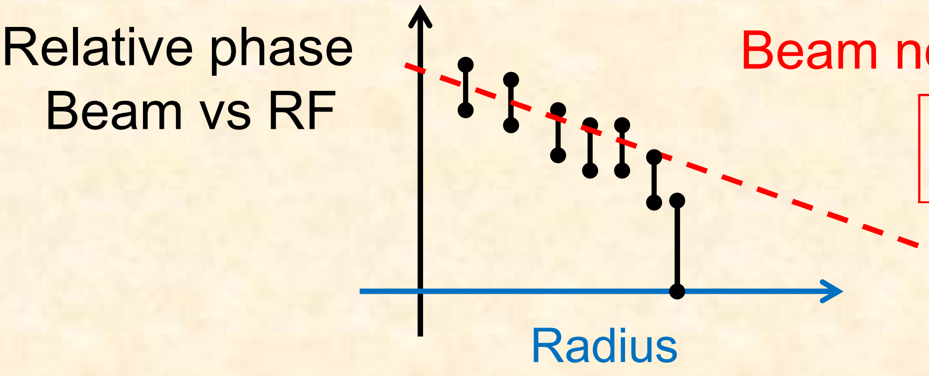
Cyclotrons

Chapter 4 : theory versus reality

- Isochronism and Phase measurement
- Isochronism 2nd approach & Kf limitation
- Resonances and tune in a cyclotron

- Research applications
- Medical applications

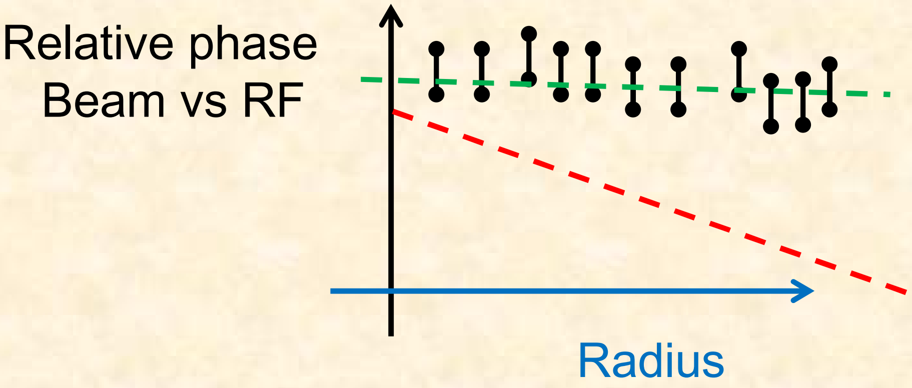
Phase measurement:
Isochronous field correction : Δ B



Beam not in phase with RF : B field not OK

$$B_z(R) \neq \quad B_{z0} / \sqrt{1-(R\omega_{rev})^2 / c^2}$$

Bz(R) not correct

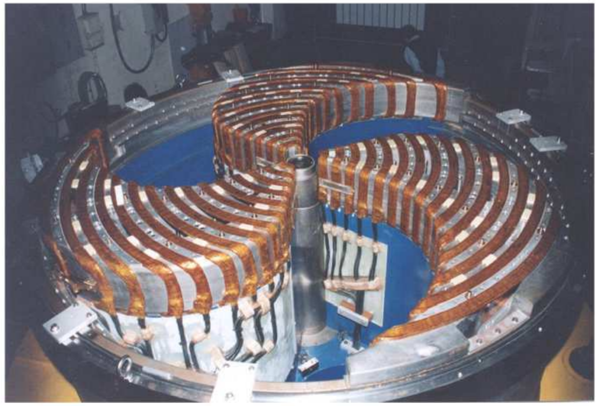


Correction of B : B($I + \Delta I$)

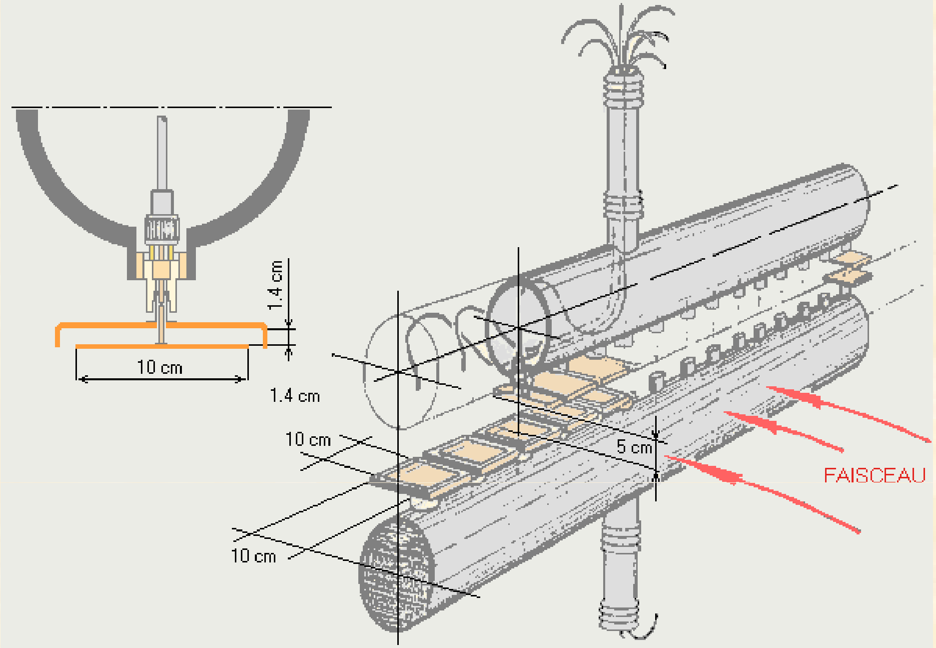
Bz(R) + Δ Bz

Bz(R) correct : Beam in phase with RF

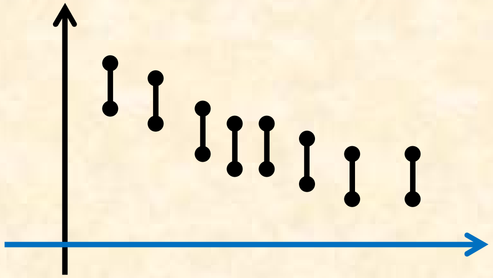
Correction trim coils, AGOR



Phase measurement: Isochronism

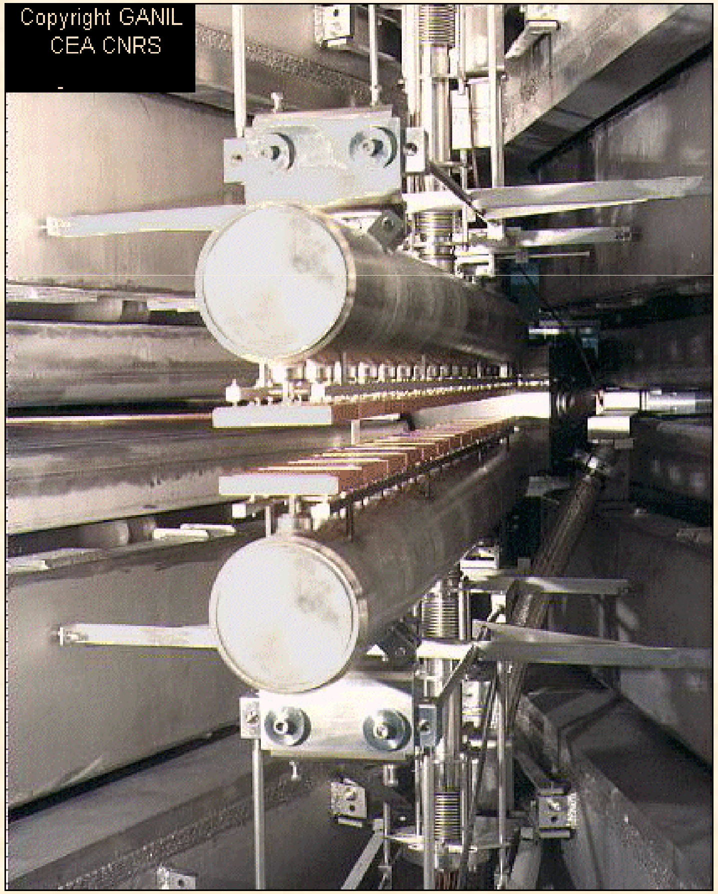


Relative phase
Beam vs RF



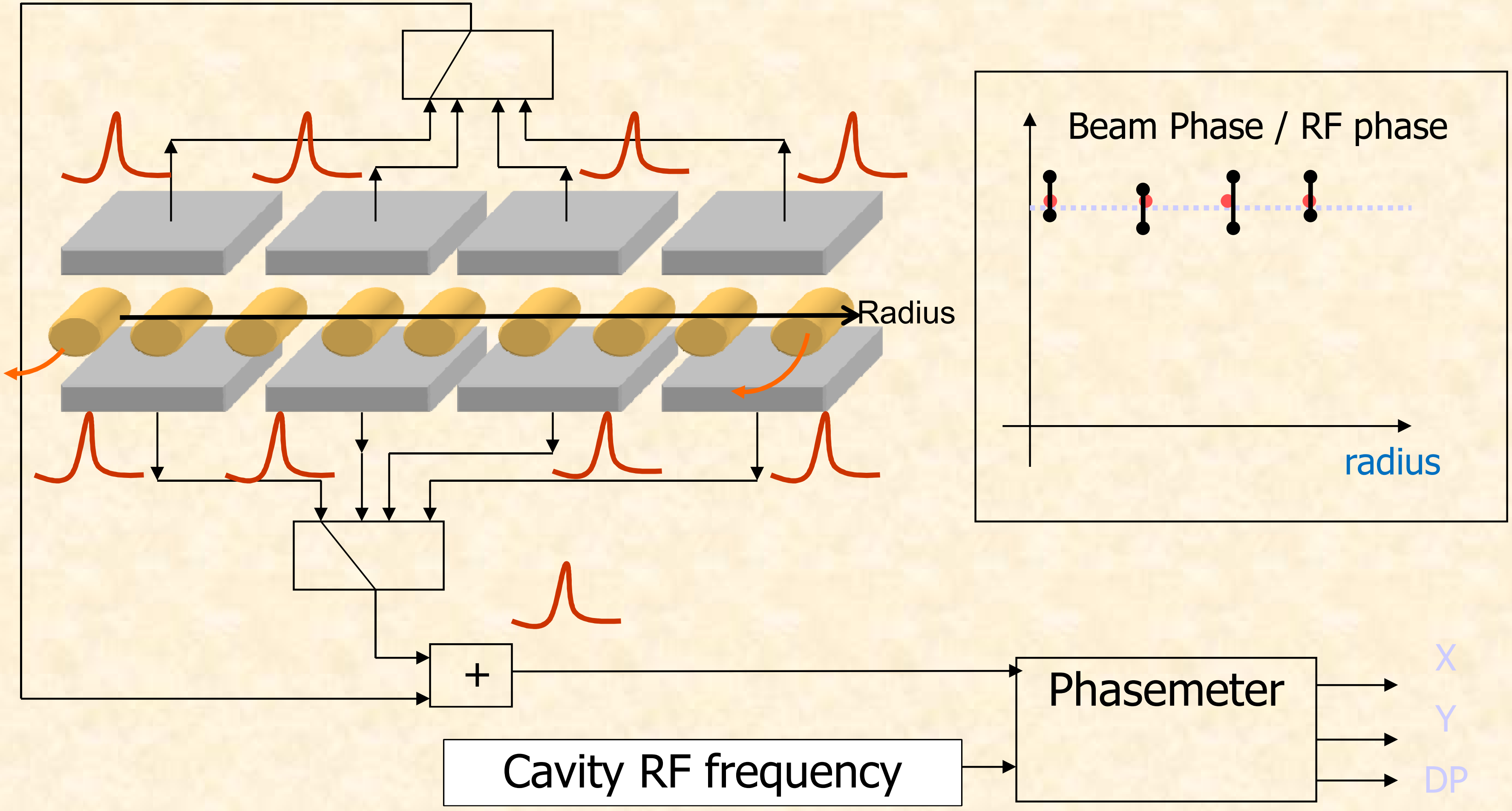
Radius

Ganil, Caen (Fr) : CSS1



Isochronism &
Phase measurement

Measuring B(R) or n(R) is difficult , While the Φ (R) is more sensitive



Radius

Beam Phase / RF phase

radius

+

Phasemeter

Cavity RF frequency

X

Y

DP

Isochronous fied B(z) = good field index n(R)

$$n = -\frac{R}{B_{0z}}\frac{\partial B_z}{\partial R} \Longleftrightarrow \frac{dB}{B} = -n\frac{dR}{R}$$

$$B\rho =< B > . < R >= \frac{p}{q}$$

$$\frac{dp}{p} = \frac{dB}{B} + \frac{dR}{R} = \boxed{(1-n)}\frac{dR}{R}$$

Longitudinal dynamics lecture

$$\frac{dp}{p} = \gamma^2\frac{d\beta}{\beta} = \gamma^2\frac{d(\omega_{rev}.R)}{\omega_{rev}.R} = \boxed{\gamma^2}\frac{dR}{R}$$

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

$$n(R) = (1-\gamma^2)$$

« At high energy » isochronism requires n <<0

Bz Azimutal modulations are not sufficient
It is a (Focusing) limit for high energy isochronous cyclotron

Max Energy for Superconducting Cyclotrons

not limited by (B x Rextraction)

Because of the focusing limitation due to the Flutter dependence on the B field, the max energy is not given by $Kb \sim 48\,(B.R\text{extraction})^2$

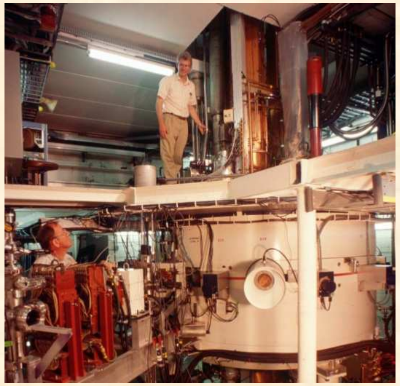
but K_f the so-called "*focusing* factor":

$$\boxed{\left[\frac{E}{A}\right]_{\max} \neq Kb\,.\left\{\frac{Q}{A}\right\}^2}$$

vertical oscillation+isochronous field condition

$$\nu_z^2 = n + \frac{N^2}{N^2-1}F\,(1+2\tan^2\varepsilon) > 0$$

$$\frac{N^2}{N^2-1}F\,(1+2\tan^2\varepsilon) > -n = \gamma^2 - 1$$



- Focusing limitation (stronger than B limitation)

$$\boxed{\left[\frac{E}{A}\right]_{\max} = Kf\,.\left\{\frac{Q}{A}\right\}^2 < Kb\,.\left\{\frac{Q}{A}\right\}^2}$$

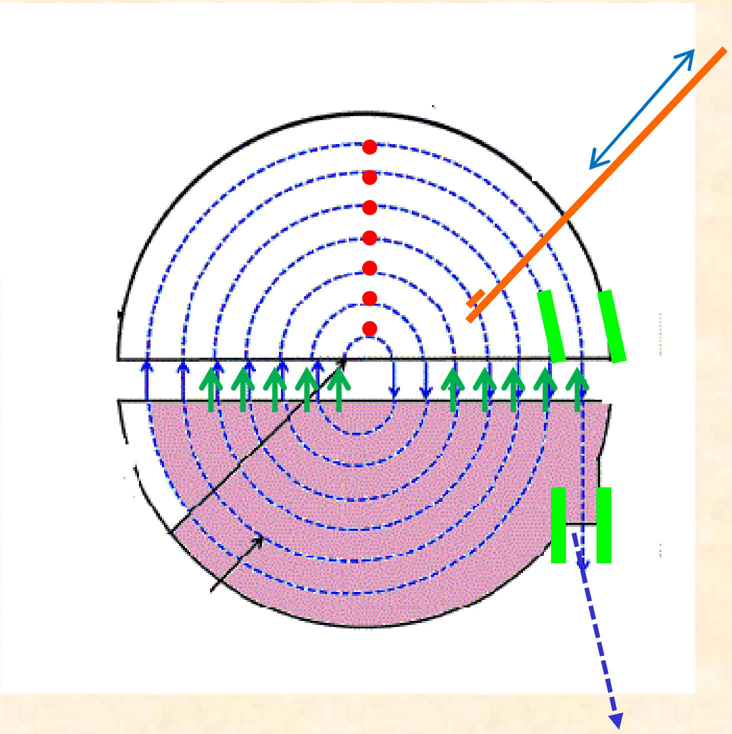
$Kb \sim 48\,(B.R\text{extract})^2$

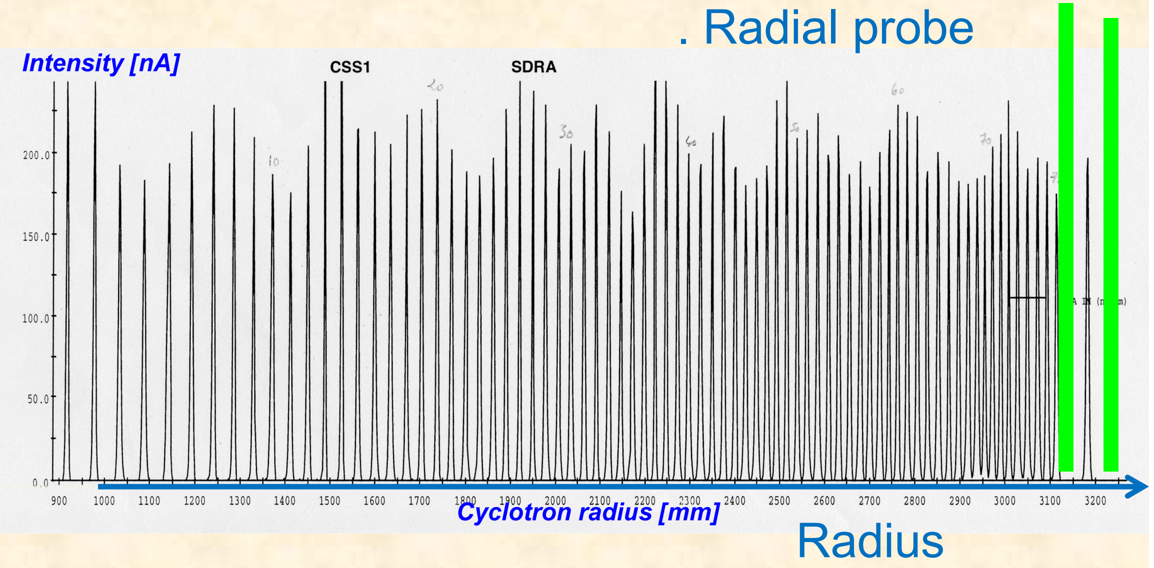
$Kf \sim f(\text{FLUTTER})$

Radial probes

usefull tool for acceleration, precession study

Monitoring turns with a
Radial probes





Radial probe : I = F(Radius)

Turn separation : δr =R(turn N) - R(turn N-1)

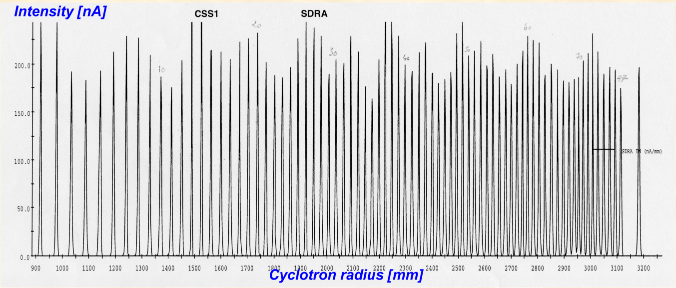
δr = Acceleration + Oscillation

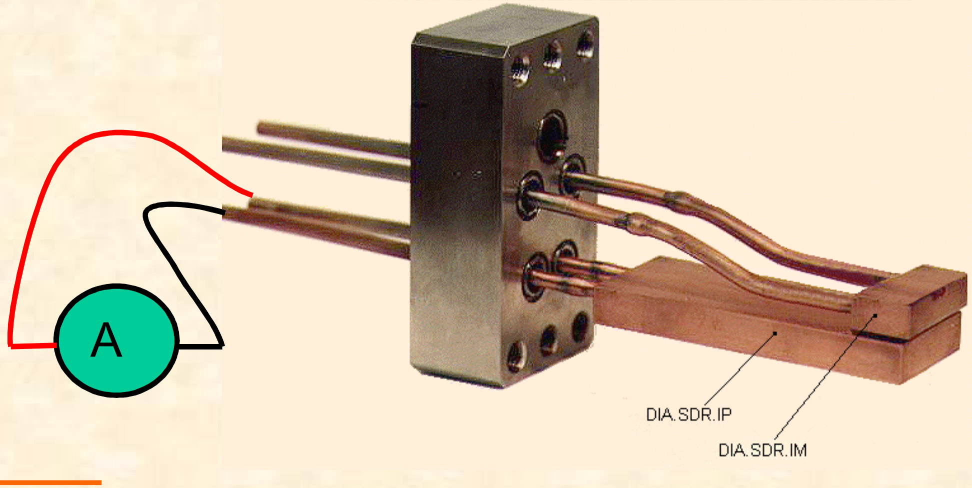
$\delta r \sim \alpha V_{RF} \cos(\phi)$ + Oscillation

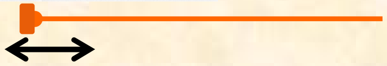
Current measurement: Radial probe

A Faraday cup on mobile Arm

I (μA)







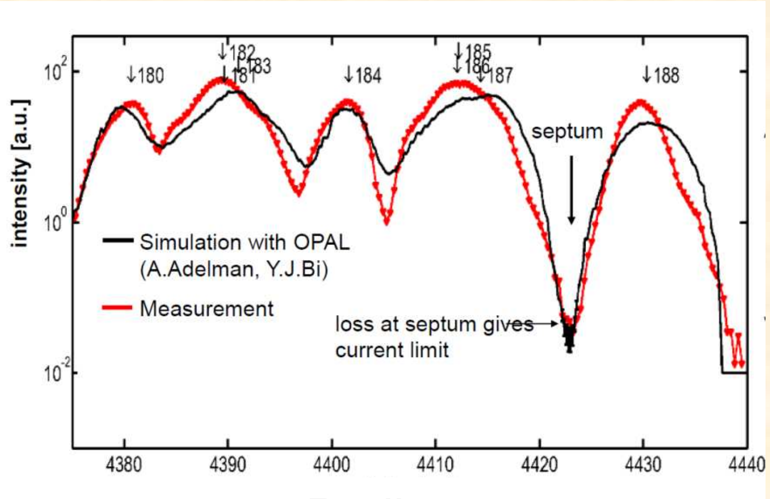
Radius

Ganil Css1 (Fr)
Kb=380 , heavy ions

Check of the
acceleration & extraction

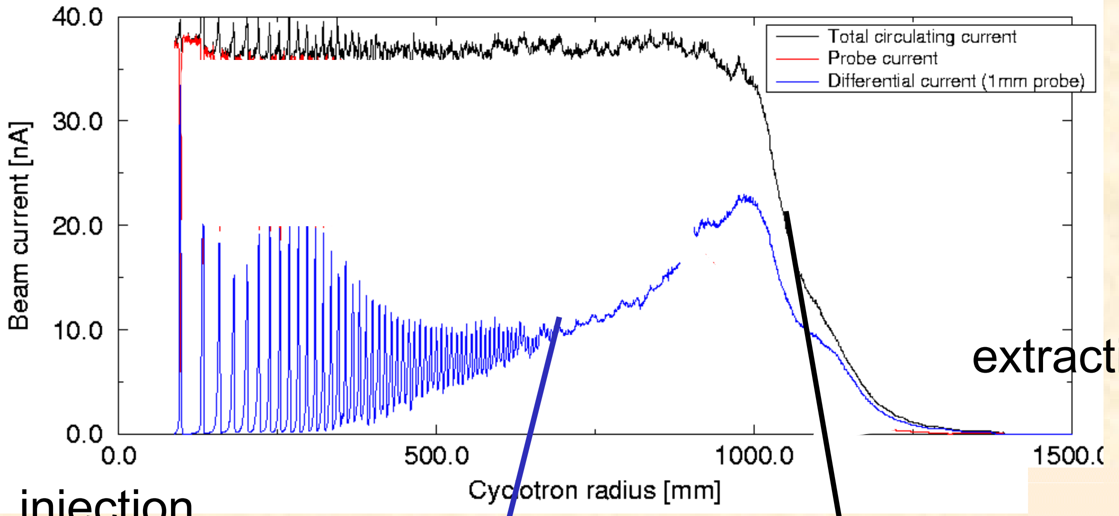
PSI
Kb=590 MeV

Check of the
extraction



Radius

Current measurement with a Radial probe
A full check of the dynamics



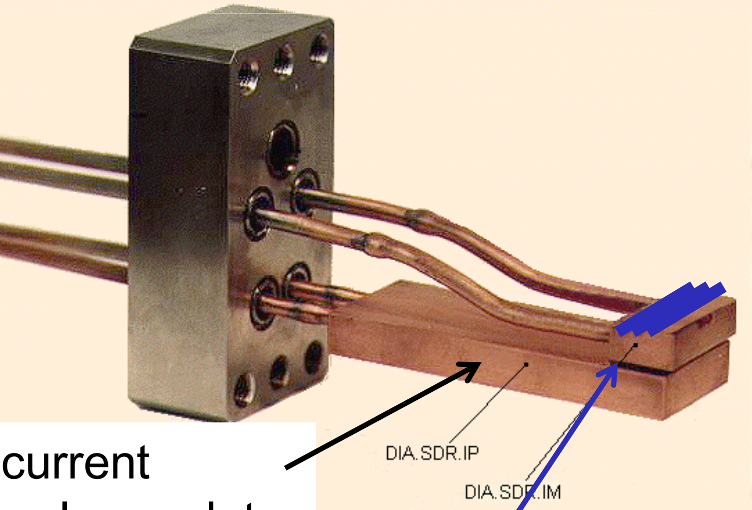
injection

extraction

Radial probes with
2 diagnostics :
-1 small finger
-1 large plate

Beam losses
Before extraction
(B field was not OK)

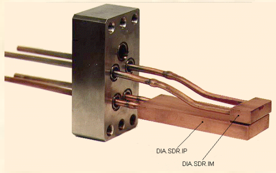
Current on small finger
of the radial probe



Total current
with a large plate

Finger current
Good resolution in r (turn separation)

Tune ν_r measurement with radial probes



:

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

$r(t) = < r(t) > + X_0 \cos(\nu_r \omega_0 t)$

$\omega_0 t$ =PHASE

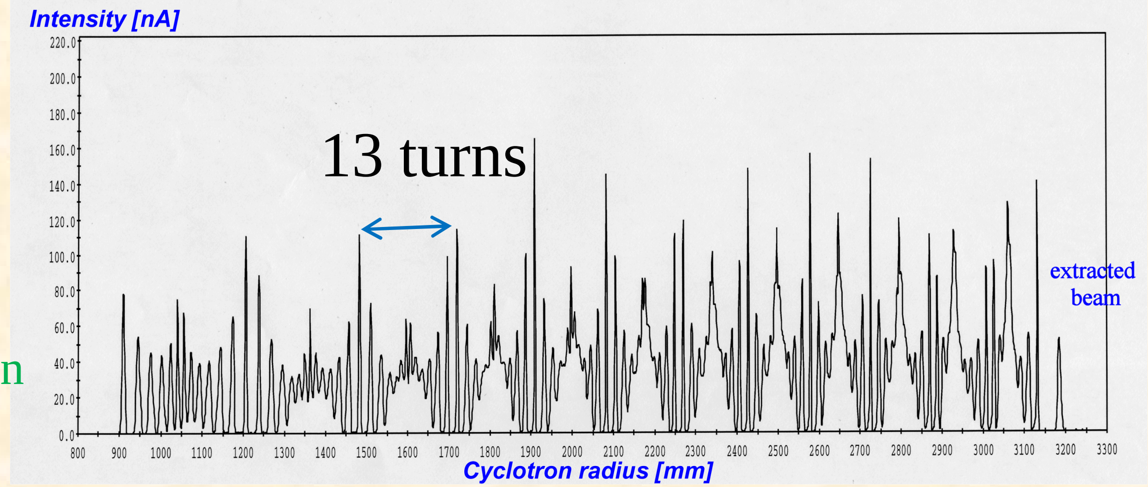
$\omega_0 \Delta t$ =360° =1 turn

Precession : $\delta r = \delta r_{acc} + X_0 \cos(\nu_r \omega_0 t)$

Centering error
At injection

Large X_0

Large Oscillation



1 period for

13 turns ⇨

ν_r =1/13 = 0.08

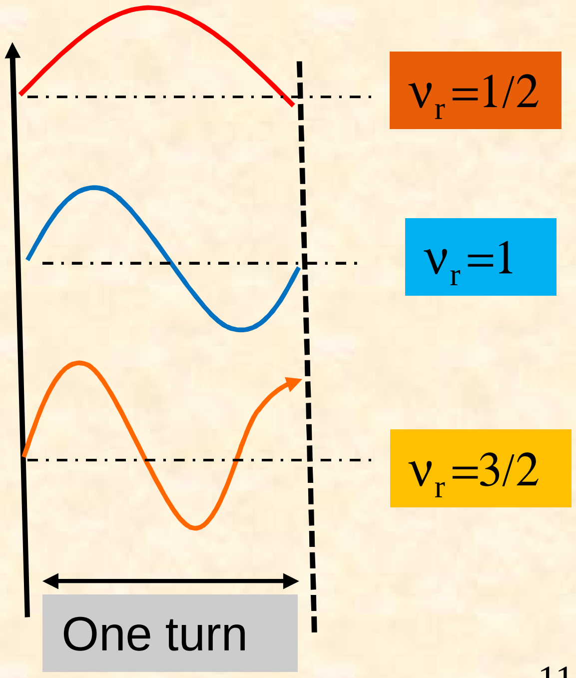
Back to dynamics
and resonances at high energy

During the acceleration, ν_r and ν_z change because $\nu_{r,z} \propto B(r)$

The plot of ν_r vs ν_z is called the **working point diagram.**

Like any oscillatory phenomenon, the amplitude of a betatronic motion can grow uncontrolled whenever an external source excites it with its own frequency.

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



Several kind of radial resonances

$x(t) = x_0 \cos(\nu_r \omega_0 t) = x_0 \cos(\nu_r\ 2\pi\ \mathrm{Nturn})$

can be excited with field defect, injection angle (unwanted)

with field bump, injection angle (desired)

What happen with P field perturbations on 1 turn

$$\ddot{z} + [\nu_z \omega_0]^2 z = \Delta \cos(P\omega_0 t)$$

Search a particular solution $z(t) \propto \cos(P\omega_0 t)$???

$$\Rightarrow \quad \frac{z(t)}{\Delta} = \frac{\cos(P\omega_0 t)}{[\nu_z \omega_0]^2 - [P\omega_0]^2}$$

<u>z/Δ diverge </u>at νz=P (integer)

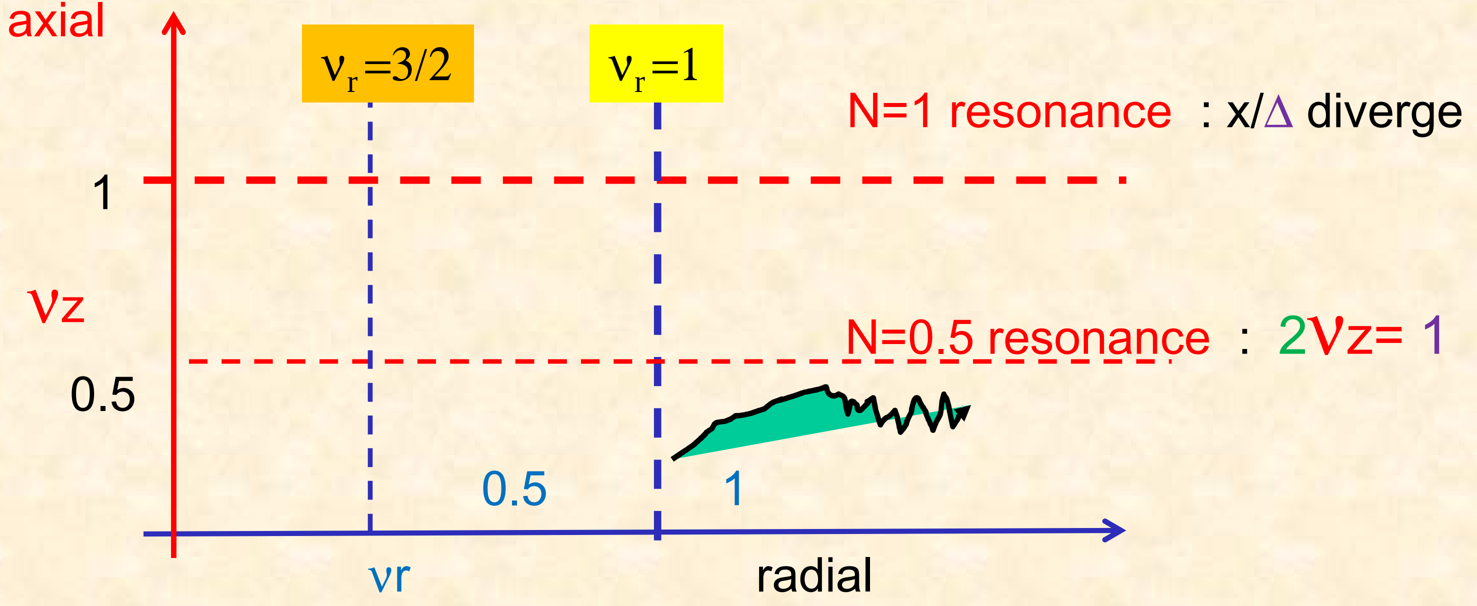
z(t) is very sensitive to any perturbation Δ

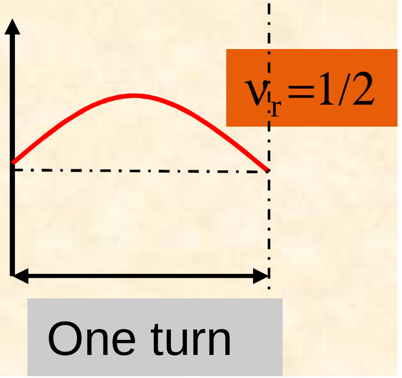
(not good : instabilities = beam losses)

With P field perturbations on L turns

z/Δ diverge at L.νz=P (integer)

Cyclotron try to avoid resonance crossing





Resonances

Systematic resonances : This **resonance occurs as the betatronic** frequency is a multiple of the "geometrical frequency" of the cyclotron. In this case, any kick given to the particle because of its particular position will be experienced again and again.

$$(K.\nu_r = P) \quad // \quad (L.\nu_z = P)$$

Coupling resonances

Under proper circumstances and frequency ratios, the 2 oscillators can be coupled and the energy stored in one motion, transferred to the other. These are coupling resonances ($K.\nu_r + L.\nu_z = P$).

$$K.\nu_r + L.\nu_z = P$$

K, L and P integer

The particle's working point curve should avoid or cross as fast as possible those lines.

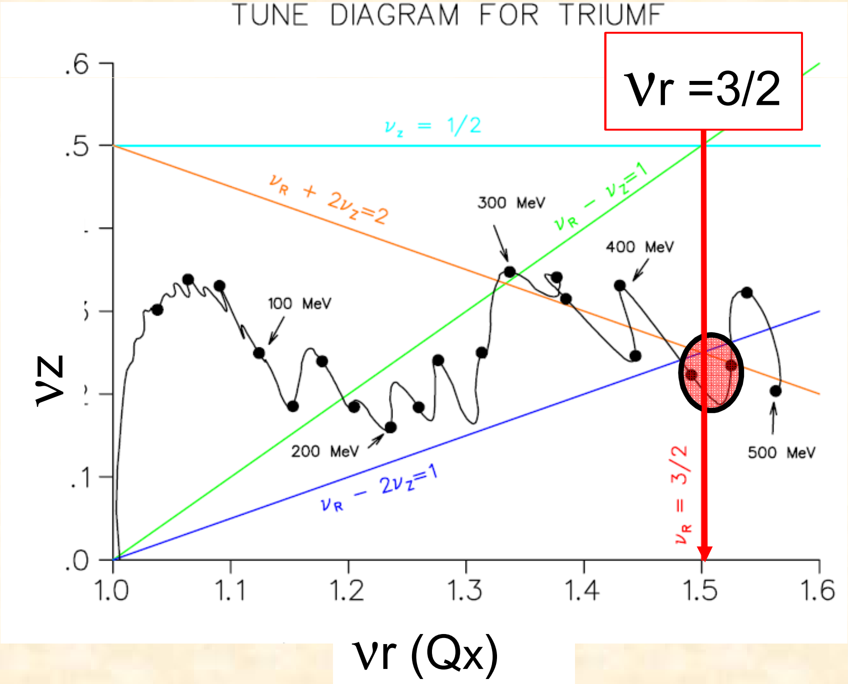
Tunes and resonances at Triumf (Canada)

(H^- cyclo, K_b=520 MeV, 6 sectors)

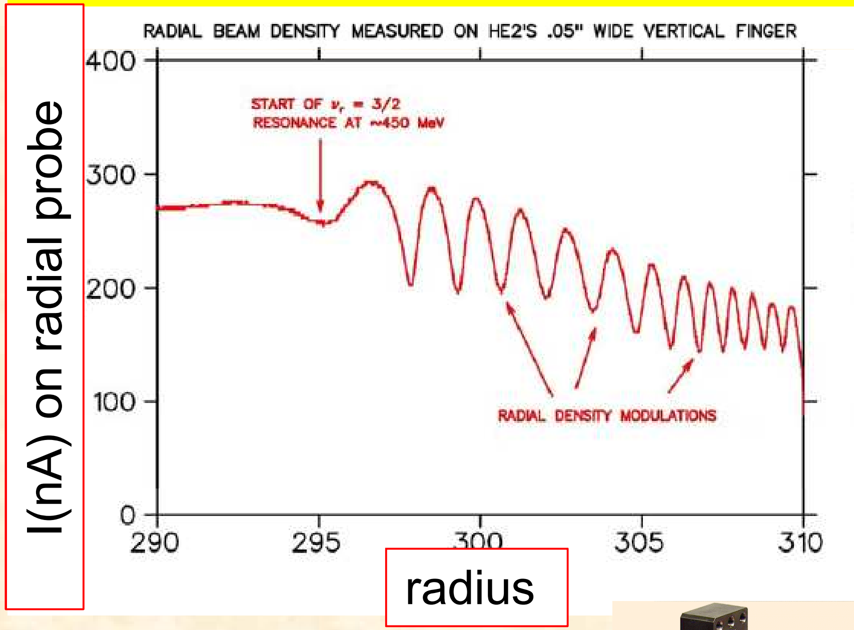
$$K.\nu_r + L.\nu_z = P$$

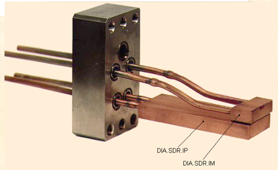
$|K| + |L|$ is called the resonance order (1, 2, 3 …)

Effect on the crossing of the resonance $2.\nu_r = 3$ **(order 2)**



Radial Oscillations : $2.\nu_r = 3$





$$\nu r^2 = 1 - n + \ldots = 1 - (1 - \gamma^2) + \ldots \sim \gamma^2$$

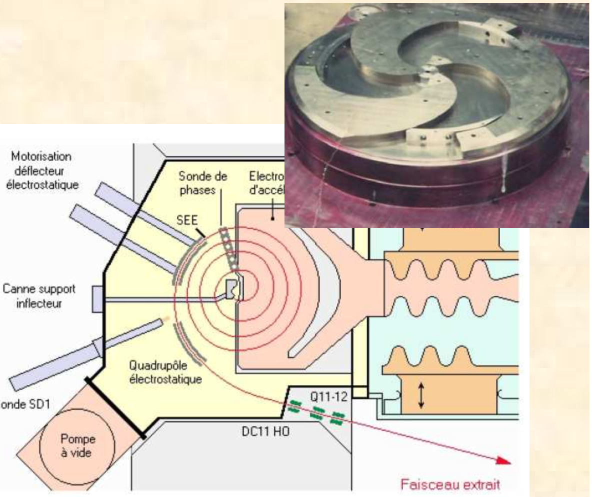
Cyclotrons in the world

Reseach laboratories with Cyclotron(s)

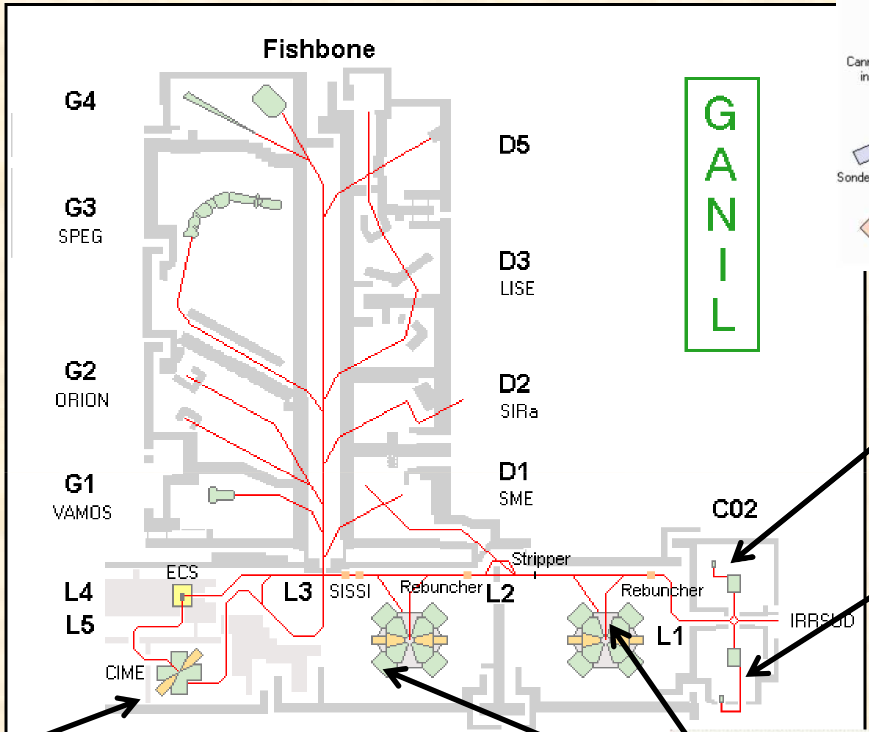
Some of the Research Facility in the world using cyclotrons

GANIL Facility (Caen, Fr)
5 cyclotrons +a new Linac

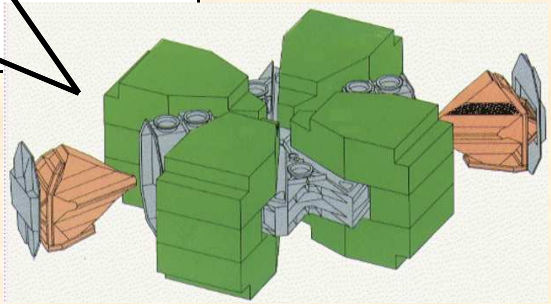
Nuclear physics
Atomic physic
Solid state
Radiobiology



2 compact cyclo
Kb=28 MeV



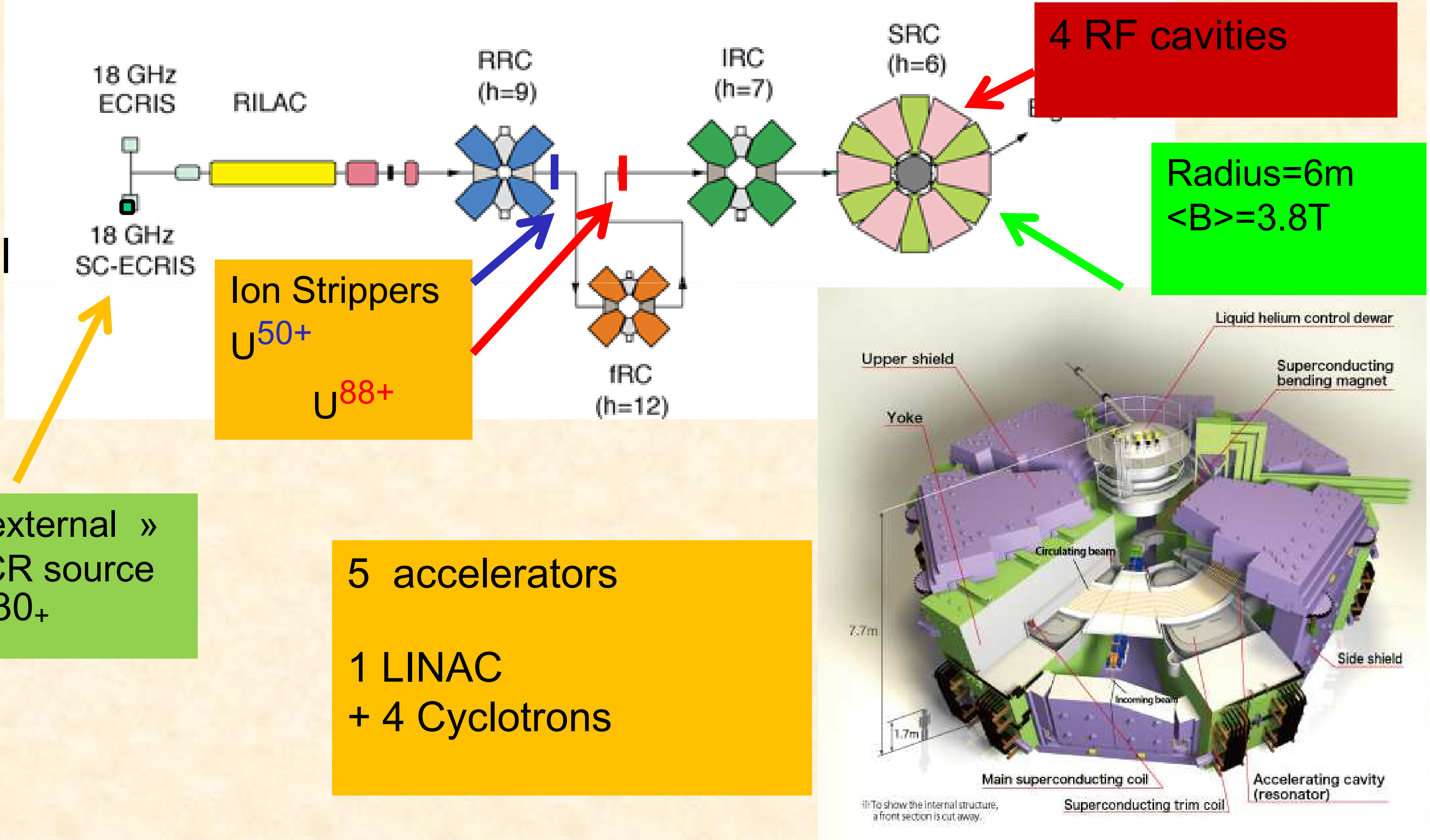
1 compact cyclo Kb =265
For radioactive ion



2 Separated Sectors cyclotrons
Kb =380 MeV

RIBF (Tokyo, Japan) :
Uranium beam $^{238}U^{88+}$ @345 MeV/A cw

Mode (1): RILAC + RRC + (stripper2) + fRC + (stripper3) + IRC + SRC



4 RF cavities

Radius=6m
<B>=3.8T

Ion Strippers
U^{50+}
U^{88+}

« external »
ECR source
U^{30+}

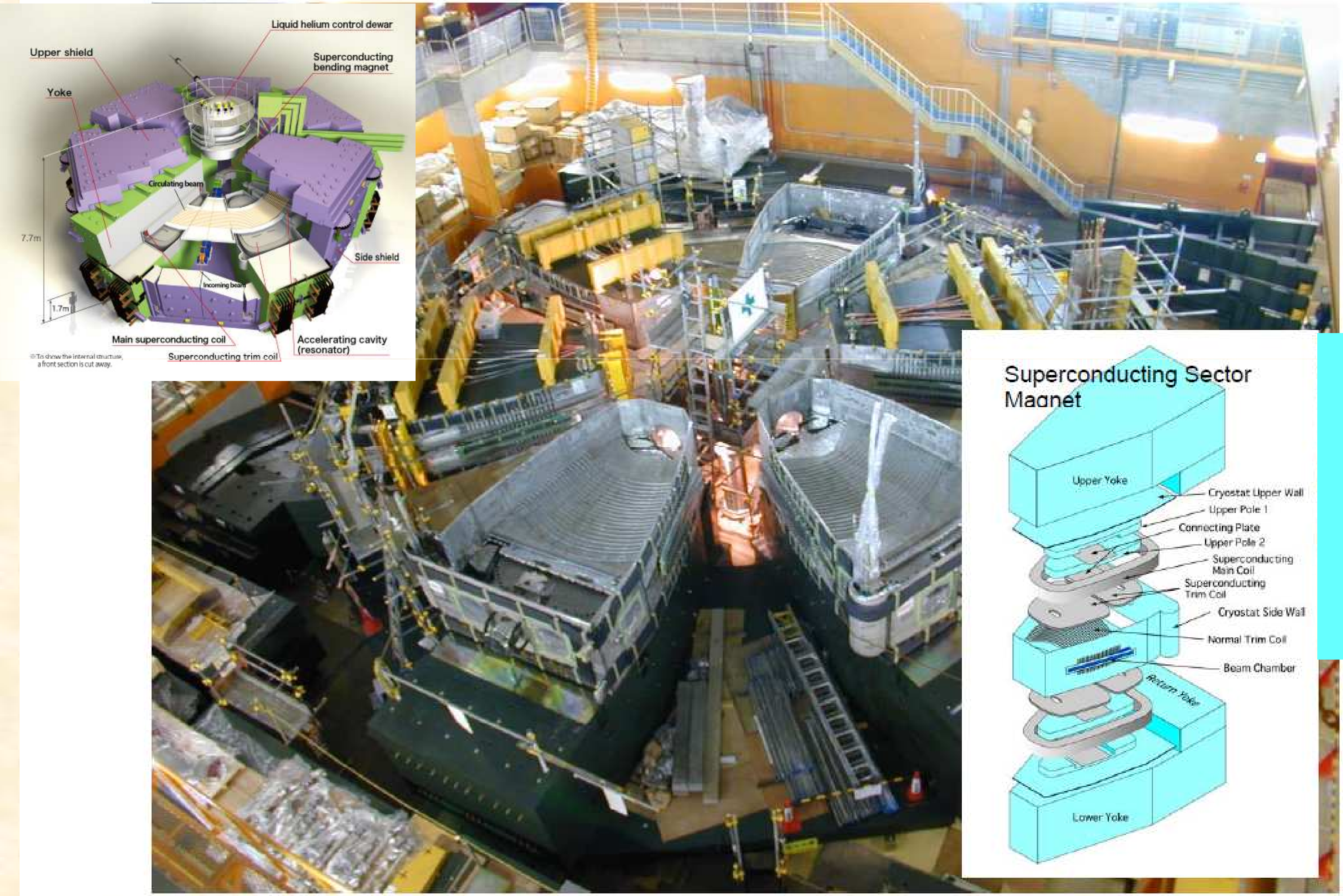
5 accelerators

1 LINAC
+ 4 Cyclotrons

RIBF (Japan) : SRC (K=2600 MeV)

the largest cyclotron in the world

Superconducting Ring Cyclo

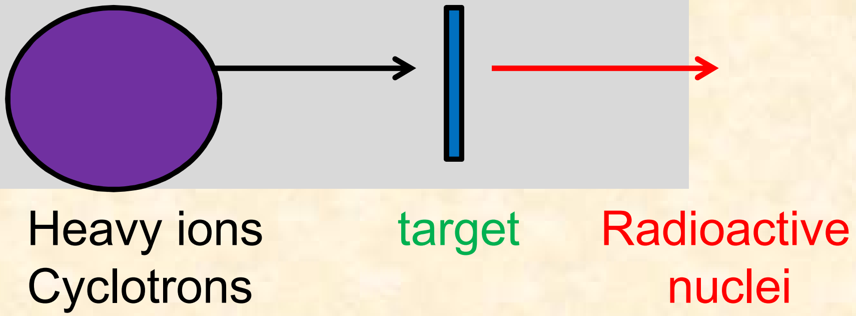


Completed November 2005 - the 140-ton cold mass cooled to 4.5K.

6 sectors :
Iron dominated magnets
With
superconducting
coils

TREND in Nuclear physics : Physics at RIBF (Tokyo)

Create Unknown "exotic" nuclei
by nuclear fragmentation
or by fission



Heavy ions
Cyclotrons

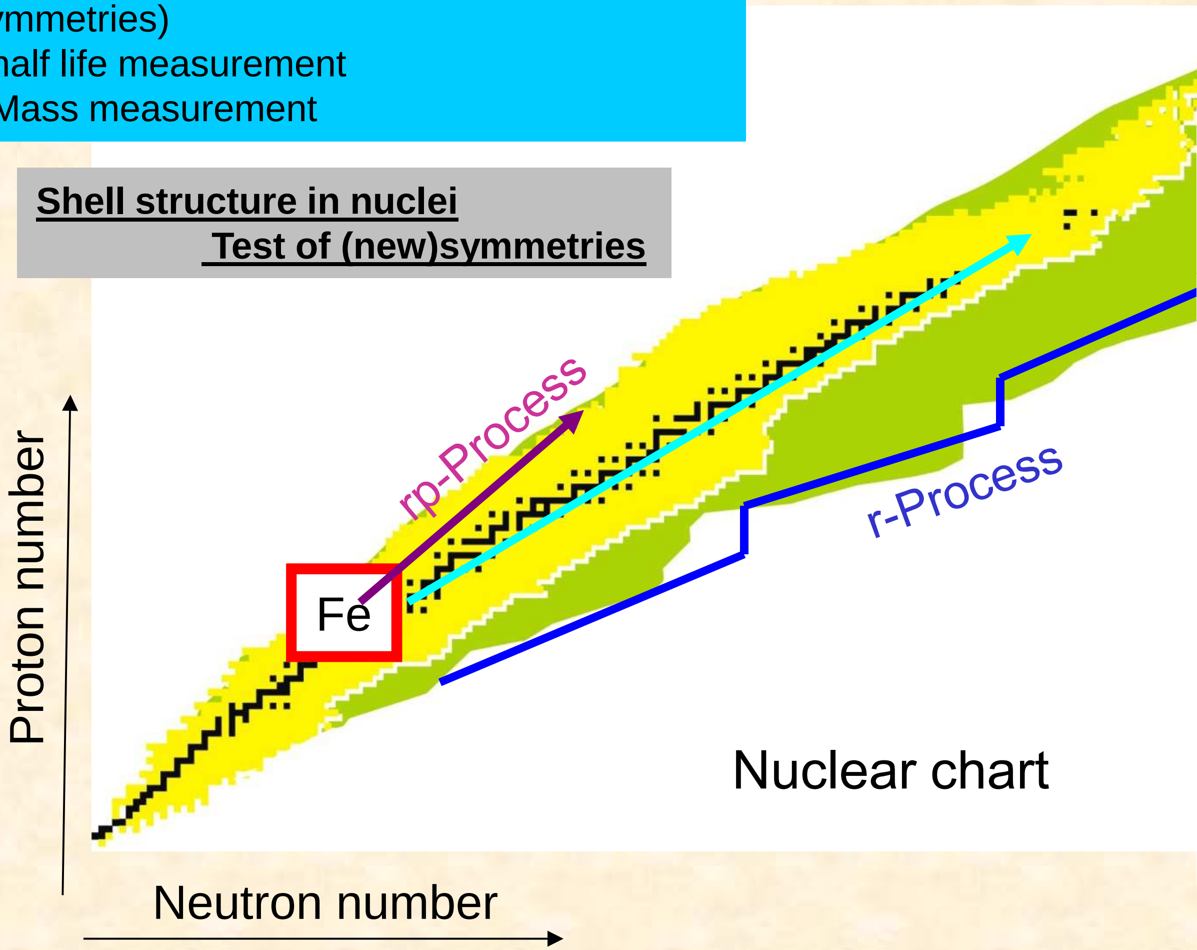
target

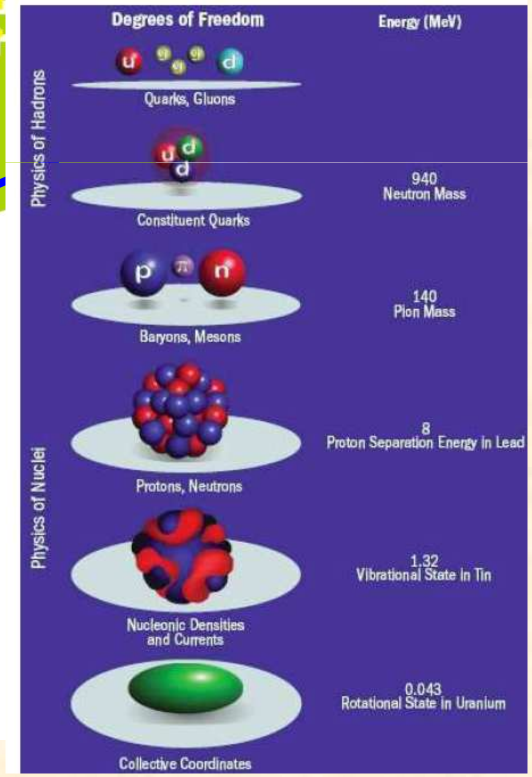
Radioactive
nuclei

Exotic Nuclei (Very large proton-neutron asymmetries)

- half life measurement
- Mass measurement

Shell structure in nuclei
Test of (new)symmetries

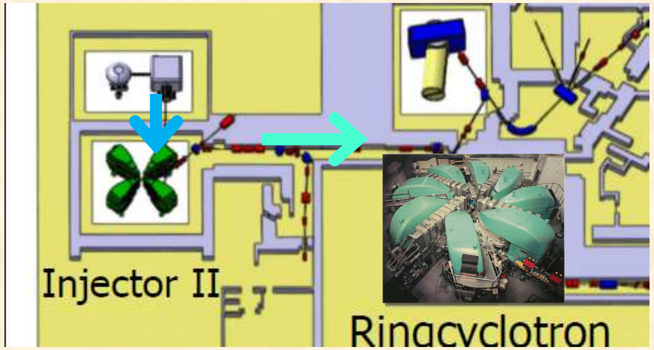


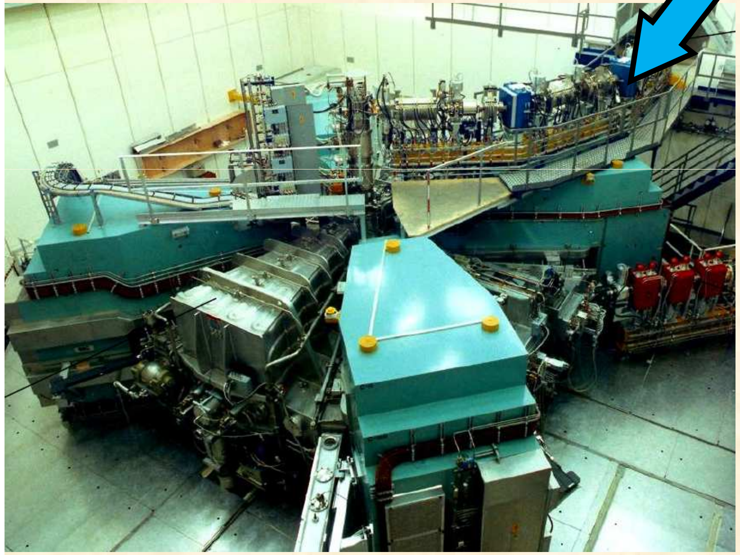


PSI 590Mev proton (Ch)

870 keV

Cokcroft-Walton



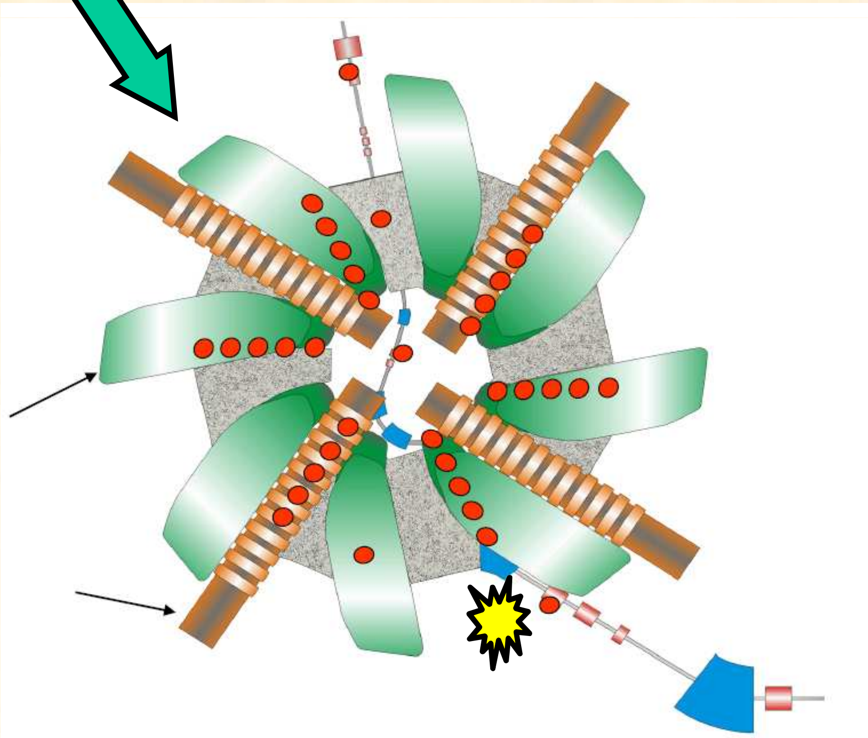


72 MeV injector 2

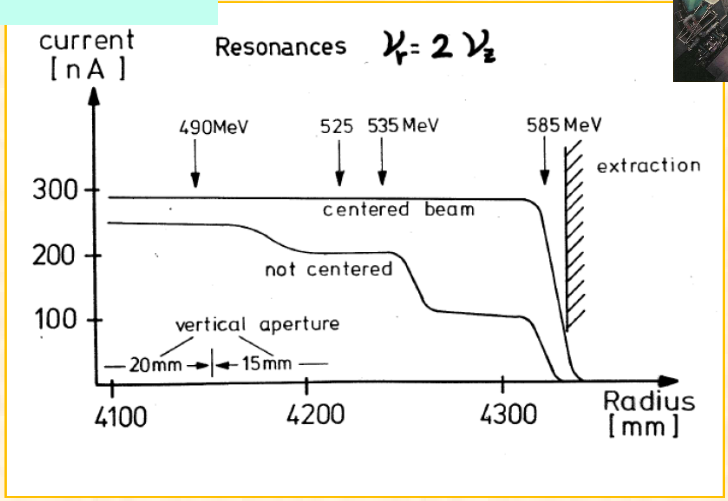
Coupling of 2 cycloton :

$$v = \left[\frac{F_{HF.\mathrm{Re}\,jec}}{h}\right]_{cycloA} = \left[\frac{F_{HF.Rinj}}{h}\right]_{cycloB}$$

590 MeV Ring cyclotron



PSI :K= 590 MeV ring cyclotron

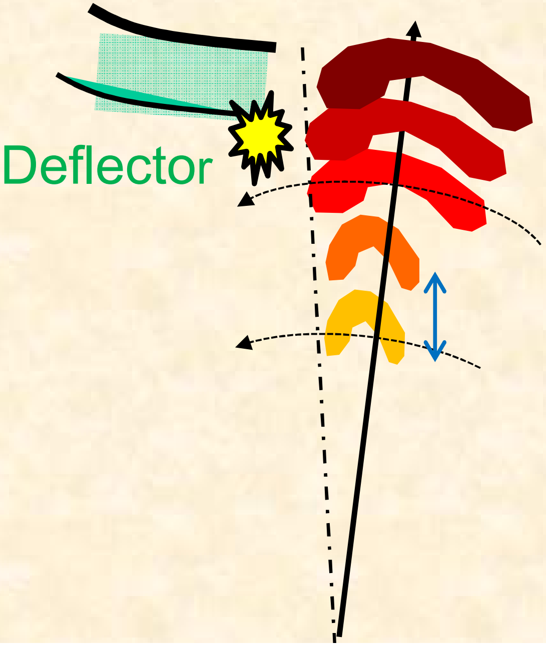


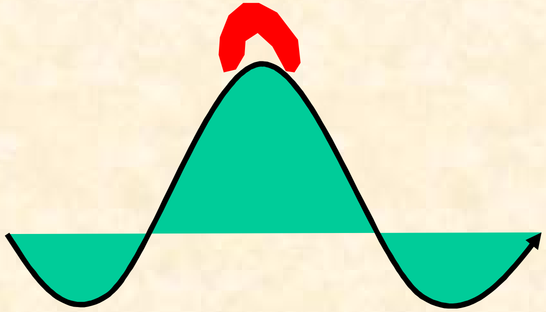
Injection centering :

Watch the resonance $2.\nu_z + \nu_r = 2$

Extraction : Watch the beam losses !

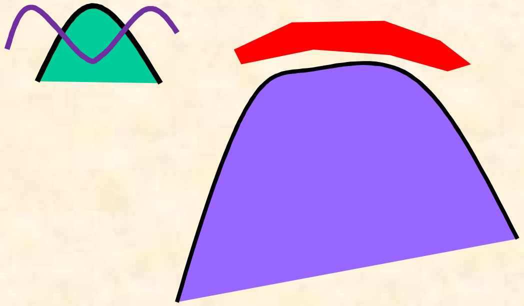
A Flat top RF cavity has been added to reduces losses: $V_{RF} = \cos(\omega t) - \alpha.\cos(3\omega t)$





Standard cavity :

$V_{RF} = \cos(\omega_{RF}\, t)$



Flat top cavity

$\cos(\omega_{RF}\, t) - \cos(3\omega t)$

Some Commercial Cyclotrons : manufacturers

IBA (Belgium)

			Cost estimate 2008
Cyclone 5/10	proton/D		1 Meuros
Cyclone 9/18	H-/D-		1.5 Meuros
Cyclone 30	H-/D-		???
ProteusOne 250 MeV	p	synchro-cyclo superconducting	
C70	p/D or H-/D-		

Sumitomo HI (Japan)

HM-12	p
HM-18	p

EBCO (Canada)

TR 9/ 18	H-/D-
TR 15/ 30	H-/D-

GE-Scanditronix (USA-Sweden)

MINI TRACE 9/18

Accel // VARIAN ……

250 MeV proton cyclo superconducting

>300 commercial cyclotrons in the World
- (10-20MeV) protons
- (230MeV) protons :develloping market

Commercial Cyclotron

Radioisotope production (5-20 MeV)

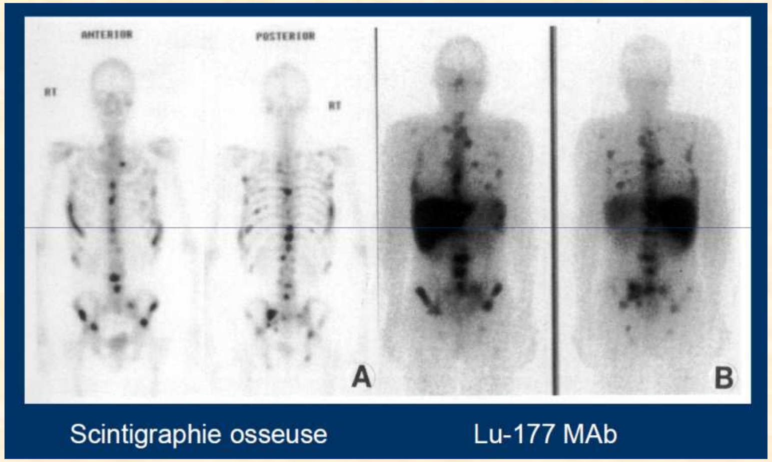
Radiotracer $^{18}F^*$: « Beta+ » emitter
Fluorine 18

$T_{1/2}$ =109.7 min

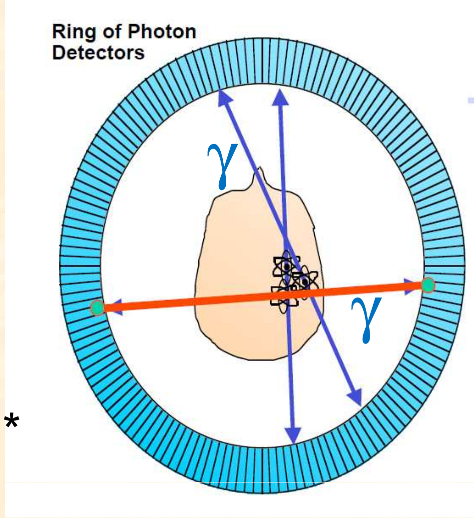
$^{18}F^*$ ⇨ ^{18}O + positon + neutrino
↳ $\gamma + \gamma$

Production With cyclotrons

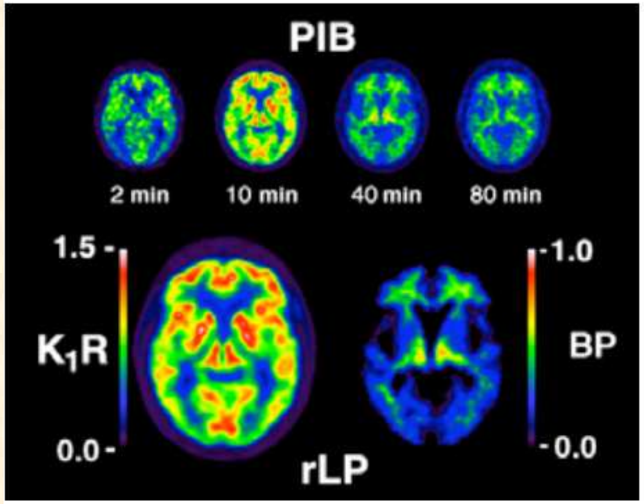
Proton 10-20MeV + ^{18}O ⇨ $^{18}F^*$ + n



Injection of $^{18}F^*$
TEP camera

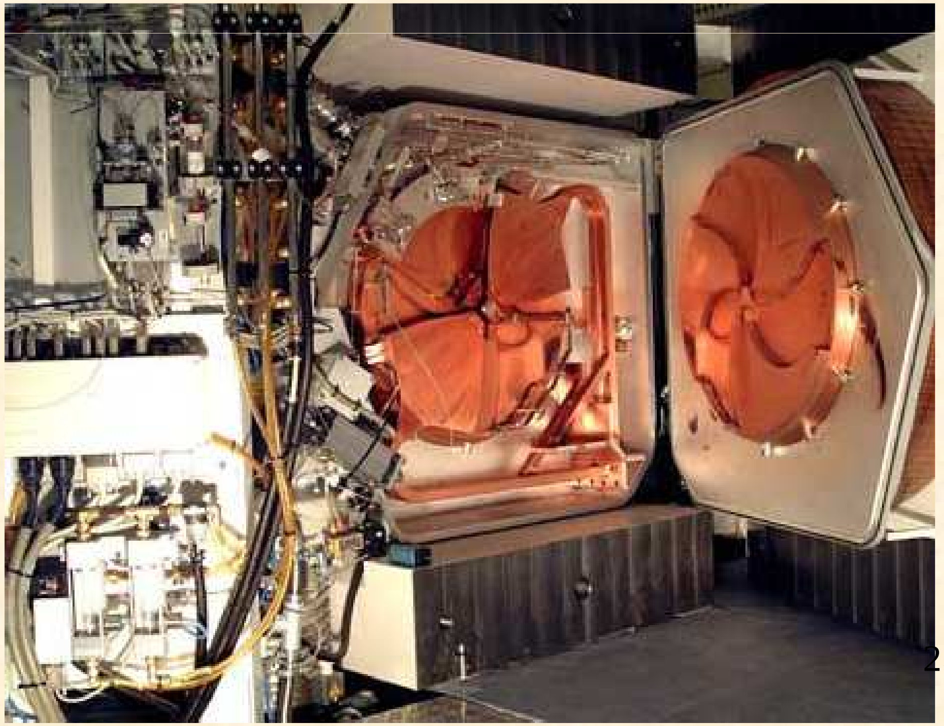


Reconstruction



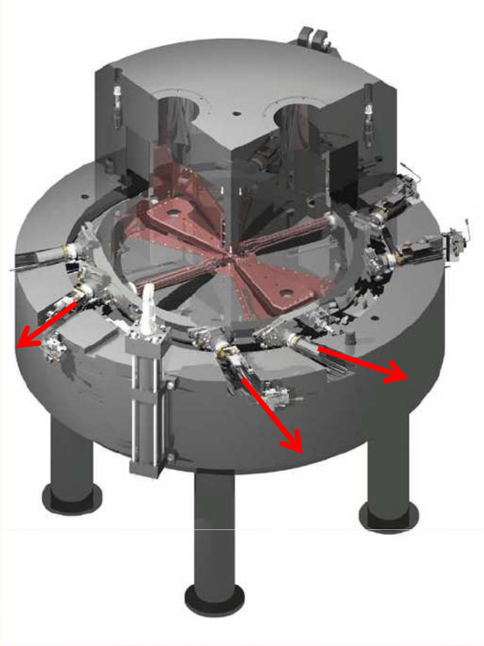
Cyclone 10/5 Mev

cyclone 3D



CYCLONE 18/9 (IBA) : H$^-$ 18 MeV

Designed for medical applications (radiotracers production)

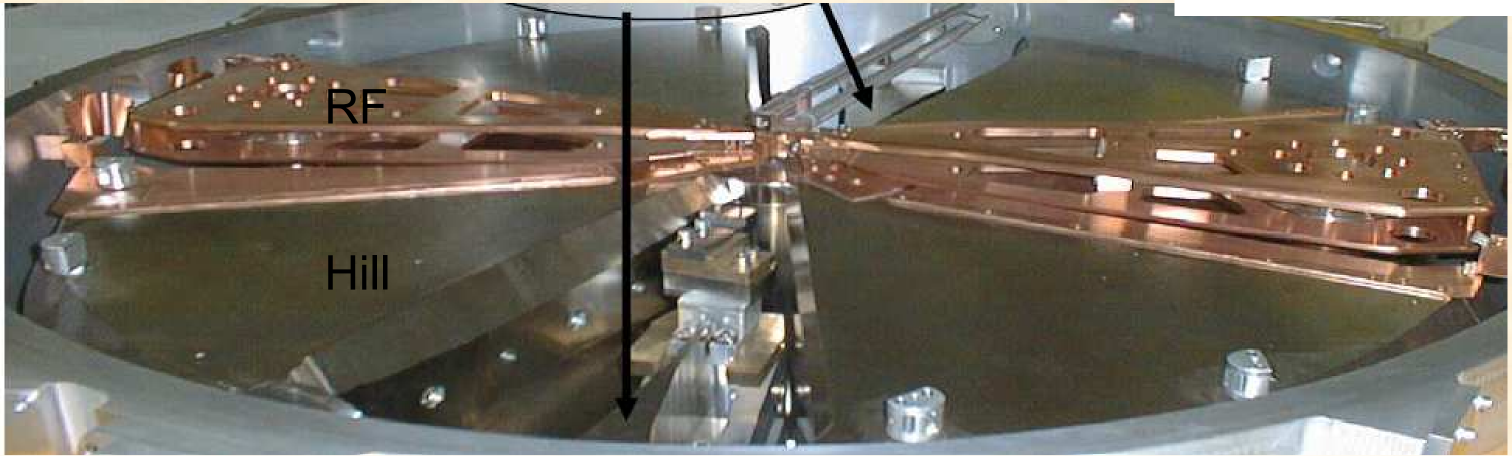


Kb=10 MeV
Fixed energy ;
4 straight sector 50°
<B> =1.35 Tesla
Hill //valley gap 3cm// 67cm
fixed Frf =42Mhz

2 Dee = 30° , 32 kV
Harmonic h=2(p) ,4 (D)
Internal source
Rextraction=0.46 m

Bρmax=0.46x 1.35=0.62 T.m

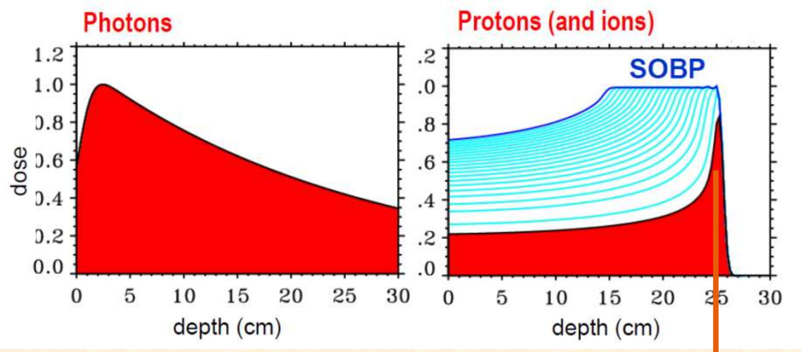
Internal PIG source, H$^-$ stripping extraction



Commercial Cyclotron :

proton therapy (230 MeV)

Photon :
(Radiotherapy)
A Dose in the
whole body



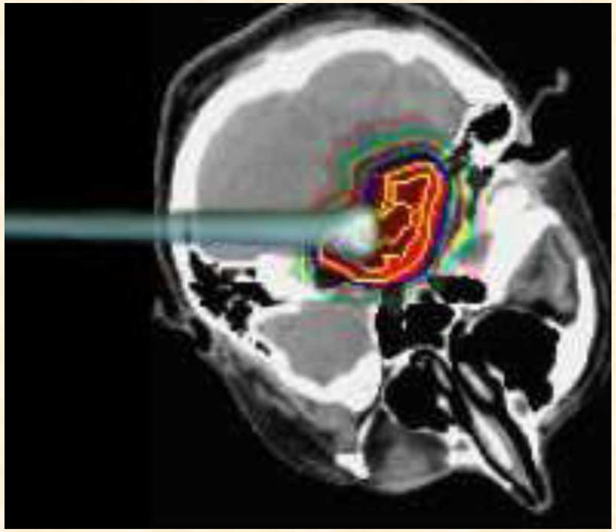
Proton :
Better than
Radiotherapy (photon)

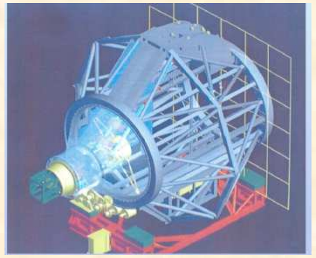
Dose inside the tumor

Bragg Peak

Brain tumor treatment with protons

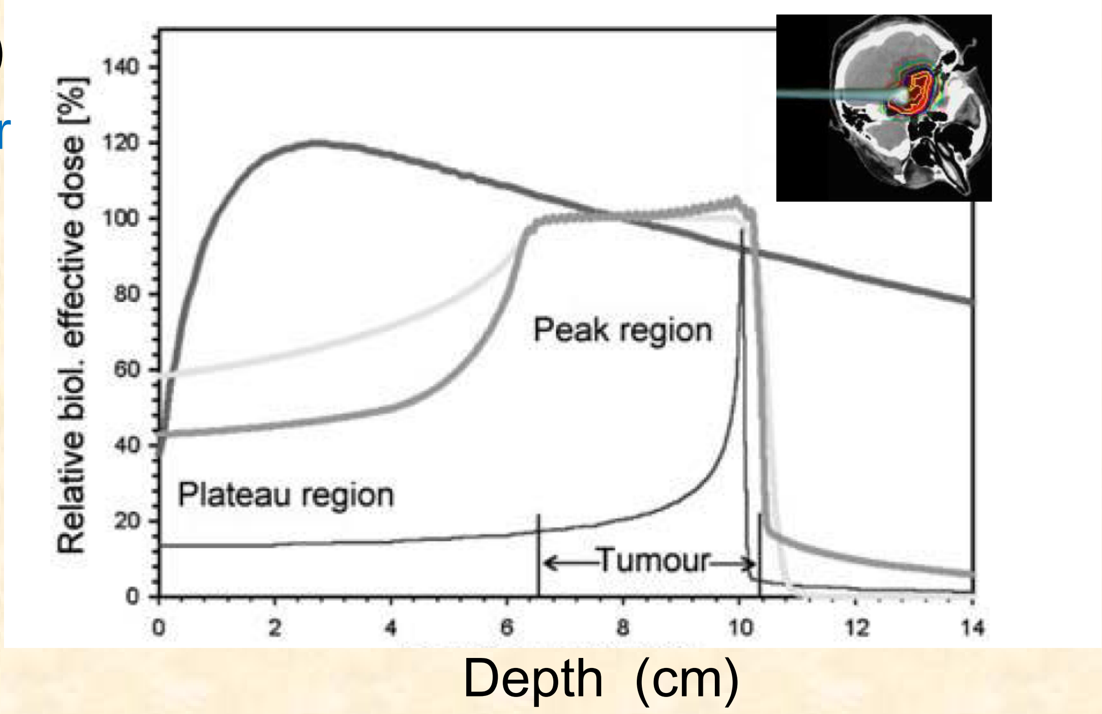
Eyes tumor treatment





Proton therapy (230 MeV)

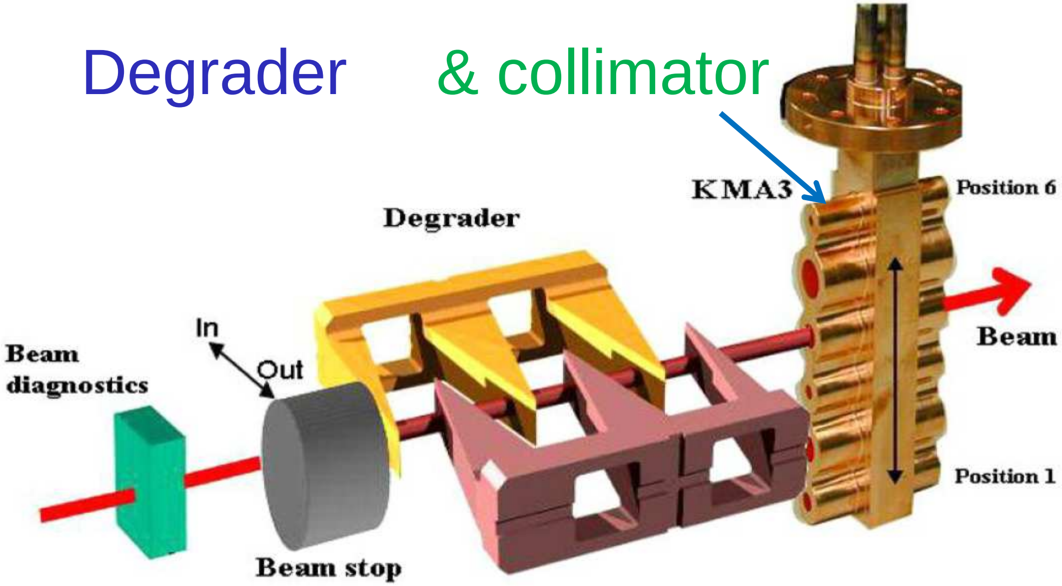
-Energy variation with degrader



Scanning the tumors :

With energy variations
induce by a degrader

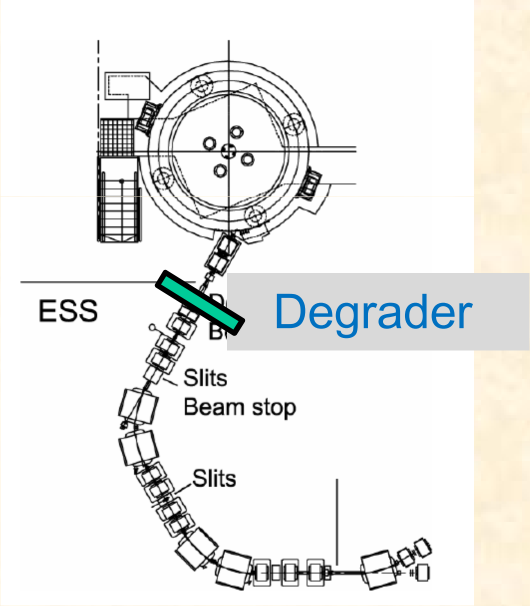
Degrader & collimator



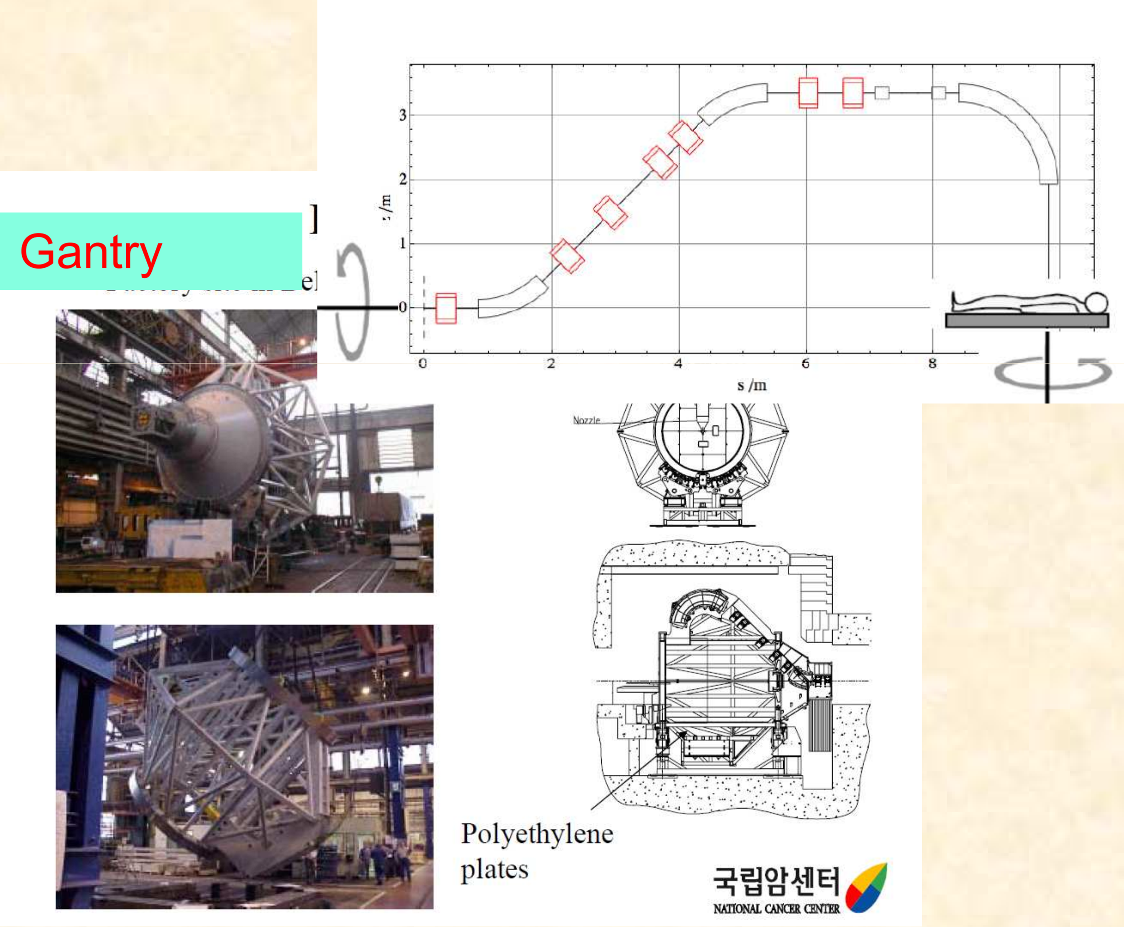
Energy variation
=
Range variation
(tumour scanning)

Proton therapy (230 MeV)
Energy variation with degrader
+ Rotating gantry

Optimal dose delivery
Scan the tumors :



Depth variation :
Tumor scanning



The gantry reduces dose in healthy tissues

END

References & Acknowledgements :

F. Chautard, Juas 2015
M. Craddock lecture on Cyclo//FFAG
W.Joho lecture on PSI facility
S. Brandenburg lecture on beam optics

P. Heikinnen, CAS Jyväskylä 1992, CERN 94-01 (1994) “Cyclotrons“ and “Injection and Extraction“

T. Stammbach, CAS La Hulpe, 1994, CERN 96-02 (1996) “Introduction to Cyclotrons“

The Cyclotron Family

isochronous cyclotron
(Azimuthally Varying Field)

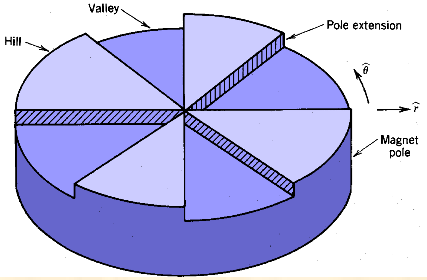
B*z (R)* = NOT uniform=f(r)
F*rev* = Constant
F*RF* = constant

Vertical focusing with B*z* = f(R,θ)

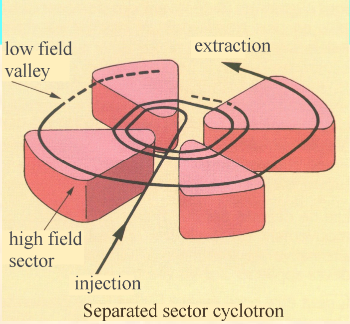
Isochronous

$$\boxed{\omega_{rev} h = \omega_{RF}}$$

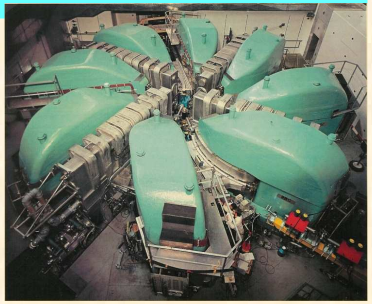
Compact cyclotron (with Hills //Valleys)
Straight or Spiralled sectors



Ring cyclotron :
Straight or Spiralled
Separated sectors



Separated sector cyclotron



Synchrocyclotron

$$\boxed{\omega_{rev}(R)/h = \omega_{RF}(t)}$$

F*rev* = NOT Constant
F*RF* = NOT Constant = beam pulsed

Not Isochronous

Cyclotron vs other RFaccelerators

	Radius	Frf	Particles
Cyclotrons	not constant	constant (isochronous)	Ions $\gamma < 2$
Synchro-cyclotrons	not constant	not constant pulsed	Ions
Synchrotrons	constant	not constant pulsed	Ions, electron
Linacs	constant	constant	Ions, electron

Cyclotron Summary

Isochronous cyclotron =

constant revolution frequency

from injection to extraction

$$\omega_{rev} = \frac{qB_z(R)}{\gamma(R)\, m} = const$$

field index n<0

$$n = -\frac{R}{B_{0z}} \frac{\partial B_z}{\partial x}$$

Vertical stability in isochronous cyclotron

requires Azimuthal field Modulation (N sectors)

$$\nu_z^2 = n + \frac{N^2}{N^2 - 1} F_l \left(1 + 2 \tan^2 \varepsilon\right) > 0$$

$z(t) \sim z_0 \exp(-i \;\nu z\, \omega_0\, t)$ **: νz real for stability**