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

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OUTLINE:

- Requests and Challenges
- Introduction: NS-FFAG?

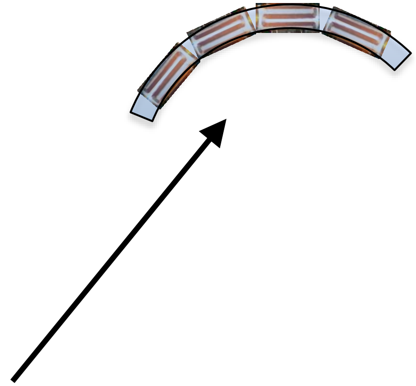
- Proton Gantries
- Permanent Magnet Gantry

- 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

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

$\Delta E_{k\ carbon}$=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]

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

$$proton\ ke_{\min} = 35\ MeV \qquad p_{\max} = 258.7\ MeV/c$$

← Permanent proton gantry

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

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

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

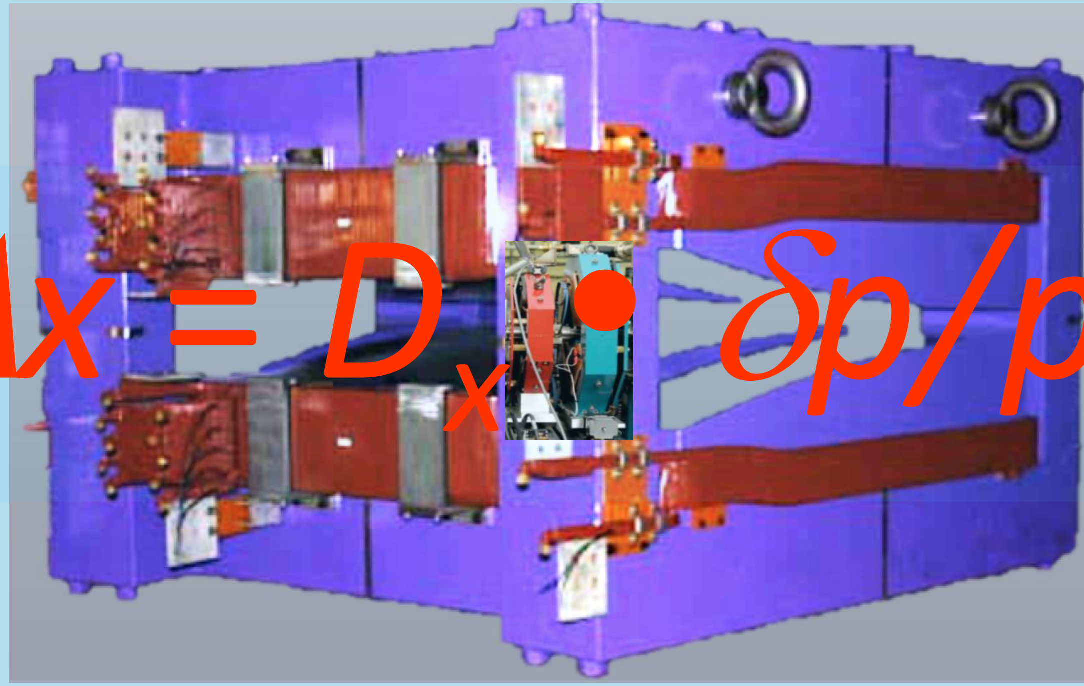
$$E_{k\min} = 195.44\ MeV/u \qquad p_{\min\ carbon} = 634.28\ MeV/c/u$$

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

← Superconducting carbon/proton gantry

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

MAKE IT SMALLER YET HIGHLY EFFECTIVE!



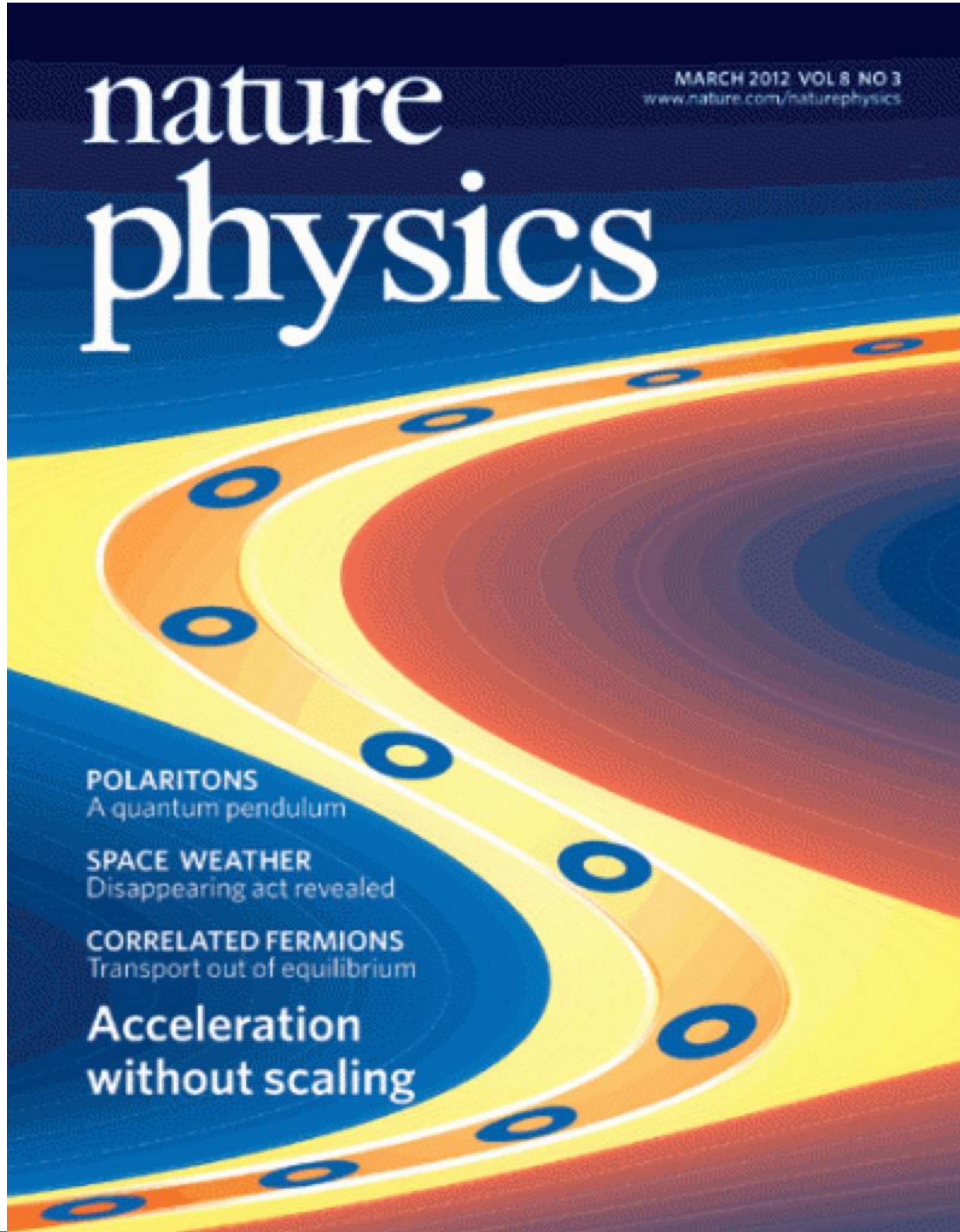
$$\Delta x = D_x \bullet \delta p/p$$

Two properties were annoying:

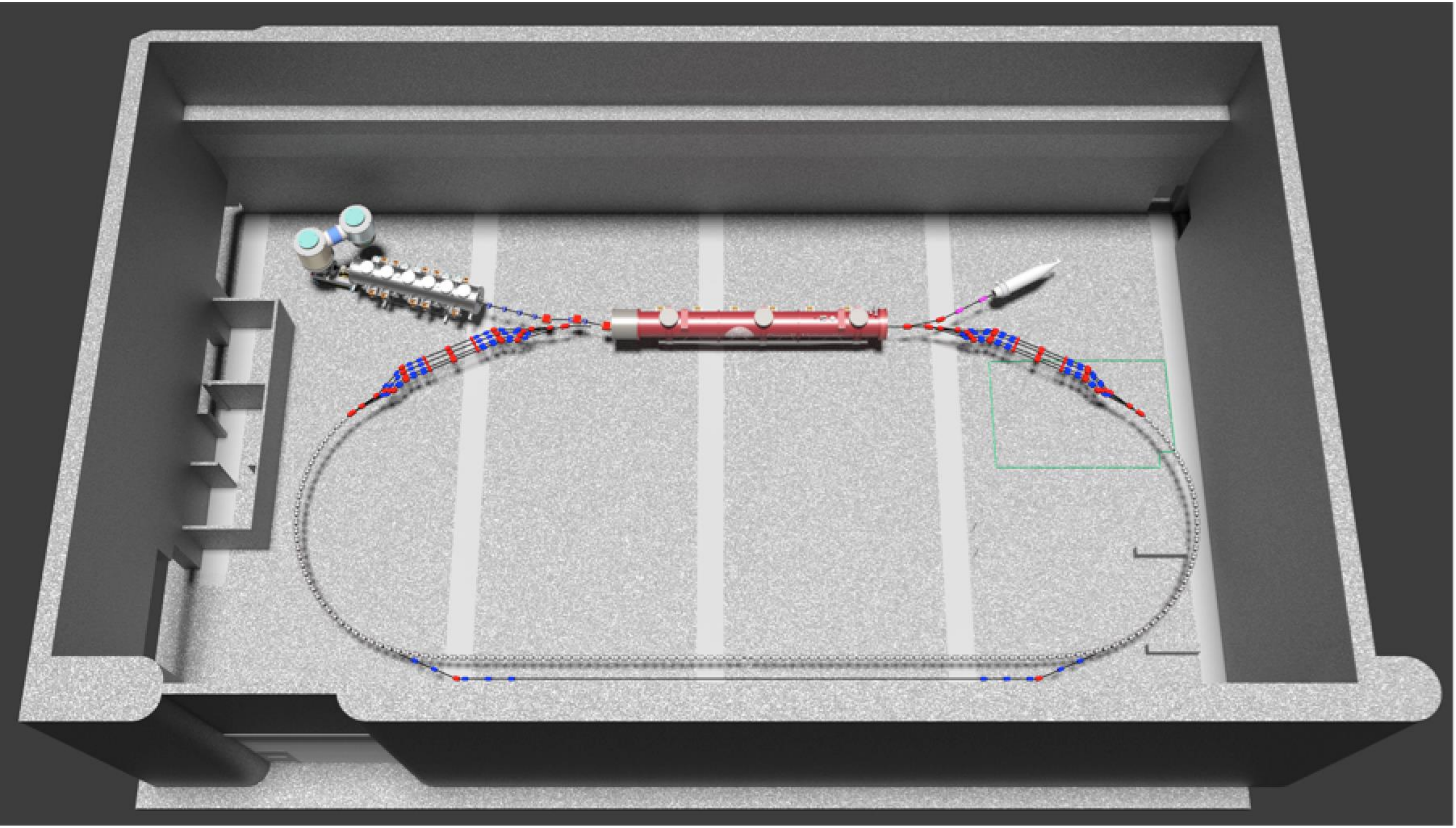
VERY LARGE MAGNET SIZE

30% OPPOSITE BEND - INNEFICIEN

?


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

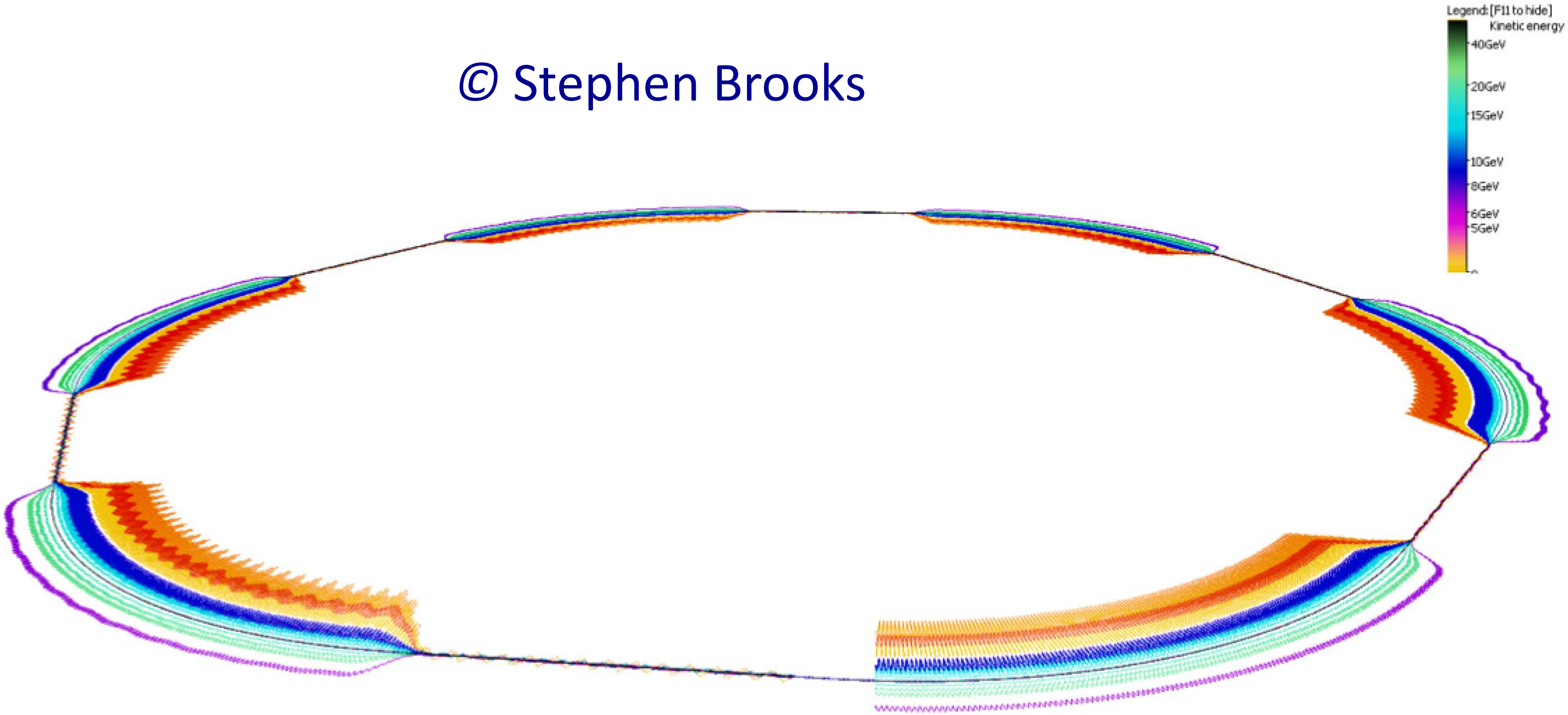
A new Energy Recovery Linac with the **Non-Scaling Fixed Field Alternating Gradient arcs and straight sections** is to be built at Cornell University Physics Department an eRHIC prototype



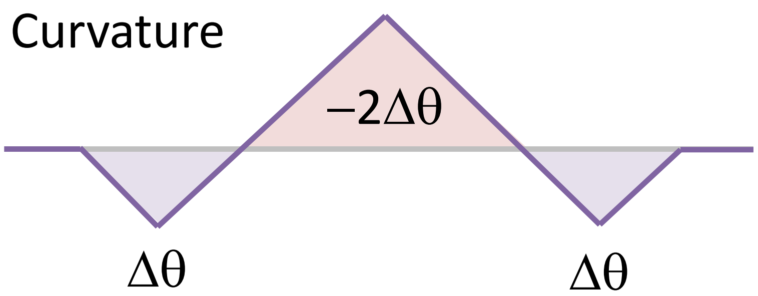
From AGS

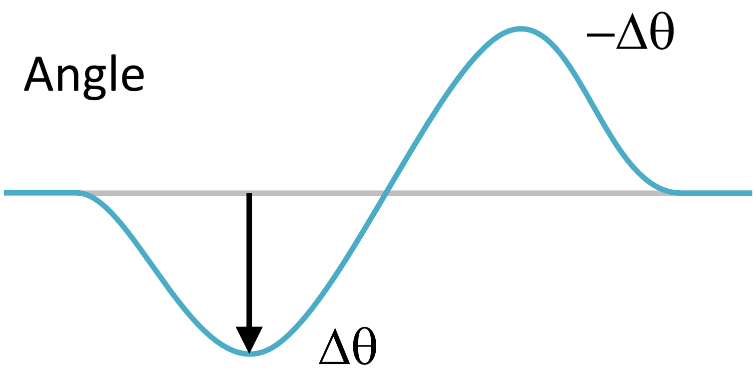
eRHIC FFAG Rings in Perspective

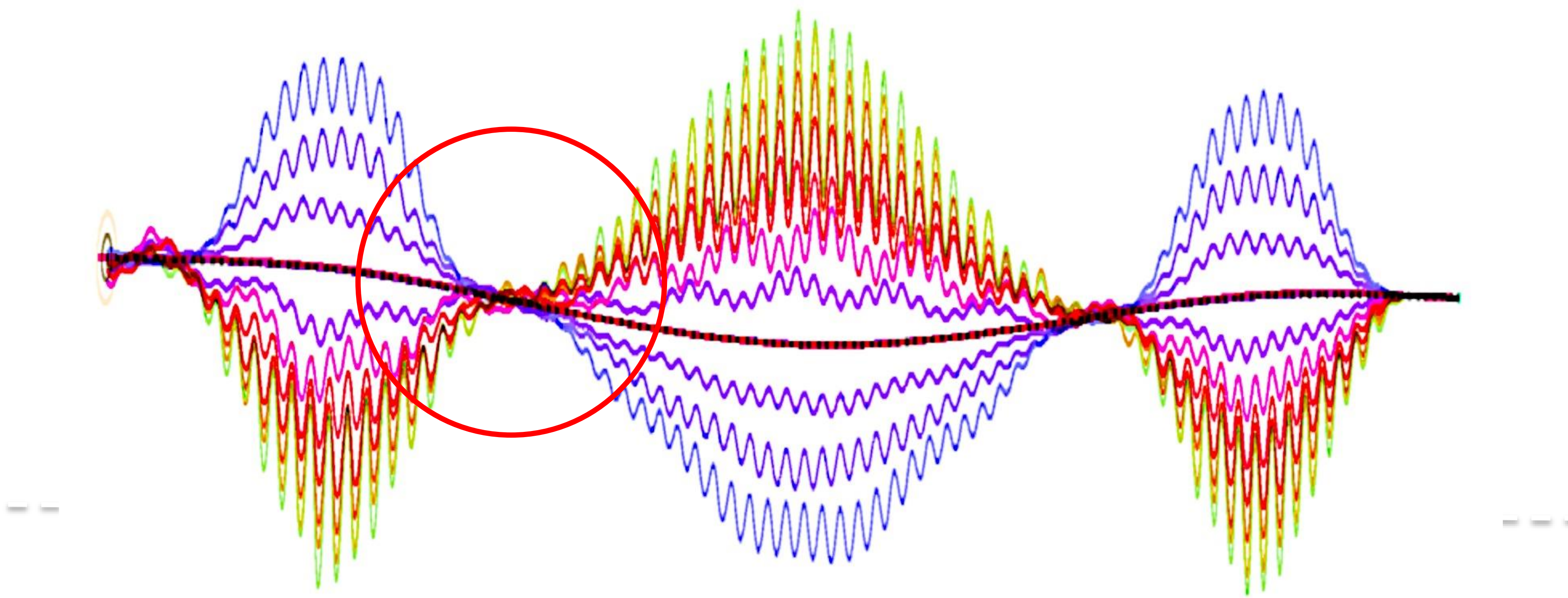
© Stephen Brooks



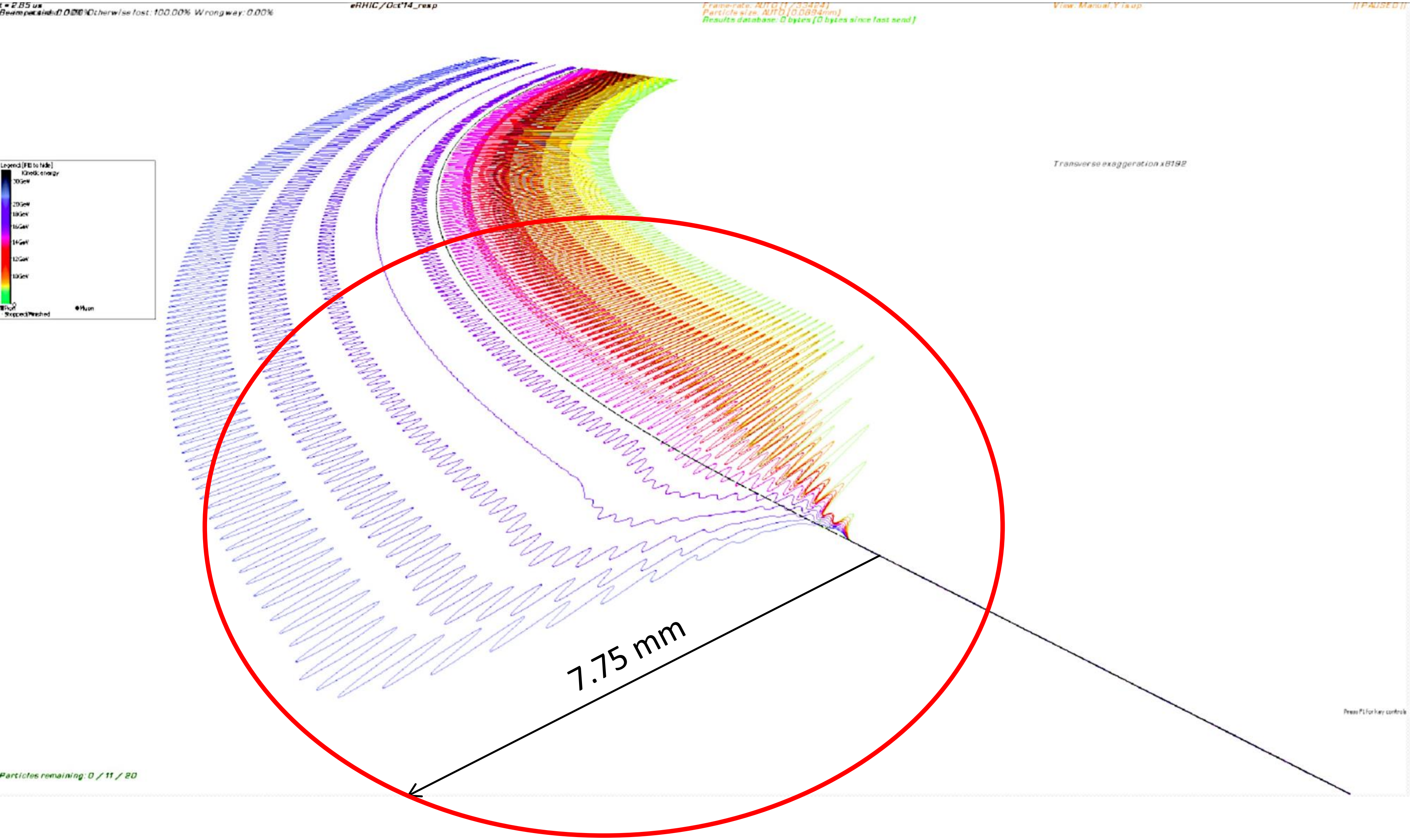
Detector Bypass Scheme: a Flexible FFAG



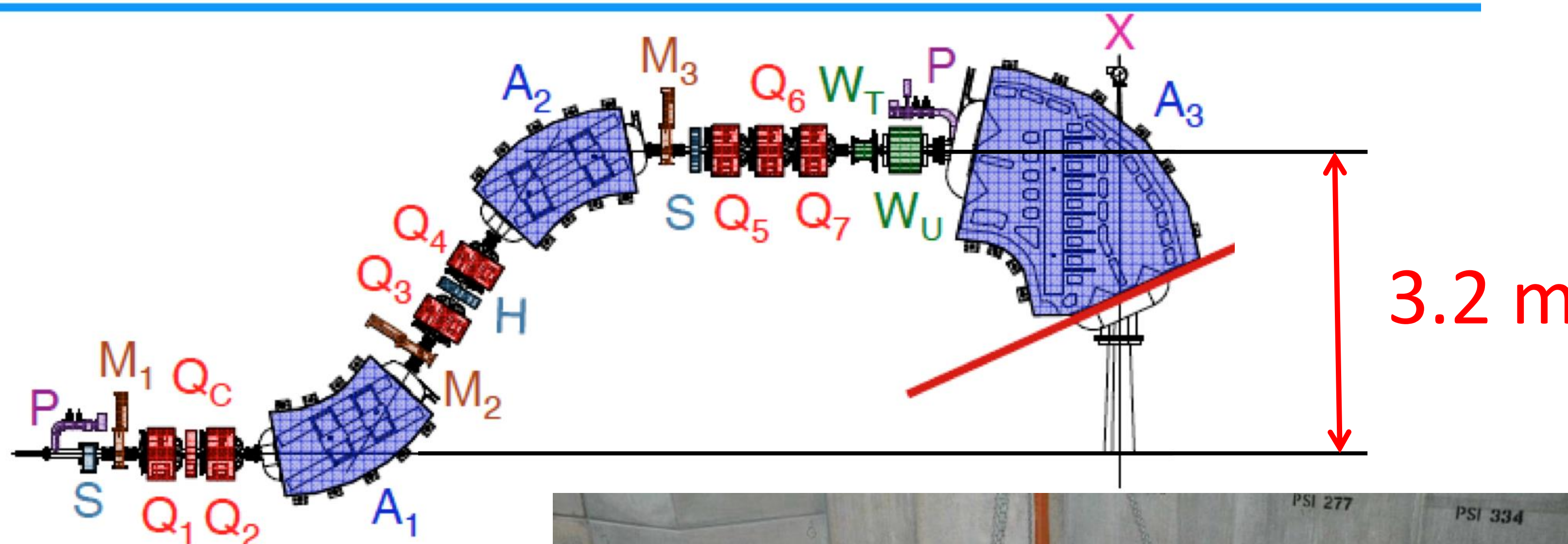




Merging FFAG arcs to the straight section in eRHIC



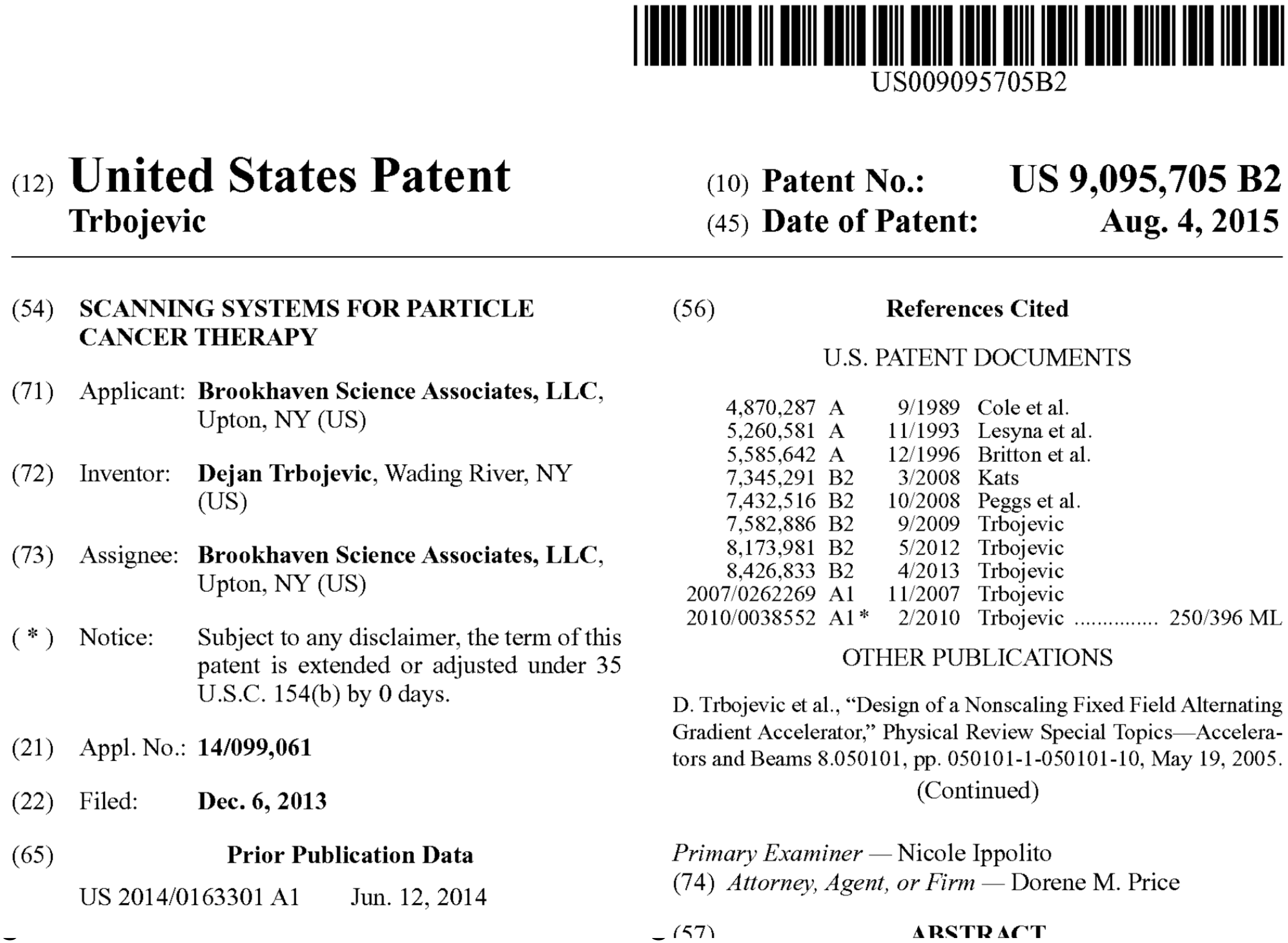
The state of the art proton gantry at PS



The state of the art proton gantry at PSI

SAD – SOURCE-TO-AXIS-DISTANCE

VIRTUAL Source to Patient Distance



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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)

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

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

(65) **Prior Publication Data**

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(Continued)

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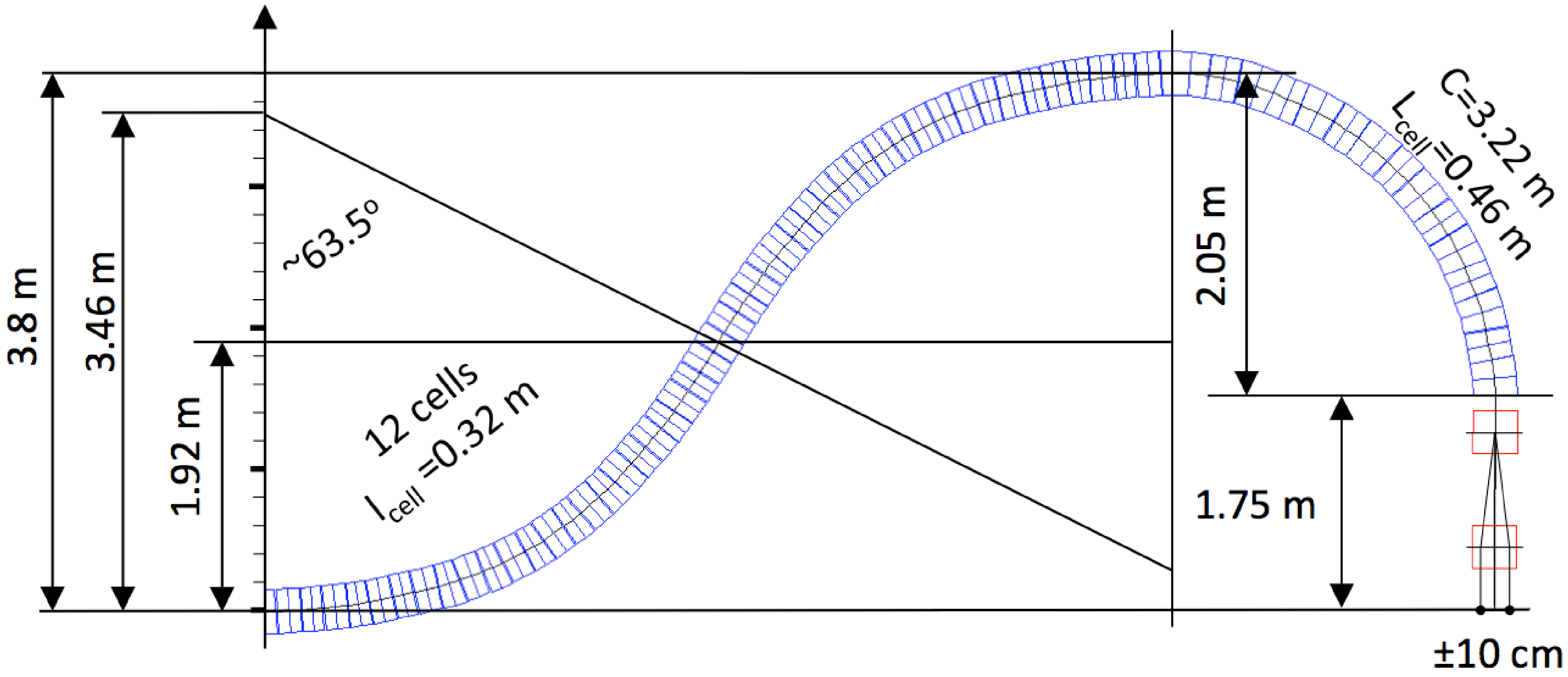
(57) ABSTRACT

Axis

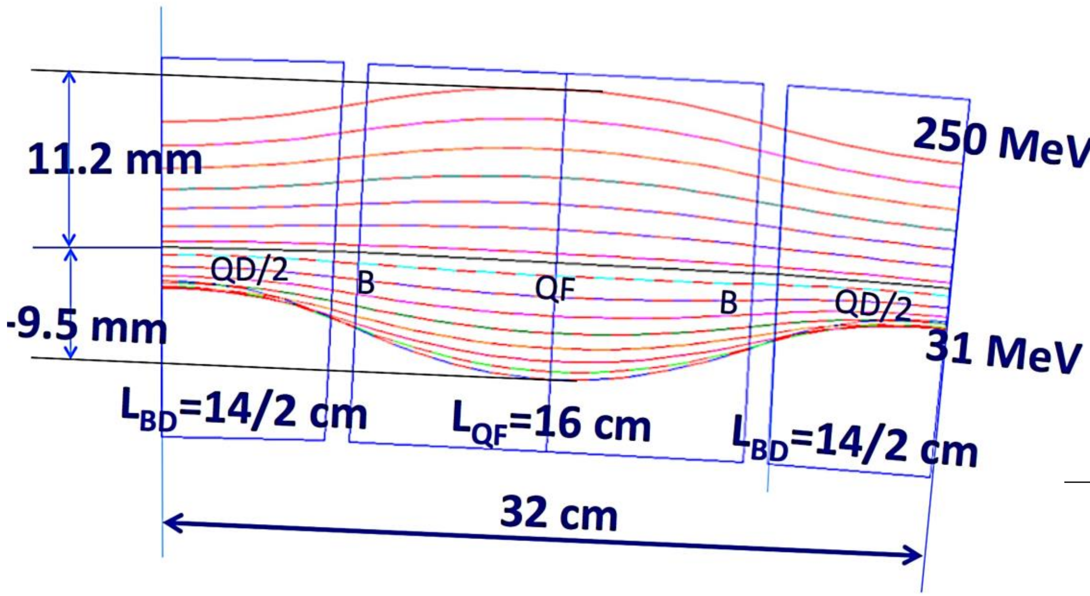
Axis

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

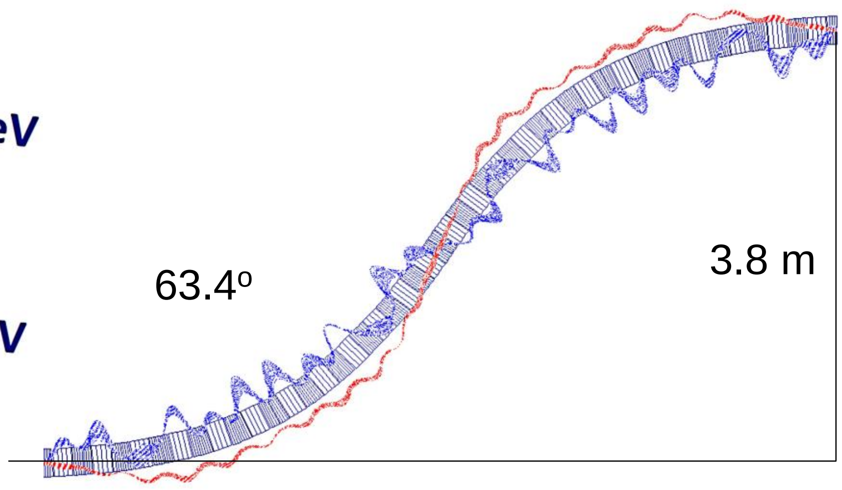


Halbach Permanent Magnet Gantry

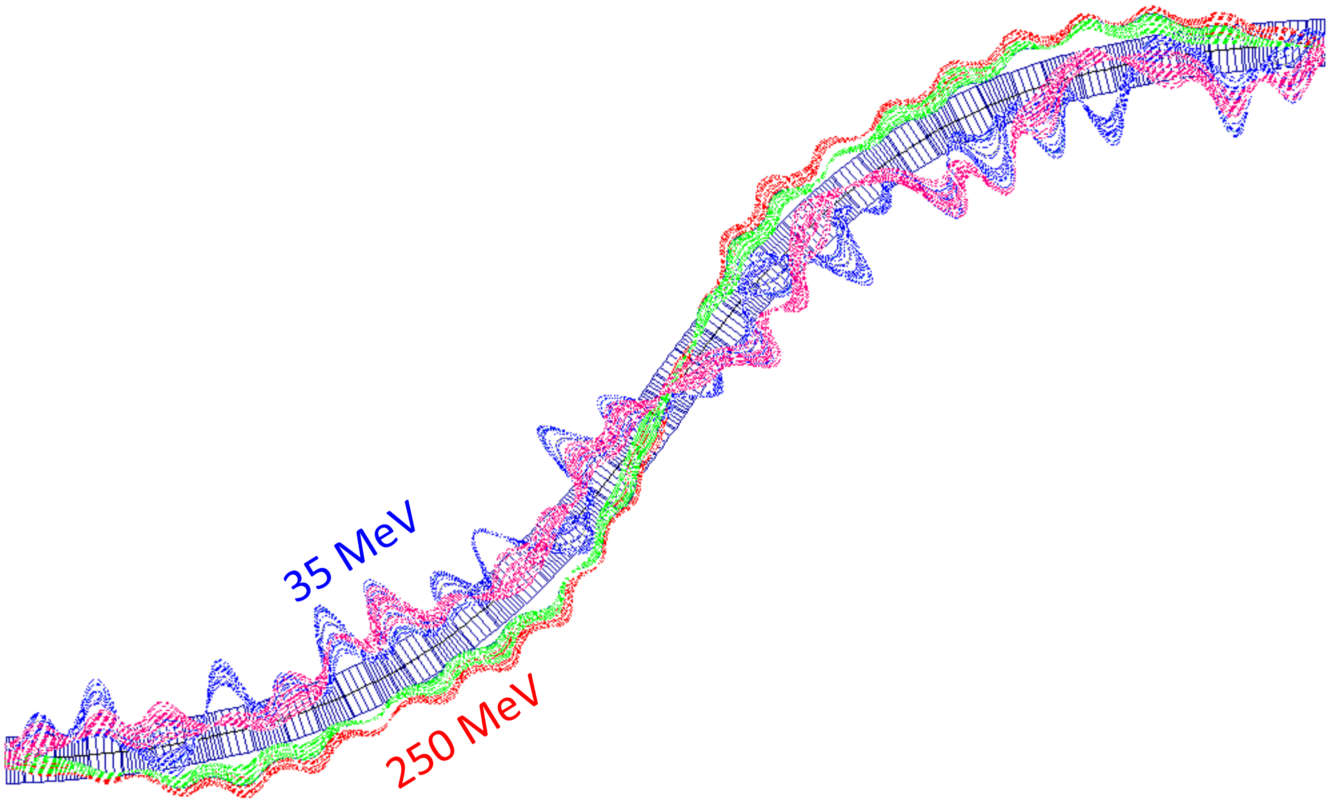
The Basic Cell



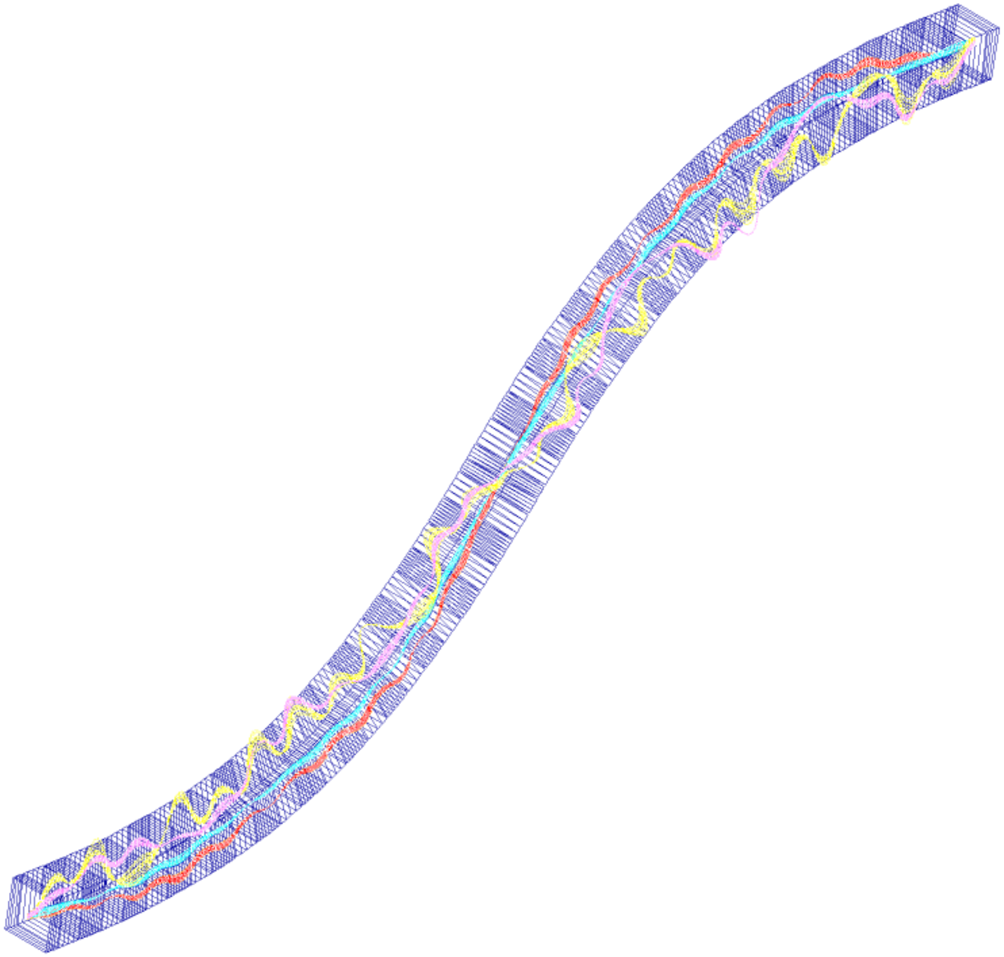
Magnified Orbit Offset for
35 MeV – 250 MeV protons



Permanent Halbach Magnet NS-FFAG Proton Gantry

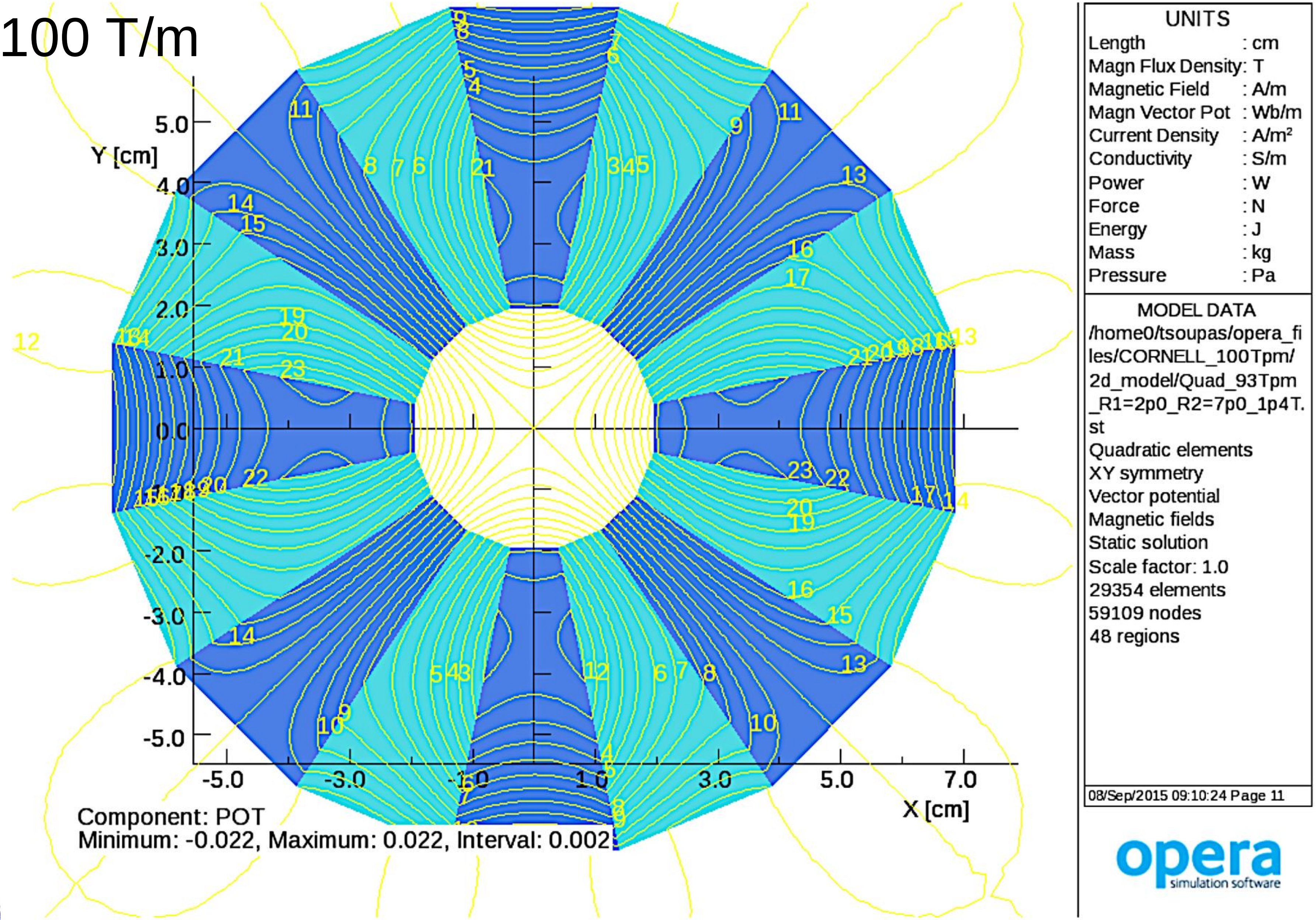


Orbits in 3D in half of the Superconducting Gantry



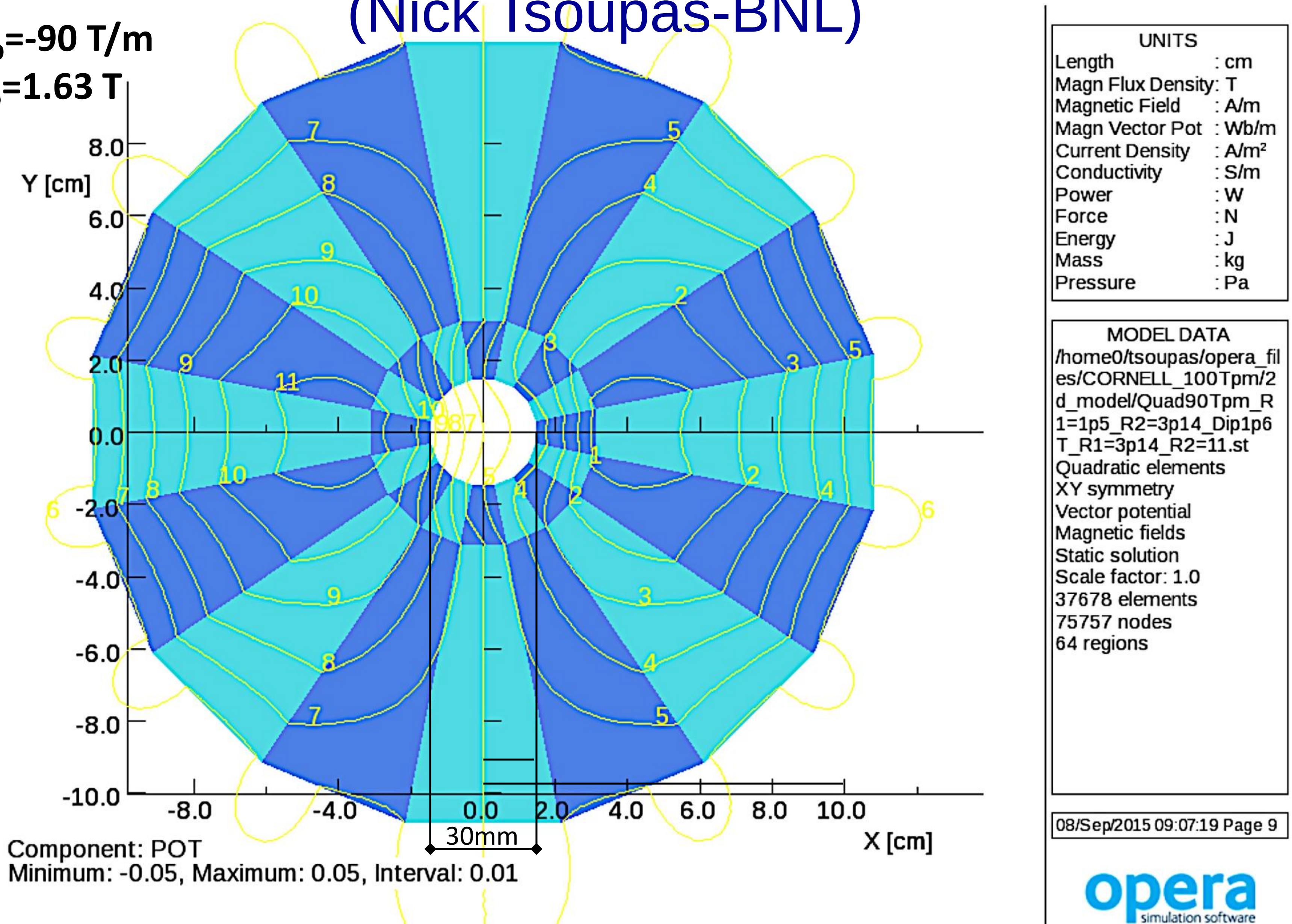
Gantry Halbach Magnet Design (Nick Tsoupas –BNL)

G=100 T/m



Gantry Halbach Magnet Design (Nick Tsoupas-BNL)

G_D=-90 T/m
B_D=1.63 T

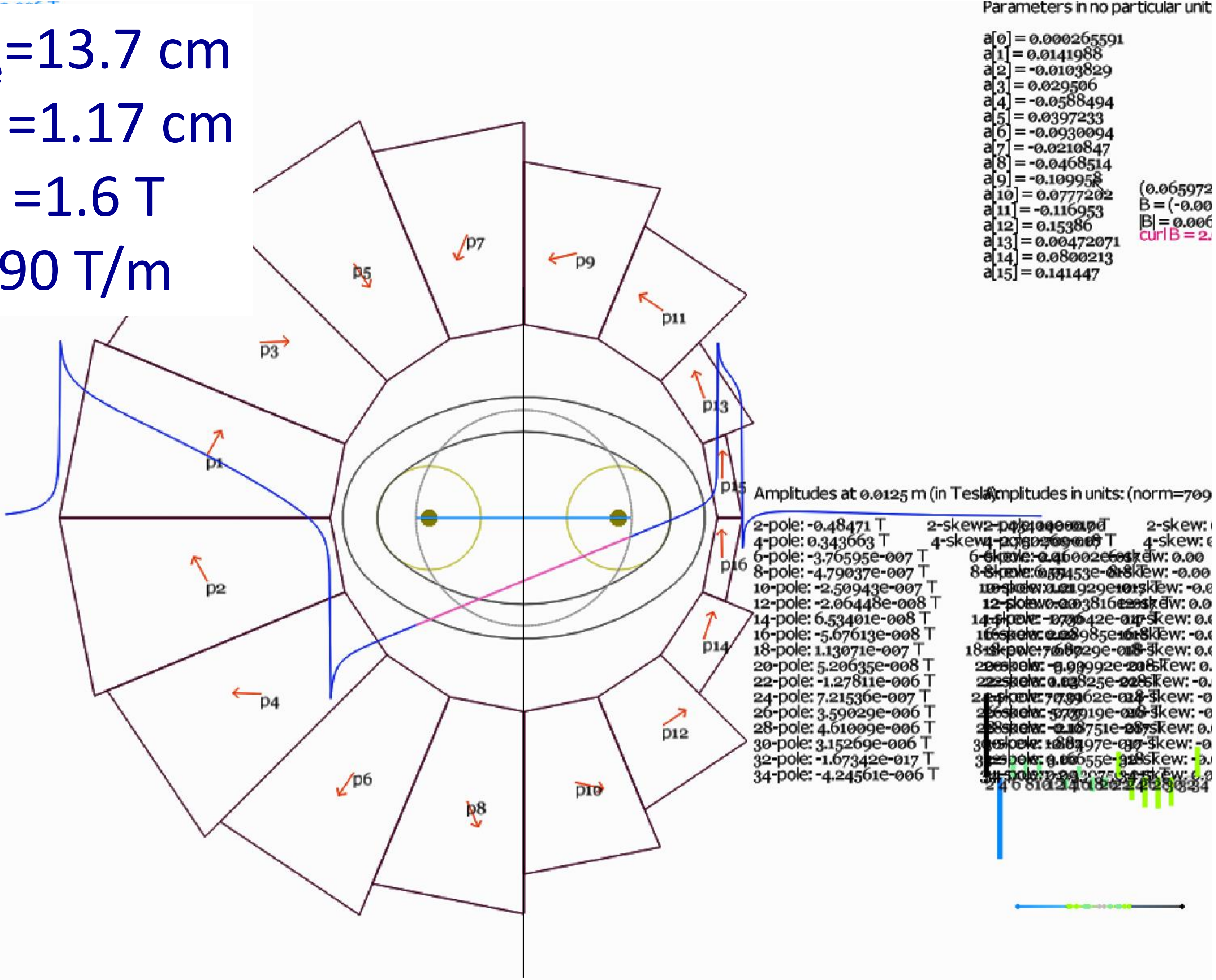


$R_{outside}$ = 13.7 cm

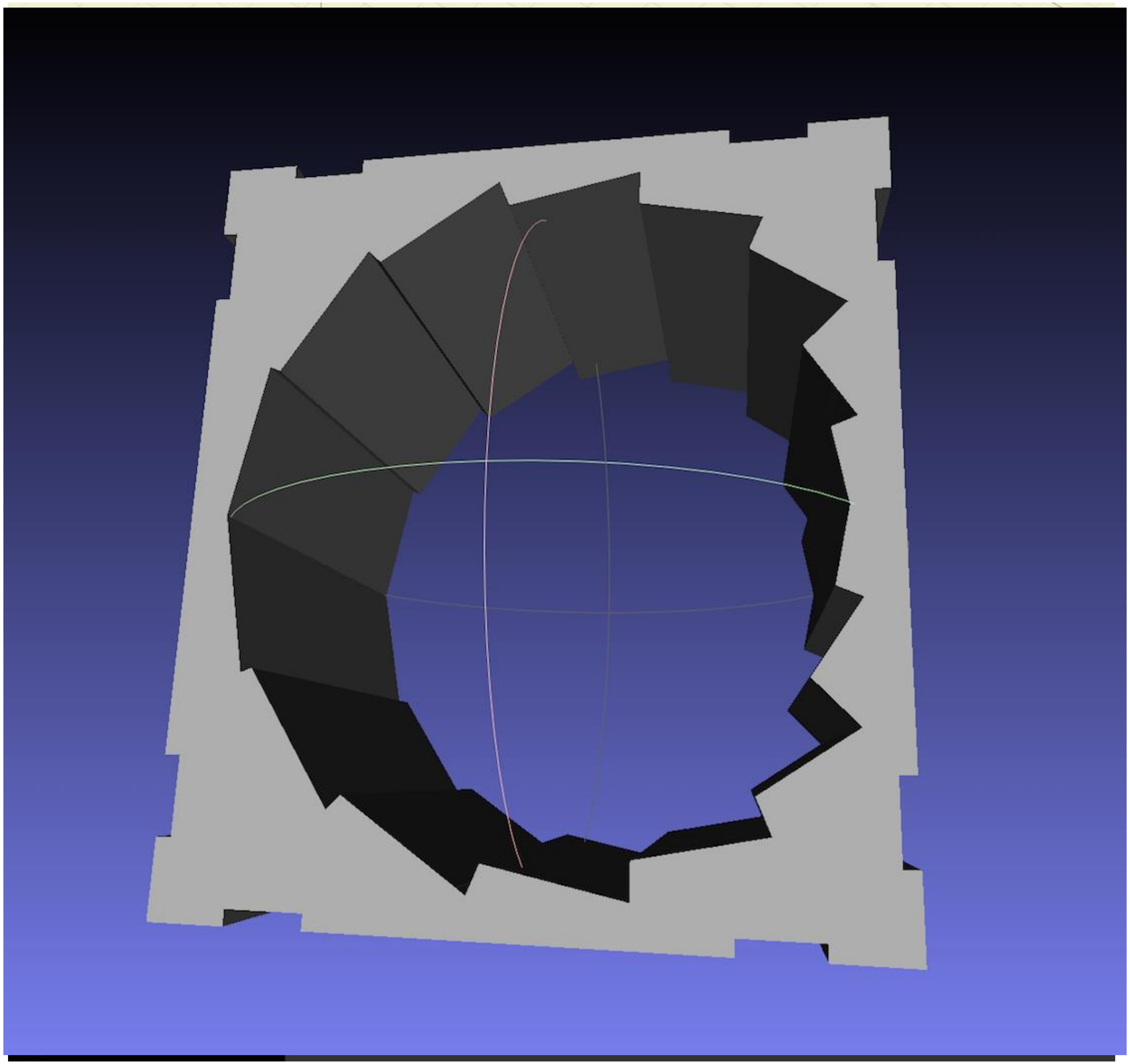
R_{inside} = 1.17 cm

B_{dipole} = 1.6 T

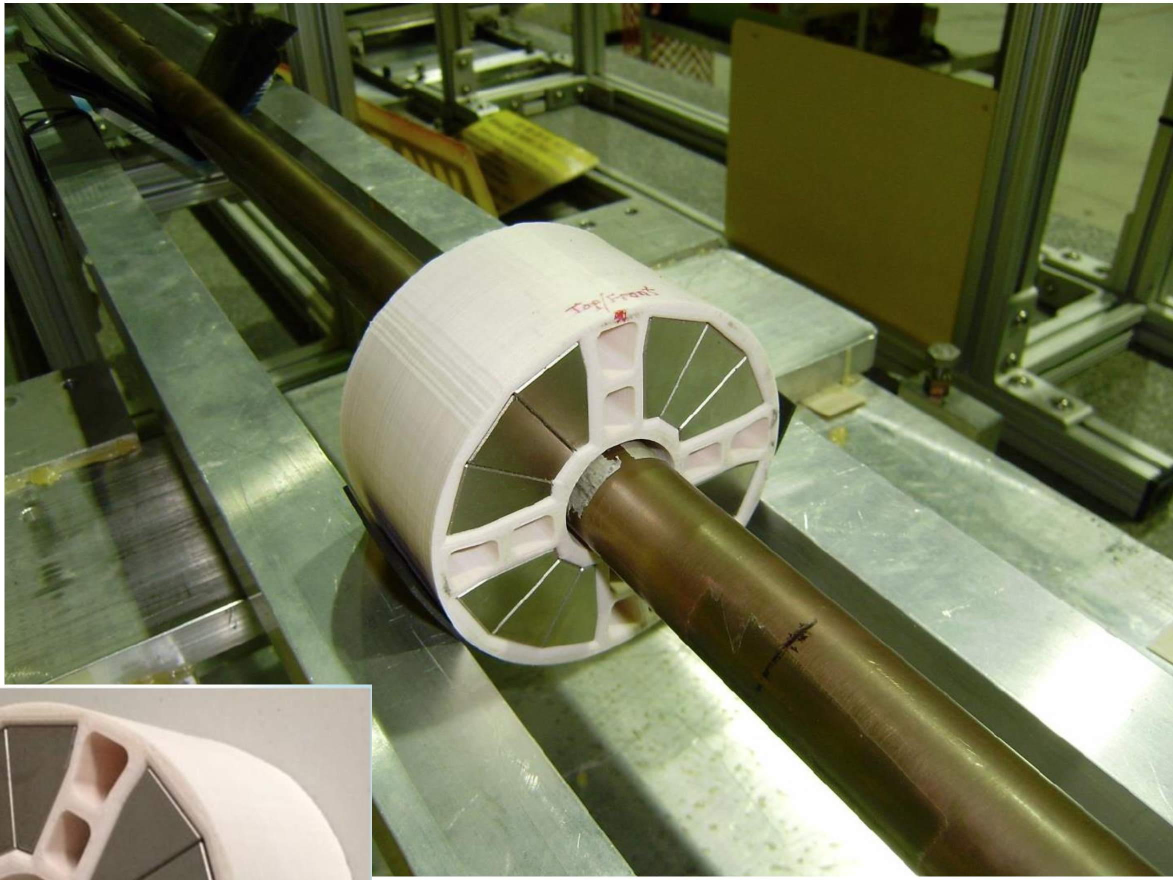
G_D = 90 T/m

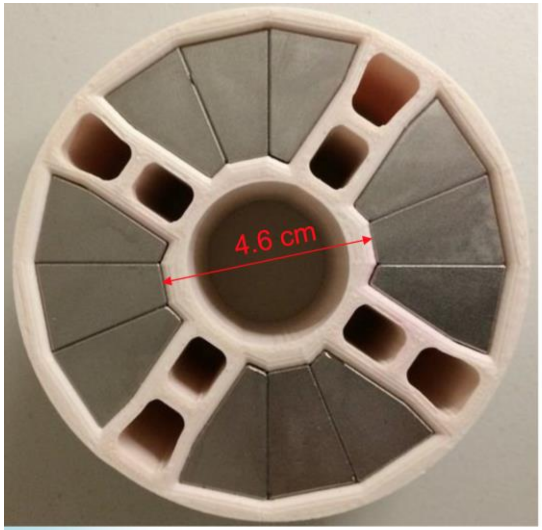


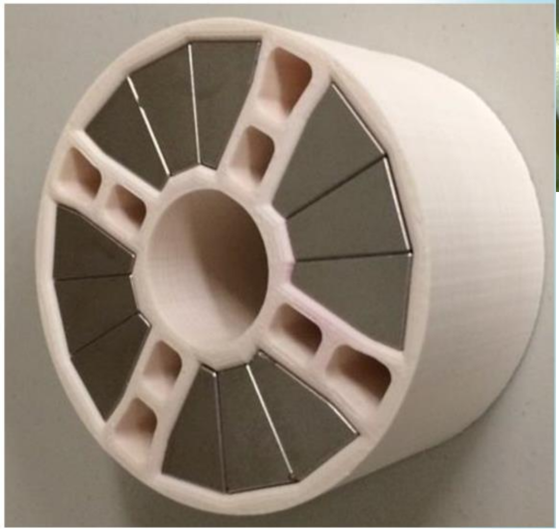
Built Models of Defocusing Modified Halbach Magnet



Modified Halbach magnets for BNL eRHIC



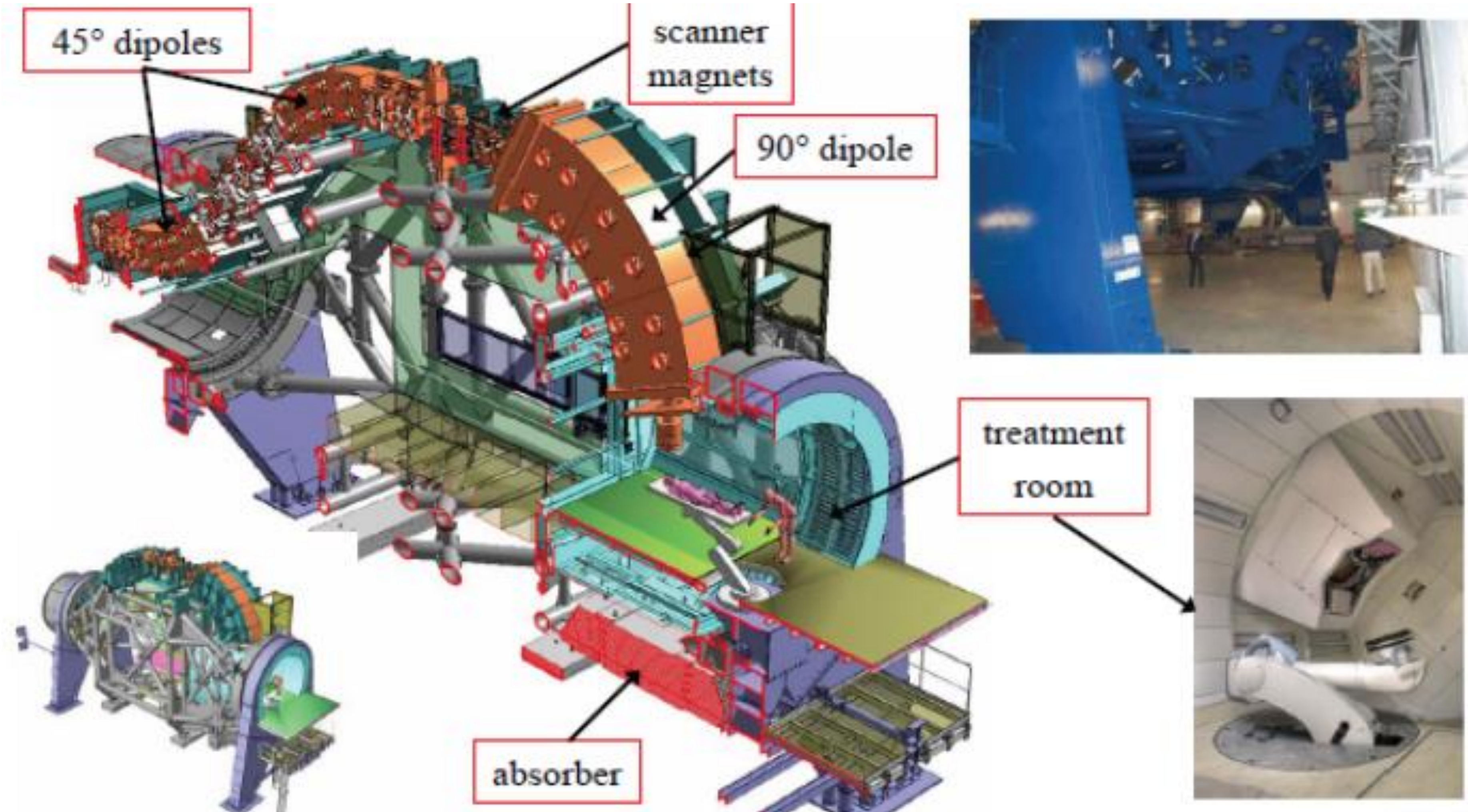


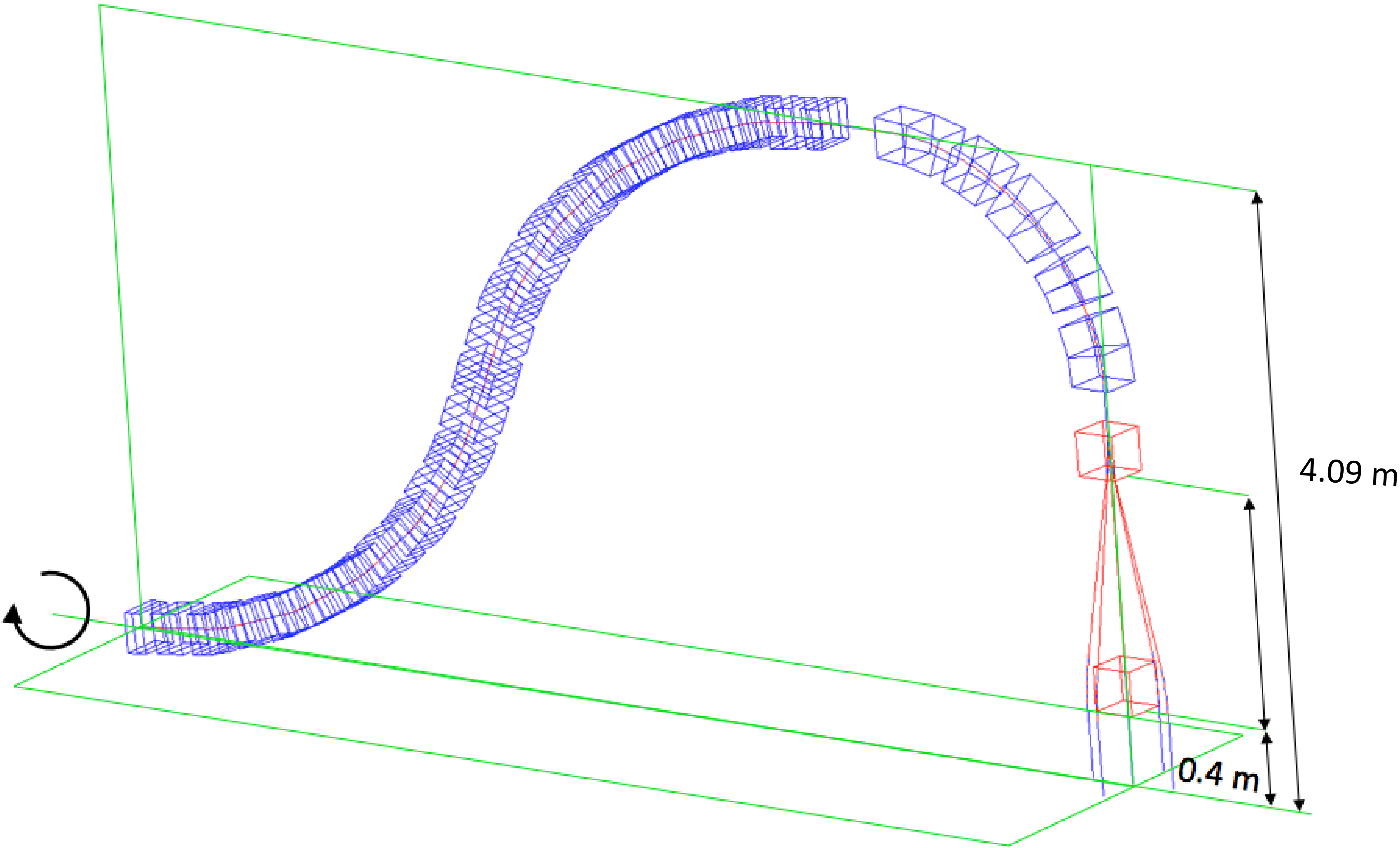


State of the art C-gantry at Heidelberg

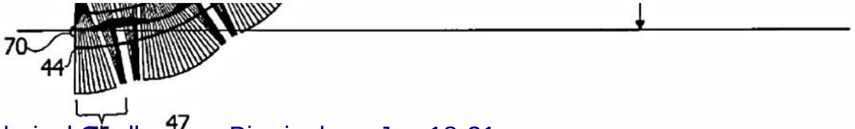
Weight of the transport components – 135 tons

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

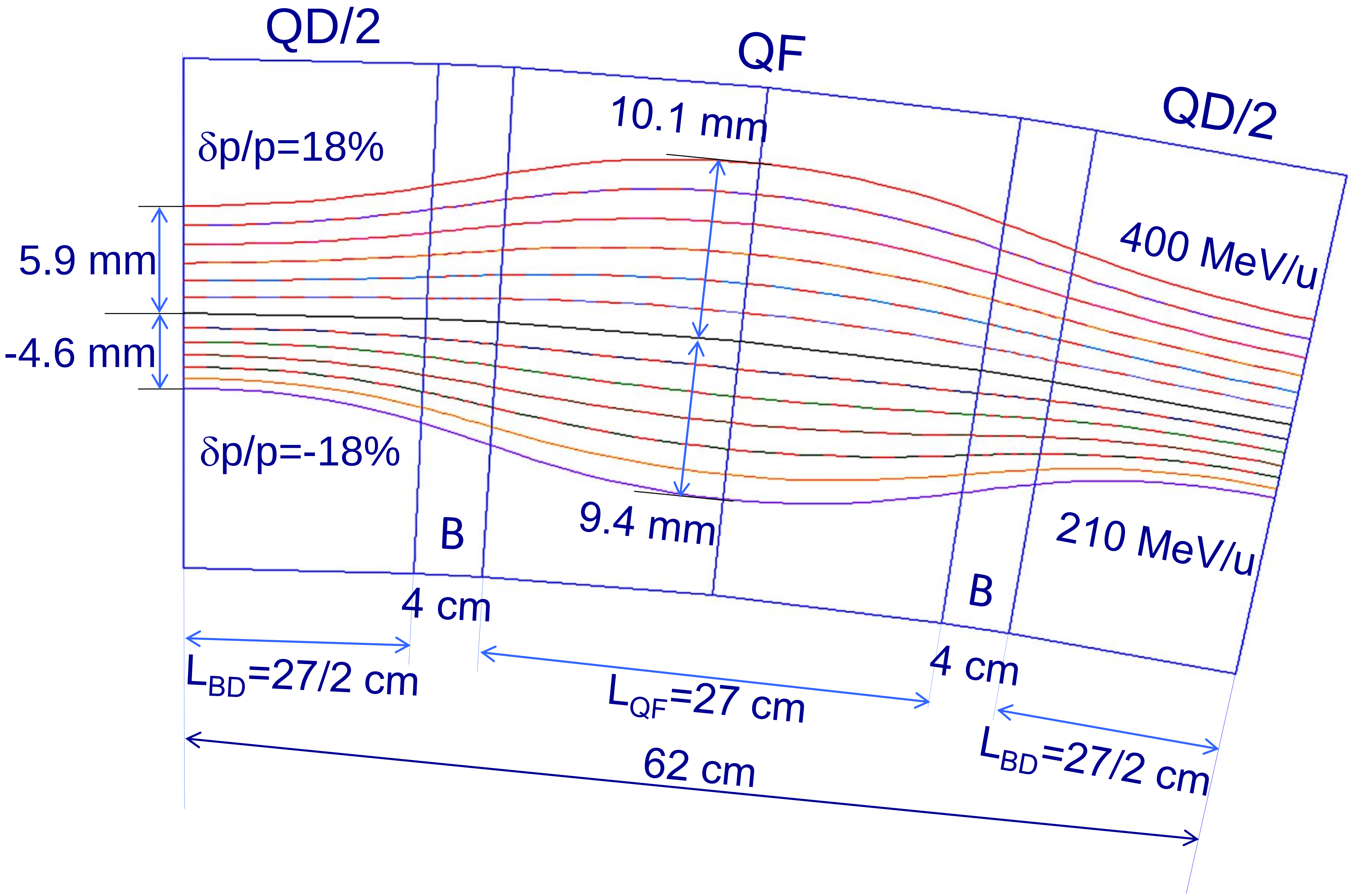




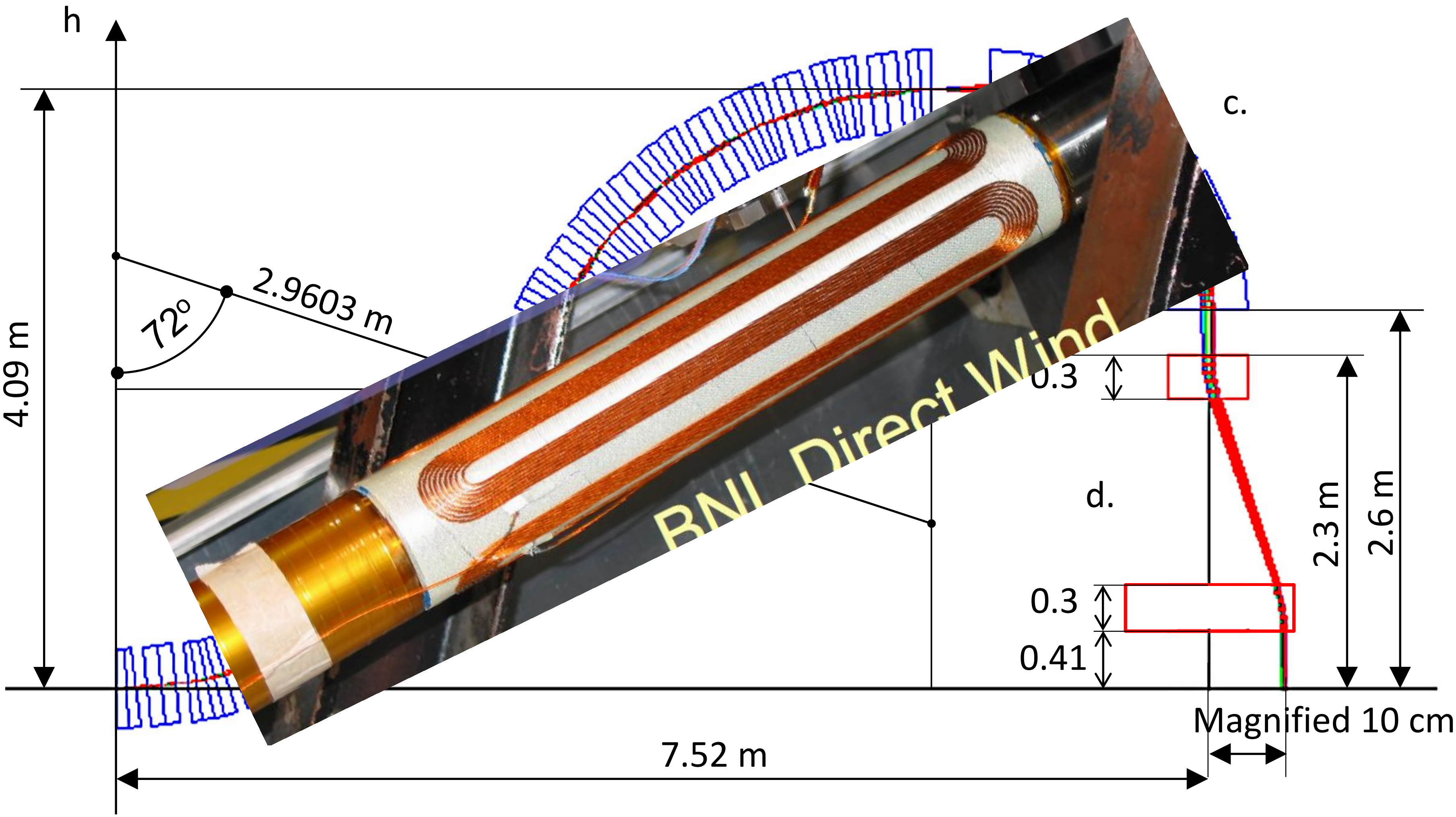
Superconducting magnets



Very strong focusing Basic Cell

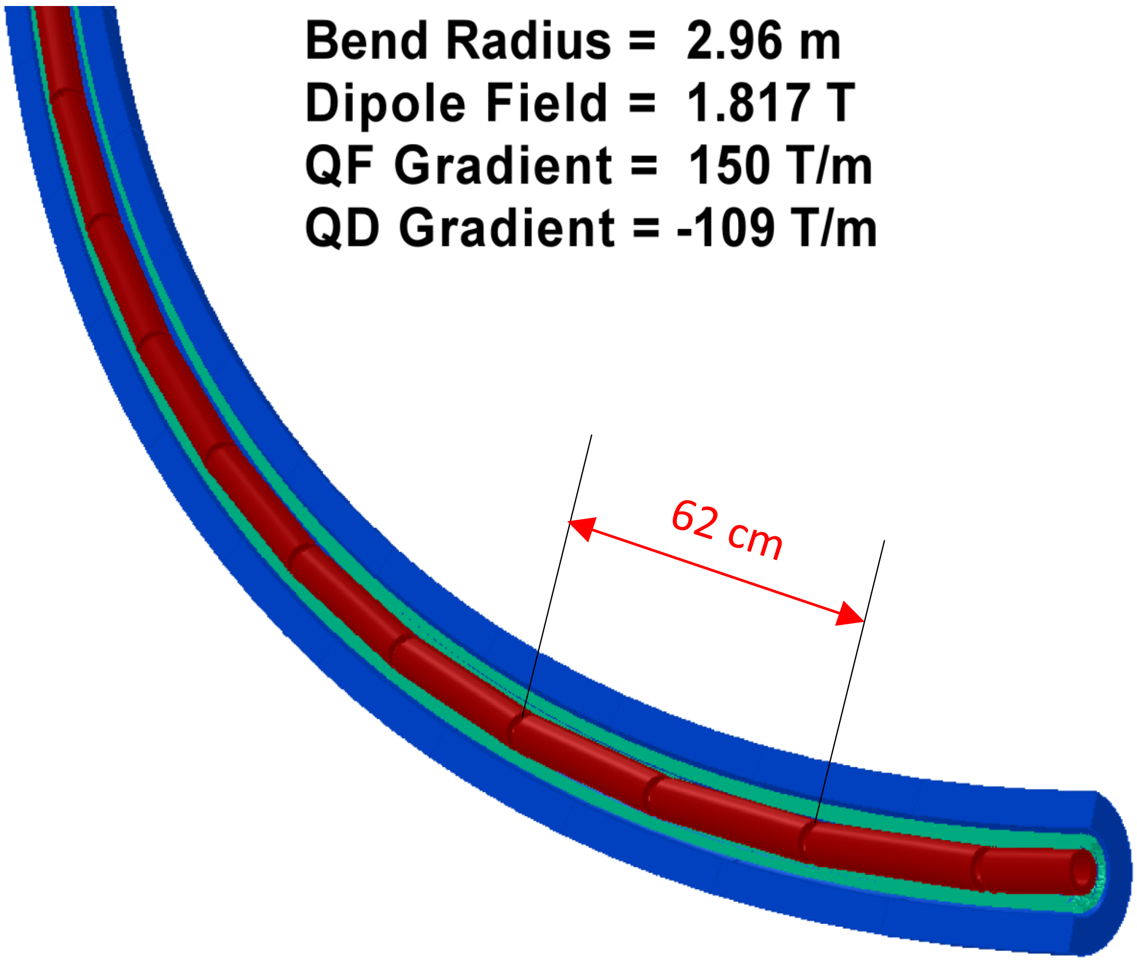


Reducing the size and weight from:
135 tons → to 3 tons

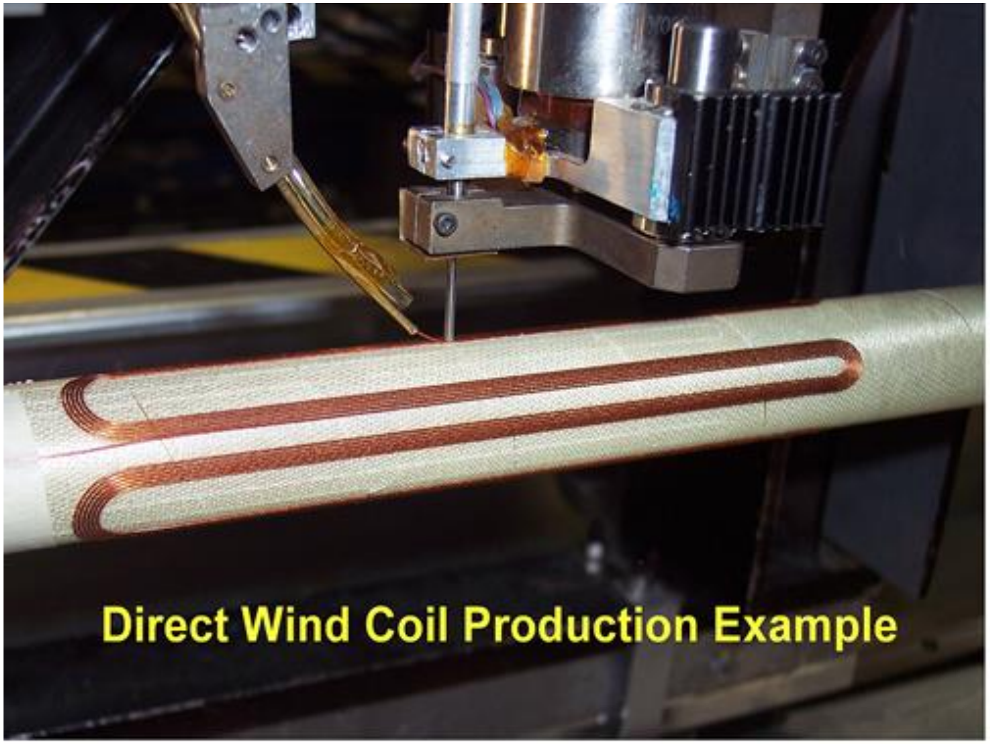


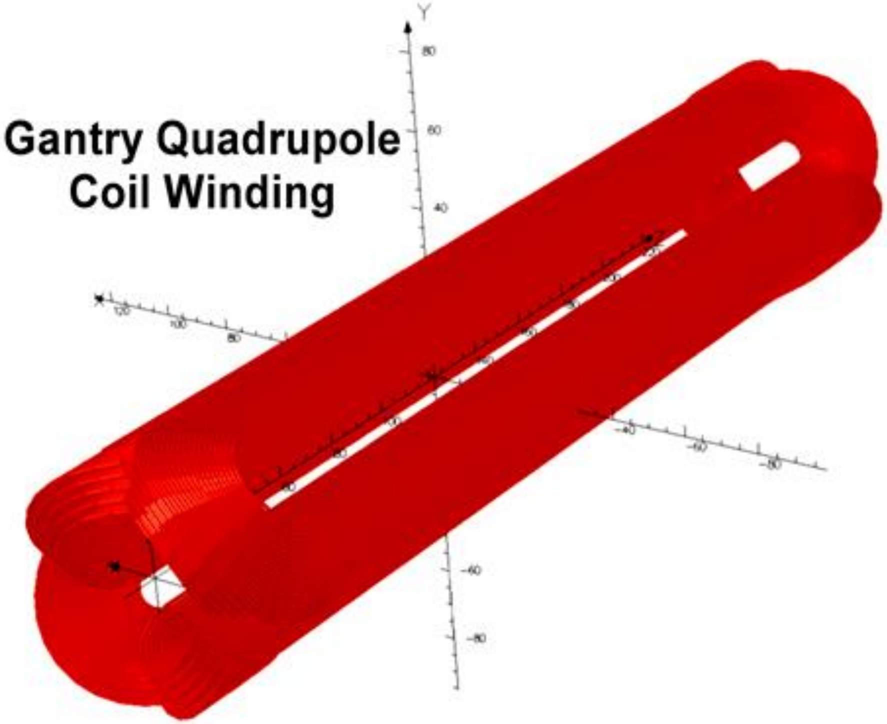
THE PROPOSAL FOR SUPERCONDUCTING CARBON/PROTON GANTRY

Bend Radius = 2.96 m
Dipole Field = 1.817 T
QF Gradient = 150 T/m
QD Gradient = -109 T/m

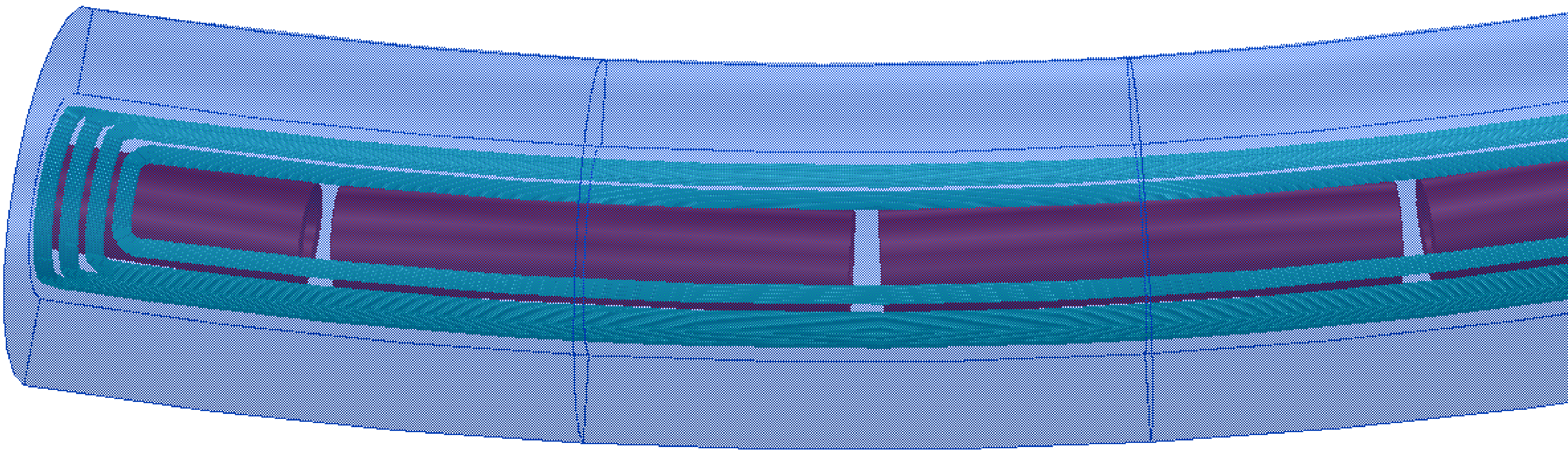


Tools and quadrupole windings (Brett Parker – BNL)

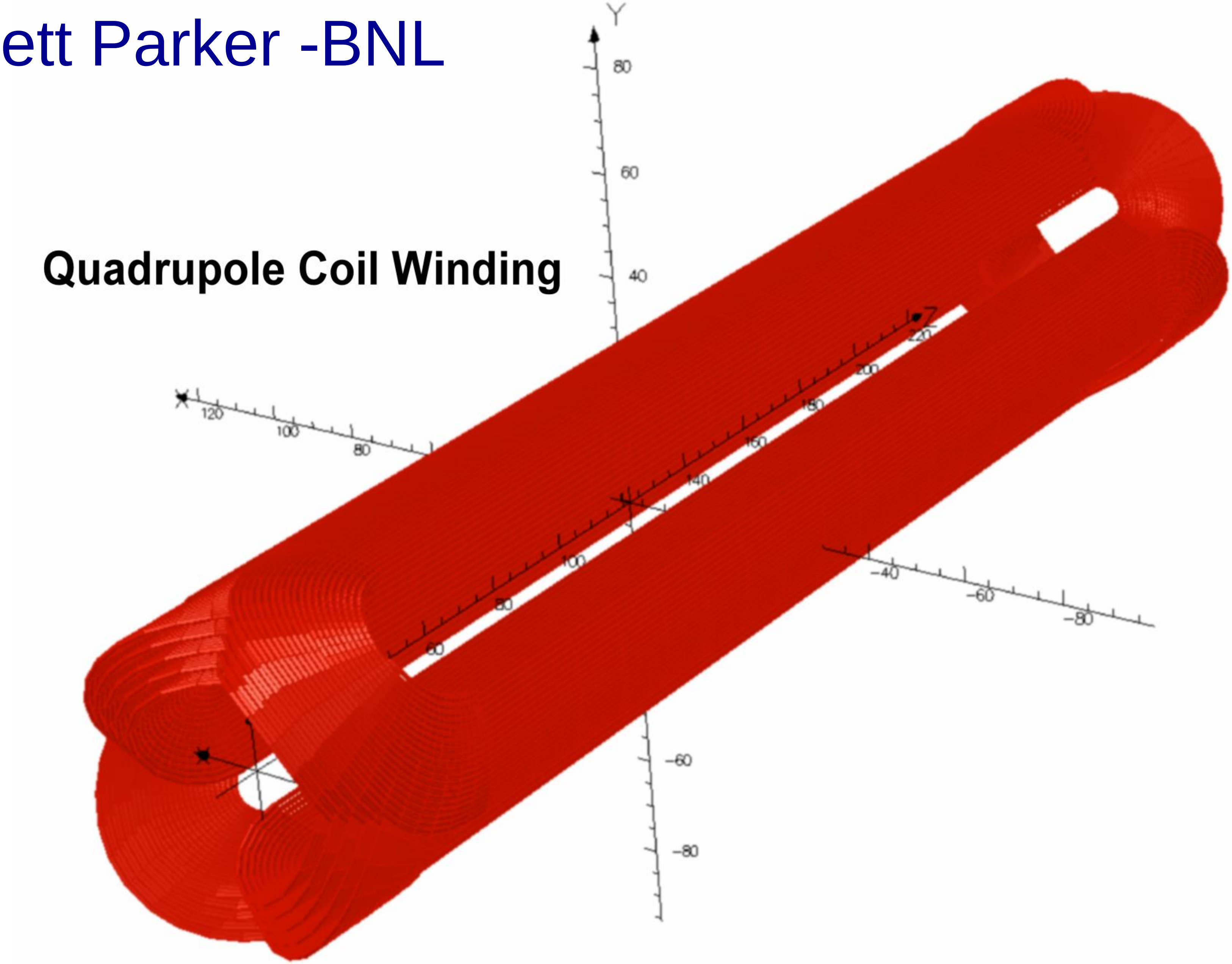




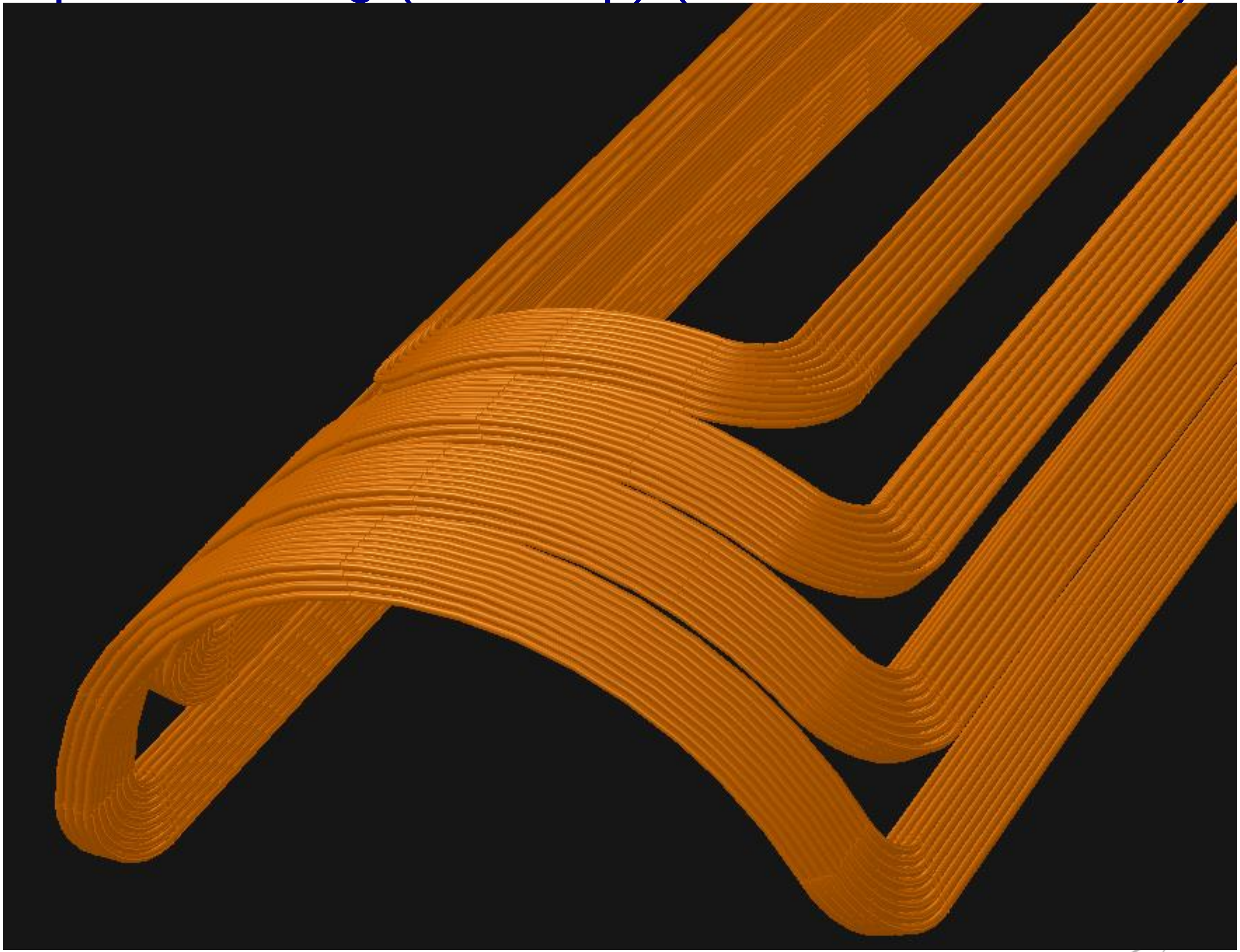
Achromatic Part of the Superconducting Gantry (Brett Parker – BNL)



Brett Parker -BNL

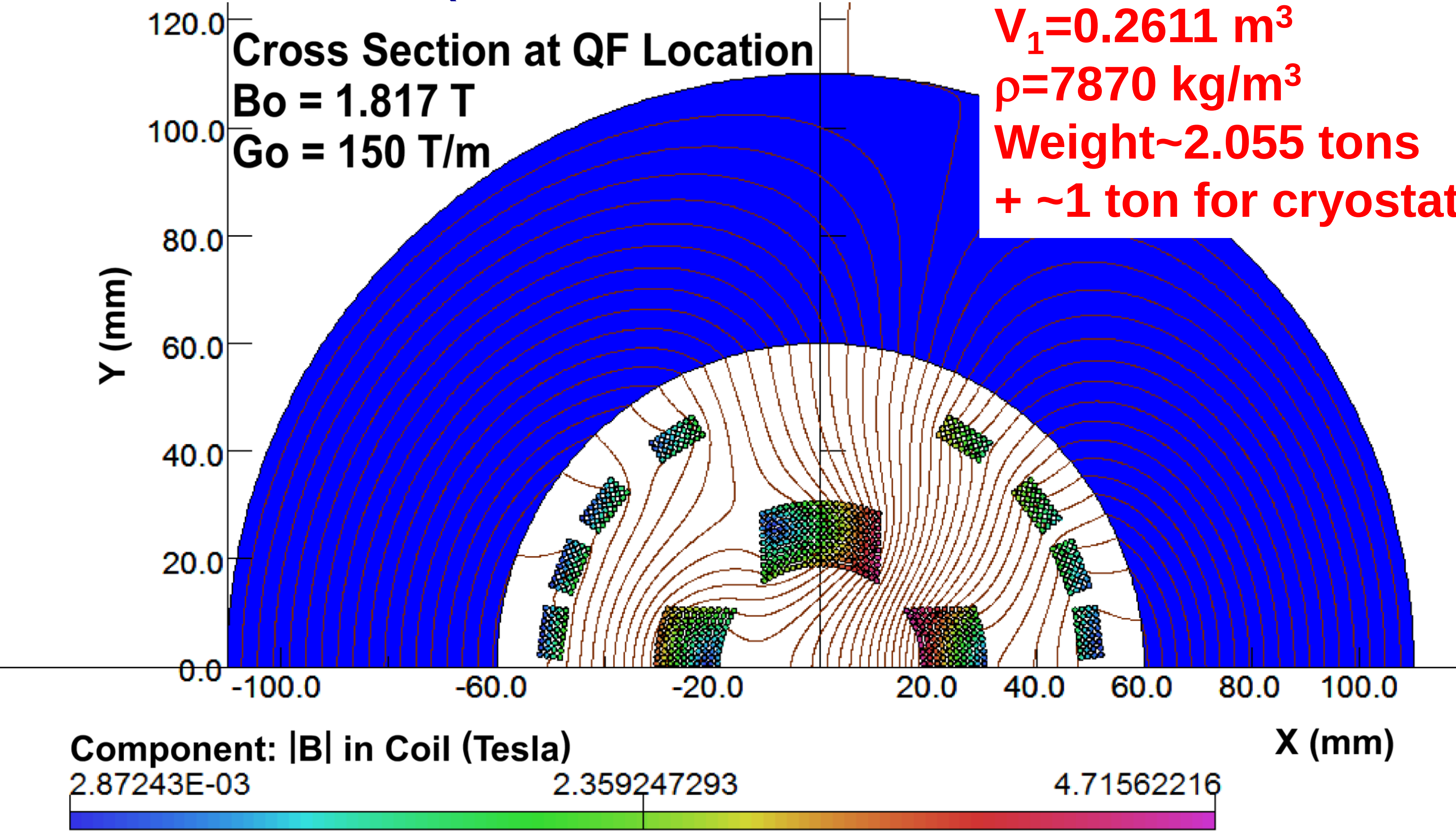


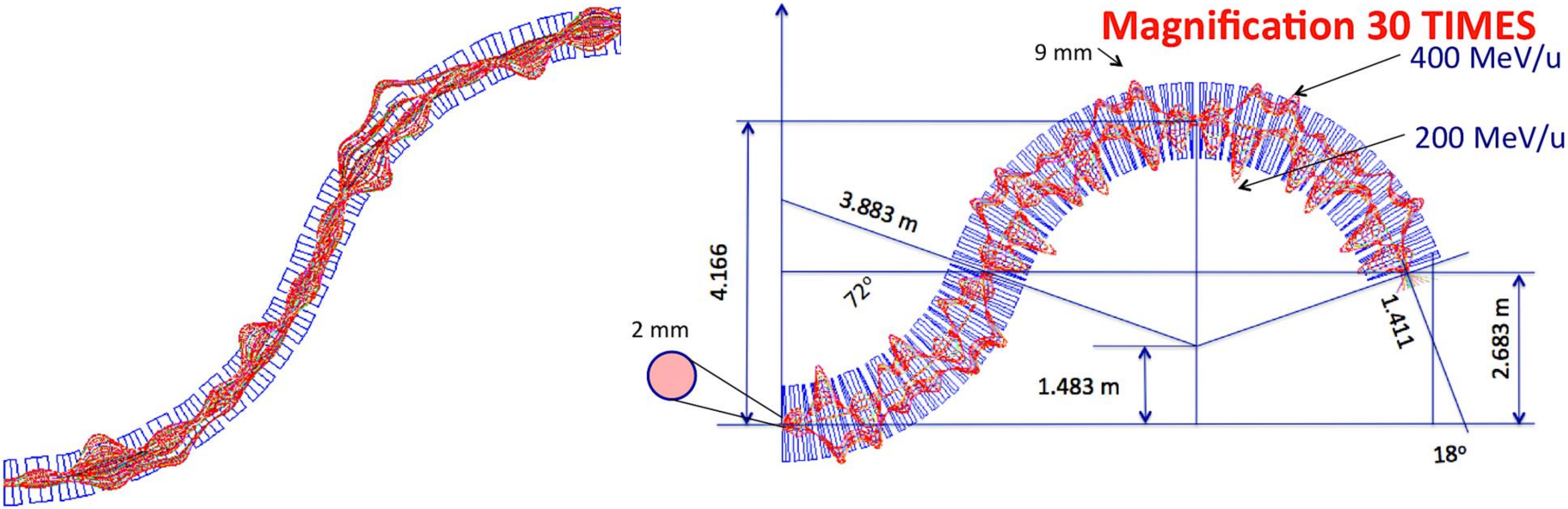
Dipole winding (close-up) (Brett Parker – BNL)



Magnetic field of the Superconducting Gantry (Brett Parker – BNL)

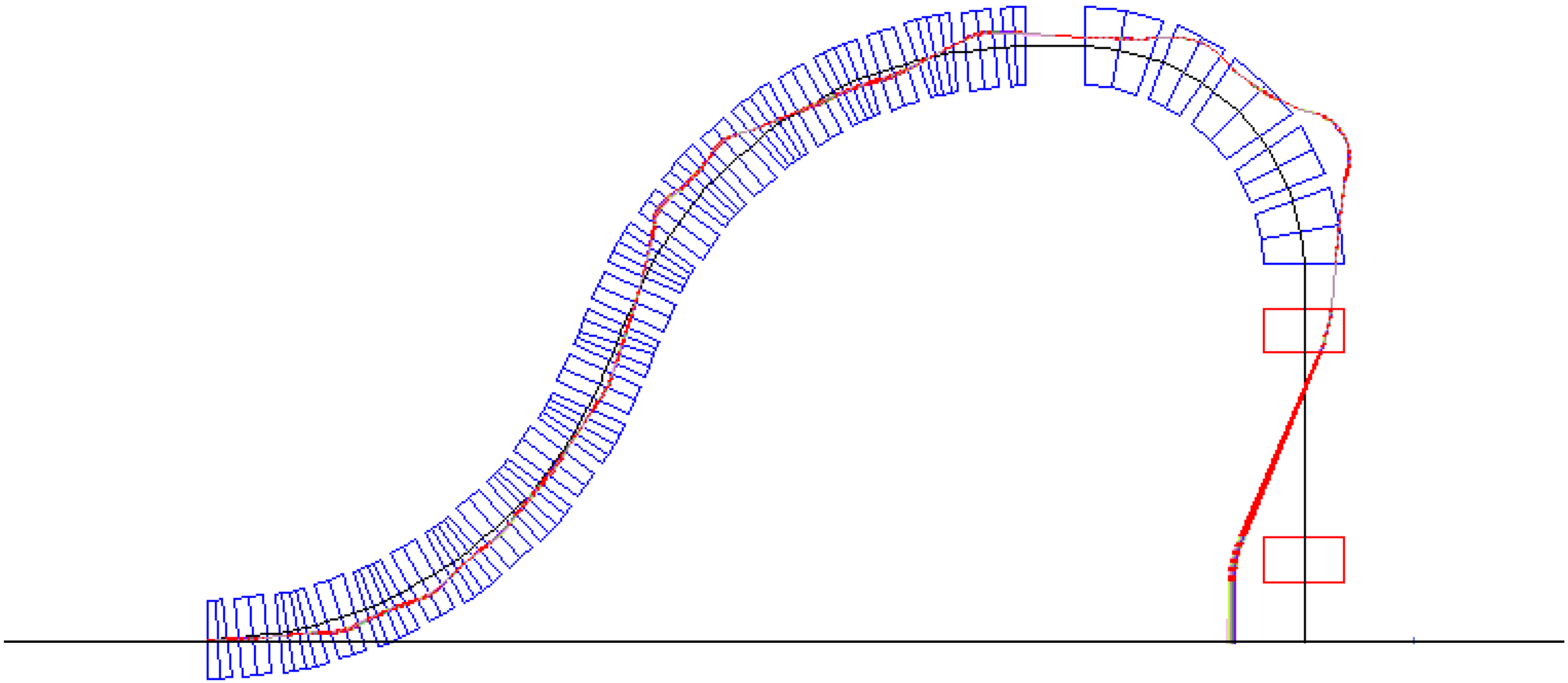
Total volume of iron
V_1=0.2611 m^3
ρ=7870 kg/m^3
Weight~2.055 tons
+ ~1 ton for cryostat

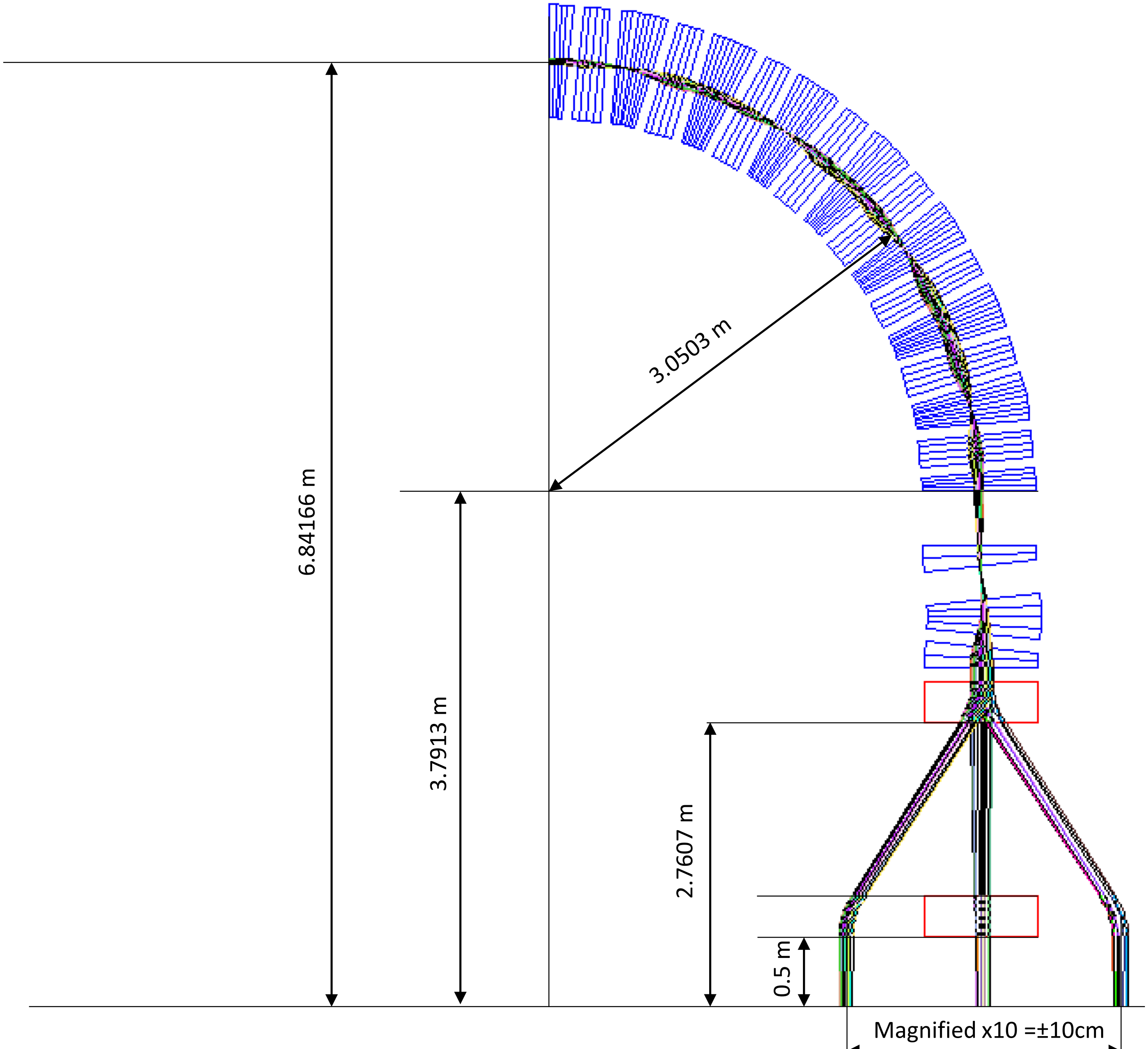


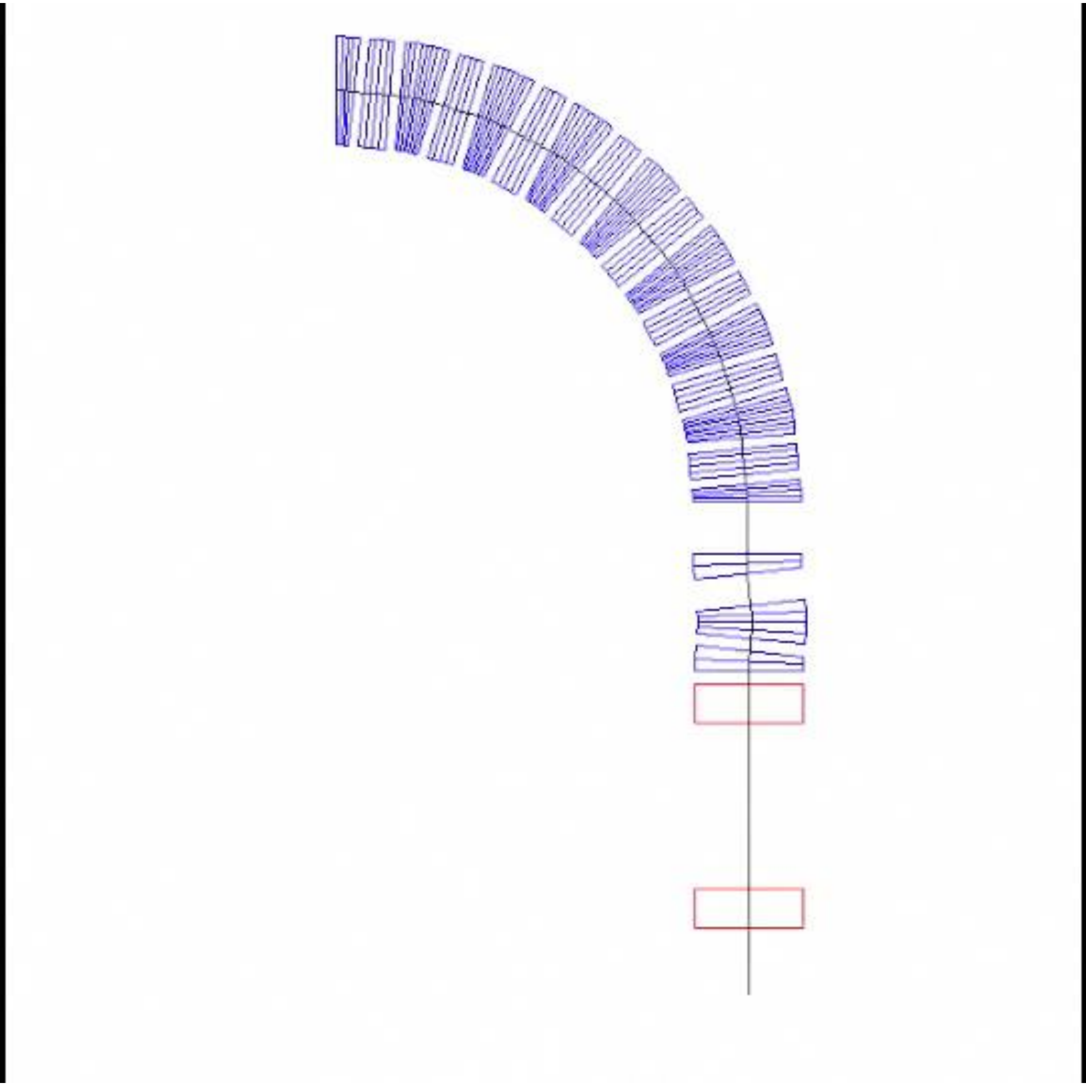

Magnification 30 TIMES
9 mm
400 MeV/u
200 MeV/u
3.883 m
4.166
72°
2 mm
1.411
2.683 m
1.483 m
18°

CARBON GANTRY h=4.091m without magnification

400 MeV/u




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

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