Innovative Design of the Isocentric Proton/Carbon Gantries

Dejan Trbojevic-BNL, Eberhard Keil-CERN, and Andrew Sessler-LBL

- Introduction
  - Basic concept of the non-scaling Fixed Field Alternating Gradient
  - Motivation for a new way of isocentric gantry design
- Carbon/proton gantries today–(Heidelberg, PSI, …)
- Spot scanning – alternative option
- The non-scaling FFAG gantries:
  - Smaller proton gantry
  - Carbon/proton gantry
- Engineering design – magnets are available
- Summary

Non-scaling FFAG concept

- Orbit offsets are proportional to the dispersion function:

$$Dx = D_x * dp/p$$

- To reduce the orbit offsets to +-5 cm range, for momentum range of dp/p ~ +- 50 % the dispersion function D_x has to be of the order of:

$$D_x \sim 5\ cm / 0.5 = 10\ cm$$

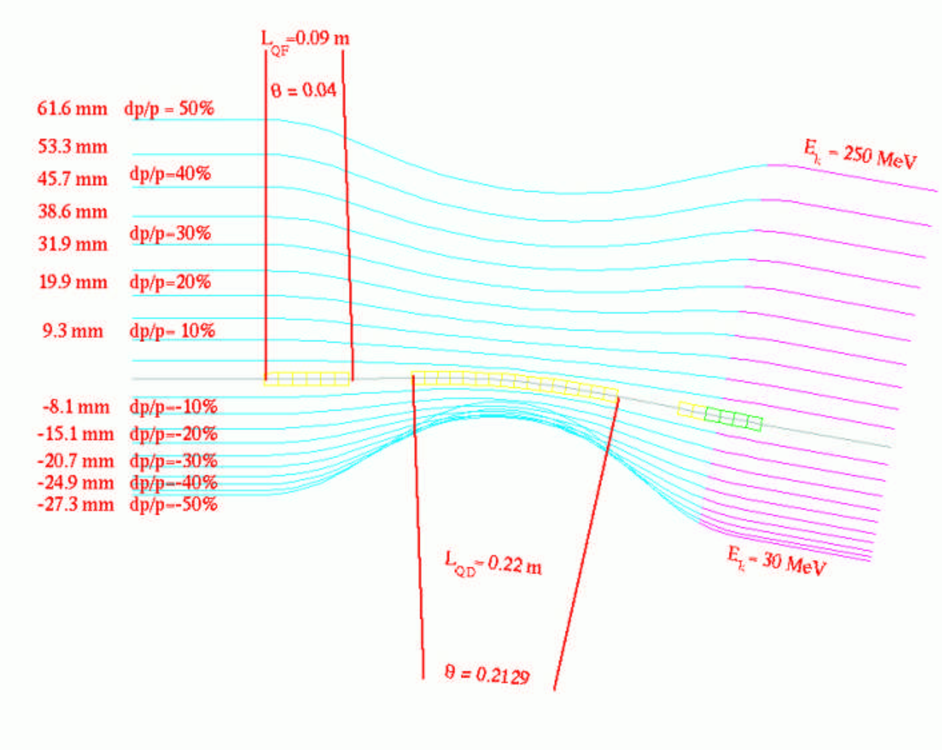
- The size and dependence of the dispersion function is best presented in the normalized space and by the H function:

$$\chi = D_x / \bullet \beta_x \text{ and } \xi = D'_x / \bullet \beta_x + D_x \alpha / \bullet \beta_x$$

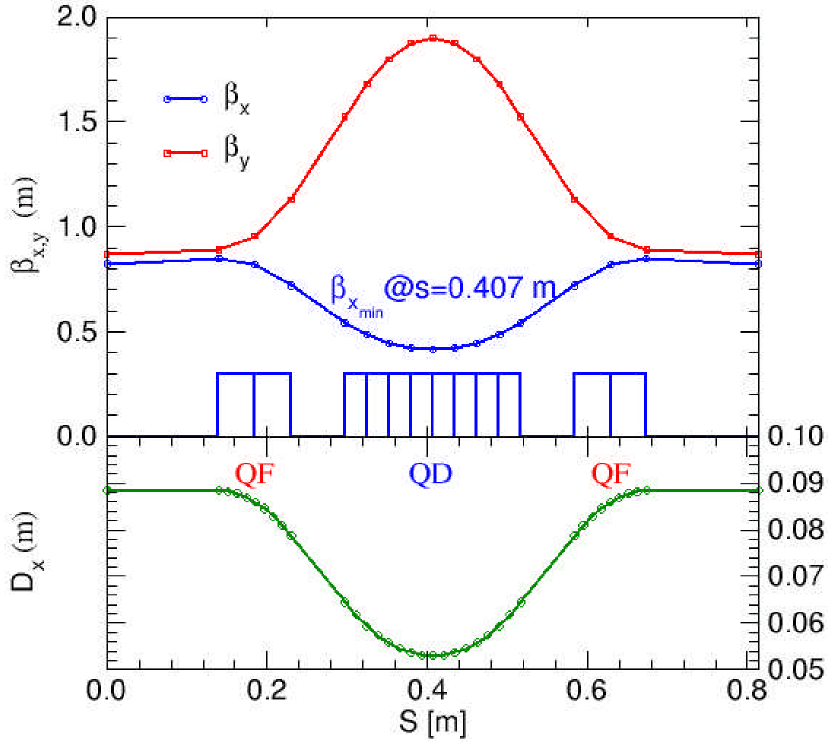
$$H = \chi^2 + \xi^2$$

Basic Properties of the Non-Scaling FFAG

A . Particle orbits



B. Lattice

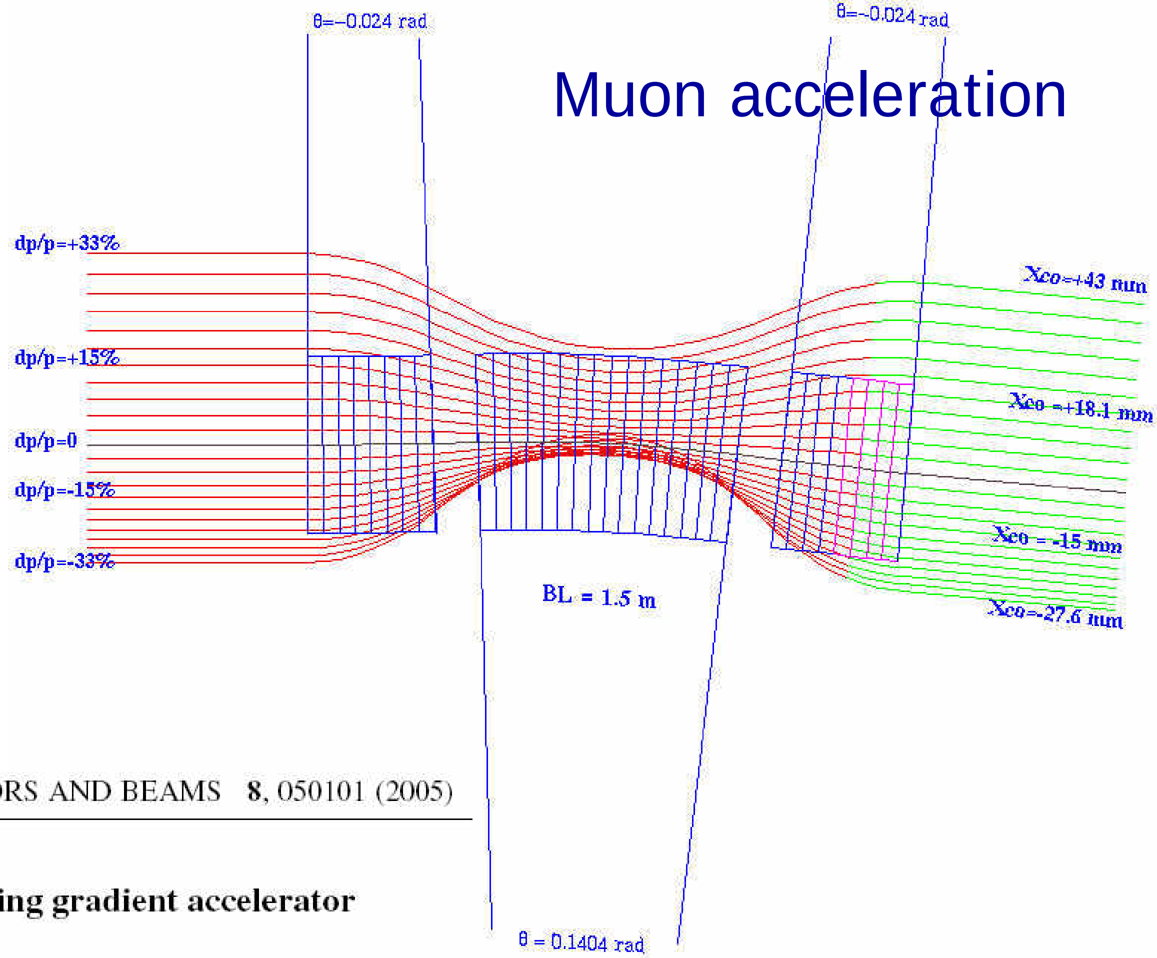


Basic Properties of the non-scaling FFAG

- Concept introduced 1999 at Montauk meeting –Trbojevic, Courant, Garren) using the light source lattice with small emittance minimized H function

- Extremely strong focusing with small dispersion function.
- large energy acceptance.
- tunes variation
- very small orbit offsets
- small magnets

Muon acceleration

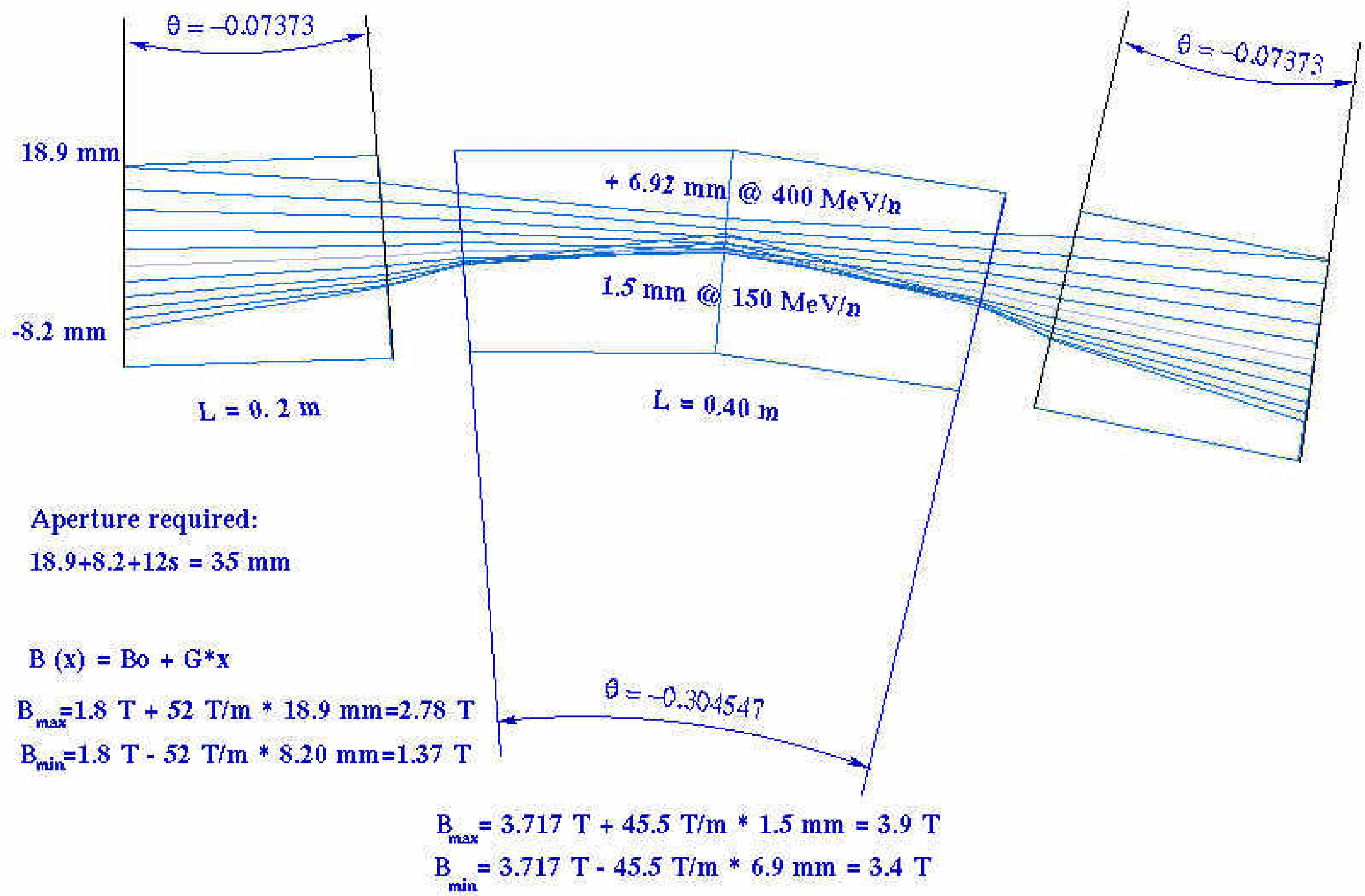


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 8, 050101 (2005)

Design of a nonscaling fixed field alternating gradient accelerator

D. Trbojevic,* E. D. Courant, and M. Blaskiewicz
BNL, Upton, New York 11973, USA

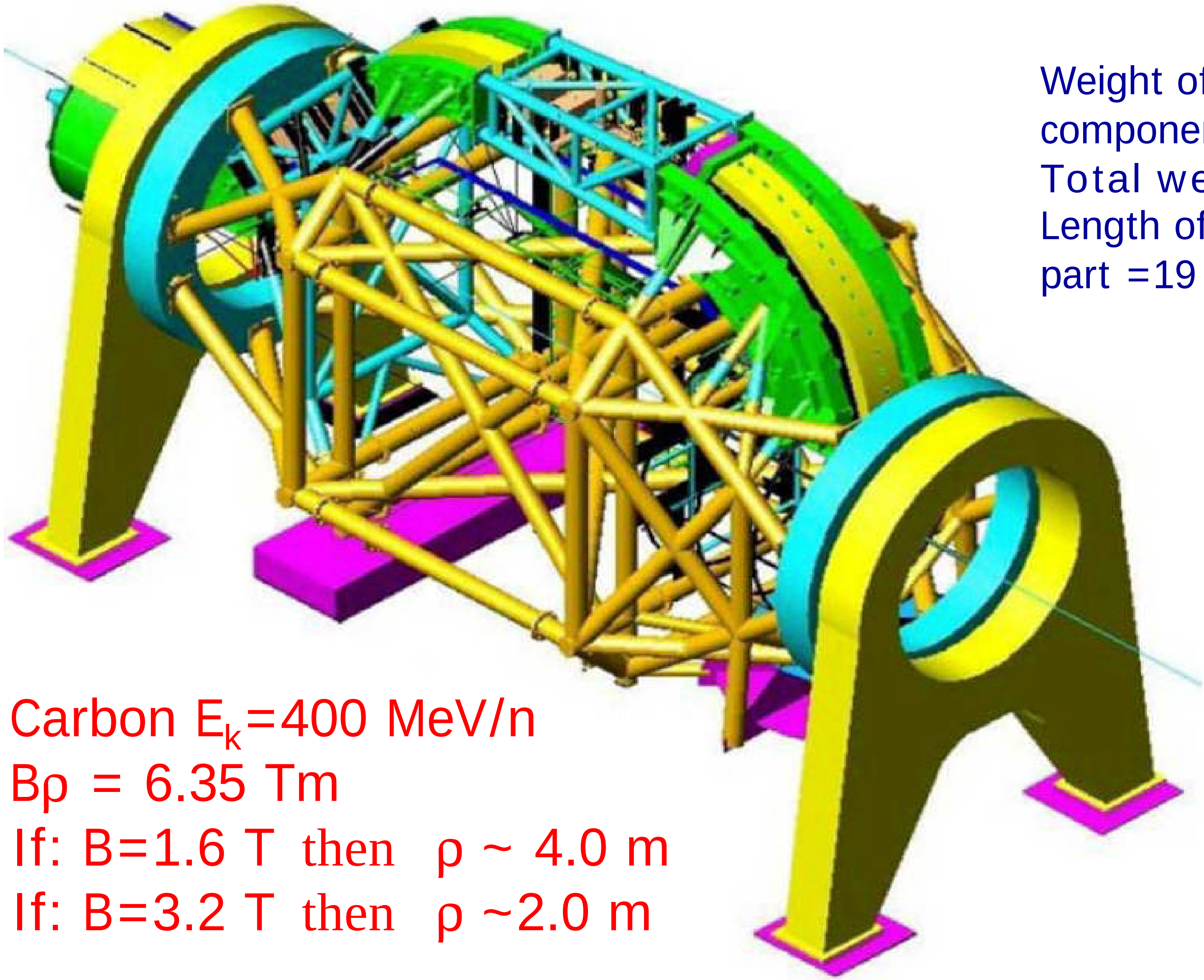
Example of the non-scaling FFAG carbon gantry-cell



MOTIVATION: large weight of the present gantries

- Large $B\rho = 6.35$ Tm for carbon ions of E_k=400 MeV/n requires large magnetic fields.
- Presently the beam scanning requires very large magnet at the end of the gantry to accommodate parallel beams to the patient.
- Results are: very large magnets and large weight of the transfer line and the whole support (630 /tons). The carbon/proton cancer therapy facilities constraints are very difficult to fulfill with the warm temperature magnets.
- This leads us to a new concept – non-scaling light small superconducting gantry.

Carbon Gantry in Heidelberg



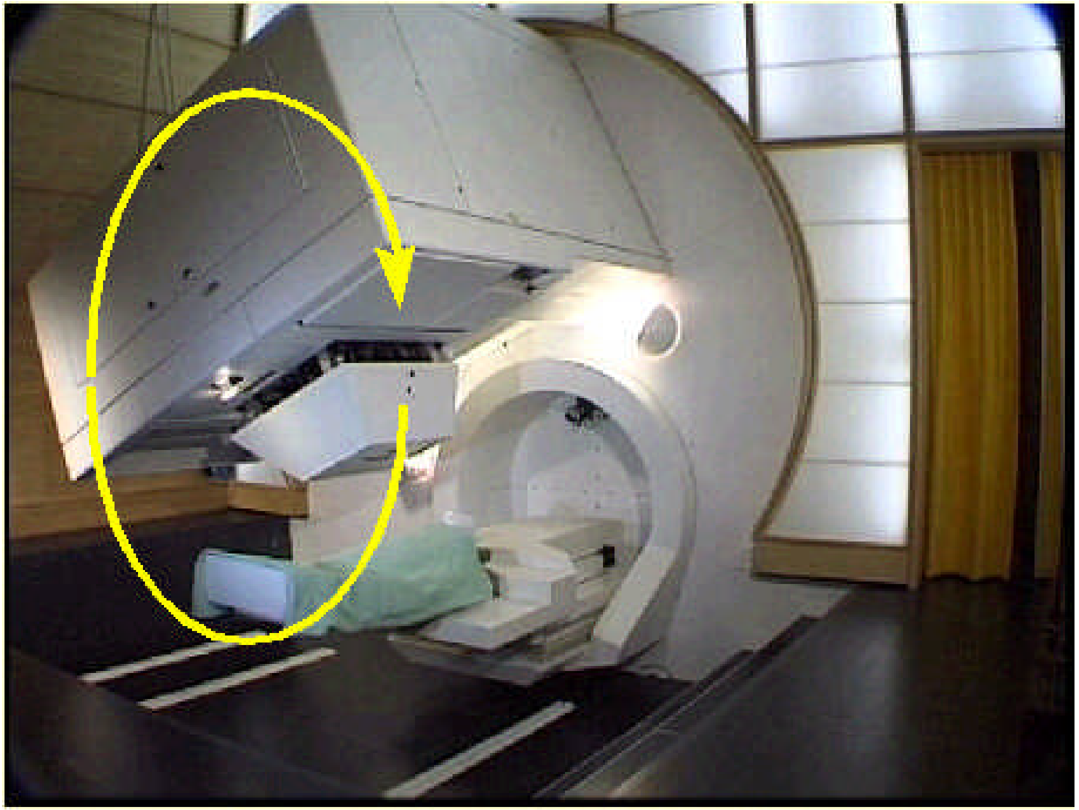
Weight of the transport components – 135 tons
Total weight = 630 tons
Length of the rotating part =19 m

Carbon E_k=400 MeV/n
$B\rho$ = 6.35 Tm
If: B=1.6 T then $\rho \sim 4.0$ m
If: B=3.2 T then $\rho \sim 2.0$ m

Schär Engine

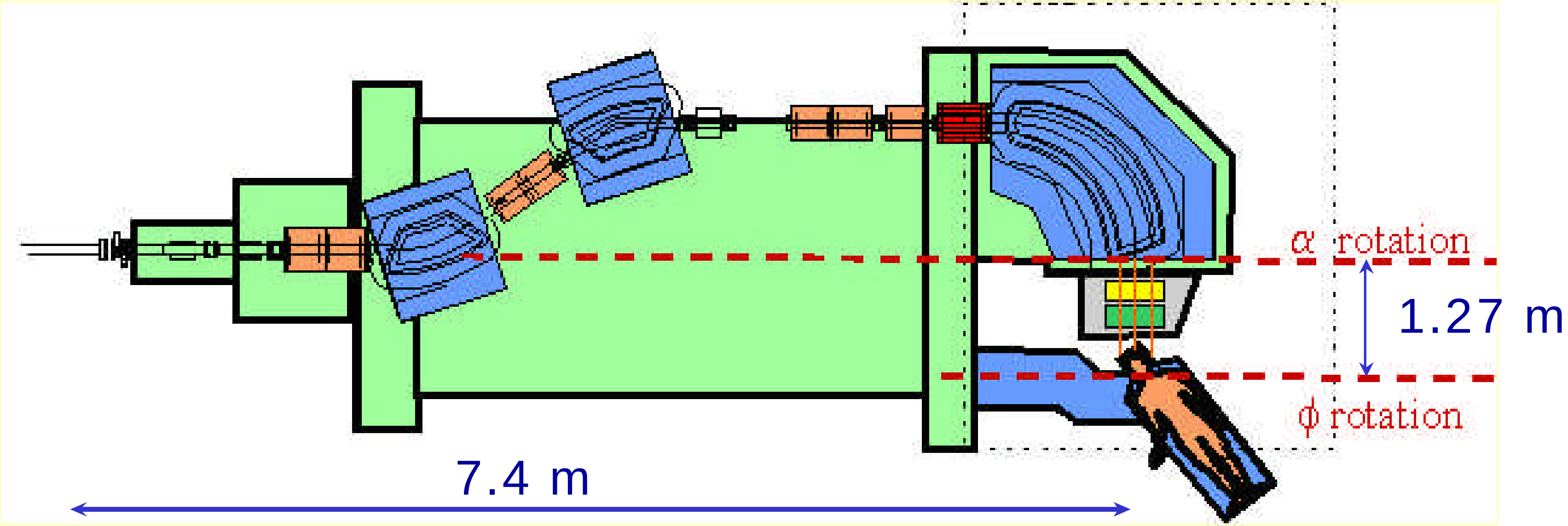
Munich and PSI proton gantries

Gantry



Proton Gantry at PSI

Cross section of the PSI gantry

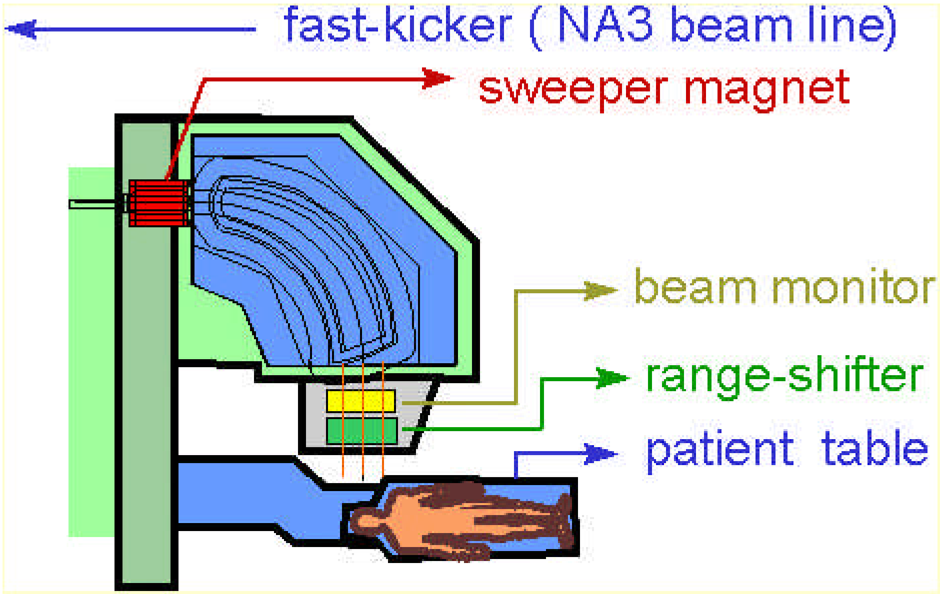


The proton beam is coming from the left. It is deflected by two 35 degrees bending magnets to be parallel (at 1.27 m distance) to the rotation axis of the gantry. It is then deflected on the patient by a large 90 degrees bending magnet. The magnets are drawn in blue, the 7 focusing quadrupoles in brown and the supporting structure of the gantry in green.
The length of the gantry, measured from the point where the beam leaves the gantry axis to the isocenter plane, is 7.4 m.

The proton gantry @ PSI

Figure 2: One 23.5-ton half of the 90 degree magnet being prepared for shipping. The 1.9 ton coils are of conventional design and could be manufactured and test assembled into the iron yoke without any major problems arising.

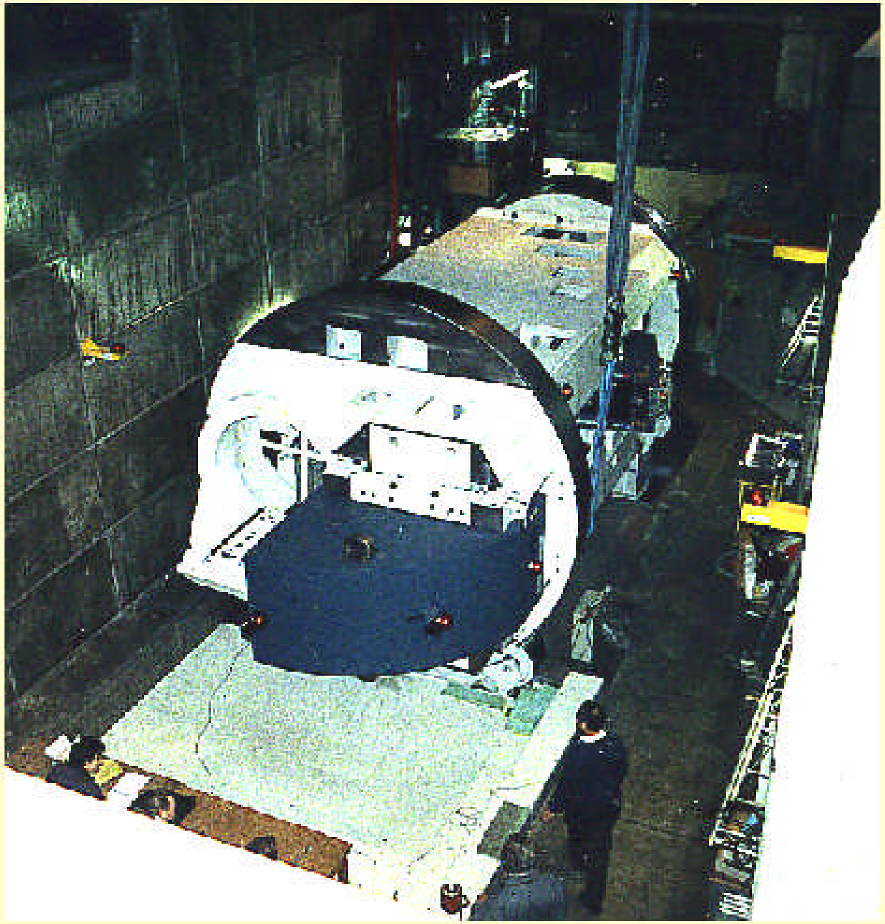
counterweight
110 tons



The mechanical support

The mechanical support of the gantry is designed for maximum rigidity of the aligenment of the beam line. The weight of the gantry is dominated by the 25 tons weight of the 90 degrees bending magnet. With the other elements of the beam line and the counterweight the gantry weighs 110 tons.
The precision at the isocenter lies within a sphere of 1 mm radius.

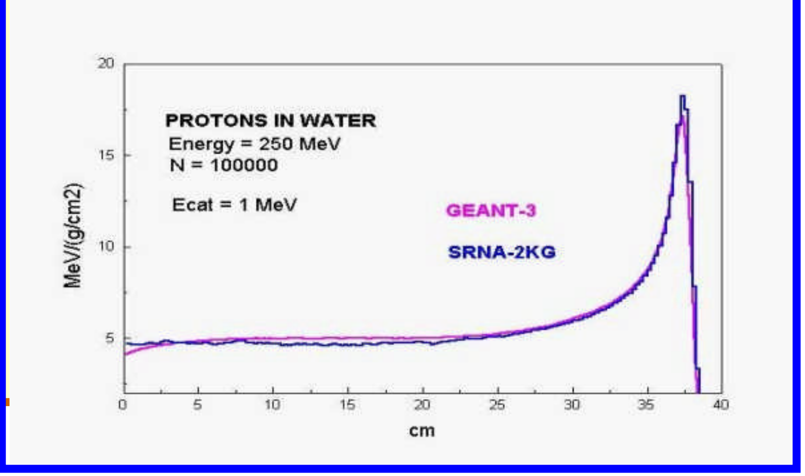
The picture below shows the gantry during assembly in 1993.



Simulation Code: "SRNA" Vinca Institute @ Joanne Beebe-Wang BNL

- Monte Carlo code SRNA-2KG originally developed by R. D. Ilic [Inst. of Nucl. Science Beograd, Yugoslavia, 2002] for proton transport, radiotherapy, and dosimetry.
- Modified at BNL to include the production of positron emitter nuclei.
- Proton energy range 0.1-250 MeV with pre-specified spectra are transported in a 3D geometry through material zones confined by planes and second order surfaces.
- Can treat proton transport in 279 different kinds of materials including elements of Z=1-98 and 181 compounds and mixtures.
- Use multiple scattering theory and on a model for compound nucleus decay after proton absorption in non-elastic nuclear interactions.
- For each energy range, an average energy loss is calculated with a fluctuation from Vavilov's distribution and with Schulek's correction. The deflection angle of protons is sampled from Moliere's distribution.
- Benchmarked with GEANT-3 and PETRA.

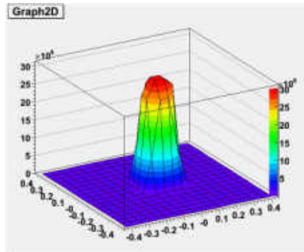
  A very good agreement was reached.

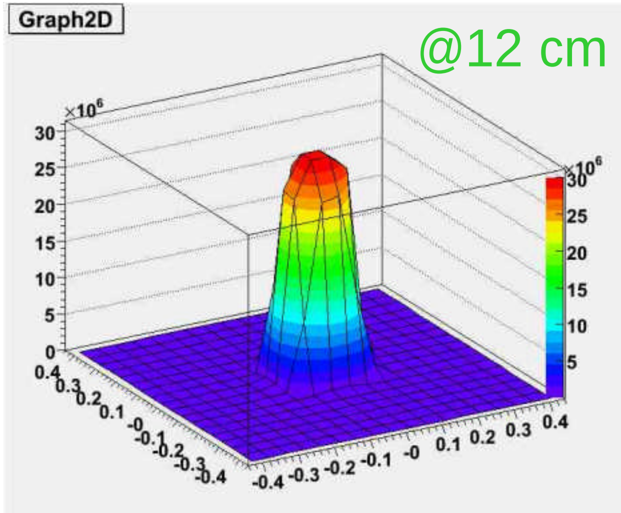


Energy deposition of the 169 MeV protons

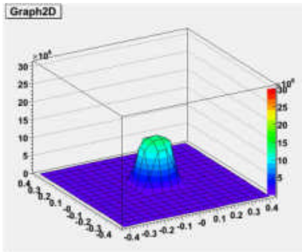
Adsorbed energy in MeV-cm^2/g
Within slices of Ds=1 cm

@ 12 cm

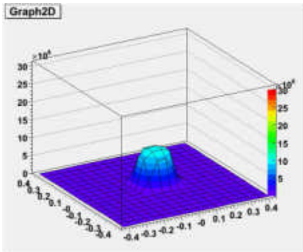




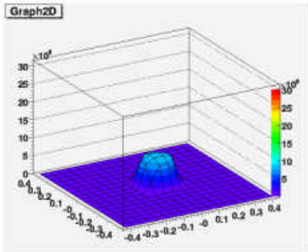
@ 11 cm



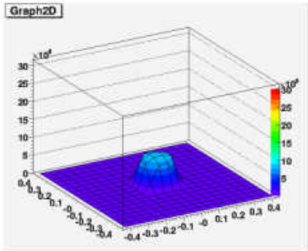
@ 10 cm



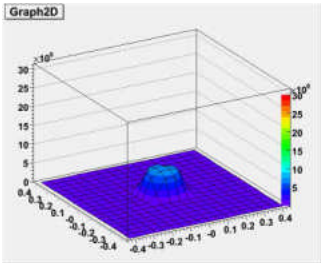
@ 9 cm



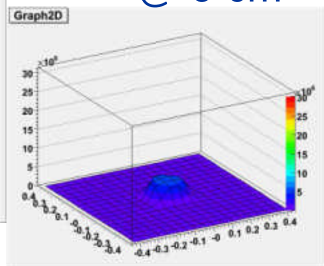
@ 8 cm



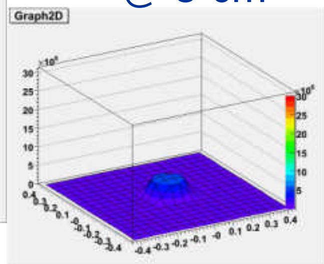
@ 7 cm



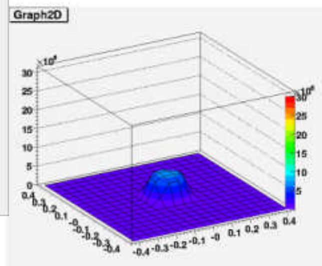
@ 6 cm



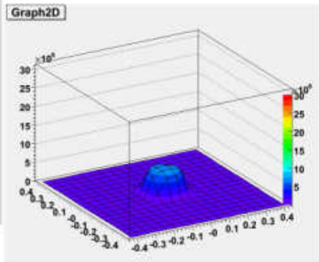
@ 5 cm



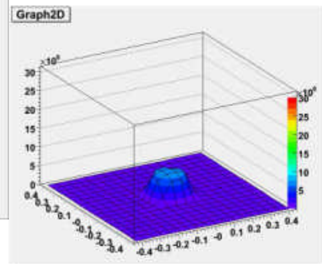
@ 3 cm



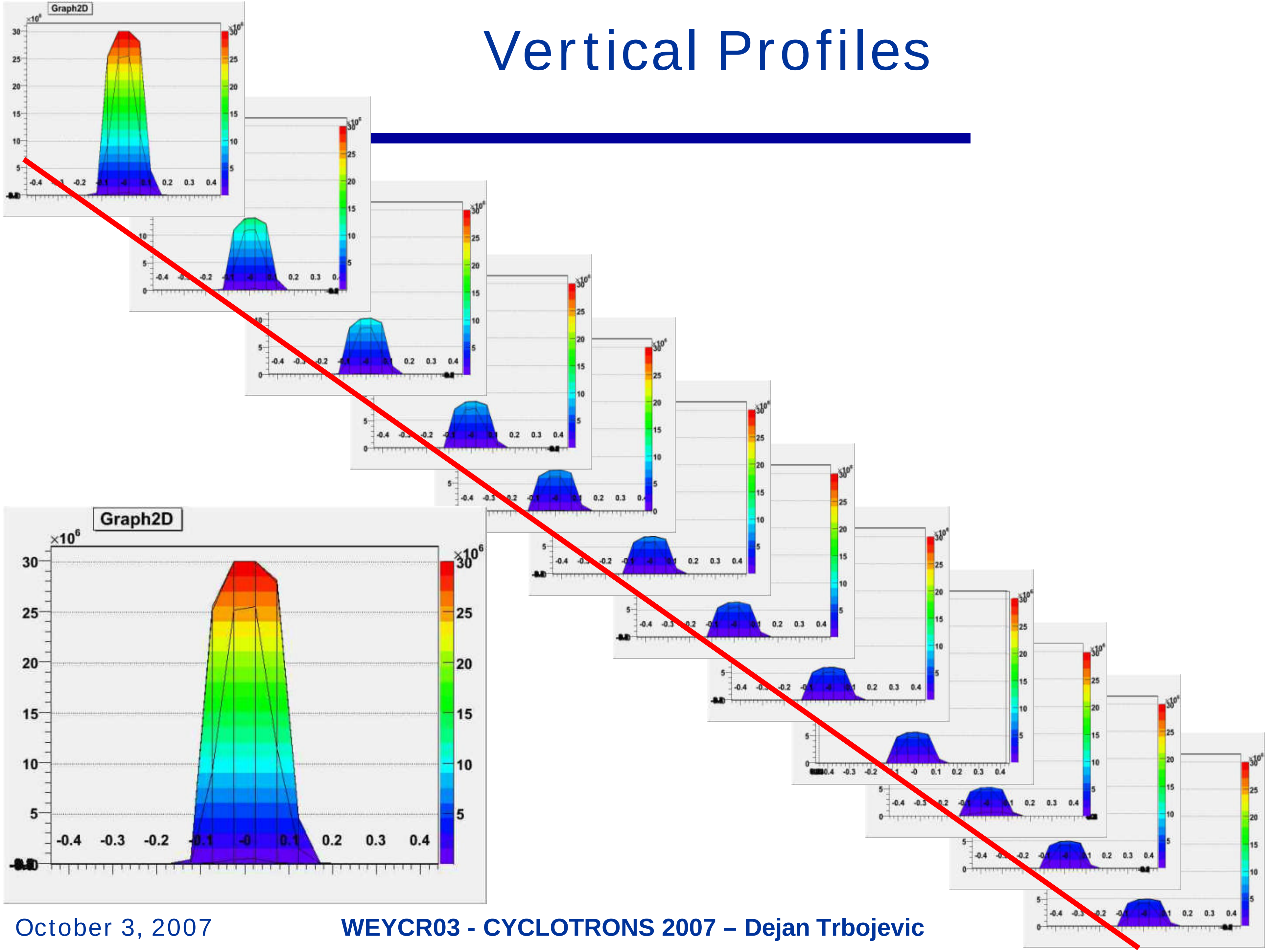
@ 2 cm



@a 1 cm depth



Vertical Profiles



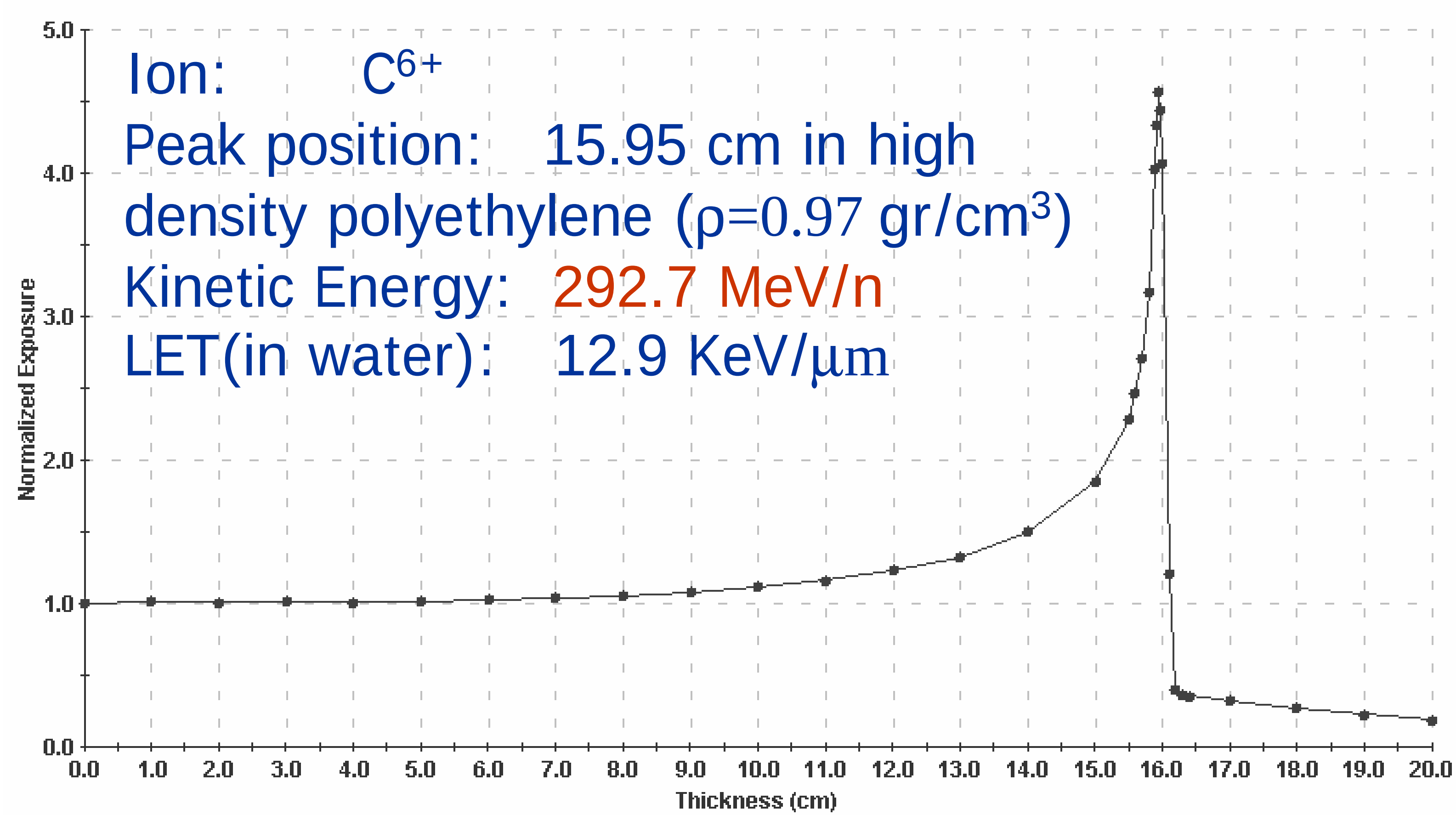
Experimental results from: NSRL Laboratory at Brookhaven National Lab - Adam Rusek

Ion: C^{6+}

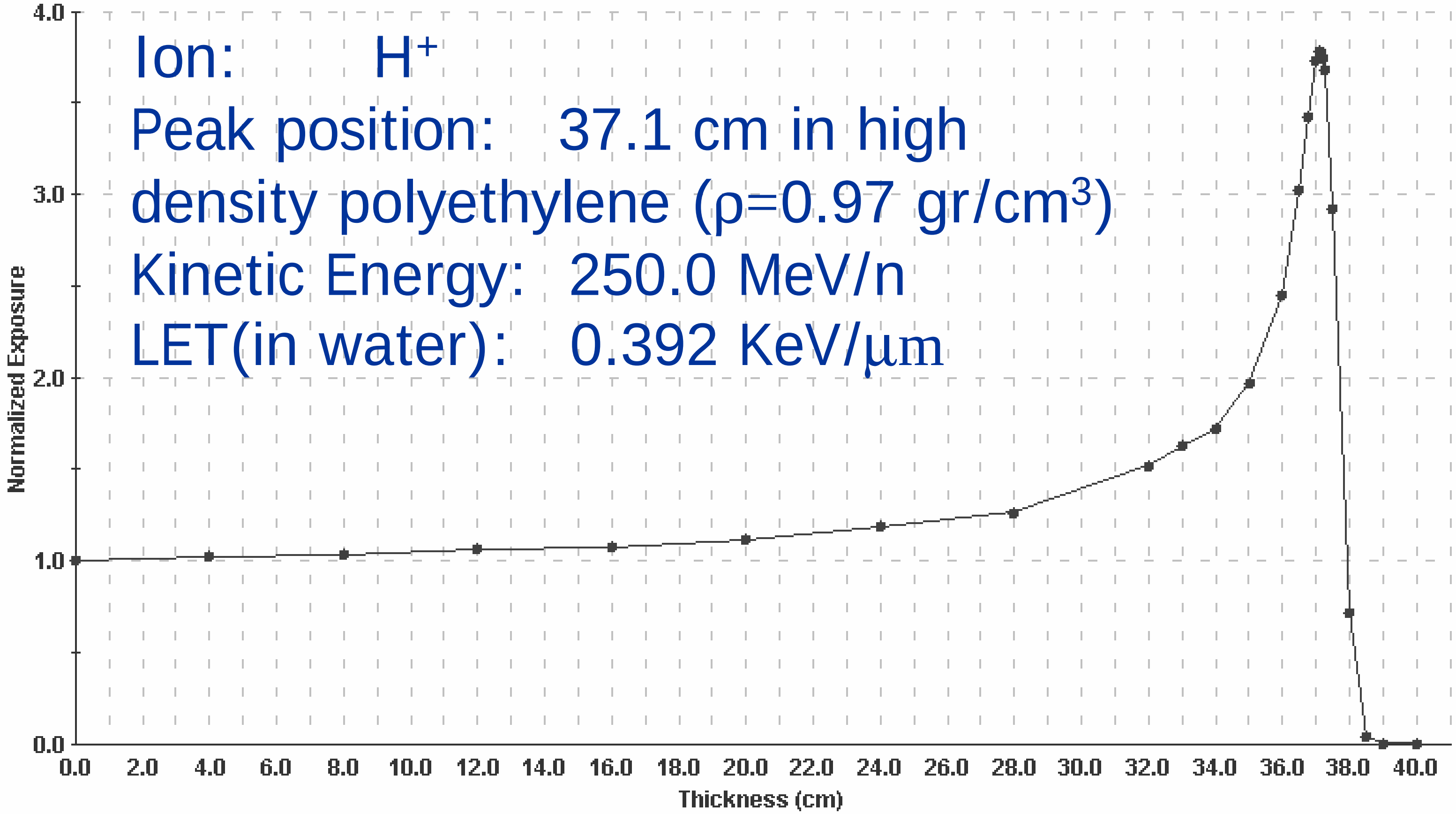
Peak position: 15.95 cm in high density polyethylene (ρ=0.97 gr/cm^3)

Kinetic Energy: 292.7 MeV/n

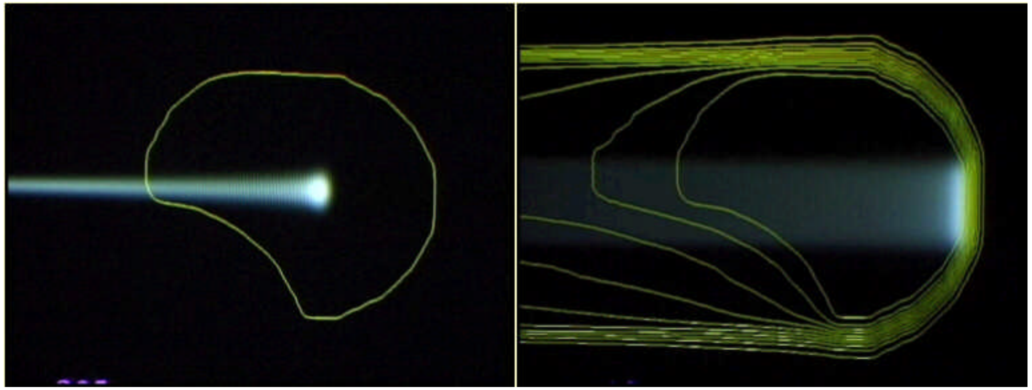
LET(in water): 12.9 KeV/μm

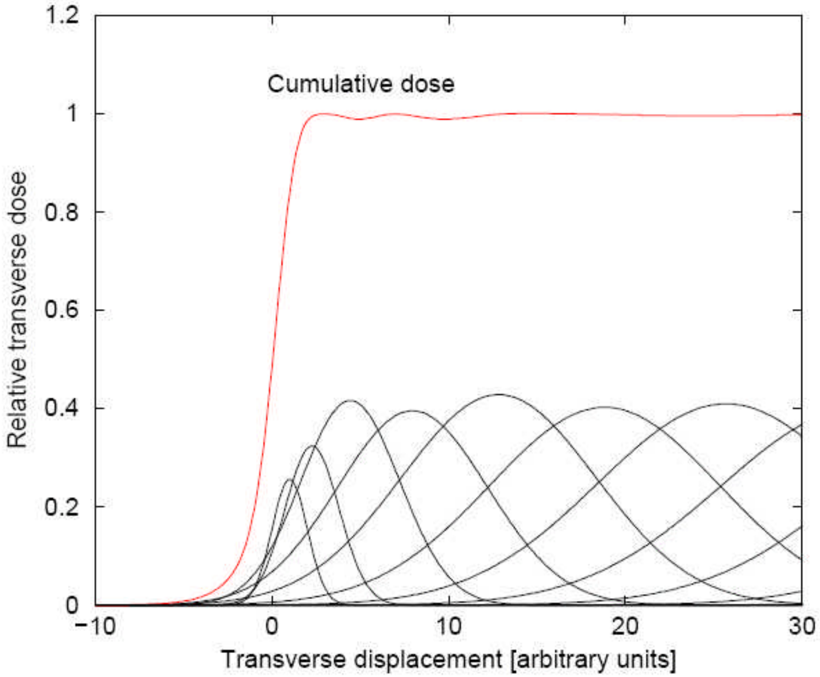


Experimental results from: NSRL Laboratory at Brookhaven National Lab - Adam Rusek



Spot scanning technique – at PSI, Heidelberg, ...





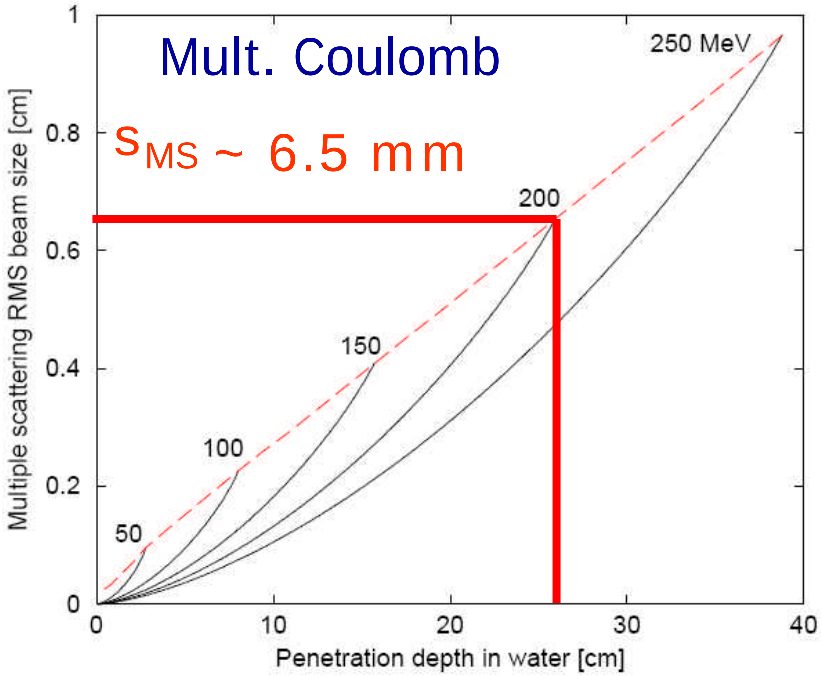
Problems with straggling and multiple Coulomb scattering require careful planning to achieve 1% accuracy in accumulated dose

Courtesy of Stephen G. Peggs

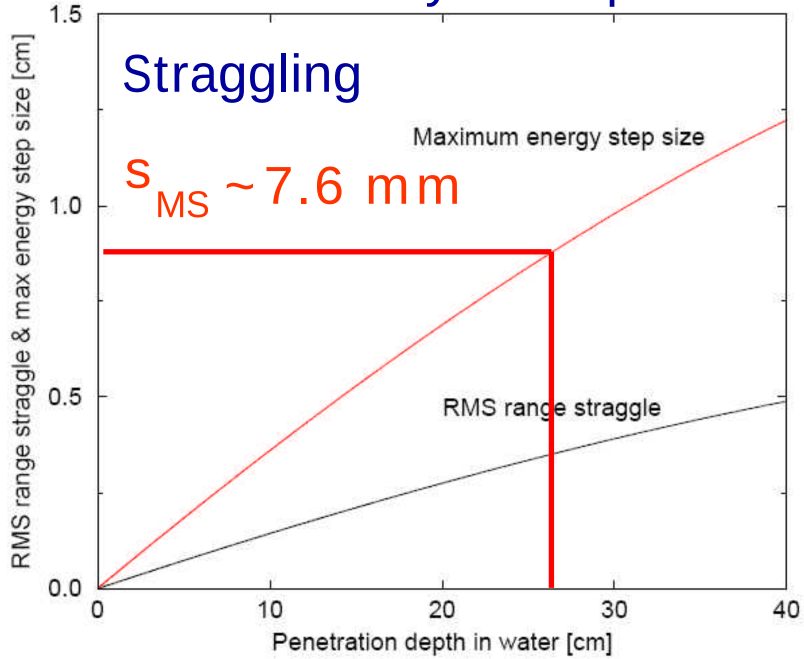
S. Peggs, "Fundamental Limits to Stereotactic Proton Therapy", IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 51, NO. 3, JUNE 2004, 677

D. C. Williams, "The most likely path of an energetic charged particle through a uniform medium", Phys. Med. Biol. 49 (2004) 2899–2911

Straggling and multiple Coulomb scattering



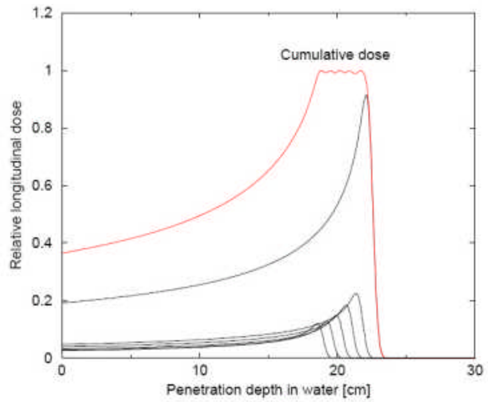
Courtesy of Stephen G. Peggs



The total beam size quadrature of the
multiple scattering beam size + optical beam size

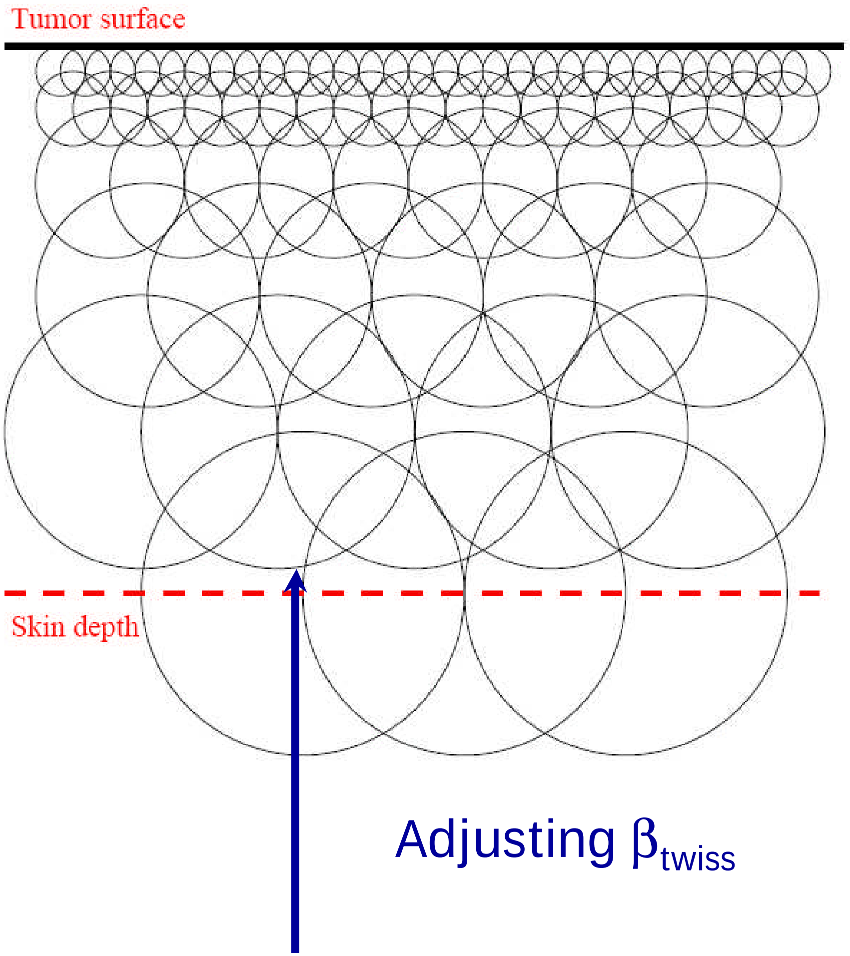
$$\sigma_b^2 = \sigma_{MS}^2 + \sigma_{OPT}^2$$

$$\sigma_{OPT}^2 = \epsilon \beta$$



Spot scanning preparation-longitudinal

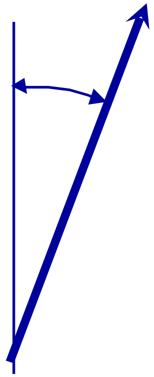
Courtesy of Stephen G. Peggs



$$x_{b+1} - x_b = 0.5\,(\sigma_{b+1} + \sigma_b)$$

Varying the beam size during therapy at different energies and transverse positions.

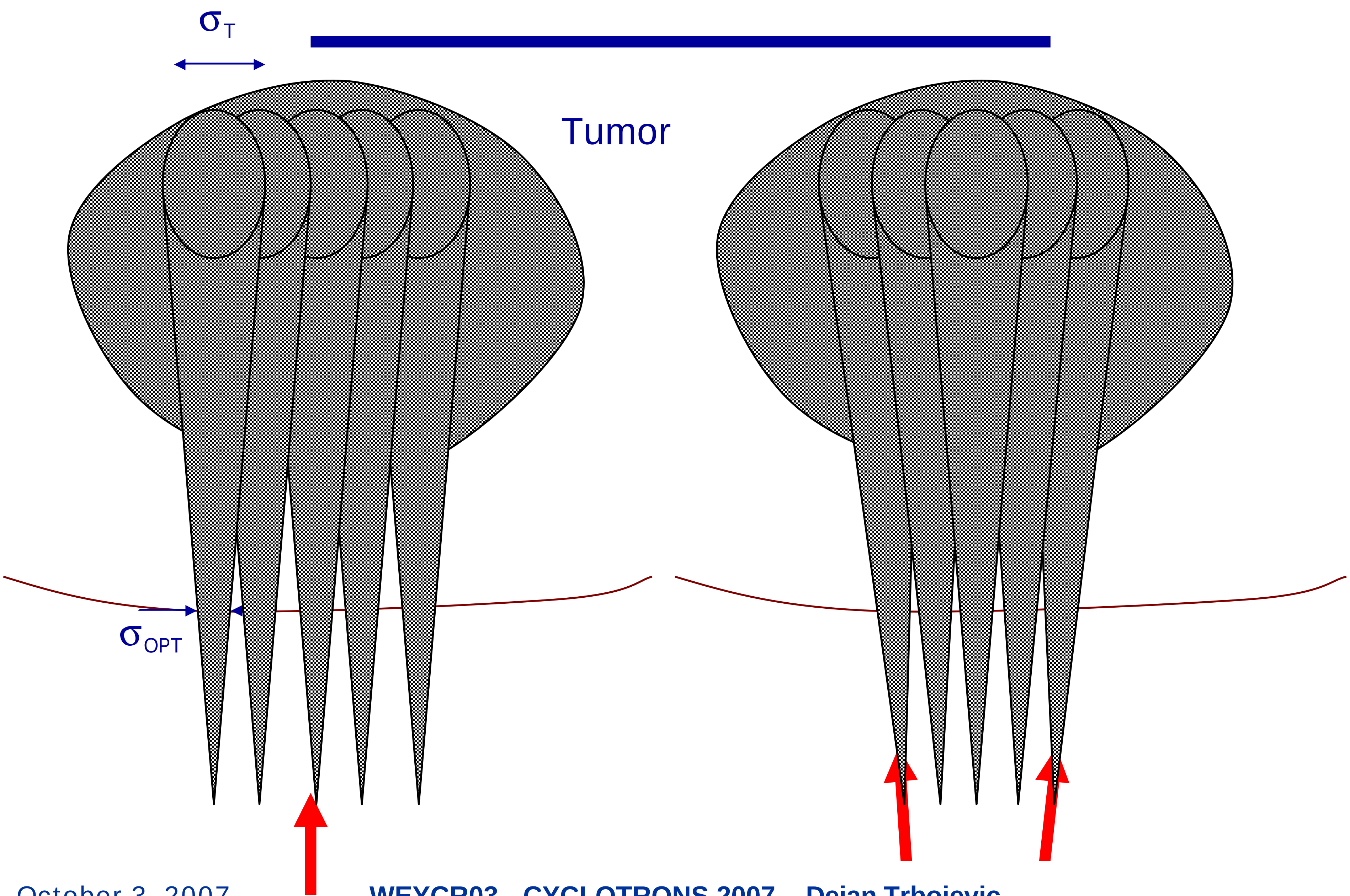
$\theta = 32$ mrad= $\tan^{-1}(10 \text{ cm}/3.2 \text{ m})$



Adjusting β_{twiss}

Beam direction

“Parallel” and 30-40 mrad angle scanning

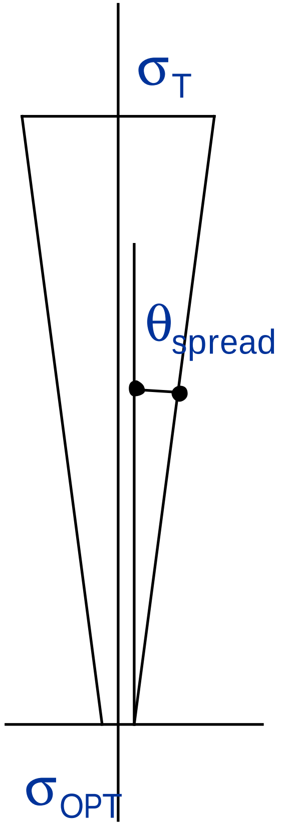


Transverse beam sizes

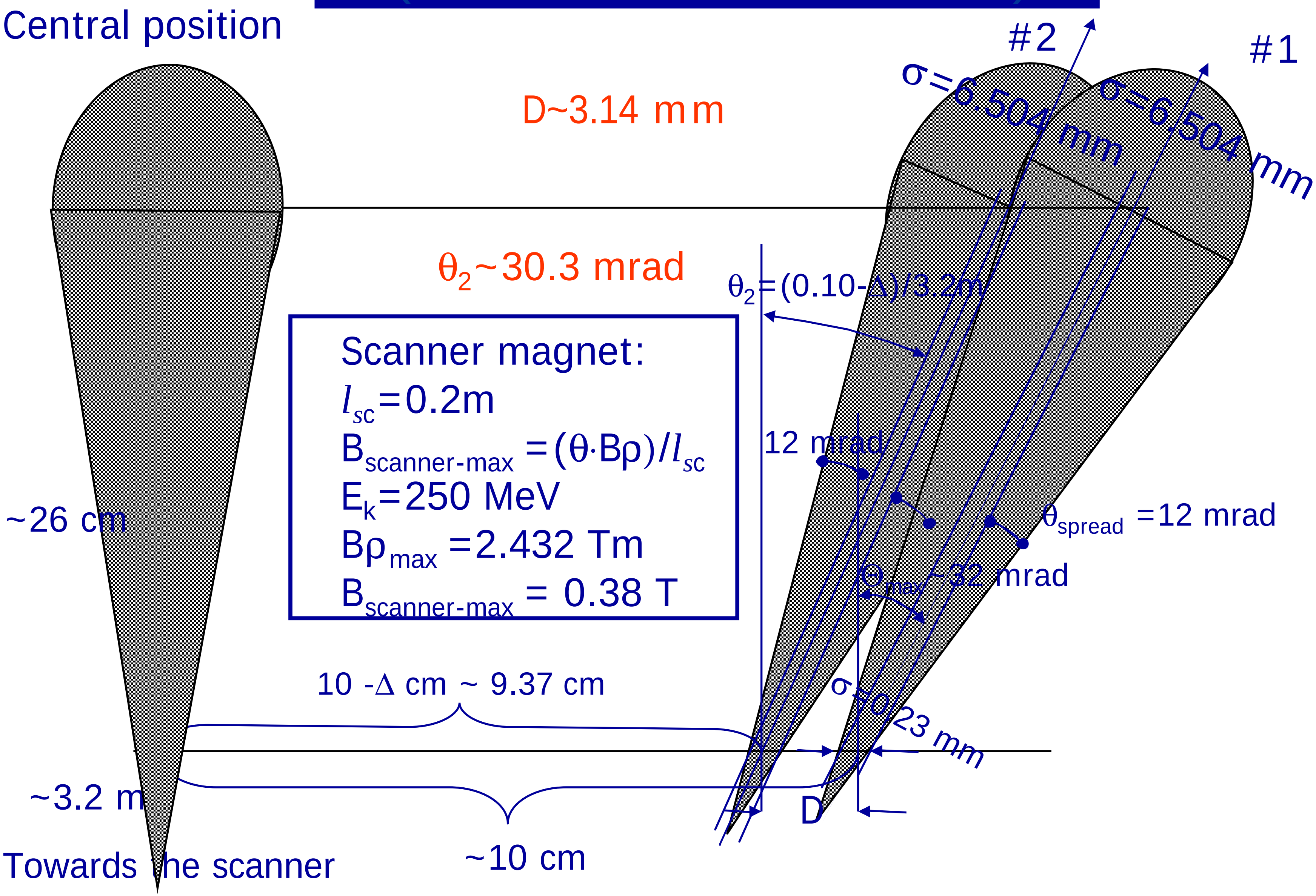
Normalized emittance $\varepsilon \cong 0.5\ \pi\ \mu m$, kinetic energy E_k=200 MeV

σ_{OPT} = Ö $[(\beta_{twiss} *\varepsilon)/(6\pi\ \beta\gamma)]$ γ=1.138272/0.938272029=1.21316 $\beta\gamma$=0.6868

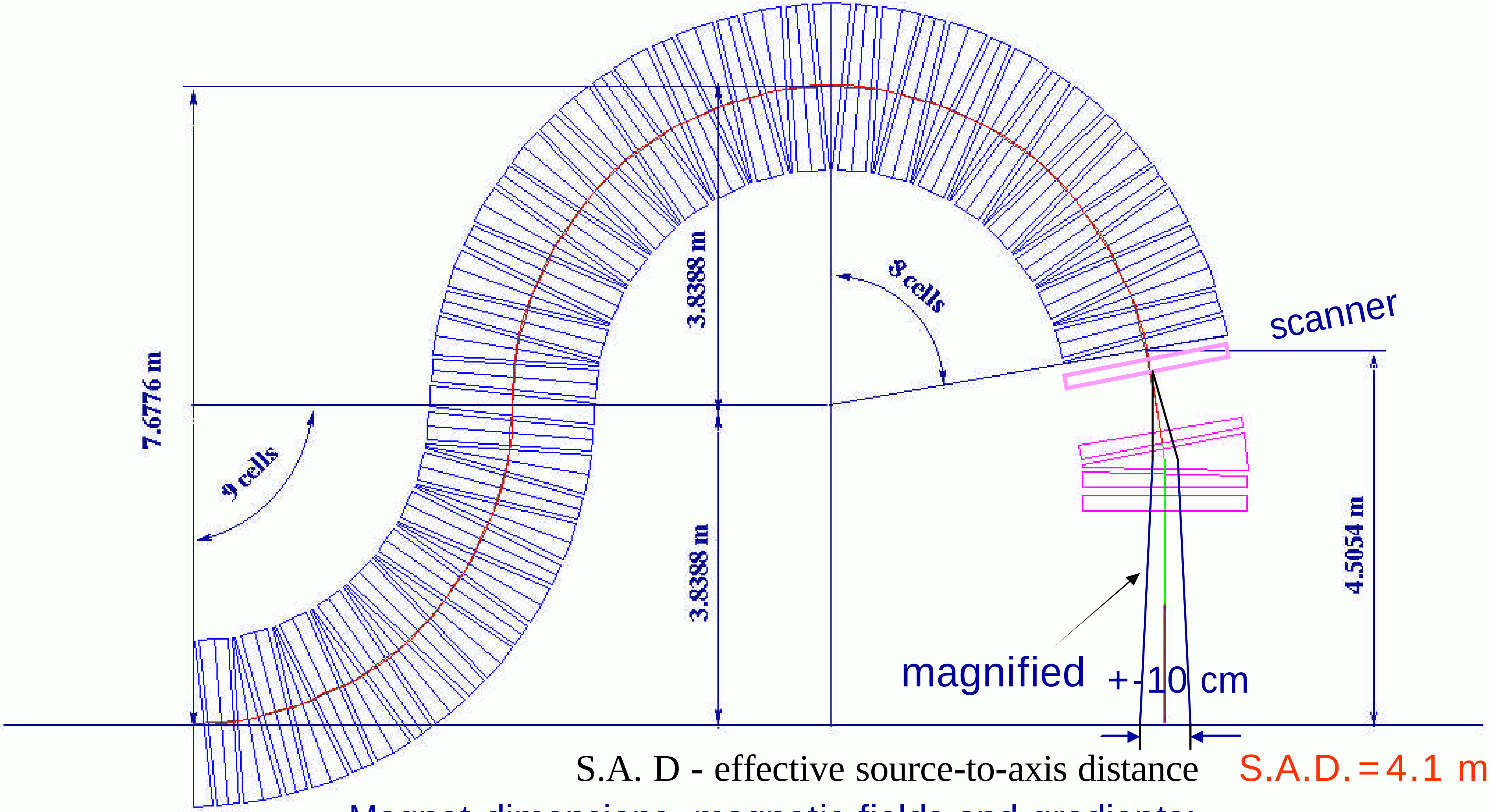
β_{twiss}(m)	σ_{OPT}(mm)	σ_{MS}(mm)	σ_T(mm)	θ_{spread}(mrad)
0.45	0.23	6.5	6.504	12.06
1	0.348	6.5	6.509	11.84
10	1.101	6.5	6.59	10.73
100	3.483	6.5	7.37	7.475



Planning carefully the scan: find the right step size Δ (start at the end ~10 cm)



Proton Gantry with triplet and scanning magnets
(it could be built with small permanent magnets Φ=2 cm)

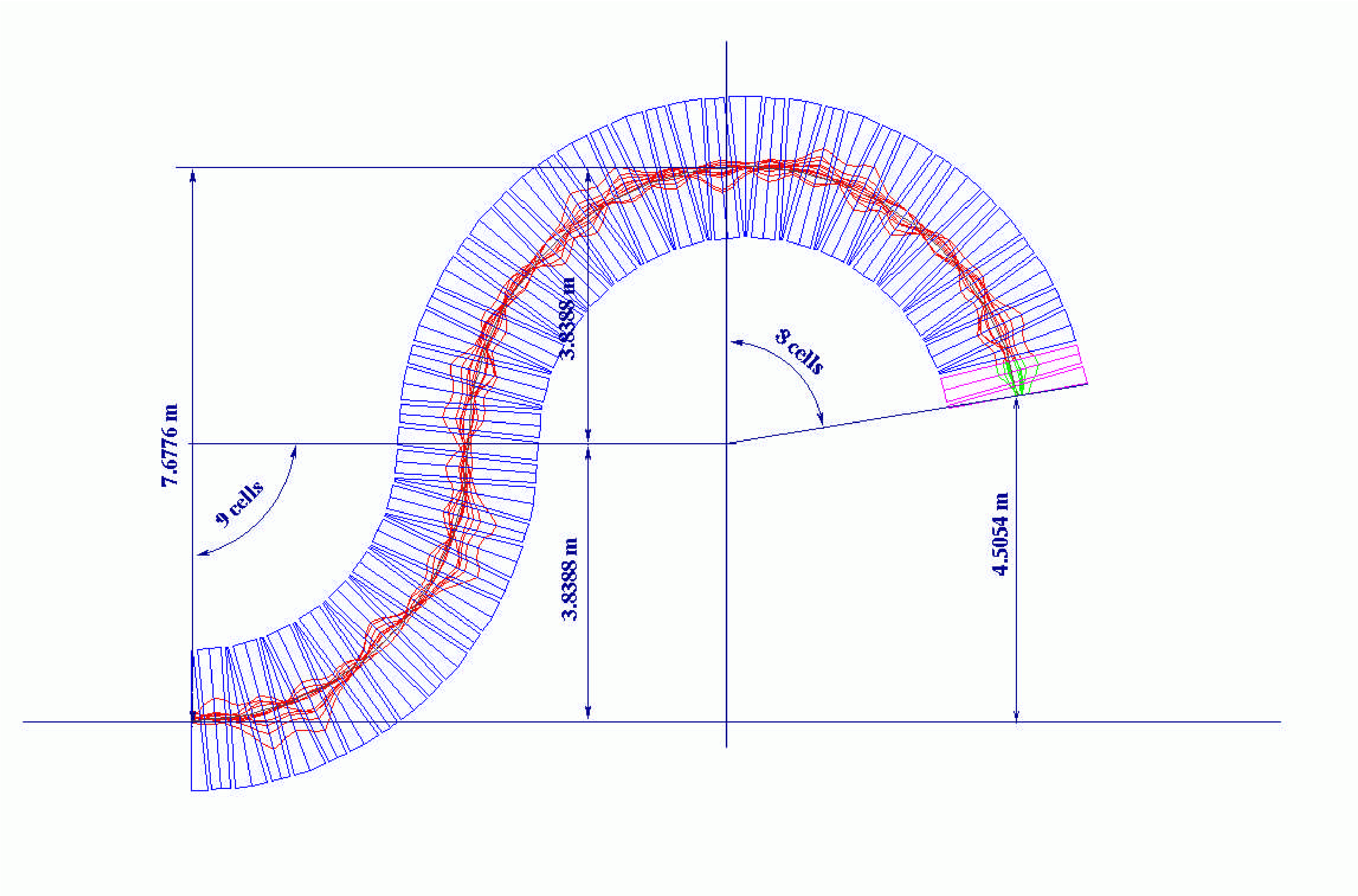


Magnet dimensions, magnetic fields and gradients:

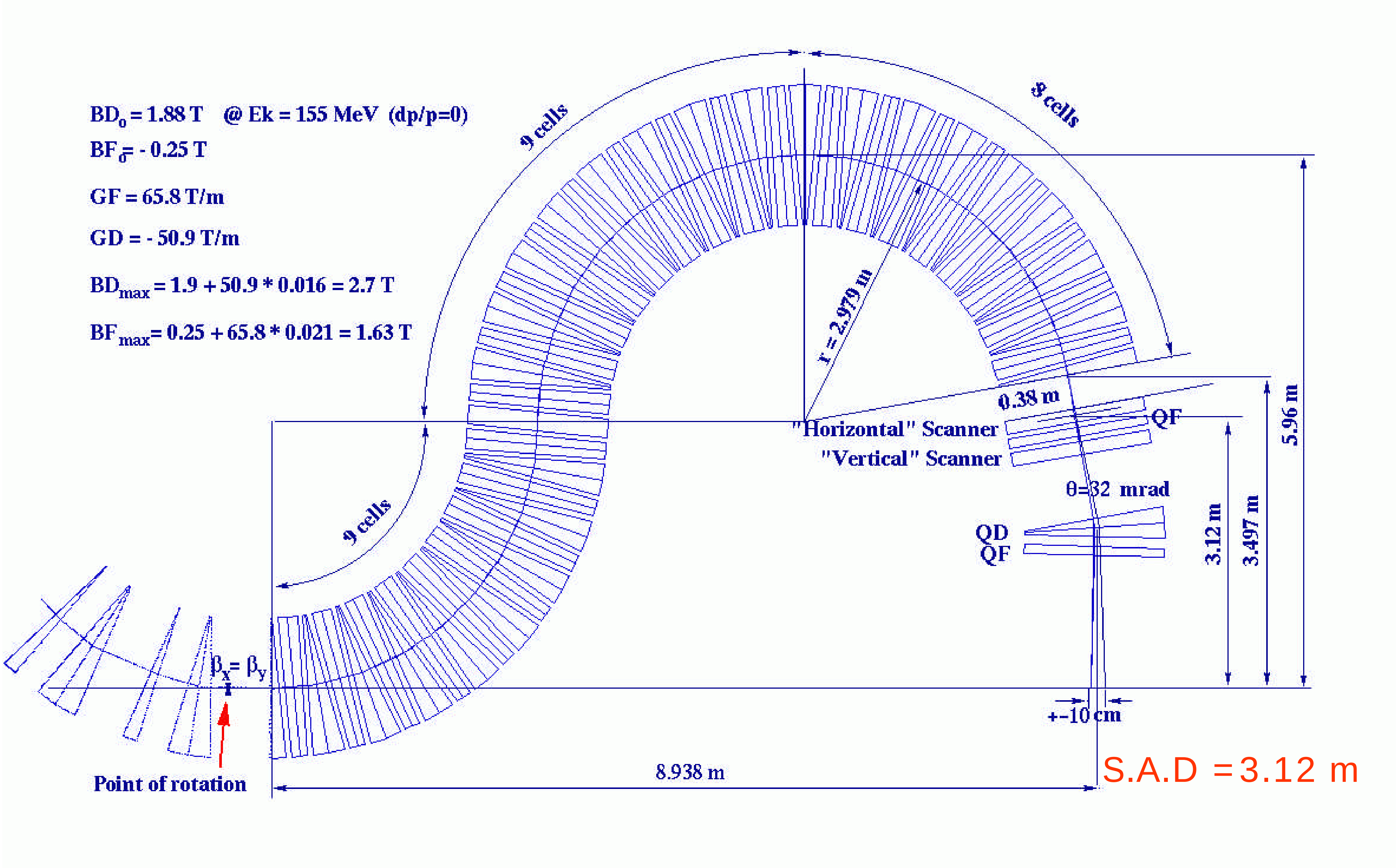
L_{BD} = 25 cm, GD =-33.7 T/m, B_{max}= 1.5 T + 33.7 T/m*0.012 mm = 1.9 T

L_{BF} = 30 cm, GF =+35.5T/m, B_{max}=-0.25 T -+ 35.5 m*0.028 mm = 1.2 T

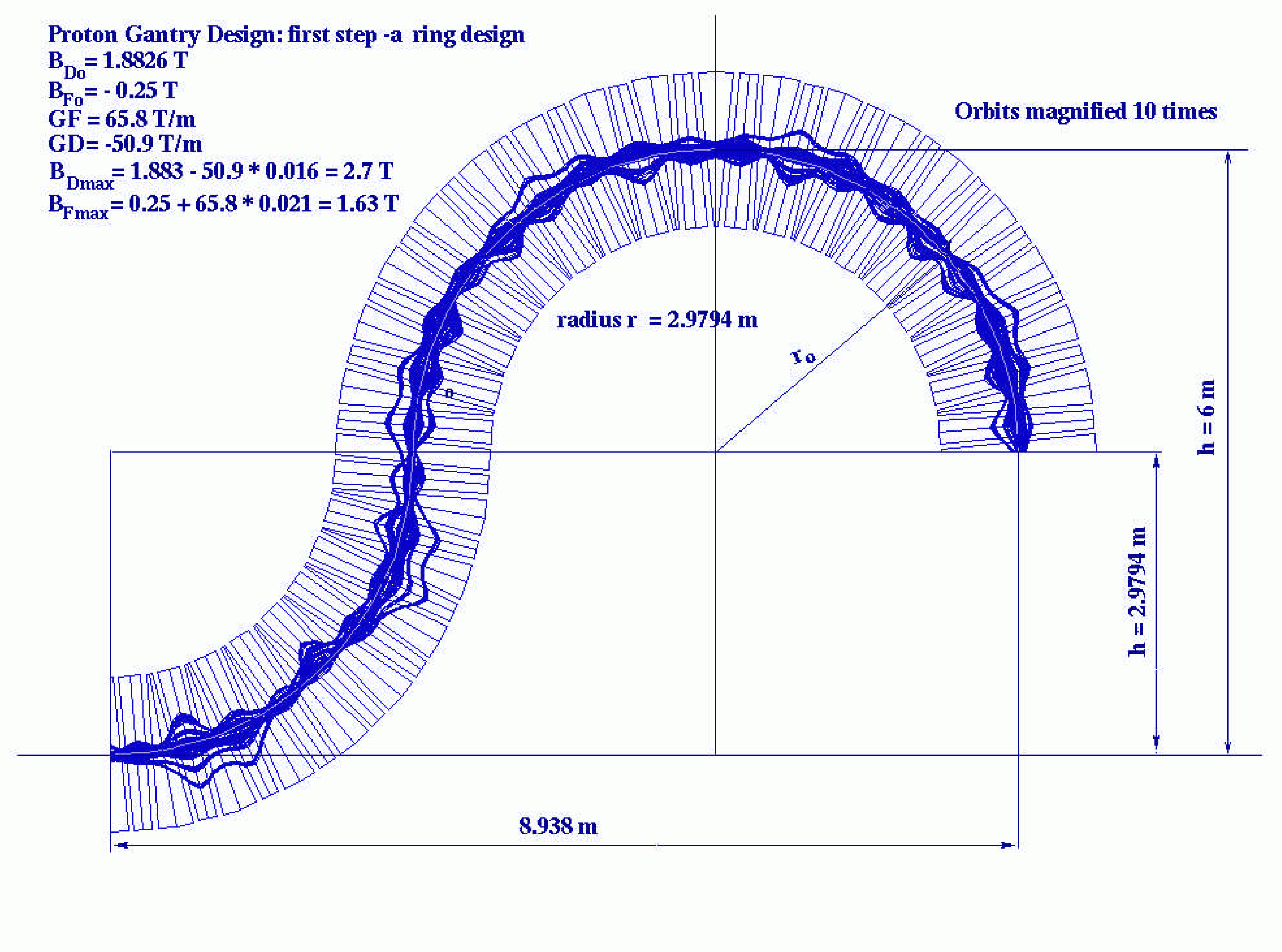
Tracking of protons @ fixed magnetic fields from 90 –250 MeV



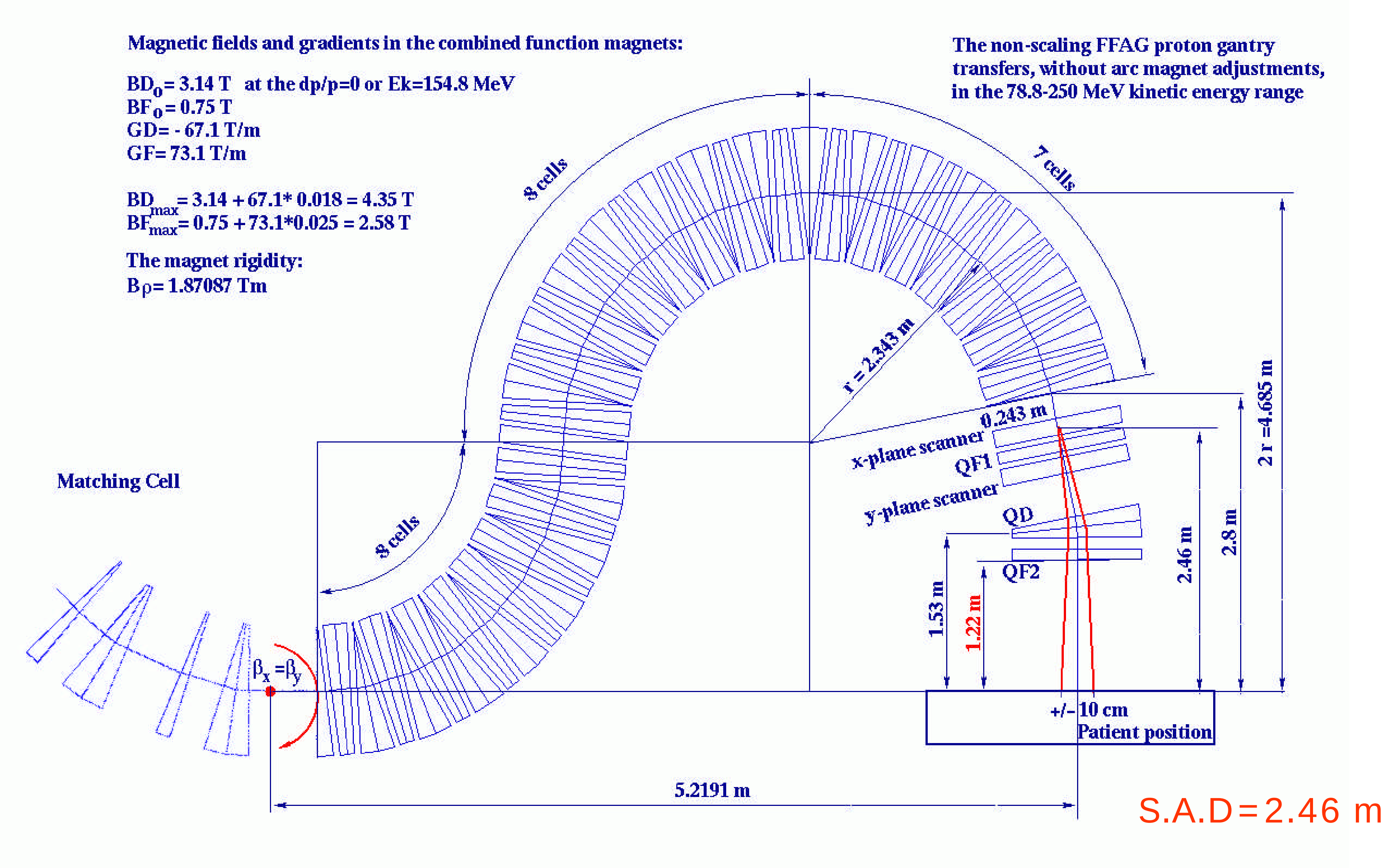
Towards smaller size-proton gantry with superconducting magnets – height ~ 6 m



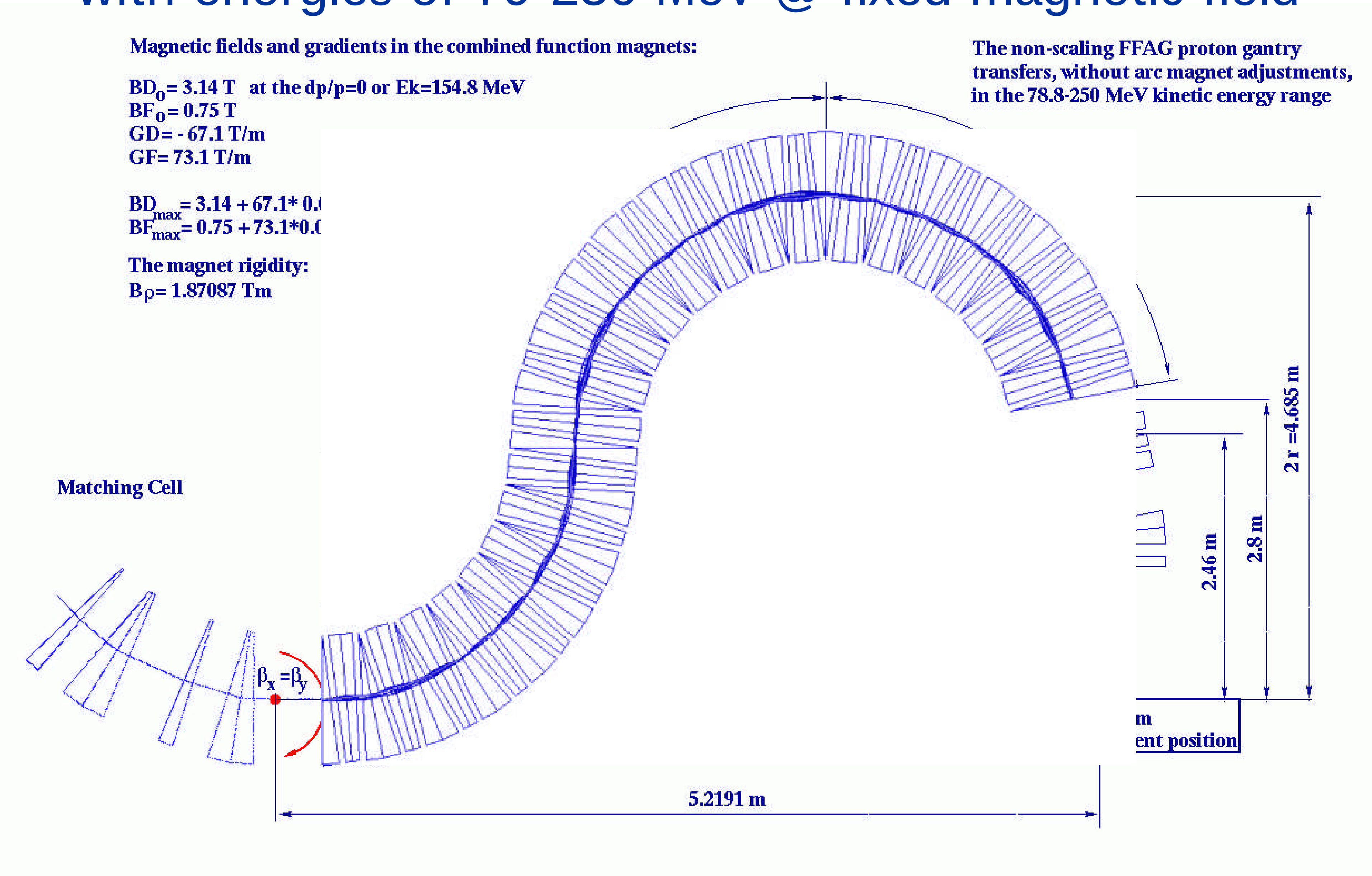
Proton gantry with superconducting magnets



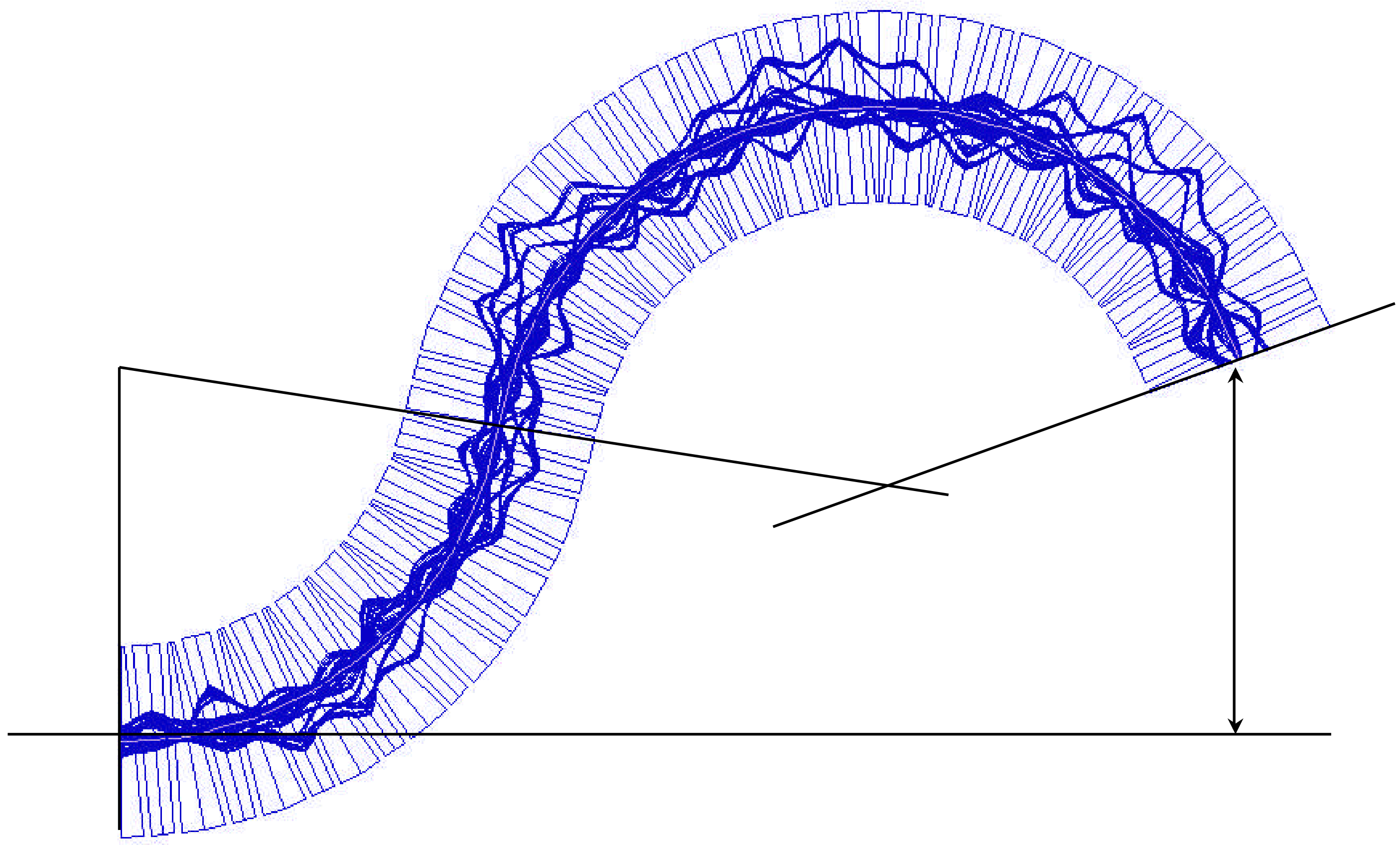
Smaller non-scaling FFAG proton gantry – height 4.7 m



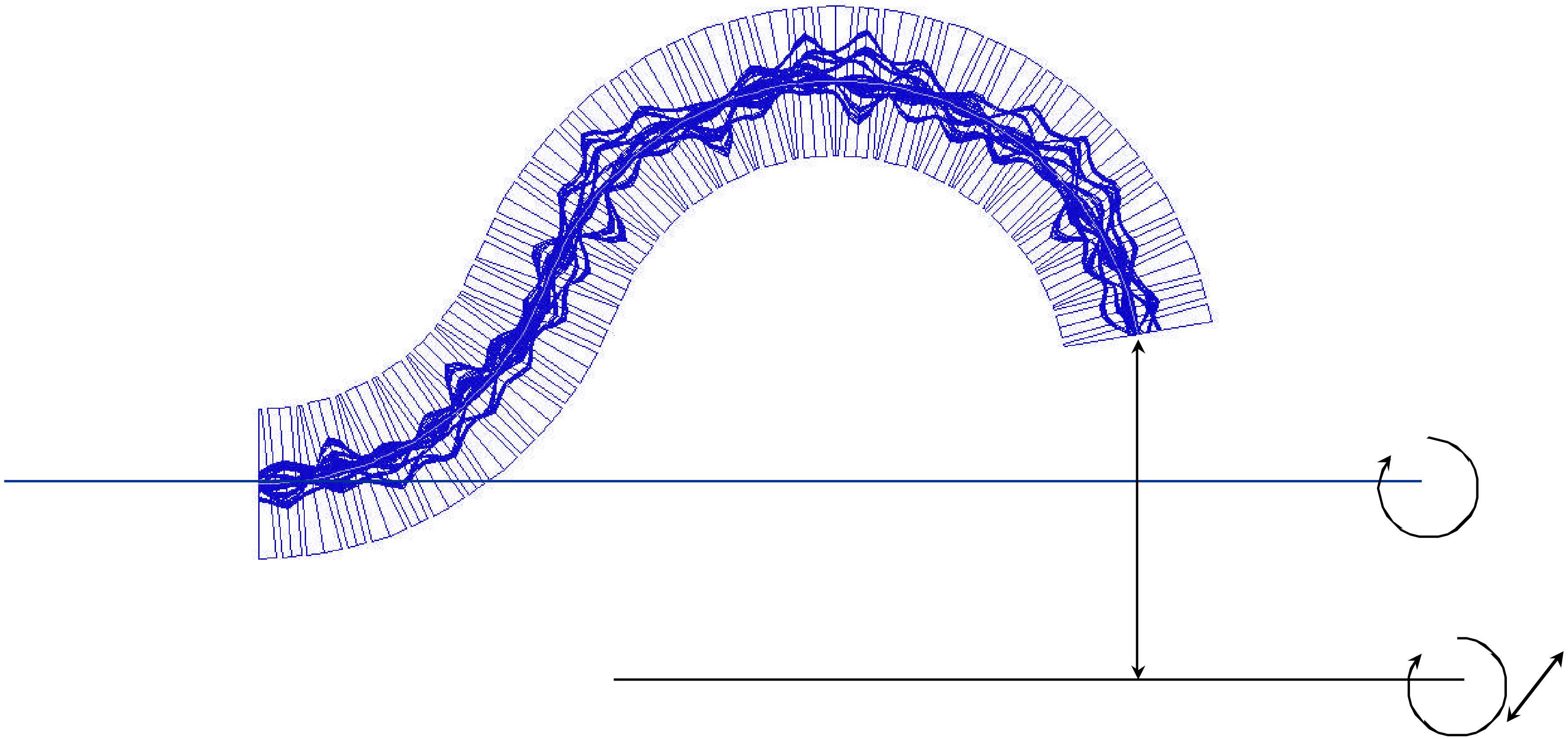
Smaller non-scaling FFAG proton gantry tracking protons with energies of 79-250 MeV @ fixed magnetic field



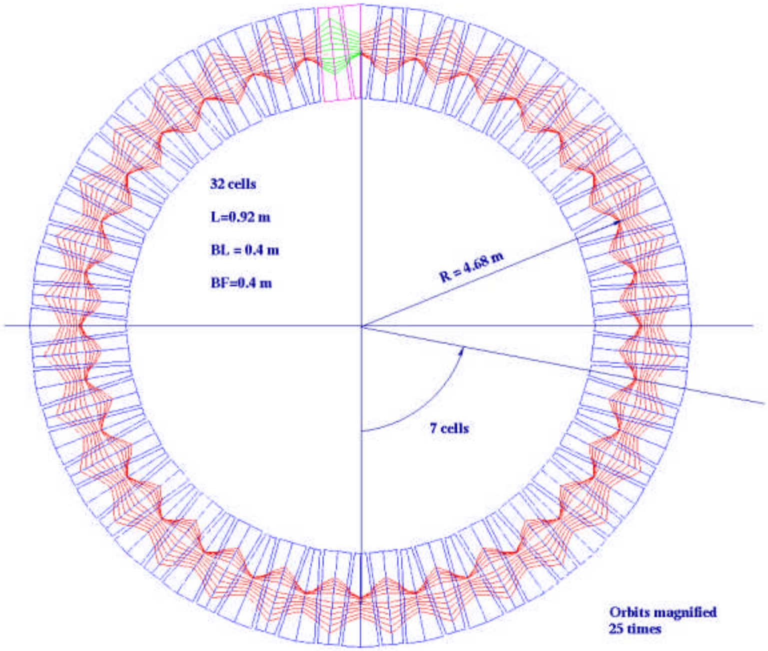
Adjustment of the height with different number of cells

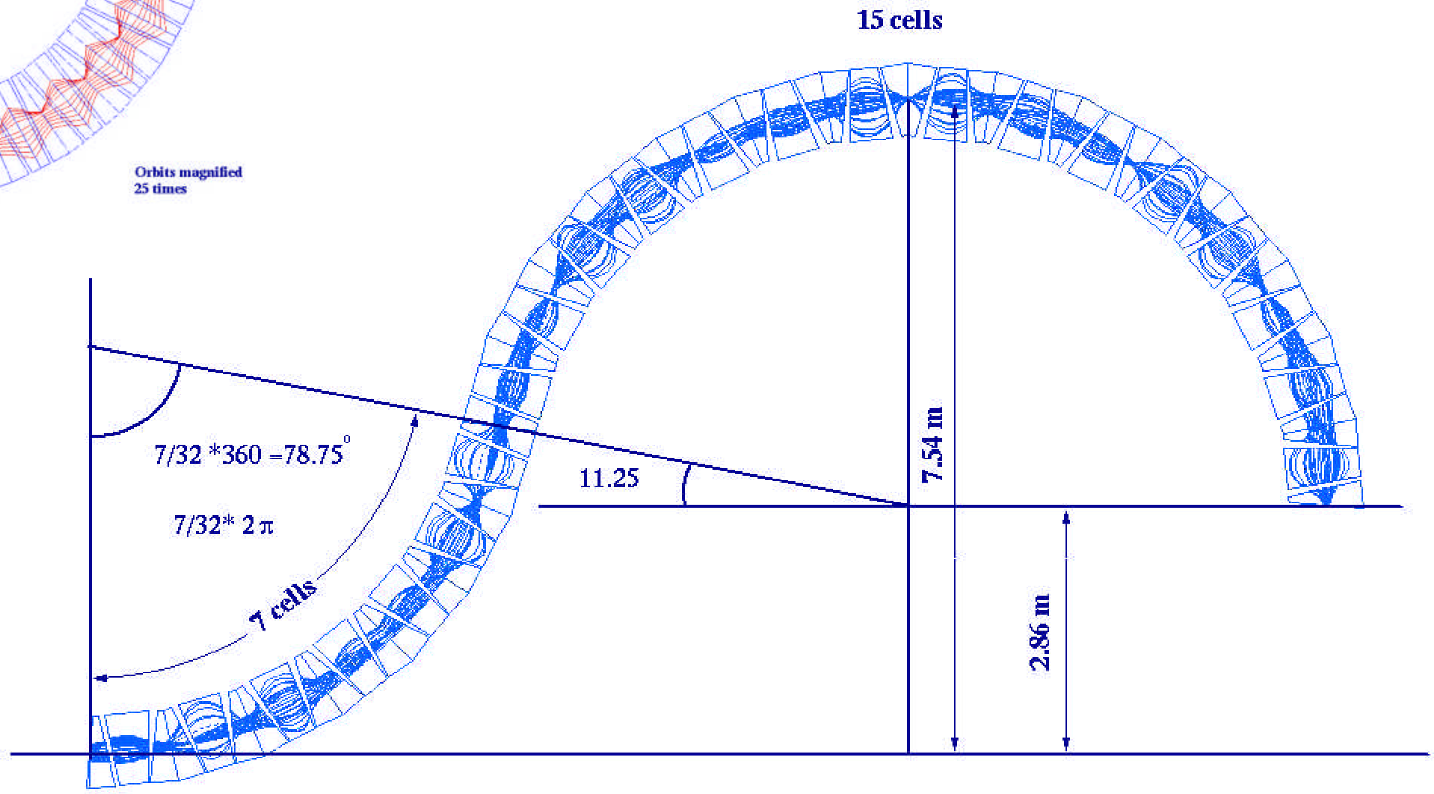


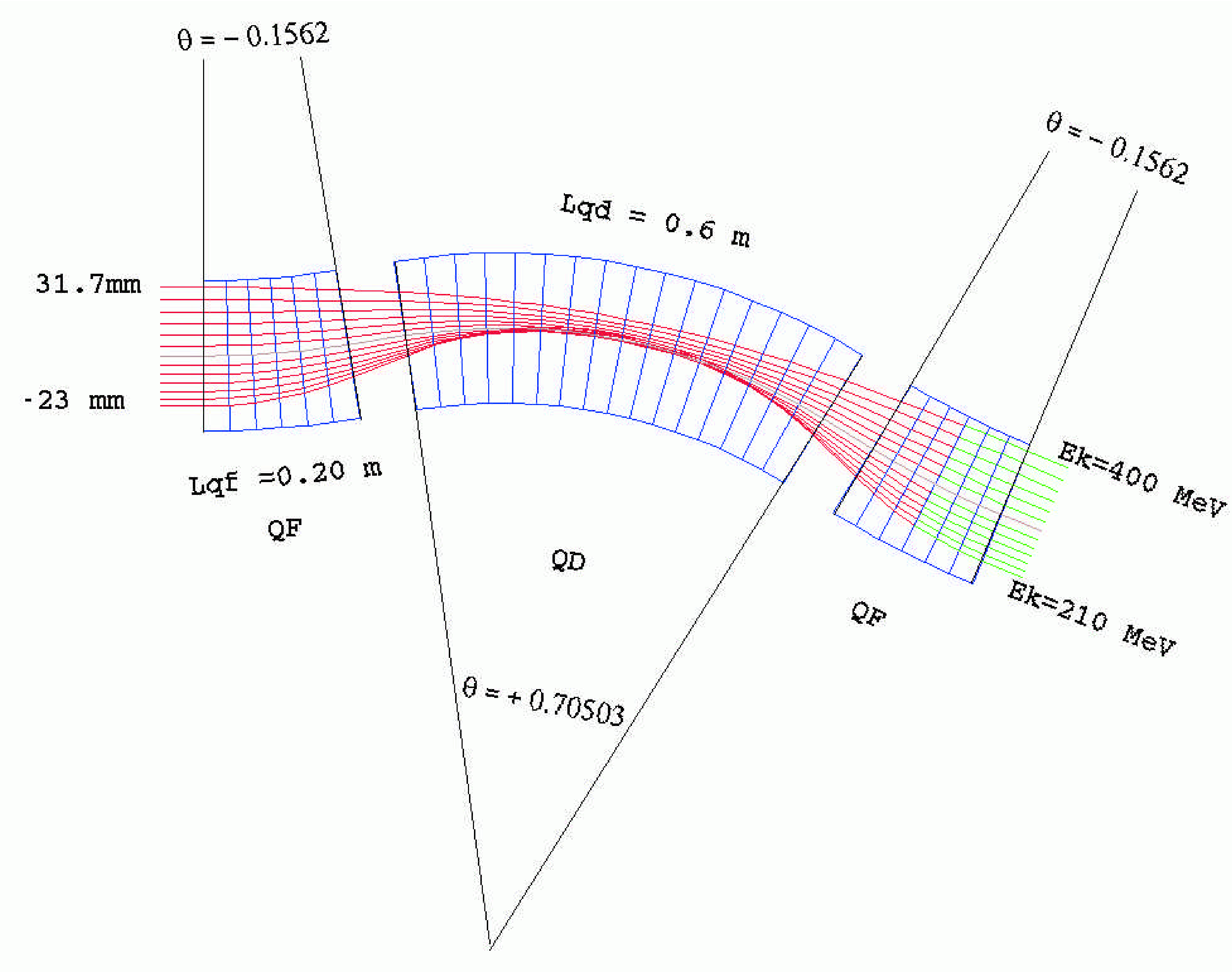
PSI solution with the non-scaling FFAG



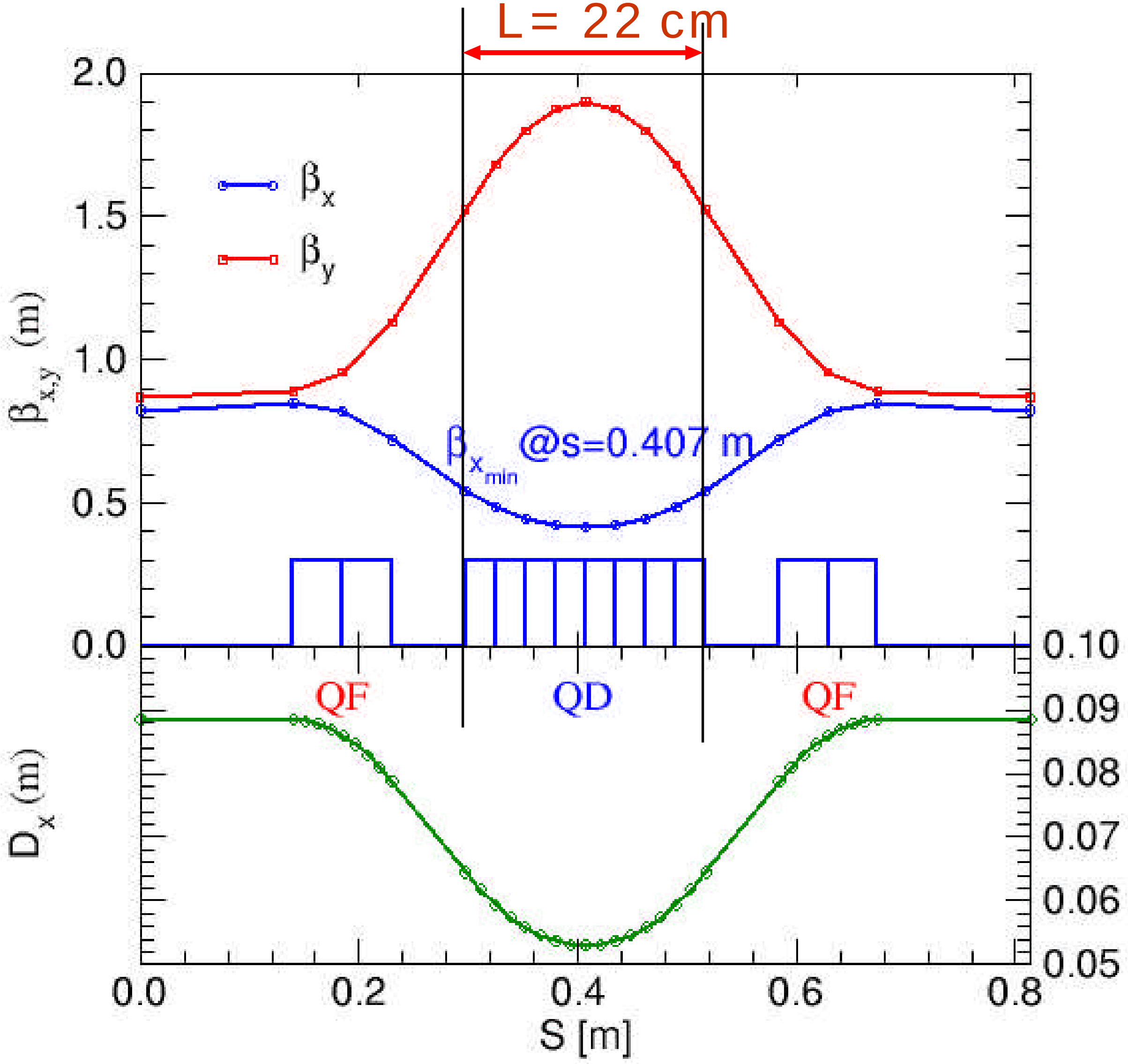
Carbon gantry design






θ = – 0.1562
θ = – 0.1562
Lqd = 0.6 m
31.7mm
-23 mm
Lqf =0.20 m
QF
QD
QF
Ek=400 MeV
Ek=210 MeV
θ = + 0.70503

Lattice functions

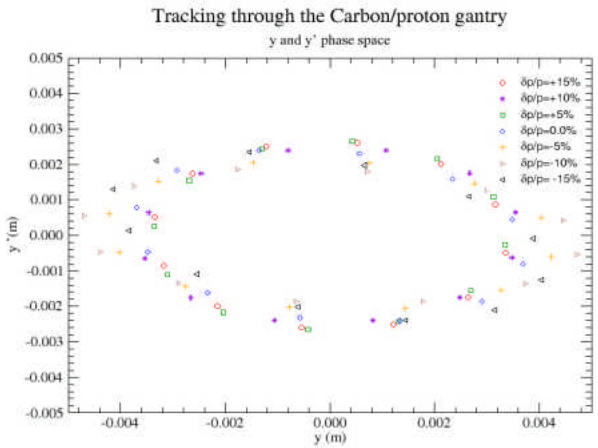


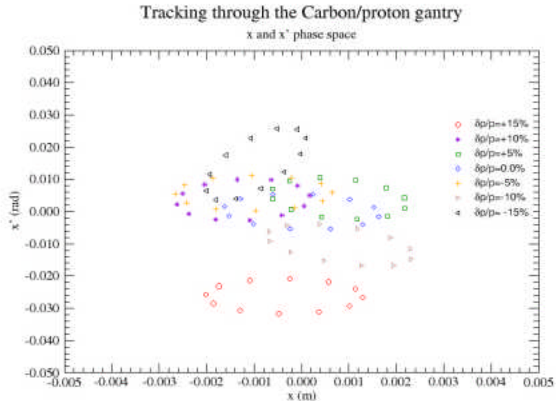
Very strong focusing:

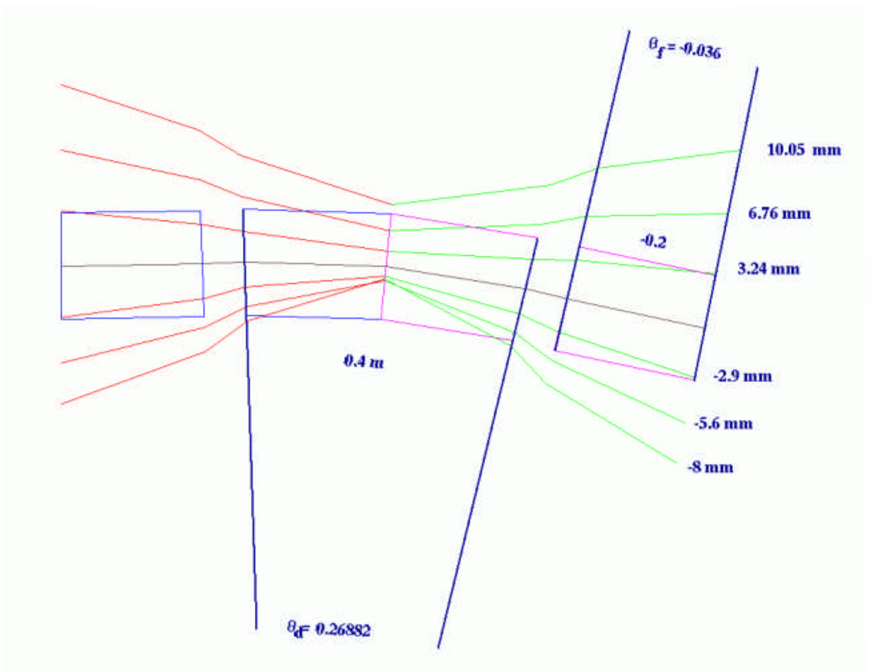
$b_{x,y}$ ~1-2 m

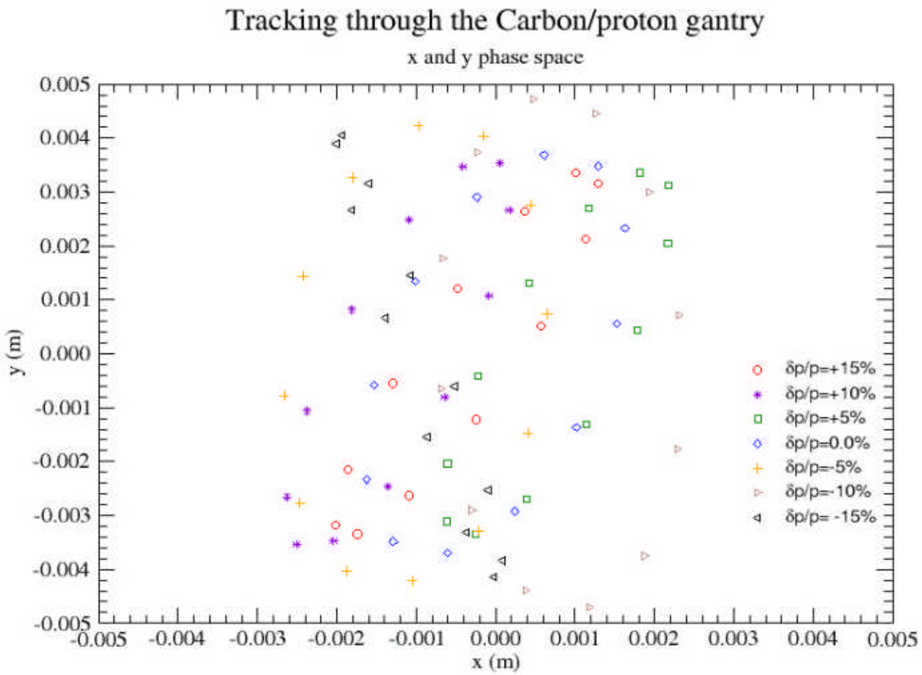
D_{max} ~ 8.8 cm

Carbon gantry presented at PAC07



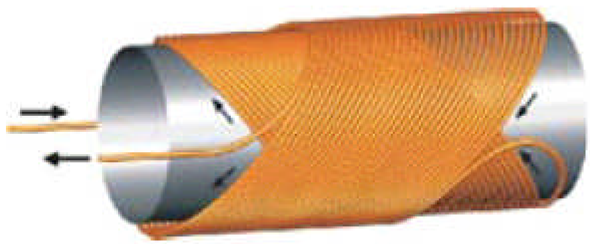




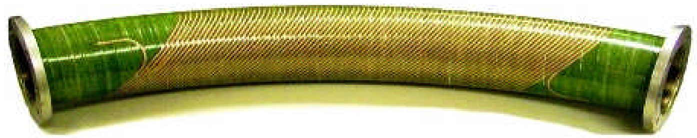


-5 mm + 5mm

Possible continuous coil magnet design for the non-scaling FFAG gantry



AML
ADVANCED MAGNET LAB
"AML Enabled"



Bent Combined Function Magnets

ENABLING
Bent, Twisted or Straight Magnets
Combined Function Magnets (dipole, quadrupole, sextupole...)
Bent Dipole - Fully Compensated Quadrupole
Compact Design
Highly Scalable in Size & Field Strength

HIGHEST QUALITY & RELIABILITY
"Perfect Fields" with Zero Systematic Errors
Uniform Field over a Large Percentage of Aperture
Unmatched Mechanical Coil Robustness
Simplified Coil Ends with High Field Quality
Conductor and Layer Stabilization
Reduced Risk of Electrical Shorts
Splice Free

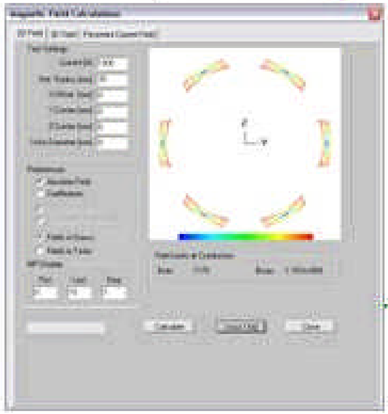
MOST COMPACT & LOWEST COST
No Manufacturing Tooling!
No Cost Penalty for Varying Length
No complex Inserts
Mitigate or Eliminate Shim Coils
Combined Function Configurations

Revolutionize your charged particle applications
For more information contact sales@magnetlab.com

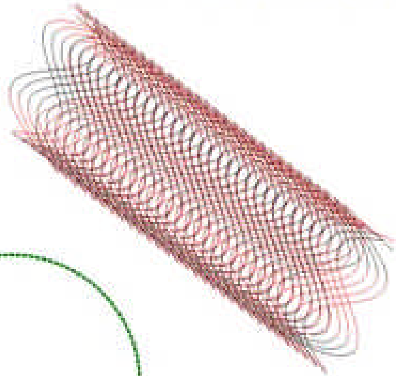
Magnets are available

FLUX TRAPPED MAGNETS - AML technology replaces permanent magnets with much higher field superconductor technology which results in a higher power density. Applications include motors, generators, medical devices, steering systems and more...

CoilCAD® 3D Design



"Perfect Field" Coil Design Output



Completed Magnet

3D Multi-Layer Manufactured Co

AML's CoilCAD® software and "Double-Helix" technology enables commercially viable superconducting products by solving key issues:
Cost, Quality & Reliability

Cost - **Efficient Design & Automated Manufacturing WITHOUT Tooling!**

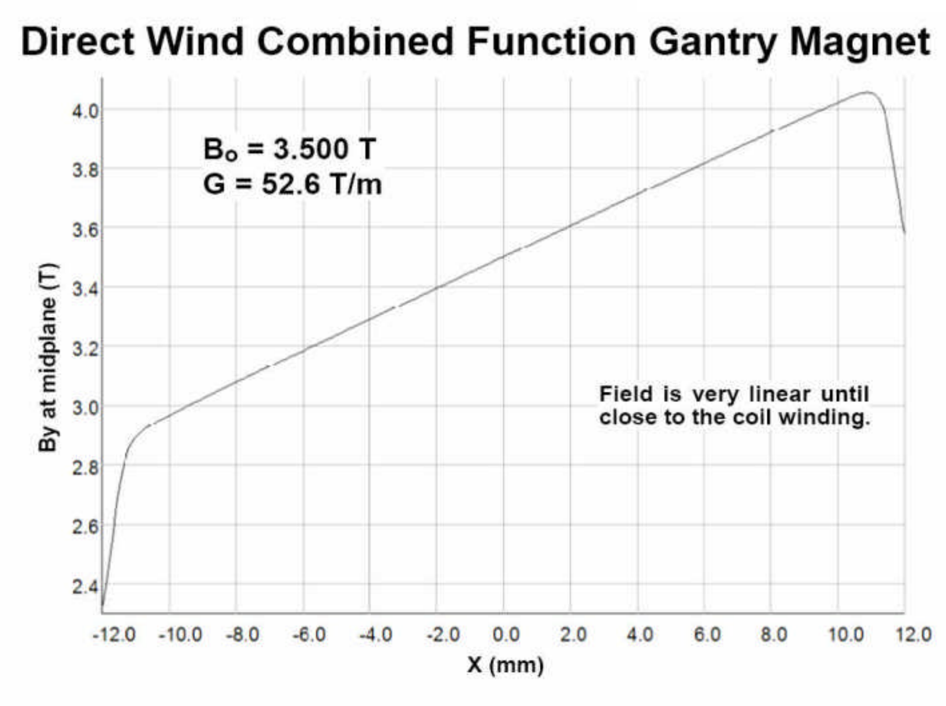
Quality & Reliability - **Precision conductor placement and stabilization!**

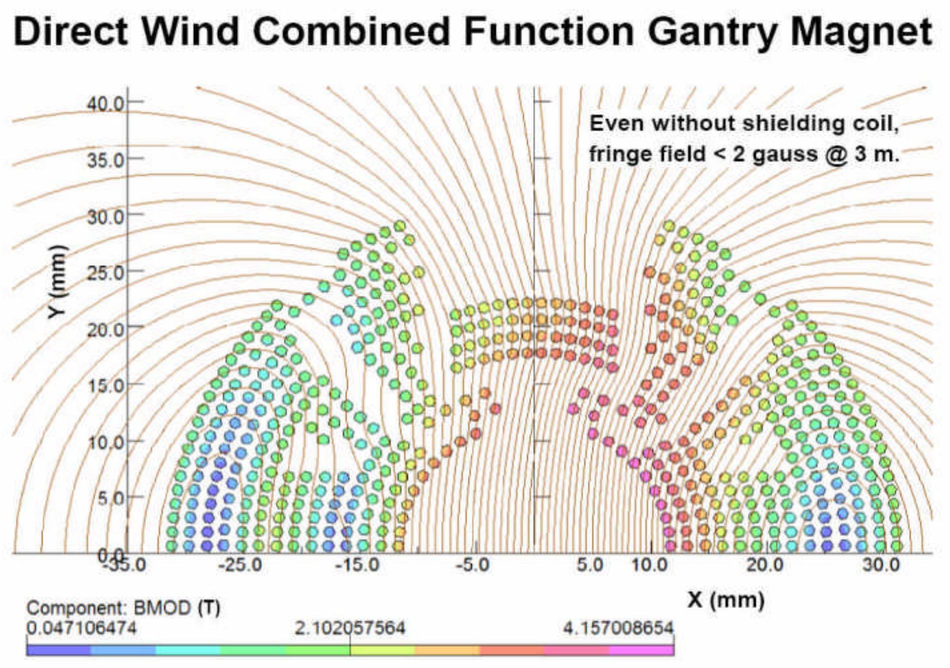
"AML *Enabled*"

Combined Function magnet for the Carbon Gantry

Table 1: Magnet properties

	L(m)	B(T)	G(T/m)	A_p(m)	B_{max}(T)
BD	0.40	3.7-4.3	-68.5	$\pm$ .008	4.24
BF	0.40	1.00	71	$\pm$ .010	1.8

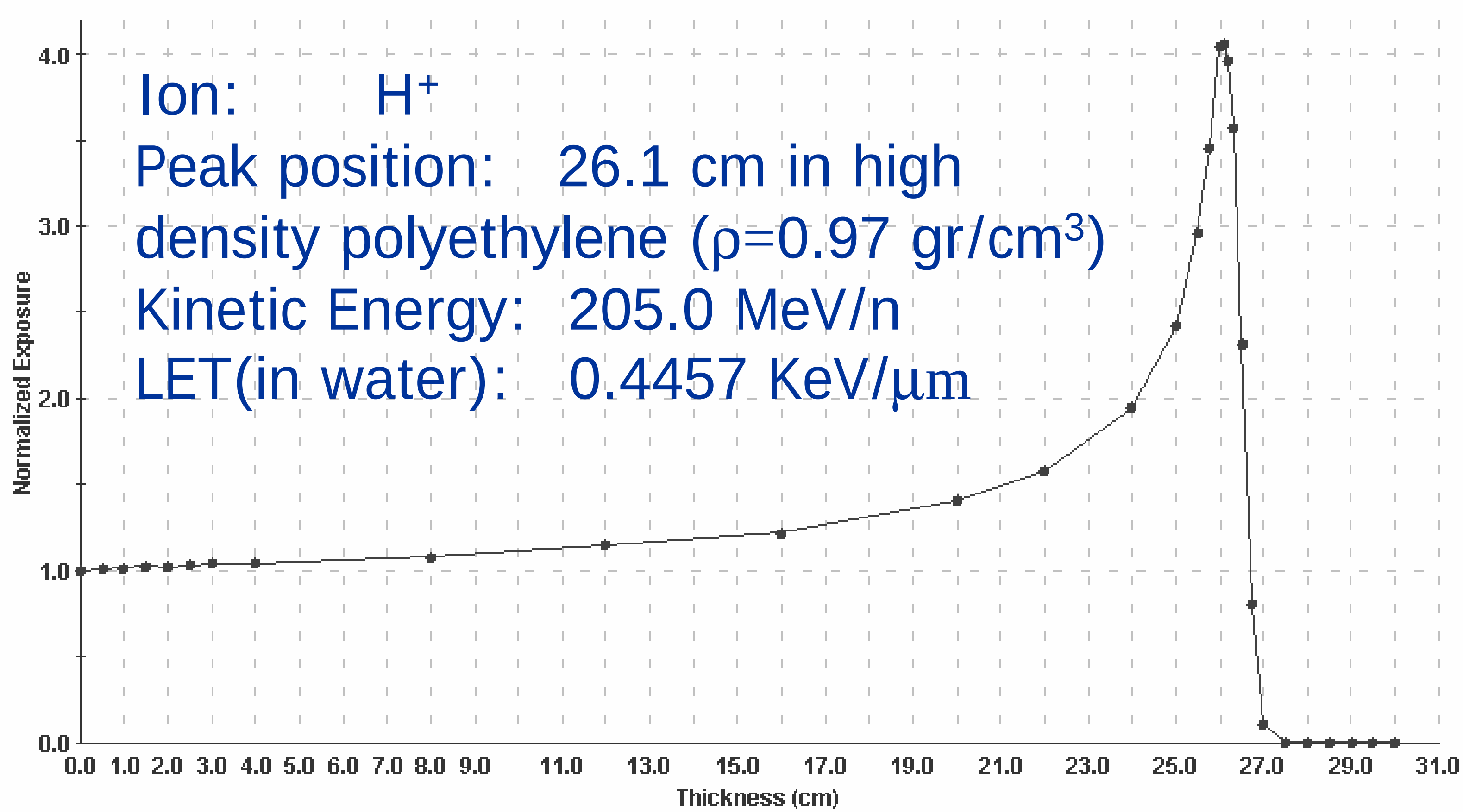




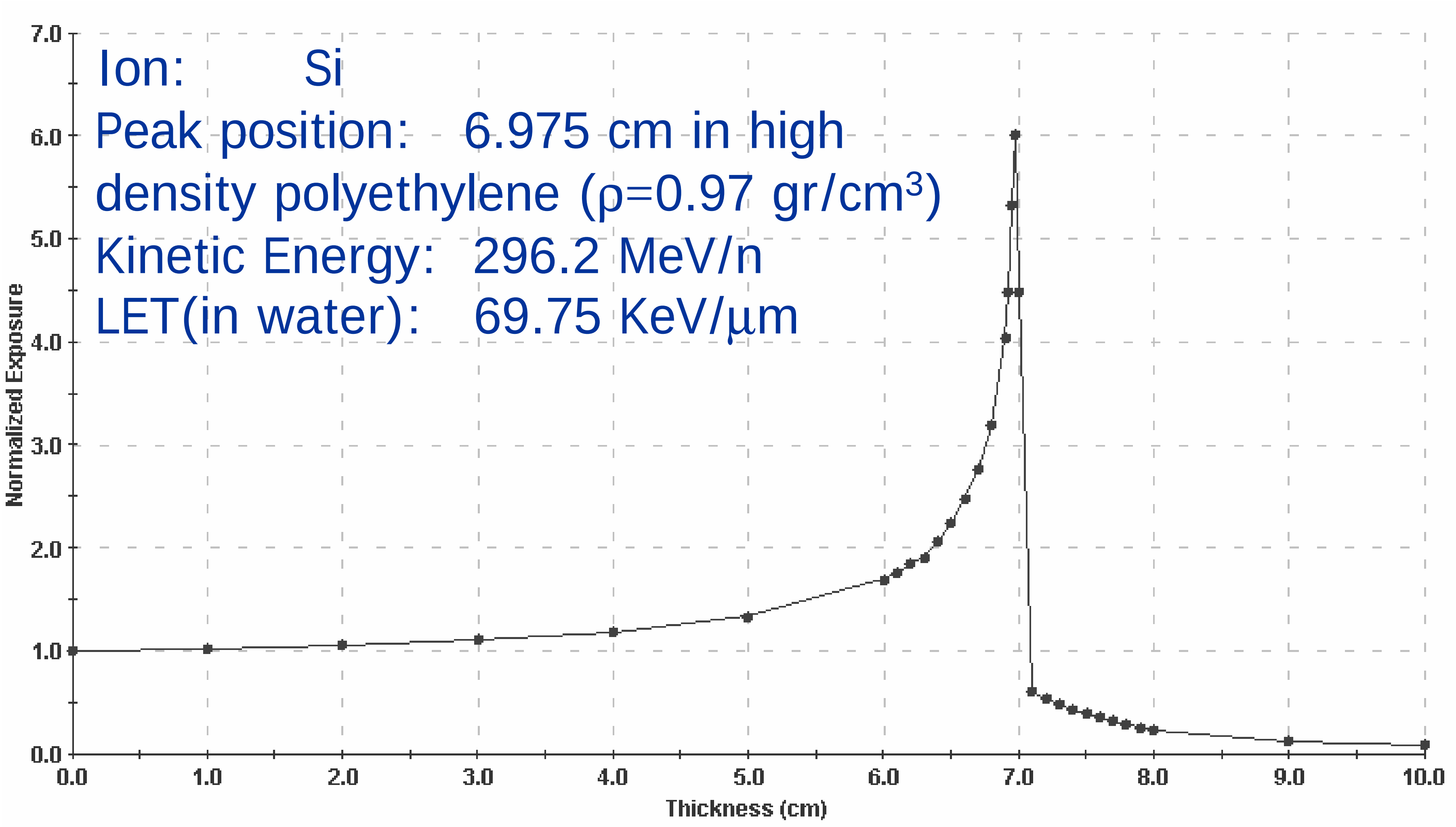
Summary

- Isocentric gantries are necessary in proton/carbon facilities but presently made of too large and heavy magnets.
- Spot scanning is very essential for therapy. We presented a real possibility of scanning at the end of the gantry.
- The non-scaling FFAG present a new solution for the isocentric gantry design. Reduction in the gantry size and weight comes from the small superconducting magnets – already available. The weight of 130 tons in the carbon isocentric gantry is reduced to 1.5 tons.
- Additional advantage: easier operation–fixed magnetic field.
- Support structure and counterweights are much lighter.
- A follow up detail study of the spot scanning from the end of the gantry will be presented soon.

Experimental results from: NSRL Laboratory at Brookhaven National Lab - Adam Rusek



Experimental results from: NSRL Laboratory at Brookhaven National Lab - Adam Rusek



Experimental results from: NSRL Laboratory at Brookhaven National Lab - Adam Rusek