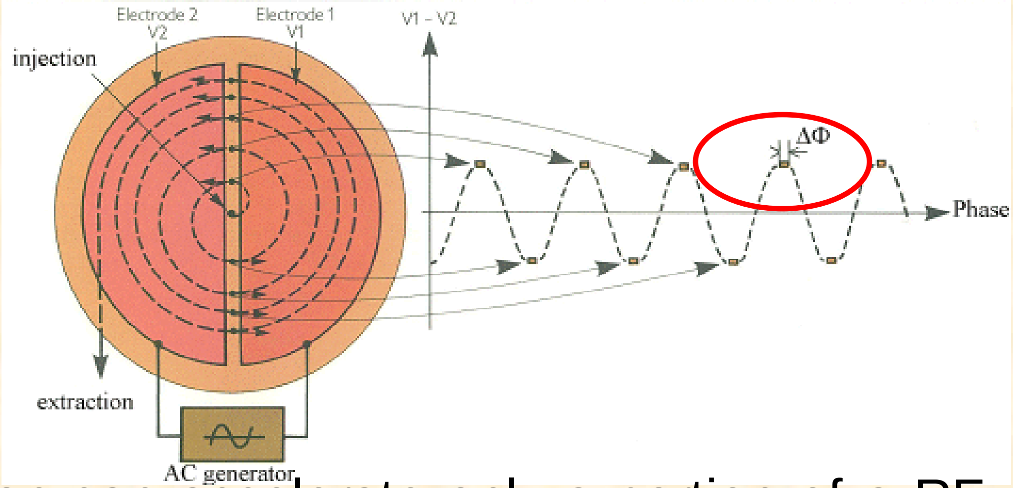
Cyclotrons

Chapter 2

- Basic Longitunal dynamics
- Acceleration
- Injection
- Extraction

Longitudinal dynamics



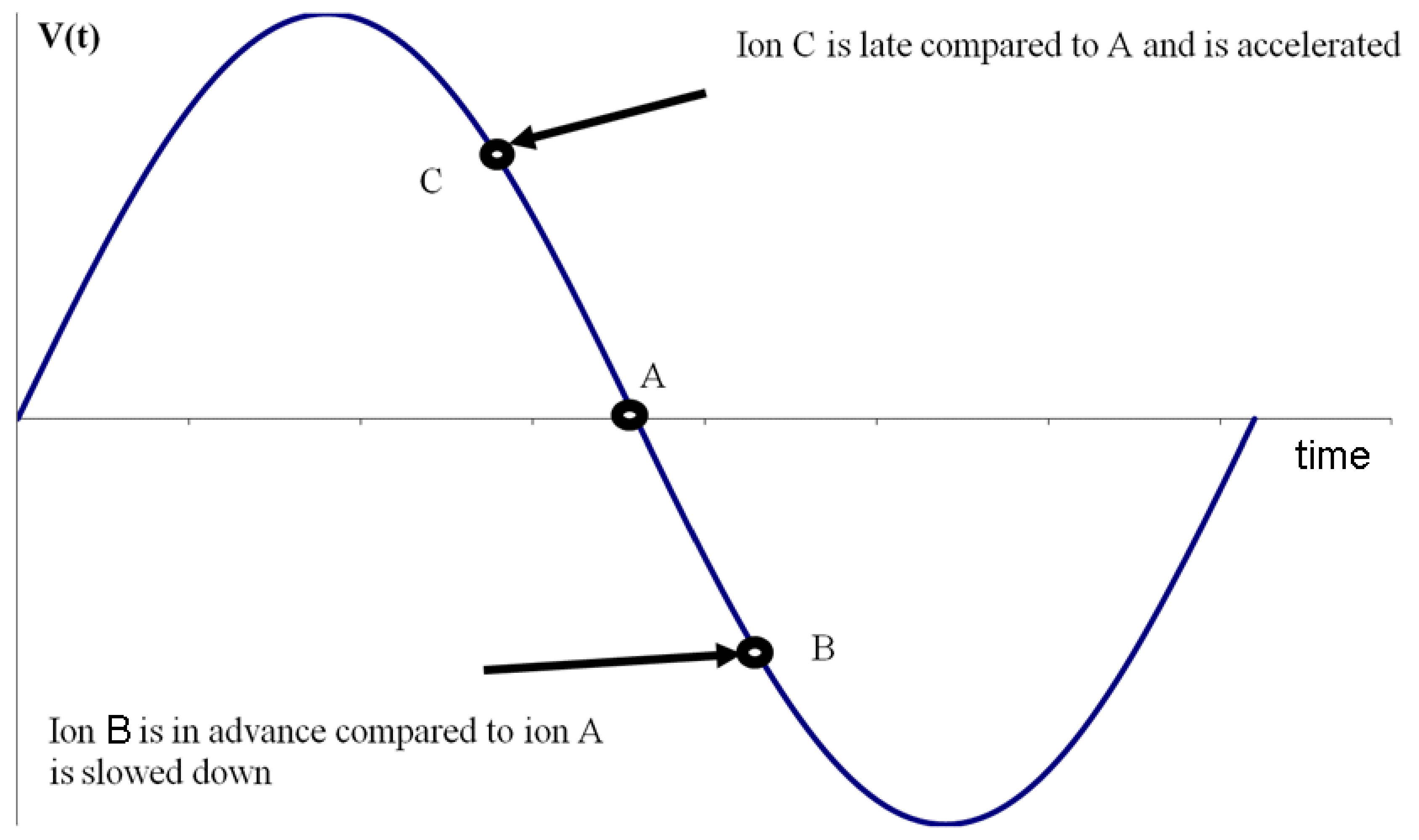
Longitudinal matching: A cyclotron can accelerate only a portion of a RF cycle

The acceptance is 20 RF (out of 360).

The external ion source, such as ECR or EBIS etc… delivers DC-beams compared to the cyclotron RF frequency.

A buncher located upstream the cyclotron injection will accelerate particles which would come late to the first accelerating gap and decelerates the ones coming too early. Then, more particles can be accelerated in the cyclotron within the ± 20° RF acceptance. Increase the efficiency by a factor 4-6

Buncher principle



Acceleration

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

If V_0 varies, the number of turn varies.

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

$$\delta W = N_g \; q \; V_0 \cos\varphi$$

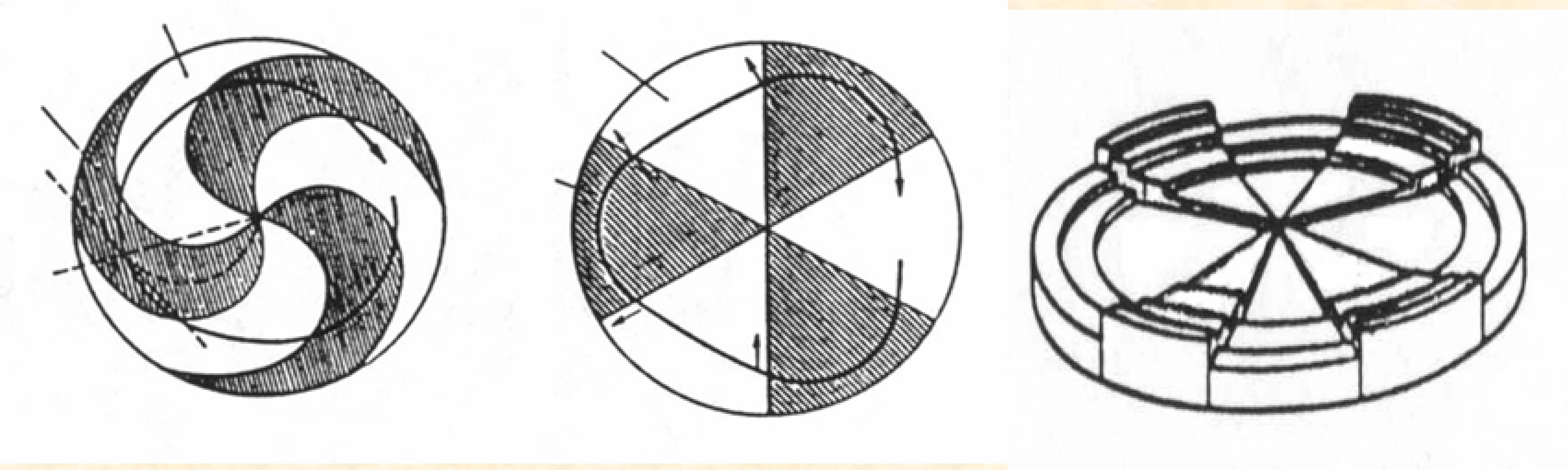
N_g : number of gaps

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

$$\frac{\delta r}{r} = \frac{1}{2}\frac{\delta W}{W} = \frac{q V_0 \cos\varphi}{2\,W} \propto \frac{1}{r^2}$$

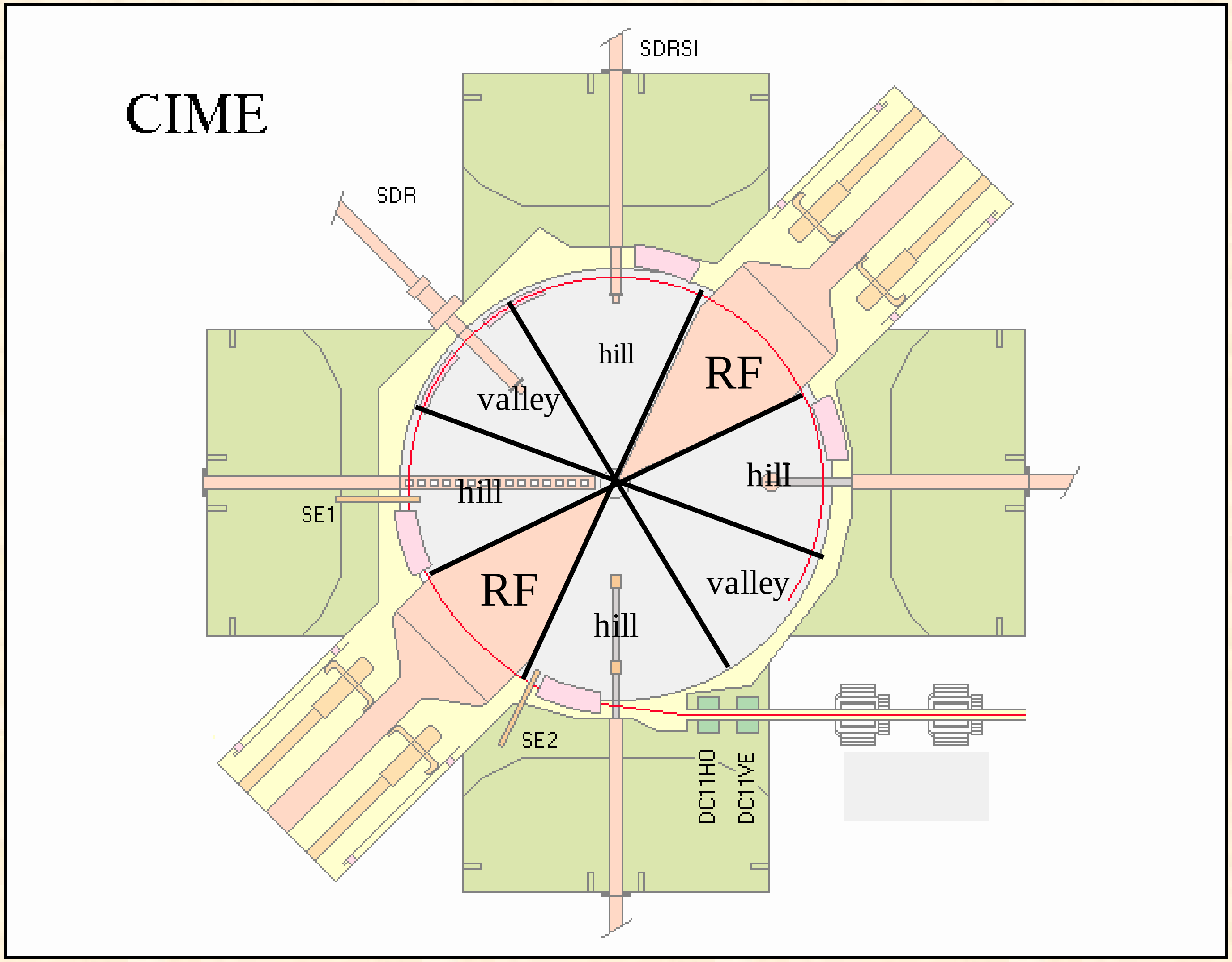
$$\boxed{\delta r \propto \frac{1}{r}}$$

RF Technology



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

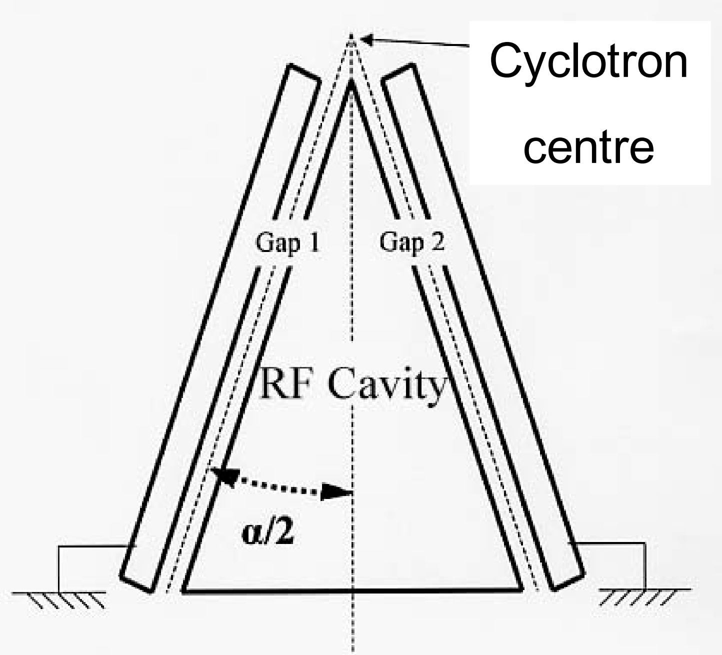
RF Cavities (not Dees)



Example of RF Cavities (not Dees)

Energy gain in 1 gap of CIME cyclotron:

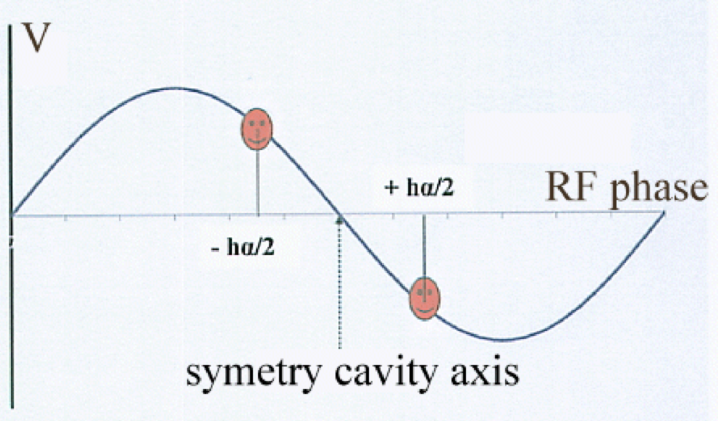
$$\delta W = qV_0 \sin\left(\frac{h\alpha}{2}\right)\cos\varphi$$



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

$$\delta W = qV_0 \sin\left(\frac{h\alpha}{2}\right)$$

h	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Sin(hα/2) $(\alpha = 40°)$	**0.64**	**0.87**	**0.98**	**0.98**	**0.86**	**0.64**	**0.34**



All the modes accelerate the particles but for h > 7 the efficiency is too low.

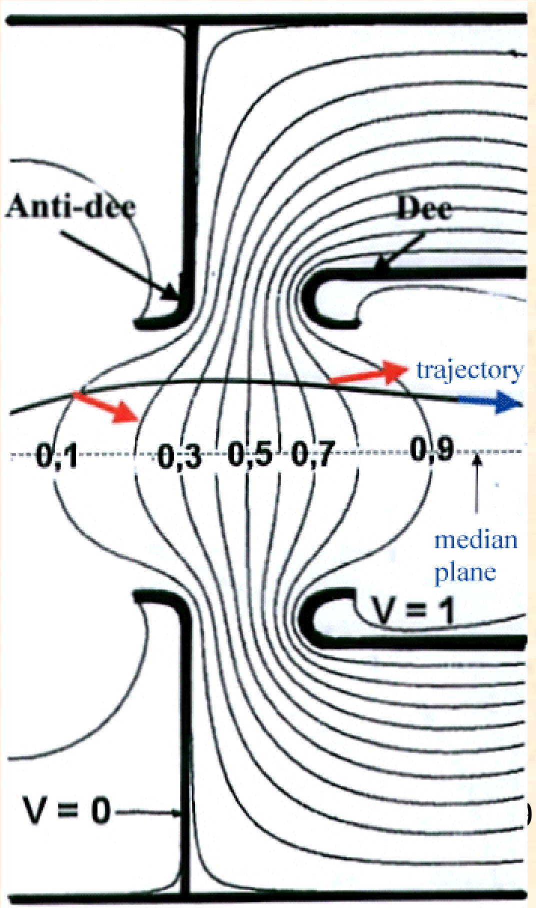
Accelerating gap

The formula $\delta W = QV_0 \sin(\frac{h\alpha}{2})$ 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:

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

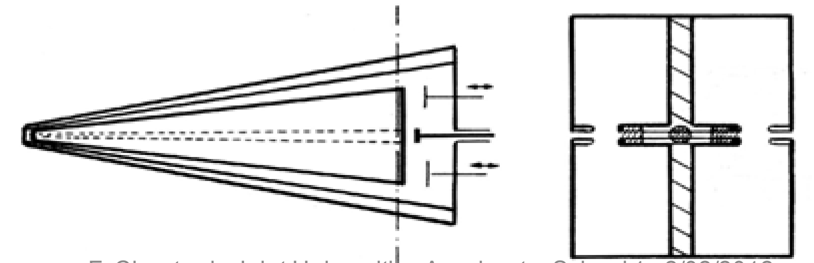
$$\boxed{\delta W = QV_0\,\tau \sin(\frac{h\alpha}{2})}$$



Introduction of pillars into the cavity to reduce the azimuthal field extension (seen in the § injection)

The Structure of a GANIL Double Gap λ/2 Resonator

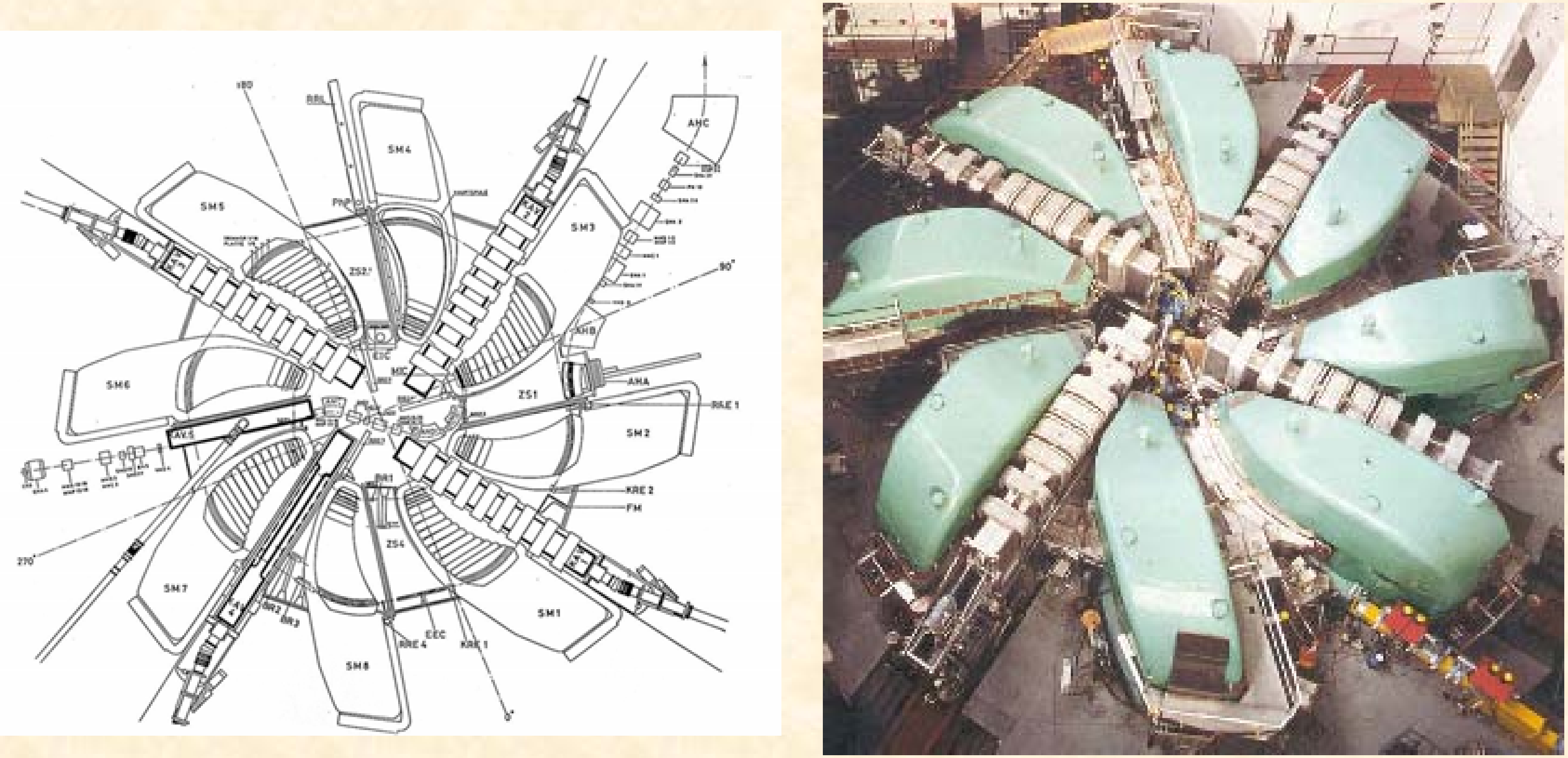
Stainless steel support frame, beam plane is visible



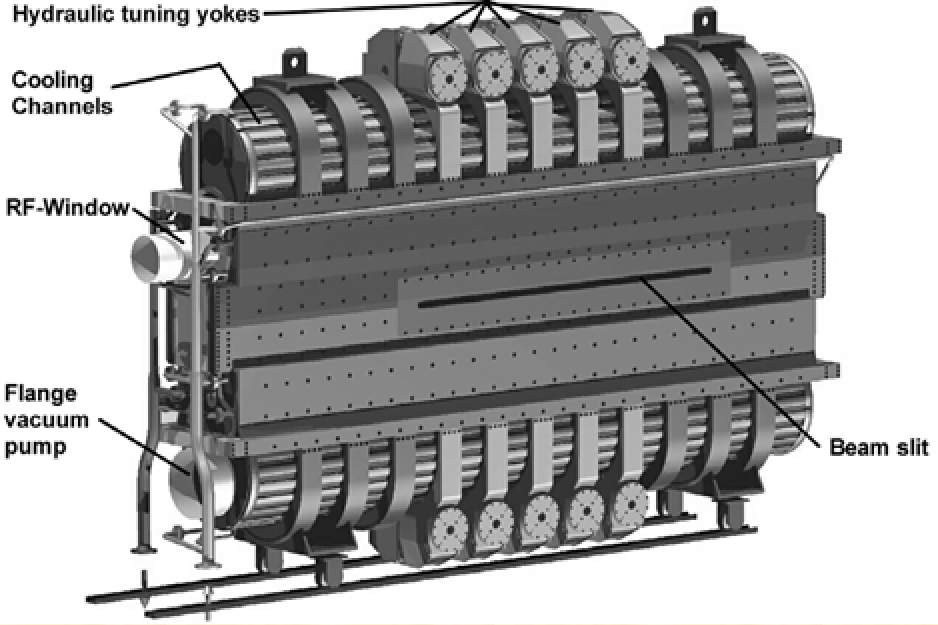
Copper skinned inner conductors with 'Dee' (inner electrode)

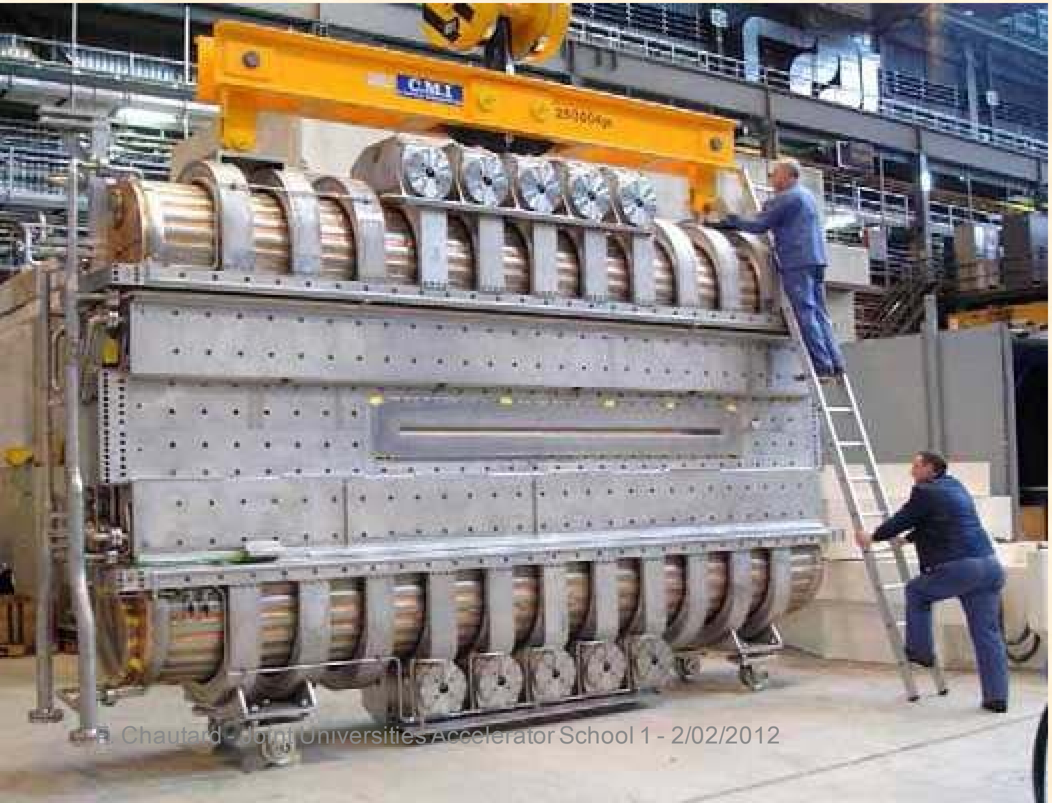
Outer shell of resonator, with support frame and beam slit

An example of a separate sector cyclotron: the PSI ring cyclotron



Typical 'Separated Sector Cyclotron' (SSC), median plane view (left), and photo (right). Shown is the PSI 590 MeV (p) ring cyclotron, with 8 sector magnets and 4 accelerating cavities





50 MHz, CW
Voltage: 1 MV

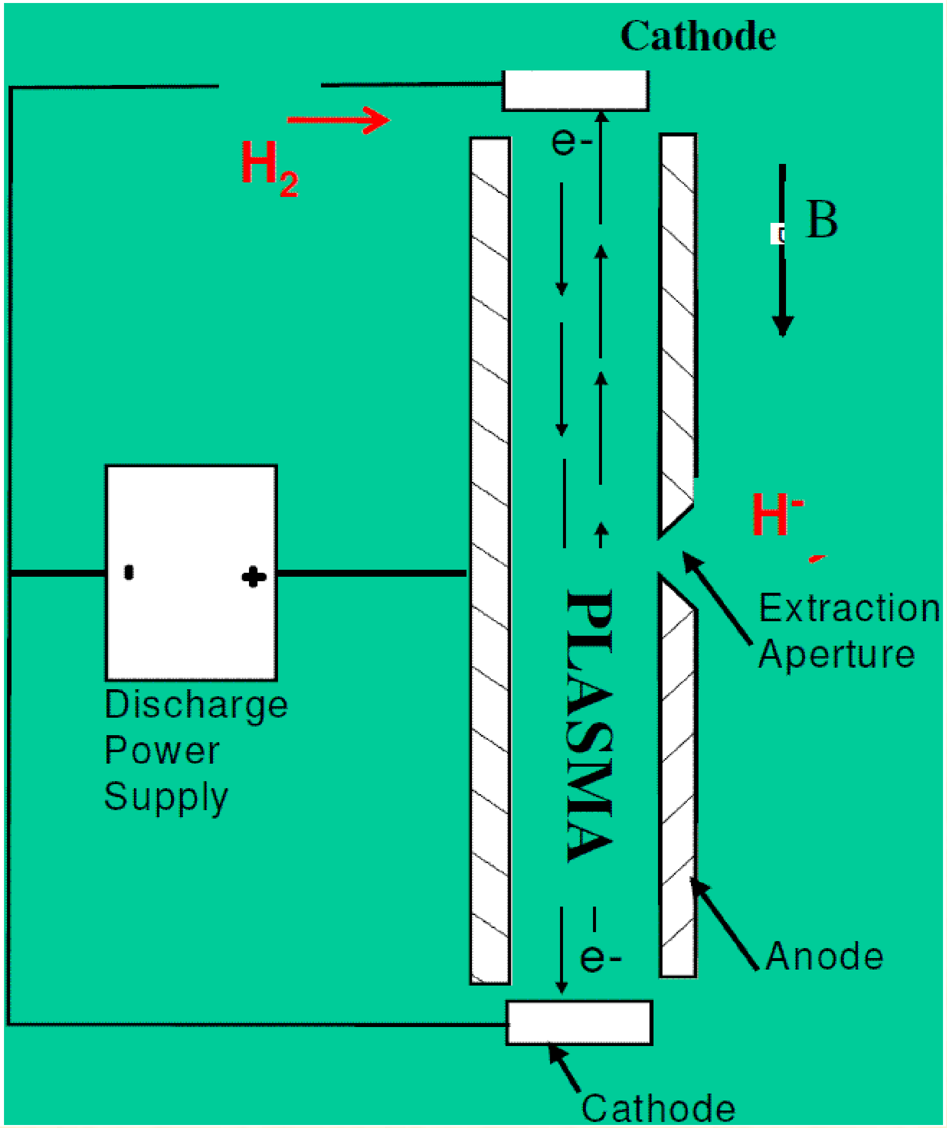
Beam injection

- Axial injection
- Radial injection

Axial injection

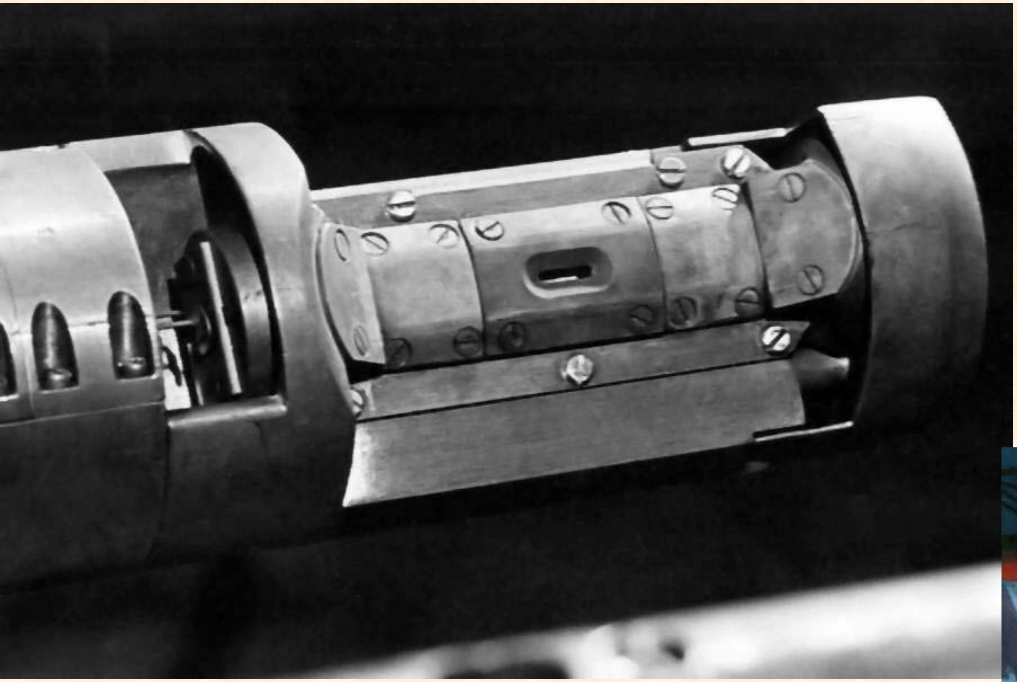
Injection of the beam through the centre of the cyclotron

Cold Cathode PIG Ion Source

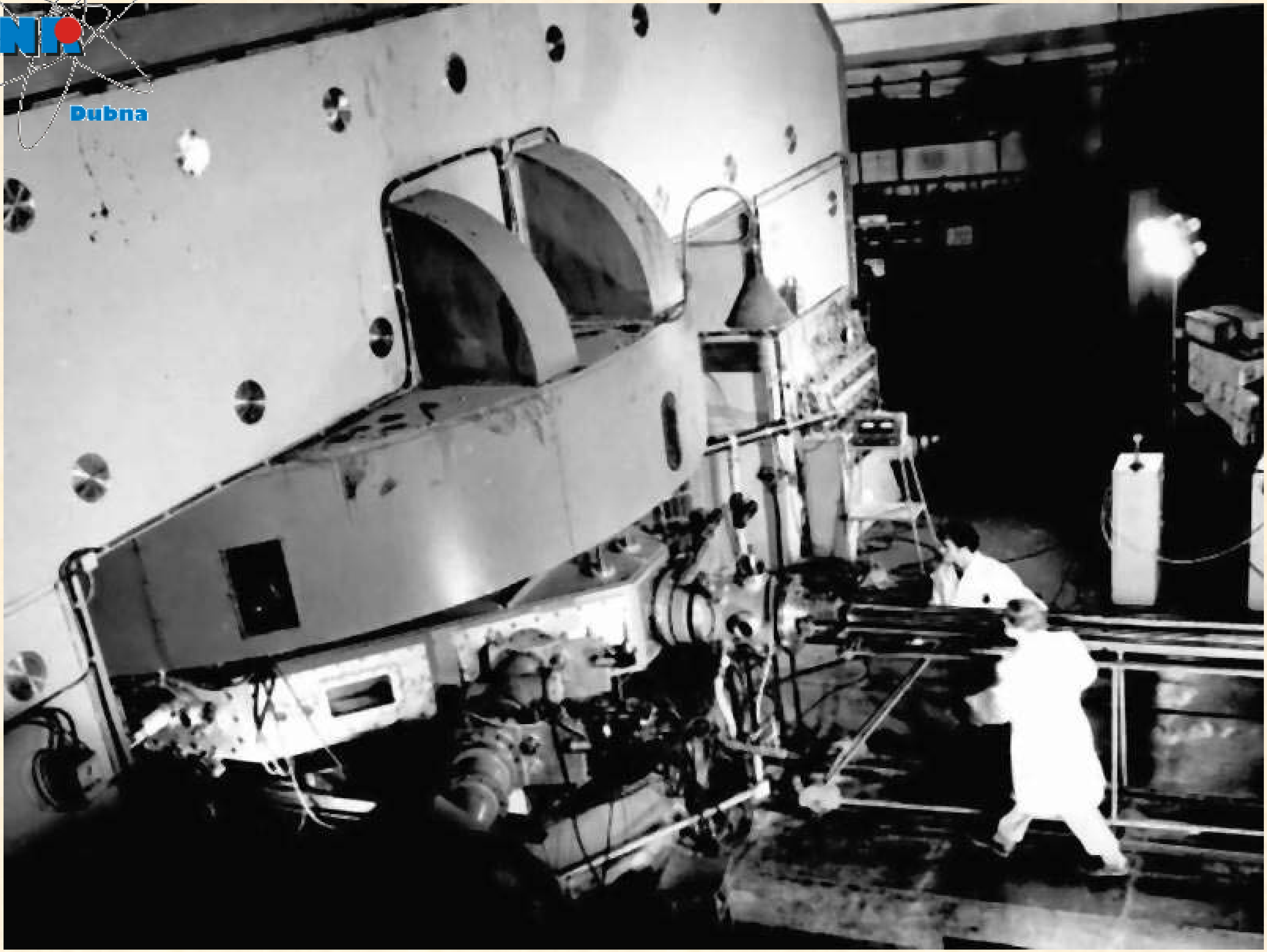


- Electron emission due to electrical potential on the cathodes
- Electron confinement due to the magnetic field along the anode axis
- Electrons produced by thermionic emission and ionic bombardment
  - Start-up: 3 kV to strike an arc
  - At the operating point : 100 V
- Cathodes heated by the plasma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

Example of PIG source



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

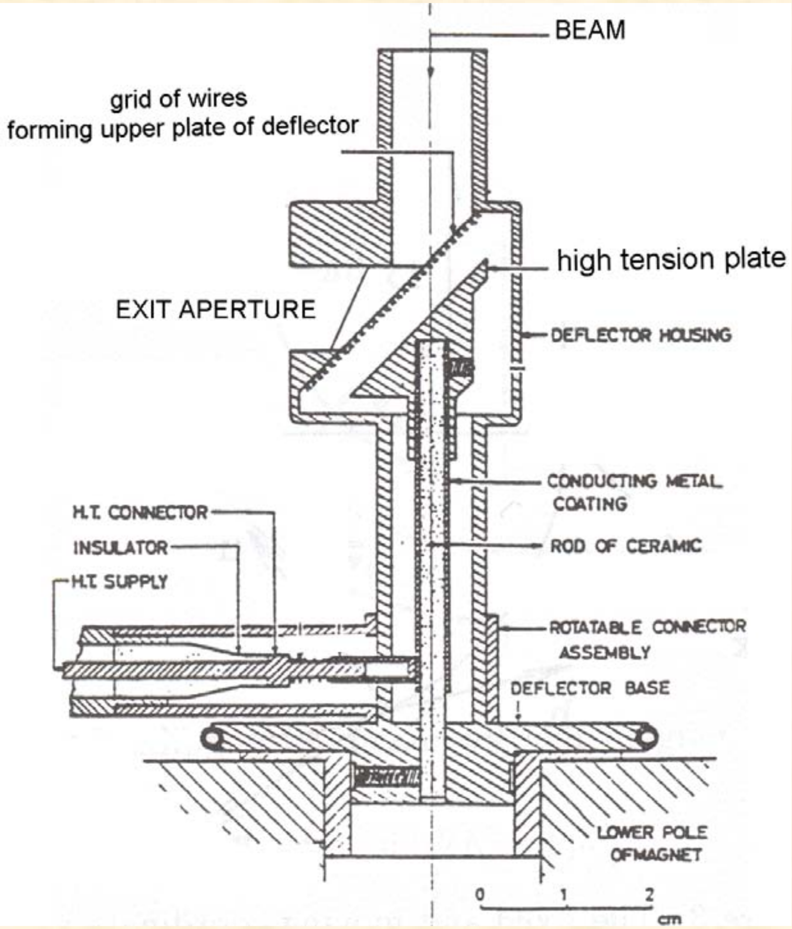


FLNR, U300, 1970.
Ion Source mounting

Remote ECR ion source

Axial injection

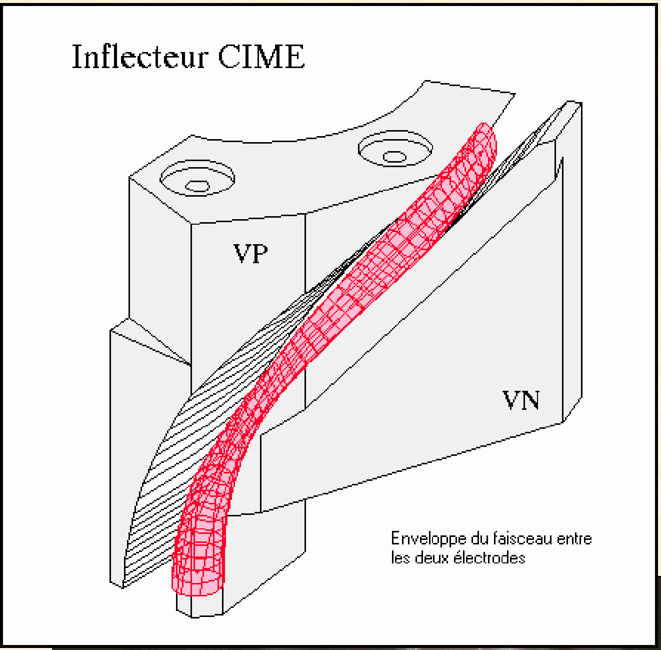
1. The electrostatic mirror
   - Simplest: A pair of planar electrodes which are at an angle of 45° to the incoming beam. The first electrode is a grid reducing transmission (65% efficiency).
   - smallest
   - High voltage

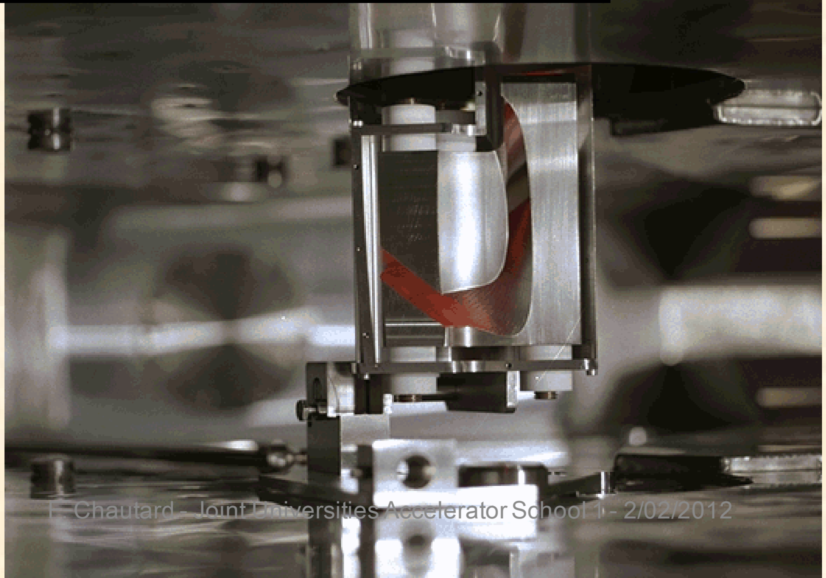


Axial injection

1. The electrostatic mirror
    - Simplest: A pair of planar electrodes which are at an angle of 45° to the incoming beam. The first electrode is a grid reducing transmission (65% efficiency).
    - smallest
    - High voltage
2. Spiral inflector (or helical channel)
    - analytical solution

Spiral inflector





- First used in Grenoble (J.L. Pabot and J.L. Belmont)
- 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

1. The electrostatic mirror
    - Simplest: A pair of planar electrodes which are at an angle of 45° to the incoming beam. The first electrode is a grid reducing transmission (65% efficiency).
    - smallest
    - High voltage
2. Spiral inflector (or helical channel)
    - analytical solution
3. The hyperboloid inflector
    - Simpler to construct because of revolution surface
    - No free parameters and <u>bigger</u> than a Spiral inflector
    - No transverse correlation. Easy beam matching
4. The parabolic inflector: not use in actual cyclotron, similar to hyperboloid
5. Axial hole

Central region

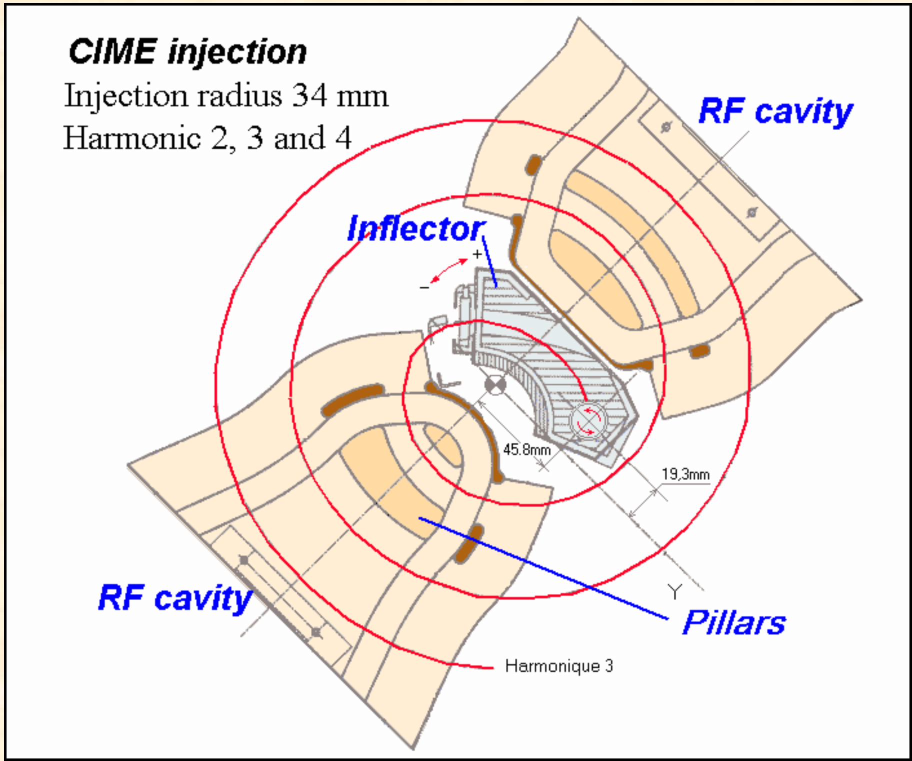
- Ion beam created by:

  -Internal source (PIG)

  -External source 1962 (ECR): The beam is injected vertically through the cyclotron yoke and reaches the horizontal trajectory

  -Dynamics problems encountered especially when running the machine for various harmonics.

- Goal : put the beam on the « good orbit » with the proper phase.
- The initial gaps are delimited with pillars/posts reducing the transit time and the vertical component of the electric field.
- The potential map are computed (in 3D if necessary)

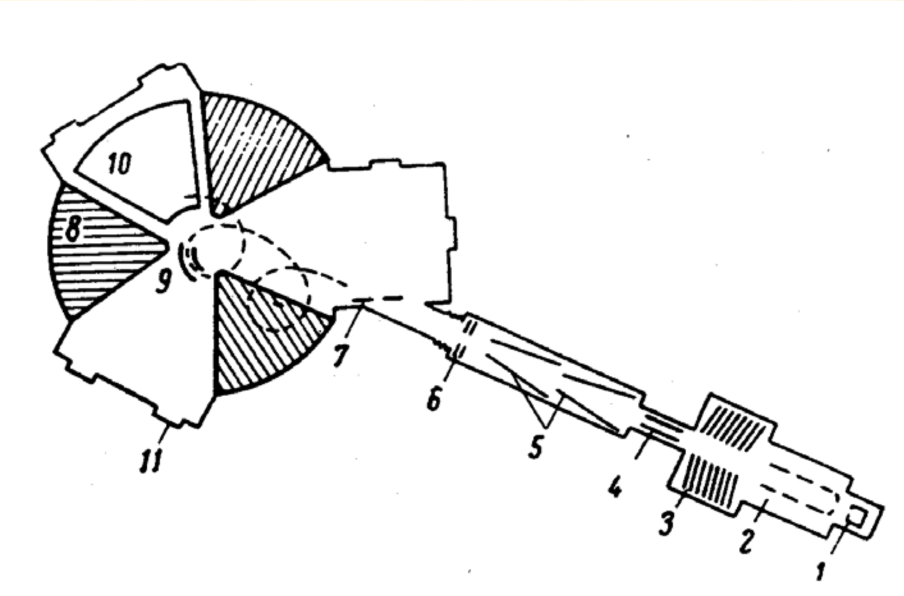


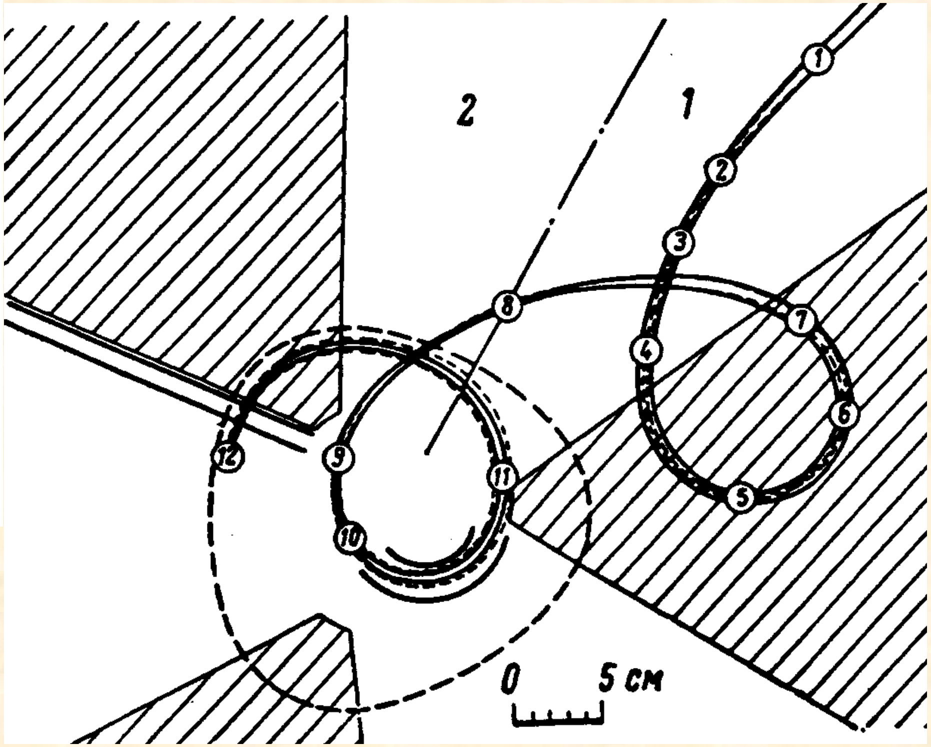
Radial injection

Injection of the beam through the magnetic gap of the cyclotron

Radial injection

1. Trochoidal (Lebedev Institute in Moscow)
    - Field difference between hill-valley to send the beam on a trochoidal trajectory to the central region. (300 keV)



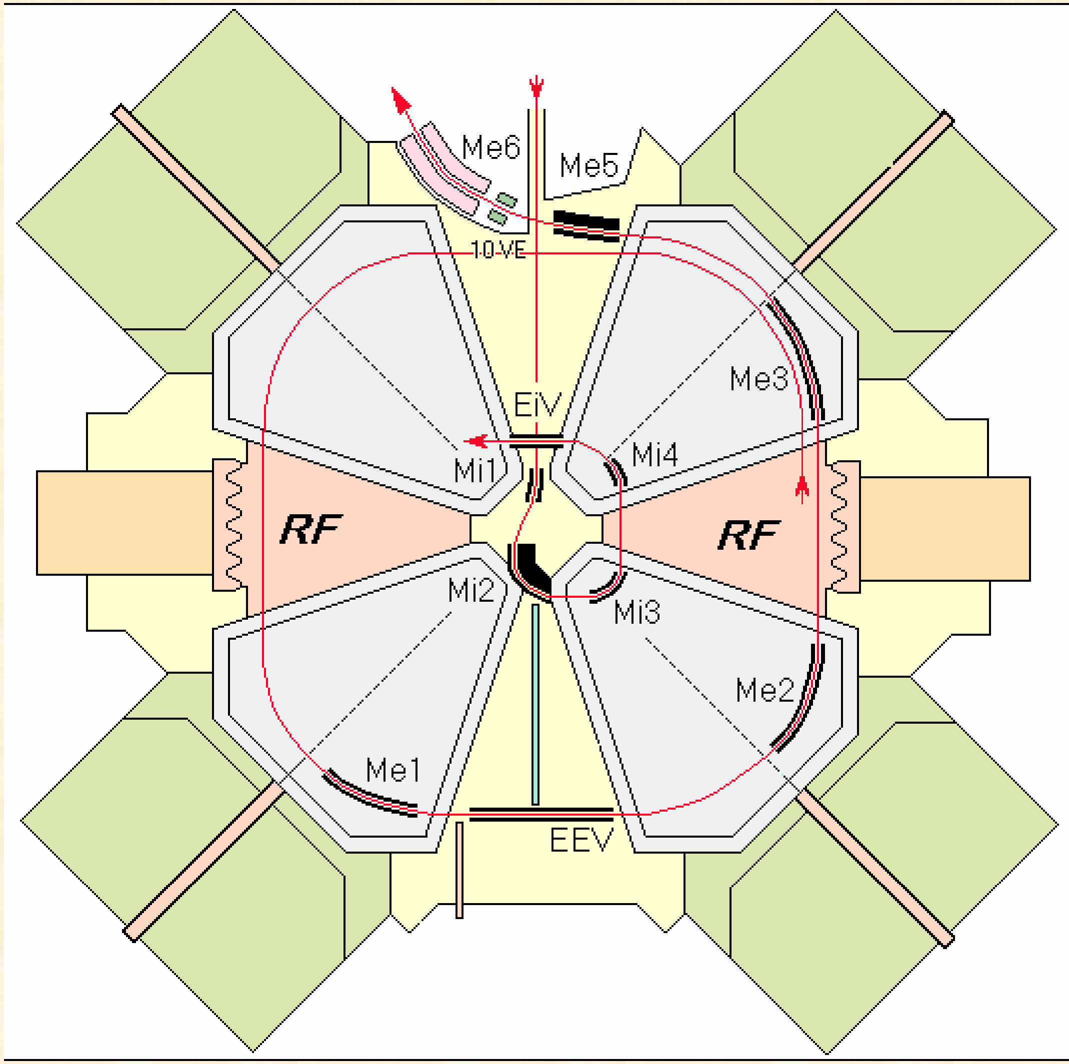


Radial injection

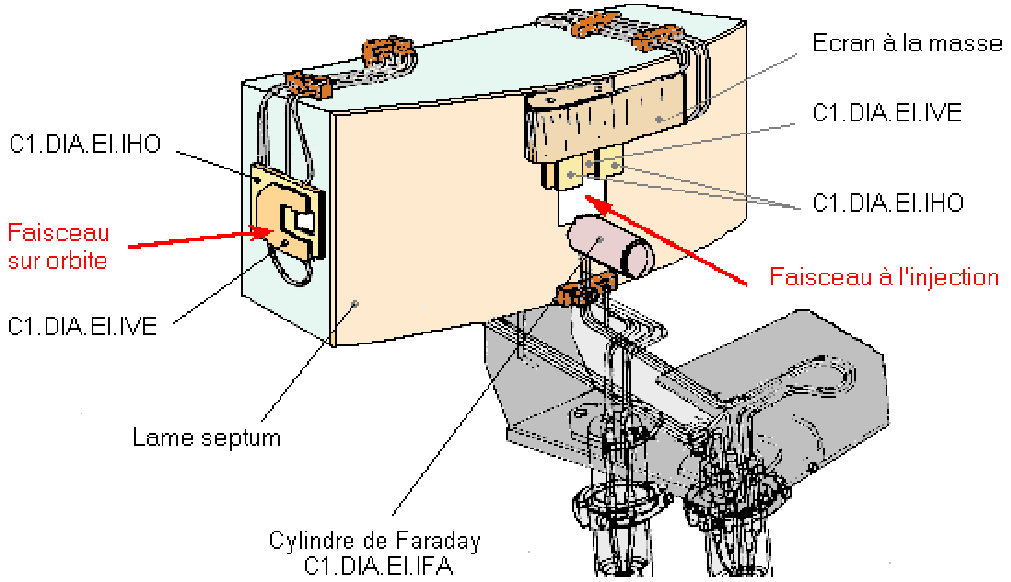
1. Trochoidal (Lebedev Institut in Moscow)
   - Field difference between hill-valley to send the beam on a trochoidal trajectory to the central region. (300 keV)
   - Not used today
2. Electric field cancelling magnetic field (Saclay, 1965)
   - system of electrodes shaped to provide horizontal electric field to cancel the force for the magnetic field to focus the beam on its path to the cyclotron centre.
   - Poor transmission (few percent)
3. Injection from another accelerator
   - Tandem + stripping + cyclotron : Oak Ridge, Chalk River
   - Matching between magnetic rigidity of the injected beam and the first cyclotron orbit rigidity
4. Injection into separated sector cyclotron
   - More room for injection pieces and excellent transmission

Example: Radial injection in SSC

- More room to insert bending elements.
- 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.



INFLECTEUR DE CSS1



Ecran à la masse

C1.DIA.EI.IVE

C1.DIA.EI.IHO

C1.DIA.EI.IHO

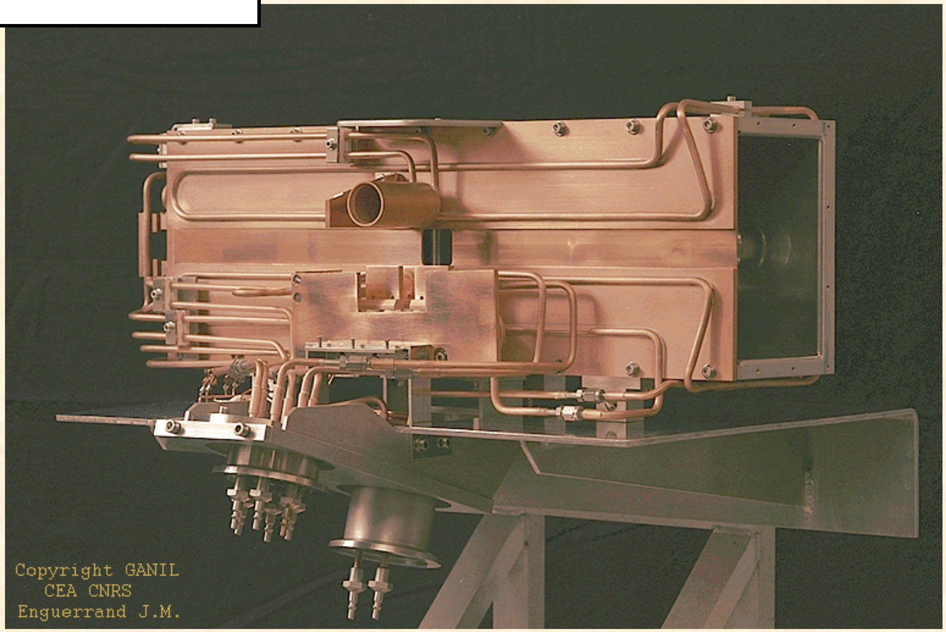
Faisceau sur orbite

Faisceau à l'injection

C1.DIA.EI.IVE

Lame septum

Cylindre de Faraday
C1.DIA.EI.IFA



Extraction

Goal : High extraction efficiency

1. Extraction by acceleration and fringe field
   - Energy gain per turn as high as possible
   - Accelerate the beam to fringing field
2. Resonant extraction
   - If turn separation not enough then magnetic perturbations are used. Particles are forced to oscillate around their equilibrium orbit with a magnetic bump
3. Stripping extraction

Extraction

1. <u>Extraction by acceleration and fringe field</u>

The orbit radial separration is : $$\delta r = r \times \frac{\delta W}{W} \times \frac{\gamma}{\gamma + 1} \times \frac{1}{\nu_r^2}$$

$\delta r \nearrow$:

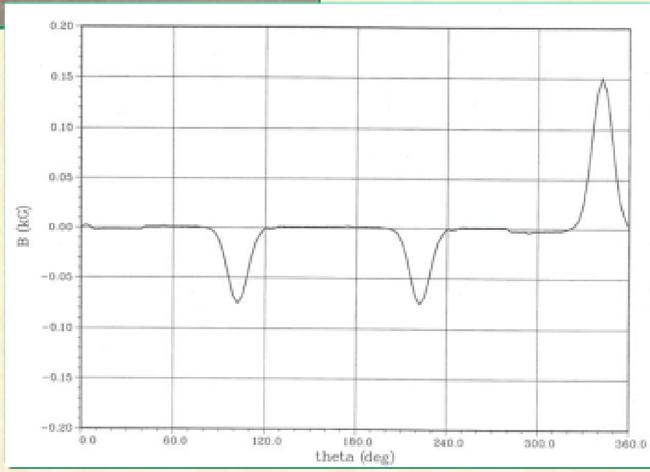
- $\delta W \nearrow$: Energy gain per turn as high as possible
- $\nu_r \searrow$: Accelerate the beam to fringing field where drop

$$\boxed{\begin{aligned} \nu_r &= \sqrt{1-n} \\ n &\approx -\frac{\partial B_z}{\partial r} \end{aligned}} \quad \begin{aligned} &\searrow \\ &\nearrow \end{aligned}$$

Extraction

1. <u>Resonant extraction</u>
   - If turn separation is not enough then magnetic perturbations are used.
   - Particles are forced to oscillate around their equilibrium orbit with a magnetic bump.
   - The integer resonance $\nu_r = N$
     - Precessional extraction : $\nu_r = 1$

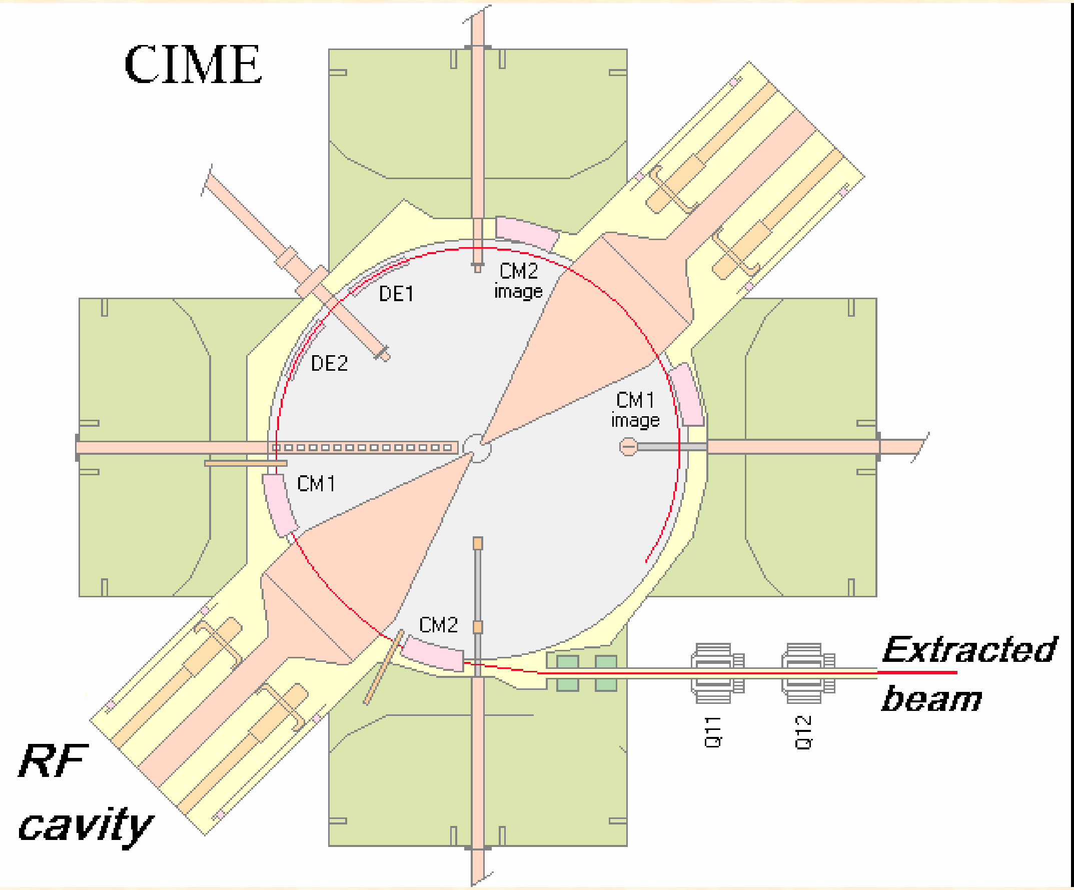
Bump with a harmonic coil <Bharm >=0

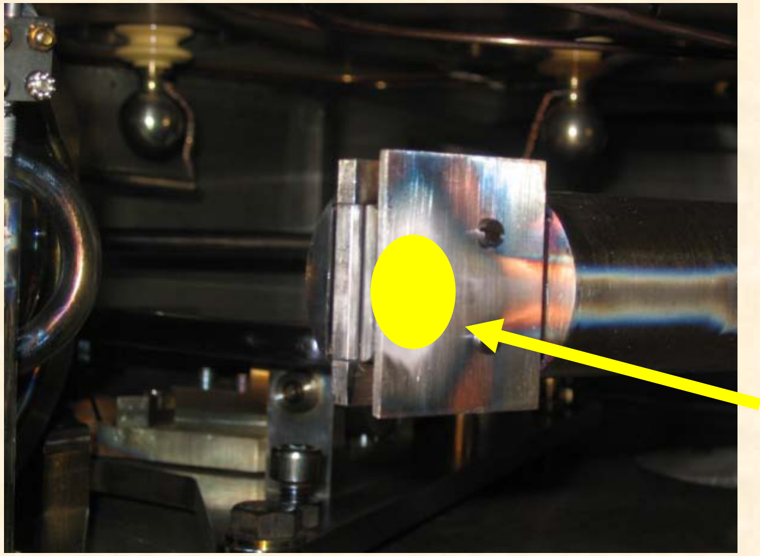


     - Half-integer resonance : $\nu_r = N/2$
     - Third order resonance: $\nu_r = N/3$ (slow extraction for synchrotron)

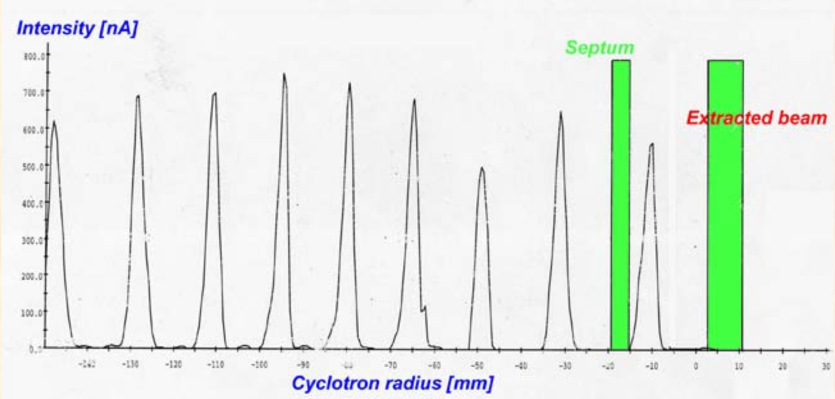
Extraction for Compact cyclotron

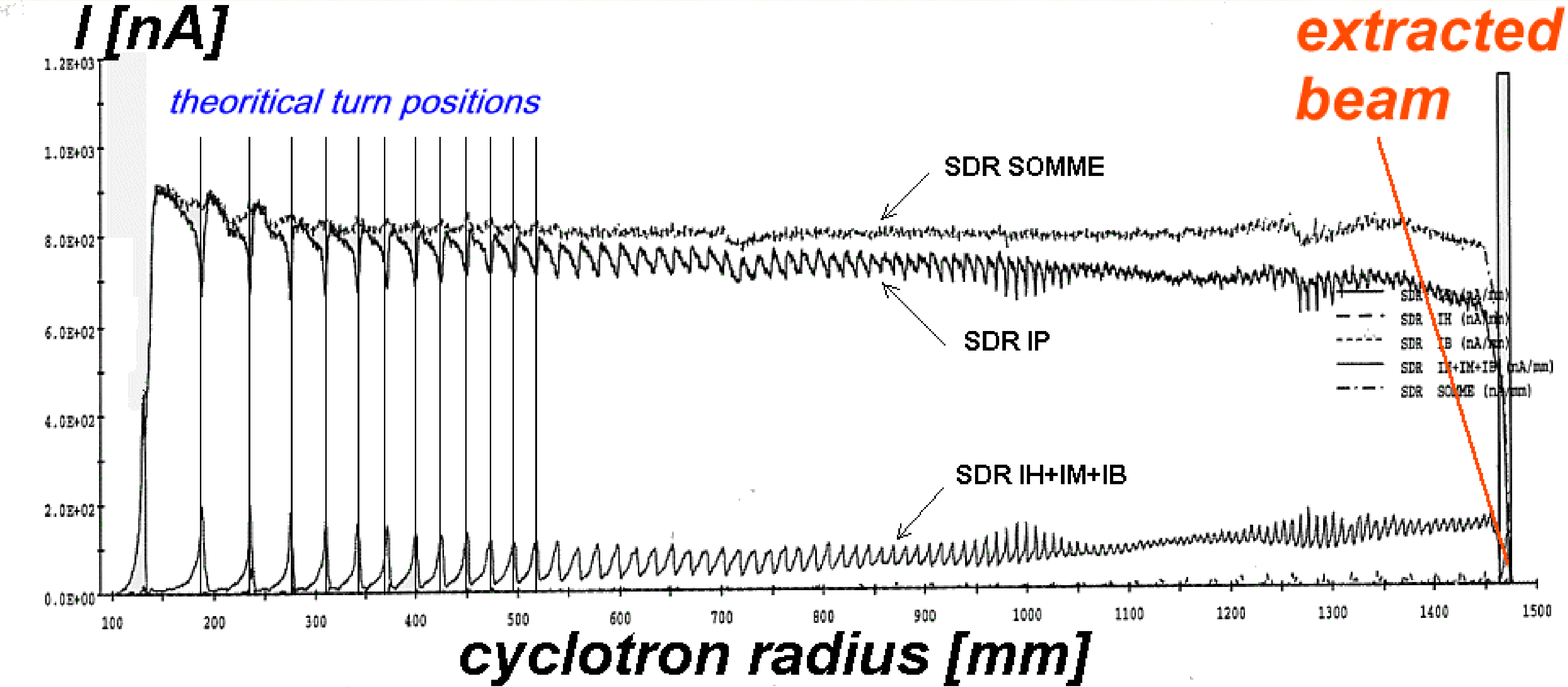
- The last turn passes first through two electrostatic septa (< 90 kV) in order to deviate to beam towards the ejection channel.
- Two movable magneto-static dipoles drive the beam across the last cavity.
- Despite the strong fringing field along the extracted beam trajectory, the simulations (confirmed by experiments) showed that the beam dynamics (envelops and alignment) can be done with a 90% efficiency
- small turn separation (overlapping turns)⇨bunch extracted over several turns





Beam


Intensity [nA]
Septum
Extracted beam
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
Cyclotron radius [mm]


I [nA]
theoritical turn positions
extracted beam
SDR SOMME
SDR IP
SDR IH+IM+IB
SDR IH (nA/mm)
SDR IB (nA/mm)
SDR IH+IM+IB (nA/mm)
SDR SOMME (nA/mm)
1.2E+03
1.0E+03
8.0E+02
6.0E+02
4.0E+02
2.0E+02
0.0E+00
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
cyclotron radius [mm]

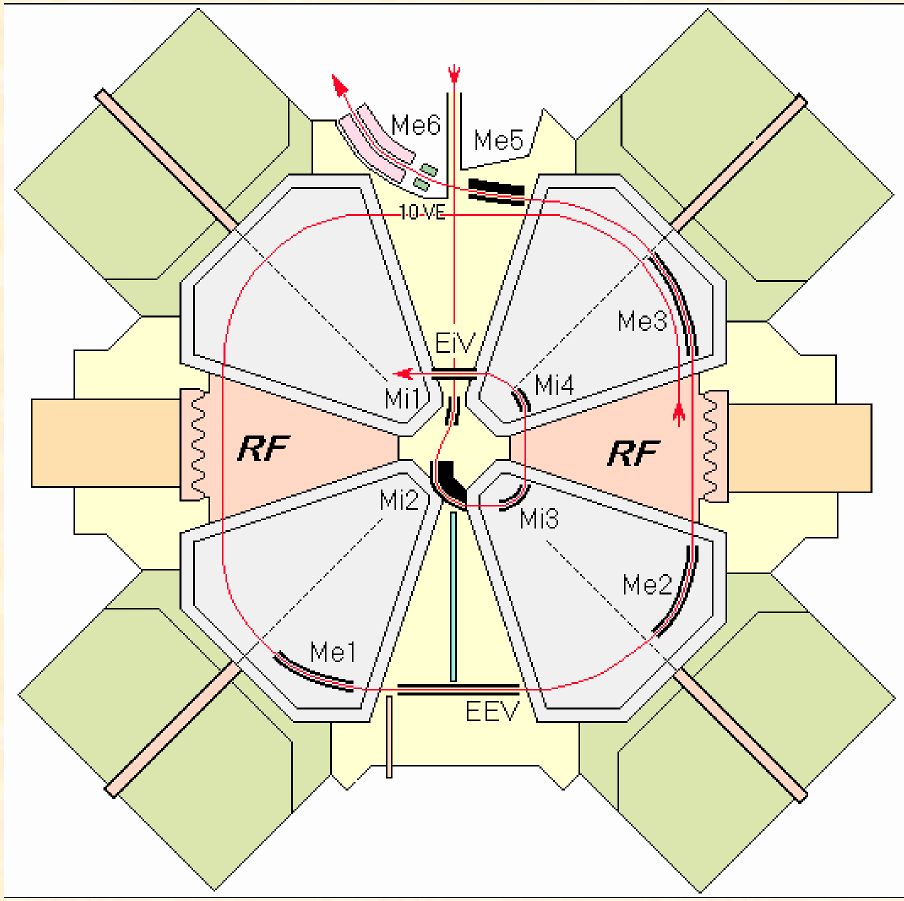
Extraction for Separated Sector Cyclotron

- As for the injection, dipoles and deflectors are placed in the cyclotron sector to deviate the beam trajectory.
- For large radii, the turn separation become narrower : $\delta r \propto {}^{1}\!/_{r}$

Find a way to increase the separation to avoid the interaction between the beam and deflector (extraction efficiency ↗):

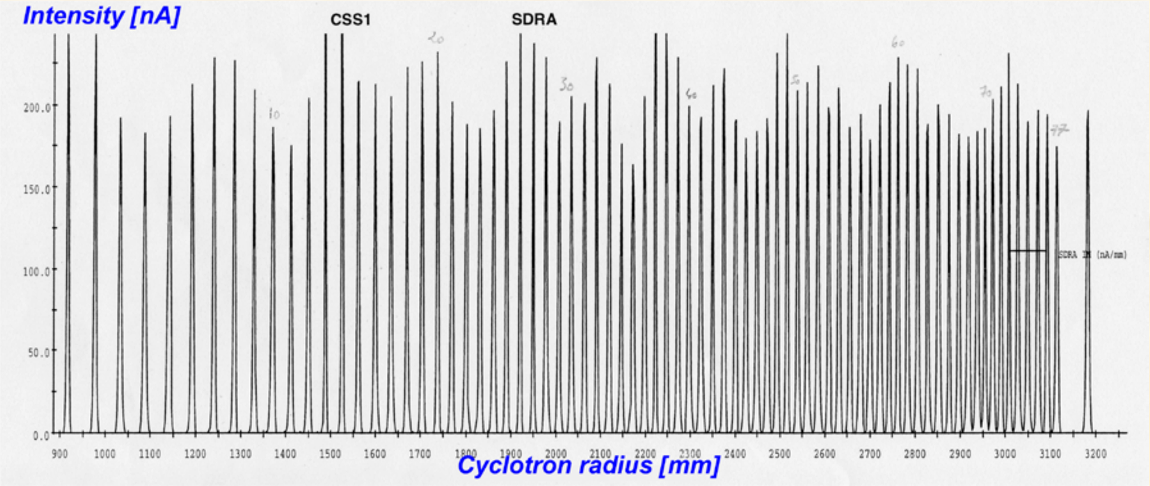
  - Electrostatic Inflector (EV) gives a small angle (<u>precession</u>)

- Extraction channel : EEV, Me1-6

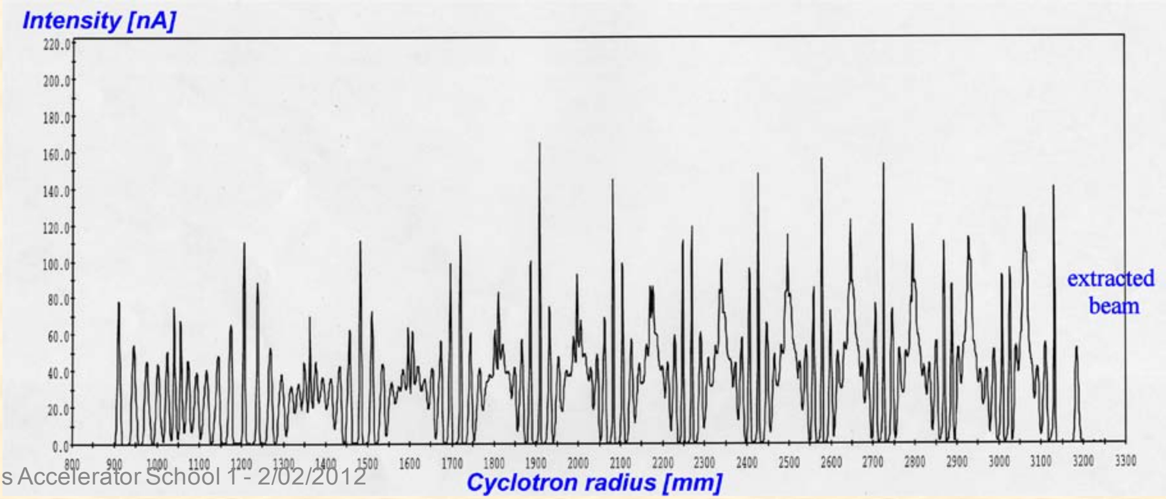


Extraction from SSC

Well centered beam orbits **SSC1** GANIL



Precession for optimized extraction **SSC2** GANIL



1 period for

13 turns ⇨

$\nu = 0.08$

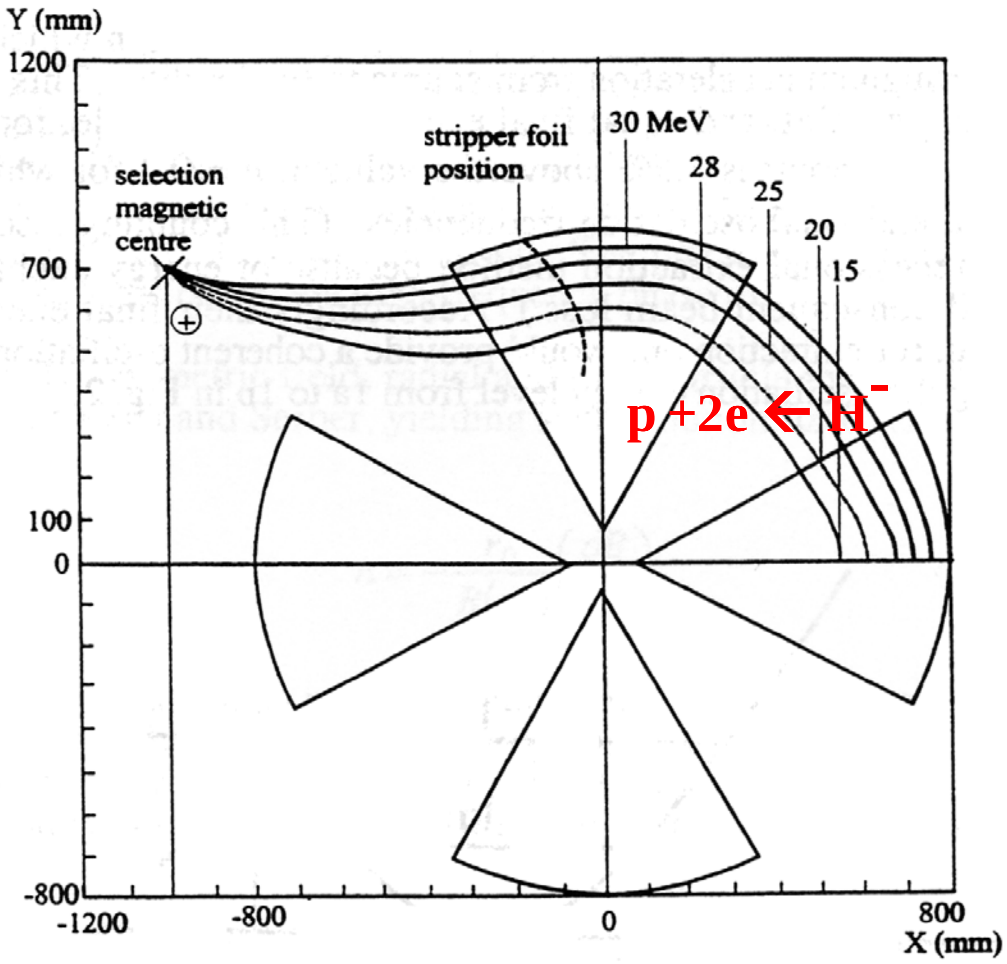
Extraction by stripping

The extraction efficiency for deflector + magnetic channel : 50 – 90%. For high intensities activation, vacuum and melting problems

- Stripping method :
  - H- ions are changed into protons (H+ ions) by stripping the electrons off, on thin stripping foil (µm carbon) :
    - Charge state -1 -> +1

  - Since the protons are positively charged, they then curve the opposite way from the negatively charged circulating beam ions.
  - Thus, the protons curve out of the cyclotron into the beamlines (Triumf (Canada), Louvain (Belgium))
  - Efficiency close to 100 %
  - Short distance in the fringing field : Less focusing problems

Extraction by stripping



Extraction orbits in the IBA Cyclone 30

IBA Cyclone 30

All energies go to one crossover point by proper foil azimuthal position

Cyclotrons

- End Chapter 2

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- Acceleration
- Injection
- Extraction