Physical issues at size reduction of cyclotrons

ECPM 2012 educational session

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Introduction

We consider the physical aspect of size reduction in cyclotrons, but keep in mind that the main driver is not the size but the cost of an installation

Especially proton therapy systems are currently very expensive and a substantial cost reduction of a full installation is needed in order to make this application available to a broader public.

Also keep in mind that for proton therapy the cost of the accelerator is not the largest part of the full cost (maybe about 20 %) => also size and cost reduction of the beam-delivery system and the building is required

Furthermore, besides costs there are other probably equally important requirements such as: reliability, availability, simplicity,….etc

What types of cyclotrons ?

For medical and other applications we need to consider compact superconducting cyclotrons (CSC), with:

i. High magnetic field

ii. Full acceleration in one stage (no injectors)

iii. Not connected to helium liquefier (use of cryo-coolers)

Compact means that the poles, the upper yokes and the return yoke are connected in one unified assembly. Three types of cyclotrons are possible:

i. Isochronous AVF-cyclotron

ii. Synchro-cyclotron

iii. Classical cyclotron?

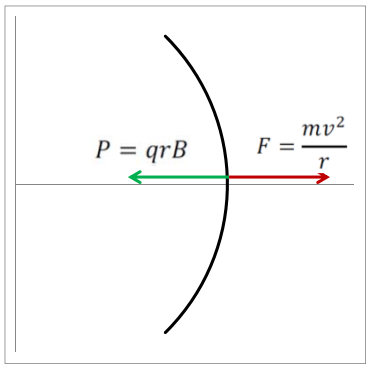
Comparison of different types of cyclotrons

SIZE REDUCTION OF CYCLOTRONS : SOME COMPARISON OF DIFFERENT TYPES OF CYCLOTRONS			
	isochronous	synchro-cyclotron	classical cyclotron
magnetic field	AVF-flutter	rotational-symmetric [1])	rotational symmetric
transverse focusing	alternating "strong"	weak => negative field-index	weak => negative field-index
longitudinal focusing	meta-stable	stable within separatrix	unstable
revolution frequency	(almost) constant	decreasing	decreasing
RF frequency and voltage	constant	periodically modulated	constant
dee-voltage	high	low because of small df/dt	very high
multi-pactor	often no-problem	to be suppressed by bias-voltage	no problem
beam injection	continuous	limited time window for capture	continuous
ion source	both internal and external	internal ion source only	both internal and external
central region size	compact if B is high	very compact (low dee-voltage)	compact if B is high
beam extraction	different ways	regenerative extraction	different ways
extraction efficiency	normally high	probably not so high	normally high
operation	CW	pulsed	CW
beam energy	medium (limited by focusing)	high and "unlimited" [2)]	low due to phase-slip
beam intensity	high	low	high
candidate for size-reduction	**yes for low to medium energies**	**yes for high energies**	**maybe for low energies**
1) synchro-cyclotron with flutter is also possible			
2) Extract before Walkinshaw resonance			

Choice of cyclotron depending on application

SIZE REDUCTION OF CYCLOTRONS : CHOICE OF CYCLOTRON TYPE DEPENDING ON APPLICATION					
application	required energy	required current	machine type		
			AVF-isochronous	synchro-cyclotron	classical cyclotron
Radio-isotopes	medium (30-70 MeV)	high (0.1-1 mA)	yes	no	no
PET	low (5 to 20 MeV)	high (0.1-1 mA)	yes	no	yes [1)]
proton-therapy	high (230-250 MeV)	low (10-300 nA)	yes	yes	no
carbon-therapy	high (400 MeV/A)	low (10-300 nA)	yes	no [2)]	no
dangerous materials detection	high (250-1000 MeV)	high (> 1 mA)	yes [3)]	no	no
1) It has to be seen what level of dee-voltage is needed to remain with an acceptable level of integrated phase slip					
2) Axial injection in a high -field synchrocyclotron seems impossible because of low dee-voltage; first orbit hits the inflector housing					
3) Flutter will be the limiting factor					

Size reduction => increase the magnetic field

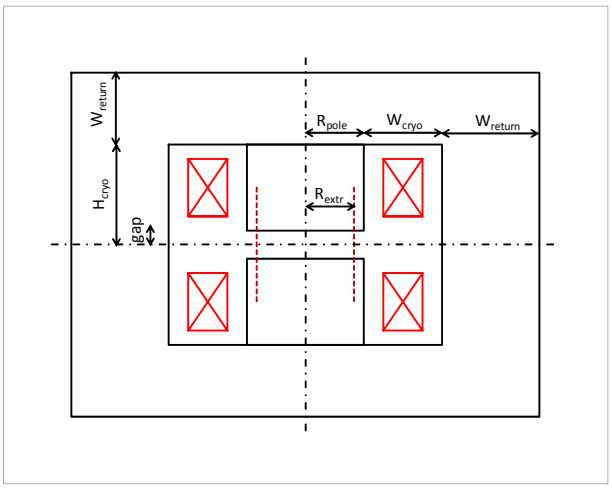


For a given extraction energy: the extraction radius is inversely proportional to the magnetic field

$$P = qrB$$

$$T_f \cong K r_f^2 B_f^2$$

Possibilities for reducing sizes



$R_{extr} \infty 1/B$

Pole radius

- $R_{pole} \cong R_{extr}$+ gap =>
- useless to reduce R_{extr} too much

Gap

- Minimum needed for RF about 8 cm

Cryostat width and height =>

- minimum isolation needed (3-5 cm)
- radially => metallic former needed to compensate hoop-stress
- thickness of cryostat walls
- In case of cold coil + cold iron => all three are not needed

Return yoke thickness =>

- see next slide

Generated magnetic flux

Generated magnetic flux (very roughly) equal to

$$\Phi \cong \pi R_{pole}^2 B$$

Maybe we have to use an effective radius $R_{eff} > R_{pole}$, but in any case

$$R_{\text{eff}} \infty \frac{1}{B} \Rightarrow \Phi \infty \frac{1}{B}$$

At the same time the inner radius of the yoke Ryoke ∞ 1/B and so

$$W_{\text{return}} \infty B^0 = \text{constant}$$

On the width of the return yoke not so much can be gained

Reducing thickness of the return yoke

Limitations arise from the following considerations:

i. When the yoke iron becomes more and more saturated, the stray field around the cyclotron starts to increase quickly (a good rule could be to allow a maximum field on the yoke surface of about 2 Tesla)

ii. External equipment with moving parts such as cryo-coolers or rotco (for synchro-cyclotron) need to be shielded with additional iron

iii. The yoke starts to behave like air for all additional magnetic flux generated by external systems or asymmetries

   i. This easily may generate median plane errors which need to be evaluated and compensated

   ii. This may generate considerable offset forces on the cold-mass which may have implications on the design of the tierods

Some rough scaling laws and challenges

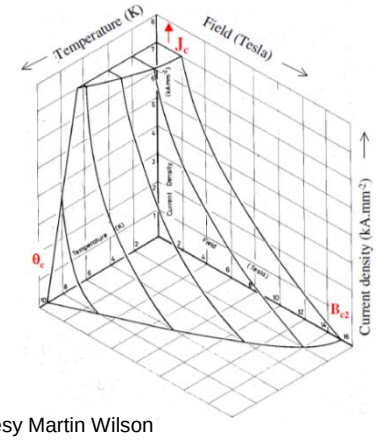
Do not take these laws at an absolute truth but look at the trend

SIZE REDUCTION OF CYCLOTRONS : ROUGH SCALING LAWS								
feature considered	Magnetic field dependence						good/bad	
	$\cong 1/B^3$	$\cong 1/B^2$	$\cong 1/B$	$\cong B^0$	$\cong B^1$	$\cong B^2$		
extraction radius			X				fine	
main coil current					X		no problem	
magnetic flux			X				fine	
return yoke thickness				X			fine	
cyclotron radius			X				fine	
cyclotron height				X			fine	
cyclotron volume		X					fine	
cyclotron weight		X					fine	
coil current density					X		challenge	cryogenic stability
maximum field on the coil					X			
stored energy density						X	challenge	quench protection
total stored energy				X?				
Hoop stress in coil					X		challenge	mechanical forces
Attractive force between coils						X		
turn-separation (extraction)			X				challenge	injection / extraction
central region size			X					
magnetic flutter		X					challenge	beam dynamics
median plane error due to external iron					X?			

Critical surface of superconductors

NbTi

critical surface for Niobium Titanium

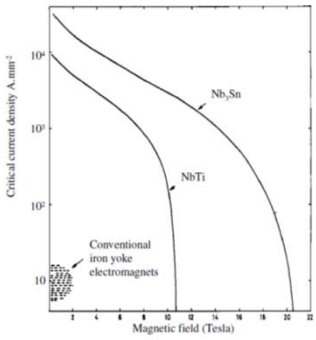


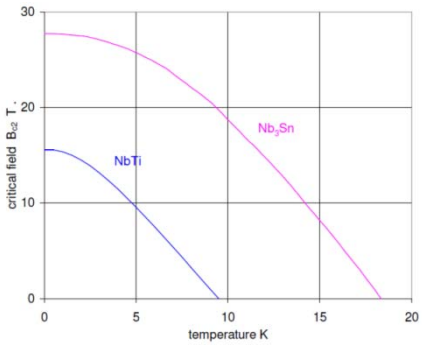
Courtesy Martin Wilson

- Almost all accelerator magnets used up to now are based on NbTi
- The **critical surface** is the boundary between the super-conducting phase and normal phase in the 3D-space of
  - Magnetic field
  - Temperature
  - Current density
- Below this surface the material is superconducting
- The **upper critical field** B_{c2} is defined (at θ=0 and j=0)
- Similarly the **upper critical temperature** θ_c is defined
- Both quantities depend only on the material composition
- The **critical current density** $J_c(B,\theta)$ depends on the material processing

The critical line

NbTi vs Nb_3Sn





- The critical surface represented at the liquid helium temperature of 4.2 K is a curve of critical current versus magnetic field
- Niobium tin Nb_3Sn has a much higher performance in terms of critical current, critical field and critical temperature as compared to NbTi
- Nb_3Sn is a brittle material which requires special care

Courtesy Martin Wilson

Choice of superconductor

NbTi

- Currently used in all existing superconducting cyclotrons
- Also used in the new IBA S2C2
- Not a logical candidate for further substantial reduction of cyclotron size

Nb_3Sn

- Used in the Monarch of Still River (Mevion)
- About twice higher critical properties
- Brittle material

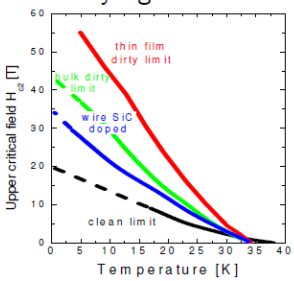
.....

Still River Monarch:
9 Tesla synchrocyclotron
Nb_3Sn superconductor

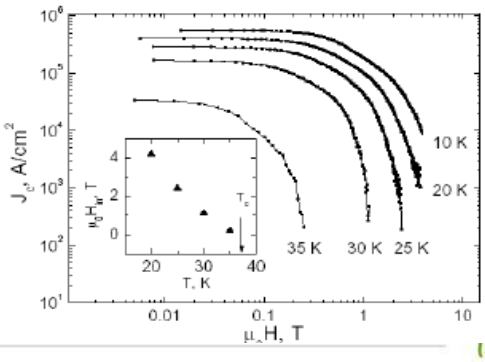
Future superconductor maybe …. MgB_2

- Medium-temperature superconductor
- Moderately high critical temperature of 39 K
- High B_c of up to 60 Tesla at low temperatures
- Large critical current densities
- Good mechanical properties
- Low cost of raw MgB_2 material

Potentially high critical field



Larger than 60 Tesla at low T

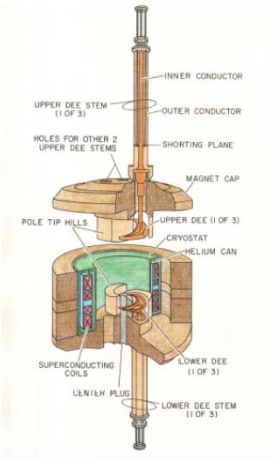


Existing superconducting cyclotrons

Research applications

- Chalk River K=520 => first one developed
- NSCL -MSU K500 => first accelerated beam
  - Milan contribution
  - TEXAS A&M
- NSCL -MSU K1200
- AGOR, Orsay ->Groningen, K=600, 3-fold, multiparticle
- Catania-Italy, K=800, multiparticle, 3-fold
- RIKEN, K=2500 SRC (Superconducting Ring Cyclotron)
- VECC Colcatta, K=500, heavy ions,

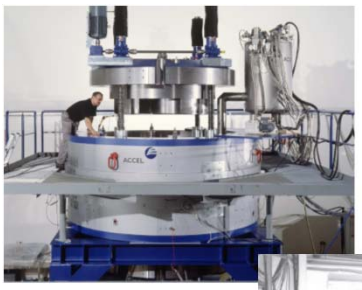
NSCL K500



Existing superconducting cyclotrons

Medical applications

- K100 – Detroit Harper Hospital, 15 uA 50 MeV D, rotating ring system, <B>=4.5 T
  - First superconducting cyclotron for medicine
  - Constructed by NSCL-MSU
  - Neutron therapy for cancer treatment
  - Mounted on a gantry and rotates around the patient
- OSCAR, H^- 12 MeV, R_{extr}=220 mm, 50 uA, <B>=2.36T, 4 tons, D=1.4 m, H=1.9 m, 3-fold,
  - Isotope production
- ACCEL, K=250
  - Proton-therapy applications



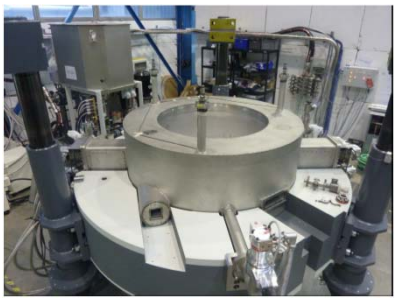
Accel K250

Oscar 12 MeV

A new step: superconducting synchrocyclotrons

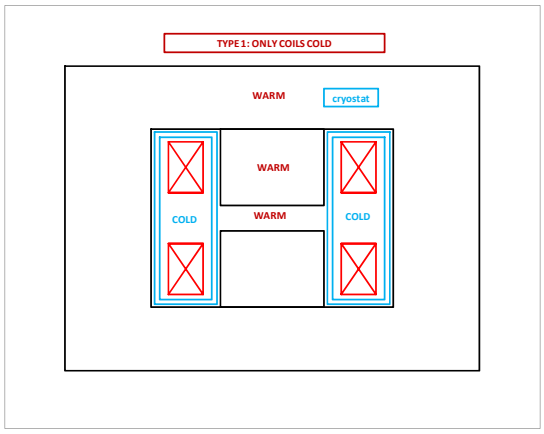
New developments

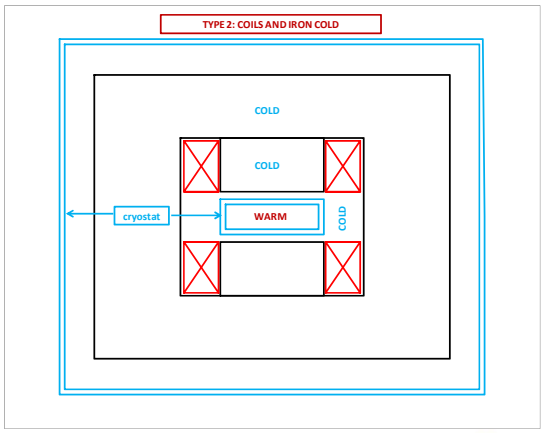
The IBA S2C2 in the assembly hall



- MEVION Medical Systems (Still River), first super-conducting synchrocyclotron, p 250 MeV, B=9 Tesla
  - TriNiobium Tin (Nb3Sn) conductor
  - Diameter 1.8 m; mounted on a gantry
  - First installation in progress in St-Louis, Missouri
  - The MEVION S250 Proton Therapy System has not yet been cleared by the USFDA for clinical use.
- IBA-AIMA collaboration, S2C2 (SuperConducting SynchroCyclotron)
  - Protontherapy: 230-250 MeV
  - B=5.6 Tesla; NbTi
  - Several posters and oral presentations at this conference

Where to apply cryogenics

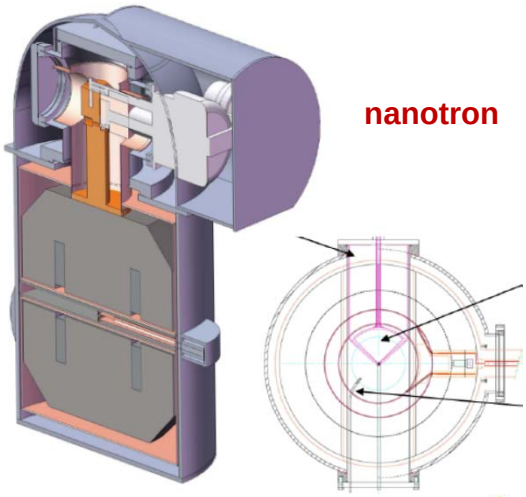




Comparison of both types

Ionetix - nanotron

application of cryogenic cooling		
	type 1	type 2
magnet coil	cold	cold
magnet iron	warm	cold
cryostat	simple	more complex
tierods	on coils	on cyclotron
access to pole for shimming	good	difficult
size of coil space	large	small
coil former	required	magnet iron
pole gap	smaller	larger
cyclotron diameter	larger	smaller
cyclotron height	larger	smaller



Courtesy Tim Antaya

Acceleration of H-minus ions in CSC

- Main advantage => easy extraction with a stripping foil => interesting for PET
- H^- is very unstable => binding energy of 2nd electron only 0.75 eV
- The H-minus beam may get lost during acceleration in a high magnetic field, because of magnetic stripping
- Half-life τ of an H^- in magnetic field from Stinson et.al., NIM 74 (1969) 333-341

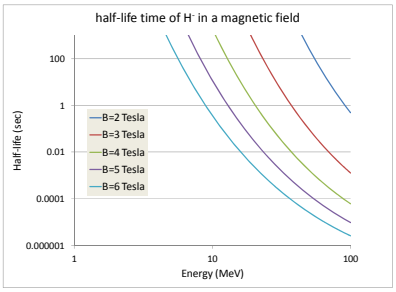
$$\tau(E) = \frac{A}{E}\exp\left(\frac{B}{E}\right)$$

E => equivalent electric field MV/cm

$E = vB$ in a co-moving Lorentz frame

A=7.96 10^{-14} MV sec/cm

B=42.56 MV/cm



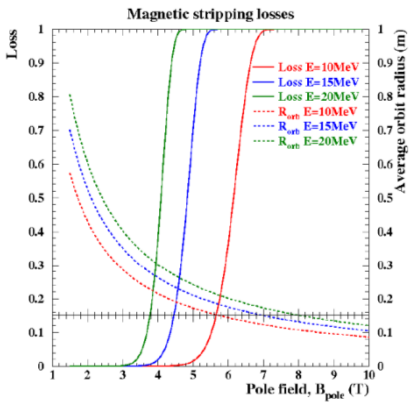
H^- losses in high-field PET cyclotrons

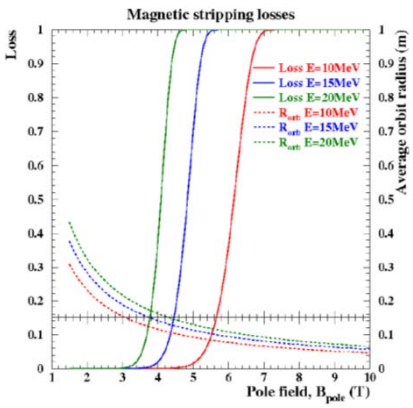
Due to magnetic stripping

AVF cyclotron
flutter=1.5 T

ΔE=80 keV/turn

Classical cyclotron
no flutter





Minimum size of PET H- cyclotrons

Allowing 15 % magnetic stripping losses

15 % seems reasonable for a PET cyclotron keeping in mind that total loss levels due to vacuum are often 30-40%

Minimum size of superconducting PET H^- cyclotron					
Allowing 15 % stripping losses					
cyclotron type		AVF		classical	
E	B_{pole}	R_{extr}	B_{ave}	R_{extr}	B_{ave}
MeV	Tesla	cm	Tesla	cm	Tesla
10	5.7	15	4.9	8	5.7
15	4.5	23	3.7	12.5	4.5
20	3.8	32	3	17.5	3.8

- Results depend strongly on reliability of half-life data for stripping
- It is probably possible to calculate the stripping probability H^- moving in a magnetic field (for verification)
- Numerically solve Schrodinger equation for 2 body system including the following interactions:
  - Spherical potential well due to nucleus
  - Coulomb interaction between two electrons
  - Equivalent electric field in co-moving frame
- Is there a candidate?

The problem of vertical focusing

Decrease of flutter when average field is increasing

Vertical betatron frequency in an AVF cyclotron

$$\upsilon_z^2 = -k + F(1 + 2\tan^2(\xi))$$

$$k = \frac{r}{B}\frac{dB}{dr} = \text{field index}$$

F=flutter

ξ = pole spiraling

Note that this is an approximation
There is also a dependency on radial gradients of the flutter. See: Hagedoorn and Verster, NIM **18,19** (1962) 201-228

For an isochronous cyclotron:

$$B = B(r) = B_0\gamma$$

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

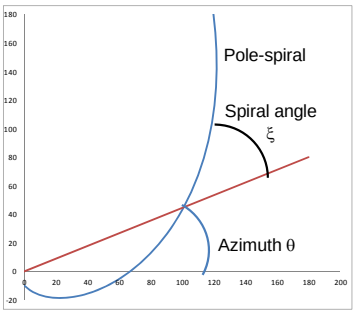
i. Two limiting factors: increasing energy => *k* increases
ii. increasing B-field => flutter *F* decreases

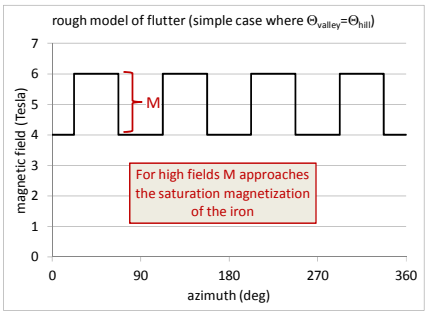
A rough model for the flutter

Definition of spiral angle

A rough model for flutter

Definition of spiral angle





$$F = \frac{\langle B^2\rangle - \langle B\rangle^2}{\langle B\rangle^2}$$

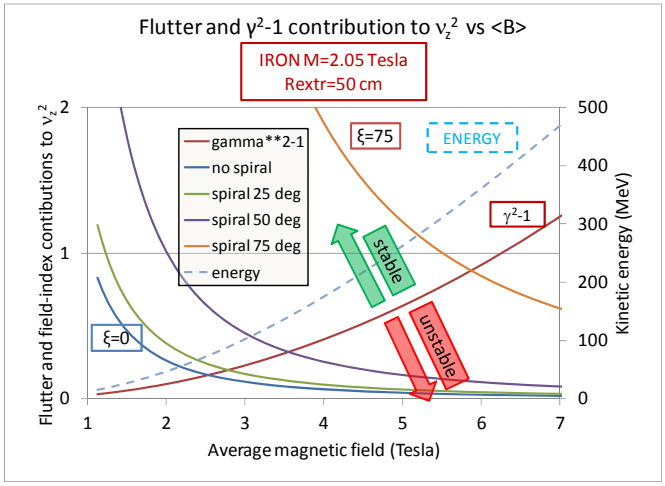
$$B = \langle B\rangle \pm \frac{M}{2}$$

$$\langle B^2\rangle = \langle B\rangle^2 + \frac{M^2}{4}$$

$$F_{max} = \frac{1}{4}\frac{M^2}{\langle B\rangle^2}$$

Isochronous focusing limit for iron poles

AVF cyclotron with R_{extr}=50 cm



Remarks:

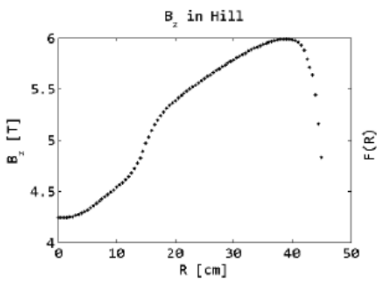
- $\Theta_{val}=\Theta_{hill}$ in this example
- Actual design always has to be verified by a Tosca model and orbit tracking
- There can be other important limits such as structural resonances
  - $2\nu_r$=3 or 4
  - $3\nu_r$=4 etc.

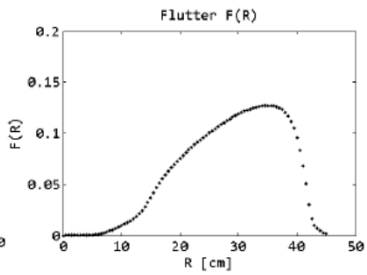
Can we use stronger magnetic material than iron

Holmium or Gadolinium

Holmium => rare earth metal with strongest magnetic dipole of all elements

- Proposed by Tim Antaya for the K=250 megatron from MIT
- M_{sat}=3.8 Tesla
- At cryogenic temperatures (T < 19 K)

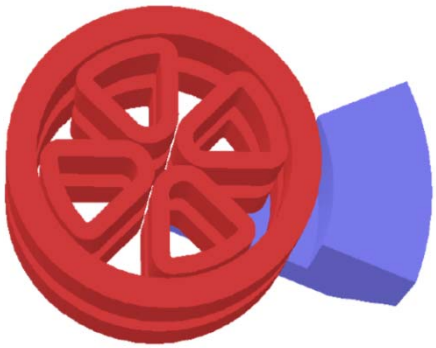


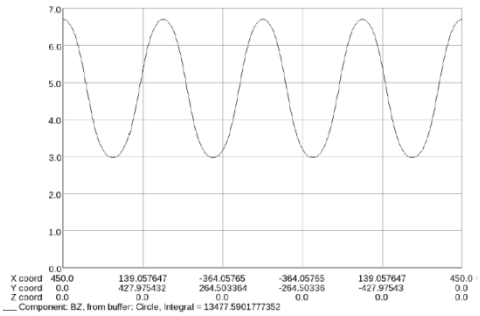


MIT MEGATRON		
K	250	MeV
I_{beam}	> 1	mA
R_{pole}	38	cm
B_{pole}	6	Tesla
symmetry	4	-
weight	40	tons

Another way to create flutter?

Flutter coils





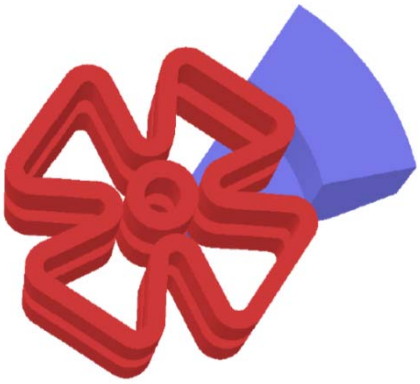
An idea which has not been worked out yet. Several questions not yet answered:

- Do we need iron for shimming?
- Is there enough flutter in the center?
- ……..

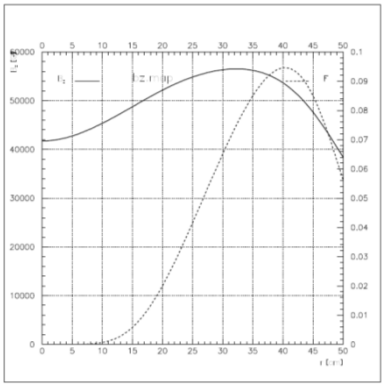
Flutter coils may also play role of main coil

Ideas are free

Flower-like main coil and separate center coil



Average field and flutter



More about the AVF focusing limit

Look at limit where there is no vertical focusing left

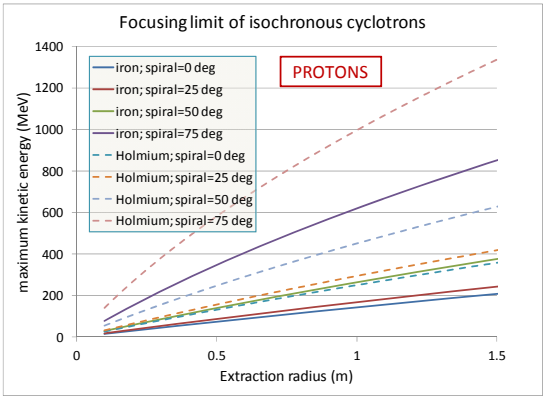
$$\nu_z^2 = 0 \Rightarrow k = F(1 + 2\tan^2(\xi))$$

$$\gamma^2 - 1 = \frac{1}{4}\frac{M^2}{\langle B\rangle^2}(1 + 2\tan^2(\xi))$$

$$\langle B\rangle = \frac{m_0 c}{q}\frac{\sqrt{\gamma^2 - 1}}{R_{extr}}$$

$$\gamma_{max} = \sqrt{1 + \frac{P_{pole}}{2}\sqrt{1 + 2\tan^2\xi}}$$

$$P_{pole} = \frac{qR_{extr}M_{pole}}{m_0 c}$$



P_{pole}: a kind of effective kinetic momentum of the pole

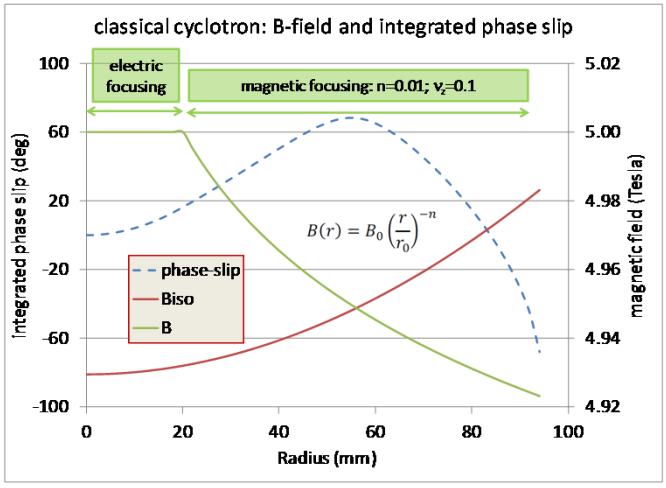
Vertical focusing limit

Remember approximations/assumptions that were made

- The most optimistic scenario
- Equation for ν_z is approximate => effect of radial gradients ignored
- In the limit there is no focusing left => beam will be lost before
- Structural resonances were not considered
- Assumed flutter is too high ($F < F_{max}$)
- Large spiral angles are difficult to realize
- An actual configuration must always be validated by Tosca calculations and beam dynamics studies

Is a classical cyclotron possible?

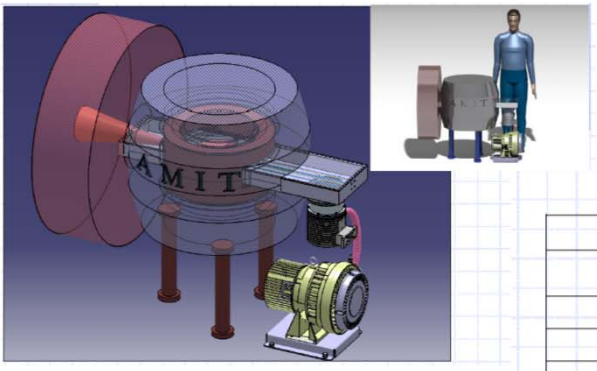
Requires high dee-voltage



classical cyclotron calculation example		
E	10	MeV
B	5	Tesla
V_{dee}	75	kVolt
N_{gaps}	2	
R_{extr}	94	mm
N_{turns}	107	
r/B dB/dr	0.01	-
ν_z	0.1	-

CIEMAT-AMIT project

Classical cyclotron



CYCLOTRON SPECIFICATIONS

PARAMETER	VALUE	UNITS
Energy	> 8.5 (1)	MeV
Current	>10 (2)	µA
Ions	H- (3)	
Magnet	Superconducting (LTc)	
Central Magnetic Field	4 (4)	T
Extraction radius	105.3	mm
Weight (exc. shielding)	< 2000	kg

Magnetic forces acting on coils and cold-mass

Hoop-stress

A general concept for pressure vessels

$$\sigma_\theta = \frac{F}{tl}$$

t=thickness of the cylinder

l=height of cylinder

F=total radial force: $F = \iint PdA$

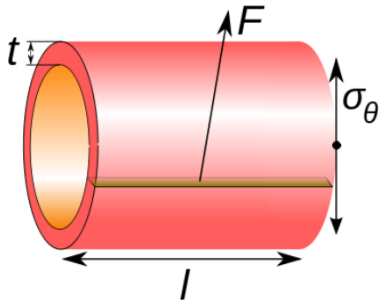
For a coil

$$\sigma_\theta = 2\pi RiB$$

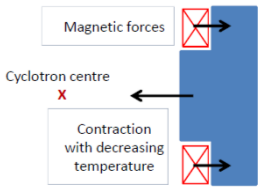
R=coil radius

i=current density in the coil

B=magnetic field on the coil



Size reduction $\Rightarrow$ $\sigma_\theta \infty 1/R$



Coil can be contained in a coil former

- Aluminum coil former shrinks when cooling down
- Completely compensates hoop stress
- Good thermal contact
- But requires extra radial space in cryostat

Magnetic forces acting on coils and cold-mass

Forces between coils: problem of deformation of coils at radial penetrations

$$F \infty \frac{I^2}{d} \Rightarrow \infty B^2$$

Forces on the cold mass due to coil displacements or rotations

- All coil movements are unstable => forces want to increase their cause
- All forces vary linear with displacement or rotation

Asymmetries in the design of the magnet give rise to additional forces on the cold-mass

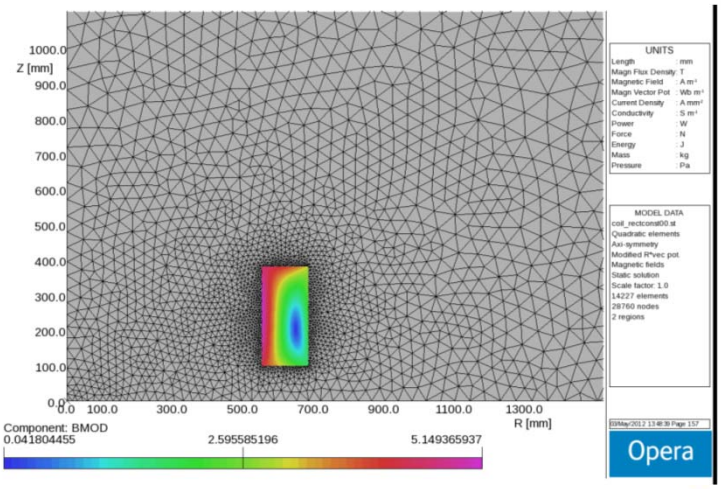
FORCES AND TORQUES ACTING ON THE MAIN COIL SYSTEM DUE TO COIL DISPLACEMENTS AND ROTATIONS

		FORCES			TORQUES		
		dFx ton/mm	dFy ton/mm	dFz ton/mm	dTx Nm/mm	dTy Nm/mm	dTz Nm/mm
coil shift	x-direction	1.99	-0.05	0.00	0	-9	8
	y-direction	-0.05	2.00	0.00	10	2	41
	z-direction	0.00	0.00	0.56	-80	-201	0
coil rotation		dFx ton/deg	dFy ton/deg	dFz ton/deg	dTx Nm/deg	dTy Nm/deg	dTz Nm/deg
	around x-axis	-0.02	0.00	-0.12	91559	-4609	-80
	around y-axis	-0.05	-0.01	-0.30	-4484	91305	79

subsystems included	Forces on cold-mass by separate subsystems					
	dFx	dFy	dFz	dTx	dTy	dTz
	N	N	N	Nm	Nm	Nm
all	24444	-7149	-16927	-799	-1128	0.1
none						
rotco-shield	19236	-3831	21	-95	-415	0
ext quads	2338	-2474	885	-1070	-994	0
cyclo-feet	202	-118	-13090	-105.4	-681	0
yoke-lifting	5525	-2018	-3690	-193	115	0
cryo-shield	2176	330	625	99	51	0

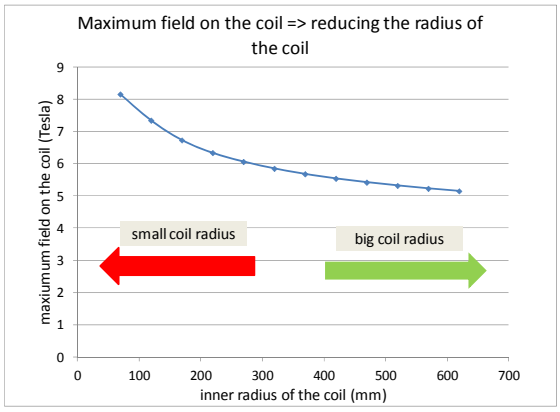
Maxiumum field on the coil cross-section

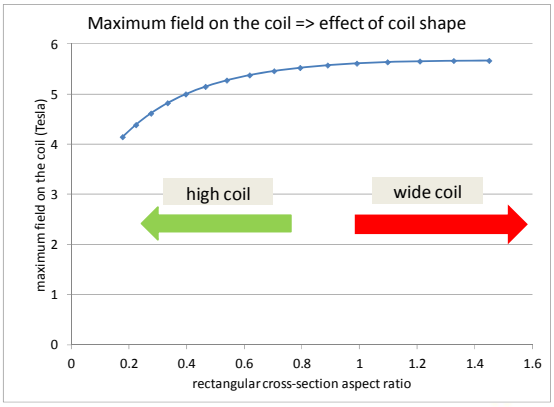
- Max field varies a lot on cross section
- Main contribution comes from the coil current => small contribution from the iron
- For cryogenic stability, it is the maximum value that counts
- How depends this maximum on the coil-geometry?



Maxiumum field on the coil cross-section

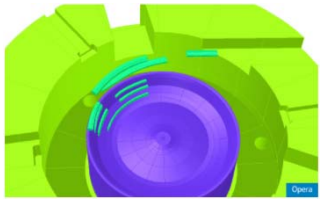
Effect of coil inner radius and cross-section aspect ratio

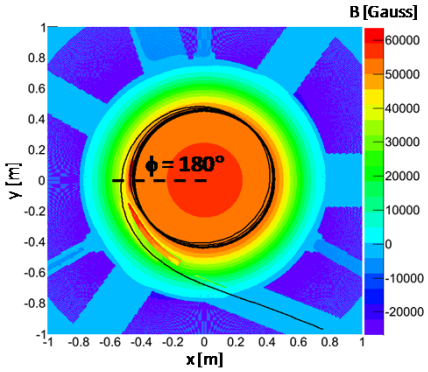


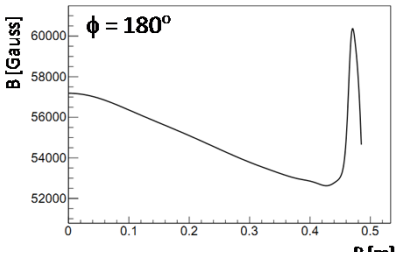


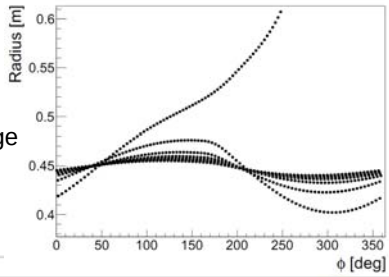
Regenerative extraction in a synchrocycloron

Synchrocyclotron:
⇒very slow acceleration
⇒precessional extraction or ESD not possible
⇒use resonant extraction









A field bump from the regenerator makes a large first harmonic and large second harmonic
- 2nd harmonic: creates $2\nu_r=2$ resonant stop-band => ν_r locks to 1
- 1st harmonic: pushes the beam radially towards the extraction channel

Many thanks to my colleagues

For the help that they give me in the preparation of this lecture

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- Emma Pearson

Thank you