Design of Ultra-Light Superconducting Proton Cyclotron for Production of Isotopes for Medical Applications

Malay Dey

VECC, Kolkata, India

CYCLOTRONS'13, TRIUMF, Canada

CONTENTS

INTRODUCTION

“COMPACT SUPERCONDUCTING CYCLOTRON”

-A Topic of Contemporary Research Interest…

- For Medical Applications:
  - Therapy
  - Radio-isotope production for nuclear medicine
  - Radiography
- High energy/power accelerator

- IMPORTANT ISSUES†
  - Beam Dynamics: sensitive issues at high magnetic field
  - Magnet Topologies: new structures for *flutter*
    - pole-tips of Rare Earth Ferromagnetic (Gd, Ho)
    - Superconducting coils for flutter
  - High Intensity: injection and extraction

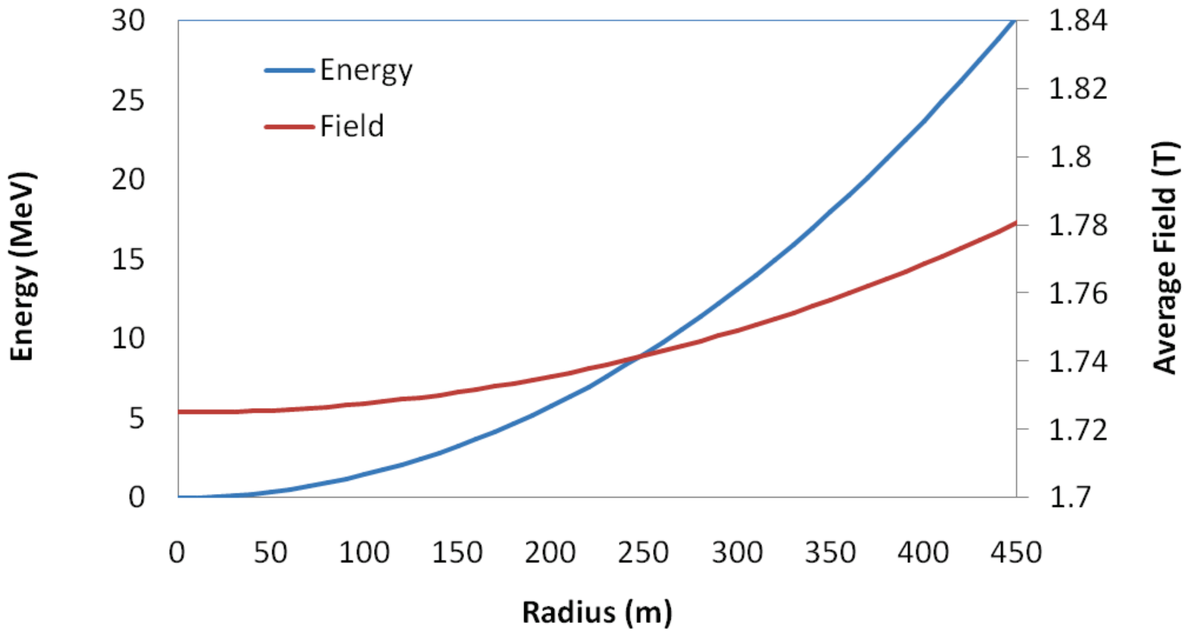
† *Timothy A. Antaya, “Compact Single-stage Superconducting Cyclotron-based Primary Accelerators”, DAEdALUS Workshop – MIT LNS – 4 February 2010.*

Design Specifications

No. of Sector Coils	4
Average magnetic field	1.735 T
Particle revolution frequency	26.42 MHz
Hill Field	2.48T
Valley field	1.2T
Injection & Acceleration	Negative Hydrogen Ion
Extraction	Proton with stripper foil, Dual beam
Extraction radius	Maximum energy at ~415 mm
Magnetic radius of spiral inflector	~14 mm
Injection energy	~28 keV
No. of Dees	2, in alternative valleys
Dee angle	~42° in outer radii
RF Frequency	~105.68 MHz
RF Mode of operation	4^{th} harmonic

Design Specifications

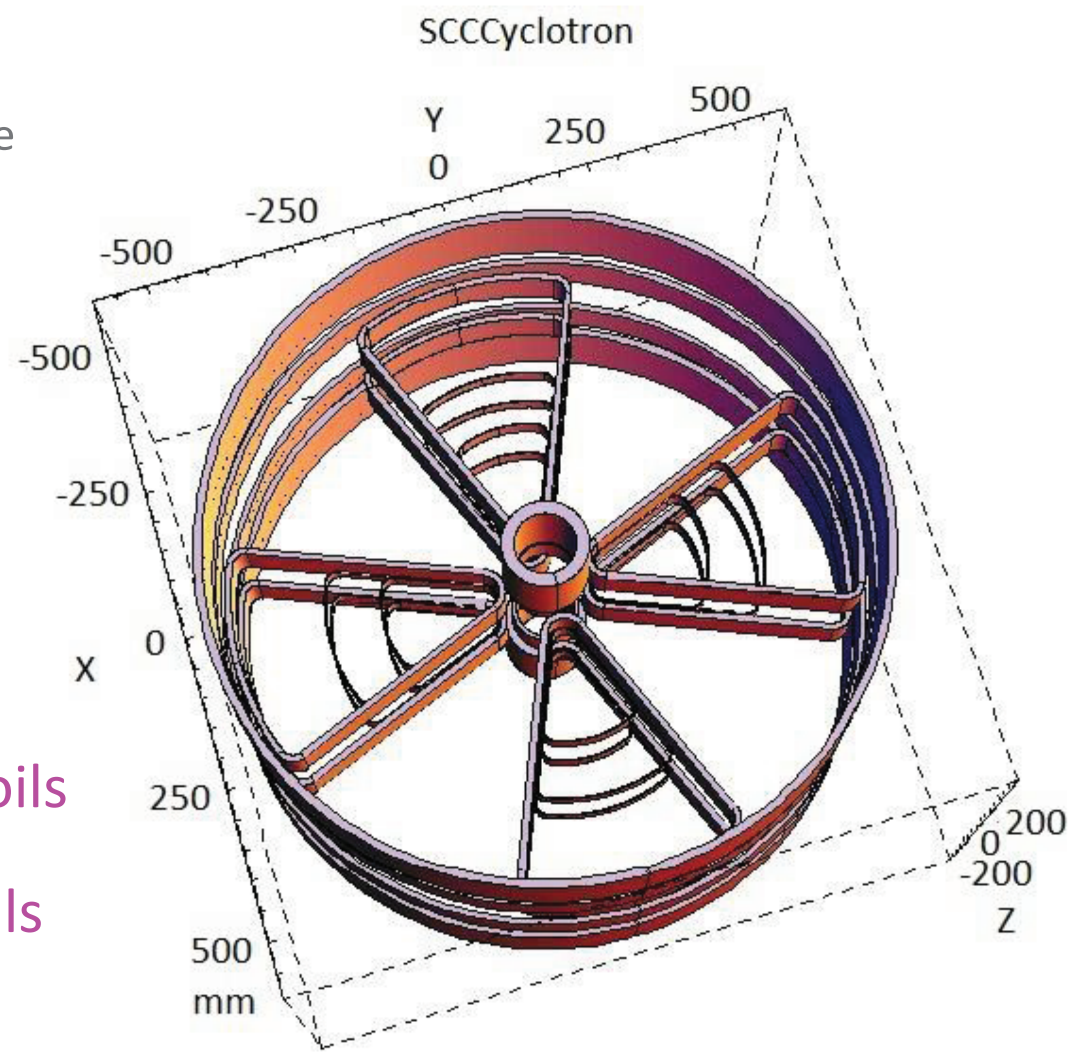
- Maximum Energy : 25 MeV
  Sufficient for ^{99m}Tc production from Mo
- Average Field : 1.73 T
  Low enough to avoid Lorentz stripping of H^- ions
- Comfortable central region and spiral inflector
- $B\rho$ = 0.794 T-m, R_{ext} = 415 mm



Special Features

Oxford Instruments: OSCAR

- No iron yoke
- Iron pole-tip within warm bore solenoid type SC magnet

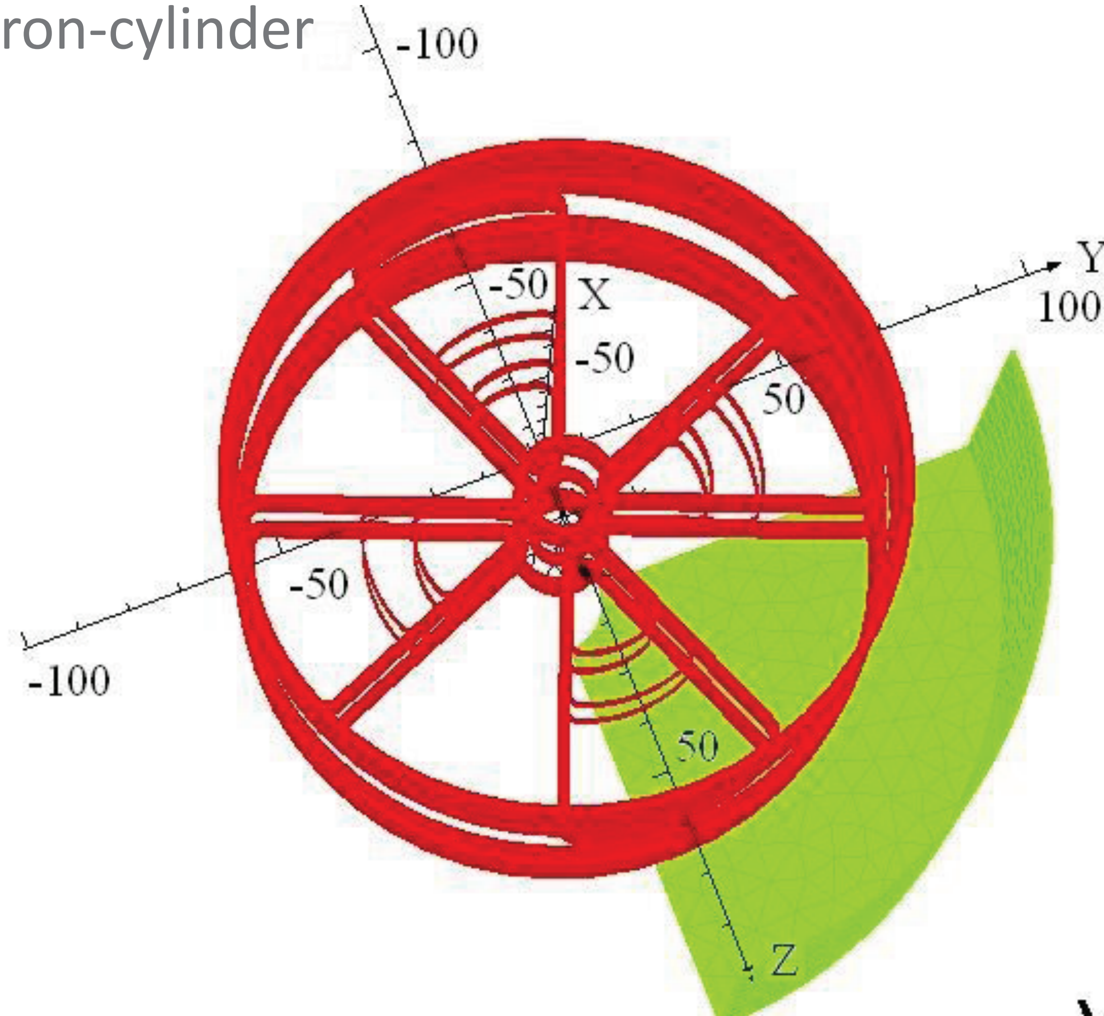


In this design:

- No iron pole tip
- 'Flutter' is created by superconducting sector coils
- Superconducting trim coils

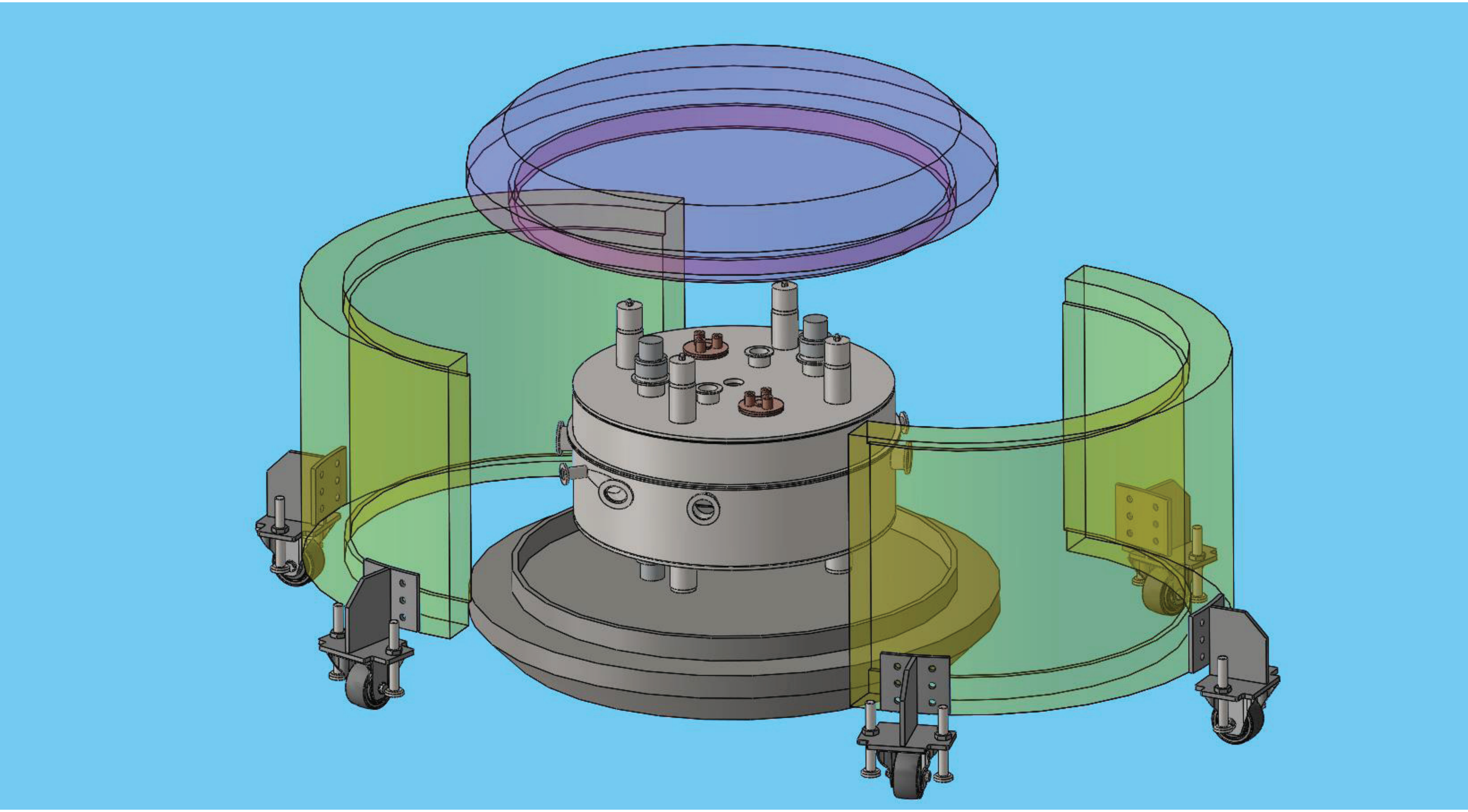
Special Features

- Magnetic shielding by external thin iron cylinder
- Alternatively: combined shielding using bucking coil and thin iron-cylinder



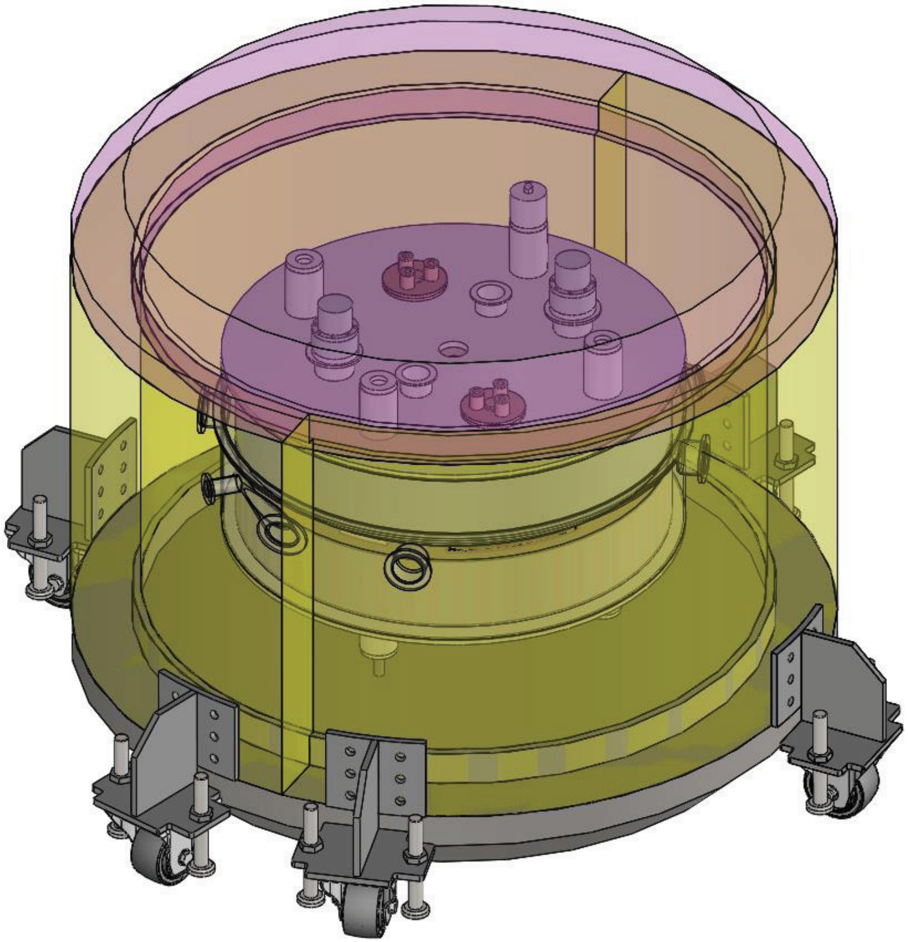
Special Features

Magnetic shielding and neutron shielding by external double wall iron cylinder poured with borated-polythene and concrete



Special Features

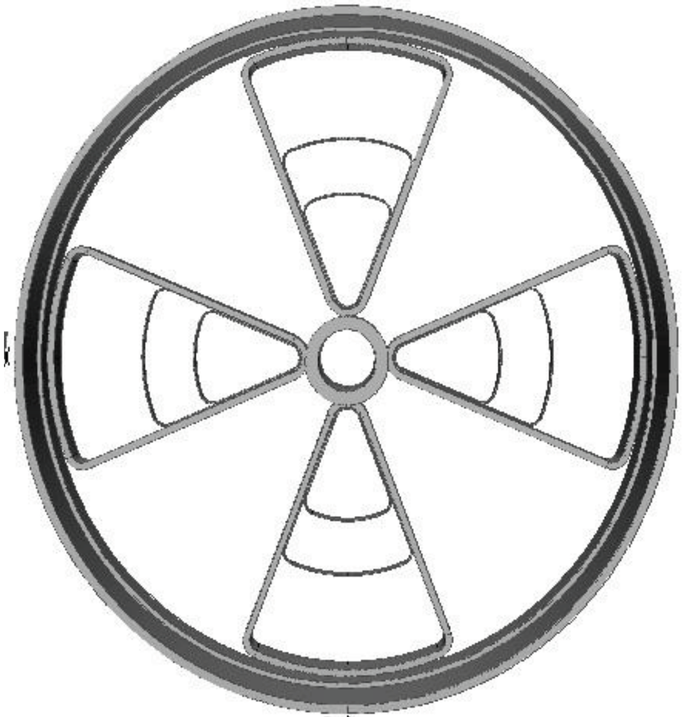
- Compact and easy access to cyclotron
- Cyclotron field is less sensitive to iron-shield position
  (an important issue in conventional sc cyclotron)

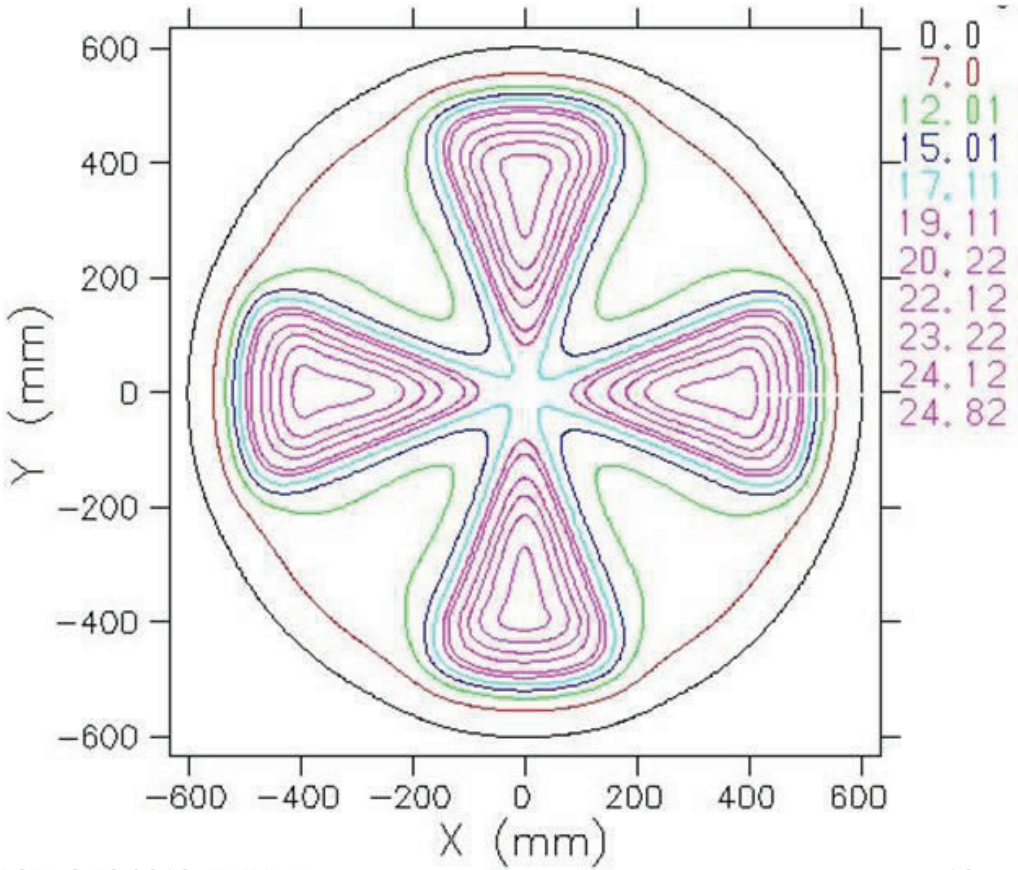


Magnetic Field Shaping

- ❑ Two sets of circular main coils at the outer radius (MC1, MC2)
- ❑ Four 45° sector coils
- ❑ Two small circular coils at the centre (CC1, CC2)
- ❑ Two trim coils inside each sector

- ❖ All the coils are superconducting
- ❖ Single cryostat





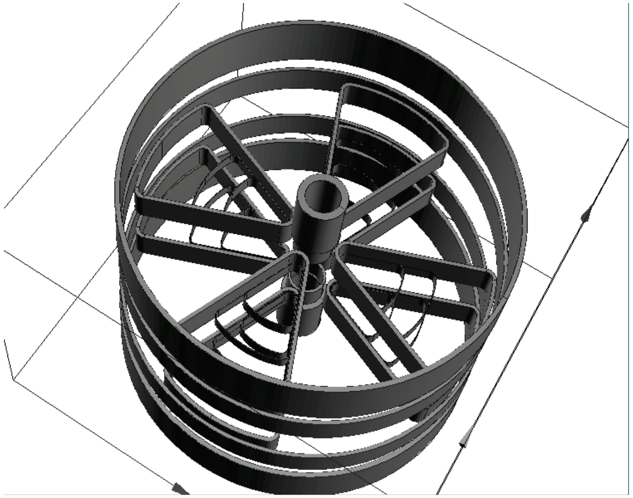
Magnetic Field Shaping

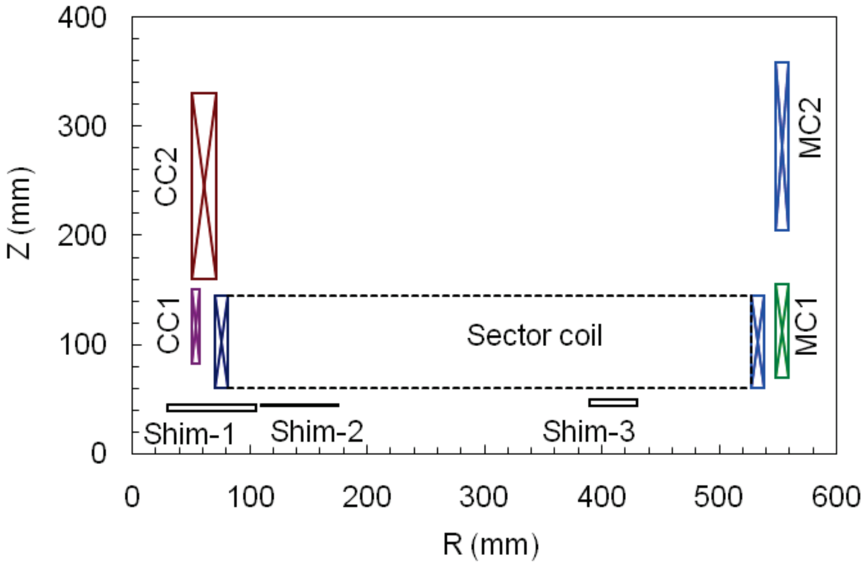
- Optimization of a parametric model:

Isochronous field and sufficient flutter

Constraints:

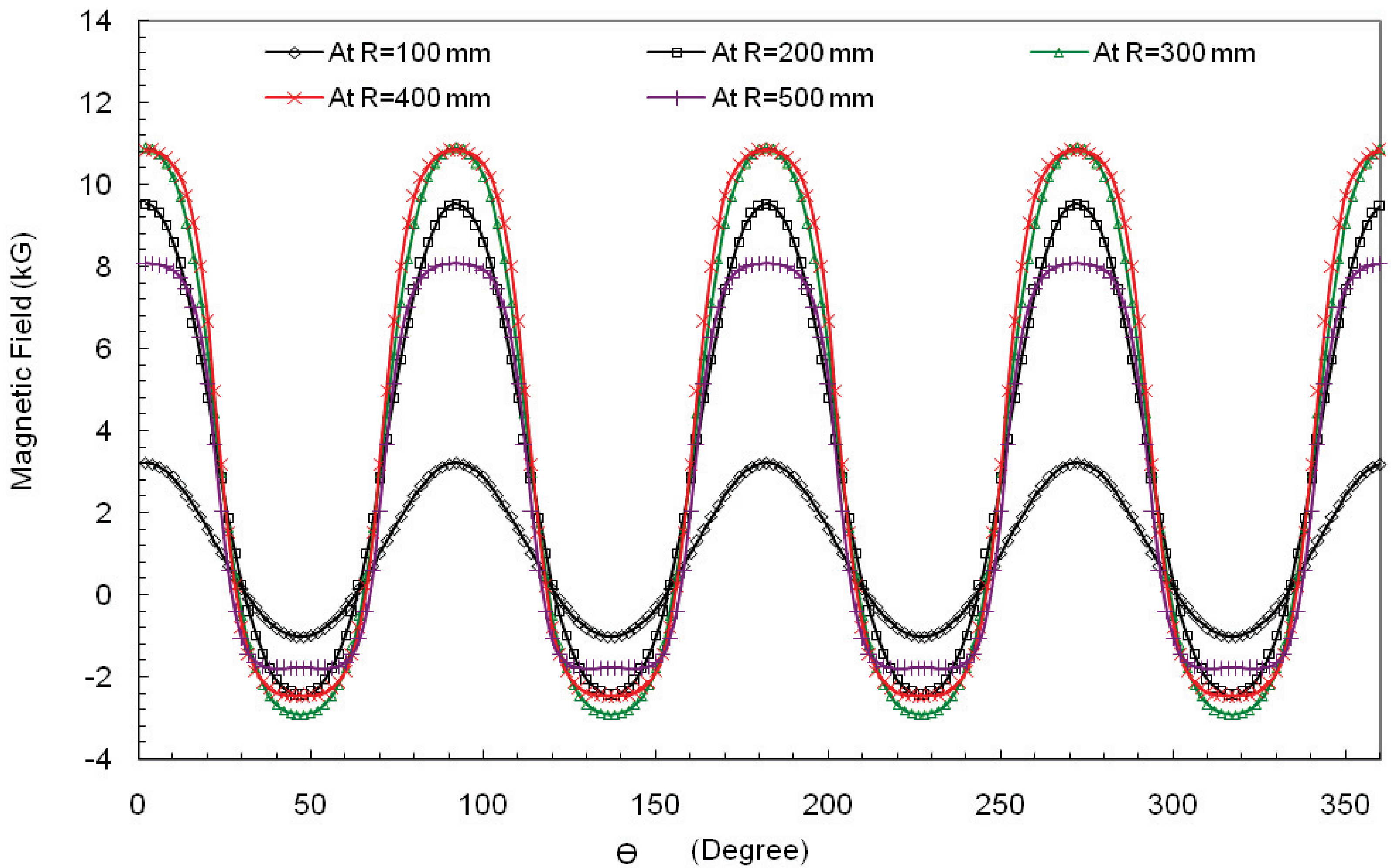
- Space required for the cryogenic system
- Multilayer thermal insulation,
- Radiation shield
- RF system (dee, liner)
- Spiral inflector and central region electrodes
- Radial penetrations for diagnostic probes
- Extraction port etc.





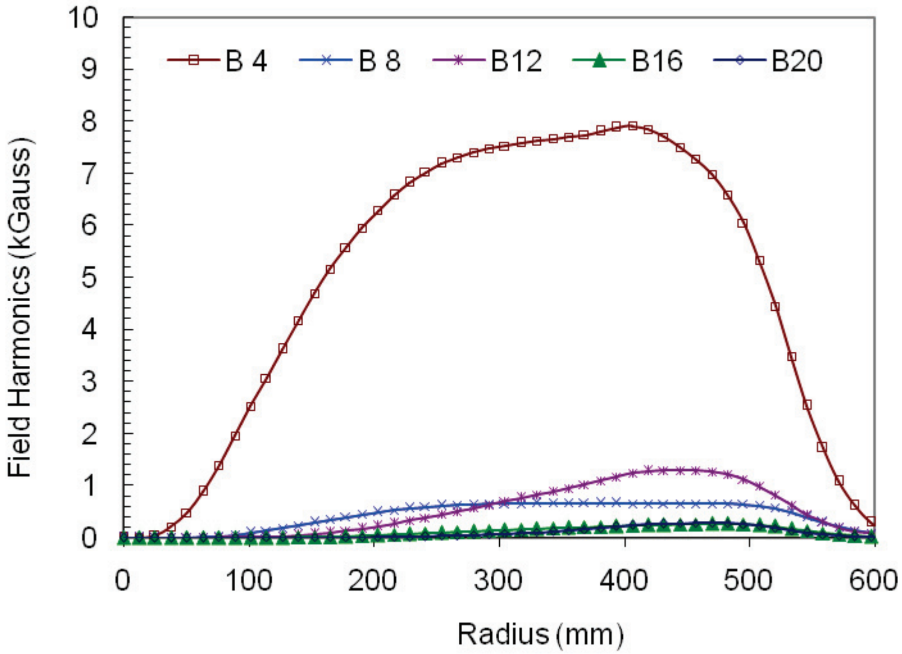
Magnetic Field Shaping

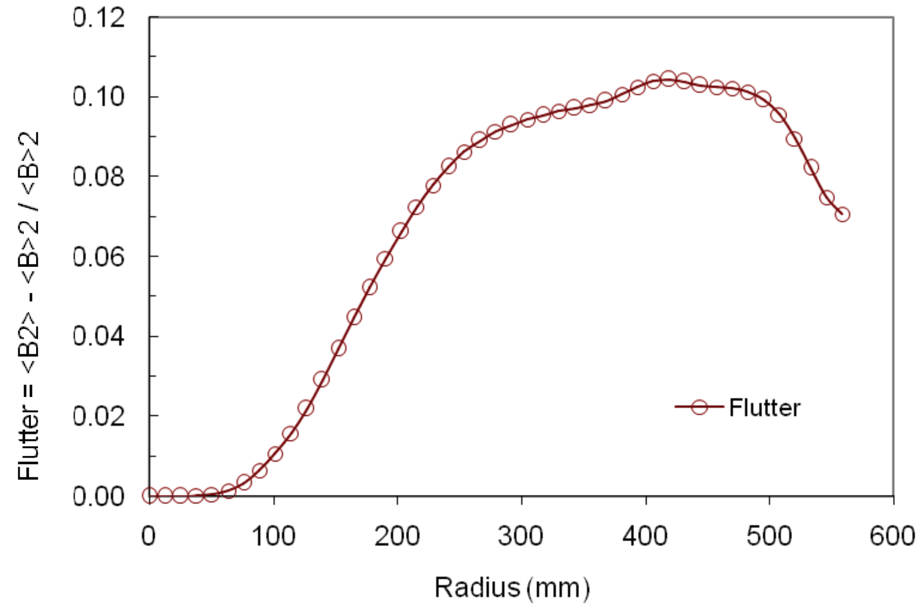
Azimuthally varying field produced by sector coils at different radii



Magnetic Field Shaping

Fourier harmonic components and Flutter





Maximum attainable kinetic energy $T/A = K_f \eta$

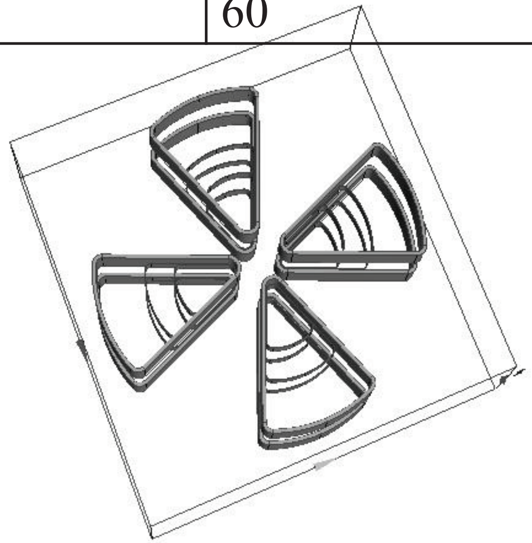
Focusing Limit $K_f = 150 * R_{ext} * B_N$

η is the ion's charge state/mass number

At R_{ext} = 415 mm, B_4 = 0.78 T, which gives K_f □ 36 MeV/A.

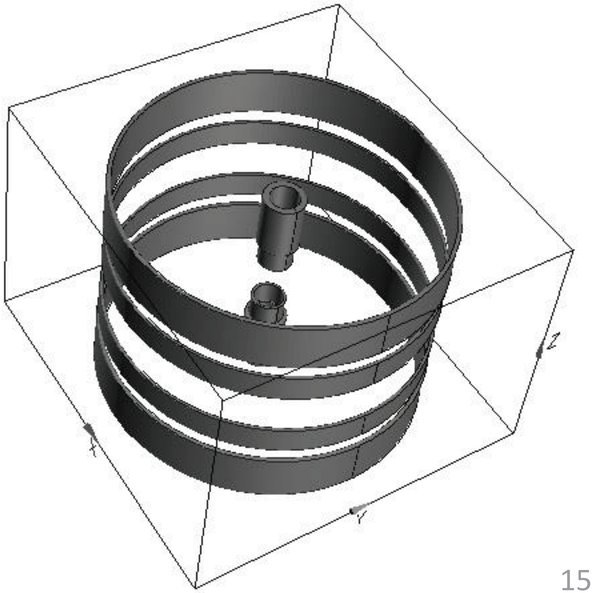
Superconducting Sector Coils

	Large	Medium	Smallest
Current	500 A		
Sector angle	22.5°		
Wire cross-section (mm^2)	1.1x1.7		
Inner Radius*	70.3	83.3	85.3
Outer Radius*	538.7	357.4	278.3
Radial length	468.4	273	193.0
No. of radial layers	10	1	1
No. of turns per layer	50	20	25
Distance from median plane*	60	60	60



Superconducting Circular Coils

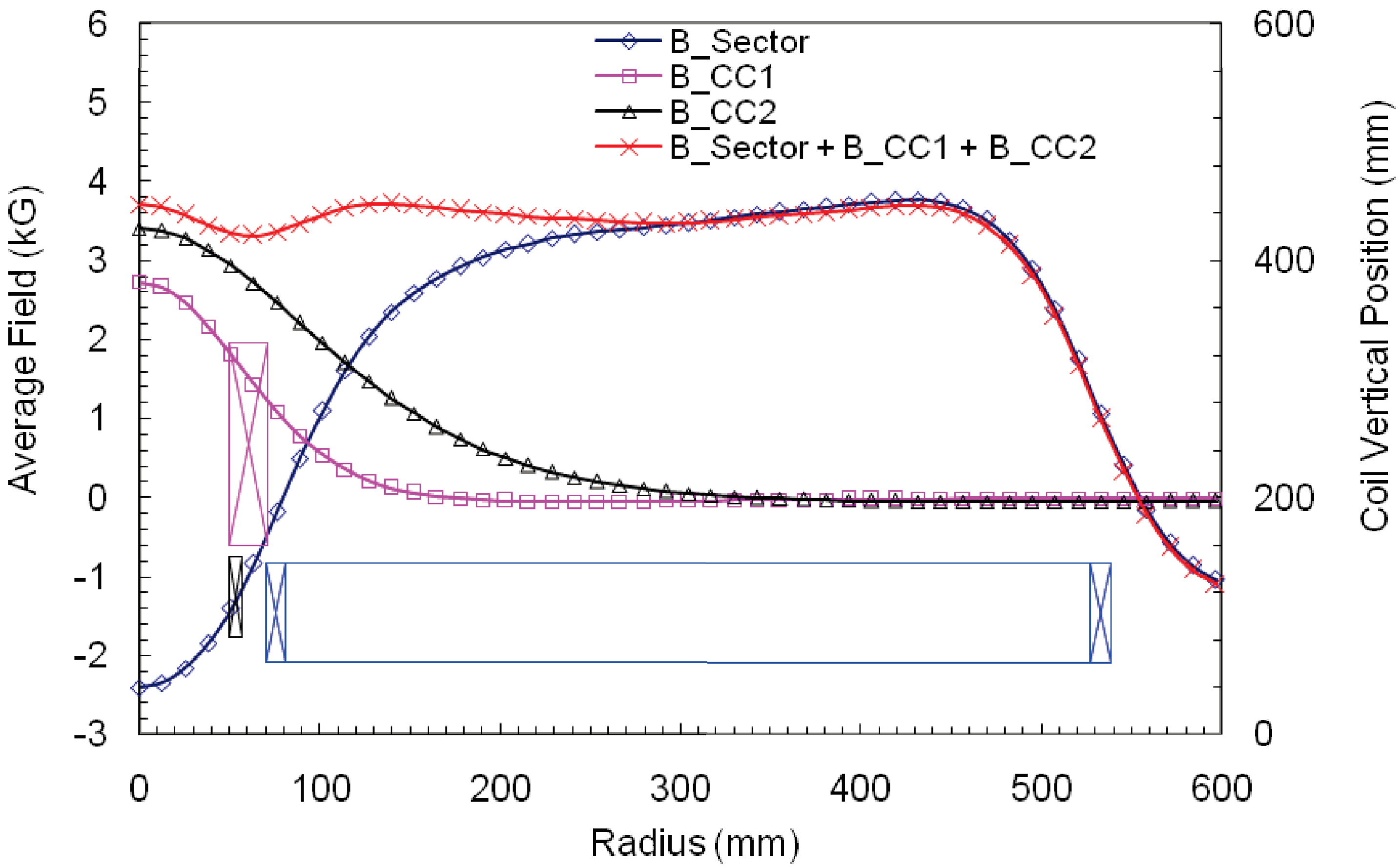
	CC1	CC2	MC1	MC2
Current (A)	500			
Inner Radius*	50	50	587	587
Outer Radius*	57	71	597	600
No. of radial layers	7	19	9	12
No. of turns per layer	40	100	12	90
Distance from median plane*	82	160	70	205



Magnetic Field Shaping

Sector coils and central circular coils

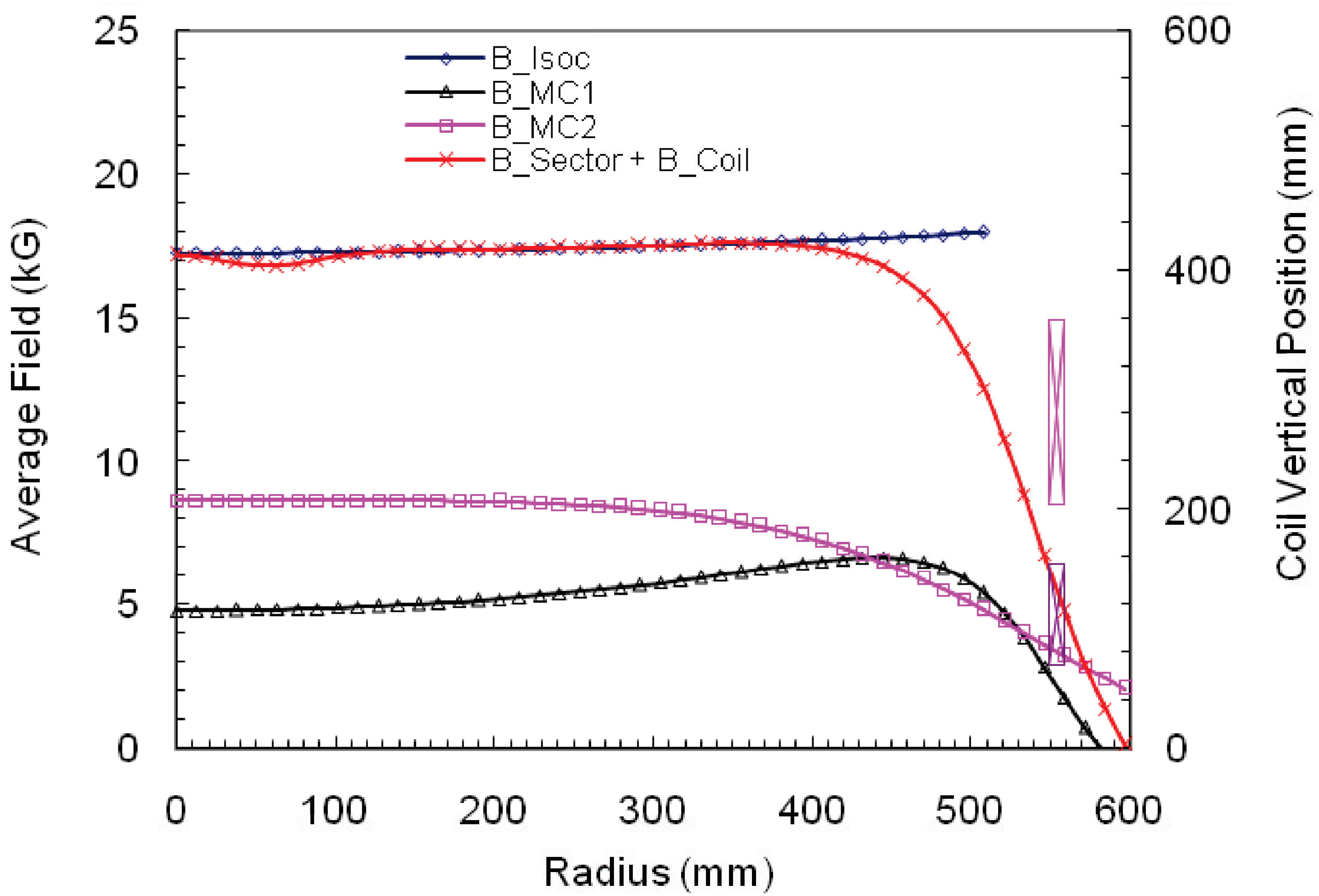
The average field profile due to the sector coils has a dip near the centre.
Central coils (CC1 and CC2) compensate this dip.



Magnetic Field Shaping

Main circular coils

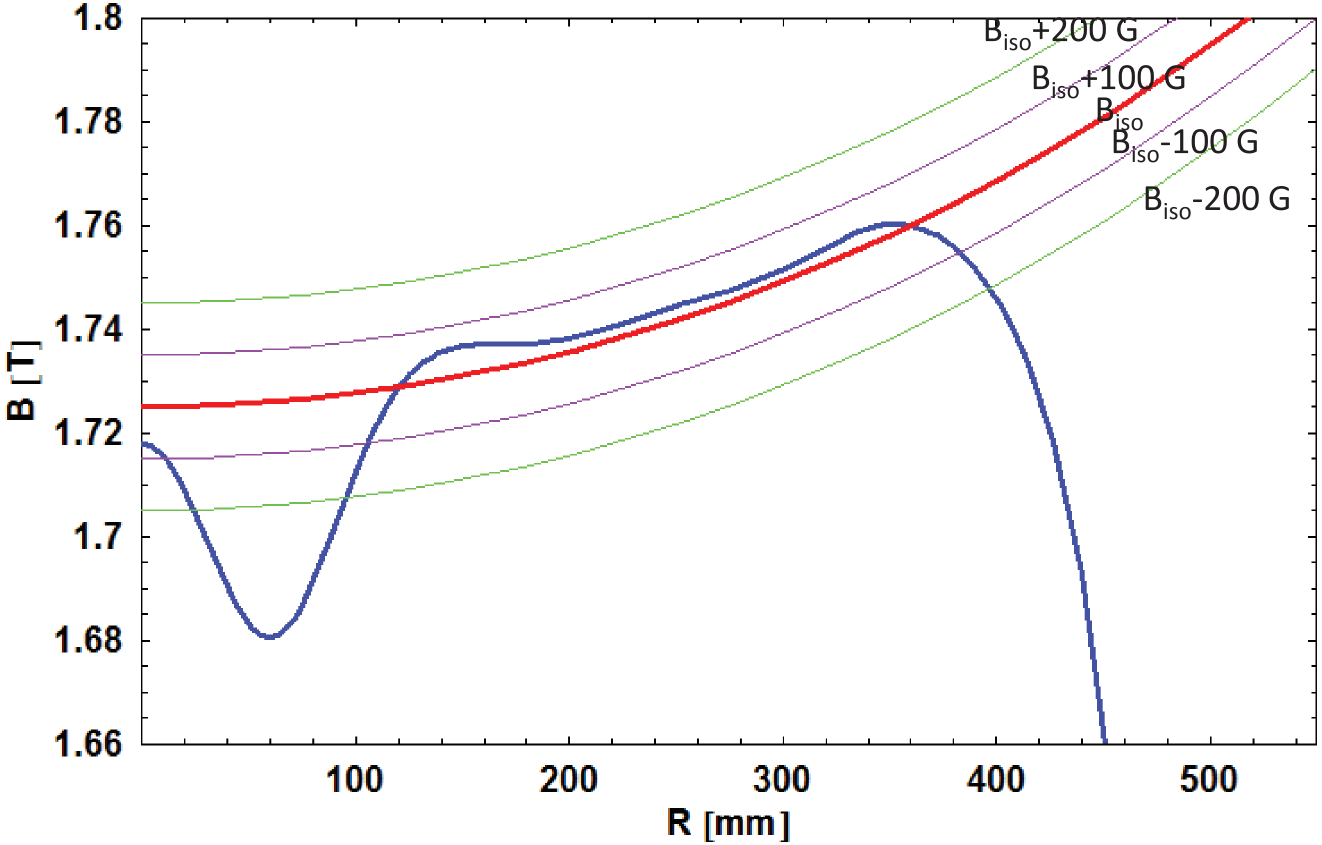
sector coils and central circular coils



Magnetic Field Shaping

Main circular coils + sector coils + central circular coils

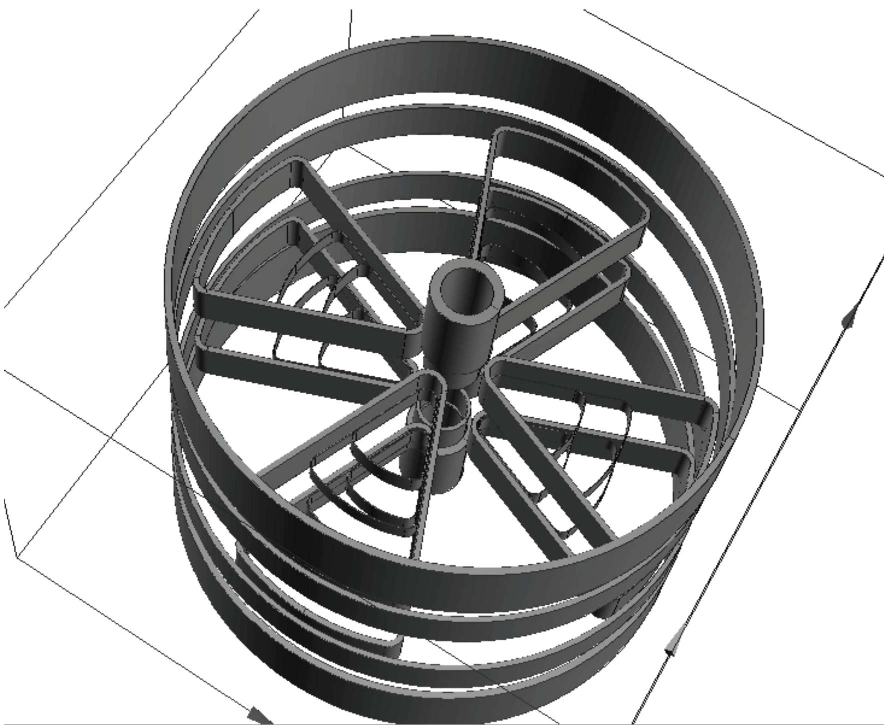
Optimized radial profile of total field is very close to the analytical isochronous field, within +/- 100 G, apart from a dip near centre and gradual fall at the extraction

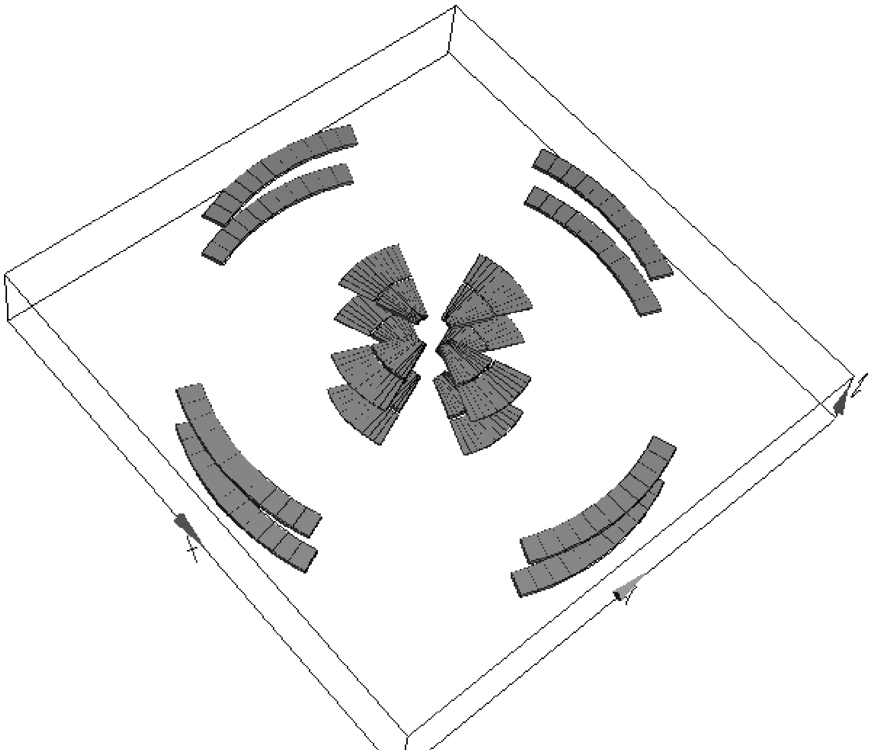


Magnetic Field Shaping

Iron shims

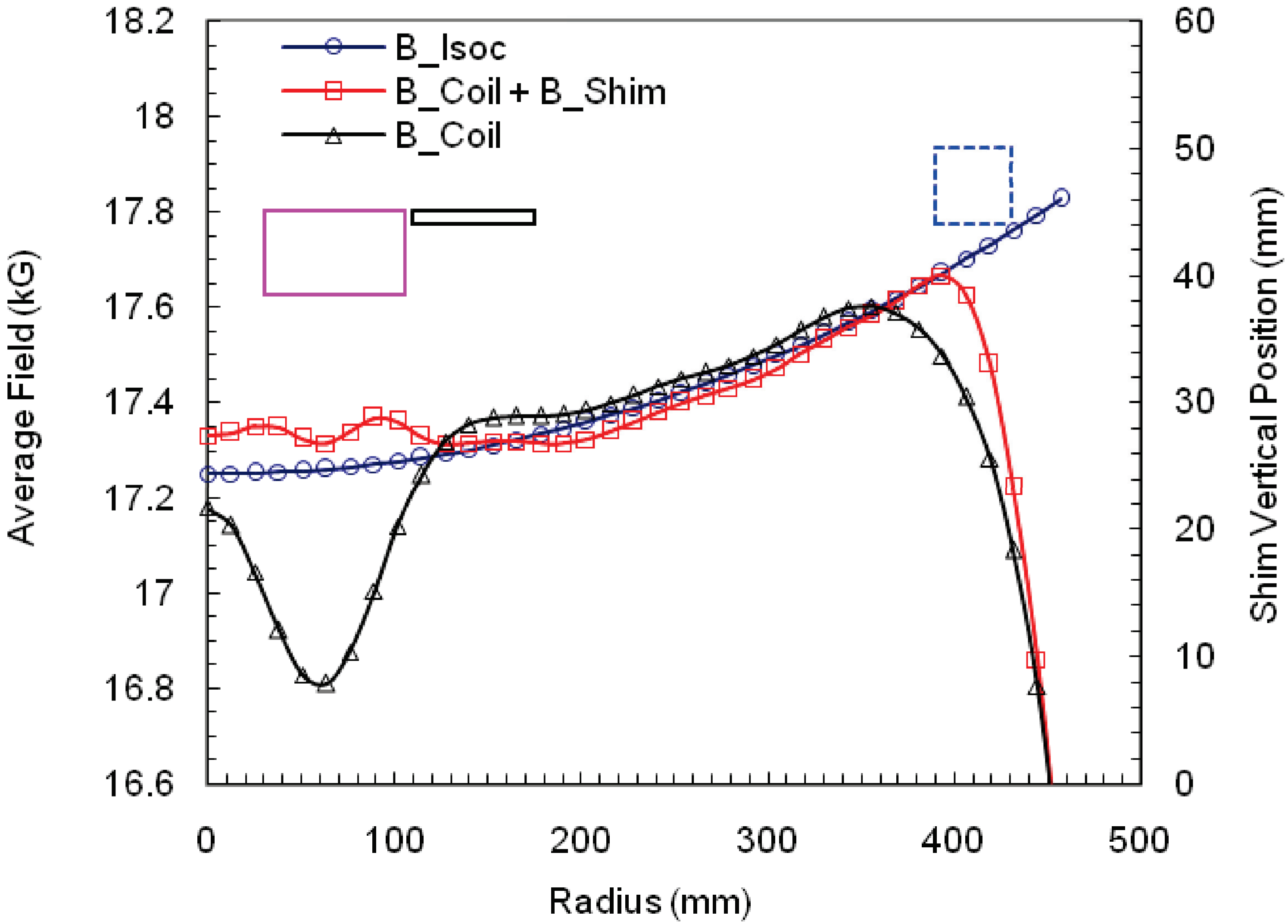
The dip near centre and gradual fall at the extraction is taken care by thin iron shims at the centre and near extraction





Magnetic Field Shaping

After Iron shimming



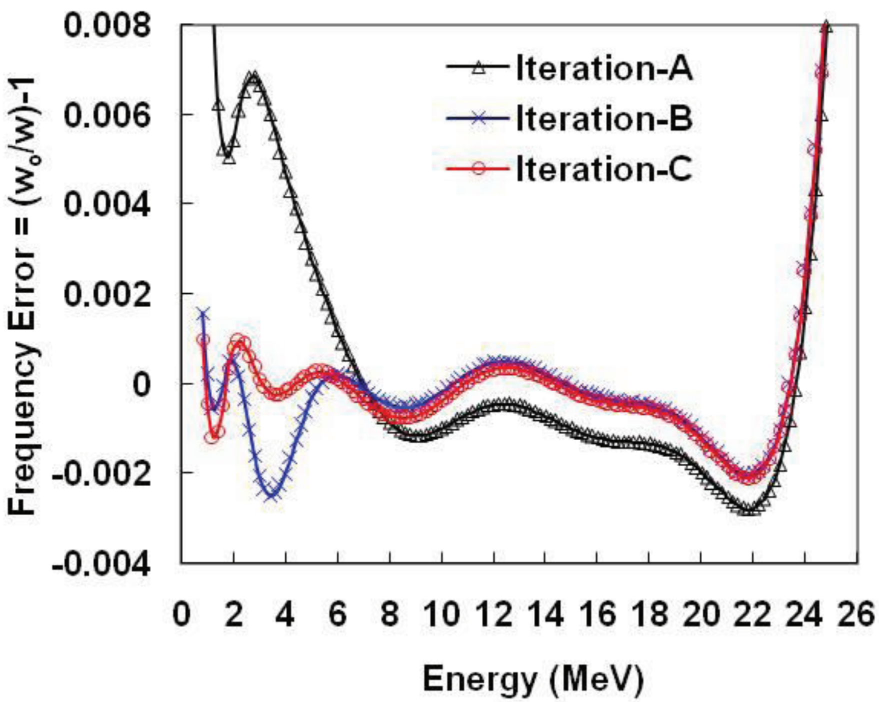
Equilibrium Orbit Properties

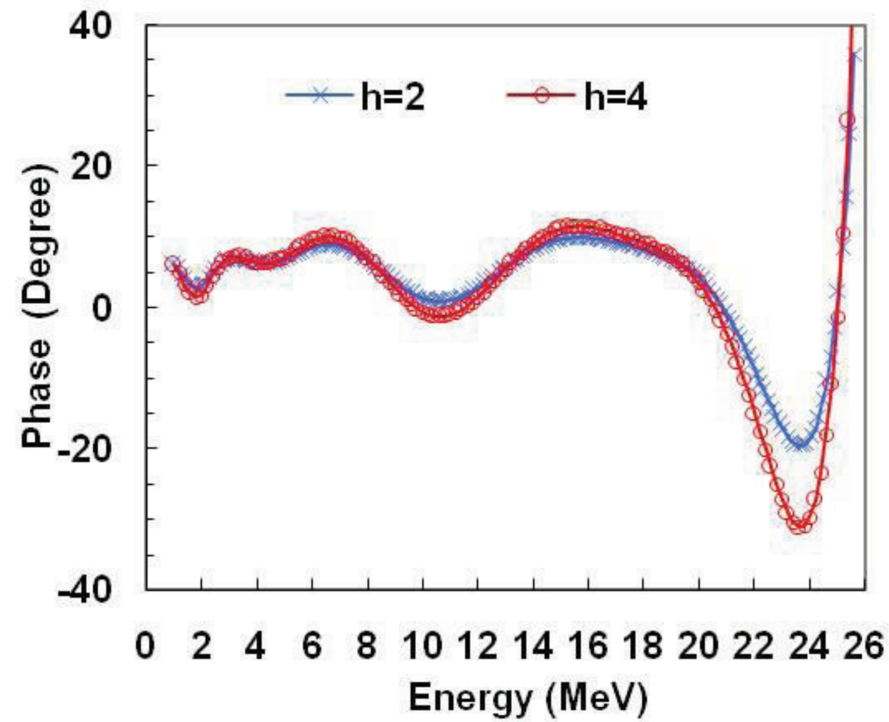
Frequency Error and Phase

Frequency Error $\Omega(E) = (\omega_0 / \omega) - 1,$

Phase $\sin\varphi(E) = \sin\varphi(E_0) + (2\pi h/qV)\, F(E)$

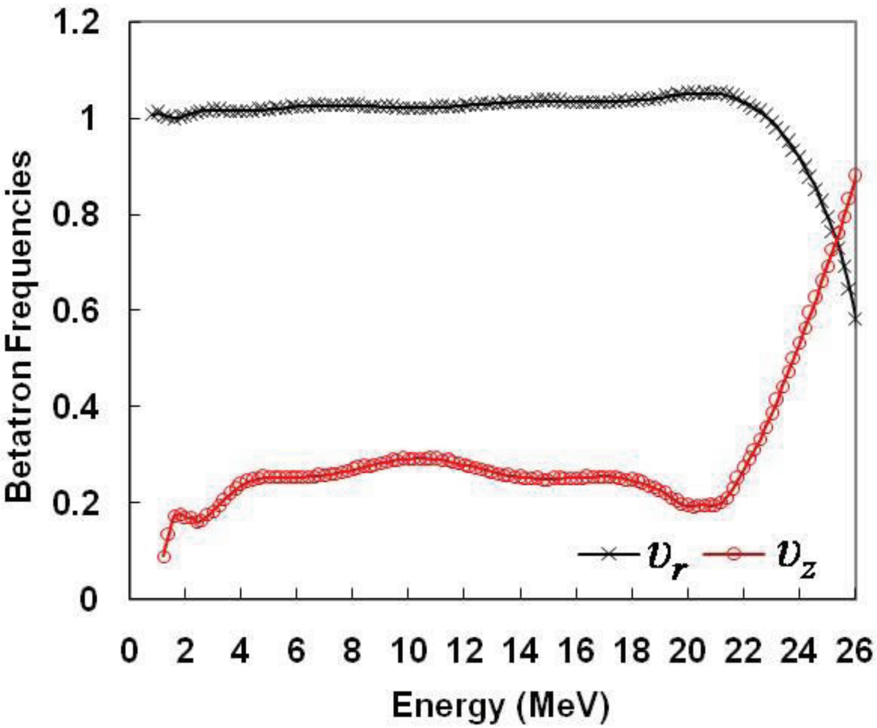
$$F(E) = \int_{E_0}^{E} \Omega(E)\, dE$$

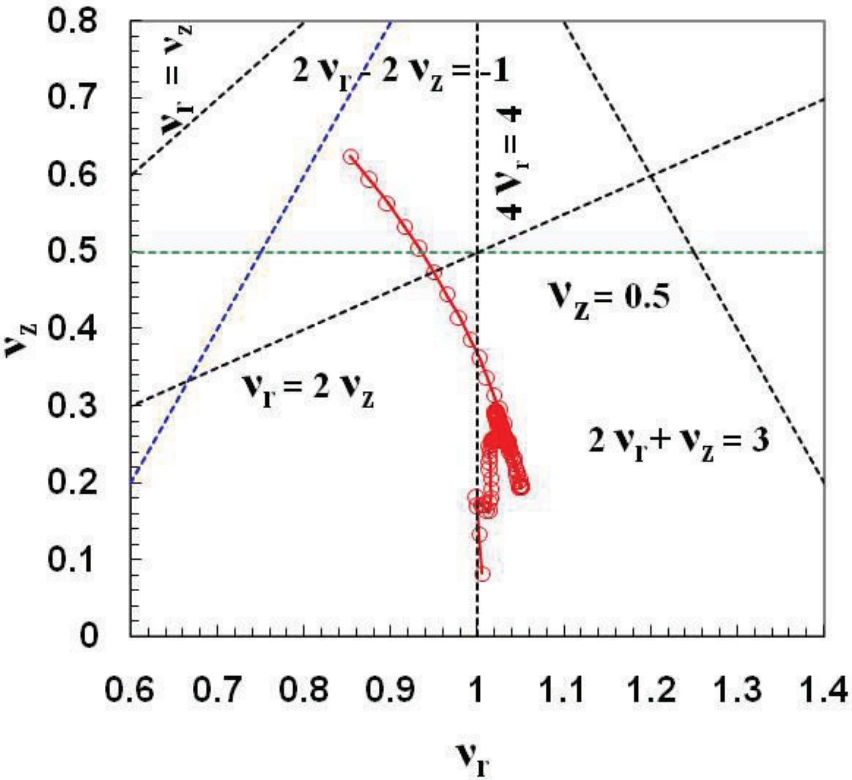




Equilibrium Orbit Properties

Betatron Frequencies and Tune Diagram



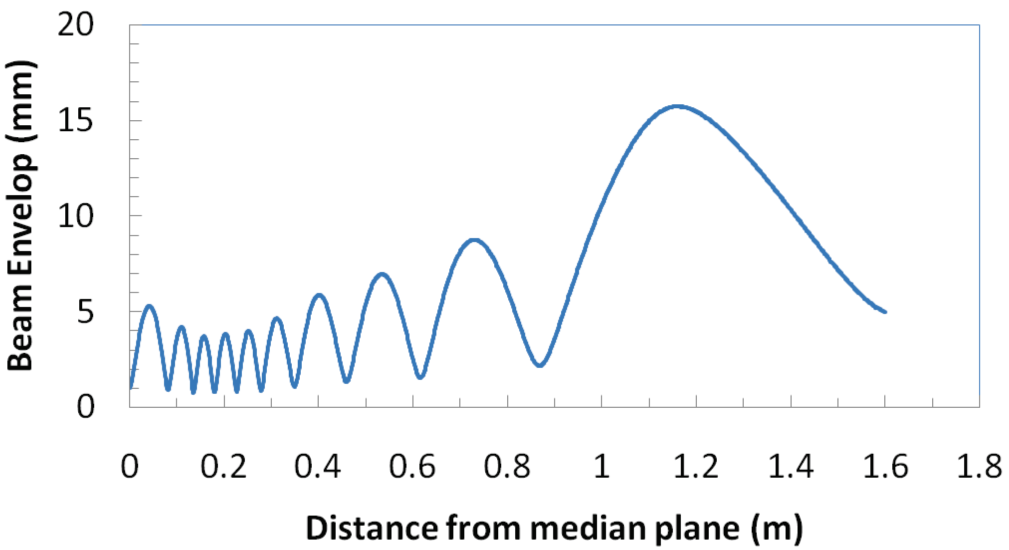


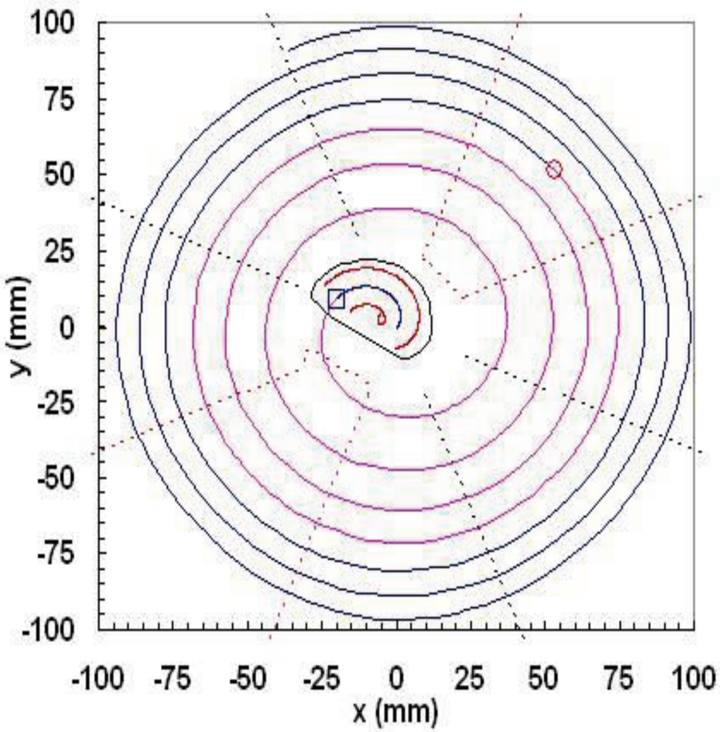
Injection From External Ion-source

- Focusing by central solenoids
- With typical injection energy of 28 keV

  in an average field of 1.735 T,

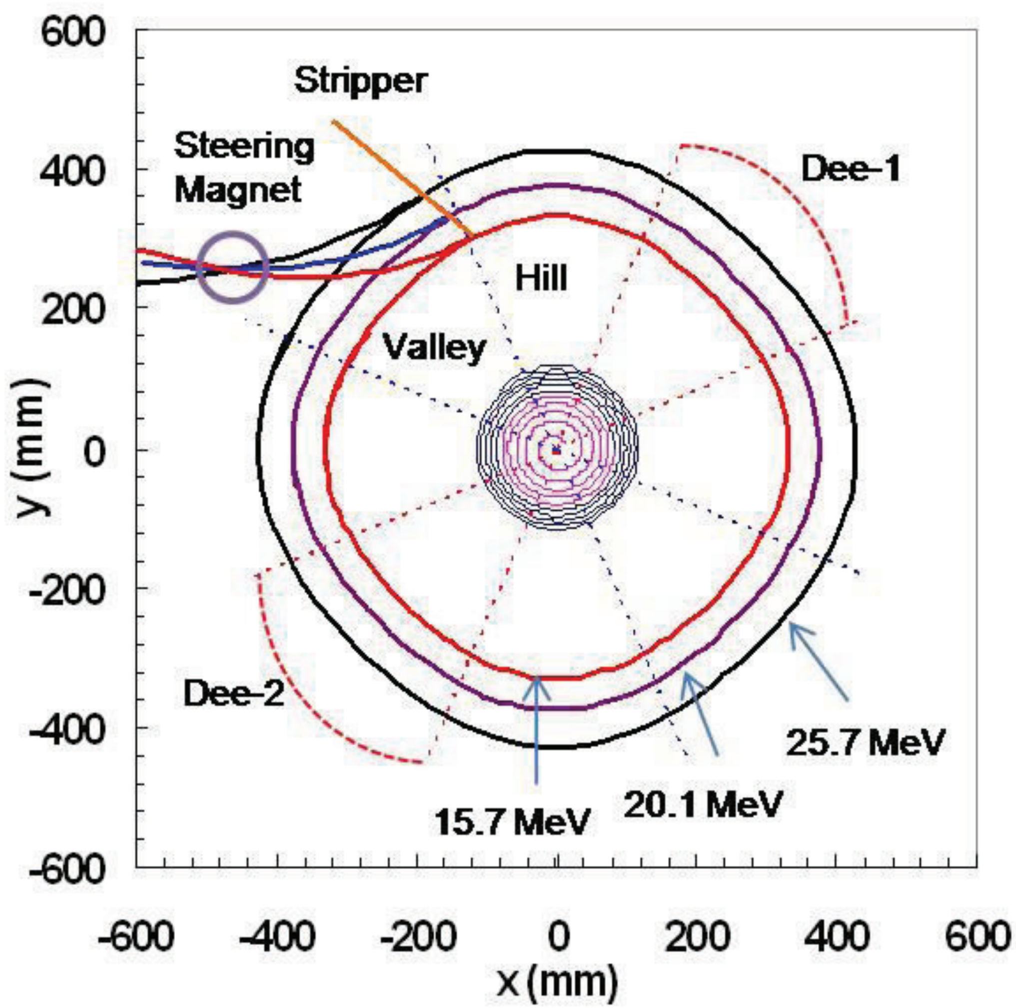
  Magnetic radius of spiral inflector, R_m = 14 mm.





Extraction by Stripping

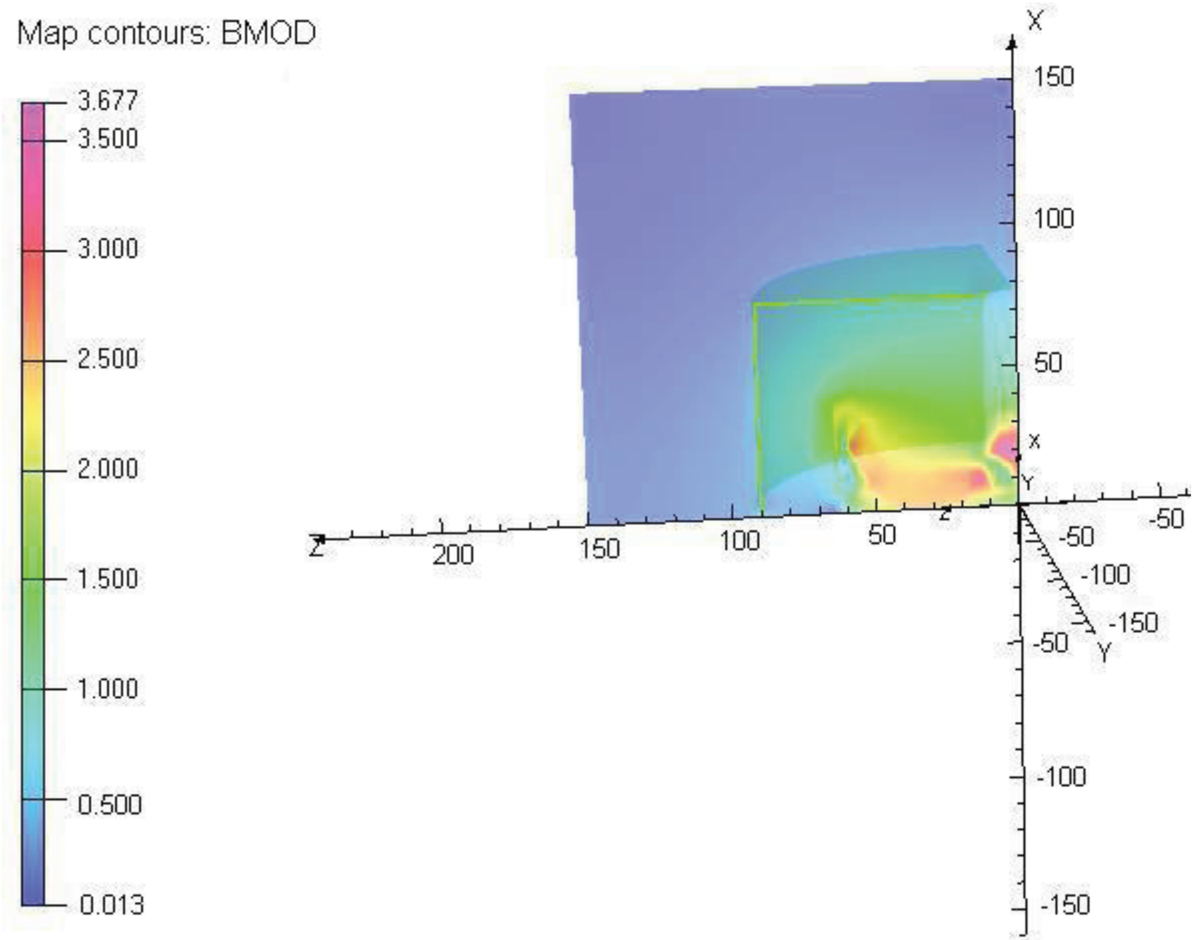
- Variable Energy from 15.7 MeV to 25.7 MeV
- Two simultaneous beam



Magnetic Shielding

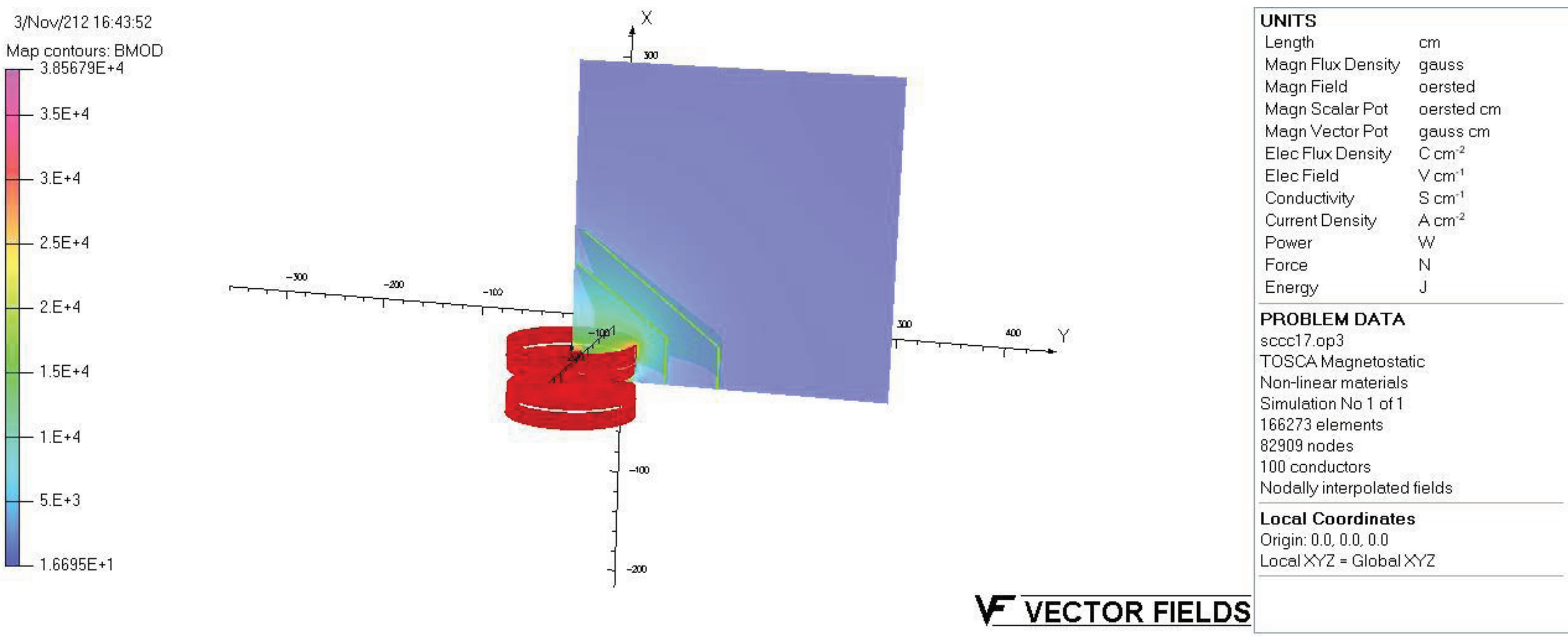
External iron cylinder

With a 6 mm thick iron cylinder of 900 mm radius and 1500 mm height (weight 630 kg), the fringing field is reduced to 137 G at 0.5 m outside the shield.



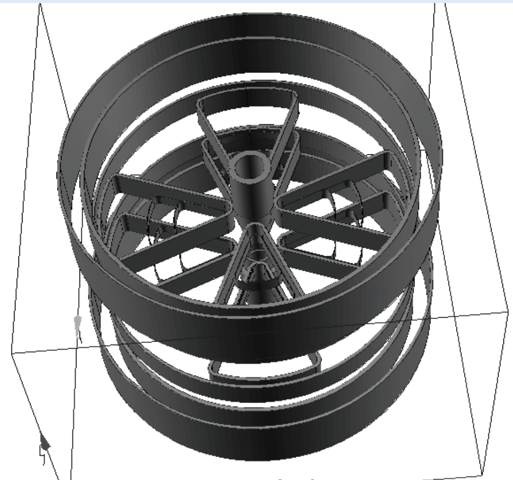
Double wall iron cylinder

Field at 0.5 m (outside the first shield) may be reduced to 20 G by adding another iron cylinder of 6 mm thickness and 1200 mm radius weighing about 820 kg around the first one.



Magnetic Shielding

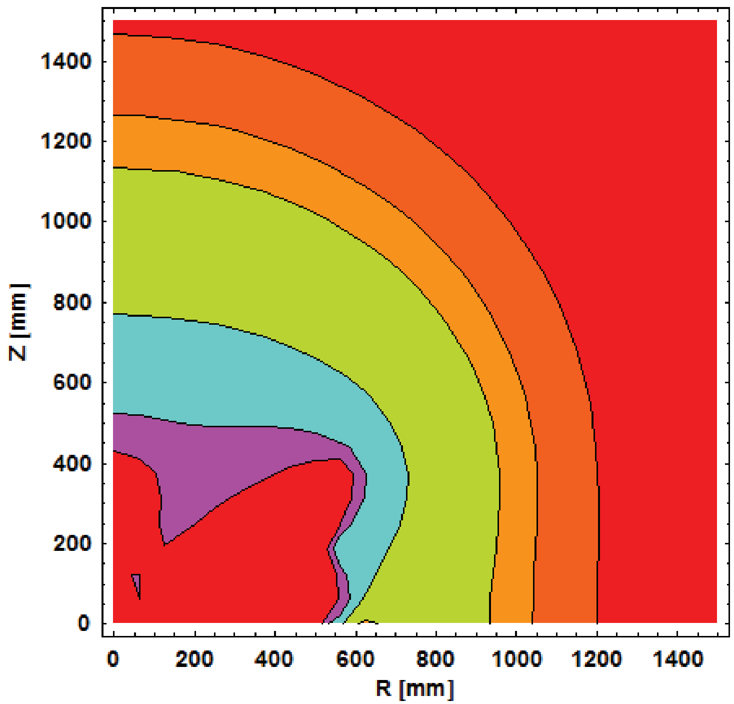
Combination of Reverse Coils and External iron cylinder



Without Reverse coils

Contours(T)

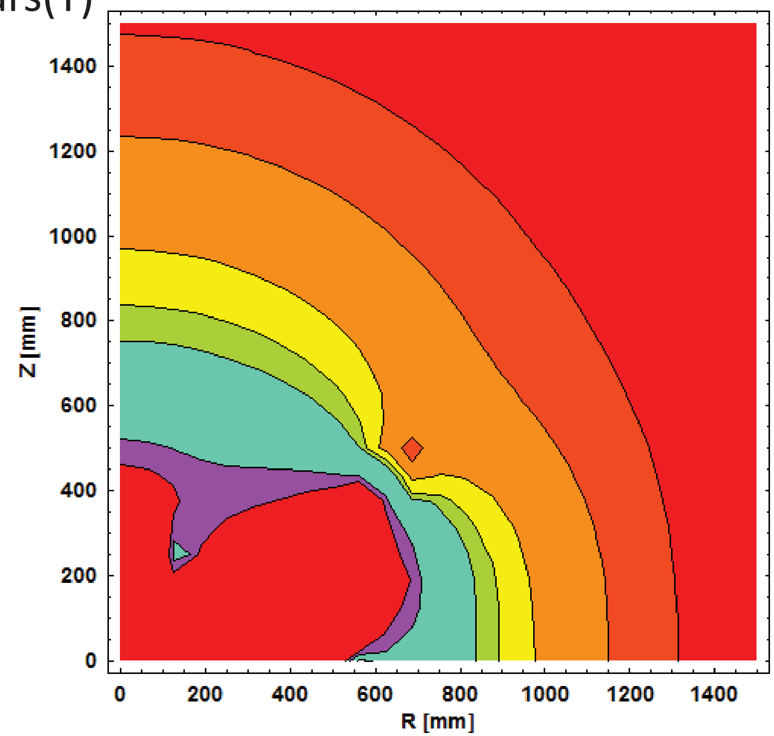
0.1
0.15
0.2
0.5
1.0
1.5



With Reverse coils

Contours(T)

0.03
0.05
0.1
0.15
0.2
0.5
0.7



Conceptual Engineering Design

Considerations:

- ➢ Compact and light weight
- ➢ Ease of fabrication, assembly, maintenance

The weights of the major components:

Former for coils: 250 kg;

SC coils: 200 kg;

Radiation shield: 150 kg;

Vacuum chamber: 550 kg;

RF system: 200 kg;

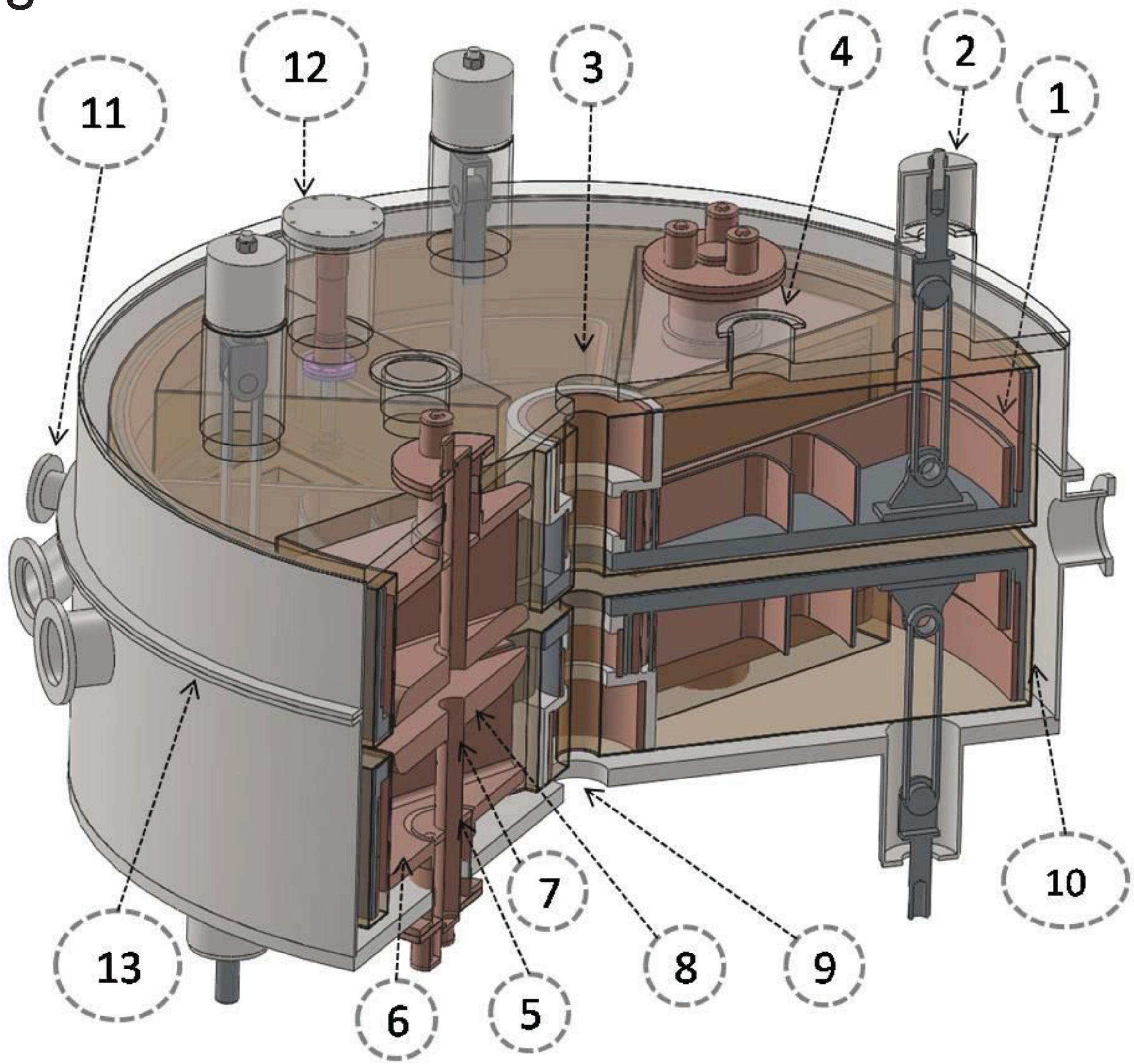
External magnetic shield: 630 kg.

Total ~2000 kG

Conceptual Engineering Design

3D Conceptual Design

1. Coil-cryostat,
2. Support link
3. Beam injection port
4. Vacuum port
5. Sliding short between cavity outer and inner conductors
6. RF liner (outer conductor)
7. Dee stem
8. Dee,
9. Port for spiral inflector
10. Liquid nitrogen shield
11. Median plane ports for beam extraction, stripper holder, beam diagnostics
12. Port for Cryo-cooler
13. Median plane O-ring joint.

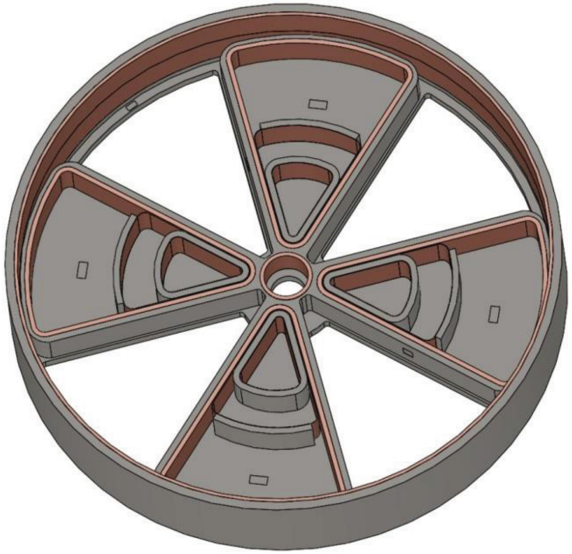


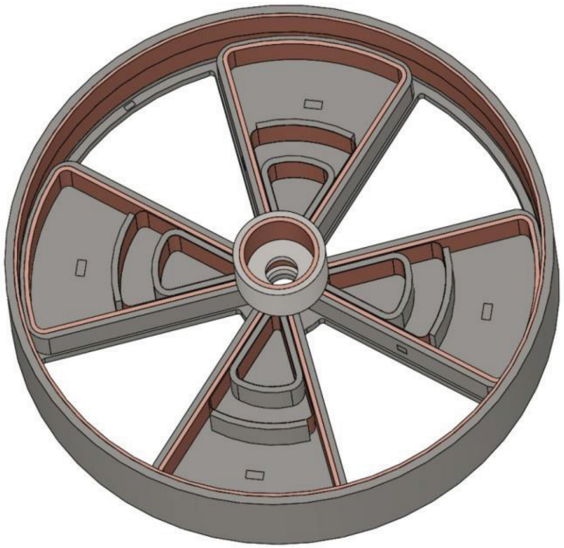
Conceptual Engineering Design

Coil assembly and Coil former

Cryogenic stability :

- Copper to superconductor ratio 20:1
- High stability against quenching.
- Two ‘formers’ (bobbins), machined out of high strength aluminium alloy blocks.
- All coils are clamped to former



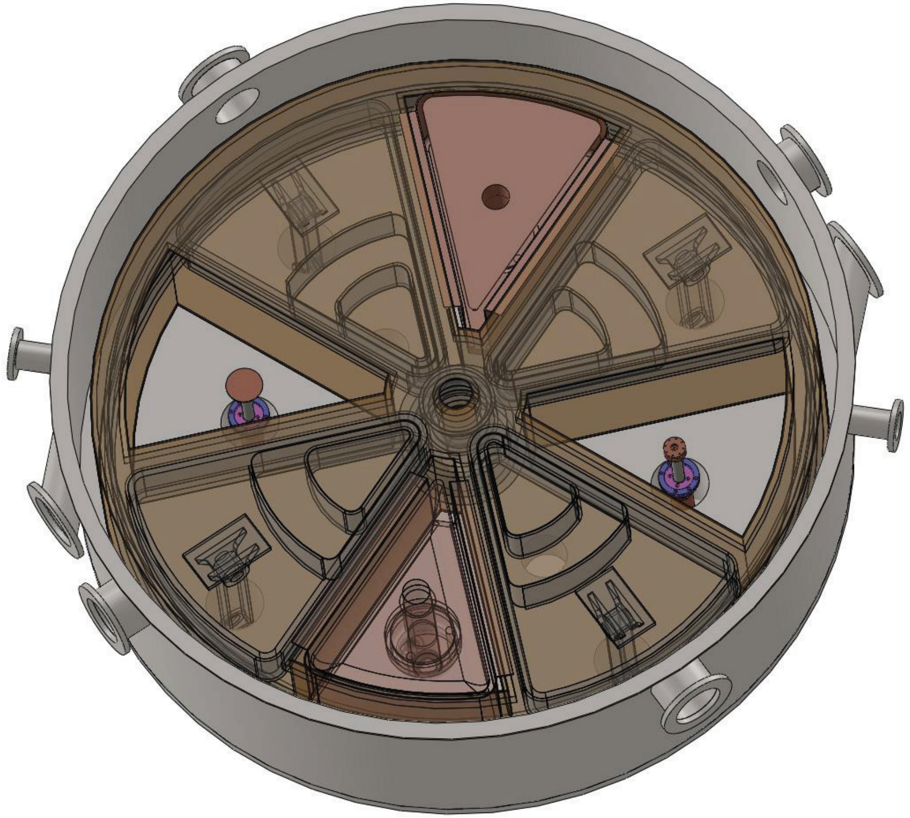


Conceptual Engineering Design

Cryostat assembly: Cryo-cooler based

Two options -

- ❖ Bath cooled, re-condensation type
- ❖ Conduction cooled, flexible thermal strips



Glass epoxy support links hold the former inside the vacuum chamber.

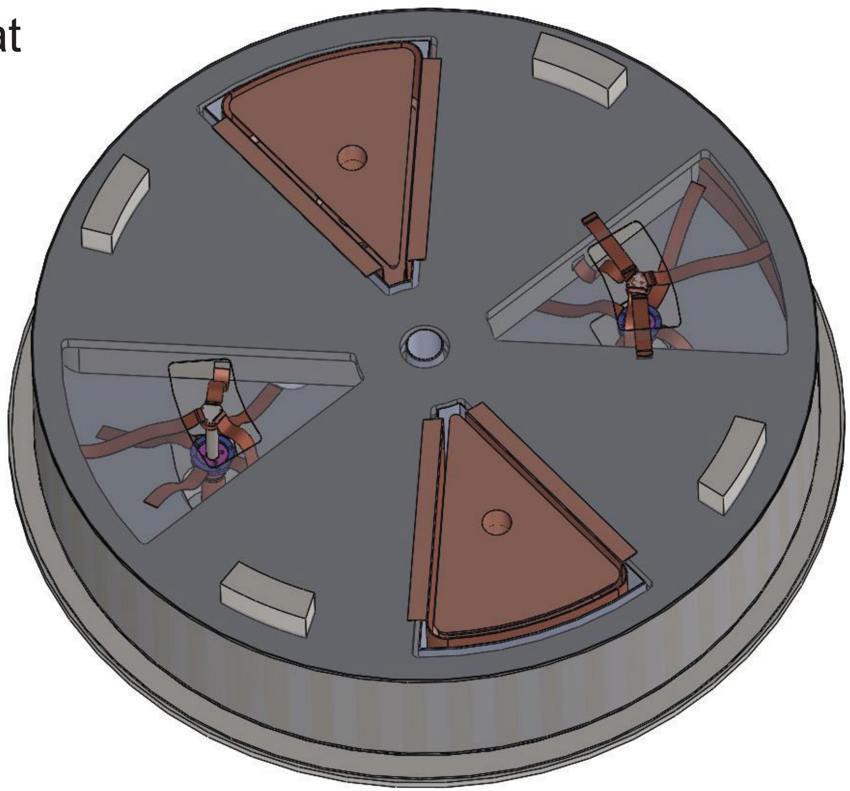
A 50 K thermal intercept from the cryo-cooler 1st stage is provided to the support links for reducing the heat load to the coils.

Optimized cold mass is about 450 kg at 4.2 K and 150 kg at 50 K.

Conceptual Engineering Design

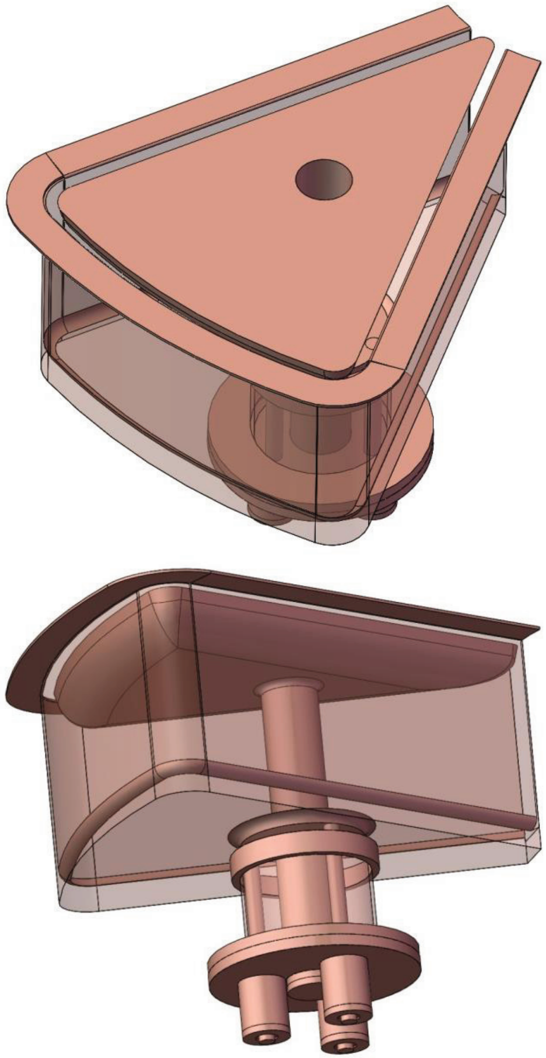
- Heat load about 4 W at 4.2 K with a 50 K radiation shield and 50 K intercepts for the conduction links.
- Eddy current power dissipation in the Al-alloy former: about 4 mW when the coils are ramped to 500 A in 2 hours.

- Four cryo-coolers for cooling the coil-blocks. Each having capacity of 35 W at 50 K (1st stage) and 1.5 W at 4.2 K (2nd stage).
- The 1st stage will be used to cool the thermal shield and the intercepts.
- The upper and lower formers are rigidly supported at the median plane, outside the beam acceleration zone, with four solid blocks to take care of the magnetic loading between the upper and lower coils.

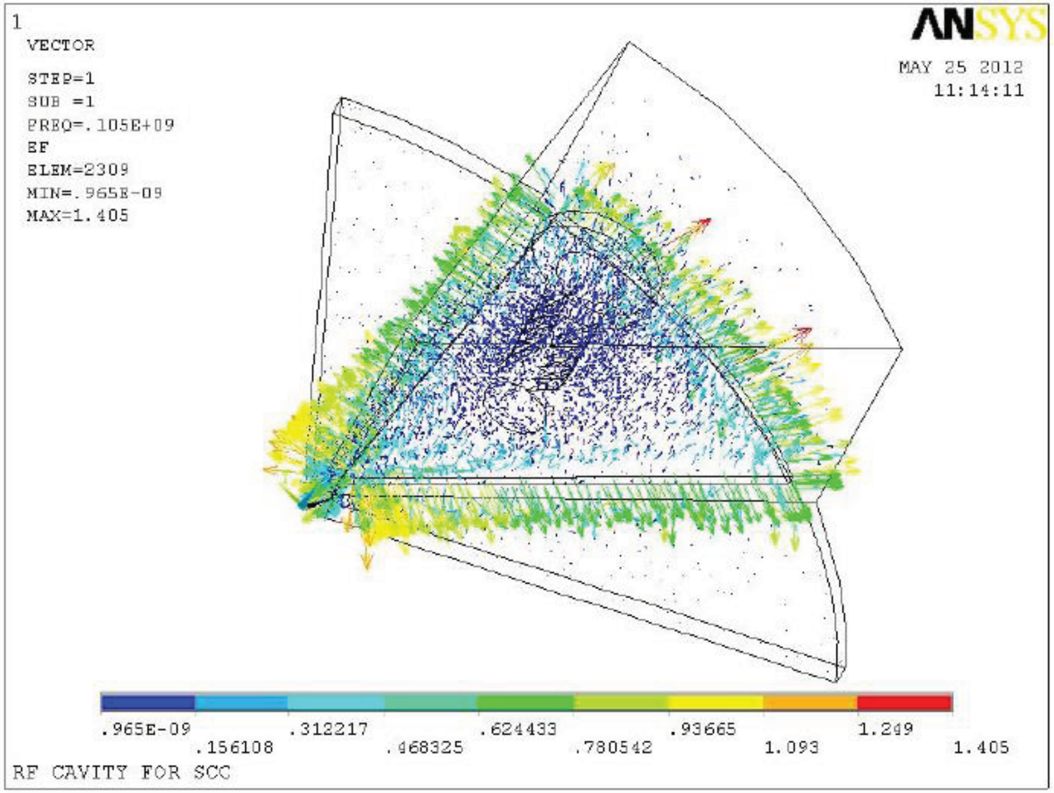


Conceptual Engineering Design

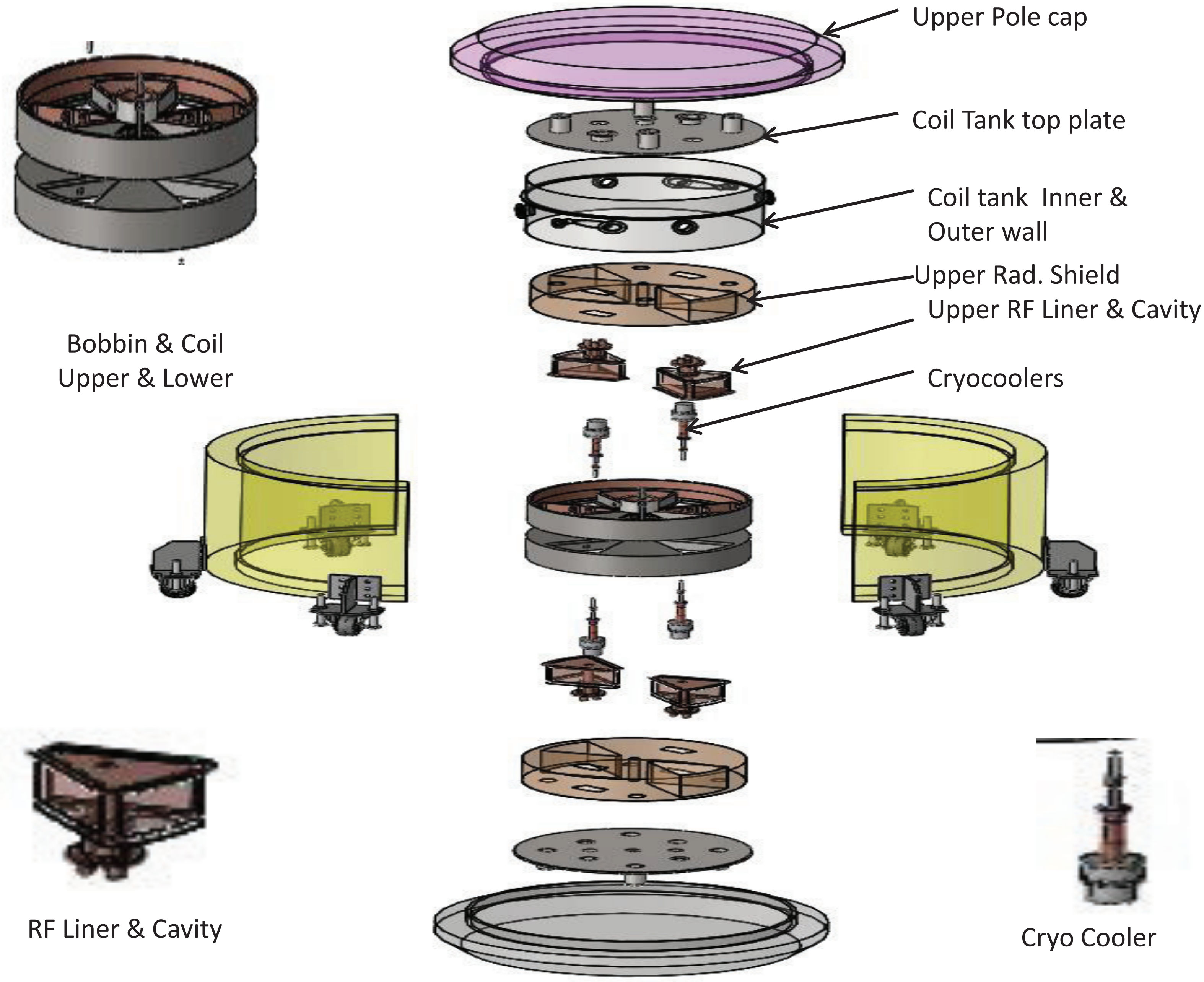
RF System



- Water-cooled copper cavity,
  Coaxial TEM structure
- RF frequency ~106 MHz



Conceptual Engineering Design



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 16, 040101 (2013)

Novel compact superconducting cyclotron for medical applications

Malay Kanti Dey, Anjan Dutta Gupta, and Alok Chakrabarti
Variable Energy Cyclotron Centre 1/AF Bidhannagar, Kolkata 700064, India
(Received 20 June 2012; published 9 April 2013)

A new design is presented for a superconducting-coil-based compact cyclotron, which has many practical benefits over conventional superconducting cyclotrons. Unlike in conventional superconducting cyclotrons, an iron yoke and poles have been avoided in this design and the azimuthally varying field is generated by superconducting sector coils. Housing the superconducting sector coils and circular coils in a single cryostat has resulted in an ultralight 25 MeV proton cyclotron weighing about 2000 kg. Further, the sector coils and the main coils are fed by independent power supplies, which allow flexibility of operation through on-line magnetic field trimming. The engineering considerations, focused on making the cyclotron ideally suited to medical applications, are described in detail.

DOI: 10.1103/PhysRevSTAB.16.040101 PACS numbers: 29.20.D−, 29.27.−a

I. INTRODUCTION

Cyclotron designs have evolved to make them suitable for a variety of applications, like scientific experiments in atomic, nuclear, and solid-state physics, as well as in medical and industrial applications. Considering its compactness and the cost factor, the cyclotron has been the ideal choice for medical isotope production [1]. Hundreds of cyclotron installations worldwide are engaged in the production of the positron emission tomography and

between conventional superconducting cyclotrons and Oxford Instrument's superconducting cyclotron was that the isochronous field along with adequate flutter was produced by superconducting main coils and iron poles only, without any iron return yoke. The magnetic efficiency of using an iron yoke was foregone to secure the advantages of low machine weight. Isochronous fields for protons or H^- ions up to 60 MeV can be produced in such an arrangement [6]. The present work is basically inspired by this scheme.

Conclusion

- Explored a new design of an ultra-light low energy medical cyclotron, eliminating the iron yoke and poles altogether.
- Azimuthal varying field is generated by superconducting sector coils
- Independently powered superconducting circular coils, sector coils trim coils further provides flexibility of operation
- All the coils are accommodated in a single cryostat.
- The basic size and shape of the other subsystems, e.g., spiral inflector, rf system, cryogenic system, extraction system etc., have been estimated realistically
- Magnet design has been optimized taking into consideration all the other subsystems
- A conceptual engineering design has also been worked out to check the feasibility of the design from the engineering point of view.


Akash Banerjee © 2009
Thanks