BROOKHAVEN NATIONAL LABORATORY

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Accelerator Physics Requirements for Magnets

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Lattice Characteristics

- FFAG: single beamline accepting a wide range of energies (42–150 MeV in our case) without magnet fields changing
- Beams in different passes go through
  - At different positions
  - With different energies
- Magnets are short relative to their aperture, and close together

Magnet-to-Magnet Variation

- Variation of field profile from magnet to magnet
- Leads to orbit deviations from design orbit
  - Deviation increases down the line
- What matters is field and gradient near each design orbit
  - Orbits for different energies are in very different parts of the magnet
- Sources of random field variation
  - Permanent magnet magnetization
  - Geometric tolerances in magnet construction
  - Temperature dependence of permanent magnet magnetization
  - Overall magnet alignment errors
  - Vibrations

Magnet-to-Magnet Variation

- Correction system designed to fix this
  - Must fix multiple energies simultaneously
  - Insufficient correctors to fix at the source
  - Algorithms allow us to to fix some level of errors
  - Algorithms don’t always work as well on the real machine as they do in simulation, at least not initially
  - Correctors imperfectly modeled
  - Need headroom for the unexpected
  - Correction system may not be able to address higher frequency effects (vibrations, current ripple)
- Magnet-to-magnet variation created problems in a previous machine of this type (EMMA)

Systematic Effects

- Nonlinearities not a real issue
  - Have a 1% 12-pole in the iron design, effect difficult to see compared to linear hard edge model
  - Comparable/large nonlinearities already exist due to
    - Significant angles beams make through magnets
    - End fields forced by Maxwell's equations, significant due to short magnets
  - Small number of passes through magnets
- Can address multi-mm orbit excursion errors with small horiozontal offsets
- If gradients come in a bit low/high, a small linac energy change can fix

Design Requirements

- Main concern is minimizing magnet-to-magnet variation
- Avoid using correctors to solve problems we can fix in the magnet design
  - Correction may not be as easy in the real machine as in our simulations
  - The correctors will be busy enough
- Systematic effects are manageable

Crosstalk

- At the design stage
  - Iron magnets, need to consider neighbors to get correct results
  - Halbach magnets, no iron: can basically superimpose magnets
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  - Error studies, transition, etc. easy: just lay out magnets
- Iron magnets
  - Create field maps with magnets placed properly
  - However, we've developed a process for accurately estimating crosstalk effects to reduce the number of times field maps must be reconstructed

Crosstalk: Iron Magnets

- Lattice behavior is nearly identical to linear hard-edge lattice
- Gradients and horizontal displacements are adjusted, correction factors easily modeled
- Small displacements and gradient corrections accurately modeled by displacing field maps with individual magnets powered, all iron in place
- Any modeling errors (in magnet design code) lead to a small systematic effect, manageable
- Random errors: amplification through coupling?
  - Coupling between magnets is at the 10% level
  - Tested shift, no amplification seen

Simulation Results

- Using a field map for iron magnets that fully includes crosstalk, have cross-checked results in two independent beam dynamics codes, and they agree
- Have studied realistic systematic effects with iron magnets, effects have been tiny
  - Same should hold true with systematics in Halbach designs

Correctable Errors

- 200 μm misalignments, plus
- Multipole random errors (relative, at 25 mm):

Order	Norm. (10^{-4})	Skew (10^{-4})	Order	Norm. (10^{-4})	Skew (10^{-4})
3	18	45	4	12	30
5	7.5	21	6	5.7	15
7	3.3	10.5	8	3	7.8
9	1.8	6	10	1.5	4.5

- Corrected with 500 G cm dipole correctors
  - Normal and skew on alternating magnets
- Multipoles are only a way of expressing field variations on orbits far off-axis

Summary: Magnet Requirements

- From the lattice perspective
  - Primary design requirement is to control magnet-to-magnet variation of field profile
  - Systematic effects are manageable
- Some level of random errors handled by correctors
  - Avoid overburdening correctors (strength and algorithm)
  - Correction may be challening on real machine
- Crosstalk between magnets
  - Requires iteration between lattice design and field map construction (by magnet design codes) in the design/simulation stage
  - We have demonstrated we can manage this
  - No problem from a beam dynamics perspective: just needs to be modeled