USPAS Accelerator Physics 2013
Duke University

Magnets and Magnet Technology

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Outline

- Section 4.1: Back to Maxwell
  - Parameterizing fields in accelerator magnets
  - Symmetries, comments about magnet construction
- Sections 4.2-3: Relating currents and fields
  - Equipotentials and contours, dipoles and quadrupoles
  - Thin magnet kicks and that ubiquitous rigidity
  - Complications: hysteresis, end fields
- Section 4.4: More details about dipoles
  - Sector and rectangular bends; edge focusing
- Extras: Superconducting magnets
  - RHIC, LHC, the future
- Section 4.5: Ideal Solenoid (homework!)
Other References

- Magnet design and a construction is a specialized field all its own
  - Electric, Magnetic, Electromagnetic modeling
    - 2D, 3D, static vs dynamic
  - Materials science
    - Conductors, superconductors, ferrites, superferrites
  - Measurements and mapping
    - e.g. g-2 experiment: 1 PPM field uniformity, 14m SC dipole

- Entire USPAS courses have been given on just superconducting magnet design
    (Ramesh Gupta and Animesh Jain, BNL)
EM/Maxwell Review I

- Recall our relativistic Lorentz force

\[
\frac{d(\gamma m \vec{v})}{dt} = q \left( \vec{E} + \vec{v} \times \vec{B} \right)
\]

- For large $\gamma$ common in accelerators, magnetic fields are much more effective for changing particle momenta

- Can mostly separate E (RF, septa) and B (DC magnets)
  - Some places you can’t, e.g. plasma wakefields, betatrons

- Easiest/simplest: magnets with constant B field
  - Constant-strength optics
    - Most varying B field accelerator magnets change field so slowly that E fields are negligible
    - Consistent with assumptions for “standard canonical coordinates”, p 49 Conte and MacKay
EM/Maxwell Review II

- Maxwell’s Equations for $\vec{B}$, $\vec{H}$ and magnetization $\vec{M}$ are

$$\nabla \cdot \vec{B} = 0 \quad \nabla \times \vec{H} = \vec{j} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} = \vec{j} \quad \vec{H} \equiv \vec{B}/\mu - \vec{M}$$

- A magnetic vector potential $\vec{A}$ exists

$$\vec{B} = \nabla \times \vec{A} \quad \text{since} \quad \nabla \cdot \nabla \times \vec{A} = 0$$

- Transverse 2D ($B_z=H_z=0$), paraxial approx ($p_{x,y}<<p_0$)
- Away from magnet coils ($\vec{j} = 0$, $\vec{M} = 0$)
  - Simple homogeneous differential equations for fields

$$\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0 \quad \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} = 0$$
Parameterizing Solutions

\[
\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0 \quad \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} = 0
\]

- What are solutions to these equations?
  - **Constant field:** \( \vec{B} = B_x x^0 \hat{x} + B_y y^0 \hat{y} \)
    - Dipole fields, usually either only \( B_x \) or \( B_y \)
    - 360 degree (2 \( \pi \)) rotational “symmetry”
  - **First order field:** \( \vec{B} = (B_{xx} x + B_{xy} y)\hat{x} + (B_{yx} x + B_{yy} y)\hat{y} \)
    - Maxwell gives \( B_n = B_{xx} = -B_{yy} \) and \( B_s = B_{xy} = B_{yx} \)
    \[
    \vec{B} = B_n (x\hat{x} - y\hat{y}) + B_s (x\hat{y} + y\hat{x})
    \]
    - Quadrupole fields, either normal \( B_n \) or skew \( B_s \)
    - 180 degree (\( \pi \)) rotational symmetry
    - 90 degree rotation interchanges normal/skew
  - **Higher order…**
Visualizing Fields I

- Dipole and “skew” dipole
  - $n = 1$

- Quad and skew quad
  - $n = 1$
  - $n = 2$

- Sextupole and skew sextupole
  - $n = 3$

T. Satogata / January 2013
USPAS Accelerator Physics
LHC dipole: $B_y$ gives horizontal bending

LEP quadrupole: $B_y$ on x axis, $B_x$ on y axis

- Horizontal focusing=vertical defocusing or vice-versa
- No coupling between horizontal/vertical motion
  - Note the nice “harmonic” field symmetries
General Multipole Field Expansions

- Rotational symmetries, cylindrical coordinates
  - Power series in radius $r$ with angular harmonics in $\theta$
    
    \[
    x = r \cos \theta \quad y = r \sin \theta
    \]

    \[
    B_y = B_0 \sum_{n=0}^{\infty} \left( \frac{r}{a} \right)^n (b_n \cos n\theta - a_n \sin n\theta)
    \]

    \[
    B_x = B_0 \sum_{n=0}^{\infty} \left( \frac{r}{a} \right)^n (a_n \cos n\theta + b_n \sin n\theta)
    \]

- Need “reference radius” $a$ (to get units right)
- $(b_n, a_n)$ are called (normal, skew) **multipole coefficients**
- We can also write this succinctly using de Moivre as

    \[
    B_x - iB_y = B_0 \sum_{n=0}^{\infty} (a_n - ib_n) \left( \frac{x + iy}{a} \right)^n
    \]
But Do These Equations Solve Maxwell?

- Yes ☺ Convert Maxwell’s eqns to cylindrical coords
  \[
  \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0 \quad \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} = 0
  \]
  \[
  \frac{\partial (\rho B_{\rho})}{\partial \rho} + \frac{\partial B_{\theta}}{\partial \theta} = 0 \quad \frac{\partial (\rho B_{\theta})}{\partial \rho} - \frac{\partial B_{\rho}}{\partial \theta} = 0
  \]

- Aligning r along the x-axis it’s easy enough to see
  \[
  \frac{\partial}{\partial x} \Rightarrow \frac{\partial}{\partial r} \quad \frac{\partial}{\partial y} \Rightarrow \frac{1}{r} \frac{\partial}{\partial \theta}
  \]

- In general it’s (much, much) more tedious but it works
  \[
  \frac{\partial r}{\partial x} = \frac{1}{\cos \theta}, \quad \frac{\partial \theta}{\partial x} = -\frac{1}{r \sin \theta}, \quad \frac{\partial r}{\partial y} = \frac{1}{\sin \theta}, \quad \frac{\partial \theta}{\partial y} = \frac{1}{r \cos \theta}
  \]
  \[
  \frac{\partial B_x}{\partial x} = \frac{\partial B_x}{\partial r} \frac{\partial r}{\partial x} + \frac{\partial B_x}{\partial \theta} \frac{\partial \theta}{\partial x} \ldots
  \]
Multipoles

(b,a)ₙ “unit” is $10^{-4}$ (natural scale)  \( (b,a)_n \text{ (US)} = (b,a)_{n+1} \)

<table>
<thead>
<tr>
<th>coefficient</th>
<th>multipole</th>
<th>field</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_0 )</td>
<td>normal dipole</td>
<td>( B_y = B_0 b_0 )</td>
<td>horz. bending</td>
</tr>
<tr>
<td>( a_0 )</td>
<td>skew dipole</td>
<td>( B_x = B_0 a_0 )</td>
<td>vert. bending</td>
</tr>
</tbody>
</table>
| \( b_1 \)   | normal quadrupole | \( B_x = B_0 \left( \frac{r}{a} \right) b_1 \sin \theta = B_0 \left( \frac{y}{a} \right) b_1 \)
\( B_y = B_0 \left( \frac{r}{a} \right) b_1 \cos \theta = B_0 \left( \frac{z}{a} \right) b_1 \) | focusing defocusing |
| \( a_1 \)   | skew quadrupole   | \( B_x = B_0 \left( \frac{r}{a} \right) a_1 \cos \theta = B_0 \left( \frac{z}{a} \right) a_1 \)
\( B_y = -B_0 \left( \frac{r}{a} \right) a_1 \sin \theta = -B_0 \left( \frac{y}{a} \right) a_1 \) | coupling            |
| \( b_2 \)   | normal sextupole  | \( B_x = B_0 \left( \frac{r}{a} \right)^2 b_2 \sin(2\theta) \)
\( B_y = B_0 \left( \frac{r}{a} \right)^2 b_1 \cos(2\theta) \) | nonlinear!          |

Elettra magnets
Multipole Symmetries

- Dipole has $2\pi$ rotation symmetry (or $\pi$ upon current reversal)
- Quad has $\pi$ rotation symmetry (or $\pi/2$ upon current reversal)
- k-pole has $2\pi/k$ rotation symmetry upon current reversal
- We try to enforce symmetries in design/construction
  - Limits permissible magnet errors
  - Higher order fields that obey main field symmetry are called allowed multipoles

RCMS half-dipole laminations (W. Meng, BNL)

“H style dipoles” (with focusing like betatron)
Multipole Symmetries II

- So a dipole (n=0, 2 poles) has allowed multipoles:
  - Sextupole (n=2, 6 poles), Decapole (n=4, 10 poles)...
- A quadrupole (n=1, 4 poles) has allowed multipoles:
  - Dodecapole (n=5, 12 poles), Twenty-pole (n=9, 20 poles)...
- General allowed multipoles: $(2k+1)(n+1)-1$
  - Or, more conceptually, $(3,5,7,...)$ times number of poles
- Other multipoles are forbidden by symmetries
  - Smaller than allowed multipoles, but no magnets are perfect
    - Large measured forbidden multipoles mean fabrication or fundamental design problems!
- Better magnet pole face quality with punched laminations
- Dynamics are usually dominated by lower-order multipoles
4.2: Equipotentials and Contours

Field-defining Iron (high permeability)

Current carrying conductors (coils)

Field lines perpendicular to iron surface

4.2: Equipotentials and Contours

- Let's get around to designing some magnets
  - Conductors on outside, field on inside
  - Use high-permeability iron to shape fields: iron-dominated
    - Pole faces are very nearly equipotentials, $\perp$ B,H field
    - We work with a magnetostatic scalar potential $\Psi$
    - B, H field lines are $\perp$ to equipotential lines of $\Psi$

$$ \vec{H} = \vec{\nabla} \Psi $$

$$ \Psi = \sum_{n=0}^{\infty} \frac{a}{n+1} \left( \frac{r}{a} \right)^{n+1} [F_n \cos((n + 1)\theta) + G_n \sin((n + 1)\theta)] $$

where $G_n \equiv B_0 b_n / \mu_0$, $F_n \equiv B_0 a_n / \mu_0$

This comes from integrating our B field expansion.
Let's look at normal multipoles $G_n$ and pole faces…
For general $G_n$ normal multipoles (i.e. for $b_n$)

$$\Psi(\text{equipotential for } b_n) \propto r^{n+1} \sin[(n + 1)\theta] = \text{constant}$$

- **Dipole** ($n=0$): $\Psi(\text{dipole}) \propto r \sin \theta = y$
  - Normal dipole pole faces are $y=\text{constant}$
- **Quadrupole** ($n=1$):
  $$\Psi(\text{quadrupole}) \propto r^2 \sin(2\theta) = 2xy$$
  - Normal quadrupole pole faces are $xy=\text{constant}$ (hyperbolic)

- So what conductors and currents are needed to generate these fields?
Dipole Field/Current

- Use Ampere’s law to calculate field in gap
  - N “turns” of conductor around each pole
  - Each turn of conductor carries current I

- Field integral is through N-S poles and (highly permeable) iron (including return path)

\[ 2NI = \int \vec{H} \cdot d\vec{l} = 2aH \quad \Rightarrow \quad H = \frac{NI}{a} \quad , \quad B = \frac{\mu_0 NI}{a} \]

- NI is in “Amp-turns”, \( \mu_0 \sim 1.257 \text{ cm-G/A} \)
  - So a=2cm, B=600G requires NI~955 Amp-turns

\[ \Delta x' = \frac{BL}{(B \rho)} \]
Wait, What’s That $\Delta x'$ Equation?

$\Delta x' = \frac{BL}{(B\rho)}$  

← Field, length: Properties of magnet  

← **Rigidity**: property of beam (really $p/q$!)

- This is the angular transverse kick from a thin hard-edge dipole, like a dipole corrector
  - Really a change in $p_x$ but paraxial approximation applies
  - The $B$ in $(B\rho)$ is not necessarily the main dipole $B$
  - The $\rho$ in $(B\rho)$ is not necessarily the ring circumference/2$\pi$
  - And neither is related to this particular dipole kick!

\[ \Delta x' \approx \frac{\Delta p_x}{p} = \frac{qLB_y}{p} = \frac{B_yL}{(B\rho)} \]
Quadrupole Field/Current

- Use Ampere’s law again
  - Easiest to do with magnetic potential $\Psi$, encloses $2NI$

$$\Psi(a, \theta) = \frac{a B_0 b_1}{2 \mu_0} \sin(2\theta)$$

$$2NI = \oint \vec{H} \cdot d\vec{l} = \Psi(a, \pi/4) - \Psi(a, -\pi/4) = \frac{aB_0b_1}{\mu_0}$$

$$\Psi = NI \sin(2\theta) = \frac{2NI}{a^2} xy$$

$$\vec{H} = \nabla \Psi = \frac{2NI}{a^2} (y\hat{x} + x\hat{y}) \quad \vec{B} = \frac{2\mu_0 NI}{a^2} (y\hat{x} + x\hat{y})$$

- Quadrupole strengths are expressed as transverse gradients

$$B' \equiv \frac{\partial B_y}{\partial x} \bigg|_{y=0} = \frac{\partial B_x}{\partial y} = \frac{2\mu_0 NI}{a^2} \quad \Delta x' = \frac{B' L}{(B \rho)} x$$

(NB: Be careful, ‘ has different meaning in $B'$, $B''$, $B'''$….)
Quadrupole Transport Matrix

- Paraxial equations of motion for constant quadrupole field

\[
\frac{d^2x}{ds^2} + kx = 0 \quad \frac{d^2y}{ds^2} - ky = 0 \quad s \equiv \beta ct
\]

\[
k \equiv \frac{B'}{(B\rho)} = \frac{2\mu_0 NI}{a^2} \left( \frac{q}{p} \right)
\]

- Integrating over a magnet of length L gives (exactly)

For Focusing Quadrupole:

\[
\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos(L\sqrt{k}) & \frac{1}{\sqrt{k}} \sin(L\sqrt{k}) \\ -\sqrt{k} \sin(L\sqrt{k}) & \cos(L\sqrt{k}) \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} = M_F \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}
\]

For Defocusing Quadrupole:

\[
\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} \cosh(L\sqrt{k}) & \frac{1}{\sqrt{k}} \sinh(L\sqrt{k}) \\ \sqrt{k} \sinh(L\sqrt{k}) & \cosh(L\sqrt{k}) \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix} = M_D \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}
\]
Thin Quadrupole Transport Matrix

Focusing Quadrupole
\[
\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos(L\sqrt{k}) & \frac{1}{\sqrt{k}} \sin(L\sqrt{k}) \\ -\sqrt{k} \sin(L\sqrt{k}) & \cos(L\sqrt{k}) \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} = M_F \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}
\]

Defocusing Quadrupole
\[
\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} \cosh(L\sqrt{k}) & \frac{1}{\sqrt{k}} \sinh(L\sqrt{k}) \\ \sqrt{k} \sinh(L\sqrt{k}) & \cosh(L\sqrt{k}) \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix} = M_D \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}
\]

- Quadrupoles are often “thin”
  - Focal length is much longer than magnet length
- Then we can use the thin-lens approximation $\sqrt{kL} \ll 1$

Thin quadrupole approximation
\[
M_{F,D} = \begin{pmatrix} 1 & 0 \\ \mp kL & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \mp \frac{1}{f} & 1 \end{pmatrix}
\]

where $f=1/(kL)$ is the quadrupole focal length

\[
\Delta x' = \frac{B'L}{(B\rho)} x
\]
Higher Orders

- We can follow the full expansion for 2(n+1)-pole:

\[ \Psi_n = NI \left( \frac{r}{a} \right)^{n+1} \sin((n + 1) \theta) \]

\[ H_x = (n + 1) \frac{NI}{a} \left( \frac{r}{a} \right)^n \sin n\theta \]

\[ H_y = (n + 1) \frac{NI}{a} \left( \frac{r}{a} \right)^n \cos n\theta \]

- For the sextupole (n=2) we find the nonlinear field as

\[ \vec{B} = \frac{3\mu_0 NI}{a^3} [2xy\hat{x} + (x^2 + y^2)\hat{y}] \]

- Now define a strength as an n\textsuperscript{th} derivative

\[ B'' = \frac{\partial^2 B_y}{\partial x^2} \bigg|_{y=0} = \frac{6\mu_0 NI}{a^3} \]

\[ \Delta x' = \frac{1}{2} \frac{B'' L}{(B \rho)} (x^2 + y^2) \]

(NB: Be careful, ‘ has different meaning in B’, B”, B”’… )
Magnets with variable current carry “memory”

Hysteresis is quite important in iron-dominated magnets

Usually try to run magnets “on hysteresis”

- e.g. always on one side of hysteresis loop
- Large spread at large field (1.7 T): saturation
- Degaussing
End Fields

- Magnets are not infinitely long: ends are important!
  - Conductors: where coils usually come in and turn around
  - Longitudinal symmetries break down
  - Sharp corners on iron are first areas to saturate
  - Usually a concern over distances of ±1-2 times magnet gap
    - A big deal for short, large-aperture magnets; ends dominate!

- Solution: simulate… a lot
  - Test prototypes too
  - Quadratic end chamfer eases sextupoles from ends (first allowed harmonic of dipole)

- More on dipole end focusing…

PEFP prototype magnet (Korea)
9 cm gap, 1.4m long
4.4: Dipoles, Sector and Rectangular Bends

- Sector bend (sbend)
  - Beam design entry/exit angles are $\perp$ to end faces
  - Simpler to conceptualize, but harder to build

- Rectangular bend (rbend)
  - Beam design entry/exit angles are half of bend angle
  - Easier to build, but must include effects of edge focusing
You did this earlier (eqn 3.109 of text)

\[
M_{\text{sector dipole}} = \begin{pmatrix}
\cos \theta & \rho \sin \theta & 0 & 0 & 0 & \rho(1 - \cos \theta) \\
-\frac{1}{\rho} \sin \theta & \cos \theta & 0 & 0 & \sin \theta & 0 \\
0 & 0 & 1 & \rho \theta & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
-\sin \theta & -\rho(1 - \cos(\theta)) & 0 & 0 & 1 & -\rho(\theta - \sin \theta) \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}
\]

Has all the “right” behaviors

- But what about rectangular bends?
Dipole End Angles

- We treat general case of symmetric dipole end angles
  - Superposition: looks like wedges on end of sector dipole
  - Rectangular bends are a special case
The edge focusing calculation requires the kick from a thin wedge

\[ \Delta x' = \frac{B_z L}{(B \rho)} \]

What is L? (distance in wedge)

\[ \tan \left( \frac{\alpha}{2} \right) = \frac{L/2}{x} \]

\[ L = 2x \tan \left( \frac{\alpha}{2} \right) \approx x \tan \alpha \]

So

\[ \Delta x' = \frac{B_z \tan \alpha}{(B \rho)} x \approx \frac{\tan \alpha}{\rho} x \]

Here \( \rho \) is the curvature for a particle of this momentum!!
Dipole Matrix with Ends

- The matrix of a dipole with thick ends is then

\[
M_{\text{sector dipole}}(x, x', \delta) = \begin{pmatrix}
\cos \theta & \rho \sin \theta & \rho (1 - \cos \theta) \\
-\frac{1}{\rho} \sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[
M_{\text{end lens}} = \begin{pmatrix}
1 & 0 & 0 \\
\frac{\tan \alpha}{\rho} & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[
M_{\text{edge-focused dipole}} = M_{\text{end lens}} M_{\text{sector dipole}} M_{\text{end lens}}
\]

\[
M_{\text{edge-focused dipole}} = \begin{pmatrix}
\frac{\cos(\theta - \alpha)}{\cos \alpha} & \rho \sin \theta & \rho (1 - \cos \theta) \\
-\frac{\sin(\theta - 2\alpha)}{\rho \cos^2 \alpha} & \frac{\cos(\theta - \alpha)}{\cos \alpha} & \frac{\sin(\theta - \alpha) + \sin \alpha}{\cos \alpha} \\
0 & 0 & 1
\end{pmatrix}
\]

- Rectangular bend is special case where \( \alpha = \theta/2 \)
End Field Example (from book)

- p. 85 of text
- Field lines go from $-y$ to $+y$ for a positively charged particle
  - $B_x < 0$ for $y > 0$; $B_x > 0$ for $y < 0$
    - Net focusing!
  - Field goes like $\sin(\alpha)$
    - get $\cos(\alpha)$ from integral length

\[
\Delta y' = \frac{B_x l_{\text{fringe}}}{(B \rho)}
\]
Other Familiar Dipoles

- Weaker, cheaper dipoles can be made by conforming coils to a beam-pipe (no iron)
- Relatively inexpensive, but not very precise
  - Field quality on the order of percent
Normal vs Superconducting Magnets

- LEP quadrupole magnet (NC)
  - Note high field strengths (red) where flux lines are densely packed together
- LHC dipole magnets (SC)
RHIC Dipole/Quadrupole Cross Sections

RHIC $\cos(\theta)$-style superconducting magnets and yokes

- NbTi in Cu stabilizer, iron yokes, saturation holes
- Full field design strength is up to 20 MPa (3 kpsi)
- 4.5 K, 3.45 Tesla
Superconducting cables: NbTi in Cu matrix

- Single 5 um filament at 6T carries ~50 mA of current
- Strand has 5-10k filaments, or carries 250-500 A
- Magnet currents are often 5-10 kA: 10-40 strands in cable
  - Balance of stresses, compactable to stable high density
Superconducting Dipole Magnet Comparison

- Tevatron 4T, 90mm
- HERA 4.7T, 75 mm
- SSC 6.8 T, 50 mm
- LHC 8.36T, 56mm
- RHIC 3.4T, 80mm
The 15-m long LHC cryodipole

1.9 K, 8.36 T
(~5 T achieved)
Superconducting Magnet Transfer Function

- Transfer function: relationship between current/field
  - Persistent currents: surface currents during magnet ramping
Quenching

- **Magnetic stored energy**

\[ E = \frac{B^2}{2\mu_0} \]

\[ B = 5 \text{ T}, \quad E = 10^7 \text{ J/m}^3 \]

- **LHC dipole**

\[ E = \frac{LI^2}{2} \]

\[ L = 0.12 \text{ H}, \quad I = 11.5 \text{ kA} \]

\[ \Rightarrow E = 7.8 \times 10^6 \text{ J} \]

22 ton magnet

\[ \Rightarrow \text{Energy of 22 tons, } v = 92 \text{ km/hr!} \]
Quench Process

- Resistive region starts somewhere in the winding at a point: A problem!
  - Cable/insulation slipping
  - Inter-cable short; insulation failure
- Grows by thermal conduction
- Stored energy $\frac{1}{2}LI^2$ of the magnet is dissipated as heat
- Greatest integrated heat dissipation is at localized point where the quench starts
- Internal voltages much greater than terminal voltage ($= V_{cs}$ current supply)
  - Can profoundly damage magnet
  - Quench protection is important!

Martin Wilson, JUAS Feb 2006
Quench Training

- Intentionally raising current until magnet quenches
  - Later quenches presumably occur at higher currents
    - Compacts conductors in cables, settles in stable position
  - Sometimes necessary to achieve operating current

"Energy Upgrade as Regards Quench Performance", W.W. MacKay and S. Tepikian, on class website
Direct-Wind Superconducting Magnets (BNL)

- 6T Iron-free (superconducting)
- Solid state coolers (no Helium)
- Field containment (LC magnet)
- “Direct-wind” construction

World’s first “direct wind” coil machine at BNL

Linear Collider magnet
FELs: Wigglers and Undulators

- Used to produce synchrotron radiation for FELs
  - Often rare earth permanent magnets in Halbach arrays
  - Adjust magnetic field intensity by moving array up/down
  - **Undulators**: produce nm wavelength FEL light from ~cm magnetic periods ($\gamma^2$ leverage in undulator equation)
    - Narrow band high spectral intensity
  - **Wigglers**: higher energy, lower flux, more like dipole synchrotron radiation
    - More about synchrotron light and FELs etc next week
    - LCLS: 130+m long undulator!
Feedback to Magnet Builders


FEEDBACK BETWEEN ACCELERATOR PHYSICISTS AND MAGNET BUILDERS

S. PEGGS

Relativistic Heavy Ion Collider, Brookhaven National Laboratory,
Upton, New York 11973, USA

Submitted to the proceedings of the LHC Single Particle Dynamics Workshop, Montreux, 1996.

1 PHILOSOPHY

Our task is not to record history but to change it. K. Marx (paraphrased)

How should Accelerator Physicists set magnet error specifications? In a crude social model, they place tolerance limits on undesirable nonlinearities and errors (higher order harmonics, component alignments, et cetera). The Magnet Division then goes away for a suitably lengthy period of time, and comes back with a working magnet prototype that is reproduced in industry.