Design and Simulation of High Momentum Acceptance Gantries for Ion Beam Therapy

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VARIAN medical systems

上海科技大学 ShanghaiTech University

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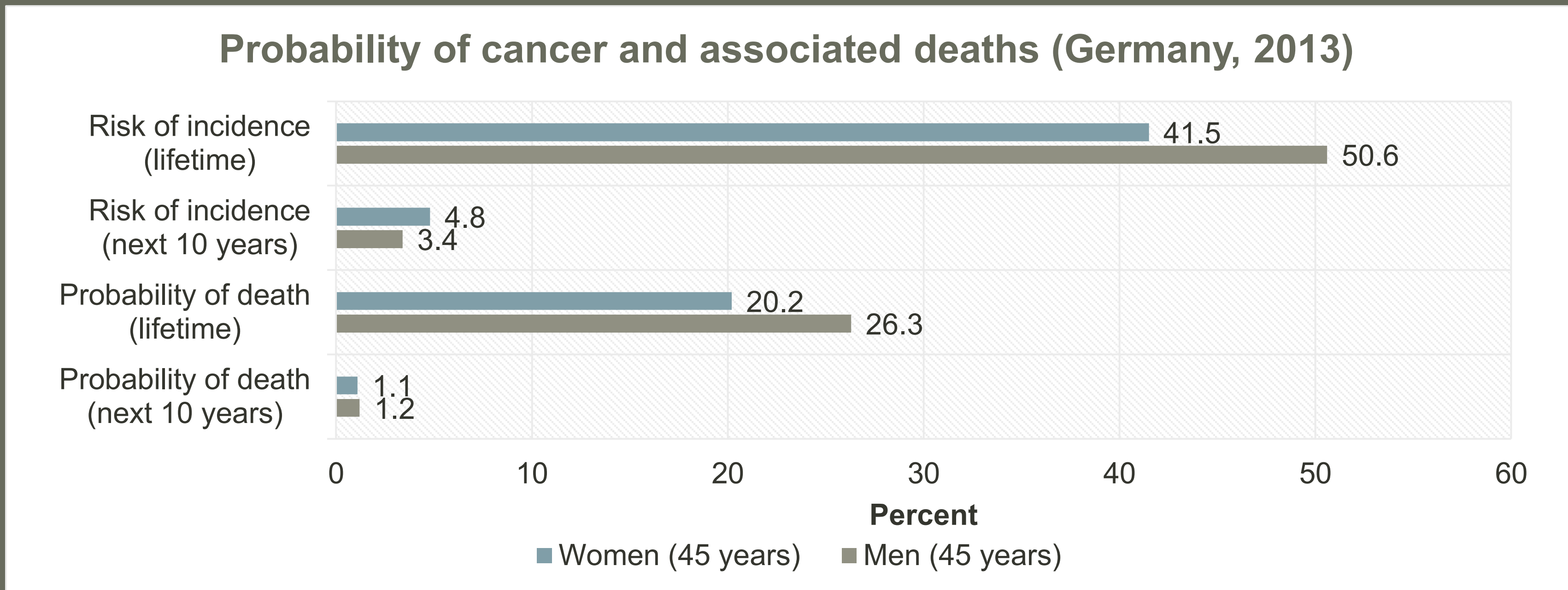
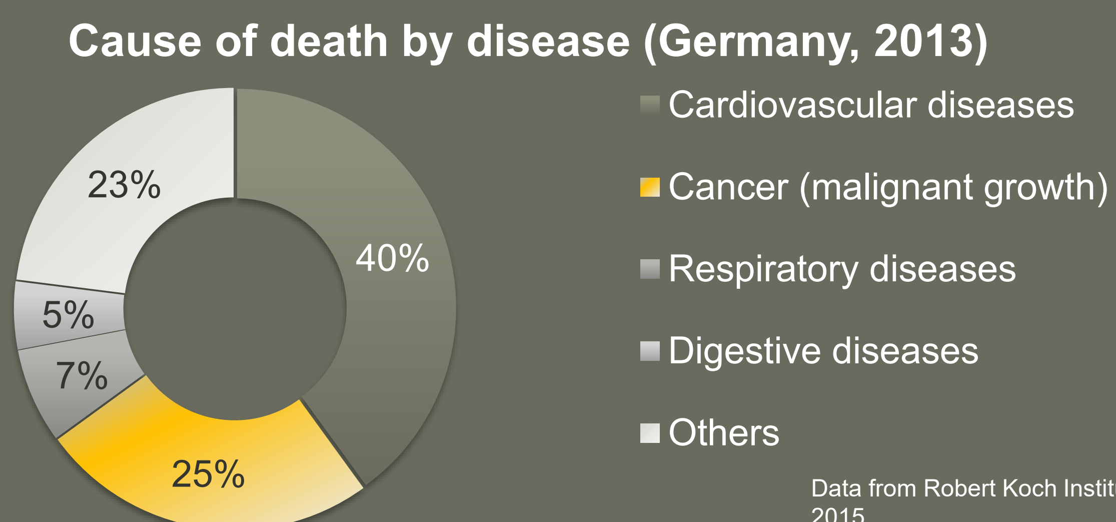
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

Outline

- Introduction/motivation
- Design methodology
- Optics of a new gantry and tracking results
- Summary

Relevance and Significance of Cancer





Data from Robert Koch Institut „Krebs in Deutschland“, 10th Edition, 2015,
and Statistisches Bundesamt (Februar 2015)

The three Treatment Options for Cancer

I. **Surgery**
   The physical removal of the tumor
II. **Chemotherapy**
   Treatment with pharmaceutical agents
III. **Radiotherapy**
   Killing of tumor cells
   with **ionizing radiation**

Often these options are combined.

Over 50 % of all treatments involve radiotherapy.

Mircoscopic mechanisms of radiotherapy:

Either: Direct hits damage DNA string of a cell core.

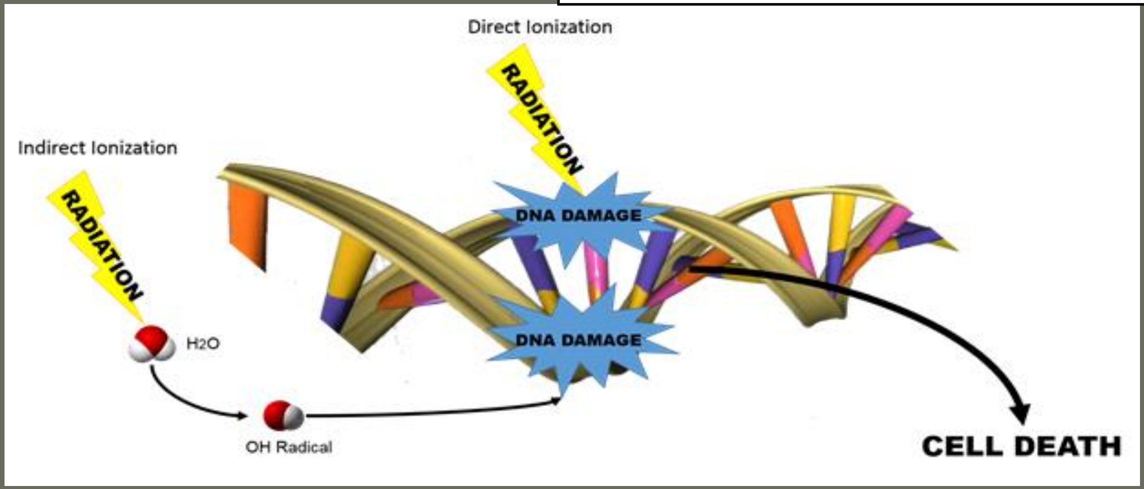
Or: Molecules are ionized, leading to aggressive radicals.
Chemical processes damage DNA strings.

Result: Cell death.

Problem:
Healthy cells are vulnerable to radiation, too.

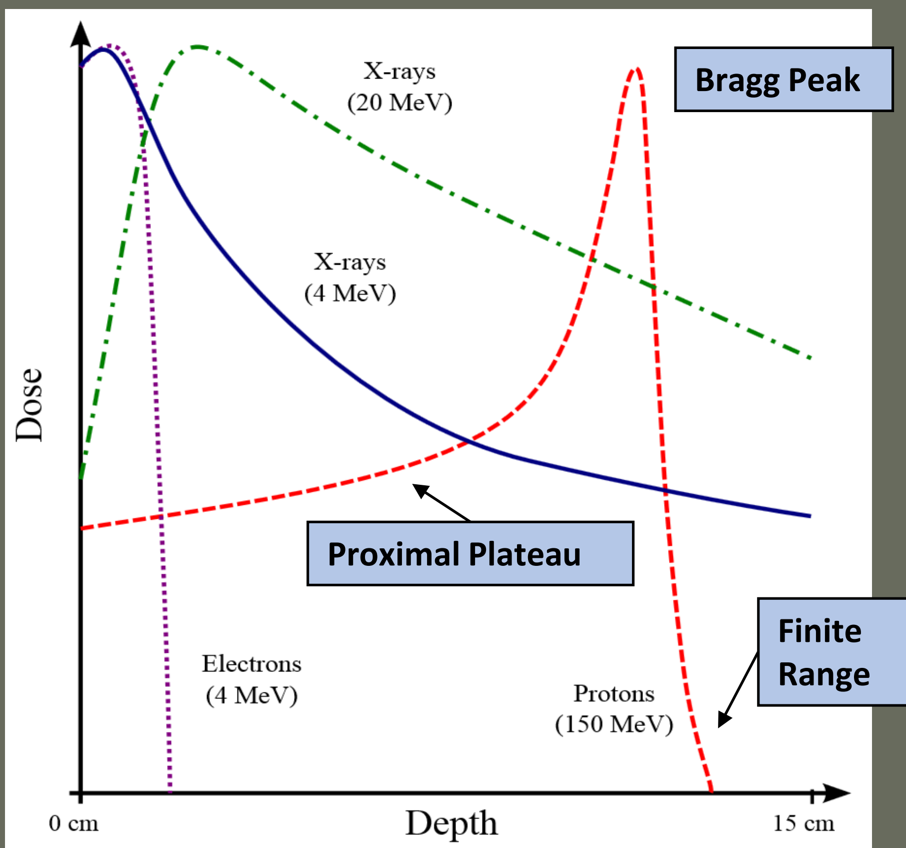
Goal:
Target tumor cells and minimize irradiation of healthy tissue.

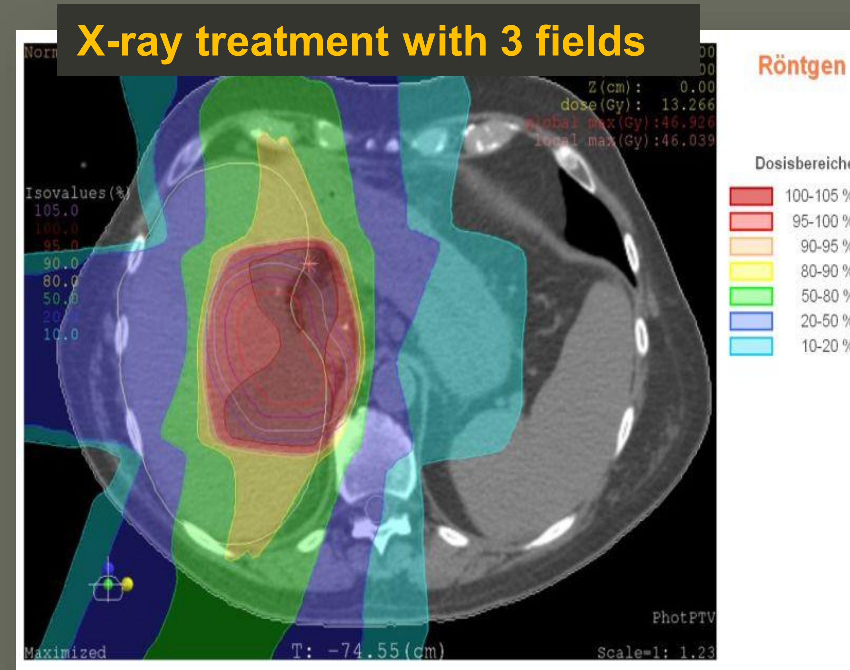
Segmenting into many fractions helps, because healthy tissue can recover faster from damage than the pathological tumor tissue.

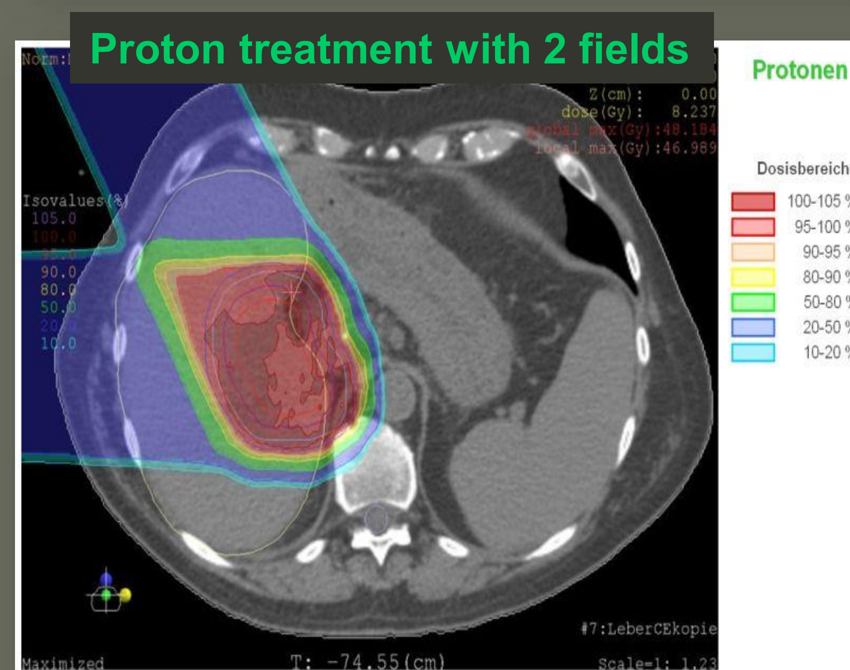


Source:
cubocube.com

The Promise of Protons

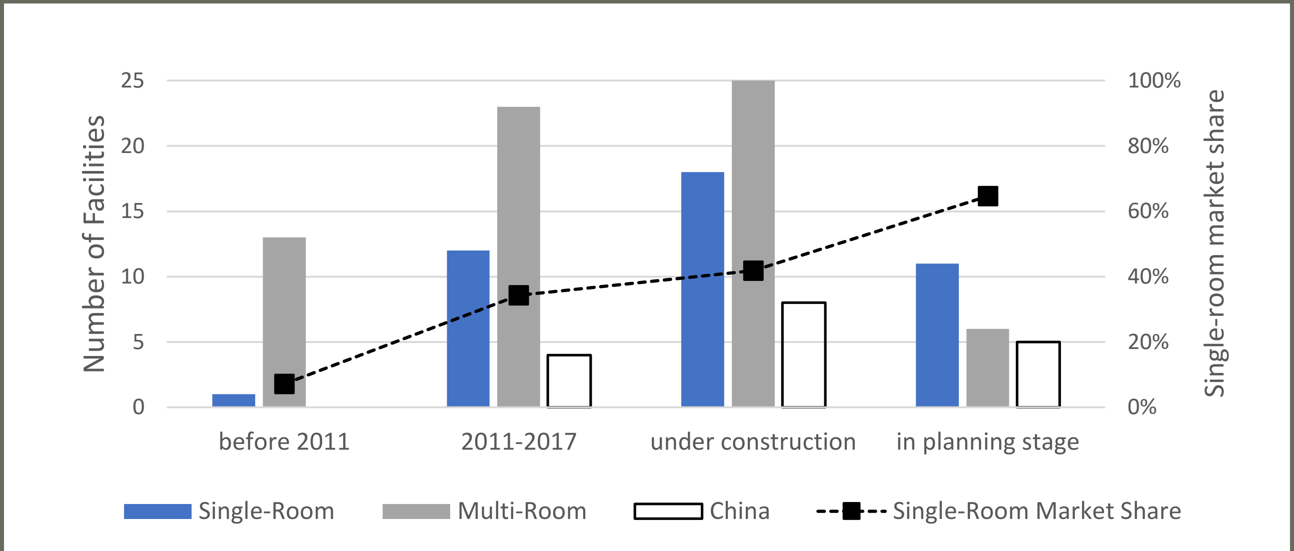




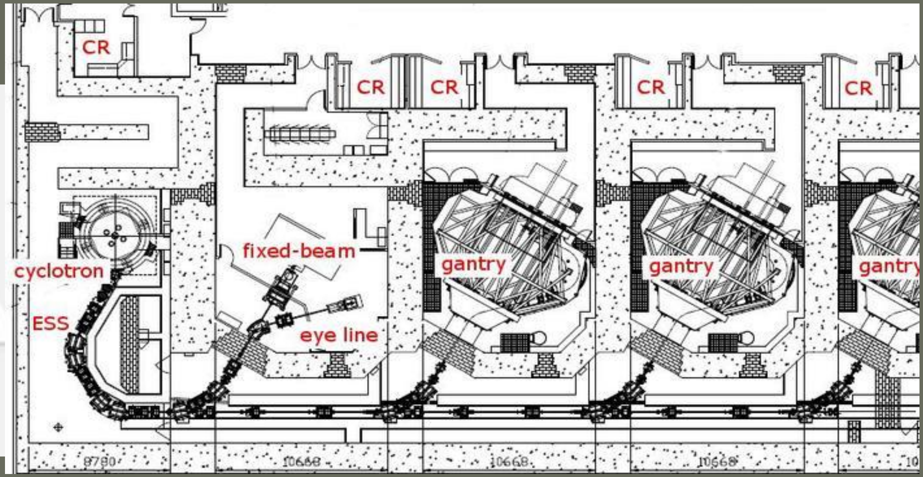


Proton Facilities and Trends

- Clear trend towards affordable (<30 M$) single-room systems.
- Gantry sizes becomes dominant --> especially crucial for construction costs that account for almost 50%.



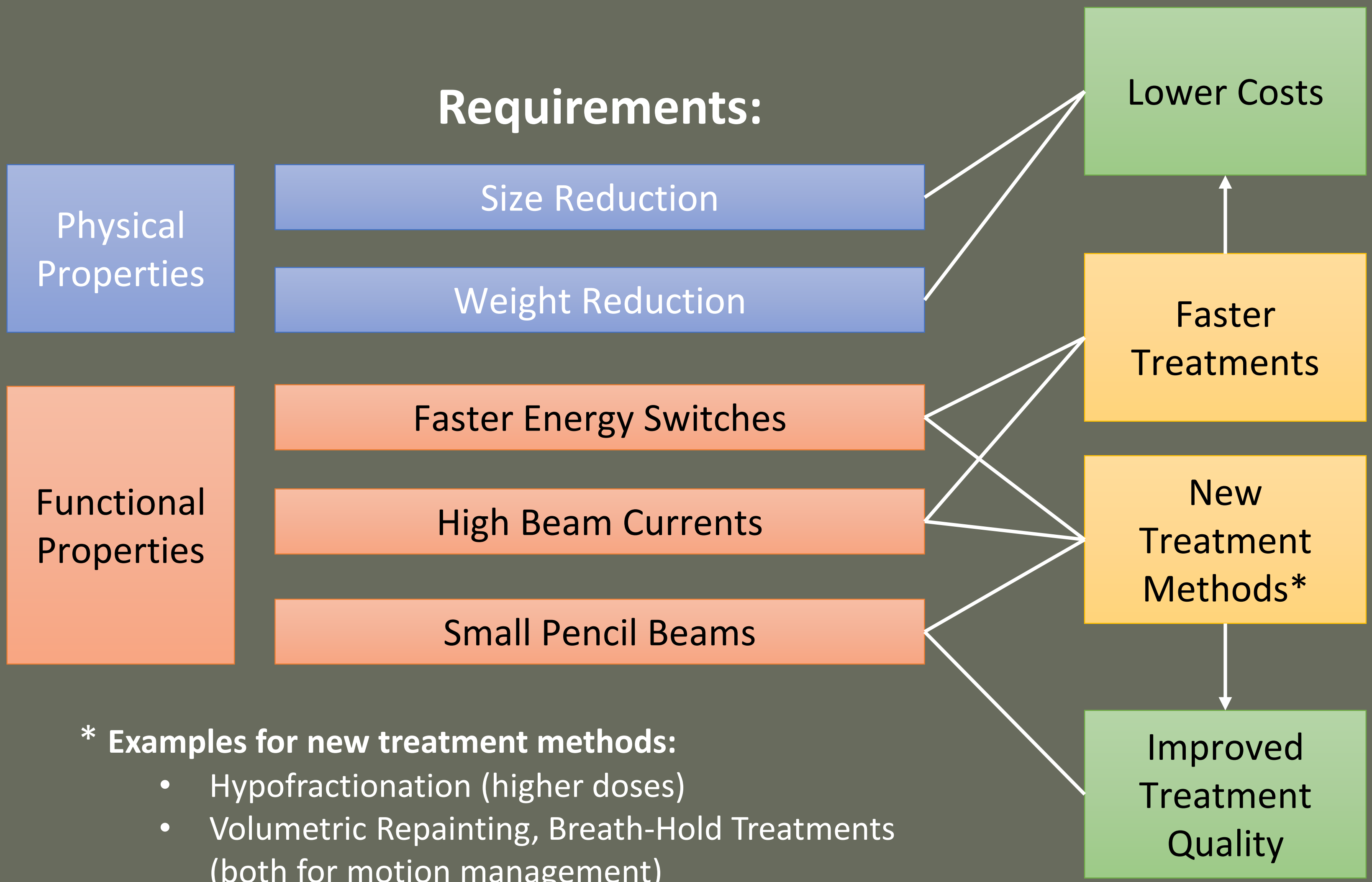
Layout of Single-Room Solution (Varian)



Layout of Multi-Room Solution (WPE Essen, IBA)

Future requirements for proton gantries

(cyclotron powered and with pencil beam scanning)

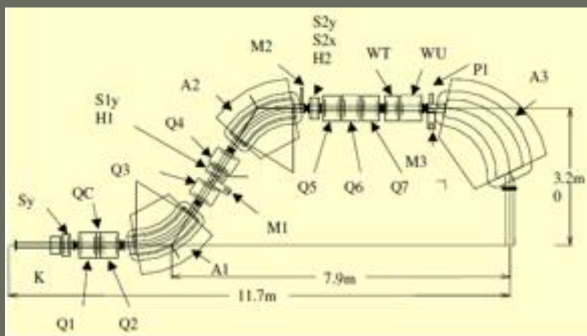


* **Examples for new treatment methods:**

- Hypofractionation (higher doses)
- Volumetric Repainting, Breath-Hold Treatments (both for motion management)

Gantries are Large and Heavy

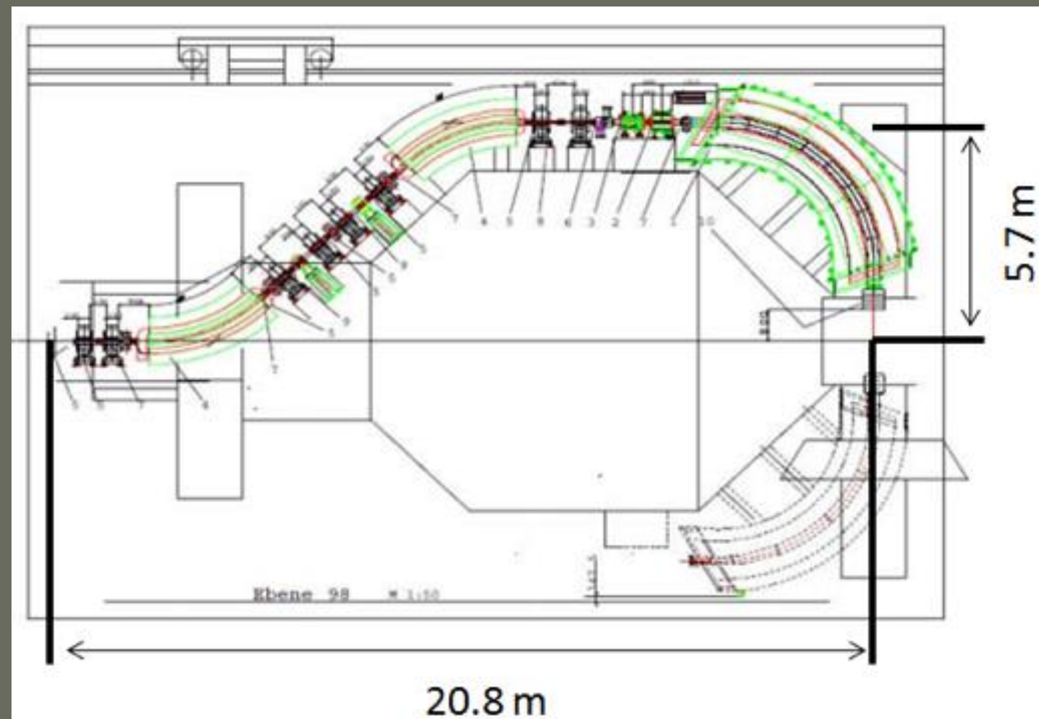
PSI-2
(Proton)



~8 m

~12 m

HIT
(Carbon)



~13 m

~22 m

Weight

- Proton gantries weight about **100 tons**
- HIT carbon gantry weighs **600 tons**

1/10 of the Eiffel Tower

courtesy of D. Robin

Ways to Make Gantries Small and Light

- Stronger bending field reduces the size. Superconducting magnets required with field > 2 T
- Weight significantly reduced due to the fact that almost no iron is needed.
- Difficulty in fast ramping leads to the desire for large momentum acceptance.
- Compared to upstream scanning gantries, downstream scanning ones are usually larger in height, but allows smaller aperture magnets.
- All the requirements above present exciting challenges to magnet and beam optics designers.

Landscape of Gantry R&D

Operational

Proton gantries only

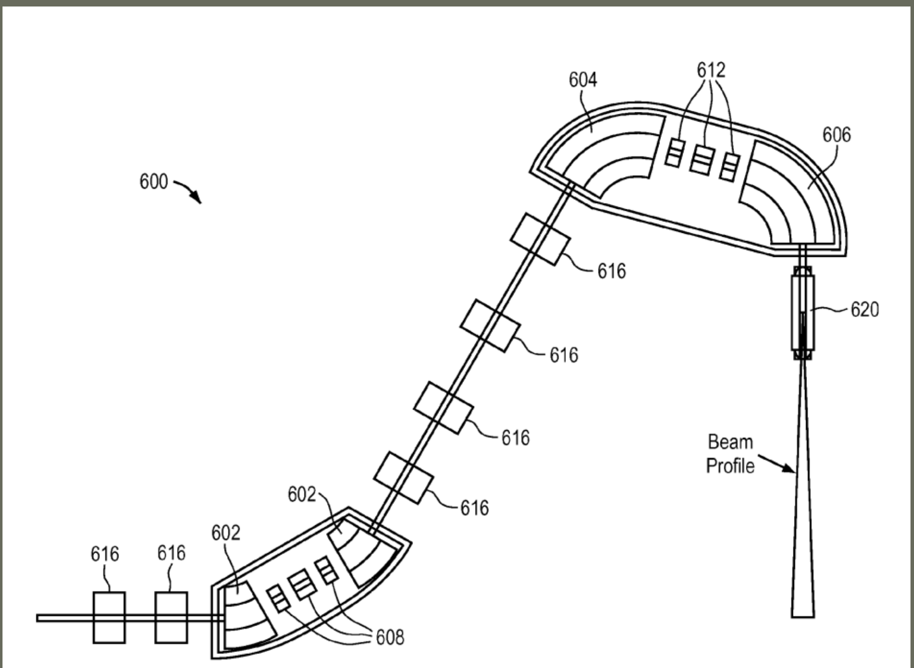
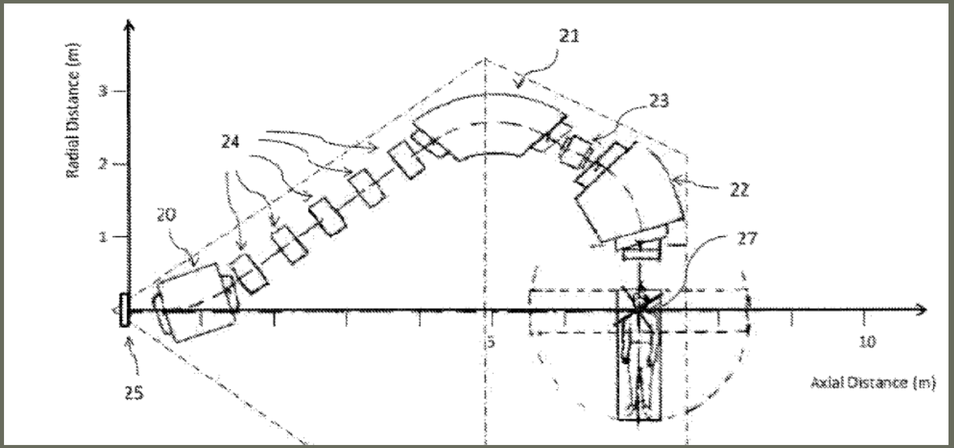


FIG. 5

John M. Cameron, Vladimir Anferov,
Timothy A. Antaya, US 2011/0101236A1

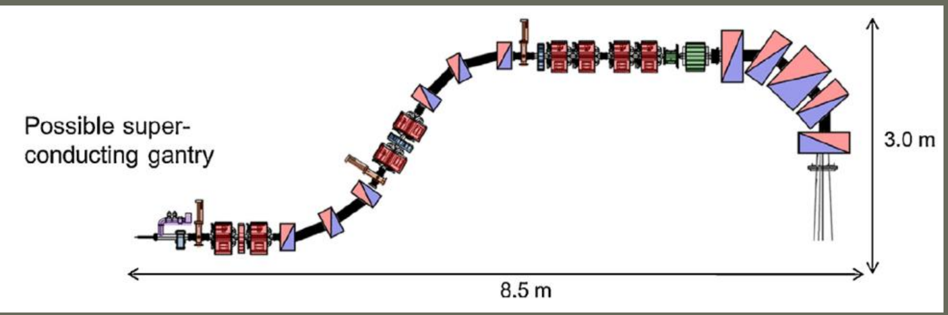
IBA Proteus ONE



Yves Jongen, US 8,766,218 B2 (2014)

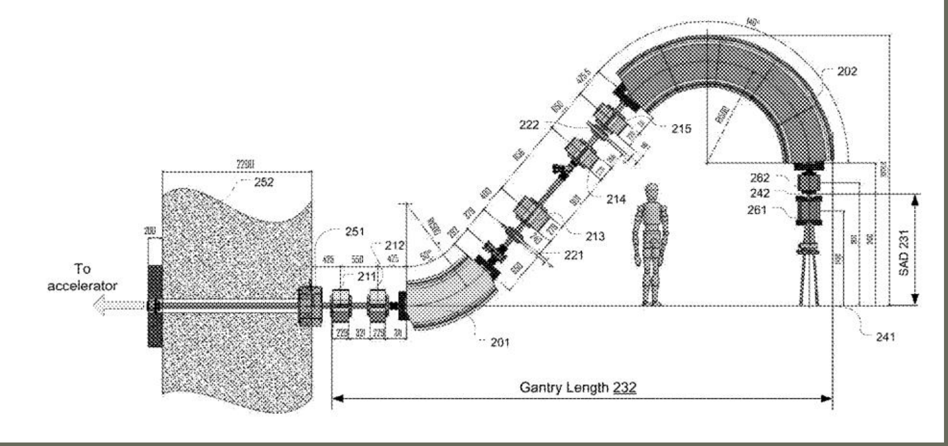
Landscape of Gantry R&D (cont)

Underdevelopment

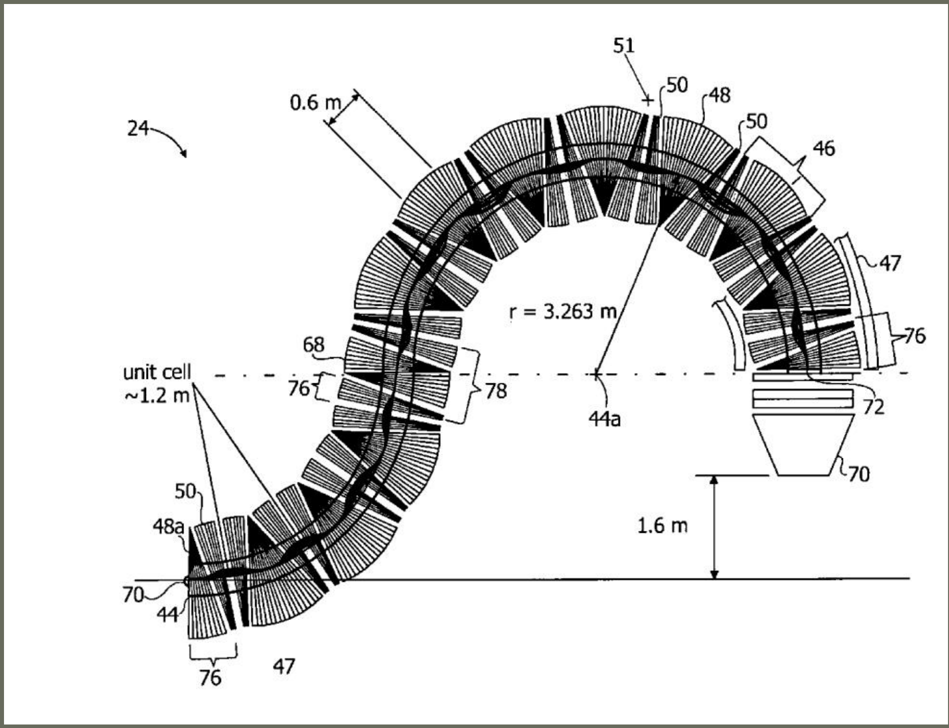


A. Gerbershagen et al. Z. Med. Phys. 26 (2016)

FFAG

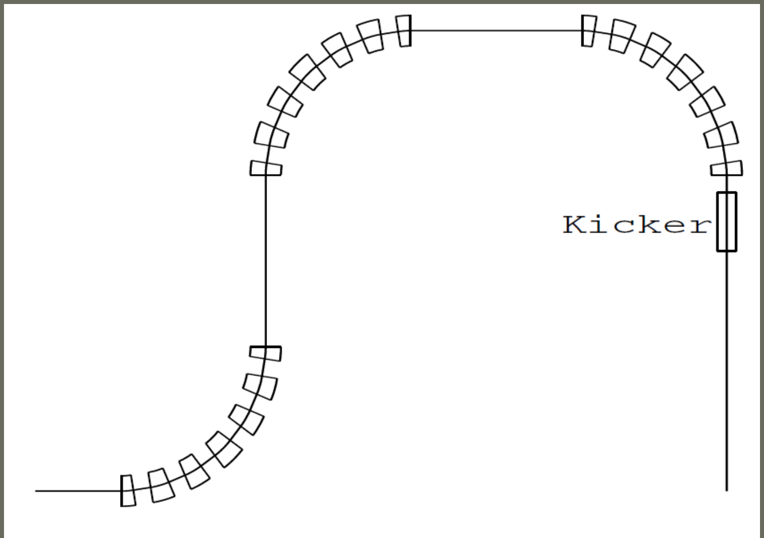


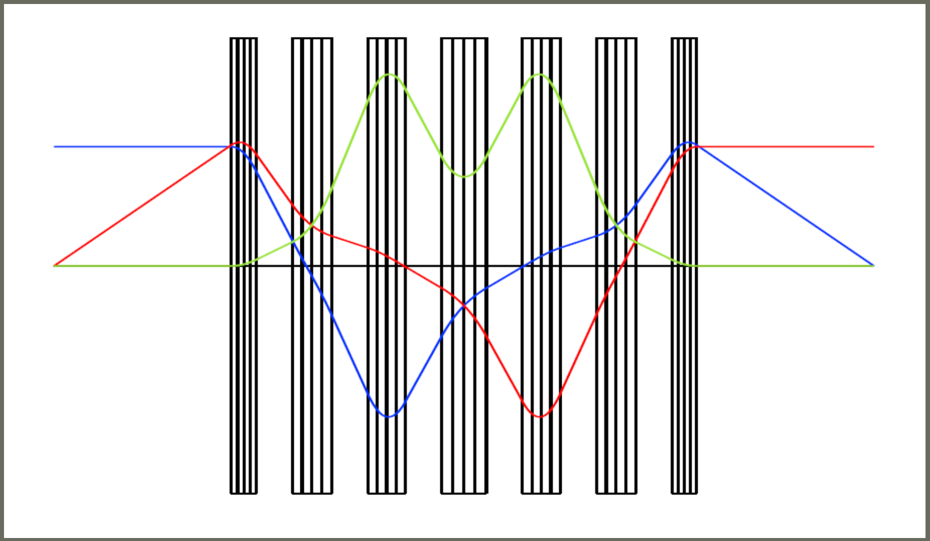
Vladimir ANFEROV, Alexander WINNEBECK
US 2018 / 0178038 A1

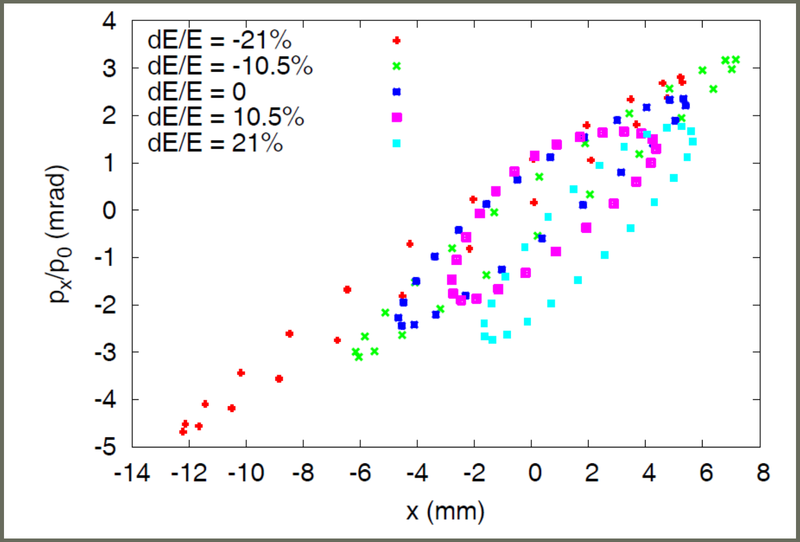


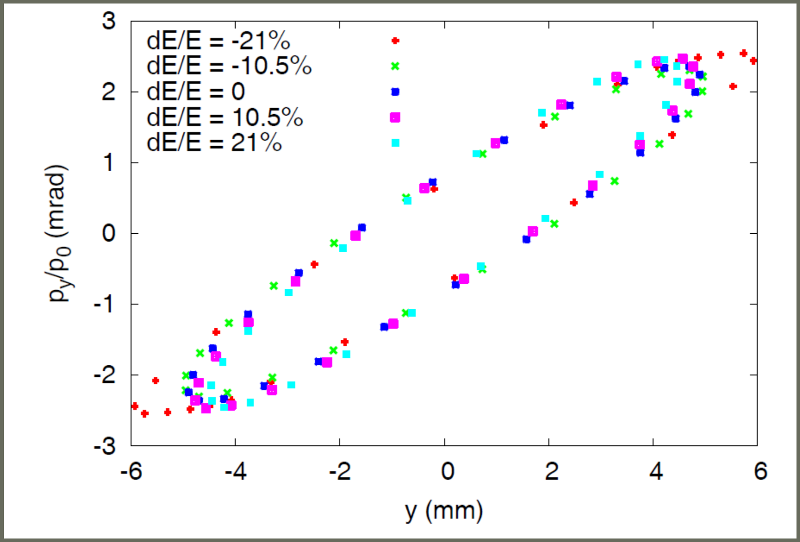
Dajen Trobjevic, US 7582886 B2

Our First Attempt





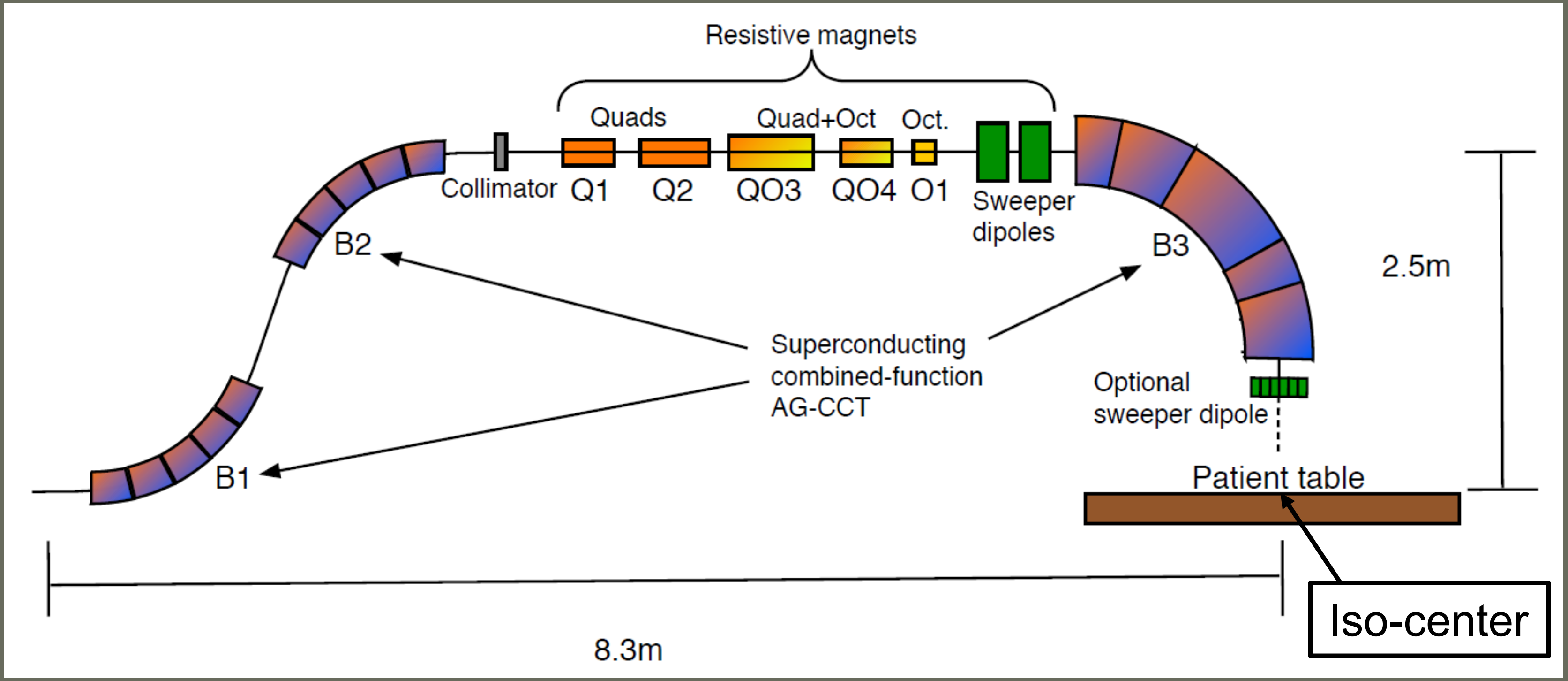




W. Wan, D. Robin, A. Sessler and C. Sun, Proceedings of IPAC2012, p4100

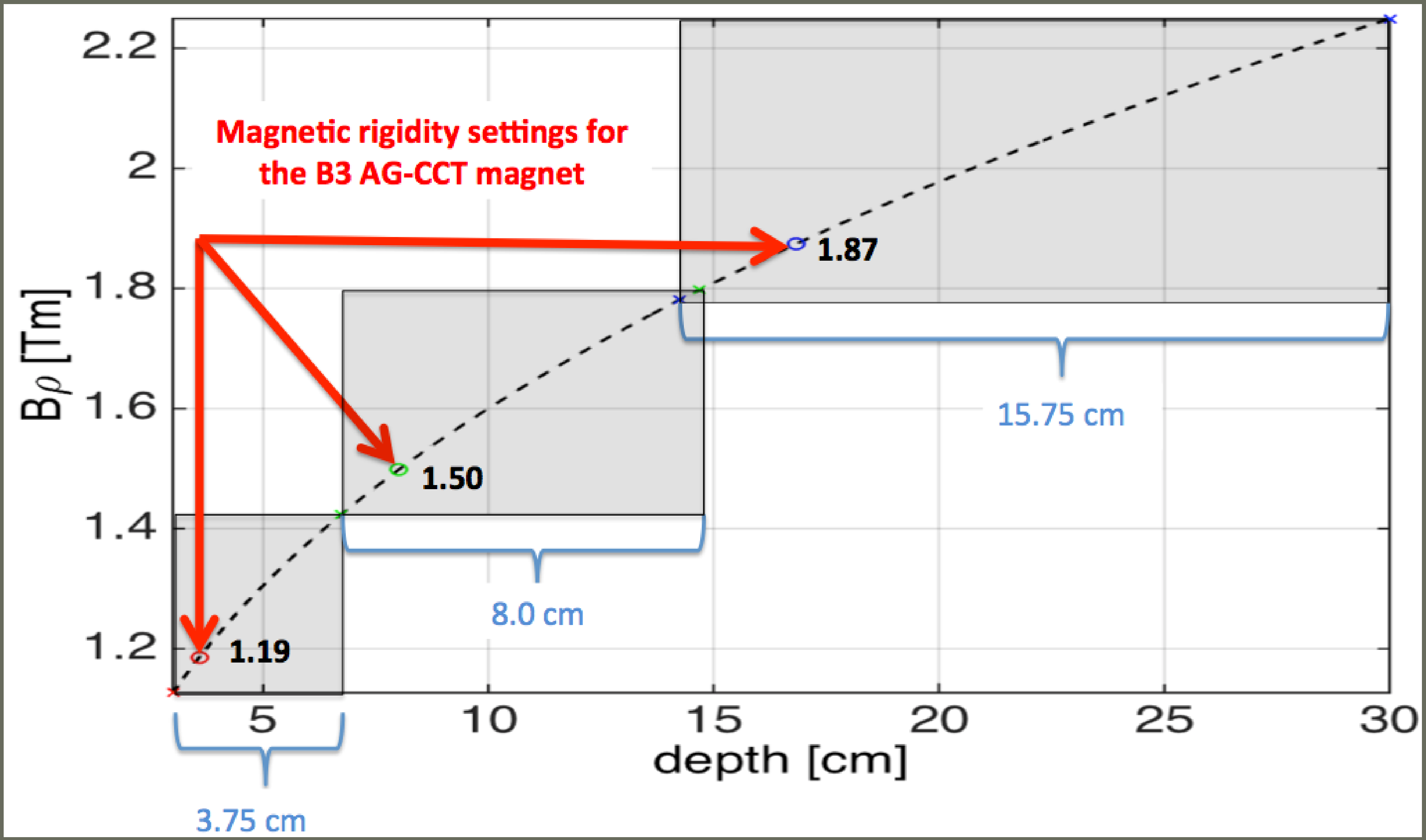
Example Design of a New Gantry

- Superconducting magnets to reduce weight and size
- Locally 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
- AG-CCT: Alternating-Gradient Canted-Cosine-Theta



W. Wan *et al.* PRST-AB**18**, 103501 (2015)

Three Regions of Fixed Field

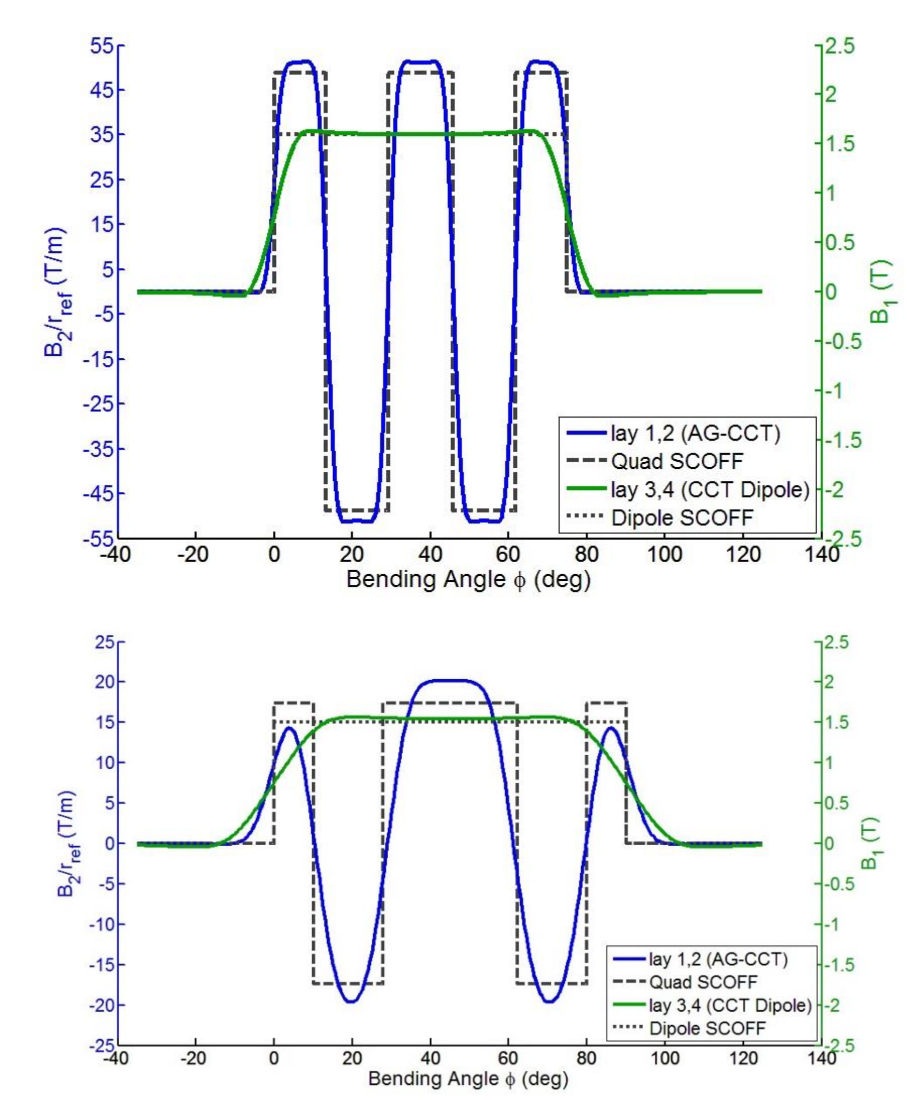


Allows the magnetic field fixed for any field of the gantry for most cases.

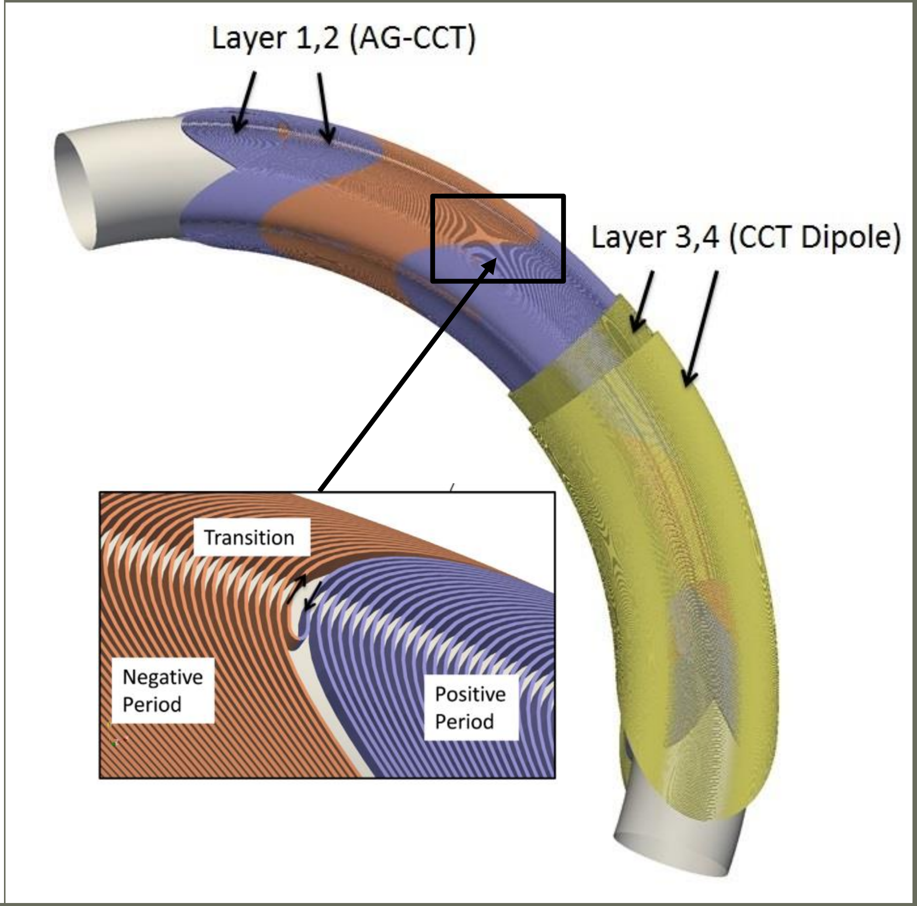
Modeling the AG-CCT Magnets

- 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 (maps up to the 7^{th} order are used here)
- Establishes closed loop between magnet design and beam optics optimization
- Enables systematic sensitivity study of parameters such as coil positions.

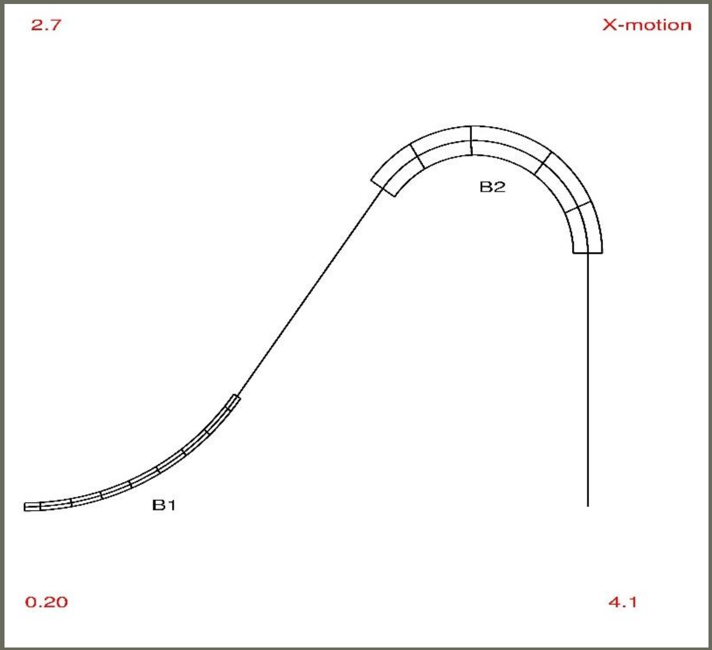
The AG-CCT Magnets: Comparison of SCOFF and Real Field

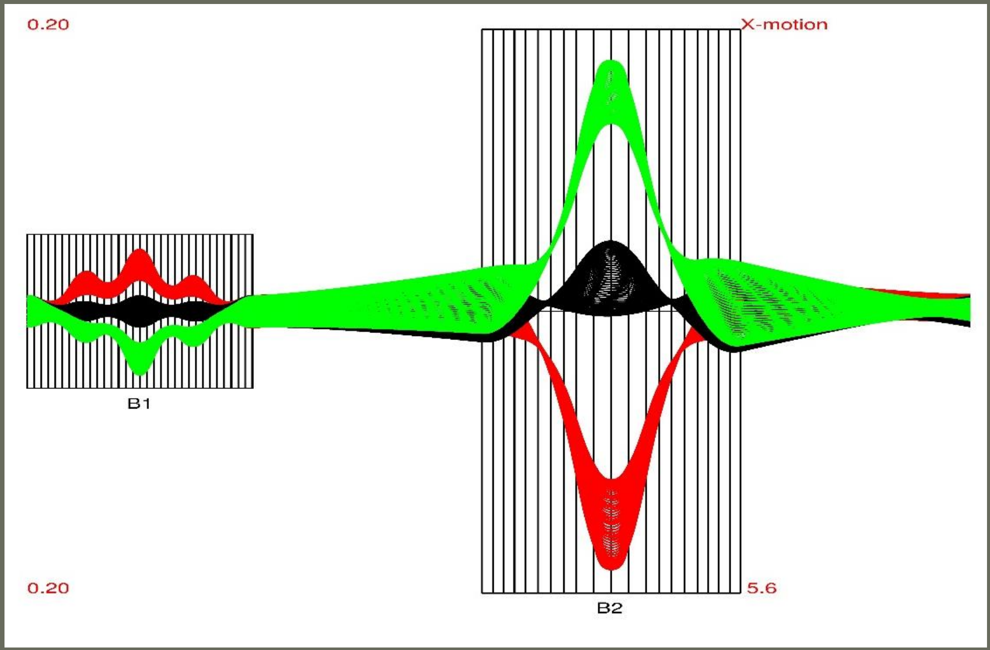


Compact winding results in short and smooth transitions

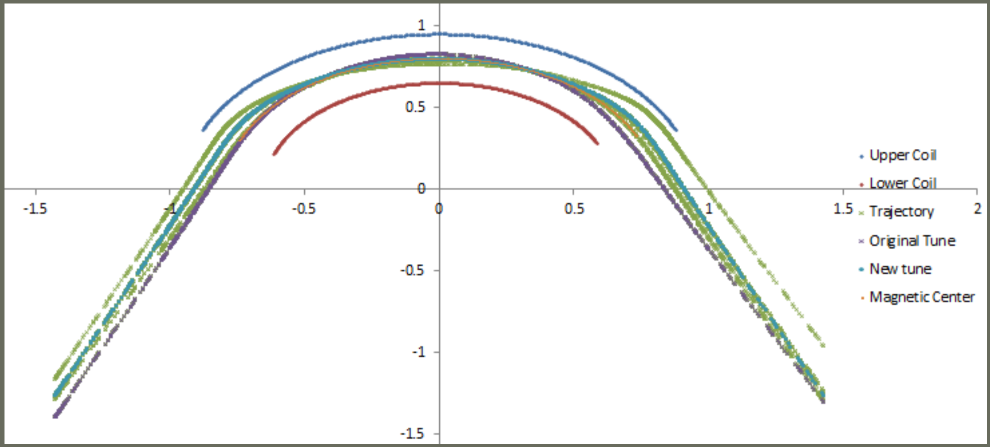


A Simplified Version of the AG-CCT Gantry



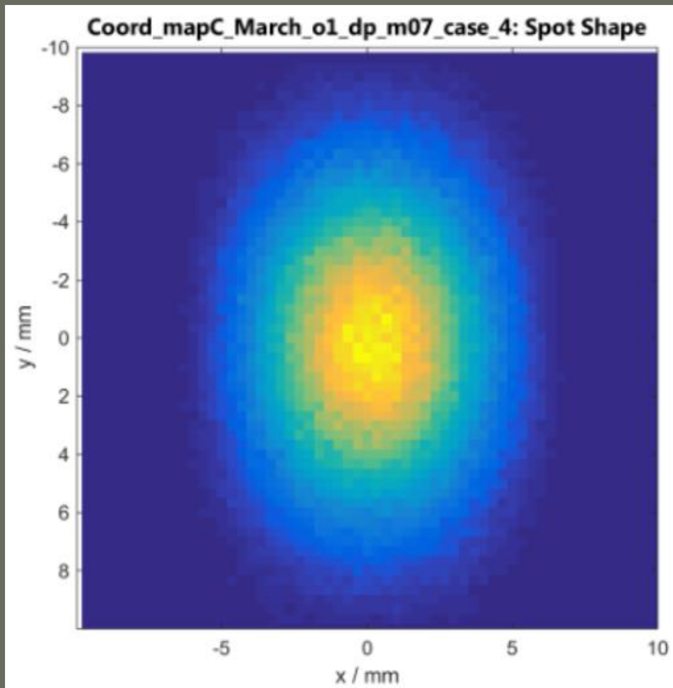


Yet another simplification is made to place the degrader on the gantry downstream of B1, making B1 a simple dipole magnet. The figure on the right shows ray-tracing results through realistic field of the AG-CCT magnet.

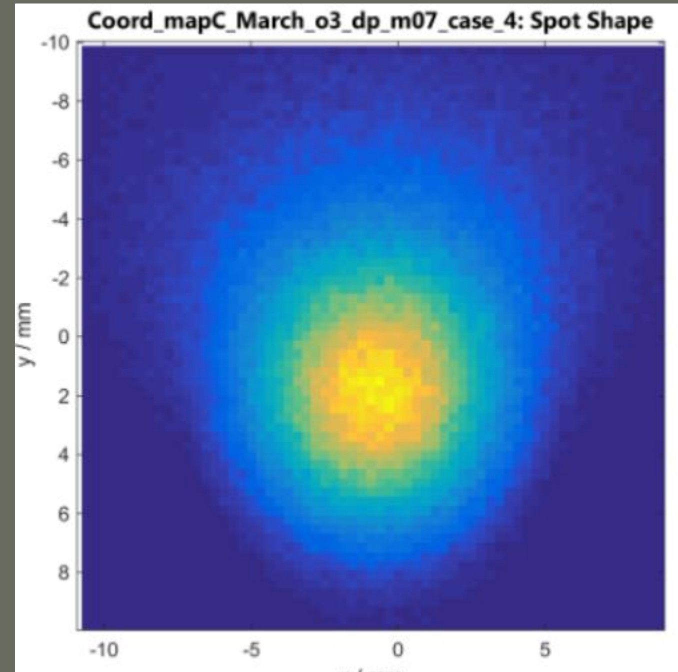


Tracking

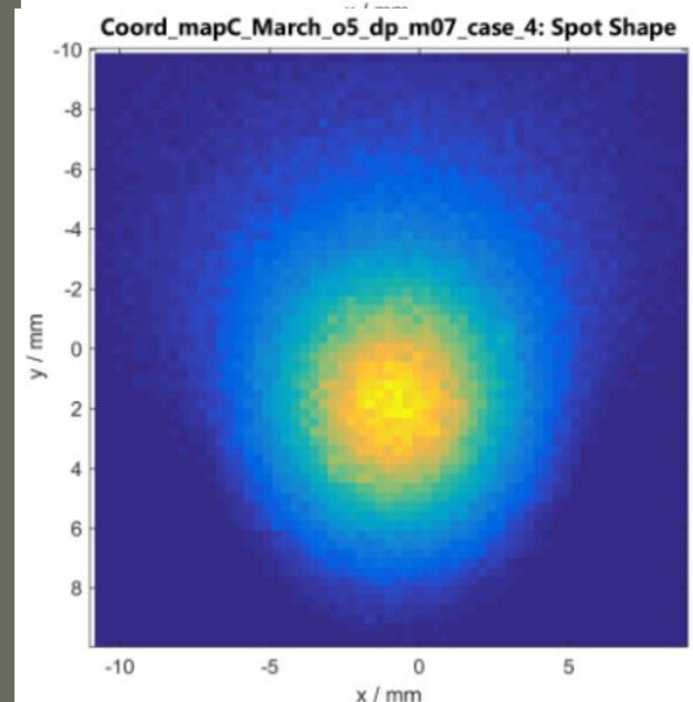
Is the 5th order high enough?



1st order



3rd order



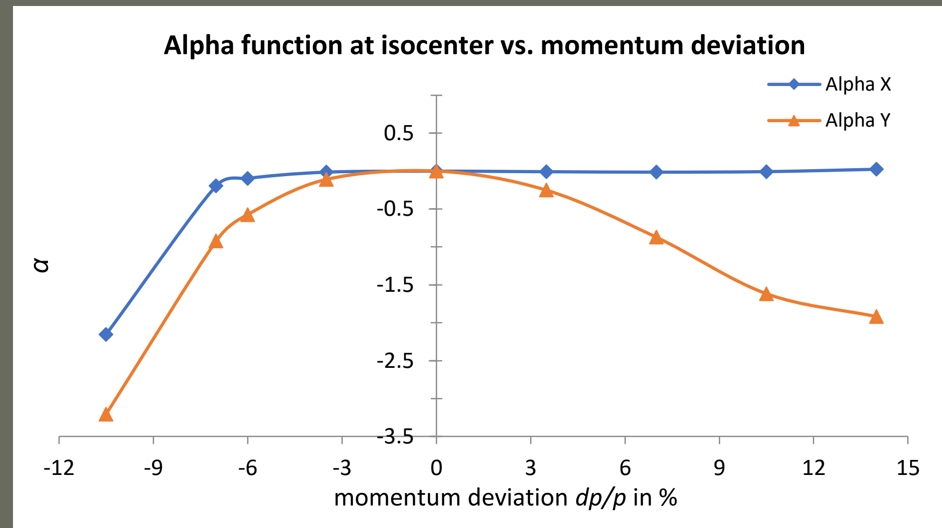
5th order

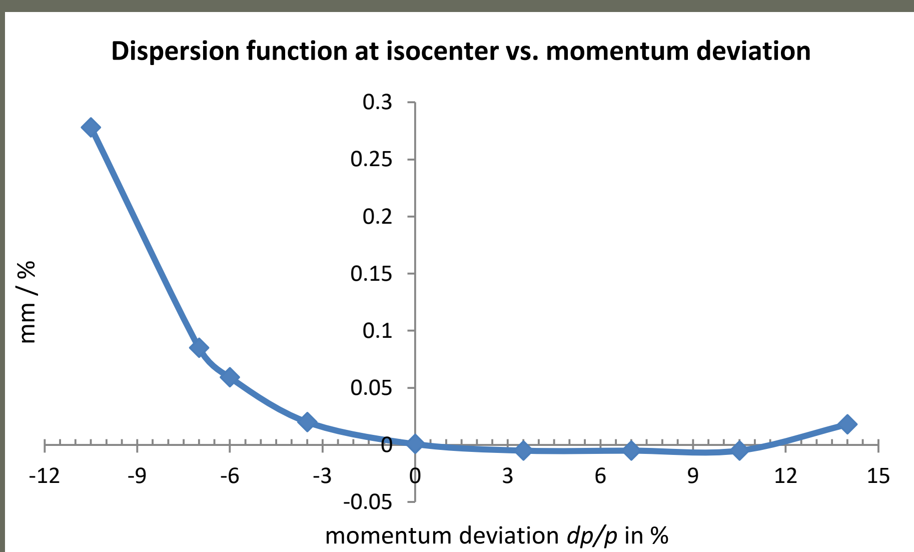
The order 3 calculation already contains all higher order deformations. No spot shape change from order 3 to 5.

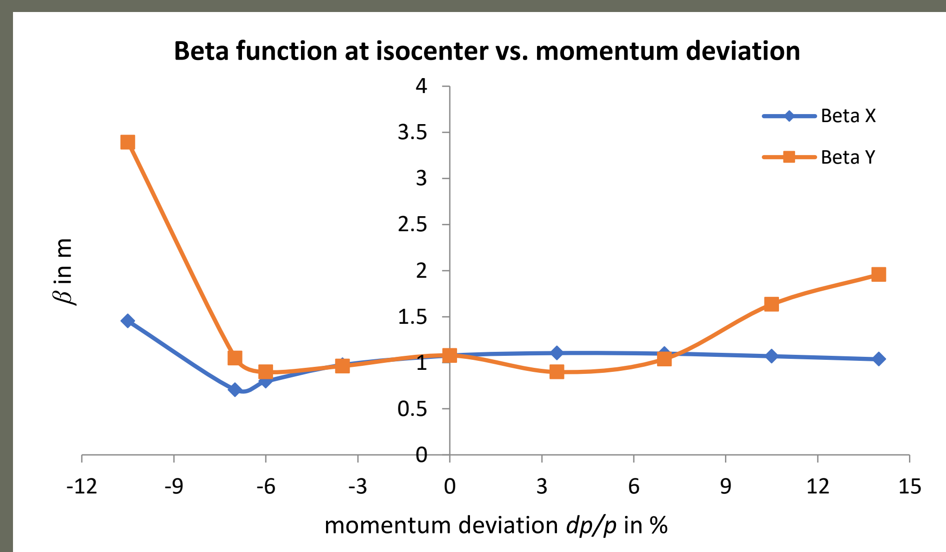
dp/p -7 %, momentum spread 4 %.

AG-CCT Beam Optics Results

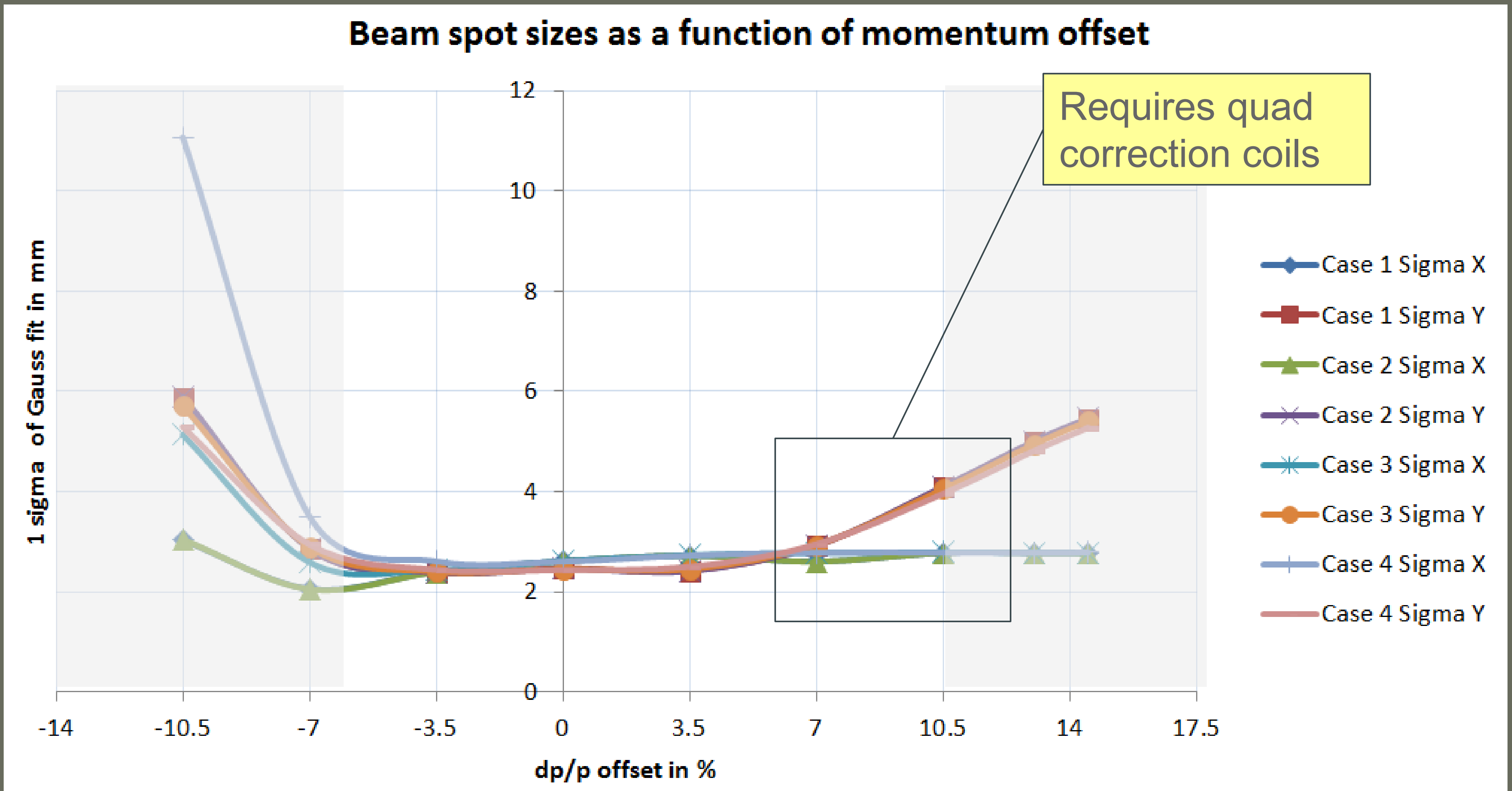
- AG-CCT results are shown for beams relative to the set-energy of the magnetic system.
- Set-energy = beam energy according to bend radius and dipole field of the magnet.
- Relative momentum = momentum deviation to the correspondung set-energy expressed in dp/p.







AG-CCT Beam Optics Results



Case 1 = no momentum spread in the beam
Case 2 = 0.5 % dp/p momentum spread
Case 3 = 1 % dp/p momentum spread
Case 4 = 2 % dp/p momentum spread

AG-CCT Beam Optics Results

Resultant momentum acceptance: 16.5 % dp/p (from -6 to +10.5%)

→ Taking momentum spread into account results in ~ 23 % dp/p acceptance

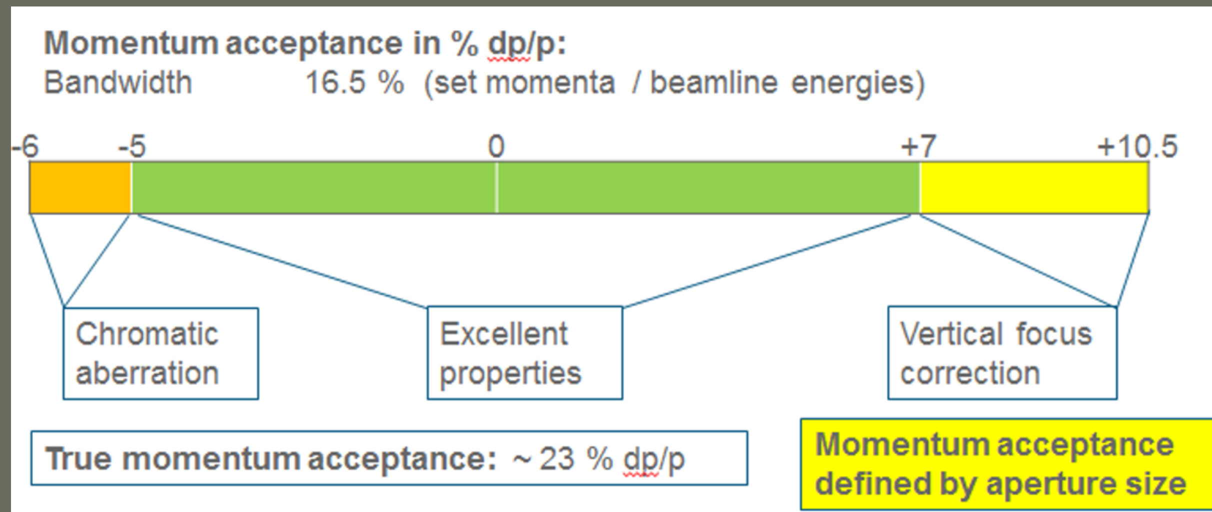
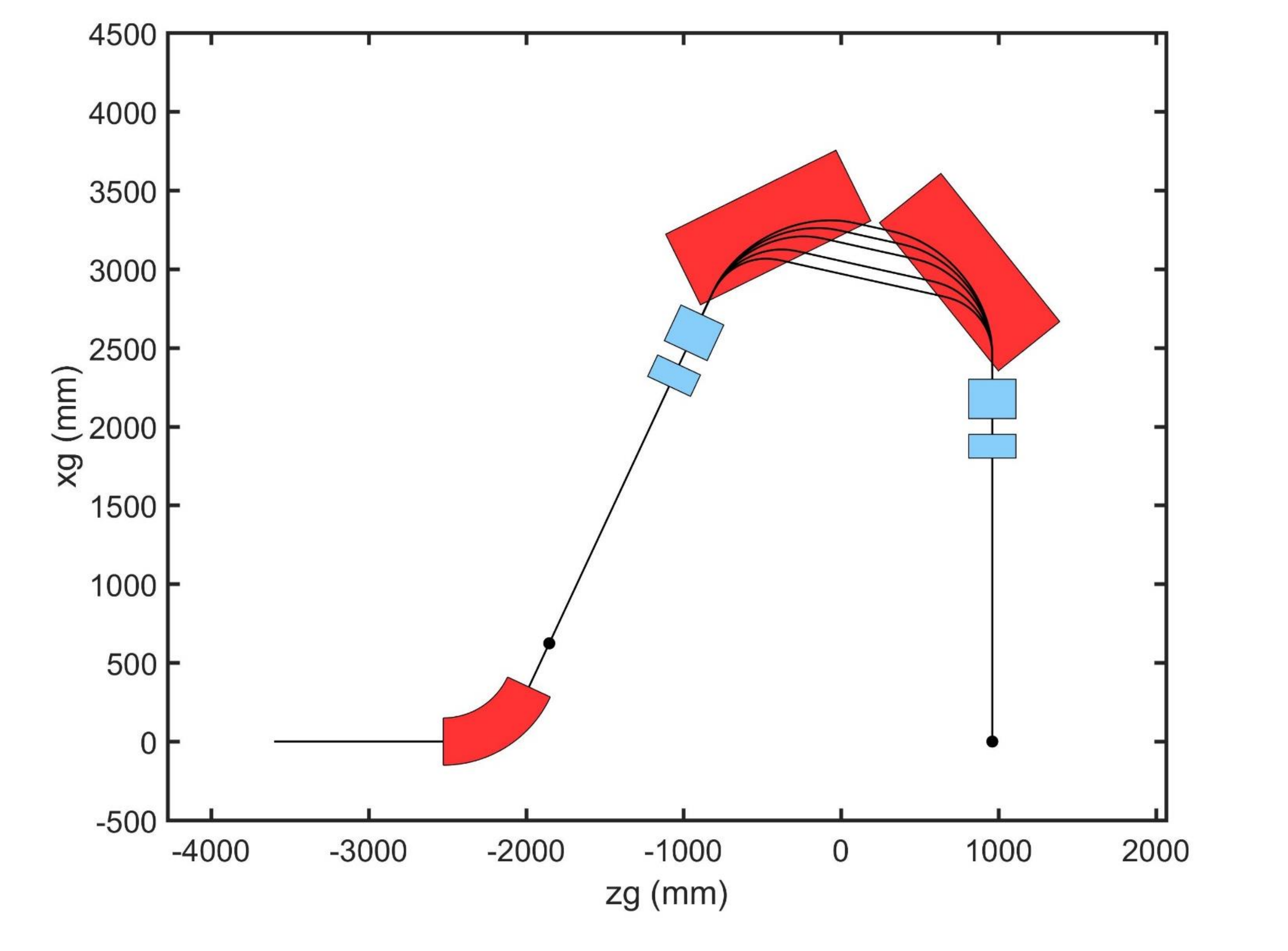


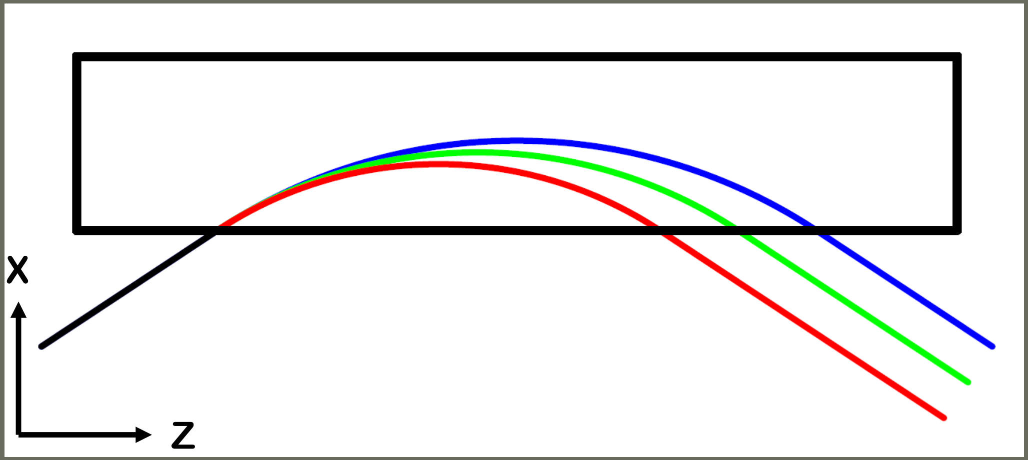
***Table 6.3**: Energy dependent range coverage.*

Magnet set point	Lowest and highest energies of acceptance window	Shortest and longest range in water	Range coverage in water: maximal applicable SOBP
78.9 MeV	70 – 95 MeV	4.1 – 7.1 cm	3 cm
106.9 MeV	95 – 129 MeV	7.1 – 12.1 cm	5 cm
144.9 MeV	129 – 174 MeV	12.1 – 20.4 cm	8.3 cm
185.0 MeV	165 – 221 MeV	18.6 – 30.8 cm	12.2 cm

How about a Fixed-Field Gantry?



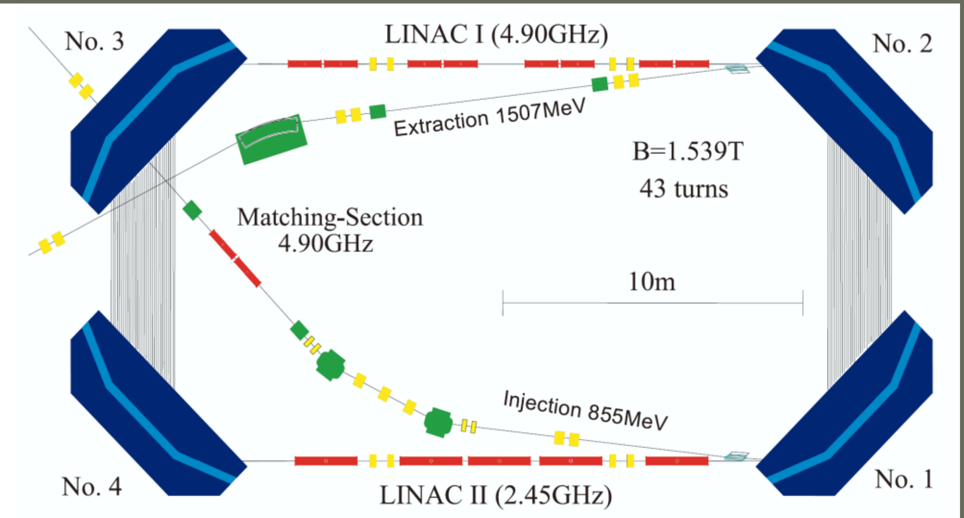
The properties of 2D bending magnets

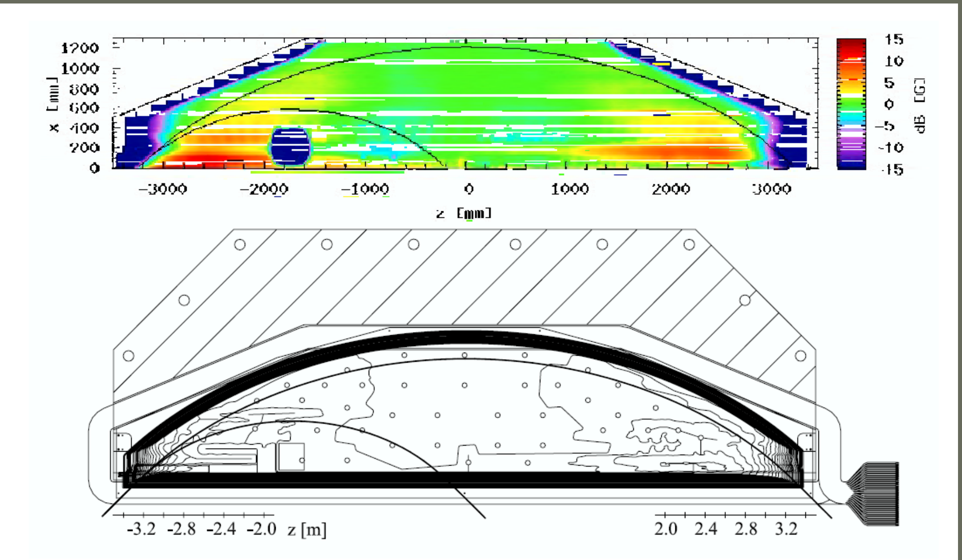


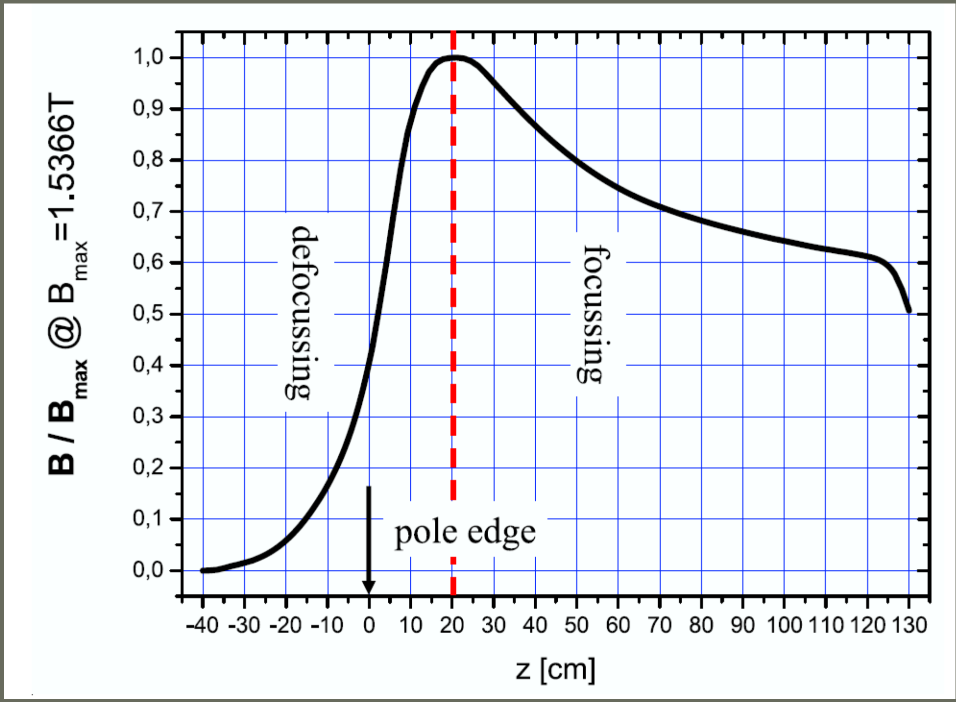
- Magnetic field is a function of X only
- Any proton, regardless momentum, exit with the angle as the entrance one.
- Two of them make an achromat (with arbitrary momentum range).

H. A. Enge RSI **34**, 385 (1963)

An Example of 2D Bending Magnets





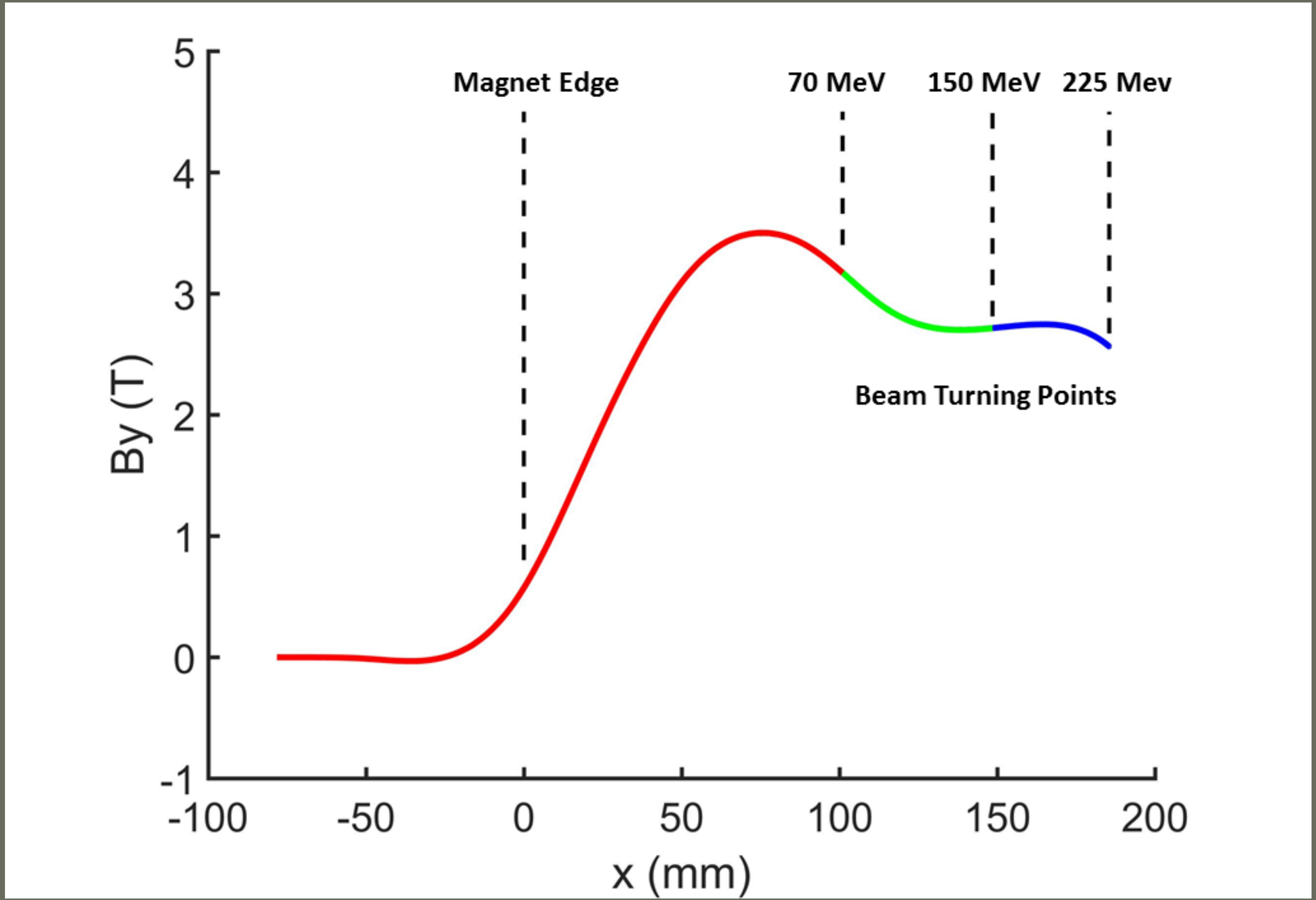


Field profile shaped to control focusing within large energy range.

A. Jankowiak, Eur. Phys. J. A 28, s01, 149 160 (2006)

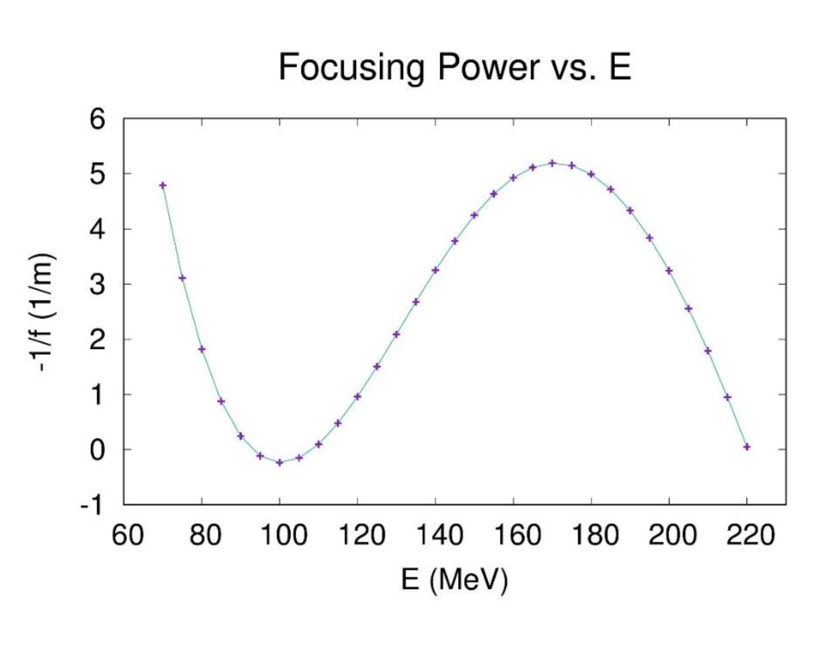
Modeling the 2D Magnets

- Field distribution along the x-axis in the midplane modeled using 3 Gaussian functions
- Establishes closed loop between magnet design and beam optics optimization

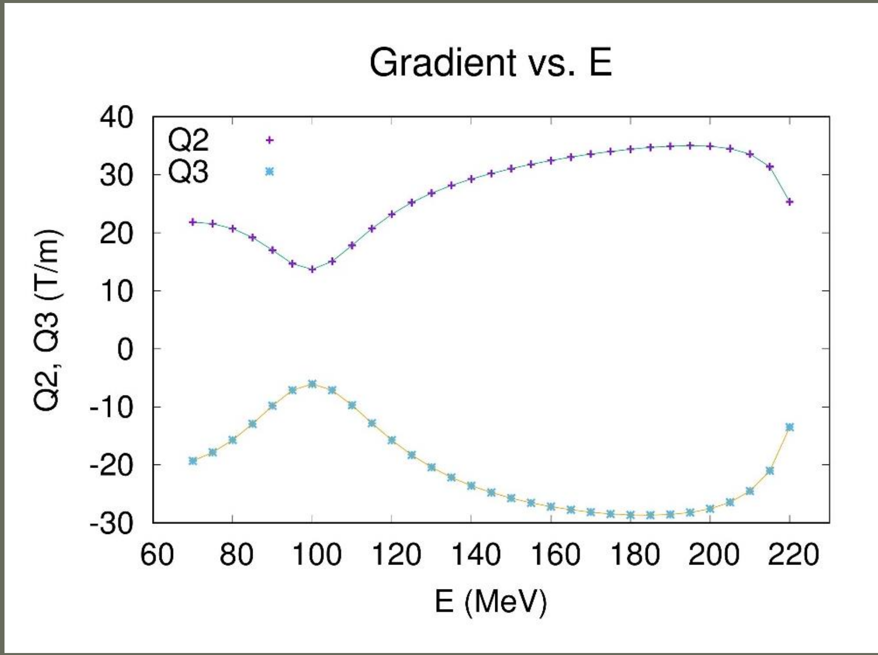


Focusing Properties

For a single bending magnet

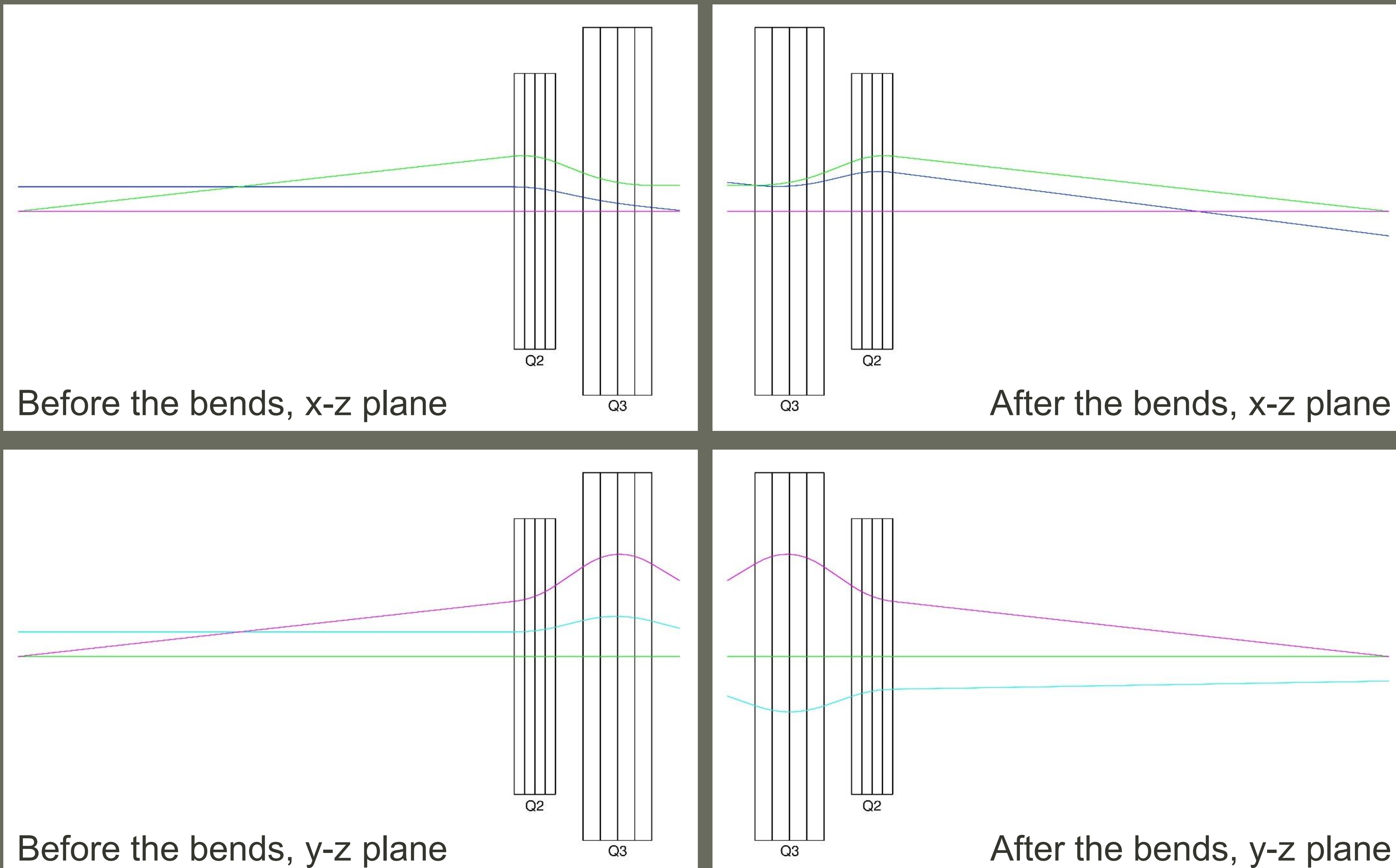


Maintaining imaging condition



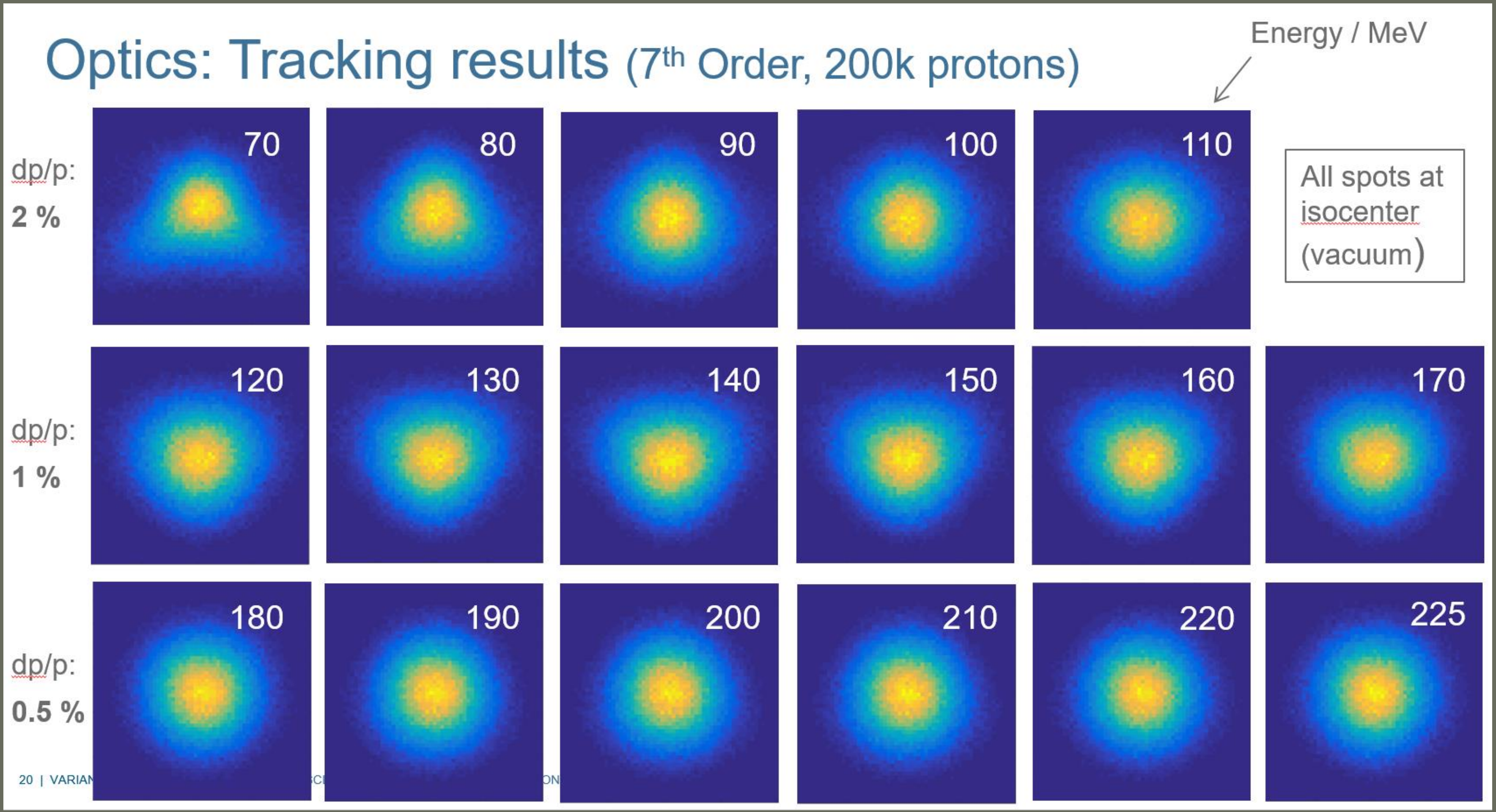
- Most of our time has been spent on iterations between optics and magnet design.
- Up to now, the optimization process has been semiautomatic.
- More insight is needed to determine the underlying relation between field distribution and focusing power.

Principle rays at 170 MeV

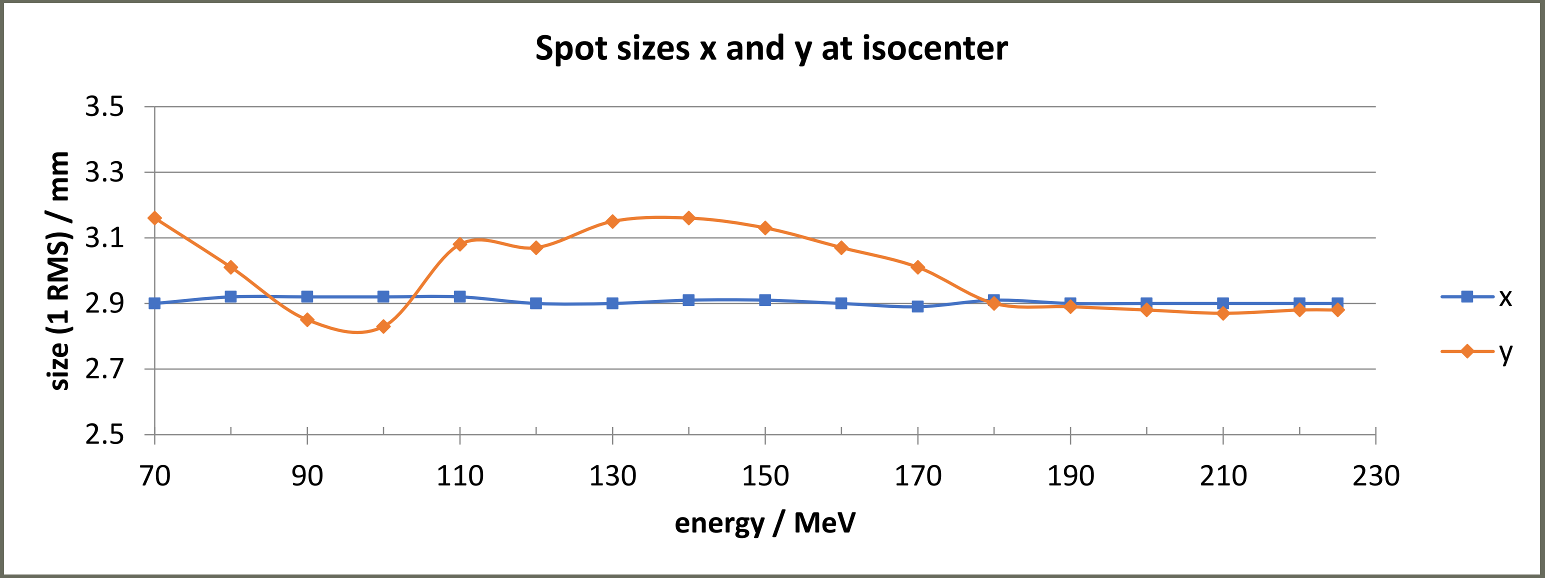


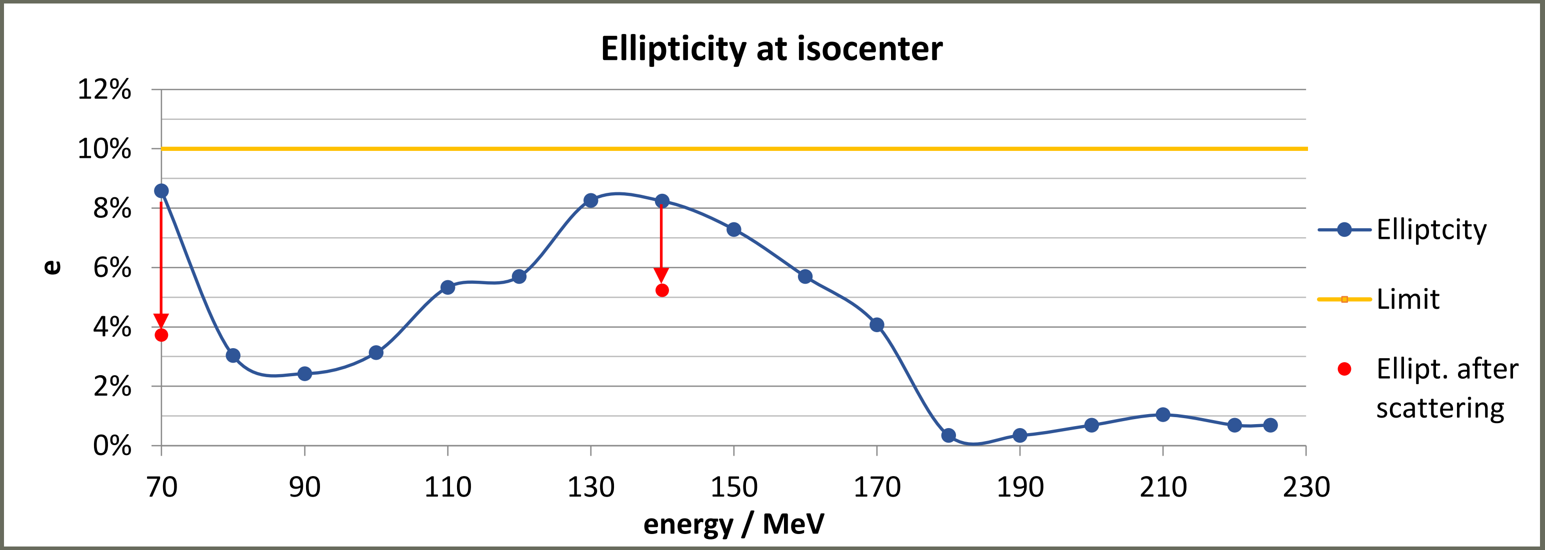
Fixed Field achromat results

Spot shapes after tracking through transfer maps to 7th order.



Fixed Field achromat results





Summary

- Beam optics for large momentum acceptance beam transfer lines, gantries as an example, is very different from their conventional counterpart.
- A good layout with small remaining aberrations is important for a good design.
- 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, leading to more efficient design process and better designs.
- Fixed-field gantries have the potential to harvest the benefit of the superconducting magnets without suffering from their difficulty of changing the field.
- Work is ongoing to finalize the magnet design of the fixed-field gantry and a prototype will be built at LBNL.