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The Magnet Design of a Compact 16 MeV Variable Energy Cyclotron for Isotope Production

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Introduction

- China is promoting the production of small cyclotron to guarantee the stable preparation of medical isotopes such as ^{18}F, ^{64}Cu, ^{225}Ac, which requires proton energies in the range of 10~16 MeV [1].
- Variable-energy cyclotron that can simultaneously produce several isotopes is more adopted to the market demand than single-energy cyclotron.
- The CIMV16 cyclotron being developed by CIM is capable of accelerating negative hydrogen ions (H^-) to variable energy in the range of 10~16 MeV. It has a maximal diameter of only 1.8 m and adopts three straight-sector poles with the third harmonic acceleration.

Generally design

The preliminary design is based on the following assumptions:

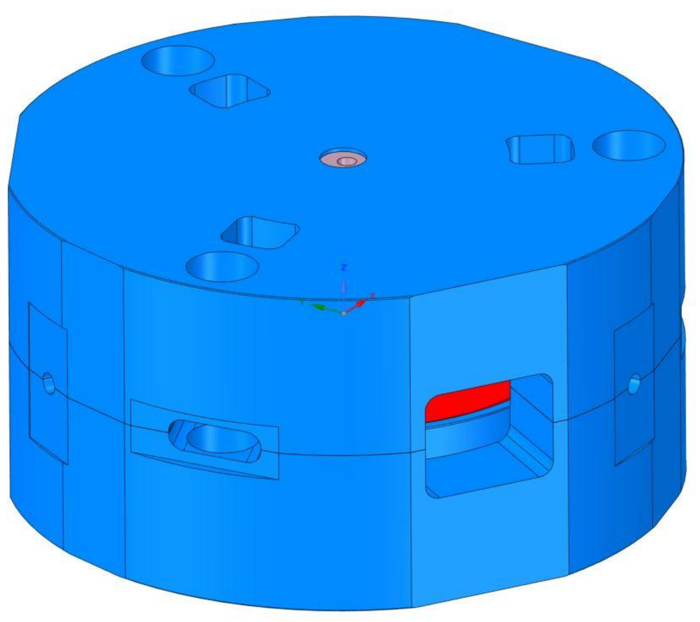
- Isochronous cyclotron
- Maximal extraction energy is 16 MeV
- Vertical betatron tune (ν_z) is in the range $0.10 < \nu_z < 0.20$
- Straight-sector poles (spiral angle $\mu = 0$)

$$\nu_z^2 \approx -\frac{R}{\langle B_z \rangle}\frac{d\langle B_z \rangle}{dR} + \frac{N_{sect}^2}{N_{sect}^2-1}F(1+2\tan^2\mu) = -kindex + \frac{N_{sect}^2}{N_{sect}^2-1}F$$

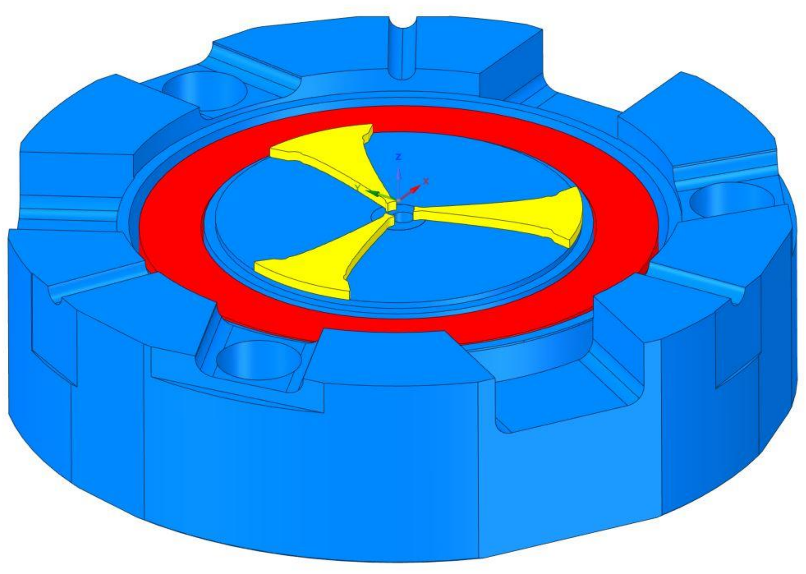
Weak positive radial gradient of the averaged field and no spiral angle requires a larger flutter. Therefore, we adopt 3 poles with the 3rd harmonic acceleration for larger ν_z.

Parameters of Magnet System

Parameter	Value	Parameter	Value
Particles accelerated	H^-	Extraction energy	10~16 MeV
Number of poles	3	Radial range of coil	455~597 mm
Max. radius of pole	423 mm	Axial range of coil	142~155 mm
Outer radius of yoke	915 mm	Cross section of coil	142 x 13 mm^2
Hill gap / Valley gap	41 / 87 mm	Number of turns	10 x 11
Total height of magnet	920 mm	Amperes x Turns	56397 A
Central field	1.364 T	Nominal current	512.5 A/turn
Max. averaged field	1.570 T	Current density	256.15 A/cm^2



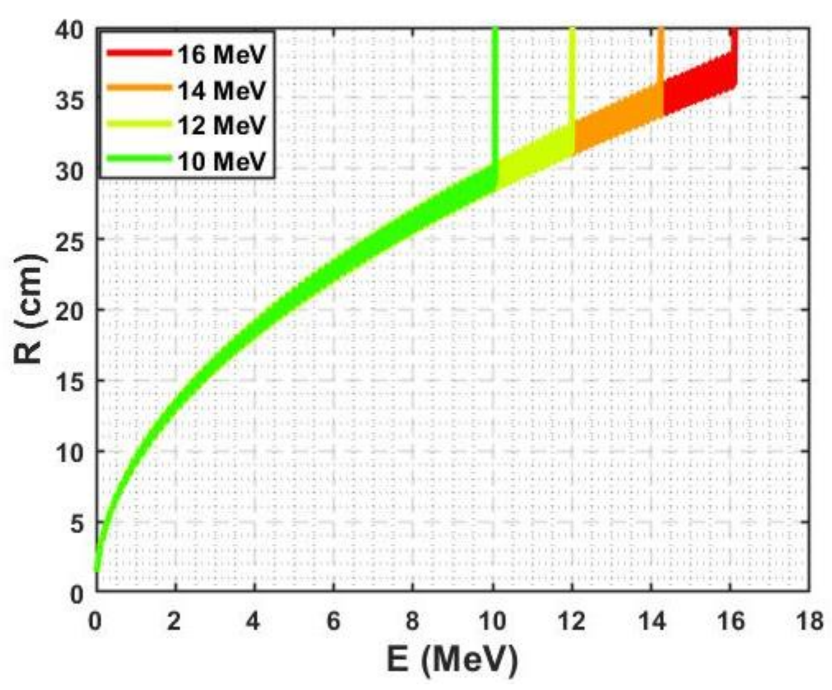
Model of magnet system (exterior)



Model of magnet system (interior)

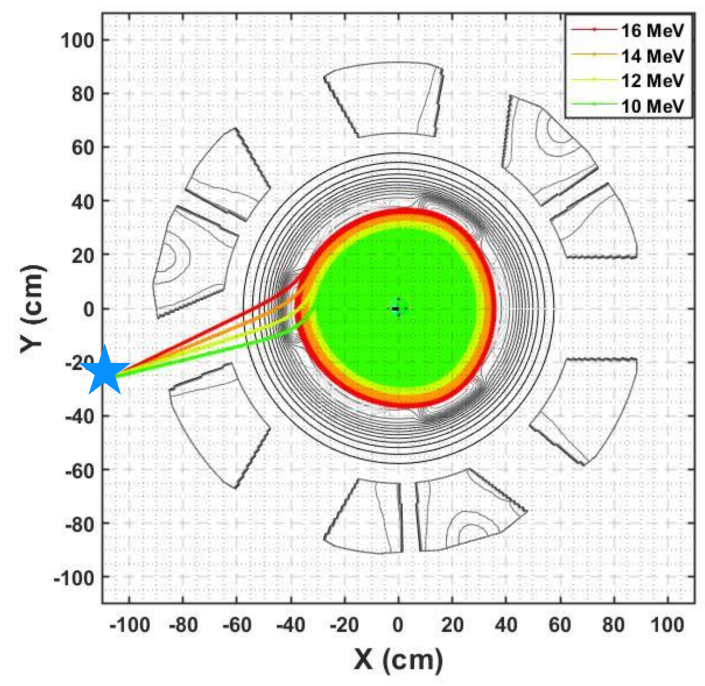
Yoke　Coil　Pole

Selection of extraction energy



Energy gain

★ Convergence point



Trajectory of center particle with different extraction energy

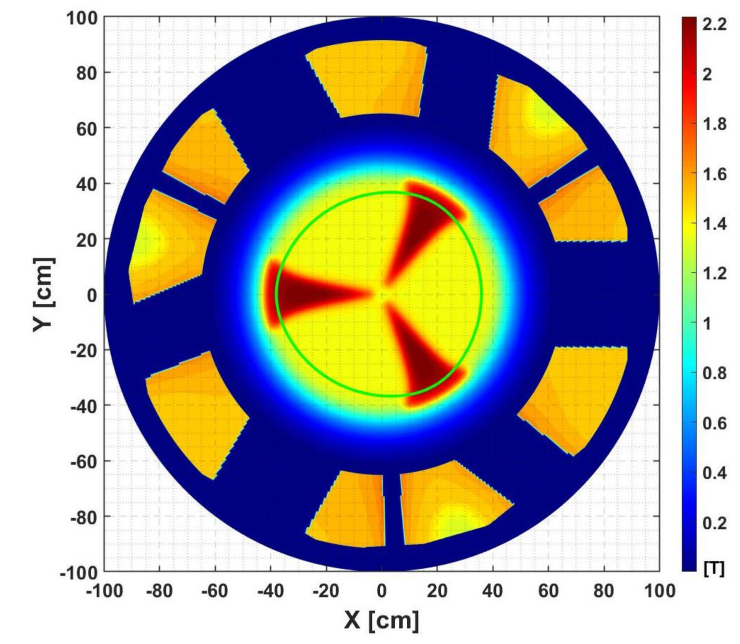
In simulation, a center particle is extracted under 10~16 MeV by setting up a stripper target in different positions. We adjust the position of stripping target to make this particle with different energy intersect at a radius of 110 cm.

Extraction energy (MeV)	16	14	12	10
Radius of stripping target (cm)	37.0	34.5	32.5	30.0
Angle of stripping target (deg)	153	158	164	170

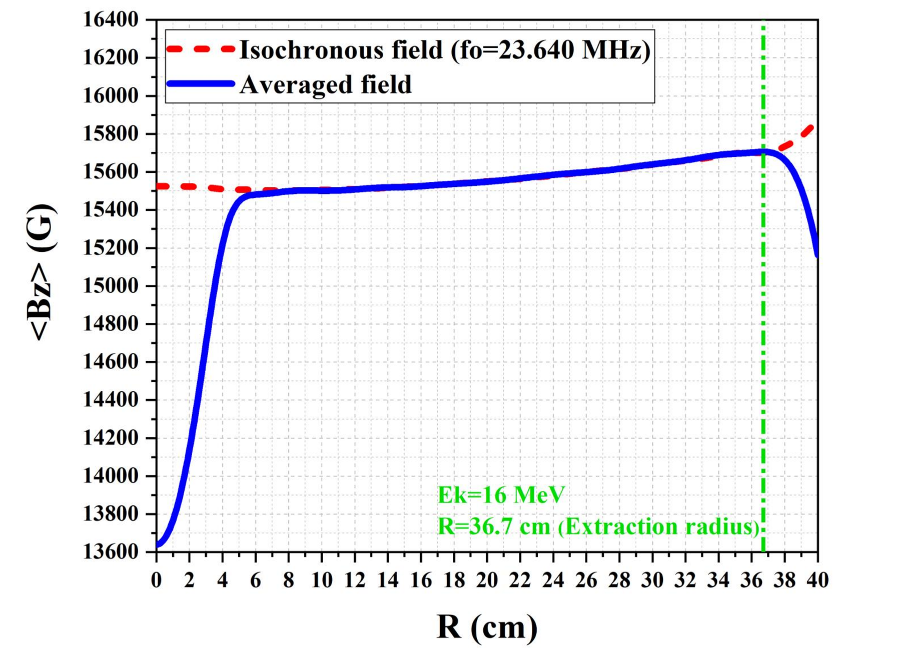
Analysis of static magnetic field

After determining the basic parameters of the magnet system, we iterate the shape of the poles and adjust the coil current to finally make the magnetic field of the cyclotron in mid-plane isochronous and meet the axial focusing requirements.

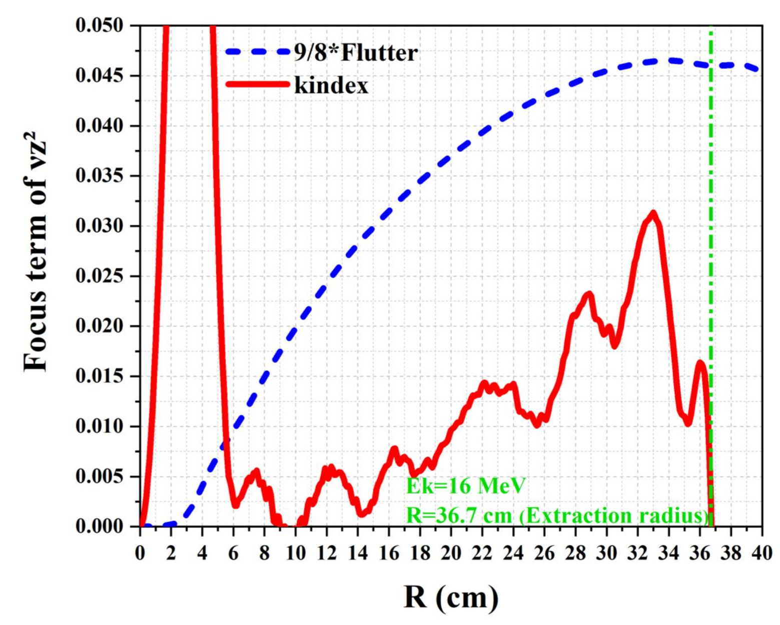
The properties of the static magnetic field are as follows:



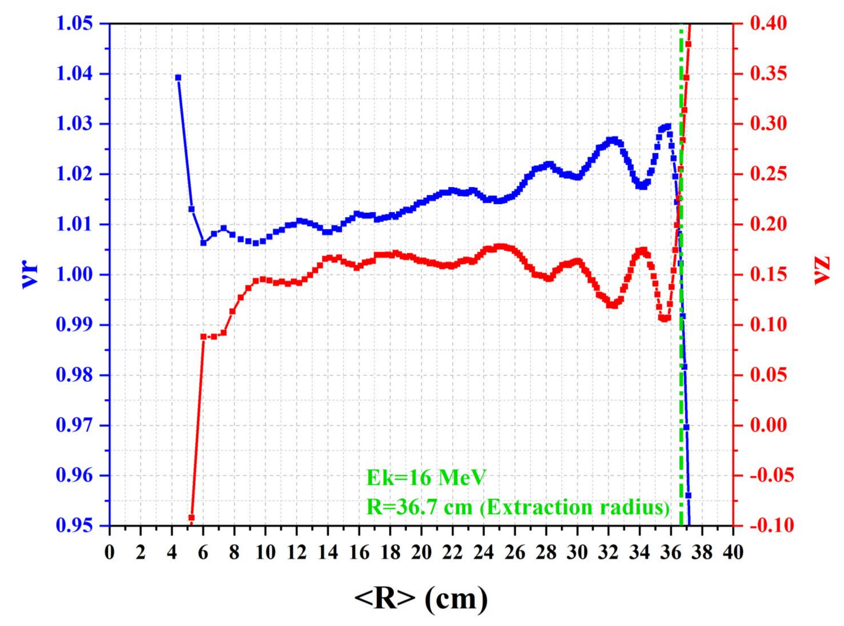
2D map of magnetic field



Comparison of averaged and isochronous field



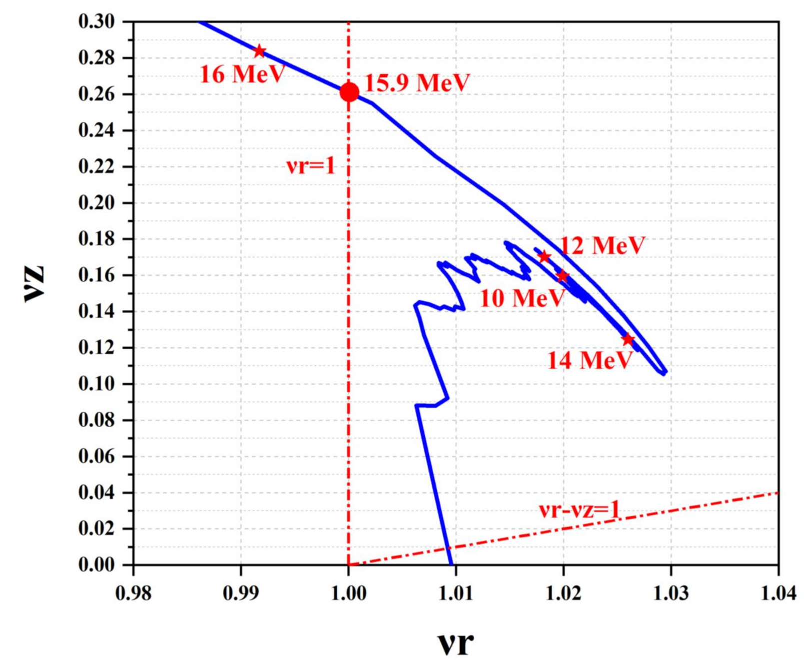
Comparison of two focusing term in ν_z^2



Betatron tune ν_r and ν_z

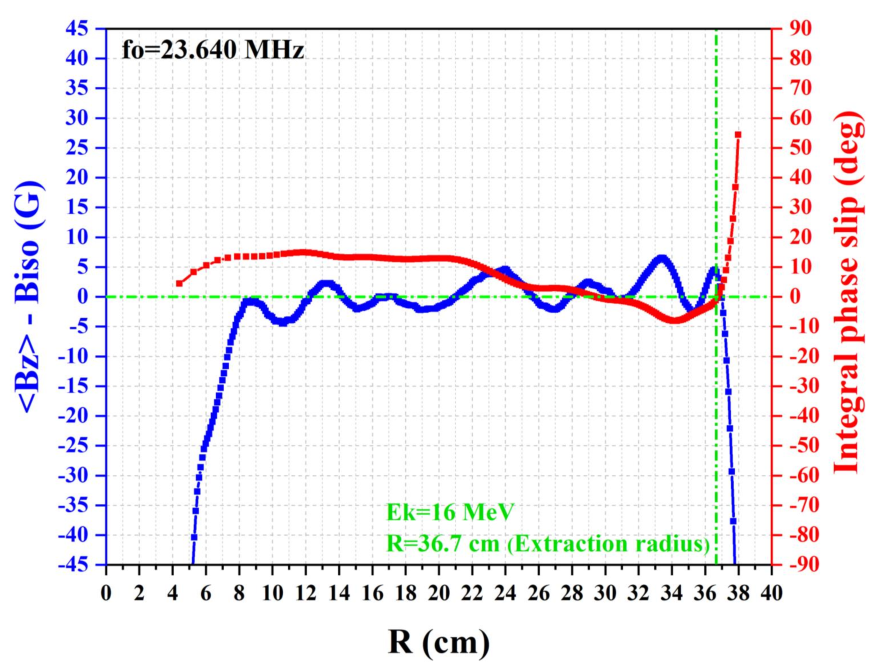
The flutter term (blue dashed line) > the radial gradient of averaged field term (red solid line)

Sufficient axial focus ($0.10 < \nu_z < 0.20$ from R > 6 cm)



Work diagram

Cross $\nu_r = 1$ resonance line when energy reaches 15.9 MeV. Not or not slowly cross other dangerous resonance lines



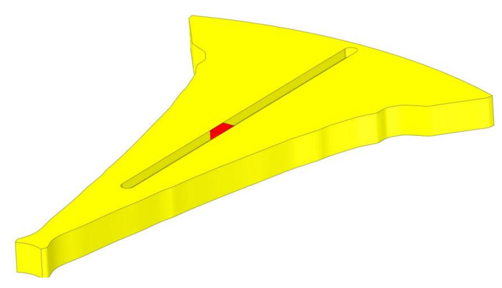
Error between averaged and isochronous field

Static integral phase slip

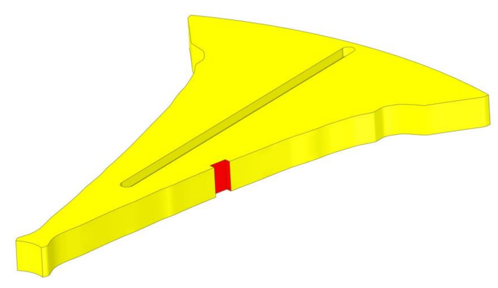
Error controls within ±10 G

Phase slip controls within ±10 deg

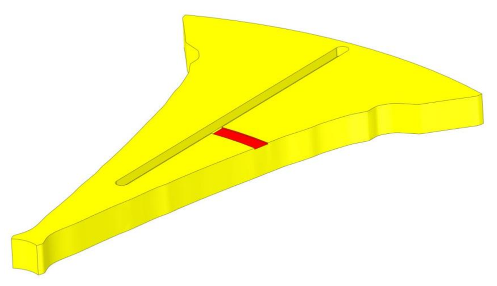
Shimming methods



Central groove shimming



Lateral shimming



Surface shimming

According to field distribution, the above 3 methods are used for shimming, and a simulated database is created for each method before shimming.

Conclusions

- Structure of 3 poles provides larger flutter for stronger ν_z
- Difference between averaged and isochronous field is controlled within ±10 G and integral phase slip is controlled within ±10 deg.
- Not or not slowly cross other dangerous resonance lines (except $\nu_r = 1$)
- Realize the extraction of particle with 10~16 MeV and make this particle with different energy intersect at a radius of 110 cm.
- 3 shimming methods are provided.

Main references

1. A. I. Papash and Yu. G. Alenitsky. Physics of Particles and Nuclei, 2008, Vol. 39, No. 4, pp. 597–631.