Electromagnetic Design of Accelerator Magnets and ROXIE User's Course

Dynamic effects

Stephan Russenschuck, CERN, 2022

Timetable

Week	Mo	Tu	We	Th	Fr
15 (03.04)		Introduction, lumped circuits	Vector fields, field harmonics	14:00 Line currents and coil design	Magnet X-sections
16 (10.04)	Coil-ends (Brookhaven session)				
17 (17.04)			Optimization techniques	X-sec optimization	Numerical field comp., BEM-FEM
18 (24.04)	Yoke design	Integrated quant./ Dynamic effects / Computations		15:30 Diff. geom. /Coil ends, CCT / Cos theta ends	
19 (01.05)		Quench simulation	Demands and future plans/ Quench simulation (TBC)		

Perhaps a Master Class later in the year

Faraday paradoxes, coil magnetometers, stretched-wire measurements, CCT, Tori, ROXIE 22

Magnetic Energy

$$W = \frac{1}{2}\int_V \mathbf{H}\cdot\mathbf{B}\,\mathrm{d}V$$

$$\mathrm{div}\,(\mathbf{A}\times\mathbf{H}) = \mathbf{H}\cdot\,\mathrm{curl}\,\mathbf{A} - \mathbf{A}\cdot(\,\mathrm{curl}\,\mathbf{H})$$

$$\begin{aligned} W &= \frac{1}{2}\int_V \mathbf{H}\cdot\,\mathrm{curl}\,\mathbf{A}\,\mathrm{d}V \\ &= \frac{1}{2}\int_V \mathrm{div}\,(\mathbf{A}\times\mathbf{H})\,\mathrm{d}V + \frac{1}{2}\int_V \mathbf{A}\cdot\,\mathrm{curl}\,\mathbf{H}\,\mathrm{d}V \\ &= \frac{1}{2}\int_{\partial V}(\mathbf{A}\times\mathbf{H})\cdot\mathrm{d}\mathbf{a} + \frac{1}{2}\int_V \mathbf{A}\cdot\,\mathrm{curl}\,\mathbf{H}\,\mathrm{d}V \end{aligned}$$

$$W = \frac{1}{2}\int_V \mathbf{A}\cdot\,\mathrm{curl}\,\mathbf{H}\,\mathrm{d}V = \frac{1}{2}\int_V \mathbf{A}\cdot\mathbf{J}\,\mathrm{d}V$$

Inner Energy

$$\int_{\partial a} \mathbf{H} \cdot \mathrm{d}\mathbf{s} = \int_a \mathbf{J} \cdot \mathrm{d}\mathbf{a}$$

$$H\, 2\pi r = \frac{I}{\pi r_0^2} \pi r^2$$

$$H = \frac{Ir}{2\pi r_0^2}$$

$$\mathrm{d}W = \frac{1}{2} BH\, 2\pi r l \mathrm{d}r = \mu_0 H^2\, \pi r l \mathrm{d}r = \frac{\mu_0 l I^2}{4\pi r_0^4} r^3 \mathrm{d}r$$

Therefore the total energy in the wire is

$$\frac{W}{l} = \frac{\mu_0 I^2}{4\pi r_0^4} \int_0^{r_0} r^3 \mathrm{d}r = \frac{\mu_0 I^2}{16\pi}$$

For one aperture of the LHC main dipole the stored energy at 8.33 T is 237 kJ/m. The energy stored in the strands is 4.3 J/m.

Inductance

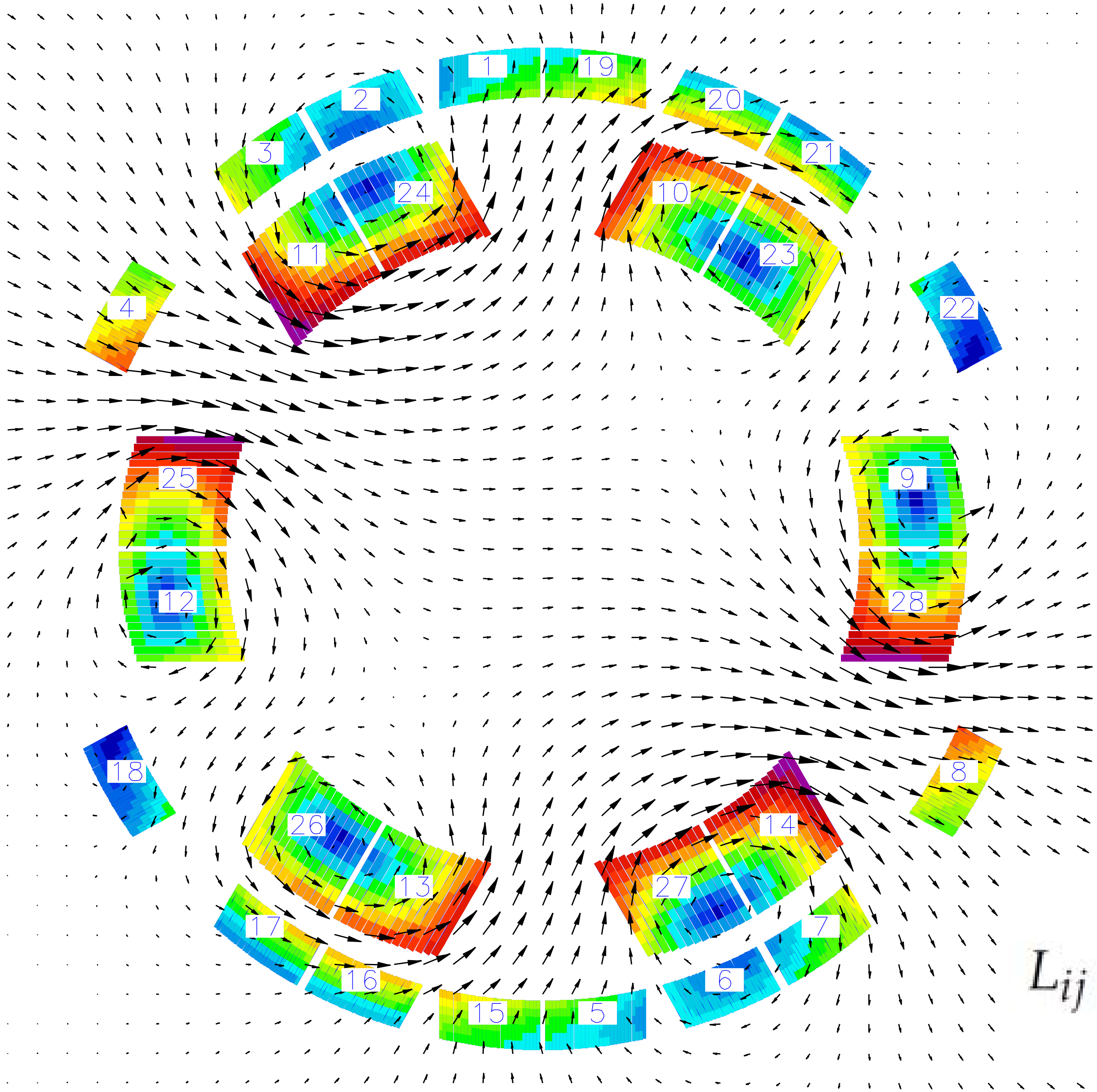
$$W = \frac{\mu_0}{8\pi} \int_V \int_{V'} \frac{\mathbf{J}(\mathbf{r}) \cdot \mathbf{J}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} \mathrm{d}V' \mathrm{d}V$$

$$W = \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} = \frac{\mu_0}{8\pi} \sum_{i=1}^{n} \sum_{j=1}^{n} \int_V \int_{V'} \frac{\mathbf{J}_i(\mathbf{r}) \cdot \mathbf{J}_j(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} \mathrm{d}V' \mathrm{d}V$$

$$= \frac{\mu_0}{8\pi} \sum_{i=1}^{n} \sum_{j=1}^{n} I_i I_j \int_V \int_{V'} \frac{\mathbf{J}_i(\mathbf{r}) \cdot \mathbf{J}_j(\mathbf{r}')}{I_i I_j |\mathbf{r} - \mathbf{r}'|} \mathrm{d}V' \mathrm{d}V$$

$$L_{ij} = \frac{\mu_0}{4\pi I_i I_j} \int_V \int_{V'} \frac{\mathbf{J}_i(\mathbf{r}) \cdot \mathbf{J}_j(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} \mathrm{d}V' \mathrm{d}V$$

Combined Dipole Sextupole Corrector



$$L_{ii} = \frac{2W_{ii}}{I^2}$$

$$L_{ij} = \frac{1}{2}\left(\frac{2W_{ij}}{I^2} - L_{ii} - L_{jj}\right)$$

Mutual Inductance Matrix

Coil	1	2	3	4	5	6	7	8
1	12.601	6.517	-0.245	0.252	0.478	-0.478	-0.252	0.245
2	6.517	12.601	-0.478	-0.252	0.245	-0.245	0.252	0.478
3	-0.245	-0.478	0.136	0.027	-0.010	0.009	-0.010	0.027
4	0.252	-0.252	0.027	0.136	0.027	-0.010	0.009	-0.010
5	0.478	0.245	-0.010	0.027	0.136	0.027	-0.010	0.009
6	-0.478	-0.245	0.009	-0.010	0.027	0.136	0.027	-0.010
7	-0.252	0.252	-0.010	0.009	-0.010	0.027	0.136	0.027
8	0.245	0.478	0.027	-0.010	0.009	-0.010	0.027	0.136

A coil of multipole order N does not couple into one of order K

Nonlinear Circuits (Differential Inductance)

$$U(t) = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}(L\,I)}{\mathrm{d}t} = L\frac{\mathrm{d}I}{\mathrm{d}t} + I\frac{\mathrm{d}L}{\mathrm{d}t}$$

$$U = L^{\mathrm{d}}\,\frac{\mathrm{d}I}{\mathrm{d}t}$$

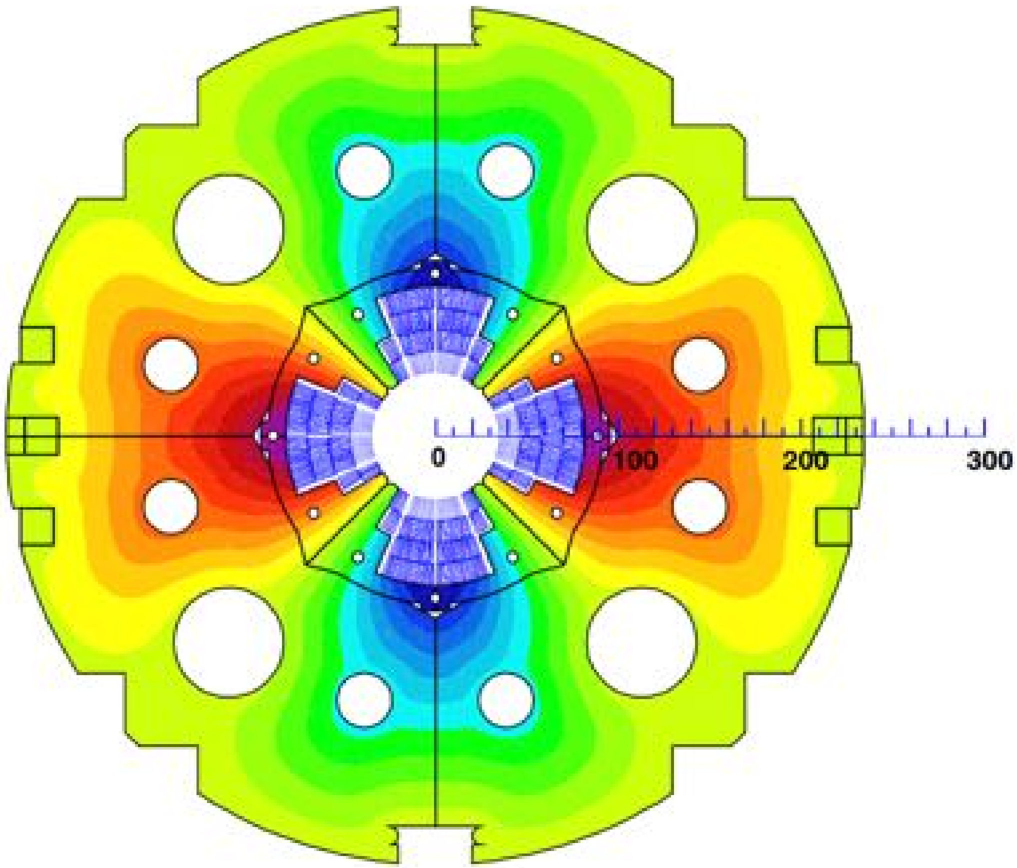
$$\mathrm{d}L = \frac{\partial L}{\partial I}\mathrm{d}I + \frac{\partial L}{\partial t}\mathrm{d}t$$

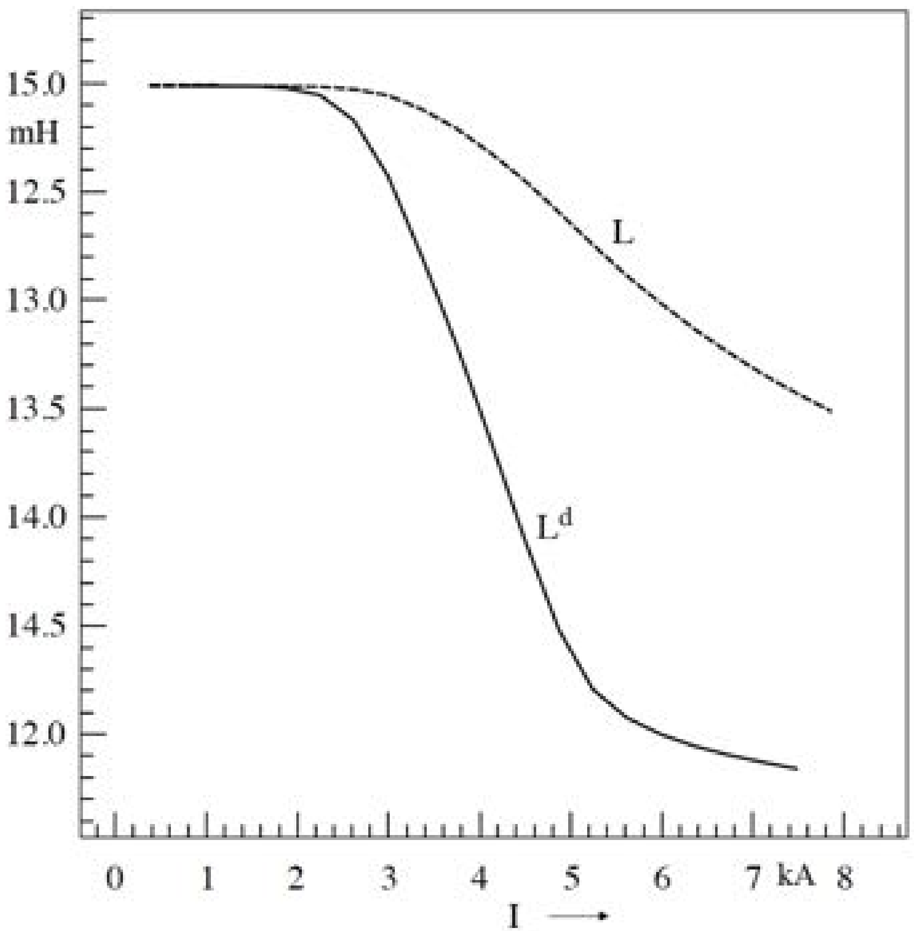
$$U(t) = \left(\frac{\partial L}{\partial I}\,I + L\right)\frac{\mathrm{d}I}{\mathrm{d}t} + I\frac{\partial L}{\partial t}$$

$$L^{\mathrm{d}} = L + I\frac{\partial L}{\partial I} = \frac{\mathrm{d}\Phi}{\mathrm{d}I}$$

For example,
machine rotor motion

Differential Inductance for the MQXY





Maxwell Stress Tensor

$$\mathbf{F}_{\mathrm{m}} = \int_{\partial\mathcal{V}} \left(\frac{1}{\mu_0} (\mathbf{B}\cdot\mathbf{n})\mathbf{B} - \frac{1}{2\mu_0} B^2 \mathbf{n} \right) \mathrm{d}a$$

$$= \int_{\partial\mathcal{V}} \left(\left(\frac{1}{2\mu_0} B_{\mathrm{n}}^2 - \frac{\mu_0}{2} H_{\mathrm{t}}^2 \right) \mathbf{n} + B_{\mathrm{n}} H_{\mathrm{t}}\, \mathbf{t} \right) \mathrm{d}a$$

$$\mathbf{F}_{\mathrm{m}} = \int_{\mathcal{V}} \frac{1}{\mu_0} \operatorname{div} \mathbf{T}_{\mathrm{m}} \, \mathrm{d}V = \int_{\partial\mathcal{V}} \frac{1}{\mu_0} \mathbf{T}_{\mathrm{m}} \cdot \mathbf{n} \, \mathrm{d}a \,,$$

$$\mathbf{T}_{\mathrm{m}} = (T_{ij}) := \begin{pmatrix} B_1^2 - \frac{1}{2}B^2 & B_1 B_2 & B_1 B_3 \\ B_2 B_1 & B_2^2 - \frac{1}{2}B^2 & B_2 B_3 \\ B_3 B_1 & B_3 B_2 & B_3^2 - \frac{1}{2}B^2 \end{pmatrix}$$

Maxwell Stress Tensor

$$\mathbf{F} = \int_{\mathscr{V}} (\rho\mathbf{E} + \rho\mathbf{v} \times \mathbf{B})\,\mathrm{d}V = \int_{\mathscr{V}} (\rho\mathbf{E} + \mathbf{J} \times \mathbf{B})\,\mathrm{d}V\,.$$

$$\mathbf{F} = \int_{\mathscr{V}} \left((\operatorname{div}\mathbf{D})\mathbf{E} + (\operatorname{curl}\mathbf{H}) \times \mathbf{B} + (\operatorname{curl}\mathbf{E}) \times \mathbf{D} - \frac{1}{c^2}\frac{\partial}{\partial t}(\mathbf{E} \times \mathbf{H}) \right) \mathrm{d}V$$

$$(\operatorname{curl}\mathbf{H}) \times \mathbf{B} = \frac{1}{\mu_0}(\mathbf{B} \cdot \operatorname{grad})\mathbf{B} - \frac{1}{2\mu_0}\operatorname{grad}(B^2)\,,$$

$$(\operatorname{curl}\mathbf{E}) \times \mathbf{D} = \epsilon_0(\mathbf{E} \cdot \operatorname{grad})\mathbf{E} - \frac{1}{2}\epsilon_0 \operatorname{grad}(E^2)\,,$$

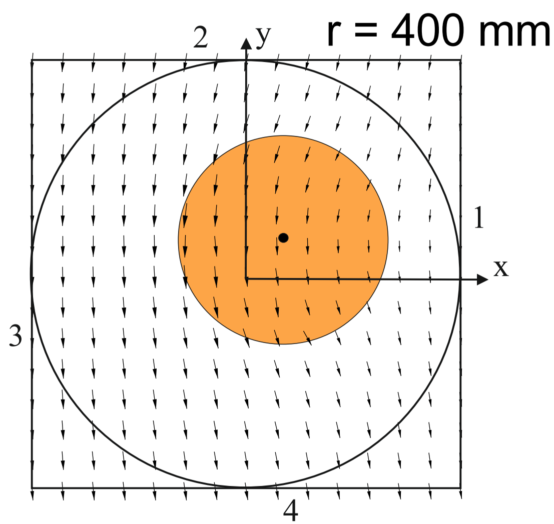
$$\mathbf{F} = \int_{\mathscr{V}} \left((\operatorname{div}\cancel{\mathbf{D}})\mathbf{E} + \epsilon_0(\mathbf{E}\cancel{\cdot\operatorname{grad}})\mathbf{E} + (\operatorname{div}\cancel{\mathbf{B}})\mathbf{H} + \frac{1}{\mu_0}(\mathbf{B} \cdot \operatorname{grad})\mathbf{B} \right.$$

$$\left. -\frac{1}{2}\operatorname{grad}\left(\epsilon_0 E^2 + \frac{1}{\mu_0}B^2\right) - \frac{1}{c^2}\frac{\partial}{\partial t}(\cancel{\mathbf{E}} \times \mathbf{H}) \right) \mathrm{d}V\,.$$

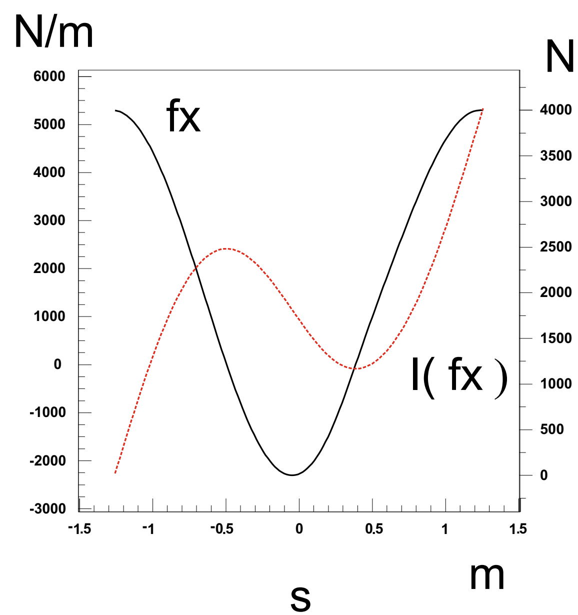
$$\mathbf{T}_{\mathrm{m}} = (T_{ij}) := \begin{pmatrix} B_1^2 - \frac{1}{2}B^2 & B_1 B_2 & B_1 B_3 \\ B_2 B_1 & B_2^2 - \frac{1}{2}B^2 & B_2 B_3 \\ B_3 B_1 & B_3 B_2 & B_3^2 - \frac{1}{2}B^2 \end{pmatrix}$$

Testcase: Conductor in homogeneous field

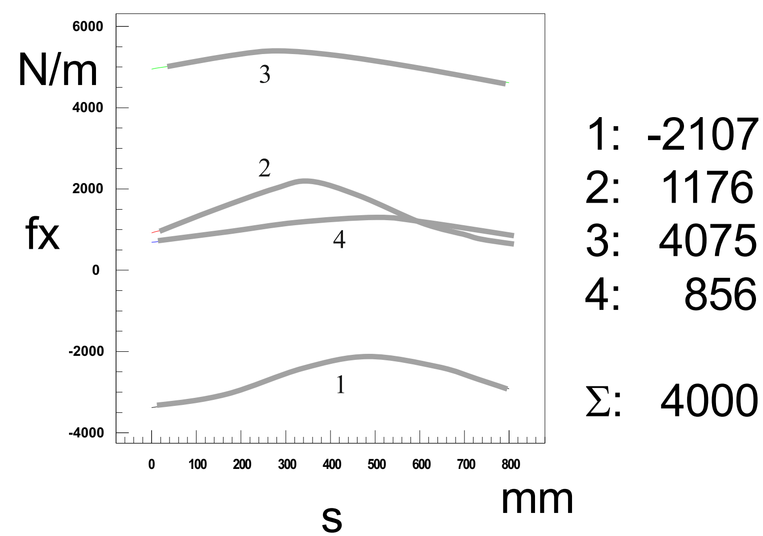
$$\mathbf{F}_{\mathrm{m}} = \int_{\partial \mathcal{V}} \left(\left(\frac{1}{2\mu_0} B_{\mathrm{n}}^2 - \frac{\mu_0}{2} H_{\mathrm{t}}^2 \right) \mathbf{n} + B_{\mathrm{n}} H_{\mathrm{t}} \, \mathbf{t} \right) \, \mathrm{d}a \, .$$



40000 A in 0.1 T dipole field
= 4000 N per meter length

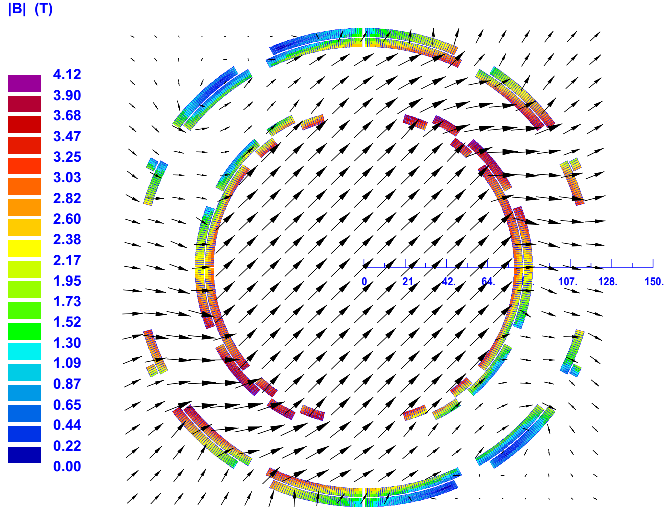


Along the circle of 400 mm

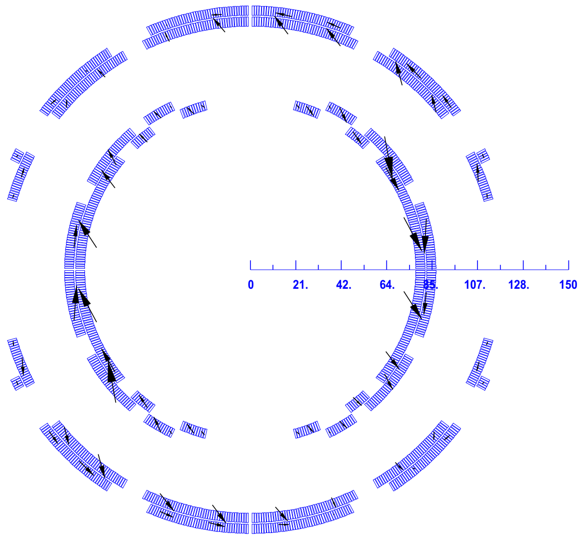


Along the sides of the box

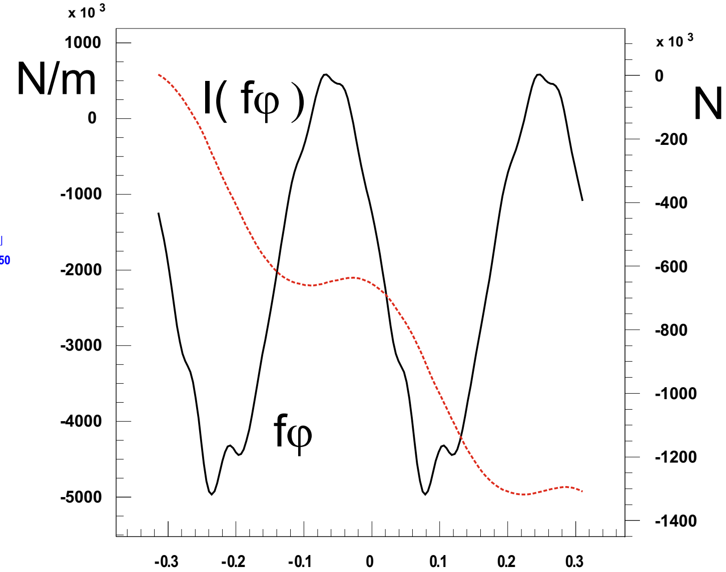
MCBXF



R = 100 mm



Integral: -1.311 10**6 N



Nominal current inner 1584

outer 1402

B1 = 2.177 T

A1 = 2.254 T

Max LL: 49.84 %

Sum of forces normal to broad face

- 1.621 10**6 N per meter length

= - 162.2 kNm torque per meter

Torque per m length

-131.57 kNm per meter

Results when using T = m x B

$$\mathbf{m} = I\mathbf{a},$$

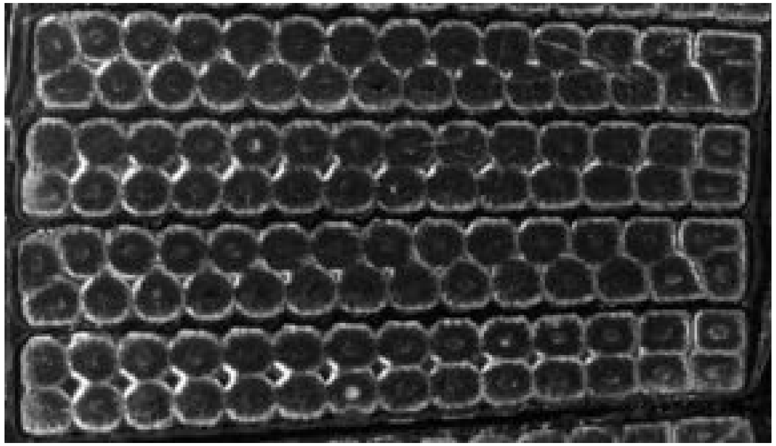
n	K_n^{rad}	K_n^{tan}
1	$N\,Lw$	$N\,Lw$
2	$N\,Lw\,r$	$N\,Lw\,r_c\cos(\frac{\delta}{2})$
3	$N\,Lw\,(\frac{w^2}{12}+r^2)$	$\frac{1}{3}N\,Lw\,r_c^2(1+2\cos(\delta))$
4	$N\,Lw\,r(\frac{w^2}{4}+r^2)$	$N\,Lw\,r_c^3\cos(\delta)\,\cos(\frac{\delta}{2})$
5	$N\,Lw\,(\frac{w^4}{80}+\frac{w^2r^2}{2}+r^4)$	$\frac{1}{5}N\,Lw\,r_c^4(1+2\cos(\delta)+2\cos(2\delta))$
6	$N\,Lw\,r(\frac{w^4}{16}+\frac{5w^2r^2}{6}+r^4)$	$\frac{1}{3}N\,Lw\,r_c^5(4\cos^2(\delta)-1)\,\cos(\frac{\delta}{2})$

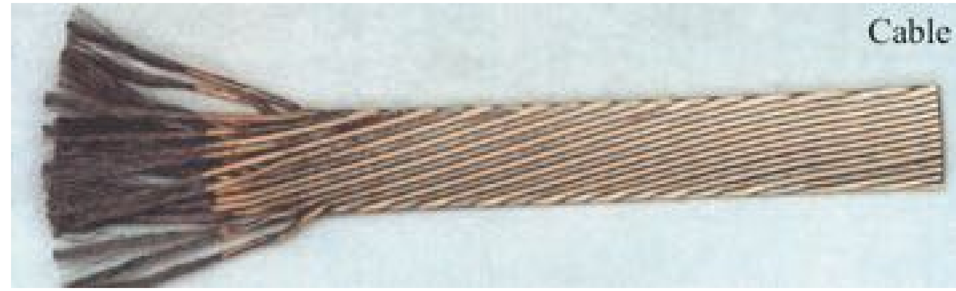
In ROXIE: use the routine for the K-values of search coils. K_1 = a

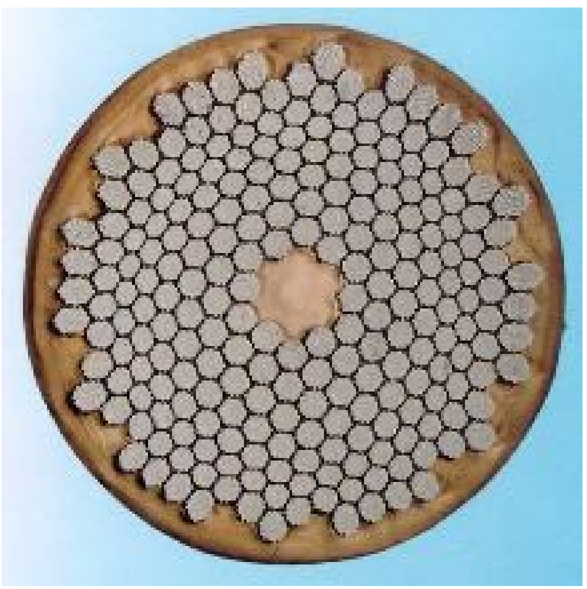
The magnetic moment of the inner coil of MCBXF at nominal excitation of 1584 A is 58668 Am**2 per meter length. The outer coil creates a homogeneous dipole field of 2.254 T, which yields 132.23 kNm per meter when m and B are at a right angle. I1 = current in inner coil, I2 current in outer coil

$\{T\}_N = \{I1\}_A * 37.04 \;\text{x}\; \{I2\}_A * 2.254/1402 = \{I1\} \;\text{x}\; \{I2\} * 0.059546$

Rutherford (Roebel) Kabel, Strand, Nb-Ti Filament

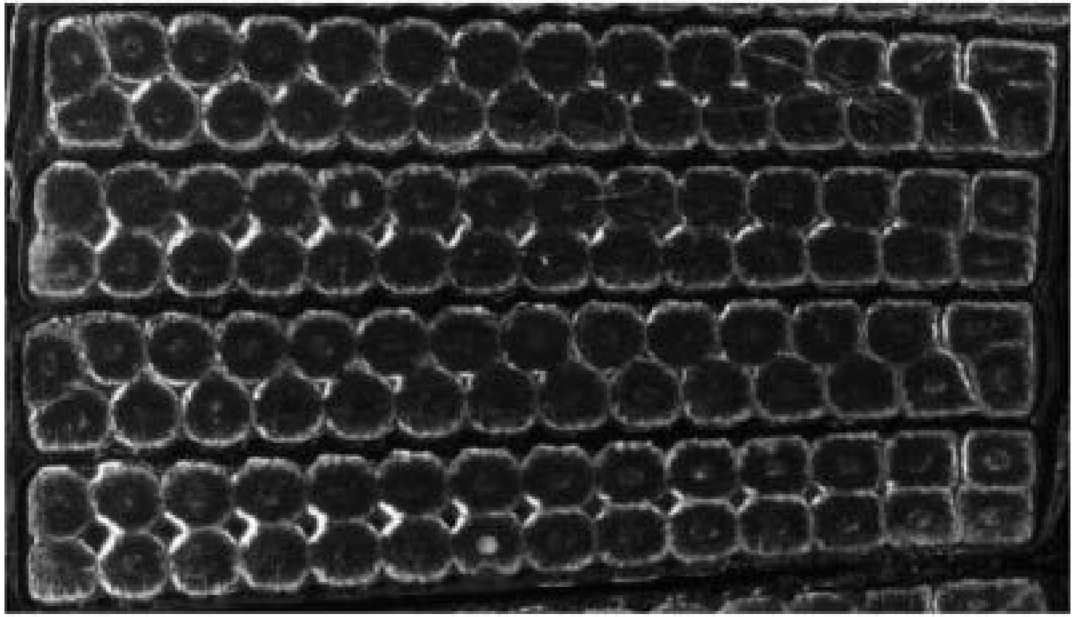






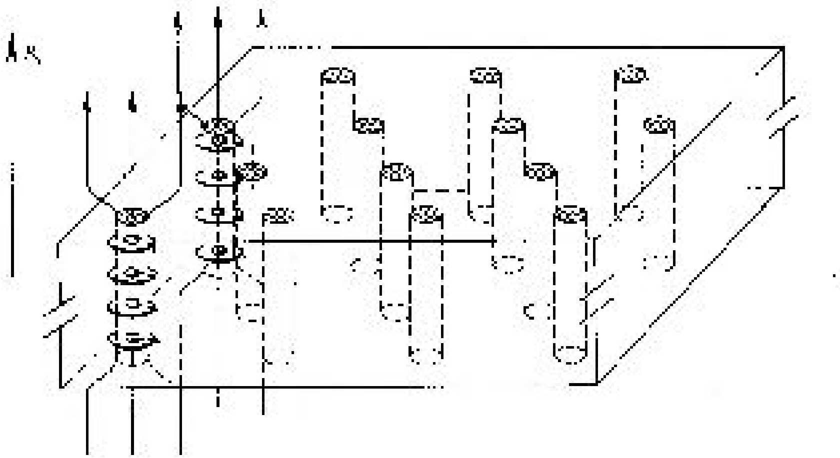
Coil Block, Pinning Centers in Filaments

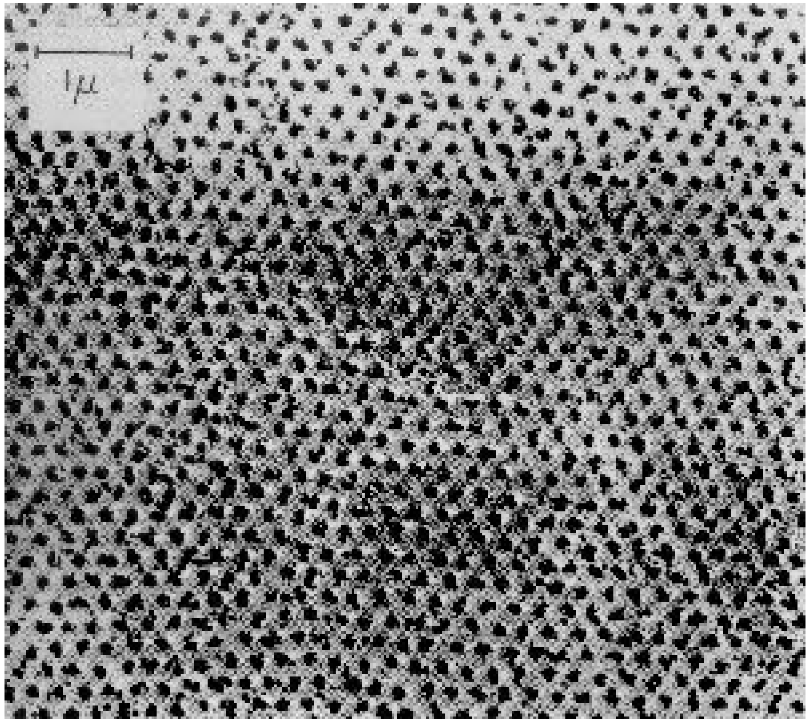
Magnetization



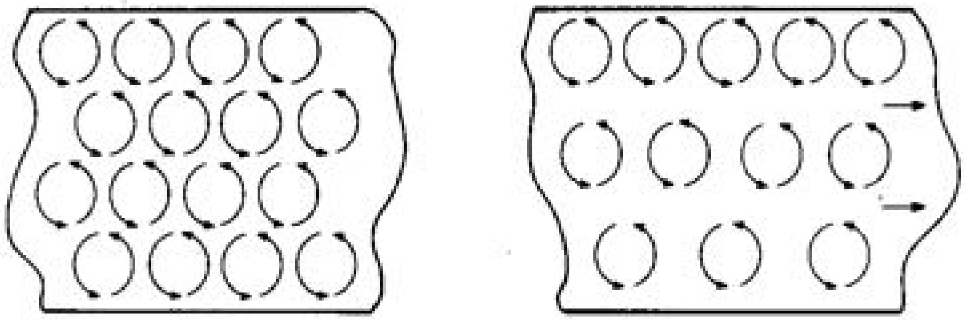
Grading of current density

Type II Superconductors and Fluxoids

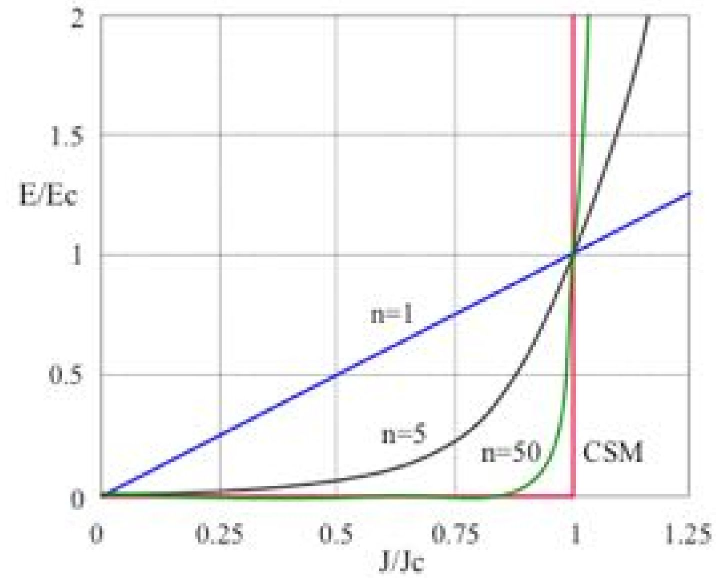


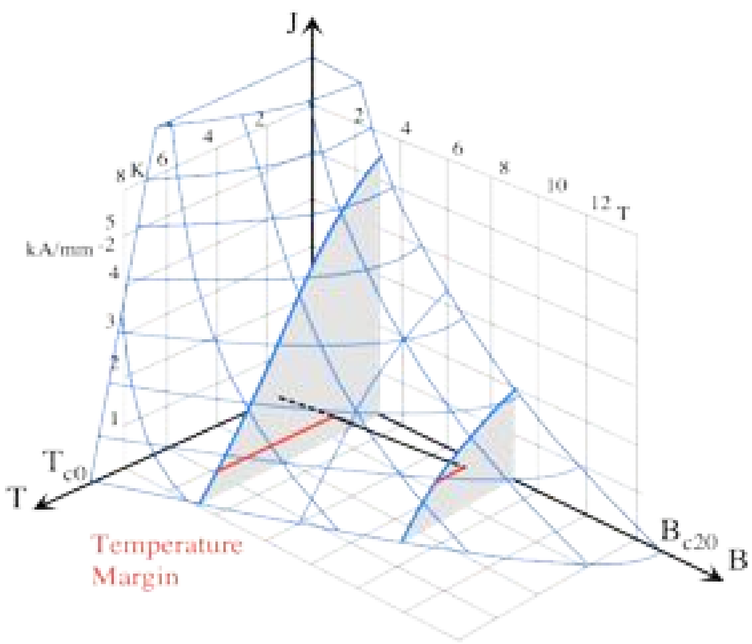


$$\mathrm{curl}\,\mathbf{H} = \frac{\partial H_y}{\partial x}\mathbf{e}_z = J_z\mathbf{e}_z = \mathbf{J}_c$$

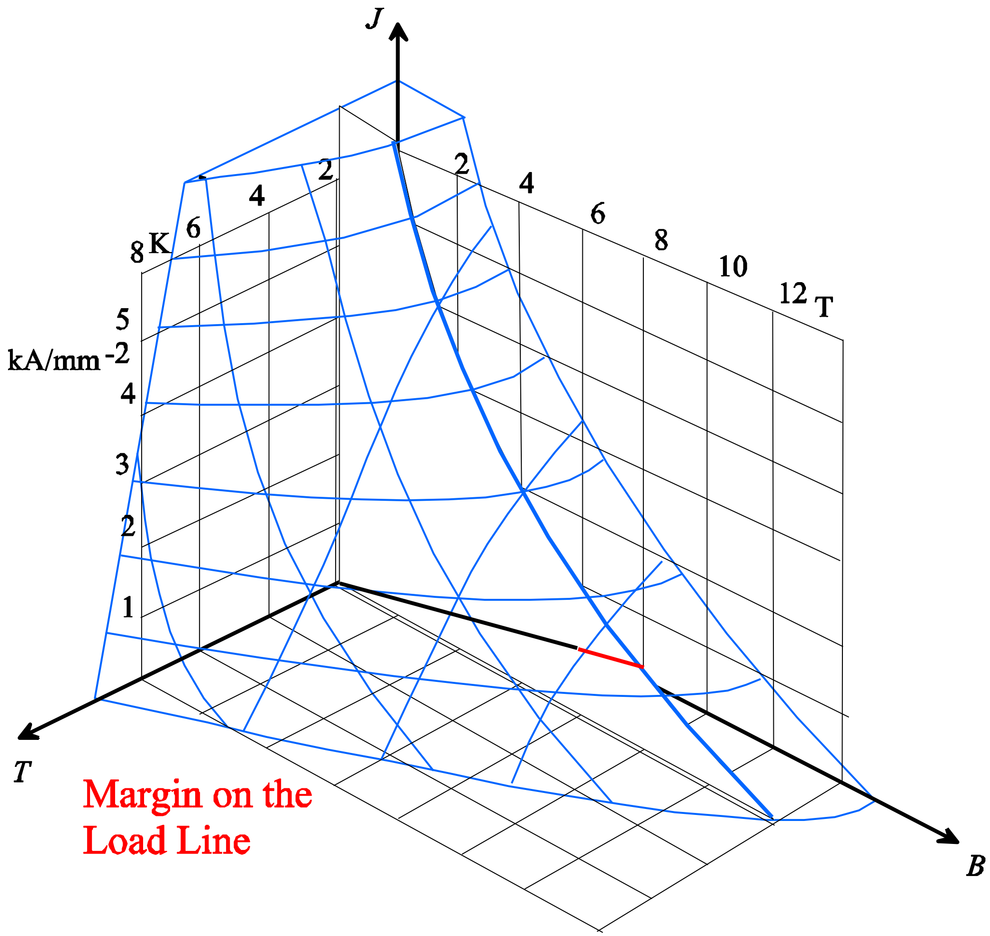


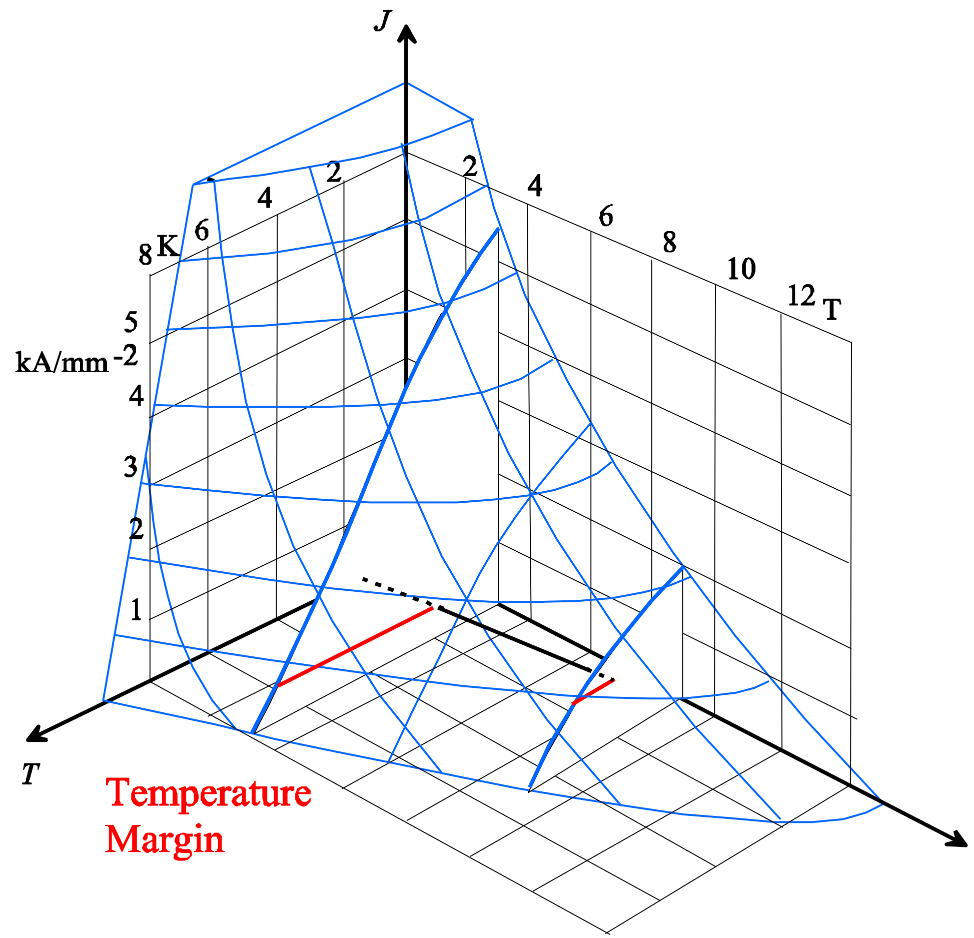
- Hard Superconductors (Type 2)
  - Magnetic field can penetrate
  - Magnetization with hysteresis
- Critical current density J_c
  - Current density at spec. electric field (E_c = 1 µV/cm)
- Critical surface
  - Dependence of J_c on T and B

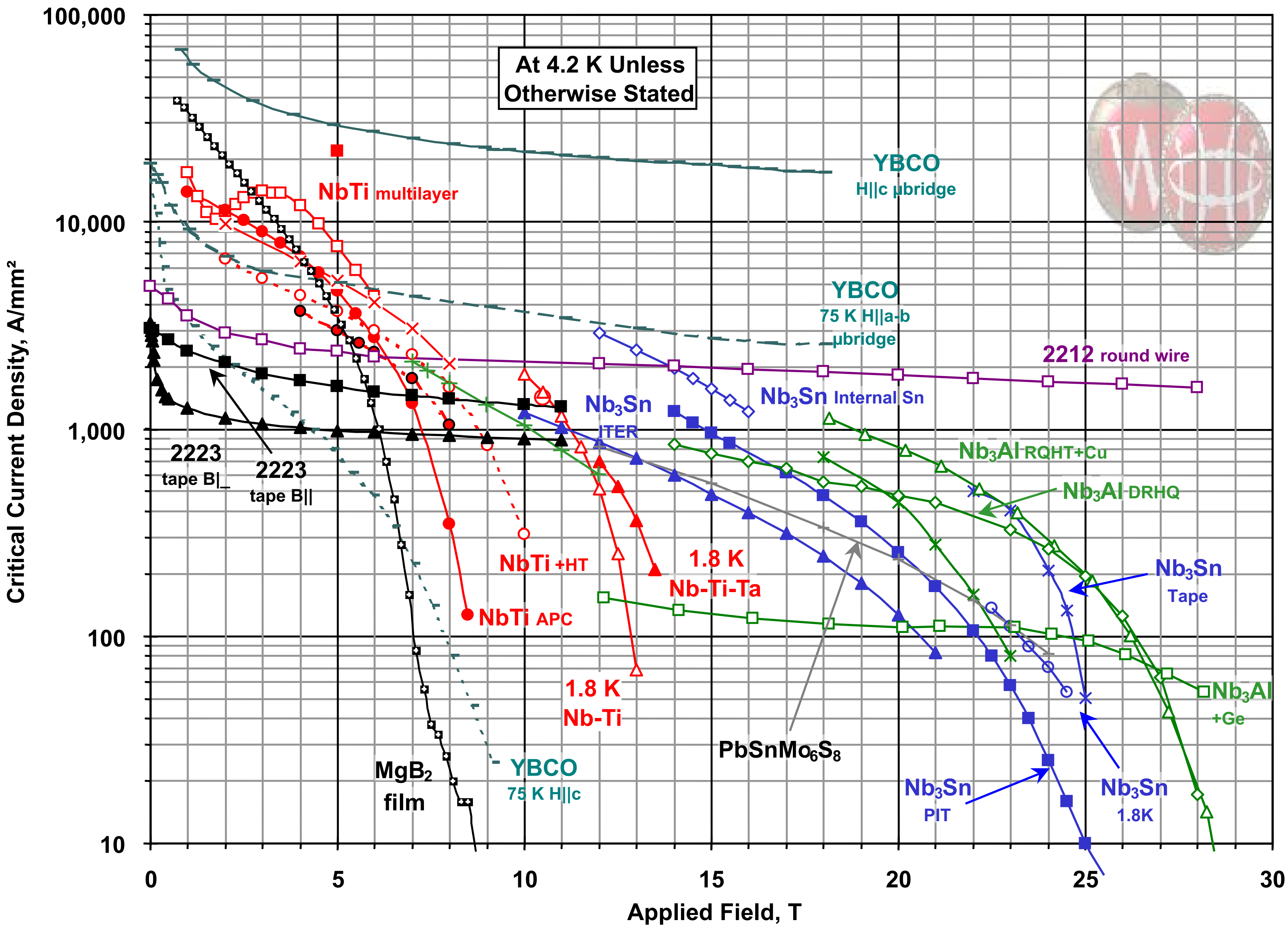




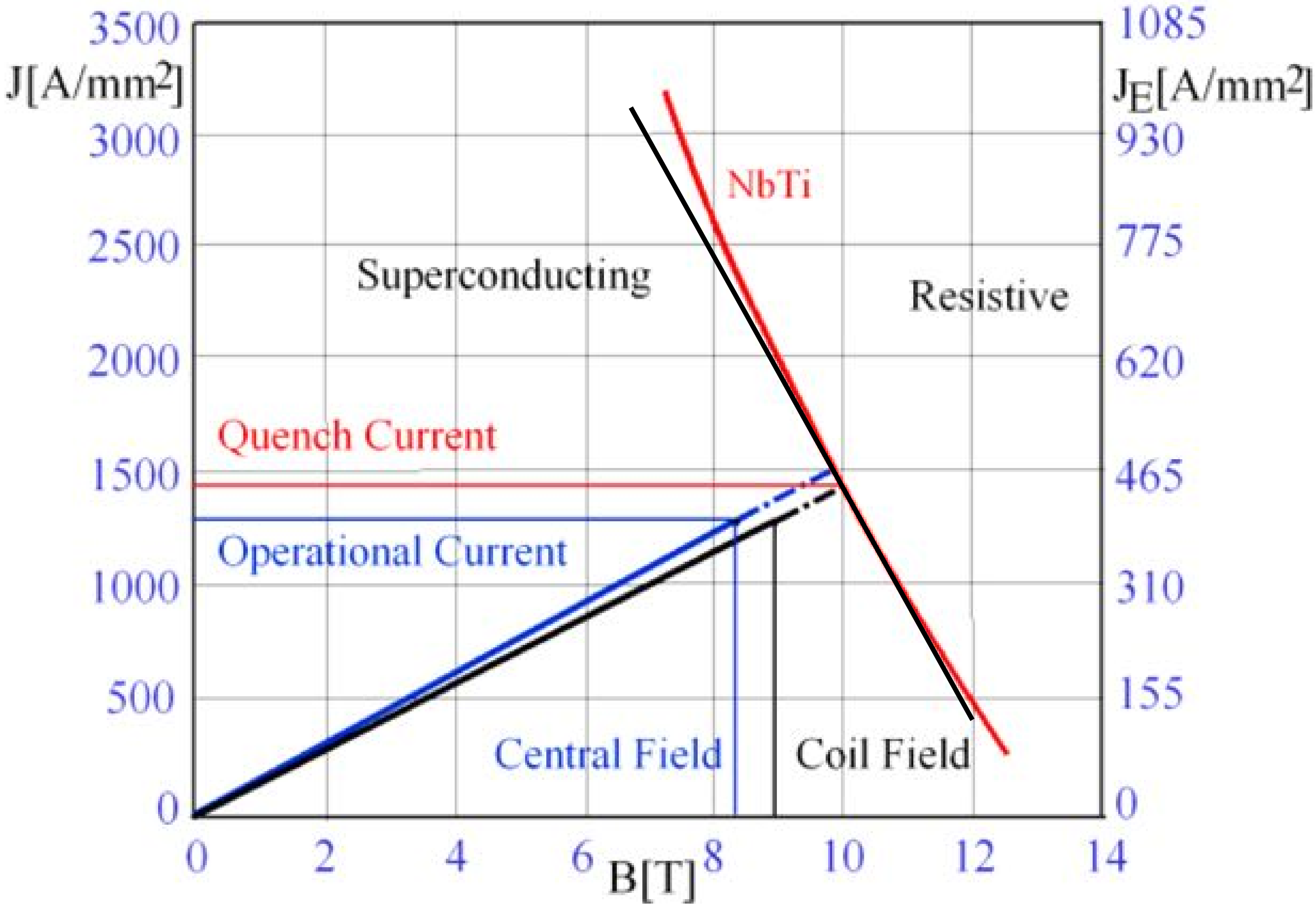
Critical Surface of NbTi



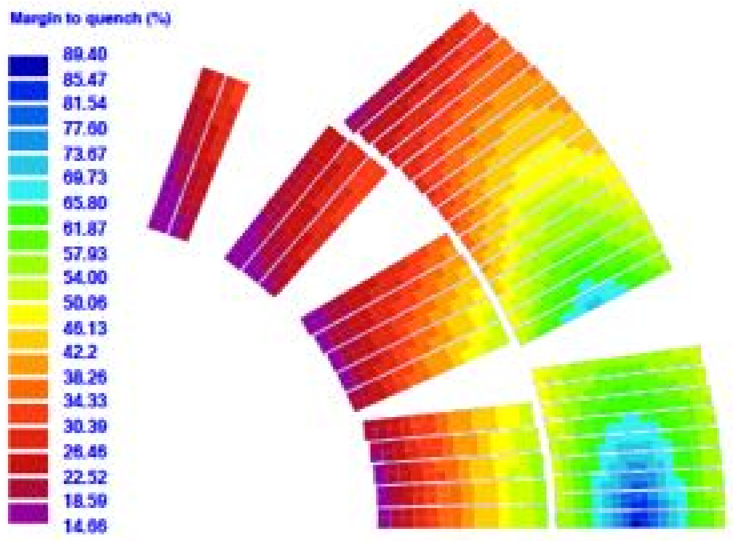


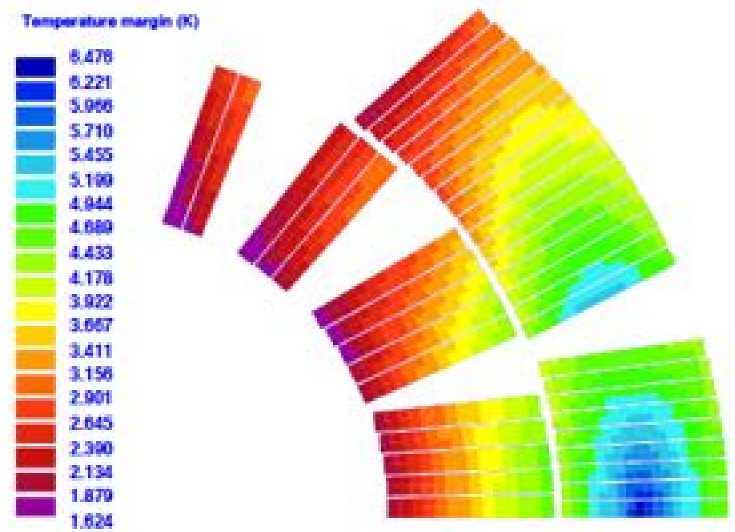

At 4.2 K Unless Otherwise Stated
Critical Current Density, A/mm²
Applied Field, T
100,000
10,000
1,000
100
10
0
5
10
15
20
25
30
YBCO H||c µbridge
NbTi multilayer
YBCO 75 K H||a-b µbridge
2212 round wire
Nb3Sn Internal Sn
Nb3Sn ITER
Nb3Al RQHT+Cu
Nb3Al DRHQ
Nb3Sn Tape
2223 tape B|_
2223 tape B||
NbTi +HT
1.8 K Nb-Ti-Ta
NbTi APC
1.8 K Nb-Ti
MgB2 film
YBCO 75 K H||c
PbSnMo6S8
Nb3Sn PIT
Nb3Sn 1.8K
Nb3Al +Ge

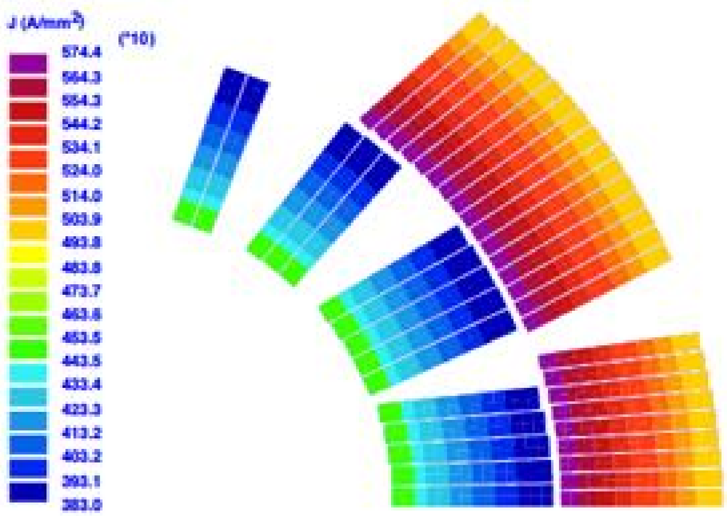
Working Point of LHC Dipole Magnets

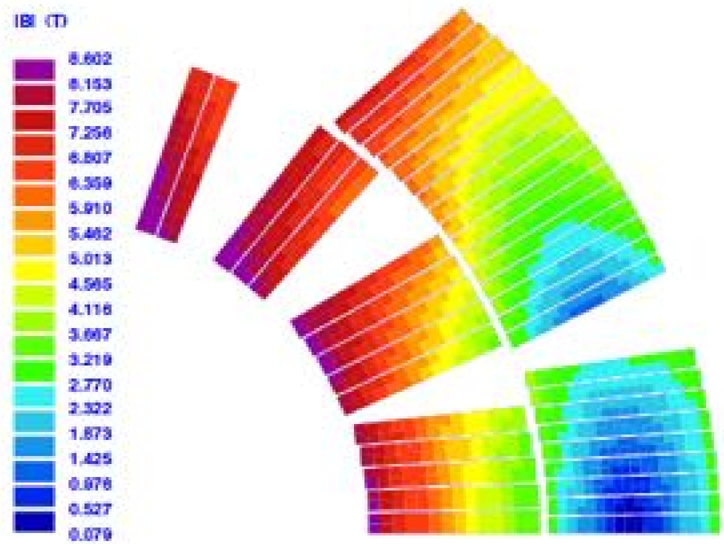


Margins


Margin to quench (%)
89.40
85.47
81.54
77.60
73.67
69.73
65.80
61.87
57.93
54.00
50.06
46.13
42.2
38.26
34.33
30.39
26.46
22.52
18.59
14.66

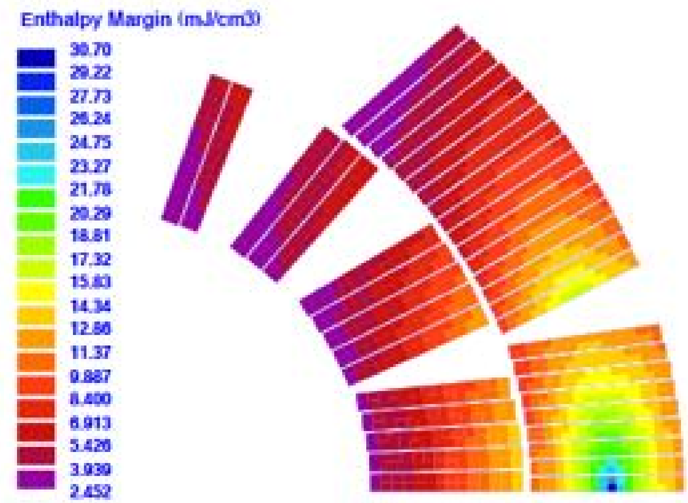

Temperature margin (K)
6.476
6.221
5.966
5.710
5.455
5.199
4.944
4.689
4.433
4.178
3.922
3.667
3.411
3.156
2.901
2.645
2.390
2.134
1.879
1.624

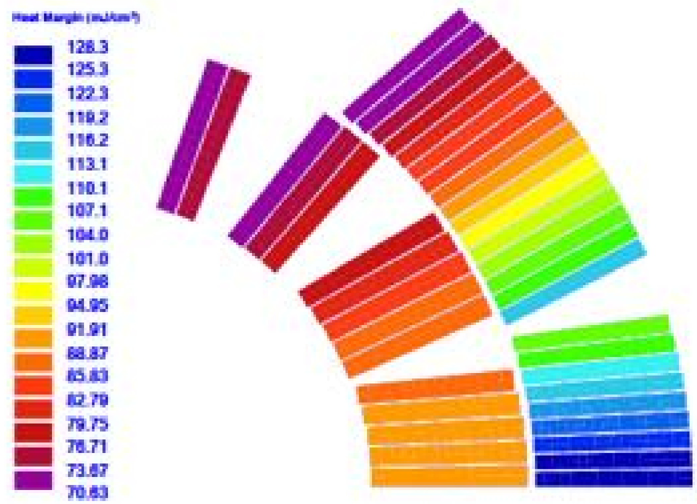

J (A/mm²)
(*10)
574.4
564.3
554.3
544.2
534.1
524.0
514.0
503.9
493.8
483.8
473.7
463.6
453.5
443.5
433.4
423.3
413.2
403.2
393.1
383.0


|B| (T)
8.602
8.153
7.705
7.256
6.807
6.359
5.910
5.462
5.013
4.565
4.116
3.667
3.219
2.770
2.322
1.873
1.425
0.976
0.527
0.079

Margins

$$\Delta h := \int_{T_b}^{T_c(J,B)} \rho\, c_p(T)\, dT\,,$$

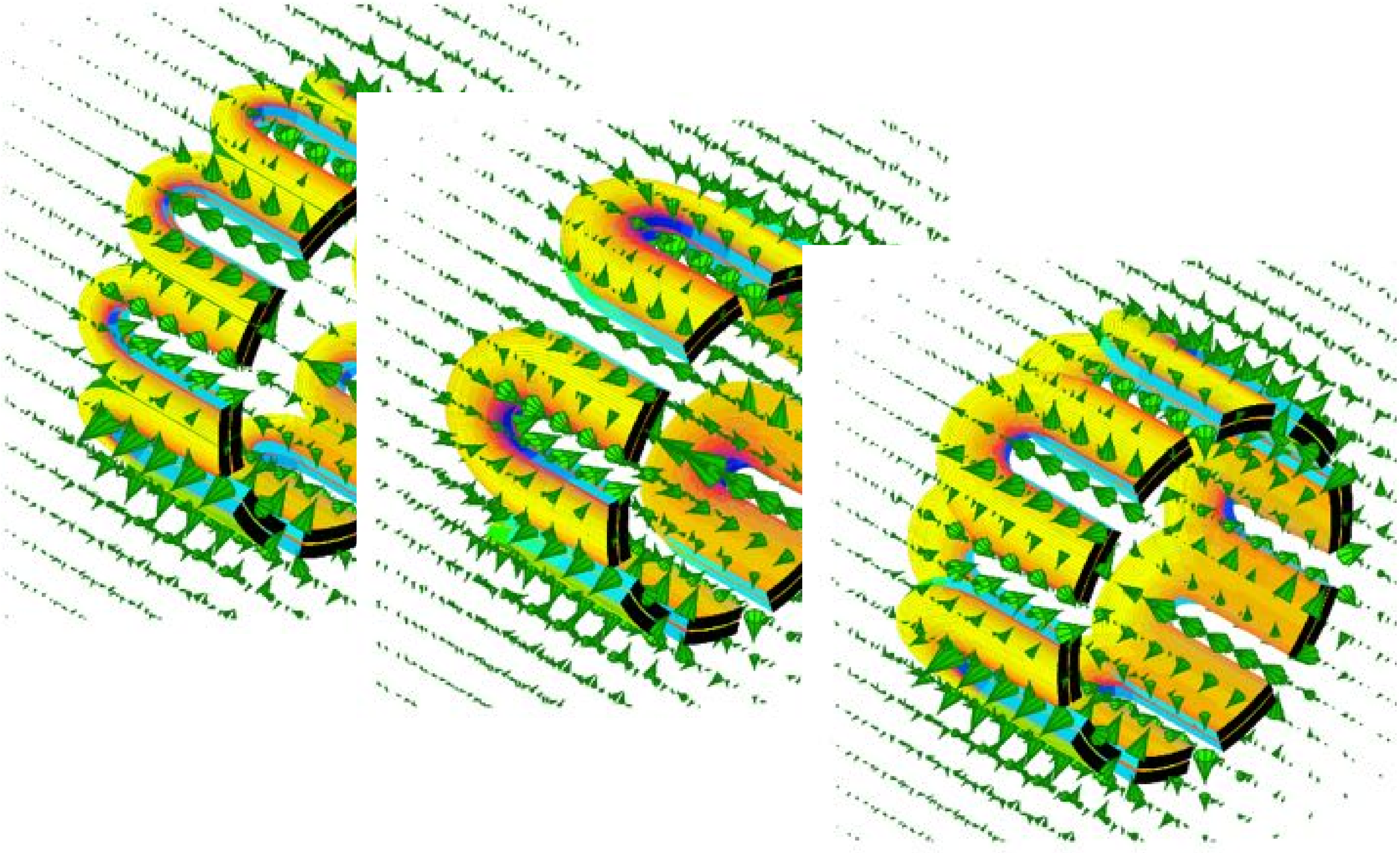




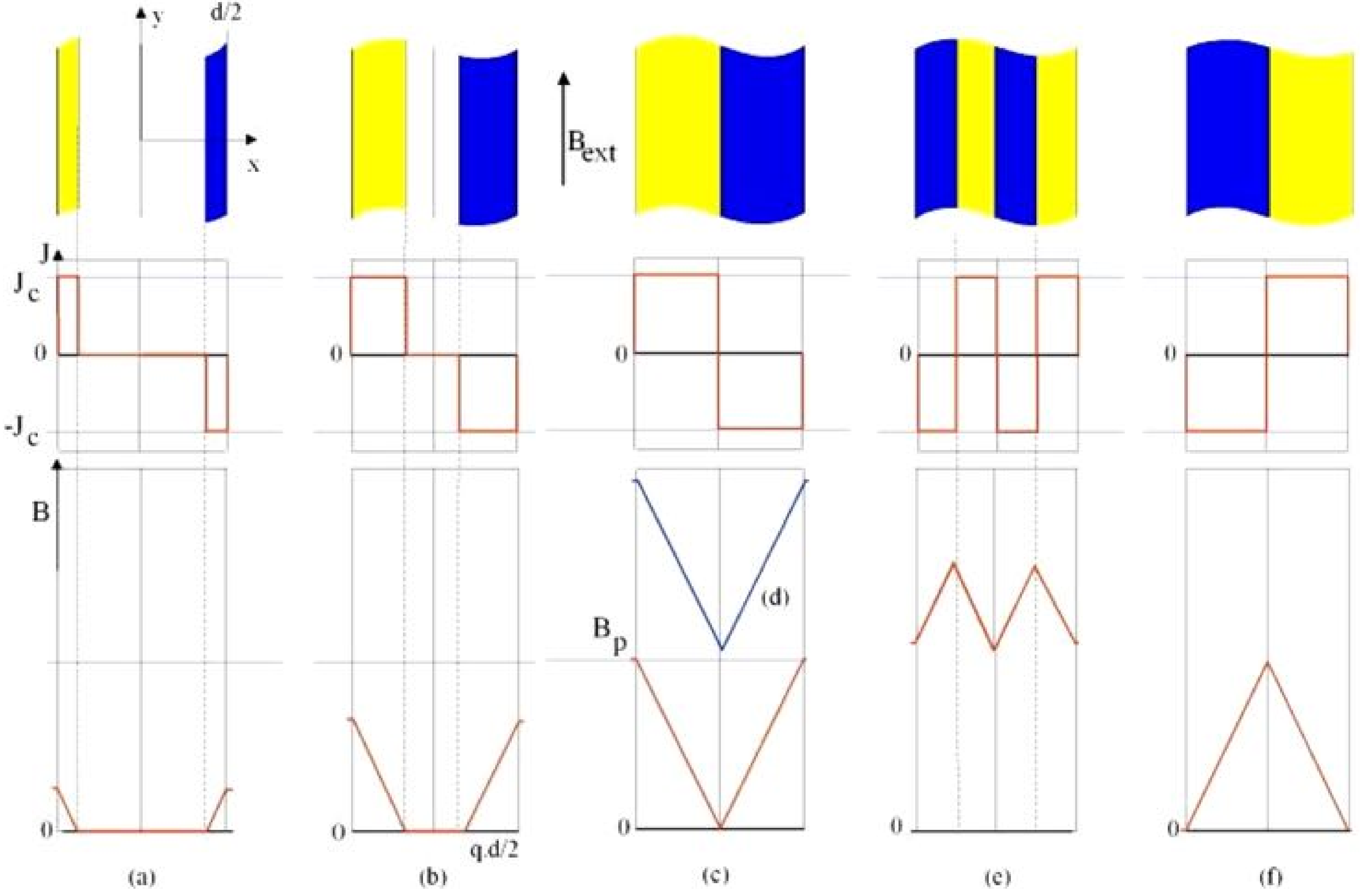
Enthalpy reserve
Heat capacity of the copper/SC strand until quench

Average heat reserve (copper, SC and helium) in the cable (slow losses). No heat transfer.

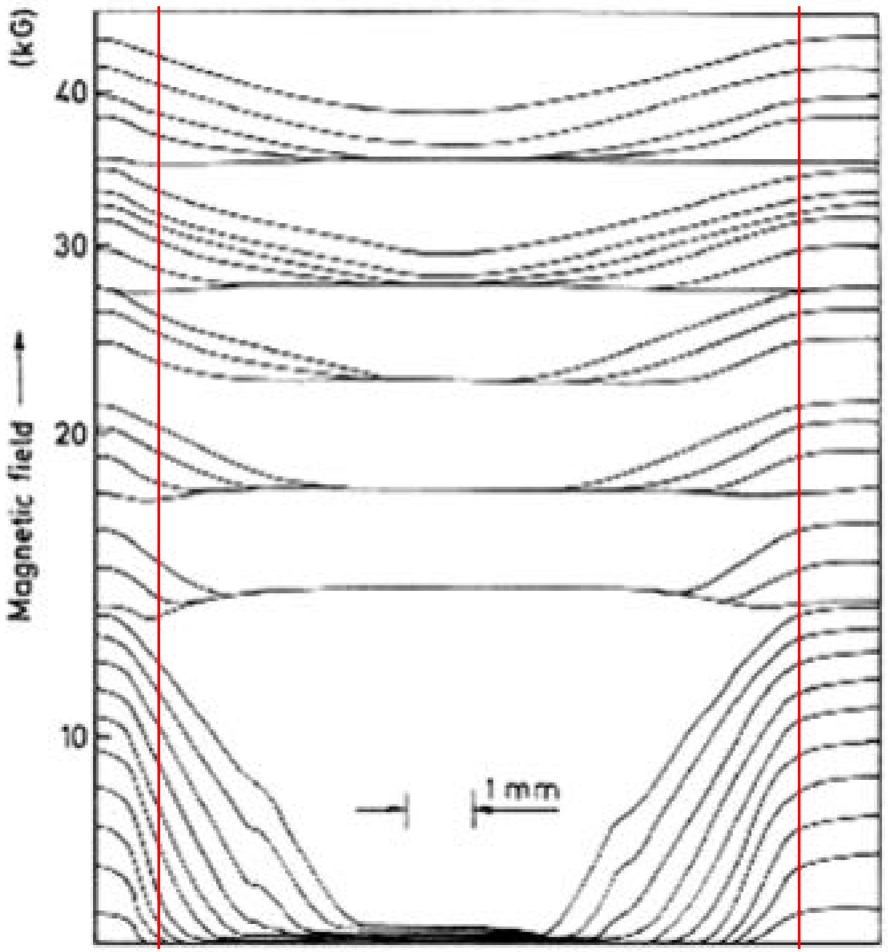
Margins



Bean's Critical State Model (CSM)



Screening Field in a Slab



$$q^* := \frac{B_{\text{ext}}}{\mu_0 J_{\text{c}}} \frac{2}{d}$$

$$B_{\text{p}} = \mu_0 J_{\text{c}} \frac{d}{2}$$

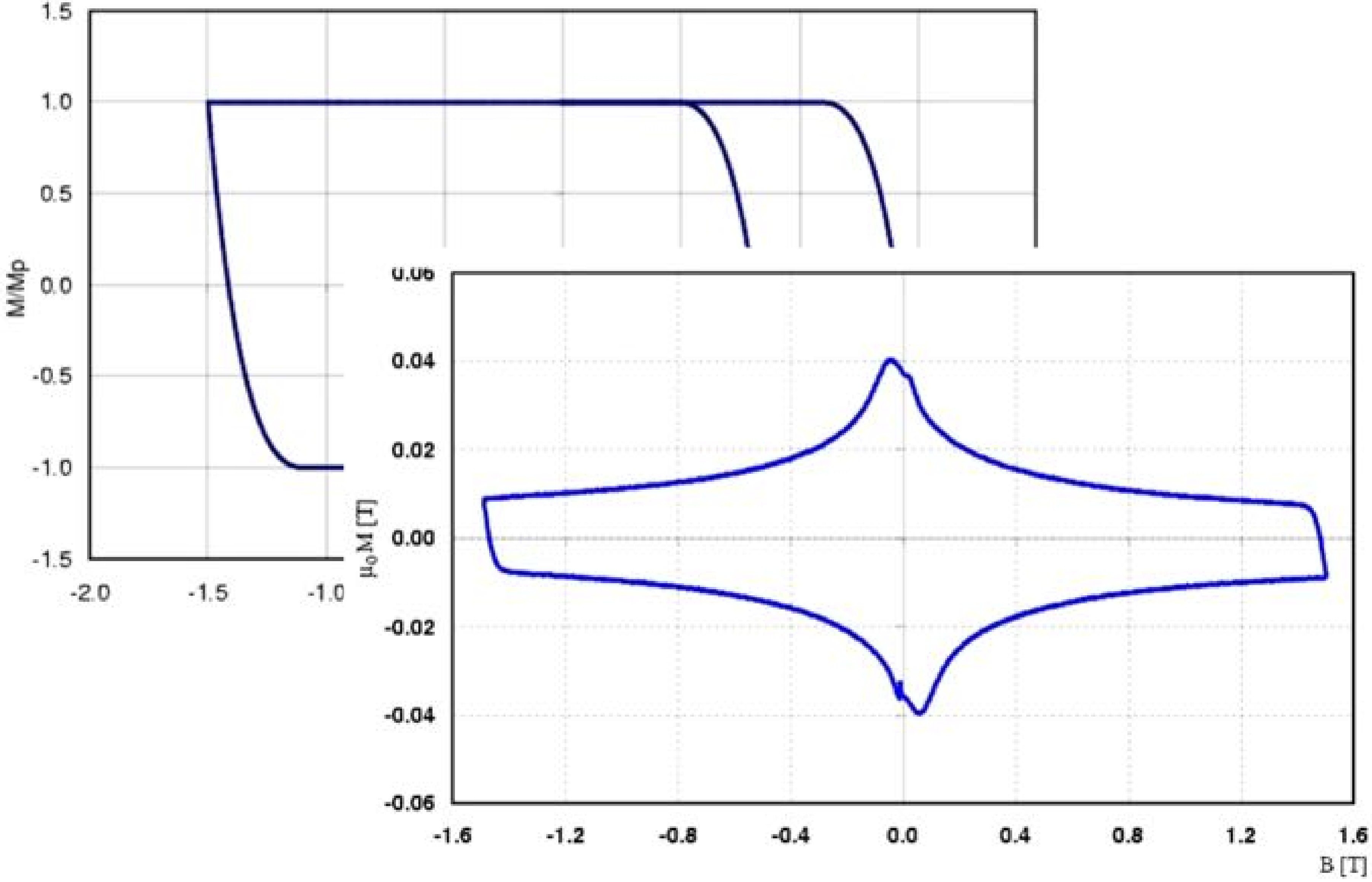
$$M = \int_{\frac{d}{2}(1-q^*)}^{\frac{d}{2}} -\frac{J_{\text{c}}\, 2x}{d} \mathrm{d}x$$

$$M_{\text{p}} = -J_{\text{c}} \frac{d}{4}$$

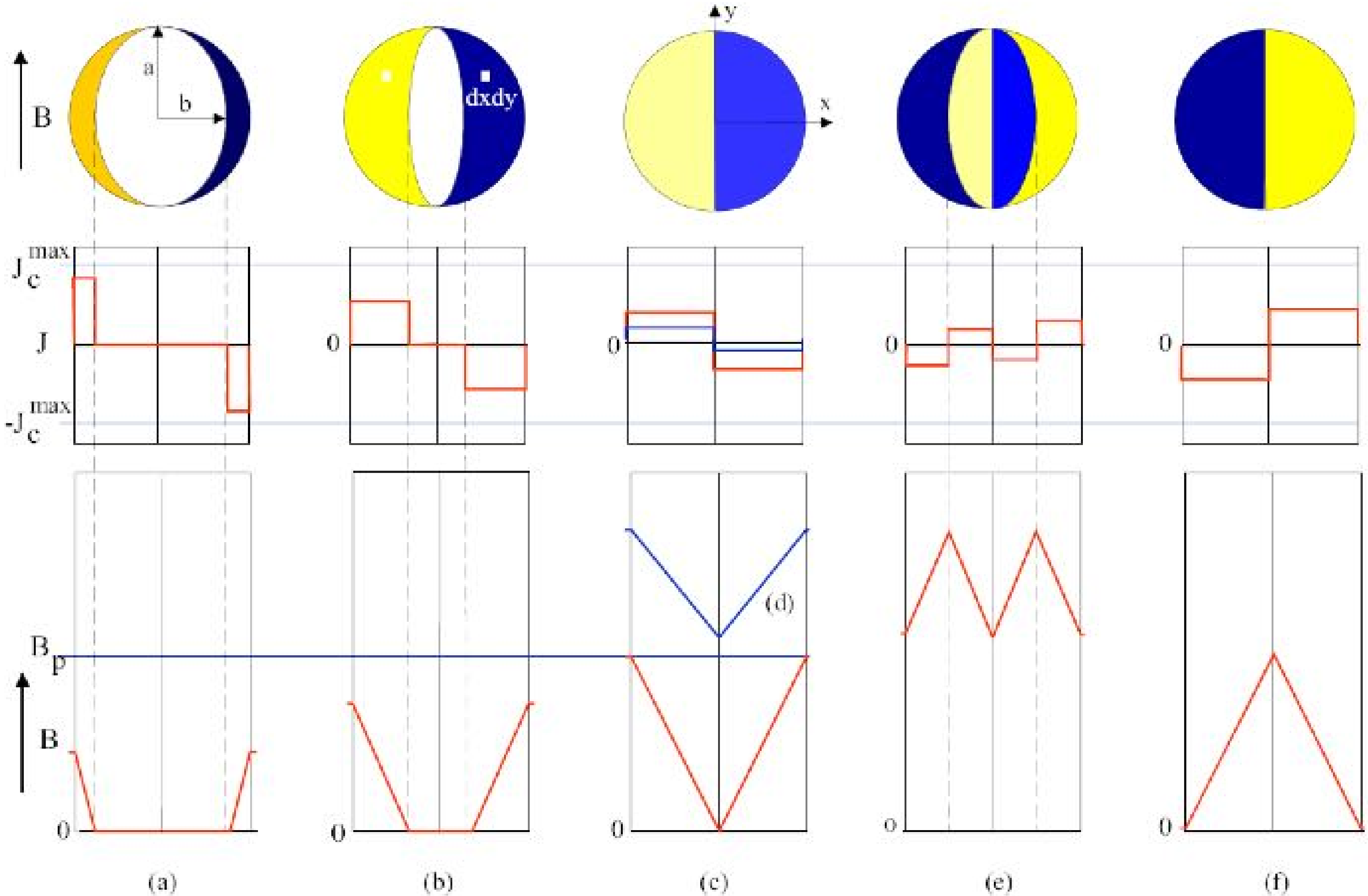
q =1 center of filament
t = modulus of shielding field

$$B_y = B_{\text{ext}} - t = B_{\text{ext}} - \mu_0 J_{\text{c}} \frac{d}{2} q$$

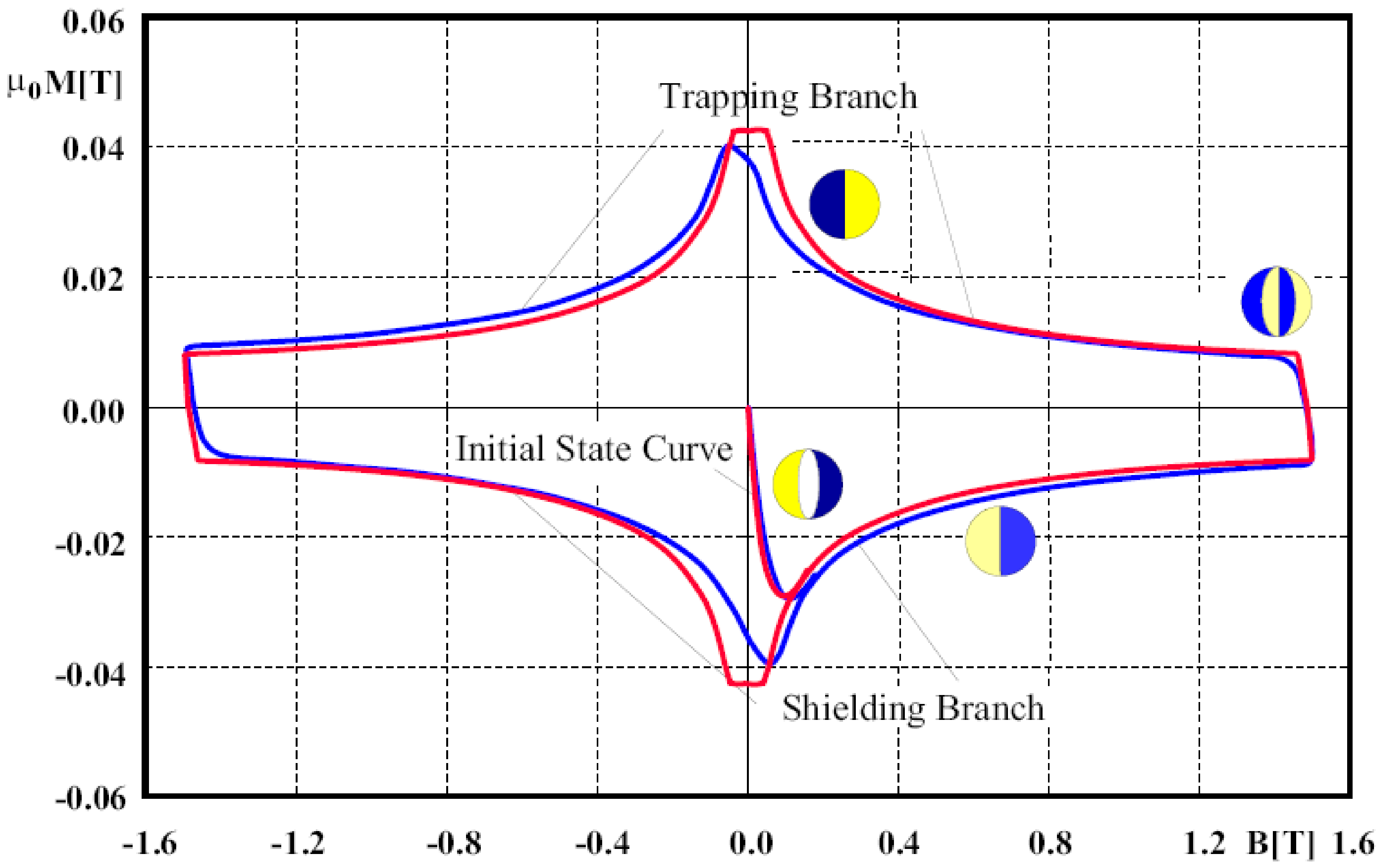
Magnetization in SC Slab, Measured in LHC Strands



The Bean, Wilson Model

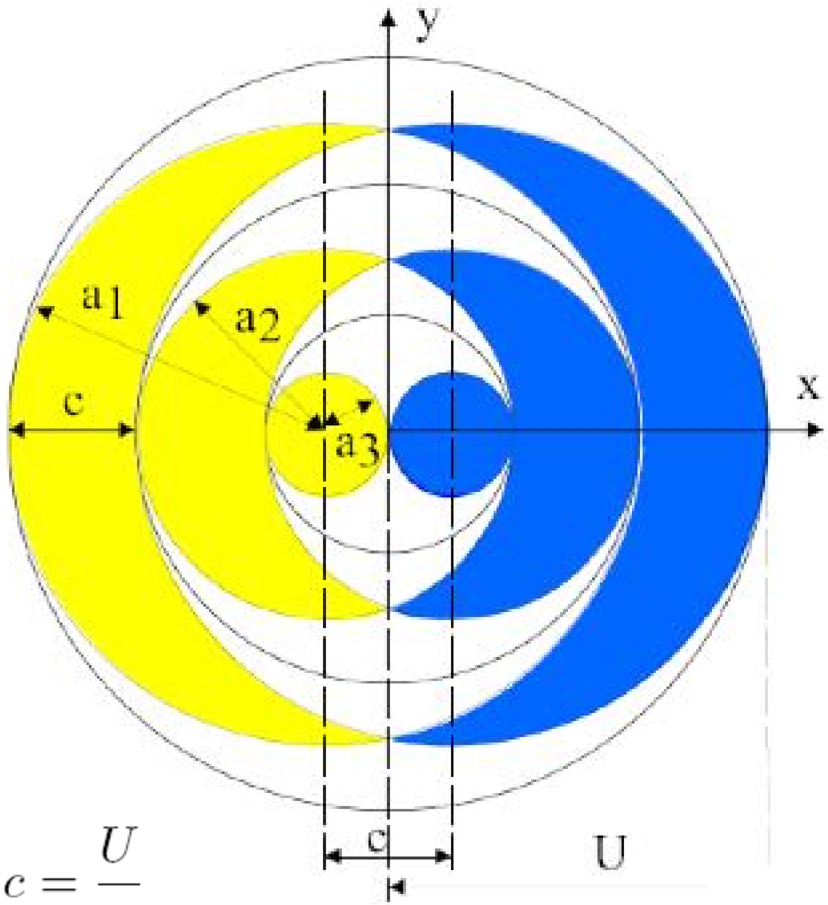


Bean-Wilson Model



Screening Field of Intersecting Circles

$$a_i = U - (2i-1)\frac{c}{2}$$



$$c = \frac{U}{n}$$

$$J_c(B,T) = \frac{J_c^{\text{ref}} C_0 B^{\alpha-1}}{(B_{c2})^\alpha}\left(1-\frac{B}{B_{c2}}\right)^\beta \left(1-\left(\frac{T}{T_{c0}}\right)^{1.7}\right)^\gamma$$

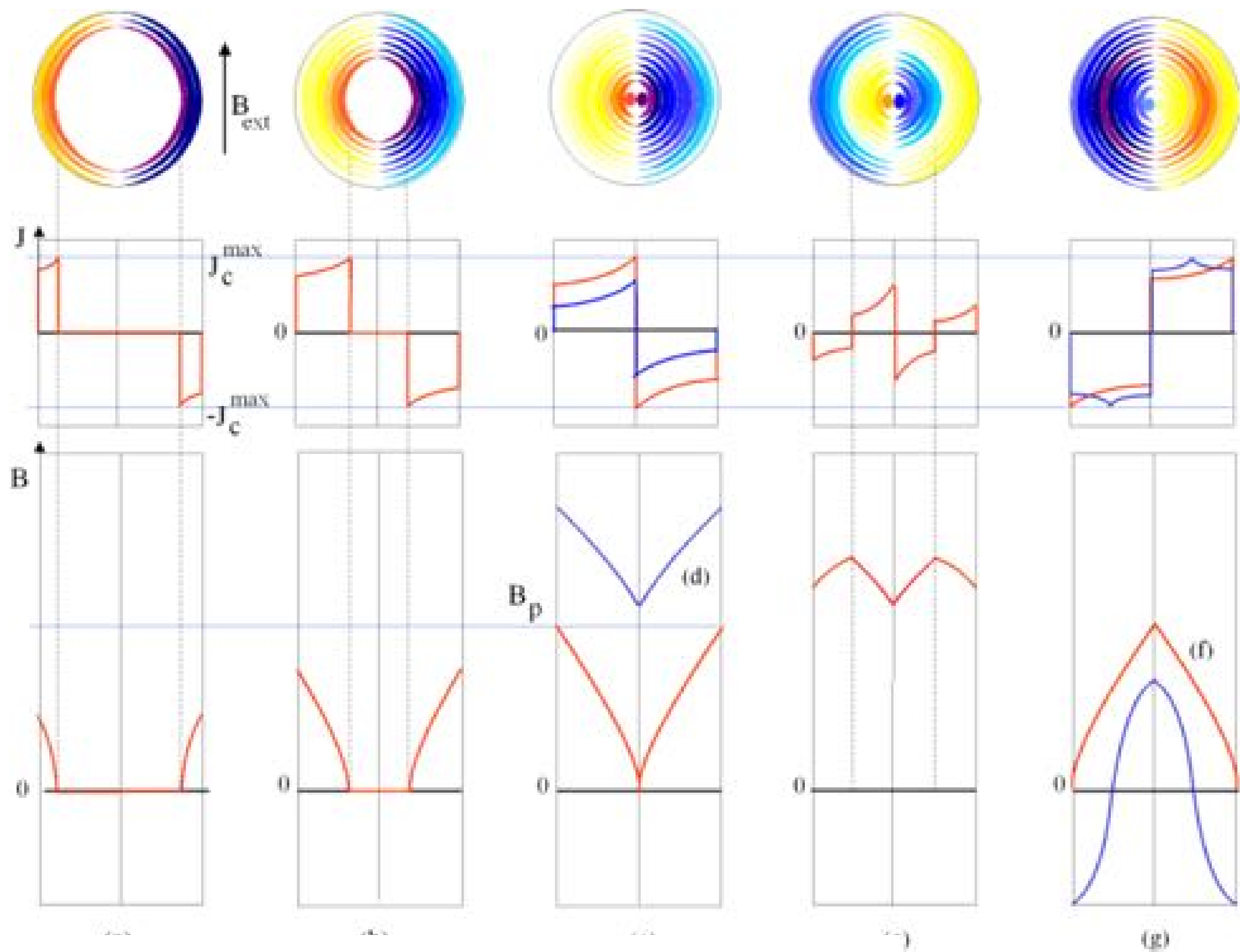
Approximation for small fields and constant temperature

$$J_c(B) \approx \frac{\mathcal{F}(B_{\text{ext}})}{\sqrt{B}} := J_c(B_{\text{ext}})\frac{\sqrt{B_{\text{ext}}}}{\sqrt{B}}$$

$$|\Delta t| = \frac{\mu_0 r}{2}\int_{q_1}^{q_2} J_c(B(q))\,\mathrm{d}q$$

$$\mathrm{d}B(q) = \xi\mu_0\,\mathcal{H}\,J_c(B(q))\,\mathrm{d}q = \frac{\xi\mu_0\,\mathcal{H}\,\mathcal{F}(B_{\text{ext}})\,\mathrm{d}q}{\sqrt{B(q)}}$$

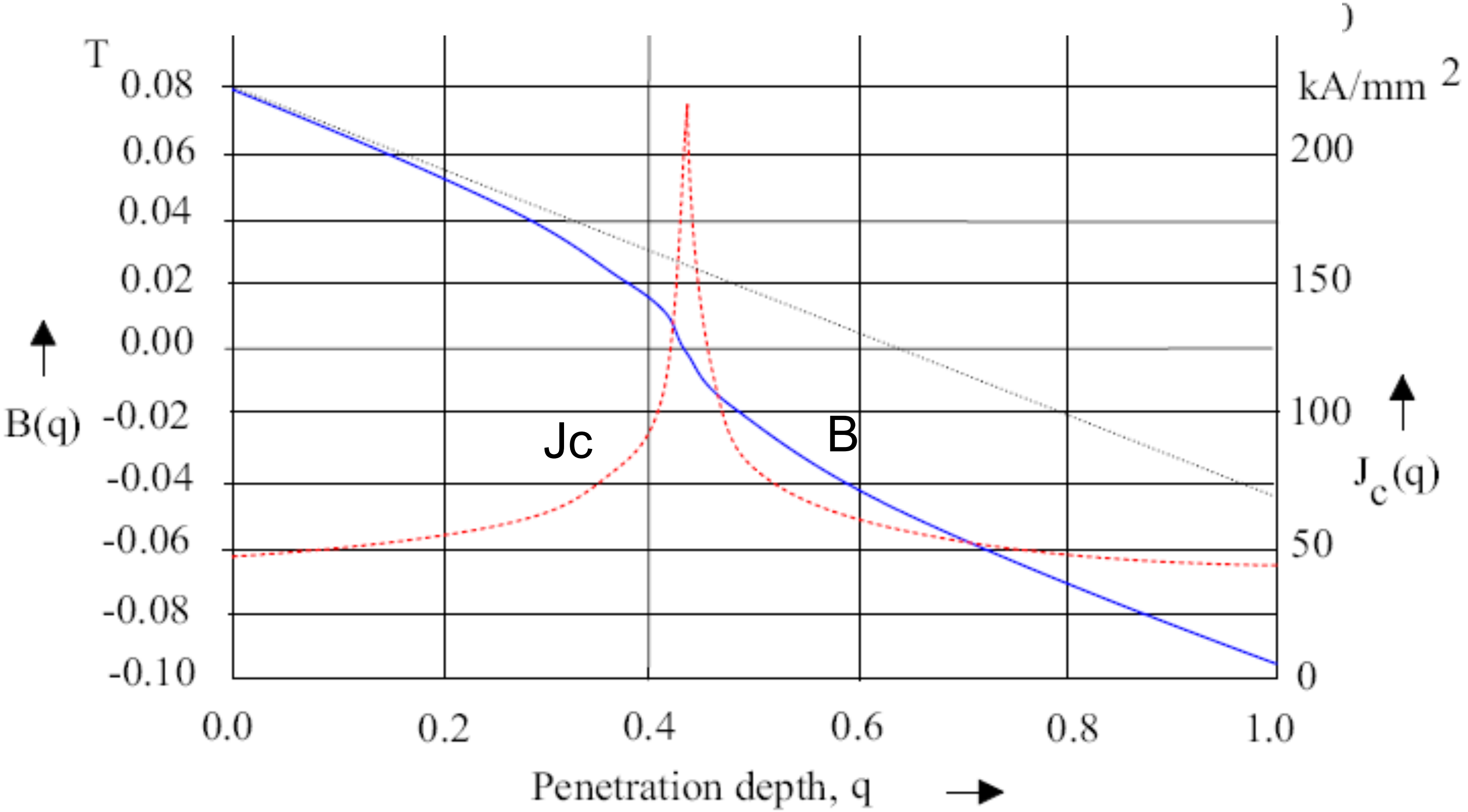
Modified CSM Model



$$dB(q) = \xi\mu_0 \frac{r}{2} J_c(B(q))\, dq = \frac{\xi\mu_0\, r\, dq}{2\sqrt{B(q)}} \mathcal{F}(B_a) \qquad \mathcal{F}(B_a) := J_c(B_a)\sqrt{B_a}$$

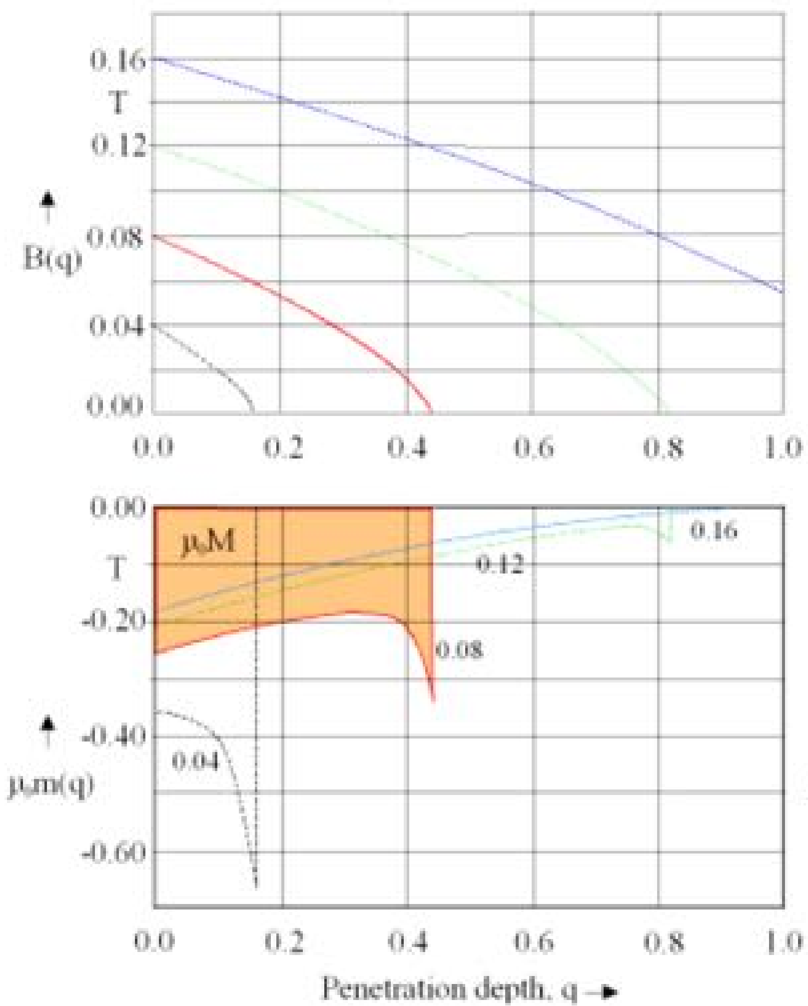
B(q)

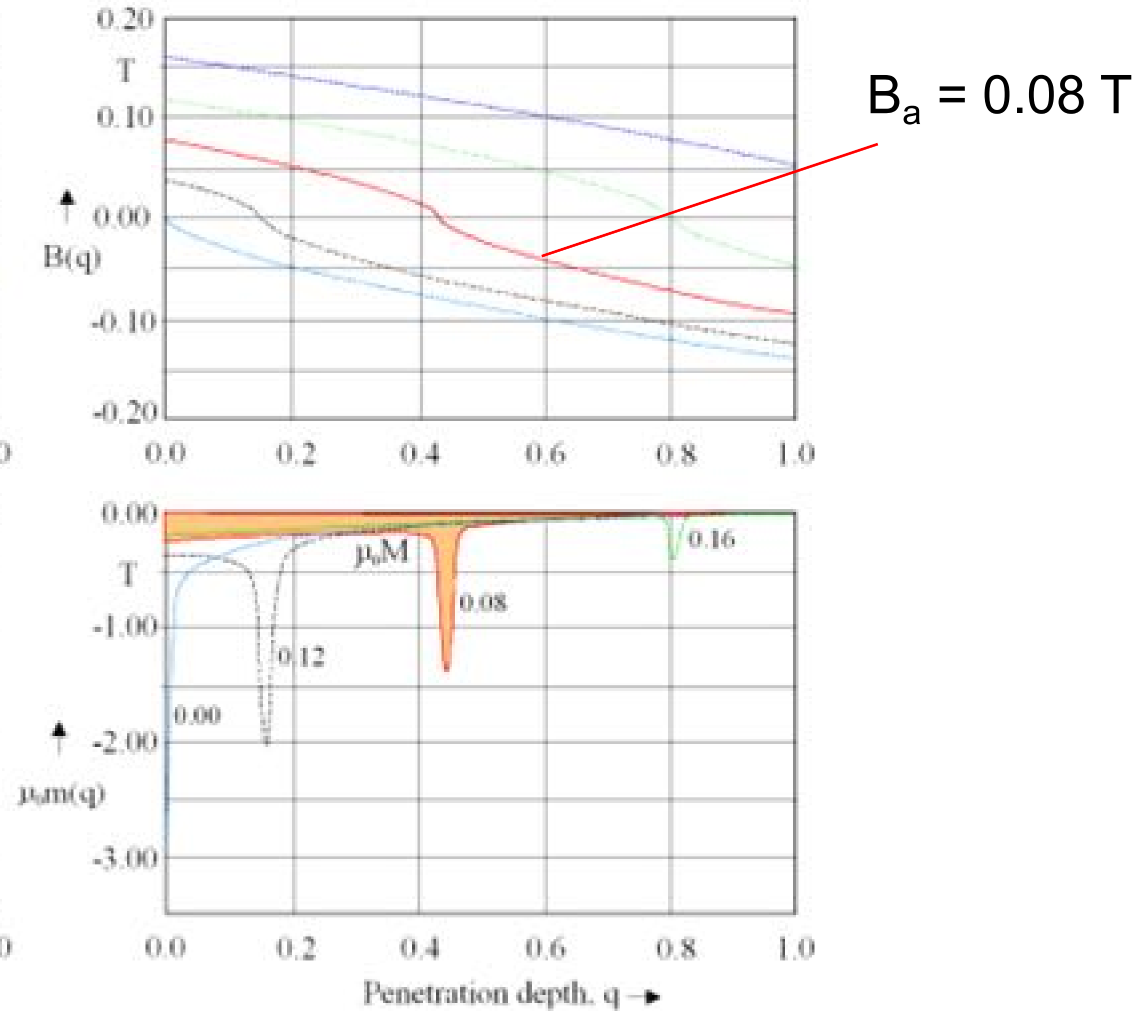
$$B(q) = \left(B_{\text{ext}}^{3/2} + \frac{3}{2} \xi \mathcal{H} \mathcal{F}(B_{\text{ext}}) \mu_0 q \right)^{2/3}$$



Seq: { 0, B_{max}, $-B_{max}$, B_a = 0.08 T }

Peak Shifting

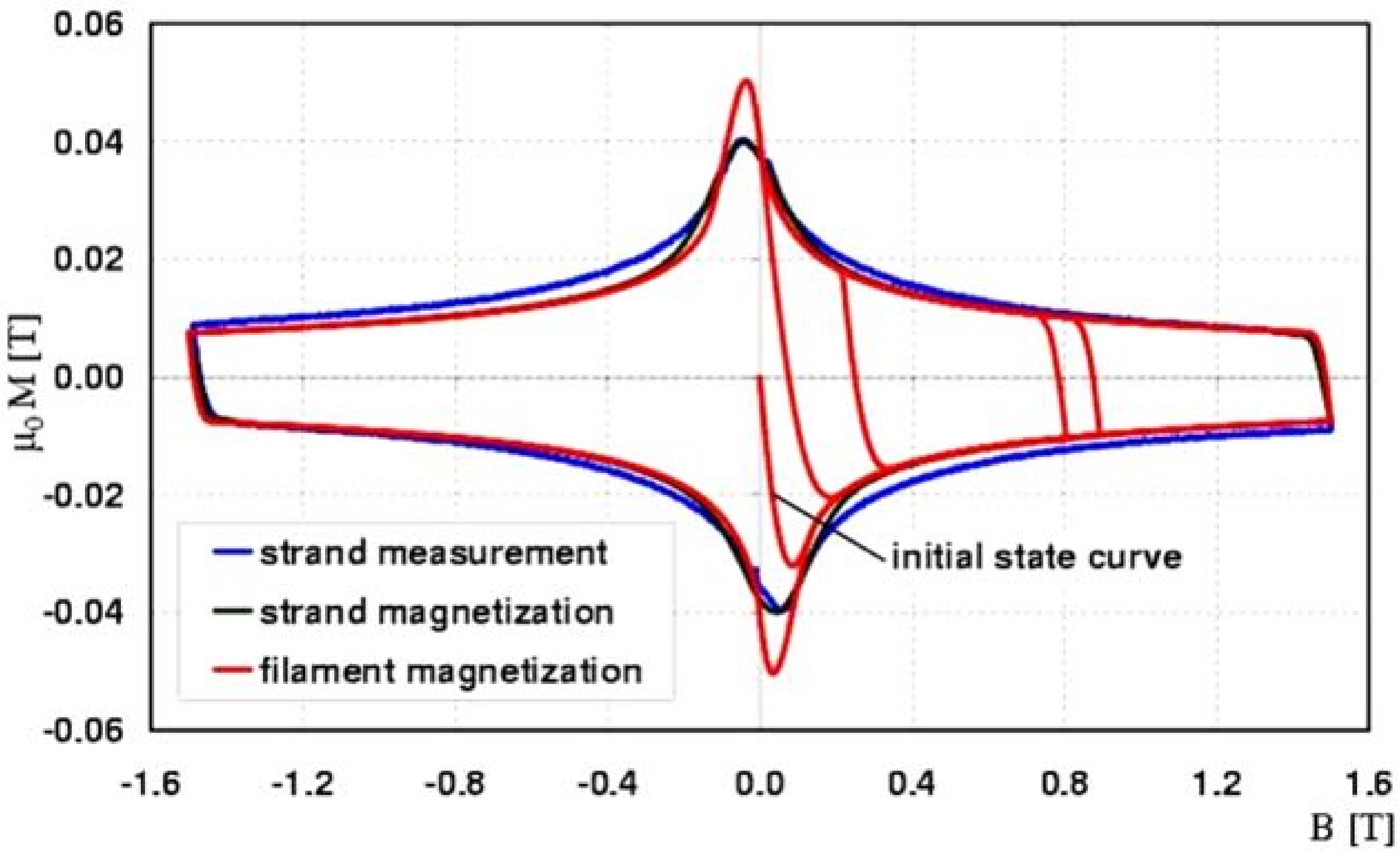




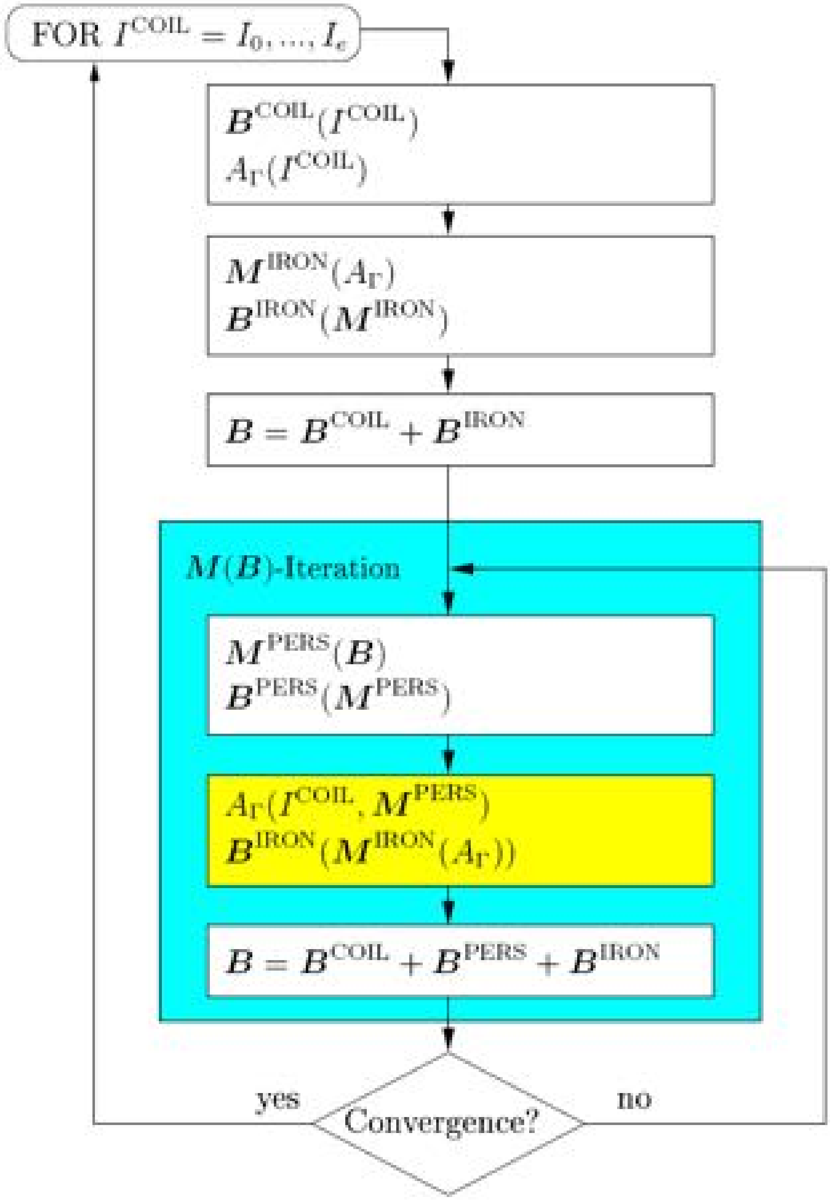
Virgin state

Seq: { 0, B_{max}, $-B_{max}$, $B_a > 0$ }

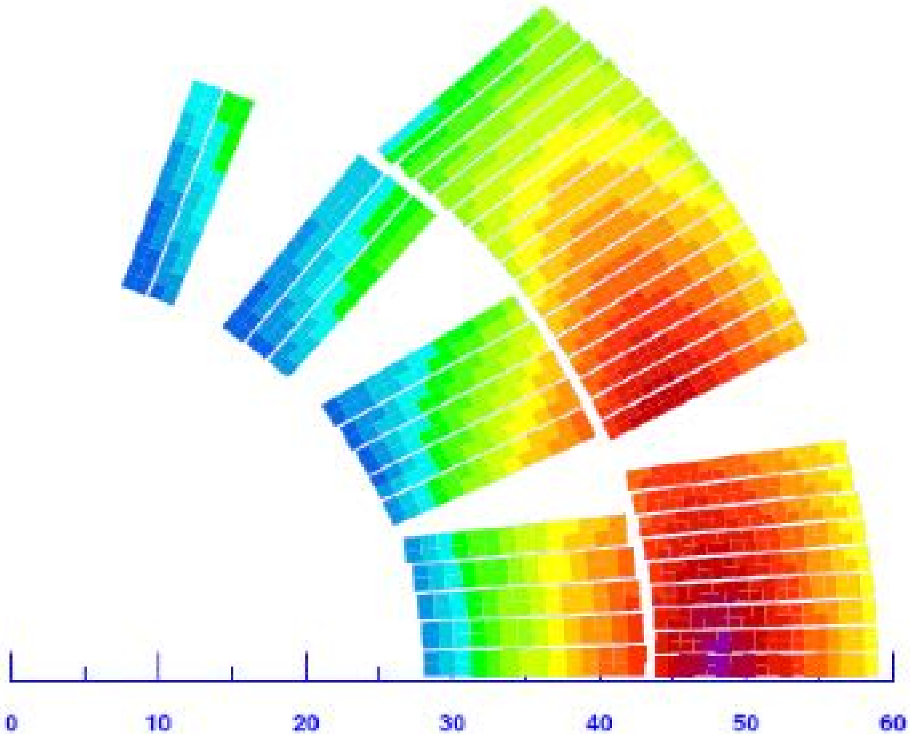
Magnetization in LHC Strands

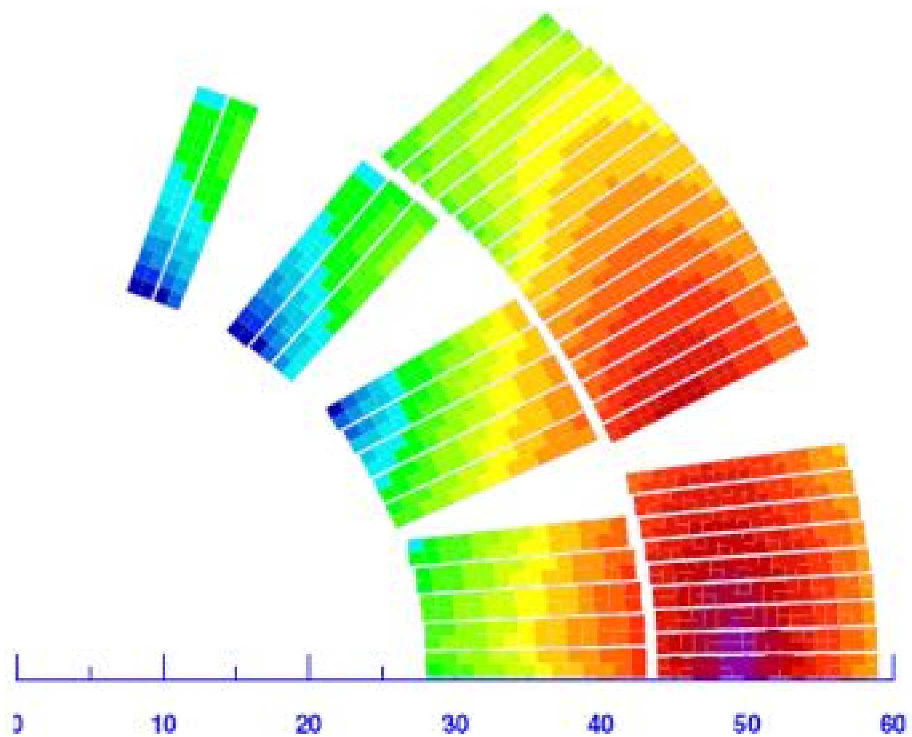


M(B) Iteration Scheme

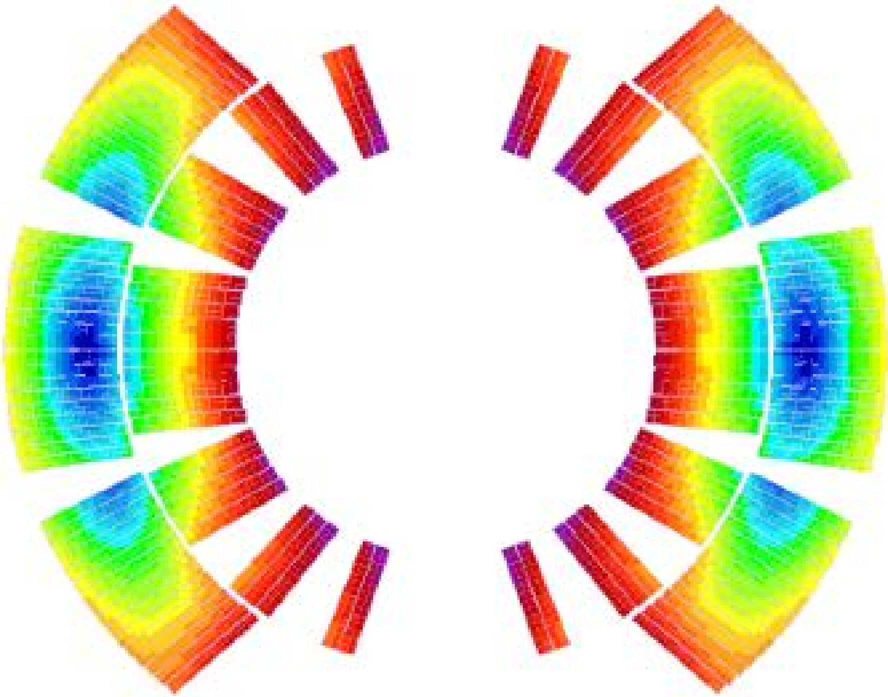


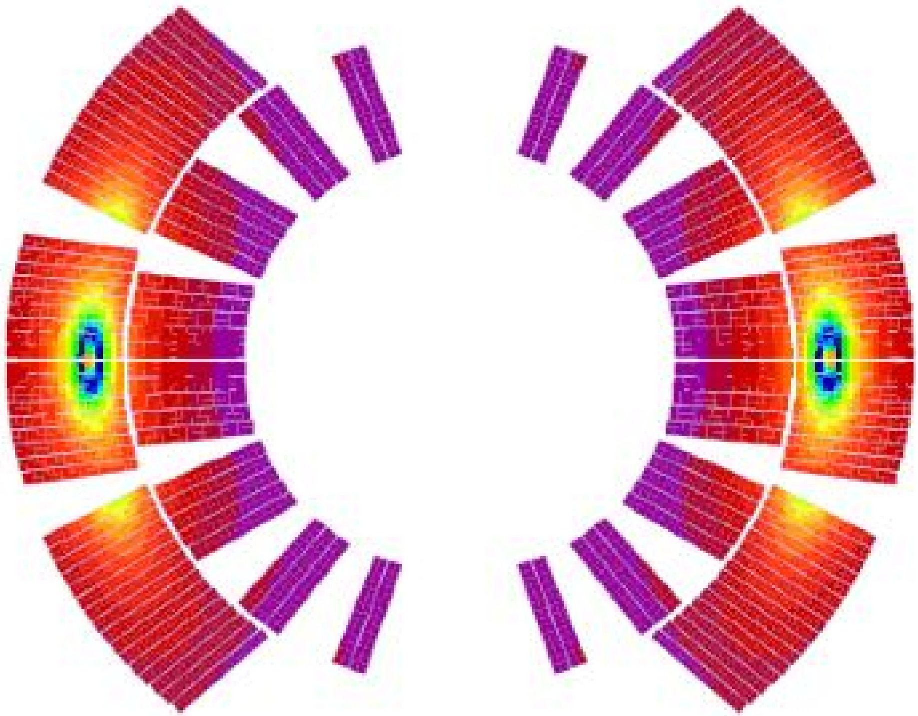
Magnetization without and with Iteration



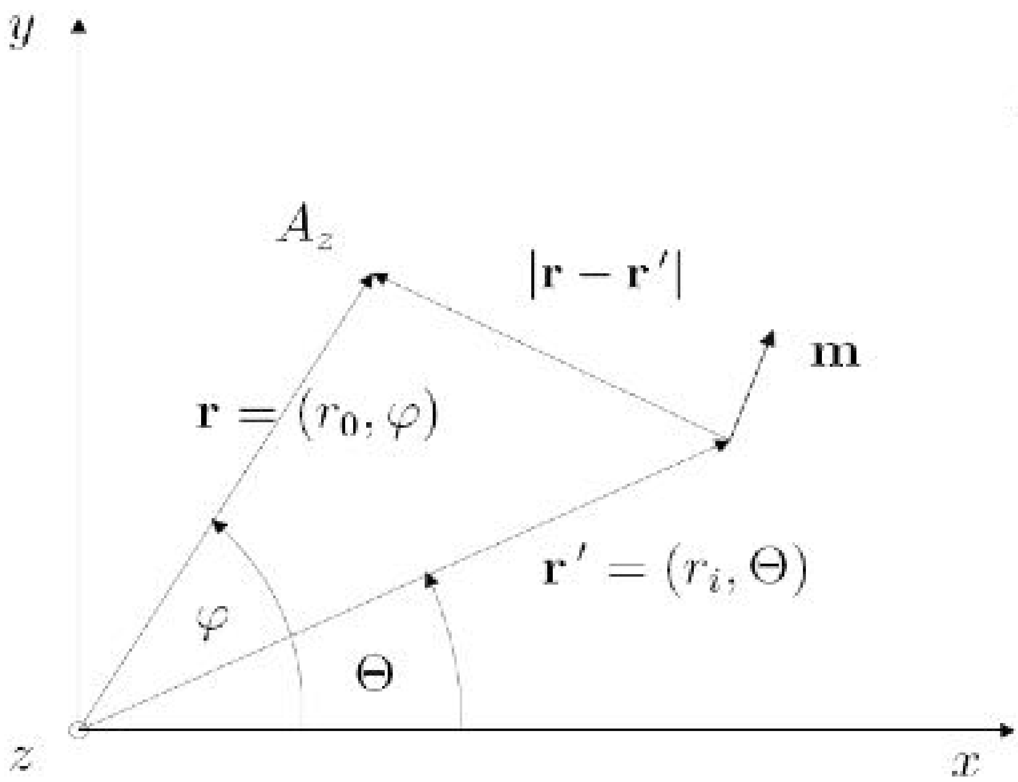


Field and SC Magnetization





Field Quality Calculation from Magnetization

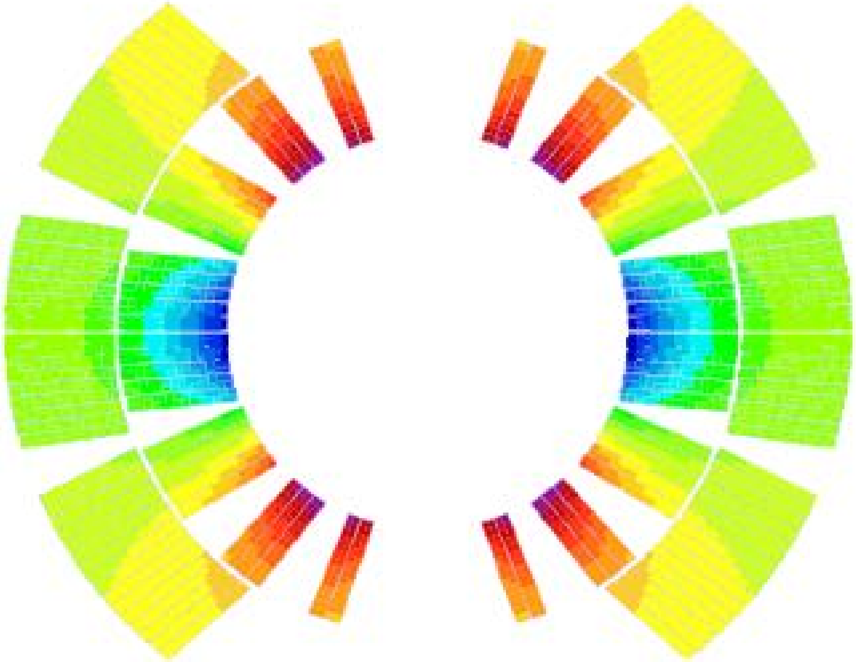


$$A_z(\mathbf{r}) = \frac{\mu_0 \mathbf{m}}{2\pi} \times \operatorname{grad}_{\mathbf{r}'} \ln\left(\frac{|\mathbf{r} - \mathbf{r}'|}{R_{\text{ref}}}\right)$$

$$A_n = \frac{\mu_0}{2\pi} \frac{r_0^{n-1}}{r_i^{n+1}} n(m_{\mathbf{r}'} \cos n\theta - m_\theta \sin n\theta)$$

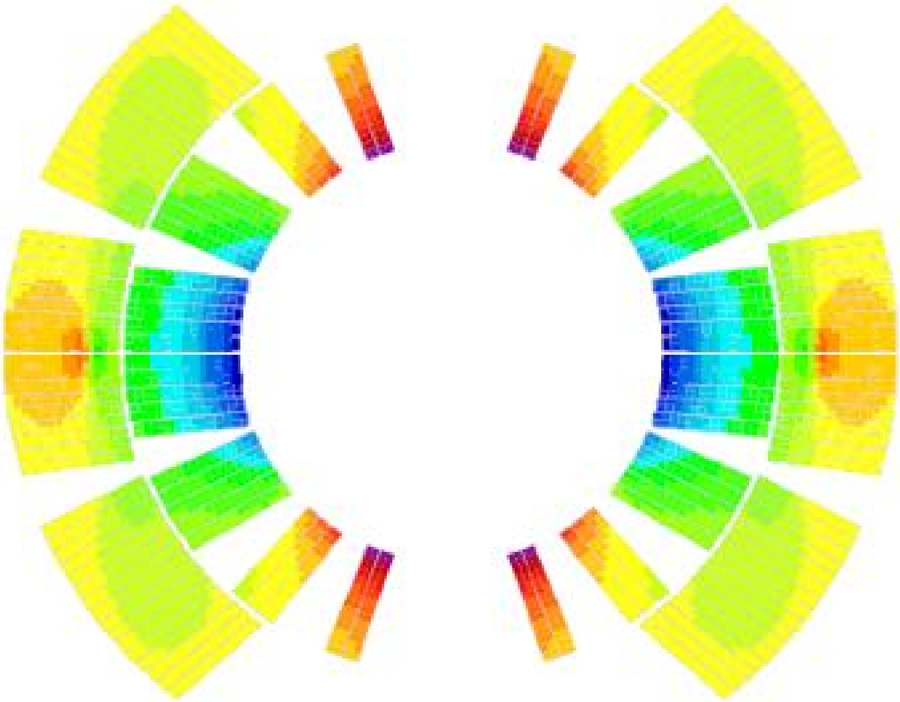
$$B_n = \frac{\mu_0}{2\pi} \frac{r_0^{n-1}}{r_i^{n+1}} n(m_{\mathbf{r}'} \sin n\theta + m_\theta \cos n\theta)$$

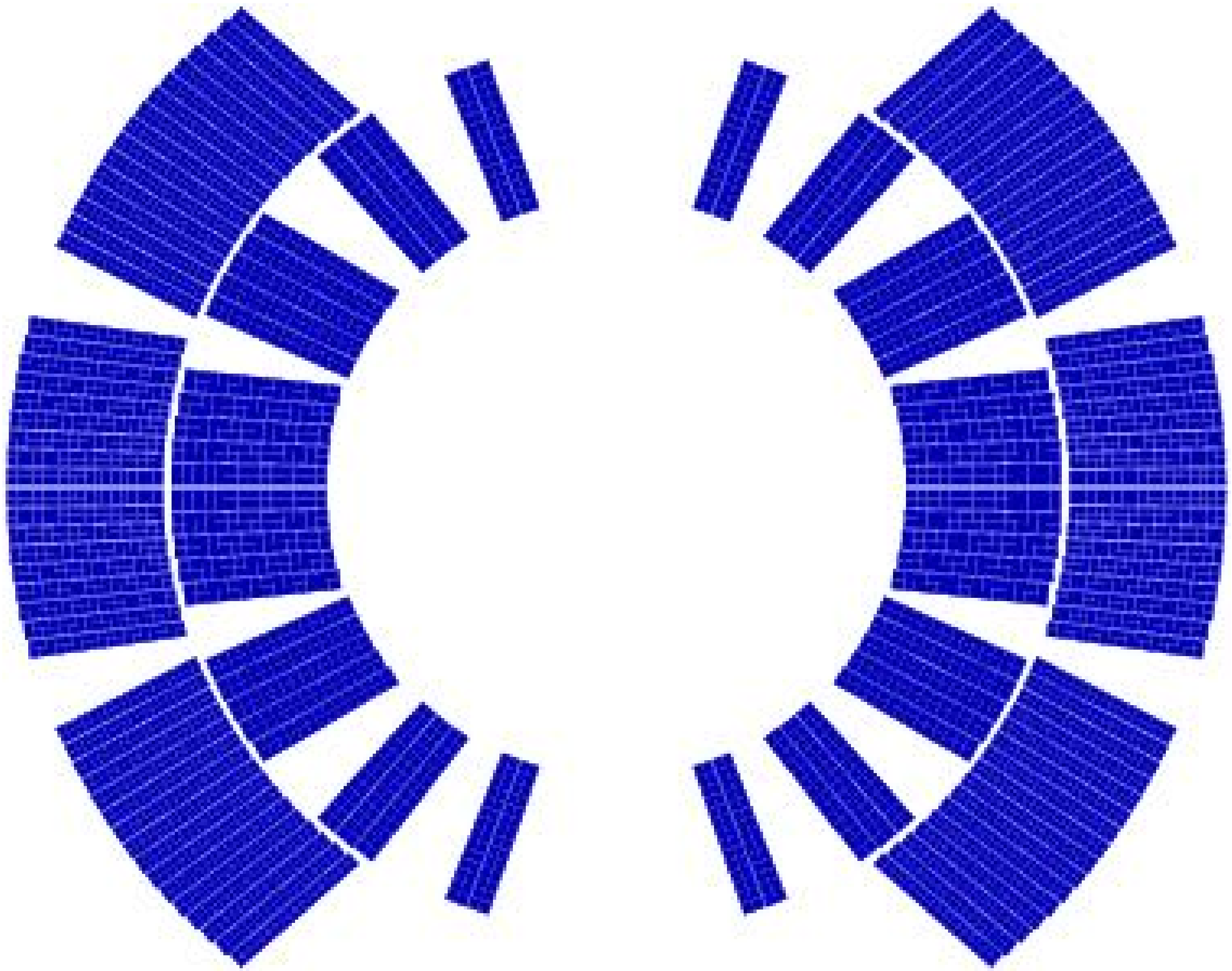
B_3 Contribution from Transport Current and Magnetization



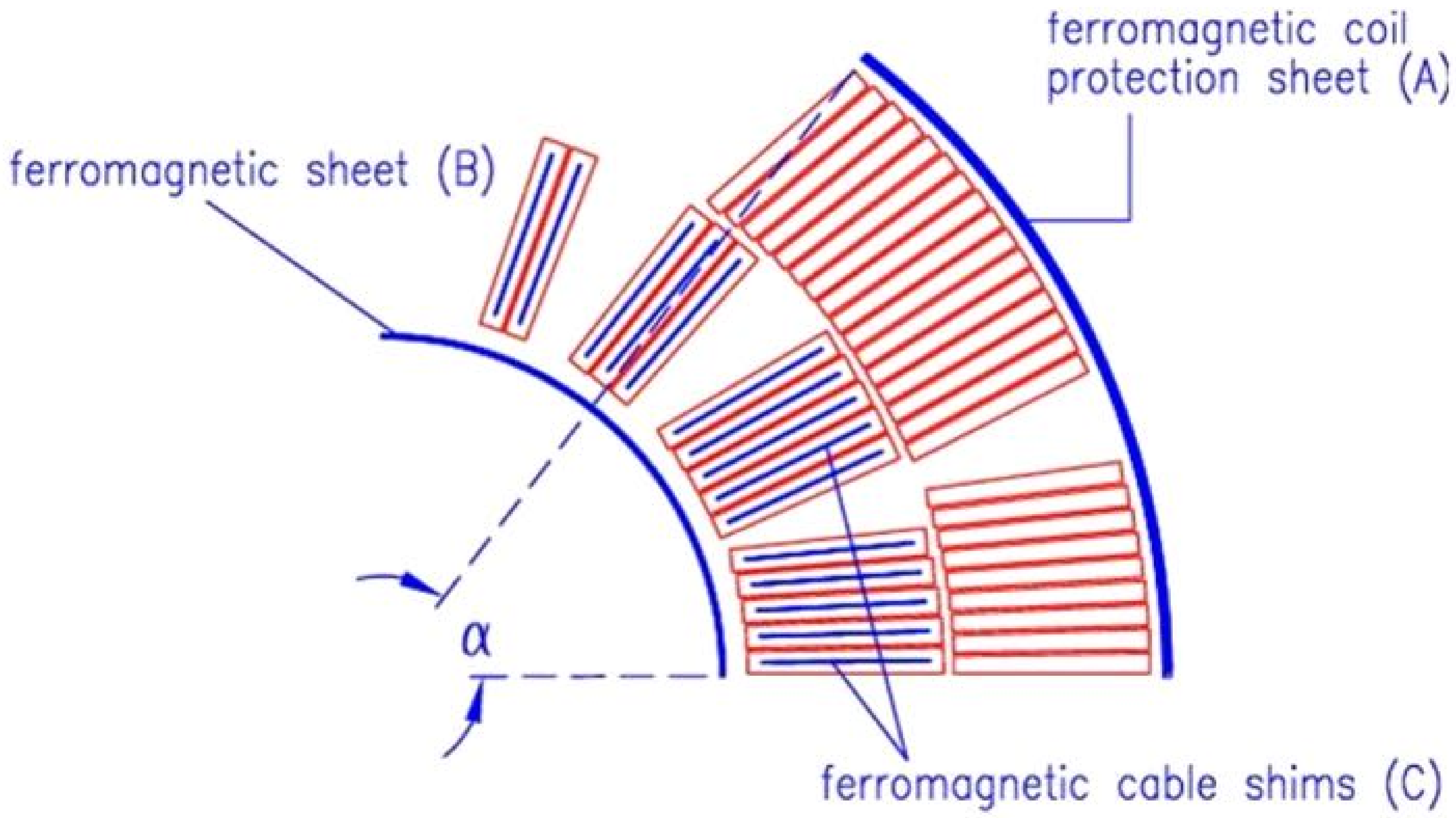
$B_3(I)$

$B_3(M)$

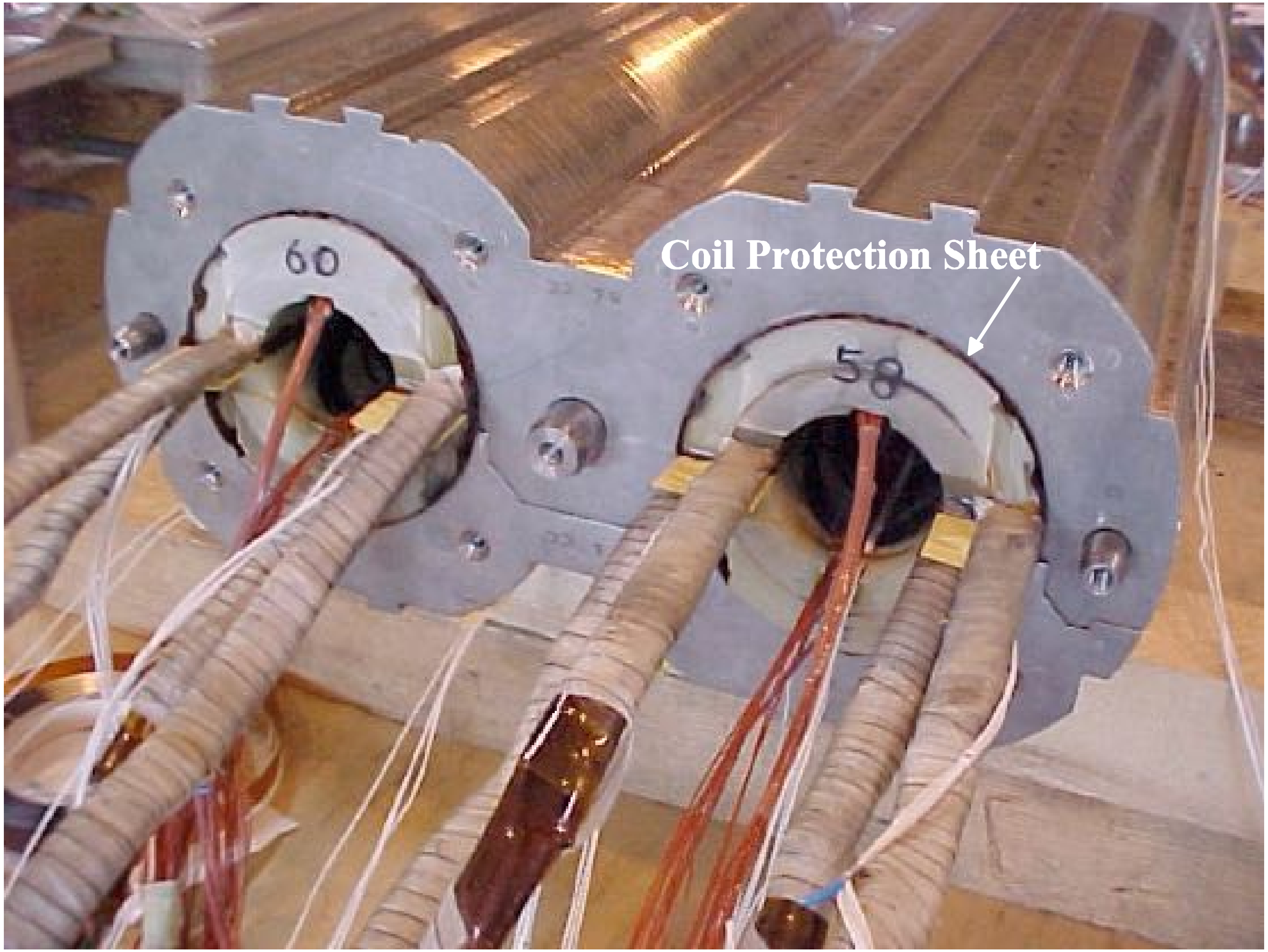




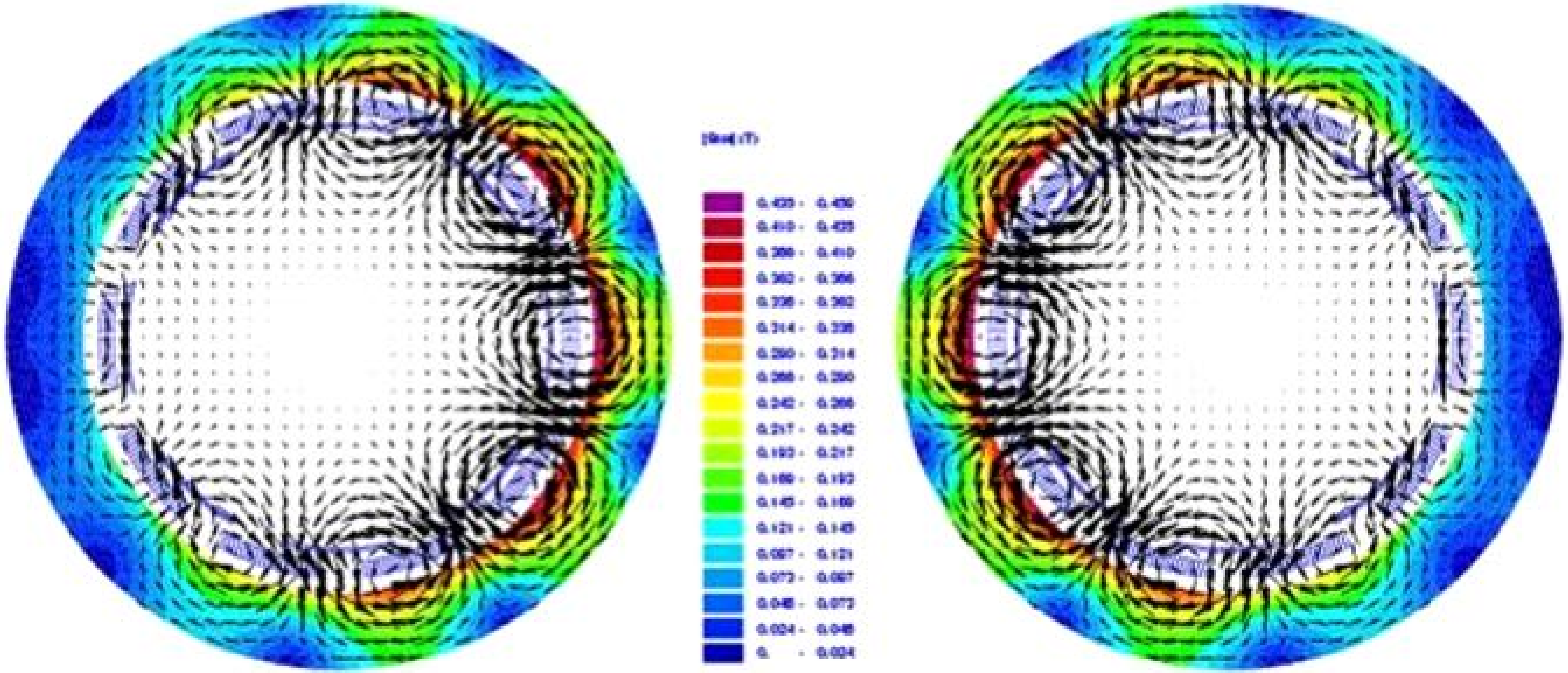
Compensation Schemes



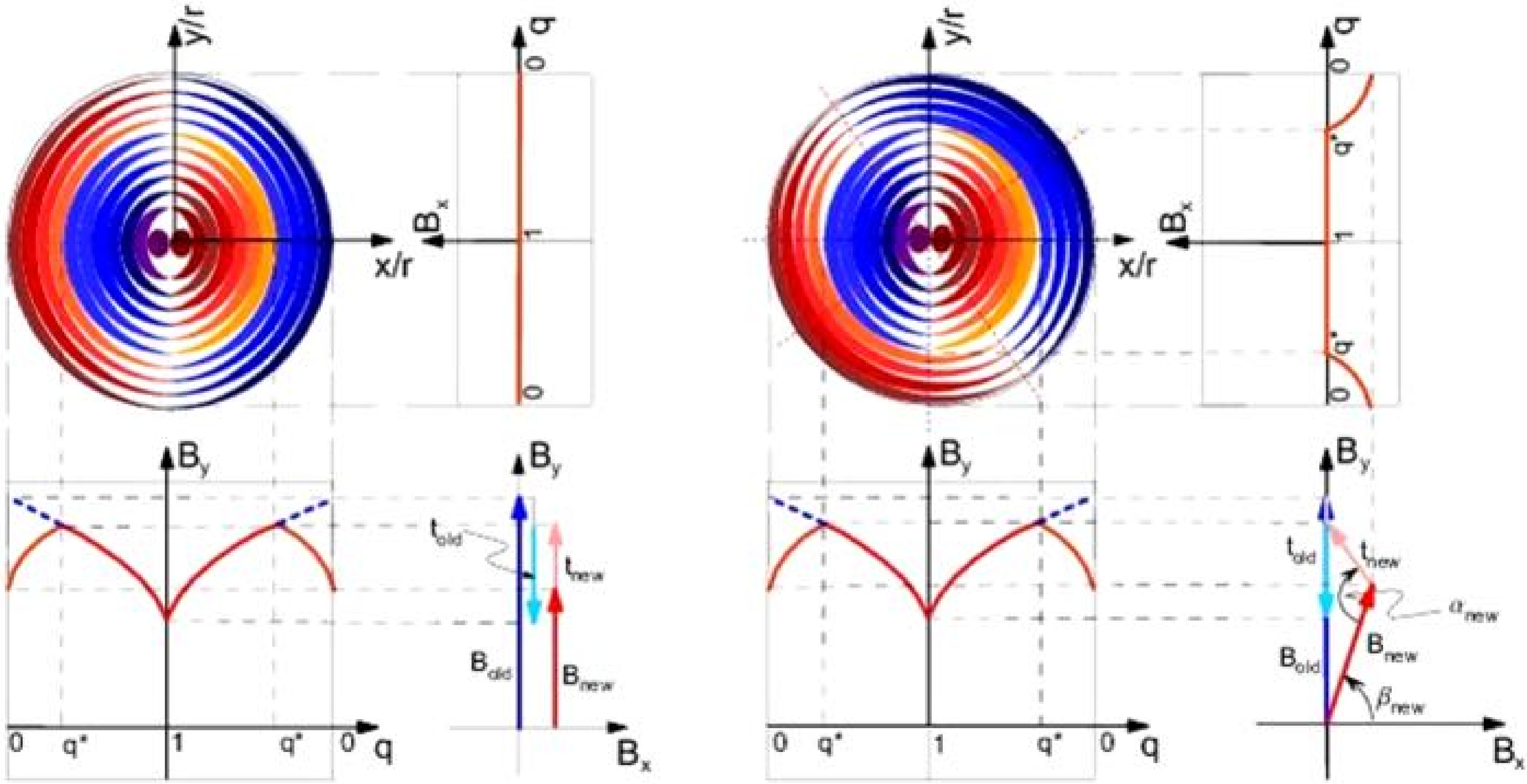
Coil Protection Sheet



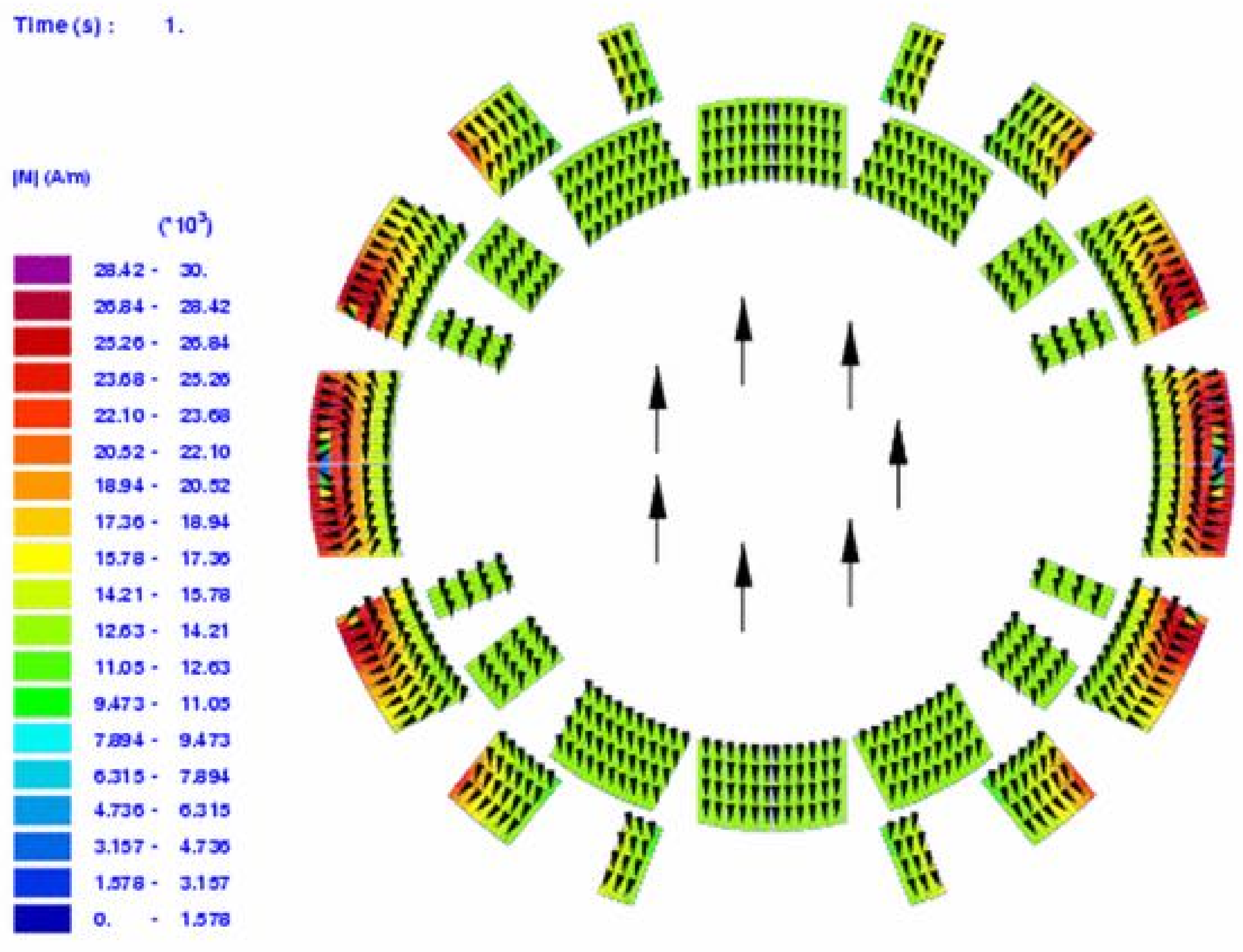
Excitation of Spool Piece Correctors

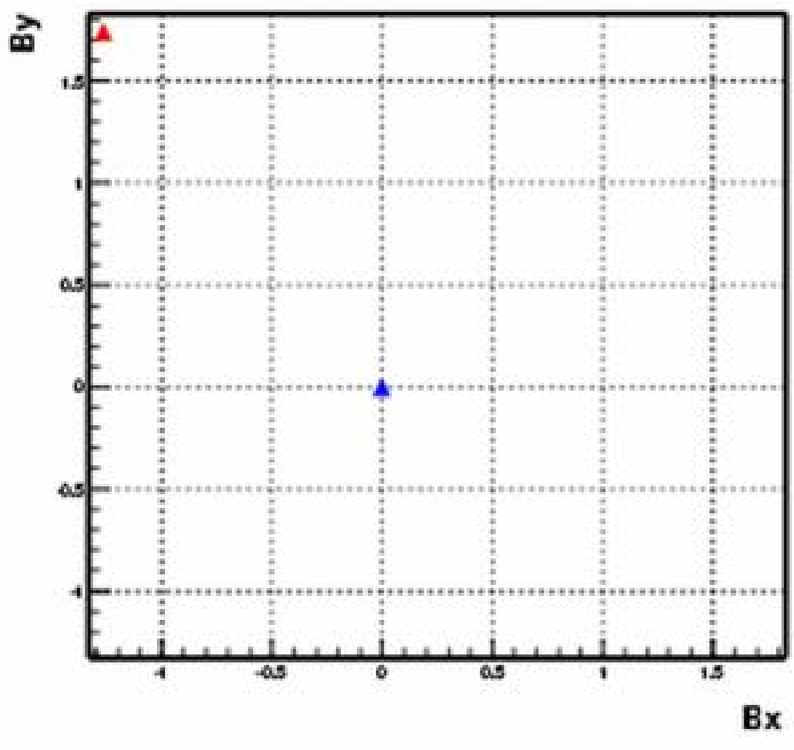


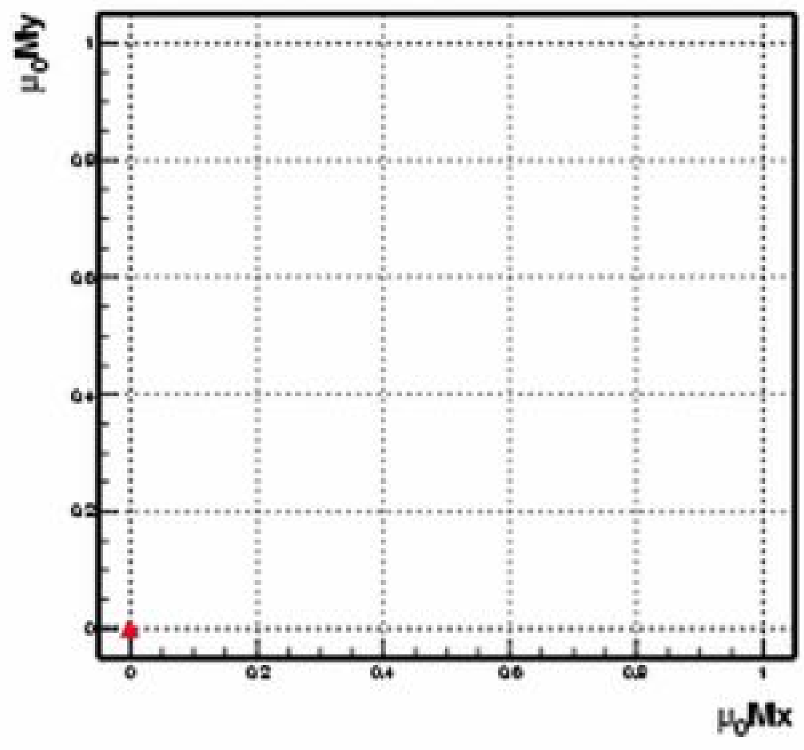
Vector-Hysteresis Model



MCBX


Time (s) : 1.
|N| (A/m)
(*10^3)
28.42 - 30.
26.84 - 28.42
25.26 - 26.84
23.68 - 25.26
22.10 - 23.68
20.52 - 22.10
18.94 - 20.52
17.36 - 18.94
15.78 - 17.36
14.21 - 15.78
12.63 - 14.21
11.05 - 12.63
9.473 - 11.05
7.894 - 9.473
6.315 - 7.894
4.736 - 6.315
3.157 - 4.736
1.578 - 3.157
0. - 1.578

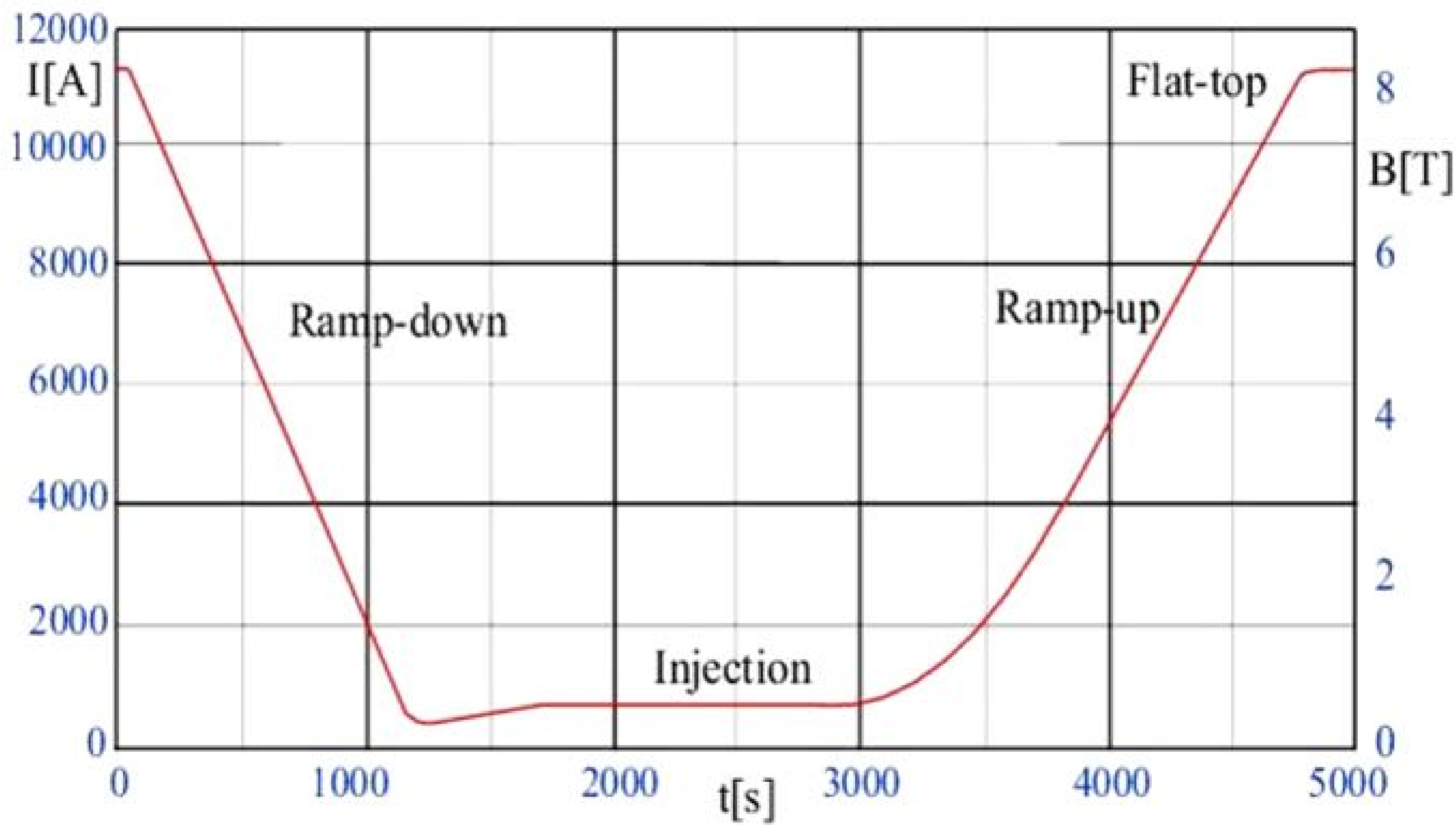

By
Bx
1.5
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
1.5


μ_0My
μ_0Mx

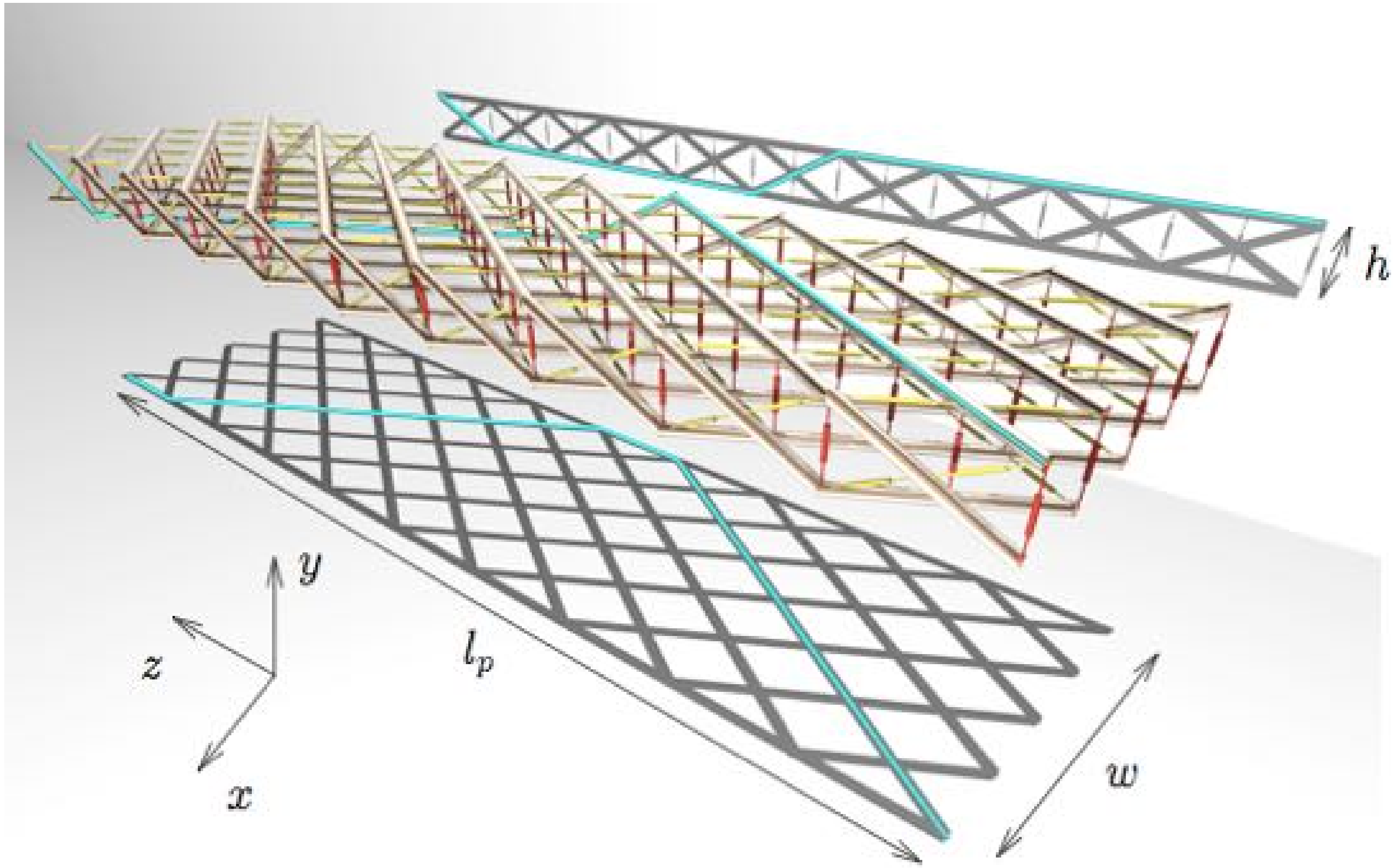
The LHC Excitation Cycle

$$V \approx 2\,E / I\,t$$

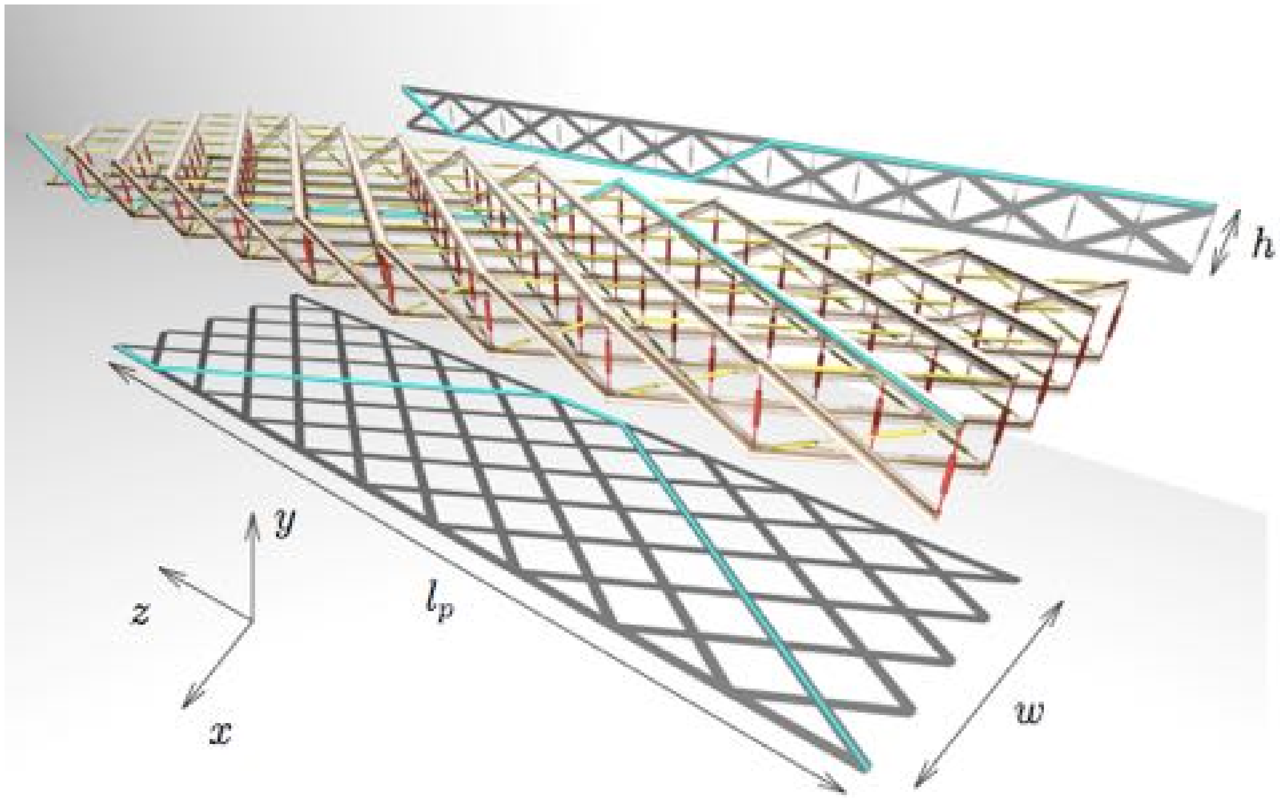
E = 1.15 TJ (320 kWh), I = 11800 A, Ramp rate 10 A/s, 155 V

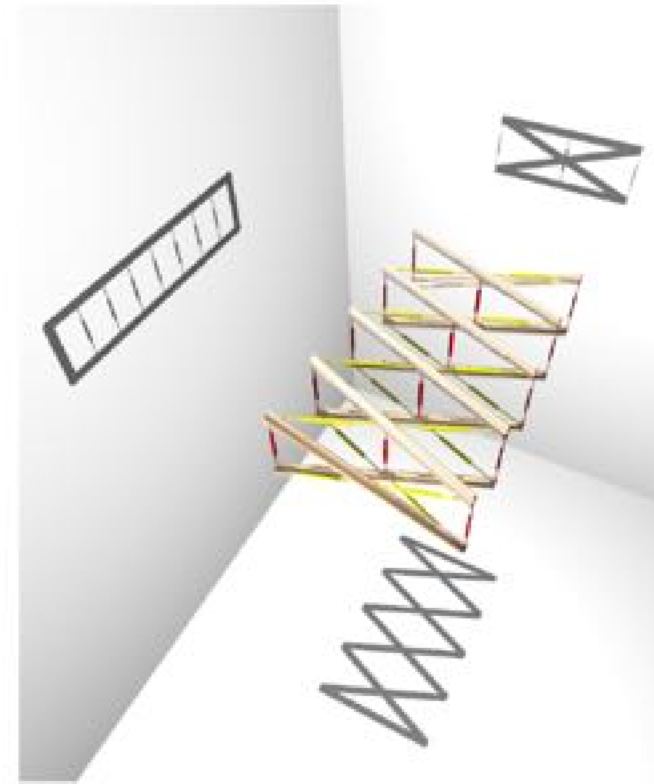


Eddy Currents in Rutherford Cables



Eddy Currents in Rutherford Cables (Algebraic Topology)



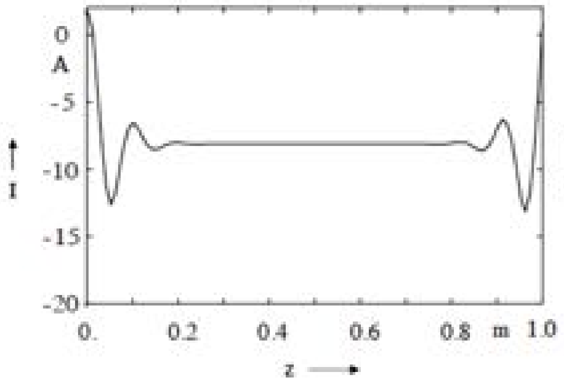


Nodes: 2 Ns * Nb + Ns
Nb = L / pitch * Ns

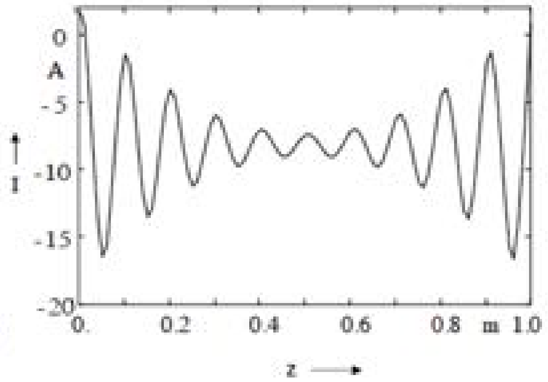
Pitch = 100 mm
Ns = 36
Nodes = 30 000 / meter
LHC main dipole = 4.2 km cable
126 Million Nodes

Boundary Induced Coupling Currents

@ 1 sec

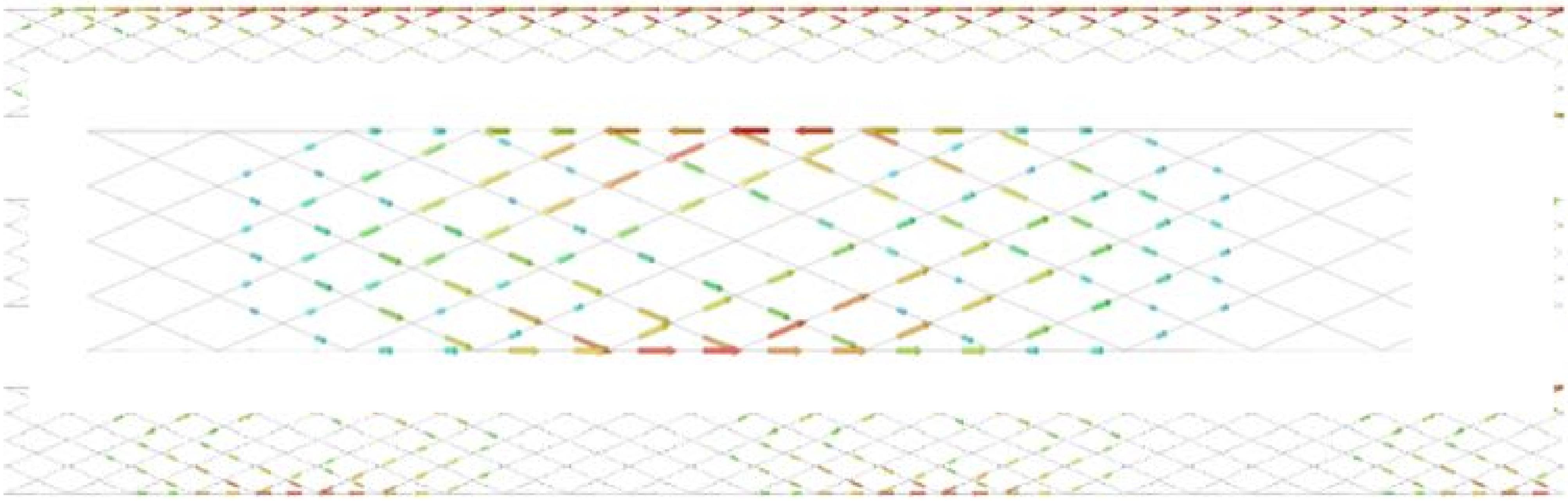


@ 10 sec

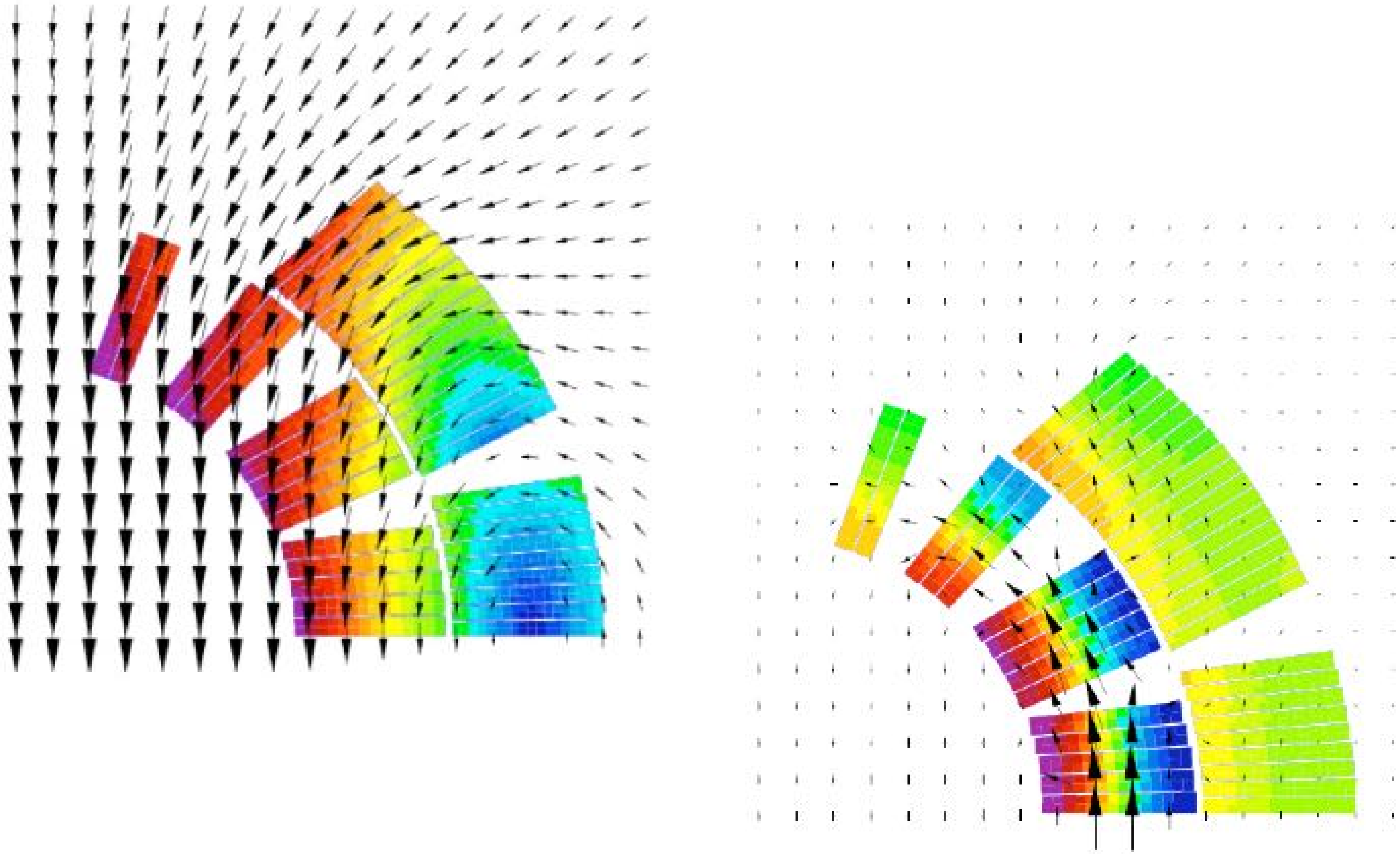


R&D Challenge

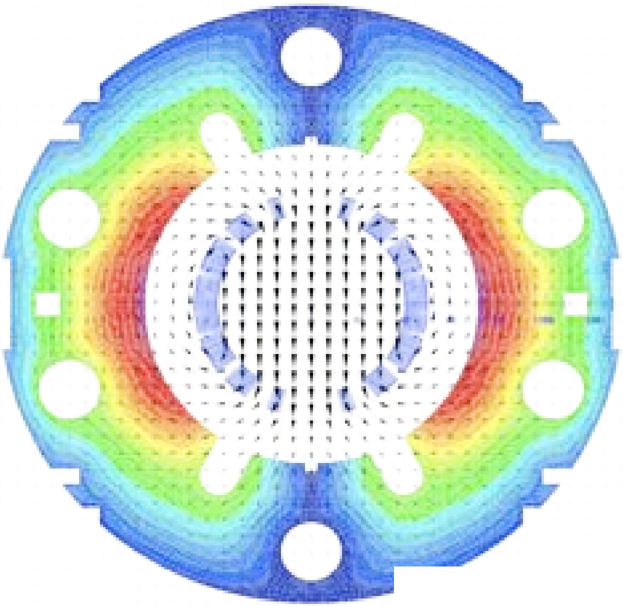
Dimensional reduction

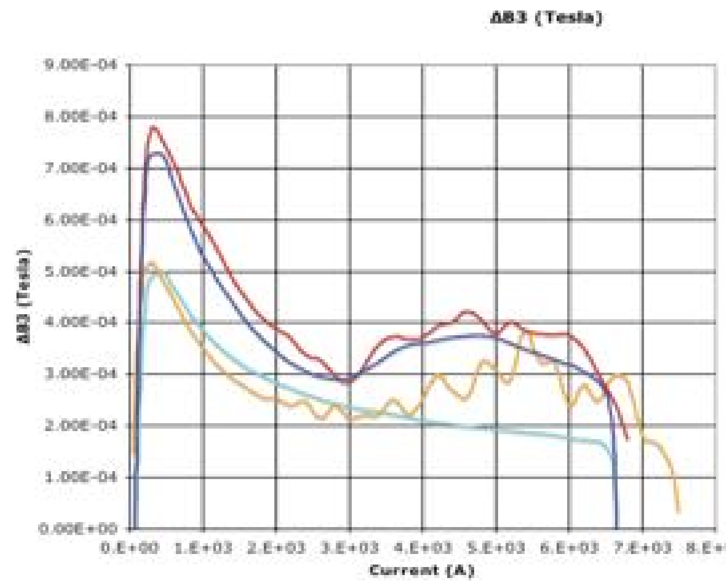


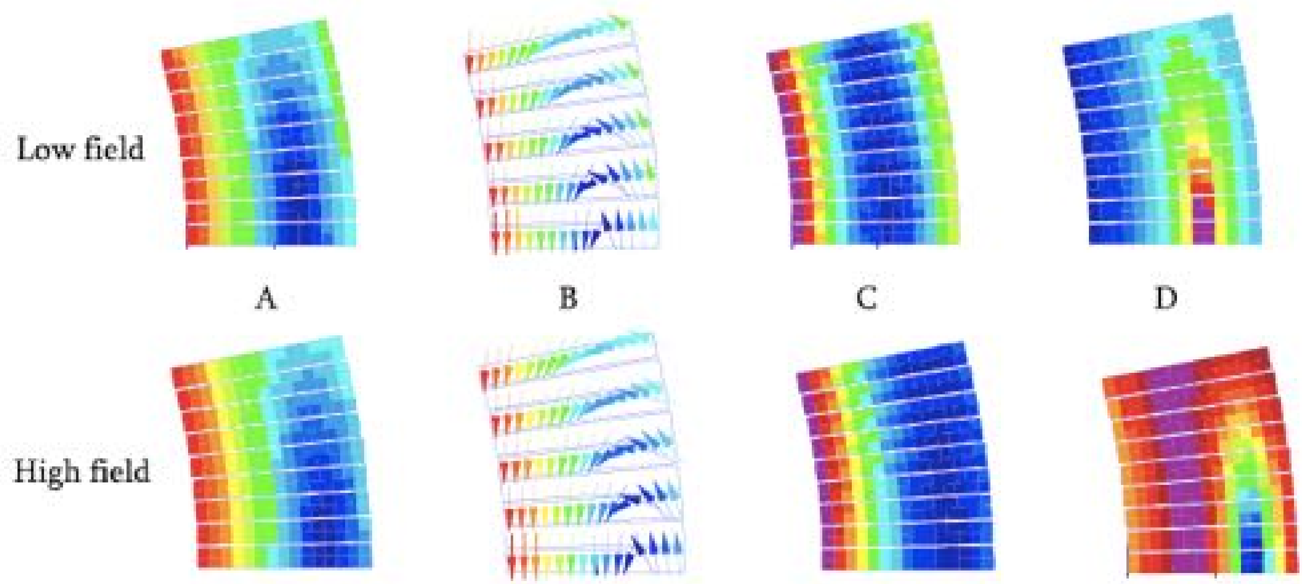
Field Generated by ISCC



2-D Transient Field Computation for GSI-001



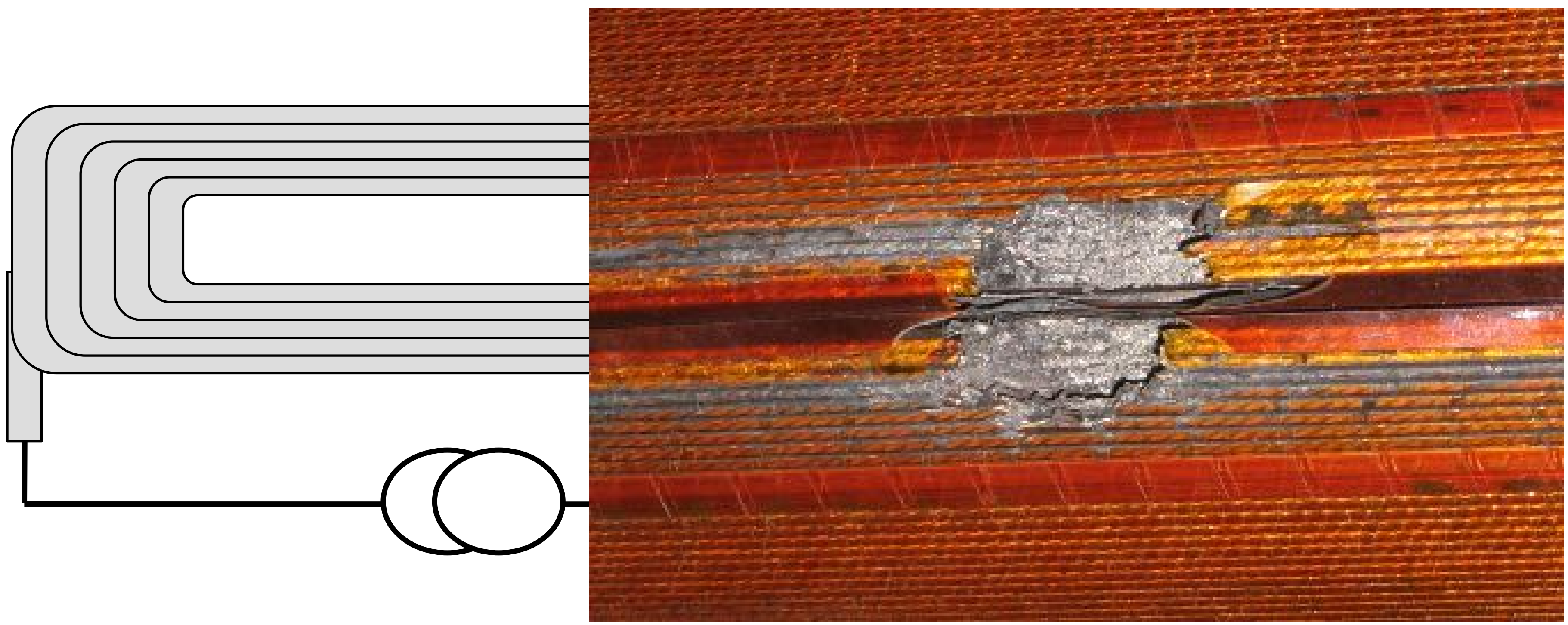


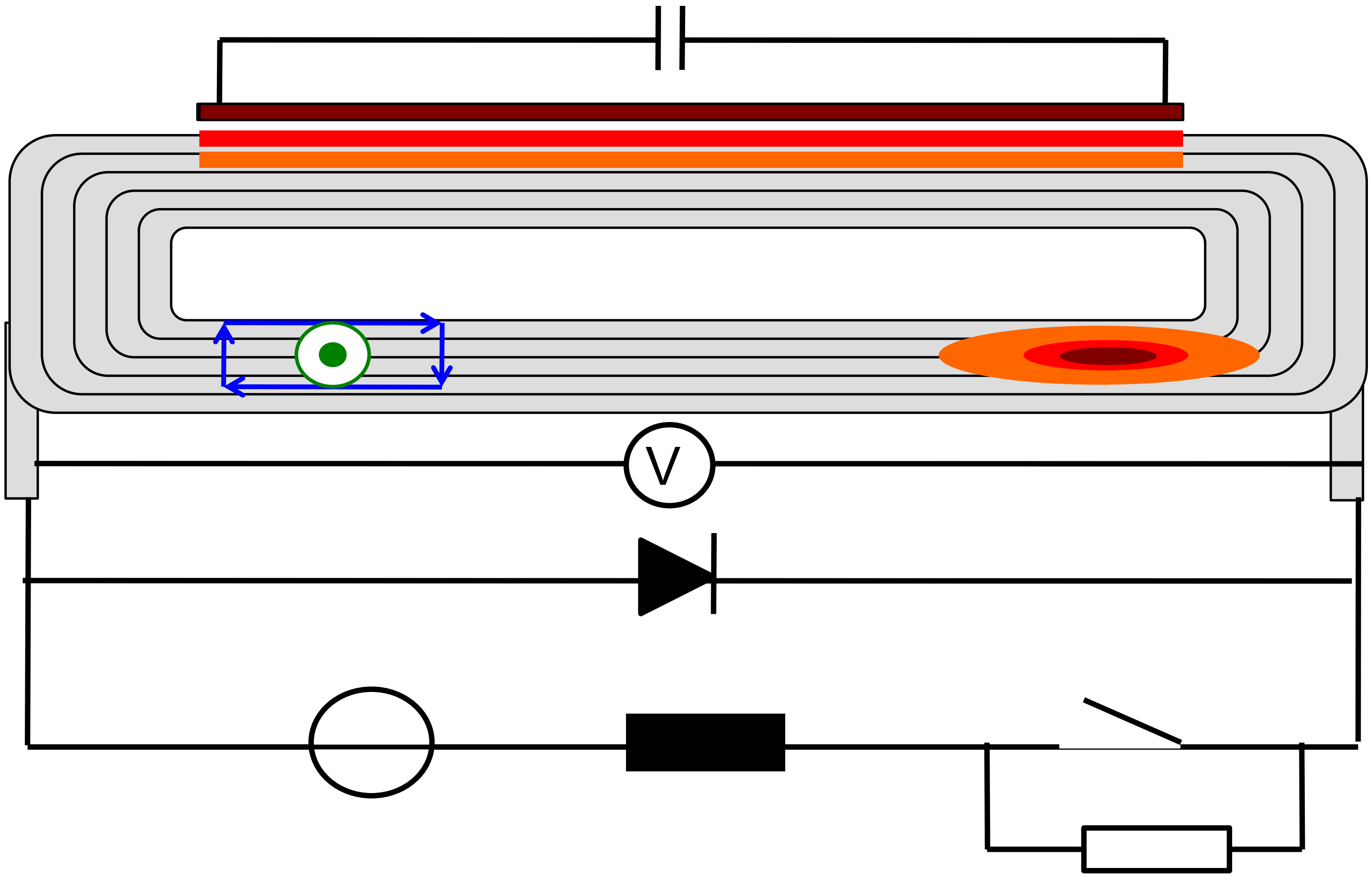


- **Quench**: Transition from SC to normal conducting state caused by

  beam losses, conductor movement, eddy currents etc.

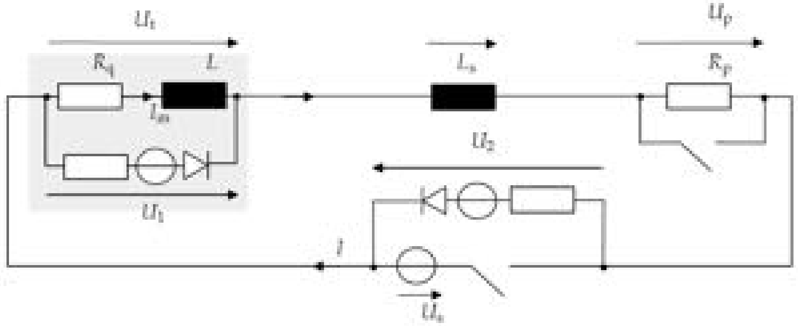
- **Propagation**:
  - Normal conducting zone generates Ohmic heat
  - Quench- und temperature distribution determined by loss-mechanisms and cooling capacity

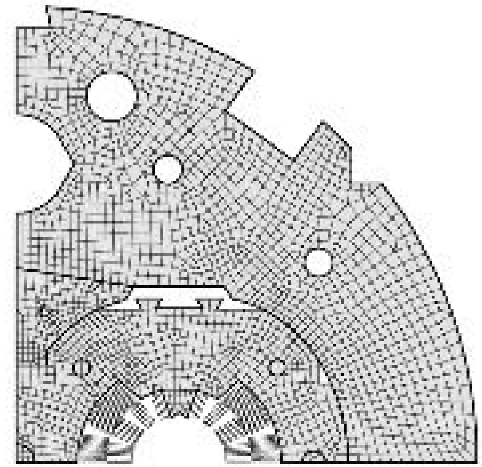


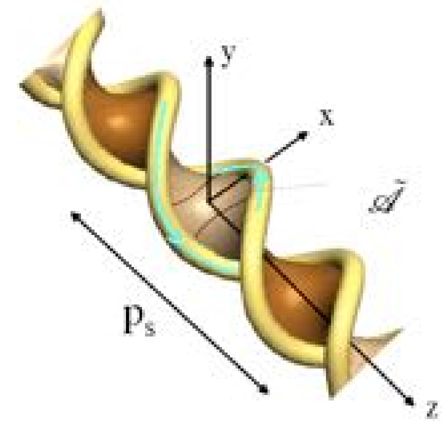

V

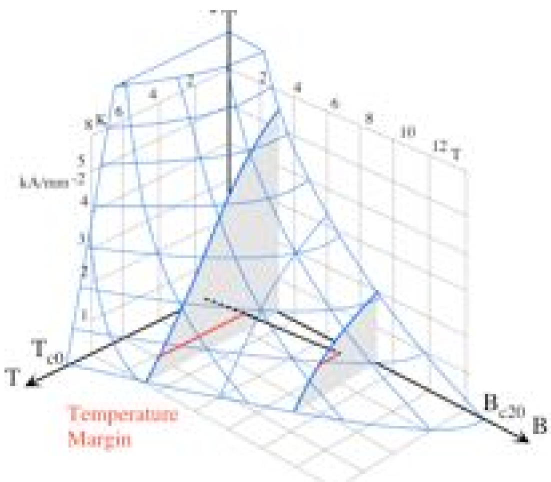
Switches and Dump Resistors

Quench Simulation (Multi-Physics, Multi-Scale)

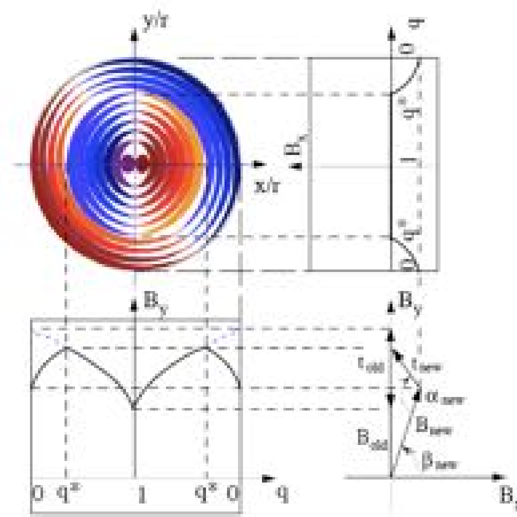


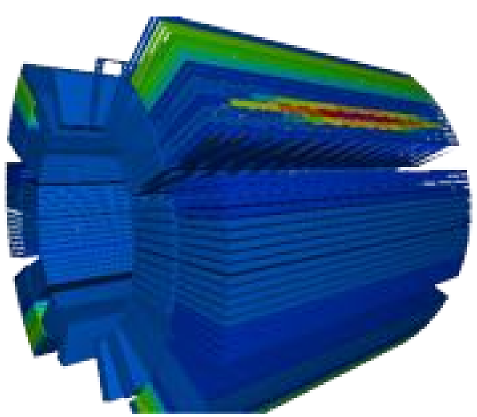


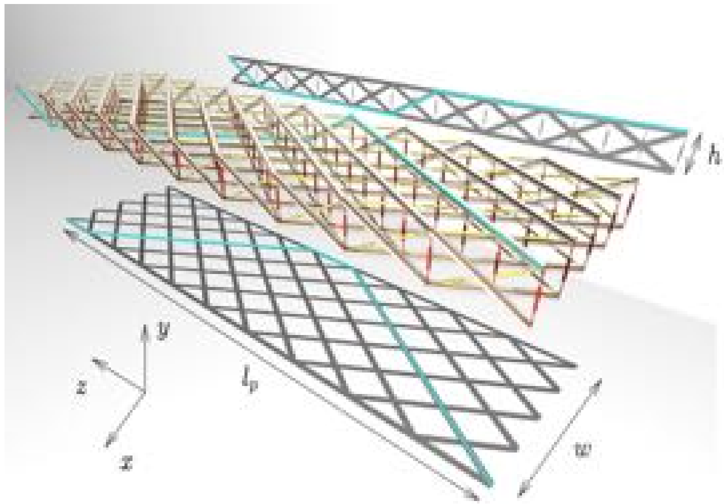




Quench Simulation in ROXIE

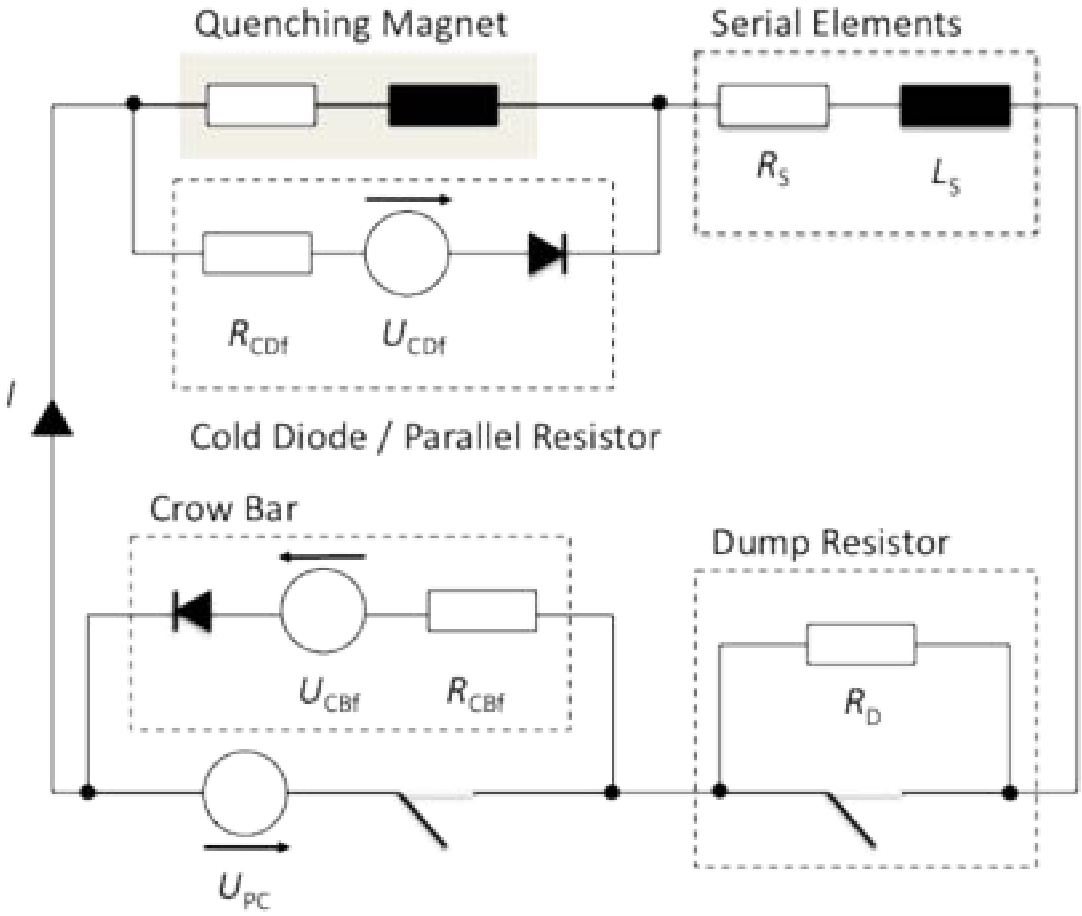






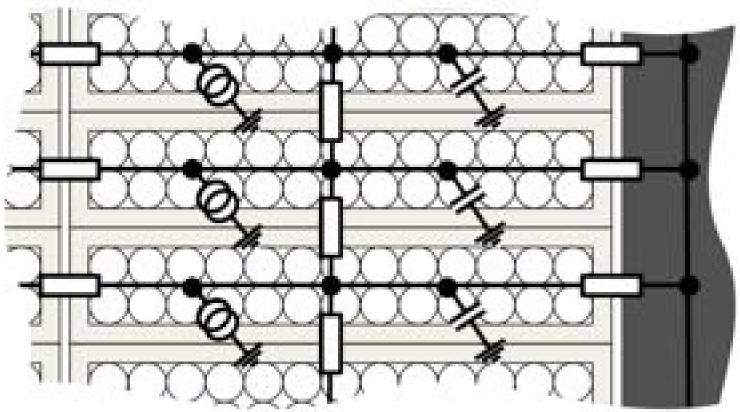
Electrical (External) Network

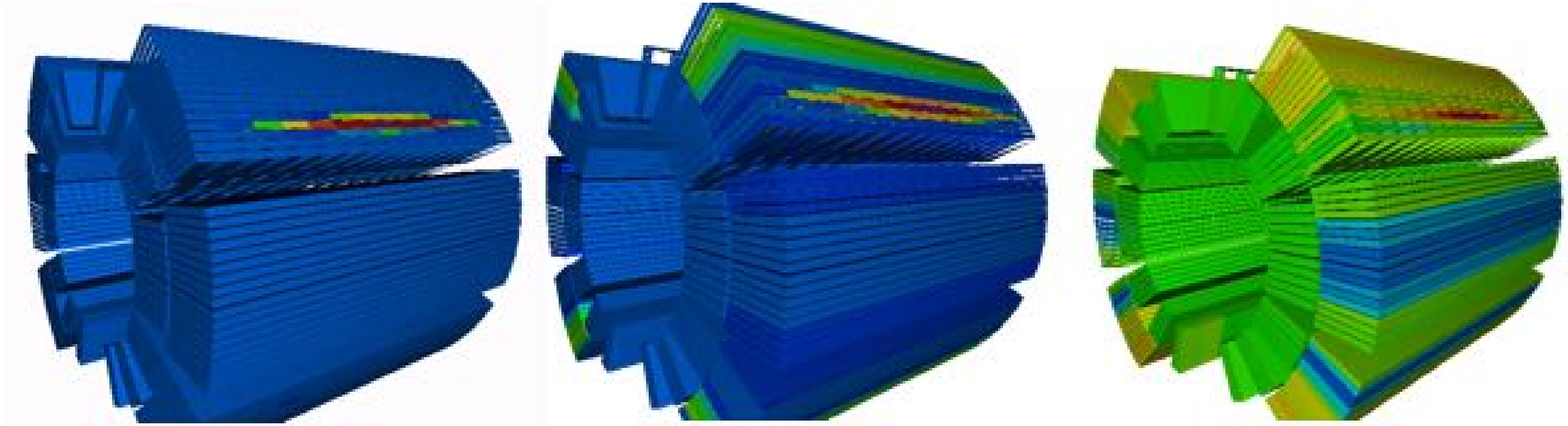
$$L_{\mathrm{d}}(B)\frac{\mathrm{d}I}{\mathrm{d}t} = U_{\mathrm{Diode}} - (R_{\mathrm{Q}}(B,T) + R_{\mathrm{P}}(t))I$$



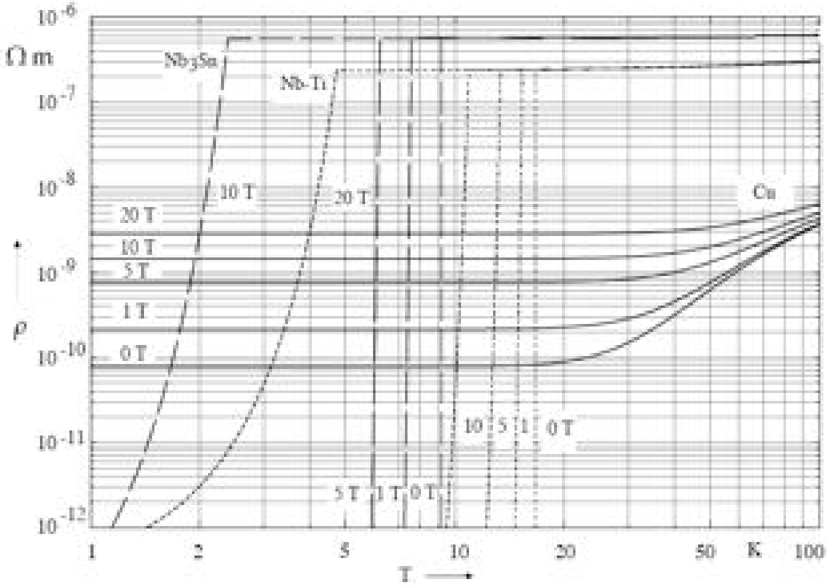
Thermal Model

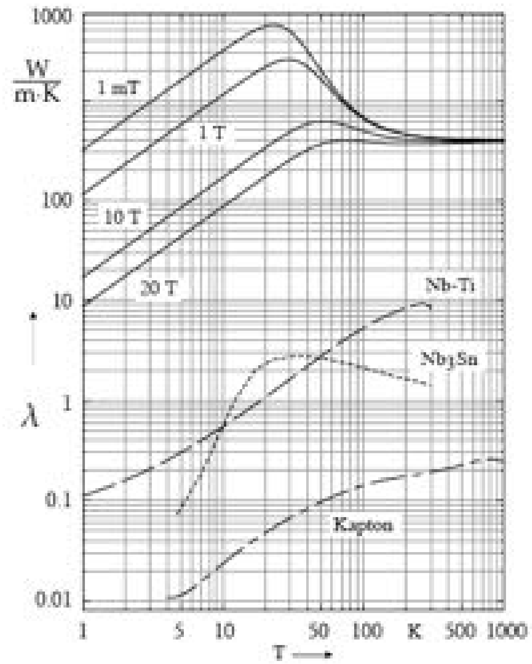
$$c(T)\frac{\mathrm{d}T}{\mathrm{d}t} = p - \vec{\nabla} \cdot \left(\kappa(T,B)\vec{\nabla}T\right)$$

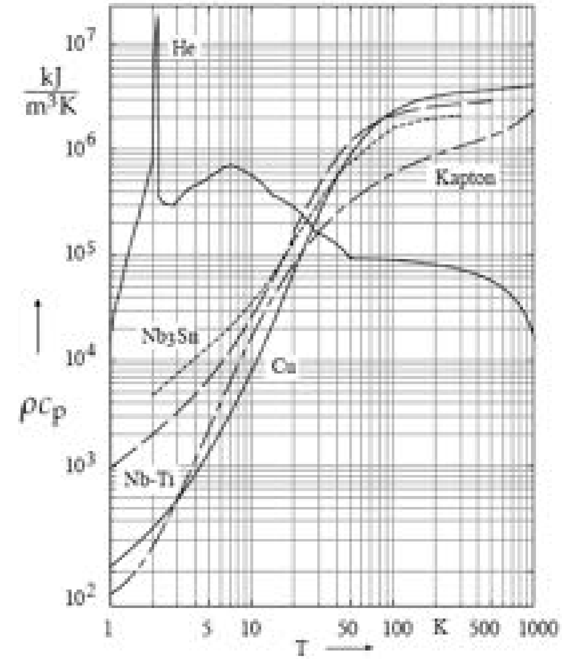




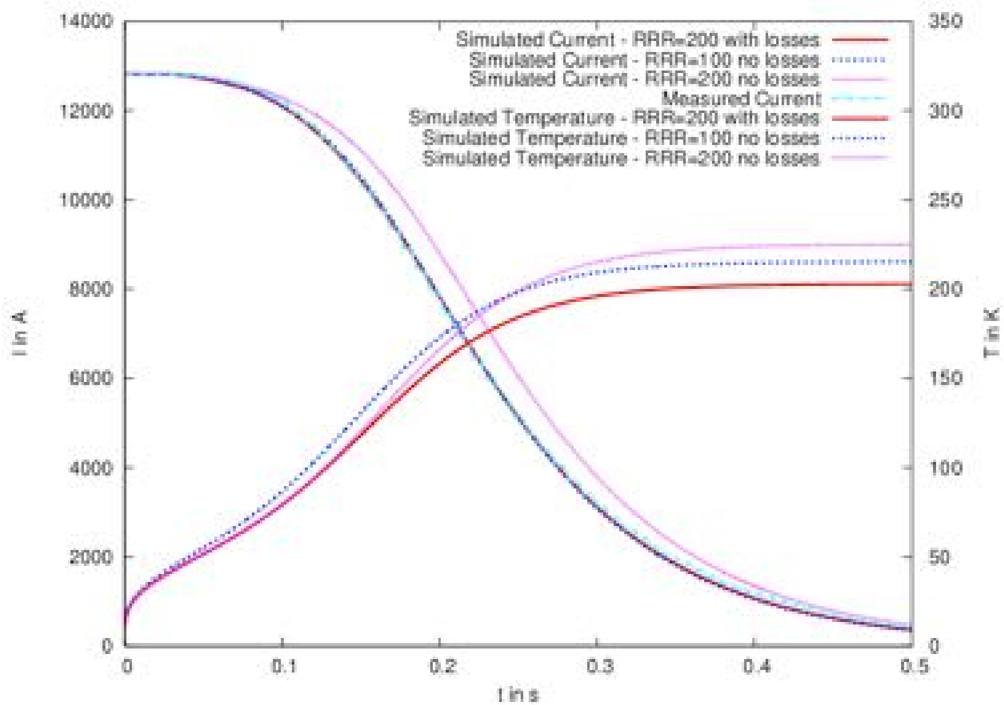
Material Parameters







Validation



Empirical parameters:

- RRR
- Ra/Rc
- IFCC effective res.
- heat conductivity
- heat capacity

→ Different families of parameters yield exactly the same observable I(t).

→ More than one solution exists.

→ Great care must be taken to model

- all relevant phenomena,
- using realistic material parameters.

Quench Simulation

The challenge of quench simulation:

Model **all relevant physical phenomena** with **adequate accuracy** so that we can be confident to **simulate internal states** of a quenching magnet and understand its behavior.

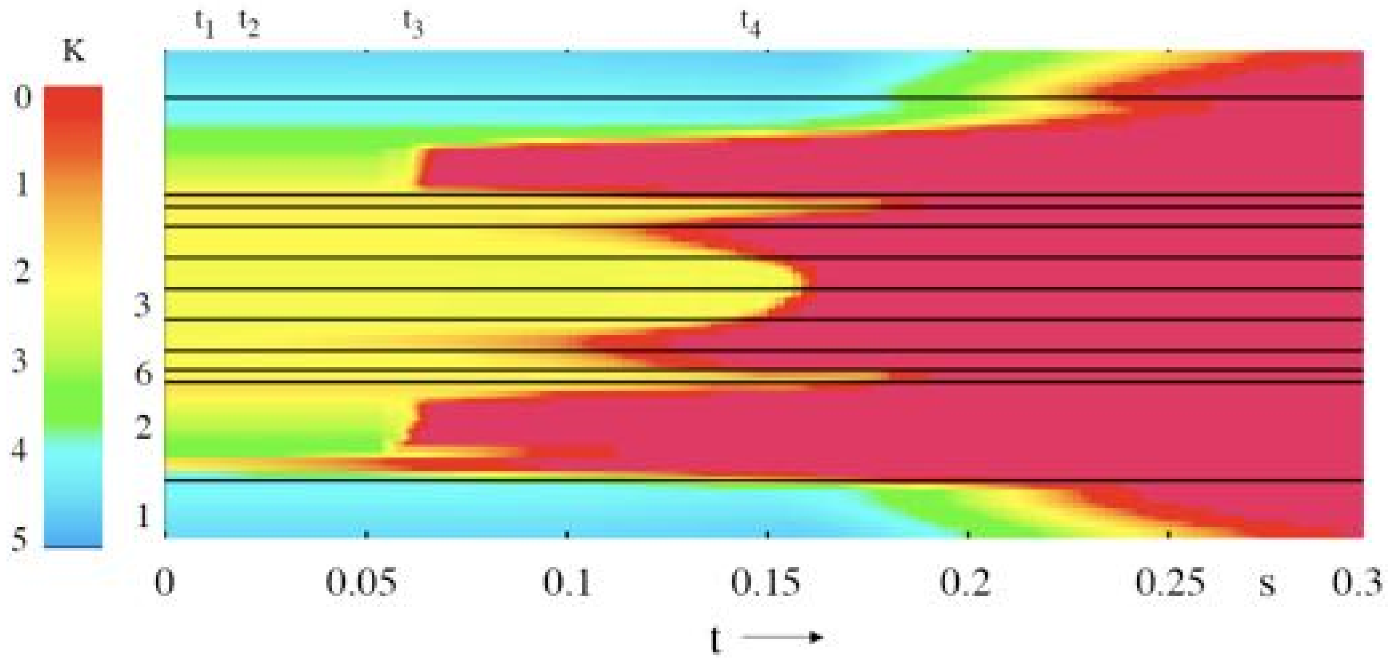
Validation:

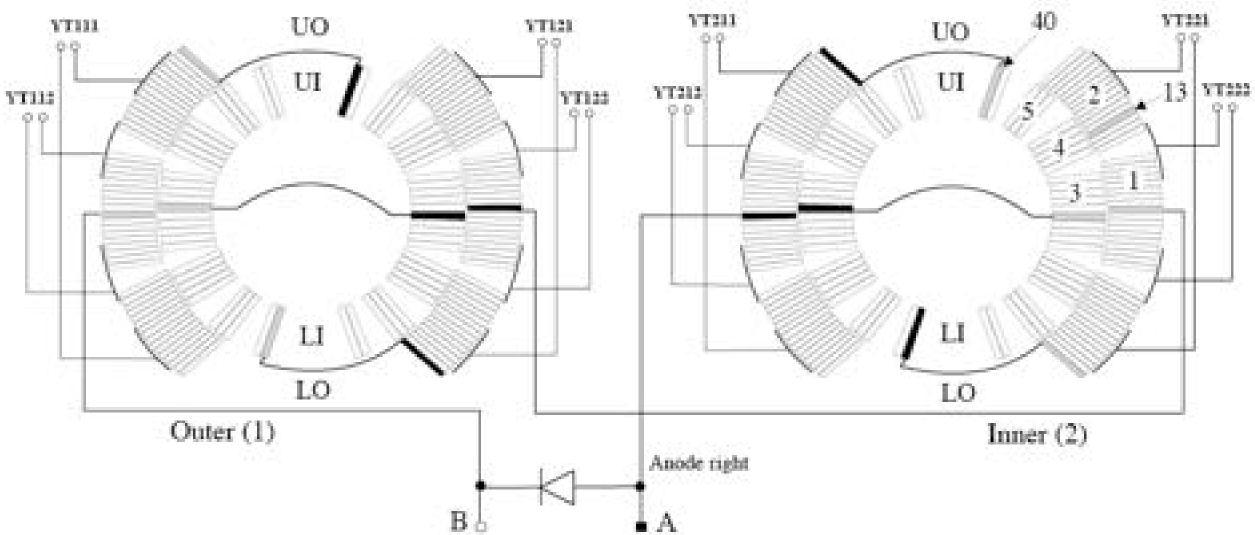
Measured quantities can be **reproduced** with all **material- and model-parameters within their range of uncertainty,**

Extrapolation and Introspection

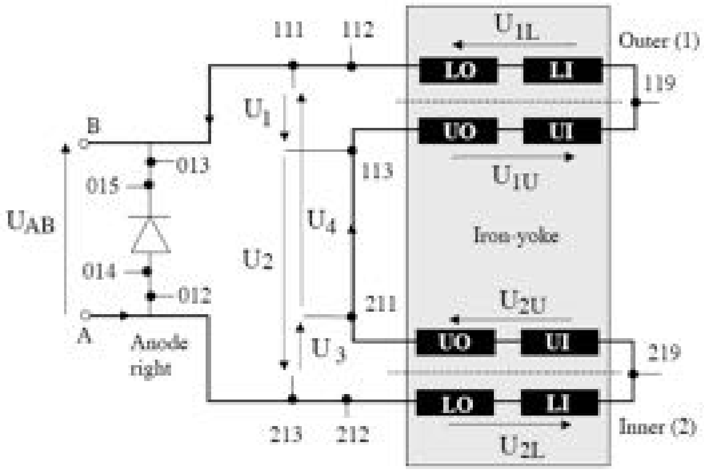
If the above criteria are reached, extrapolated results will match measurements **without adaptation of material- and model parameters**. It is then also possible to **simulate internal states** of the magnet that escape measurements.

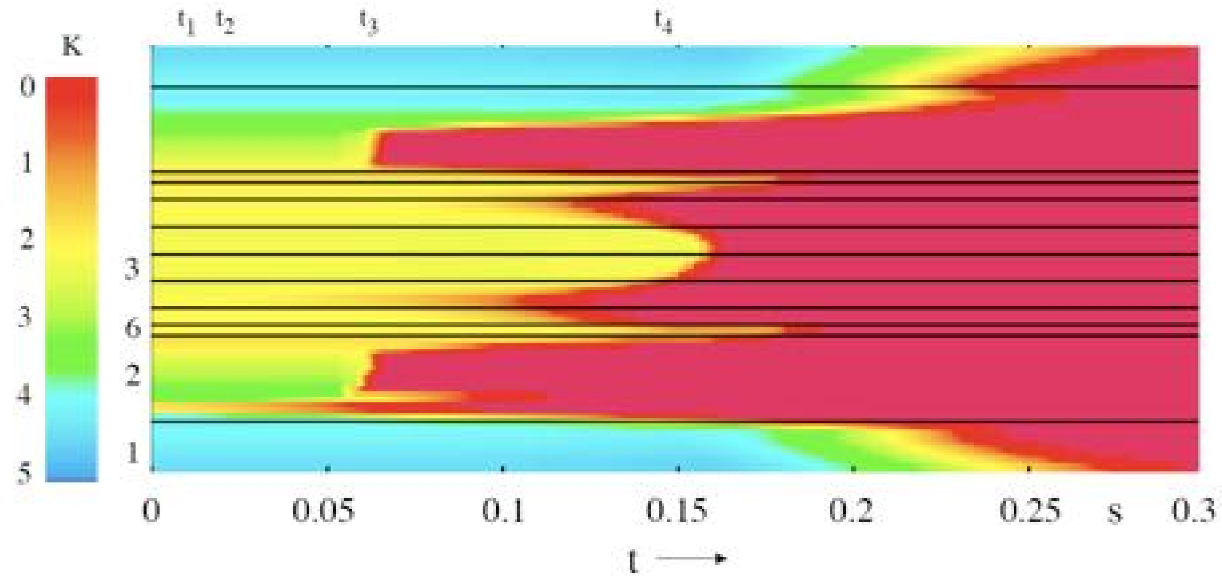
Introspection (Quench Margin)

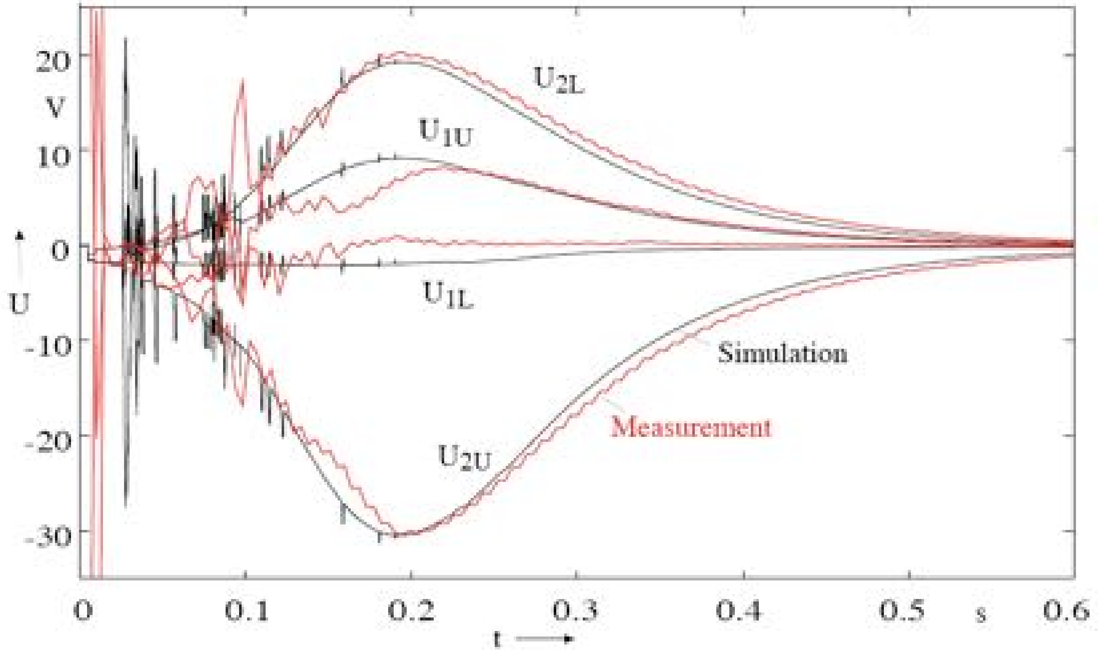




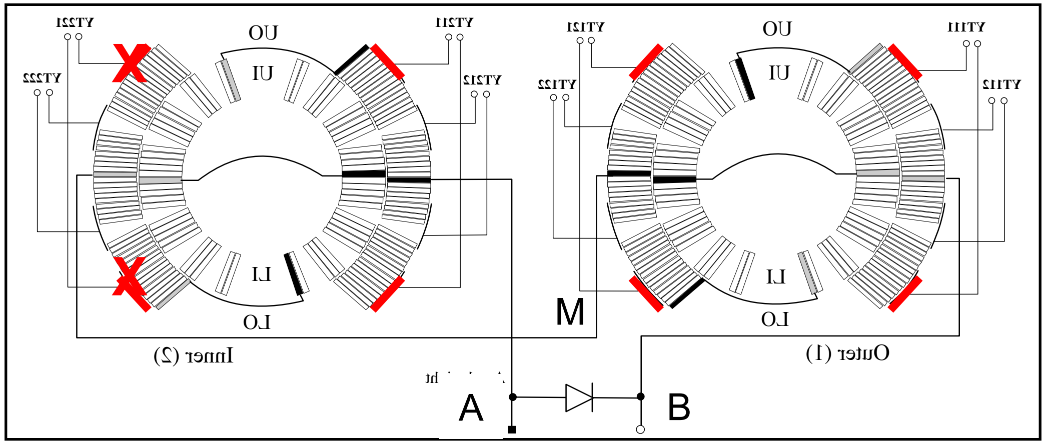
Introspection (Voltage Ripples)

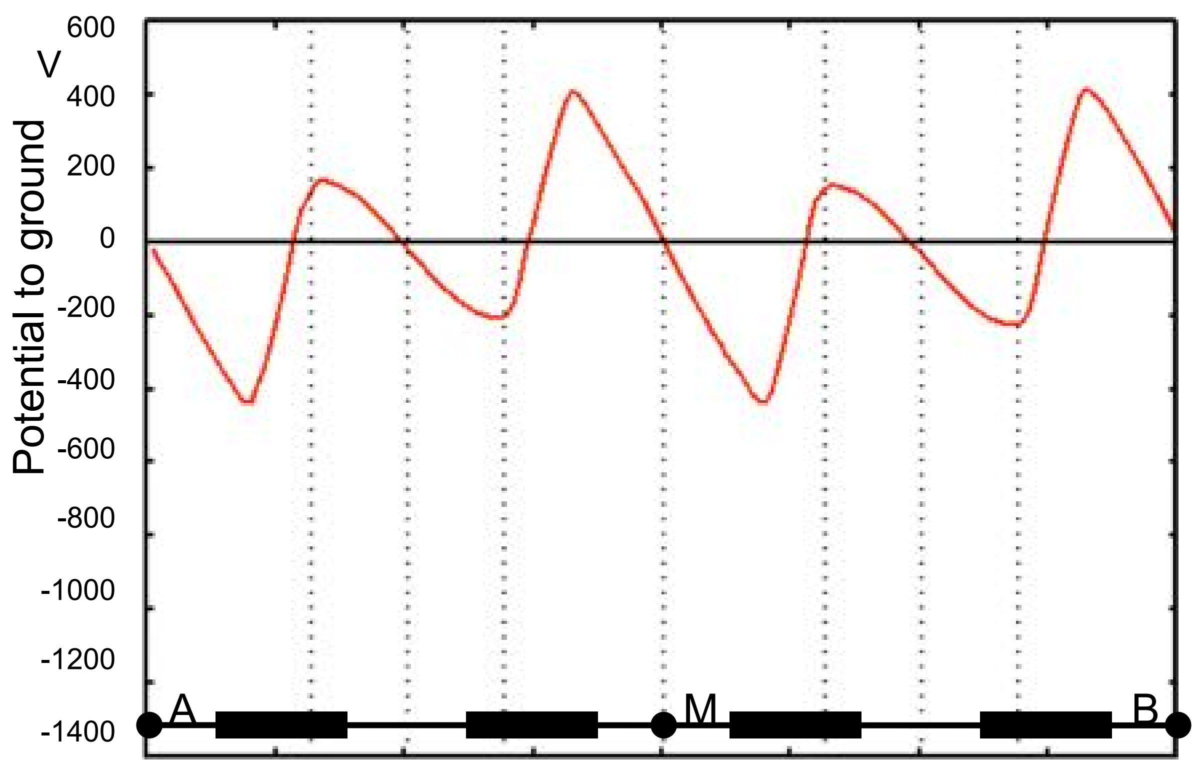




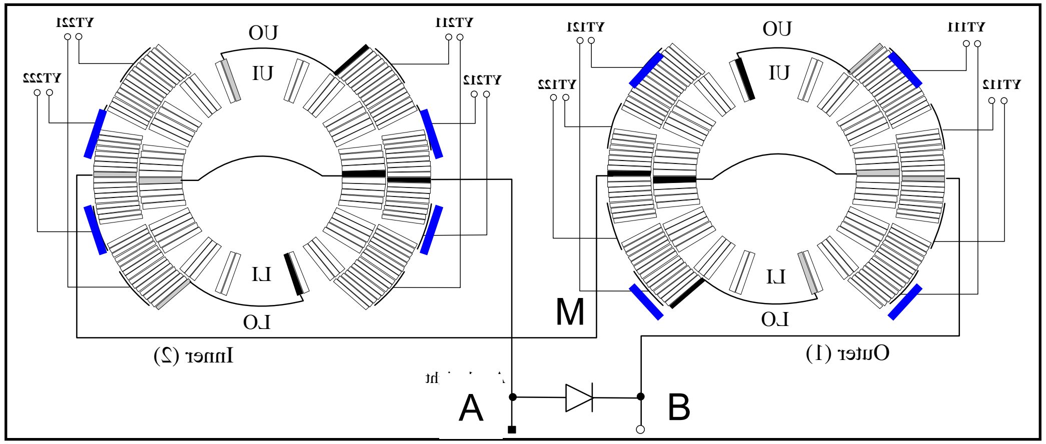


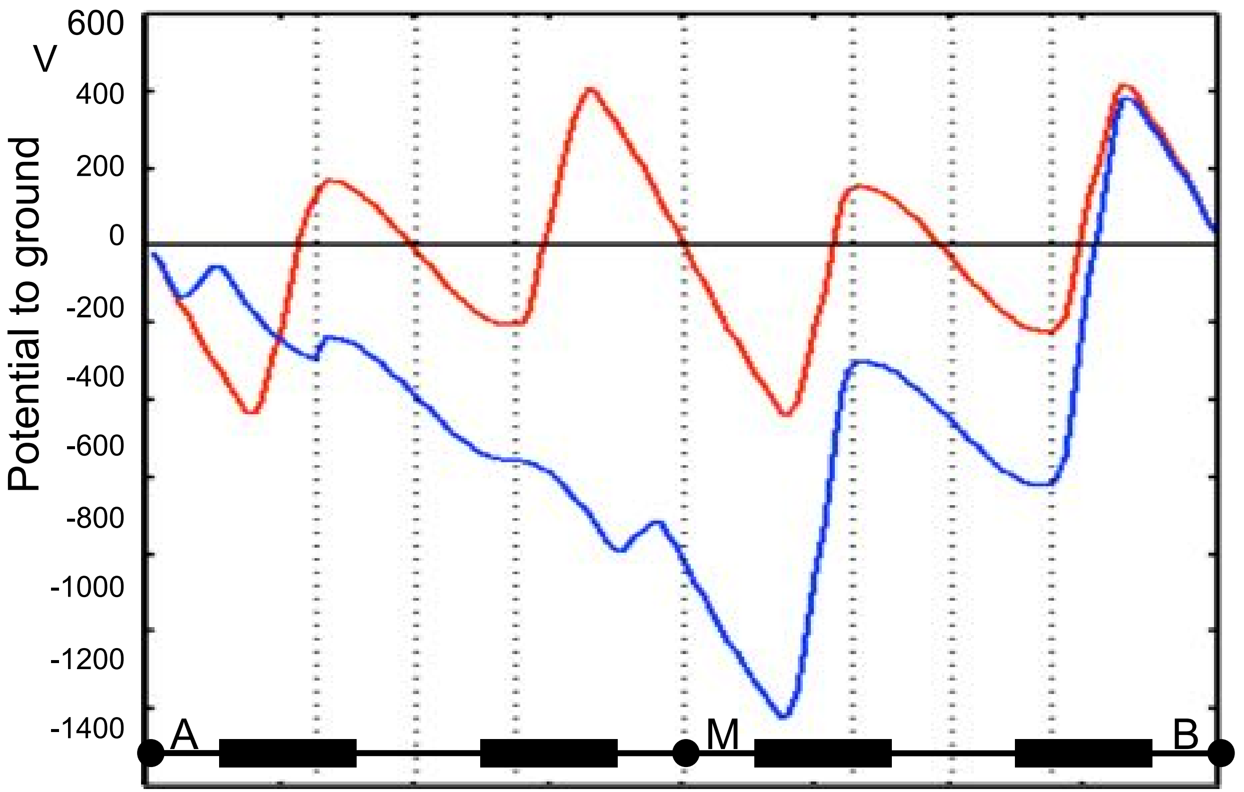
Defect on Quench Heater Circuit





Defect on Quench Heater Circuit





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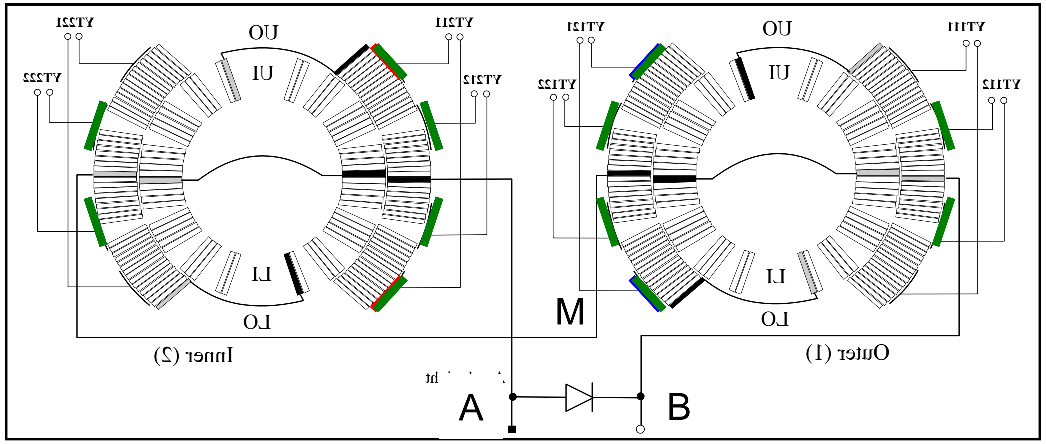

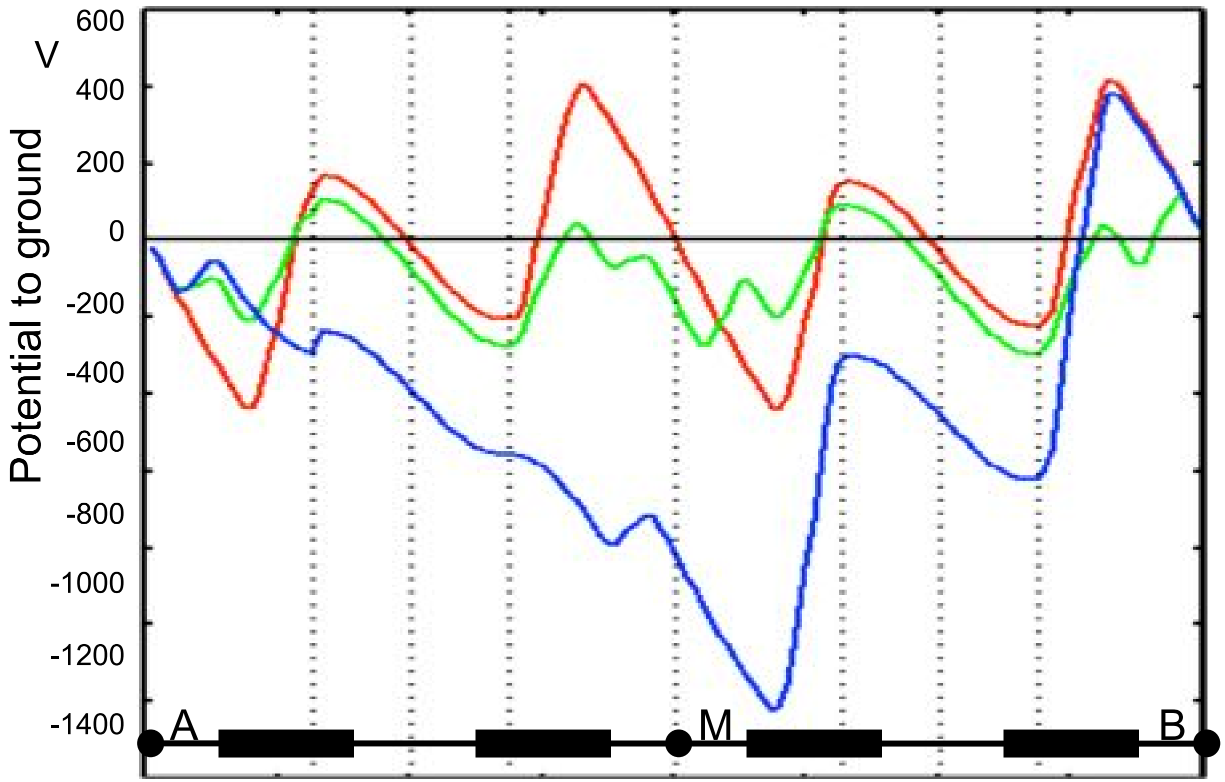

Challenges

- Multiscale
  - Filaments 6 µm
  - Strands 1 mm
  - Cable 0.1 m
  - Magnet 10 m
  - String 3.2 km
- Multiphysics
- The smallest time constant determines the Runge-Kutta step
- More advanced methods
  - New software framework