NS-FFAG GANTRY DESIGN

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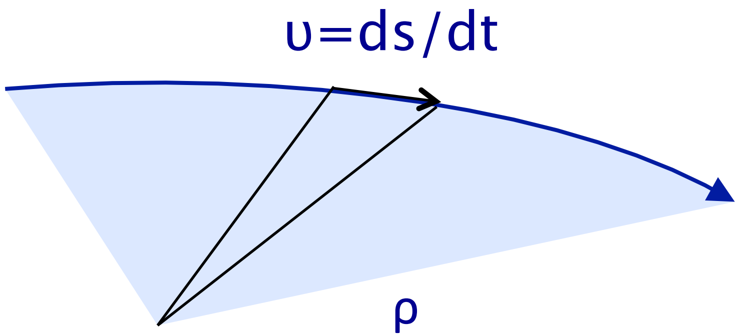
INTRODUCTION

- Future gantries for the ion cancer therapy need to have large momentum acceptance - longitudinal scanning - conclusions from the ion cancer workshop organized in January 2013, by NIH (US National Institute of Health), NCI (US-National Cancer Institute), DOE (US Department Of Energy) and DOD (US-Department of Defense).
- Efforts should be put on: **reducing the gantry cost**, **size**, and **complexity** of operation.
- Work on markers to be used for in city during the real time of treatment to provide information on ion-tumor interaction but also on the very low intensity beam measurements: **precise dose, beam position, profile, and energy**. There are some simple ideas at BNL of using the vacuum windows for determining the beam position, beam transverse profile and even the intensity (dose) (Peter Thieberger).
- For the reduction of size in both carbon or proton gantries the **superconducting magnets** are clearly needed. The larger the field the smaller the size.
- S.A.D **without large magnets** (Except the second scanner magnet still large 20 (30) cm aperture.

The **NEW** carbon ion gantry replaces the **135 ton** magnets of the Heidelberg gantry **with 2 ton** small BNL superconducting magnets.

Lawrence equation

$$\frac{d\vec{p}}{dt} = ze\left(\vec{E} + \vec{\upsilon} \times \vec{B}\right)$$



$$B\rho\,[Tm] = \frac{A}{z} 3.336\, p \;\; [GeV/c/u]$$

E_{oC}=0.93149 GeV/u

E_{op}= 0.938272 GeV

$E = E_k + E_o$

$p/c = \sqrt{E^2 - E_o^2}$

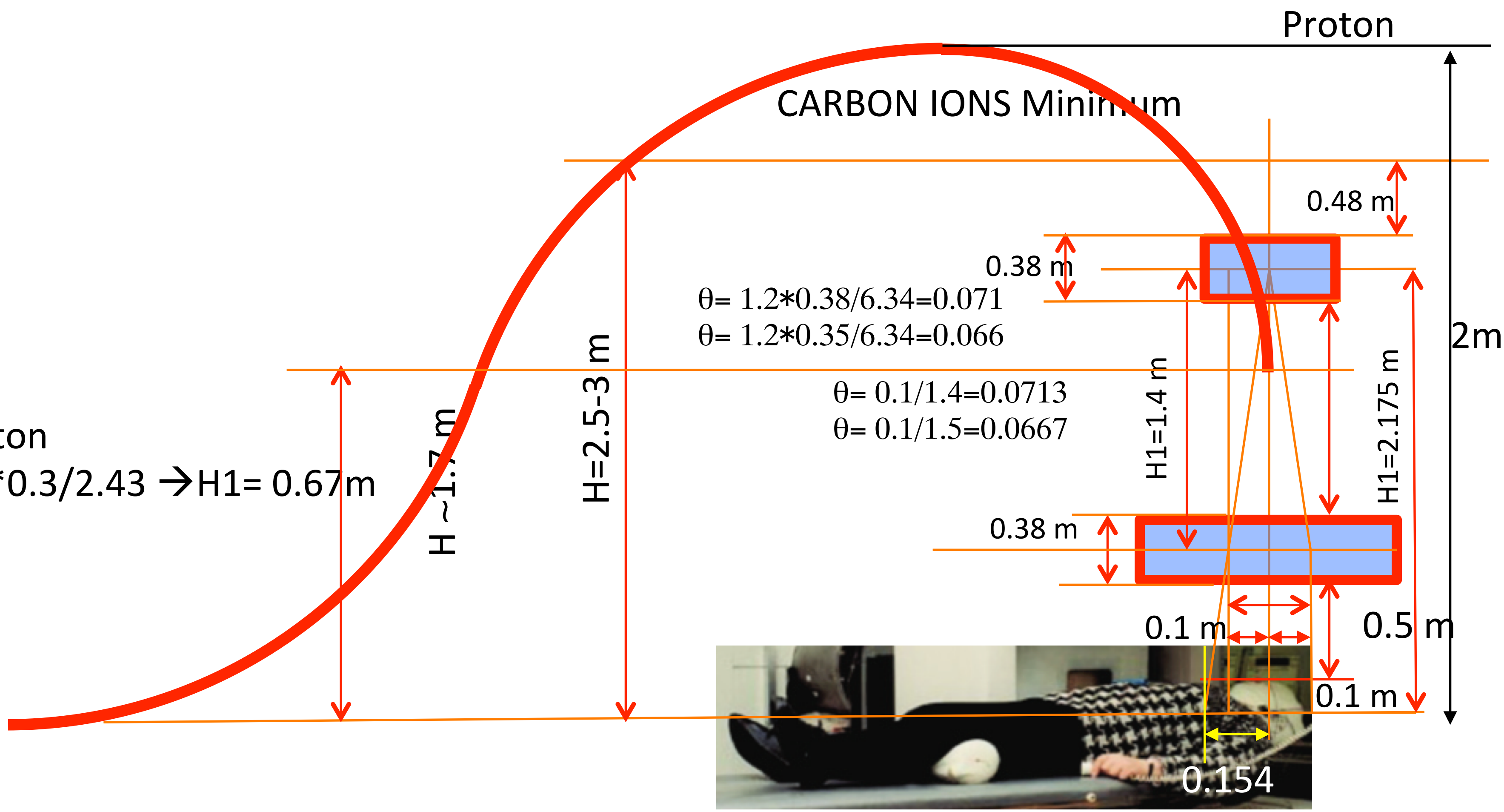
$p_{proton\ 250\ MeV}$ =0.729 *GeV/c*

$p_{carbon\ 400\ MeV/u}$=0.95142 *GeV/c/u*

$B\rho_{\ proton\ 250\ MeV}$ [Tm] = 2.432 Tm

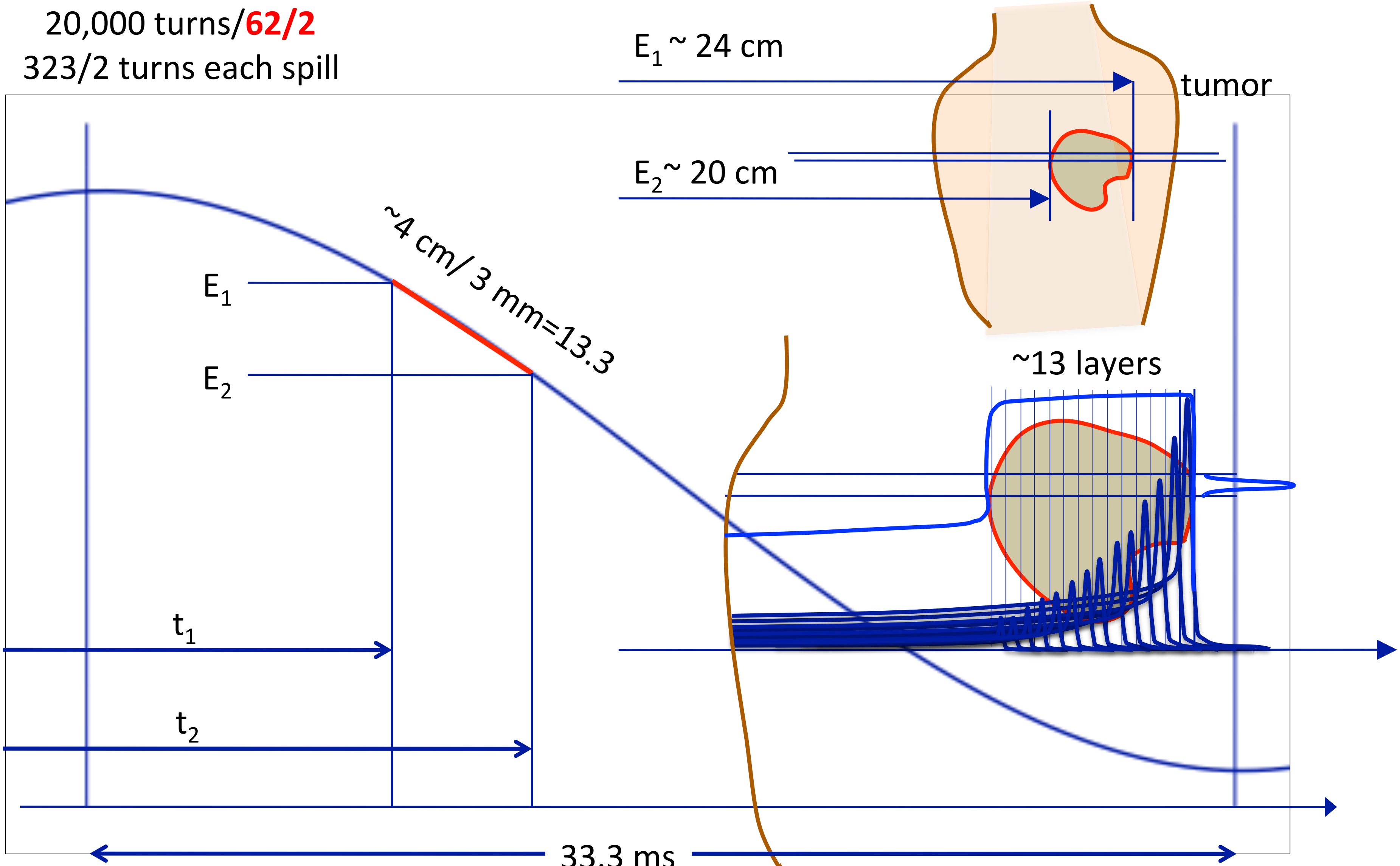
$B\rho_{\ carbon\ 400\ MeV/u}$ [Tm] = 6.348 Tm

Scanning above the patient



Spill extraction

τ≈10 ms
20,000 turns/**62/2**
323/2 turns each spill



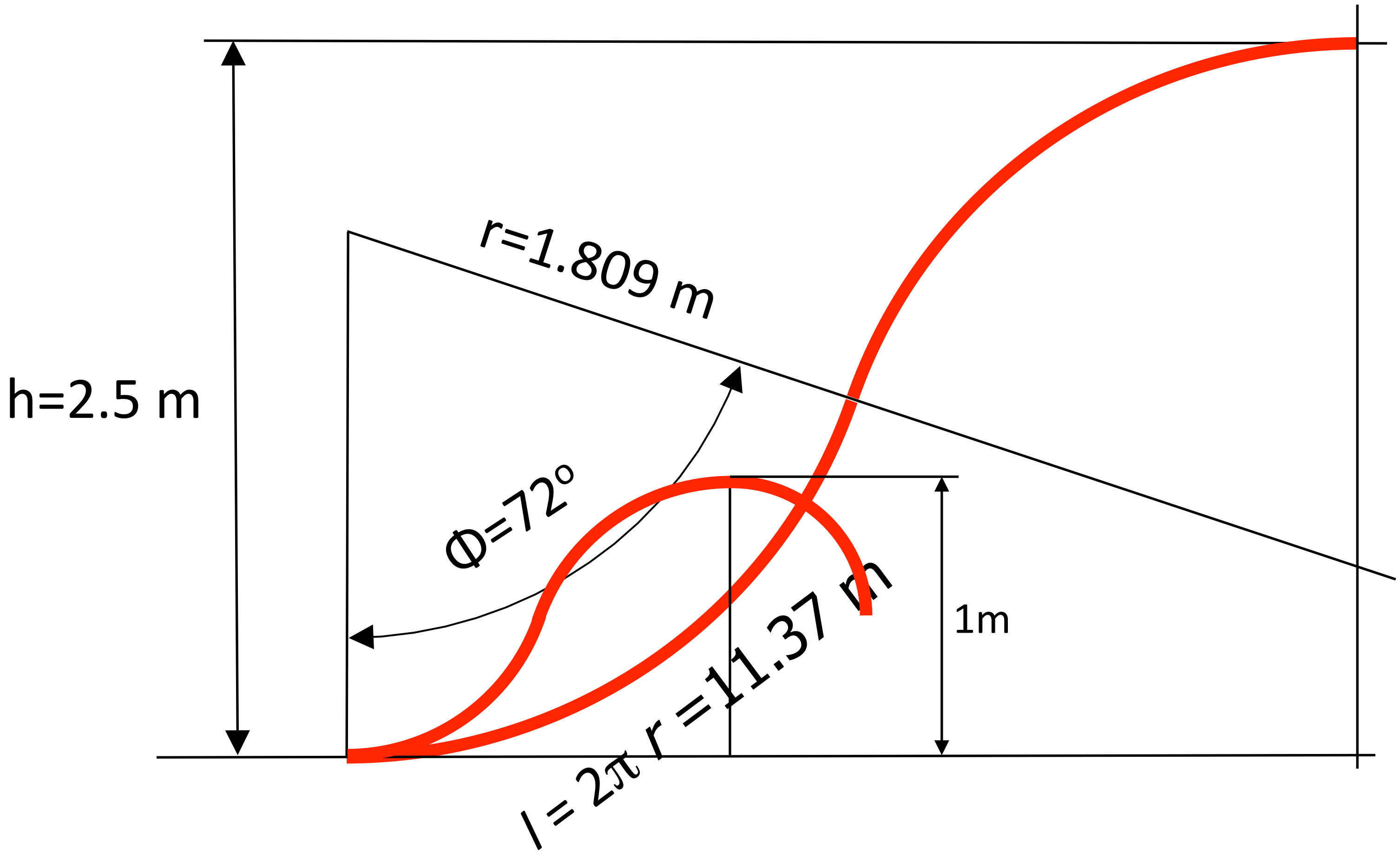
τ ≈0.298 μs → time of one turn around circumference of 64 m at 400 MeV/u

τ ~ 1.63 μs @ 8 MeV/u

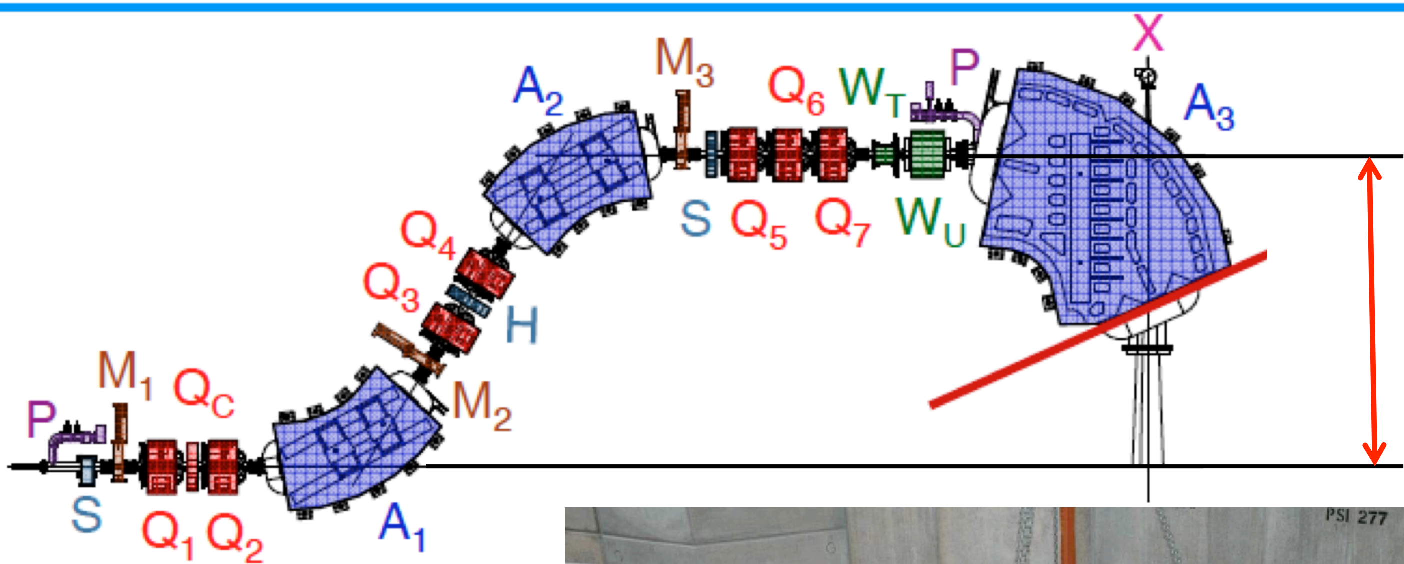
Construction of the gantry

Proton Gantry – E_k=250 MeV → E=250 + 938.27 MeV → $p=\sqrt{E^2 - E_o^2}$
$B\rho = p/c$ = 2.432 Tm **θ = Bl/*B*ρ if B ~ 5T → then r = 0.486 m**

$B_{avrg} = B\rho/r$ = 1.344 T → If we raise the field to the superconducting



The state of the art proton gantry at PSI

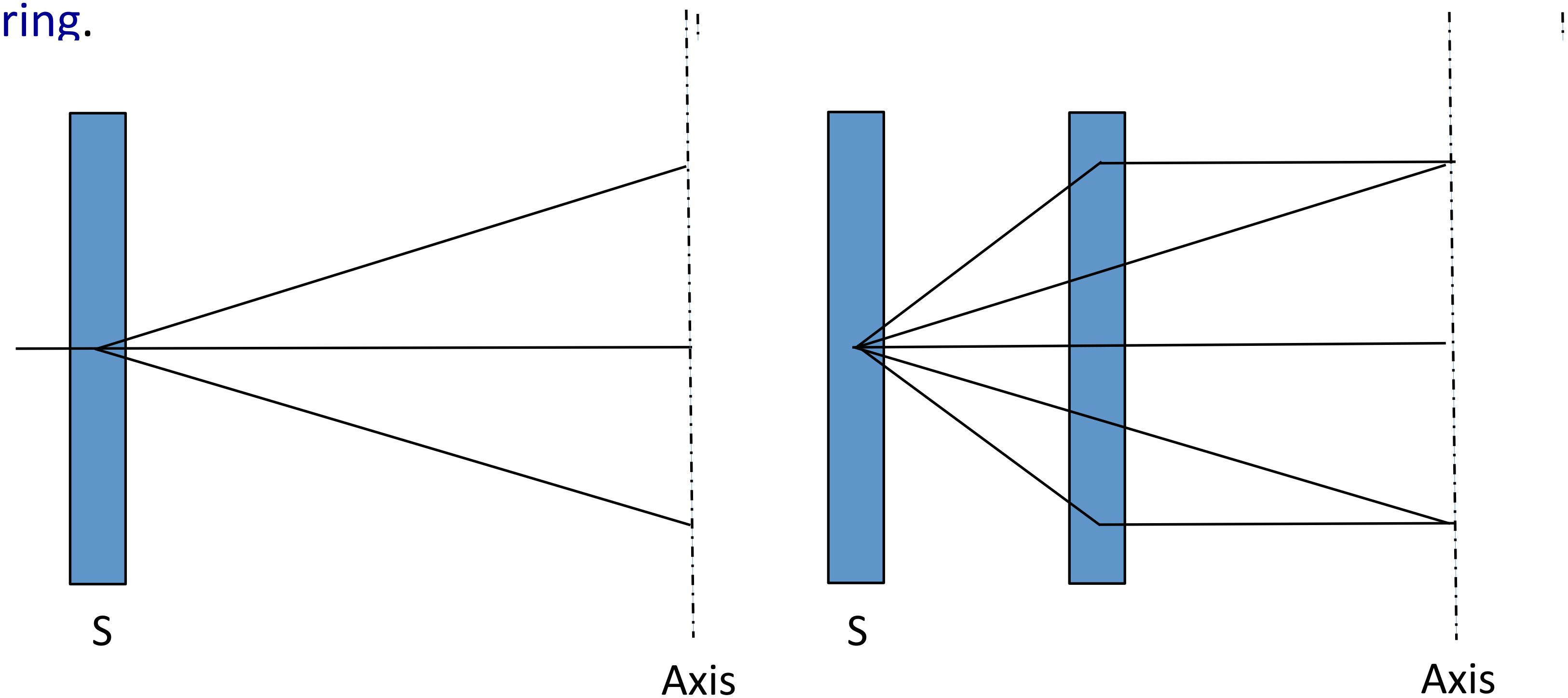


The state of the art proton gantry at PSI

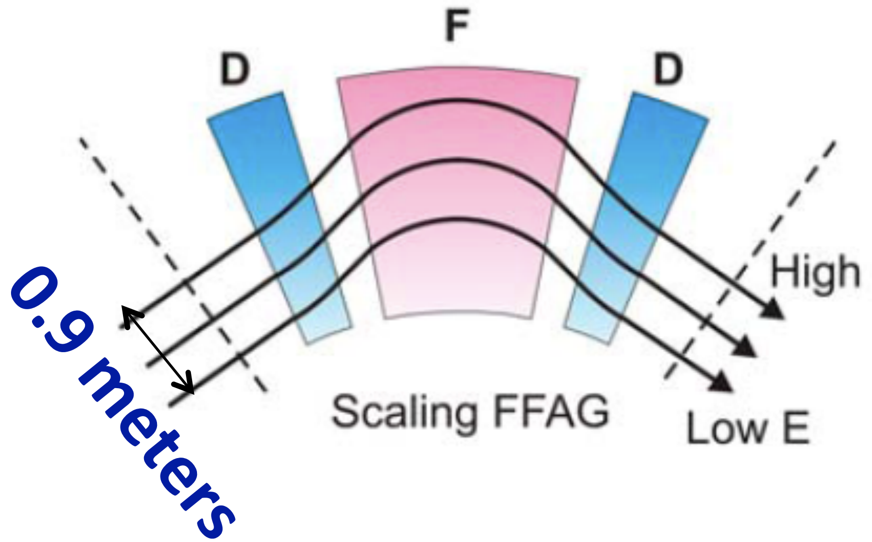
SAD – SOURCE-TO-AXIS-DISTANCE

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.

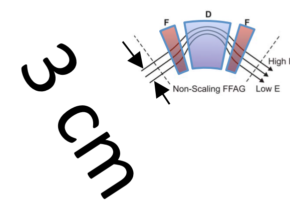


SCALING VS. NON-SCALING FFAG



Linear magnetic field:

$B = B_o + r\ G_o$



- Orbit offsets are proportional to the dispersion function: $\Delta x = D_x * \delta p/p$
- To reduce the **orbit offsets to ±4 cm range**, for momentum range of $\delta p/p \sim \pm 50\ \%$ the dispersion function D_x has to be of the order of:

$$D_x \sim 4\ cm / 0.5 = 8\ cm$$

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]

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

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

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

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

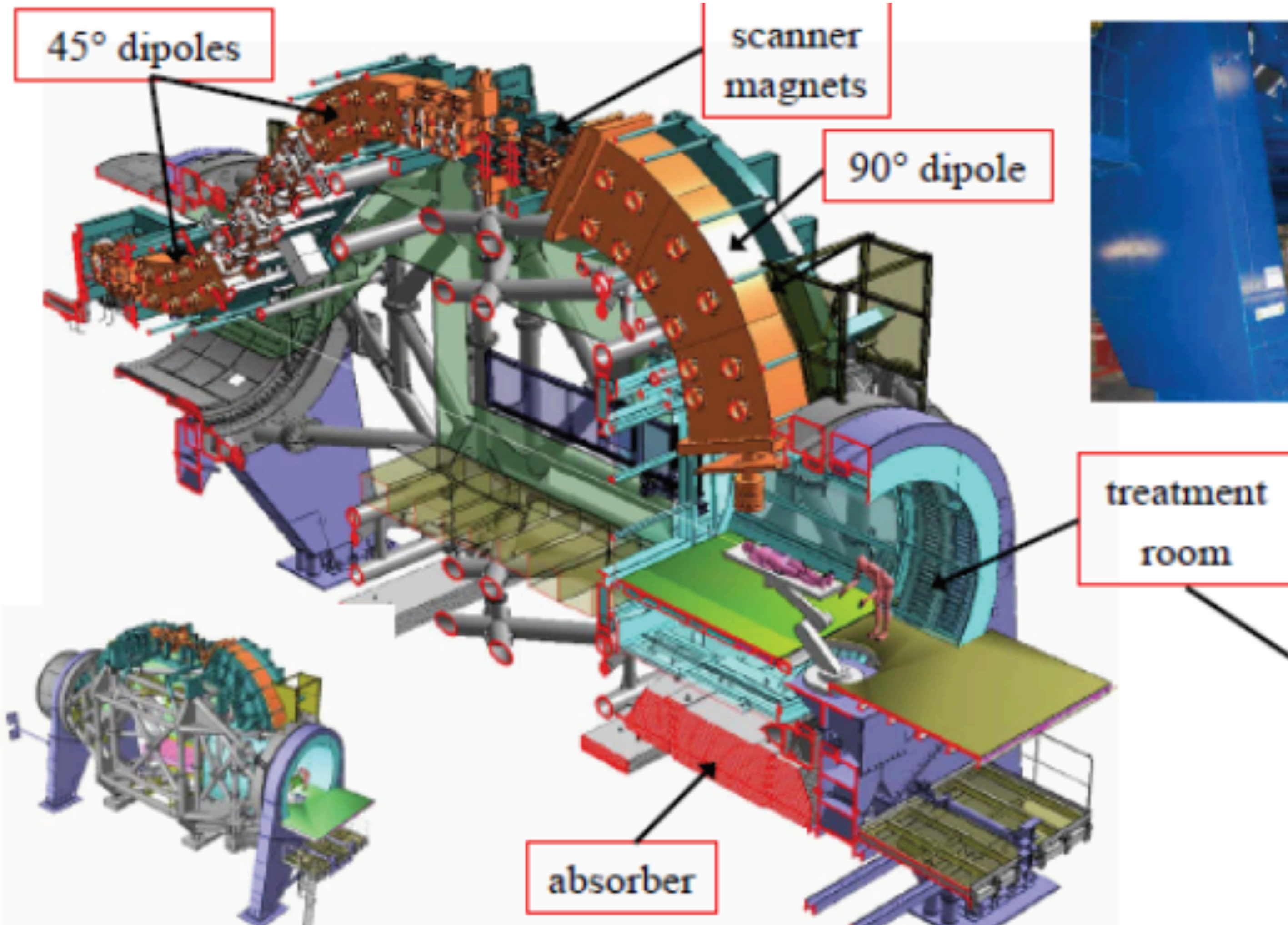
$p_{o\ proton} = 607.611\ MeV/c \qquad E_{ko} = 179.56\ MeV$

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

State of the art C-gantry at Heidelberg

Weight of the transport components – 135 tons

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



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Trbojevic (43) **Pub. Date: Nov. 15, 2007**

(54) **GANTRY FOR MEDICAL PARTICLE THERAPY FACILITY**

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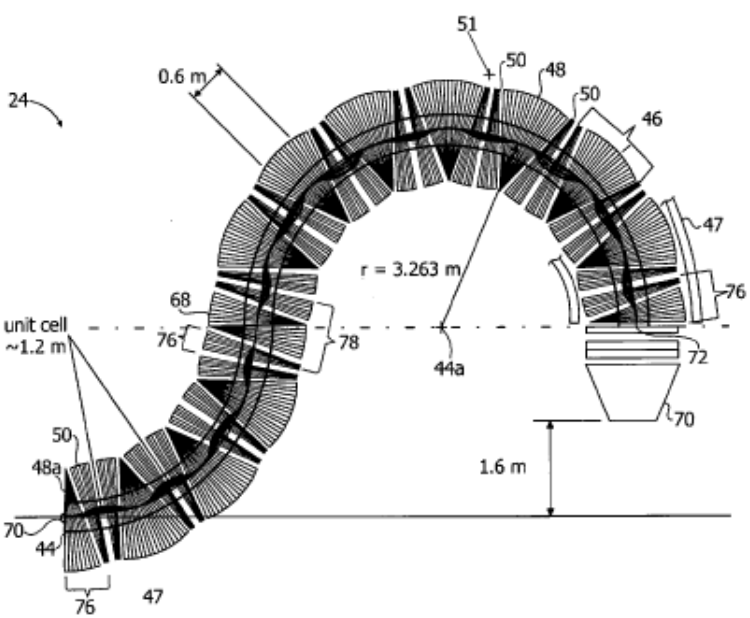
A61N 5/10 (2007.01)

(52) **U.S. Cl.** .... **250/492.3**; 250/398; 250/396 ML

(57) **ABSTRACT**

A particle therapy gantry for delivering a particle beam to a patient includes a beam tube having a curvature defining a particle beam path and a plurality of fixed field magnets sequentially arranged along the beam tube for guiding the particle beam along the particle path. In a method for delivering a particle beam to a patient through a gantry, a particle beam is guided by a plurality of fixed field magnets sequentially arranged along a beam tube of the gantry and the beam is alternately focused and defocused with alternately arranged combined function focusing and defocusing fixed field magnets.



2. TITLE OF INVENTION

Innovative Scanning System for the ion cancer therapy

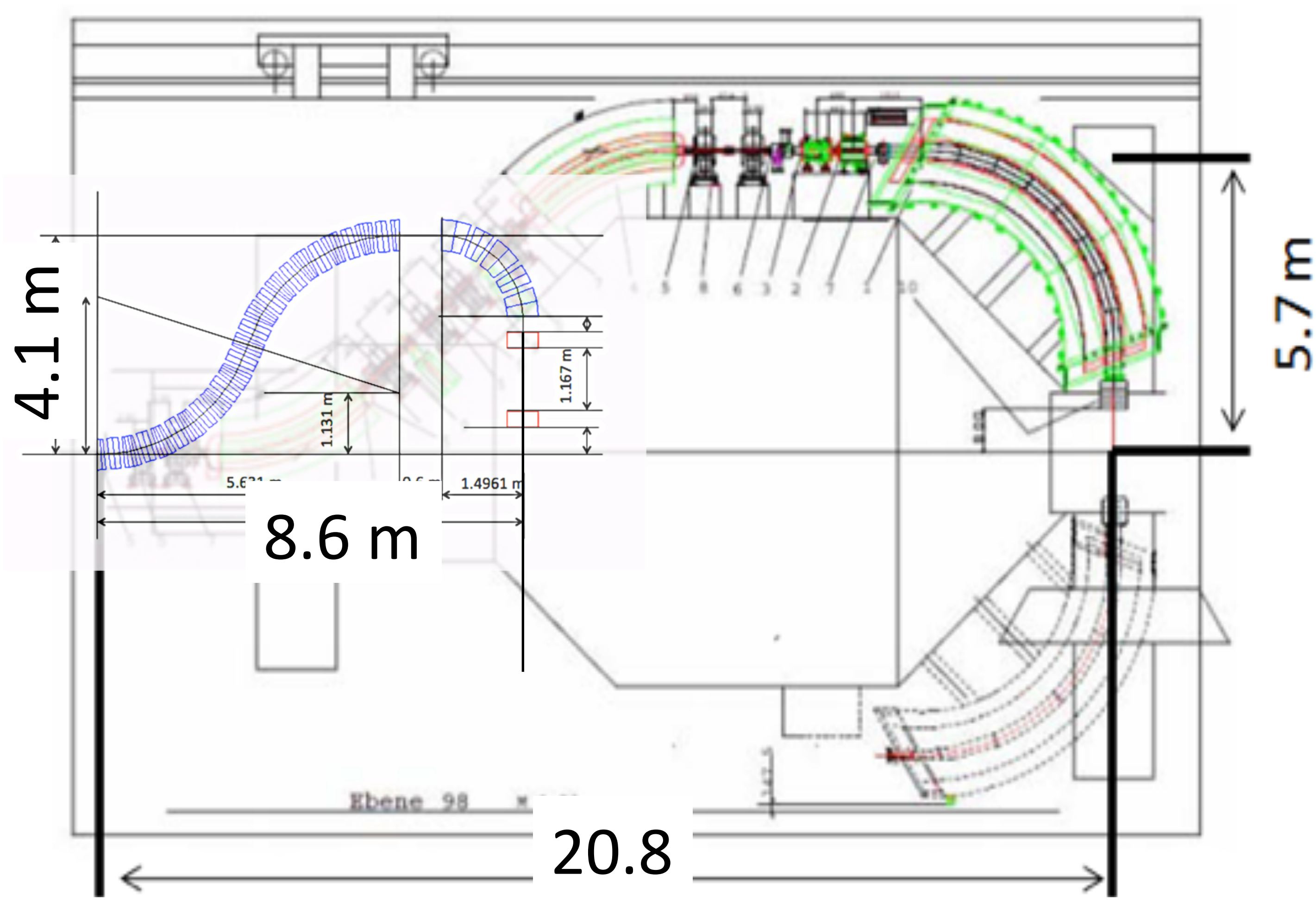
a. GENERAL DESCRIPTION. Outline briefly what your invention is about and the manner in which the advantages of your invention are achieved. If it is only a part of a larger system that includes known components, concentrate on the new development. If pertinent, attach illustrations and refer to them in the description. Please address the following issues:

i. What is the problem to be solved?
ii. What prior attempts were used to solve the problem?
iii. What are the disadvantages or shortcomings of previous attempts to solve the problem?
iv. How does the invention work?
v. Give a detailed description of the invention.
vi. Describe known variants of the invention.
vii. What further development remains to be accomplished?

If more space is needed, attach a sheet.

Number of the hadron cancer therapy facilities in the word has an exponential growth due to clear advantages with respect to any other radiation treatment. Deposited ion energy in the patient body is localized in the Bragg peak precisely in the cancerous tumor without affecting living cells around. The transverse spot scanning system (TSSS) moves the beam to cover tumor transverse size ±10 cm, while the selected energy defines the longitudinal position of the Bragg peak.

DIMENSIONS of the CARBON GANTRY



Carbon E_k=400 MeV/u → Bρ = 6.35 Tm ($\theta = Bl/B\rho$)

Warm iron magnets: B=1.6 T then ρ ~ 4.0 m

Superconducting magnets B=3.2 T then ρ ~ 2.0 m

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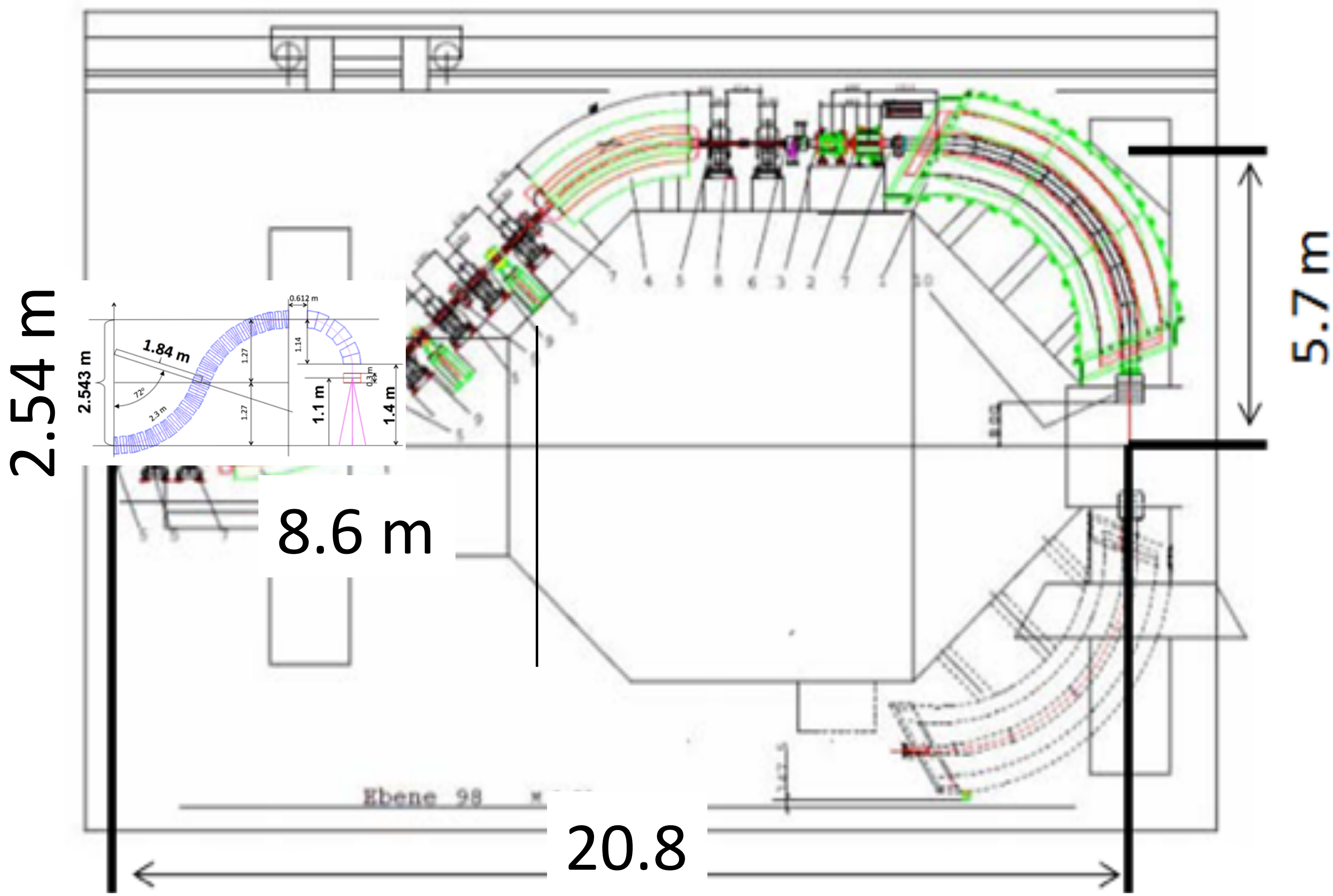

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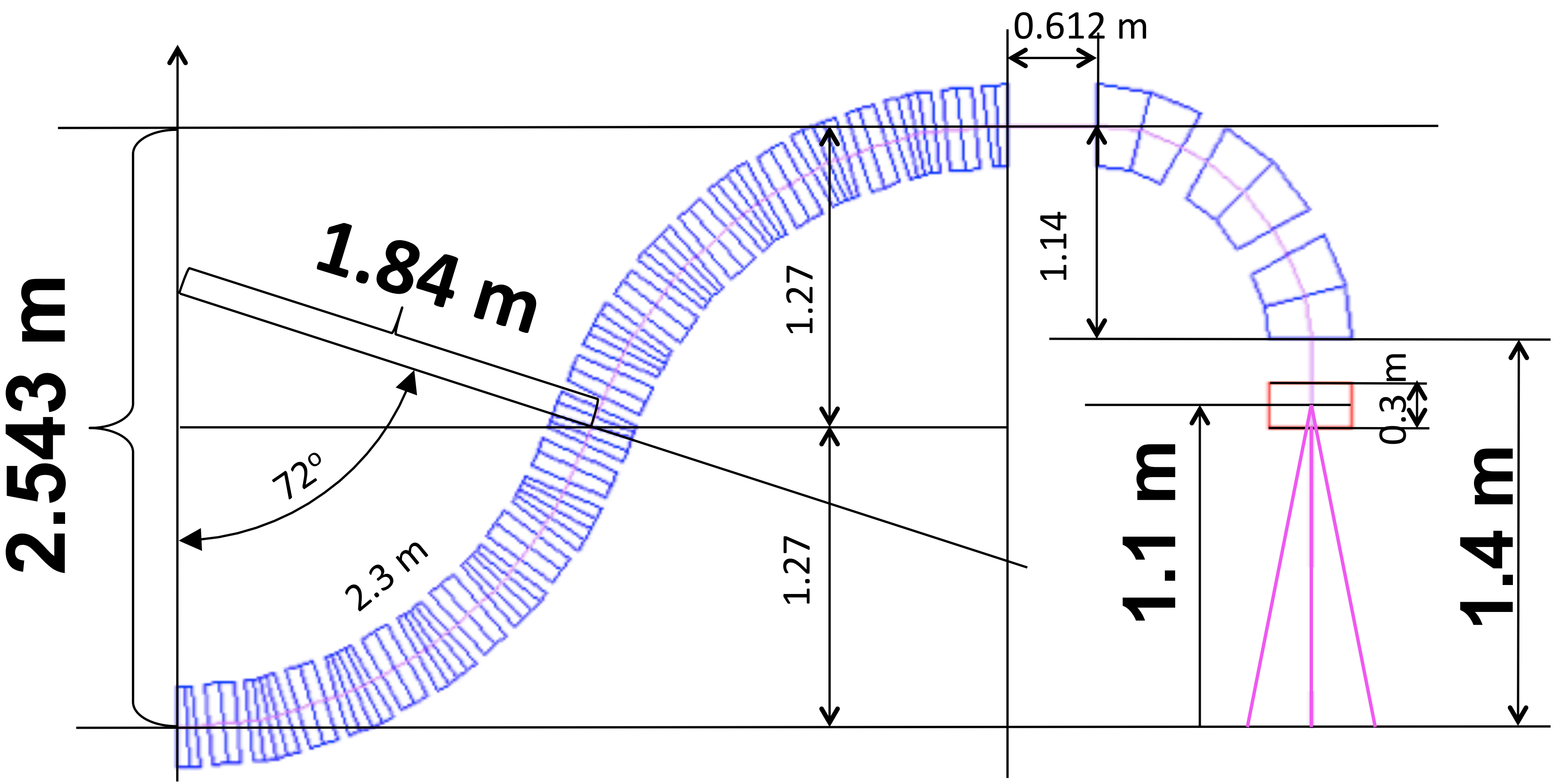
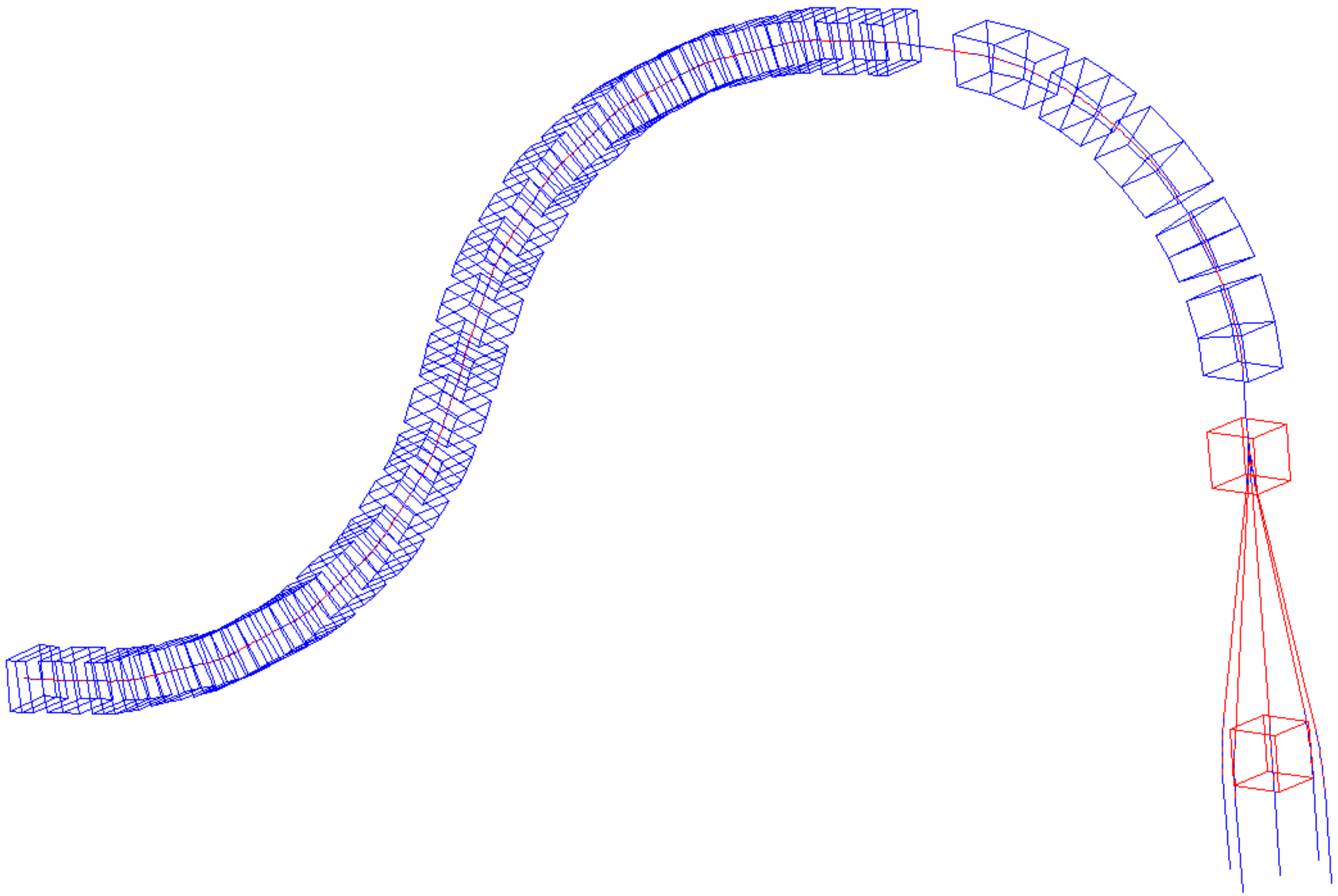
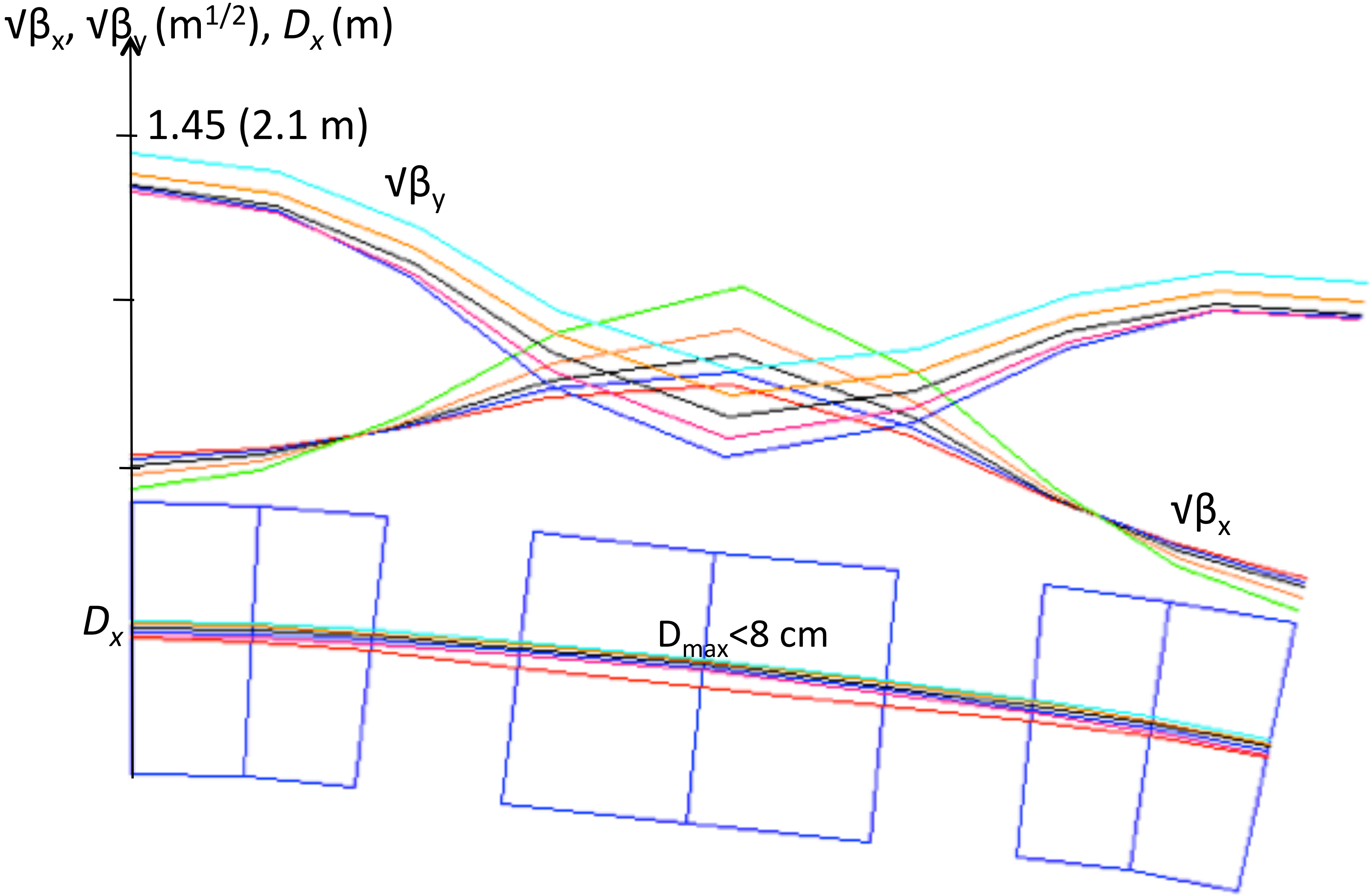
Reducing the size and weight of the carbon gantry(135 tons→ 2 tons) with fixed field



Three Dimensional picture



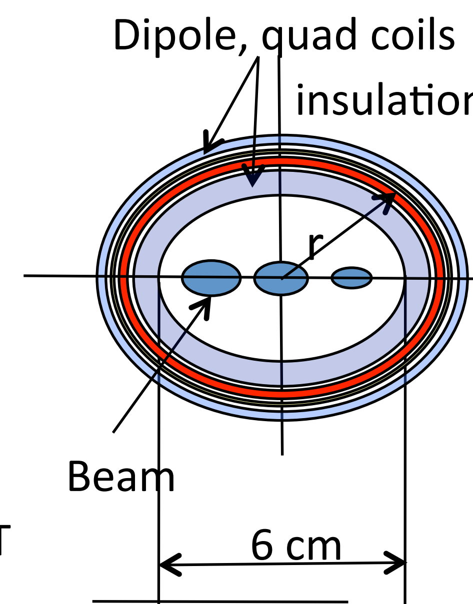
Amplitude functions in the carbon gantry



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

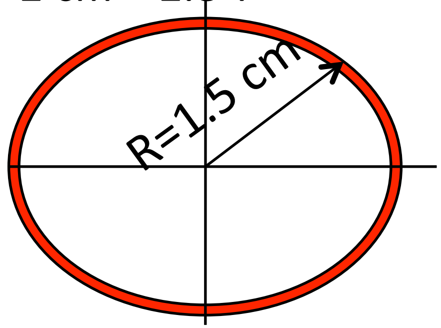
$$B_{D\,max} = B_d + G_D\,x = 4.27 - 102 * \left\{ \begin{array}{ll} 4.54\ mm & 3.80\ T \\ -2.90\ mm & 4.6\ T \end{array} \right.$$

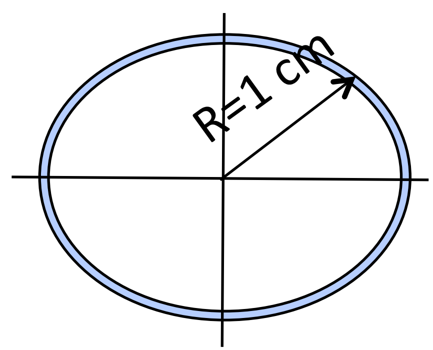
$$B_{F\,max} = B_f + G_F\,x = -0.52 + 141.8 * \left\{ \begin{array}{ll} 7.5\ mm & 0.54\ T \\ -6.64\ mm & -1.46\ T \end{array} \right.$$



Quadrupole Coil

140 T/m * 2 cm = 2.8 T





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

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

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

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

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

AML combined function magnet design

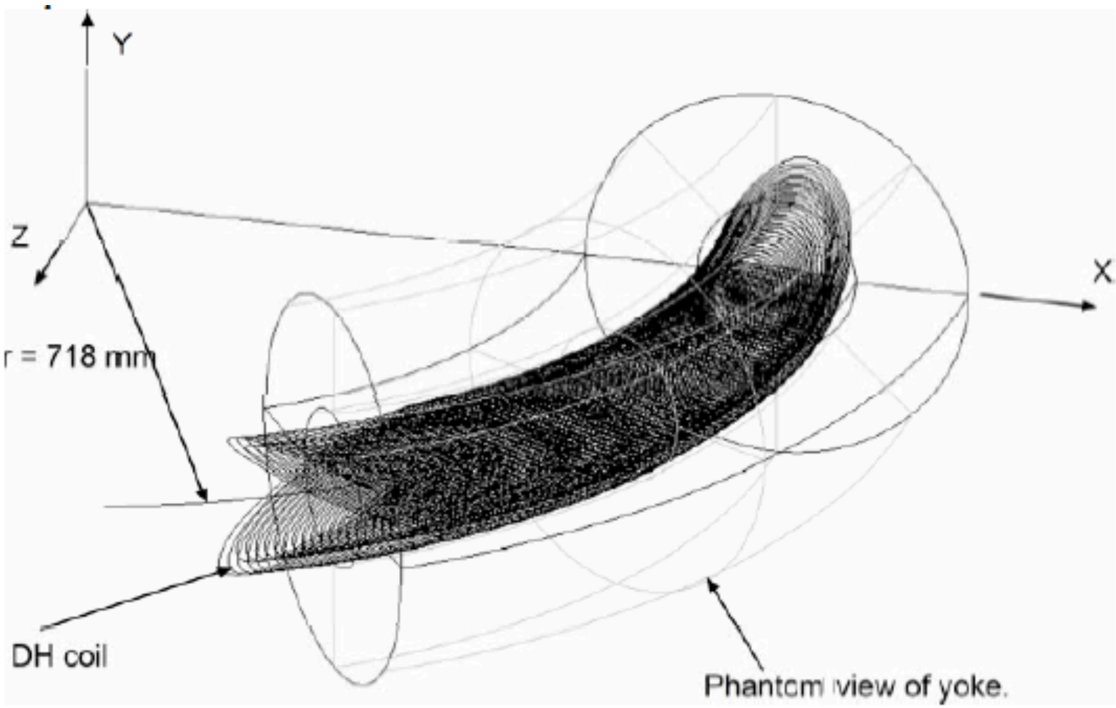


Figure 3. Diagram of a proposed 4-layer double-helix coil used in a 180° beam channel bend.

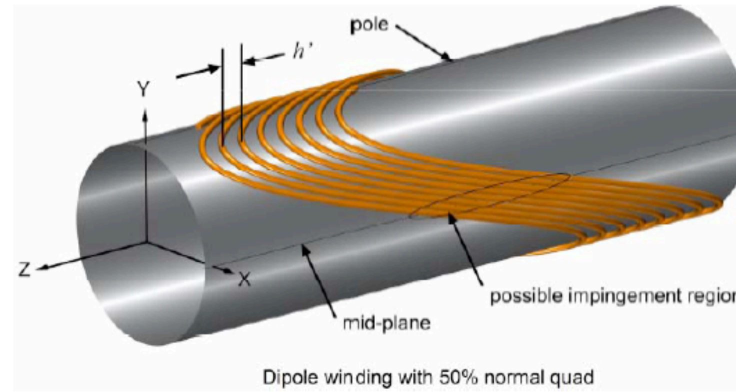
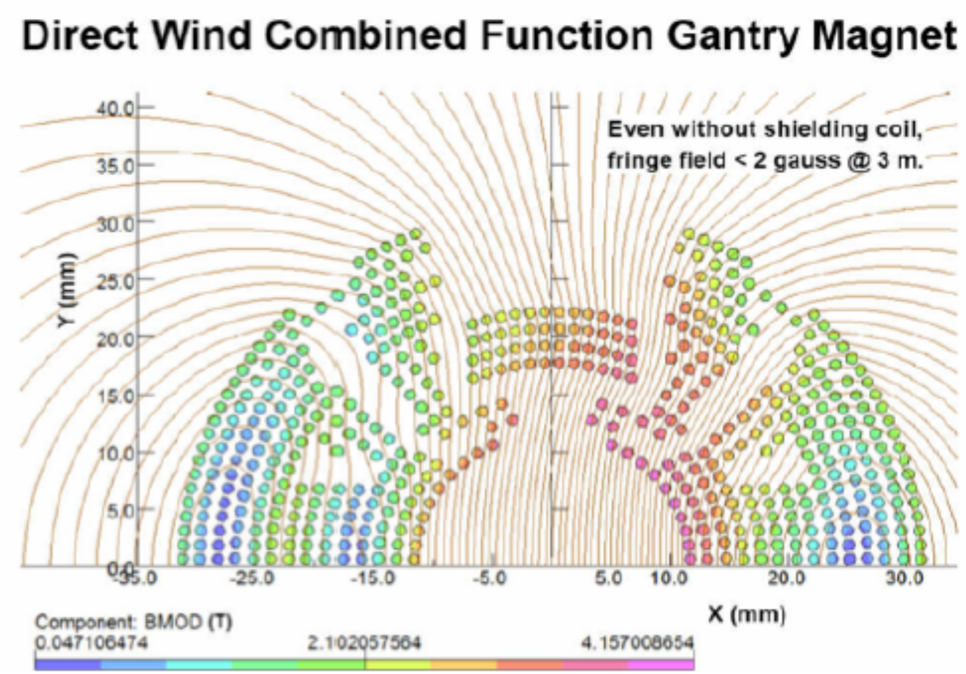
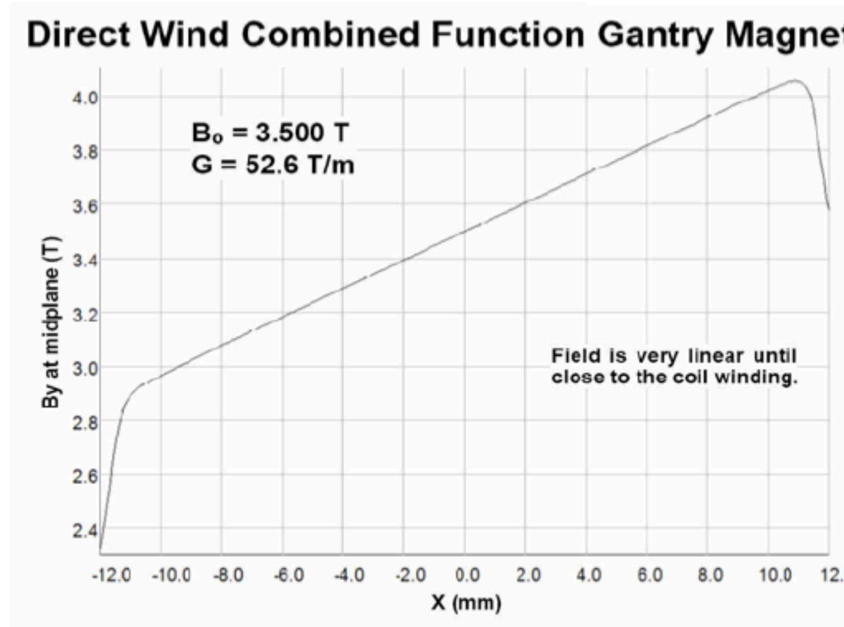


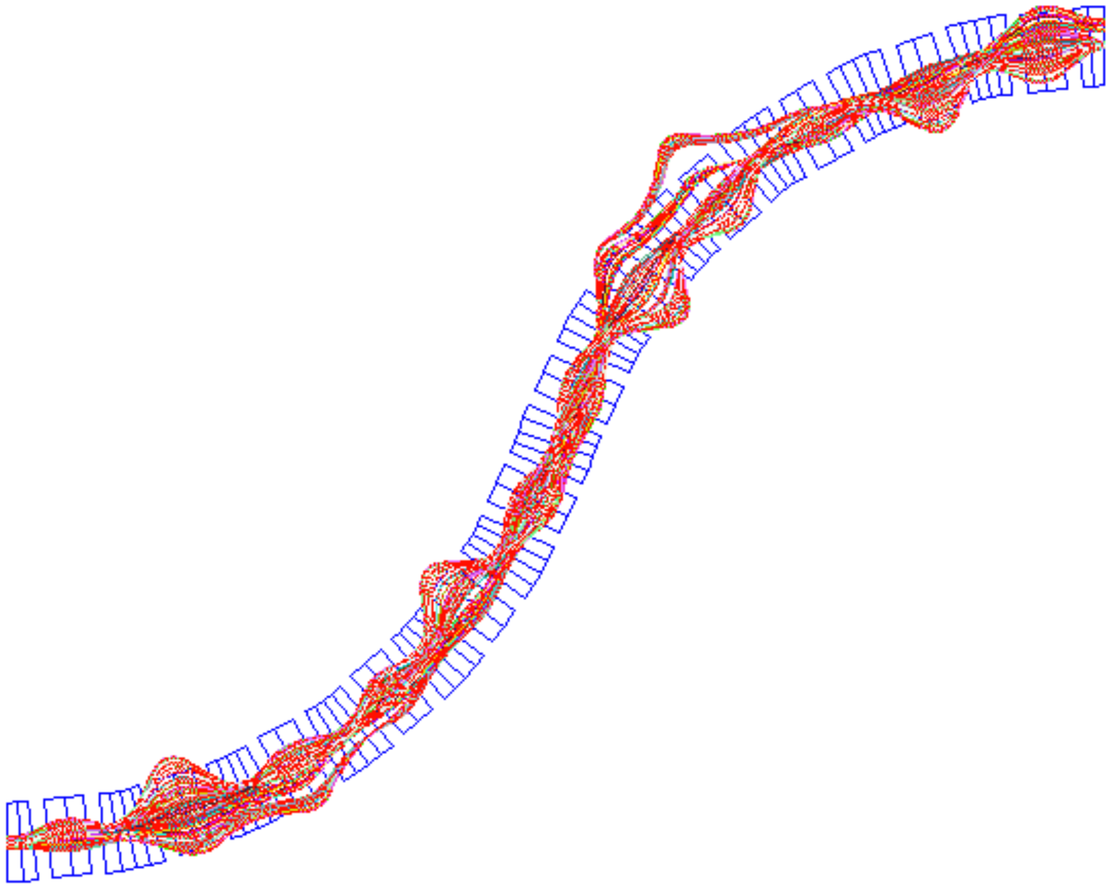
Figure 2. Dipole windings with 50% normal quad amplitude. The turn spacing, *h'*, has been increased due to the conductor impingement effect at the mid-plane.

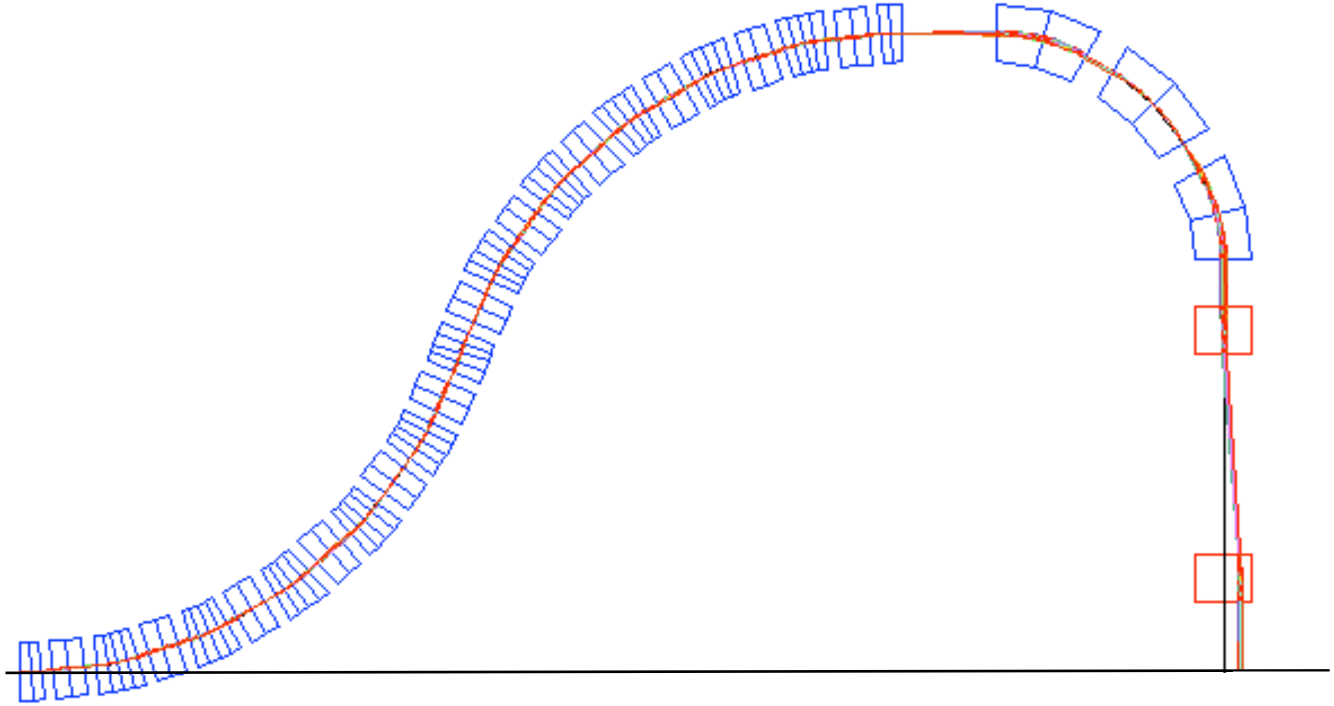
BNL- combined function magnet design

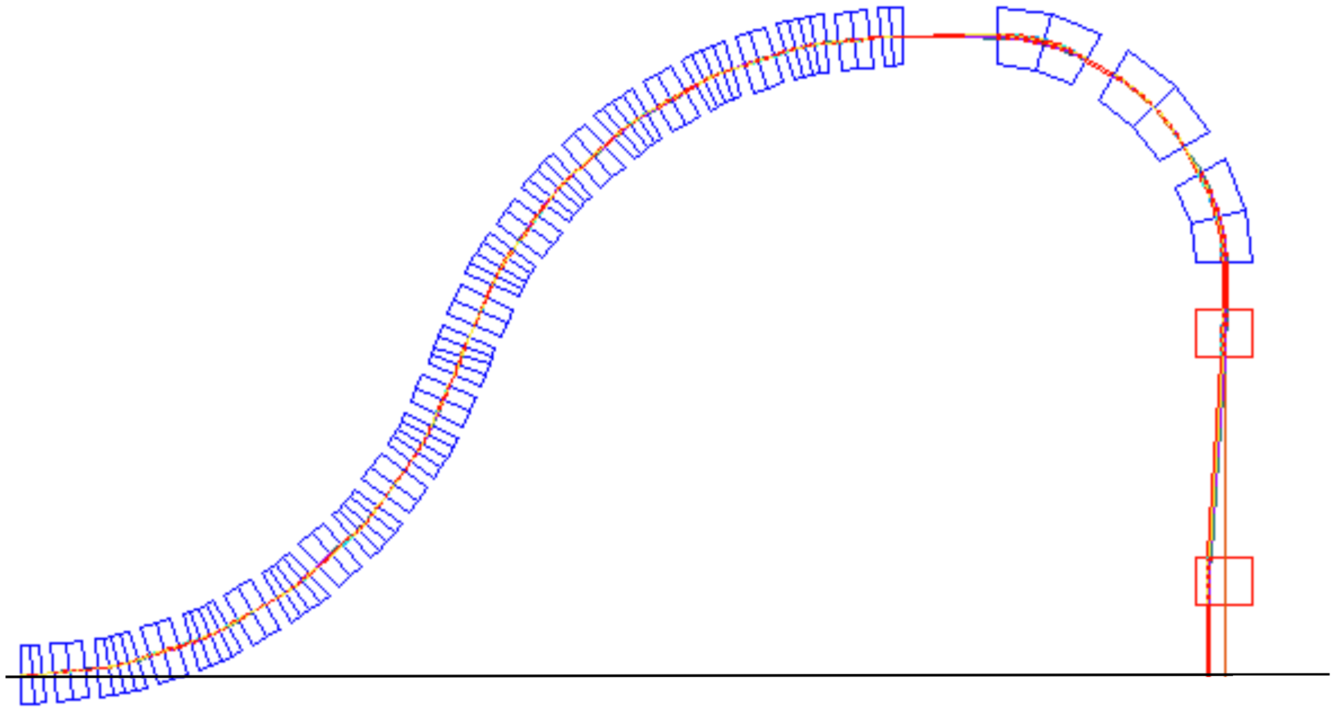




Tracking particles in the carbon gantry for the energy range of 210-400 MeV/u

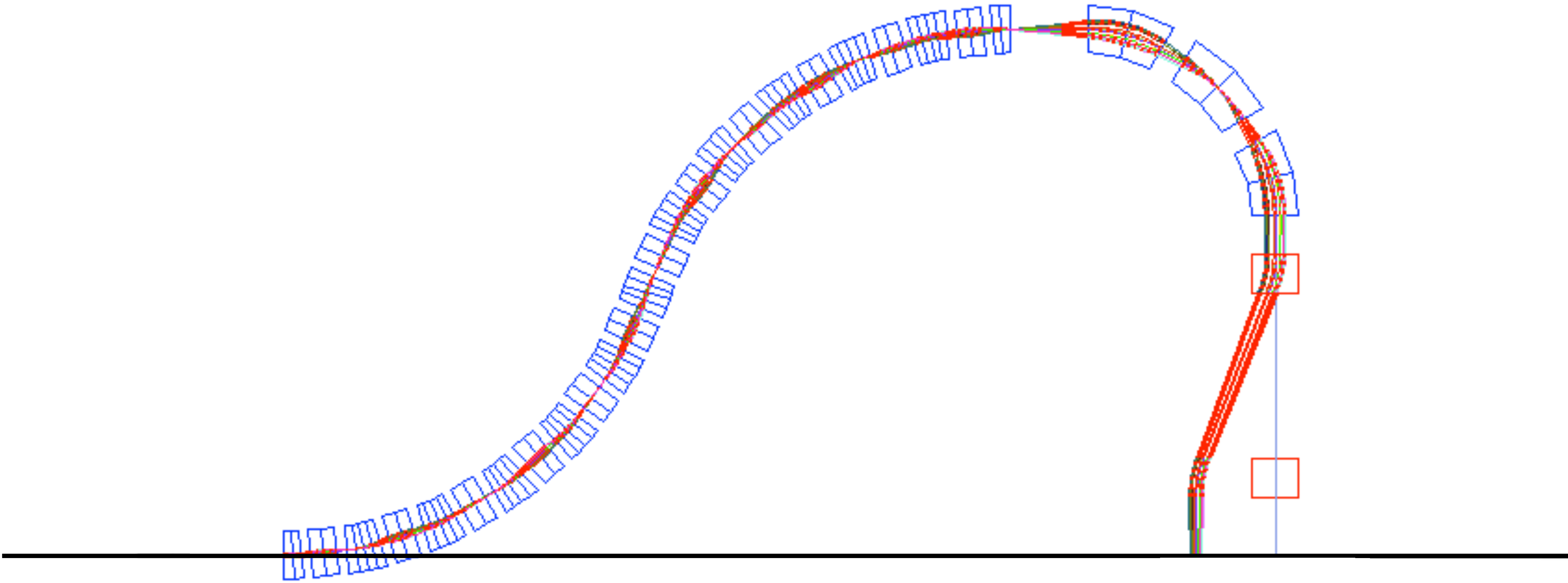






CARBON GANTRY height 4.091m

5X magnification, scanning ±10 cm



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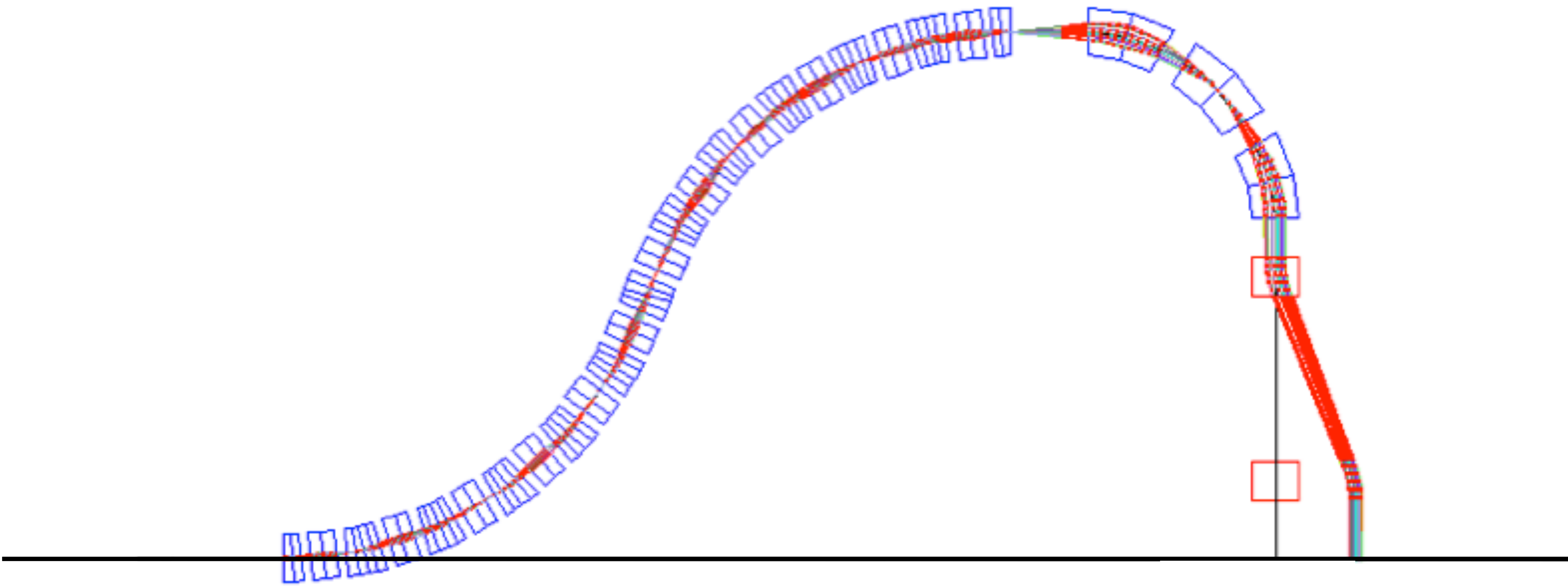
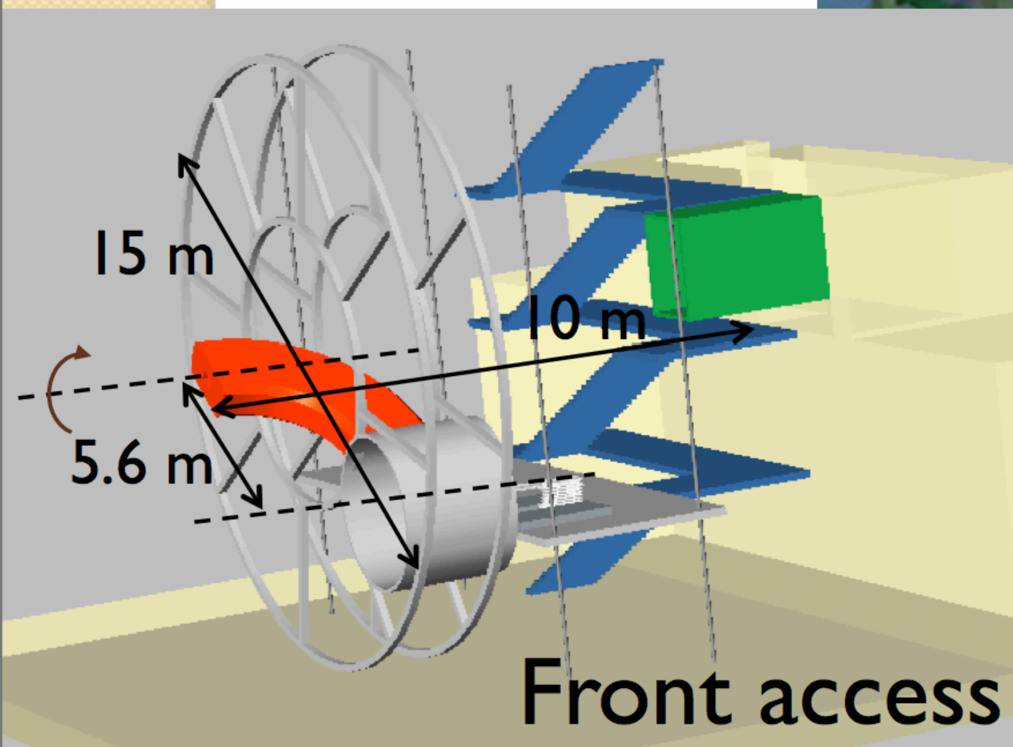


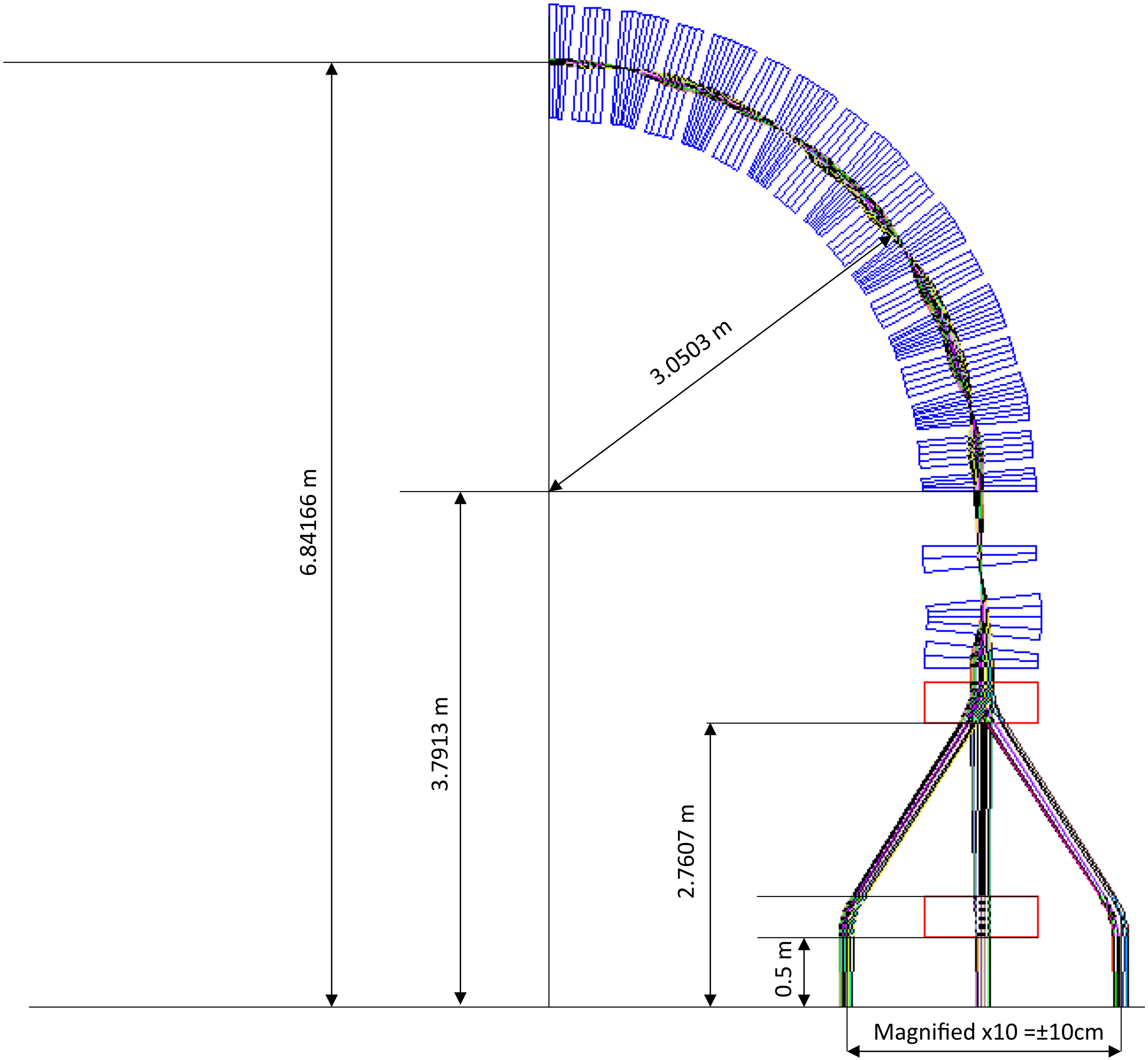
Mobile isocenter - 2

Patient positioned
in a small room "somewhere"



Gantry is longer, than just the last magnet but at small *r*

The CNAO 90° magnet during installation in the vertical line. The size is the same as for a gantry final magnet.

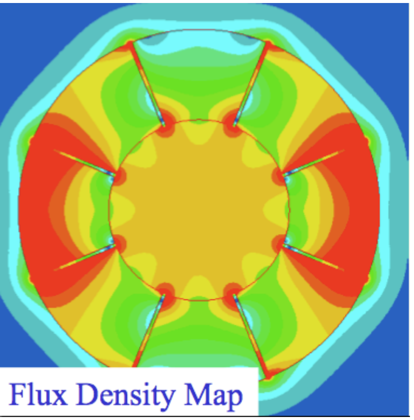

6.84166 m
3.0503 m
3.7913 m
2.7607 m
0.5 m
Magnified x10 =±10cm

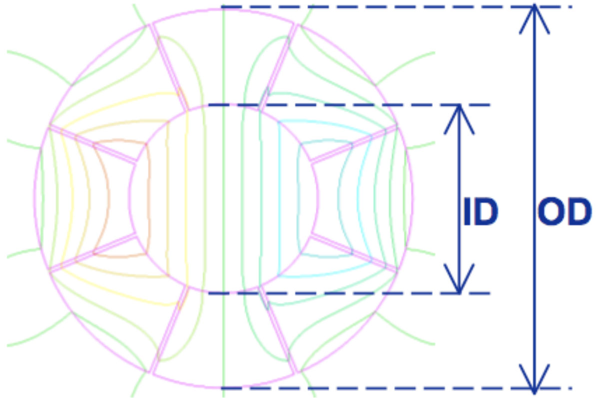
CRYO-COOLERS: reliable, maintenance free, easy to operate

4K Cryocooler Specification Chart

	Watts @ 50 Hz		Watts @ 60 Hz	
	1st Stage Capacity	2nd Stage Capacity	1st Stage Capacity	2nd Stage Capacity
RDK-101D	3.0 W @ 60 K	0.1 W @ 4.2 K	5.0 W @ 60 K	0.1 W @ 4.2 K
RDK-305D	15 W @ 40 K	0.4 W @ 4.2 K	20 W @ 40 K	0.4 W @ 4.2 K
RDK-205D	3.0 W @ 50 K	0.5 W @ 4.2 K	4.0 W @ 50 K	0.5 W @ 4.2 K
RDK-408D2	34 W @ 40 K	1.0 W @ 4.2 K	44 W @ 40 K	1.0 W @ 4.2 K
RDK-415D	35 W @ 50 K	1.5 W @ 4.2 K	45 W @ 50 K	1.5 W @ 4.2 K

NS-FFAG gantry with permanent magnets

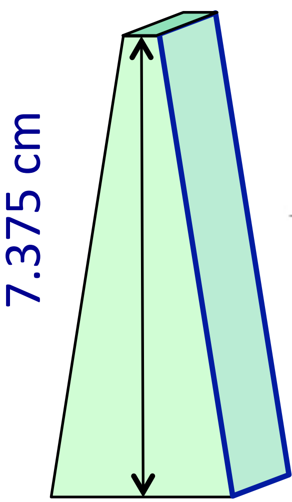


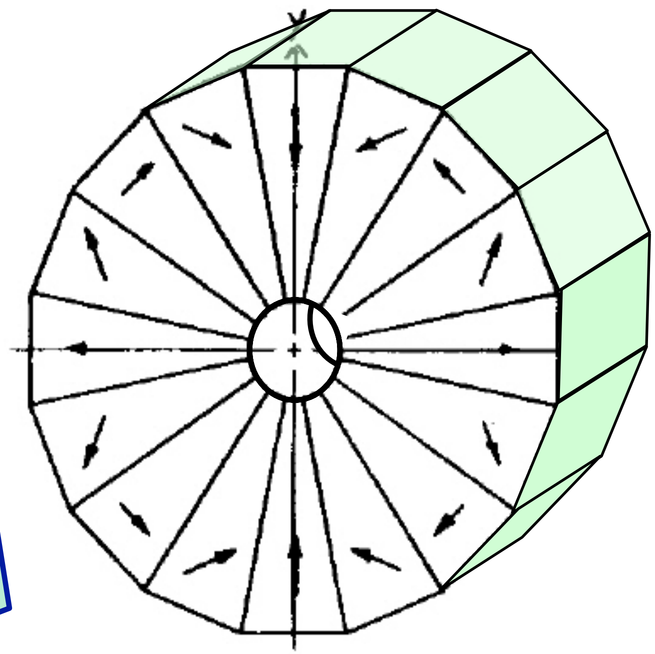


Halbach PM Dipole Structures:

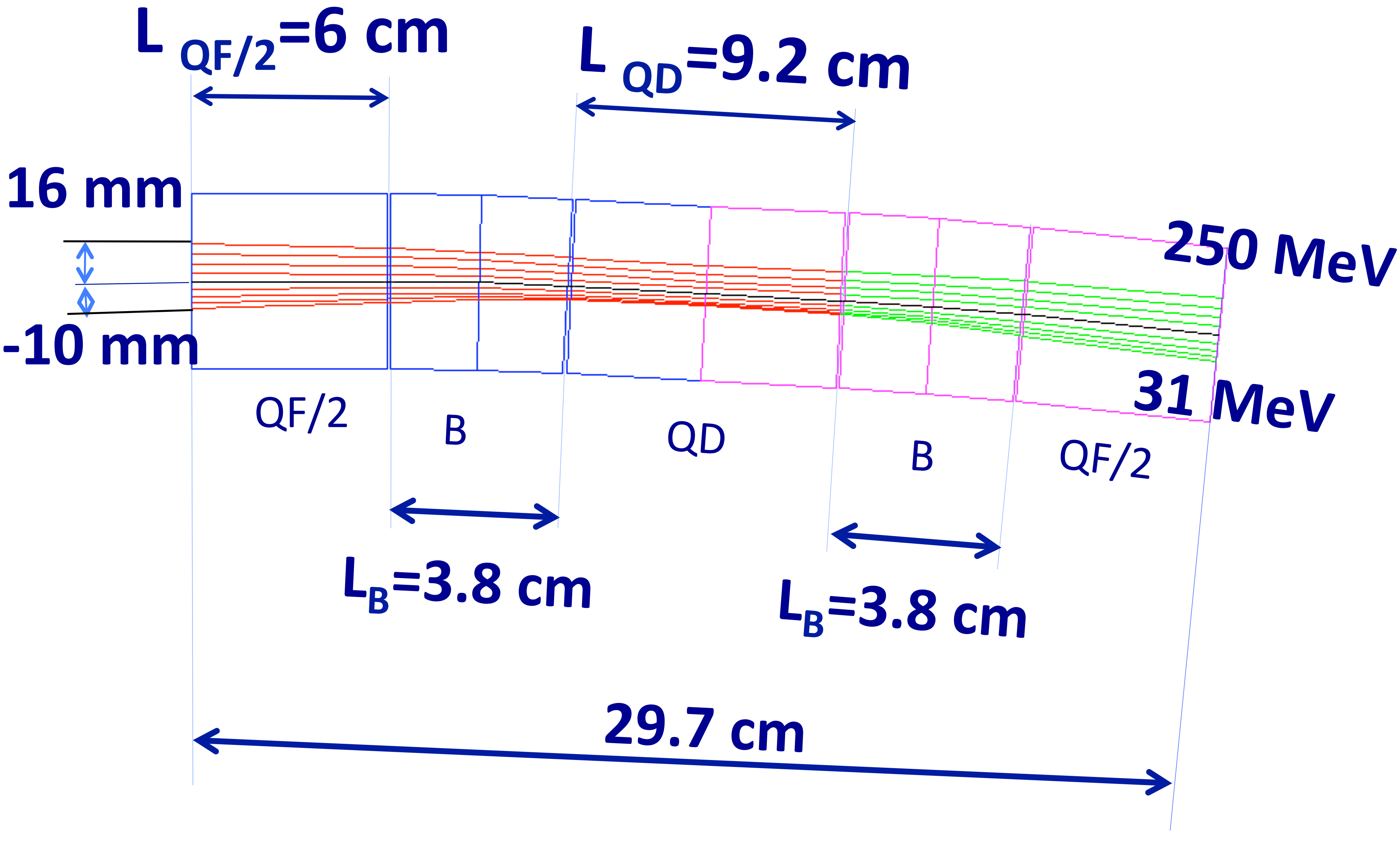
$$B_g = B_r \ln(OD/ID)$$

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

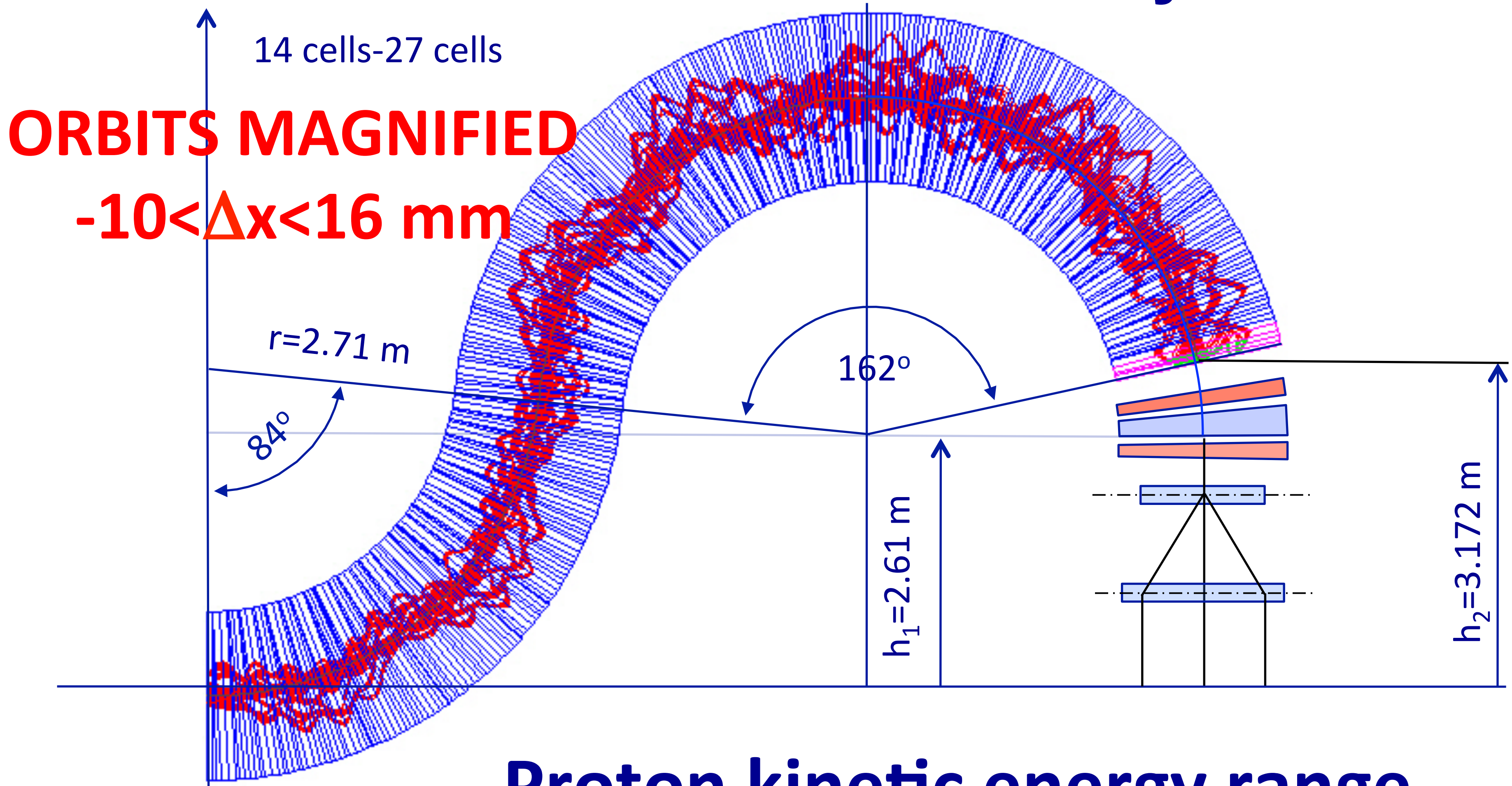




What is innovative? The extreme focusing



Permanent Halbach Magnet
NS-FFAG Proton Gantry



Proton kinetic energy range
30 – 250 MeV

SUMMARY:

1. NS-FFAG gantries provide transfer of carbon ions with $\Delta p/p = \pm$ 20% (**200-400 MeV – or - 100-200 MeV**) allowing **longitudinal scanning as fast as the front accelerator** can change the energy of the beam because the magnetic field is fixed for the required energy range
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. Triplet magnets do not need to be superconducting