Overview of simulation software, measurement equipment and assignments

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Program layout

Three simulation and three measurement assignments

Simulations:

1. Dipole/quadrupole fields
   - Code Magnet/Poisson
2. Cavity modeling
   - Code Superfish
3. Synchrotron radiation
   - Code SynRad

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Measurements:

1. Dipole or quadrupole fields
   - Hall probe
2. Microwave cavity
   - Network analyzer

2 Days

2 Days

1Days

Final project: Design an accelerator (for high energy physics or for synchrotron radiation) …2 Days!

Note: the simulation and measurement lab is 30% of your grade

Lab groups

Eight teams – labwork is a group effort!

TEAM 1
Denny Newland, Oak Ridge National Lab/SNS, msne
Kenneth Quinn, Fermilab, bscpe
Lester Richardson, III, Jefferson Lab, ms
Wilson Simeon, Jr., Universidade Fed. Do Rio Grande do Sul (Brazil), gs

TEAM 2
Paul Gibson, Oak Ridge National Lab/SNS, mba
Mohamed Gouighri, Sciences Faculty Ain Chock (Morocco), gs
Matt Hodek, Michigan State University, gs

TEAM 3
Shigang Yuan, Brookhaven National Lab, bsee
Alexandre Bonatto, Universidade Federal Do Rio Grande do Sul (Brazil), gs
Brian G. Freeman, Jefferson Lab, bs

TEAM 4
Marianne Keck, Keystone High School and MSU, gs
Nicholas Leioatts, Florida Institute of Technology, ug
Michael Spaar, Oak Ridge National Lab /SNS, bsp
Zaipeng Xie, University of Wisconsin, Madison and ORNL, gs

TEAM 5
Anas Ali Almuqhim, King Abdulaziz City for Sc. & Tech. (Saudi Arabia), bsp
Ryan Carey, Cornell University, bsee
Saravan Kumar Chandrasekaran, Michigan State University/NSCL, gs
Karen Fiuza, Universidade Federal do Rio Grande do Sul (Brazil), gs

TEAM 6
Adel Abdullah Alzeanidi, King Abdulaziz City for Sc. & Tech. (Saudi Arabia), bsp
James P. Schubert, UT Battelle/ORNL - SNS, msme
Cary Long, Oak Ridge National Lab / SNS, mscs
Jared Nance, Jefferson Lab, bsp

TEAM 7
Ramakrishna Bachimanchi, Jefferson Lab, bsee
Jeremiah Holzbauer, Michigan State University, gs
David Schaub, Michigan State University/NSCL, bs

TEAM 8
Michael Aiken, Jefferson Lab, bs
Ilkyoung Shin, University of Connecticut, gs
Michael Sigrist, Canadian Lightsource, bsep
Heidi Lesser, Oak Ridge National Lab /SNS, bs

Workgroups

Eight teams – labwork is a group effort!

- Labwork is designed as 2-day exercise (lab+simulation)
    - Each exercise will require a written report, due the following day
- The last 2-day exercise will consist of the design of a storage ring
    - Storage ring design is due Friday morning, before the final exam

	Measurement lab	Computer lab
1a	Dipole Field measurements	Dipole Calculations
1b	Quadrupole field measurements	Quadrupole calculations
2		Insertion device radiation properties
3	Microwave cavity measurements	Cavity simulation
4	*Design of a storage ring*	

Day\Group #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
6/4/2007	*Lab and Calculations Overview*							
6/5/2007	1	2	3	4	8	6	7	8
6/6/2007	2	1	4	3	7	8	8	3
6/7/2007	8	6	7	8	1	2	3	4
6/8/2007	6	8	8	6	2	1	4	7
6/11/2007	7			7	6			6
6/12/2007		7	6			7	6	
6/13/2007	*Design of a Storage Ring*							
6/14/2007								

Key

1	1a-M
2	1a-C
3	1b-M
4	1b-C
5	2-M
6	2-C
7	3-M
8	3-C

* Lab assignments due

Introduction to lab exercises: Dipole/quadrupole exercise

Learn about design and purpose of magnetic elements

Simulations:

Dipole and quadrupole magnetic system design

Goal: understand excitation curves, saturation effects, purpose of poles and yokes, field harmonics, beam steering and focusing using the code Magnet

Measurements:

Dipole ***or*** quadrupole field measurements

Goal: Learn to assemble a model magnet and a Hall probe; measure spatial field profiles, excitation curves; understand current and current density, integrated fields, and beam steering or focusing as a function of current

The magnetic elements form the backbone of a storage ring:

- *Dipoles steer the beam, bending it on a circular path;*
- *Quadrupoles focus the beam, essential to keep the electrons from diverging*

Introduction to lab exercises: Accelerating cavity exercise

Learn about RF cavity design and measurements

Simulations:
RF cavity simulation
Goal: understand electric and magnetic fields that can exist in a cavity; find resonant modes and frequencies, distinguish modes from harmonics

Measurements:
Pillbox cavity measurements
Goal: Estimate base resonant frequency from geometry of a cavity; understand fields excited by two antennas installed in the device; measure resonant curve and impact of geometry on cavity tune

Accelerating cavities serve:

- *in booster rings, to bring electrons up to nominal operating energy,*
- *in the main ring to compensate for radiation energy loss (e.g. synchrotron radiation)*

Introduction to lab exercises: Accelerating cavity exercise

Learn about insertion devices for synchrotron radiation

Simulations:
Synchrotron radiation generation
Goal: understand the radiation characteristics associated with bending magnets, wigglers, and undulators, including spectral range and photon beam polarization

Insertion devices characterize third generation SR sources:

- *Provide intense SR tailored to specific scientific experiments*

They also serve in damping rings to reduce emittance

Introduction to lab exercises: Storage ring design

Use knowledge learned during the course to design a ring

Design process:

Choose to design either a SR storage ring or a HEP machine

Choose basic design point: electron or proton energy, ring diameter

Choose realistic ring elements (dipole field strengths, quadrupole fields, etc)

Incorporate elements discussed during the course (particle sources, accelerating structures, chromatic aberration correction, vacuum components, etc)

Simulate performance using program BeamOptics: plot betatron functions, perform particle tracking, modify design to yield reasonable lifetime

There are a large number of design choices in the design of a storage ring; the scientific purpose serves to dictate the optimal parameter choices

Two-dimensional static fields

Magnetic field described in terms of potentials:

In free-space, the magnetic field can be determined from a scalar potential V:

$$\vec{B} = -\nabla V \quad \left(\text{results from } \nabla \times \vec{B} = 0 \text{ and identity } \nabla \times \left(\nabla V\right) = 0,\ \forall V\ \right)$$

and from a vector potential A:

$$\vec{B} = \nabla \times \vec{A} \quad \left(\text{results from } \nabla \cdot \vec{B} = 0 \text{ and identity } \nabla \cdot \left(\nabla \times \vec{A}\right) = 0,\ \forall \vec{A}\right)$$

In two dimensions, A is a scalar and we can use complex notation:

$$B_x - iB_y = B^* = i\frac{dF}{dz} = i\frac{d}{dz}\left(A + iV\right)$$

$$z = x + iy \qquad \frac{df}{dz} = \frac{\partial f}{\partial x} = -i\frac{\partial f}{\partial y}$$

$$\left.\begin{array}{l} \dfrac{\partial u}{\partial x} = \dfrac{\partial v}{\partial y} \\ \dfrac{\partial u}{\partial y} = -\dfrac{\partial v}{\partial x} \end{array}\right\} \text{Cauchy Riemann}$$

F is an analytic function in a good-field region, and can be expanded as a Taylors series for $|z|<|z_0|=r_0$:

$$F(z) = F(x+iy) = F\left(re^{i\theta}\right) = \sum_{n\geq 0} c_n z^n \quad \Rightarrow B^*(z) = i\sum_{n\geq 1} nc_n\left(z\right)^{n-1}$$

$$\left.\begin{array}{l} c_n = \lambda_n + i\mu_n \\ a_n = \dfrac{n\mu_n}{B_0} r_0^{\,n-1} \\ b_n = -\dfrac{n\lambda_n}{B_0} r_0^{\,n-1} \end{array}\right\} \Rightarrow B^*(z) = -B_0 \sum_{n\geq 1}\left(a_n + ib_n\right)\left(\frac{z}{r_0}\right)^{n-1}$$

Note: the coefficients are a function of the reference radius and the characteristic field. By tradition:
a_n: "skew" coefficients
b_n: "normal" coefficients

Two-dimensional static fields

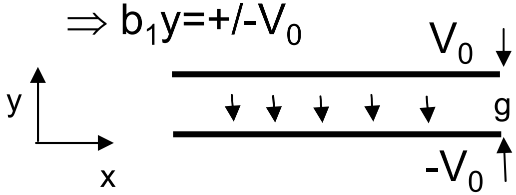
Magnetic field described in terms of multipoles:

$$F(x,y) = A(x,y) + iV(x,y) = \sum_{n\geq 0}(\lambda + i\mu_n)(x+iy)^n$$

$$\Rightarrow A(x,y) = -B_0\left[b_1 x + a_1 y + \frac{b_2}{2r_0}(x^2-y^2) + \frac{a_2}{r_0}xy + \dots\right]$$

$$\Rightarrow V(x,y) = B_0\left[a_1 x - b_1 y + \frac{a_2}{2r_0}(x^2-y^2) + \frac{b_2}{r_0}xy + \dots\right]$$

Example: V describes geometry of magnetized surfaces to yield a multipole field;
for a pure normal dipole:
$\Rightarrow$ only b_1 non-zero
$\Rightarrow$ $b_1 y = +/- V_0$



$$B_y = \frac{2V_0}{g}$$

In cylindrical coordinates:

$$F(x,y) = A(x,y) + iV(x,y) = \sum_{n\geq 0}(\lambda + i\mu_n)(x+iy)^n = \sum_{n\geq 0}(\lambda + i\mu_n)\left(re^{i\theta}\right)^n$$

$$\Rightarrow A(r,\theta) = -B_0 r_0 \sum_{n\geq 1}\left(-\frac{b_n}{n}\cos(n\theta) + \frac{a_n}{n}\sin(n\theta)\right)\left(\frac{r}{r_0}\right)^n$$

$$\Rightarrow V(r,\theta) = -B_0 r_0 \sum_{n\geq 1}\left(-\frac{a_n}{n}\cos(n\theta) + \frac{b_n}{n}\sin(n\theta)\right)\left(\frac{r}{r_0}\right)^n$$

Example: A describes current distribution to yield a multipole field;
for a pure normal dipole:
$\Rightarrow$only b1 non-zero
$\Rightarrow$current on a cylinder satisfies $I(\theta) \sim I_0\cos(\theta)$

Introduction to lab exercises: General issues

- Working as a group
  - Read through the days lab/simulation assignment and plan your approach for efficiency
  - Proceed with the experiments in a safe and orderly manner
    - Be sure power supplies are off (unplug them as well) when connecting leads and/or performing assembly
    - Be careful with heavy/clumsy magnet parts (in particular the dipole measurement)
    - The Hall probes are sensitive, expensive equipment; handle with care. You can tape them to glass rods, etc, but do not allow the tape to adhere to the probe itself.
  - Clean up your experimental area after finishing the days lab; messy areas will be noted!
  - Remember that the homework is due after both the lab and simulation component are finished; plan your days accordingly

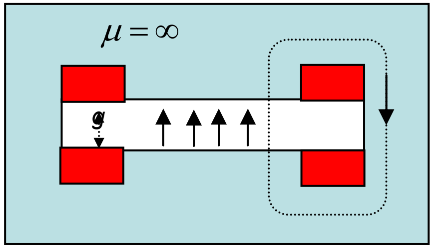
- Things to consider
  - For iron-dominated magnets, Amperes law provides much insight:

$$\oint \vec{H}\cdot d\vec{l} = 2I = Hg + \int_{iron} \vec{H}\cdot d\vec{l}$$

$$B = \mu\mu_0 H$$

In air: $\mu = 1$

In iron: $\mu >> 1 \Rightarrow \int_{iron} \vec{H}\cdot d\vec{l} \approx 0$



  - When possible, the simulations should correspond to the geometry used in the measurements
  - Lab grades will be based on your understanding of the technical issues; if some measurements do not look “clean”, discuss possible reasons and how the measurements could be improved with appropriate equipment

The purpose of the labs and simulations is to provide insight into hardware and design software associated with accelerators – each report should include discussion of issues

Introduction to lab exercises: General issues

- Software:
  - Resonant frequencies of pillbox cavities are purely a function of the geometry. The code *TMModeFreq.tcl* is in your folder and will evaluate these frequencies.
  - Wideroe drift tube lengths can be calculated using the script *calcDriftTubeLengths.tcl*, given linac rf frequency, initial beam energy, energy gain per gap, and number of drift tubes,
  - Cavity fields can be calculated and plotted using the script *runUrmel.tcl*, which reads a cavity description file **.urmi*.
  - FODO cells can be analyzed with the script *FODOcells.tcl*, which plots Twiss functions (β and η functions) and matched and mismatched trajectories.
  - Necktie diagrams, which describe FODO cell stability regions, can be generated with the script *NecktieDiagrams.tcl*. Either the trace of the transfer matrix or the phase advance can be plotted.
  - Magnetostatics, ,e.g. dipole and quadrupole magnetic fields, can be calculated using the code Poisson. Example scripts *(*.am)* are available. These are evaluated by right-click,run-autofish). The resulting **.T35* files can be plotted (double-click) or data evaluated (right-click, Interpolate). Multipole data is available in the *OUTPOI.txt* file.
  - The program SynRad provides radiation properties for a wide variety of storage rings and SR sources, including brightness, flux, and power calculations. New storage ring and source parameters can also be analyzed.
  - The program BeamOptics_APS.exe provides a forum for the design of a storage ring. The lattices of existing rings can be reviewed, or a new ring can be built "from the ground up". This program will serve as the foundation for the final project: "Storage Ring Design".

–**Software location:**

- Please use your *c:\studenti* directory for all calculations. If you plan to modify an input file, make a copy with a new name, so that the original can be reviewed in case of problems during running. Example input files are available in the folder *C:\LANL\Examples*.
- The code SynRad is located in the folder C:\Program Files\Stanford University\SynRad.
- The code *BeamOptics_APS.exe* is located in *C:\Program Files\APS\Beam Optics (APS version)*.

The software is generally intuitive, and is best learned by trial. Input files are available that can be copied and modified as needed for the problems.

Homework for Day I

1. Show that in free-space, the complex function B* is analytic (hint: a complex function is analytic if it satisfies Cauchy-Riemann)
2. Find the 3rd order (I.e. sextupole) terms in the expansion of A and V in Cartesian coordinates
3. Field about an infinite line-current
   a) Find the field B_r about an infinite line current on a circle of radius r
   b) Find the field $B_y(x,y=0)$ for an infinite line located at $(x_0=0,y_0)$
4. The vector potential of a line current located at (r_0,θ) is given by

$$A(r,\phi) = -\frac{\mu_0 I}{2\pi}\sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{r}{r_0}\right)^n Cos\left(n(\phi-\theta)\right)$$

What is the multipole field associated with the current distribution on the circle $r=r_0$ defined by

$$I(r=r_0,\theta) = I_0 Cos\left(m\theta\right)$$

Hint: replace I in the expression for A with $I(\theta)$ and integrate from 0 to 2π

5. Assume I_0=10kA, r_0=0.01meters, and m=1. What is the field (Bx,By) at (x=0.005,y=0).
   Note: μ_0 (permeability of free space) = $4\pi\ 10^{-7}$

$$B_\theta(r,\theta) = -\frac{\partial A_z(r,\theta)}{\partial r}$$

From Maxwell Equations to Wave Equation

$$\nabla \cdot \mathbf{E} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{B} = \mu_0\epsilon_0\frac{\partial}{\partial t}\mathbf{E}$$

$\mathbf{E} = \mathbf{B} = 0$ is a solution, but there might be other solutions as well. Let us employ a useful identity from vector calculus.

$$\nabla \times (\nabla \times \mathbf{A}) = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2\mathbf{A}$$

Where $\mathbf{A}$ can be any vector function. Taking the curl of the curl equations and applying the identity, we get the following.

$$\nabla^2\mathbf{E} = \mu_0\epsilon_0\frac{\partial^2}{\partial^2 t}\mathbf{E}$$
$$\nabla^2\mathbf{B} = \mu_0\epsilon_0\frac{\partial^2}{\partial^2 t}\mathbf{B}$$