

Large Momentum Acceptance Superconducting and Permanent Magnet Non-Scaling FFAG Gantries

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OUTLINE:

- Requests and Challenges
- Introduction: NS-FFAG?

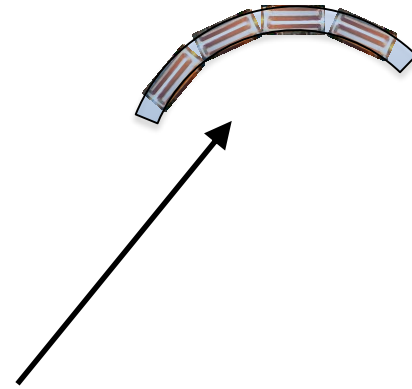
- Proton Gantries
- Permanent Magnet Gantry

- 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

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

{

$\Delta E_{k \text{ carbon}} = 400-195.4 \text{ MeV/u} \quad [27.3-8.2 \text{ cm}]$
 $\Delta E_{k \text{ carbon}} = 195.4-91.5 \text{ MeV/u} \quad [8.2-2.2 \text{ cm}]$
 $\Delta E_{k \text{ proton}} = 250-118.81 \text{ MeV} \quad [37.8-10.4 \text{ cm}]$
 $\Delta E_{k \text{ proton}} = 118.81-54.6 \text{ MeV} \quad [10.4-2.6 \text{ cm}]$

$$proton \text{ } ke_{\max} = 250 \text{ MeV} \quad p_{\max} = 729.13 \text{ MeV} / c$$

$$proton \text{ } ke_{\min} = 35 \text{ MeV} \quad p_{\max} = 258.7 \text{ MeV} / c \quad \leftarrow \text{Permanent proton gantry}$$

$$proton \text{ } ke_{cen} = 155.7 \text{ MeV} \quad p_{cent} = 562. \text{ MeV} / c$$

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

$$E_{k \text{ center}} = 291.73 \text{ MeV} / u \quad p_{center \text{ carbon}} = 792.848 \text{ MeV} / c / u$$

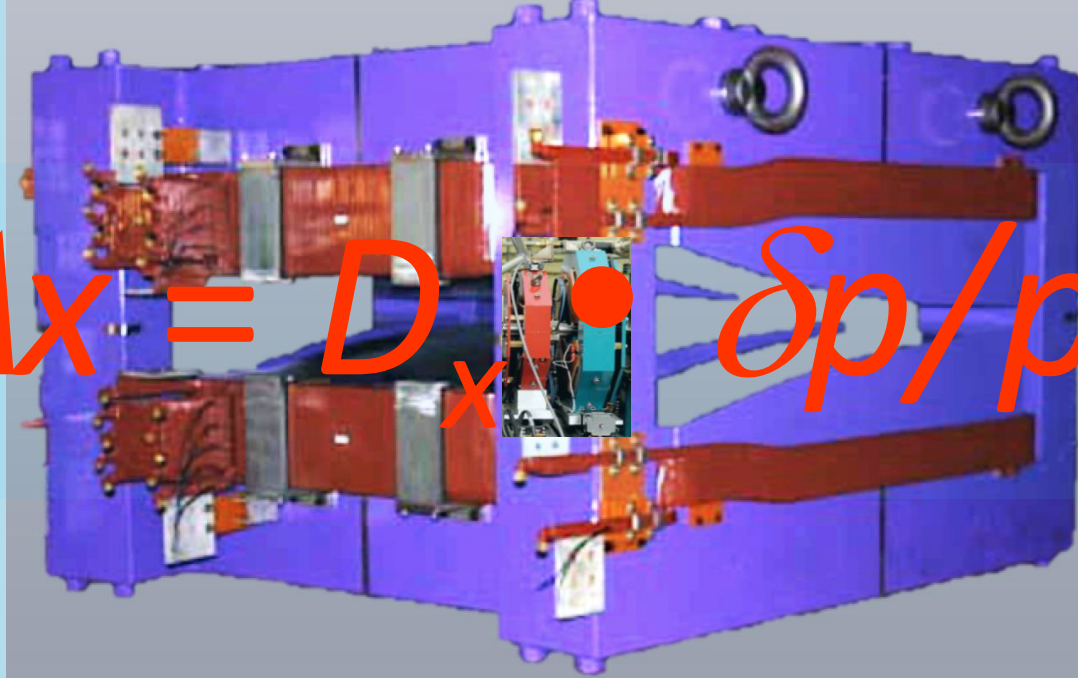
$$E_{k \text{ min}} = 195.44 \text{ MeV} / u \quad p_{\min \text{ carbon}} = 634.28 \text{ MeV} / c / u \quad \leftarrow \text{Superconducting carbon/proton gantry}$$

$$E_{k \text{ max}} = 400.00 \text{ MeV} / u \quad p_{\min \text{ carbon}} = 951.42 \text{ MeV} / c / u$$

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

MAKE IT SMALLER YET HIGHLY EFFECTIVE!

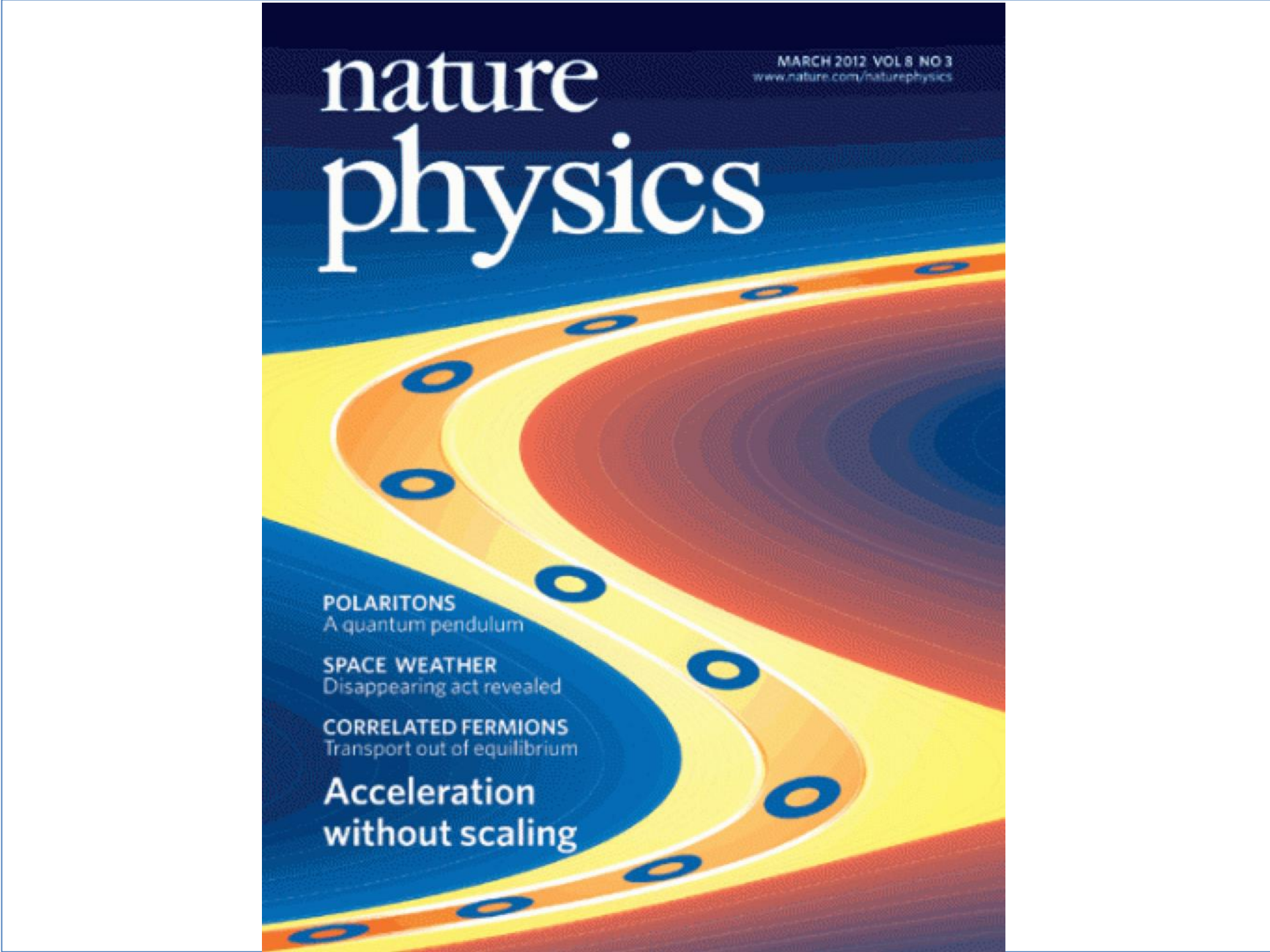
$$\Delta x = D_x \bullet \delta p/p$$



?

Two properties were annoying:
VERY LARGE MAGNET SIZE
30% OPPOSITE BEND - INNEFICIENT

nature physics



MARCH 2012 VOL 8 NO 3
www.nature.com/naturephysics

POLARITONS

A quantum pendulum

SPACE WEATHER

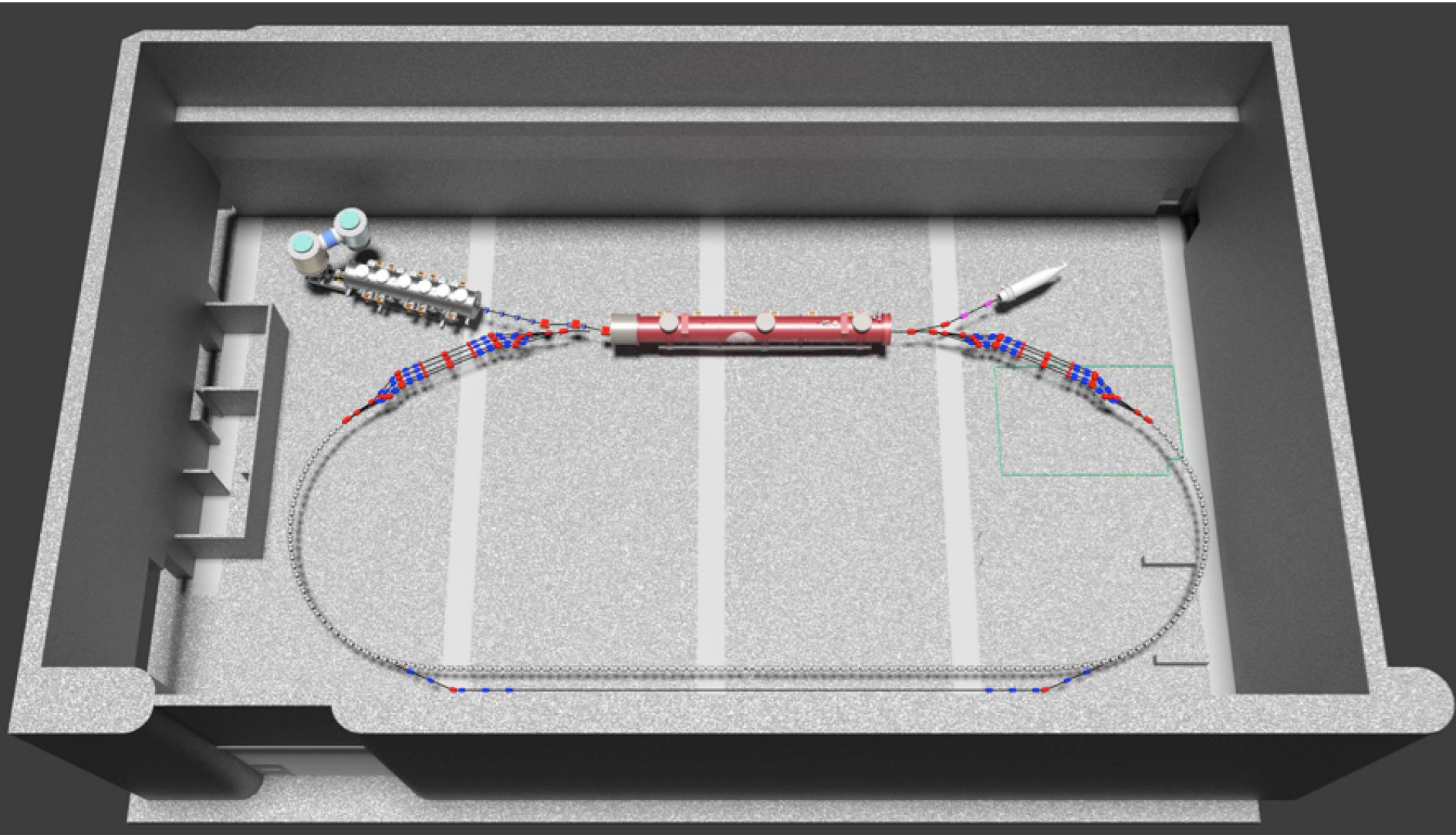
Disappearing act revealed

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 as an eRHIC prototype



FROM AGS

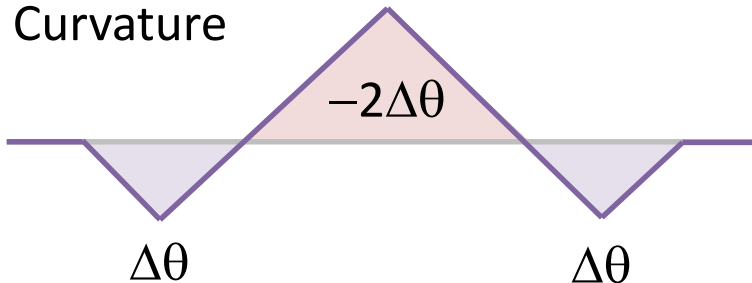
eRHIC FFAG Rings in Perspective

© Stephen Brooks

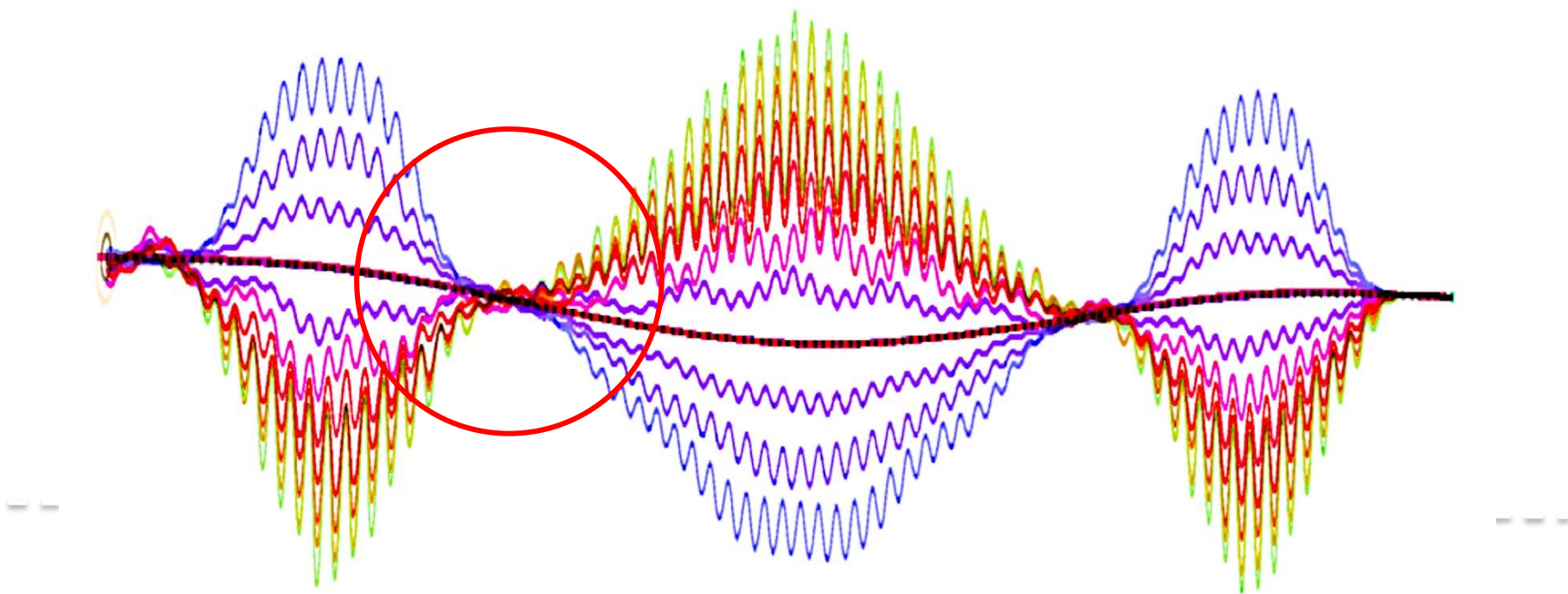
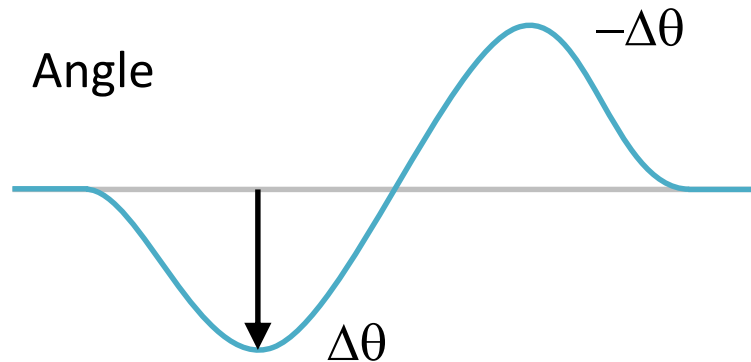


Detector Bypass Scheme: a Flexible FFAAG

Curvature



Angle



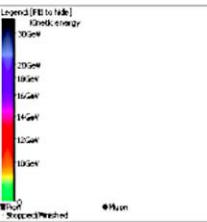
$t = 2.85 \mu s$
 Redmap gained: 0.00% Otherwise lost: 100.00% Wrongway: 0.00%

eRHIC/Oct'14_gexp

Frame-rate: AUTO (1/33424)
Particle size: AUTO (0.0894mm)
Results database: 0 bytes (0 bytes since last send)

[View Manual, Y in ap](#)

[[FALSED]]

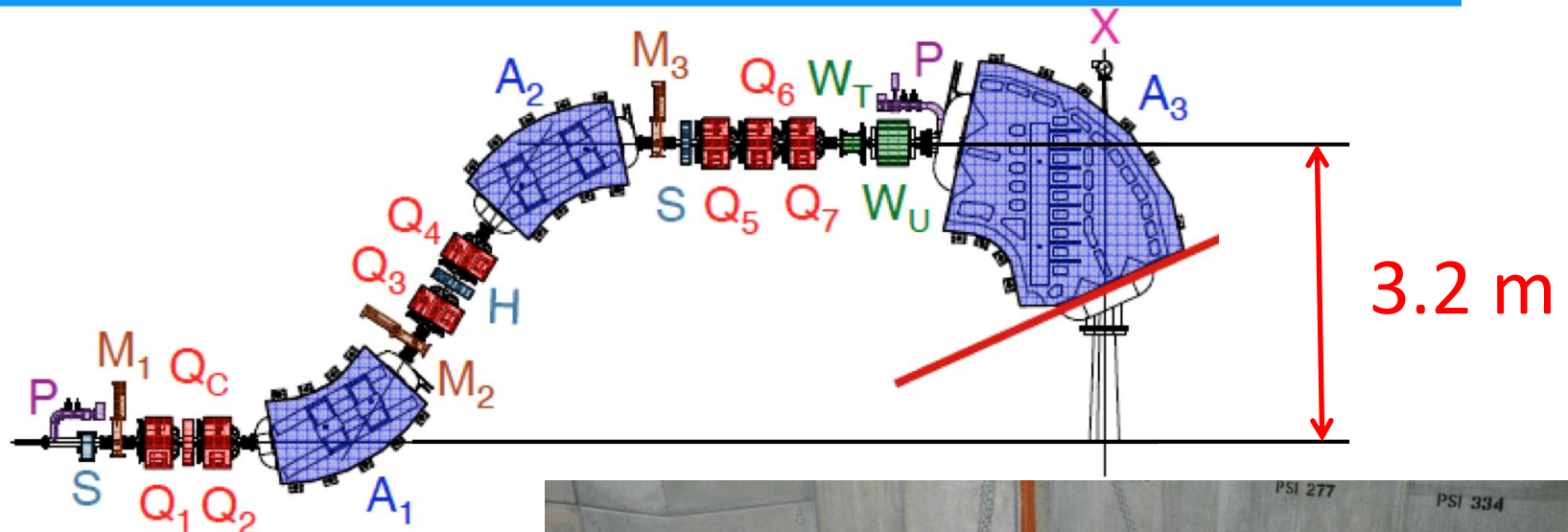


Transverse exaggeration x8192

Press P1 for key controls

Particles remaining: 0 / 11 / 20

The state of the art proton gantry at PSI



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**

(56) **References Cited**

U.S. PATENT DOCUMENTS

(71) Applicant: **Brookhaven Science Associates, LLC**,
Upton, NY (US)

4,870,287 A 9/1989 Cole et al.
5,260,581 A 11/1993 Lesyna et al.
5,585,642 A 12/1996 Britton et al.

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

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

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2007/0262269 A1 11/2007 Trbojevic
2010/0038552 A1* 2/2010 Trbojevic 250/396 ML

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

OTHER PUBLICATIONS

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

D. Trbojevic et al., "Design of a Nonscaling Fixed Field Alternating
Gradient Accelerator," Physical Review Special Topics—Accelerators
and Beams 8.050101, pp. 050101-1-050101-10, May 19, 2005.

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

(Continued)

(65) **Prior Publication Data**

Primary Examiner — Nicole Ippolito

US 2014/0163301 A1 Jun. 12, 2014

(74) *Attorney, Agent, or Firm* — Dorene M. Price

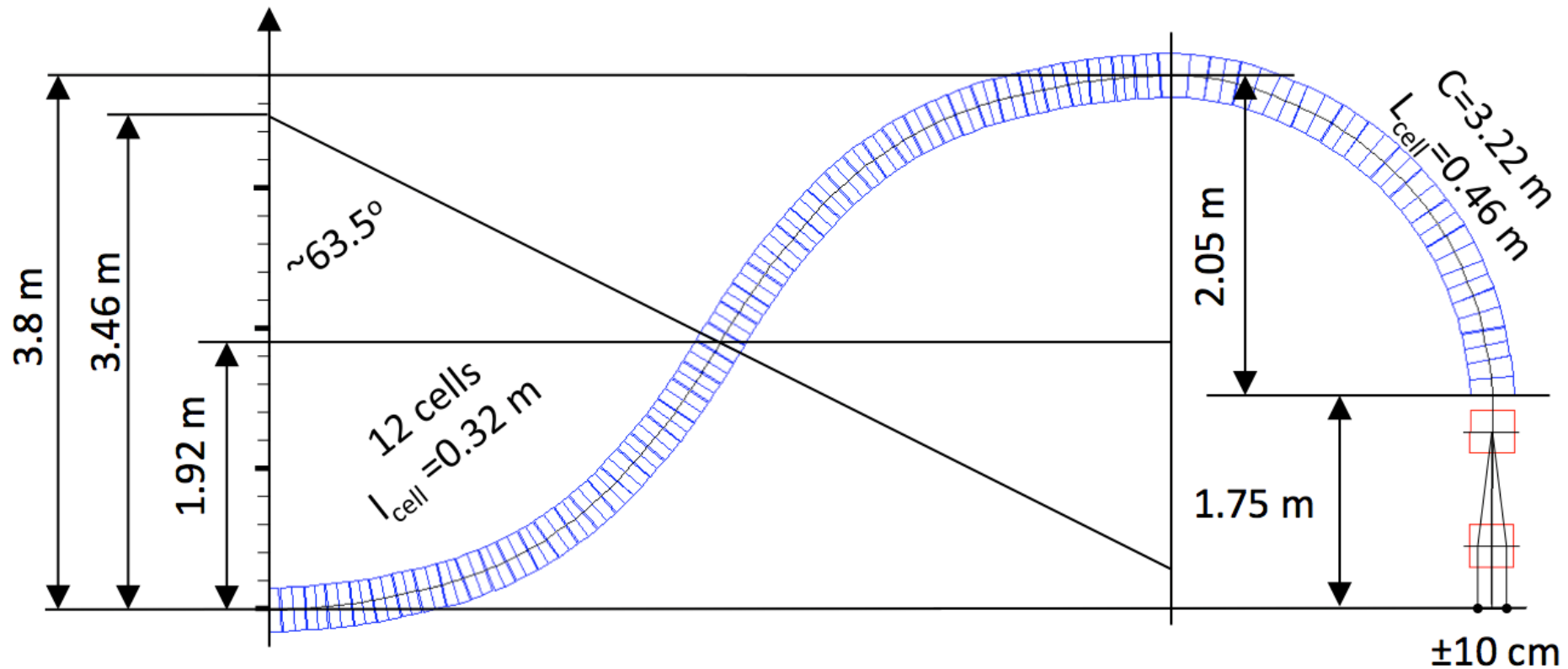
— (57)

ABSTRACT

Axis

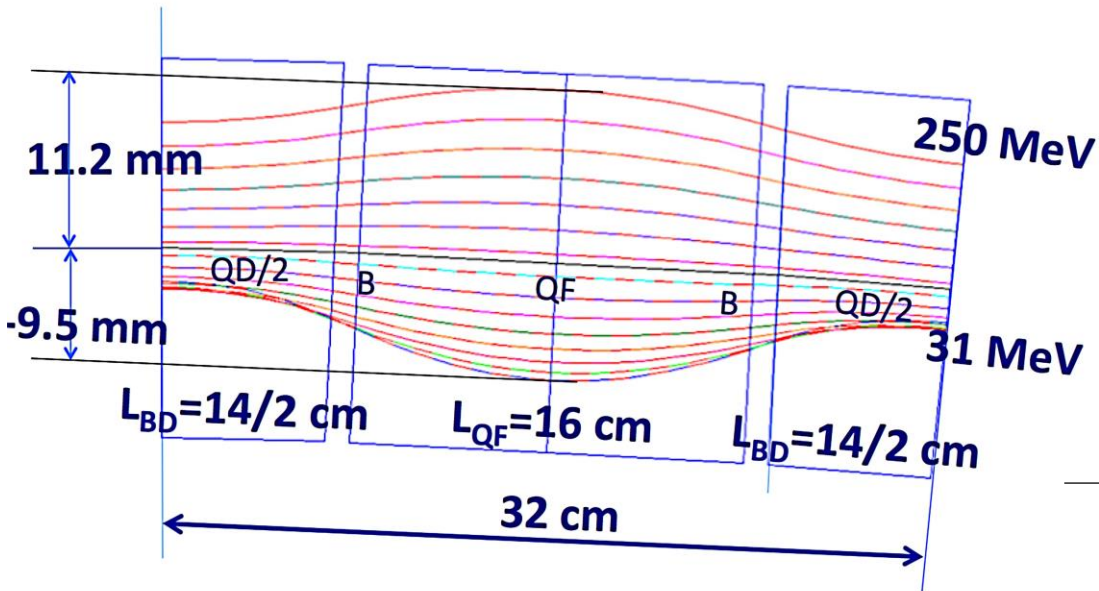
Axis

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

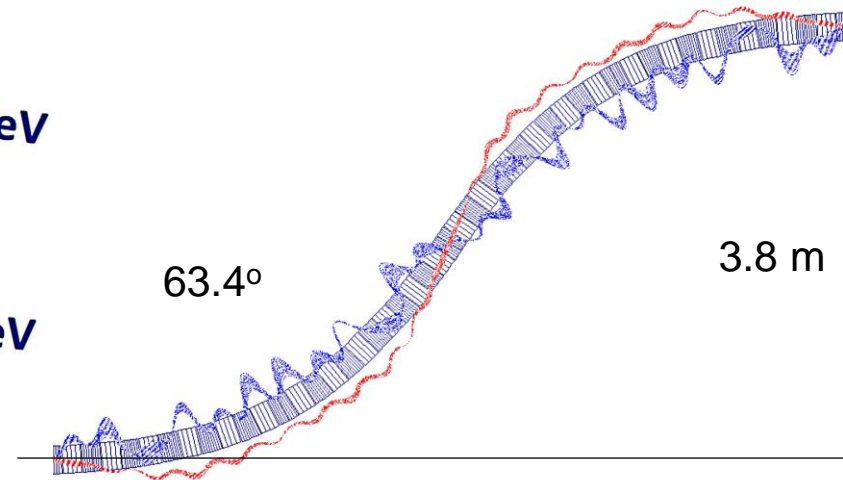


Halbach Permanent Magnet Gantry

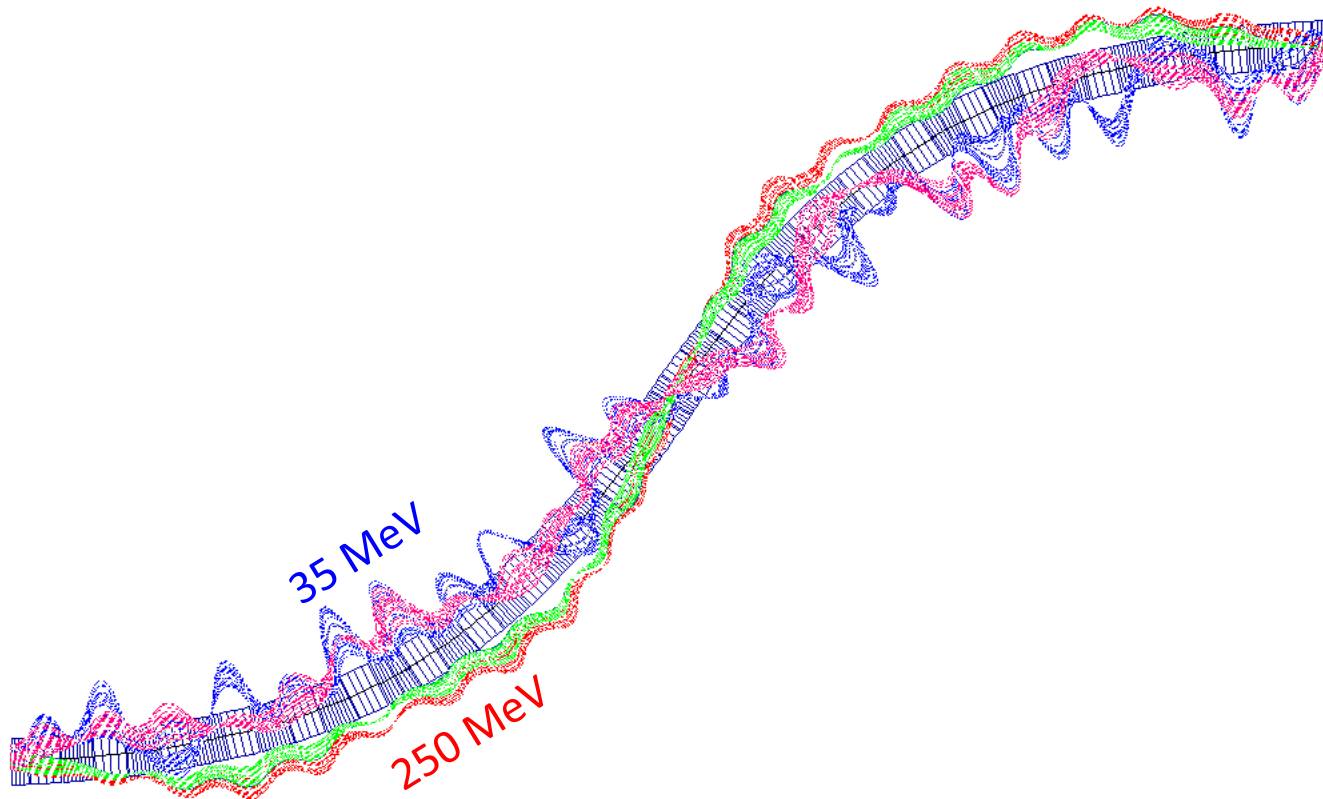
The Basic Cell



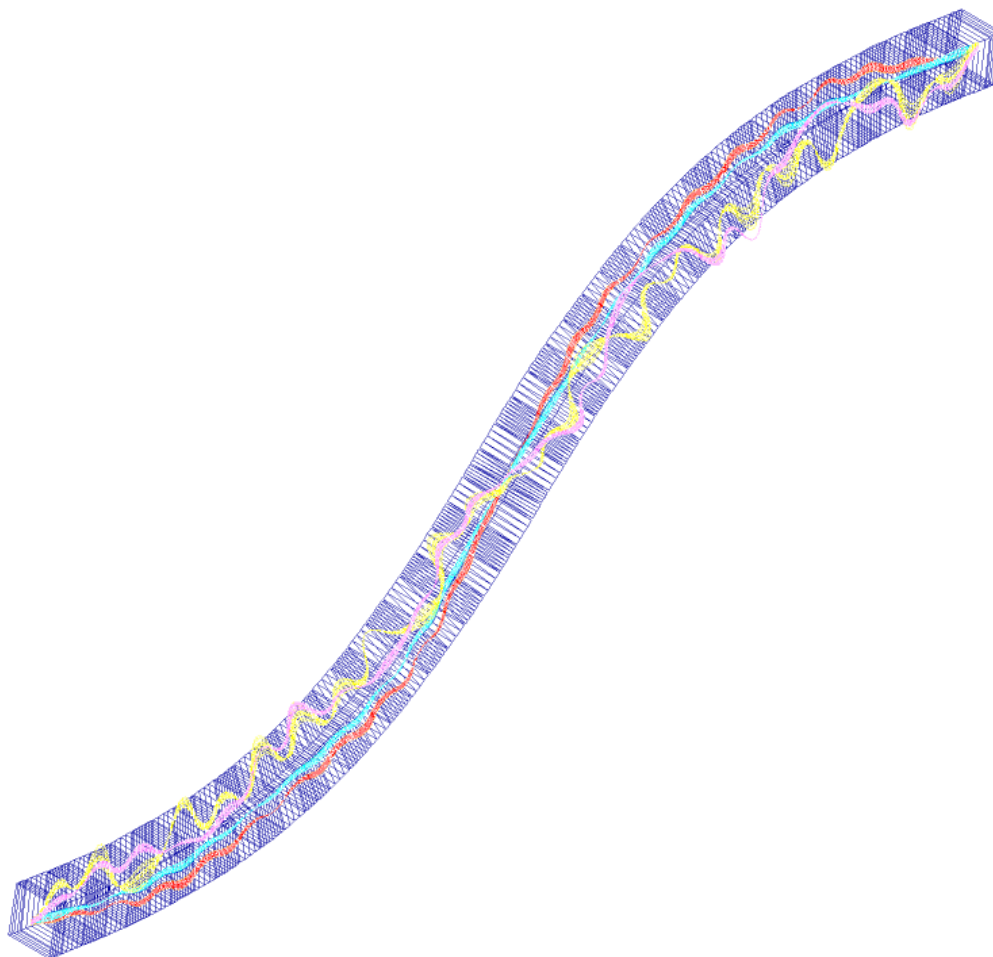
Magnified Orbit Offset for 35 MeV – 250 MeV protons



Permanent Halbach Magnet NS-FFAG Proton Gantry

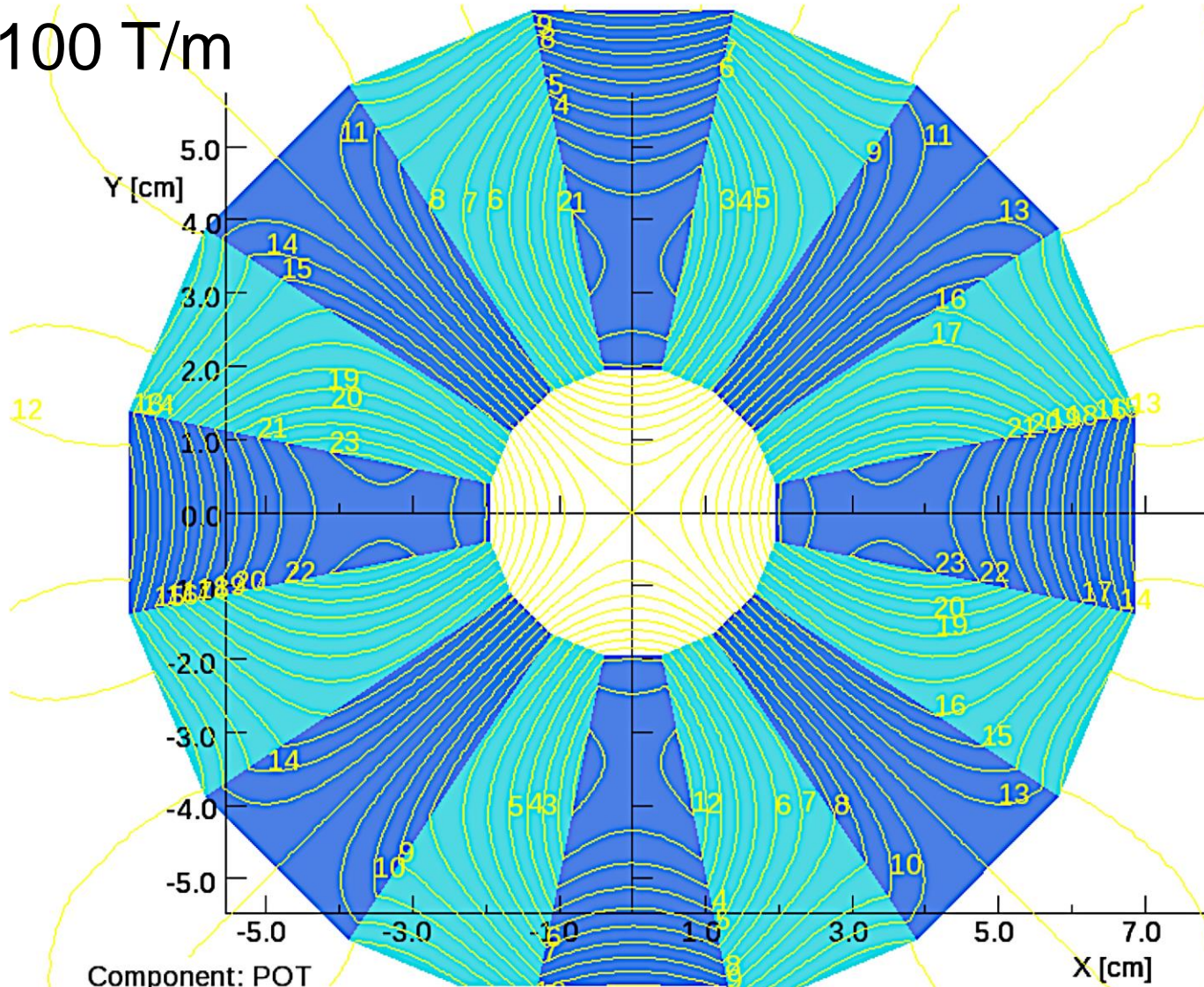


Orbits in 3D in half of the Superconducting Gantry



Gantry Halbach Magnet Design (Nick Tsoupas –BNL)

$G=100 \text{ T/m}$



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

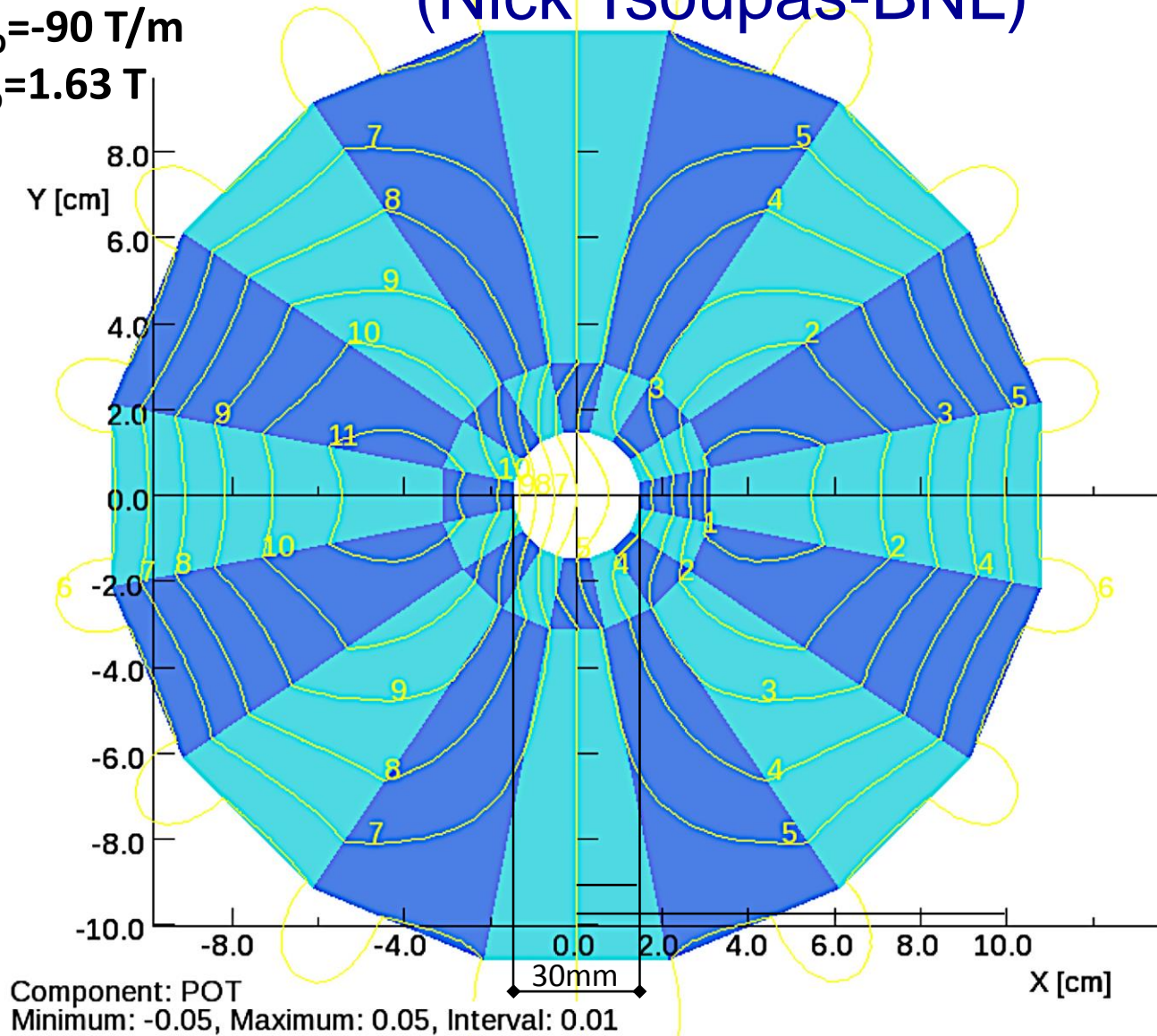
08/Sep/2015 09:10:24 Page 11

opera
simulation software

Gantry Halbach Magnet Design (Nick Tsoupas-BNL)

$G_D = -90 \text{ T/m}$

$B_D = 1.63 \text{ T}$



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

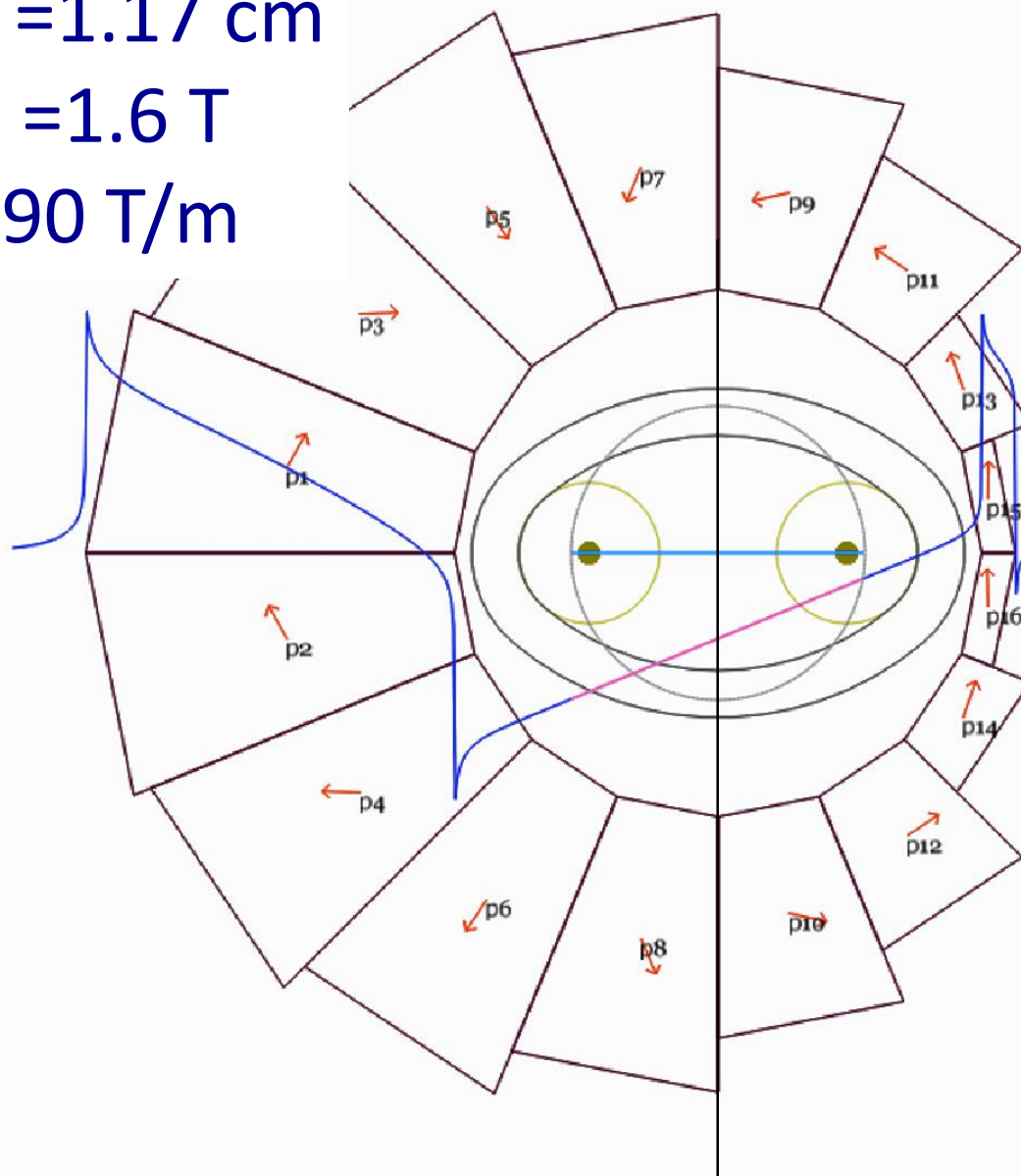
MODEL DATA

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Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor: 1.0
37678 elements
75757 nodes
64 regions

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opera
simulation software

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



Parameters in units (norm=709)

```

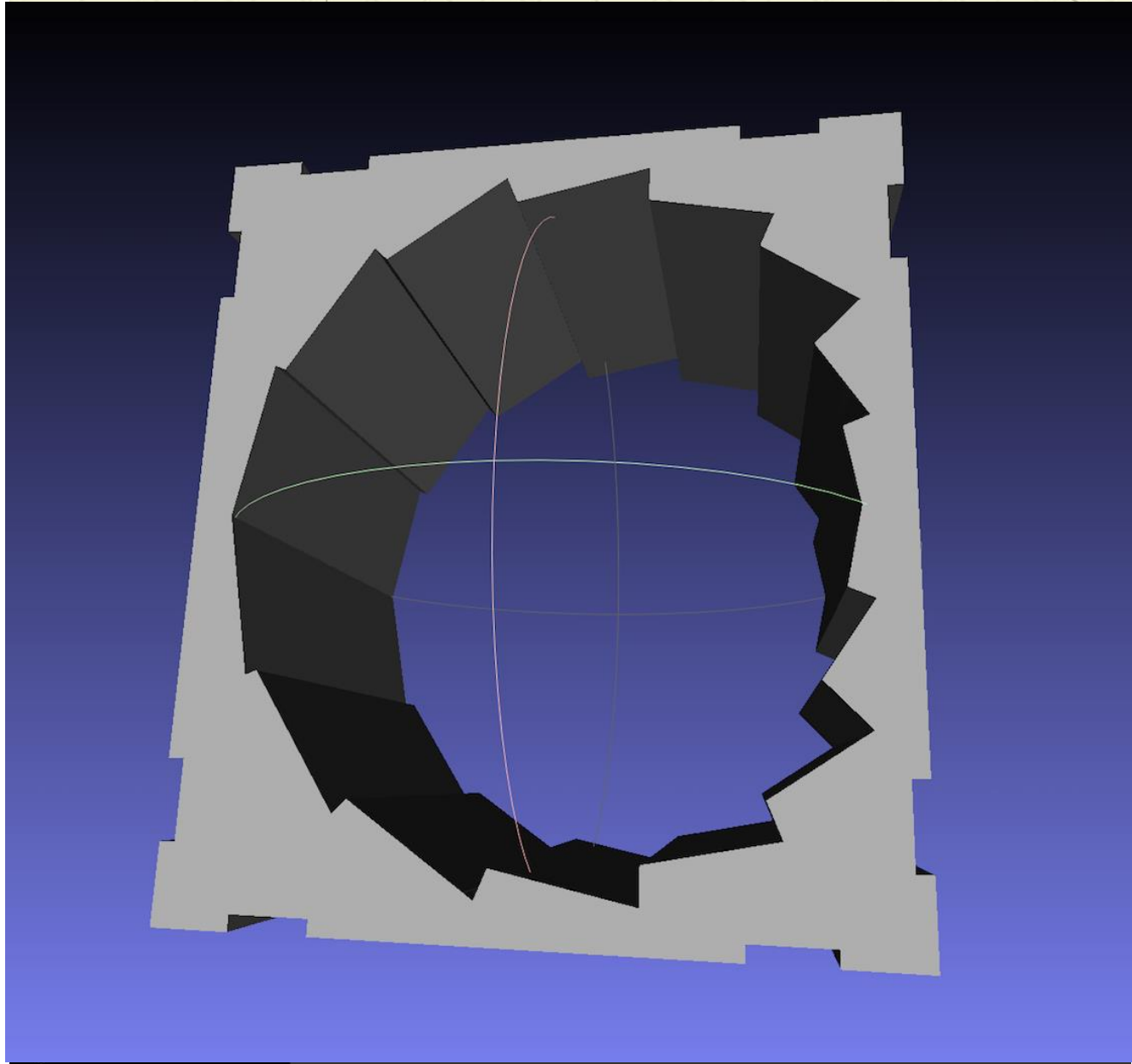
a[0] = 0.000265591
a[1] = 0.0141988
a[2] = -0.0103829
a[3] = 0.029506
a[4] = -0.0588494
a[5] = 0.0397233
a[6] = -0.0930094
a[7] = -0.0210847
a[8] = -0.0468514
a[9] = -0.109958
a[10] = 0.0777202
a[11] = -0.116953
a[12] = 0.15386
a[13] = 0.00472071
a[14] = 0.0800213
a[15] = 0.141447
    
```

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

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

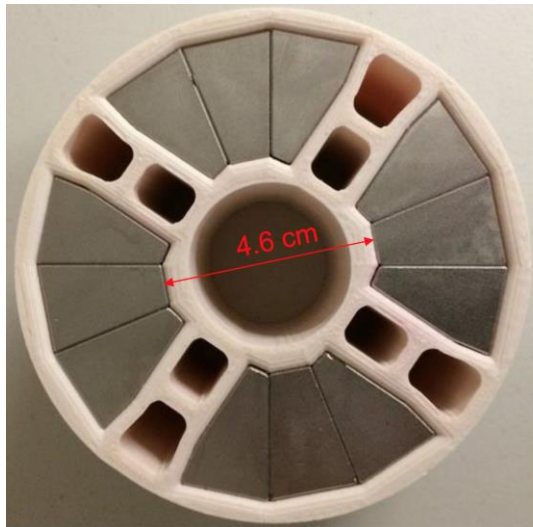
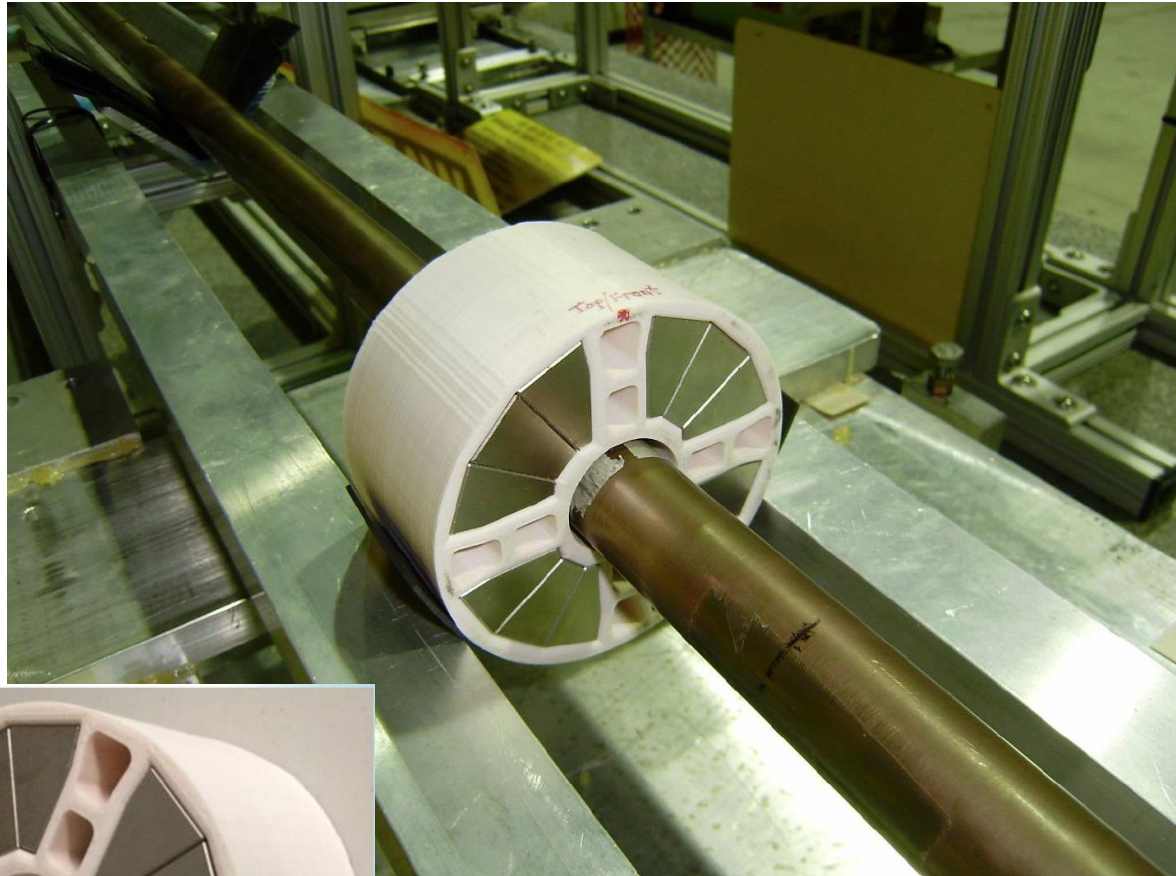
2-pole	4-pole	6-pole	8-pole	10-pole	12-pole	14-pole	16-pole	18-pole	20-pole	22-pole	24-pole	26-pole	28-pole	30-pole	32-pole	34-pole
-0.48471 T	0.343663 T	-3.76595e-007 T	-4.79037e-007 T	-2.50943e-007 T	-2.06448e-008 T	6.53401e-008 T	-5.67613e-008 T	1.13071e-007 T	5.20635e-008 T	-1.27811e-006 T	7.21536e-007 T	3.59029e-006 T	4.61009e-006 T	3.15269e-006 T	-1.67342e-017 T	-4.24561e-006 T
2-skew: 0.000000	4-skew: 0.000000	6-skew: 0.000000	8-skew: 0.000000	10-skew: 0.000000	12-skew: 0.000000	14-skew: 0.000000	16-skew: 0.000000	18-skew: 0.000000	20-skew: 0.000000	22-skew: 0.000000	24-skew: 0.000000	26-skew: 0.000000	28-skew: 0.000000	30-skew: 0.000000	32-skew: 0.000000	34-skew: 0.000000

Built Models of Defocusing Modified Halbach Magnet



D. Trbojevic - Ion Beam Therapy: Clinical, Scientific, and Technical Challenges -Birmingham Jan 18-21, 2016

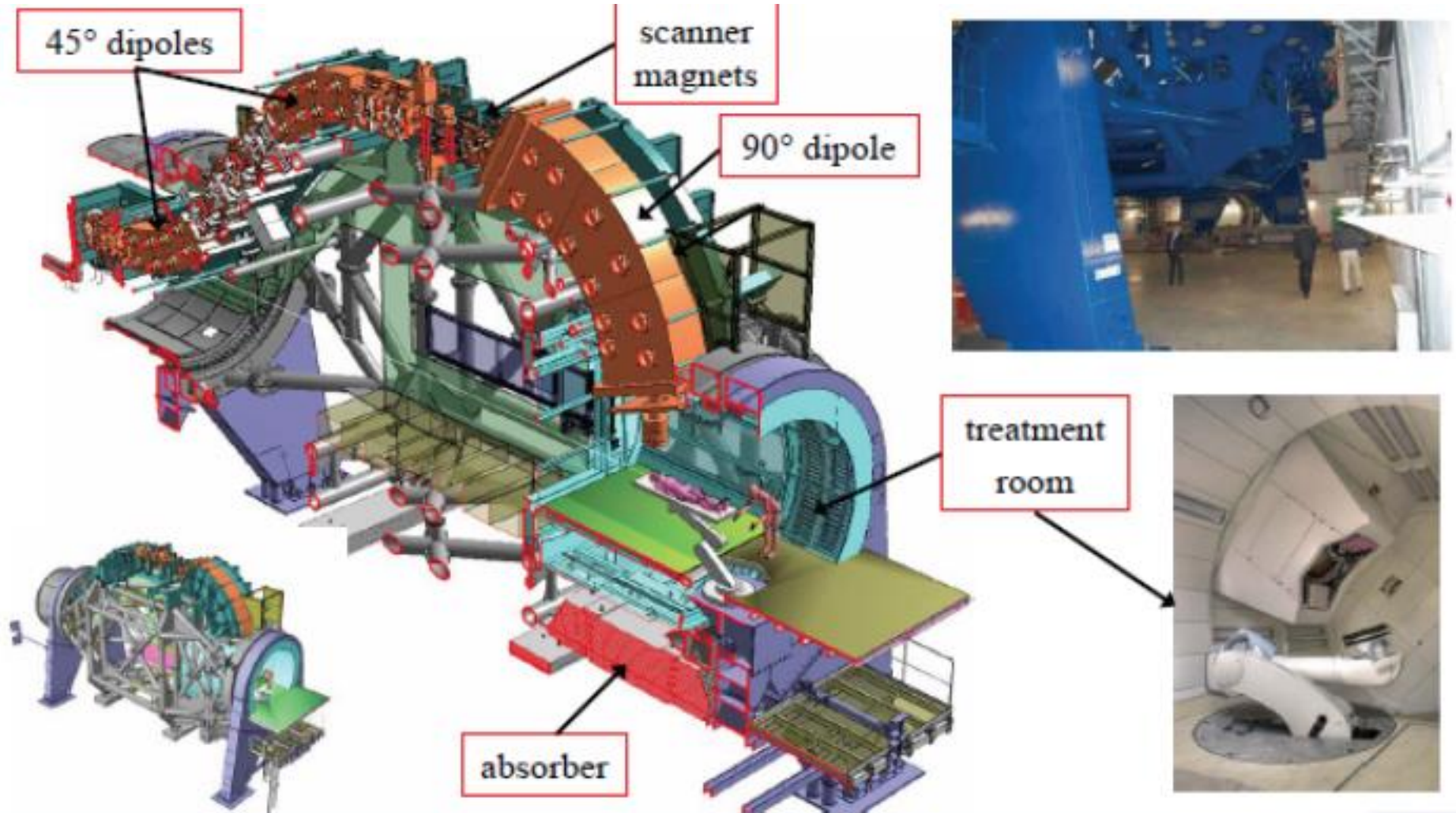
Modified Halbach magnets for BNL eRHIC

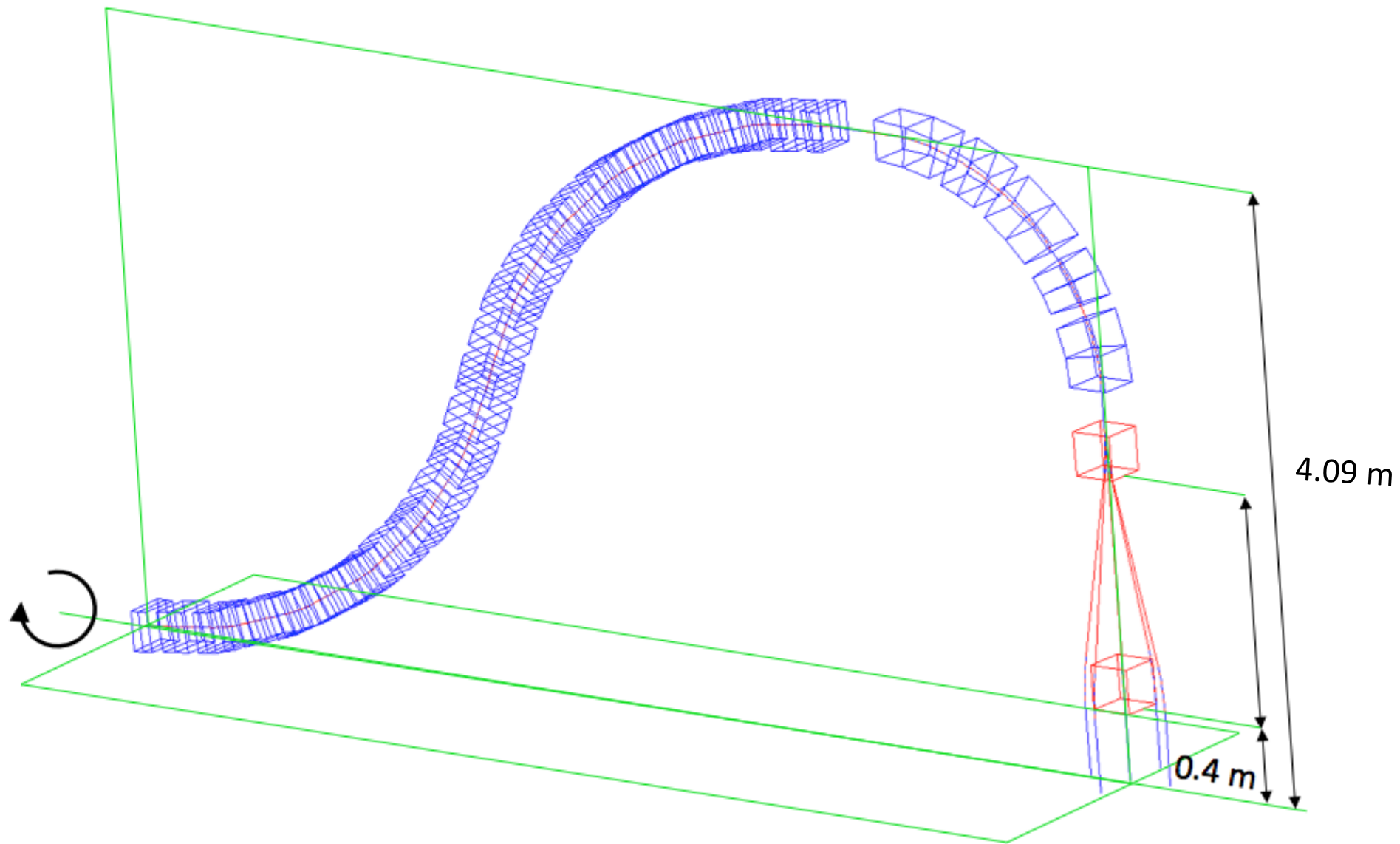


State of the art C-gantry at Heidelberg

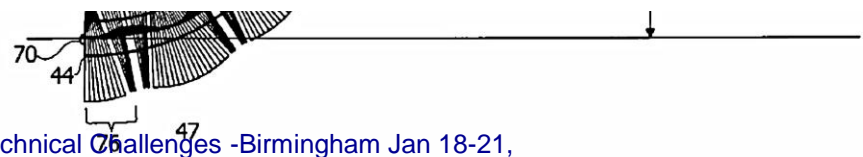
Weight of the transport components – 135 tons

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

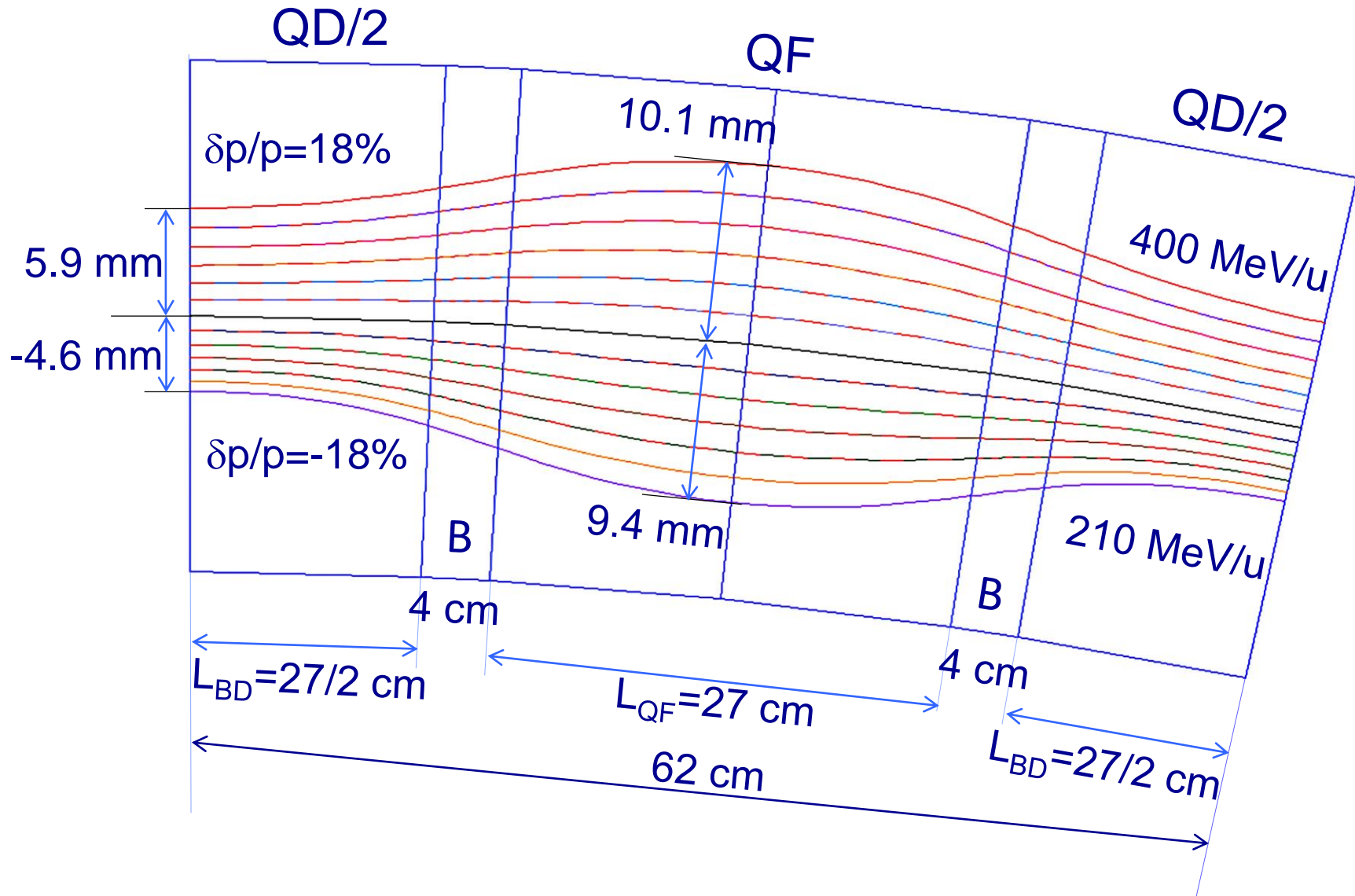




Superconducting magnets

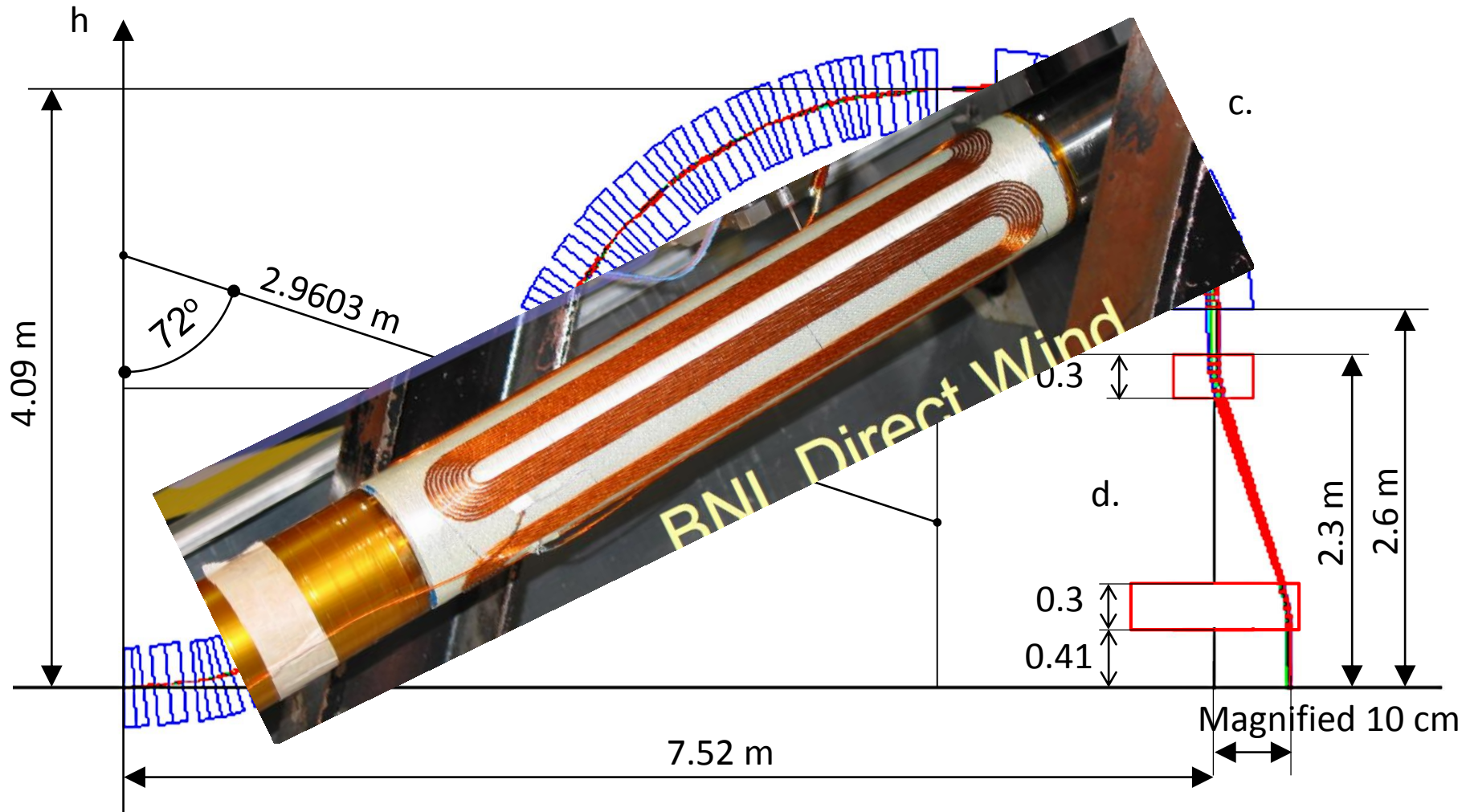


Very strong focusing Basic Cell

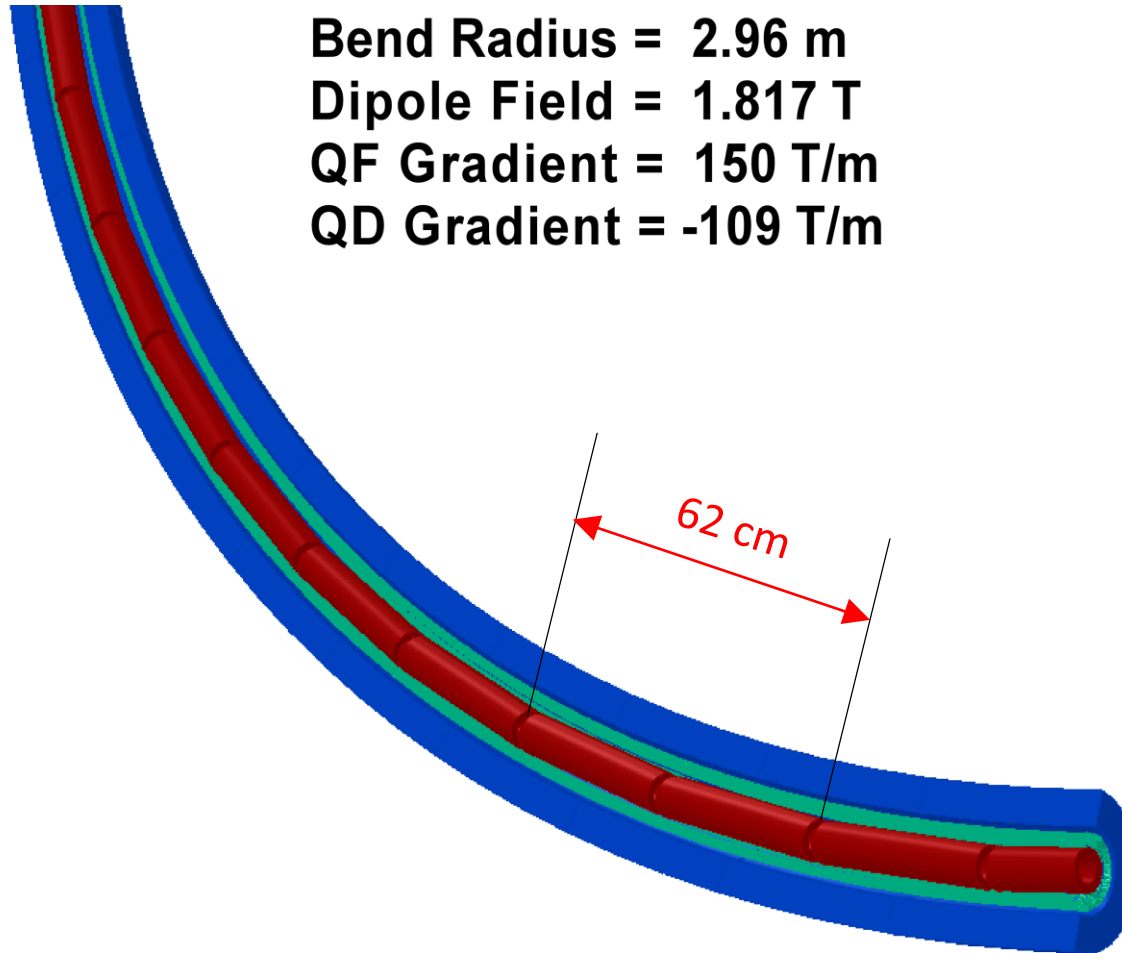


Reducing the size and weight from:

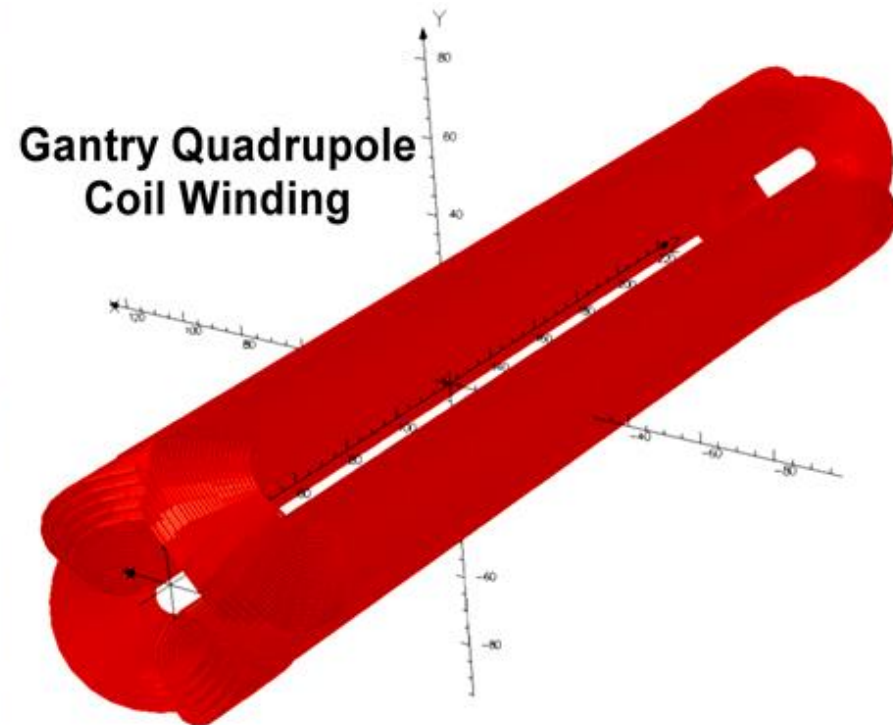
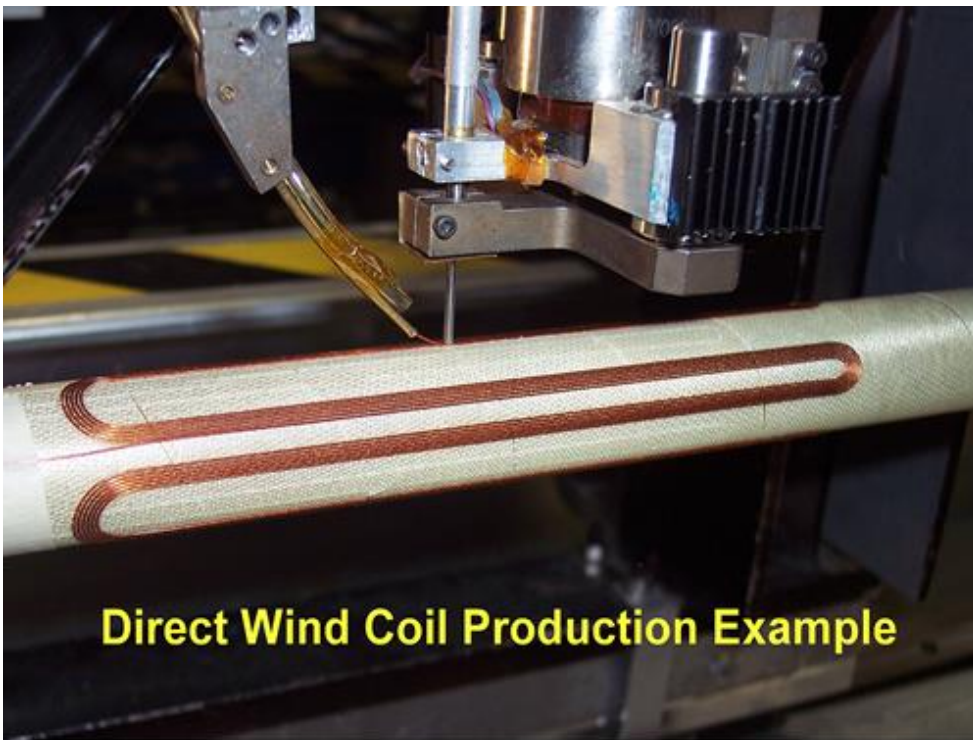
135 tons \rightarrow to 3 tons



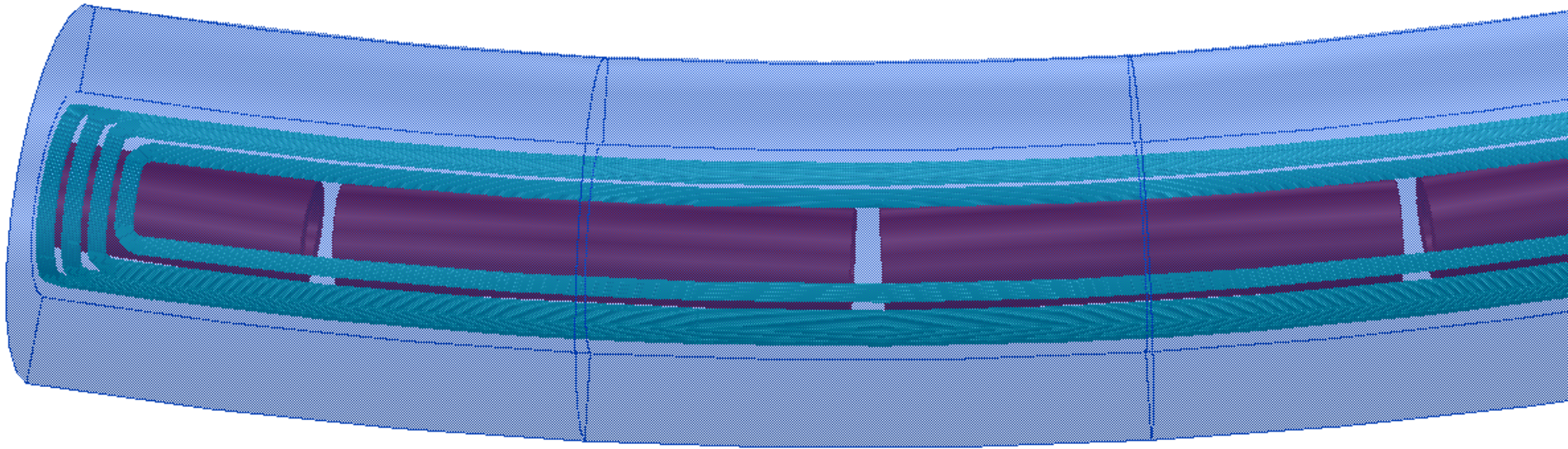
THE PROPOSAL FOR SUPERCONDUCTING CARBON/PROTON GANTRY



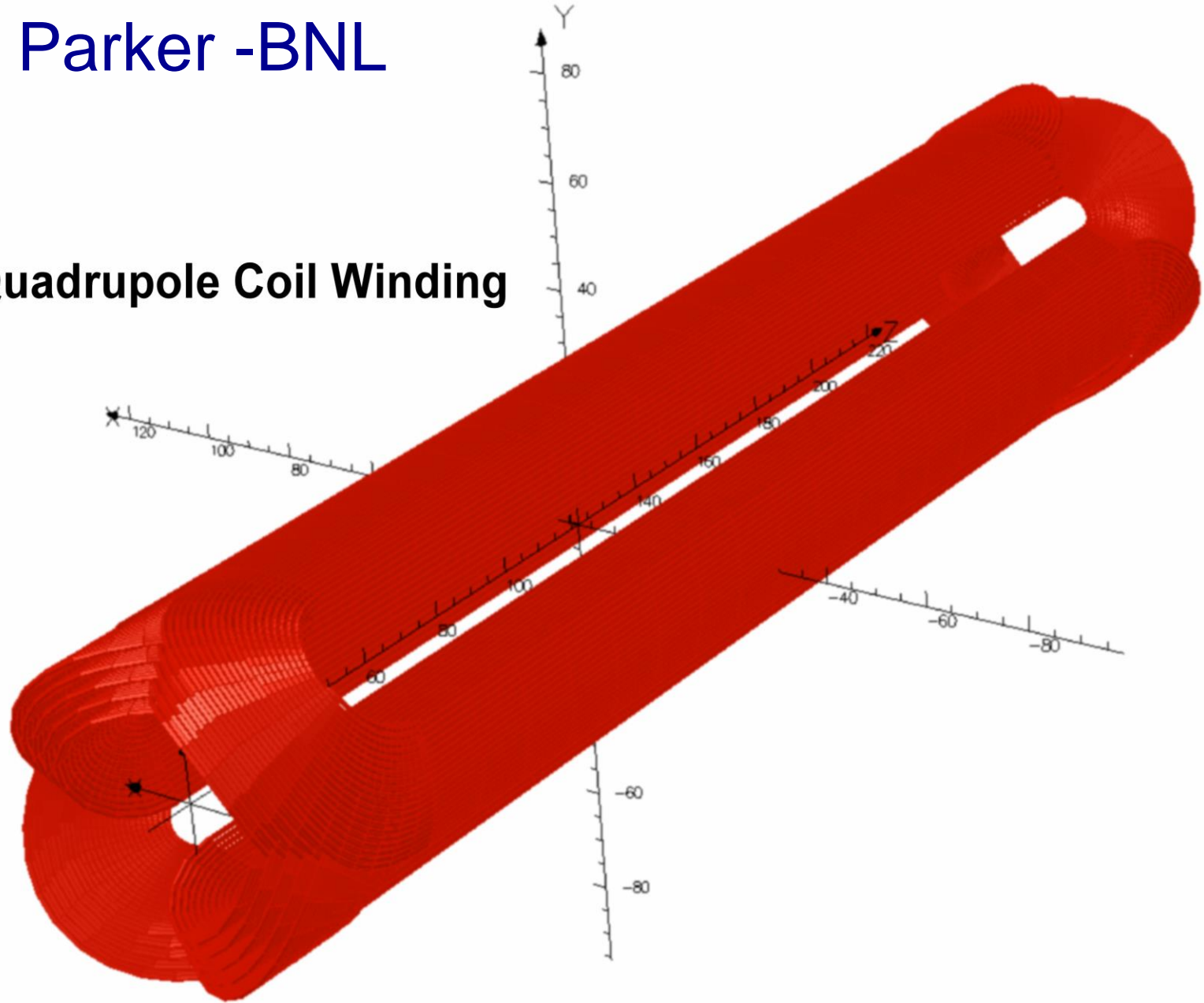
Tools and quadrupole windings (Brett Parker – BNL)



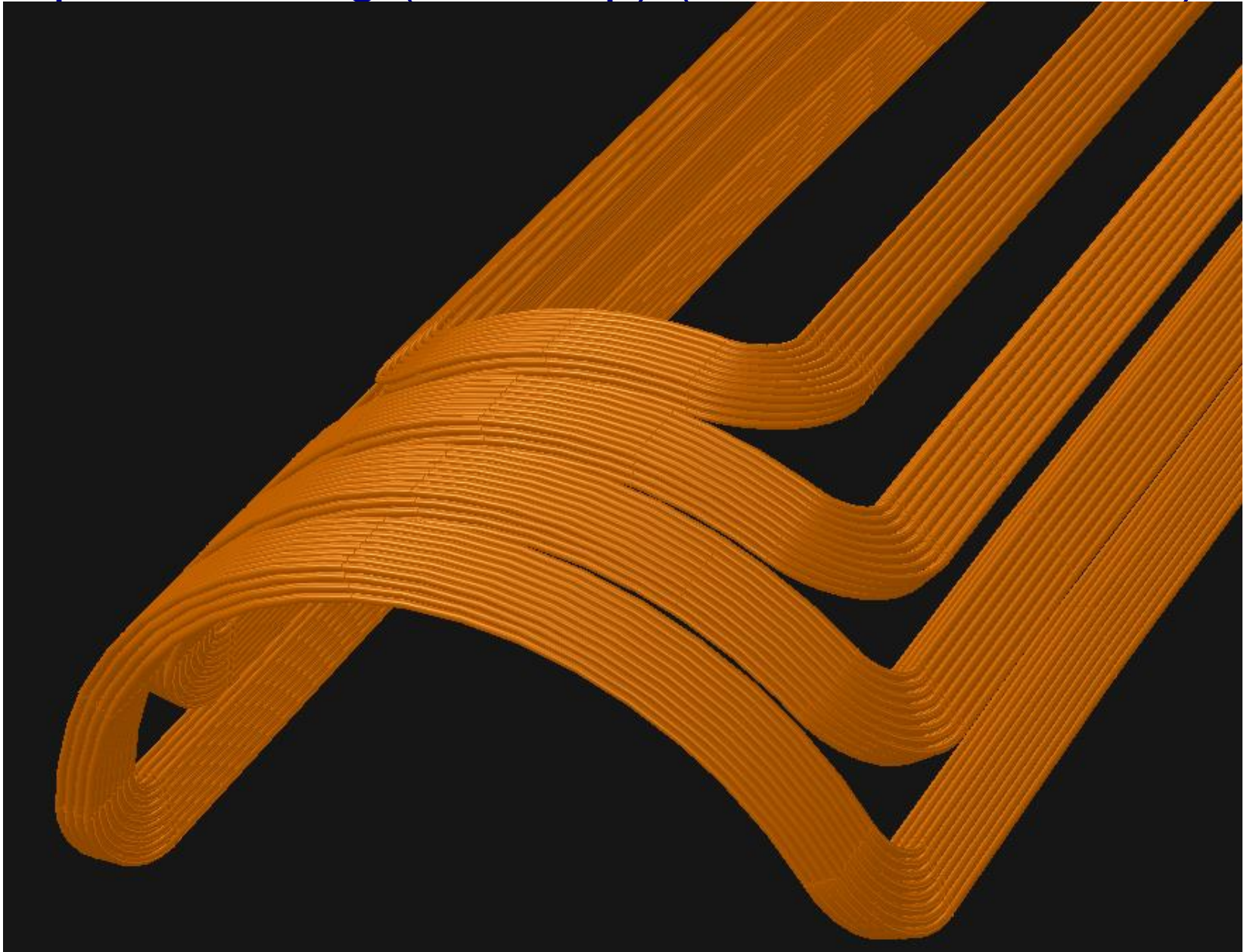
Achromatic Part of the Superconducting Gantry (Brett Parker – BNL)



Quadrupole Coil Winding



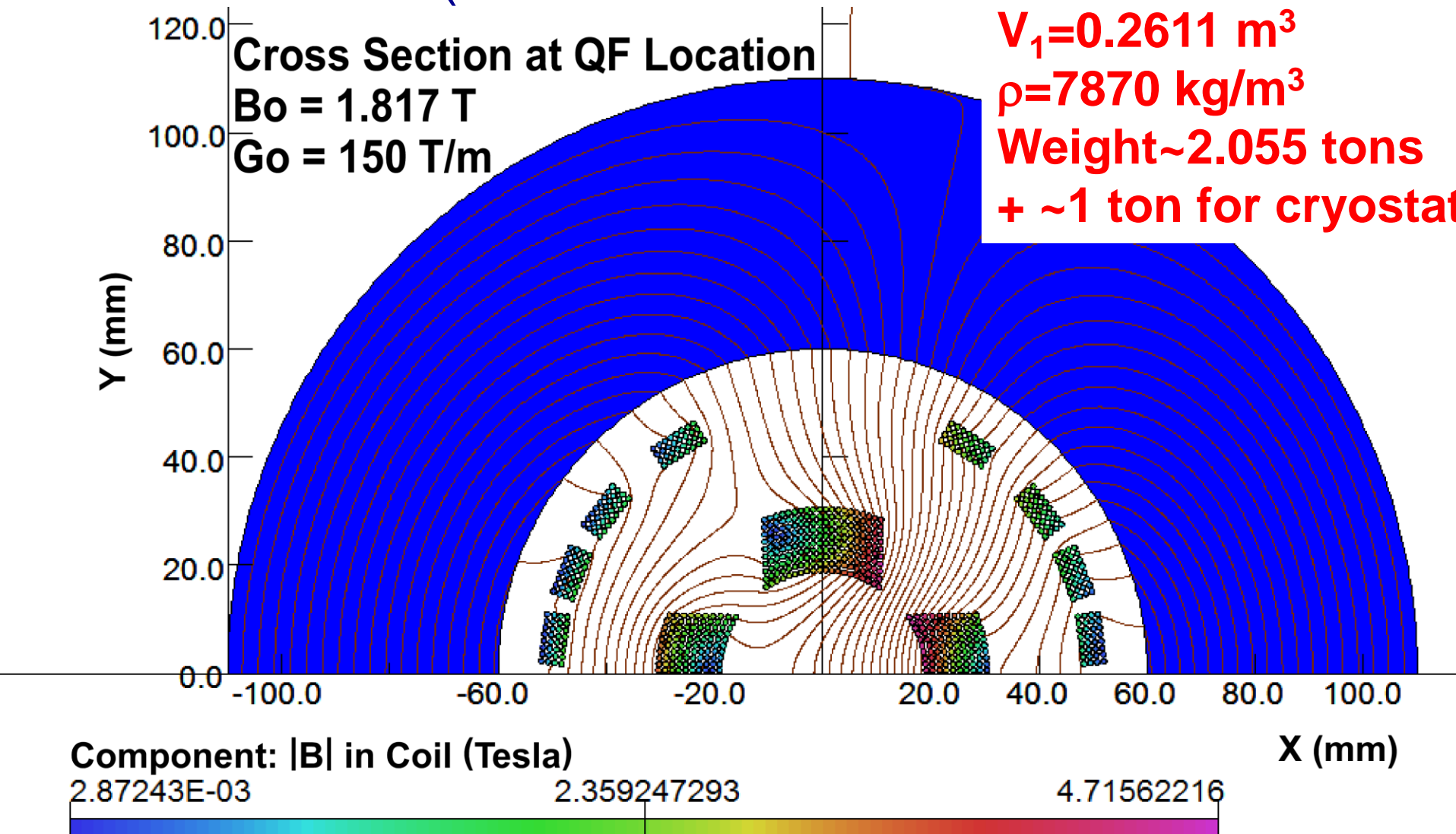
Dipole winding (close-up) (Brett Parker – BNL)

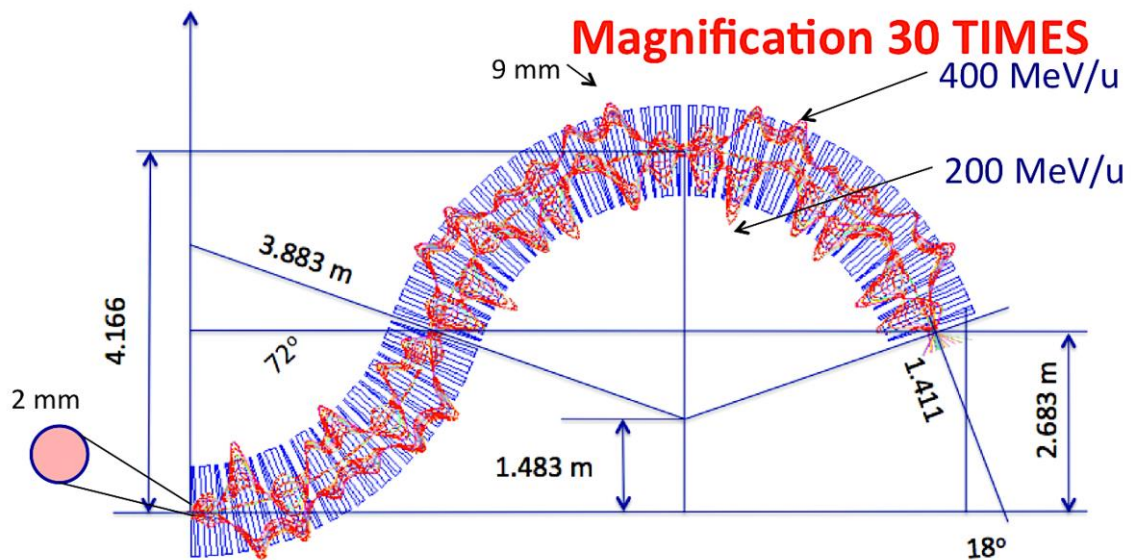
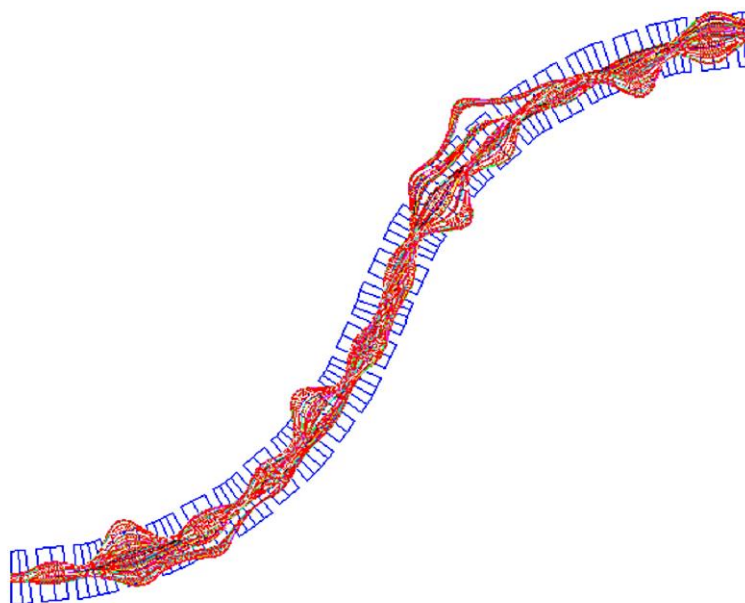


Magnetic field of the Superconducting Gantry

(Brett Parker – BNL)

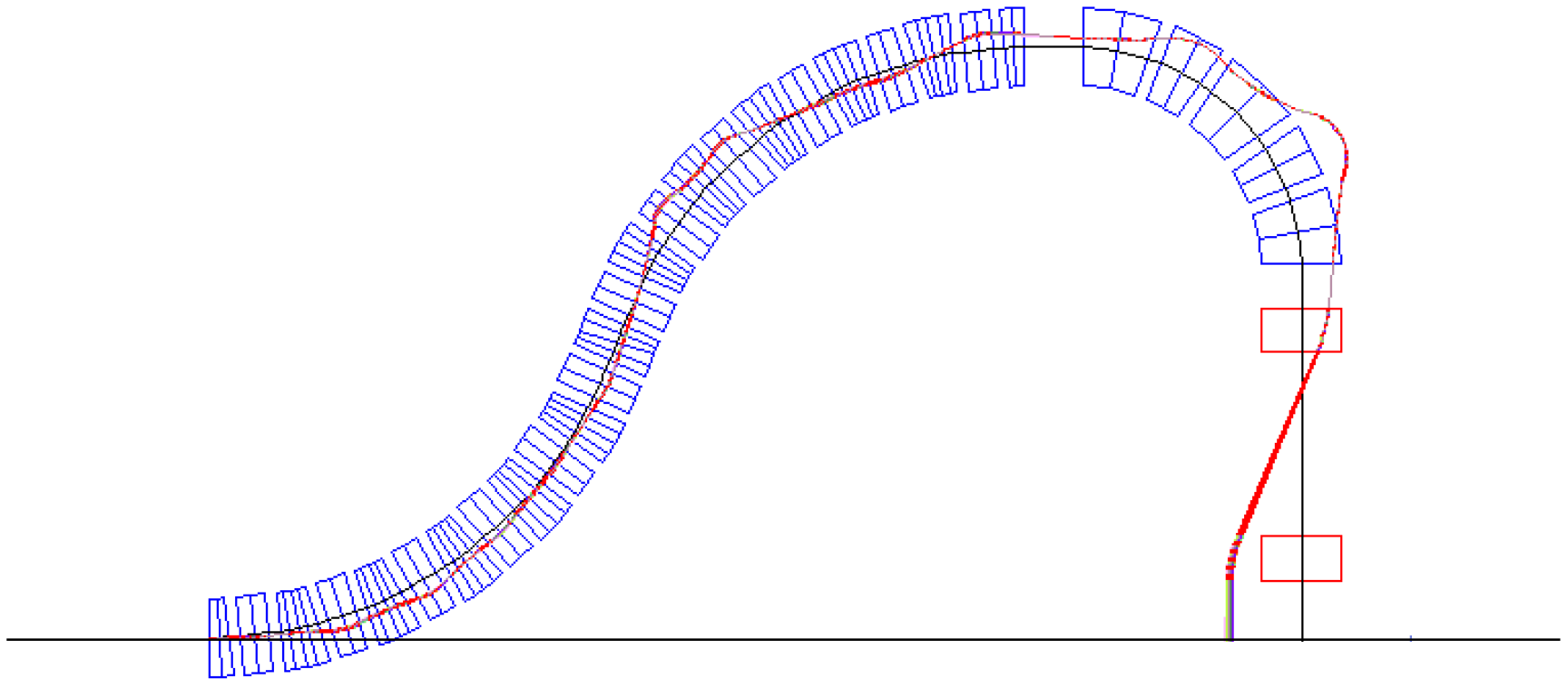
Total volume of iron
 $V_1 = 0.2611 \text{ m}^3$
 $\rho = 7870 \text{ kg/m}^3$
Weight ~2.055 tons
+ ~1 ton for cryostat

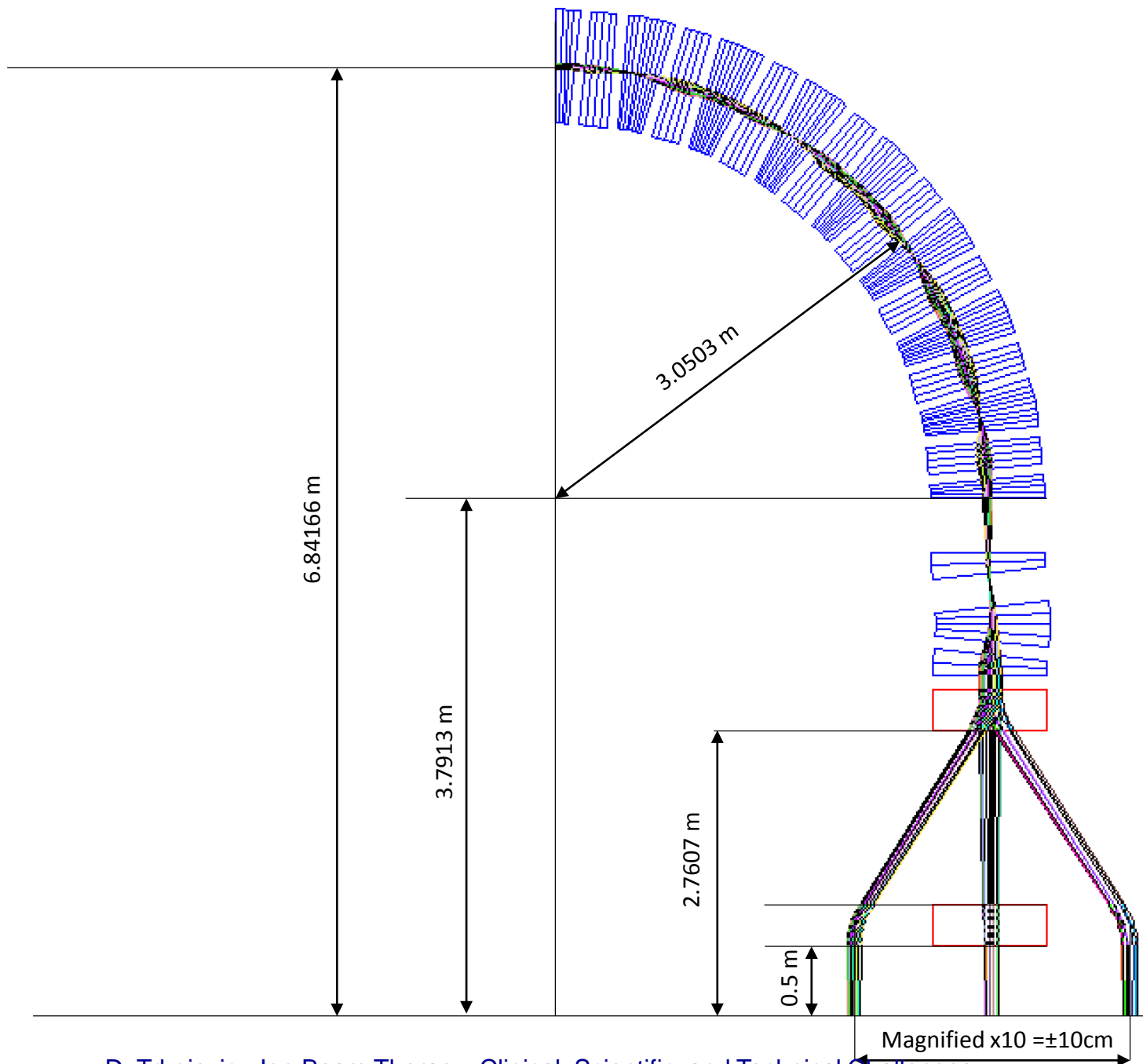


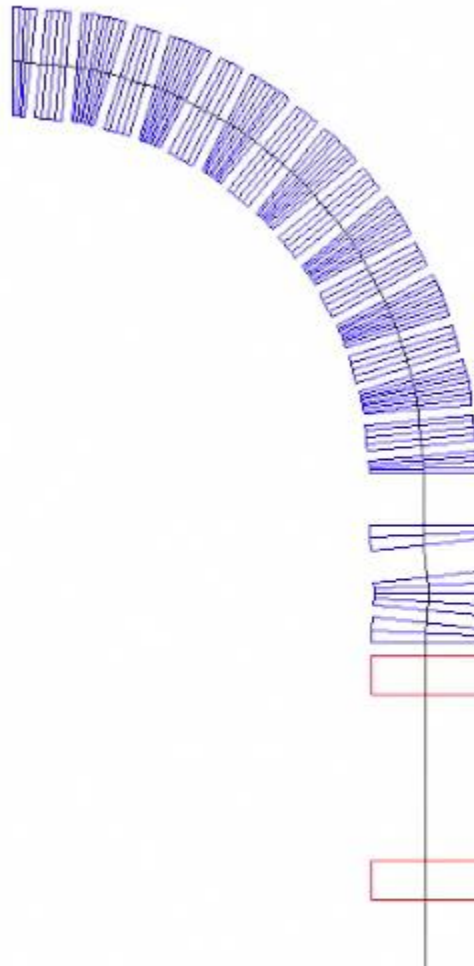


CARBON GANTRY $h=4.091\text{m}$ without magnification

400 MeV/u







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

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