Cyclotrons

Chapter 5 : theory versus reality,examples

- Cyclotron versus synchrotron or linac
- Isochronism and Phase measurement
- Radial probe and Intensity measurement
- Resonances and tunes in a cyclotron

- Research applications
- Medical applications

Cyclotron vs other RF accelerators

	Radius	Frf	Particle
Isochronous cyclotrons	not constant	constant :CW (isochronous)	Ions limit $\gamma < 2$
Synchro-cyclotrons	not constant	not constant pulsed, Frf (t)	Ions
Synchrotrons	constant	not constant pulsed Frf (t)	Ions, electrons no limits for γ, limit €
Linacs	constant ∞	constant	Ions, electrons limit €

LINAC VERSUS CYCLOTRON

to get ˜20 MeV protons

Proton Source

LEBT

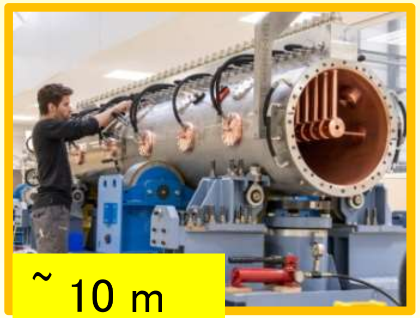
RFQ

MEBT

DTL

Drift Tube Linac

˜20 m total



˜ 10 m

I cw ˜ up to 1–5 mA
Linac Cost ˜ up to 10 Meuros
+ building (˜ 300m2)

– Not Compact (beam lines +linac)
– Specific design € €

Internal source
H- with stripping extraction

Rextraction ~0.4 m
Total size < 2m

I cw ~ 0.05 up to 0.3 mA in H–
CYCLO Cost ˜ 1.5– 3 Meuros

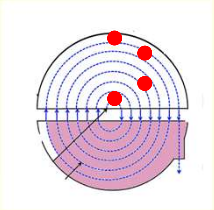
Several industrial manufacturers

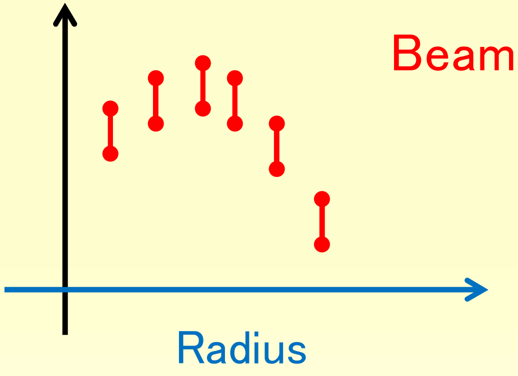
Compact

Standard design (1300 cyclo in the world)
Operation easy

Phase measurement: n(R) check and field correction : Δ B

Relative phase Beam vs RF



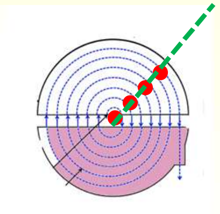


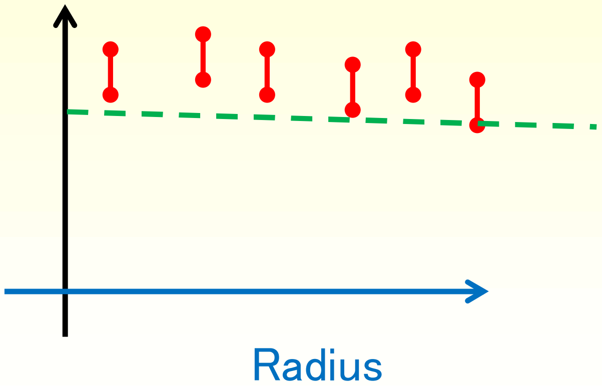
Beam not in phase with RF : B field not OK

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

Bz(R) not correct

Relative phase Beam vs RF



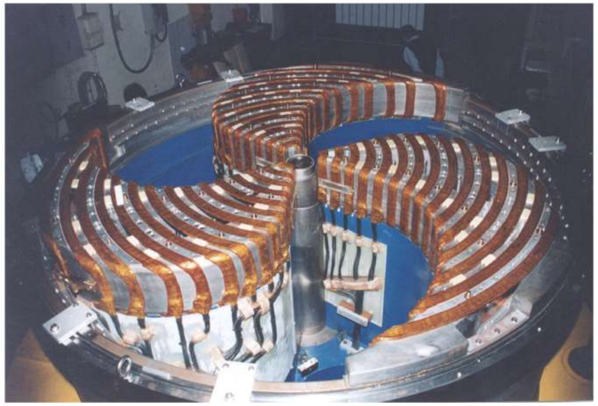


Correction of B : B($I+\Delta I$)

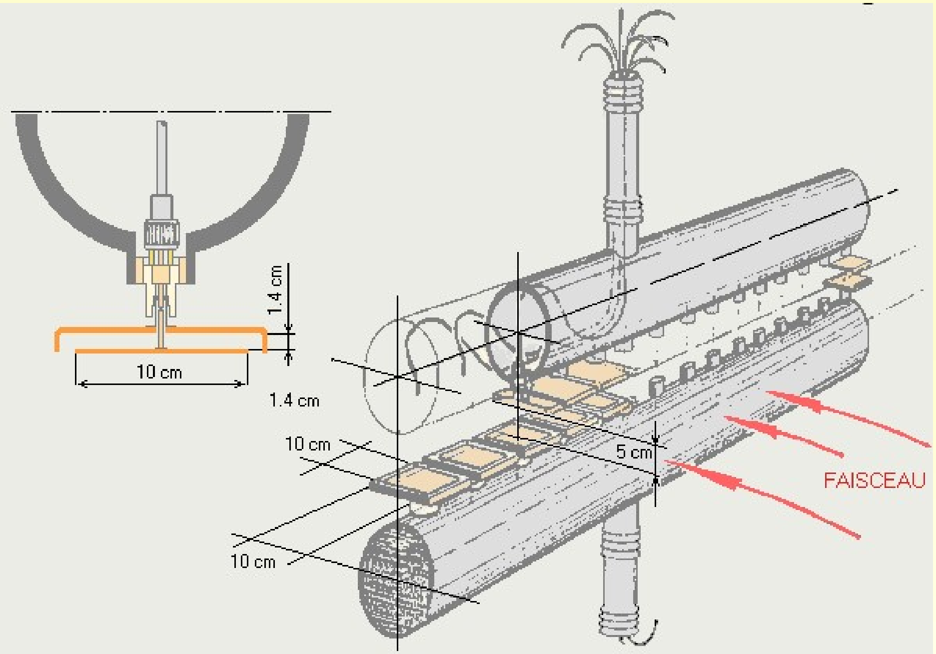
Bz(R) + Δ Bz

Bz(R) correct : Beam in phase with RF

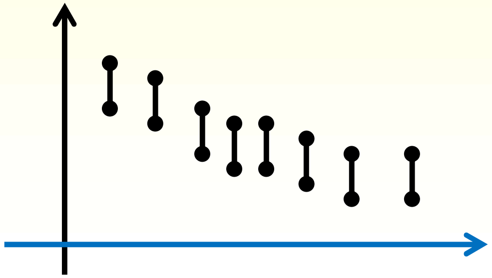
Correction trim coils, AGOR



Phase measurement: Isochronism

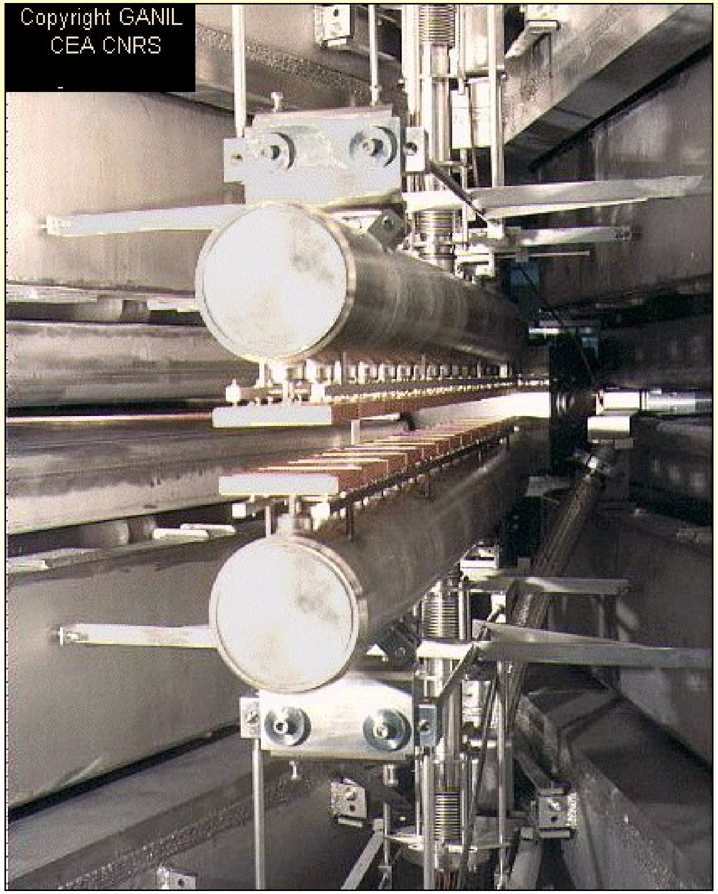


Relative phase
Beam vs RF



Radius

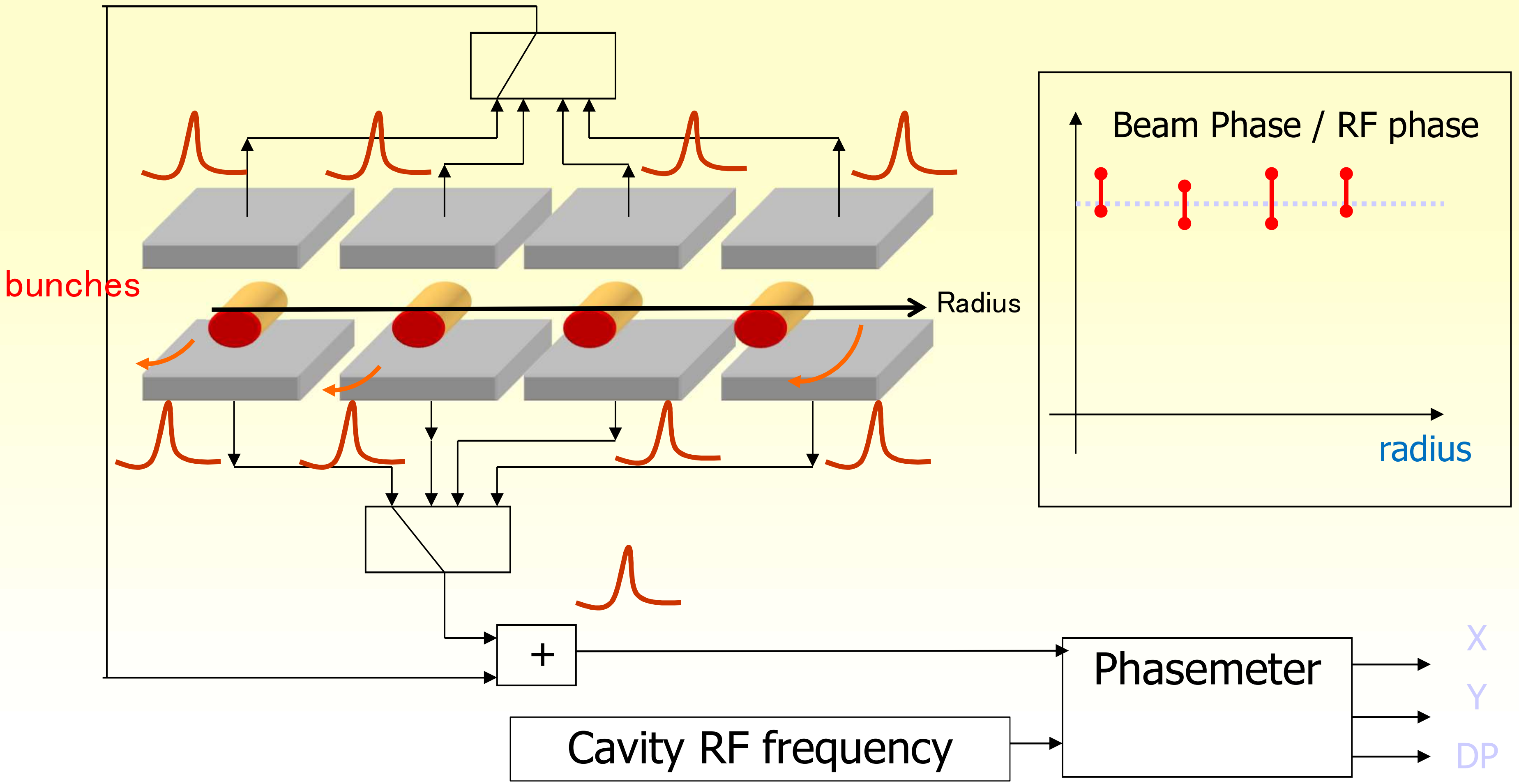
Ganil, Caen (Fr) : CSS1



Copyright GANIL
CEA CNRS

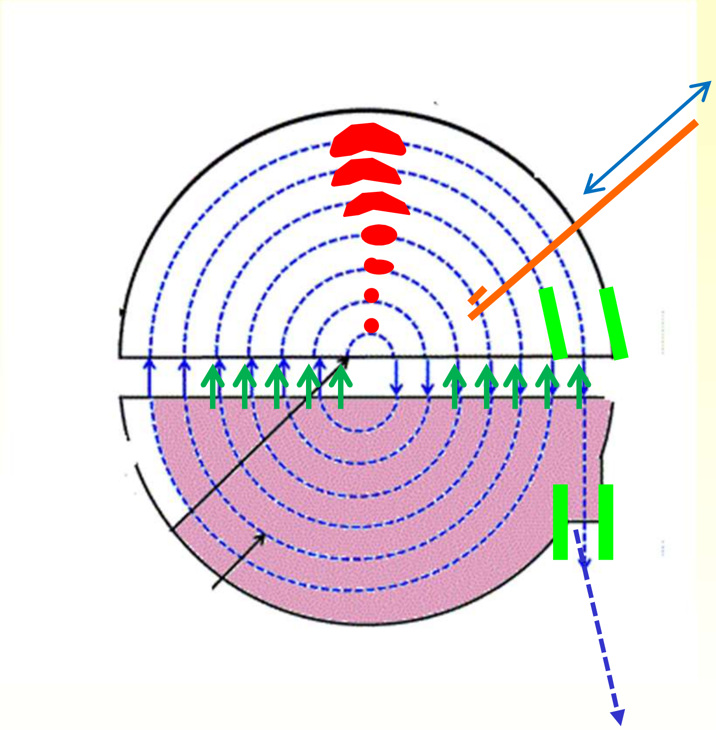
Isochronism &
Phase measurement

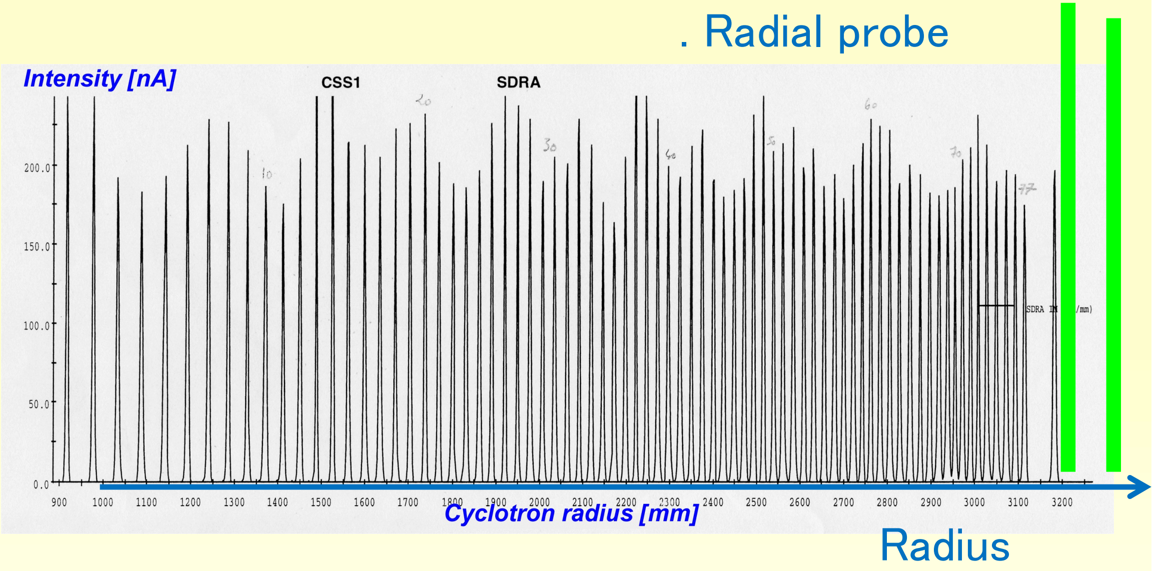
Measuring B(R) or n(R) is difficult , While the Φ (R) is more sensitive



Radial probes
useful tool for acceleration, precession study

Monitoring turns
With a mobil Radial Probe





Radial probe : Intensity = F(Radius)

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

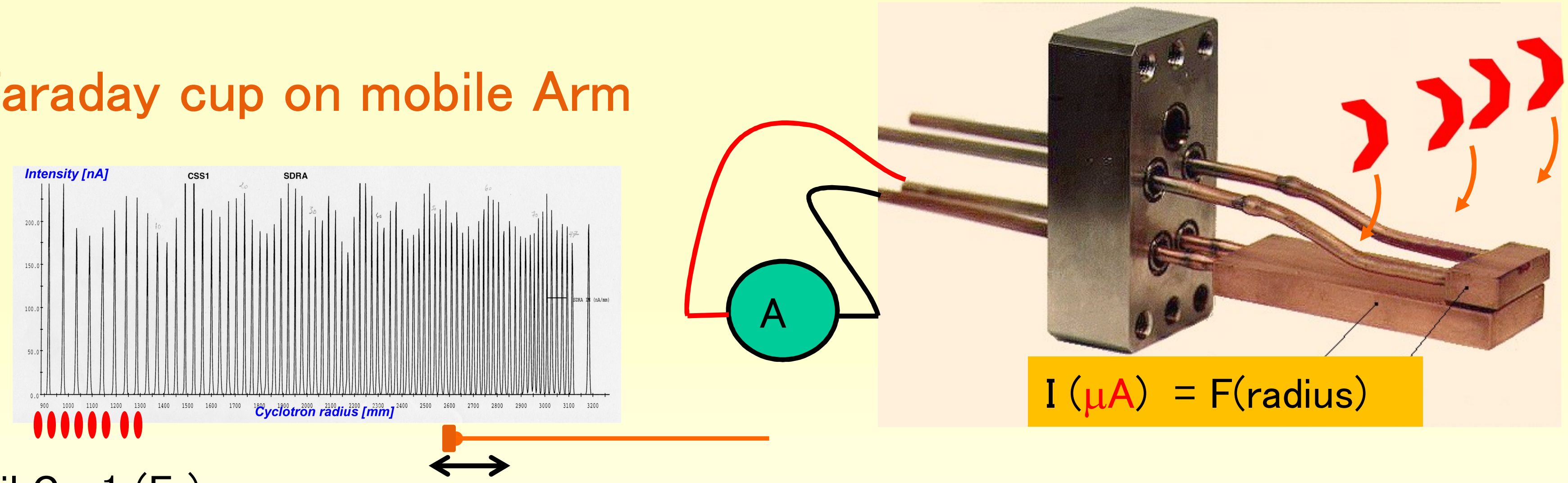
δr = Acceleration + Oscillation

$\delta r \sim \alpha$ VRF cos (ϕ) + Oscillation

Current measurement I_{beam}=F(R) : Radial probe

A Faraday cup on mobile Arm

I (μA)



I (μA) = F(radius)

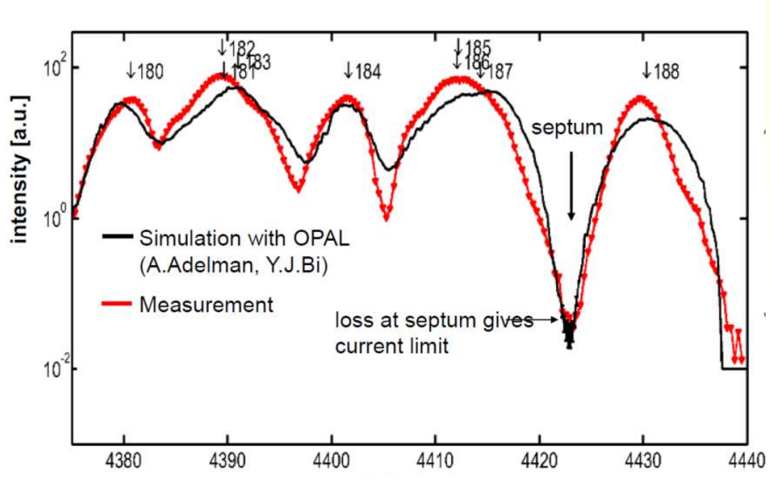
Radius

Ganil Css1 (Fr)
Kb=380 MeV , heavy ions

Check of the acceleration & extraction

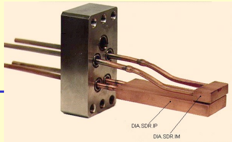
PSI
Kb=590 MeV

Check of the extraction



Radius

Tune Q_r measurement with radial probes



Turn separation δr gives **Qr** : $r(t) = \langle R(t) \rangle + X_0 \cos(\mathbf{Q_r}\, \omega\, t)$

$\omega . t = \text{phase} = \theta$

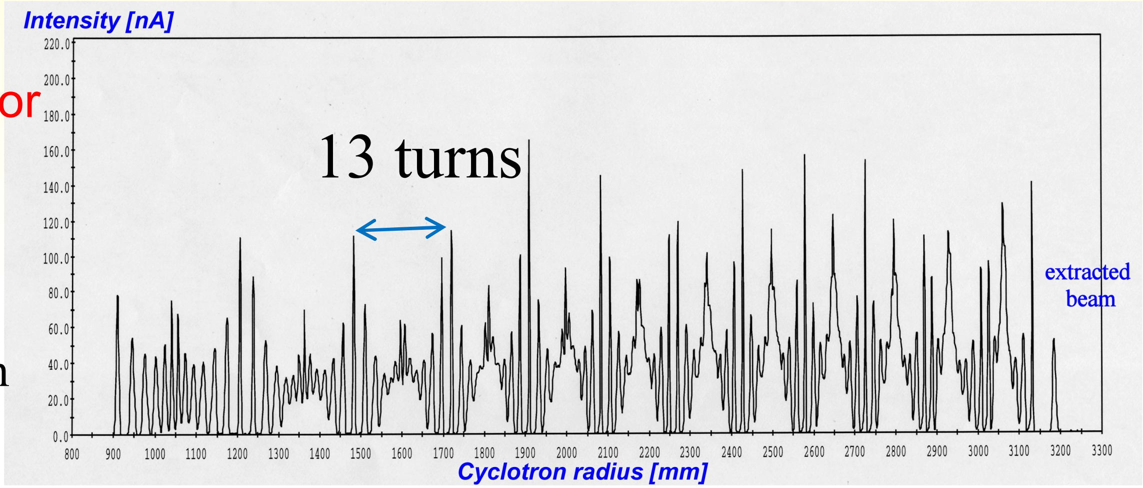
$\omega . \Delta t = 360° = 1 \text{ turn}$

<u>Precession</u> : $\delta r = \delta r_{\text{acceleration}} + X_0 \cos(Q_r\, \omega\, t)$

Centering error
At injection

Large X_0

Large Oscillation



1 period for

13 turns

$\mathbf{Q_r = 1 + 1/13}$

Back to dynamics
and resonances at high energy

During the acceleration, Q_r and Q_z change because $Q_{,z} \propto \gamma\ (R)$

The plot of Q_r vs Q_Z is called the **working point diagram.**

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

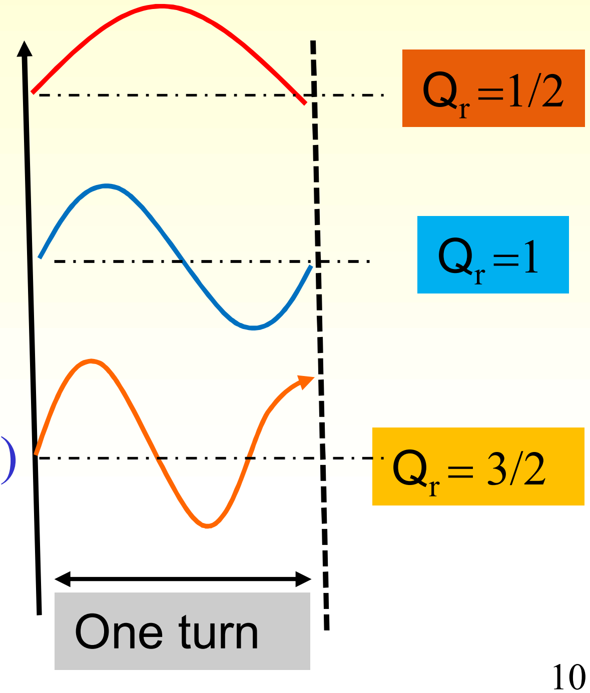
$$\frac{d^2x}{dt^2} + \omega^2 {Q_r}^2\, x = 0$$

Several kind of radial resonances

$x(t) = x_0 \cos(Q_r \omega t) = x_0 \cos(Q_r\ 2\pi\ \mathrm{Nturn})$

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

with field bump, injection angle (desired)



Resonances: What happens with P field perturbations on 1 turn ?

$$\left[\frac{d^2z}{dt^2} + \omega^2 {Q_r}^2\, z\right] = A\cos(P\theta)$$

Search a particular solution ⇒ Z(t) = cos(P ω t)

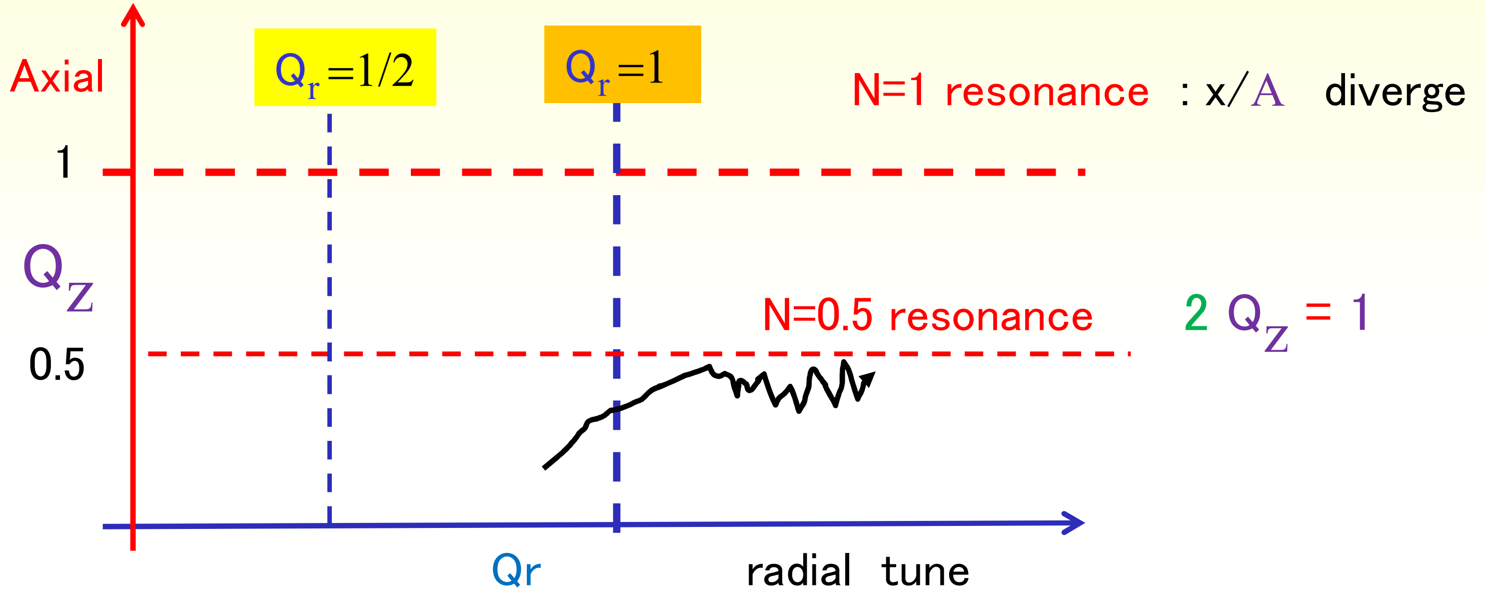
$$\frac{Z(t)}{A} = \frac{A\cos(P\omega t\,)}{[\,Q_r\omega]^2 - [P\omega]^2}$$

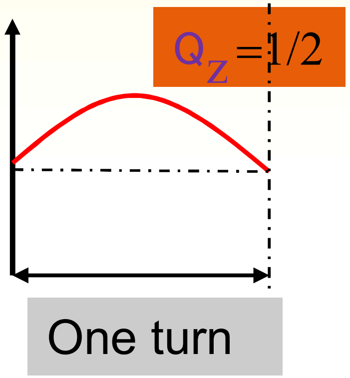
Z(t)/A diverge at Qz=P (integer)

z(t) is very sensitive to any perturbation A

(not good : large oscillation = beam losses)

The cyclotrons try to avoid resonance crossing





Resonances on cyclotron and synchrotron

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

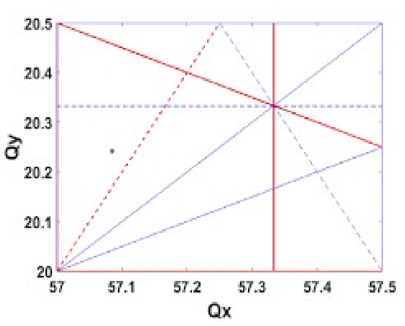
$$(K.\,Q_r = P) \qquad // \qquad (L.\,Q_z = P)$$

Coupling resonances: the 2 oscillations (vertical and horizontal) can be coupled and the energy stored in one motion, transferred to the other. These are **coupling resonances** ($K.\nu_r + L.\nu_z = P$).

$$K.\,Q_r + L.\,Q_z = P$$

K, L and P integer

The accelerator working point curve should avoid to those lines



We must tune the machine such as $K.\,Q_r + L.\,Q_z \neq P$

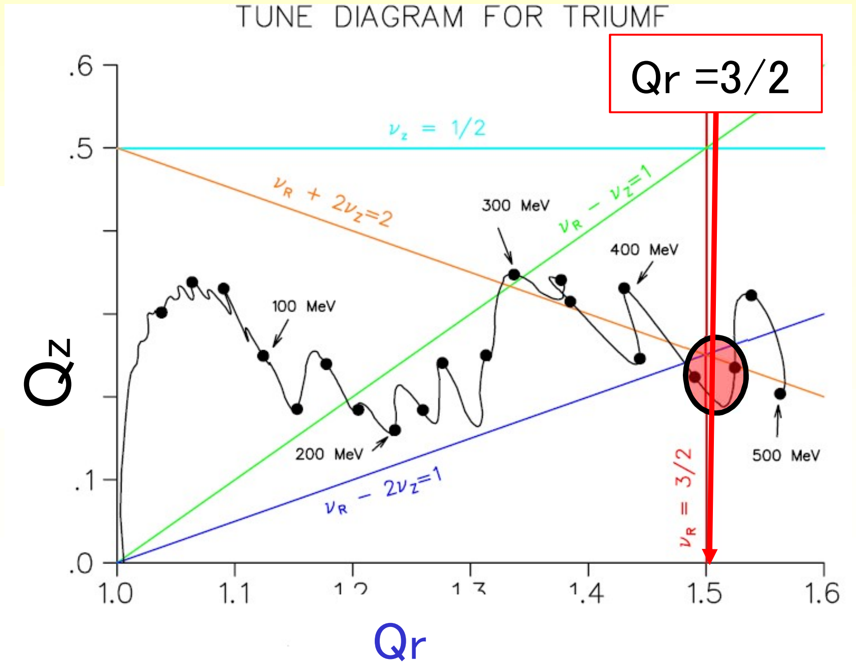
Tunes and resonances on a cyclotron at Triumf (Canada)

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

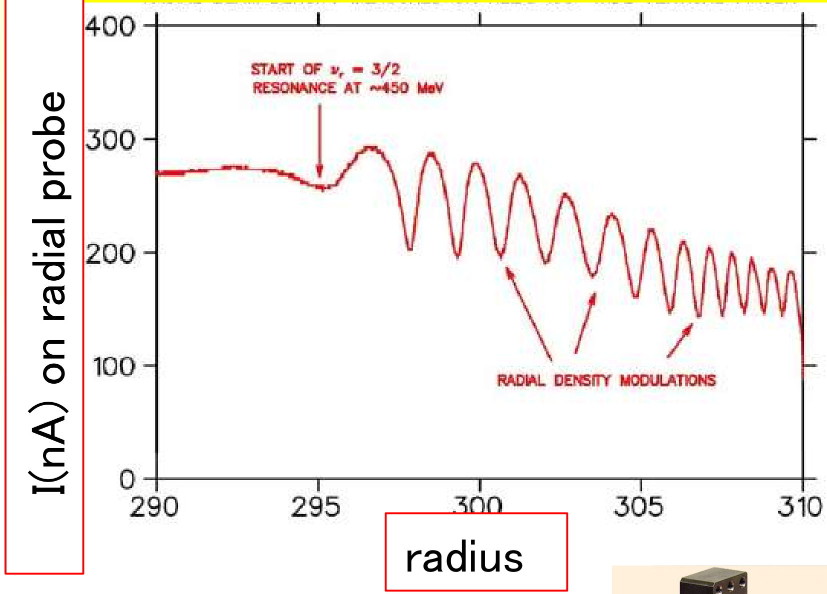
$$K.\,Q_r + L.\,Q_z = P$$

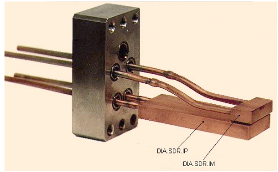
$|K| + |L|$ is called the resonance order (1, 2, 3 …)

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



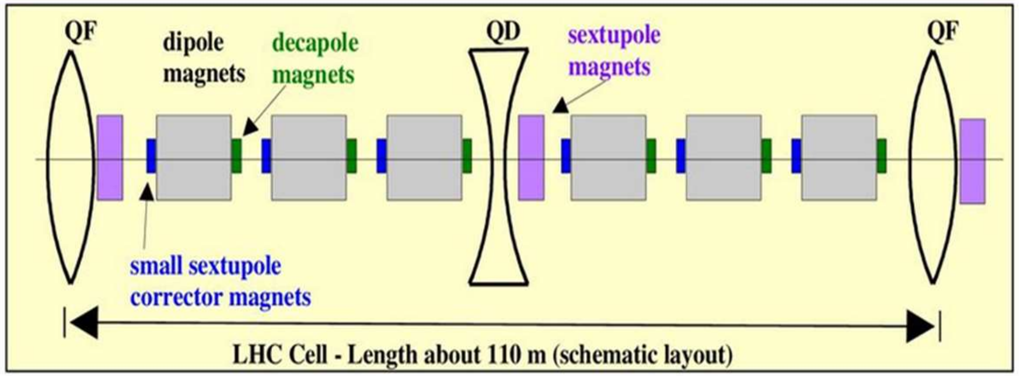
Radial Oscillations : $2.Q_r = 3$

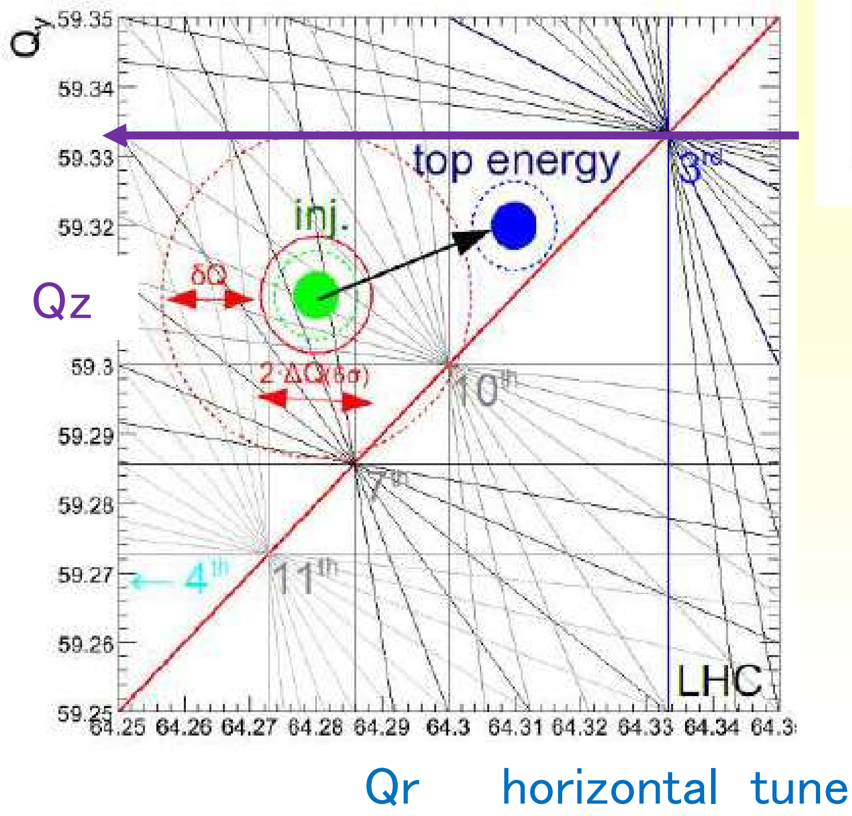




$$Q_r^{\,2} = 1 - n + \cdots = 1 - (1 - \gamma^2) + \cdots \sim \gamma^2 + \cdots$$

Resonances on Synchrotron : LHC example





The accelerator working point curve should avoid to those lines :

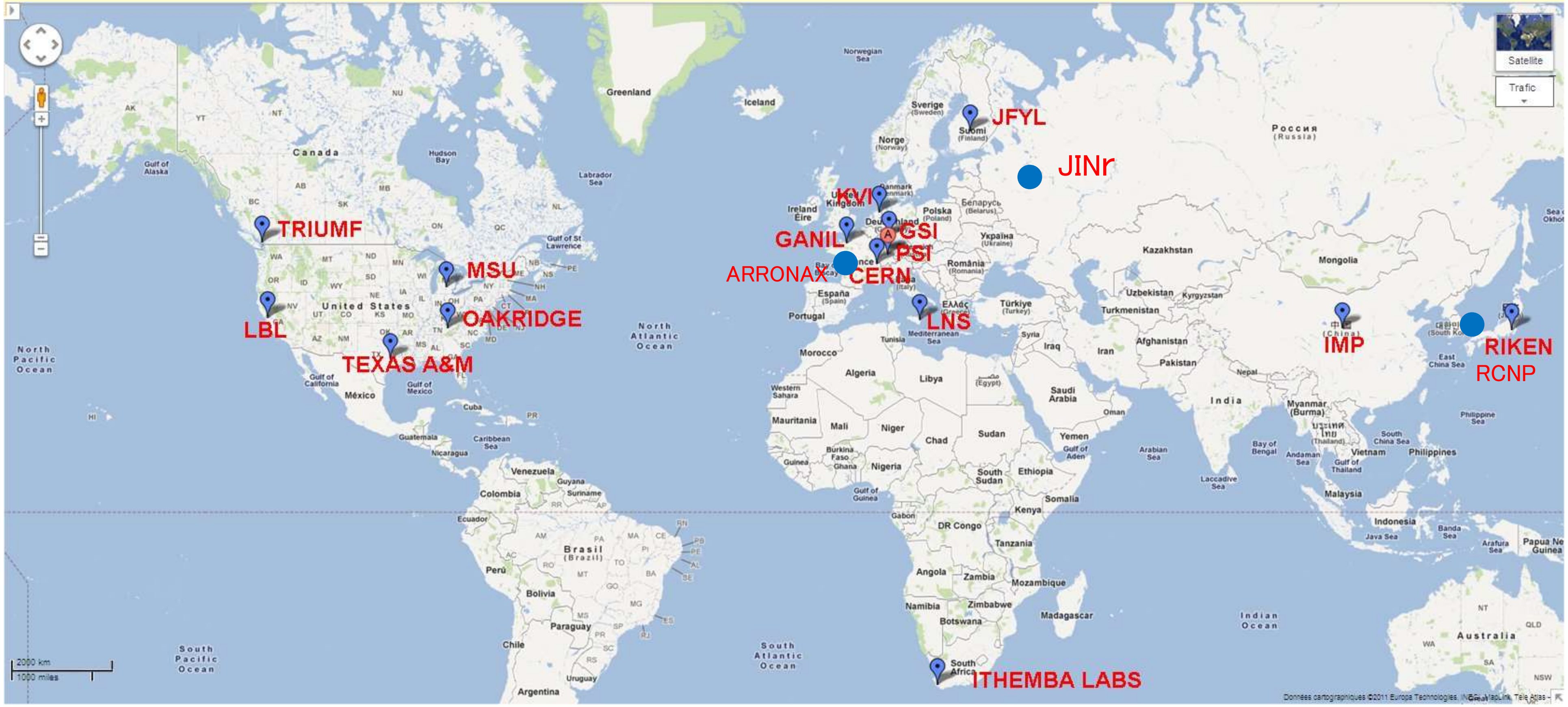
Tune the quad such as $K . Q_r + L . Q_z \neq P$

$Q_r \neq 64$ $Q_z \neq 59$

$Q_z \neq 59.33 = (3x59+1) / 3$

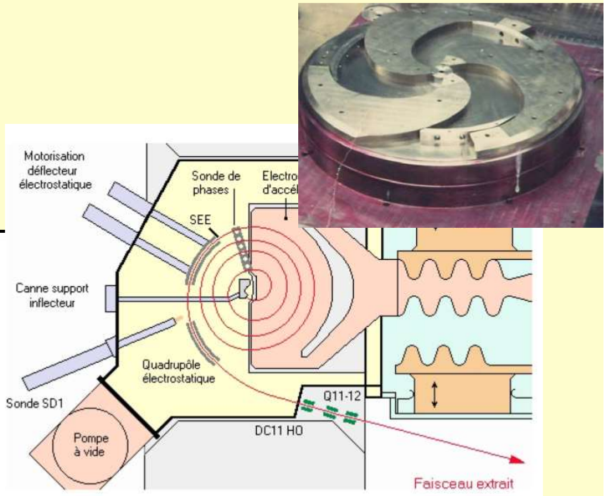
Cyclotrons in the world

Some research laboratories with Cyclotron(s)

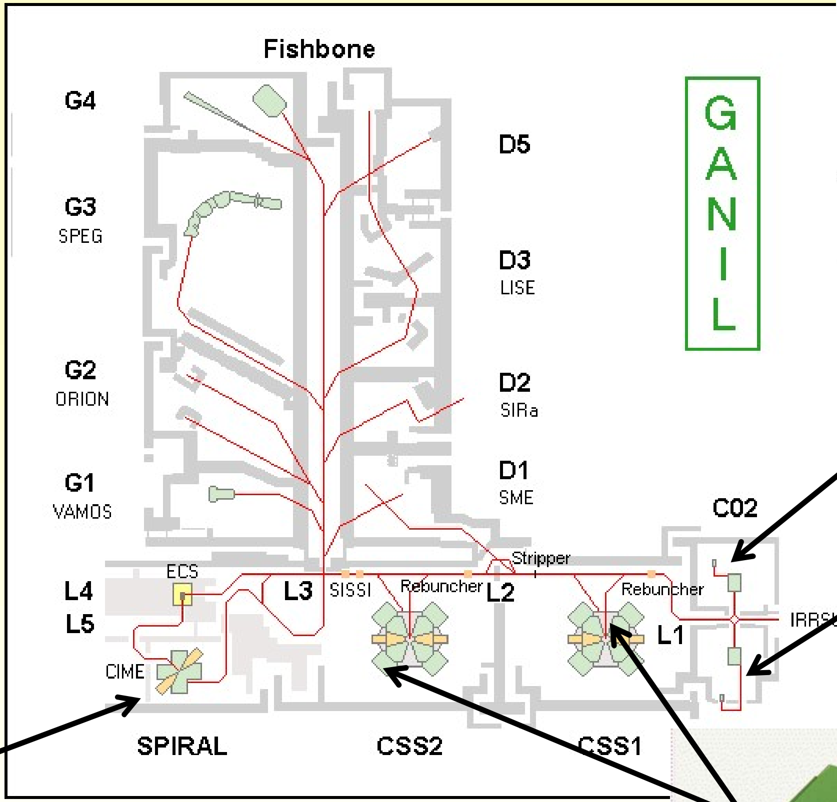


Some of the Research Facility in the world using cyclotrons

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

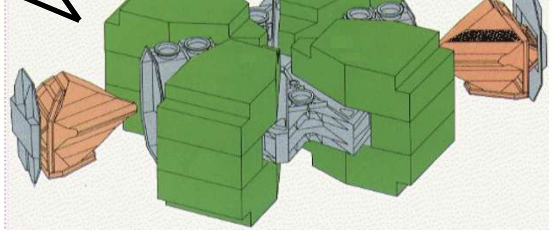


- –Nuclear physics
- –Atomic physics
- –Solid state
- –Radiobiology
- – Irradiation for industry



2 compact cyclotrons
Kb=28 MeV

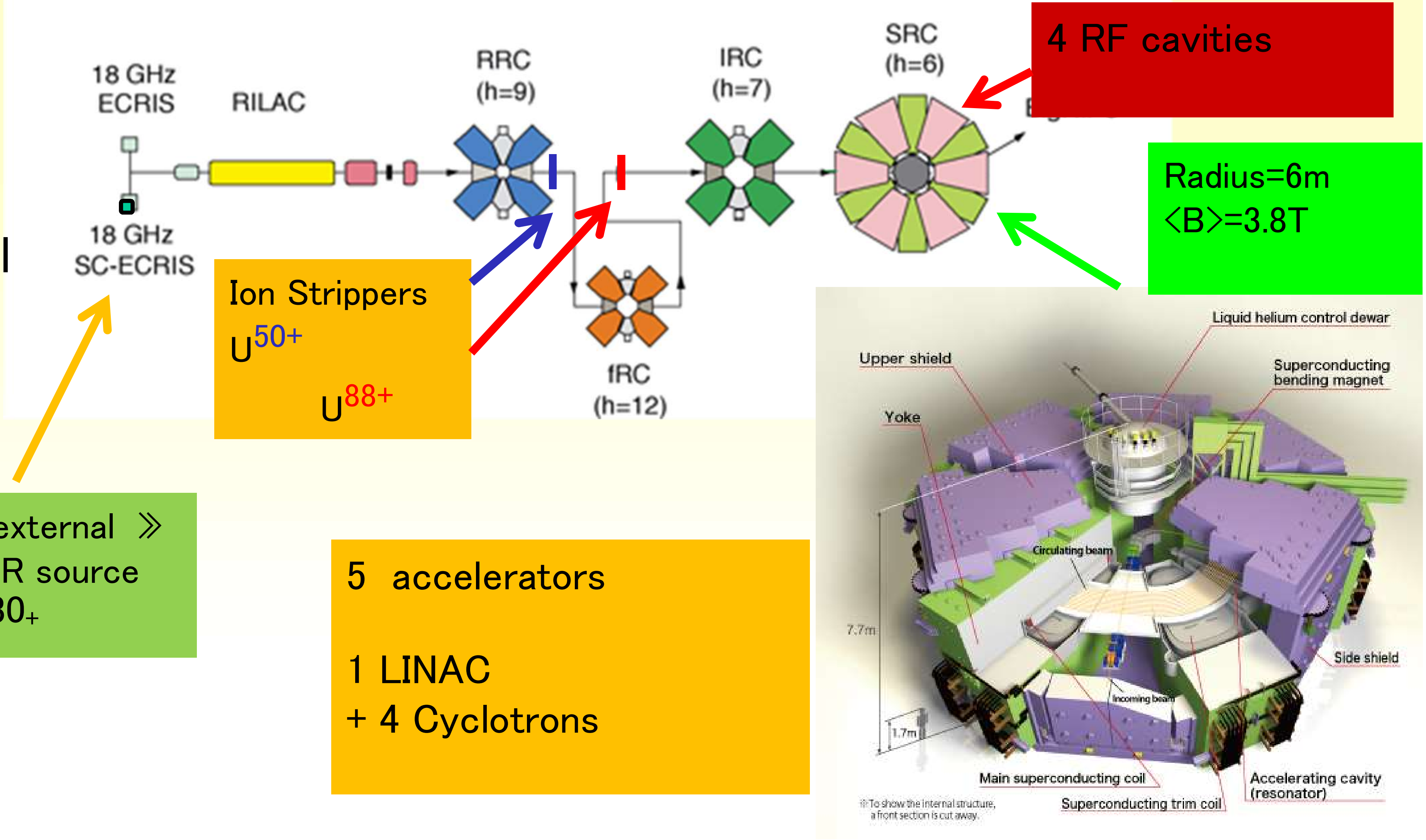
1 compact cyclo Kb =265
For radioactive ions



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

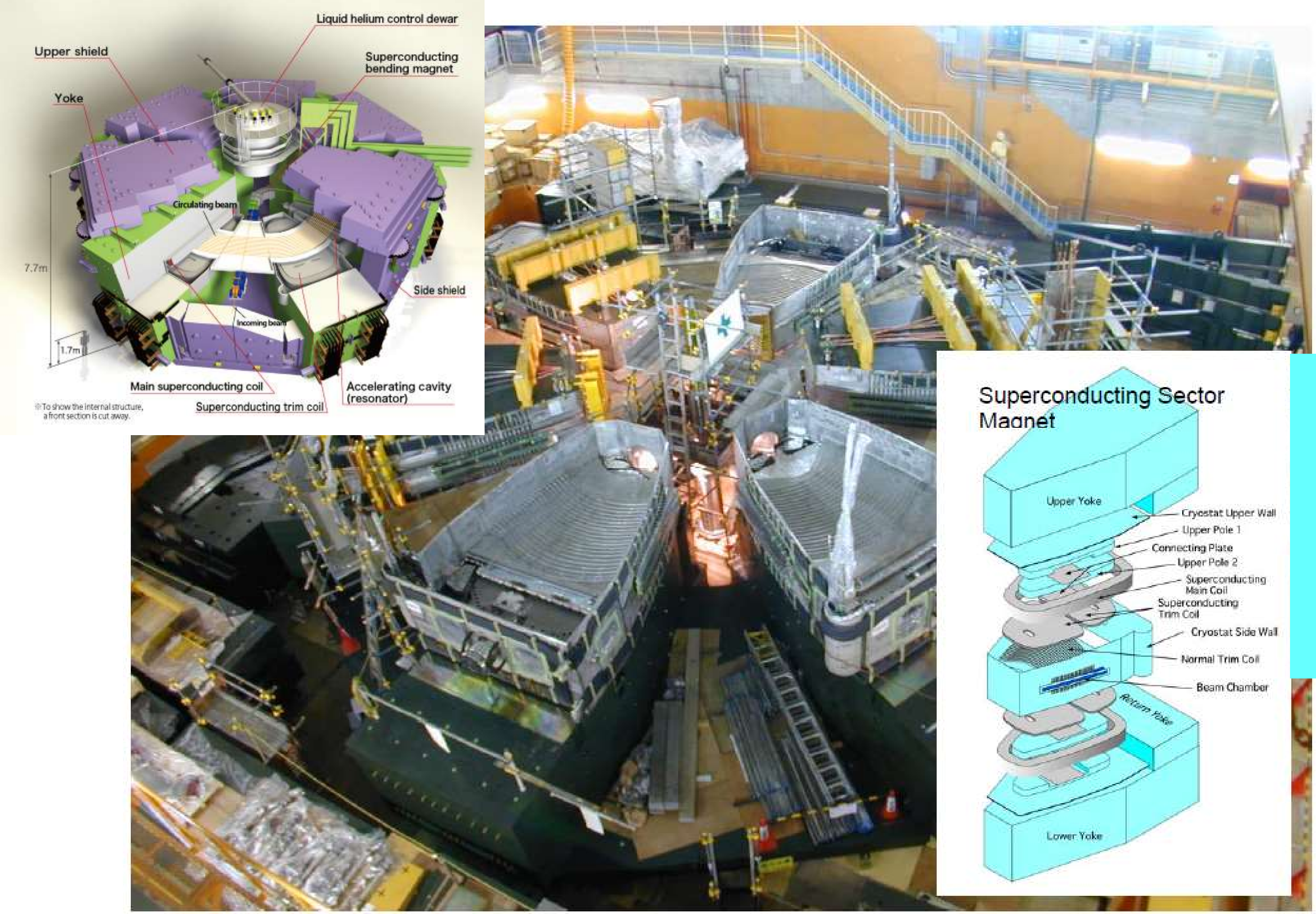
Ion Strippers
U^{50+}
U^{88+}

《 external 》
ECR source
U^{30+}

5 accelerators

1 LINAC
+ 4 Cyclotrons

RIBF (Japan) : SRC (K_b=2600 MeV)
the strongest cyclotron in the world
Superconducting Ring Cyclo

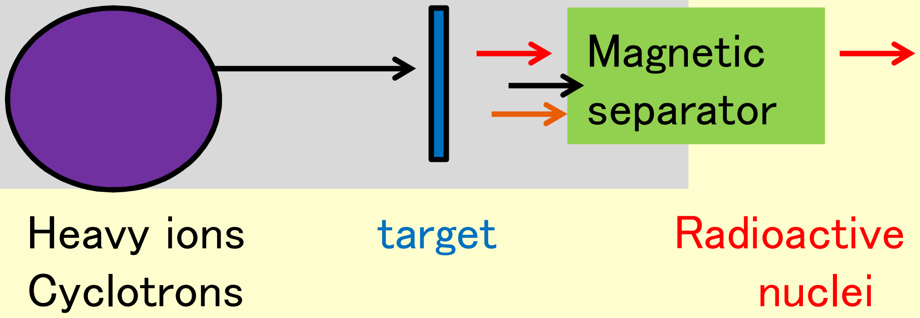


6 sectors :
≪ Iron dominated magnets ≫
With superconducting coils

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

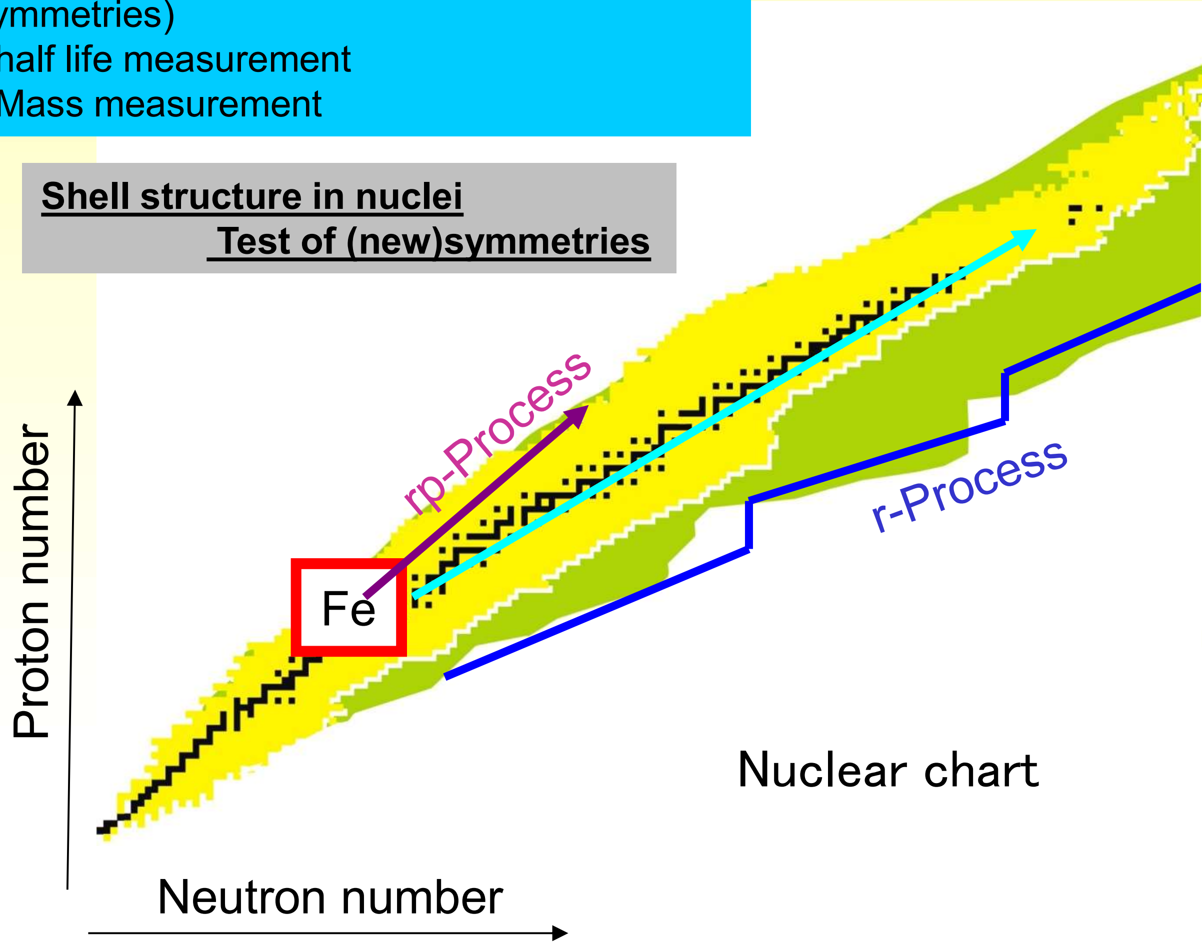
TREND in Nuclear physics : Physics at RIBF (Tokyo)

Create Unknown “exotic” nuclei
by nuclear fragmentation
or by fission

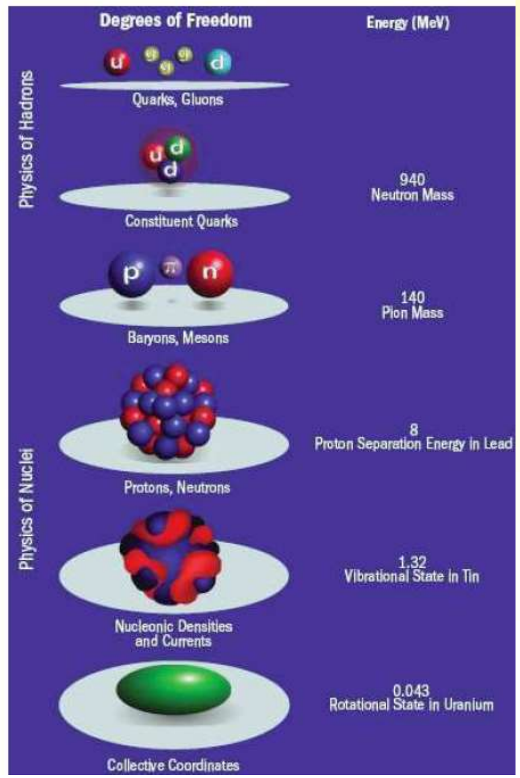


Exotic Nuclei (Very large proton-neutron asymmetries)
- half life measurement
- Mass measurement

Shell structure in nuclei
Test of (new)symmetries



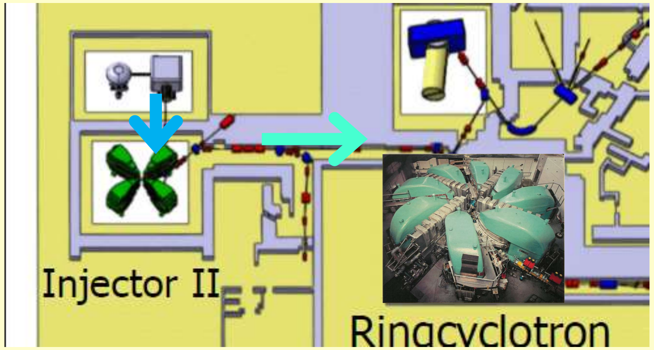
Nuclear chart



PSI 590Mev proton (Villigen,Ch)

870 keV

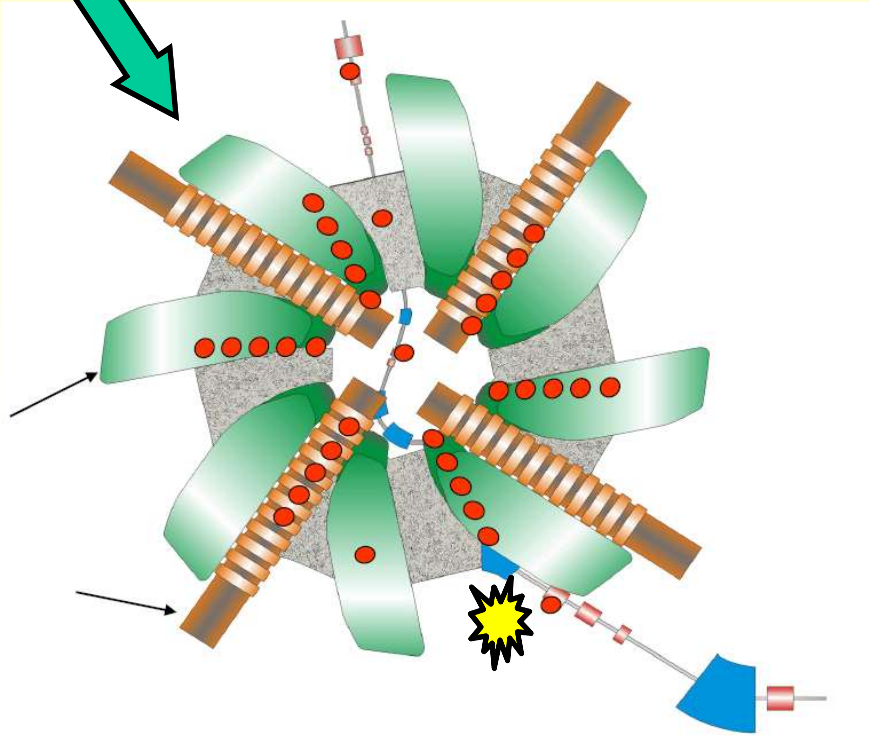
Cokcroft-Walton



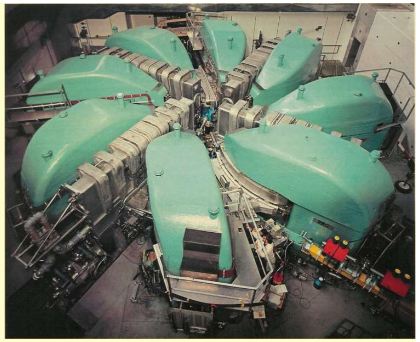
kb=72 MeV (injector 2)

Coupling of 2 cyclotrons

590 MeV Ring cyclotron

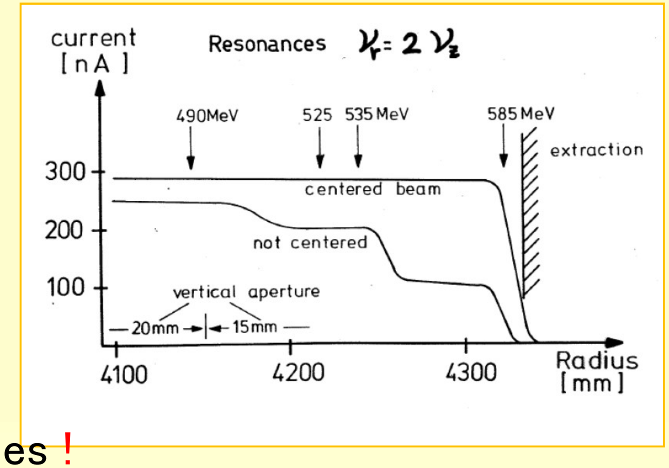


PSI :K= 590 MeV ring cyclotron P_{beam}= 1.4 Mwatt



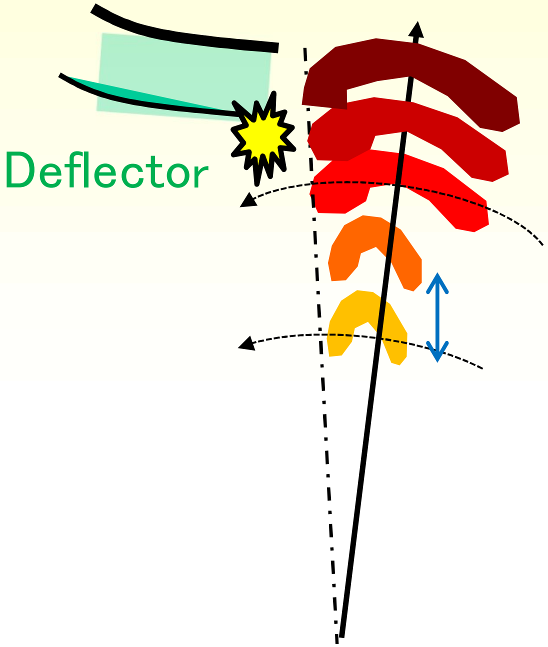
1) Injection centering :

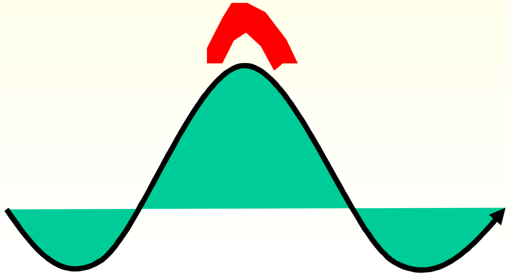
Watch the resonance $2.Q_z + Q_r = 2$



2) Extraction: Watch the beam losses !

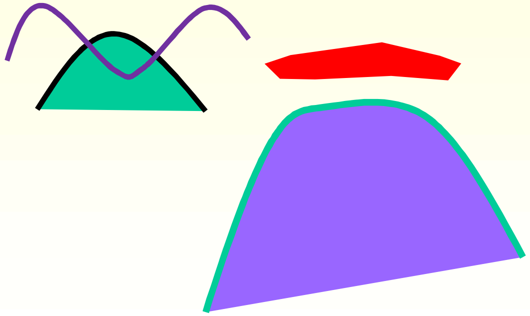
A Flat top RF cavity has been added to reduce losses: V_{RF}= Cos(ωt) – α.cos (3ωt)





Standard cavity :

V_{RF}= cos(ω_{RF} t)



Flat top cavity

cos(ω_{RF} t) – cos (3ωt)

Some Commercial Cyclotrons : manufacturers

IBA (Belgium)

				Cost estimate 2010
Cyclone	5/10	proton/D		1 Meuros
Cyclone	9/18	H-/D-		1.5 Meuros
Cyclone	30	H-/D-		….
S2C2	230 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

>1300 commercial cyclotrons in the World (2021)

- (10-20MeV) protons
- (230MeV) protons : develloping market

Commercial Cyclotron

Radioisotope production (5-20 MeV)

Radiotracer $^{18}F^*$: 《 Beta+ 》 emitter

Fluorine 18

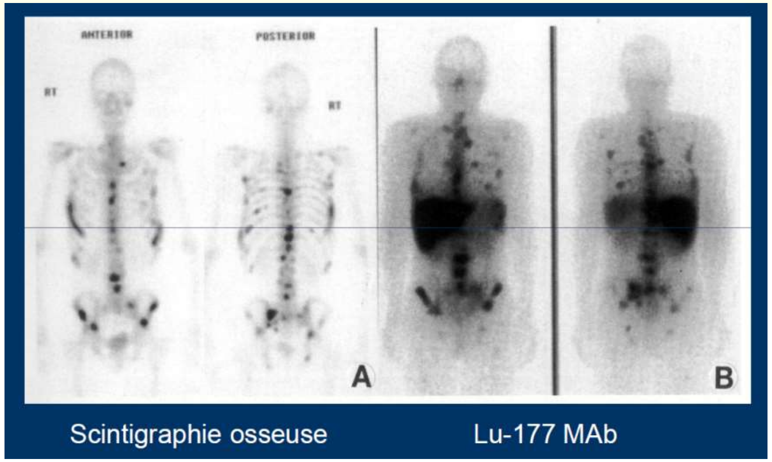
$T_{1/2}$ =109.7 min

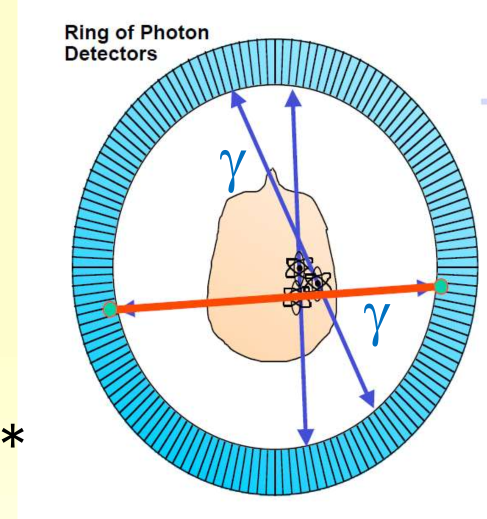
$^{18}F^* \Rightarrow {}^{18}O$ + positon + neutrino

↳ $\gamma + \gamma$

Production With cyclotrons

Proton 10–20MeV + $^{18}O \Rightarrow {}^{18}F^* + n$

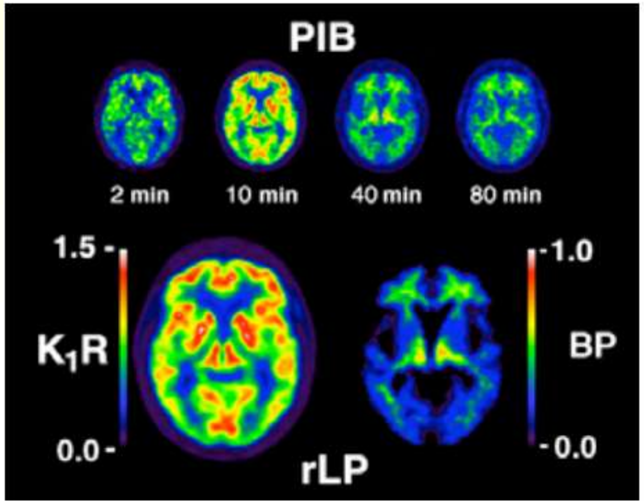




Injection of $^{18}F^*$

TEP camera

Reconstruction of the emitter position

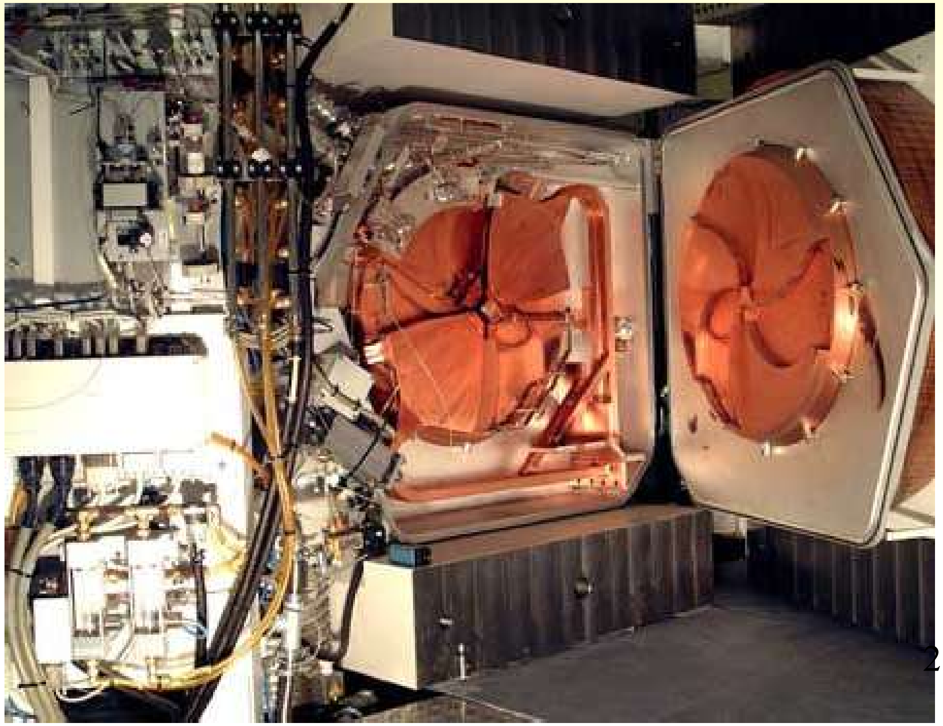


Cyclone 10/5 MeV (IBA)

= 10 MeV proton （Kb=10MeV）

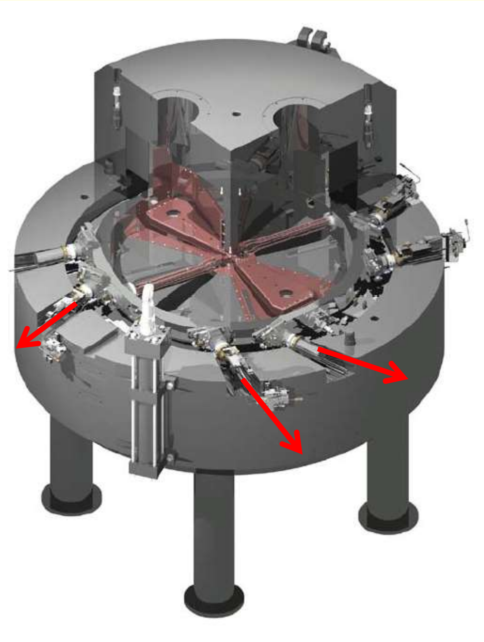
= 5 MeV Deuteron

cyclone 3D (“vertical implantation”)



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

Designed for medical applications (radiotracers production)



Internal PIG source, H$^-$ stripping extraction

Kb=18 MeV

Fixed energy ;

4 straight sector 50°

<B> =1.35 Tesla

Hill //valley gap 3cm// 67cm

fixed Frf =42Mhz

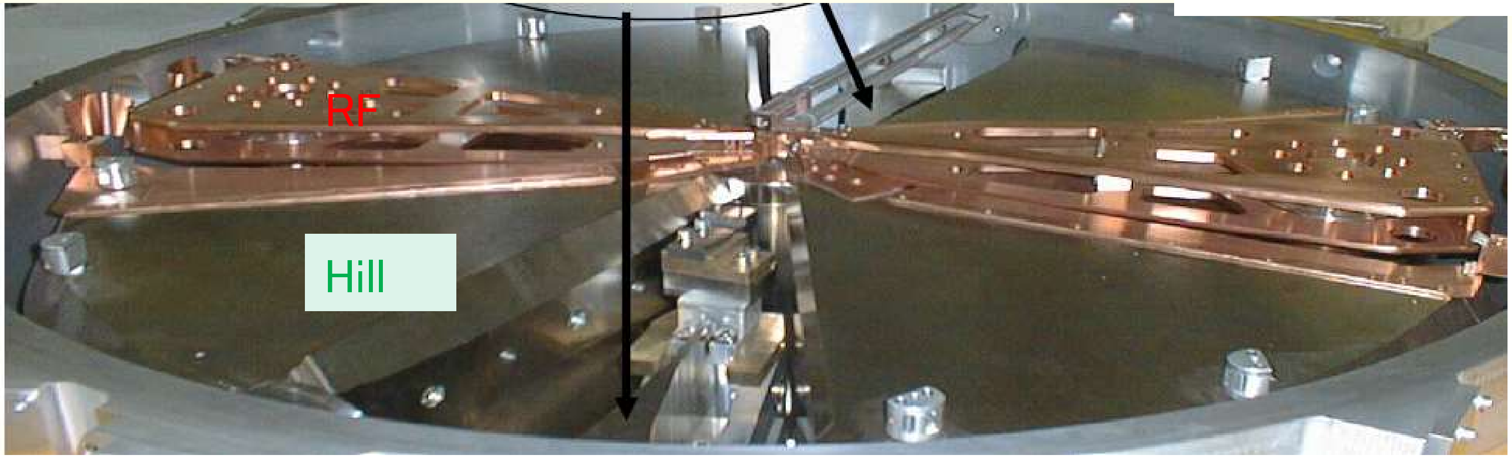
2 Dee = 30° , 32 kV

Harmonic h=2(p) ,4 (D)

Internal source

Rextraction=0.46 m

Bρmax=0.46x 1.35=0.62 T.m



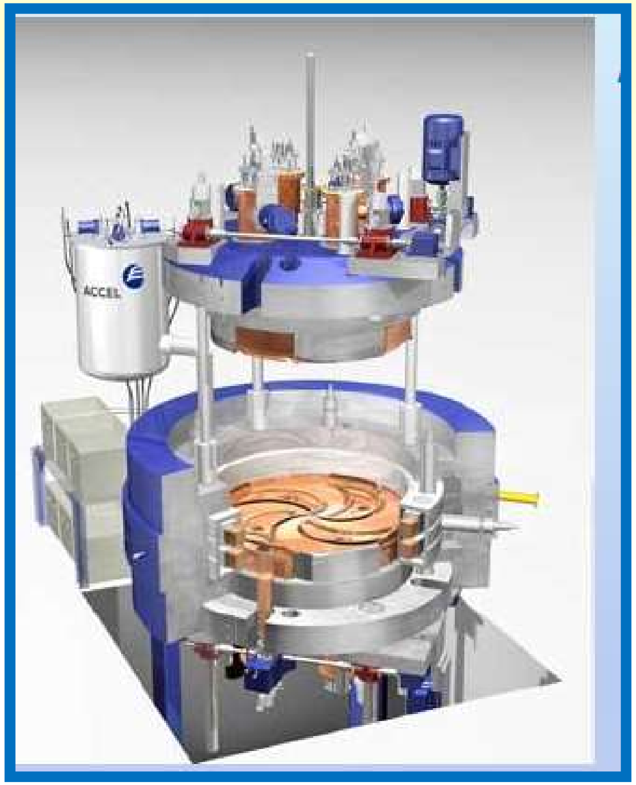
Commercial Cyclotron:
proton therapy (230-250 MeV)

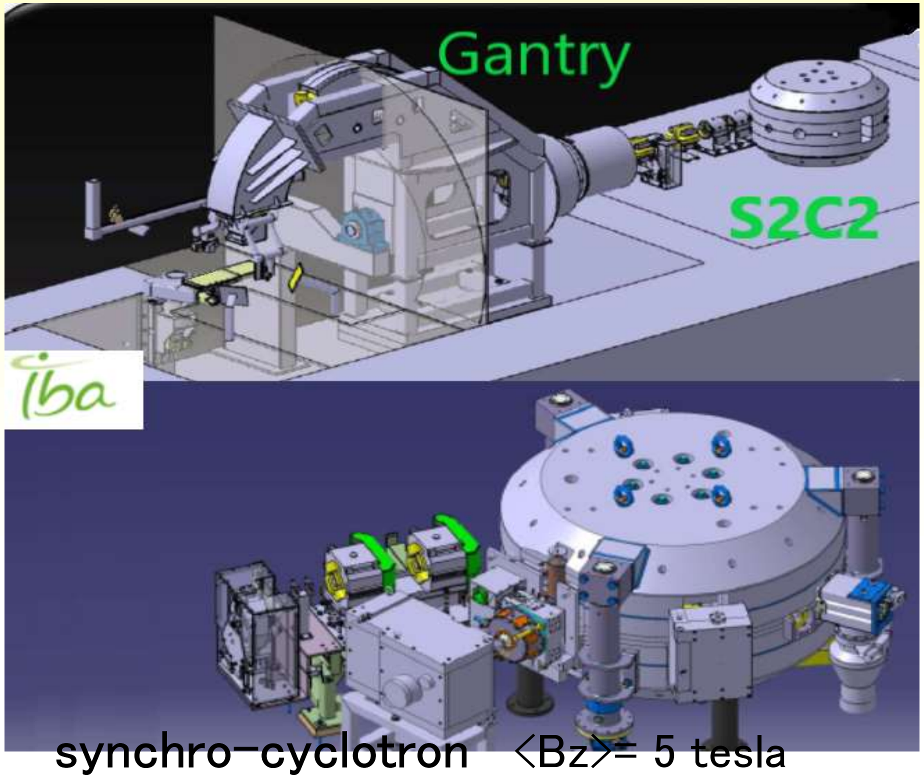
2 technologies in competition :

a) **AVF Isochronous cyclotron** (superconducting : <B> up 2 Tesla

a) **Synchro-cyclotron** <Bz> up to 5 tesla (R=50cm)

Machine cost ~ infrastructure size

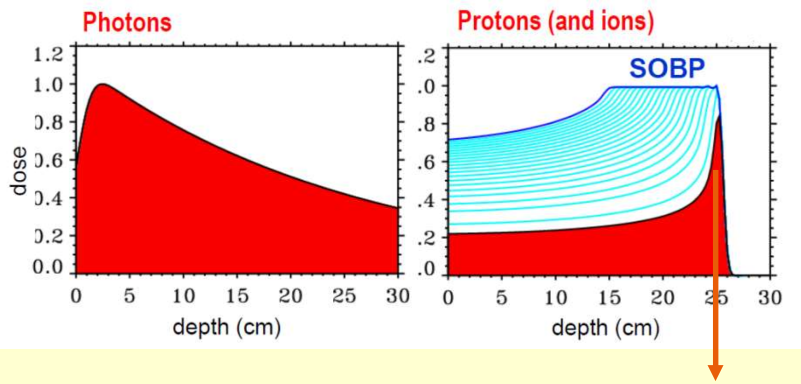




synchro-cyclotron <Bz>= 5 tesla

Commercial Cyclotron :
For proton therapy (230 MeV)

Photon :
(Radiotherapy X)
A Dose in the
whole body

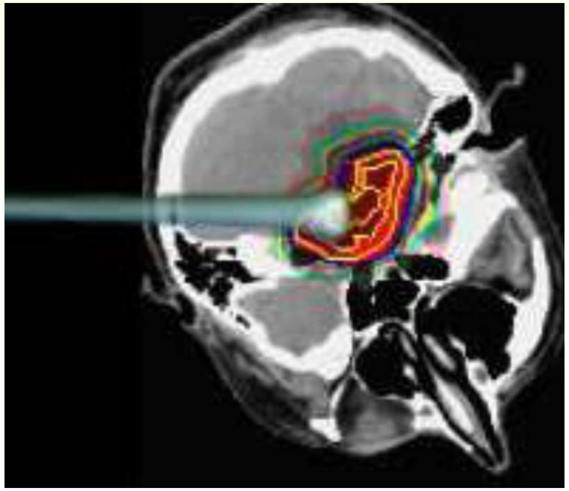


Protons :
Better than
Radiotherapy (photons)

Dose inside the tumor

Bragg Peak

Brain tumor treatment with protons

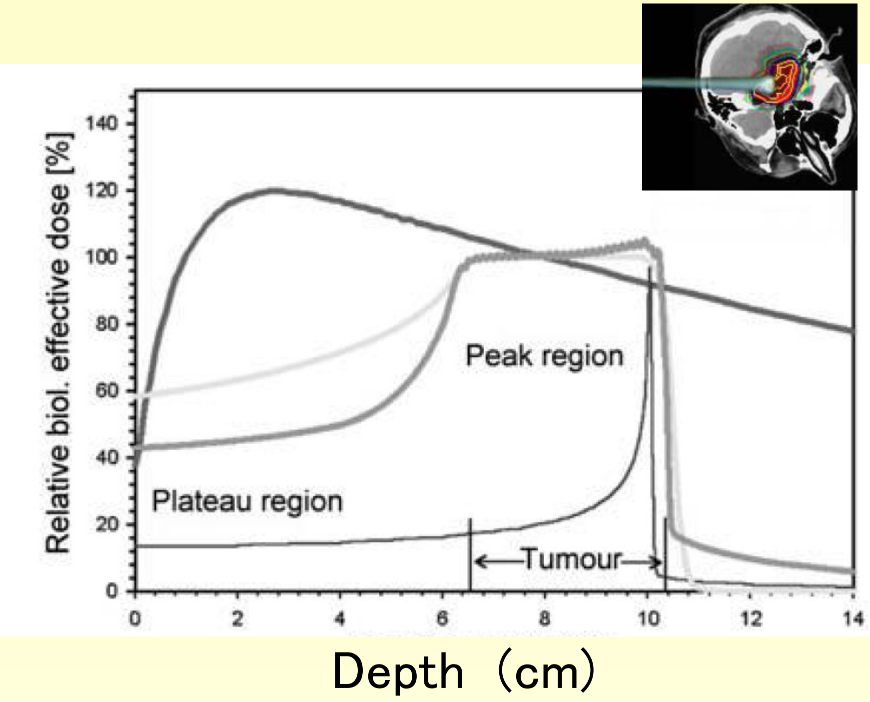


Eyes tumor treatment

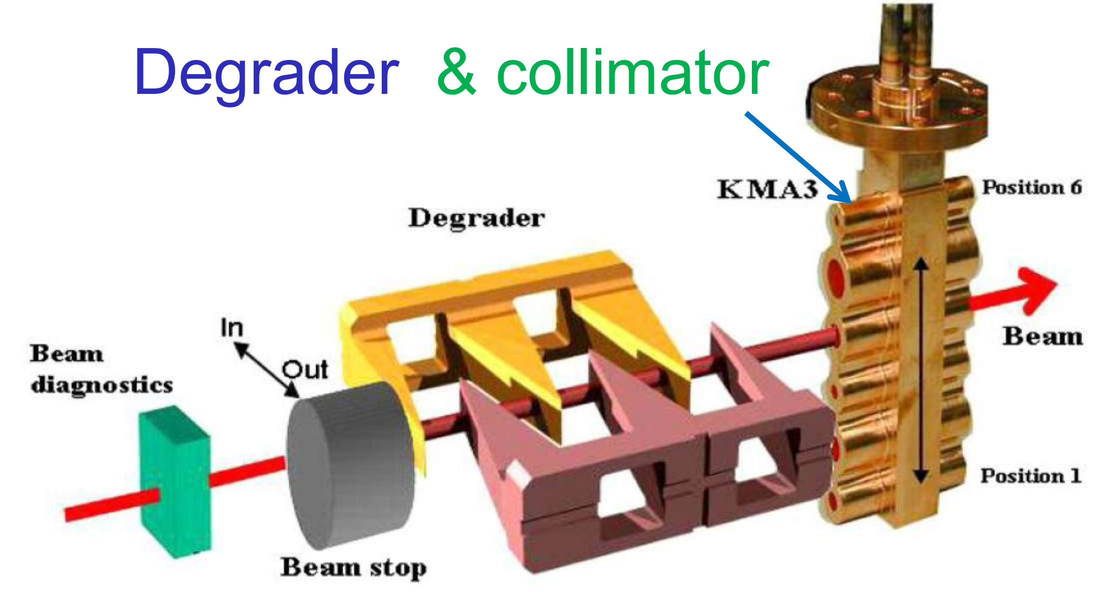
Proton therapy (230 MeV)
-Energy variation with degrader

Scanning the tumors :

With energy variations induced by a degrader



Degrader & collimator



Energy variation

=

Range variation (tumor scanning)

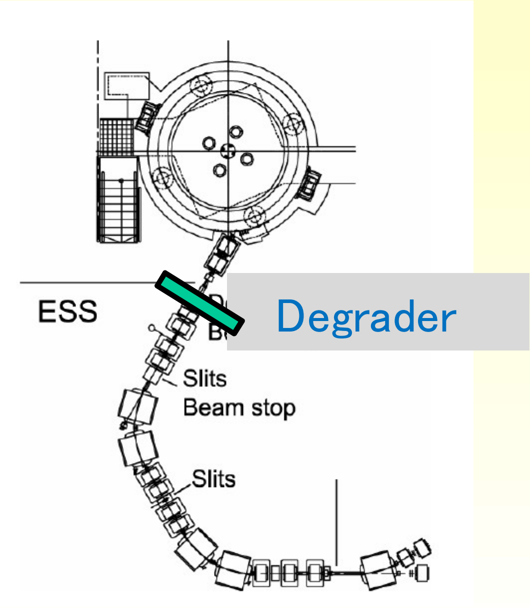
Proton therapy (230 MeV)

Energy variation with degrader

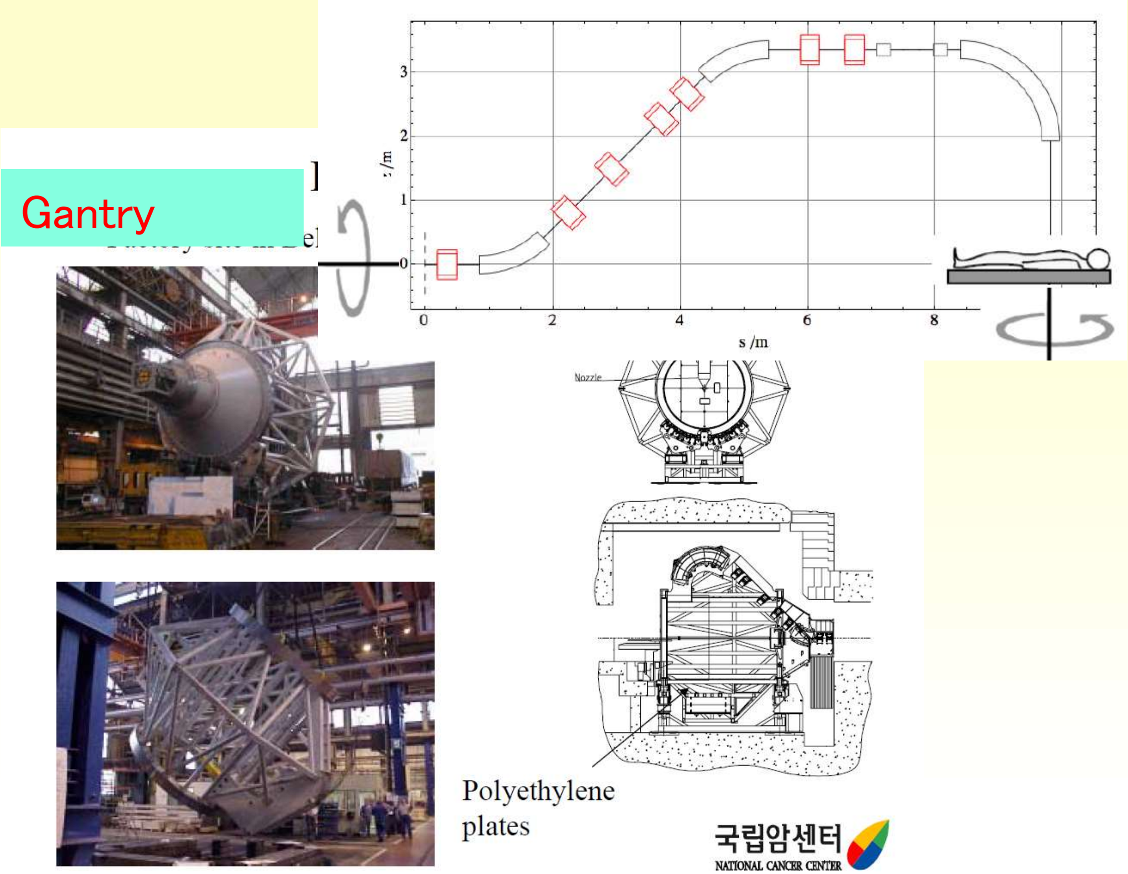
+ Rotating gantry

Optimal dose delivery

Scan the tumors :



Depth variation in patient body: 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

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... & Many others