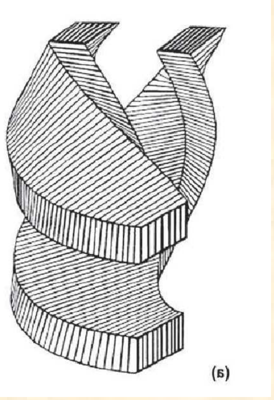
Cyclotrons : specific techniques

- Acceleration and RF cavities



- Injection
- Extraction
  (stripping, turn separation, precession…)

Acceleration

•The final energy is independent of the accelerating potential $V = V_0 \cos\varphi$.

If V_0 varies, the number of turn varies.   ($B\rho$ *final* =<B>.R*extraction*)

• The energy gain per turn depends on the peak voltage V_0, but is constant, if the cyclotron is isochronous (φ =const):

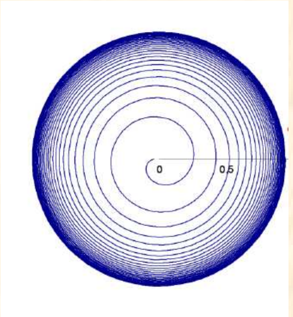
$$\delta E = N_g \, q \, V_0 \cos\varphi$$

N_g : number of gaps per turn

• The radial separation δr between two turns varies as 1/r ($\gamma \sim 1$) :

$$\frac{\delta r}{r} = \frac{\delta B\rho}{B\rho} = \frac{\delta p}{p} = \frac{\gamma}{\gamma+1}\frac{\delta E}{E} \approx \frac{q V_0 \cos\varphi}{2E} \propto \frac{1}{r^2}$$

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



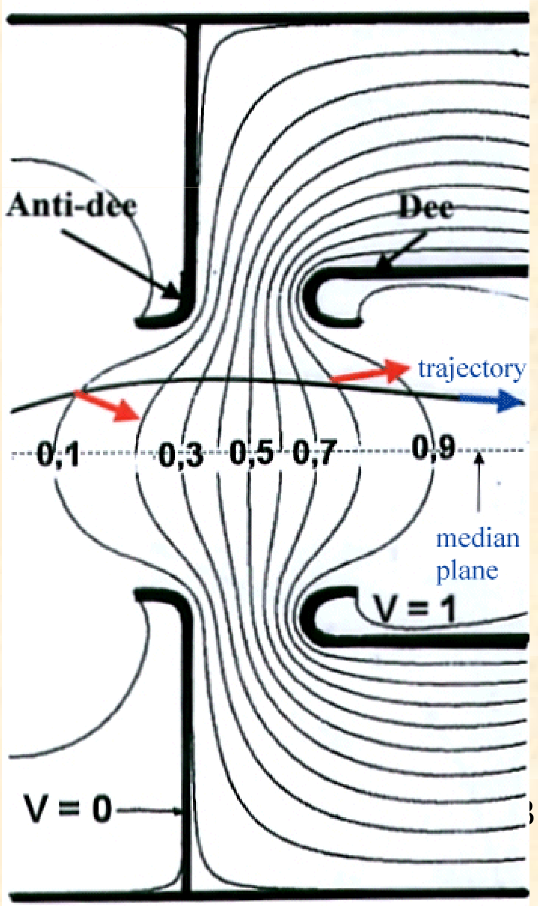
Accelerating gap & Transit Time

The formula $\delta E = QV_0 \cos\varphi$ corresponds to small accelerating gaps

Because of the gap geometry, the efficiency of the acceleration through the gap (g**) is modulated** by the transit time factor τ:

$$\delta E = QV_0 \tau \cos\varphi$$

$$\tau = \frac{\sin\left\{\frac{hg}{2r}\right\}}{\frac{hg}{2r}} < 1$$

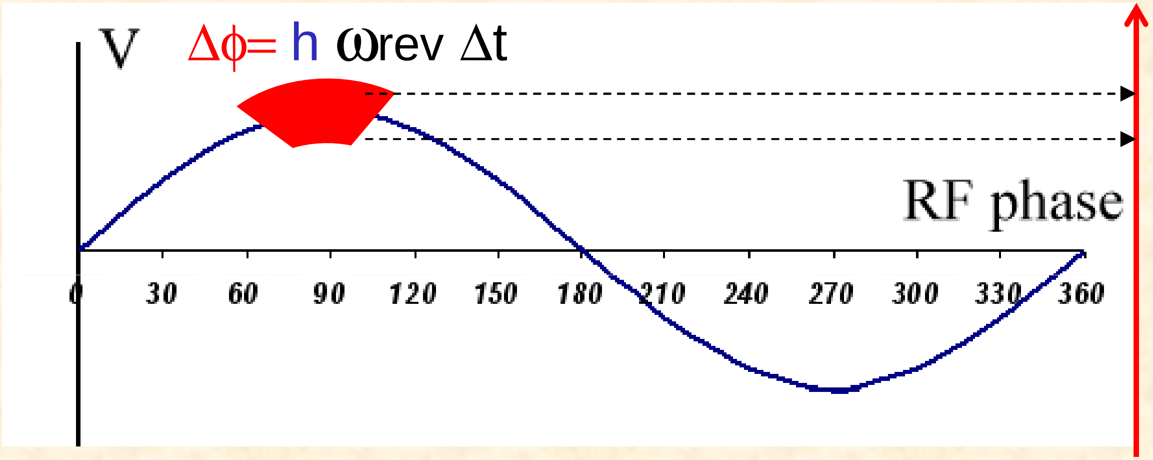


Introduction of pillars into the cavity to reduce the azimuthal field extension

Acceleration & bunch length Δt

- The bunch length Δt induces energy dispersion

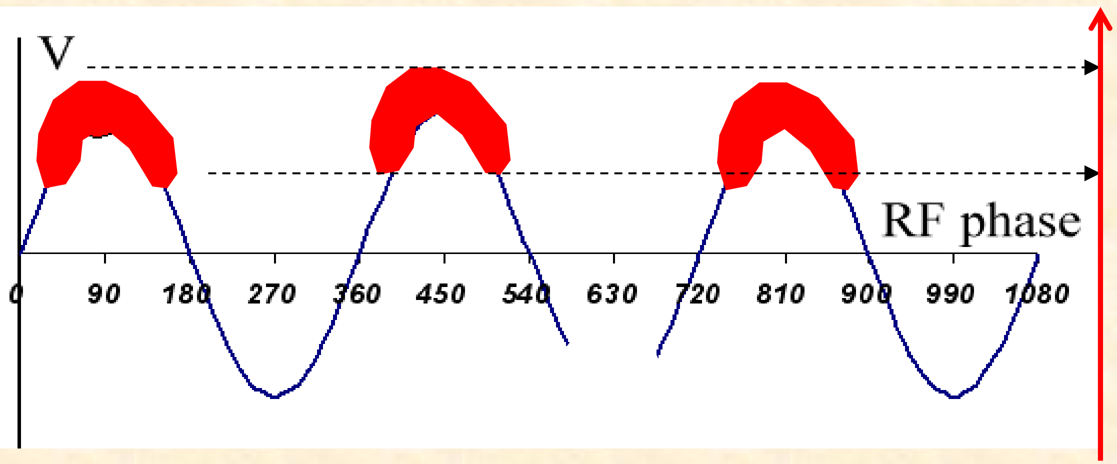
$$\frac{\delta r}{r} = \frac{\delta\ B\rho}{B\rho} = \frac{\gamma}{\gamma+1}\frac{\delta\ E}{E} \approx \frac{1}{2}\frac{\Delta[qV_0 \cos(\ h\omega_{RF}\ t)]}{E}$$



harmonics=1

Δr ~ qV ωrf Δt

harmonics >1



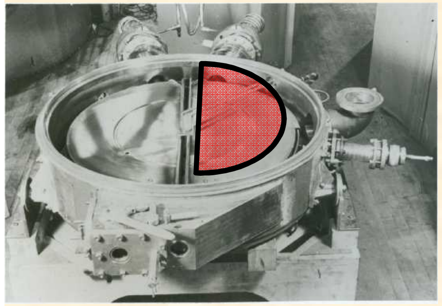
Worst beam quality

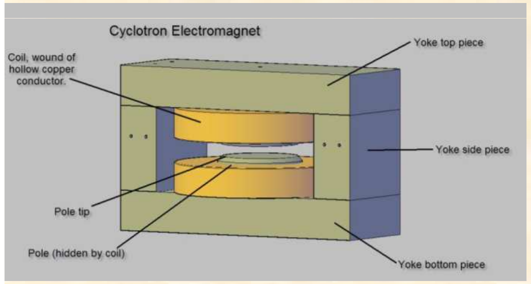
Δr larger ~ qV H ωrf Δt

Energy dispersion larger

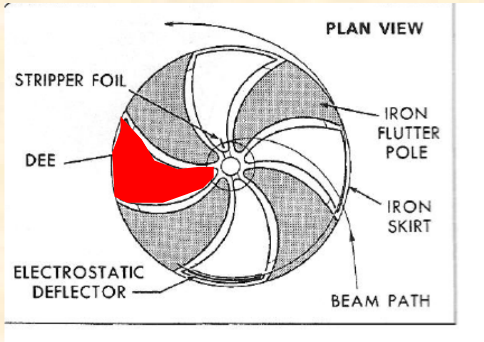
Acceleration RF Technology

Magnetic structure => RF cavity's shape



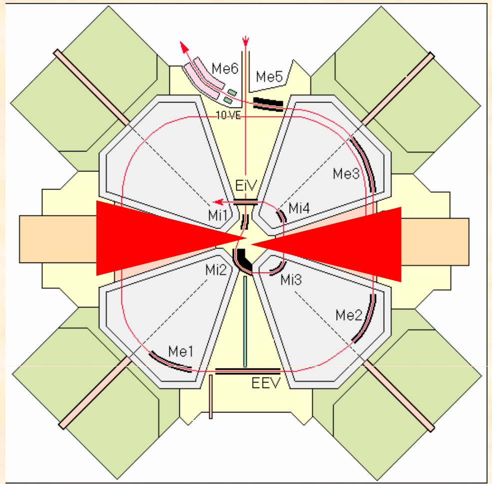


The classical "D" shape



"Curved sector"

For spiral AVF

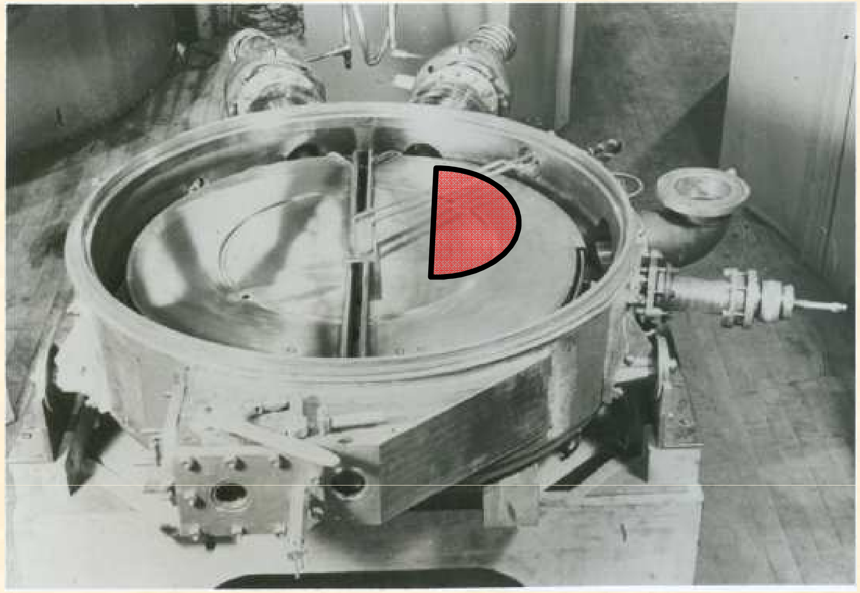


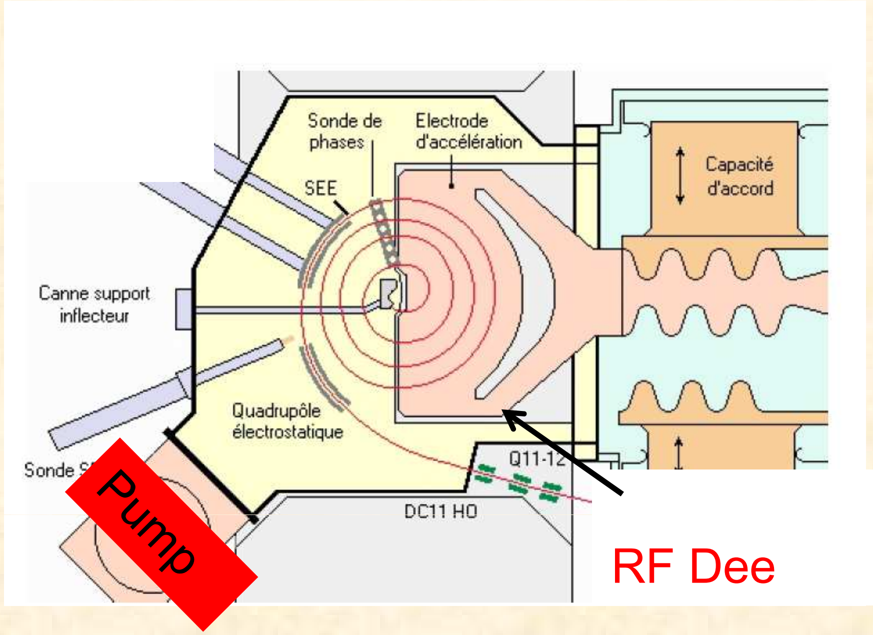
"Triangle" shape

For separated sector cyclo

The choice of the pole shape and the number of sectors have a great impact on the available space for RF systems. Dees, and possibly stems and liners have to fit into the gaps and/or valley sections

RF Cavities : Dees 180°





Dees 180°:

H=1,3,5 odd number allowed

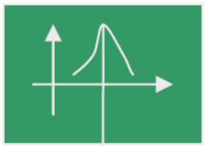
H=2,4 even number forbidden

Dee should change its voltage every half turn of a bunch

RF Cavities : The resonance of the cavity

Resonance for a cavity
= minimal impedance (Z) for maximal Voltage

$|1/Z|$

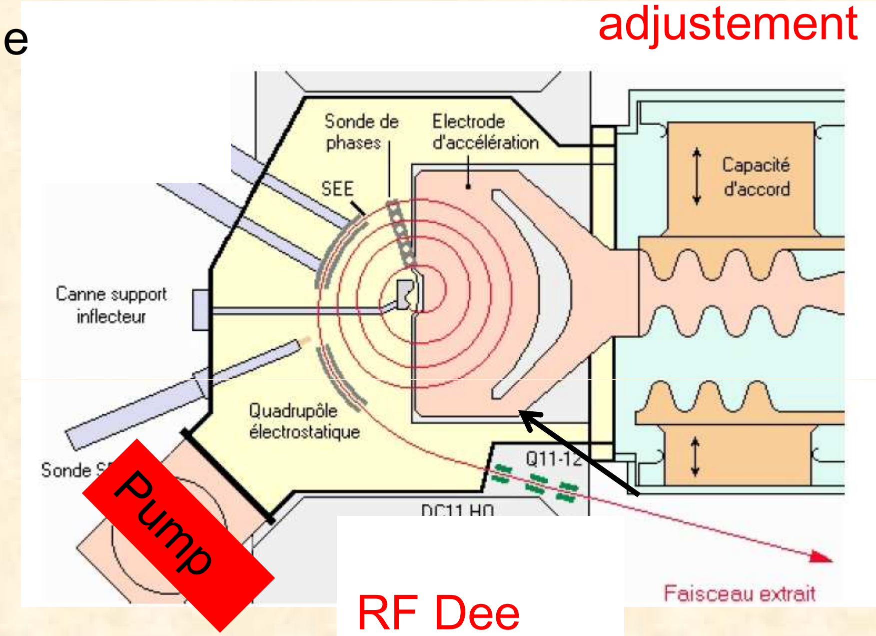


$\omega_{res}^2 = 1/LC$

Cyclotron : Variable Energy with
B and Frf variable

$$1/Z = 1/R + j\omega(C - 1/L\omega^2)$$

$$\omega_{rev} = \frac{qB}{\gamma m} = H\omega_{RF}$$

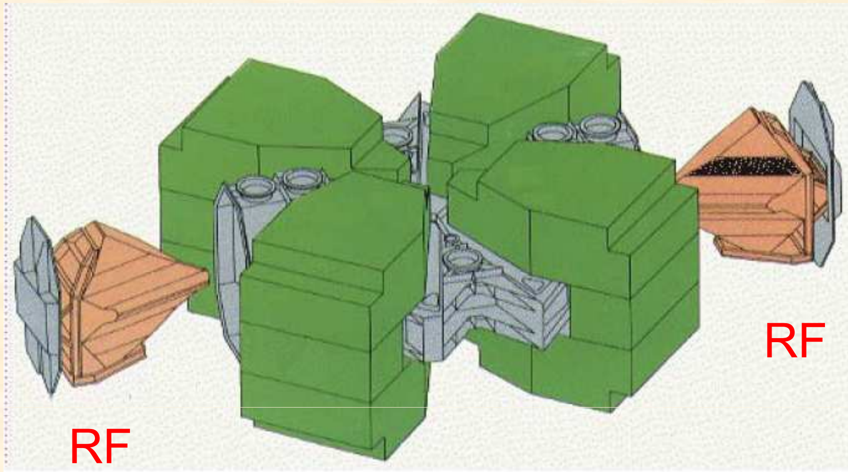


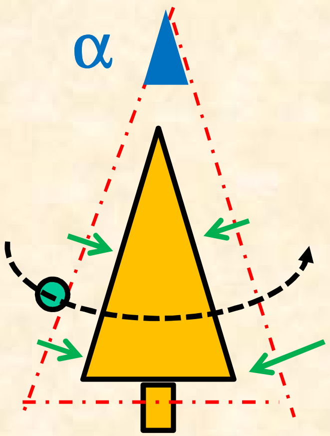
Variation of the Capacity C :

to adjust ωresonance

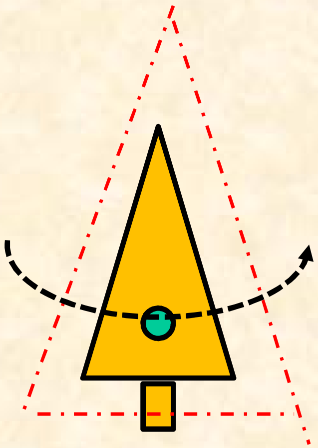
ωresonance = ωrf= ωrev / h

RF Cavities : example 1
for Separated Sectors Cyclo

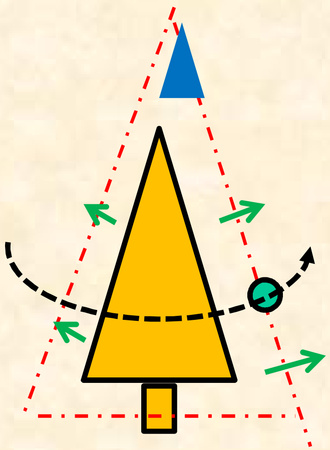




$V(t)=V_0 \cos(\phi - h\alpha/2)$



$V(t)=V_0 \cos(\phi)$



$V(t)=V_0 \cos(\phi + h\alpha/2)$

Example 1: RF Cavities (not Dees)

Energy gain in 1 gap :

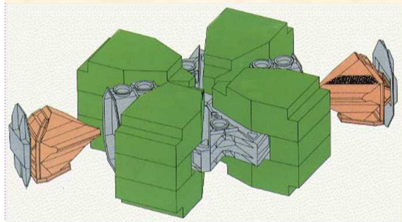
$$\delta E = qV_0 \sin(\frac{h\alpha}{2}) \cos\varphi$$

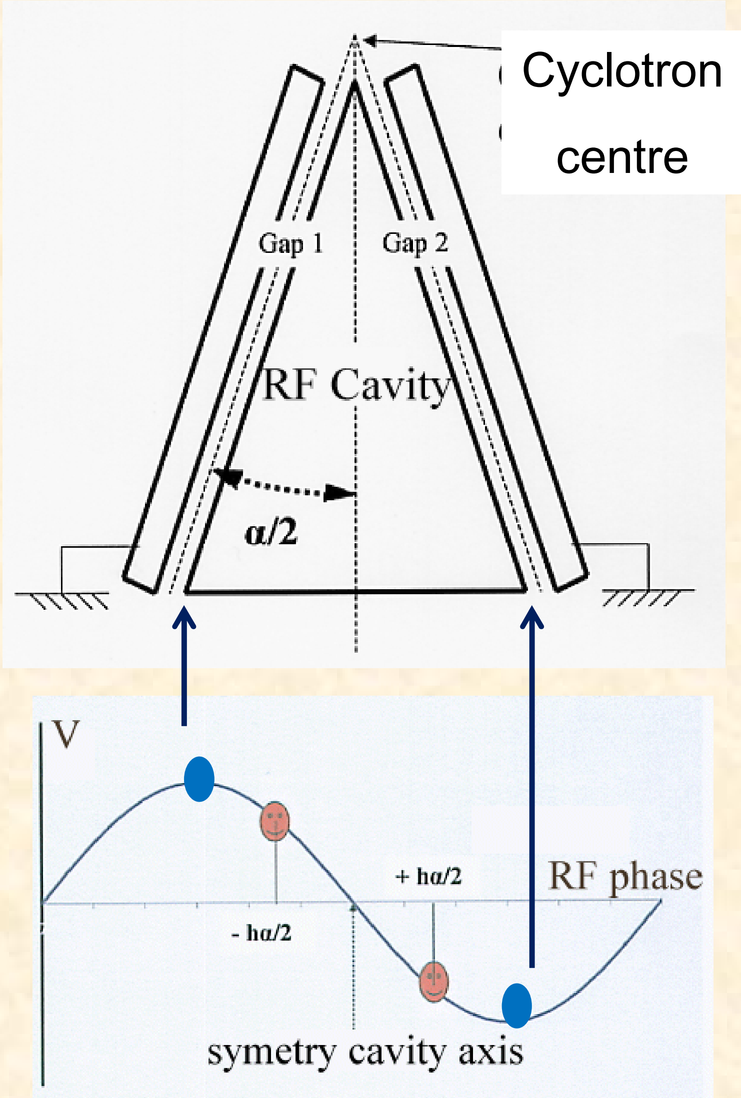
- For a maximum energy gain $(\cos\varphi = 1)$ the particle passes the symmetry cavity axis
- Energy gain per gap for the various harmonic mode

$$\delta E = qV_0 \sin(\frac{h\alpha}{2})$$

δE optimum is

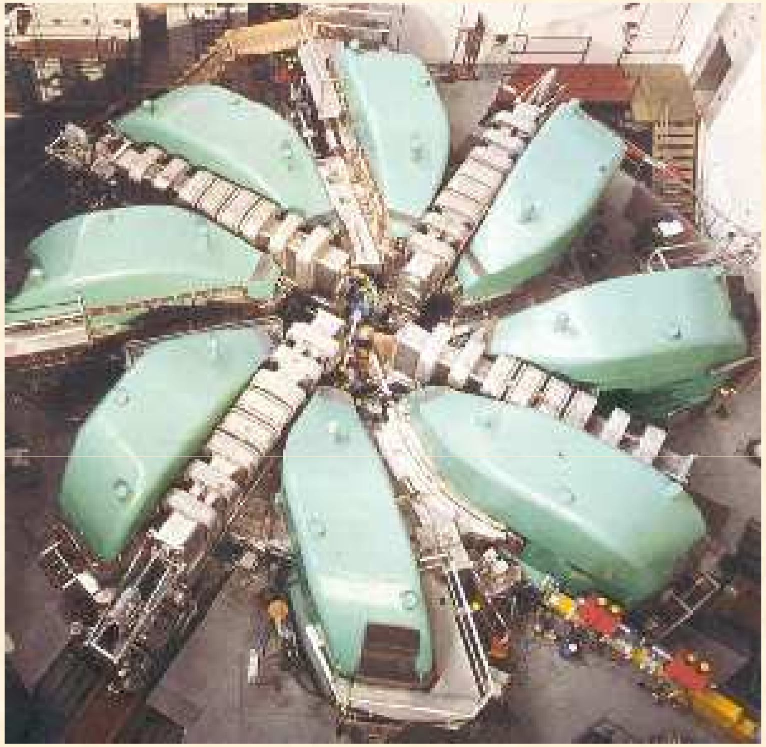
for h.α/2 =90 degree

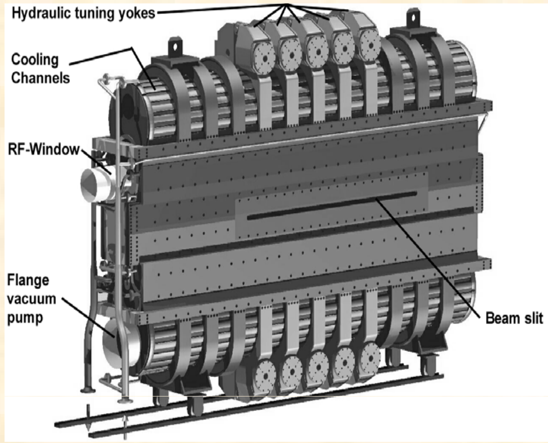




example 2 :separated sector cyclotron:

the PSI ring cyclotron (proton 590 MeV)





$R_{extraction}$ =4.5 m

Kb= 590 MeV

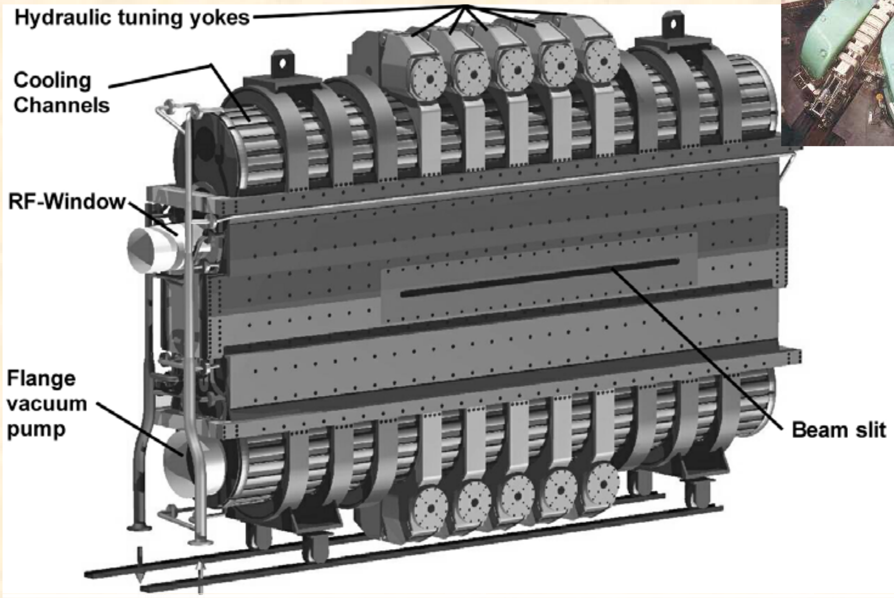
4 RF Cavities

Typical 'Separated Sector Cyclotron' (SSC). the PSI 590 MeV (p) ring cyclotron, with 8 sector magnets and 4 accelerating cavities

PSI Proton Beam ~1 Mwatt

The Challenge :
Single turn extraction

Turn separation δr large
But Δr small



4 cavities : 50 MHz, CW
Voltage: 0.9-1 MVolt

Harmonics h=6

Proton Beam ~1 Mwatt
(I=2 mA)

if δr (~ N*gap* .Vrf) Large
No beam losses
T= 99.99%

Beam injection

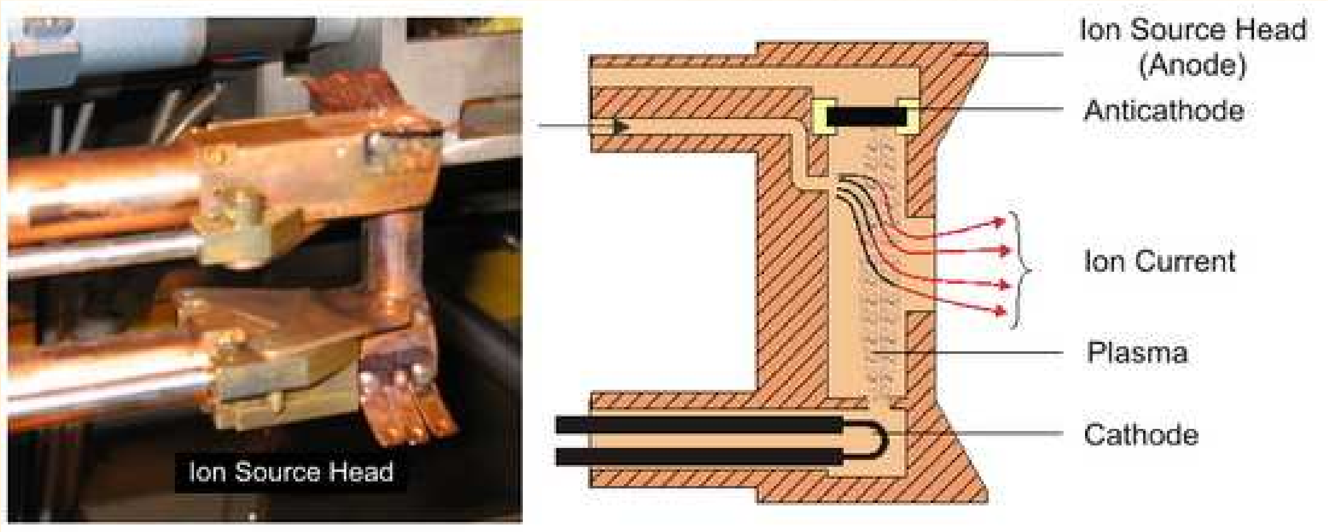
-THE ION SOURCES (internal and external)

Low energy :
AXIAL INJECTION FOR COMPACT CYCLOTRON
- Infector (spiral, hyperboloid;...)

Higher energy :
RADIAL INJECTION FOR SEPARATED SECTOR CYCLOTRON

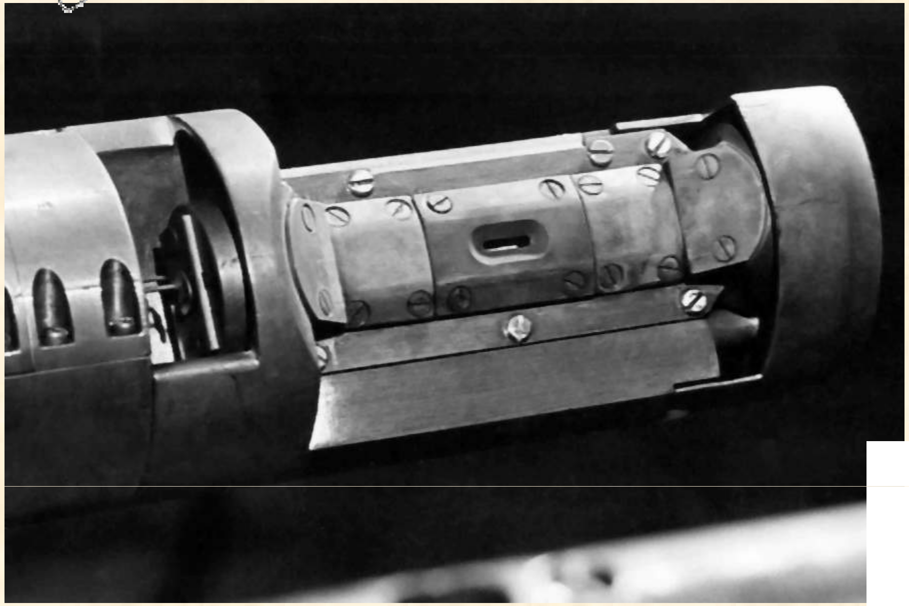
Cold Cathode PIG Ion Source

Penning or Philips Ionization Gauge (*PIG*) *ion source*



- Electron emission due to electrical potential on the cathodes
- Electron confinement due to the magnetic field along the anode axis
- Electrons produced by thermionic emission and ionic bombardment
  - Start-up: 3 kV to strike an arc
  - At the operating point : 100 V
- Cathodes heated by the plasma (100 V is enough to pull an outer e- off the gas atoms)

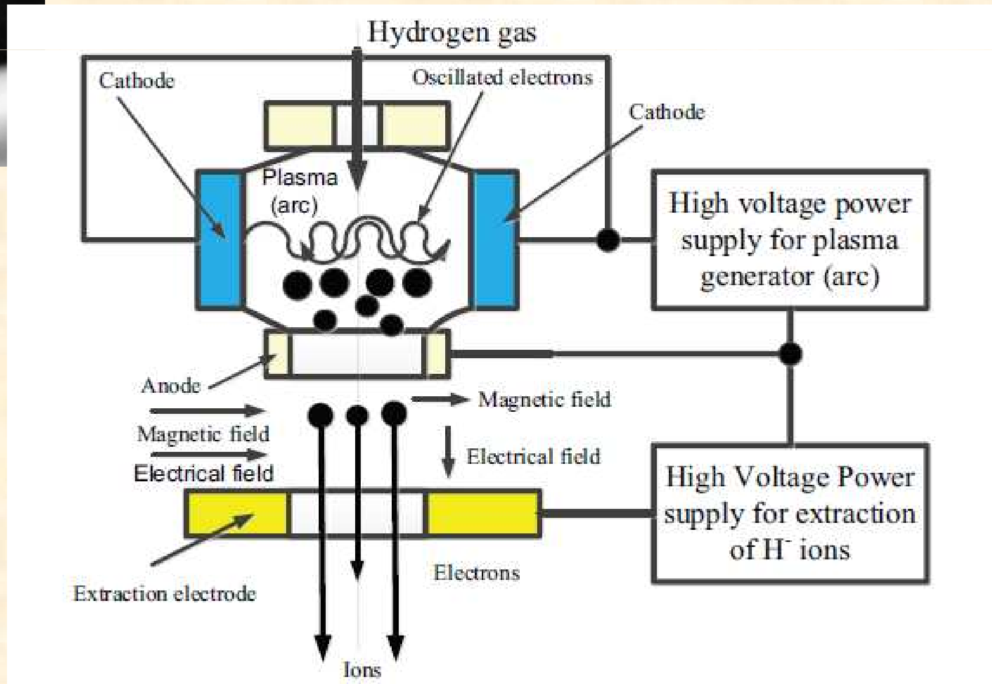
Example of PIG source



Small size

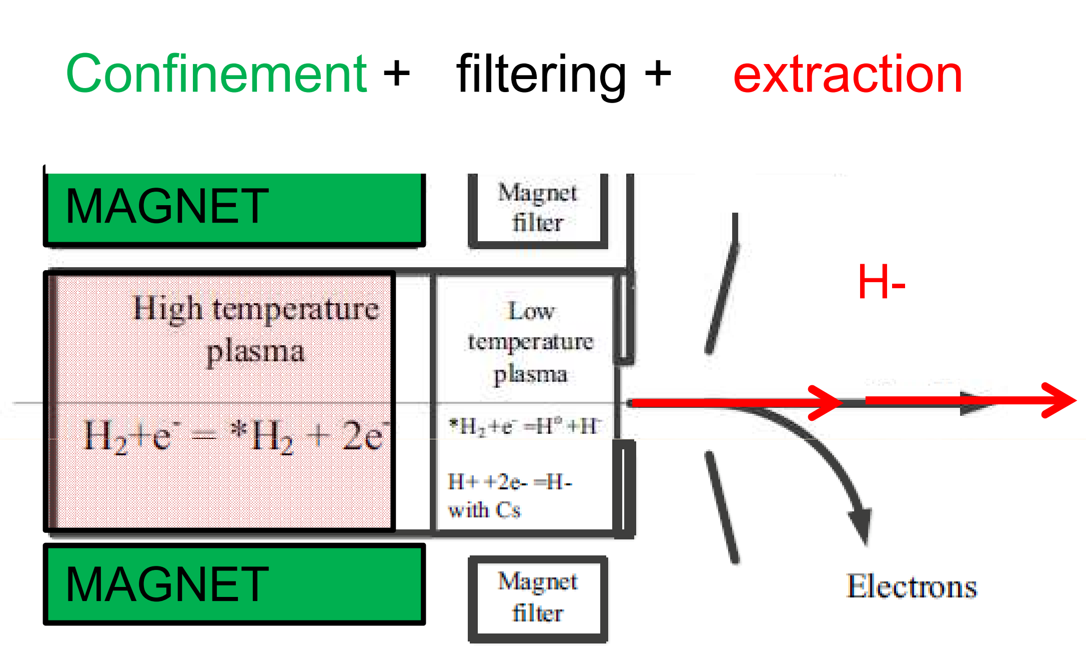
Inserted in the cyclotron gap

FLNR, PIG test-bed, 1992.
The head of MC400 cyclotron vertical ion source



Multi-CUSP source

negativ ions : H-//D- with high current



$e- + H_2 \Rightarrow e- + p + H-$

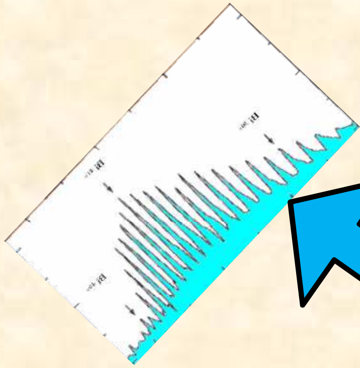
- Larger Than the PIG source (Magnets)
- Better emittance
- Larger current (Magnet confinement+ Filter)

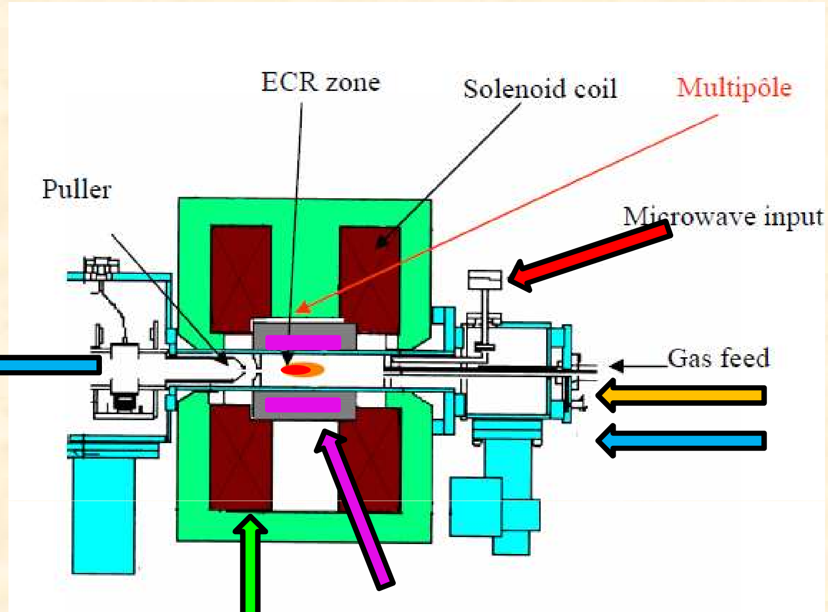
Larger Size ⇨ External Source

ECR ion source :
positiv Heavy ions

Pantechnic
Nanogan®

Charge state distribution

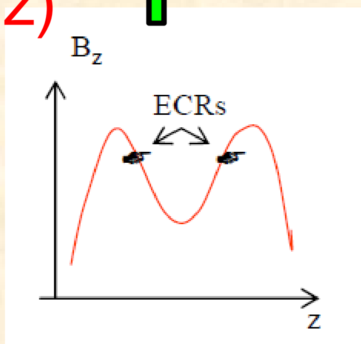


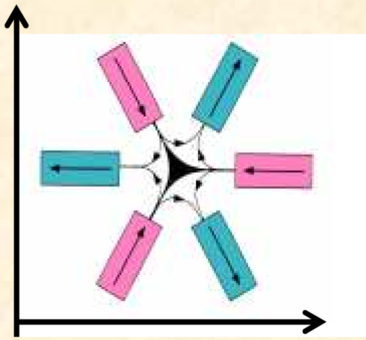


Gas (he,O,..) + RF(microWave 10-18Ghz)
Plasma (ions + electrons) :
+ ATOMS

electrons + ions impacts

Ionize any injected heavy atoms
(He,Li,…….U)

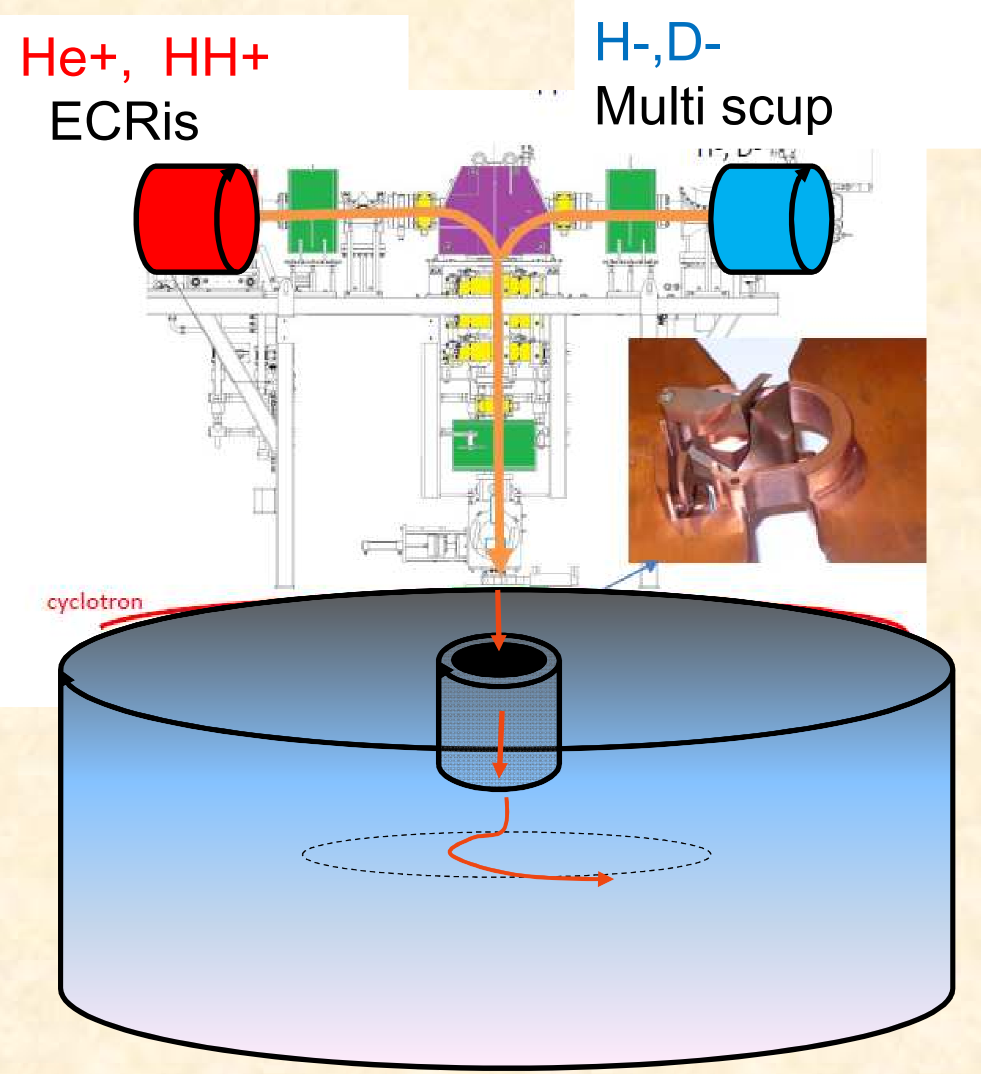




Bz + Br
3D plasma confinement

Exemple ARRONAX (Nantes, Fr)
2 external sources in a Kb=70 MeV cyclotron

Kb=70 MeV
- RadioIsotopes production
- Radio-Biology studies
- Irradiation



Injection from the Top (AXIAL injection)

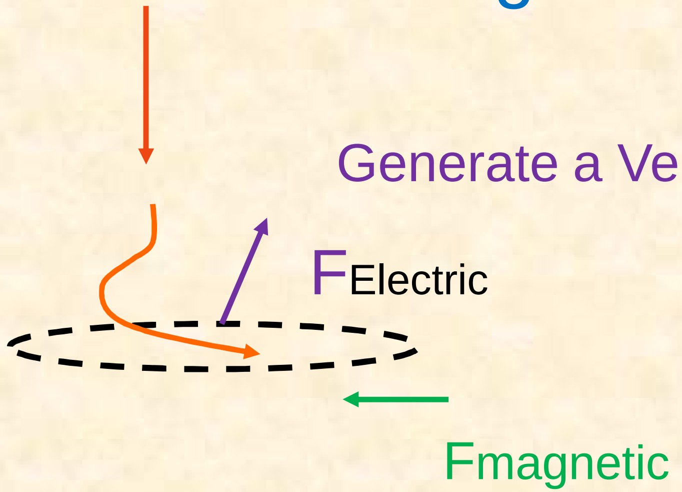
Axial injection with inflector

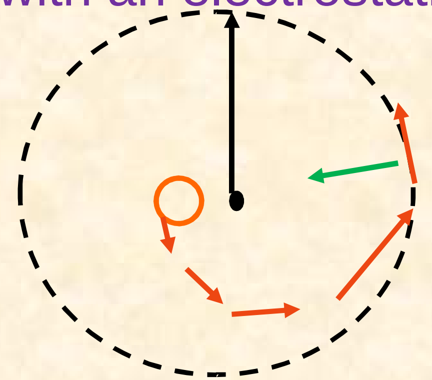
➢ Goal :

Put the beam on the « good orbit » at the good phase

with a very compact geometry

Generate a Vertical force with an electrostatic device





Outside cyclotron

axial motion (vertical)

Inside cyclotron (Magnetic force is radial)

radial motion (horizontal)

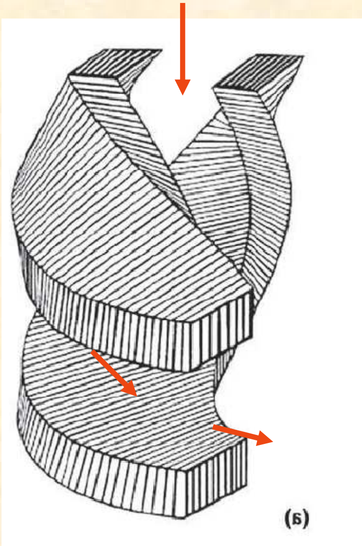
$R_m = B\rho \ / \ B_{center}$

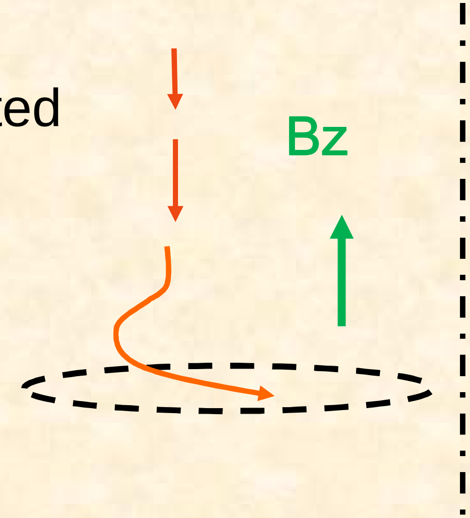
$R_E = mV^2/Q \ / \ E_{inflector}$

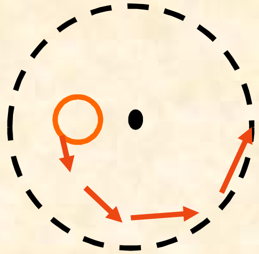
Axial injection : Spiral inflector

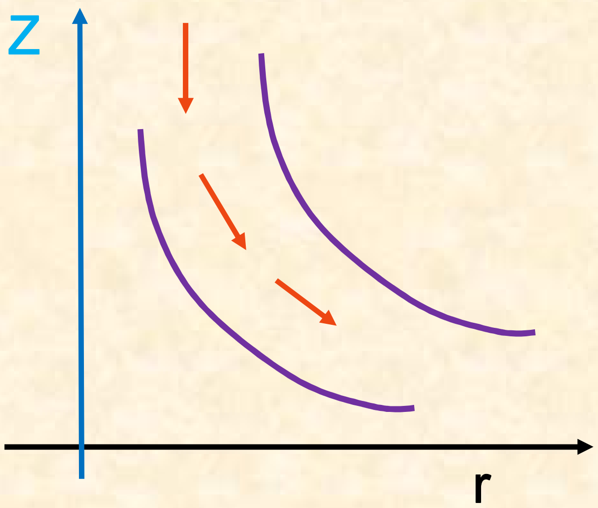
1. Spiral inflector (or helical channel)

principle: 90° electrostatic deflector twisted





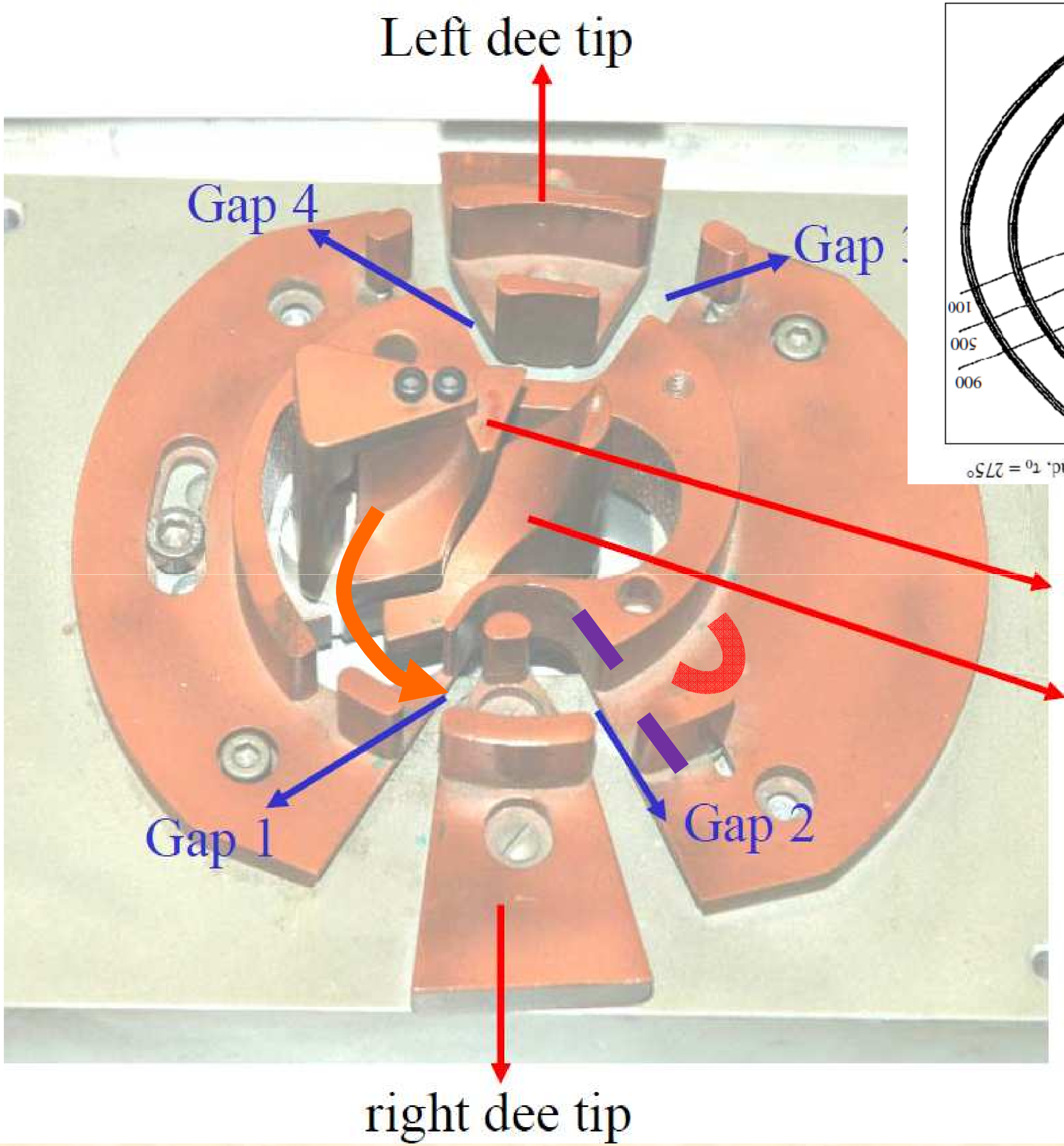


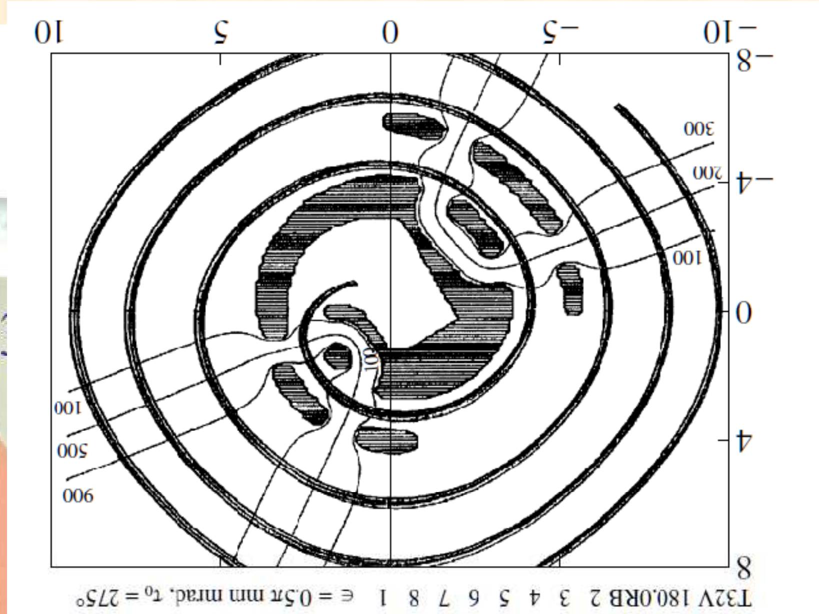


E always perpendicular to v

B=Bz constant (cyclo center)

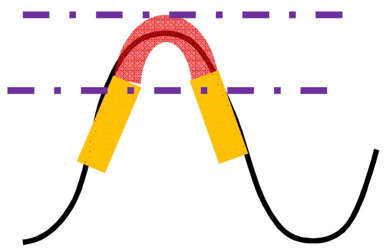
Complex geometry , very compact





Phase selection

ΔΦ~ΔE/E ⇨ΔR



Axial injection 1: Spiral inflector

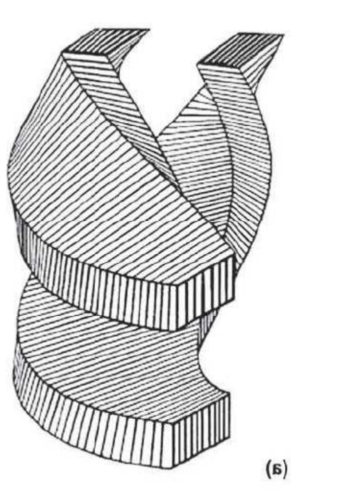
$$m\ddot{x} = qE_x - qv_yB_0,$$
$$m\ddot{y} = qE_y + qv_xB_0,$$
$$m\ddot{z} = qE_z.$$

Trajectory Equations are very funny :

Parametric equation of the trajectory θ= [0,π/2]

$$x_c = \lambda(1 - \sin k\theta \sin\theta - \cos k\theta \cos\theta)$$
$$y_c = \lambda(\sin k\theta \cos\theta - \cos k\theta \sin\theta) \quad ,$$
$$z_c = A(\sin\theta - 1)$$

$$k = A/R_m + k'$$
$$\lambda = A/(k^2 - 1)$$



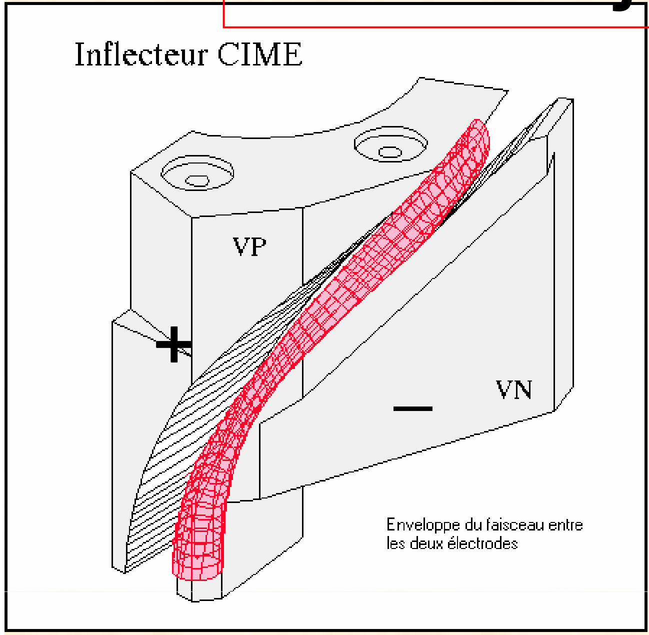
Two parameters : A the inflector Height
k' the tilt

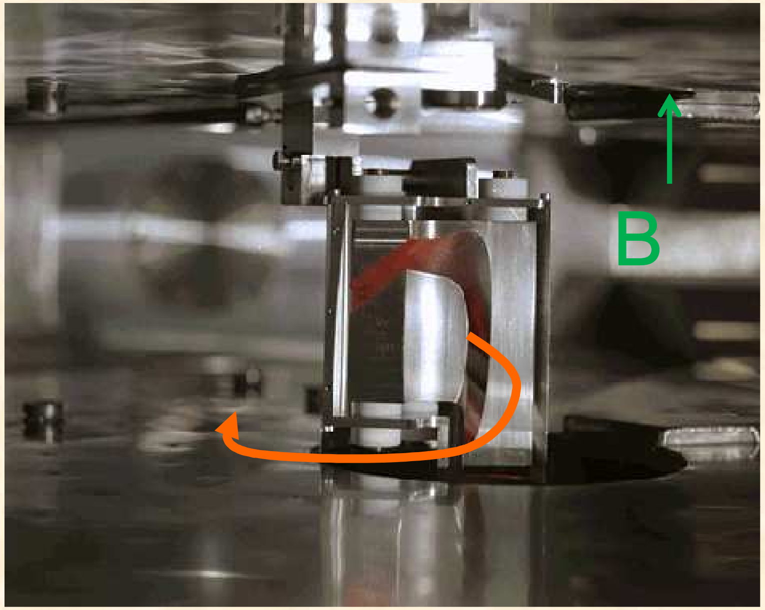
2 forces bend the beam

Electric radius $A = R_E = mV^2/Q / E_o$

Magnetic radius $R_m = B\rho / B_o$

Axial injection 1: Spiral inflector





•Consists of 2 cylindrical capacitors which have been twisted to take into account the spiraling of the ion trajectory from magnet field.

• $\vec{v}_{beam} \perp \vec{E}$: central trajectory lies on an equipotential surface. Allows lower voltage than with mirrors.

• 2 free parameters (spiral size in z and xy) giving flexibility for central region design

• 100 % transmission

Axial injection 2: hyperboloid inflector

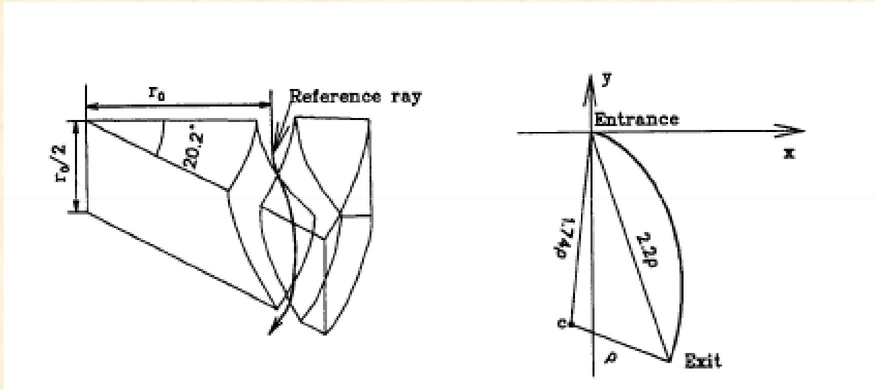
Spiral electrodes are complex :

hyperboloid inflector have simpler electrode

two electrodes equation : $r^2 - 2z^2 = r_1$ $r^2 - 2z^2 = r_2$

$V = -Kz^2/2 + Kr^2/4 + c$

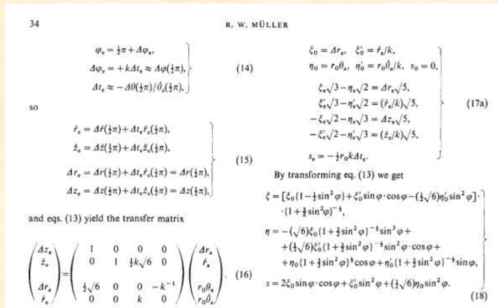
Vertical field $E_z = -Kz$



$$x = \frac{r_0}{2}\{-b\cos(akt) + a\cos(bkt)\},$$
$$y = \frac{r_0}{2}\{-b\sin(akt) + a\sin(bkt)\},$$
$$z = \frac{r_0}{2}\sin(kt),$$
$$k^2 = \frac{qK}{m},$$
$$r_0 = (2\sqrt{6})\rho.$$

$k^2 = -qv^2/2$

$r0 = 2.\ 6^{1/2}\ Rm$


34 R. W. MÜLLER

By transforming eq. (13) we get

and eqs. (13) yield the transfer matrix

Simpler geometry than spiral inflector

But No free parameter (Rinjection=Rm fix all parameters)

Radial injection

Radial Injection for pre-accelerated beam :

- Compact inflector not possible (axial inj. not possible) :

-Higher rigidity (electrostatic field have “low efficiency”)

need space to bend the beam with large magnet !!

1. Injection into separated sector cyclotron (most common)
   - More room for injection pieces and excellent transmission

2. Specific examples (not described here)

- Injection with Charge exchange (internal stripper foil)

in a compact superconducting cyclotron NSCL

- 3 ....

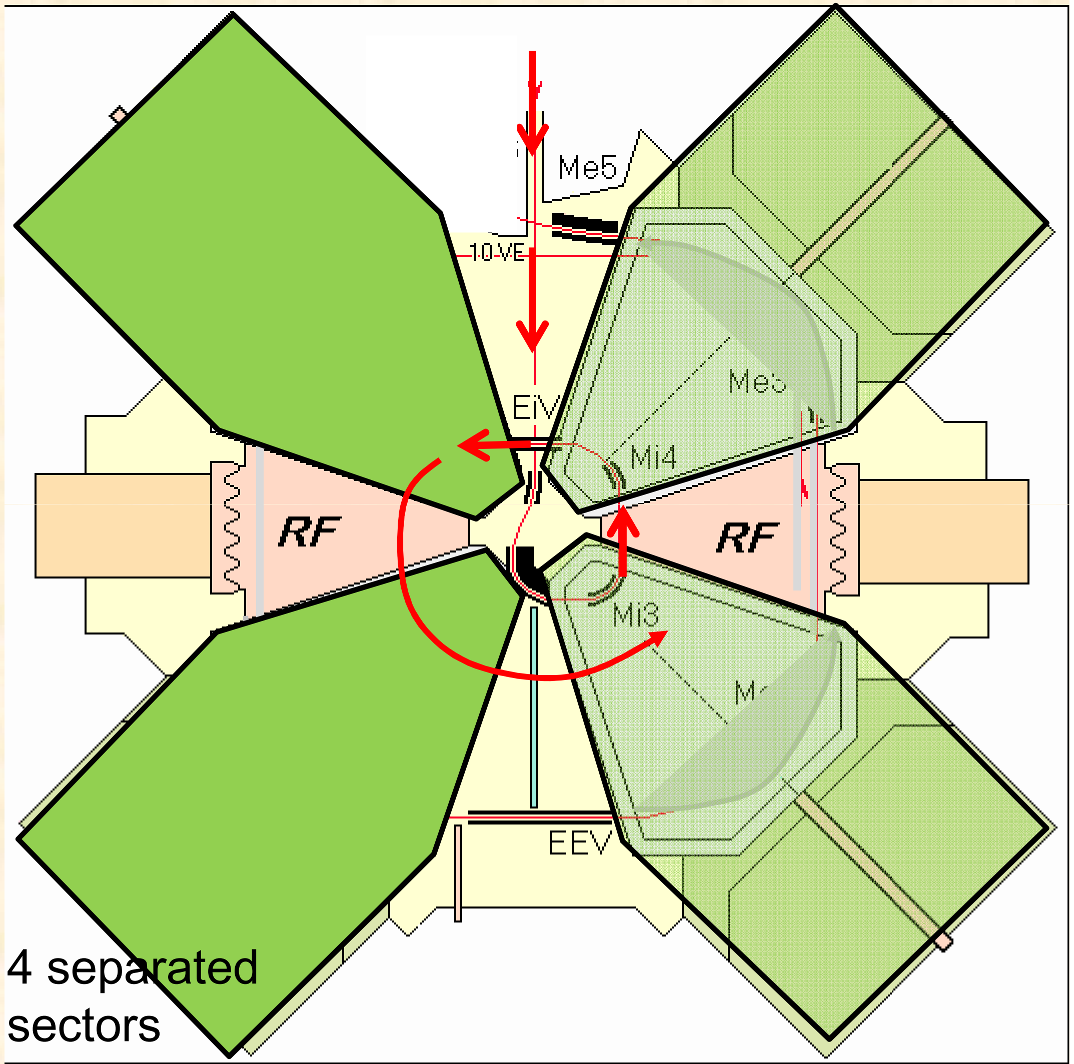
Example: Radial injection in ring cyclotron

• More room to insert bending elements.

Beam injected between sector magnets

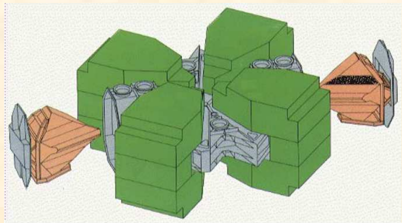
• The beam coming from the pre-injector enters the SSC horizontally.

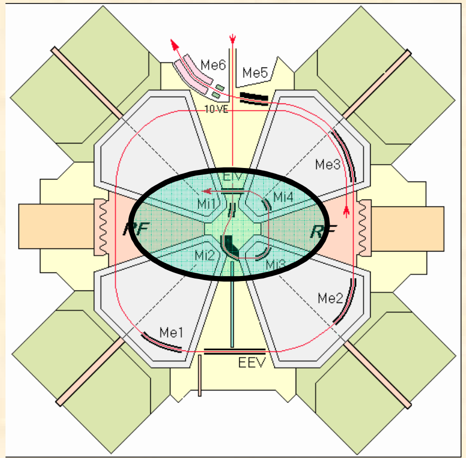
• It is guided by 4 magnetic dipoles to the "good trajectory", then an electrostatic inflector deflect the beam behind the dipole yokes.

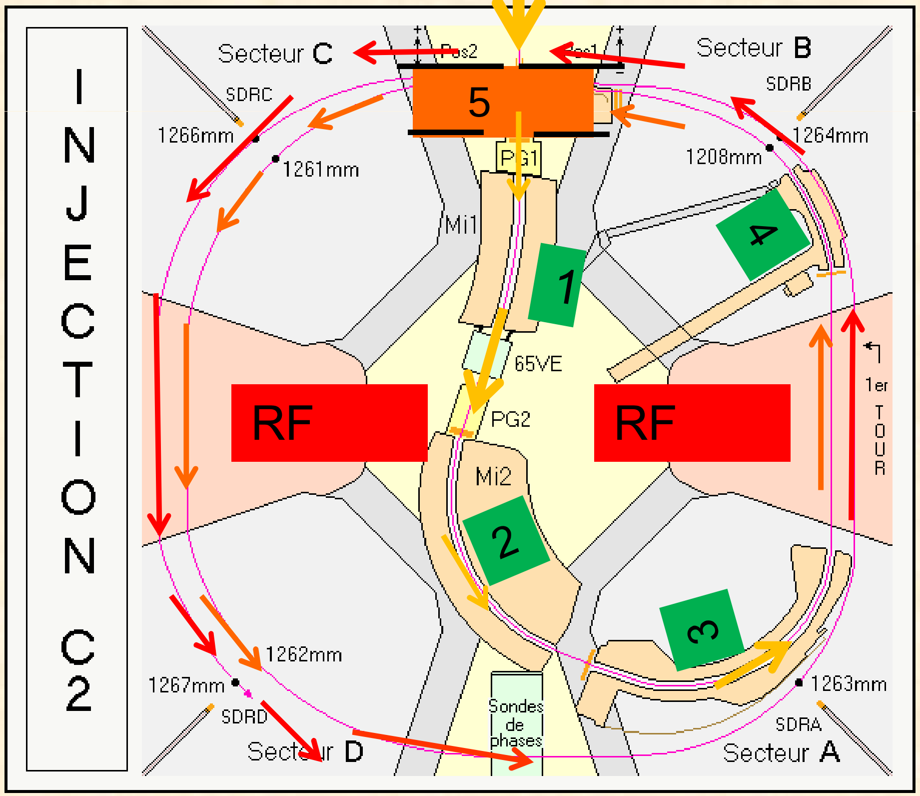


Example: Radial injection

Beam from coming
an other accelerator







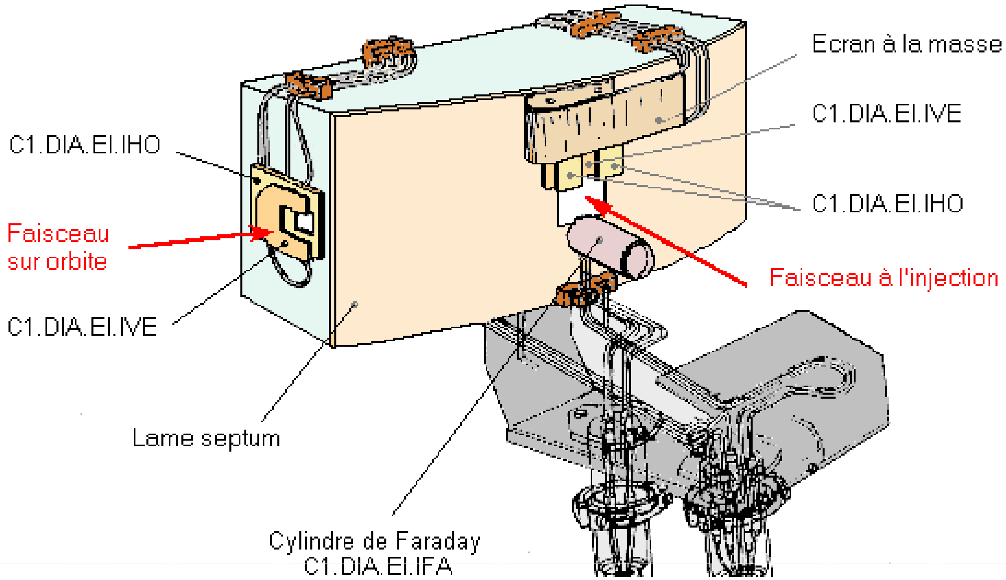
1-4 :magnetic dipoles

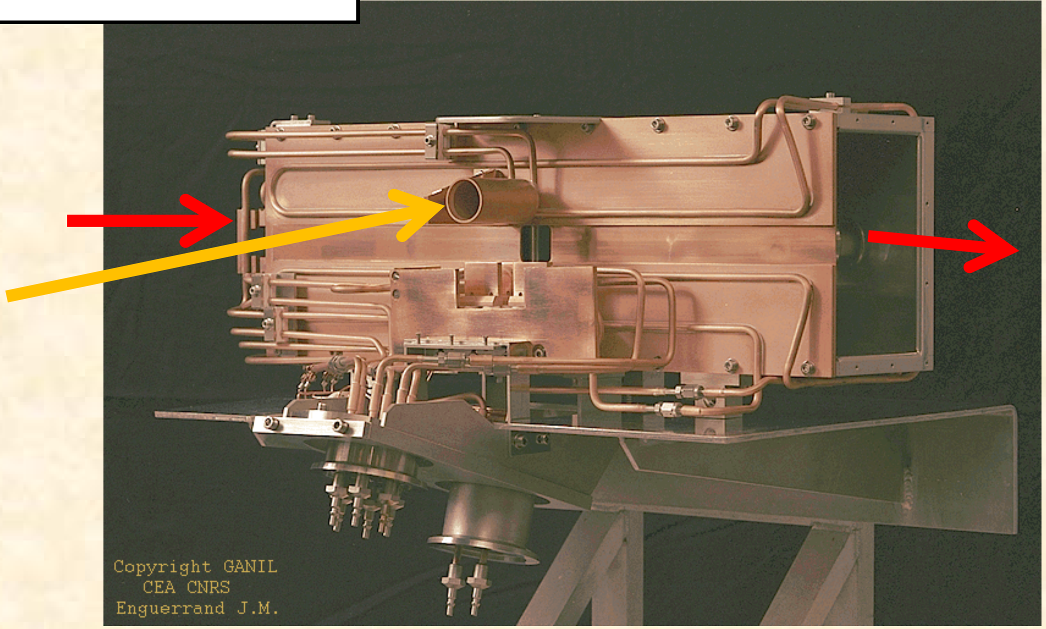
5 : electrostatic inflector

-**Very carefull centering**

-RF Phase adjustement with bunches

INFLECTEUR DE CSS1





Extraction

1. Extraction by stripping negative ion

simpler and low cost , but restricted to H isotopes

100% efficiency

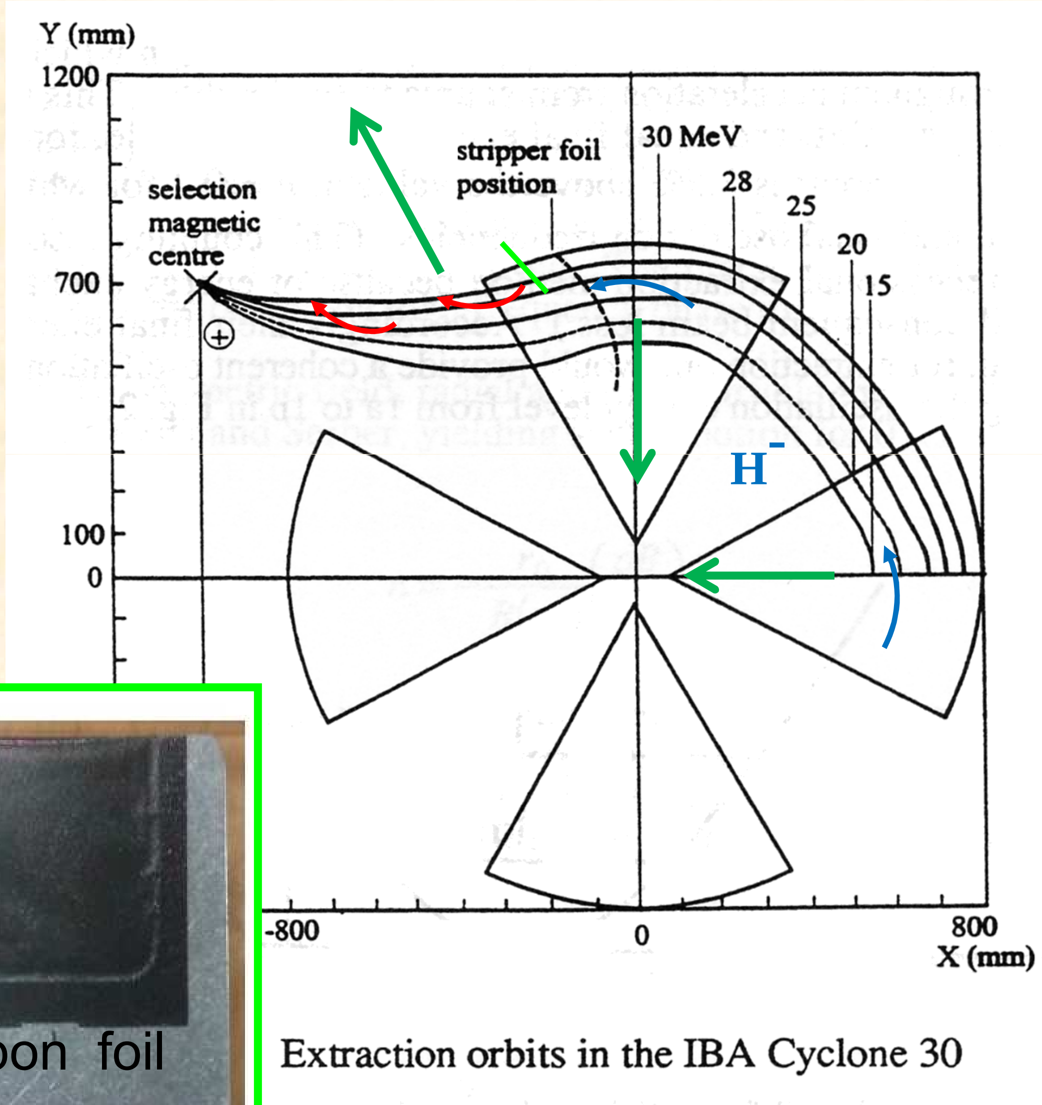
2. Extraction using the radial separation

between turn n°N & n°N+1

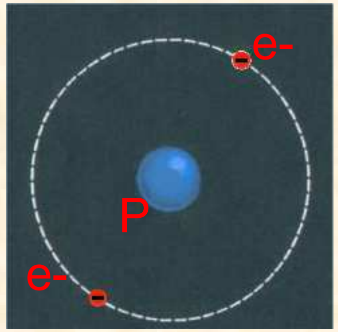
...

Extraction by stripping negativ ions

easy and efficient with H^-



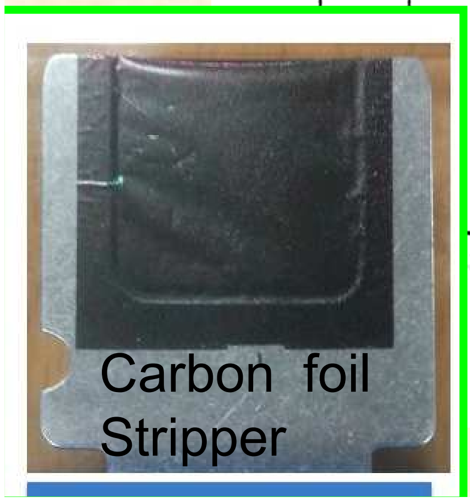
Extraction orbits in the IBA Cyclone 30



$H^- \Rightarrow H^+ + 2e-$

The magnetic force is inverted

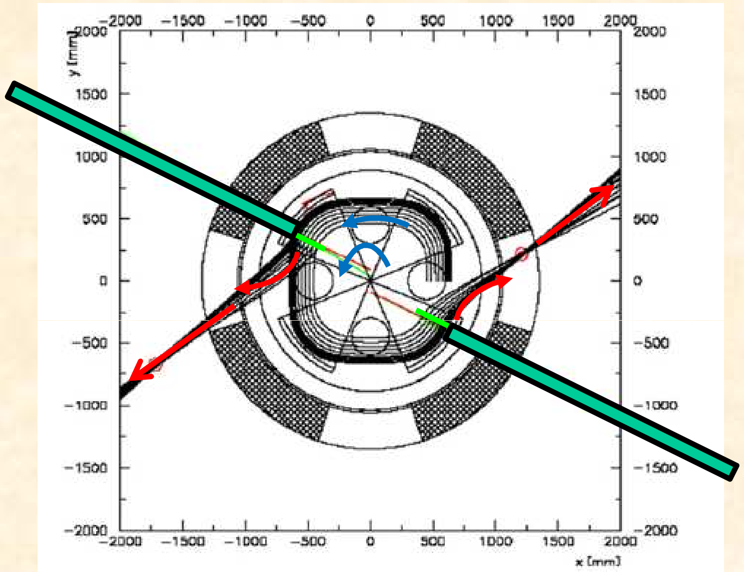
$F_r \sim - v.Bz \Rightarrow + v.Bz$



H^- & D^- commercial cyclotrons with two extracted beam

Low cost extraction beam line(s) :

less complex than electrostatic deflectors



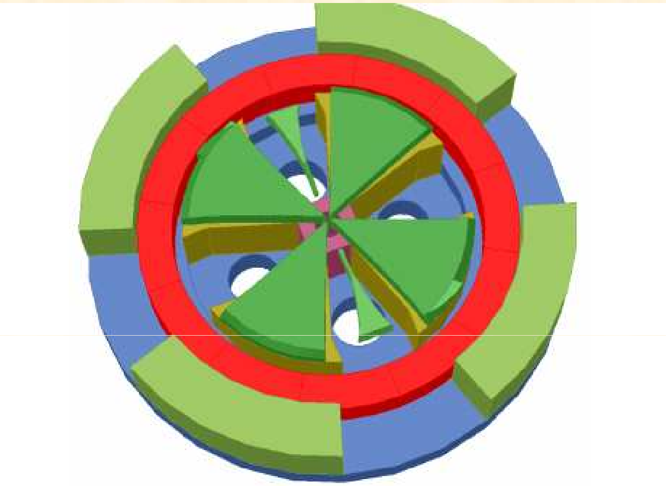


Figure 8: Final Cyclone® 30XP model.

H^- production or **D^-** production with an internal source (PIG)

2 strippers at extraction radius :

H^- => **H^+**

good beam quality, easy maintenance

Extraction by turn separation

1. Extraction by acceleration (and fringe field)

The orbit radial δr separation between 2 turns is :

$$\delta r = r \times \frac{\delta E}{E} \times \frac{\gamma}{\gamma + 1} \times \frac{1}{\nu_r^2}$$

- δE : Energy gain per turn as high as possible (RF)
- ν_r : Accelerate the beam to fringing field (Bz decrease,n>0, $\nu_r \searrow$)

Demonstration :

$$\frac{\delta B}{B} = -n \frac{\delta r}{r}$$

$$\frac{\delta r}{r} = \frac{\delta B\rho}{B\rho} = \frac{\delta < B > R}{< B > R} = \frac{\delta R}{R}\Big|_{acc} - \frac{\delta B}{B}$$

$$= \frac{\delta P_{acc}}{P} + n \frac{\delta r}{r} = \frac{\delta P_{acc}}{P} \frac{1}{(1-n)} \approx \frac{\delta P}{P} \frac{1}{\nu_r^2} \approx \frac{1}{2} \frac{\delta E_{acc}}{E} \frac{1}{\nu_r^2}$$

$$\nu_r = \sqrt{1-n}$$

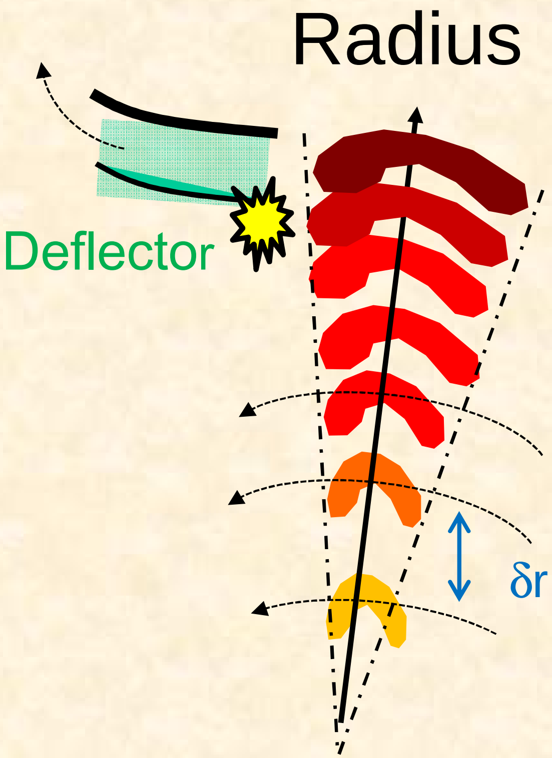
Extraction using turn separation δr

if Δr < δr Each turn separated

Extraction with an electrostatic deflector

100% efficiency

SINGLE TURN EXTRACTION



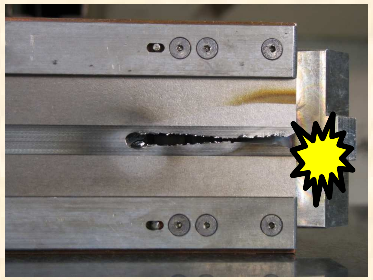
Δr > δr (size> turn separation)

last turns are not separated

Beam losses in the extraction channel

Multi TURN EXTRACTION

Deflector sparking or damaged



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

Extraction : 3 mechanisms possible

Goal : High extraction efficiency with well separated orbit

Δr = Acceleration + Precession + increase oscillation
by a field bump
(resonance extraction)

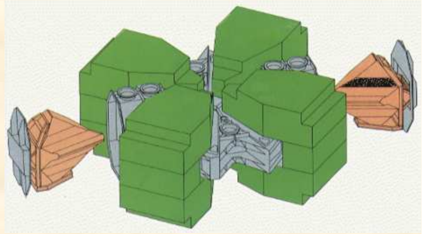
1. Extraction by acceleration (and fringe field + deflector)
   - Energy gain per turn as high as possible...
2. Precession extraction : radial oscillations help to separate orbits

$$r(N) = r_0(N) + x_0 \sin(\nu_r . \omega_0 t)$$

3. Resonant extraction : increase the precession by a field bump

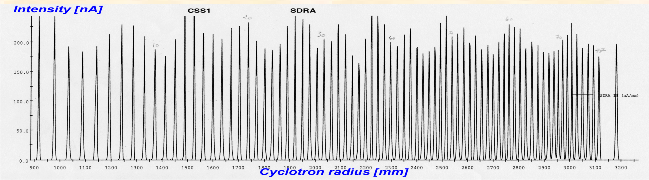
If turn separation not enough then magnetic perturbations are used. Particles are forced to oscillate around their equilibrium orbit with a magnetic bump

Example: Ejection SSC

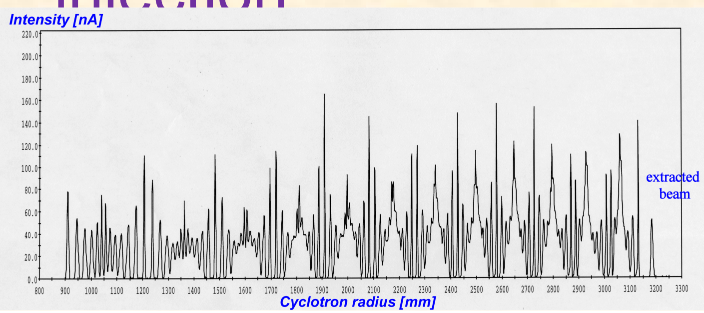


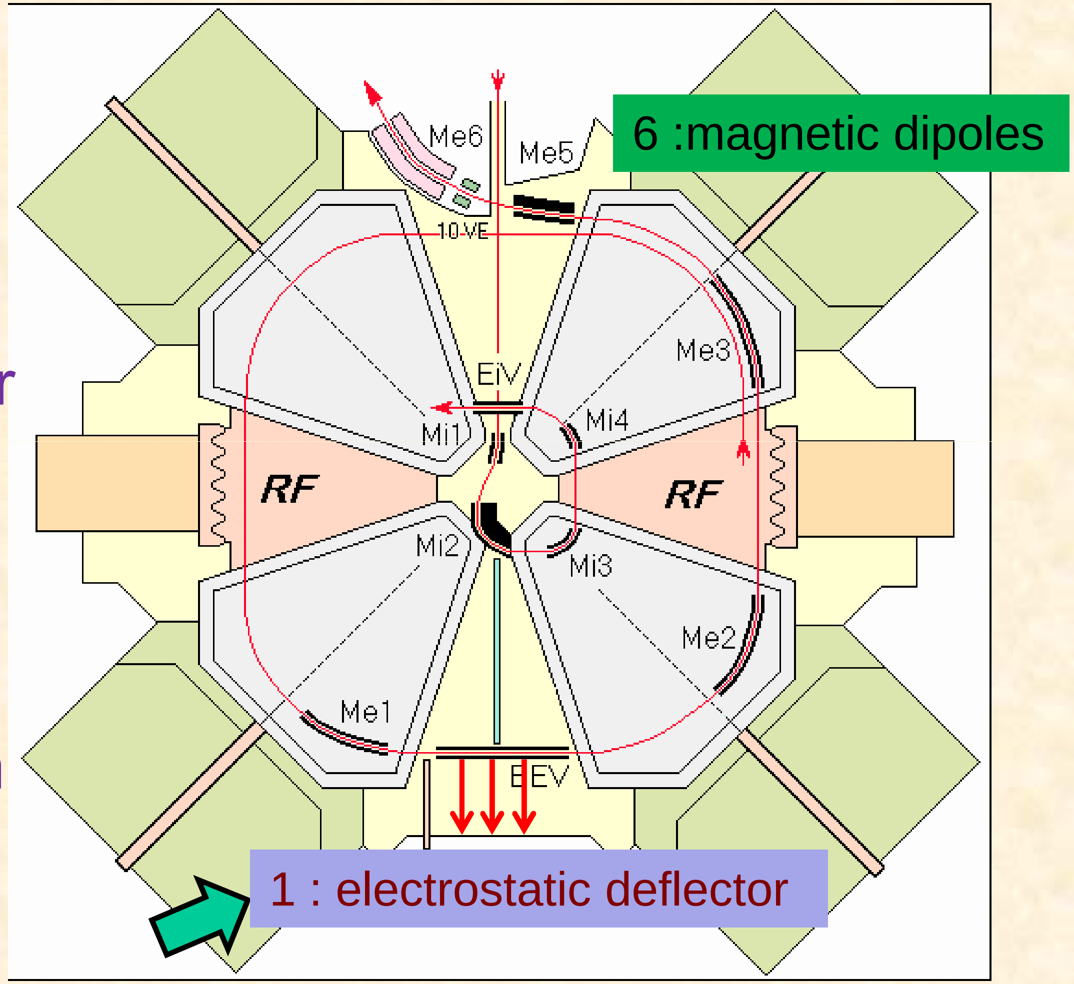
- Acceleration (2 RF cavities)

+ Radial kick on the extracted turn With an electrostatic deflector



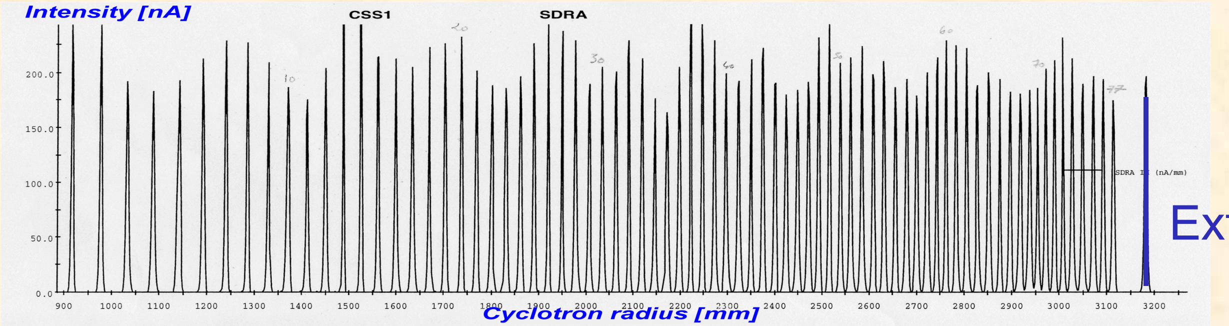
+ Precession : excited from injection





Extraction with precession

Well centered beam orbits **Separated Sector Cyclo N°1** GANIL



Turn separation sufficient

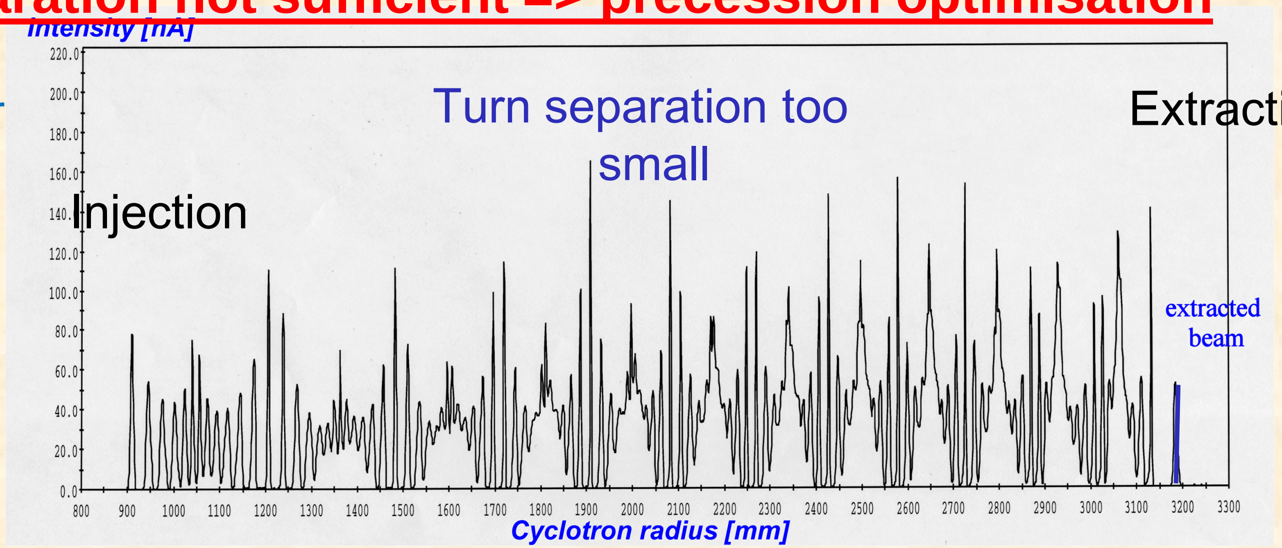
Extracted turn

$\Delta r < \delta r$

Precession for optimized extraction **Separeted Sector Cyclo N°2** GANIL

Turn separation not sufficient => precession optimisation

$\Delta r > \delta r$

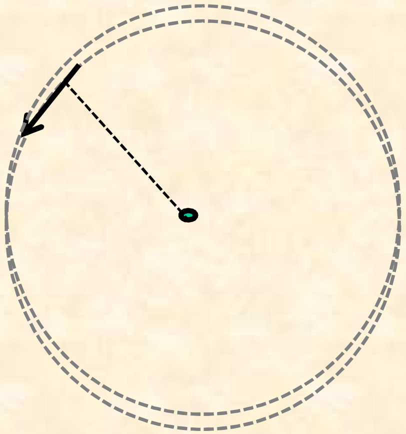


Extraction

transmission 95%

Resonant extraction : with $Q_x=\nu_r \sim 1$

Step 1 : circular motion
+ small oscillations

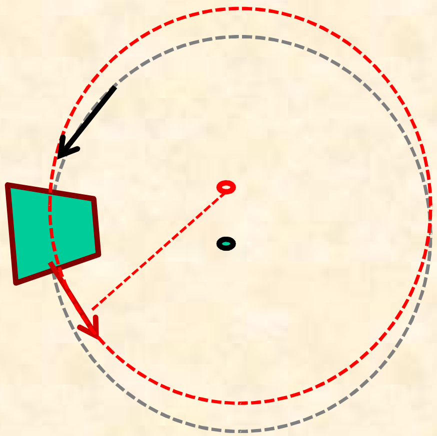


$$\ddot{x} + \nu_r^2 \omega_0^2 \cdot x = 0$$

$\nu_r \sim 1$: 1oscillation per turn

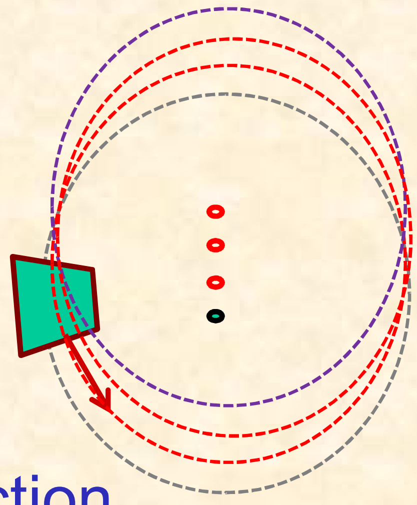
$$\delta r \approx \left[\frac{1}{2} \frac{\delta E_{RF}}{E} \right] + \Delta x_0 \sin(\nu_r . \omega t)$$

Step 2 : A magnetic bump
shift of the orbit center
larger deviation



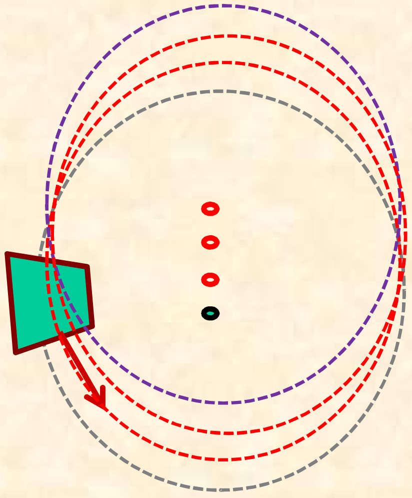
Step 3 : Several turns
produce
Large amplitude oscillation

Larger &Larger &Larger



Large δr =easy extraction

Resonant extraction shown by equations



Radial Equation without Perturbation

$$\ddot{x} + \nu_r^2 \omega_0^2 \cdot x = 0$$

Equation with Perturbation δBz ~ $b_M(r)$ cos(M θ)

$$\ddot{x} + [\nu_r \omega_0]^2 x = \omega_0^2 \frac{r}{B} \frac{db_M}{dr} \cos(M \omega_0 t)$$

Driven oscillator excited at the « frequency » M

if the excitation is at the resonance frequency M= ν_r
you get Large amplitude oscillations

One field Bump correspond to harmonic M=1

~ $b_1 . \exp(-\theta^2)$

Cyclotrons

- End Chapter 2