Beam Optics in Large Aperture Magnets

Weishi Wan[1], Lucas Brouwer[1,2], Shlomo Caspi[1], Soren Prestemon, Alexander Gerbershagen[3], Jacobus Maarten Schippers[3] and David Robin[1]

[1]ALS, Lawrence Berkeley National Laboratory

[2]Dept. of Nuclear Engineer, University of California at Berkeley

[3]Paul Scherrer Institut,

Workshop on Superconductivity and other new Developments in Gantry Design for Particle Therapy

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BERKELEY LAB

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ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

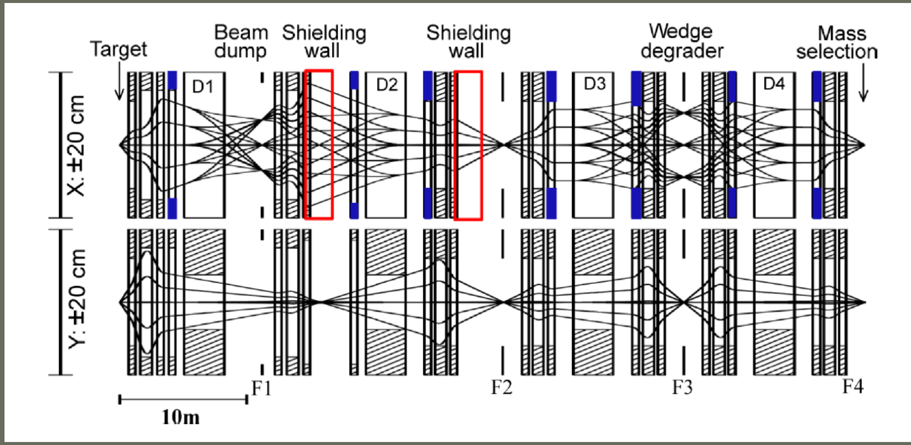
Outline

- Introduction/motivation
- Method of simulation (transfer maps)
- Optics of a new gantry
- Aberration correction and results

Motivation

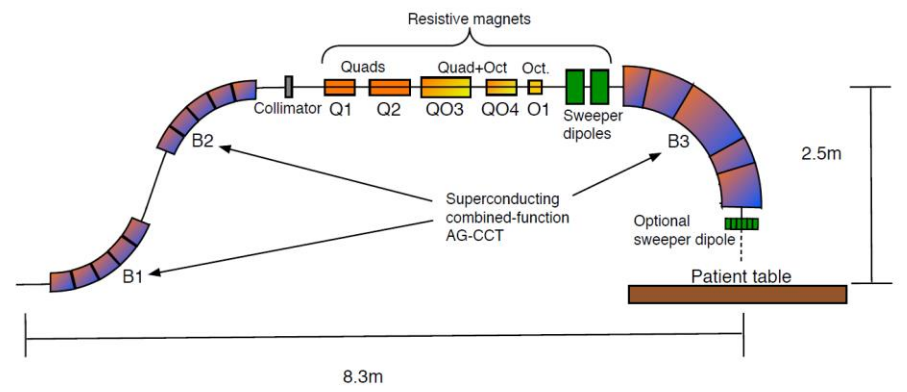
- Transporting charged particle beams with large emittance, momentum spread and scanned range necessary in nuclear physics, high energy physics and ion beam therapy
- Large aperture magnets required
- Beam optics non-trivial due to large aberrations
- Paraxial (small angle) approximation no longer valid
- Fringe field starts to play a significant role

In-flight fragment separator of RISP



J. Y. Kim *et al.* RSI **86**, 083302 (2015)

A superconducting gantry design



W. Wan *et al.* PRST-AB **in press**

How to model a beam transport system?

Traditional method #1: ray tracing

- accurate but slow

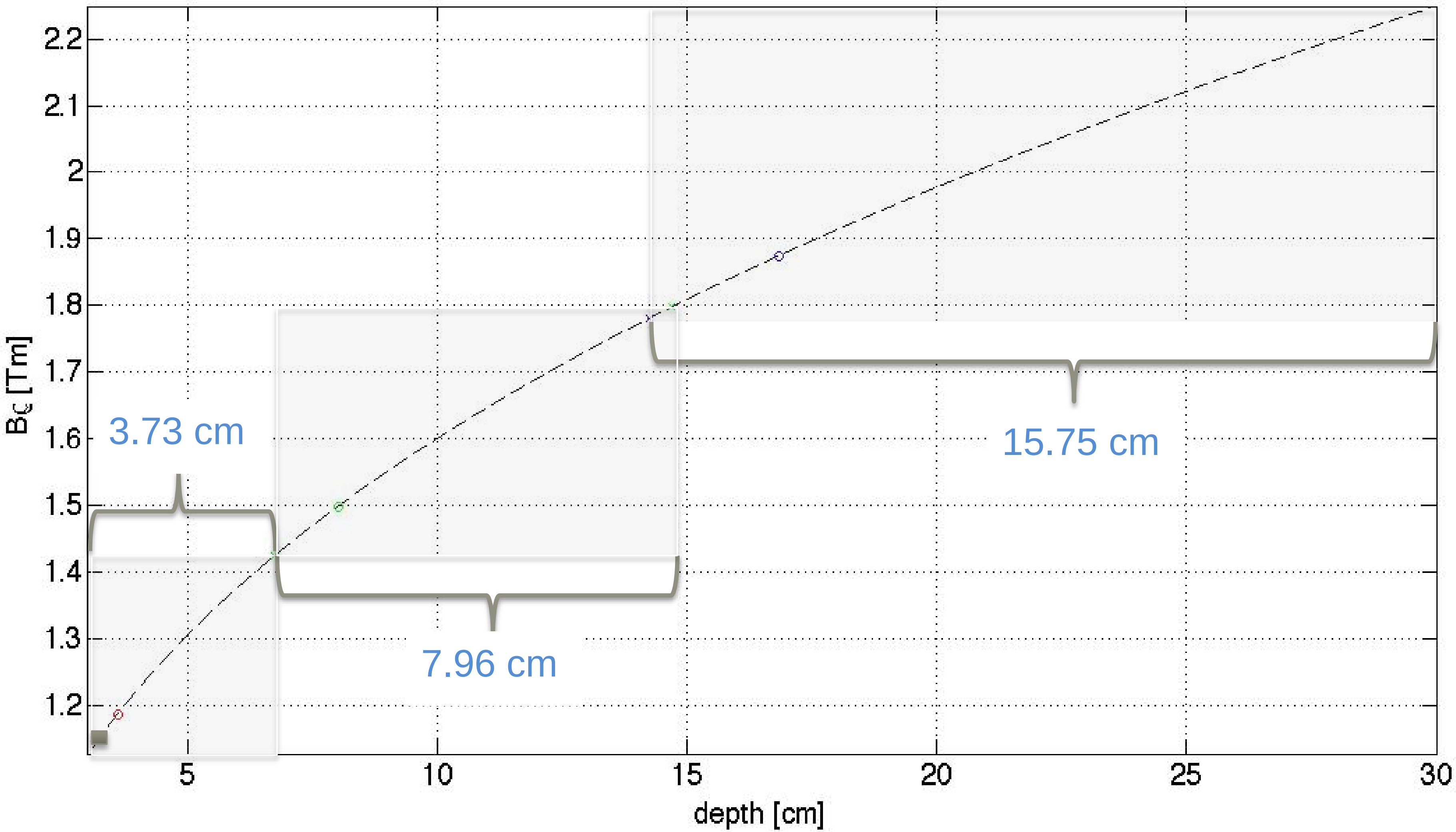
Traditional method #2: analytical Taylor maps of individual magnets

- fast but limited to relatively simple field distribution and low order, examples: MAD, TRANSPORT, MARYLIE, *et al.*

Our method: differential algebra (DA)

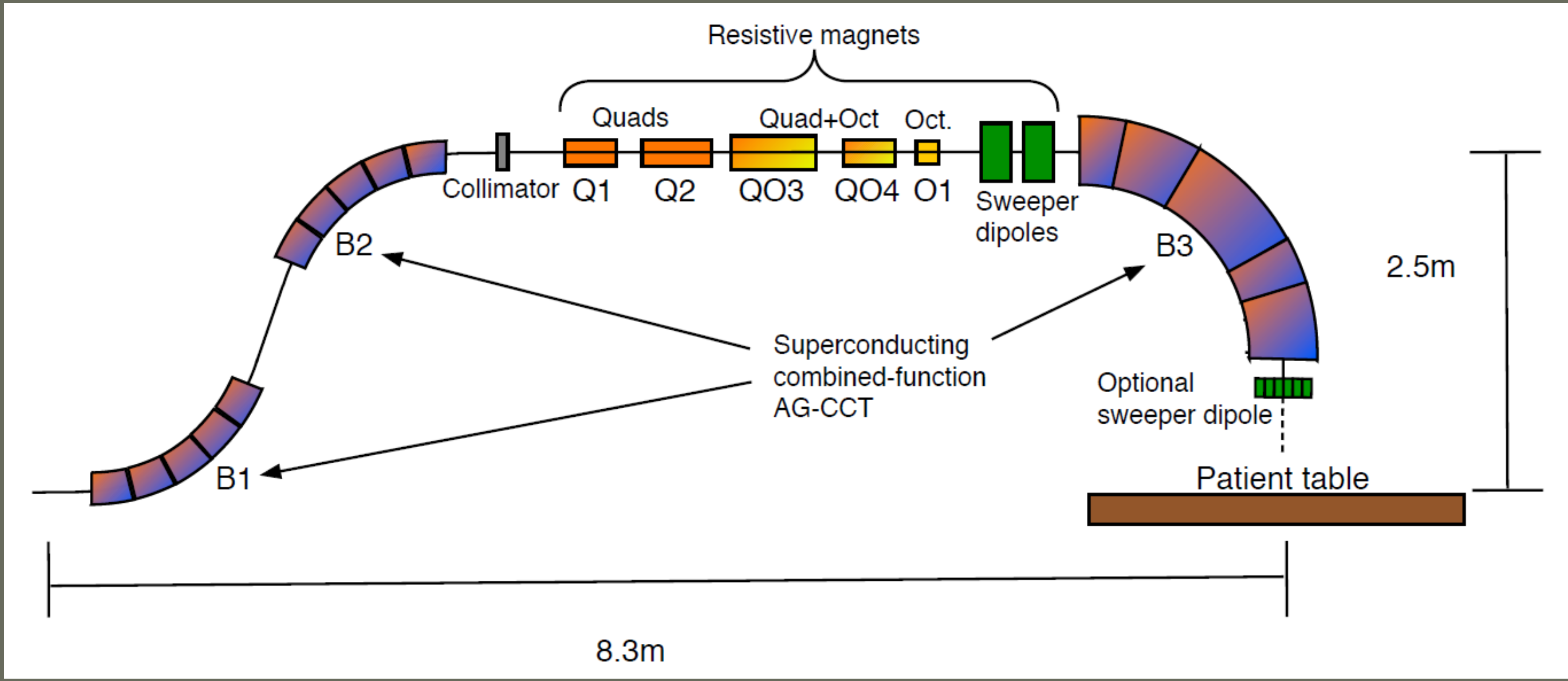
- accurate and fast, examples: COSY INFINITY, MADX, *et al.*
- DA: numerically integrating the equation of motion with Taylor expansion, obtaining ALL aberrations up to any given order after one pass. (need differentiable functions)
- Greatly expand the types of field that can be accurately modeled: from extended fringe field of large bore magnets to electrostatic reflecting mirrors.

Depth versus Momentum:
Example 1% versus 25% momentum range



Example Design of a New Gantry

- Superconducting magnets to reduce weight and size
- Locally FFAG achromatic bending section (AG-CCT) to increase momentum acceptance and hence reduce the demand on the speed of ramping the field
- A test of the feasibility of the AG-CCT concept



Summary of Functional Requirements

Parameter	Acceptable	Desirable
Angular range of gantry (°)	180	360
Proton acceptance (2σ) (π mm-mrad)	10	30
Beam size at iso-center (2σ) (mm)	6	4
Beam energy range (MeV)	70 to 220	60 to 250
Minimum space from the last magnet to the iso-center (m)	1	1
Minimum SAD (m)	2	3
Maximum sweeper angle (mrad)	± 80	± 60
Transverse scanning field (cm^2)	20×20	30×40
Transverse scanning speed	few cm/ms	few cm/ms
Momentum range w/o ramping superconducting magnets (%)	$> \pm 10\%$	$\pm 50\%$
Momentum scanning rate, dp/dt	10%/s	10%/s
Transverse field scanning rate (using 5 mm steps)	1 step/ms	1 step/ms

Design Considerations and Consequences

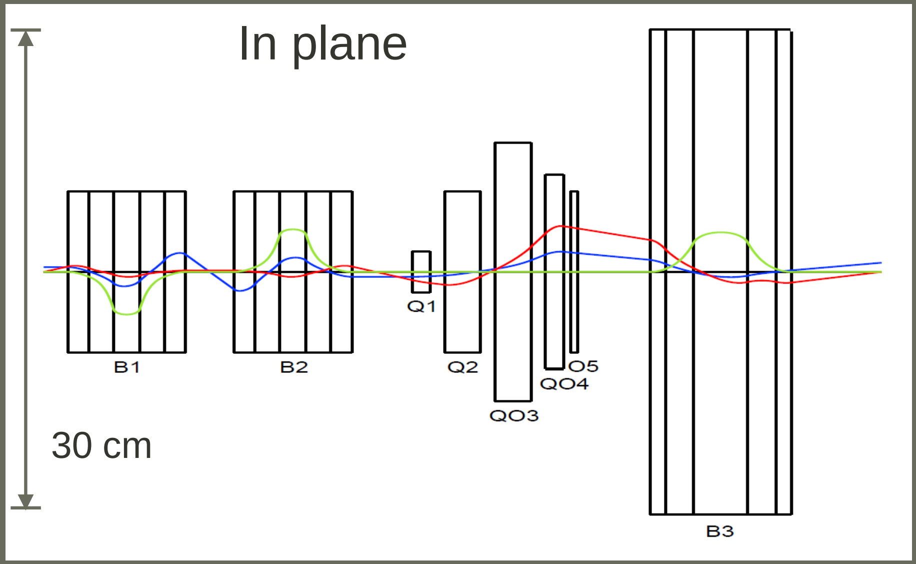
- Relatively large SAD (3 m or more roughly), leading to short focal length for B3 and large excursion of scanned beam in the magnet thus nonlinearity
- Resistive quadrupoles necessary to form image with reasonable beam size at the iso-center
- Short focal lengths of the resistive quadrupoles lead to large beam size in QO3, generating large 3rd order geometrical aberrations
- 3 resistive octupoles added to minimize 3 main 3rd order geometrical aberrations

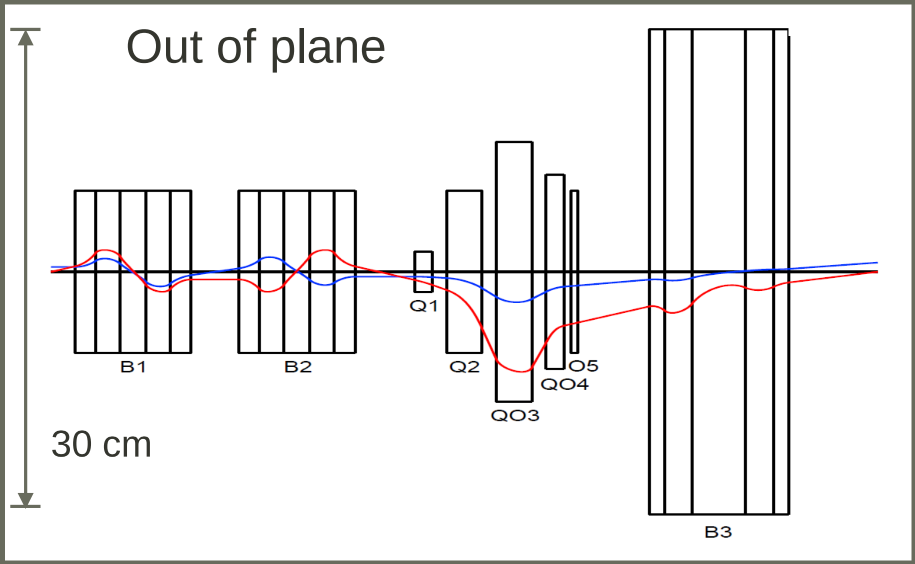
From Simple to Realistic Models

1. Start with the sharp cut off field (SCOFF) model
   - Principle ray of the whole gantry
   - Centroid of the scanned beam
2. Full field model of the AG-CCT magnets

The Principal Rays

- Illustration of the principal rays using the SCOFF model
- A stigmatic one to one image formed after B2, where a collimator can be placed to define the beam entering the next section
- A stigmatic image is formed at the iso center to control the size of the beam spot

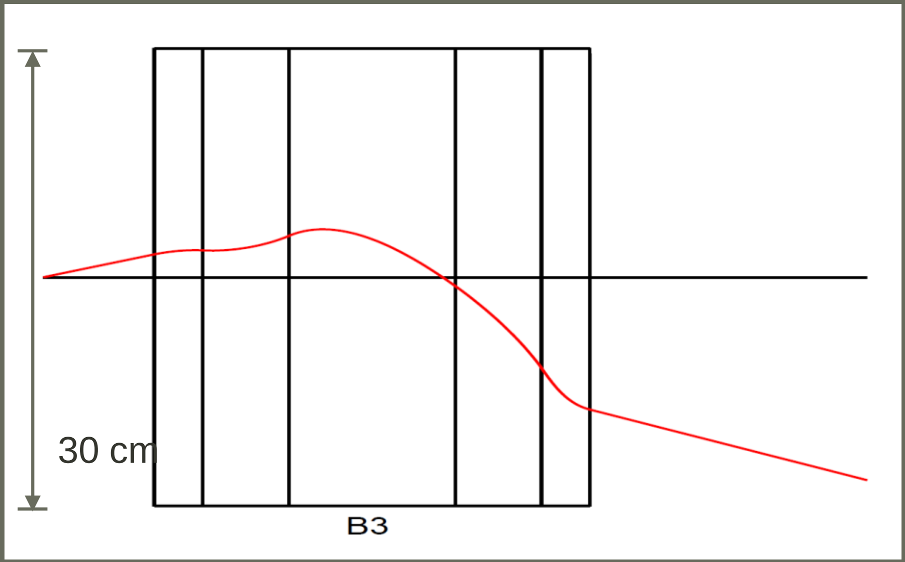




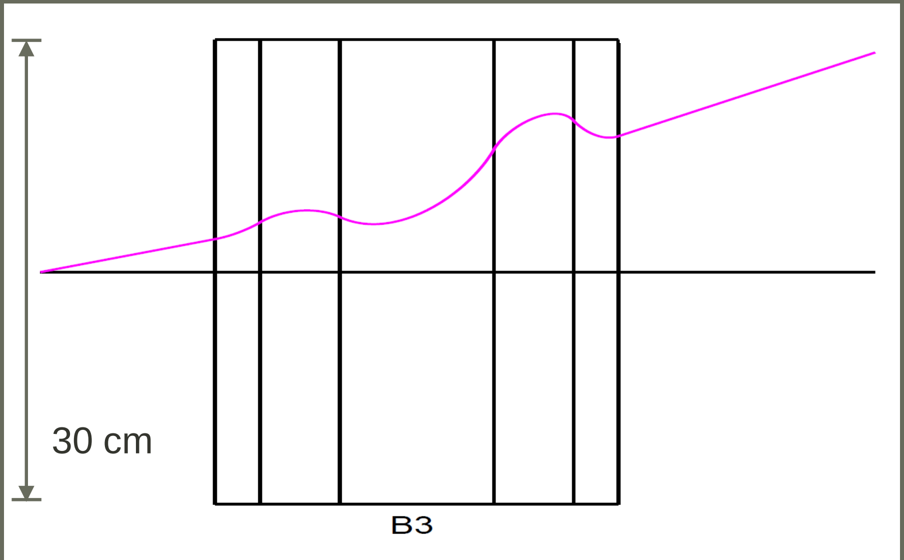
The bore diameters of B1, B2 and B3 are 10, 10 and 30 cm, respectively

Centroid of the Scanned Beam

- Illustration of the beam centroid being scanned using the SCOFF model
- The source to axis distances are 3.6 m and 3.3 m for in-plane and out-of-plane, respectively



In plane

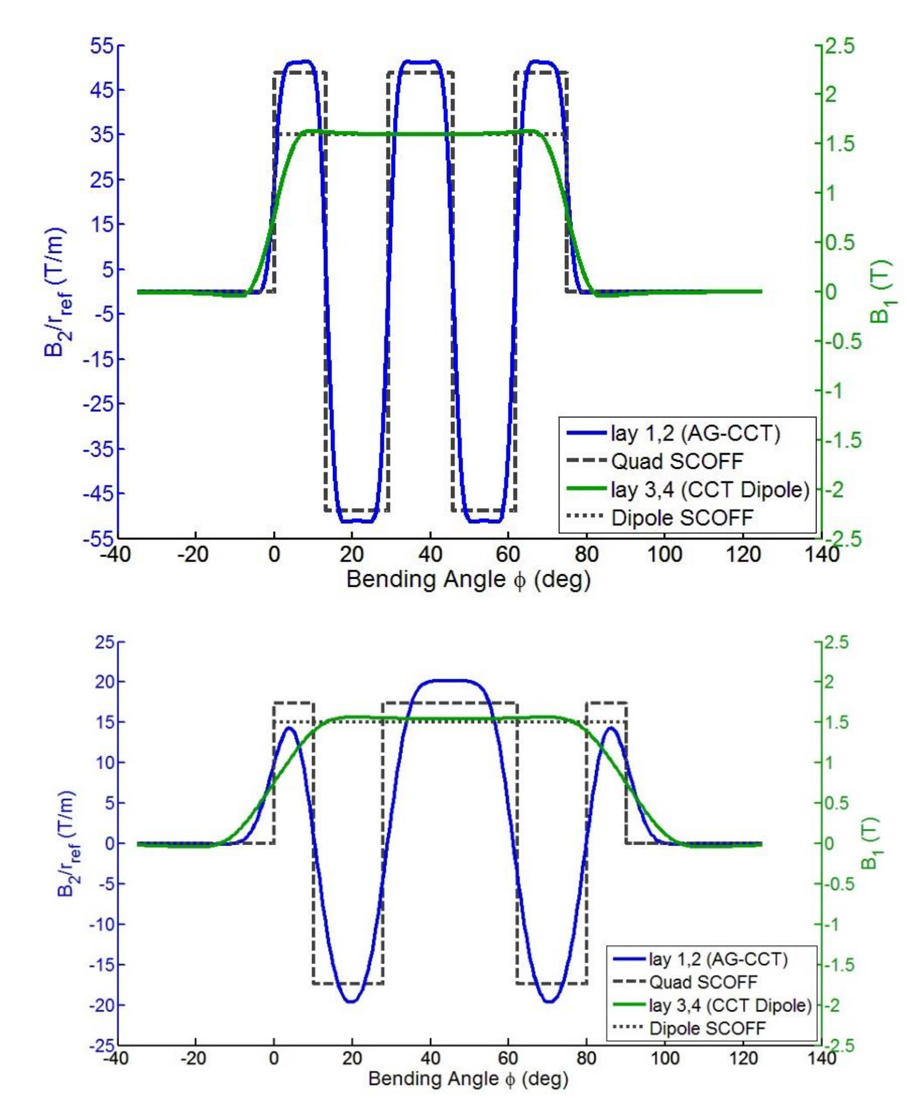


Out of plane

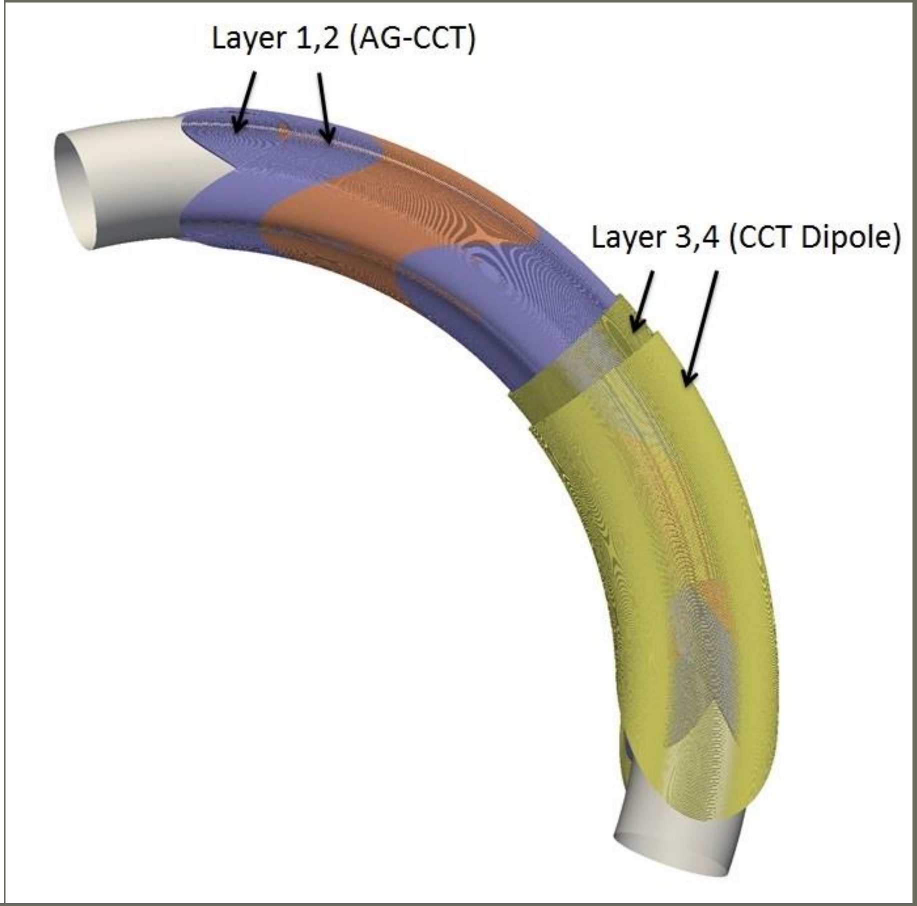
Modeling the AG-CCT Magnets

- Field in the bore generated by the coils, allowing the modeling of the field distribution using the coils only (Biot-Savart law)
- Field model infinitely differentiable, enabling the computation of Taylor maps of any given order (5^{th} order map used here)
- Establishes closed loop between magnet design and beam optics optimization
- Enables systematic sensitivity study of parameters such as coil positions.

The AG-CCT Magnets: Comparison of SCOFF and Real Field



Compact winding results in short and smooth transitions



Lists of Parameters

TABLE II. Properties of the 90° and 75° AG-CCT magnets (SCOFF model)

	75° (B1,B2)	90° (B3)
Bore radius (mm)	50	150
Bending radius (m)	1.25	1.25
Gradient (T/m) at 217 MeV	48.74	17.43
F Angle (degree)	13.38	10.02
D Angle (degree)	15.80	17.79
F Angle (degree)	16.63	34.39
D Angle (degree)	15.80	17.79
F Angle (degree)	13.38	10.02

TABLE III. Properties of the normal conducting resistive magnets

	Q1	Q2	QO3	QO4	O5
Radial aperture (mm)	12.5	50	80	60	50
Length (m)	0.25	0.5	0.5	0.25	0.1
Gradient (T/m)[a]	7.55	18.0	-12.1	16.2	0.0
Octupole (T/m^3)[a]	0.0	0.0	-17.8	426	-1069

[a] Note that the quadrupole and octupole strengths are peak values at 217 MeV.

TABLE IV. Beam and linear gantry properties calculated from SCOFF model

Emittance[a]	30 πmm-mrad
Beam size at entrance[b]	3 mm
Beam divergence at entrance[b]	10 mrad
Beam size at collimator[b]	3 mm
Beam divergence at collimator[b]	10 mrad
Beam size at iso-center[b]	5.7 mm
Beam divergence at iso-center[b]	5.26 mrad
Beam energy range (MeV)	70 to 220
In-plane SAD	3.6 m
Out-of-plane SAD	3.3 m
Space from the end of B3 to the iso-center	1.25 m
Maximum sweeper angle	±30 mrad
In-plane sweeper response at iso-center	4.4 mm/mrad
Out-of-plane sweeper response at iso-center	5.7 mm/mrad

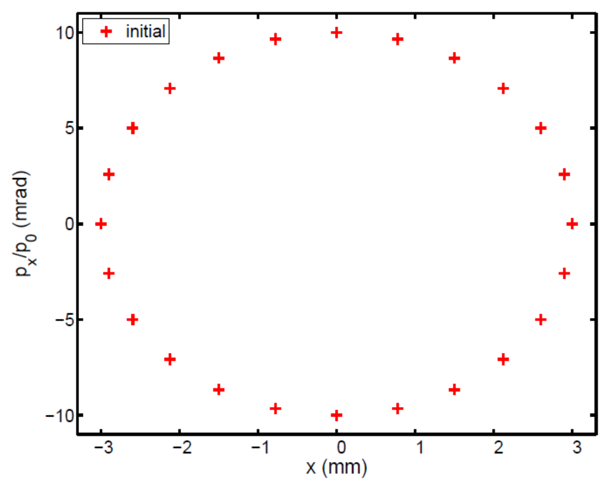
[a] Emittance is the same for in-plane and out-of-plane directions
[b] Beam is round at this location

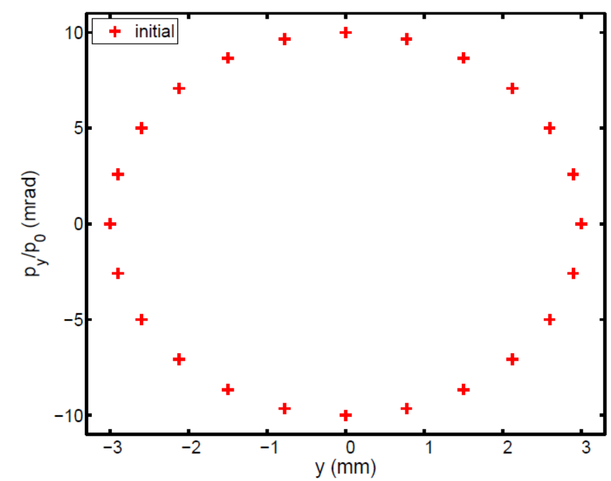
For the full field from the coils, gradient of B1, B2 and B3 are stronger by 4%, 13%, respectively. The in-plane SAD is 8.4% longer and the out-of-plane SAD is 4.6% shorter. The in-plane and out-of-plane sweeper responses are 10.3% stronger and 7.5% weaker, respectively.

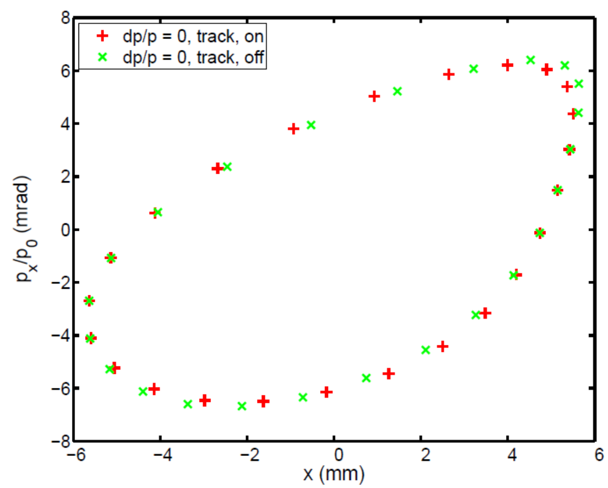
Organization of Modeling Results

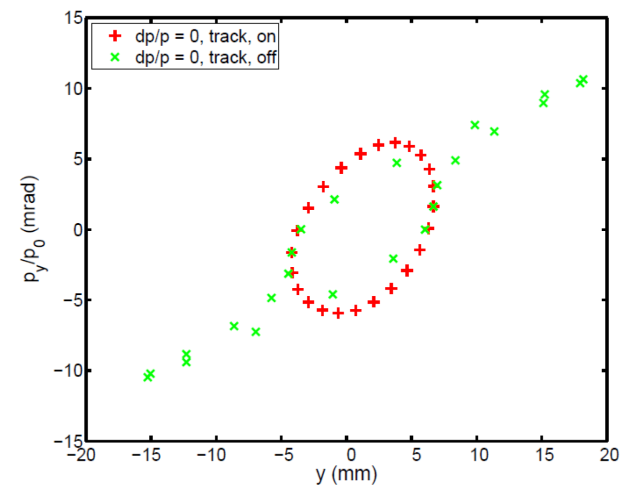
1. On-momentum, no scanning
2. Off-momentum, no scanning
3. Scanning with zero emittance beam
4. Scanning with full emittance beam

1. On-Momentum: Effect of the Aberrations







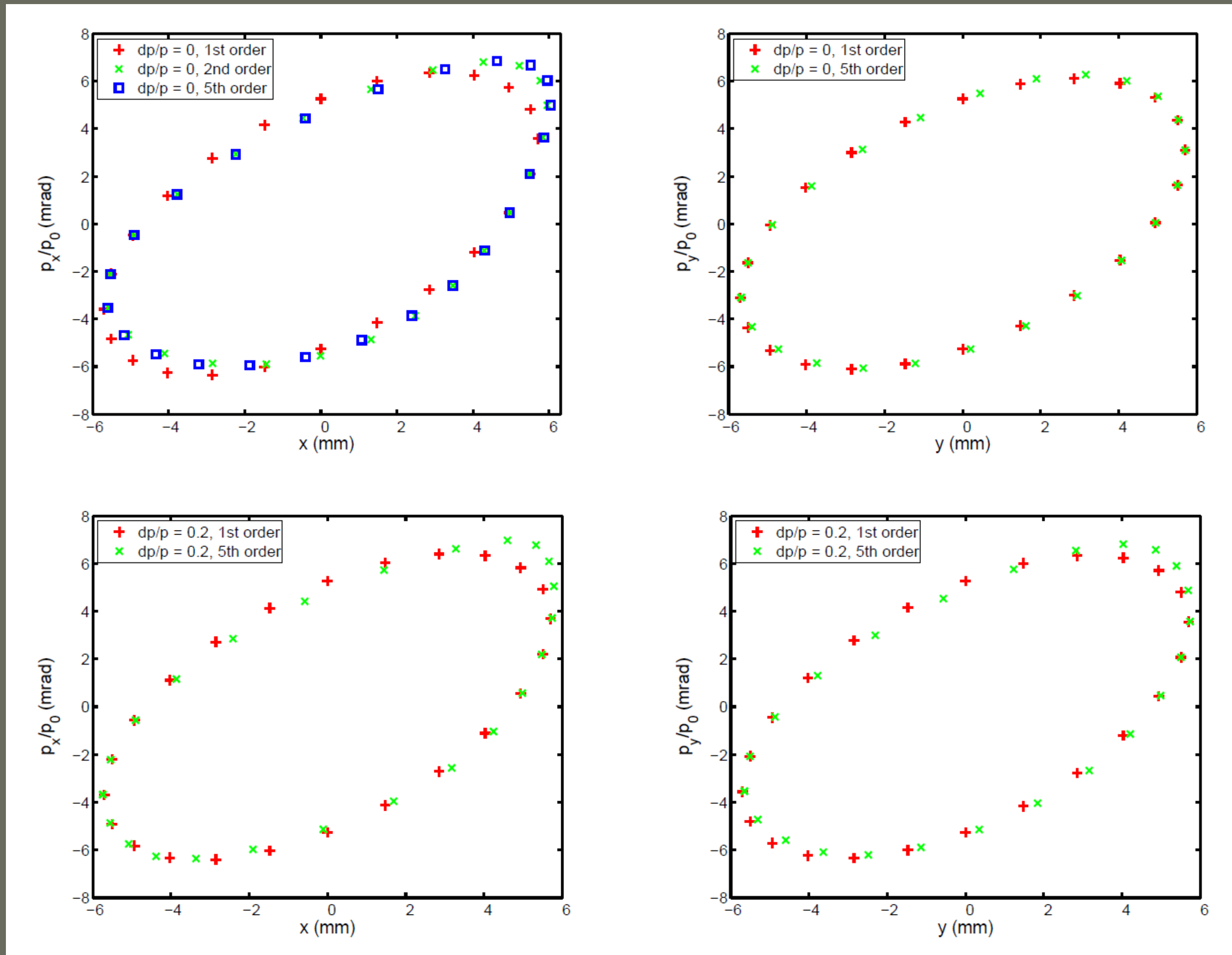


Correcting the spherical aberrations allows the restoration of the image

2. Large Momentum Range

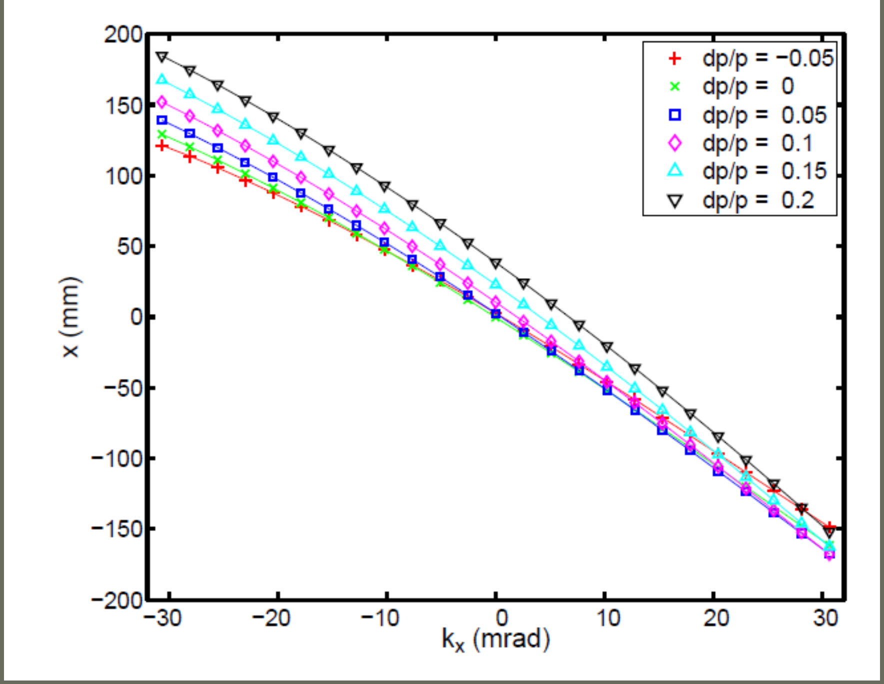
dp/p = 0

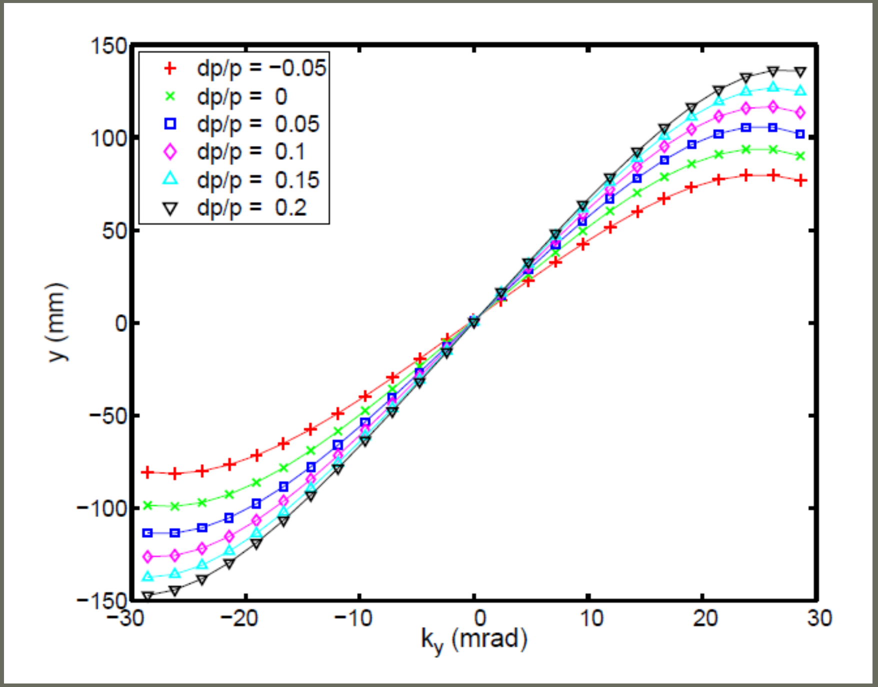
dp/p = 20%



- Upper left plot shows that the remaining aberrations are second-order geometrical. Three octupoles correct aberrations in a large range of momentum.
- Quadrupoles and octupoles are adjust for each momentum, AG-CCT are fixed

3.The Effect of the Aberrations on Scanning



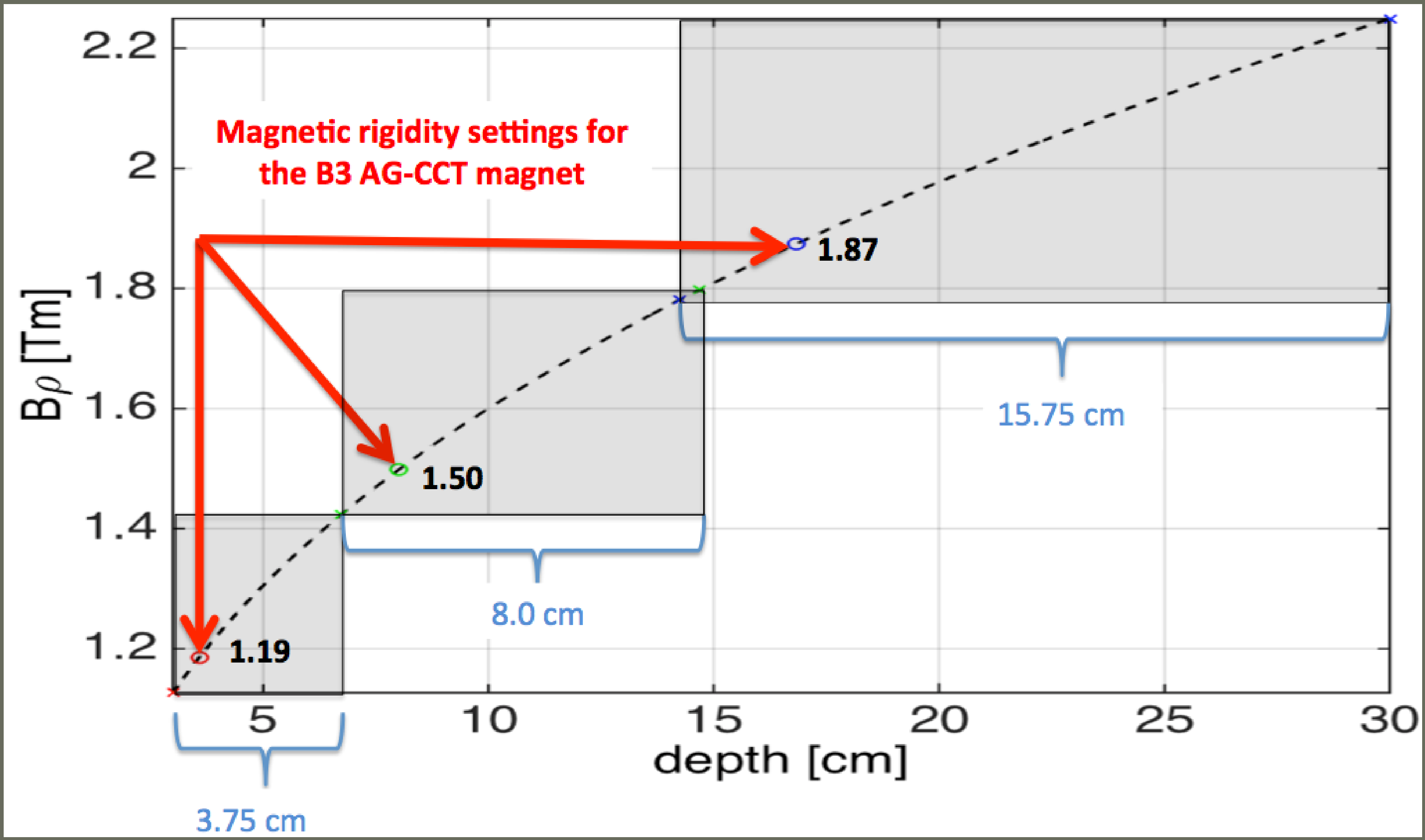


In-plane

Out-of-plane

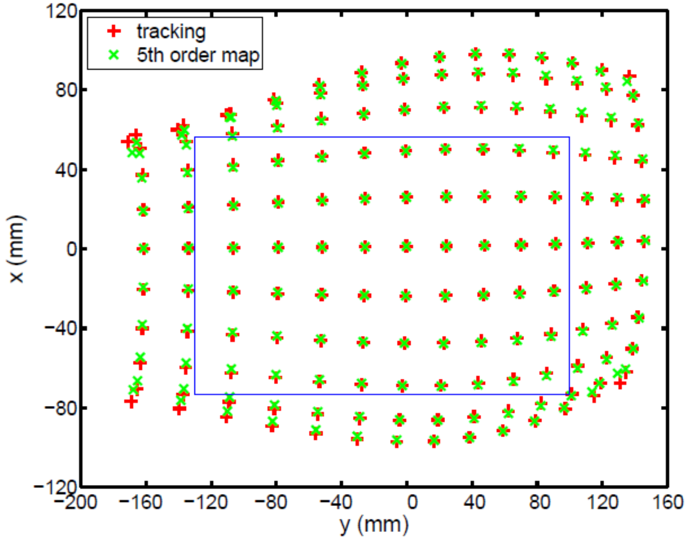
For dp/p < -5%, the scanning field is severely limited, thus the momentum acceptance of -5% to +20% (25% total). With appropriate sextupole and octupole fields, it is conceivable that that nonlinearity can be minimized.

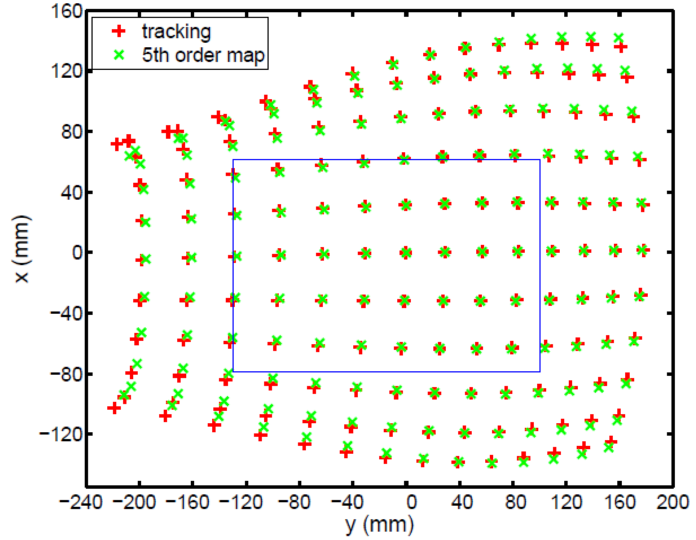
3. Regions of Fixed Field

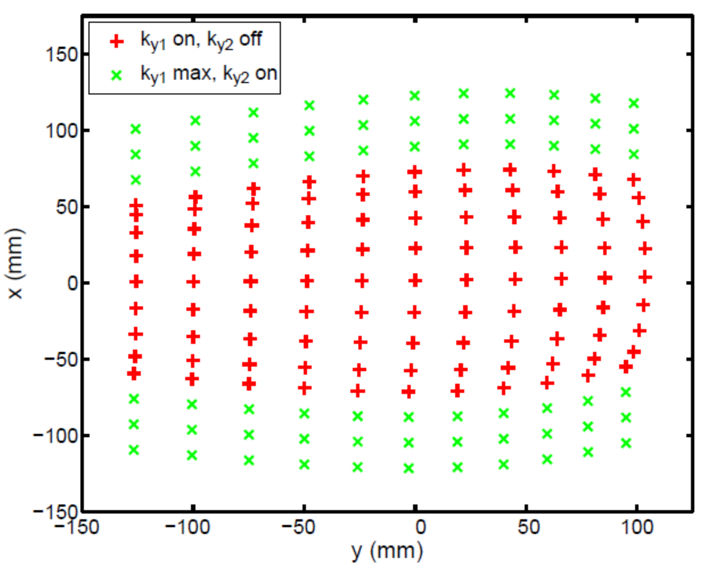


Allows the magnetic field fixed for any field of the gantry for most cases.

3. Shape of the Scanning Field

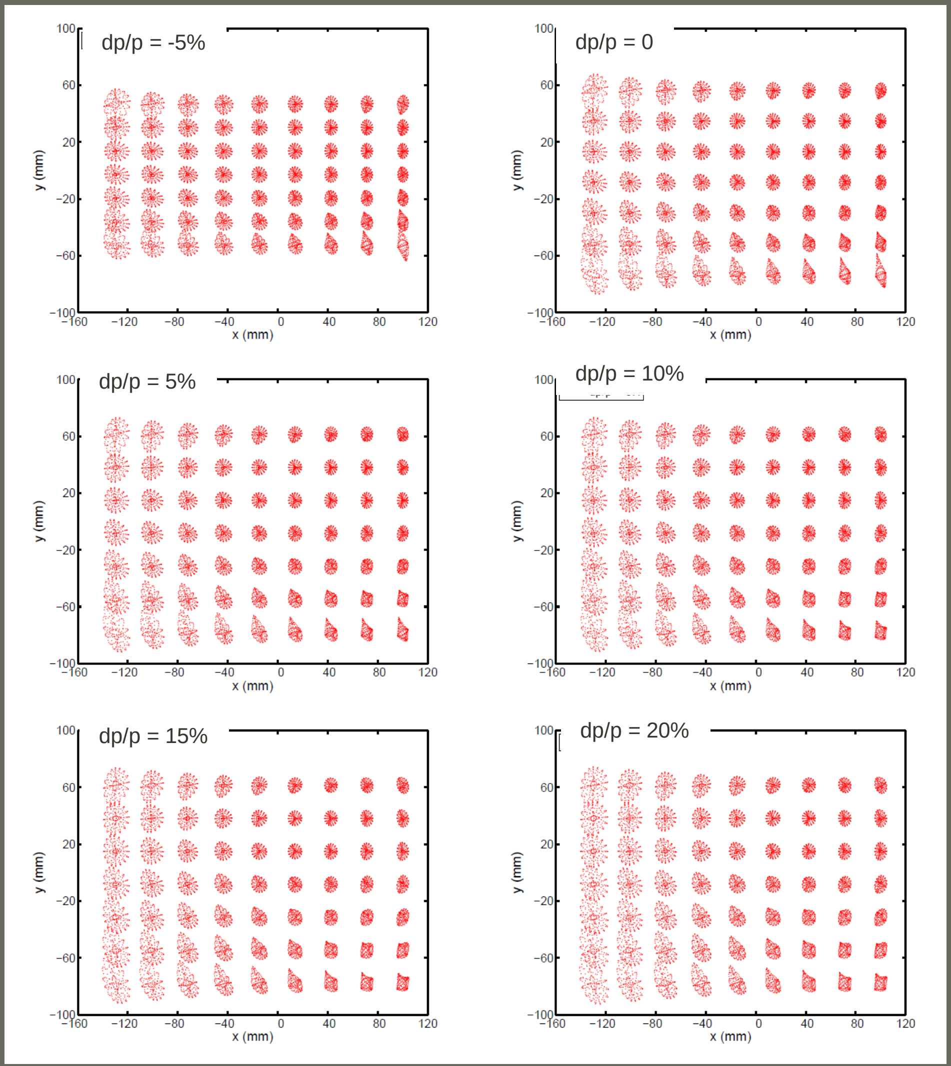


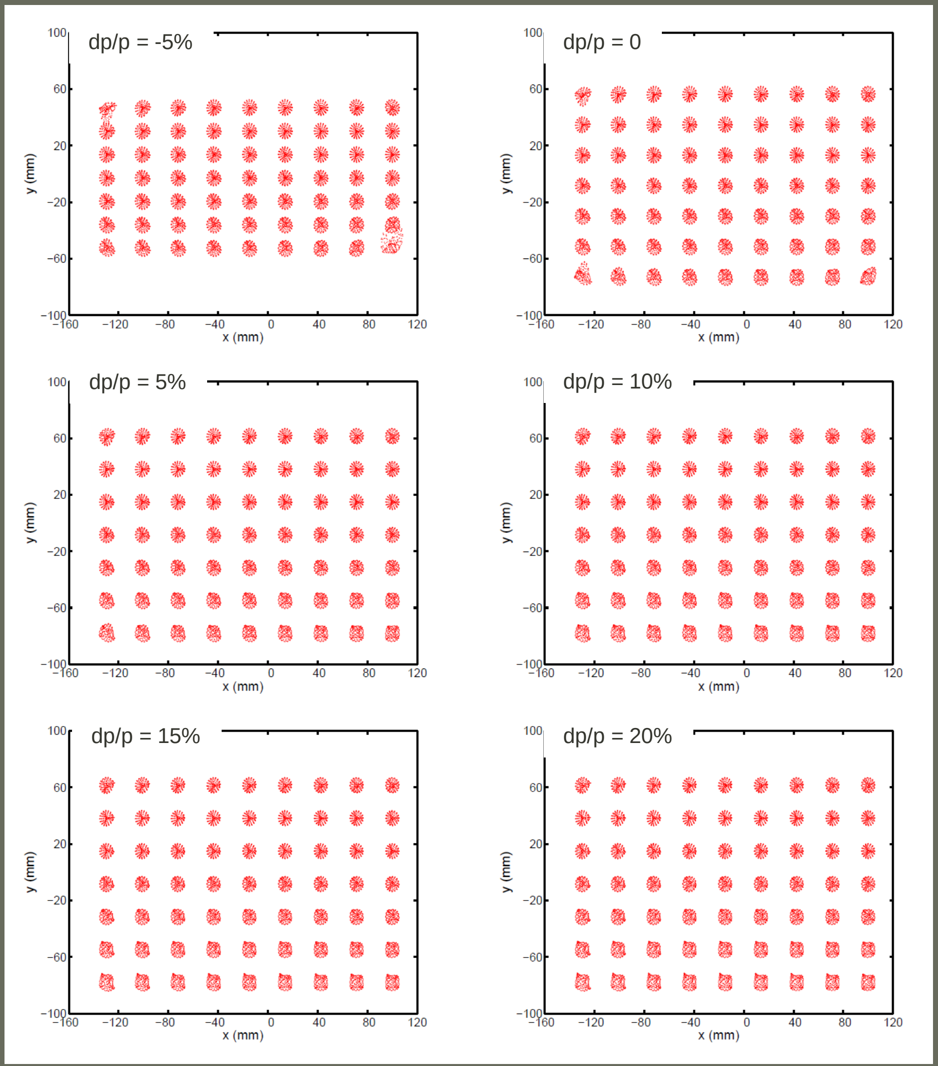




- The field of 230 mm by 140 mm can be achieved for 0 < dp/p < 20%.
- The field of 230 mm by 100 mm for dp/p = -5%.
- With a post scanning magnet, the field for dp/p = -5% can be enlarged.

4. Regions of Fixed Field





For each layer, adjusting only the scanning magnets

For each layer, adjusting all resistive magnets with the scanning magnets

Summary

- Beam optics for large aperture magnets is rather different from that for small aperture magnets
- A good layout with small remaining aberrations is important for a good design
- Aberration correction becomes a necessity
- Large bore AG-CCT superconducting magnets make possible new generation of light weight and cost effective gantries
- Modern map method enables close collaboration between magnet design and beam optics, which tends to lead to more efficient design process and better designs.
- More generally, AG-CCT magnet concept can be extended to include other multipoles (dipole, sexutpoles, octupoles, et al.

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