Design study of a 250MeV superconducting isochronous cyclotron for proton therapy

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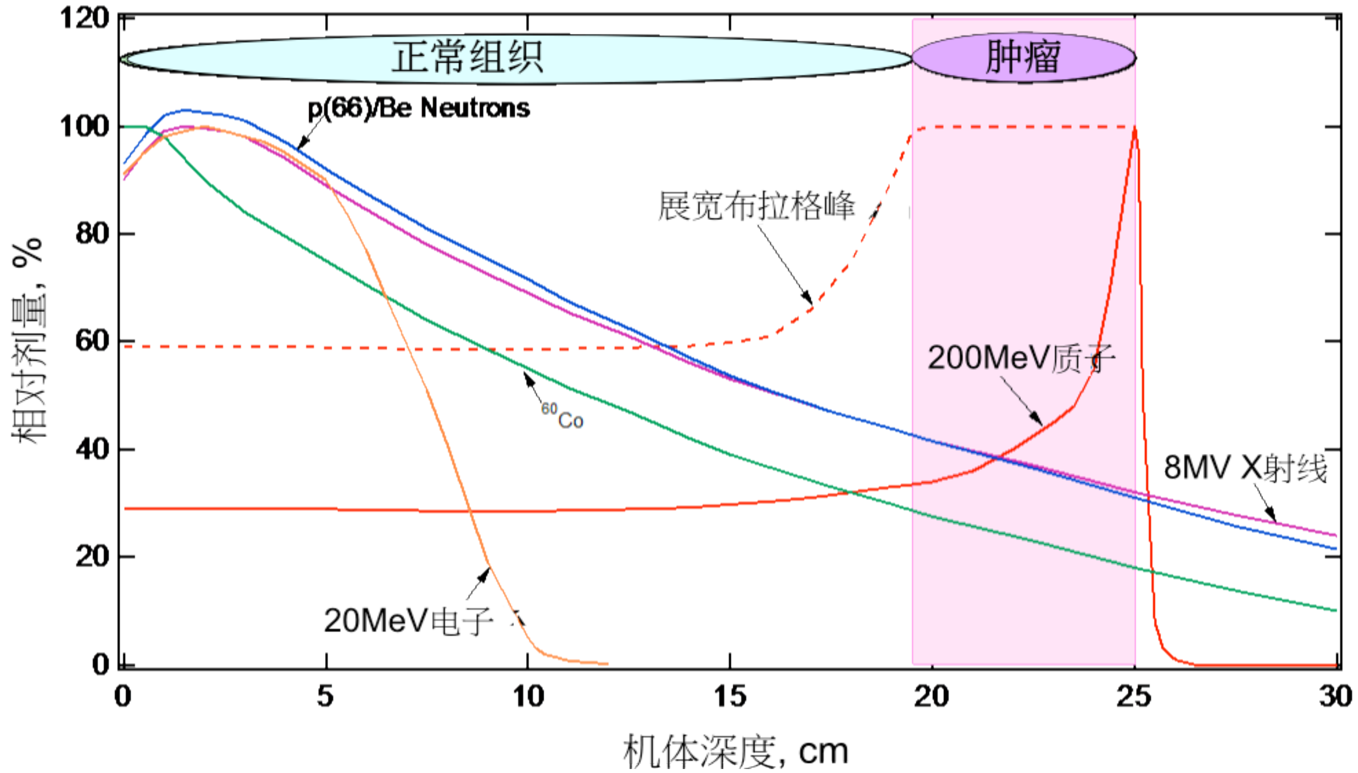
OUTLINE

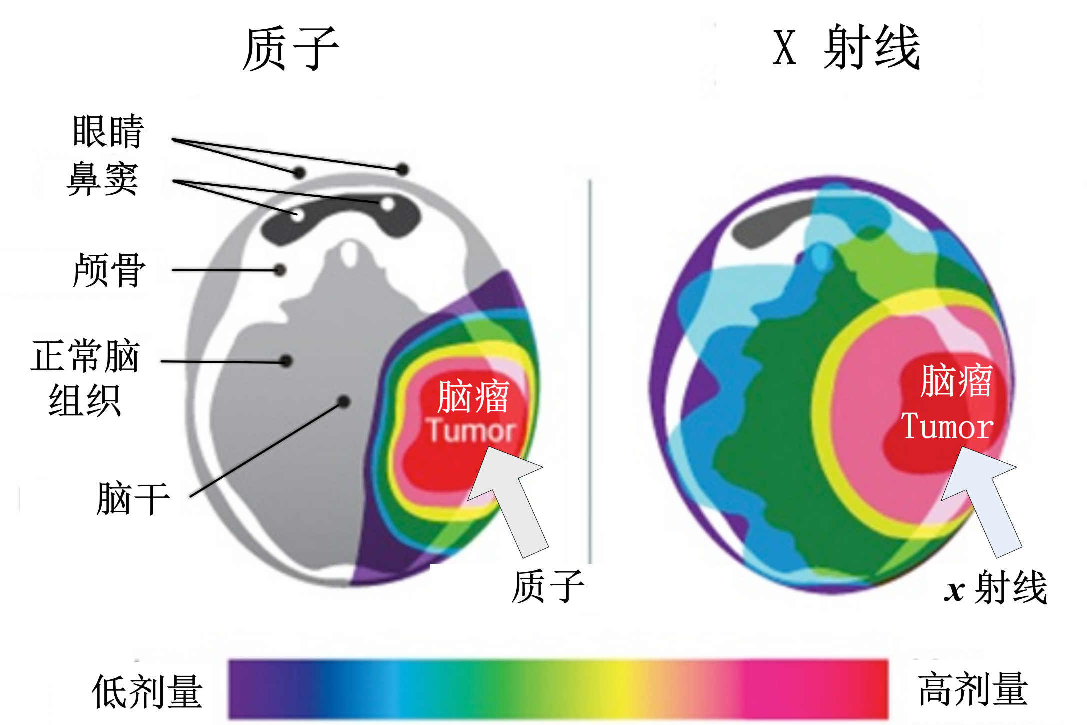
- Motivation & schemes comparison
- Design study
- Conclusions

Motivation

- 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
- In China, the survival and cure rate for cancer patients is about 12%;
- 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;
  - 27 proton therapy centers located in worldwide, more than 50,000 patients treated, cure rate higher than 80%

Dose distribution of proton beams





Protons, electrons, X-ray and Gamma-ray （^{60}Co） for cancer therapy

- For X-rays generated by linacs, absorbed dose, exponential decrease after initial peak (only 1/3 dose reached 20-25cm)
- For proton beams, location of Bragg peak can be modulated by proton energy precisely

Proton therapy centers world wide

Courtesy of U. Amaldi et al., Nucl. Instru. Meth A, 620 (2010) 563

Centre	Country	Acc.	Max. clinical energy (MeV)	Beam direction[a]	Start of treat.	Total treated patients	Date of total
ITEP, Moscow	Russia	S	250	H	1969	4024	Dec-07
St. Petersburg	Russia	SC	1000	H	1975	1327	Dec-07
PSI, Villigen[b]	Switzerland	C	72	H	1984	5076	Dec-08
Dubna[c]	Russia	SC	200	H	1999	489	Dec-08
Uppsala	Sweden	C	200	H	1989	929	Dec-08
Clatterbridge[b]	England	C	62	H	1989	1803	Dec-08
Loma Linda	USA	S	250	3G, H	1990	13,500	Dec-08
Nice[b]	France	C	65	H	1991	3690	Dec-08
Orsay[d]	France	SC	200	H	1991	4497	Dec-08
iThemba Labs	South Africa	C	200	H	1993	503	Dec-08
MPRI(2)	USA	C	200	H	2004	632	Dec-08
UCSF[b]	USA	C	60	H	1994	1113	Dec-08
TRIUMF, Vancouver [b]	Canada	C	72	H	1995	137	Dec-08
PSI, Villigen [e]	Switzerland	C	250	G	1996	426	Dec-08
HZB (HMI), Berlin[b]	Germany	C	72	H	1998	1227	Dec-08
NCC, Kashiwa	Japan	C	235	2G, H	1998	607	Dec-08
HIBMC, Hyogo	Japan	S	230	2G, H	2001	2033	Dec-08
PMRC(2), Tsukuba	Japan	S	250	2G, H	2001	1367	Dec-08
NPTC, MGH, Boston	USA	C	235	2G, H	2001	3515	Oct-08
INFN-LNS, Catania[b]	Italy	C	60	H	2002	151	Dec-07
Shizuoka	Japan	S	235	2G, H	2003	692	Dec-08
WERC,Tsuruga	Japan	S	200	H, V	2002	56	Dec-08
WPTC, Zibo	China	C	230	3G, H	2004	767	Dec-08
MD Anderson Cancer Centre, Houston, TX[f]	USA	S	250	3G, H	2006	1000	Dec-08
FPTI, Jacksonville, FL	USA	C	230	3G, H	2006	988	Dec-08
NCC, Ilsan	South Korea	C	230	2G, H	2007	330	Dec-08
RPTC, Munich [g]	Germany	C	250	4G, H	2009	Treatments started	Mar-09
TOTAL						50,879	

- 27 centers, 50000 patients treated ;
- Europe: 12, USA: 6, Japan: 5;
- Synchrotron 7; Cyclotron 17; Synchro-cyclotron 3

Planned Proton/Carbon Therapy Center

Courtesy of U. Amaldi et al., Nucl. Instru. Meth A, 620 (2010) 563

Location	Country	Particle	Max. energy (MeV) - Acc.	Beams [a]	Rooms	Foreseen start date
University of Pennsylvania	USA	p	230 cyclotron	4G, 1H	5	2009
PSI, Villigen	Switzerland	p	250 SC cyclotron	1G additional to 1G, 1 H	3	2009 (OPTIS2), 2010 (Gantry2)
WPE, Essen	Germany	p	230 cyclotron	3G, 1H	4	2009
HIT, Heidelberg	Germany	p, C	430/u synchrotron	1G for C ions, 2H	3	2009
CPO, Orsay	France	p	230 cyclotron	1G additional to 2H	3	2010
CNAO, Pavia	Italy	p, C	430/u synchrotron	2H, 1 H+V	3	2010
PTZ, Marburg	Germany	p, C	430/u synchrotron	3H, 1 OB	4	2010
NIPTRC, Chicago	USA	p	250 SC cyclotron	2G, 2H 1H (research)	4	2011
NRoCK, Kiel	Germany	p, C	430/u synchrotron	1H, 1V+OB, 1H+V	3	2012
Trento	Italy	p	230 cyclotron	1G, 1H	2	2012
Skandionkliniken, Uppsala	Sweden	p	250 SC cyclotron	2G, 1H	3	2013
Med-AUSTRON, Wiener Neustadt	Austria	p, C	400/u synchrotron	1G (p only), 1V, 1V+OB	3	2013
Shanghai	China	p, C	430/u synchrotron	1H, 1V+OB, 1H+V	3	?
iThemba Labs	South Africa	p	230 cyclotron	1G, 2H	3	?
RPTC, Koeln	Germany	p	250 SC cyclotron	4G, 1H	5	?
ETOILE, Lyon	France	p, C	?	?	?	?

- For new proton therapy centers, energy covers 210MeV-250MeV (>25cm penetration depth), all adopt (superconducting) cyclotrons;
- Carbon ions (C_{12}^{6+}) , more heavy, more effective for radio-resistant tumors; 25cm penetration depth requires 400MeV/u energy (magnetic rigidity ~ 1.2GeV proton) → synchrotrons adopted for most cases;

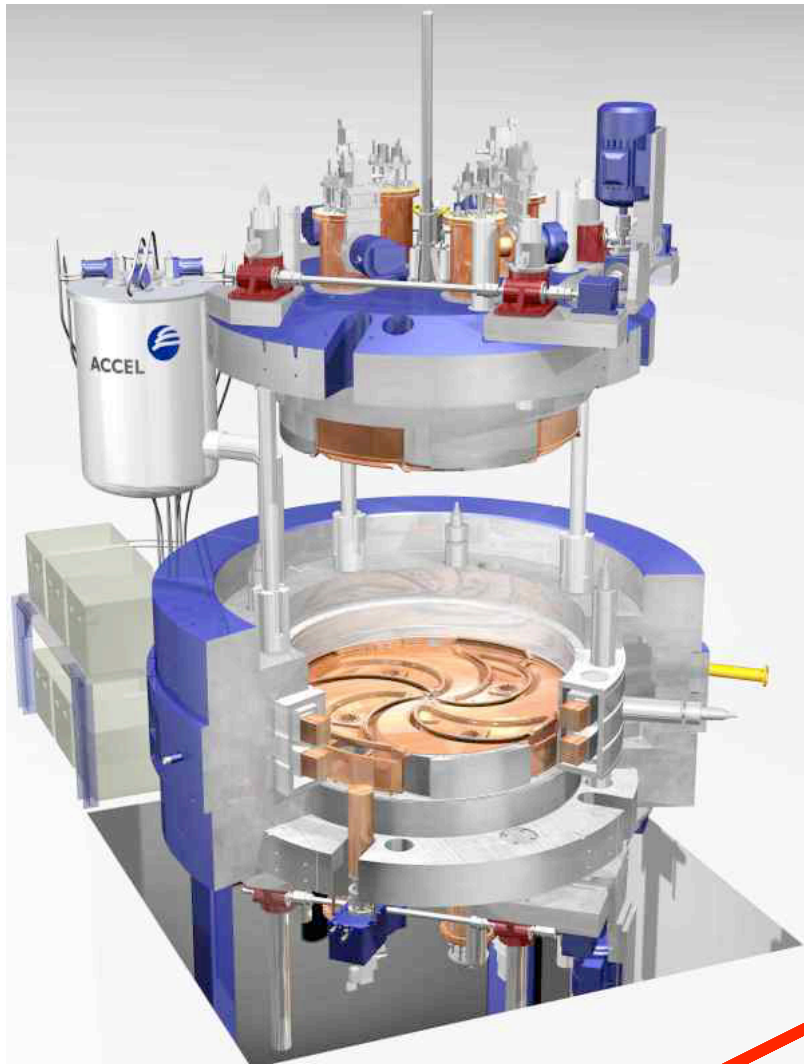
R&D of hadron therapy facilities in China

- Shanghai Proton therapy facility, proposal by Prof. FANG Shouxian et al., (IHEP, SINAP), Synchrotron scheme (2009)
- R&D initiated in CIAE, Synchrocyclotron scheme
- For carbon therapy, IMP (Lanzhou) HIRFL-CSR has performed experiments on shallow-seated tumors (104 cases, 2006-2009) and deep-seated tumors (110 cases, 2009-2013); new carbon therapy centers at Lanzhou & Wuwei are under-constructed
- Initial stage for proton therapy facilities

Comparison of different schemes

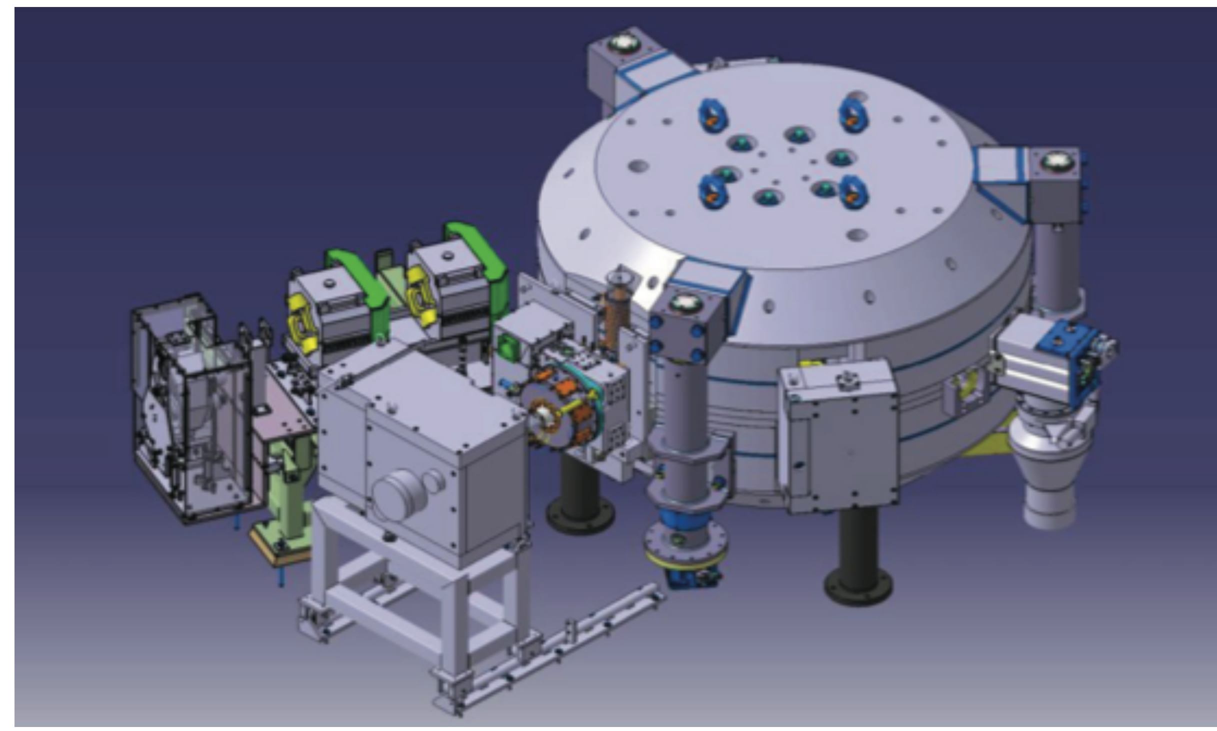
	Synchrotrons	(Superconducting) Cyclotrons	Linacs / FFAG (Fixed-field alternating gradient) accelerators
Type of beam	Pulse beam (<100Hz)	CW beam	Pulse beam 100~1000Hz
Beam energy	Proton(250MeV), Carbon (400MeV/u)	Proton(250MeV)	Proton(250MeV), Carbon(400MeV/u)
Energy variable?	Yes	No, ESS (Energy Selection 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)

Two main schemes for proton machines



We chose

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

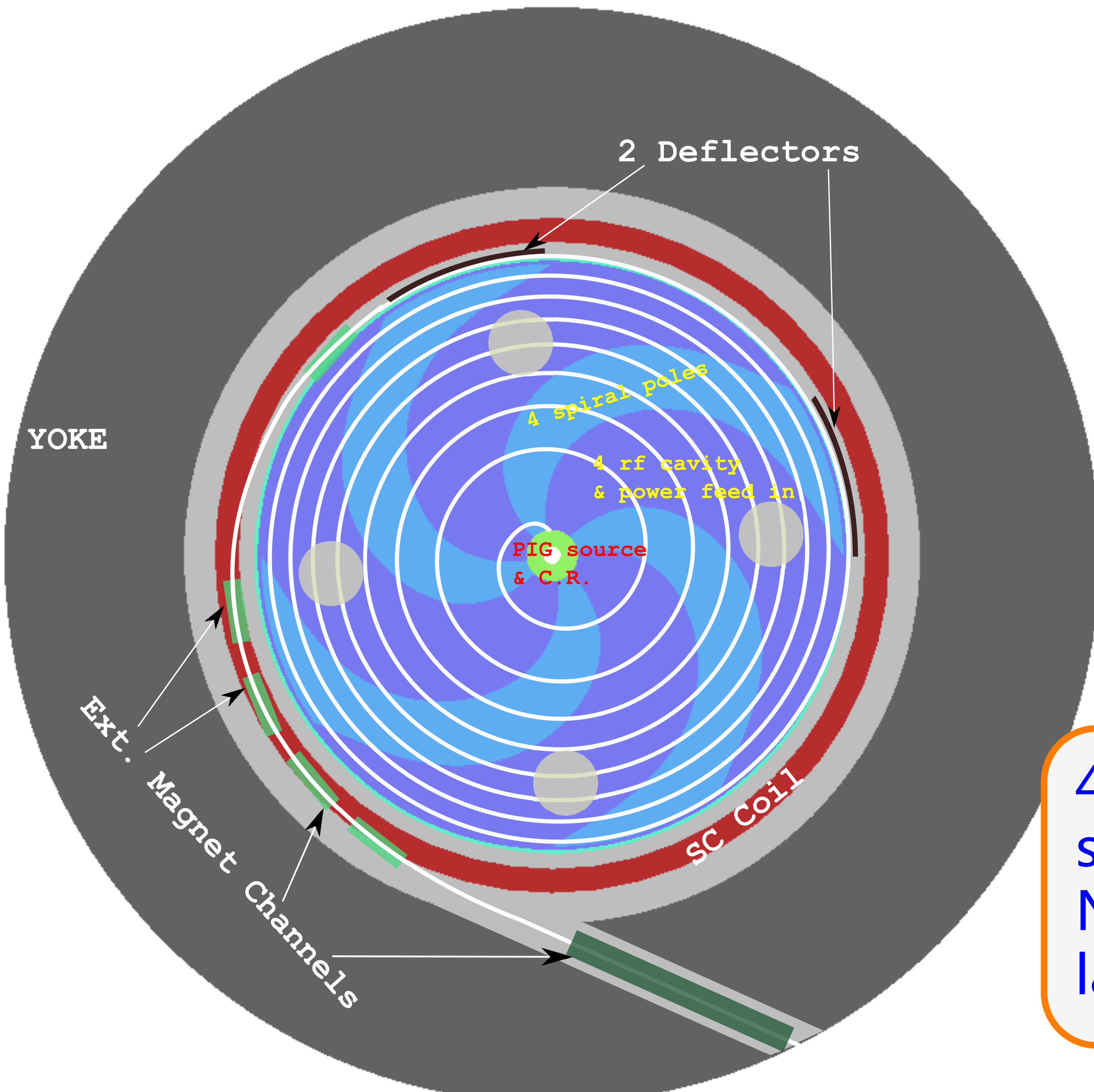


IBA S2C2 (superconducting synchro-cyclotron): max. 5.7T@C.R., 2.5m diameter, internal cold cathode PIG; 1k Hz rotco RF
(Coutesy of W. Kleeven, MO4PB02, CYC2013)

OUTLINE

- Motivation & & schemes comparison
- Design study
  - Overall considerations
  - Spiral magnet design
  - Isochronous field trimming
  - Precessional extraction
- Conclusions

General features of s.c. 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

2) 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.

Vector Fields
software for electromagnetic design

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Overall parameters

Table 1: Overall parameters

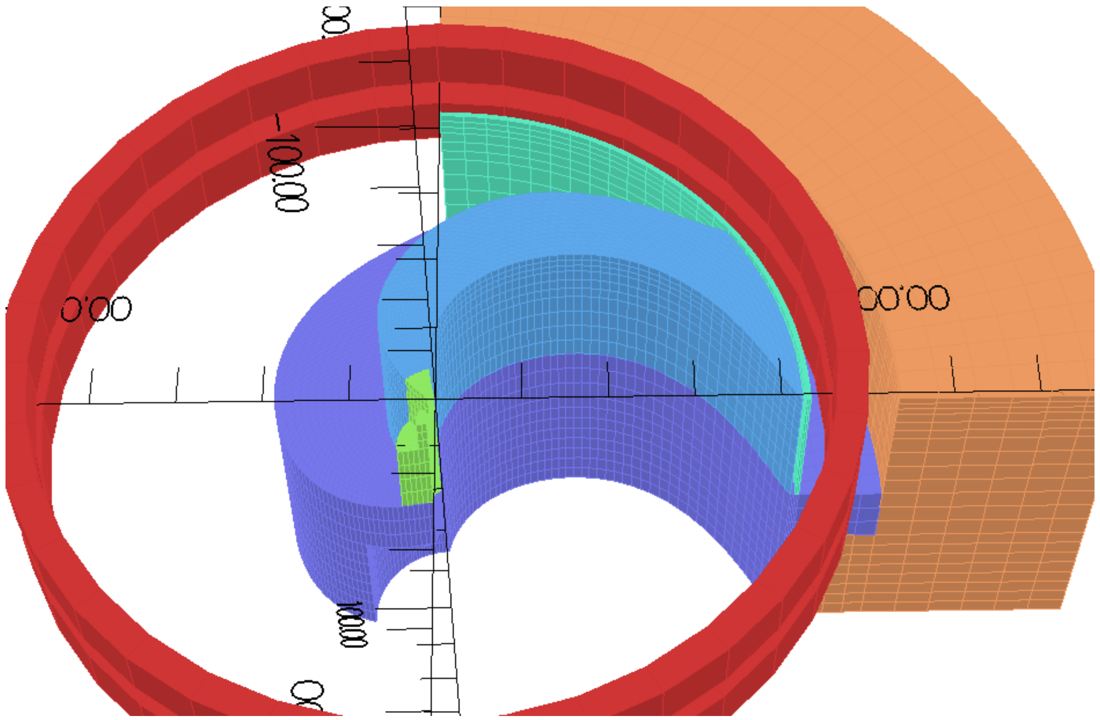
Extraction energy	250 MeV
Ion source	Internal P.I.G. source
Beam intensity	$\approx$ 500nA
Emmittance	$5\pi\text{mm} \cdot \text{mrad}$
Injection / extraction field	2.45 / 3.1 T
Spiral angel (maximum)	66 degrees
Pole gap at hill	5 cm
Pole radius	84 cm
Total ampere turns	$1.2\text{MA} \cdot \text{T}$
RF frequency	74MHz (harmonic mode=2)
Energy gain per turn	$\approx$ 400keV
Extraction scheme	Precessional extraction

Spiral shape magnet

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

$$\nu_r^2 = 1 + k + \frac{3N^2}{(N^2-1)(N^2-4)} F(1+\tan^2 \xi)$$

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



For axial focusing, to compensate

$$-k = -(\gamma^2 - 1)$$

, spiral angle must be introduced

Flutter optimization and max. spiral angle

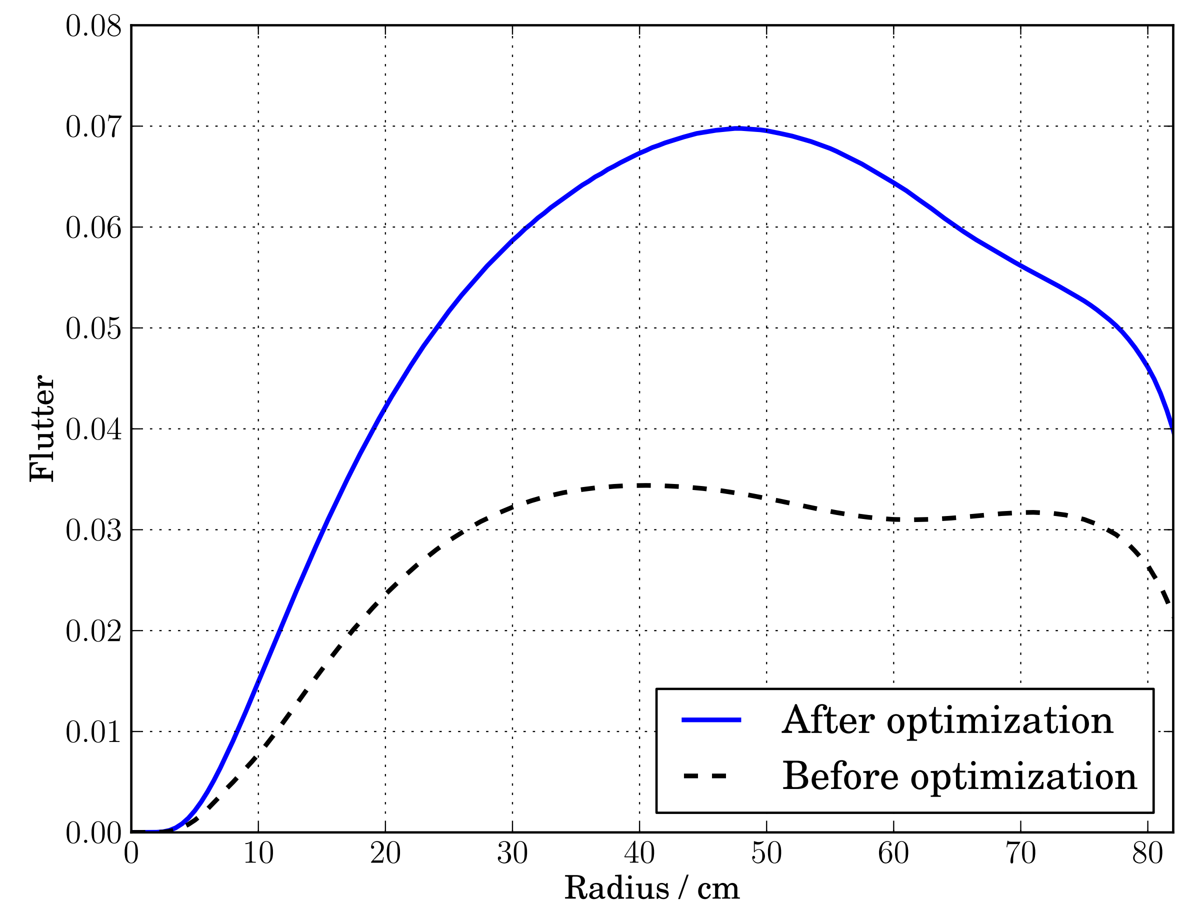
- Installation of RF cavity and higher RF voltage need the spiral angle as small as possible
- Spiral angle is modulated along the radius, reach maximum at extraction

$$\nu_z^2 \approx -k + F\cdot(1+2\tan^2\zeta)$$

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

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

→ $\zeta_{ext} \approx 65°$

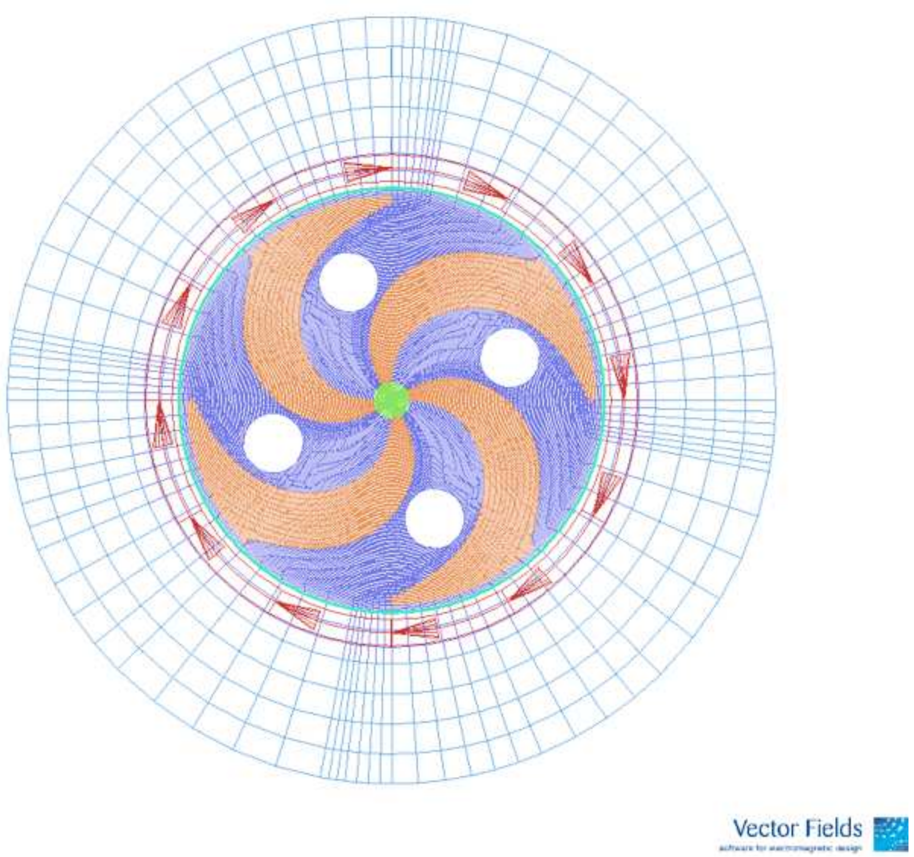


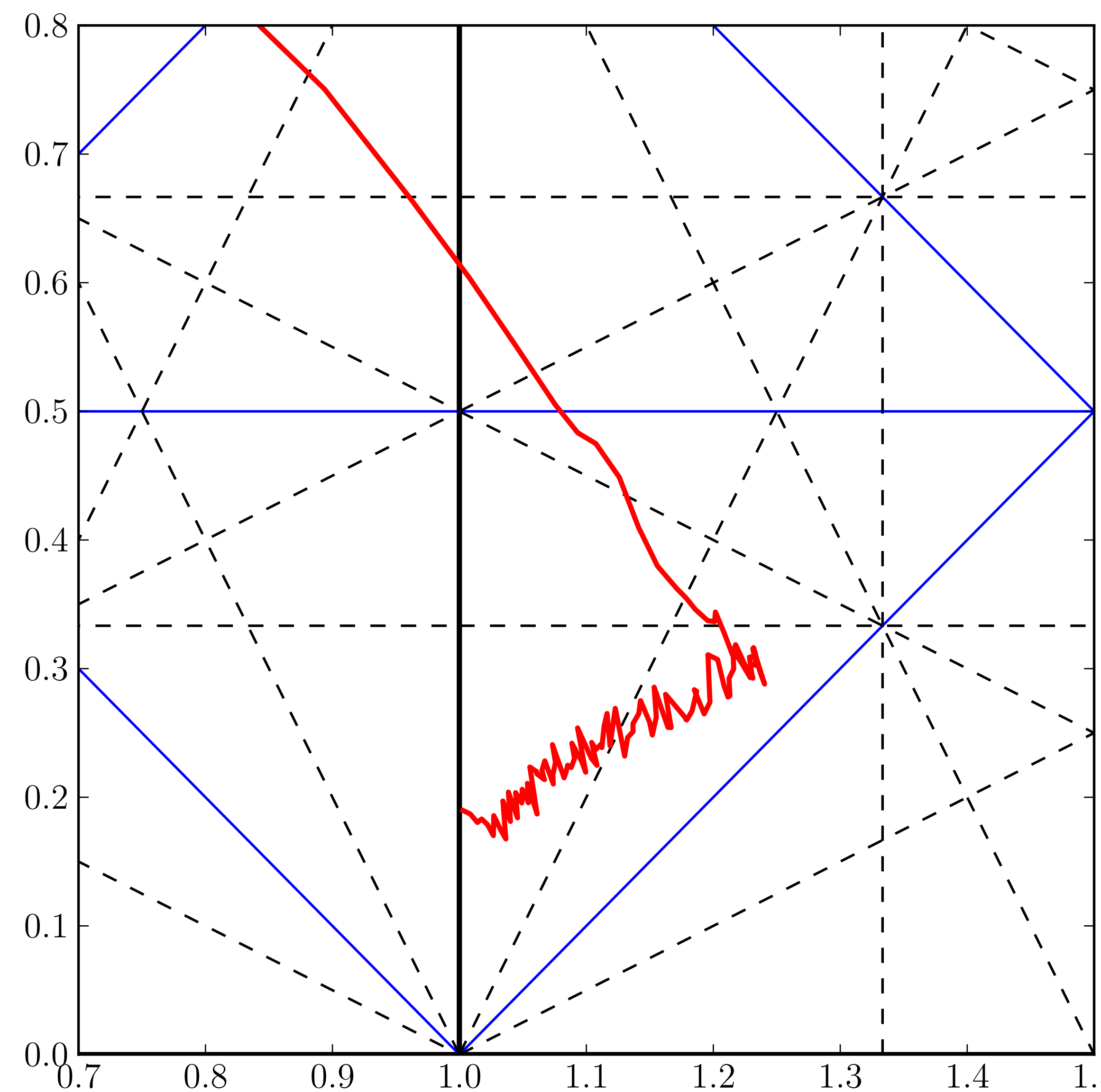
Enhanced field flutter by optimizing the magnet structure

Stabilization of axial motion and tune diagram

- ν_r varies smoothly as $\nu_r \approx \gamma$

- ν_z controlled by local spiral angle → 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

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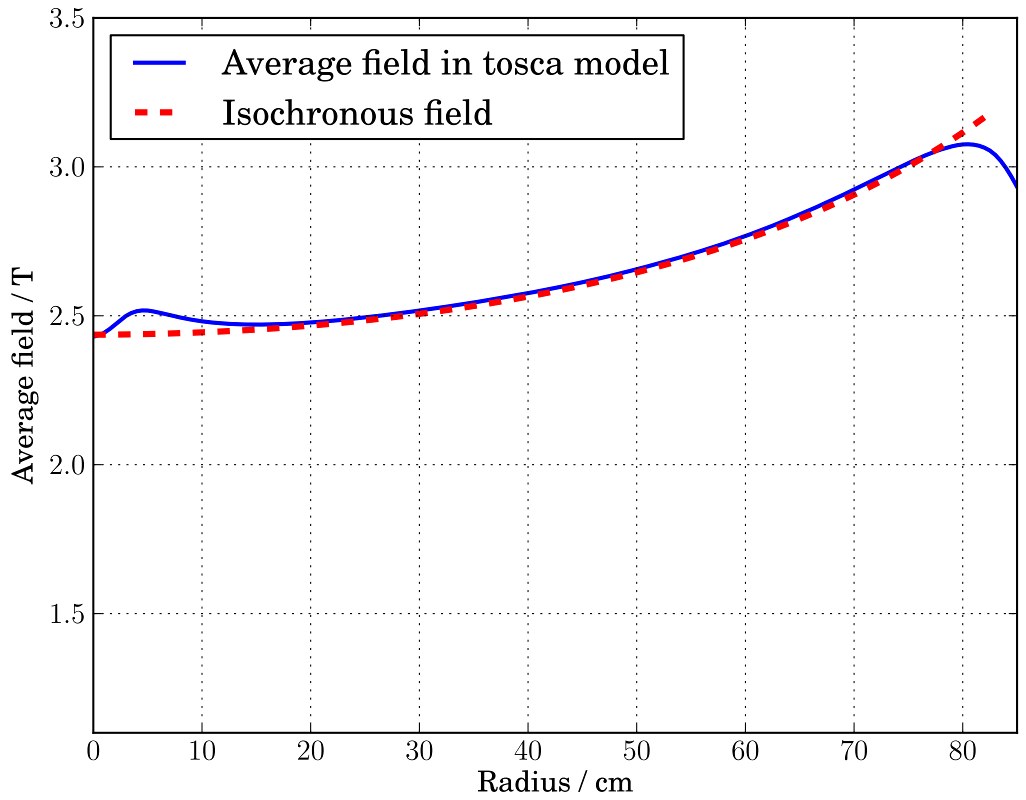
Isochronous field shaping / trimming

Magnet poles saturated in high magnetic field, pole shimming is not so efficient

Two steps:

1) For meeting initial isochronous field condition, the hill pole width is increased from the central region to the pole end, Field error can be limited within 150 Gs.

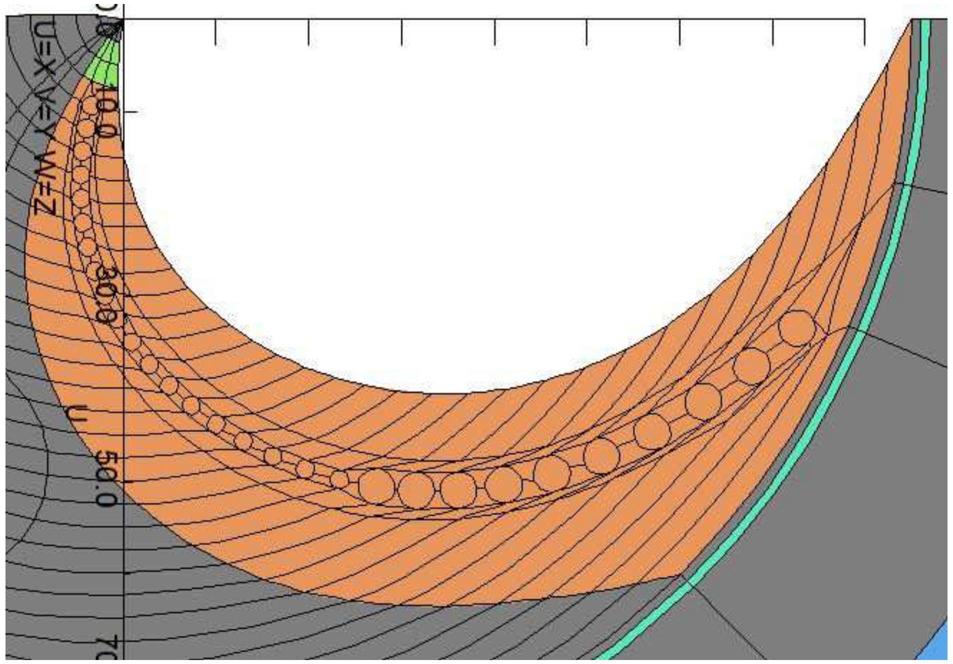


Average field with initial isochronous shaping; iterative process by evaluating tosca models.

Isochronous field shaping / trimming

Two steps:

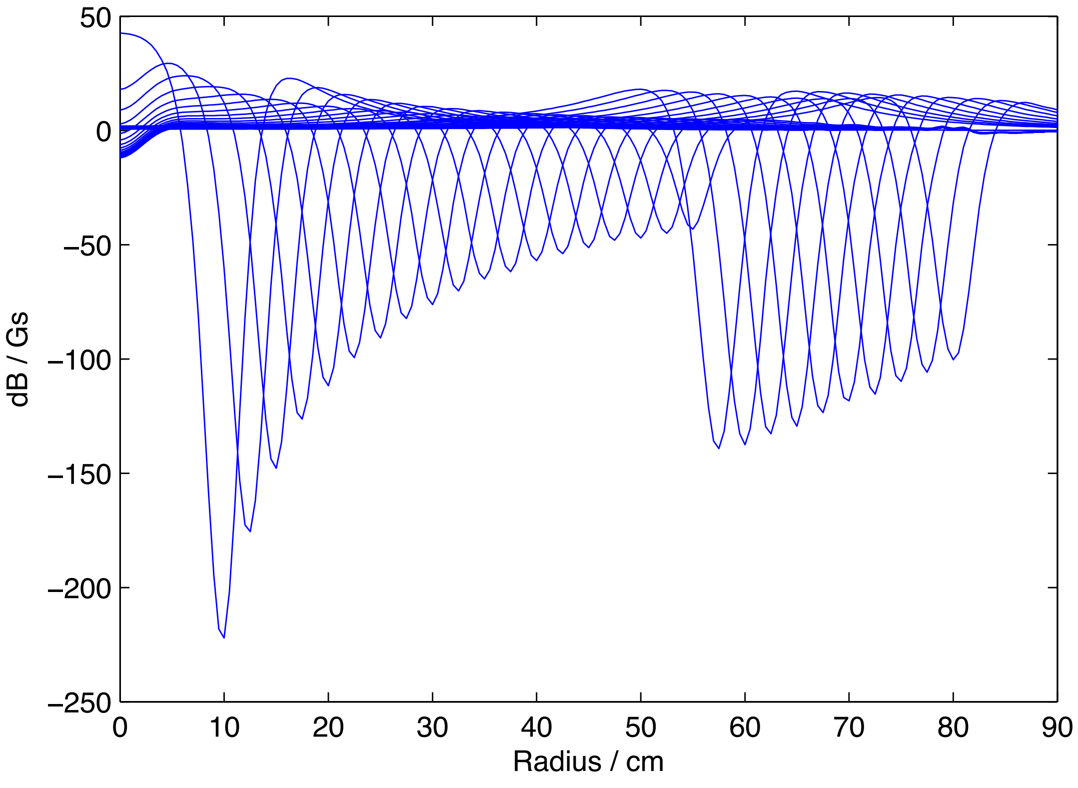
2) Fine shimming by using trim rods.



Combination of trim rods position based on the least square fitting from the correlation matrix:

$$\boldsymbol{y} = \boldsymbol{X} \cdot \boldsymbol{\beta}$$

$$\overline{\boldsymbol{\beta}} = (\boldsymbol{X}^T \cdot \boldsymbol{X})^{-1} \cdot \boldsymbol{X}^T \cdot \boldsymbol{y}_{\text{iso}}.$$



Limitations:

1) Nonlinear relations between rods depth & trimming effect;
2) Technical difficulties for arbitrary depth adjustment
3) Two positions are adopted for each rods, +/-15 degrees total phase slip achieved

Precessional extraction – beam centering by A.E.O

For high efficient resonant extraction, beams need be pre-centered using accelerating E.O.

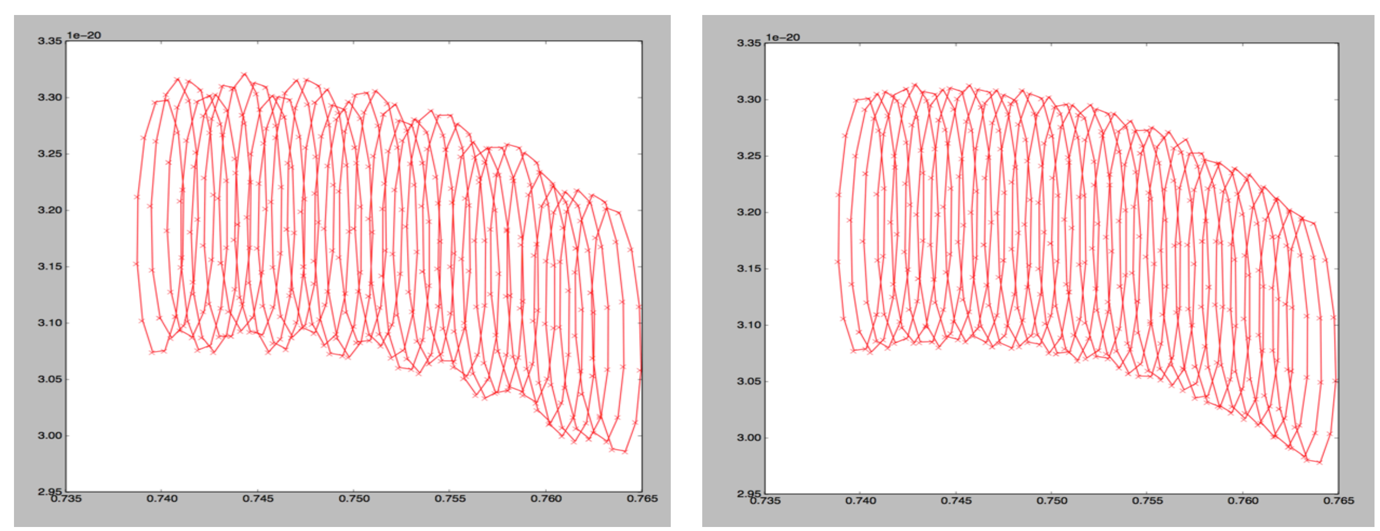
→To remove coherent oscillation effects

→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

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

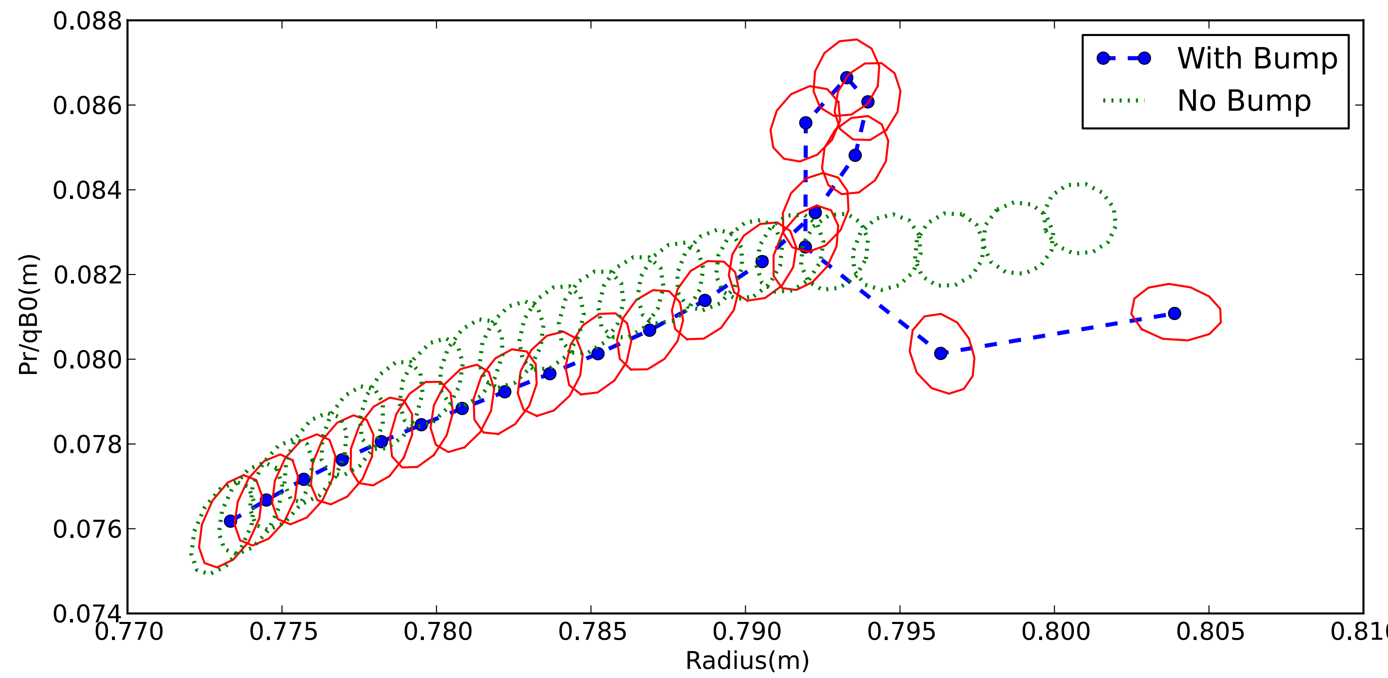
Before resonance crossing $\nu_r = 1$, at θ_0 , a coherent oscillation is created and

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

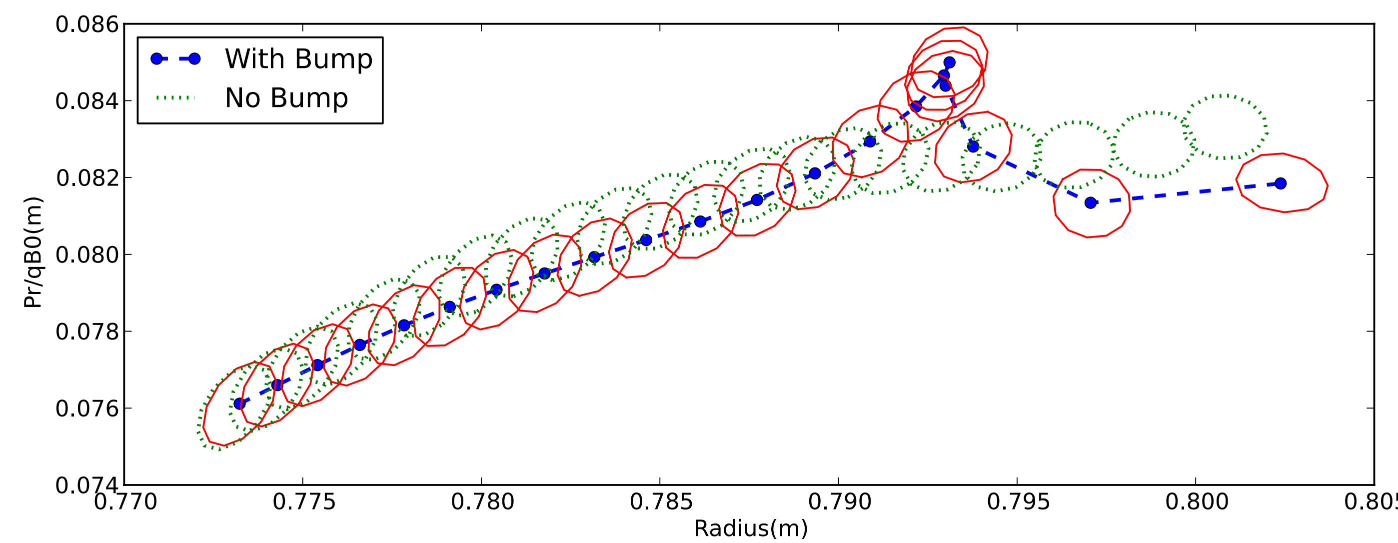
effective turns during coherent oscillation

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

- 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)

Conclusions

- A 250 MeV/ 500nA isochronous superconducting cyclotron for proton therapy was proposed by HUST, and collaborated with CAS-IPP;
- Preliminary design considerations including overall scheme, main magnet, resonant extraction and rf etc. are introduced;
- The central region, the extraction structure (septum, high voltage feed in, deflectors, magnetic channel) are under design progress;
- Considering the target patients for Asia area, 235MeV extraction energy is also a choice.

Thanks for attention!

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