Magnetic measurements

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PHY 542 – 01. Fundamentals of Accelerator Physics and Technology with Simulations and Measurements Lab

Outline

- Low emittance required
- ERL layout: typical magnets
- Various magnetic measurements technics
- Hall probe
- Stretched Wire Measurements
- Rotated Coil

Emittance: smaller => better

- In colliders luminosity:

$$L = f_c \frac{N_1 N_2}{A} \cong f_c \frac{N_1 N_2}{2\pi \sqrt{\beta_{x1}\varepsilon_{x1} + \beta_{x2}\varepsilon_{x2}} \sqrt{\beta_{y1}\varepsilon_{y1} + \beta_{y2}\varepsilon_{y2}}}$$

$$N_{A\to B} = \sigma_{A\to B} \cdot L$$

- Numbers of events

- In injectors Brightness:

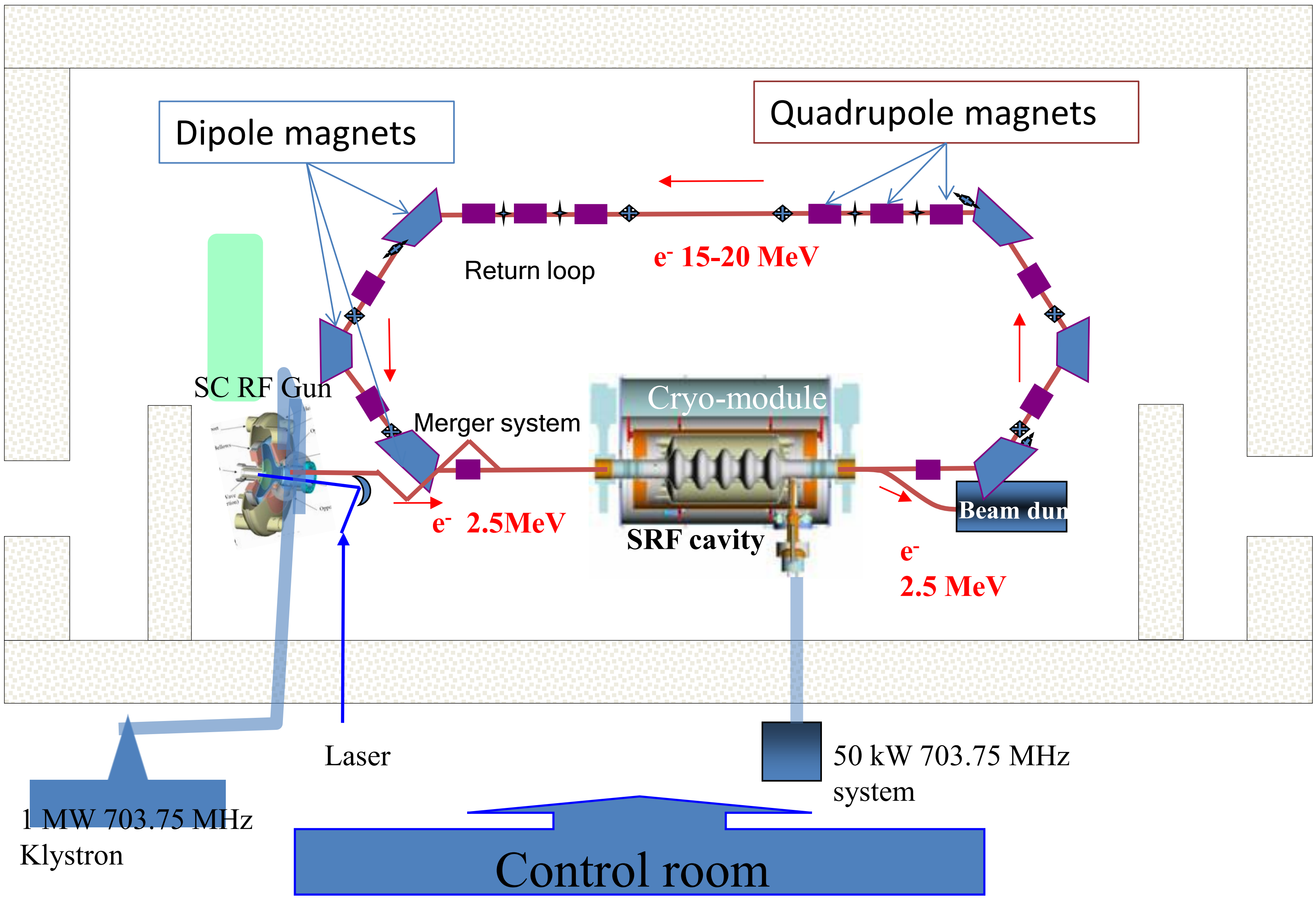
The peak normalized rms brightness is given by

$$B_n = \frac{2I}{\varepsilon_{n,x}\varepsilon_{n,y}} \qquad I = Q/\left(\sqrt{2\pi}\sigma_z\right)$$

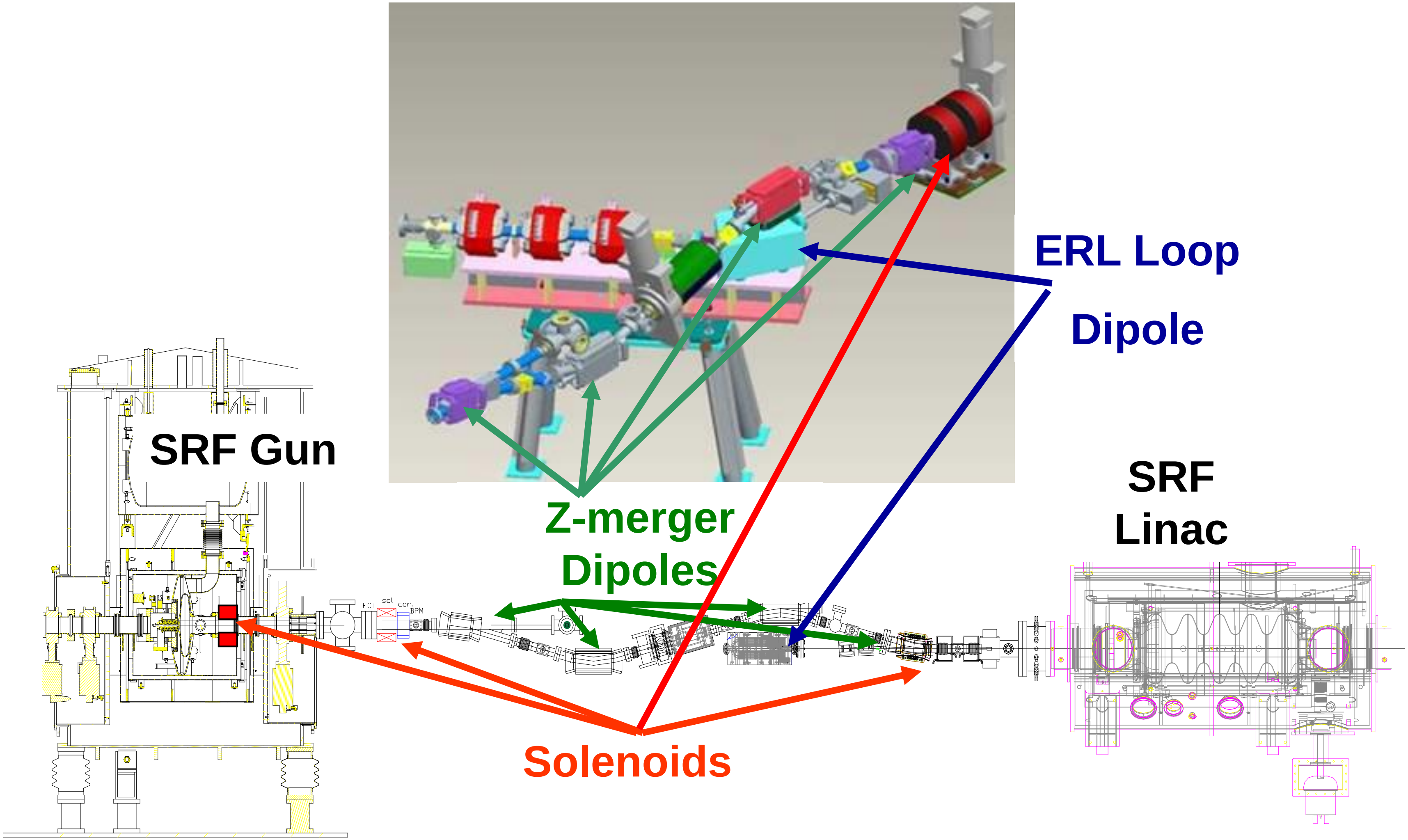
$$\varepsilon_{n,s} = \beta\gamma\sqrt{\langle s^2\rangle\langle s'^2\rangle - \langle ss'\rangle^2}$$

where s is either x or y.

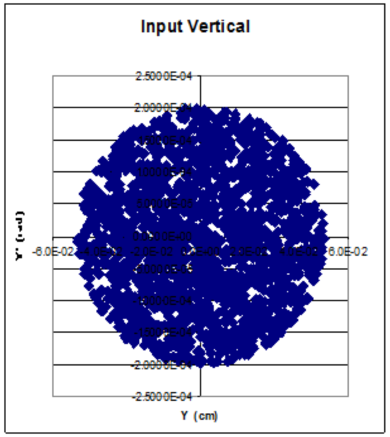
Schematic Layout of the BNL ERL



BNL R&D ERL SRF Injector layout



Linear transformation preserves emittance.



ε_{ny}= 0.96 um
β_y= 249 cm
α_y= 0.0012
σ_y=0.25mm

Dipole magnet:

$x=x_0\cos(phi)+x_0'R*\sin(phi)$

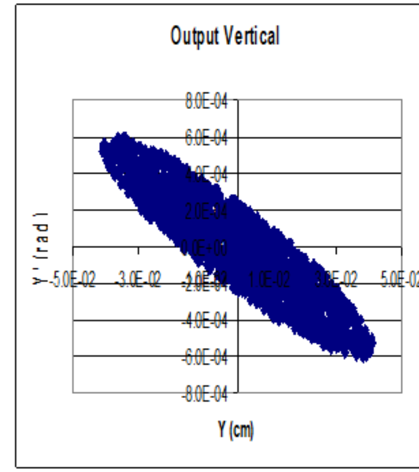
$x'=-x_0/R*\sin(phi)+x_0'\cos(phi)$

Thin focusing lens with f- focal length:

$x=x_0$; $x'=x'_0 - x_0/f$

Drift space L - length :

$x=x_0+L*x_0$; $x'=x'_0$

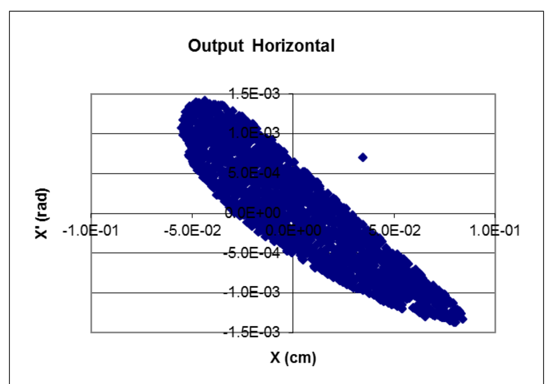


ε_{ny}= 0.960 um
β_y= 168 cm
α_y= -2.20
σ_y=0.20 mm

Nonlinear transformation increases emittance:

Thin Sextupole:

$x=x_0$; $x'=x_0'-S*x_0^2$



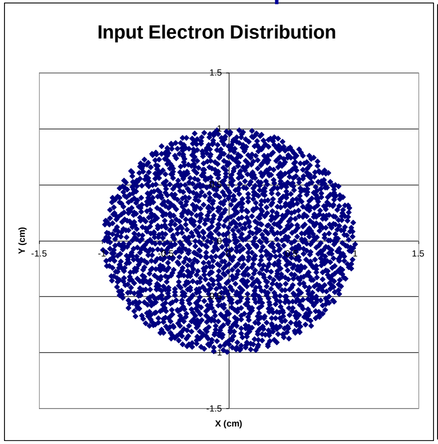
Injection combine function magnets

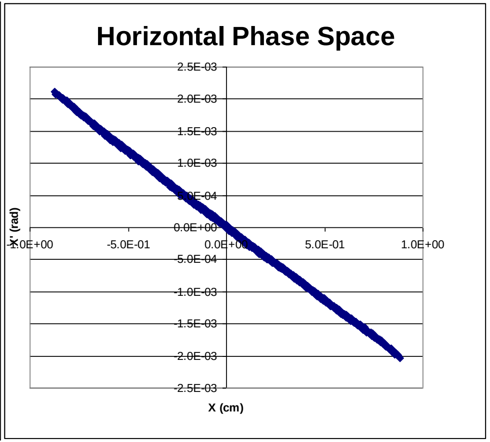
Window-frame dipole for Z-bend

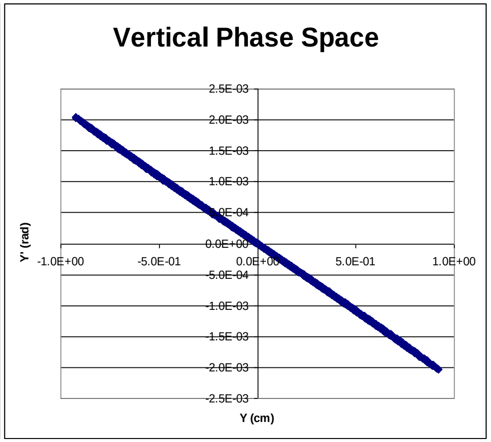
Due to very small real estate and large beam size: each magnet includes 4 sets of coils: 1) vertical bend, 2) quadrupole focusing, 3) sextupole correction and 4) horizontal steering.

The quadrupole coil is used to split focusing equally between the planes

The amount of the sextupole component is controlled by the gap between the yoke and the main dipole coil. A small additional coil in the corners is a sextupole trim coil, intended for use if sextupole component needs to be adjusted to reduce emittance growth







initial emittances 0

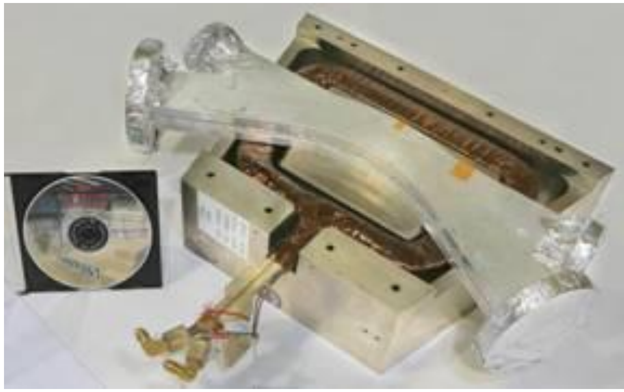
After tracking emittances:

ε_{xn}=0.6 mm-mrad

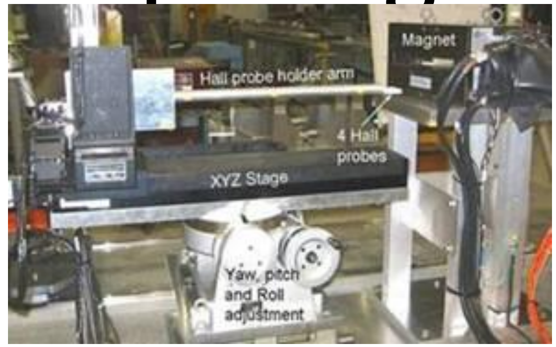
ε_{yn}=0.6 mm-mrad

Analysis predicts that the influence of various field components on the emittance growth are complicated by the fact that the beam trajectory bends significantly in the fringe fields. Hence, direct tracking in the calculated fields extracted from Opera3d was used of test beam to evaluate and to minimize influence of magnetic field on the beam emittance

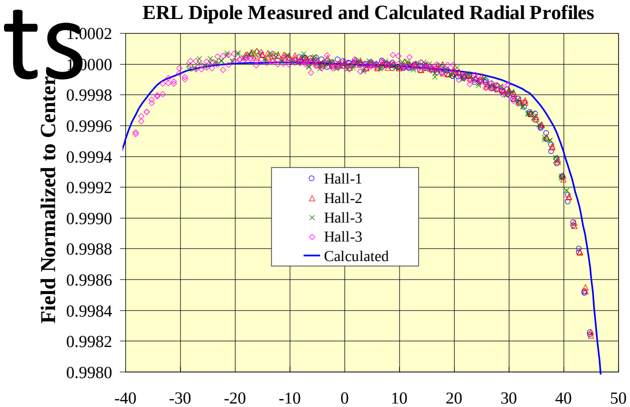
Loop Magnets



ERL 60 dipoles with vacuum chamber assembly



Measurement setup



Agreement between the measurements and simulations

Dipoles: the R&D ERL 60° dipole magnets have a rather small bending radius of 20 cm. 15° edges are used to split very strong focusing evenly between the horizontal and vertical planes (so-called chevron-magnet);

Magnetic measurements of the ERL magnets employs both rotating coil and Hall probe array mapping

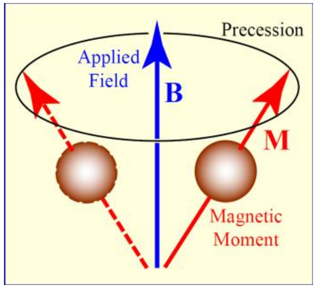
Quadrupoles: The requirements on field quality of the loop's quadrupoles had been determined by the requirement to preserve a very low normalized transverse slice emittance of electron beam (εn~ 1mm-mrad).

We used direct tracking of a sample electron beam to verify a high degree of the emittance preservation. Each quadrupole is equipped with a dipole trim coil, which can be also used to excite a sextupole component, if required, for emittance preservation of e-beam with a large energy spread.

W.Meng et al., "**Unique Features in Magnet Designs for R&D Energy Recovery Linac at BNL",PAC2007**

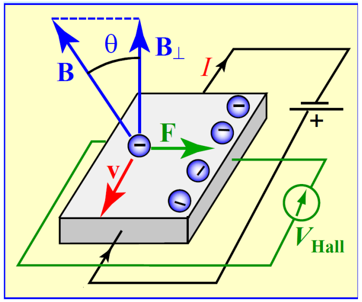
Various Magnetic Measurement Techniques *

- **N**uclear **M**agnetic **R**esonance (NMR)
- **E**lectron **P**aramagnetic **R**esonance (EPR)



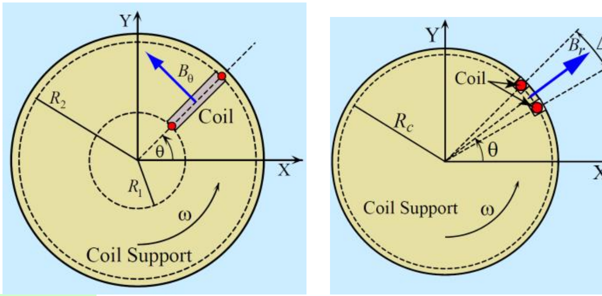
Frequency =γB
γ= Gyromagnetic ratio

- Hall Probes

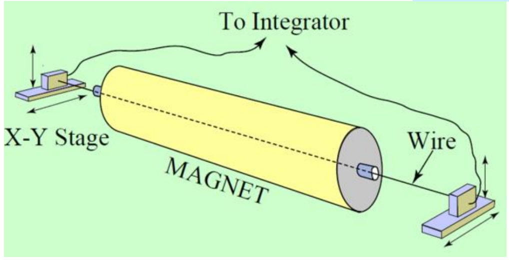


$$V_{\text{Hall}} = G \cdot R_H \cdot I \cdot B \cos\theta$$

- Flux Measurements with Pick Up Coils (rotated coil)

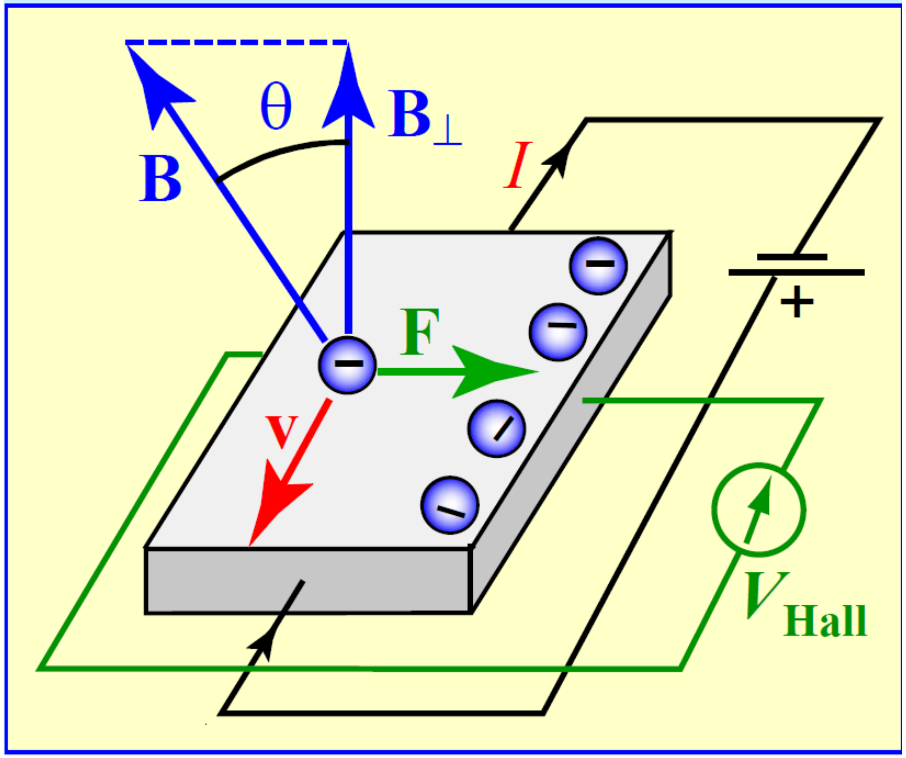


- Stretched Wire Measurements



*) Animesh Jain, **Overview of Magnetic Measurement Techniques,** USPAS 2003

The Hall Effect



$$V_{\text{Hall}} = G \cdot R_H \cdot I \cdot B \cos\theta$$

- Charge carriers experience a **Lorentz force**in the presence of a magnetic field.
- This produces a steady state voltage in a direction perpendicular to the current and field.

G= Geometric factor R_H= Hall Coefficient

Hall Measurement Specifications

- Typical Range: < 1 mT to 30 T
- Typical Accuracy ~ 0.01% to 0.1%
- Typical dimensions ~ mm
- Frequency response: DC to ~ 20 kHz (~ a few Hz for fully compensated signal)
- Time Stability: ±0.1% per year

Hall Measurement Advantages

- Simple, inexpensive devices, commercially available.
- Small probe size makes it suitable for a large variety of applications.
- Can measure all components of field.
- Particularly suited for complex geometries, such as detector magnets.
- Can be used for fast measurements.
- Can be used at low temperatures.

Hall Measurement Disadvantages

- Non-linear device, requires elaborate calibration of sensitivity for each probe.
- Sensitive to temperature: Calibrate as a function of temperature; Keep temperature stable; Design compensated probes.
- Long term calibration drift.
- Planar Hall effect can pose a problem for mapping 3-D fields. Special geometries are needed for measuring minor components.

Hall probe measurements stand used for ERL dipoles measurements *

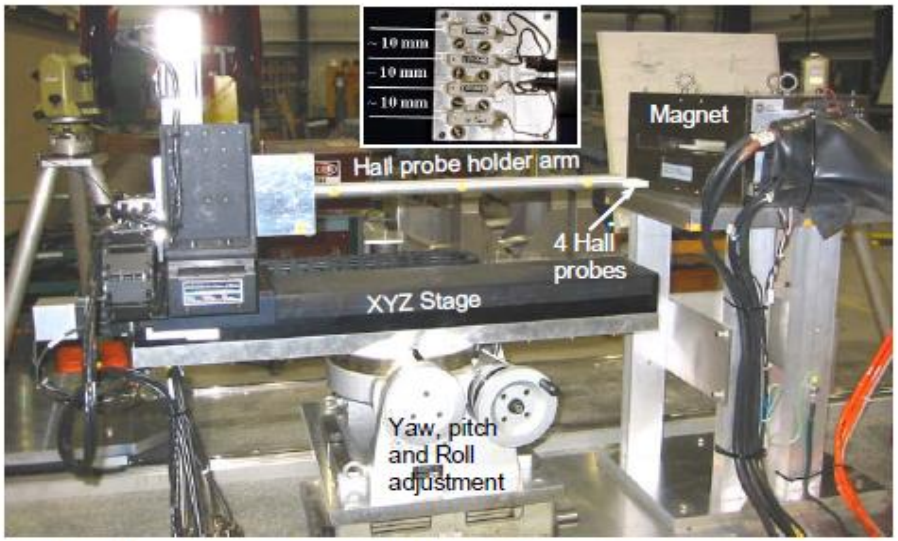


Fig. 1 Hall probe mapping system for the 3D60 dipoles. The inset shows the arrangement of the Hall probes.

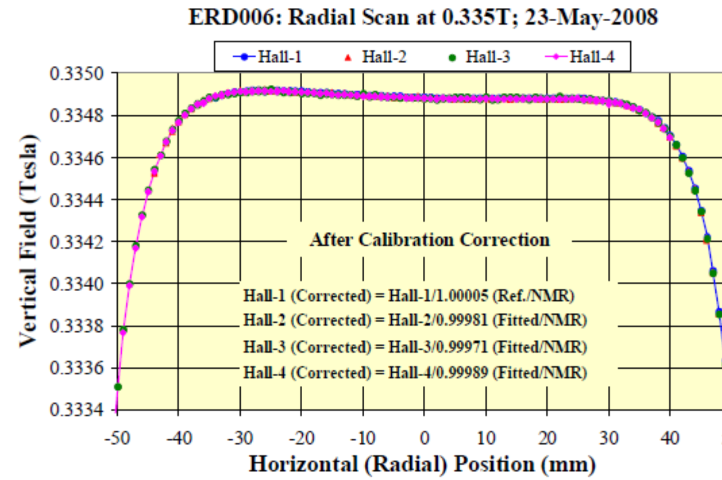


Fig. 6 Horizontal (radial) profiles of the vertical field measured by the four Hall probes in 3D60 dipole #6 after calibration corrections are applied.

Magnetic Measurements of the ERL Magnets

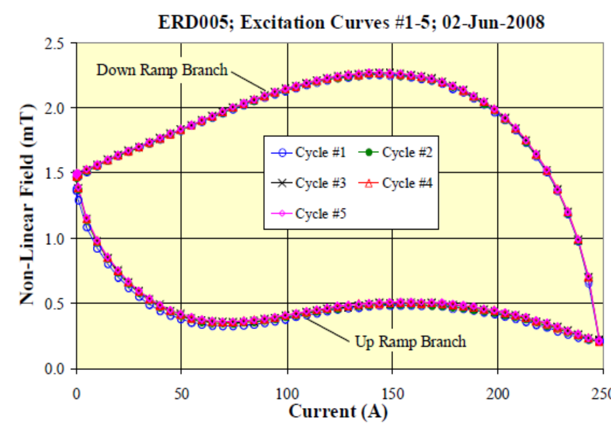
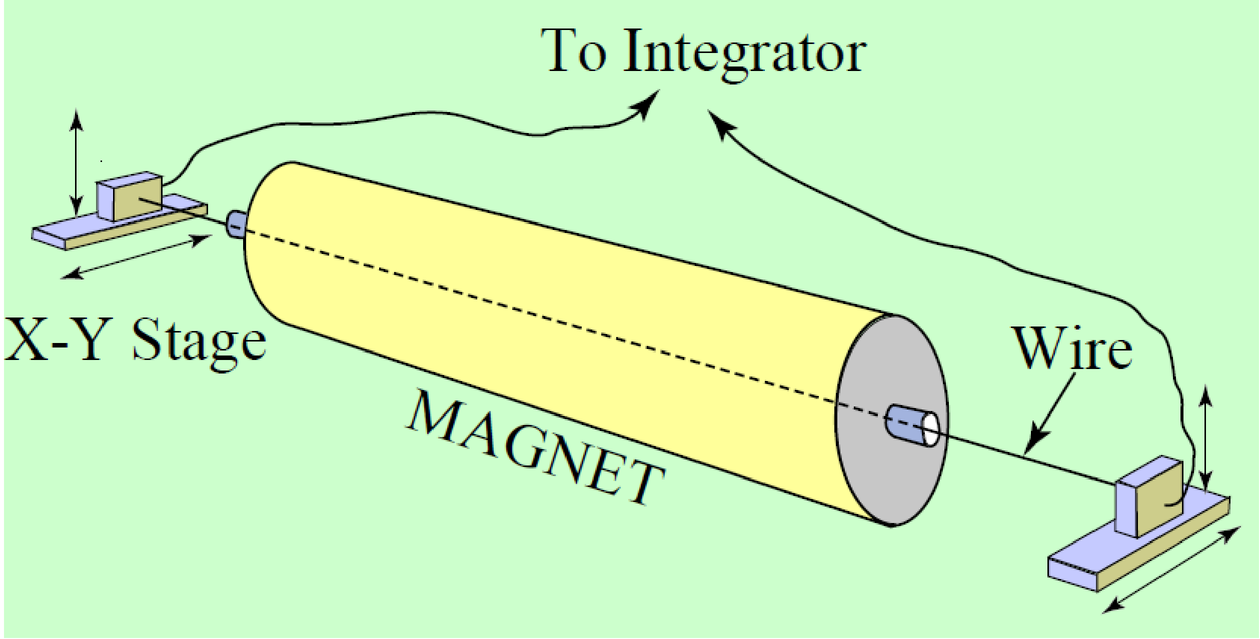


Fig. 4 Non-linear part of the vertical field in the center of the magnet as a function of current for 5 successive excitation cycles in 3D60 dipole #5. No appreciable cycle to cycle difference is seen, except for the low current end of the up ramp branch in the very first cycle.

*) **R&D ERL: Magnetic Measurements of the ERL Magnets ,** C-A/AP/#385 August 2010

Stretched Wire Measurements



Ddetermination of Magnetic Center (quadrupoles, sextupoles etc.)

1) Move a stretched wire in a magnet

2) Measure change in flux for various types of motion.

- Use expected field symmetry to locate the magnetic center.

3) Apply sinusoidal current

- By moving (X&Y) wire minimize vibration.

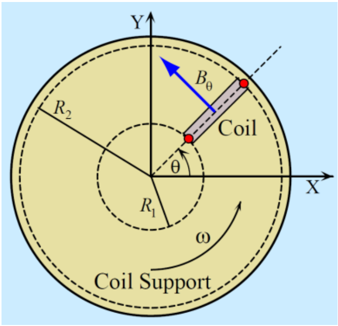
Harmonic Coil (rotating coil)

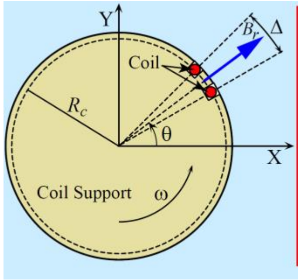
- For most accelerator magnets, a harmonic description of the field is often used, both for characterizing the field quality, as well as for particle tracking studies.

$$B_r(r,\theta) = \sum_{n=n_0}^{\infty} \left[B_n \sin\{(n-n_0+1)\theta)\} + A_n \cos\{(n-n_0+1)\theta)\} \right] \left(\frac{r}{R_{ref}} \right)^{n-n_0}$$

$$B_\theta(r,\theta) = \sum_{n=n_0}^{\infty} \left[B_n \cos\{(n-n_0+1)\theta)\} - A_n \sin\{(n-n_0+1)\theta)\} \right] \left(\frac{r}{R_{ref}} \right)^{n-n_0}$$

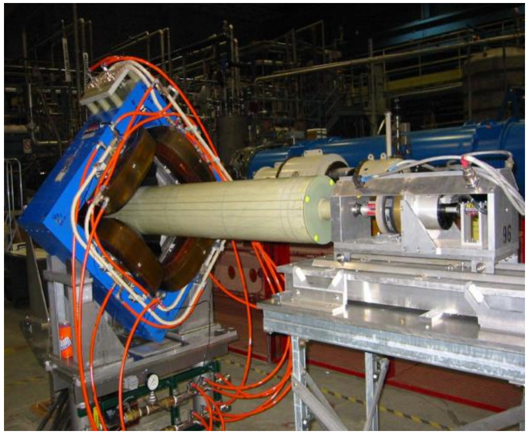
- The "Harmonic Coil" technique, employing rotating coils, is the most convenient, accurate, and widely used technique for the measurement of harmonic coefficients in accelerator magnets.
- The harmonic coefficients are related to the azimuthal variation of the field components





Measurements with Pick up Coils

- **Simple**, **passive**, **linear**, **drift-free** devices.
- Require **changein flux** ⇒ramp field with static coil, or move coil in a static field. Pay attention to ramping/moving details.
- Measure **flux**, not **field**. ⇒**Calibration of geometry** very important; limits accuracy.
- Field variations across the coil area must be accounted for ⇒ **harmonic analysis**.
- Field harmonics can be measured at ppm level.
- **Field direction** can be measured to ~ 50µrad.



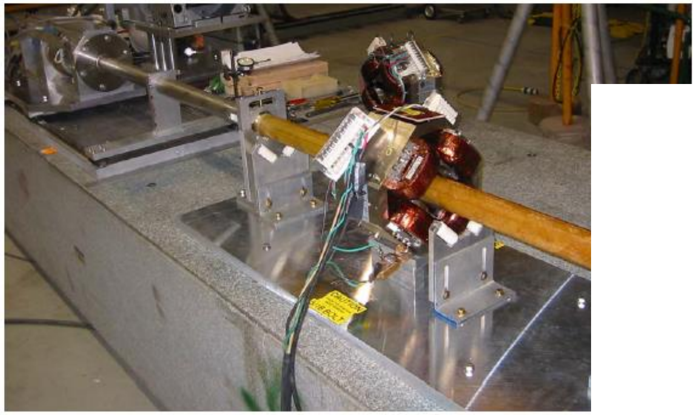


Fig. 11 Rotating coil setup for field quality measurements in 6Q12 quad

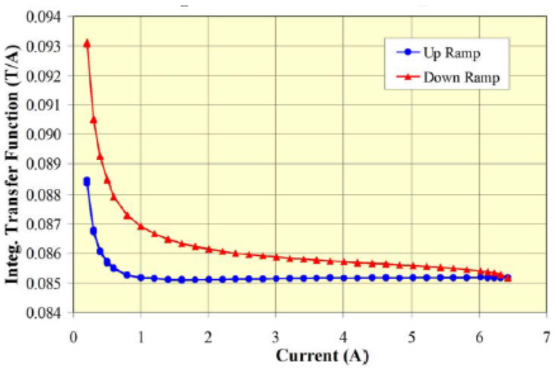


Fig. 14 Integral transfer function ($\int G.d\ell / I$) measured in three successive cycles in 6Q12 magnet # 13. Data from the three cycles are practically indistinguishable.

Optional homework

Using direct calculation prove that emittance:

$$\sqrt{\overline{x^2} \cdot \overline{x'^2} - \left(\overline{xx'}\right)^2}.$$

1. Preserved for thin lens:

$x=x_0$; $x'=x'_0 - x_0/f$

2. Degraded for thin sextupole:

$x=x_0$; $x'=x_0'-S*x_0^2$