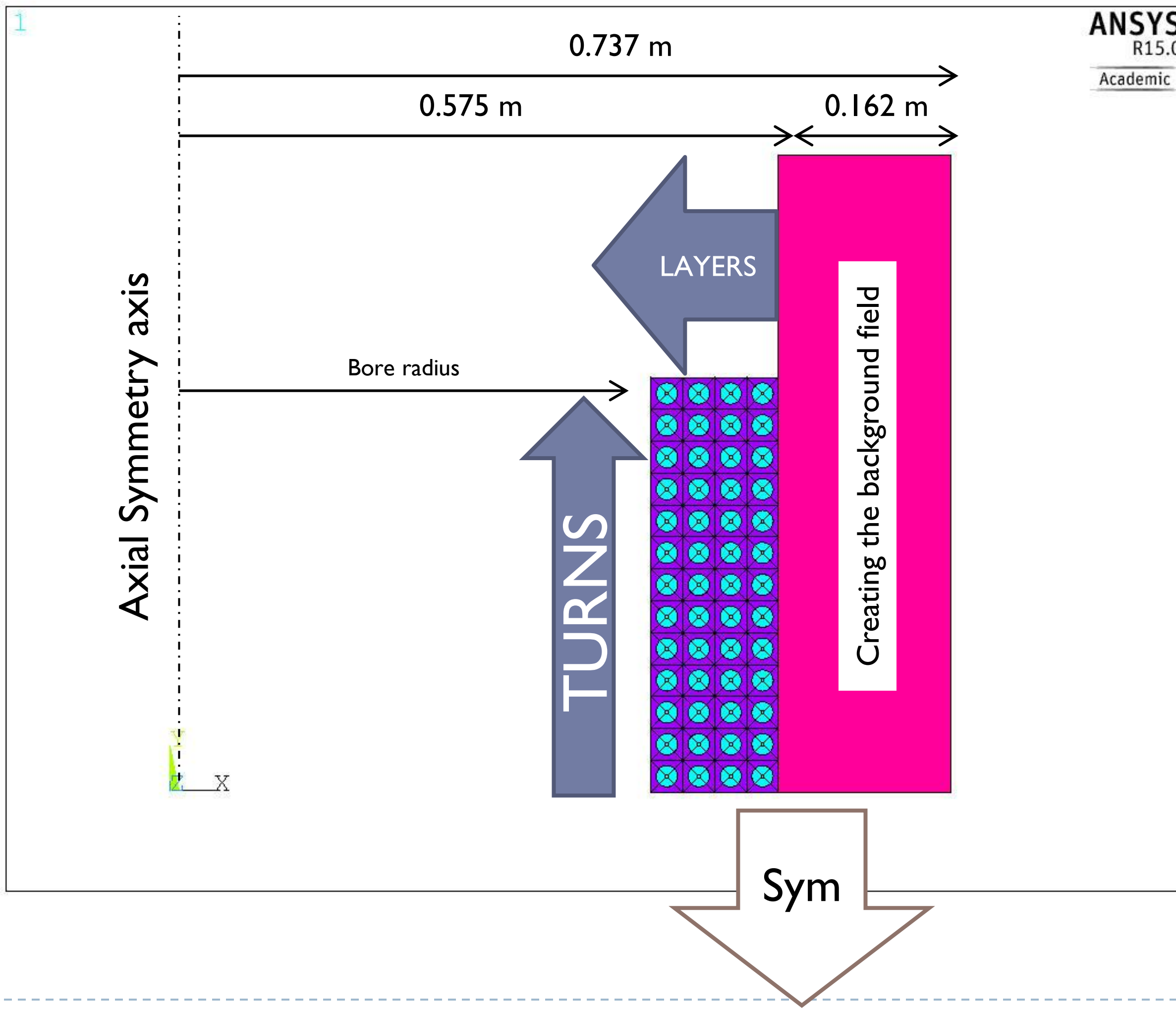


inspired by the MIT concept for twisted-stacked tape CICC

cooling central channel

Fundamental Design driver:
industrial process feasibility

Finite Element Model description



Finite element modelling

- Parametric approach taking advantage of ANSYS parametric design language (APDL)
  - 2D axial symmetric
  - Magneto-static analysis, using the magnetic vector potential (MVP), with:
    - Background field 12 T
    - Current inside the bore 22.4 KA
  - Magneto-structural analysis with loads:
    - Lorentz forces, from magnetic analysis results
  - Same mesh (no interpolation needed), switching from magnetic (PLANE13) to thermo-mechanical elements (PLANE42)
  - Temperature-dependent material properties

Standard Trial-and-Error design approach

Number of turns	Number of layers	Total conductor Length [m]	Max Field B [T]	Bore Diameter [m]	Max Von Mises [MPa]	B variability in axial direction [%]	B variability in radial direction [%]
26	3	252	13.7	0.97	218	0.53	0.61
26	4	322	14.3	0.91	216	0.52	0.64
10	6	169	14.1	0.79	204	0.62	1.45
8	6	135	13.8	0.79	203	0.70	1.61
10	5	147	13.8	0.85	204	0.62	1.35
8	7	149	14.0	0.73	205	0.77	1.65
6	9	129	13.9	0.61	208	0.96	1.79
4	14	94	13.8	0.31	224	1.75	1.70
6	14	141	14.9	0.31	231	1.21	1.43
8	3	78	13.1	0.97	208	0.65	1.33
6	3	58	13.0	0.97	212	0.69	1.52

➢ An **optimization methodology** is adoped to minimize the needed HTS cable length (**HTS material costs minimization**) to achieve a **peak field** of **17 T**, withstanding the relative Lorentz forces

Mathemathical definition of optimization

Optimization is a **mathematical process**:

Find $\mathbf{X}$ to minimize (or maximize)

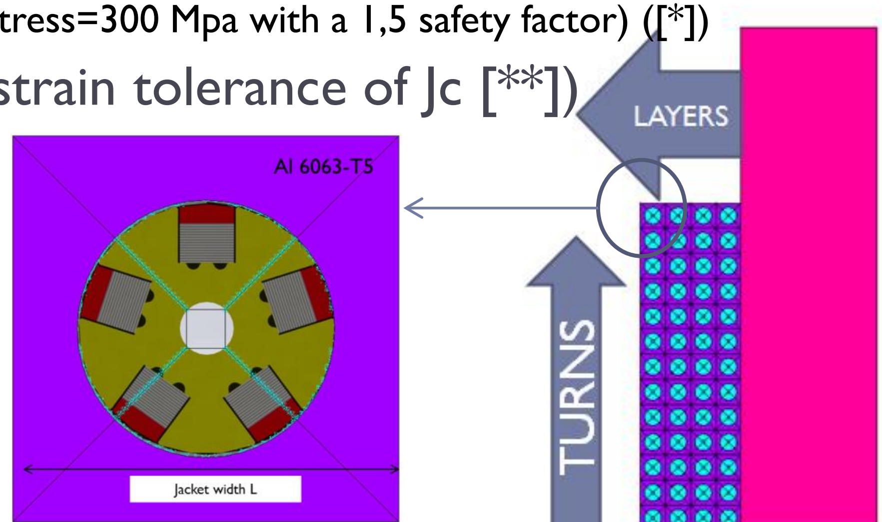
$$F(\mathbf{X}) \text{ objective}$$

where:

$$\mathbf{X} = \{x_1, x_2, \ldots, x_n\} \text{ design variables}$$

Numerical approach to optimization

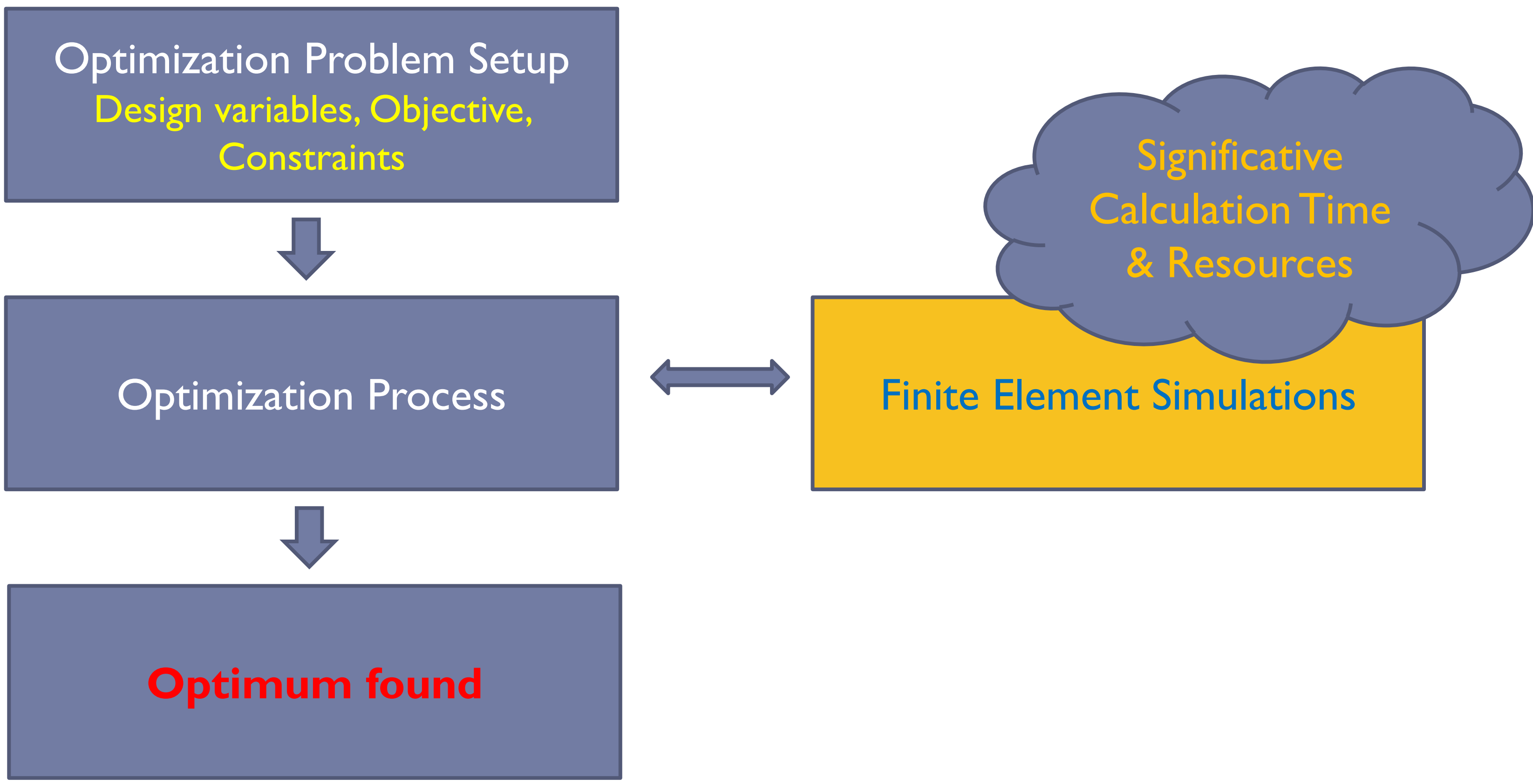
- Numerical Optimization aimed to:
  - minimize the total conductor length (**cost reduction**) of the high field HTS insert demonstration magnet, with:
  - achieving Bmax ≥ 17 T (background field: 12 T)
  - Failure criterion:
    - Von Mises stress < 200 MPa (yield stress=300 Mpa with a 1,5 safety factor) ([*])
  - Internal bore diameter ≥ 30 cm (strain tolerance of Jc [**])
  - Design variables:
    - jacket width L [25 ÷ 40 mm]
    - Number of turns and layers



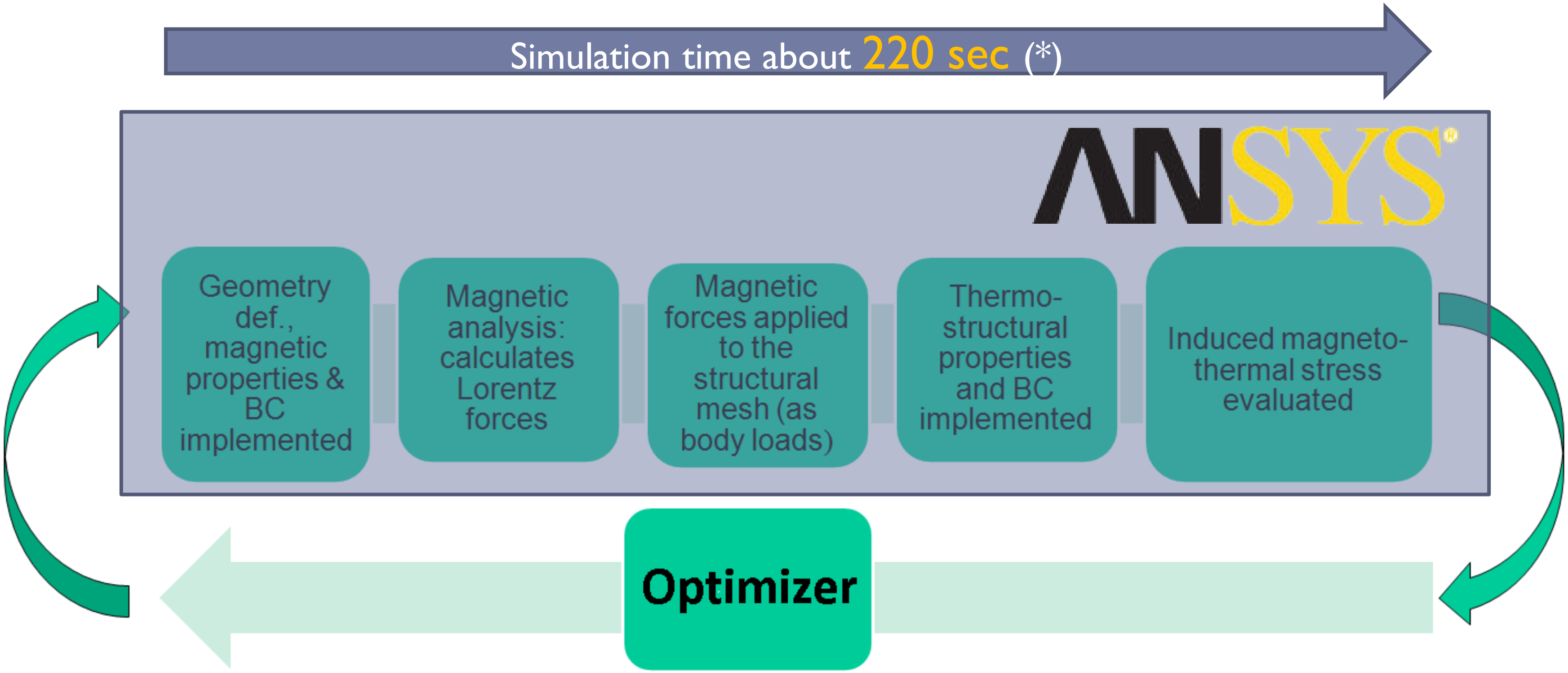
[*] Weiss K-P, Bagrets N, Sas J, Jung A, Schlachter SI, della Corte A, et al., Mechanical and thermal properties of central former material for high current superconducting cable, presented at EUCAS2015, poster presentation, 3PoBD_04

[**] G. De Marzi *et al.*, "Bending Tests of HTS Cable-In-Conduit Conductors for High-Field Magnet Applications," in *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, pp. 1-7, June 2016.

Direct Optimization

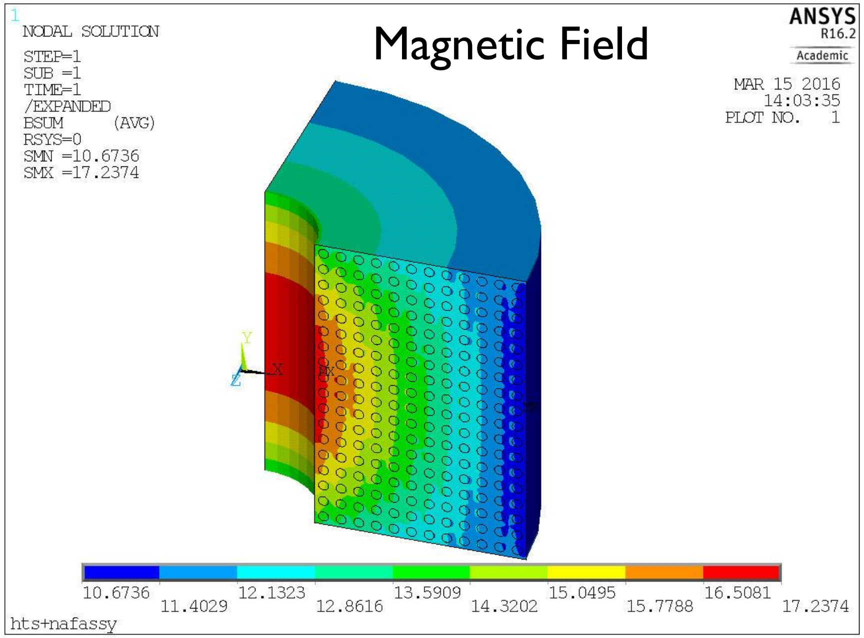


Direct Optimization loop



(*) Intel® Xeon® CPU E5645 @ 2.40 GHz RAM 24 GB

FE Direct Optimization results



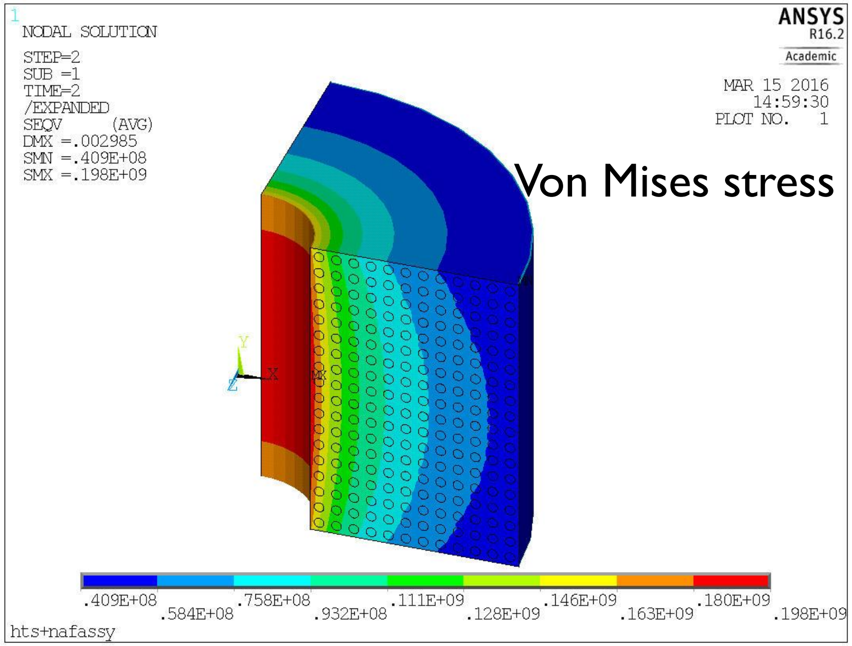
Optimal conductor Length = 360 m

Number of turns = 16
Number of layers = 12
Jacket width L = 35.4 mm

} Optimal design variables set

Max B ≈ 17.2 T

Max Von Mises stress = 198 MPa

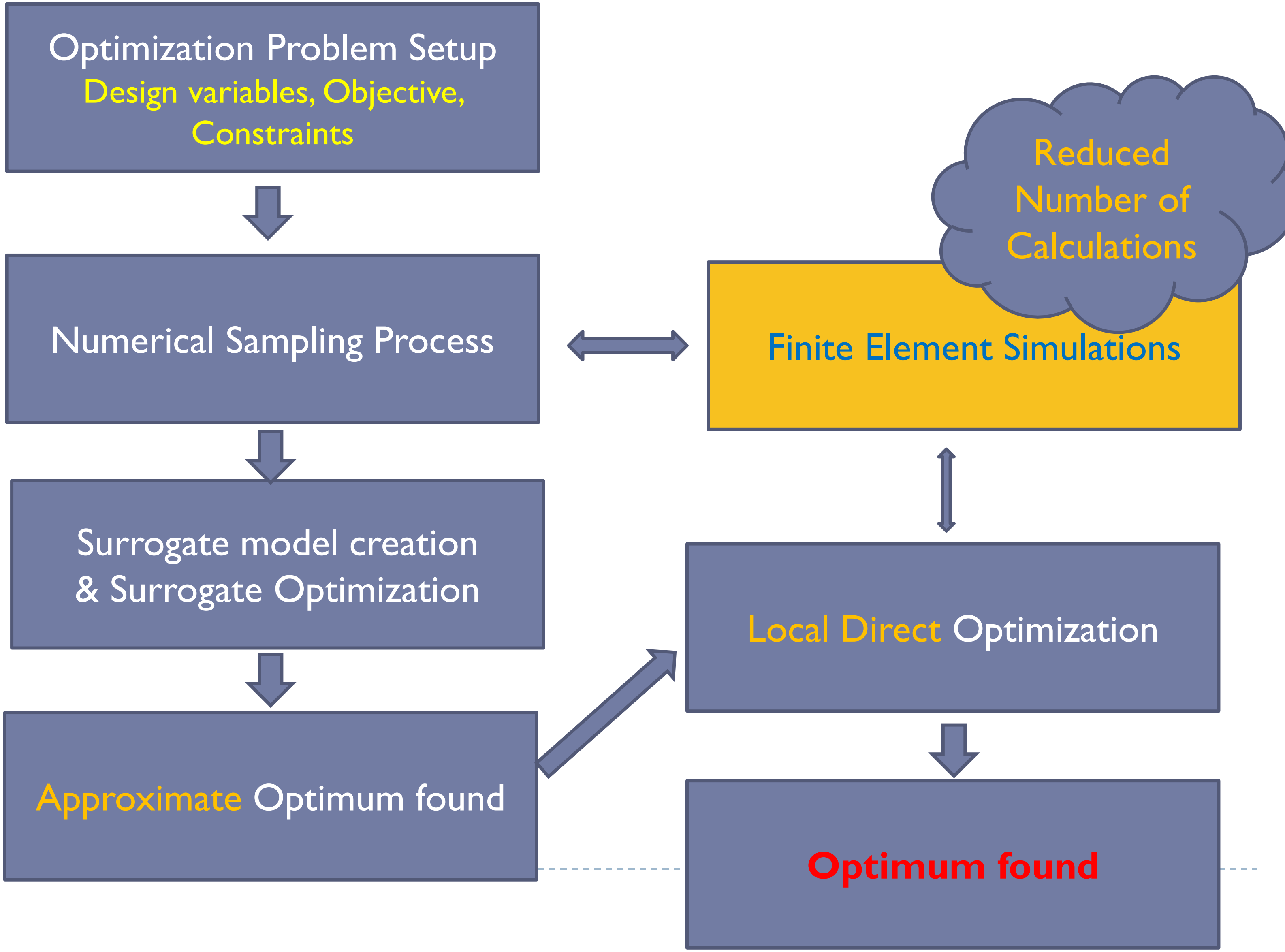


Computational Effort :

Total time for optimization: 4 days

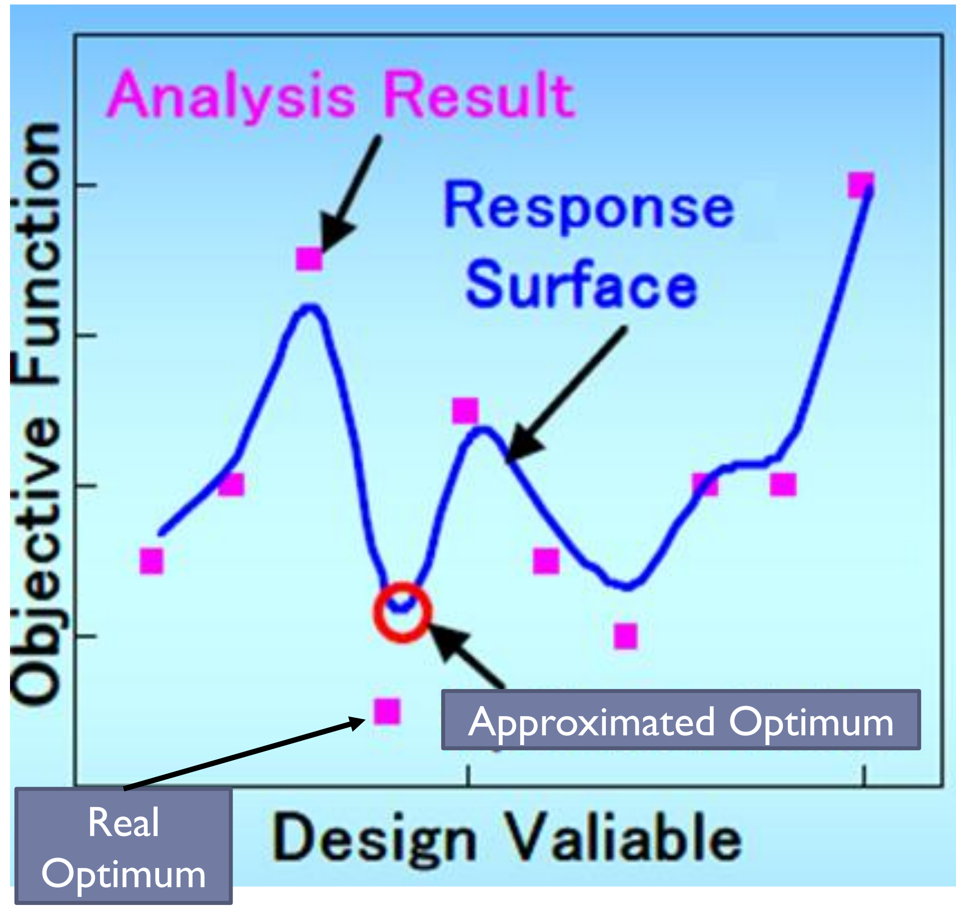
Total FE simulations: 1498

Surrogate Optimization

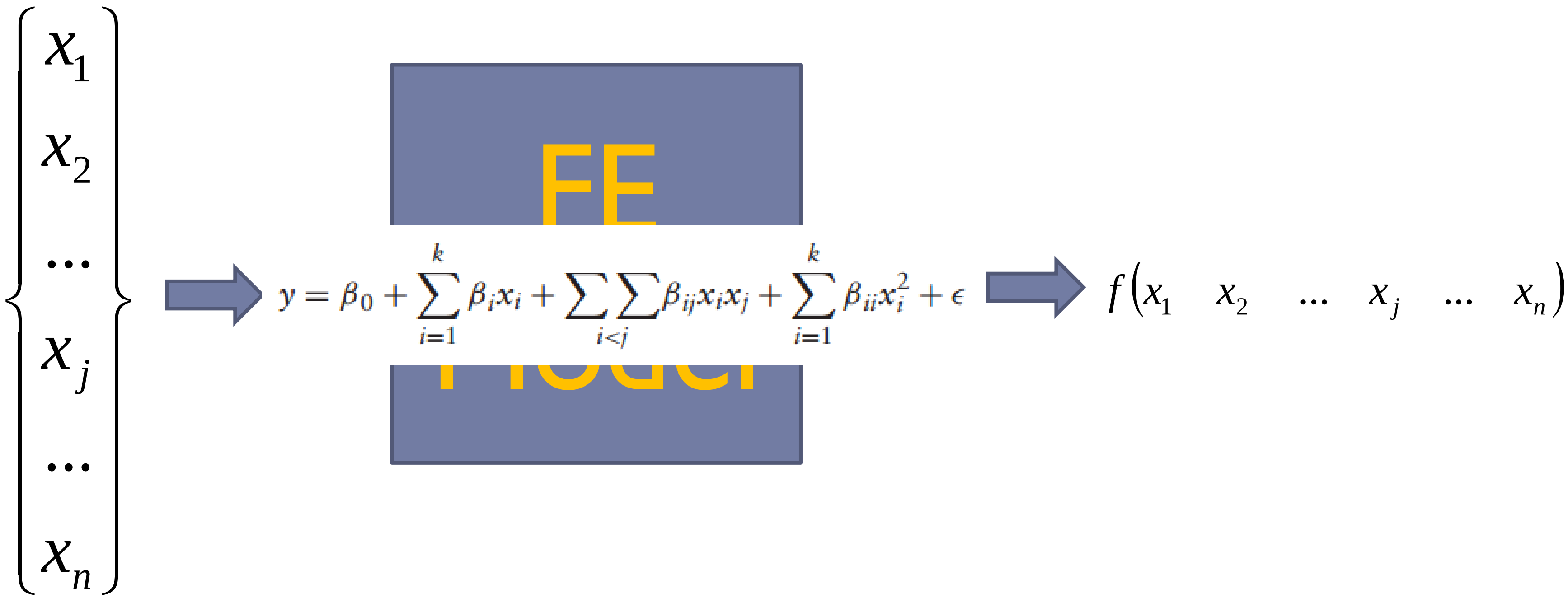


Surrogate Optimization

- CPU-intensive calculations for constraints and/or objective functions are replaced by approximations
- Approximations are then used to find approximated optima
- Starting from approximated optima, a direct FE optimization is performed locally



Response Surface Methodology / 1



$$\begin{Bmatrix} x_1 \\ x_2 \\ \cdots \\ x_j \\ \cdots \\ x_n \end{Bmatrix} \Rightarrow y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j}\sum \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \epsilon \Rightarrow f(x_1 \quad x_2 \quad \dots \quad x_j \quad \dots \quad x_n)$$

- From Statistics: Response Surface Methodology (RSM)
- With RSM, a simple polynomial model is fitted to a set of data collected at the points of a sampling set
- Since nonlinearity is expected in the surface shape, the model also considers cross-product terms and / or pure quadratic terms

Response Surface Methodology /2

- With RSM:
  - an approximated relationship between y and $x_1, x_2, \dots, x_k$ that can be used to predict response values for any given set of the control variables

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j} \sum \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \epsilon$$

  - to do this, a series of n numerical experiments should first be carried out (sampling), in each of which the response y is measured for specified settings of the control variables

Response Surface Methodology /3

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j}\sum \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \epsilon$$

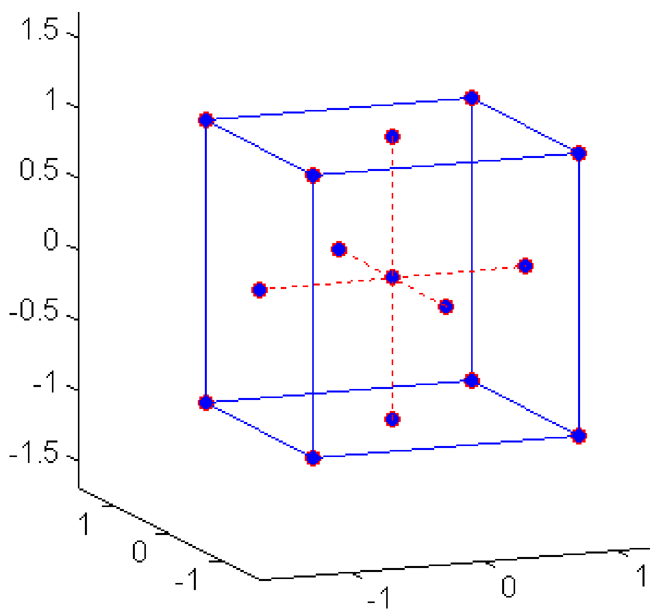
- Model coefficients *beta* are calculated using the least square criterion on a set of "numerical experiments"
- Industrial process are always smooth in a limited factor range, so RSM can be trusted to approximate the FE model
- Any continuous and differential function can be arbitrarily well approximated by a Taylor series in a given interval

Sampling Strategy

- A set of "numerical experiments" is used to tune the surrogate model to replace the FE model
- The set of "numerical experiments" should supply a relationship between input factors and output responses, with best precision and least computational cost
- With Design of Experiments (DOE), an estimation of interaction and even quadratic effects is achieved

Response Surface Designs: CCD

- To calibrate quadratic models, Central composite designs (CCDs) are much more efficient than full factorial designs, using three or five levels for each factor, but not using all combinations of levels
- Each CCDs design consists of a factorial design (the corners of a cube) together with center and star points that allow for estimation of second-order effects.



Direct vs. Surrogate Optimization

Direct FE Optimization:

$$\left\{\begin{matrix} Turns\_number \\ Layers\_number \\ Jacket\_width \end{matrix}\right\} \Rightarrow \text{ANSYS} \Rightarrow \left\{\begin{matrix} Max\_Von\_Mises \\ Peak\_Magn\_Field \end{matrix}\right\}$$

ANSYS

220 sec

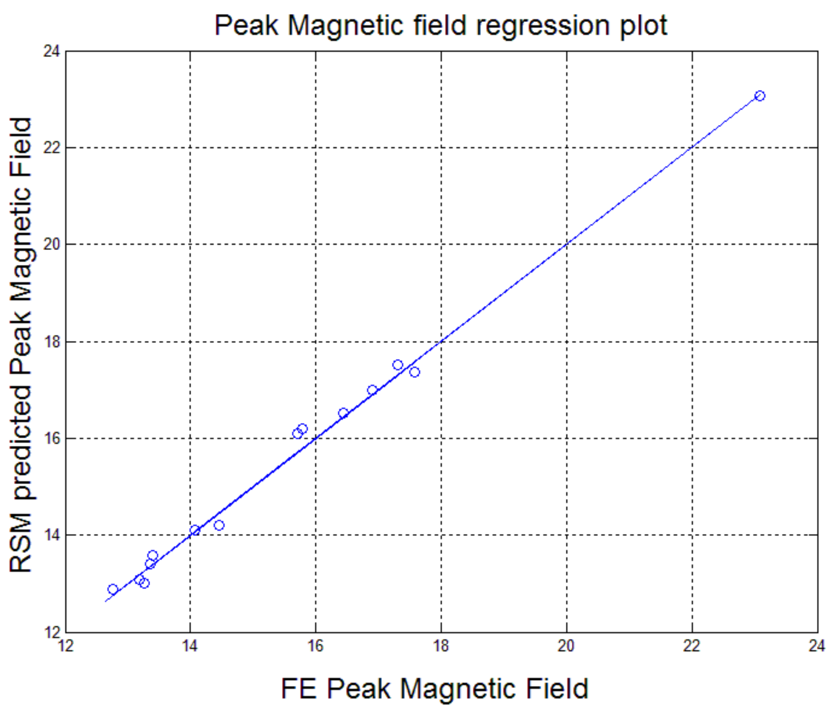
RSM Surrogate Optimization:

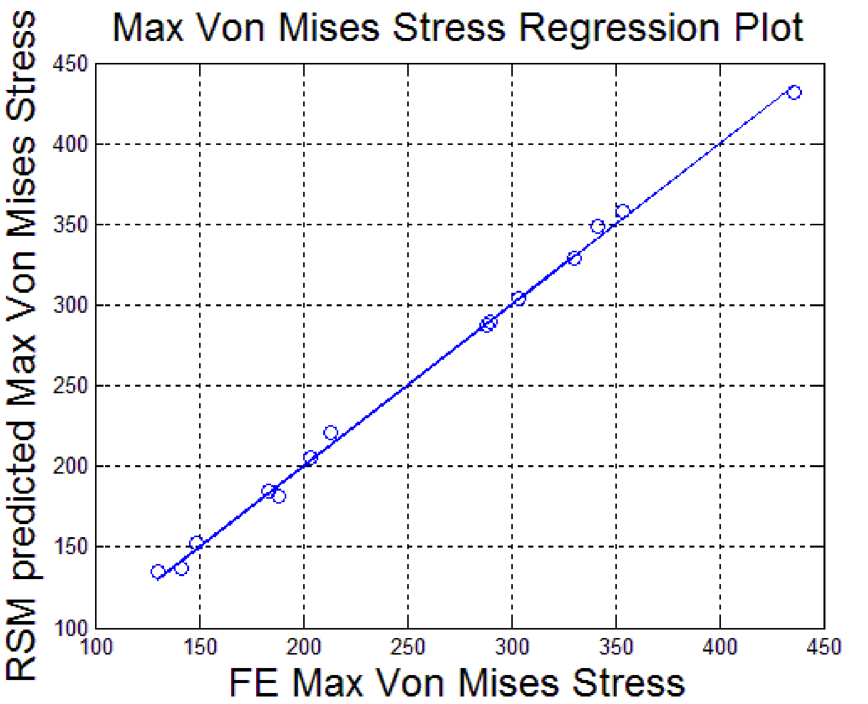
$$\left\{\begin{matrix} Turns\_number \\ Layers\_number \\ Jacket\_width \end{matrix}\right\} \Rightarrow \text{RSM approx. Surrogate Model} \Rightarrow \left\{\begin{matrix} Approx\_Max\_Von\_Mises \\ Approx\_Peak\_Magn\_Field \end{matrix}\right\}$$

RSM approx.
Surrogate
Model

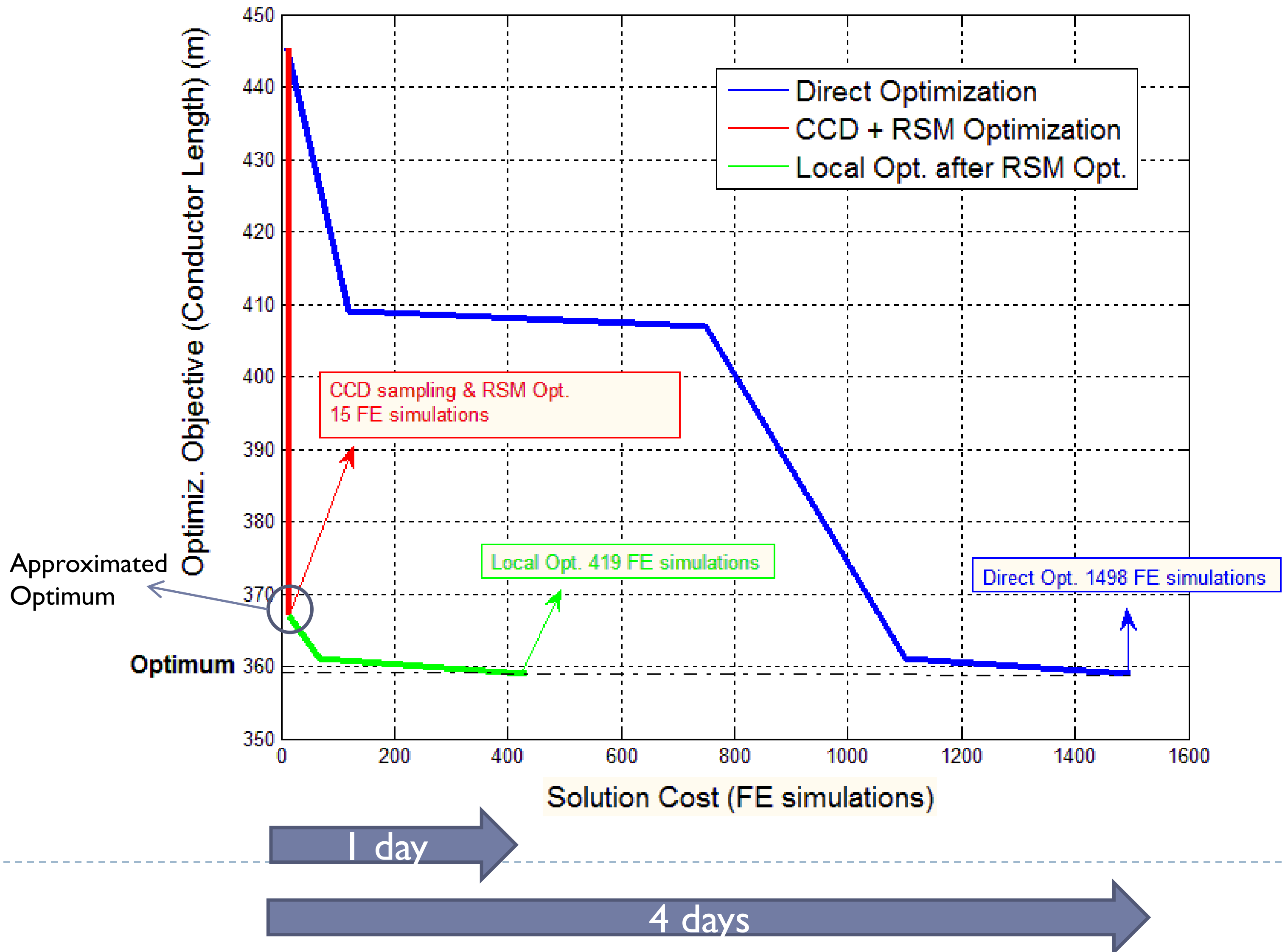
< 1 sec

RSM Surrogate Model Regression Plots





Results: solution cost comparison



Conclusions

- A new design approach was proposed, which guarantees HTS material costs minimization, avoiding the standard trial-and-fail design approach, which does not

- By means of the direct optimization, an optimal 360 m total conductor length, achieving 17 T, was determined in terms of *jacket width* and *number of turns and layers*, that ensures structural integrity, with a solution cost of 1498 FE simulations (4 days of calculations)

- With surrogate RSM optimization, the same configuration is determined with 434 FE simulations (about 1 day of calculations), taking full advantage of statistics derived from numerical sampling

Direct FE Optimization	Surrogate RSM Optimization
1498 FE Simulations	434 FE Simulations
4 days of optimization time	1 day of optimization time

- Thanks for your kind attention!