ACCELERATORS AND CRYOGENIC SYSTEMS

Cyclotrons : general description and adaptation to the Technofusion requirements

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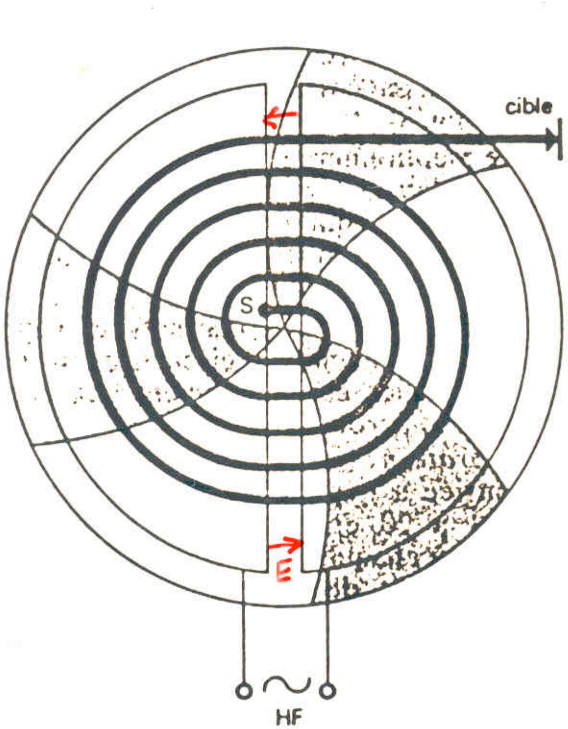
A very simple idea !



$$r = \frac{p}{eB} = \frac{mv}{eB} \Longrightarrow \frac{T}{2} = \frac{\pi m}{eB}$$

$$\omega_r = 2\pi f_r = \frac{2\pi}{T} = \frac{eB}{m}$$

Synchronism : $\omega_{rf} = h\,\omega_r$

h : harmonic number

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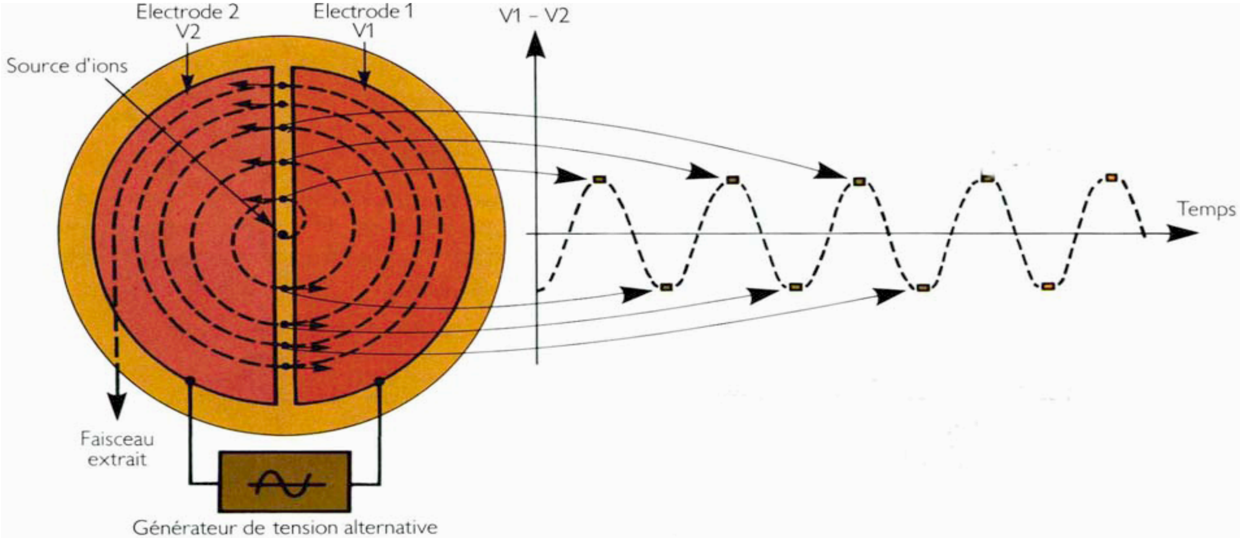
Practical relationships



K factor : $K_{MeV} = 48.244 \times B^2R^2$ (tesla,m)

$E_{AMU} = K .(n/A)^2 = 48.244 \times B^2R^2 \times (n/A)^2$

F_{part} (MHz) = $15.36 \times B \times n/A$

F_{HF} (MHz) = $h \times F_{part} = h \times 15.36 \times B \times n/A$

n : charge number

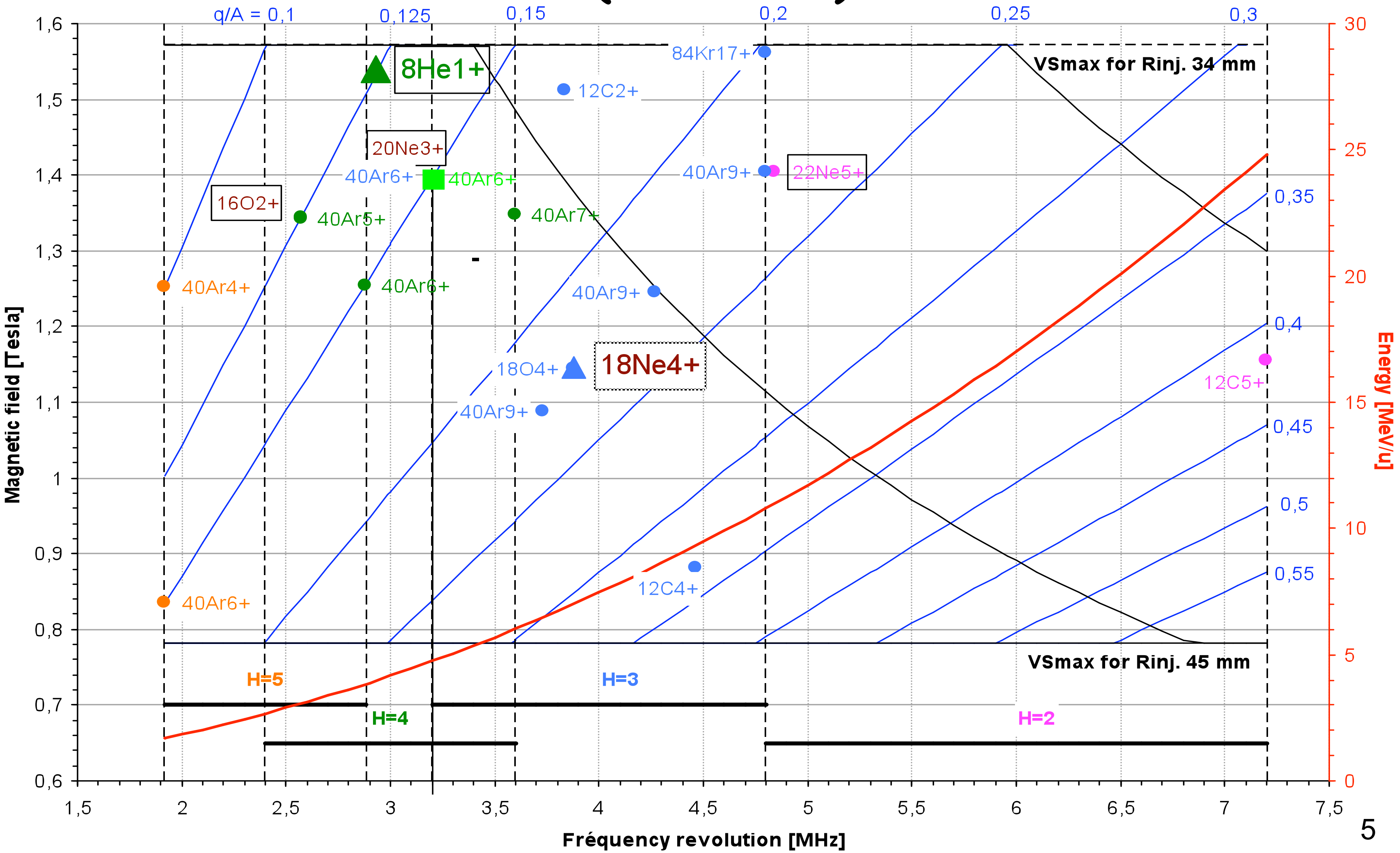
A : mass number

h : harmonic number

Examples of preliminary design

		Room temperature cyclotron	Superconducting cyclotron
	B (tesla) Rext (m)	**1,5** **0,61**	**3** **0,305**
Proton	n A E(MeV) Frev. (MHz)	1 1 **40,4** 23,0	1 1 **40,4** 46,1
Carbon	n A E (MeV)/AMU Frev. (MHz)	4 12 **4,5** 7,7	4 12 **4,5** 15,4

Example : running diagram of CIME (GANIL)



Effect of the mass increase

- The mass of the particle increases with its kinetic energy :

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

- As $\omega = qB/m$, B must remain proportionnal to m.
- $v = \omega.r = 2\pi.Frev\ .\ r$,
- we get (approximatly) : **$(dB/B_0)_{\%} = 5\ .(B_0.n.r/A)^2$**

		Room temperature	Superconducting
	B (tesla)	1,5	3
	Rext (m)	0,61	0,305
Proton	E(MeV)	40,4	40,4
	dB/B_0 %	**4,19**	**4,19**
Carbon	E (MeV)/AMU	4,5	4,5
	dB/B_0 %	**0,47**	**0,47**

Isochronism

- It is mandatory to maintain the revolution frequency constant.
    - (suppose 1% error, and h =3, after 1 turn, the phase shift is already : 0.01*3*360 = 10.8°, after 9 turns, the particle start to be decelerated !)
- As shown before, B must follow a field law which is particle and energy dependant.
- A certain number of correcting coils are necessary to adjust the field law for every particle and every final energy.

Correcting coils in the GANIL cyclotrons

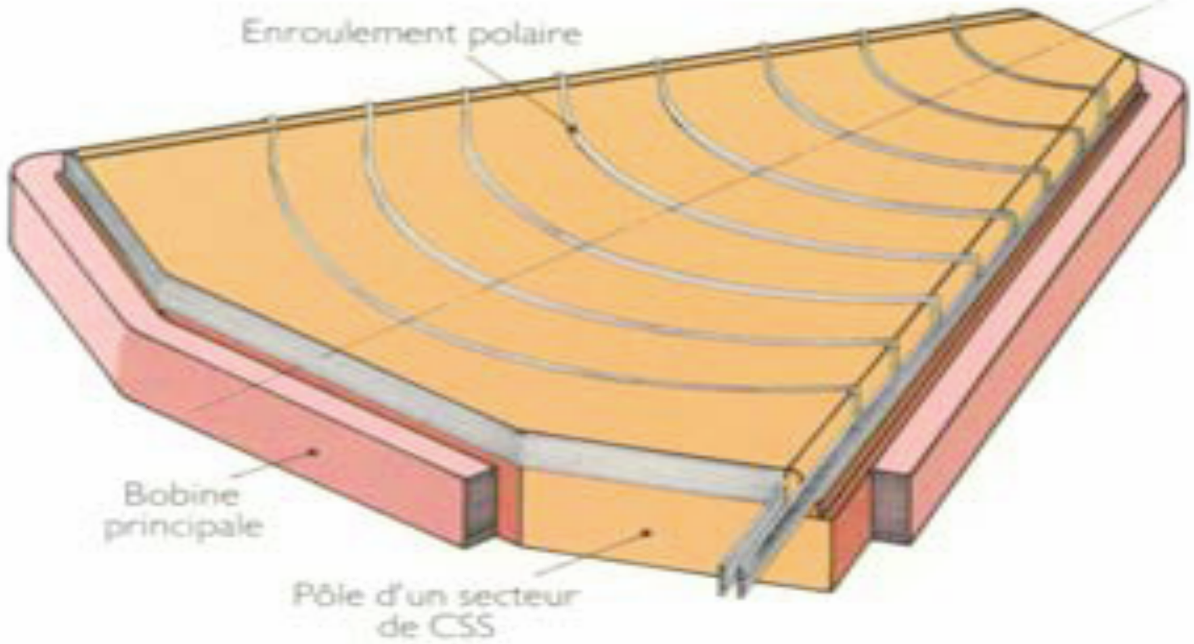


Schéma de principe de la disposition des enroulements polaires

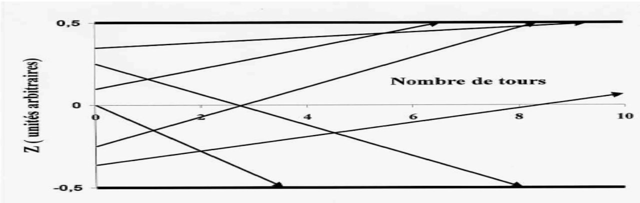
Focusing

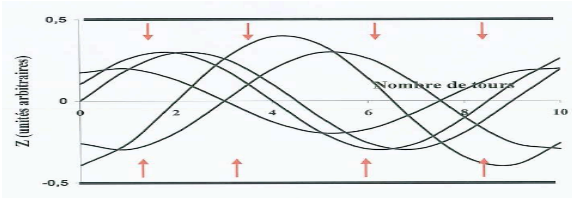
If the magnetic field is « flat » (B(r) = Constant), there are no focusing forces acting on the particles, they are rapidly lost (figure left below).

One can show that there are focusing forces if B is decreasing when r increases.

We know that, at the contrary, B(r) must increase with r for isochronism.

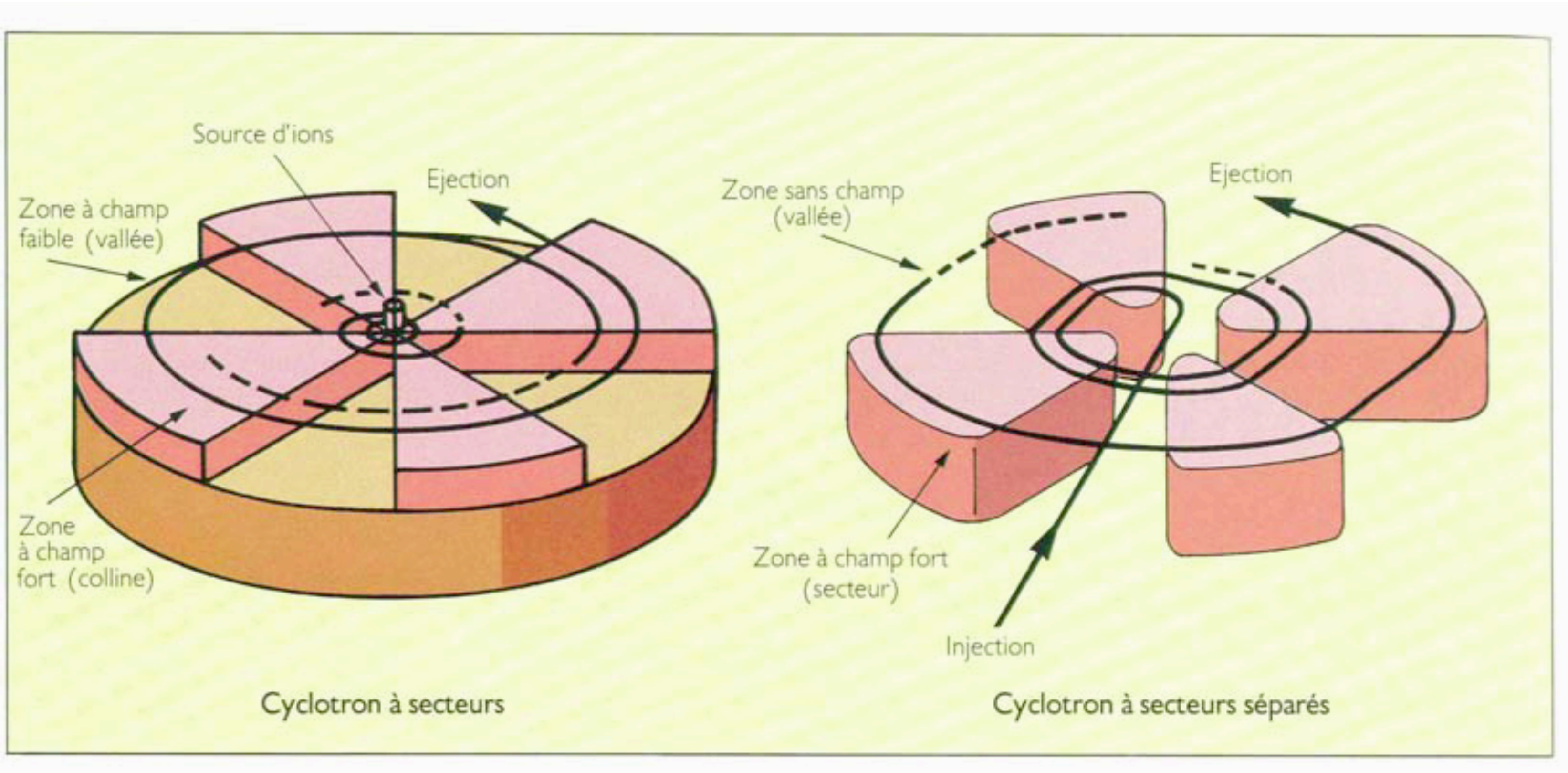
Contradiction : its why the energy of the first cyclotrons was limited to less than 10 MeV.

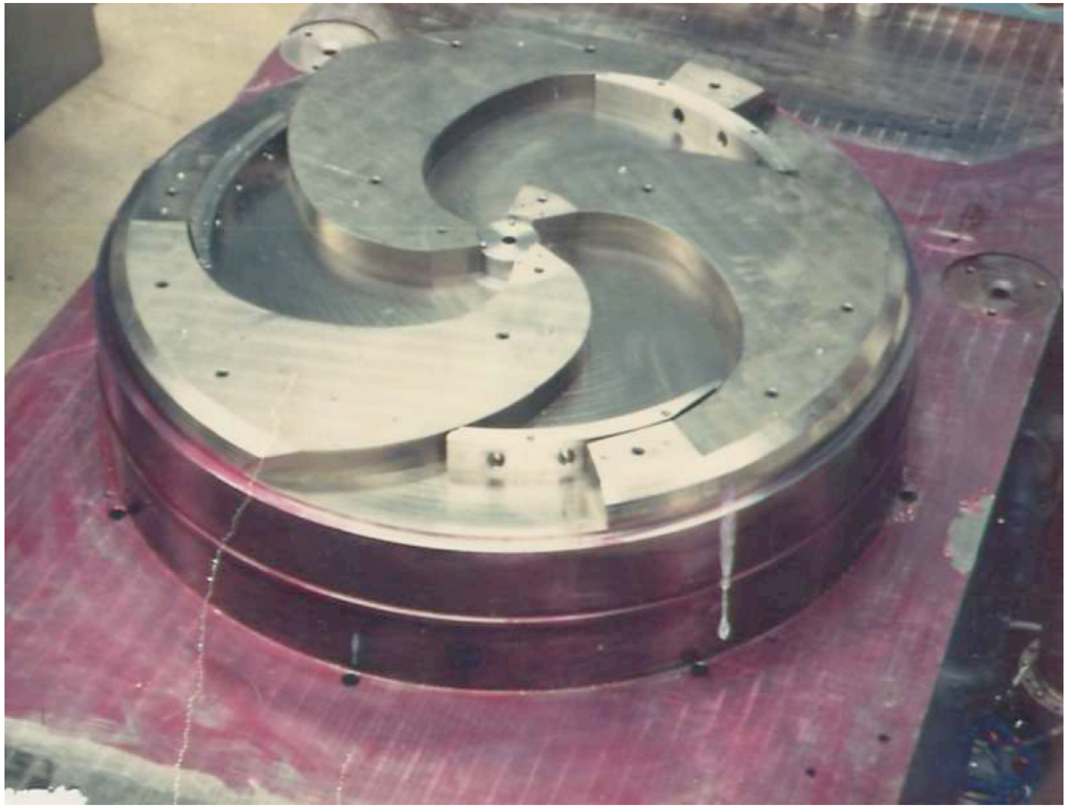




Solutions for focusing

- 2 solutions where successively developped :
  - Synchrocyclotron : the field decreases with r (focusing), the RF frequency varies in accordance (isochronism). You can get very high energy but only for one bunch of particle at each acceleration cycle.
  - Cyclotron isochrone relativiste : the field varies azimuthally, there are « hills » and « valleys », focusing forces are effective at every transition between hills and valleys, the mean magnetic field increases with r for isochronism, the net result is focusing. (L.H. Thomas : first publication,1938, Courant, Snyder and Livingston : principle of strong focusing, 1952)


Source d'ions
Ejection
Zone à champ
faible (vallée)
Zone
à champ
fort (colline)
Cyclotron à secteurs
Zone sans champ
(vallée)
Ejection
Zone à champ fort
(secteur)
Injection
Cyclotron à secteurs séparés



GANIL (Caen) C_0 : injector cyclotron

PSI (Villigen) protons 2 mA, 590 MeV

Ion sources

- Production of protons is simpler than production of multicharged heavy ions,
- As a consequence, the ion sources and the injection methods are usually different.

Proton sources

- The source can be relatively simple and small.
- One example is the PIG source (Penning Ion Gauge) which can be placed directly in the center of the cyclotron; the extraction voltage is provided by the RF voltage.

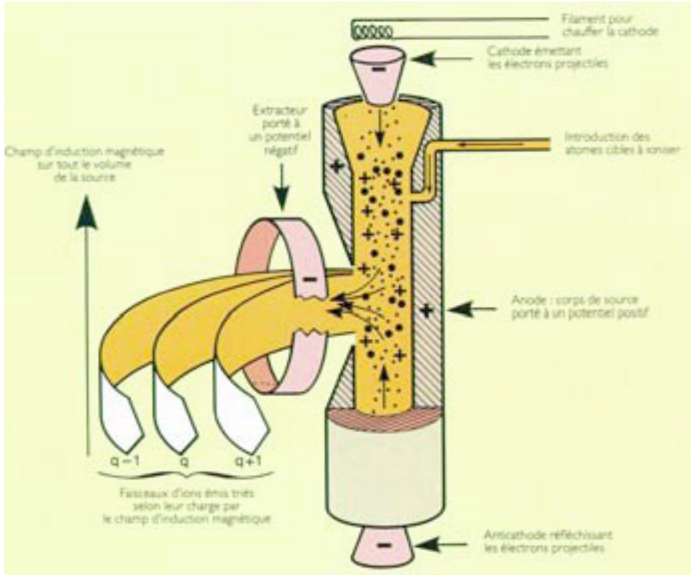
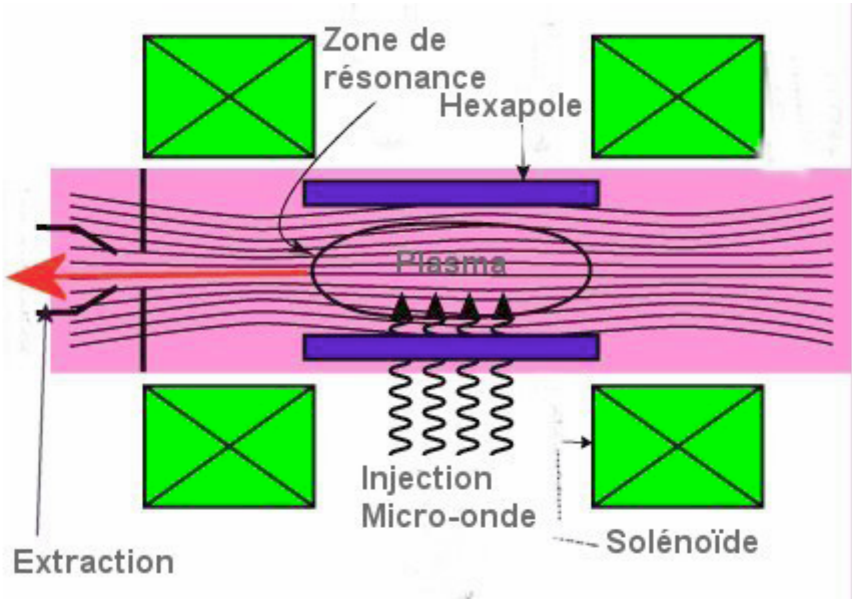


Schéma de principe d'une source d'ions lourds multichargés.

Multicharged heavy ion source

- The most convenient source for a cyclotron is the ECR one (Electron Cyclotron Resonance) :
  - Can deliver relatively high charge states,
  - Produces a DC beam,
  - Easy to operate (at least for gaseous materials)
  - Robust, limited maintenance.
- But the ECR source cannot be *inside* the cyclotron, you need injection line and axial injection system.



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An example of ECR source

The attached table gives some values of the intensities produced
By the *hypernanogan* source commercialized by PANTECHNIK.
(intensities extracted of the cyclotron will be 3 to 10 times lower)

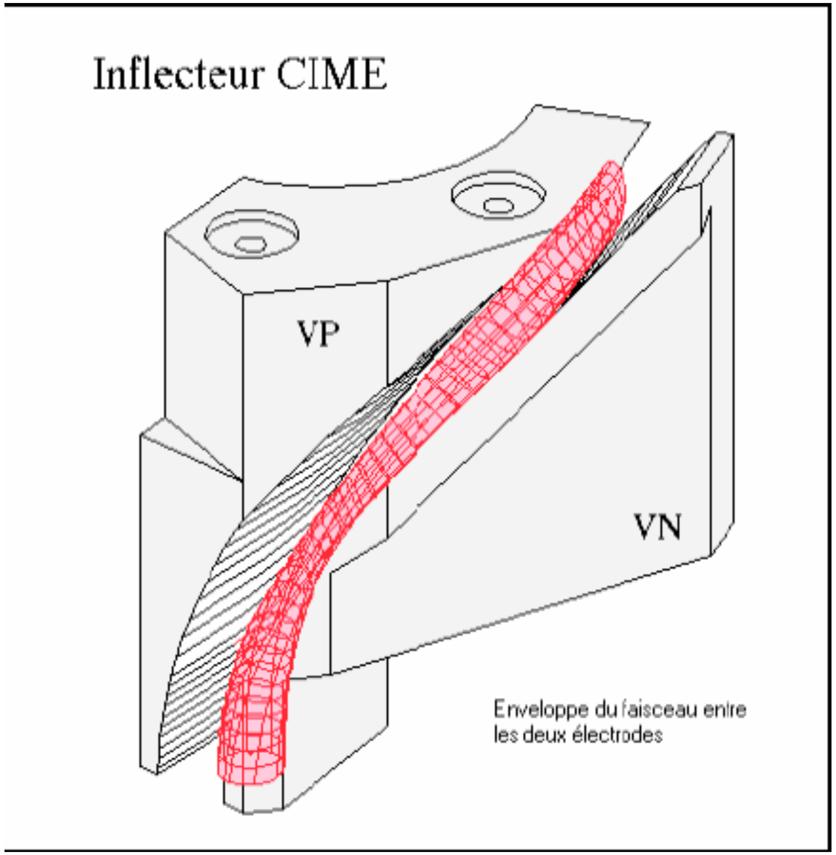
Element	Charge state	Current	
		eμA	pμA
H	1	2000	2000
O	4	1450	362,5
	5	655	131,0
	6	723	120,5
Ca	11	100	9,1
	12	50	4,2
Pb	24	16	0,7
	25	20	0,8
	27	24	0,9
	28	12	0,4

Metallic ions

- Metallic ions can be produced also by ECR sources, different solutions can be worked out :
  - An *oven* attached to the source can inject the metallic vapor into the source.
  - For some metals, it exist gaseous compounds : the *metallocenes* (ex : $(C_5H_5)_2Fe$) which can be injected (often unstable, poisonous)
  - For very refractory metals, a *sputtering electrode* can be introduced into the plasma, it must be movable and polarized.
- All these solutions engage a special design of the source and a dedicated manpower to run it.

Axial injection

- Several functions must be present :
  - High voltage for ions extraction,
  - Focusing,
  - Charge state selection,
  - Bunching,
  - Injection in the cyclotron center (hyperboloid inflector : Belmont, Pabot).



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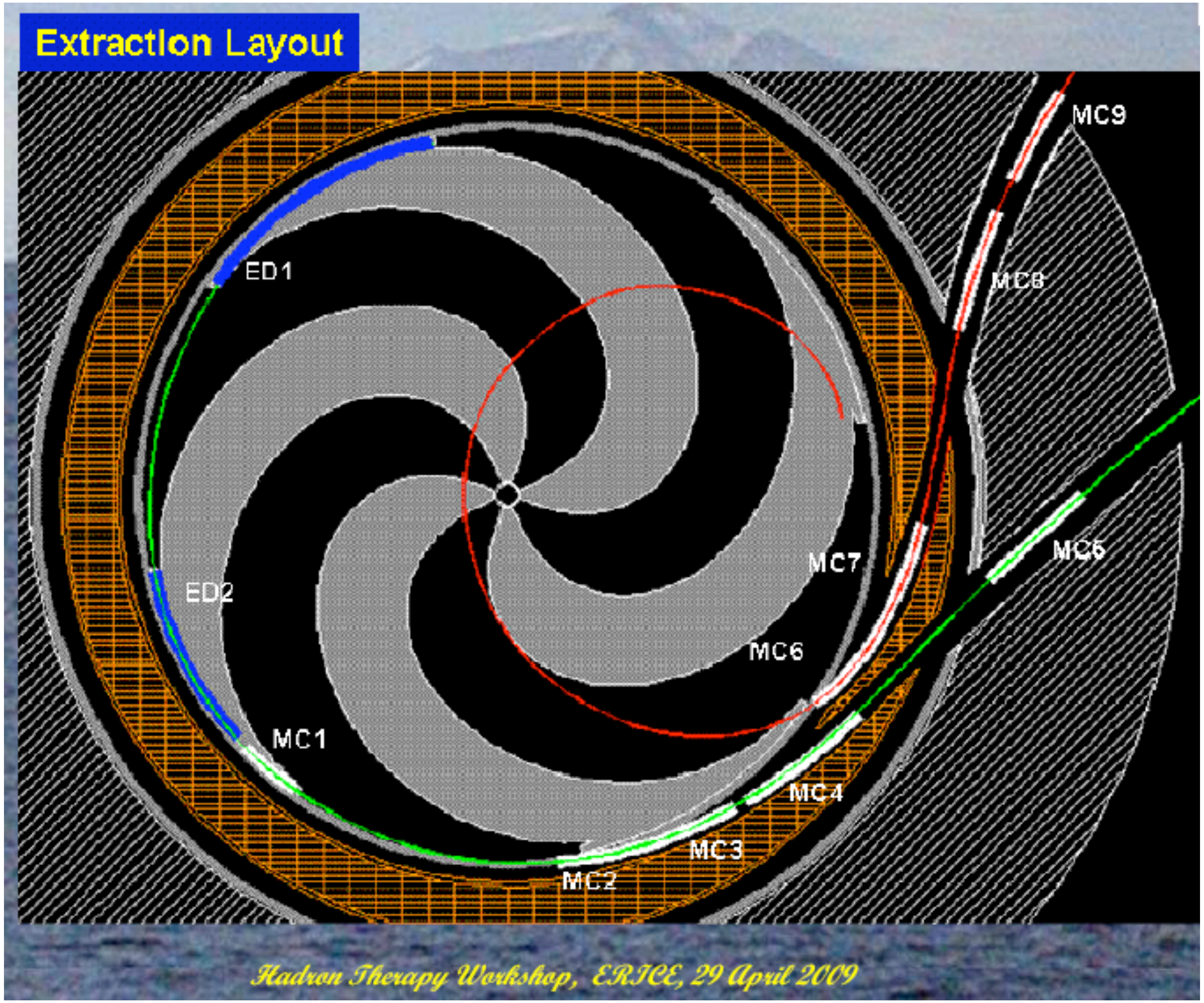
Extraction of the beam

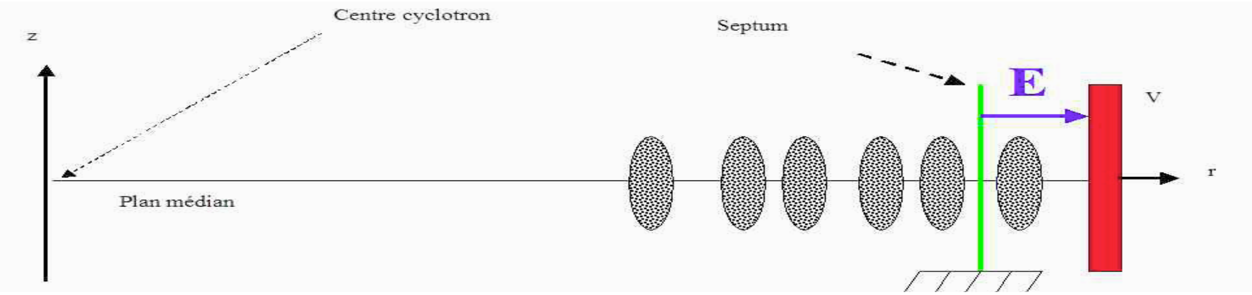
- After acceleration, the beam must be extracted, it is not so easy to leave the magnetic field and get a beam having good optical properties (emittance).
- The conventional way uses an electrostatic channel followed by a magnetic one and eventually focusing quadrupoles.
- More exotic methods uses a stripping foil in the last turn.



Example of a sophisticated extraction scheme : the K300 superconducting INFN/IBA cyclotron

Turn separation

- One can show that the separation of the turns is inversely proportional to the radius and to B square :
- $DR = K2/B^2R \times A/n$



Some existing cyclotrons

	Superconducting		Room Temperature		
	INFN/IBA	VARIAN/ACCEL	C30/IBA	C70/IBA ARRONAX	GANIL CIME
K	1200	250	30	70	265
B mean (ext)	3,15	3	1,7	1	1,34
r extraction	1,32	0,8	0,5-0,75	1,2	1,75
RF mode	fixed	fixed	fixed	fixed	variable
RF Frequency	97	72,8	66	30,4	9,6-14,5
Magnet weight	350	90	45	120	500
p (MeV)	260	250	15-30	30-70	
α (MeV/A)				70	
C (MeV/A)	300				
Heavy ions					2-25
Comment			stripping extraction	Stripping and conv.	

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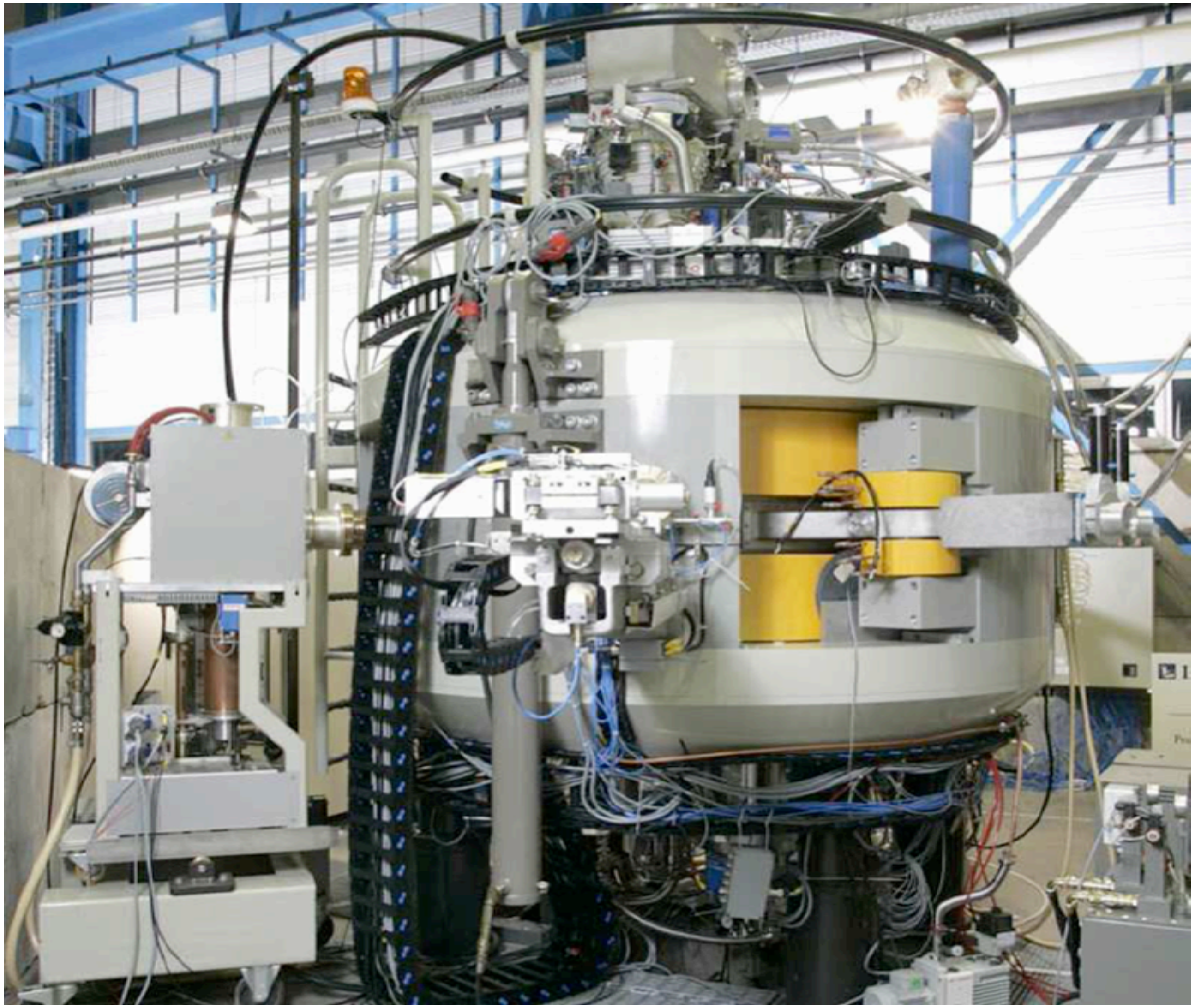
IBA C30



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IBA C70 (Arronax, Nantes)+

TechnoFusion requests

Isotope -	E/AMU	Intensity (pμA)
^{1}H goal	10 - 40	100 - 1500
^{1}H accepta	15 - 30	id.
^{12}C	8	8
^{18}O	12,5	1,6
^{27}Al		
^{28}Si	12	1,4
^{56}Fe	6,9	0,8
^{184}W	2	0,03

Only one cyclotron or two ?
(a few lines for reflexion)

- The very large energy range (2 – 40 MeV/AMU) means a sophisticated machine if there is only one cyclotron :
  - Axial injection,
  - Variable frequency RF,
  - Variable magnetic field,
  - Powerfull trim coils,
  - Large range of harmonic numbers.

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Only one cyclotron or two ?
(a few lines for reflexion)

- If there is one cyclotron dedicated for protons only, such a machine can be very compact and can probably be directly ordered from factory :
  - Example : C30 from IBA delivers protons 15 – 30 MeV with probably sufficient intensities.
- Such a machine is very reliable and needs very limited manpower for operation and maintenance.

Only one cyclotron or two ?
(a few lines for reflexion)

- Heavy ions cyclotron:
  - This machine is more sophisticated, the specifications are for a K = 110 MeV.
  - Questions : -
    - Only one energy for each isotope ? (no energy adjustment)
    - Do you accept small changes (a few%) in the specified energies ?
  - If the answer is yes at these two questions, it seems possible to design a cyclotron working with a fixed RF frequency, with limited field variations, some trim coils and a limited number of working harmonics.
  - Such a machine needs a dedicated design, but it does not present any particular issue.

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Superconducting or not ?
(a few lines for reflexion)

- Superconducting cyclotrons are more compact and are less power consuming.
- But, they are more difficult to design (everything is more compact, but the fields are larger !)
- Superconducting cyclotrons are less flexible than conventional ones.
- At a first approach it does not seems useful to design a superconducting cyclotron for a k=110 which remains a relatively small machine.