

Small Large Momentum Acceptance Gantries for Proton and Carbon Cancer Therapy

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OUTLINE:

- Requests and Challenges
- Introduction: NS-FFAG?

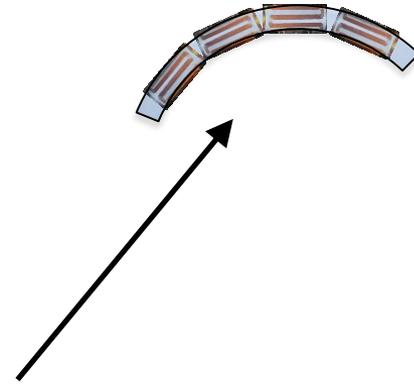
- Proton Gantries
- Permanent Magnet Gantry

- Carbon Gantries
- Proposal to the DOE

- Summary: smaller, less weight, simpler, large $\delta p/p$

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. 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). 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 (Virtual–Source–to patient distance) **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** smaller BNL superconducting magnets.

Range of momentum = range kinetic energy

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

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

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

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

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

$$proton \ ke_{\max} = 250 \text{ MeV}$$

$$p_{\max} = 729.13 \text{ MeV} / c$$

$$proton \ ke_{\min} = 35 \text{ MeV}$$

$$p_{\max} = 258.7 \text{ MeV} / c$$

← Permanent proton gantry

$$proton \ ke_{cen} = 155.7 \text{ MeV}$$

$$p_{cent} = 562. \text{ MeV} / c$$

$$- 54\% \leq \frac{\Delta p}{p} \leq 0.30 \%$$

$$E_{kcenter} = 291.73 \text{ MeV} / u$$

$$p_{center \ carbon} = 792.848 \text{ MeV} / c / u$$

$$E_{kmin} = 195.44 \text{ MeV} / u$$

$$p_{\min \ carbon} = 634.28 \text{ MeV} / c / u$$

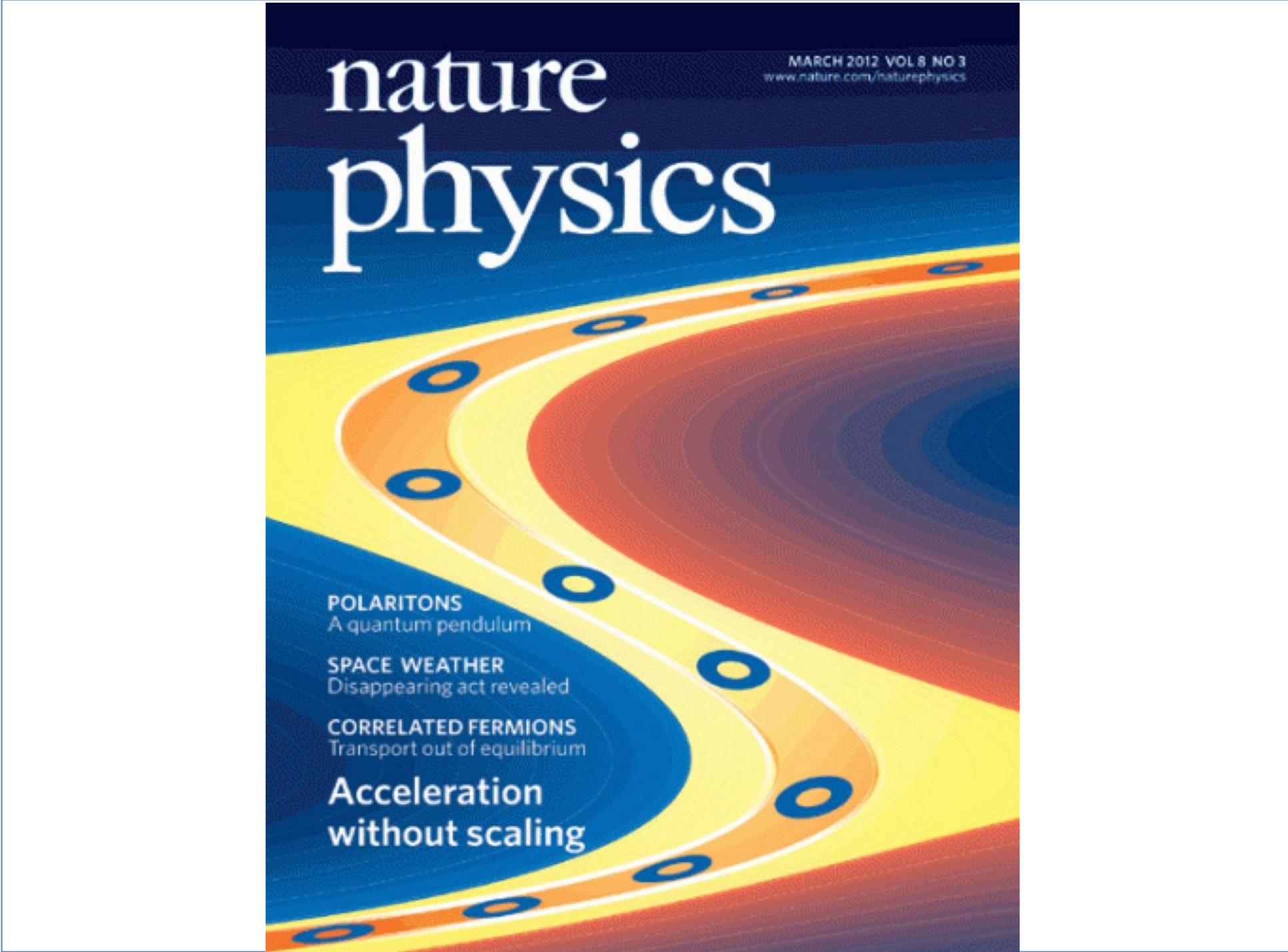
← Superconducting carbon/proton gantry

$$E_{kmax} = 400.00 \text{ MeV} / u$$

$$p_{\min \ carbon} = 951.42 \text{ MeV} / c / u$$

$$- 20\% \leq \frac{\Delta p}{p} \leq 0.20 \%$$

nature physics



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www.nature.com/naturephysics

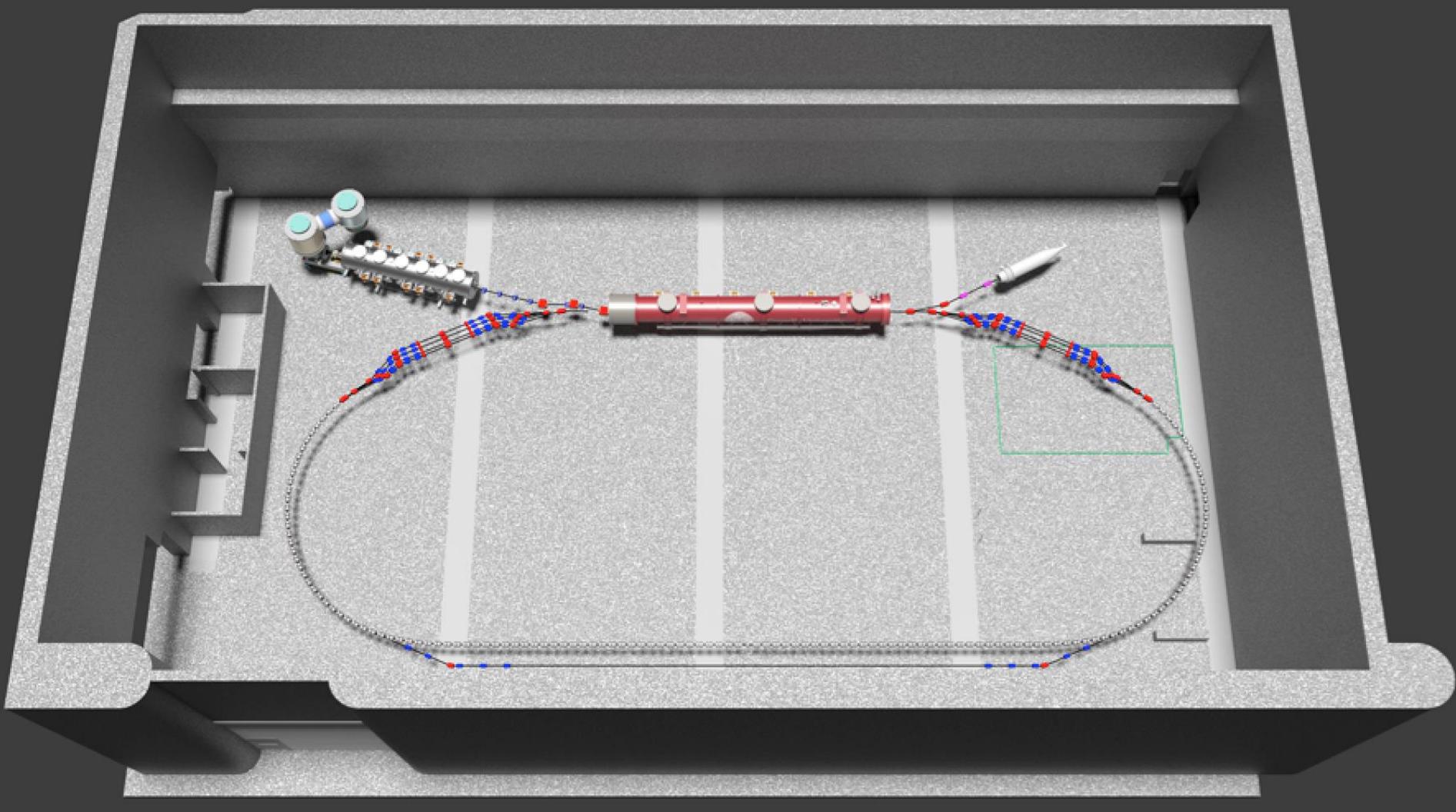
POLARITONS
A quantum pendulum

SPACE WEATHER
Disappearing act revealed

CORRELATED FERMIONS
Transport out of equilibrium

**Acceleration
without scaling**

A new Energy Recovery Linac with the **Non-Scaling Fixed Field Alternating Gradient arcs and straight sections** is to be built at Cornell University Physics Department an eRHIC prototype

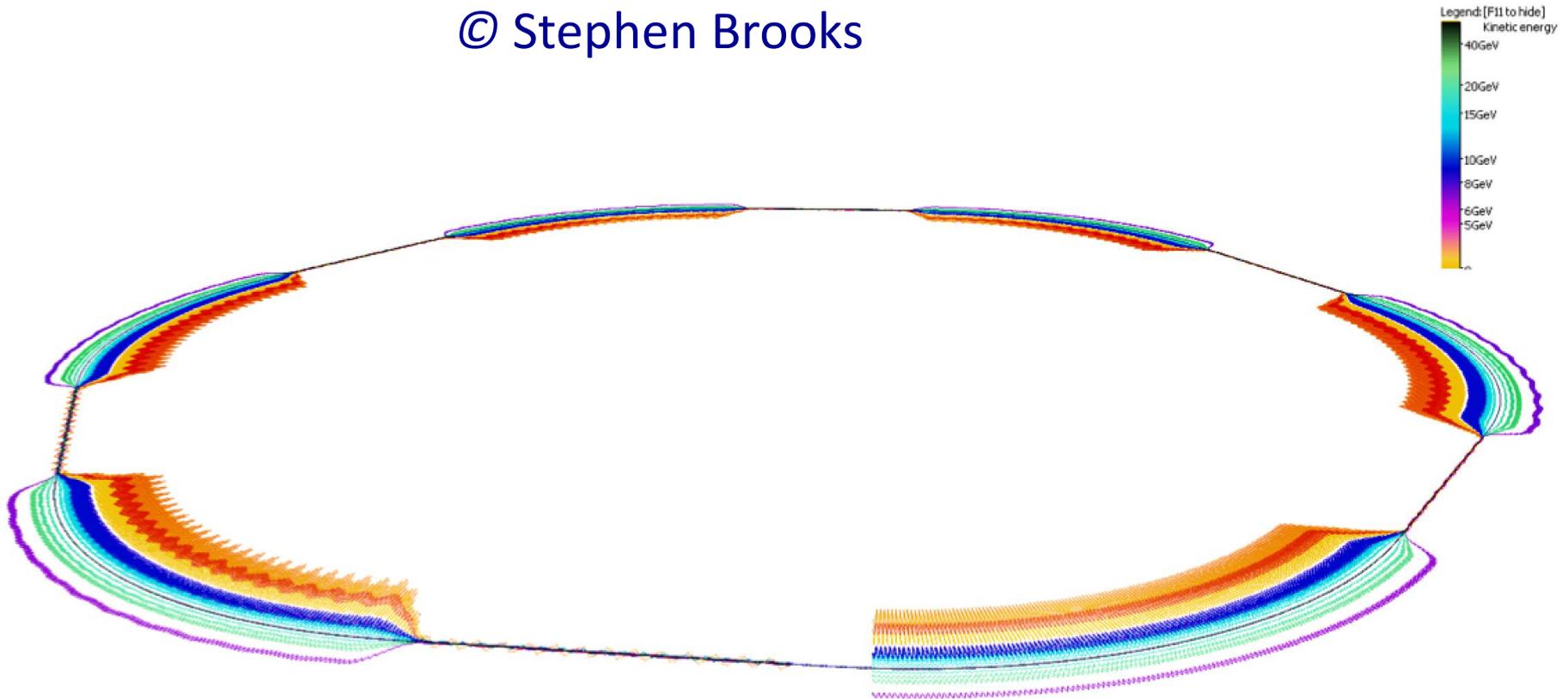


FRUITAGE

eRHIC FFAG Rings in Perspective

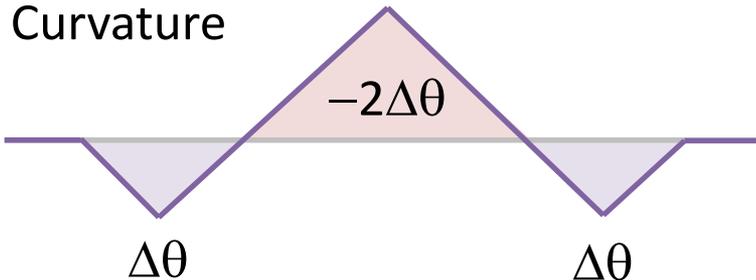
Orbits exaggerated transversely 5000x, shape of hexagonal RHIC is evident

© Stephen Brooks

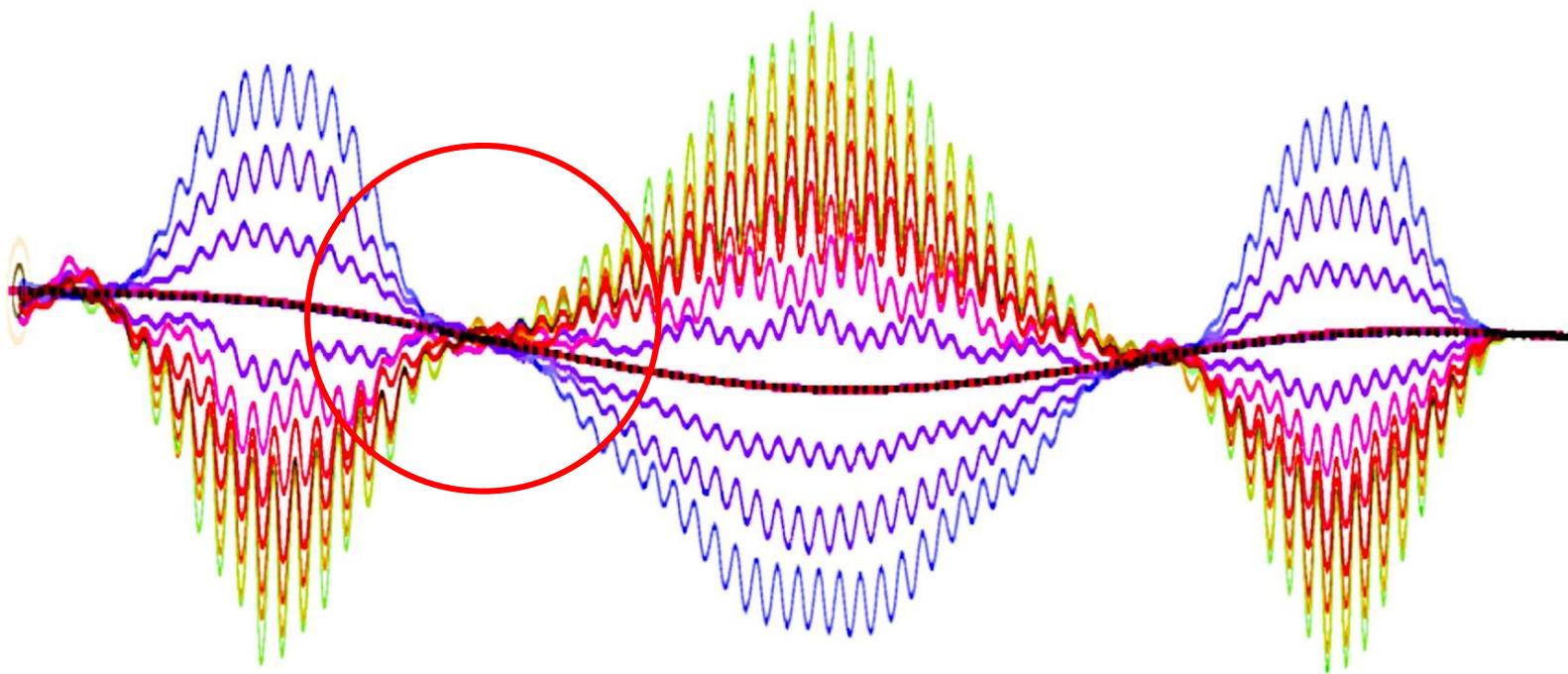
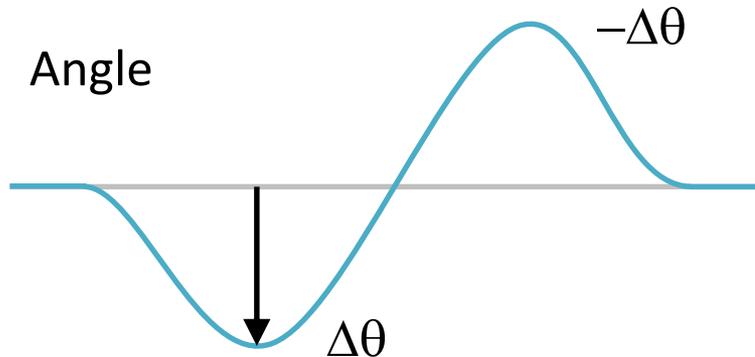


Detector Bypass Scheme: a Flexible FFAAG

Curvature

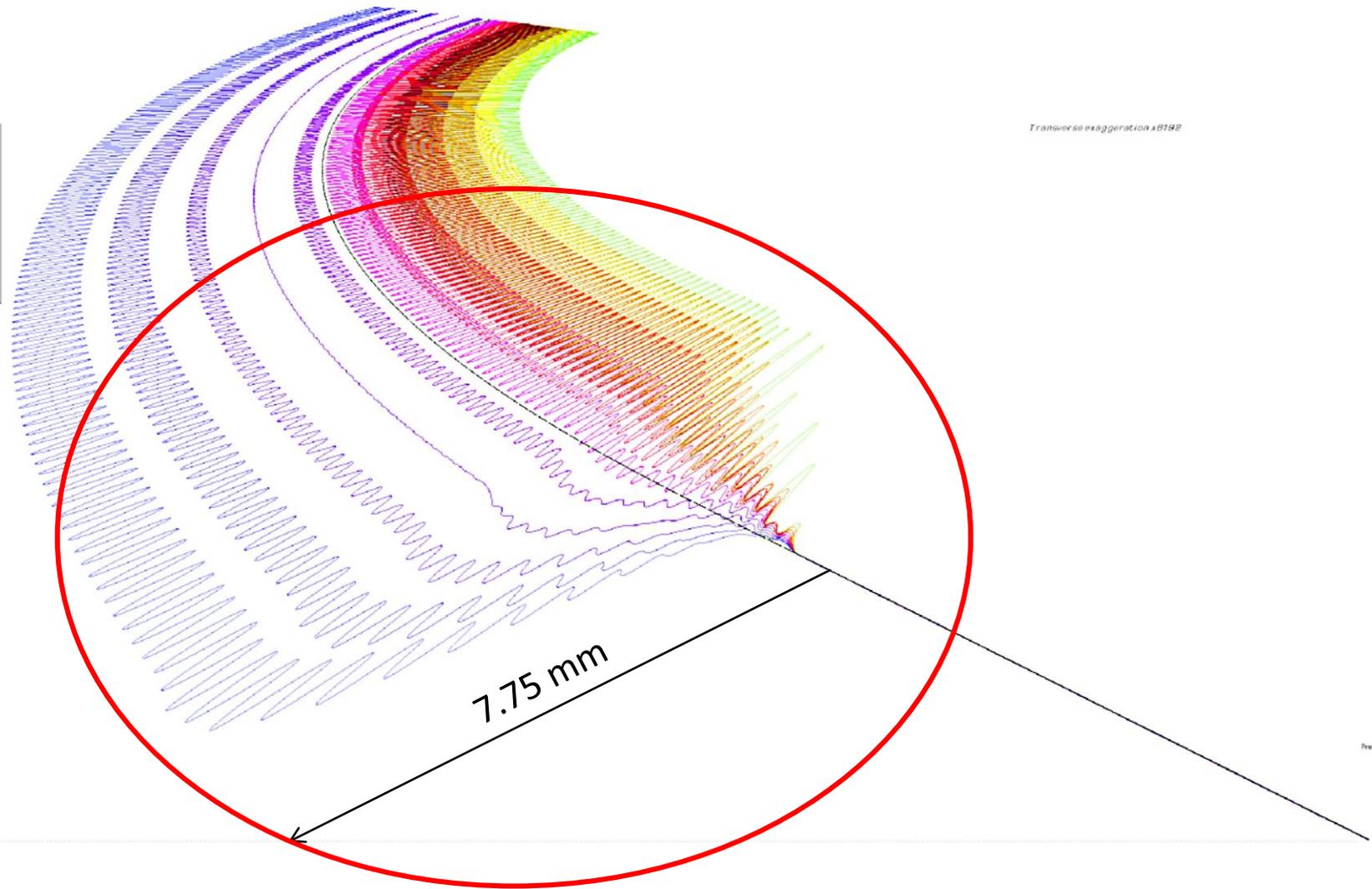
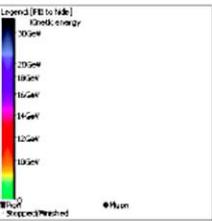


Angle

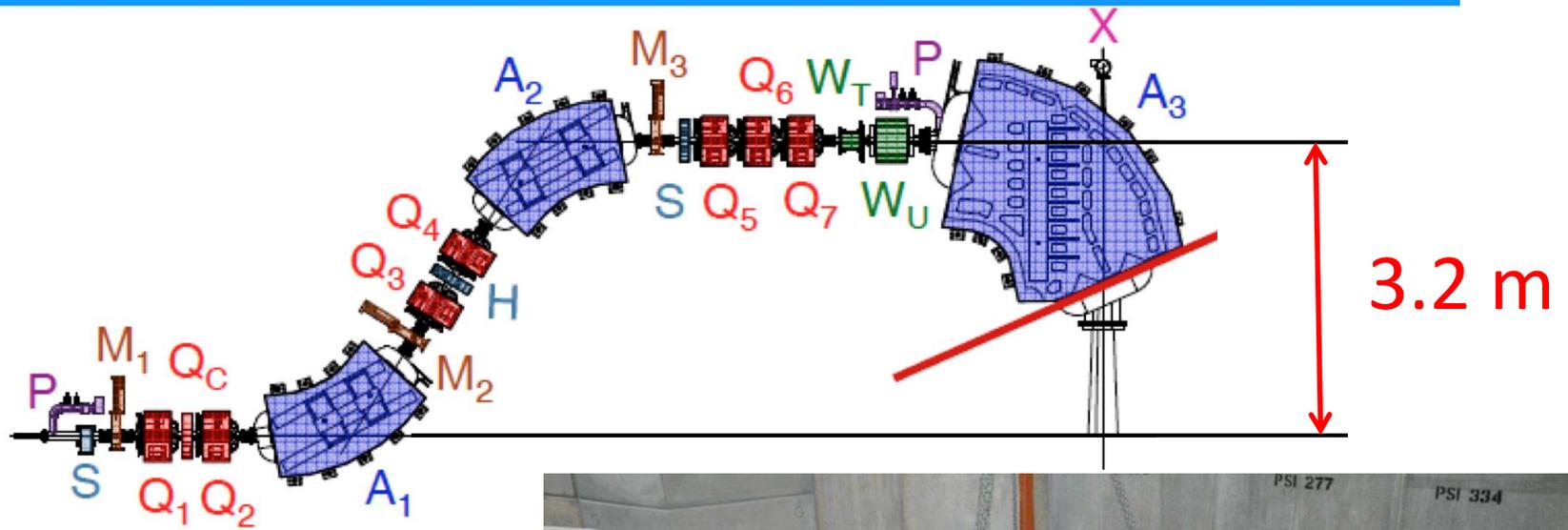


Merging FFAG arcs to the straight section in eRHIC

t = 2.85 us Beam pack size: 0.026% otherwise lost: 100.00% Wrong way: 0.00% eRHIC/0414_resp Transfer rate: 401.011 (21.0000) Particle size: 30720 (0.0004000) Results database: 0 bytes (0 bytes since last send) View: Manual, Y (auto) [PAUSE]



The state of the art proton gantry at PSI



SAD – SOURCE-TO-AXIS-DISTANCE VIRTUAL Source to Patient Distance



US009095705B2

(12) **United States Patent**
Trbojevic

(10) **Patent No.:** **US 9,095,705 B2**
(45) **Date of Patent:** **Aug. 4, 2015**

(54) **SCANNING SYSTEMS FOR PARTICLE
CANCER THERAPY**

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(72) Inventor: **Dejan Trbojevic,** Wading River, NY
(US)

(73) Assignee: **Brookhaven Science Associates, LLC,**
Upton, NY (US)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/099,061**

(22) Filed: **Dec. 6, 2013**

(65) **Prior Publication Data**
US 2014/0163301 A1 Jun. 12, 2014

(56) **References Cited**

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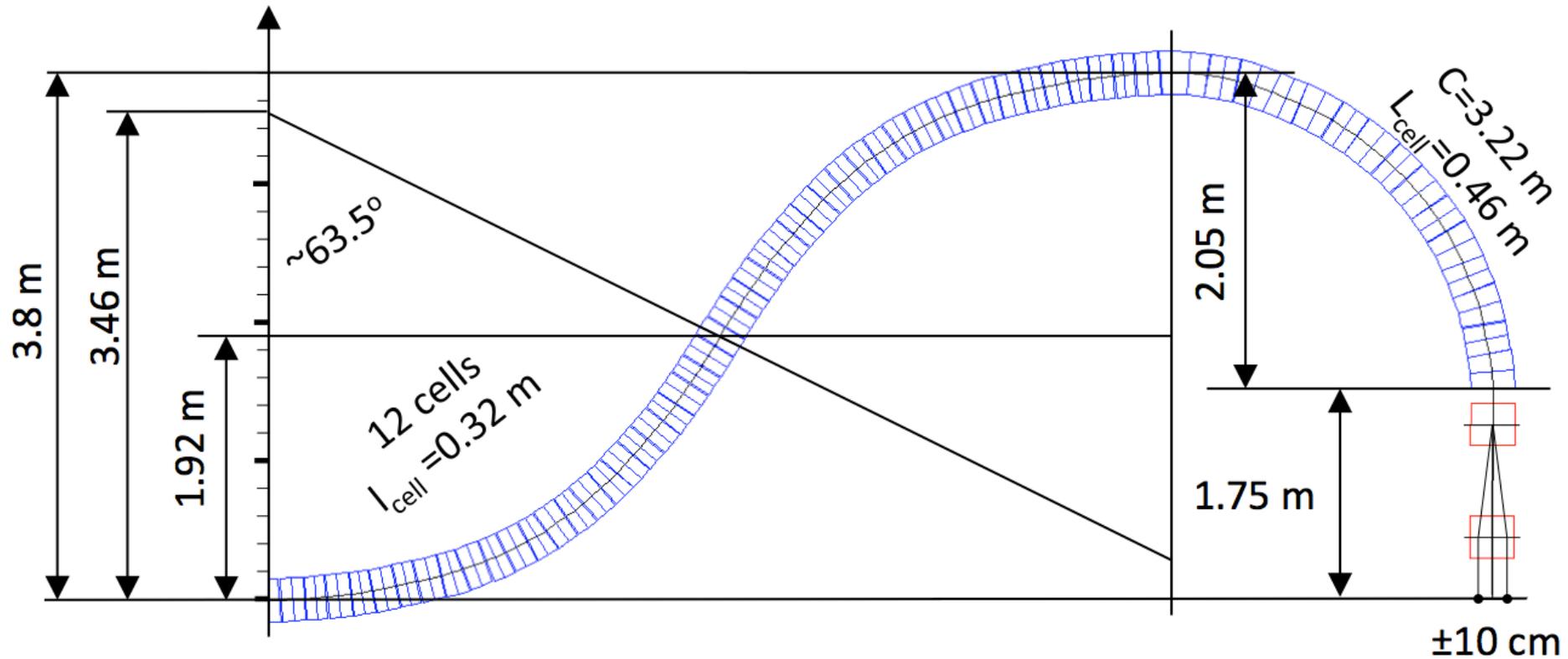
(Continued)

Primary Examiner — Nicole Ippolito
(74) *Attorney, Agent, or Firm* — Dorene M. Price

(57) **ABSTRACT**

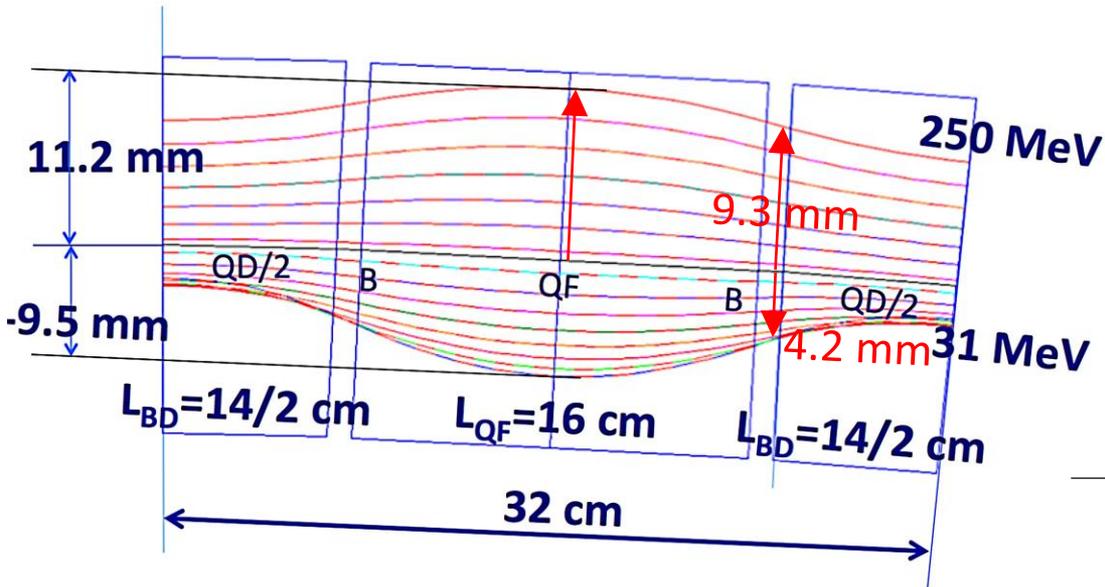


Permanent Halbach Magnet NS-FFAG Proton Gantry 35-250 MeV

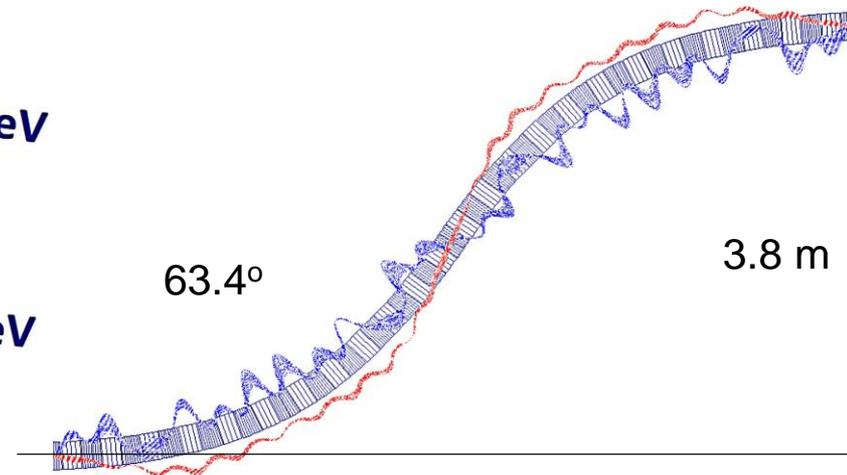


Halbach Permanent Magnet Gantry

The Basic Cell

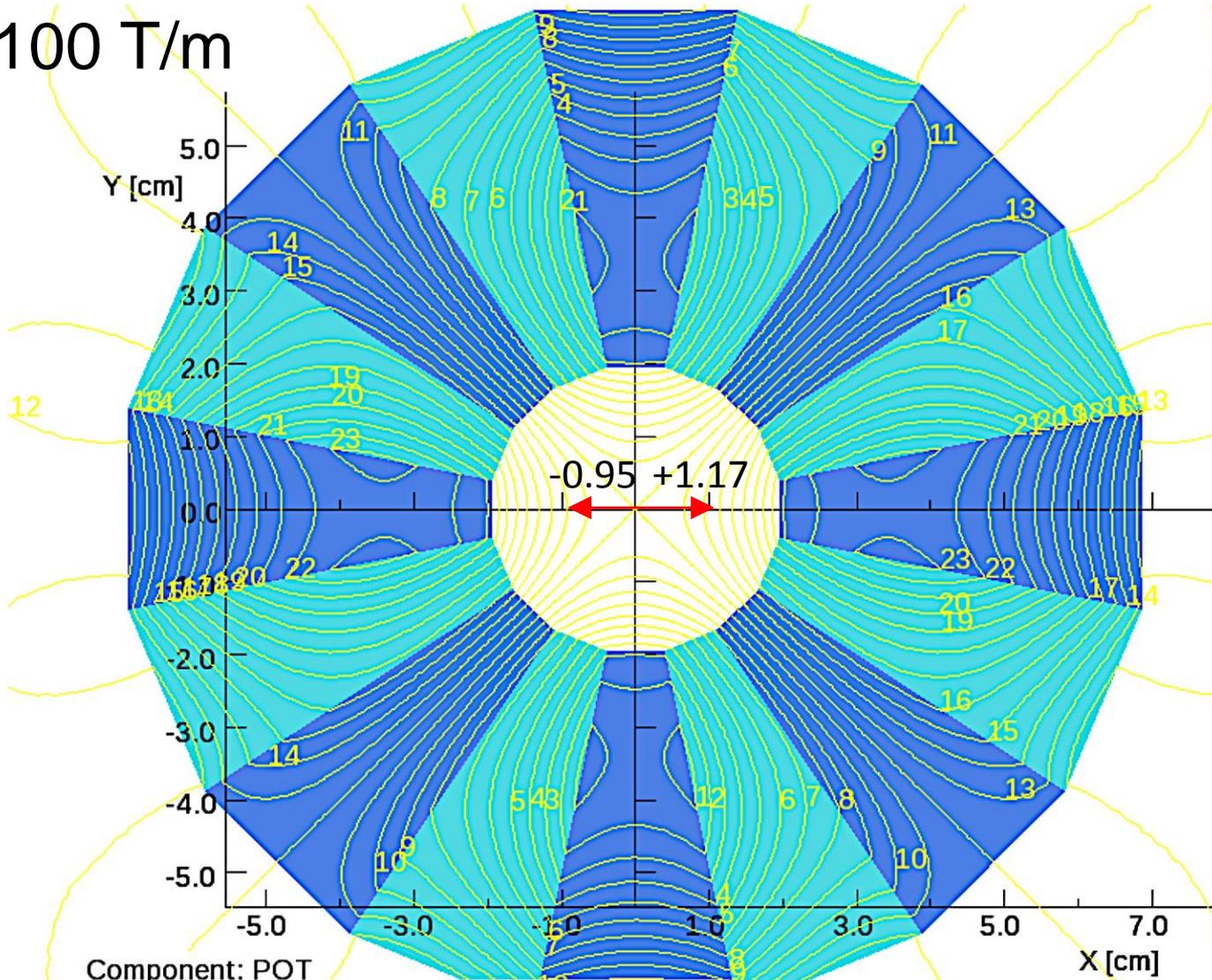


Magnified Orbit Offset for 35 MeV – 250 MeV protons



Gantry Halbach Magnet Design (Nick Tsoupas –BNL)

G=100 T/m



Component: POT
 Minimum: -0.022, Maximum: 0.022, Interval: 0.002

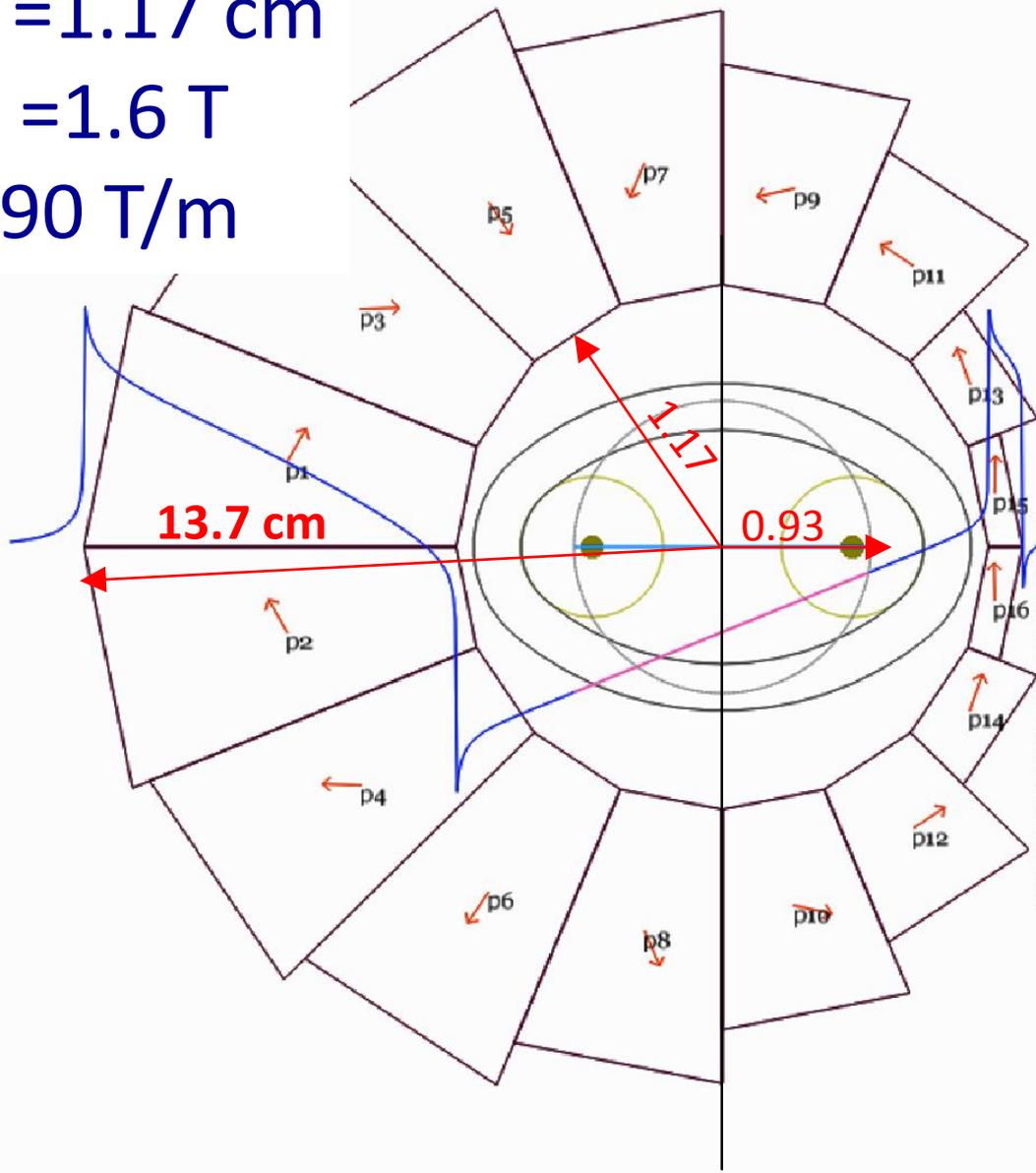
UNITS	
Length	: cm
Magn Flux Density	: T
Magnetic Field	: A/m
Magn Vector Pot	: Wb/m
Current Density	: A/m ²
Conductivity	: S/m
Power	: W
Force	: N
Energy	: J
Mass	: kg
Pressure	: Pa

MODEL DATA	
/home0/tsoupas/opera_files/CORNELL_100Tpm/2d_model/Quad_93Tpm_R1=2p0_R2=7p0_1p4T.st	
Quadratic elements	
XY symmetry	
Vector potential	
Magnetic fields	
Static solution	
Scale factor: 1.0	
29354 elements	
59109 nodes	
48 regions	

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$R_{\text{outside}} = 13.7 \text{ cm}$
 $R_{\text{inside}} = 1.17 \text{ cm}$
 $B_{\text{dipole}} = 1.6 \text{ T}$
 $G_D = 90 \text{ T/m}$



- a[0] = 0.000265591
- a[1] = 0.0141988
- a[2] = -0.0103829
- a[3] = 0.029506
- a[4] = -0.0588494
- a[5] = 0.0397233
- a[6] = -0.0930094
- a[7] = -0.0210847
- a[8] = -0.0468514
- a[9] = -0.109958
- a[10] = 0.0777202
- a[11] = -0.116953
- a[12] = 0.15386
- a[13] = 0.00472071
- a[14] = 0.0800213
- a[15] = 0.141447

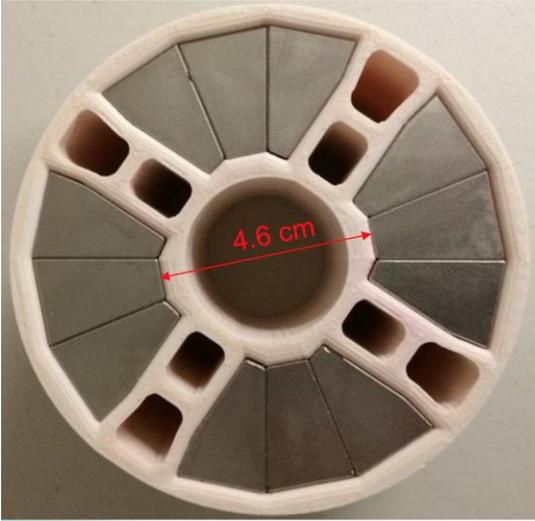
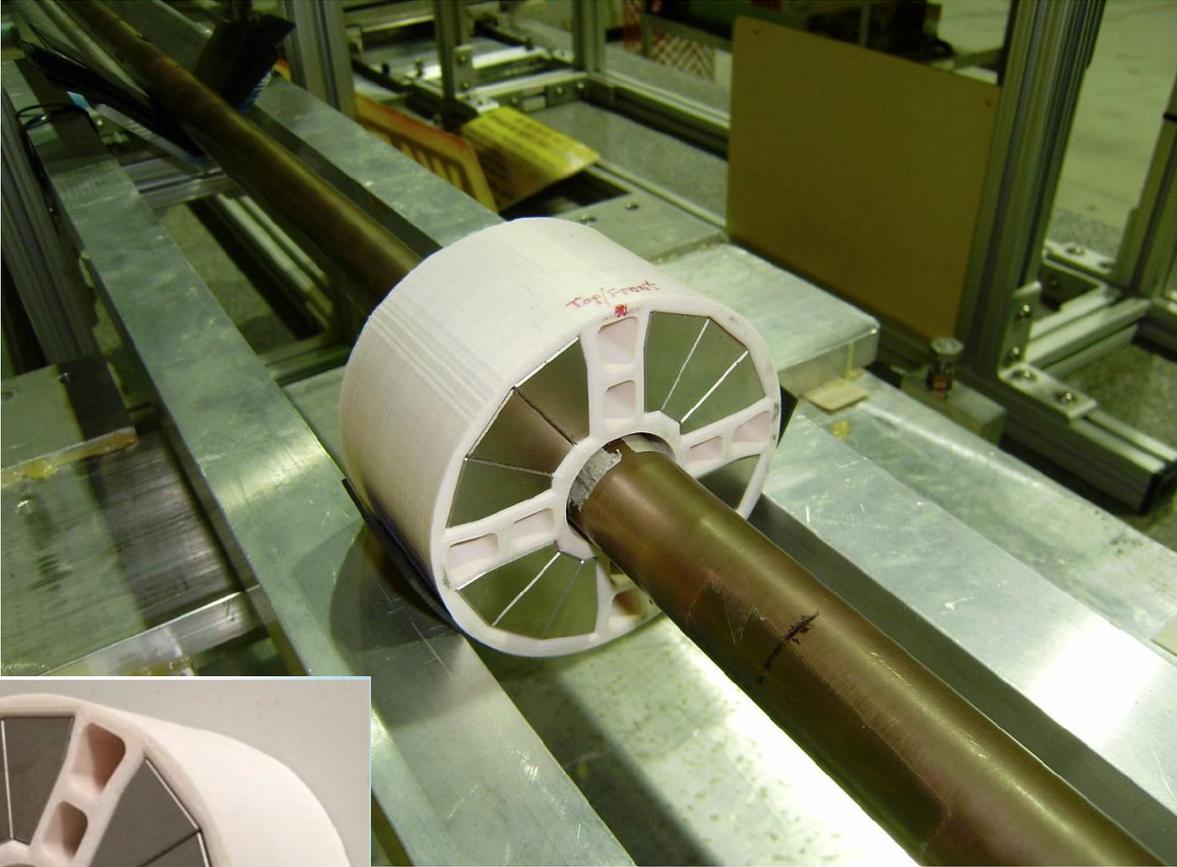
(0.065972
 $B = (-0.00$
 $|B| = 0.006$
 $\text{curl } B = 2.$

Amplitudes at 0.0125 m (in Tesla) Amplitudes in units: (norm=709

2-pole: -0.48471 T	2-skew: 0.000000 T	2-pole: 0.000000 T	2-skew: 0.000000 T
4-pole: 0.343663 T	4-skew: -0.000000 T	4-pole: 0.000000 T	4-skew: 0.000000 T
6-pole: -3.76595e-007 T	6-skew: 0.000000 T	6-pole: 0.000000 T	6-skew: 0.000000 T
8-pole: -4.79037e-007 T	8-skew: 0.000000 T	8-pole: 0.000000 T	8-skew: 0.000000 T
10-pole: -2.59943e-007 T	10-skew: 0.000000 T	10-pole: 0.000000 T	10-skew: 0.000000 T
12-pole: -2.06448e-008 T	12-skew: 0.000000 T	12-pole: 0.000000 T	12-skew: 0.000000 T
14-pole: 6.53401e-008 T	14-skew: 0.000000 T	14-pole: 0.000000 T	14-skew: 0.000000 T
16-pole: -5.67613e-008 T	16-skew: 0.000000 T	16-pole: 0.000000 T	16-skew: 0.000000 T
18-pole: 1.13071e-007 T	18-skew: 0.000000 T	18-pole: 0.000000 T	18-skew: 0.000000 T
20-pole: 5.20635e-008 T	20-skew: 0.000000 T	20-pole: 0.000000 T	20-skew: 0.000000 T
22-pole: -1.27811e-006 T	22-skew: 0.000000 T	22-pole: 0.000000 T	22-skew: 0.000000 T
24-pole: 7.21536e-007 T	24-skew: 0.000000 T	24-pole: 0.000000 T	24-skew: 0.000000 T
26-pole: 3.59029e-006 T	26-skew: 0.000000 T	26-pole: 0.000000 T	26-skew: 0.000000 T
28-pole: 4.61009e-006 T	28-skew: 0.000000 T	28-pole: 0.000000 T	28-skew: 0.000000 T
30-pole: 3.15269e-006 T	30-skew: 0.000000 T	30-pole: 0.000000 T	30-skew: 0.000000 T
32-pole: -1.67342e-017 T	32-skew: 0.000000 T	32-pole: 0.000000 T	32-skew: 0.000000 T
34-pole: -4.24561e-006 T	34-skew: 0.000000 T	34-pole: 0.000000 T	34-skew: 0.000000 T



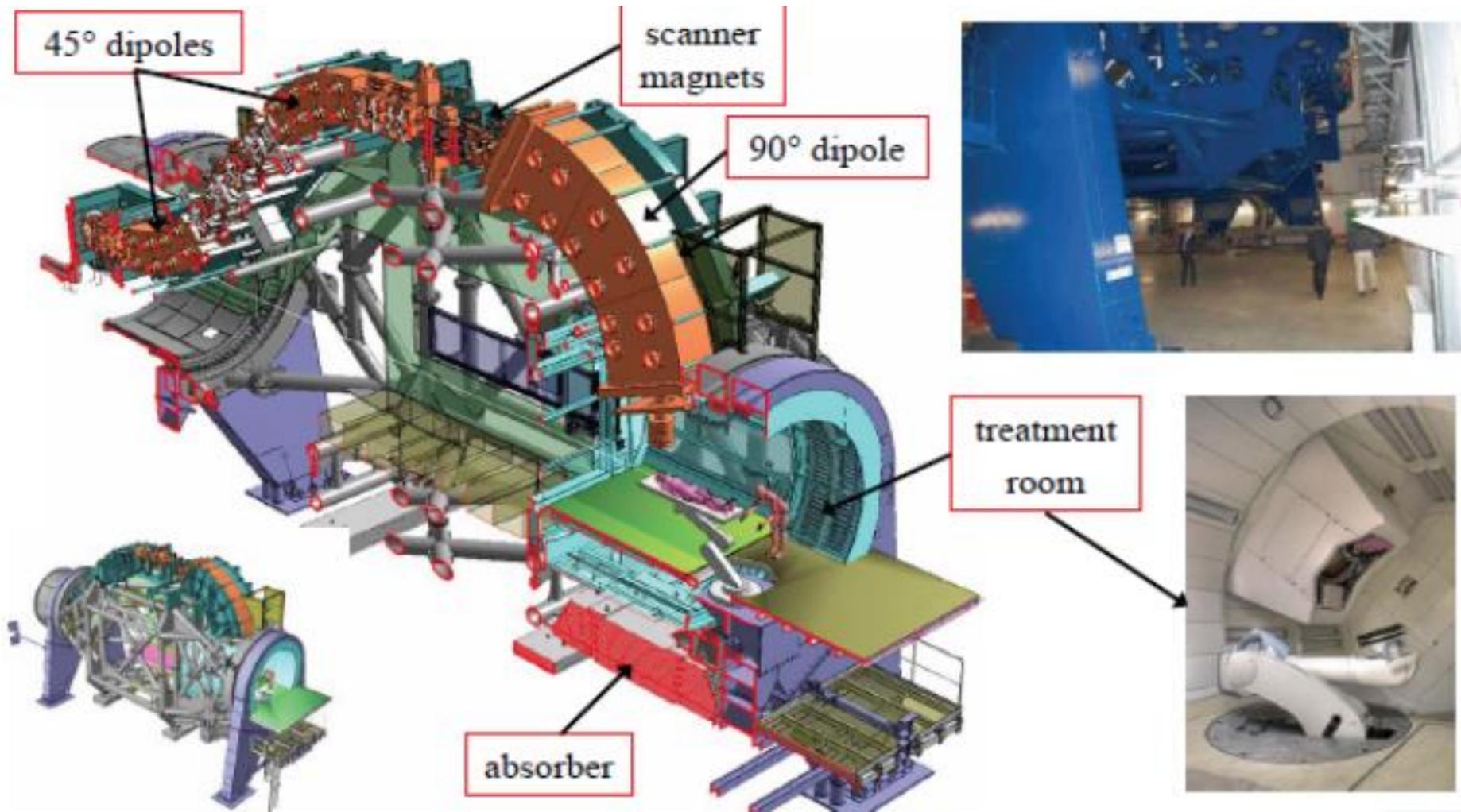
Modified Halbach magnets for BNL eRHIC

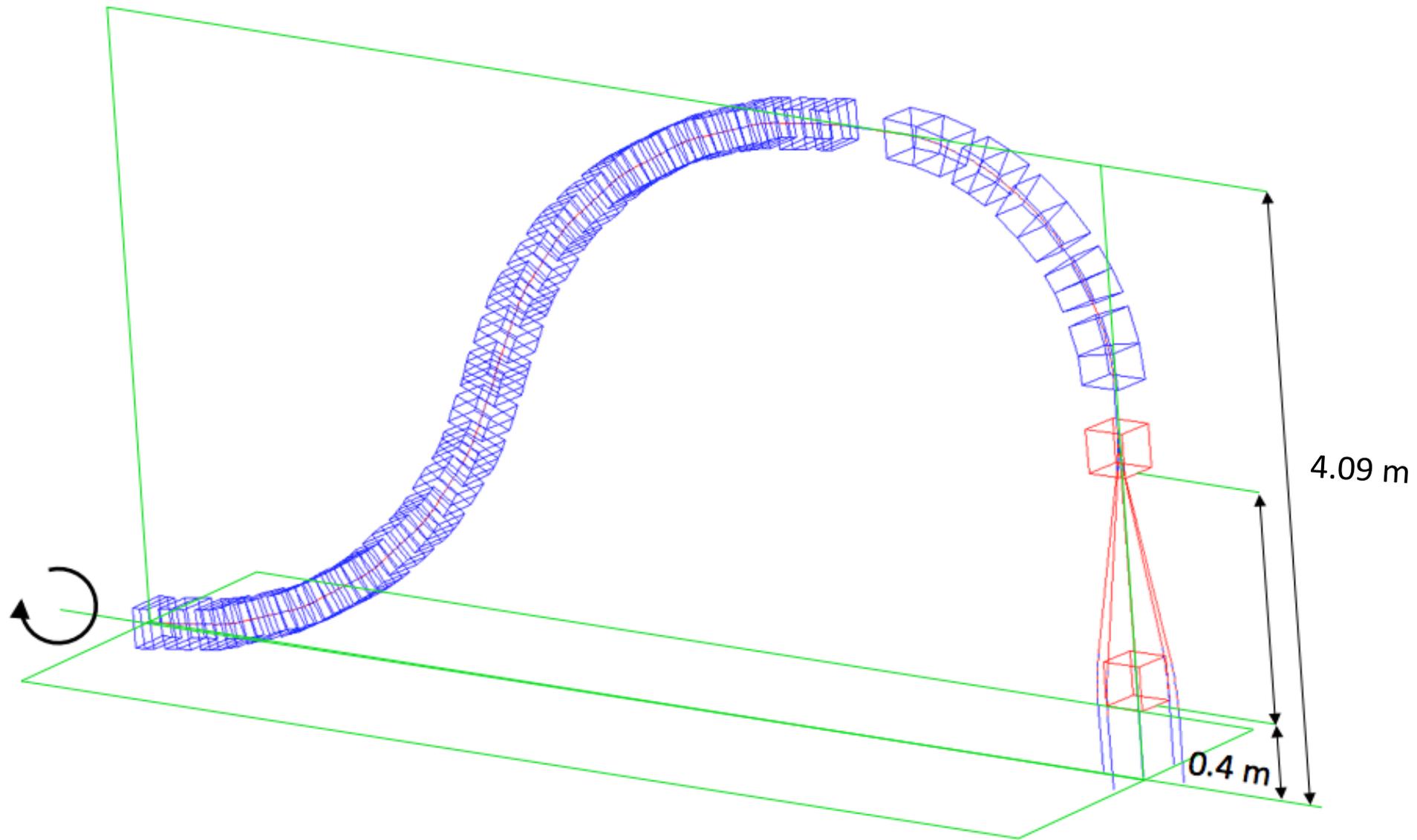


State of the art C-gantry at Heidelberg

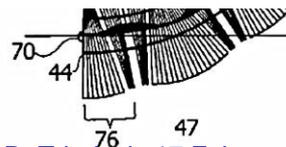
Weight of the transport components – 135 tons

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

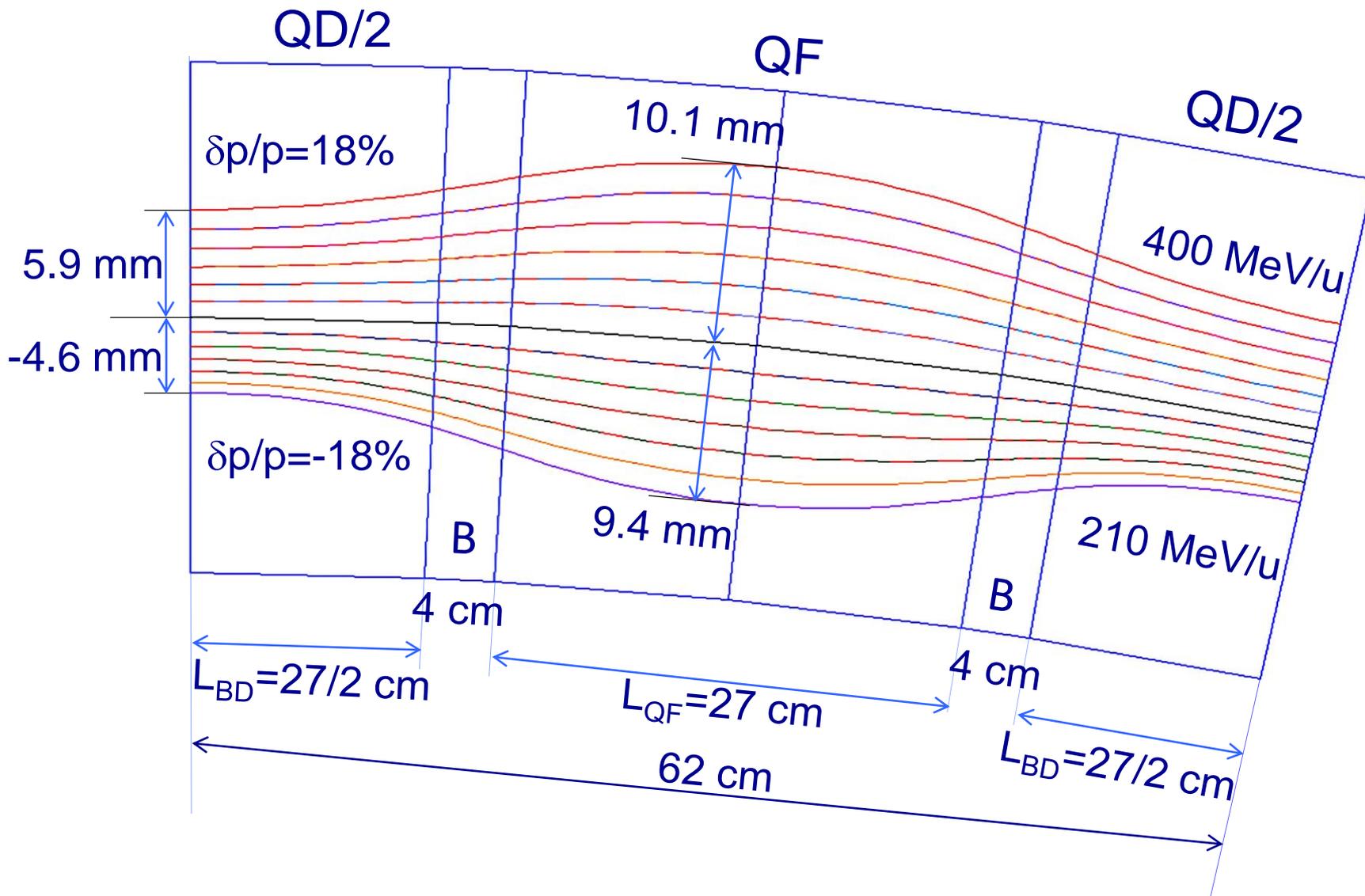




Superconducting magnets

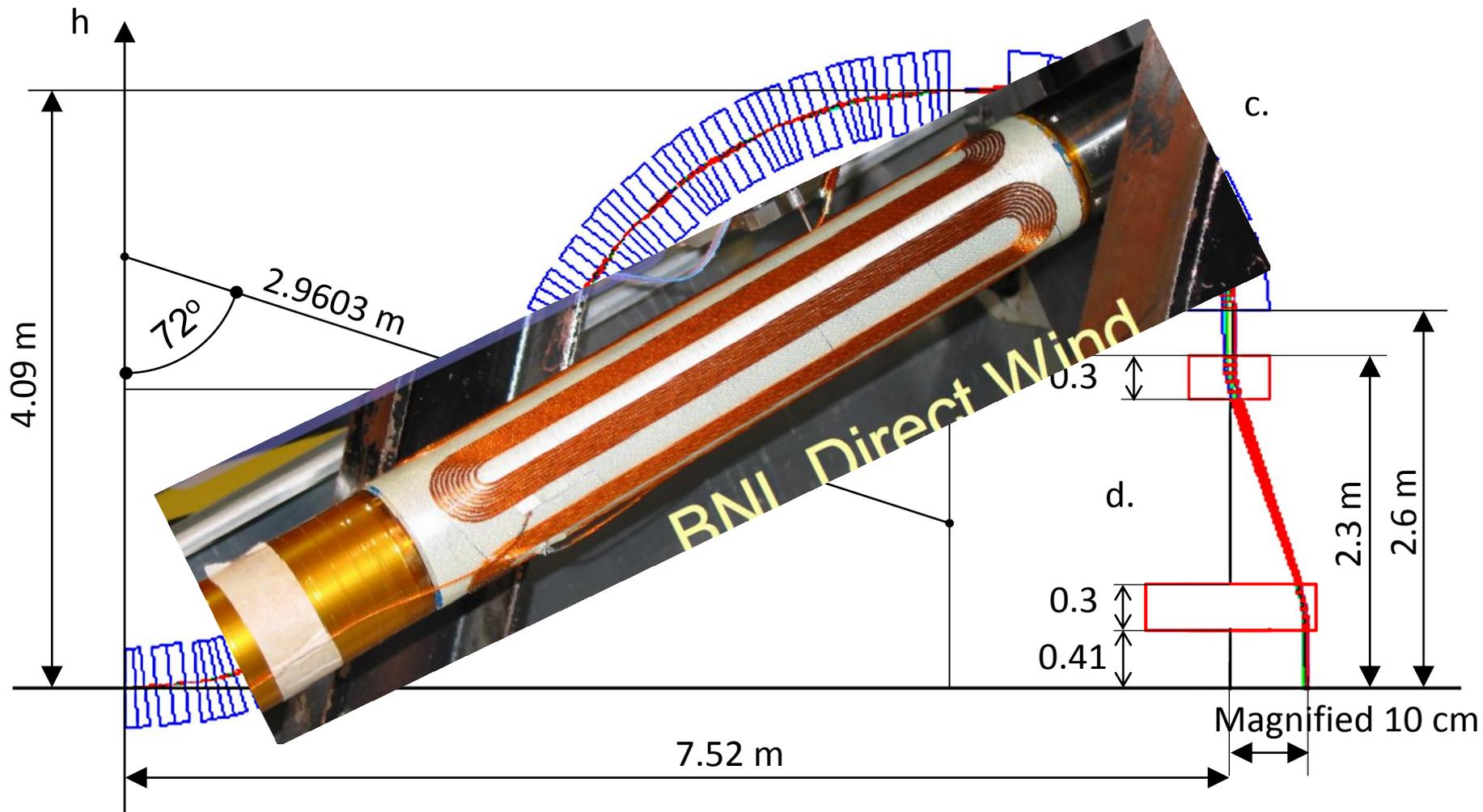


Very strong focusing Basic Cell

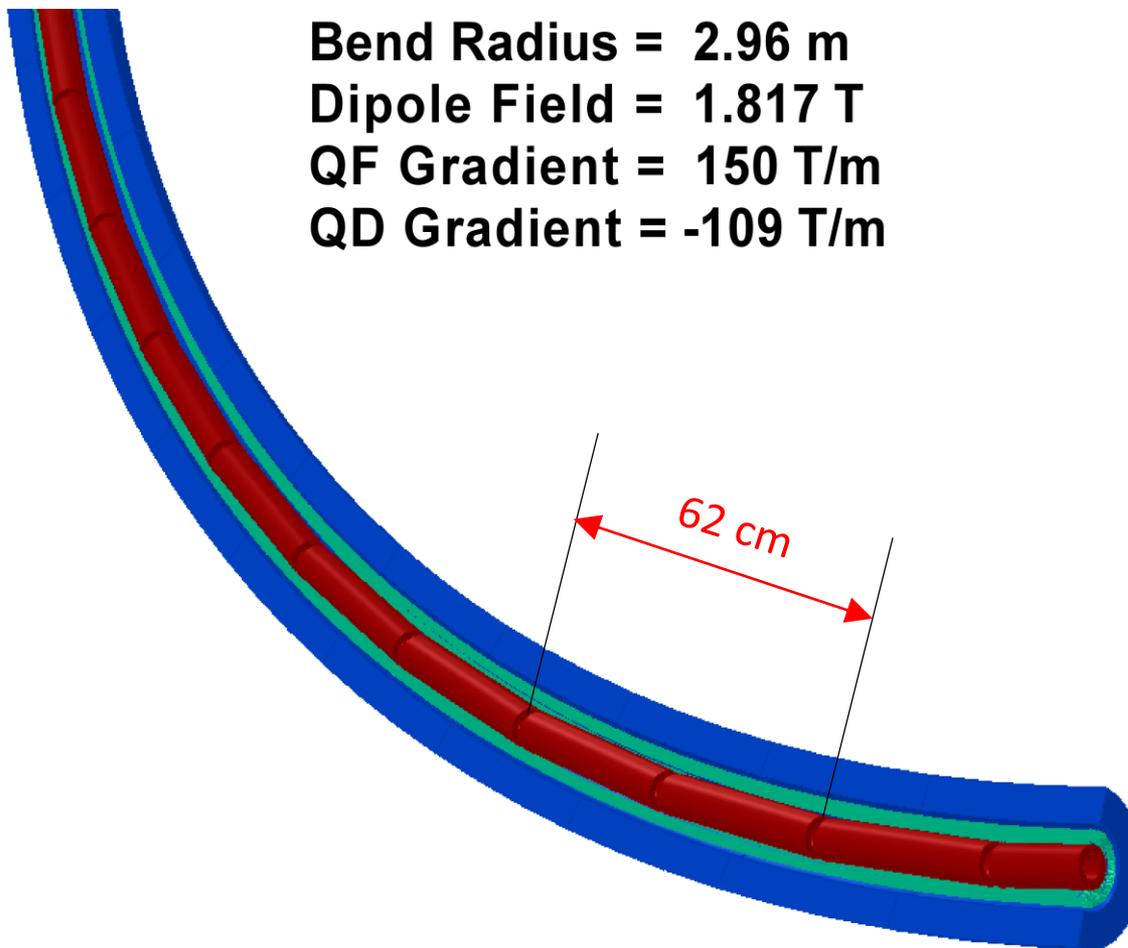


Reducing the size and weight from:

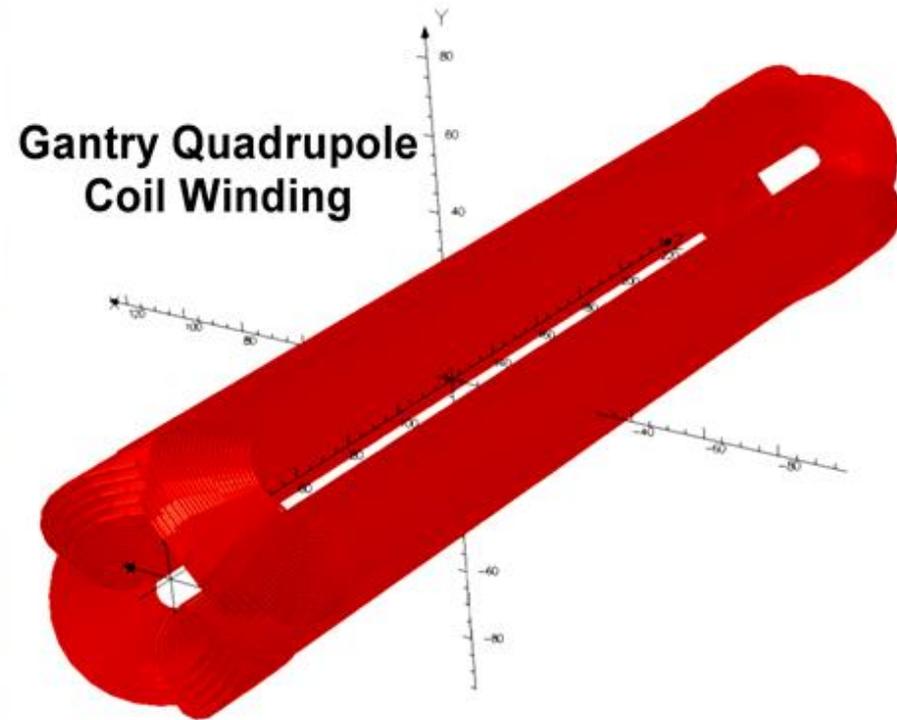
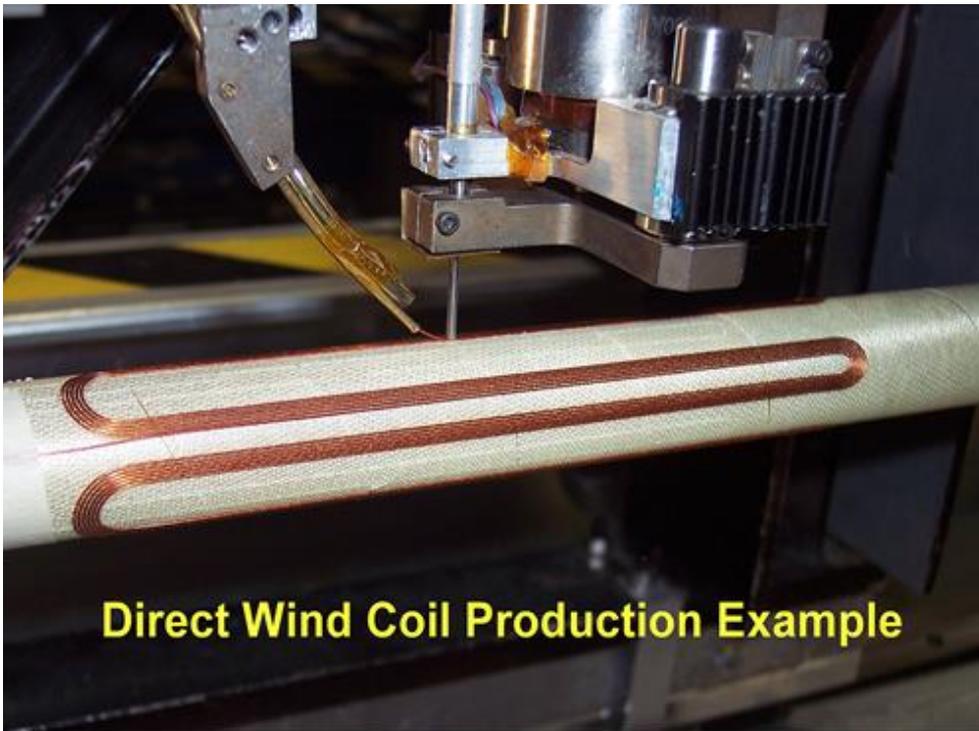
135 tons \rightarrow to 3 tons



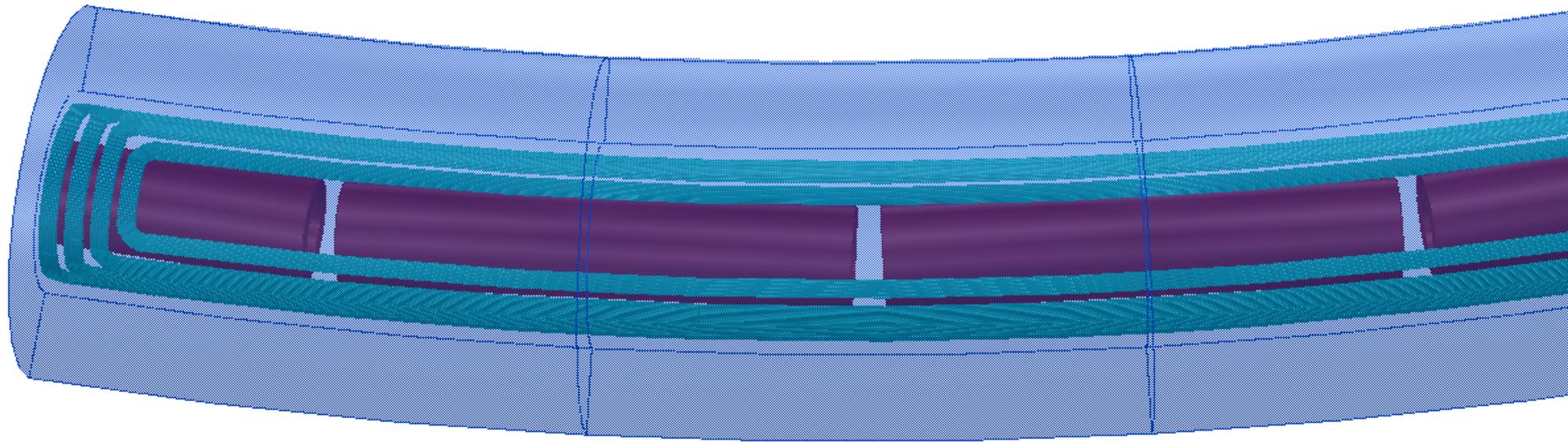
THE PROPOSAL FOR SUPERCONDUCTING CARBON/PROTON GANTRY



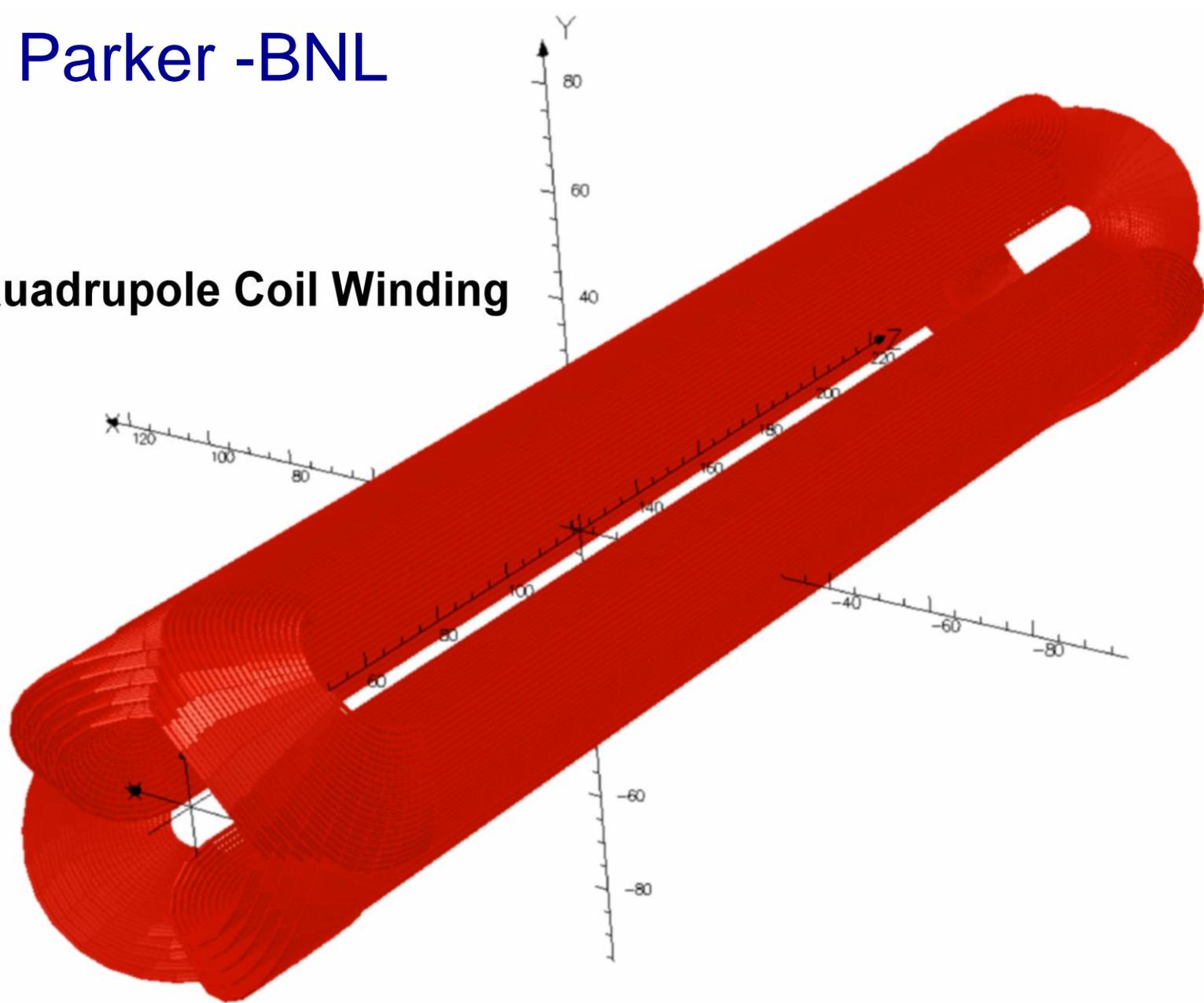
Tools and quadrupole windings (Brett Parker – BNL)



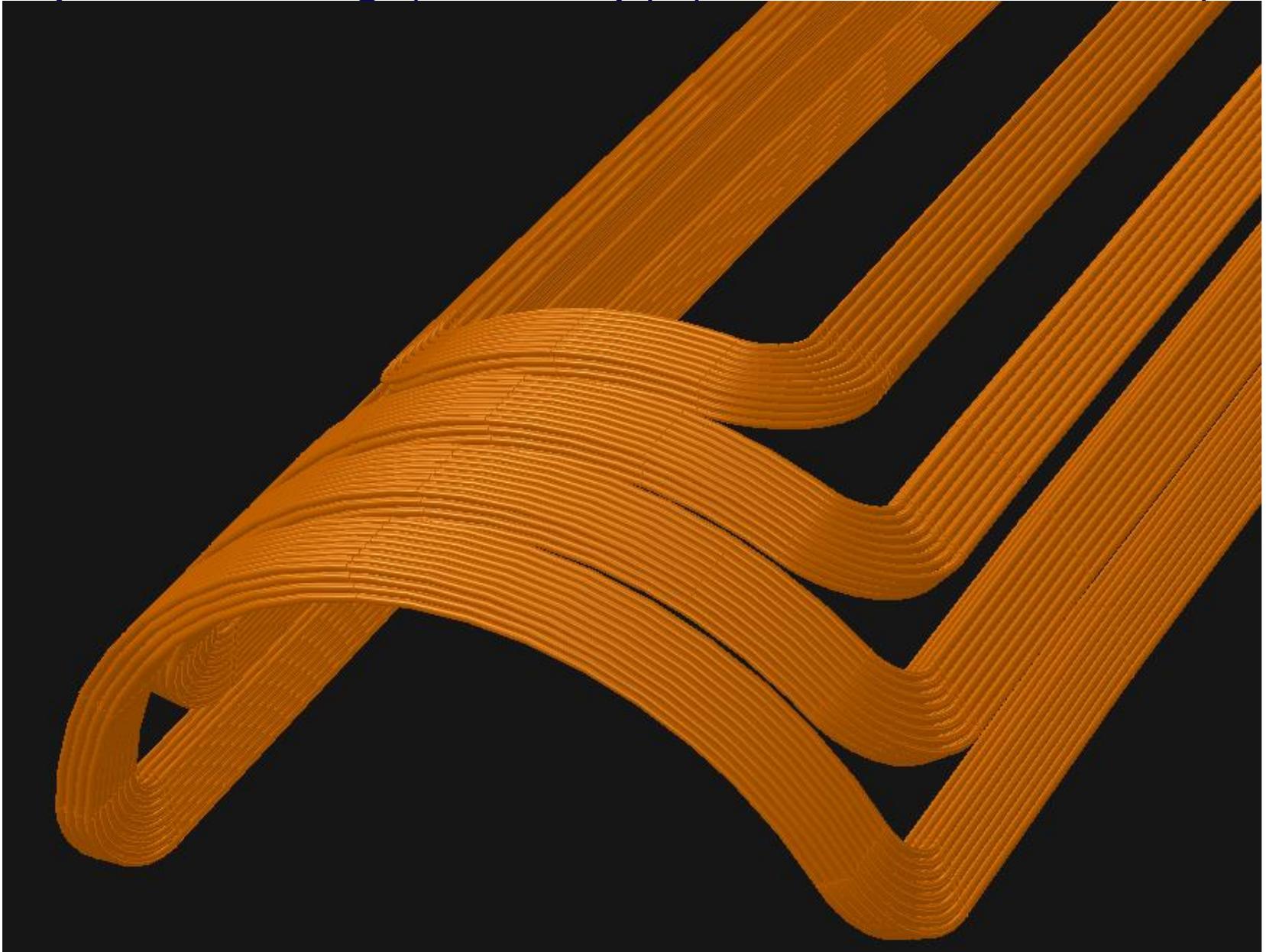
Achromatic Part of the Superconducting Gantry (Brett Parker – BNL)



Quadrupole Coil Winding



Dipole winding (close-up) (Brett Parker – BNL)



Magnetic field of the Superconducting Gantry

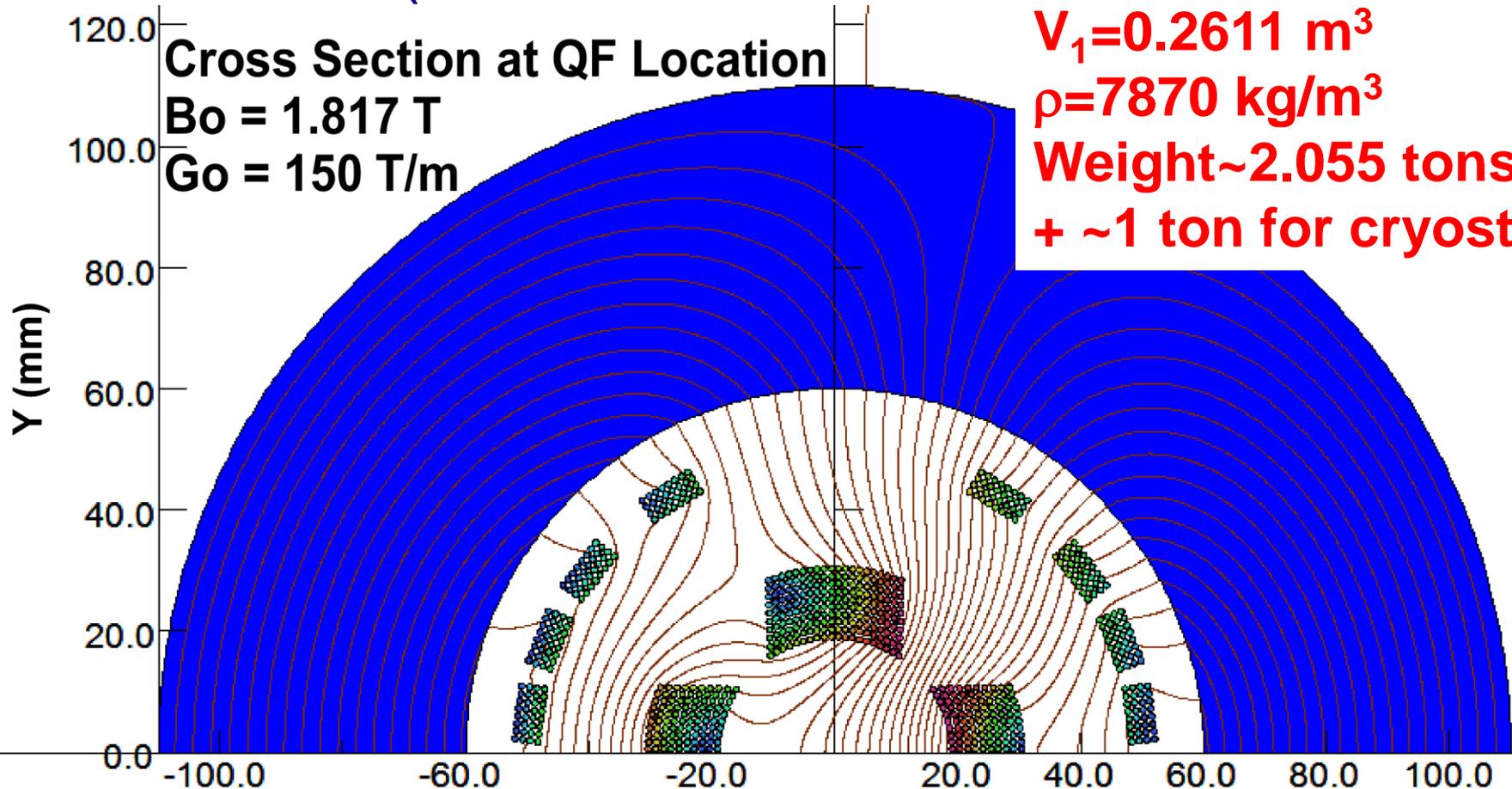
(Brett Parker – BNI **Total volume of iron**

$V_1 = 0.2611 \text{ m}^3$

$\rho = 7870 \text{ kg/m}^3$

Weight ~ 2.055 tons

+ ~ 1 ton for cryostat



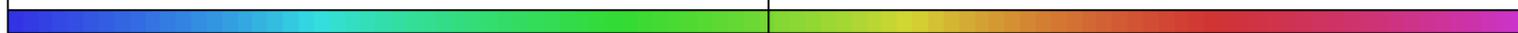
Component: |B| in Coil (Tesla)

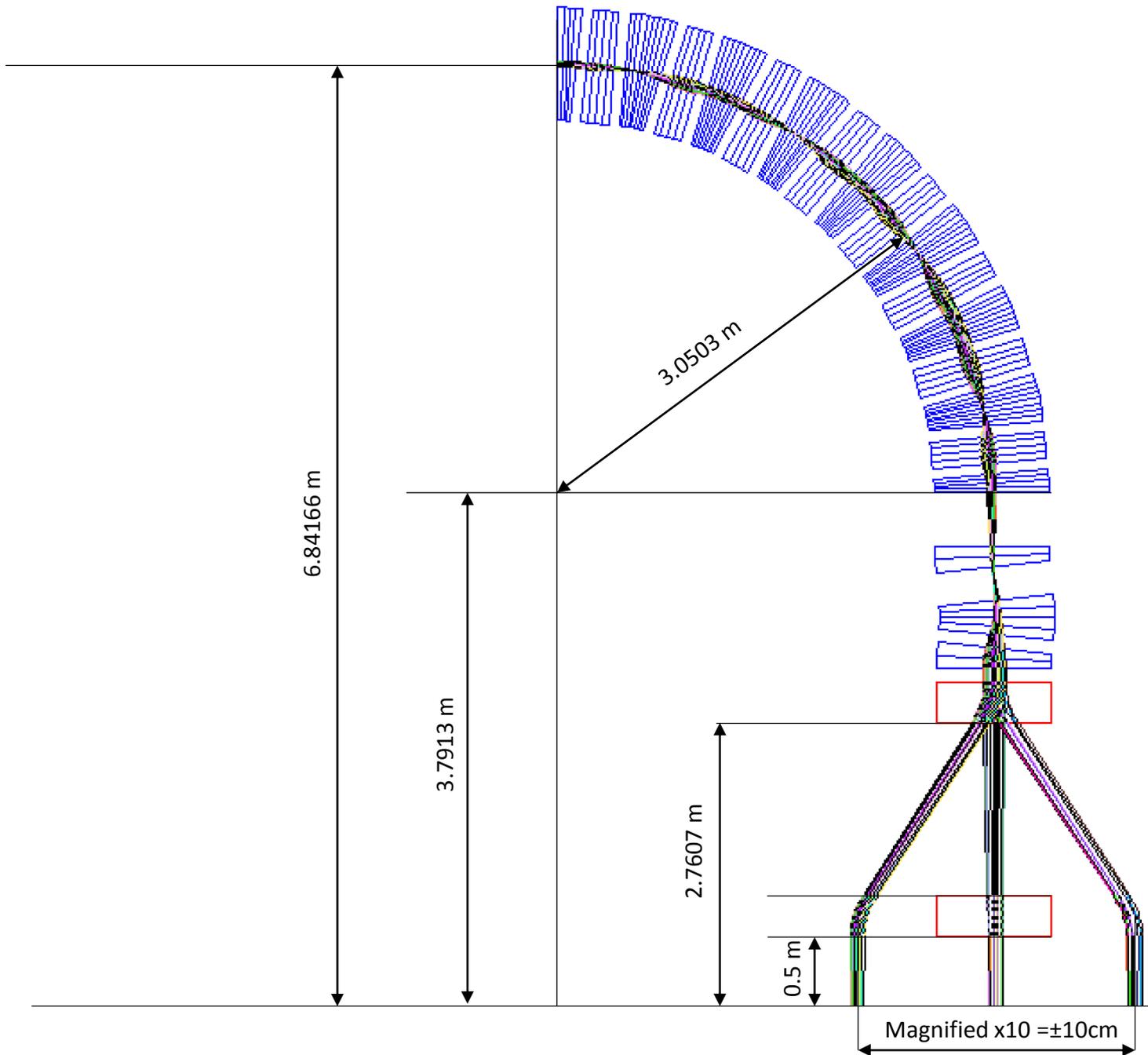
2.87243E-03

2.359247293

4.71562216

X (mm)





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

SUMMARY:

1. NS-FFAG gantries provide transfer of carbon ions with large momentum range: $\delta p/p = \pm 20\%$ (**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