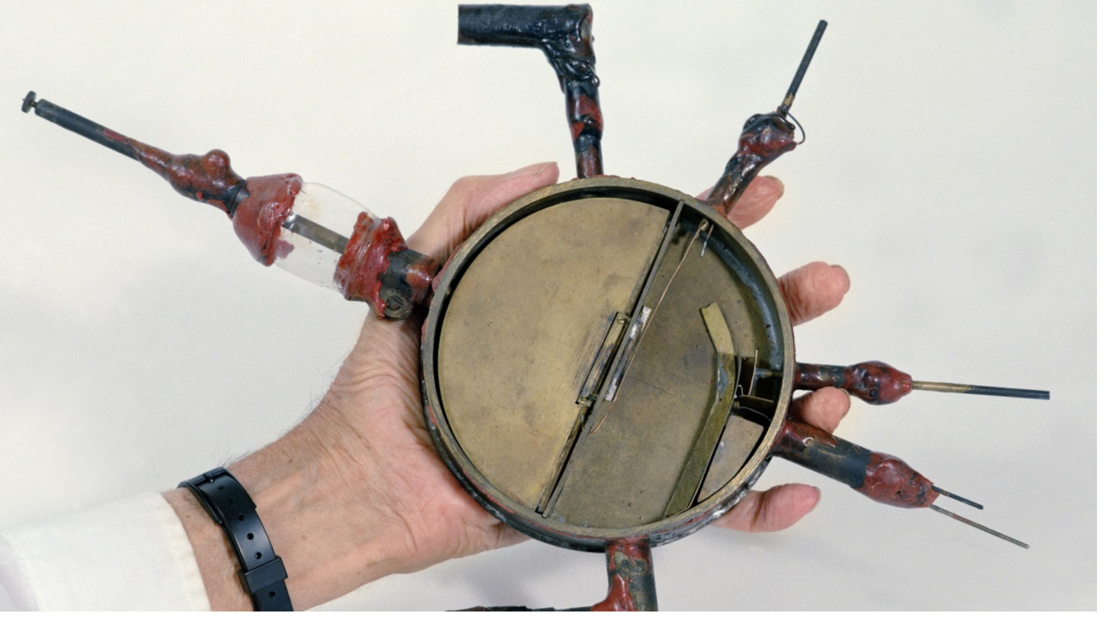
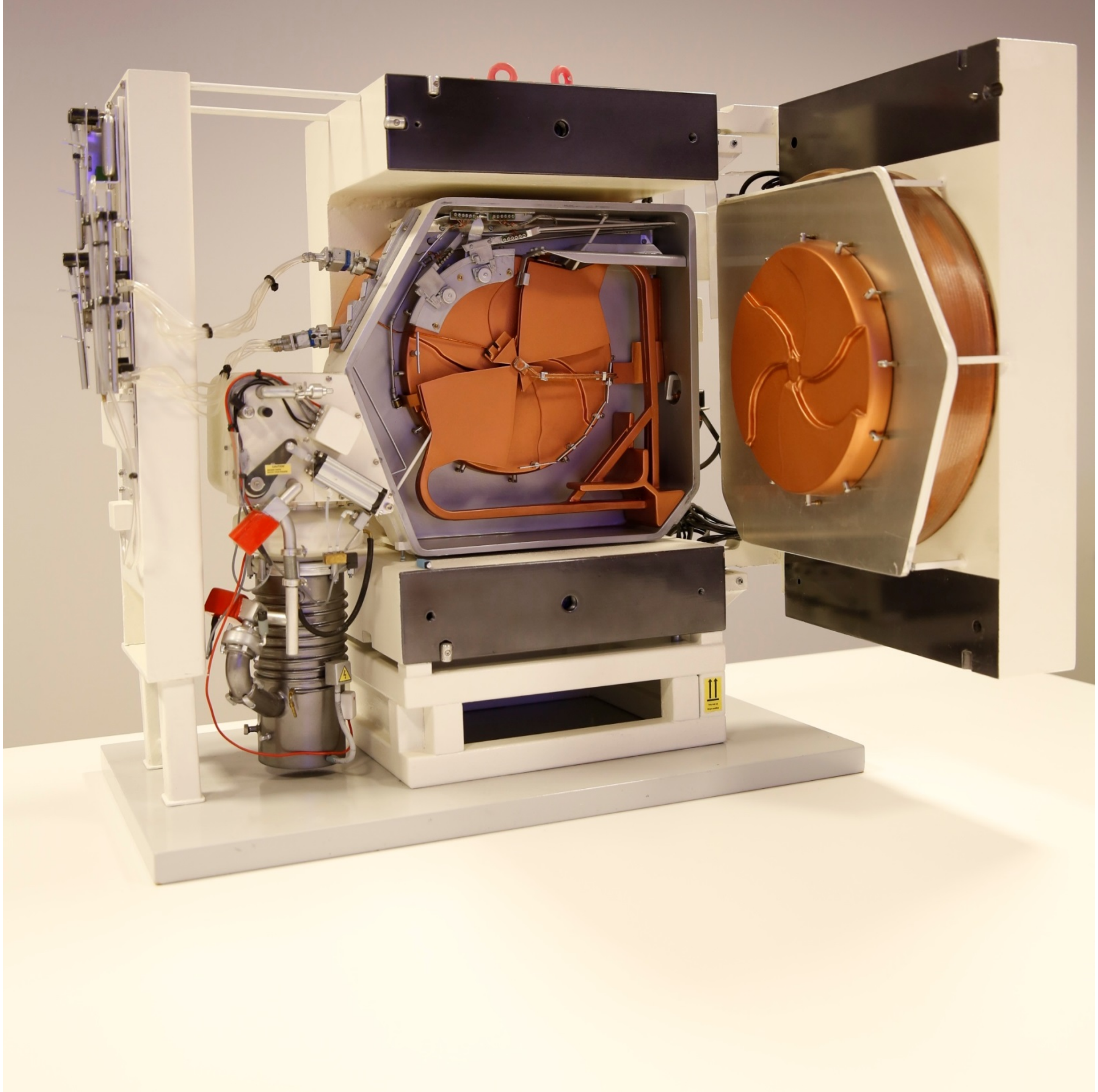
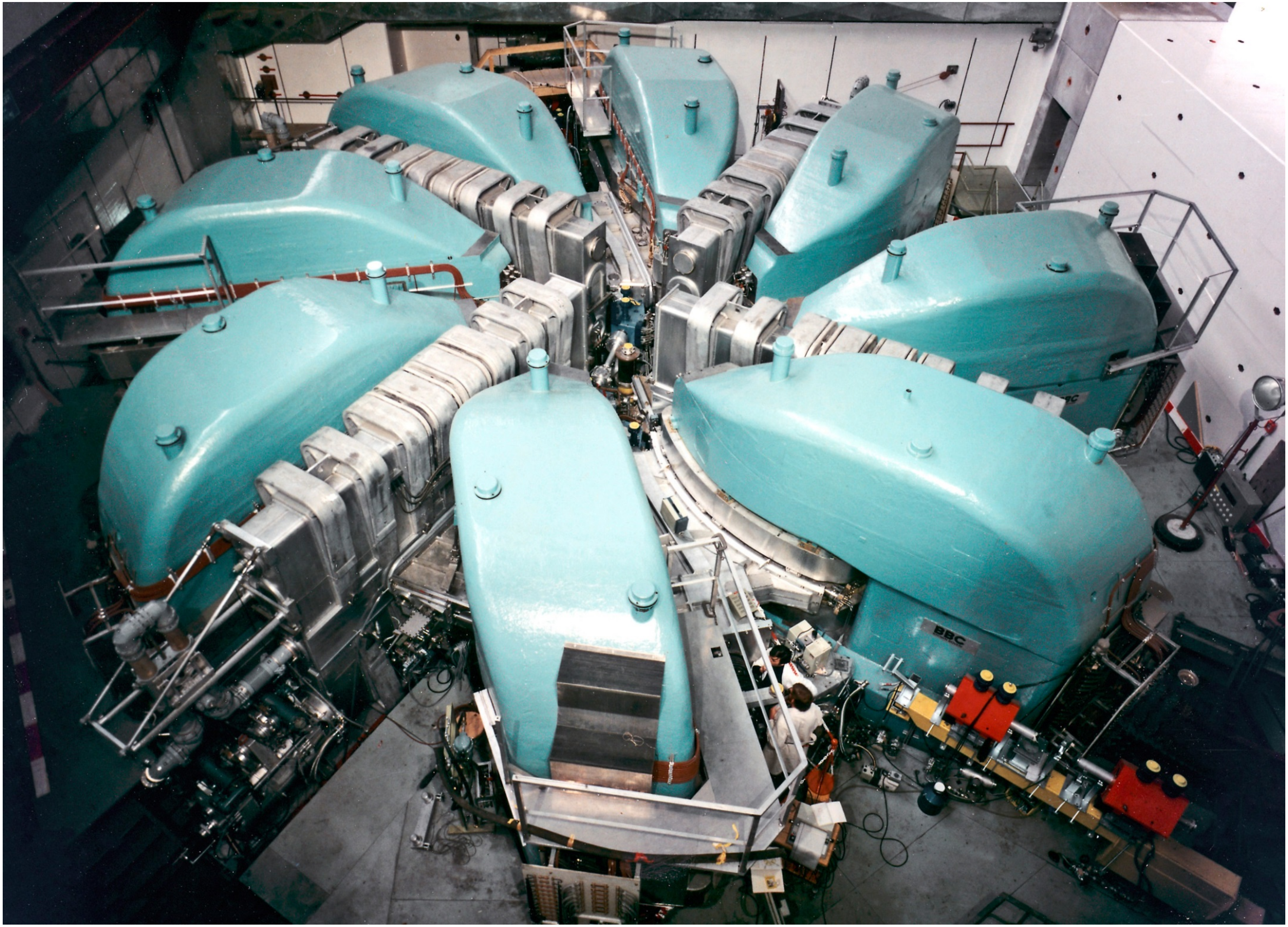
Cyclotrons

- Classical cyclotron
- Synchrocyclotron
- Isochronous cyclotron



Ernest O. Lawrence, 1932
Nobel Prize, 1939

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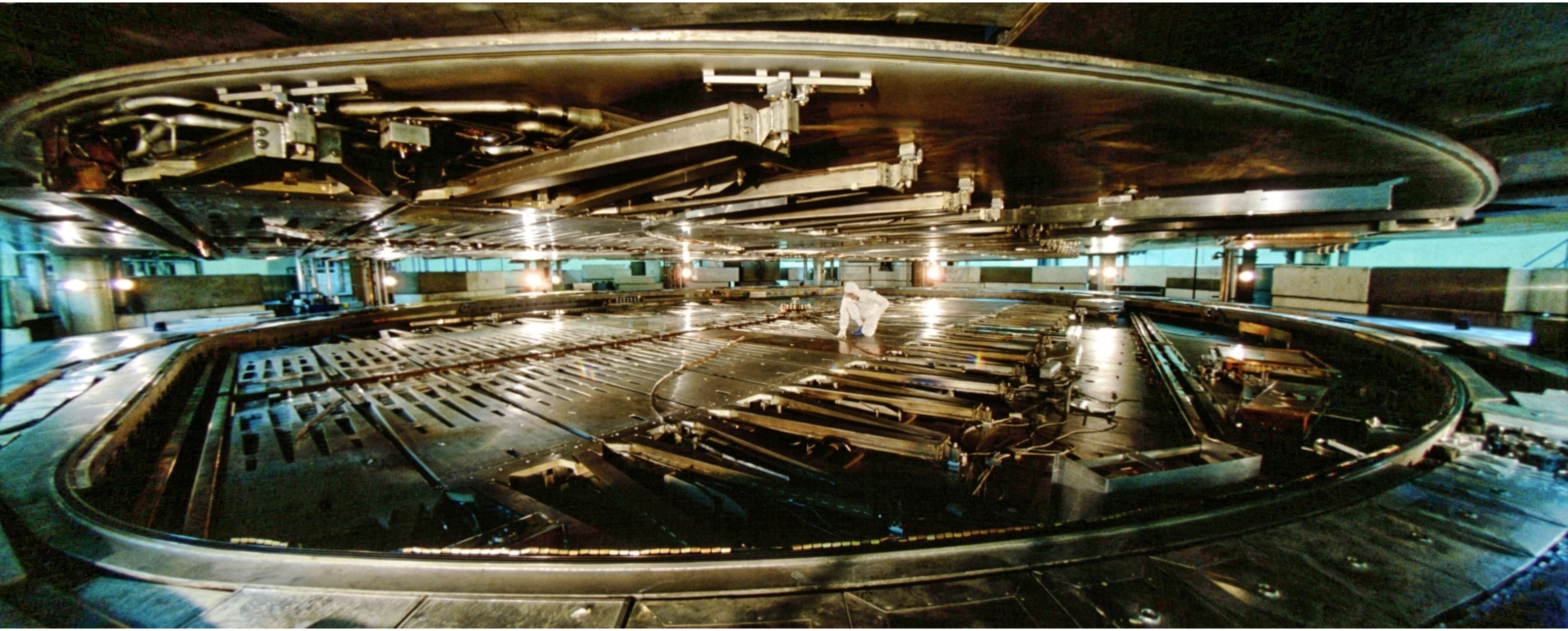
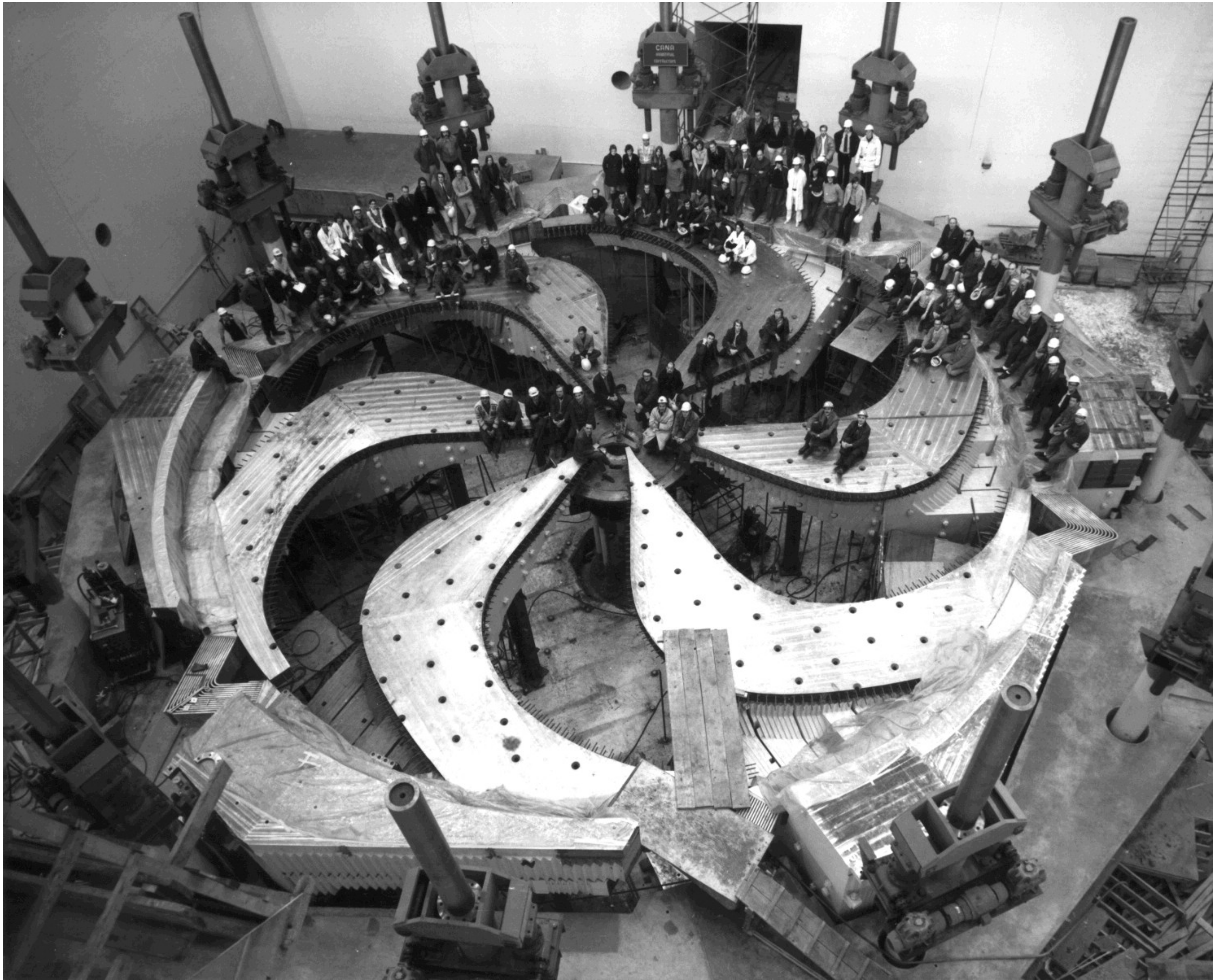



CANA

Classical Cyclotron

(B ≈ constant)

- a charged particle (q, m) in a magnetic field (B)

$\vec{v} \perp \vec{B}$

centripetal force = magnetic force

$$\frac{mv^2}{r} = qvB \iff Br = B\rho = \frac{p}{q}$$

$$\iff \frac{v}{r} = \omega = \frac{qB}{m}$$

$\omega = \omega_c$ = cyclotron frequency

$f_{RF} = \frac{\omega_c}{2\pi}$ = accelerating frequency = $\frac{\omega_{RF}}{2\pi}$

Non-relativistic bending limit:

$$E_k = \frac{p^2}{2m} = \frac{(B\rho q)^2}{2m} = \frac{Q^2}{A}\frac{(B\rho e)^2}{2u} = \frac{Q^2}{A}K_b$$

Example:

ρ = 1 m

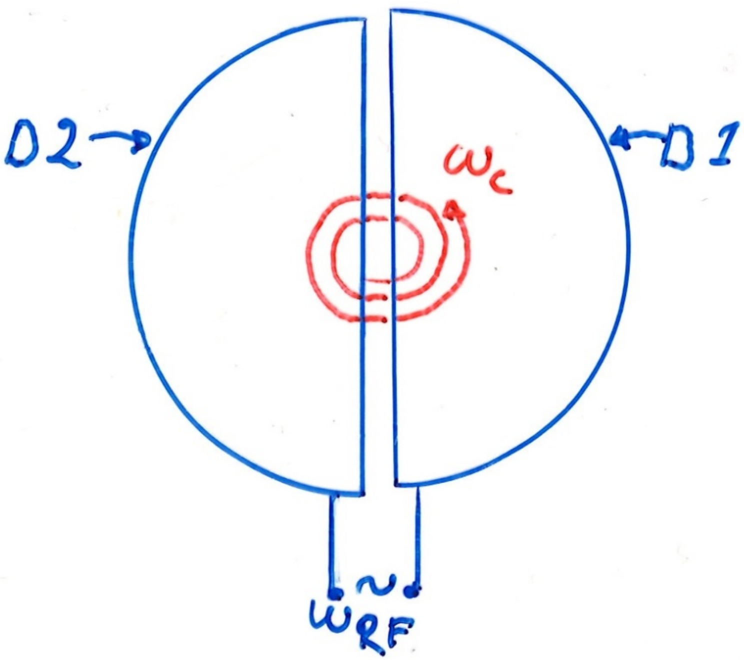
B = 1.7 T

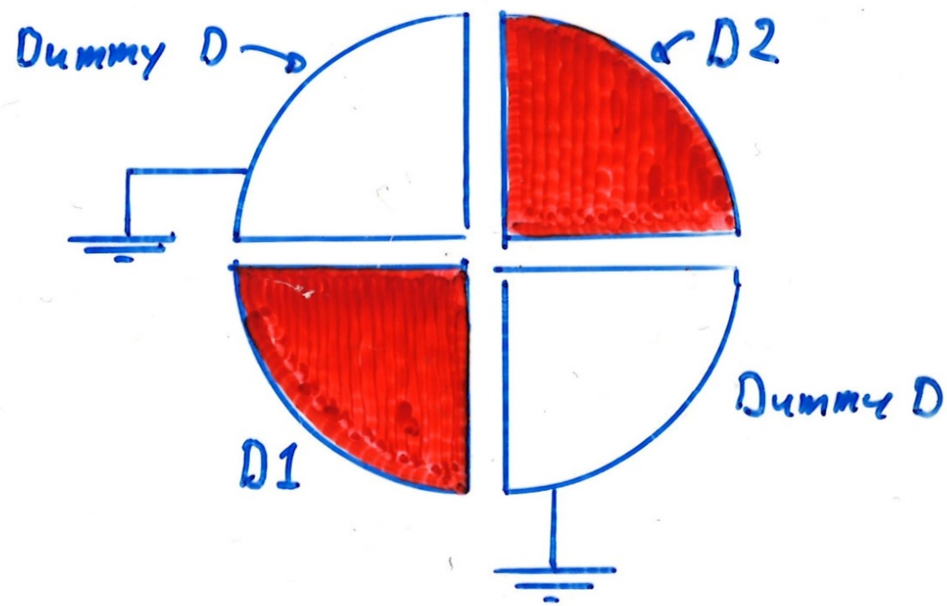
K_b = 139 MeV

Also

$$\omega_{RF} = h \, \omega_c \qquad h = 1, 2, 3, \dots$$

↑ harmonic number





$$\phi(D1) = \phi(D2) \quad \text{or} \quad \phi(D1) = \phi(D2) + \pi$$

- polarity of electrode changes when the particle is inside Dee → new acceleration in next gap

compare with Videröe

example 1. $B \leq 2\,T$ → proton: $f_{RF} \leq 30.5$ MHz

example 2. $B = 1.5\,T$, $r = 43$ cm

$$\rightarrow \quad E_p = \frac{p^2}{2m} = \frac{(B\rho)^2 e^2}{2m} \simeq 20 \text{ MeV}$$

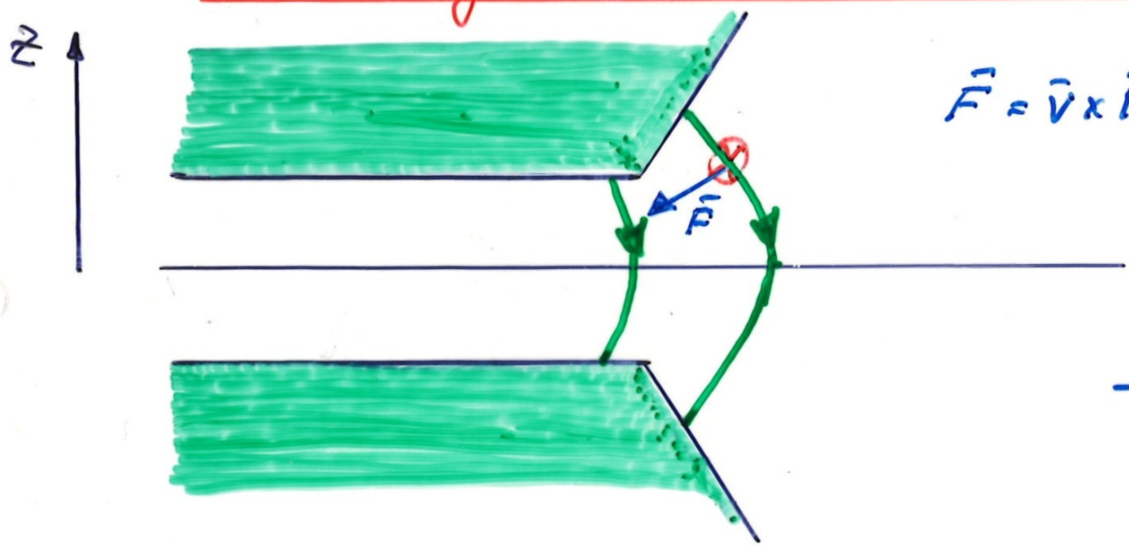
↑ not possible in a classical cycl.

Energy limit in classical cyclotrons

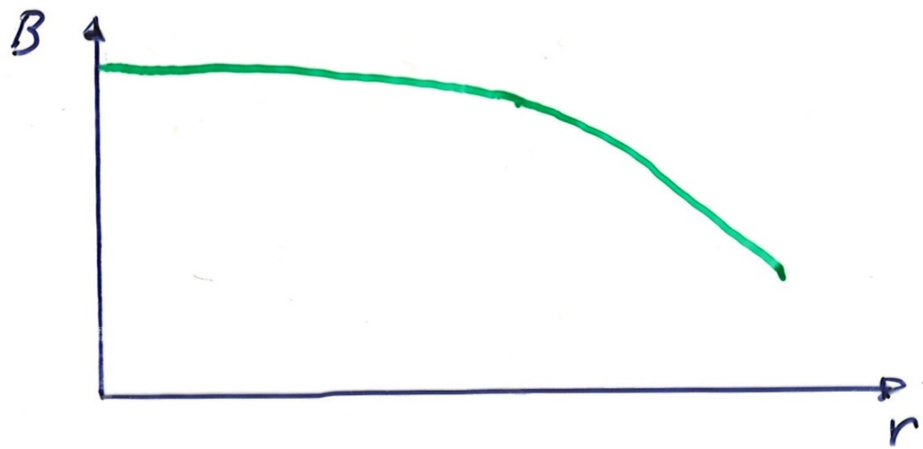
$$\frac{\Delta m}{m} = \frac{E_k}{E_0} \approx 1\%$$

$$\rightarrow \quad E_p^{max} \approx 10 \text{ MeV} \qquad (E_0 = 938 \text{ MeV})$$

Focusing - betatron oscillations



- Focusing in z-direction if B decreases as r increases
- B = constant : no focusing
- B increases : defocusing



Let's look at the focusing conditions in more detail.

Kerst-Serber equations

Consider a moving particle in a classical cyclotron

$B \neq B(\theta)$, $B = (r, z)$

near equilibrium orbit. (EO)

On EO (bending radius $= \rho$)

$$\frac{mv^2}{\rho} = q B_0 v \iff \frac{q}{m} B_0 = \frac{v}{\rho} = \omega_c$$

Write: $B = B_0 \left(1 + k \frac{x}{\rho}\right) = -B_z$ (gradient normalized with ρ)

1° Radial focusing

$$m\ddot{r} = -qBv + m\frac{v^2}{r} \qquad r = \rho + x \rightarrow \ddot{r} = \ddot{x}$$

$$m\ddot{x} = -qvB_0\left(1+k\frac{x}{\rho}\right) + mv^2(\rho+x)^{-1}$$

$$\cong -qvB_0\left(1+k\frac{x}{\rho}\right) + mv^2\,\frac{1-\frac{x}{\rho}}{\rho}$$

$$= -qvB_0 - qvB_0 k\frac{x}{\rho} + m\frac{v^2}{\rho} - m\frac{v^2}{\rho}\frac{x}{\rho}$$

$$= -qvB_0 k\frac{x}{\rho} - qvB_0\frac{x}{\rho}$$

$$\ddot{x} = -\Big(\underbrace{\frac{qB_0}{m}}_{\omega_c} k \underbrace{\frac{v}{\rho}}_{\omega_c} + \underbrace{\frac{qB_0}{m}}_{\omega_c}\underbrace{\frac{v}{\rho}}_{\omega_c}\Big)x$$

$$\Leftrightarrow \quad \ddot{x} + (\omega_c^2 k + \omega_c^2)\, x = 0$$

$$\ddot{x} + \omega_c^2 (1+k)\, x = 0$$

$$\rightarrow \quad x = A \cos\left(\sqrt{1+k}\, \omega_c t + \phi_0\right)$$

limited if $k > -1$

2° Axial focusing

$$m\ddot{z} = -q v B_x$$

$$\nabla \times \vec{B} = 0 \Rightarrow \frac{\partial B_z}{\partial x} = \frac{\partial B_x}{\partial z}$$

$$\Rightarrow B_x = z \frac{\partial B_z}{\partial x} = -z \cdot k \frac{B_0}{\rho}$$

$\Rightarrow$

$$m\ddot{z} = q v z k B_0/\rho$$

$\Leftrightarrow$

$$\ddot{z} = \underbrace{\frac{q}{m} B_0}_{\omega_c} \underbrace{\frac{v}{\rho}}_{\omega_c} k z$$

$\Leftrightarrow$

$$\ddot{z} - \omega_c^2 k z = 0$$

$\Rightarrow$ $$z = A_z \cos\left(\sqrt{-k}\,\omega_c t + \phi_0\right)$$

limited if $k < 0$

$\therefore$ FOCUSING IN BOTH PLANES IF

$$-1 < k < 0$$

Note! Often in the literature

$$-k = n = -\frac{\frac{dB}{B}}{\frac{dr}{r}} = -\frac{r}{B}\frac{dB}{dr}$$

$$\therefore \quad 0 < n < 1$$

n, k field index

Betatron frequencies ν_r, ν_z (Q_r, Q_z)

$$\nu_r = \frac{\omega_r}{\omega_c} = \sqrt{1+k}$$

$$\nu_z = \frac{\omega_z}{\omega_c} = \sqrt{-k}$$

Particles oscillate around EO
with frequencies ω_r and ω_z

ν_r periods / turn radially

ν_z — " — axially

Synchrocyclotron

E_k increases → m increases → ω_c decreases

(ω_c decreases also due to focusing condition)

→ Decrease accelerating frequency with increasing energy = synchrocyclotron

ADVANTAGES

+ higher energy
+ possibility for better axial focusing

DISADVANTAGES

- only one (few) pulse at the time can be accelerated → intensity goes down

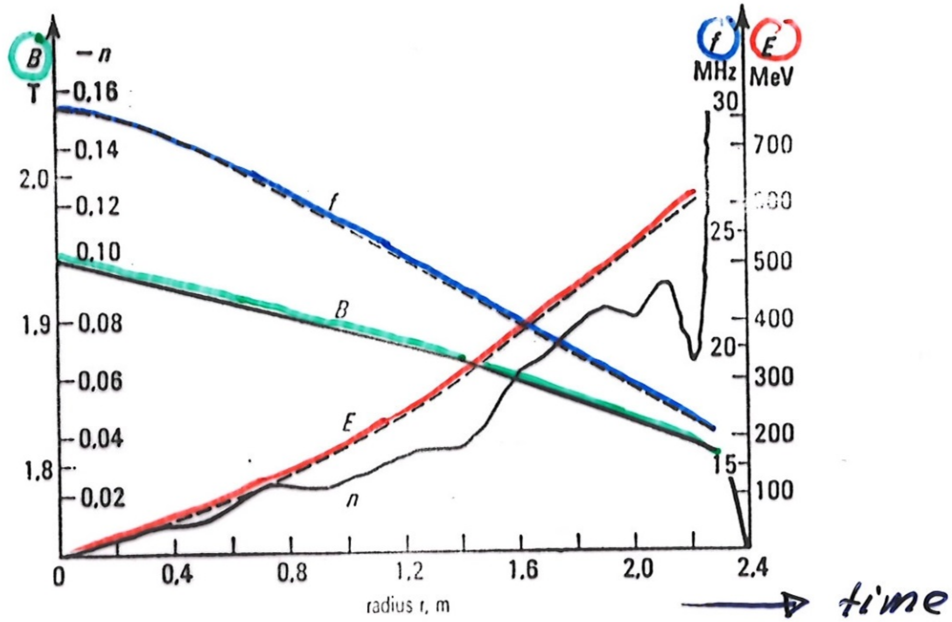


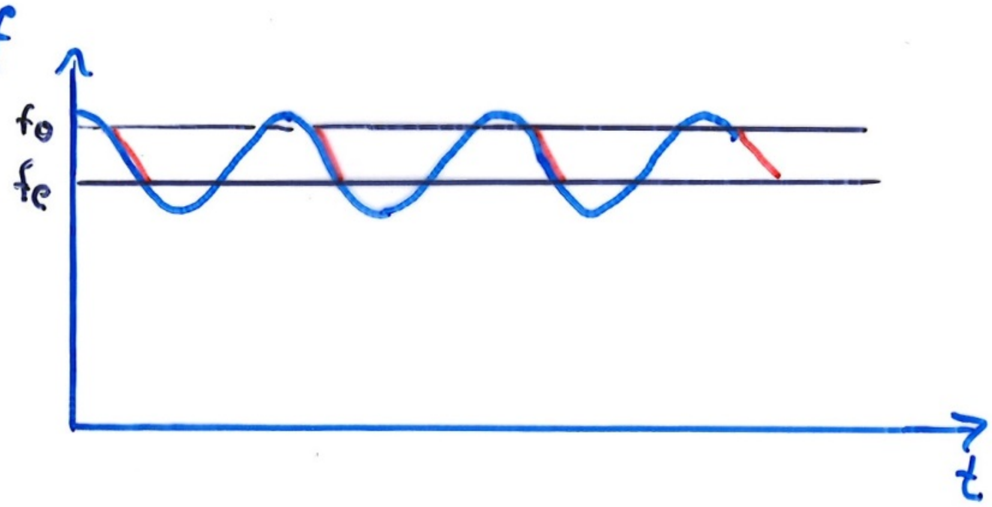
Figure 3.7 Parameters of 600-MeV CERN synchrocyclotron (B — induction, E — proton energy, f — accelerating-voltage frequency, n field index)

Synchrocyclotron frequency

$$\omega_c = \frac{q}{m_0} B$$

$$\rightarrow \quad \frac{\omega_{sc}}{\omega_c} = \frac{m_0}{m} = \frac{1}{\gamma} = \frac{E_0}{E_0 + E_k} = \frac{1}{1 + E_k/E_0}$$

$$f_{sc} = \frac{f_c}{1 + E_k/E_0}$$



frequency modulated

—— = acceleration of one pulse

U = 10 - 30 kV

↳ repetition rate / cycling rate = 50 - 500 Hz

Isochronous cyclotron
= sector focusing cyclotron
= AVF cyclotron (Azimuthally Varying Field)

Another way to compensate for the mass increase or frequency decrease is to increase magnetic field with radius (energy)

BUT:

Kerst-Serber: axial defocusing
⇒ axial focusing must be increased by modifying the magnetic field so that the synchronous condition is fulfilled

- cannot be done radially (synch. condition)

→ Question: Can axial focusing be increased modifying the field azimuthally so that $\langle B \rangle_\theta$ corresponds to synchronous field?

Answer: YES

Try sectors and examine the components of Lorenz force

$$\bar{F} = q\, \bar{v} \times \bar{B}$$

$$\bar{v} \times \bar{B} = \begin{vmatrix} \hat{r} & \hat{\theta} & \hat{z} \\ v_r & v_\theta & v_z \\ B_r & B_\theta & B_z \end{vmatrix}$$

$$= \cdots + \hat{z}\,(v_r B_\theta - v_\theta B_r)$$

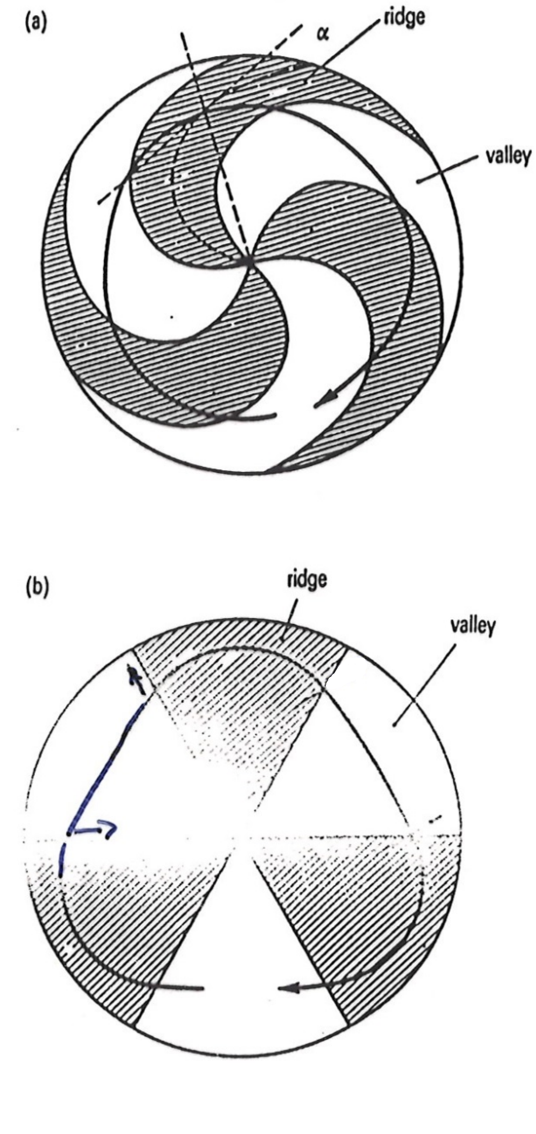
"Primary" motion v_θ

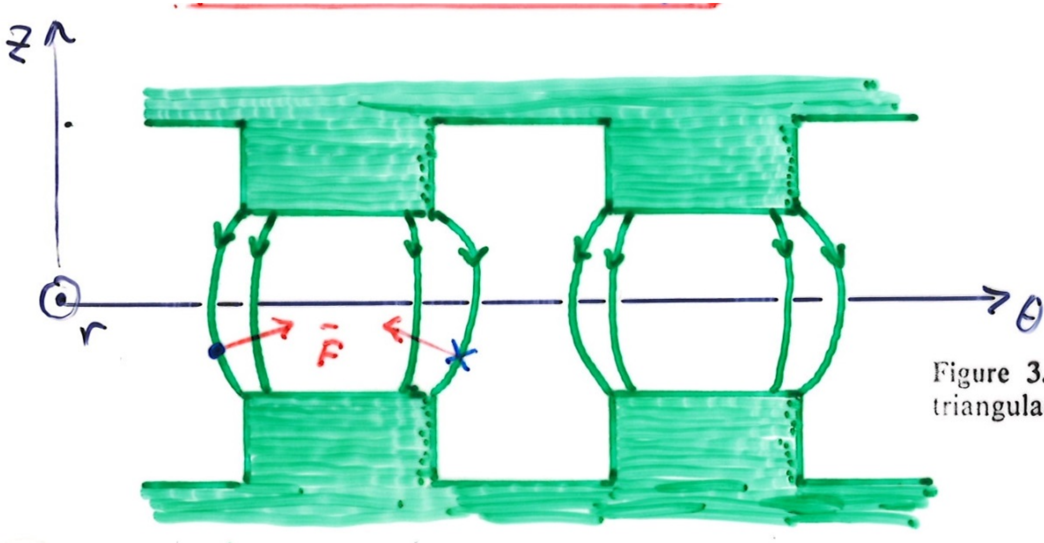
at the sector edge

$v_r \neq 0$

→ **Thomas focusing**

ISOCHRONOUS CYCLOTRONS





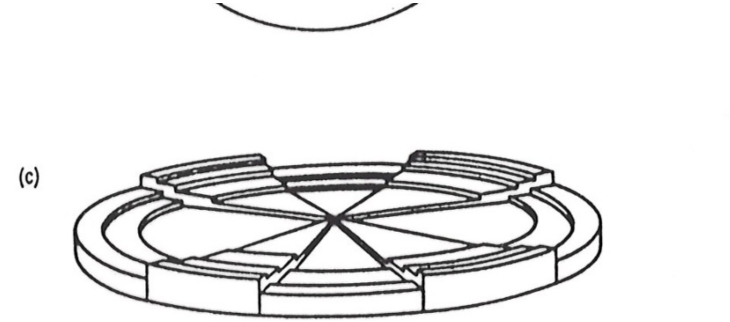


Figure 3.14 Magnetic field in isochronous cyclotron: (a) spiral sect
triangular sectors; (c) view of pole face consisting of four triangular secto

$F_z = q\, v_r\, B_\theta$ = Thomas force

ALWAYS towards the median plane

∴ axial focusing

Spiral effect

At the sector edge ($z \neq 0$) $B_r \neq 0$

Into hill (sector) $B_r > 0$

Out from hill $B_r < 0$

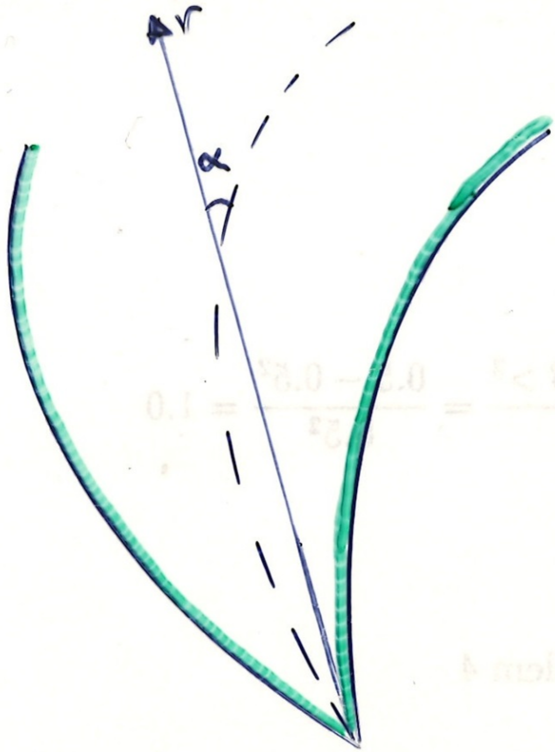
↳ FOCUSING – DEFOCUSING – FOCUSING – DEFOCUSING – ...

$\therefore$ Totally FOCUSING (compare with light optics)

SO:

"Axial focusing that was lost due to the isochronous condition was gained back with (spiral) sectors"

Spiral angle α



Define FLUTTER F:

$$F = \frac{\langle B^2 \rangle - \langle B \rangle^2}{\langle B \rangle^2}$$ "normalized variance"

$$\Rightarrow \quad \nu_z^2 \simeq -k + \frac{N^2}{N^2-1} F \left(1 + 2\tan^2\alpha\right) + \cdots$$

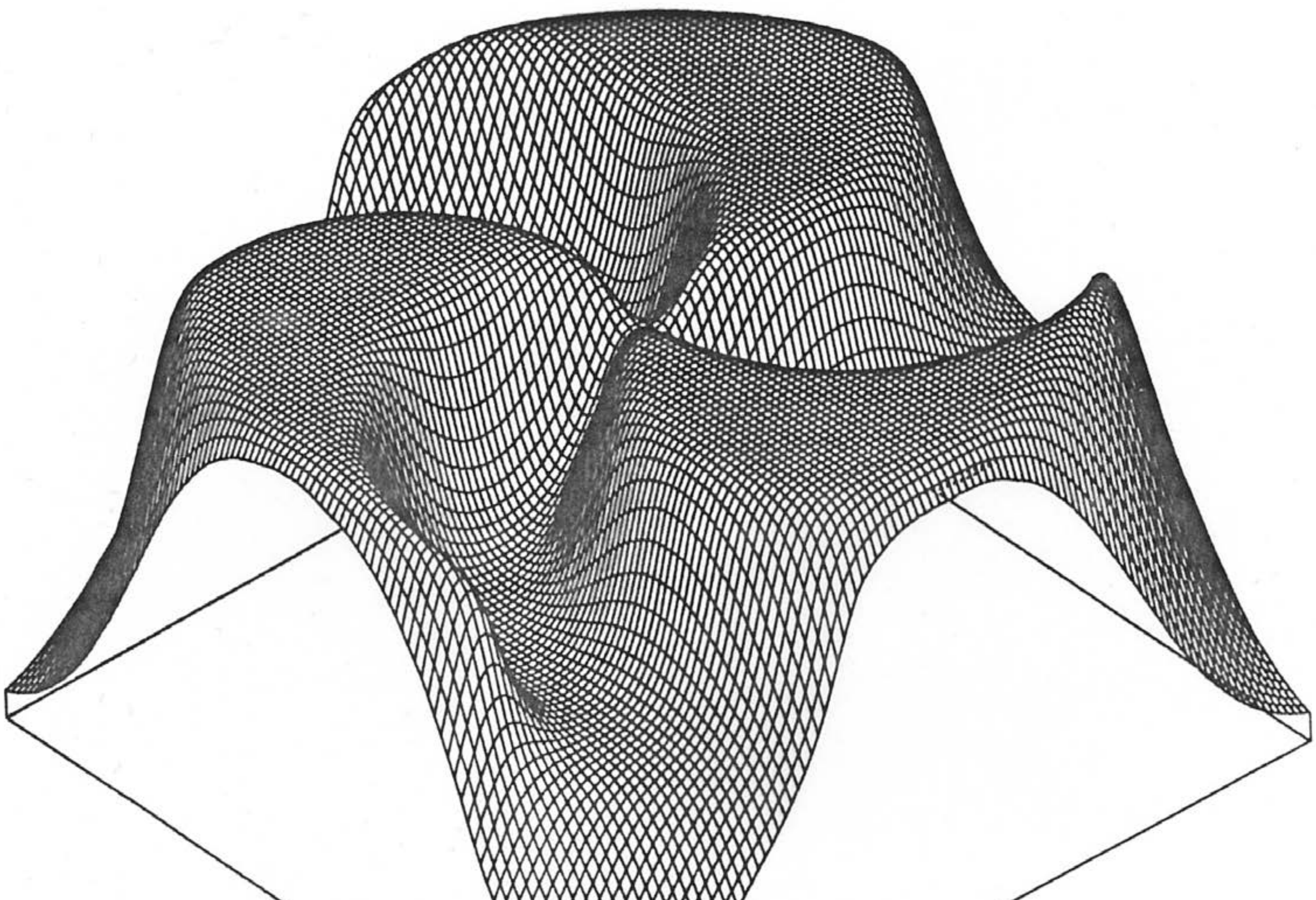
N = number of sectors

3 sector cyclotron:

$$\nu_r^2 = 1 + k + 0.675\, F\left(1 + \tan^2\alpha\right) + \cdots$$

Note!

Adding sectors decreases flutter $\xrightarrow[N \to \infty]{} 0$



Synchronous condition:

$$B = \frac{m}{q}\omega_c$$

$$= \gamma \frac{m_0}{q}\omega_c = \gamma B_0$$

$$= \frac{B_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \boxed{\frac{B_0}{\sqrt{1-\left(\frac{r\omega_c}{c}\right)^2}}} = B$$

Field shape (radially) ?

$$k = \frac{r}{B} \frac{dB}{dr}$$

$$= \frac{r B_0}{B} \frac{d}{dr} \left(1 - \frac{\omega^2}{c^2} r^2\right)^{-\frac{1}{2}}$$

$$= \frac{r B_0}{B} \frac{\omega^2 r}{c^2} \left(1 - \frac{\omega^2 r^2}{c^2}\right)^{-3/2}$$

$$= \underbrace{\frac{B_0}{B}}_{1/\gamma} \underbrace{\beta^2}_{1 - \frac{1}{\gamma^2}} \gamma^3$$

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

field index corresponding to isochronous field

$$\nu_z^2 \cong -k + F(1 + 2\tan^2\alpha)$$

$$= 1 - \gamma^2 + F(1 + 2\tan^2\alpha) > 0$$

$$F(1 + 2\tan^2\alpha) > \gamma^2 - 1$$

Focusing condition

$$\gamma = \frac{E_k + m_0 c^2}{m_0 c^2}$$

For room temperature cyclotrons (B < 2 T)

- Flutter F does not depend on B
    - So, maximum γ (v or E/A) limited by magnet geometry

For superconducting cyclotrons (B >> 2 T) iron is saturated

- $\langle B^2 \rangle - \langle B \rangle^2$ = constant (given by sector geometry)
    - Hence, Flutter decreases as $1/B^2$
    - Focusing limit:

$$\frac{E}{A} = K_f \frac{Q^2}{A^2}$$

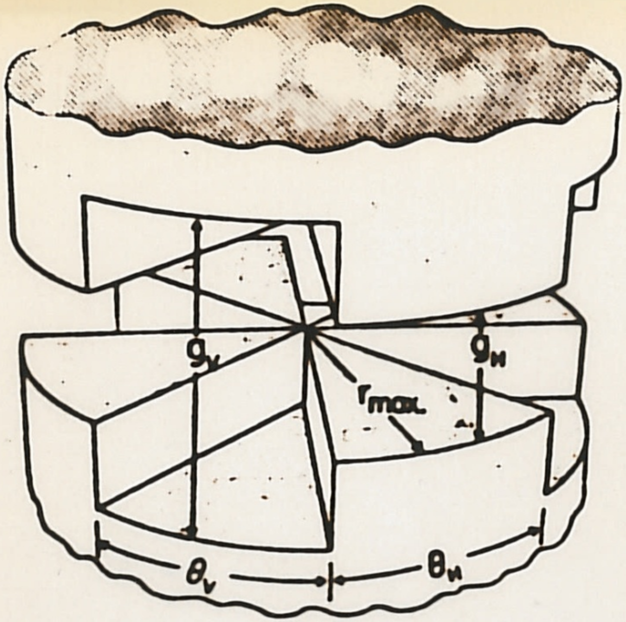


Fig. 2. Schematic drawing of the pole tip geometry assumed in our calculations. The hillgap "g_h" and the valley gap "g_v" are everywhere uniform. Likewise the hill angular width "θ_h" and the valley angular width "θ_v" are independent of radius although in special cases the angular position of the hill edge varies with radius (sect. 4). The sector number is given by $N = 360/(\theta_h+\theta_v)$. The pole outer radius is designated "r_{max}".

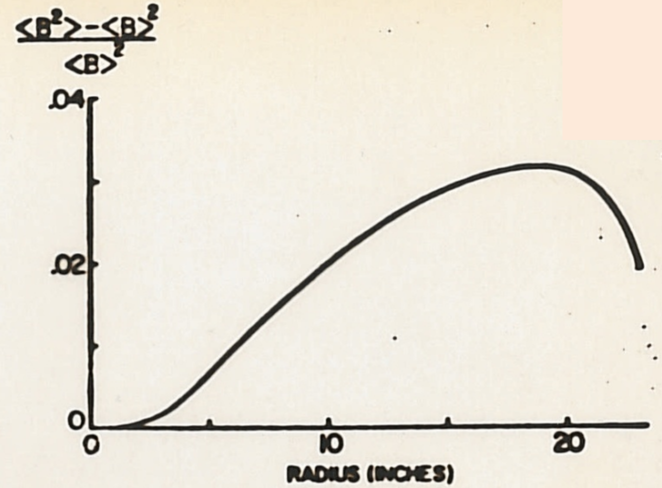


Fig. 3. Flutter [eq. (1)] vs radius for the "standard case" pole tip, which has $\theta_h = \theta_v = 45°$, $g_h = 3"$, $g_v = 36"$, $r_{max} = 24"$ and $\langle B\rangle$ as in eq. (3) (≈ 3.5 T). The focusing is adequate for about [illegible] MeV/nucleon.

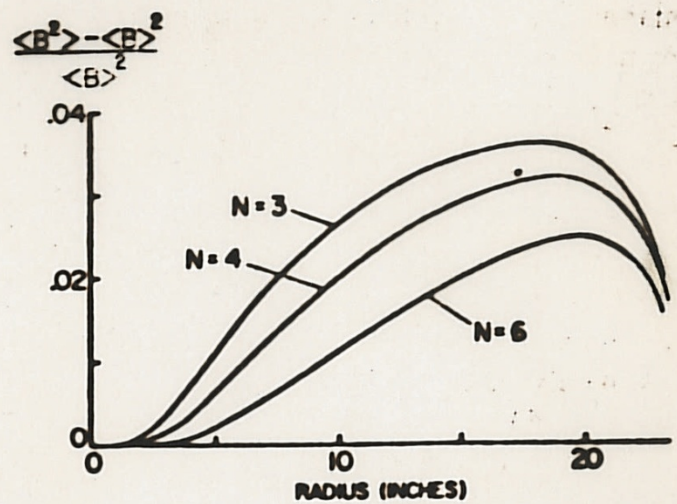


Fig. 4. Flutter vs radius for the standard four-sector case, compared with values for three sectors and six sectors. In all cases $\theta_h = \theta_v$ and other parameters are the standard case values.

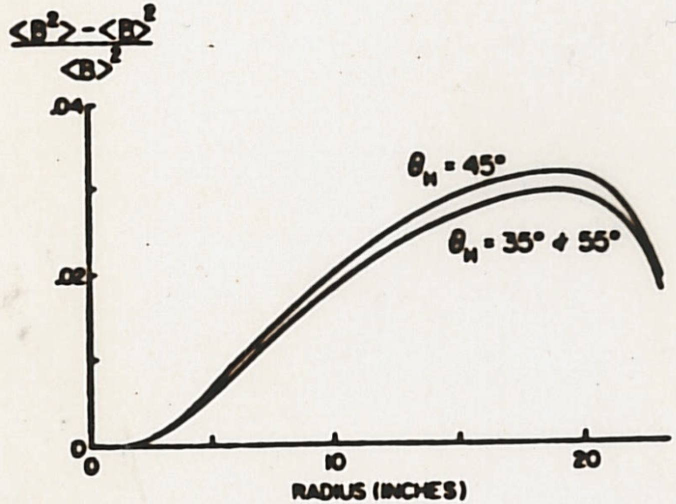


Fig. 5. Flutter vs radius for the standard case $\theta_h = 45°$, and for narrower and wider hills, $\theta_h = 35°$ and $55°$ (flutter identical). In all cases $\theta_v + \theta_h = 90°$ and other parameters are the standard case values.

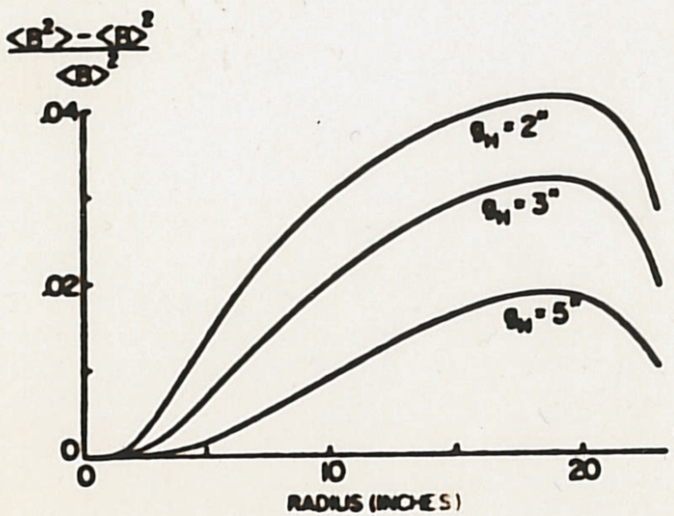


Fig. 6. Flutter vs radius for [illegible] stan[illegible] case, $g_h = 3''$, and for smaller and larger hill gaps, $g_h = 2''$ and $g_h = 5''$. All other parameters are the standard case values.

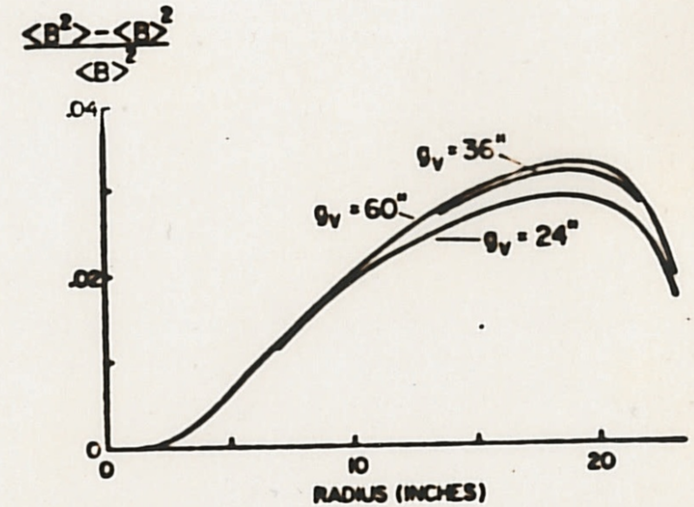


Fig. 7. Flutter vs radius for the standard case, $g_v = 36''$, and for smaller and larger valley gaps $g_v = 24''$ and $g_v = 60''$. All other parameters are the standard case values.

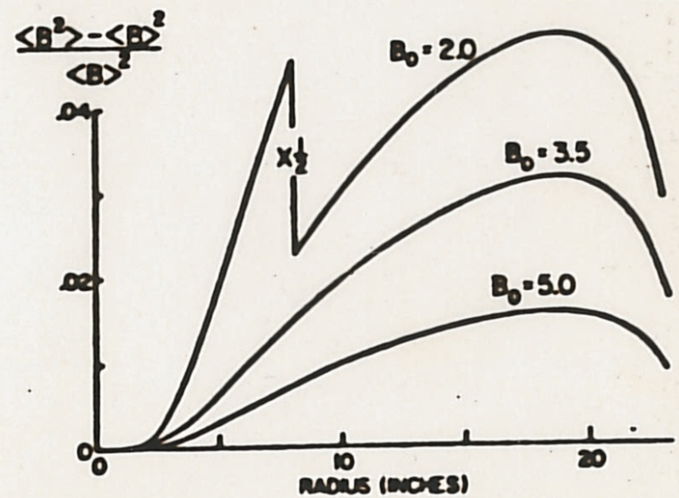
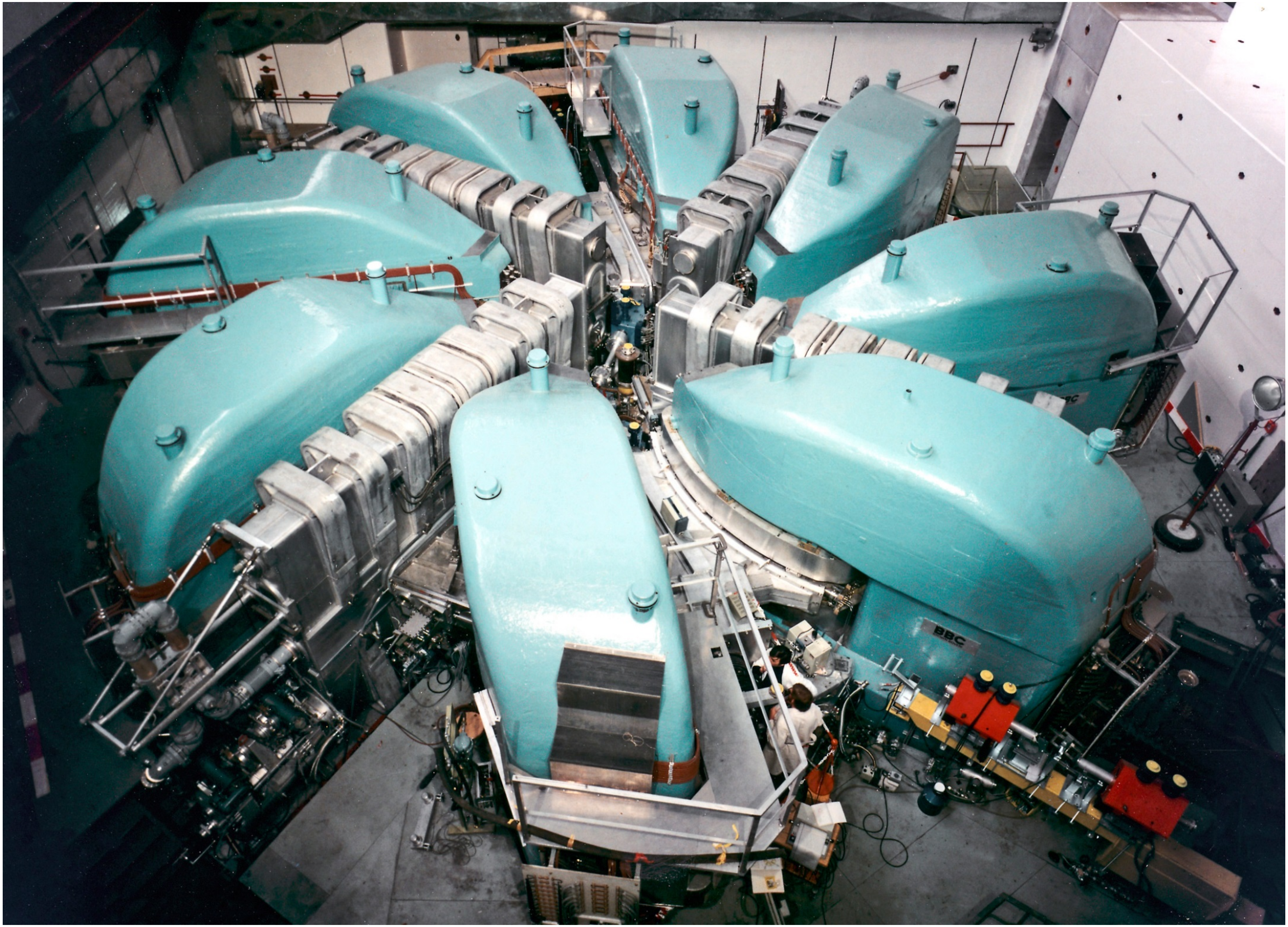


Fig. 8. Flutter vs radius with the central field at the 3.5 T standard case value, and lowered and raised to 2.0 T and 5.0 T. All o[illegible]er parame[illegible]ers ar[illegible] the s[illegible]anda[illegible] cas[illegible] [illegible]ues. [illegible] peak value for the 2.0 curve is 0.0[illegible].

Separated sector cyclotrons

- For higher energy light ions, axial focusing sets the limit
  - Increase spiral angle
  - Increase flutter F
    - Zero field in the valleys
      - Separated sectors
        - » Space for equipment between the sectors (dipoles)
          - Effective resonators for high accelerating field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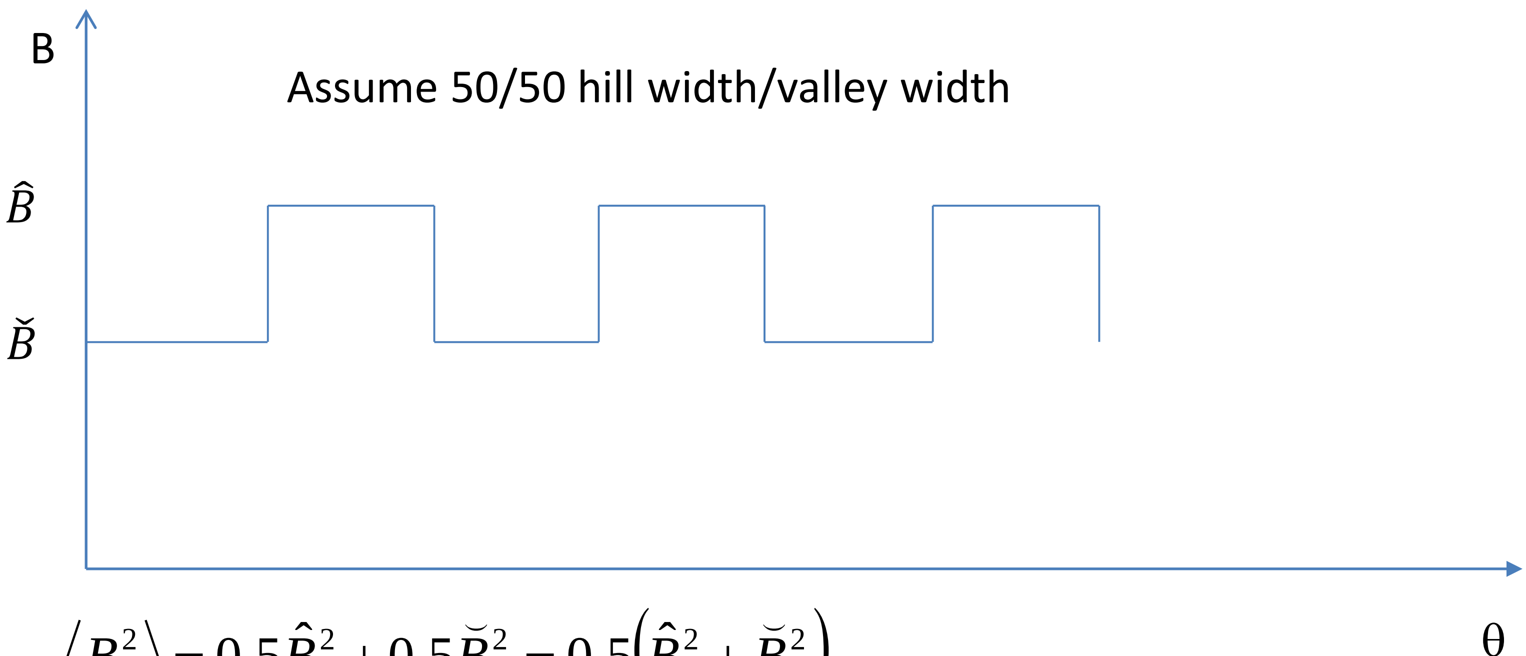
Flutter



$$\left\langle B^2 \right\rangle = 0.5\hat{B}^2 + 0.5\breve{B}^2 = 0.5\left(\hat{B}^2 + \breve{B}^2\right)$$

$$\left\langle B \right\rangle^2 = \left(\frac{\hat{B}+\breve{B}}{2}\right)^2 = 0.25\left(\hat{B}^2 + \breve{B}^2 + 2\hat{B}\breve{B}\right) = 0.25\left(\hat{B}^2 + \breve{B}^2\right) + 0.5\hat{B}\breve{B}$$

$$F = \frac{\left\langle B^2 \right\rangle - \left\langle B \right\rangle^2}{\left\langle B \right\rangle^2} = \frac{0.5\left(\hat{B}^2 + \breve{B}^2\right) - 0.25\left(\hat{B}^2 + \breve{B}^2\right) - 0.5\hat{B}\breve{B}}{0.25\left(\hat{B}+\breve{B}\right)^2}$$

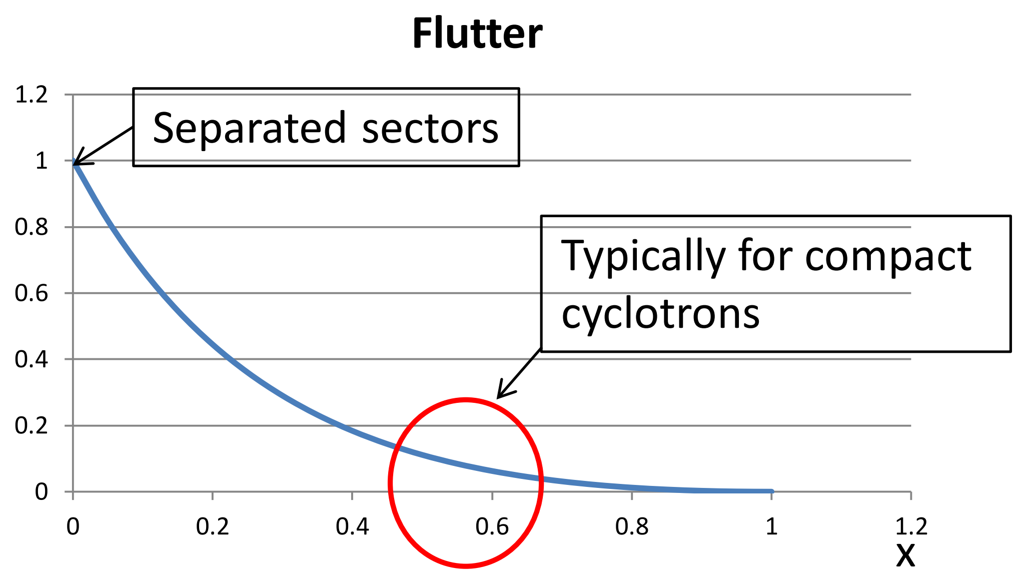
$$= \frac{0.25\left(\hat{B}^2 + \breve{B}^2\right) - 0.5\hat{B}\breve{B}}{0.25\left(\hat{B} + \breve{B}\right)^2} = \frac{\hat{B}^2 + \breve{B}^2 - 2\hat{B}\breve{B}}{\left(\hat{B} + \breve{B}\right)^2}$$

$$= \frac{\left(\hat{B} - \breve{B}\right)^2}{\left(\hat{B} + \breve{B}\right)^2}$$

$$\breve{B} = x\hat{B}$$

$$\Rightarrow$$

$$F = \frac{(1-x)^2}{(1+x)^2}$$



Remember: $F\left(1 + 2\tan^2\alpha\right) > \gamma^2 - 1$

For high E/A, choose separated sectors


SCANDITRONIX
MANUAL
AUTO
IN
OUT
SPEED


Passive focusing channels
Electromagnetic channel
Deflector
Central region + inflector

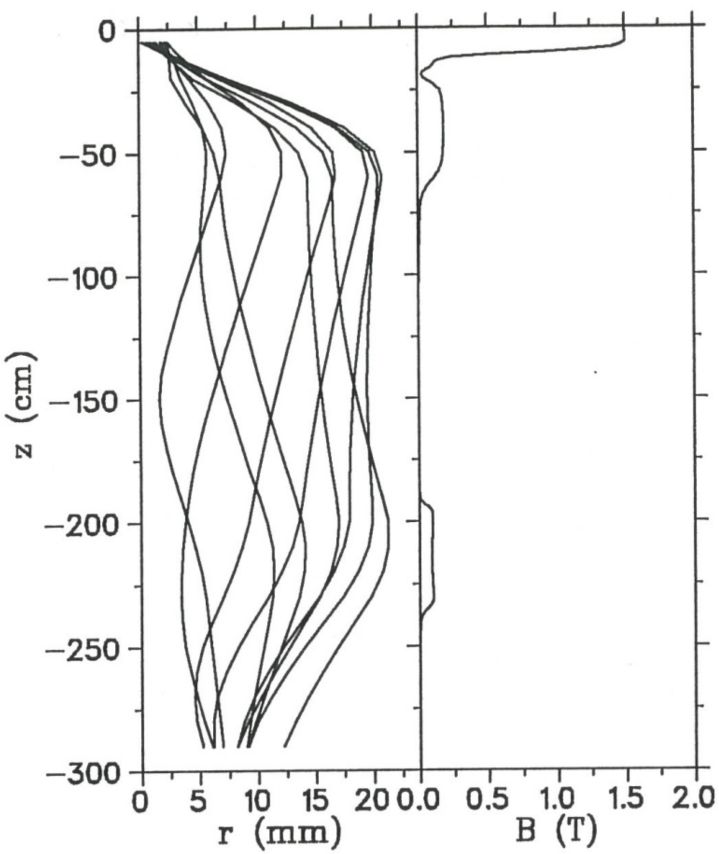
Spiral inflector

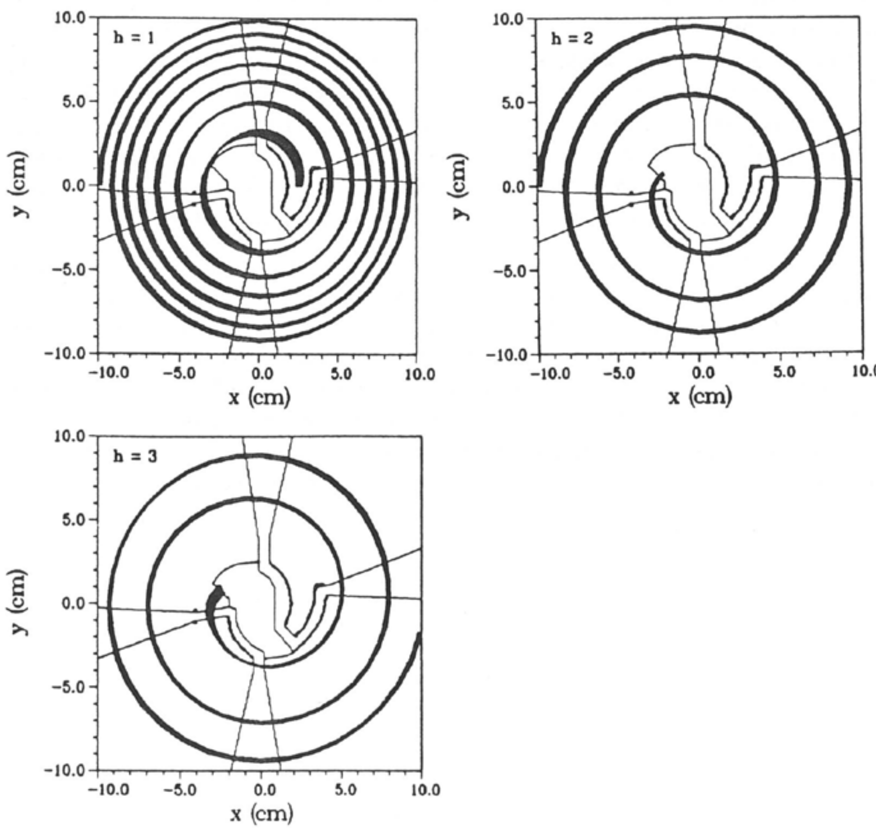

Stripper
Valley
Hill

Injection/central region and extraction

Injection

- External ion source
- Matching the beam into the cyclotron's
    - Central region acceptance
    - Accelerated equilibrium orbit "eigen ellipses"
- Low-energy beam
    - Possible space charge limitation





Forces in the cyclotron

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Typically $\widehat{E} \cong 10\ \mathrm{MV/m}$

$B \cong 1.5\ \mathrm{T}$

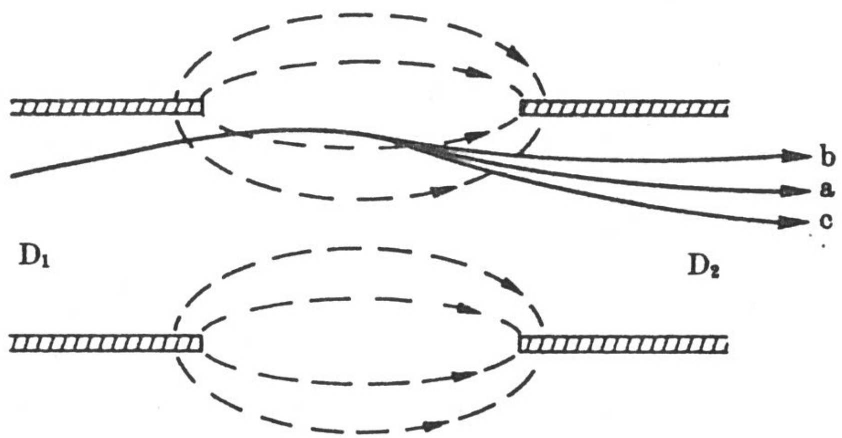
$$F_E = F_B$$

$$\Rightarrow v \cong 0.02\, c$$

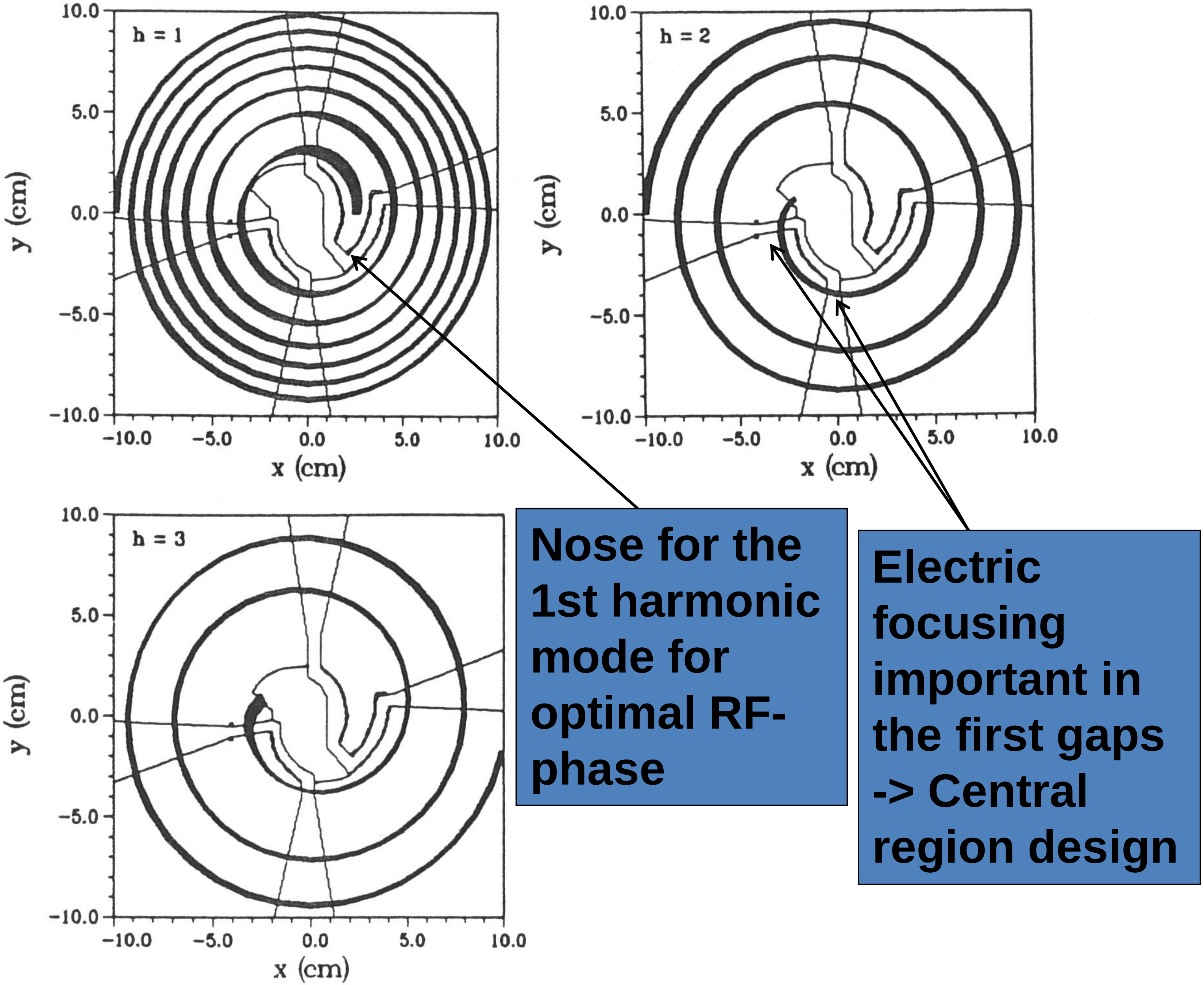
$$\Rightarrow \frac{E}{A} \cong 200\ \mathrm{keV/n}$$

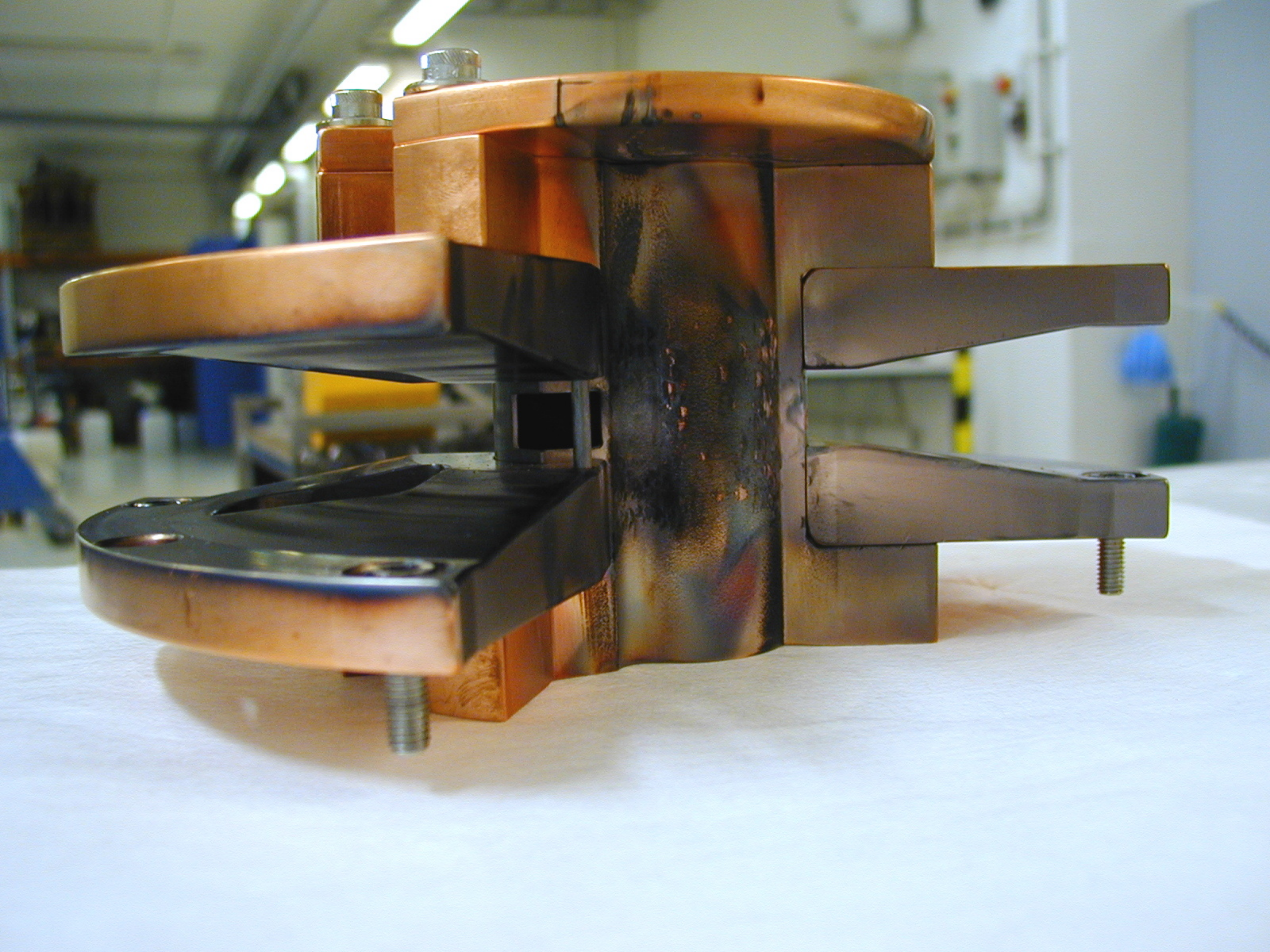
This energy is reached during 1 – 2 turns

Outside the central region only magnetic forces (bending, focusing) are relevant.
However, electric focusing is important along the first 1 – 2 turns.

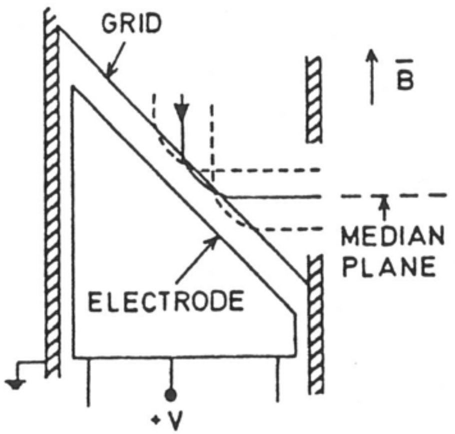


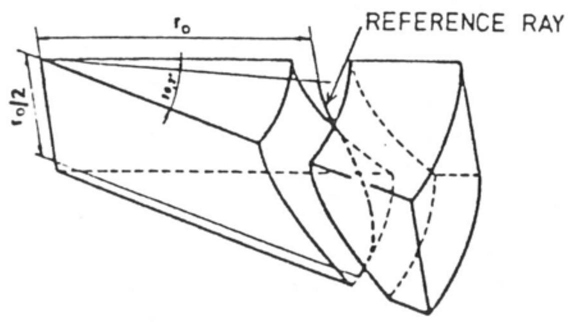
Transit time effect in an accelerating gap in a) static field, b) increasing field and c) decreasing field. The effect is exaggerated

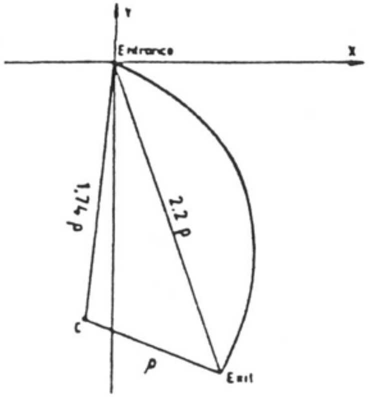

h = 1
h = 2
h = 3
y (cm)
x (cm)
10.0
5.0
0.0
−5.0
−10.0
Nose for the 1st harmonic mode for optimal RF-phase
Electric focusing important in the first gaps -> Central region design

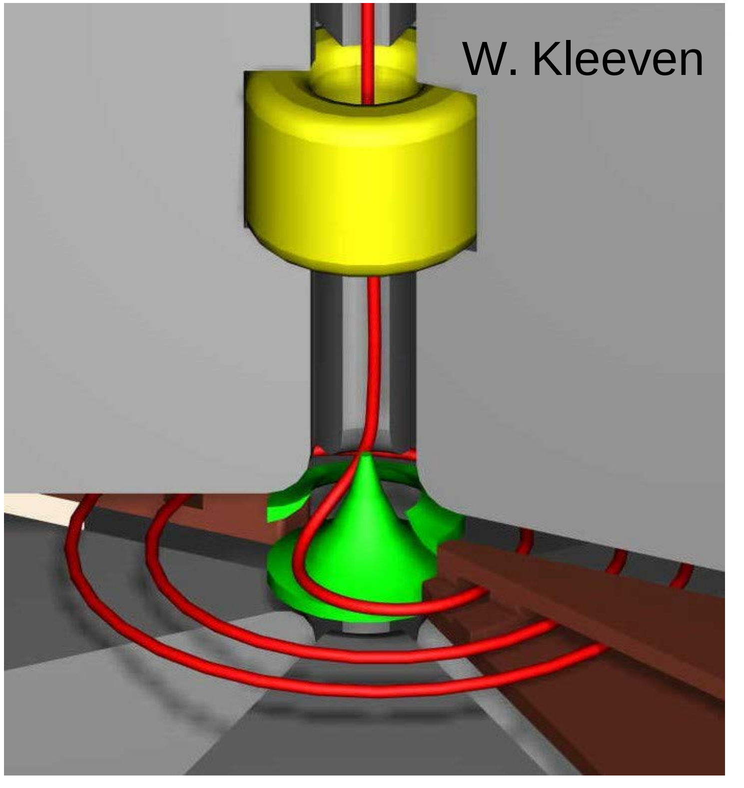


Inflectors

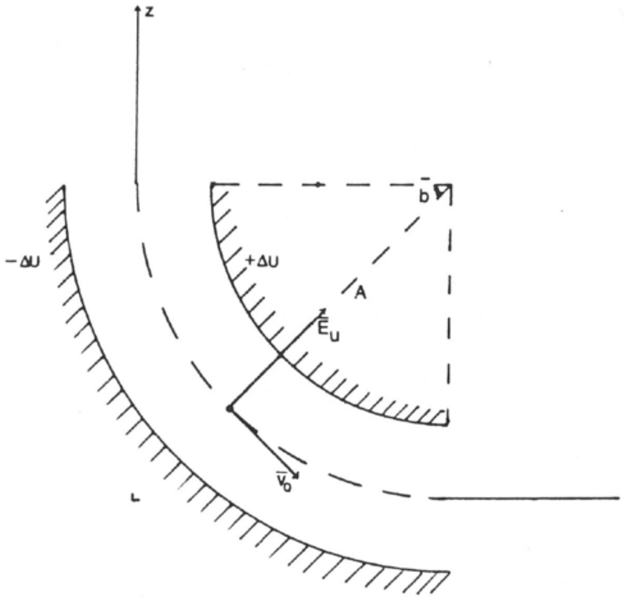

GRID
B
MEDIAN
PLANE
ELECTRODE
+V


r0
REFERENCE RAY
r0/2

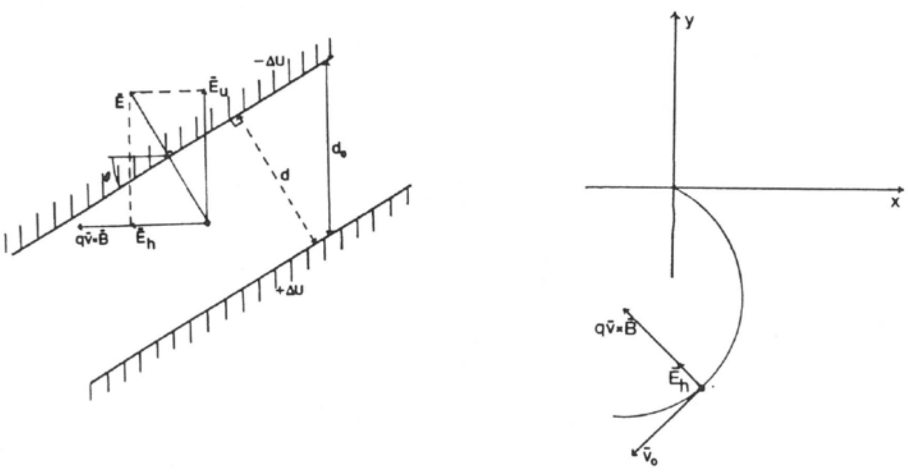

Entrance
Exit
1.74 ρ
2.2 ρ
ρ


W. Kleeven

Spiral inflector

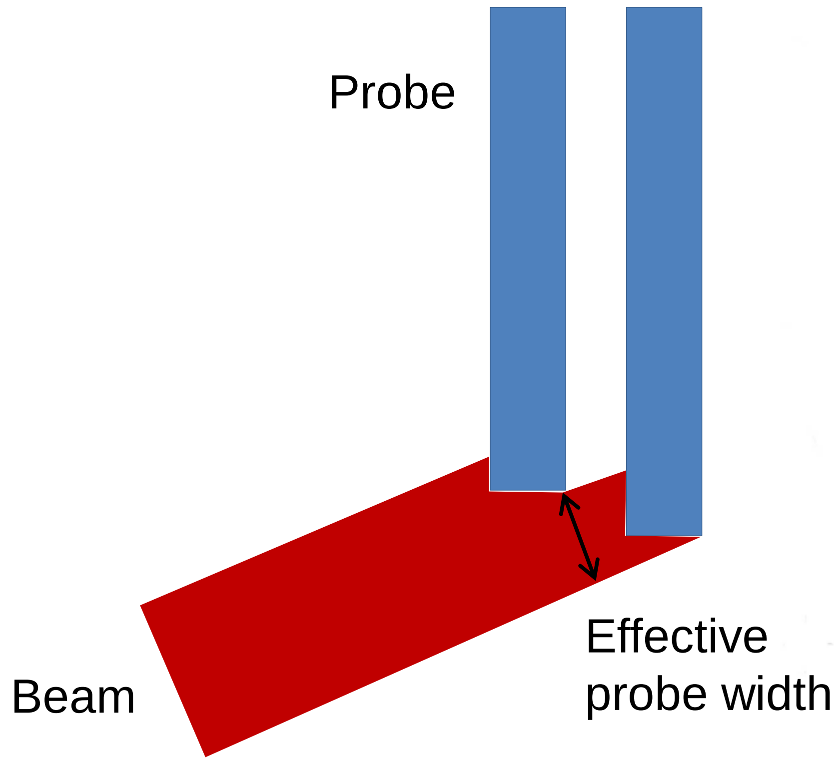


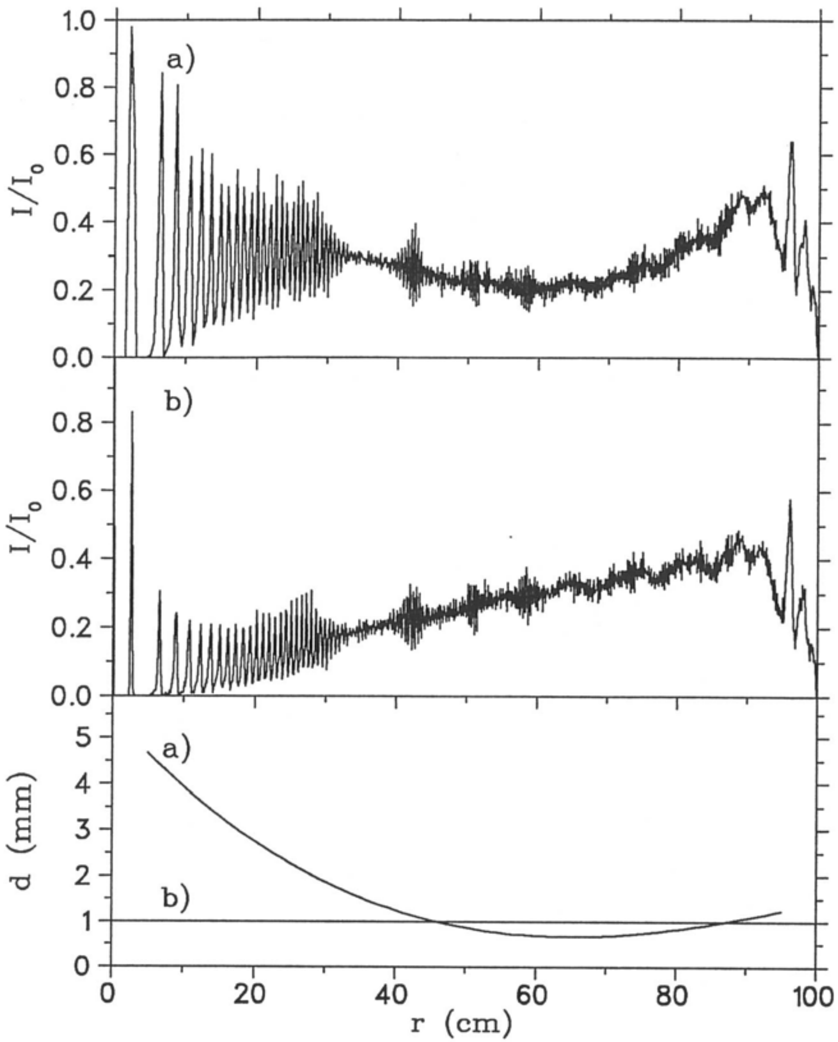
Beam bending without magnetic field



a) Cross-section of the spiral electrodes and b) beam projection on xy plane

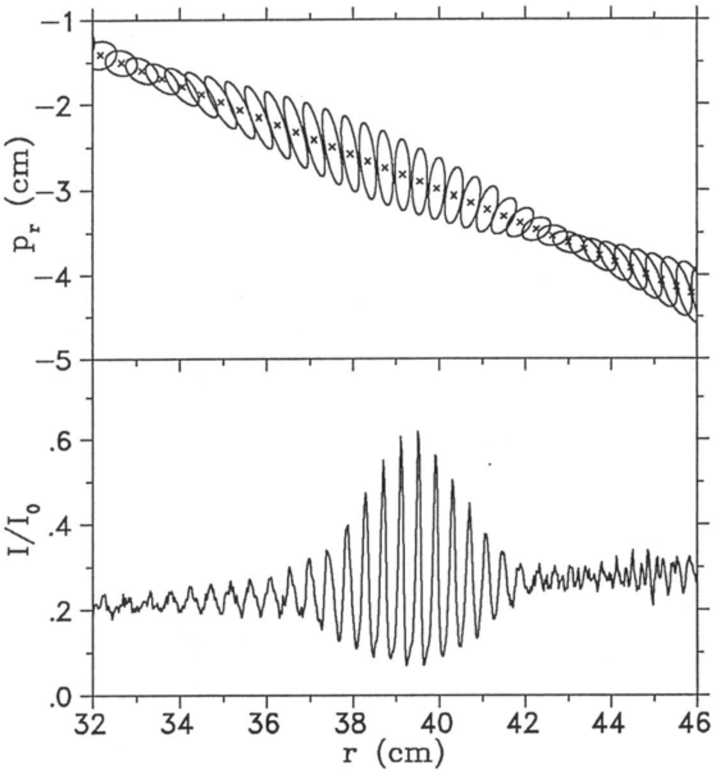
Injection has an effect on beam behaviour in the cyclotron

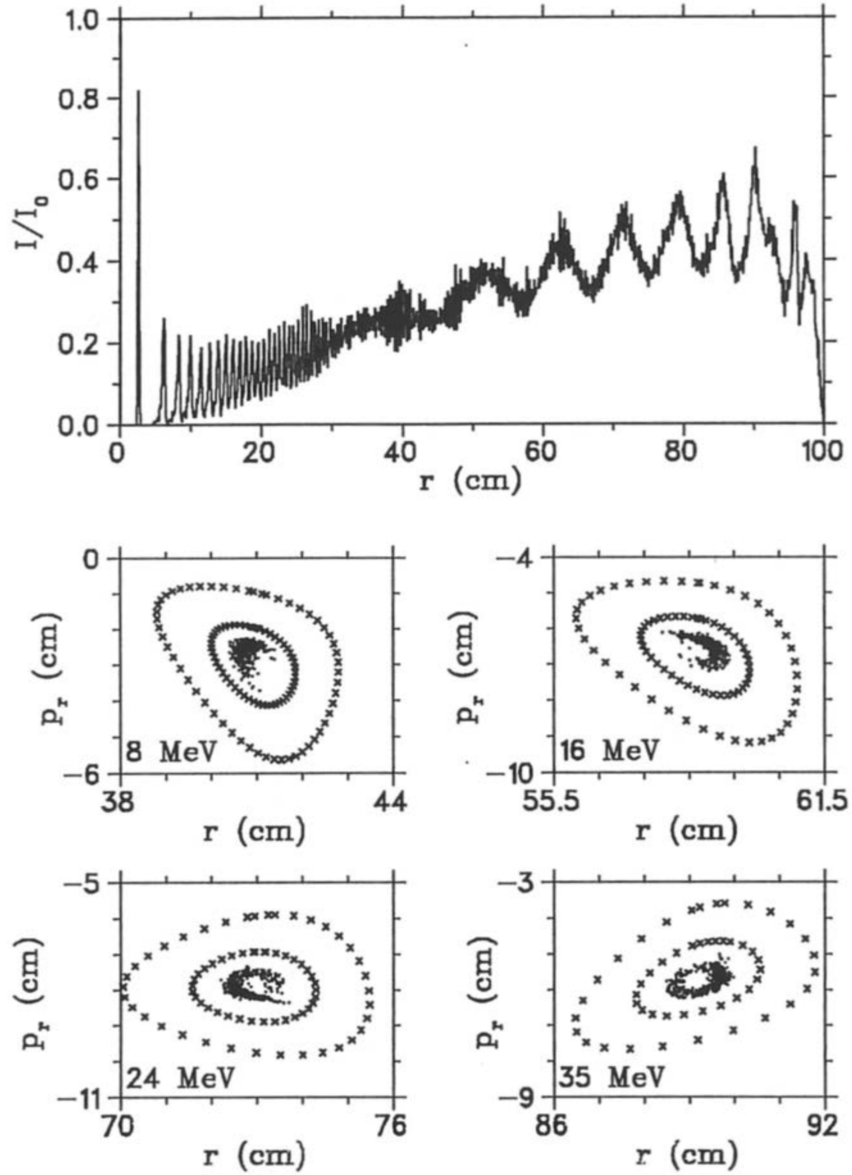




Differential probe scan with a) a changing effective probe width and b) with a constant effective probe width.

The beam rotates at the radial betatron frequency

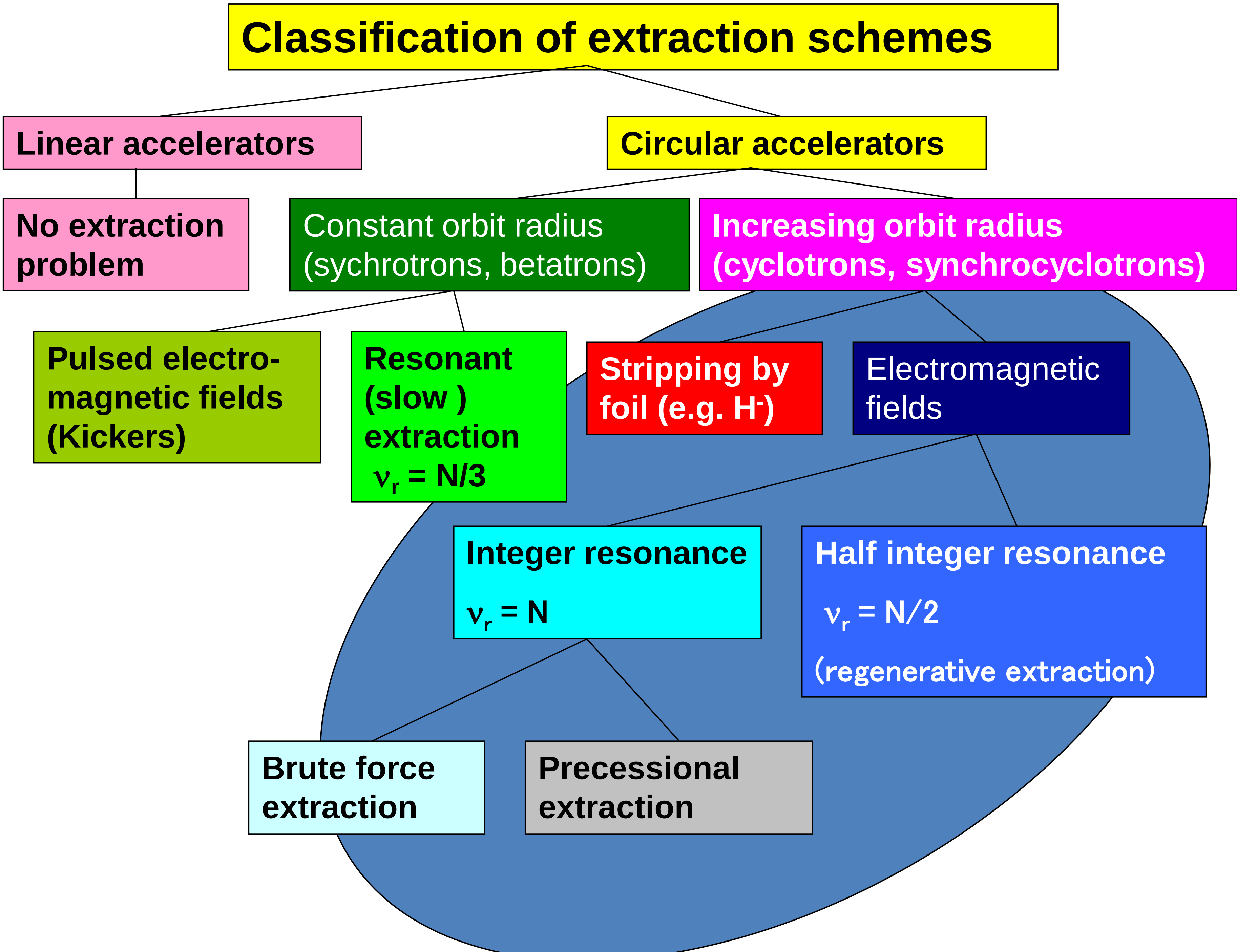




⟶ Match the beam into the acclerated equilibrium orbit eigen ellipses with quadrupoles (4)

⟶ Center the beam

Extraction from cyclotrons


Classification of extraction schemes
Linear accelerators
Circular accelerators
No extraction problem
Constant orbit radius (sychrotrons, betatrons)
Increasing orbit radius (cyclotrons, synchrocyclotrons)
Pulsed electro-magnetic fields (Kickers)
Resonant (slow) extraction
ν_r = N/3
Stripping by foil (e.g. H^-)
Electromagnetic fields
Integer resonance
ν_r = N
Half integer resonance
ν_r = N/2
(regenerative extraction)
Brute force extraction
Precessional extraction

Extraction by acceleration

Radial increase of the orbit

- By acceleration
- By magnetic pumps

$$\frac{dR}{dn} = \frac{dR}{dn}(\text{accel}) + \frac{dR}{dn}(\text{magn})$$

$$\frac{dR}{dn}(\text{accel}) = R\,\frac{E_{\text{g}}}{E}\,\frac{\gamma}{\gamma+1}\,\frac{1}{\nu_r^2}$$

Three ways to get a high extraction rate

1. Build cyclotrons with a large average radius (without increasing the maximum energy)
2. Make the energy gain per turn as high as possible
3. Accelerate the beam into the fringe field, where ν_r drops

This also calls for high energy gain, since phase slip in the fringe field must be kept small

Item 1. Remember that for the same maximum field and the same energy gain per turn

$$\frac{dR}{dn}(\text{accel}) \propto \frac{1}{R}$$

Item 3. especially important for high energy cyclotrons

$$\nu_r \approx \gamma$$

Remember: for an isochronous field

$$k = \frac{r}{B}\frac{dB}{dr}$$

Field index

$$= \gamma^2 - 1$$

And e.g. for a 3-sector magnet

$$\nu_r^2 \approx 1 + k + 0.675F\left(1 + \tan^2\alpha\right) + \ldots$$

So, e.g. for the PSI 580 MeV cyclotron in the isochronous extraction region

$\nu_r = 1.6$ and at the extraction in the fringe field $\nu_r = 1.1$

Factor of 2 in turn separation

Resonant extraction

Normally the radial gain per turn by acceleration in not enough

•Magnetic perturbations to enhance the turn separation

The integer resonance ν_r=*N*

Brute force

Bump in the axial field $$\Delta B(r,\theta) = b_N \cos N(\theta - \theta_N)$$

ν_r close to *N* ⟶

The beam is driven off centre, maximum additional radial gain per turn being

$$\frac{dR}{dn}(\text{brute force}) = \pi R \frac{b_N}{NB_0}$$

For a typical conventional cyclotron (B_0=1.7 T) a bump of 0.1 mT introduces a radial gain of about 0.2 mm!!

To get a desired turn separation bigger bumps are needed

- "Brute force"
- This method has been used for example in the AEG compact cyclotron

Precessional extraction

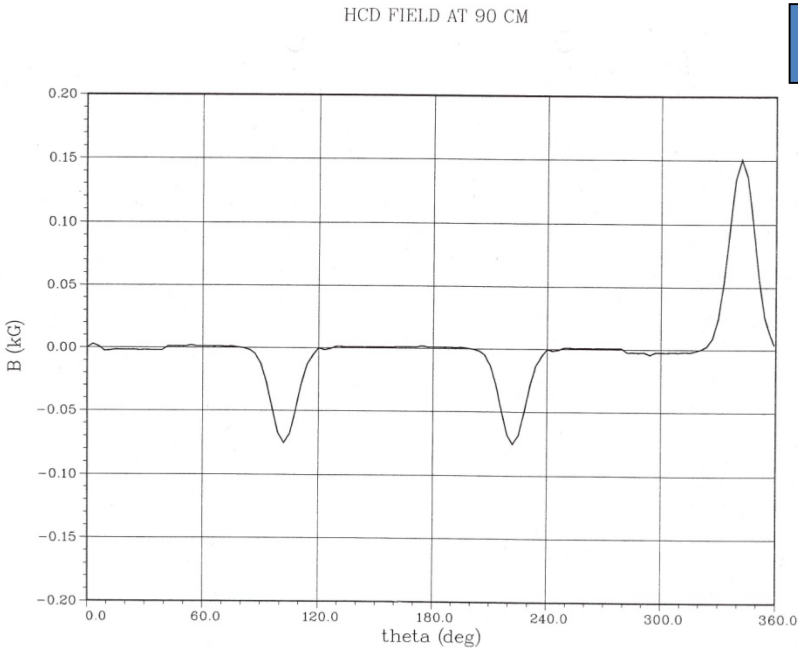
The beam goes through $\nu_r=1$ resonance with a first order perturbation

- Beam starts to oscillate around its equilibrium orbit with a frequency

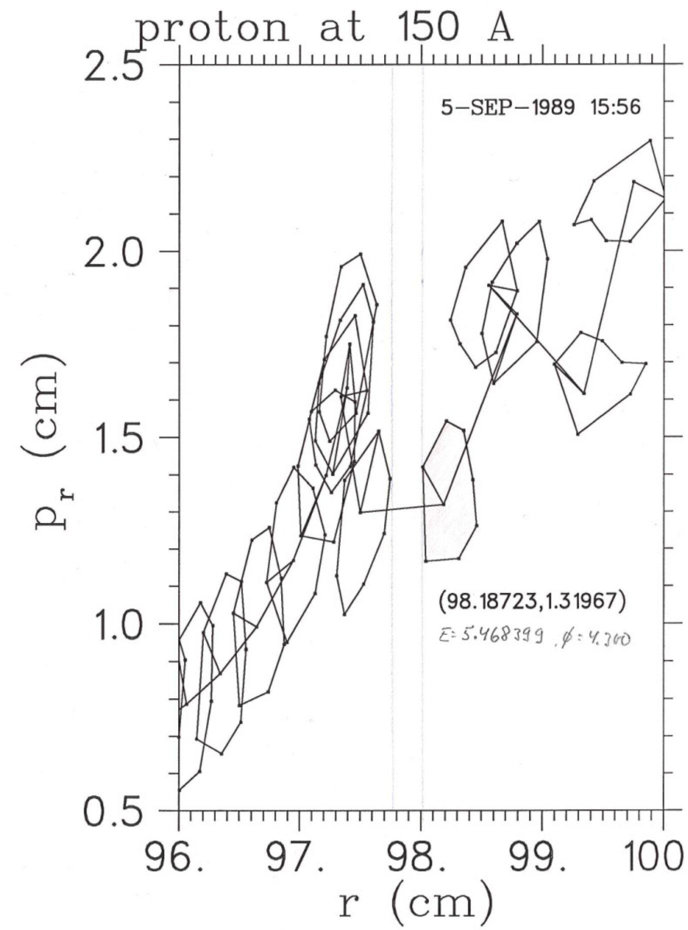
$$|\nu_r - 1|$$

- ν_r decreases with radius
  - Two consecutive turns oscillate with a slightly different frequency
    - Phase difference between the turns increases
      - Turn separation increases

Bump with a harmonic coil $\langle B_{harm} \rangle = 0$



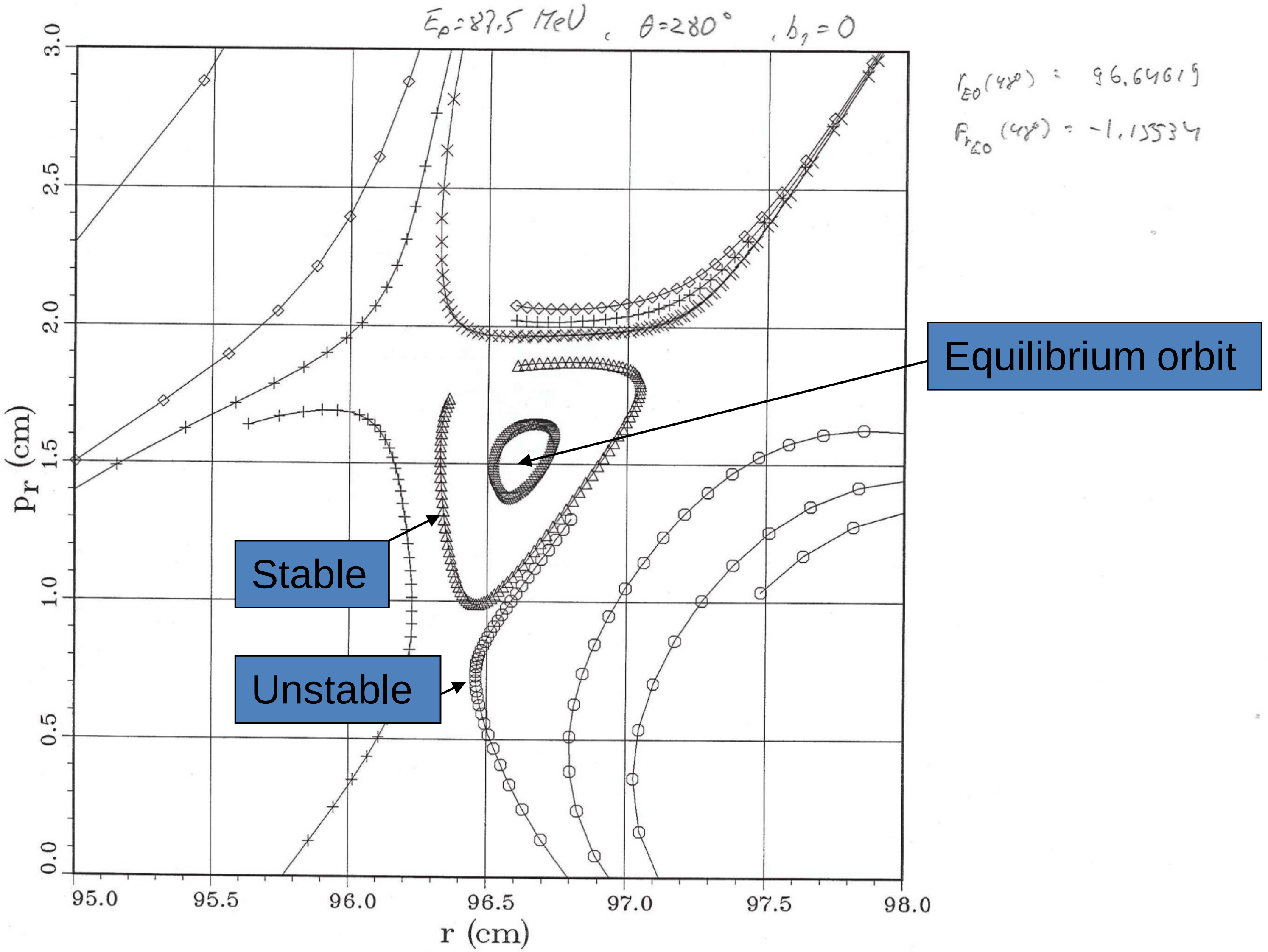
Contribution of harmonic coils in three valleys



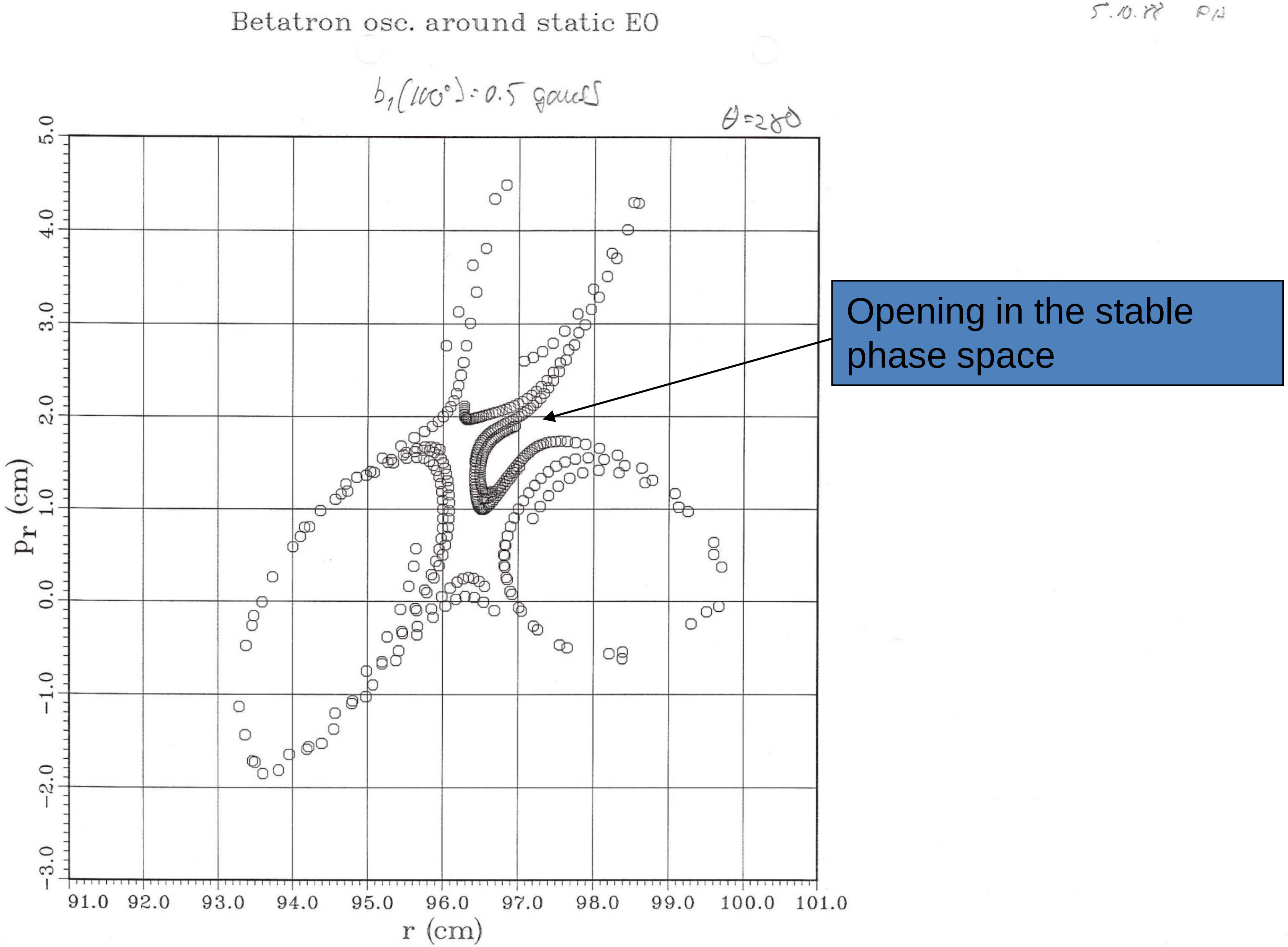
Precession after $\nu_r = 1$ resonance

4.10.88 PH

Betatron osc. around static E0



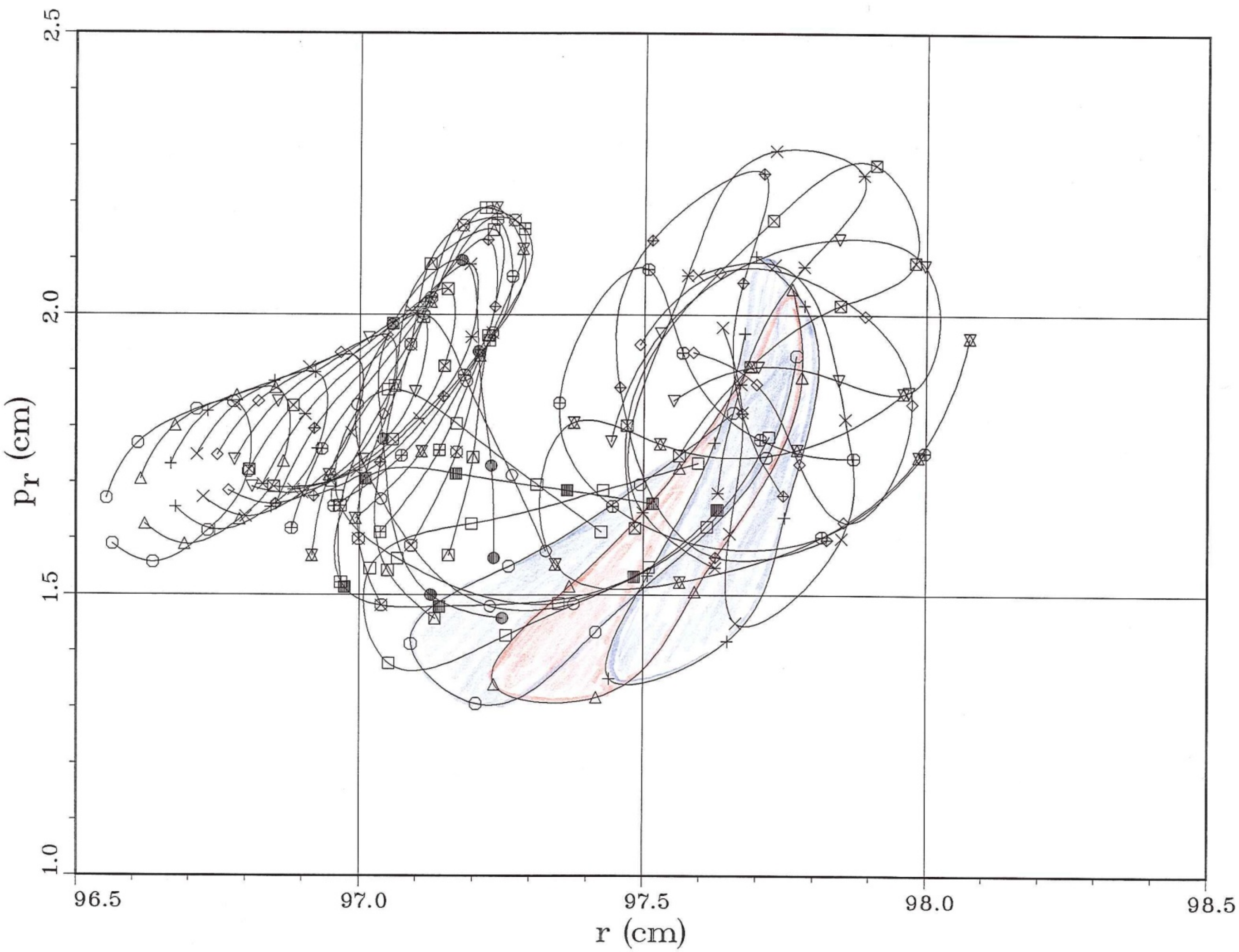
Radial phase space without a 1st order perturbation



Radial Phase space with a 1st order perturbation

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

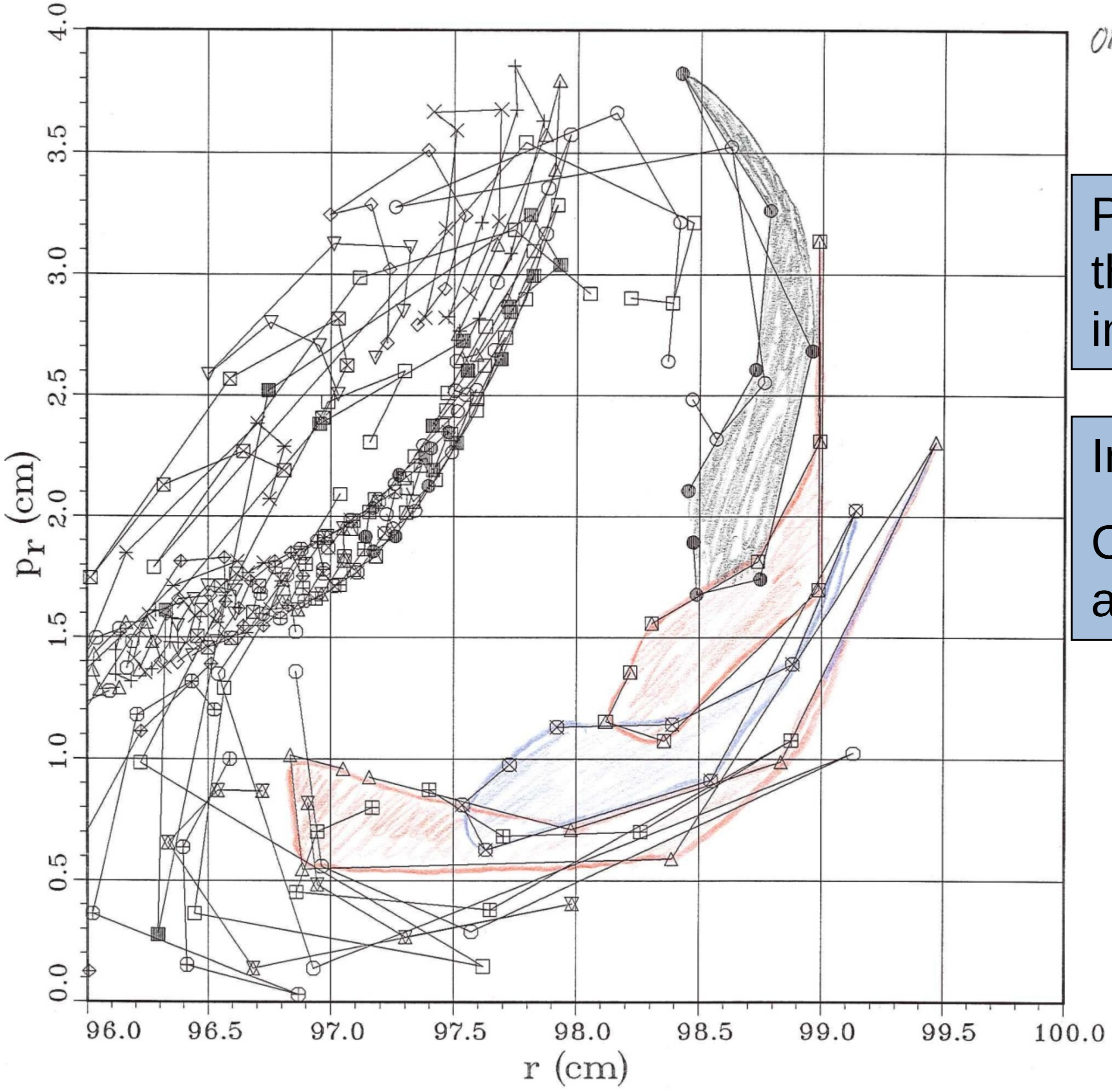
10.10.88 ρ11



Phase and amplitude of the perturbation is important!

$B_1 = 2$ gauss / $\theta_{b1} = 100$ / $\theta = 280$

7.10.98 FM

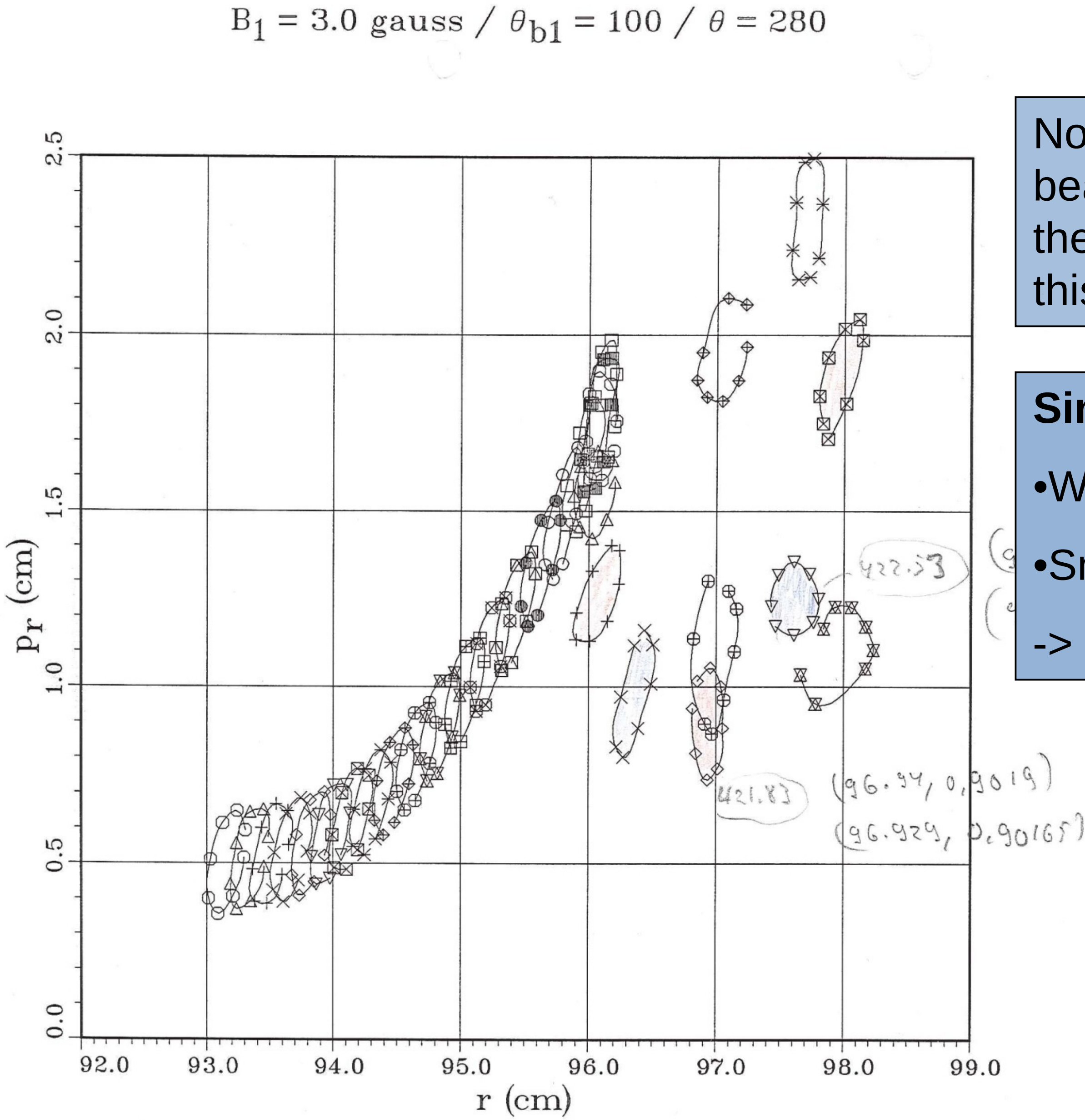


Obviously too big B1

Phase and amplitude of the harmonic perturbation important

Implication:

Centering of the beam is also important!



Note: **Mono-energetic** beam was started from the equilibrium orbit in this tracking!

Single turn extraction:

- Well centered beam
- Small RF phase width

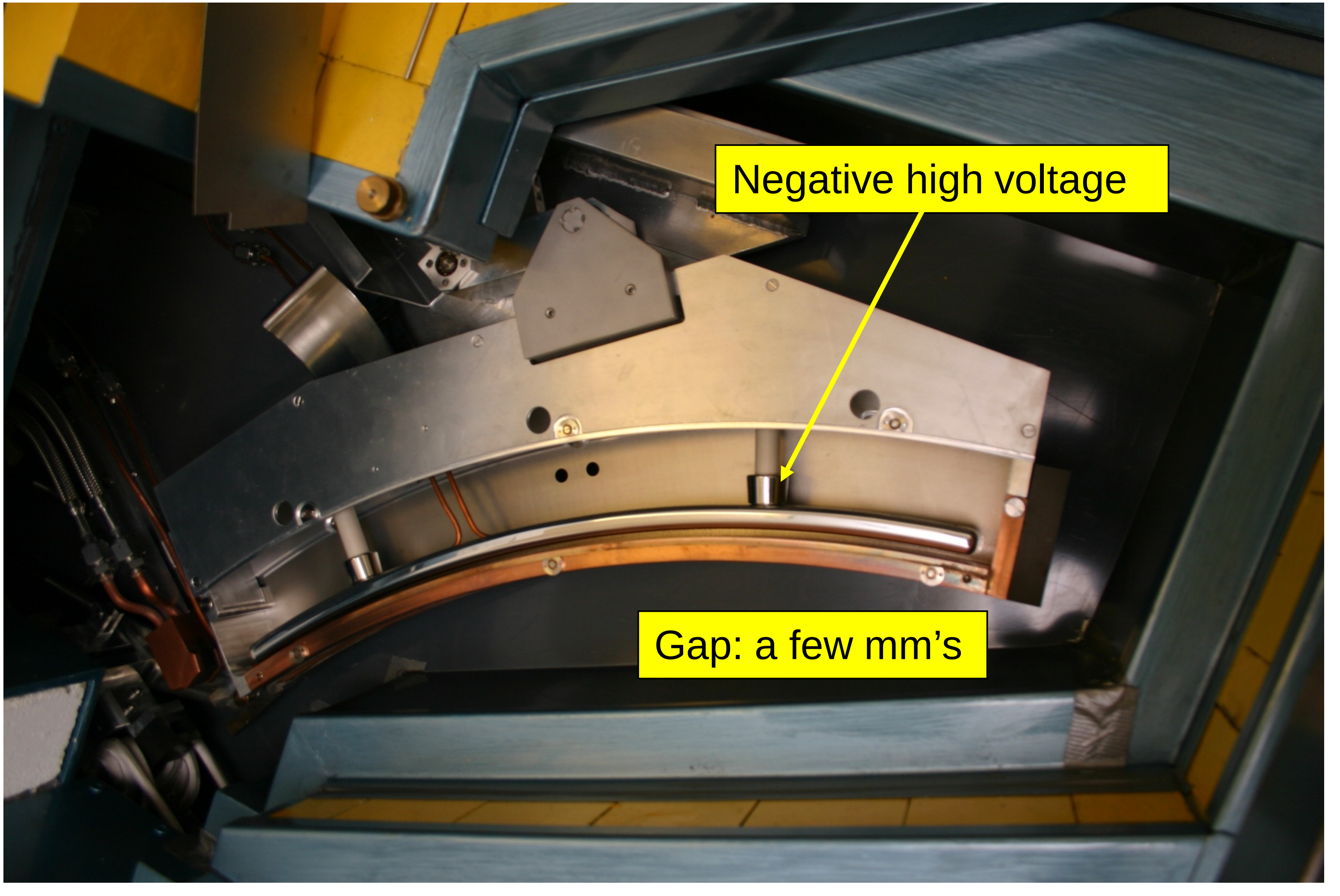
-> phase slits

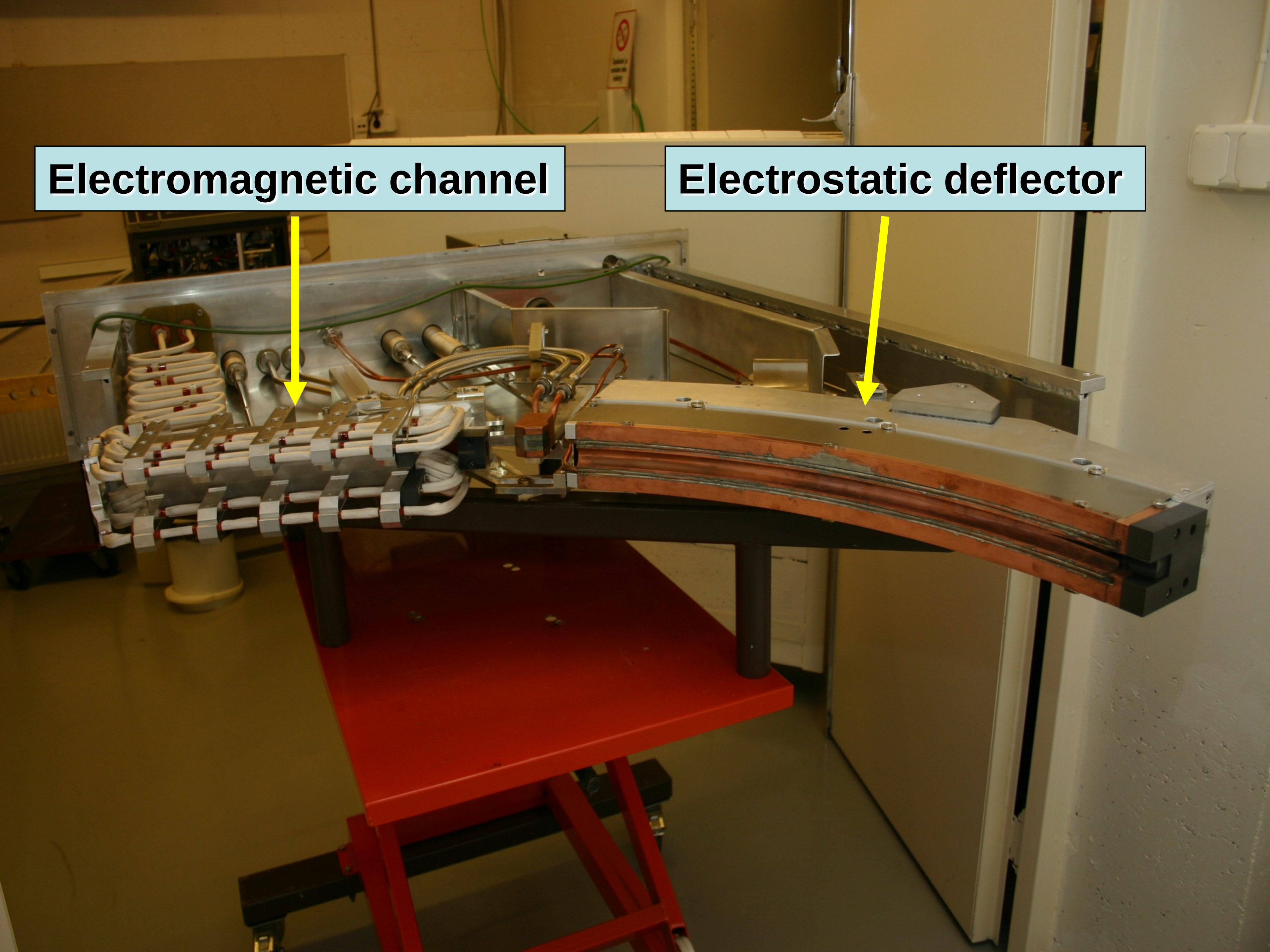
Nice behavior with a proper 1st harmonic perturbation

Extraction elements

- (Harmonic coils)
- Electrostatic deflector
- Electromagnetic channel
- (Passive) focusing channels
- Stripper

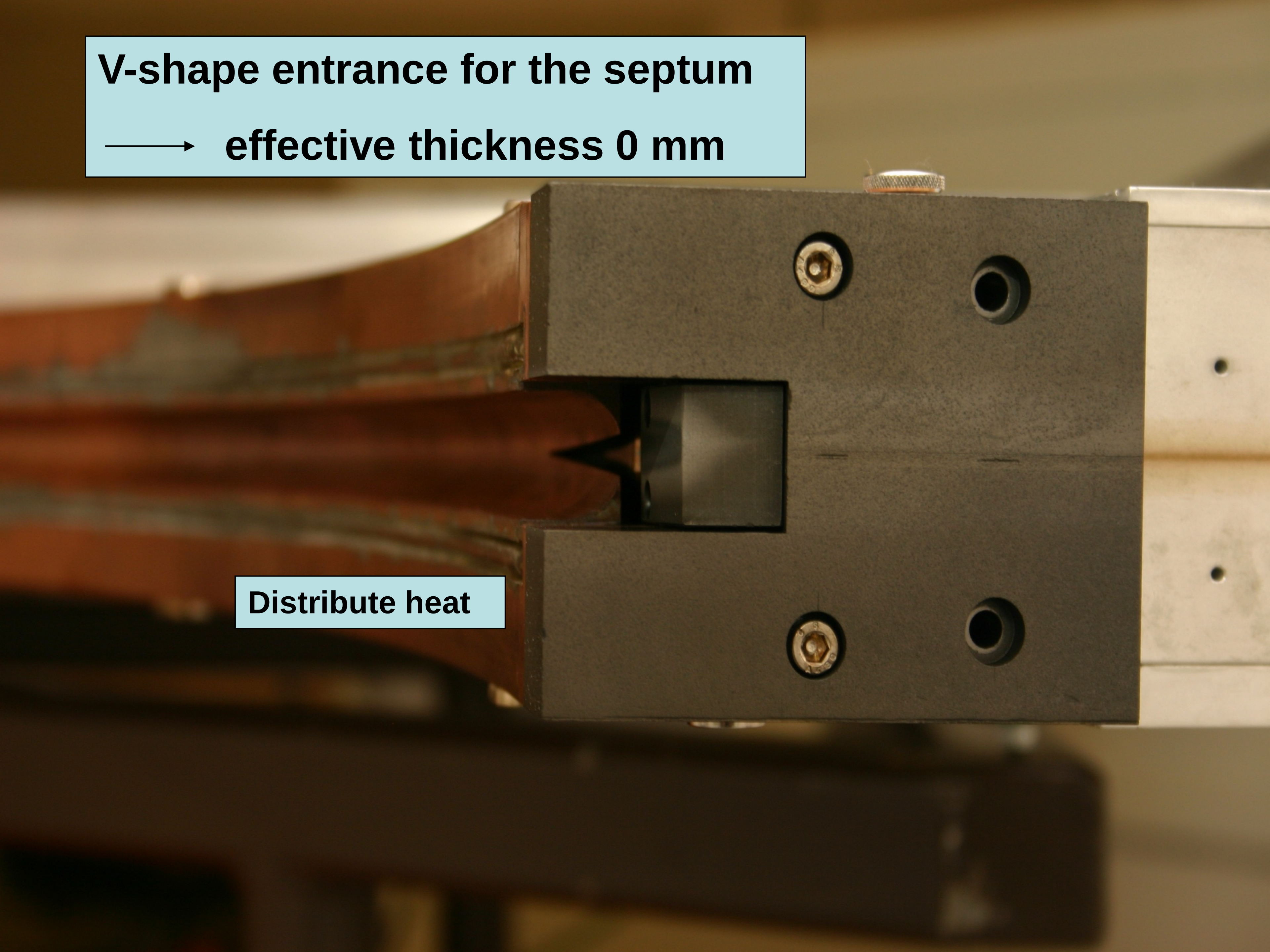
Electrostatic deflector




Electromagnetic channel
Electrostatic deflector

V-shape entrance for the septum

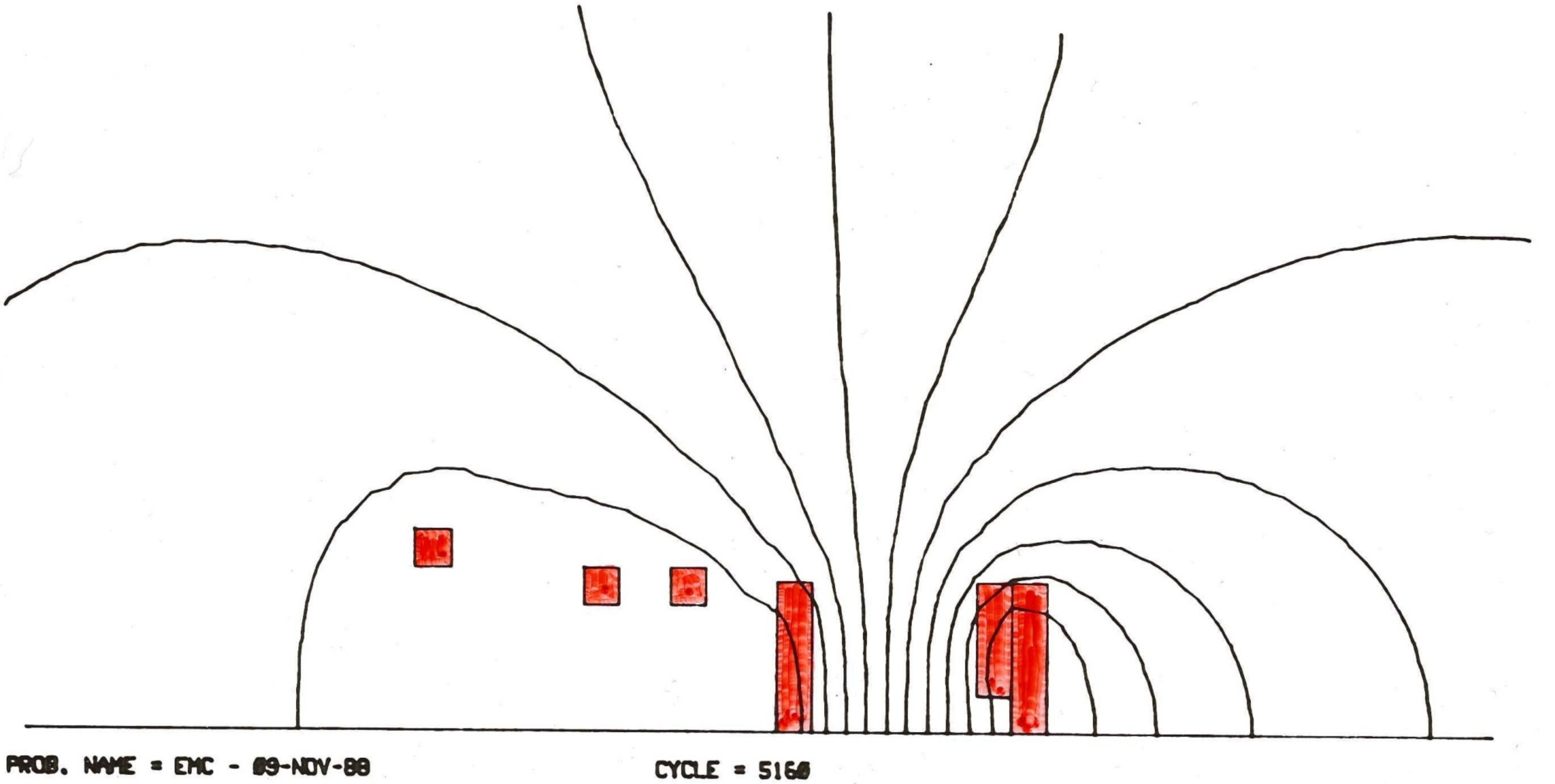
→ effective thickness 0 mm

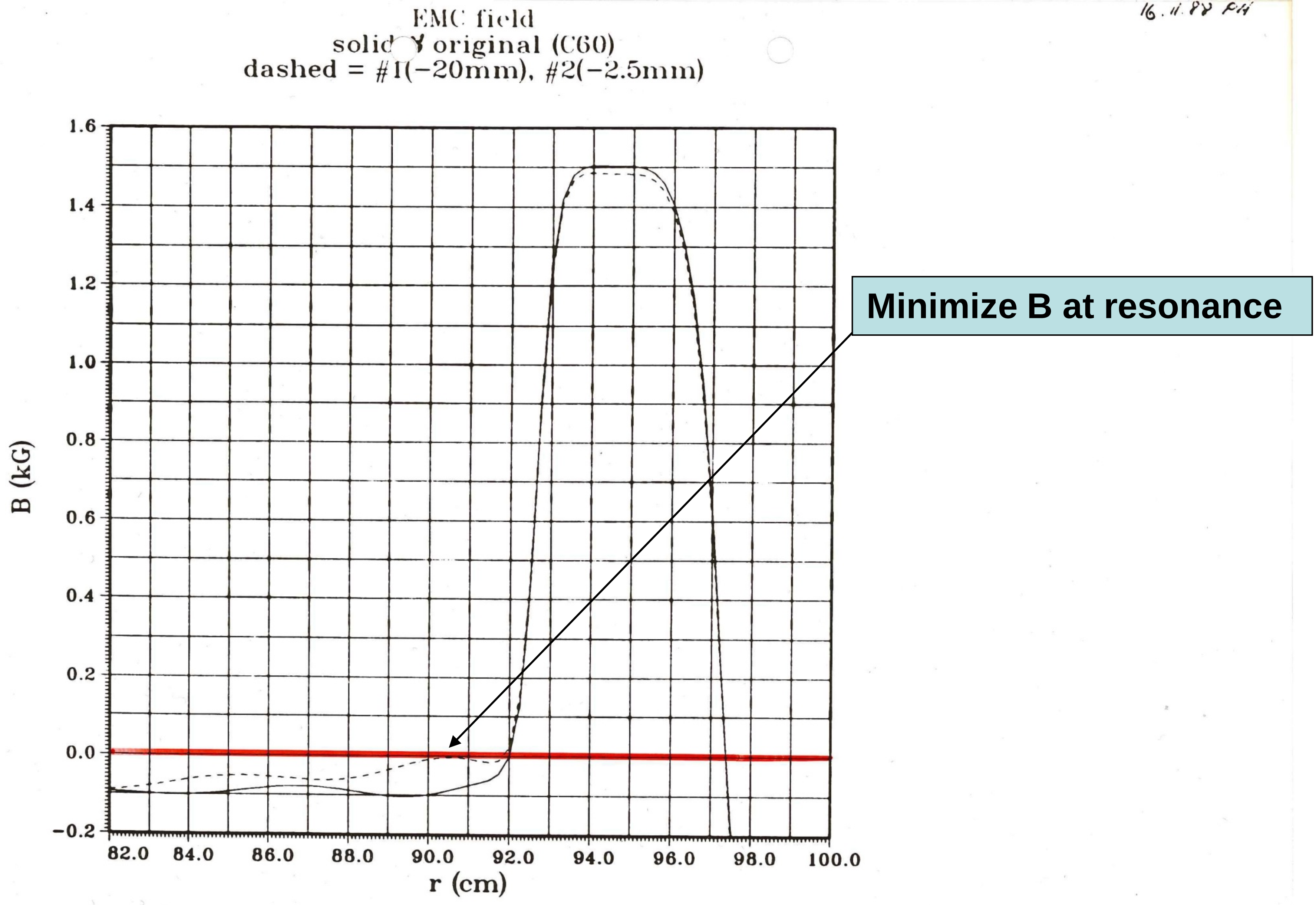


Electromagnetic channel

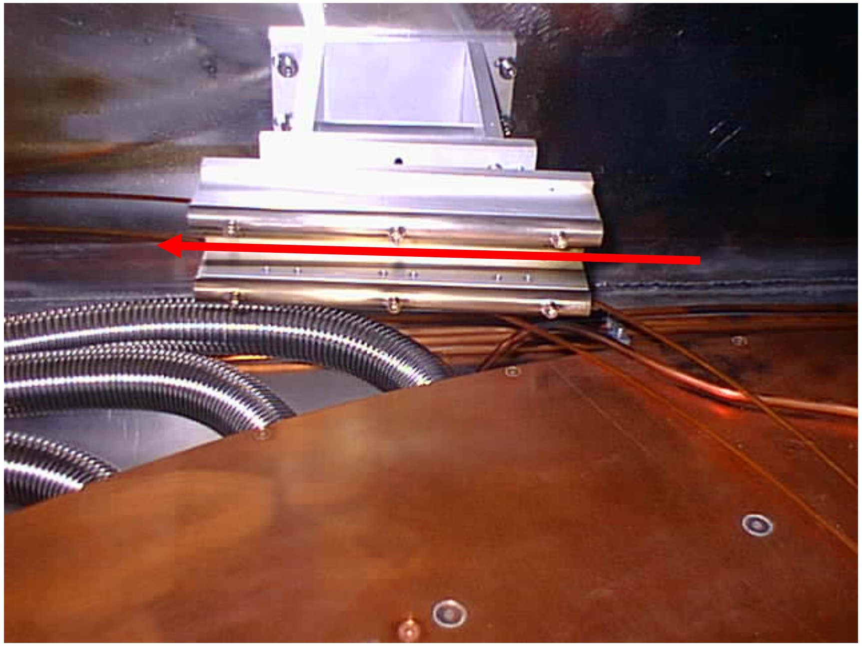
High current in the EMC coil

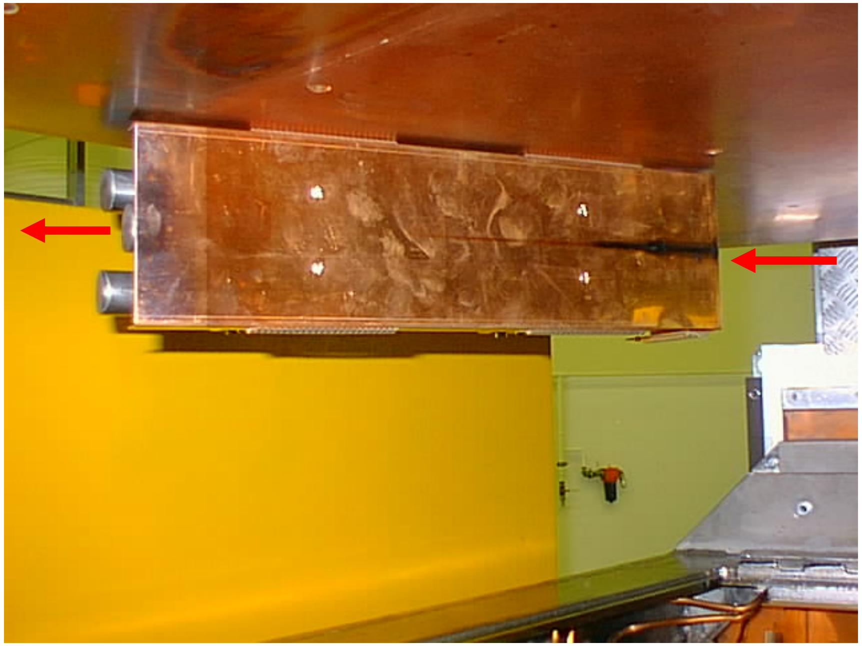
- Main coil current + booster current




EMC field
solid = original (C60)
dashed = #1(−20mm), #2(−2.5mm)
16.11.88 PH
B (kG)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
82.0
84.0
86.0
88.0
90.0
92.0
94.0
96.0
98.0
100.0
r (cm)
Minimize B at resonance

Passive focusing channel



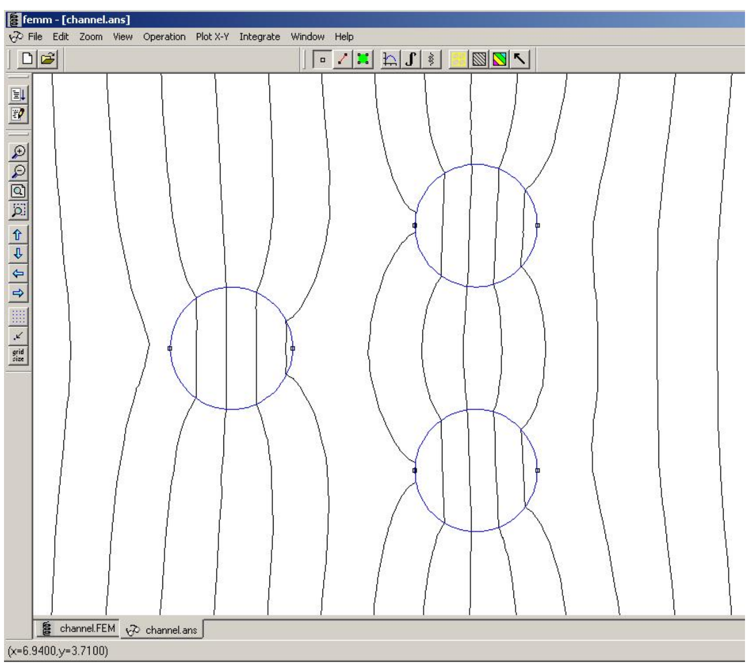


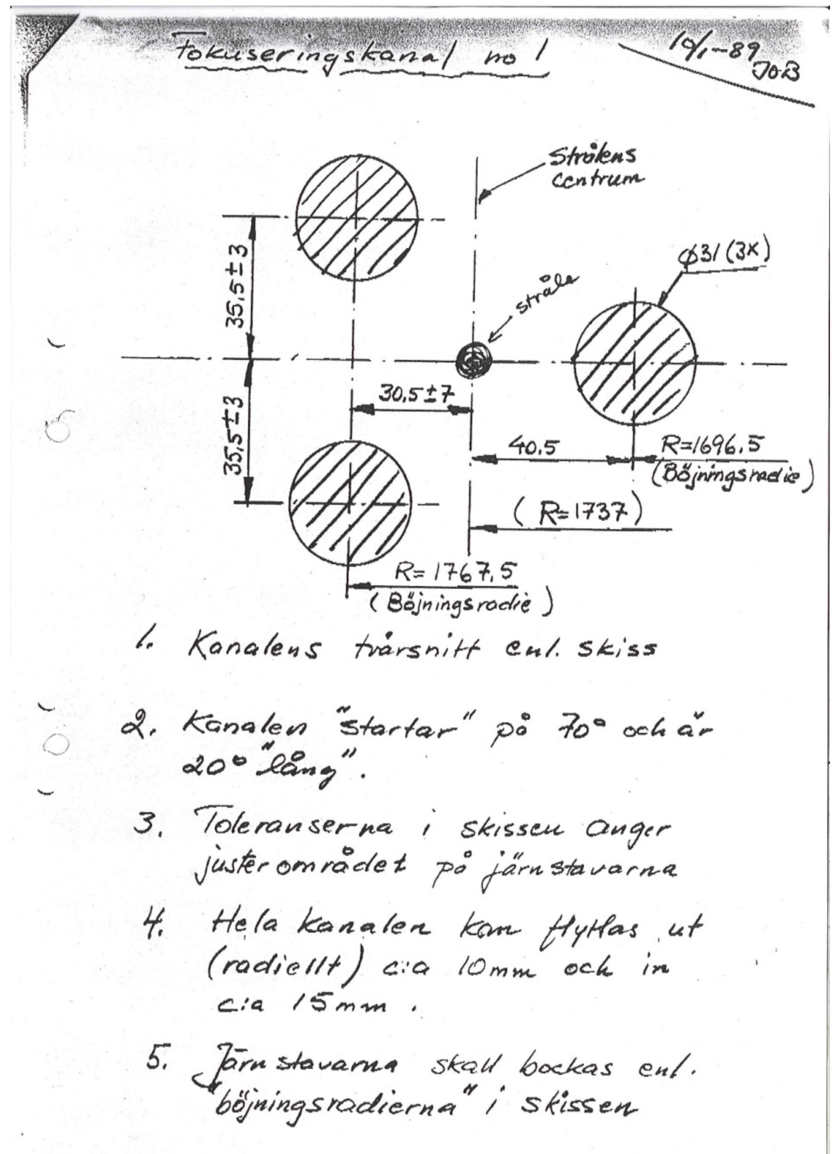
Vertically focusing **Horizontally focusing**

Iron bars are magnetized by the cyclotron magnetic field

Focusing channel

- Extracted beam travels in the fast decreasing fringe field
  - Horizontally defocusing
  - More focusing by shaping the field (gradient) by passive channels

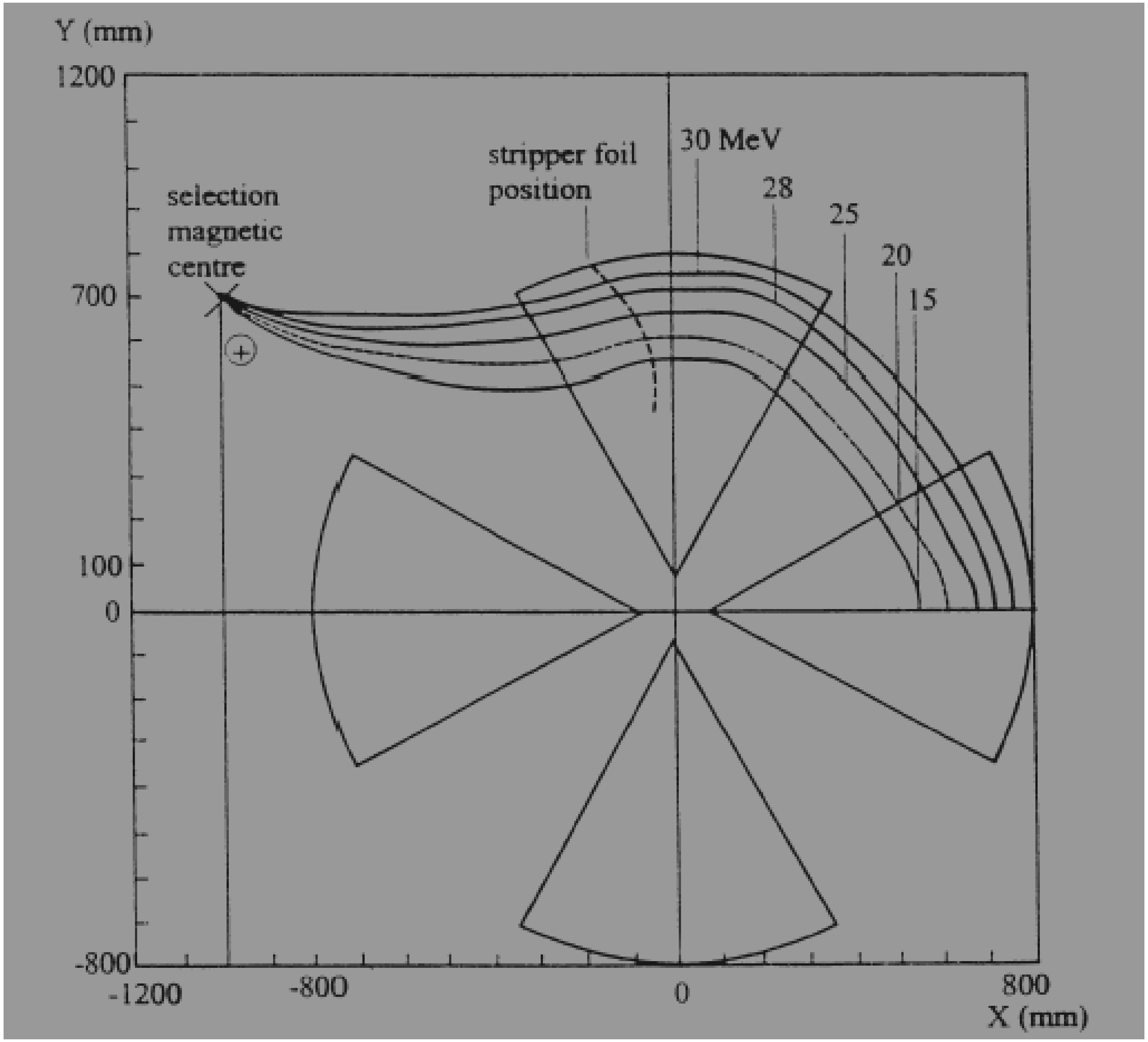




Stripping extraction

- The extraction efficiency for deflector + EMC is typically 50 – 90 %.
  - For high intensities activation, vacuum and melting problems
- For negative ions (H^-, d^-) stripping
  - 1 – 2 μm carbon foil strips both electrons away
    - Charge state -1 -> +1
  - Efficiency close to 100 %
  - Short distance in the fringing field
    - Less focusing problems
- Caution! Electromagnetic stripping at high B and high velocity
  - Electron affinity (binding energy) for H^- is 0.75 eV

W. Kleeven



IBA Cyclone 30

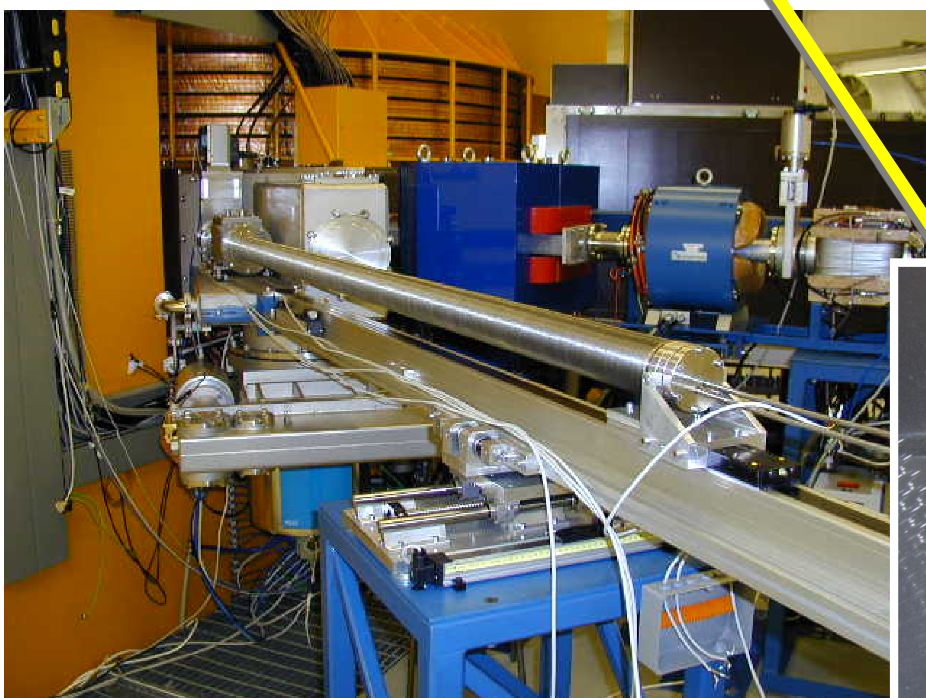
Extraction by stripping

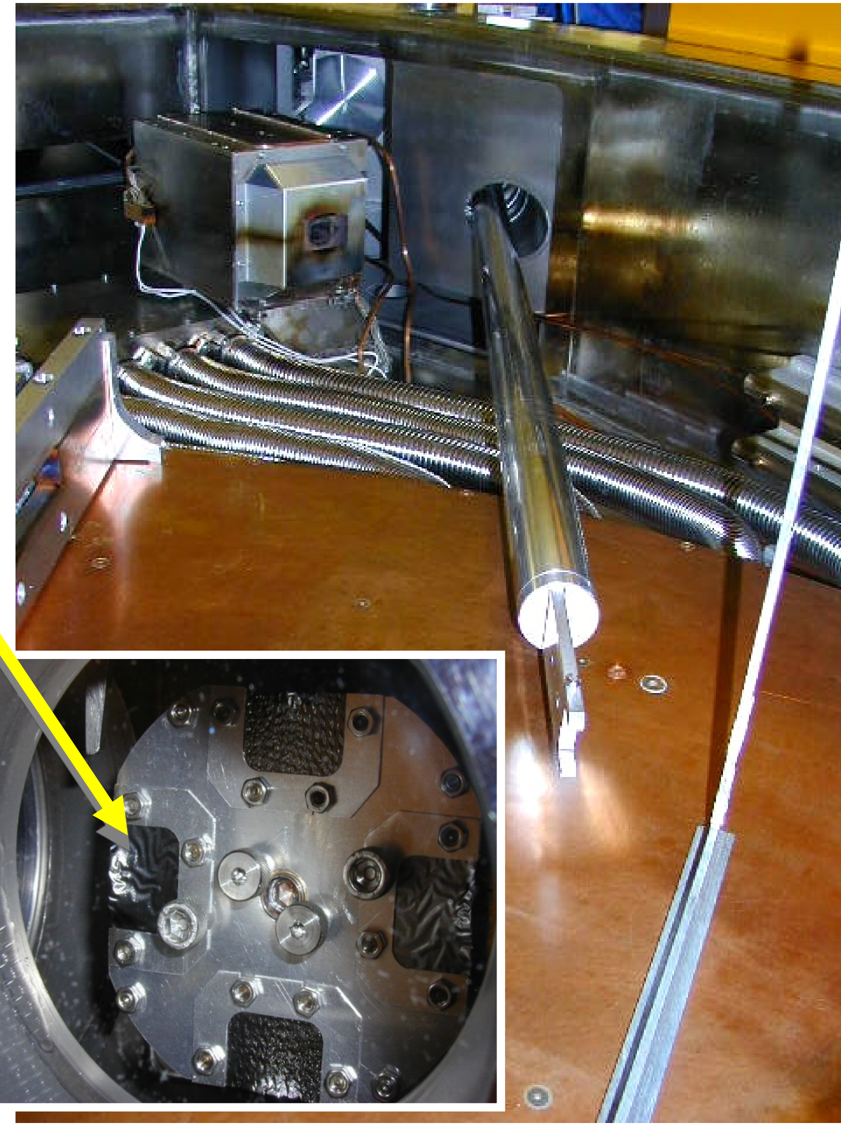
All energies go to one crossover point by proper foil azimuthal position

Place combination magnet at crossover

Stripper

- 4 carbon foils (16x22 mm)
- thickness 1 and 2 μm





Stripping extraction for heavy ions

- Typically $q_2=2q_1$ *(1.4 – 4)*
  - Initially moderate charge state
    - Limits the maximum energy
  - Motivation
    - High extraction efficiency
      - Naked ion after stripping (no charge distribution)
      - e.g. 300 AMeV Cyclotron proposal (INFN)
    - Easy
      - If not fully stripped then a distribution
        - » Only one charge state has the right trajectory
      - e.g. Dubna

L. Calabretta