A Superferric Superconducting Scheme Using Spiral FFAG for Carbon Therapy

(i) Motivation
(ii) Parameters of the scheme
(iii) Pole Material
(iv) Preliminary results according to field requirement

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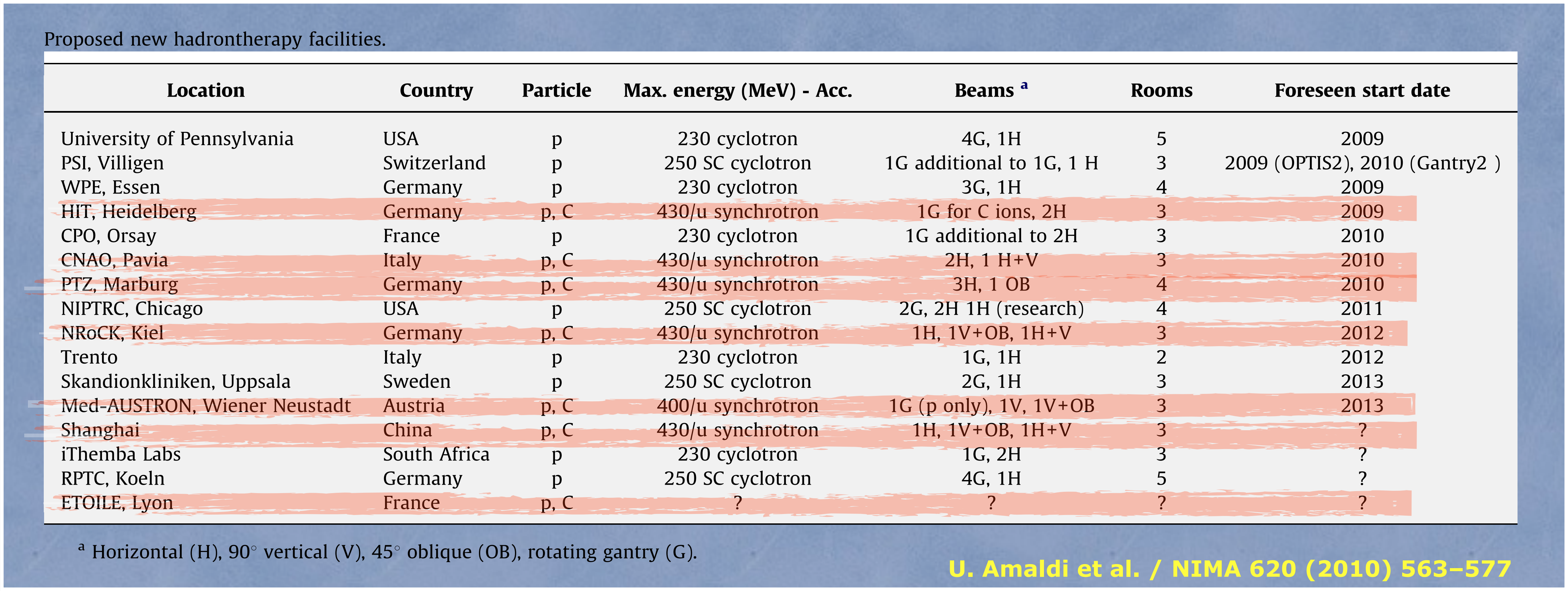
FFAG WORKSHOP 2010, Oct 30, 2010

Motivation: carbon therapy

- Larger biological effect compared with protons/X ray, more efficient against hypoxic and radioresistant tumors
- Carbon requires much more B-rho compared with proton: 25cm depth tissue, 200MeV proton , but 375MeV/u for carbon, factor of magnetic rigidity 2.85
- Advantage of FFAGs for carbon therapy:
  - ✓ Variable energy (vs. cyclotron)
  - ✓ Strong focusing, leads to small beam size (vs. cyclotron)
  - ✓ High repetition pulse beam, suitable for spot scanning (vs. synchrotron)
  - ✓ Simpleness and easy for operation (vs. synchrotron)
  - ✓ Smaller excursion due to high field gradient (vs. cyclotron)

Existing machines & Proposals for Carbon Therapy

- Existing carbon therapy centers: synchrotrons
  - Japan: HIMAC, Hyogo Medical Center, Gunma University
  - Germany: Heidelberg/GSI



Proposed new hadrontherapy facilities.

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	?	?	?	?

[a] Horizontal (H), 90° vertical (V), 45° oblique (OB), rotating gantry (G).

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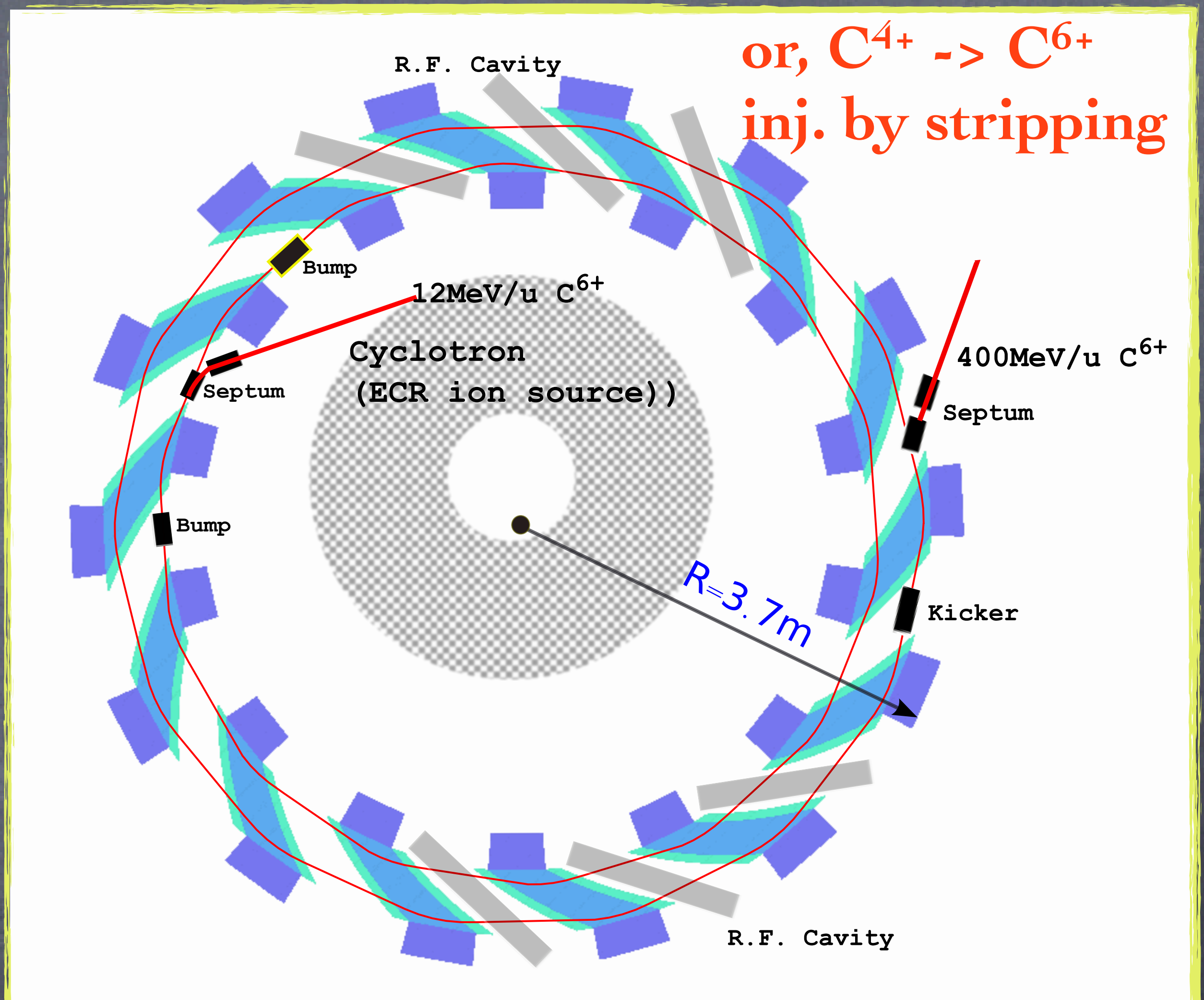
- Non-scaling FFAG:
  - 3-stage NS FFAG rings for H^+/C^{6+} (E. Keil et al.)
  - PAMELA project (T. Yokoi et al.)
  - 2-stage embedded NS rings for C^{6+} (C. Johnstone et al.)
- Scaling FFAG:
  - Normal conducting 3-stage DFD rings (T. Misu, 2004)

Let’s recall the 700MeV spiral ring lattice...

High field spiral C^{6+} FFAG ring using superferric superconducting magnet

Basic parameters

Injector	Cyclotron or Linac (50keV/u ~ 12MeV/u)
Injection energy / $B\rho$	12 MeV/u , 1.0 T.m
Extraction energy / $B\rho$	400MeV/u, 6.36 T.m
Momentum ratio	6.36
field index	6.0
Bz @ R_{ext}	5.0 T
packing factor	0.42
R_{ext}	3.03m
R_{inj}	2.33m
Radius excursion	0.7m
lattice	14 cell, spiral sector
spiral angle	57 deg.
cell tune	Qx=0.2, Qy=0.13



or, C^{4+} -> C^{6+} inj. by stripping

Schematic plan of the carbon therapy machine: (Cyclotron injector + Superconducting spiral FFAG ring)

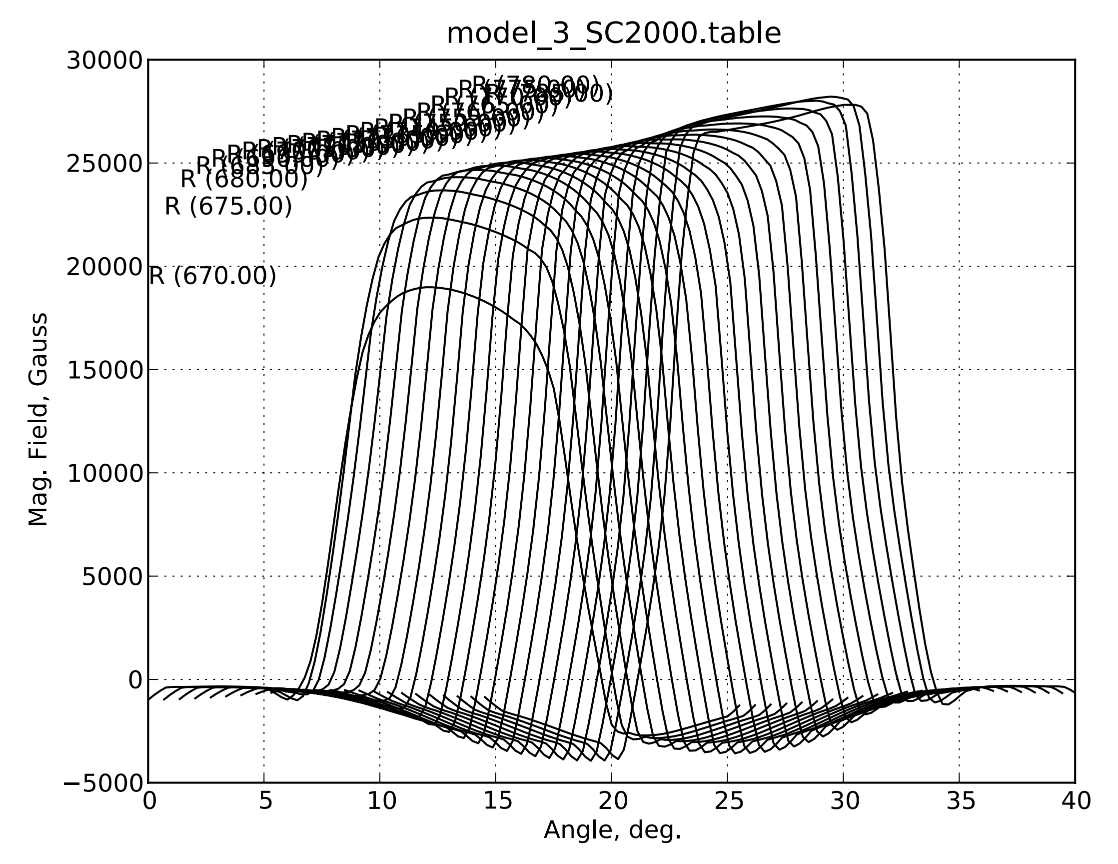
Challenges if not using “cos(θ) multipole combination” superconducting scheme

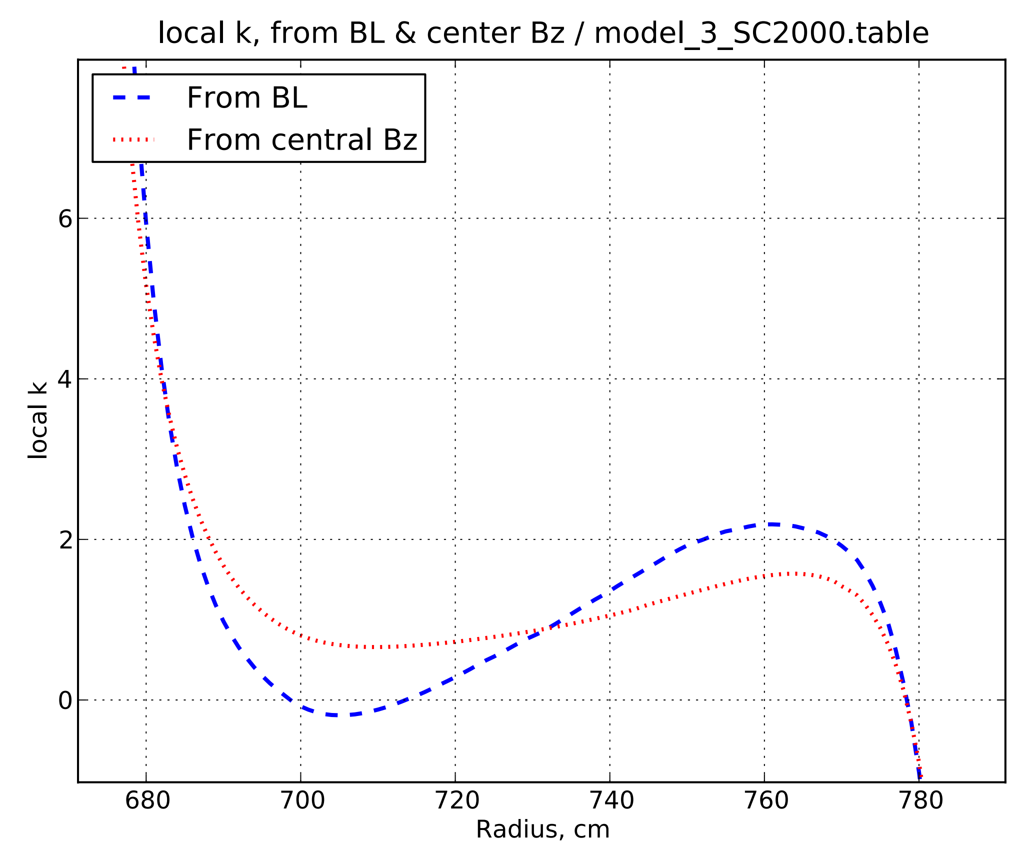
A) High magnetic field about 5T with superferric superconducting scheme

B) High field gradient with k>6.0 using pole shaping

- ➡ Material solutions for the magnet sector pole
  - ➡ Low carbon iron: superconducting cyclotron used, such as ACCEL 250MeV proton / IBA 400MeV carbon machine
    - ➡ Possible for 3T, but..
    - ➡ forget field gradient (k_{max} ~ 2.0)
  - ➡ Higher permeability materials: Holmium, Gadolinium, etc... (MuR>10 at high magnetic field)

Result: low carbon iron





- ➡ The same model of 700MeV spiral sector
- ➡ 320000 A.T

High permeability materials

D. B. Barlow et al. NIMA 313, 311-314

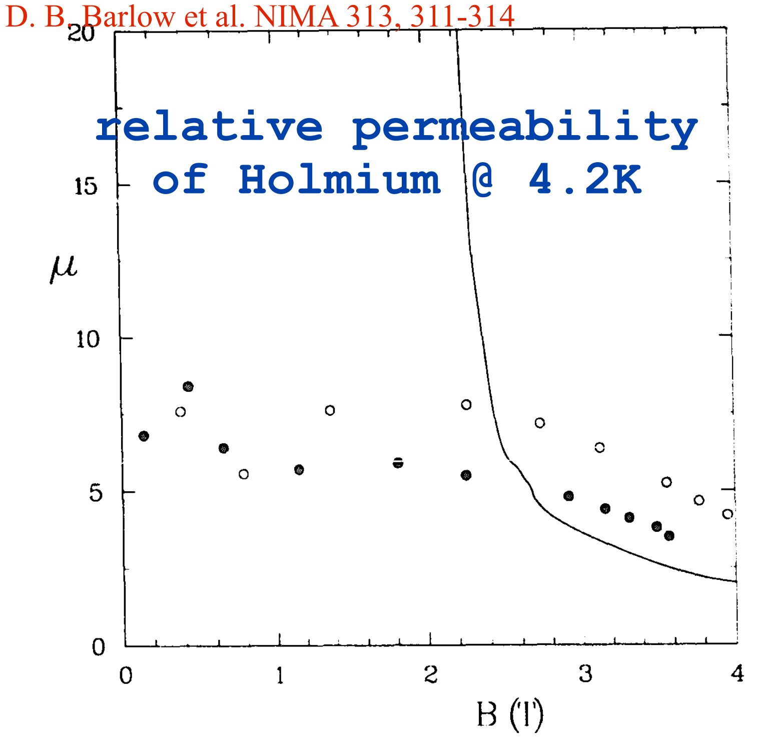


Fig. 3. Measured μ vs B for holmium at 4.2 K from this experiment (solid points) and from Rhodes et al. [3] (open points). The solid curve is for iron.

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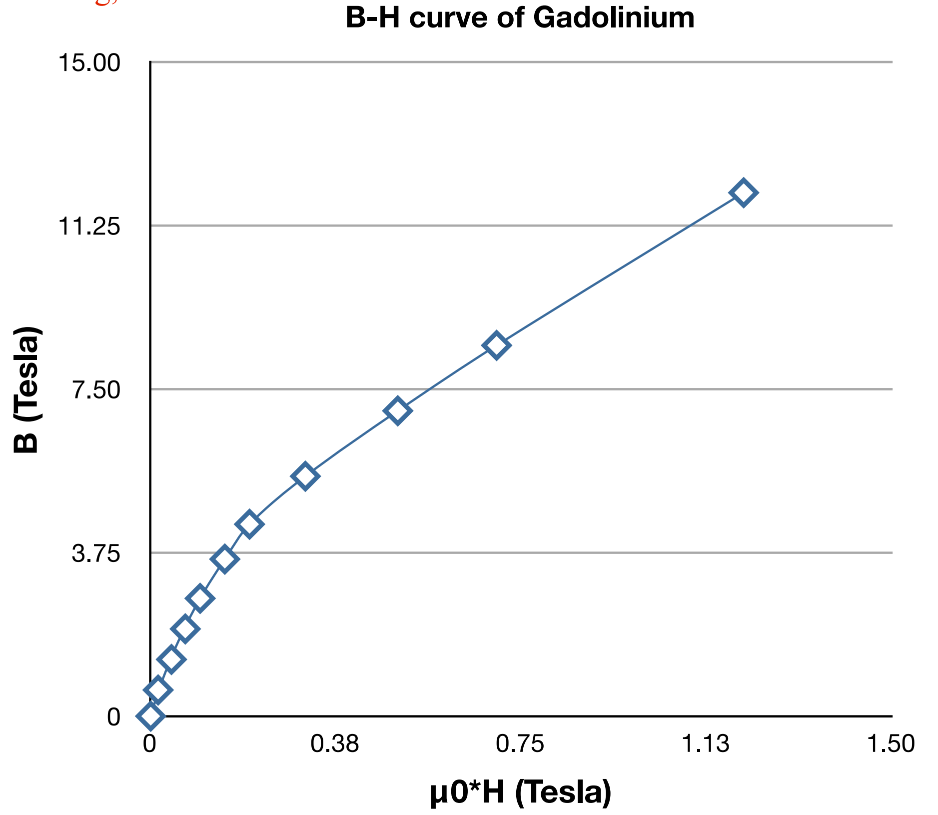
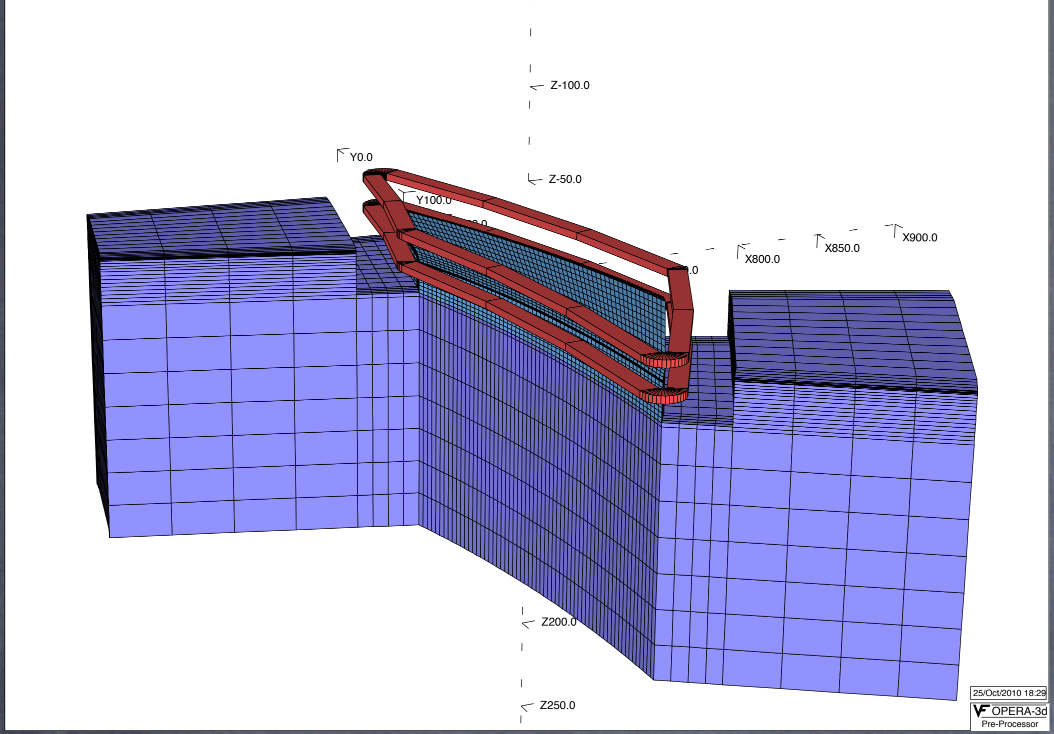
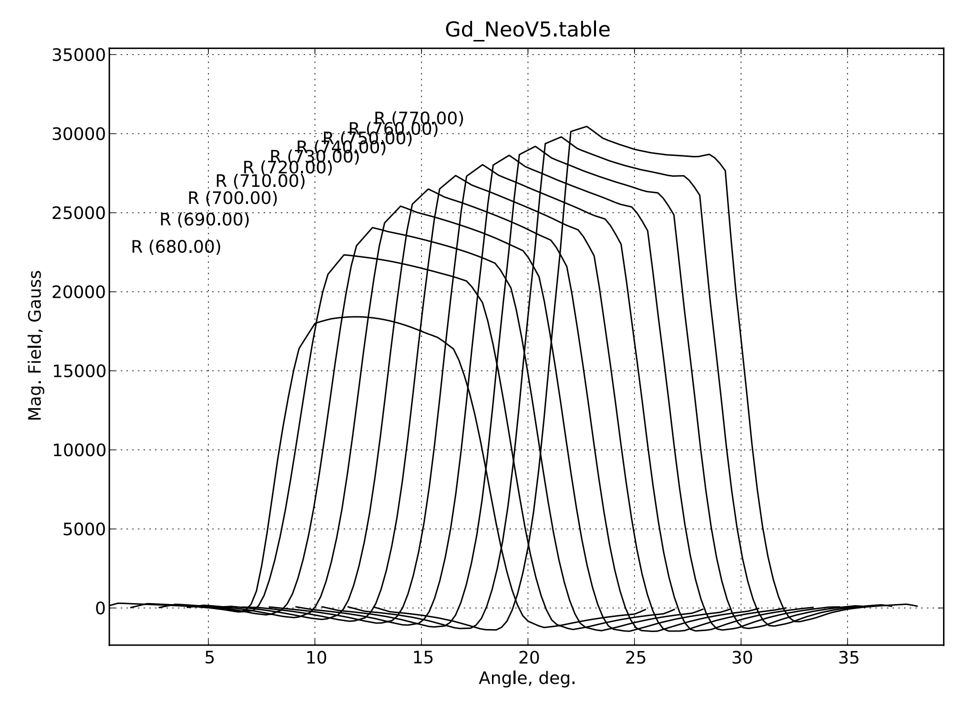


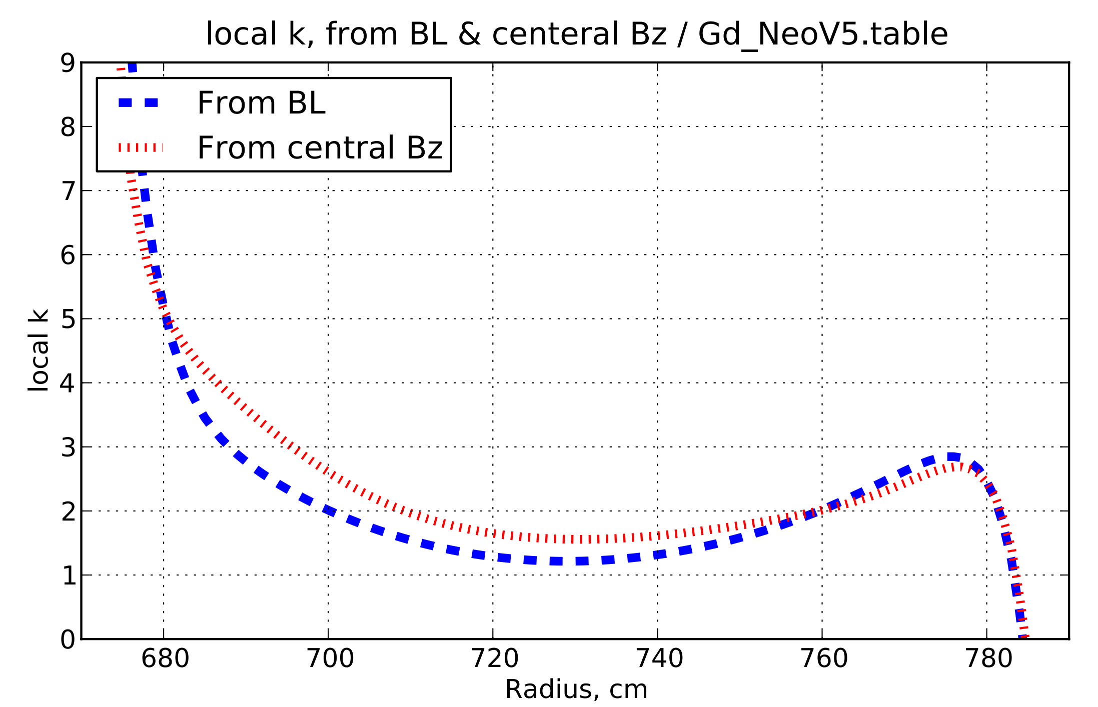
- Features of Holmium and Gadolinium material: almost linear relative permeability
  - At normal field B<1.8T, $\mu_r \ll \mu_{r,iron}$
  - At high fields B>2T, $\mu_{r,Holmium} \approx 7$; $\mu_{r,Gd} \approx 10$~30 ($\mu_{r,Gd} = 17$ @ 5T), much larger than saturated $\mu_{r,iron}$
  - Curie temperature: Holmium :20K; Gadolinium: 290K
  - Saturated field > 10T

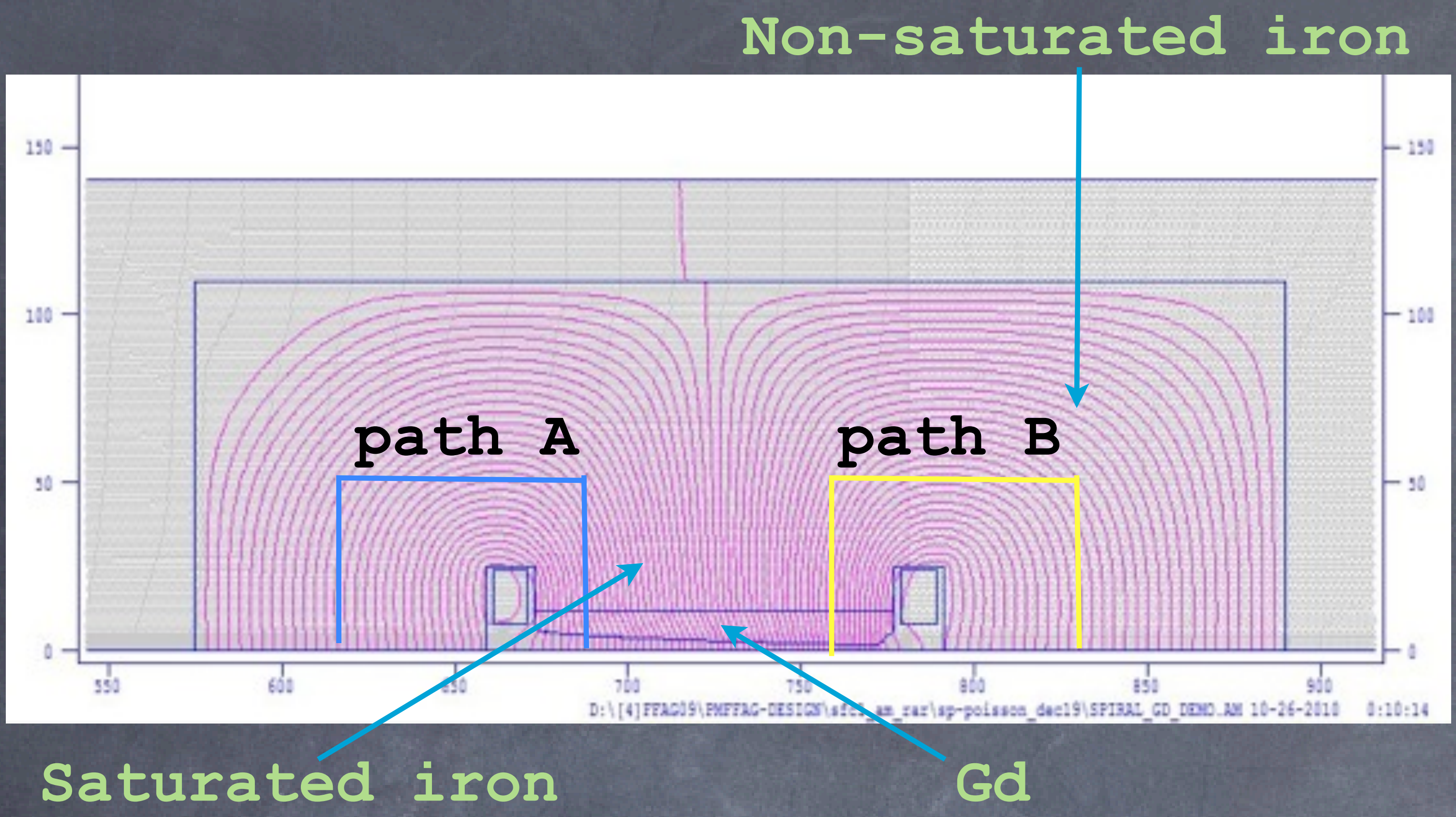
But.. not so easy to achieve high magnetic field with high field index

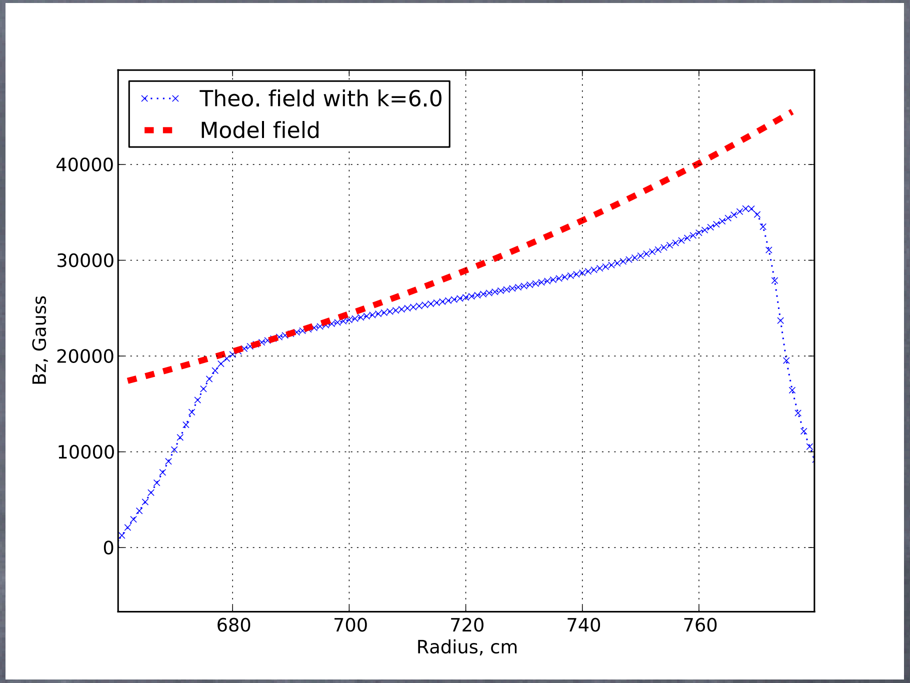


- ➡ Gd pole layer + Iron yoke
- ➡ 160000 A.T









For normal magnet, for $\mu_r^{iron} \gg 1 \Longrightarrow B_{z,a}\cdot g_a = B_{z,b}\cdot g_b$

$$NI = \oint_{pathA} H\cdot dl = \frac{B_{z,a}\cdot g_a}{\mu_0} + \frac{B_{yoke}}{\mu_r^{iron}\mu_0}\cdot l_{yoke}$$

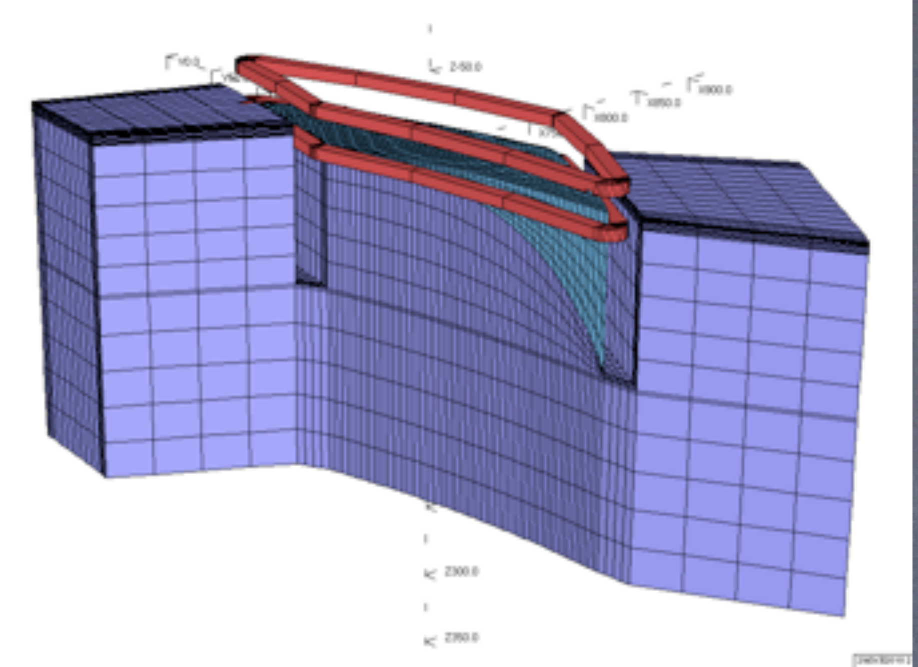
$$NI = \oint_{pathB} H\cdot dl = \frac{B_{z,b}\cdot g_b}{\mu_0} + \frac{B_{yoke}}{\mu_r^{iron}\mu_0}\cdot l_{yoke}$$

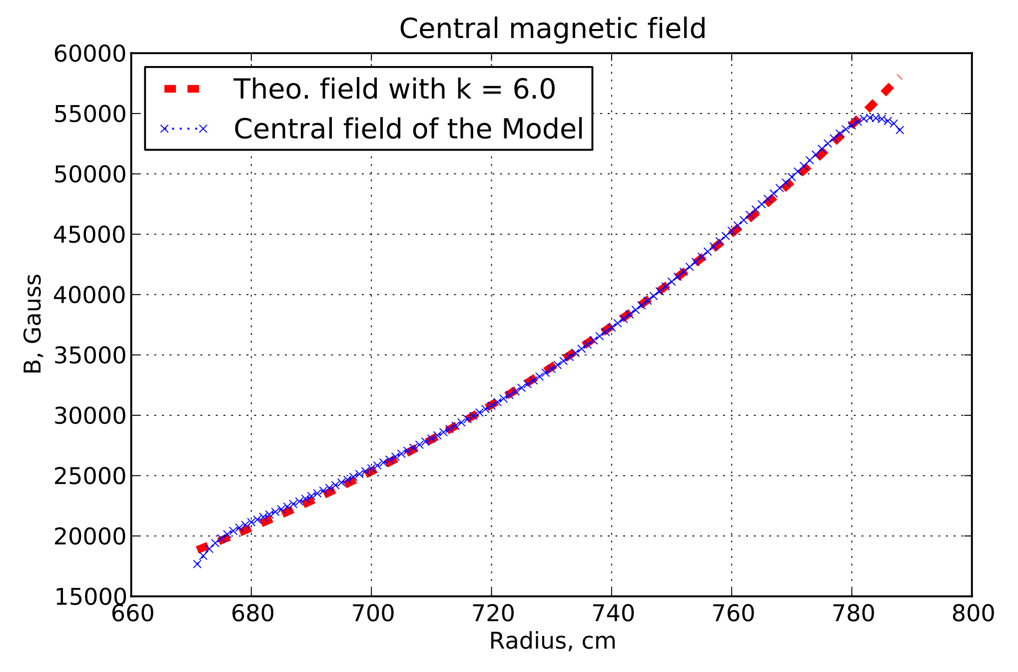
to increase $B_{z,b}$,,
$l_{1,b}\uparrow$, $l_{2,b}\downarrow$ to balance the reluctance at each loop.

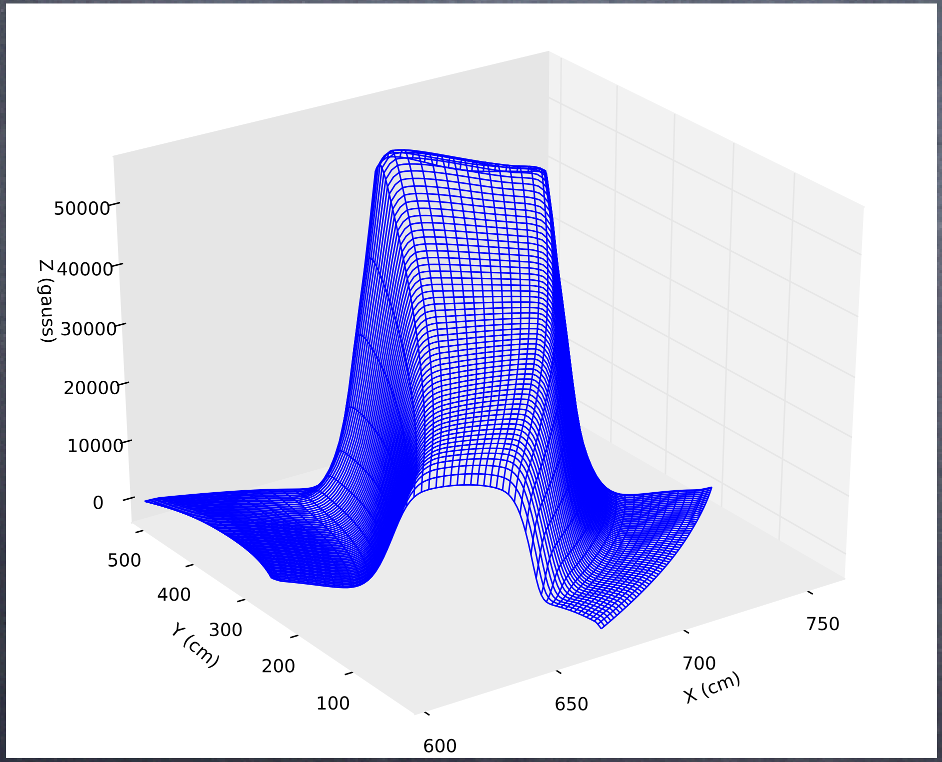
But, for Gd+Iron pole case, $\mu_r^{Gd} \approx 20$, $\mu_r^{Saturated-iron} \approx 2$

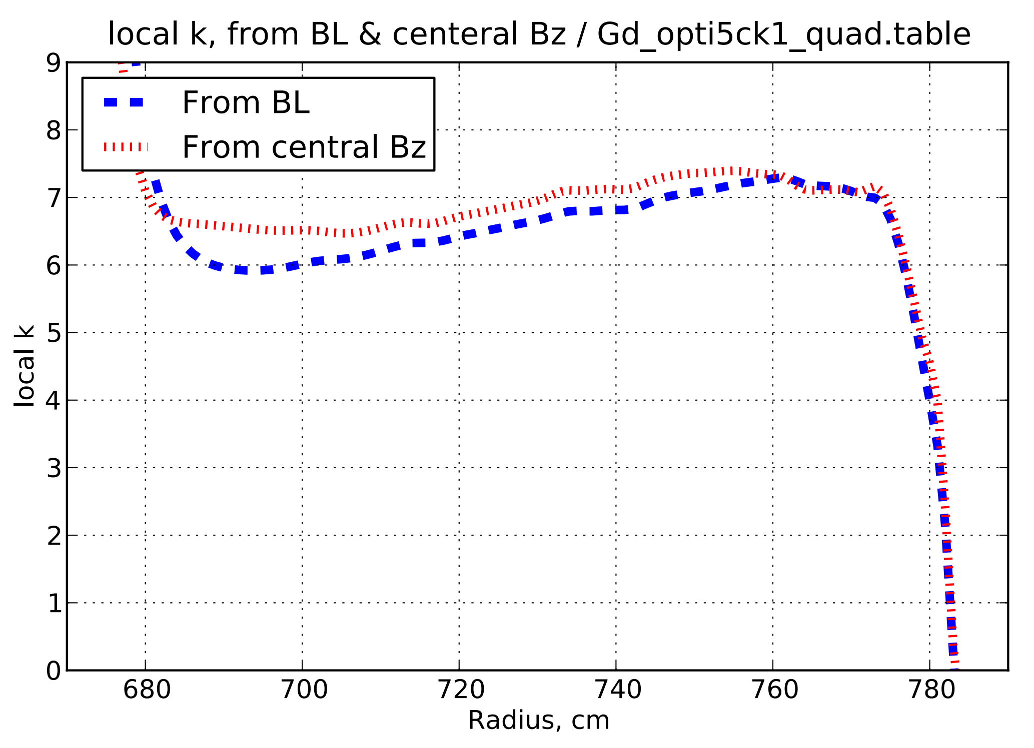
$$\begin{array}{lcccl}
NI = \oint_{pathA} H\cdot dl = & \frac{B_{z,a}\cdot g_a}{\mu_0} & + & \frac{B_{Gd,a}\cdot l_{1,a}}{\mu_r^{Gd}\cdot\mu_0} + \frac{B_{iron,a}\cdot l_{2,a}}{\mu_r^{Saturate-iron}\cdot\mu_0} & + H_{yoke}\cdot l_{yoke} \\
 & \parallel & & \parallel & \\
NI = \oint_{pathB} H\cdot dl = & \frac{B_{z,b}\cdot g_b}{\mu_0} & + & \frac{B_{Gd,b}\cdot l_{1,b}}{\mu_r^{Gd}\cdot\mu_0} + \frac{B_{iron,b}\cdot l_{2,b}}{\mu_r^{Saturate-iron}\cdot\mu_0} & + H_{yoke}\cdot l_{yoke}
\end{array}$$

Optimized model with variable Gd layer height





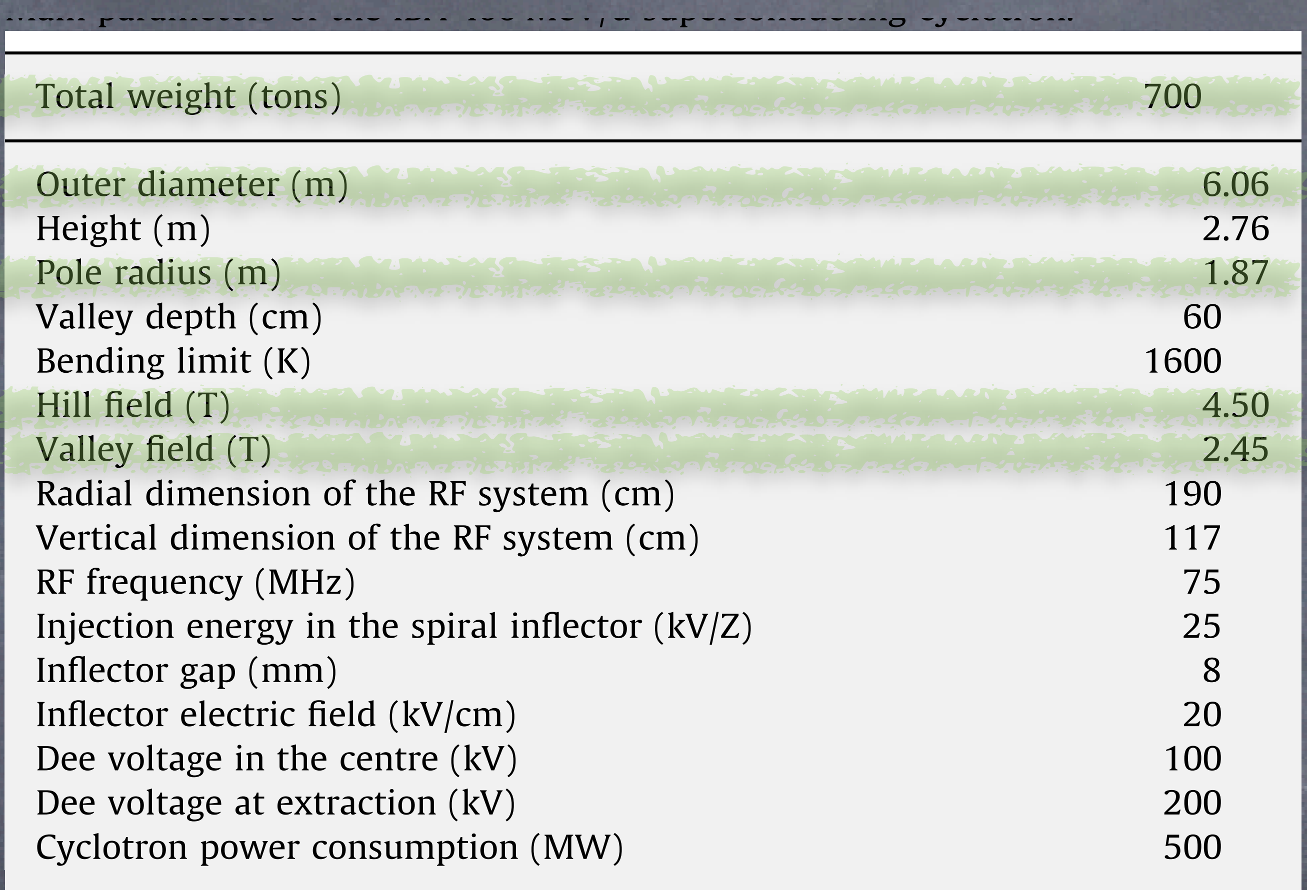




It’s possible for Bmax=5T @ k=6.0 !

Discussion: compared with SC-cyclotron scheme

Main parameters of IBA 400MeV/u carbon cyclotron



Main parameters of the IBA 400 MeV/u superconducting cyclotron.

Total weight (tons)	700
Outer diameter (m)	6.06
Height (m)	2.76
Pole radius (m)	1.87
Valley depth (cm)	60
Bending limit (K)	1600
Hill field (T)	4.50
Valley field (T)	2.45
Radial dimension of the RF system (cm)	190
Vertical dimension of the RF system (cm)	117
RF frequency (MHz)	75
Injection energy in the spiral inflector (kV/Z)	25
Inflector gap (mm)	8
Inflector electric field (kV/cm)	20
Dee voltage in the centre (kV)	100
Dee voltage at extraction (kV)	200
Cyclotron power consumption (MW)	500

- Total size of this scheme is very small and comparable to the SC cyclotron (less weight duo to small pole excursion)
- pf ~ 0.4, which provides more space for rf, inj / ext and instrumentations
- Energy change for FFAG only 1ms (possible for 3d spot scanning); SC cyclotron requires energy selection system for variable energy (100ms), difficult for spot scanning.

Summary

- A very rough idea for compact superconducting scaling ffag ring
- Feasibility study for high magnetic field combing with high field index
- Simpleness compared with combined function superconducting scheme

Thank you for

your attention!