



PSI's **SC** cyclotron “**COMET**” for proton therapy

Marco Schippers

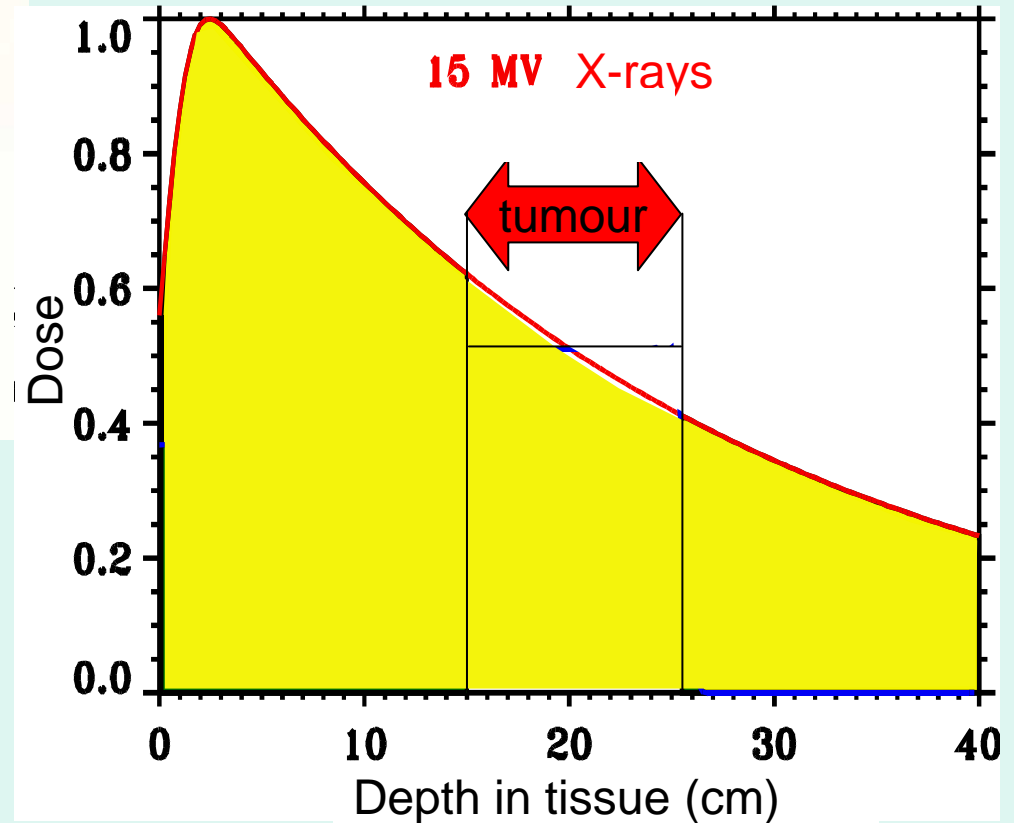
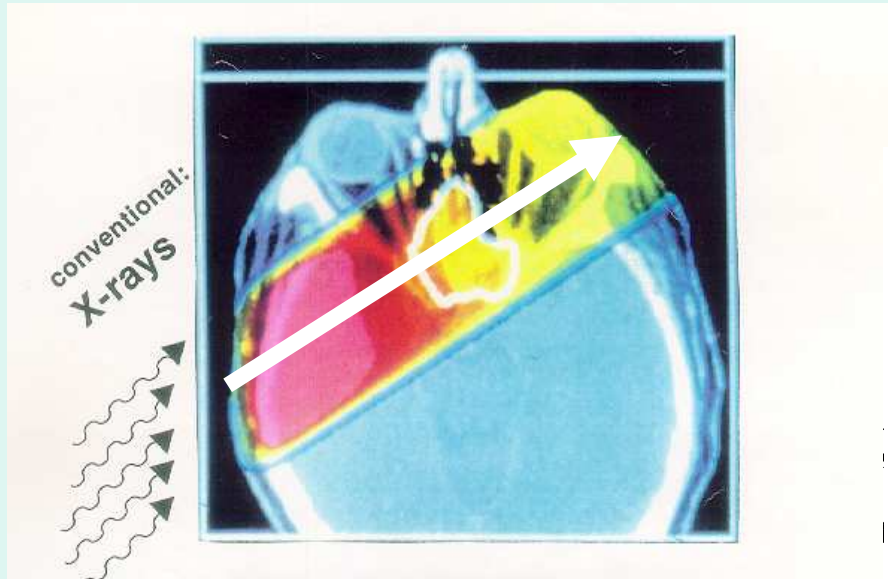


Contents

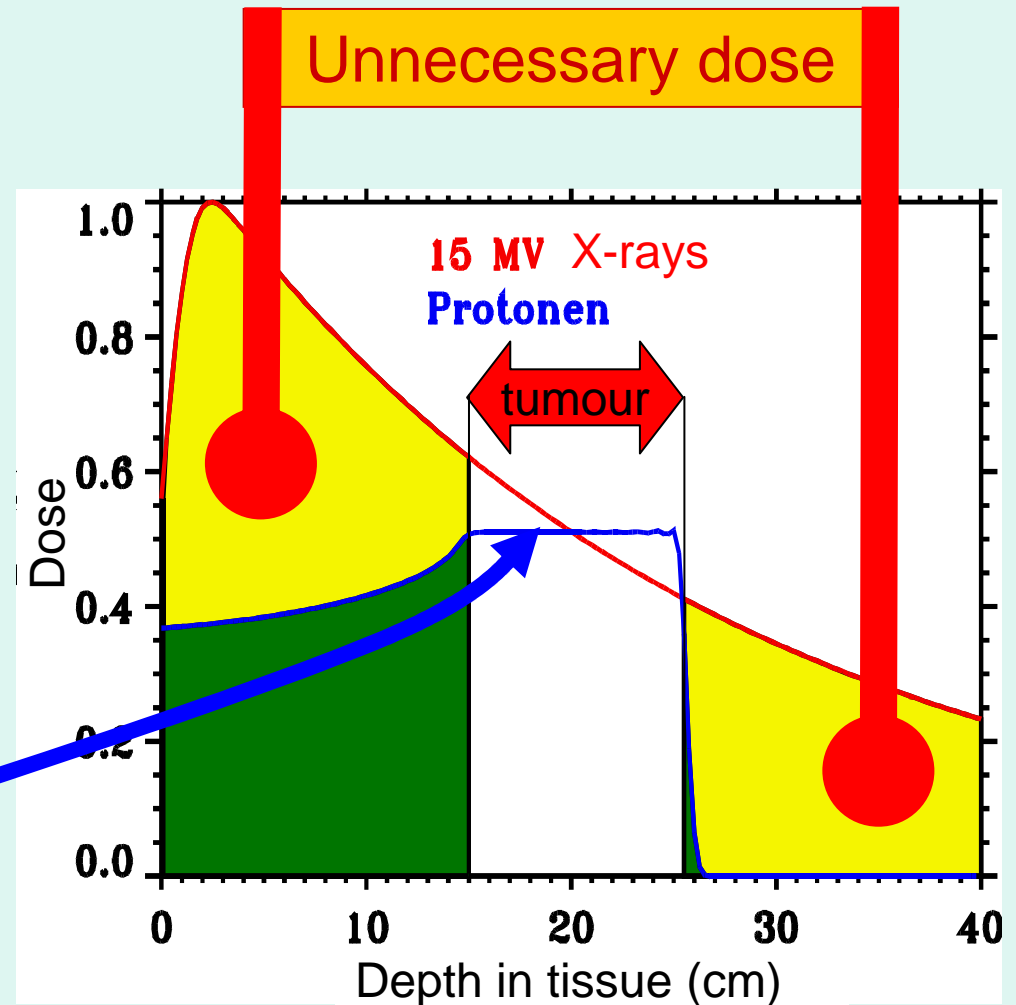
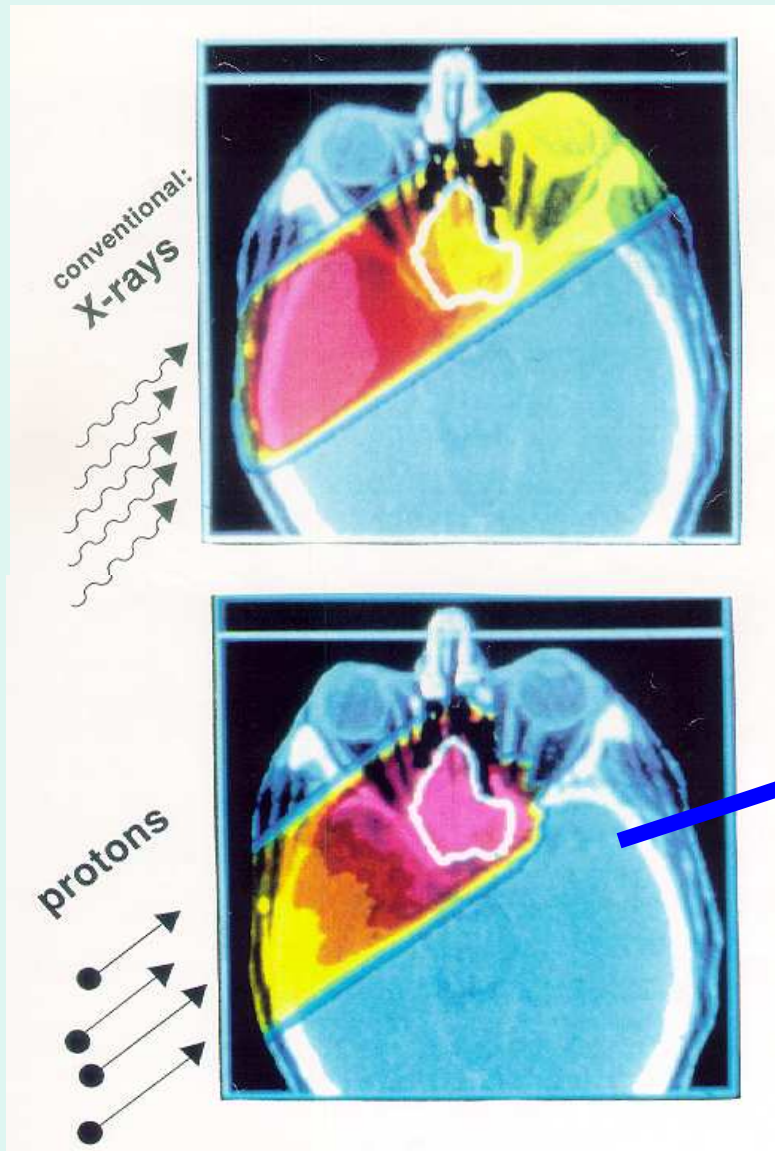
- **Proton therapy**
- **Dose delivery techniques**
- **Cyclotron**



X-rays vs. Protons

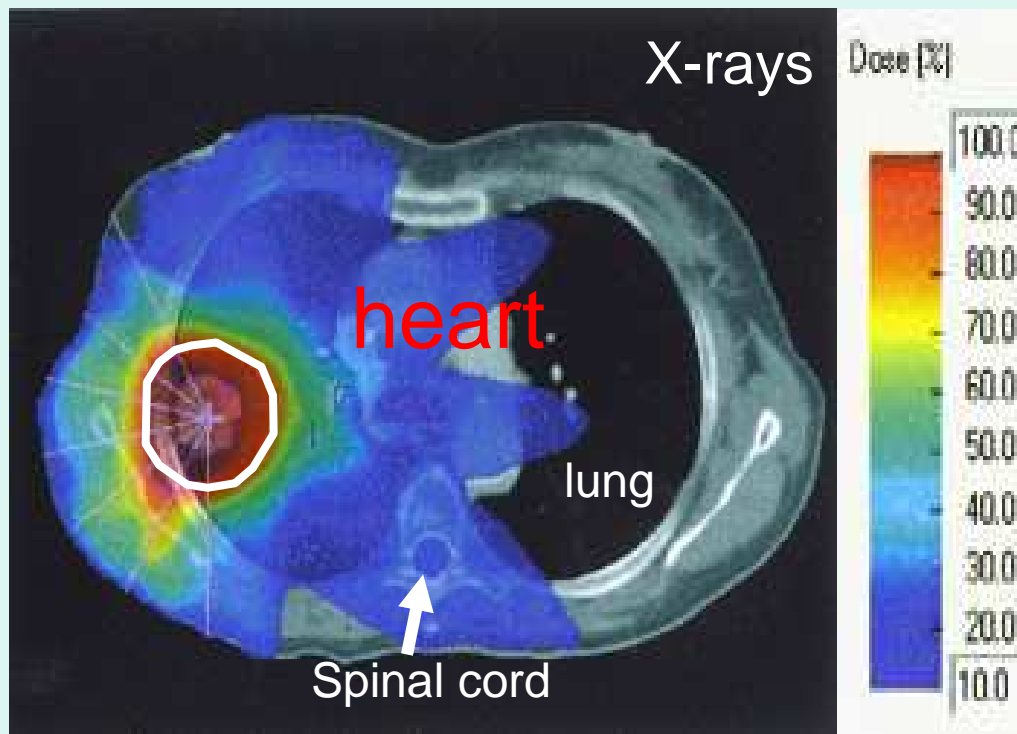


X-rays vs. Protons

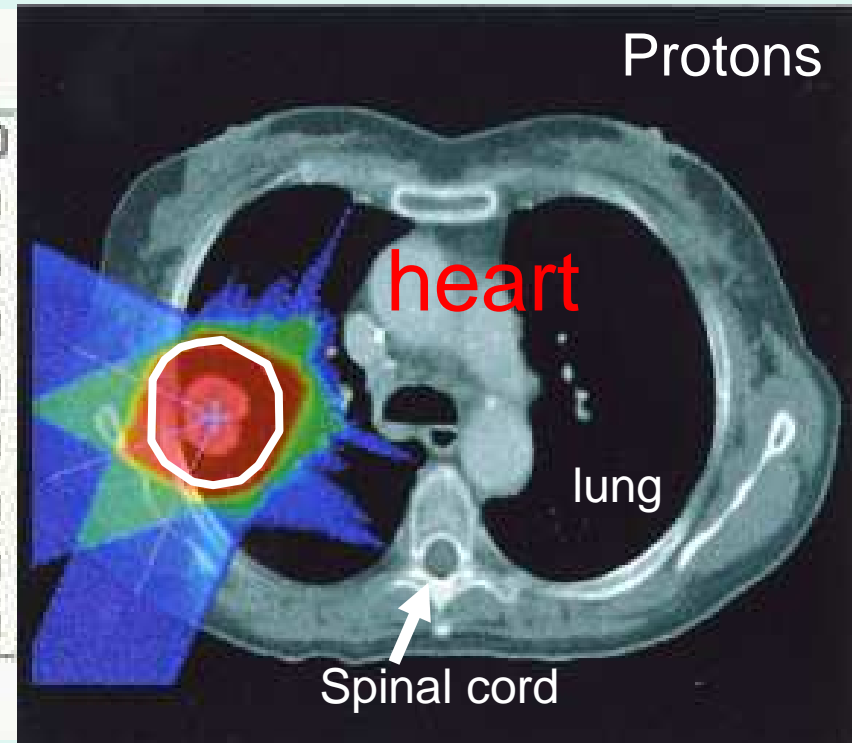


X-rays vs. Protons

X-ray beams (IMRT)
from 7 directions

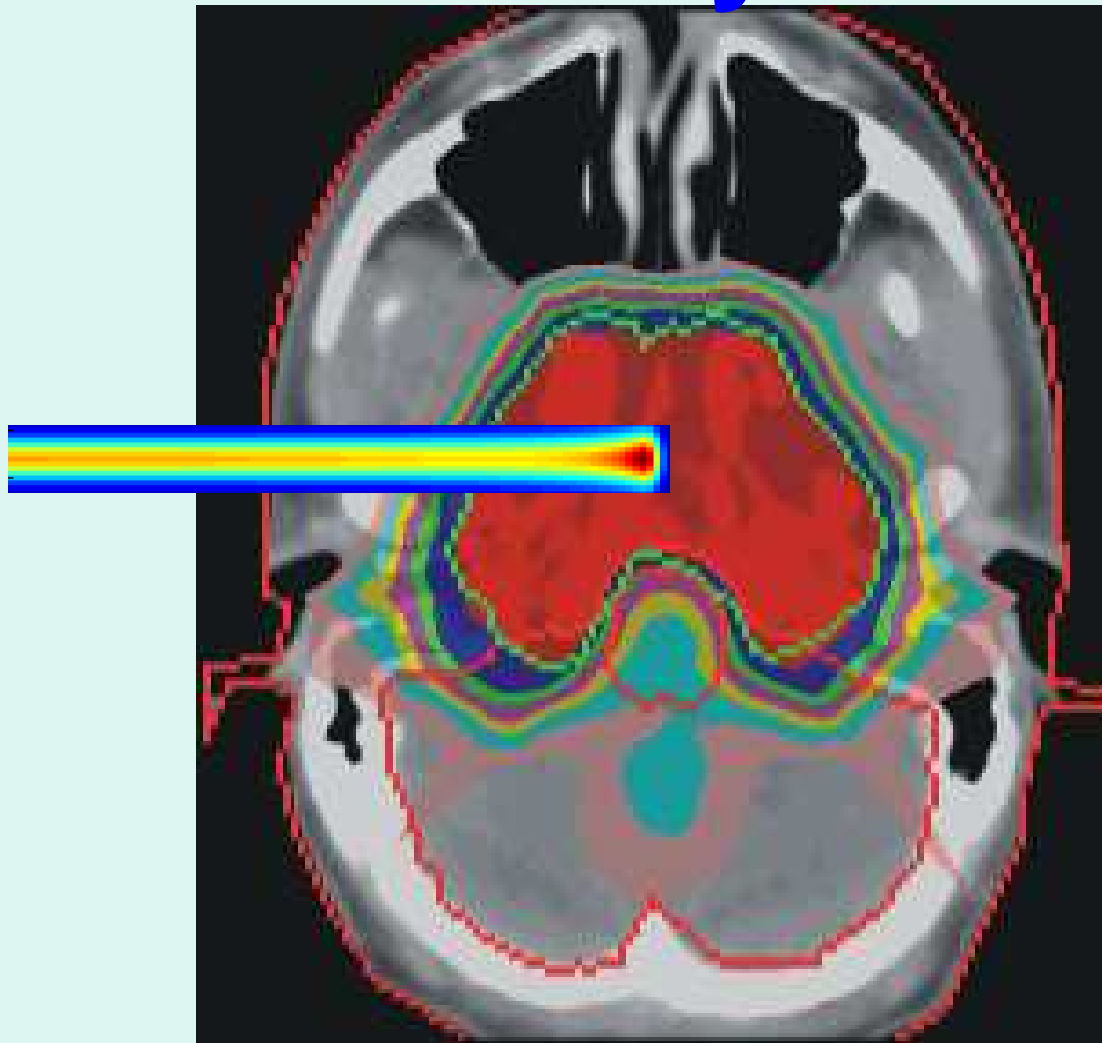


Proton beams
from 3 directions

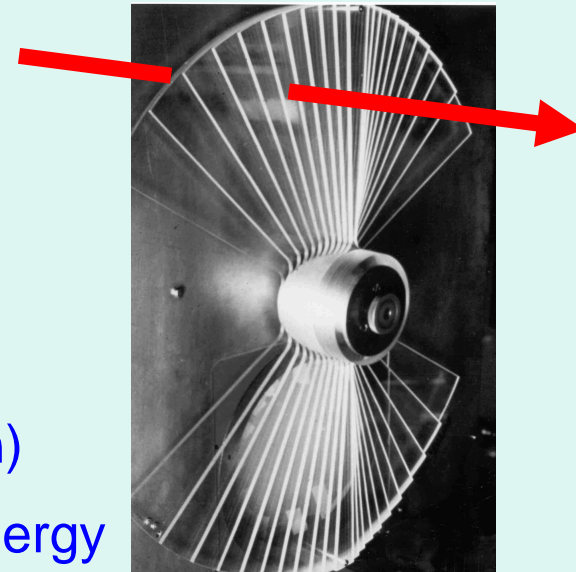
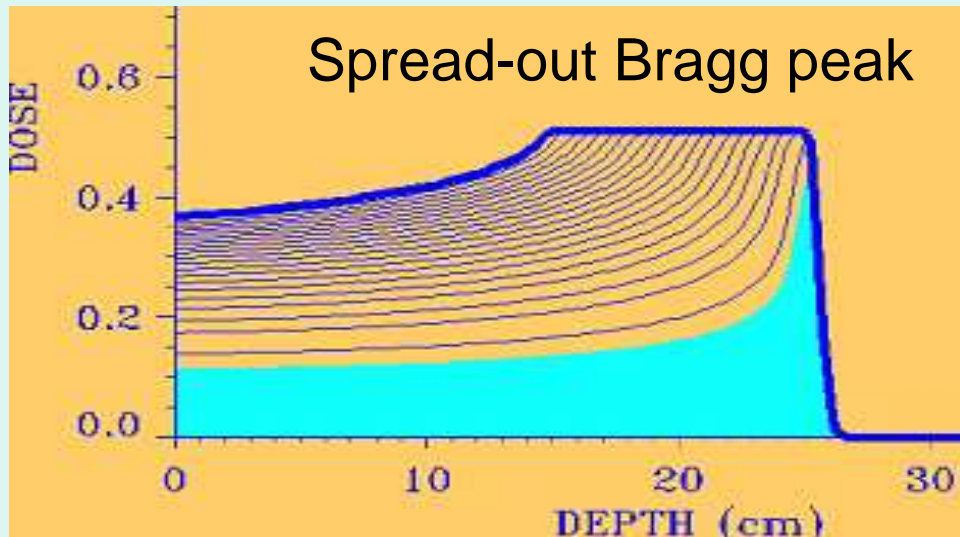


pictures: MedAustron

Dose delivery techniques



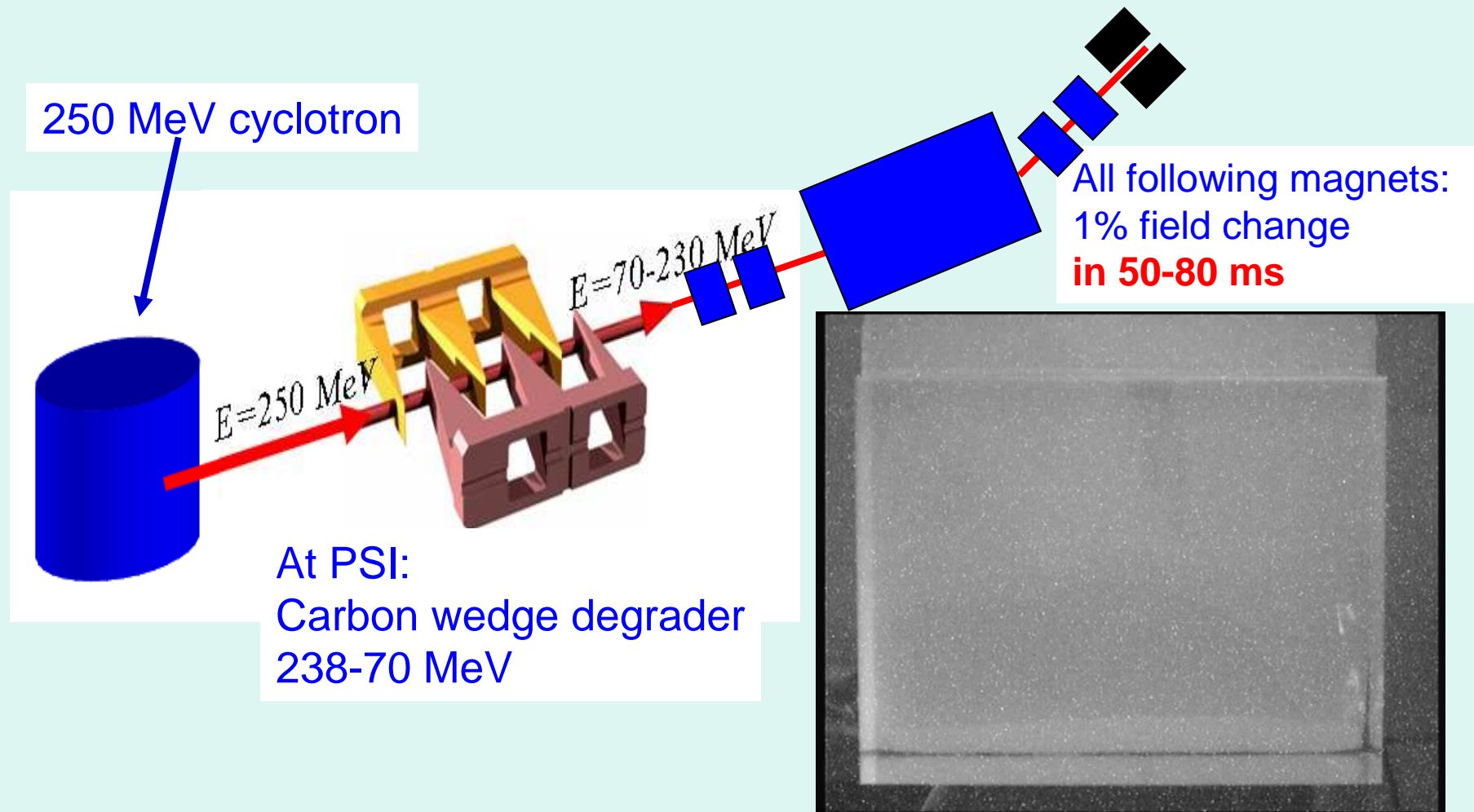
Dose delivery techniques: **Depth**



Methods to control depth:

- 1) **Vary energy** in accelerator (**synchrotron**)
- 2) **Slow down** from a fixed to the desired energy
 - modulate “just” before patient (in “nozzle”)
 - at start of beam transport (**cyclotron**)

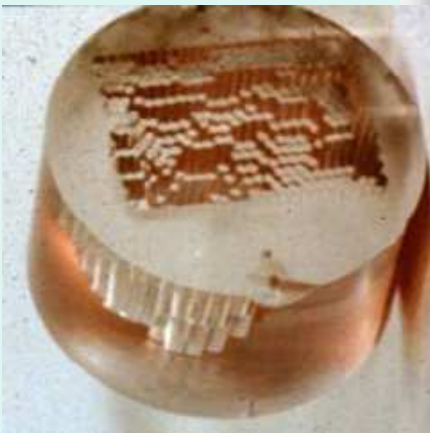
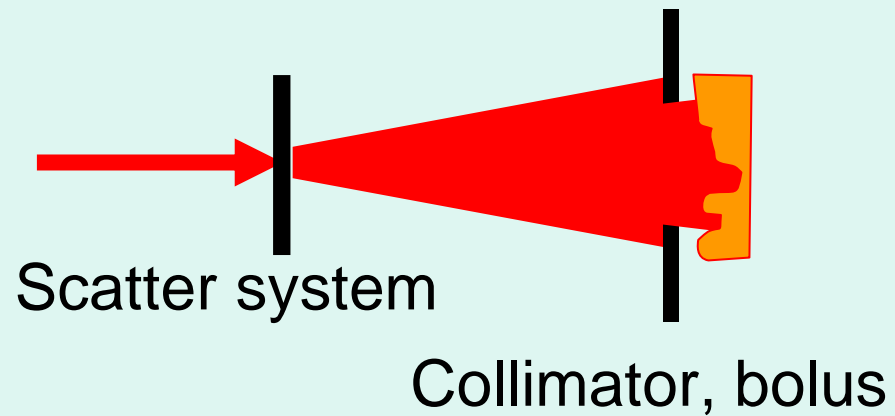
Dose delivery techniques: **Depth**



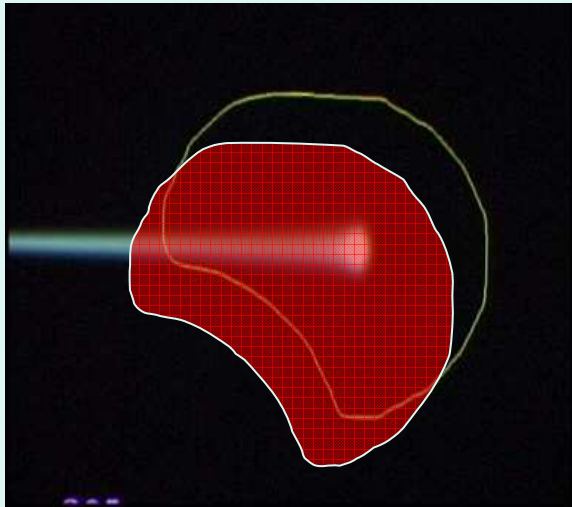
- fast treatment
- fast room switching

Dose delivery techniques: lateral

Scatter technique

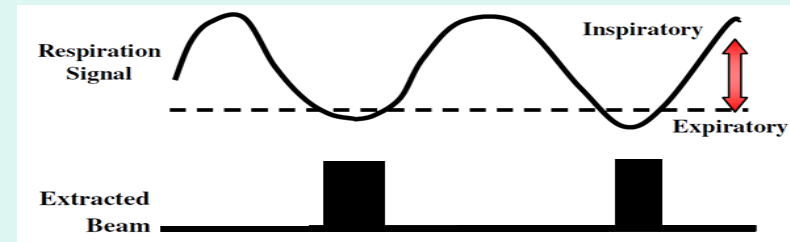


Organ motion

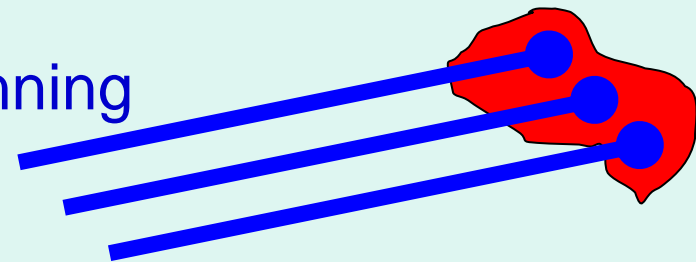


Possible solutions:

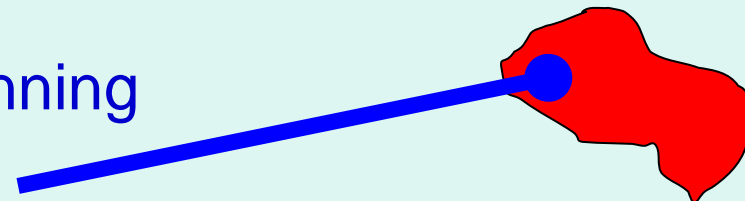
- Gating



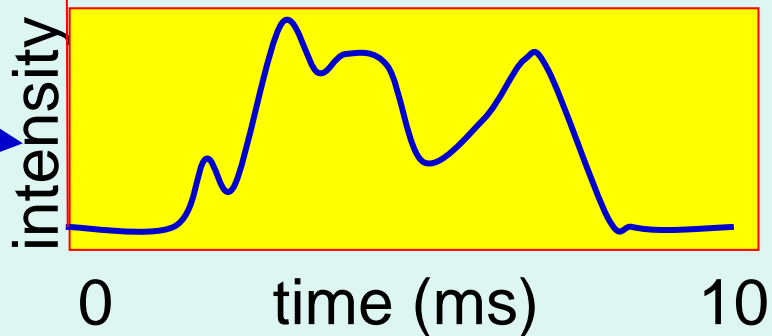
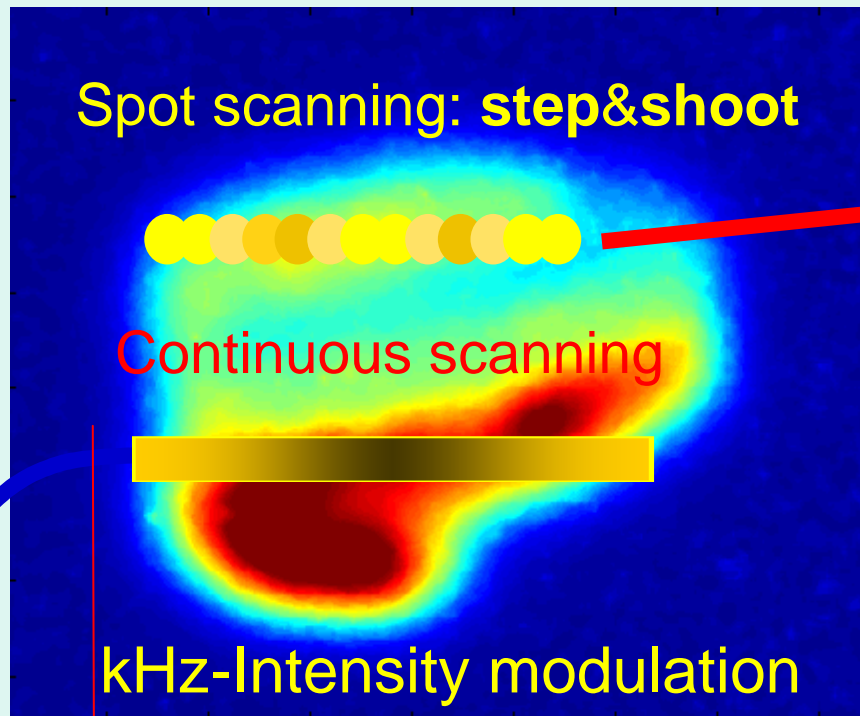
- Adaptive scanning
(tumor tracking)



- Fast rescanning



Pencil beam scanning



Requirements for accelerator:

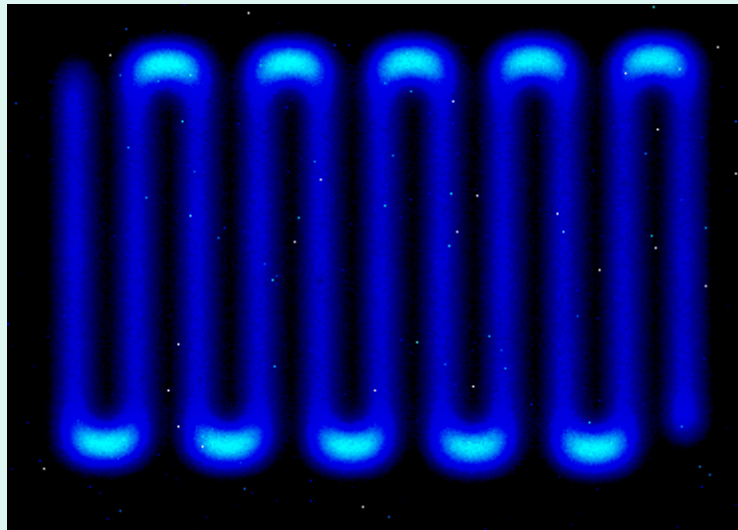
- stable beam position

allows fast target **repainting**:
15-30 scans / 2 min.

Requirements for accelerator:

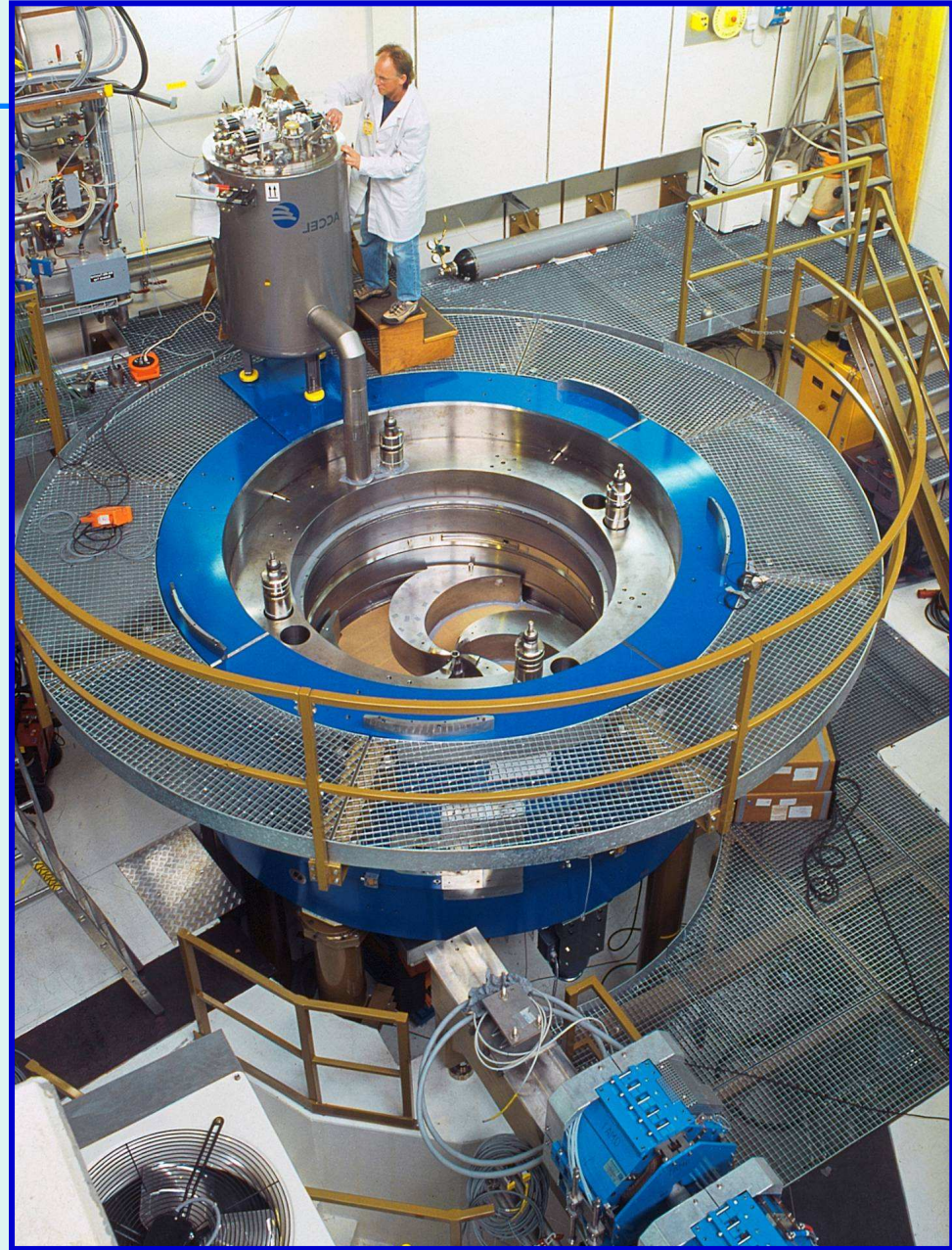
- stable beam position
- continuous and stable beam
- fast adjustable beam intensity
- fast adjustable beam energy

PSI Gantry-2: fast 3D scanning

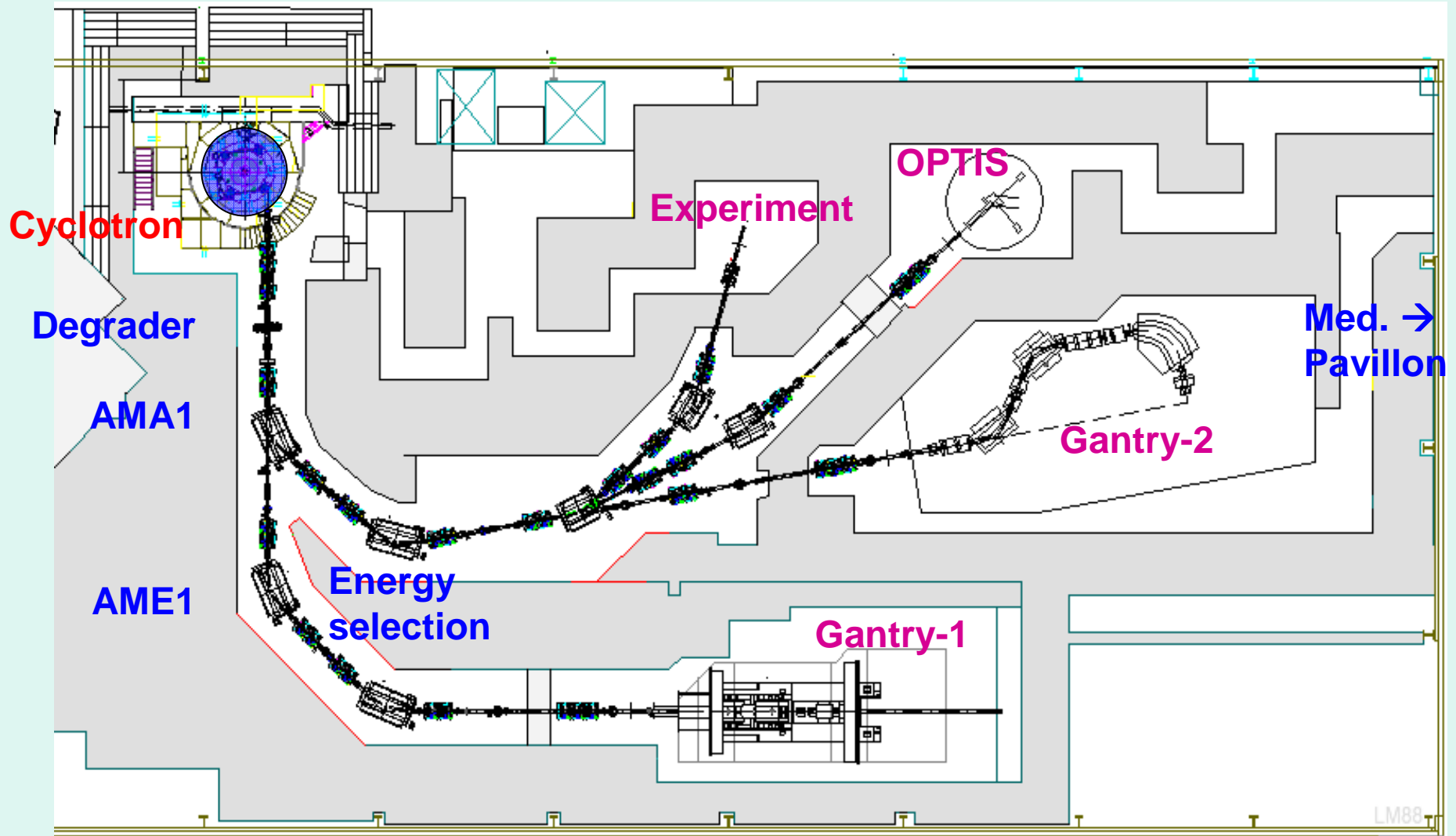


PSI-"Gantry-2"
Eros Pedroni
David Meer

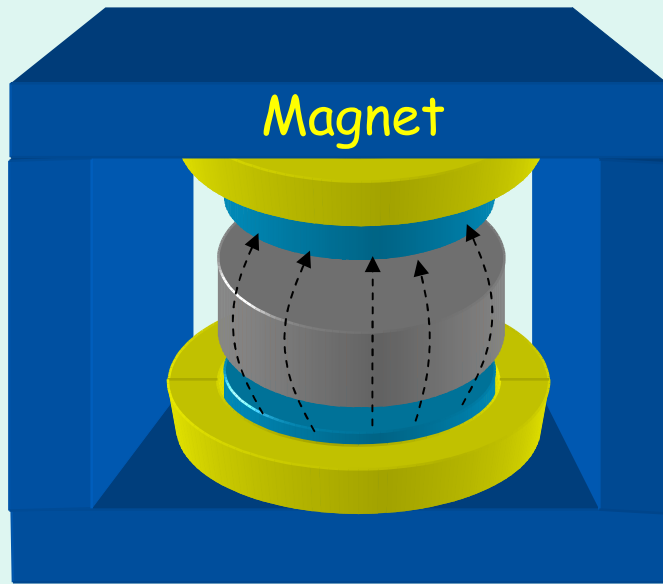
The SC cyclotron at PSI



the PROSCAN facility



Cyclotron (1930)



Magnet

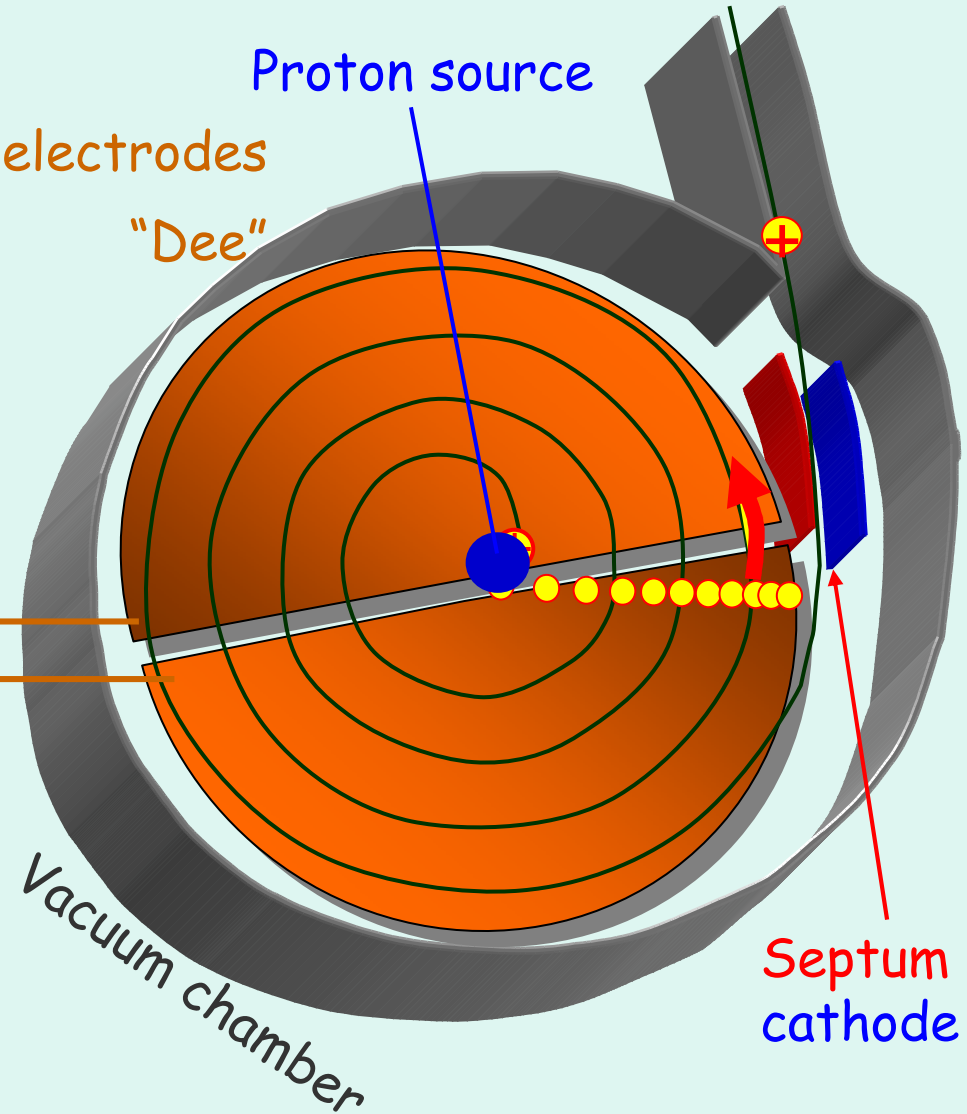
Proton source
RF electrodes
"Dee"

RF-Voltage "Vdee"

RF frequency f

At electrode slit crossing:

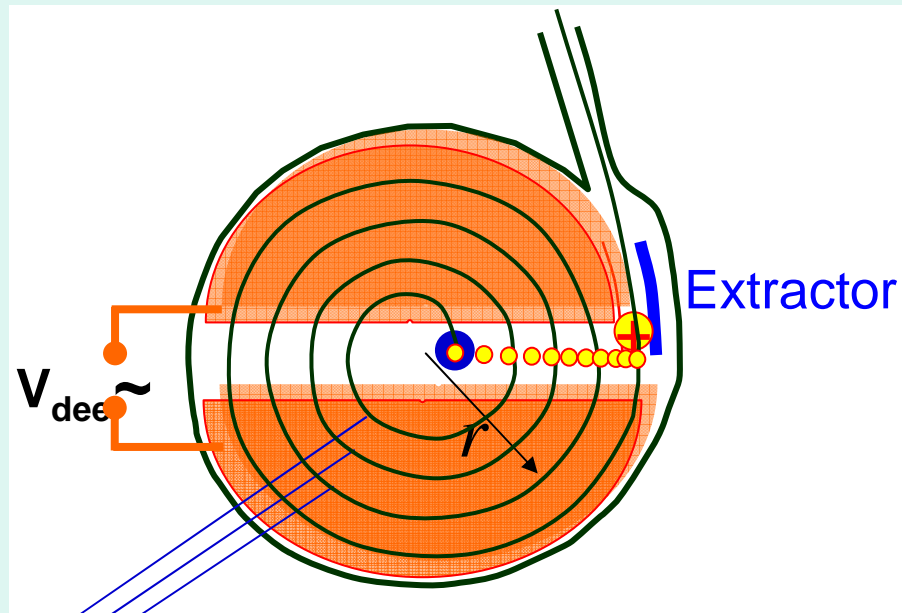
Energy gain $\Delta E = qV_{dee}$



Vacuum chamber

Septum cathode

Cyclotron



Circular orbits:

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

$$\Rightarrow T_{circle} = \frac{2\pi \cdot r}{v} = \frac{2\pi \cdot m}{Bq}$$

$\Rightarrow T_{circle}$ independent from orbit radius r

m = mass

v = speed

r = orbit radius

B = magnetic field

q = charge

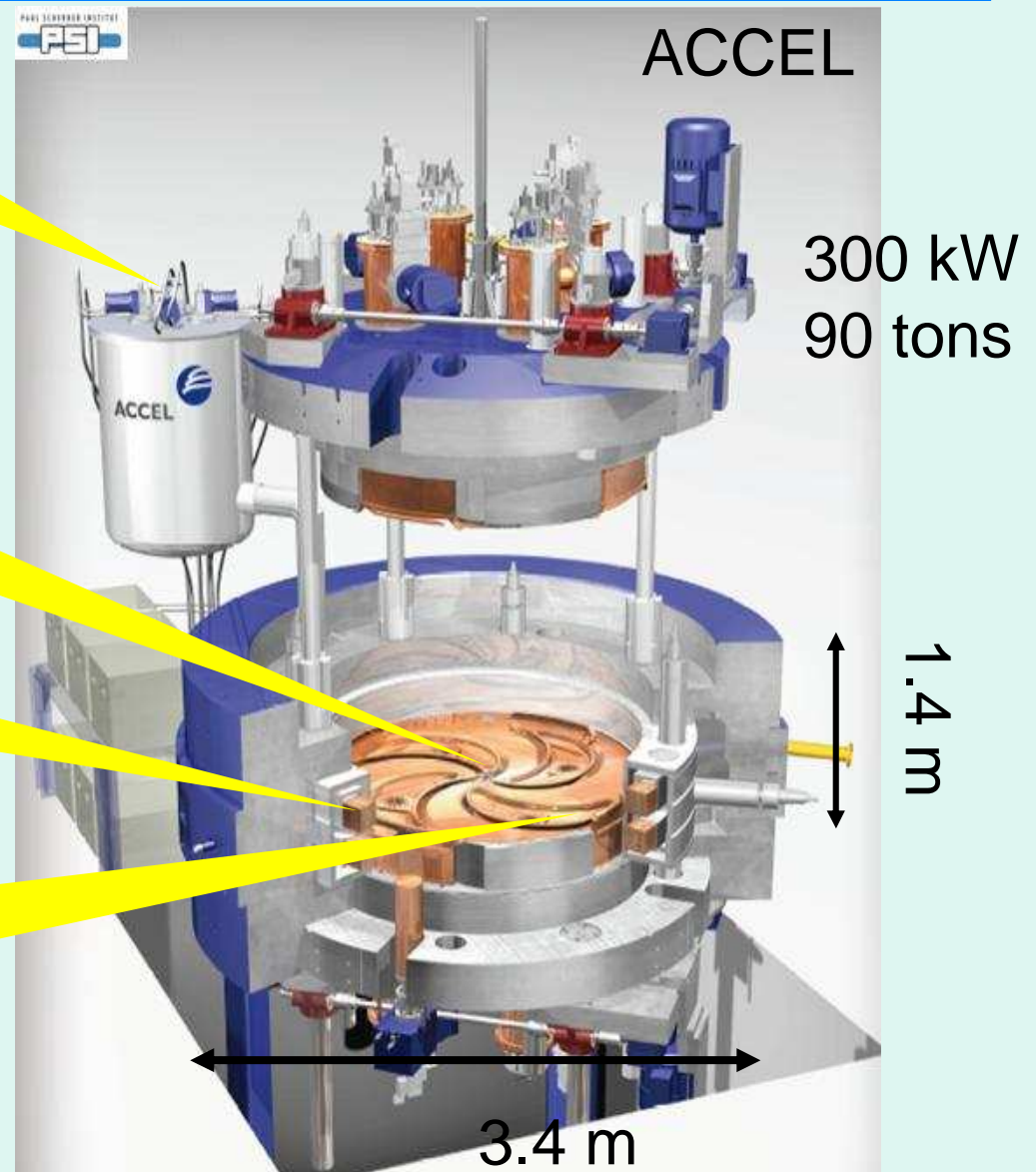
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

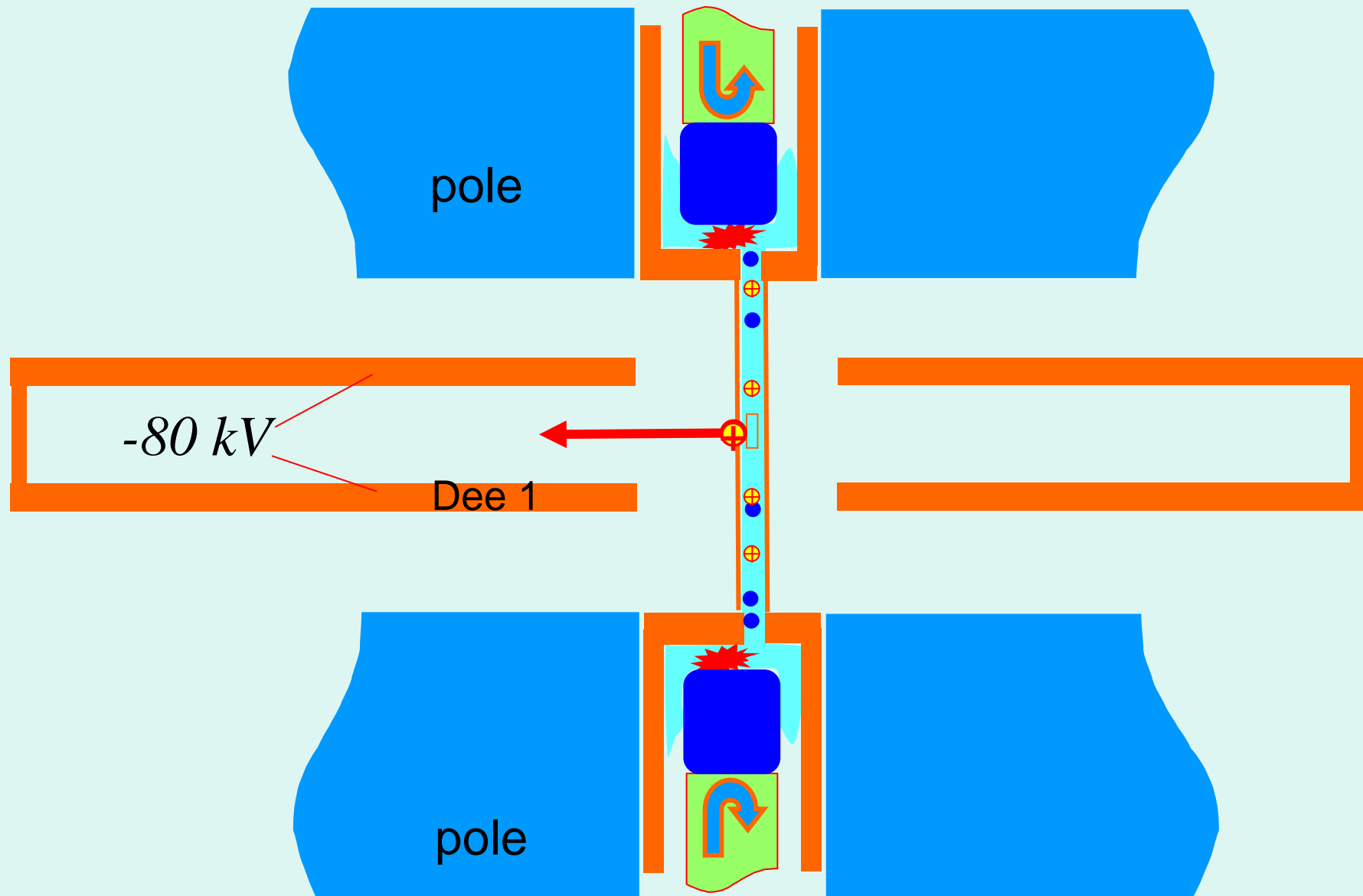
Proton source

superconducting coils
=> 2.4 - 3.8 T

4 RF-cavities:
72 MHz (h=2)
~80 kV

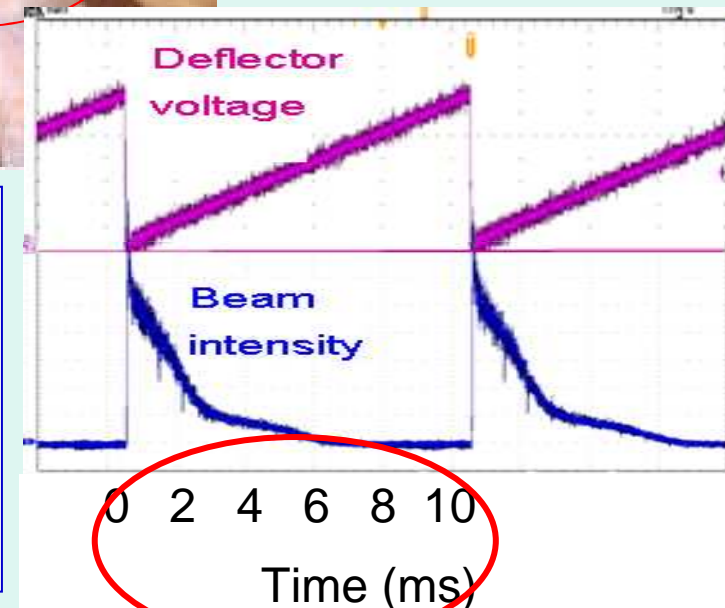
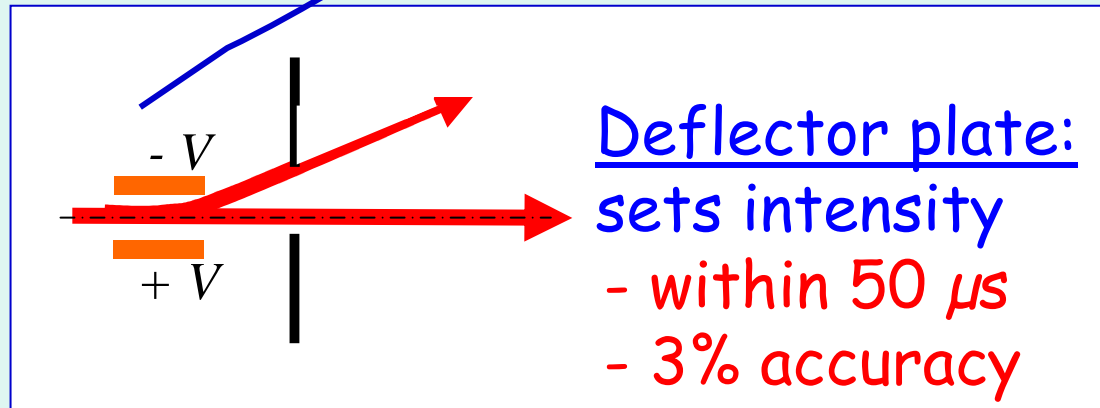
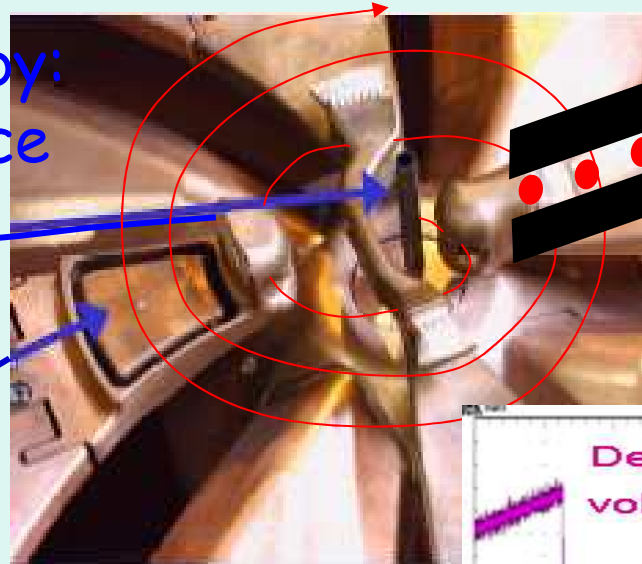


Internal proton source



intensity control

Max. intensity set by:
proton source



Relativity in high-E cyclotrons

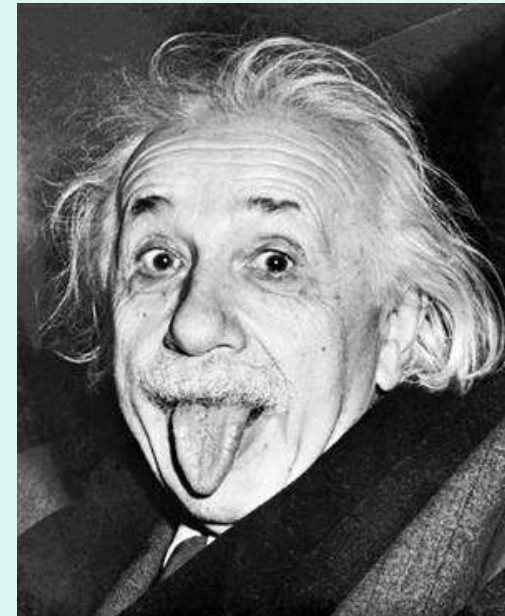
Cyclotron essential: $T_{circle} = \frac{2\pi \cdot m}{Bq} \Rightarrow T_{circle}$ constant for all radii

However, when $v \rightarrow c$: $m = \frac{m_0}{\sqrt{1 - v^2/c^2}} = \gamma \cdot m_0$

e.g: 10 MeV p: $v/c=0.14 \Rightarrow m=1.01 m_0$

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

$\Rightarrow T_{circle}$ increases with radius \Rightarrow **particles lose pace with RF.**



Relativity in high-E cyclotrons

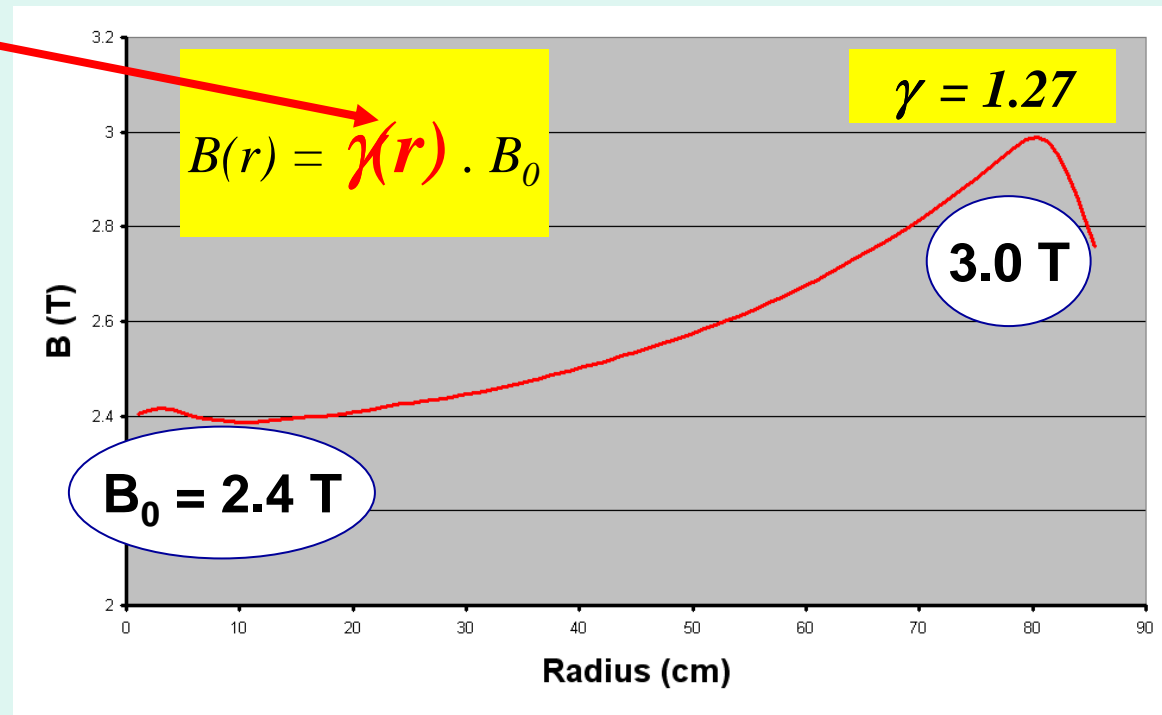
$$T_{circle} = \frac{2\pi \cdot m}{q \cdot B}$$

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

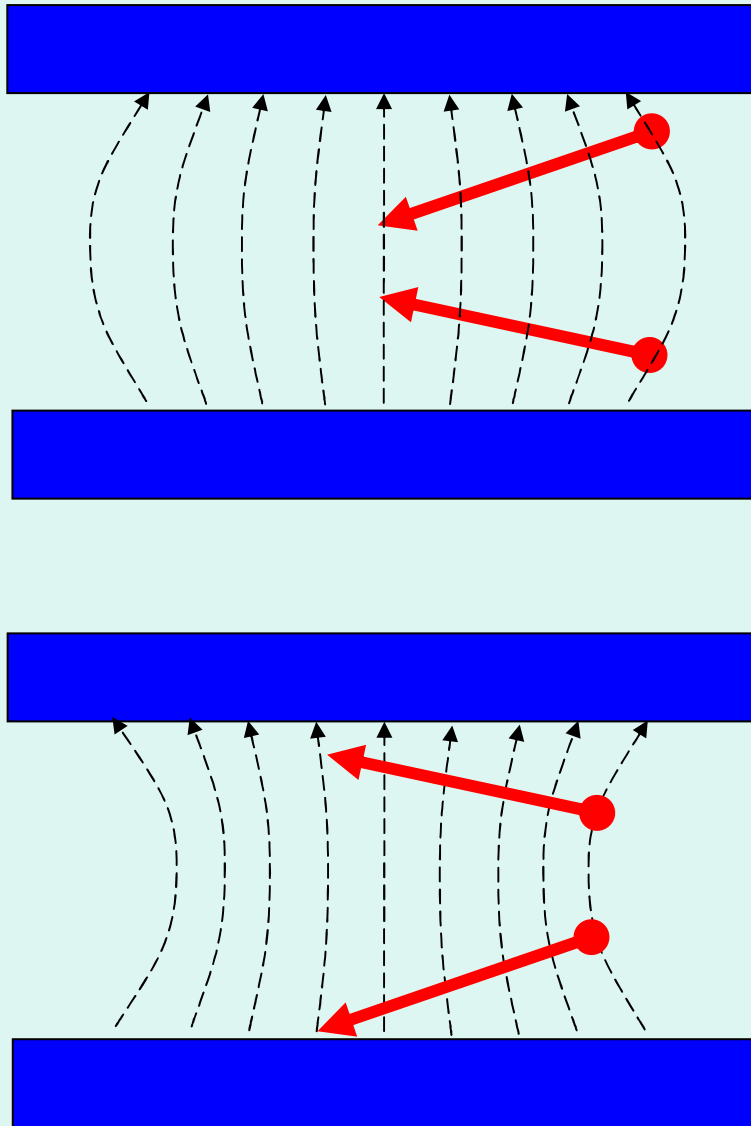
$\gamma(r)$

Remedies when T_{circle} increases with radius:

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



Relativity in high-E cyclotrons



Radial variation of field (field index):

Vertical focusing: $v_z^2(R) = n(R)$

$$n(R) = - [R/B(R)] [dB(R)/dR]$$

$dB/dr < 0 \rightarrow n > 0 \rightarrow v_z$ exists

When B decreases with radius:

Automatic vertical stability

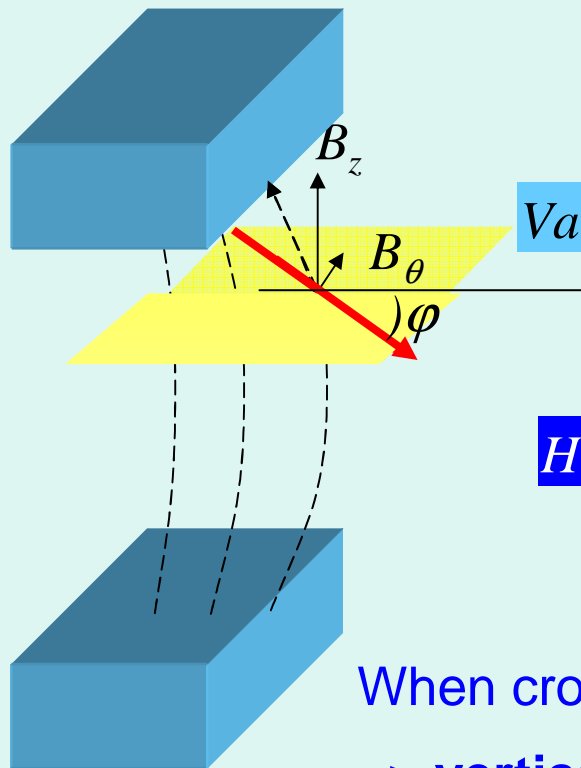
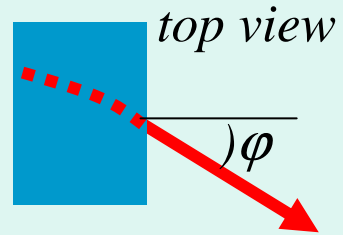
When B increases with radius:

No vertical stability

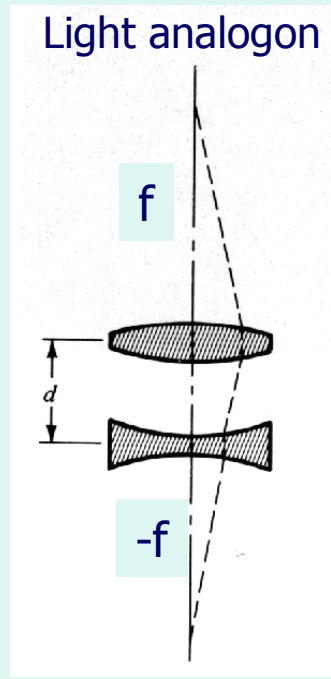
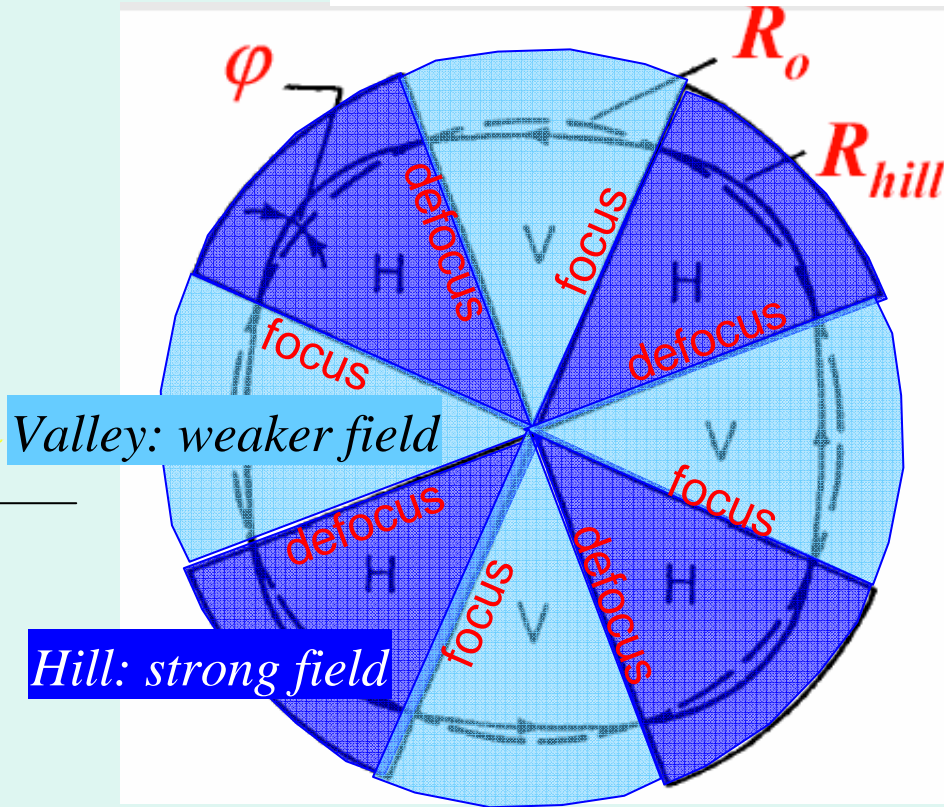
$dB/dr > 0 \rightarrow n < 0 \rightarrow$ no v_z

$$n(R) = - [R/B(R)] [dB(R)/dR] = - (\gamma^2 - 1)$$

Vertical focussing: Azimuthally Varying Field



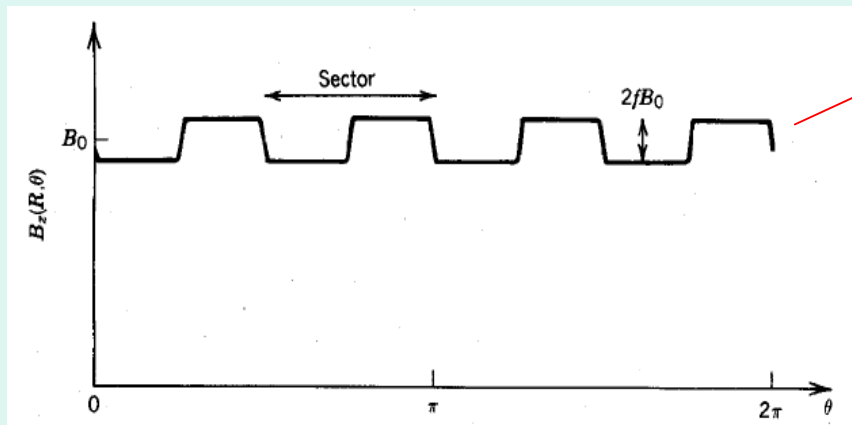
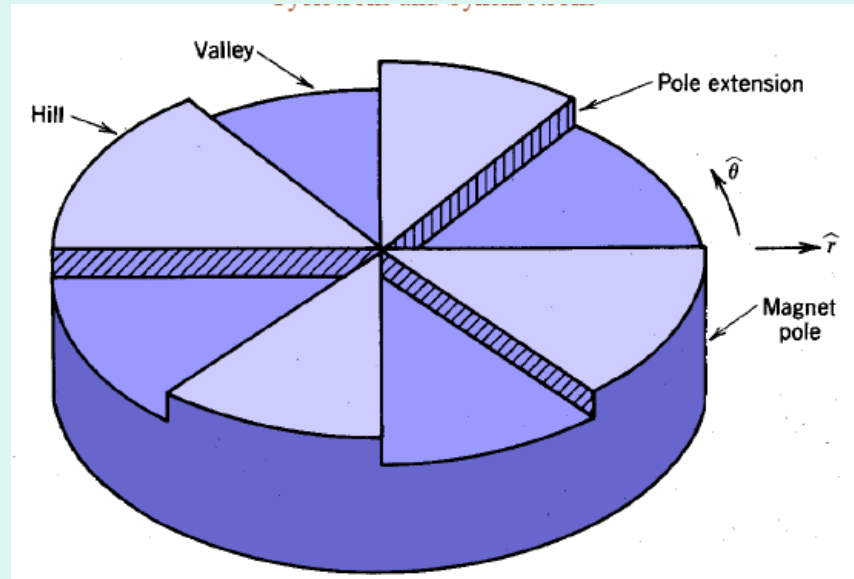
Thomas-Cyclotron (1938)



$$f_{\text{comb}} = f^2/d$$

When crossing B change **not** \perp
 \Rightarrow vertical force from $B_{\theta} \times v$

Vertical focussing: Azimuthally Varying Field



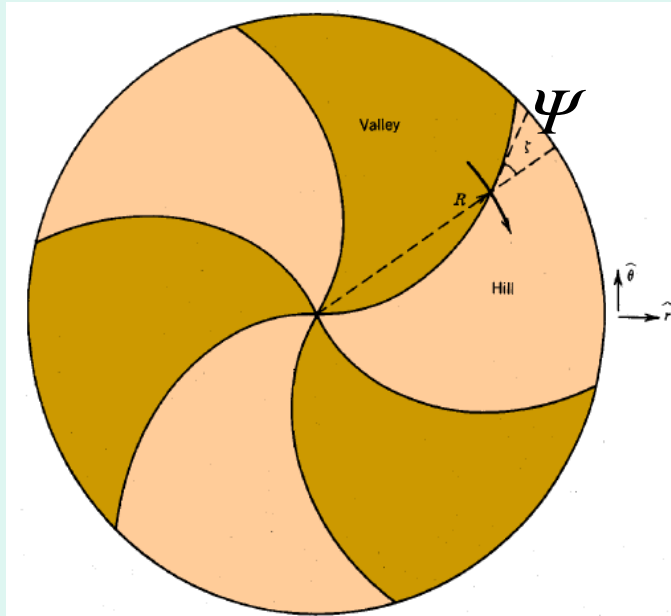
Flutter function

$$F(R) = \overline{[(B_z(R, \theta) - B_o(R))/B_o(R)]^2}$$

Thomas focusing: $\nu_z^2(R) = n(R) + F(R)$

Vertical focussing

Azimuthally Varying Field cyclotron



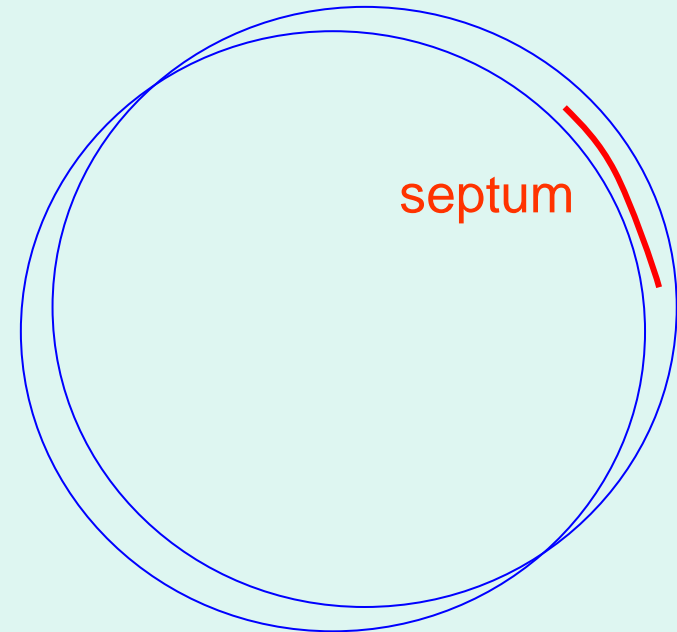
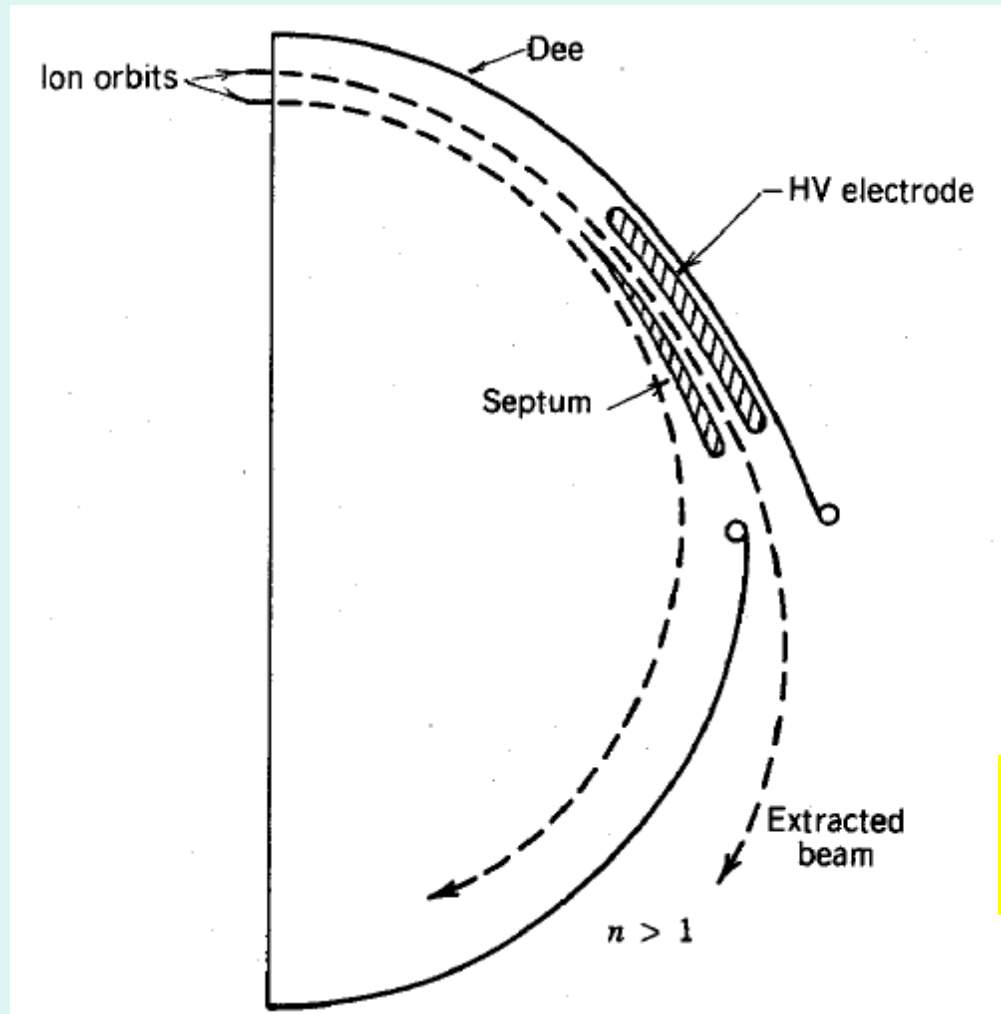
$$v_z^2(R) = n(R) + F(R) \cdot (1 + 2 \tan(\psi(R)))$$

to compensate :

- increasing $B\rho$
- Increasing defocussing by main field

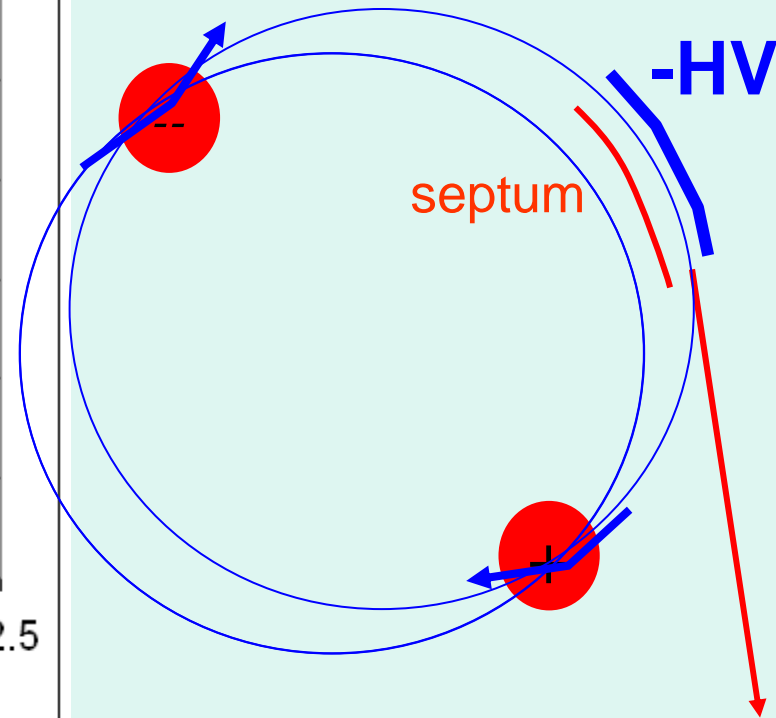
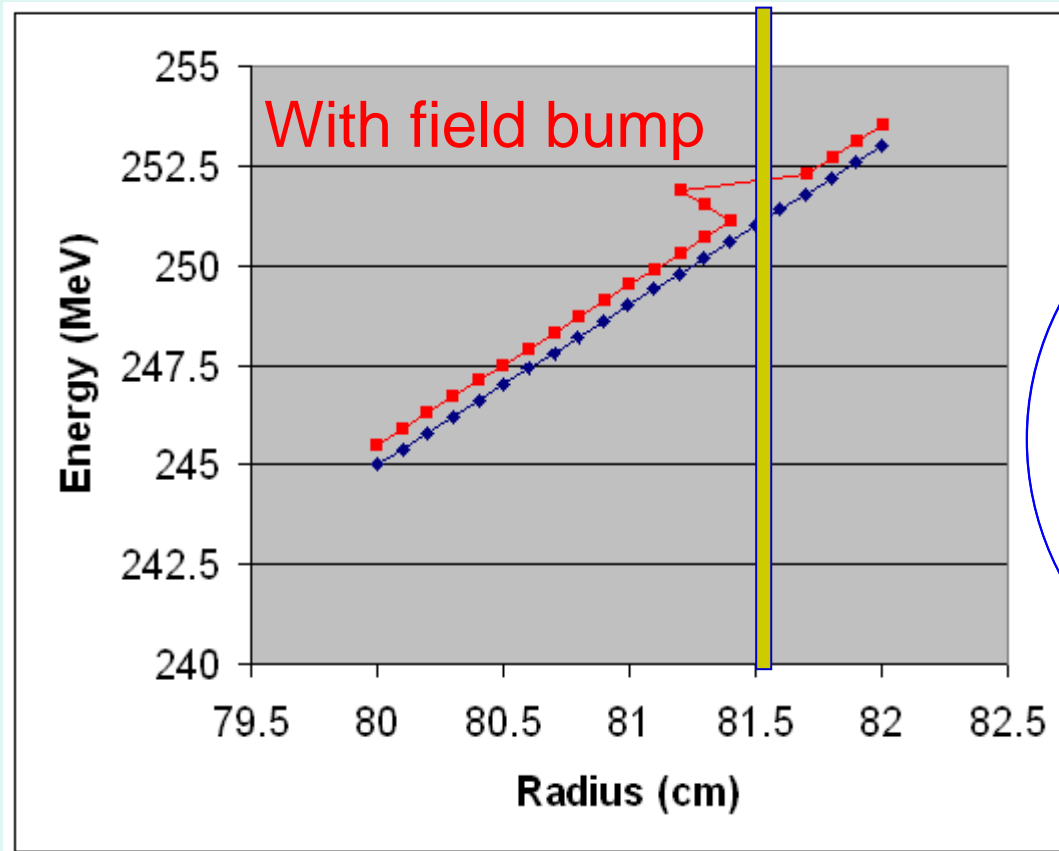
=> increase angle Ψ with radius => spiral shape

Extraction from cyclotron

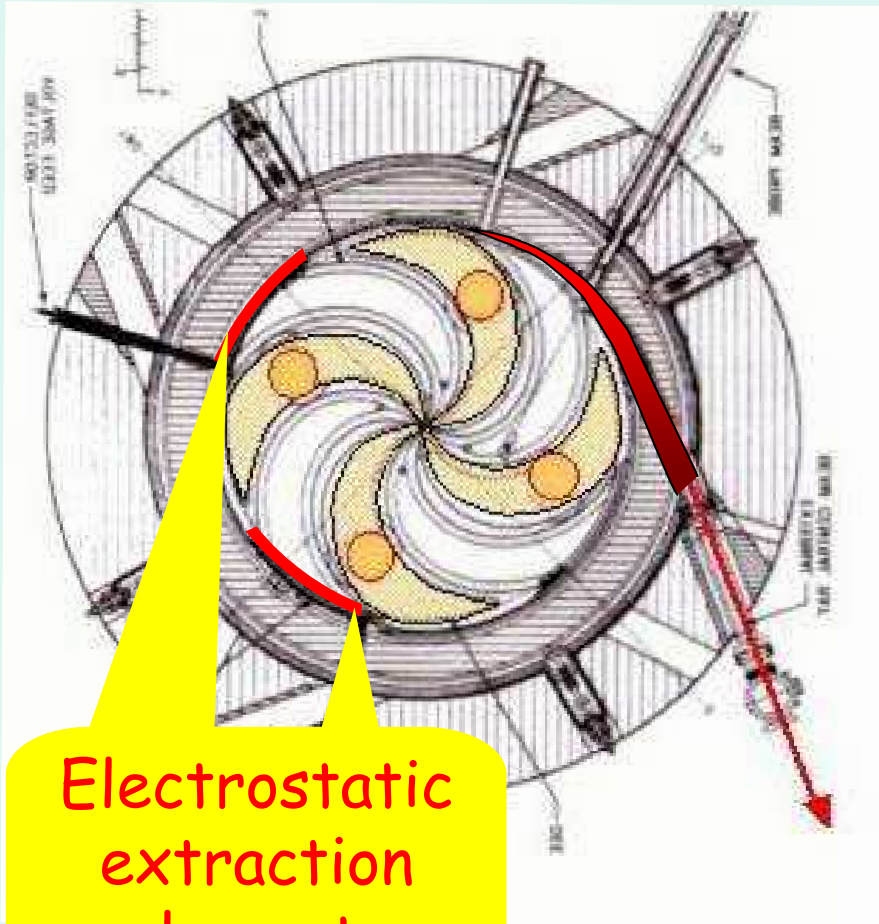


Resonant extraction: use $V_r=1$

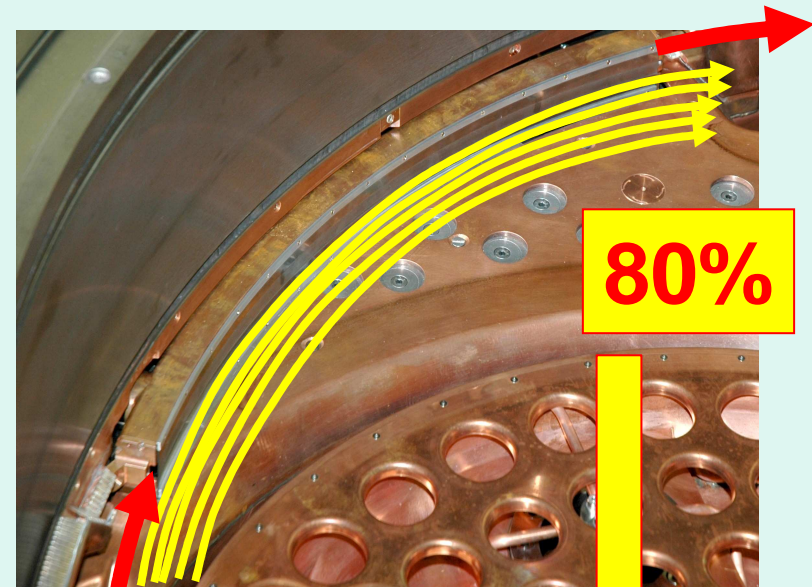
resonant extraction



Extraction from cyclotron



Electrostatic
extraction
elements



80%

Low radioactivity

(ACCEL / Varian)

Advantages of a cyclotron

=> a cyclotron provides:

- continuous beam
- any intensity
- very fast adjustable intensity
- accurate intensity control
- great reliability

+ range change of 5 mm < 50 ms

(with fast degrader and good magnets + power supplies)

