R&D of a PET Cyclotron in HUST

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Motivation

Design and Optimization of a 10 MeV PET Cyclotron : CYCHU-10

- Magnet design with a SVG (small valley gap) scheme
- Isochronous field shimming
- Beam dynamics considerations and central region design

Construction Progress

- Magnet
- Field mapping system

Potential R&D of FFAG Accelerators in HUST

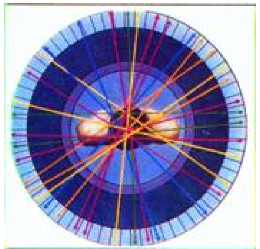
Motivations

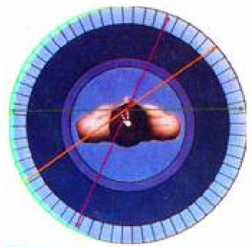
- Increasing demands on compact cyclotrons in medical applications
- More than 10 PET / PET-CT facilities were install in Chinese hospitals per year
- Total 116 PET-CTs (GE 56; Siemens 41; Philips 19, data from June 2009)

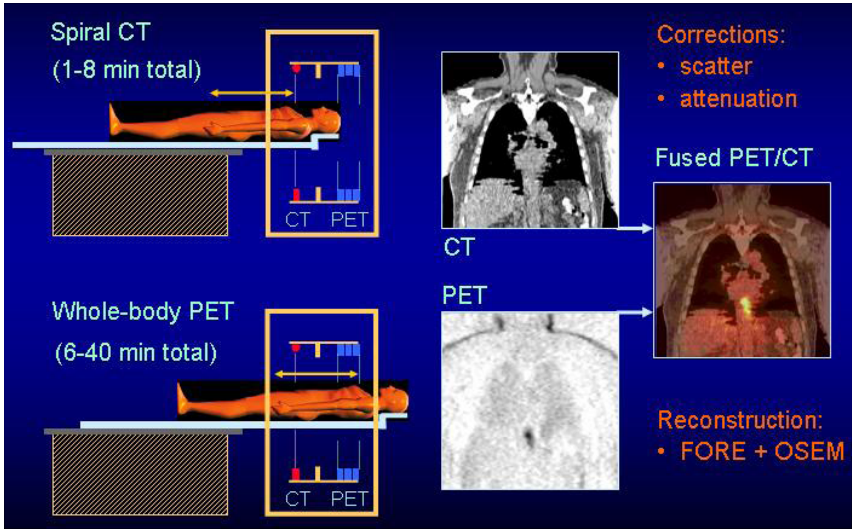
Product	PET Trace, GE	MiniTrae GE	RDS 111 CTI	KOTRON-13 KIRAMS
Ion and Energy (MeV)	H-, 16.5; D-, 8.4	H-, 9.6	H-, 11	H-, 13
Beam current (uA)	0~75	0~50	50	80
Extraction radius (m)	0.32	0.28	0.4	0.39
RF (MHz)	45	101	72.2	73.3
Dee voltage	35	35	30~80	45
Ion source	PIG	PIG	PIG	PIG

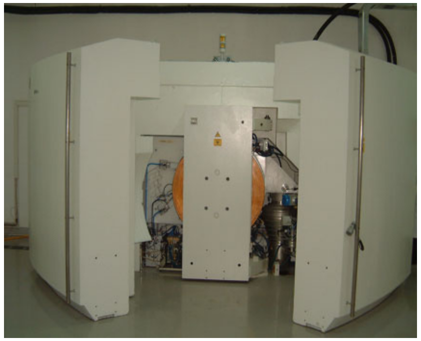
PET – Positron Emission Tomography

- **Show the image of organ "function" or physiology**
- **Has the ability to detect changes in tissue biochemistry and metabolism level**
- **A powerful tool for earlier cancer diagnosis.**









Huazhong PET Center, Wuhan, China

(Built in 2003, now it performs diagnosis on about 200~300 patients per month)

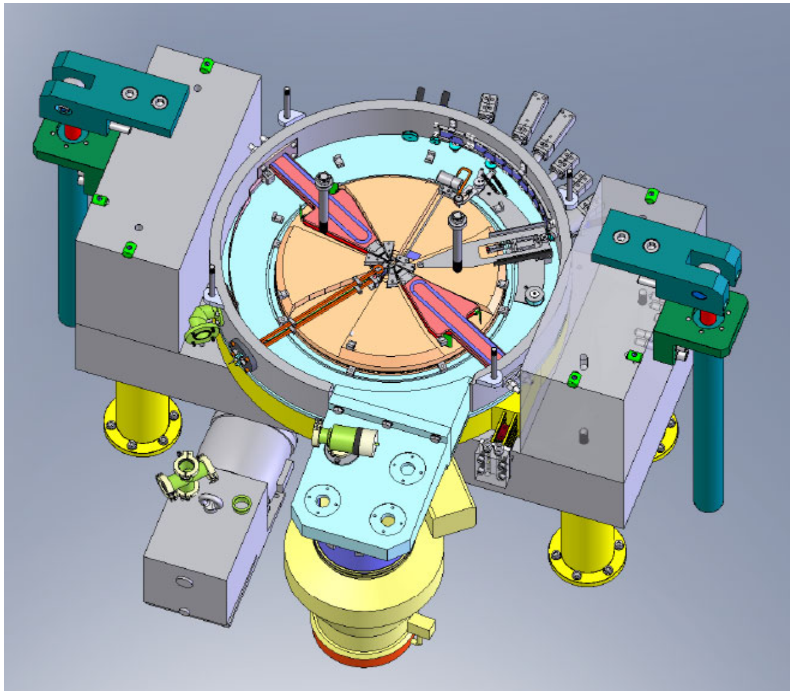
PET – Positron Emission Tomography

PET used cyclotron

- Low energy (9~13MeV) proton beam for short-lived isotopes production (^{11}C, ^{15}O and ^{18}F)
- Moderate beam current (<100uA)
- Compact, robustness, easy operation / maintenance and energy saving

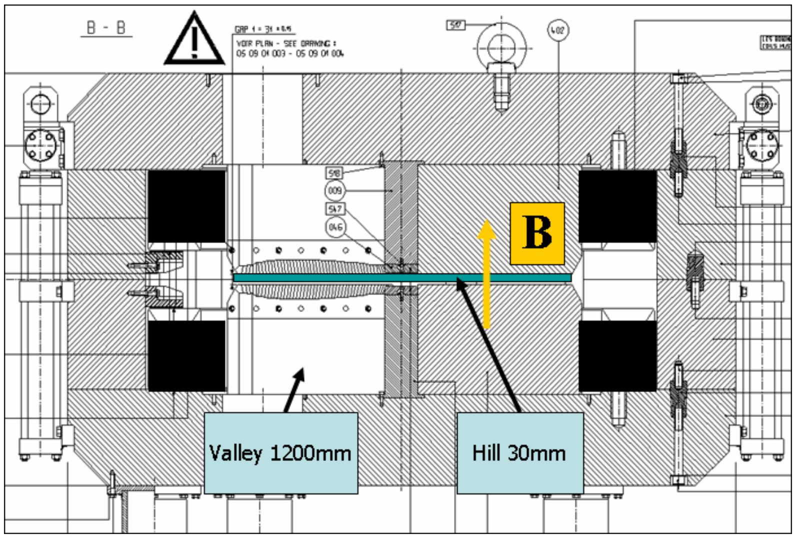
Specifications of CYCHU-10

- **Adopt internal PIG ion source for compactness and reducing cost**
- **Small Valley Gap (SVG) magnet**



Parameter	**Value**
Beam species	H^-
Ion source	Cold-cathode PIG source
Maximum beam energy	10 MeV
Beam current	40 uA
Sector numbers	4
Sector open angle	48~53 deg.
Hill / valley gap size	2.4 cm / 9.6 cm
Central magnetic field	1.63 T
Radio frequency	99 MHz
Dee voltage	35 kV
Extraction	Foil stripping

Small valley gap vs. Deep valley



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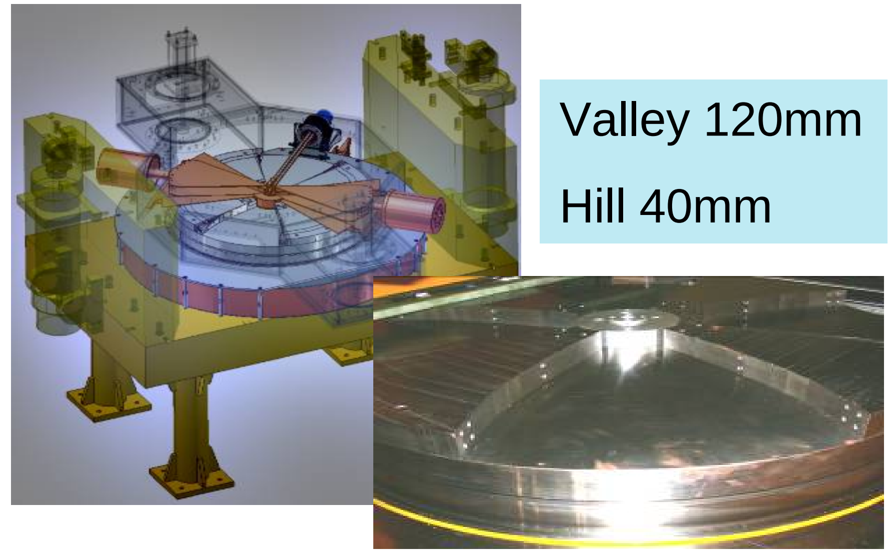
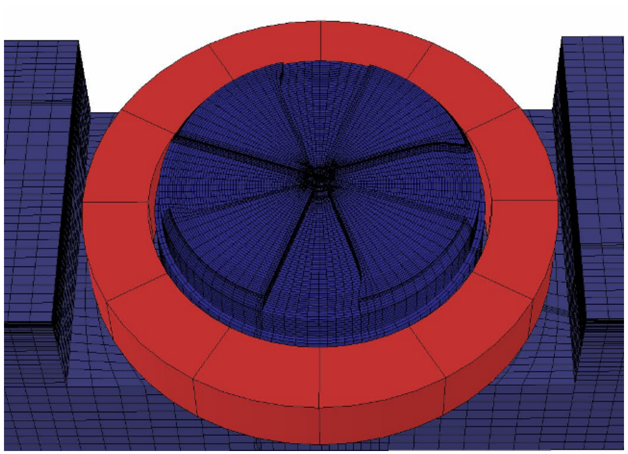


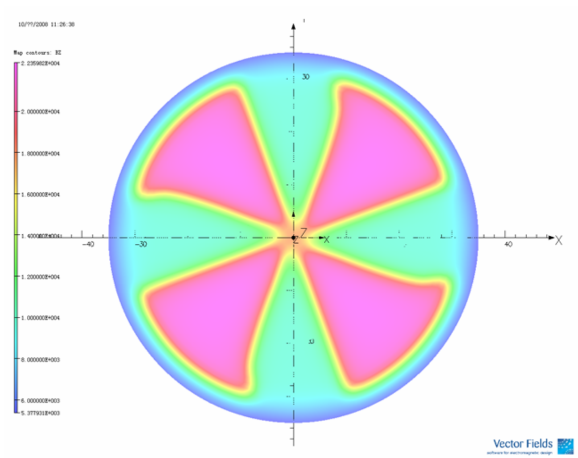
KIRAMS 13

- Deep valley: larger flutter for vertical focusing, relative large space for RF & measurement instrumentation.
- Small valley gap (SVG): weaker focusing, but higher average field with compact magnet pole. ***Careful design & optimization should be performed.***

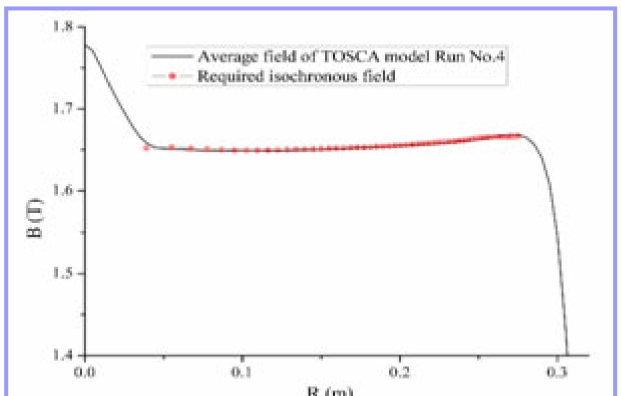
Magnet with SVG Scheme



Parameter	Value
Extraction energy	10 MeV
Pole number / open angle	4 / 48~53 deg.
Extra. radius	27.9cm
Hill / Valley gap	24 mm / 96 mm
Field on Hill / Valley	2.1T / 1.1T
Average field	1.63 T
Gyration frequency	24.8 MHz

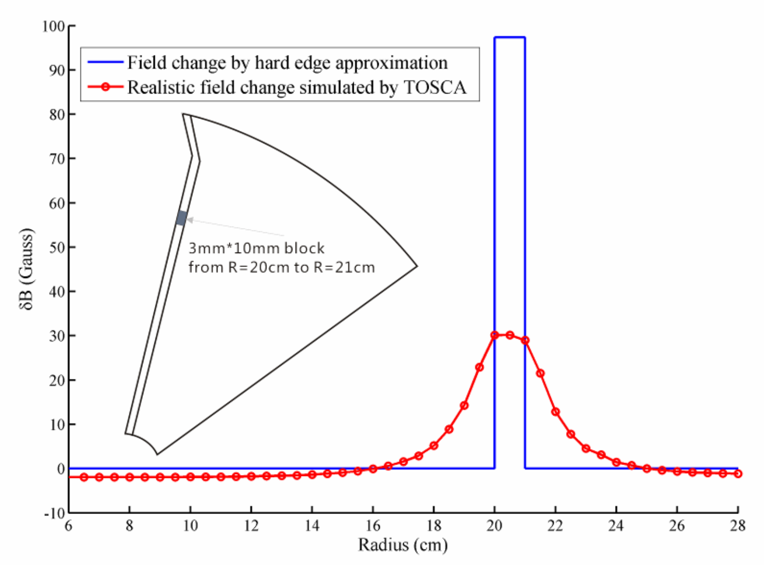


OPERA3D / TOSCA calculation

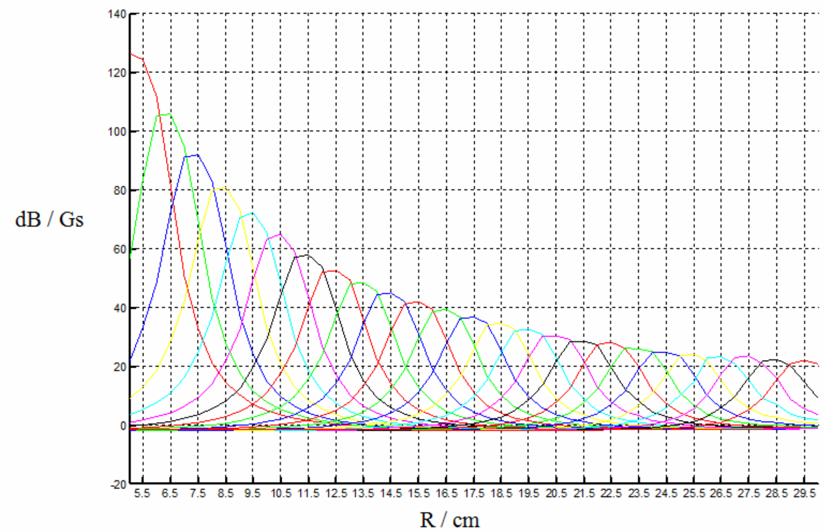


Average magnetic field

Matrix Method for Isochronous Field Shimming



Compare of the field change with hard edge approximation and realistic simulation by TOSCA



Field change at different cutting radius (simulation by TOSCA)

- Multiple linear regression model $\boldsymbol{y} = \mathbf{X} \cdot \boldsymbol{\beta} + \boldsymbol{\varepsilon}$
  can be applied on magnet shaping process with assumptions:
  - Field change is proportional to the cutting area on magnet pole;
  - The accumulated shimming effect is the superposition of independent pole cutting along the radius

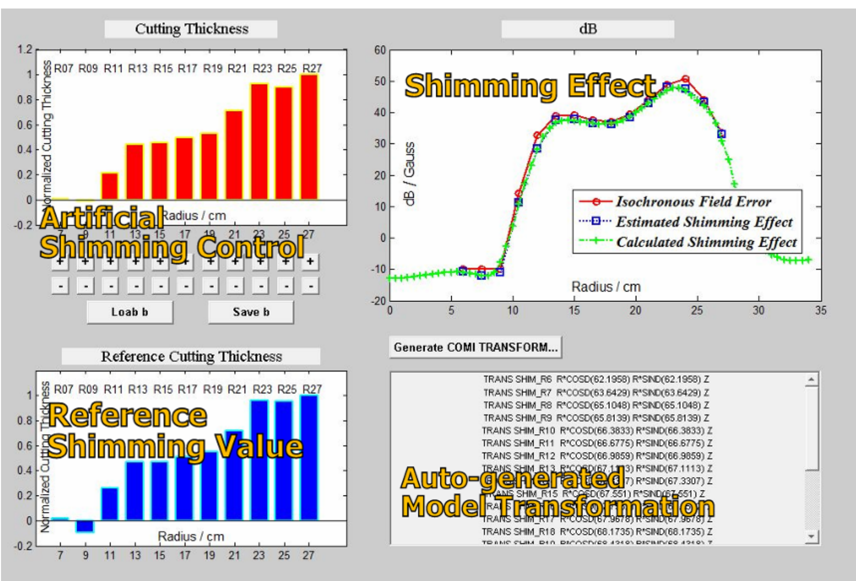
For a given field error vector ***y*** calculated by

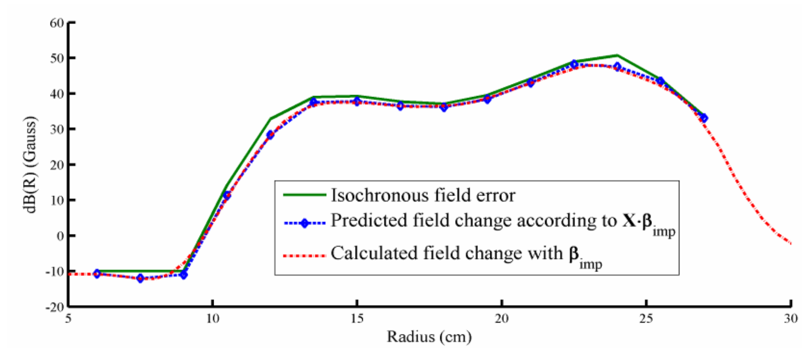
$$\Delta B(r) \equiv B(r) - B_{\rm iso}(r) = B_{\rm iso}(r)\cdot\gamma^2(r)\cdot\Delta f(r) = B(r)\cdot\frac{\gamma^2(r)\cdot\Delta f(r)}{1+\gamma^2(r)\cdot\Delta f(r)}$$

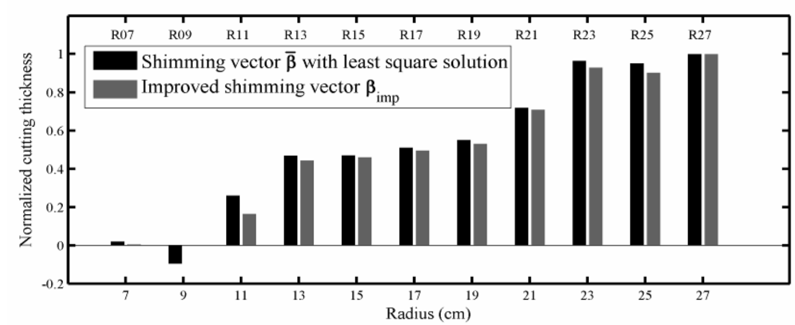
The Least square solution is

$$\bar{\beta} = (\mathbf{X}'\cdot\mathbf{X})^{-1}\mathbf{X}'\cdot y$$

But, the result contains oscillations and unwanted shimming values that should be adjusted



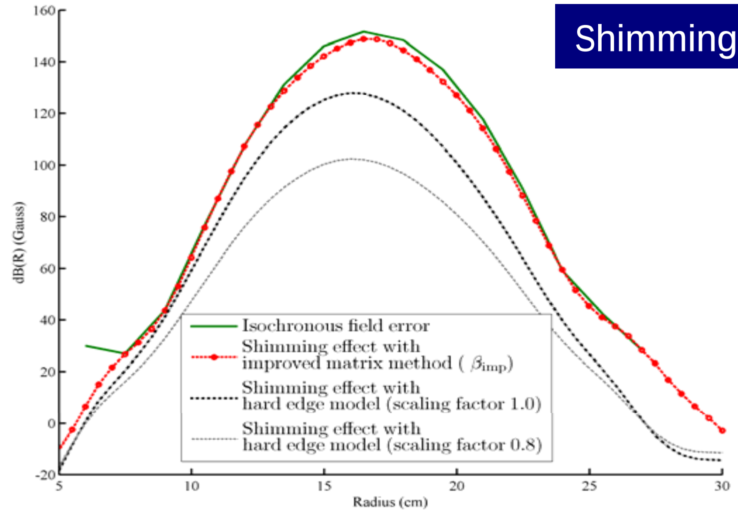


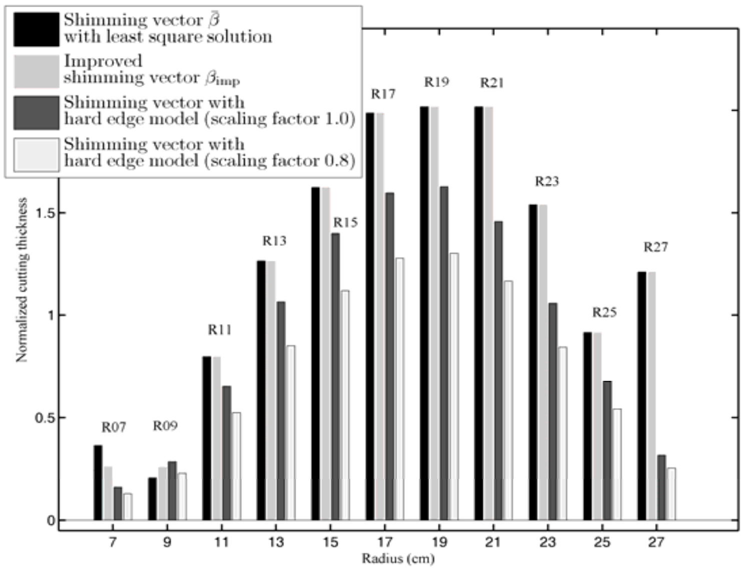


A Matlab tool for magnet shimming using the improved matrix method

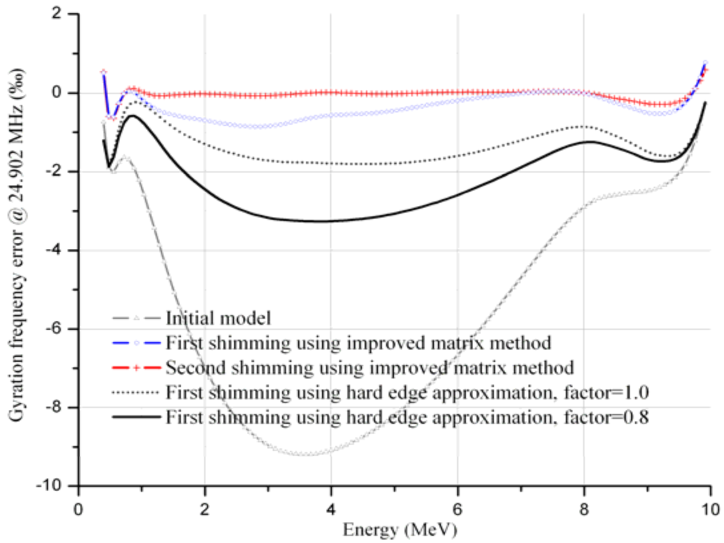
Comparative results: Matrix method vs. Hard edge model

Shimming effects



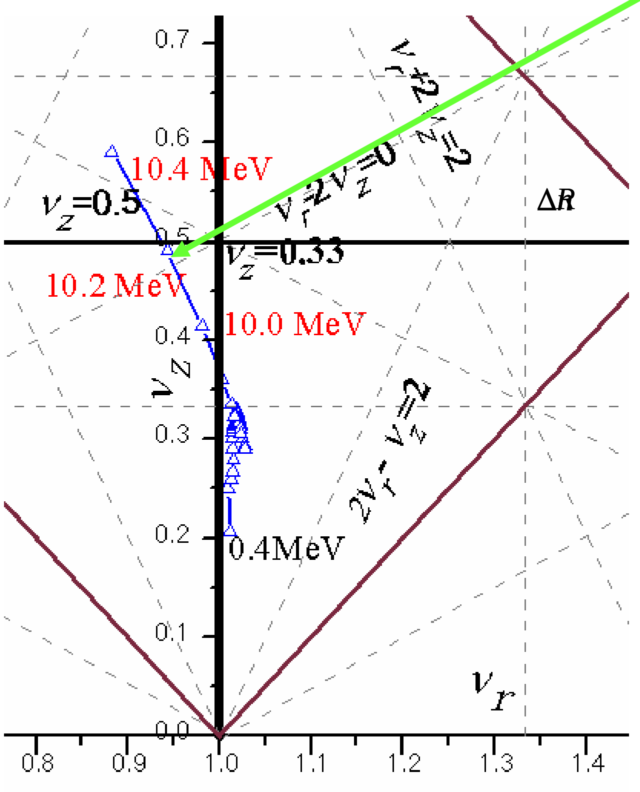


Comparative shimming vector for the initial magnet model



Gyration frequency error after shimming

Walkinshaw Resonance Crossing at Extraction



Tune diagram

Nonlinear resonance crossing: $\nu_R - 2\nu_Z = 0$

$$K^w = \frac{2\sqrt{y_0}}{\nu_Z}(\mu' + \mu'' + \nu_z^2)$$

(From R. Baartman)

$$\mu' = \frac{R}{\overline{B}}\frac{\partial \overline{B}}{\partial R}, \quad \mu' = \frac{R^2}{\overline{B}}\frac{\partial^2 \overline{B}}{\partial R^2}, \quad y_0 = \frac{1}{R_0^2}(x_0^2 + \frac{\nu_z^2}{2})$$

Radial width of resonance:

$$\Delta R = \frac{2K^w}{(\frac{d\nu_R}{dR} - 2\frac{d\nu_Z}{dR})}$$

Vertical/Radial beam size exchange

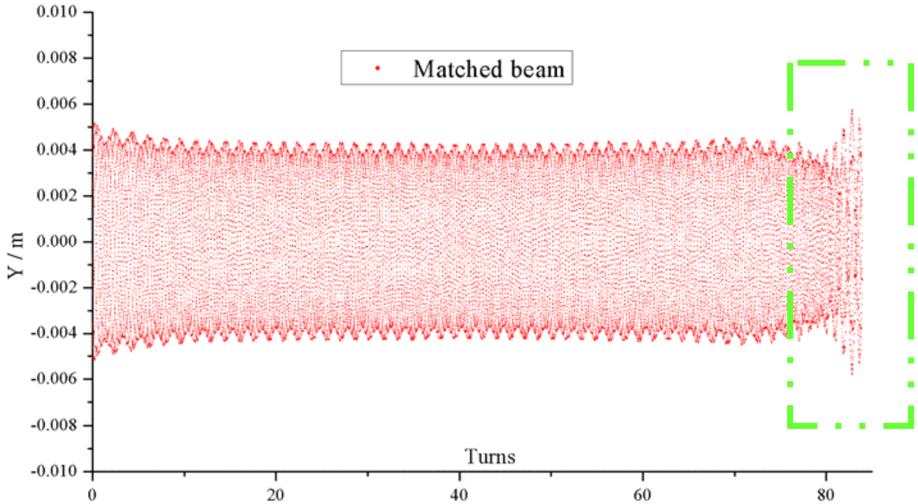
$$\frac{dZ}{dn} = -\frac{dX}{dn} = 4\pi R_0 y_0$$

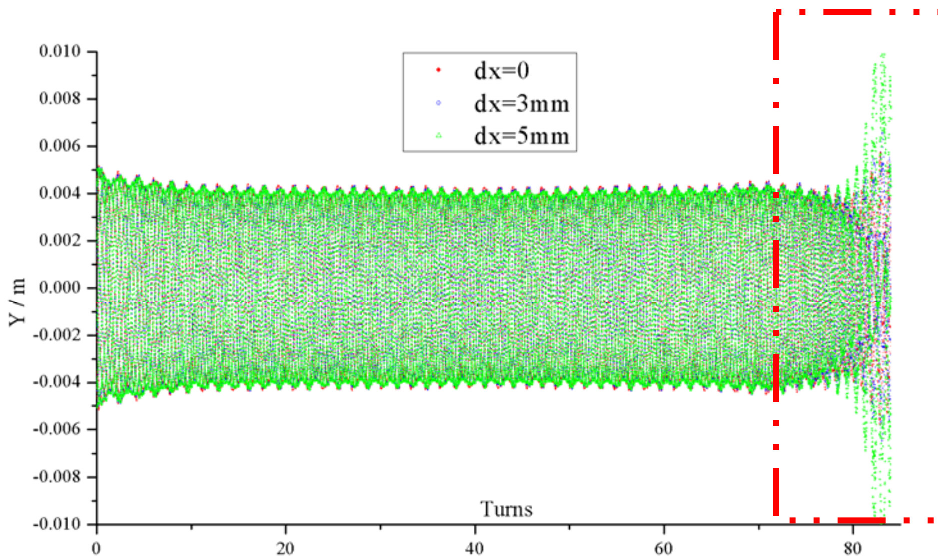
At extraction region of pole edge, the field decreases rapidly with:

$$\frac{\partial \overline{B}}{\partial R} = -20\text{Gs/cm}; \quad \frac{\partial^2 \overline{B}}{\partial R^2} = -100\text{Gs/cm}^2$$

X0	Z0	ΔR	Δn	dZ/dn	Z total
3mm	5mm	2mm	1	0.9	6 mm
5mm	5mm	5.7mm	4	1.5	11 mm

Radial matched beam with dx=0





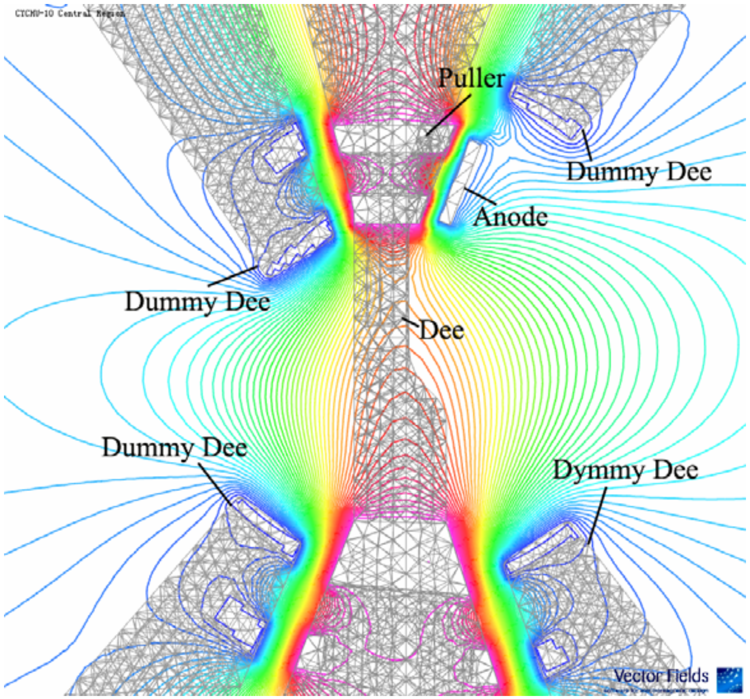
Vertical beam amplitude growth : dx≠0

The simulation result implies the radial beam amplitude A_radial <=3mm should be fulfilled in central region;

And when A_radial=5mm, the vertical beam size will be doubled at extraction!

Design of Central Region with Internal PIG source

- Relative low beam intensity (about 60uA) suitable for short-lived isotopes production such as ^{18}F, ^{15}O
- Internal PIG ion source: without beam manipulation by external injection line, the CR should be carefully designed.

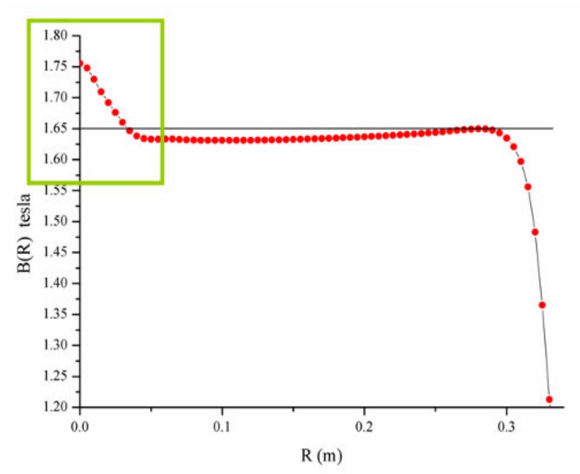


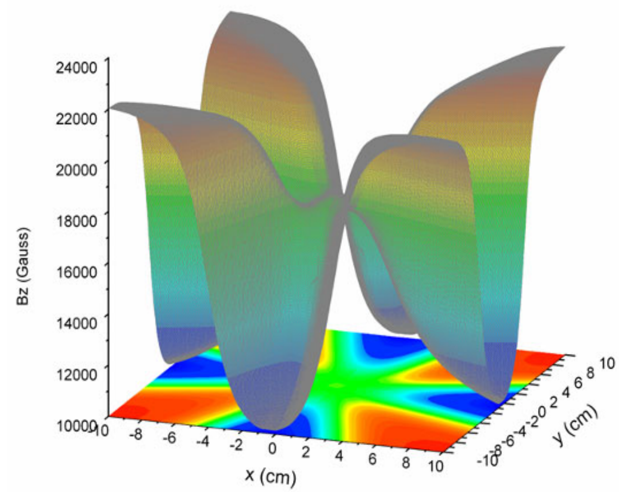
CR Structure & E field Simulation

Basic parameters

Parameters	Value
Dee width	31deg.
Dee voltage	35 kV
Harmonic mode	4
Injection radius	1.6 cm
Central magnetic field	1.67T

Magnetic Field in CR





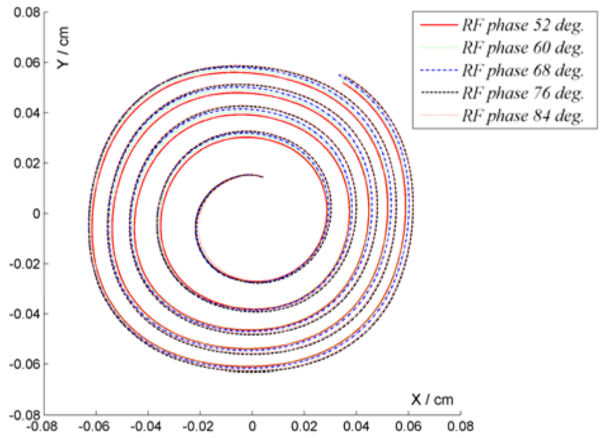
Negative gradient field in CR (TOSCA simulation)

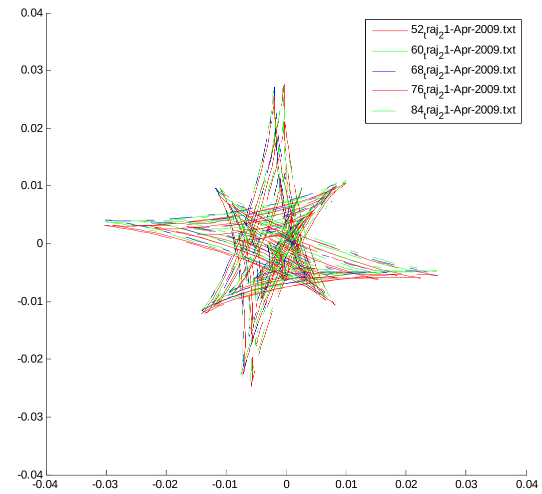
$$\nu_z^2 \approx -k + N^2 F(1+2\tan^2\zeta)/(N^2-1)$$
$$= -k + 1.07F$$

***R* / cm**	2.0	3.0	4.0	5.0	6.0
k	-0.025	-0.04	-0.025	0.0	0.005
F	2E-4	3E-3	0.014	0.03	0.044
ν_z^2	**0.025**	0.04	0.04	0.032	0.042

- Additional electric focusing required at first turn

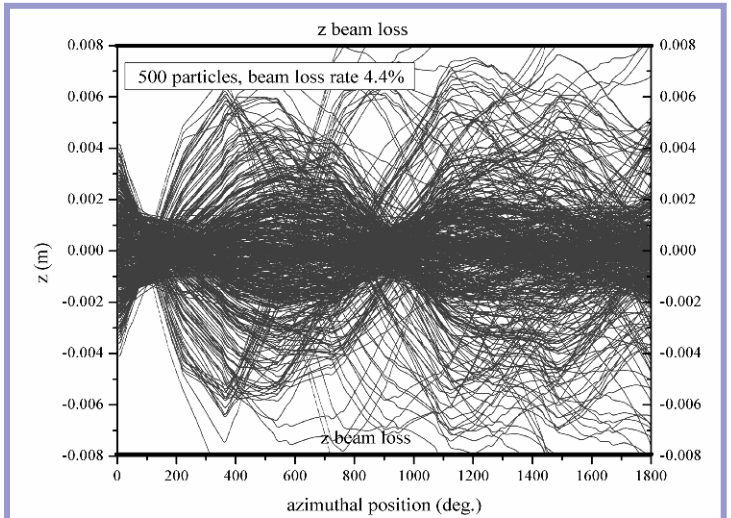
Optimization of CR





Particle trajectories, start RF phase 52° ~ 84°

The motion of orbit centers



Vertical beam motion in the first 5 turns with multi-particle tracing

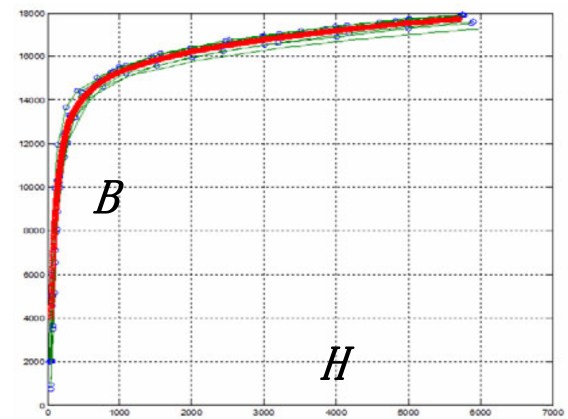
$$R_{rms} = 0.4\text{mm},\ Z_{rms} = 3\text{mm},\ R'_{rms} = Z'_{rms} = 5\text{mrad},\ \Delta\phi = 20^{\circ}$$

- RF acceptance about 35° ;
- The vertical beam loss rate less than 5% with the ion source aperture 0.8*5mm

Current Status of CYCHU-10 Magnet

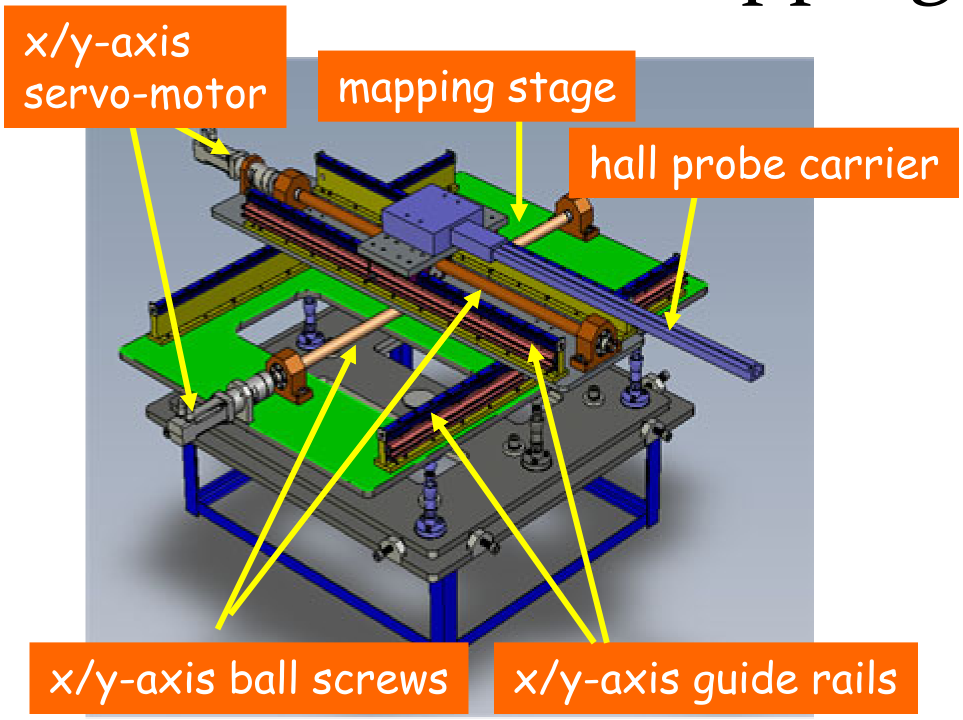
- **Steel Ingots**: Low carbon DT8 steel purchased from Taiyuan Iron & Steel Company Ltd. (TISCO) with carbon contents < 0.02%

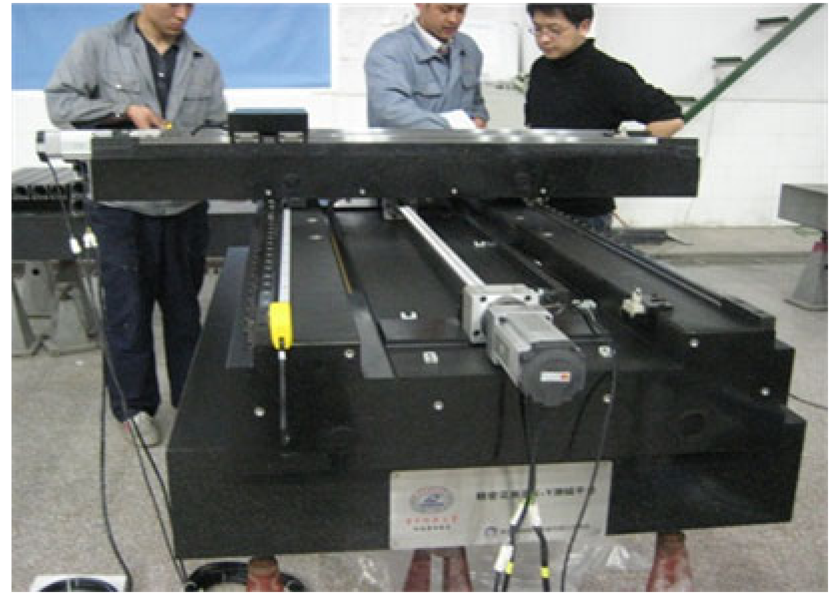




- **Machining**


Cartesian field mapping system (granite base)





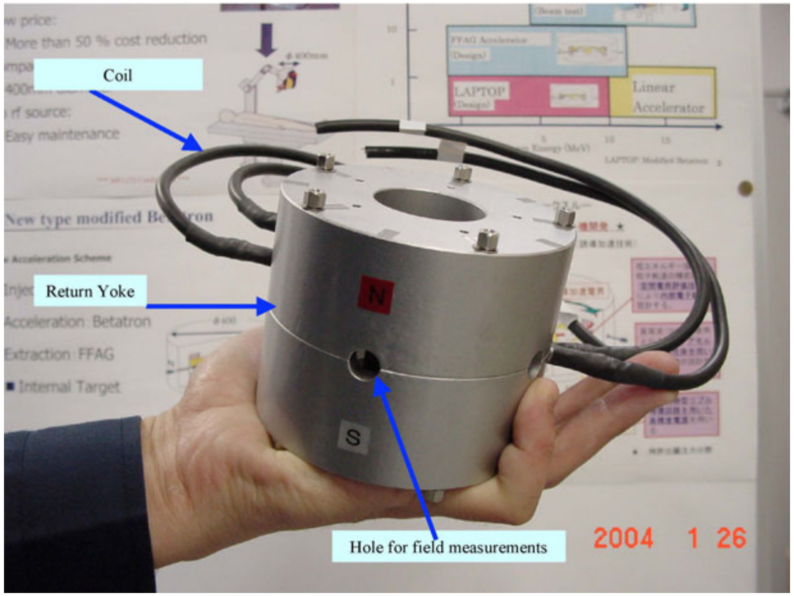
System specification	***Value***
X scan capability	1100mm
Y scan capability	1100mm
Mechanical resolution	5 um
Range of magnetic field	2.5T
Random error	0.01%

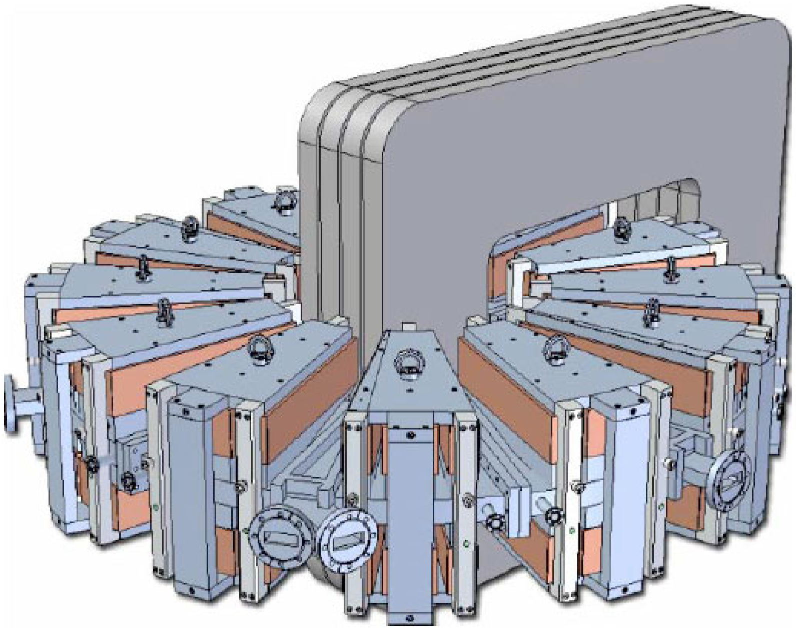
SUMMARY

- Physical design of CYCHU-10 has been accomplished
  - Magnet, central region and extraction, RF
  - Improved matrix shimming method for fast isochronous field convergence
  - Beam amplitude growth duo to Walkinshaw resonance at extracion
- Magnet machining is nearly accomplished. Field mapping and shaping will be finished in spring of 2010.
- Field mapping system, coils, power supply, cooling system are ready.
- The RF system is under development.

Can We Find a Potential R&D of FFAG Accelerators in HUST?

- *Isotopes Production*?
  - Not competitive with cyclotrons
- *Proton therapy*?
  - RACCAM, Ibaraki Med. Acc. (scaling spiral FFAG) PAMELA (non-scaling FFAG)
  - Suitable and competitive (high repetition rate for spot scanning mode, variable energy, fast extraction etc), but …
- *Electron FFAG for Industrial Irradiation (1~20MeV)* ?
  - Seems promising with considerable demands for medical product sterilization, food and industrial materials irradiation, and security
  - High beam intensity while maintaining compactness and low price





- Hybrid type laptop e-FFAG developed by Mitsubishi Electric. Co. for industrial X-rays applications.
- Very compact (100mm, 3kg)
- 1 MeV electron beam with high beam current (5mA, 8A peak)

- Radiotron developed by RadiaBeam Co. (FFAG Betatron)
- 5 MeV high power electron beam
- Applied both in industrial and security applications

Thanks for attention!