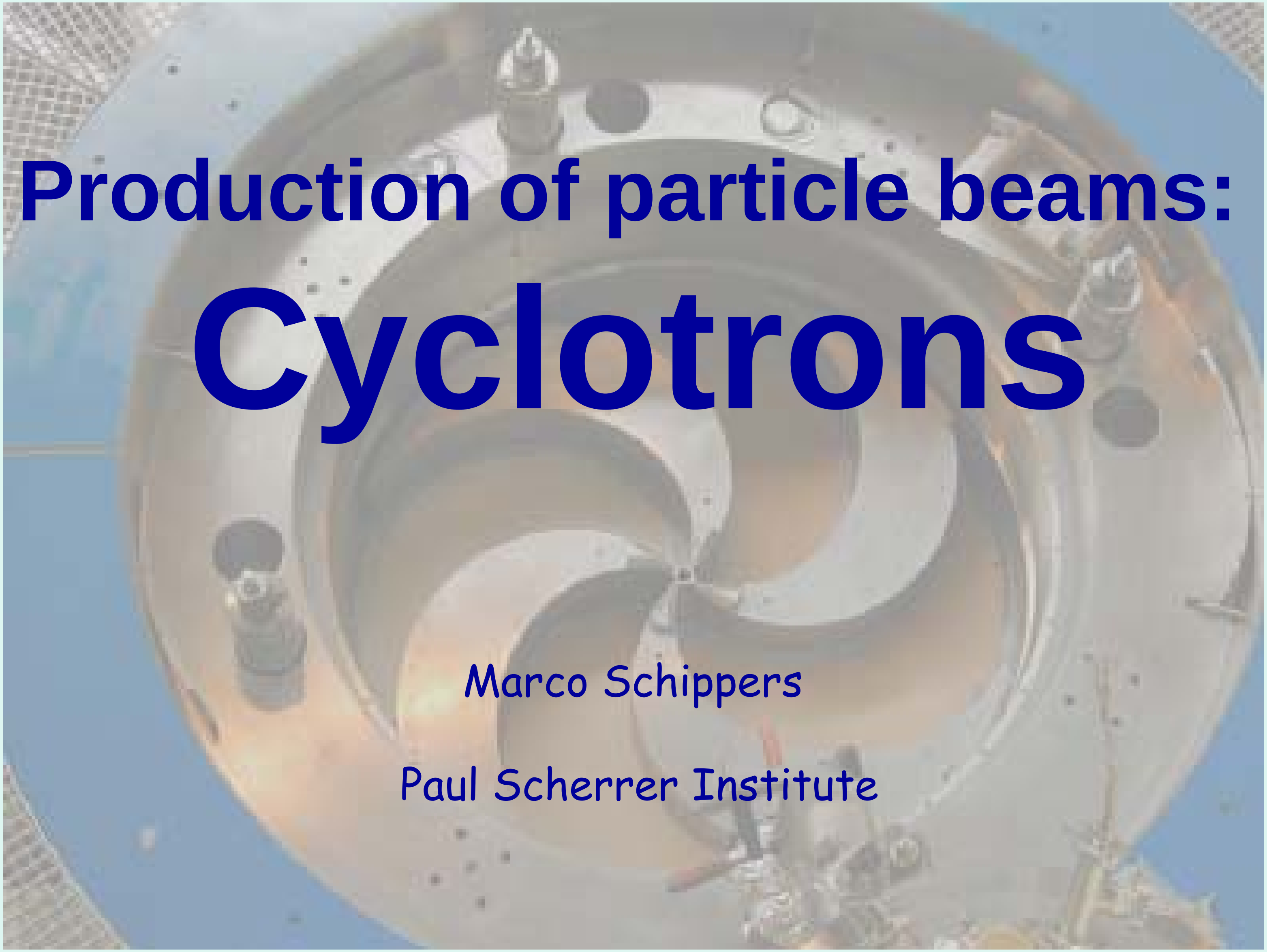
Particle Therapy Co-Operative Group



Production of particle beams:

Cyclotrons

Marco Schippers

Paul Scherrer Institute

Production of particle beams: cyclotrons

- **Dose delivery techniques**
- **How does a cyclotron work:**
  - **Magnet**
  - **Ion source**
  - **RF**
  - **Extraction**
- **Very small cyclotrons**
- **Cyclotrons for carbon-ions**

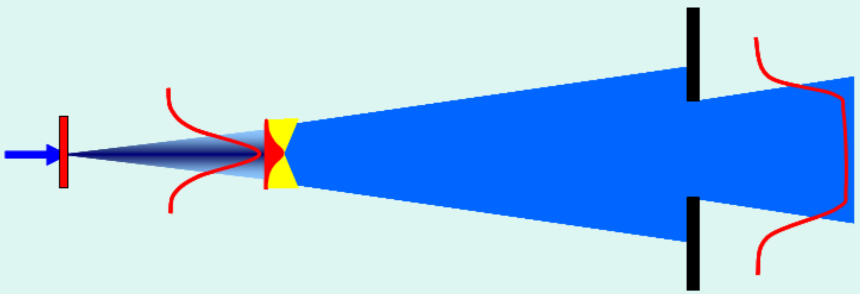
Dose delivery techniques

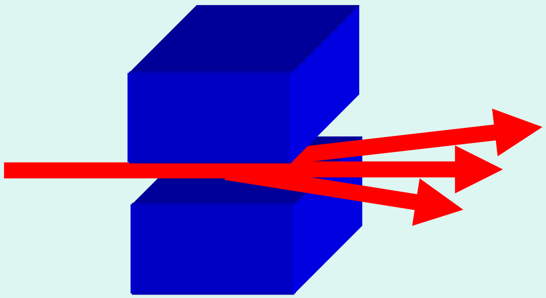
Dose delivery techniques: **Width**

transversal spread:

scattering
(protons only)

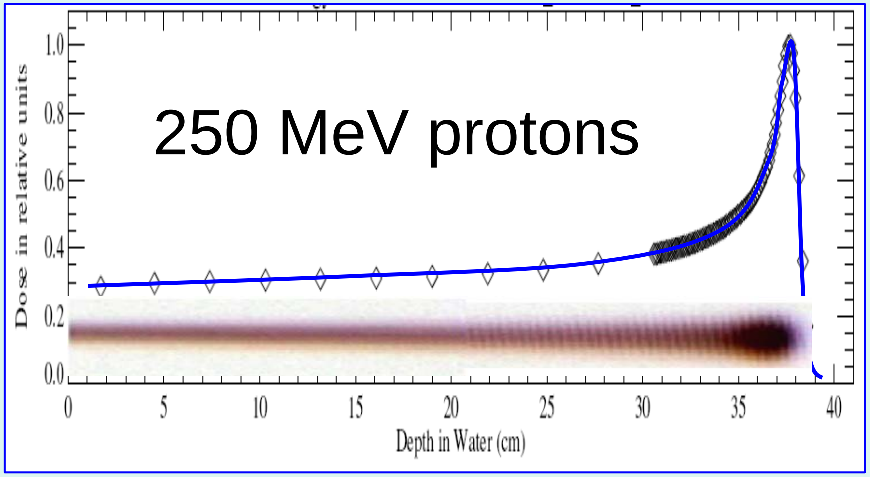
scanning
(all hadrons)

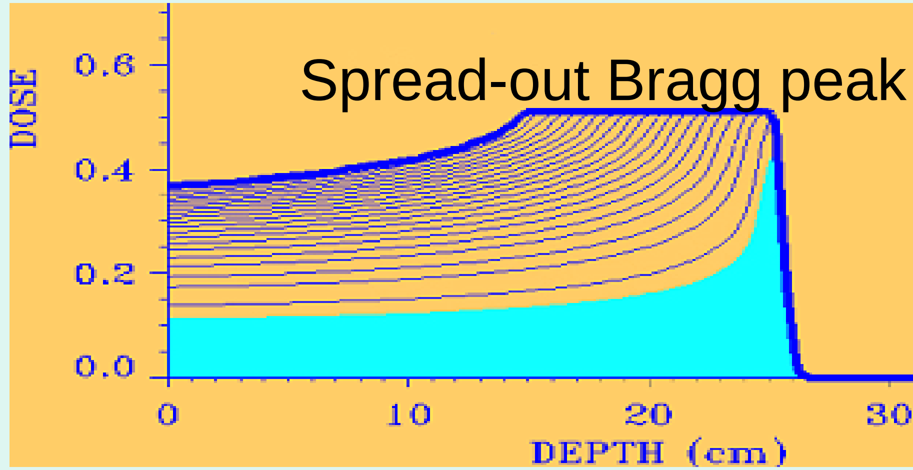




Scatter system   Collimator   Scanning magnet

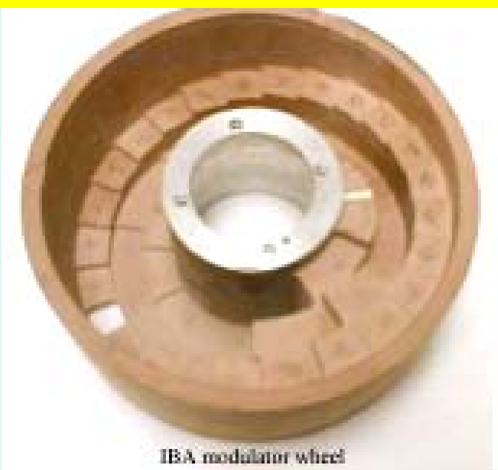
Dose delivery techniques: **Depth**

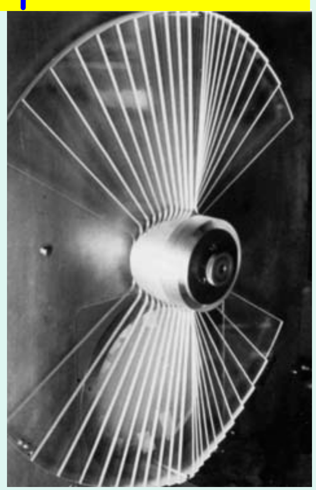




Cyclotron has fixed energy => slow down (degrade) to desired energy

Just before the patient





Entrance of beam line

fast degrader (PSI)

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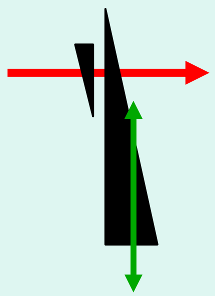
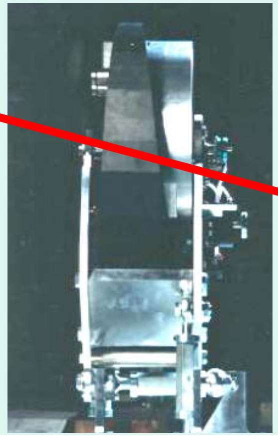
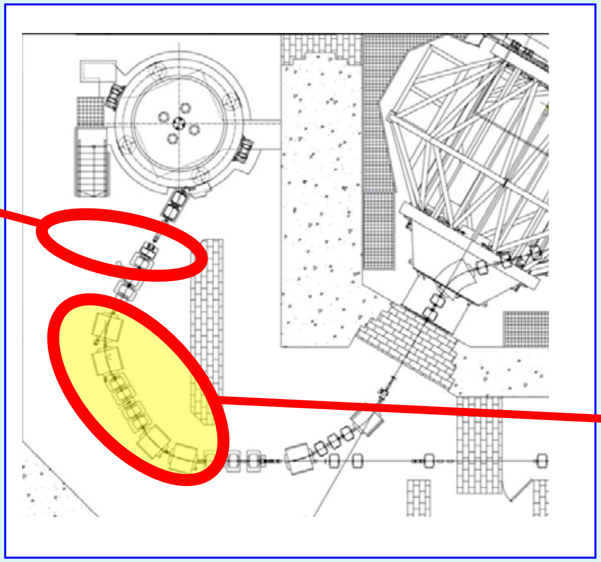
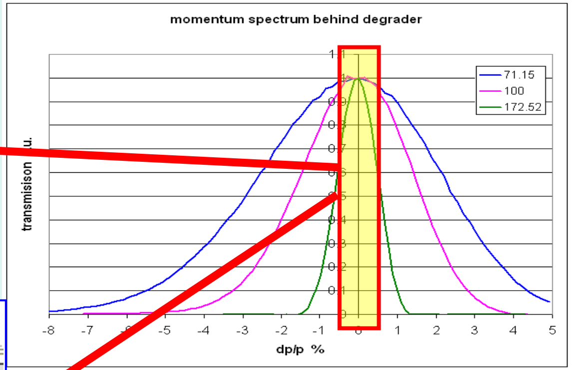
Energy selection system



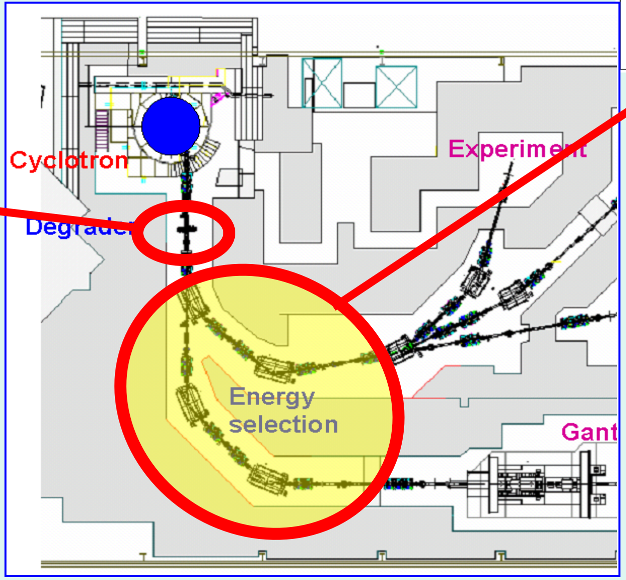


Rolled-up wedge degrader
220-70 MeV **(IBA)**





Multiple wedge degrader
238-70 MeV (PSI)
5 mm ΔRange in 50 ms



Beam analysis:
energy selection
dp/p < ± 1%

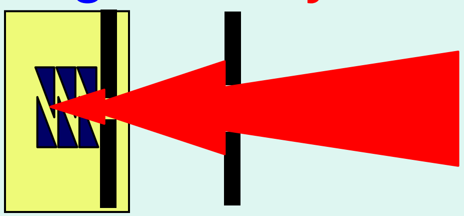
Intensity loss by degrader and collimator

Degrader purpose: **decrease** energy

however: - **energy spread** increases

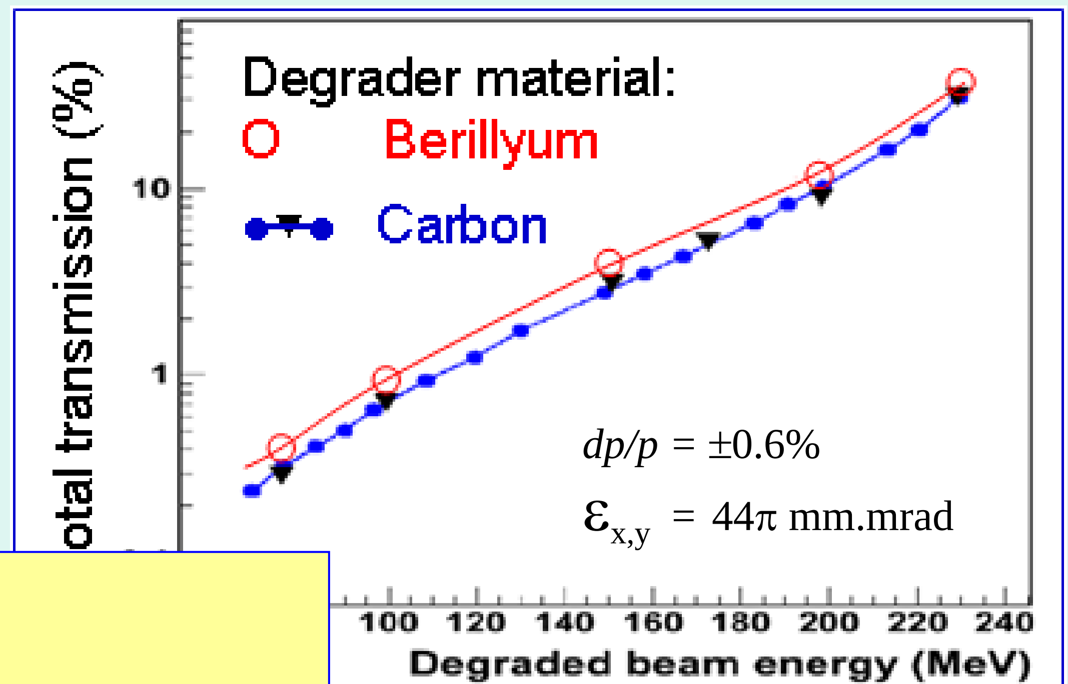
- **beam loss** due to nuclear reactions in degrader
- **beam size** increases due to multiple scattering

degrader system



Collimators define

transmitted beam size



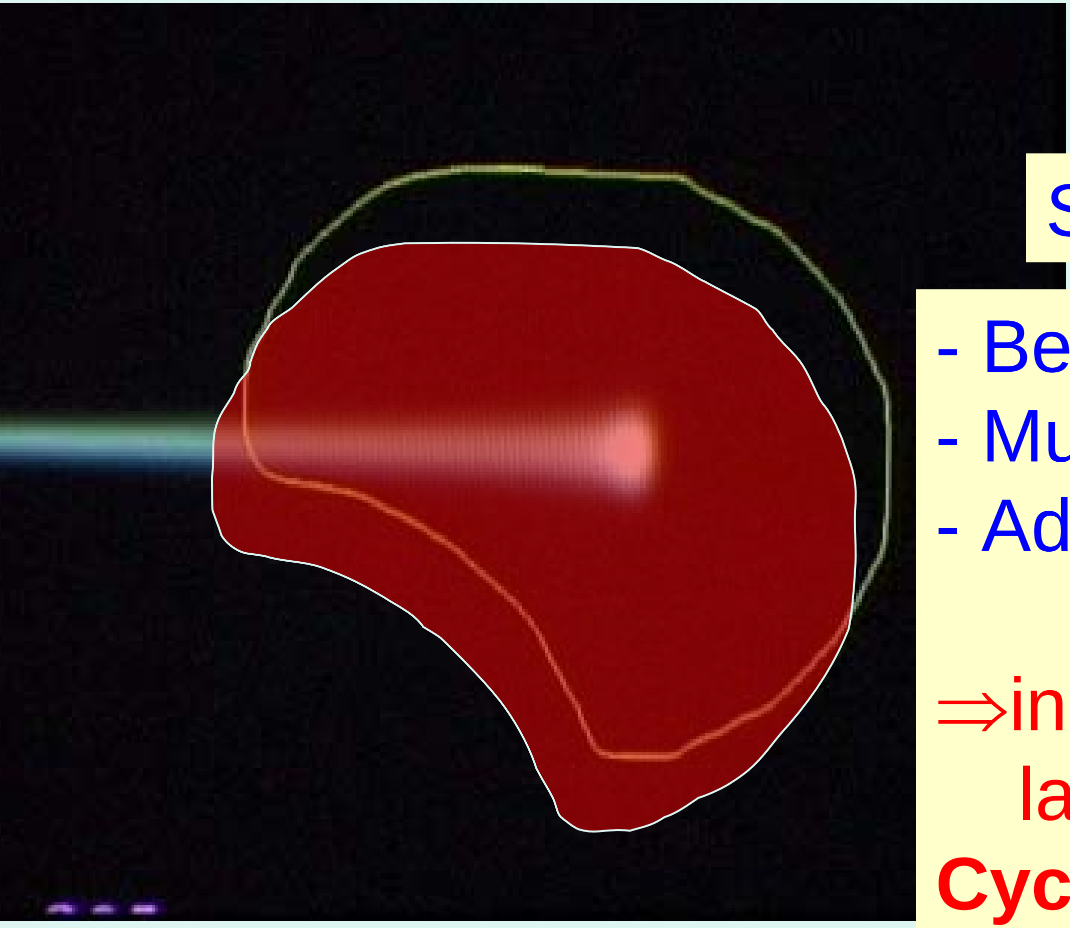
➔Beam intensity from

the cyclotron must be high enough

Van Goethem et al., Phys. Med. Biol. 54 (2009)5831

The problem in dynamical treatments:

Organ movement



➔Danger to underdose and overdose

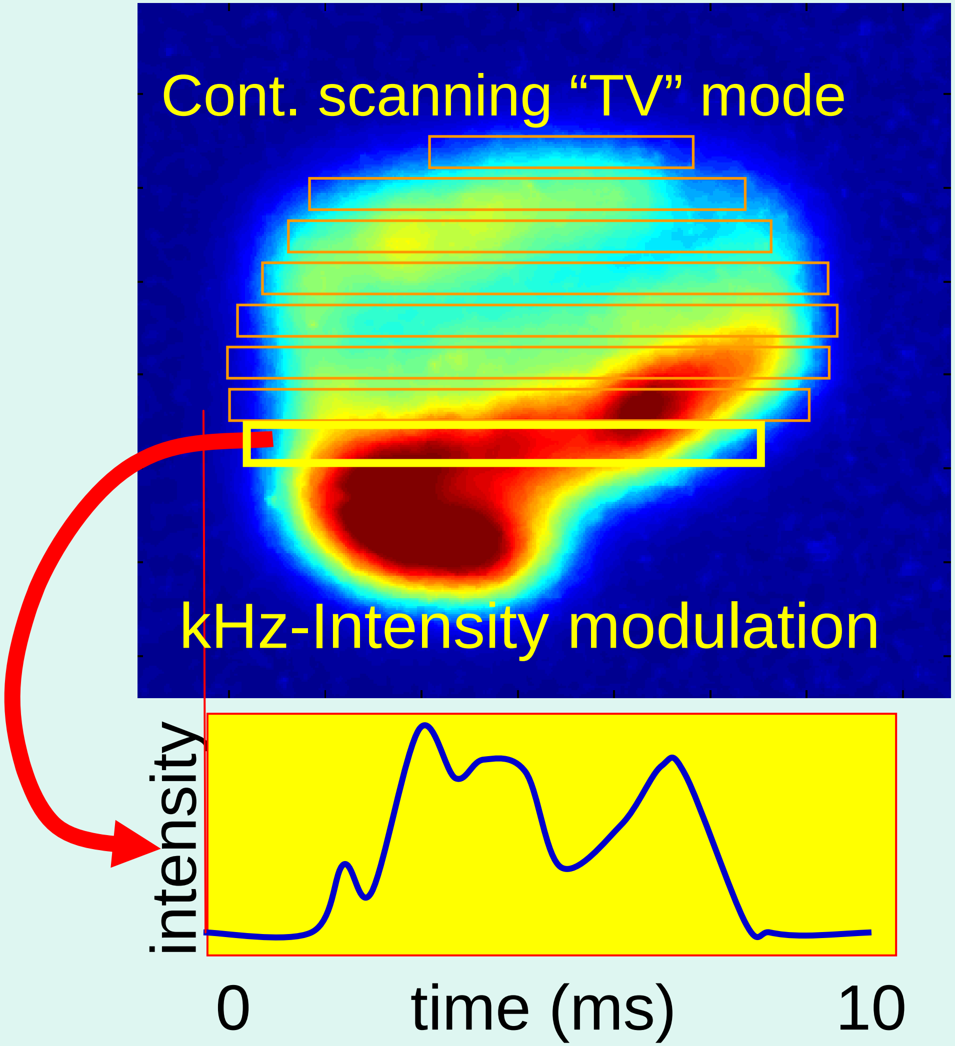
Solutions:

- Beam gating
- Multiple scans of tumor
- Adaptive scanning

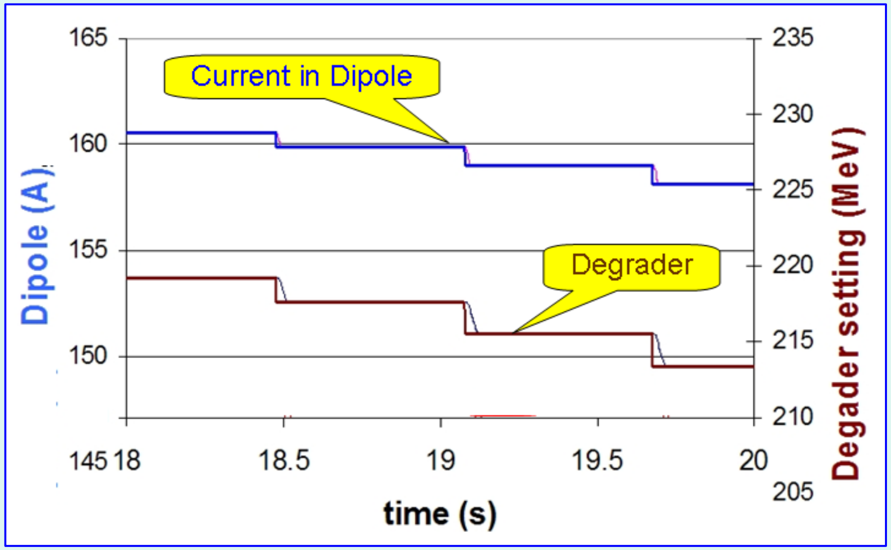
⇒increase scan speed laterally + in depth

Cyclotron optimal for this

Fast pencil beam scanning



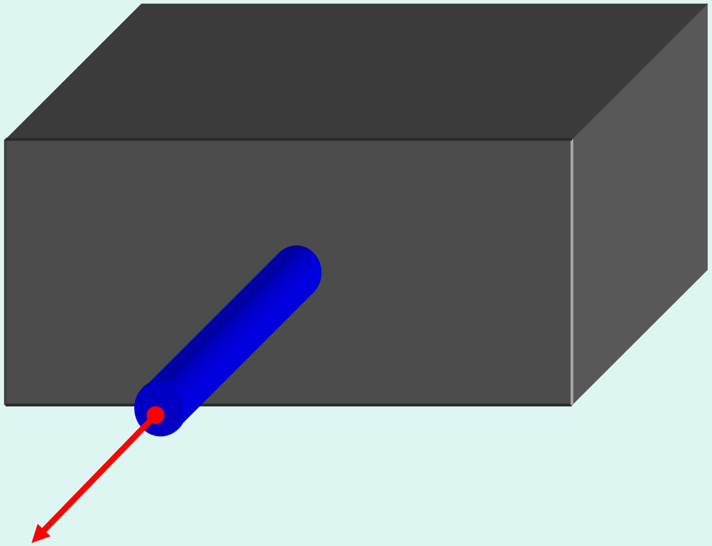
After each layer:
Energy change in 80 ms



7 s for a 1 liter volume.
Target repainting:
15-30 scans / 2 min.

How does a cyclotron work ?

Cyclotron as seen by a medical physicist

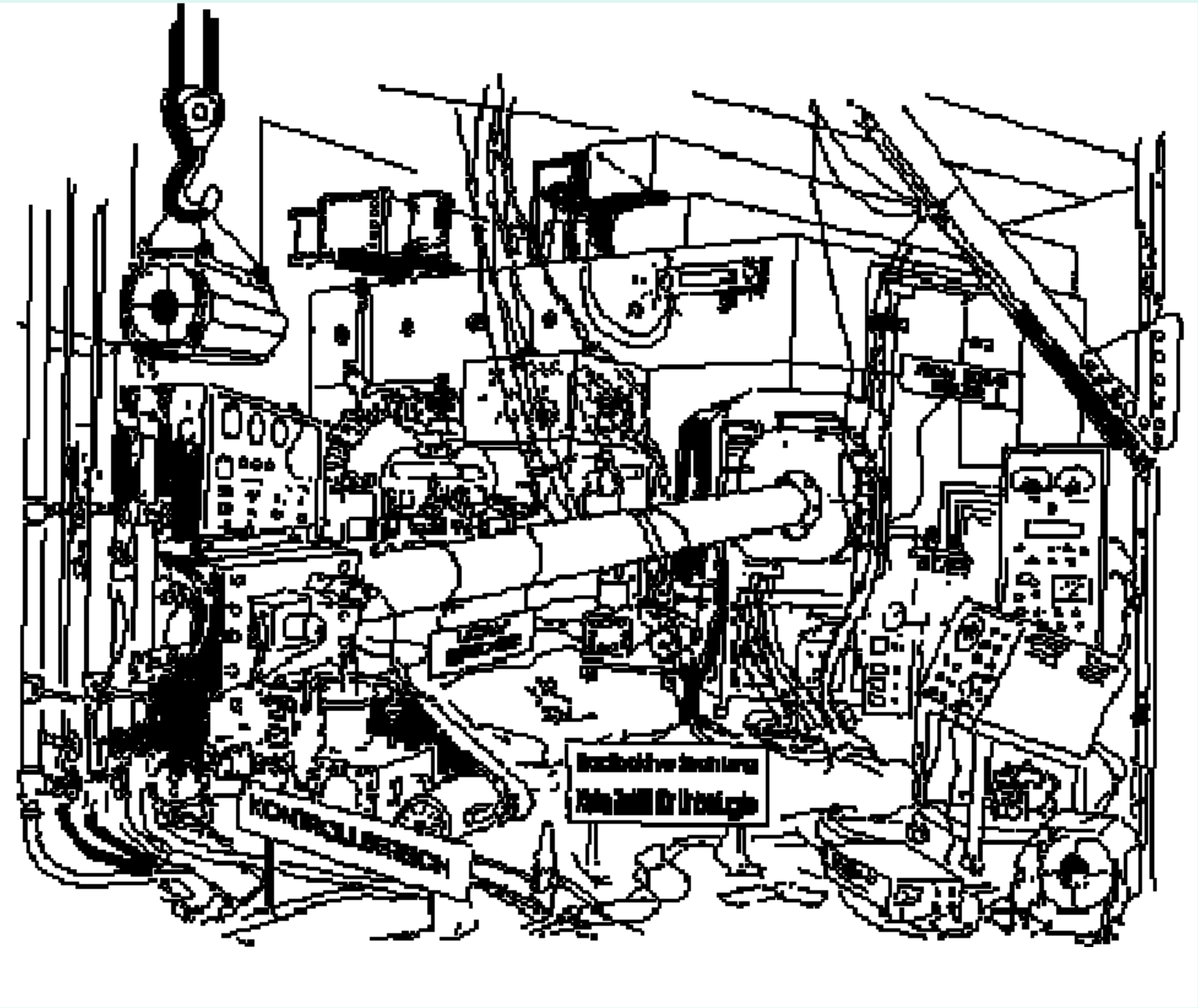


$E = 250 \pm 0.1$ MeV

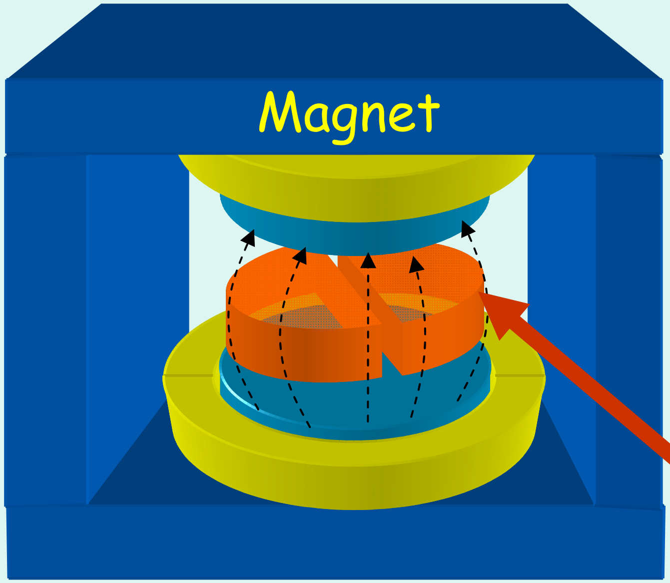
$I = 100\text{-}1000$ nA

$\varepsilon = 2$ mm x 2 mrad

Cyclotron as seen by a medical doctor

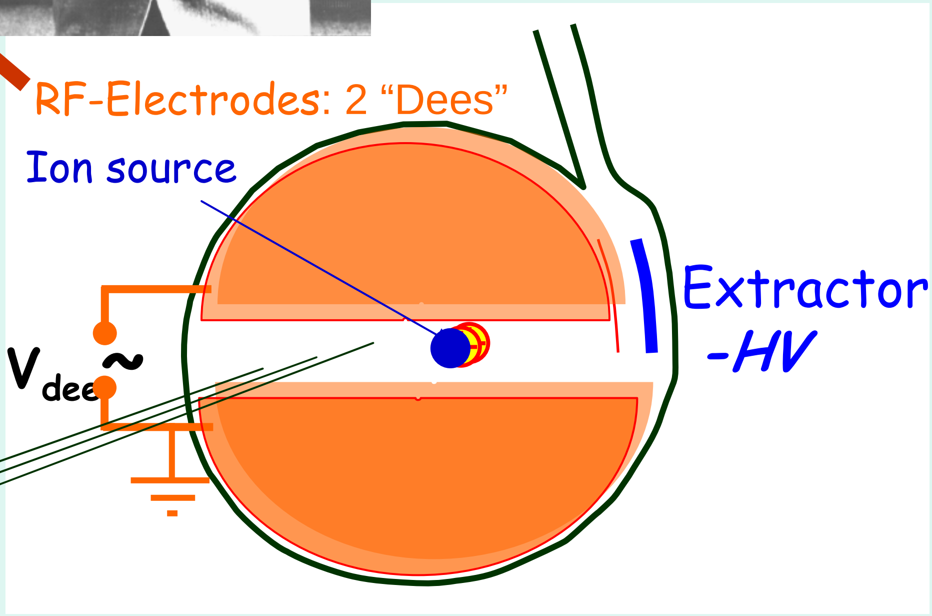


Cyclotron (1930)



Ernest Lawrence

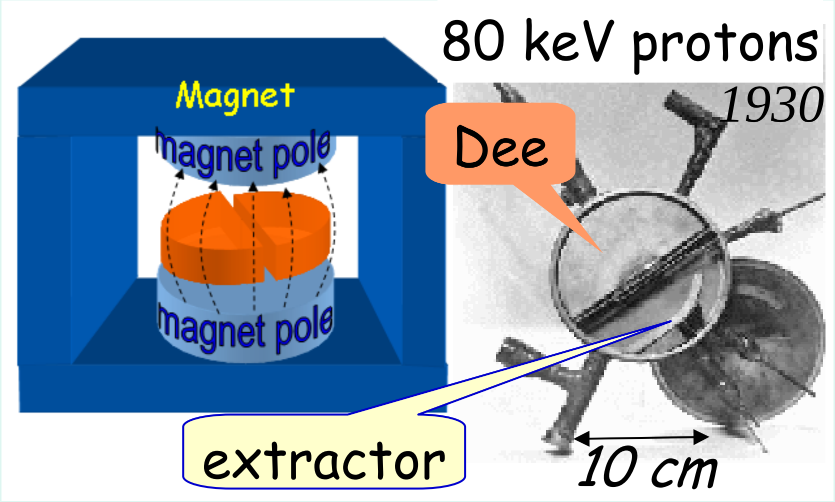
(1901-1958)

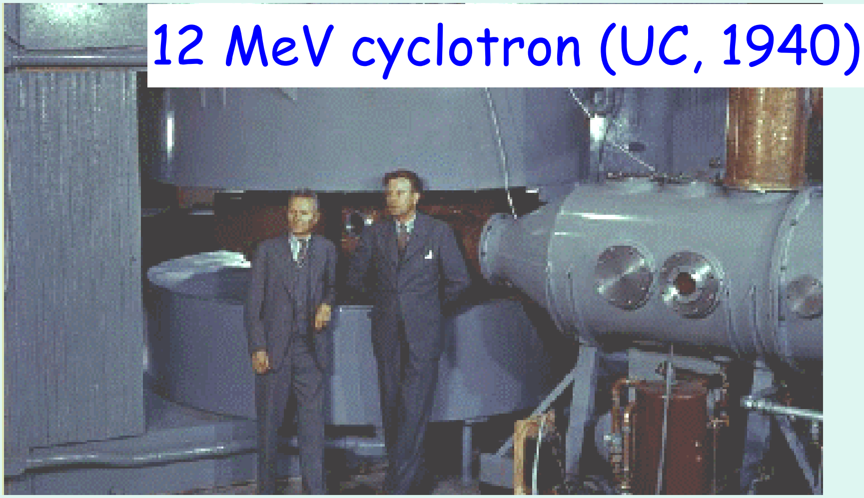


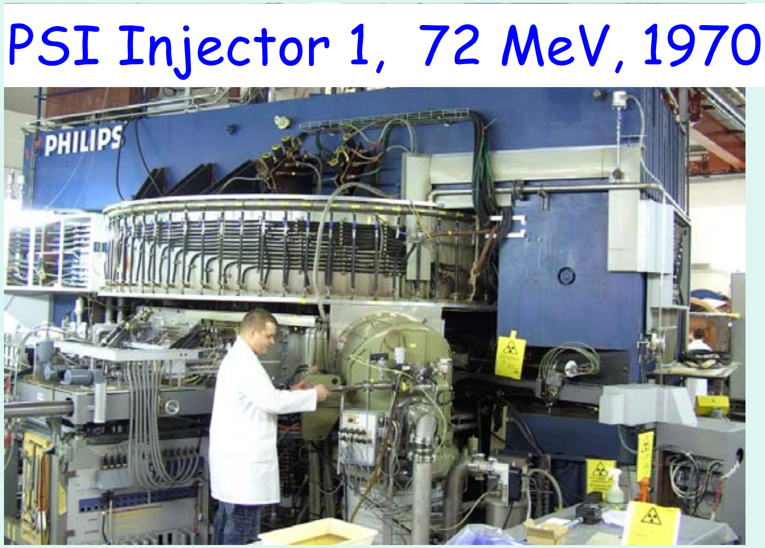
At each electrode border:

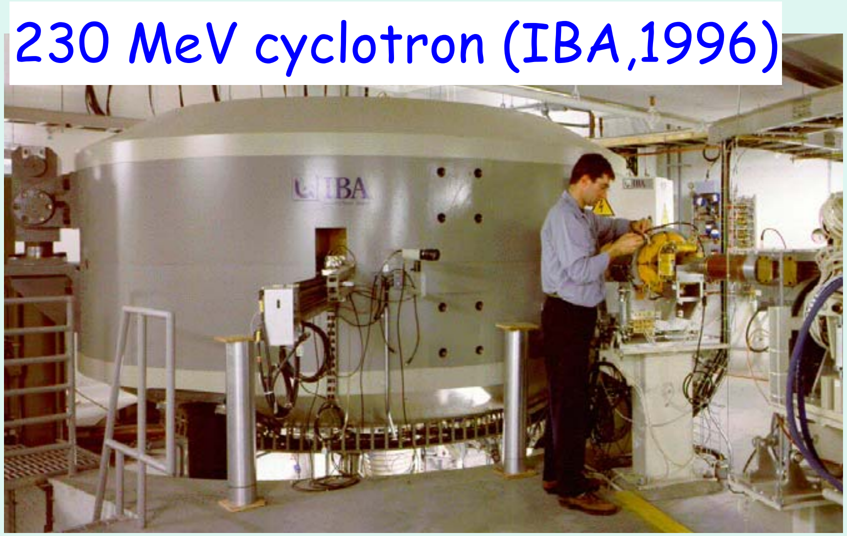
Energy gain $\Delta E = V_{dee}$

Cyclotron


80 keV protons
1930
Magnet
magnet pole
magnet pole
Dee
extractor
10 cm


12 MeV cyclotron (UC, 1940)


PSI Injector 1, 72 MeV, 1970
PHILIPS


230 MeV cyclotron (IBA,1996)
IBA

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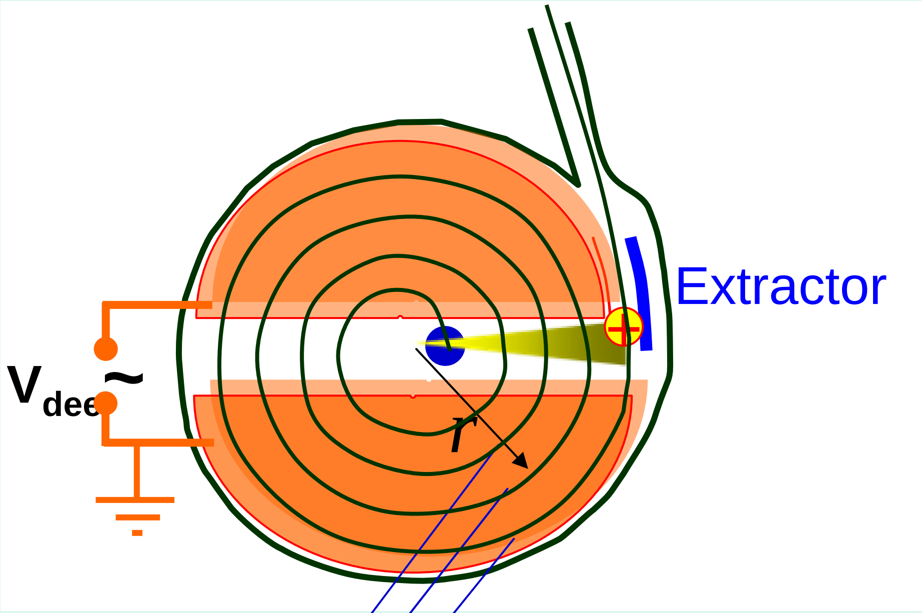
Cyclotron



Circular orbits:

Centripetal force = Magnetic force $$\frac{mv^2}{r} = Bqv$$

=> $$T_{circle} = \frac{2\pi.m}{Bq}$$

=> T_{circle} independent of orbit radius r

m = mass

v = speed

r = orbit radius

B = magnetic field

q = charge

Relativity in high-E cyclotrons

Circular orbits:

$$T_{circle} = \frac{2\pi . m}{q.B}$$

=> T_{circle} independent from radius r

m = mass

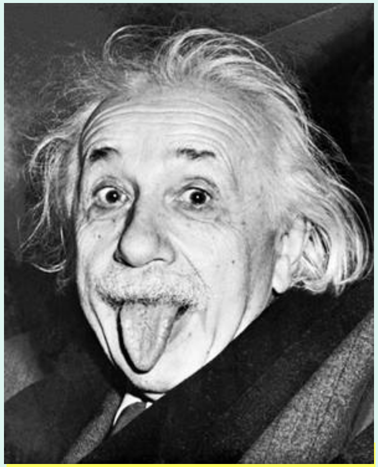
B = magnetic field

q = charge

v = velocity

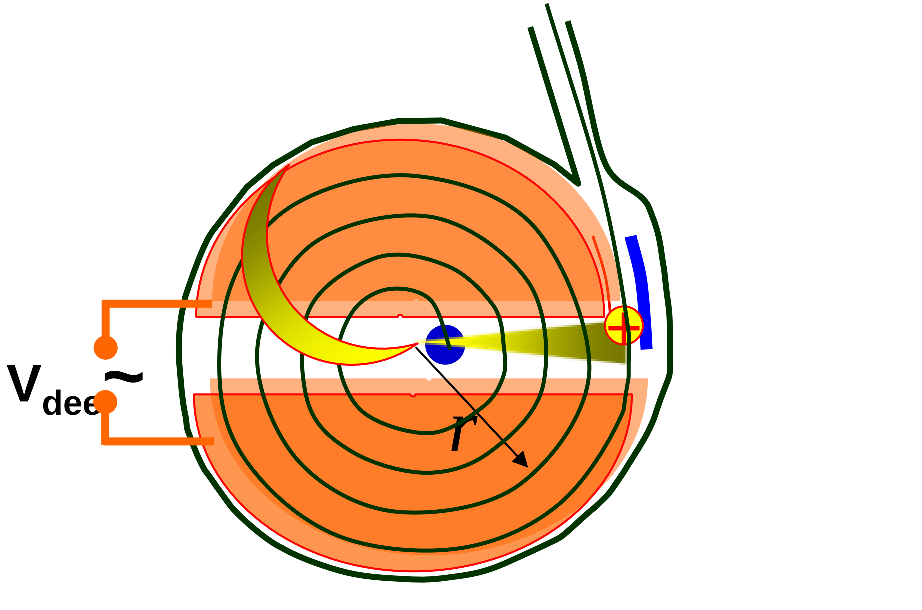
c = speed of light

However



when $v \rightarrow c$:

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$



250 MeV p: $v/c = 0.61 \Rightarrow m = 1.27 m_0$

$\Rightarrow T_{circle}$ increases with radius

$\Rightarrow$ particles lose pace with frequency of Vdee (RF).

Relativity in high-E cyclotrons

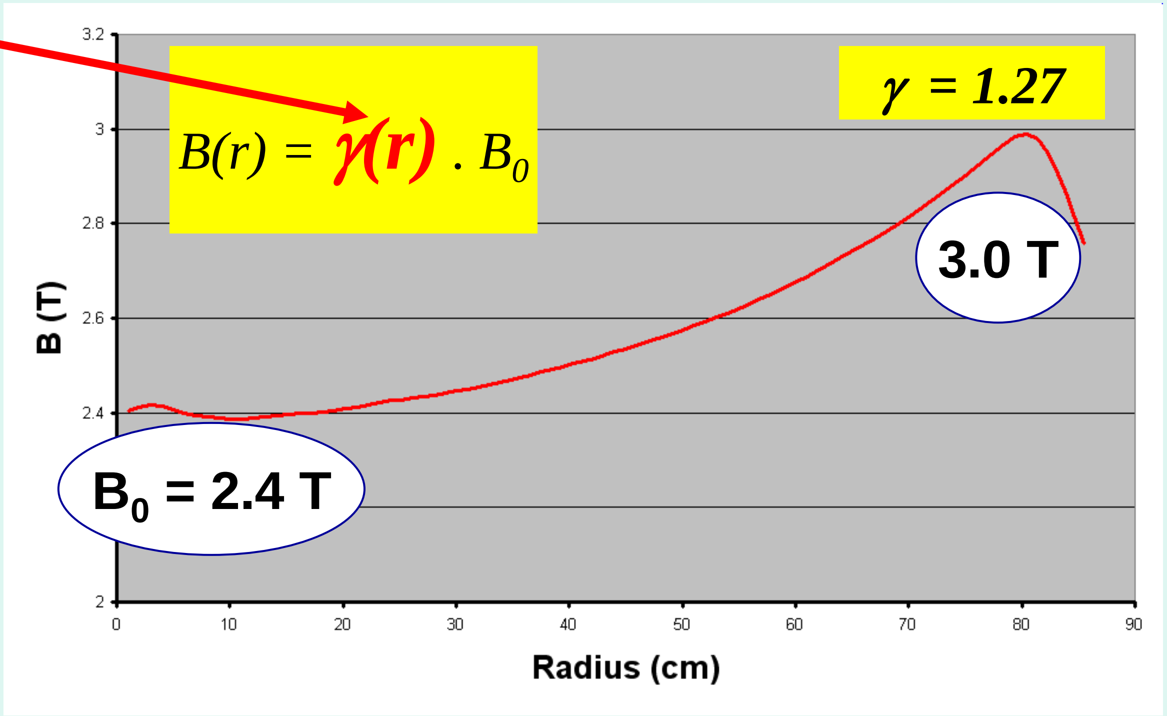
$$T_{circle} = \frac{2\pi . m}{q . B}$$

$$m = \frac{1}{\sqrt{1 - v^2/c^2}} . m_0$$

$\gamma(r)$

Remedies when T_{circle} increases with radius:

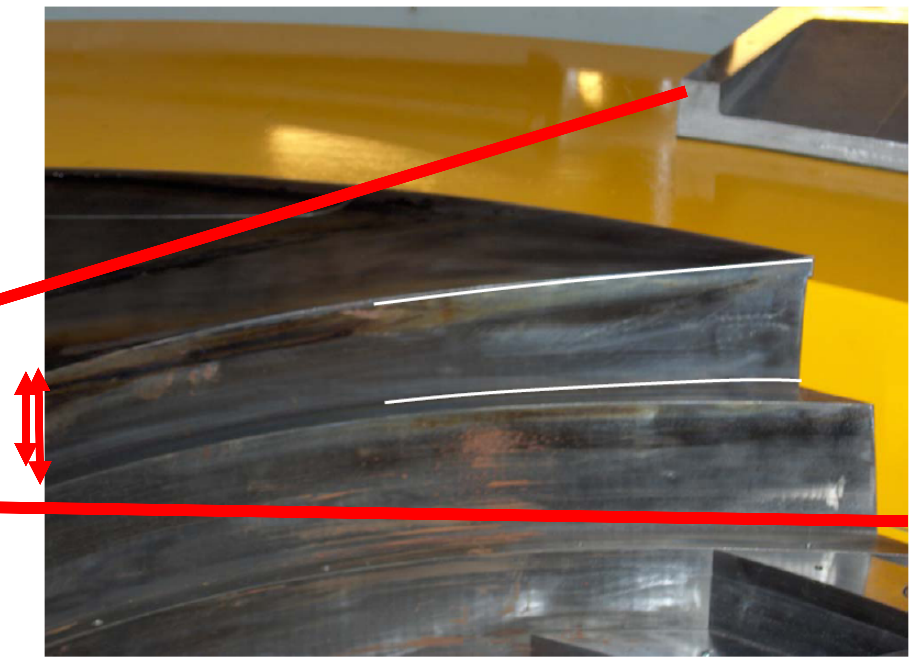
1) decrease f_{RF} with radius.
   (*synchro-cyclotron;* pulsed)
2) **increase B with radius**



How to increase field with radius

1) Decrease pole gap at large Radius (IBA)

Elliptical gap between poles C235

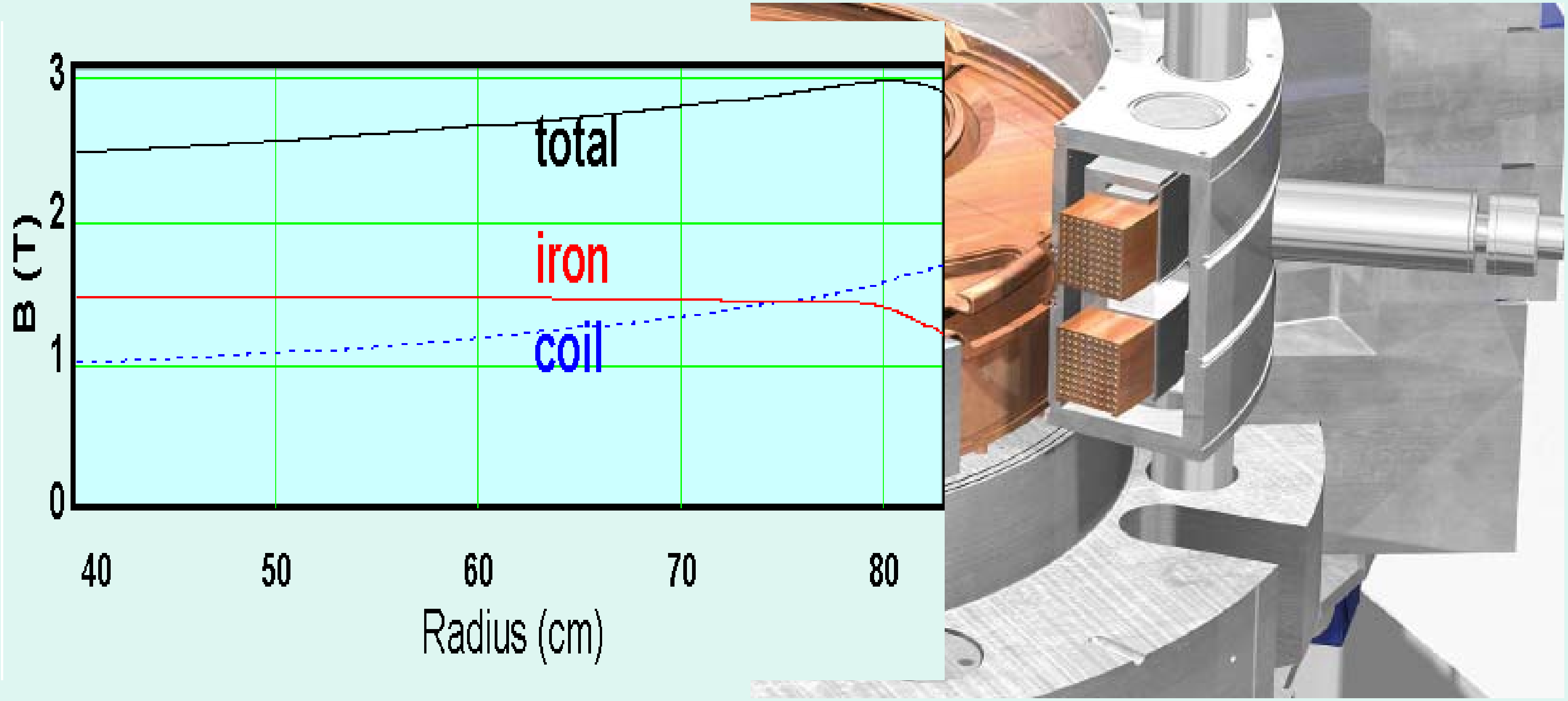


How to increase field with radius

2) Use SC coils to employ very strong electric current

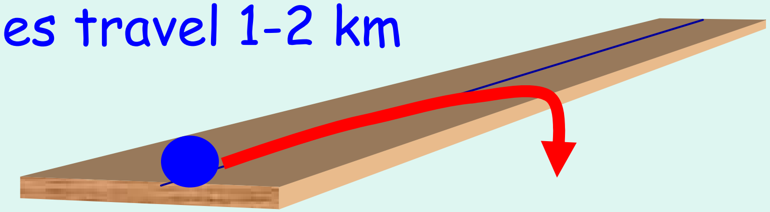
→ very strong magnetic field

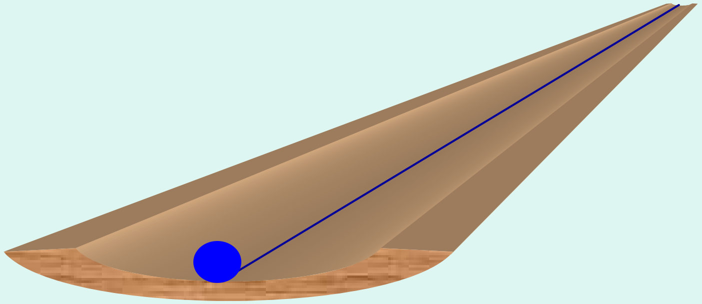
→ coil field adds to shape of magnetic field (ACCEL / Varian)

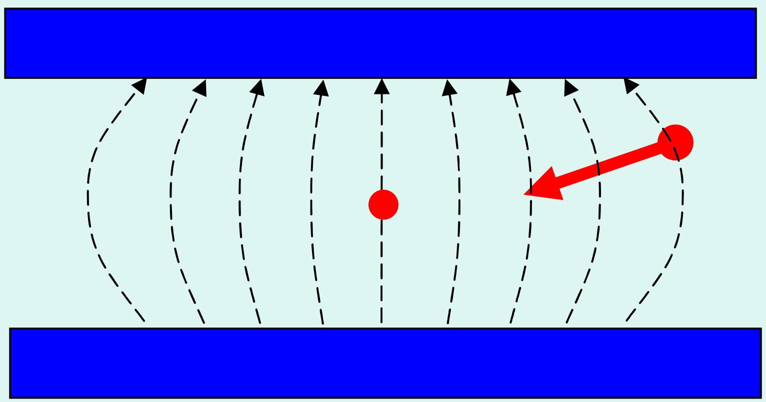


Vertical focussing is important

Particles travel 1-2 km

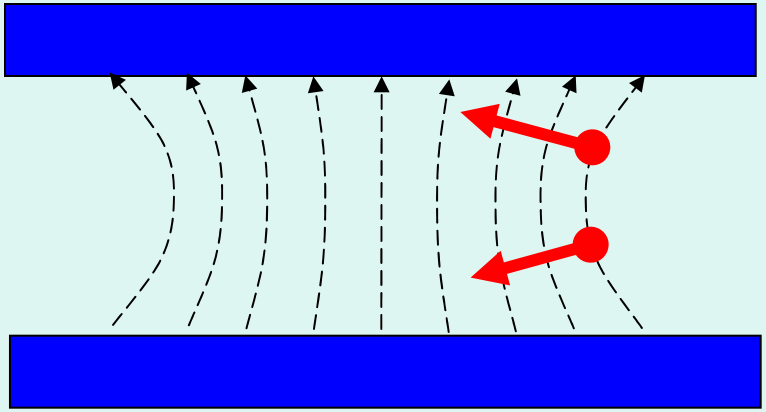






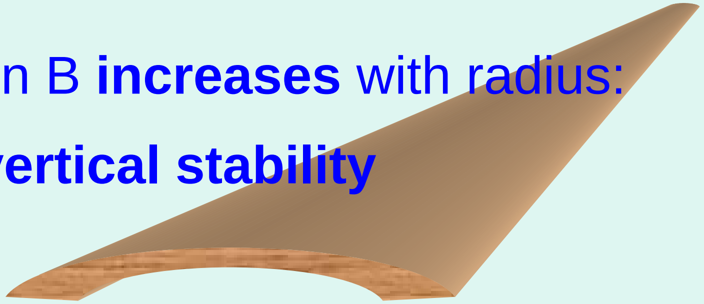
When B **decreases** with radius:

Automatic **vertical stability**



When B **increases** with radius:

No **vertical stability**



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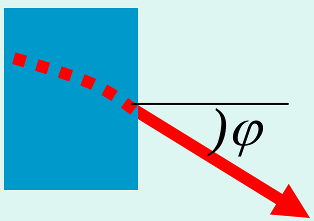
Vertical focussing

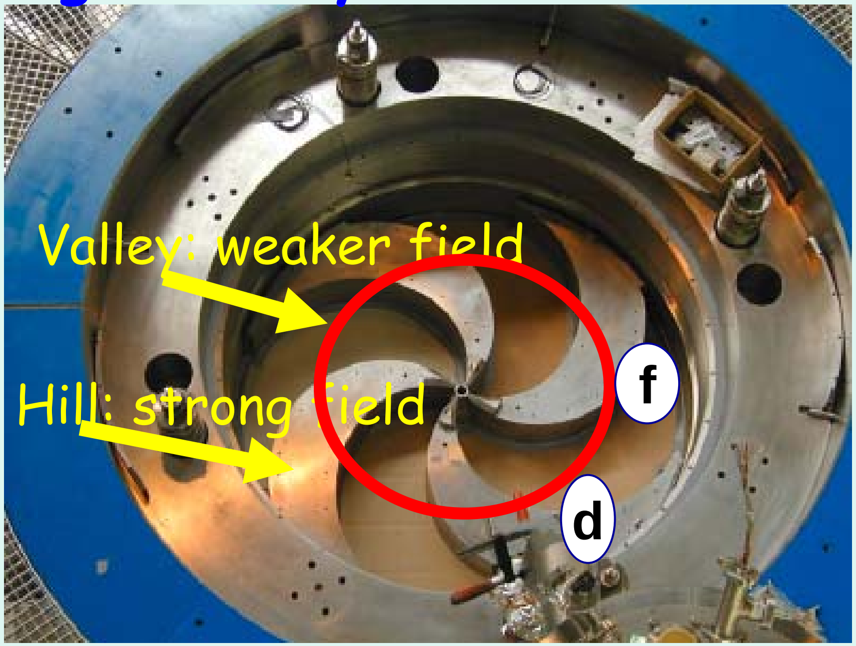
Azimuthally Varying Field cyclotron



When $\varphi \neq 0$:

$$\vec{B}_\theta \times \vec{v}$$

=> vertical force



Main field increases with radius

=> φ must also increase to maintain vertical focusing

=> spiral shaped "hills"

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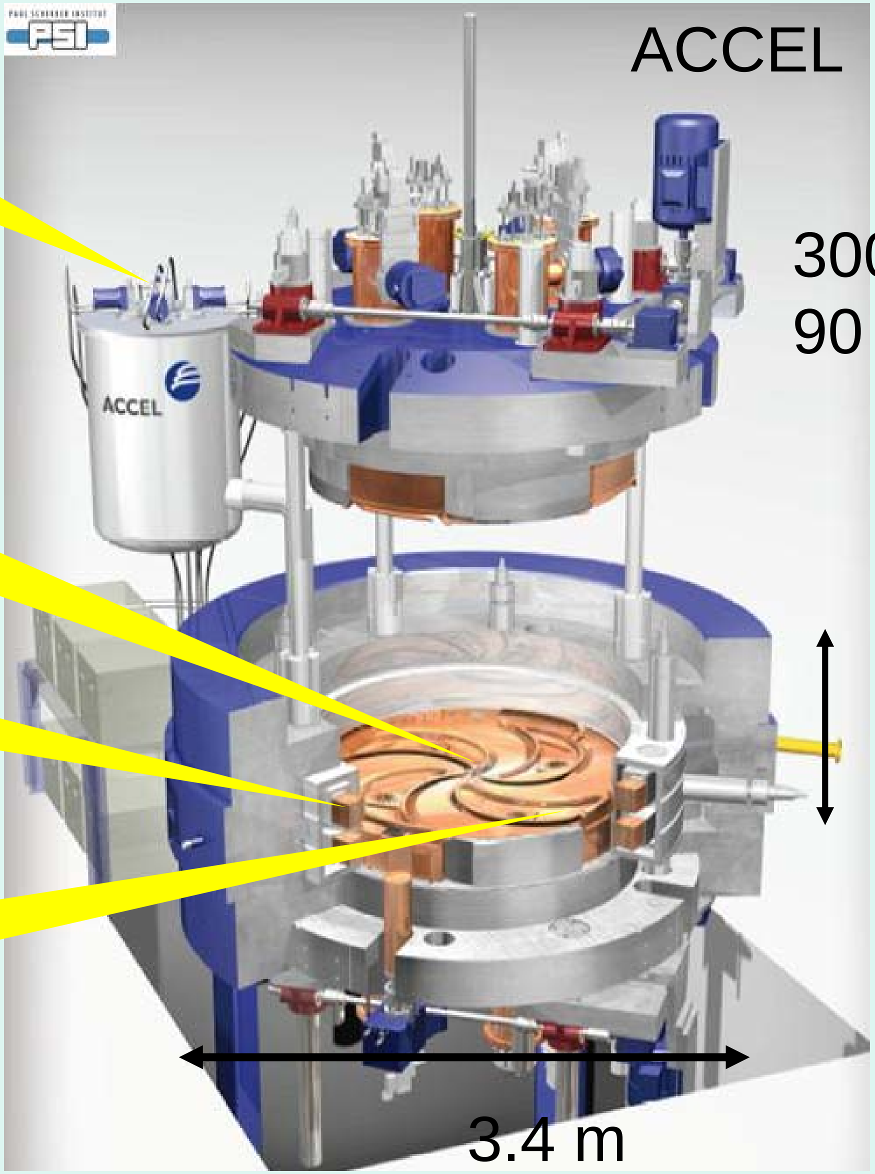
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

Proton source

superconducting coils
=> 2.4 - 3.8 T

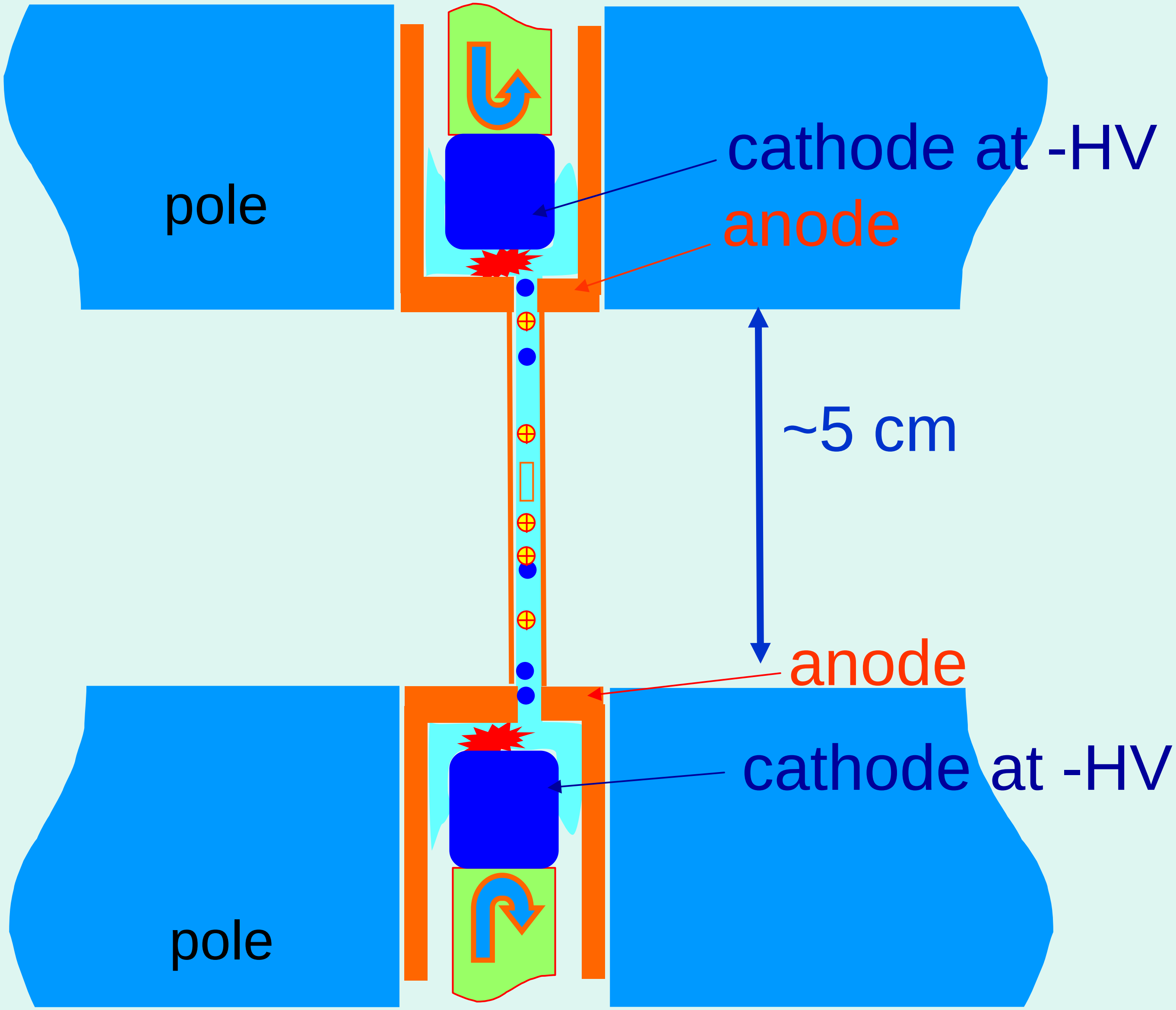
4 RF-cavities
~100 kV on 4 Dees



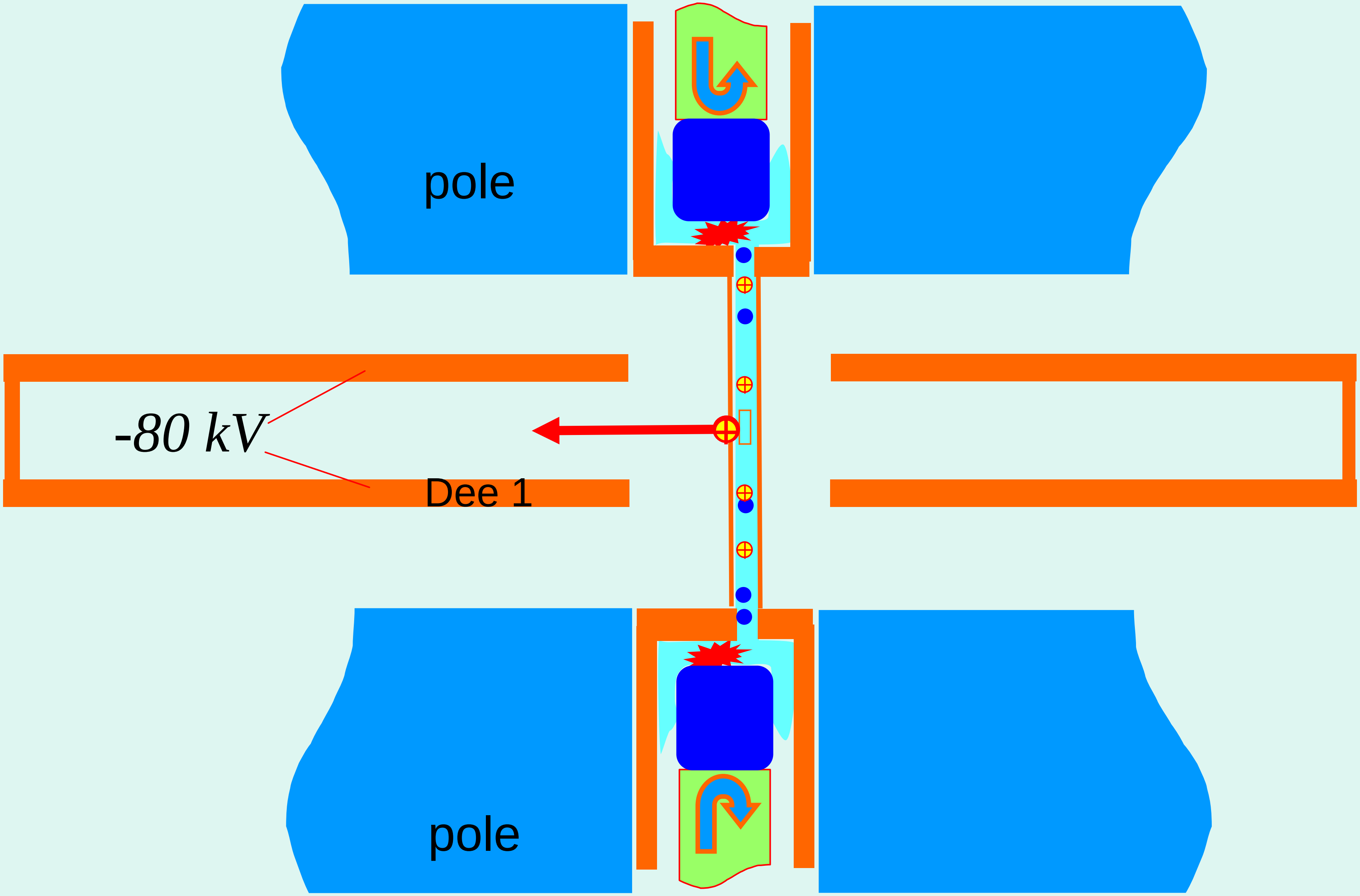
300 kW
90 tons

1.4 m

Internal proton source

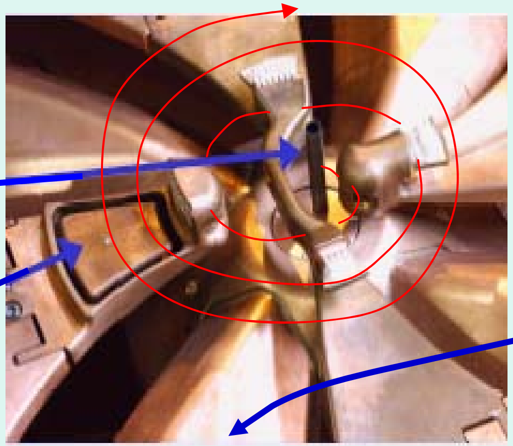


Internal proton source

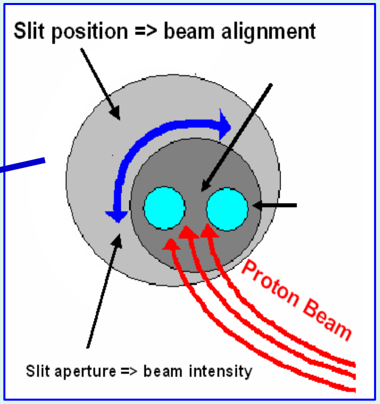


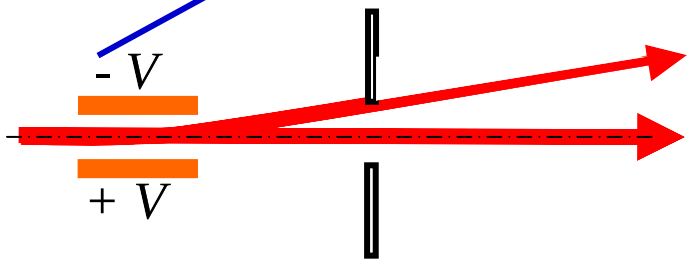
Intensity control

Max. intensity set by:
proton source

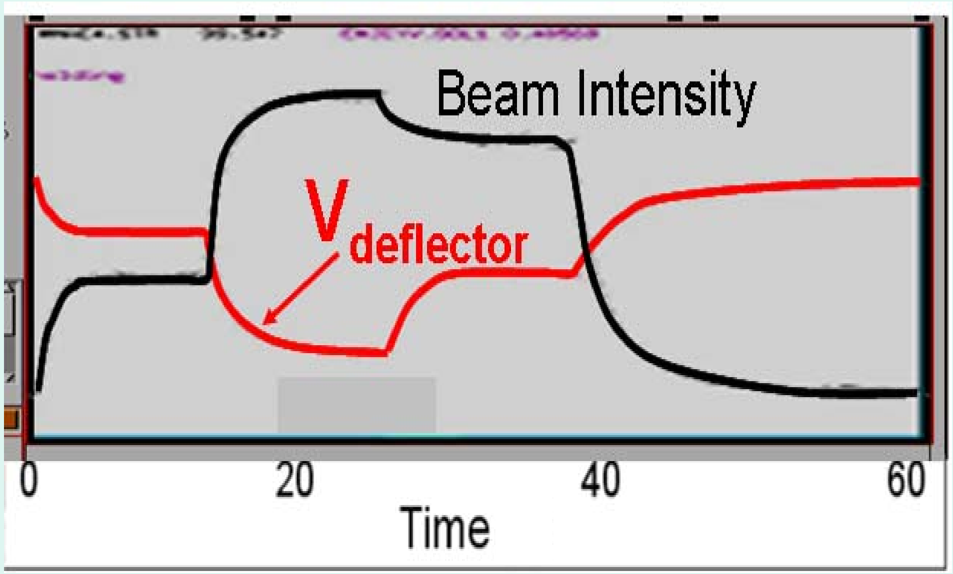


+ slits

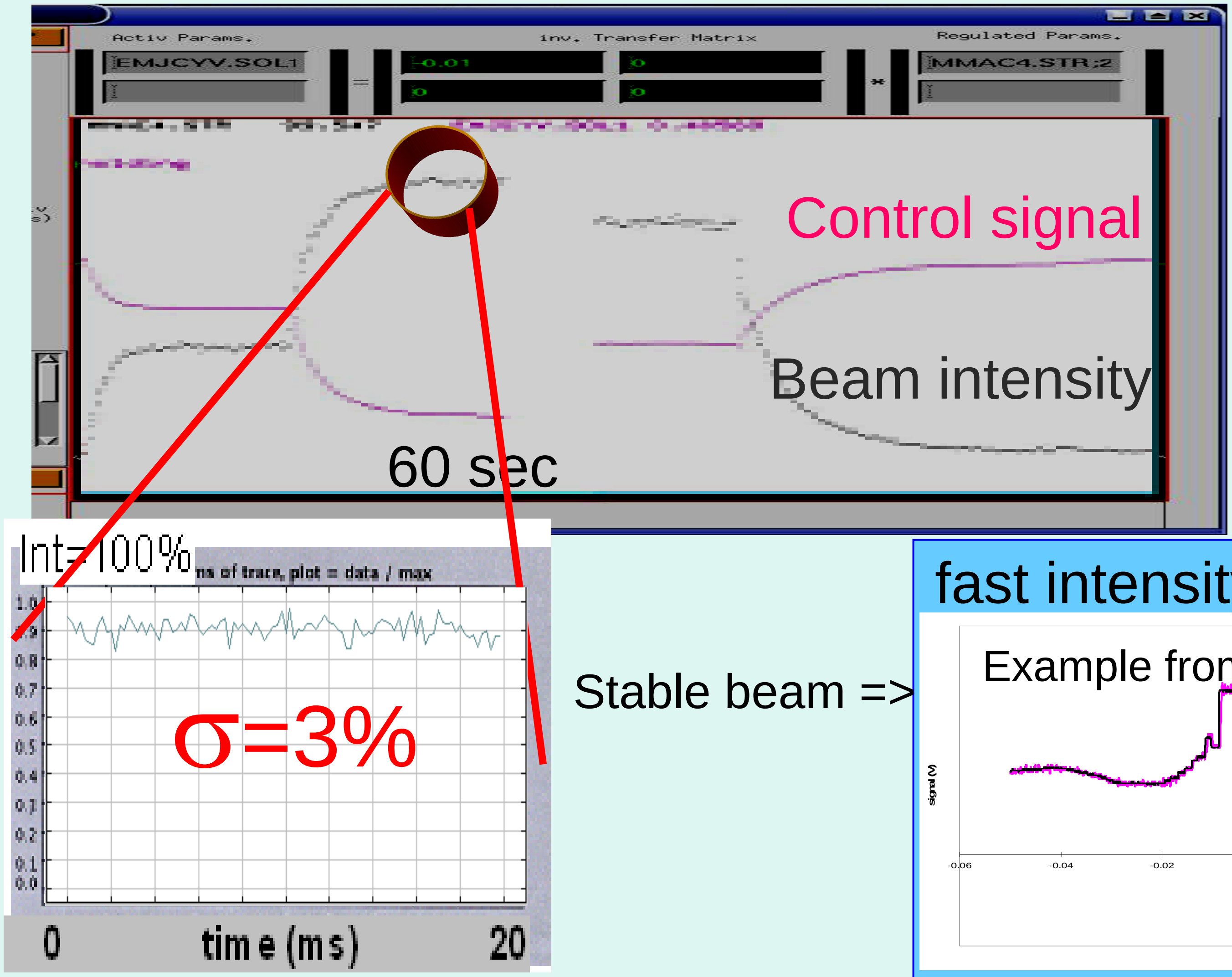




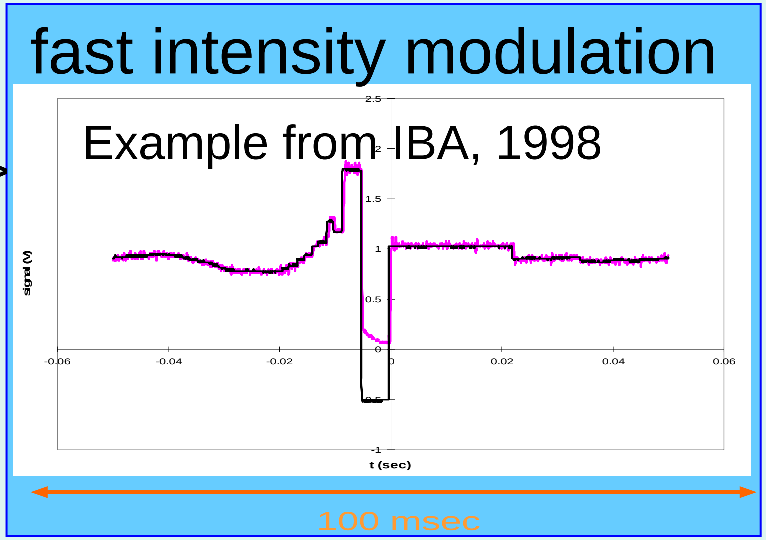
Deflector plate:
sets requested intensity
- within 50 μs
- 5% accuracy



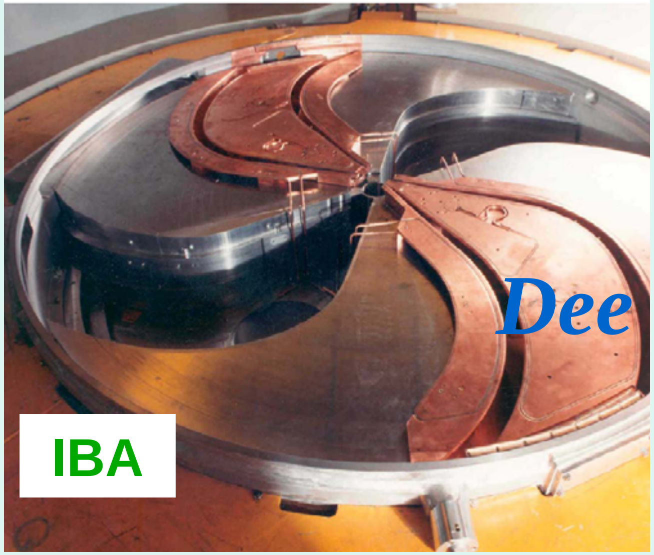
Cyclotron beam structure: regulated, DC

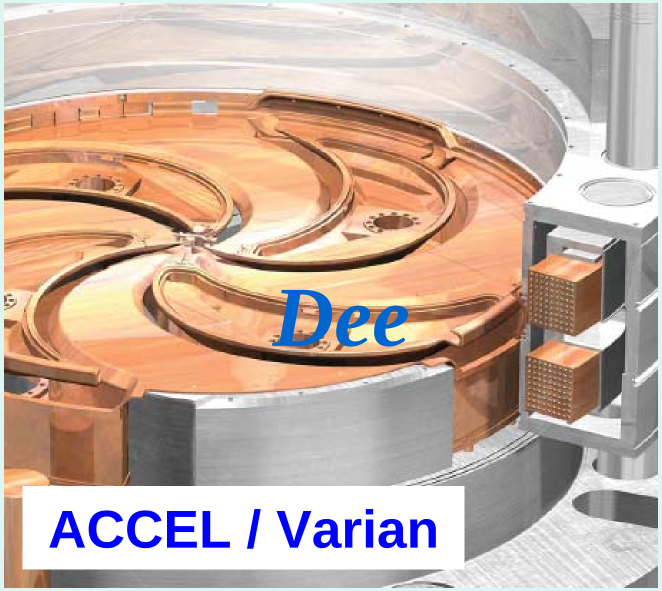


Stable beam =>



RF system





Important parameters:

Voltage on Dee

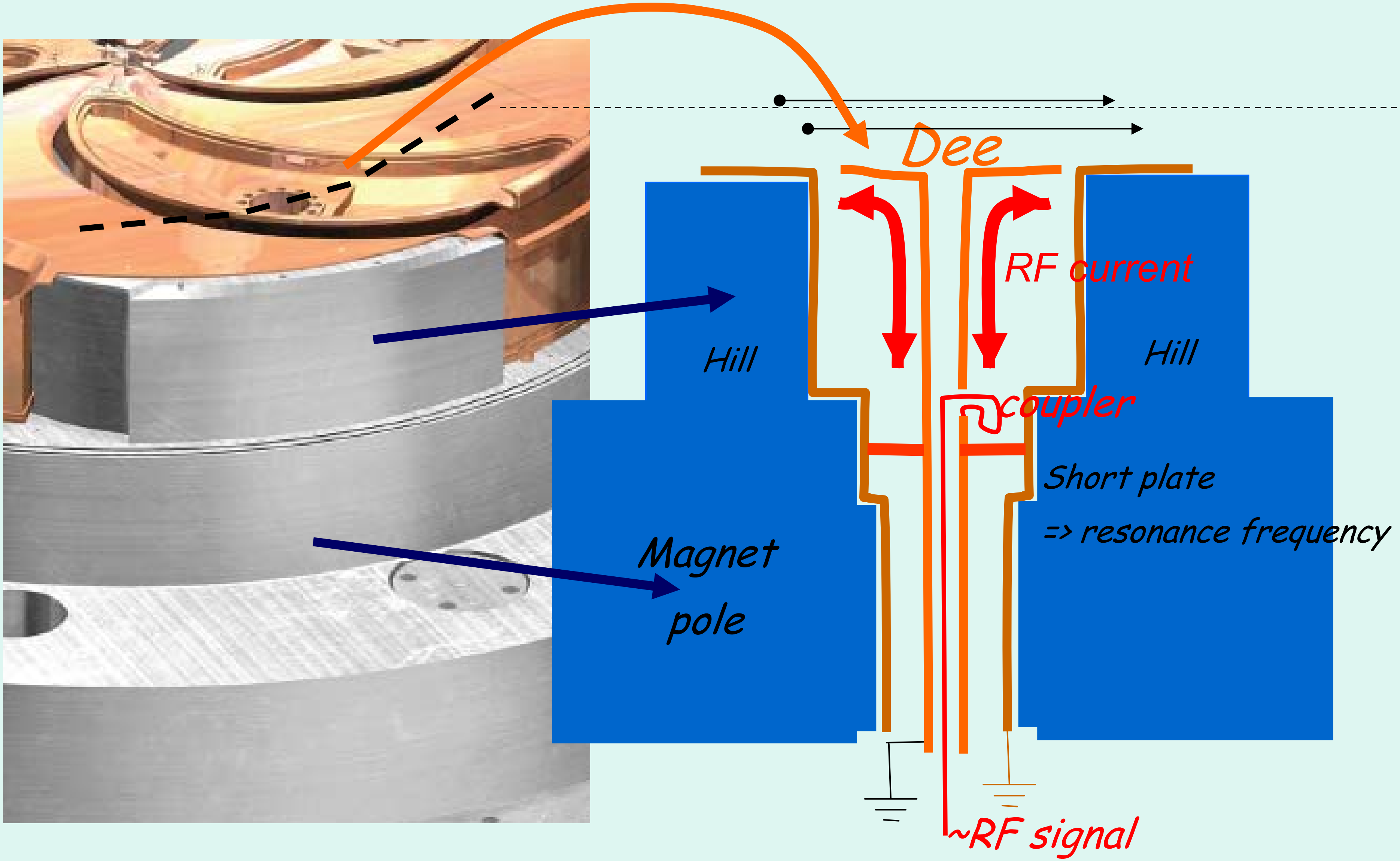
Number of Dee's

⇒ Energy gain per turn

⇒ Orbit separation

⇒ Extraction efficiency

RF system: Dee



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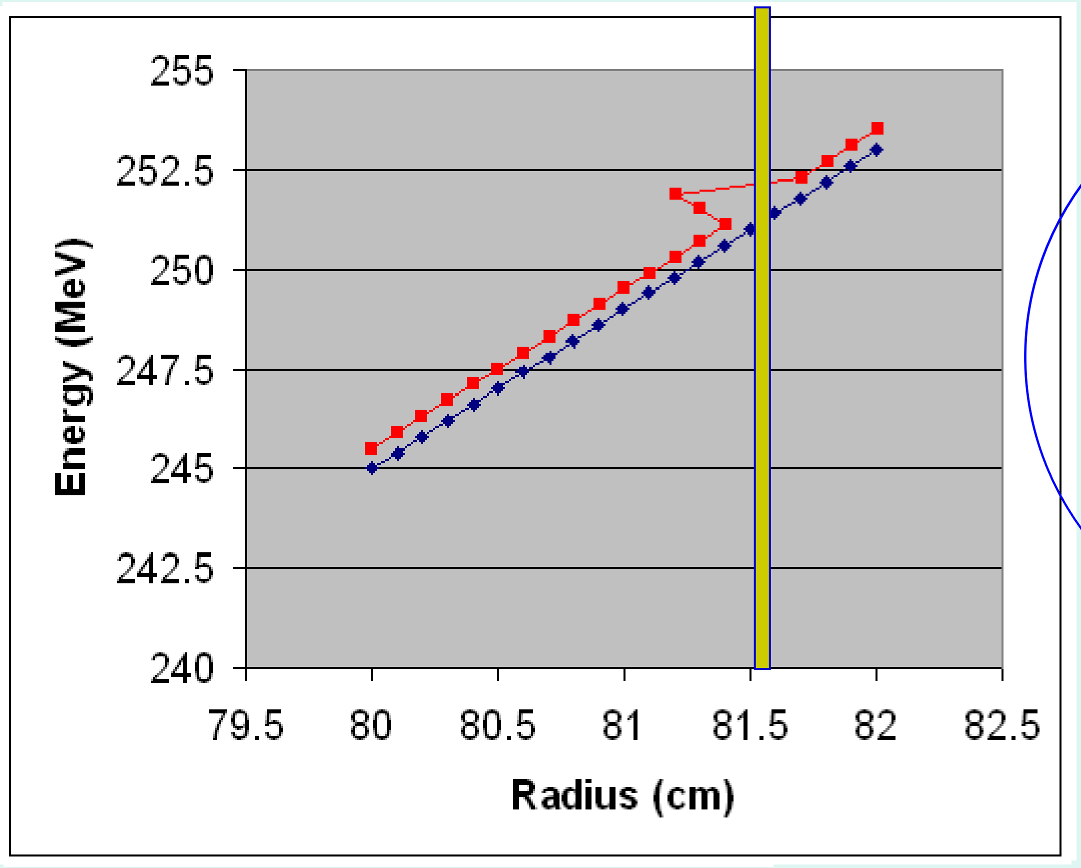
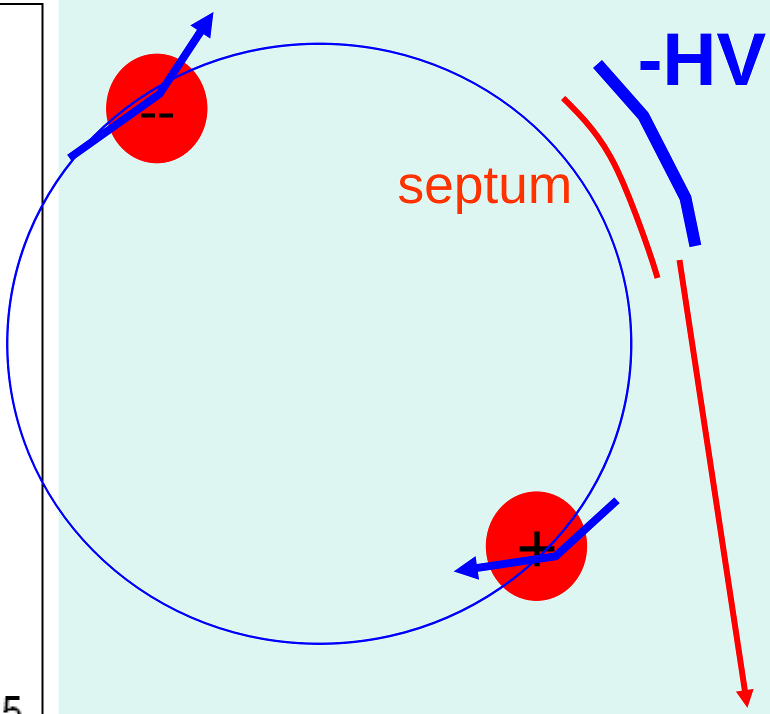
resonant extraction

With field bump



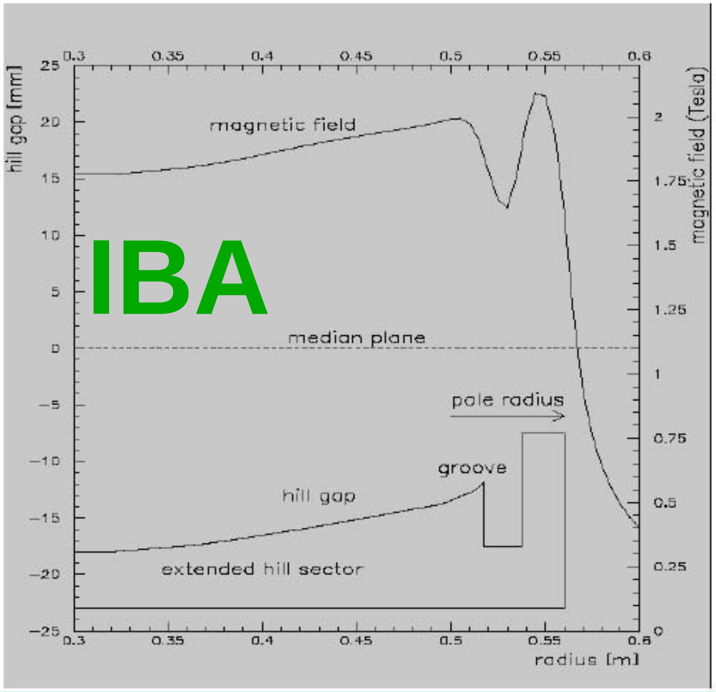


Extraction from cyclotron

Self-extraction: Realization by IBA

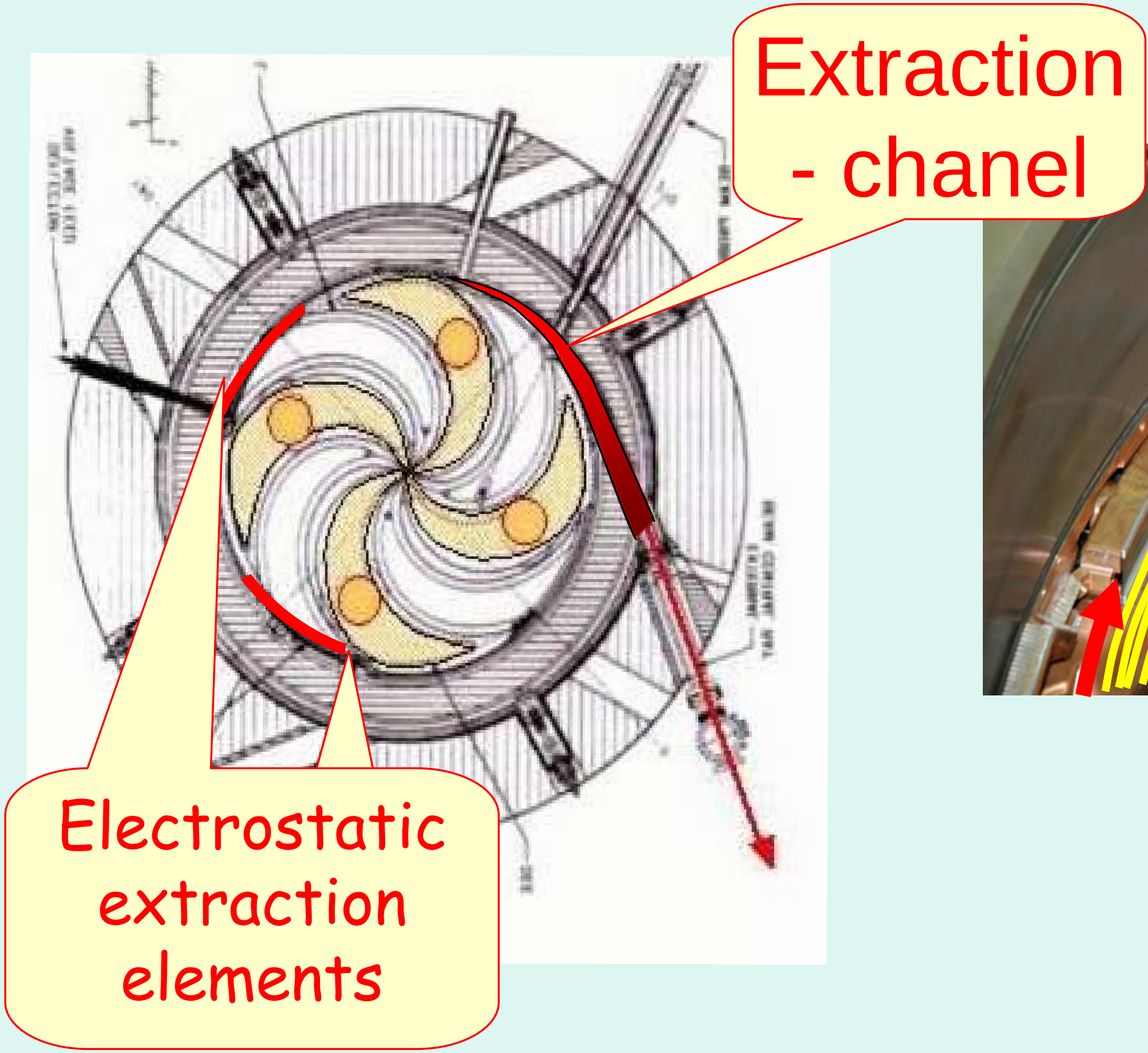
Small elliptical hill gap ⇒ allows for sharp radial gradients

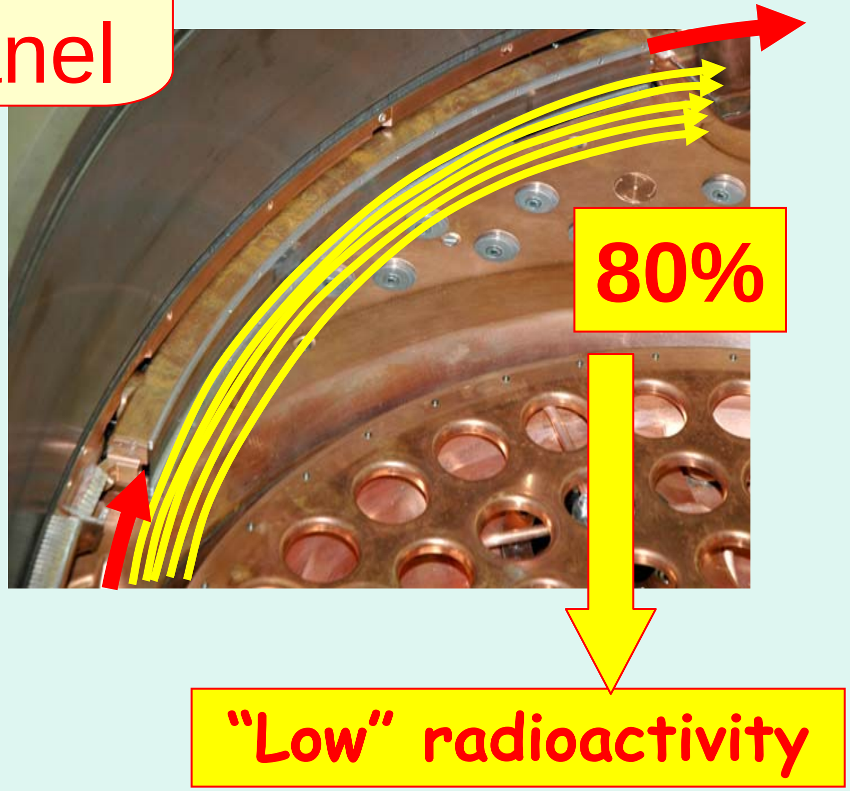
'magnetic septum' ⇒ groove machined in the pole



Pole with goove

Extraction from cyclotron





(ACCEL / Varian)

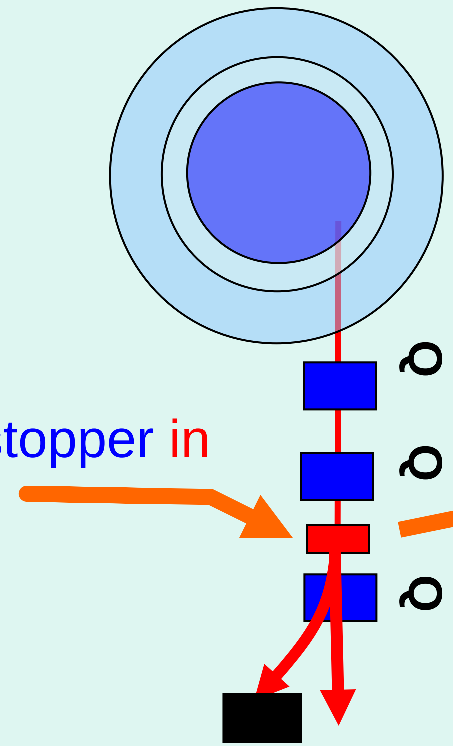
beam on/off

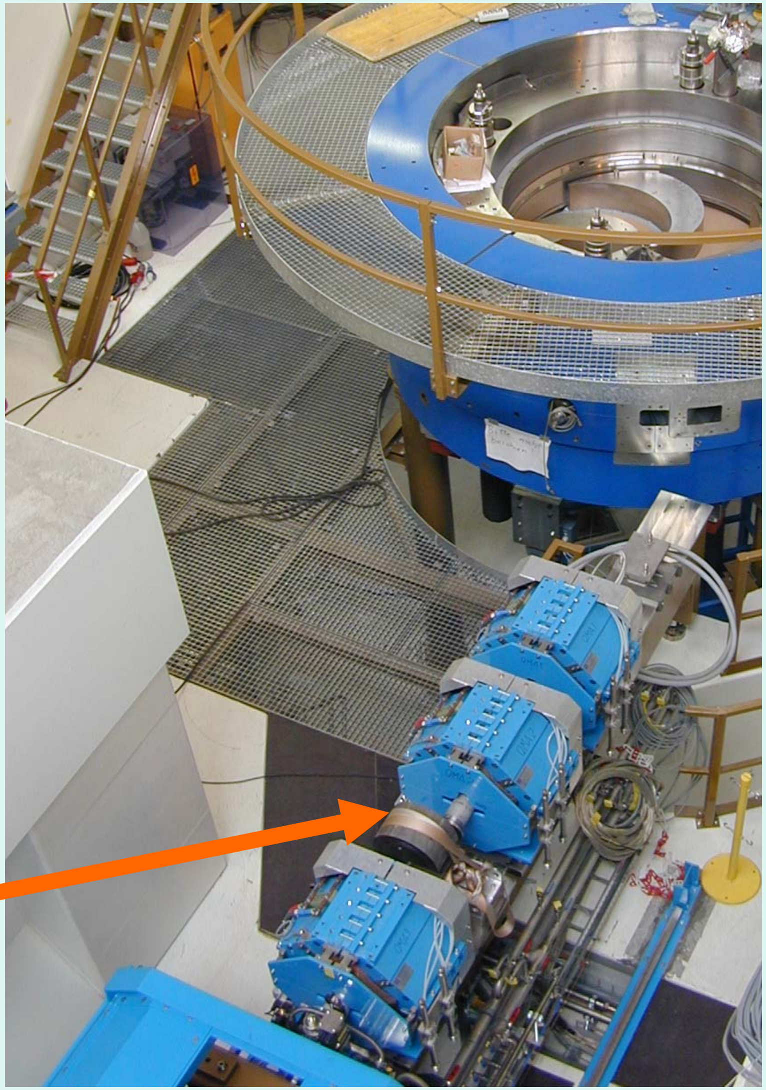
In cyclotron:

- vertical deflector plate → Vmax
- RF → Power off or low
- ion source → off
- mechanical stopper → in

In beam line:

- mechanical beam stopper in
- fast kicker magnet





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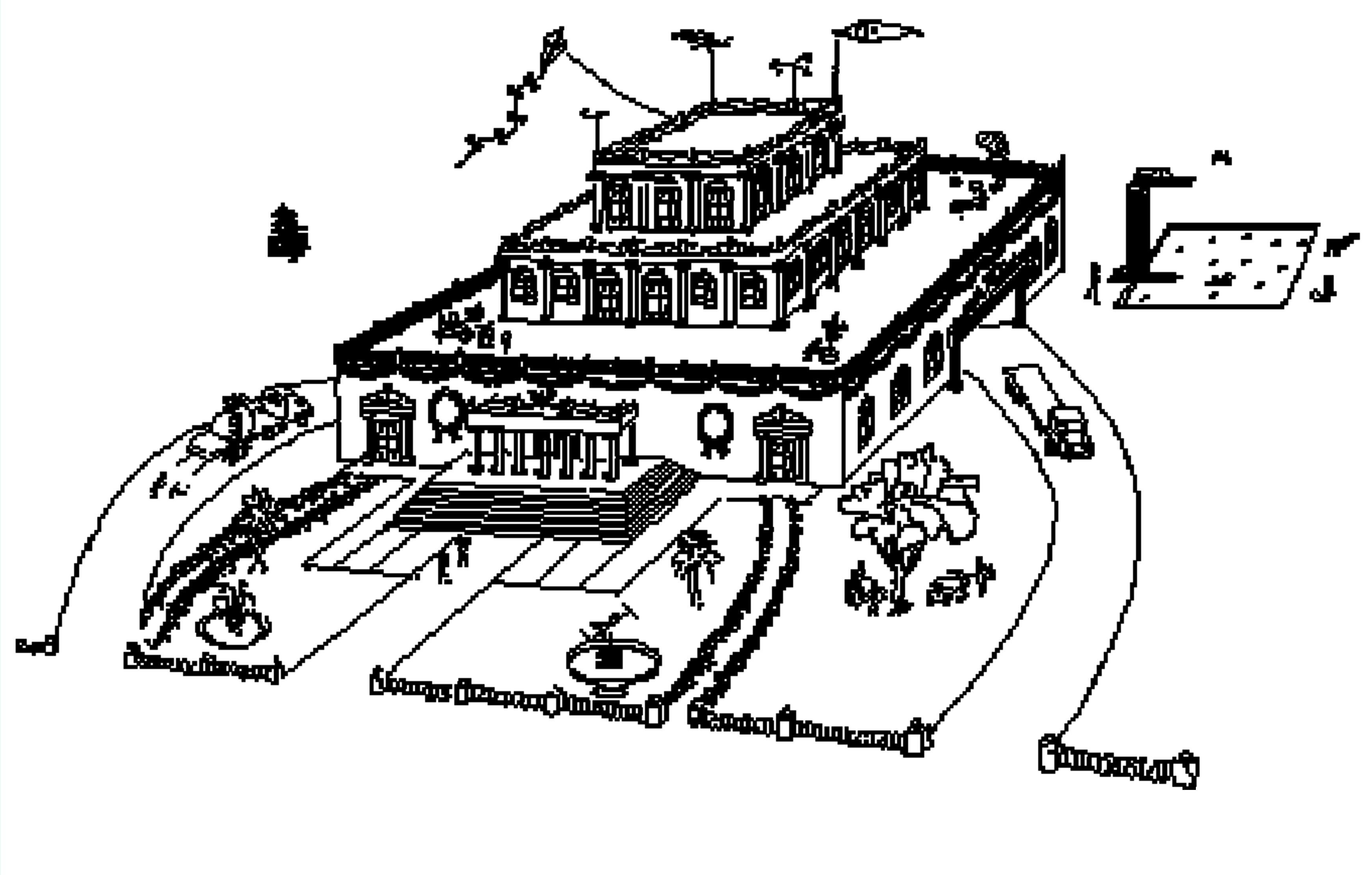
Cyclotron as seen by the financial director



Small cyclotron on a gantry

Proposal of H.Blosser et al.,1989:
-250 MeV
-52 tons, on gantry
-B(0)=5.5 Tesla

H. Blosser, NSCL (~1990):
cyclotron for neutron therapy;
30 MeV p, mounted on a gantry
Used in Harper Hospital, Detroit

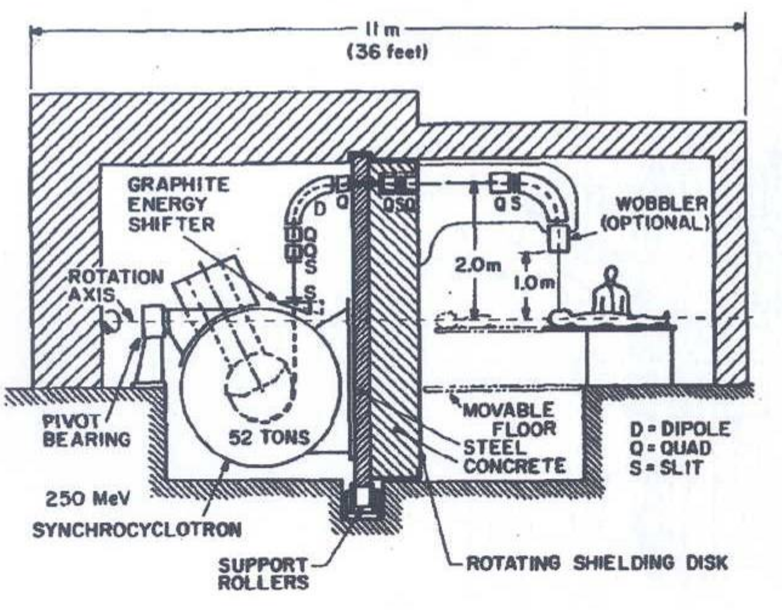


FIG. 9 -- Drawing showing synchrocyclotron rotating gantry arrangement with energy shifting wedge just after the cyclotron. Energy shifting can optionally be accomplished just ahead of the patient.

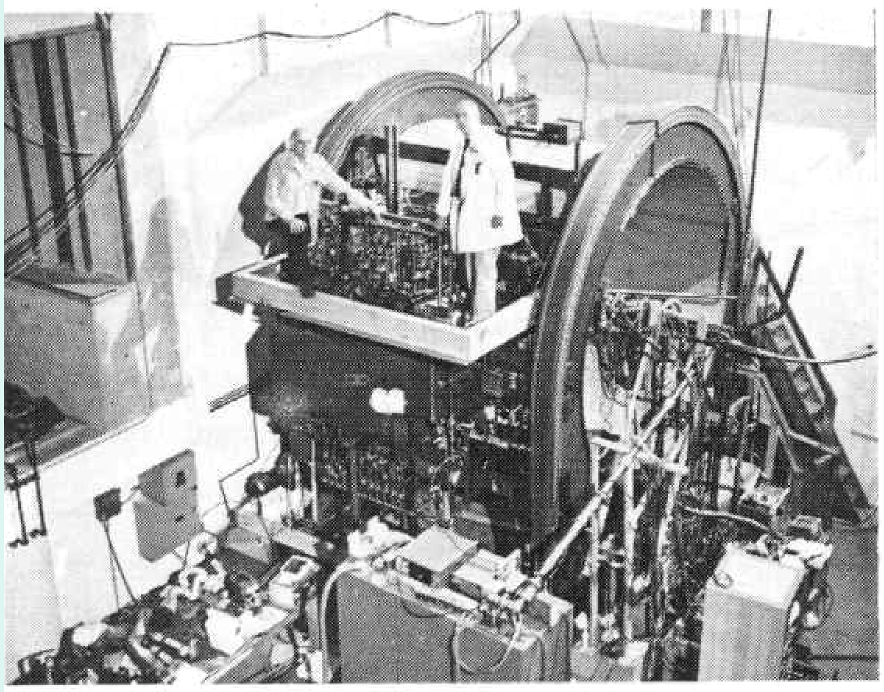
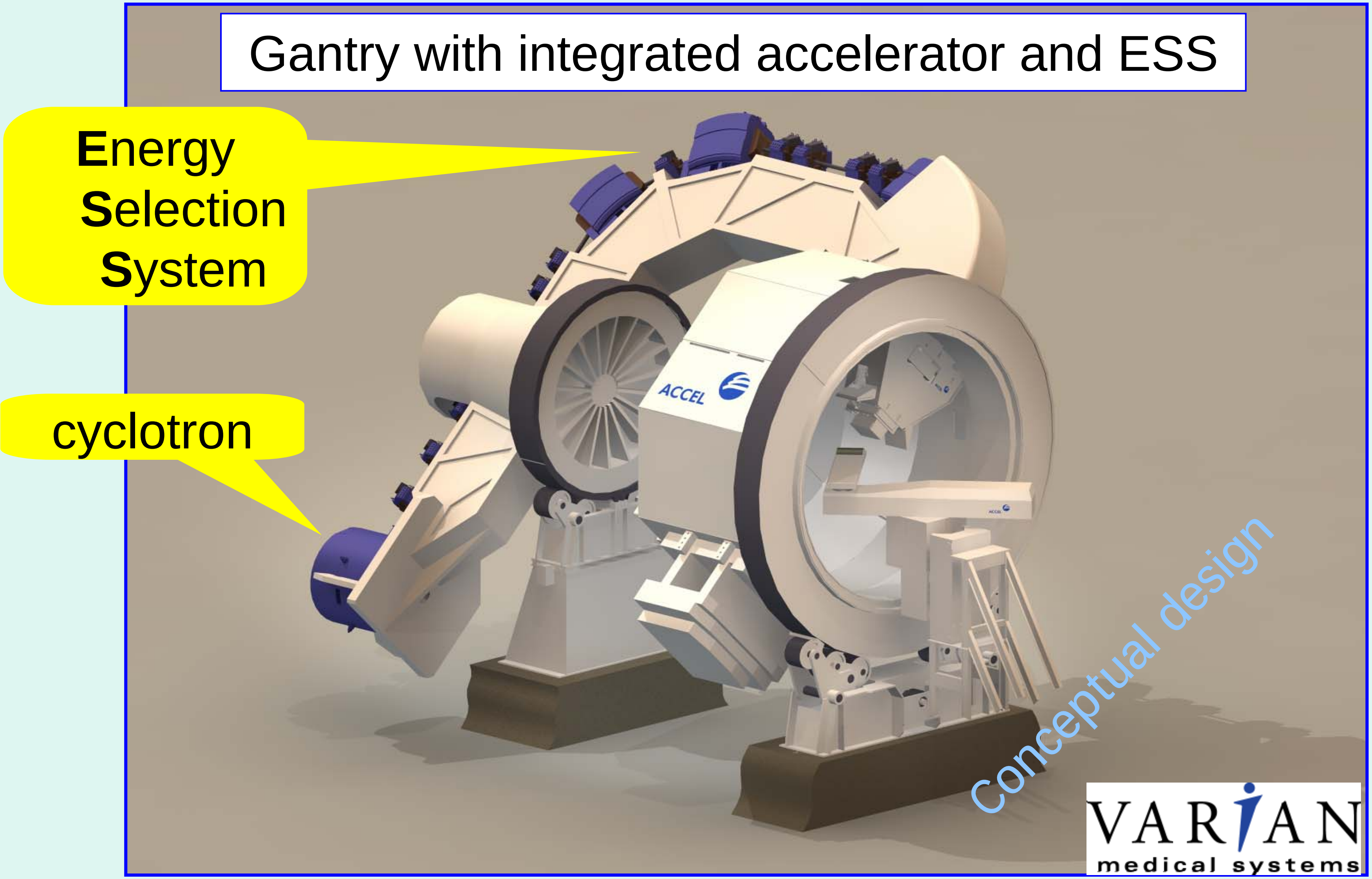


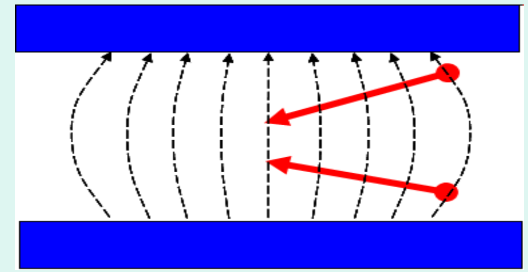
Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and

Small cyclotron on a gantry



Small cyclotrons with strong field

Small cyclotron => **very strong** magnetic field



=> iron is saturated („air like“)

=> hills and valeys do not work

=> vertical focussing only by **decreasing** ***B(r)***

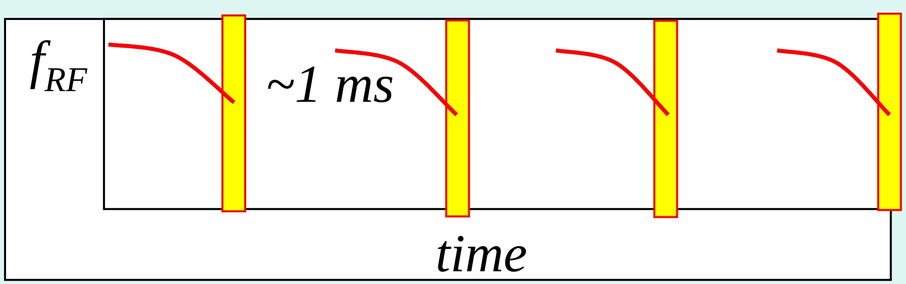
and: ***m*** **increases** with energy (relativity)

=> T_{circle} increases with radius

$$T_{circle} \uparrow = \frac{2\pi . m \uparrow}{q . B \downarrow}$$

Remedy:

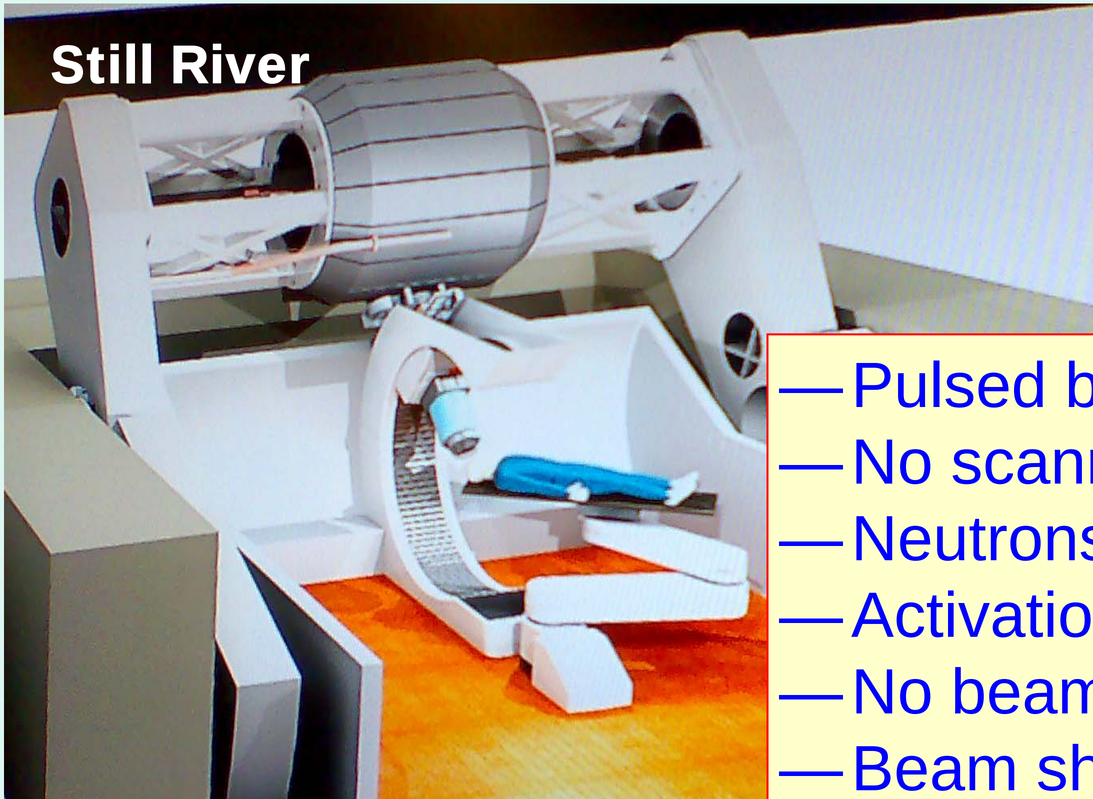
=> decrease f_{RF} with radius. (synchro cyclotron)



=> pulsed beam (1 kHz)

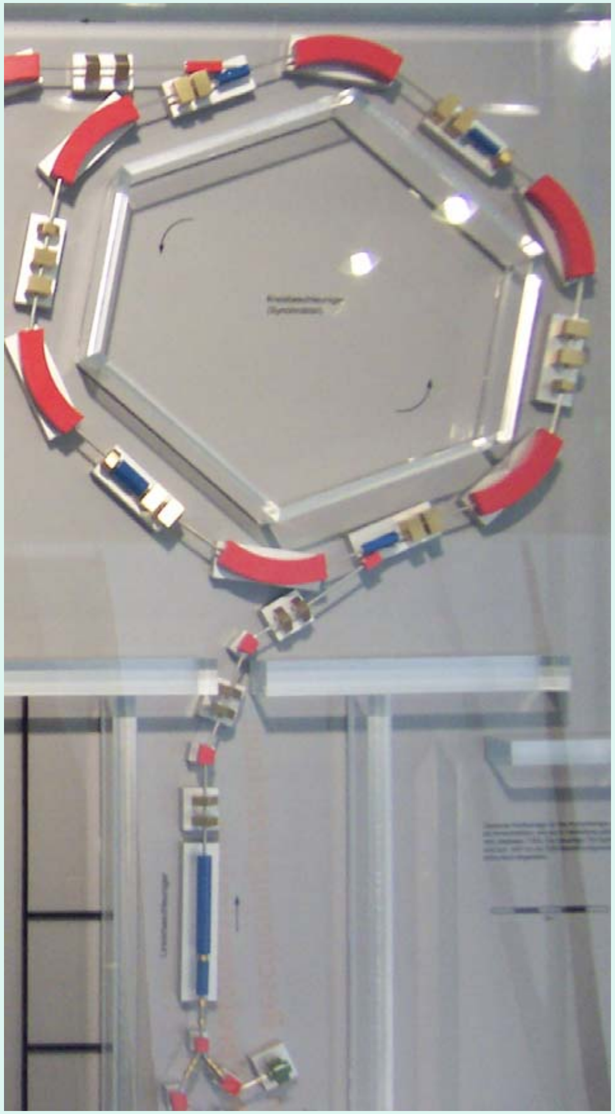
Synchro-Cyclotron

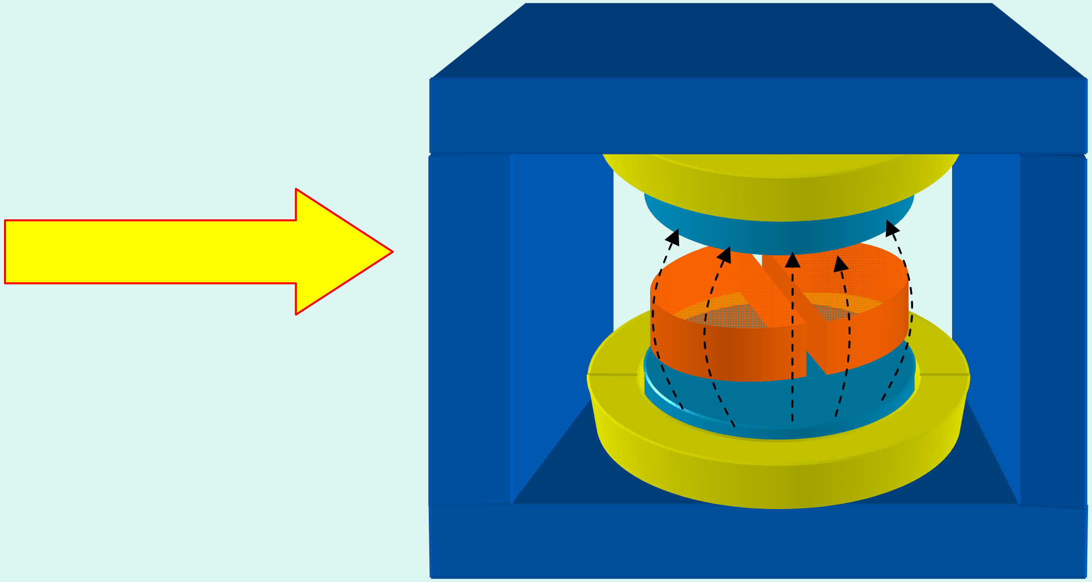
8-10 T Synchro-cyclotron on a gantry



- Pulsed beam
- No scanning
- Neutrons ?
- Activation ?
- No beam analysis
- Beam sharpness ?
- Reliability ?
  (@ limit of current technology)

Carbon-ion cyclotrons





Particle Therapy Co-Operative Group

Carbon-ion cyclotrons

Proton (250 MeV)	Helium 2+ (α) (250 MeV/nucl)
Range in water =38 cm	
2.43 Tm	4.86 Tm

Carbon 6+ (450 MeV/nucl)
Range in water =33 cm
6.83 Tm

$\Rightarrow$ For carbon ions cyclotron needs **2.8** times larger radius

$\Rightarrow$ So ~2.8^2 = 8 x more iron => 700-800 tons

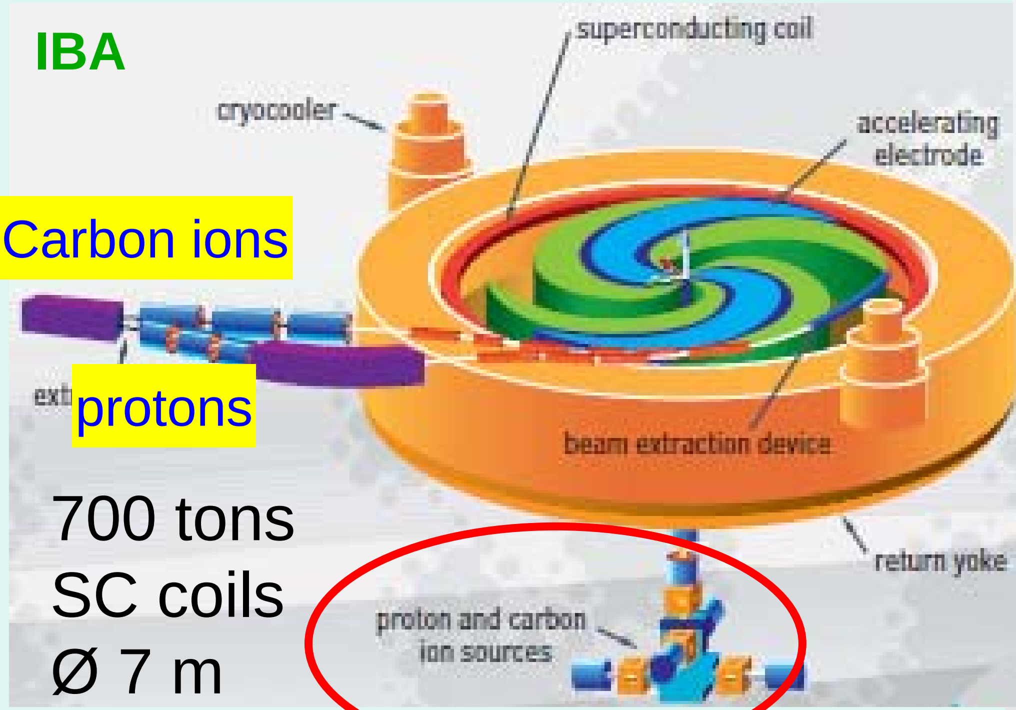
Synchrotron ∅ = 25 m + injection

Cyclotron ∅ = 7 m

Particle Therapy Co-Operative Group

Archade project

IBA



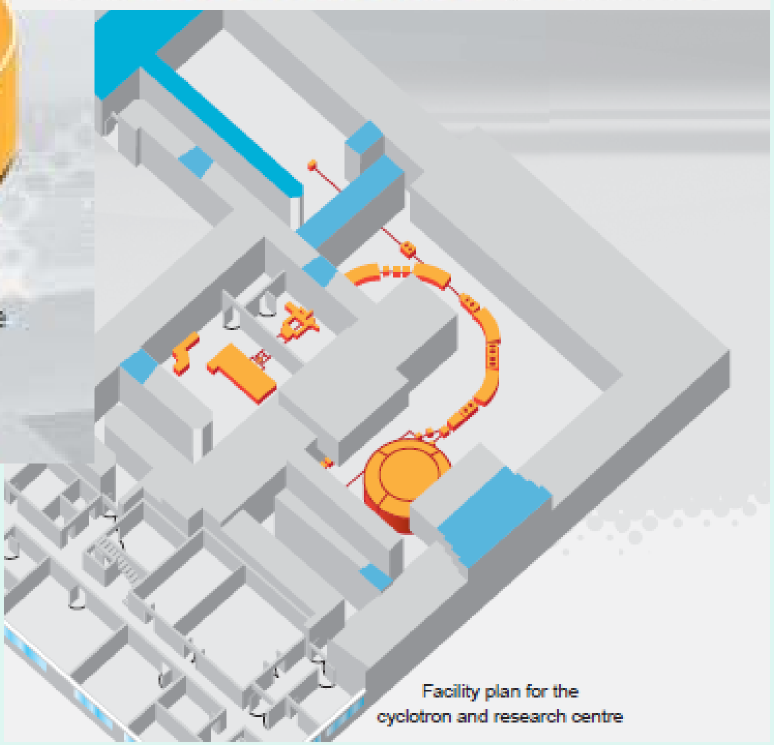
Carbon ions

protons

700 tons
SC coils
Ø 7 m

Archade

ADVANCED RESOURCE CENTRE FOR HADRONTHERAPY IN EUROPE



Int. Conf. Cyclotron and appl, Tokyo 2004

IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY

Y. Jongen, M. Abs, W. Beeckman, A. Blondin, W. Kleeven, D. Vandeplassche, S. Zaremba, IBA, Belgium
V. Aleksandrov, A. Glazov, S. Gurskiy, G. Karamysheva, N. Kazarinov, S. Kostromin, N. Morozov, E. Samsonov, V. Shevtsov, G. Shirkov, E. Syresin, A. Tuzikov, JINR, Russia.

Catania design 250 → 300 MeV/nucl

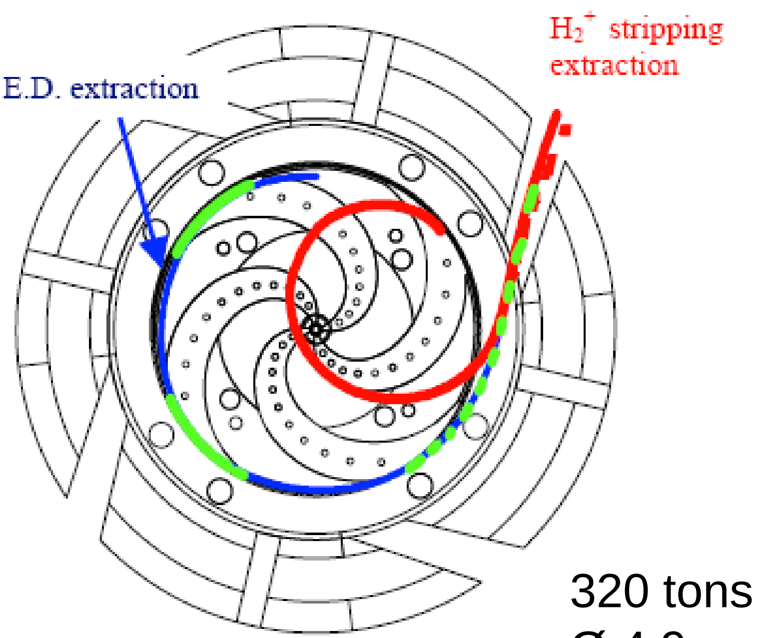


Figure 3: Layout of the cyclotron with overdrawn the extraction trajectories by E.D. and by stripper. The E.D. and the M.C. positions are also shown.

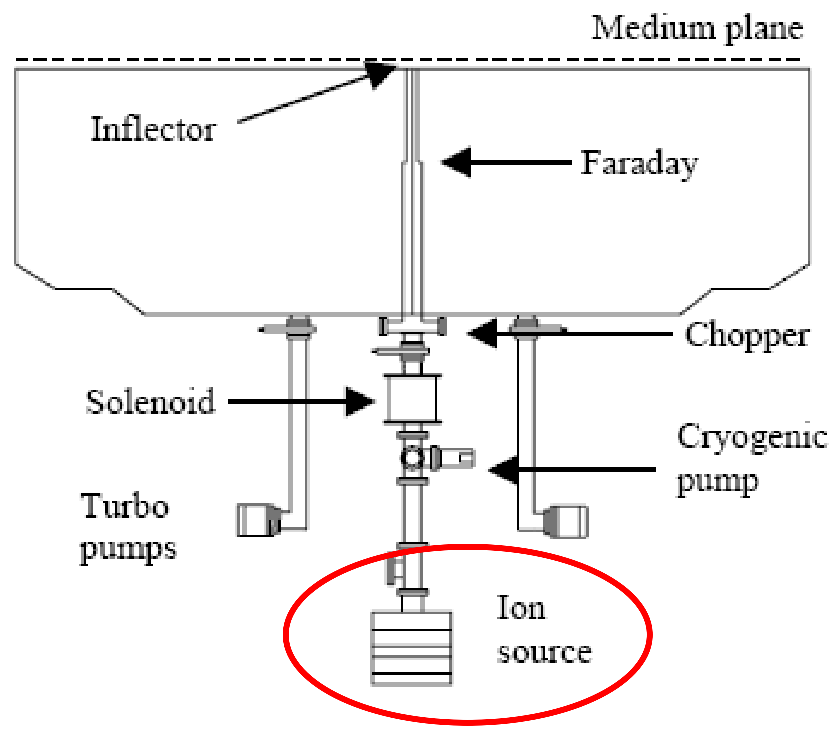


Figure 4: Layout of the axial injection line and part of vacuum plant

LNS CATANIA PROJECT FOR THERAPY AND RADIOISOTOPE PRODUCTION

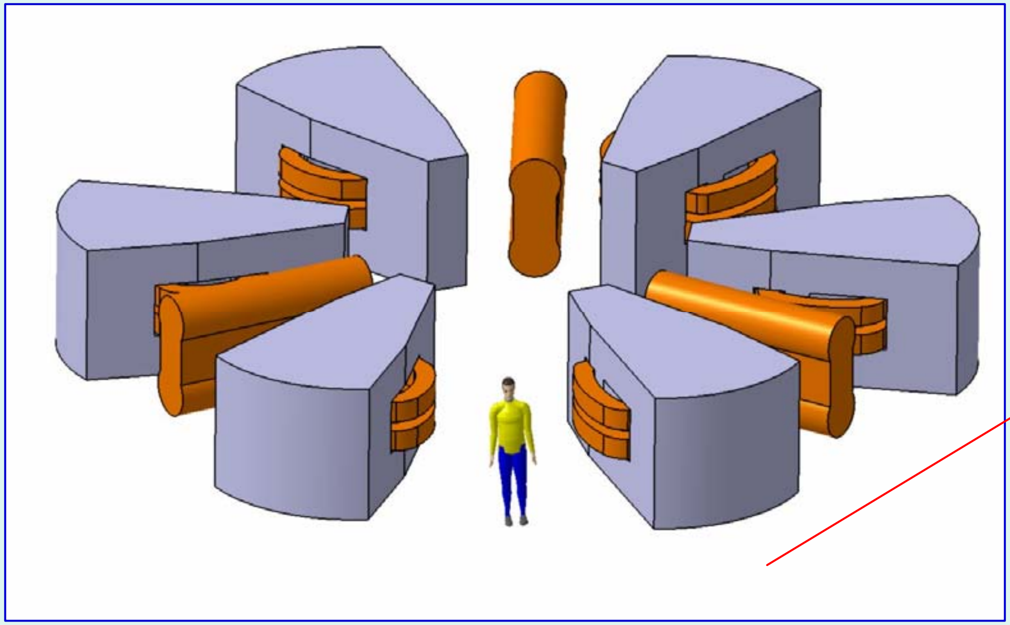
L.Calabretta, G. Cuttone, M. Re, D. Rifuggiato, LNS-INFN, Catania, Italy
M.Maggiore, University of Catania, LNS-INFN, Italy

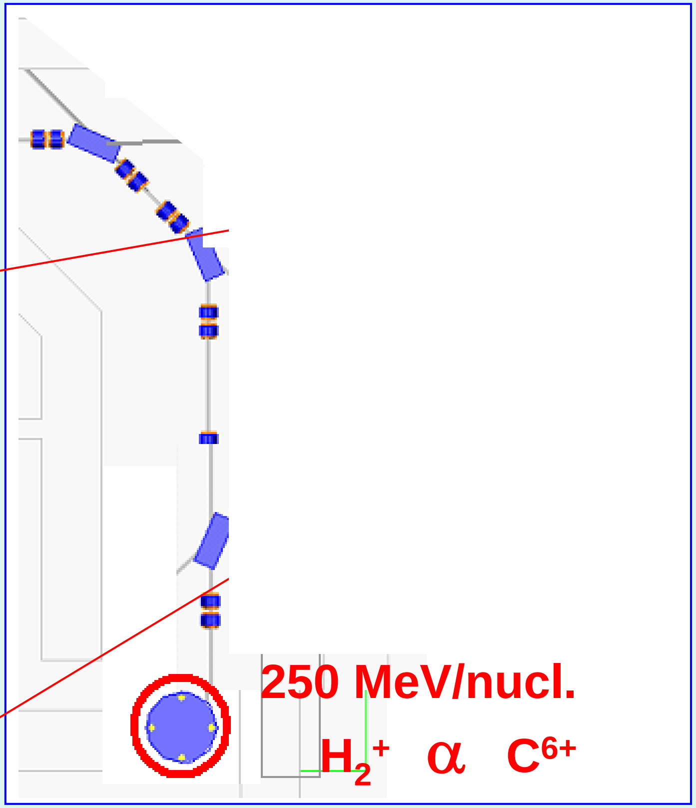
Cyclotron conference, Tokyo 2004

PSI design for 2-step approach

Start with protons AND

- α + (up to 12.5 cm:) Carbon
- Second step: also 450 MeV/nucl Carbon





Particle Therapy Co-Operative Group

Relevant cyclotron specs for therapy

- Energy + its stability
- Beam size (emittance)
- Beam intensity + stability (kHz) + adjustability (range, speed)
- Extraction efficiency

- Frequency of unplanned beam interrupts
- Start up time after „off“ and after „open“
- modular control systems + comprehensive user interface
- Maintenance interval, maintenance time, maintenance effort
- Activation level (person dose per year)

- Ions: time to switch ion species
- Synchro cycl: rep. rate, dose/pulse adjustable (scanning)?

Thank you !!