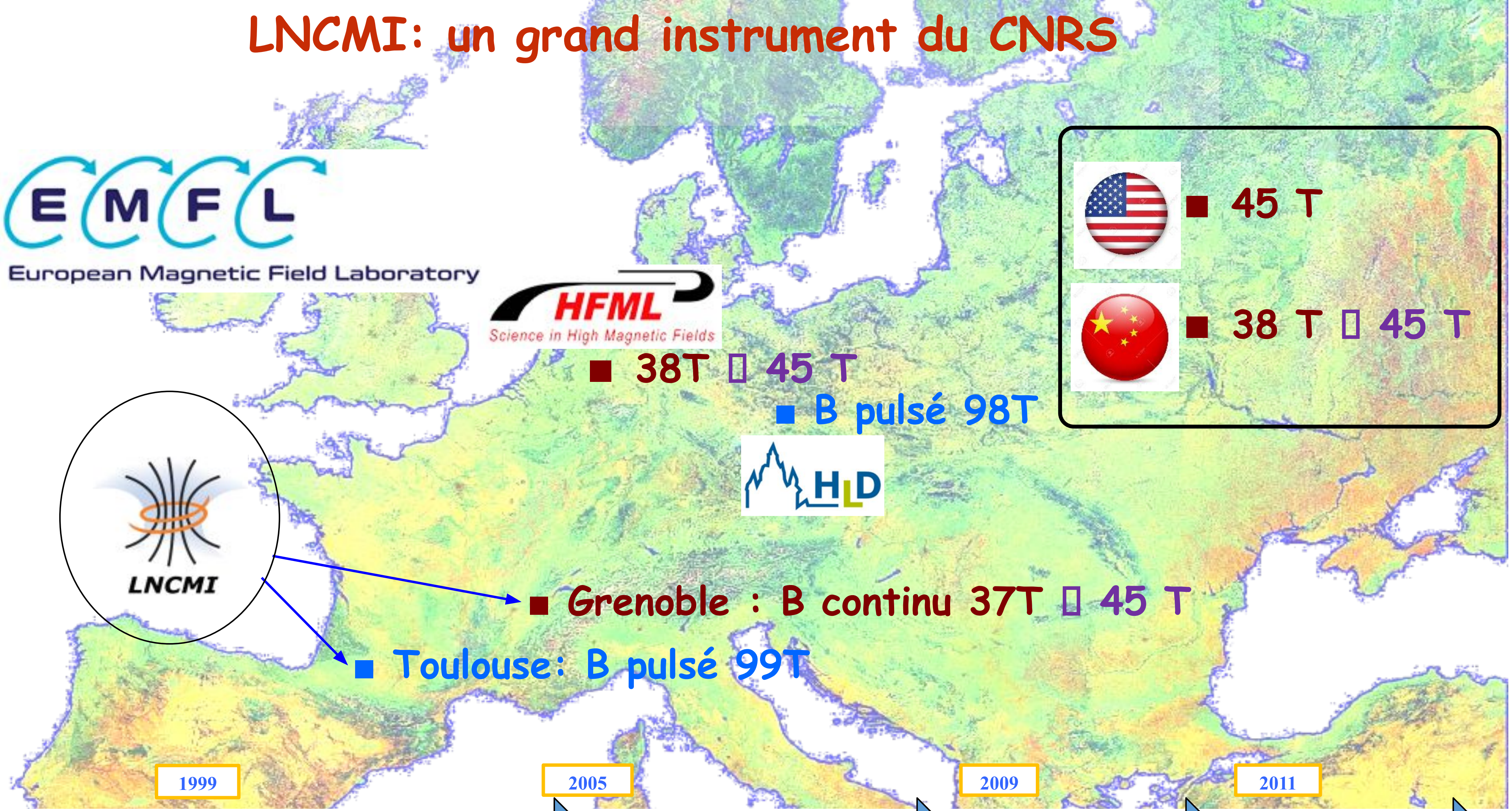
Laboratoire National des Champs Magnétiques Intenses

Christophe Trophime, LNCMI

LNCMI: un grand instrument du CNRS



European Magnetic Field Laboratory

HFML
Science in High Magnetic Fields

- 38T → 45 T
- B pulsé 98T

HLD

- 45 T
- 38 T → 45 T

LNCMI

- Grenoble : B continu 37T → 45 T
- Toulouse: B pulsé 99T

1999	2005	2009	2011
Laboratoire Franco Allemand	LCMI CNRS (UPR)	LNCMI CNRS	EMFL

Grenoble:
3000 Heures de Champs
100 Projets
20 Chercheurs, 10 Ingénieurs

P = 30 MW → 36 MW T
Refroidissement: 300 l/s
Matériaux: Alliages Cuivre (90% Limite Elastique)
1 M€, 1 an (Elaboration mat. + Usinage)

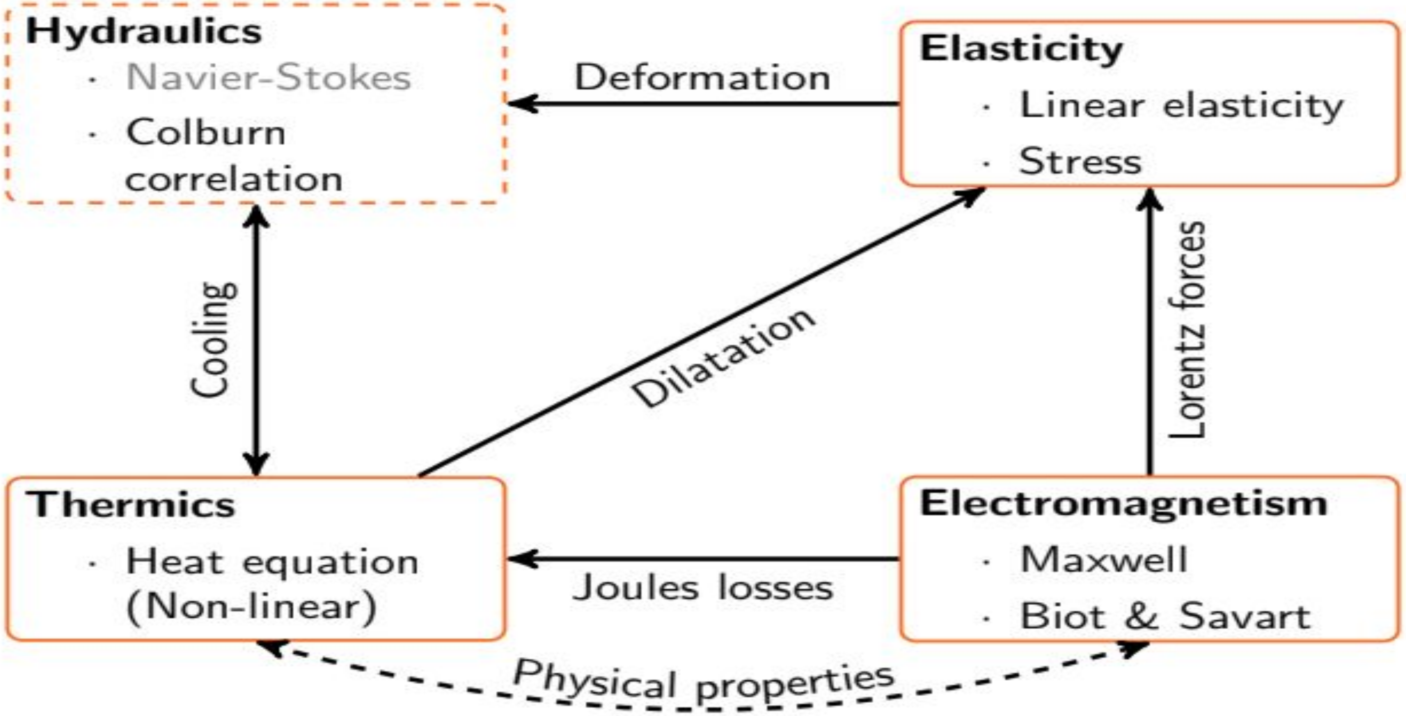
High Field Magnet Modeling

Non-Linear MultiPhysics

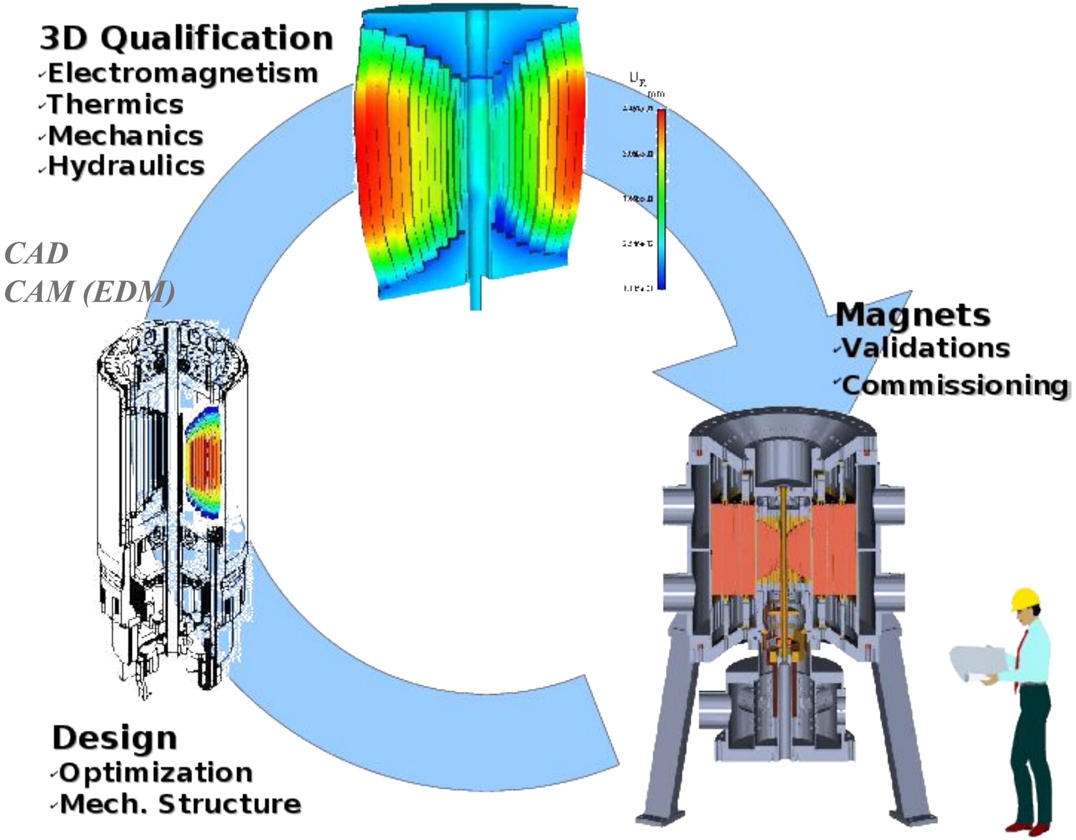
- **Different models for different purposes**
  - for Magnet Users
  - for Magnet Designers
  - for Magnet Operators

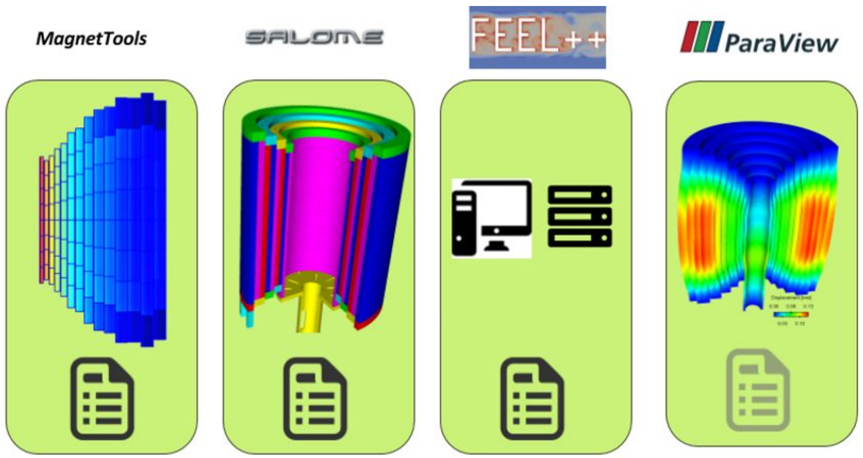
- **Uncertainties**
  - Materials
  - Geometries

- **Few InSitu measurements**



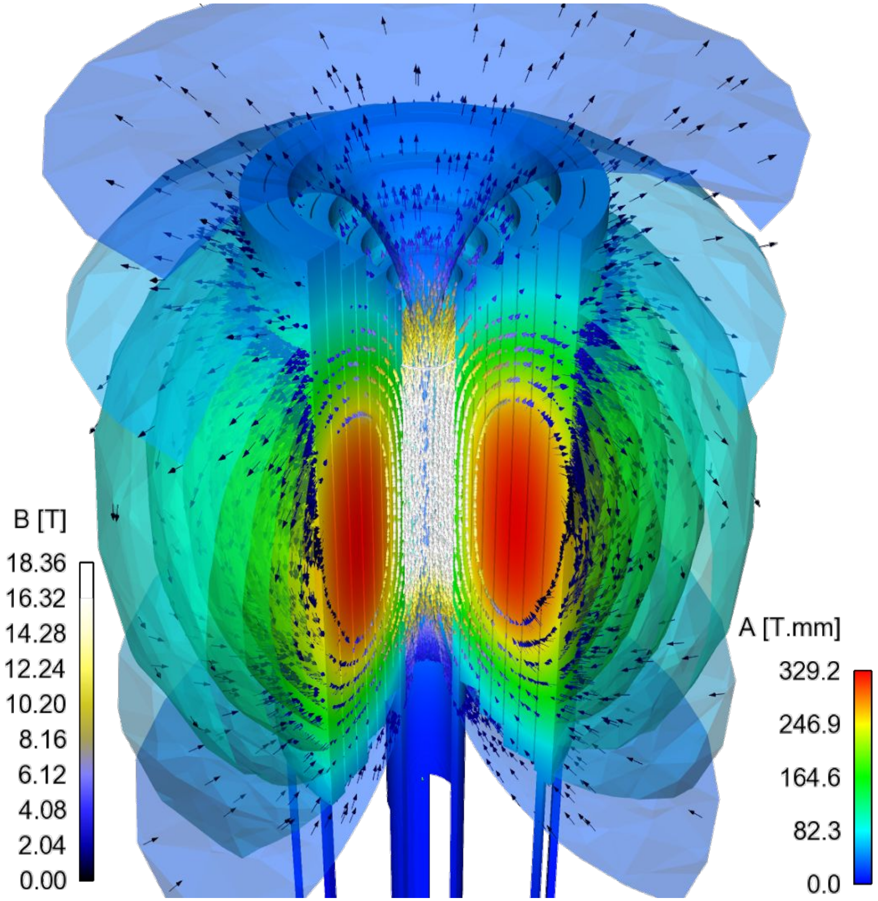
HifiMagnet une chaine logicielle





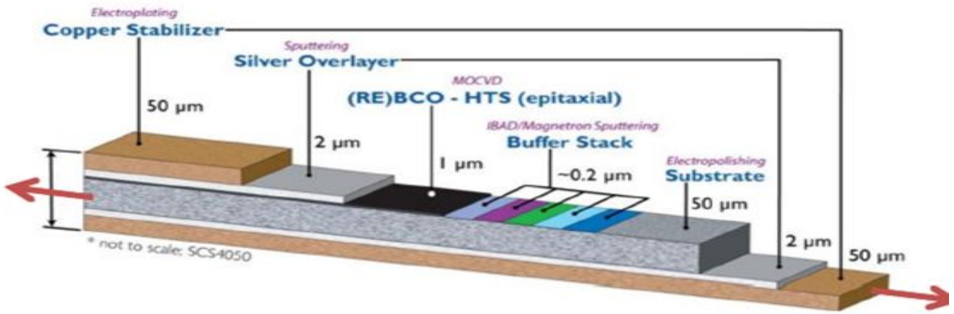
3D NL MultiPhysics
70 Billions Elem.
2 T RAM
256 Cores
1 to 3 hours

CIMENT PRACE

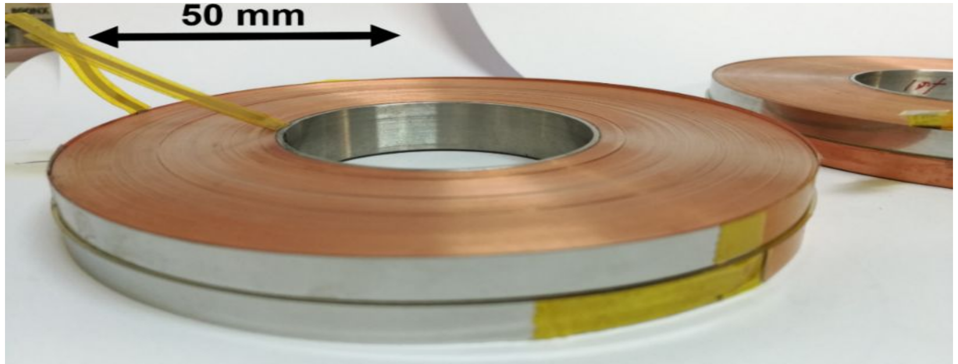


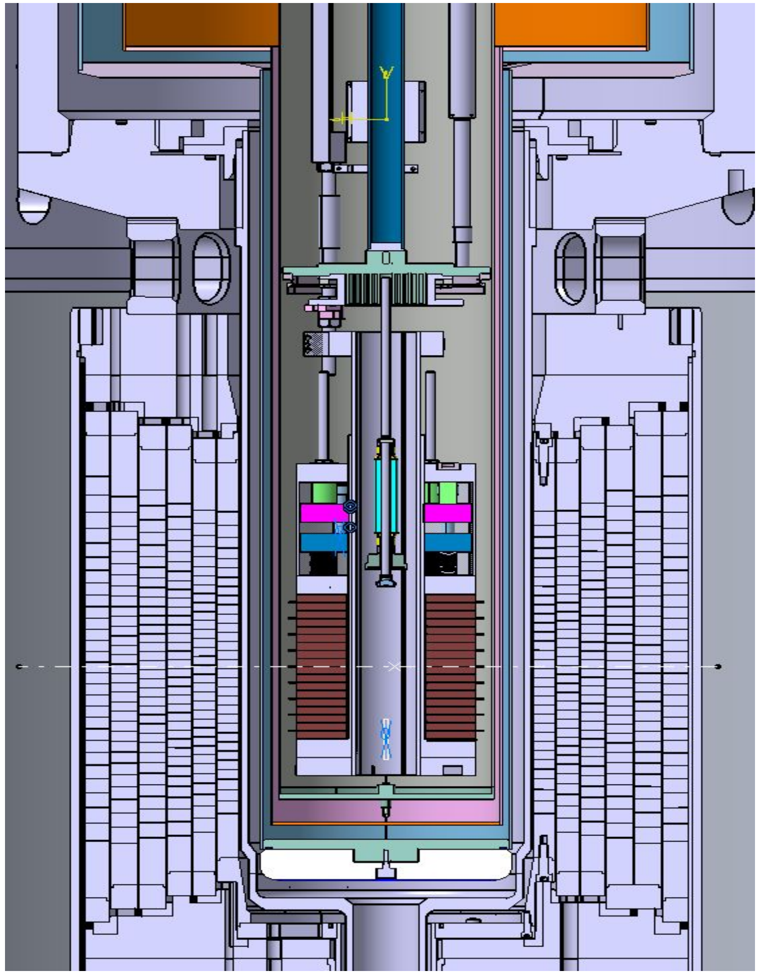
Project Nougat: an HTS insert - Record field of 32.5 T

☺ High transport current under high magnetic field
☺ High mechanical strength due to Hastelloy



☺ Affordable for 100-200 m pieces ☞ pancake coils





Toward 40 Tesla all superconductor magnet (Project H2020 SuperEMFL)

Maxwell Equations

div $\boldsymbol{b} = 0$ $\quad$ $curl\ \boldsymbol{h} = \boldsymbol{j}$ $\quad$ $curl\ \boldsymbol{e} = -\partial \boldsymbol{b}/\partial t$,

with

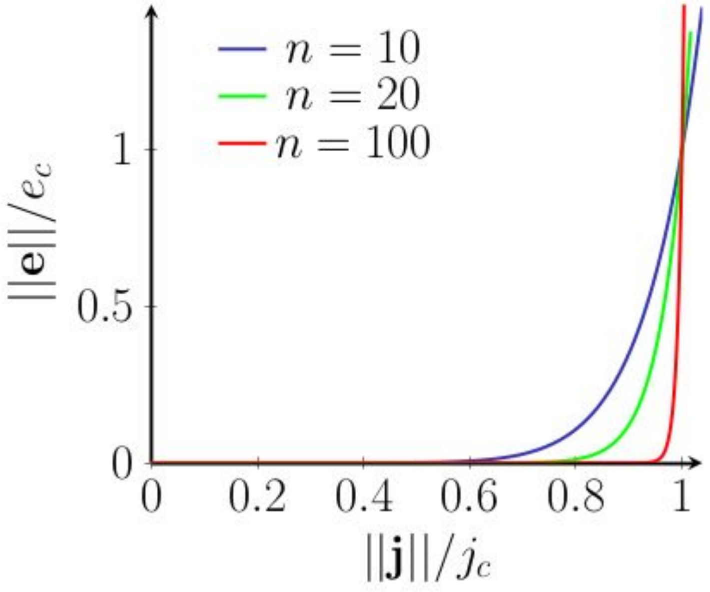
$\boldsymbol{b}$, the magnetic flux density (T),
$\boldsymbol{h}$, the magnetic field (A/m),
$\boldsymbol{j}$, the current density (A/m2)
$\boldsymbol{e}$, the electric field,

Need constitutive relationships relating $\boldsymbol{b}$ to $\boldsymbol{h}$ and $\boldsymbol{e}$ to $\boldsymbol{j}$.

Constitutive laws

1. High-temperature superconductors (SC):

$$\mathbf{e} = \rho(||\mathbf{j}||)\,\mathbf{j} \quad \text{and} \quad \mathbf{b} = \mu_0\,\mathbf{h},$$



where the electrical resistivity is given as

$$\rho(||\mathbf{j}||) = \frac{e_c}{j_c}\left(\frac{||\mathbf{j}||}{j_c}\right)^{n-1},$$

with $e_c = 10^{-4}$ V/m,
j_c, the critical current density,
n, the flux creep exponent,
$n \in [10, 1000]$.

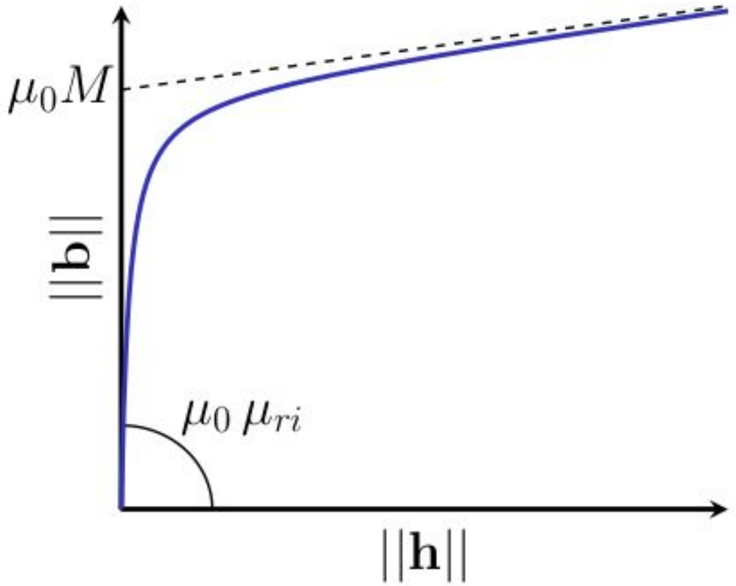
C.J.G. Plummer and J. E. Evetts, IEEE TAS **23** (1987) 1179.

E. Zeldov et al., Appl. Phys. Lett. **56** (1990) 680.

Constitutive laws, cont'd

2. Ferromagnetic materials (FM): a non-linear, but anhysteretic law:

$$\mathbf{b} = \mu(\mathbf{b})\,\mathbf{h} \quad \text{and} \quad \mathbf{j} = 0.$$



Typical values (supra50):

- initial relative permeability $\mu_{ri} = 1700$,
- saturation magnetization $\mu_0 M = 1.3$ T.

Eddy currents are neglected.

a-formulation (or A-v formulation)

- Introduce the vector potential **a** and electric potential v:

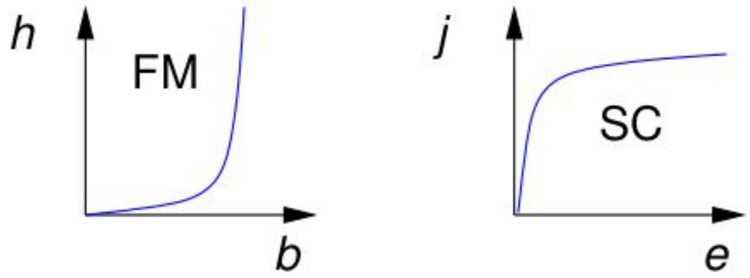
$$\mathbf{b} = \mathbf{curl}\,\mathbf{a} \quad \text{and} \quad \mathbf{e} = -\partial_t\,\mathbf{a} - \mathbf{grad}\,v.$$

  This guarantees $\mathbf{div}\,\mathbf{b} = 0$ and $\mathbf{curl}\,\mathbf{e} = -\partial_t\,\mathbf{b}$.

- There remains to solve $\mathbf{curl}\,\mathbf{h} = \mathbf{j} = \sigma\,\mathbf{e}$,

$$\Rightarrow \quad \mathbf{curl}\,(\nu\,\mathbf{curl}\,\mathbf{a}) = -\sigma\,(\partial_t\,\mathbf{a} + \mathbf{grad}\,v),$$

  where $\nu = 1/\mu$ and $\sigma = 1/\rho$ are defined region-wise.



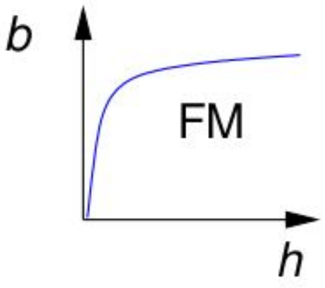
h-formulation

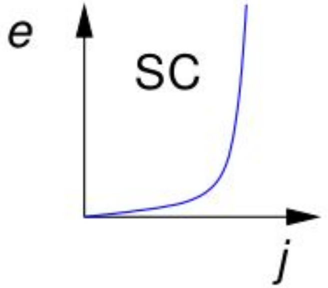
- In the non-conducting domain, we have **curl h** $= \mathbf{0}$ (no current!). Thus, introduce the scalar magnetic potential ϕ such that $\mathbf{h} = -\mathbf{grad}\ \phi$.
- Need to solve **curl e** $= -\partial_t$ **b**, together with **curl h** $=$ **j**:

$$\mathbf{curl}\ (\rho\ \mathbf{curl\ h}) = -\partial_t\ (\mu \mathbf{h}),$$

where μ and ρ are defined regionwise.

- Side note: **div b** $= 0, \forall t$, if it does for $t = 0$, as **curl e** $= -\partial_t$ **b**.

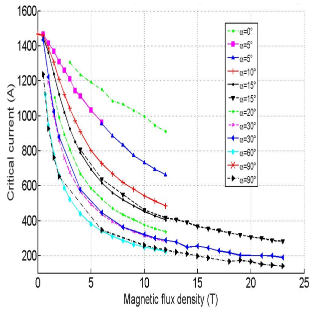




Objectifs

- Reprendre les formulations/exemples de Dular *Finite-Element Formulations for Systems With High-Temperature Superconductors, IEEE TRANS. APP. SUPER., VOL. 30, NO. 3, APRIL 2020*
- Modélisation(s) électromagnétique(s) MQS
  - Formulation(s) classique(s) (eg. A-V potential magnétique et électrique)
  - Modélisation d'aimant Supraconducteur HTS (Loi de puissance)

$$\mathbf{j} = j_c/e_c\left(\frac{||e||}{e_c}\right)^{\frac{(1-n)}{n}} \mathbf{e}$$



Déroulement

- Etude du papier, Reproduire exemples avec Getdp (Life-HTS)
- Implémentation des formulations dans Feel++
- Validations: comparaisons avec Getdp (Life-HTS)

Perspectives

- Prolongation en stage M2,
- Possibilité de thèse,

Contexte

Projet Hybride: 42 Tesla (9 Outsert Supra + 33 Insert Resistifs)
Projet Nougat: Aimant Supra HTC 32.5 Tesla (20 Insert Resistifs)
Projet SuperEMFL