NEW DEVELOPMENTS IN LIGHT SOURCE MAGNET DESIGN

Soren Prestemon
Steve Marks
Ross Schlueter

Lawrence Berkeley National Laboratory
Outline

- Introduction
- Magnet system developments
  - Combined function magnets
  - Superbends
  - Permanent magnet systems
    - Chicane
- Insertion device developments
  - Cryogenic in-vacuum
  - Superconducting devices
Introduction

- Developments in light source magnet design are occurring on a number of fronts:
  - Lattice magnets
    - Combined function designs
    - Permanent magnet systems
    - Superconducting magnet systems
  - Kicker magnets (single-bunch….)
  - Insertion devices
    - Novel spectral characteristics
    - Dynamic multipole compensation
    - Cryogenic permanent magnet
    - Superconducting (planar and variable polarization)

Some discussion here...

And more discussion here…

S. Prestemon, LBL       PAC 2007
Lattice magnet developments

- Trend is to optimally combine magnet functions:
  - reduce space requirements of lattice magnets
  - Improve overall efficiency
  - Minimize overall magnet cost

- Industry has provided cost effective solutions:
  - Examples – Soleil (Paris), Canadian Light Source, Australian Light Source, etc
  - Improvements in machining and fabrication tolerances, measurement and quality control capabilities
ALS Superbends

- Stronger field, shorter length:
  - Higher critical photon energy – key for hard x-ray research
- Three-fold symmetry at ALS
- First operation of superconducting lattice magnet on a 3rd generation ring
- Operating since 2001
  - Excellent operational record


Fig. 1. Superbend cold mass assembly: 1 – superconducting coils with steel poles, 2 – laminated steel yoke, 3 – suspension straps, 4 – LHe vessel, 5 – LN2 vessel, 6 – HTS leads, 7 – cryocooler, 8 – 50 K thermal connection, 9 – 4 K thermal connection, 10 – cooldown tube, 11 – warmup heater.
Example of combined function magnet

- **ALS sextupole**
  - “Traditional” sextupole with additional capabilities:
    - Vertical steering
    - Horizontal steering
    - Skew quadrupole
  - Designed using Halbach perturbation theory

- Similar concept used in Soleil sextupoles

- MaxLab proposes combined multipole magnets for the MAX IV lattice (**quadrupoles** with **sextupole** and possibly **octupole** content)
  - May serve as a template for future light source lattice designs

Permanent magnets for lattice functions

- The trend in Light Sources is towards full-energy injection and in many cases top-off injection
  - Can consider “unconventional” approaches
    - Permanent magnets for the lattice!?
      - Idea not new:
        - “Workshop on Permanent Magnet Storage Rings”, LBL, 1994
        - Used for antiproton storage rings (Fermilab recycler)
  - Advantages
    - Significant reduction in infrastructure (water, power,…)
    - Stable operation – no beam loss due to power outage (motivation for e⁺ ring)
    - May provide enhanced performance if apertures can be made small
  - Issues:
    - Radiation damage mitigation
    - Field control (perturbation level)
    - Field error mitigation
The ALS now uses a pure permanent magnet for the chicanes
- No hysteresis
- Control of multipoles – excellent combined-function capabilities
- Scalable strength, built-in capability for fabrication and installation error compensation

Insertion device developments

- Excellent review by J. Chavanne and P. Elleaume, EPAC 2006
- Recent workshop on ID developments, sponsored by B. Diviacco, ELETTRA (Nov. 2006)
  - Progress on devices with novel spectral properties
  - Dynamic multipole compensation
  - Research on FEL application-specific issues
  - New results in cryogenic in-vacuum permanent magnet development
  - New results in superconducting insertion devices – planar and variable polarization
Devices with novel spectral properties

- Variable polarization devices are becoming the ID of choice for soft x-ray applications
  - Also becoming more common on high-energy rings
  - Some companies developing fabrication expertise

- Quasi-periodic capabilities are intriguing
  - Reduced perturbation of energy states by harmonics transmitted through the monochrometer
  - Can be implemented on variable polarization devices as well

Quasi-periodicity

- Idea: Interlace two periodic devices
  - Modification: interlace two devices with same period, different field strength

Planar:
- B. Diviacco et al, EPAC 1998;
- J. Chavanne et al, EPAC 1998

EPU:
- B. Diviacco, APS Workshop, 2002
EPU accelerator issue: Dynamic multipoles

- Vertical focusing of planar insertion devices is well-known
  - Emanates from $f_z \sim v_x B_z$ off-axis
  - Can be compensated using lattice and/or corrector quadrupoles

- For EPU’s:
  - varying field configurations result in focusing properties that vary with phase shift (i.e. polarization mode)
  - fast field roll-off results in nonlinear focus/defocus properties
  - Noted and evaluated by P. Elleaume et al; detailed solution tested/implemented by J. Bahrdt et al., I. Blomquist, B. Diviacco,…
Example: ALS EPU’s

- ALS has three 50mm period APPLE II’s
- One 90mm device will soon be installed (MERLIN)
- Top-Off will require dynamic multipole correction for reasonable injection efficiency

Dynamic aperture needed for top-off at the ALS
Solution: addition of magnetic correctors

- Magnetic material, correctly dimensioned and located on the different quadrants, can partially compensate the nonlinear effect

*Idea originally proposed by J. Chavanne and P. Elleaume*
Impact of magnetic corrections

- Calculations suggest dynamic aperture is recovered in most polarization modes for the ALS (C. Steier et al., EPAC 2006)
Developments in novel insertion devices

- CIVID developments
- Superconducting undulators
  - Planar
  - Variable polarization

Nice review of progress can be found at http://www.elettra.trieste.it/UM14/
Cryogenic permanent magnet R&D

- Main groups: SPring8, ESRF, Brookhaven
  - Some industrial efforts (e.g. ADC)
  - Prototypes have been built and tested
  - No prototypes have used higher remanence material

- Motivation:
  - Increase in Remanance by as much as ~12%
  - Increase in Coercivity allows use of higher remanance material
  => Theoretical increase of ~30% - motivates research

\[ T. \ Tanaka, \ New \ Frontiers \ in \ ID's, \ ELETTRA, \ Nov. \ 2006 \]
CIVID Issues

- Key concerns:
  - Phase error correction: does room temperature correction apply at cryogenic temperatures?
    - Tentative data from SPring-8: yes
    - Awaiting ESRF confirmation measurements
  - Can enhanced coercivity be leveraged?
    - Cannot bake-out devices! Will devices “Cryopump” at 150K? Can sufficient pumping be provided without baking?

- Note: enhanced coercivity may nevertheless be useful for applications where demagnetization due to thermal / radiation loads is a concern
Superconducting insertion devices

- Many superconducting wigglers are being installed (Canadian Light Source, Brazilian Light Source,…; ALBA planning SC wiggler)
- ANKA has detailed performance data for first NbTi undulator
  - First spectral data (Rossmanith, ASC 2006)
  - Thermal load measurements
- EU funded collaboration (ANKA, MAXLAB, ESRF, ELETTRA) (Rossmanith, New Frontiers in ID’s, ELETTRA, Nov. 2006)
  - Cryogenic systems
  - Magnet measurements
- ANKA proceeding with procurement of a second superconducting undulator; considering Nb₃Sn long-term
- LBL: successful test of a Nb₃Sn prototype
- APS: continuing Nb₃Sn research following collaboration with LBL

R&D issues: 1) Phase error correction
2) Magnetic measurements of cold device
2) Calorimetry for beam-based heating

Excellent case for multi-facility collaborative project!!
**LBL Superconducting undulator prototype**

- Third LBL prototype – reached “short sample”
  - $J_{\text{eng}} = 1760 \text{A/mm}^2$
  - 14.5mm period; would yield $B \sim 1.6 \text{T}$ for a magnetic gap of 6mm

![Graph showing load-line and short-sample data](image)

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Variable polarization superconducting undulators

- Multiple design concepts have been proposed
- Typically do not provide significant field enhancement over permanent magnet devices

Advantages
- No moving parts
- Possibly enhanced spectral control
- Possible enhanced spectral range (period doubling/halving)

Disadvantages
- Superconductors not well-suited for rapid field (polarization) change
- Phase-error correction and field measurement needs to be addressed
Polarization control: LBL SC-EPU concept
Generating variable elliptic polarization

- Add a second 4-quadrant array of such coil-series, offset in z by \( \lambda / 4 \) (coil series \( \alpha \) and \( \beta \)).
- With the following constraints the eight currents are reduced to four independent degrees of freedom:

\[
I_C^\alpha = -I_A^\alpha, \quad I_D^\alpha = -I_B^\alpha \\
I_C^\beta = -I_A^\beta, \quad I_D^\beta = -I_B^\beta
\]

- The \( \alpha \) and \( \beta \) fields are 90° phase shifted, providing full elliptic polarization control via

\[
\vec{B}^\alpha (I_A^\alpha, I_A^\alpha, z), \quad \vec{B}^\beta (I_A^\beta, I_B^\beta, z) :
\]

\[
\begin{pmatrix}
B_x^\alpha \\
B_y^\alpha
\end{pmatrix} = \eta \begin{pmatrix}
\cos(\psi) & -\cos(\psi) \\
\sin(\psi) & \sin(\psi)
\end{pmatrix} \begin{pmatrix}
I_A^\alpha \\
I_B^\alpha
\end{pmatrix} \sin\left(\frac{2\pi z}{\lambda}\right)
\]

\[
\begin{pmatrix}
B_x^\beta \\
B_y^\beta
\end{pmatrix} = \eta \begin{pmatrix}
\cos(\psi) & -\cos(\psi) \\
\sin(\psi) & \sin(\psi)
\end{pmatrix} \begin{pmatrix}
I_A^\alpha \\
I_B^\alpha
\end{pmatrix} \sin\left(\frac{2\pi z}{\lambda} - \frac{\pi}{2}\right)
\]

Note: \( B_{x,y}^a = \sum_n a_{n,x,y} \sin\left(\frac{2\pi nx}{\lambda}\right) \); typically \( a_{n} < 2\% \).
A conceptual design for the SC-EPU

- Four-quadrant, iron-free design
- Performance limited by AC losses (dB/dt-induced heating) of coil
- Period halving/doubling requires “switchyard” – superconducting switch needs to be demonstrated
Spectral range and Brightness of example SC-EPU
$\lambda=28\text{mm}$ device and PM-EPU $\lambda=32\text{mm}$

**Beam Parameters:**
- $I=0.5A$
- $\beta x/y=13.65 / 2.25\text{m}$
- $\varepsilon x/y=6.3 / 0.03\text{nm}$
- $0.06\text{ disp. in x}$
- Energy spread not included

Limited by aperture

Circular $2\lambda$

$\lambda$ linear polarization

$2\lambda$ linear polarization

Photon Energy

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Summary

- There are a wide variety of magnetic systems in light sources – here we only discussed a small subset
- There are “new” ideas being researched
  - often new opportunities for “old” ideas, with renewed interest stemming from developments in neighboring fields
- We can expect more diverse systems in the future – superconducting, permanent magnet, and “traditional” electromagnets designed to optimally address target applications