Cyclotrons for hadron therapy

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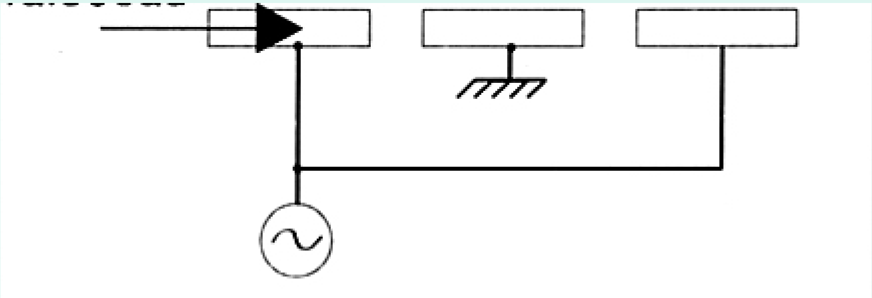
Outline of this lecture:

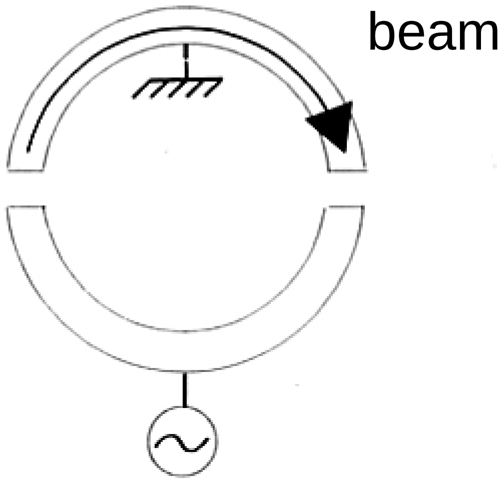
- i. Basic concepts and operation
- ii. Cyclotron
  - a. Source
  - b. Central region
  - c. RF system
  - d. Magnetic field
    - Synchro-Cyclotron
  - e. Extraction
- iii. Summary and conclusions

Metamorphosis



Wideroe’s linear accelerator

how to
re-use
the RF



$$\left.\begin{array}{l} \dfrac{mv^2}{r} = Bqv \\[2em] v = \dfrac{2\pi r}{T_{circle}} \end{array}\right\}$$

$$T_{circle} = \frac{2\pi r}{v} = \frac{2\pi m\cancel{r}}{Bq\cancel{r}} = \frac{2\pi . m}{Bq}$$

„**r cancels r**…. don‘t you see what this means?

The resonance condition **does not depend on radius**!“

(Lawrence to his PhD student, while bursting into his lab; 1930)

Cyclotron(1930)

(almost) circular orbits:

=> $T_{circle} = \frac{2\pi.r}{v} = \frac{2\pi.m}{Bq}$

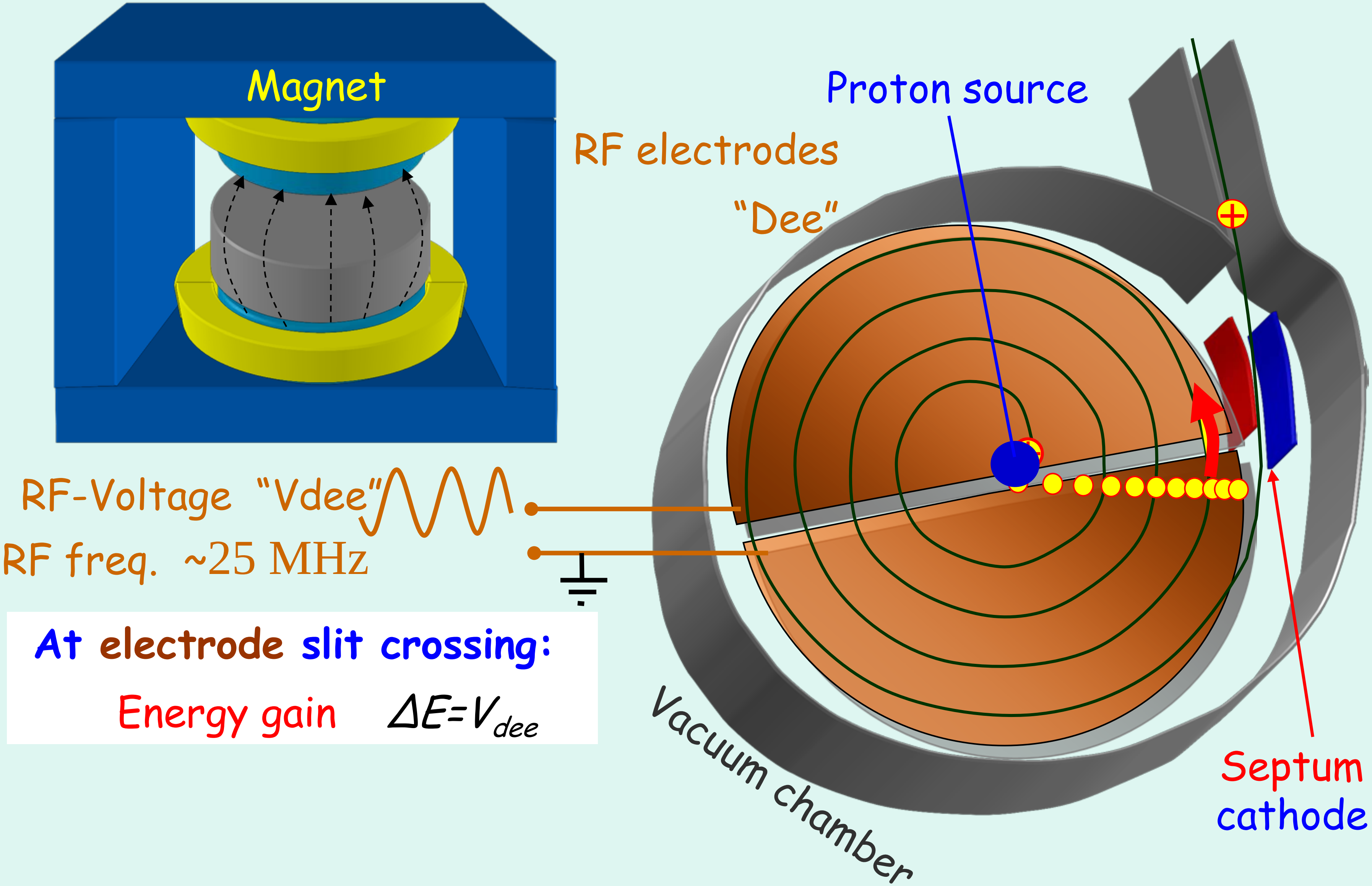
$\boxed{B=2T=>T=40\text{ ns}}$

magnetic rigidity: **Bρ (= p/q):**

magnet strength B to
bend with radius ρ

70 MeV p:	Bρ = 1.2 Tm
250 MeV p:	Bρ = 2.4 Tm
450 MeV/nucl C^{6+}:	Bρ = 6.8 Tm

Cyclotron



At electrode slit crossing:

Energy gain $\Delta E = V_{dee}$

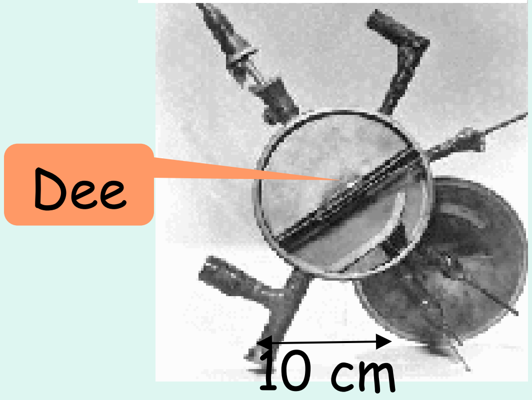
Cyclotron

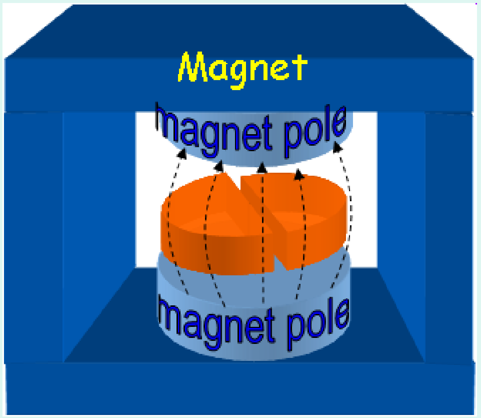
Ernest Lawrence

(1901-1958)

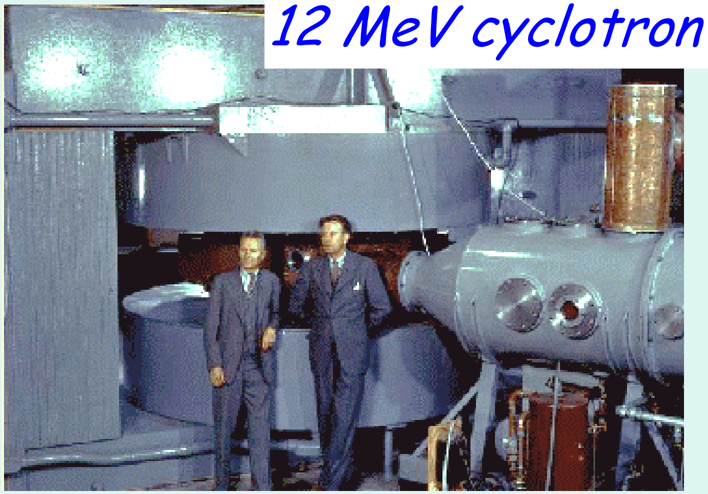
1930:

80 keV protons





12 MeV cyclotron (UC, 1940)



Cyclotrons for therapy

Protons	in use	∅2-3.5-5 m	30-100-200 tons
Carbon ions	in design	∅7 m	700-800 tons

Superconducting Cyclotron

250 MeV proton cyclotron (ACCEL/Varian)

Closed He system

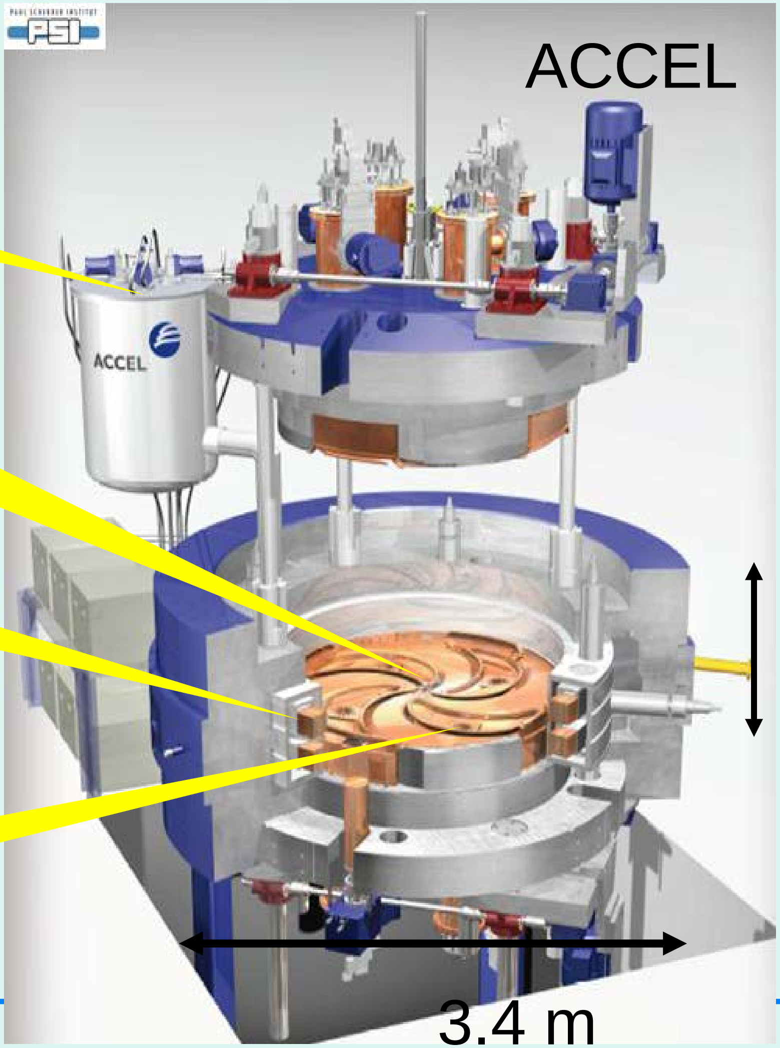
4 x 1.5 W @4K

Proton source

superconducting coils =>
2.4 - 3.8 T

4 RF-cavities:

72 MHz ~80 kV

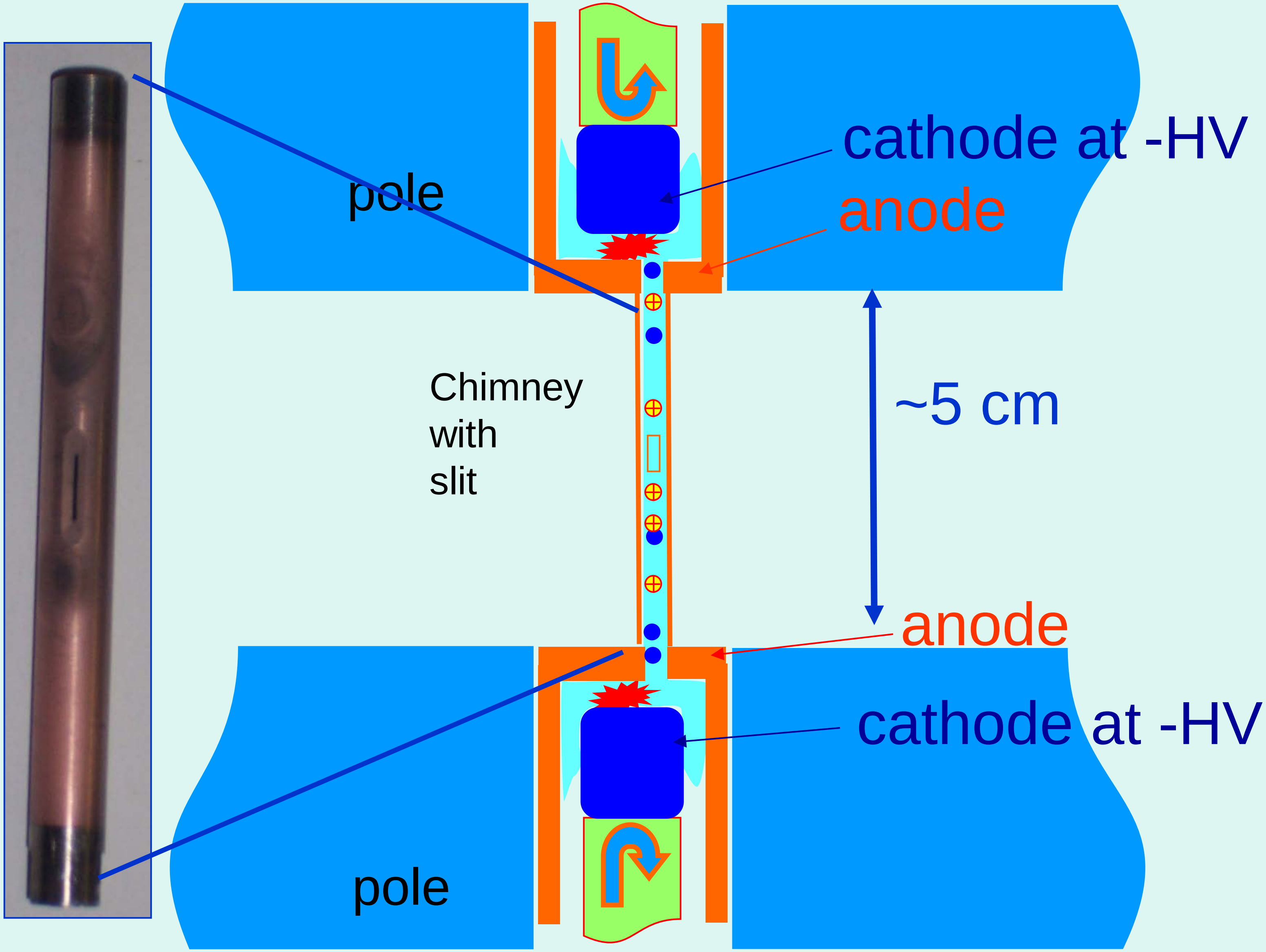


300 kW

90 tons

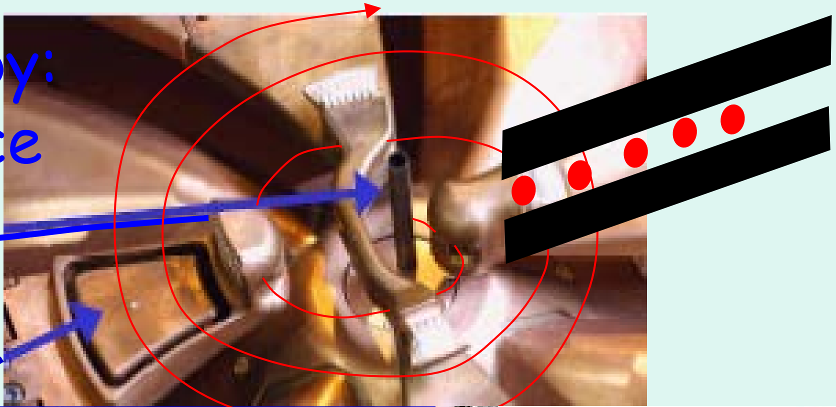
1.4 m

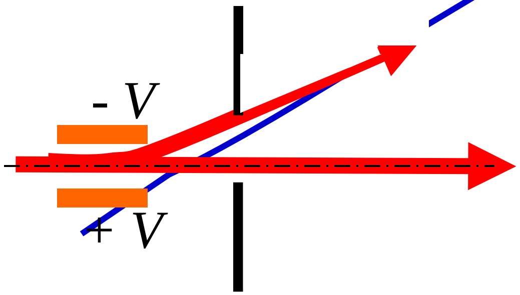
Internal proton source



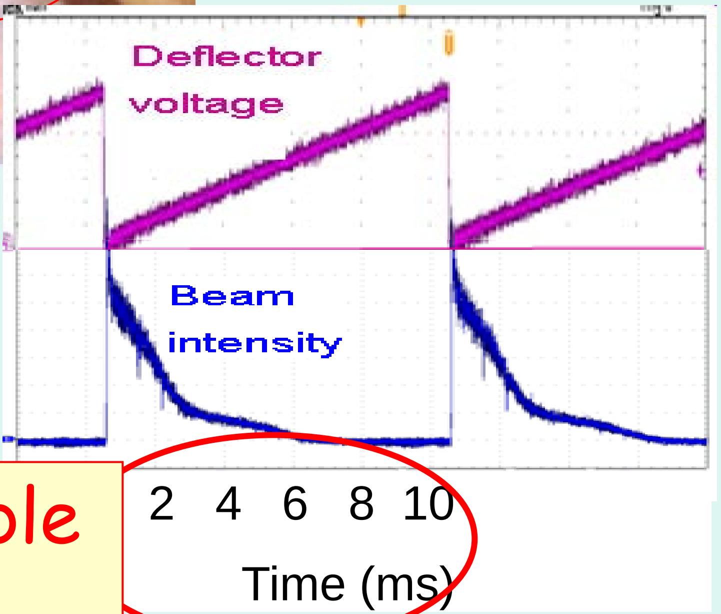
intensity control

Max. intensity set by:
proton source



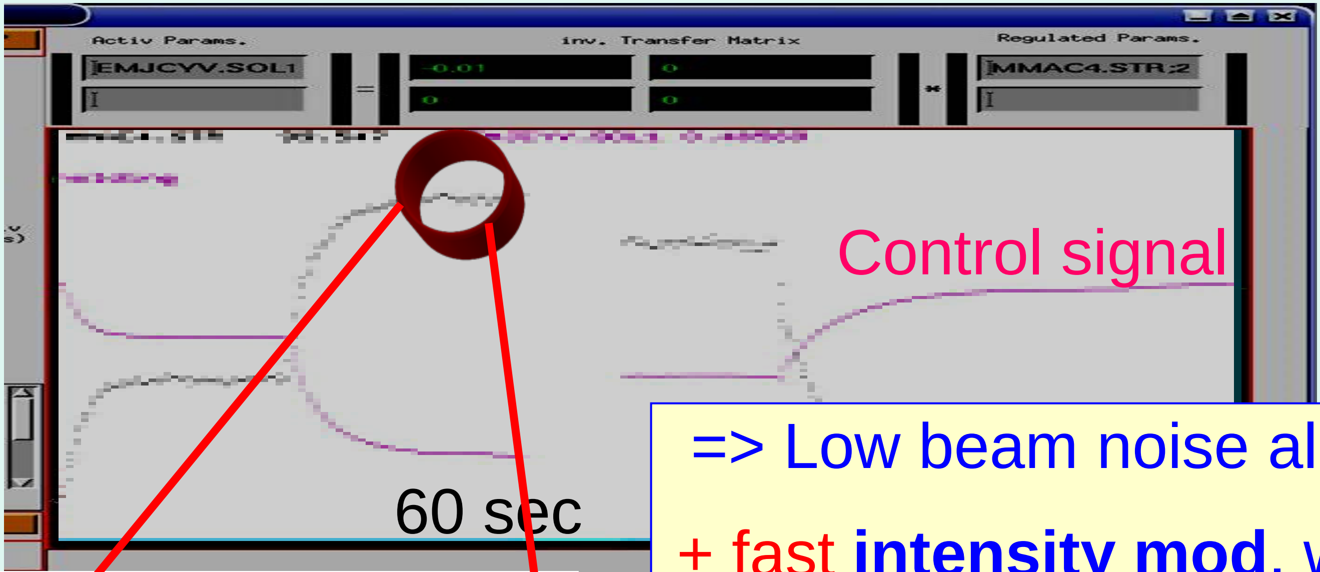


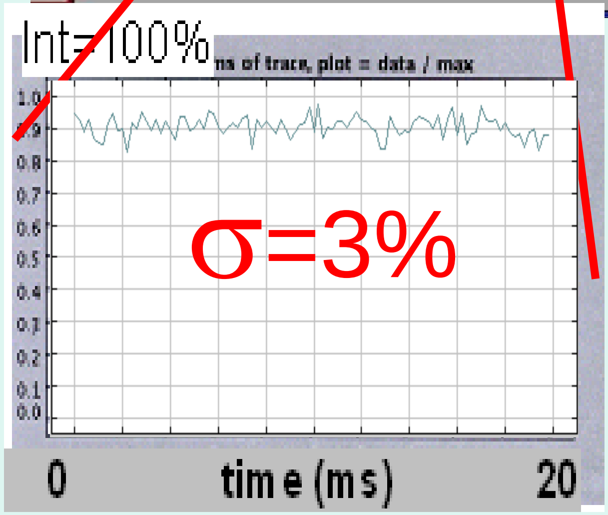
Deflector plate:
sets intensity
- within 50 μs
- 3% accuracy



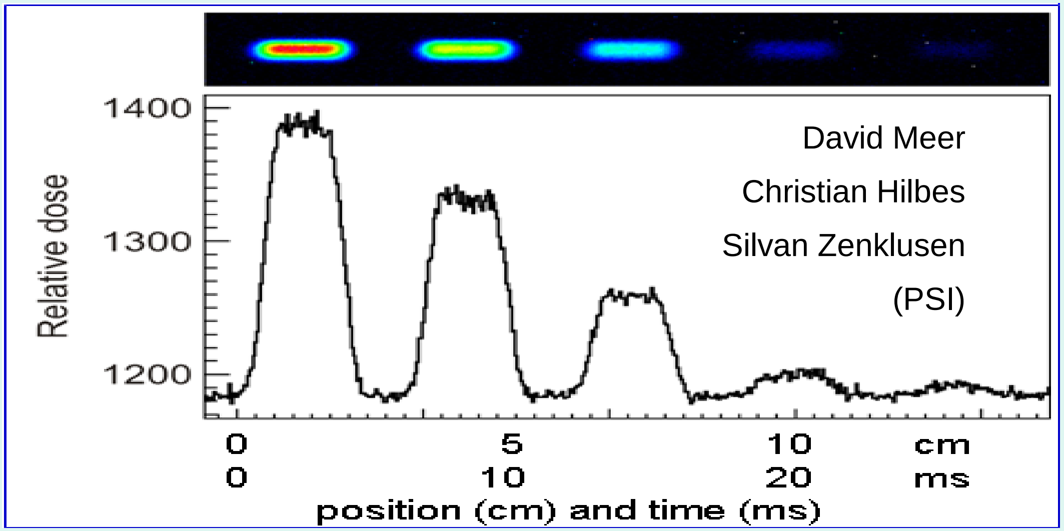
currently only possible with a **cyclotron**

Cyclotron beam structure: regulated, DC

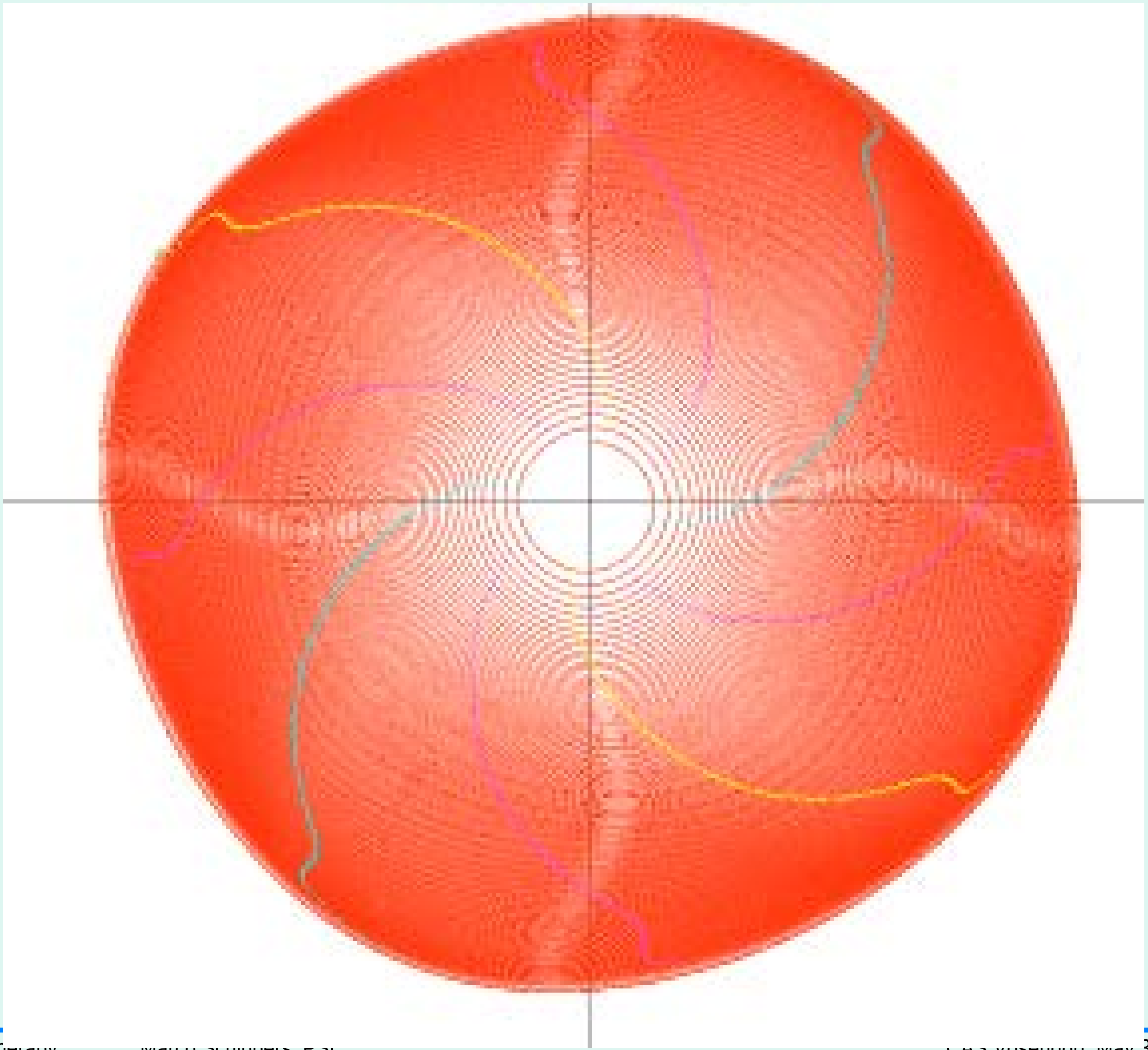




=> Low beam noise allows **accurate** + fast **intensity mod**. while scanning

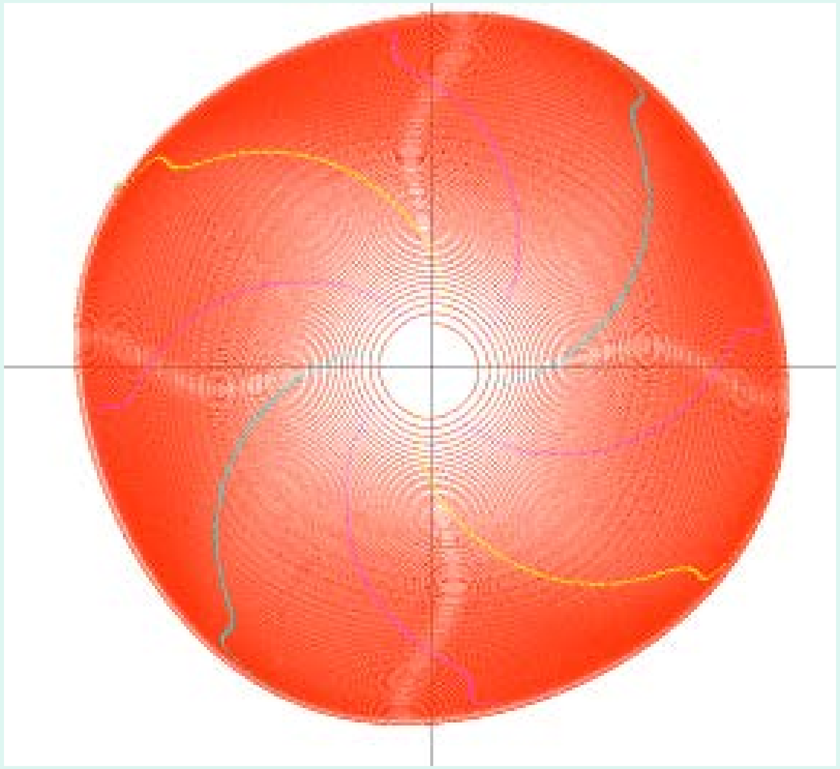


Acceleration and beam dynamics

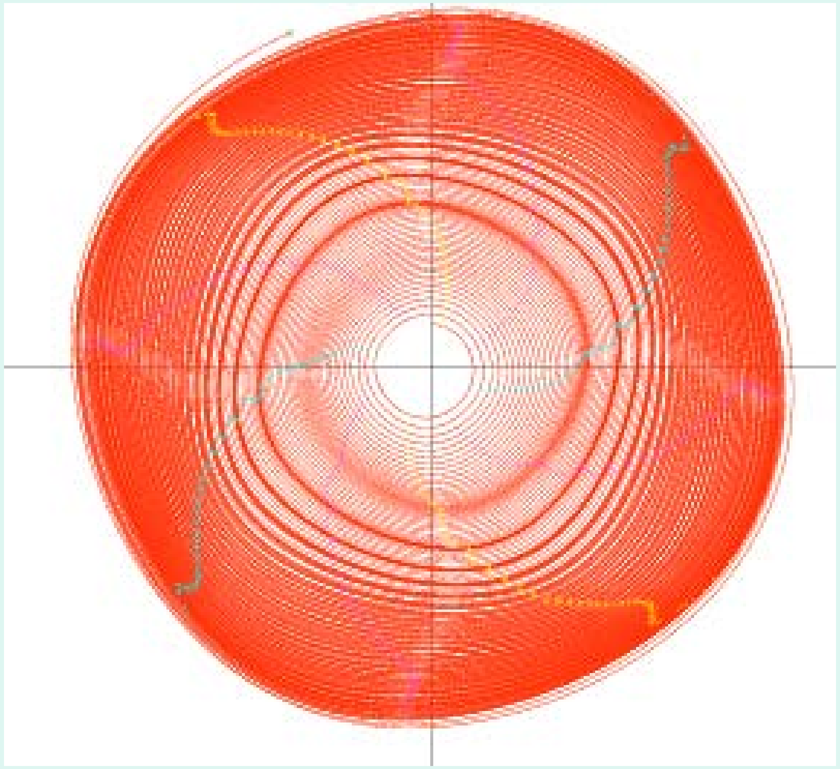


beam centering

good centering



bad centering

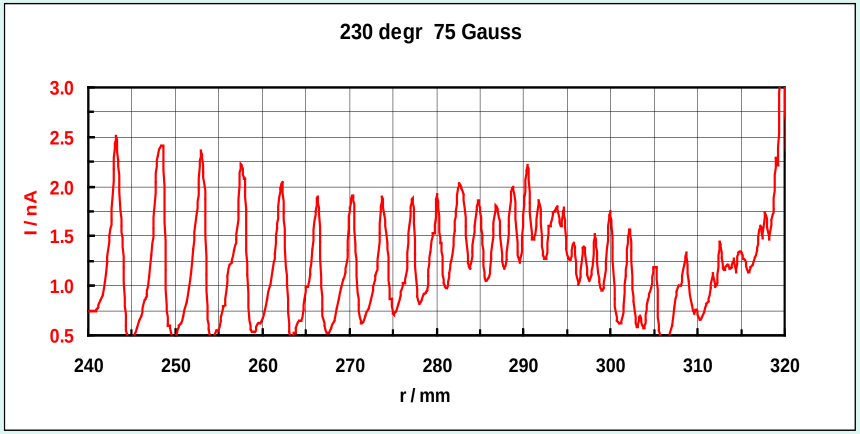


beam centering

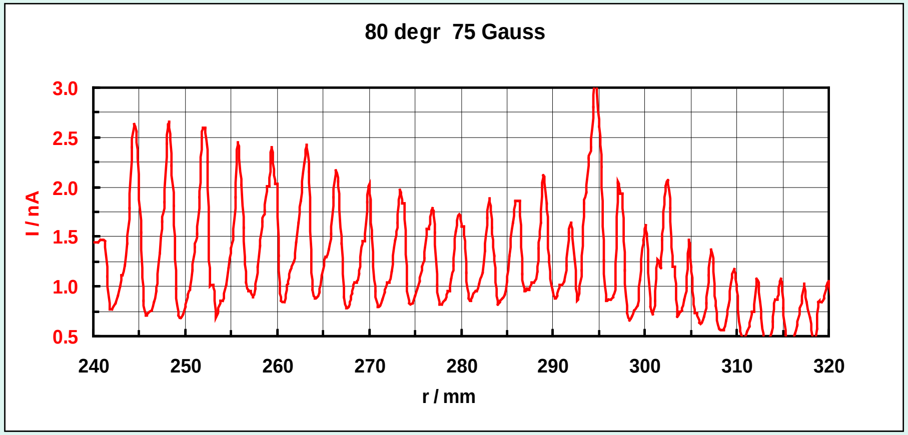
Measurement of the beam intensity

in the cyclotron as a function of radius:

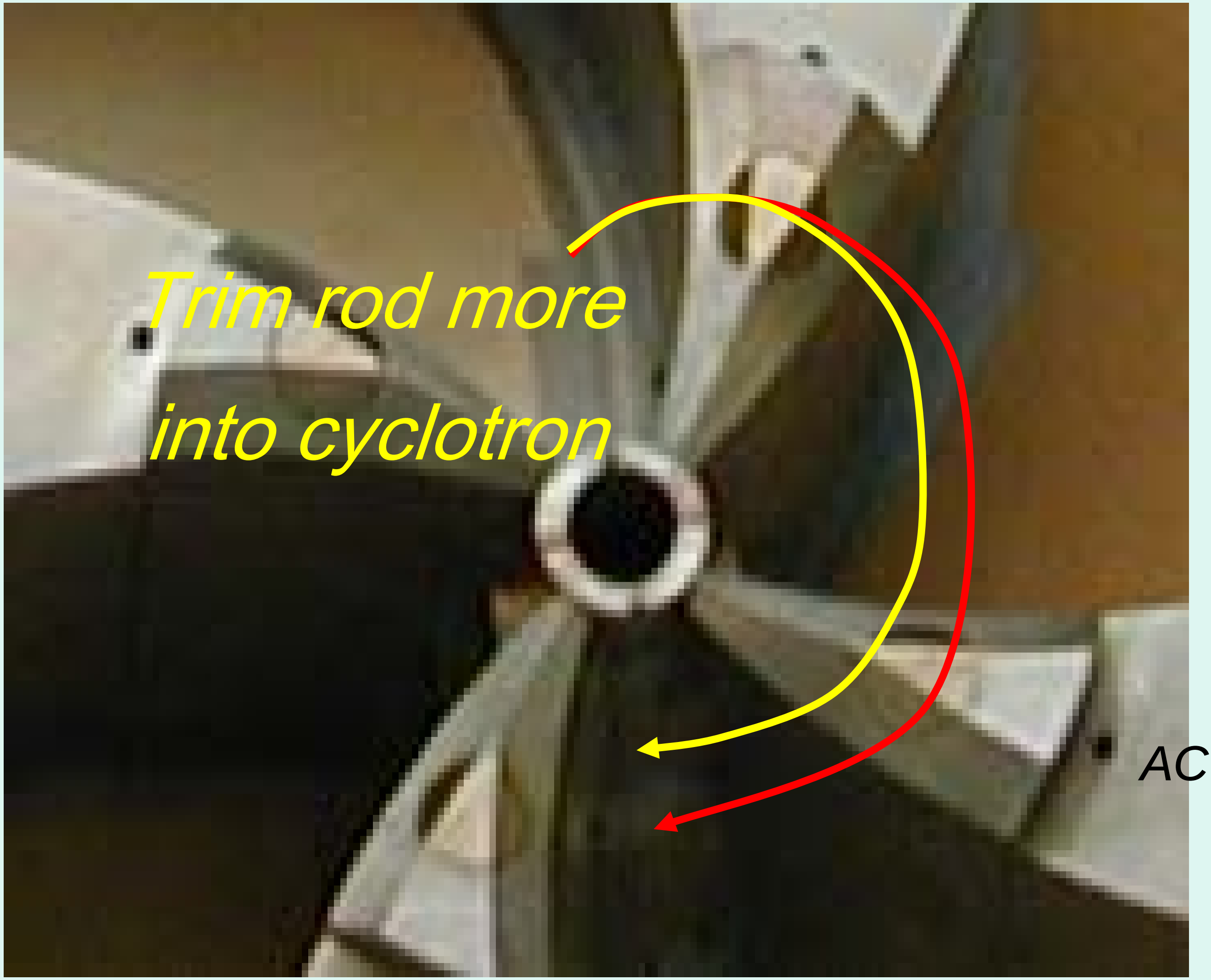
bad centering



good centering

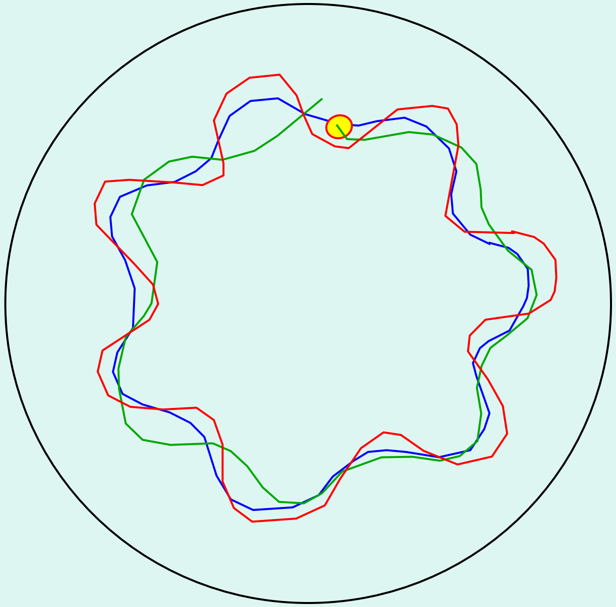


beam centering with trim rods



ACCEL/varian

Betratron oscillations

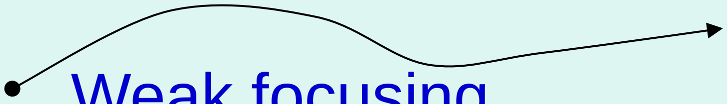


betatron freq $\nu \neq$ k . revolution freq

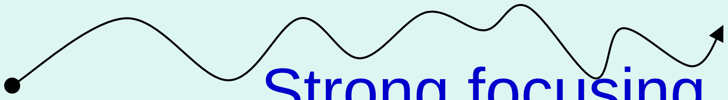
(in general avoid: $n\nu_r + m\nu_z = p$; i.e.closed orbit)

Otherwise: Resonance → Beam loss

Focusing strength: $\sim\nu^2$

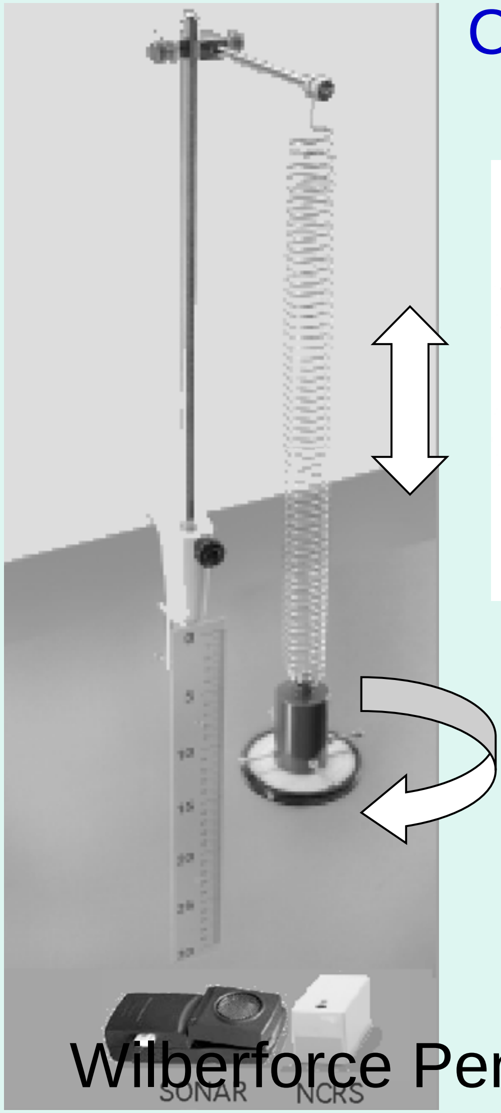


Weak focusing

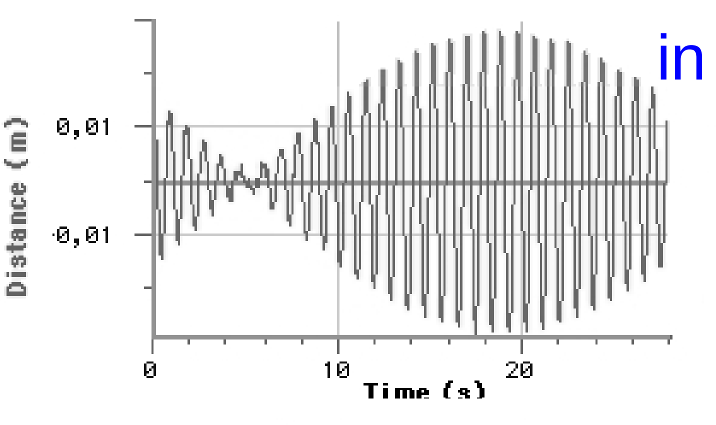


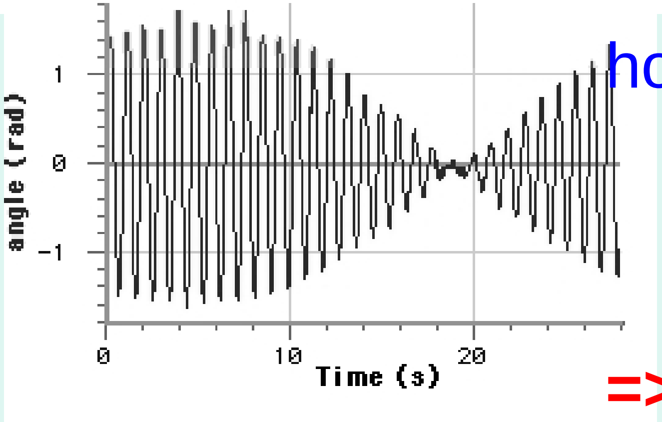
Strong focusing

Betatron oscillations



Coupled oscillations





Example of dangerous coupling resonance in cyclotrons:

$\nu_r - 2\nu_z = 0$

horizontal oscillation

←→ vertical oscillation

=> beam loss

Wilberforce Pendulum - YouTube.flv

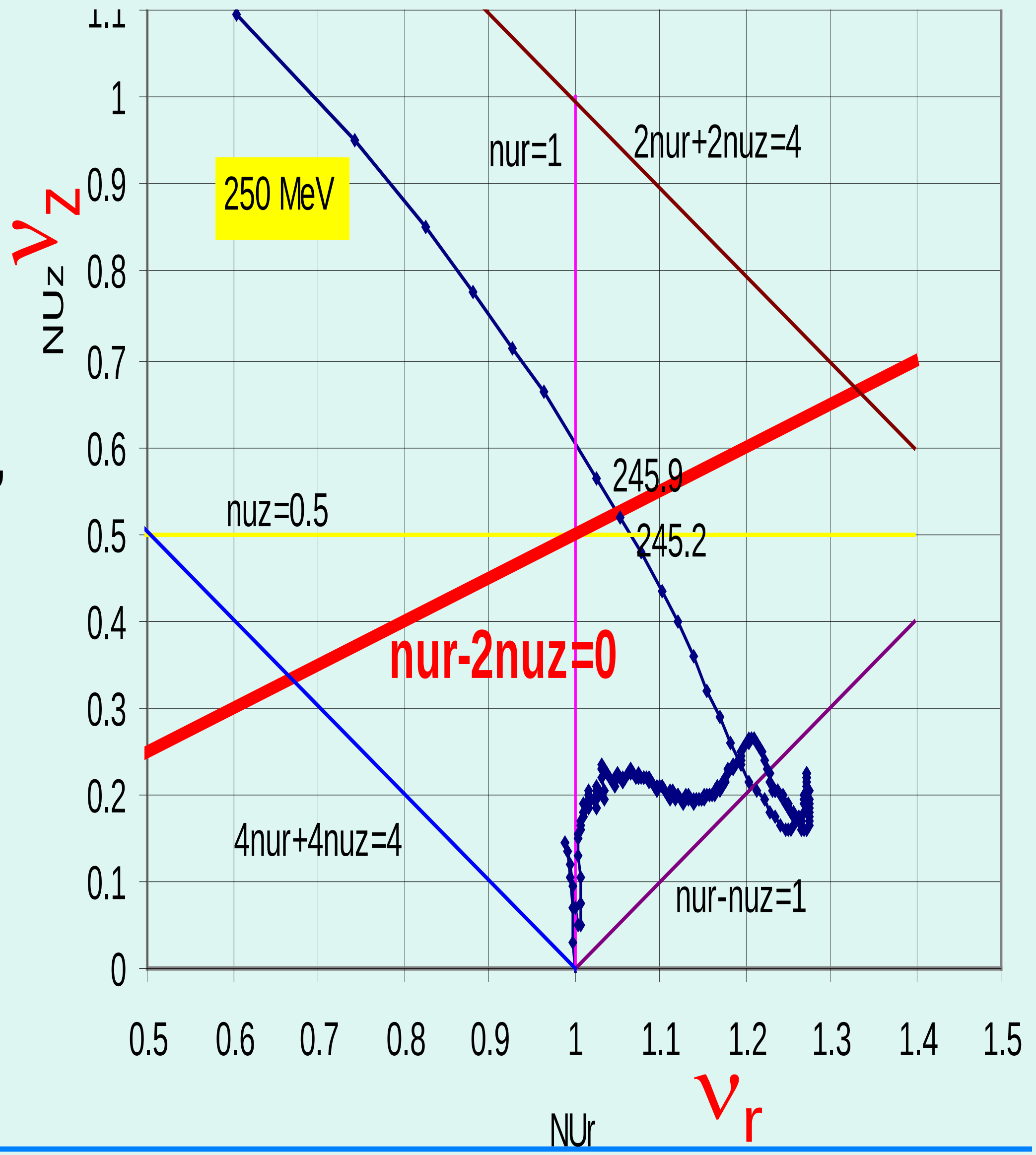
http://www.padova.infm.it/torzo/WilberGIREP.pdf

Betatron oscillations: tune diagram

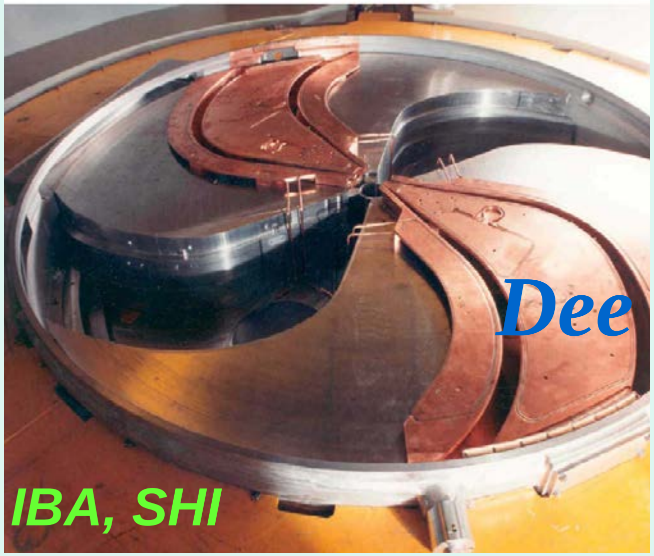
ν_r(E) and ν_z(E)

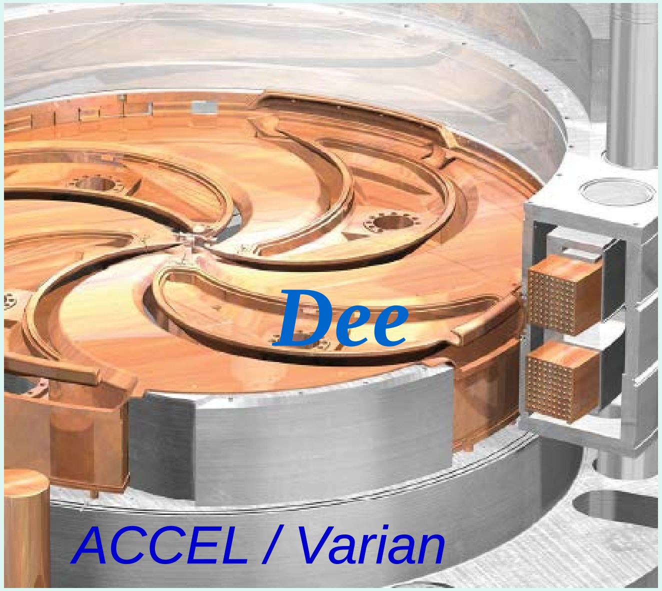
In a cyclotron, since n=n(r),

the tunes vary during acceleration



RF system





Important parameters:

Frequency: 20-80 MHz

Voltage amplitude on Dee : 30-80 kV

Number of Dee‘s: 2, 3, 4

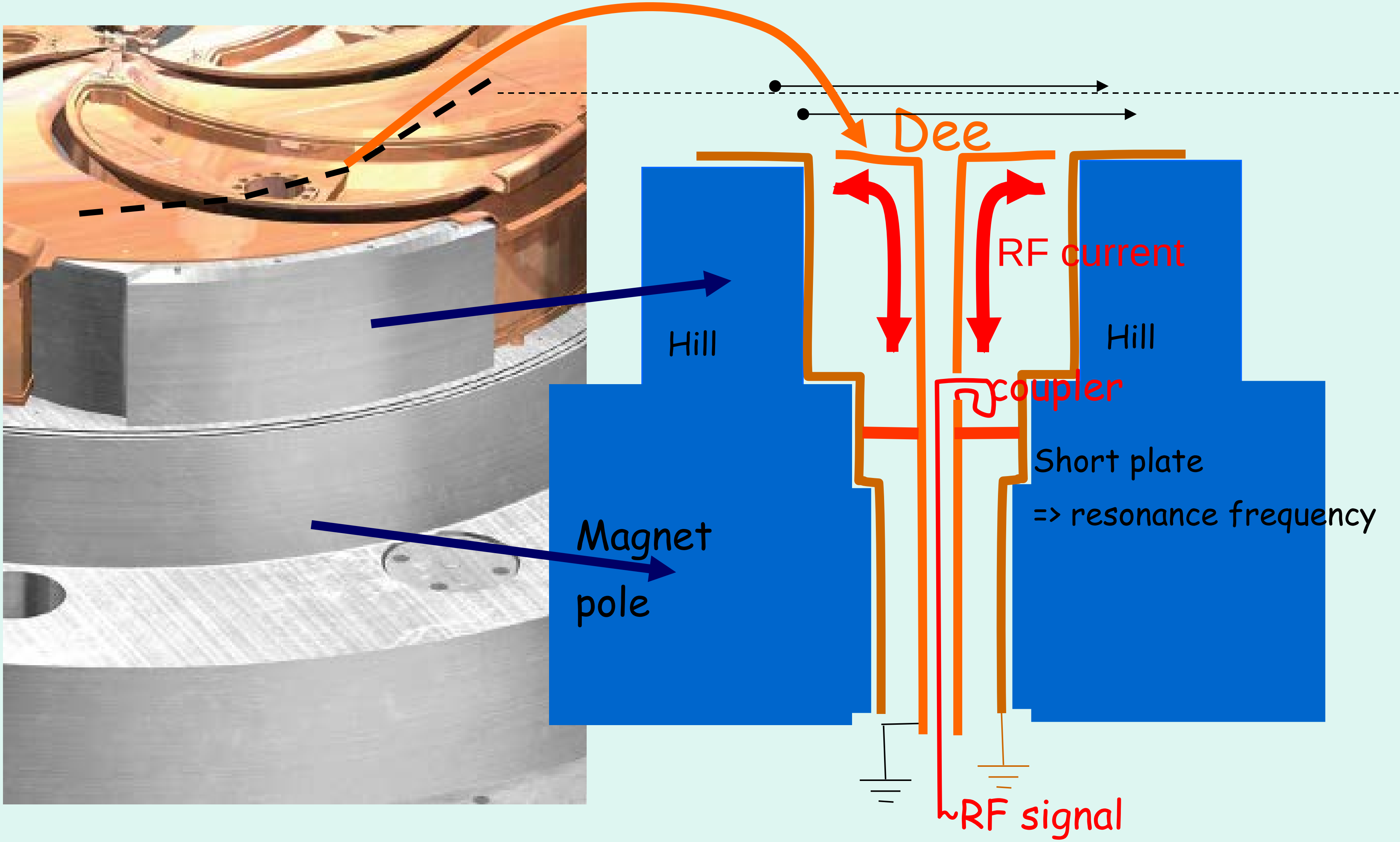
Harmonic $h=f_{RF}/f_{orbit}$: 1,2, …

$\Rightarrow$ Energy gain per turn

$\Rightarrow$ Orbit separation

$\Rightarrow$ Extraction efficiency

RF system


Dee
RF current
Hill
Hill
coupler
Short plate
=> resonance frequency
Magnet
pole
~RF signal

Acceleration

Final energy is independent of V_{RF}

V_{RF} → enery gain dW per turn

$dW = N_{gaps}.V_{0RF}.\cos\varphi$ (=constant if φ constant)

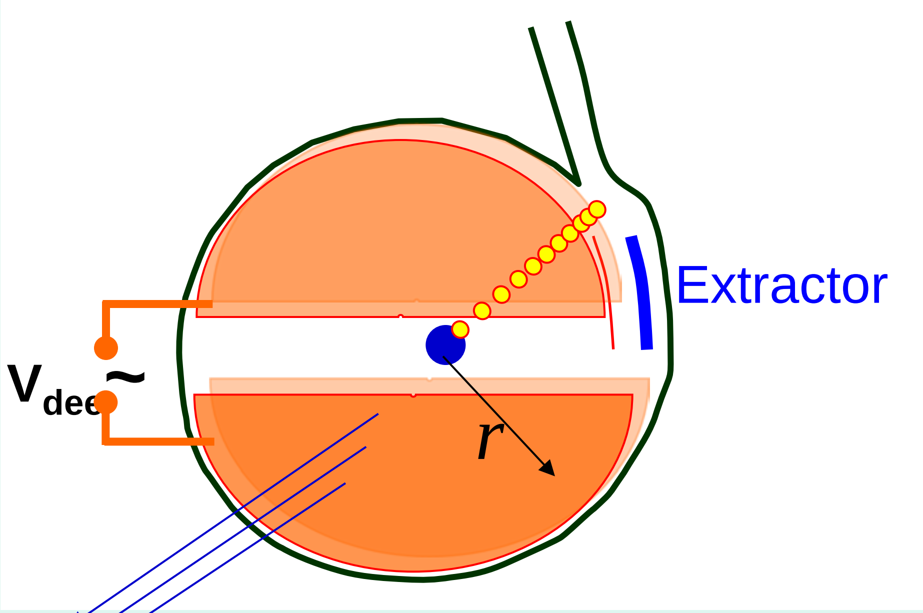
→ Number of turns

$$\frac{dr}{r} = 0.5\,\frac{dW}{W} \quad \rightarrow \quad \boxed{\delta r \propto \frac{1}{r}}$$

→ turn separation dr decreases with energy

$$\frac{dr}{dn} = \frac{\gamma}{\gamma+1}.r.q.n_{cav}V_{dee}\cdot\frac{1}{E}\,\frac{f^2}{\upsilon_r^2}$$

Small cyclotron



Circular orbits:

Centripetal force = Magnetic force at extraction: $$\frac{mv^2}{\boxed{r}} = \boxed{B}qv$$

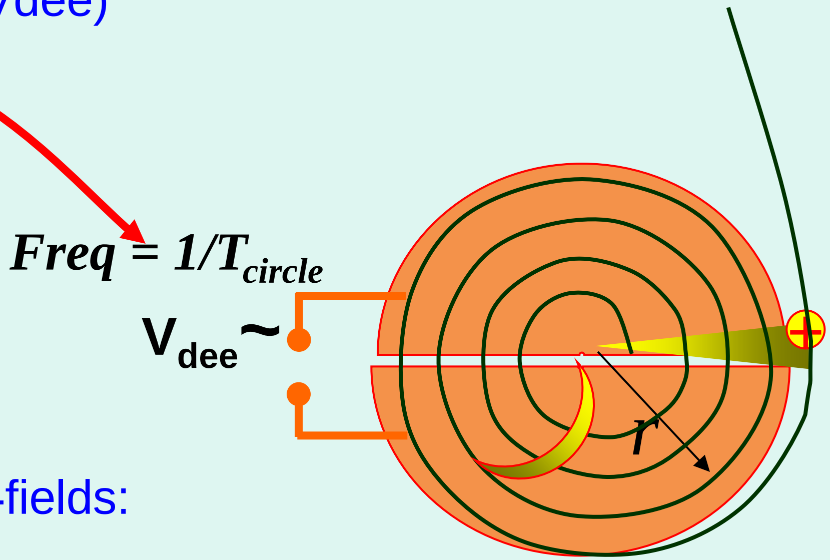
=> Small cyclotron: **r ↓ then B must ↑**

Small cyclotron; strong field

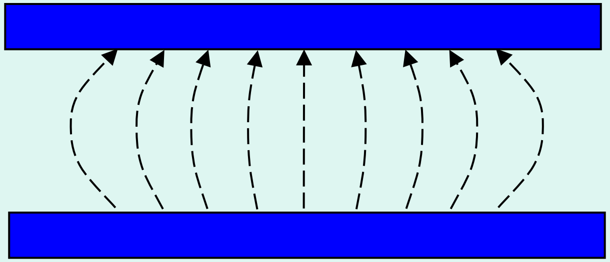
Cyclotron works while: T_{circle} independent from radius:

(particles move in pace with Vdee)

$$T_{circle} = \frac{2\pi.m}{q.B}$$



However: at very strong magnetic B-fields:



m = mass

B = magnetic field

q = charge

⇒ Magnetic field decreases with radius ⇒ $T_{circle} \uparrow$

⇒ particles lose pace with RF.

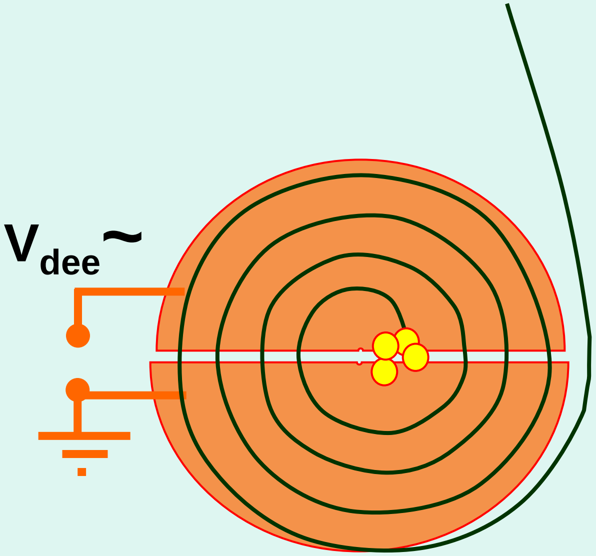
Synchro-Cyclotron

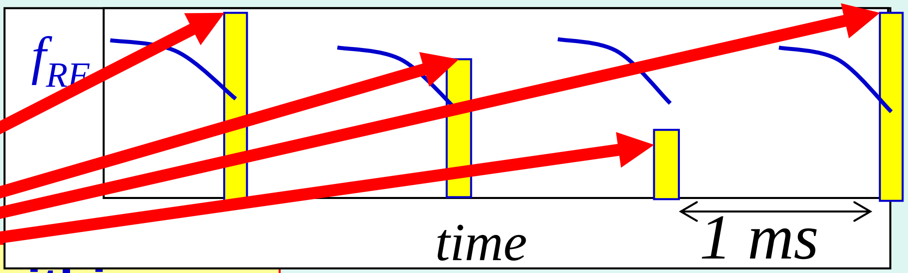
T_{circle} increases with radius.

T=1/f

SO: decrease f_{RF} with radius and extract

Repeat 1000 x per sec





Each pulse: set intensity at source **within ms**

(=> typ 10-30% accuracy)

=> Spot scanning requires >2 pulses per spot.

Synchro-Cyclotron

Proposal of
H.Blosser, F.Marti, et al.,1989:
-250 MeV
-SC, 52 tons, **on a gantry**
-B(0)=5.5 Tesla

H. Blosser, NSCL (~1990):
SC-cyclotron for neutron therapy;
30 MeV p, mounted on a gantry in Detroit

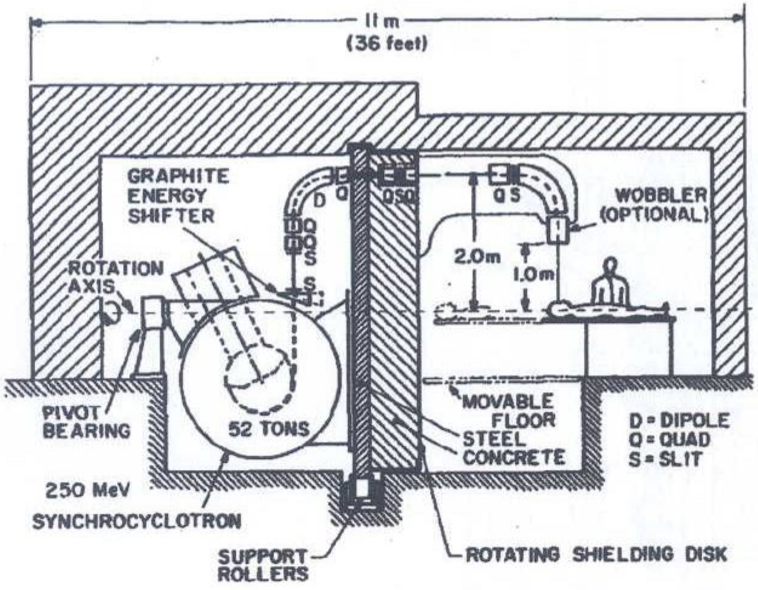


FIG. 9 -- Drawing showing synchrocyclotron rotating gantry arrangement with energy shifting wedge just after the cyclotron. Energy shifting can optionally be accomplished just ahead of the patient.

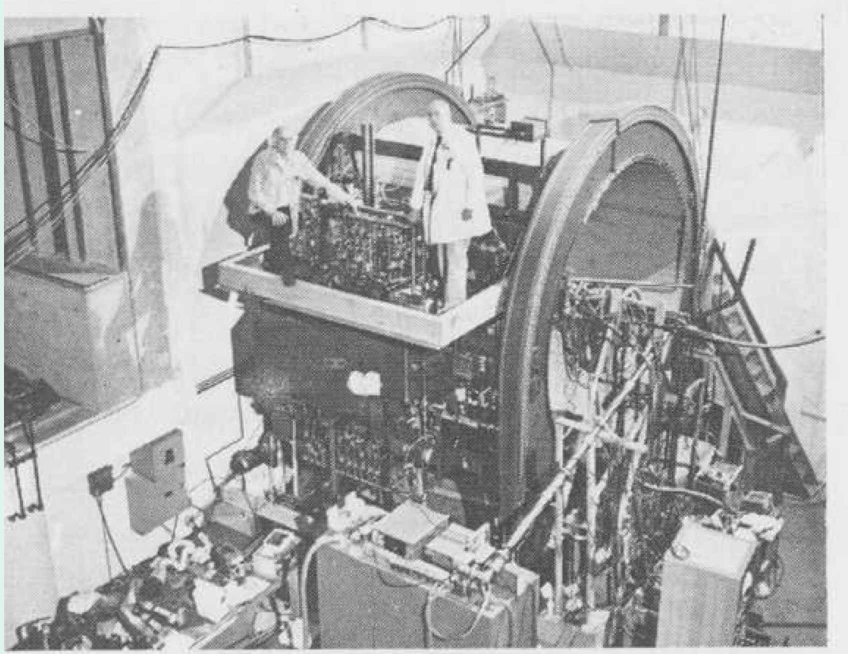


Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and

Synchro-Cyclotron

MEVION medical systems

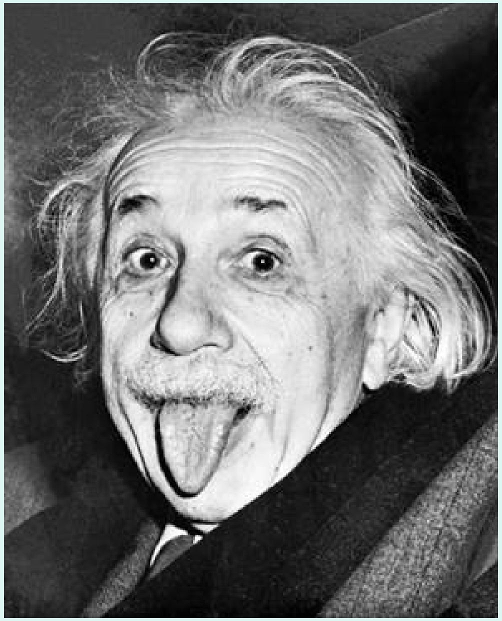
iba **S2C2**

First beam extracted in May 2010

First beam at IBA in 2013

Relativity in high-E cyclotrons

Cyclotron essential: $T_{circle} = \frac{2\pi . \enclose{circle}{m}}{Bq}$ => T_{circle} constant for all radii



However, when v→ c: $m = \frac{m_0}{\sqrt{1-v^2/c^2}} = \gamma \cdot m_0$

e.g: 10 MeV p: v/c=0.14 => m=**1.01** m_0

250 MeV p: v/c=0.61 => m=**1.27** m_0

=> T_{circle} increases with radius.

Relativity in high-E cyclotrons

$$T_{circle} = \frac{2\pi . m}{q . B}$$

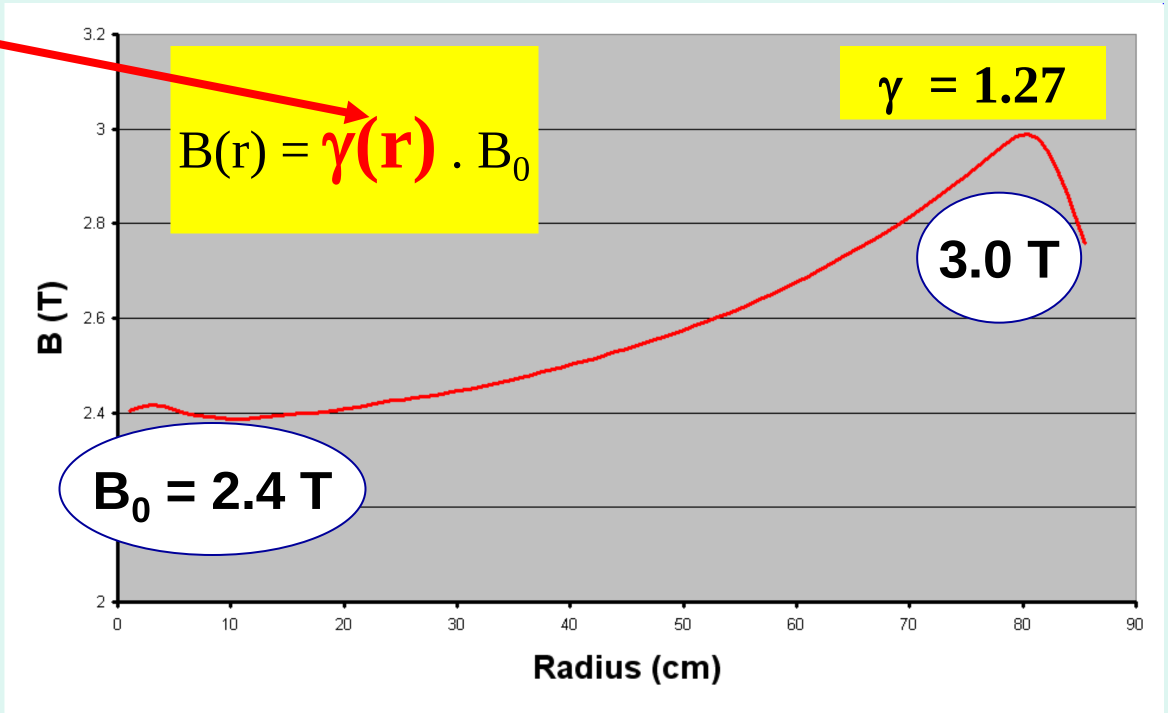
$$m = \frac{1}{\sqrt{1 - v^2 / c^2}} . m_0$$

$\gamma(r)$

Remedies when T_{circle} increases with radius:

1) decrease f_{RF} with radius: *synchro-cyclotron*

2) increase B **with radius: to** compensate *m*-increase


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

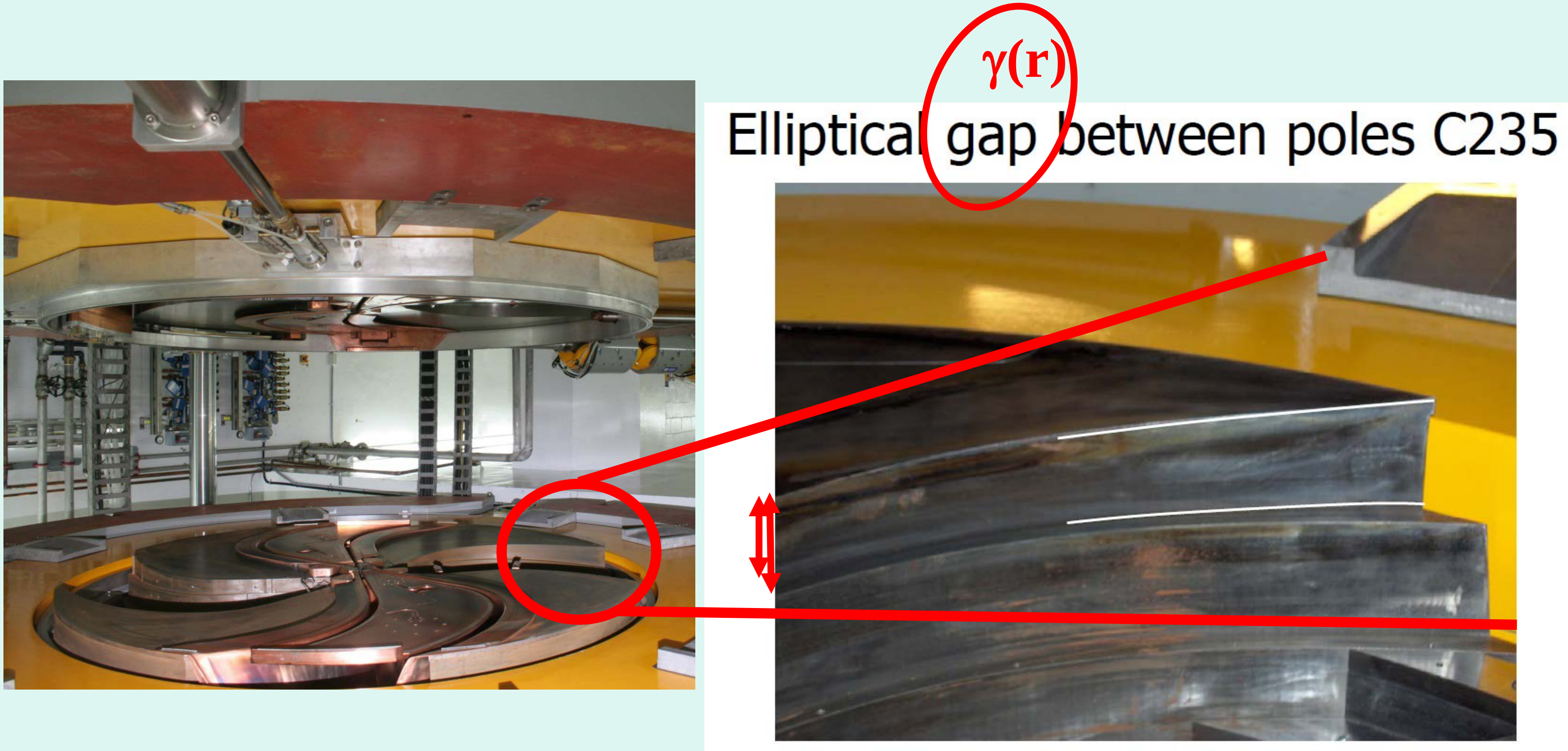
$\gamma = 1.27$

3.0 T

$B_0 = 2.4$ T

How to increase field with radius

1) Decrease pole gap at large Radius (IBA)



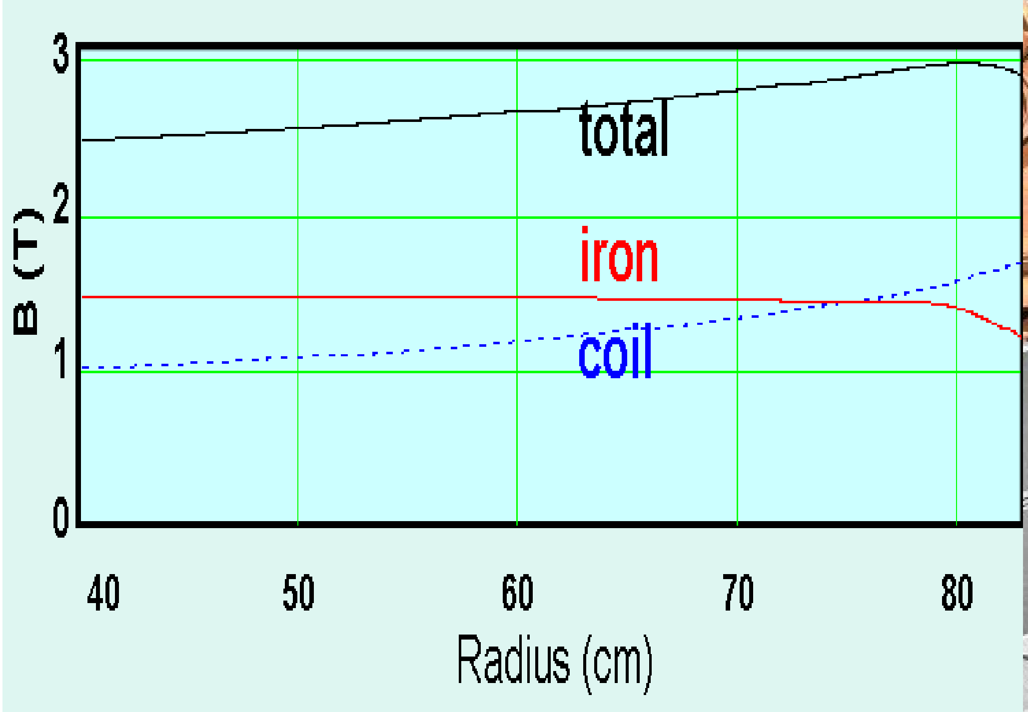
Elliptical gap between poles C235

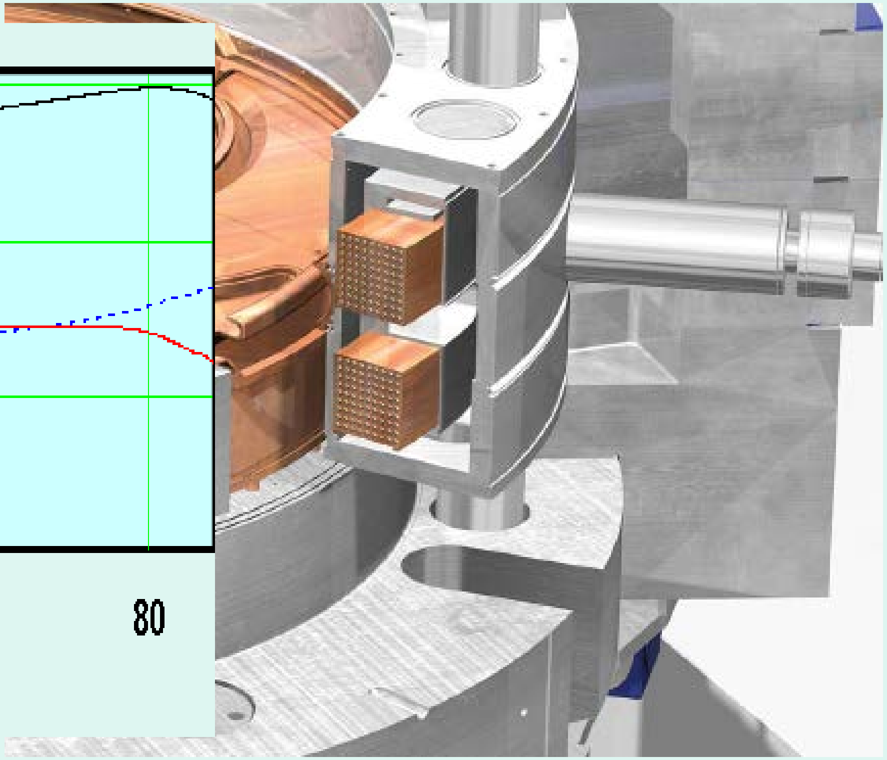
How to increase field with radius

2) Use SC coils to employ very strong electric current

→ very strong magnetic field

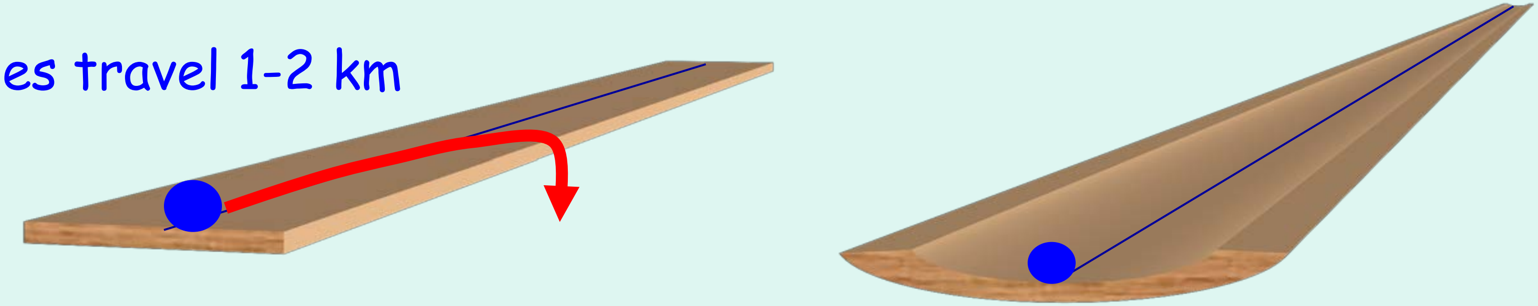
→ coil field shapes magnetic field (ACCEL / Varian)

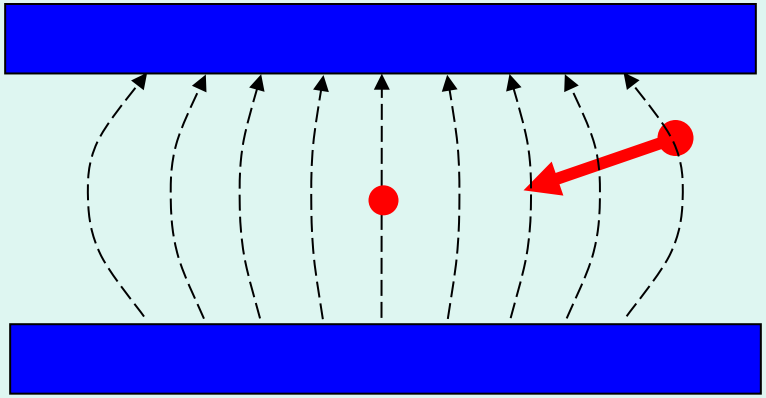




Vertical focusing

Particles travel 1-2 km

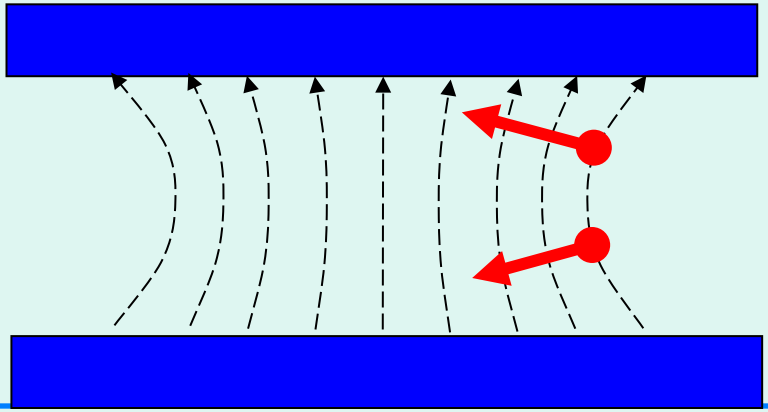




When B **decreases** with radius:

n>0 => Automatic **vertical stability**

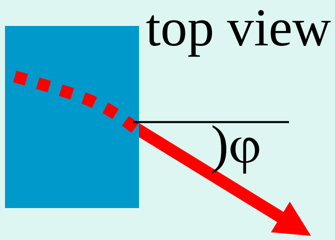
($\nu^2=n$)

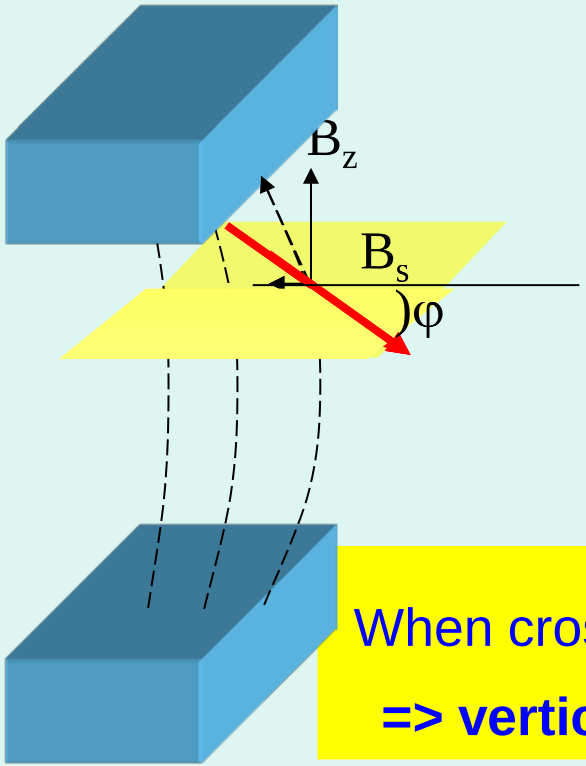


When B **increases** with radius:

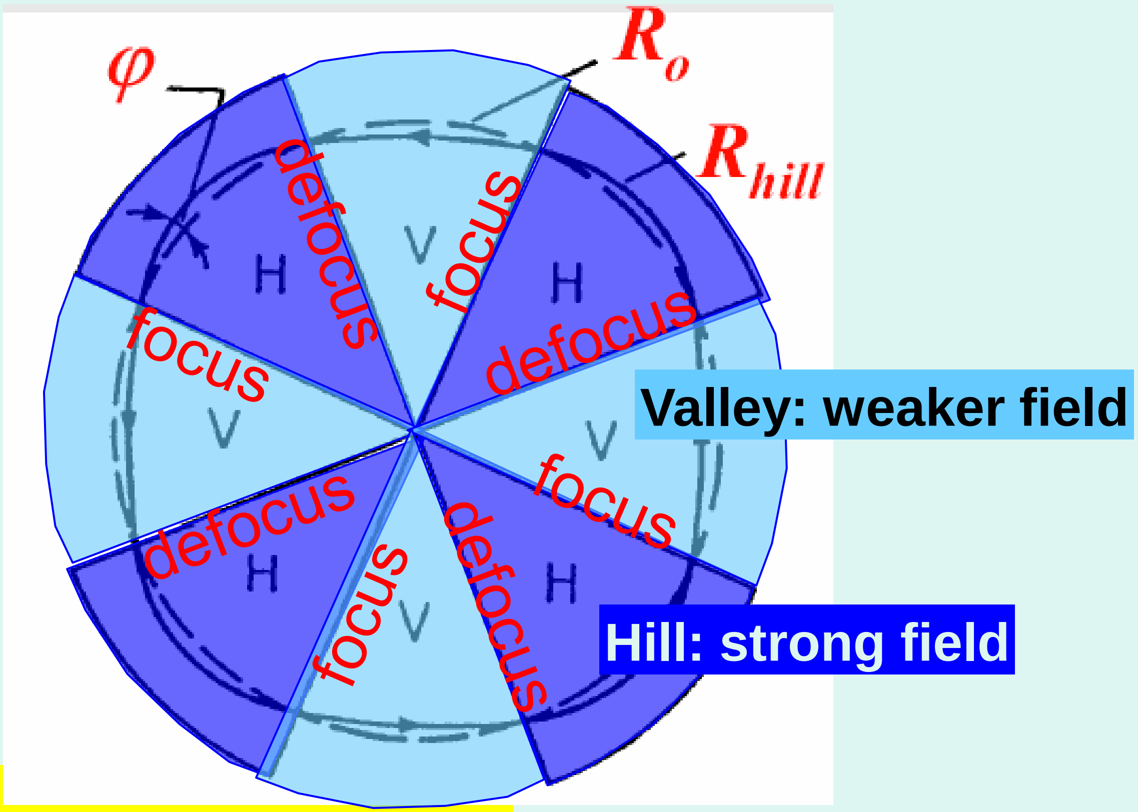
=> **n<0** => no **vertical stability**

Azimuthally Varying Field





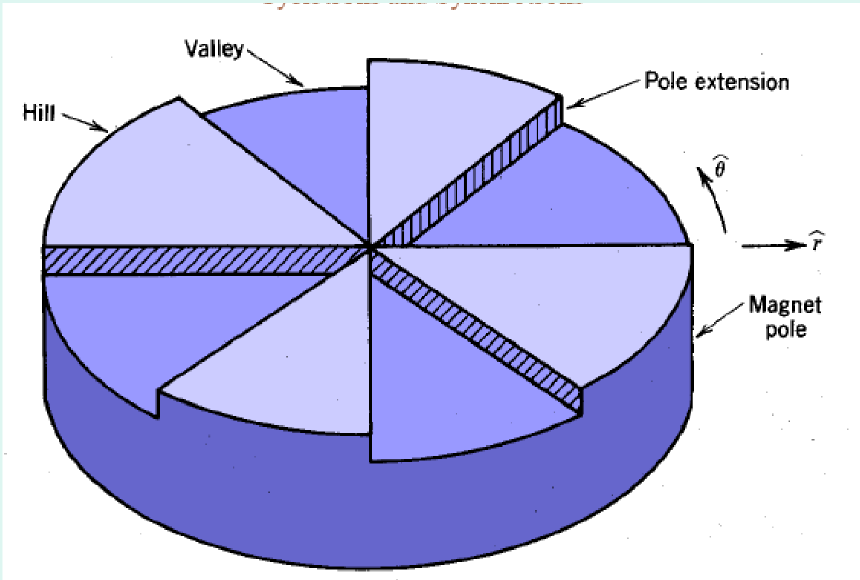
Thomas-Cyclotron (1938)

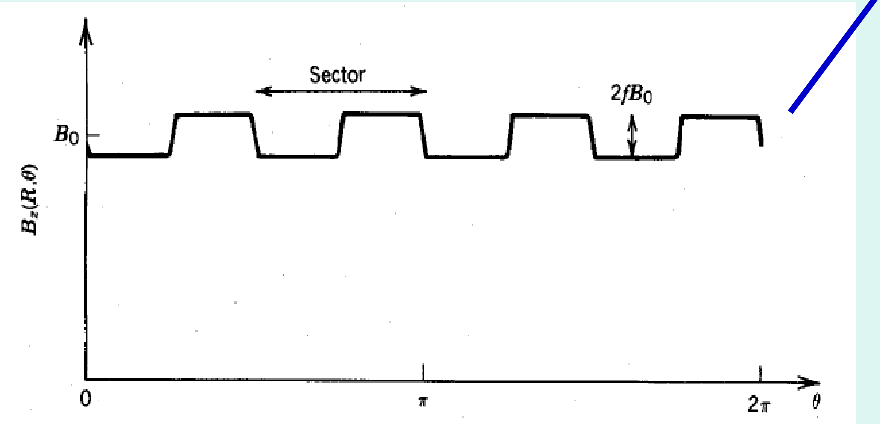


When crossing B-change **not** ⊥

=> vertical force from $B_s \times v$

Vertical focusing: AVF





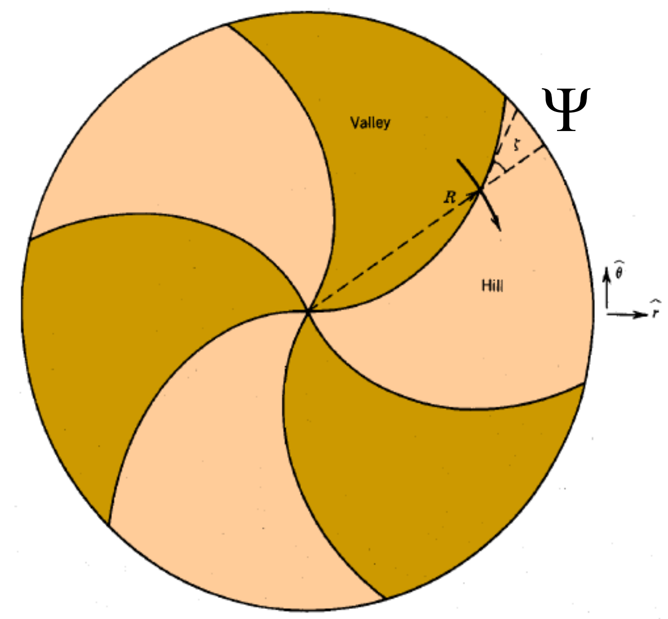
Flutter function:

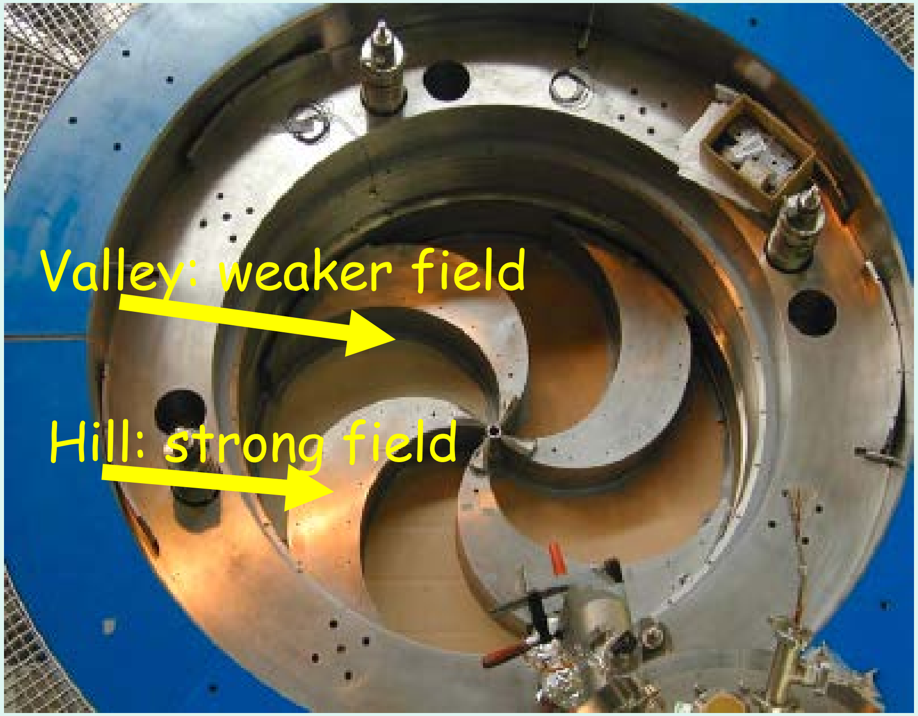
$$F(r) = \overline{\left(\frac{B(r,\theta)-\overline{B(r)}}{\overline{B(r)}}\right)^2}$$

Thomas focusing:

$$\nu_z^2(r)=\underset{\boxed{<0\,!}}{n}(r)+F(r)$$

AVF - Cyclotron




Valley: weaker field

Hill: strong field

$$\upsilon_z^2(R) = n(R) + F(R).(1+2\tan(\psi(R)))$$

to **compensate** :

- increasing Bρ
- Increasing defocussing by main field

=> increase angle Ψ with radius => **spiral**

AVF – Cyclotron: what tune diagram?

When crossing coupling resonance:

Beam centering reduces hor. betatron ampl.

approaching extraction: field edge

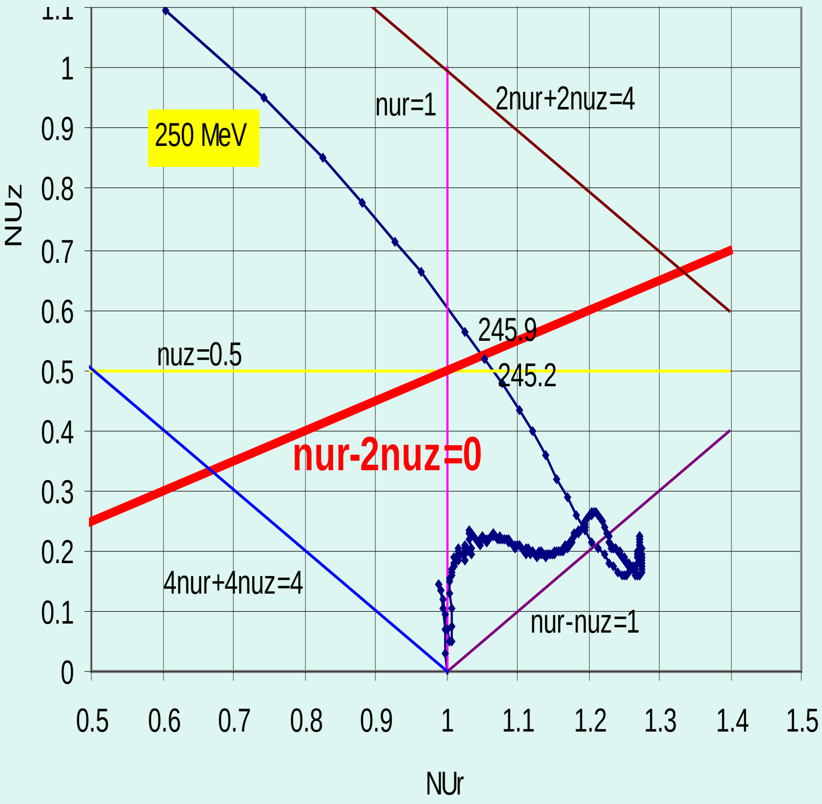
=> strong vertical focusing

=> In few turns towards extraction

r=10 -80 cm: $\nu_r(r)$ follows $\gamma(r)$

In central region: homogeneous field
=> No vertical focusing

AVF - Cyclotron



Design **shape of hills** such that:

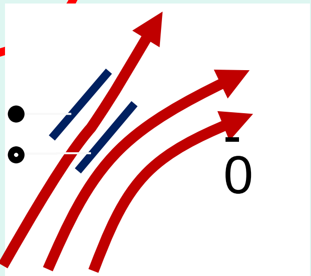
- enough vertical focusing: $\nu_z > 0.15$
- resonances are avoided
- resonances are crossed quickly

Extraction: maximize turn separation

Turn separation $$\frac{dr}{dn} = \frac{\gamma}{\gamma+1}.r.q.n_{cav}V_{dee}.\frac{1}{E}\frac{f^2}{\upsilon_r^2}$$

What will help:

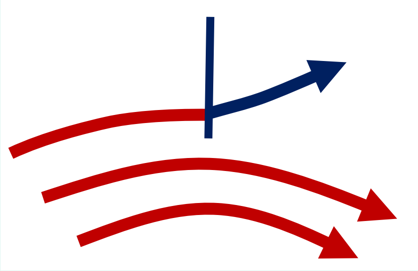
- Large radius of cyclotron
- Many high voltage cavities
- Exploit dropping of ν_r (=> fast drop of field)



In addition one could:

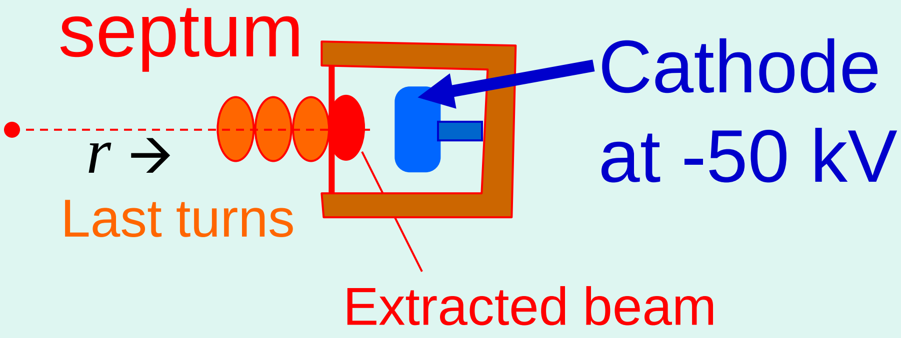
- Use resonances

  and increase betatron amplitude
- Use stripping reactions to change q



Extraction from cyclotron

$$\delta r \propto \frac{1}{r}$$



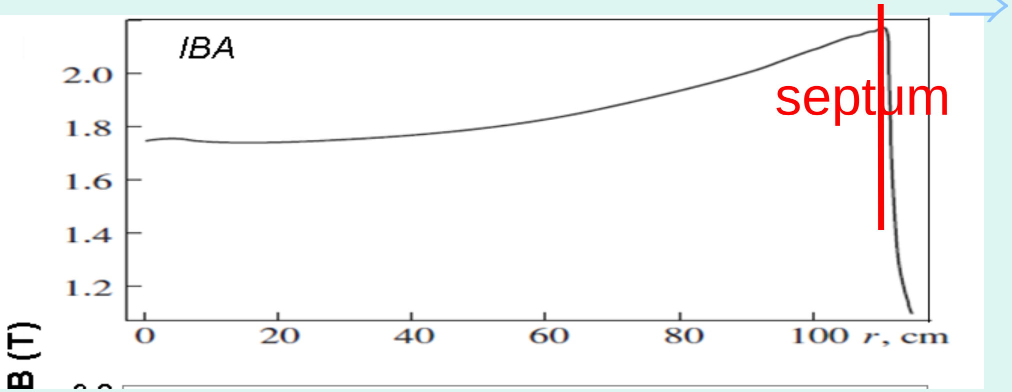
septum

Cathode
at -50 kV

r →

Last turns

Extracted beam



IBA and SHI: elliptical pole gap

⇒ Fast field drop at outer radius

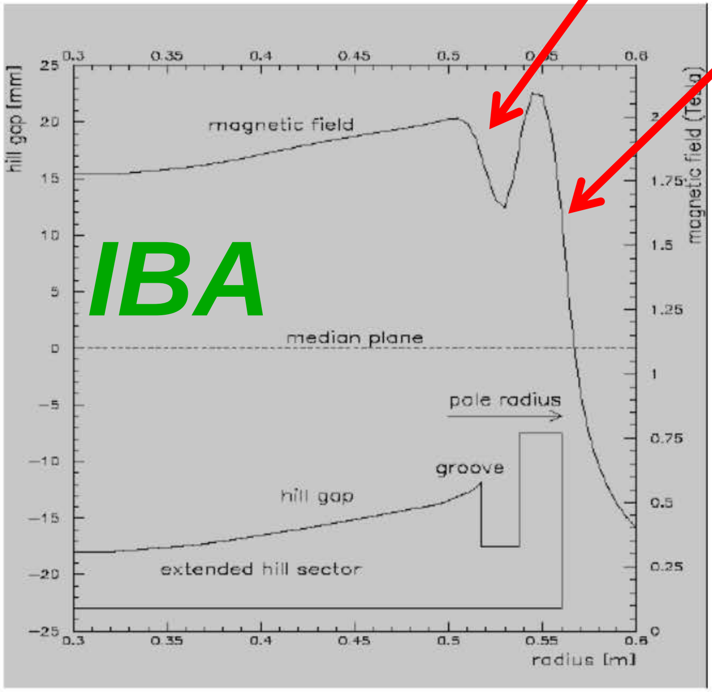
⇒ Cathode + weaker field quickly pull the beam „out“

Extraction from cyclotron

Self-extraction: Realization *by IBA*

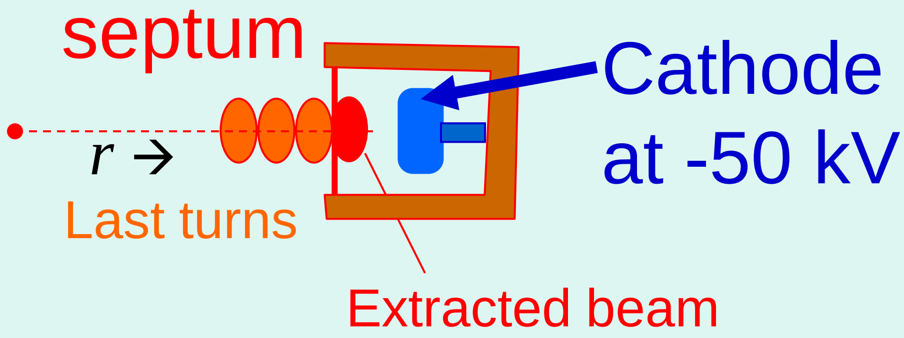
Small elliptical hill gap ⇒ allows for sharp radial gradients

‘magnetic septum’ ⇒ groove machined in the pole



Pole with goove

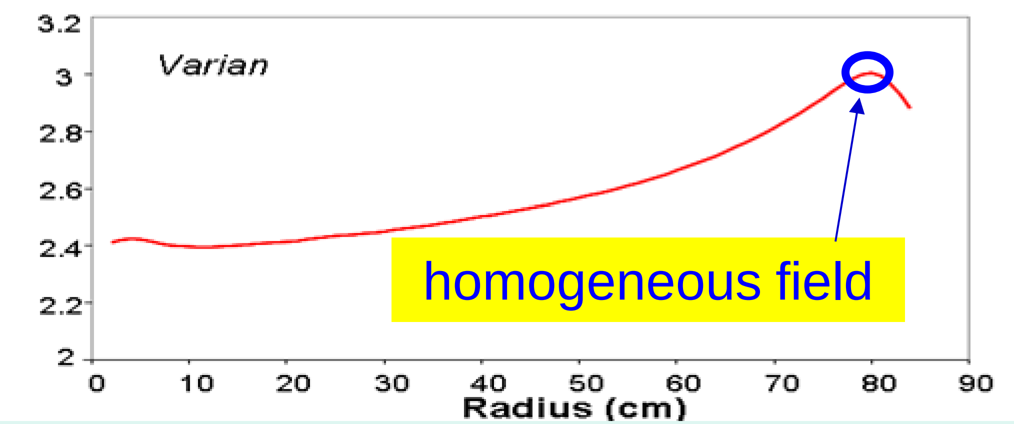
Extraction from cyclotron



Varian:

flat poles & stronger field

=> Use resonance

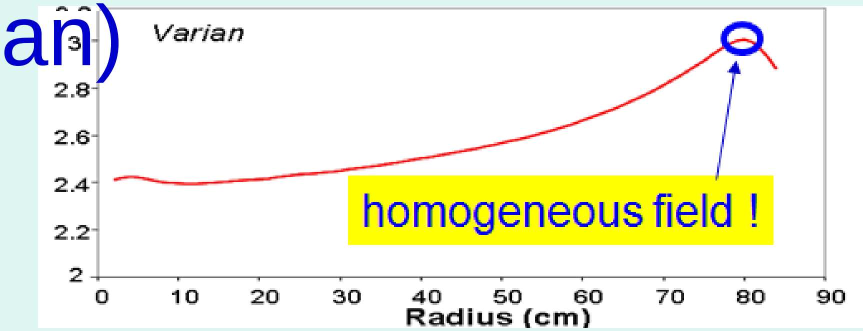


Extraction from cyclotron

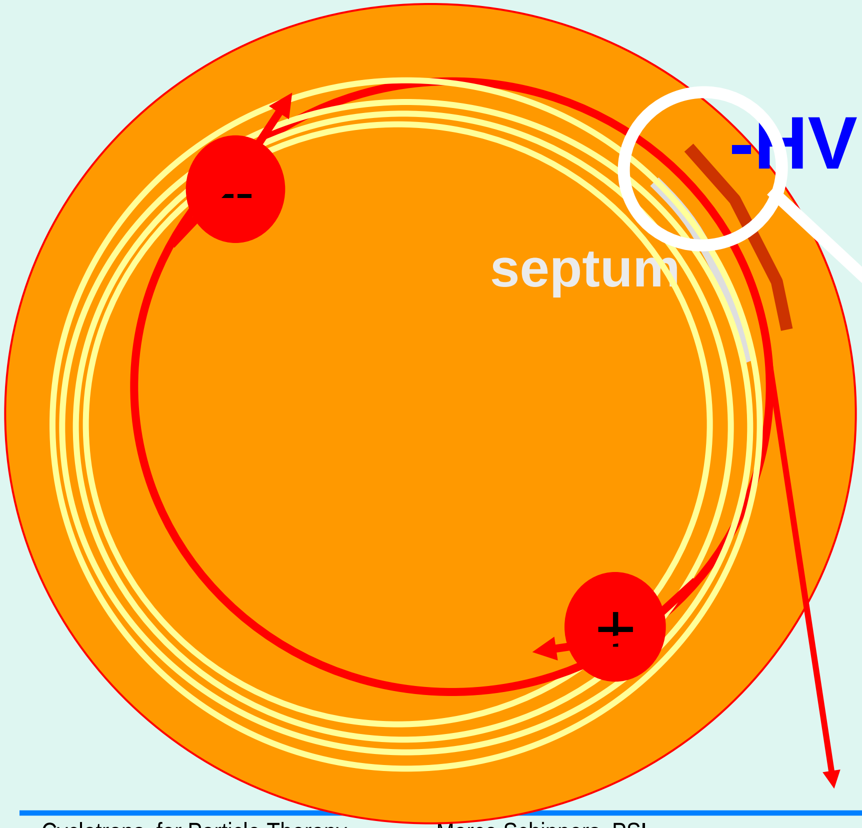
Resonant extraction (Varian)

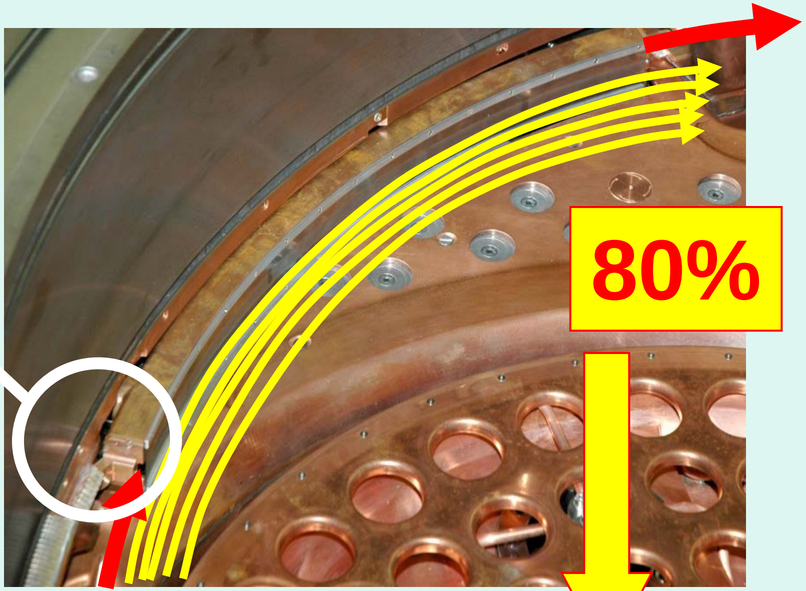
uses homogeneous field ! $\nu_r=1$

→ Field bump shifts beam:



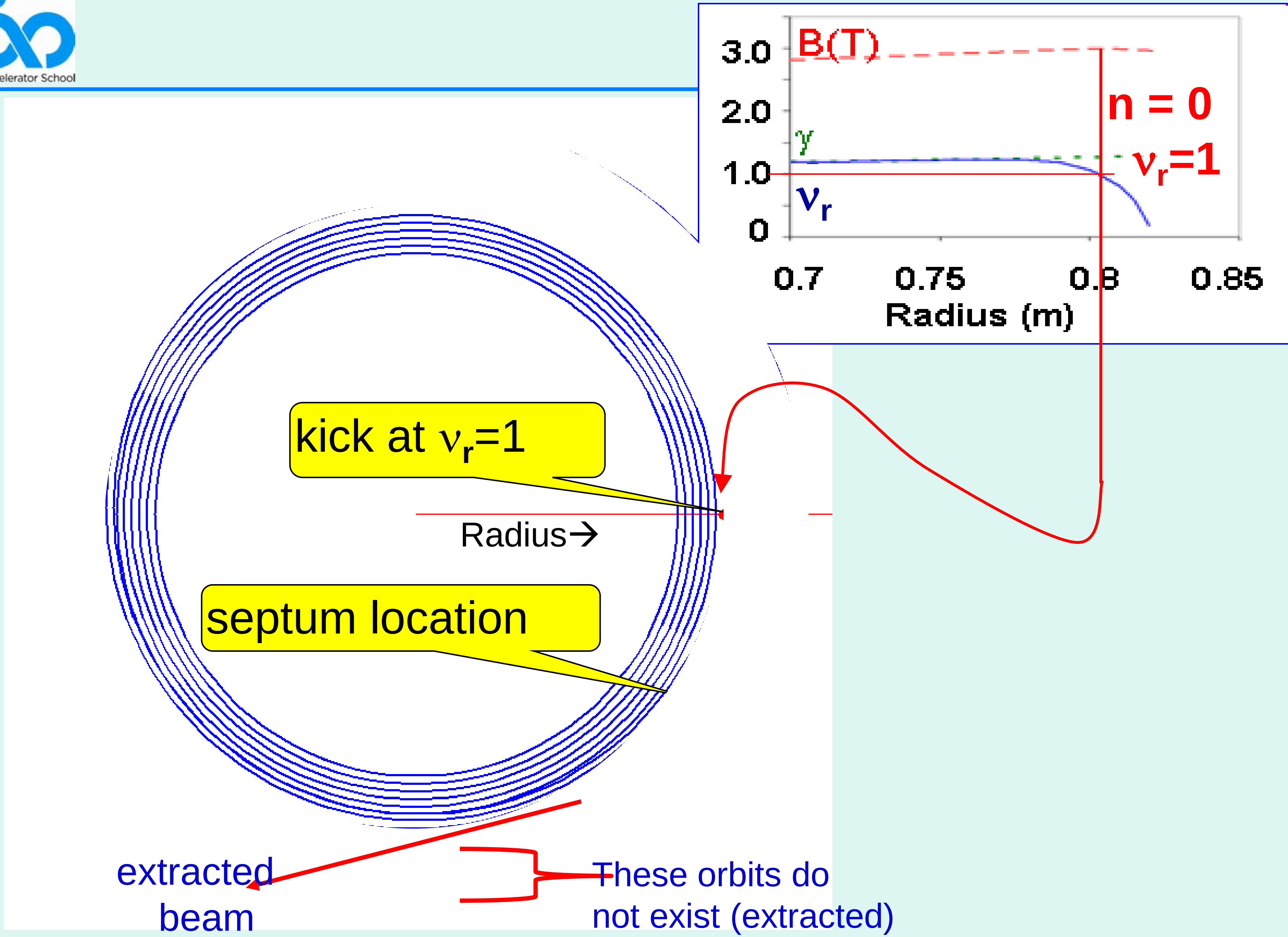
homogeneous field !





80%

Low radioactivity



kick at ν_r=1

Radius→

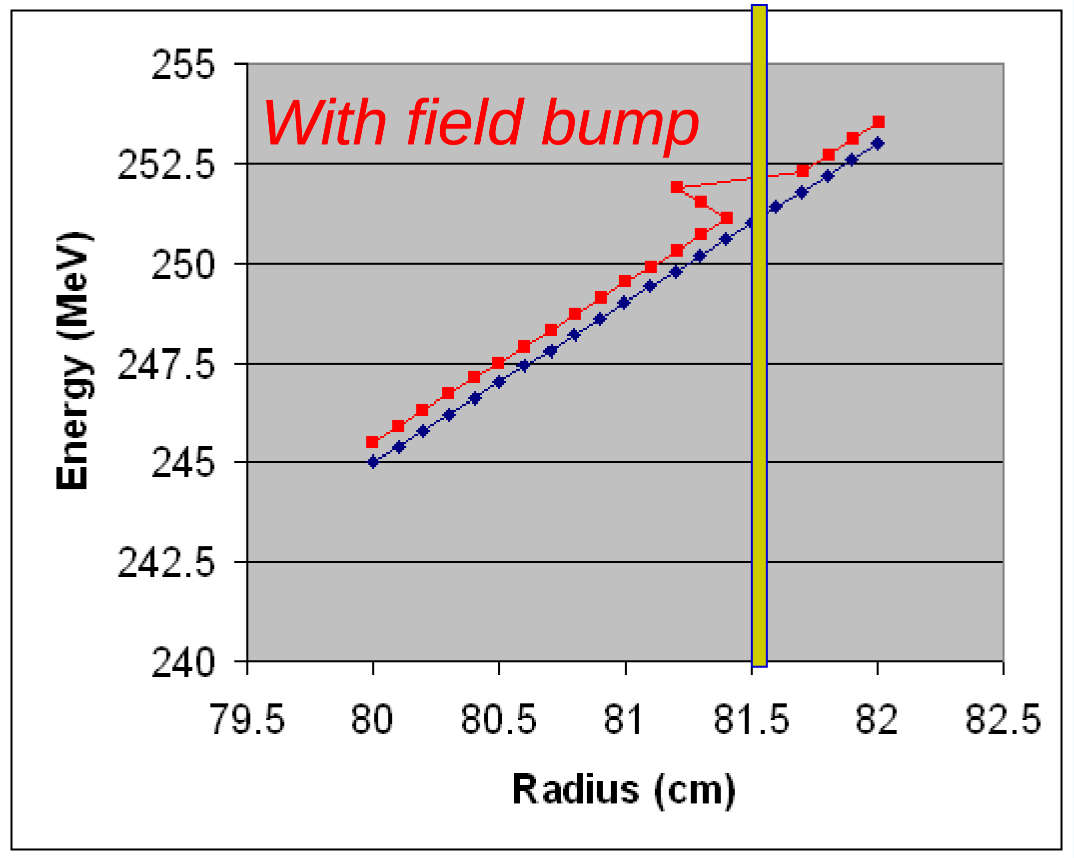
septum location

extracted beam

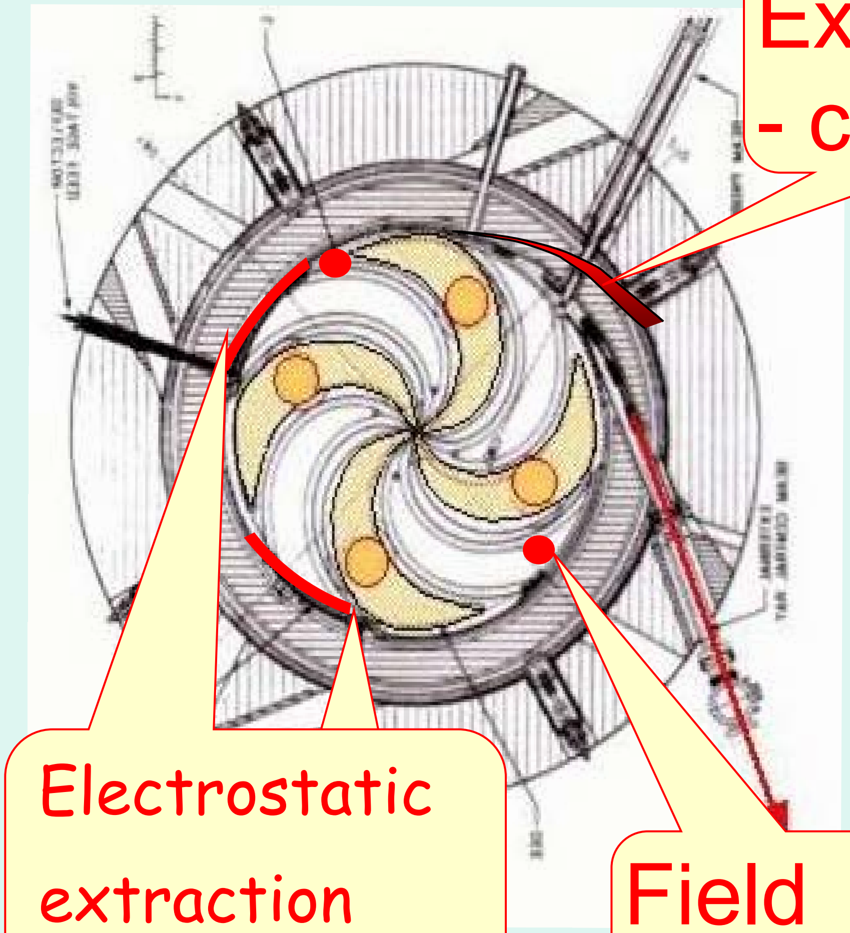
These orbits do not exist (extracted)

Extraction from cyclotron

resonant extraction



Extraction from cyclotron



Extraction - chanel

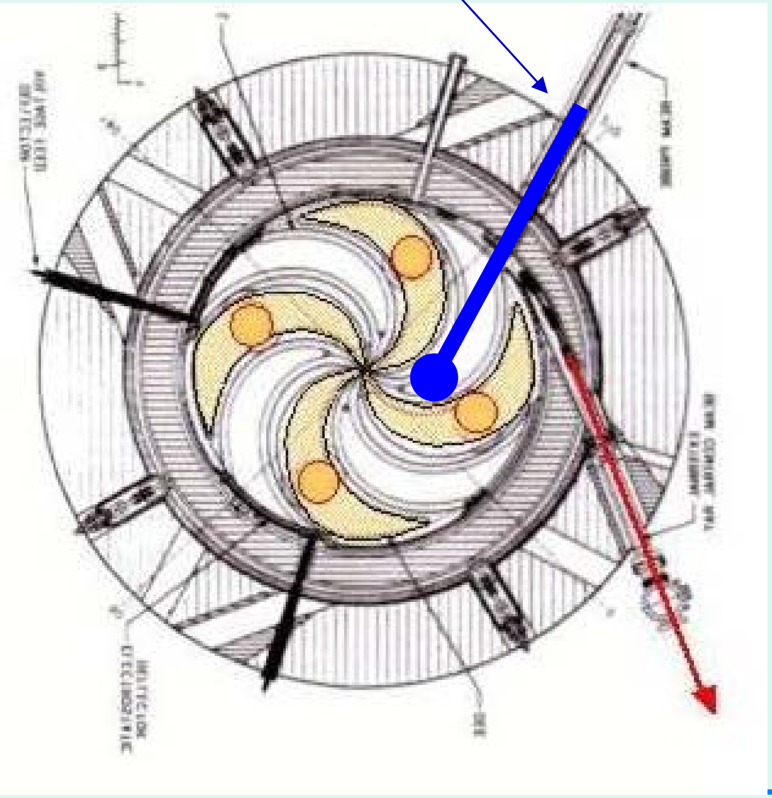
Electrostatic extraction elements

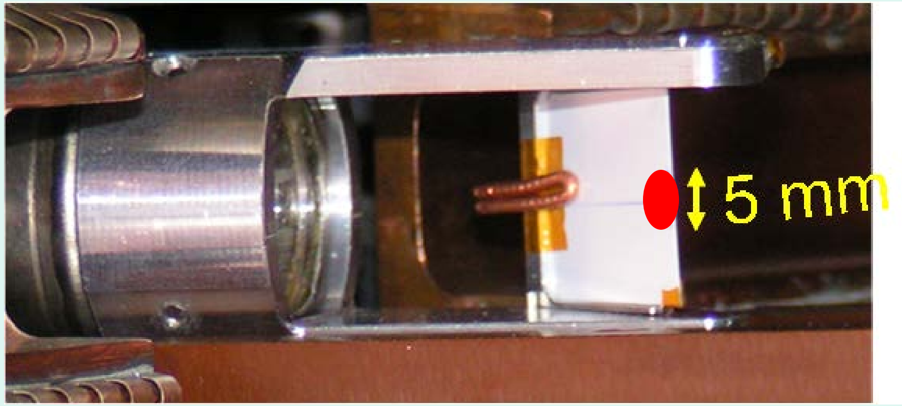
Field bump

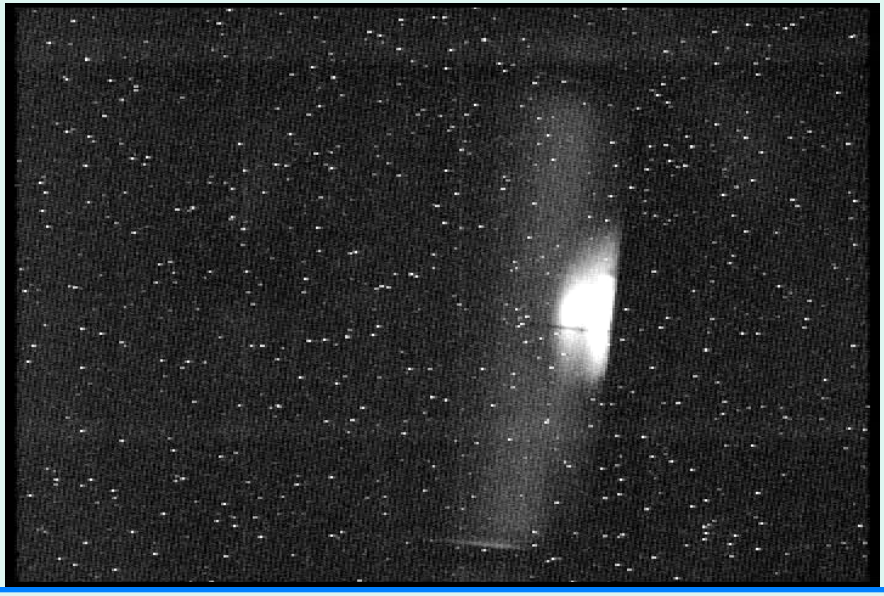
CEL / Varian)

Effect of centering just before extraction

Radial probe with camera + screen

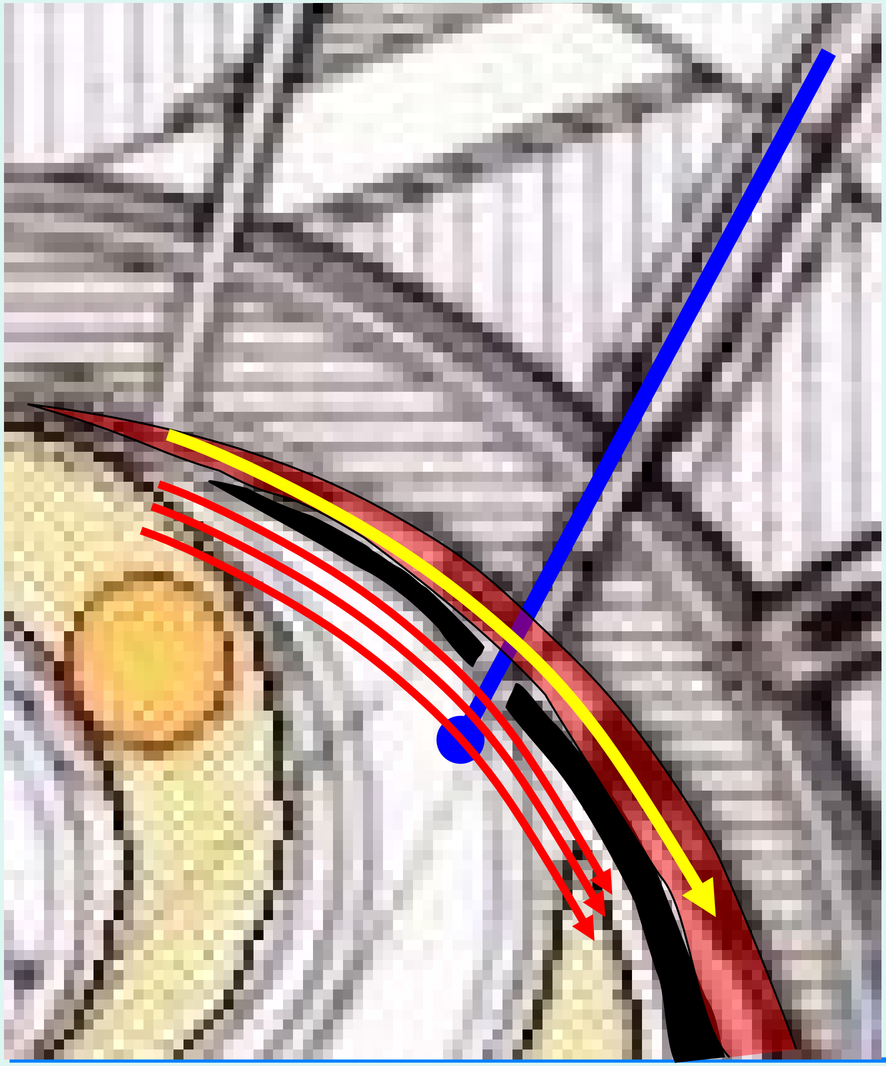


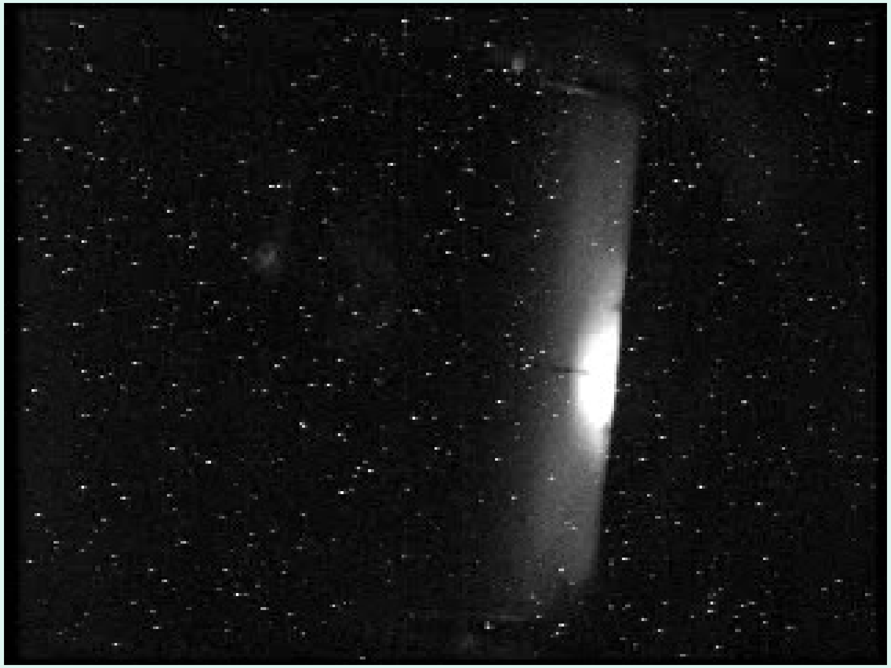




bad340d050G-1580-1285-01.mpg 1:01

through the extraction channel





After centering

Extraction-roxio1.mpg *0:40*

Summary and Conclusions

Advantages of a cyclotron

=> a cyclotron provides:

- continuous beam
- «any» intensity
- very fast adjustable intensity
- accurate intensity control
- great reliability (few components)

\+ range change of 5 mm < 100 ms

(with fast degrader and good magnets + power supplies)

Disadvantages: - activation of components near degrader

- no carbon ions (yet)

Relevant cyclotron specs for therapy

- Energy + its stability
- Beam size (emittance)
- Beam intensity: structure, stability (kHz) , adjustability (range, speed)
- Extraction efficiency

- Reliability
- Needed start up time after „off“ and after „open“
- modular control systems + comprehensive user interface
- Maintenance interval, maintenance time, maintenance effort
- Activation level (person dose per year)

- Ions: time to switch ion species
- Synchro cycl: rep. rate, dose/pulse adjustable (scanning)?

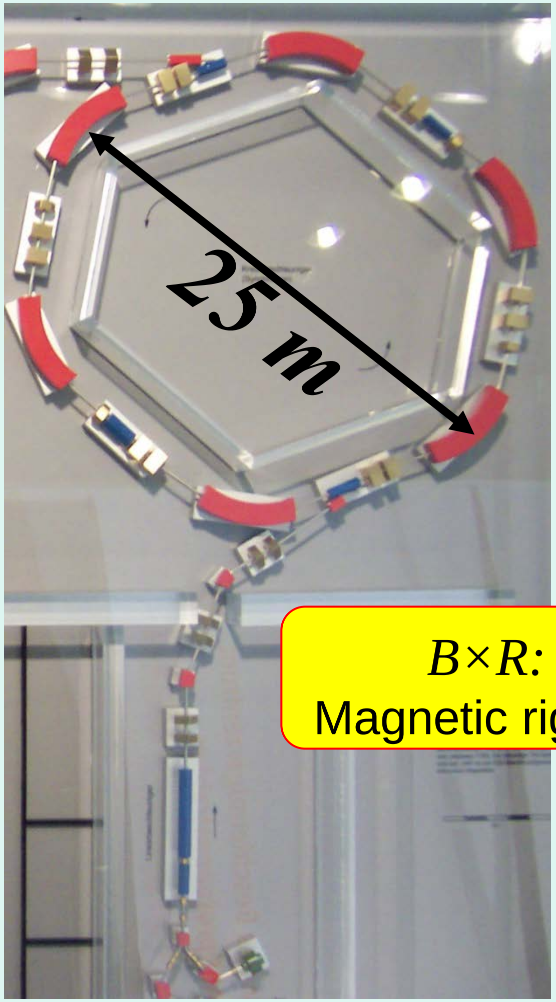
some differences…

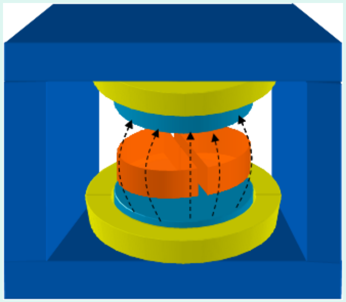
	cyclotron	synchro-cycl
Time structure	continuous	pulsed
Intensity	“any”	low
Size ∅	3.5 - 5 m	<2m
Scattering	ok	ok
Spot scanning	**ok**	>2 pulses/spot
Fast continuous scanning	**ok**	no


Achtung Magnetfelder!
Attention Magnetic fields!
cm ab
Oberfläche
SMA 1X/Y

Thank you !!

Carbon-ion cyclotrons





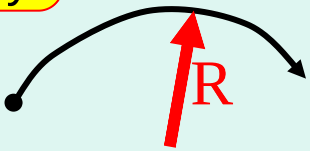
Carbon 6+
(450 MeV/nucl)

6.83 Tm

Proton
(250 MeV)

2.43 Tm

B×R:
Magnetic rigidity



⇒ Cyclotron radius of C is **2.8** x R proton cyclotron

⇒ pole area x 2.8^2 = 8 x more iron => **700-800 tons**

Cyclotron for carbon ions

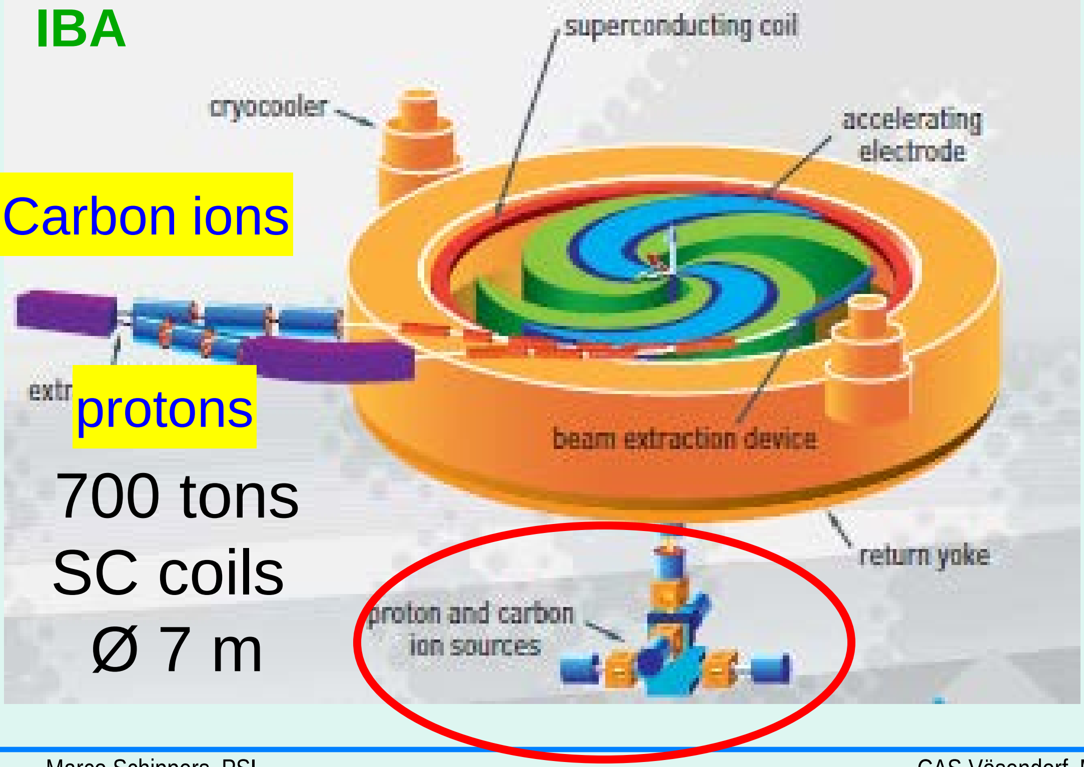
Archade project, Caen (Fr)

Int. Conf. Cyclotron and appl, Tokyo 2004

IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY

Y. Jongen, M. Abs, W. Beeckman, A. Blondin, W. Kleeven, D. Vandeplassche, S. Zaremba,
IBA, Belgium
V. Aleksandrov, A. Glazov, S. Gurskiy, G. Karamysheva, N. Kazarinov, S. Kostromin,
N. Morozov, E. Samsonov, V. Shevtsov, G. Shirkov, E. Syresin, A. Tuzikov, JINR, Russia.

Archade
ADVANCED RESOURCE CENTRE
FOR HADRONTHERAPY IN EUROPE



IBA

Carbon ions

protons

700 tons
SC coils
Ø 7 m