The cyclotron and its applications

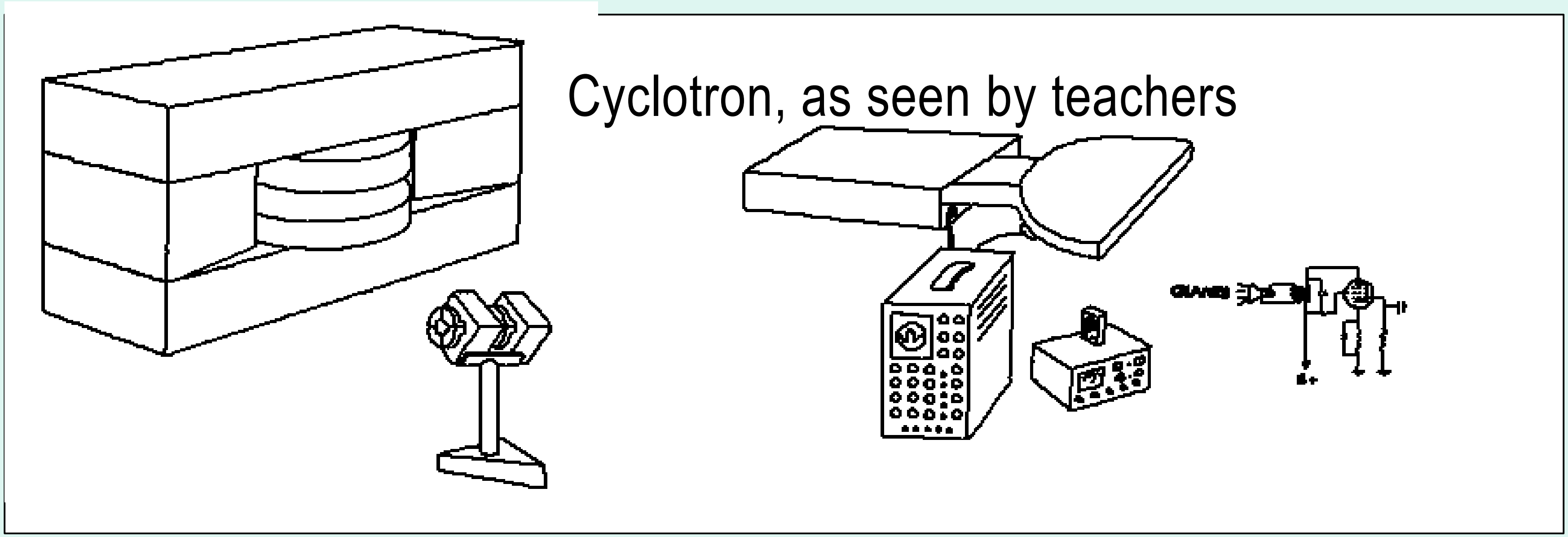
Marco Schippers

PAUL SCHERRER INSTITUT

Univ. Med. Center Groningen

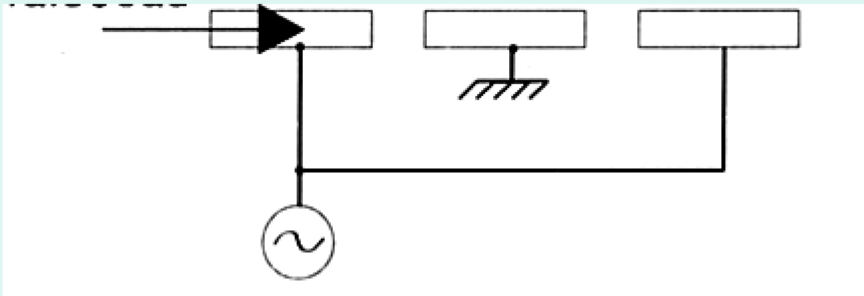
Slides contain material and images from many collegues at PSI and various companies

Contents:



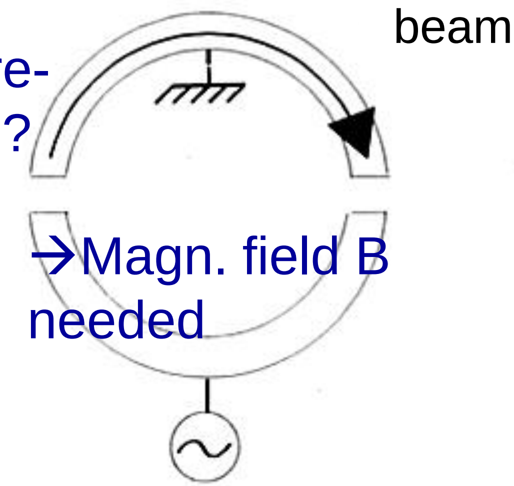
- How has the cyclotron **evolved**?
- **Isochronicity**: a basic operation principle
- Ion source, Acceleration, Intensity, Extraction

Metamorphosis



Wideroe's linear accelerator (1927)

Could one re-use the RF ?



→Magn. field B needed

Centrifugal force
= Lorentz force

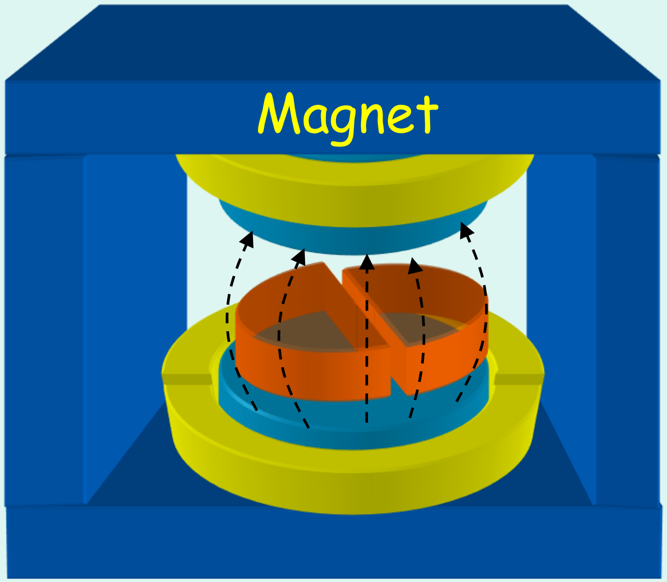
$$\frac{mv^2}{r} = Bqv \qquad T_{circle} = \frac{2\pi r}{v} = \frac{2\pi m r}{Bqr} = \frac{2\pi . m}{Bq}$$

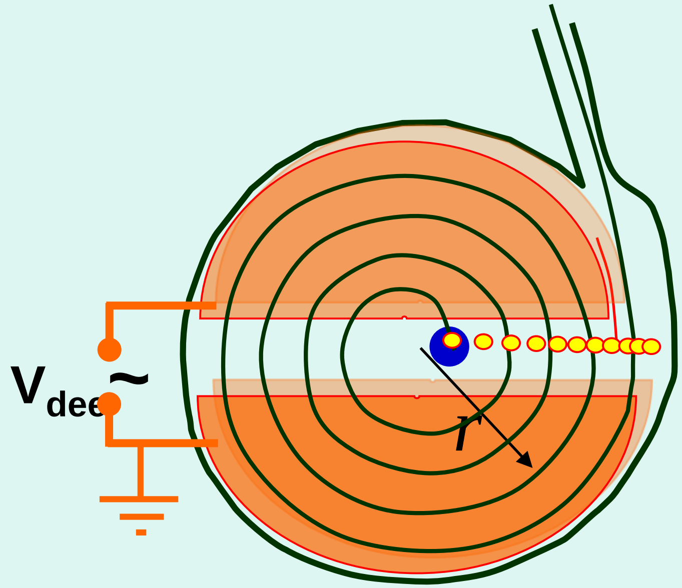
„r cancels r…. don't you see what this means?

T does neither depend on radius nor on Energy!"

(Ernest 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 → orbit=spiral

$$E_{max} \sim N \,.\, \Delta E \quad \Rightarrow \quad E/A = K.(q/A)^2$$

$$K = \frac{(eBr_{max})^2}{2m_a}$$

e.g. K=600: $^{12}C^{6+}$: 600*(36/144)=150 MeV/nucl

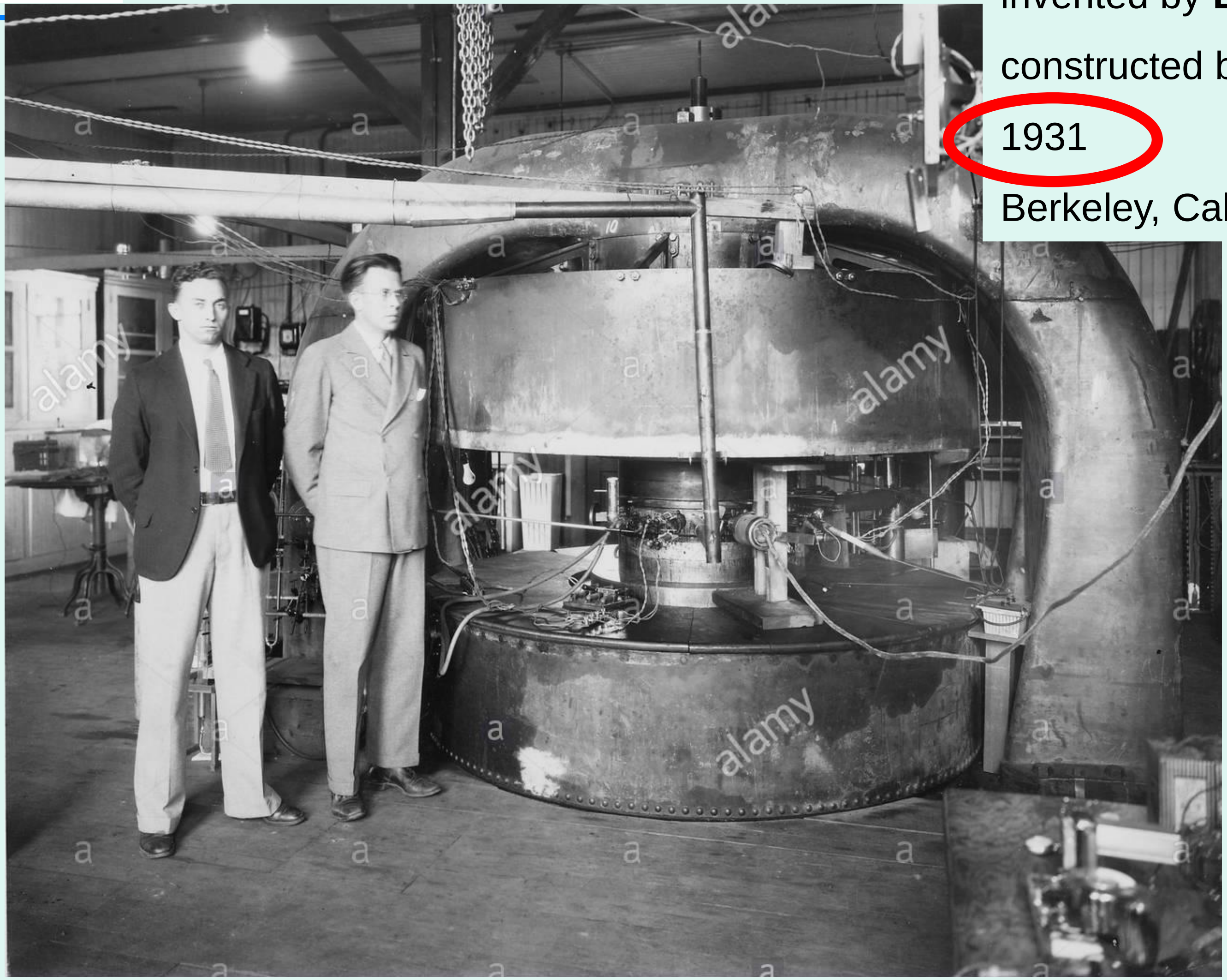
the first Cyclotron

invented by **Lawrence**,

constructed by Livingston

1931

Berkeley, California



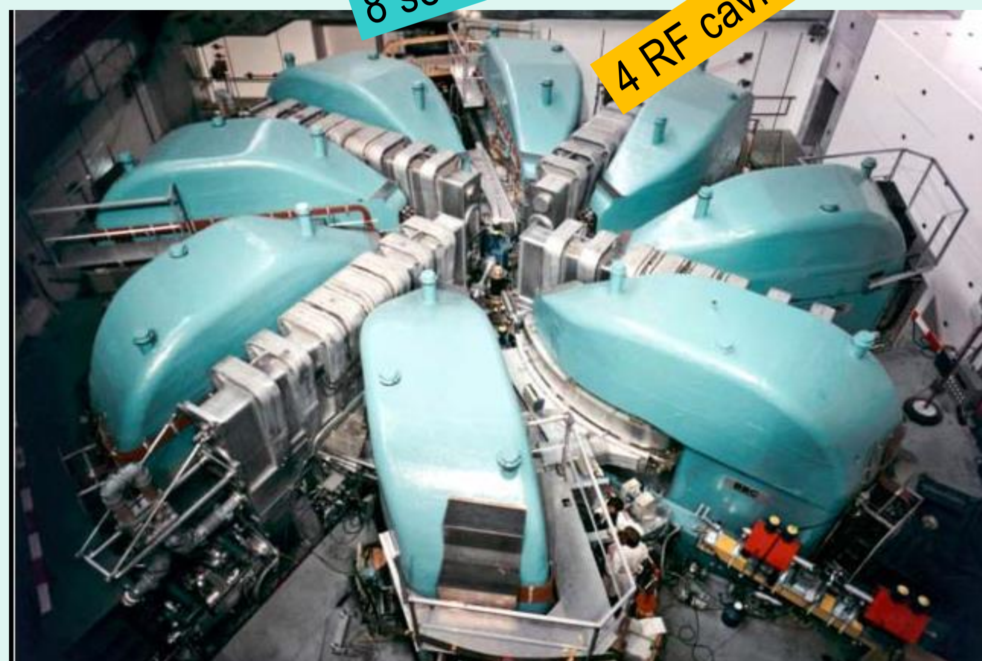
Stanley Livingston (L) and Ernest Lawrence in front of 27-inch cyclotron (several MeV), Berkeley 1934.

credit:
Lawrence Berkeley Nat'l Lab

Big Cyclotrons

single magnet → sector magnets

UCL 1946:
-Magnet:184-inch 4300-tons
-Dees at 1 or 2 MV



590-MeV RING cyclotron
(PSI, 1974)

compact cyclotrons: for isotope production: 10-30 MeV

CYCLONE 30 (IBA) : H^- 15 à 30 MeV

Vertical orientation

proton therapy cycl.: 230 / 250 MeV

Superconducting Coils

IBA (1996) ,
SHI

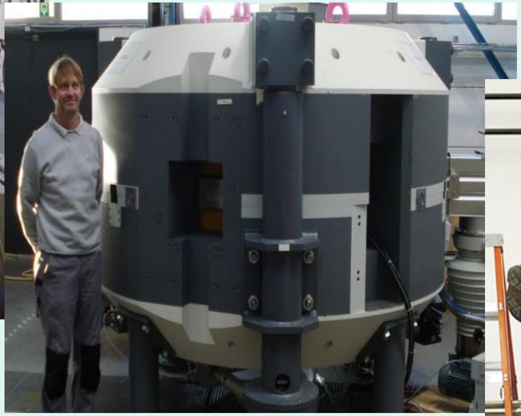
250 Tons

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

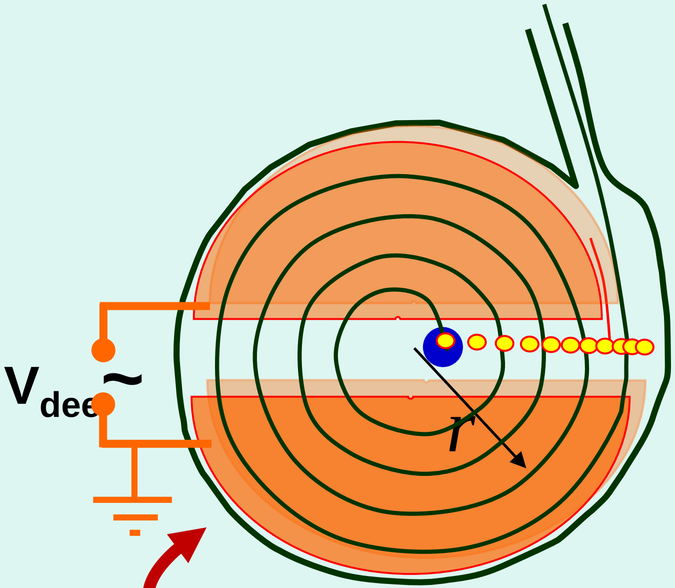
B → (almost) circular orbits:

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

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

oscillating voltage at

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



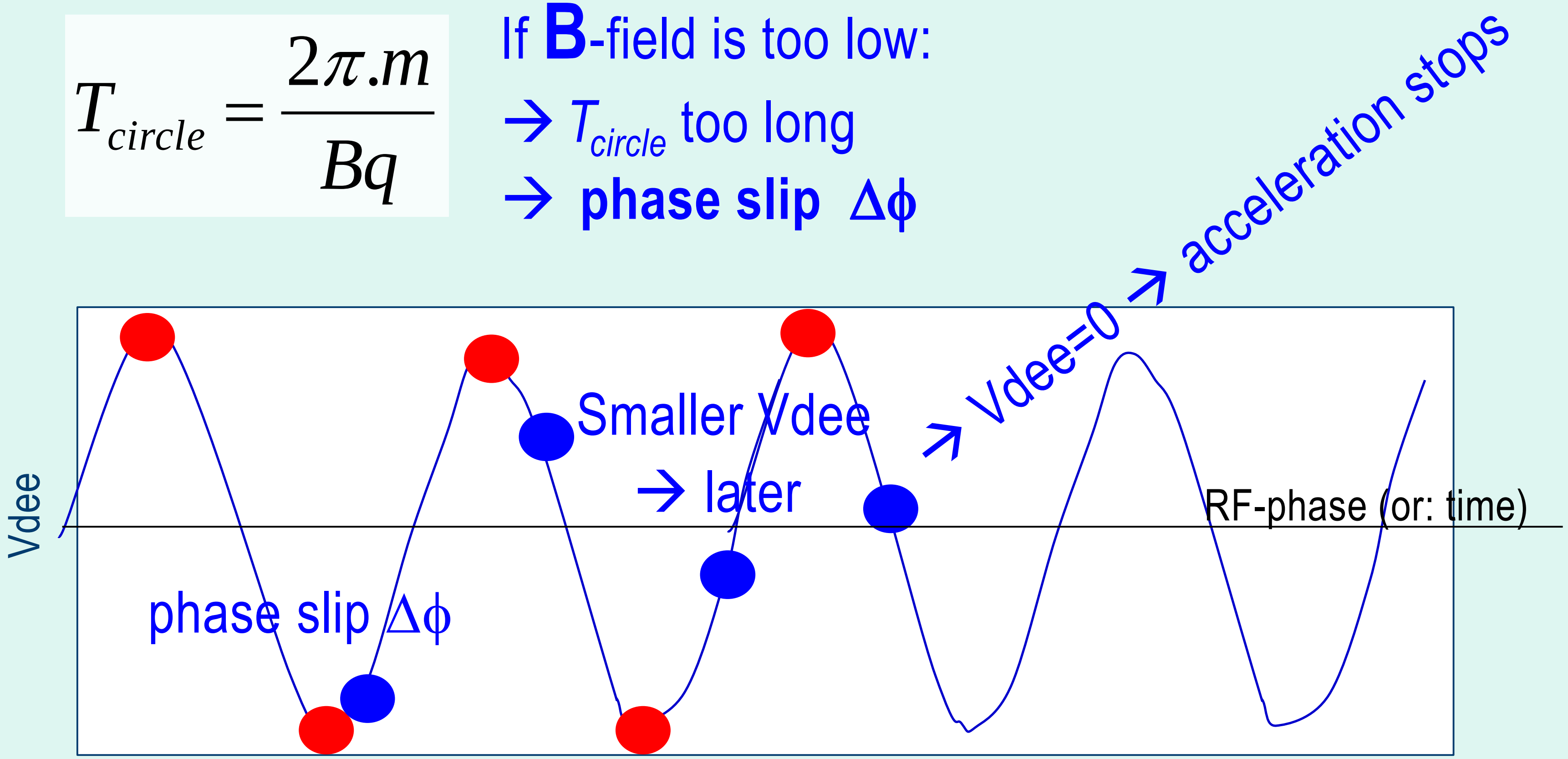
Cyclotron

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

If **B**-field is too low:

→ T_{circle} too long

→ **phase slip Δϕ**

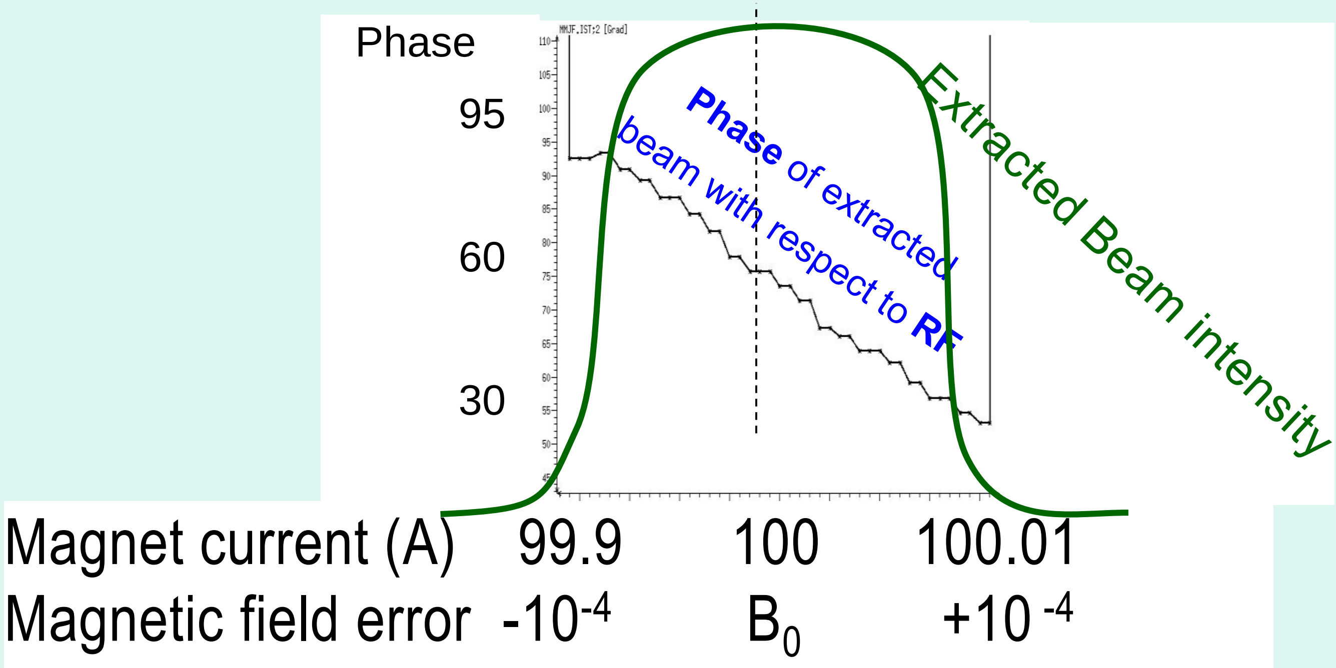


Acceleration stops when ϕ= π/2 is reached after n x phase slip of Δϕ

Isochronicity in a cyclotron

Given f_{RF} → B must be correct within 10^{-4}

→ particles cross the gap at right phase



Resonance curve (Smith Garren, 1963)

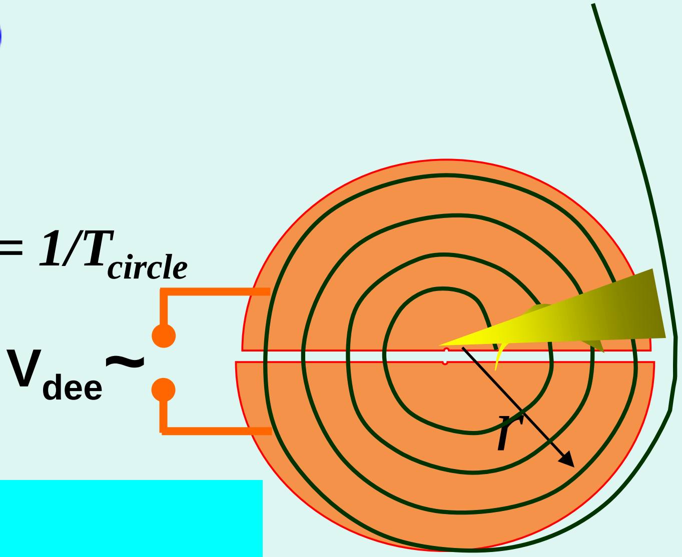
> 30 MeV cyclotron

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

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

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

Synchro-Cyclotron

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

REMEDY 1:

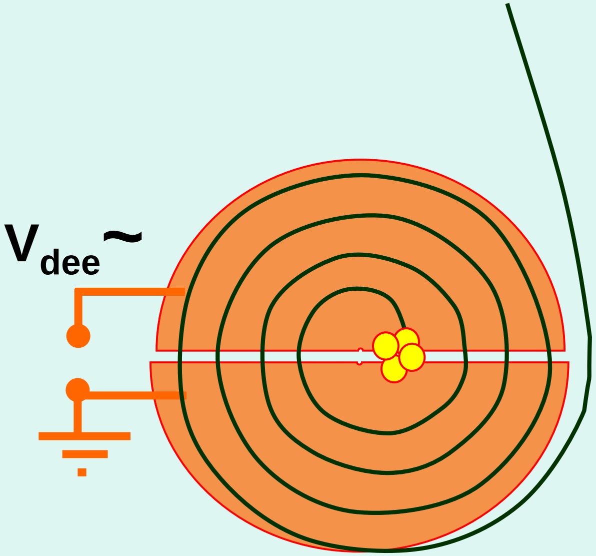
Decrease f_{RF} with **1/T_{circle}** in time, **synchronous** to mass increase:

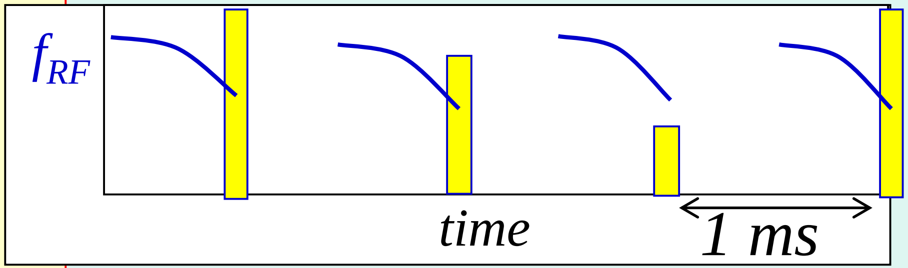
$$\omega_{rf}(t) = \frac{qB}{m(t)}$$

….. and extract

Repeat 300-1000 x per sec

→ Pulsed beam 300-1000 Hz

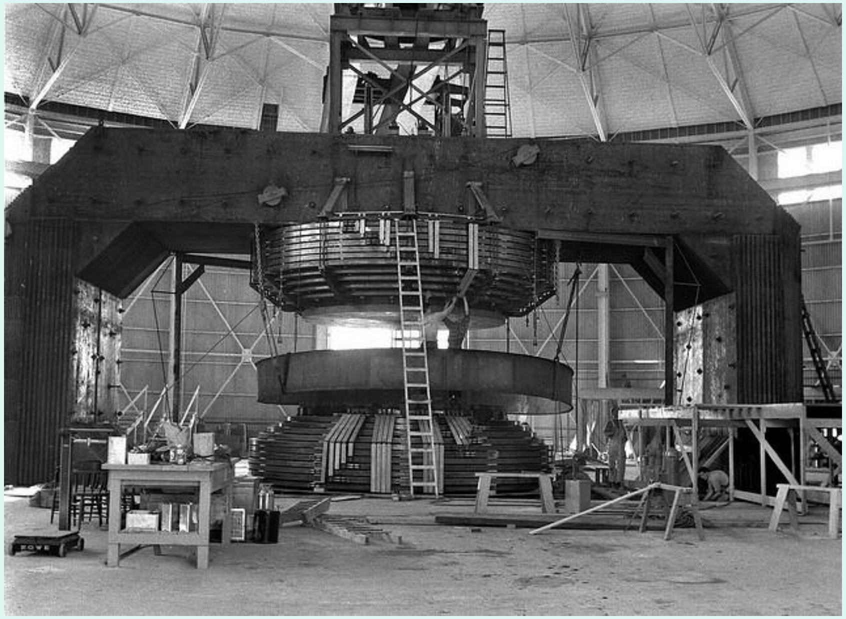




Synchro-cyclotron

synchro-cyclotron: High energies ...1000 MeV

Fields of 1.5-2 T => large magnet poles



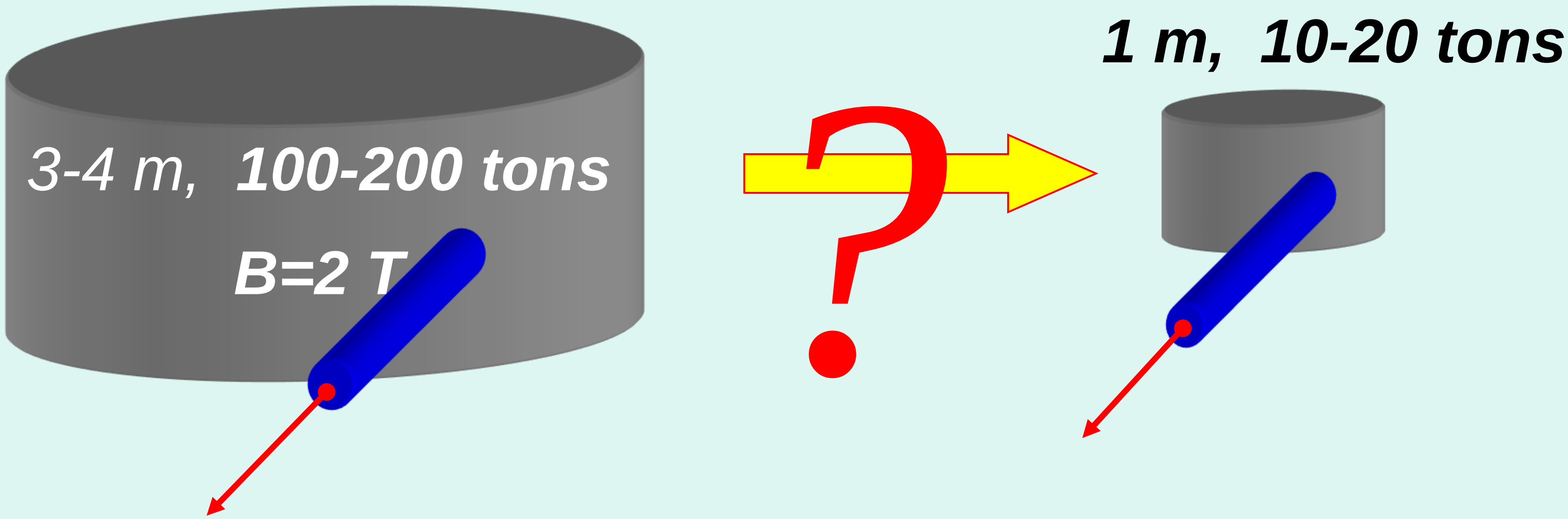
4.7 m∅ (4300 tons) Cyclotron (in 1942)

380 MeV , 1957: 720 MeV

UCL Lawrence Berkeley Nat'l Lab

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

Small cyclotron

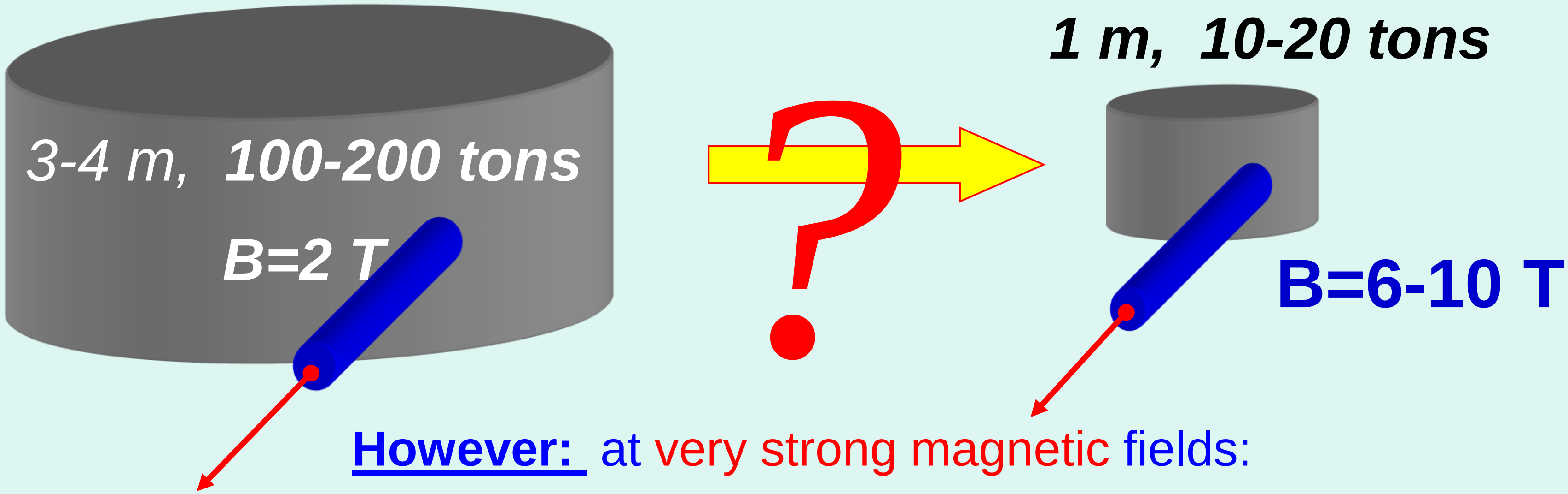


Solution:

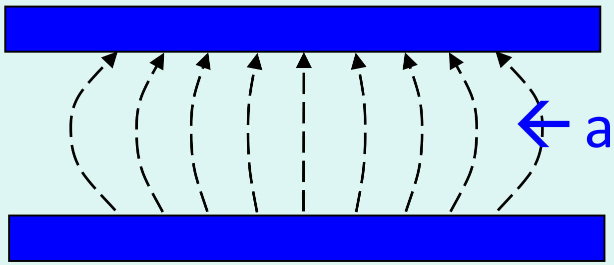
Increase magnetic field: ***B=6-10 T***

=> Smaller orbit radius

Small cyclotron



However: at very strong magnetic fields:



← at magnet edge
weaker B-field

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

T_{circle} increases with radius.

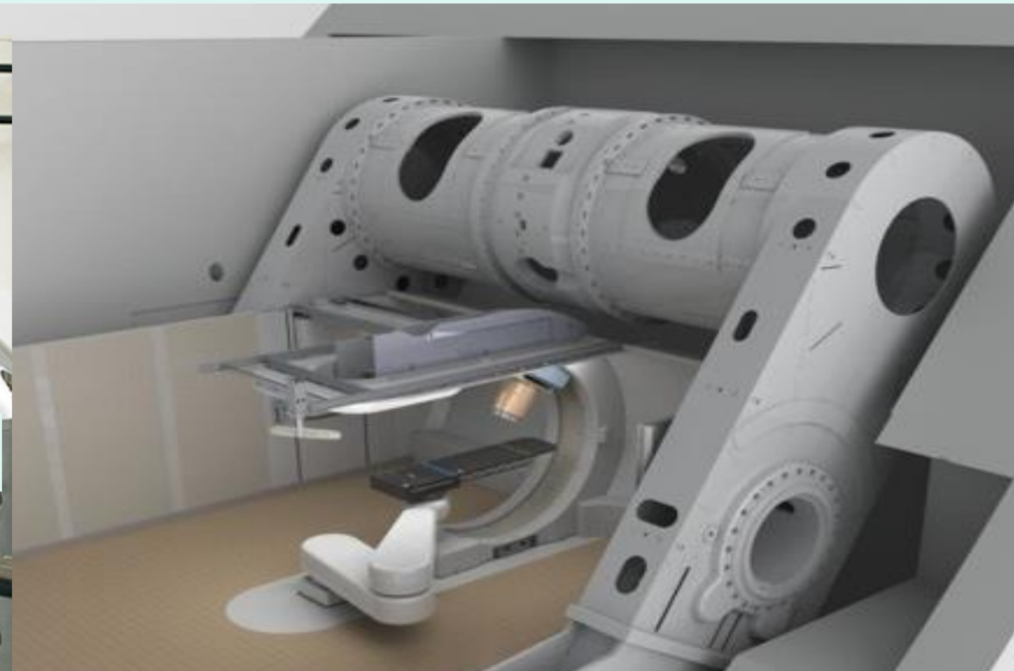
→ **Similar effect** as mass increase! → decrease f_{RF} with radius and extract

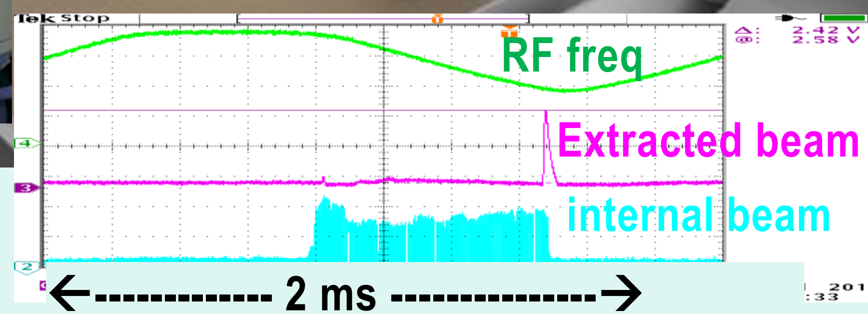
Synchro-cyclotron

2013: 250 MeV Synchro-cyclotron on a gantry

MEVION medical systems

8.5 T, 250 MeV, 500 Hz





Relativity in high-E cyclotrons

REMEDY 2:

Correct with B-field:

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

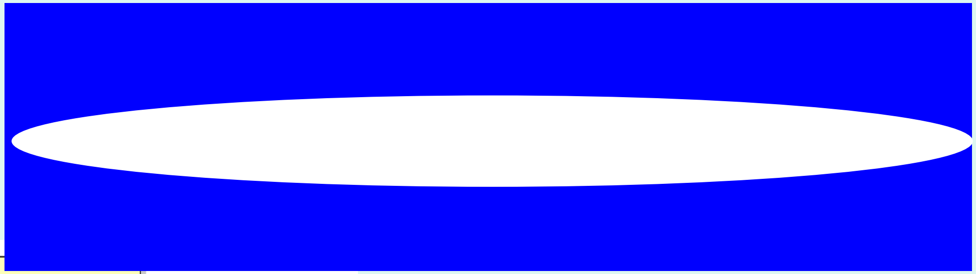
$$B(r)=\gamma(r)\ .\ B_0$$

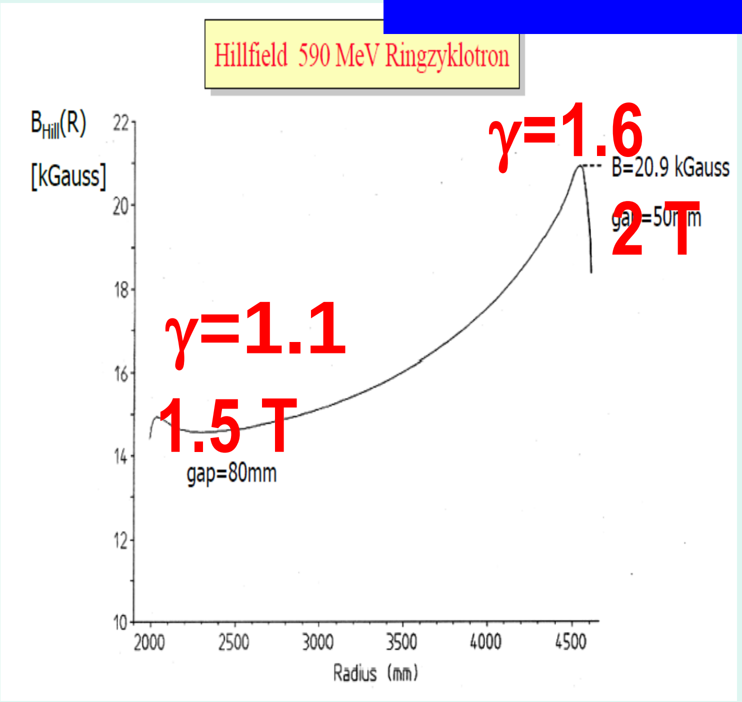
$$T_{circle} = \frac{2\pi.m}{q.B}$$

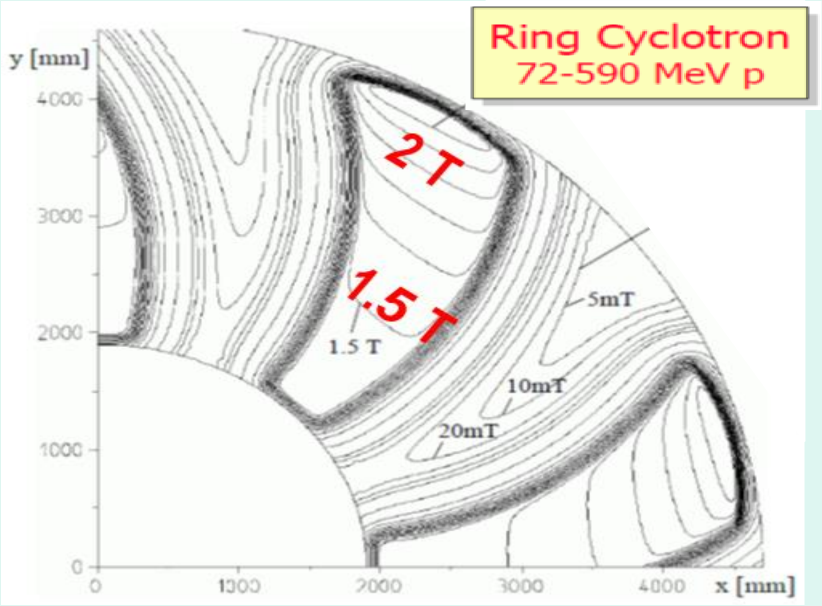
isochronous cyclotron

decrease pole gap + use trim coils

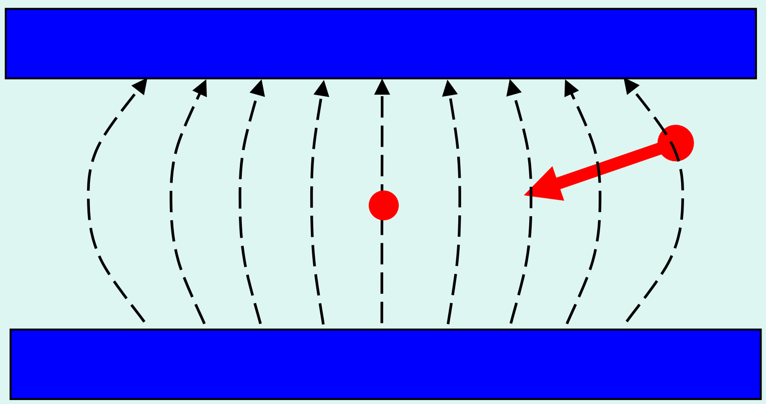
Increase the field strength with radius
→ **Decrease** Pole gap with r







Vertical focusing



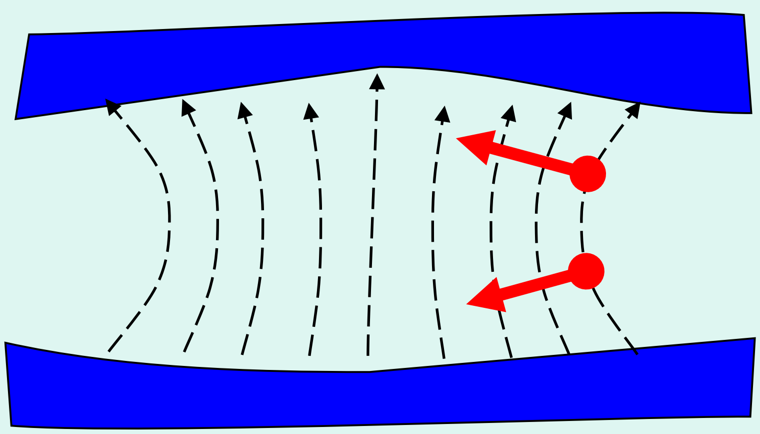
Inhom. field: field index $n \neq 0$:

$$n(r) = -\frac{dB(r)}{dr}\frac{r}{B(r)}$$

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

=> Automatic **vertical stability**

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



When B **increases** with radius:

……….

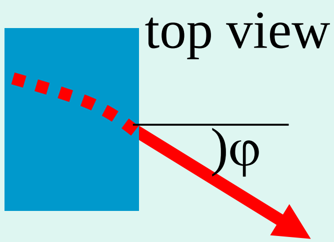
$n<0$ => no **vertical stability**

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

Vert.focusing by Varying Field: AVF

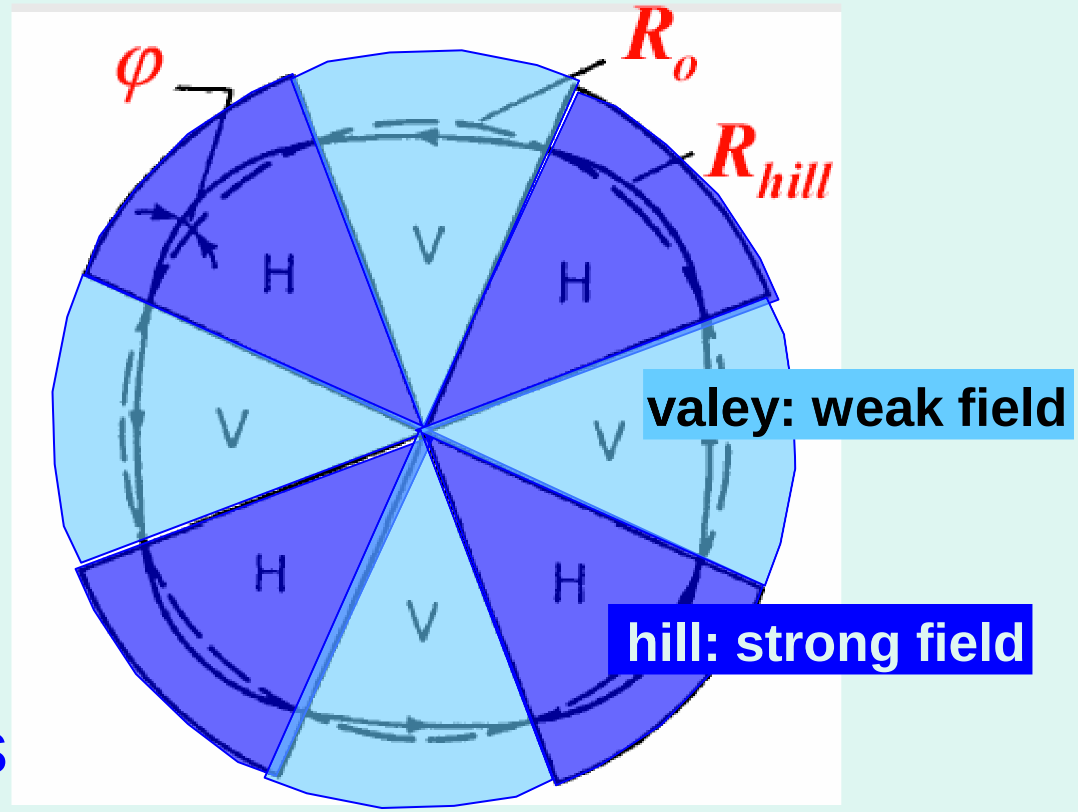
If B-step is not crossed ⊥ :

=> vertical force

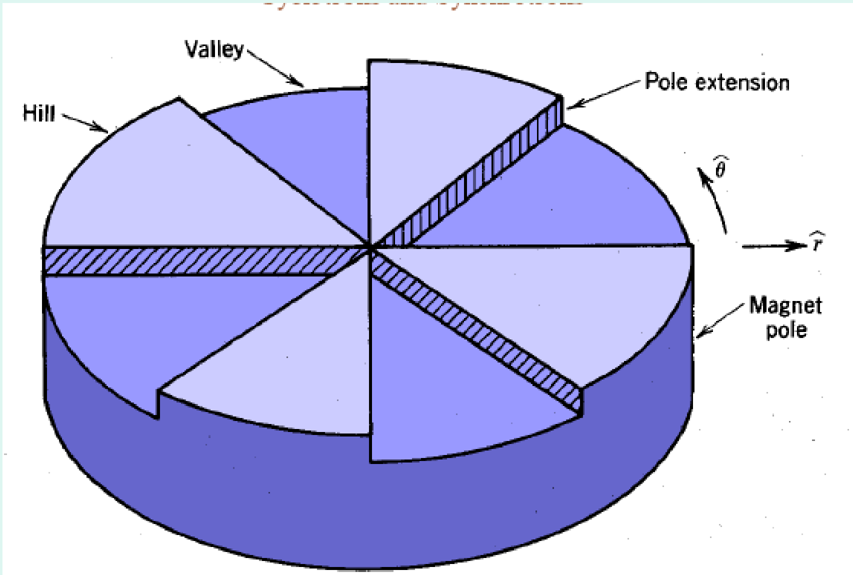


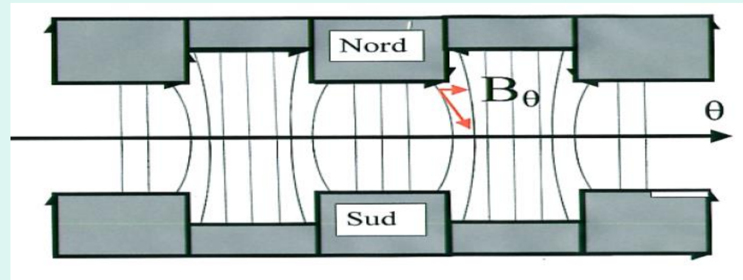
AVF = Azimuthally Varying Field →

Vertical focusing at hill-valey boundaries



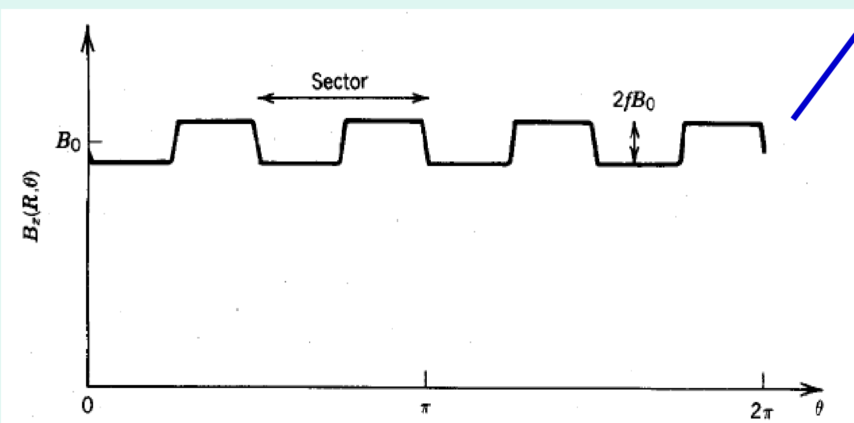
Vertical focusing: Azimuthally Varying Field





Flutter function:

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

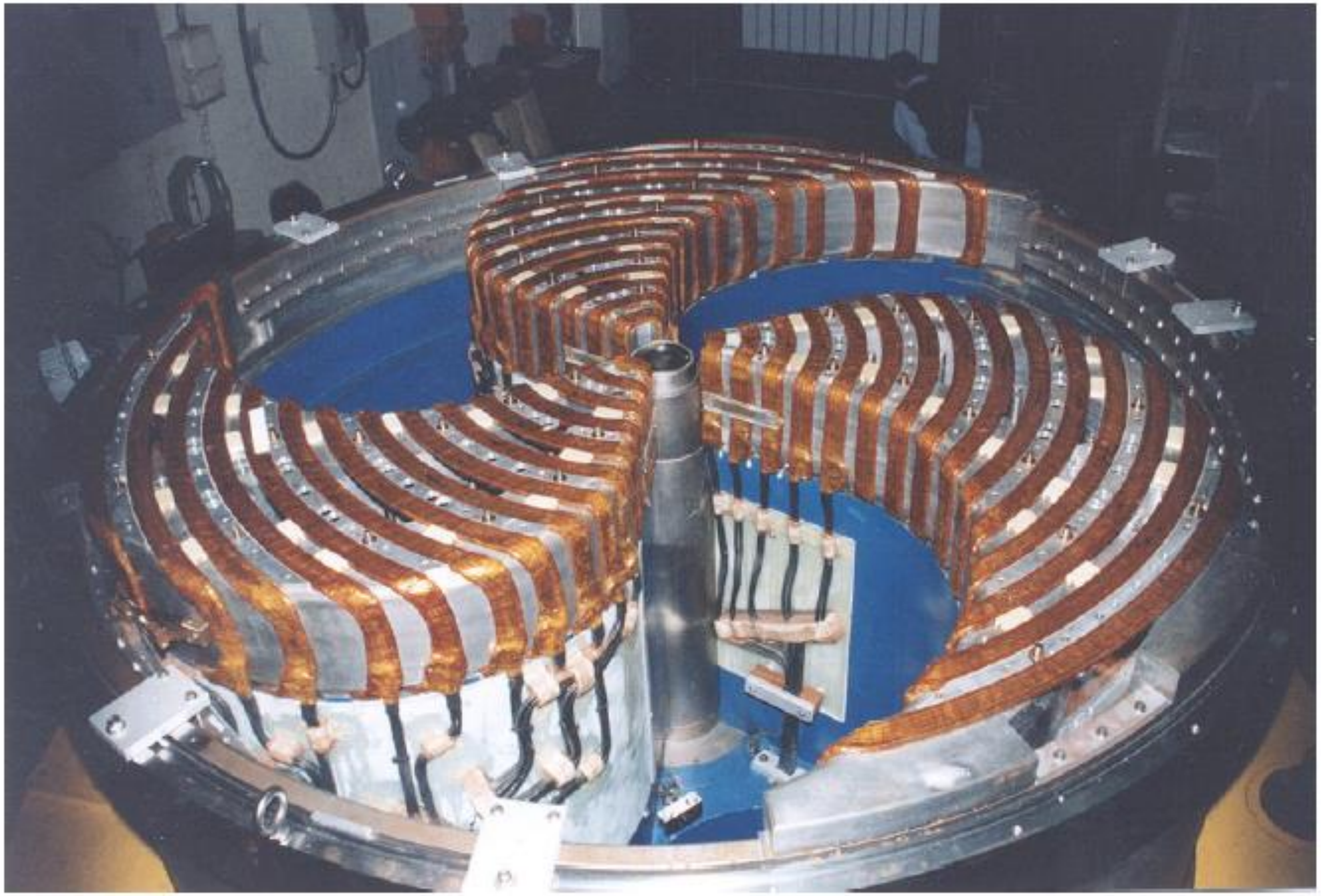


Thomas focusing:

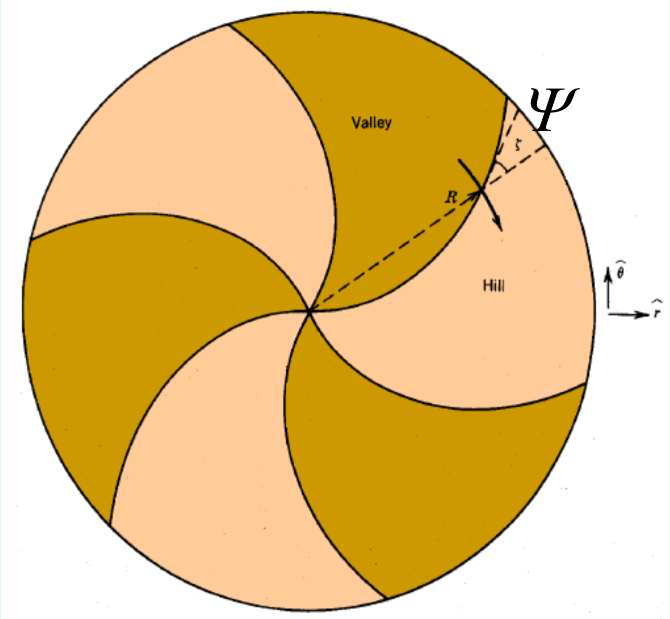
$$\nu_z^2(R) = n(R) + F(R)$$

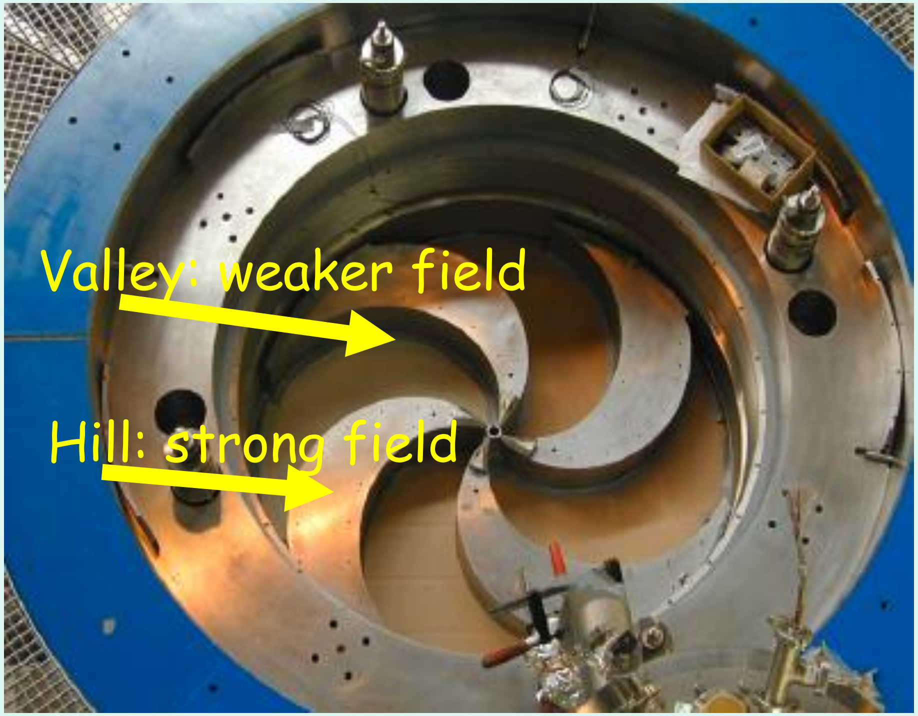
< 0 !

Pole of AGOR cyclotron



Azimuthally Varying Field cyclotron





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

to **compensate** :higher energy

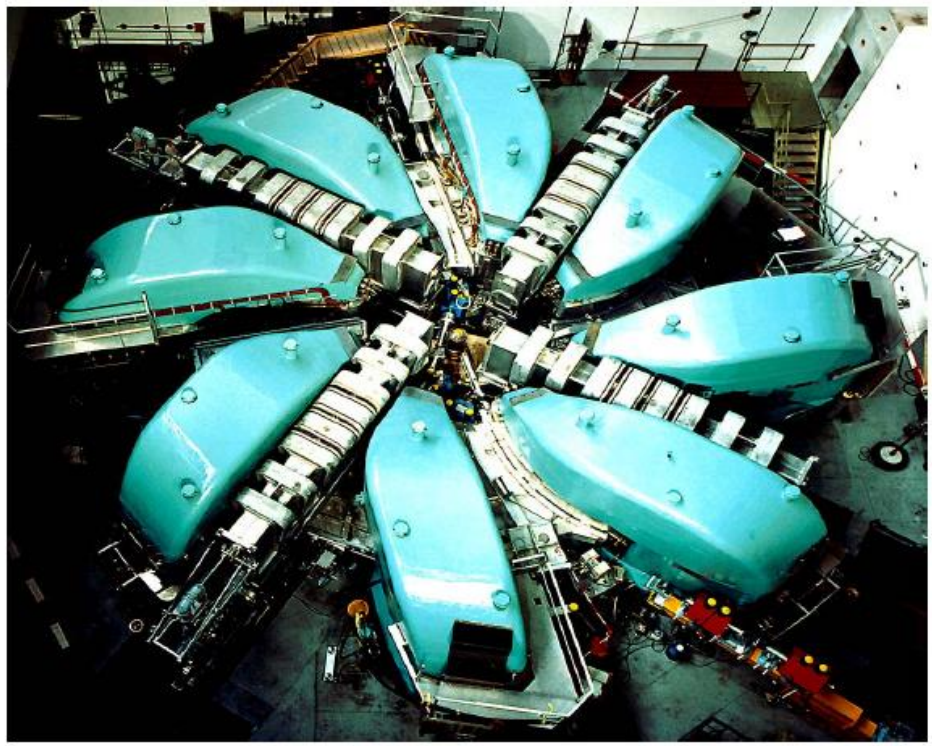
=> increase angle Ψ with radius => **spiral shape**

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 %

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**)

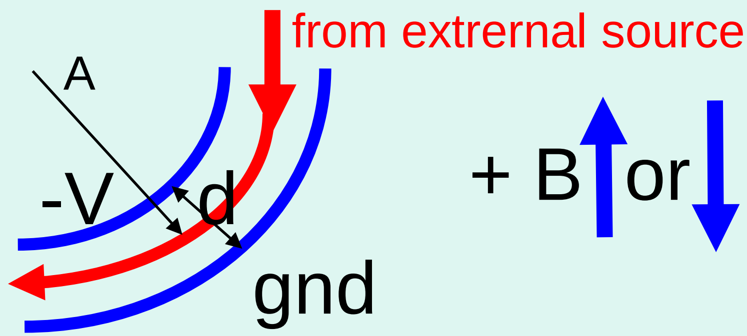
… but vertical focusing must be added

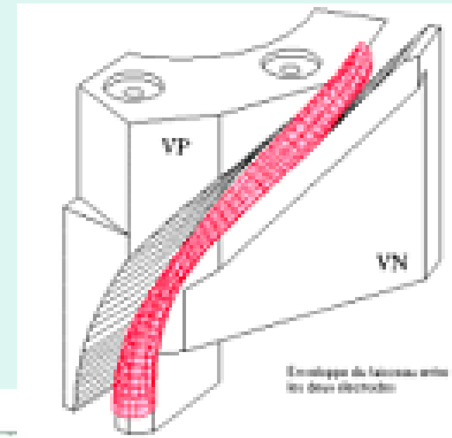
Central region:

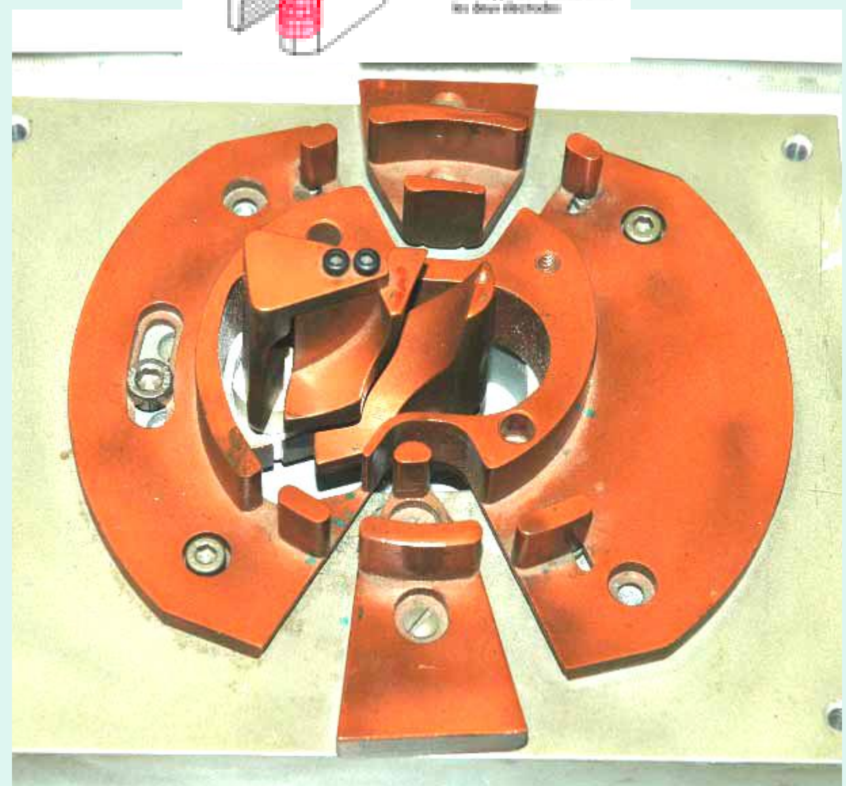
Either -injection of externally coming beam

Or: -ion source

Axial injection : spiral inflector







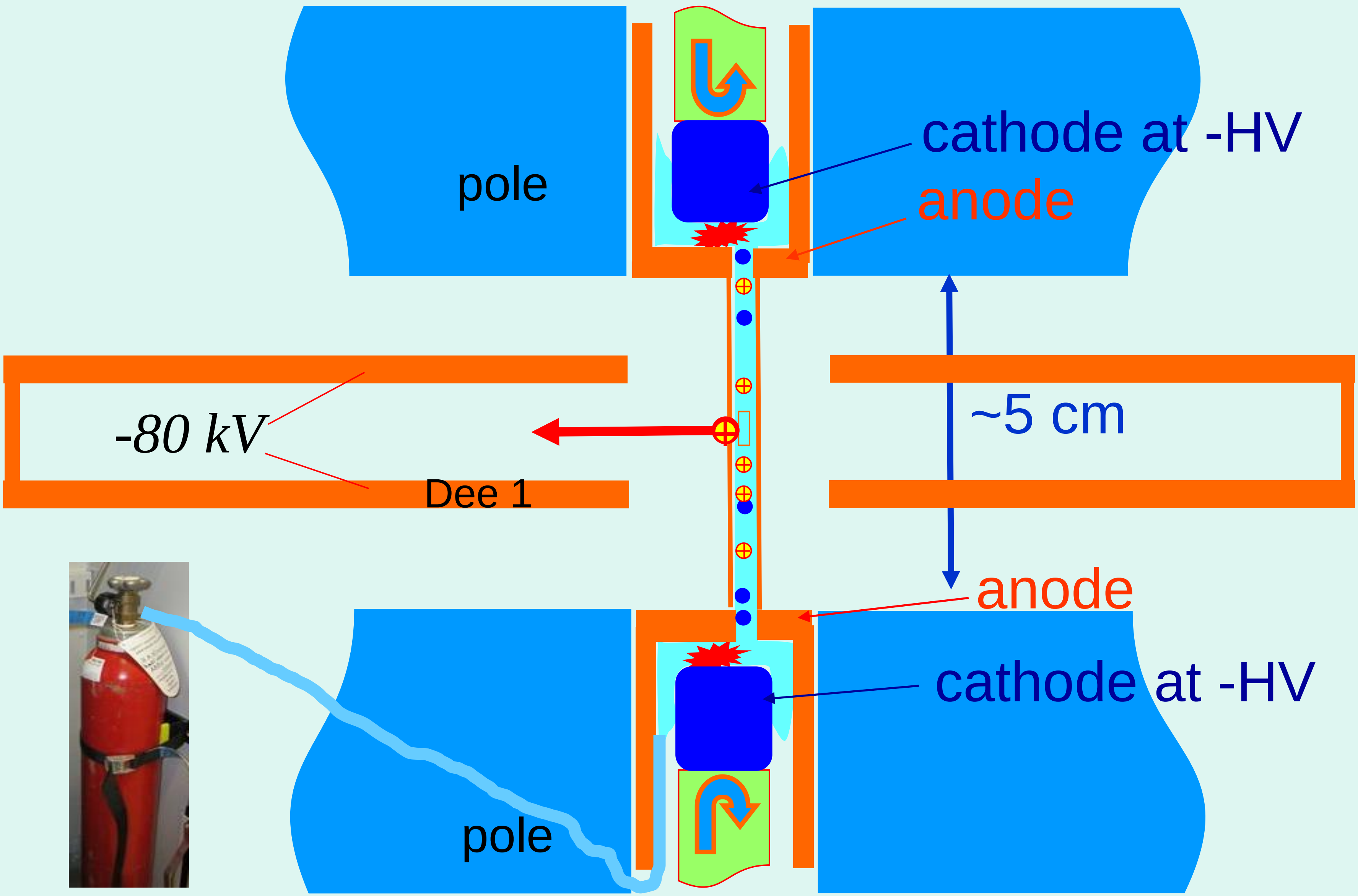
Inflector:

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

Internal ion source:

(usually protons, He)

Internal ion source



RF cavities

Important parameters:

Voltage amplitude on Dee : 30-80 kV

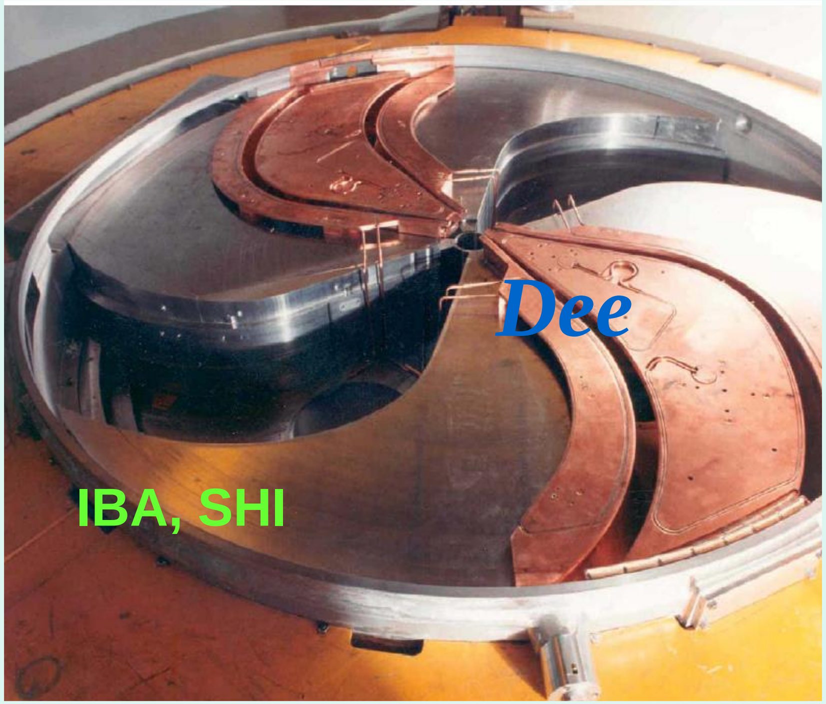
Number of Dee‘s: 1,2,3,4

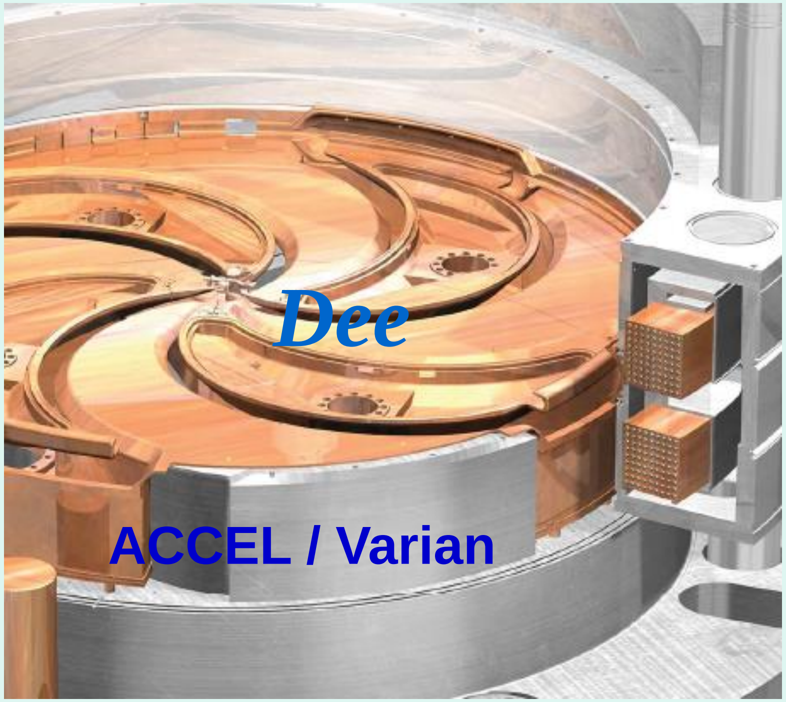
⇒ Energy gain per turn

⇒ Orbit separation

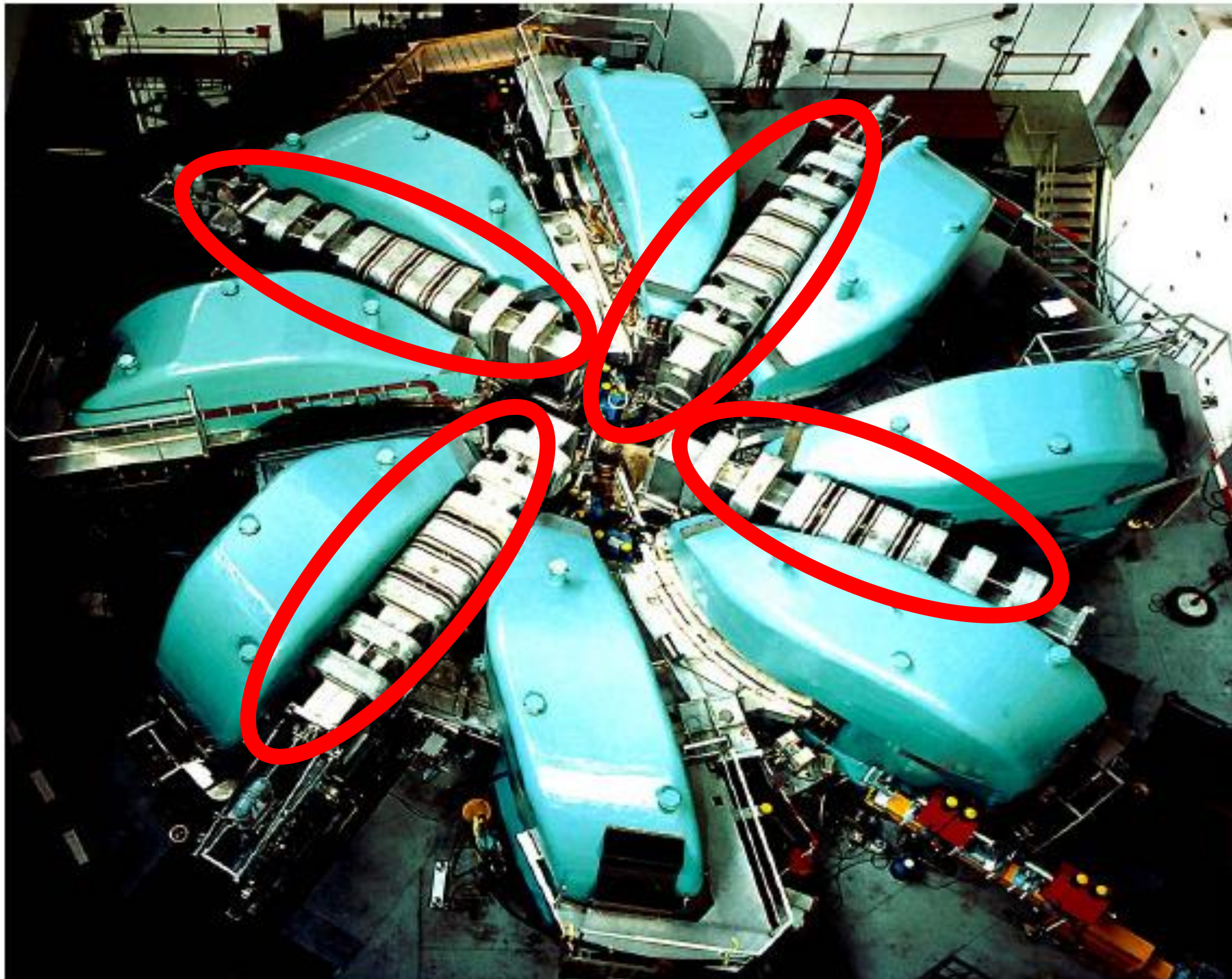
⇒ Extraction efficiency

Dual gap: Dee





PSI Ring cyclotron



Ringcyclotron

590 MeV Protons

1.3 MW Beam Power (world record!)

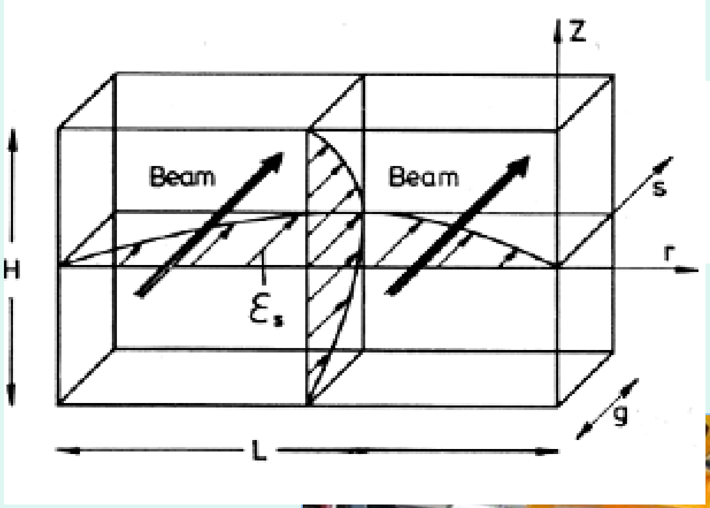
8 Magnet à 250 Tons

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

Extraction ≈ 99.97 %

Single gap cavities (ring cyclotrons)

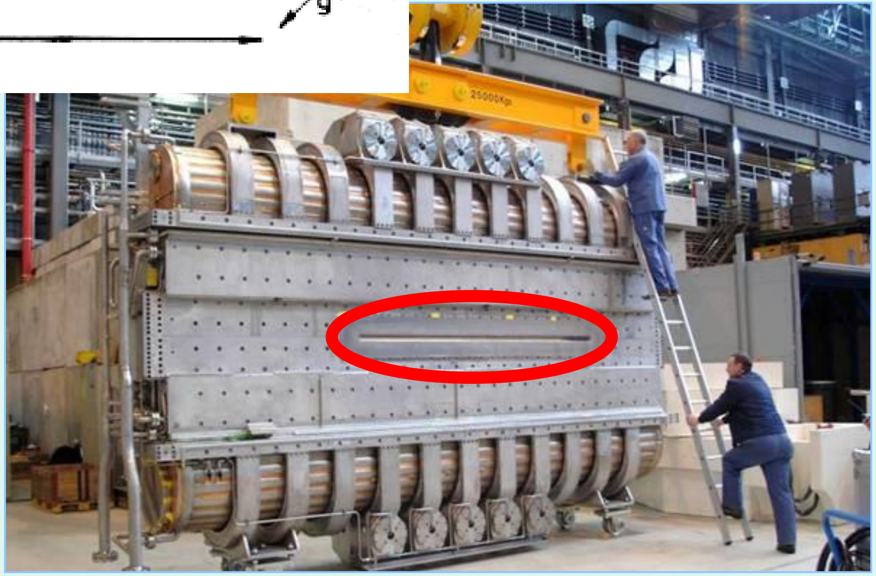
Ring Cyclotron 590 MeV , 50.7 MHz



copper , V = 1 MV

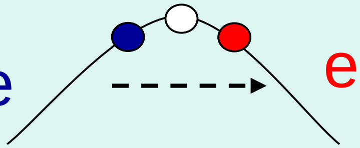
400 kW power loss

160 turns , current limit > 3 mA ?

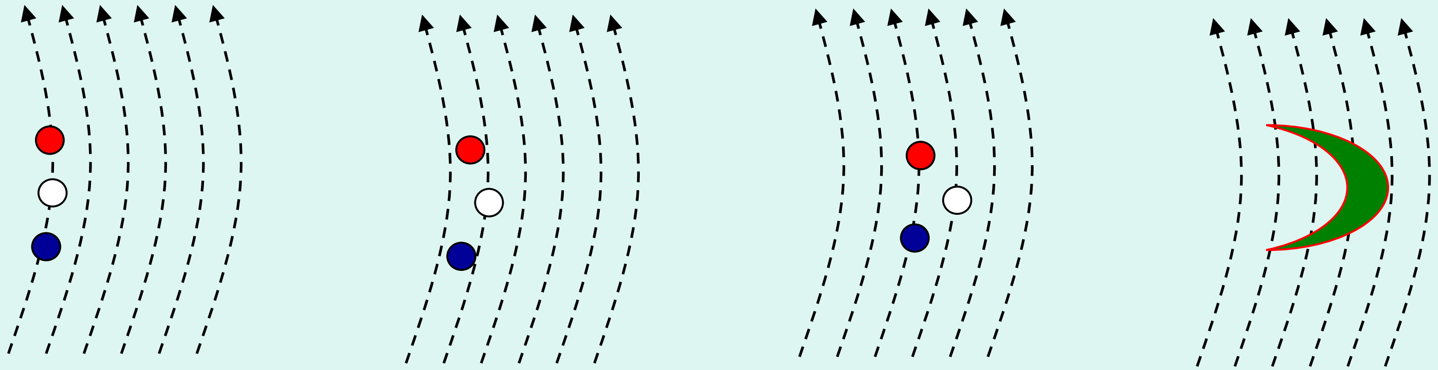


Phase mixing

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



Both late and early get less energy

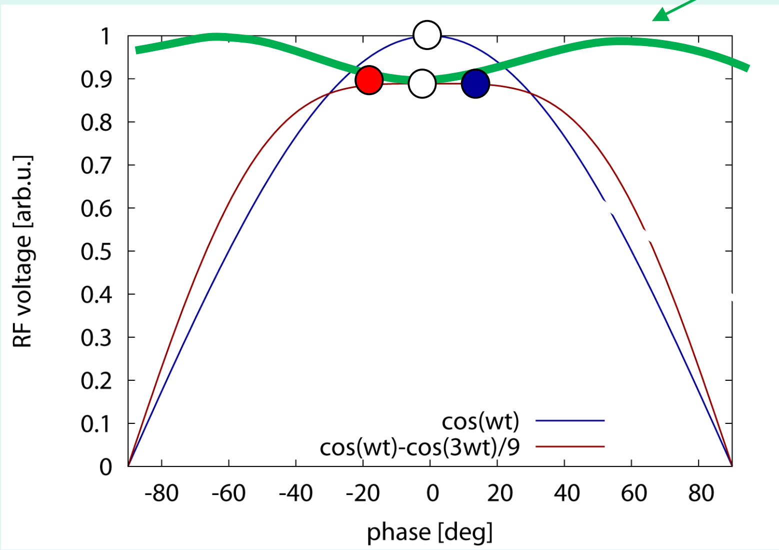


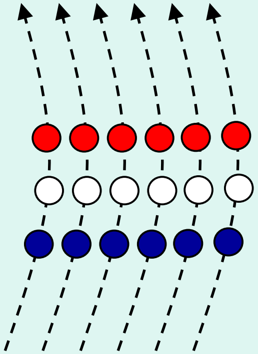
→ Large phase width → broad beam

→ **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: $U_{tot} = U_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$





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

Intensity

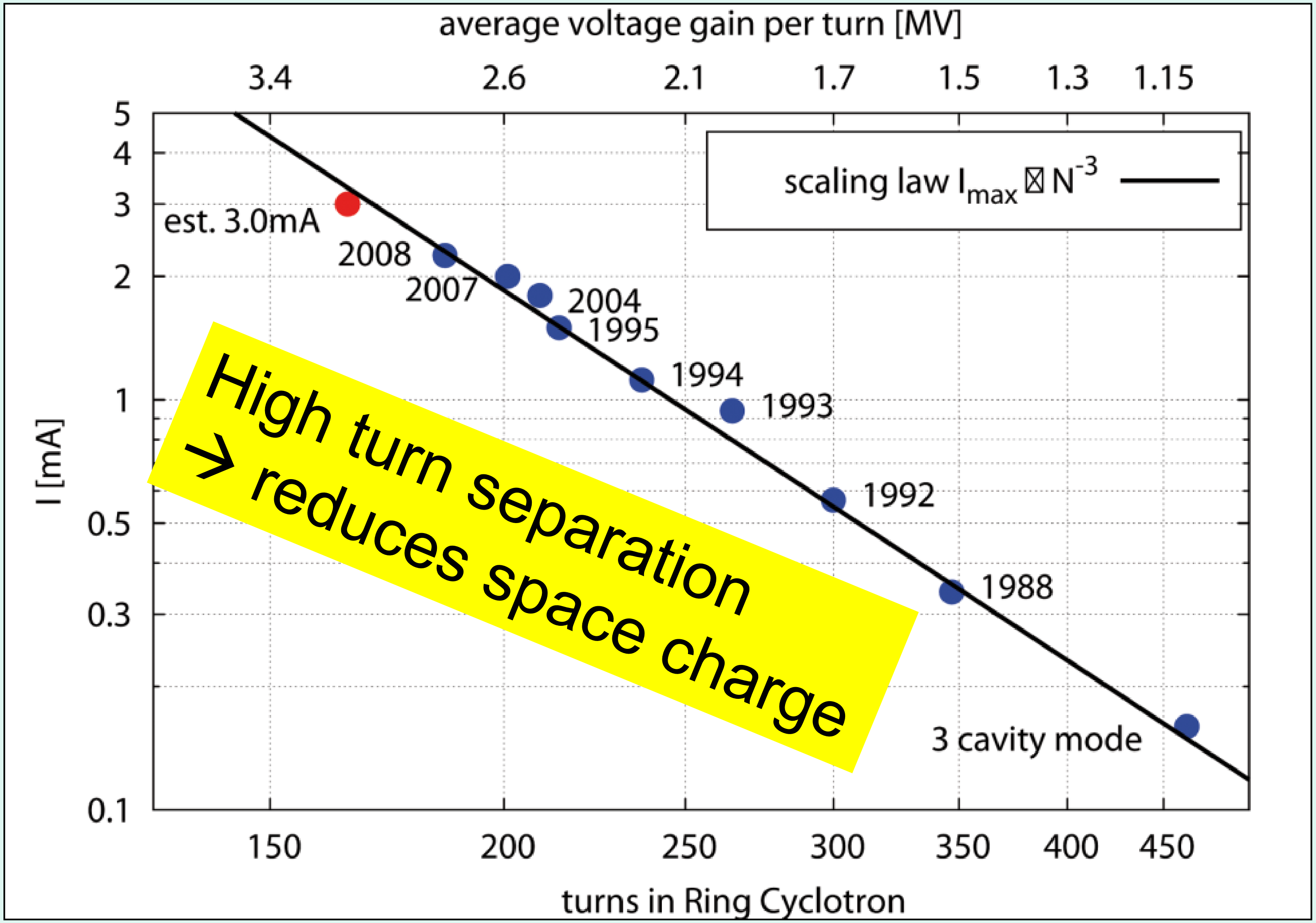
high intensity+ high energy:

=>high **beam power**

$$I_{beam}(\mu A)\times E(MeV) = P(W)$$

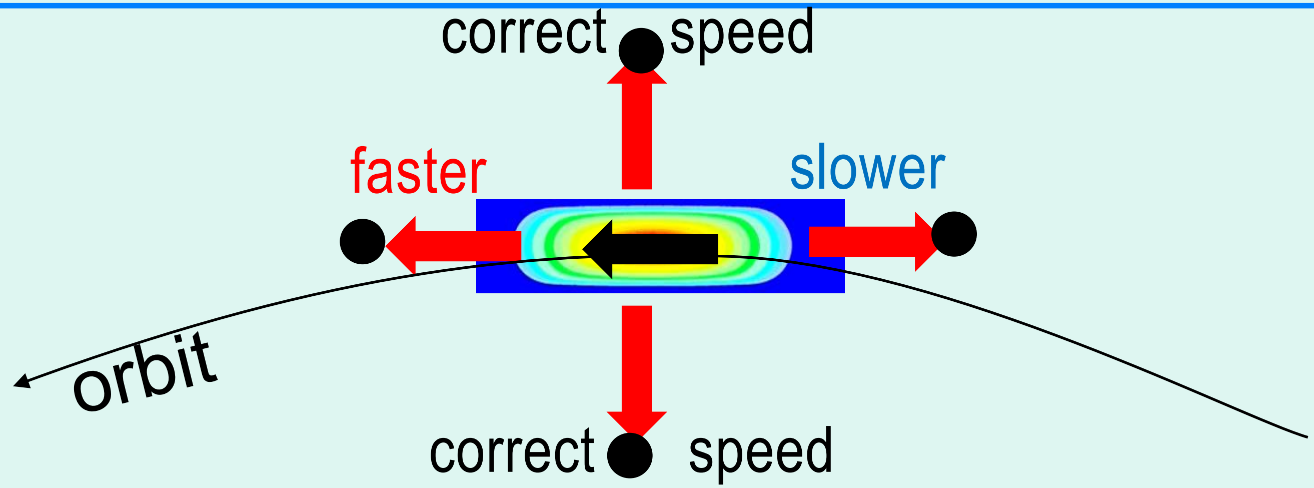
At PSI: 2000 $\mu A \times$ 590 MeV = 1.18 MW

high intensity needs high ΔE/turn

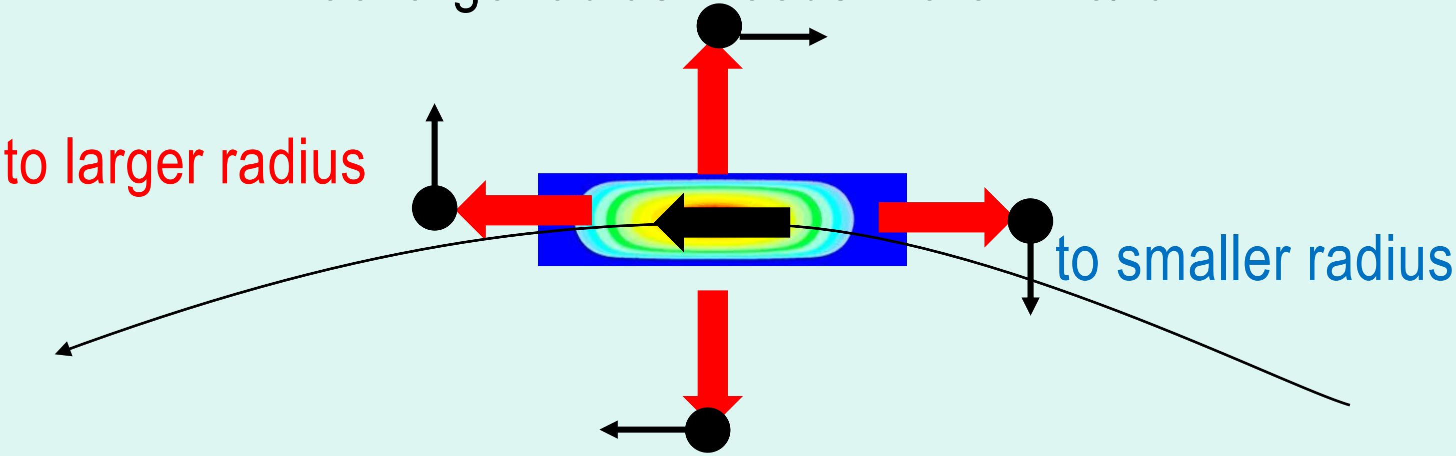


W. Joho, Cyclotron Conference Caen 1981

Vortex or Spagetti effect



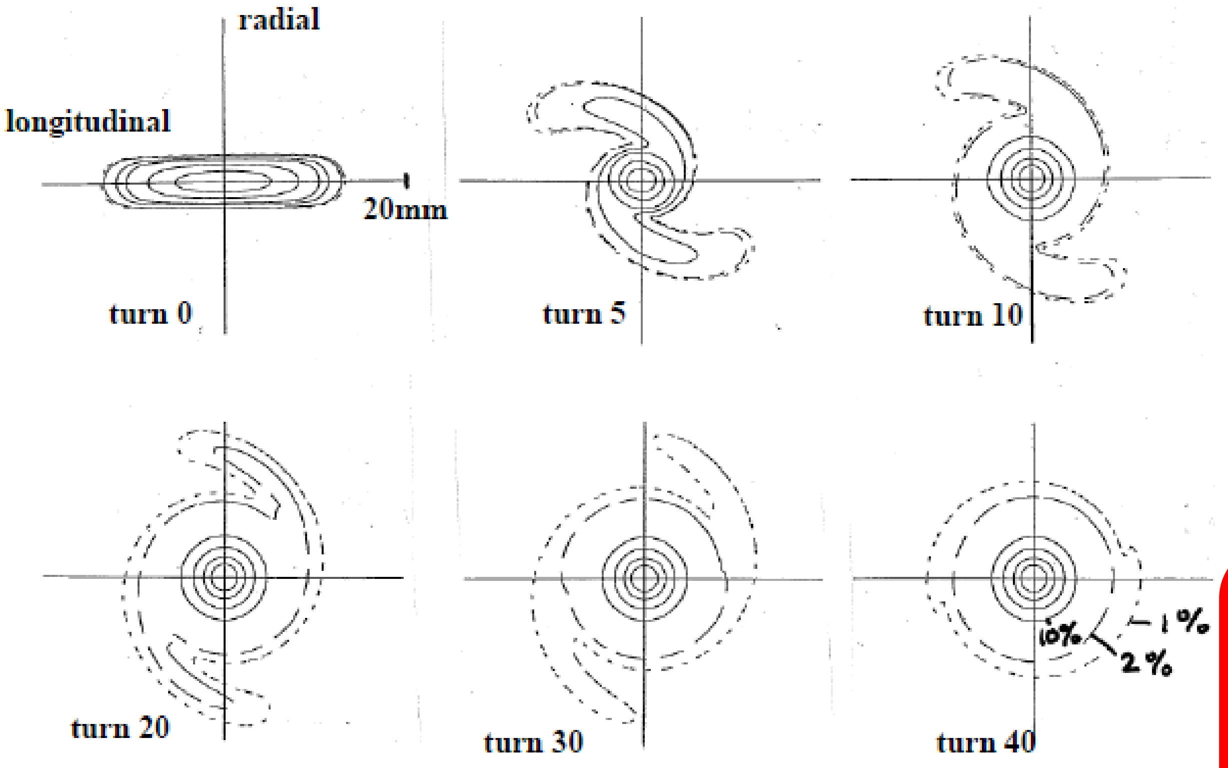
→ too large radius: needs more time/turn



→ too small radius: needs less time/turn

Vortex or Spagetti effect

Longitudinal Space Charge in Cyclotron



Simulation of a 1mA beam, circulating in Injector II at 3 MeV for 40 turns without acceleration.

The core stabilizes faster than the halos (calculations by Stefan Adam)

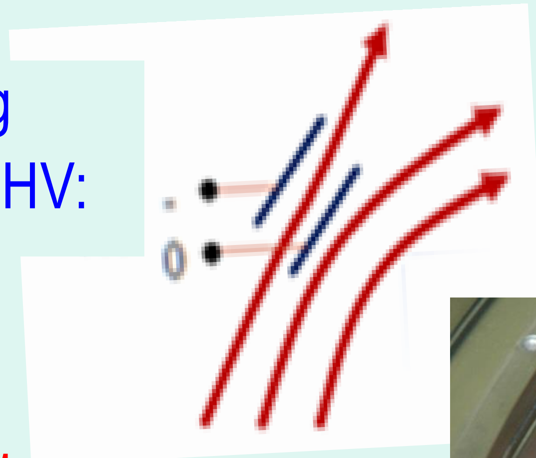
→ Automatic space charge compensation!

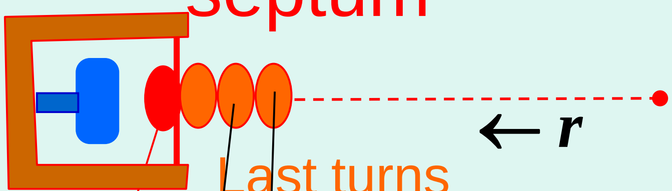
Extraction:

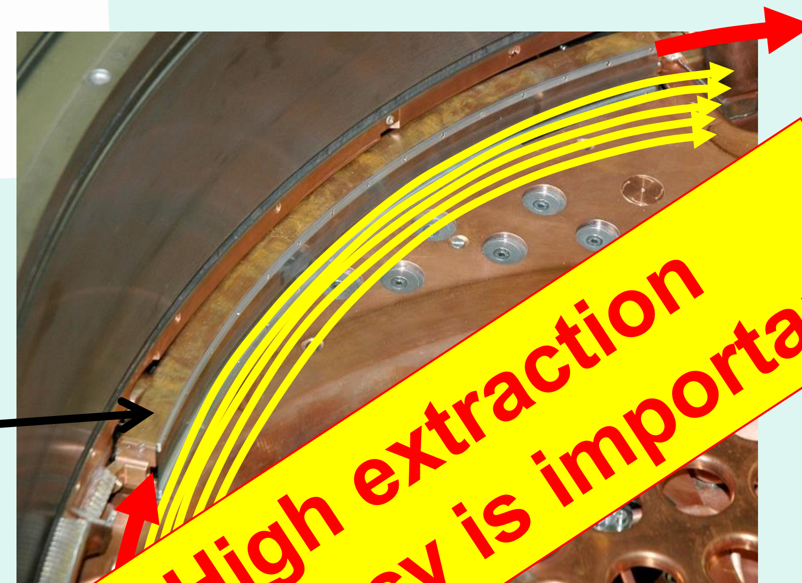
How to get out?

Extraction from cyclotron

Extraction using septum and HV:





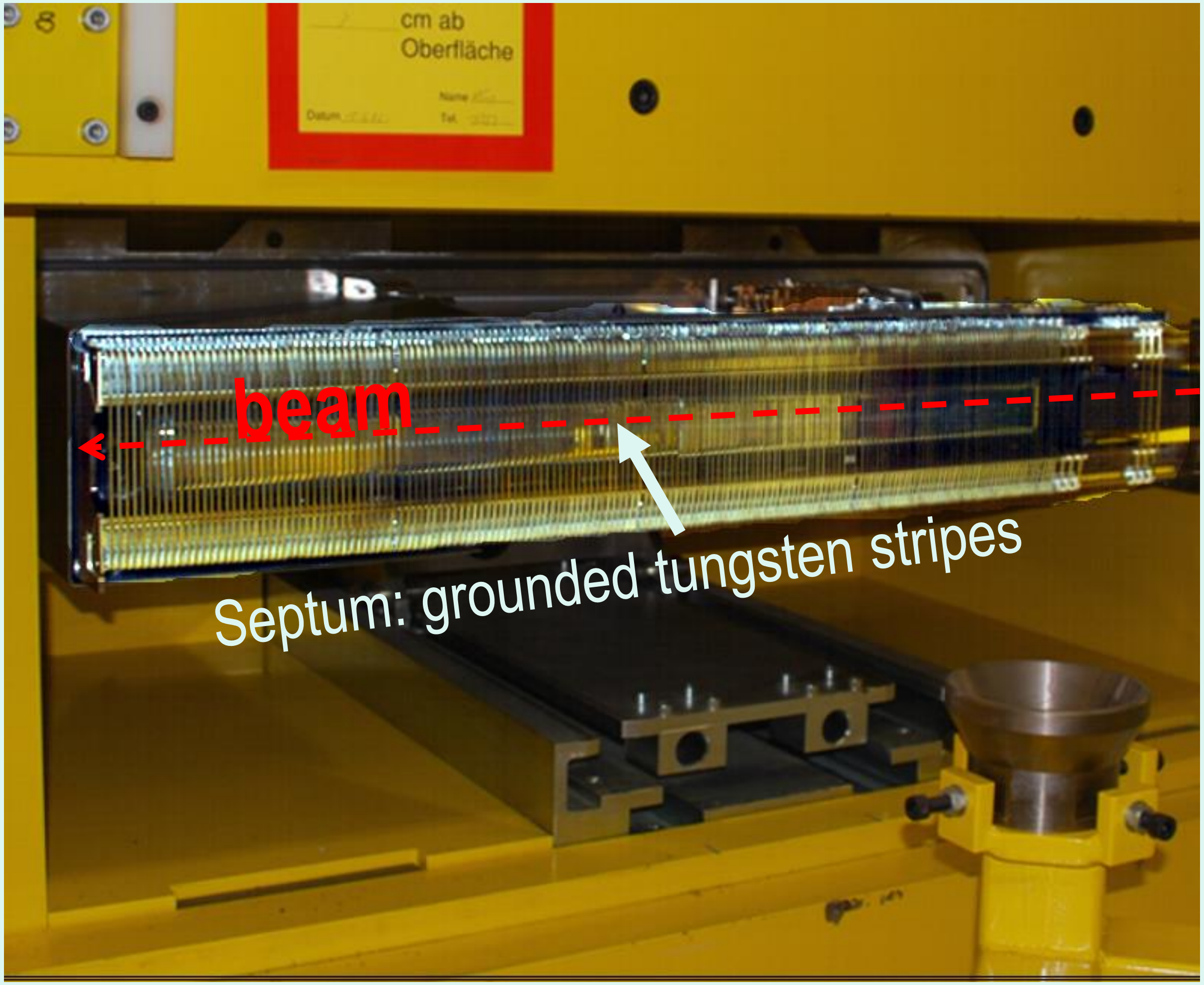


High extraction Efficiency is important

δr

Extraction: Electrostatic deflection

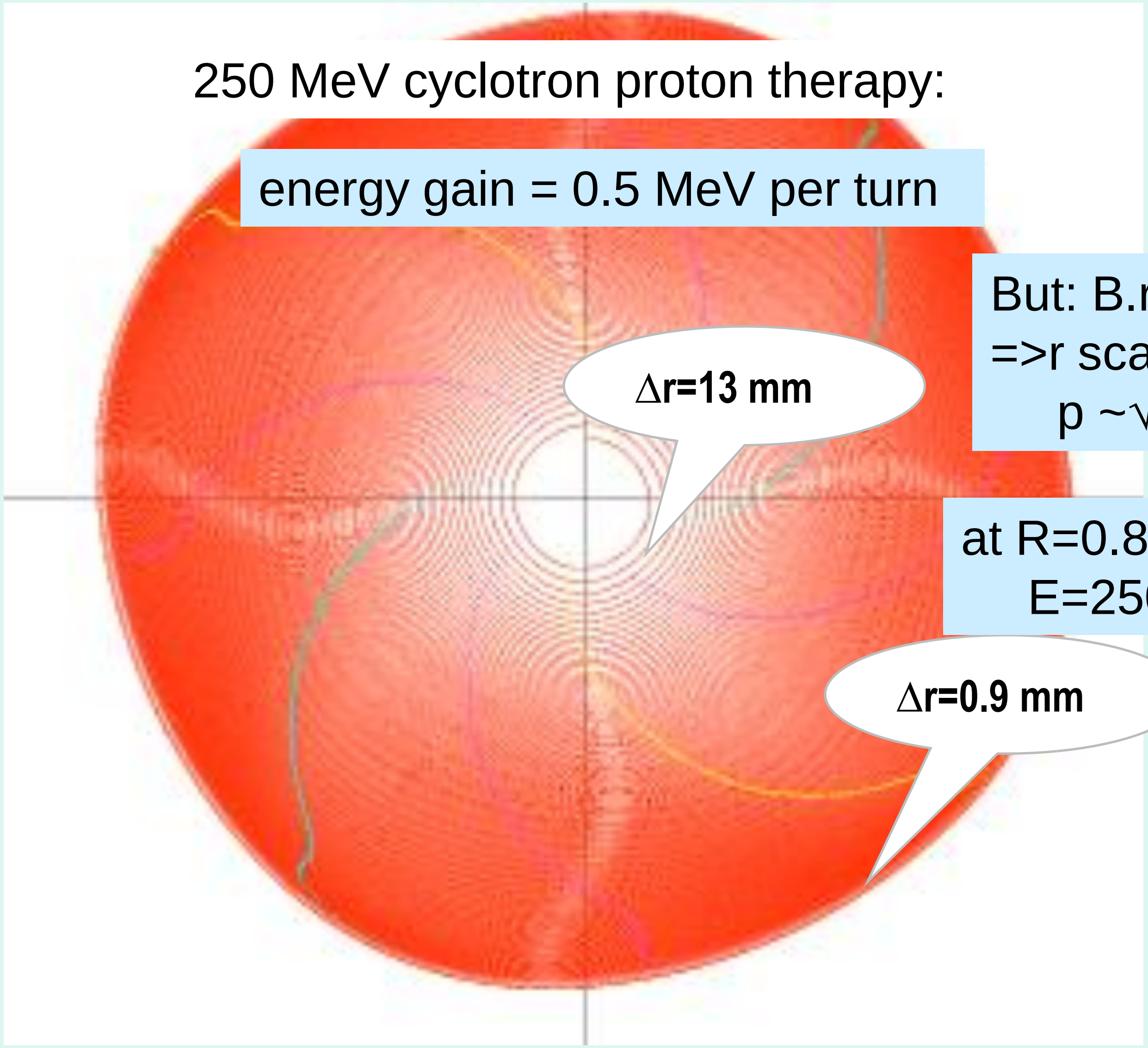
Extraction Channel 2 mA 590 MeV p at PSI: 145 kV



Turn separation

250 MeV cyclotron proton therapy:

energy gain = 0.5 MeV per turn



But: B.r = p/q
=>r scales with p:
p ~√E → **Δr~ 1/r**

at R=0.8 m:
E=250 MeV

Extraction from cyclotron

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

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

What will help:

→ High V_{dee} → **high ΔE / turn**

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

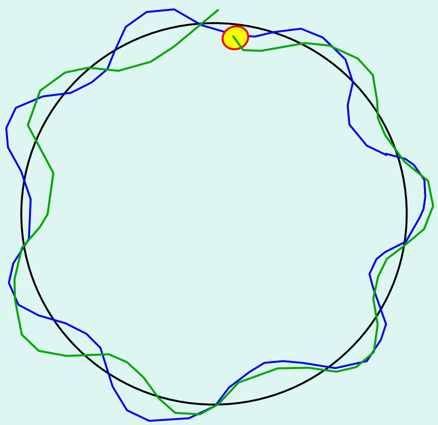
→ **High E_k** but keep γ <2 →heavy ions with **low speed**

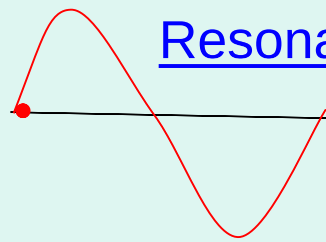
→ protons: **Emax ~1 GeV**

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

Use betatron oscillations

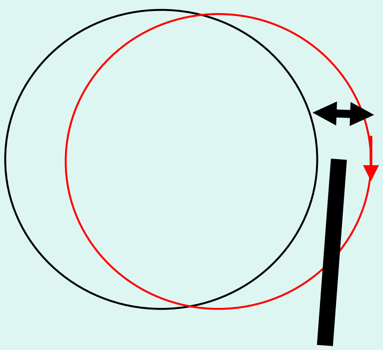
Important betatron oscillation in cyclotrons:





Resonance at ν_r =Qr=1 :

→ increase of turn separation



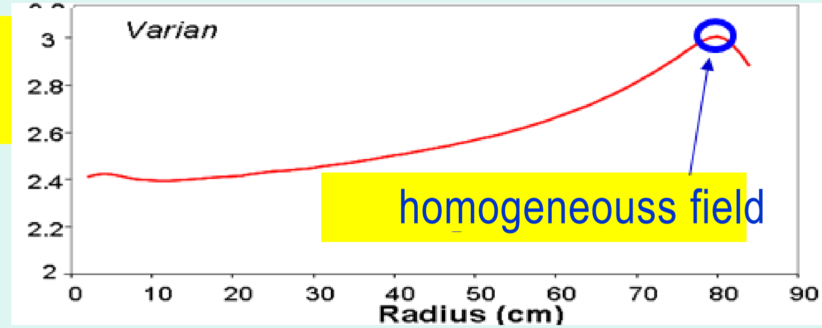
=effectively an orbit shift

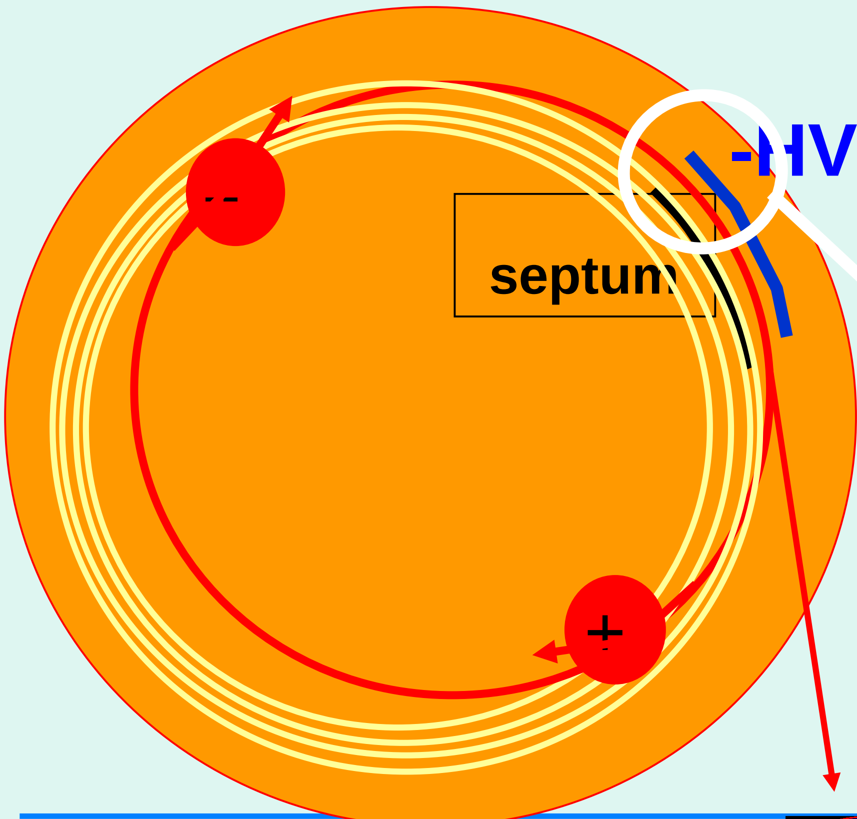
Extraction septum

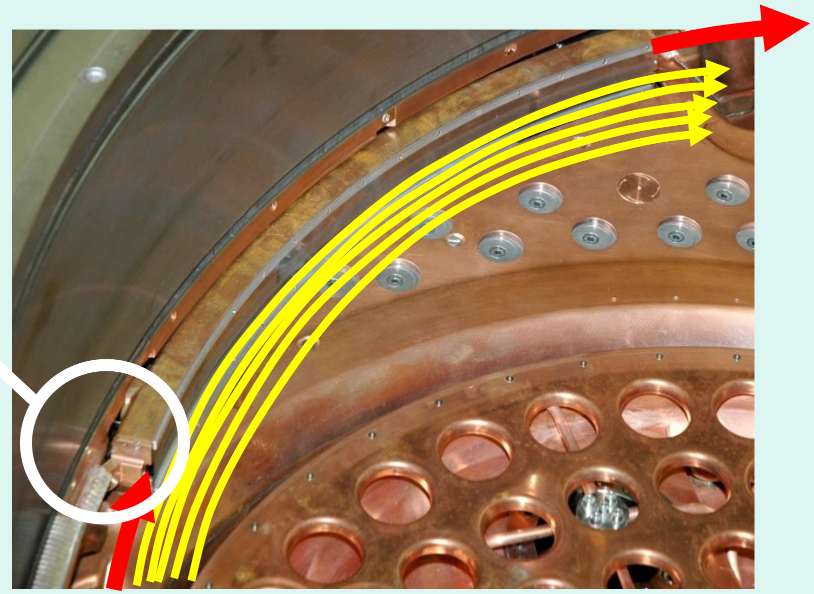
Resonant Extraction from COMET

Uses the homogeneous field ! $\nu_r=1$

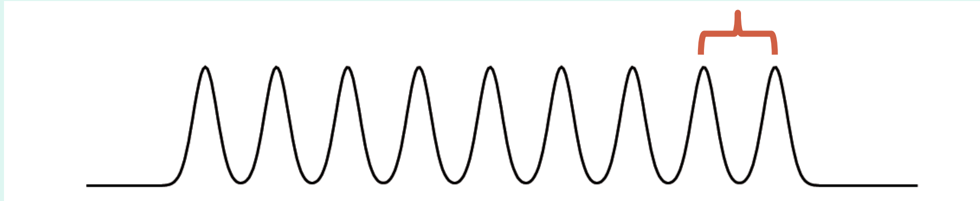
→ Locale field chsnges (bumps) shift the ebam:





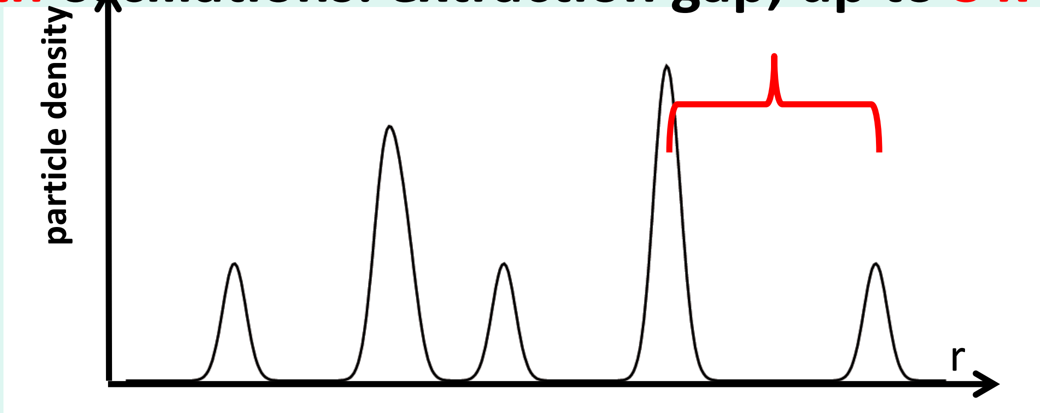


PSI: without oscillations: Δr from E_k-gain: 6 mm



Betatron oscillation is excited:
→ adds precession to orbits
→ **increases** the radial **turn separaton** by a **factor 3** !

with oscillations: extraction gap; up to 3 x Δr : 18 mm



Extr eff >99.98%

Extraction by charge exchange

Accelerate H^-

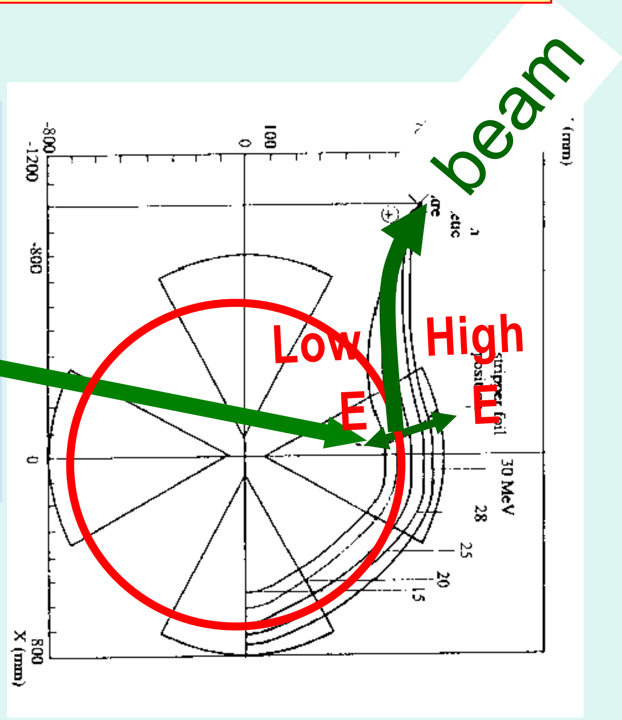
Extraction by **charge exchange**

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.

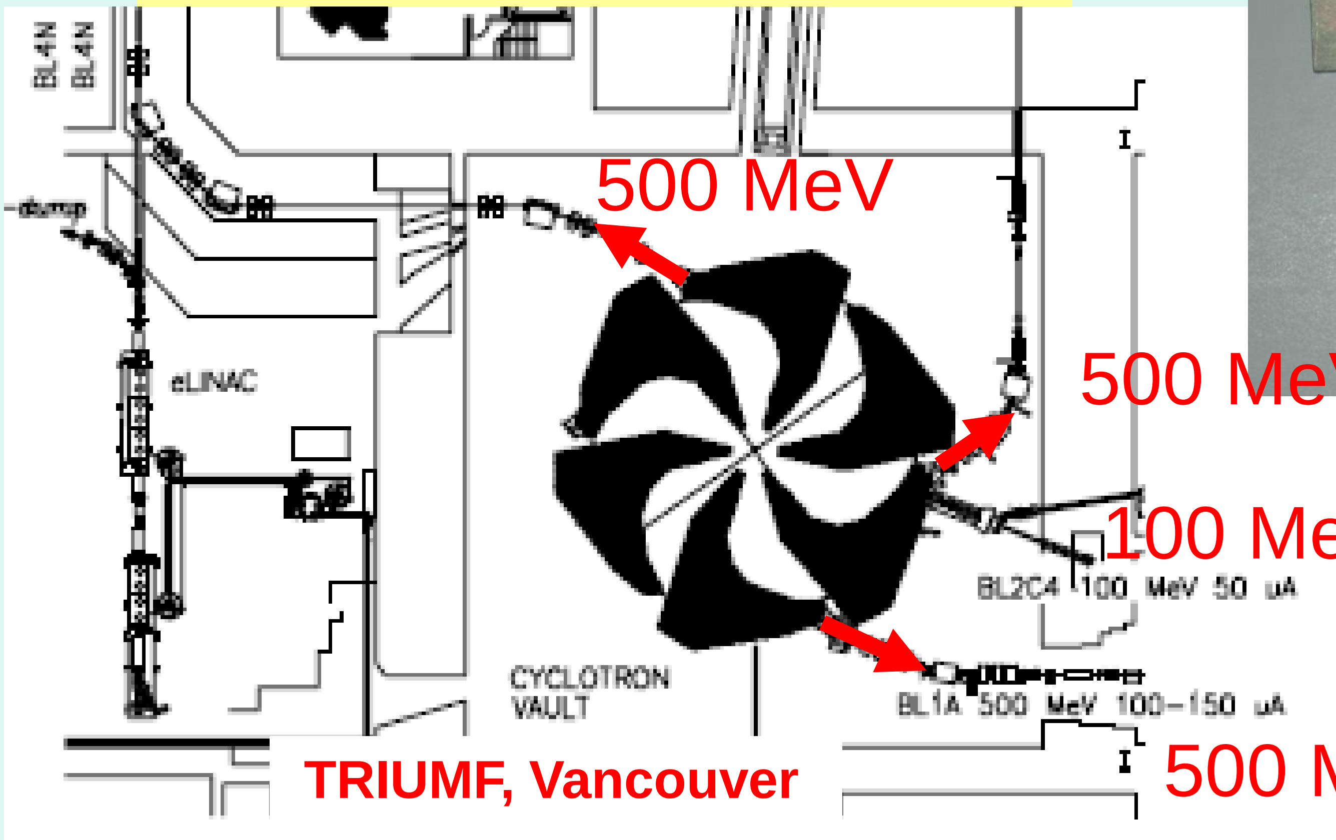
$$B < \frac{11}{\sqrt{E}} \quad [T]$$

+ losses due to stripping by residual gas

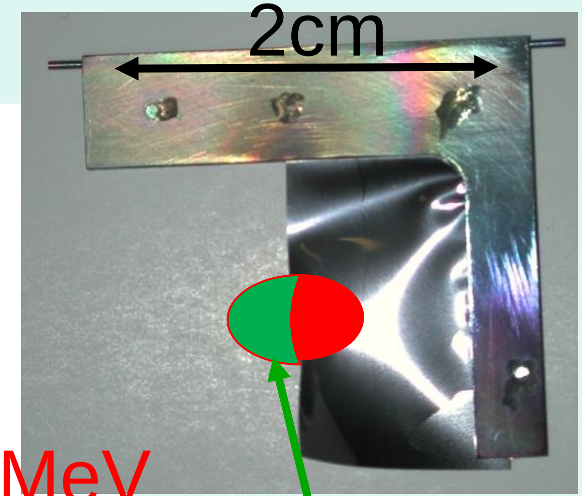
Extraction by stripping

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

Simultaneous extraction!



TRIUMF, Vancouver



Used at other foil

Applications of cyclotrons

Application	typ E(MeV/A)	typ Intens
physics (p+ions)	50-200	nA-μA
make beams of n,π	>30n 500π	μA-mA
isotope production	30	1-100 μA
particle therapy	70, <250	<1μA

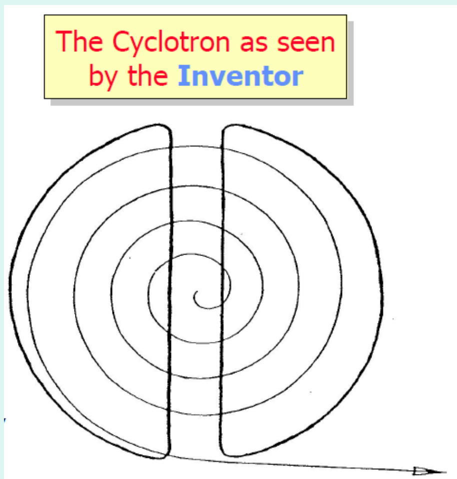
Conclusions on cyclotrons

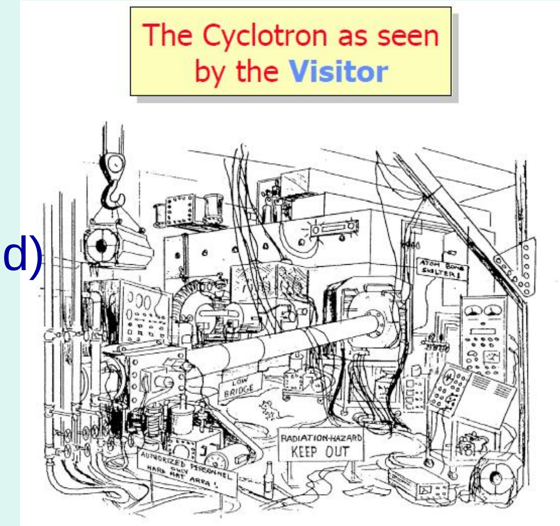
Advantages of a cyclotron

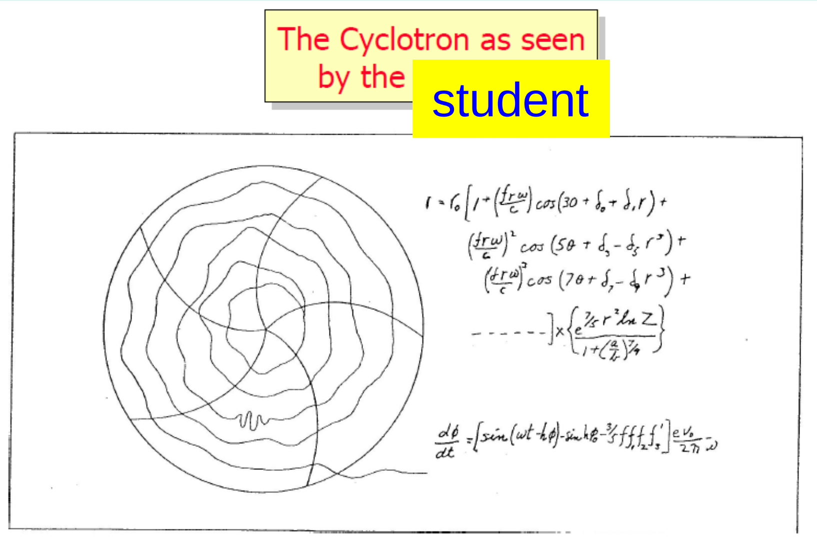
A cyclotron provides:

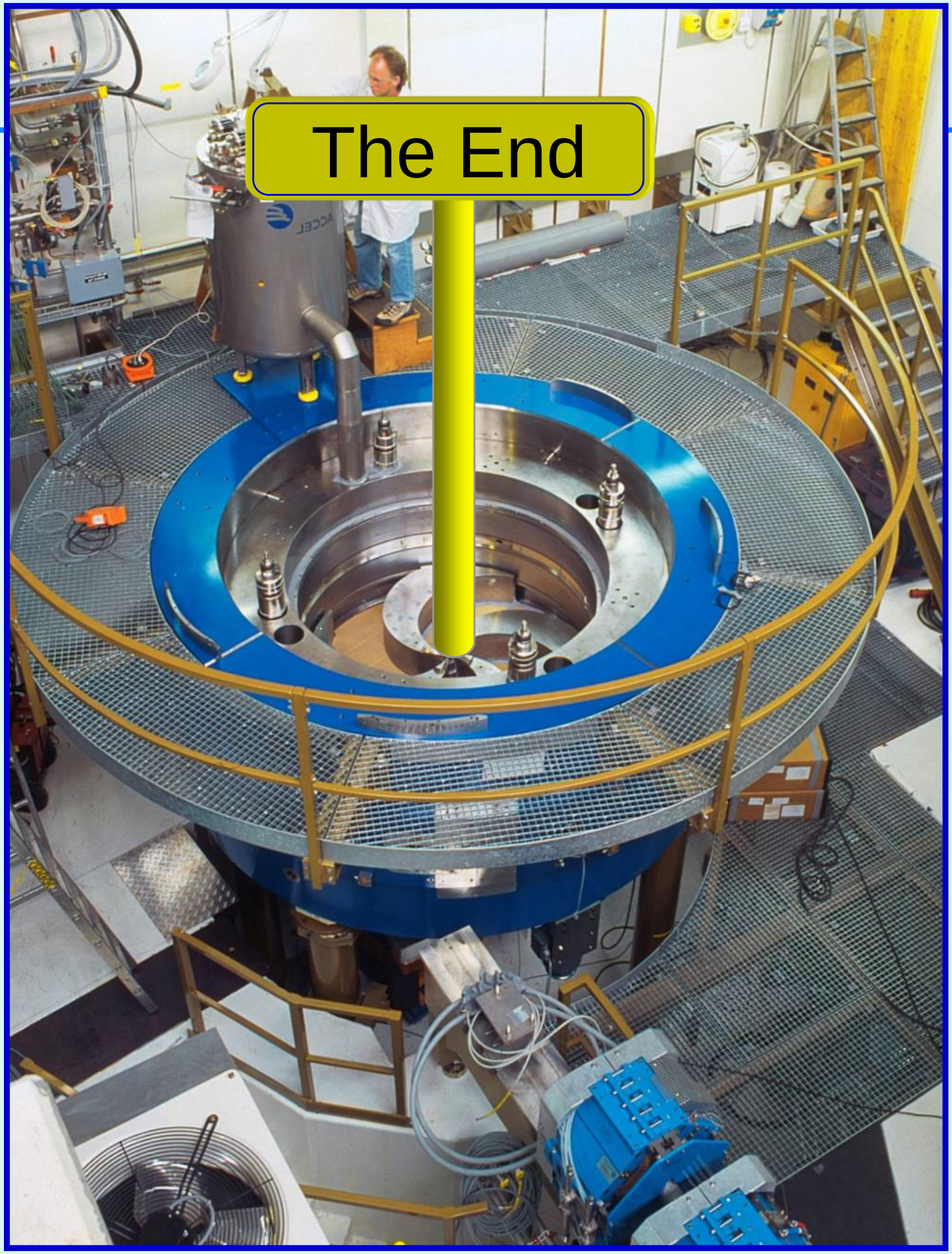
- continuous beam (Synchr.Cycl: pulsed)
- intensity nA-mA (Synchr.Cycl: <<μA)
- great reliability (few components)
- protons with energy up to 1 GeV

-ions up to 500 MeV/nucl.








The End