Non-scaling FFAG Gantry for the Carbon/Proton therapy

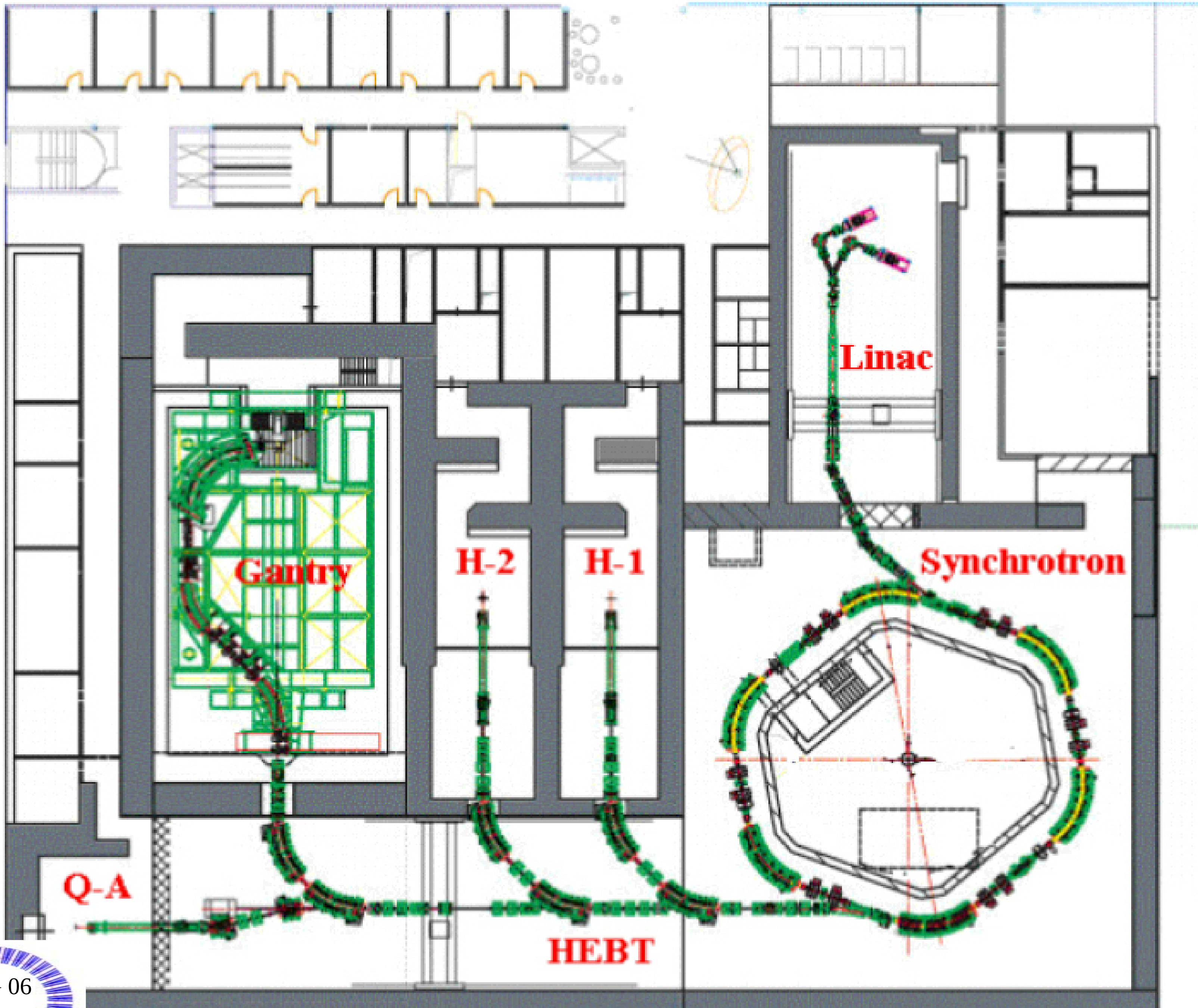
Dejan Trbojevic
BNL

- Introduction: Present design of the gantry in Heidelberg.
- Basic properties of the non-scaling FFAG an example.
- An example for possible improvements for future gantry designs.

Basic Properties of the Heavy Ion Facility in Heidelberg:

The key parameters of the facility will be the following:

- treatment with low and high LET-ions
- relatively fast change of ion species
- 3 treatment areas for up to 1000 patients per year
- integration of an isocentric gantry
- main ion-species: p, He, C, O
- ion-range in water: 20 -300 mm
- ion-energy: 50 -430 MeV/u
- extraction-time: 1 – 10 s
- beam-diameter: 4 – 10 mm FWHM
- ions/spill: $1*10^6$ to $4*10^{10}$

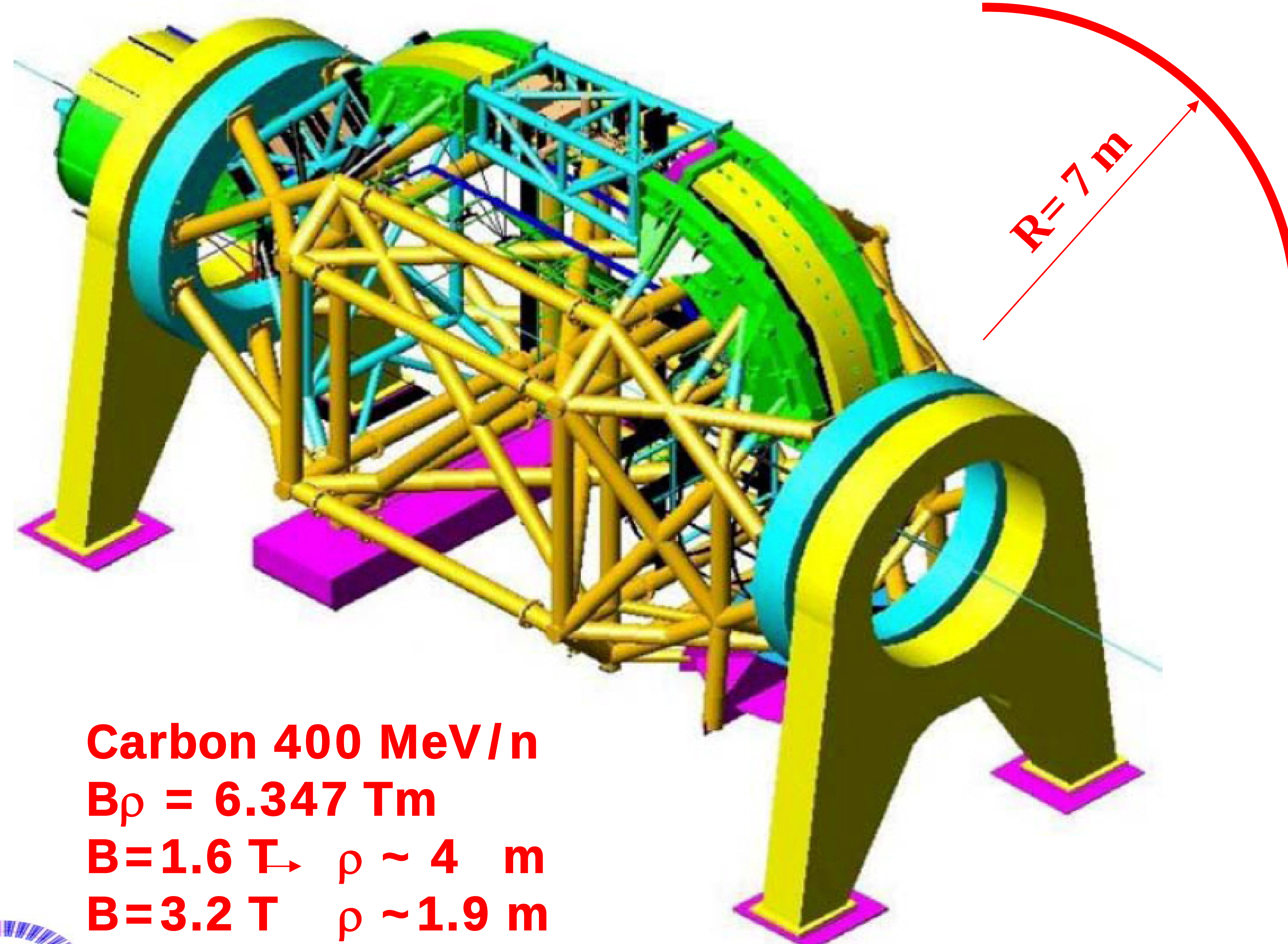


bojevic

Elements of the Gantry in Heidelberg:

Intensive discussions led to an isocentric gantry design with the integration of the rasterscan components. Together with other components such as vacuum chambers and treatment monitor devices the following beam transport elements are included:

One 90°-dipole	(D3)
Two 45°-dipoles	(D1, D2)
Eight quadrupoles	(Q1 – Q8)
Two scanner magnets	(SCV, SCH)
Two steerer magnets	(STH, STV)
Two diagnostic chambers	(DC1, DC2)

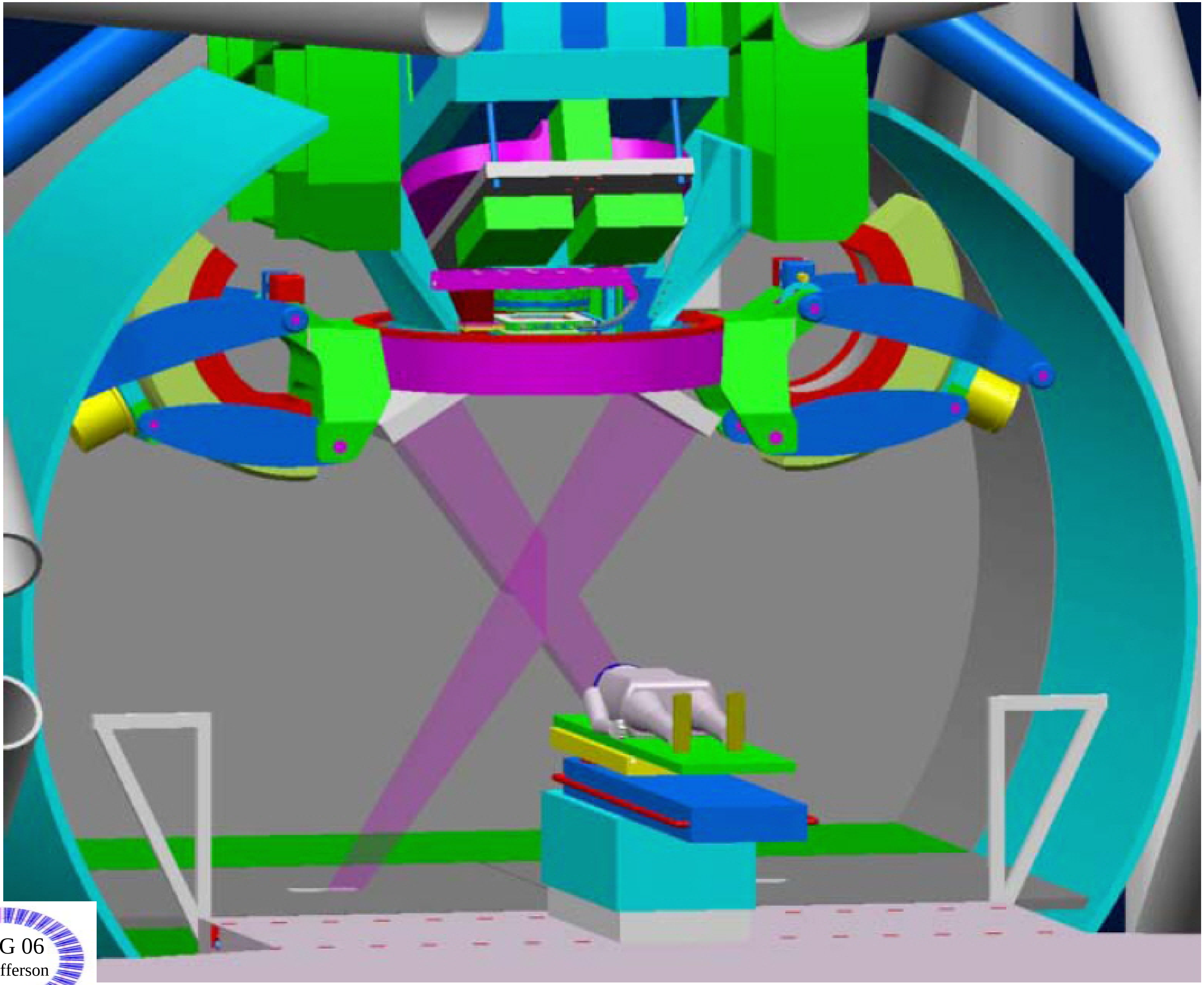


Carbon 400 MeV/n

Bρ = 6.347 Tm

B=1.6 T $\rightarrow$ ρ ~ 4 m

B=3.2 T ρ ~1.9 m



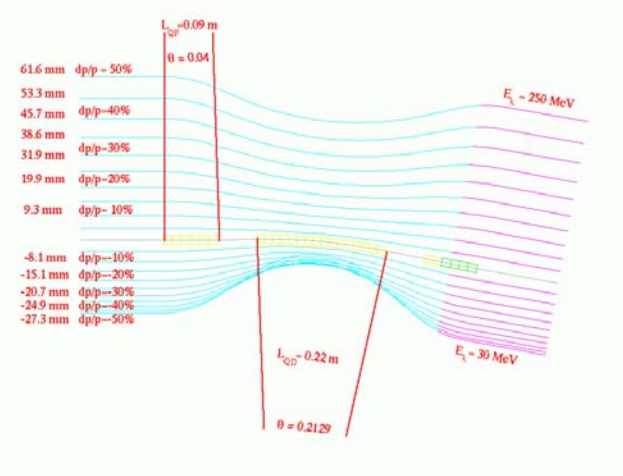
Heidelberg Gantry building:

Weight of Elements of the Gantry in Heidelberg:

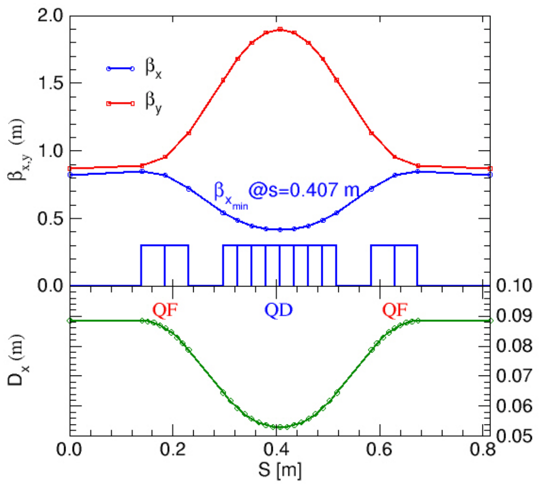
weight of beam transport components	135 tons
total weight of rotating part	570 tons
total weight of the system	630 tons
diameter of rotating part	14 m
length of rotating part	19 m
overall length	22 m

Basic Properties of the Non-Scaling FFAG

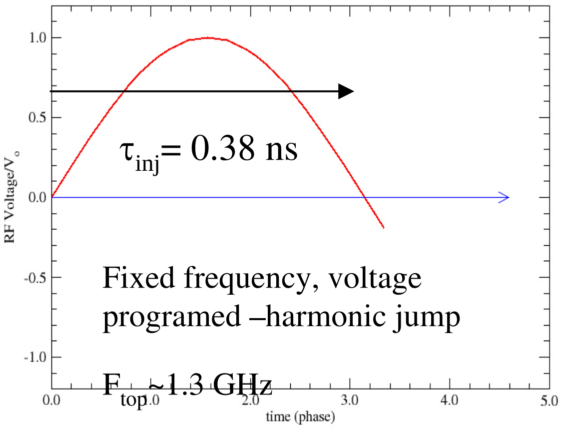
A . Particle orbits



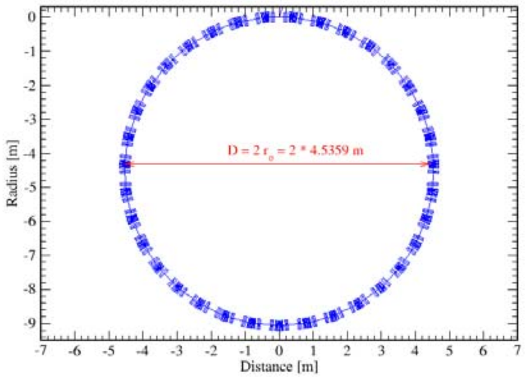
B. Lattice functions

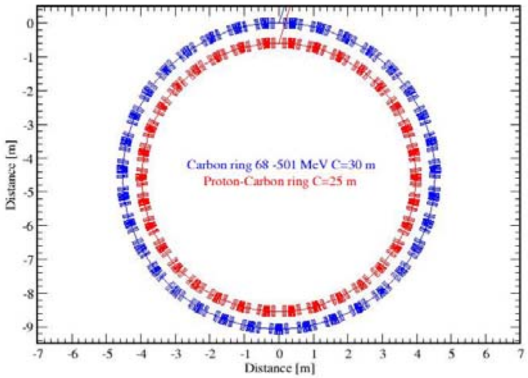


C. Acceleration



D. Lattice design and update





Recent non-scaling FFAG Phys. Rev. Spec. Topics article

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 050101 (2005)

Design of a nonscaling fixed field alternating gradient accelerator

D. Trbojevic,* E. D. Courant, and M. Blaskiewicz
BNL, Upton, New York 11973, USA
(Received 7 February 2005; published 19 May 2005)

We present a design of nonscaling fixed field alternating gradient accelerators (FFAG) minimizing the dispersion action function H. The design is considered both analytically and via computer modeling. We present the basic principles of a nonscaling FFAG lattice and discuss optimization strategies so that one can accelerate over a broad range of momentum with reasonable apertures. Acceleration schemes for muons are discussed.

DOI: 10.1103/PhysRevSTAB.8.050101 PACS numbers: 29.20.−c, 41.75.Lx

I. INTRODUCTION

The fixed field alternating gradient (FFAG) configuration, introduced independently by Ohkawa [1], Symon [2], and Kolomensky [3], has received much attention in recent years. A "proof of principle" machine has been built at KEK [4], followed by a 150 MeV proton synchrotron which is being commissioned [5]. In the scaling FFAG design the particle orbits "scale" with momentum, and acceleration over a large range of momentum requires large apertures. In nonscaling FFAGs the aperture requirements can be significantly reduced.[1] Nonscaling FFAGs have been discussed as a part of the general FFAG family [8] and in the context of muon acceleration [9–14], where the short muon lifetime prohibits slow ramping of the magnetic fields. The FFAG acts similar to a recirculating linear accelerator (RLA), but all the orbits go through the same lattice, obviating the need for separated arcs.

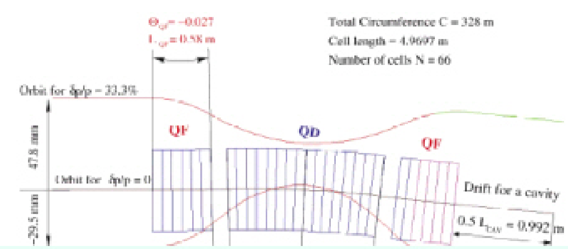
A. The Basic Cell

We end up with the rather simple configuration of Fig. 1. The accelerator is composed of a large number (66 in our case) of identical unit cells. Each cell contains a magnet triplet, with a relatively long gradient bending magnet QD ("combined function") having a strong central field and negative gradient (horizontally defocusing) at the center, flanked by a pair of negative bend magnets QF that are

II. PARTICLE MOTION AT VERY LARGE MOMENTUM OFFSET

We consider a particle of momentum p and a reference particle with momentum p_0 and charge q; the momentum offset is $\delta = (p - p_0)/p_0$. The magnetic rigidity of the reference particle is $(B\rho)_0 = p_0/q$; the reference particle is on a reference orbit (assumed planar) with local radius of curvature ρ_0 and vertical field $B_0(s) = (B\rho)_0/\rho_0(s)$. In the cases considered here the field $B_0(s)$ and with it the radius of curvature $\rho_0(s)$ are constant in each magnet, so that the reference orbit consists of circular arcs in the magnets and straight sections between the magnets; we also assume that the magnet edges are straight at right angles to the reference orbit. We assume that the magnetic field in the dipole magnets is linear:

$$B_y = B_0 + Gx, \tag{1}$$



Scaling or non- scaling FFAG?

Scaling FFAG properties:

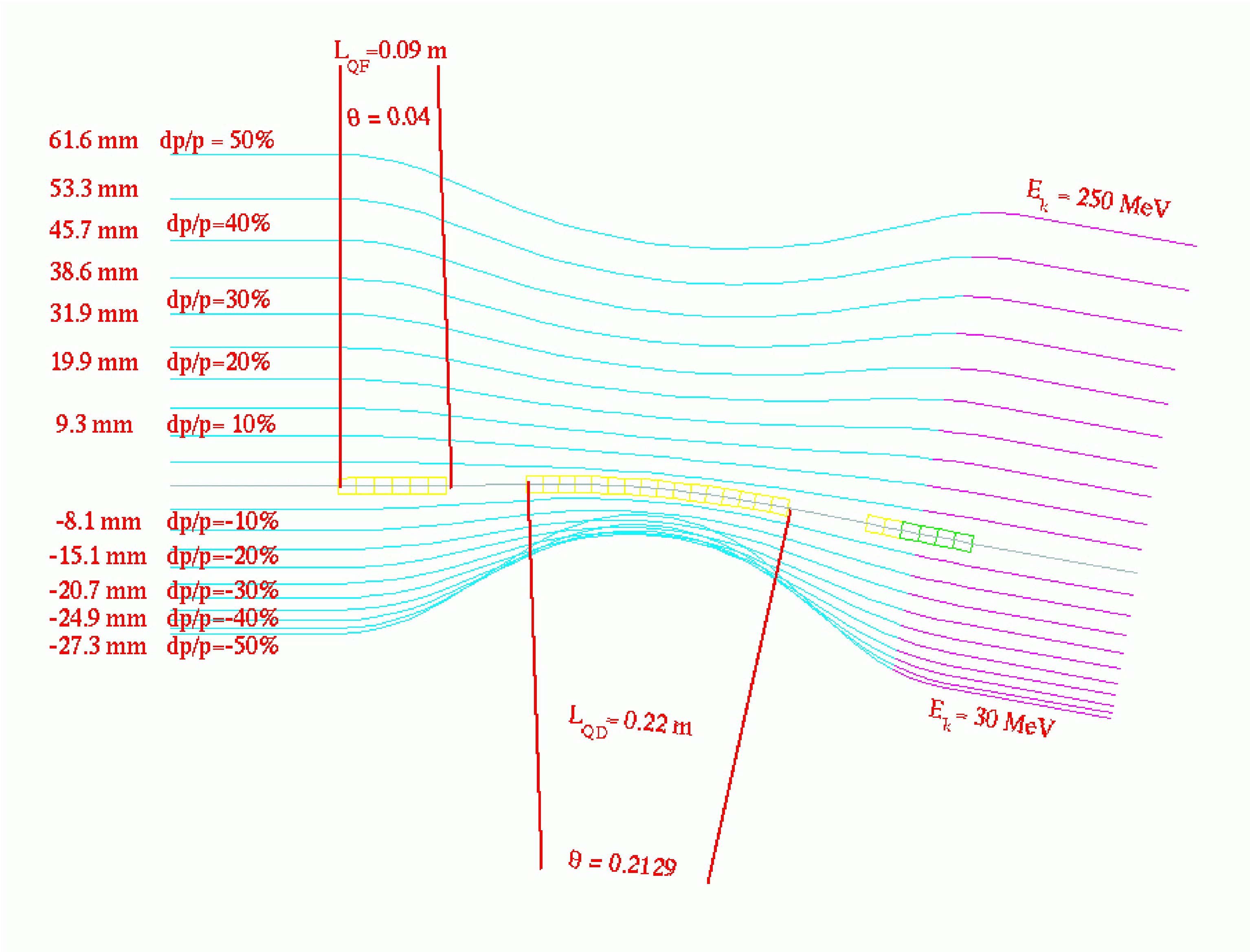
- Zero chromaticity.
- Orbits parallel for different energies.
- Large momentum acceptance.
- Relatively large circumference (θ_1/θ_2).
- Relatively large physical aperture.
- RF:large aperture-follows the energy.
- Tunes are fixed for all energies.
- Negative momentum compaction.
- Orbits of the high energy particles are at high field, low energy particles at low field.

Non-Scaling (linear) FFAG properties:

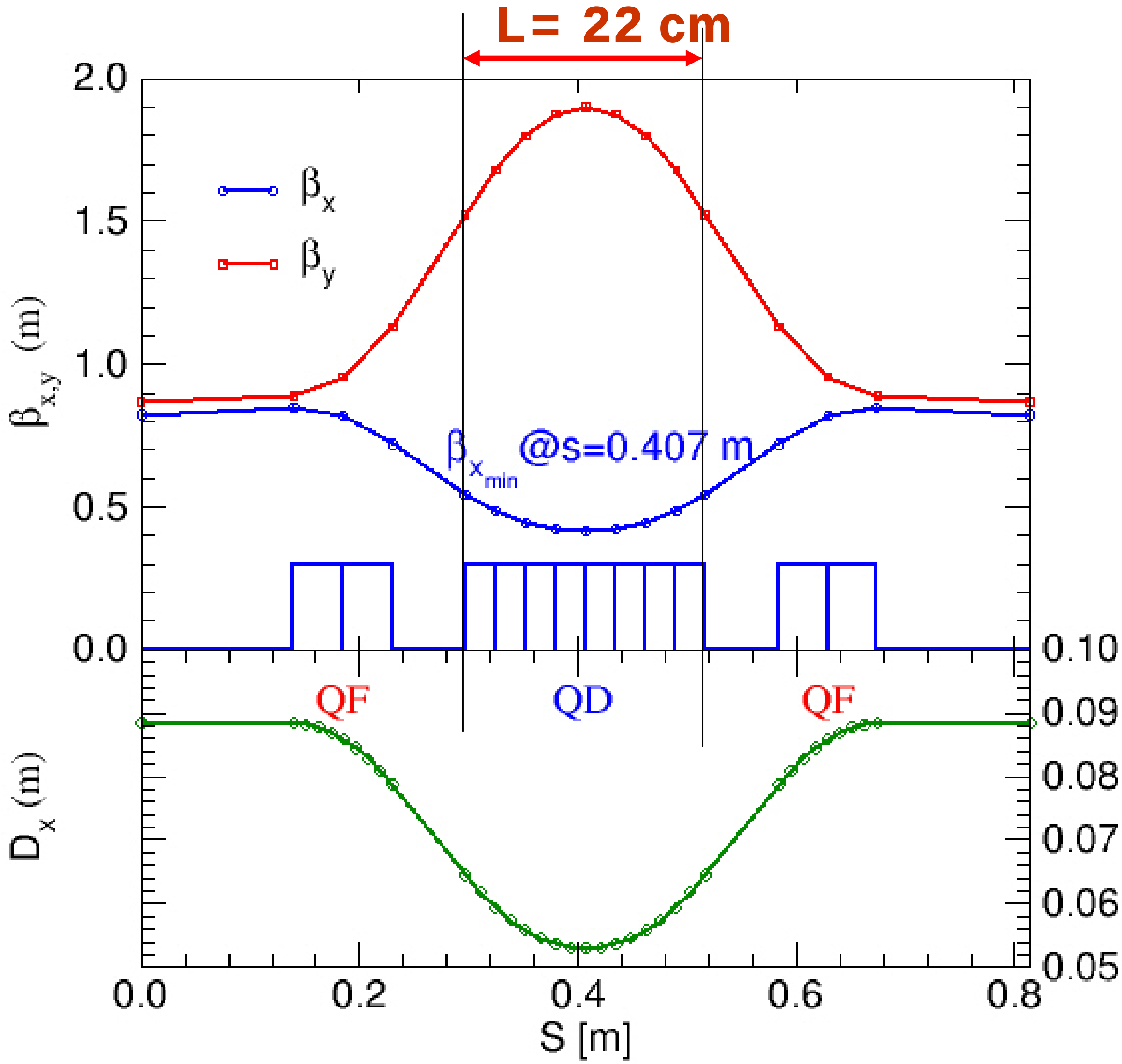
- Chromaticity is changing.
- Orbits are not parallel.
- Large momentum acceptance.
- Relatively small circumference.
- Relatively small physical aperture.
- RF:small aperture-at the crest.
- Tunes move 0.4-0.1 in basic cell.
- Momentum compaction changes.
- Orbits of the high energy particles are at high field, low energy particles at low field.

150 MeV FFAG at KEK

Particles orbits



Lattice functions



Very strong focusing:

$\beta_{x,y}$~1-2 m
D_{max}~8.8 cm

The magnetic field and Size of magnets proton/carbon ring

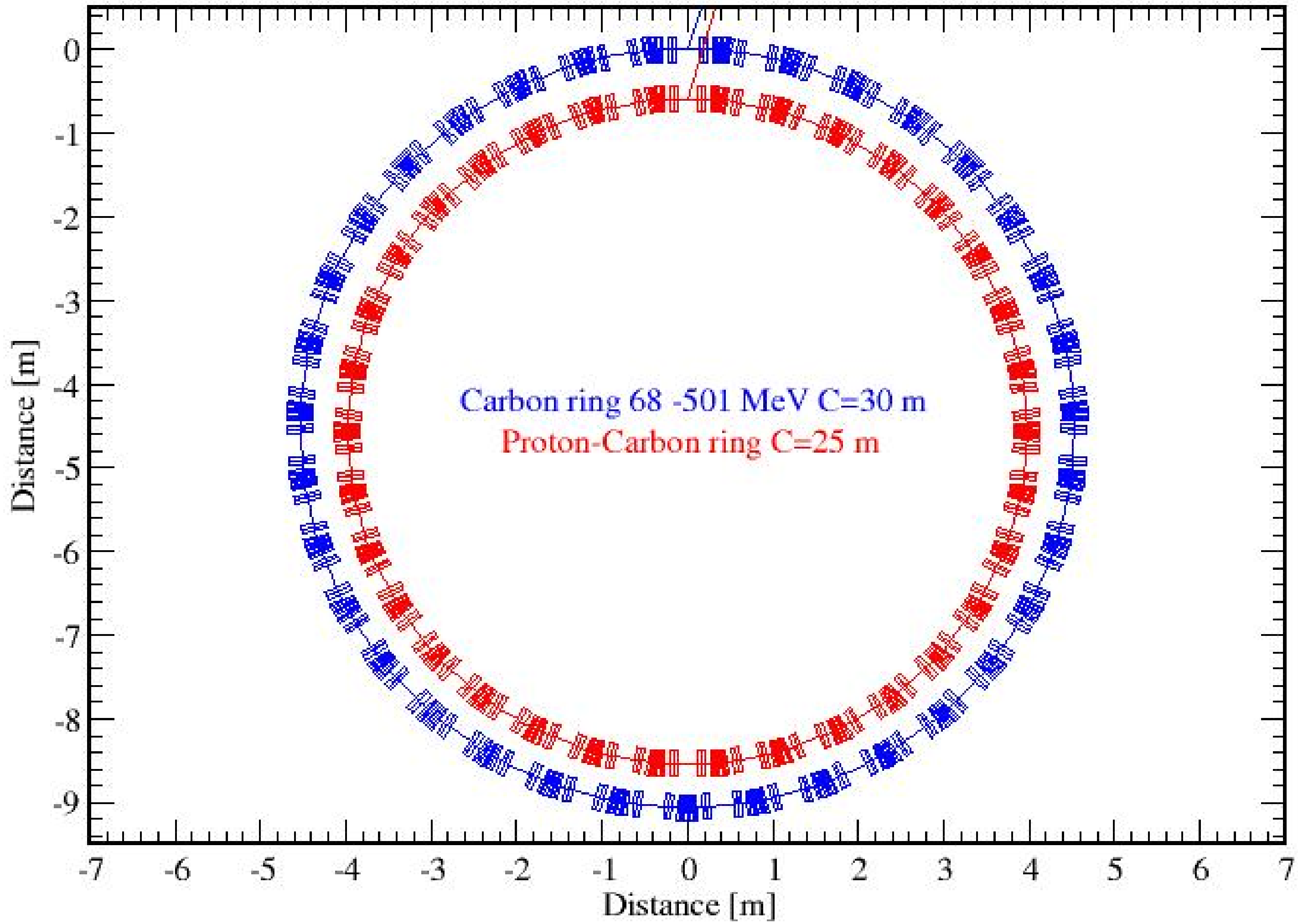
TABLE 2. MAGNET PROPERTIES FOR THE FFAG LATTICE FOR PROTON ACCELERATION FROM 30 TO 250 GeV KINETIC ENERGY

Combined function magnet	QF focusing gradient	QD defocusing gradient
Length	0.09	0.22
Bending Field (T)	0.30	1.563239217
Bending angle (rad)	0.016718929	0.212957438
Gradient (T/m)	41.227598	28.954765
Length of cavity drift (cm)	28.077650	
Drift between magnets (cm)	6.6675464	

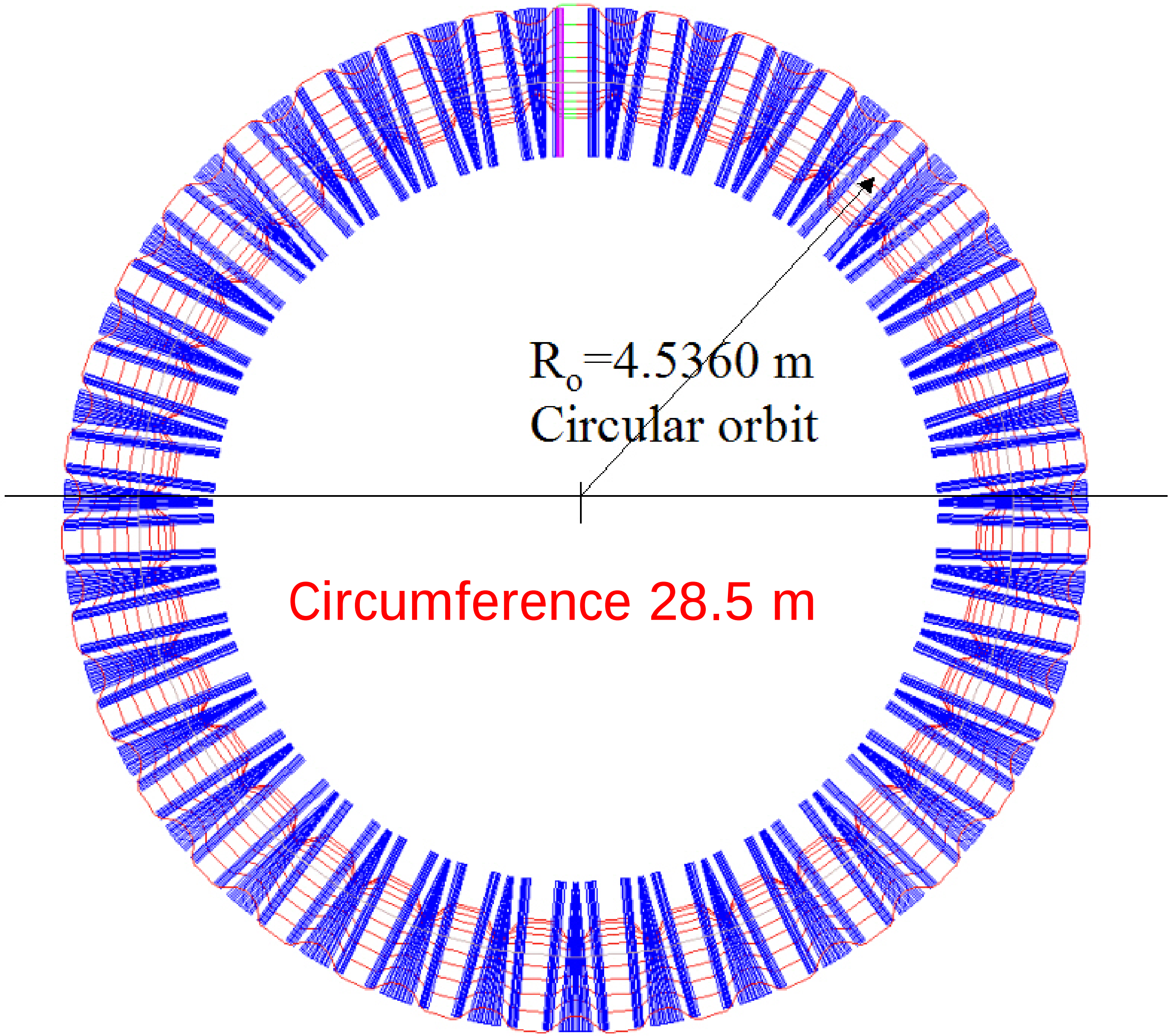
The magnetic field and Size of magnets
500 MeV carbon ring

TABLE 5. MAGNETIC PROPERTIES FOR THE *NON-SCALING* FFAG LATTICE FOR CARBON ACCELERATION FROM 68.27 MeV/nuc. TO 501.79 MeV/nuc. KINETIC ENERGY

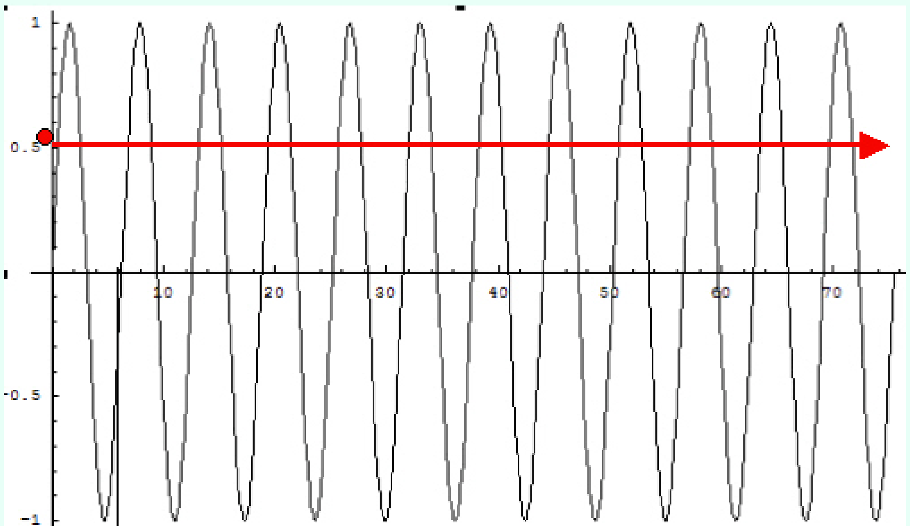
Combined function magnet	QF focusing gradient	QD defocusing gradient
Length	0.09	0.22
Bending Field (T)	4.689711518	0.900000000
Bending angle (rad)	0.212957490	0.016718955
Gradient (T/m)	123.6833	-86.864685
Length of cavity drift (cm)	28.077920	
Drift between magnets (cm)	6.6753299	


Carbon ring 68 -501 MeV C=30 m
Proton-Carbon ring C=25 m
Distance [m]
Distance [m]
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7

Orbits in the whole ring



Acceleration with harmonic jump (Sandro's talk)



Variable for $\beta < 1$

$$f_{rf} = h \times f_{rev}$$

Frequency of cavity voltage

Harmonic number

τ = 350.6 ns = one turn

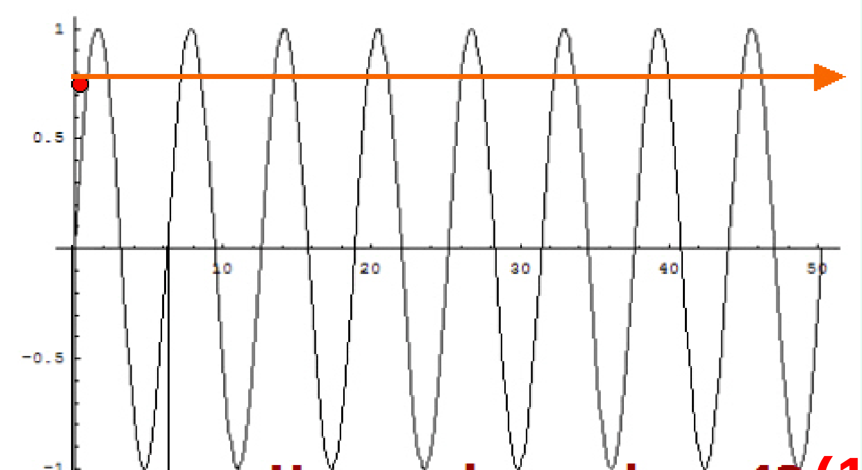
C=32 m

Harmonic number=100

$\tau = 3.506$ ns

$f_{rf} = 1/\tau_{rf}$ =285.2 MHz

τ = 149.4 ns = one turn



Harmonic number=43 (194)

f_{rf} =285.2 MHz

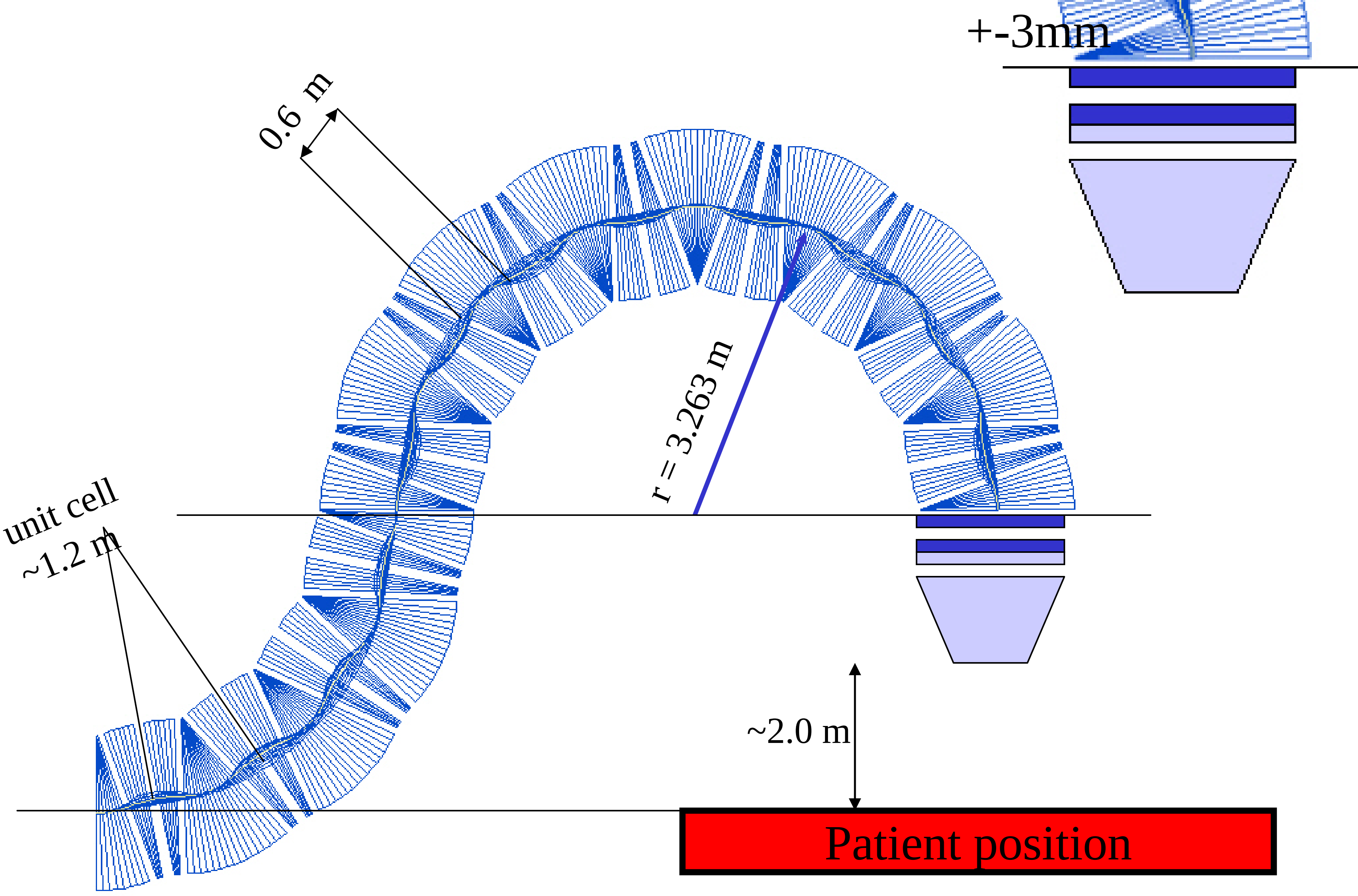
Number of turns=57 (186)

Voltage per turn changes

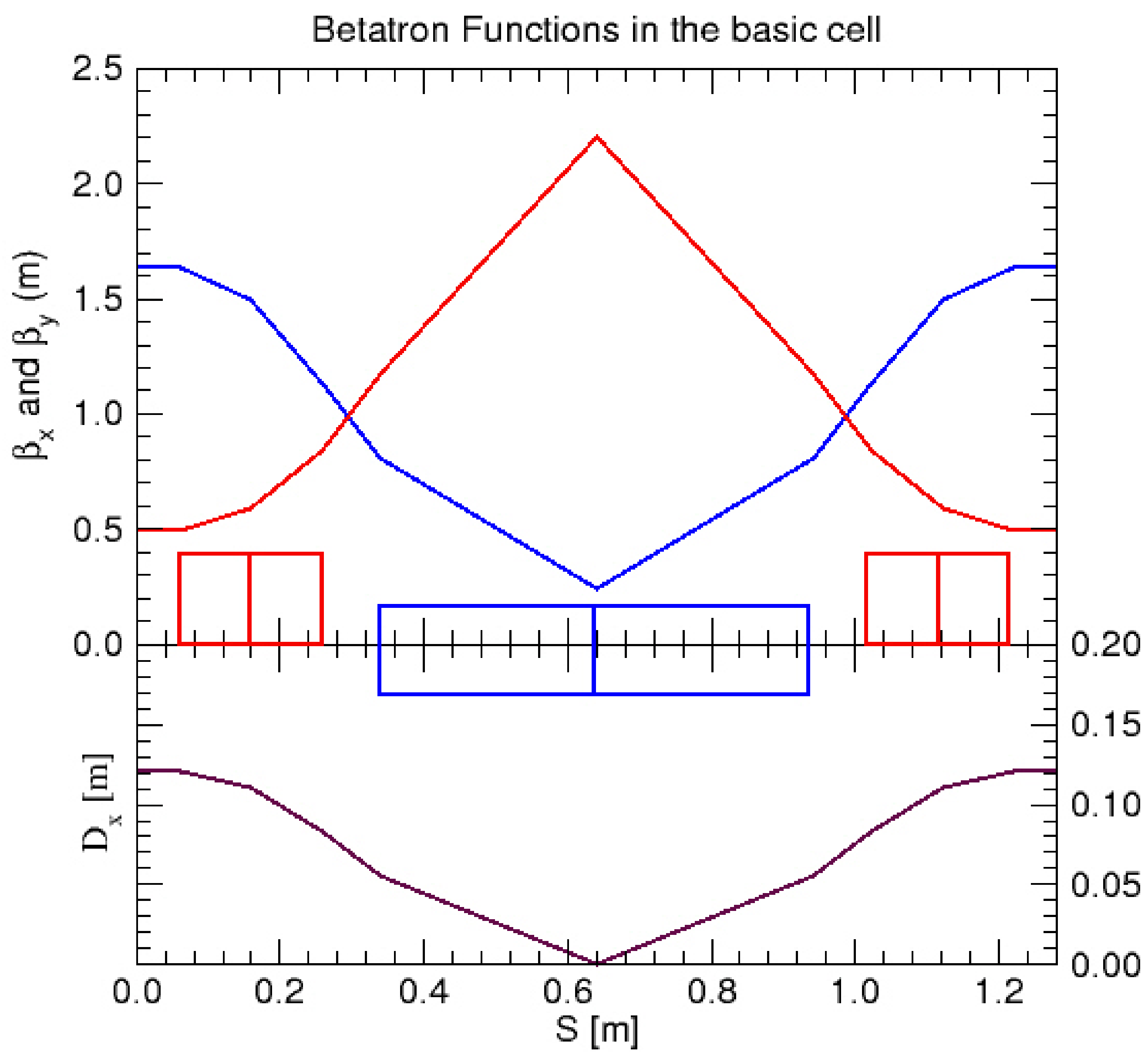
but average ~5MeV (1.1 MeV)

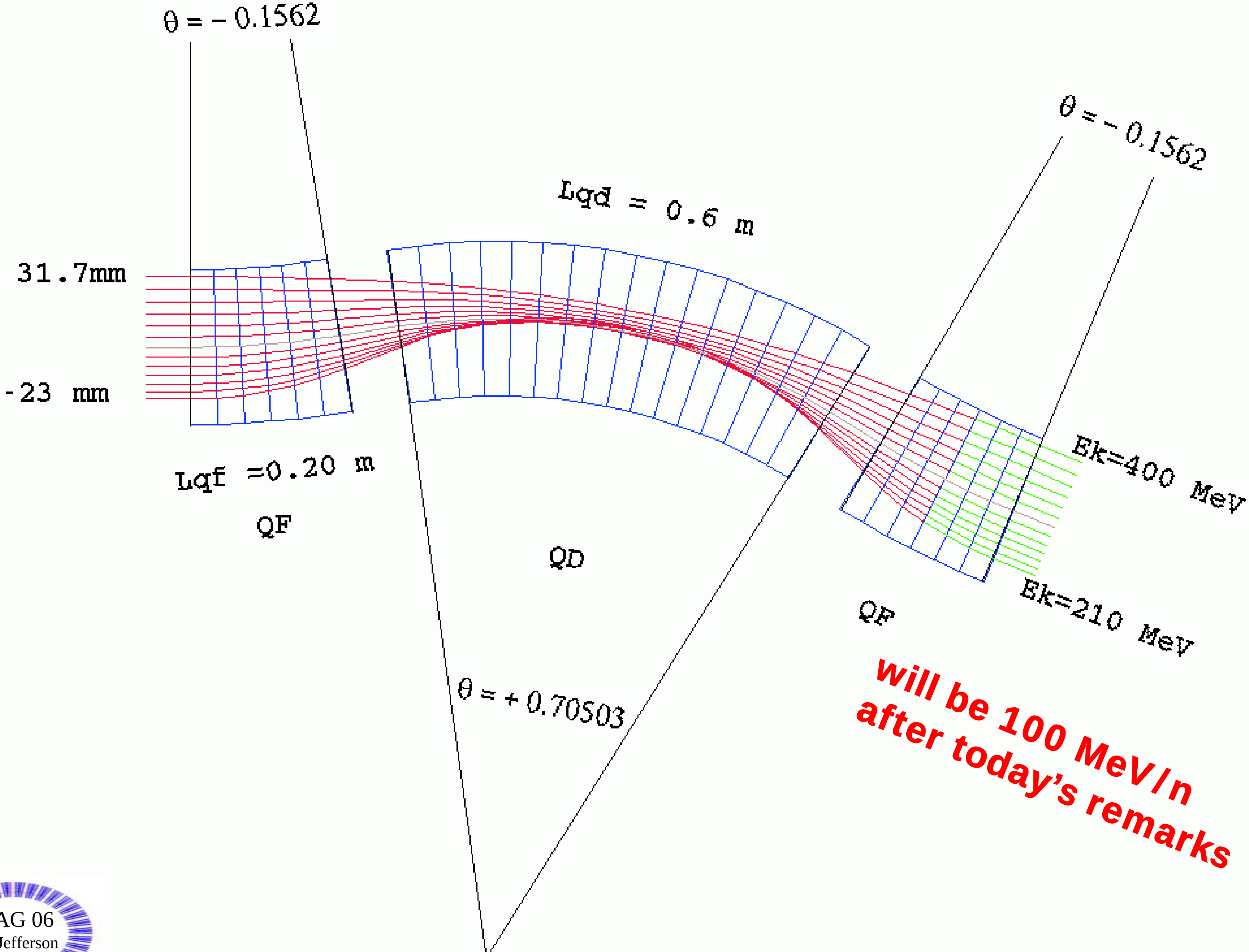
(or for 1.3 GHz harmonic number 380)

L-bend (cheaper) 1.3 GHz reduces the required voltage/4.6


+-3mm
0.6 m
r = 3.263 m
unit cell
~1.2 m
~2.0 m
Patient position

Non-scaling FFAG Gantry - Basic Cell



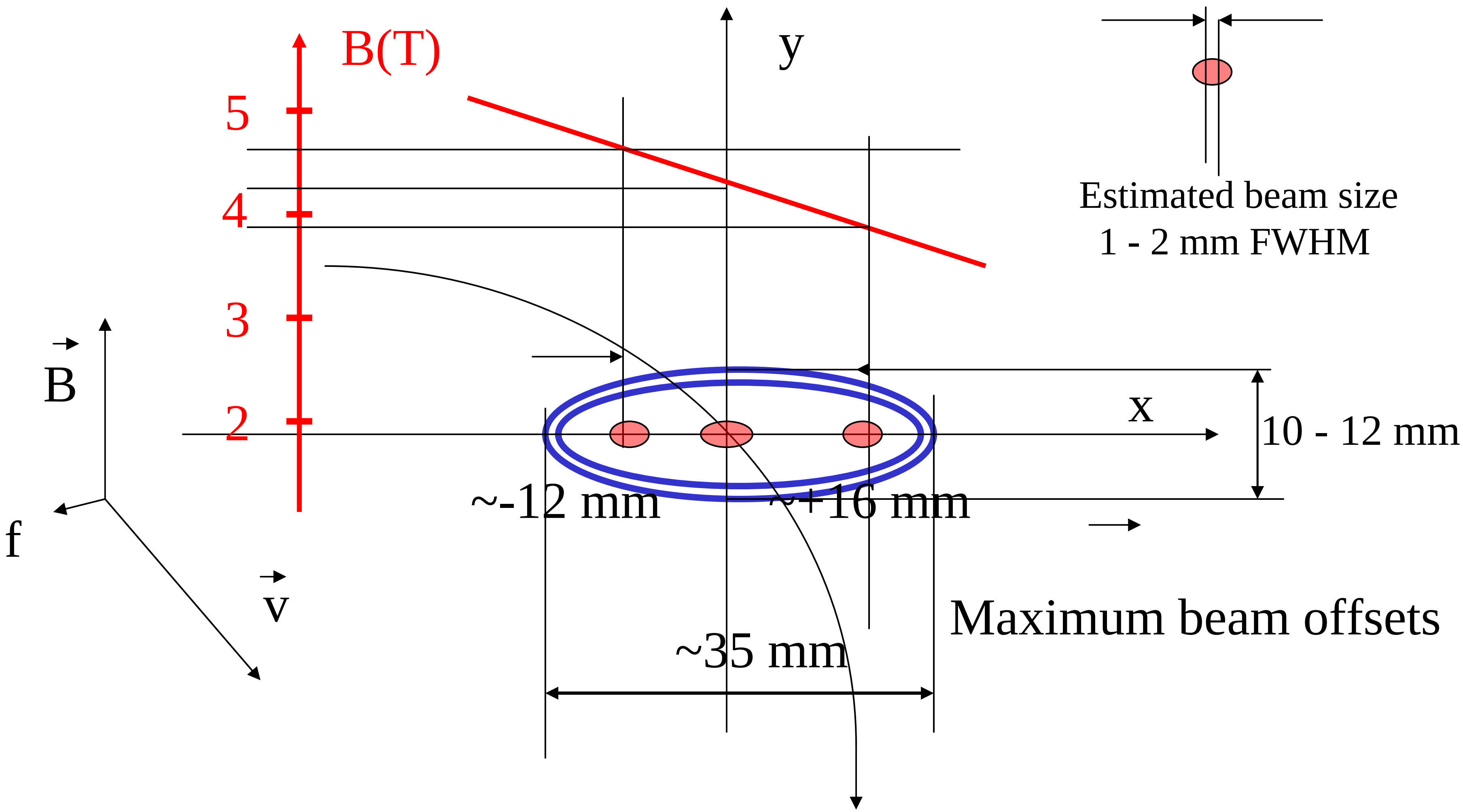


will be 100 MeV/n after today's remarks

FFAG 06
Port Jefferson

Dejan Trbojevic

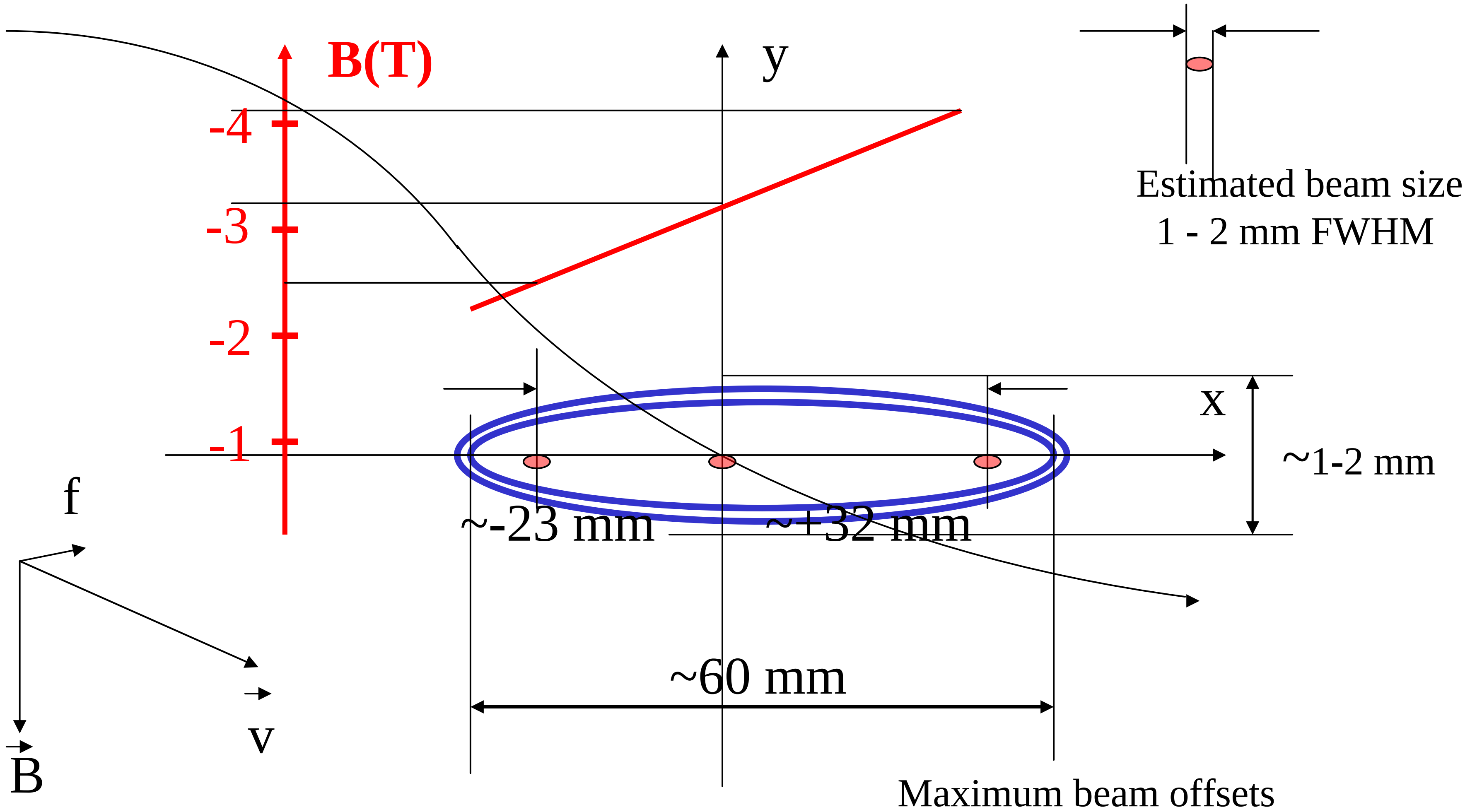
Estimated beam pipe size and magnetic field at the major bend a combined function magnet with defocusing gradient

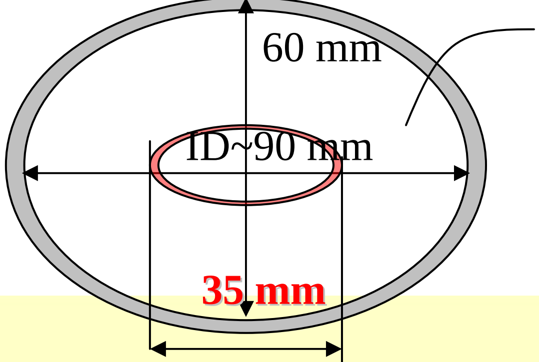


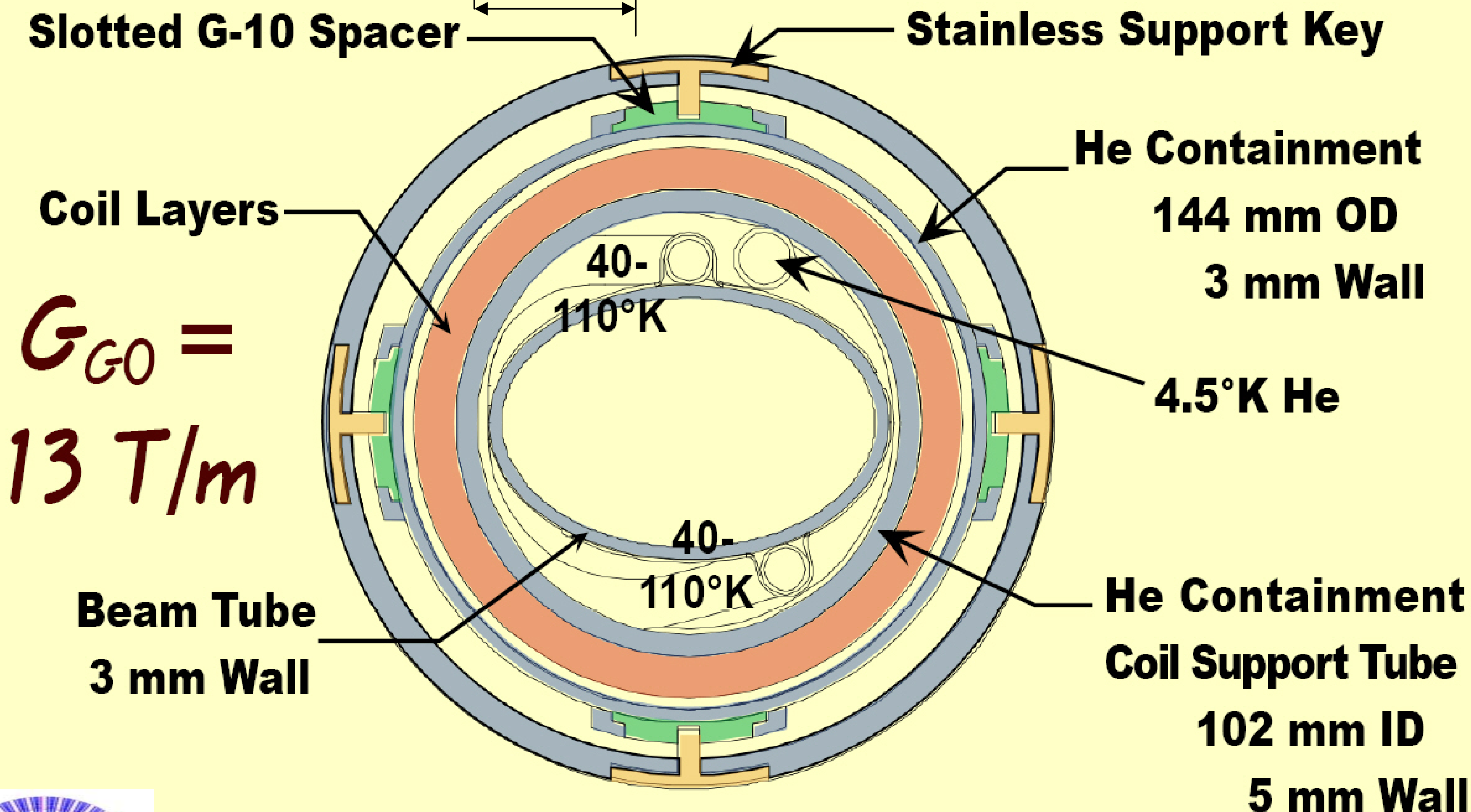
FFAG 06
Port Jefferson

Dejan Trbojevic

Estimated beam pipe size and the magnetic field values at the opposite bend focusing combined function magnet

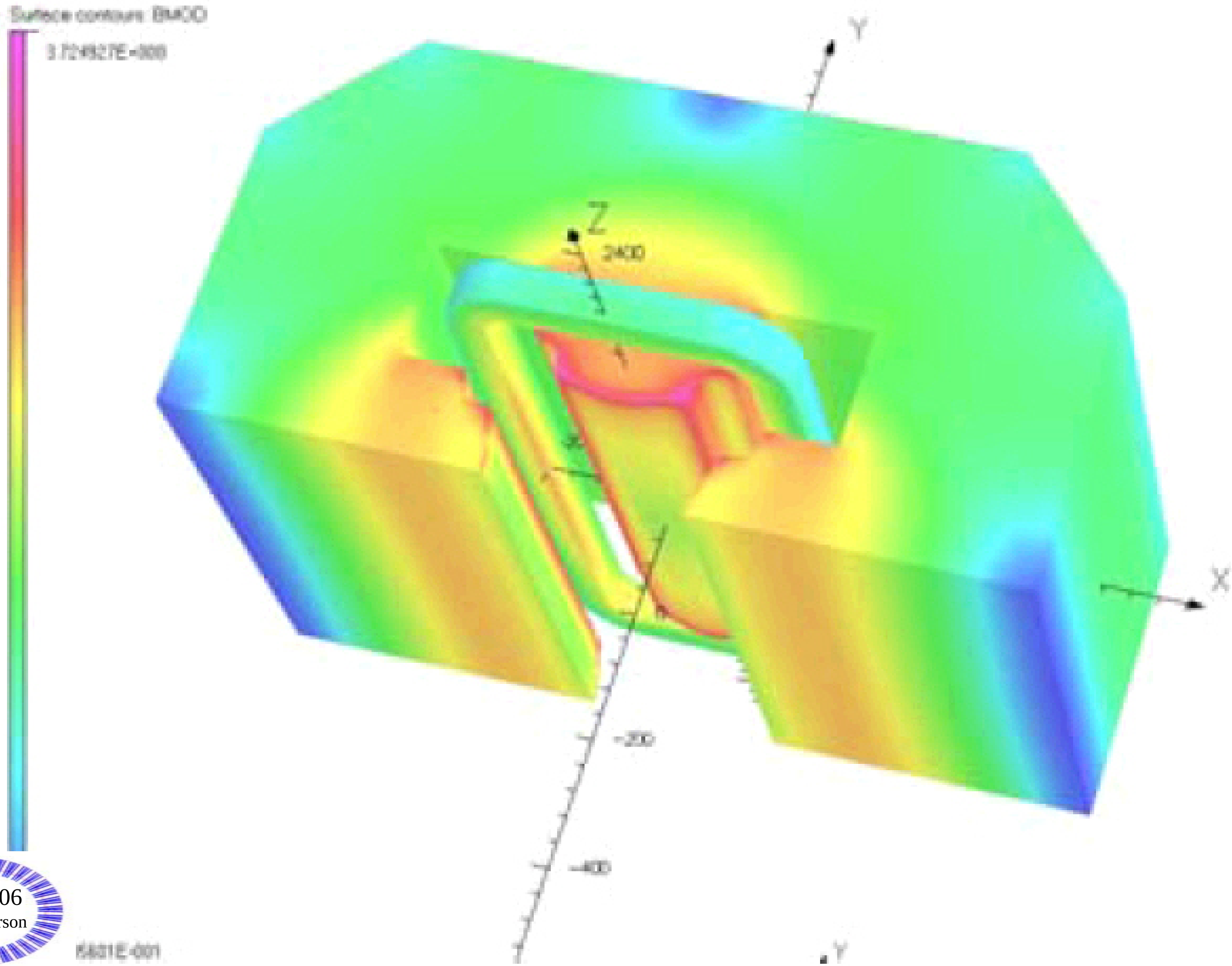




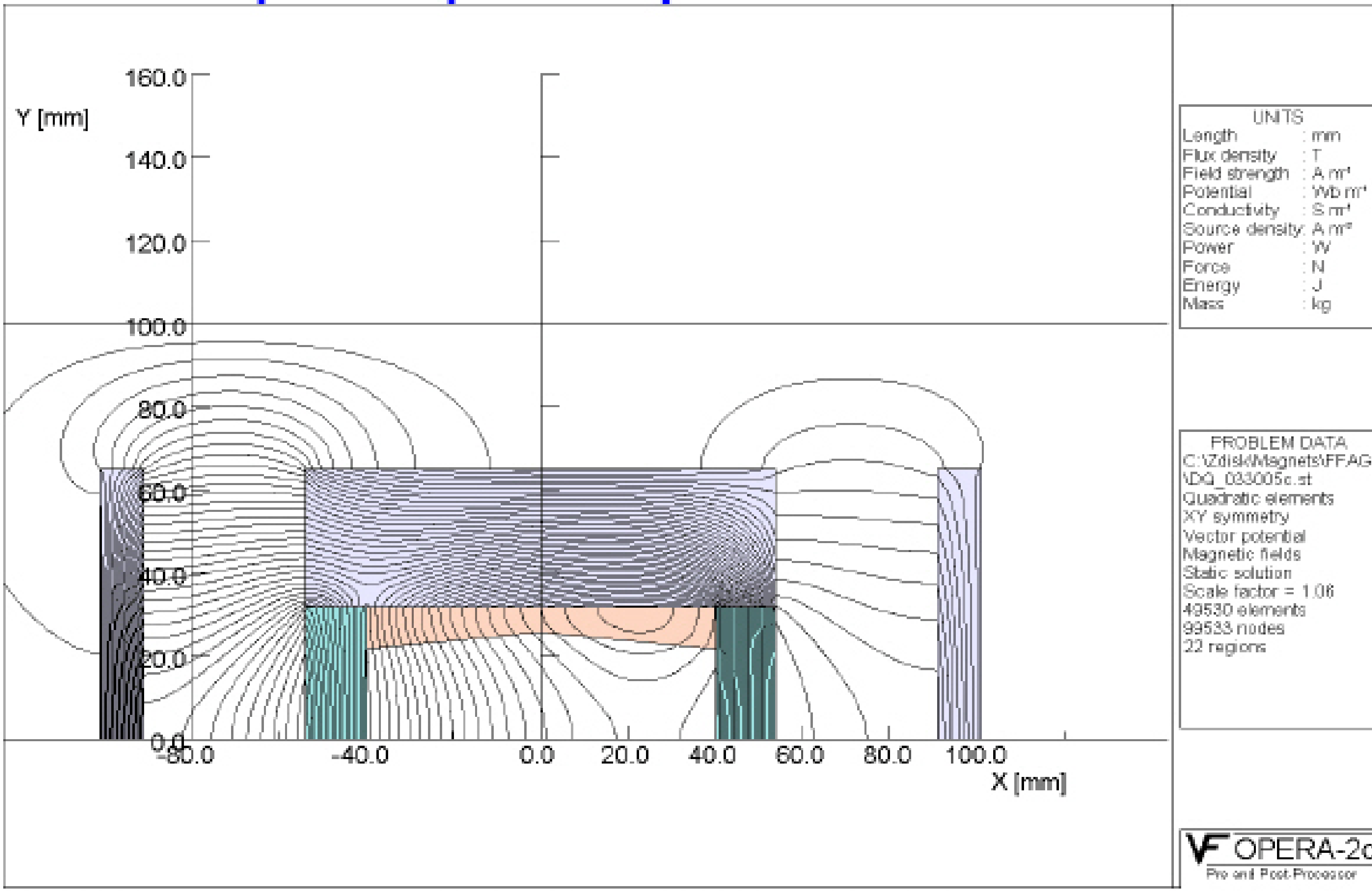


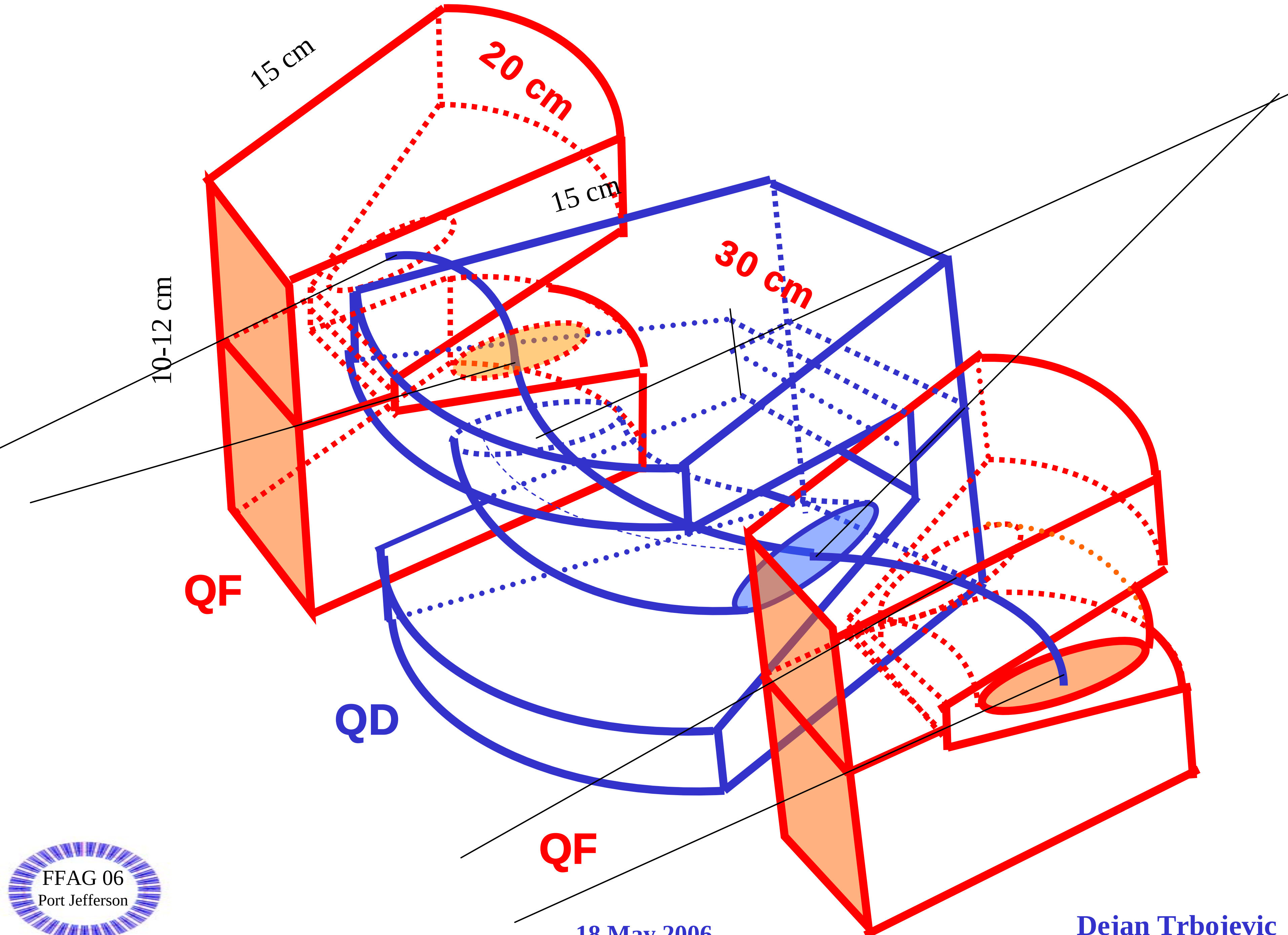
GO Cryostat Cross Section

SCQ Test Winding


Surface contours: BMOD
Y
Z
X
-200
-400

Dipole plus quad field lines





FFAG 06
Port Jefferson

Dejan Trbojevic