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Designing superconducting magnets using simple genetic algorithms

V. Calvelli
IRFU/DACM/LEAS

09/07/2020

SUMMARY

The challenges in designing superconducting magnets

- Magnets for particles detection
- Magnets for particles accelerators

Why AI methods can be useful

Examples of Genetic Algorithms Applications for Superconducting Magnets

- Description
- Ex : how to optimize the conductor cost in a 3D magnet design : the MADMAX dipole
- Ex: how to optimize the magnetic field quality in a 2D magnet design : the F2D2 dipole

Conclusions

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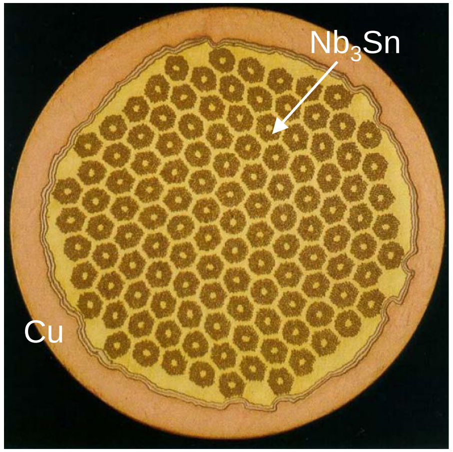
Challenges in Superconducting Magnets Design

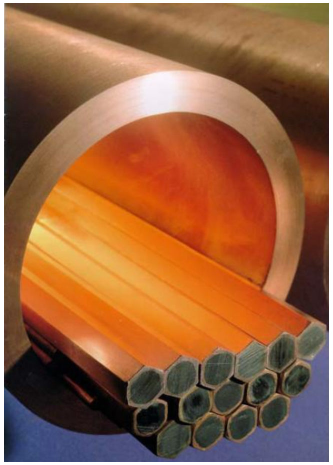
9/1/2020

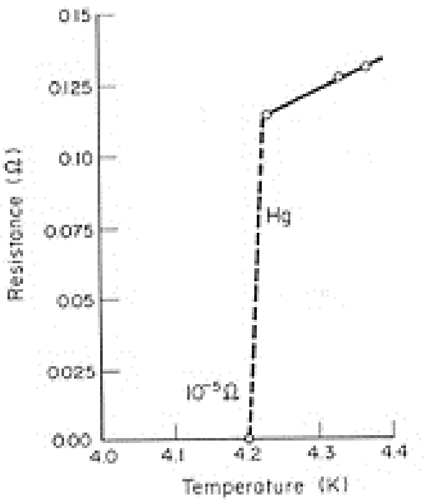
Why superconductivity?

Superconductive materials show zero electric resistance
→ they can transport a lot of current without heating

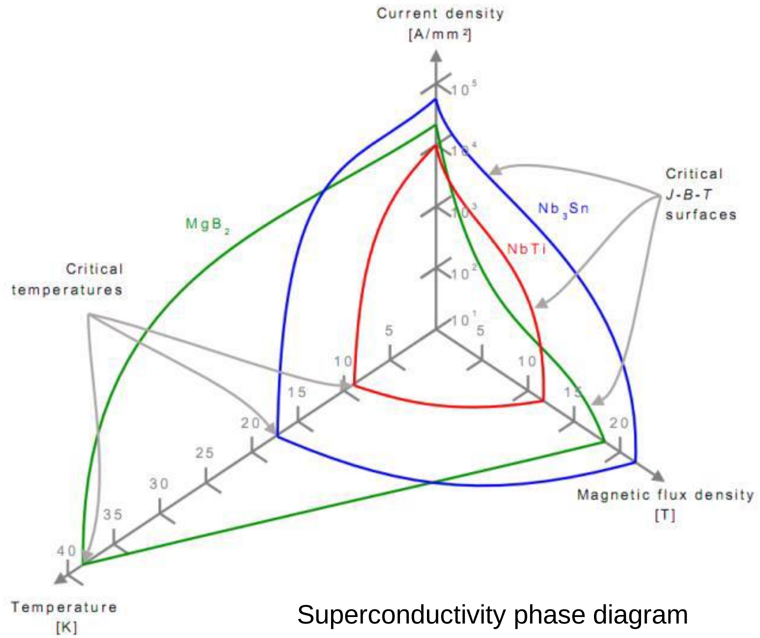


Nb_3Sn bronze-process wire [1]





Hg resistivity



Superconductivity phase diagram

The superconducting state is limited by
- $\vec{B}$ magnetic field
- $\vec{J}$ current density inside the material
- T temperature

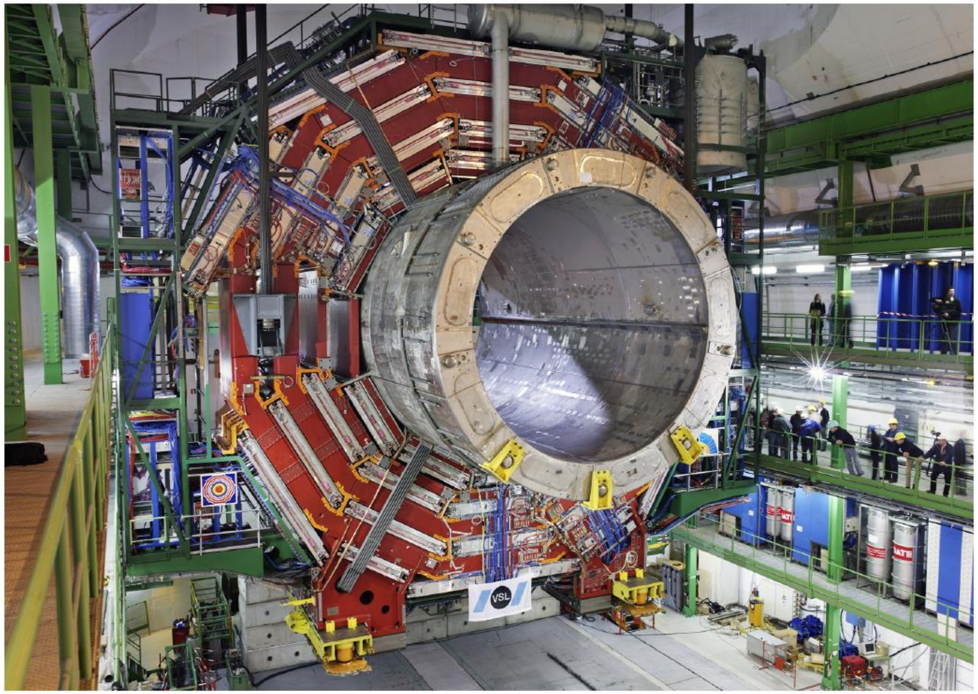
Challenges in Designing Superconducting Magnets

Why superconducting magnets?

Advantages:

- Very high magnetic field (up to 40T)
- Reduced dimensions (10x compared to copper magnets)
  → scale economy, better quality control in performances
- No ohmnic power dissipation → reduced comsumptions

The CMS solenoid at CERN



YB0 landing in the CMS experiment hall

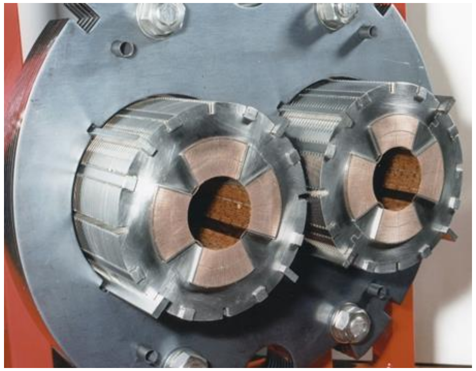
CHALLENGES IN DESIGNING SUPERCONDUCTING MAGNETS

Why superconducting magnets?

Drawbacks:

- Must work in cryogenic environment (1.8 K to 70 K)
- The superconducting state is very fragile → even a deposit of few *mJ* can make a magnet transit to the normal state
- High magnetic field + High current → High forces & high energy density in the materials

The Nougat solenoid (32.5 T) @ LCNMI Grenoble



The quadrupoles MQYY for Hi-Lumi LHC, designed and assembled by CEA

The ISEULT MRI @ Neurospin

Which challenges?

- **Field quality**
  $\Delta B/B \sim 10^{-4}$ for particle accelerators
  $\Delta B/B \sim 10^{-8}$ for MRI

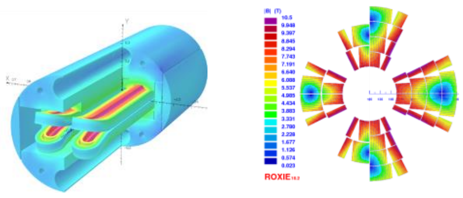
- **Mechanics**
  Stress can reach 300 MPa on the conductor

- **Cryogenics**
  Must cool down tons of materials

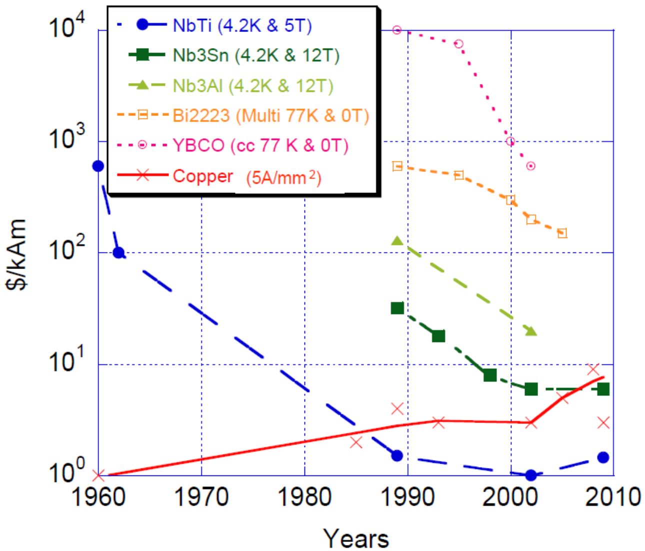
- **Protection**
  Transition to the normal state means 1000s A in ~mm² wires (normal Cu wire carries some A)

- **Cost**
  Superconductors can cost up to 1000$/kAm

FCC Dipole & Quadrupole



US$ 150/kg ↔ ~1 $/kAm



P. Fazilleau – Ecole des accelerateurs 2016

WHY USING AI METHODS?

Field Quality

Depends on:

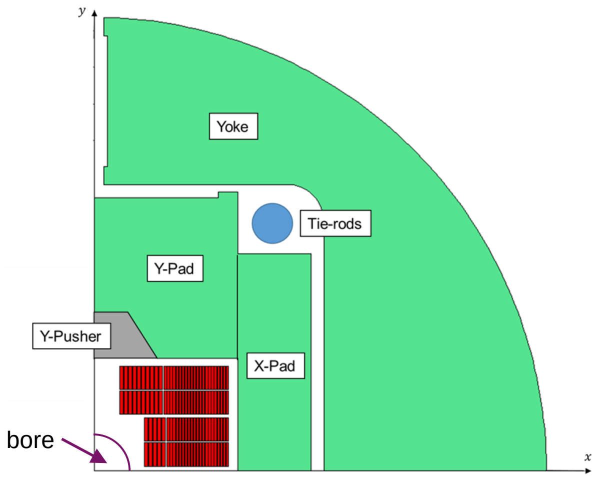
- Position of the coils → linear contribution to B
- Position of the ferromagnetic materials → non linear contribution to B

Cost

Depends on:

- The volume of conductor needed
- The quantity of superconducting material needed in the cable to stand the magnetic field peak

Not possible to write down an analytical function



Problem is :
Given a certain B according to specs,

Field Quality
Minimization of the ratio $\Delta B/B$ in the bore region

Cost
Minimization of the ratio $\Delta B/B$ on the conductors

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Examples of Genetic Algorithms Applications for Superconducting Magnets

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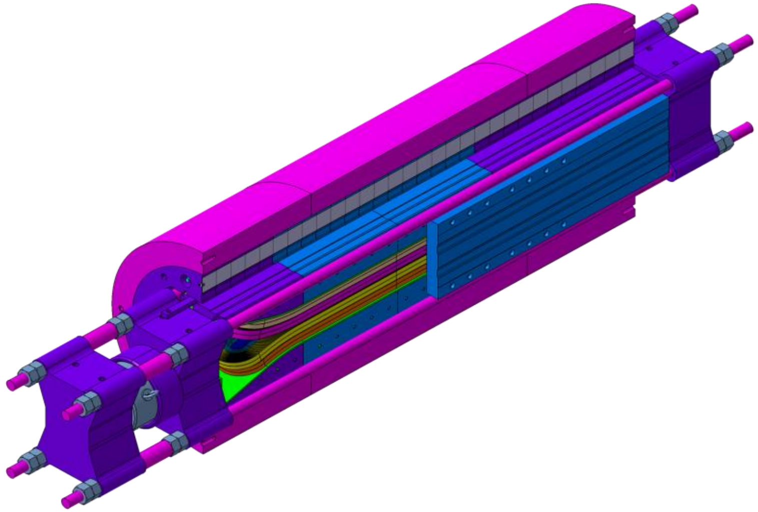
Examples of Genetic Algorithms Applications

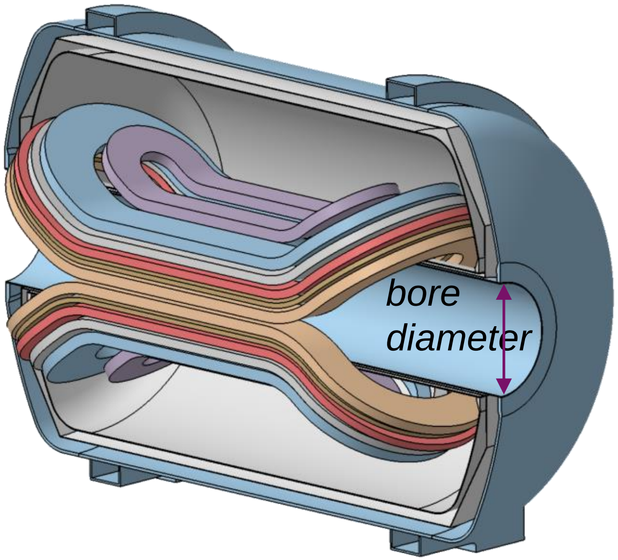
Field Quality

F2D2
The 16 T graded Nb_3Sn flared ends dipole to prove the feasibility of the Future Circular Collider at CERN.

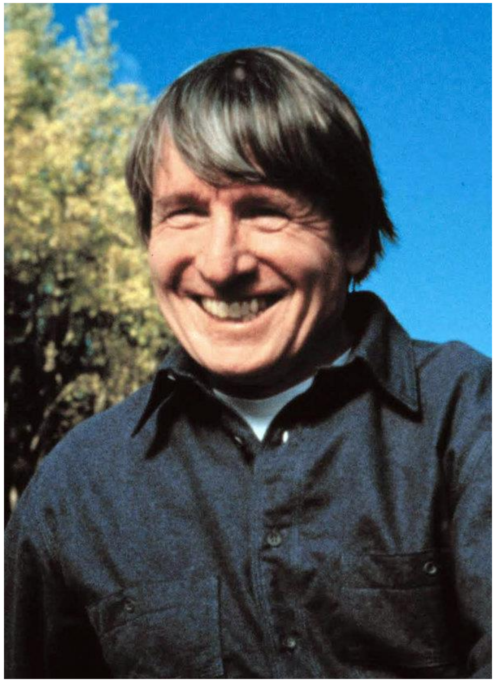


Cost

MADMAX
The 9 T NbTi, 1.3 m of useful diameter dipole (the biggest in the world) to find axions-like particles.



One of the first AI methods

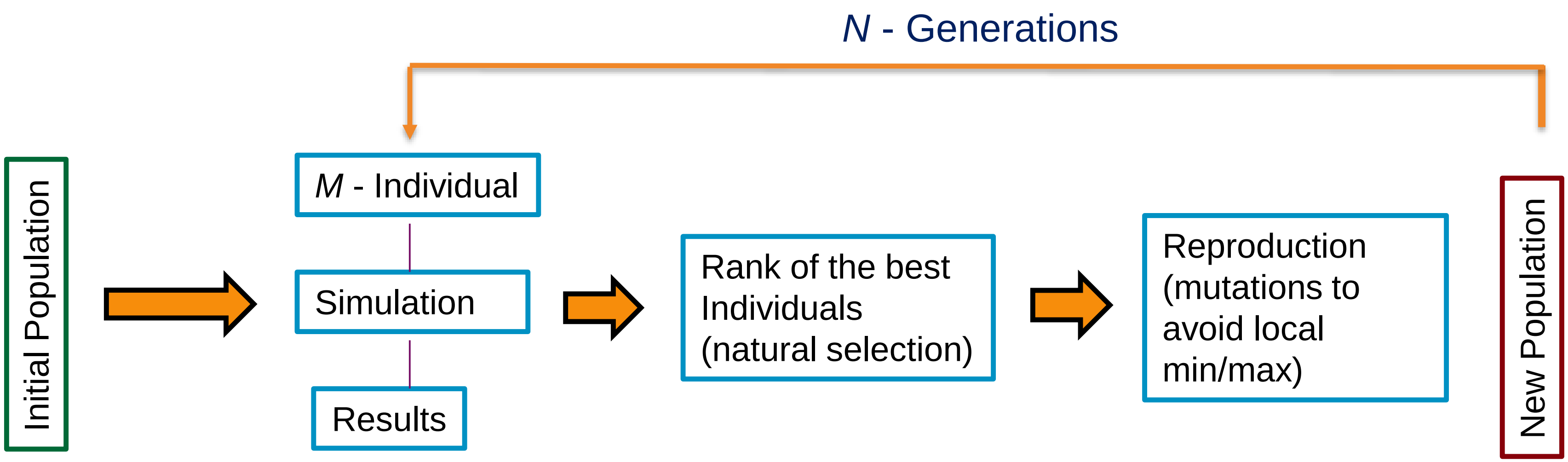


- Invented by *John Henry Holland,* prof. at University of Mitchigan, in Adaptation in Natural and Artificial Systems (1975, MIT Press)
- They mock the darwinian evolution
- Used in physics, engineering, finance… to find maximum/minimum of unknown functions

Concepts:

- Each parameter = GENES
- Set of parameters = INDIVIDUAL
- Set of individuals = POPULATION
- Evolution of the population = GENERATION

Working Principles



Initial Population

Step 1
Choose the parameters (genes) and their range
Ex:

$$L_{xy1} \in [-2,1]$$
$$L_{xy2} \in [-3,4]$$
$$\dots$$

Step 2
Build an individual (by randomic PDF generation). 1 number for each gene

$$L_{x1} = \begin{pmatrix} L_{x11} = 0.5 \\ L_{x12} = 1.2 \\ \dots \end{pmatrix}$$

Step 3
Build a population

$$L_1 = \begin{pmatrix} L_{11} = (L_{111}, L_{112}, \dots) \\ L_{12} = (L_{121}, L_{122}, \dots) \\ \dots \end{pmatrix}$$

How to choose correctly

ν number of parameters (degree of freedom) of the problem

m number of individuals $\geq D_{\nu,2} = \frac{\nu!}{(\nu-2)!}$

n generations* $> 2^{\nu-1}$

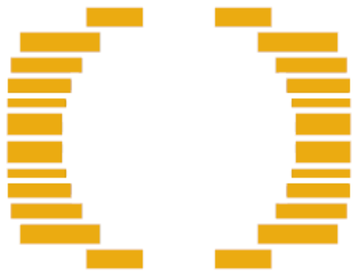
Minimal number of simulations

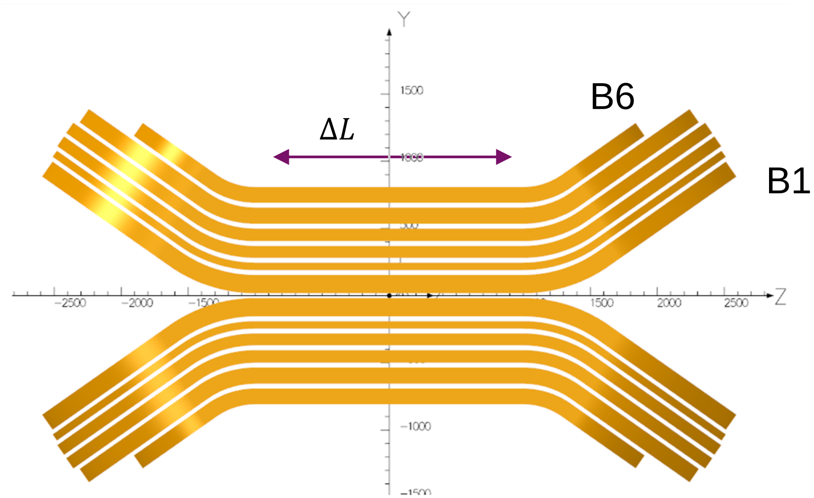
$$m \times n = 2^{\nu-1} \frac{\nu!}{(\nu-2)!}$$

Limit the number of parameters

*criteria (*n* actually depends on how fast the function goes to min / max)

Example: MADMAX Block Dipole





GA parameters:
- $0 < \Delta L < 300$ mm B1→B4
- $0 < \Delta L < 400$ mm B5
- $0 < \Delta L < 500$ mm B6

Population = 30 individuals
Generations = 32

Tot forecast 3D simulations = 960

Simulation

Step 1 – Fitness Function
Choose what do you want to evaluate

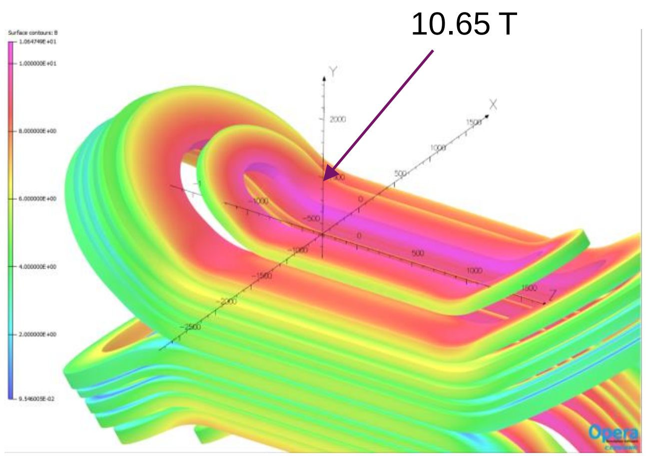
Ex: Volume – Cost function for the conductor

$$\begin{cases} C_{cond} = V_{cond}\left(C_{Cu}\left(1 - \frac{J_E}{J(B_{peak})}\right) + C_{NbTi}\left(\frac{J_E}{J(B_{peak})}\right)\right) \\ J(B_{peak}) = (1-m)J_c\left(\frac{B_{peak}}{1-m}, T_0\right) \end{cases}$$

Where:
- V_{tot} conductor volume
- J_E engineering current density
- T_0 operating temperature
- $m = 0.1$ LL margin
- C_{Cu} copper volume cost
- C_{NbTi} NbTi volume cost

Step 2
Evaluate the fitness function (simulations) for each individual

$$C_{cond}(L_{11}), C_{cond}(L_{12}), \ldots$$



Rank of the best individuals

Step 1 – Choose if you want to find *min* or *max* of your fitness function

Ex: min of $C_{cond}(V_{cond}, B_{peak})$

Step 2 - Ranking

Rank the individual according to which one has the minimal value.

Ex:

$L_{11} = 2000$
$L_{12} = 1500$
$L_{13} = 1700$
$L_{14} = 1900$
$L_{15} = 1600$
$L_{16} = 2100$

→

$1. L_{12} = 1500$
$2. L_{15} = 1600$
$3. L_{13} = 1700$
$4. L_{14} = 1900$
$5. L_{11} = 2000$
$6. L_{16} = 2100$

Step 3

Assign a probability of reproduction to the individuals according to the rank

Criteria:

i rank position

$$\boldsymbol{p_i} = \frac{\frac{\boldsymbol{m-i}}{\boldsymbol{m}}}{\sum_{\boldsymbol{i=1}}^{\boldsymbol{m}} \frac{\boldsymbol{m-i}}{\boldsymbol{m}}}$$

$$\begin{aligned}
1. L_{12} &\longrightarrow p(L_{12}) = 0.333 \\
2. L_{15} &\longrightarrow p(L_{15}) = 0.267 \\
3. L_{13} &\longrightarrow p(L_{13}) = 0.200 \\
4. L_{14} &\longrightarrow p(L_{14}) = 0.133 \\
5. L_{11} &\longrightarrow p(L_{11}) = 0.067 \\
6. L_{16} &\longrightarrow p(L_{16}) = 0.000
\end{aligned}$$

GENETIC ALGORITHMS FOR MADMAX

Reproduction

Step 1 – Coupling
Random extraction of two numbers x_1, x_2 with an uniform PDF [0,1]

Ex: $x_1 = 0.3$, $x_2 = 0.7$

Calculate the cumulative function $\int p_i$, assigning the respective parameter

$$1. L_{12} \longrightarrow [0{,}0.333]$$
$$2. L_{15} \longrightarrow (0.333{,}0.6]$$
$$3. L_{13} \longrightarrow (0.6{,}0.8]$$
$$4. L_{14} \longrightarrow (0.8{,}0.933]$$
$$5. L_{11} \longrightarrow (0.933{,}1]$$

Where x_1, x_2 falls, you have your couple ;)
No self reproduction allowed.

Step 2 – Cross-over
Random extraction of two numbers c_1, s_2
c_1 uniform PDF [cross-over,1]
s_2 uniform PDF [0,1]

Generally, cross-over > 0.7

If $x_1 < c_1$ and $x_2 < c_1$
Reproduction! ;))

$$L_{211} = s_2 \cdot L_{121} + (1 - s_2)L_{131}$$
$$L_{212} = s_2 \cdot L_{122} + (1 - s_2)L_{132}$$
$$L_{213} = s_2 \cdot L_{123} + (1 - s_2)L_{133}$$
...

For every gene

Else

$$L_{21} = L_{12}$$

Until we replace L_1

Bonus: Mutation

Step 1
For each gene,
Random extraction of one number
x_3 uniform PDF [0,1]

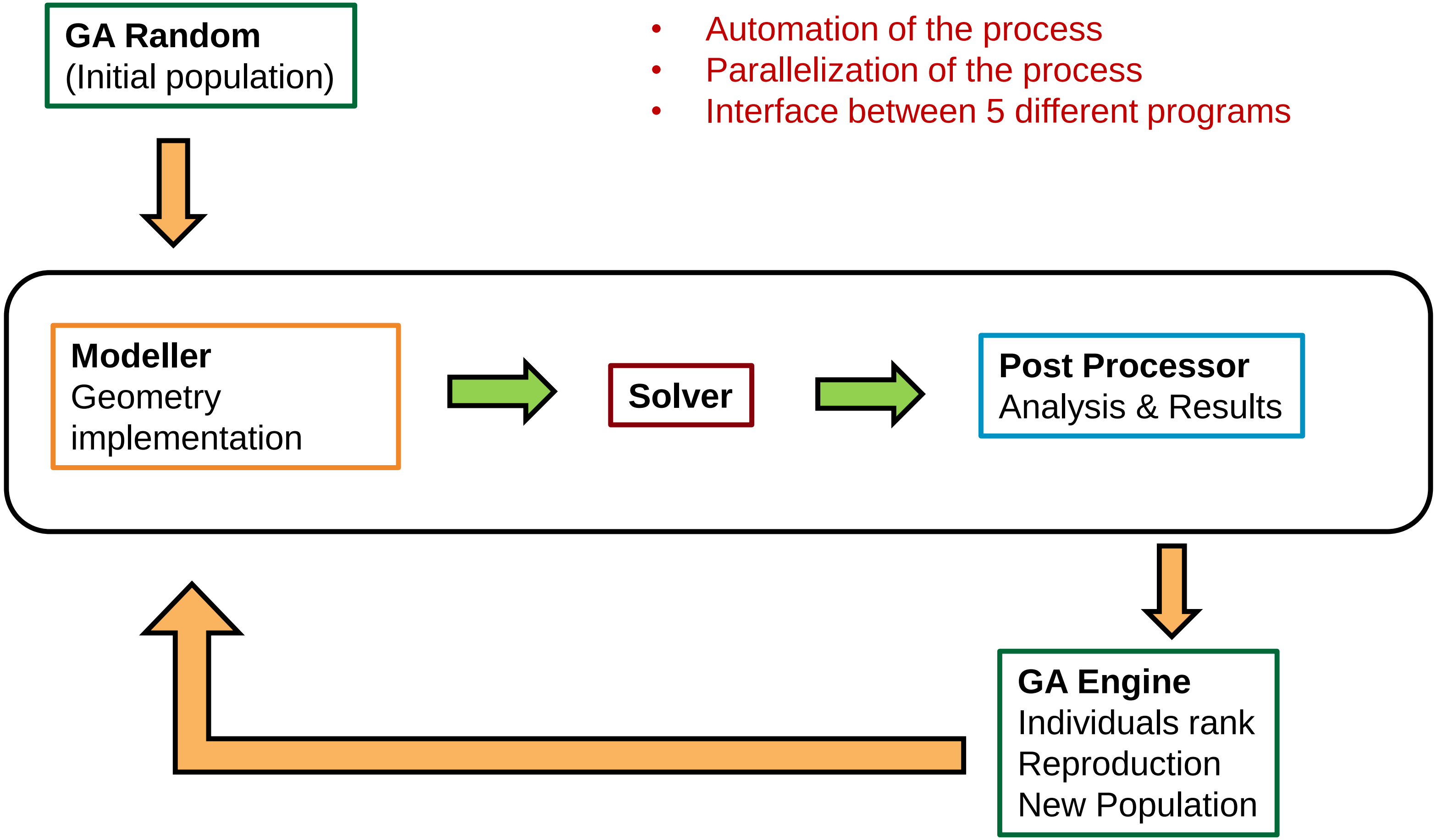
If $x_3 < p_{mutation}$
Then rebuild the gene (step 1 Initial population)

Generally $p_{mutation} < 0.1$

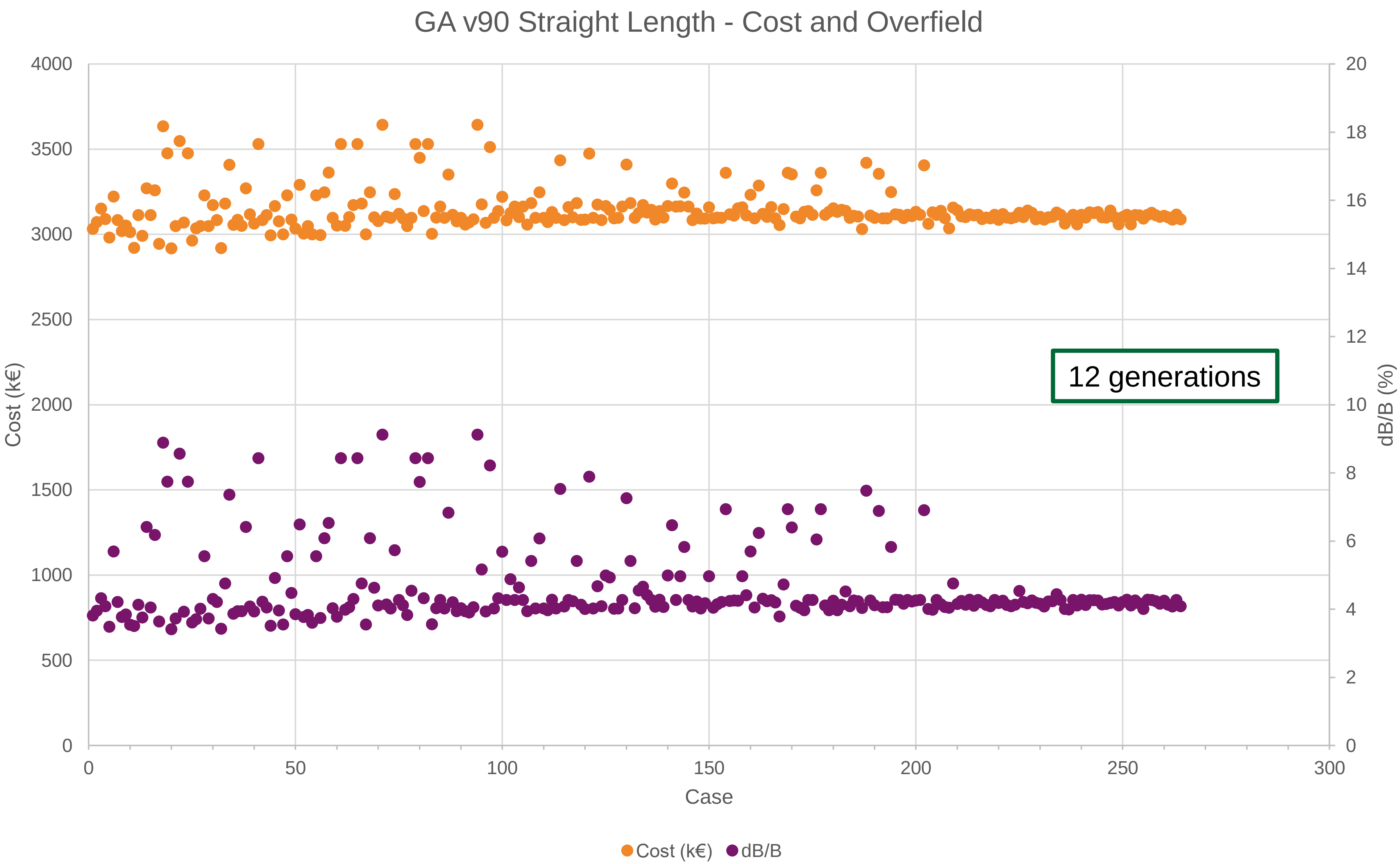
Repeat for each generation

Implementation in OPERA 3D

- Automation of the process
- Parallelization of the process
- Interface between 5 different programs

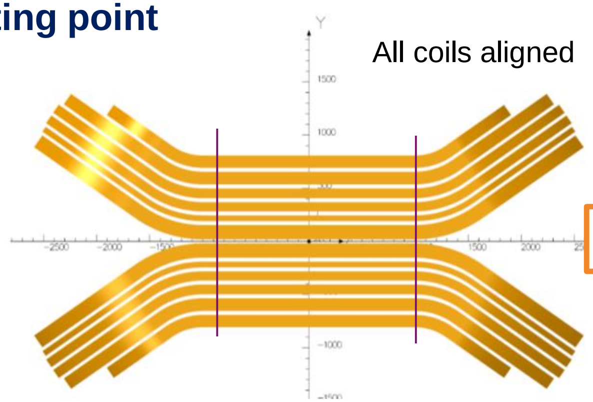


Results on MADMAX Version 9.0



Starting point

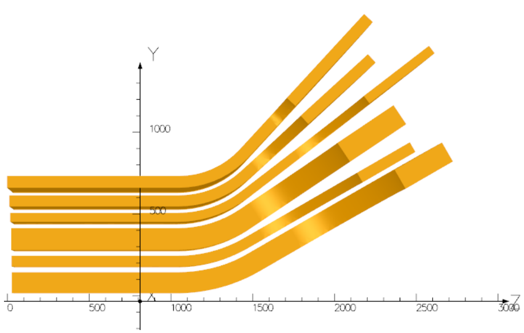
All coils aligned



7980 k€

Intermediate solution

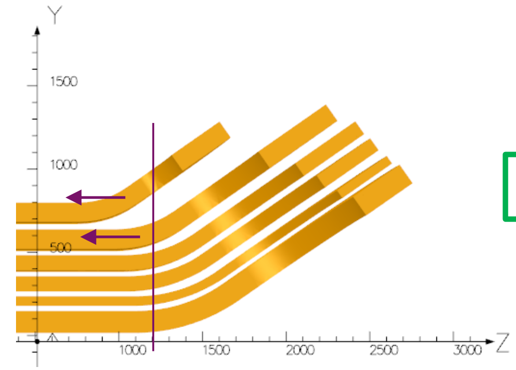
GA study varying many parameters



2816 k€

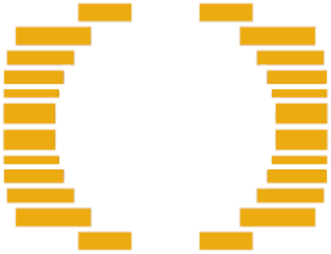
but not feasible for assembly

Final solution

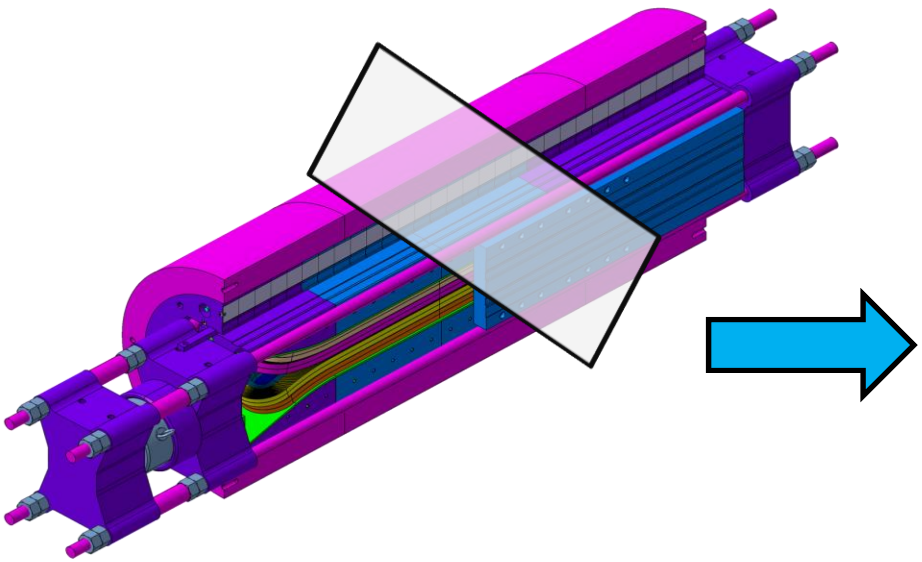


3088 k€

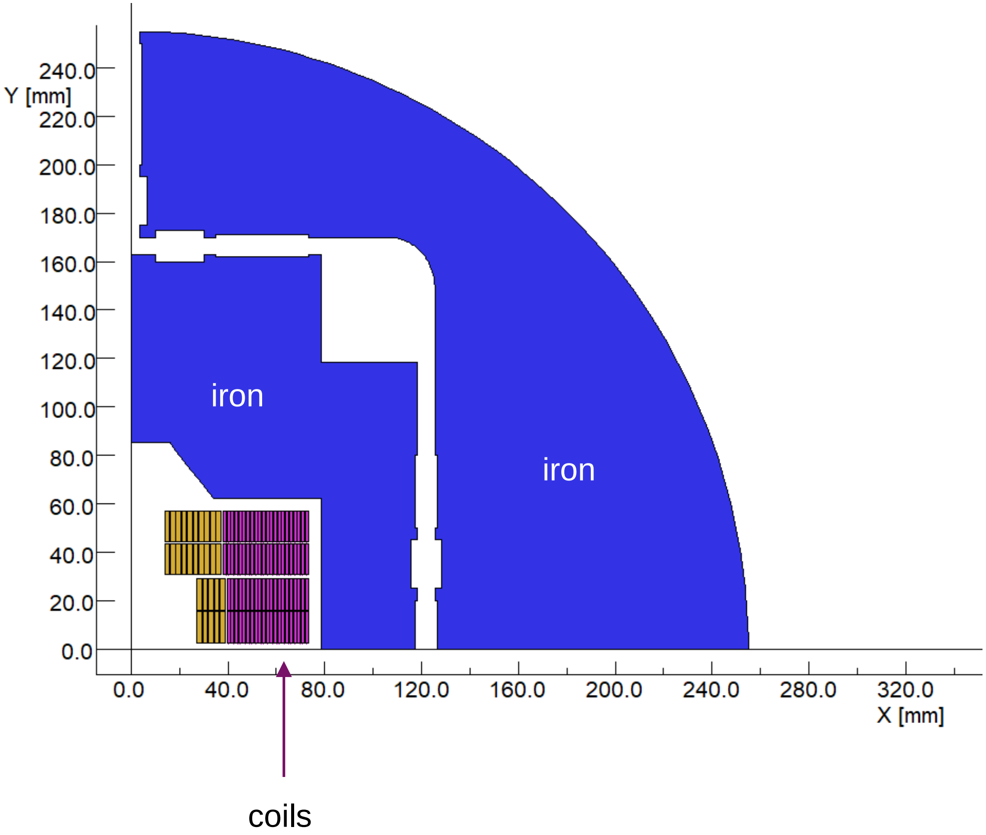
GA + parametric study
to understand the sensitivity of parameters



3D assembly



2D magnetic



F2D2 – Field Quality

Fourier expansion of the magnetic field

$$B_r = \sum_{n=1}^{\infty} \left(\frac{r}{r_{ref}}\right)^{n-1} [B_n \sin(n\theta) + A_n \cos(n\theta)]$$

$$B_\theta = \sum_{n=1}^{\infty} \left(\frac{r}{r_{ref}}\right)^{n-1} [B_n \cos(n\theta) - A_n \sin(n\theta)]$$

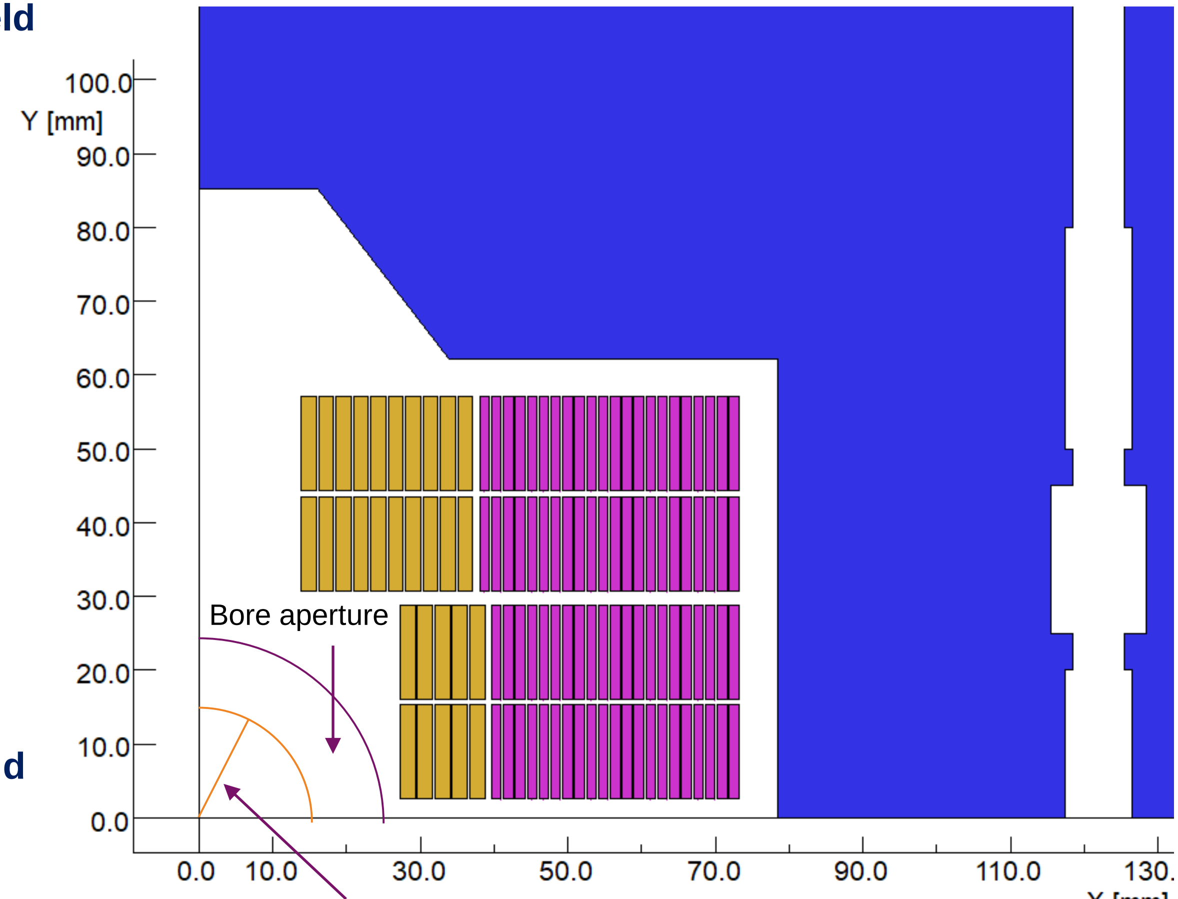
Harmonics

$$b_n = \frac{B_n}{B_{ref}} \cdot 10^4$$

$$a_n = \frac{A_n}{B_{ref}} \cdot 10^4$$

Series expansion of the magnetic field

$$B_y + iB_x = 10^{-4} B_0 \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{x + iy}{r_{ref}}\right)^{n-1}$$



$$r_{ref} = \frac{2}{3} r_{bore}$$

F2D2 – GA Study

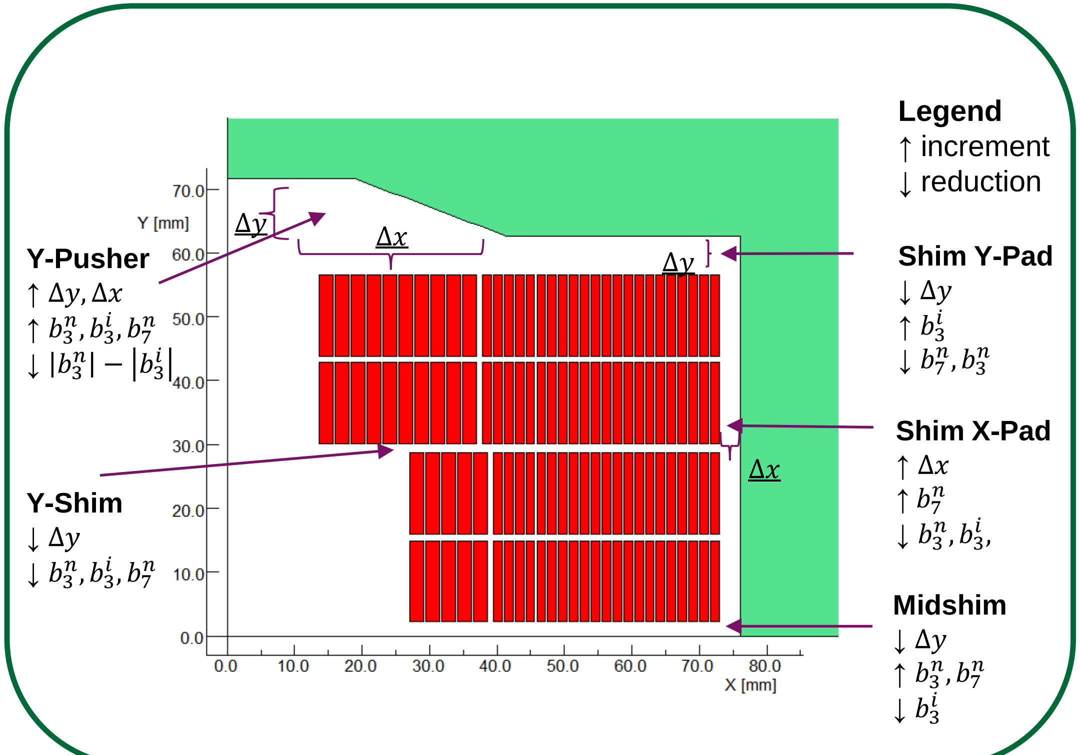
Parameters

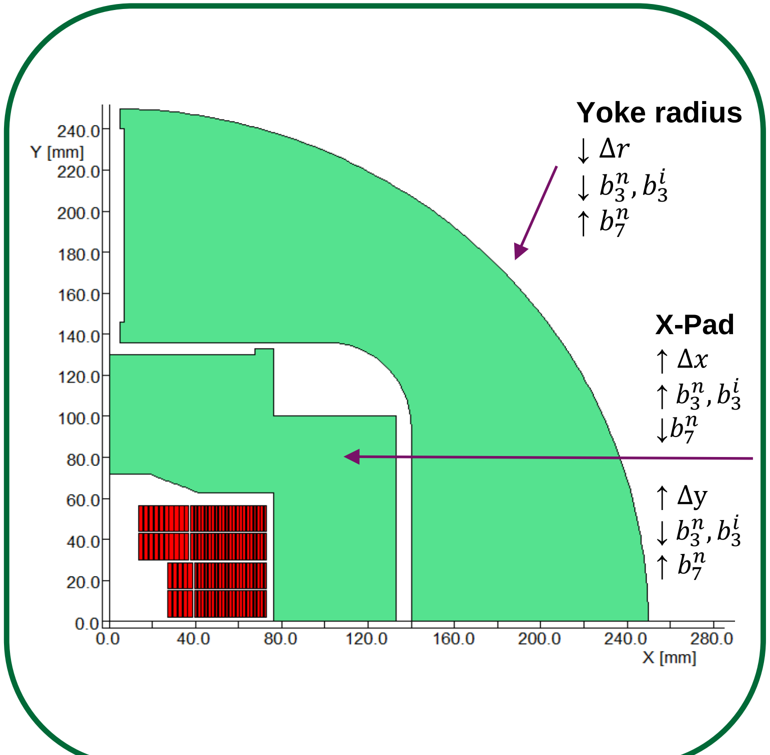
- Turns and position of the coil without iron → analytical
- Position of the coils & position of the iron → GA

Criteria

$-3 \leq b_n \leq 3$ @ 15.5 T

$-15 < b_3 < 15$ @ 1.04 T (induction)





F2D2 – FIELD QUALITY

GA study:

Number of parameters = 9
Forecast number of individuals = 72
Forecast number of generations = 256

Forecast number of simulations = 18432

Time per simulation = 115 s
Total time = 24.5 d

GA study coil + iron:

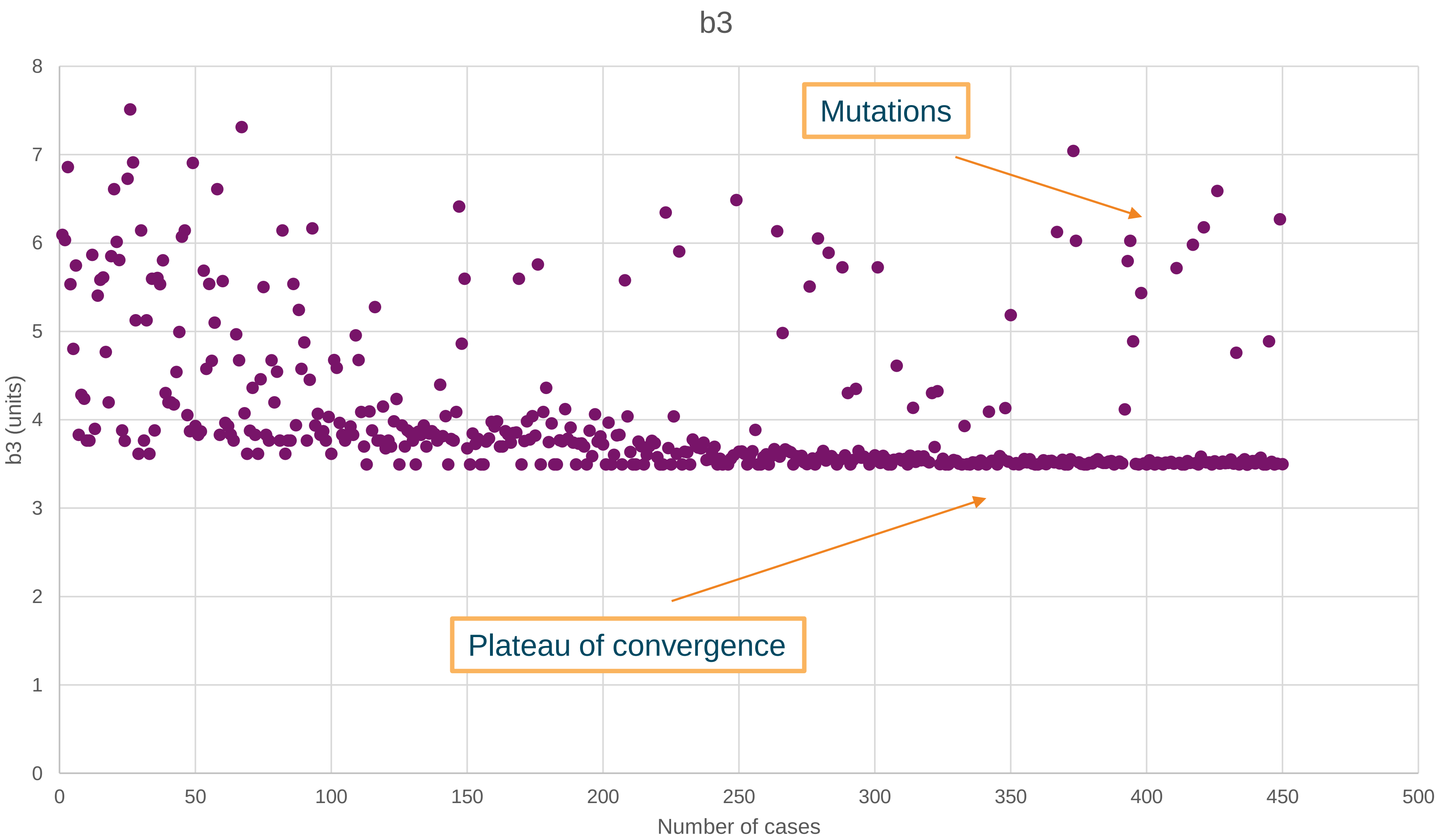
Number of parameters = 3 (coils) + 6 (iron)
Forecast number of individuals = 3 + 30
Forecast number of generations = 8 + 64

Forecast number of simulations = 1944

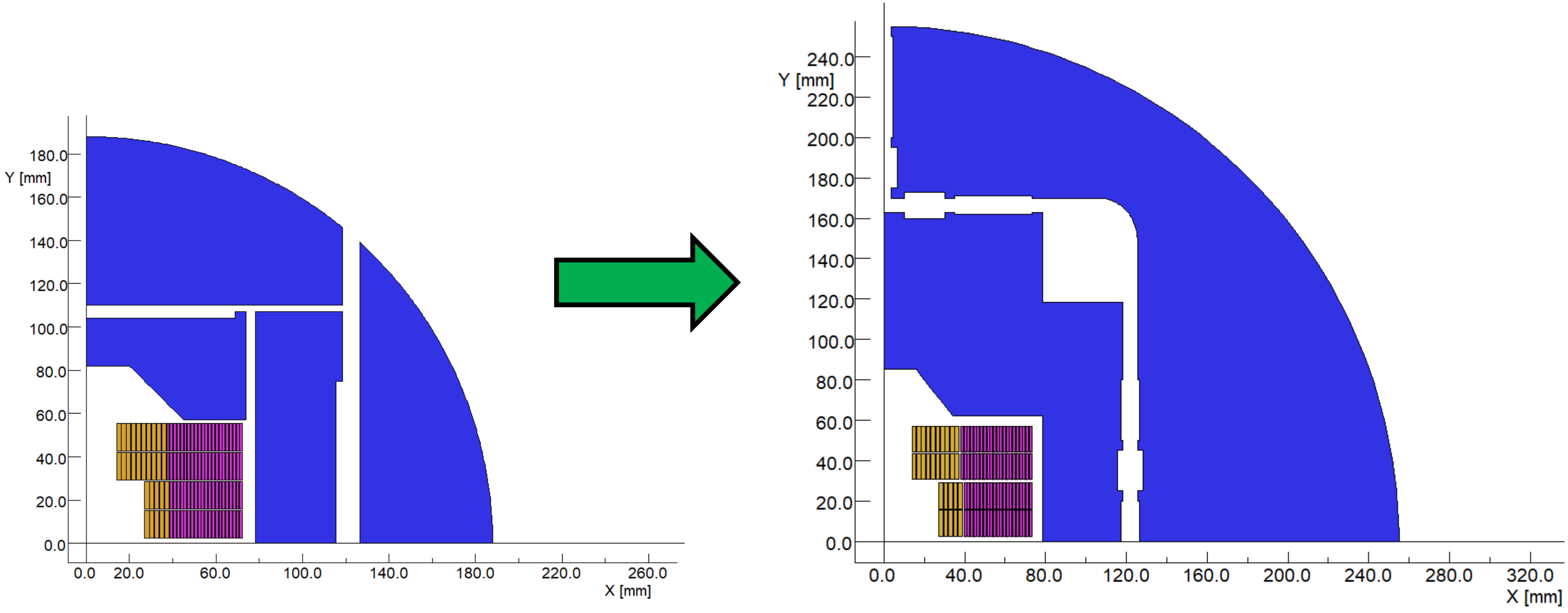
Time per simulation = 45 s
Total time = 2.6 d

Procedure :
1) GA for iron
2) Adaptation of parameters for coils

F2D2 – Results for B3



F2D2 – From Beginning to Final Design



When to Use?

GA can be used for :

- Minimization problem
- Maximization problem

When you don’t know how to write down a function (or a part of).

Warnings:

- To be used with a limited number of variables (as a function of your resolution time)
- How to rank the individuals is one of the hardest problem if you look for multiple fitness functions (ex: *minimize both Bpeak and Volume*)
- They will always find an approximate solution
- Save all the data and look at them in real time → you can converge faster than you thought

THANK YOU FOR YOUR ATTENTION

REFERENCES

1. *A. Devred, (2006)* « Practical low-temperature superconductors for electromagnets », *CERN-2004-006,*
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3. *H. Felice; et all (2019)* « F2D2: A Block-Coil Short Model Dipole Towards FCC », *IEEE Transaction on Applied Superconductivity, vol. 29, Issue: 5*
4. *E. Rochepault; et all (2020)* « 3D Conceptual Design of F2D2, the FCC Block-Coil Short Model Dipole », *IEEE Transaction on Applied Superconductivity, vol. 30, Issue: 4*
5. *V. Calvelli; et all (2020)* « 2D and 3D Conceptual Design of the MADMAX Dipole », *IEEE Transaction on Applied Superconductivity, vol. 30, Issue: 4*