QuickField Analysis for Superconductors

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QuickField Analysis for Superconductors

- Superconductivity Basics
- Specifying Superconductors in QuickField
- Superconducting Plates
- Hollow Superconducting Shells
  - Inductance Calculations
  - Flux Trapping
- Superconducting Magnetic Levitation
- Nonlinear B-H Characteristics of Superconductors
- Coupled Magnetostatic and Stress Analysis of Superconductors
- Superconducting vs. Permeable Magnetic Shields

Superconductivity Overview

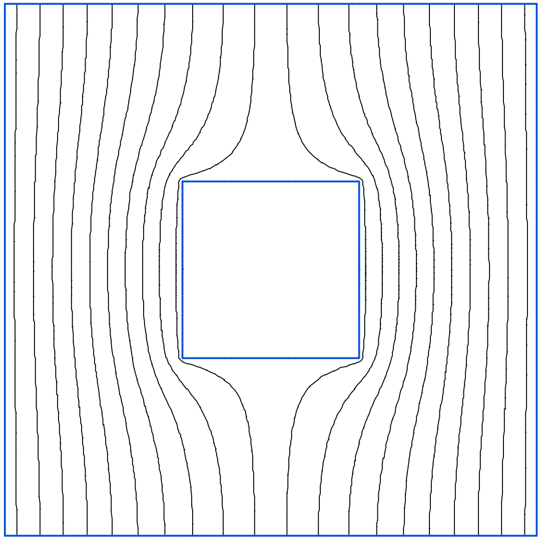
- Superconductivity is a macroscopic quantum phenomenon where superconducting electrons are described by a single wavefunction in the bulk of the superconductor

$$\Psi(r)=|\Psi|\exp(i\phi$$

- Zero electrical resistivity below a critical transition temperature $T_{c.}$
- External magnetic fields are expelled from superconductors (Meissner effect).
- The superconducting state is abolished by sufficiently high magnetic fields and currents.

The Meissner Effect

- London’s equations predict that magnetic flux is expelled from the interior of a superconductor except for thin layer.
- The superconductor exhibits perfect diamagnetism.



Modeling Superconductors in QuickField Modules:

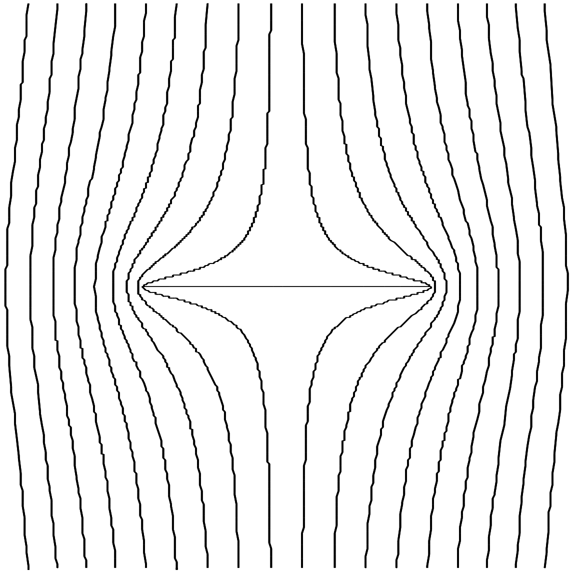
- Magnetostatics
- AC Magnetics
- Transient Magnetics

Specifying superconducting regions

- The appropriate boundary condition is zero normal flux density on simply connected superconducting surfaces.
- This condition can be applied implicitly by choosing the relatively permeability of the superconductor to be nearly zero ($\mu_r << 1$).
- For hollow superconductors, the appropriate boundary condition depends on whether the superconductor is field cooled or cooled in zero magnetic field.

Superconducting strip in an external field B-field

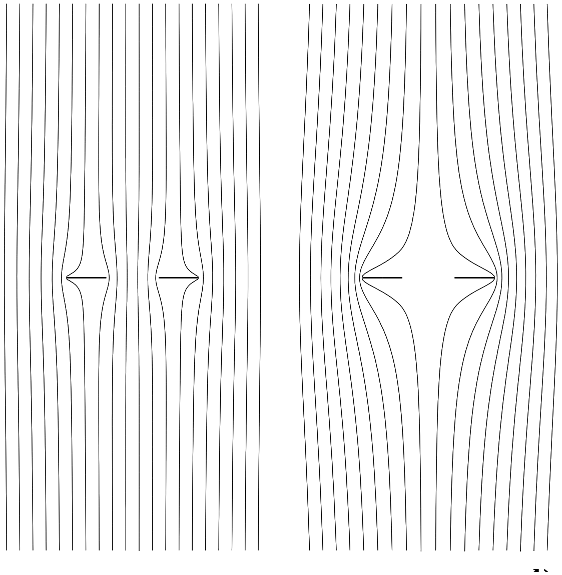
- A superconducting strip can be modeled as a single boundary with zero normal magnetic field



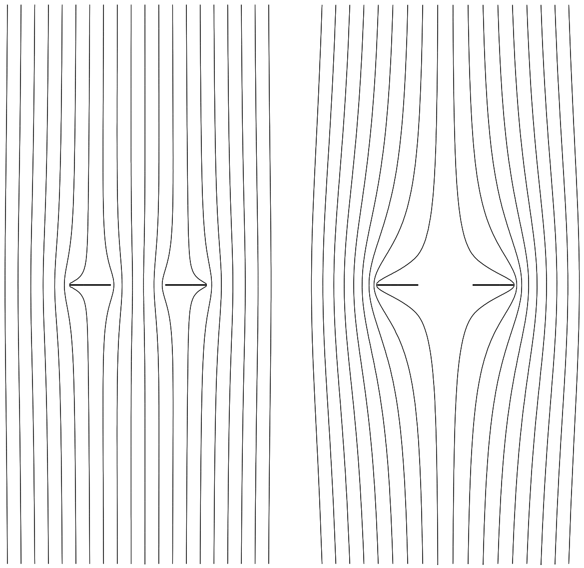
Superconducting Sphere in an External B-field

- Modeled using (1) near zero permeability (2) boundary conditions
- Once the field is calculated, the supercurrent density at the surface of the superconductor may be determined by the discontinuity in the tangential component of the field strength H_t

Hollow Superconducting Shells

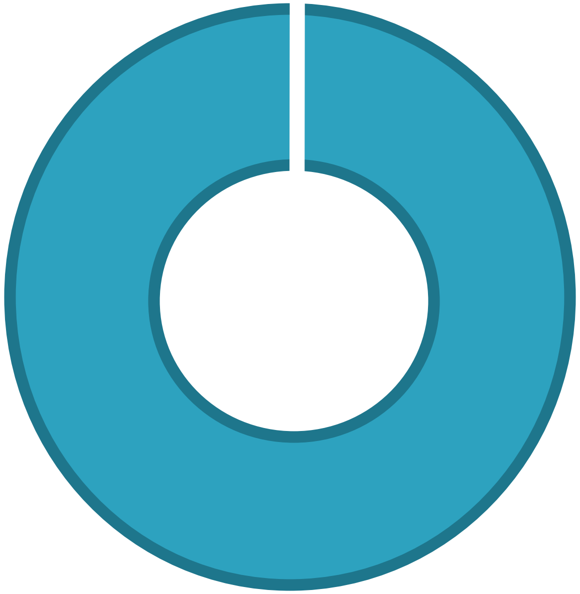


Field-Cooled (FC) boundary condition: normal B equal zero on the superconductor
– flux penetrates the opening of the superconductor

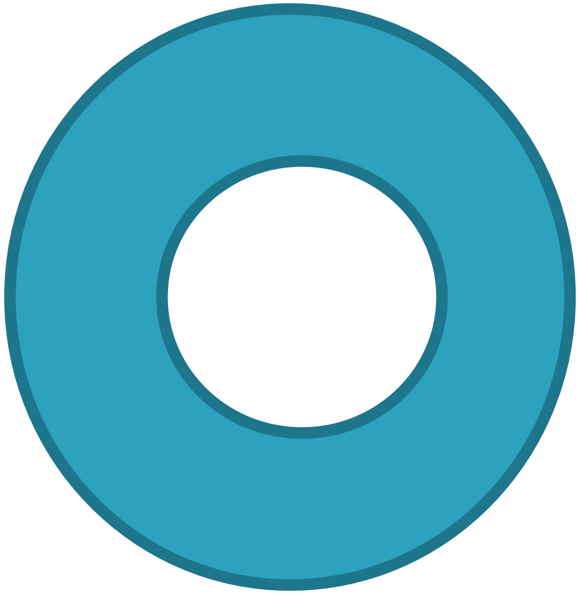


Zero-Field-Cooled (ZFC) boundary condition: zero vector potential specified on the superconductor – flux is expelled from the opening

Superconducting Rings (top view)



Flux Focuser
(normal B =0)



Continuous Ring
(FC: normal B =0)
(ZFC: A = 0)

$$\Phi = \iint_{\text{surf}} B \cdot da = \oint_{\Gamma} A \cdot d\ell$$

Calculation of Inductance

- The inductance L of a superconductor is calculated from

$$\Phi_{\text{app}} = LI$$

Applied Flux

Total supercurrent

$$\Phi_{\text{app}} = \iint_{\text{surf}} \mathbf{B} \cdot d\mathbf{a}$$

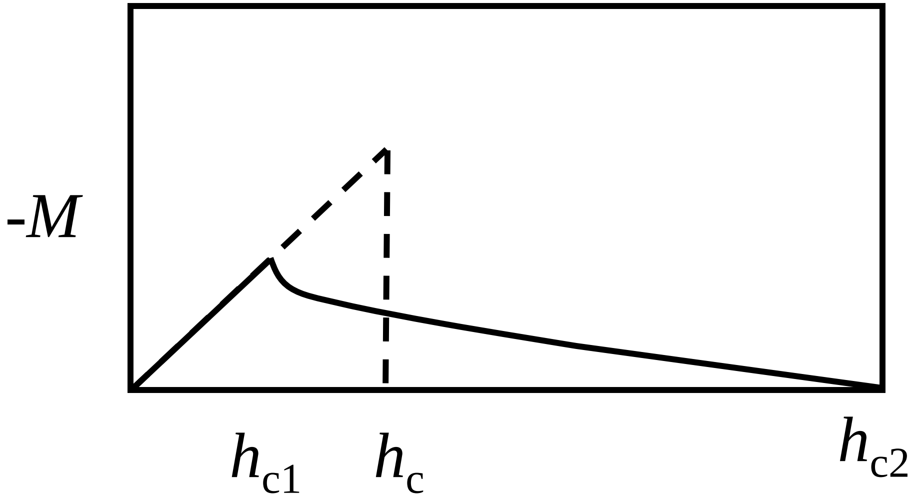
$$\mu_0 I = \oint_{\Gamma} \mathbf{B} \cdot d\ell$$

Type I and Type II Superconductivity

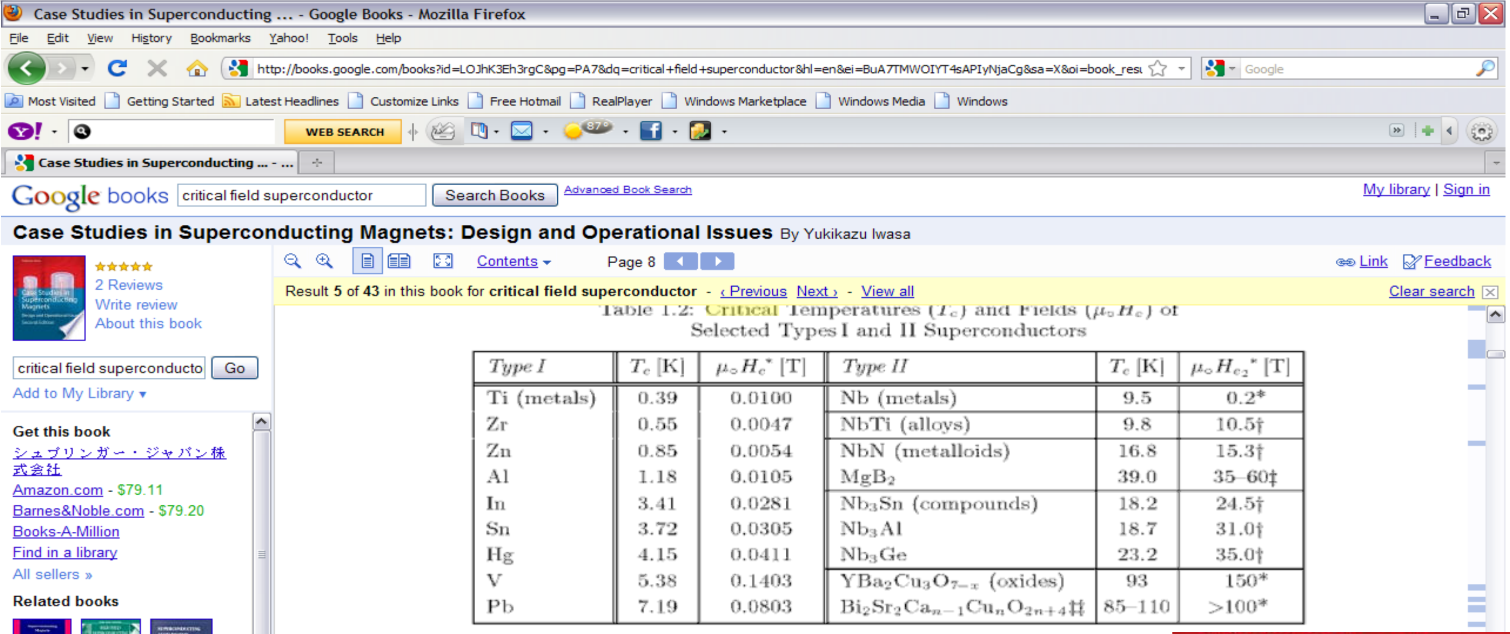
- Type-I superconductors, such as lead, become normal in magnetic fields greater than the thermodynamic critical field h_c which decreases with increasing temperature.

- Type-II superconductors such as Nb_3Sn are characterized by two critical fields h_{c1} and h_{c2}. Flux is expelled from the superconductor below h_{c1} and the sample becomes normal above h_{c2}.

Modeling nonlinear B-H characteristics



Magnetization curves for Type I (----) and
Type II (——)superconductors



critical field superconductor

Case Studies in Superconducting Magnets: Design and Operational Issues By Yukikazu Iwasa

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Table 1.2: Critical Temperatures (T_c) and Fields ($\mu_\circ H_c$) of Selected Types I and II Superconductors

Type I	T_c [K]	$\mu_\circ H_c{}^*$ [T]	*Type II*	T_c [K]	$\mu_\circ H_{c_2}{}^*$ [T]
Ti (metals)	0.39	0.0100	Nb (metals)	9.5	0.2*
Zr	0.55	0.0047	NbTi (alloys)	9.8	10.5†
Zn	0.85	0.0054	NbN (metalloids)	16.8	15.3†
Al	1.18	0.0105	MgB_2	39.0	35–60‡
In	3.41	0.0281	Nb_3Sn (compounds)	18.2	24.5†
Sn	3.72	0.0305	Nb_3Al	18.7	31.0†
Hg	4.15	0.0411	Nb_3Ge	23.2	35.0†
V	5.38	0.1403	$YBa_2Cu_3O_{7-x}$ (oxides)	93	150*
Pb	7.19	0.0803	$Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$‡‡	85–110	>100*

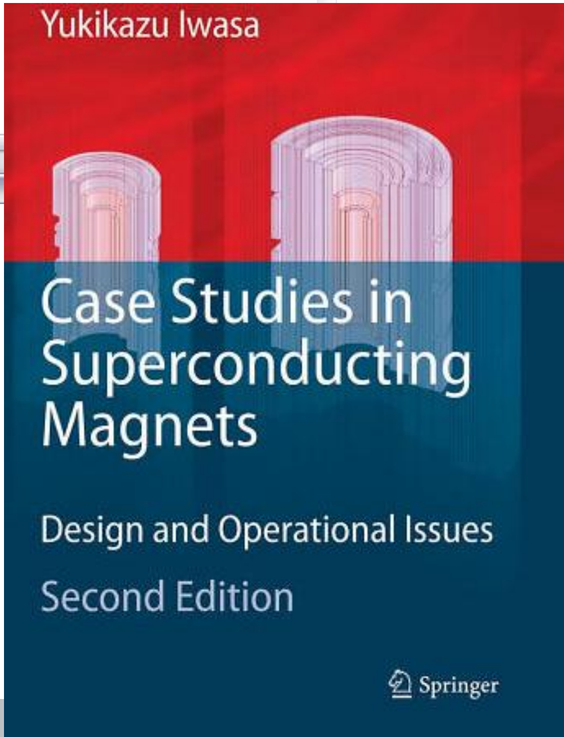
* 0 K, estimated.

† 4.2 K, measured.

‡ 4.2 K, estimated (35 T, ∥ field, 60 T, ⊥

‡‡ $n=2$, Bi2212; $n=3$, Bi2223.

$$h_c(T)=h_0\left[1-\left(\frac{T}{T_c}\right)^2\right]$$



Yukikazu Iwasa

Case Studies in Superconducting Magnets

Design and Operational Issues

Second Edition

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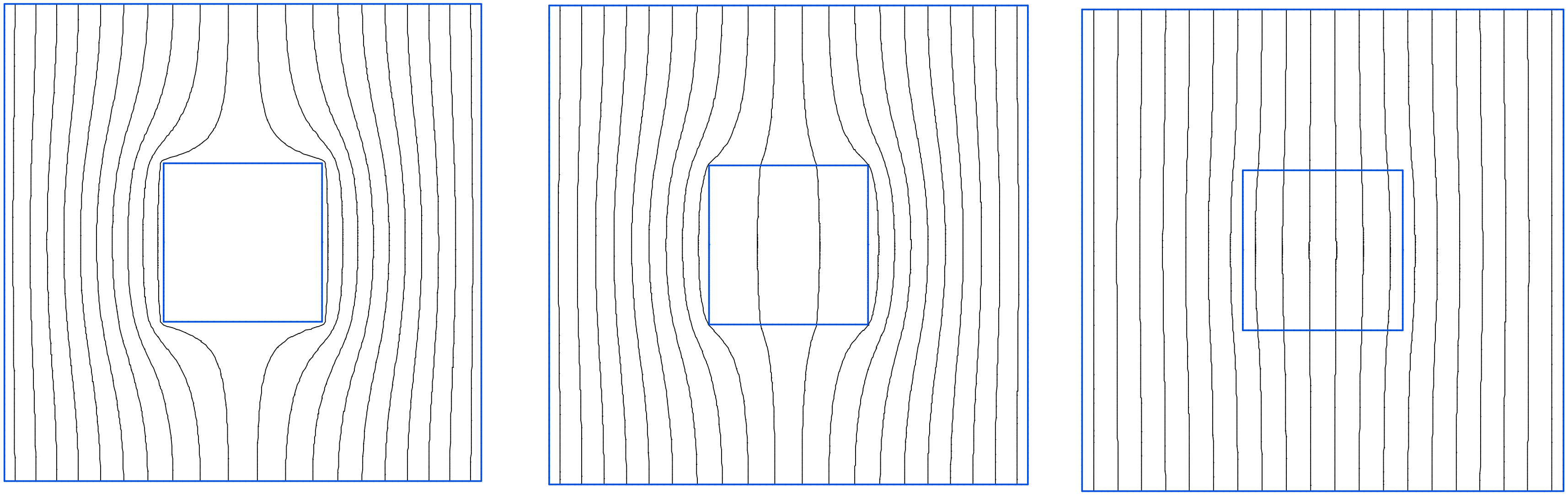
Modaeling Field Penetration in Superconductors



(a)

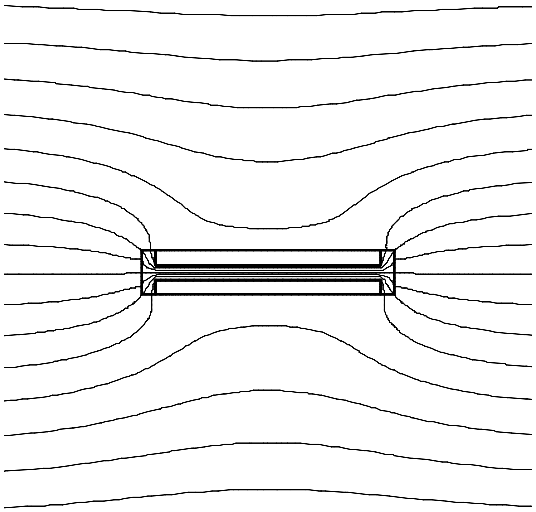
(b)

(c)

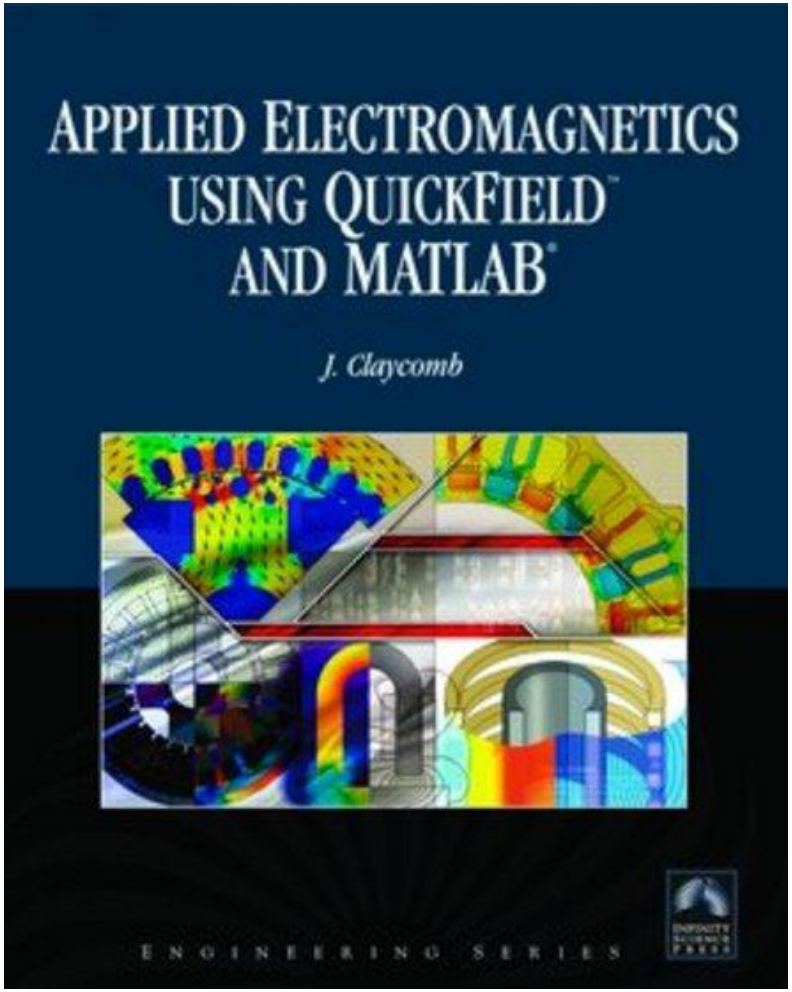
Flux penetration into a superconductor with a nonlinear B-H curve for

(a) B=0.07 T (b) B=0.2 T (c) B= 0.7 T

Layered Superconducting and Permeable Shields



Permeable plate surrounded by two superconducting plates in a transverse B-field



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