Injection and Extraction for cyclotrons

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

Part 1: Injection Into a Cyclotron

- Injection: transfer of the beam from the ion source onto an equilibrium orbit in the center of the cyclotron
- Two approaches:

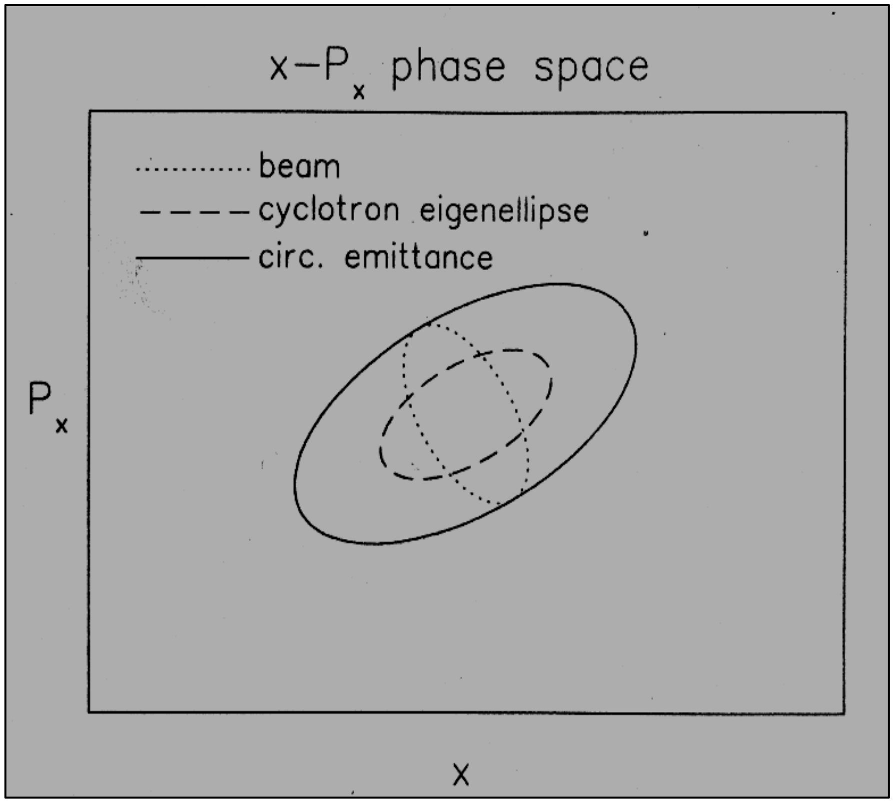
1. Internal Ion Source:
   - ➢ Ion source placed in the center of the cyclotron
   - ➢ Source is integrated part of the accelerating stucture
   - ➢ Trivial but important case for compact cyclotrons
2. External Ion Source:
   - ➢ ion source placed oustside of the machine
   - ➢ injection line with magnets and/or electrostatic inflector is needed

Some Important Design Goals

1. Centering of the beam with respect to the cyclotron center

   Equivalent to placing of the beam on the correct equilibrium orbit given by the injection energy
2. Vertical centering with respect to the median plane
3. Matching of the beam phase space into the cyclotron acceptance or eigenellipse
4. Longitudinal matching (bunching)
5. Minimum beam losses between ion source and the cyclotron center

Why Matching and Centering?



- Both off-centering and mis-match lead to coherent beam oscillations
- After many turns this will increase the emittances and beam sizes
- More sensitive to resonances
- Extraction more difficult
- Loss of beam quality for internal and extracted beam

Constraints Influencing The Design

1. Magnetic structure
   - Magnetic field value and shape in the center
   - Geometrical space available for CR, inflector, ion source etc
2. Accelerating structure
   - The number of accelerating dees (one,two,three or four)
   - The dee-voltage
   - The harmonic mode of acceleration
3. Injected particle
   - Charge and mass of the particle(s)
   - Number of ion sources to be placed (one or two)
   - Injection energy

Internal Source

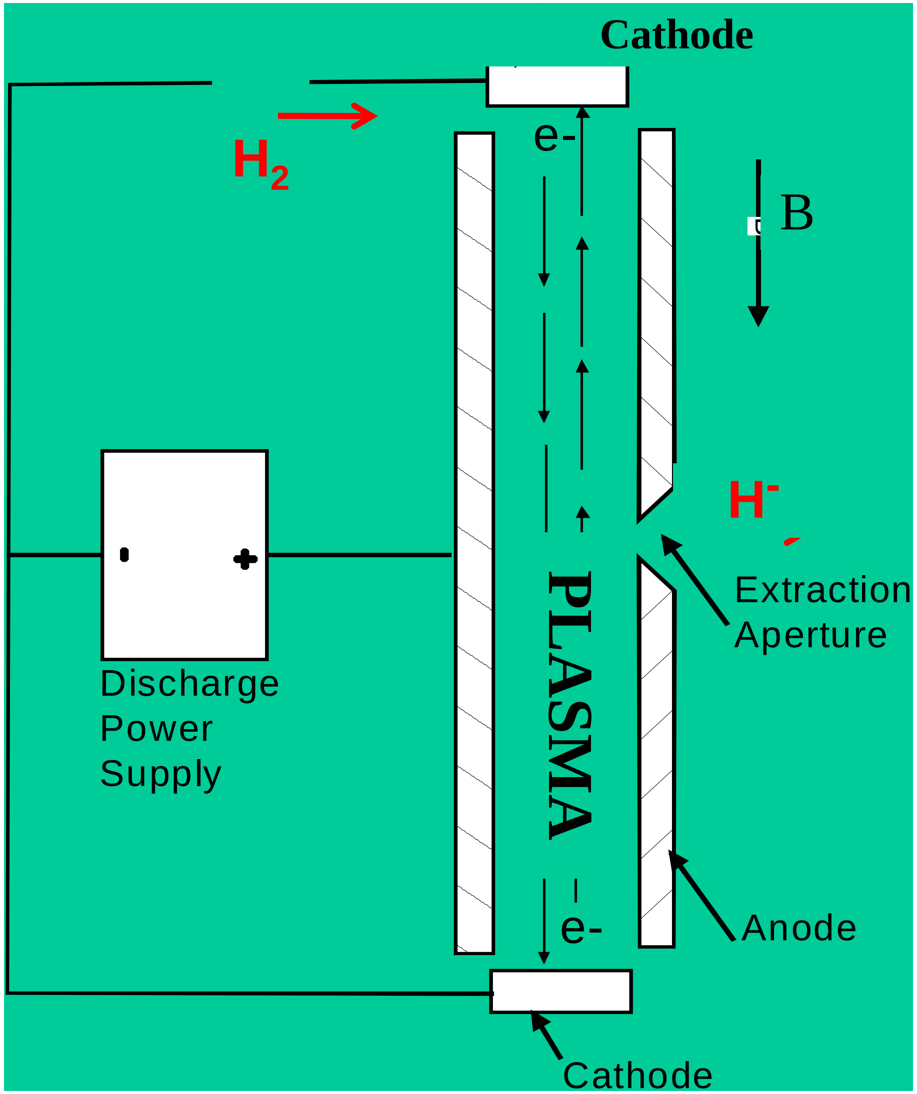
Some advantages

- Simple and cheap: simple ion source; No injection line needed
- Compact: two ion sources can be placed simultaneously

Some disavantages/limitation

- Low to moderate beam intensities
- Simple ion species (H^+,H^-,deuterons,He-3, He-4)
- Beam matching/bunching/manipulation not possible
- Carefull CR design in order to obtain good centering and focusing
- Gas-leak directly into the cyclotron (bad for negative ions)
- Machine has to be stopped for ion source maintenance

Cold Cathode PIG Ion Source



➢Electron emission due to electrical potential on the cathodes

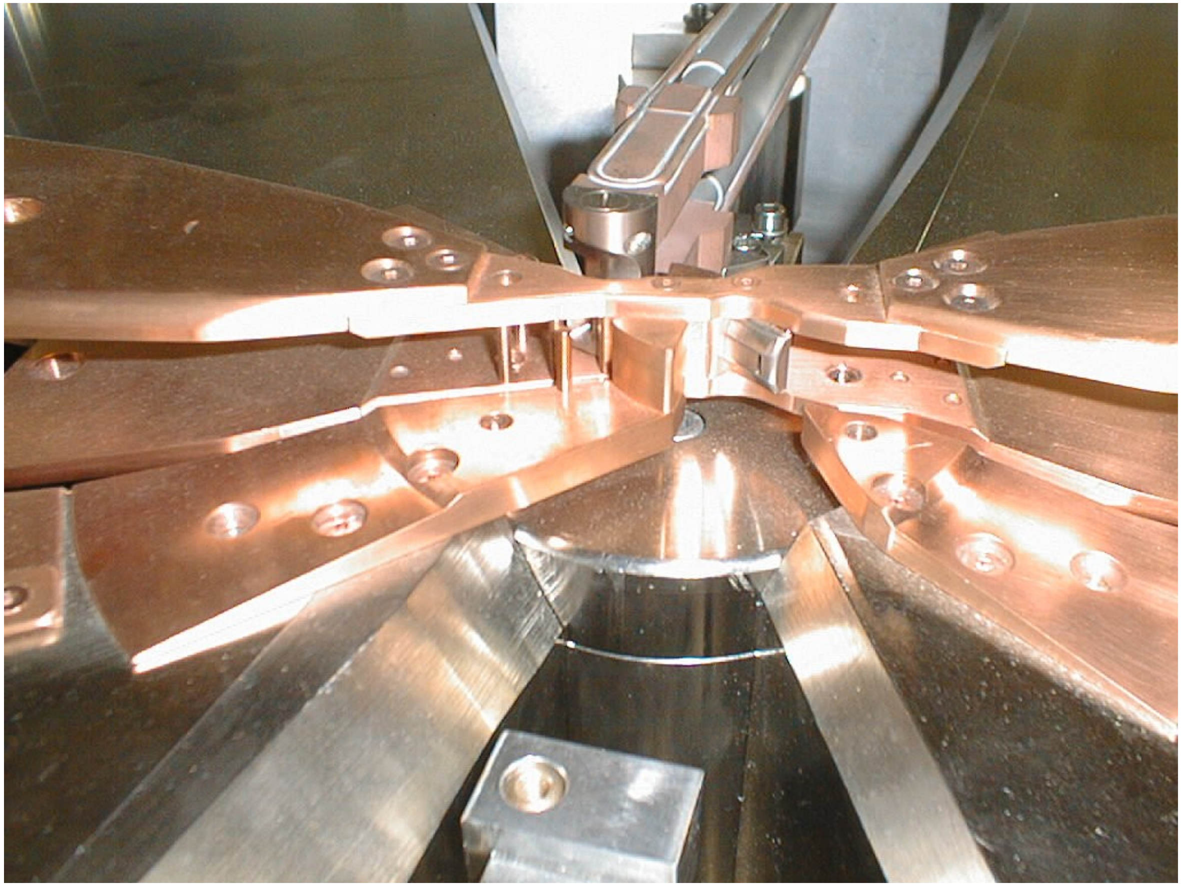
➢ Electron confinement due to the magnetic field along the anode axis

➢ 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)

Central region



4 poles

2 dees (4 gaps)

2 ion sources (H^- and D^-)

Puller at V_{dee}

Central plug to adjust field in the center

Chimney, cathodes and puller

Chimney: copper-tungsten ⇒ good heat properies; machinable

Cathodes: tantallum ⇒ high electron emission (low workfunction)

CR design for an internal source (1)

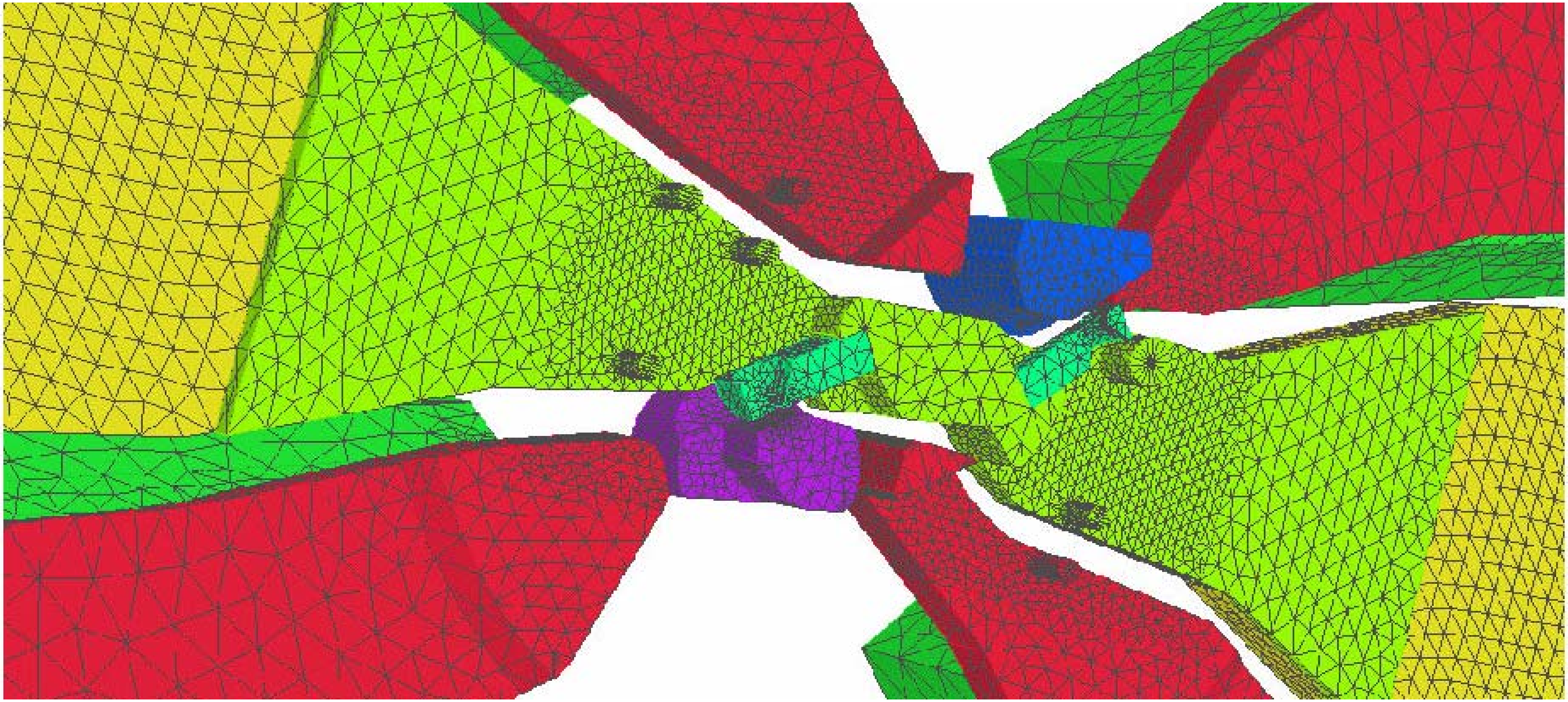
1. Start with crude model, refine step by step

   - Use uniform B-field
   - Hard edge approximation and uniform E-field in gaps
   - Find approximate position of source and gaps using analytical formulas
   - First look at median plane motion only

CR design for an internal source (2)

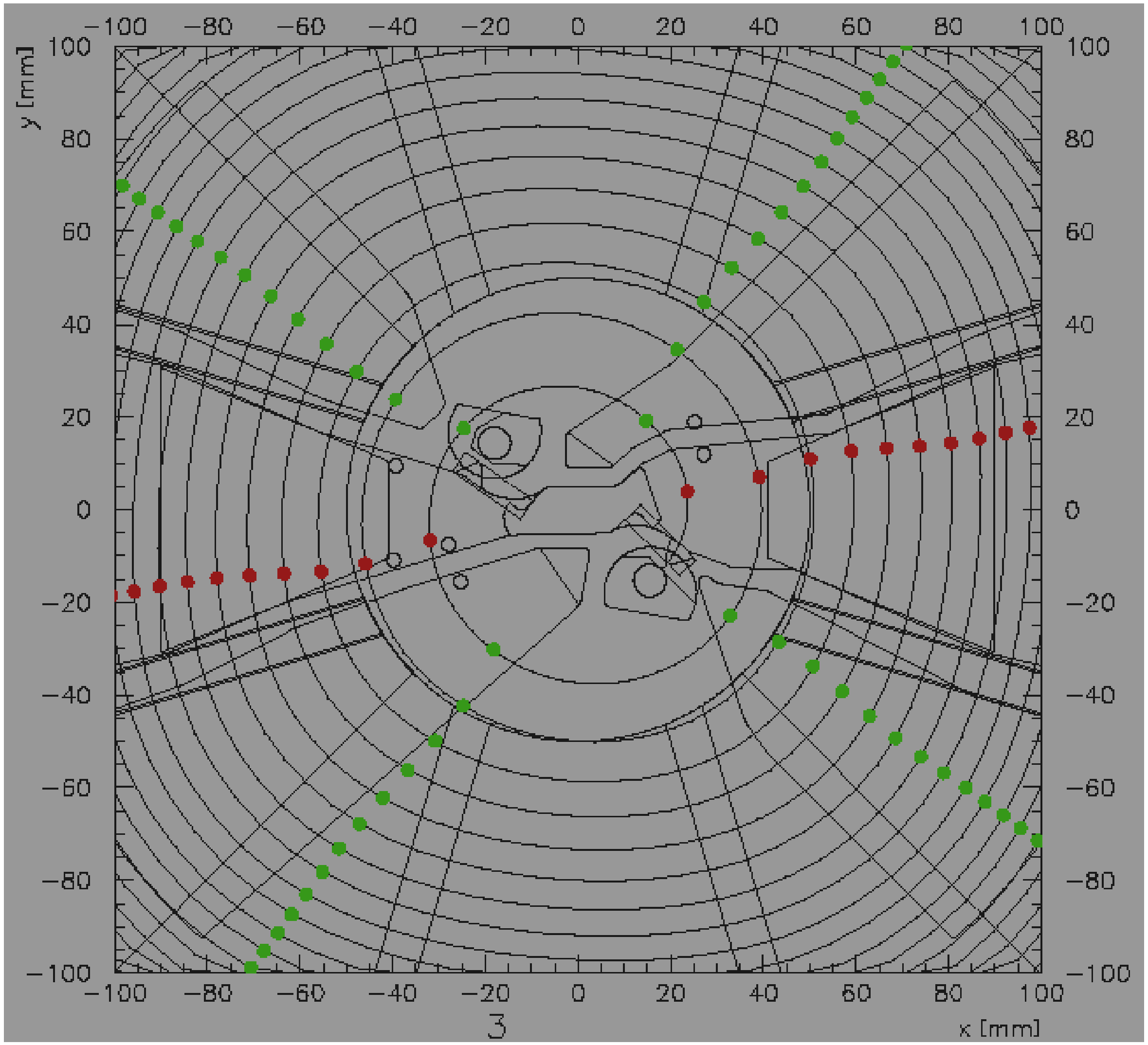
2. Refine using orbit integration program
   - Artificial E-field with Gaussian profiles in the gaps ⇒ easy to generate and modify
   - Include vertical motion and optimize gap position
3. Create 3D model of CR to solve Laplace equation
   - RELAX3D (Triumf)
   - TOSCA fromVector Fields (Finite Elements)
   - Fully parametrize the model for easy modification/optimization
   - E-field measurements no longer needed
4. Track orbits in realistic B-field (field map or 3D FE models)
5. Track a full beam (many particles) to find beam losses
6. Fine tune beam centering and vertical focusing

3D finite element model of CR



- Fine meshing where needed $\Rightarrow$ source puller gap
- Modeling of complete accelerating structure
- Parametrize for easy modification and optimization

Orbit tracking (C18/9 cyclotron)



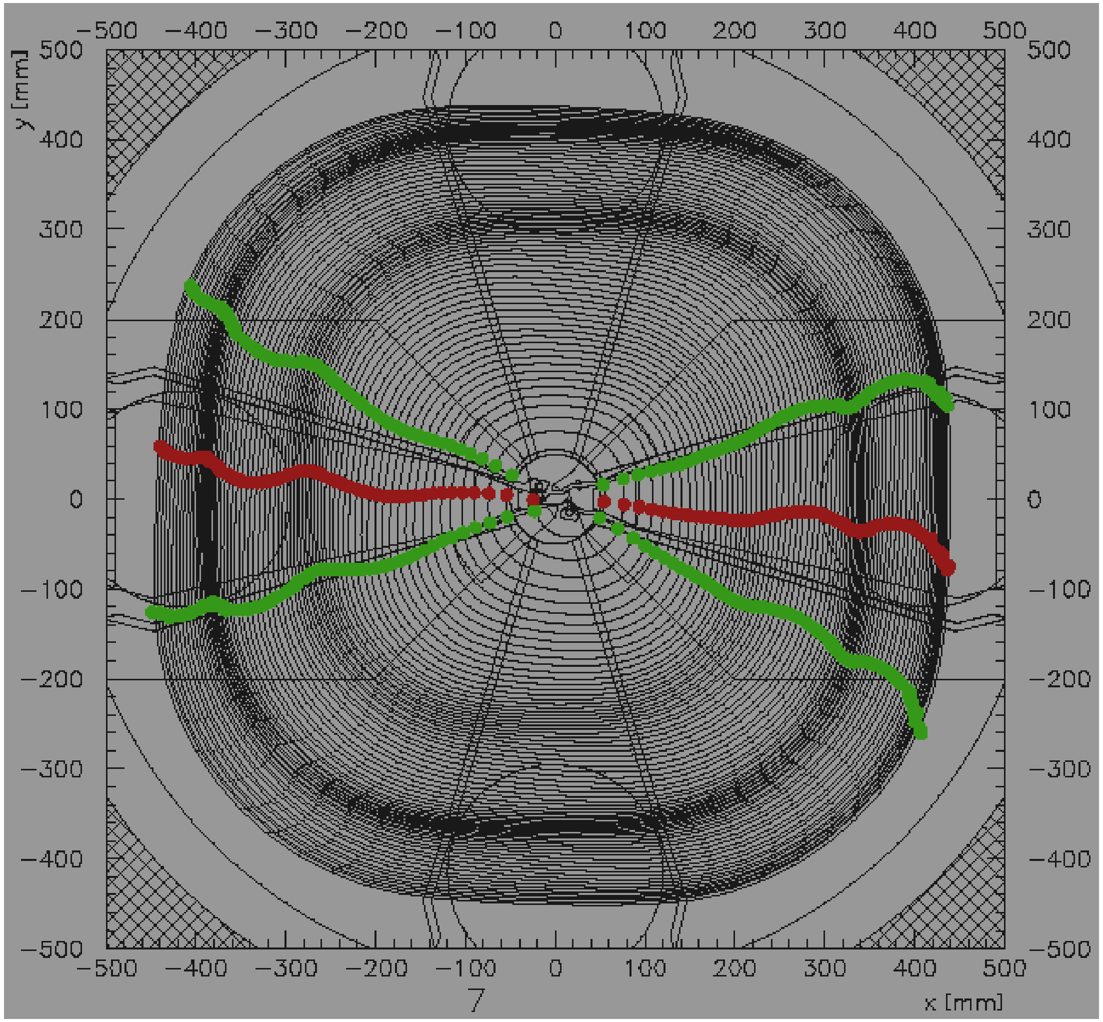
Compact scale 20 cm

H^- + D^- source. Cut D^- chimney for H^- passage

Red dots: position of particle when V_{dee} =0

Green dots: position of particle when V_{dee} =V_{max}

An off-centered beam



Beam off-centered due to bad CR design

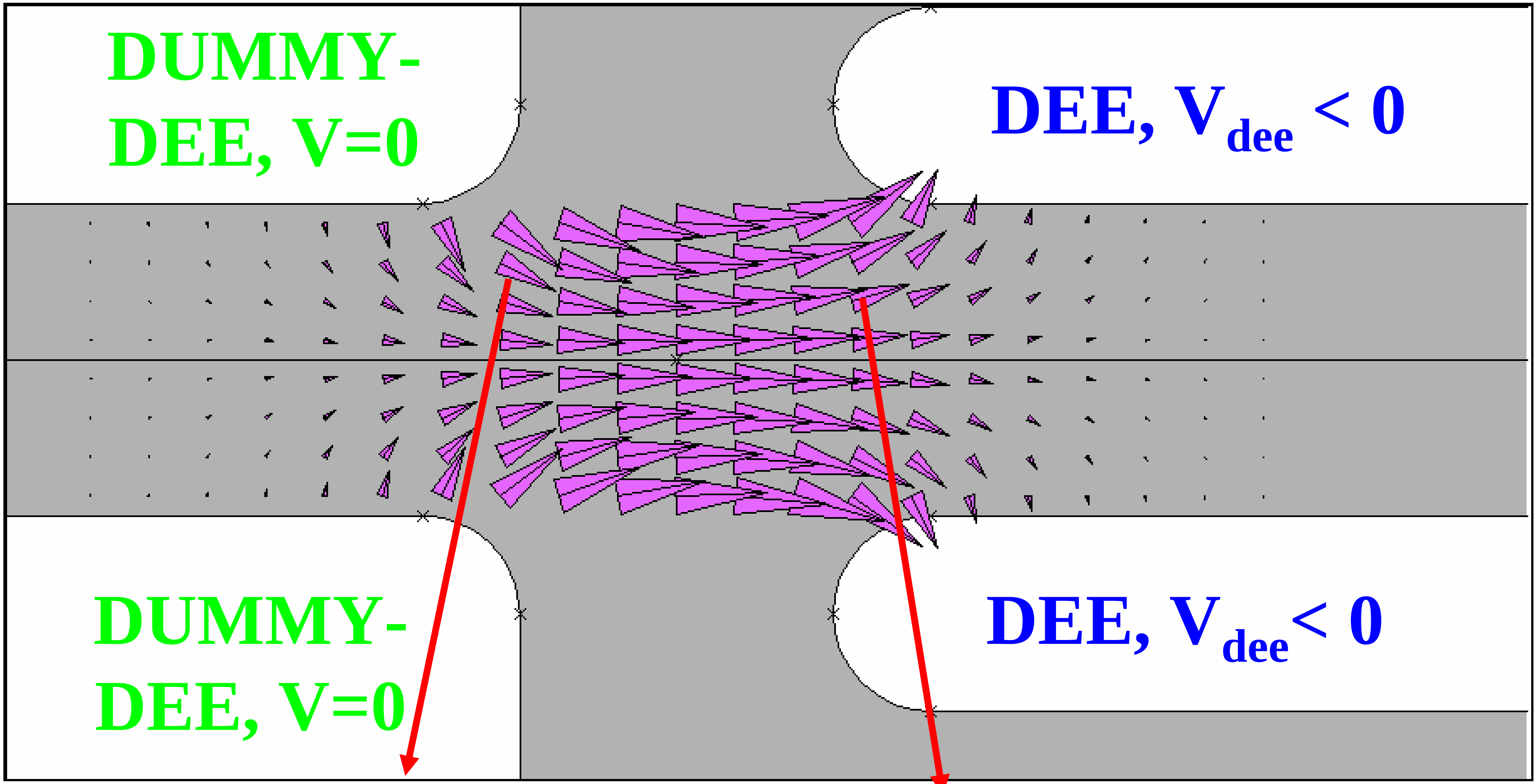
Density modulations due to betatron oscillations (precession $\nu_r > 1$)

Observe transverse-longitudinal coupling

Vertical focusing in the center

- Azimuthal Field Variation (AVF) goes to zero in the cyclotron center $\Rightarrow$ magnetic vertical focusing disappears
- Two remedies
  - Add a magnetic field bump in the center $\Rightarrow$ negative field gradient creates vertical focusing: field bump of a few hundred Gauss $\Rightarrow$ central plug
  - The first few accelerating gaps provide electrical focusing $\Rightarrow$ proper positioning of accelerating gaps to get phase focusing

Electrical Vertical Focusing

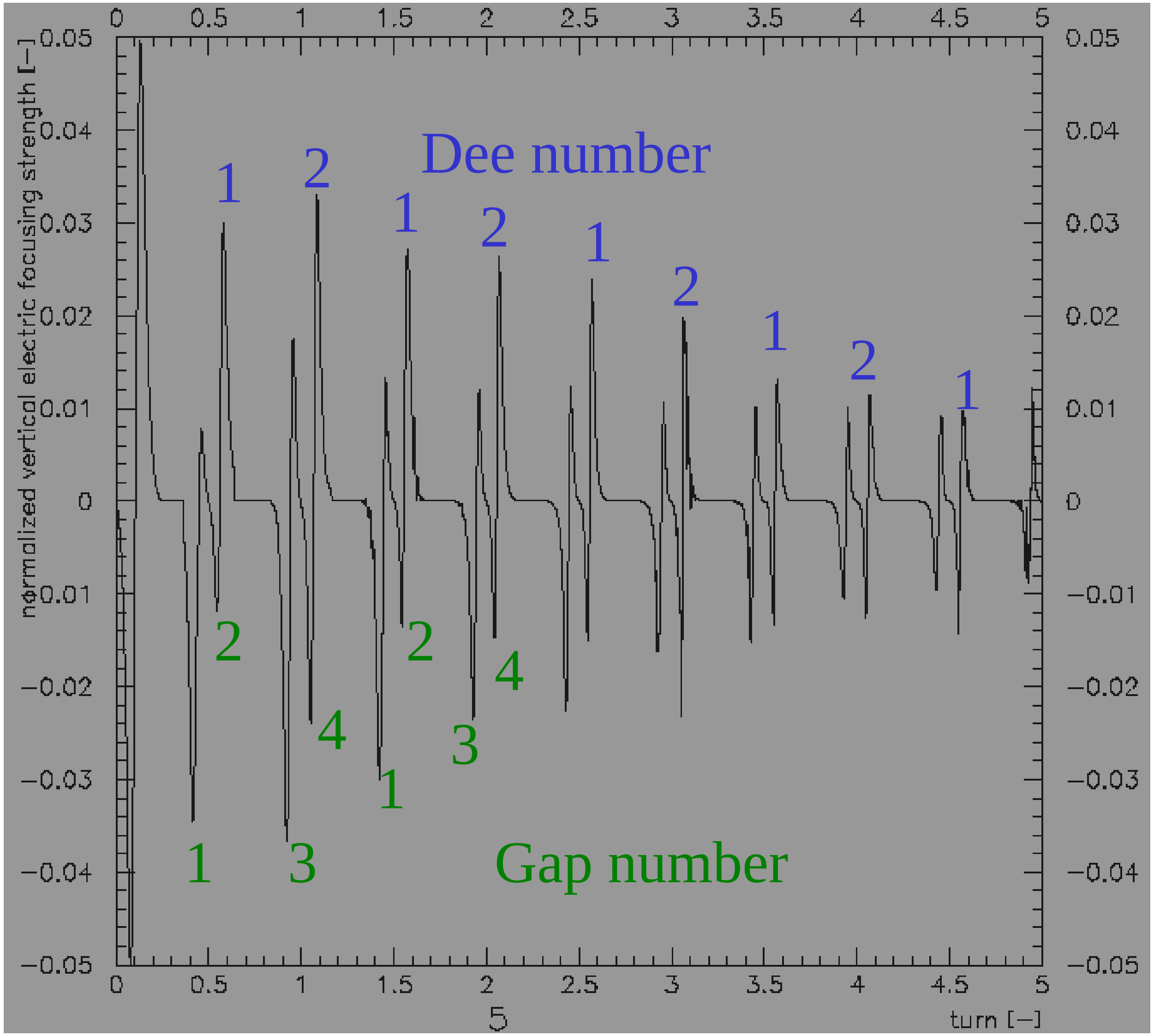


First half gap focusing

Second half gap defocusing

Falling slope of RF sine wave ⇒ net focusing (phase focusing)

Vertical Electrical Forces



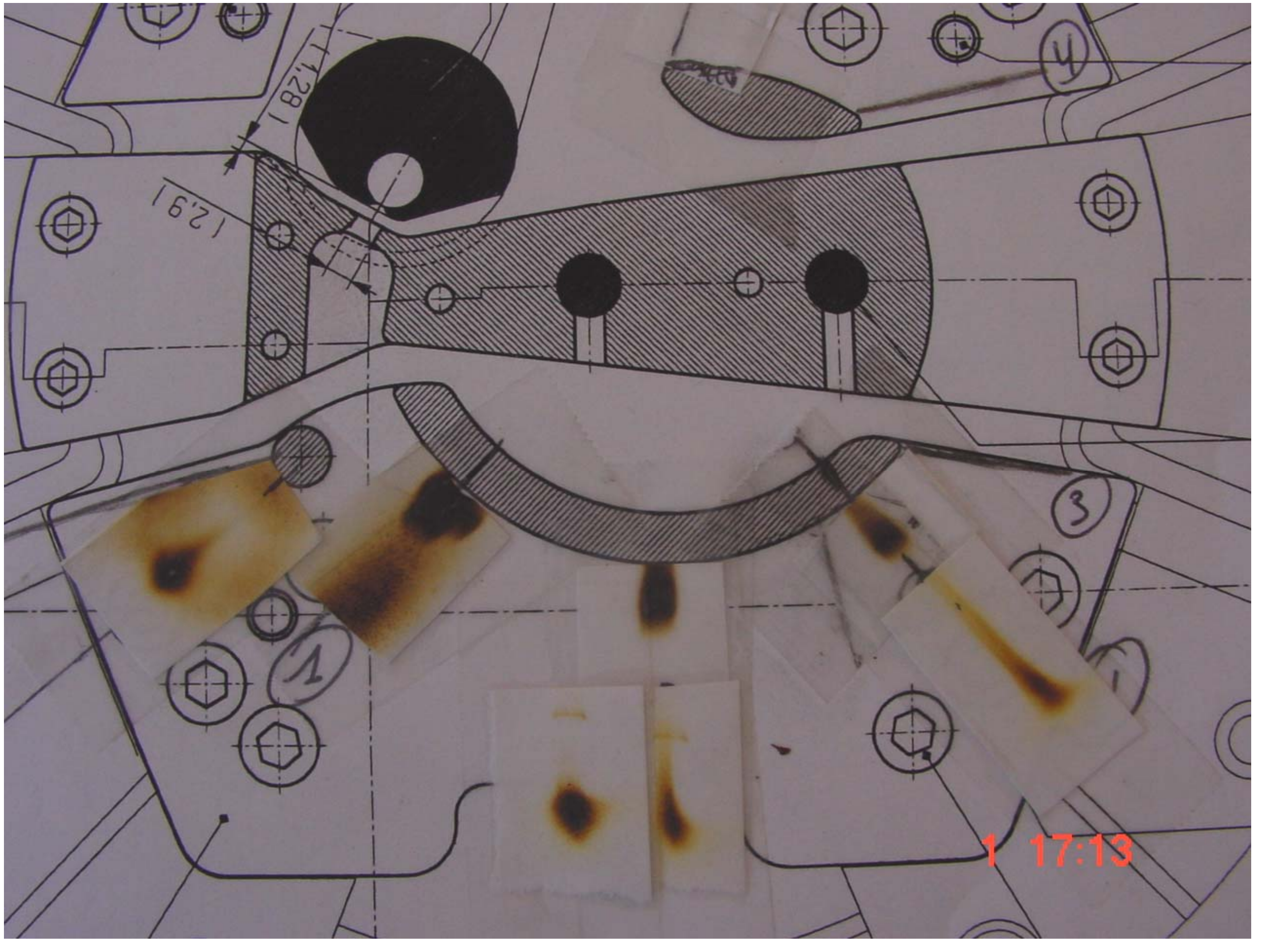
Particle tracking (5 turns)

2-dee system (4 gaps)

Minus sign ⇒ focusing

Focusing weakens with energy

C14SE: Finding The Beam



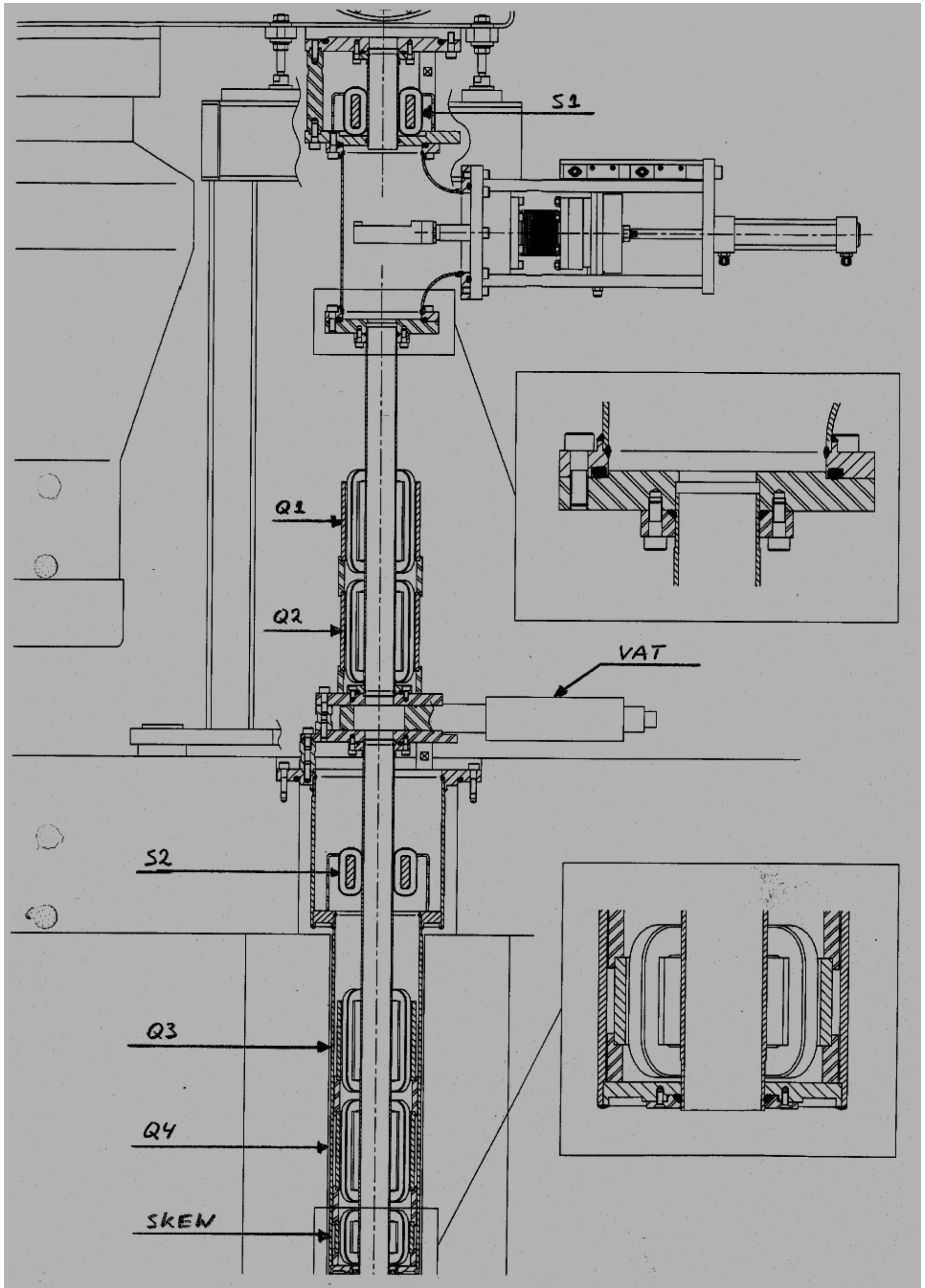
Burning paper with the beam in order to find its position in the cyclotron center

Different Ways of Injection (1)

1. Axial injection $\Rightarrow$ most relevant for small cyclotrons
   - Along the vertical symmetry axis of the cyclotron
   - In the center, the beam is bent by an angle of 90 degrees into the median plane
   - For this an electrostatic or magnetostatic inflector device is used
2. Injection by stripping
   - A stripper foil positioned in the center changes the particle charge state and local radius of curvature in order to put the beam on the EO

Different Ways of Injection (2)

3. <u>Horizontal injection</u>
   - The beam is traveling in the median plane from the outside towards the cyclotron center
   - Complicated due to vertical magnetic field acting on (low energy) the beam
     - Use electrode system to cancel the magnetic field
     - Live with this field (trochoidal injection, complicated and no longer used)
   - In the center an electrostatic deflector places to particle on the EO
4. <u>Special case: separate sector cyclotron</u>
   - A lot of space available to place magnetic bending and focusing elements
   - Injection at much higher energy is possible



Axial injection line

4 quads for matching

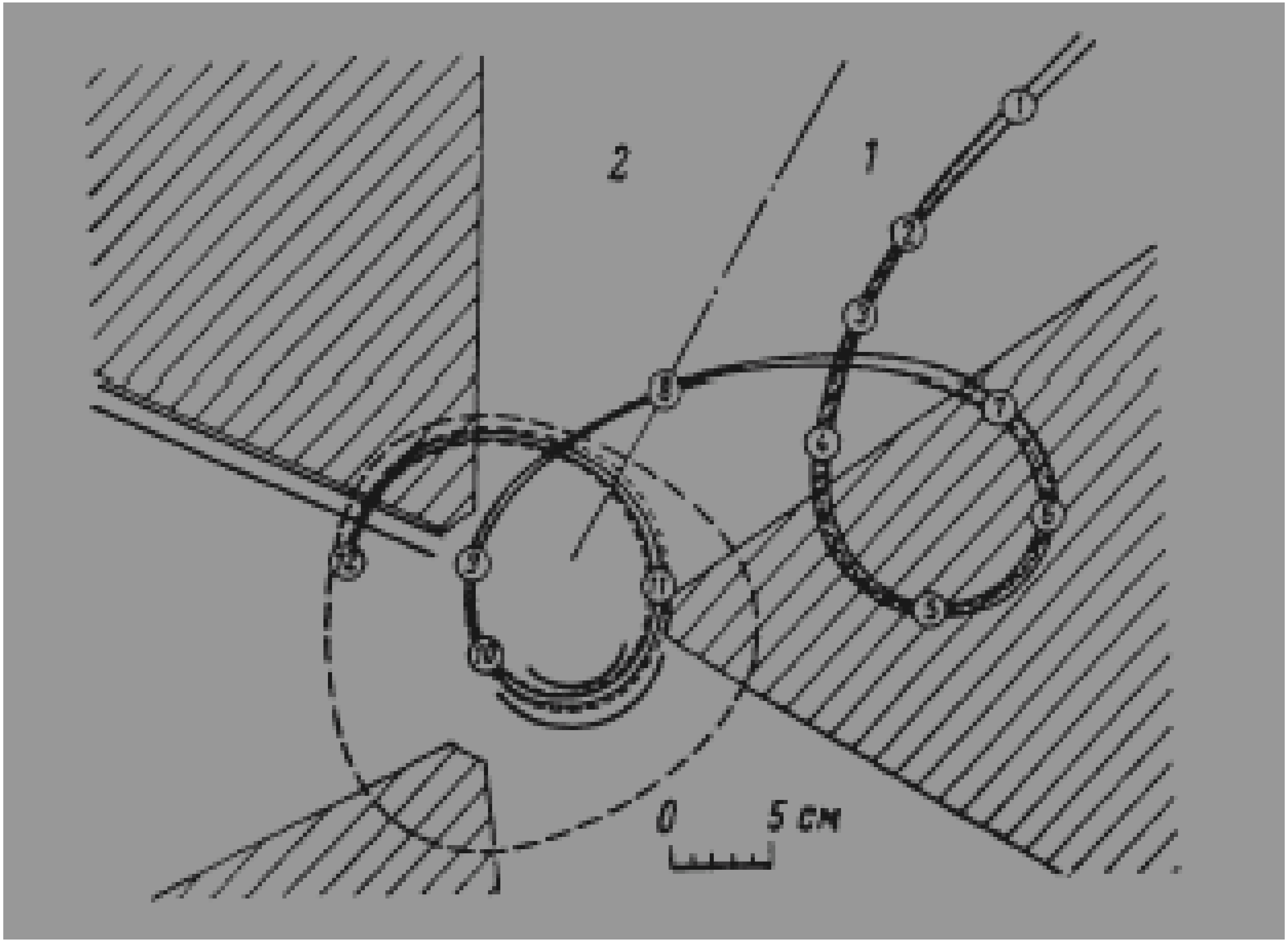
steering magnets for beam alignment

One skew quad

Buncher not shown

One faraday cup

Horizontal Injection

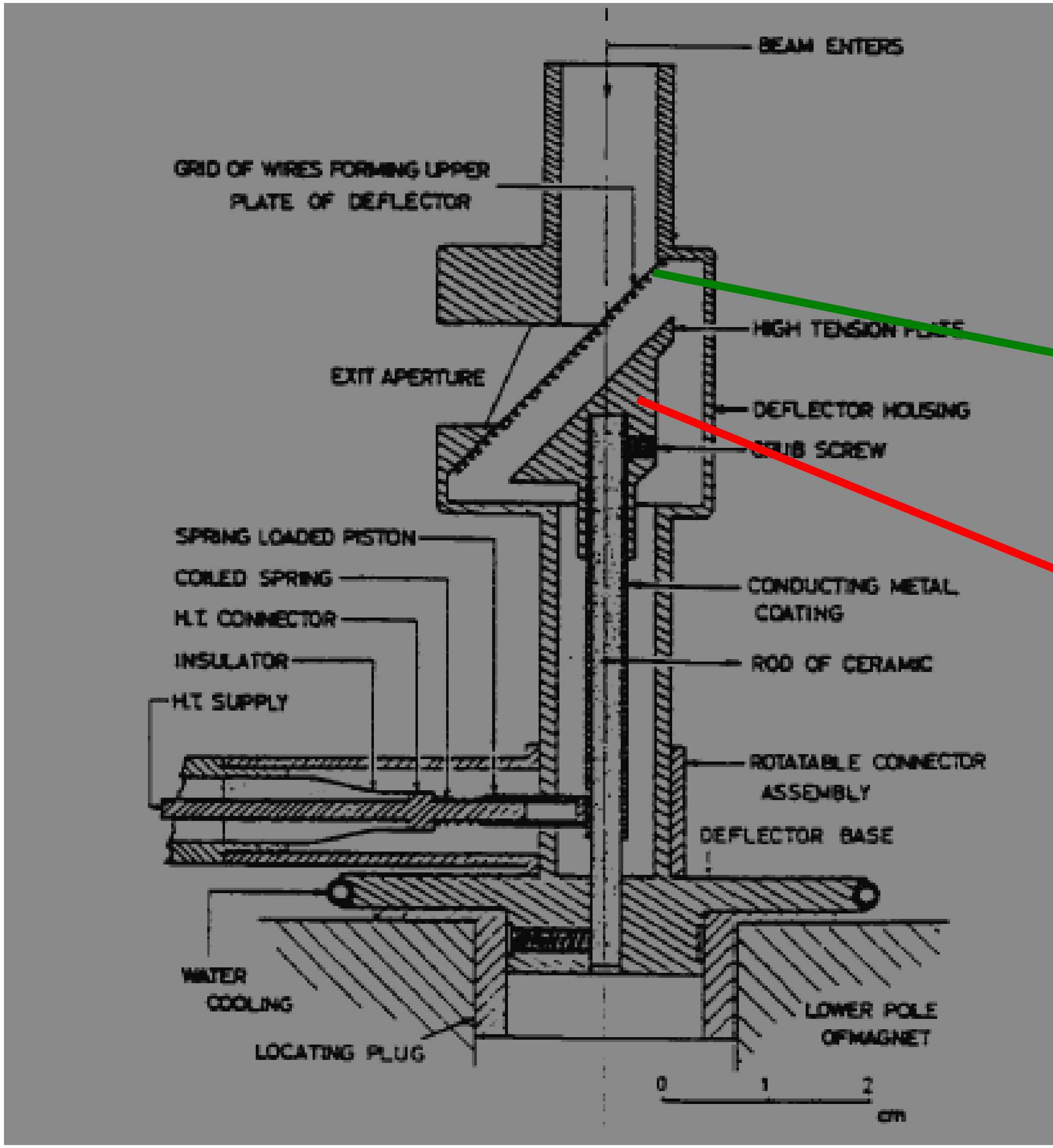


Inflectors for Axial Injection (1)

The E-field between 2 electrodes bends the beam 90° from vertical to horizontal. The presence the cyclotron B-field creates a complicated 3D orbit and this complicates the inflector design. Four different types are known:

1. Mirror inflector: planar electrodes placed at 45° wrt beam. Opening in one electrode for particle entrance and exit.
   - Advantage: relatively simple in design
   - Disadvantage: Orbit not on an equipotential surface ⇒ high electrode voltage (comparable to injection voltage) needed to decelerate and re-accelerate the beam
   - wire grid needed for good field quality ⇒ maintenance problem

Mirror Inflector



Ground electrode

High voltage electrode

Inflectors for Axial Injection (2)

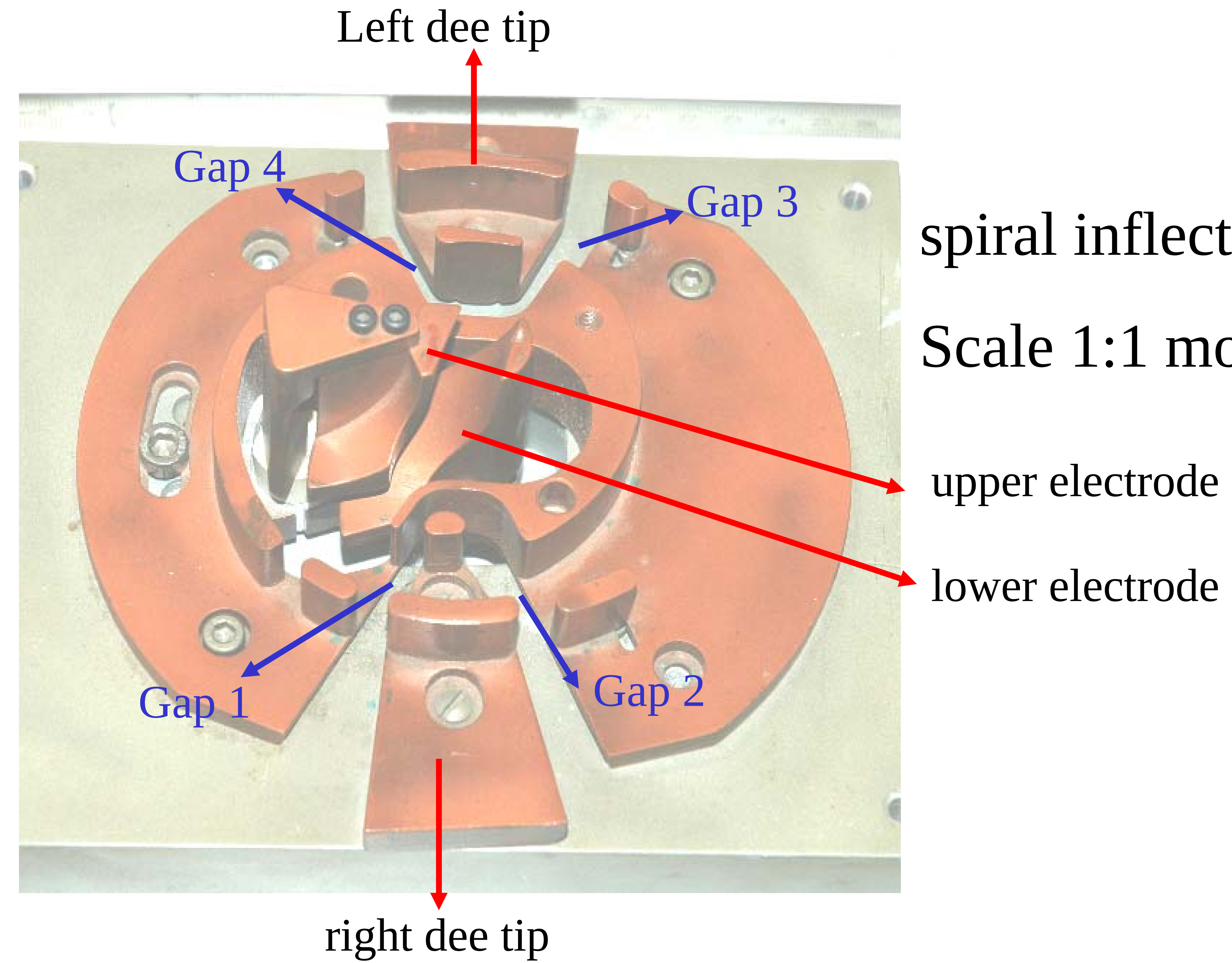
2. Spiral inflector: basicly a cylindrical capacitor which is gradually twisted to take into account the spiraling of the trajectory induced by the vertical magnetic field
   - E-field always perpendicular to velocity ⇒ orbit on equipotential ⇒ much lower electrode voltage

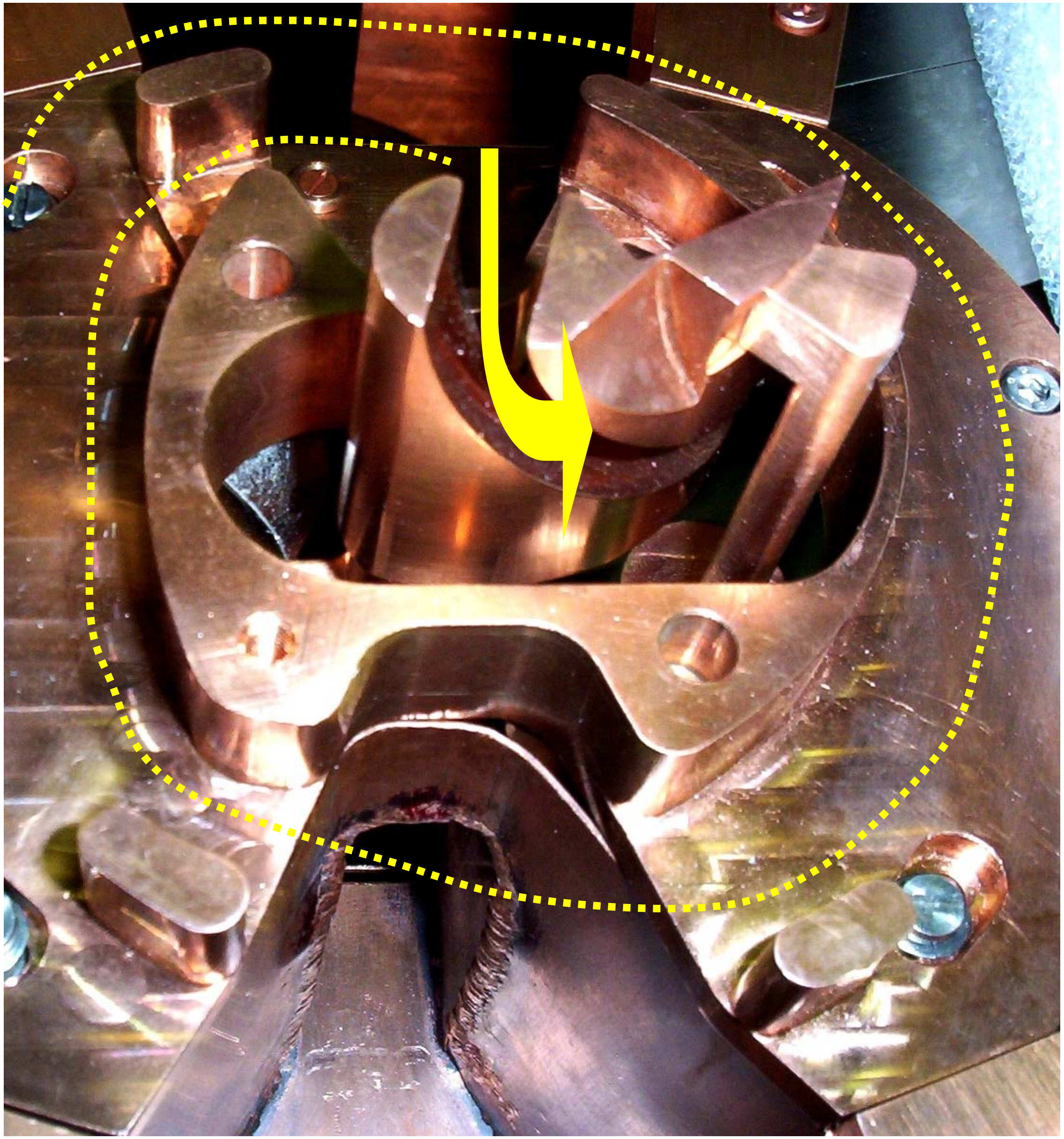
$$V/d = 2E_k/qA$$

   - Two free design parameters available to obtain orbit centering
     1. Electric radius A (equivalent to height of inflector)
     2. Tilt parameter k’ (equivalent to a change of magnetic field)
   - Very compact geometry
   - Complicated electrode structure more difficult to machine (5 axis milling machine)

spiral inflector

Scale 1:1 model



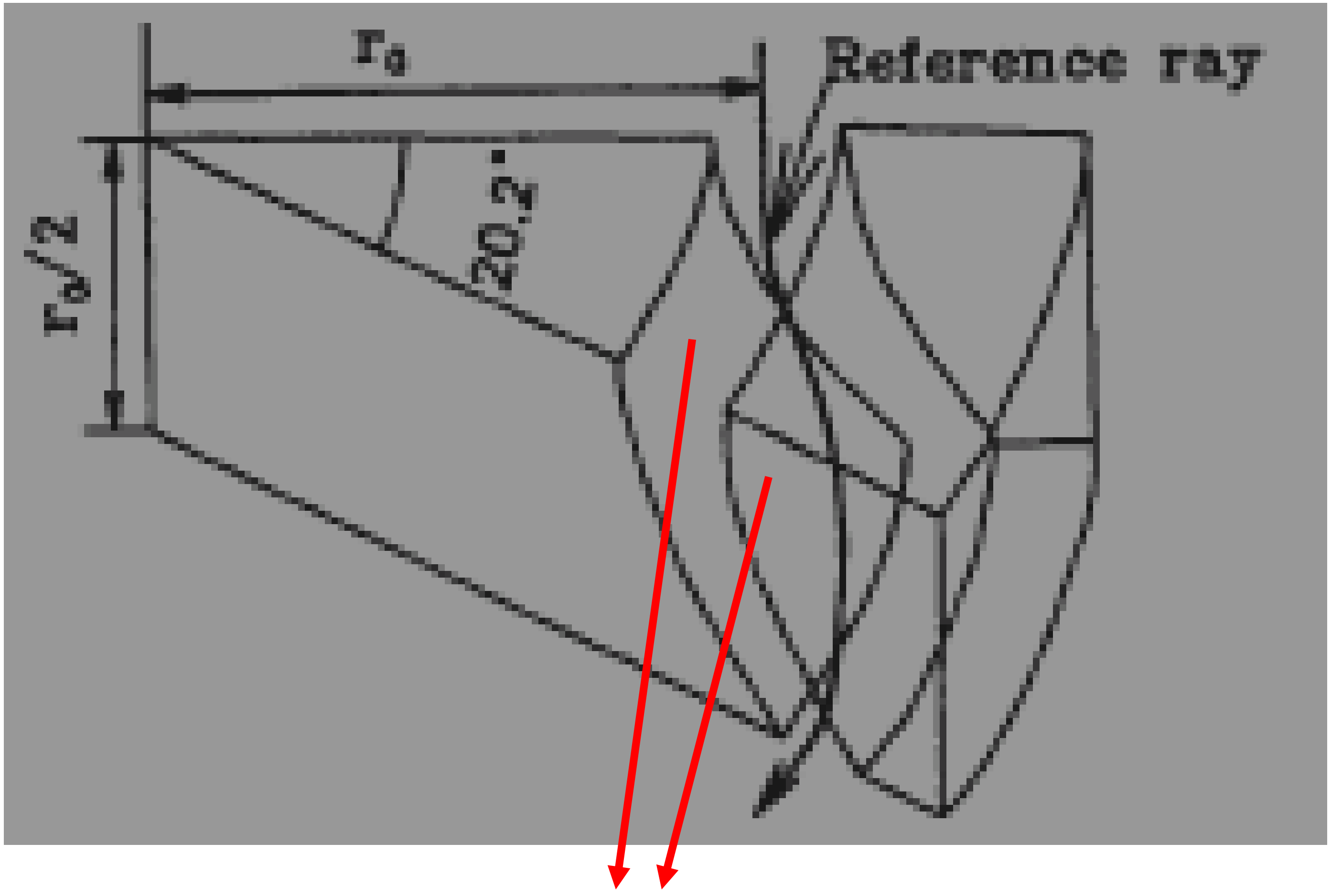


Another example of
a spiral inflector

Inflectors for Axial Injection (3)

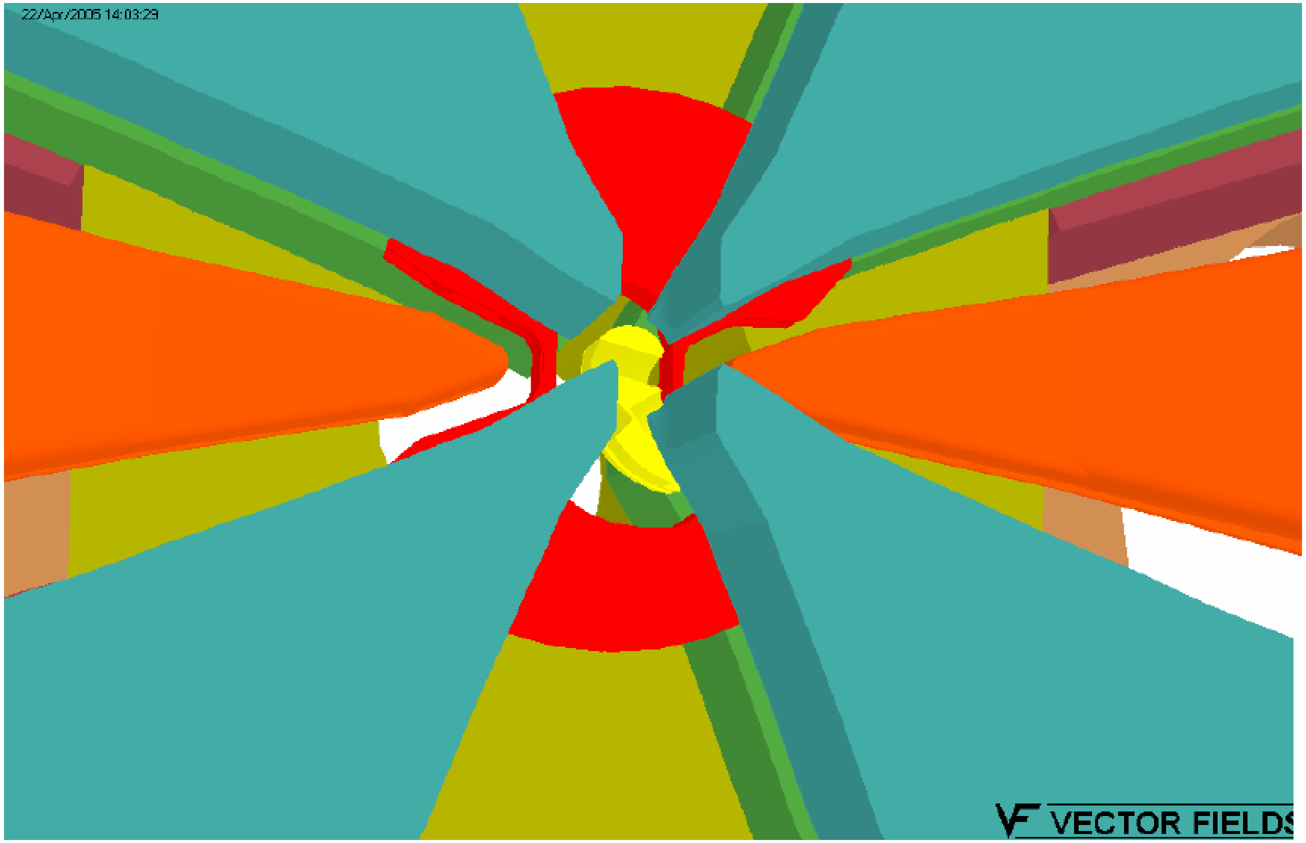
3. Hyperbolic inflector: hyperbolic electrode surfaces with rotational symmetry around z-axis
   - E-field perpendicular to velocity $\Rightarrow$ low electrode voltage
   - No free design parameters (geometry is fixed for given particle charge and mass, injection energy and B-field)
   - Relatively large geometry
   - Easy to machine on a lathe due to rotational symmetry
4. Parabolic inflector: electodes obtained from bending sheet metal plates into a parabolic shape. This inflector has the same advantages and dis-advantages as the hyperboloid: relatively low voltage and ease of construction, but no free design parameters and relatively large geometry

Hyperboloid Inflector



Hyperbolic surfaces

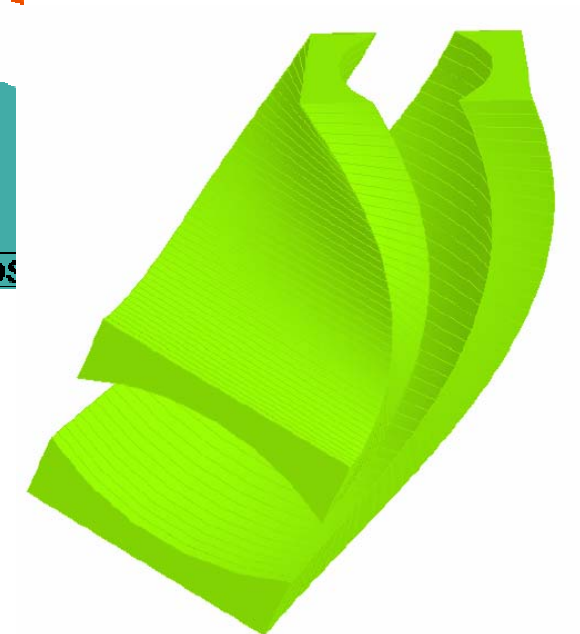
3D Finite Element Simulations (1)



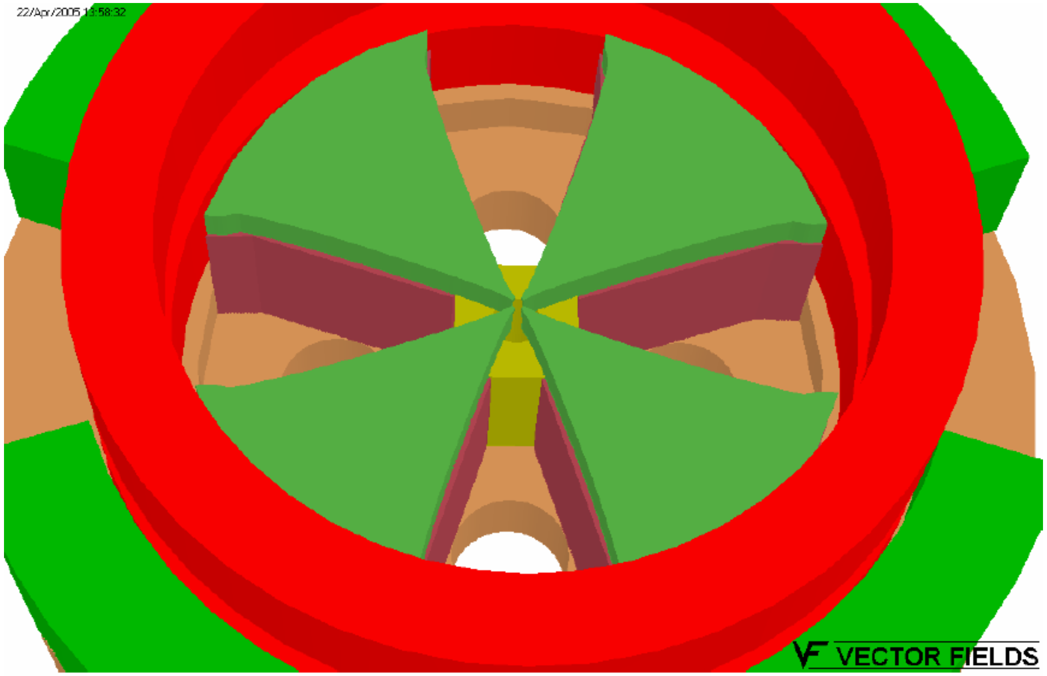
Inflector + central region
Magnet structure

OPERA3D from Vector Fields

Inflector with curved electrodes to improve field quality near edge



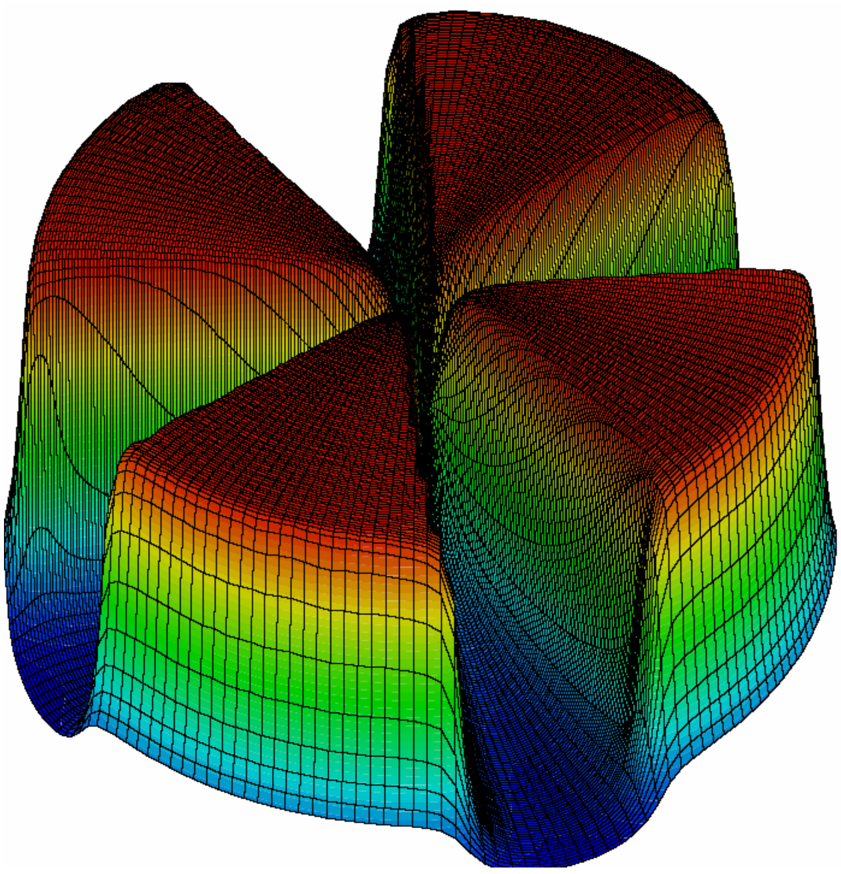
3D Finite Element Simulations (2)



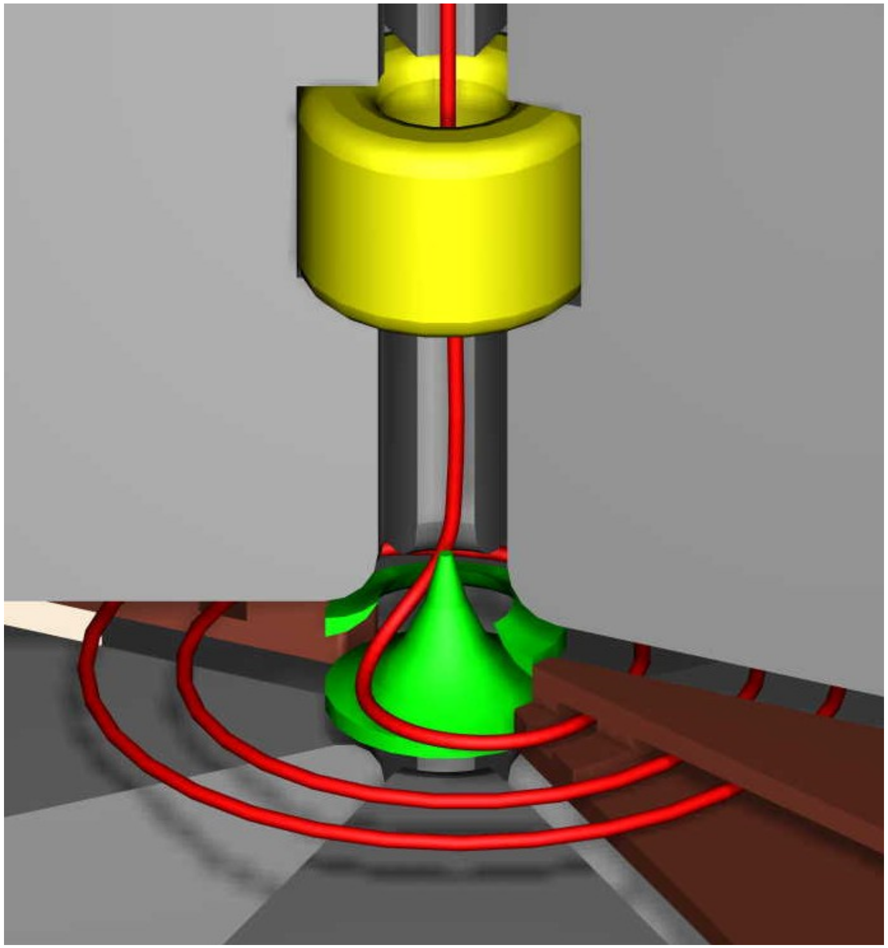
3D model of Cyclone 30 magnet

3D B-field needed on cyclotron axis and inflector volume

Calculated magnetic field



New Idea: Magnetostatic Inflector



- Preliminary concept of injection $\Rightarrow$ soft iron inflector magnet poles magnetized by the cyclotron magnetic field
- Rotational symmetry
- No electrical isolation or sparking problem $\Rightarrow$ high injection voltage 60 kV
- Axial injection optical elements have to steer the beam out of the cyclotron vertical axis $\Rightarrow$ orbit centering

Part 2: Extraction From a Cyclotron

- Extraction: transfer of the beam from an internal orbit to a target oustide of the magnetic field
- Difficult process. Why?
  1. magnetic field trap $\Rightarrow$loss of isochronism
  2. Orbits pile up: R=sqrt(E) $\Rightarrow$ small turn-separation
  3. Beam quality destroyed in fringe field

Extraction: Overview Of Solutions

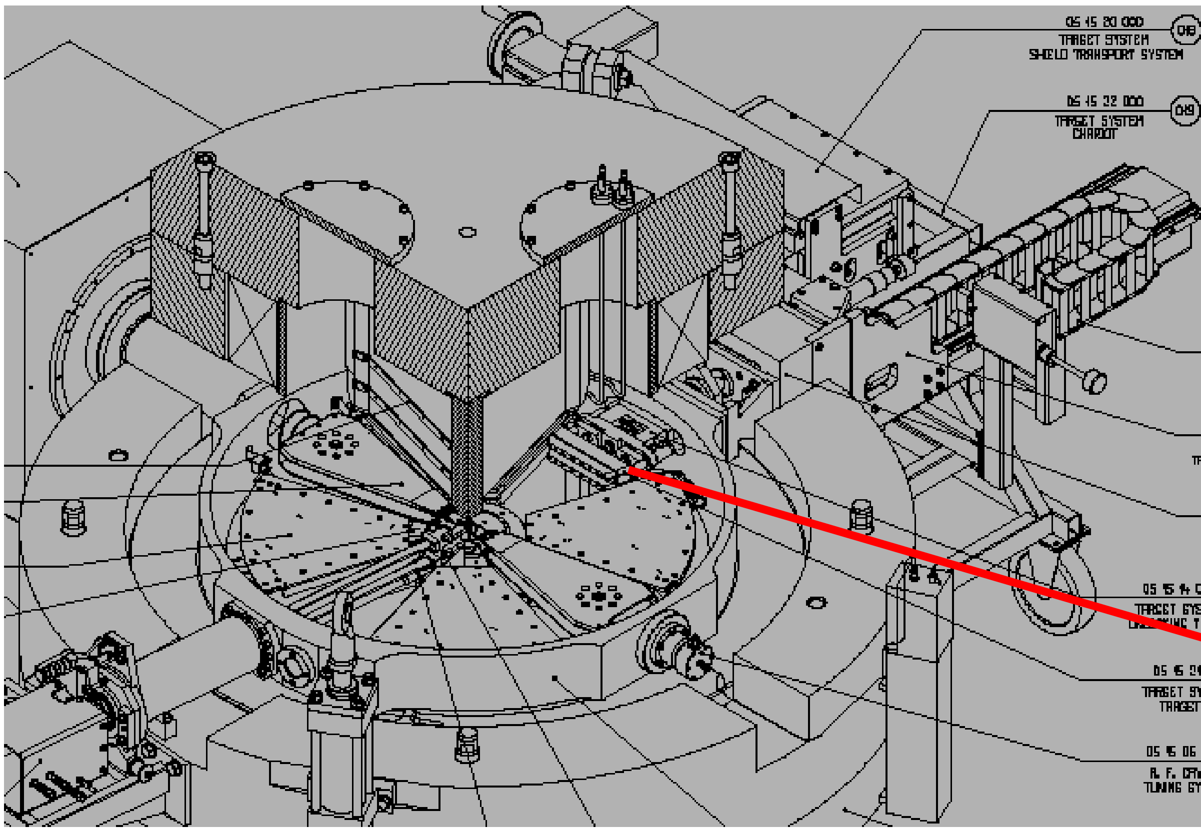
1. Internal Target (trivial but important)
2. Stripping Extraction
3. Electrostatic septum $\Rightarrow$ peel of last orbit
4. Self-Extraction

Cases 3. and 4. require some way to <u>increase the turn separation</u> between the last and before last orbit

Avoid Extraction: Internal Target

- Target in the isochronous field region
- Used for medical isotope production (Pd/Tl)
- Advantage:
  1. Simple and cheap
  2. Energy can be selected
- Disadvantage:
  1. Dirty $\Rightarrow$ contamination of the machine
  2. Dissipated heat handling (small beam spot)
  3. Reflection of a part of the beam

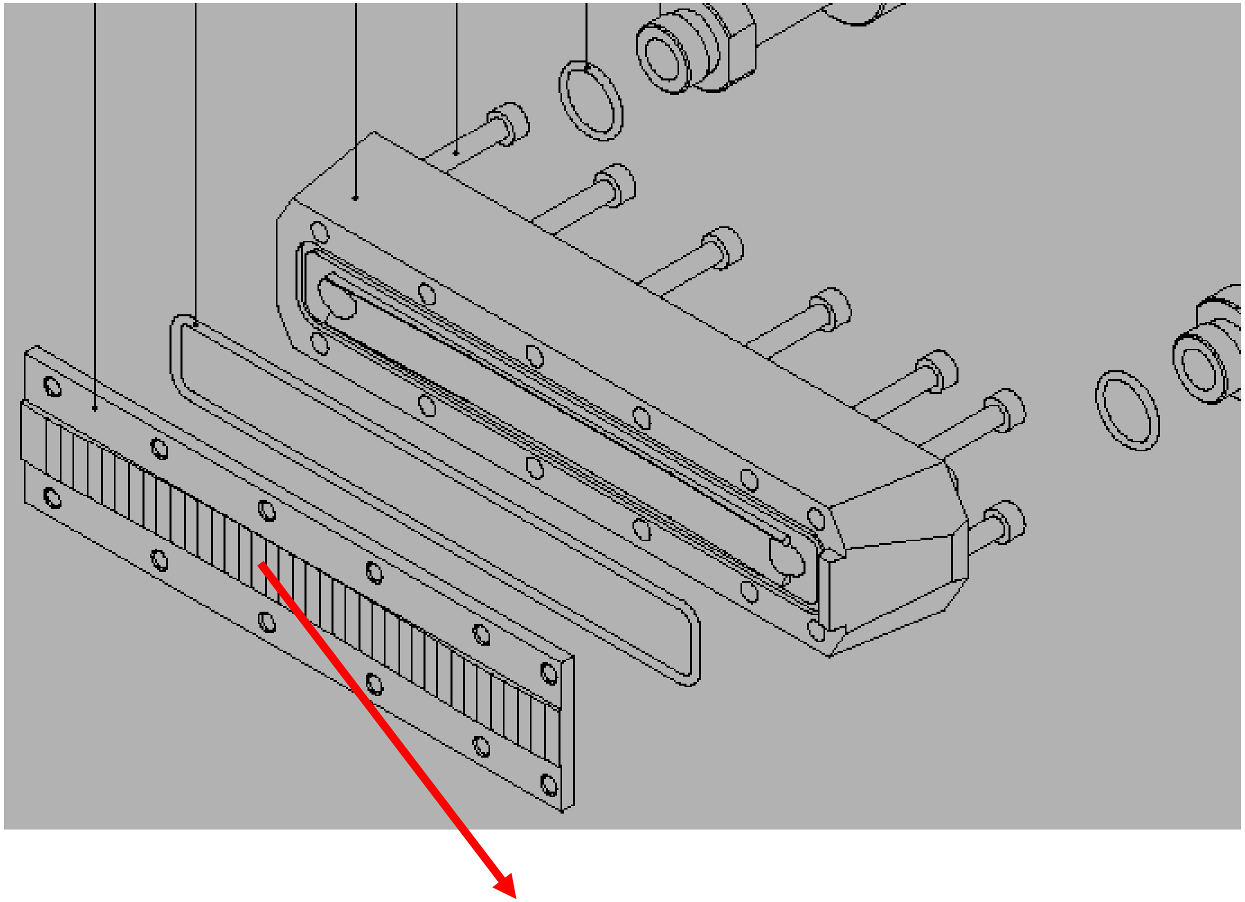
IBA C18+ with internal target



- ➢16 machines sold to one customer
- ➢Pd for Brachytherapy
- ➢Remote target handling

Rhodium target

High Power Internal Target



Copper support plated with Rhodium

- ➢30 kWatt target (2 mA/15 MeV)
- ➢Heavy water cooling
- ➢Surface profile following EO shape
- ➢Large beam spot
- ➢Try to minimize reflection

Stripping Extraction (1)

2. Beam passes thin foil to remove electrons and sudden change of orbit curvature

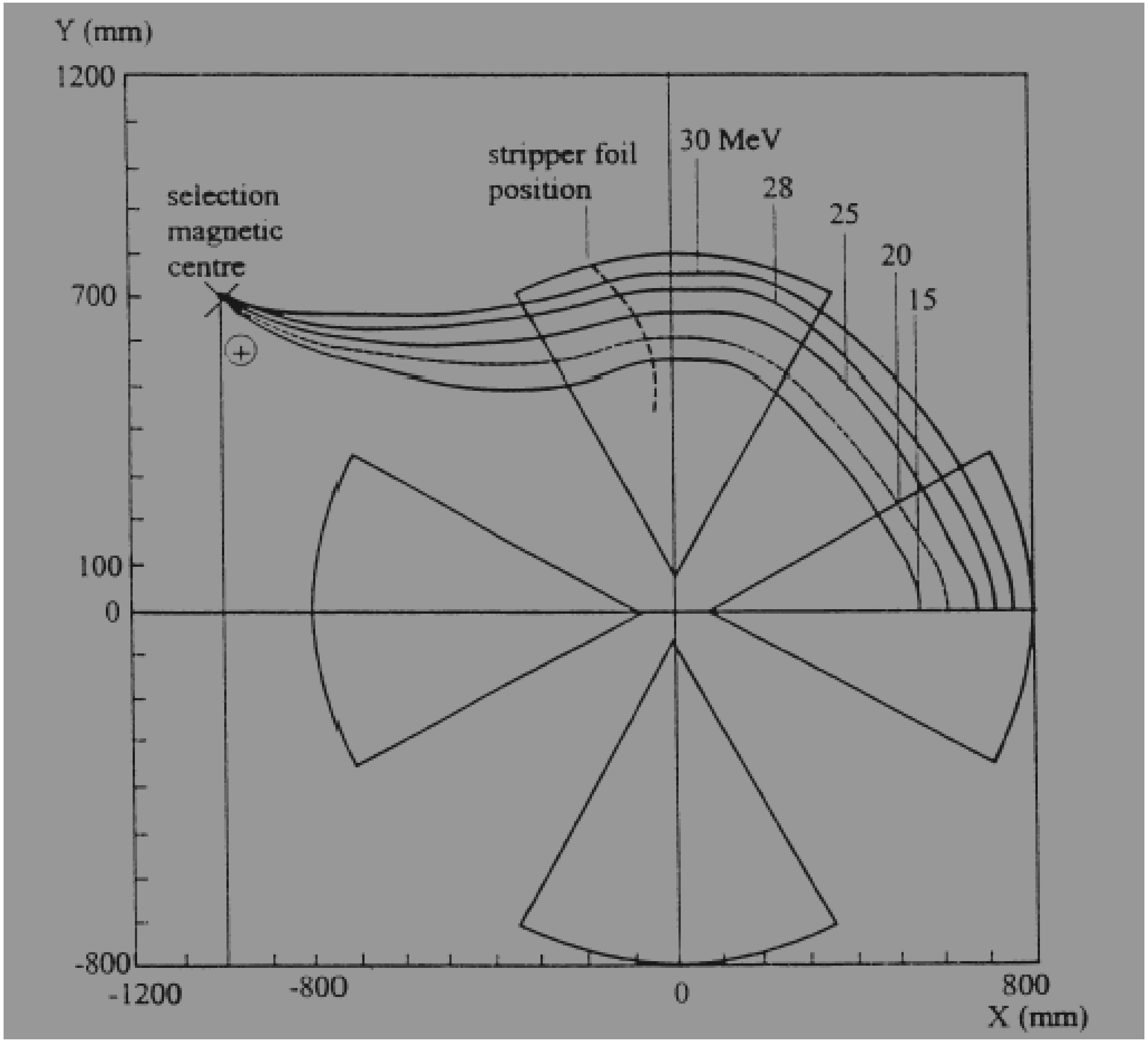
$$\rho_f = (Z_i/Z_f) * (m_f/m_i) * \rho_i$$

- Example H-minus ($\rho_f = -\rho_i$)

  $H^- \Rightarrow H^+ + 2e^-$ (IBA C18/9, C30, Ebco TR30, GE)

- Example H_2^+ $\Rightarrow$ K-value x4 $\Rightarrow$ large machine

  $H_2^+ \Rightarrow 2H^+ + e^-$ ($\rho_f = \rho_i/2$) (more difficult optics)

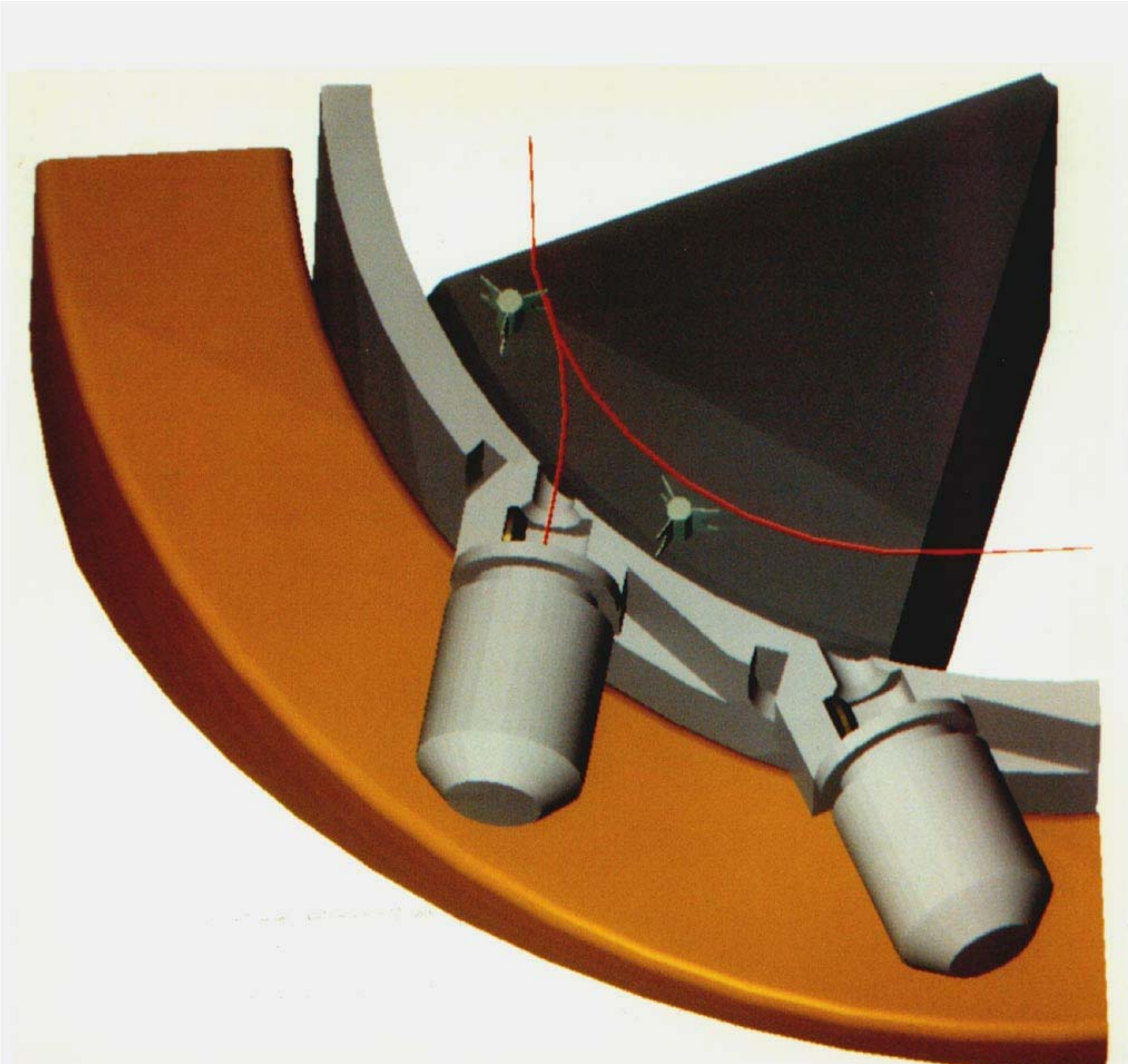


IBA Cyclone 30

Extraction by stripping

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

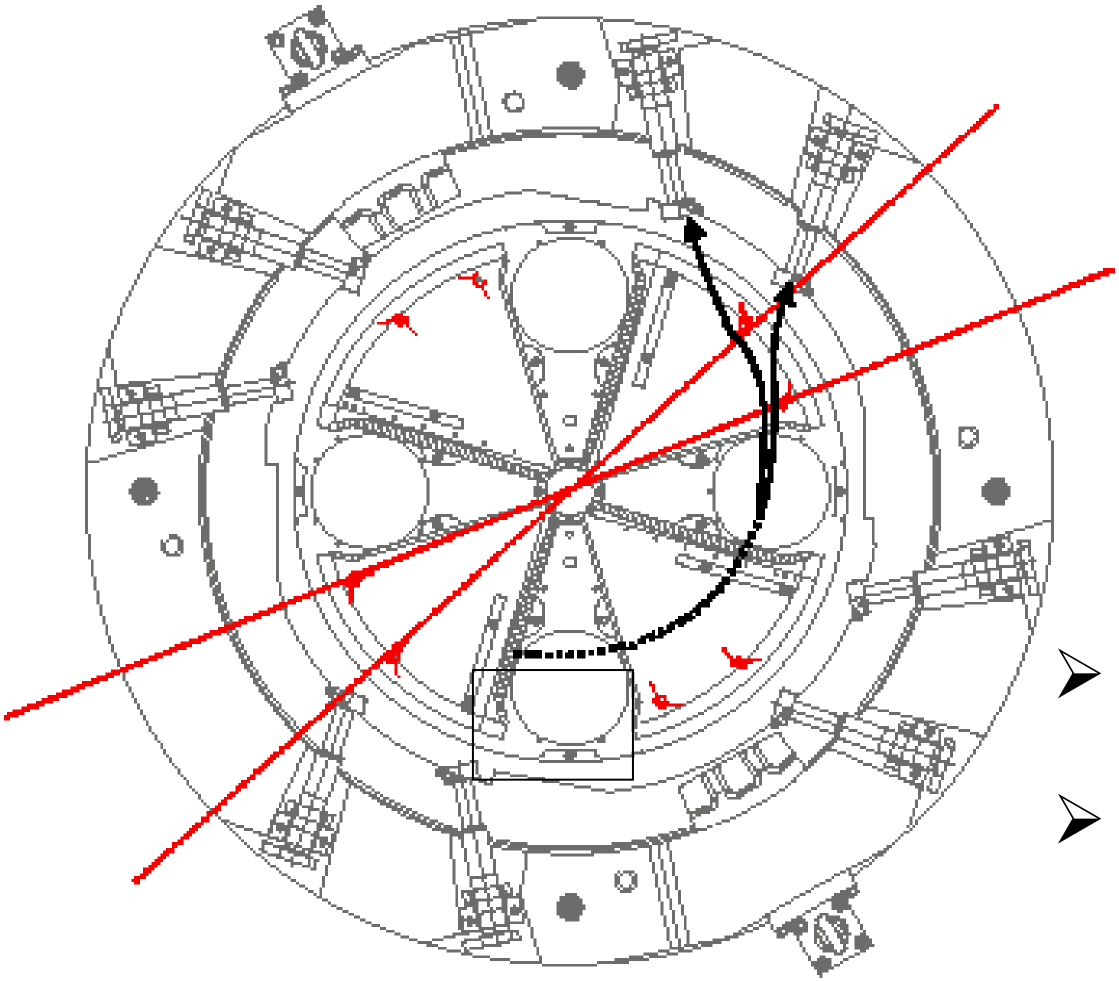
Place combination magnet at crossover



H$^-$ Extraction by stripping

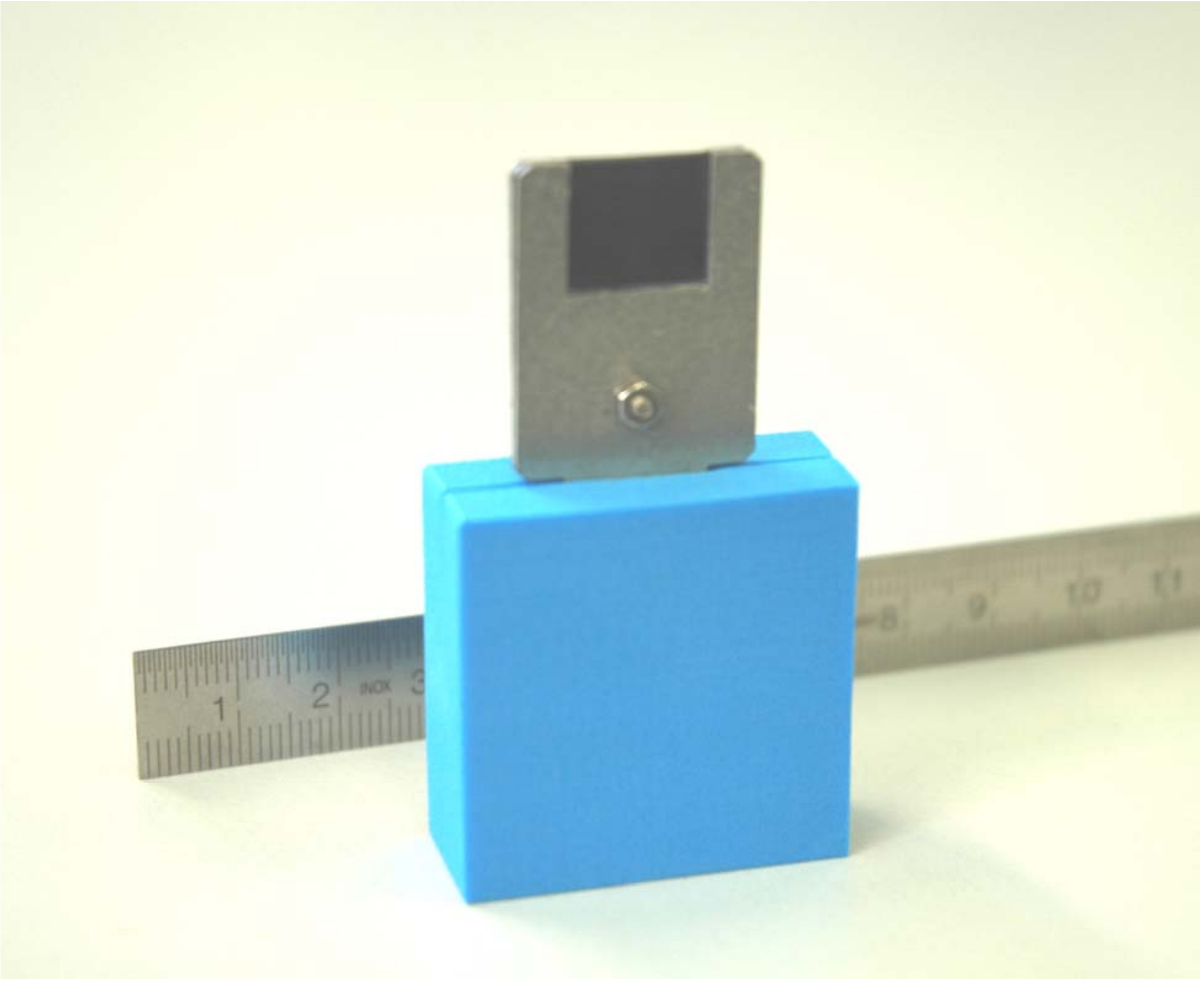
- ρ changes sign
- Good optics
- Targets in return yoke ⟹ shielding

Example: C18/9 H-minus Cyclotron



- Eight target stations
- Dual beam operation

Thin Carbon Stripper Foil



Stripping Extraction (2)

- Advantages
  - Very simple extraction device
  - 100 % extraction efficiency
  - Energy variable
  - Multiple targets around the machine
  - Dual beam
  - Good beam optics

- Limitations due to stripping losses
  - Low B-field $\Rightarrow$large magnet (Triumf 500 MeV/3 kG)
  - Good vacuum required (expensive)

Turn Separation (1)

Coherent beam oscillation in a cyclotron

$$r(\vartheta) = \overbrace{r_0(\vartheta)}^{\text{EO}} + \overbrace{\underbrace{x(\vartheta)}_{\text{amplitude}}\sin\left(\underbrace{\nu_r\vartheta + \vartheta_0}_{\text{phase}}\right)}^{\text{Betatron oscilation}}$$

Radial increase per turn

$$\Delta r(\vartheta_i) = \overbrace{\Delta r_0(\vartheta_i)}^{\text{acceleration}} + \overbrace{\Delta x \sin\left(2\pi n(\nu_r - 1) + \vartheta_0\right)}^{\text{resonance}}$$

$$\overbrace{+2\pi(\nu_r - 1)x\cos\left(2\pi n(\nu_r - 1) + \vartheta_0\right)}^{\text{precession}}$$

Turn Separation (2)

a. By acceleration $\Rightarrow$ high dee-voltage $\Rightarrow$ IBA C235

b. By resonances (coherent beam oscillations)

- Brute force
  - Beam is extracted during resonance built up
  - Change of oscillation amplitude between two turns
  - First harmonic dipole bump creates the resonance at ν_r~1
- Precessional extraction (more subtle)
  - Create oscillation amplitude with first harmonic dipole bump
  - Accelerate into fringe field where ν_r~0.7
  - Turn separation obtained from betatron phase advance
- Regenerative extraction (even more subtle)
  - Second harmonic gradient bump: 2 ν_r=2
  - ν_r is locked to one in the stopband
  - Exponential growth of betatron amplitude
  - Requires an initial coherent amplitude

Deflecting and Guiding the Beam Out

In four steps

1. Harmonic coils

   $\Rightarrow$ tickle the beam (create a turn separation)

2. Electrostatic deflectors

   $\Rightarrow$ Provide initial radial kick (peel off last turn)

3. Gradient corrector channels

   $\Rightarrow$ Reduce B-field and minimize optical damage when passing the fringe field

4. First quadrupole doublet

   $\Rightarrow$ as close as possible to handle beam divergencies

   $\Rightarrow$ (in return yoke)

Harmonic Extraction Coil

Not so easy as it seems due to loss of resonance when beam is passing through the bump region

Vertical gap limitation

Heat limitation

- goal: create coherent oscillation
- radial position at ν_r=1 (no phase advance)
- All kicks (turn after turn) in same direction
- Minimize radial extension ($\Delta\nu_r$~0)
- Shaped like equilibrium orbit

Electrostatic Deflector

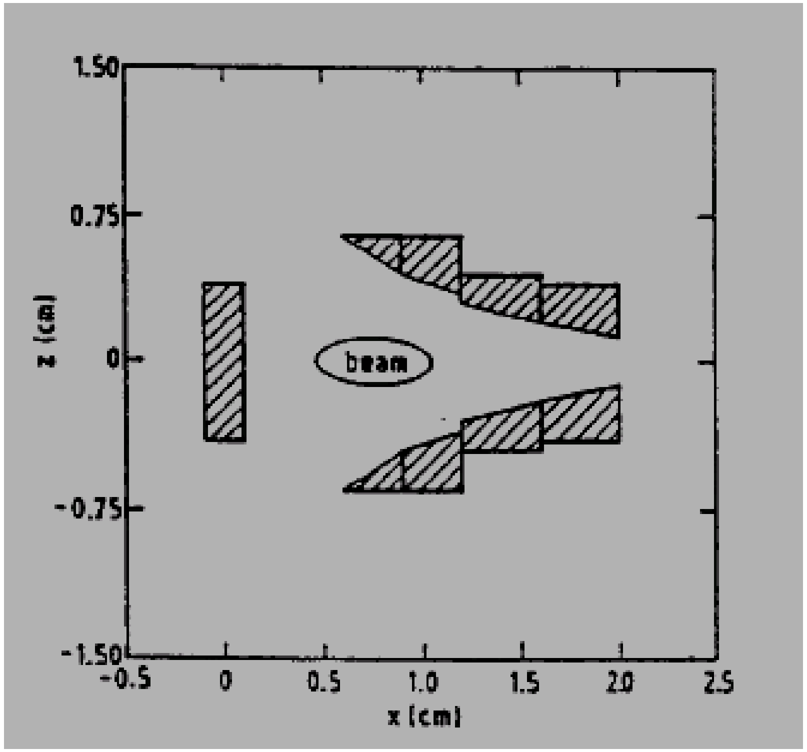
- DC radial E-field creates initial angular kick to deflect beam
- Inner electrode (septum) on ground potential
  - No disturbance on inner orbits
  - Knife thin (0.1 mm) and
  - V-shape at entrance (distribute heat)
  - Water cooled $\Rightarrow$ limitation for maximum beam intensity
- Outer electrode on negative potential
- Electrode shape = orbit shape

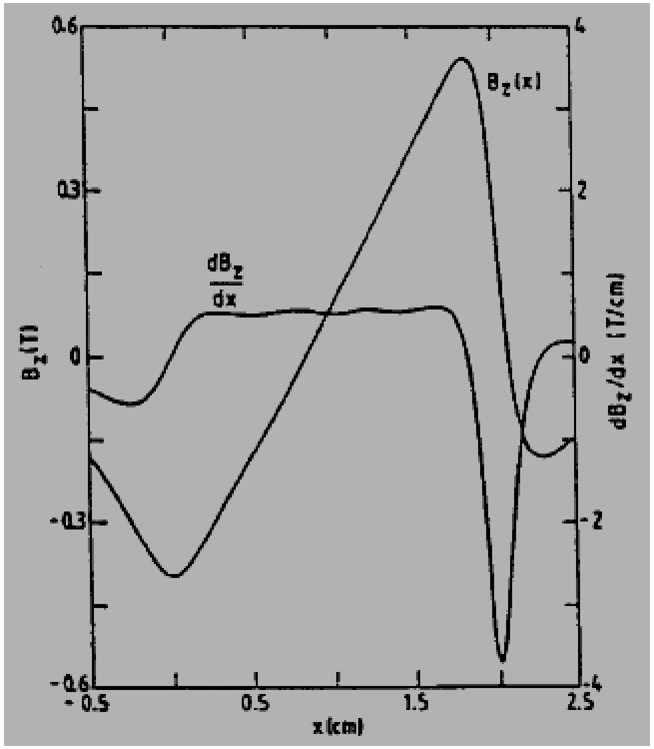
Deflector For IBA C235

Gradient Corrector Focusing Channel

- Goal:
  - Lower magnetic field on extraction path
  - reduce vertical/increase radial focusing through fringe field
- Different types
  - Passive: soft iron magnetized by the main field
  - Active:
    - Using current conductors
    - Using permanent magnets
- Designed in such a way as to minimize adverse effects on internal orbits

Passive Corrector in ILEC TUE





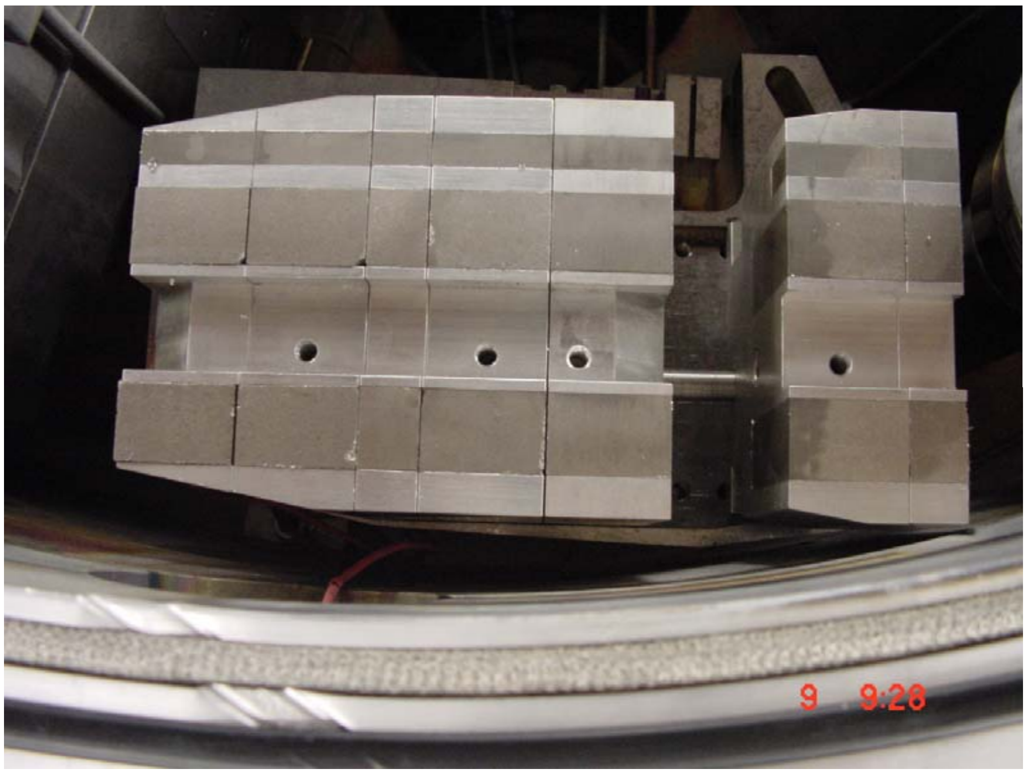
Vertical cross section

Profiled iron bars

Constant gradient in

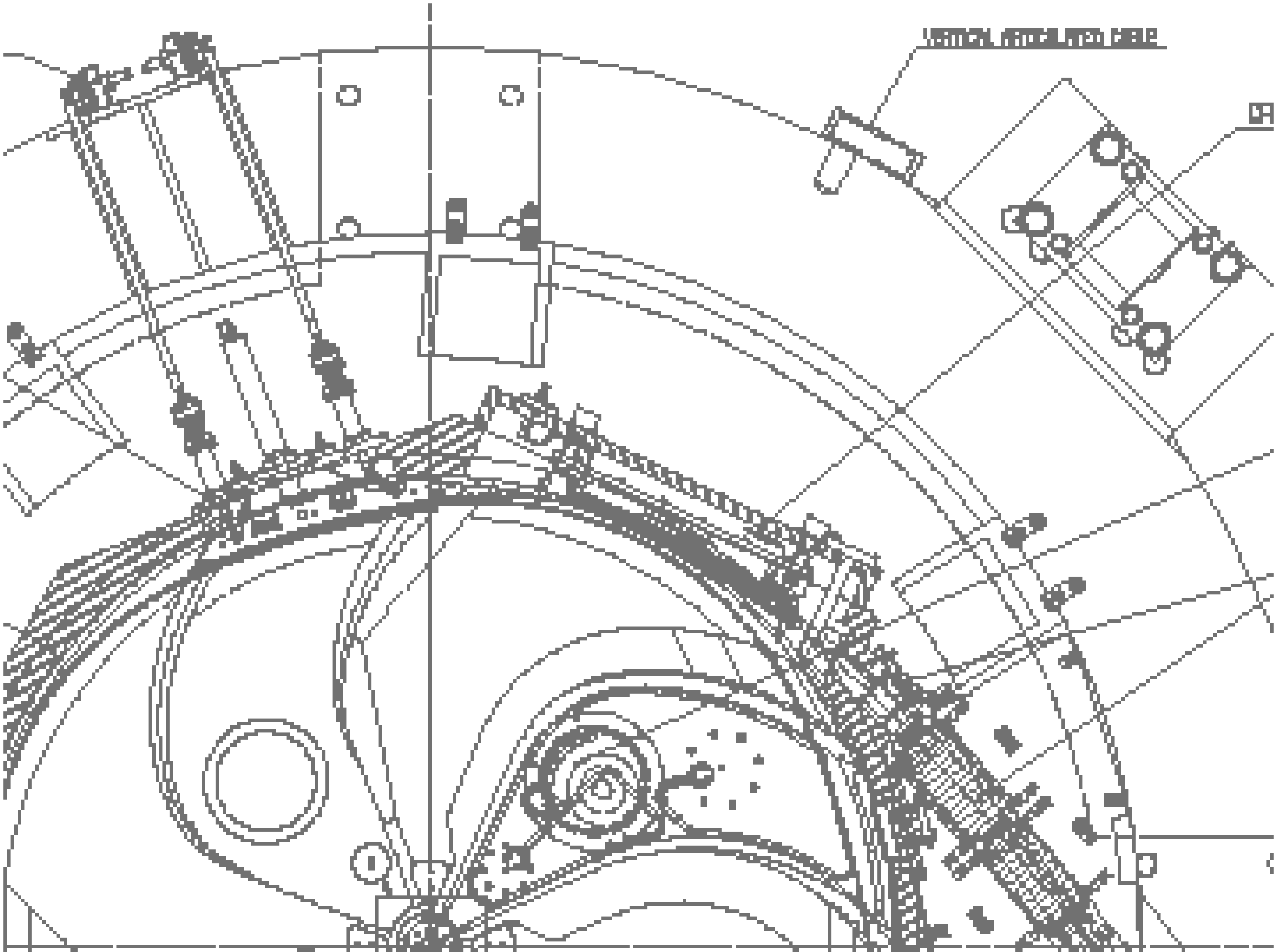
the channel

Gradient Corrector For Self Extracting Cyclotron

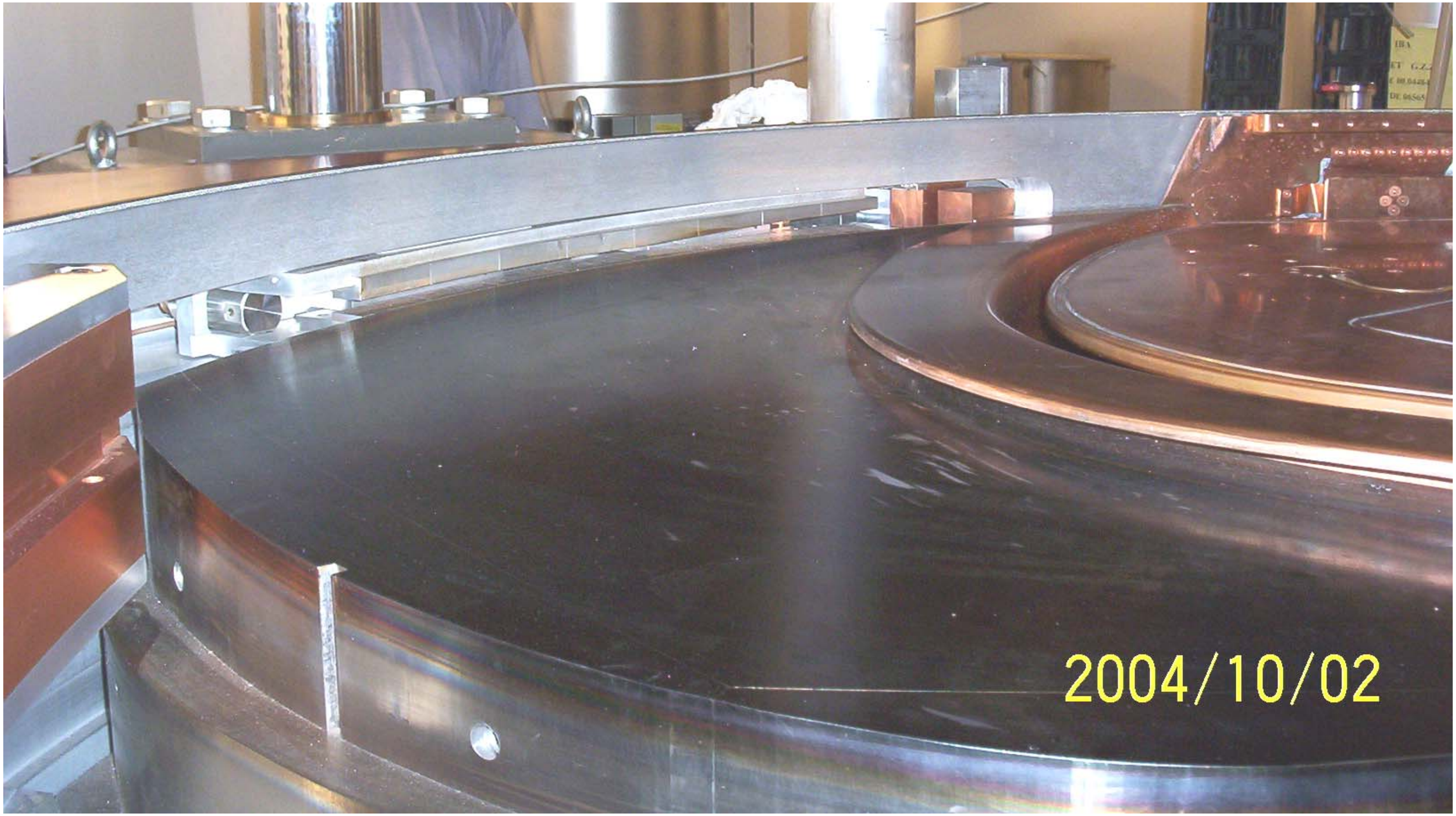


- Doublet
- SmCo permanent magnets
- Small correction magnets to reduce inner orbit perturbations

C235 Extraction Scheme



C235 Gradient Corrector



C235 Permanent Magnet Doublet

Self-extraction: Principle

At the pole radius $\langle B(r) \rangle$ starts to drop.

This limits the maximum energy of the cyclotron.

There are 2 limits:

1. Stability: highest EO with $\nu_r > 0$ (field index = -1)
2. Acceleration (loss of isochronism): $\Phi_{RF}=90°$ (depends on V_{dee})

Large pole gap: limit 2 before limit 1

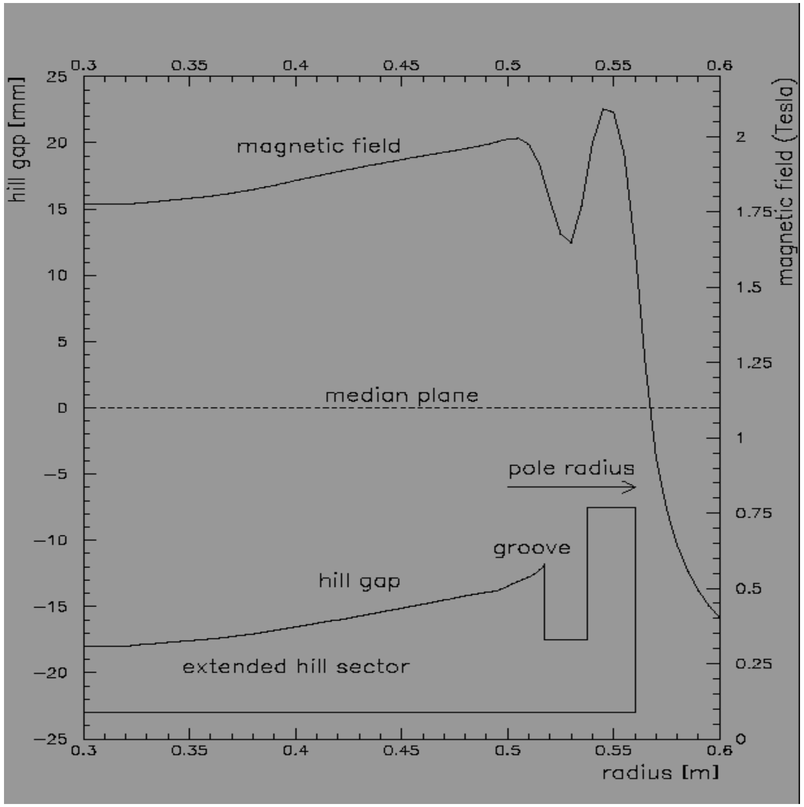
Small (elliptical) pole gap: limit 1 before limit 2 $\Rightarrow$ self-extraction

Problem: beam comes out in all directions

Self-extraction: Realization

Small elliptical hill gap ⇒ allows for sharp radial gradients

'magnetic septum' ⇒ groove machined in the pole



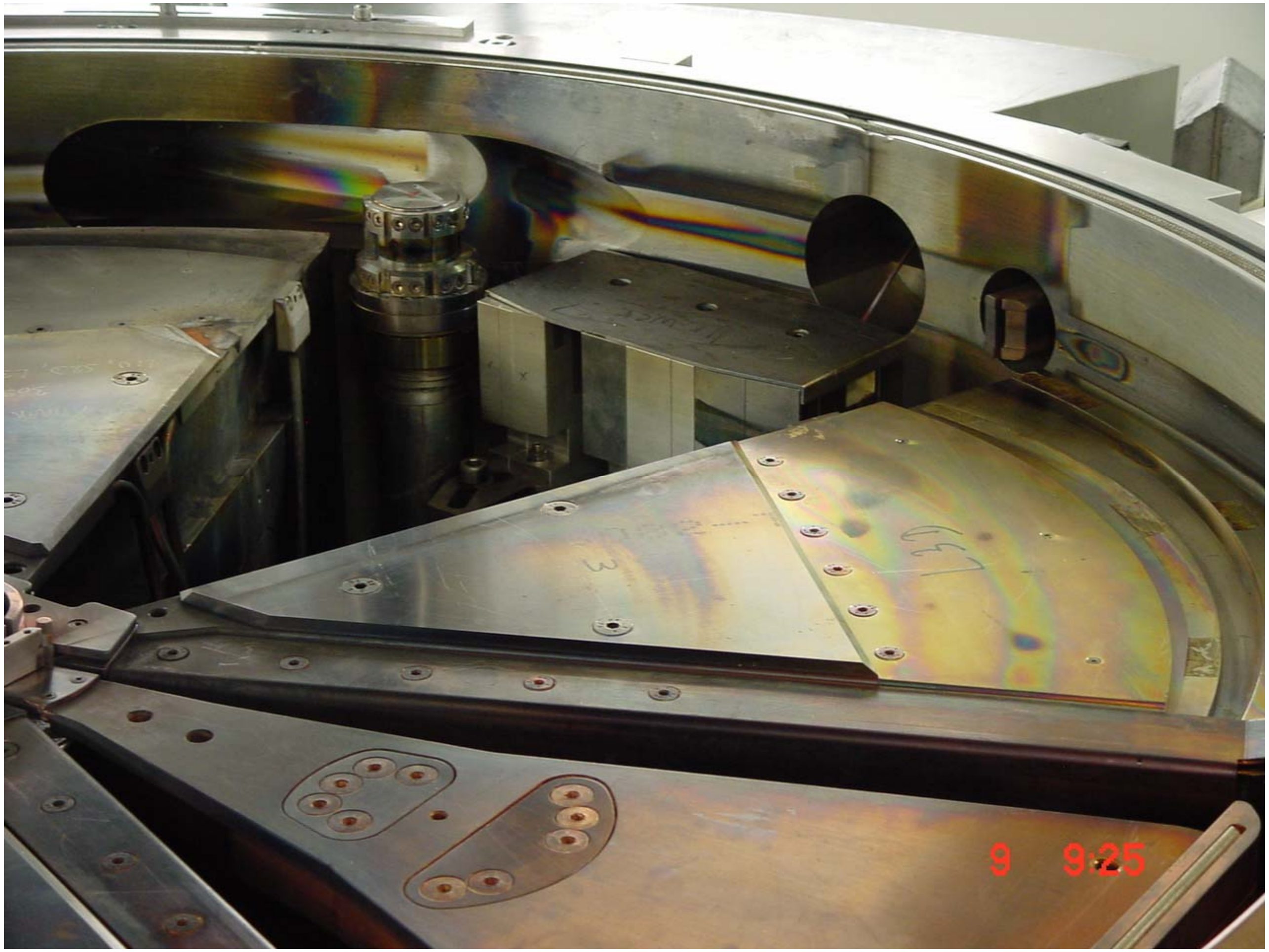
Pole with goove

Self-extraction Scheme

Comparable to the usual resonant precessional extraction

- Harmonic coils create coherent oscillation
- Accelerate into fringe field where ν_r~0.6
- Groove creates a kind of magnetic septum action
- Gradient corrector: permanent magnet doublet in valley
- Part of the beam which is not well extracted is intercepted on a high power beam catcher

IBA 14 MeV SE Cyclotron



2 mA extracted

η= 80 %

ε =300 π mm-mrad

Thank You