Magnets for Cyclotrons

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CAS, Zeegse, The Netherlands, 24 May – 2 June 2005

Summary

- Designed or calculated
- Trends and consequences
- Isochronism and methods to obtain it
- Initial magnet design
- Calculations of 2-D models
- Calculations of 3-D models
- Few words about mechanical design

Designed or Calculated ?

- Cyclotron magnet design should always consider interaction with subsystems:
  - RF system
  - vacuum pumping
  - ion source or injection system
  - extraction system or internal target
  - diagnostic probes

Designed + Calculated

- Design + Calculations = iterative process
  - start: rough, simple model
  - loop1: fast calculations by hand
  - loop2: calculations of 2-D magnet models
  - loop3: detailed calculations of 3-D magnet models
  - stop: cyclotron magnet well designed

Cyclotrons - general trends

- Purpose of the cyclotron
  - Past and now
    - less and less of nuclear physics
  - Now and future
    - specific applications
    - sometimes single task (p-therapy, Pd production)

Trend consequences

- Very important for end-user and designer:
  - low radiation doses for personnel
  - reliability, cost and simplicity
- Important for end-user, interesting for designer (=challenging):
  - occupied space, weight
  - beam quantity, beam quality

Consequences cont'd

- Less important for end-user, interesting for designer:
  - consumed electric power
- Now not important
  - versatility

Well designed cyclotron magnet

- Isochronous magnetic field during acceleration
- Axial (vertical) and radial focusing of beam
- Operation point far from resonances
  - Fast passage through resonance(s) zone(s)
- Possibility to install all subsystems

Isochronous field

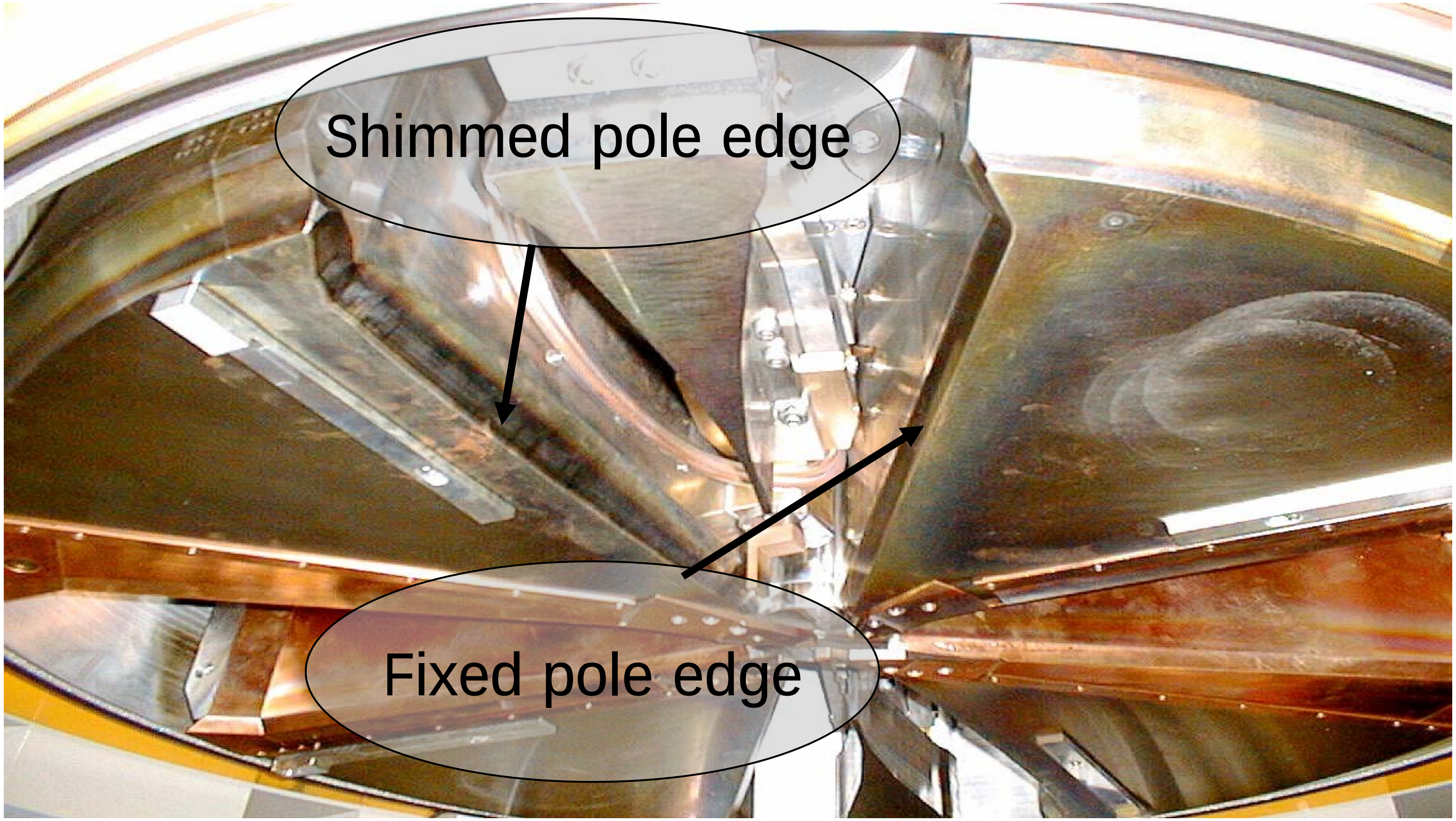
- The isochronous magnetic field for compensation of relativistic mass increase and synchronism with a phase of RF system
- The requested field shape can be obtained by different methods or, more frequently, combination of methods

Methods to obtain isochronism

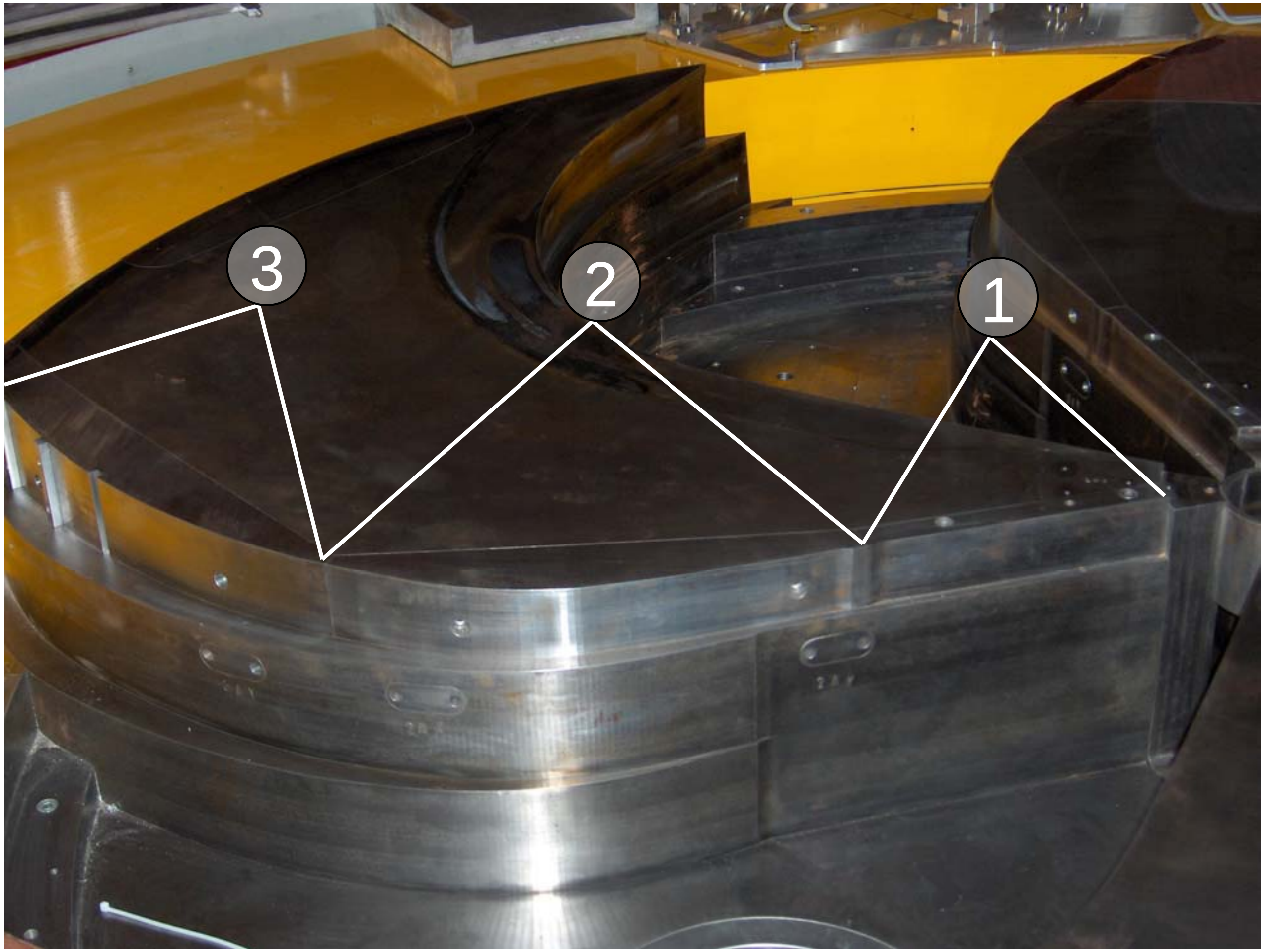
- With iron of the magnet poles
  - Increase hill angle/valley angle ratio
  - Shimming of pole edges or shims based on equation:

$$\frac{\Delta B(r)}{B(r)} = \gamma^2(r)\,\frac{\Delta f_p(r)}{f_p(r)}$$

Shimmed pole edge, C18/9



Removable pole edges C235



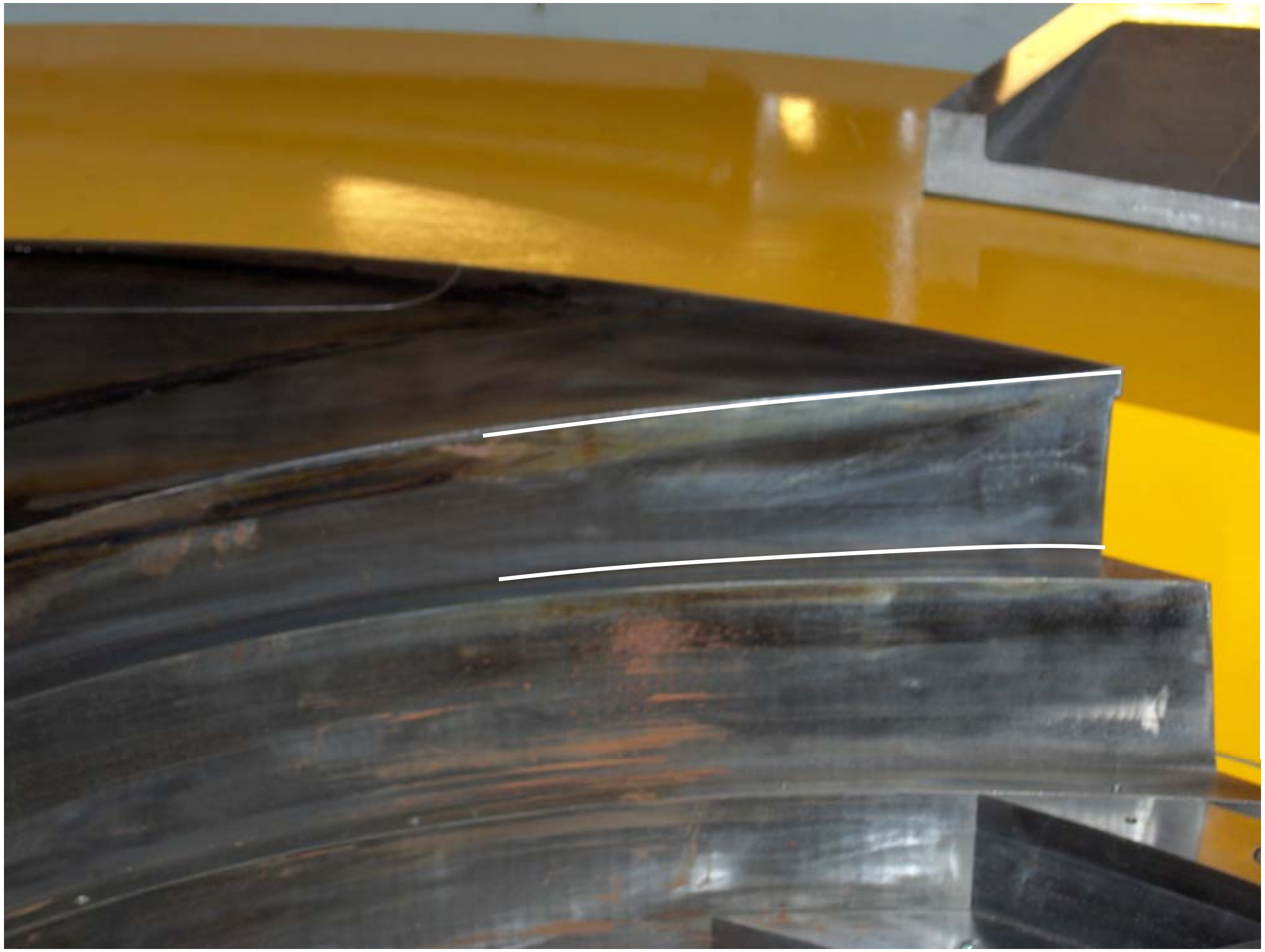
Methods to obtain isochronism

- With iron of the magnet poles
  - decrease gap between poles as a function of radius e.g. C235, 235 MeV protons

$$\frac{r^2}{1120^2} + \frac{(halfgap)^2}{48^2} = 1 \qquad halfgap_{\min} = 4.5$$

  - added iron shims in the valley

Elliptical gap between poles C235

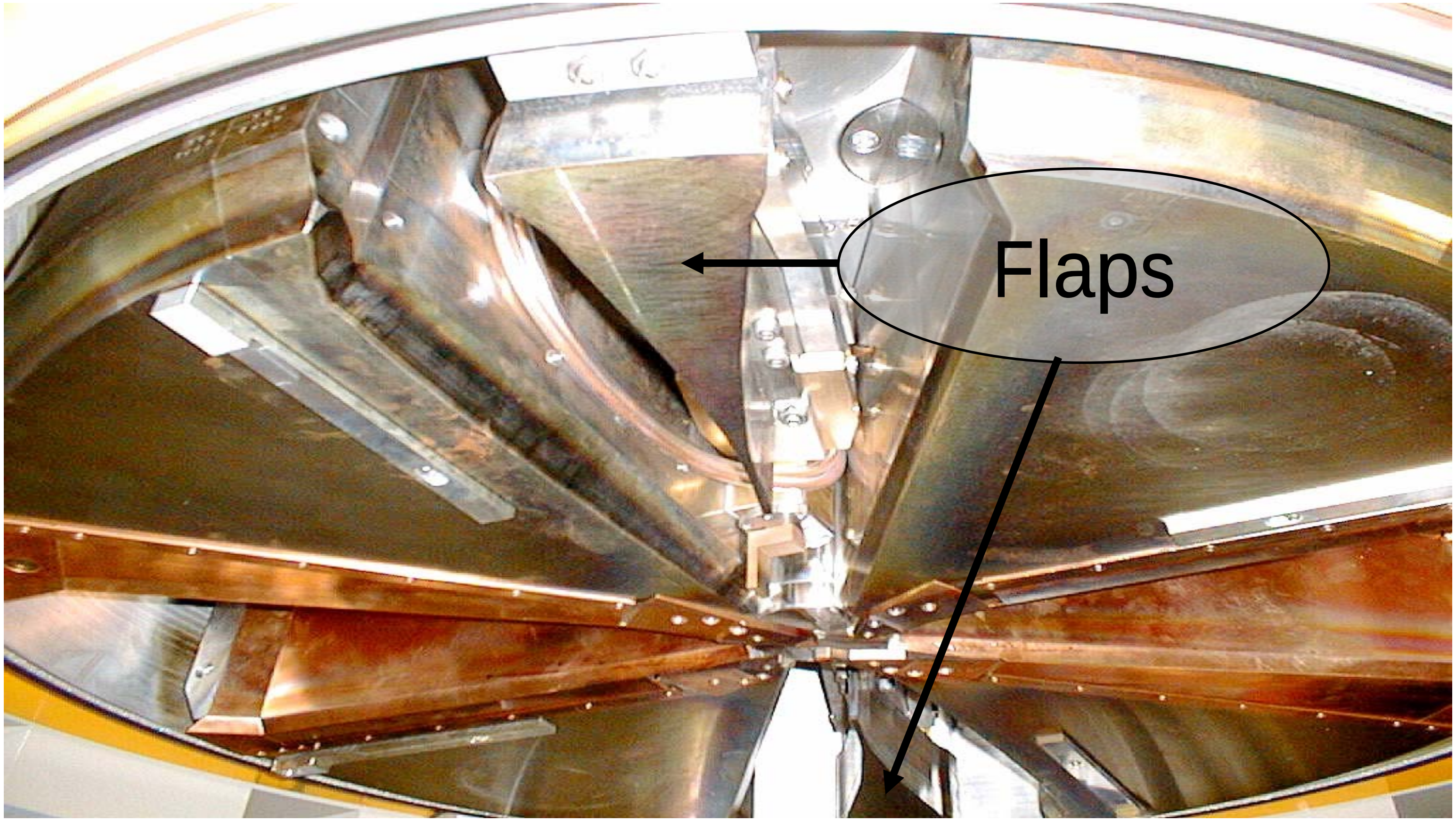


Isochronism for two types of ions

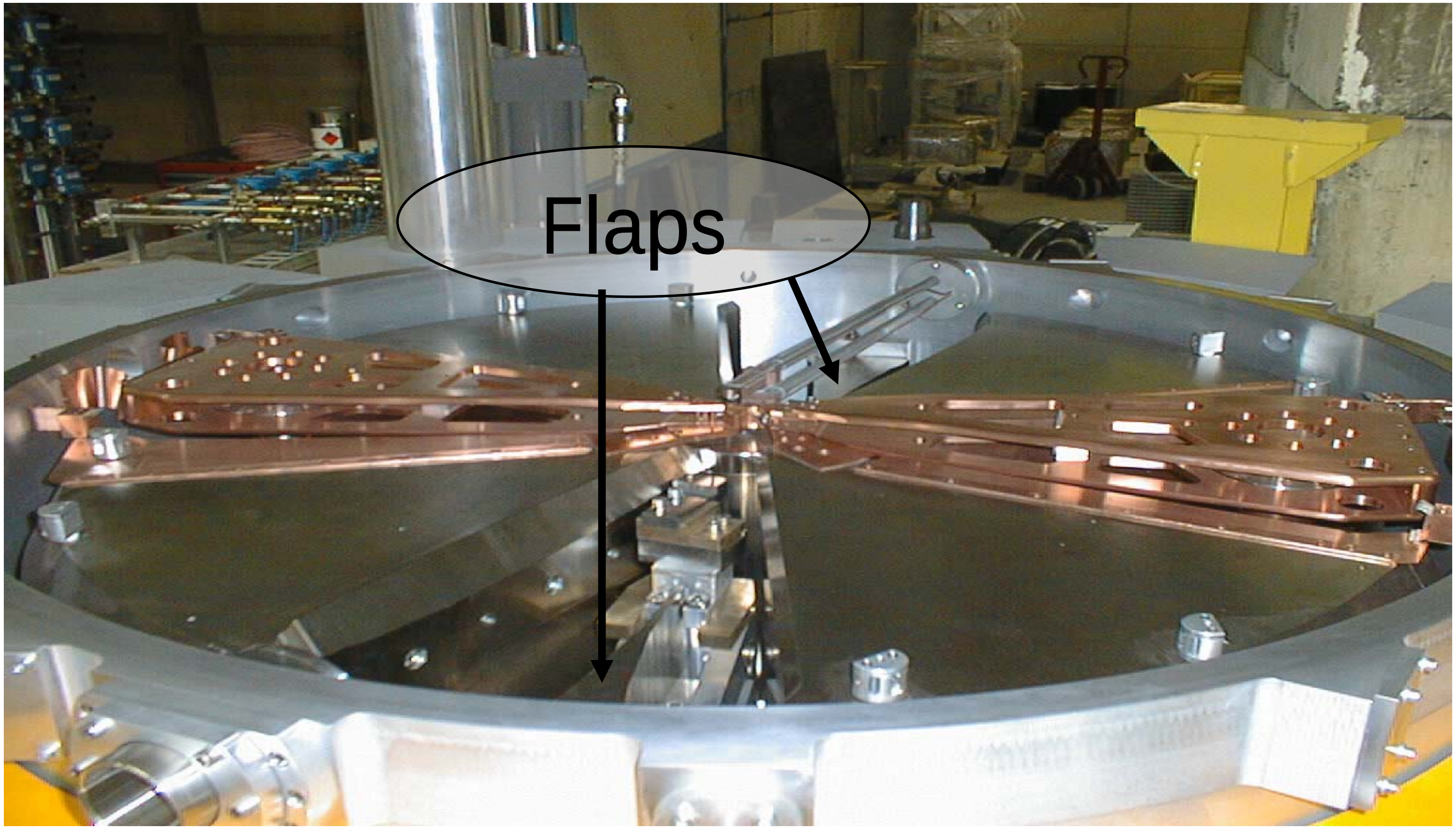
- Movable iron shims for two different (*q/m* ratio) types of ions.
  - the shape of iron shims obtained using previous methods e.g.

    C18/9, 18 MeV H^- and 9 MeV D^- cyclotron,
    C10/5, 10 MeV H^- and 5 MeV D^- cyclotron.
  - two positions of shims

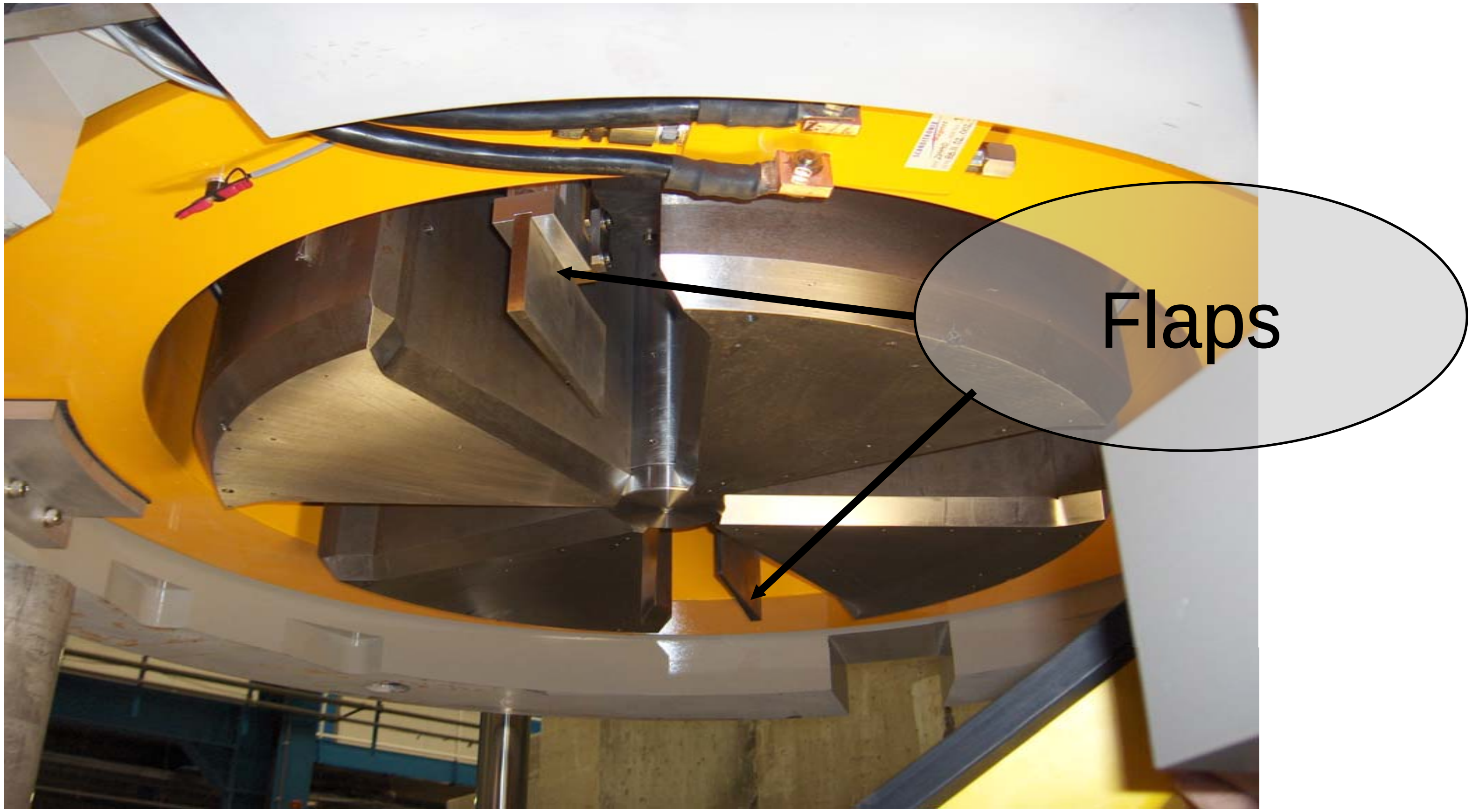
Movable iron shims, C18/9



Movable iron shims, C18/9



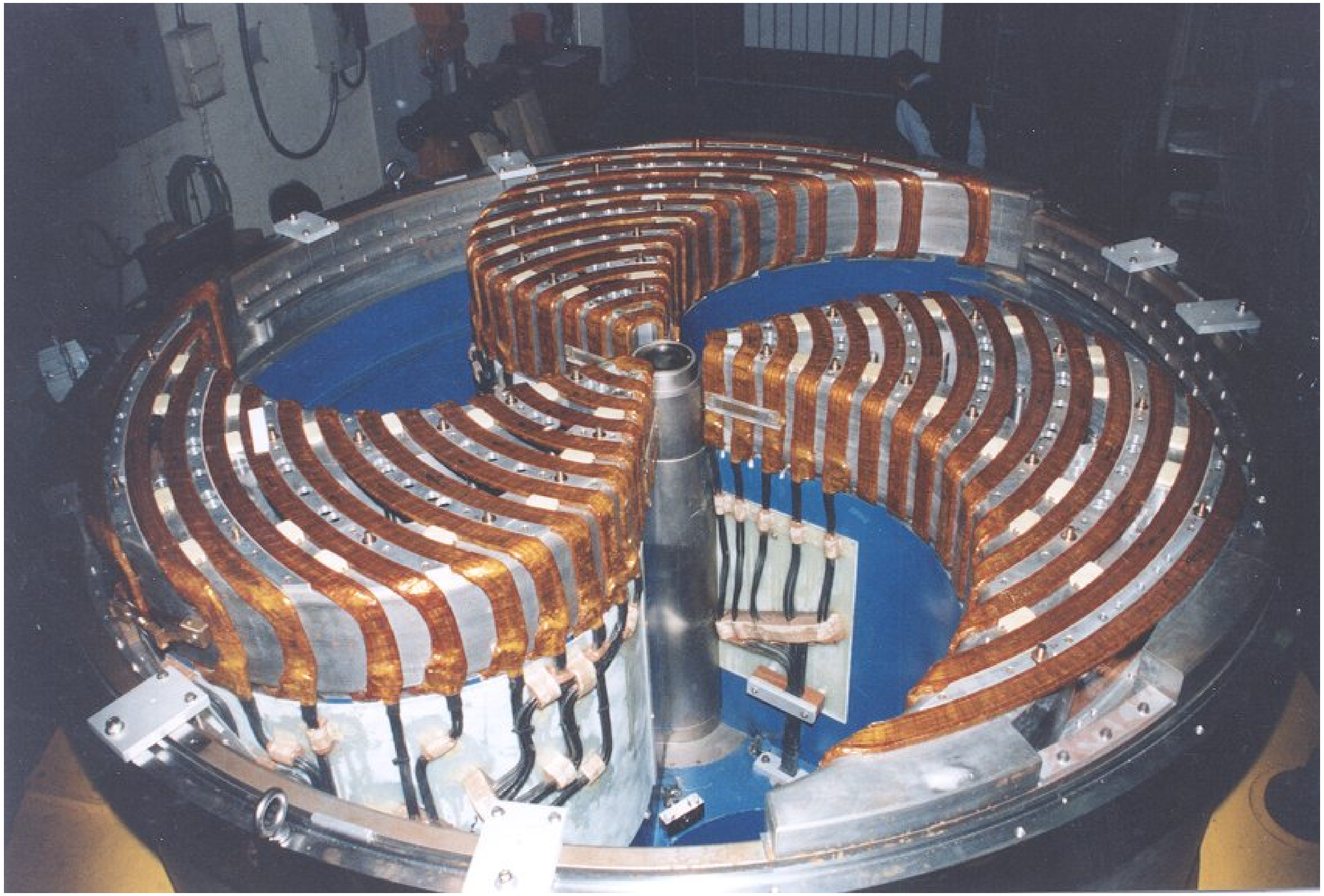
Movable iron shims, C10/5



Isochronism for many types of ions

- Correction trim coils
  - frequently on poles
  - sometimes around poles e.g. AGOR, 15 trim coils around poles
  - variable final kinetic energy
  - flexibility against cost
- Trimming rods

Correction trim coils, AGOR



Magnet – initial calculations

- The maximum kinetic energy T determines magnetic rigidity

$$B \cdot \rho = \sqrt{T^2 + 2TE_0} \,/\, (300 \cdot Z)$$

where: B – field (Tesla), ρ – bending radius (m), Z – charge state, T – kinetic energy and E_0 - rest mass (MeV)

Strategic decisions of design

- To decide
  - magnetic field level on poles, B_{hill}
  - pole mechanical radius
  - gap between poles
  - valley gap and field, B_{valley}
  - number of sectors, N
  - median plane:horizontal or vertical

Magnetic field on poles

- Determined by the type of accelerated ions
  - negative ions, H^- and D^-
    - low field then large pole radius (EM stripping)
    - easy, 100% extraction by stripping
  - fully stripped positive ions
    - high field, small pole radius
    - complicated extraction system or self-extraction

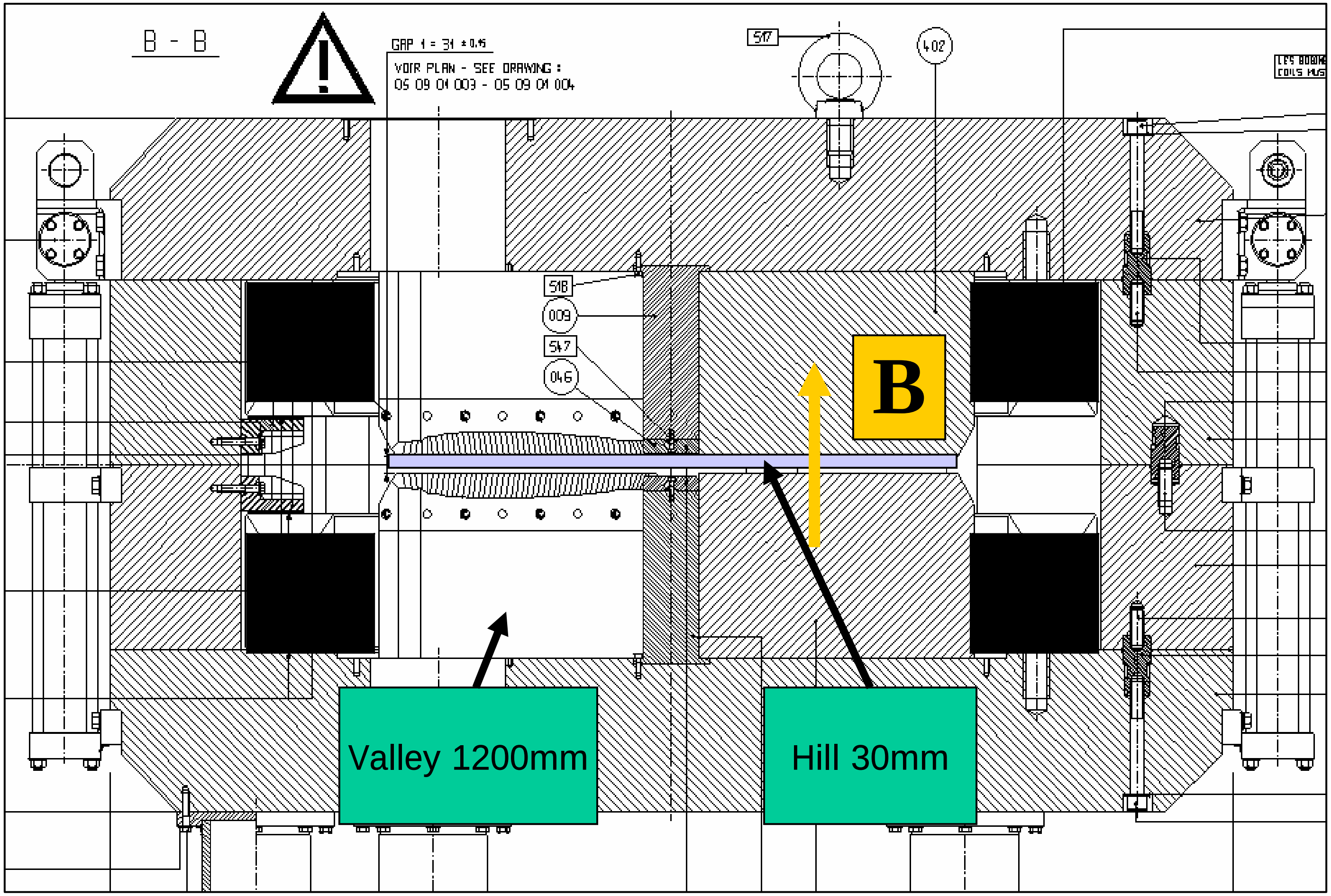
Gap between poles

- Compromise between
  - small gap
    - reduced number of At of coils
    - pole radius reduced, orbits close to outer edge
  - large gap
    - large space: injection, extraction, probes
    - easier vacuum pumping
    - lower field

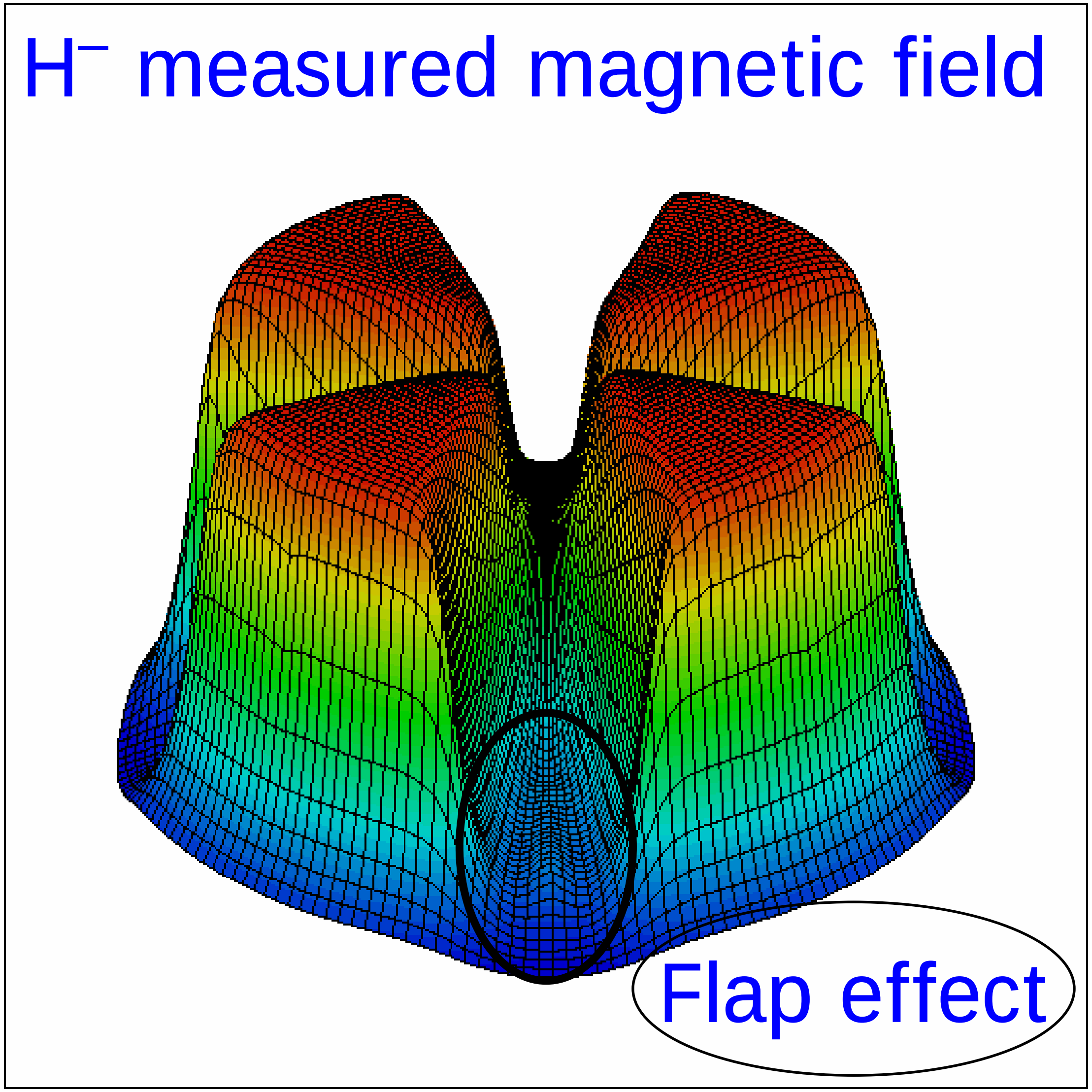
Valley gap

- Compromise between
  - small gap
    - low flutter
    - axial focusing problems
    - spiralization of poles necessary
  - large gap
    - deep valley design

Deep valley design



Azimuthally varying field



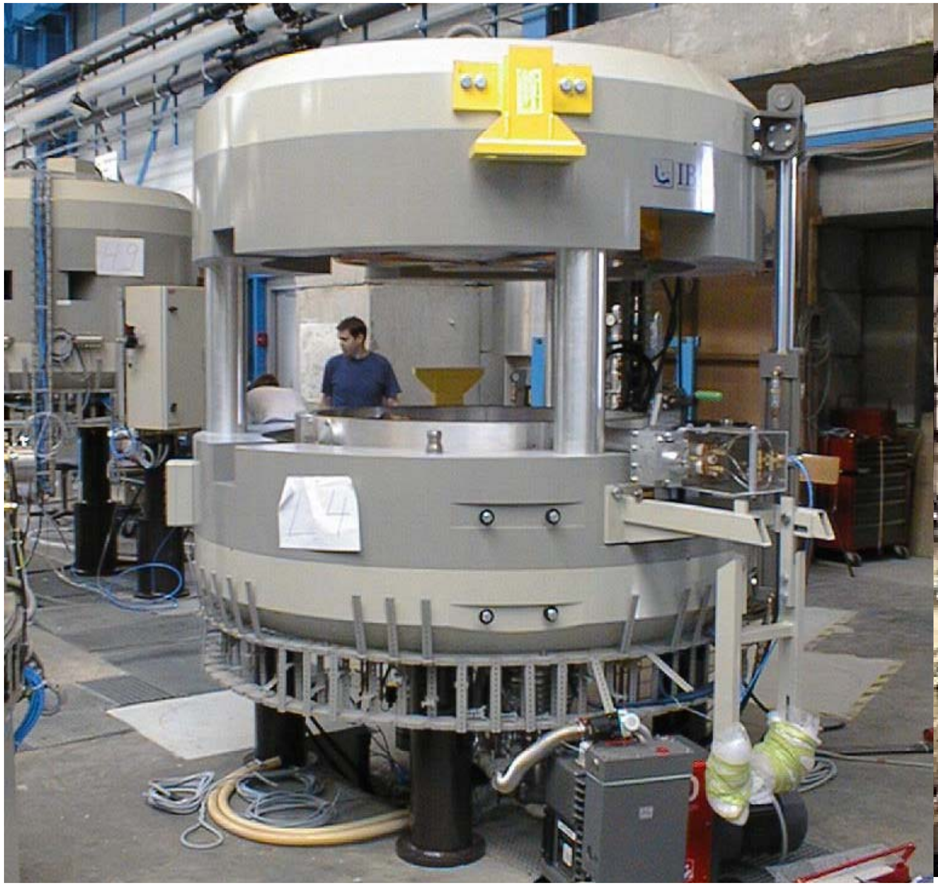
Two measured magnetic field in C18/9 cyclotron

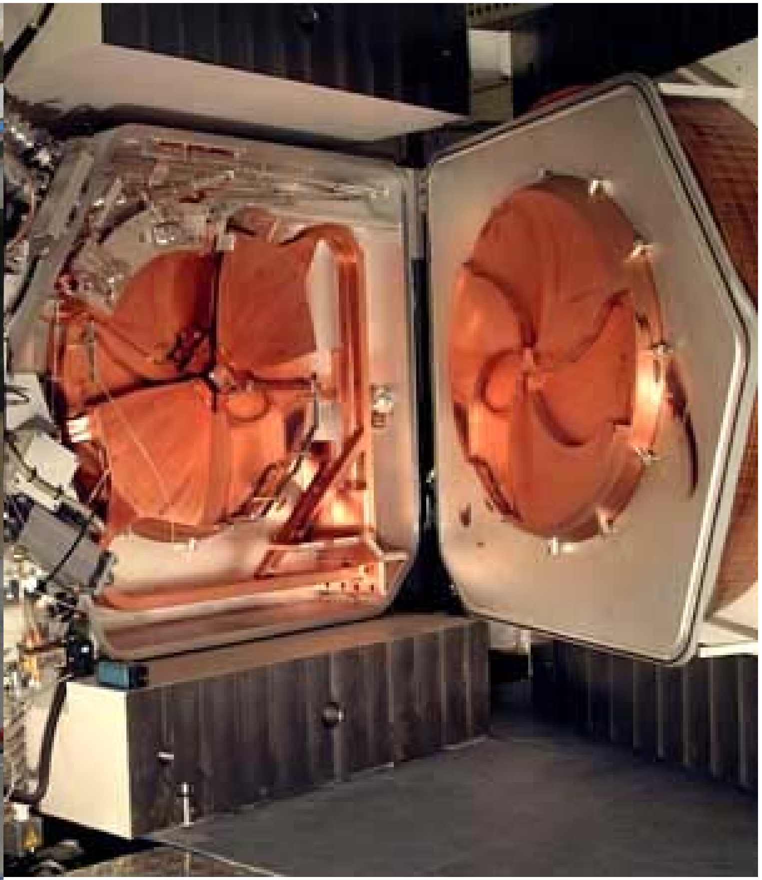
Difference between magnetic fields provided by iron insert (flap) movement.

Number of sectors

- 1 or 2 - we’re serious designers, isn’t it
- 3 - large gap between poles, 3 dees, only harmonic modes=3, 6 if resonators coupled, more if independent
- 4 - two valleys with RF cavities, all harmonic modes possible, two valleys for other devices
- >4 - better for SSC

Median plane orientation





Initial calculations, cont 'd

- from $B\rho$: $\langle B(\rho)\rangle$ and radius ρ
- α - pole fraction on one symmetry period: $\langle B(\rho)\rangle = \alpha \cdot B_{hill} + (1-\alpha)\cdot B_{valley}$
- analytically flutter and betatron frequencies

$$F = \langle B^2(\rho)\rangle / \langle B(\rho)\rangle^2 - 1 = \alpha \cdot (1-\alpha)\cdot \left(B_{hill} - B_{valley}\right)^2 / \langle B(\rho)\rangle^2$$

$$\nu_z^2 = 1 - \gamma^2 + N^2 / \left(N^2 - 1\right)\cdot F \cdot \left(1 + 2\cdot \tan^2 \xi\right)$$

$$\nu_r^2 = \gamma^2 + 3N^2 / \left(\left(N^2 - 1\right)\left(N^2 - 4\right)\right)\cdot F \cdot \left(1 + 2\cdot \tan^2 \xi\right)$$

Initial calculations, cont 'd

- total magnetic flux $\Phi = B_{hill} \cdot S_{all\ poles}$
- Ampere-turns from Ampere's law

$$\oint \vec{H} \cdot d\vec{l} = \frac{1}{\mu_0} \cdot \left(B_{hill} \cdot gap\right) + \frac{1}{\mu_0\, \mu_{iron}} \cdot \left(B_{iron} \cdot L_{iron}\right) = nI$$

- coil cooling estimation

$$\Delta T\left({}^{o}C\right) = 60 \cdot P\left(kW\right) / \left(4.19 \cdot N\left(l / \min\right)\right)$$

Initial calculations exampl

Fixed energy 235 MeV

Magnetic rigidity
Bρ = 2.35 T.m

Non superconducting coils

Maximum field limited by coil power efficiency

High B obtained using ELLIPTIC gap
Bmax ~ 3T close to coil
B min ~ B coil
ΔB = saturation magnetization 2.1 T

At high radii,
<B> = k*Bhill+ (1-k)*Bvalley
k = Staking factor = hill angle/90°

For best RF efficiency, k=0.5
BUT
to decrease machine dimensions
k >0.5 (more hill, thus more field)
CHOICE : k=0.67 (60° hills)

<B> near coil is thus
0.67*3 + 0.33*(3-2.1) = 2.31 T

Isochronous

B(r) = B0*γ(r)

B increases with radius

Radially focusing
Axially defocusing

Extra axial focusing needed

Azimuthal field modulation (flutter)
Spiral shape of poles

$$\nu_z^2 = n + \left(\frac{N^2}{N^2-1}\right) \cdot F \cdot (1 + 2\tan(\xi))$$

$$n = -\left(\frac{d\langle B\rangle}{dr}\right)\left(\frac{r}{\langle B\rangle}\right) = 1 - \gamma^2$$

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

Small gap and little axial focusing possible thanks to the small current (300 nAmps) required for treatment

Radius close to coil is R~ 2.35/2.31 = 1.02m

γ(235 MeV) = 1.25 thus central field B0 ~2.31/1.25 =1.8 T

CHOICE : νz = 0.2

Flutter and spiral not too large
Field gradient can be strong

Coil dimension, position and current to match these values, taking into account power consumption and cooling

Return yoke dimensions function of
Flux to transport
Allowed iron saturation

Spiral angle of pole completely determined since n, N, F and νz are known

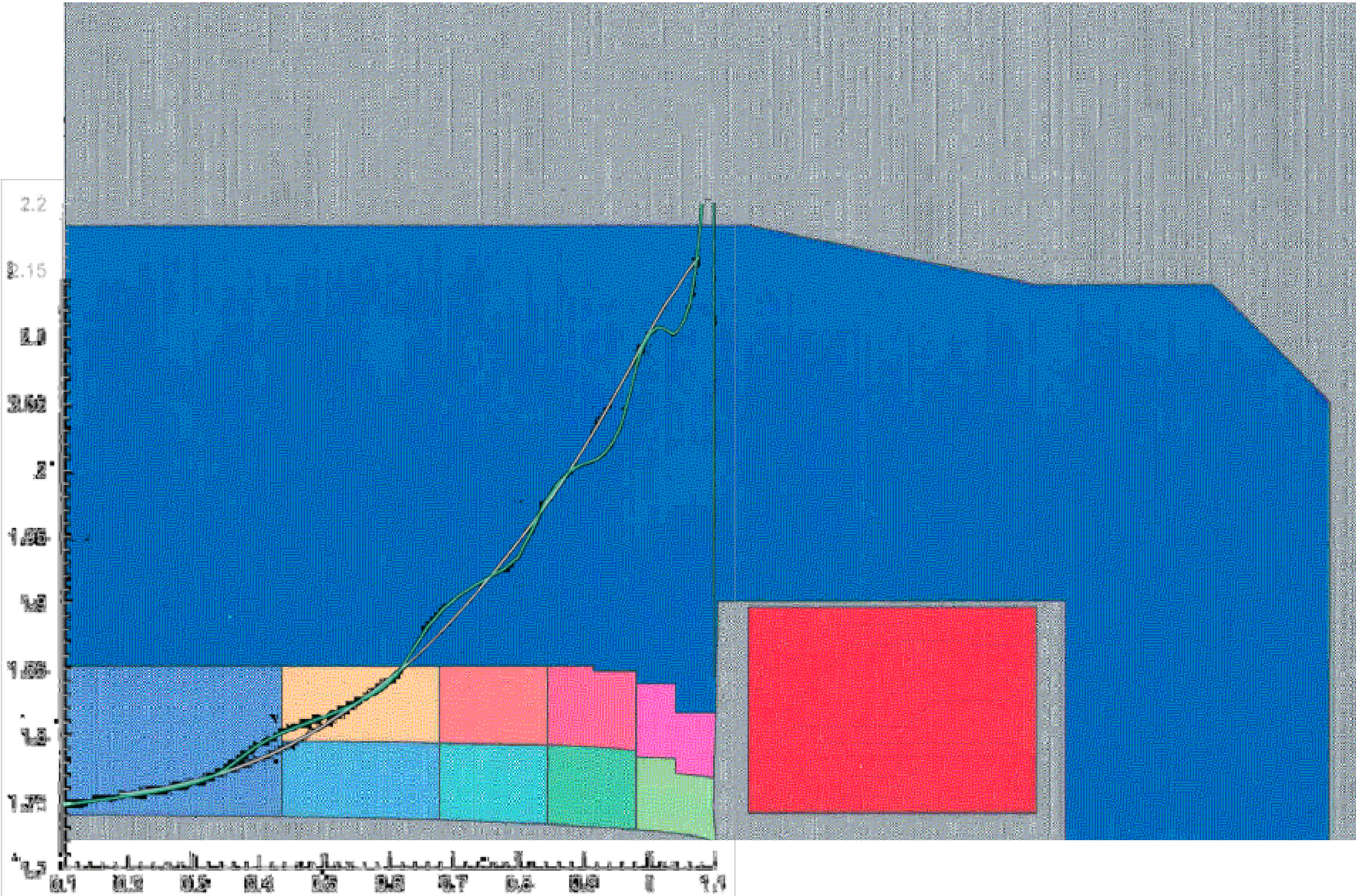
Calculations of 2-D models

- confirmation of initial design
- very small grid-size possible
- usage of stacking factors *k*
- modification of the field induction

$$B_k = \mu_0 \cdot H + k \cdot \left(B - \mu_0 \cdot H\right)$$

- very efficient for highly saturated iron

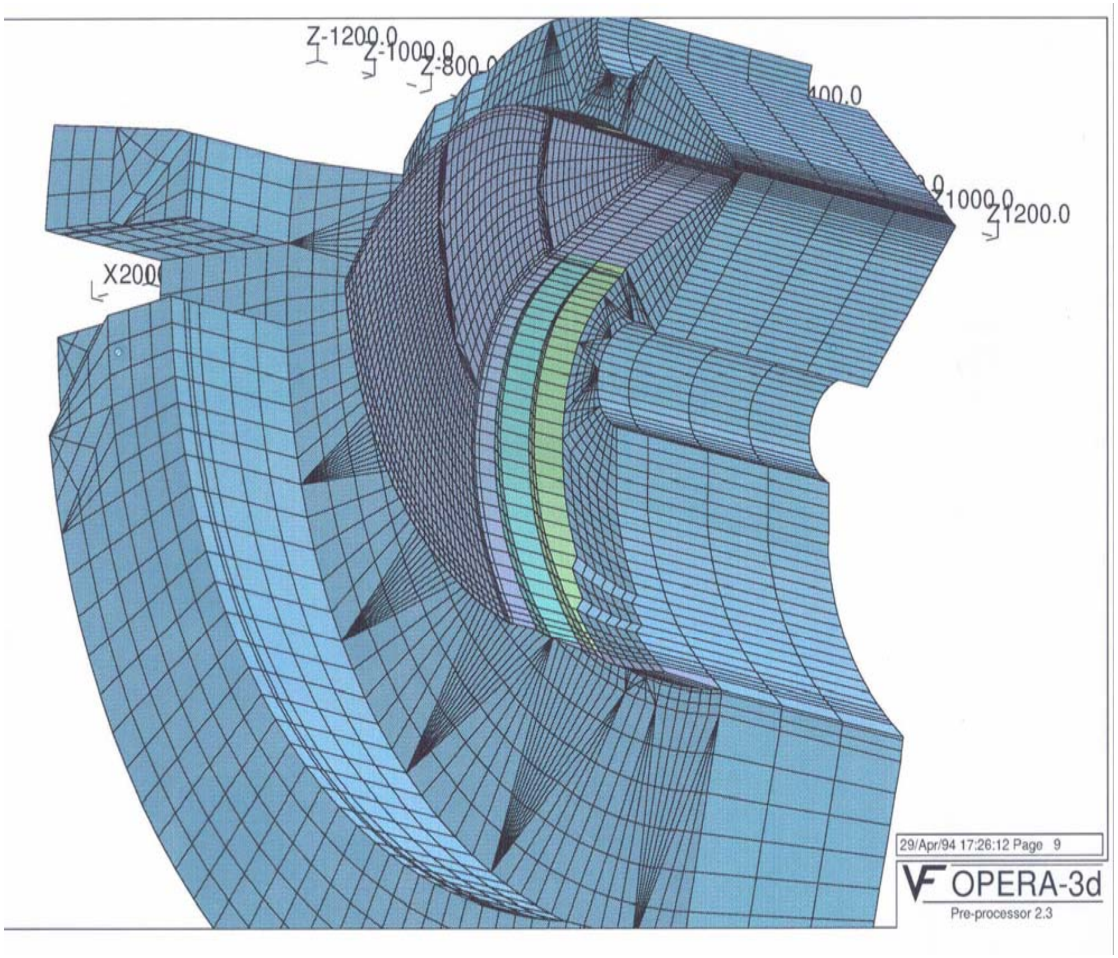
2-D Modelling, C235



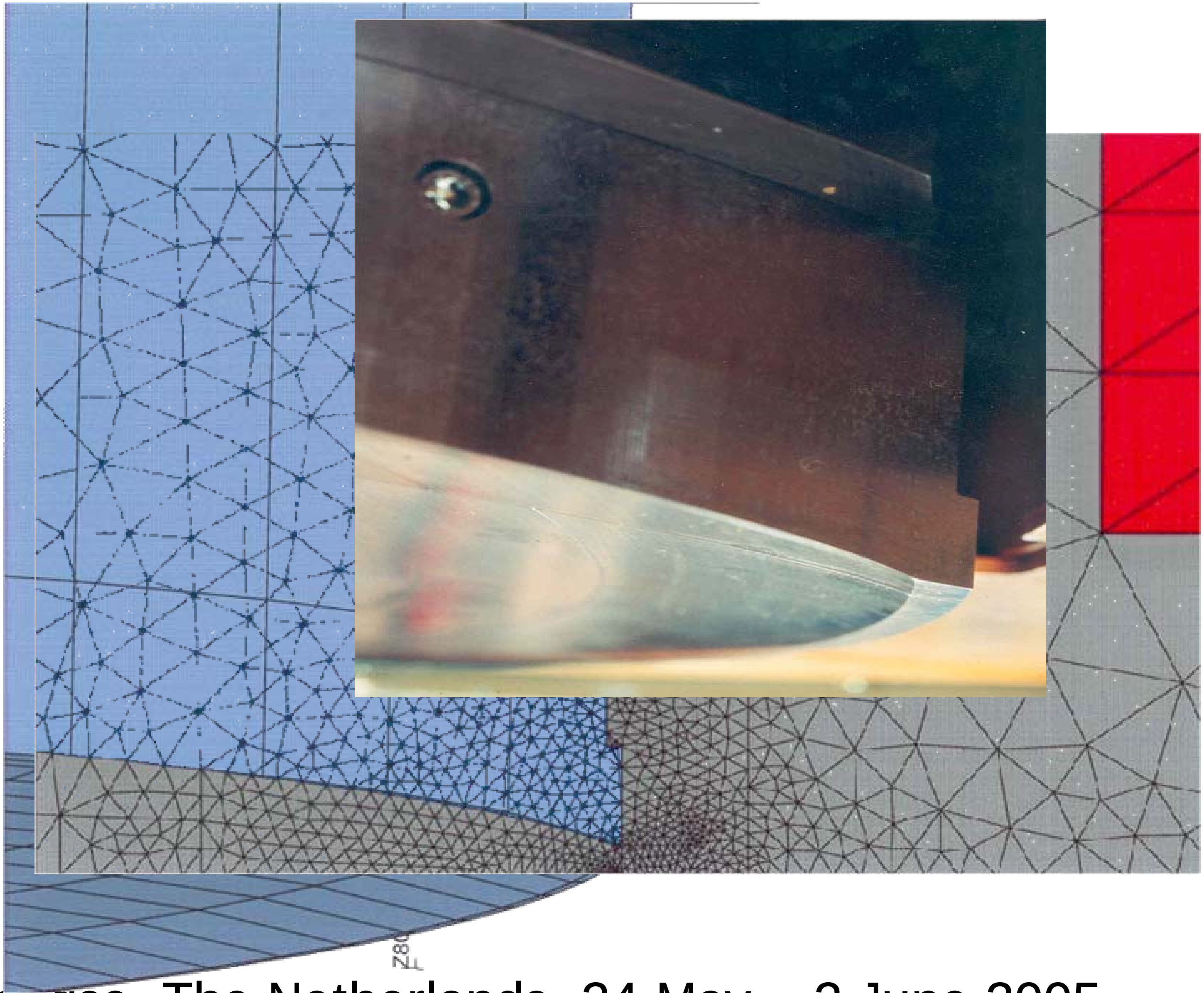
Calculations of 3-D models

- confirmation of previous designs
- model size limited only by computer hardware
- model as close to reality as possible, variable mesh size
- calculation results and measurements differ less than 3 percent

3-D modelling, C235



2-D and 3-D Modelling, C235



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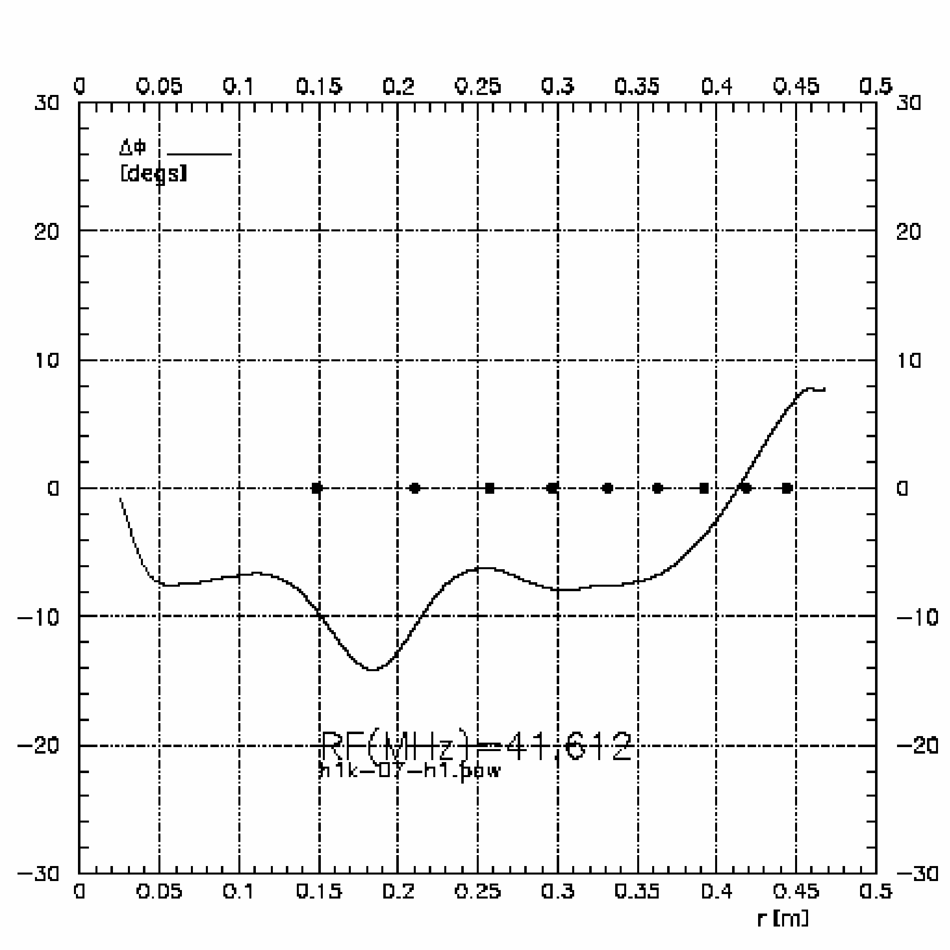
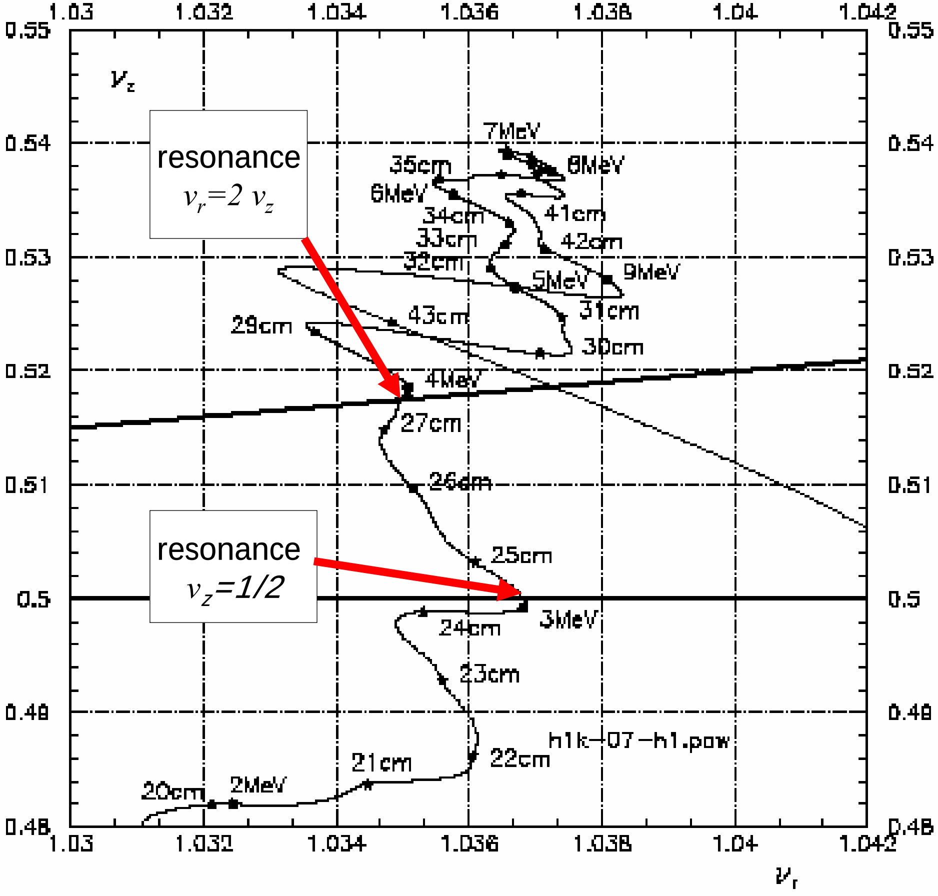
Calculations of 3-D models, cont ’d

- creation of magnetic field maps
- calculation of equilibrium orbits: frequency error, integrated phase shift, betatron frequencies, operation point
- iterative changes of 3-D model until isochronism of the field, correct focusing, absence of resonances

Integrated phase shift, C18/9, D^-



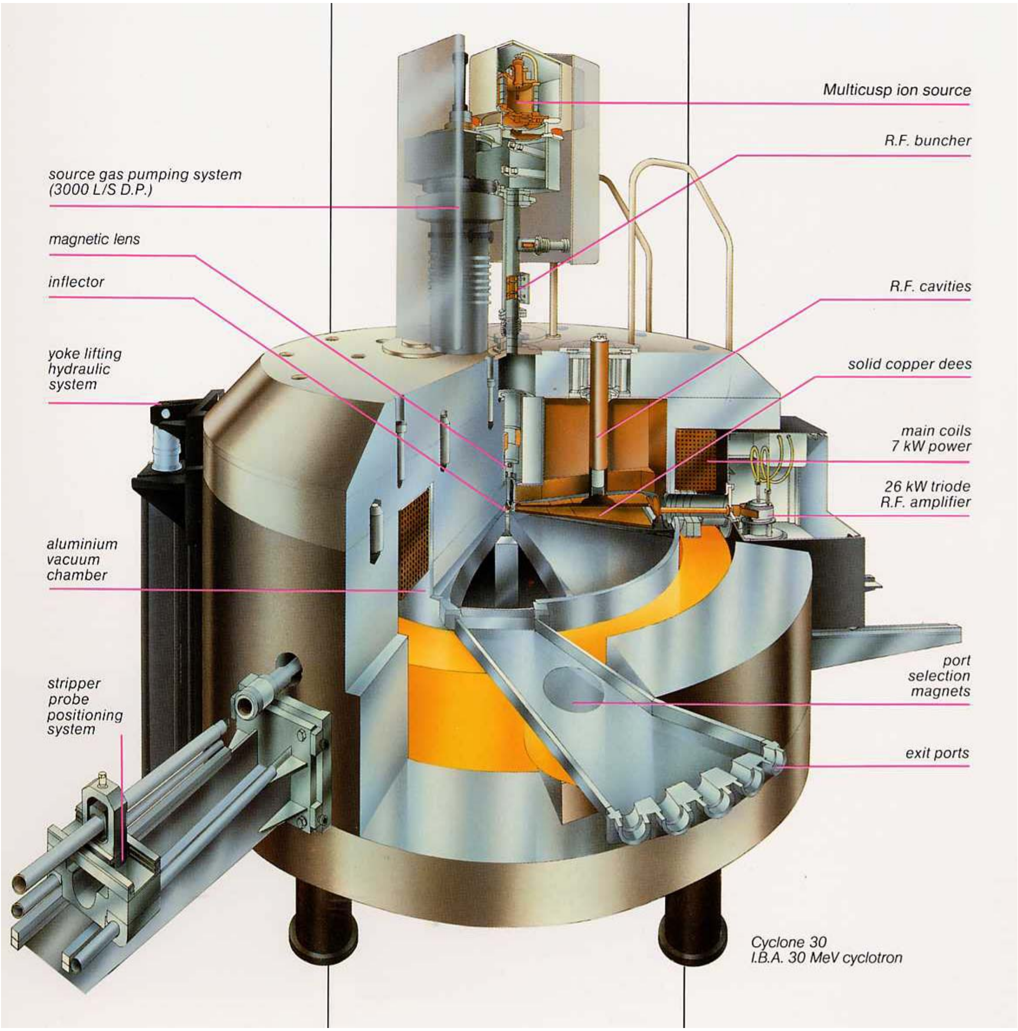
Operation point, C18/9, D$^-$



Few words about mechanical design

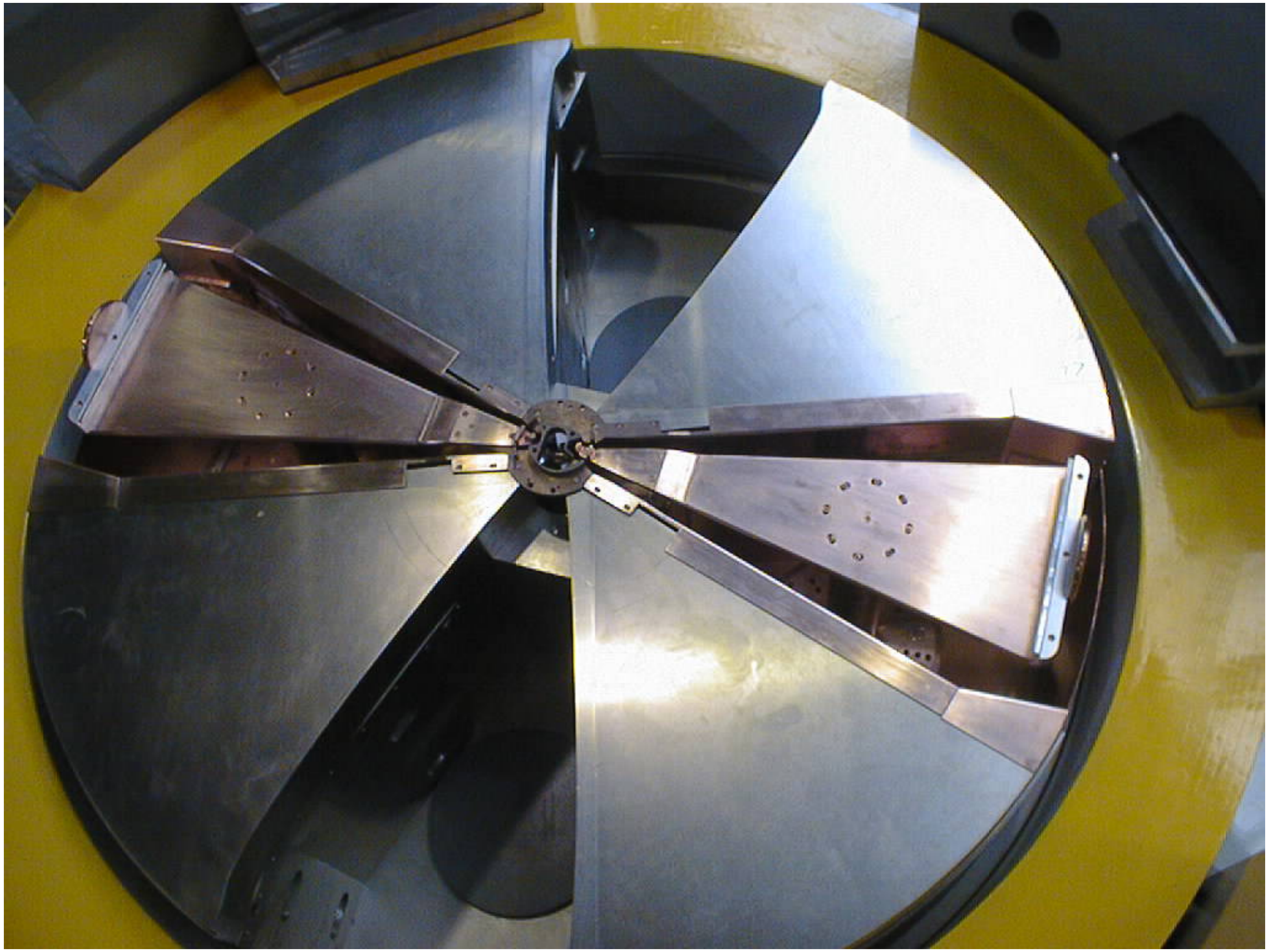
- analysis of mechanical deformations
  - weight
  - magnetic forces
  - pressure due to vacuum
- mechanical partition of the magnet
  - minimum deformation
  - practical aspects of handling
- fitting together other subsystems

C30 artist view

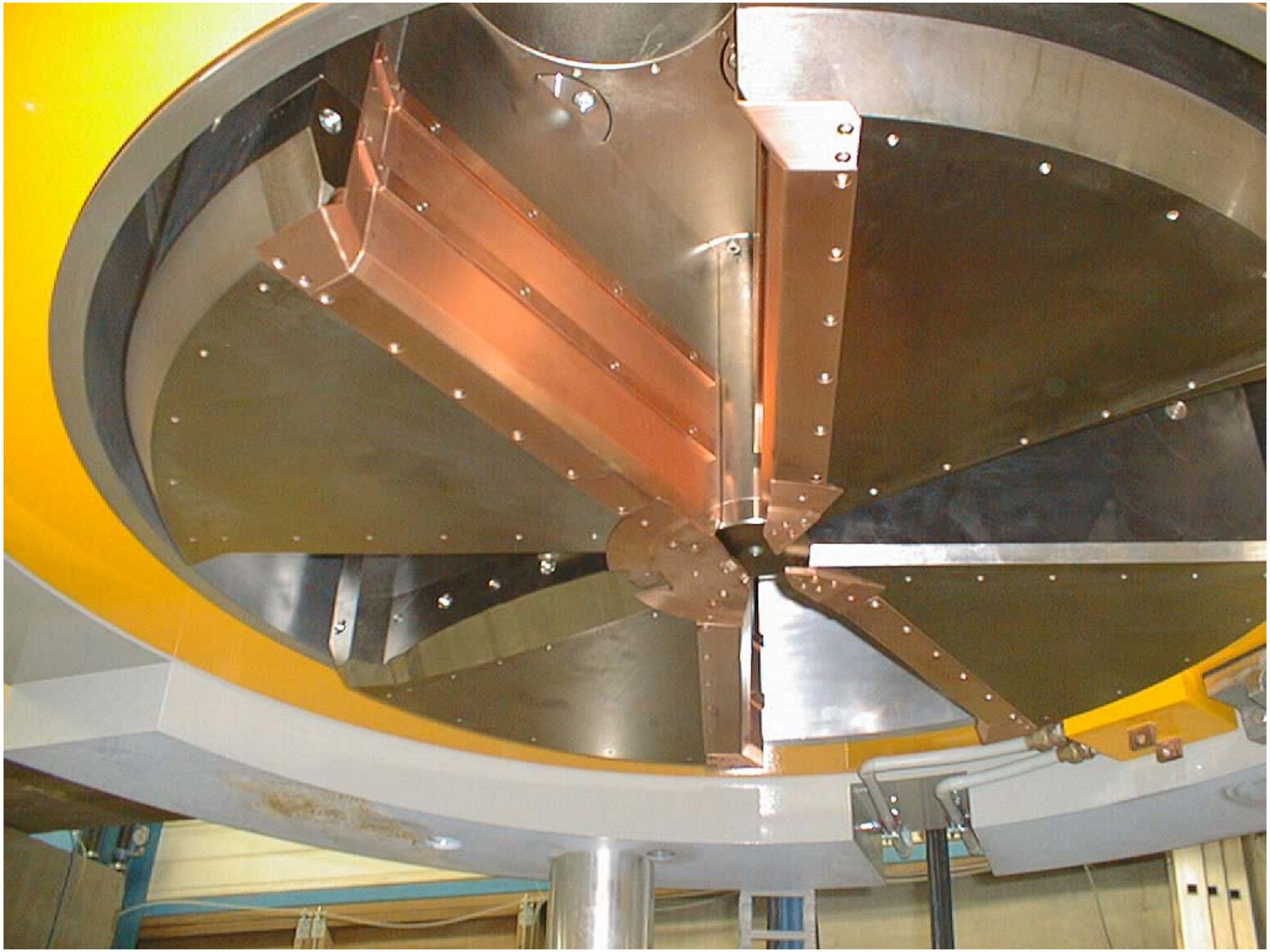


C30

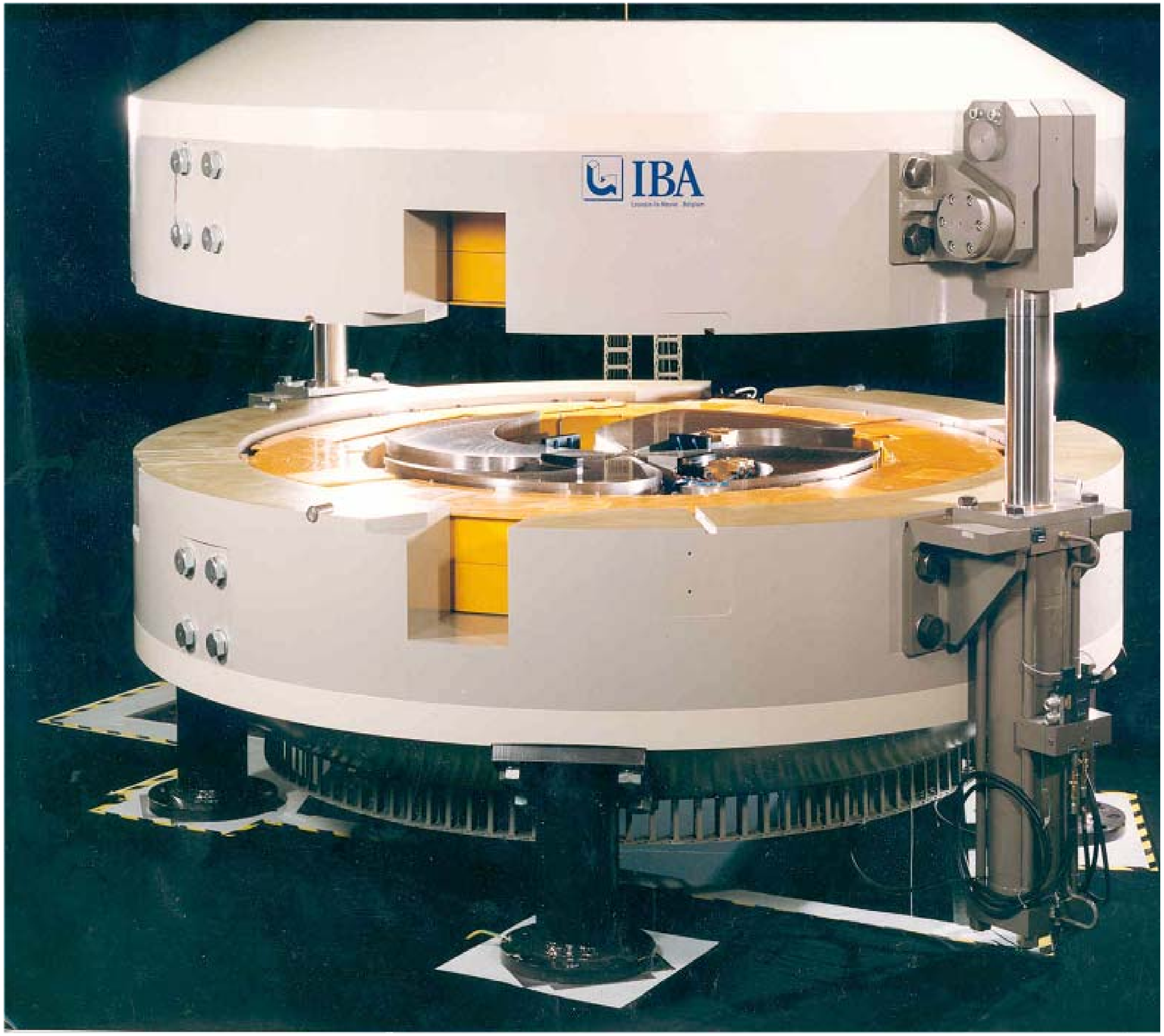
C30 poles and valleys



C18/9 poles and valleys

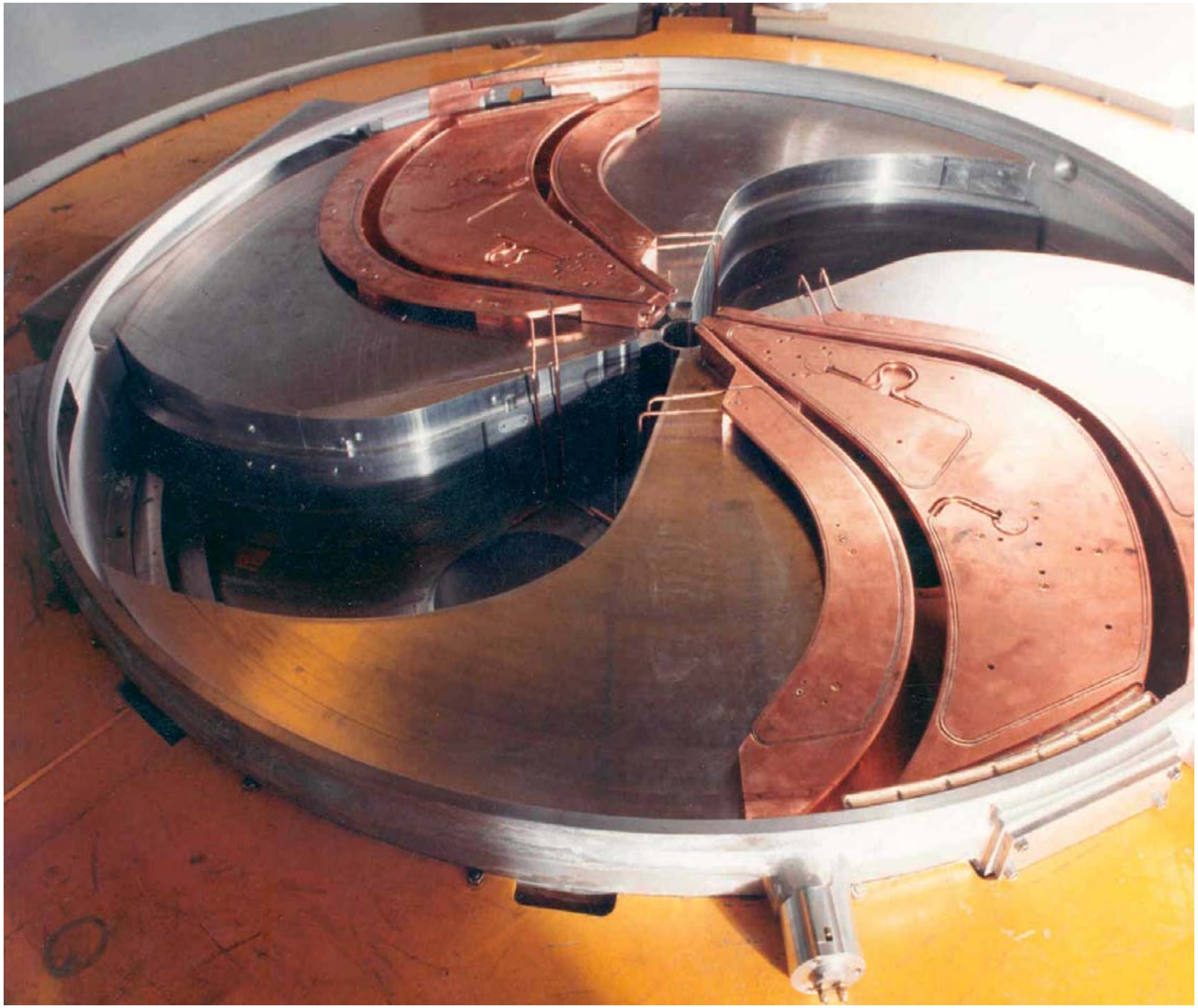


C235



C235 lower part

C235 poles and valleys



Conclusions

- Cyclotron magnet design and calculations should always consider interaction with:
  - RF system
  - vacuum pumping
  - ion source or injection system
  - extraction system
  - diagnostic probes

How the technology works

The IBA cyclotron, a 2 meter wide washing-machine like vessel constructed of 15 cm thick iron walls, contains a vacuum chamber. A “target substance” of gas, liquid or solid material is placed inside the vacuum chamber and then is bombarded with high energy (up to 30 million volts) RF waves (Radio frequency). This causes the nuclear particles (neutrons and deuterons) of the target to “accelerate” inside the vacuum chamber. As the highly charged atomic particles spiral their way around the cyclotron, they are separated by very powerful magnet called a “stripper” which in effect “strips away” individual particles to deliver radio-active isotopes.

THE END

Thank you for your attention

Questions welcome