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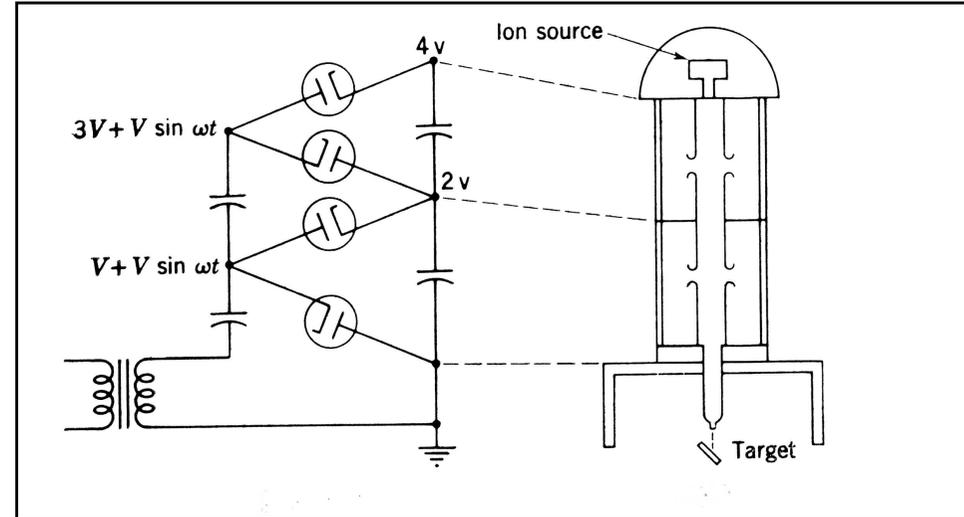
Le Cyclotron, un outil pour la médecine

IPHC 13 septembre 2013

- Généralités sur les cyclotrons
- Aspects importants des cyclotrons
- Différents types de cyclotron
- Avantages des cyclotrons
- Applications médicales
- Cyclotrons utilisés pour la médecine
- Conclusion

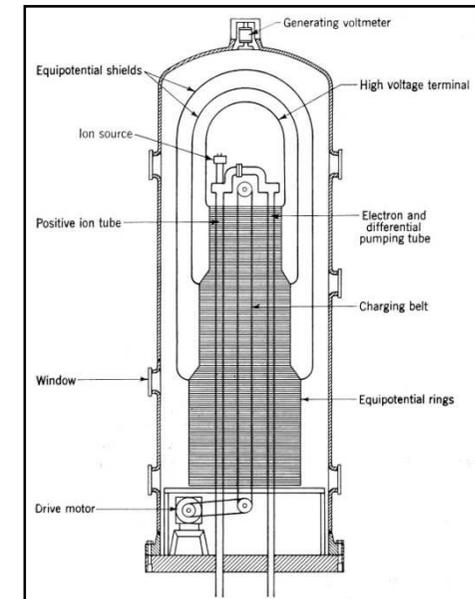
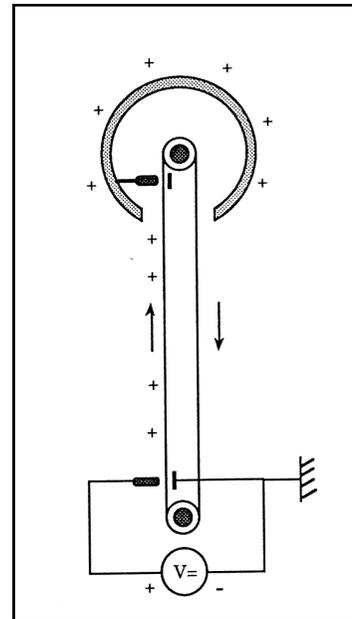


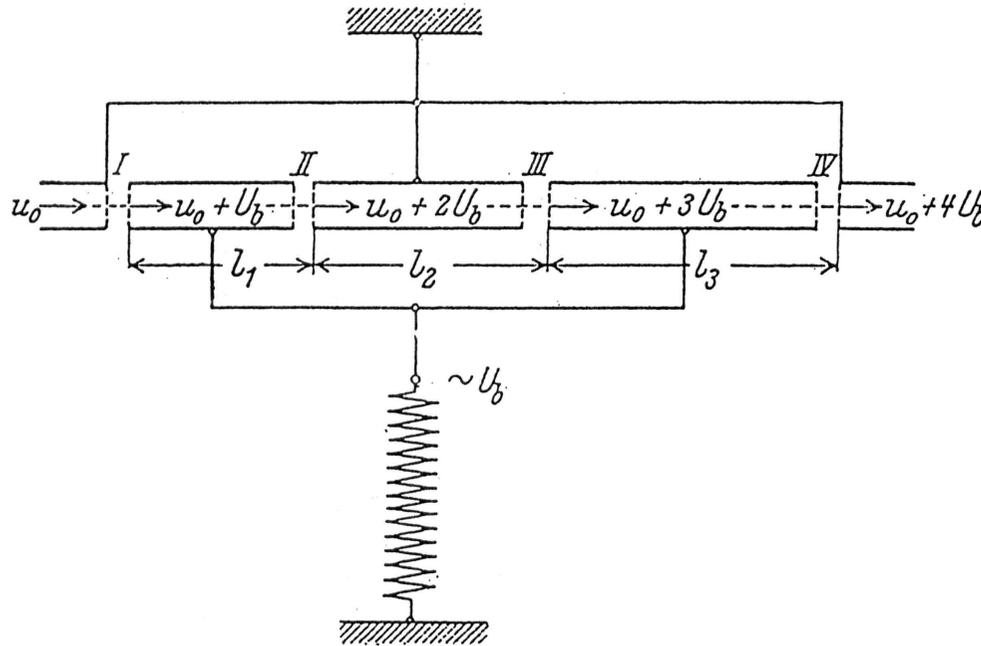
Cockcroft-Walton
(1932)



Robert Van de Graaf
(1930-1932)

**Limitations en énergie
et courant**





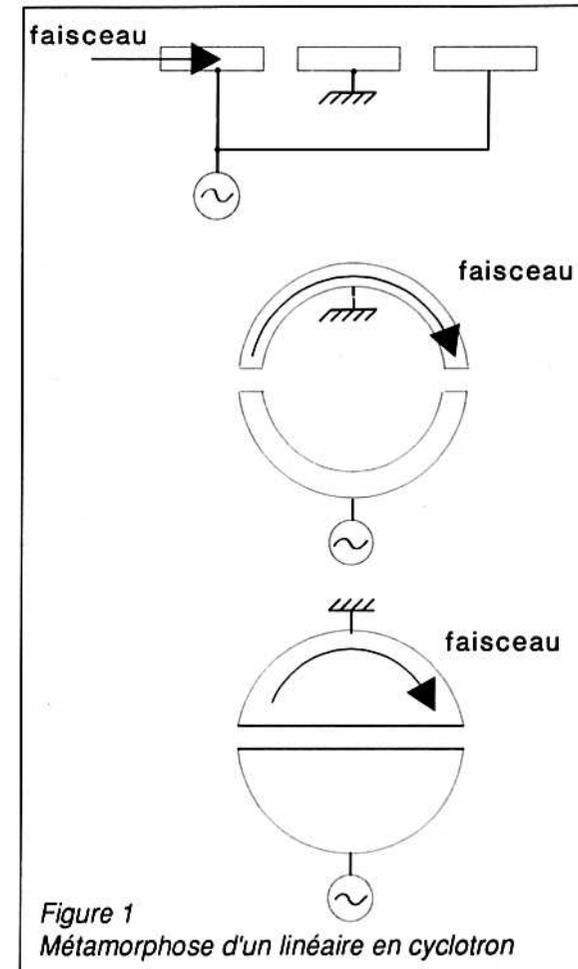
RF utilisée une seule fois: fort courant, grande longueur pour grandes énergies
Différent pour les e-



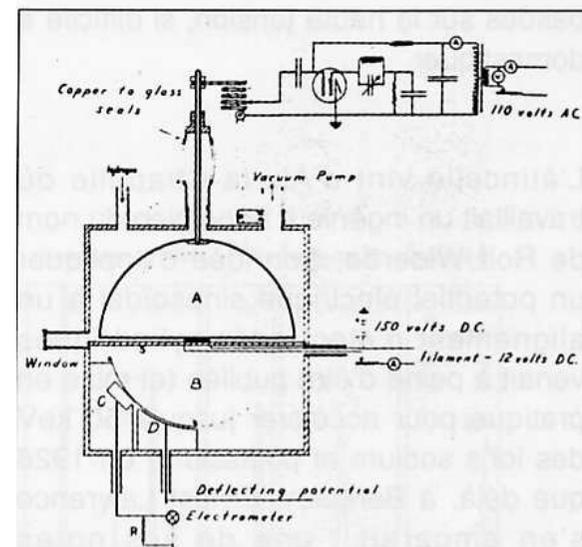
Wideroe 1928

CERN LINAC2 50 MeV p+

- **Idée 1** : limitation de HT
- **Idée 2**: les accélérateurs linéaires tendent vers des longueurs et des puissances dissipées dans les cavités RF irréalistes
- **Idée 3** : courber les trajectoires avec un champ magnétique et une seule cavité RF



Cyclotron de Lawrence (1931)



*Sketch of the first cyclotron.
Diameter of the dee : 5 inches*

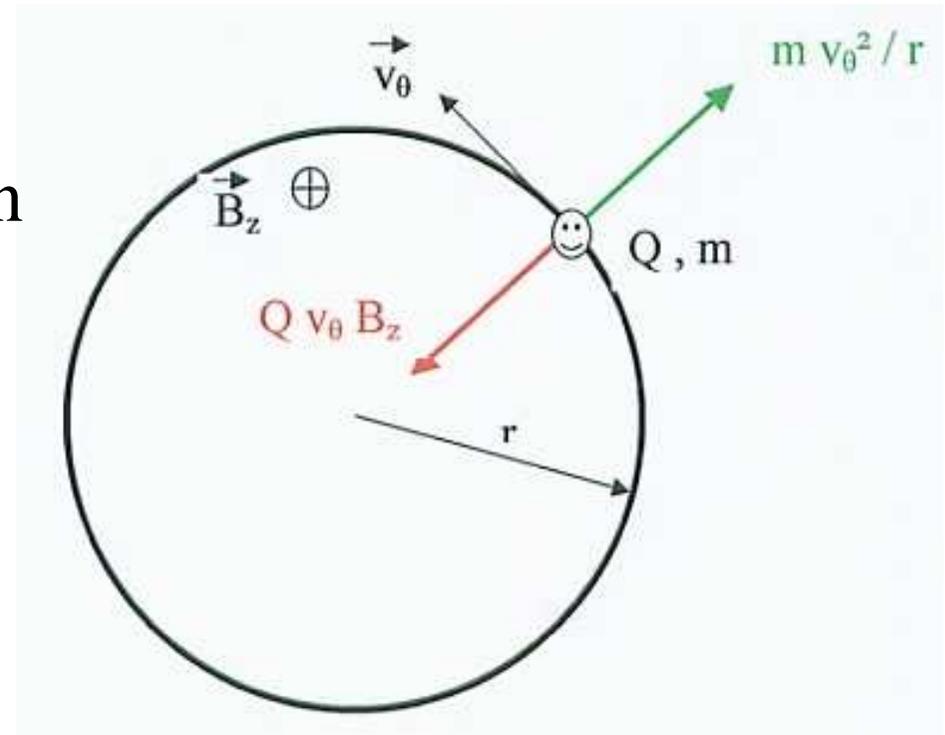
- (Q, m) ion, vitesse v , se déplace sur un cercle de rayon r tel que

$$mv_{\theta}^2/r = Qv_{\theta}B_z$$

- vitesse angulaire:

$$\omega = v_{\theta}/r = QB_z/m$$

$$f_{\text{rev}} = \omega/2\pi$$



Isochronisme : indépendant de l'Energie

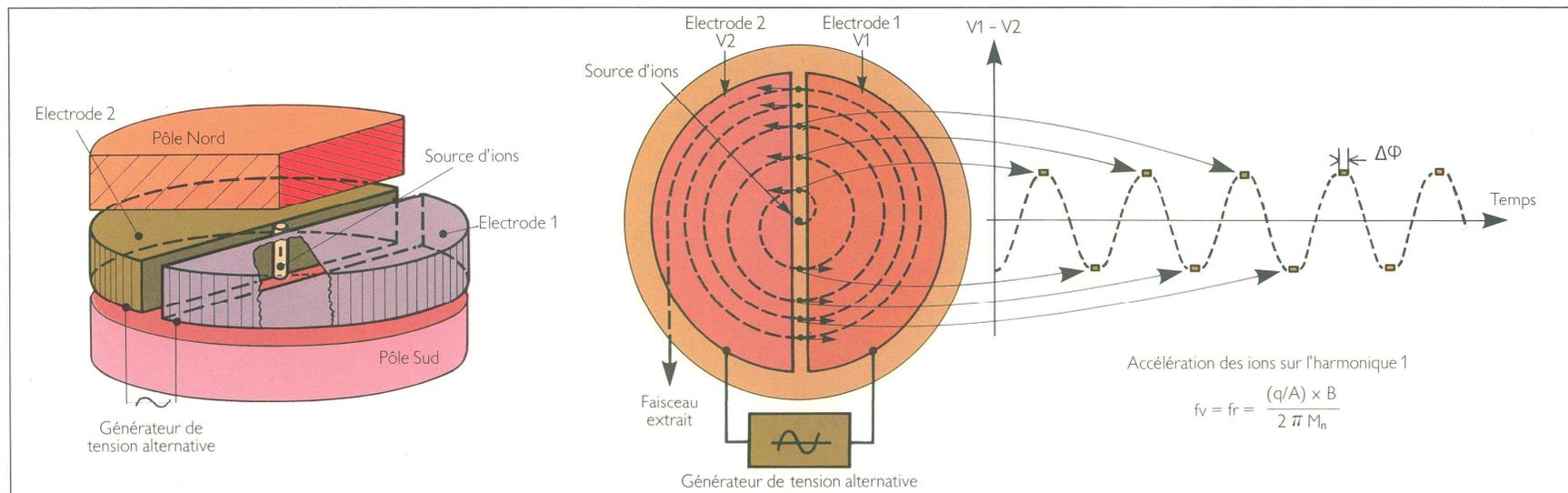
(non relativiste)

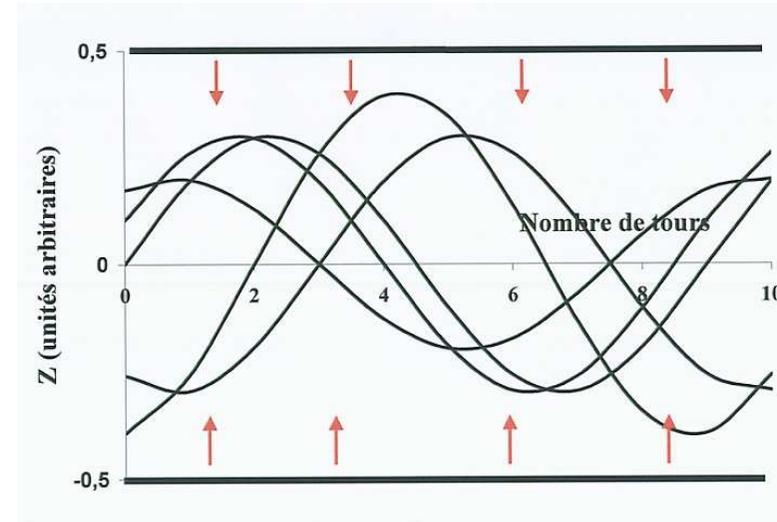
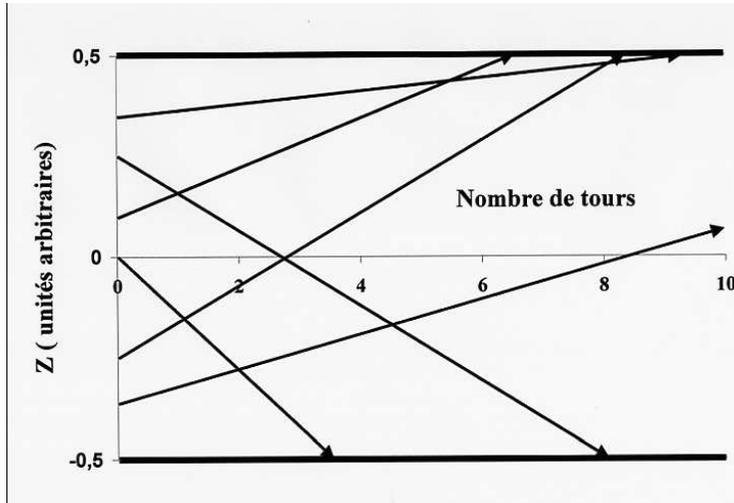
Appliquer une tension RF sur le « Dee » à la fréquence:

$$f_{\text{HF}} = h f_{\text{rev}} . \quad h : \text{rang harmonique}$$

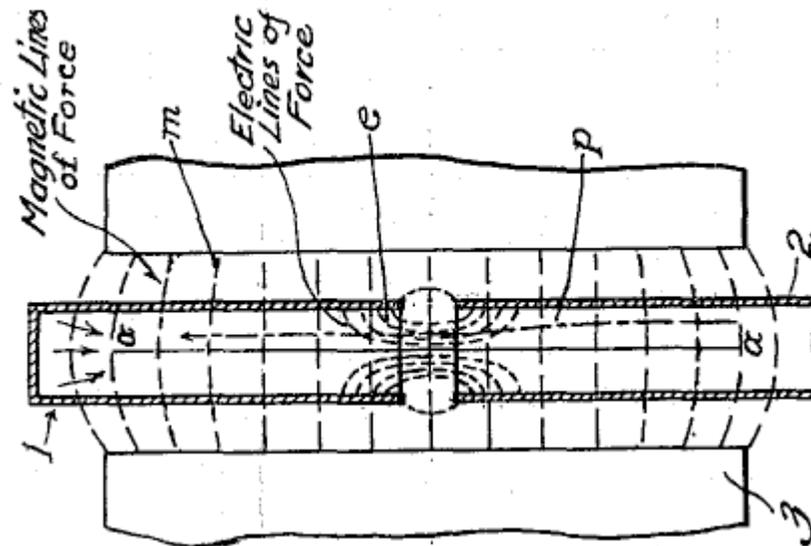
Avec $v_{\theta} = QB_z r/m$

→ Le rayon augmente avec l'énergie et décrit une sorte de spirale.





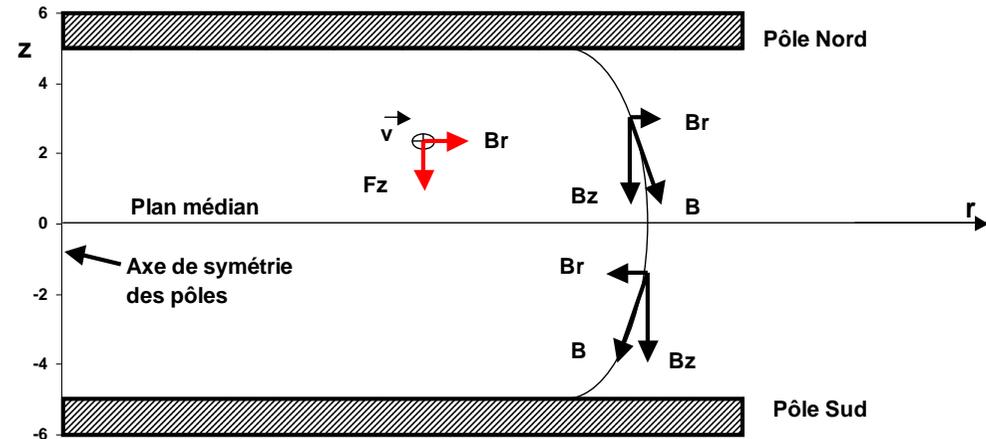
NON!



Trouver une force de rappel verticale!

Entre les pôles, les lignes de champ s'incurvent :
composante B_r

Field index k



$$k = \frac{r}{B_z} \frac{dB_z}{dr}$$

Décroissant avec le rayon

$v_{r,z}$: nombre d'onde

$$z = z_0 \cos(v_z \theta) \quad v_z^2 = -k$$

$$x = x_0 \cos(v_r \theta) \quad v_r^2 = 1 + k$$

Stabilité : $-1 < k < 0$

Mais perte d'isochronisme!

$$m = m_0 \gamma = \frac{m_0}{\sqrt{1 - \beta^2}} \quad , \quad \beta = \frac{v}{c}$$

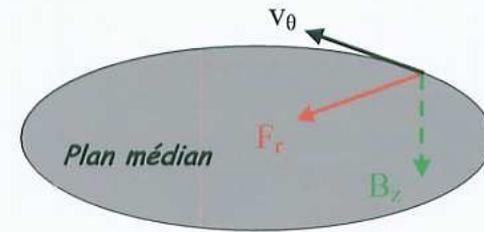
$$\omega = \frac{Q B_0 \gamma}{m_0 \gamma}$$

Champ croissant avec R: défocalisation

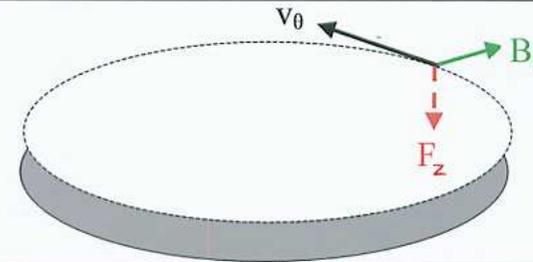
Réponse : Synchrocyclotrons ou Thomas (1938)

$$\mathbf{F}_z = \mathbf{v}_r \mathbf{B}_\theta$$

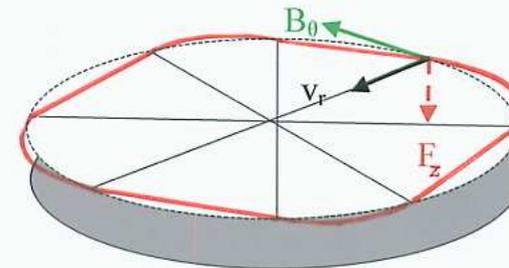
La trajectoire n'est plus un cercle : alternance de champ fort/faible



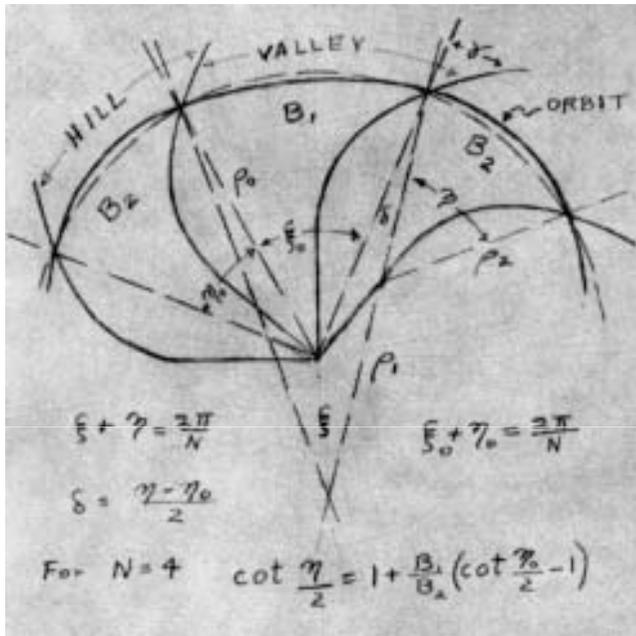
1) La composante verticale de \mathbf{B} produit la force radiale qui maintient l'ion sur un cercle



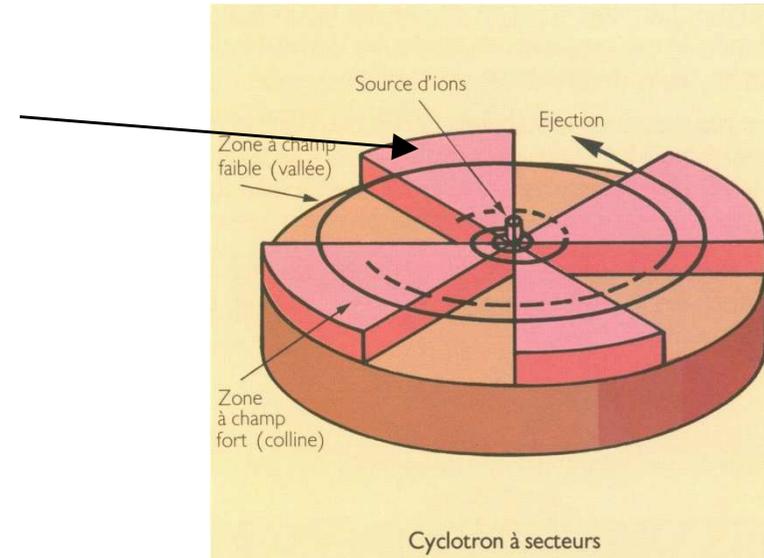
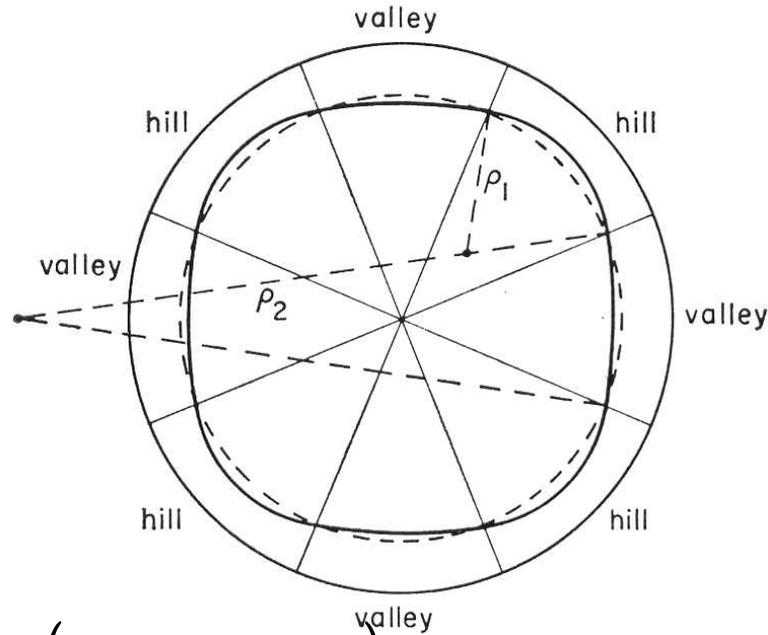
2) La composante radiale de \mathbf{B} (si l'indice est négatif) produit une force verticale



3) La composante azimutale de \mathbf{B} produit une force verticale (si l'orbite n'est pas circulaire)

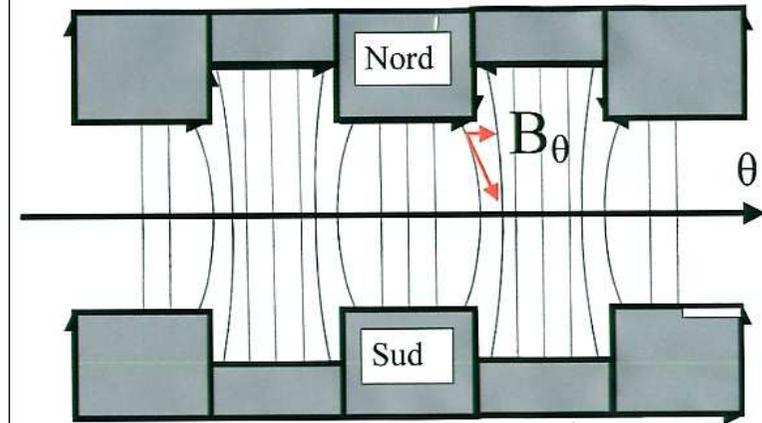


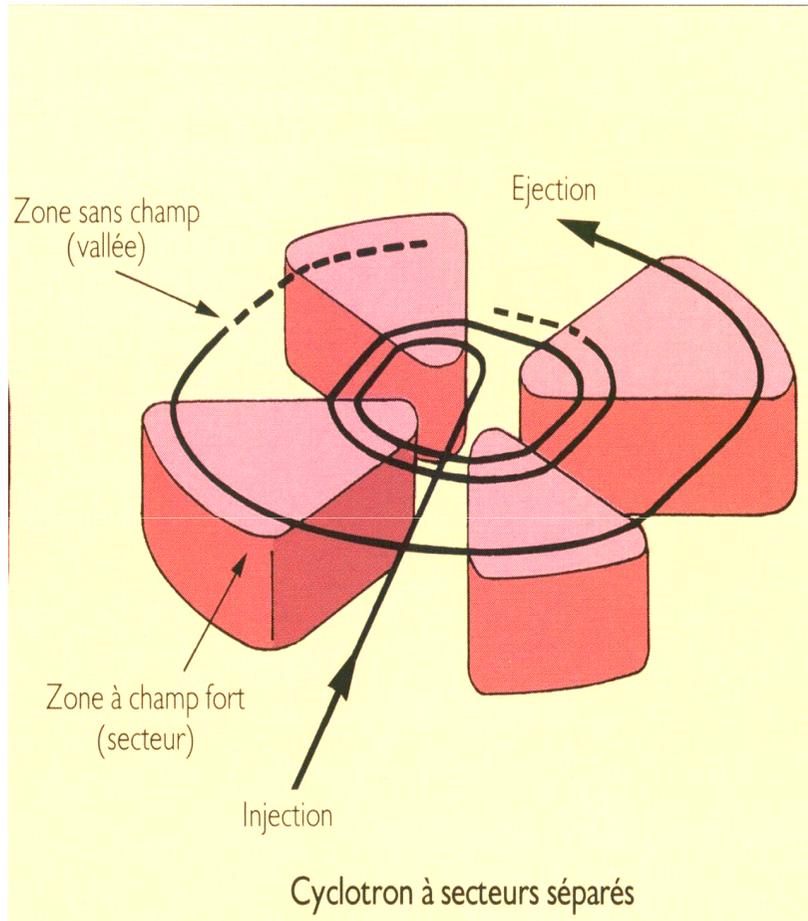
Kerst (1954)



$$Fl = \frac{(\langle B^2 \rangle - \langle B \rangle^2)}{\langle B \rangle^2}$$

$$v_z^2 = -k + \frac{N_{\text{secteur}} - 1}{N_{\text{secteur}}^2} Fl (1 + \text{tg}^2 \zeta)$$





PSI 590 MeV p+
2 mA 1.2 MW

$$\bar{B}_z(r) = \bar{B}_z(r=0) \gamma$$

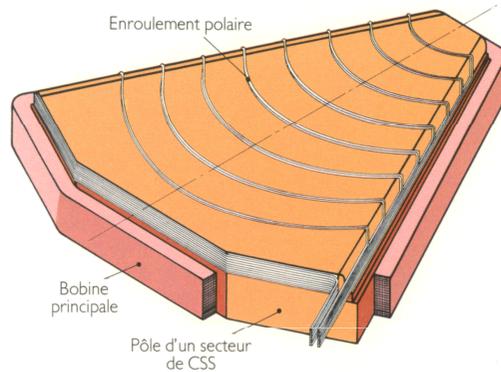
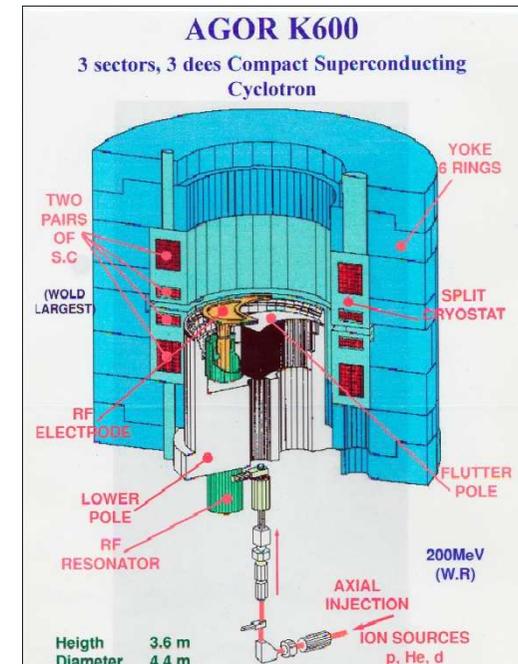
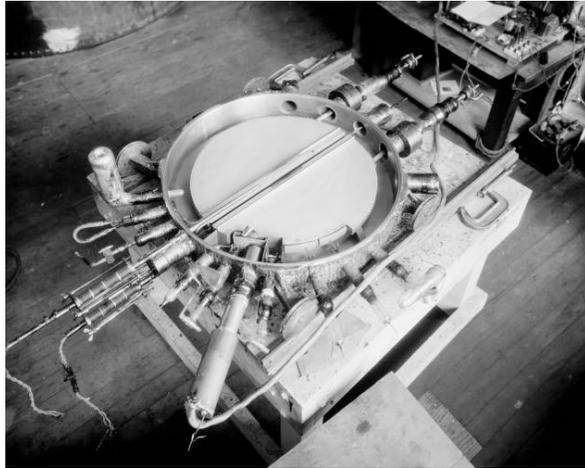


Schéma de principe de la disposition des enroulements polaires

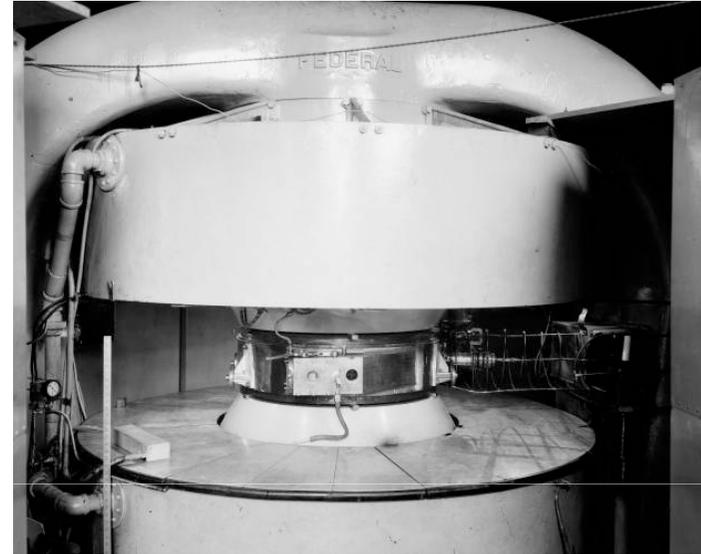


Utiliser des bobines de correction ou une partition des bobines supraconductrices





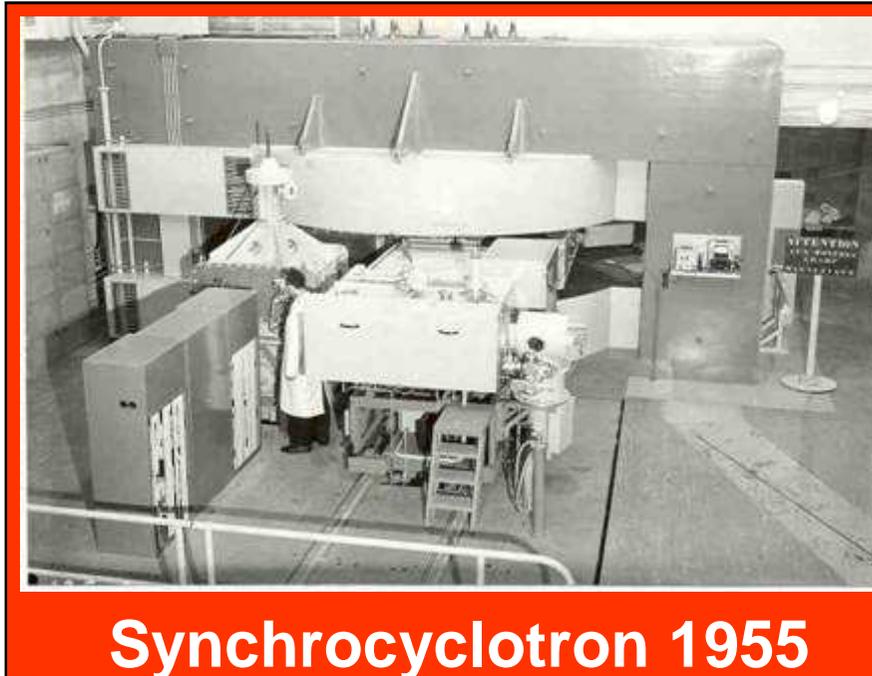
27-inch (3.6 MeV proton, 1932)



37-inch (8 MeV deuteron 1937)



60-inch (16 MeV proton, 1939)



IPN Orsay puis CPO



1977-2011

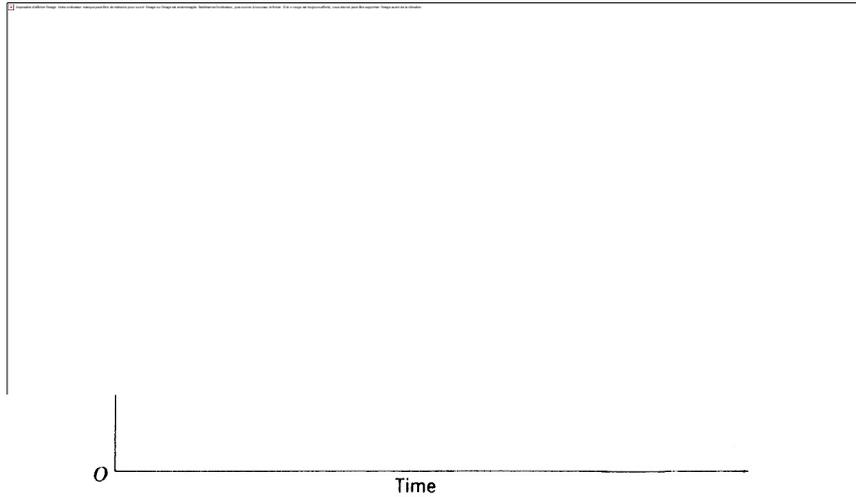


Fig. 11-4. Typical frequency-modulation cycle obtained with a variable capacitor in an LC circuit.

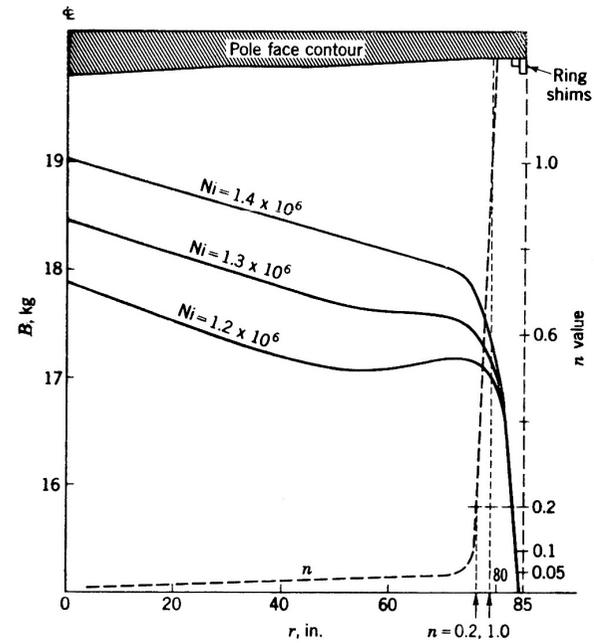


Fig. 11-10. Magnetic field versus orbit radius for the Chicago synchrocyclotron magnet.⁸ The pole-face contour used to produce the radially decreasing field is shown, along with the variation of n value.

Condensateur rotatif

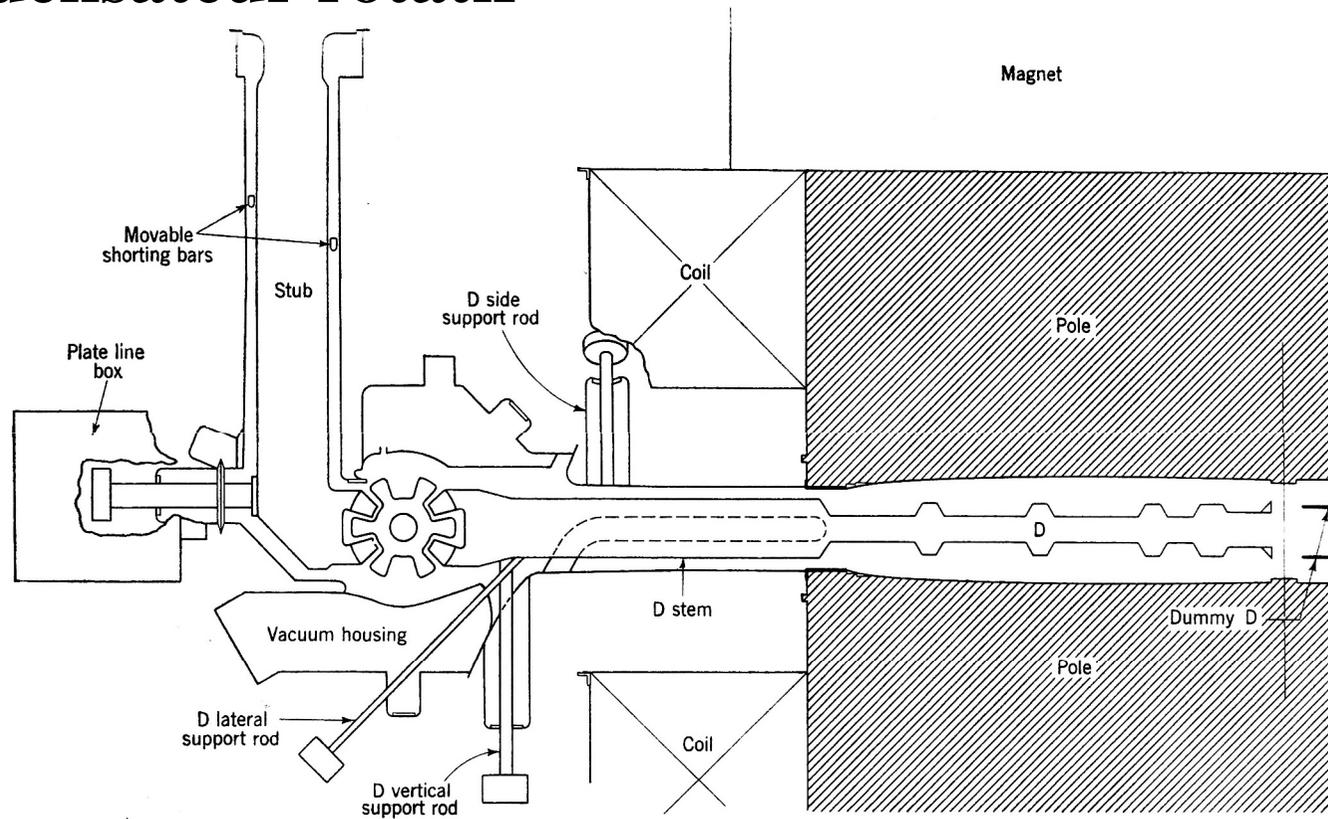
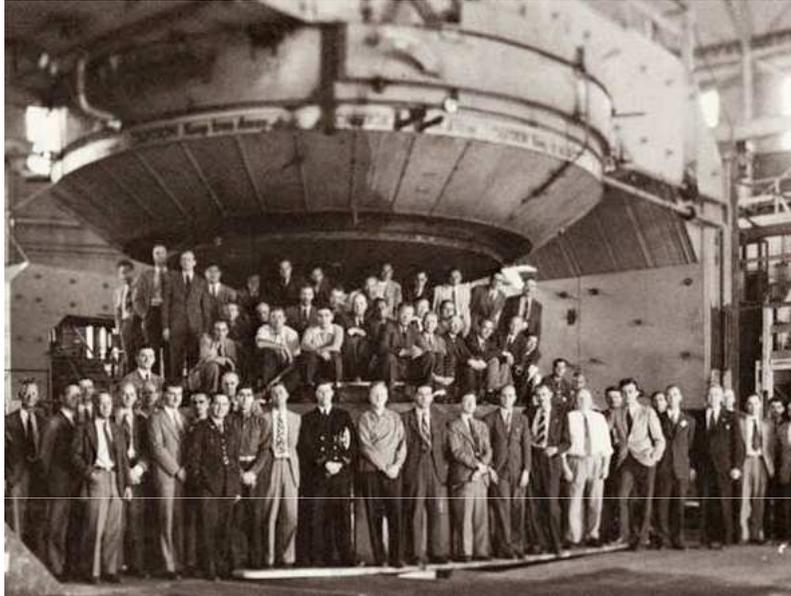


Fig. 11-12. Radiofrequency system for the University of Chicago synchrocyelotron.⁸ The oscillator circuit is not shown.

Orsay SC: 440 Hz 15 KV



Berkeley 184-inch
(340 MeV protons, 1946)

Gatchina StPetersburg
(1 GeV protons, 1967)
8 000 t, 7 m diamètre



$$W (\text{MeV /nucleon}) = \frac{Cst}{1+\gamma} \left\{ \frac{Q}{A} \right\}^2 (B r)^2$$

$$W = K (q/A)^2$$

K : « puissance » du cyclotron

- Accelerate any kind of ions (positive or negative)
- Energy variation through magnetic field B or charge-to-mass ratio Q/A
(even by stripping of positive or negative ions at different radii r)
- K de 10 à 2500 MeV
- Maximum energy :
 - ~ 600 MeV (protons)
 - ~ 350 MeV/nucleon
- Intensity : up to 2 mA (protons) 10^{13} to 10^{14} pps (heavier ions)

with DC operation !

Résonance quand :

$$\mathbf{m} \mathbf{v}_r + \mathbf{n} \mathbf{v}_z = \mathbf{p}$$

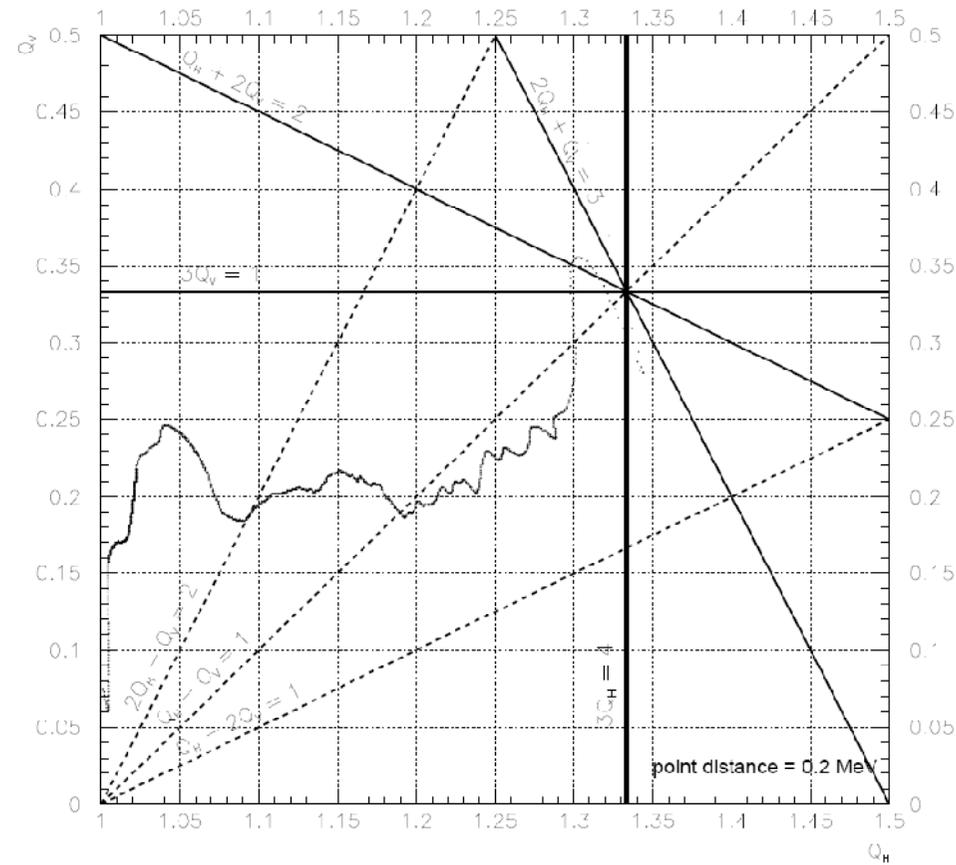
m, n, p : entiers

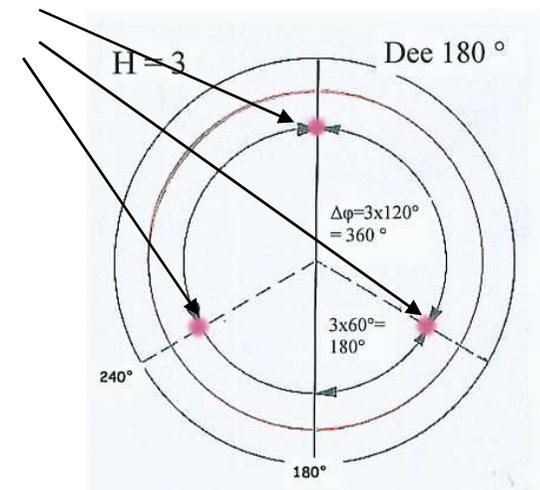
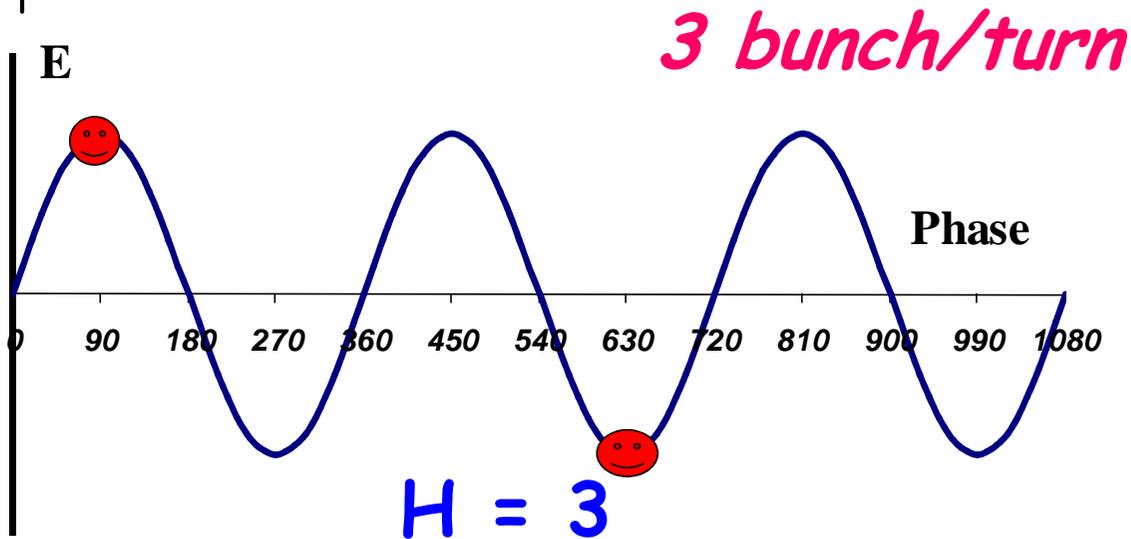
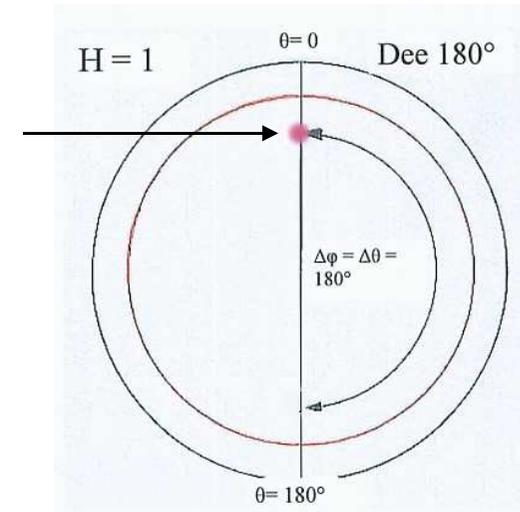
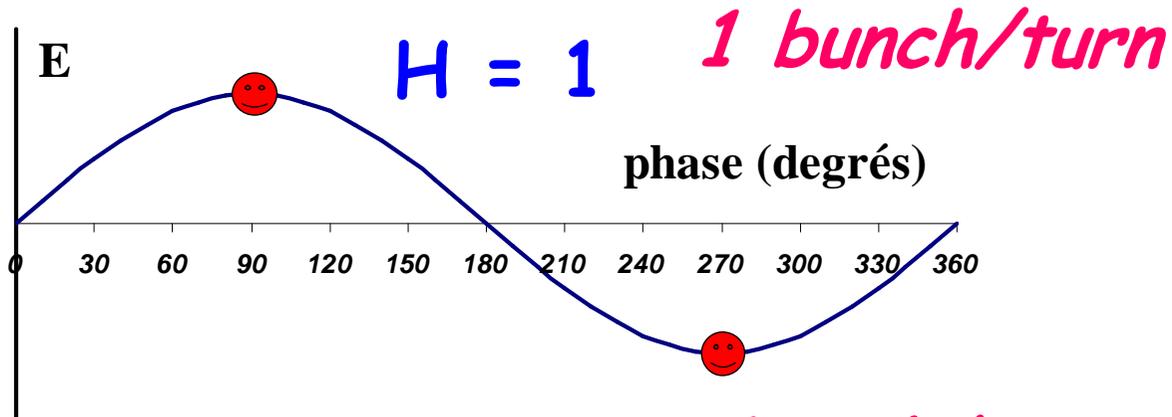
$m+n$: ordre de la resonance (dipole, quadrupole etc...)

p : rang harmonique de la « driving force »

Résonances : Somme et Différence

Respect des symétries de champ important

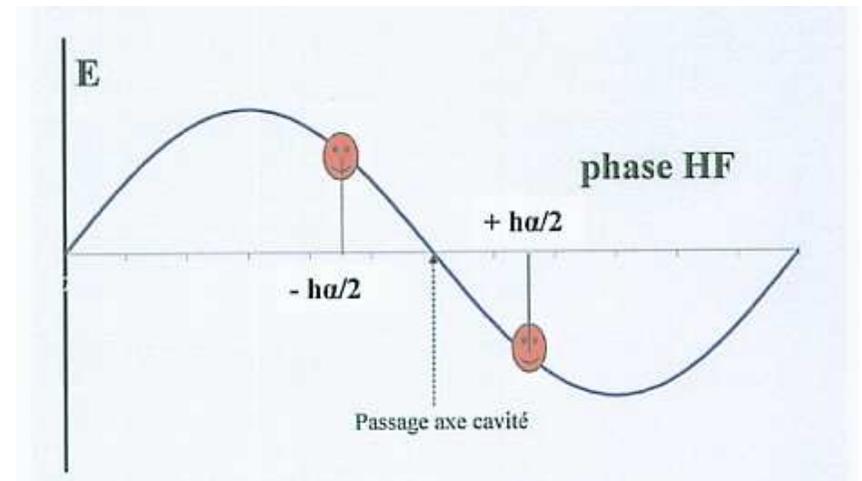
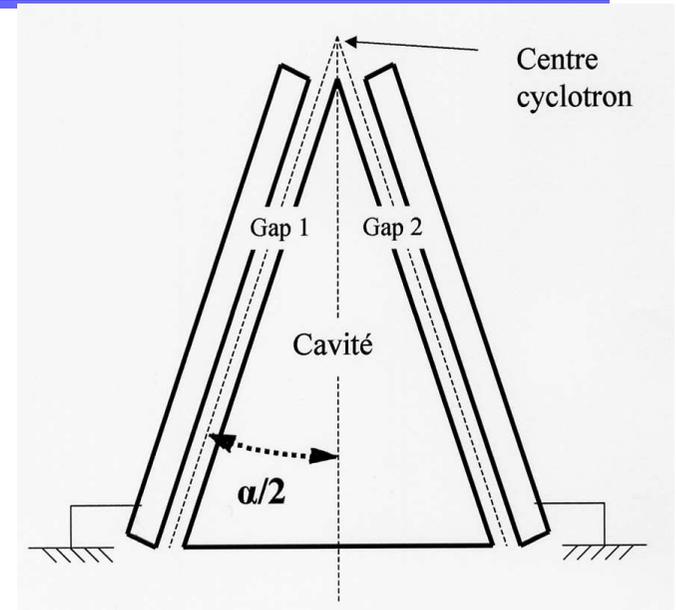


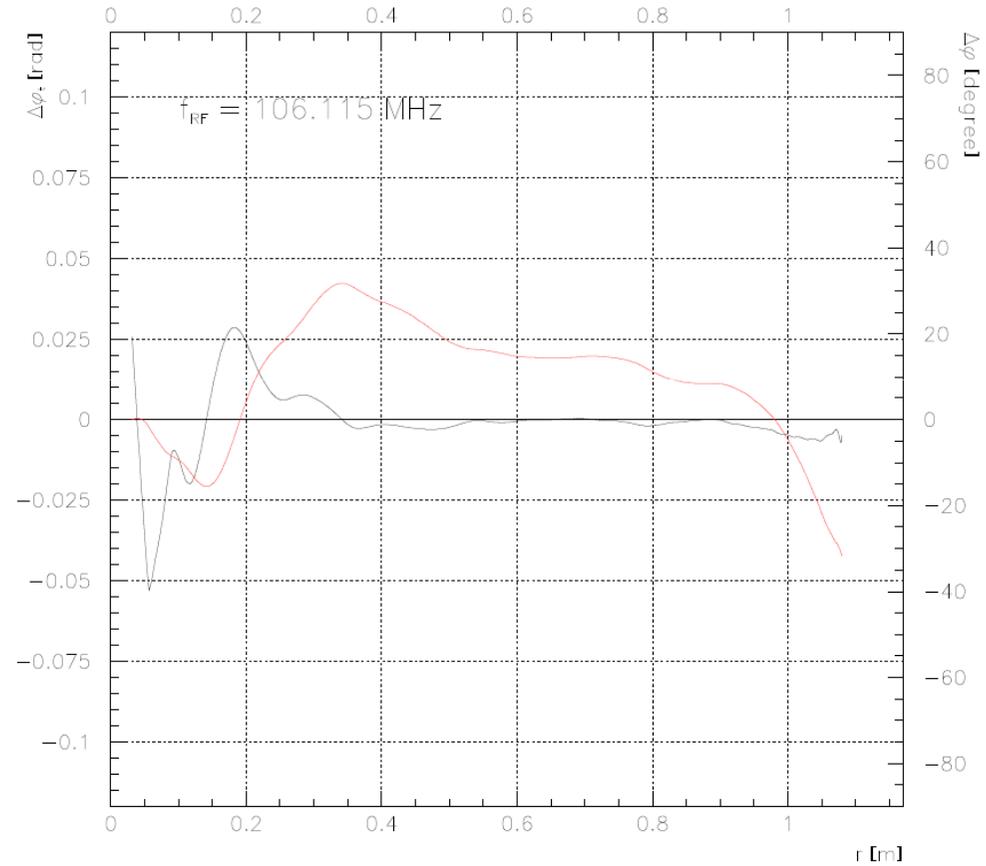


$$\delta W = \frac{Q}{A} V_0 \sin\left(\frac{h\alpha}{2}\right)$$

h	2	3	4	5
Sin(hα/2)	0,643	0,866	0,985	0,985

$$\alpha = 40^\circ$$





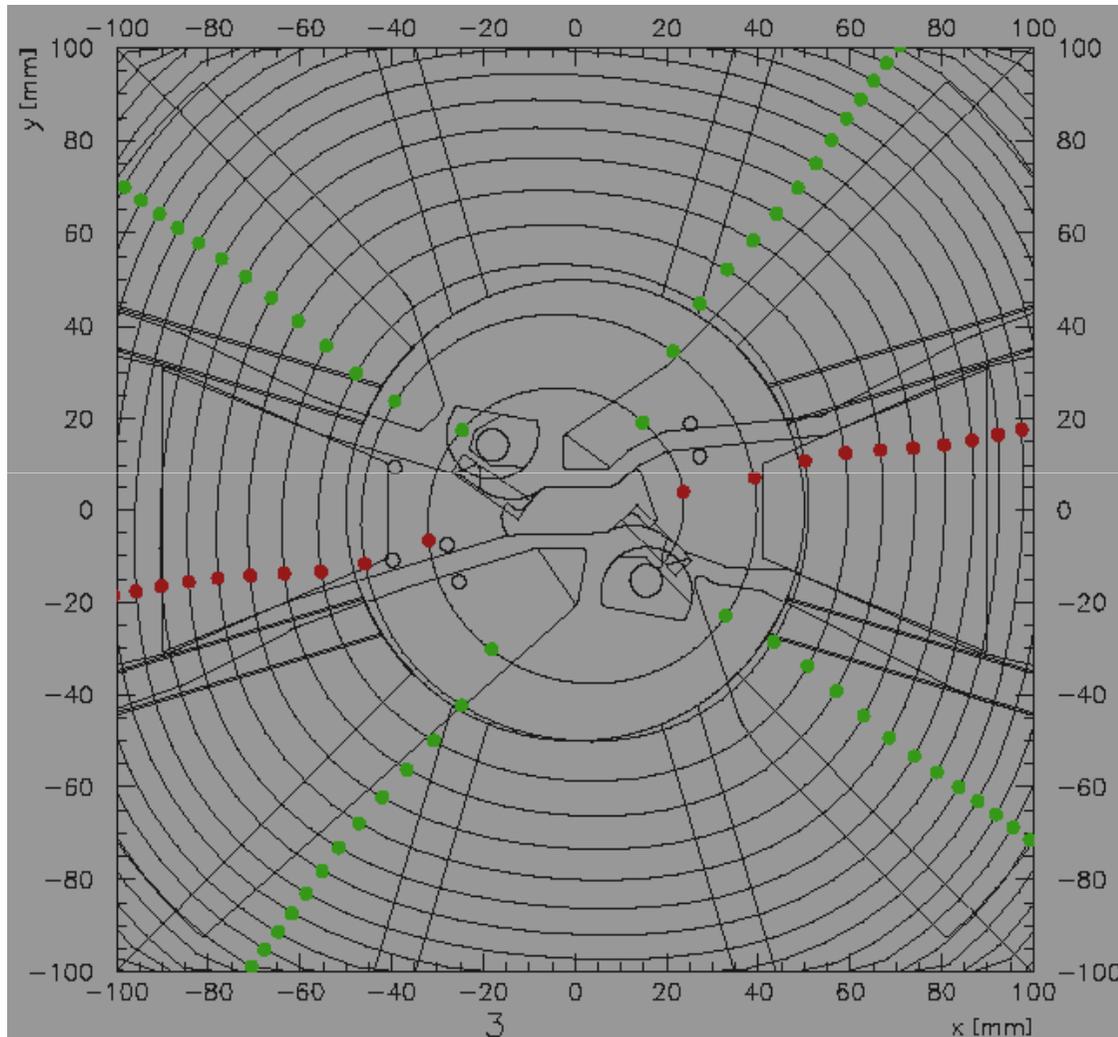
- Source interne (PIG)
- Source externe (ECR or H-)

Avantages source interne:

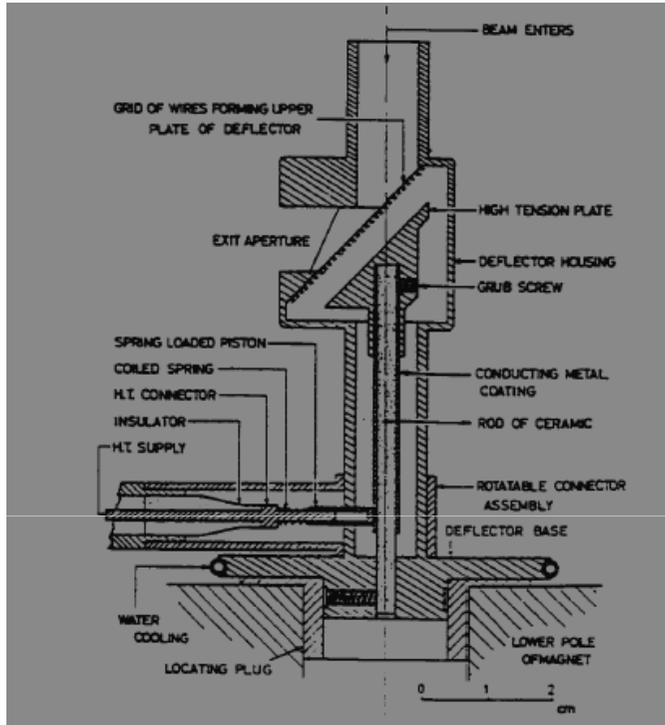
- simple
- compacte
- pas de ligne d'injection

Inconvénients source interne:

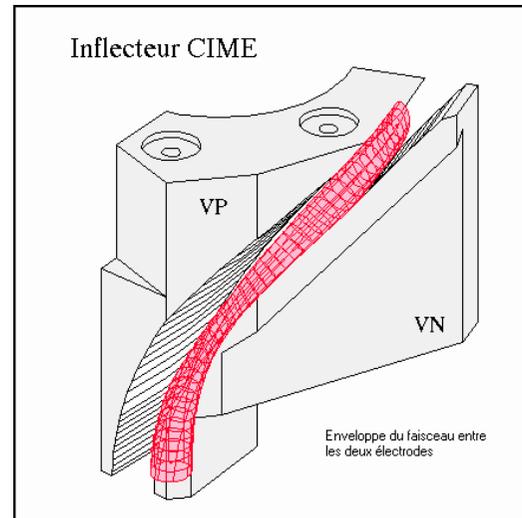
- intensité limitée
- ions lourds limités en état de charge
- pas de paramètres pour l'adaptation
- débit de gaz



3D for E, B



Miroir électrostatique



Inflecteur spiral (Pabot&Belmont)

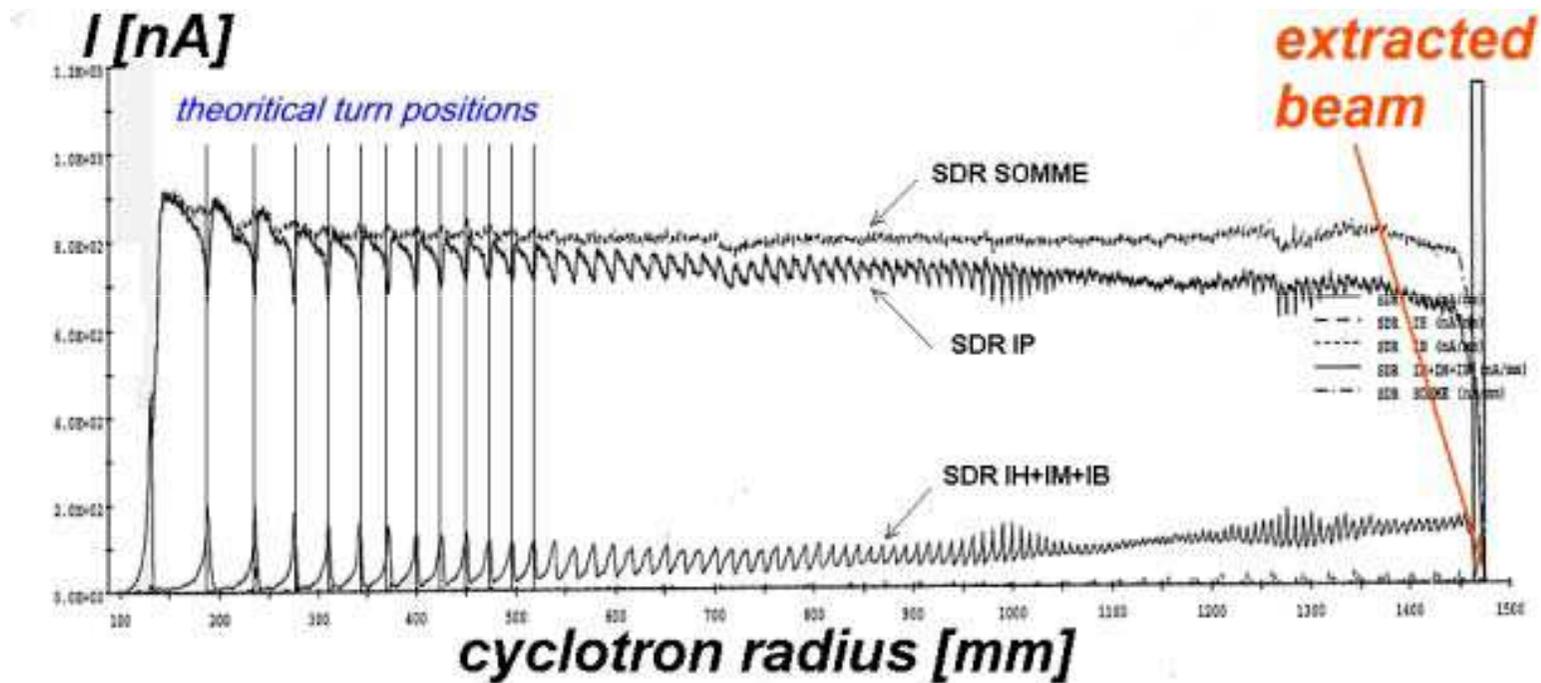


C01 GANIL

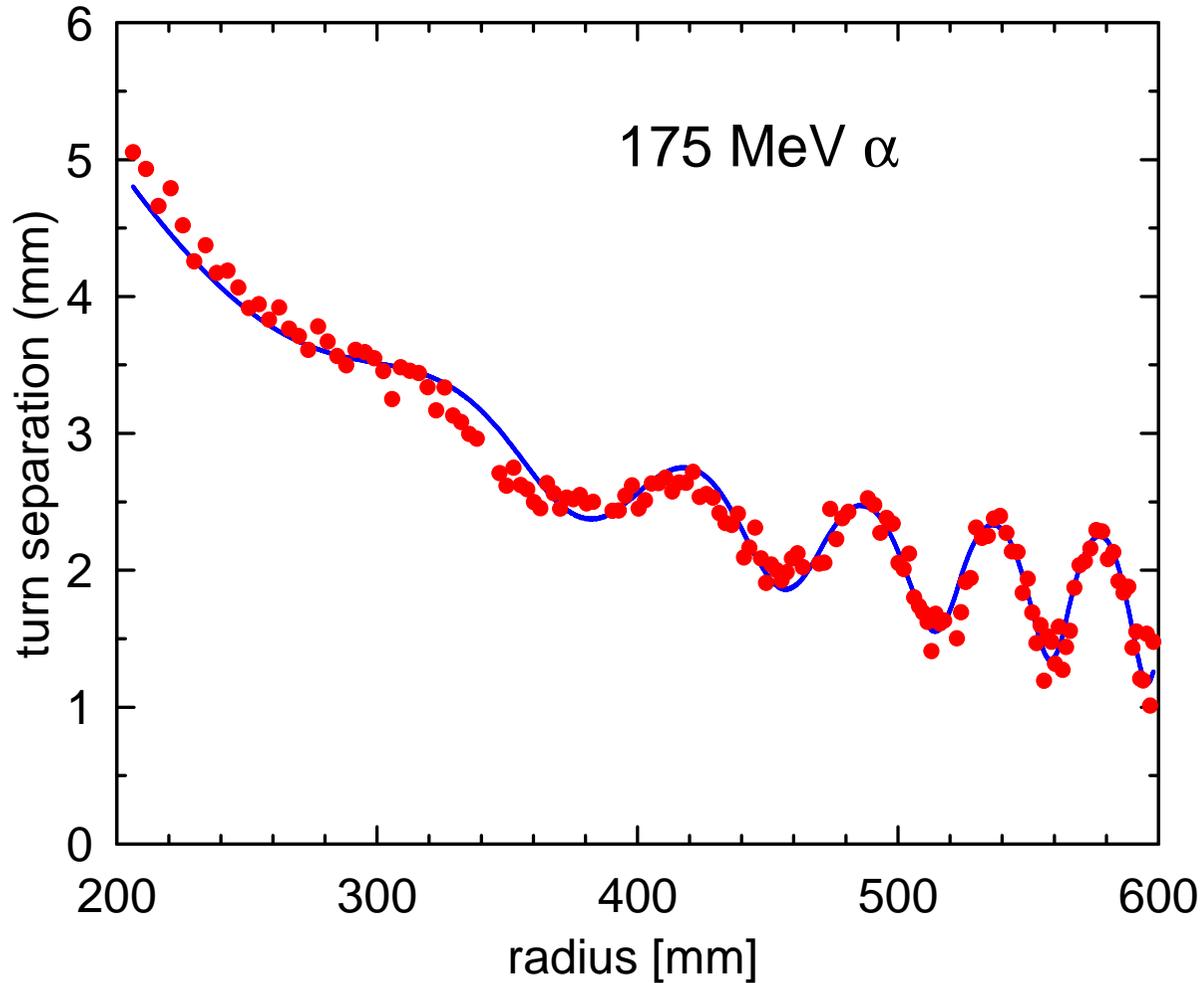


IBA C235

Sonde intégrale et différentielle (Δr)



CIME (GANIL)



Off centered beam
Decrease due to range

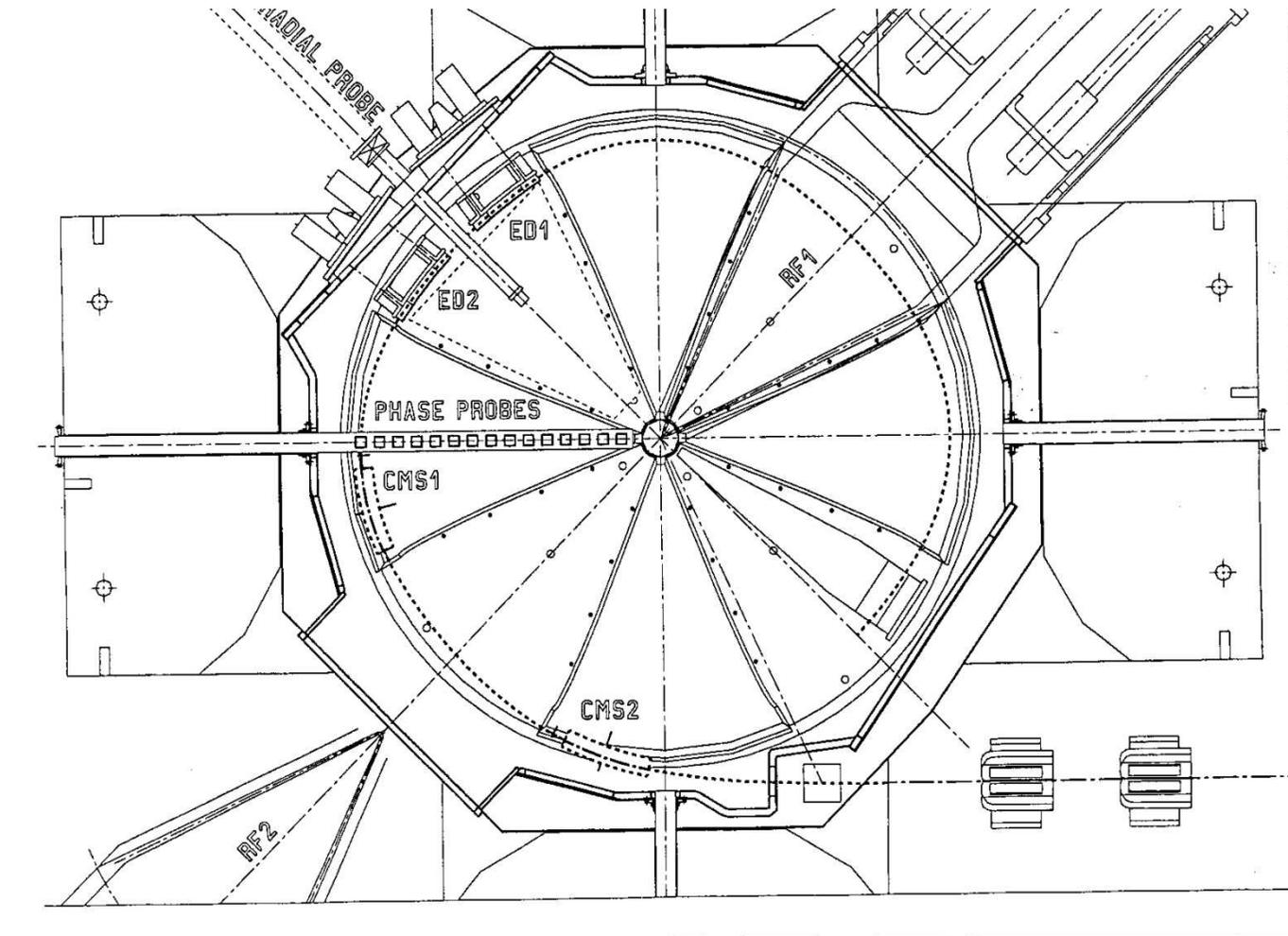
Séparation des tours :

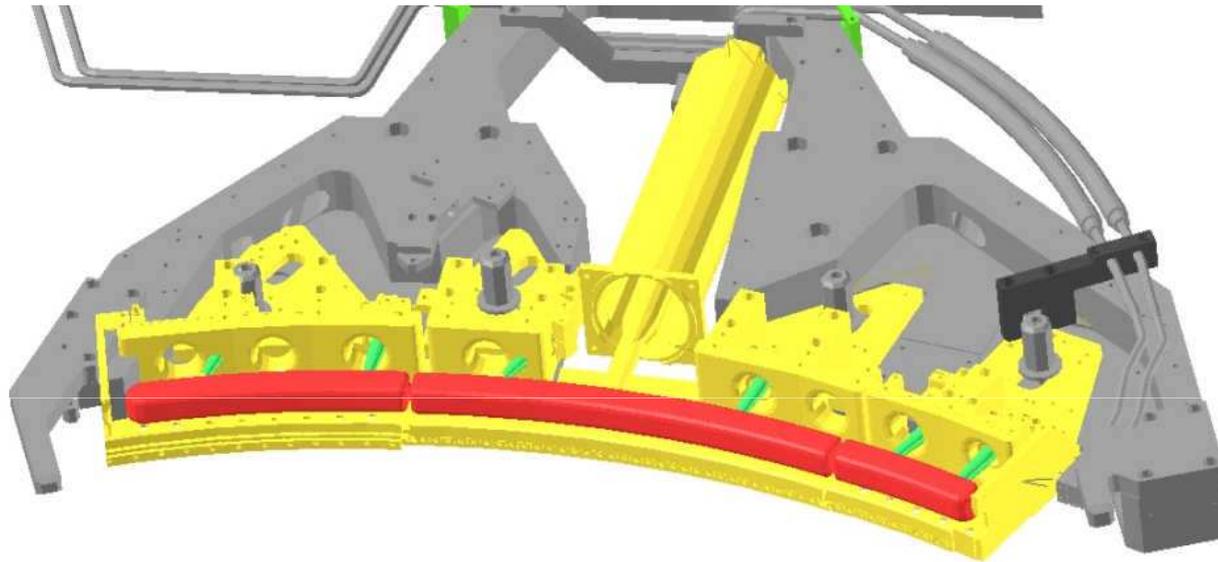
$$\frac{\delta r}{r} = \frac{1}{2} \frac{\delta W}{W} = \frac{\frac{Q}{A} V_0 \cos(\varphi_s)}{W} \approx \frac{1}{r^2} \quad \delta r \approx \frac{1}{R}$$

Pour l'augmenter:

- augmenter le gain par tour (tension, nbre de Dee)
- $\varphi_s \approx 0$ (diminuer $\Delta\varphi_s$ diminuer la largeur du faisceau)
- Utiliser une précession ou une résonance

Extraction



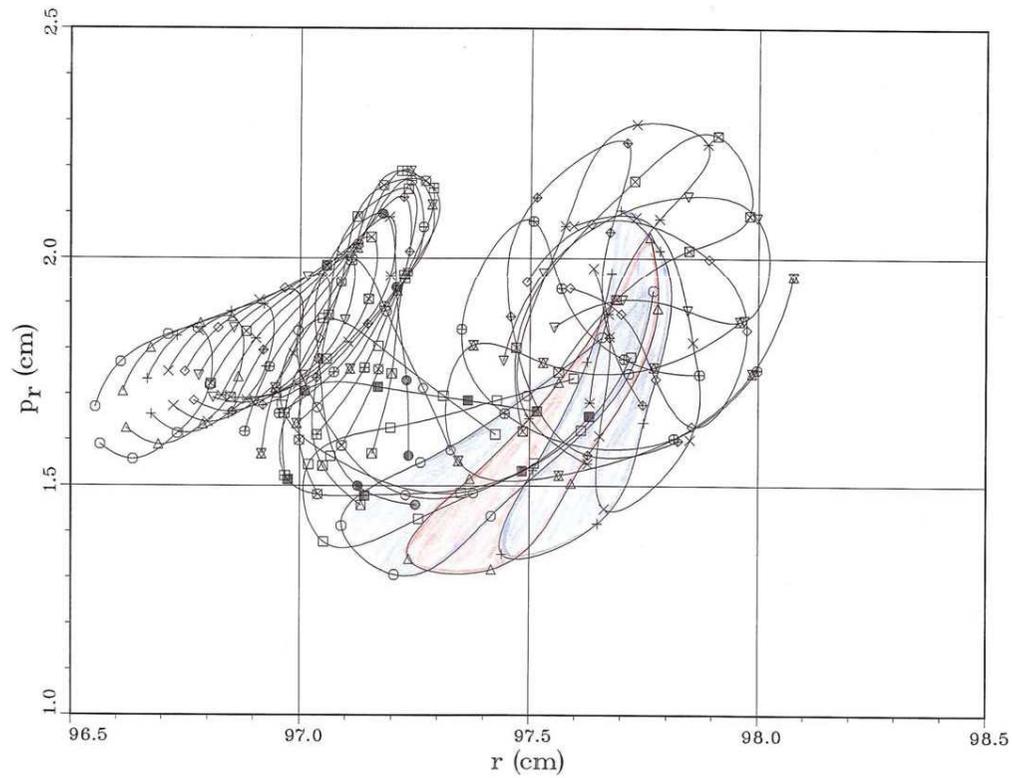


AGOR : gap 7 mm, 105 KV/cm

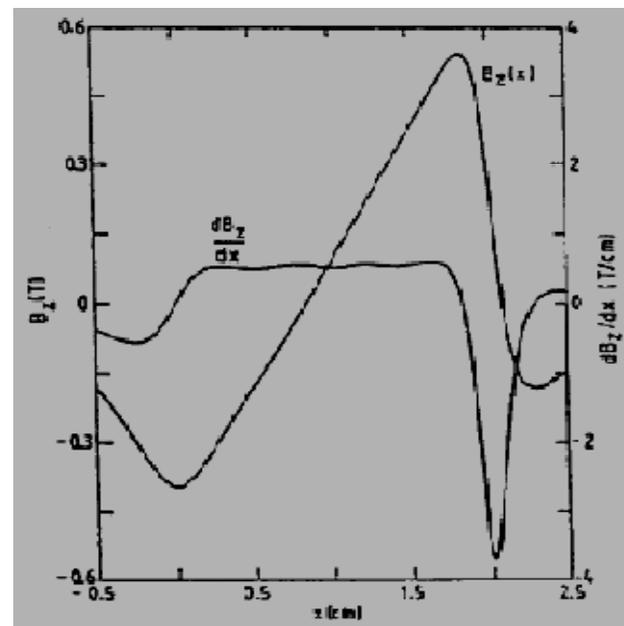
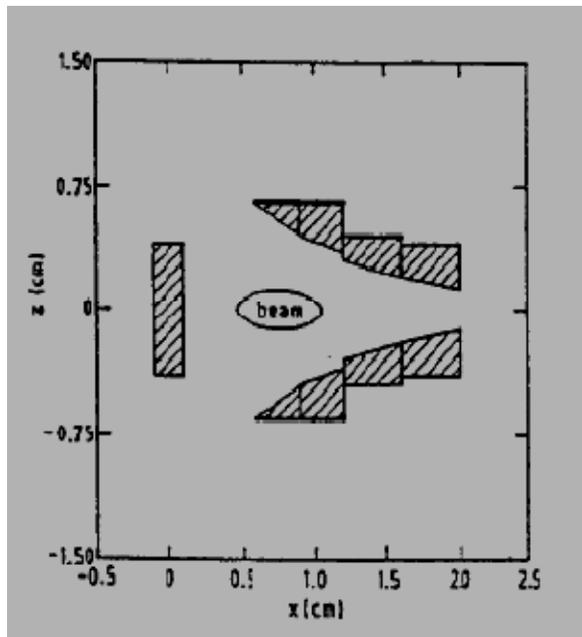
Extraction résonante

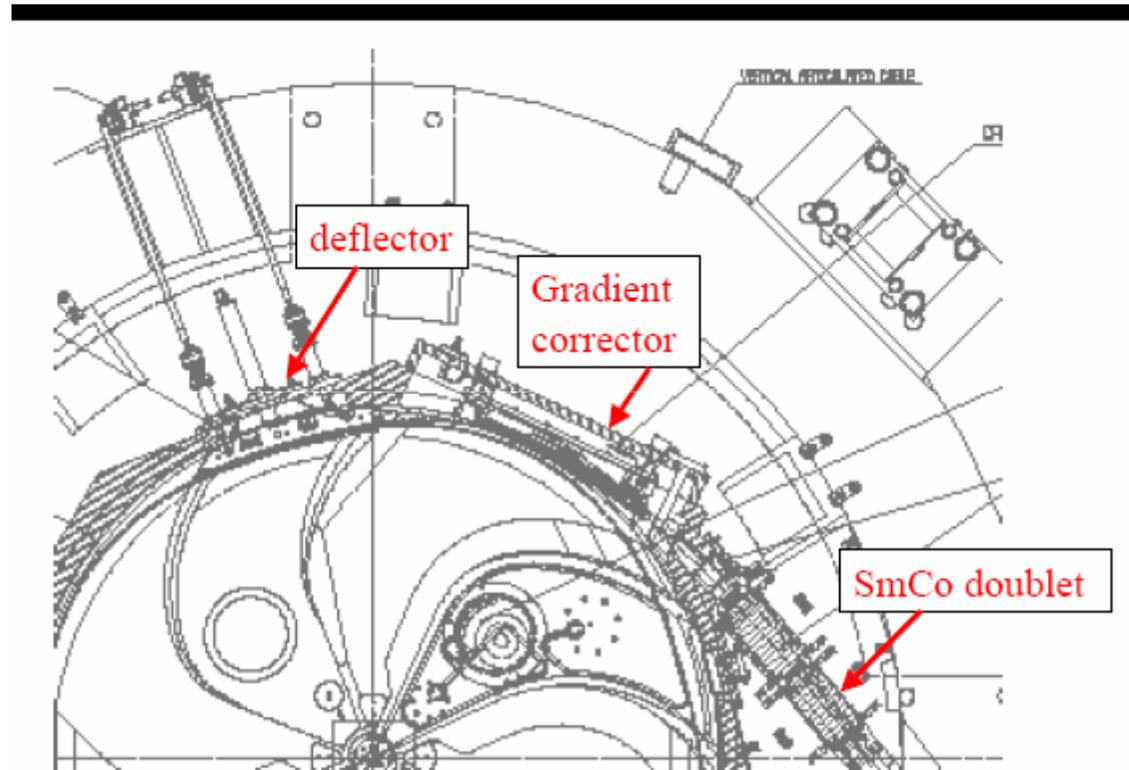
$B_1 = 1.0 \text{ gauss} / \theta_{b1} = 160 / \theta = 280$

10.10.22 R11

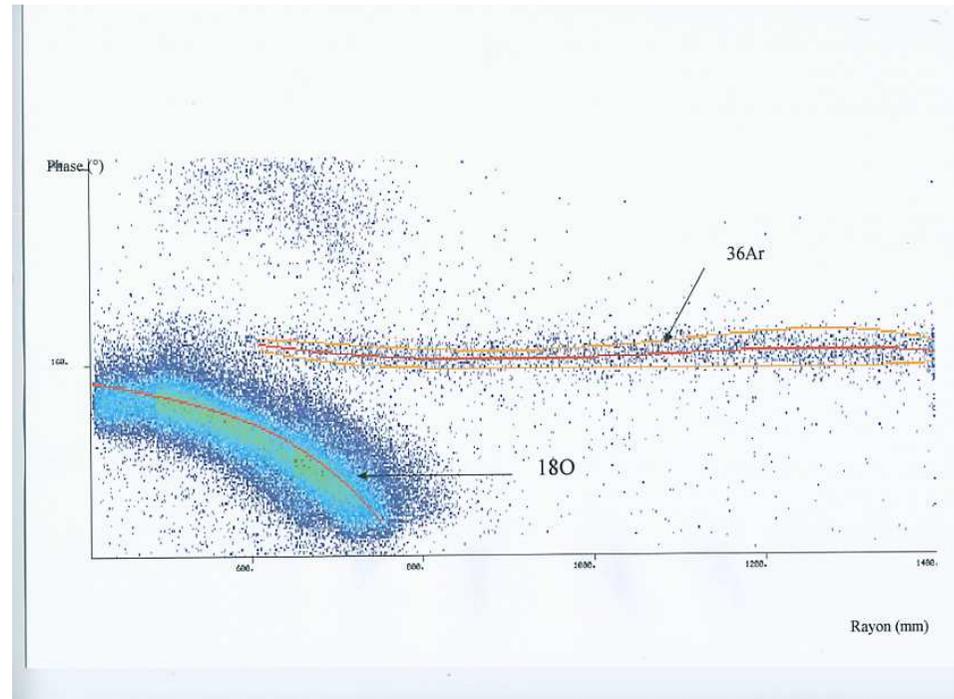


correcteur de gradient





$$\frac{\delta \left(\frac{m}{Q} \right)}{\frac{m}{Q}} = \frac{1}{2 \pi h N_t}$$



Mesure scintillateur CIME

- **Avantages** : compacité, coût, simple, séparateur naturel
- **Inconvénients** : puissance dissipée, changement d'énergie complexe, courant maximum limité (qqes mA), stabilité nécessaire, complexe à haute énergie

Progrès: bobines supraconductrices, accélération de H-, monoparticule/mono énergie

Parfaitement adapté aux applications médicales

- **Hadronthérapie**
- **Production de radioisotopes:**
 - PET (Positron Emission Tomography)
 - SPECT (Single Photon Emission Computed Tomography, scintigraphie)
 - Thérapie (molécules)

- **Infrastructure**
 - Accès patients et conformité des locaux
 - Environnement pour situations critiques (ex: anesthésie)

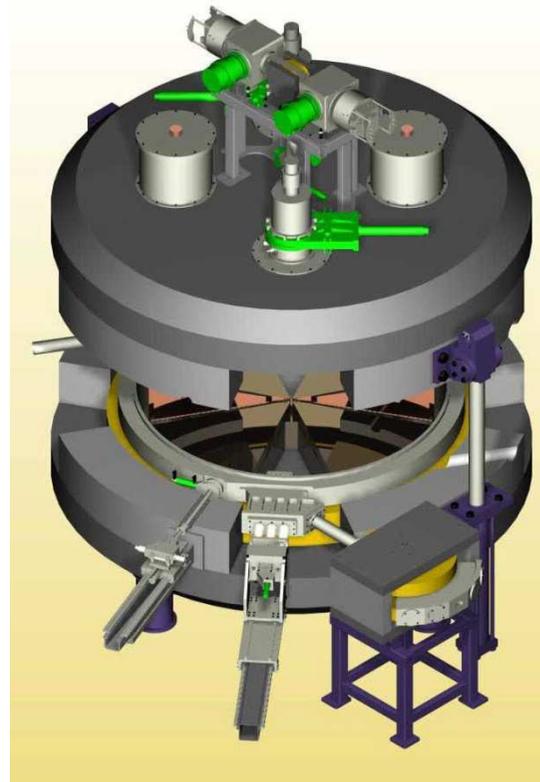
- **Personnels**
 - Accueil et prise en charge
 - Présence médicale et responsabilités associées

- **Dispositifs**
 - Conformité – autorisation
 - Fiabilité – niveau de support interne et externe - contrôle qualité
 - maintenance, intervention, développements ... maîtrisés

En 2012:

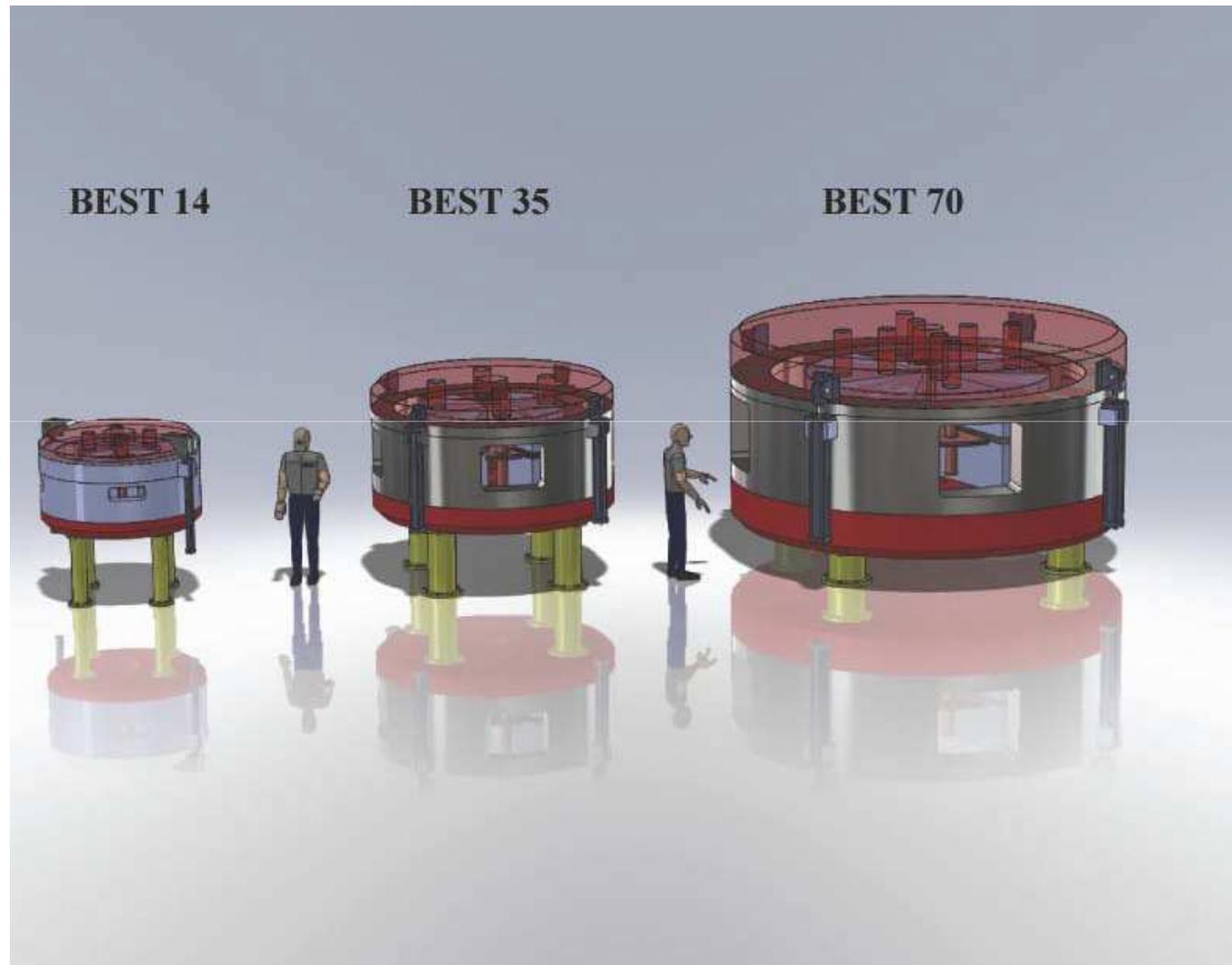
- 36 centres proton (toutes tailles)
- 6 centres carbone
- > 100 000 patients traités (95% p+)

Cyclone 10/5
Cyclone 18/9
Cyclone 30
Cyclone 70



Number of sectors: 4
Max hill magnetic field: 2,9 T
Max valley magnetic field: 0,9 T
Average magnetic field at extraction:
2,188 T
Magnetic field at the centre: 1,76 T
AT : 5.234 10E5
Current density : 155 A/cm²
Power per coil: 110 KW
Coil weight: 2 * 10,4 t
Iron weight: 200 t

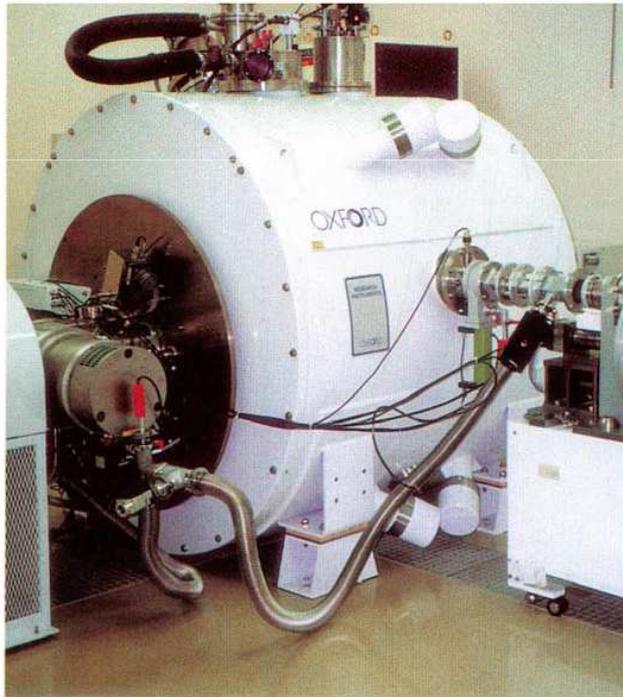




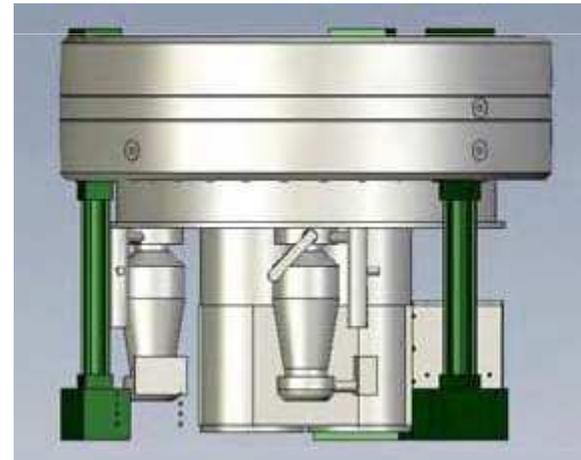
TR14, TR18, TR19, TR24, TR30

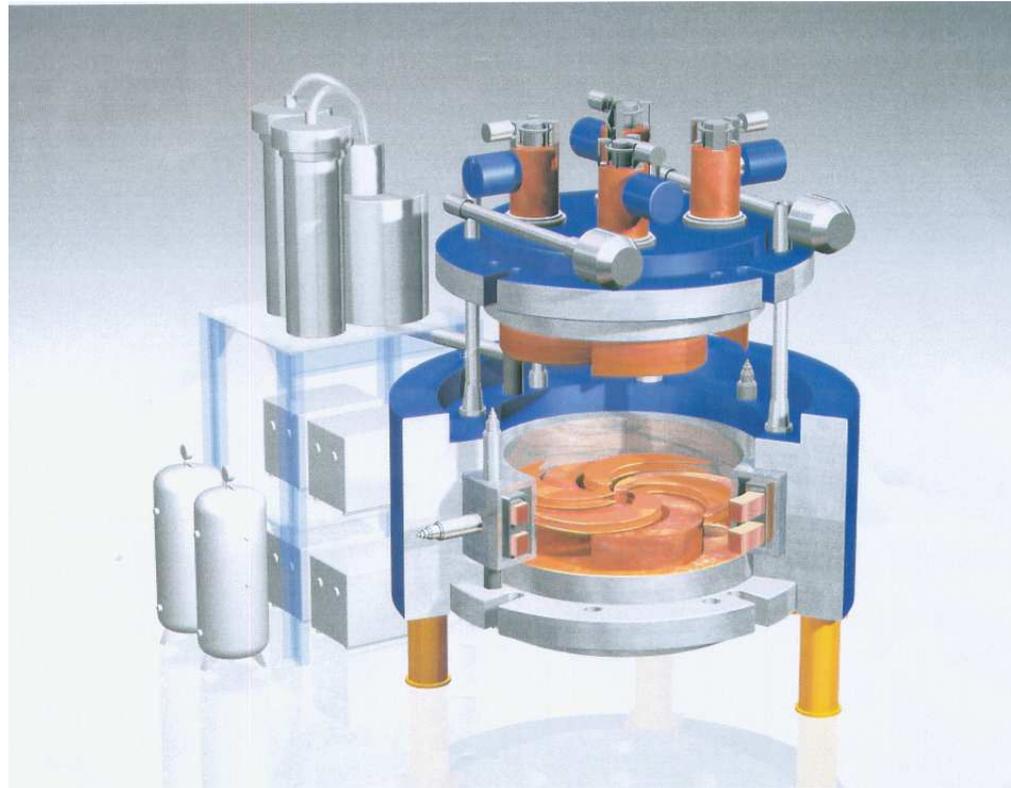


Oxford OSCAR
(EuroMeV, ALCEN)
12 MeV



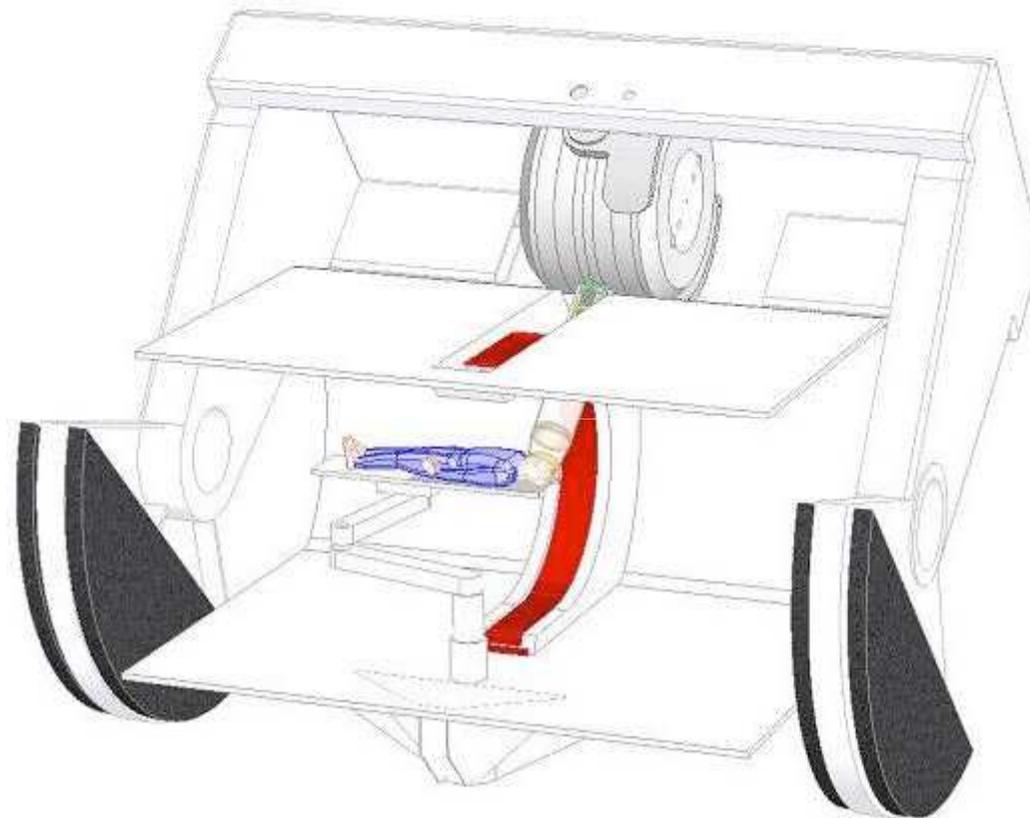
ABT, 7.5 MeV





250 MeV Superconducting cyclotron for protontherapy

Still Rivers USA





Accelerated Beam	Extracted Beam	Extracted Energy (MeV)	Beam Intensity (eμA)	Exit Ports
H ⁻	H ⁺	30 - 70	750	dual
D ⁻	D ⁺	15 - 35	50	dual
⁴ He ²⁺	⁴ He ²⁺	70	70	single
HH ⁺	HH ⁺	35	50	single

Avantage principal: extraction par stripping, double extraction et énergie variable
MAIS

Lorentz stripping

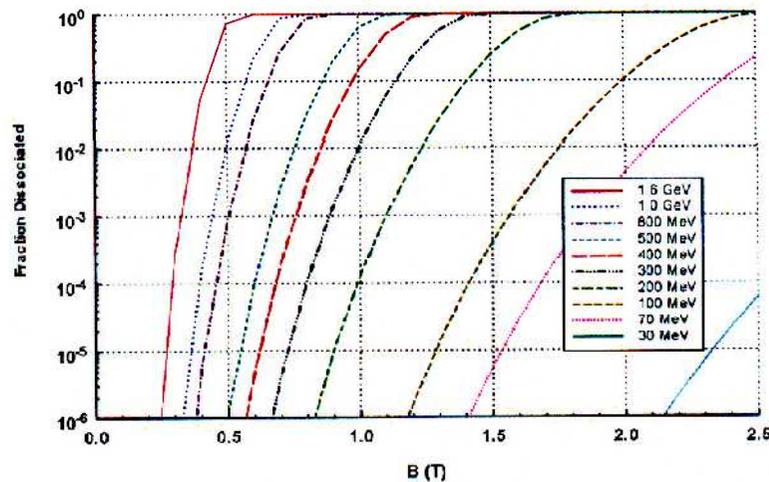


Figure 1: Fractional Lorentz stripping over a 1 m path for various energies as a function of B.

Gas stripping

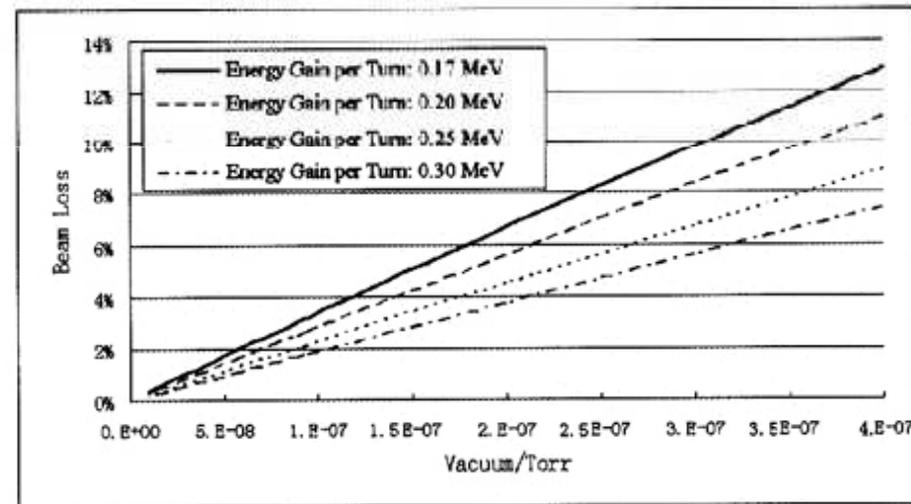
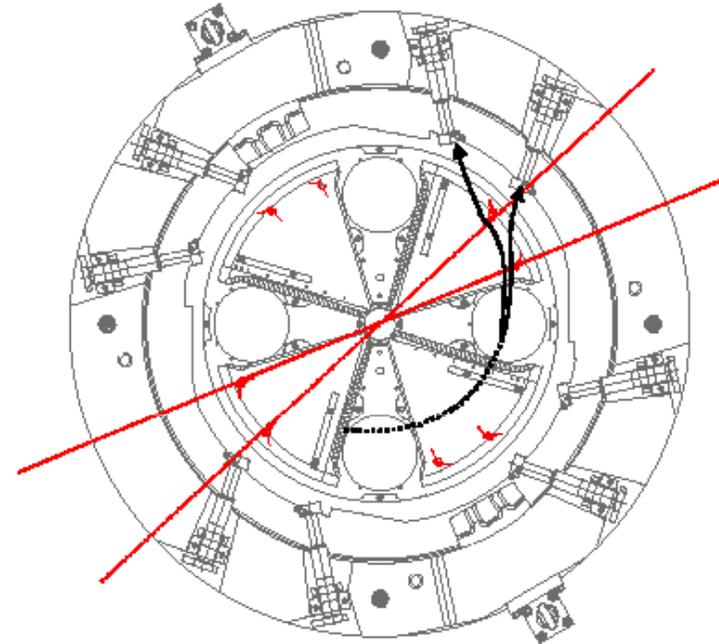
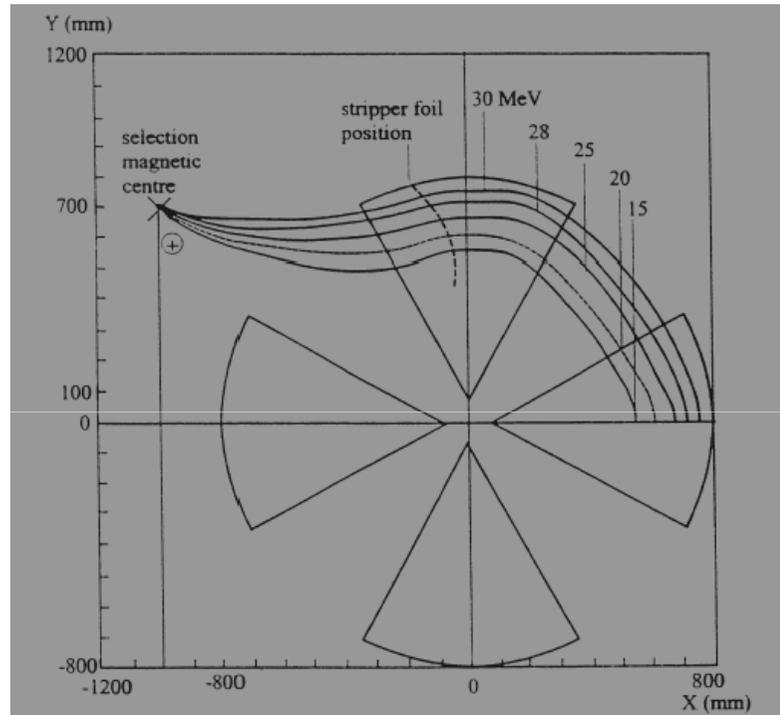


Figure 3: H⁻ beam loss versus N₂ equivalent pressure.

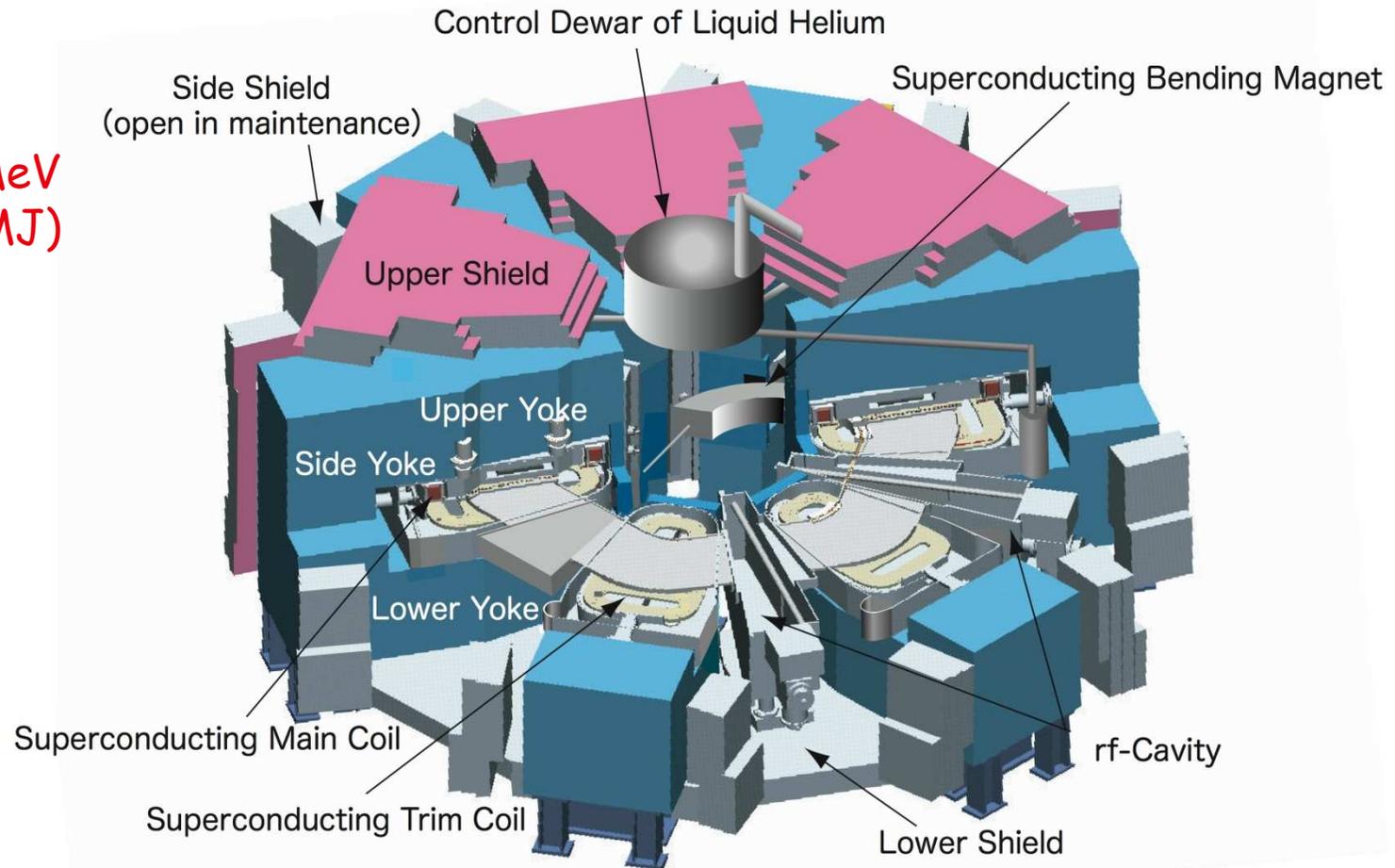
Faible B et bon vide!

Extraction de H-





K = 2 500 MeV
3.8T (240 MJ)
18-38 MHz
8,300 tons

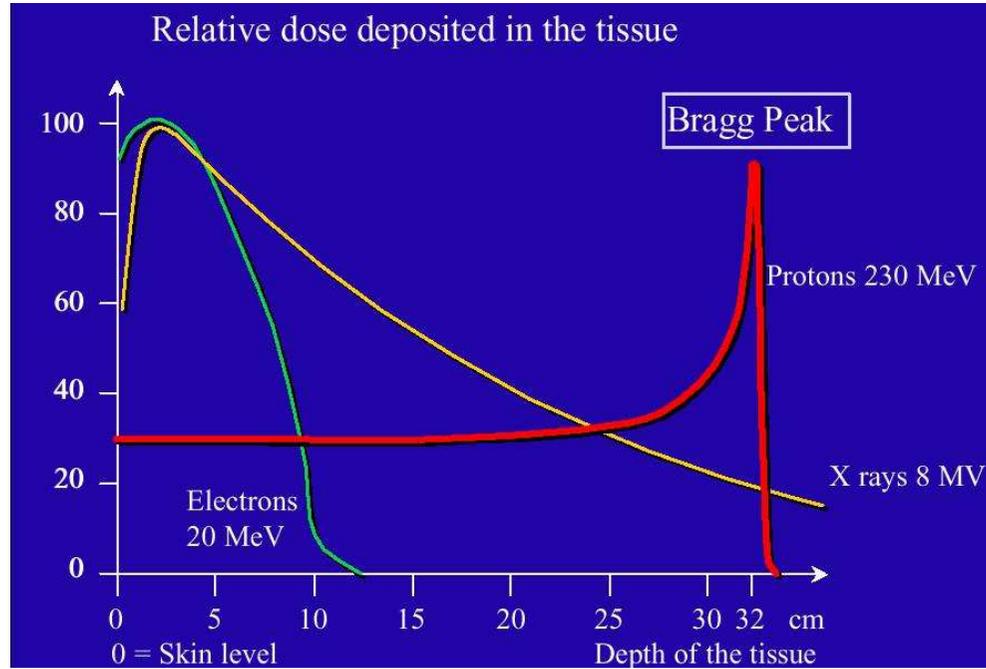


RIKEN, Japon

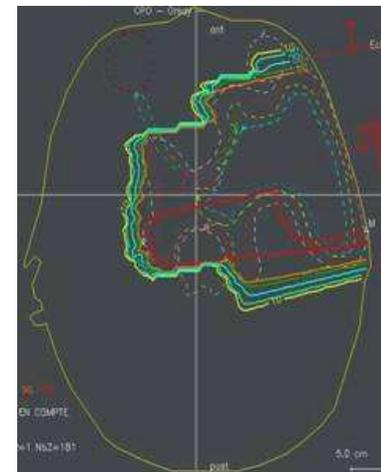
- Source externe cusp
- cryopompe + Turbo sur la ligne d'injection
- 16-25 MeV
- $> 500 \mu\text{A}$
- PET et SPECT possibles
- basé sur EBCO TR30 (1990)
- 2.1 T
- 85.085 MHz
- 24 t
- 120 KW



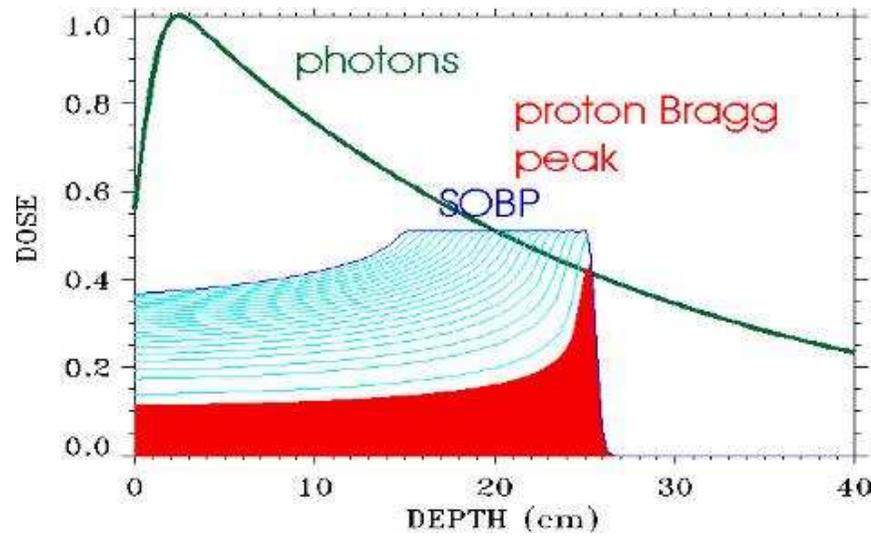




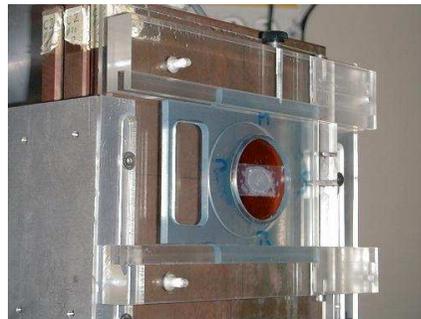
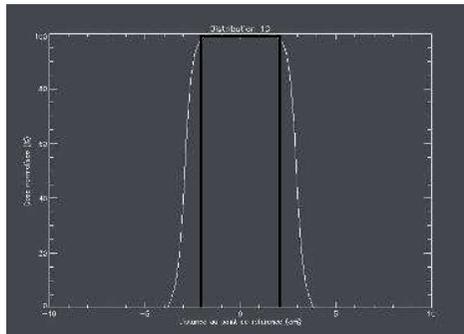
Photon



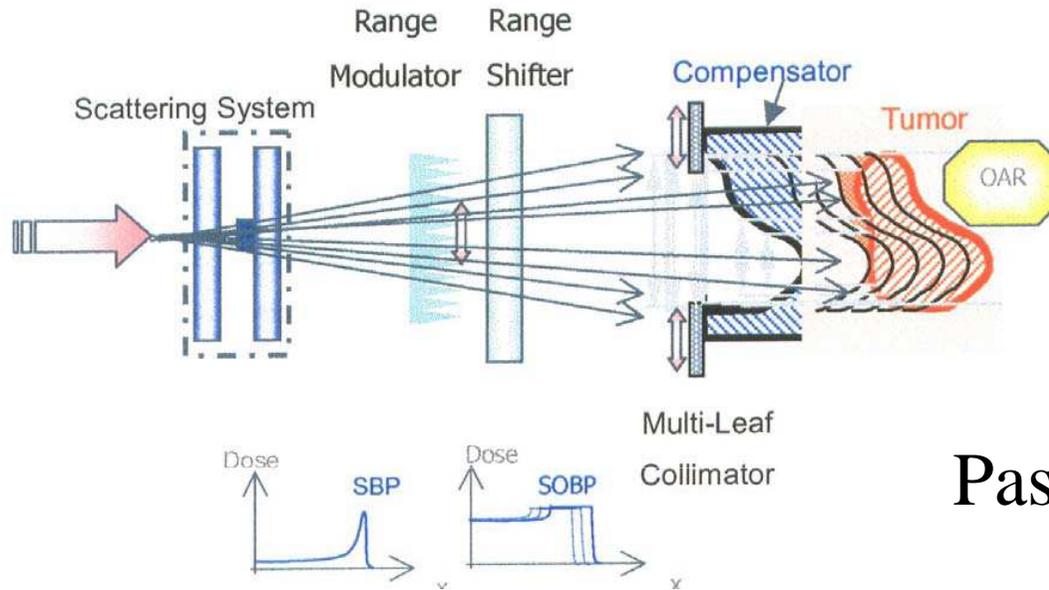
Proton



Energy

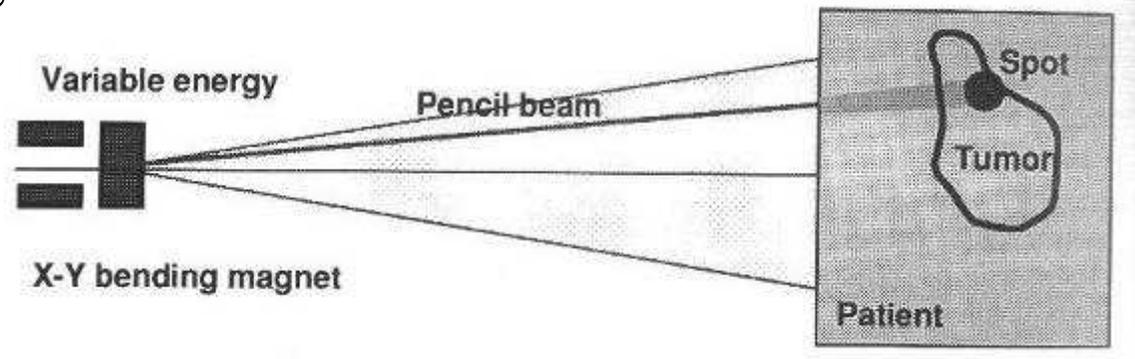


Forme

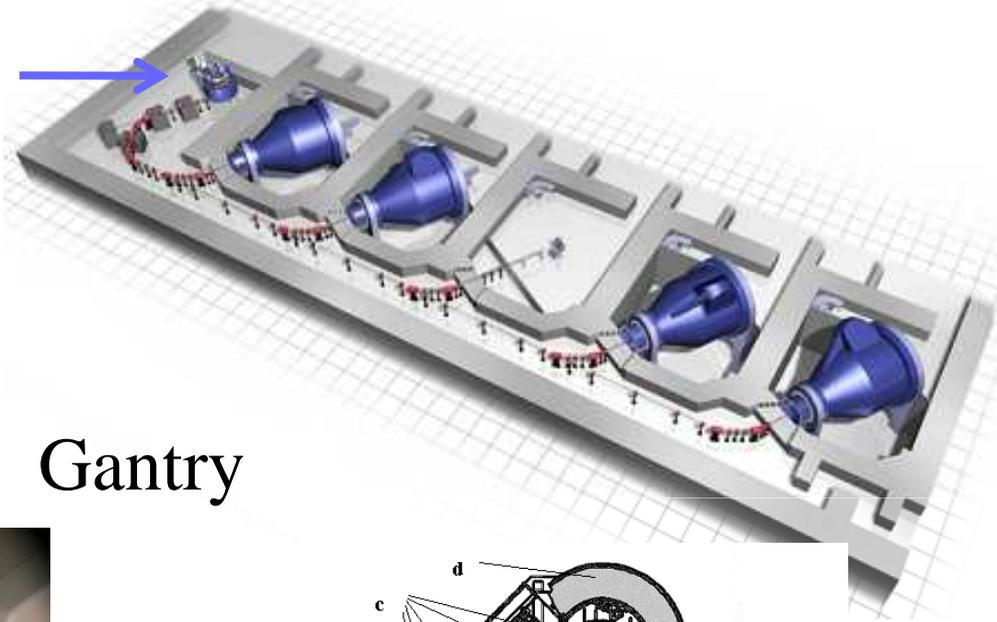


Passive (scattering)

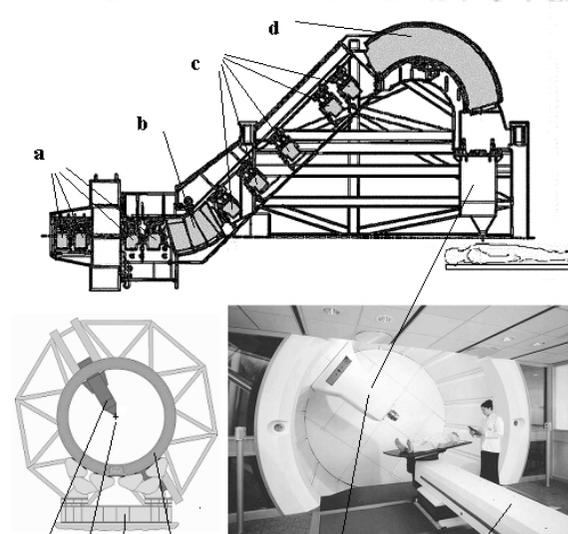
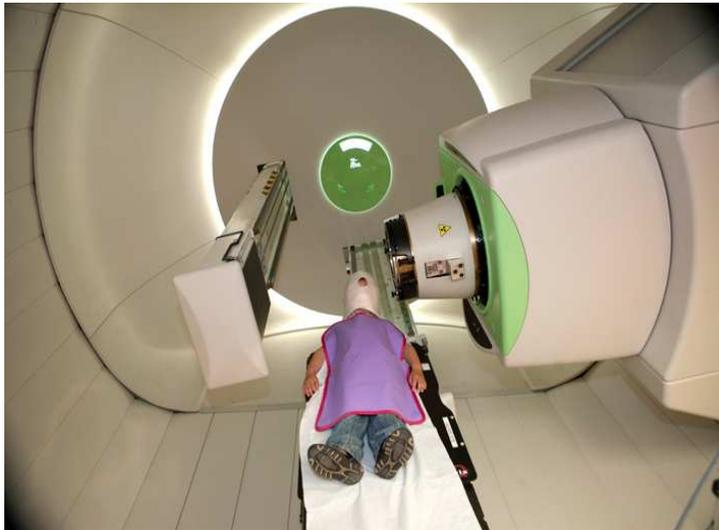
Active scanning

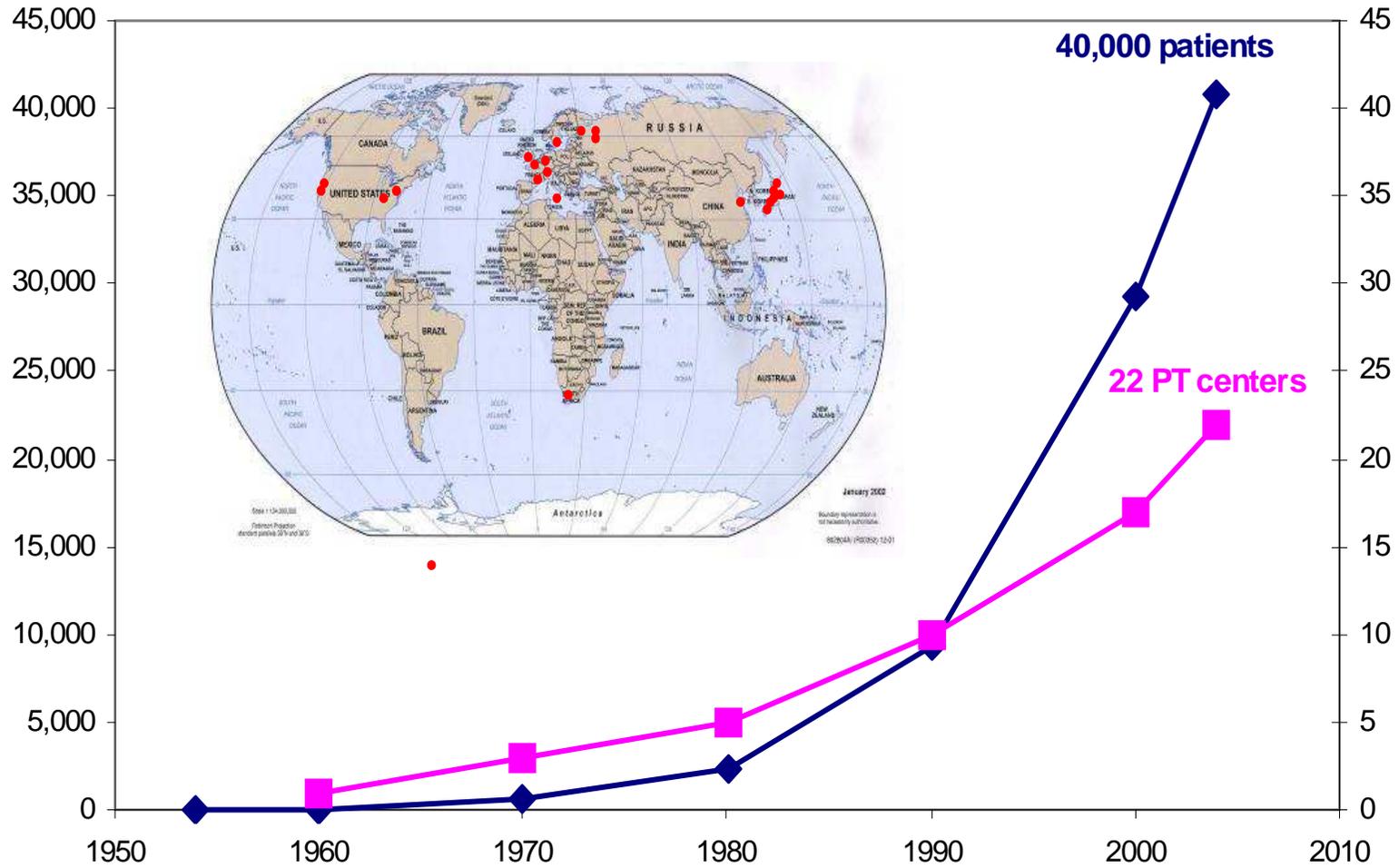


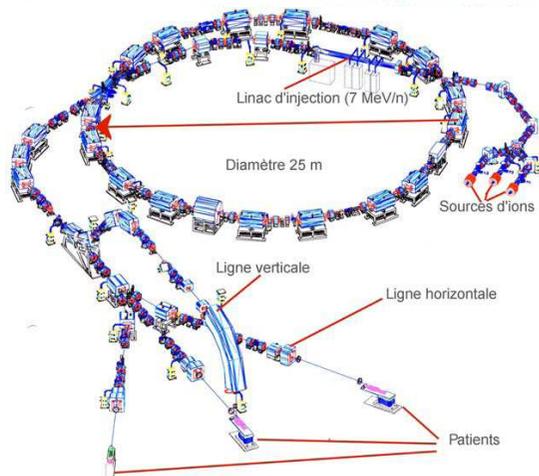
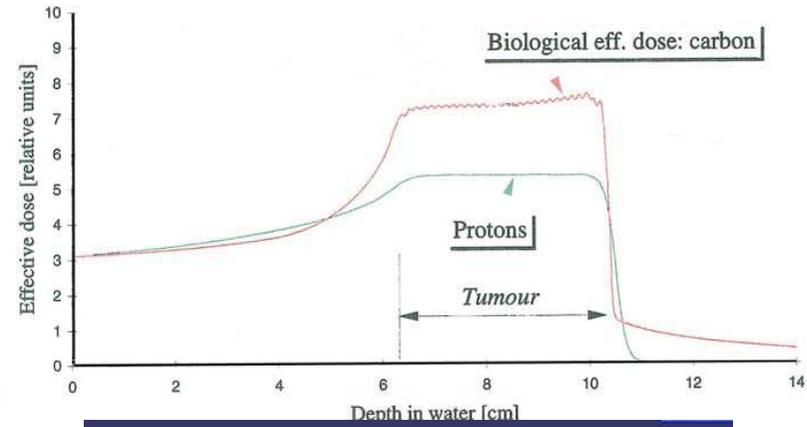
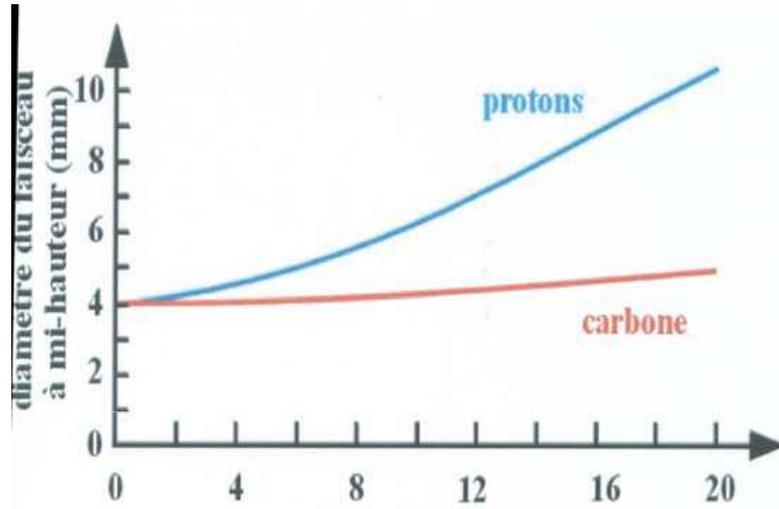
Accélérateur



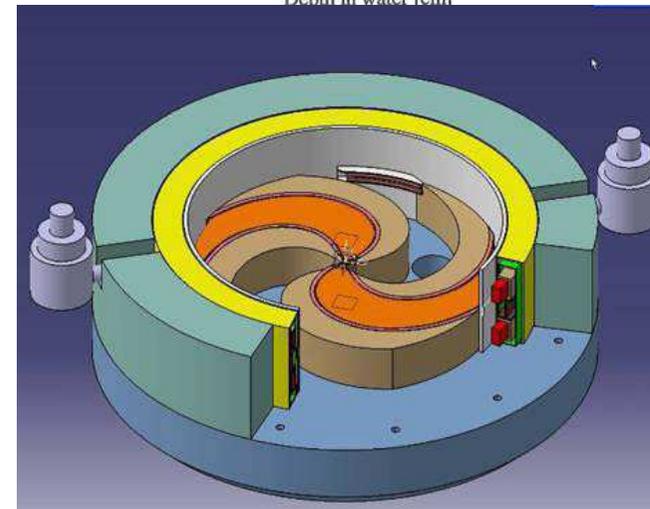
Gantry







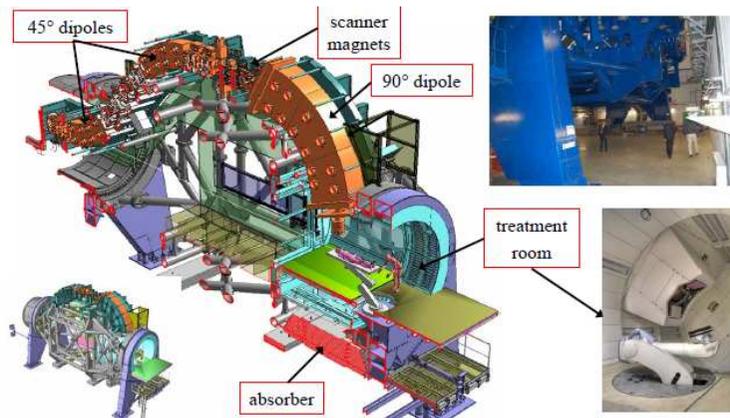
Synchrotron (CNAO)



Superconducting Cyclotron (IBA)

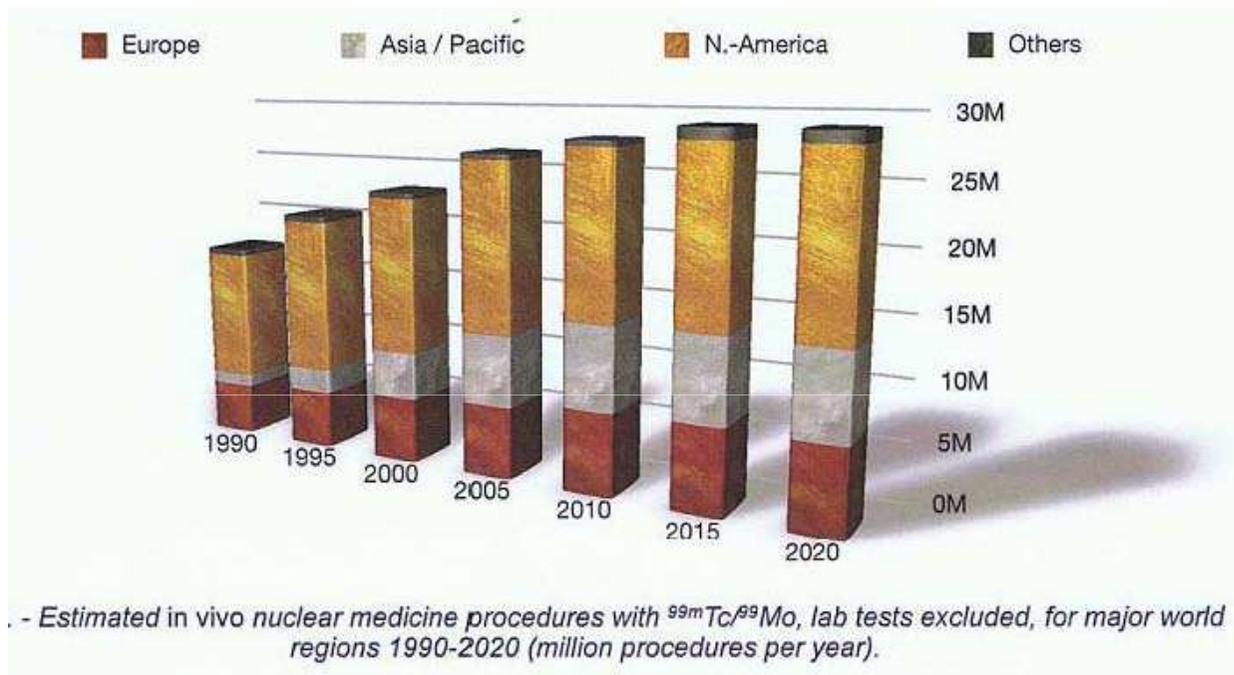


Effet biologique supérieur
Moins de diffusion angulaire
Fragmentation
6.6 T.m BR
2.4 T.m proton



Heidelberg GANTRY
22m long
13m Diameter
450t

Innovation nécessaire!



Réacteurs disponibles en diminution, mais problèmes des déchets liés à l'Ur

- Réflexions en cours sur linac supra vs cyclotrons
- Cibles supportant les forts courants?
- Réduction de taille des cyclotrons (énergie et courant) pour diminuer le blindage
- Fonctionnement automatisé
- Développement probable (remplacement des réacteurs)