Optimisation topologique en génie électrique

Séminaire GDR SEEDS – GT Systèmes Complexes

Théodore Cherrière
Maître de conférences – CentraleSupélec, GeePs

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SORBONNE UNIVERSITÉ

cnrs

GeePs
Génie électrique et électronique de Paris

CentraleSupélec

université PARIS-SACLAY

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2) Principes de l’optimisation topologique

3) Applications aux machines électriques

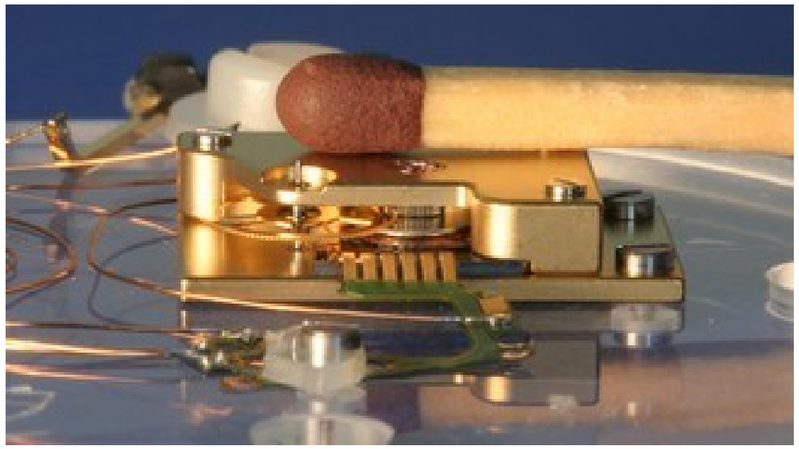
4) Applications à d’autres domaines du génie électrique

5) Conclusion, perspectives

1) Motivations

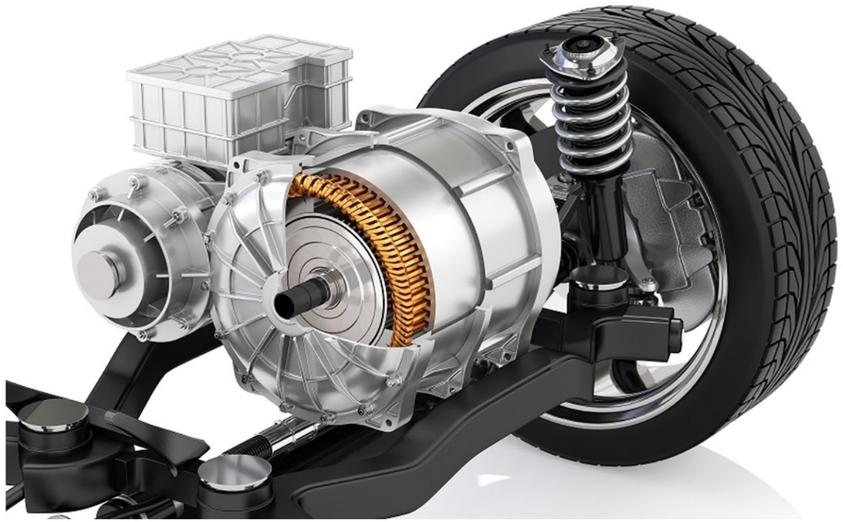
Illustration : machines électriques

Moteurs électriques : typologies

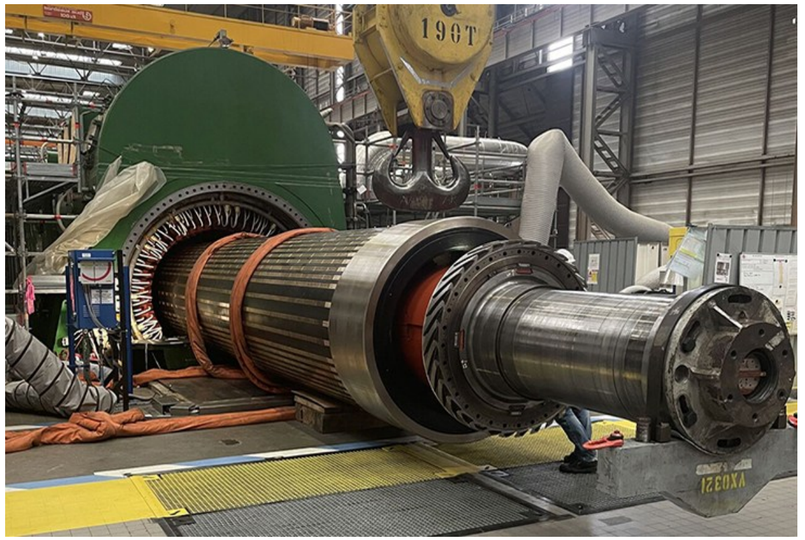


https://phys.org/

https://bivacor.com/

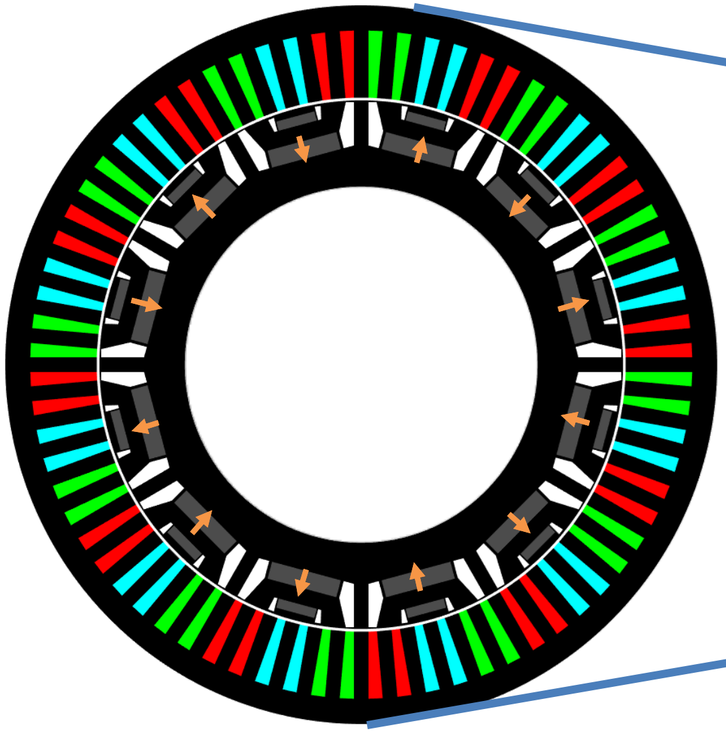


https://rpmweb.ca



https://www.jeumontelectric.com

Moteurs électriques : éléments constitutifs

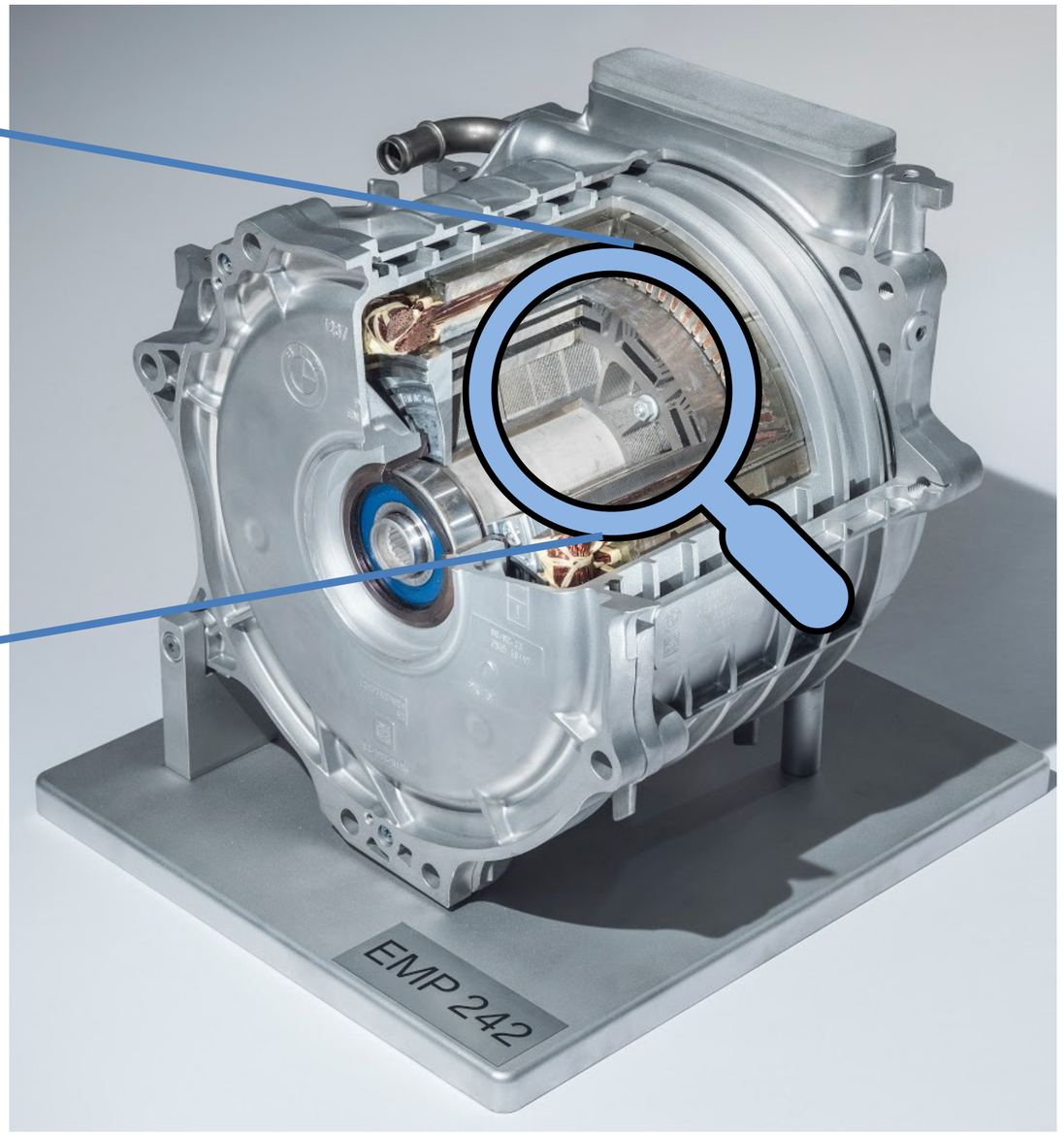


Acier

Air

Aimant

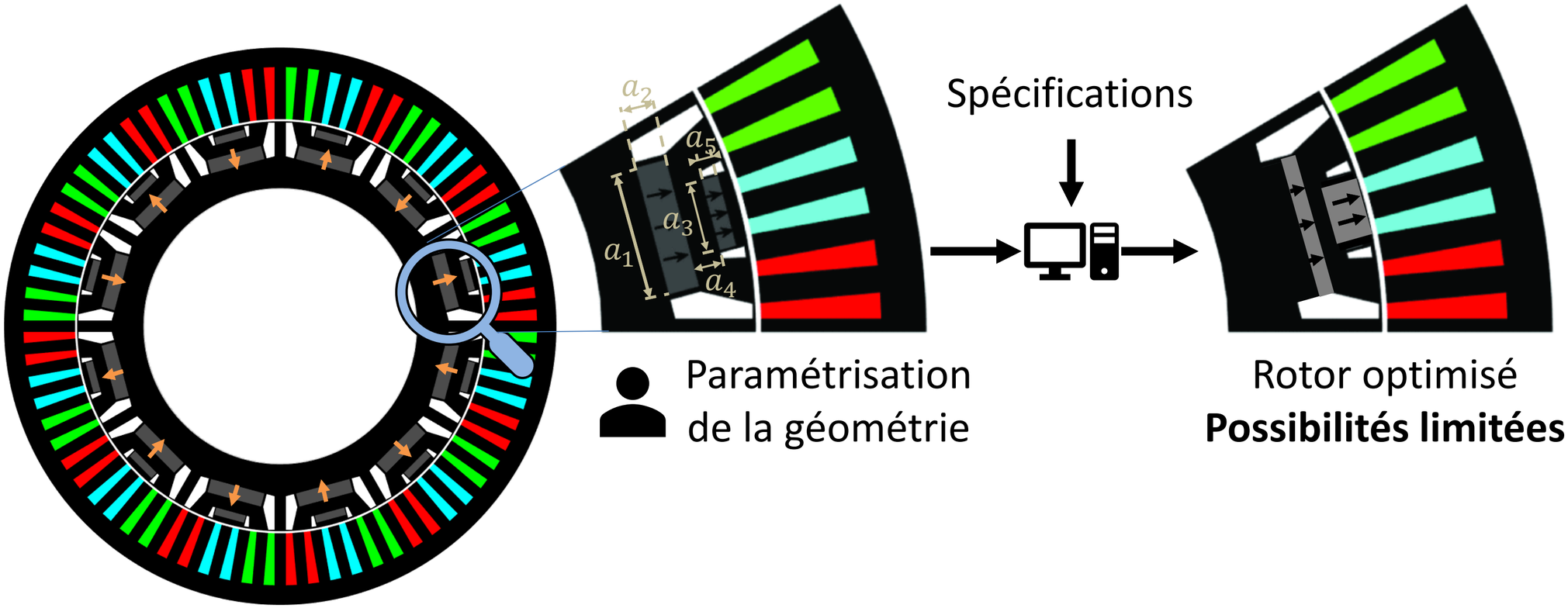
Conducteurs électriques



Moteur BMW i3

(G. Dilevrano et.al, 10.1109/ECCE50734.2022.9947472.)

Moteurs électriques : conception



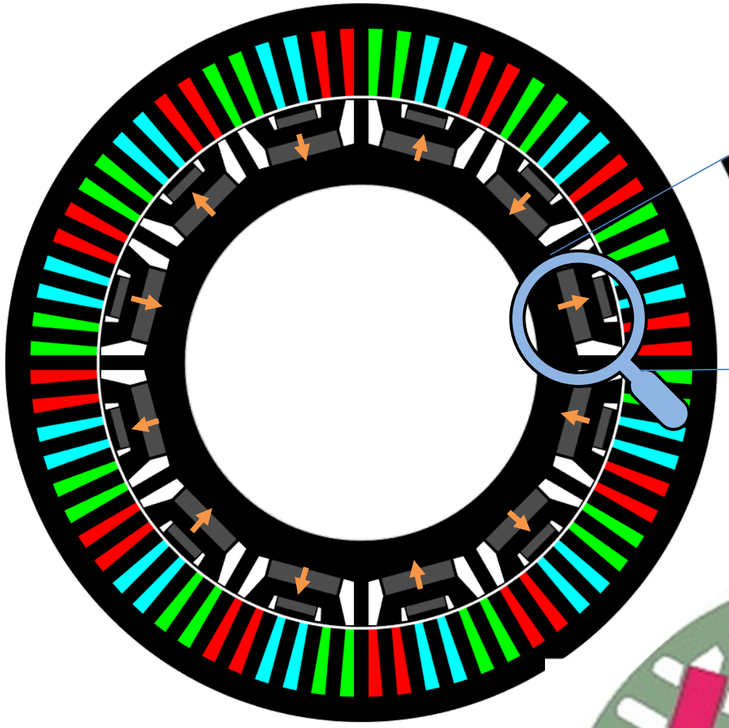
Acier

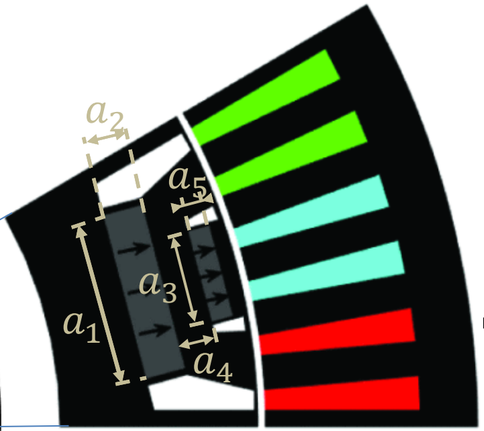
Air

Aimant

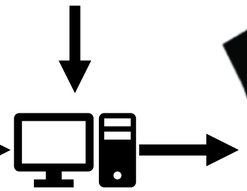
Conducteurs électriques

Moteurs électriques : conception



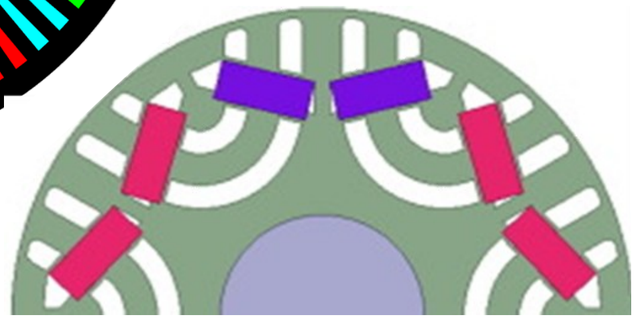


Spécifications

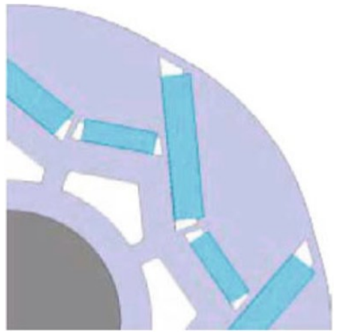


Paramétrisation de la géométrie

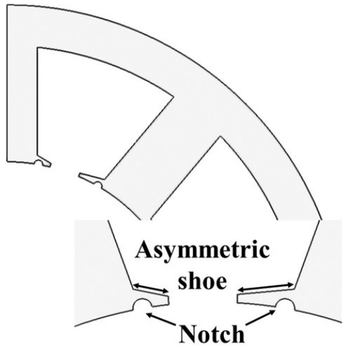
Rotor optimisé
Possibilités limitées



Autres dispositions d'acier et d'aimants ? [1]



Assymétrie ? [2]



Stator ? [3]

Acier

Air

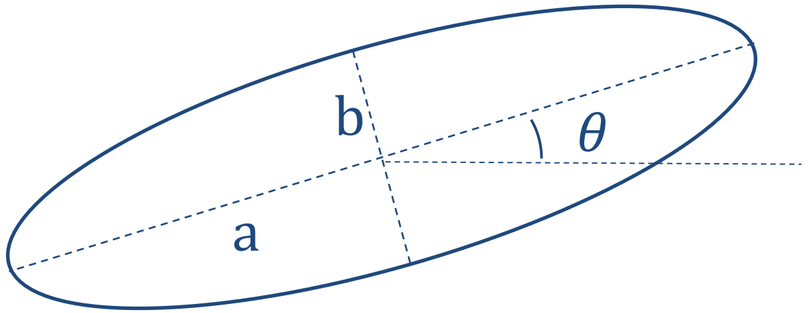
Aimant

Conducteurs électriques

[1] Kashif & Singh (2022) ; [2] Zhang, Shi, Liu et. al. (2021); [3] Moon & Kang (2022)

Optimiser la distribution de matériaux

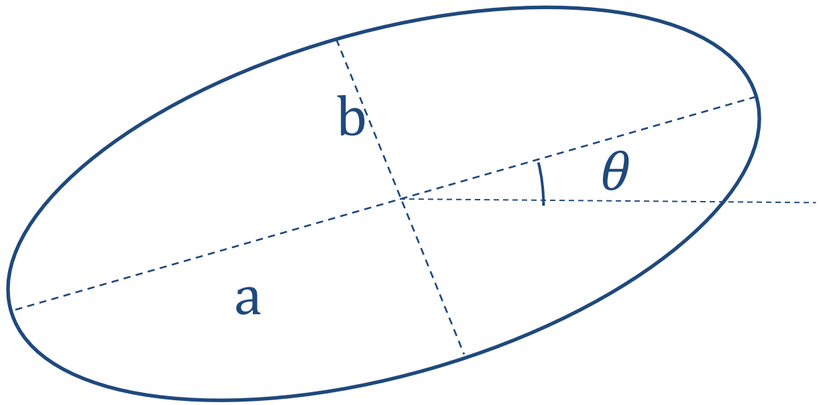
Situation initiale ✕



Solution optimale

Optimiser la distribution de matériaux

Situation initiale ✕



Solution optimale

Optimiser la distribution de matériaux

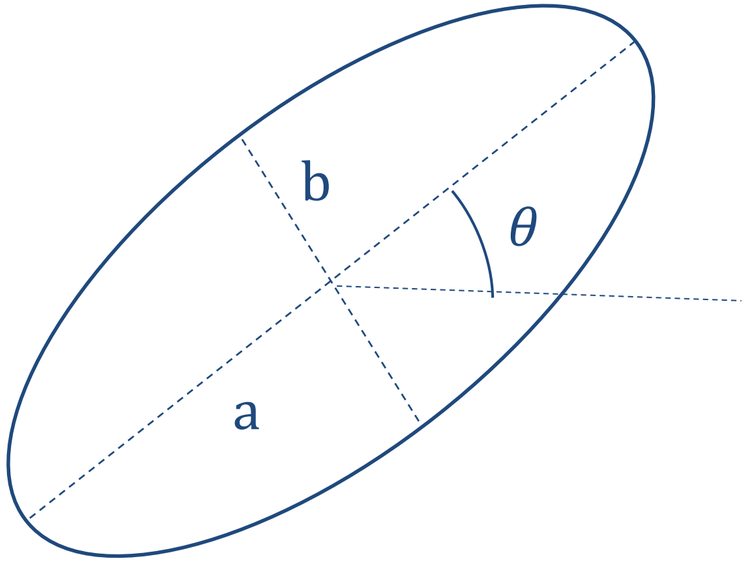
Espace de toutes les formes atteignables

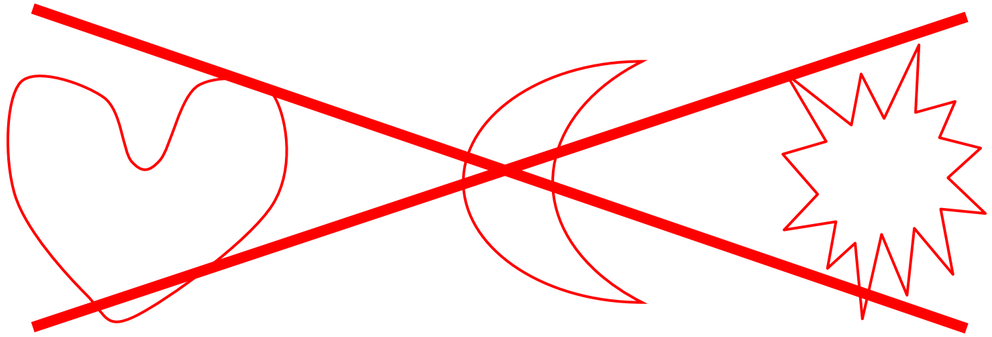
On veut une approche **non-paramétrique**

Situation initiale

Optimisation paramétrique

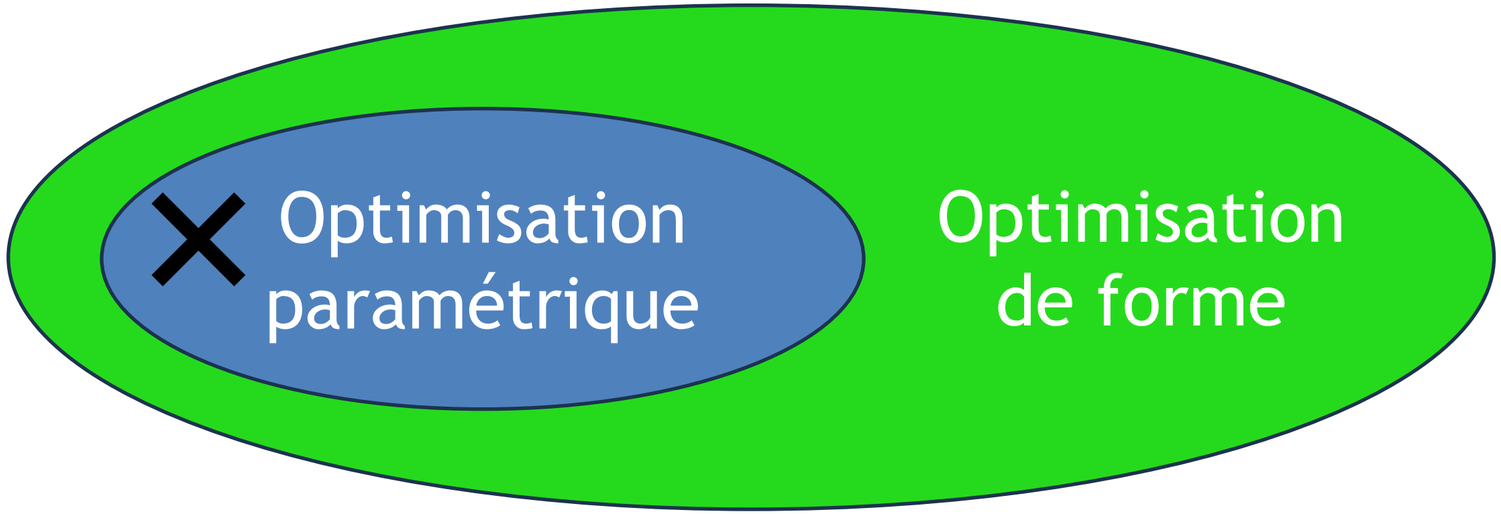
Solution optimale

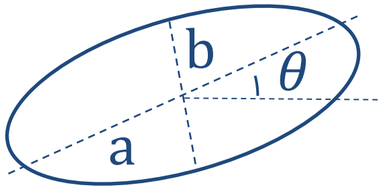


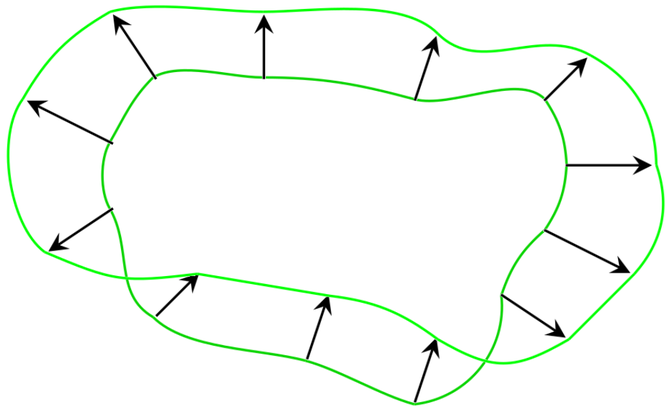


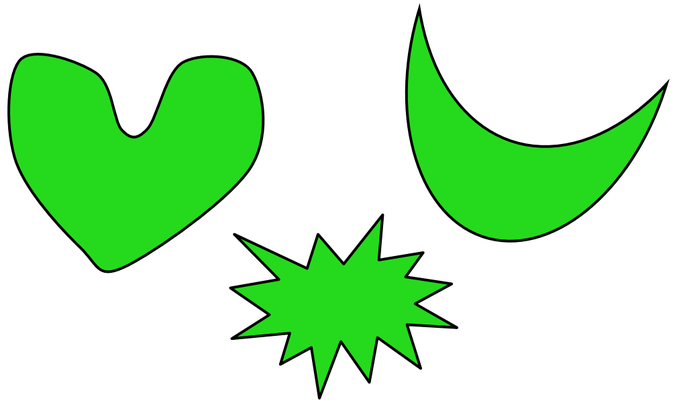
Optimiser la distribution de matériaux

On veut être capable de changer la **topologie** (créer des trous)

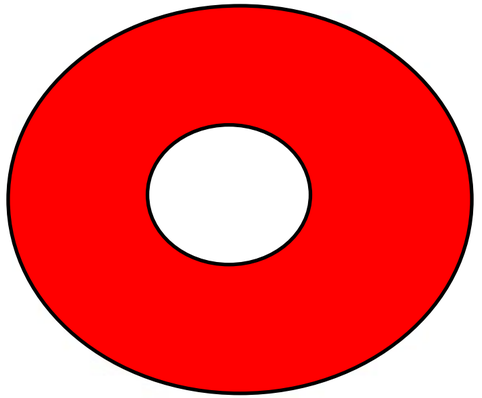








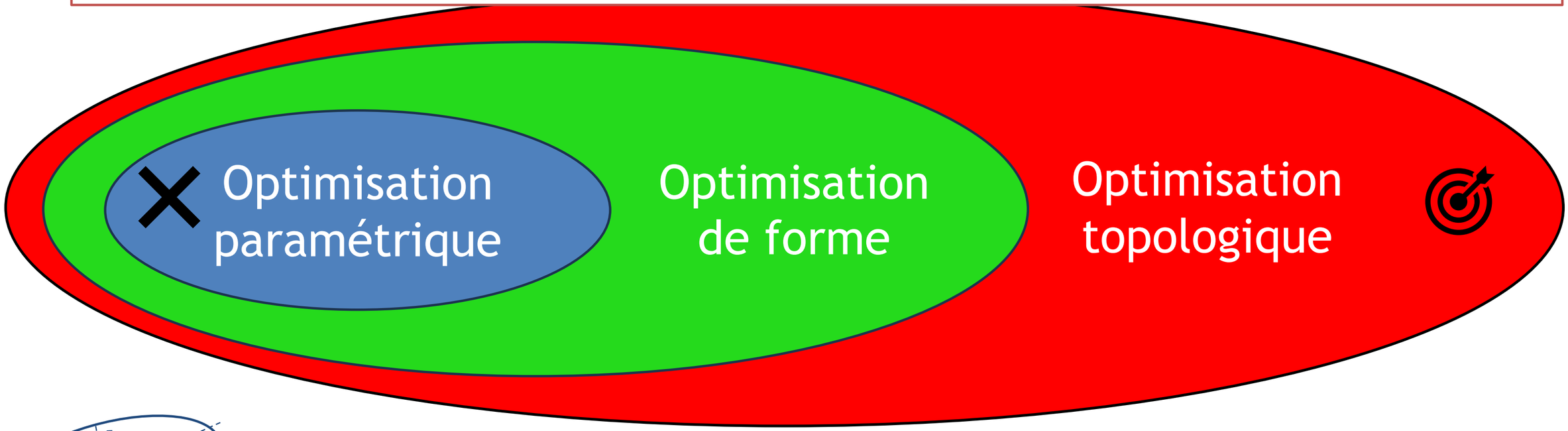
Formes atteignables

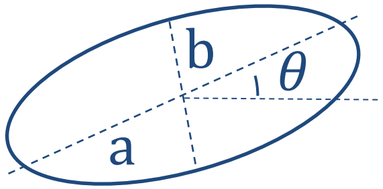


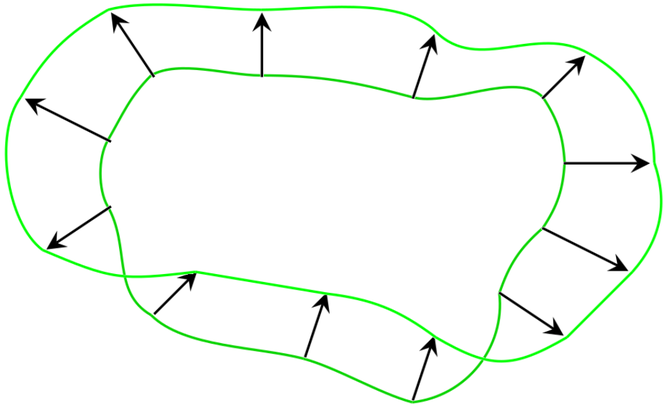
Forme inatteignable

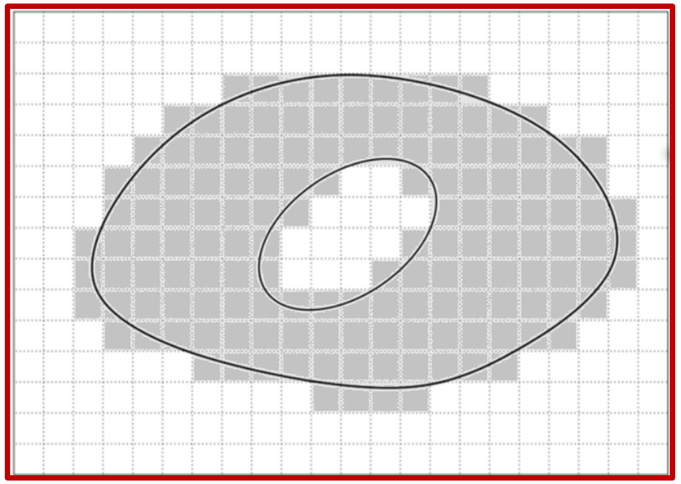
Optimiser la distribution de matériaux

On veut être capable de changer la **topologie** (créer des trous)





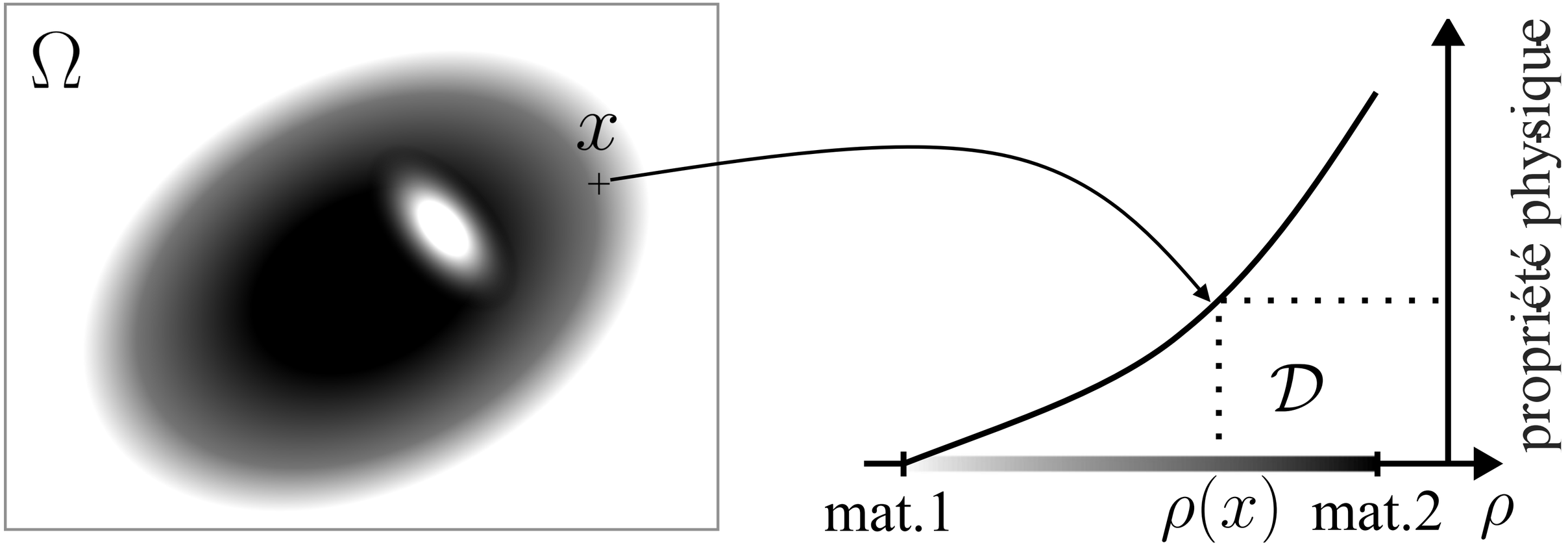




2) Principes de l’optimisation topologique

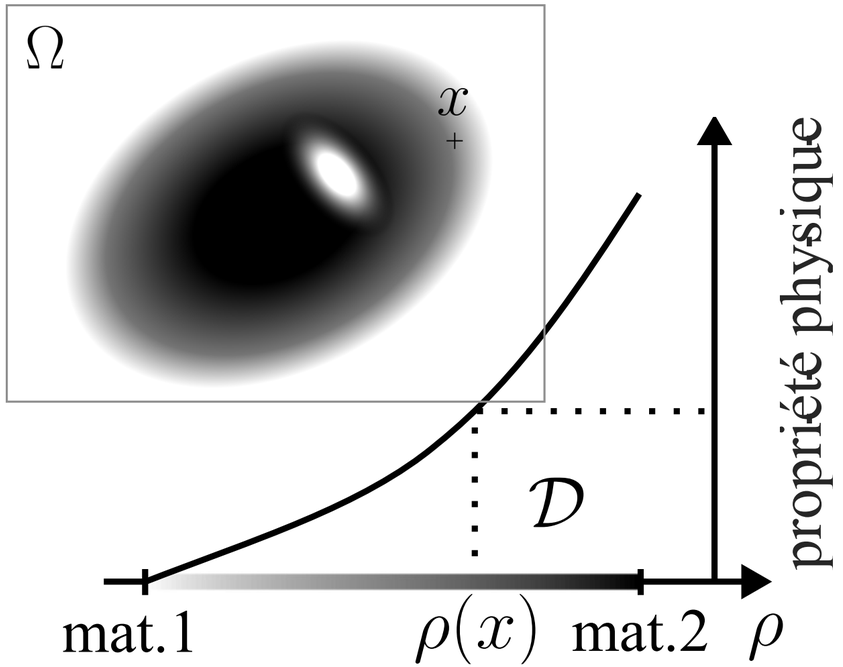
Méthodes à densité

Méthode à densité : principes



Bendsøe, M. P. (1989). “Optimal shape design as a material distribution problem”. *Structural Optimization*

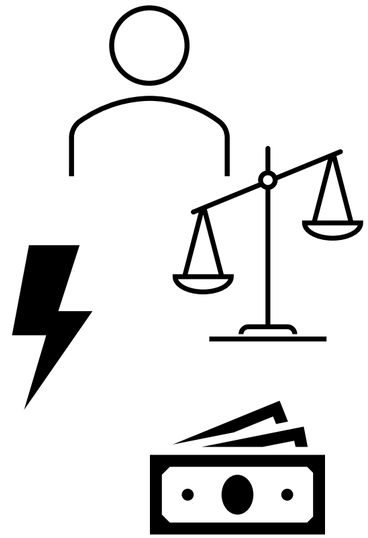
Méthode à densité : principes



+

$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

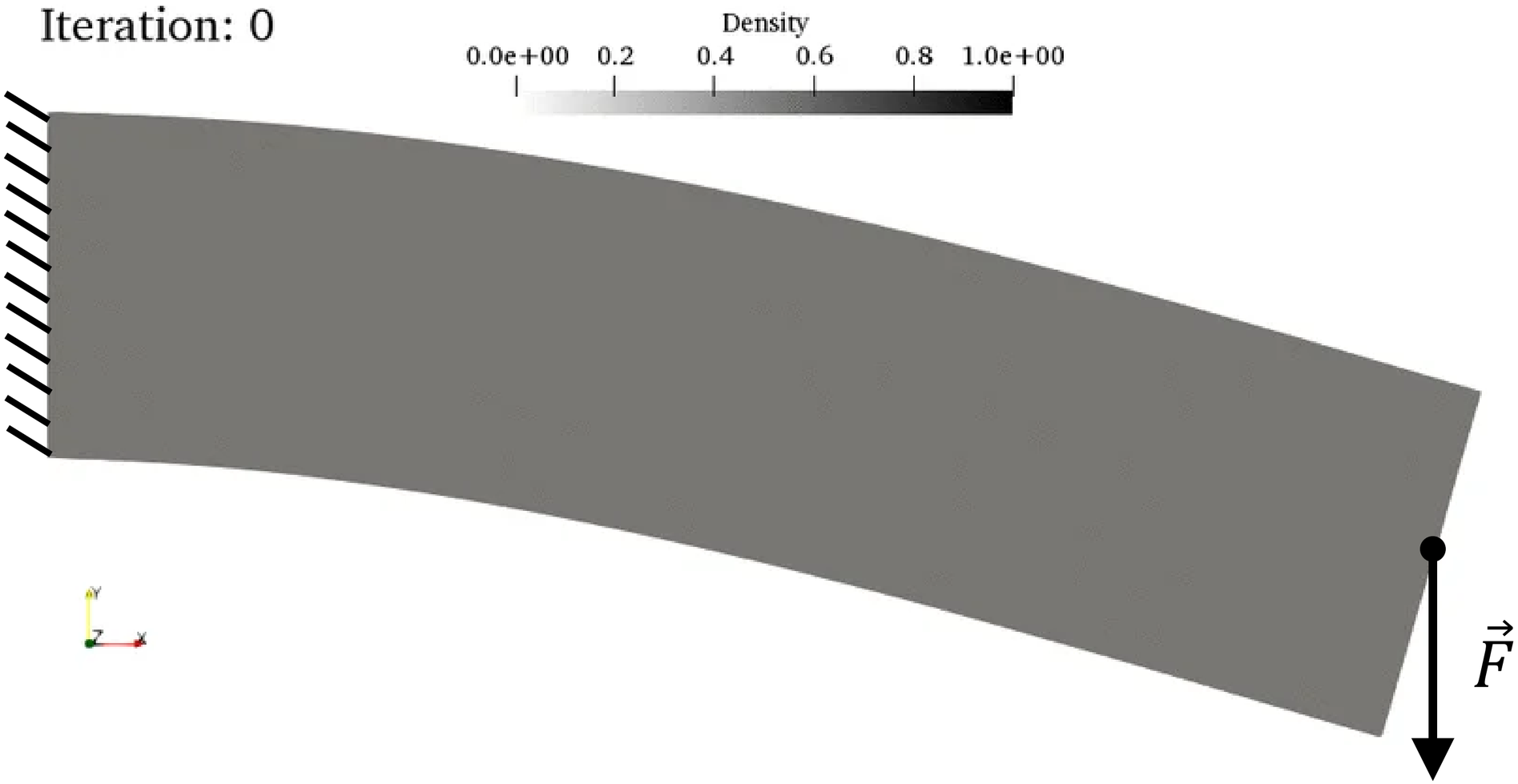
+



Description géométrique — Equations physiques — Objectif et contrainte

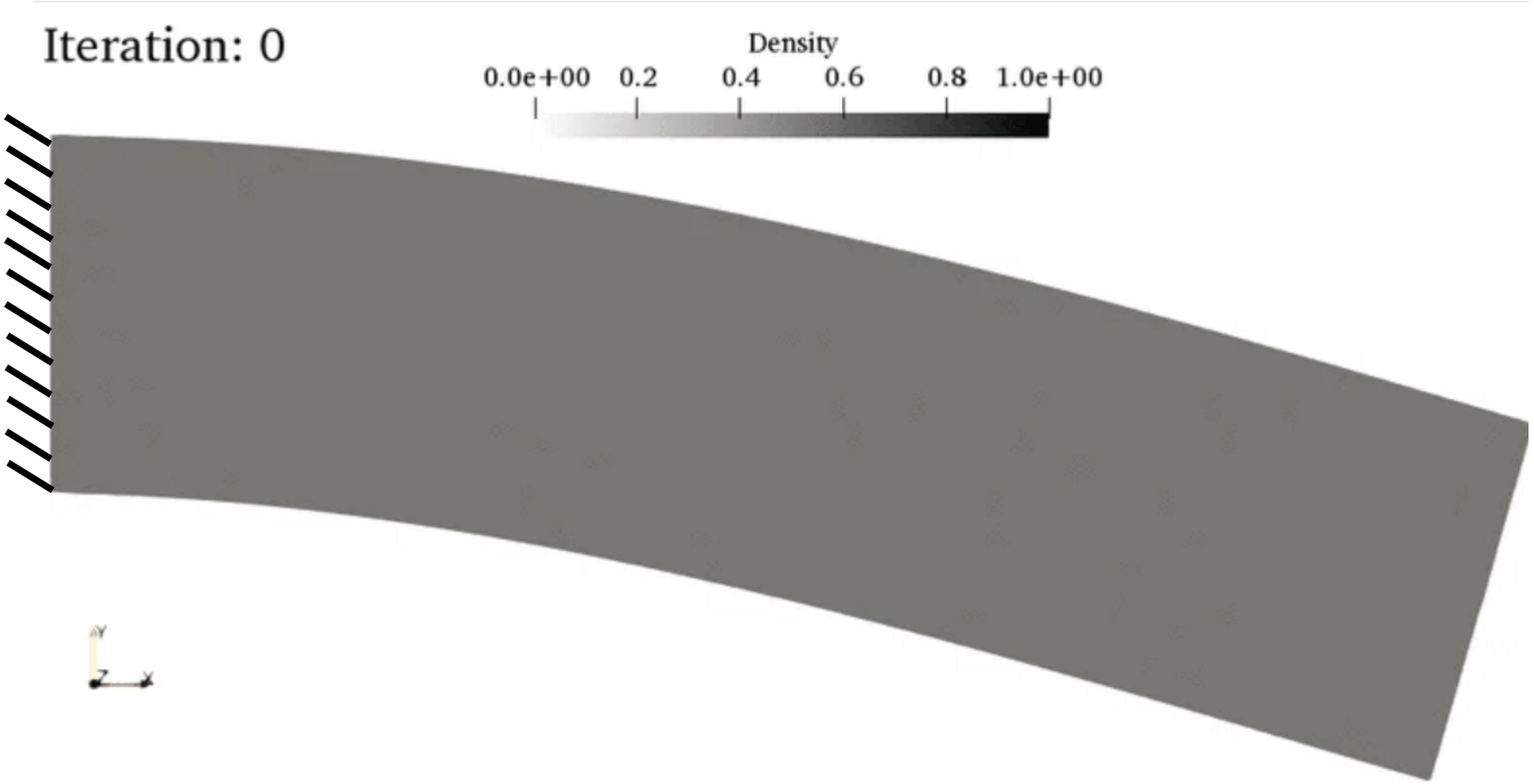
Problème d'optimisation ⇒ algorithmes efficaces

Méthode à densité : exemple (poutre)



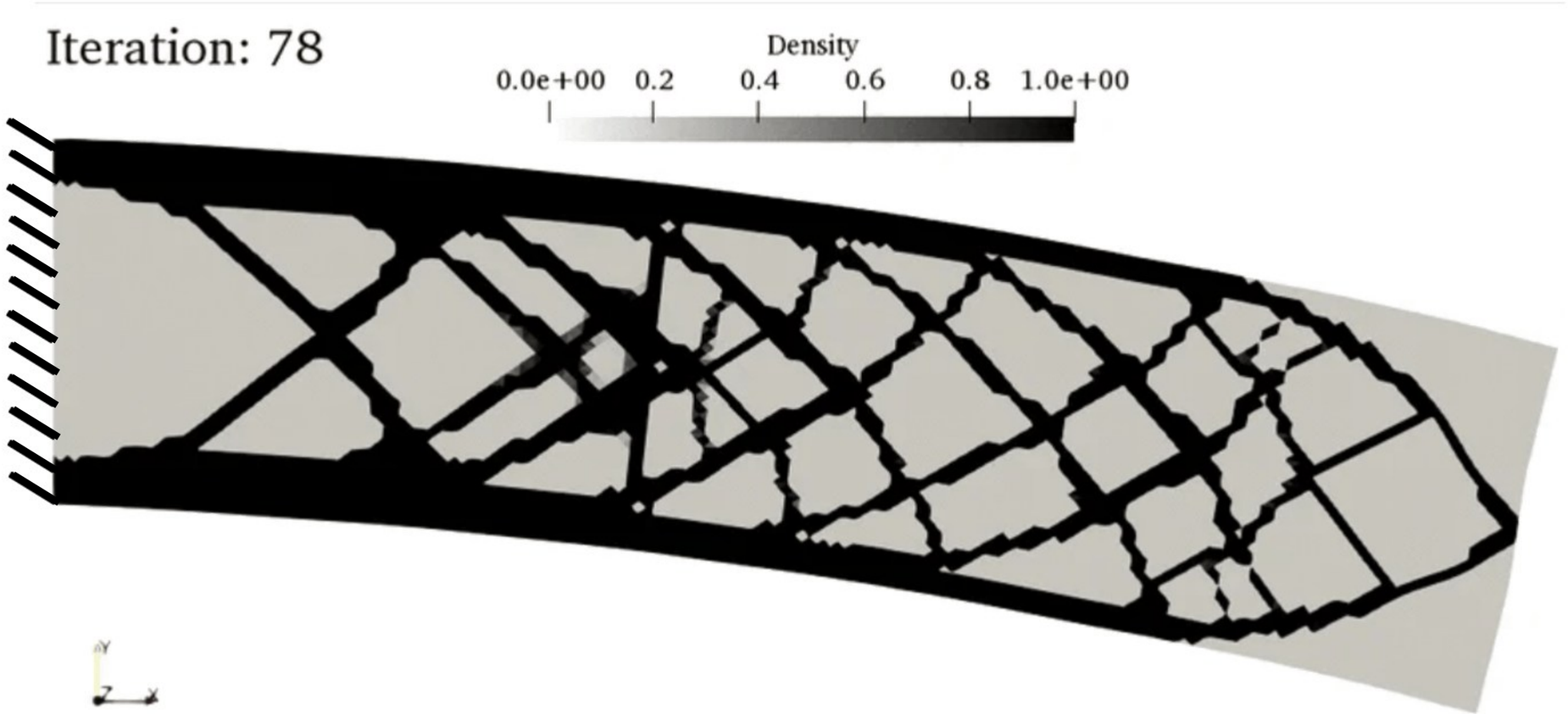
https://comet-fenics.readthedocs.io/en/latest/demo/topology_optimization/simp_topology_optimization.html

Méthode à densité : exemple (poutre)



https://comet-fenics.readthedocs.io/en/latest/demo/topology_optimization/simp_topology_optimization.html

Méthode à densité : exemple (poutre)



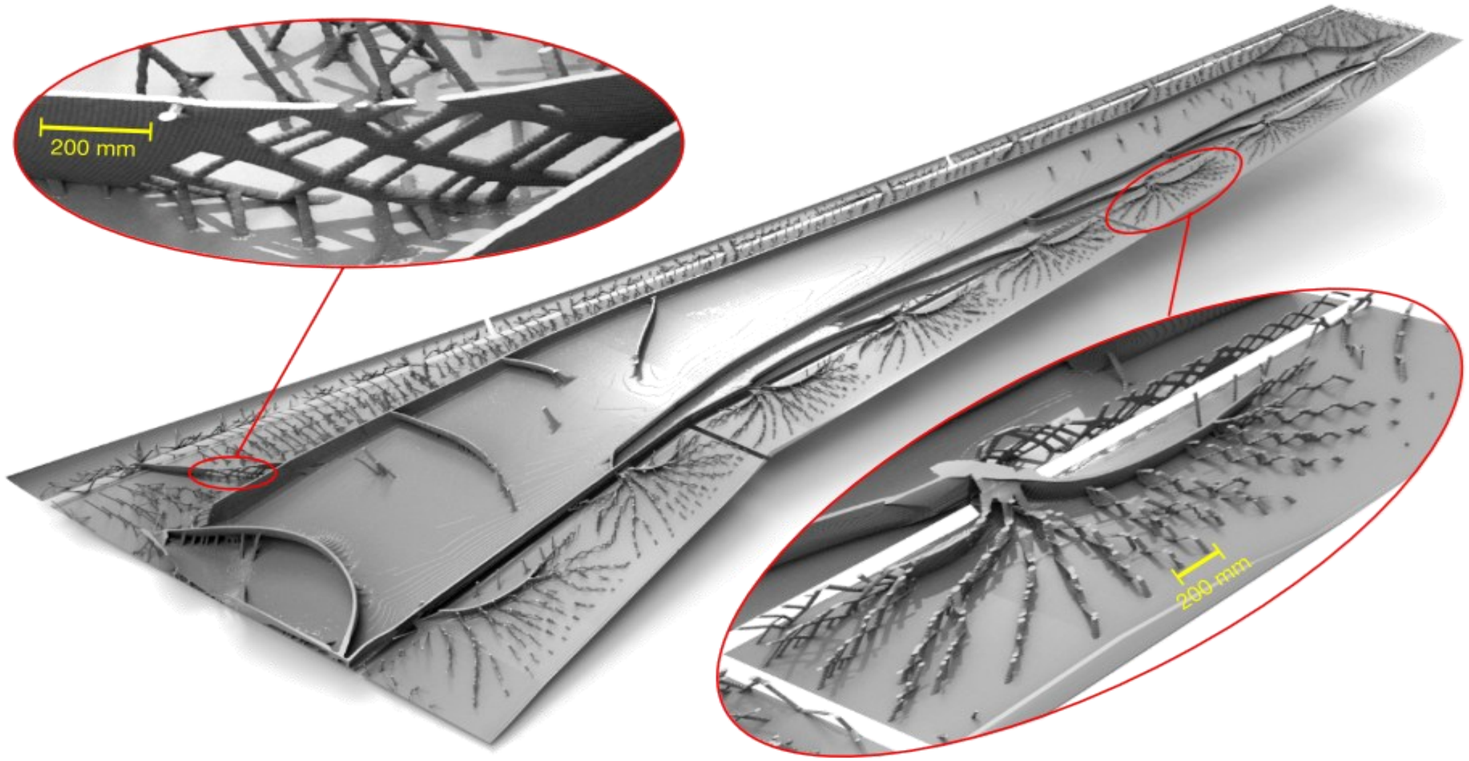
https://comet-fenics.readthedocs.io/en/latest/demo/topology_optimization/simp_topology_optimization.html

Méthode à densité : exemple (aile d'avion)

Giga–voxel computational morphogenesis for structural design

| NATURE | VOL 550 | 5 OCTOBER 2017

Niels Aage[1,2], Erik Andreassen[1], Boyan S. Lazarov[1] & Ole Sigmund[1]



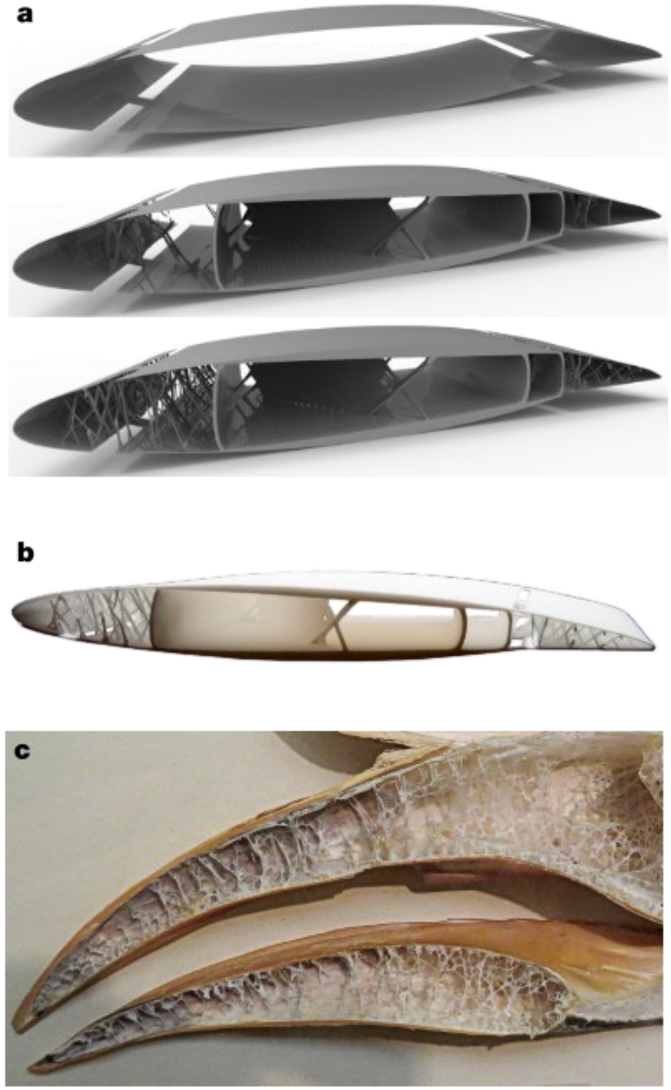
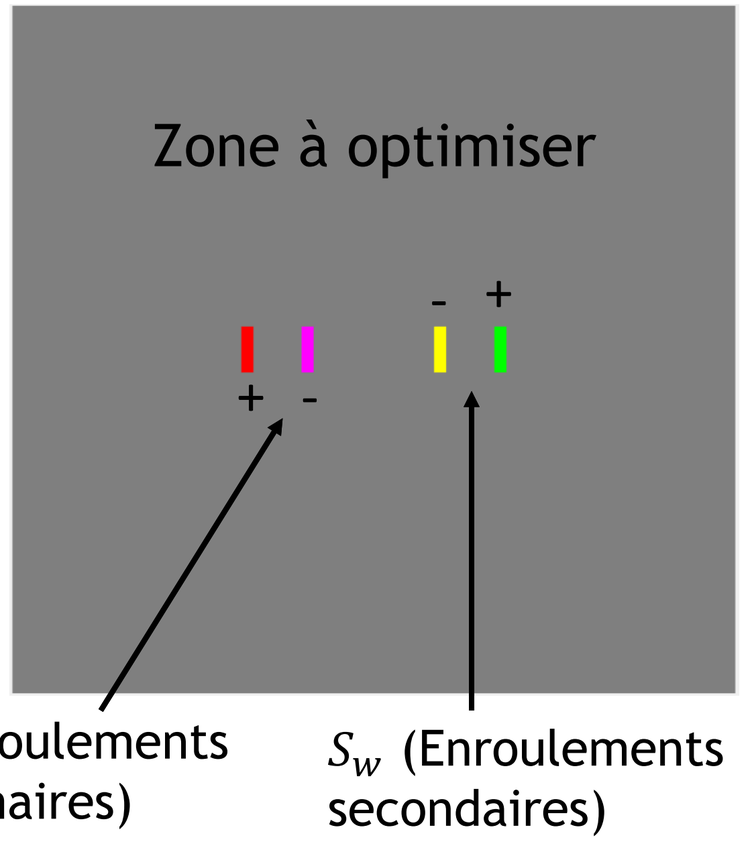


Figure 2 | Morphogenesis evolution, 3D printing and comparison to the hornbill bird beak. a, Steps of the morphogenesis process for the full-wing

N. Aage, E. Andreassen, B. S. Lazarov, and O. Sigmund, "Giga-voxel computational morphogenesis for structural design," *Nature* (2017), doi: 10.1038/nature23911.

Méthode à densité : exemple (transformateur)

Situation initiale



Hypothèses :

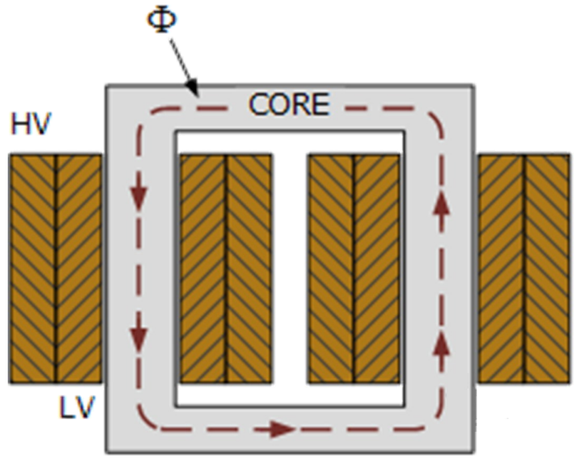
- Positions des bobines fixées
- Courant imposé au primaire
- Secondaire à vide

Objectif

Trouver la distribution de fer qui **maximise le flux magnétique** au secondaire.

Résultat attendu

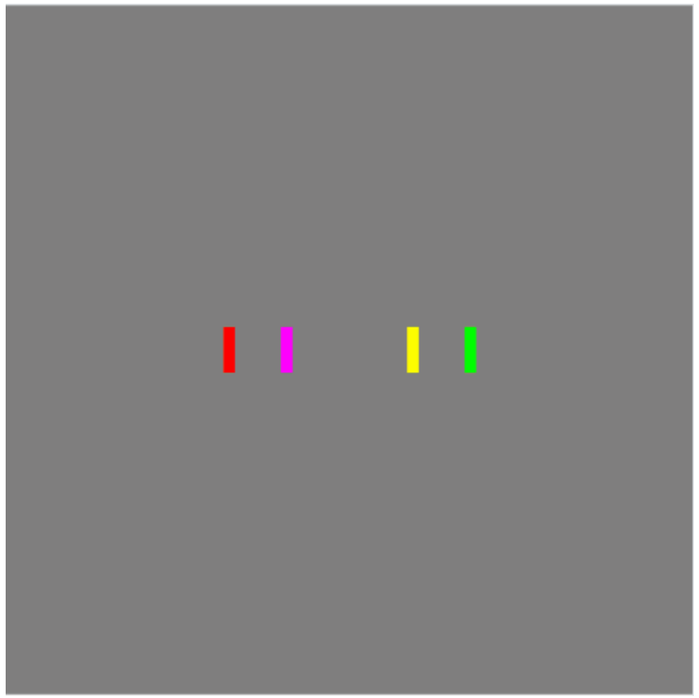
https://www.transfosmary.com



Core-type Construction

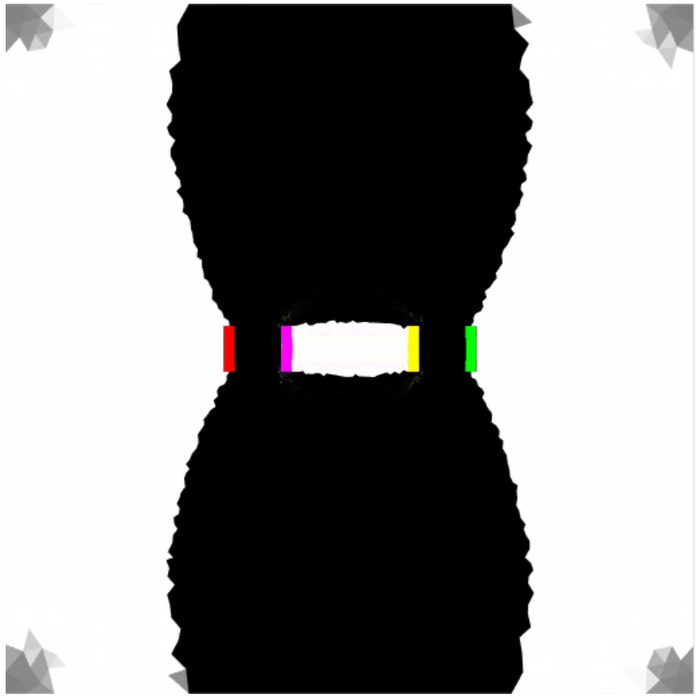
https://www.electronics-tutorials.ws/transformer/transformer-construction.html

Méthode à densité : exemple (transformateur)

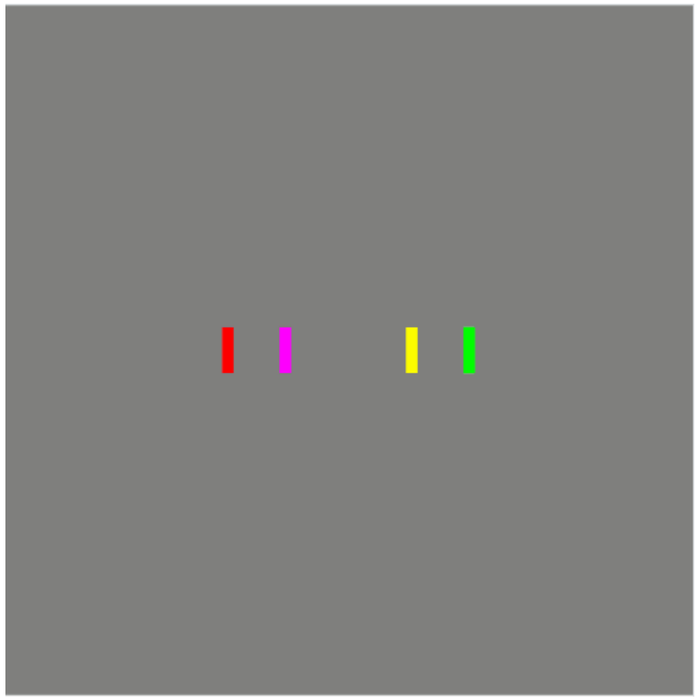


Sans contrainte de volume

Méthode à densité : exemple (transformateur)

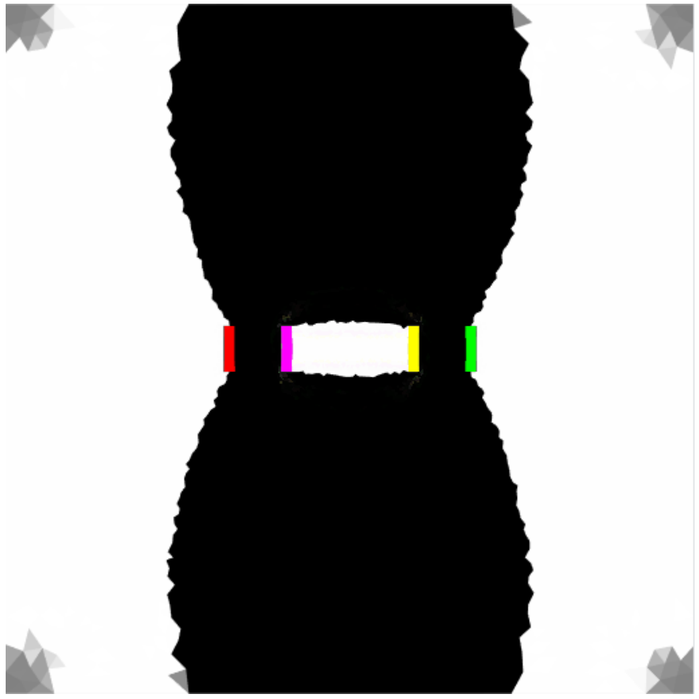


Sans contrainte de volume

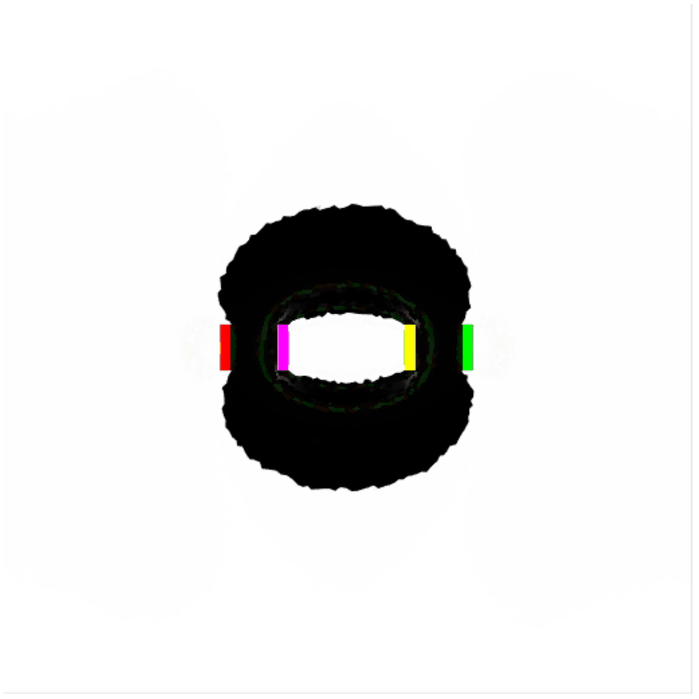


Avec pénalisation sur le volume

Méthode à densité : exemple (transformateur)



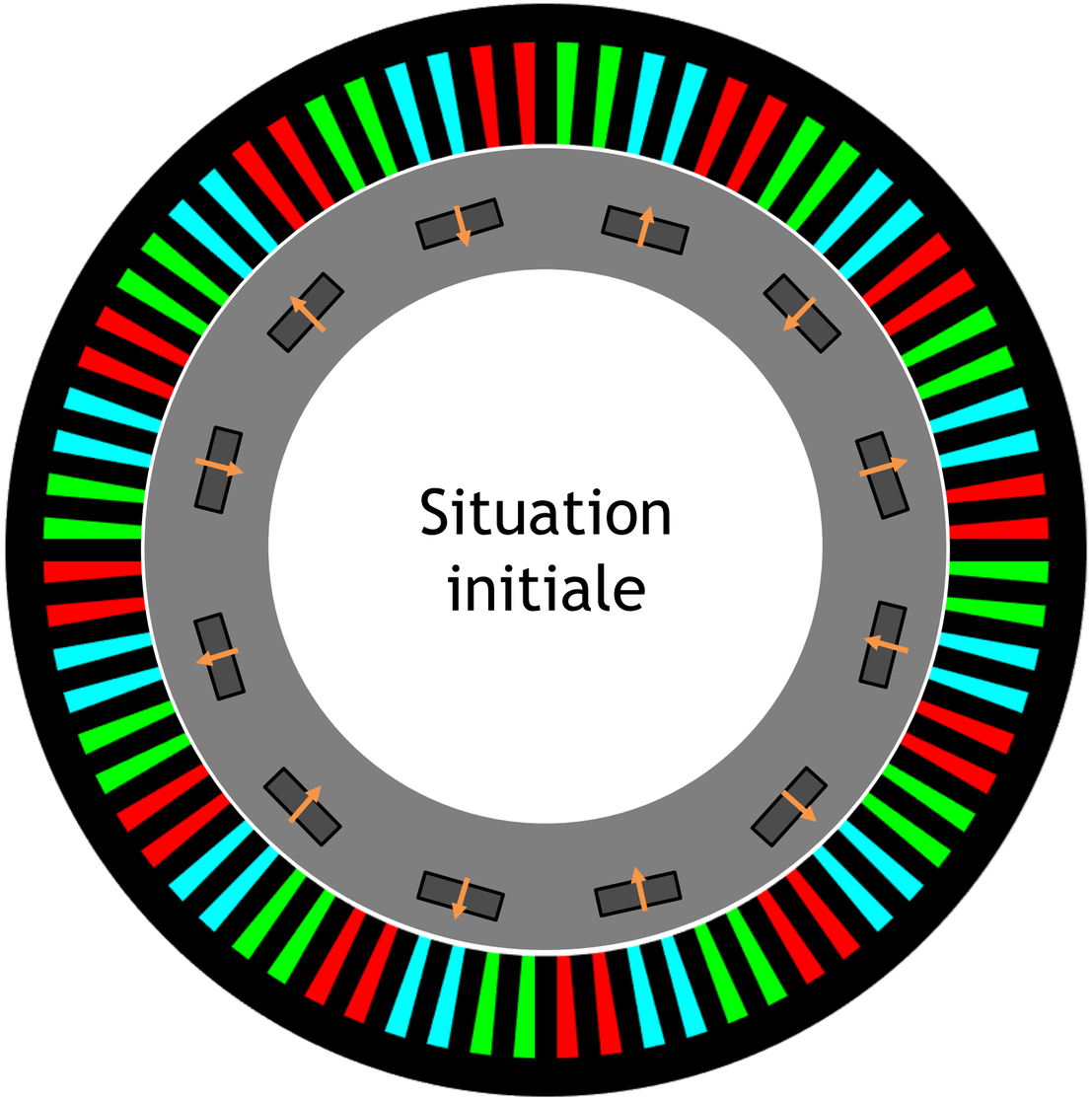
Sans contrainte de volume



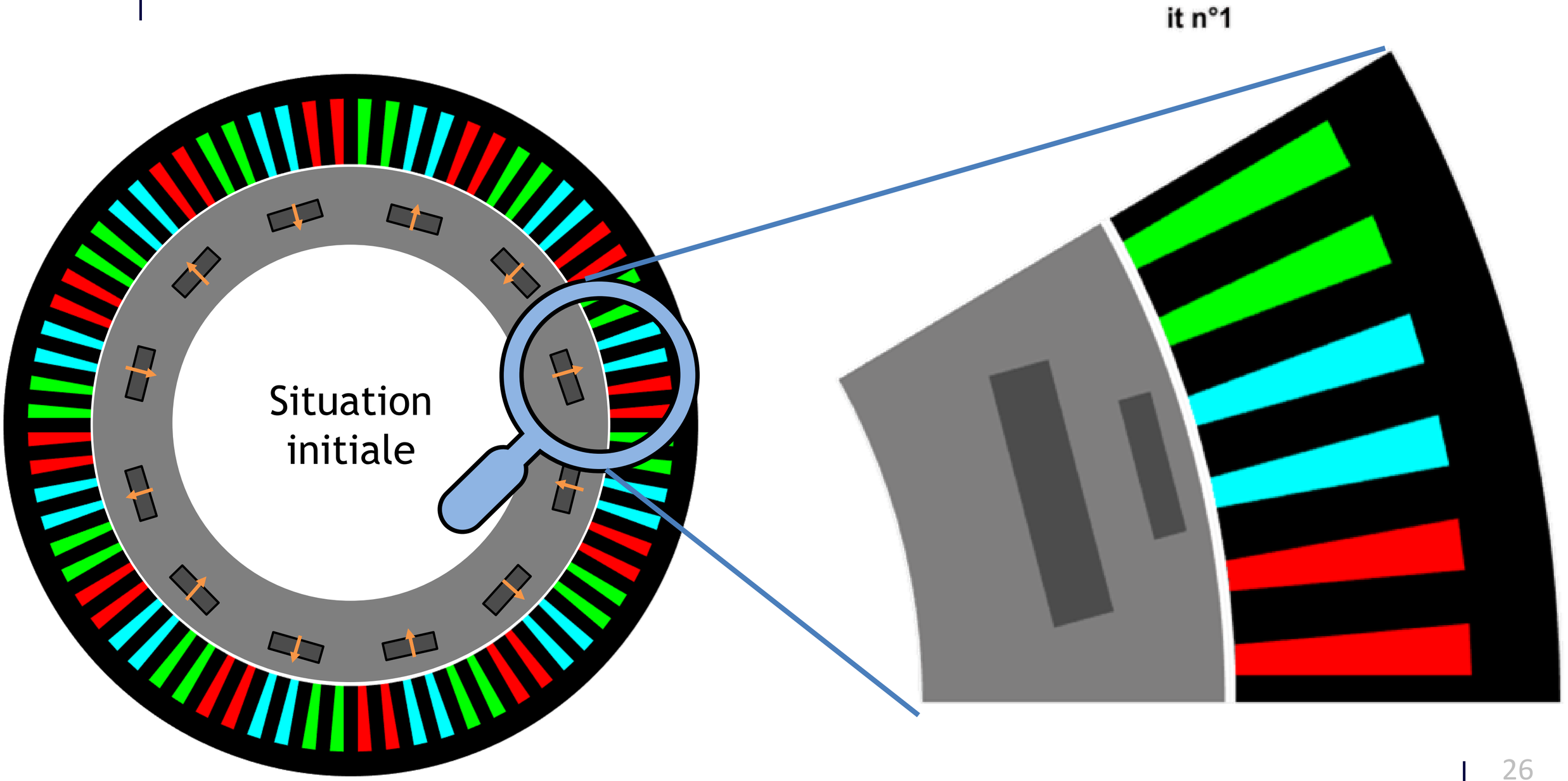
Avec pénalisation sur le volume

3) Application aux machines électriques

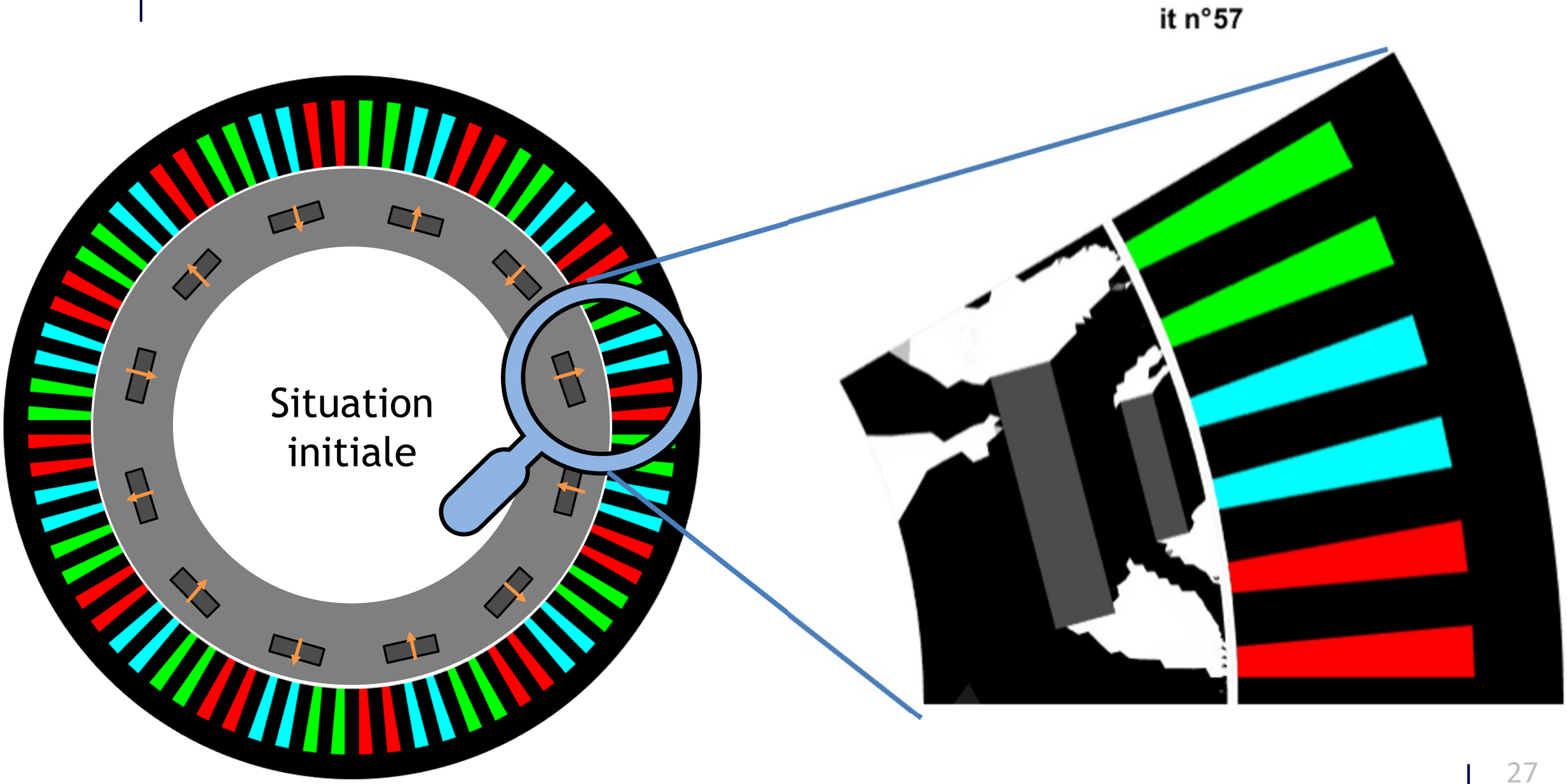
Optimisation d’un rotor (aimants fixés)



Optimisation d’un rotor (aimants fixés)



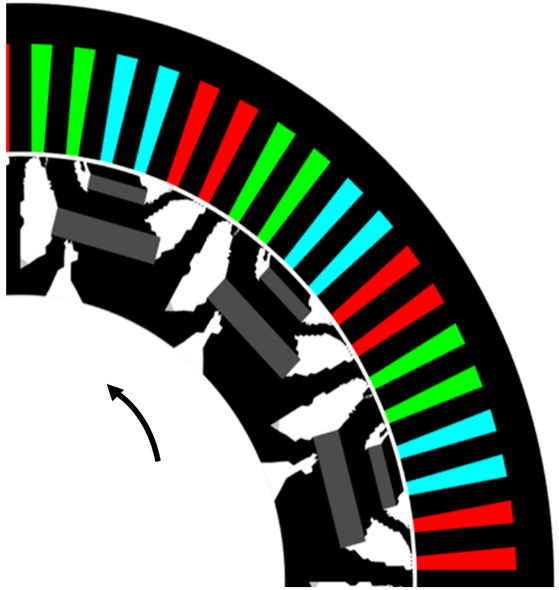
Optimisation d’un rotor (aimants fixés)



Optimisation d’un rotor (aimants fixés)

La machine optimisée n’est ***symétrique*** que si son *utilisation* l’est aussi

100% moteur

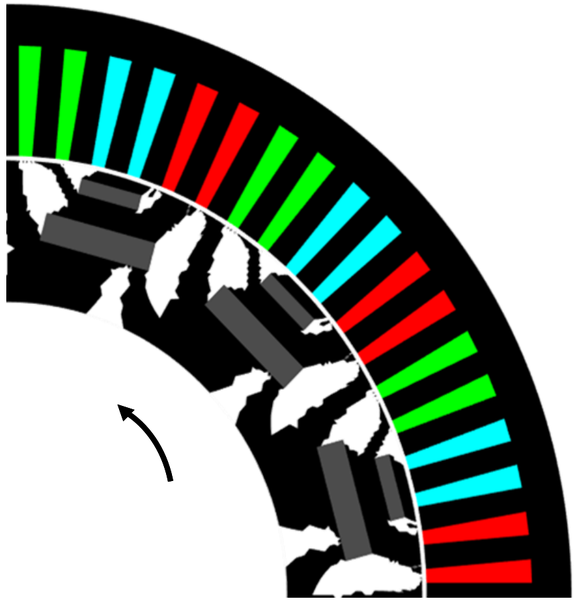


- $\langle C_m \rangle = 2552\ Nm/\mathrm{m}$
- $\langle C_g \rangle = -1595\ Nm/m$

50% moteur / 50% générateur

- $\langle C_m \rangle = 2499\ Nm/m$
- $\langle C_g \rangle = -2501\ Nm/m$

100% générateur

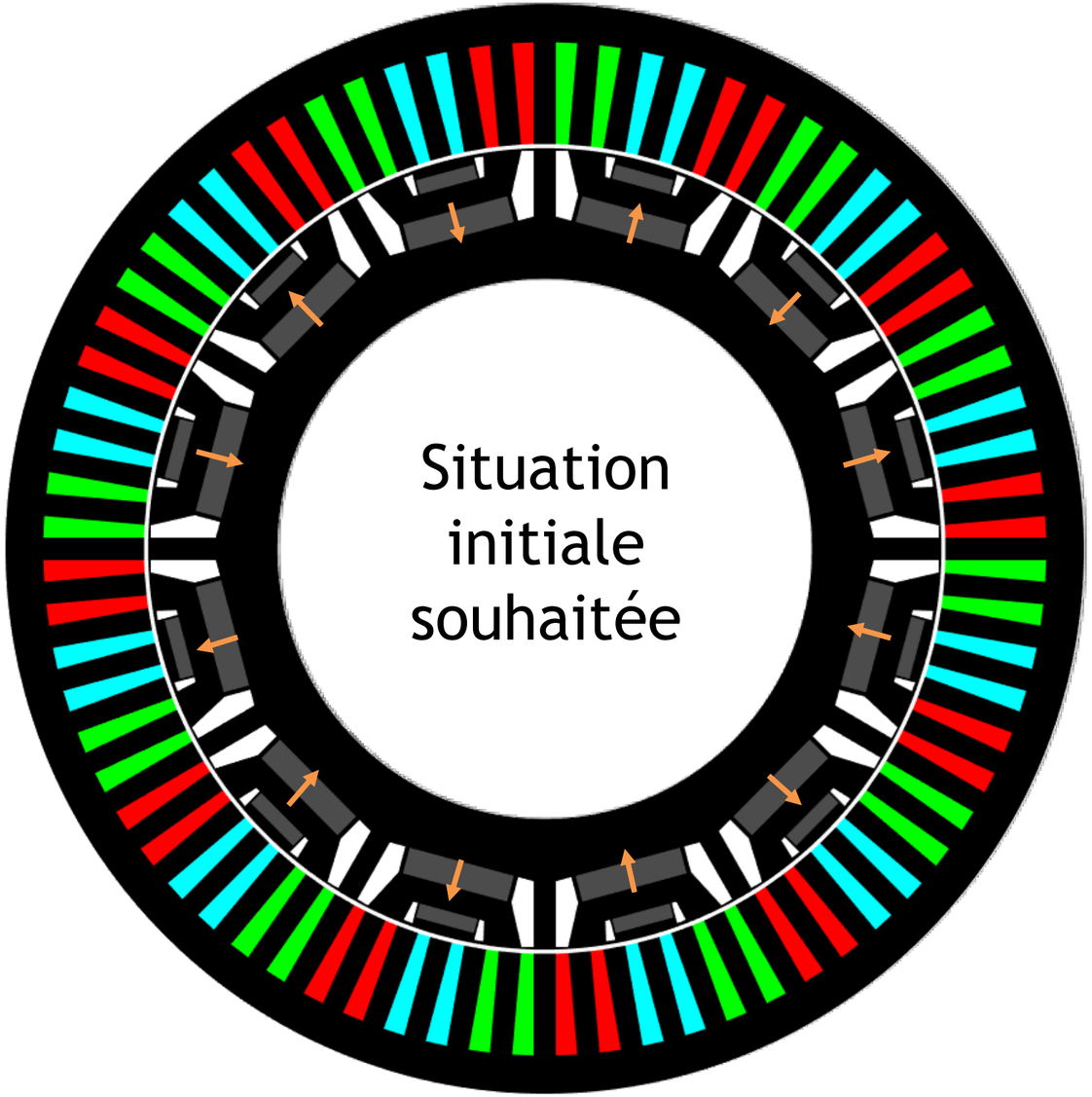


- $\langle C_m \rangle = 1612\ Nm/m$
- $\langle C_g \rangle = -2553 Nm/m$

TC, S. Hlioui, L. Laurent, F. Louf et. al. (2022) "Topology Optimization of an Asymmetric PMSM Rotor" *ICEM 2022*.

Méthode à densité : limites

Un actionneur électrique complet doit aussi comporter des sources

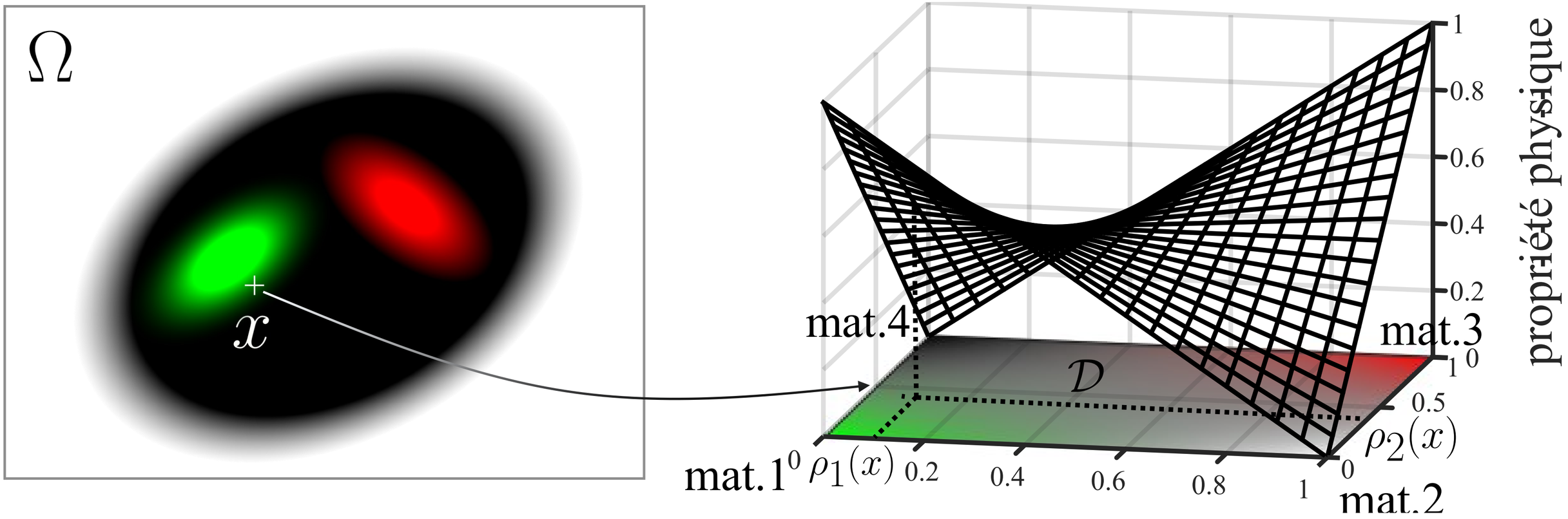


Matériaux à considérer dans l'optimisation

- Acier
- Air
- Conducteurs électriques
- Aimants

Multi-matériaux : principes

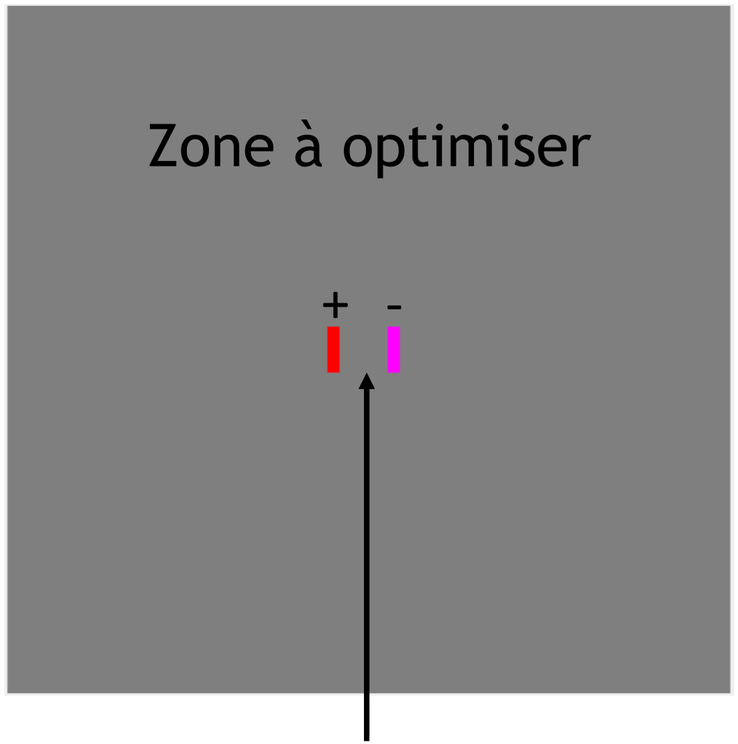
Extension à plusieurs natures de matériaux



TC, L. Laurent, S. Hlioui, F. Louf et. al. (2022) “Multi-material topology optimization using Wachspress interpolations for designing a 3-phase electrical machine stator ». *Structural and Multidisciplinary Optimization*

Multi-matériaux : exemples (transformateur)

Situation initiale



Hypothèses :

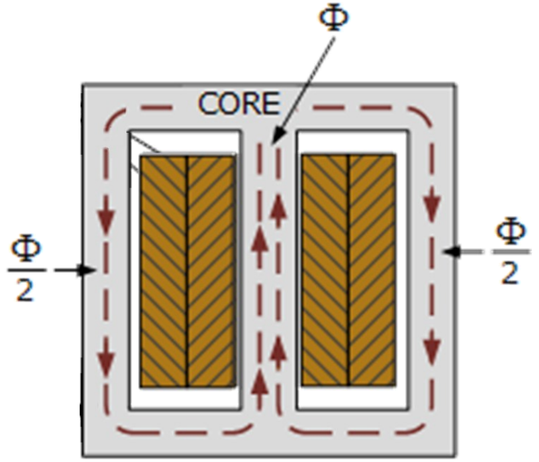
- Courant et bobinage primaires imposés
- Secondaire à vide (position libre)

Objectif

Trouver la distribution de fer et le bobinage secondaire qui **maximise le flux magnétique** au secondaire.

Résultat attendu

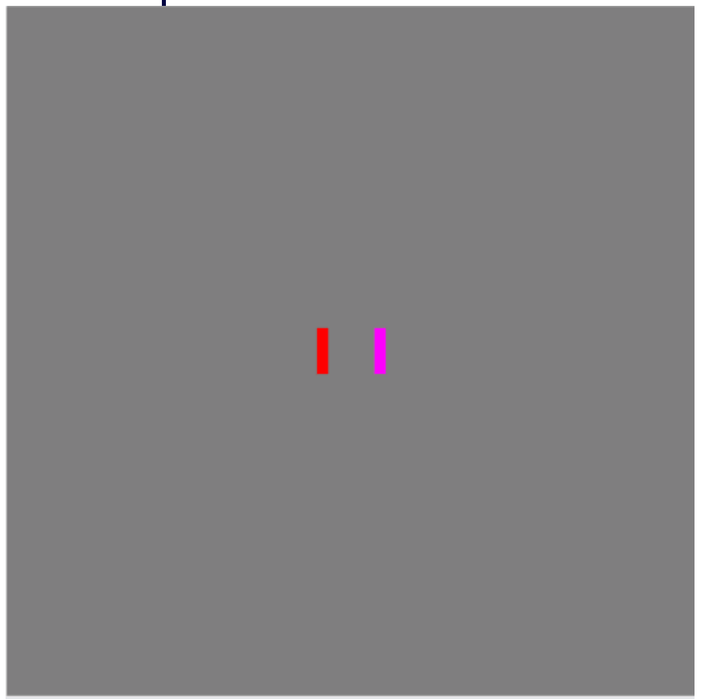
https://www.transfosmary.com

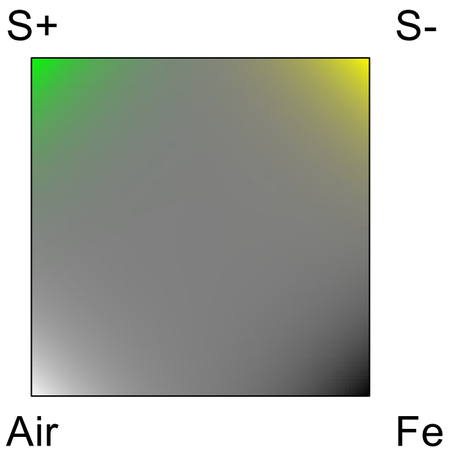


Shell-type Construction

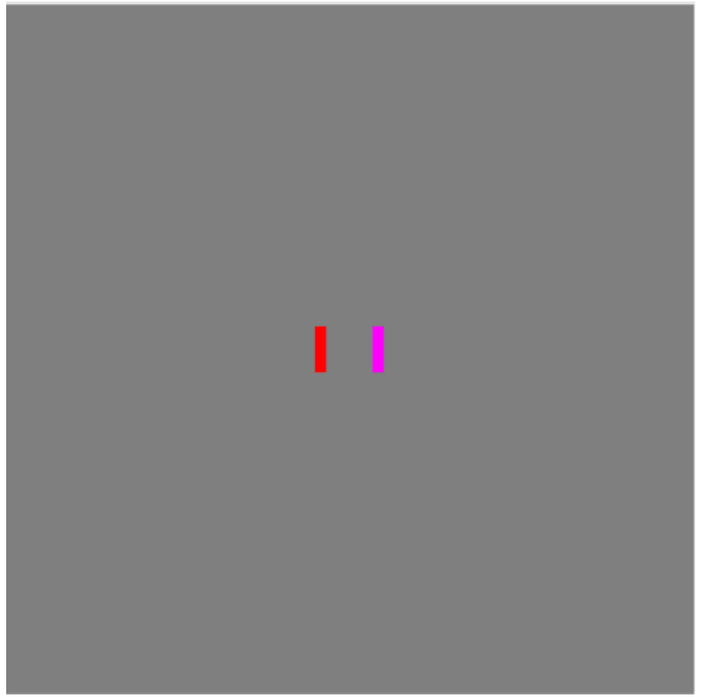
https://www.electronics-tutorials.ws/transformer/transformer-construction.html

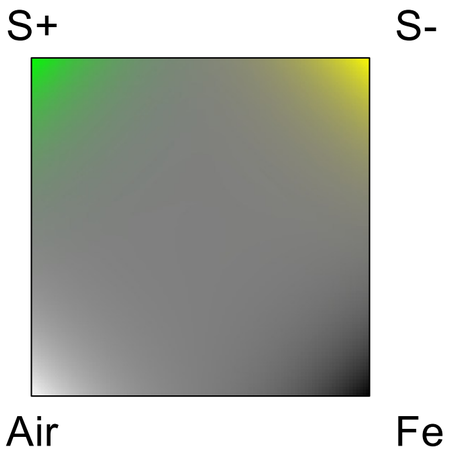
Multi-matériaux : exemples (transformateur)

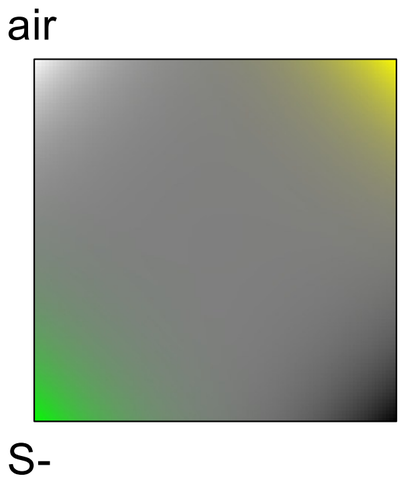




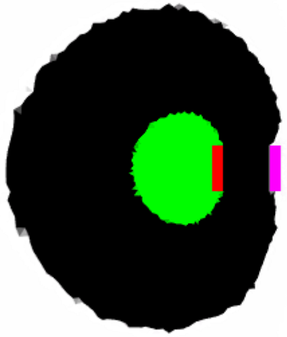
Multi-matériaux : exemples (transformateur)

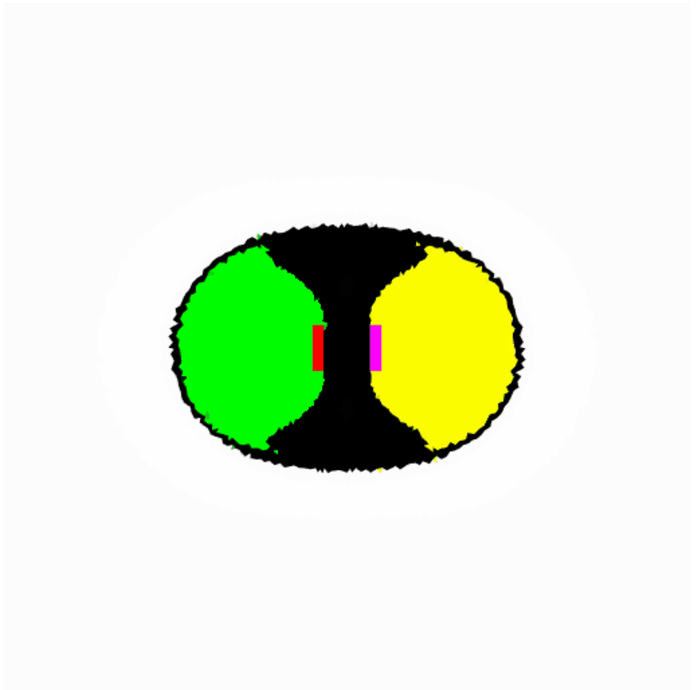


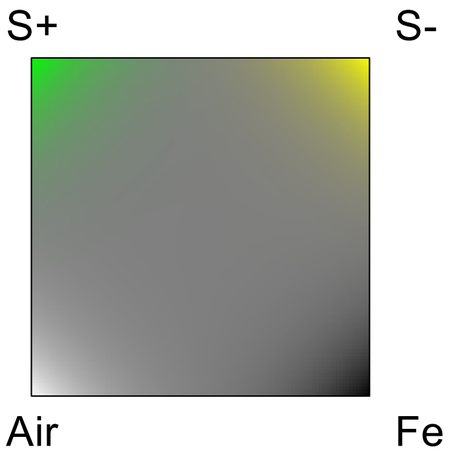


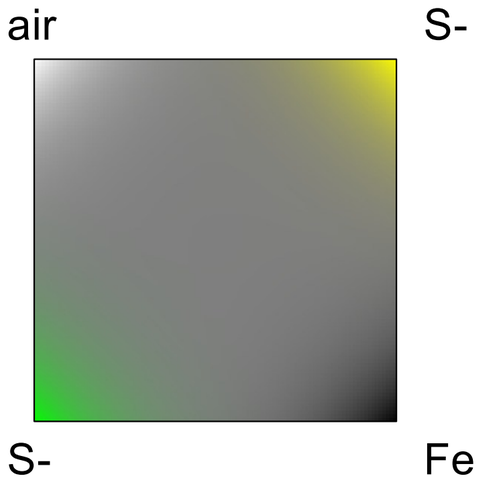


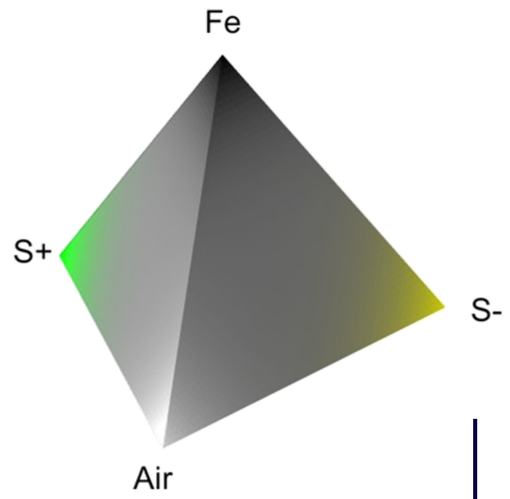
Multi-matériaux : exemples (transformateur)



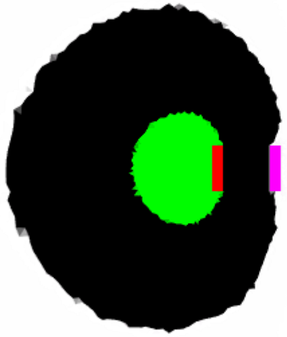


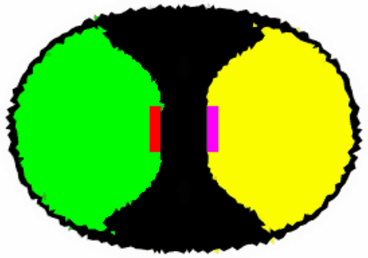


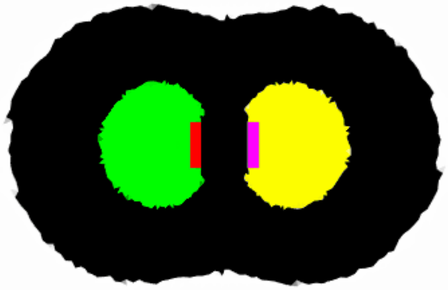


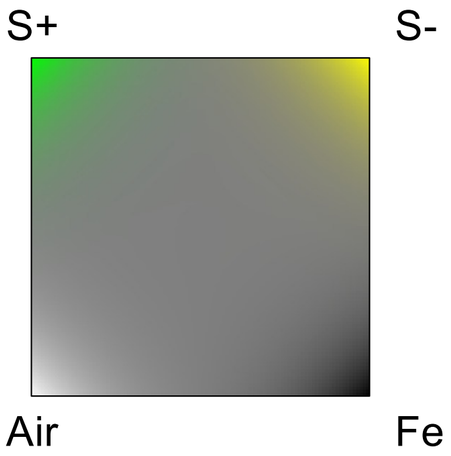


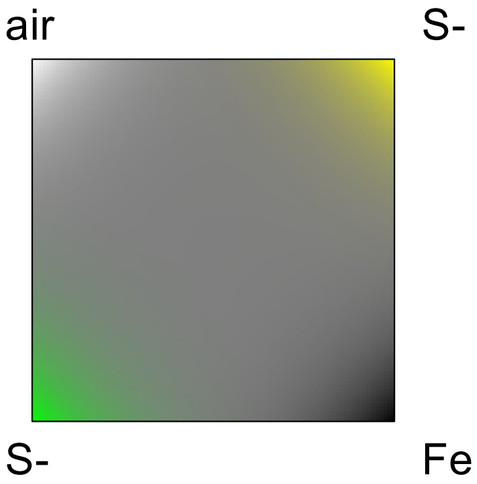
Multi-matériaux : exemples (transformateur)

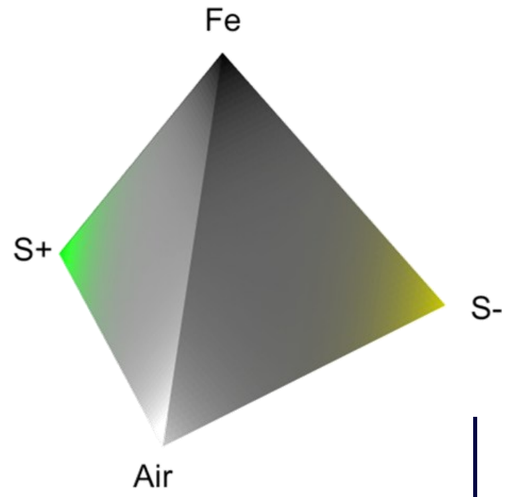




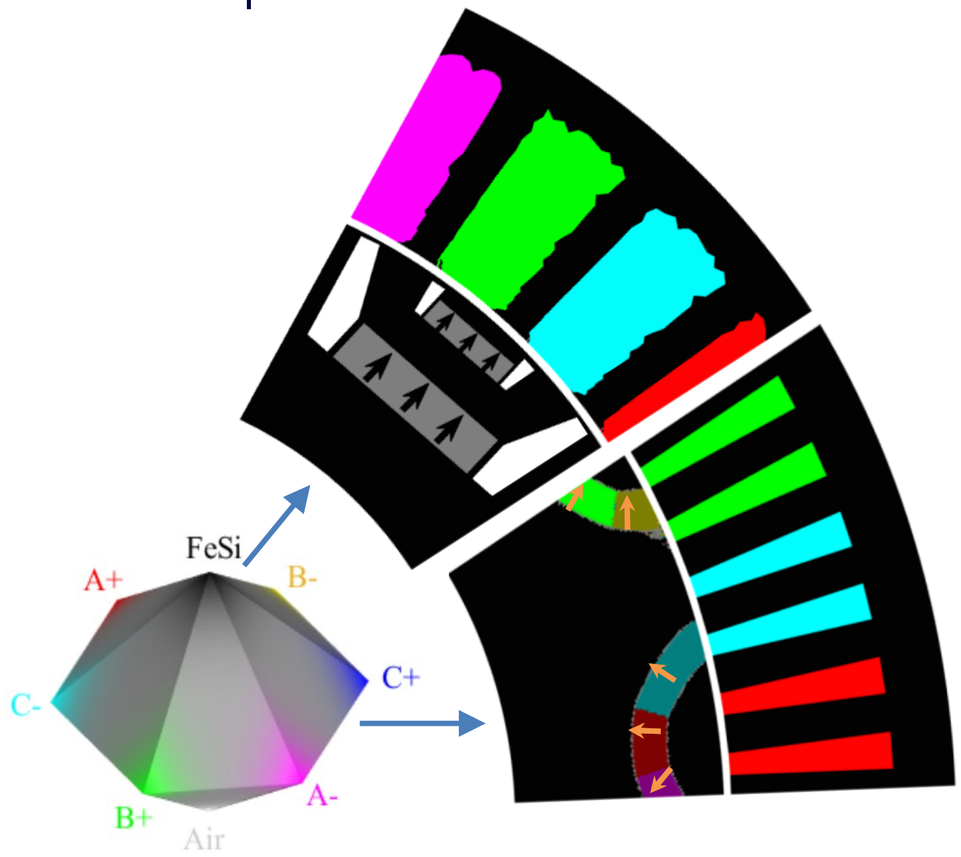


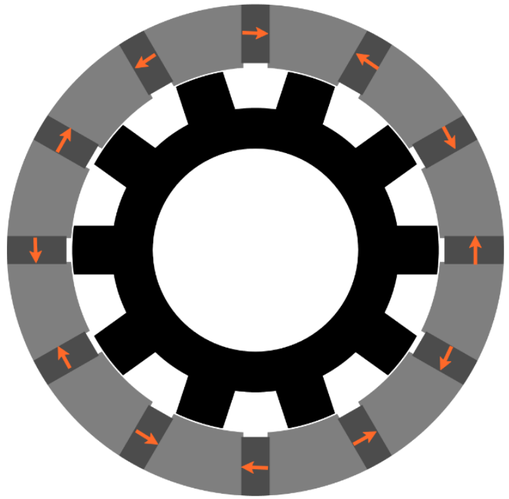


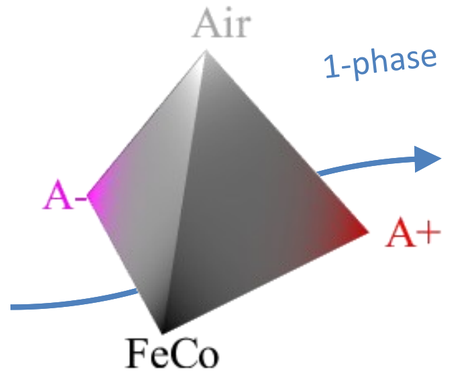


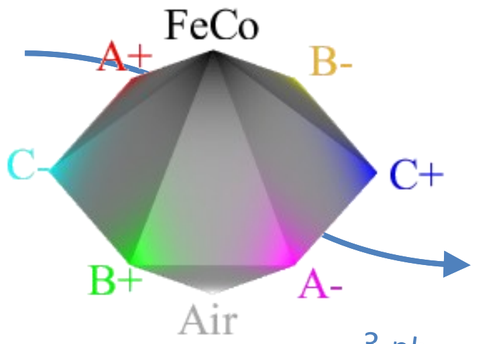


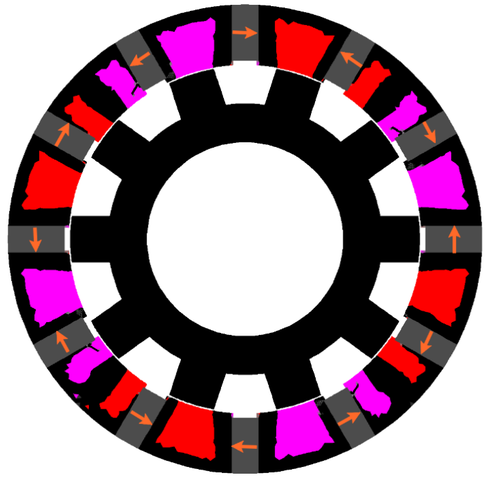
Multi-matériaux : exemples (machines à aimants)

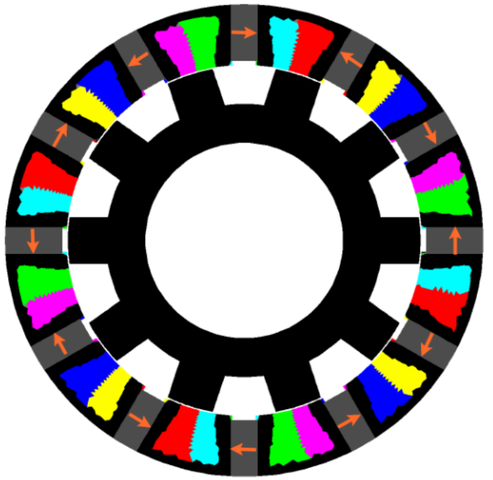










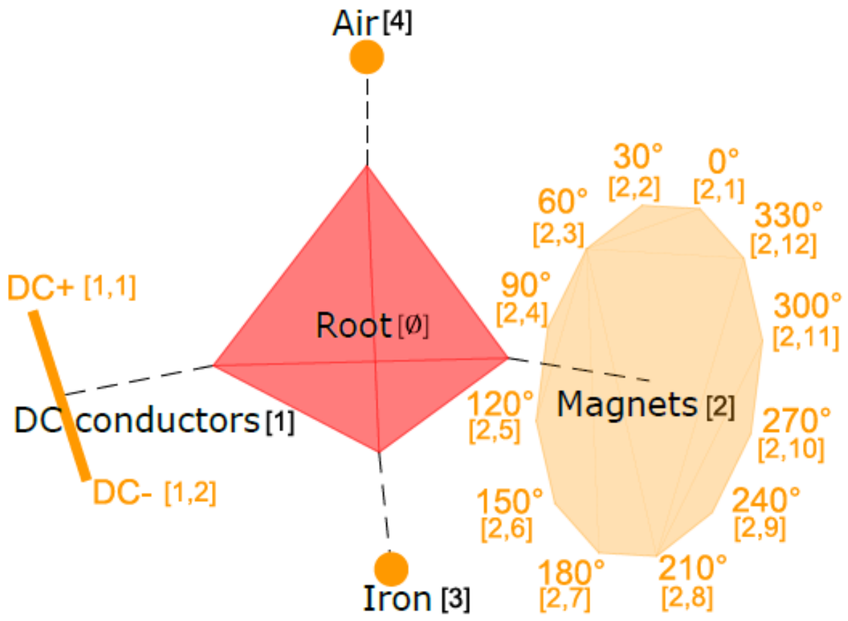


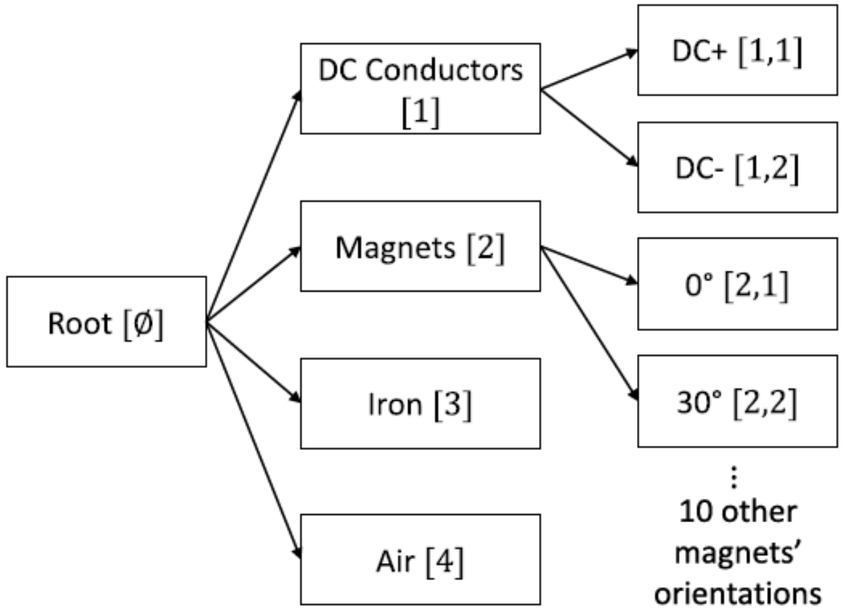
Machines synchrones à aimants [1,2]

Machines à commutation de flux [3]

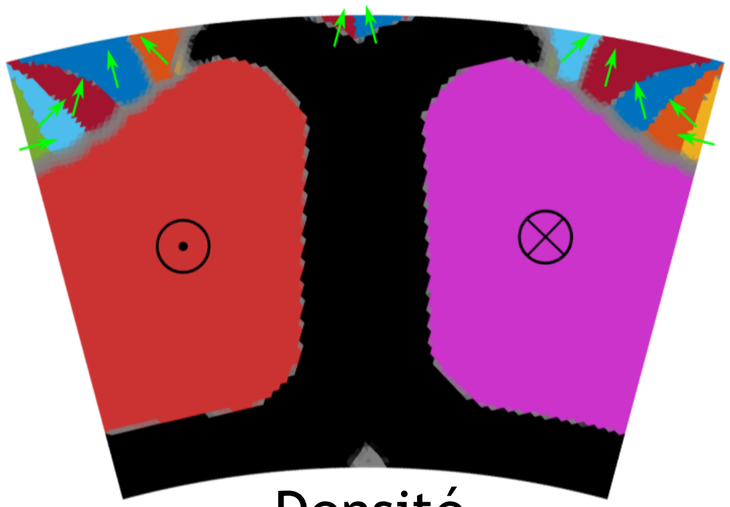
[1] TC, S. Hlioui, L. Laurent, F. Louf, et. al. (2024), IEEE Transactions on Magnetics, doi : 10.1109/tmag.2023.3317700
[2] TC, S. Hlioui, F. Louf , L. Laurent (2024) COMPEL, doi : 10.1108/COMPEL-10-2023-0546
[3] TC, S. Hlioui, L. Laurent, F. Louf et. al. (2023) Science and Technology for Energy Transition 10.2516/stet/2023037

Multi-matériaux : exemples (machine à double excitation)

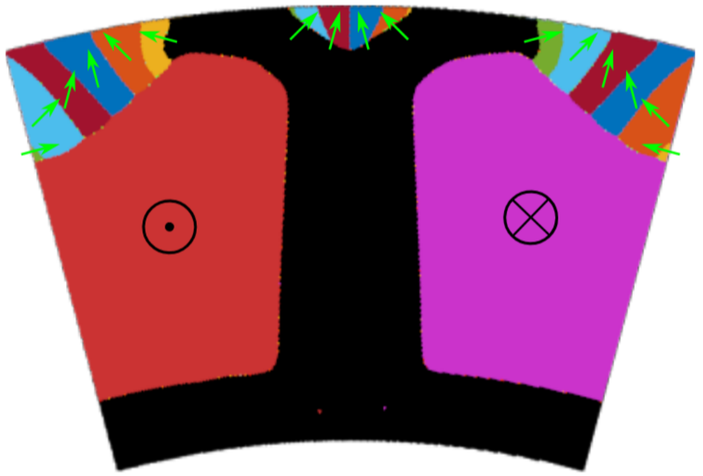




Interpolation d'interpolations (récursives)



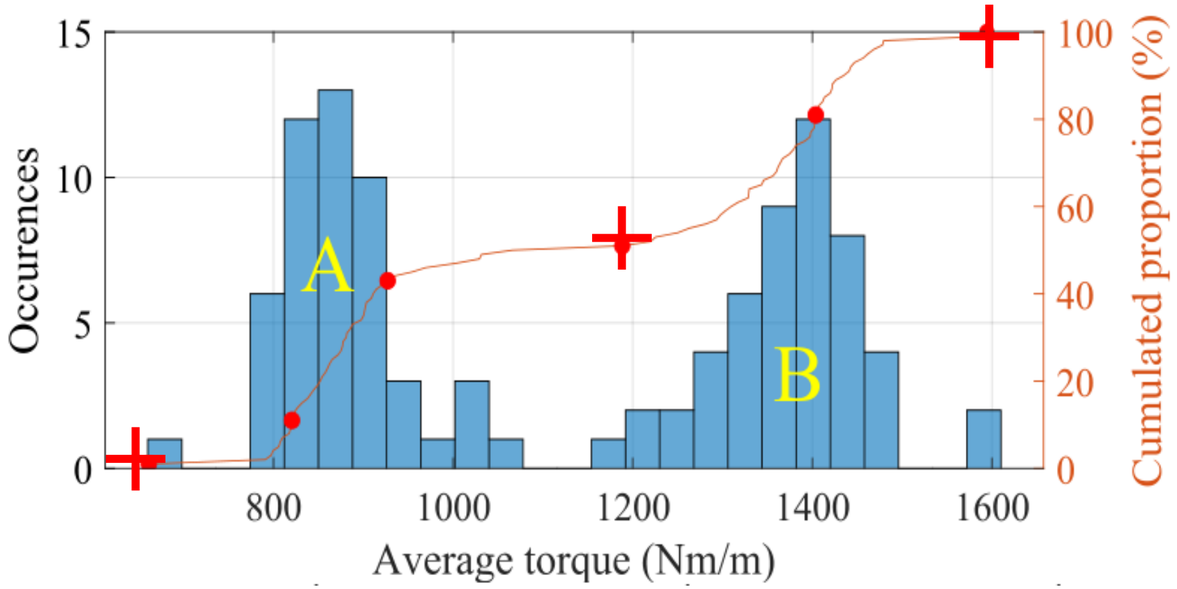
Densité

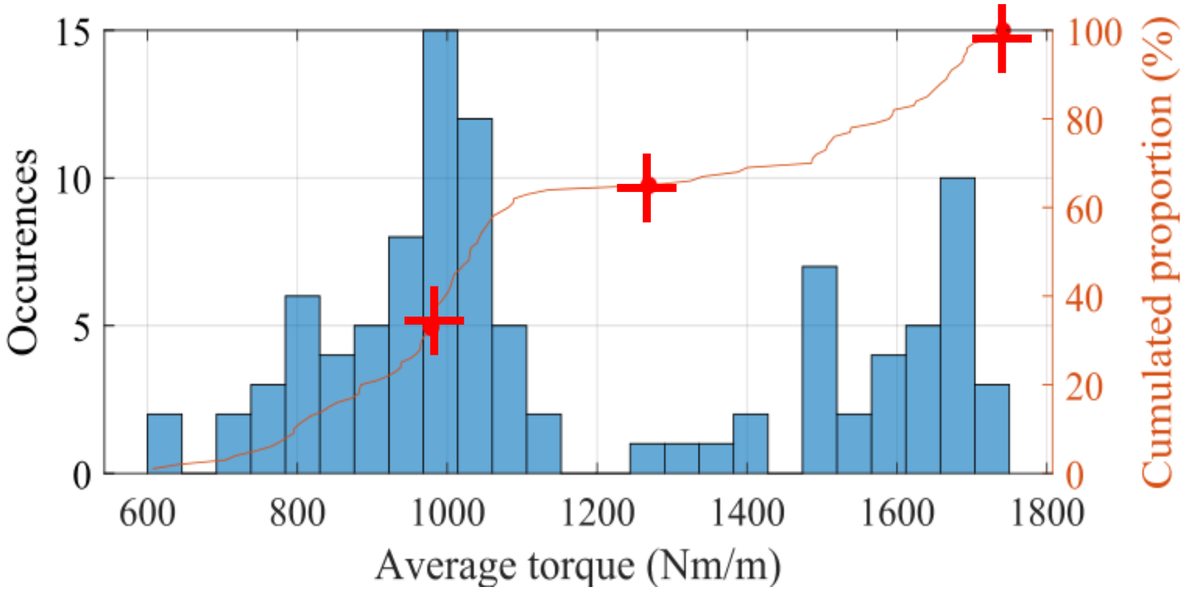


LS + Dérivée topologique

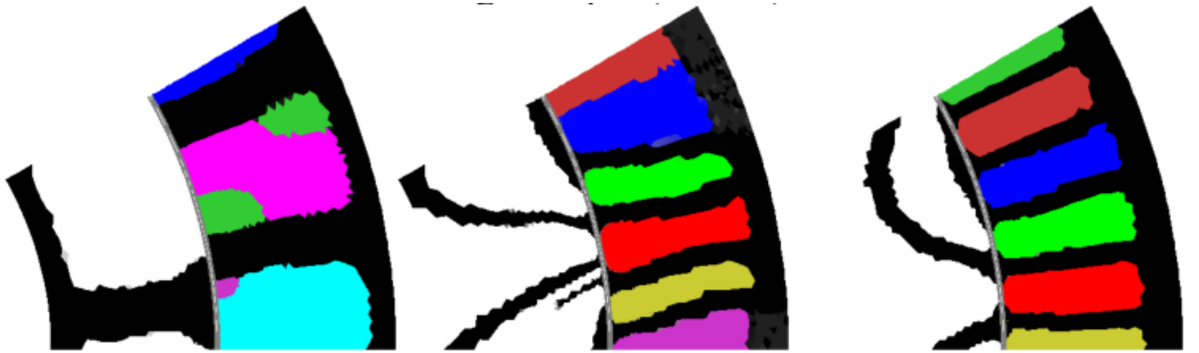
TC, P. Gangl and N. Krenn, "Topology optimization with arbitrarily many materials: density versus level-set applied to a hybrid excited rotor," in *IEEE Transactions on Magnetics*, doi: 10.1109/TMAG.2025.3630504

Multi-matériaux : exemples (machines entières)





3 phases



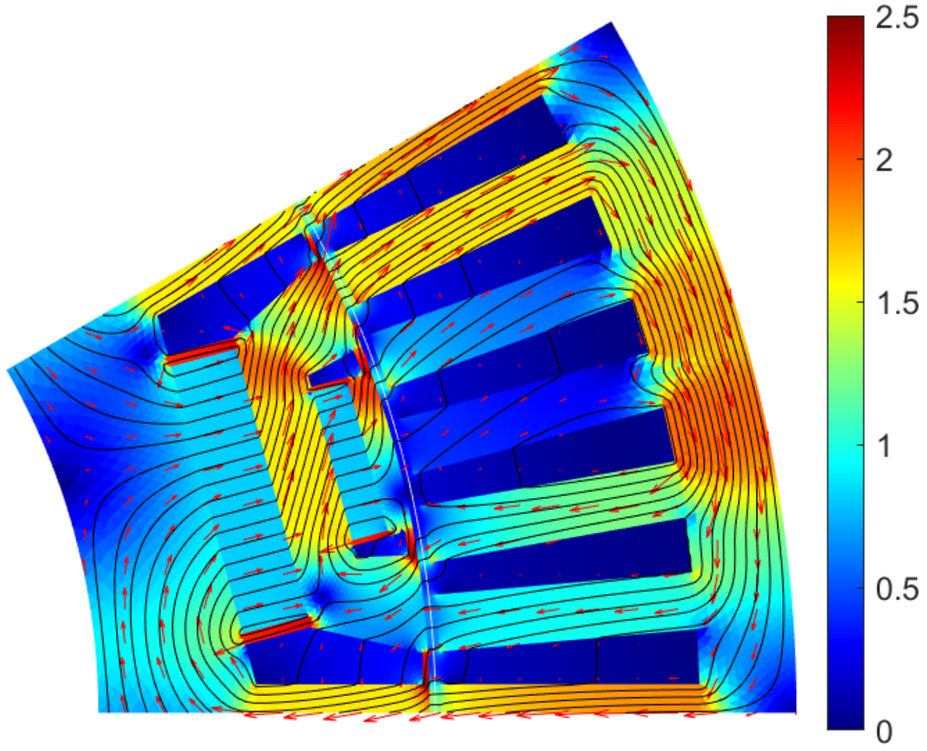
5 phases

TC et.al (2024) "Topology Optimization of a Complete Reluctance Machine with no Initial Information on its Geometry,« ICEM *2024*

Optimisation magnéto-mécanique : difficultés

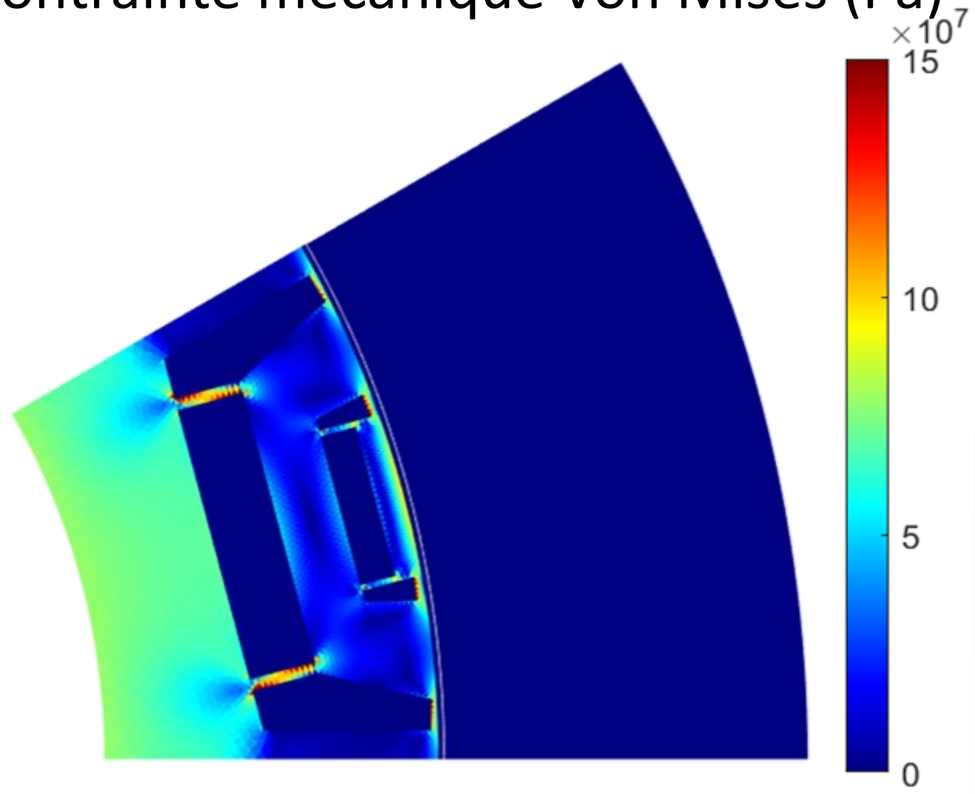
Objectifs magnétiques et mécaniques contradictoires

Induction magnétique (T)



Court-circuits magnétiques
⇒ ponts en acier à **supprimer** !

Contrainte mécanique Von Mises (Pa)

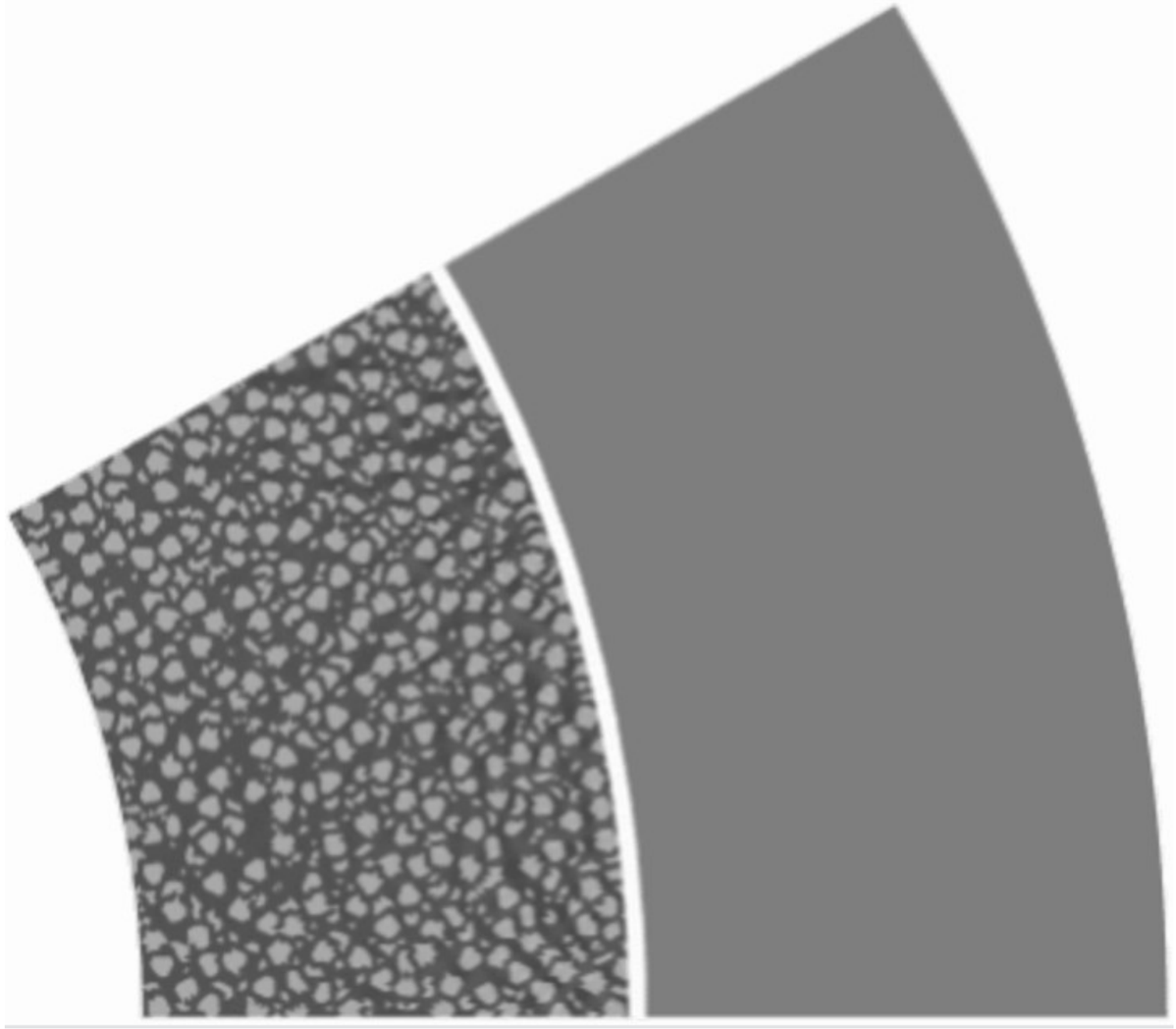


Concentration de contrainte, risque de **rupture** ⇒ ponts en acier à **élargir** !

Optimisation magnéto-mécanique : résultats (rotor)

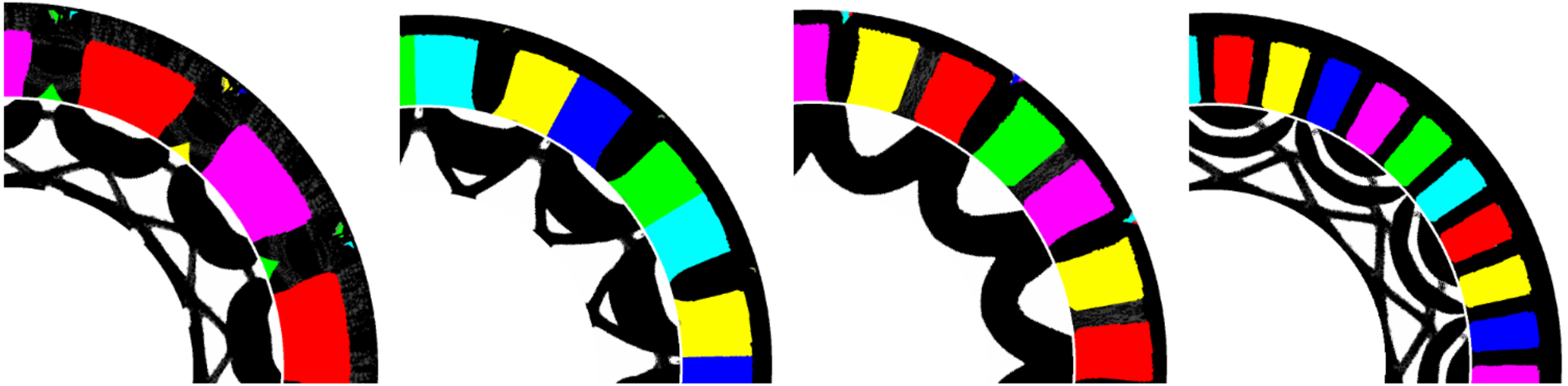
TC et. al. (2024) "Optimisation topologique magnéto-mécanique d’un rotor de machine électrique synchro-réluctante. " *16ème Colloque National en Calcul de Structures*

Optimisation magnéto-mécanique : résultats (machines complètes)



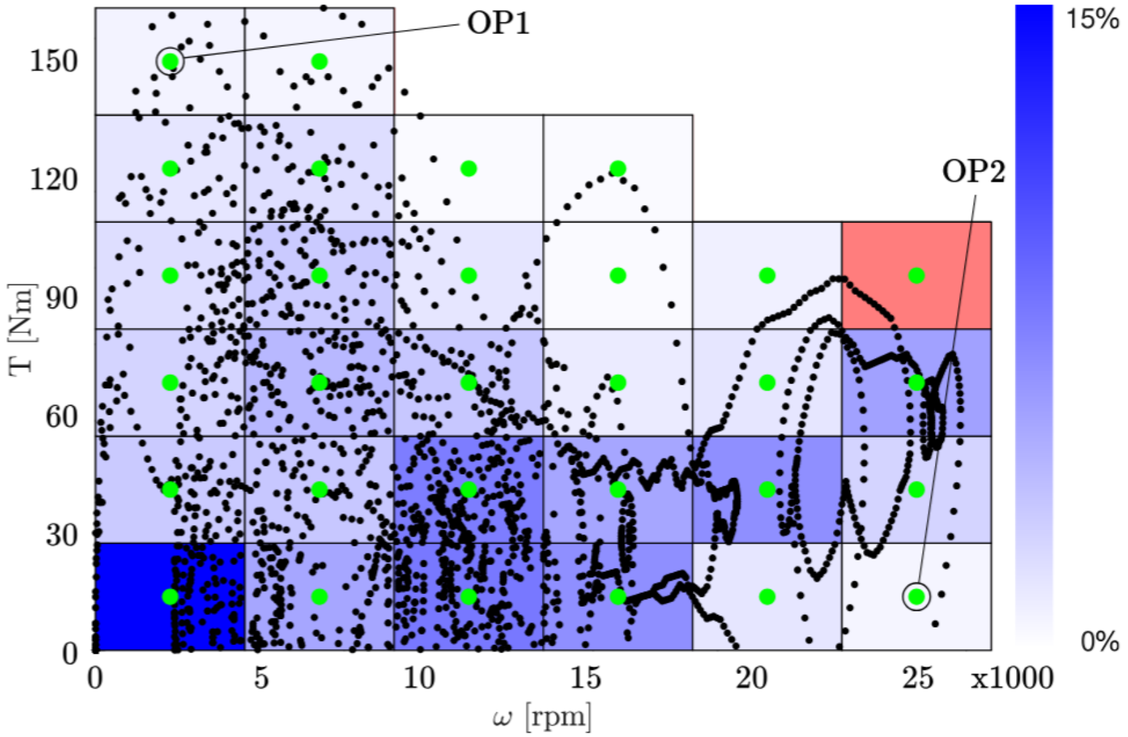
Optimisation magnéto-mécanique : résultats (machines complètes)

Optimisation magnéto-mécanique : résultats (machines complètes)

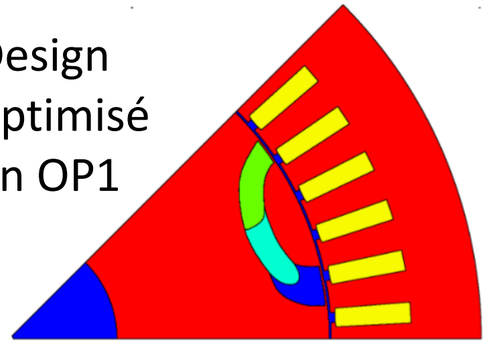


TC (2023) "Élaboration d’outils logiciels pour l’optimisation topologique magnéto-mécanique de machines électriques tournantes”. Thèse de doctorat, Université Paris-Saclay, p. 227

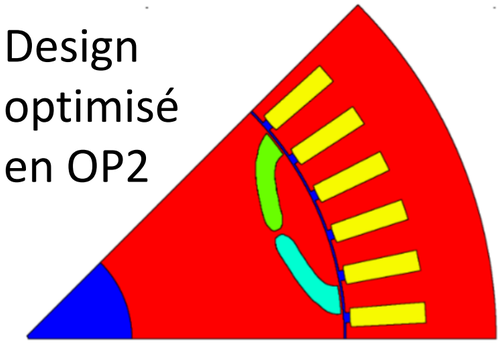
Optimisation sur cycle de conduite



Design optimisé en OP1

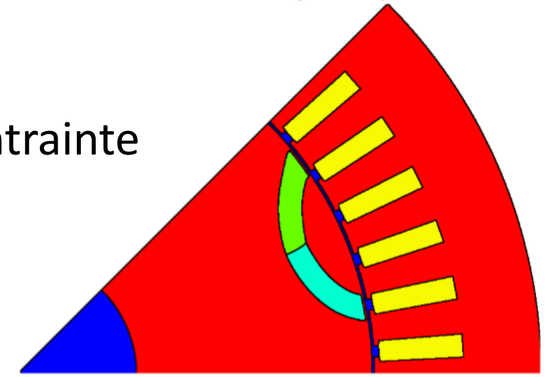


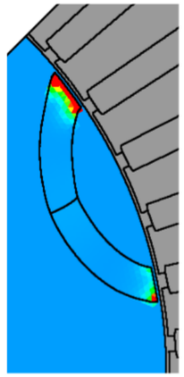
Design optimisé en OP2

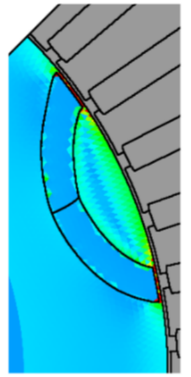


Design optimisé | Pertes | Contraintes

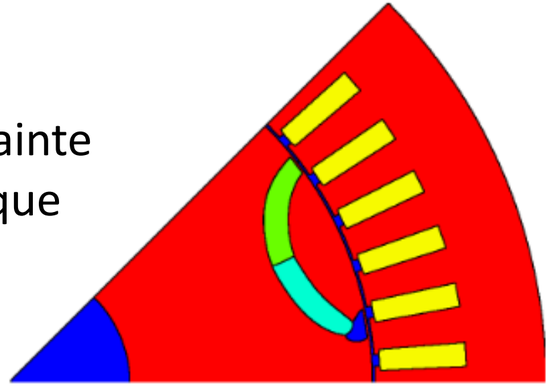
sans contrainte

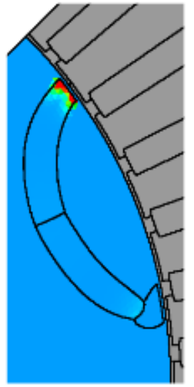


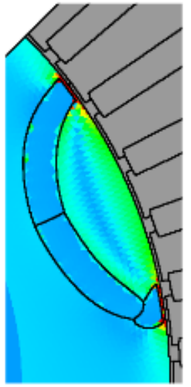




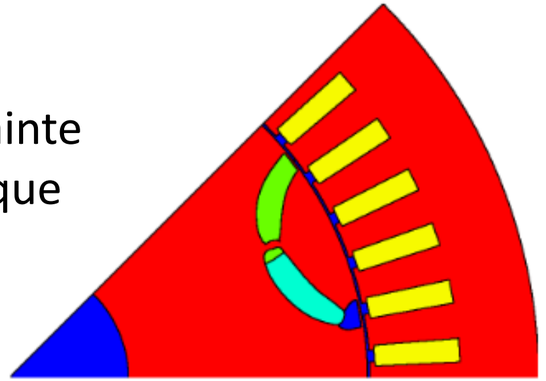
+ contrainte thermique

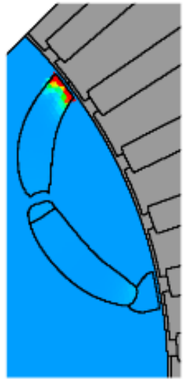


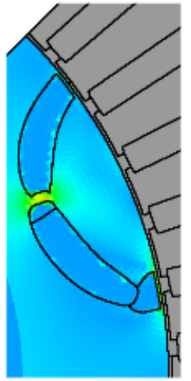




+ contrainte mécanique



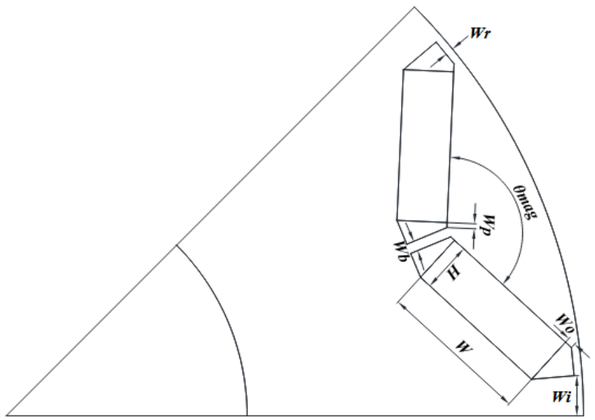


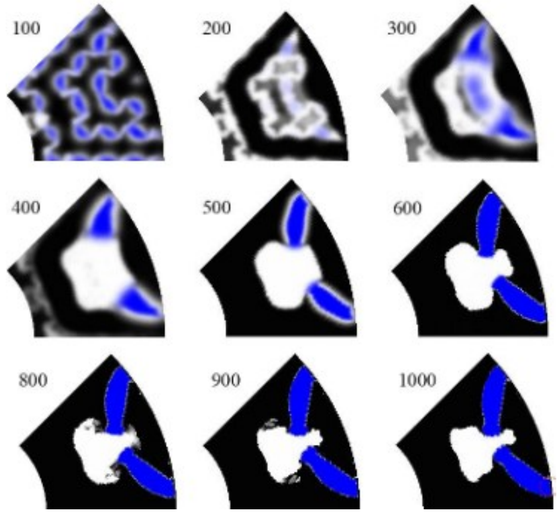


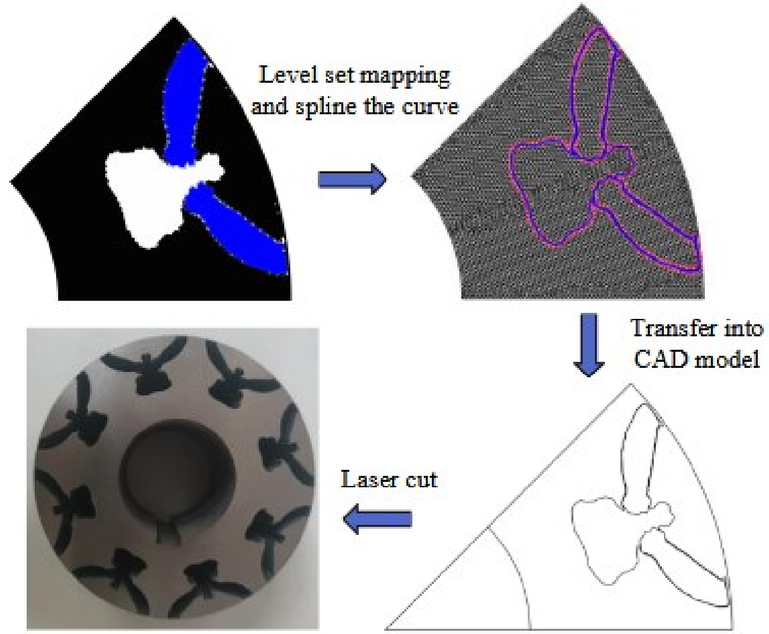
Collaboration RICAM (Autriche)

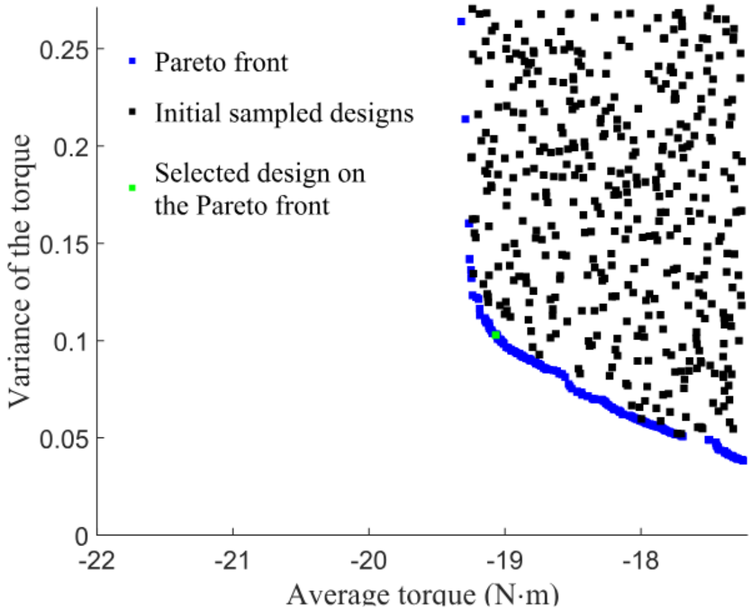
N. Krenn*, TC, S. Schöps and P. Gangl, "Electro-thermal topology optimization of an electric machine by the topological derivative considering drive cycles," in *IEEE Transactions on Magnetics*, doi: 10.1109/TMAG.2025.3630345

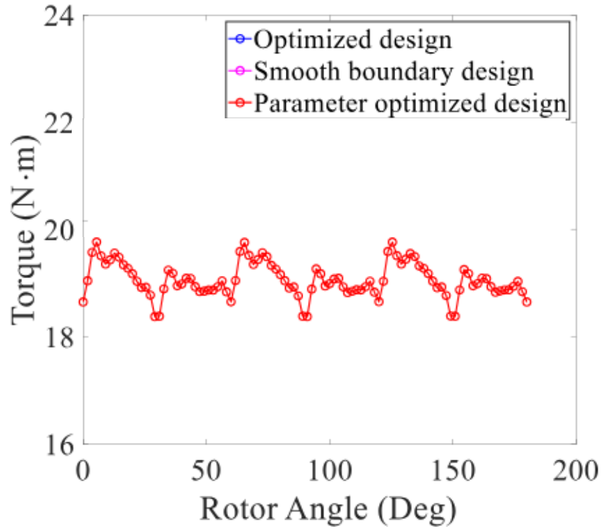
Optimisation magnéto-mécanique : jusqu'à la fabrication











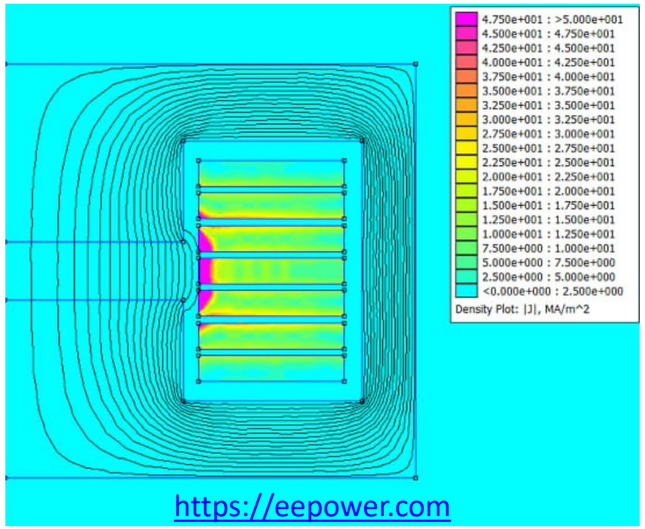
Y. Li*, B. Ma, TC et al., "Topology optimization for Generating Optimal Free-Form Rotor Structures in PMSMs," in *IEEE Transactions on Energy Conversion*, 10.1109/TEC.2025.3646612

Collaboration Hunan Institute of Engineering (Chine)

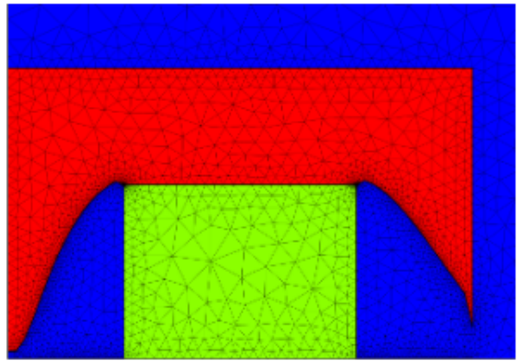
4) Application à d’autres domaines du génie électrique

Optimisation de forme de l’entrefer d’une inductance

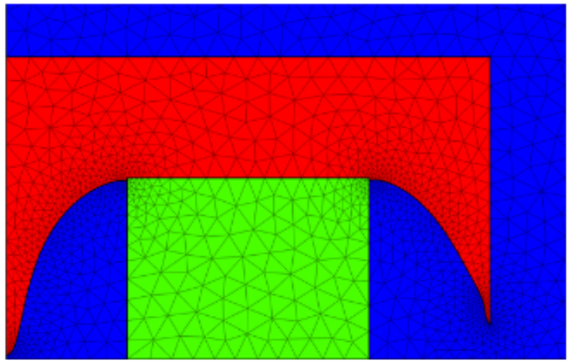
https://info.triadmagnetics.com



https://eepower.com

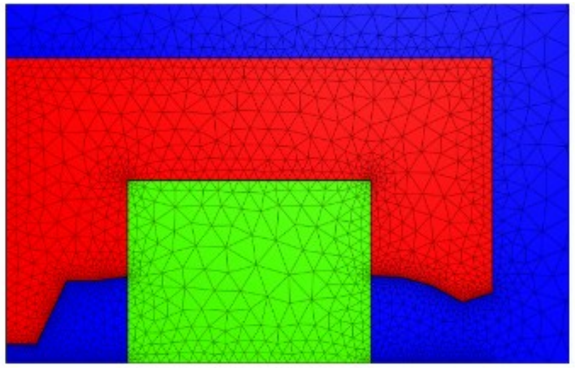


(a) Optimized design using 30 control points (gradient based)

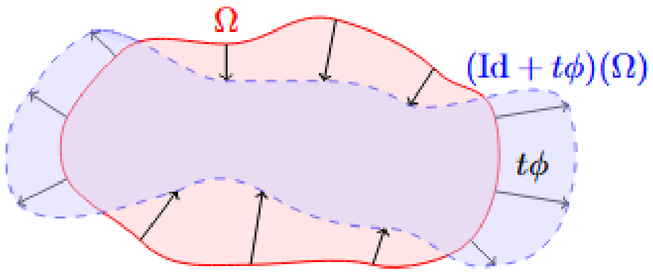


(b) Optimized design using adaptative mesh deformation

Minimisation des pertes par effet de proximité



(a) Differential evolution

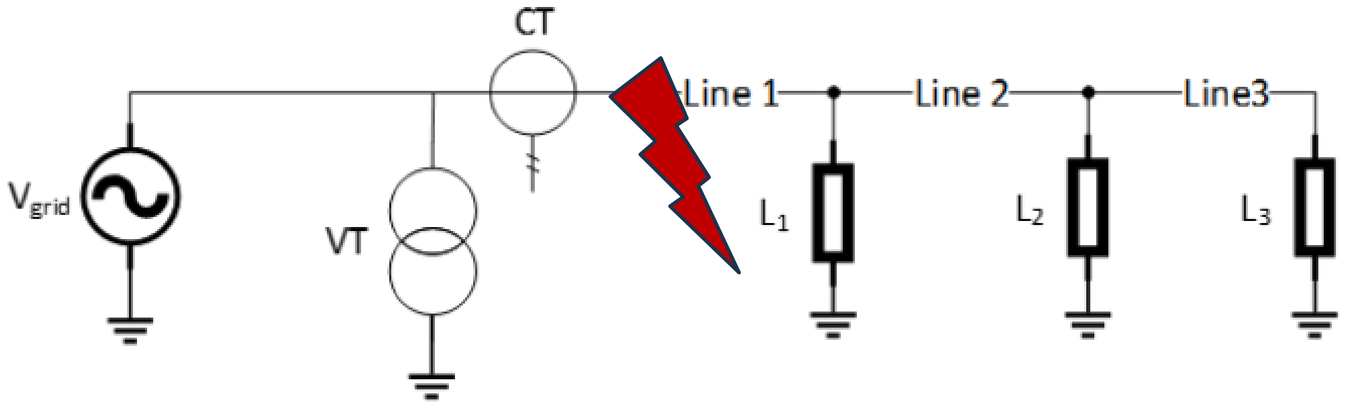


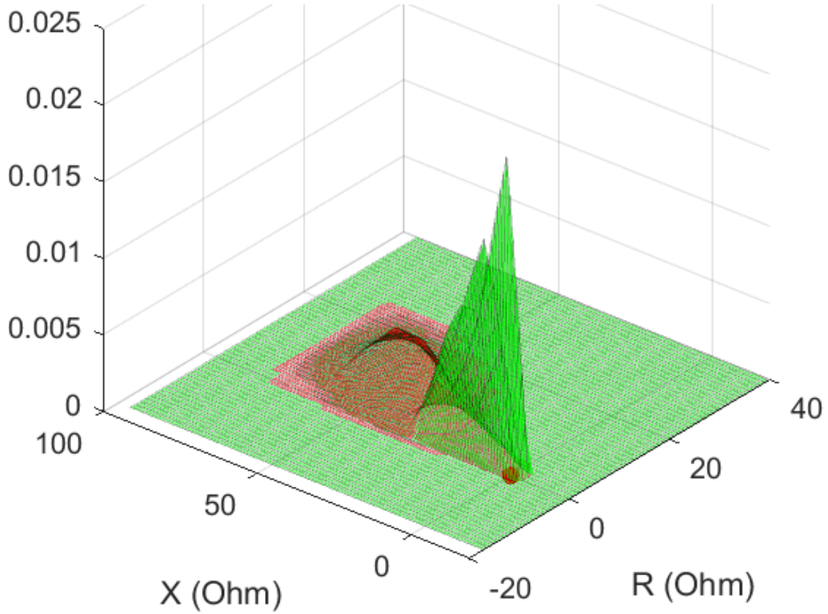
Optimization Type	Magn. solves	P (W)	L (mH)
Reference	-	13.16	1.00
Differential evolution (avg)	*6385*	7.85	$1\,\mathrm{mH} \pm 5\%$
Gradient-based control points	310	3.80	1.00
Adaptative mesh deformation	604	3.76	1.00

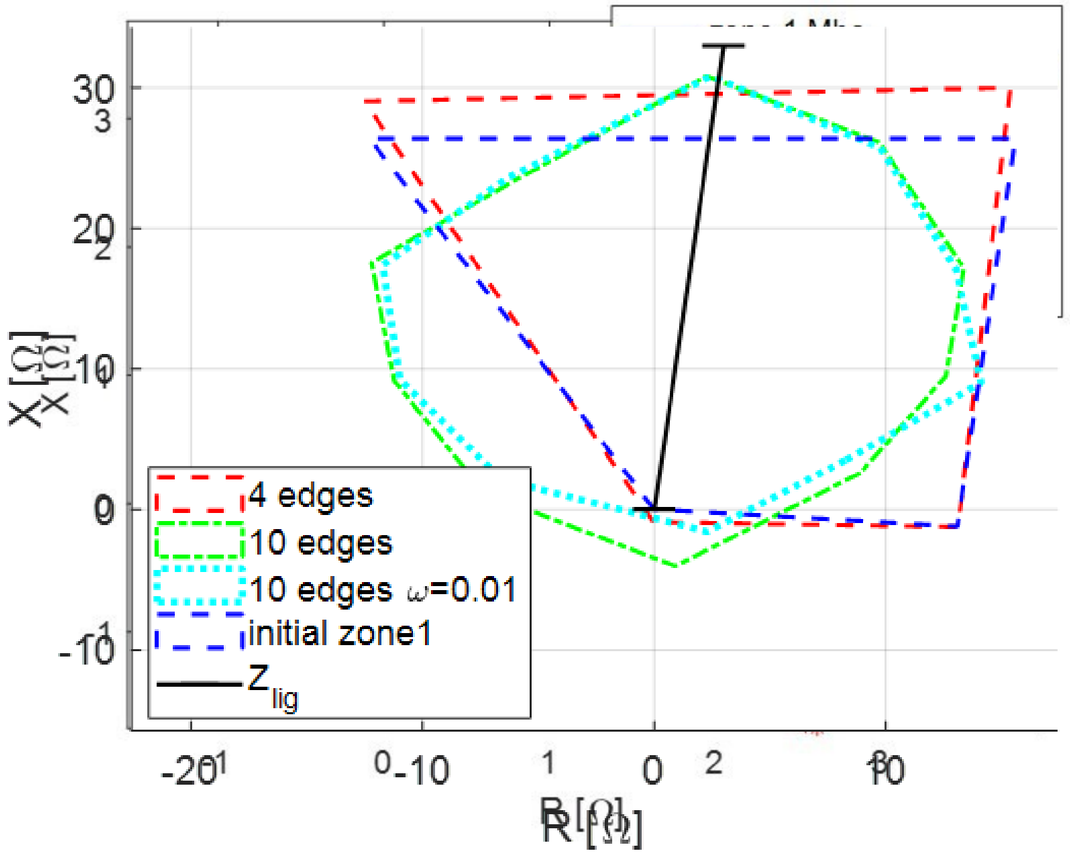
Collaboration G2ELab / RICAM (Autriche)

S. Gaydier*, I. Zehavi, TC and P. Gangl, "Air Gap Shape Optimization for Minimizing Proximity Losses in an Inductor," in *IEEE Transactions on Magnetics*, doi: 10.1109/TMAG.2026.3651849

Optimisation de forme de protection de distance



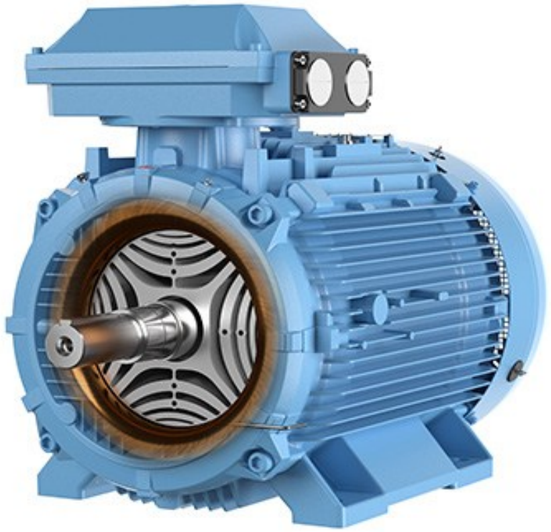




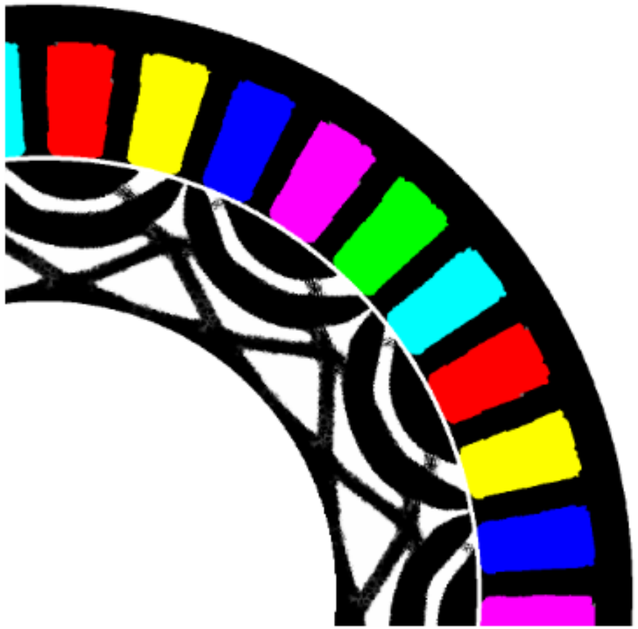
A. Bach*, P. Henneaux, and TC, "A shape optimisation framework to design robust distance elements considering uncertainties," *DPSP Europe 2025*, https://hal.science/hal-05020656

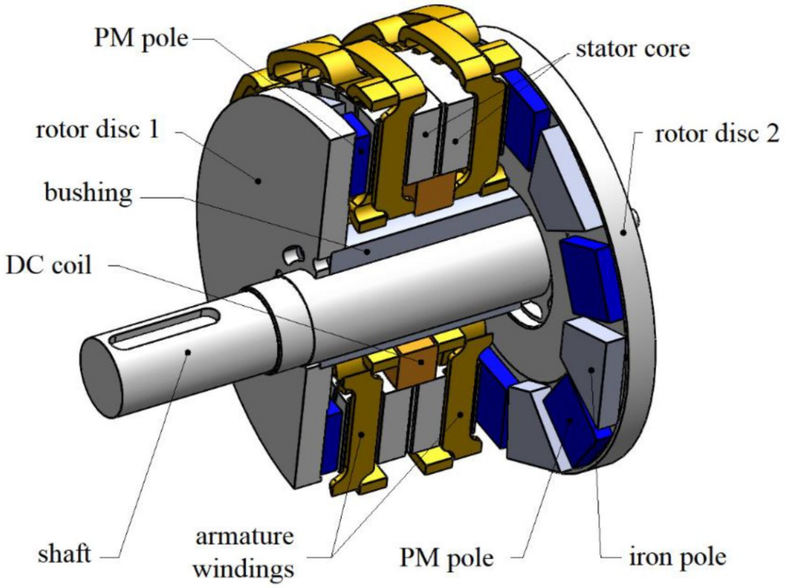
5) Conclusion et perspectives

Conclusion et perspectives



Moteur synchro-réluctant ABB





Machine à flux axial (3D)
[Prajzendanc & Paplicki, 2022]

- L'optimisation topologique permet de retrouver voire de surpasser l'état de l'art
  … mais une expertise en ingénierie reste requise pour valider les résultats et orienter l'algorithme.
- **Objectifs** : 3D, multiphysique, accélération, et intégration à des suites numériques.
- **Travaux en cours :**
  - Applications aux designs de shields supraconducteurs (L. Quéval, Z. Houta, GeePs)
  - Application aux bobinages des machines aéronautiques (A. Pons, G. Krebs, A. Mercier, Safran Tech)
  - Nouveaux outils mathématiques (projet DOLMEN, C. Dapogny, LJLL)

Merci de votre attention!
Questions?

Optimisation topologique en génie électrique

Théodore Cherrière

Maître de conférences – CentraleSupélec, GeePs

Séminaire GDR SEEDS – GT Systèmes Complexes

30 mars 2026, Paris

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