華中科技大學
HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

R&D of particle accelerators for medical and industrial applications at HUST

Bin Qin, for Accelerator Group

State Key Laboratory of Advanced Electromagnetic Engineering and Technology (AEET)
Huazhong University of Science and Technology

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OUTLINE

1. Electron accelerators for industrial irradiation

- **Motivation**
- **ICT type high voltage accelerator (0.3-1MeV)**
- **Considerations of semi-isochronous scaling FFAG (5-10MeV)**

2. HUST proton therapy project

- Status and challenges of proton therapy in China
- Proposal of a proton therapy system based on superconducting cyclotron scheme
- Design considerations

Irradiation processing using electron beams

Economic scale: In U.S. ~200 billion dollars, 3.9% GDP; In China, predicted growth 15% per year; 10% growth rate world wide

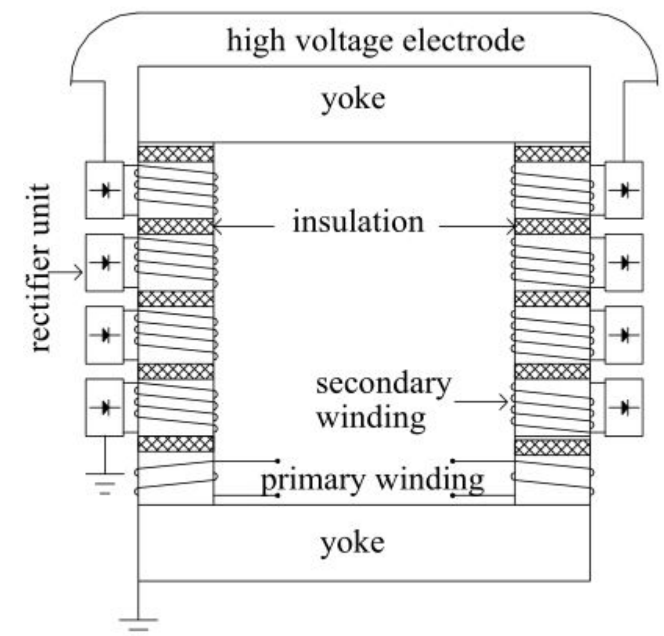
➡ Applications of low energy electron accelerators (<1 MeV)

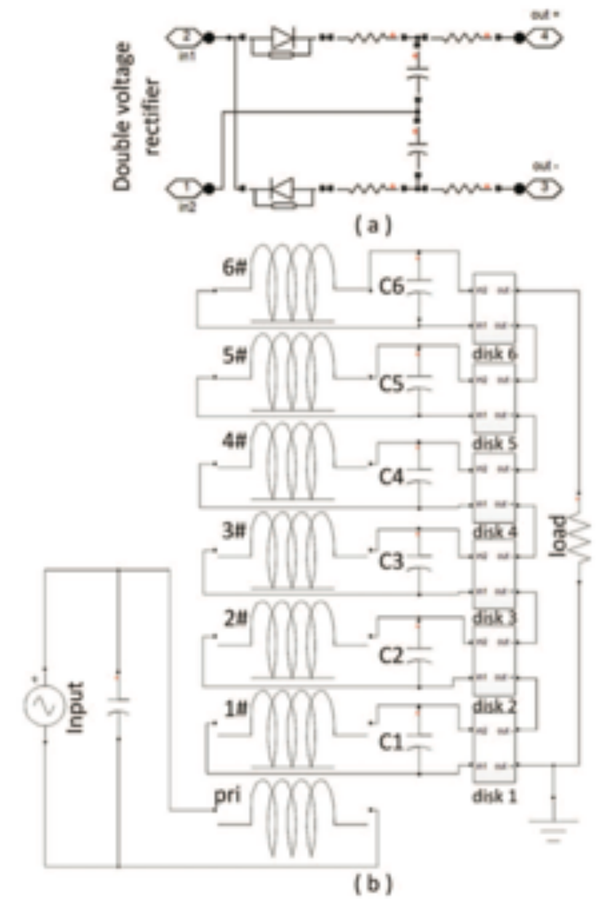
Applications	Electron beam energy
vulcanization of rubber	≤ 500 keV
Surface coating	80-300 keV
Battery Separator	≤ 300 keV
Waste water processing	0.5-1 MeV
Flue gas cleaning	125 keV
hydrogel product	≤ 300 keV
Dioxin processing	300 keV

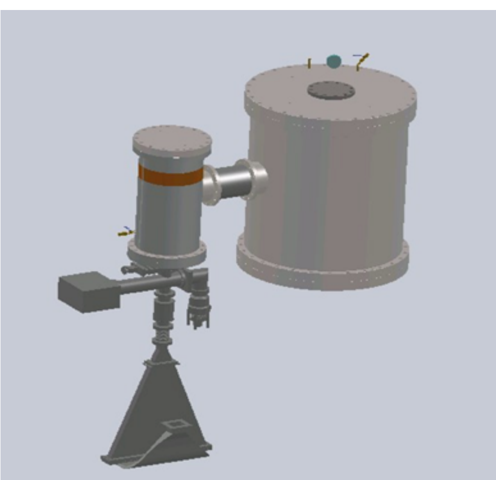
R&D of ICT electron accelerator for industrial irradiation

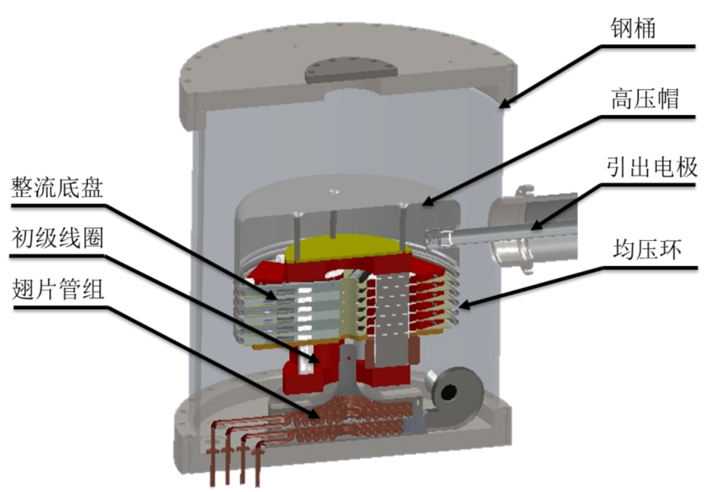
ICT (insulated core transformer) type electron accelerator is an optimum choice for low energy applications

- **High efficiency (>85%)**
- **Energy range 0.3-1MeV**
- **High power, up to 100kW**







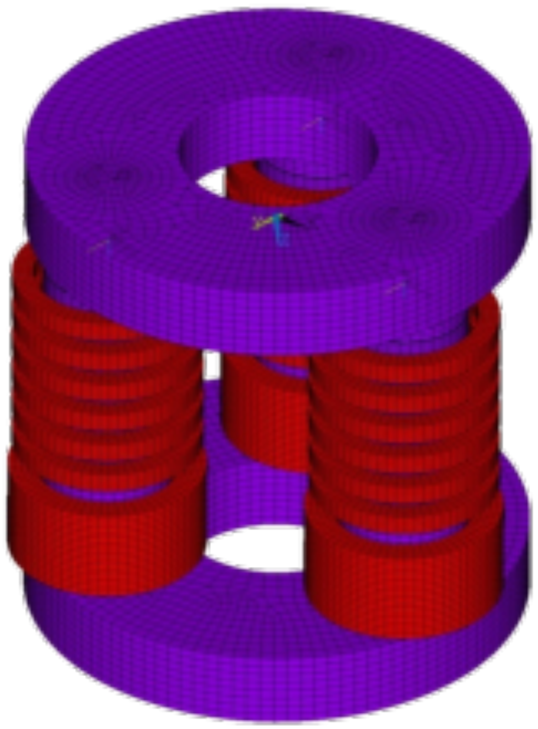


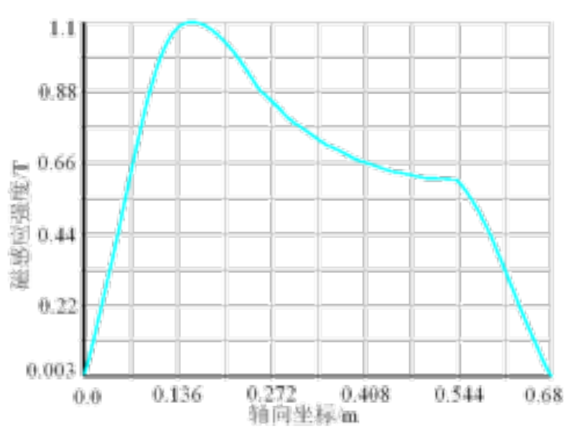
L. Yang, J. Yang et al., Rev. Sci. Instrum. 85, 063302 (2014)

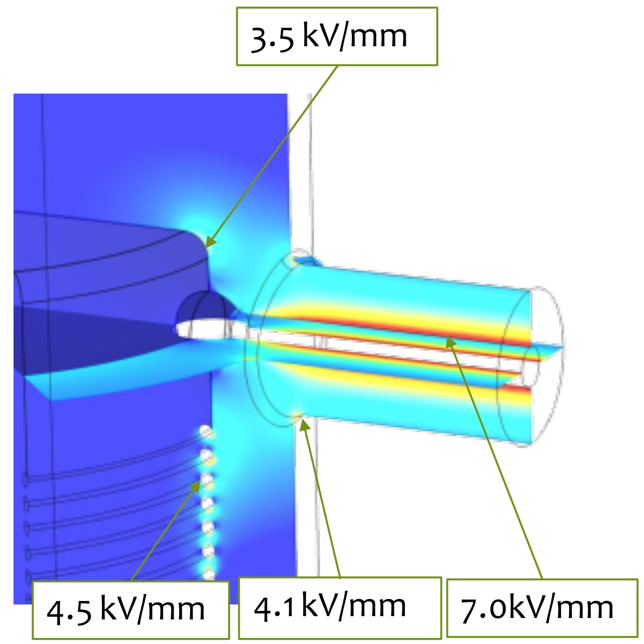
- ICT high voltage power supply proposed by Van De Graaf [1];
- 1 primary coil + multiple secondary coils, output from rectifiers connected in series to achieve high voltage

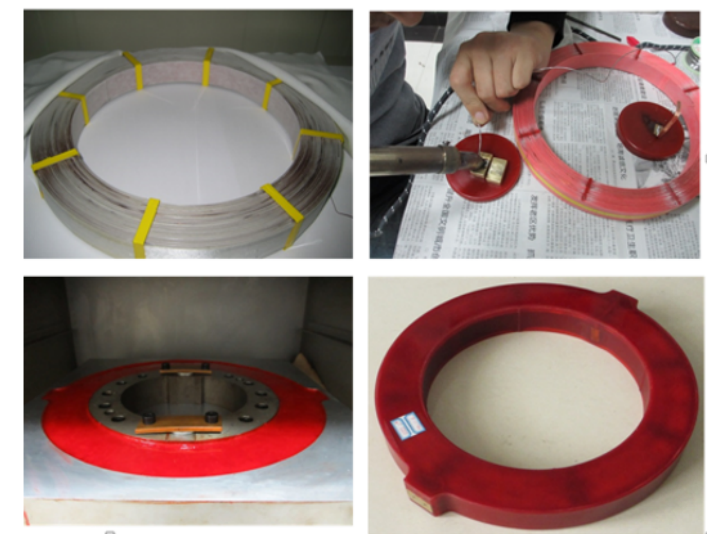
[1] R. J. Van de Graaff, "High voltage electromagnetic apparatus having an insulating magnetic core," U.S. patent 3,187,208 (1 June 1965).

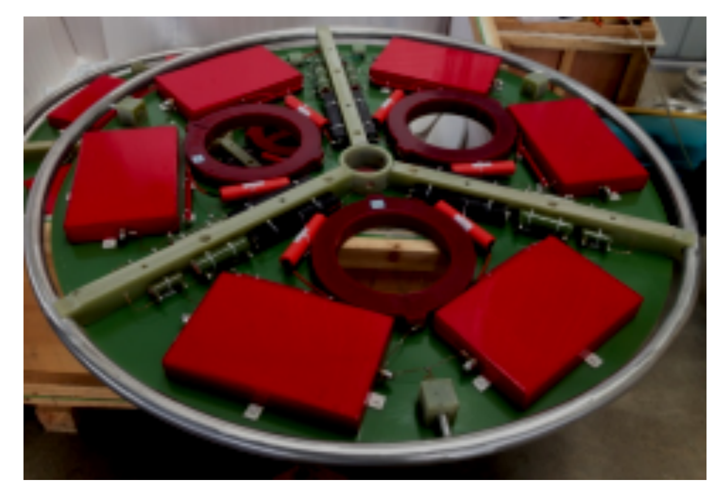
Design and Development of an 300keV/30mA ICT









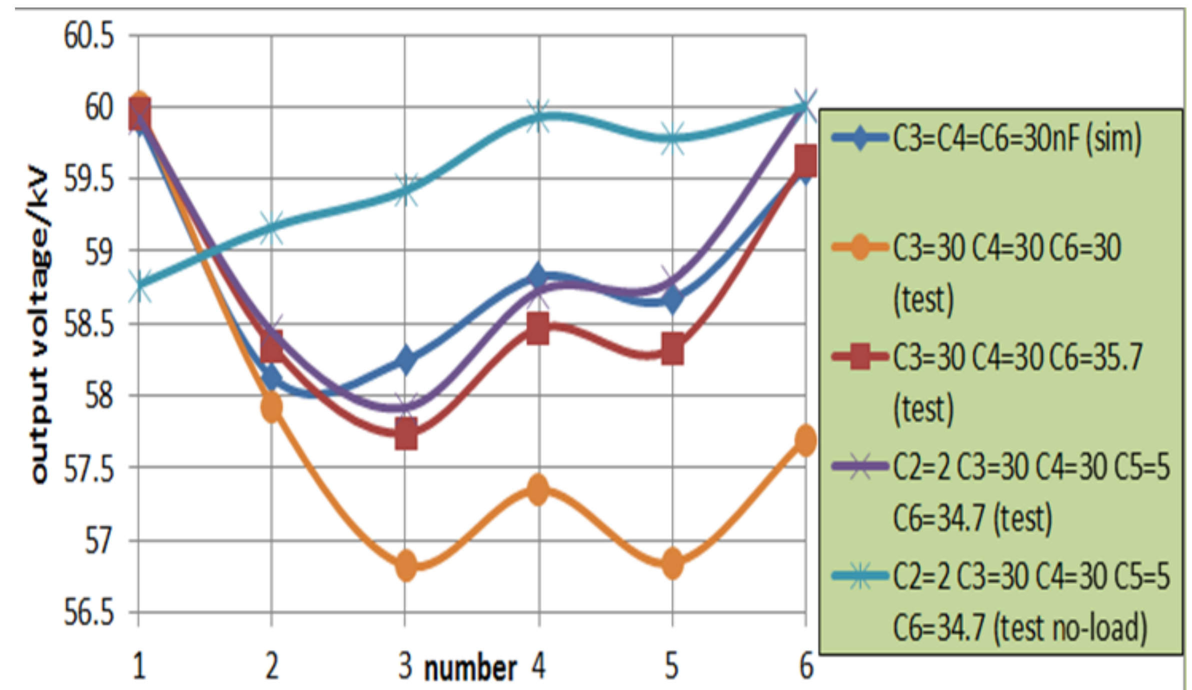


- Challenges: high level magnetic flux leakage at upper layers, lead to significant voltage decrease
- Compensation using increased turns number and parallel capacitors

Courtesy of Jun Yang

Huazhong University of Science & Technology

Design and Development of an 300keV/30mA ICT



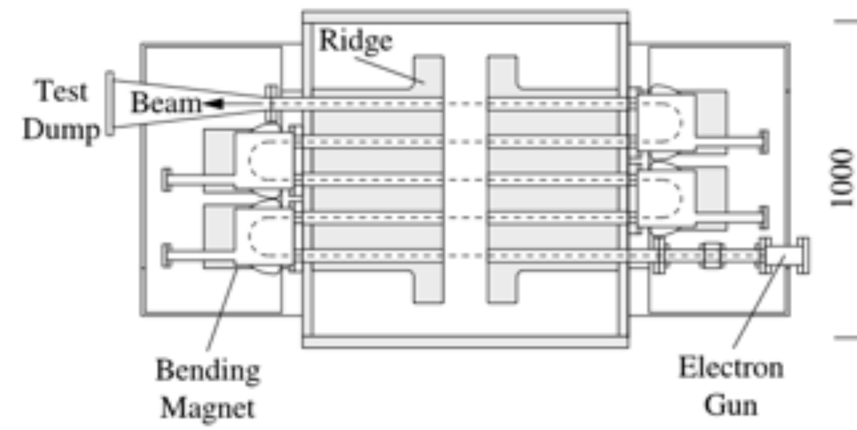
- Test result for ICT power supply: <3.5% for non-uniformity of voltage distribution

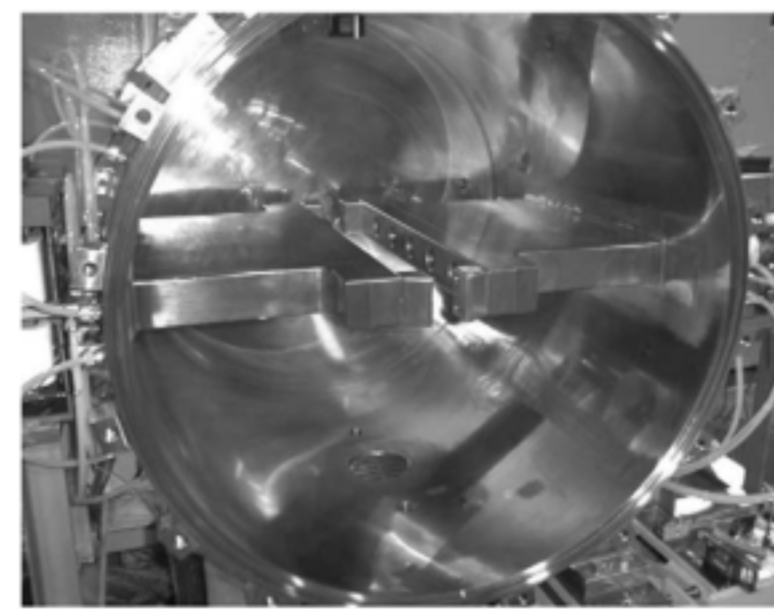
Courtesy of Jun Yang

Considerations of (c.w.) semi-isochronous scaling FFAG (5-10MeV)

- Demands: Sterilization for medical products and foods
  - Replacement of Co-60 sources
  - Irradiated food permitted in 57 countries: Garlic (China), Potatoes (Japan), Fruites(US)
- CW beam required for high beam intensity
  - For fast irradiation processing, normally beam intensity > 20mA
  - IBA's Rhodotron, 500-700kW, max. energy 10 MeV

from IBA website





"Ridgetron", N. Hayashizaki et al. / Nucl. Instr. and Meth. in Phys. Res. B 188 (2002) 243–246

Considerations of (c.w.) semi-isochronous scaling FFAG (5-10MeV)

- **Serpentine acceleration in scaling FFAGs**

$$B_z(r) = B_0 \cdot (r/r_0)^k \longrightarrow (p/p_0) = (r/r_0)^{k+1} \longrightarrow \frac{T}{T_s} = 1 + \frac{\Delta\phi}{2\pi h} = \frac{C/\beta}{C_s/\beta_s} = \frac{\beta_s}{\beta} \cdot \left(\frac{p}{p_s}\right)^\alpha$$

$$= \frac{\gamma}{\gamma_s}\left(\frac{\gamma^2-1}{\gamma_s^2-1}\right)^{\frac{\alpha-1}{2}}$$

$$\Delta\phi = 2\pi h\left(\frac{\gamma}{\gamma_s}\left(\frac{\gamma^2-1}{\gamma_s^2-1}\right)^{\frac{\alpha-1}{2}} - 1\right) \longleftarrow$$

$$\begin{cases} \dfrac{d\phi}{d\theta} = h\left(\dfrac{\gamma}{\gamma_s}\left(\dfrac{\gamma^2-1}{\gamma_s^2-1}\right)^{\frac{\alpha-1}{2}} - 1\right) \\ \dfrac{dE}{d\theta} = m_0c^2\dfrac{d\gamma}{d\theta} = \dfrac{eV}{2\pi} \cdot \sin\phi \end{cases}$$

$$H(\gamma,\phi;\theta) = h\left(\frac{1}{1+\alpha} \cdot \frac{(\gamma^2-1)^{\frac{\alpha+1}{2}}}{\gamma_s(\gamma_s^2-1)^{\frac{\alpha-1}{2}}} - \gamma\right) + \frac{eV_0}{2\pi m_0c^2} \cdot \cos\phi$$

E. Yamakawa, T. Uesugi, J.B. Lagrange et al., Serpentine Acceleration in Zero-Chromatic FFAG Accelerators, Nucl. Instrum. Methods Phys. Res. A, Vol. 716(11) 2013, 46-53.

S. Koscielniak Optimum Serpentine Acceleration In Scaling FFAG, Proceedings of Cyclotrons 2013, Vancouver, BC, Canada, MOPPT025.

Considerations of (c.w.) semi-isochronous scaling FFAG (5-10MeV)

- **Example for serpentine channel formation, ~9MeV @ extraction**

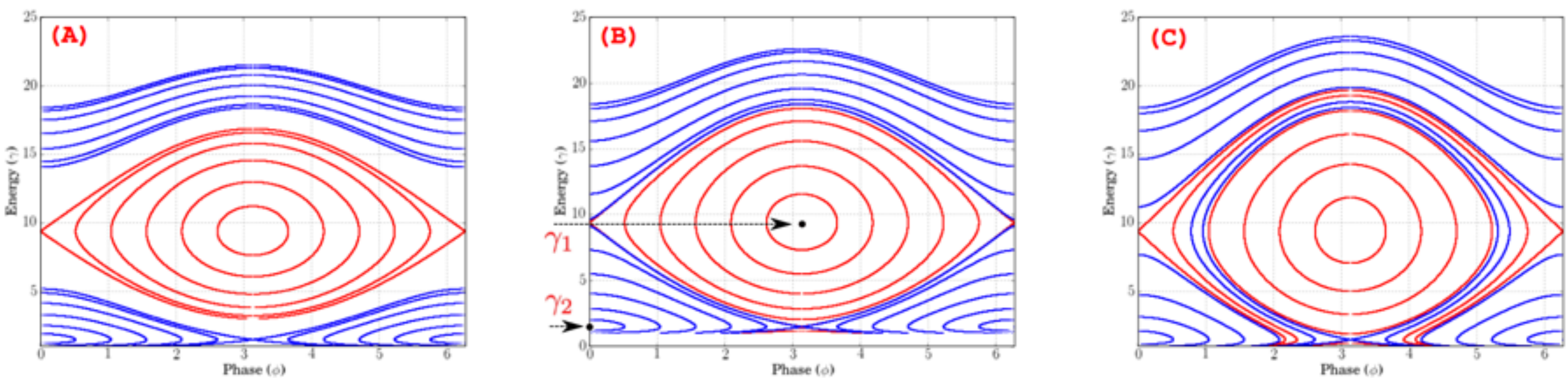


Figure 1: Formation of the serpentine channel, with $k = 6.5$, $\gamma_1 = 1.51$, $\gamma_2 = 9.42$, transition energy $\gamma_t = \sqrt{1+k} = 2.74$, V_c=706kV. (A) Before the formation of the serpentine channel, $V_{rf} = 500kV$; (B)critical condition when $V_{rf} = V_c = 706kV$; (C) formation of the serpentine channel when $V_{rf} = 900kV > V_c$

Considerations of (c.w.) semi-isochronous scaling FFAG (5-10MeV)

- **Critical voltage for rf**

$$H(\gamma_1, \pi) = H(\gamma_2, 0)$$

$$\frac{eV_c}{E_0} = \pi h \frac{(\gamma_2 - \gamma_1)(\gamma_1\gamma_2\alpha - 1)}{\gamma_1\gamma_2(1+\alpha)}$$

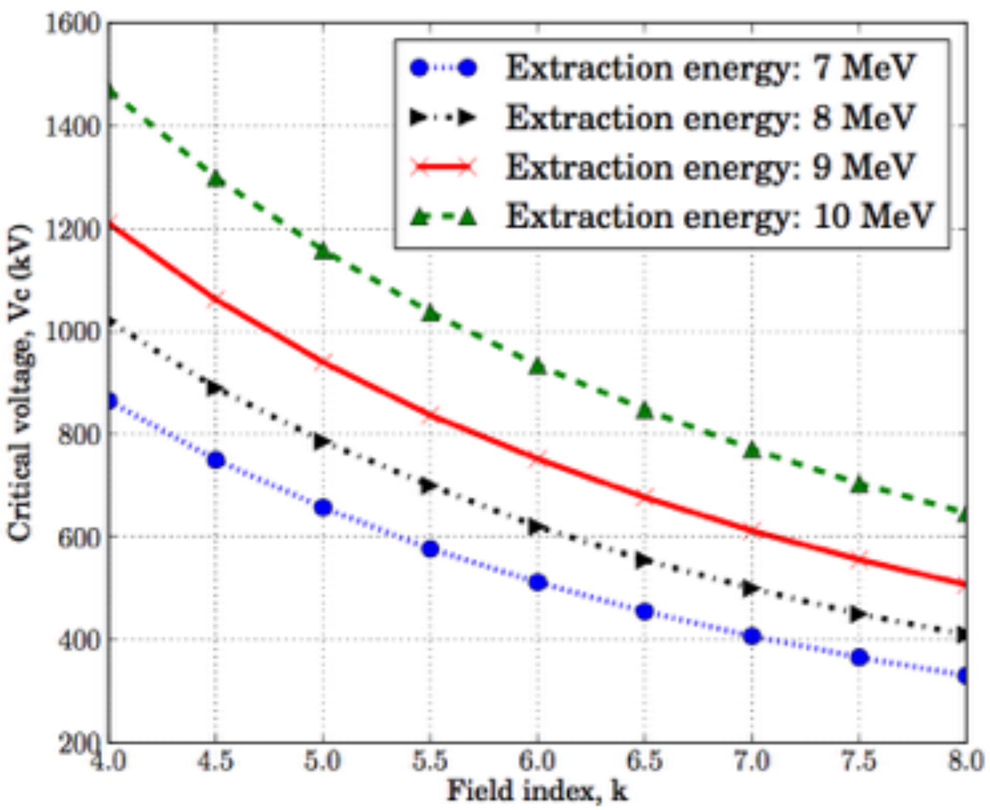


Figure 2: Relations between the critical voltage V_c and field index k (4.0-8.0), for extraction energy 7-10 MeV

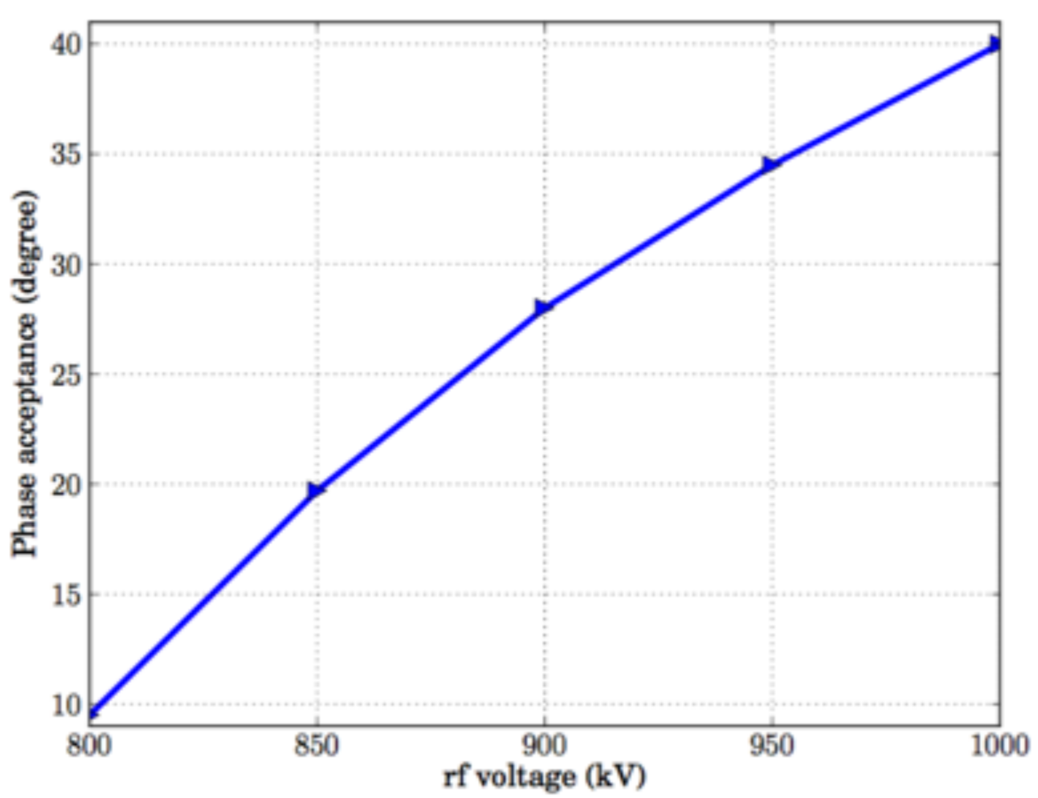


Figure 3: Phase acceptance with various rf voltage, $E_{ext} = 9MeV$, $k = 6.0$

Considerations of (c.w.) semi-isochronous scaling FFAG (5-10MeV)

- **Case study of a 9 MeV cw FFAG**

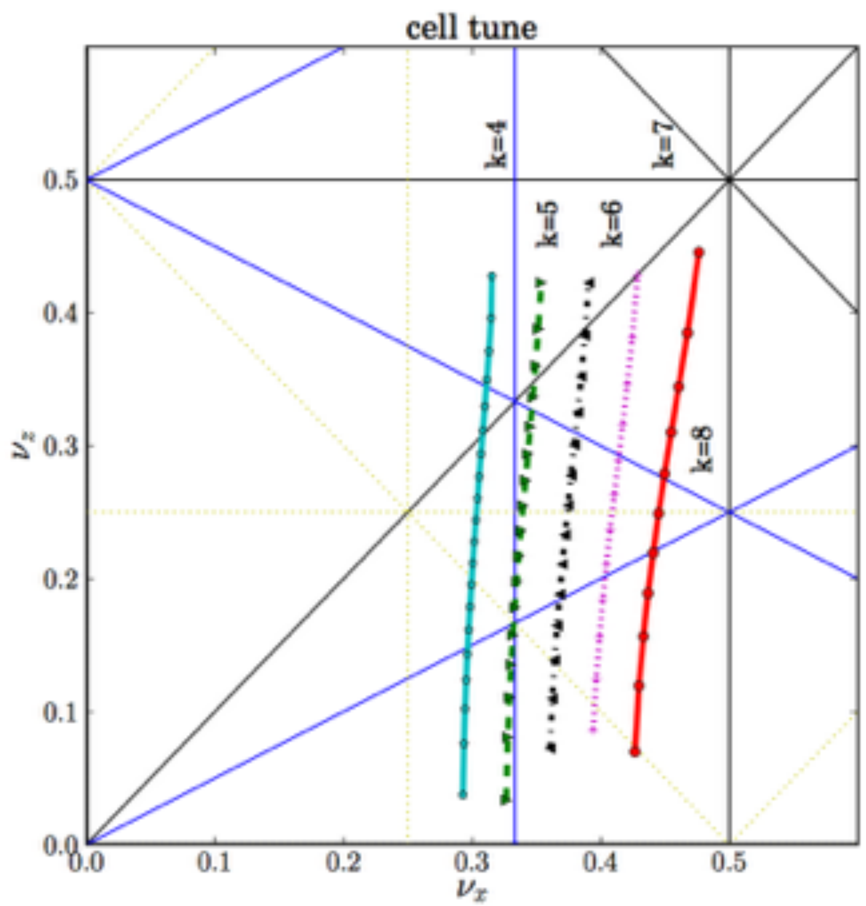


Figure 4: Search of the working point with $k = 4.0 - 8.0$, F/D ratio ≈ 2.1, using FDF triplet lattice

Table 1: Lattice parameters of a FDF triplet

Lattice	Radial FDF triplet
Number of cells	8
Injection / Extraction energy	240 keV / 9 MeV
Momentum ratio	17.26
Mean radius @ 9 MeV	0.8m
Injection radius @ 240keV	0.583m
Field index k	8.0
F/D ratio	2.14 (exactly 2.139)
Open angle F / D	7.0 degree / 3.5 degree(half)
Space between F/D	3.0 degree
Cell tune	$\nu_r = 0.46, \nu_z = 0.34$
Ring tune	$\nu_r = 3.68, \nu_z = 2.72$
Magnetic field B_F, B_D @ 9MeV	0.19T, 0.15T
Gap size 240keV / 9MeV	25.15cm / 2cm (gap ratio=12.5754)

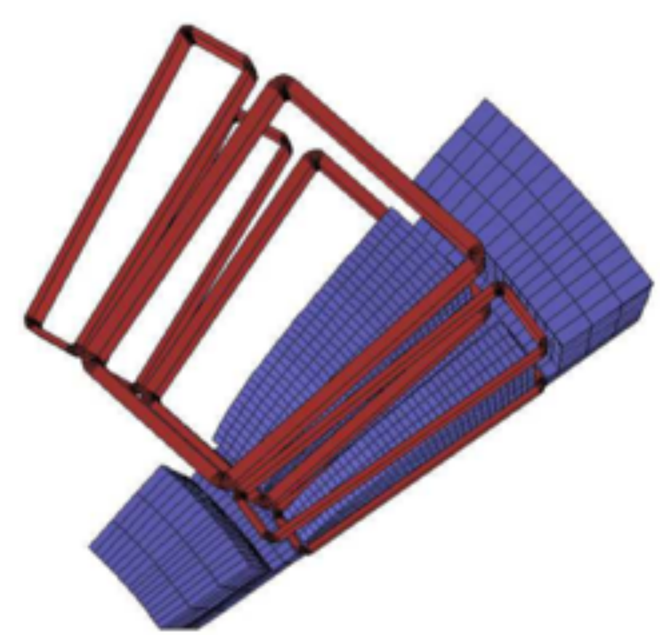


Figure 5: Magnet model for one FDF cell

- **9MeV, k=8.0, Vc ~ 800kV, technique challenges for rf system, also for magnet (high k, large gap at injection, fringe field)**
- **When the extracted energy is decreased to 7MeV, k=6.5, Vc=470kV for good 25 degrees rf phase acceptance**

Summary (1)

- Demands for EB in industrial applications, both for low energy (<1 MeV), and high energy (5-10 MeV)
- Low energy regime, ICT type high voltage accelerator with high power transfer efficiency (~85%)
- Higher energy regime, cw mode scaling FFAG will be a good choice. However, accelerating voltage provided by rf is challenging, as well as the complexity of the magnet and significant fringe field at injection due to large k should be considered

OUTLINE

1. Electron accelerators for industrial irradiation
   - Motivation
   - ICT type high voltage accelerator (0.3-1MeV)
   - Considerations of Isochronous scaling FFAG (7-10MeV)
2. **HUST proton therapy project**
   - **Status and challenges of proton therapy in China**
   - **Proposal of a proton therapy system based on superconducting cyclotron scheme**
   - **Design considerations**

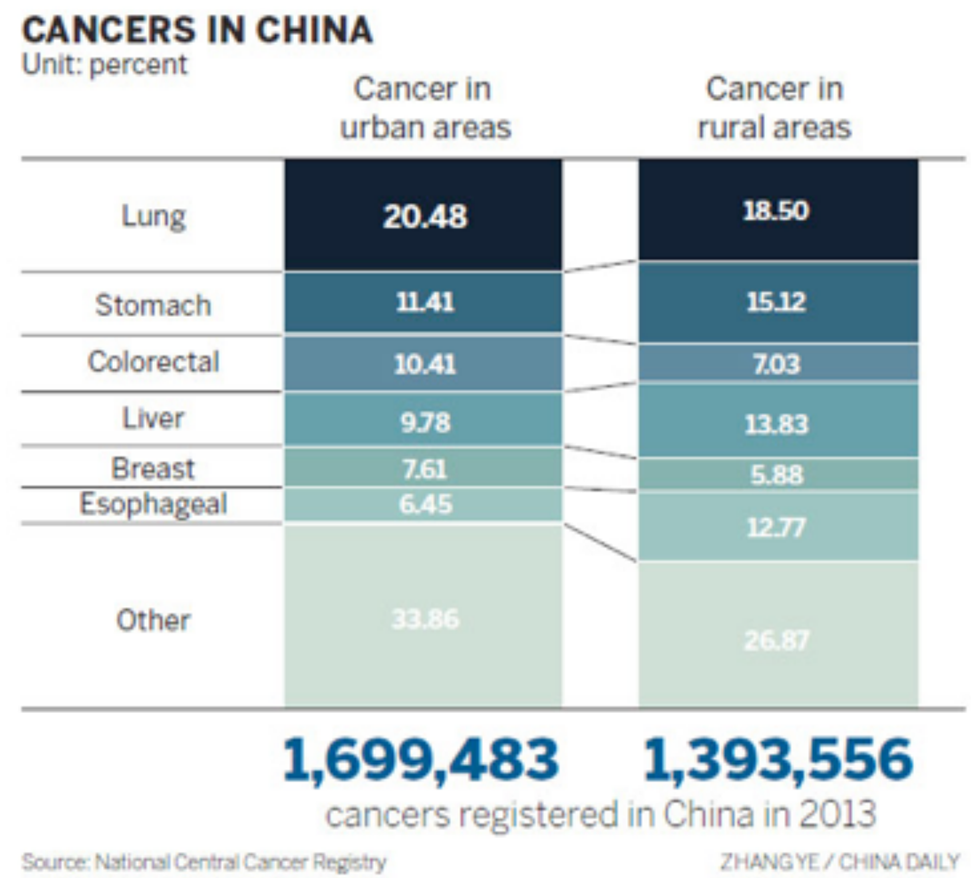
Status and challenges of proton therapy in China

- The cancer is a leading cause of death worldwide. According to WHO's report, the number of new cancer cases and deaths will reach 15 million and 10 million in 2020; In China, 6.6 million and 3 million respectively

- Compared to X-ray, gamma-ray, and electron beams, Proton therapy is the most effective method in radiation therapy,
  - Minimum damage to healthy tissues surrounding at the target tumor, due to its unique 'Bragg peak' of dose distribution;
  - 48 proton therapy centers located in worldwide, more than 100,000 patients treated, cure rate higher than 80%

Cancer situation in China

- **30.9% overall cure rate**
- **Proton therapy in China:**
  - **Zibo Tumor Hospital (IBA 230 MeV cyclotron),;**
  - **Shanghai proton & heavy ion therapy center, start treatment from May-8 2015**
- **Limited resources:**
  - **Some patients go to US, Germany and Japan**
  - **RPTC @ Munich, 25% patients come from China**
  - **Expensive compared to domestic treatment, 3-4 times**



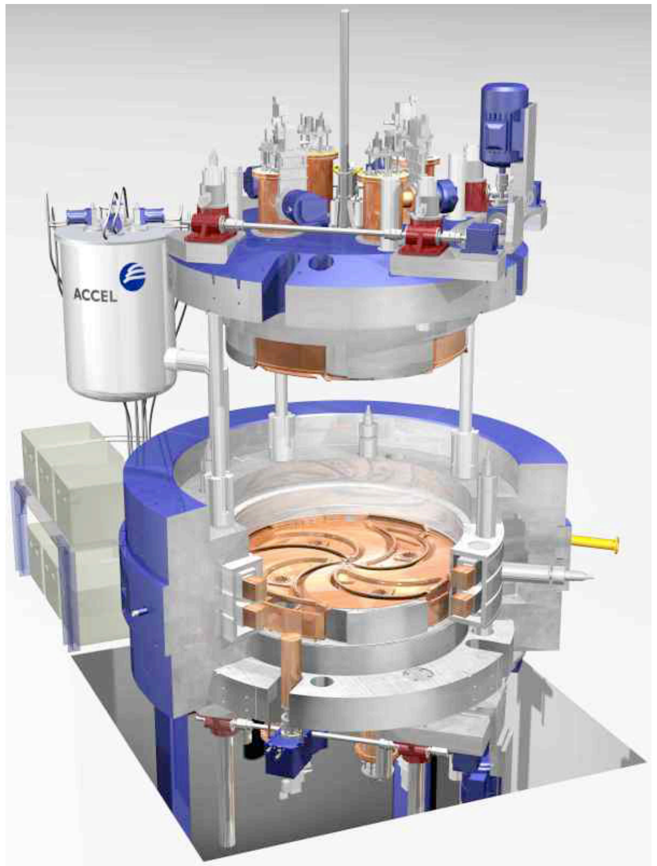
Background of HUST Proton Therapy Project

- HUST, collaborated with Cyclotron Division of CIAE, are proposing a proton therapy project with the PT center located at Wuhan
  - 250 MeV / 500 nA superconducting cyclotron provides cw proton beam, for fast pencil beam with IMPT (intensity modulated proton therapy)
  - 2 Gantry rooms with +/- 180 degrees range, for 1st phase
  - For center site: A new International Medical Center of HUST is under planning and construction, which includes a proton therapy center covering function of research, development and clinic experiment.

Comparison of different schemes for proton accelerator

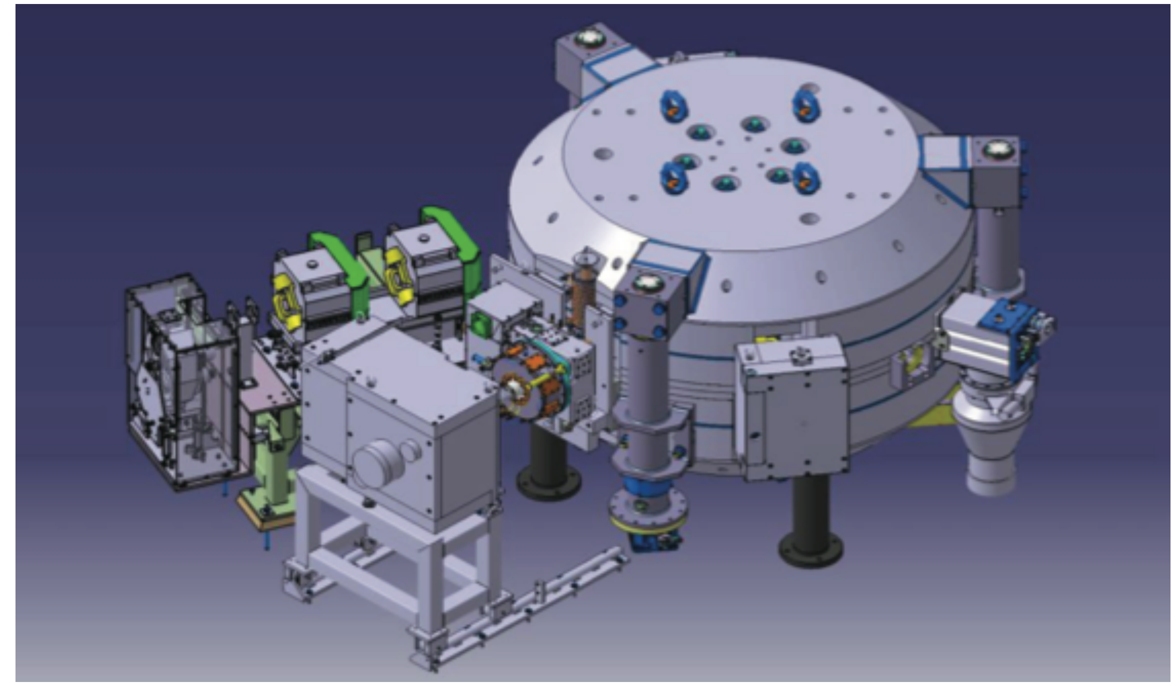
	Synchrotrons	(Superconducting) Cyclotrons	Linacs / FFAG (Fixed-field alternating gradient) accelerators
Type of beam	Pulse beam (<100Hz)	CW beam	Pulse beam 100~1000Hz
Beam energy	Proton(250MeV), Carbon(400MeV/u)	Proton(250MeV)	Proton(250MeV), Carbon(400MeV/u)
Energy variable?	Yes	No, ESS (Energy Selection System) required	Yes
Machine size (ring diameter, 250 MeV protons)	6-8m	<=3m (with s.c. coils) 4-5m (room-temperature magnet)	~24m (Linacs) 4~6m (FFAG)
Comments	RFQ-Linac injector required; main choice for carbon machines	Internal cold cathode PIG source can be used, compact when using s.c. technique	Expensive for Linacs, Prototyping stage for FFAGs (attractive scheme for carbon machines)

Isochronous cyclotron & synchro-cyclotron, with superconducting magnets

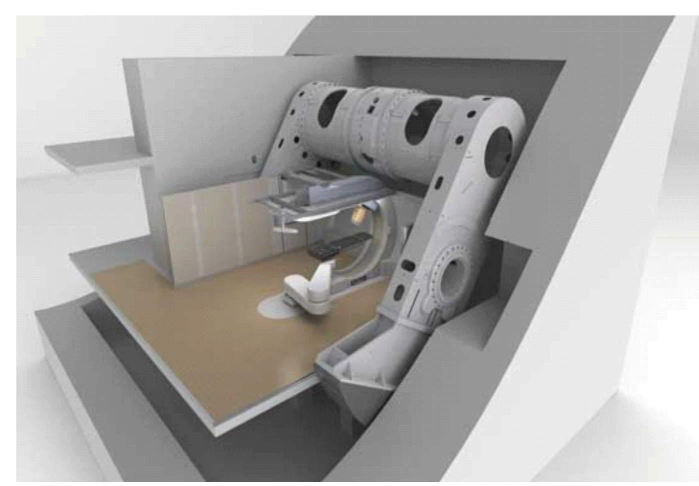


MSU/PSI/Accel scheme
Superconducting isochronous cyclotron: 3T @ ext., 3.2m diameter, internal cold cathode PIG; fixed RF
(H. Rocken, CYC2010)

SCENT project @ INFN
(L. Calabretta, "PRELIMINARY STUDY OF THE SCENT PROJECT")

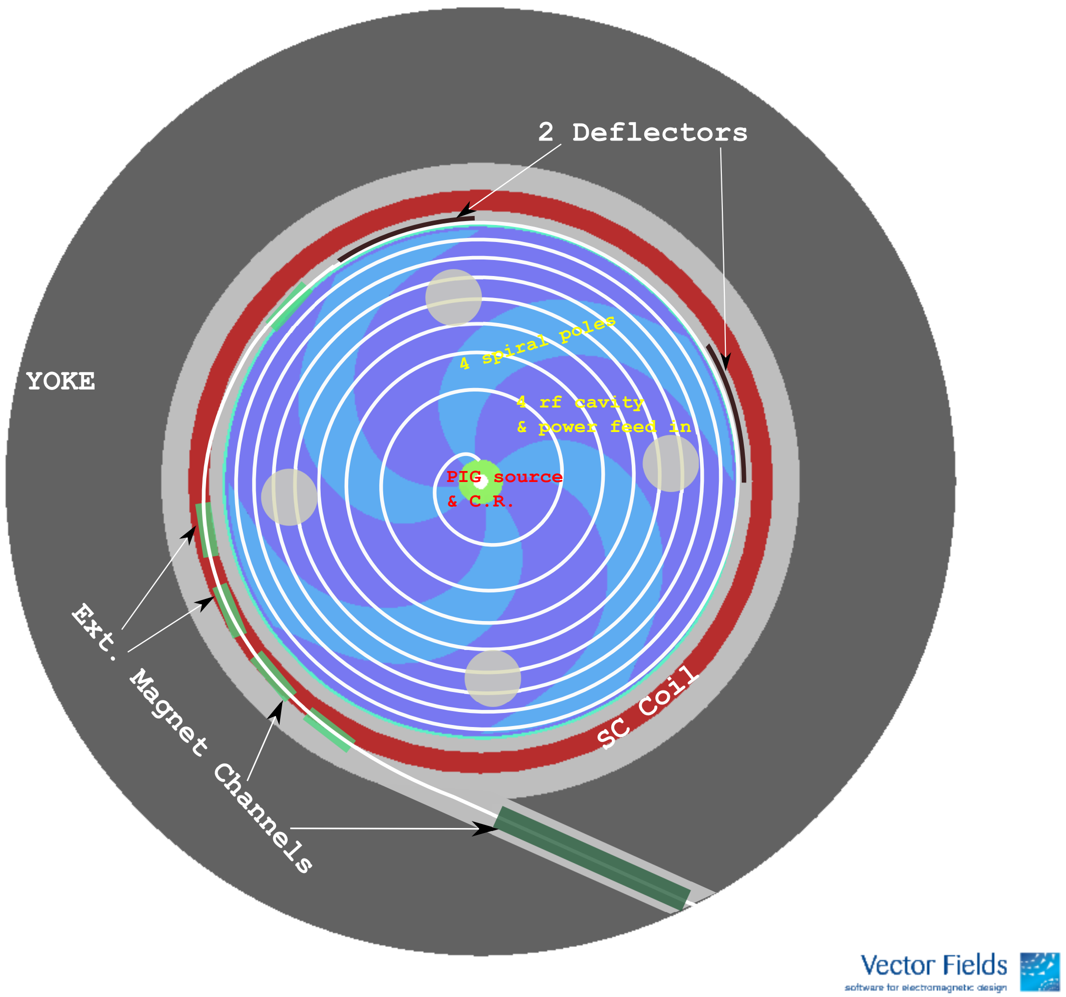


IBA S2C2 (superconducting synchro-cyclotron): max. 5.7T@C.R., 2.5m diameter, internal cold cathode PIG; 1k Hz rotco RF
(W. Kleeven, MO4PB02, CYC2013)



Mevion S250, http://mevion.com/

Overall considerations of HUST SCC-250 Superconducting Cyclotron



1) Internal cold cathode PIG source, simplification of injection, for moderate intensity ~500nA

2) Spiral shape magnet, for stable axial focusing in low flutter condition

3) NbTi/Cu composite superconductor with liquid Helium cooling, maximum 3.2 T average field at extraction

4) Precessional extraction: by generating small first harmonic bump before Nu_r=1.0 resonance crossing, enlarge last turn separation.

Design of spiral magnet pole

- Superconducting coil induced field possesses dominant part, and the field flutter contributed from pole hill and valley structure is much lower. (F<0.1)

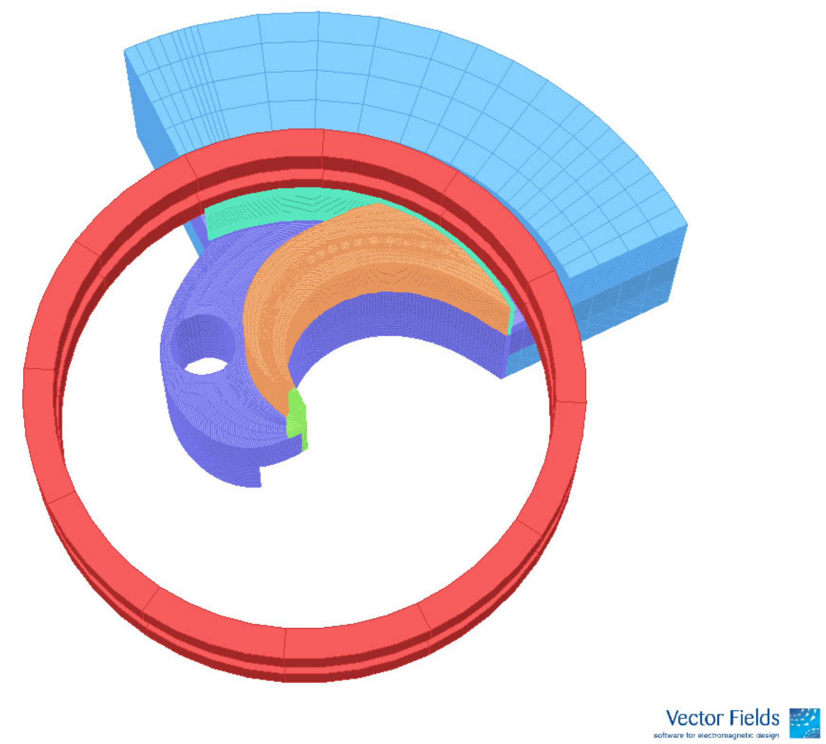
$$\nu_z^2 = -k + \frac{N^2}{N^2-1} F(1 + 2\tan^2 \xi)$$

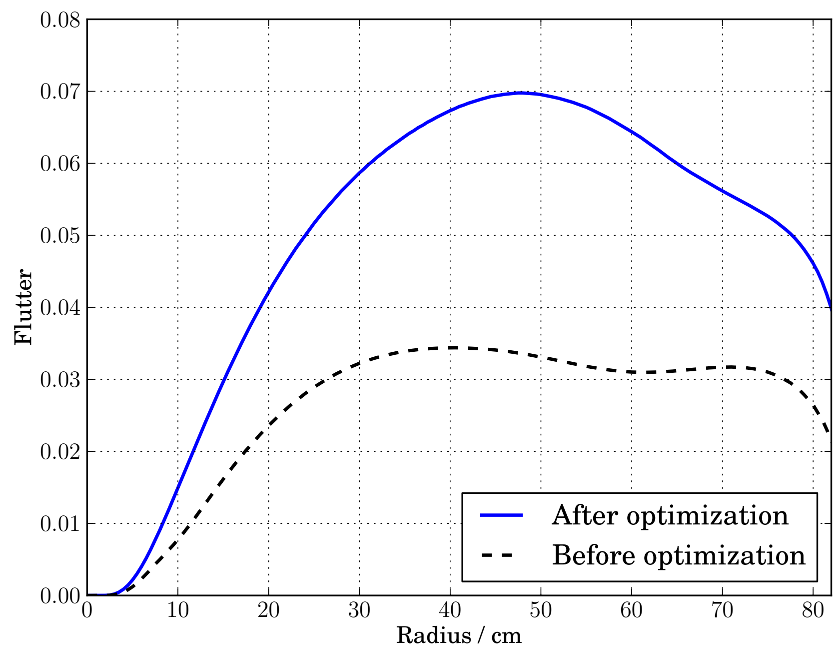
- Installation of RF cavity and higher RF voltage need the spiral angle as small as possible
- Spiral angle is modulated along the radius, reach maximum at extraction

k_{ext} is pre-determined by field isochronism condition

$$k_{ext} = \gamma_{ext}^2 - 1 \approx 0.6$$

$$\rightarrow \zeta_{ext} \approx 65^\circ$$

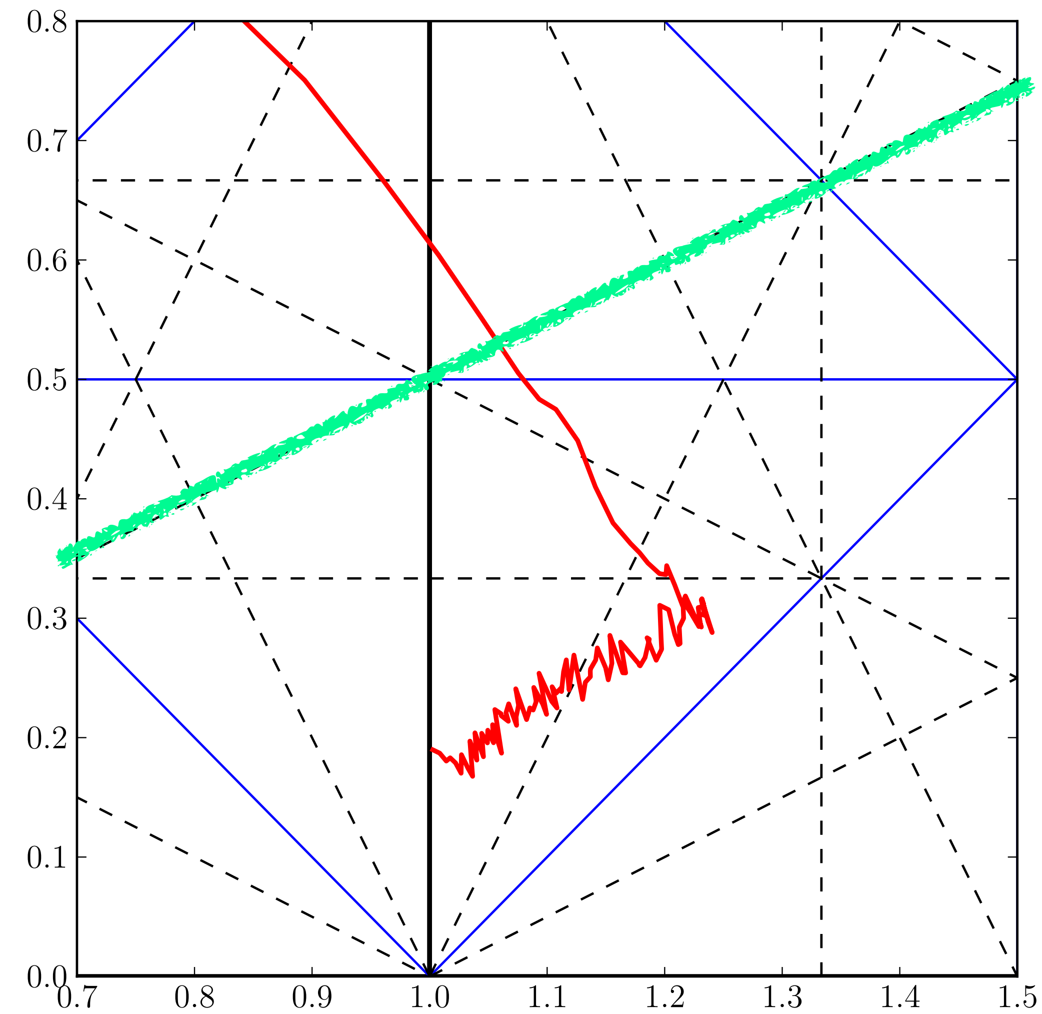




Enhanced field flutter by optimizing the magnet structure

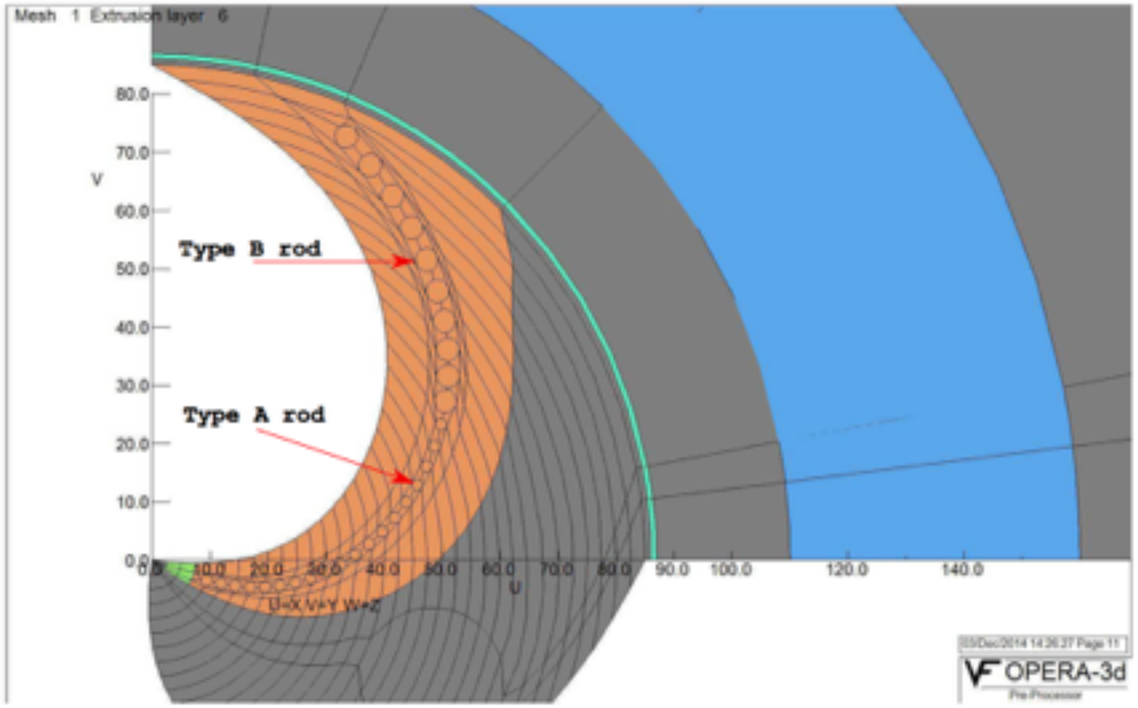
Stabilization of tune variation

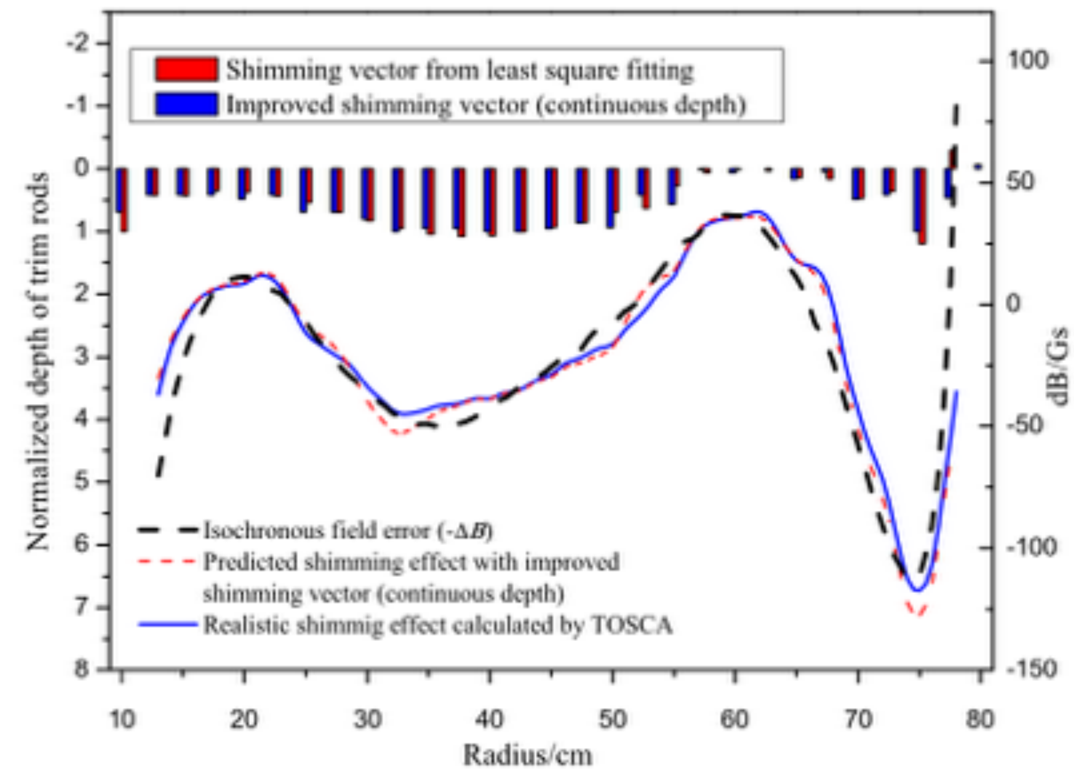
- ν_r varies smoothly as $\nu_r \approx \gamma$
- ν_z affected by local spiral angle & flutter→ modified according to the tune values iteratively, automatically by a Python script

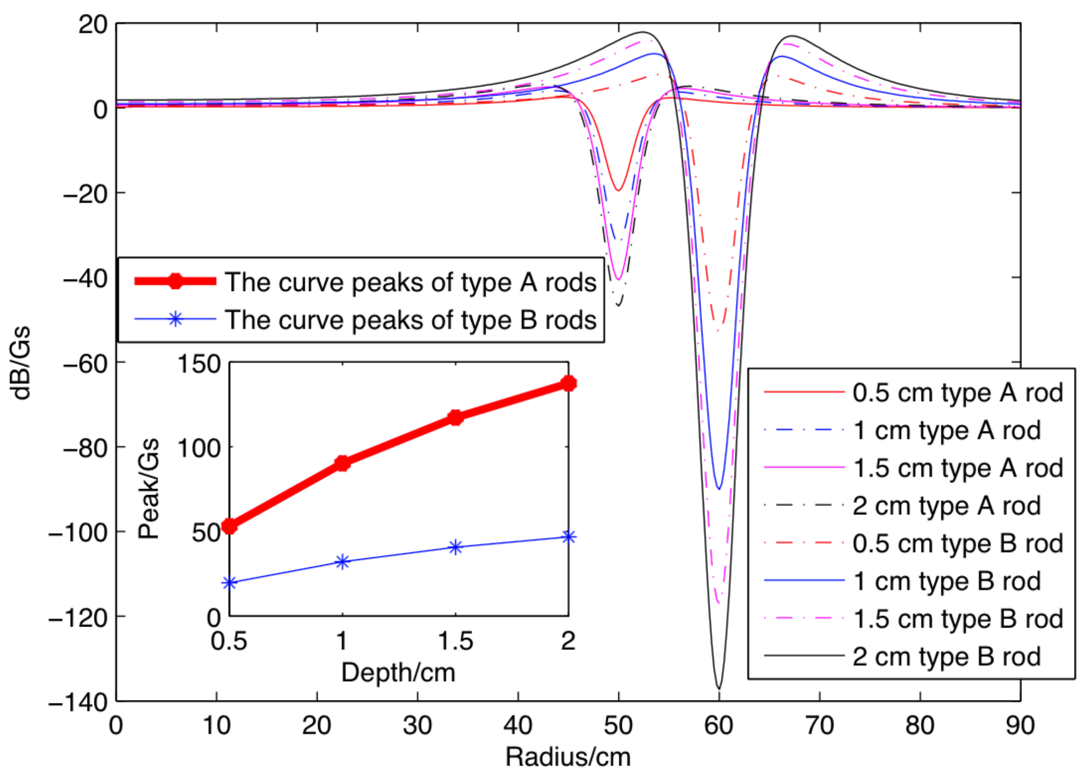


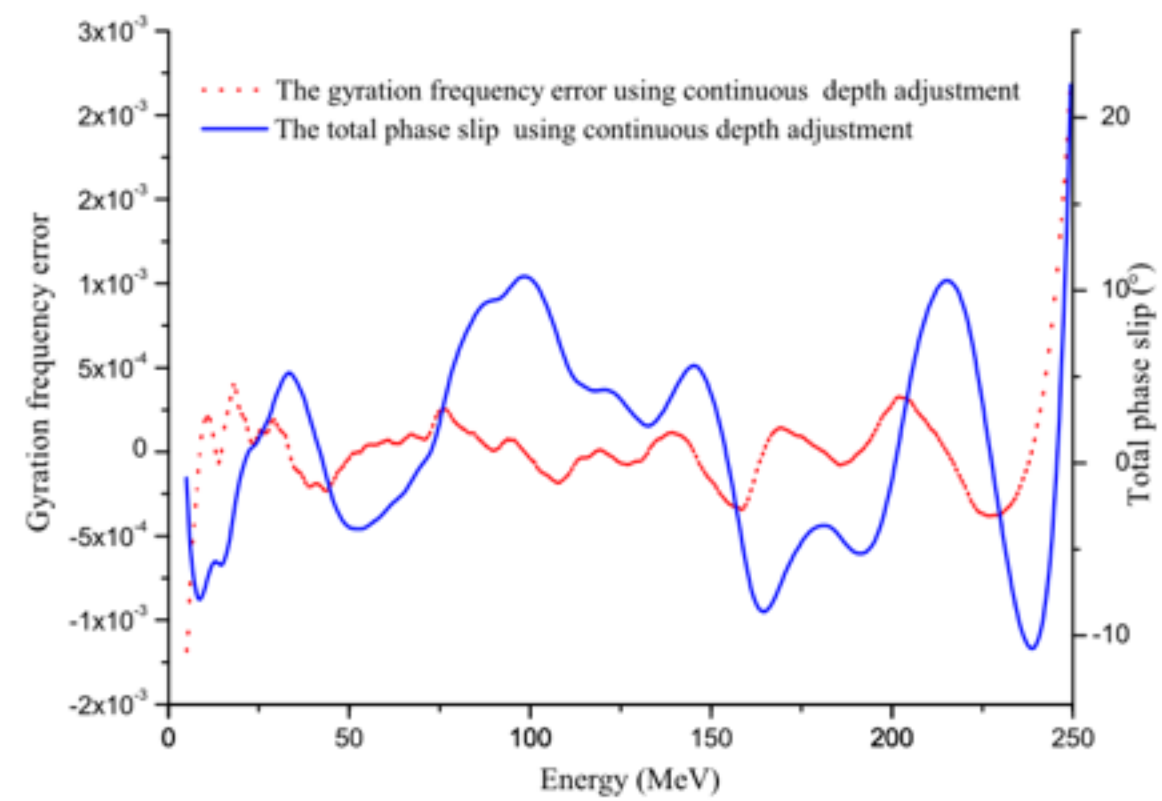
- $\nu_r - \nu_z = 1$ avoided;
- Walkinshaw resonance $\nu_r - 2\nu_z = 0$ avoided in main acceleration region

Field isochronism with trim rods



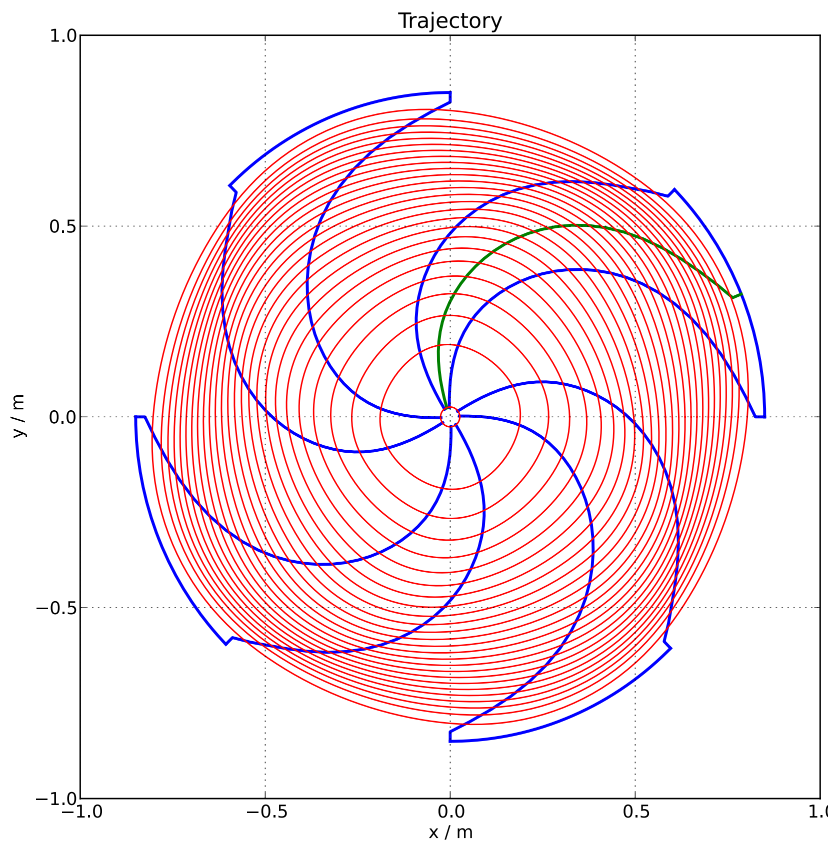






Precessional extraction – beam centering by A.E.O

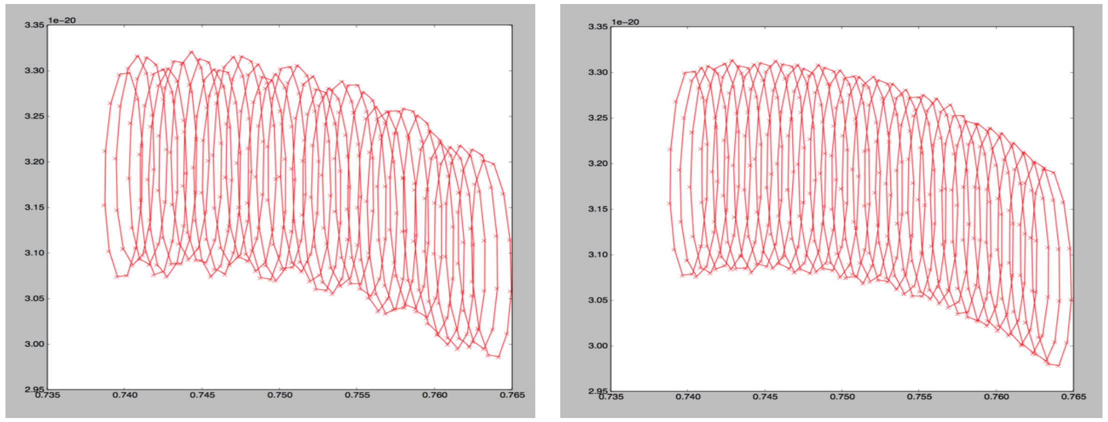
- ➡For high efficient resonant extraction, beams need be pre-centered using accelerating E.O.
  - ➡To remove coherent oscillation effects
  - ➡Turns are evenly spaced, before using the field bump



Gordan's method[1]: Quasi-fixed center, (x,px) to be the same after one turn acceleration

$$x(E,\theta) = r(E,\theta) - r_e(E,\theta)$$
$$p_x(E,\theta) = p_r(E,\theta) - p_{re}(E,\theta)$$

(r_e, p_{re}) refers to coordinates in static equilibrium orbit



210-230MeV, 0.6MeV/turn, (L)not centered; (R)centered

[1]M. M. Gordon, Single turn extraction, IEEE Trans. Nucl. Sci., 13 (4), 48-57

Precessional extraction

By generating a first harmonic field

$$b1(r,\theta) = b1(r)\cdot\cos(\theta-\theta_0)$$

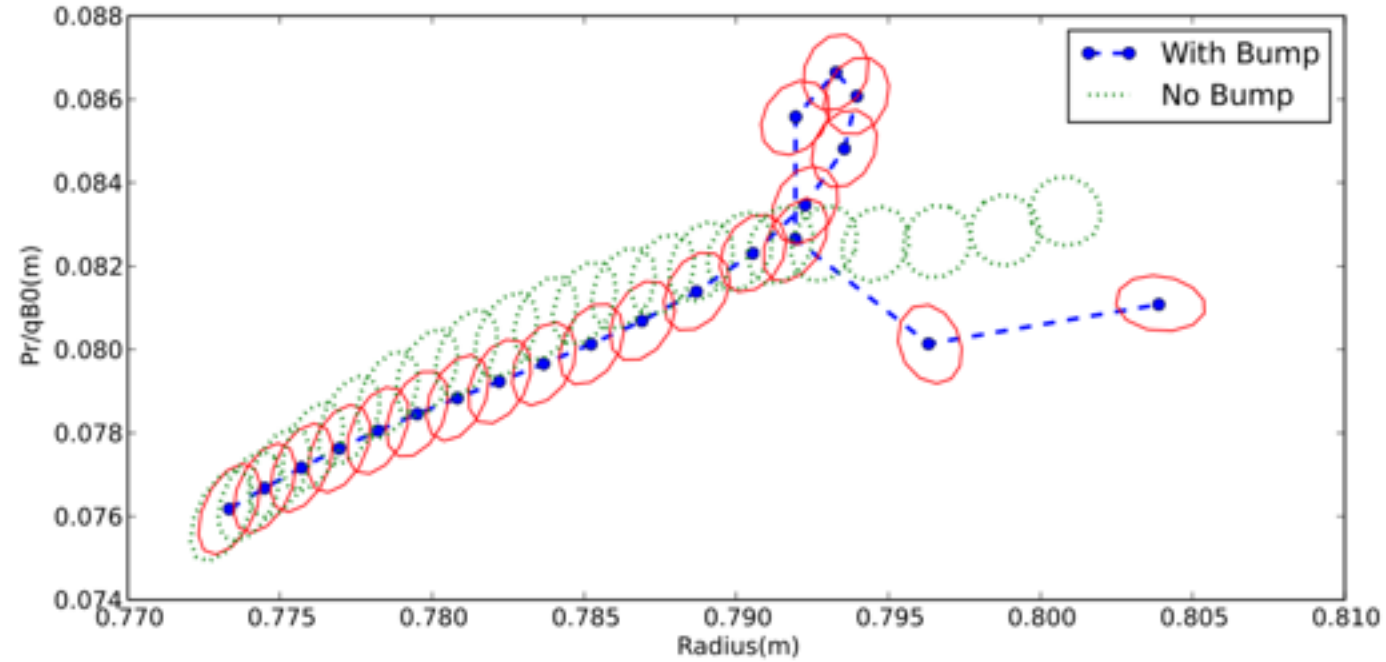
Before resonance crossing $\nu_r = 1$, at θ_0 , a coherent oscillation is created and

$$\Delta R_{pre} = \pi R\cdot\Delta\tau(b1/\overline{B}(R))$$

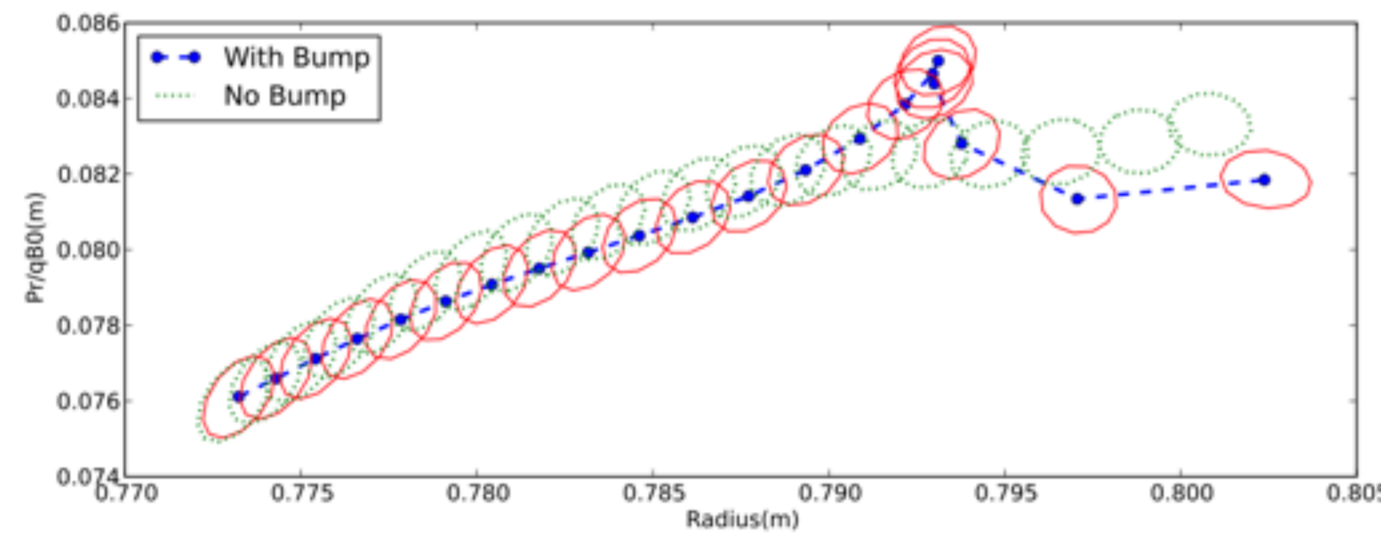
effective turns during coherent oscillation

$$\Delta\tau = ((\Delta\nu_r/\Delta E)\cdot E_{gain}))^{-1/2}$$

- The radial and azimuthal position of the field bump is very sensitive;
- b1 ban be generated by harmonic coil or trim rod



b1=10Gs, θ_0=30 deg., dR~8mm



b1=6Gs, θ_0 =30 deg., dR~5mm (coincident with theoretical 4.3mm, eff. Turns = 9)

Summary (2)

- **Demands for proton therapy and limited sites in China**
- **Isochronous cyclotron is an optimum choice to provide cw beam for fast spot / line scanning with IMPT**
- **250 MeV / 500 nA Superconducting cyclotron is proposed in HUST; Proton therapy center, with two gantry rooms, planned in International Medical Center of HUST.**

Thanks for attention!