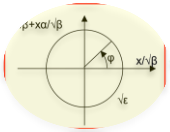
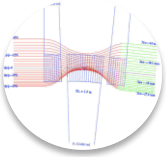
Non-Scaling Linear Smallest
Carbon Cancer Therapy Gantry

Dejan Trbojevic

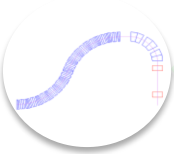
NS-FFAG GANTRIES:



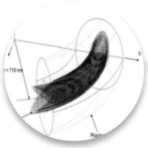
INTRODUCTION



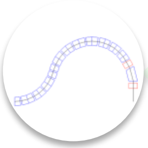
NS-FFAG



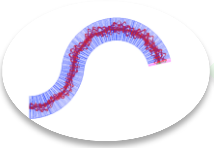
CARBON GANTRY



MAGNETS

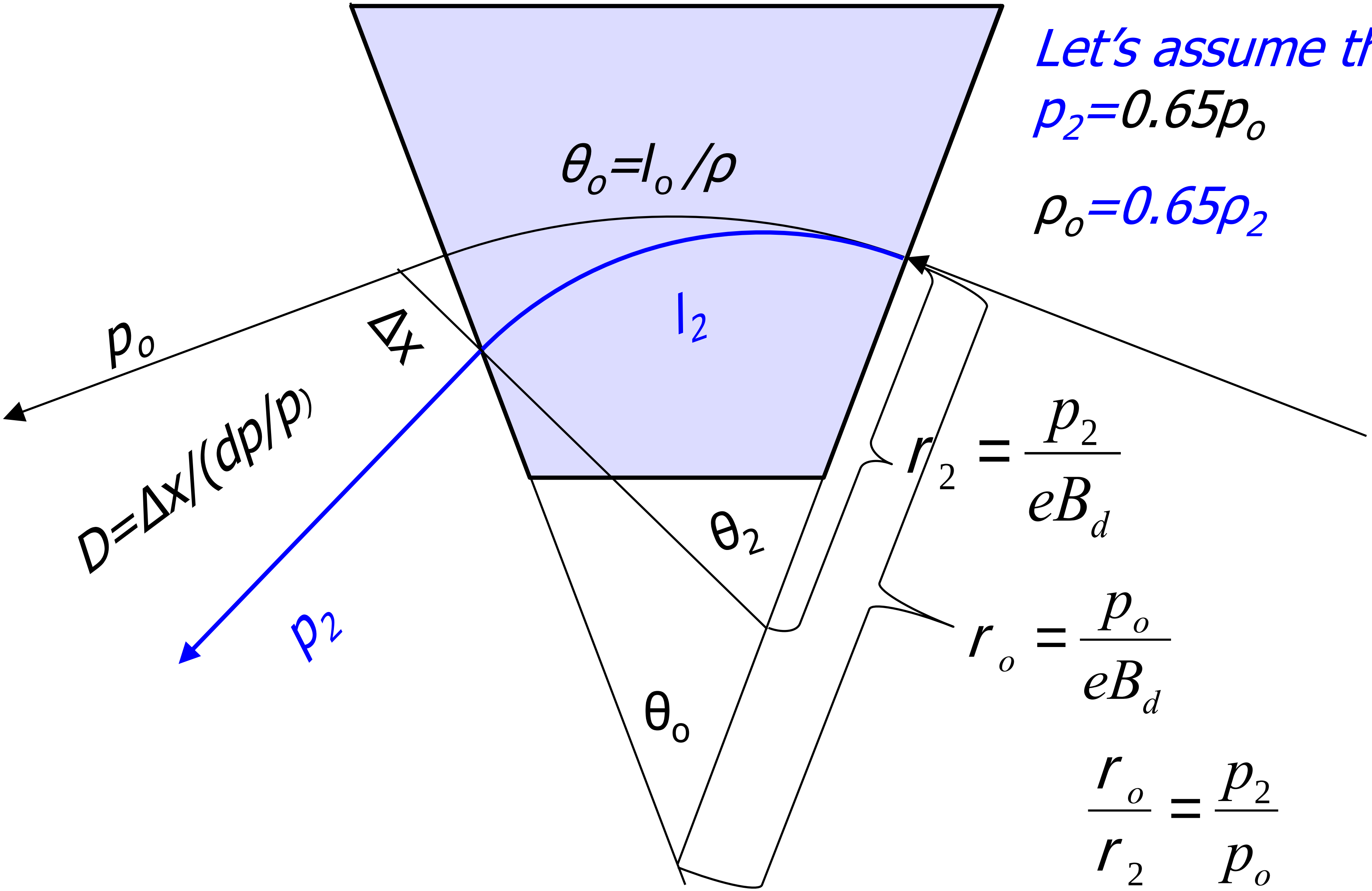


PROTON GANTRY



PERMANENT MAGNETS

Dispersion function - momentum



Let's assume that:

$p_2 = 0.65 p_o$

$\rho_o = 0.65 \rho_2$

$$r_2 = \frac{p_2}{eB_d}$$

$$r_o = \frac{p_o}{eB_d}$$

$$\frac{r_o}{r_2} = \frac{p_2}{p_o}$$

Range of momentum = range kinetic energy

$$\frac{\Delta p}{p} = \frac{p_{\max} - p_o}{p_o} = \frac{p_{\min} - p_o}{p_o} = \pm 20\%$$

$\Delta E_{k\ carbon}$=400-195.4 MeV/u [27.3-8.2 cm]

$\Delta E_{k\ carbon}$=195.4-91.5 MeV/u [8.2–2.2 cm]

$\Delta E_{k\ proton}$=250-118.81 MeV [37.8-10.4 cm]

$\Delta E_{k\ proton}$=118.81-54.6 MeV [10.4-2.6 cm]

$carbon\ 400\ MeV/u$ $\qquad p_{\max} = 951.4\ MeV/c/u$

$proton\ 250\ MeV$ $\qquad p_{\max} = 729.13\ MeV/c$

$p_{o\ carbon} = 792.848\ MeV/c/u$ $\qquad E_{k\ o} = 291.73\ MeV/u$

$p_{\min\ carbon} = 634.28\ MeV/c/u$ $\qquad E_{k\ \min} = 195.44\ MeV/u$

$p_{o\ proton} = 607.611\ MeV/c$ $\qquad E_{k\ o} = 179.56\ MeV$

$p_{\min\ proton} = 486.89\ MeV/c$ $\qquad E_{k\min} = 118.81\ MeV$

Why the non-scaling FFAG for the gantries?

❿ Orbit offsets are proportional to the dispersion function:

$$\Delta x = D_x * \delta p/p$$

❿ To reduce the orbit offsets to ±20 mm range, for momentum range of $\delta p/p \sim \pm 50\ \%$ the dispersion function D_x has to be of the order of:

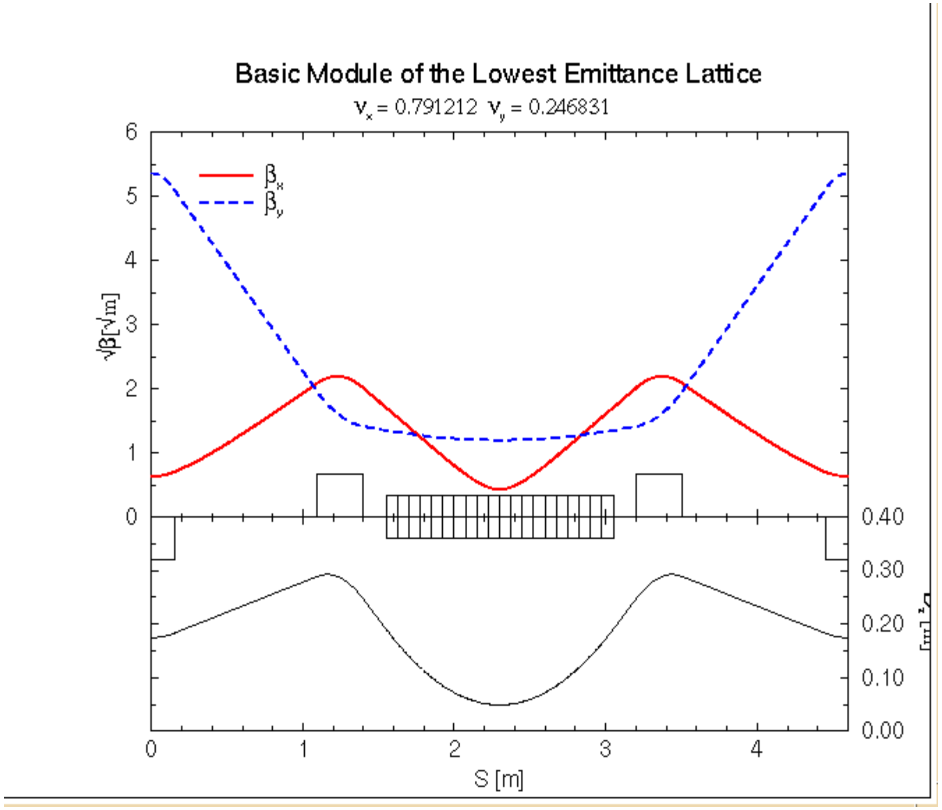
$\delta p/p \sim \pm 50\ \% \rightarrow E_k$ [52 , 400 MeV/u]

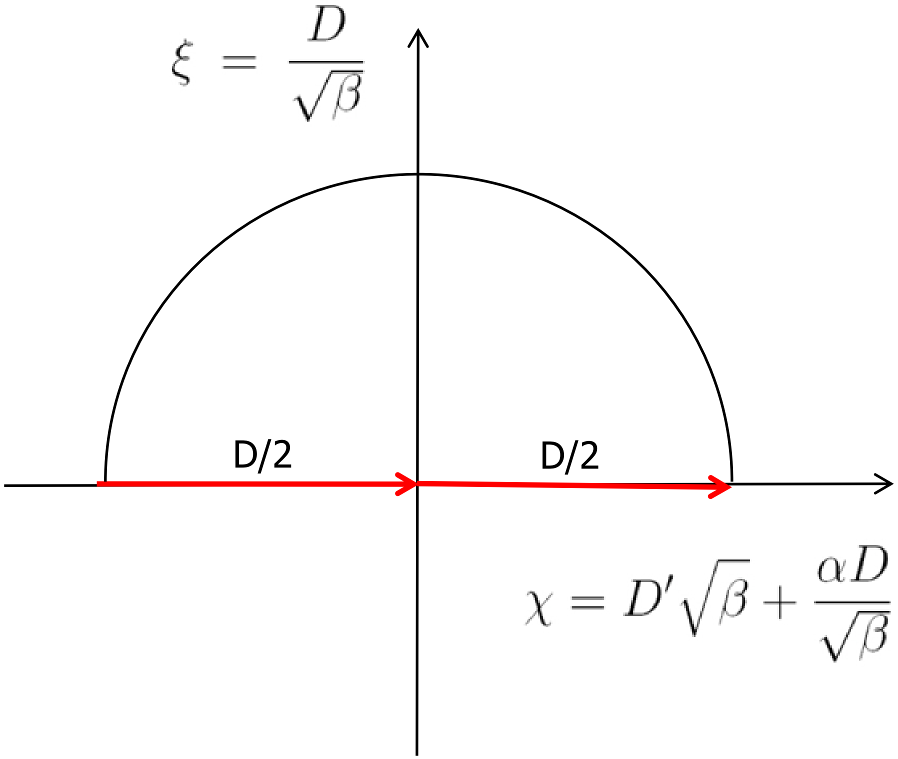
$$D_x \sim 2\ cm / 0.5 \leq 4\ cm$$

❿ The small aperture, the small magnet, less weight, easier to build easier to operate.

Minimizing *H* function

$$\xi = \frac{D}{\sqrt{\beta}} \quad and \quad \chi = D'\sqrt{\beta} + \frac{\alpha D}{\sqrt{\beta}} \qquad H(D,D') = \xi^2 + \chi^2$$



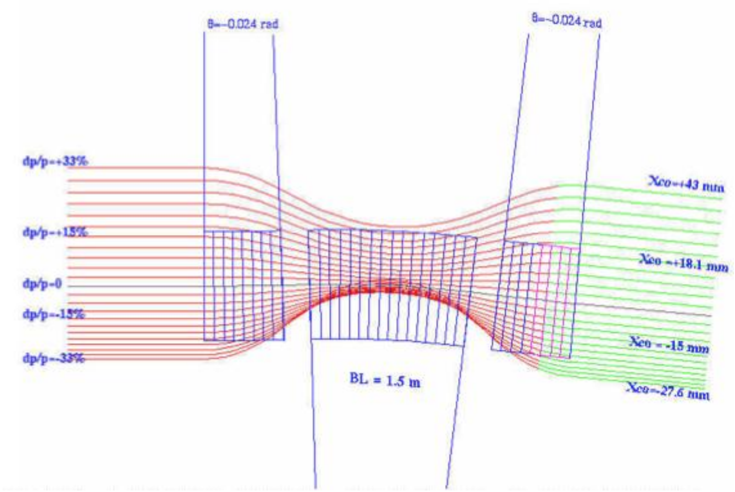


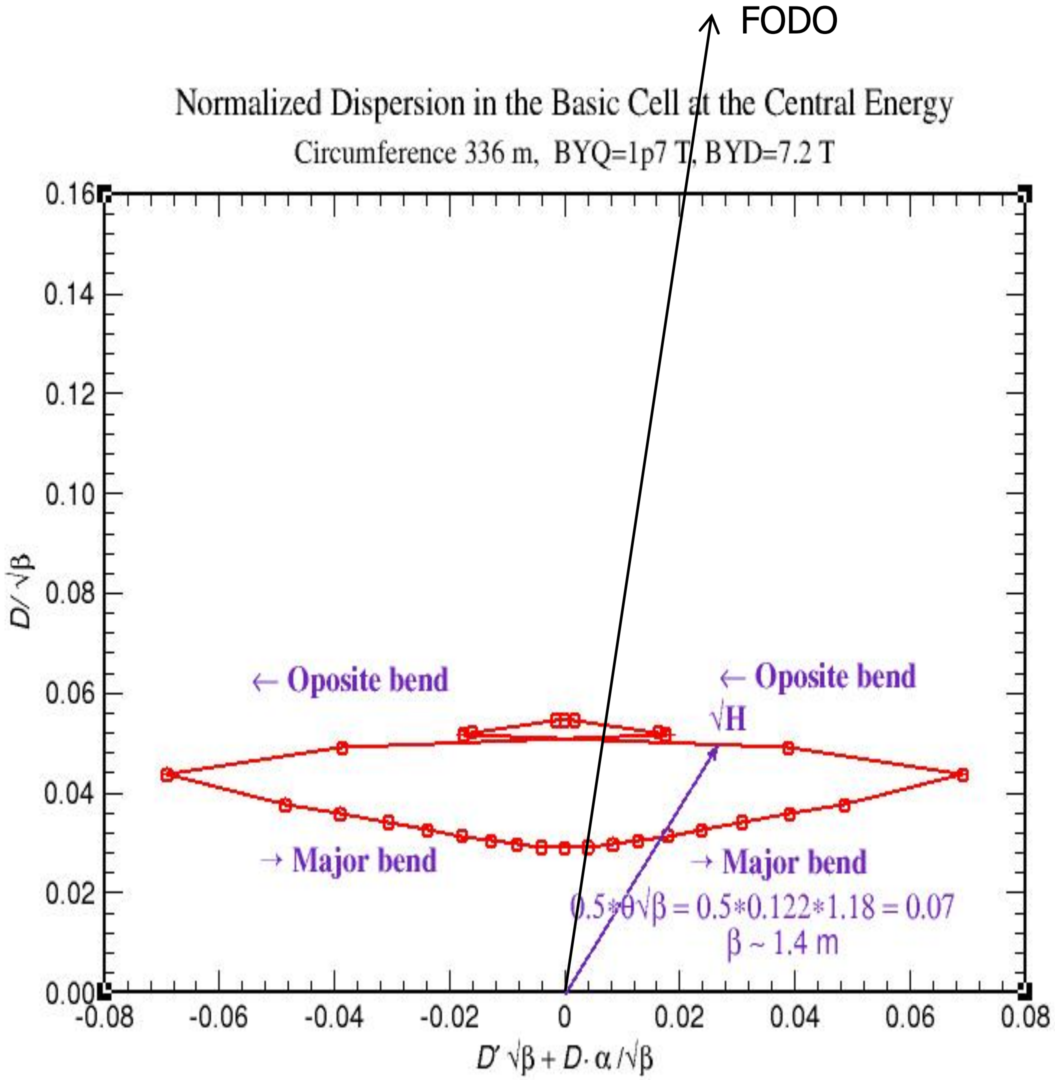
$$\xi = \frac{D}{\sqrt{\beta}}$$

$$\chi = D'\sqrt{\beta} + \frac{\alpha D}{\sqrt{\beta}}$$

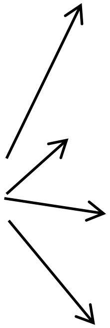
Optimizing H function – Normalized dispersion

Minimization of the H function applied for the FFAG design





NS-FFAG GANTRIES



Motivation for the NS-FFAG gantries

Carbon E_k=400 MeV/u

$B\rho$ = 6.35 Tm $(\theta = Bl/B\rho)$

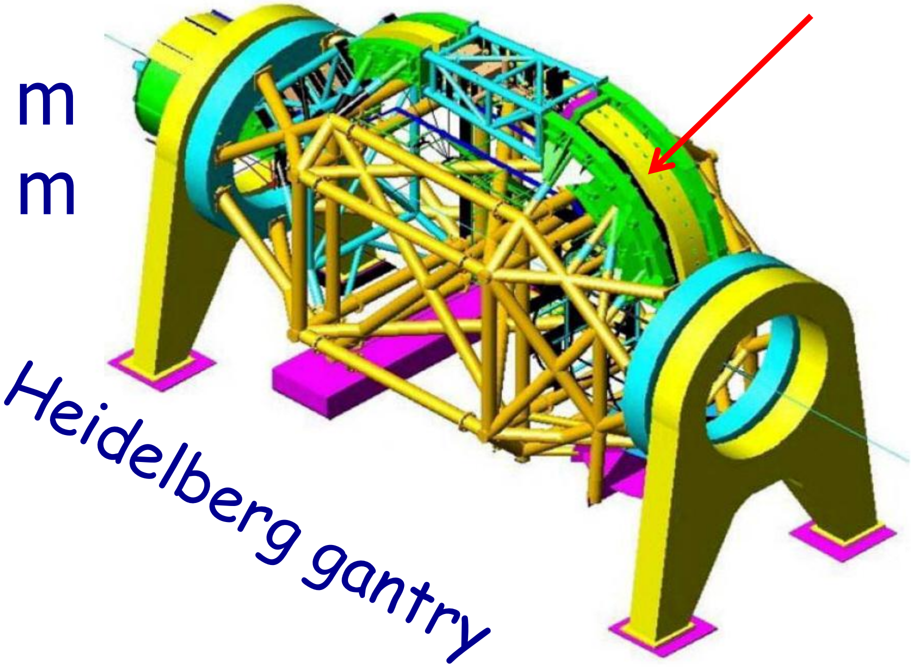
If: B=1.6 T then $\rho \sim$ 4.0 m

If: B=3.2 T then $\rho \sim$ 2.0 m

Weight of the transport components – 135 tons

Total weight = 630 tons

Length of the rotating part 19 m long.

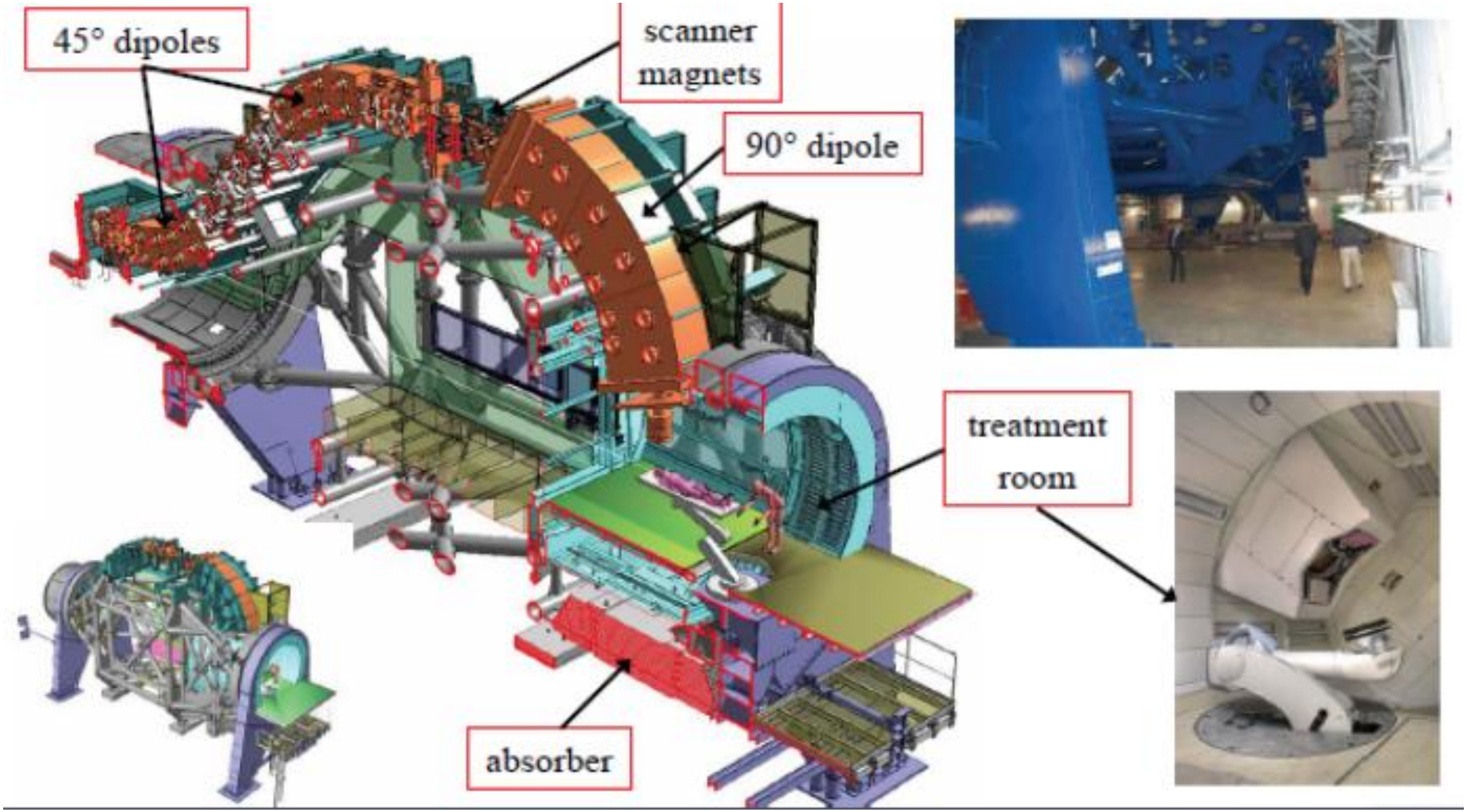


Heidelberg gantry

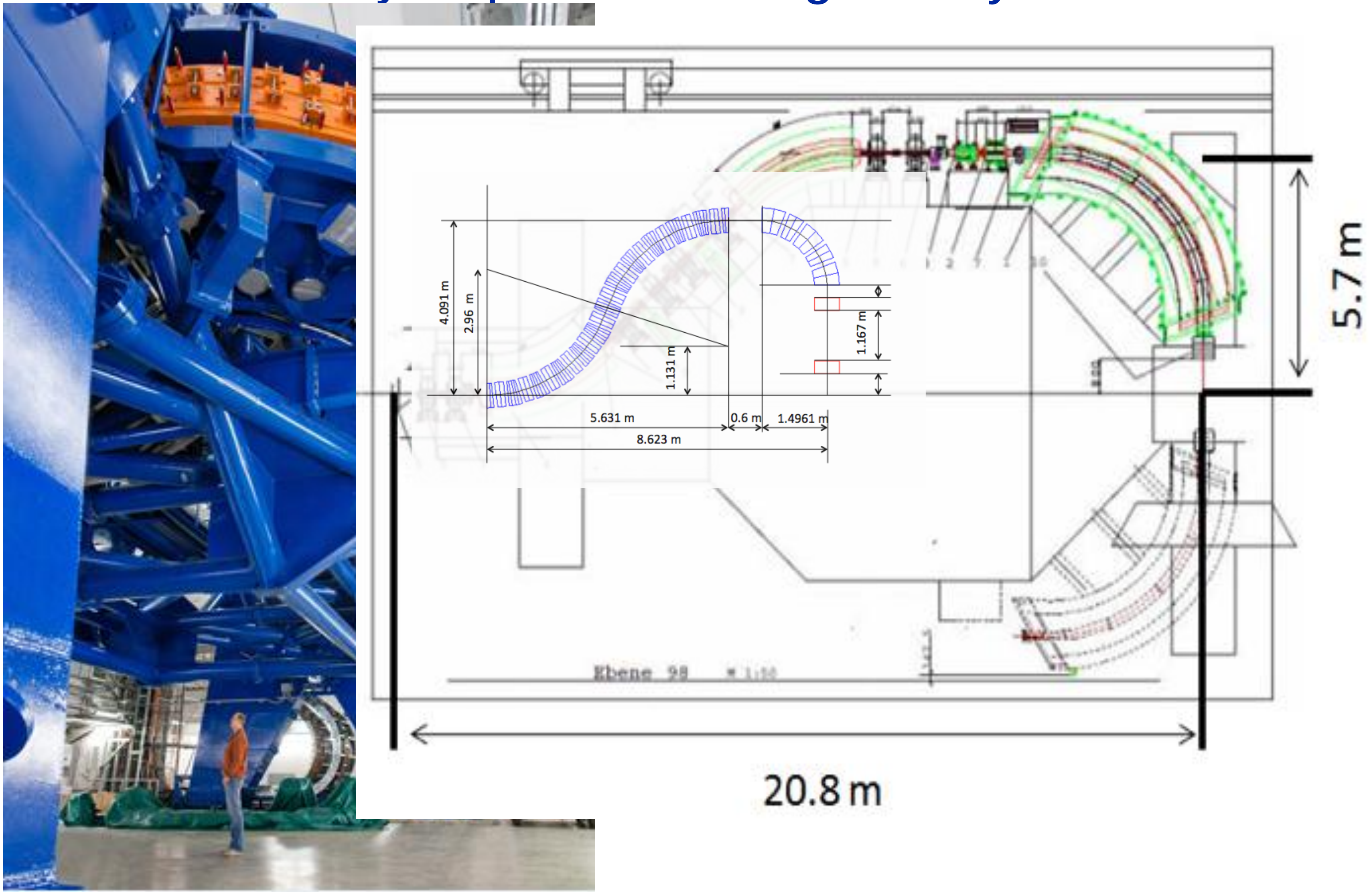
State of the Art Gantry at Heidelberg

Weight of the transport components – 135 tons

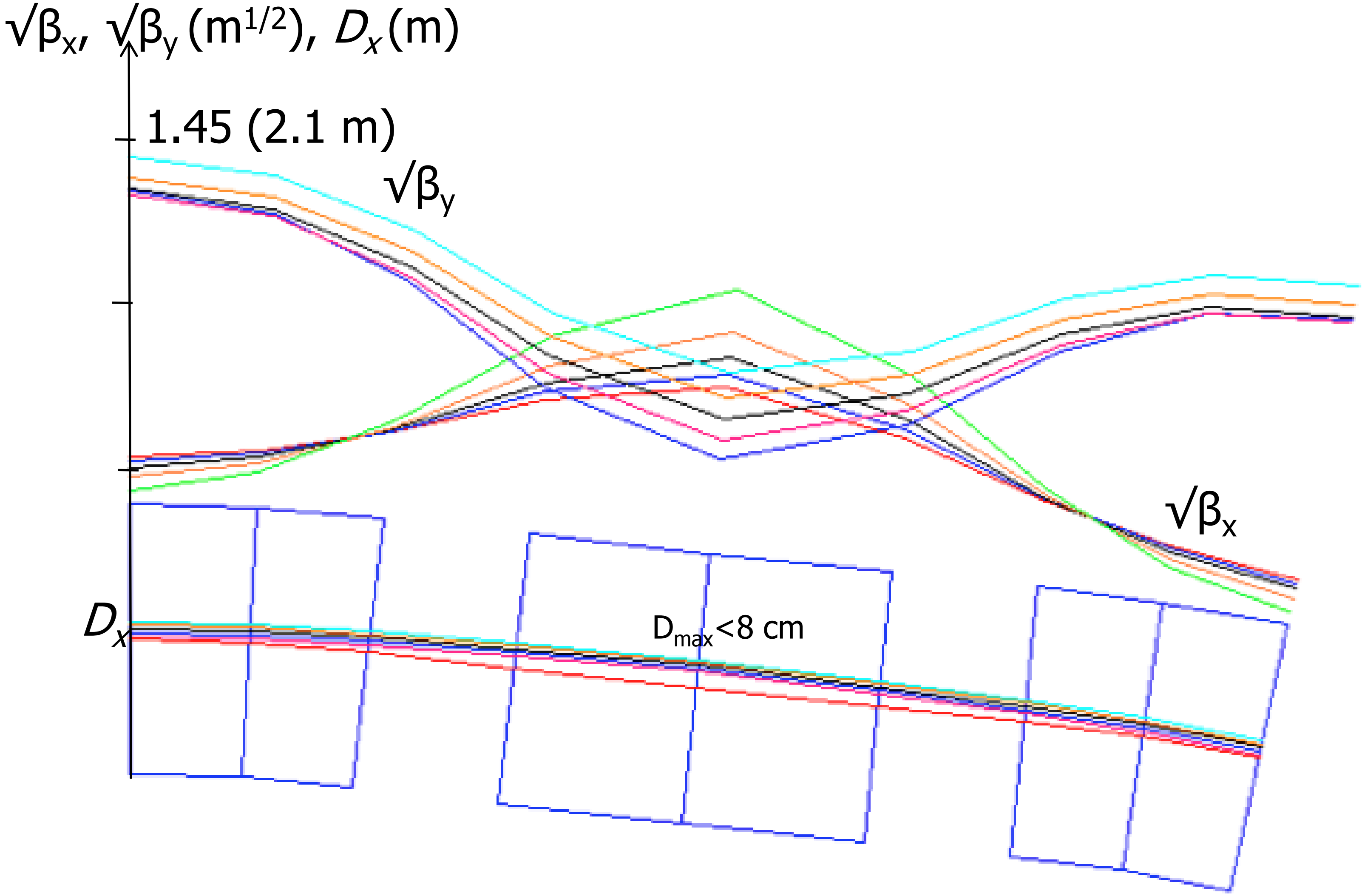
**Total weight = 630 tons - ** 19 m long. WEIGHT and SIZE



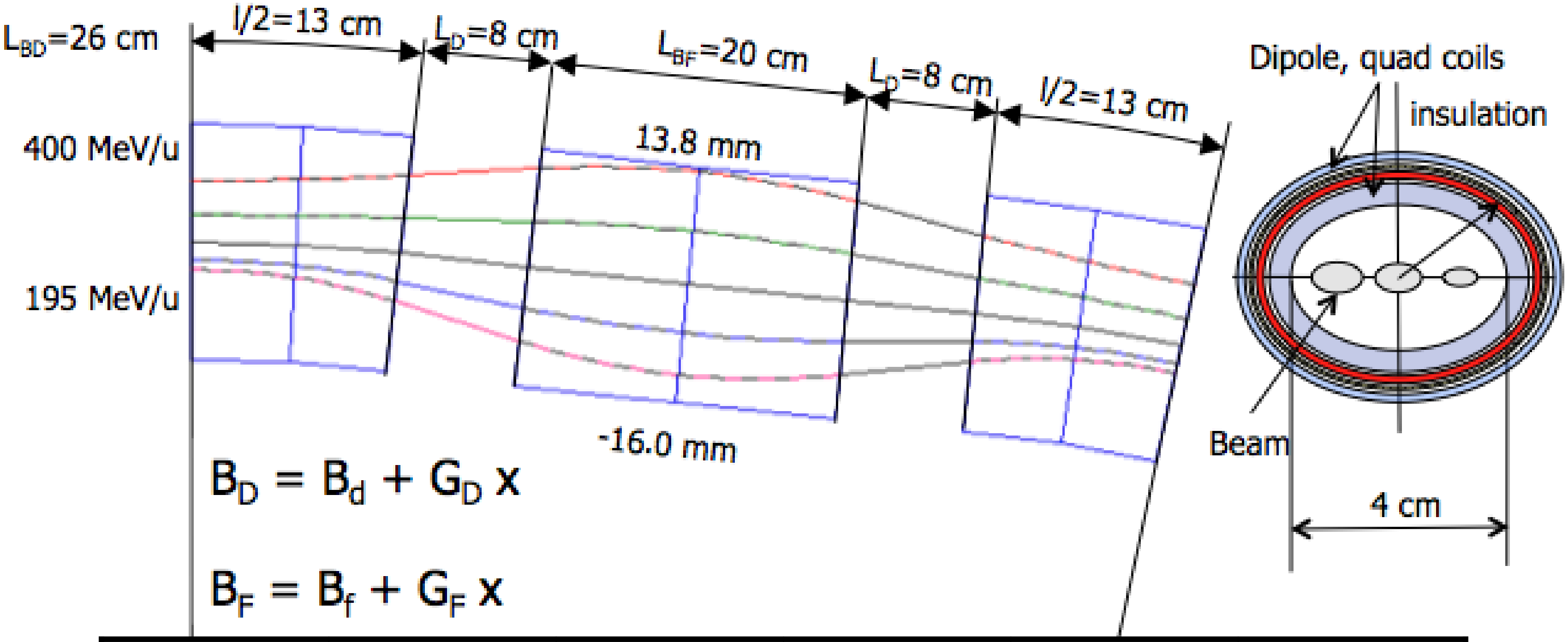
Why Superconducting Gantry?



Amplitude functions in the carbon gantry



Orbit offsets in the carbon NS-FFAG gantry



$$B_D = B_d + G_D\, x$$

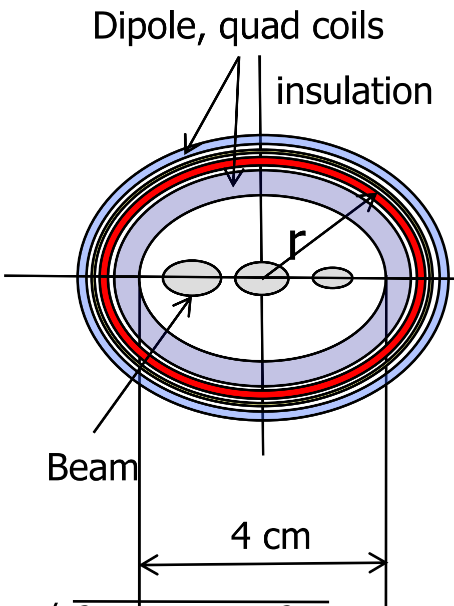
$$B_F = B_f + G_F\, x$$

ANGD	ANGF	B_D (T)	B_F (T)	G_D(T/m)	G_F(T/m)
0.112	-0.0146	4.557	-0.3851	-90.8	151.1

Magnetic field required in the pipe and estimated maximum field in the coils

$$B_{D\,max} = B_d + G_D\,x = 4.56 - 90.8 * \left\{ \begin{array}{c} 9.7\text{ mm} \\ -6.75\text{ mm} \end{array} \right\} \begin{array}{c} 3.67\text{ T} \\ 5.17\text{ T} \end{array}$$

$$B_{F\,max} = B_f + G_F\,x = -0.385 + 151.1 * \left\{ \begin{array}{c} 13.96\text{ mm} \\ -13.75\text{ mm} \end{array} \right\} \begin{array}{c} 1.72\text{ T} \\ 1.69\text{ T} \end{array}$$



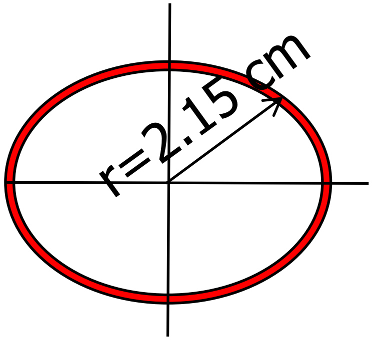
Beam size : $\sigma_T = \sqrt{\sigma^2 + (D\,dp/p)^2}$

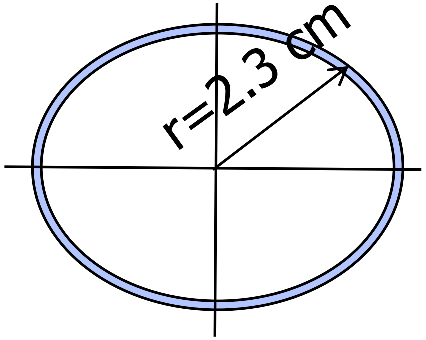
$$\sigma_{twiss-\max} = \sqrt{\frac{N\varepsilon_n \beta_{twiss}}{6\pi\,\gamma\,\beta}} = \sqrt{\frac{0.5\cdot 0.5}{6\cdot 0.452}} = 0.3\,mm$$

$$\sigma_\delta = 0.04 * 10^{-3} = 0.04\,mm \quad If\ D = 7m \rightarrow \sigma_\delta = 7\,mm$$

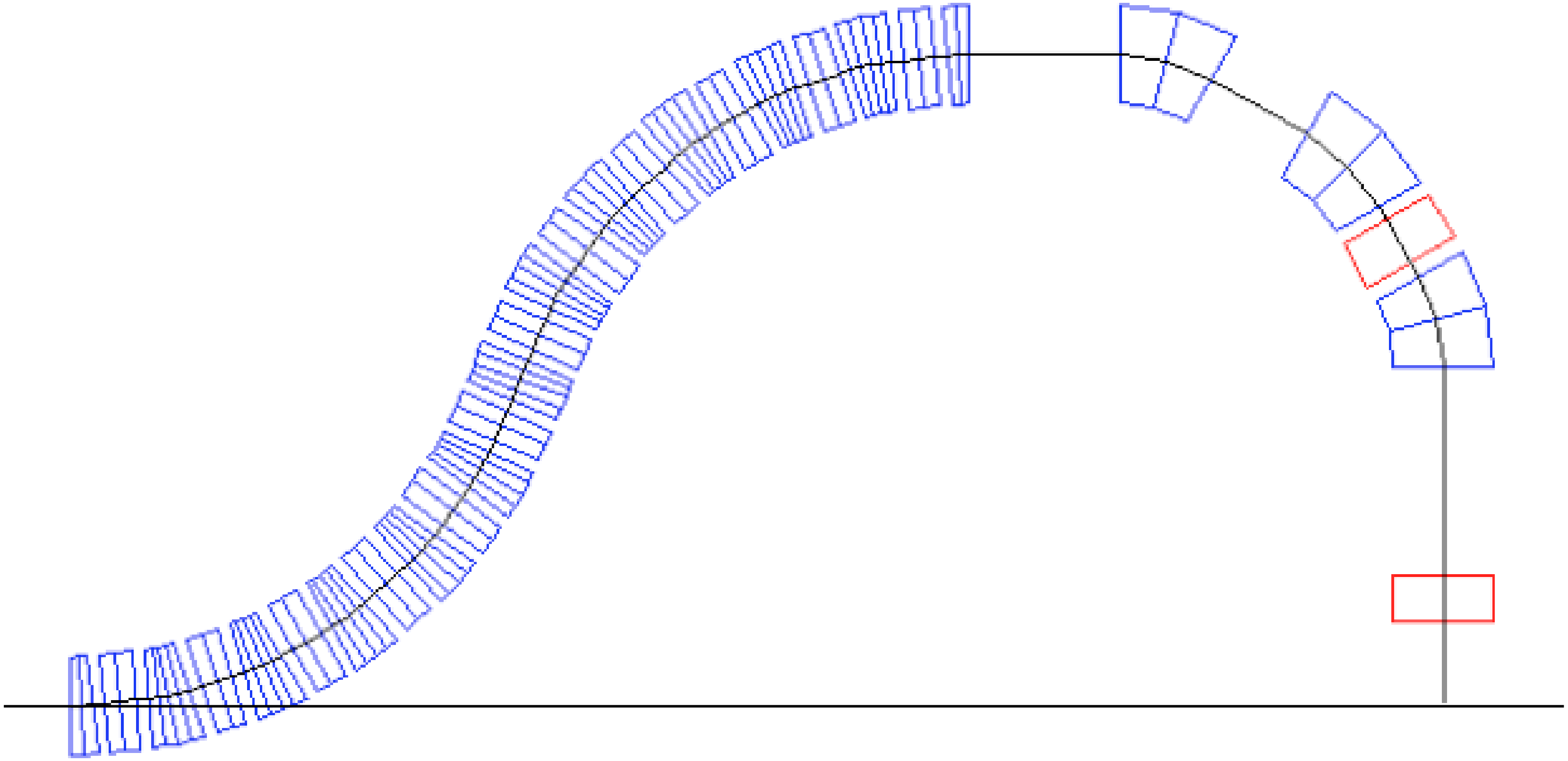
$$\varepsilon_N = 0.5\pi - 3\pi \quad mm\,mrad\ \ for\ \varepsilon_N = 3\pi\ \mu mrad\,\sigma_{twiss-\max} = 0.74\,mm$$

$$6\sigma = 2\,mm \quad \left(for\,\varepsilon_N = 3\pi\ \mu mrad\ 6\sigma_T = 4.5\,mm \right)$$



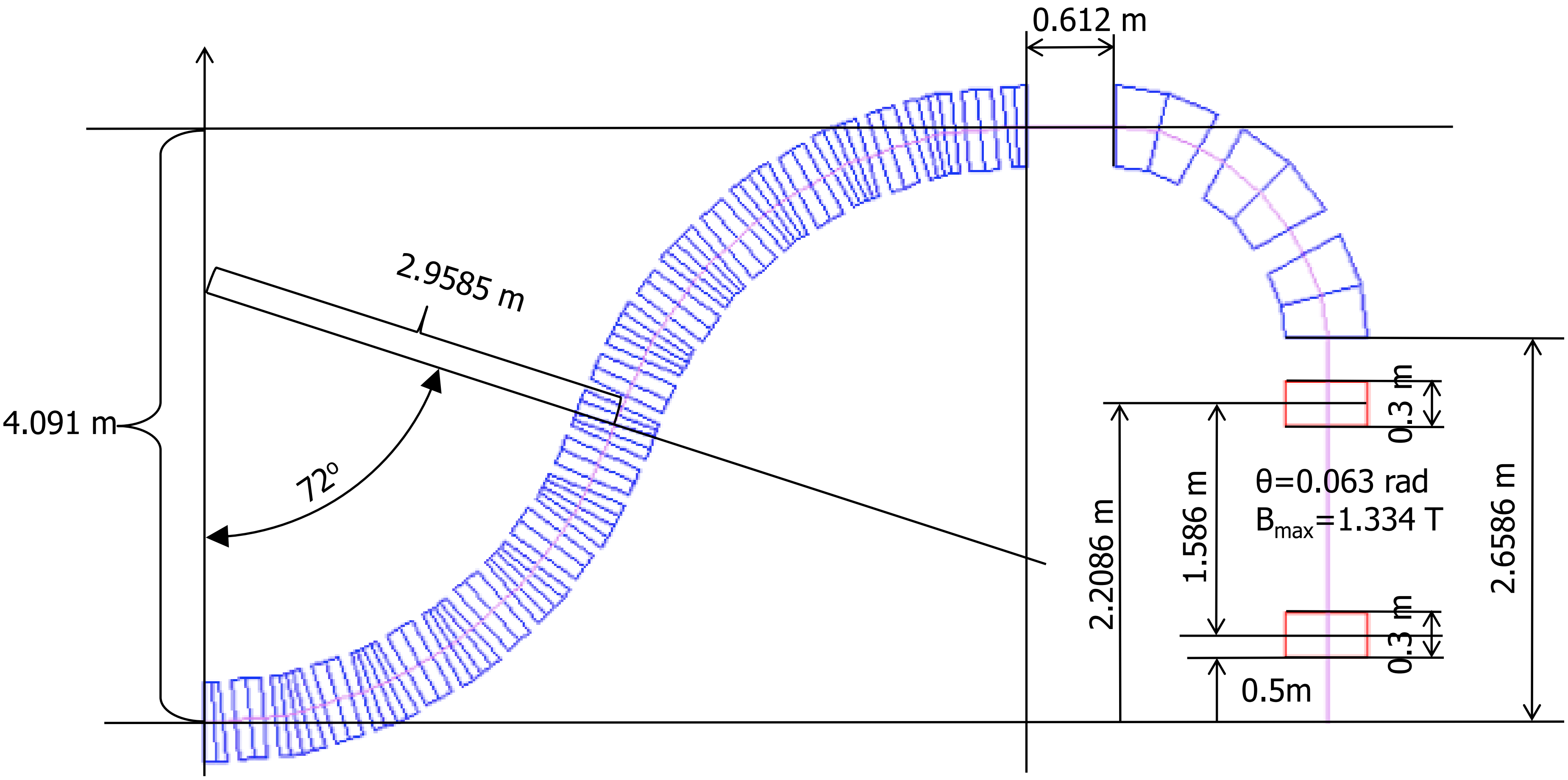


NS-FFAG superconducting gantry with scanning through the last quadrupole

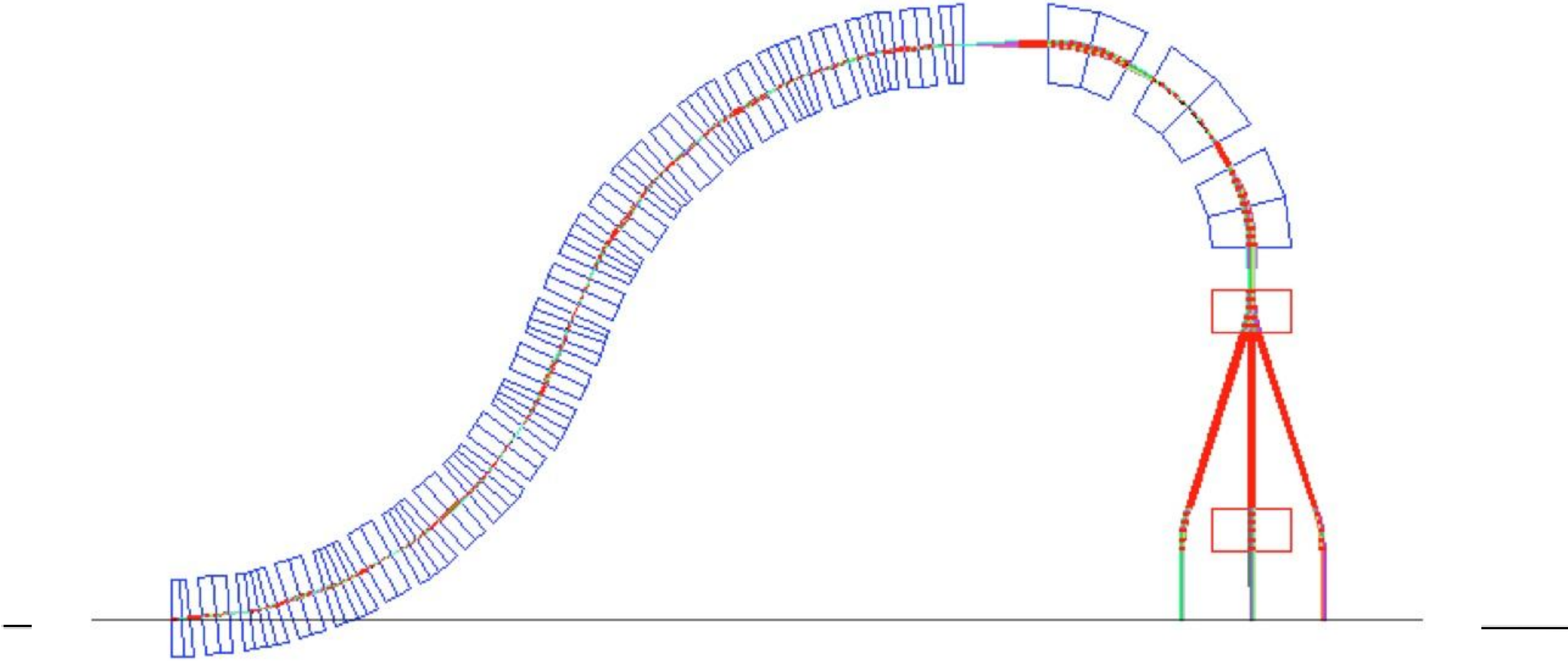


NS-FFAG superconducting carbon gantry

protected by the patent number: US 2007/0262269 A1

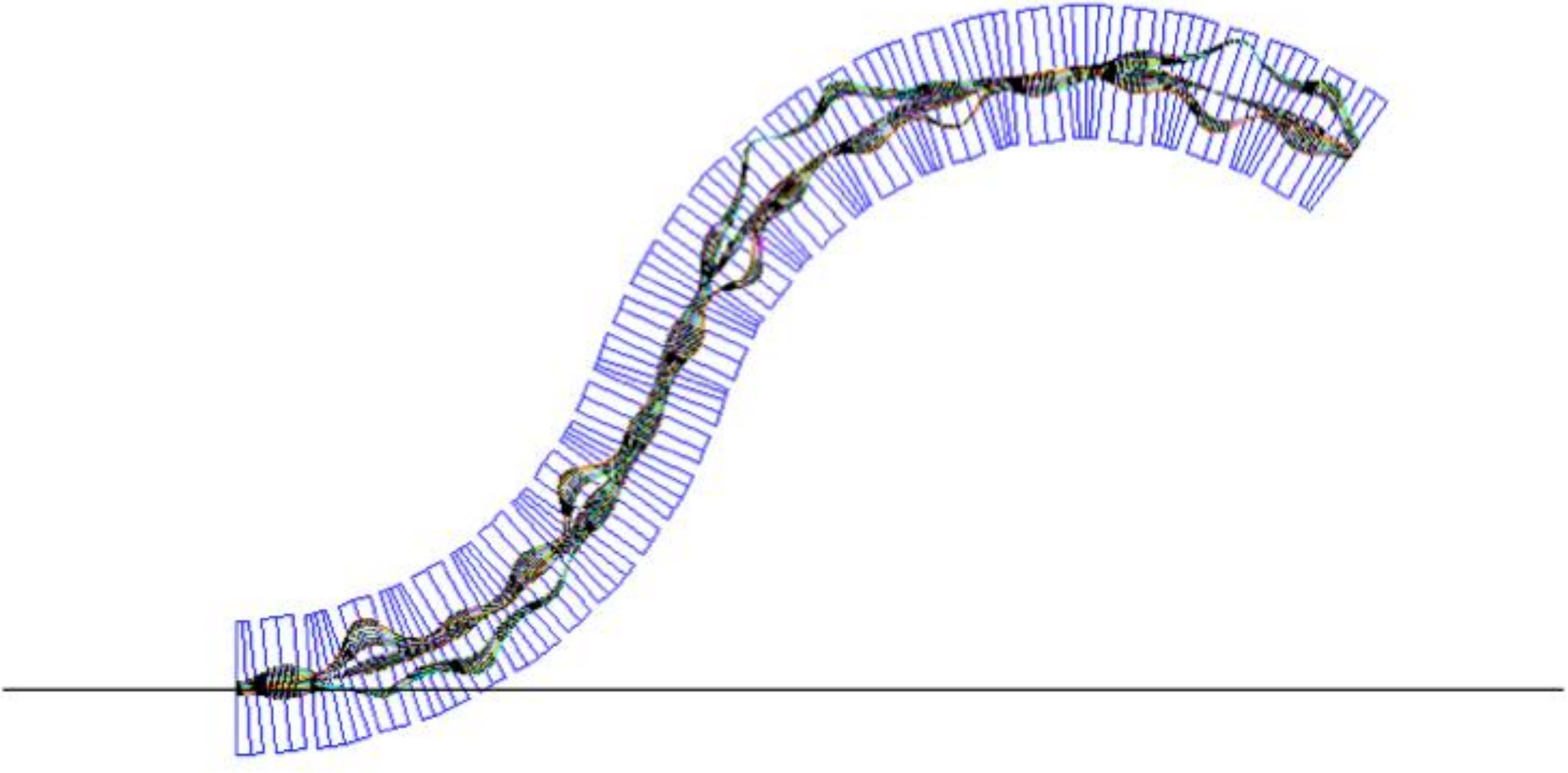


CARBON GANTRY height 4.091m

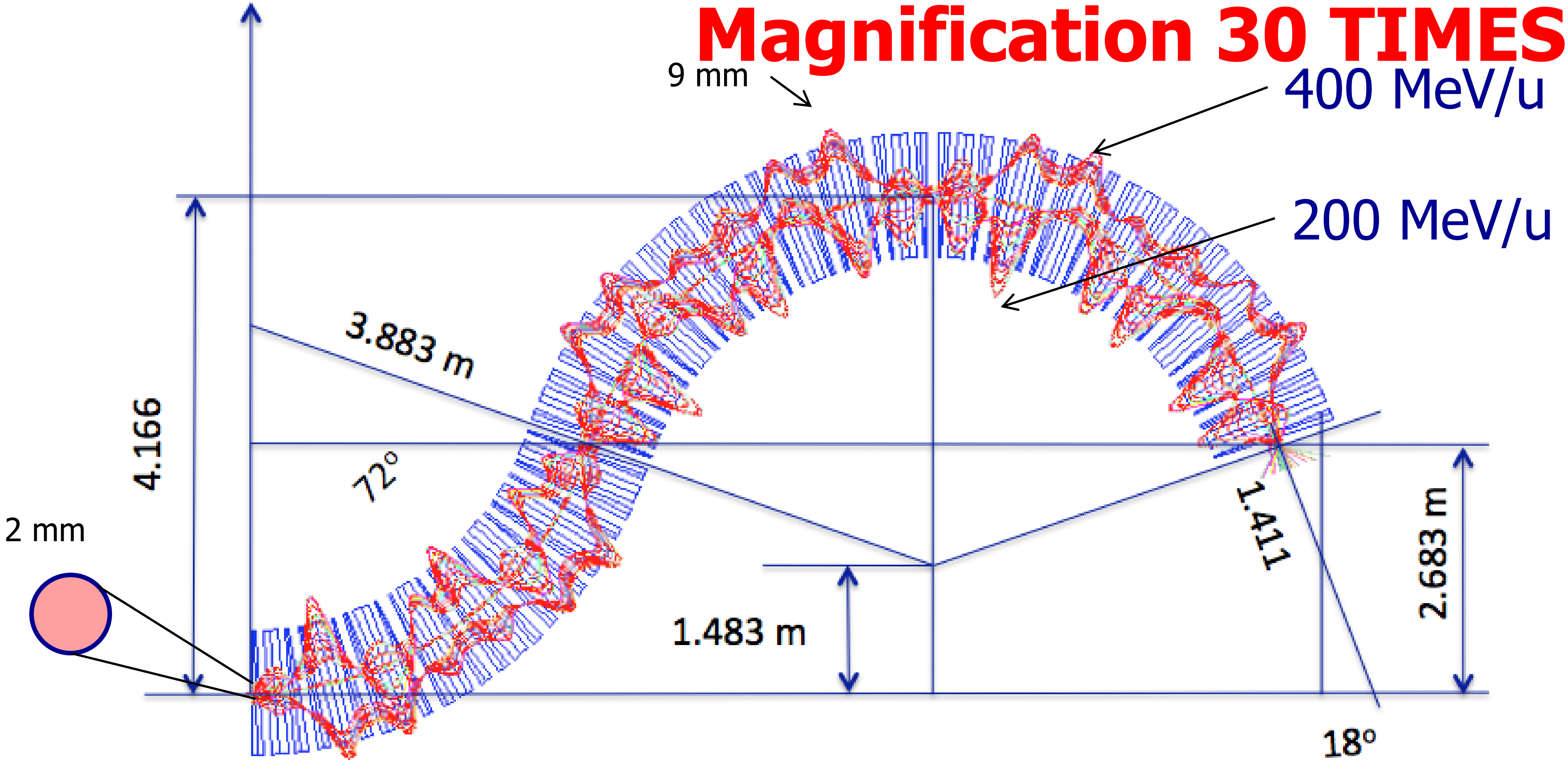


Tracking particles in the carbon gantry for the energy range of 190-400 MeV/u

collaboration with Vasily Morozov-Jefferson Lab for the six gradients adjustment

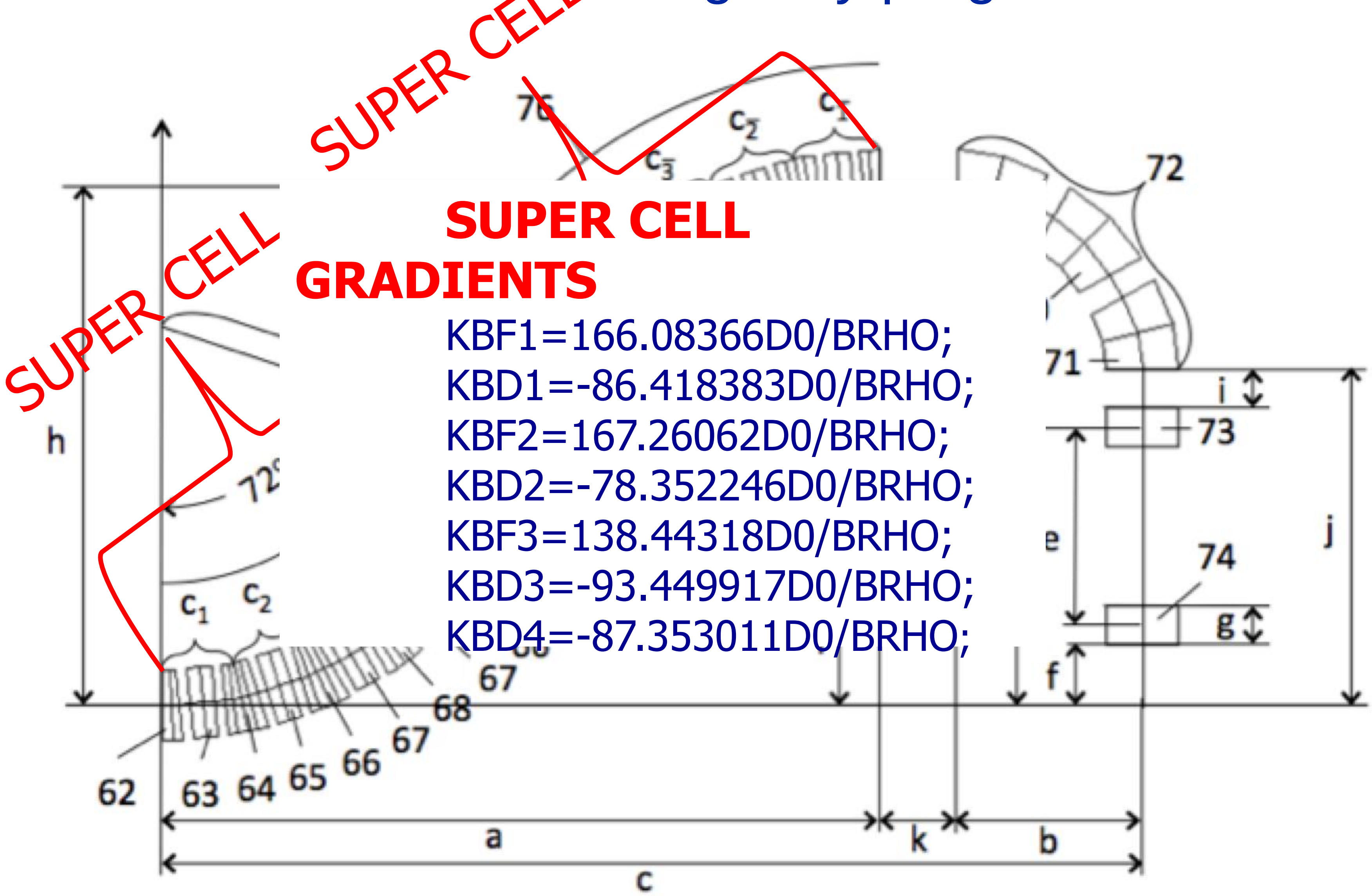


All at once: Fixed field & fixed focusing



Magnification 30 TIMES

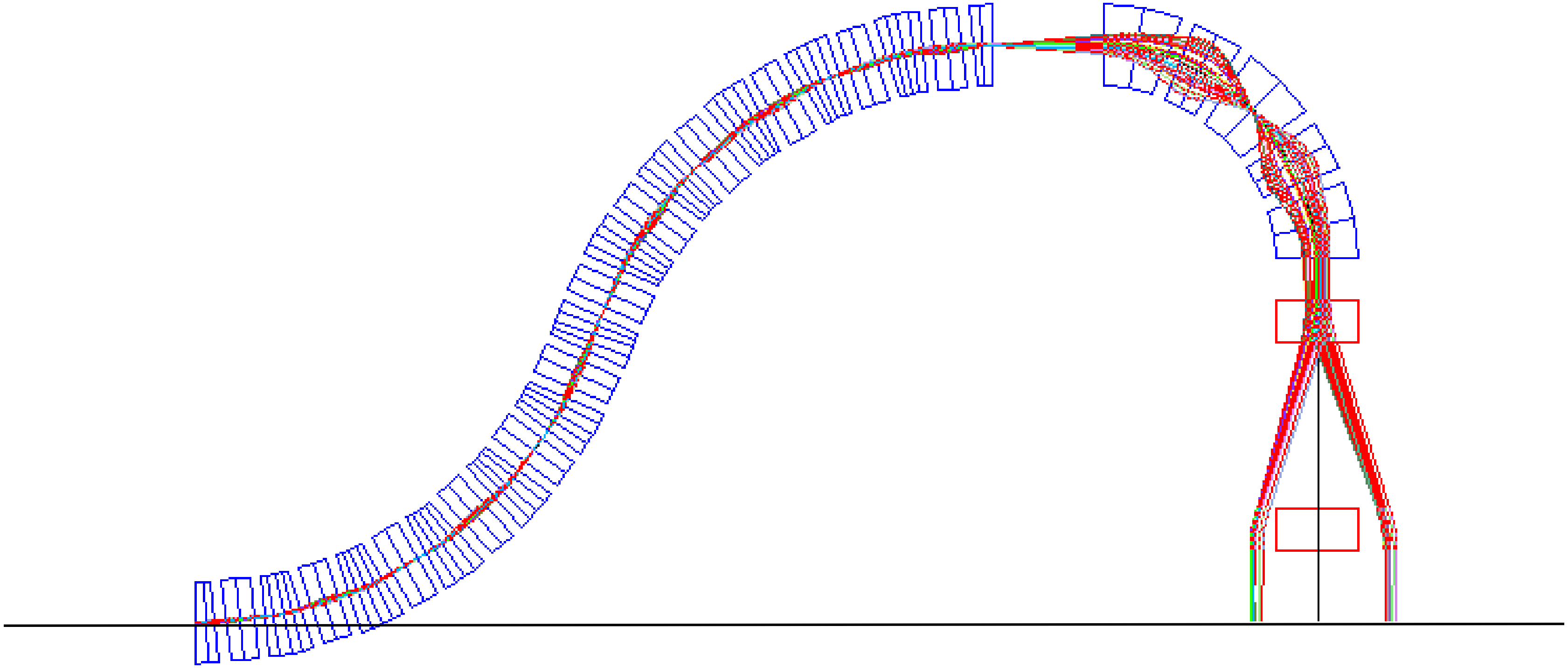
Data from the PTC gantry program:



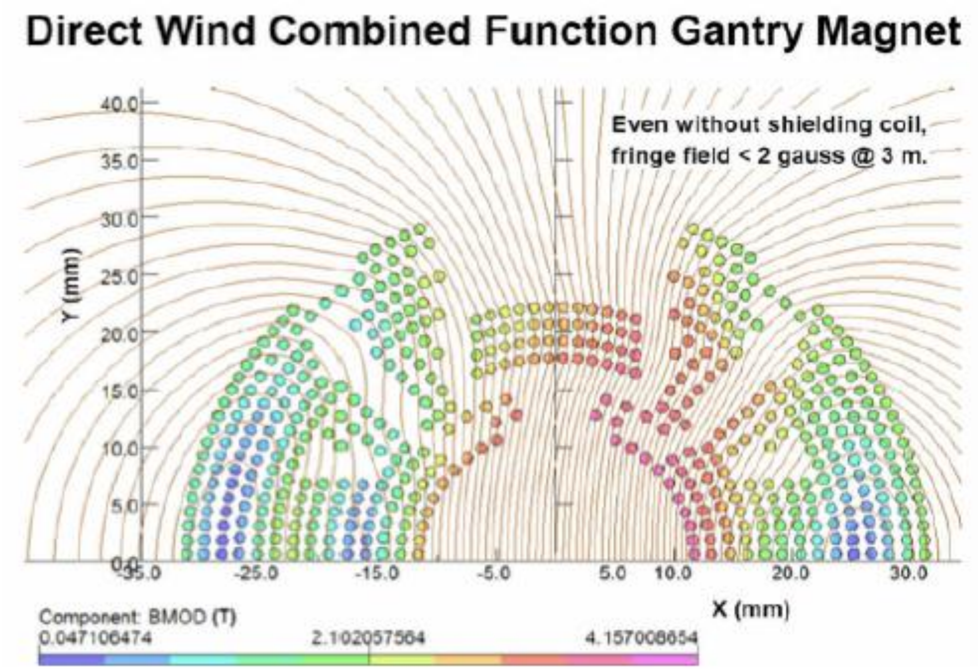
SUPER CELL

GRADIENTS

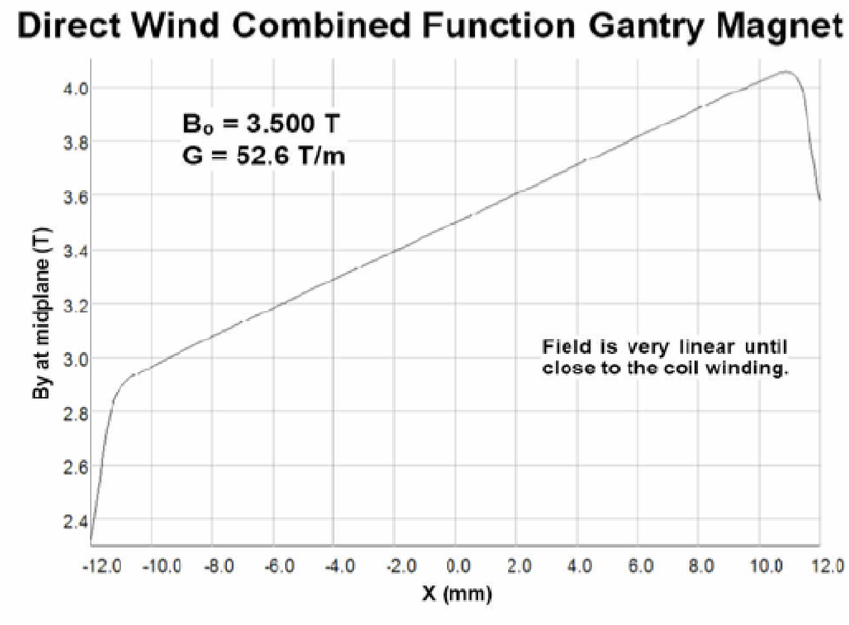
KBF1=166.08366D0/BRHO;
KBD1=-86.418383D0/BRHO;
KBF2=167.26062D0/BRHO;
KBD2=-78.352246D0/BRHO;
KBF3=138.44318D0/BRHO;
KBD3=-93.449917D0/BRHO;
KBD4=-87.353011D0/BRHO;



BNL-preliminary combined function magnet design


Direct Wind Combined Function Gantry Magnet

Even without shielding coil, fringe field < 2 gauss @ 3 m.

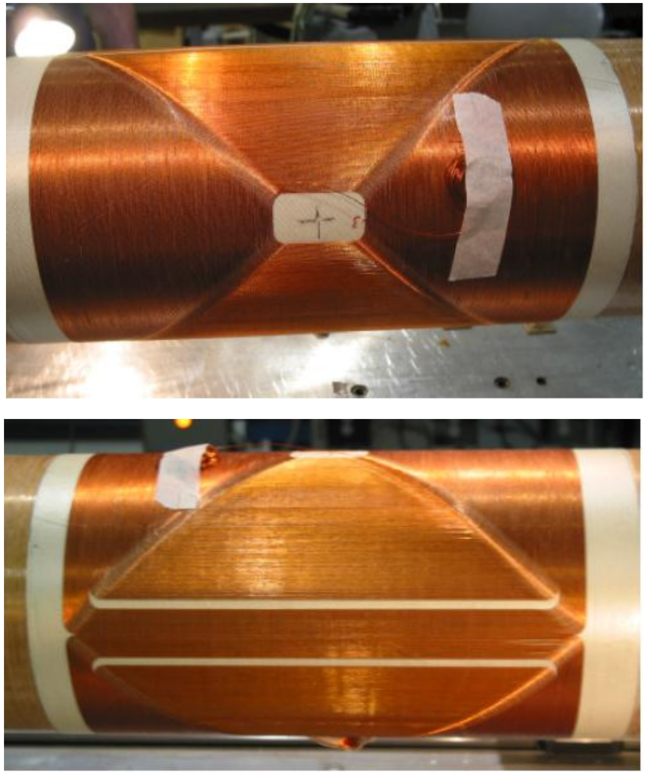

Direct Wind Combined Function Gantry Magnet

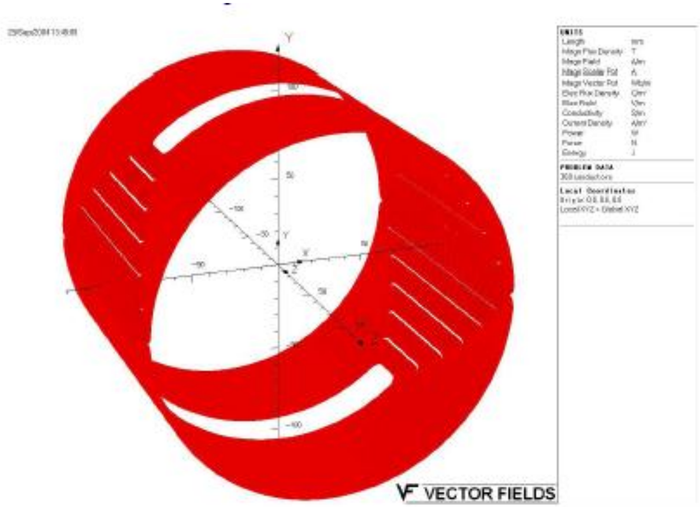
B_o = 3.500 T
G = 52.6 T/m

Field is very linear until close to the coil winding.

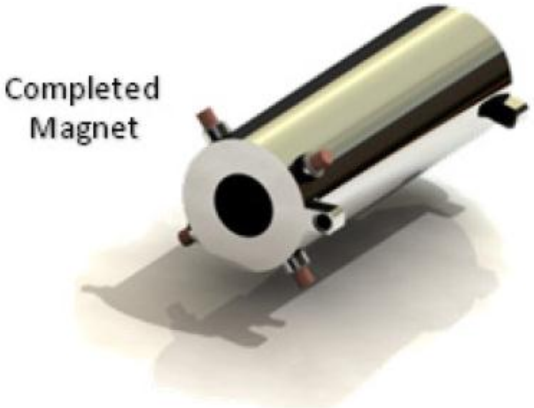
Magnet design

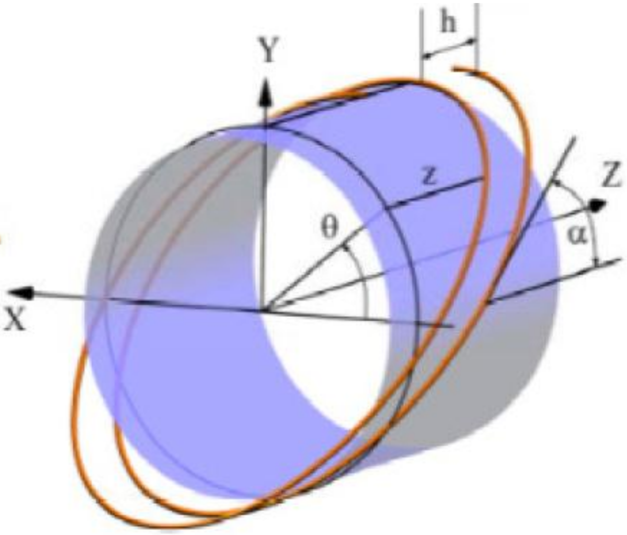
In a quadrupole, the coil length limits the fill factor in the cross-section when it becomes less than one fourth of the circumference. We used six spacers (wedges) in the cross-section to make the first six allowed harmonics nearly zero. Once again, a large integral transfer function is obtained since the mid-plane turns span the entire end-to-end coil length. The design has a coil diameter of 200 mm and coil length of 90 mm (less than half the radius). Quad with Coil Length Less Than Coil Radius Sextupole with Coil Length 2/3 Coil Radius We carried out a similar exercise for a 200 mm aperture sextupole having an end-to-end coil length of 66 mm. This is ~1/3 of diameter. We were again able to get a design with low harmonics and a good integral transfer function.

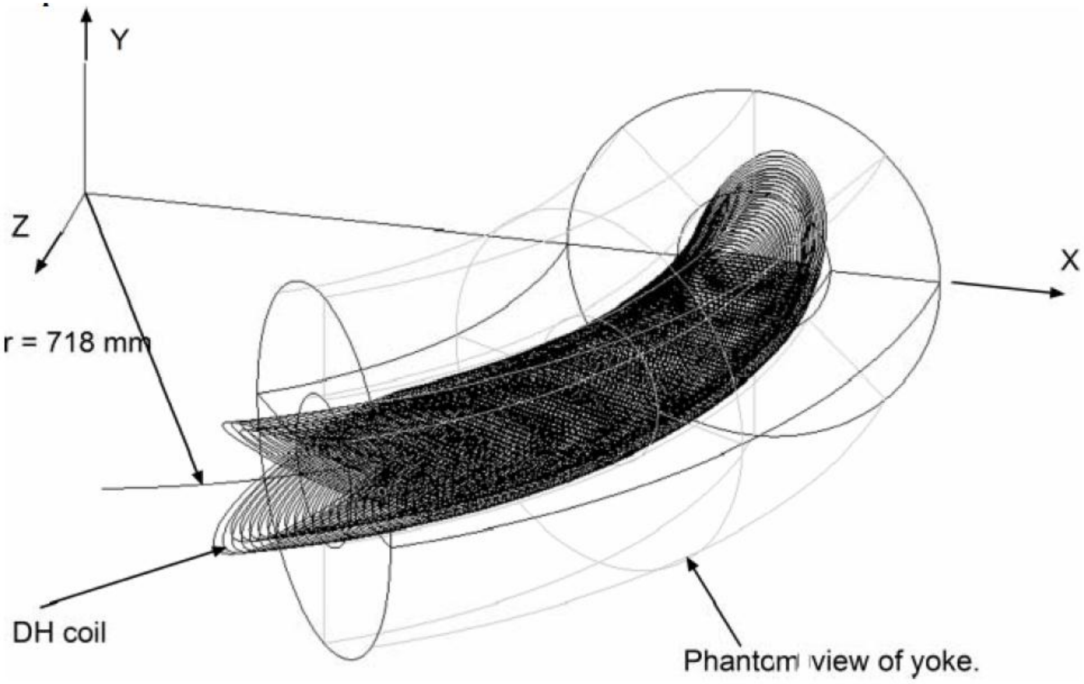




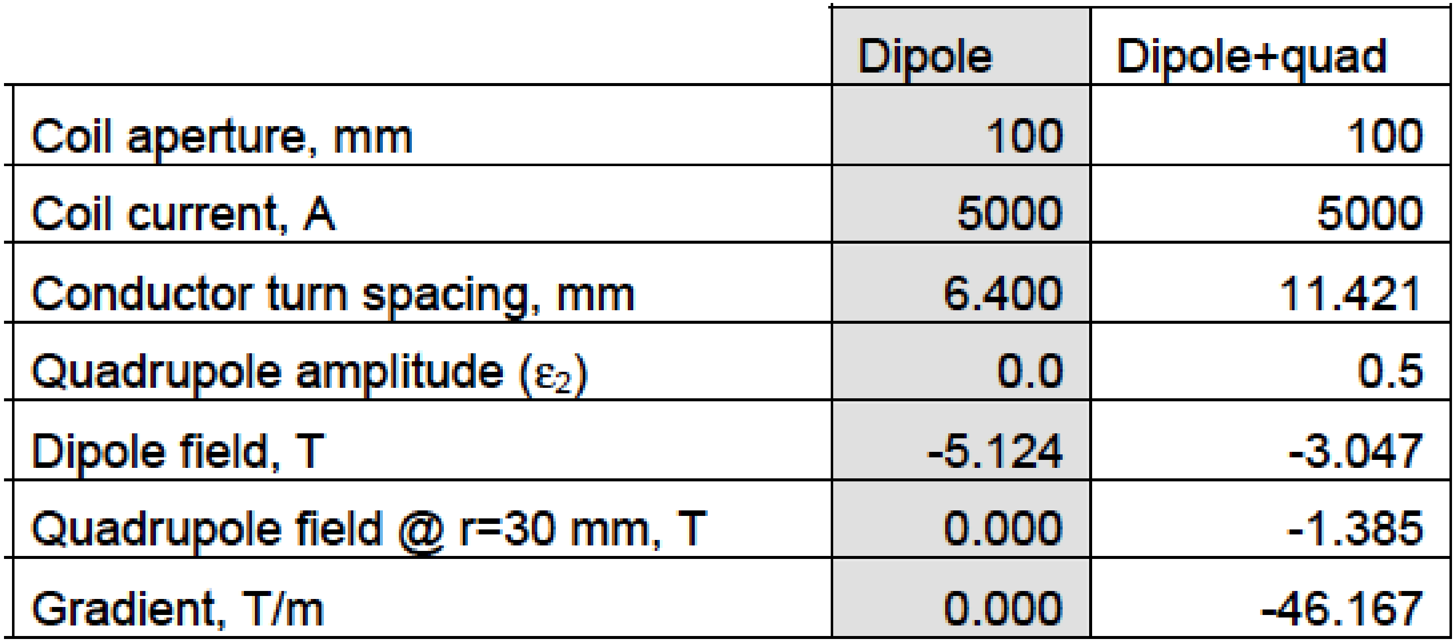
OPERA3d model of a short length dipole based on the Optimum Integral Design. Coil length is ~175 mm and coil diameter is 200 mm.


Completed
Magnet


Y
h
z
θ
Z
α
X


Y
Z
X
r = 718 mm
DH coil
Phantom view of yoke.

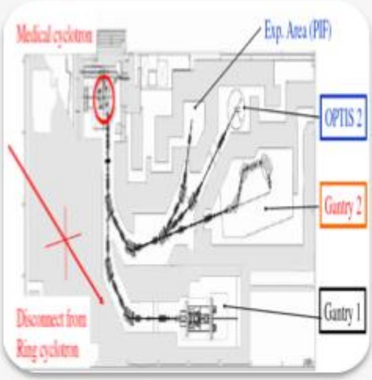
AML combined function magnet design

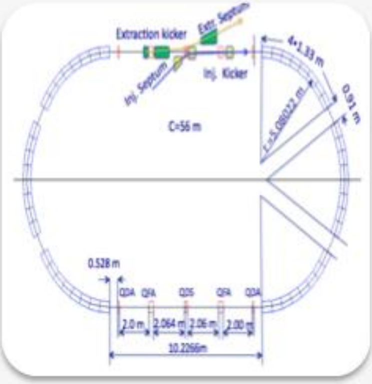


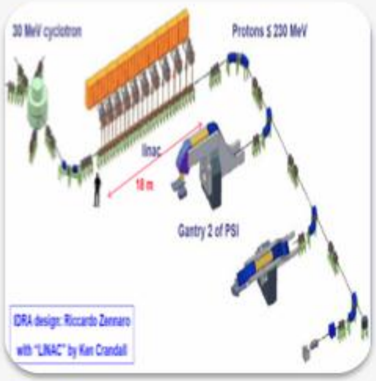
	Dipole	Dipole+quad
Coil aperture, mm	100	100
Coil current, A	5000	5000
Conductor turn spacing, mm	6.400	11.421
Quadrupole amplitude (ε_2)	0.0	0.5
Dipole field, T	-5.124	-3.047
Quadrupole field @ r=30 mm, T	0.000	-1.385
Gradient, T/m	0.000	-46.167

A = 4 cm

Possible applications of the NS-FFAG gantries:







CYCLOTRON – energy degrader

Spot scanning

Multi-leaf collimator

Slow extraction slow cycling synchrotrons

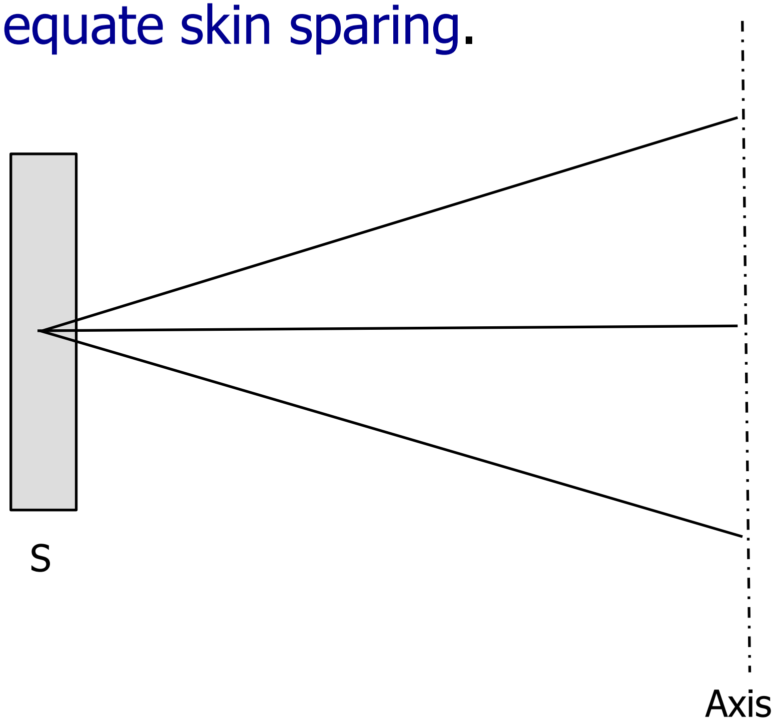
Fast cycling synchrotrons

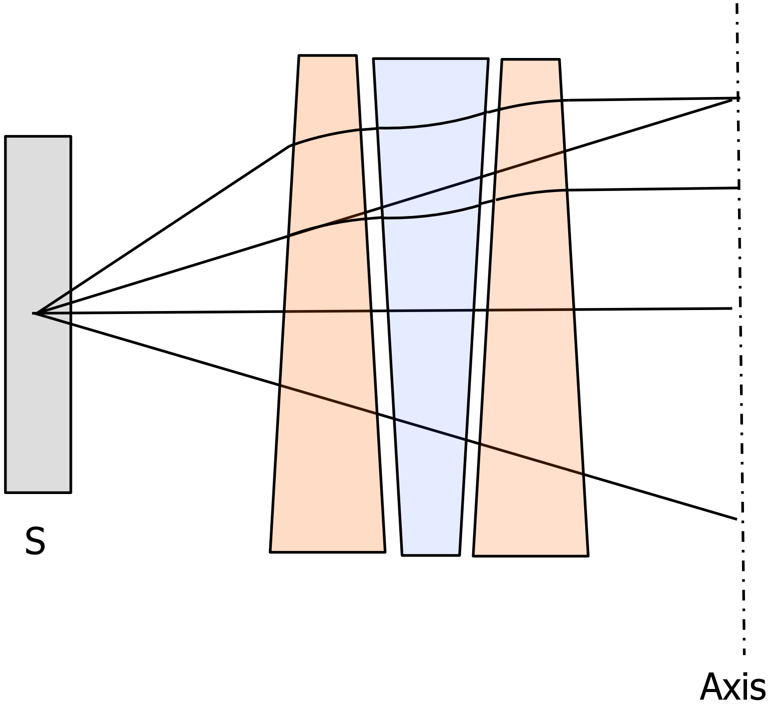
Linac modules

SAD – SOURCE-TO-AXIS-DISTANCE

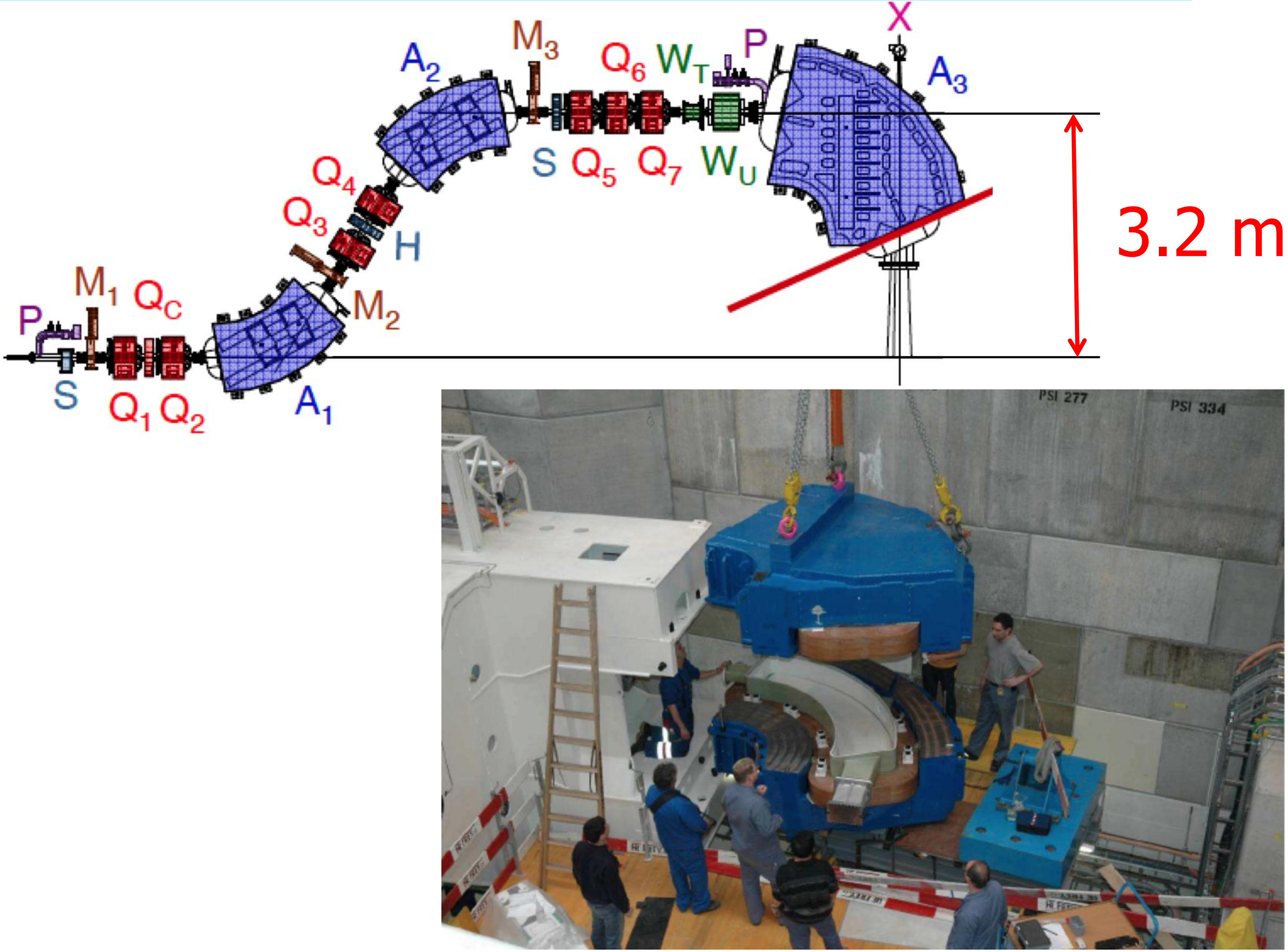
Scanning system: applied for patent by BNL

The maximum dose to the patient surface relative to the dose in the SOBP increases as the effective source-to-axis distance (SAD) decreases. For a fixed, horizontal beam, large SAD's are easy to achieve; but not for gantry beam lines. A smaller gantry with a physical outer diameter of less than 2 meters may have important cost implications. Such a gantry would require magnetic optics to ensure that the effective source-to-axis distance is large enough to provide adequate skin sparing.

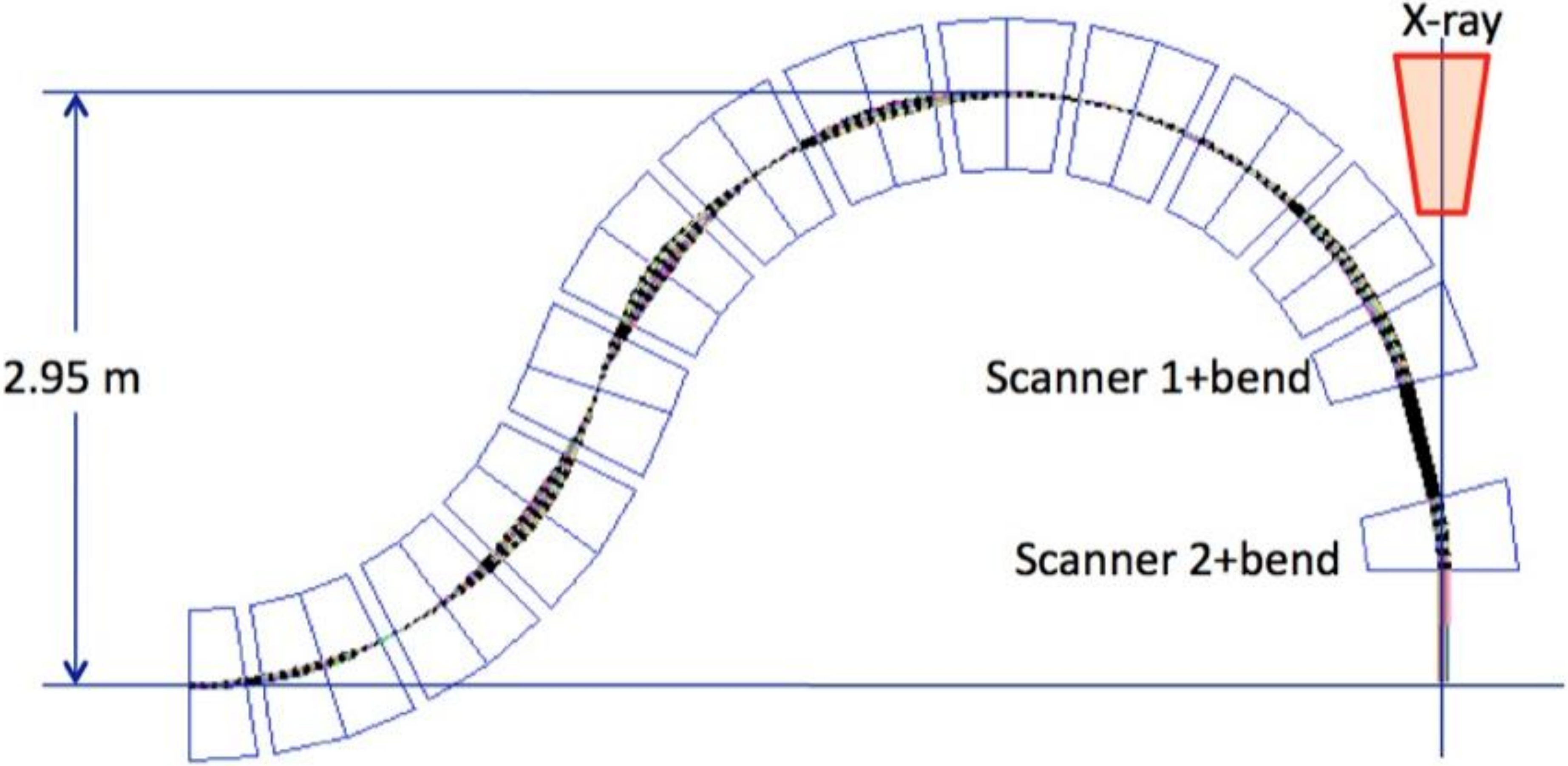


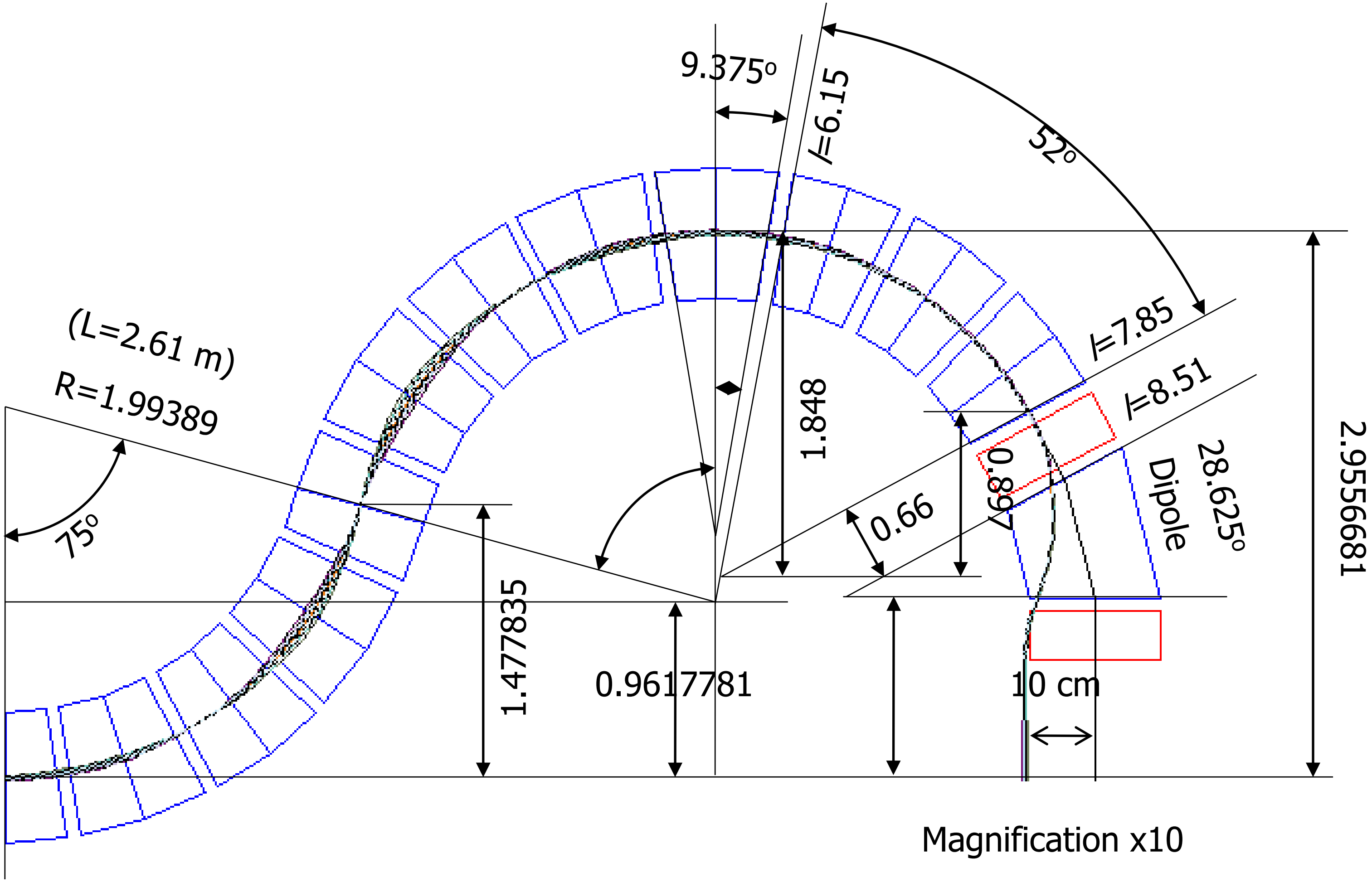


The state of the art proton gantry at P

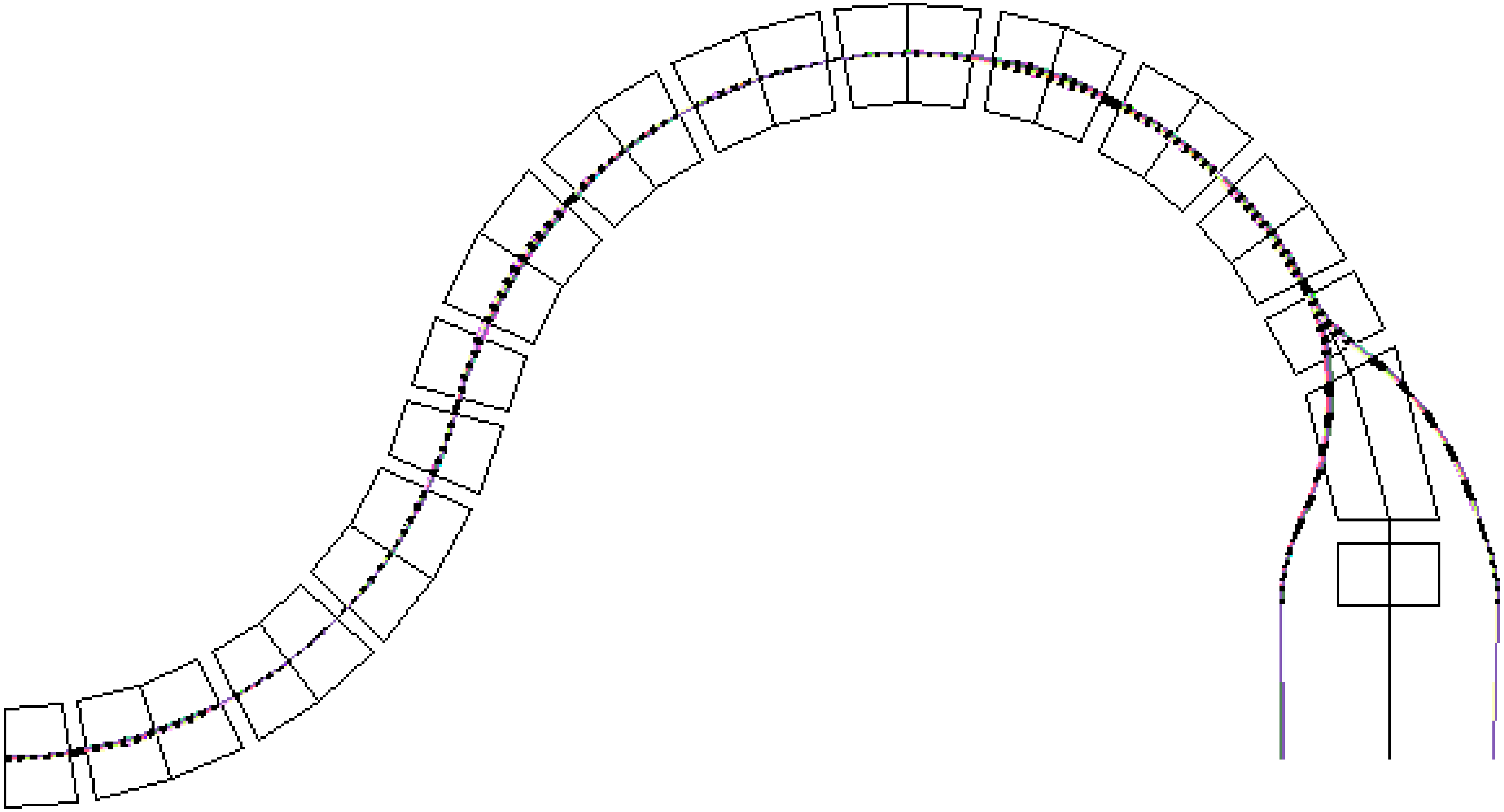


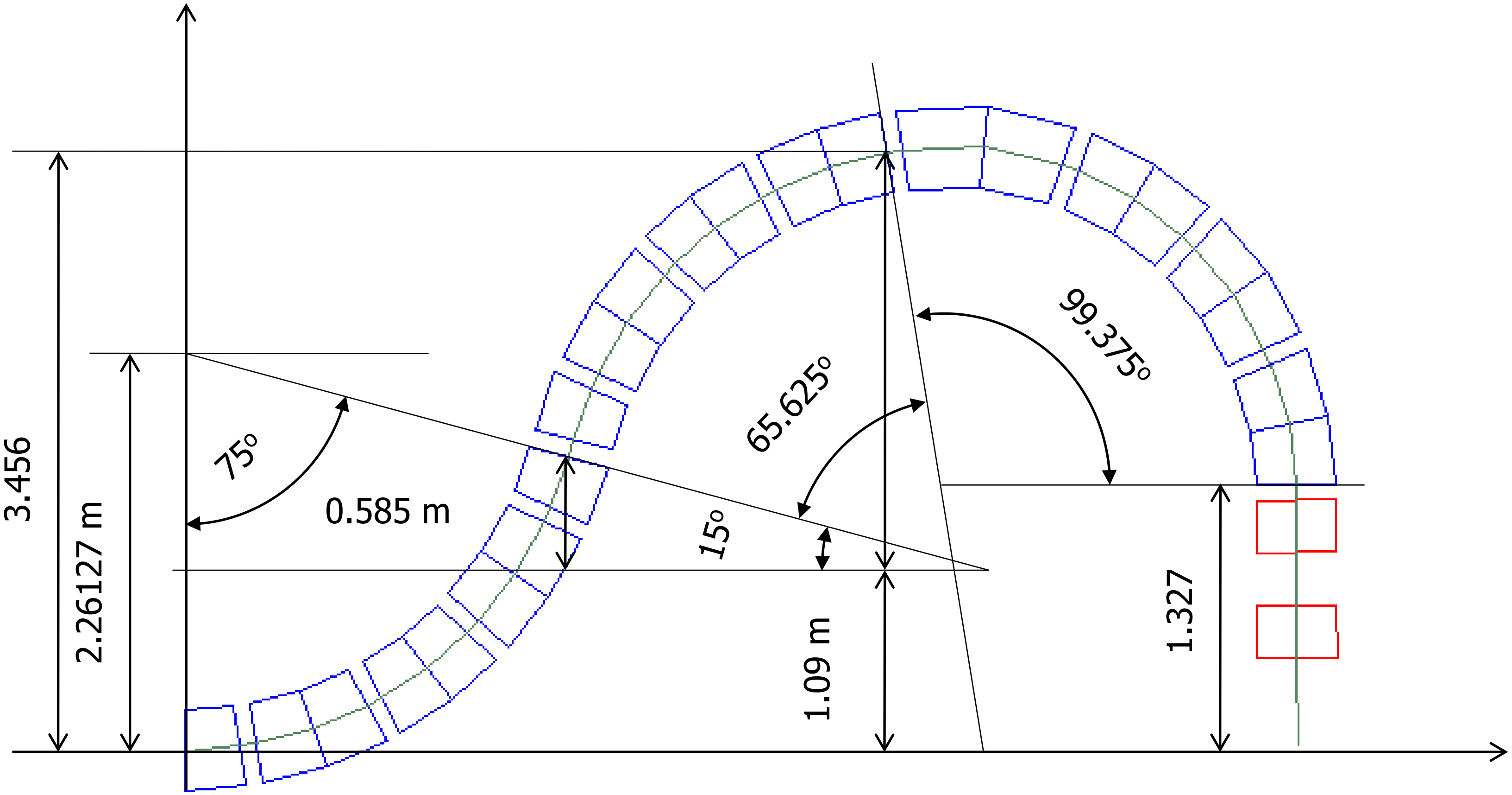
The state of the art proton gantry at PSI

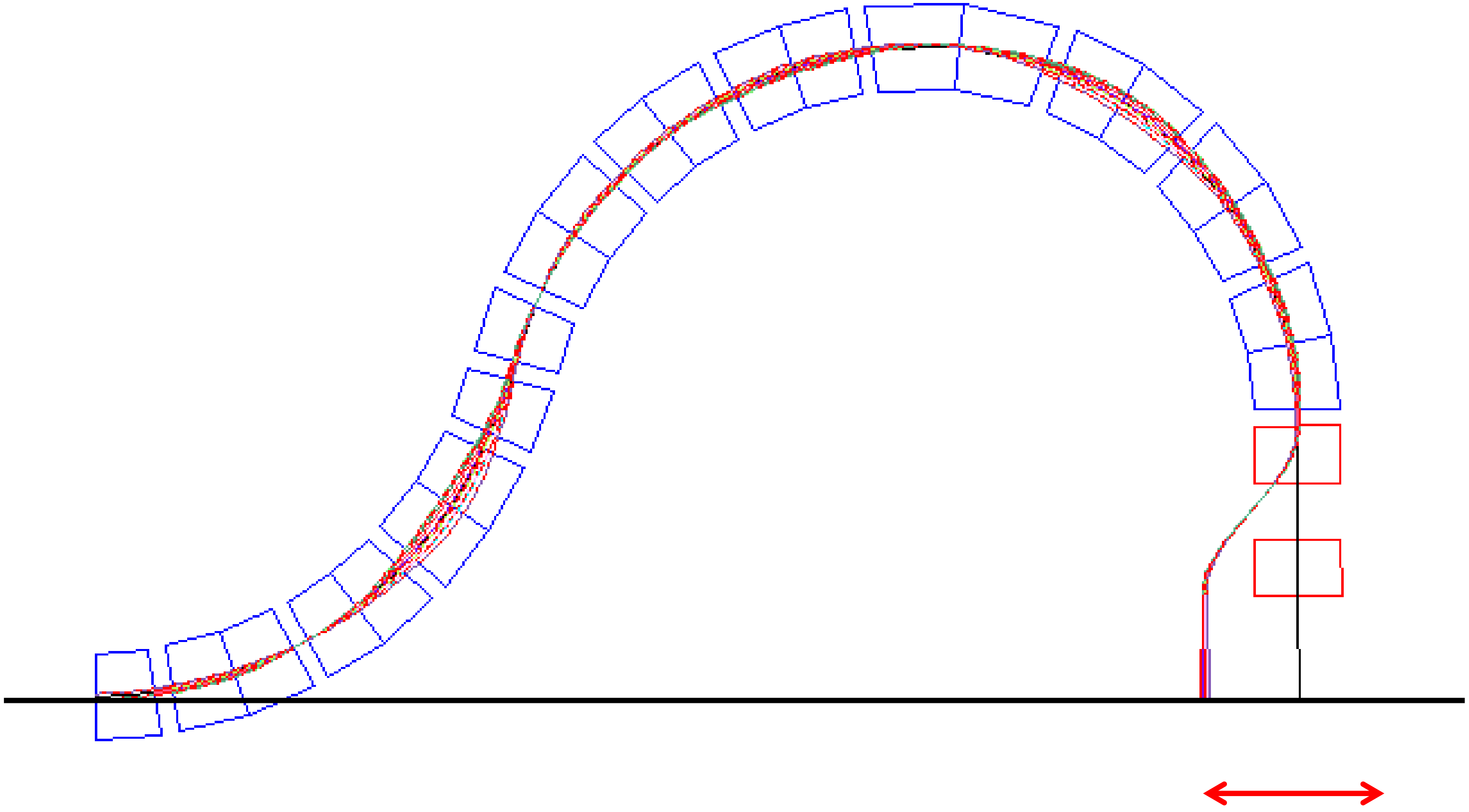

X-ray
2.95 m
Scanner 1+bend
Scanner 2+bend



Magnification x10

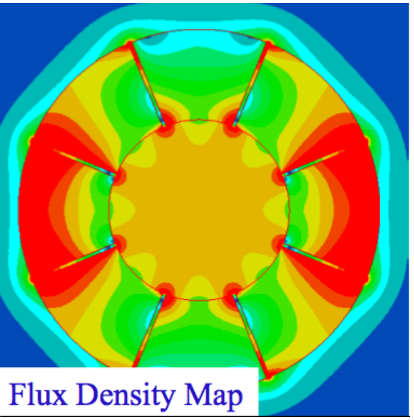


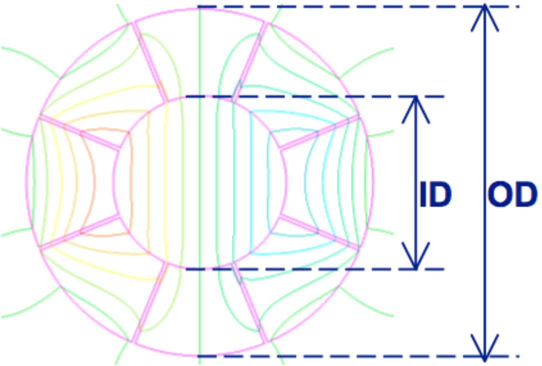

3.456
2.26127 m
75°
0.585 m
15°
65.625°
99.375°
1.09 m
1.327



±10 cm
Magnification 5X

NS-FFAG gantry with permanent magnets

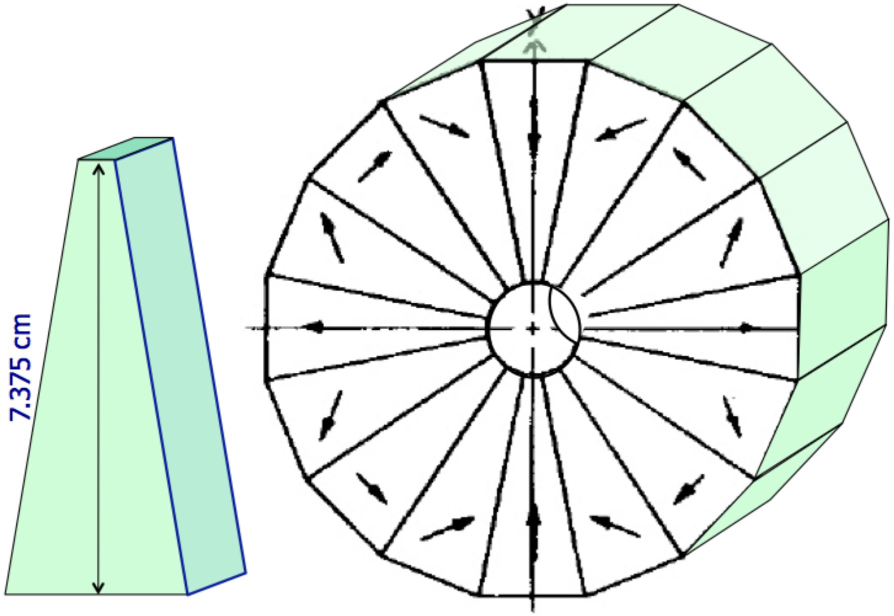

Flux Density Map



Halbach PM Dipole Structures:

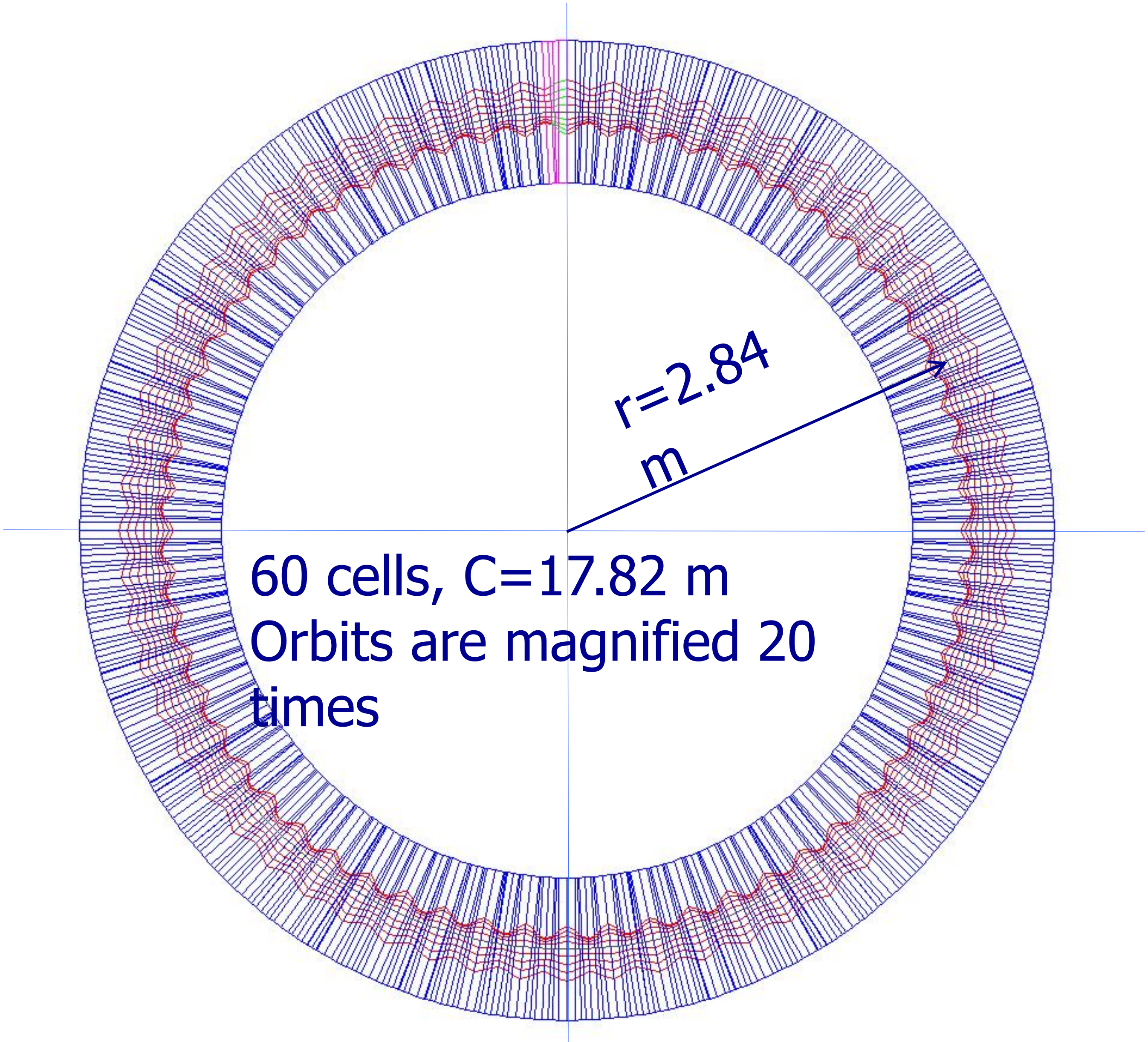
$$B_g = B_r \ln(OD/ID)$$

There is no upper limit for air gap flux density in Halbach dipole structures according to equation.



NS-FFAG ring with permanent Halbach magnets

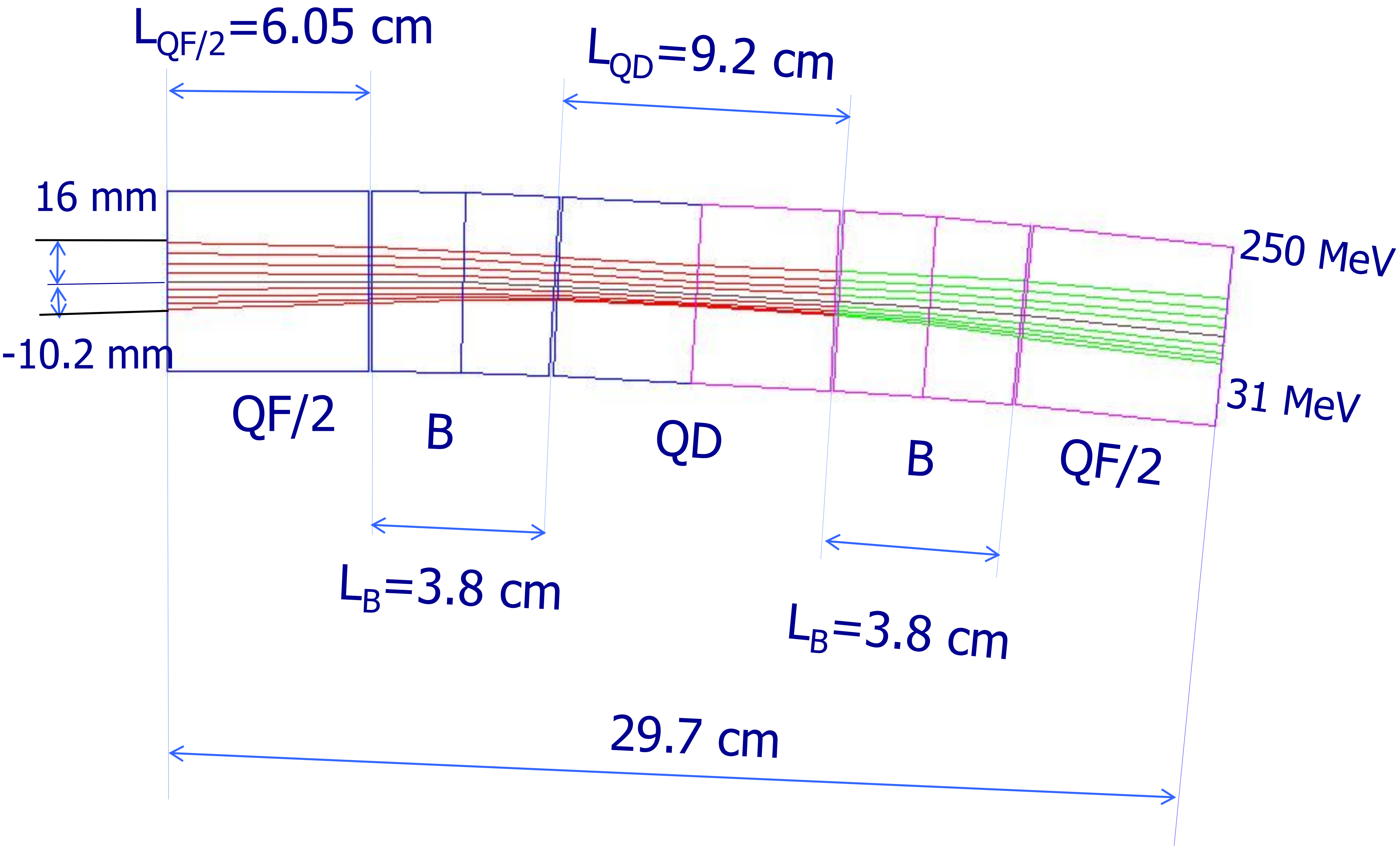
Accelerates protons from 31-250 MeV



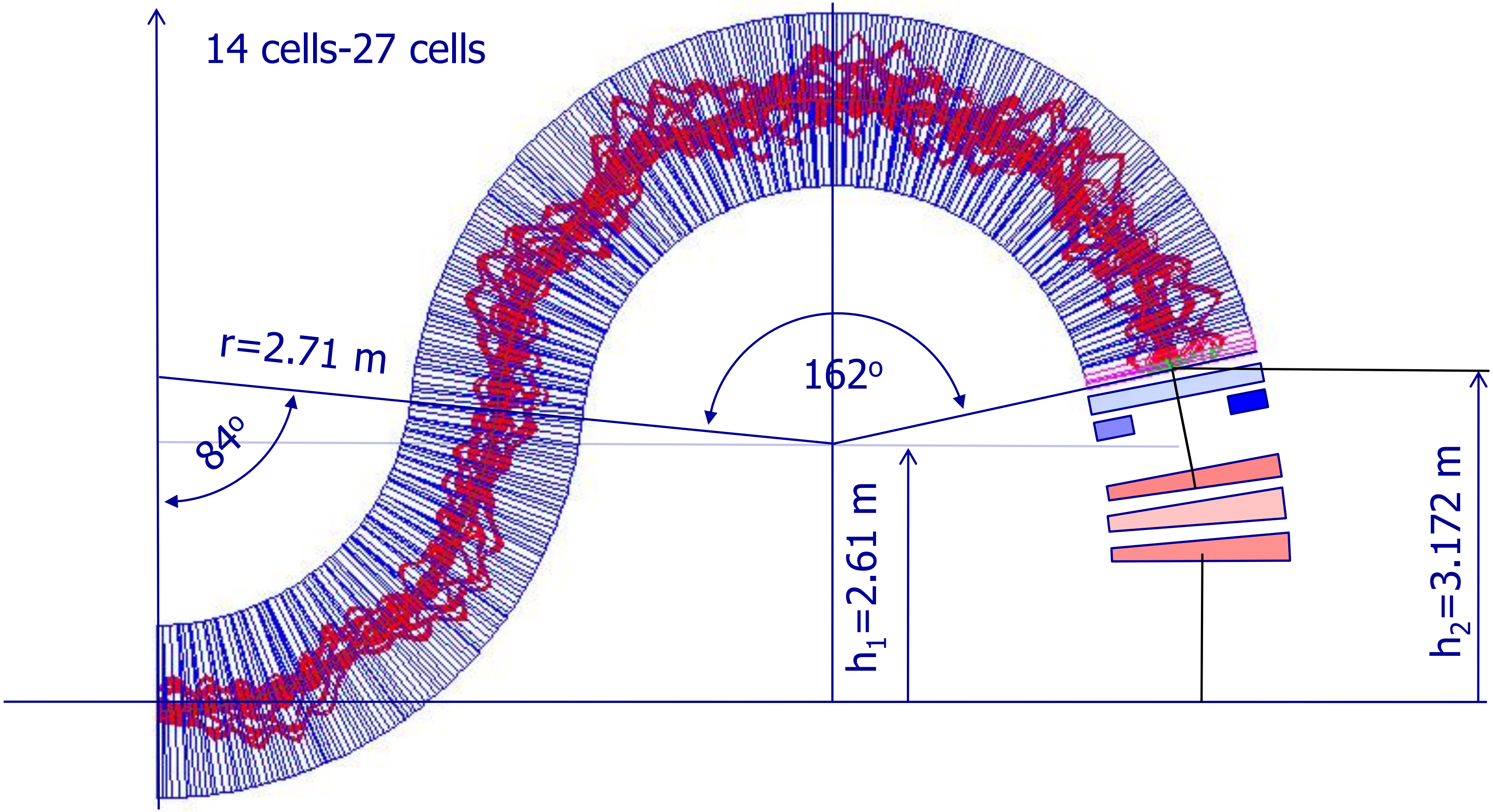
r=2.84 m

60 cells, C=17.82 m
Orbits are magnified 20 times

What is innovative: extreme focusing



Permanent Halbach magnet NS-FFAG gantry



BRHO = 1.7372345376900 Tm ANG=2π/120 = 0.05235987755982988

BYD= 2.0214 T KF =160.0 T/m KD= -175.0 T/m

L_{CELL}=0.285081466313463

SUMMARY:

1. NS-FFAG gantries transfer carbon ions with Δp/p=±20%
2. Weight is reduced for one or two orders of magnitude.
3. Size of NS-FFAG the carbon gantry is of PSI proton one.
4. Operation is simplified as the magnetic field is fixed.
5. Scanning system is with SAD=∞.
6. Beam size is adjustable with the triplet magnets.
7. It is possible to transfer in one pass beam with all energies after the multi-leaf collimator.
8. Triplet magnets do not need to be superconducting