Introduction to the cyclotron

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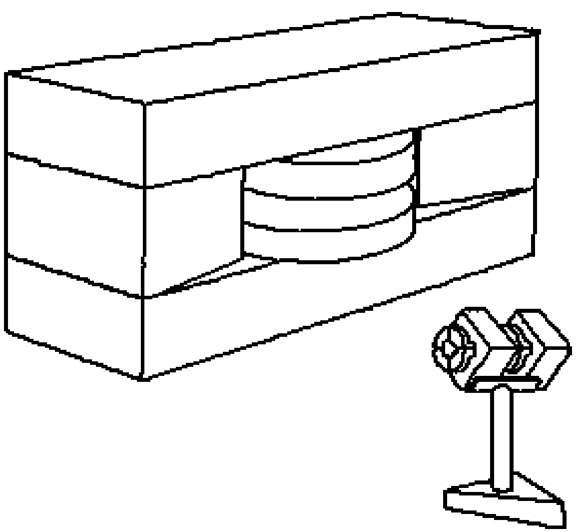
Slides contain material and images from many collegues at PSI and various companies

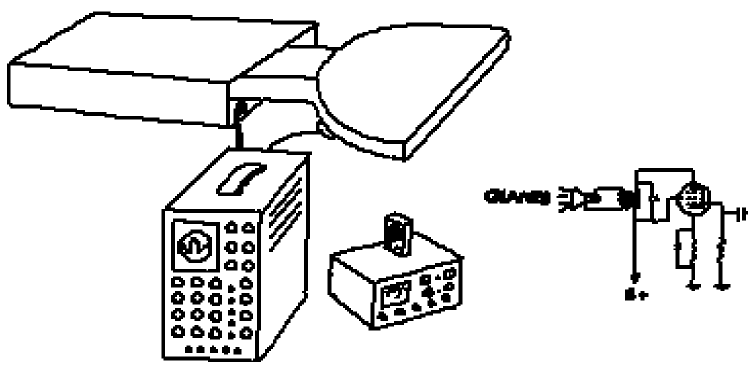
CYCLOTRON

Contents:

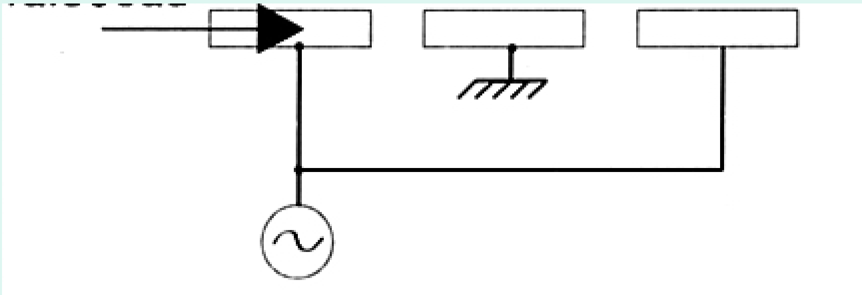
- How has the cyclotron **evolved**?
- **Isochronicity**: a basic operation principle
- Ion source, Acceleration, Extraction



Cyclotron, as seen by teachers

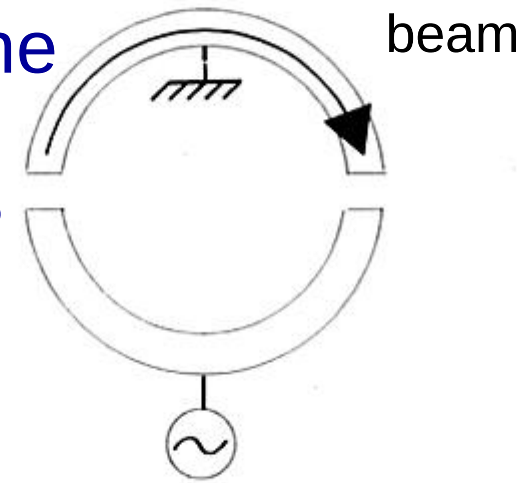


Metamorphosis



Wideroe's linear accelerator (1927)

Could one re-use the RF ?



$$\frac{mv^2}{r} = Bqv$$

$$v = \frac{2\pi r}{T_{circle}}$$

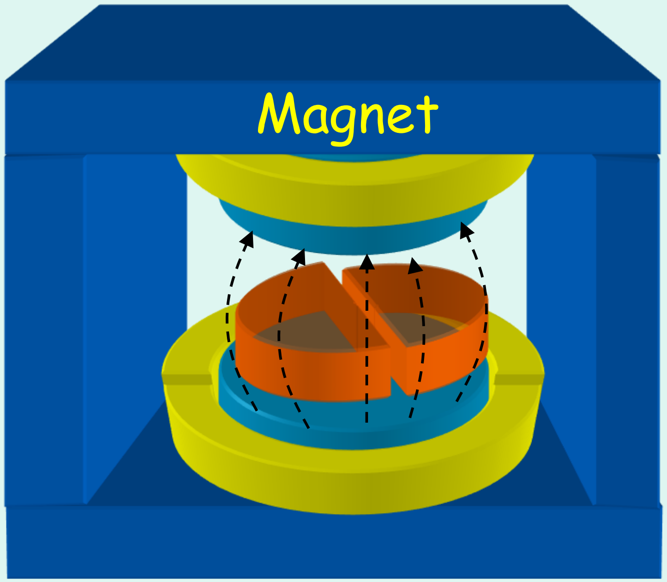
$$T_{circle} = \frac{2\pi r}{v} = \frac{2\pi m r}{Bqr} = \frac{2\pi . m}{Bq}$$

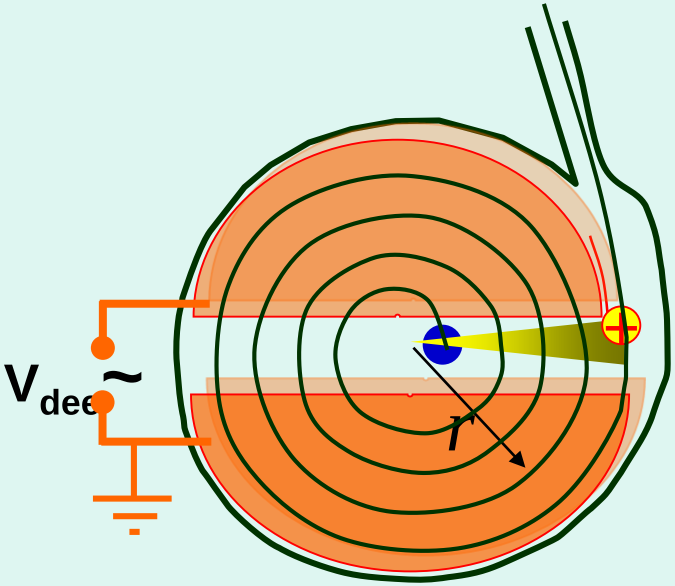
„r cancels r…. don't you see what this means?

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

(Lawrence to his PhD student, while bursting into his lab, 1931)

Cyclotron





Only particles that cross gap at right moment **are accelerated**

At electrode slit crossing: Energy gain $\Delta E = q.V_{dee}$

Larger E → larger r → spiral

Since T_{circle} = constant, all particles cross acc. gap **at same moment** !

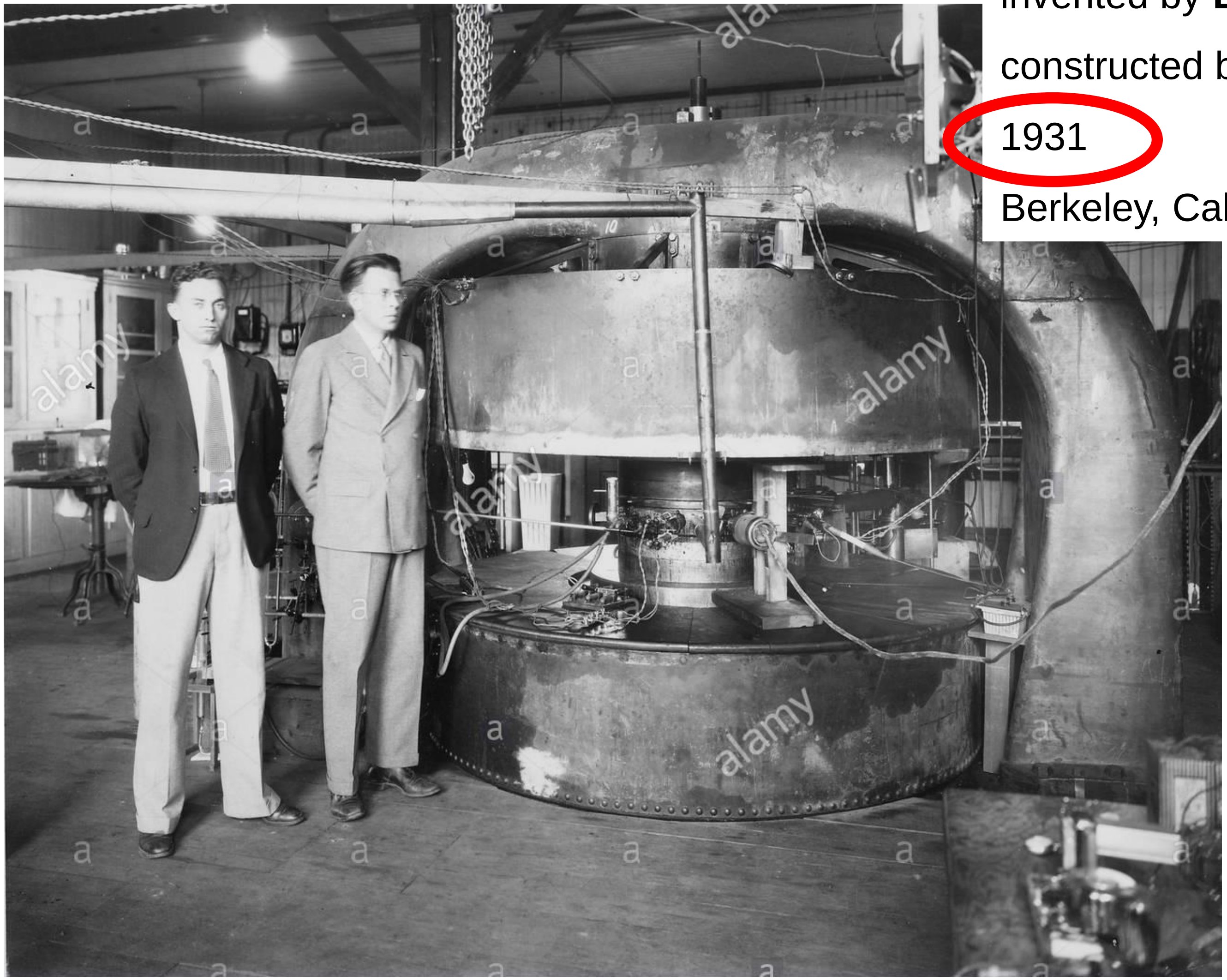
the first Cyclotron

invented by **E.O.Lawrence**,

constructed by M.S.Livingston

1931

Berkeley, California



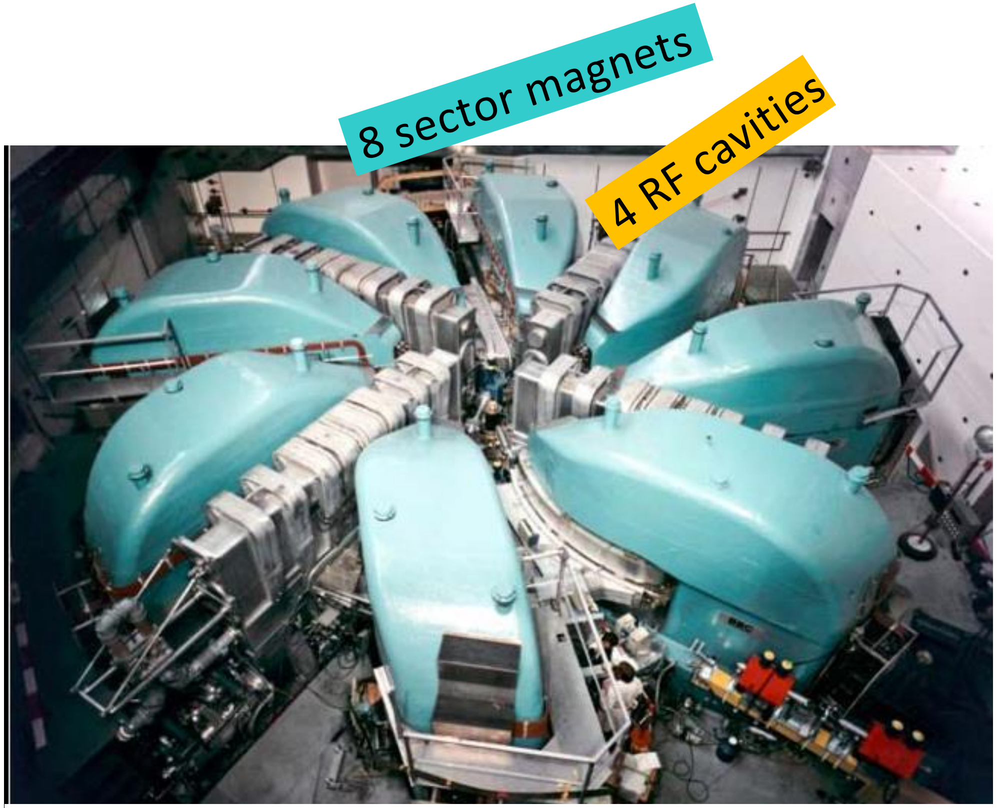
Stanley Livingston (L) and Ernest Lawrence in front of 27-inch cyclotron (several MeV), Berkeley 1934.

credit:
Lawrence Berkeley Nat'l Lab

Big Cyclotrons

single magnet → sector magnets

UCL 1946:
-Magnet:184-inch 300-ton
-Dees at 1 or 2 MV
e.g. 400 MeV He



590-MeV RING cyclotron
(PSI, 1974)

compact cyclotrons for isotope production: 10-30 MeV

Vertical orientation

proton therapy cycl.: 230 / 250 MeV

Superconducting Coils

IBA (1996) , SHI

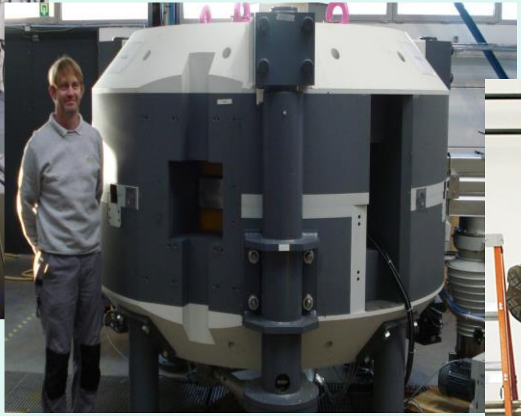
250 Tons

Isochronous Cyclotron

Varian (2005)

90 Tons

Isochronous Cyclotron



IBA (2018)

60 Tons

Synchrocyclotron

MEVION (2013)

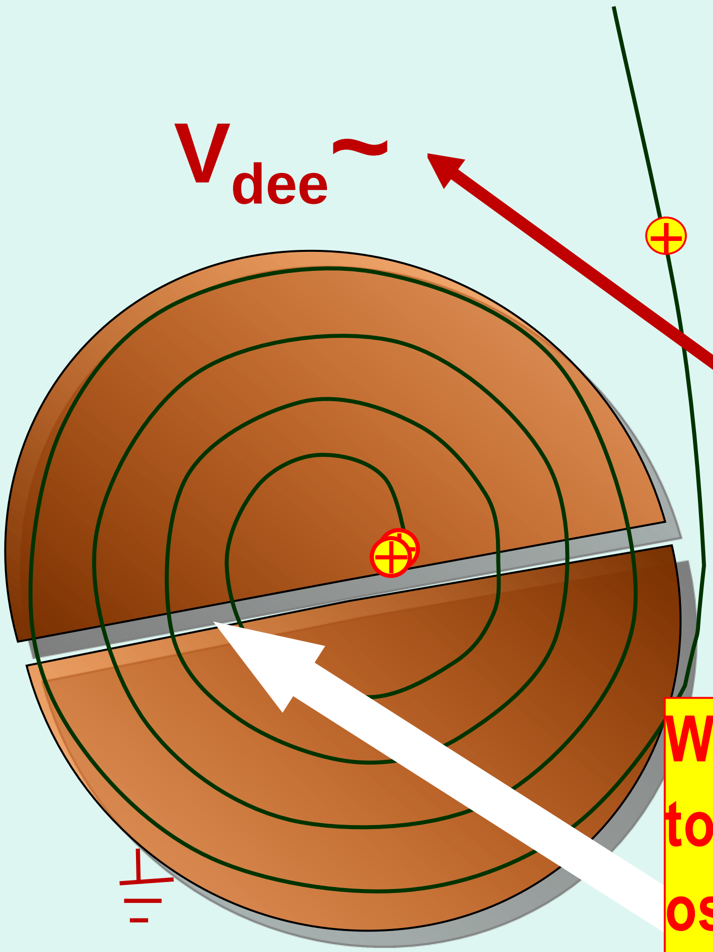
17 Tons

Synchrocyclotron

Isochronicity

Cyclotrons for 30-1000 MeV:
Isochronicity = be on time

Isochronicity



B → (almost) circular orbits:

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

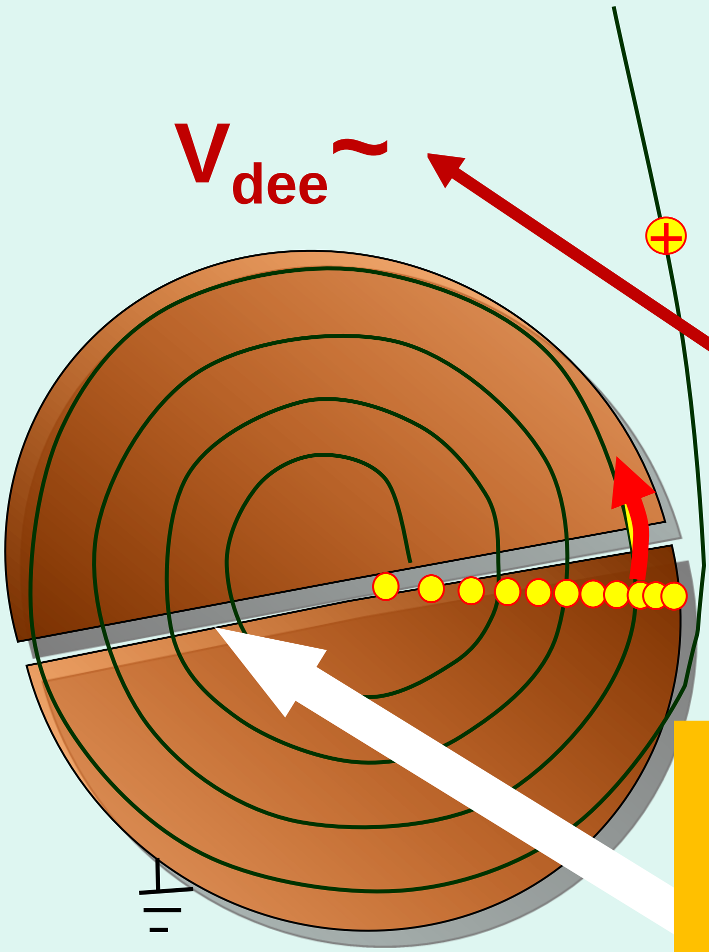
⇒ at B=2.4T: $T_{circle} \approx 30$ ns

oscillating voltage at

RF freq = 1/ T_{circle} = **33 MHz**

What will happen with particles that are too early or too late with respect to oscillating voltage phase (+/-) ?

Isochronicity



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

⇒ at B=2.4T: $T_{circle} \approx$ 30 ns

RF freq = 1/ T_{circle} = **33 MHz**

Only when the gap is crossed
at the right RF-phase,
→ Voltage is **accelerating**
→ Otherwise **particles get lost**

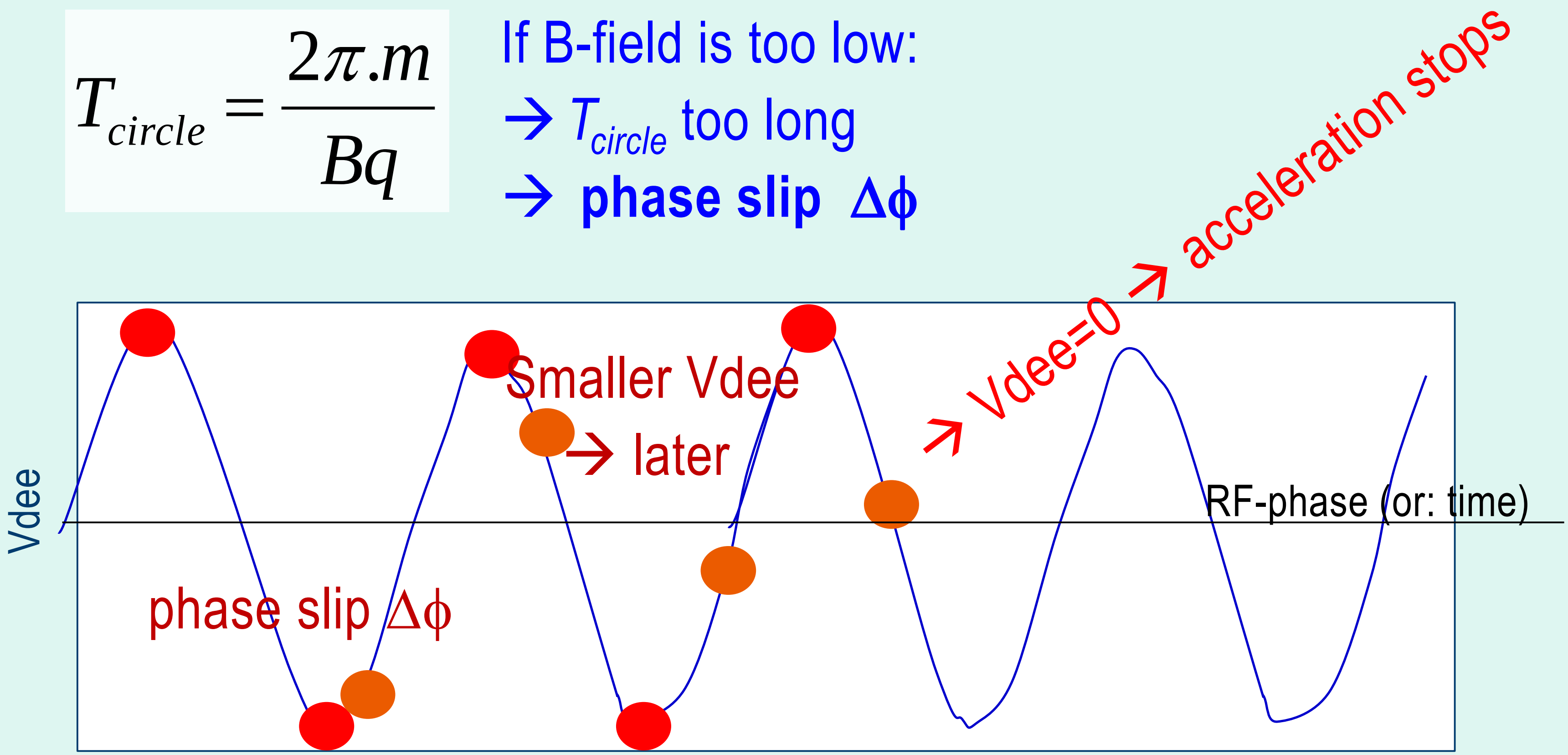
Cyclotron

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

If B-field is too low:

→ T_{circle} too long

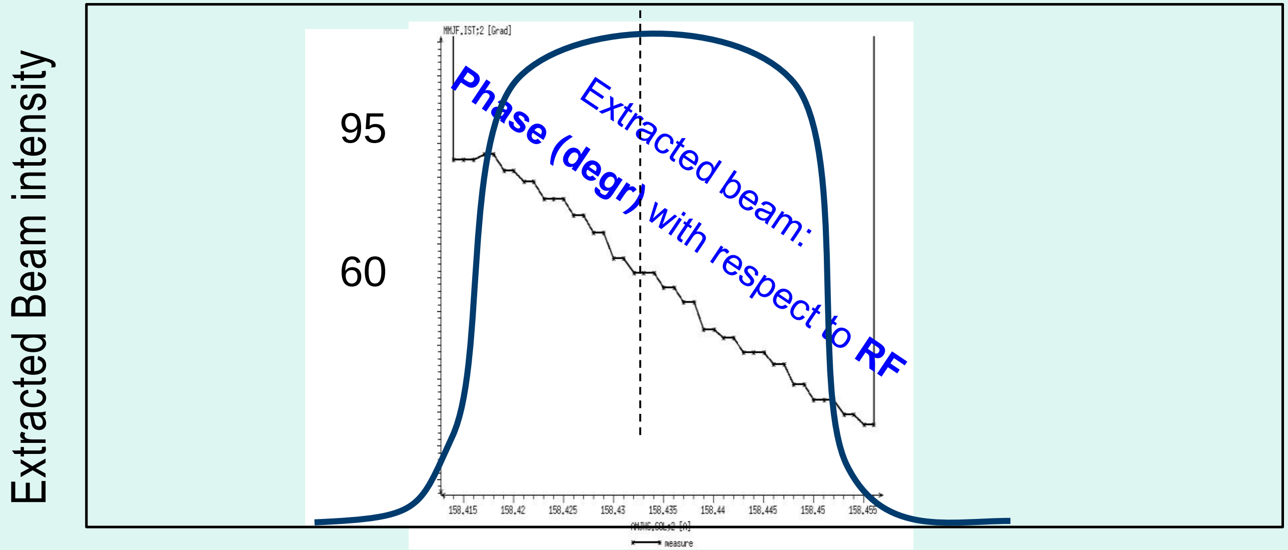
→ **phase slip Δϕ**



ϕ= π/2 →Acceleration stops after n x phase slip of Δϕ

Isochronicity in a cyclotron

At a given f_{RF}, B must be correct within 10^{-4}
to have particles crossing the gap at right phase



Magnetic field error -10^{-4} B_0 $+10^{-4}$

Magnet current 99.99 100 100.01 (A)

Resonance curve (Smith Garren, 1963)

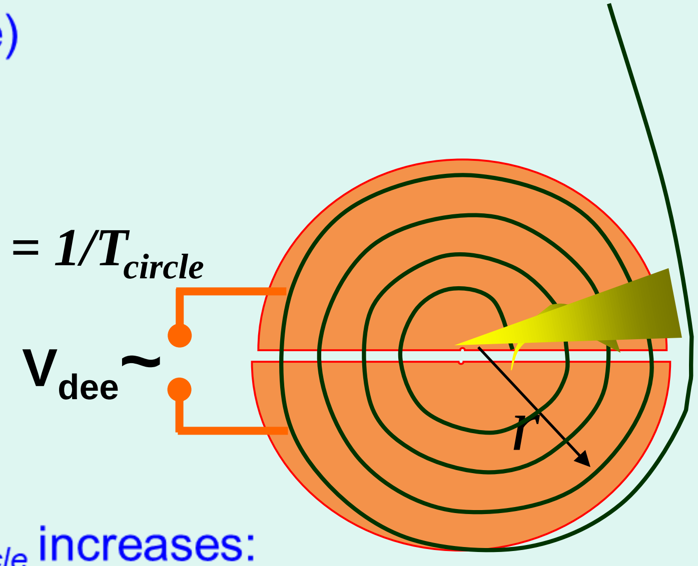
> 30 MeV cyclotron

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

(particles move in pace with Vdee)

BUT…. $m=\gamma m_0$ $\quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$

$Freq = 1/T_{circle}$



At high energy ***m*** increases

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

⇒ T_{circle} increases:

10 MeV p:	v/c=0.14	=>	m=**1.01** m_0
250 MeV p:	v/c=0.61	=>	m=**1.27** m_0
590 MeV p:	v/c=0.79	=>	m=**1.63** m_0

Remedy 1:

Synchro-cyclotron

Synchro-Cyclotron

So: Problem = T_{circle} increases with radius.

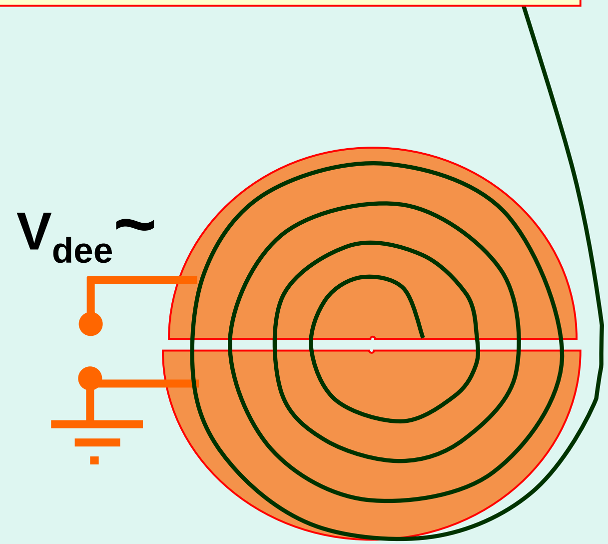
REMEDY 1:

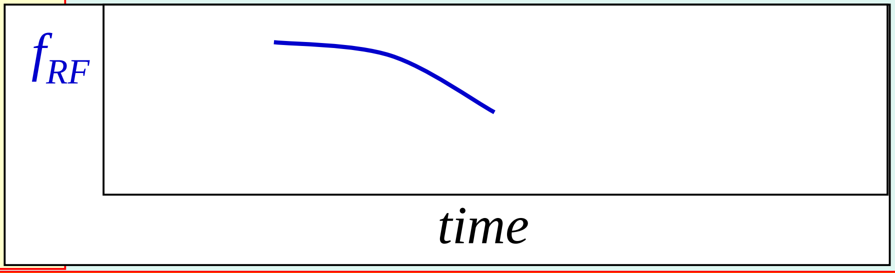
Decrease f_{RF} with $1/T_{circle}$ in time, synchronous to mass:

$$\omega_{rf}(t) = \frac{qB}{m(t)}$$

….. and extract

Repeat 300-1000 x per sec





How will the time structure of the outcoming beam look like?

Synchro-Cyclotron

So: Problem = T_{circle} increases with radius.

REMEDY 1:

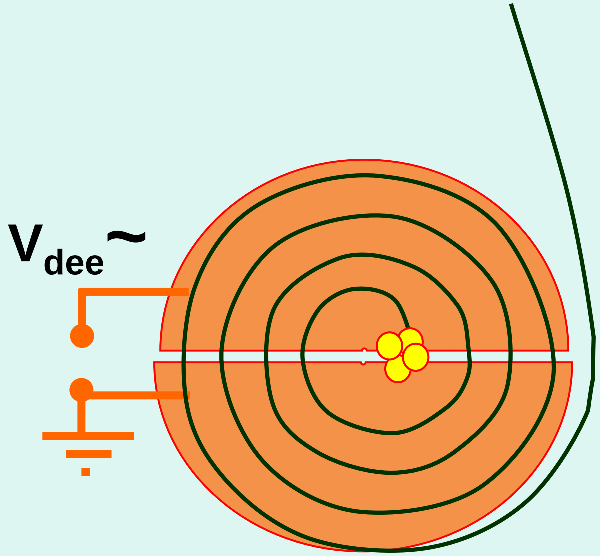
Decrease f_{RF} with $1/T_{circle}$ in time, synchronous to mass:

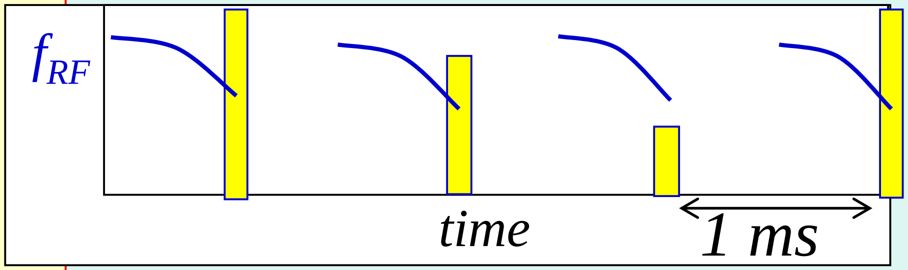
$$\omega_{rf}(t) = \frac{qB}{m(t)}$$

….. and extract

Repeat 300-1000 x per sec

→ Pulsed beam 300-1000 Hz

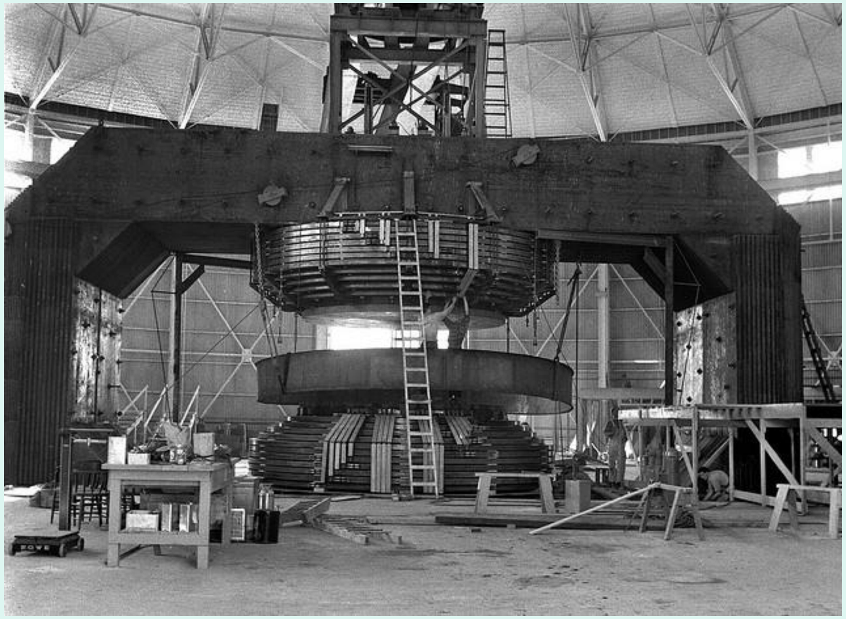




Synchro-cyclotron

synchro-cyclotron: High energies …1000 MeV

Fields of 1.5-2 T => large magnet poles



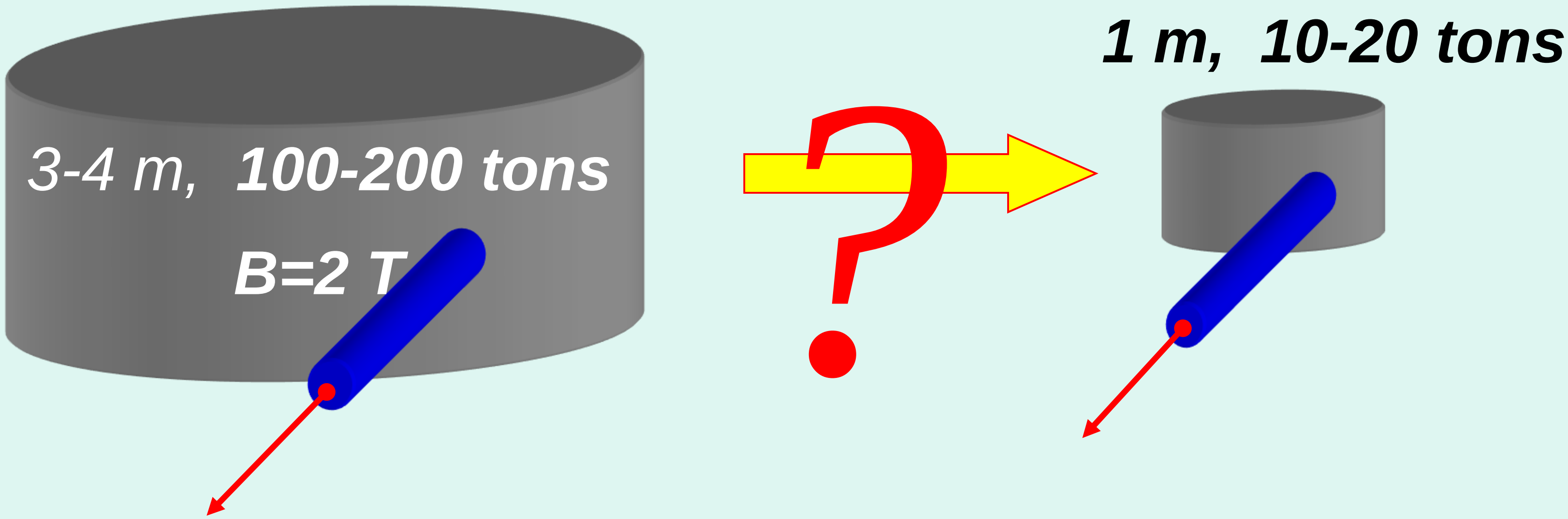
4.7 m∅ (4300 tons) Cyclotron (in 1942)

380 MeV , 1957: 720 MeV

credit: Lawrence Berkeley Nat'l Lab

CERN: 600 MeV proton Synchro-Cylotron 1957-1991.

Small cyclotron



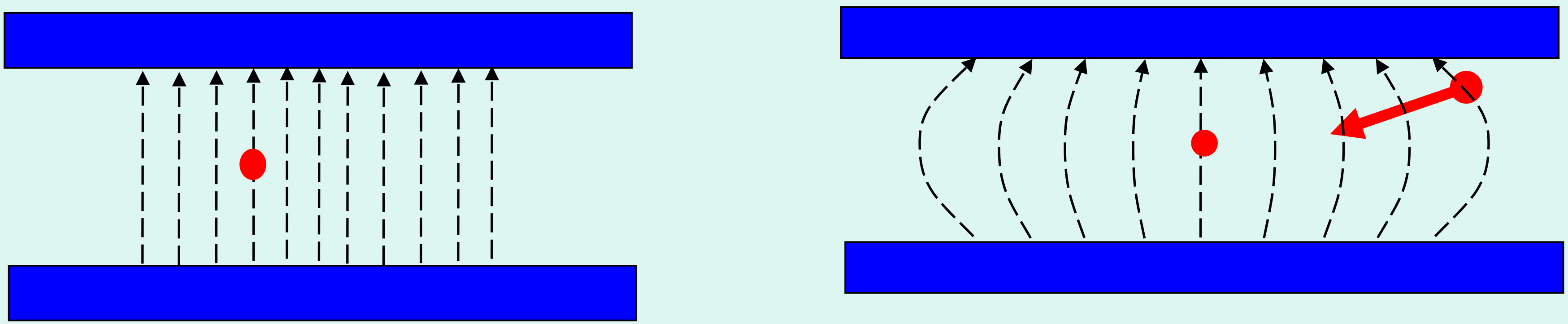
Solution:

Increase magnetic field: ***B=6-10 T***

=> Smaller orbit radius

Synchro-Cyclotron

very strong magnetic field:



homogeneous field → no vertical focusing

→ reduce field with radius

→ weak vertical focusing

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

T_{circle} increases with radius.

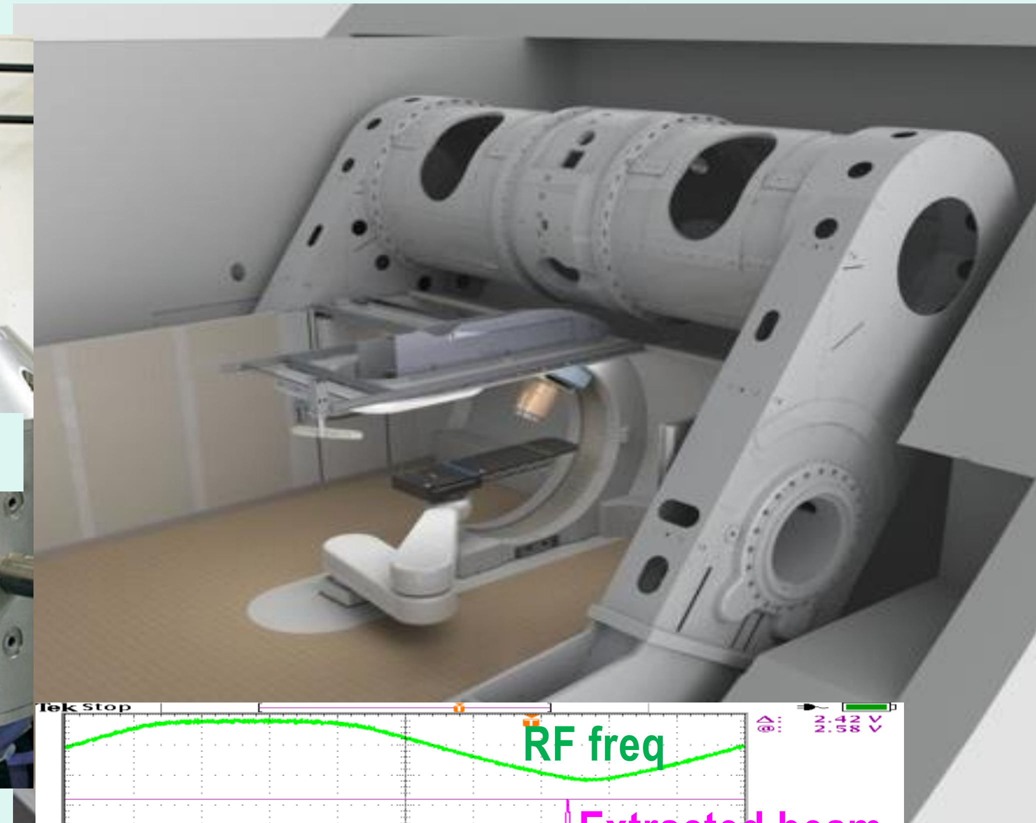
→ Similar effect as mass increase! → decrease f_{RF} with radius and extract

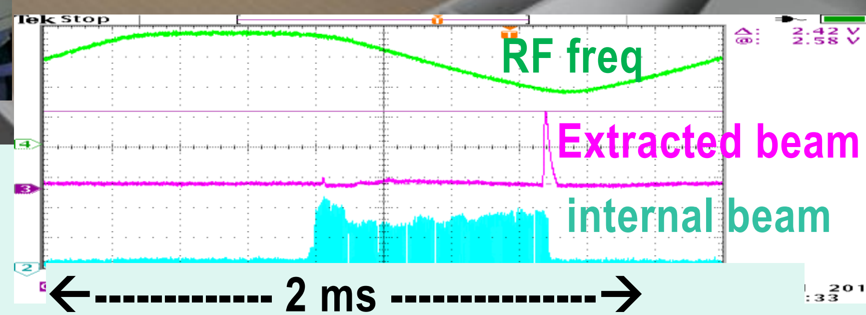
Synchro-cyclotron

2013: 250 MeV Synchro-cyclotron on a gantry

MEVION medical systems

8.5 T, 250 MeV, 500 Hz





REMEDY 2:

Correct with B-field:

Increase B with radius, **(=** r~*m*):

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

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

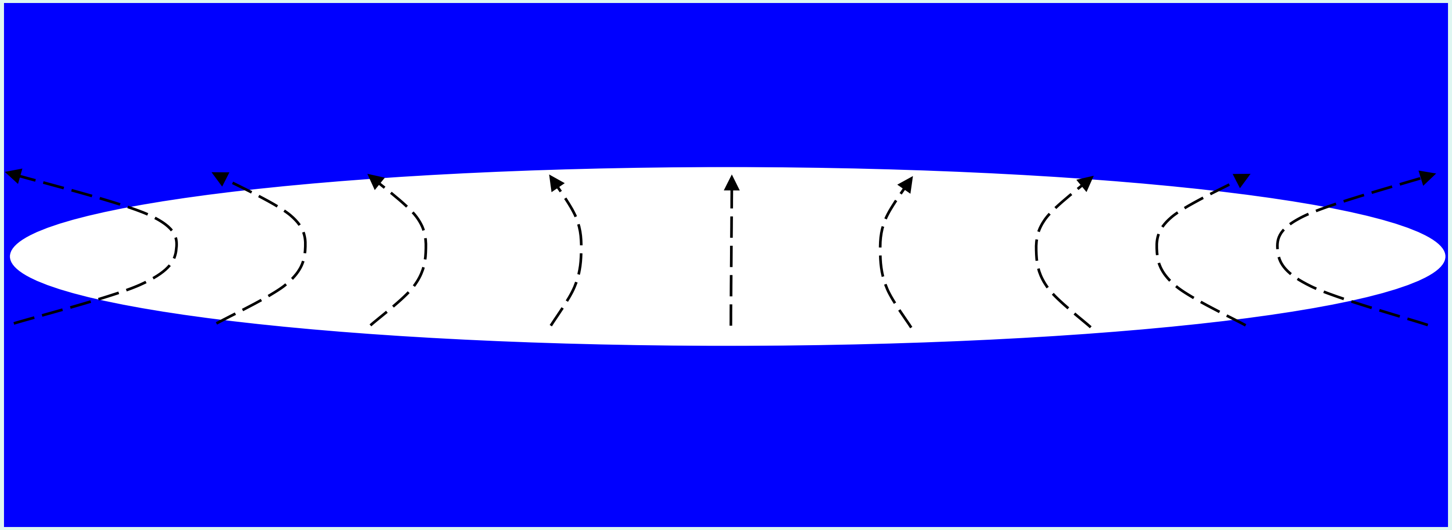
isochronous cyclotron

Remedy 2:

Increase the field strength with radius

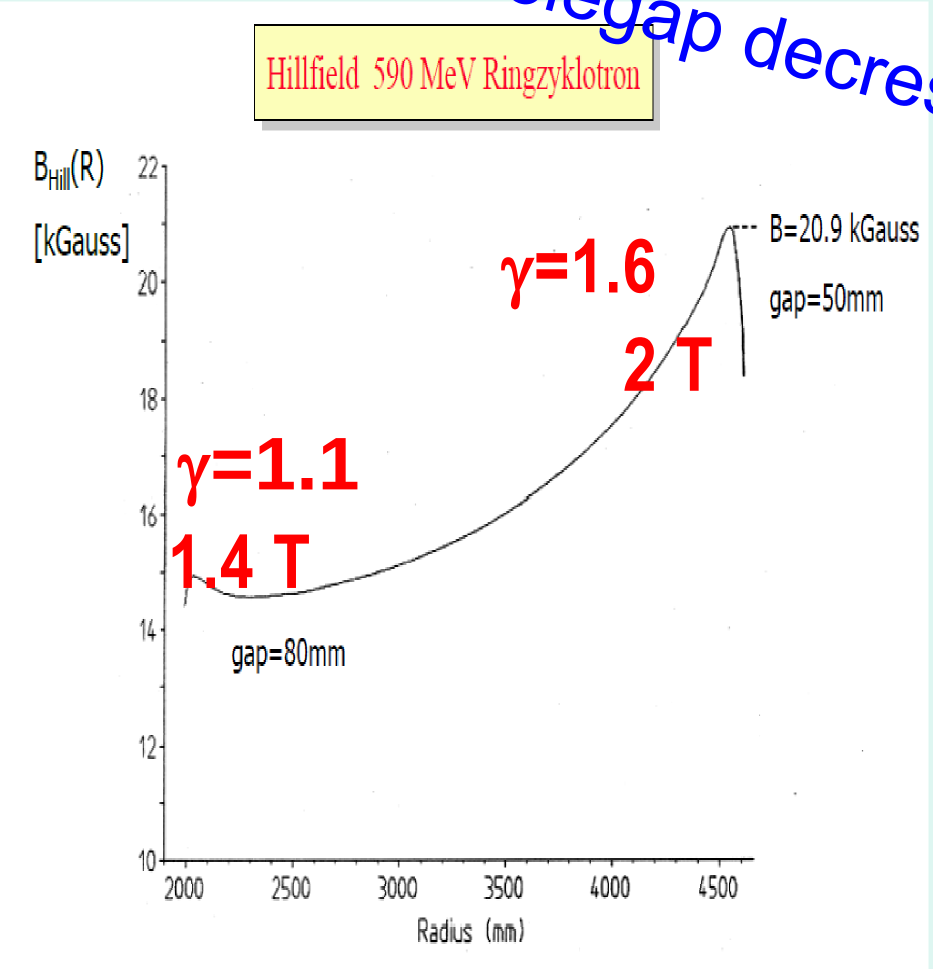
How?

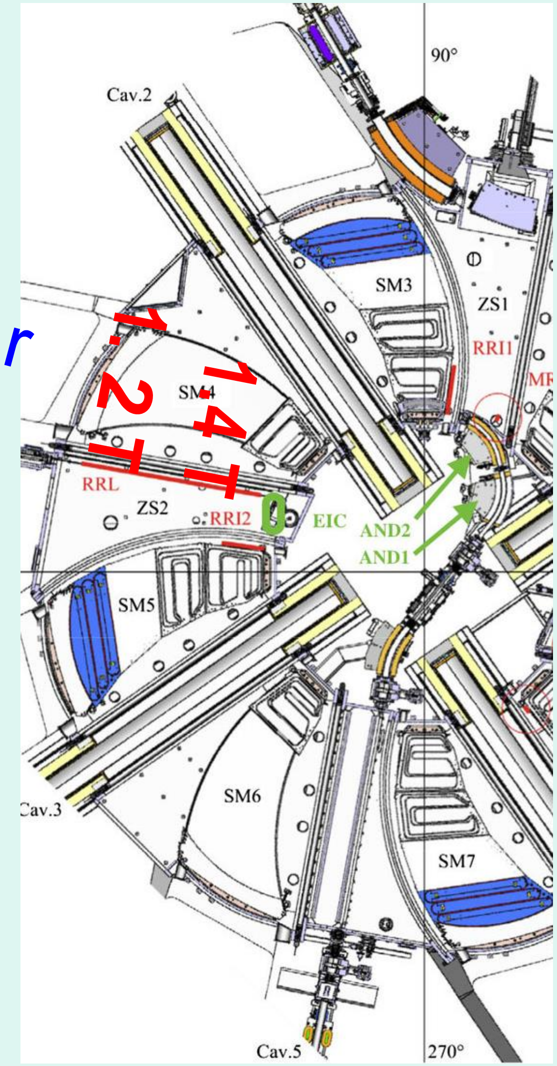
Decrease pole gap at large Radius



decrease pole gap + use trim coils

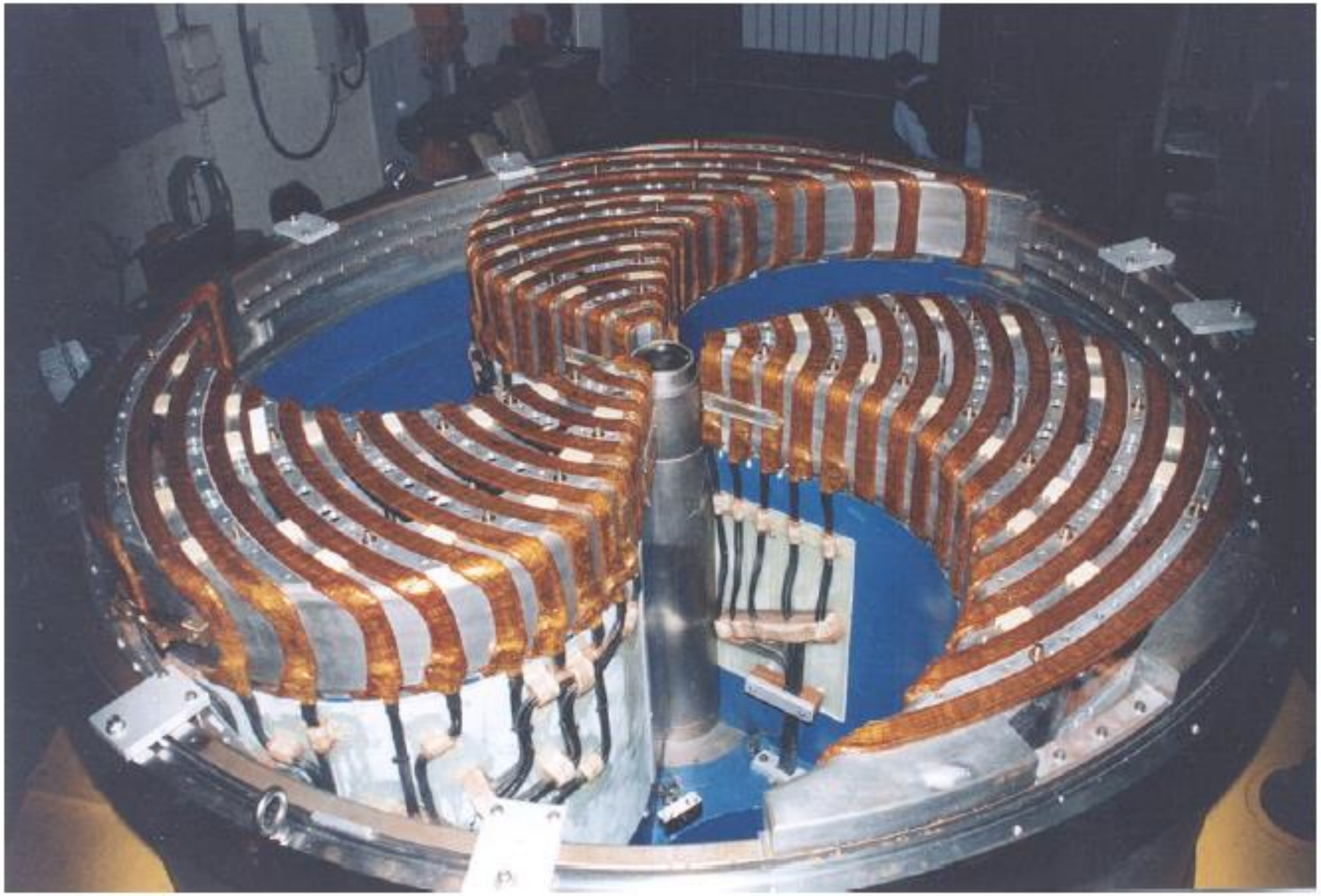
Polegap decreses with r



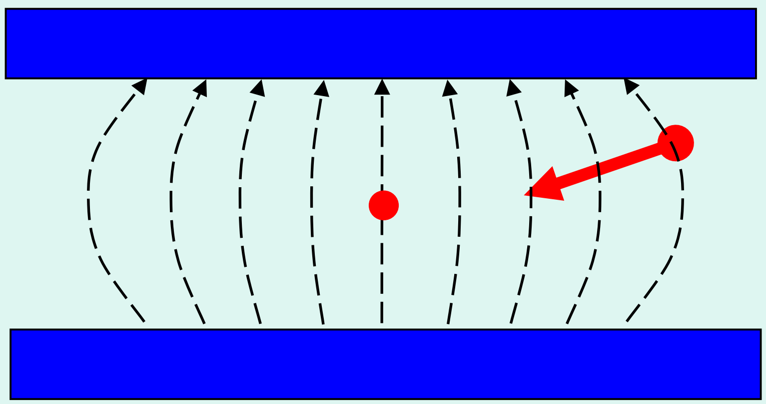


Shape the field for high E

Correction trim coils, AGOR



Vertical focusing



Inhom. field: field index $n \neq 0$:

$$n(r) = -\frac{\mathrm{d}B(r)}{\mathrm{d}r}\frac{r}{B(r)}$$

When B **decreases** with radius: $n>0$

=> Automatic **vertical stability**

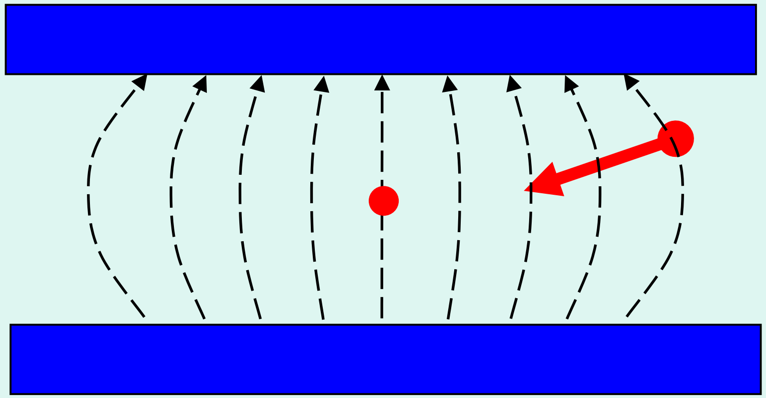
vertical betatron freq. = $\nu_z = \sqrt{n}$

What will happen with the vertical stability if B increases with radius?

When B **increases** with radius:

……….

Vertical focusing



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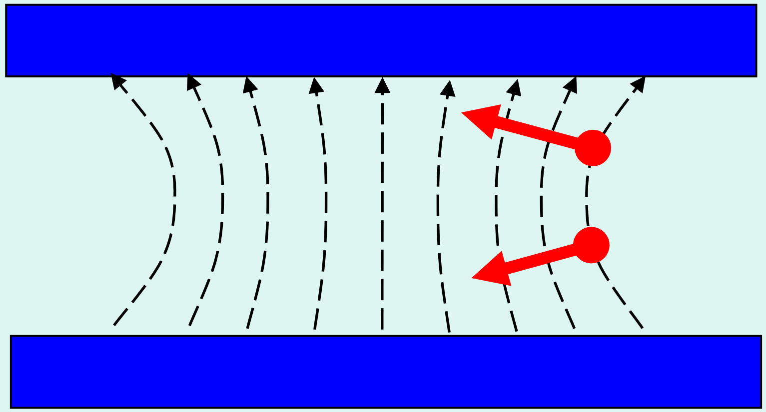
vertical betatron freq. = $\nu_z = \sqrt{n}$



When B **increases** with radius:

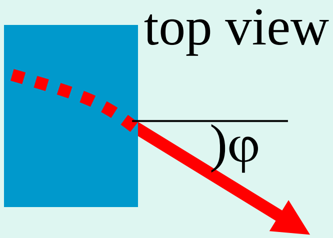
$n<0$ => no **vertical stability**

($\nu_z = \sqrt{n} = \sqrt{neg.nr}$ = imaginary)

Vert.focusing by Varying Field: AVF

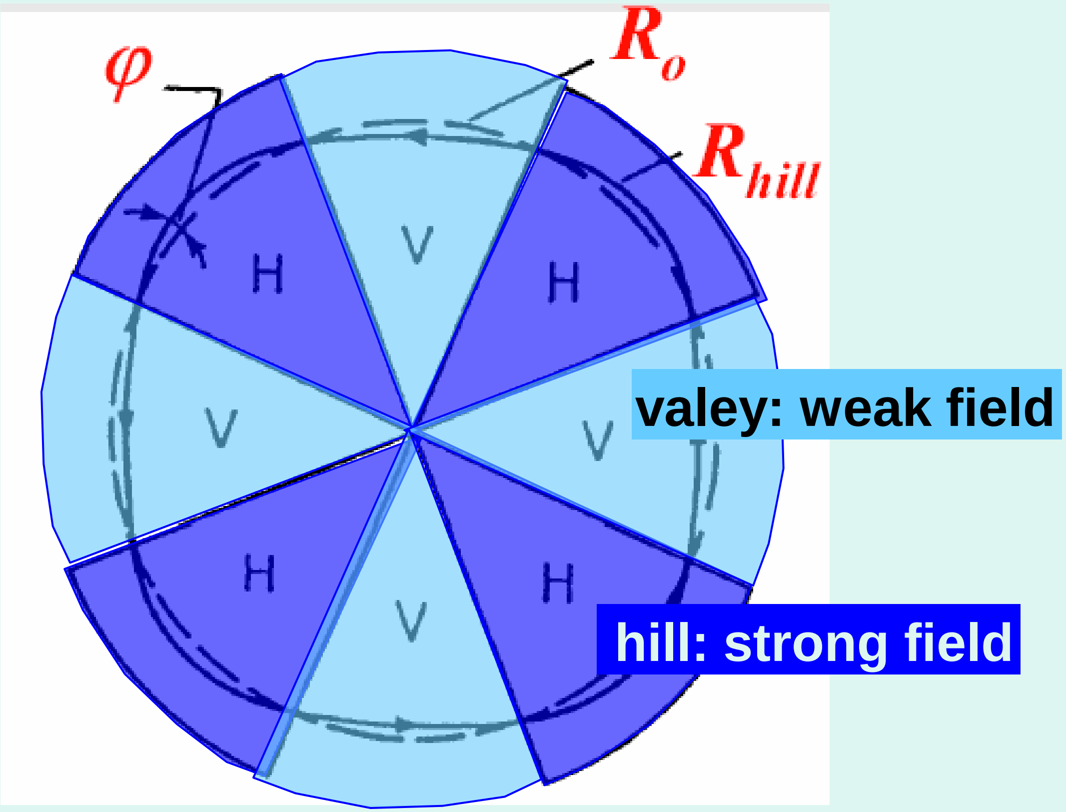
If B-step is not crossed ⊥ :

=> vertical force



AVF = Azimuthally Varying Field →

Vertical focusing at hill-valey boundaries

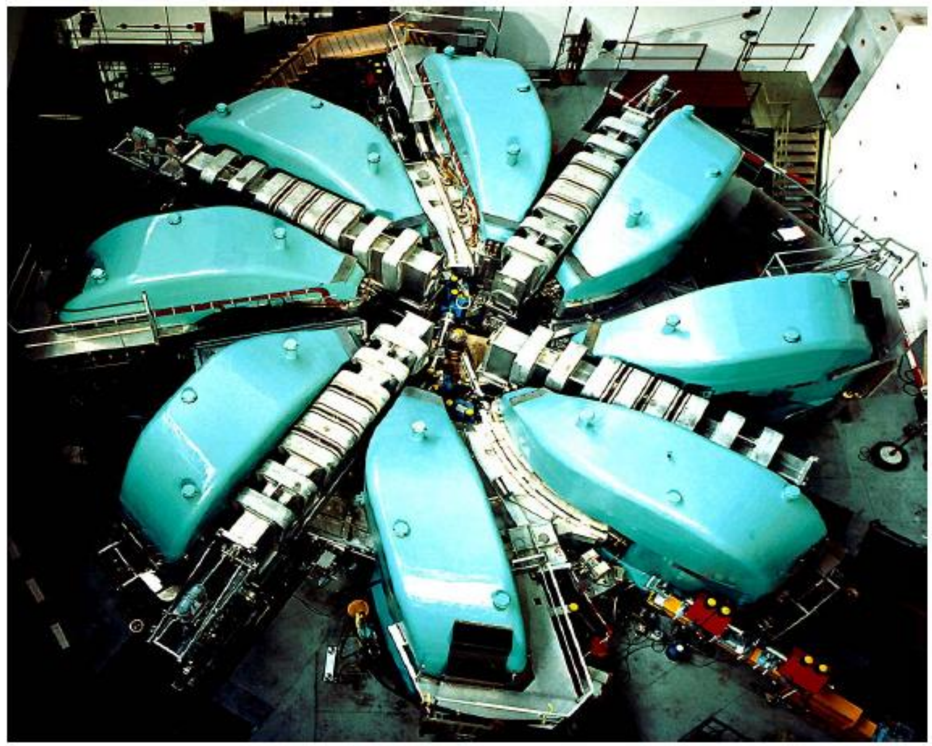


Azimuthally Varying Field

Extreme AVF:

separated sector cyclotron

4 Sector Magnets	~0.36 T
2 cavities 50 MHz:	450 kVp
-beam energy:	72 MeV
- number of turns:	81
- max. beam current:	**2.7 mA**



Ringcyclotron

590 MeV Protons

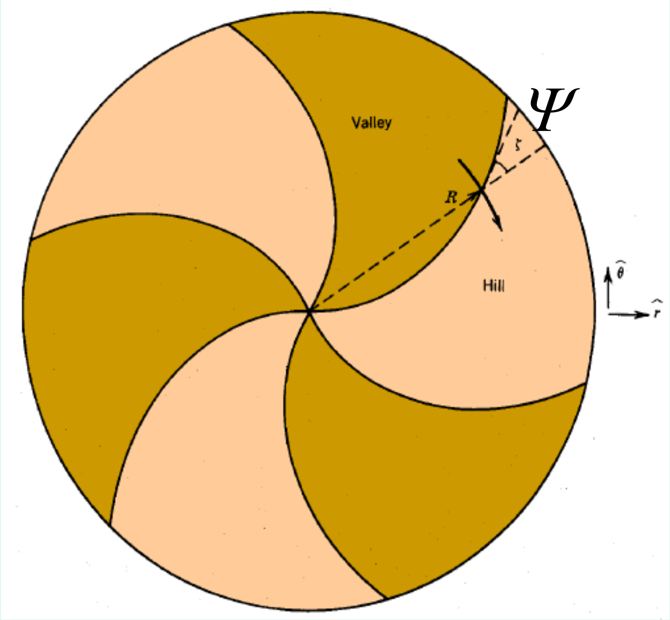
1.3 MW Beam Power
(world record!)

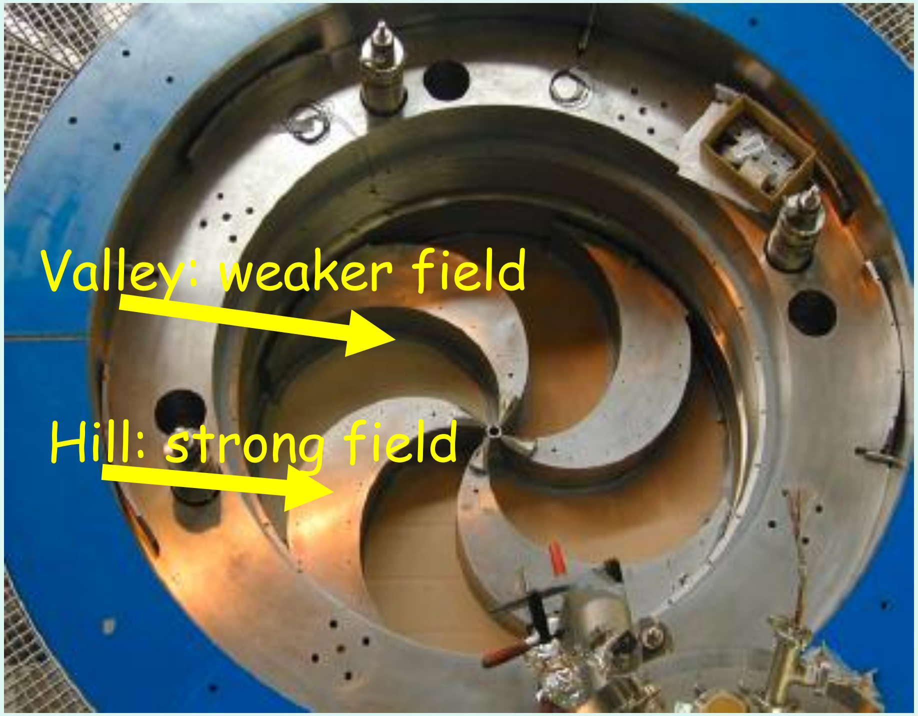
8 Magnet à 250 Tons

4 Cavities à 700 kV
(upgraded to 1MV
in 2008)

Extraction ≈ 99.97 %

Azimuthally Varying Field cyclotron



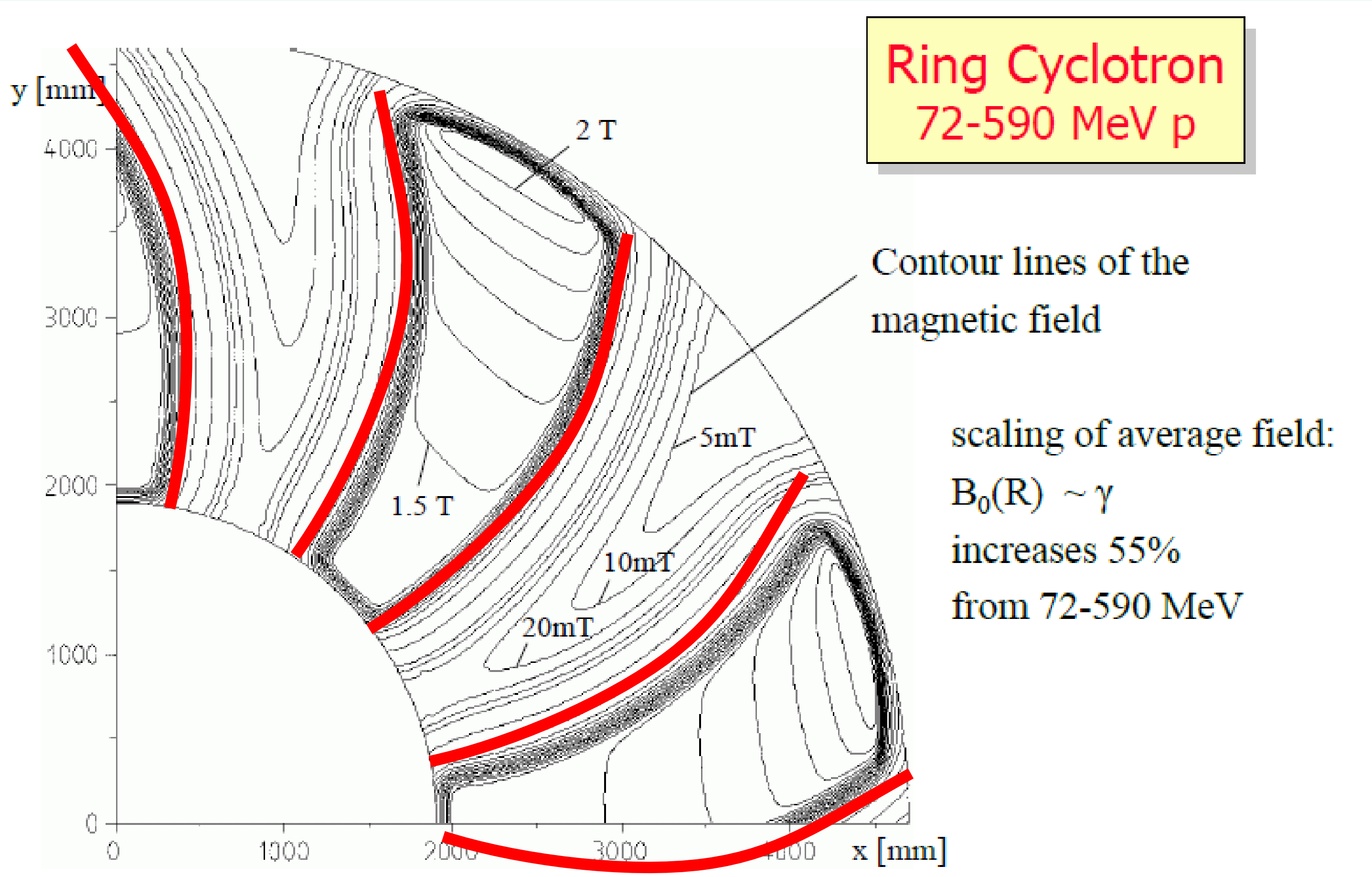


$$\upsilon_z^2(R) = n(R) + F(R).(1 + 2\tan(\psi(R)))$$

to **compensate** :higher energy

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

Extreme AVF: separated sector cyclotron



scaling of average field:

$B_0(R) \sim \gamma$

increases 55%

from 72-590 MeV

Summary high energy cyclotrons

Remedies when T_{circle} increases with radius:

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

2) increase B with radius (**Isochronous Cyclotron**)

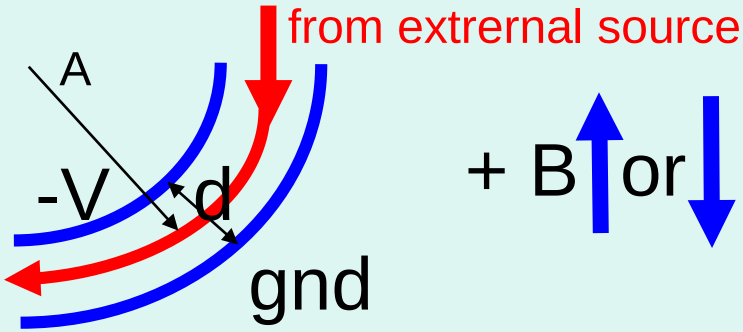
… but vertical focusing must be added

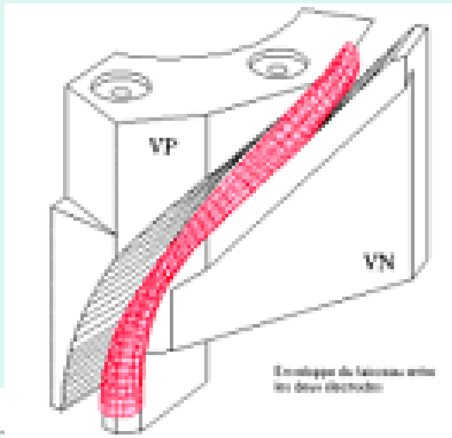
Central region:

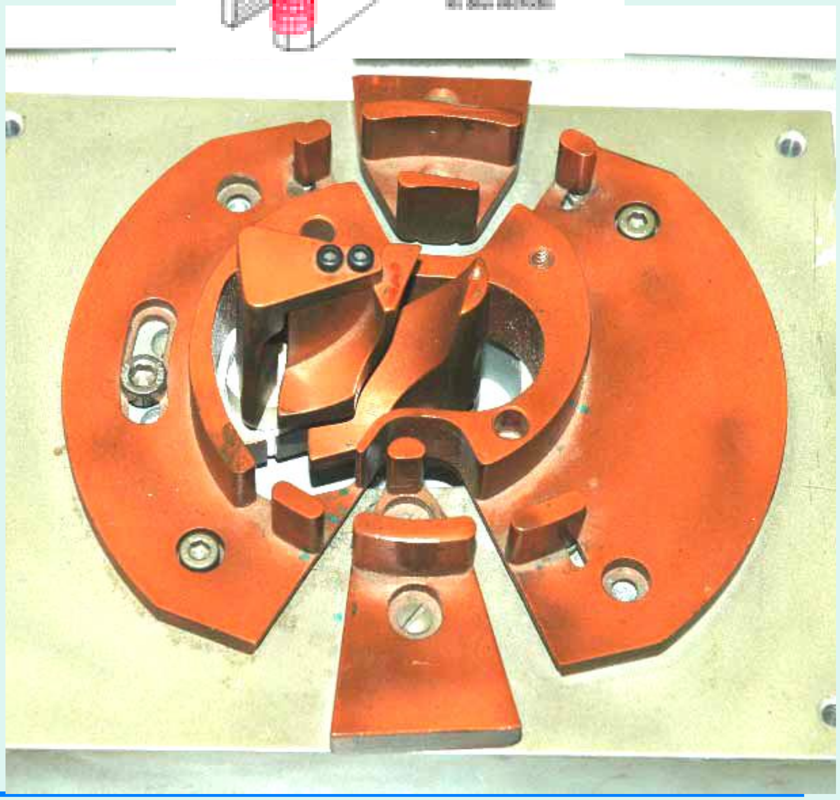
Either -injection of externally coming beam

Or: -ion source

Axial injection : spiral inflector







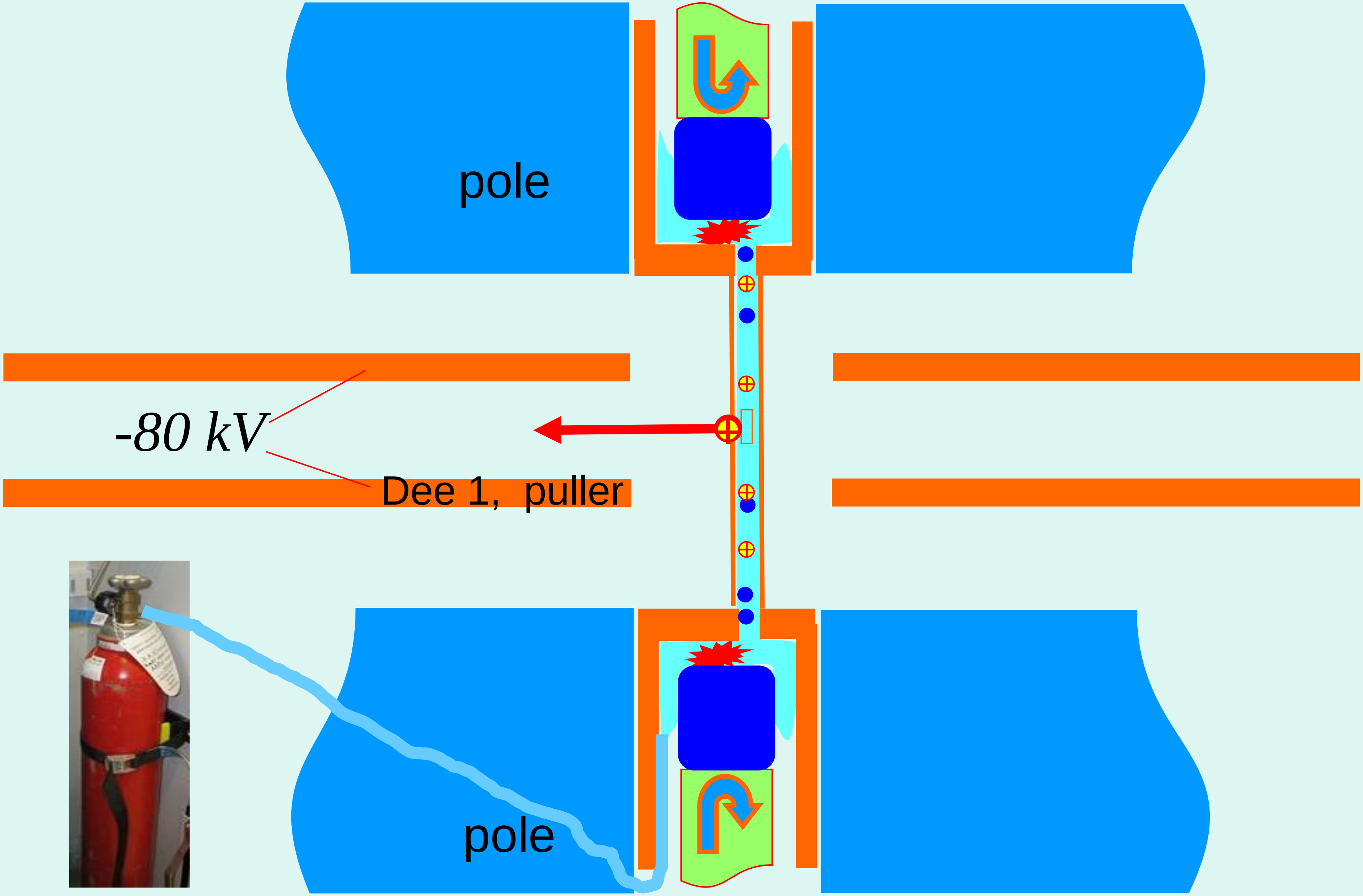
Spiral inflector:

$V/d = 2E / (qA)$

Internal ion source:

(usually protons, He)

Internal ion source



RF cavities

Important parameters:

Voltage amplitude on Dee : 30-80 kV

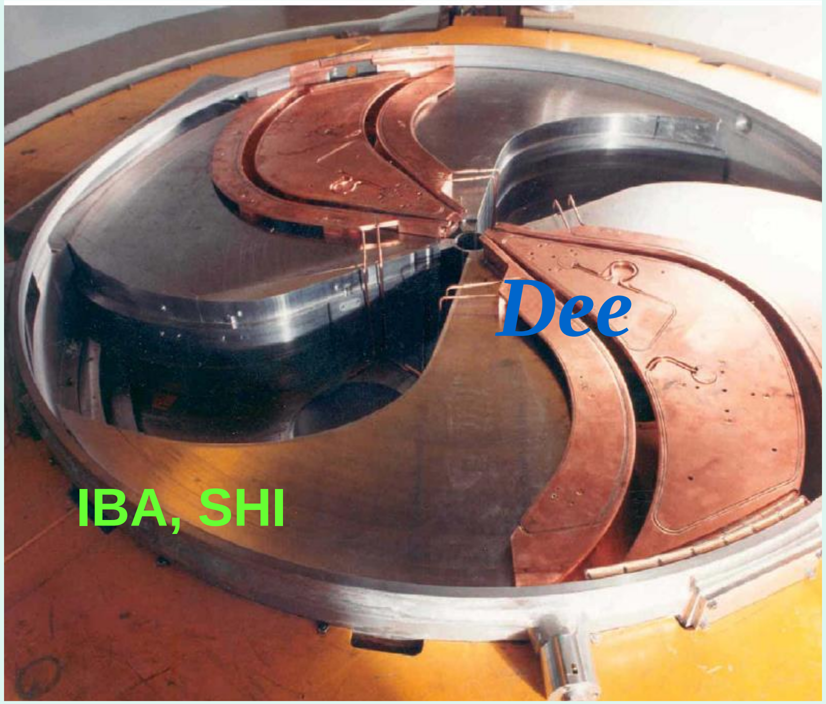
Number of Dee‘s: 1,2,3,4

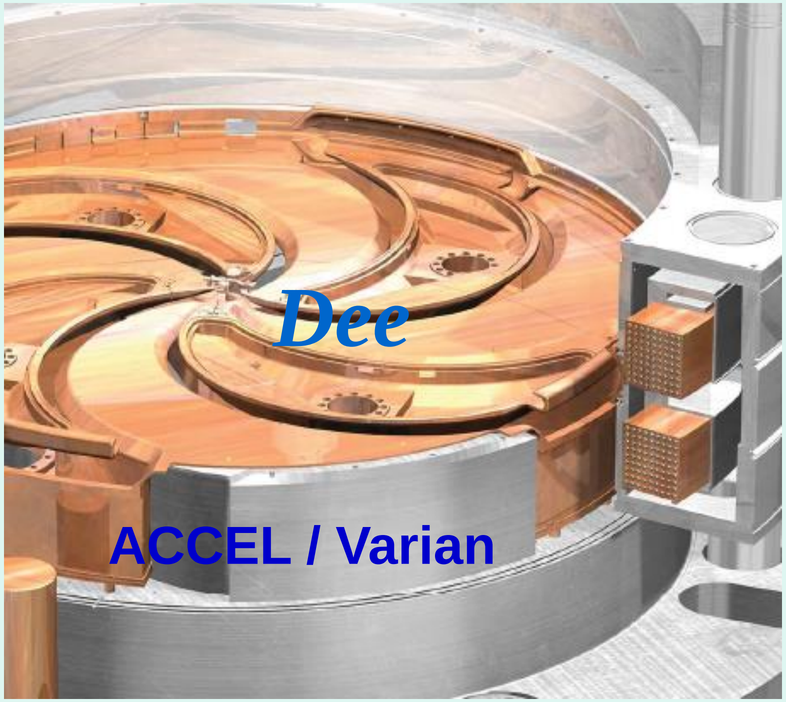
$\Rightarrow$ Energy gain per turn

$\Rightarrow$ Orbit separation

$\Rightarrow$ Extraction efficiency

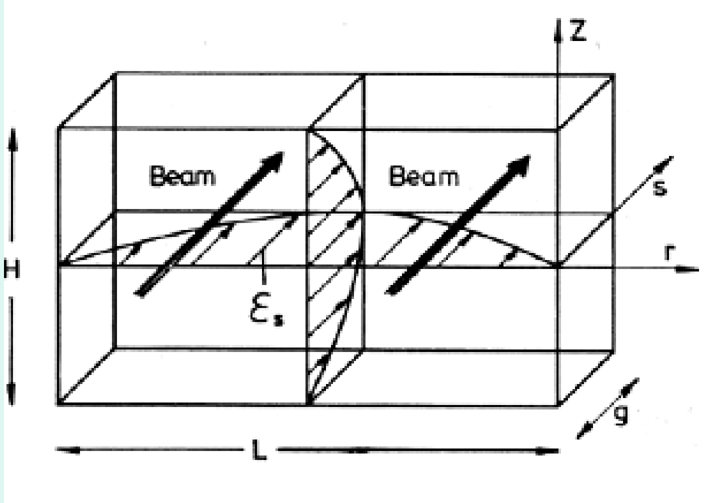
Dual gap: Dee





Single gap cavities (ring cyclotrons)

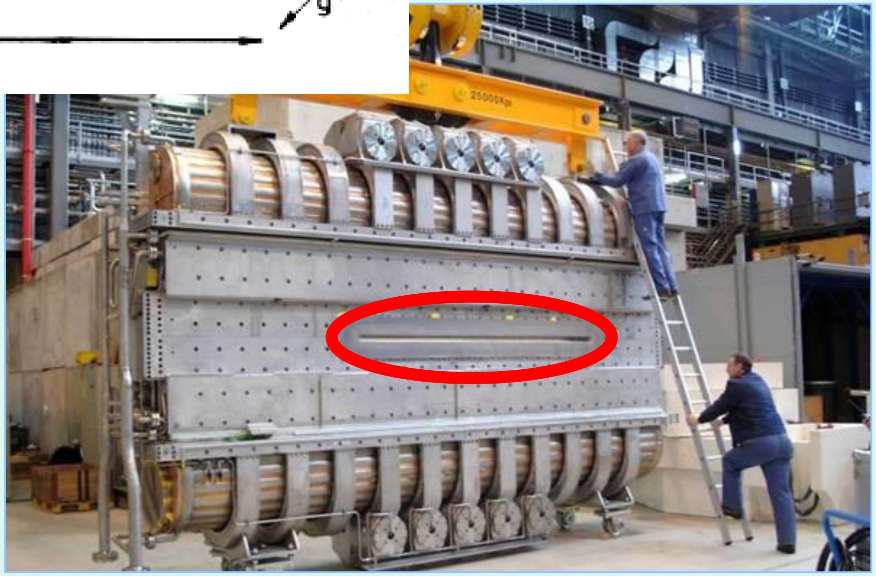
Ring Cyclotron 590 MeV , 50.7 MHz



copper , V = 1 MV

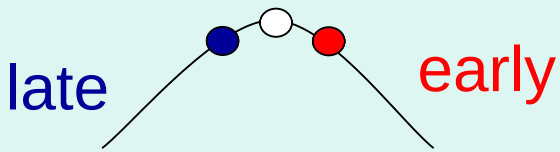
400 kW power loss

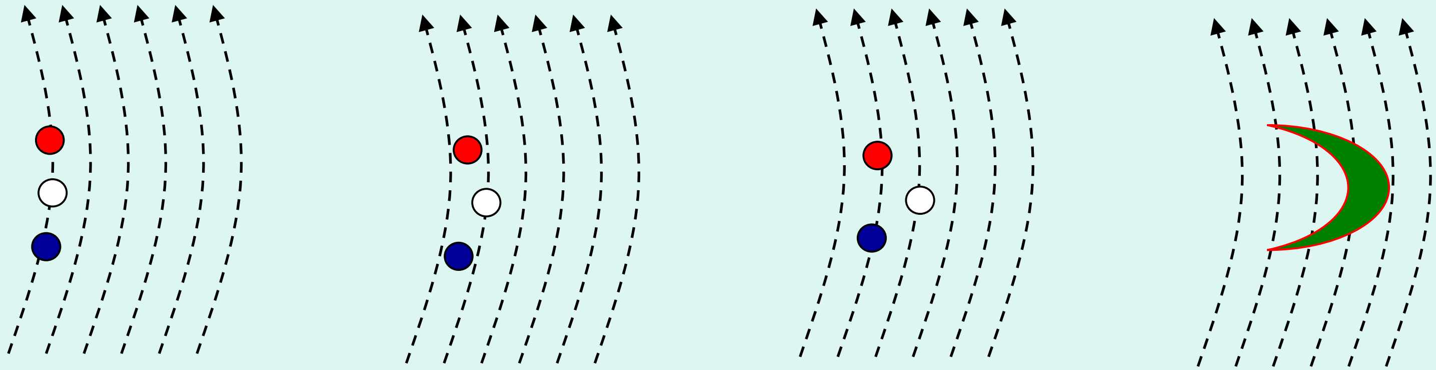
160 turns , current limit > 3 mA ?



Phase mixing

Let's look at one bunch, accelerated on the RF-top:



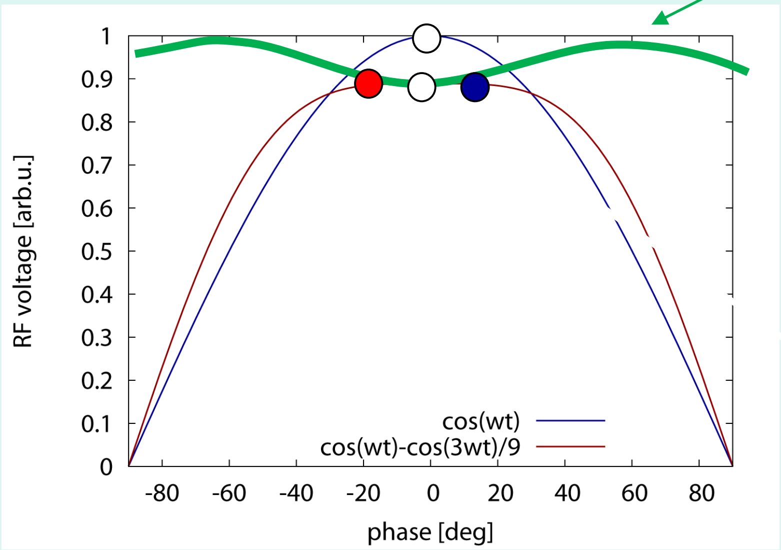


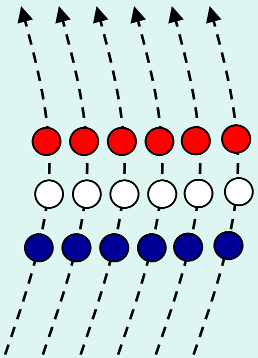
→ Large phase width → broad beam

→ Small phase width needed at RF-top

Flattop resonator

- variation of accelerating voltage over the bunch length **increases energy spread**
- thus a third harmonic flattop resonator is used to **compensate the curvature** of the resonator voltage w.r.t. time
- optimum condition: $U_{\mathrm{tot}} = U_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$





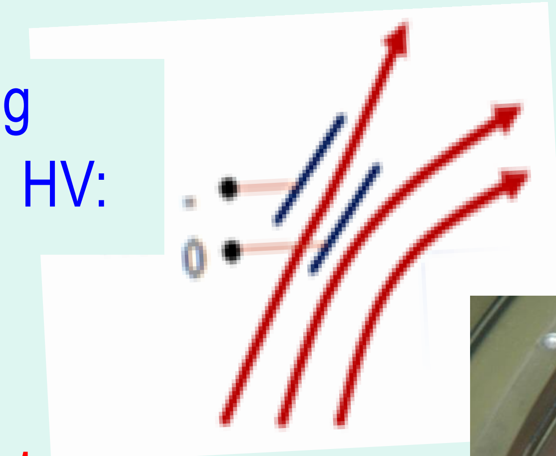
broader flat region for bunch:
→ no energy spread
→ ΔE/turn reduced
→ Reduced turn overlapping

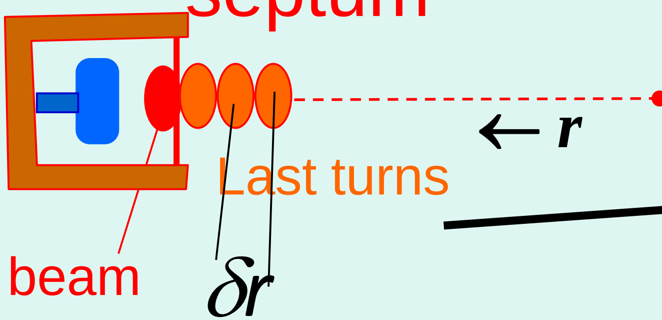
Extraction:

How to get out?

Extraction from cyclotron

Extraction using septum and HV:

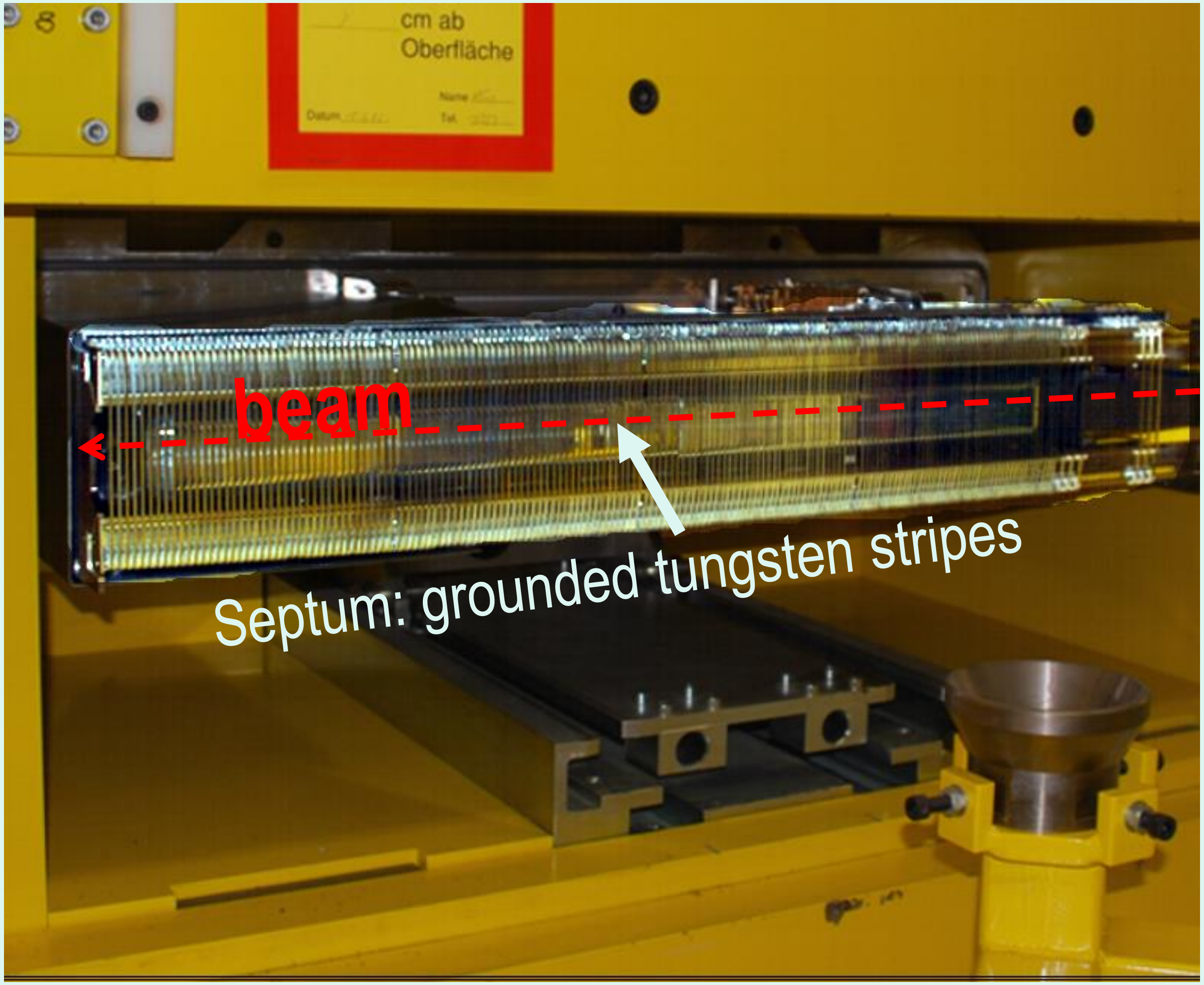




High extraction Efficiency is important

Extraction: Electrostatic deflection

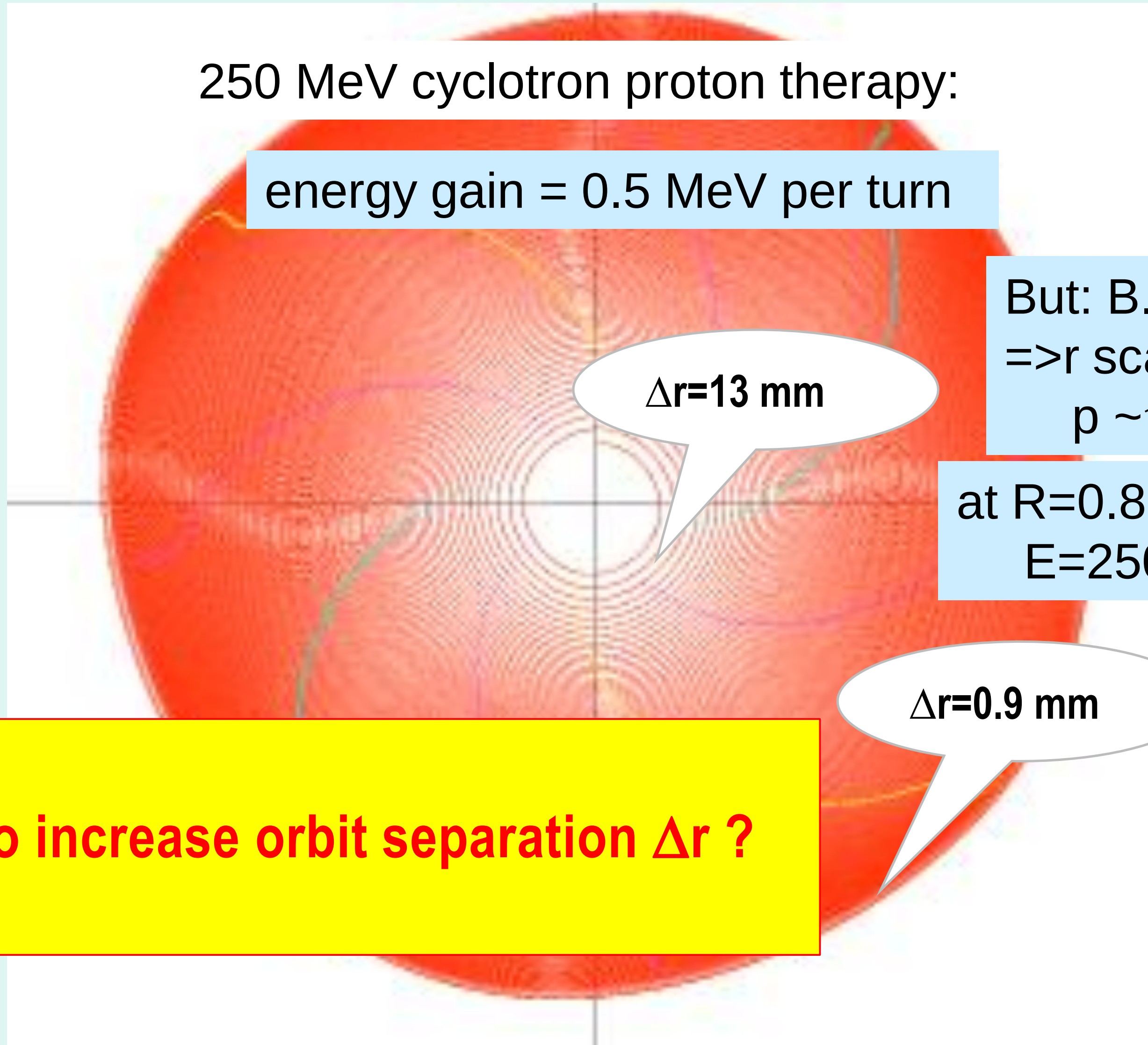
Extraction Channel 2 mA 590 MeV p at PSI: 145 kV



Turn separation

250 MeV cyclotron proton therapy:

energy gain = 0.5 MeV per turn



But: B.r = p/q
=>r scales with p:
$p \sim \sqrt{E} \rightarrow \Delta r \sim 1/r$

at R=0.8 m:
E=250 MeV

How to increase orbit separation Δr ?

Extraction from cyclotron

At extraction the turn separation dr/dn should be as large as possible

$$\frac{dr}{dn} \approx \frac{E_k .r}{\gamma(\gamma+1)} qZV_{Dee}$$

What will help:

→ High V_{dee} → **high ΔE / turn**

→ Large cyclotron radius *R* (→ not too **strong field *B***)

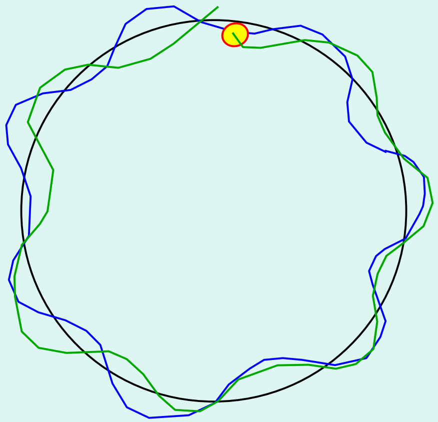
→ **High E_k** but keep γ <2 →heavy ions with **low speed**

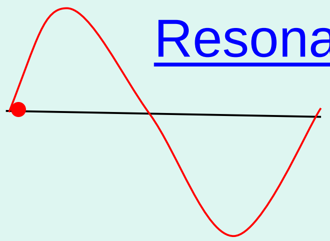
→ protons: **Emax ~1 GeV**

How to make larger **orbit separation** Δ*r* ?

Use betatron oscillations

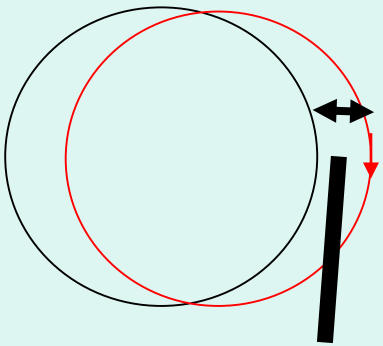
Important betatron oscillation in cyclotrons:





Resonance at ν_r =Qr=1 :

→ increase of turn separation



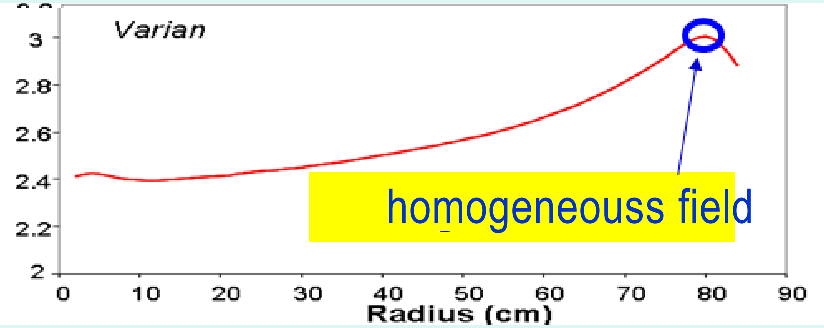
=effectively an orbit shift

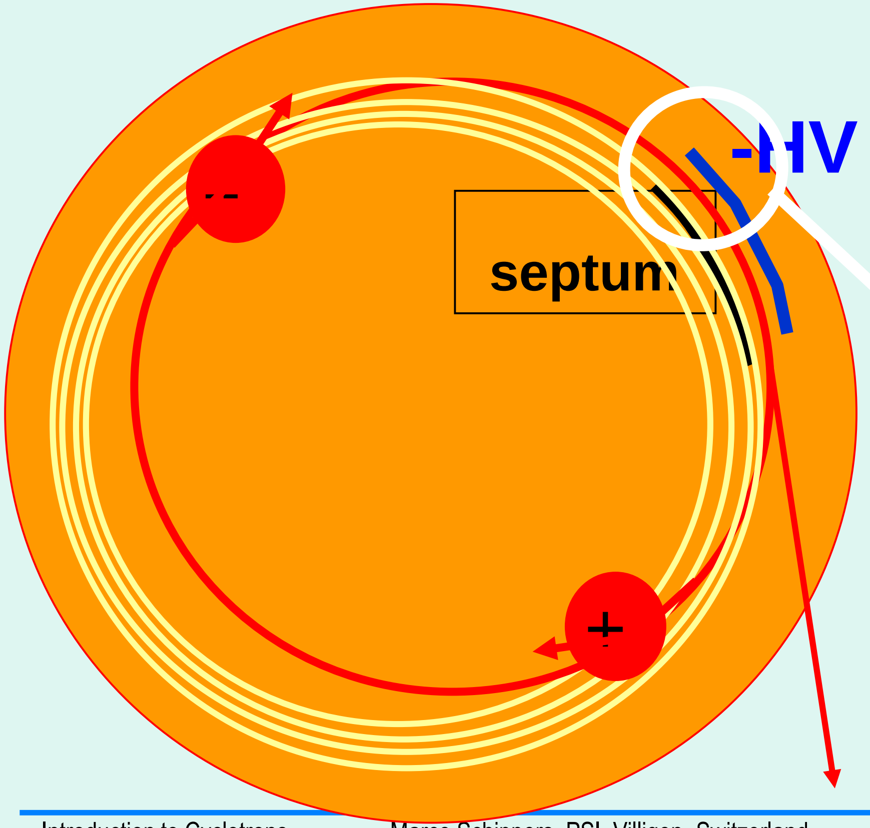
Extraction septum

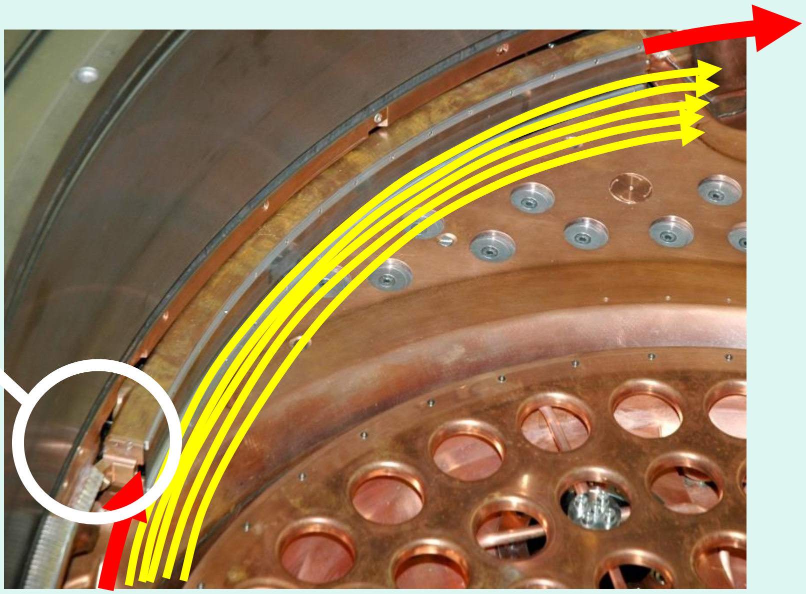
Resonant Extraction from COMET

Uses the homogeneous field ! ν_r=1

→ Locale field chsnges (bumps) shift the ebam:







Extraction by charge exchange

Accelerate H^-

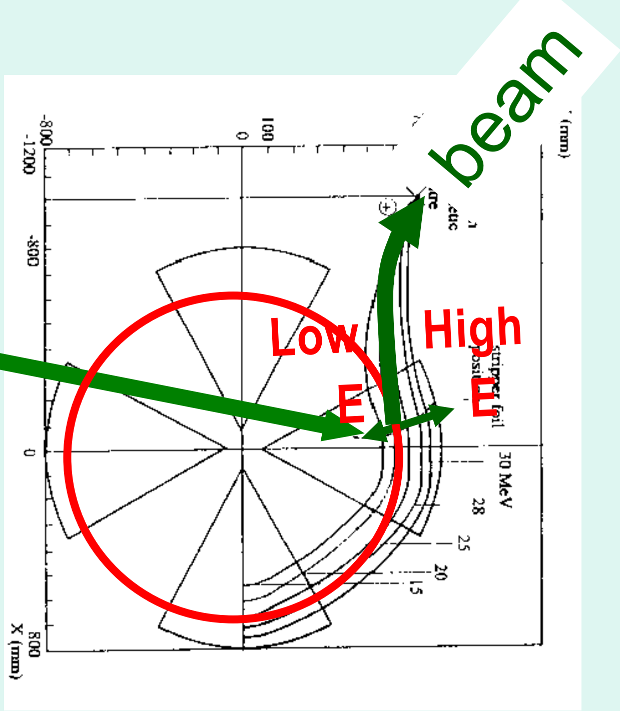
Extraction by charge exchange

flips Lorentz Force.

$$H^- \rightarrow p^+ + 2e$$

Advantages of charge exchange:

- Almost 100% efficiency
- Radial **position** of stripper foil sets extracted beam **energy**



Limit in magn.field: Lorentz stripping.

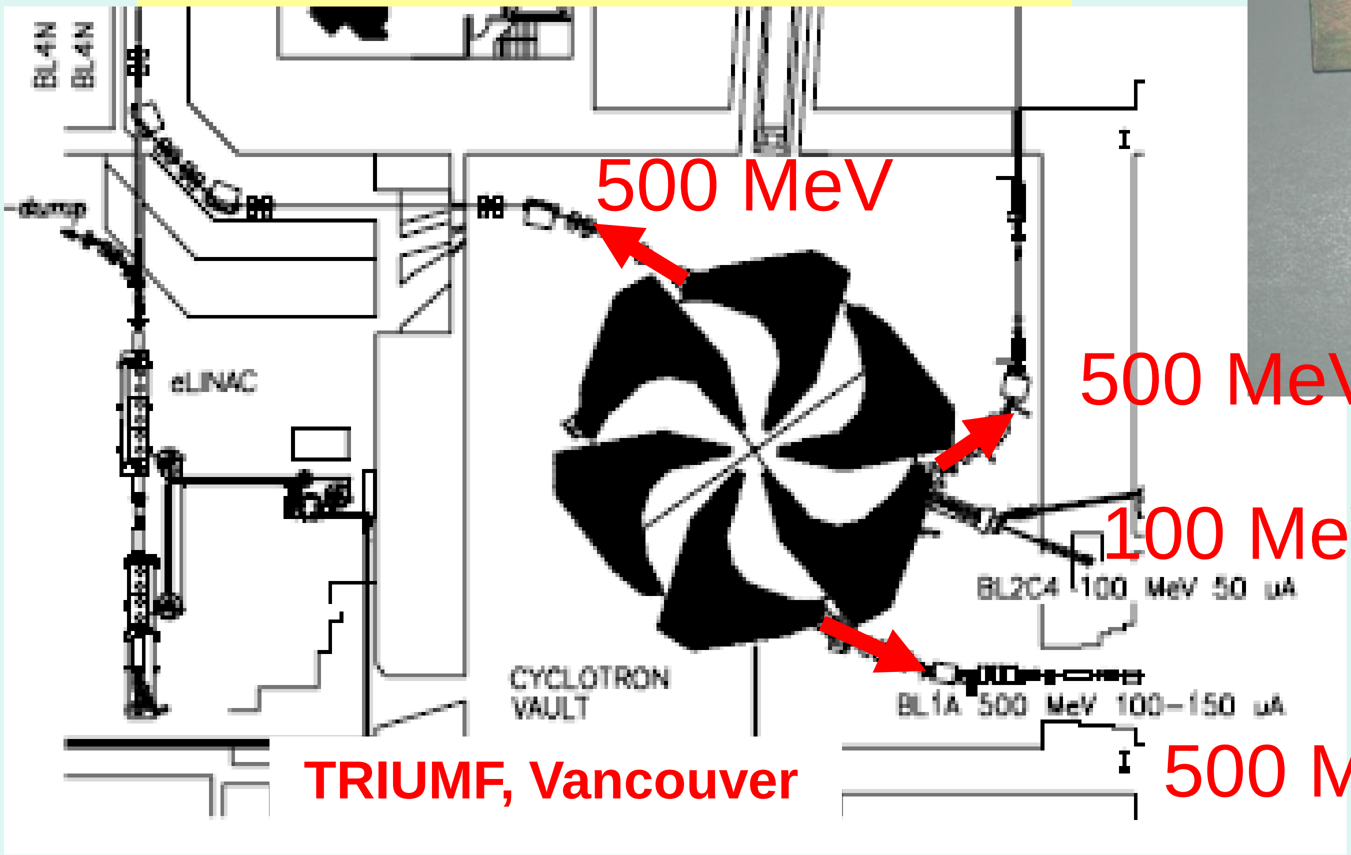
$$B < \frac{11}{\sqrt{E}} \quad [T]$$

+ losses due to stripping by residual gas

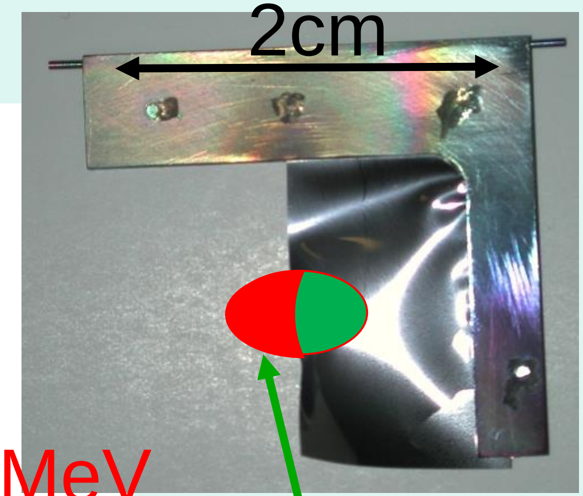
Extraction by stripping

$$H^- \rightarrow p^+ + 2e$$

Simultaneous extraction!



TRIUMF, Vancouver



Used at other foil

Typical use of cyclotrons

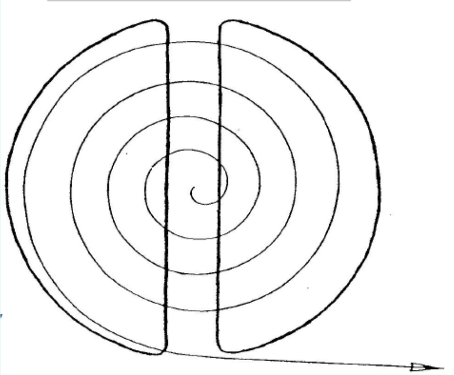
- medical applications ≤250 MeV
- isotope production several 10 MeV
- heavy ions (physics reseach)
- very high intensity proton beams (TRIUMF: **100 kW**, PSI:**1.2 MW**)

Advantages of a cyclotron

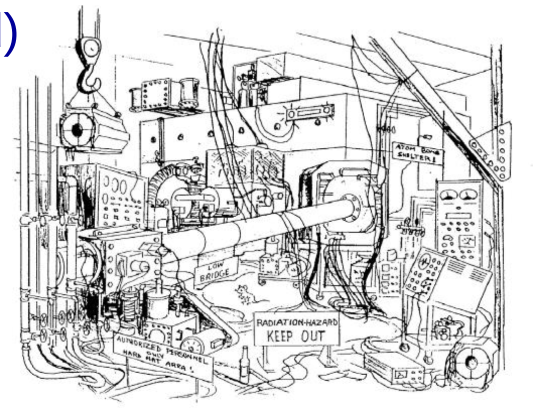
A cyclotron provides:

- continuous beam (Synchr.Cycl: pulsed)
- any intensity (Synchr.Cycl: low)
- great reliability (few components)
- Protons with energy up to 1 GeV

The Cyclotron as seen by the **Inventor**

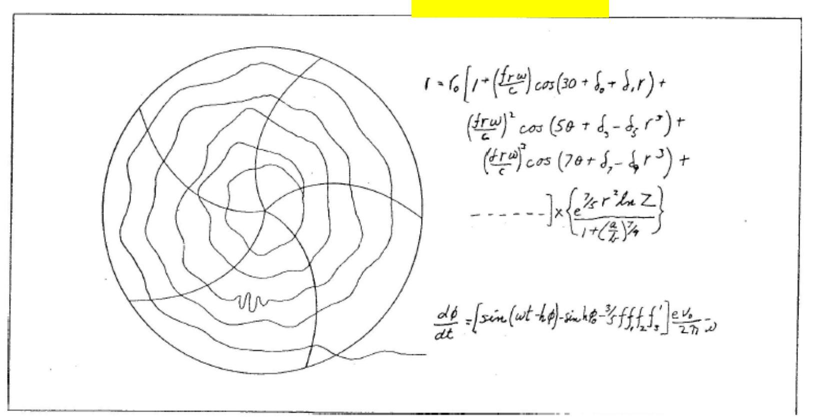


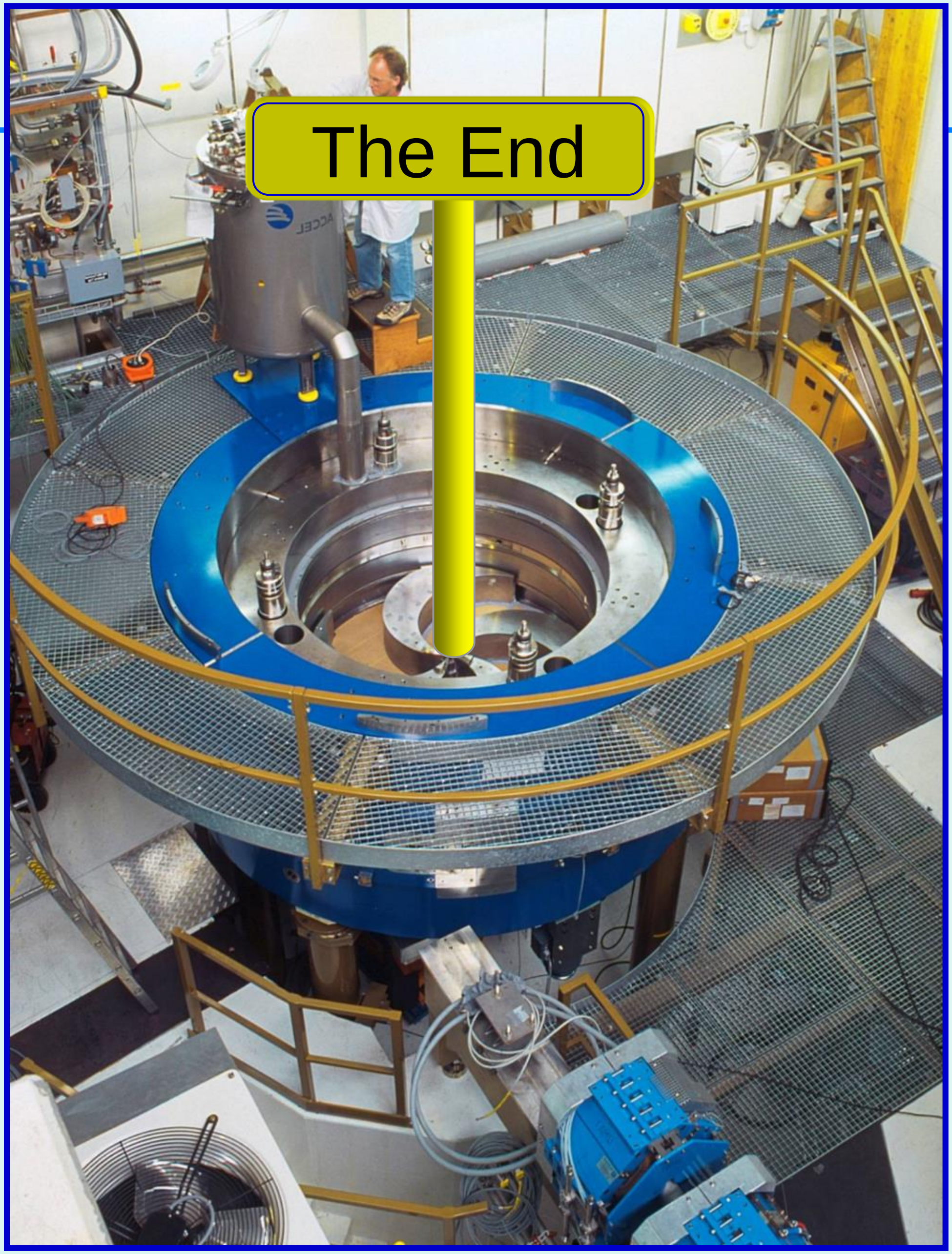
The Cyclotron as seen by the **Visitor**



… so now you are cyclotron experts….

The Cyclotron as seen by the student

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