Accelerators and Techniques in Hadron Therapy

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See also:

- J.M. SchippersCERN Accelerator School, 2016 , p165-176,
- https://cds.cern.ch/record/2271793/files/33-8-PB.pdf
- H. Paganetti (ed.), Proton Therapy Physics, Chapter 3.

Contents

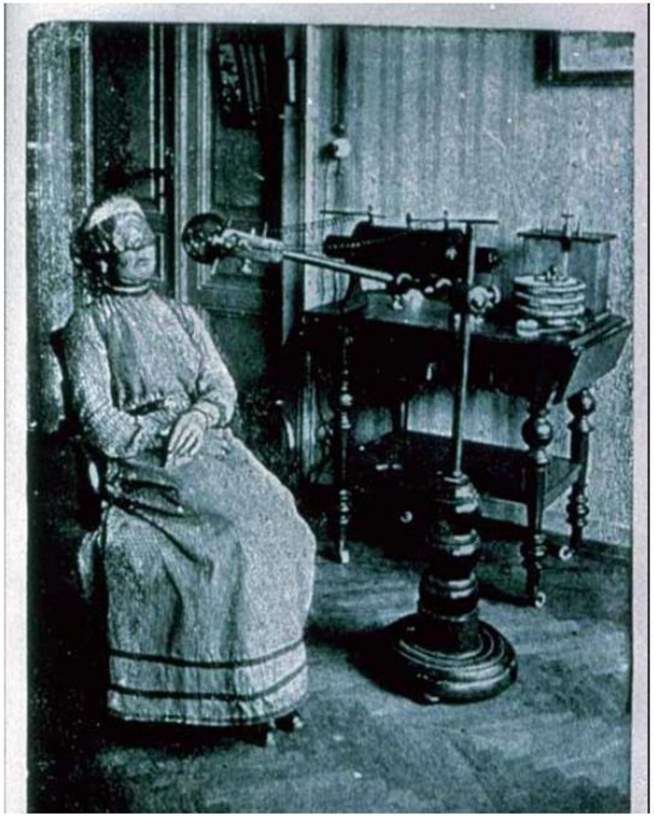
- Radiotherapy:

  Irradiations with X-rays, protons, ions
- Dose delivery techniques
- Accelerators
  - Synchrotron
  - Cyclotron
- Gantries
- Recent developments

Radiotherapy: started with X-rays

1895: Röntgen discovers x-rays

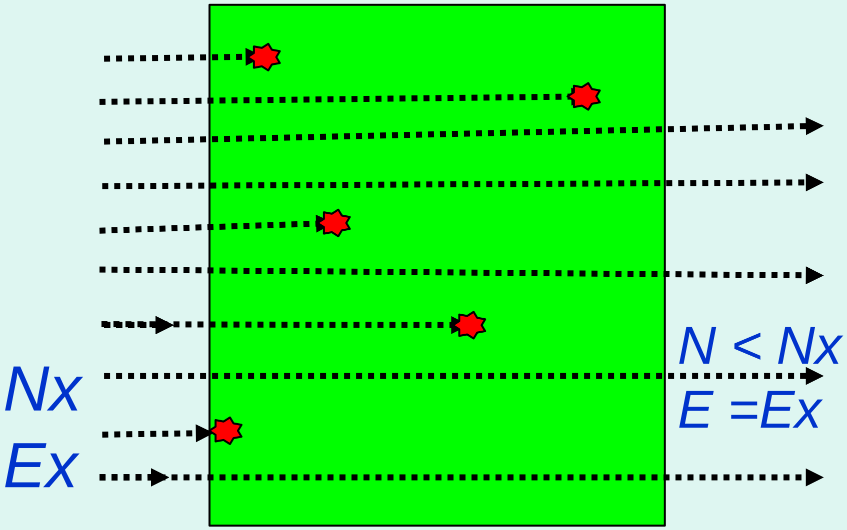
1896: Emil Grubbe, a Chicago 'electrician' and metallurgist, first treated the recurrent breast cancer of a 55-year-old woman in the last days of January 1896 - only weeks after the announcement of Roentgen's discovery.



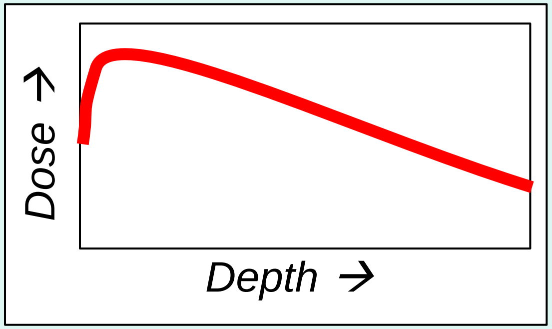
1897: Note that the eyes are shielded for protection.

X-ray photons

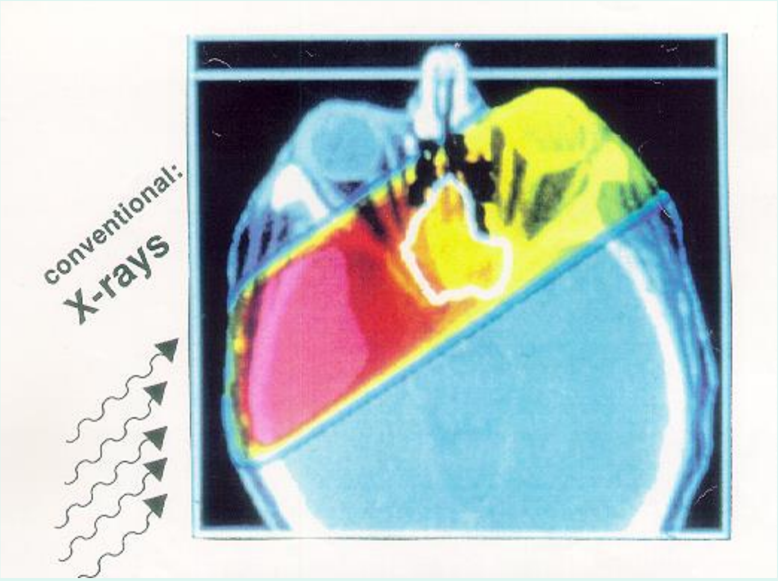
X-rays



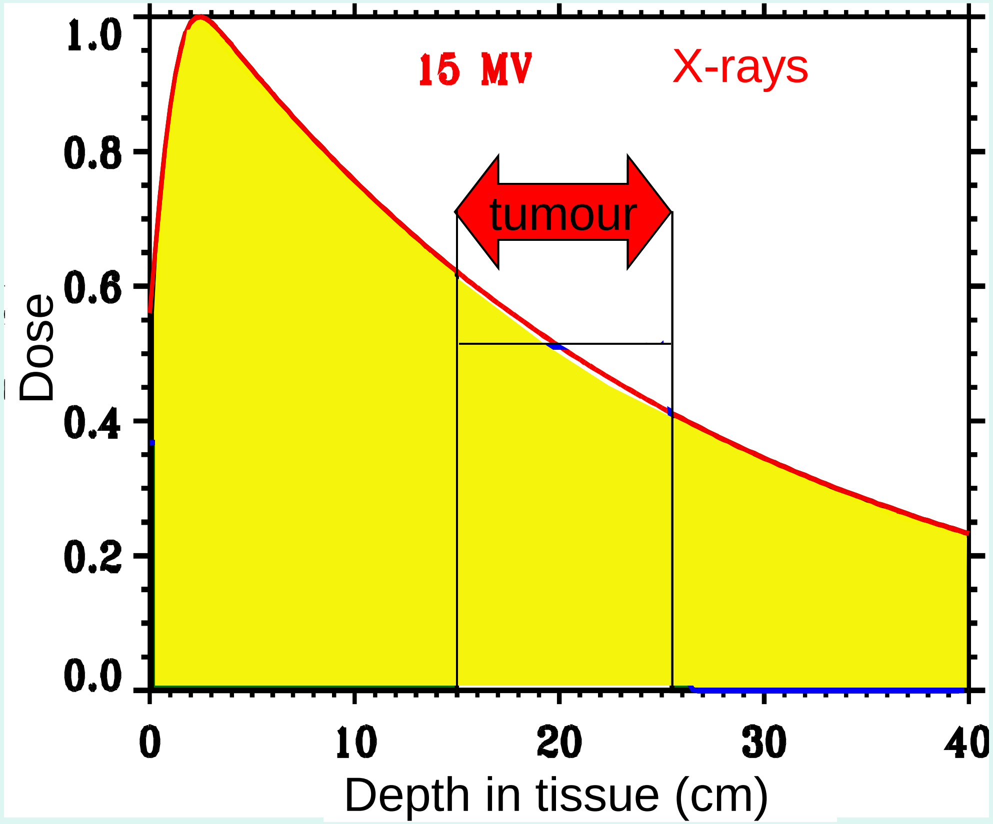
Absorbtion → dose



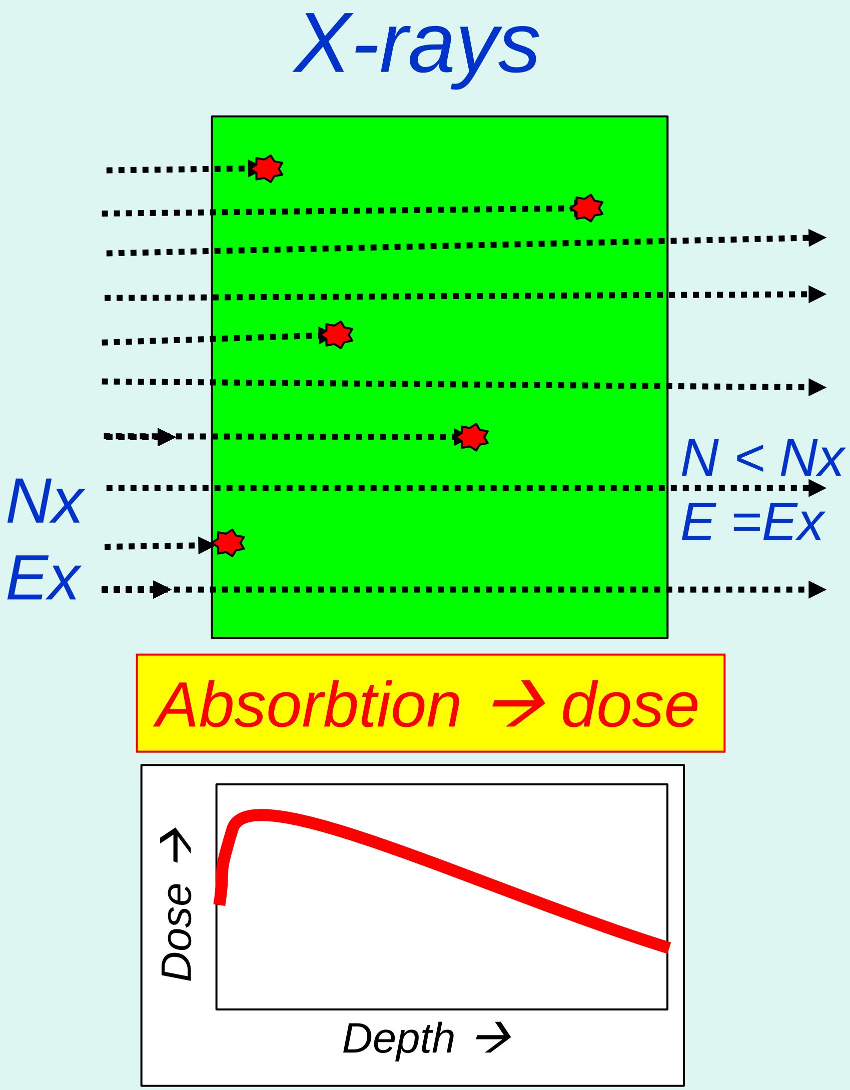
Irradiation with X-rays (photons)

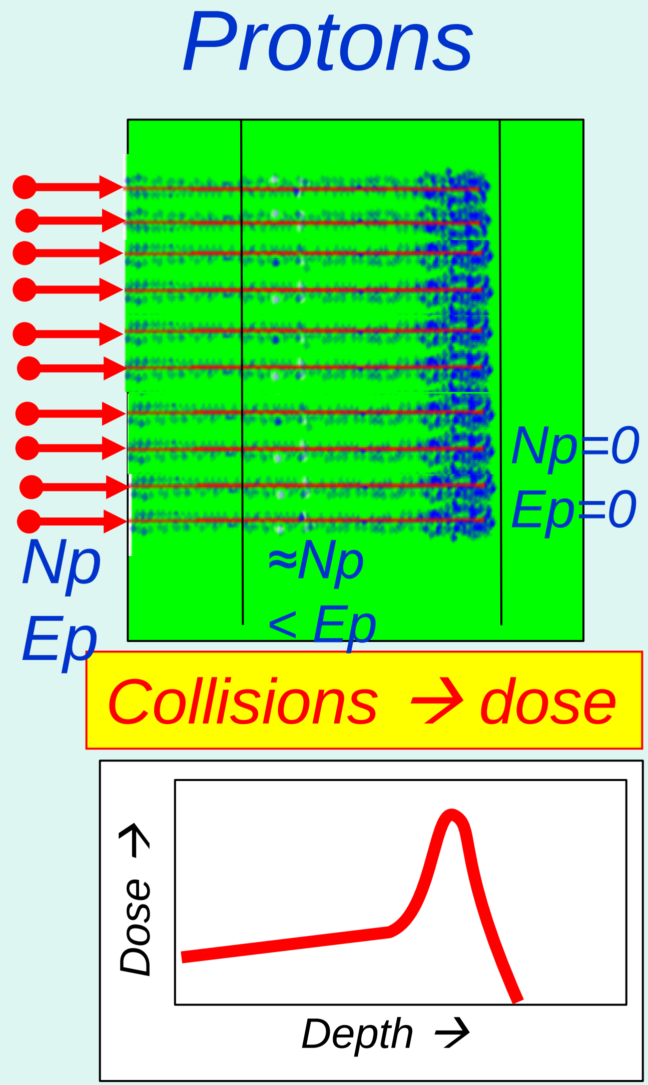


Depth-dose curve:

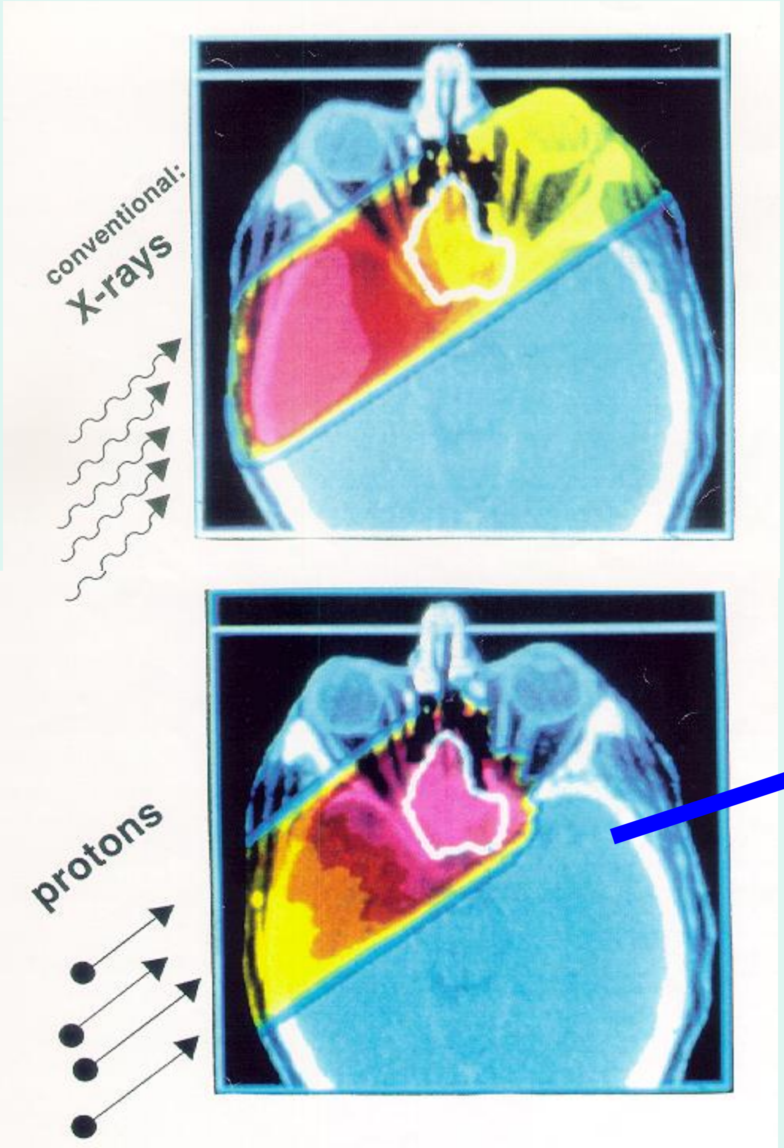


X-ray photons ↔ Protons

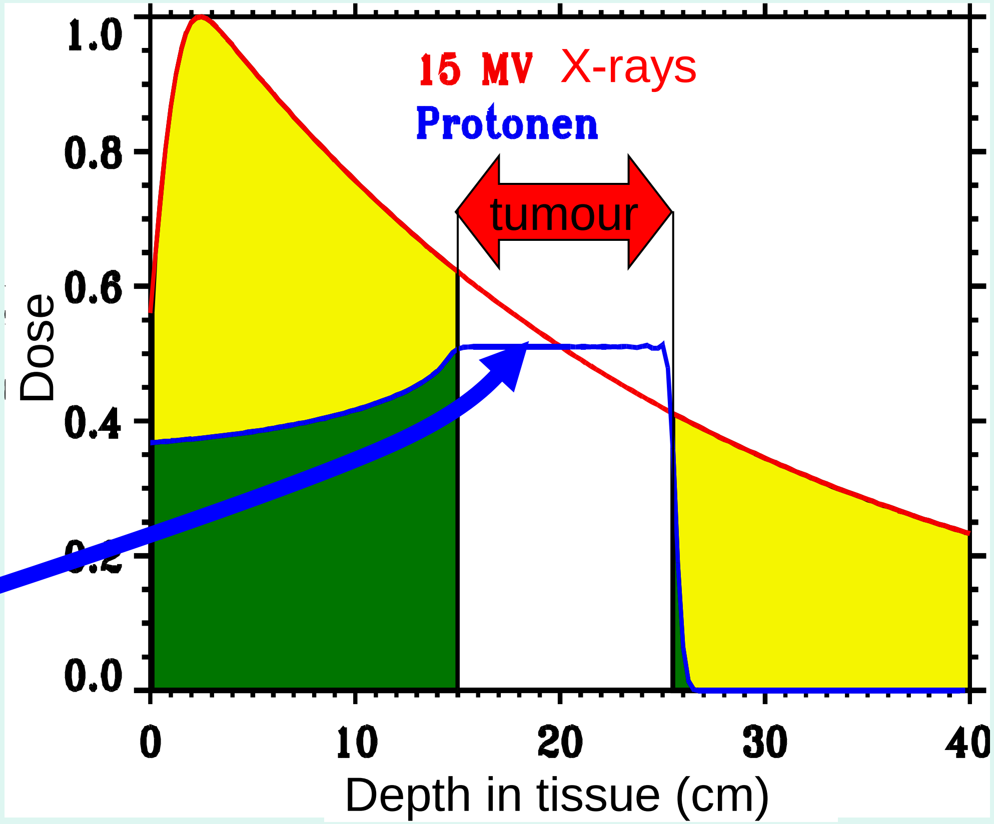




Why Protons or Ions?



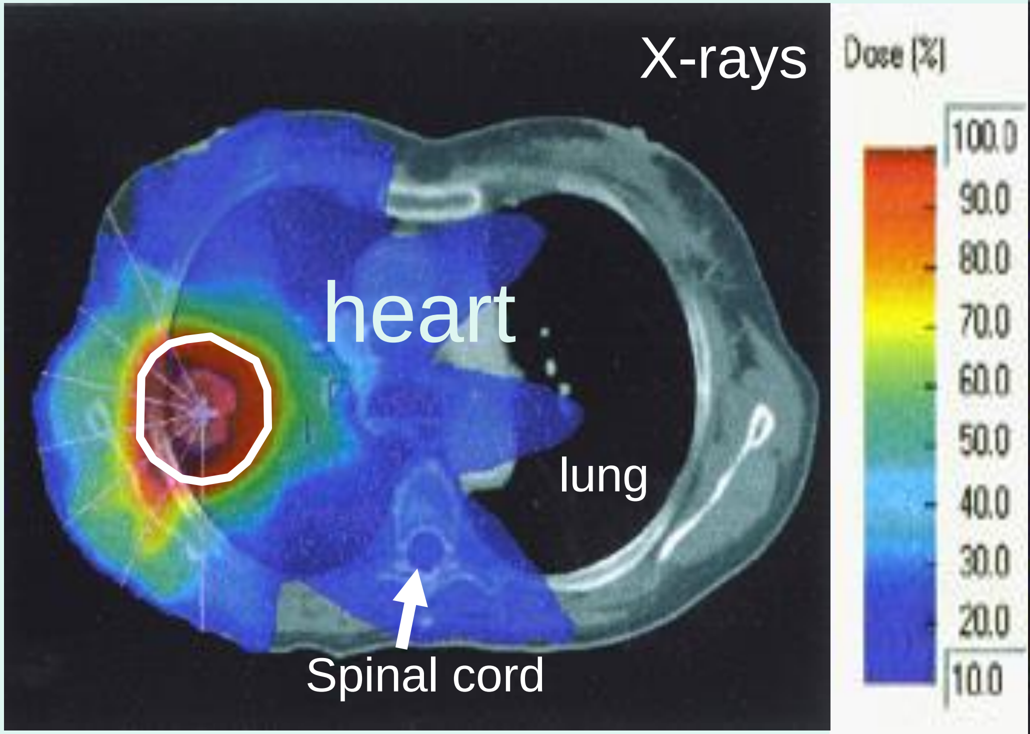
Depth-dose curve:

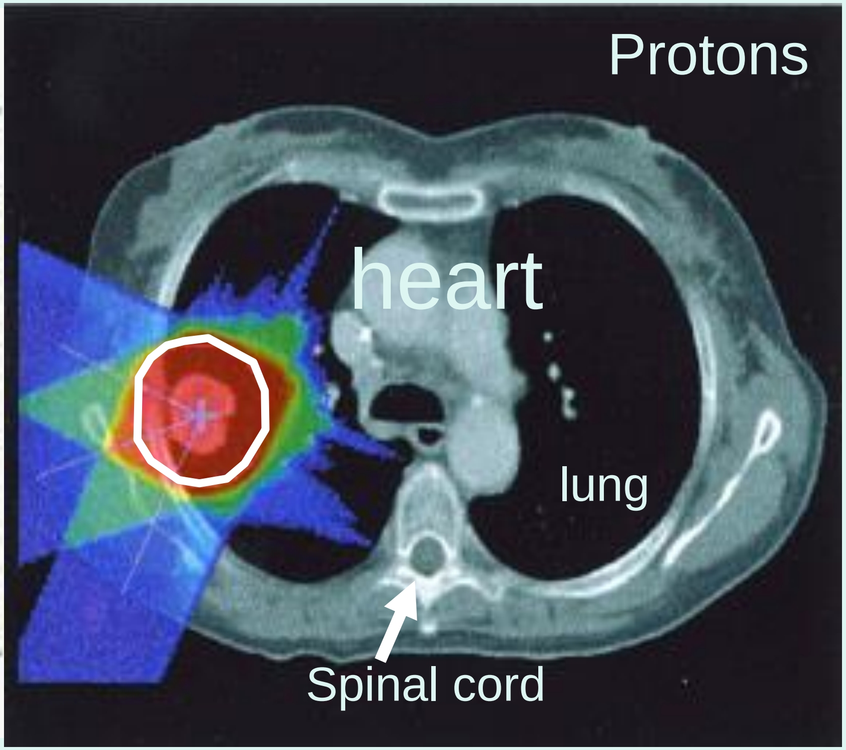


X-rays vs. Protons

X-ray beams (IMRT)
from 7 directions

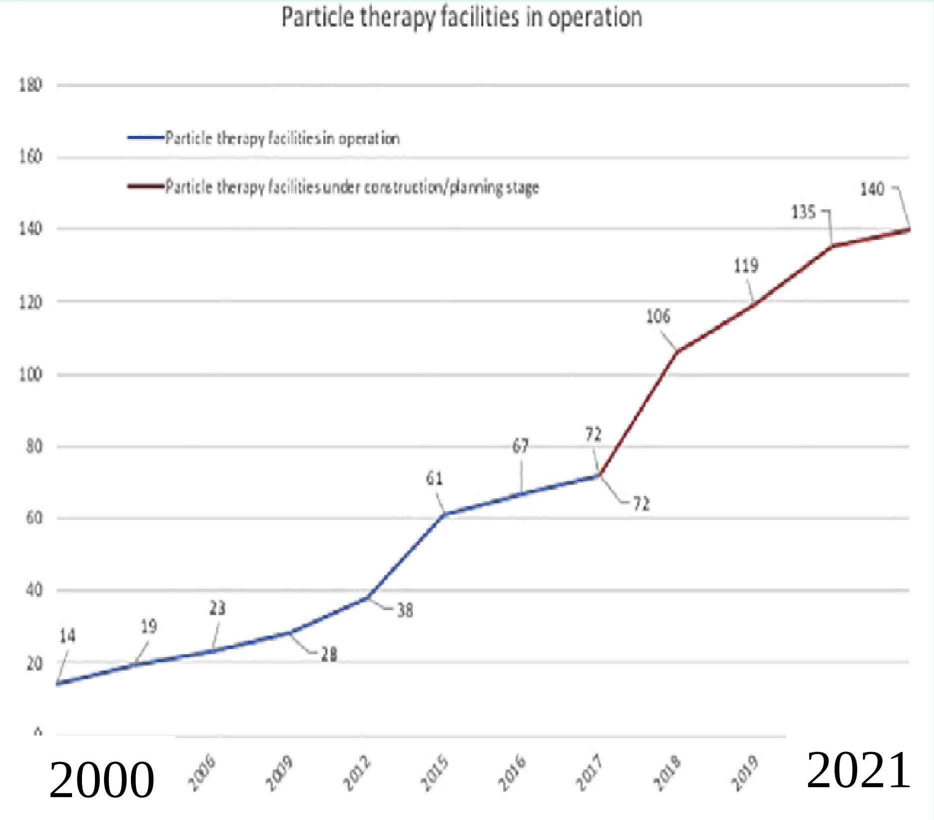
Proton beams
from 3 directions

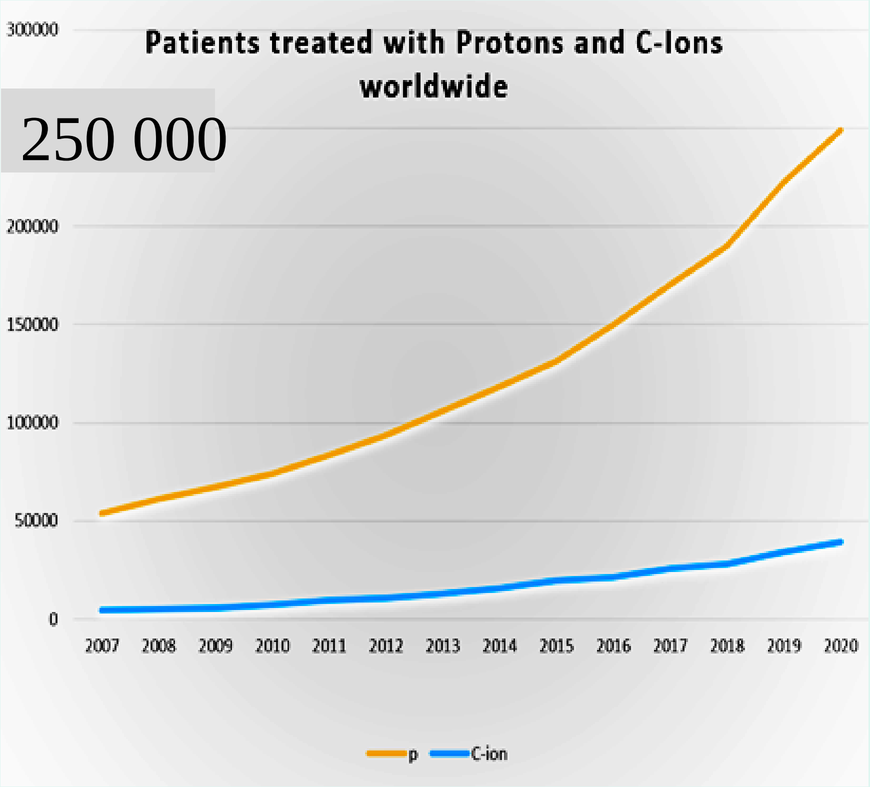




pictures: Medaustron

The boost in particle therapy





Hadron therapy facilities (http://www.ptcog.ch/index.php).

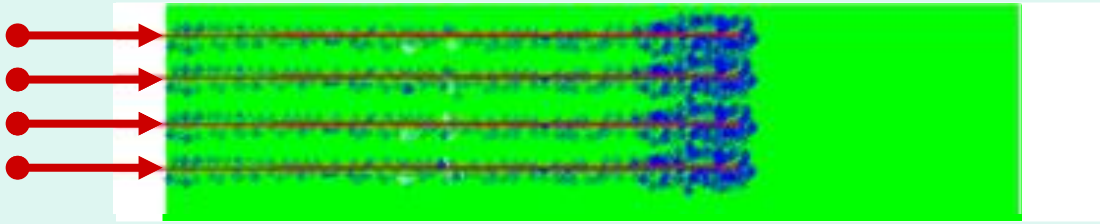
Proton depth-dose curve

Bethe-Bloch formula:

Energy loss (ΔE) per unit length (Δx):

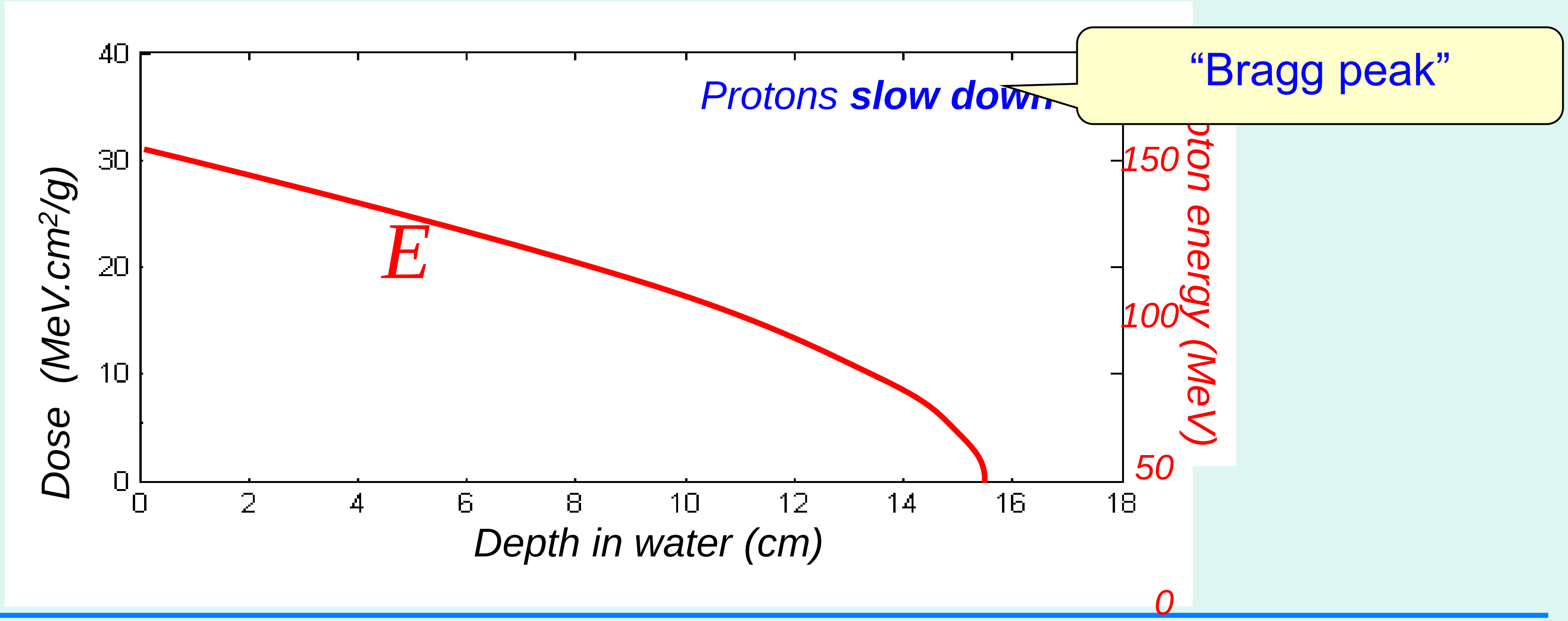
$$\frac{\Delta E}{\Delta x} \sim -\frac{\rho\, q^2}{v^2} \frac{Z}{A}$$

velocity



q = charge of particle

ρ,A,Z= material properties



Typical Therapeutic Dose of Protons

Some orders of magnitude:

Typical dose in tumor: ~70 Gy = 70 J/kg applied in fractions of **2 Gy**

Suppose each proton loses ~100 MeV in tumor of 1 kg

→ $\mathbf{10^{11}}$ **protons needed** $\left(\approx \frac{2}{1.6E-11}\right)$

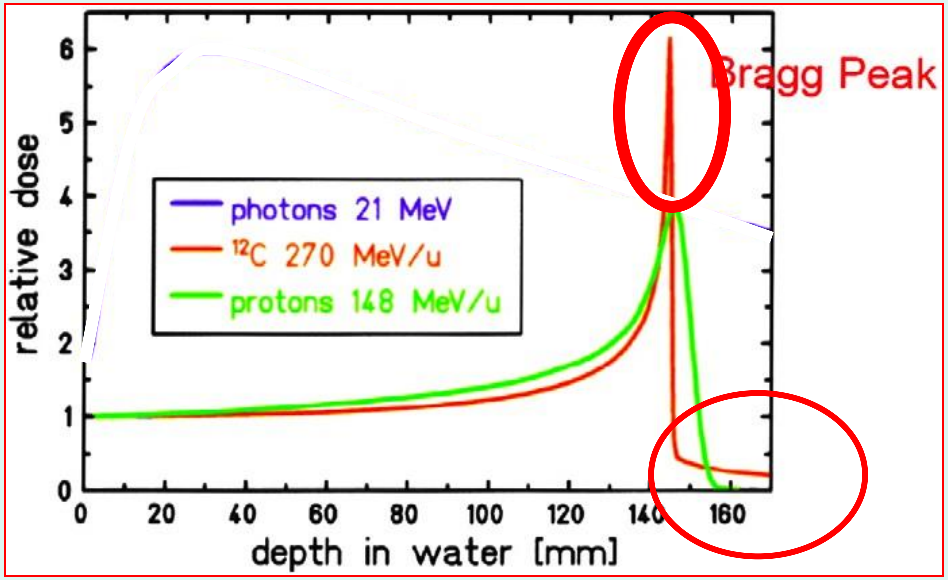
Irradiation time: 1 min → beam intensity **0.25 nA**

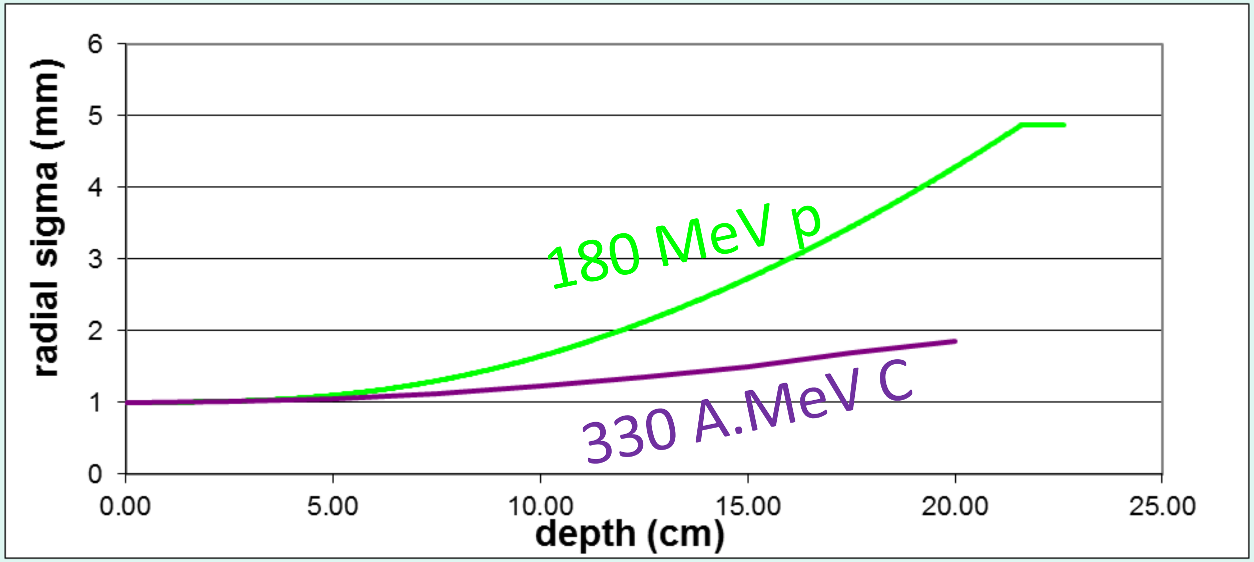
= 1.5 x 10^9 protons/sec

what could Carbon ions bring?

Difference with protons:

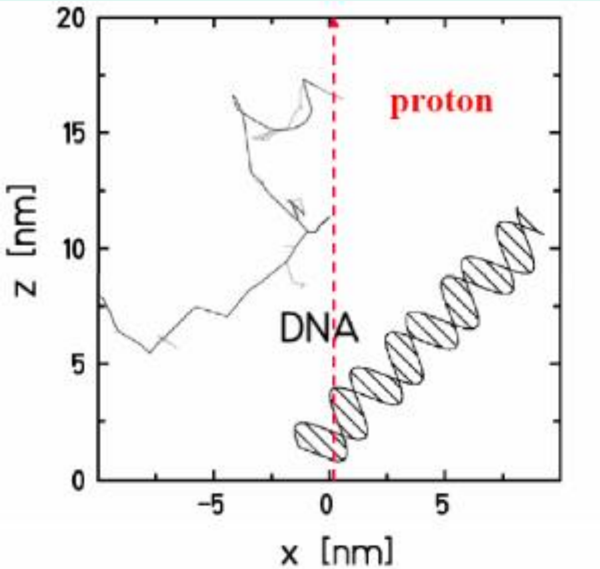
- Sharper Bragg peak
- Tail
- Less Scattering
- Larger RBE



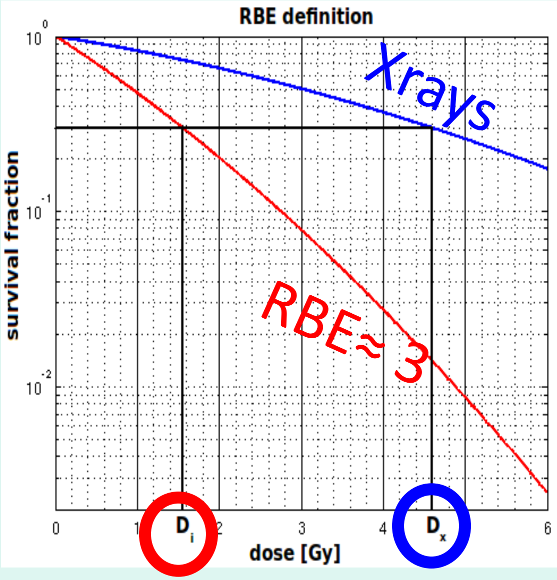


Biological effect of Carbon ions

Radio **B**iological **E**ffectiveness: **RBE carbon** $= \frac{D_{Xray}}{D_{Carbon}}$ for same cell killing.



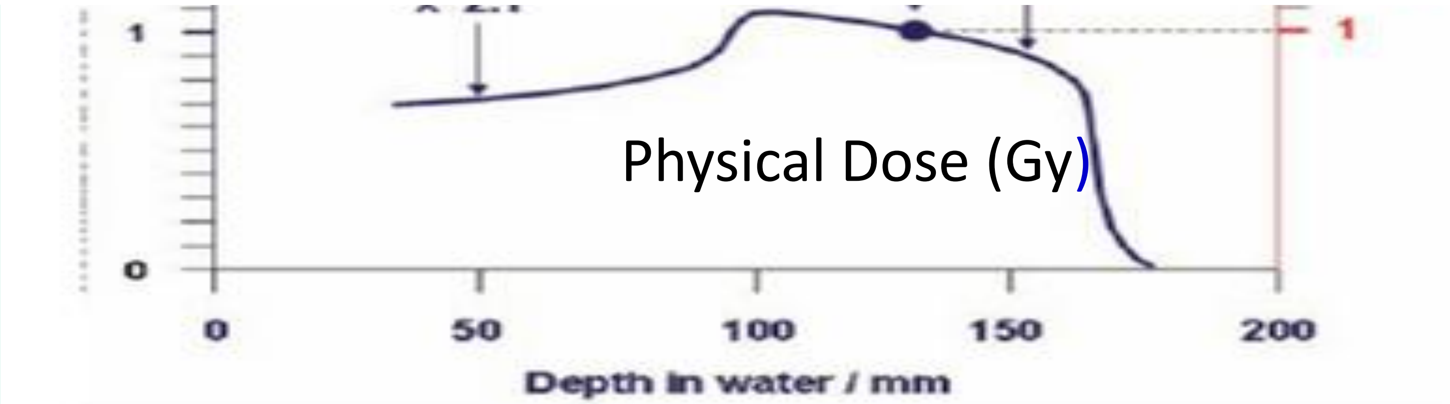
q^2



electron track (or energy) density at μm scale effects RBE (this means: RBE≠ 1)

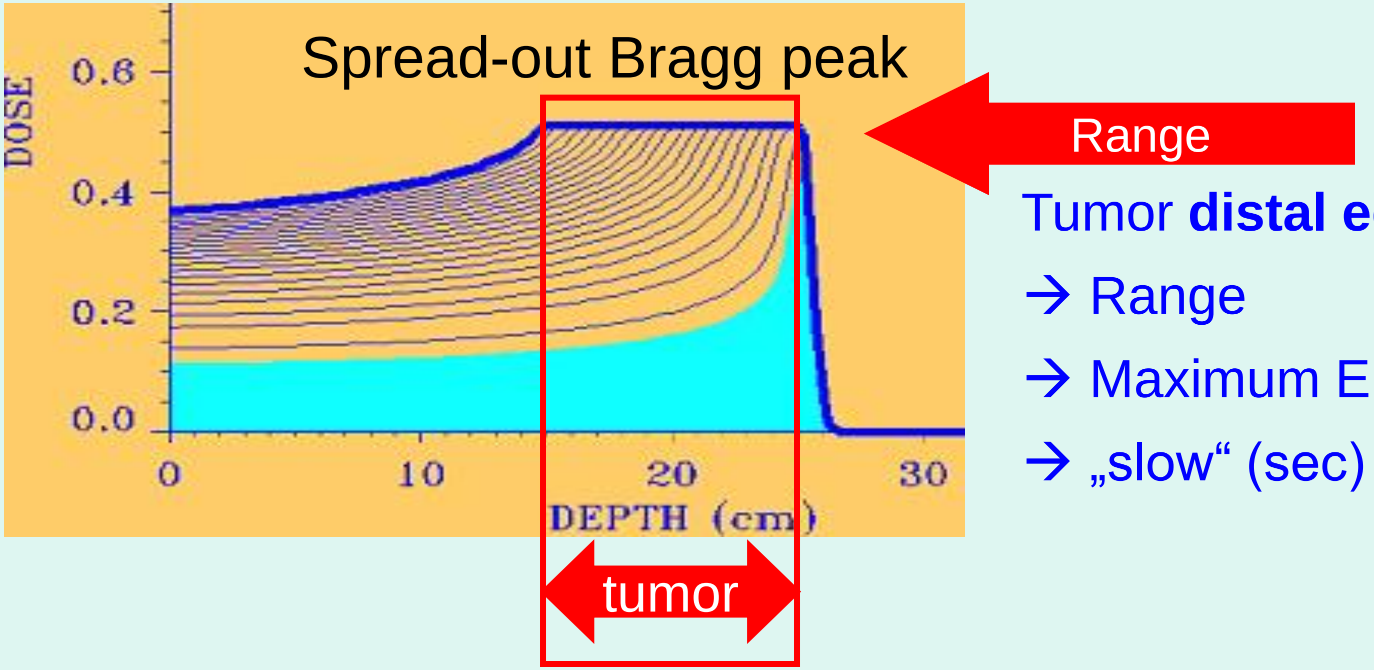
Biological effect of Carbon ions

Radio **B**iological **E**ffectiveness: Dcarbon/Dxray giving same effect



Dose delivery techniques

Dose delivery techniques: Depth



Tumor **distal edge**
→ Range
→ Maximum Energy
→ „slow“ (sec)

Tumor **thickness**
→ spread-out Bragg peak
→ energy modulation
→ „**fast**“ (<0.1 sec)

Methods:

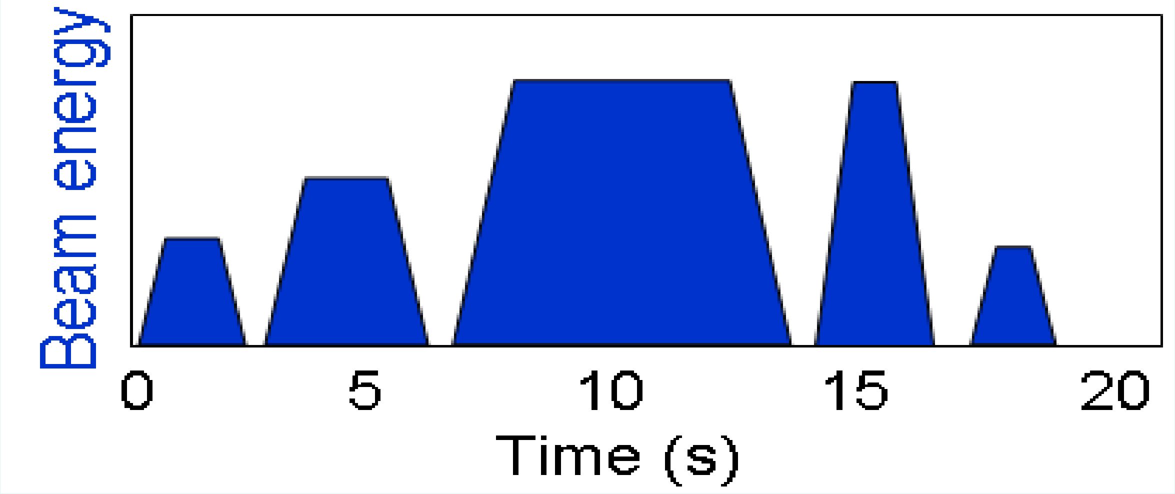
1) at accelerator
2) just before patient (in “nozzle”)

Dose delivery techniques: Depth

Vary energy at accelerator:

Synchrotron

accelerates until energy has been reached

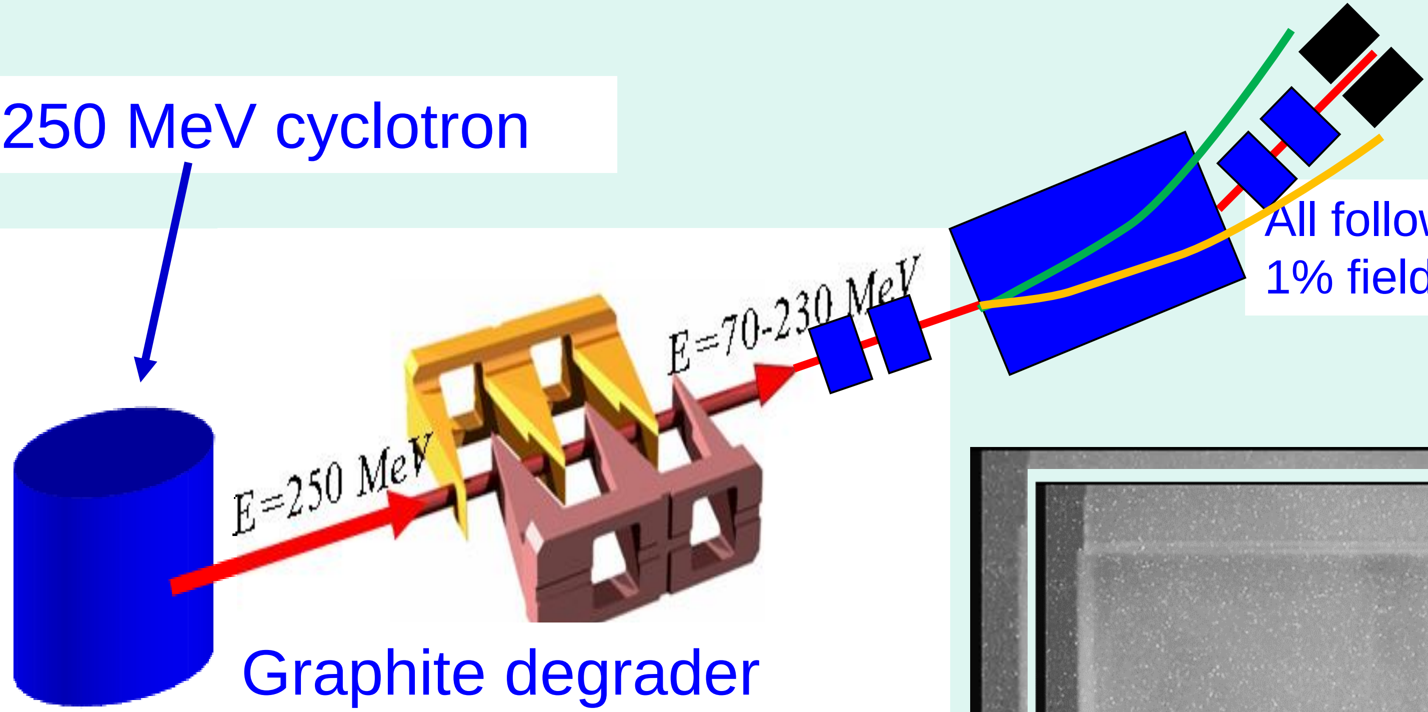


➔ Sets range only

➔ energy modulation in nozzle (=before patient)

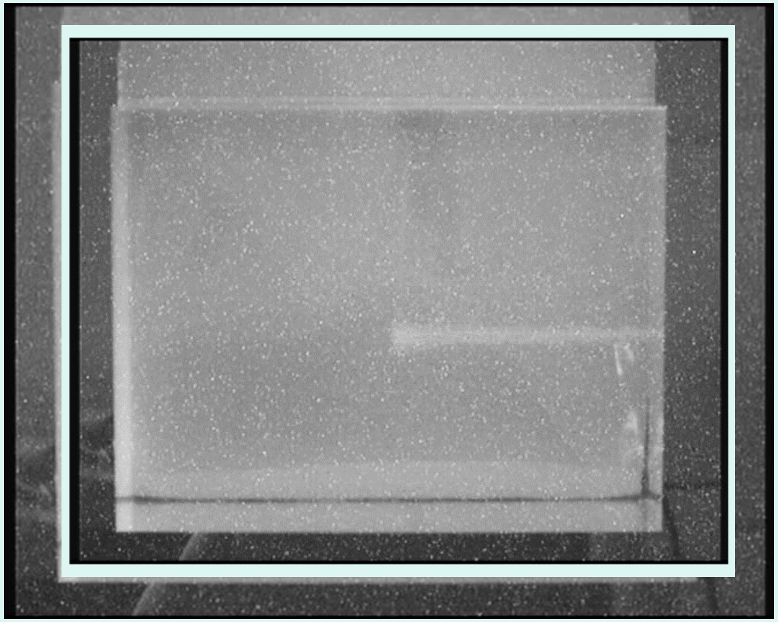
E-adjustment with cyclotron

250 MeV cyclotron



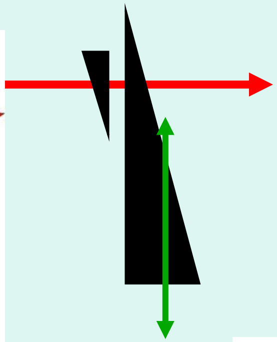
All following magnets:
1% field change

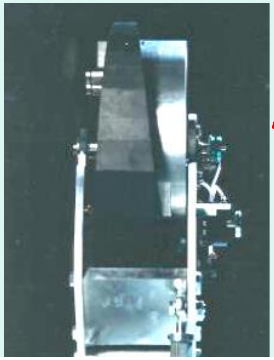
Graphite degrader
E-Steps →
ΔR≈5 mm in 100 ms



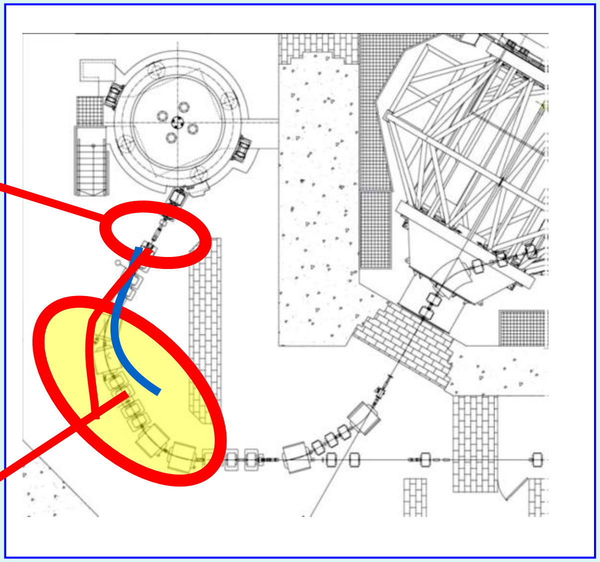
Energy selection system

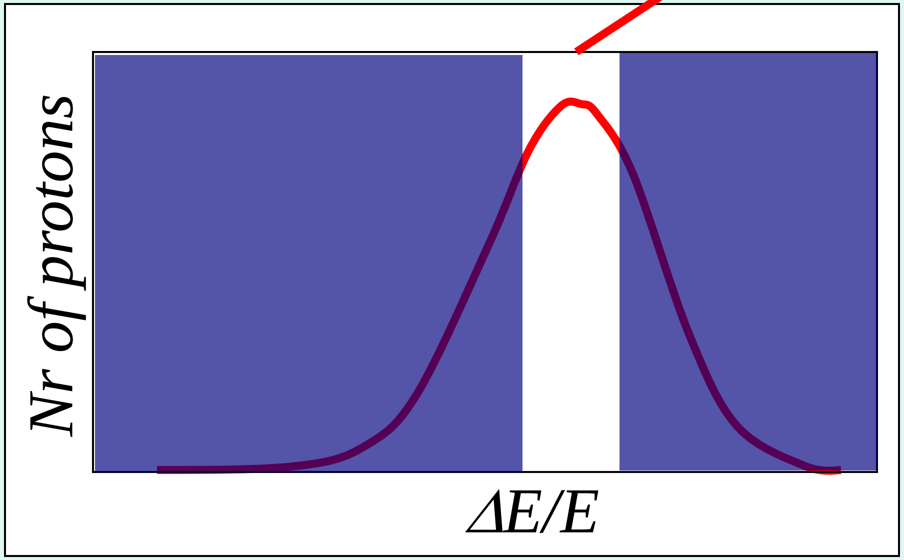
multi-wedge
235-67 MeV (PSI)





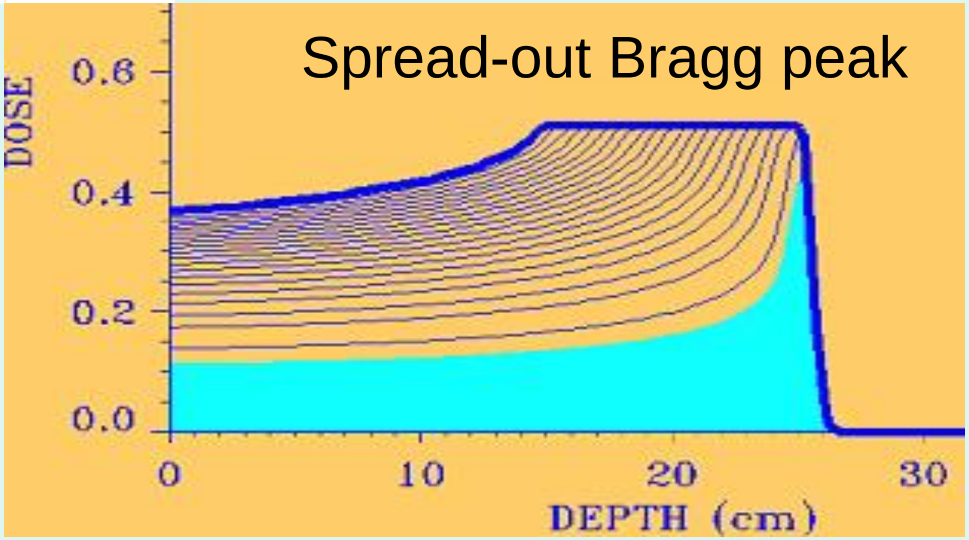
Rolled-up wedge
220-70 MeV **(IBA)**





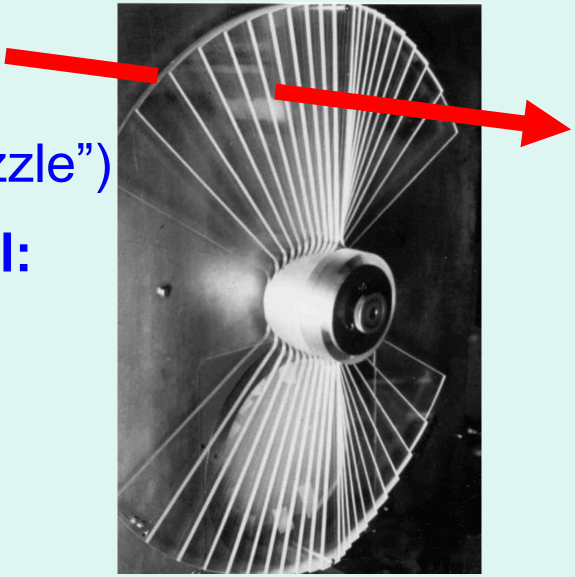
Beam analysis:
energy selection
ΔE/E < ± 2%

Dose delivery techniques: Depth

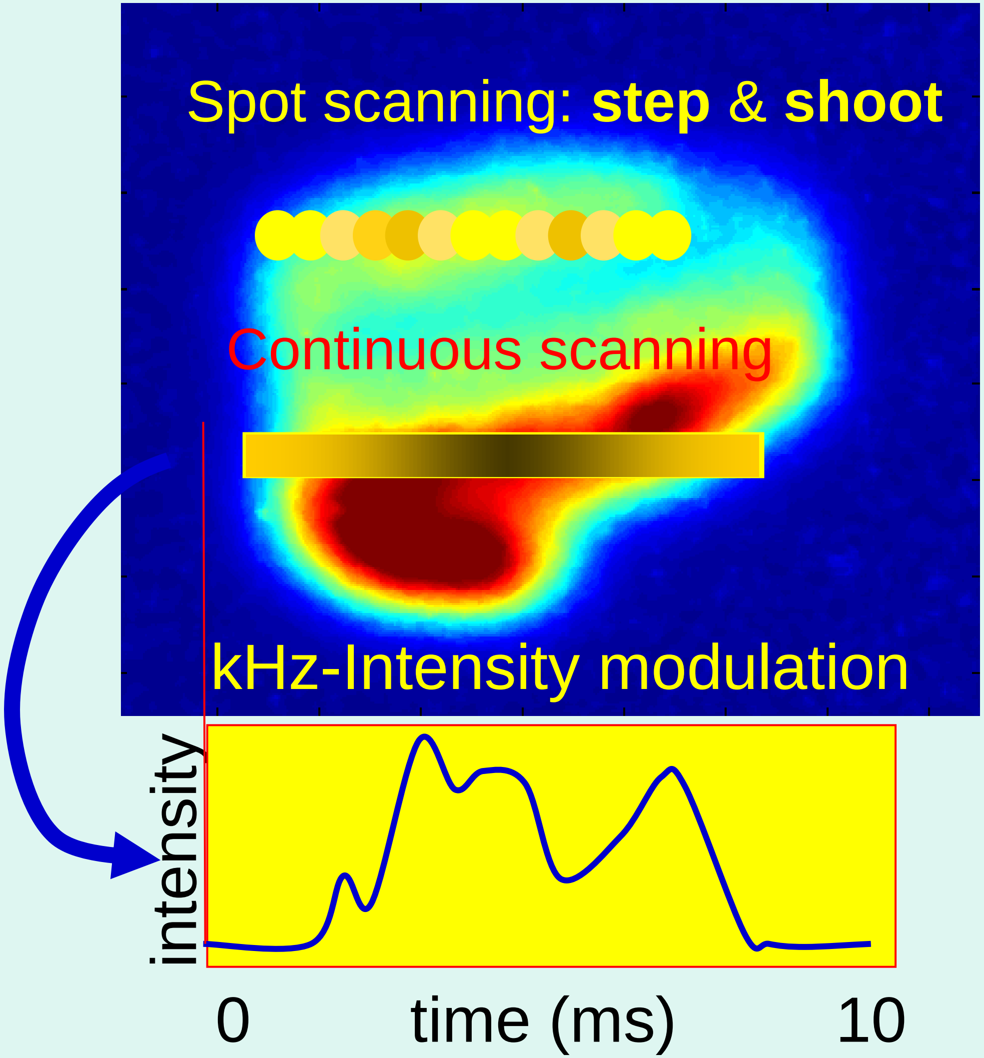


Energy adjustment just before patient (in “nozzle”)

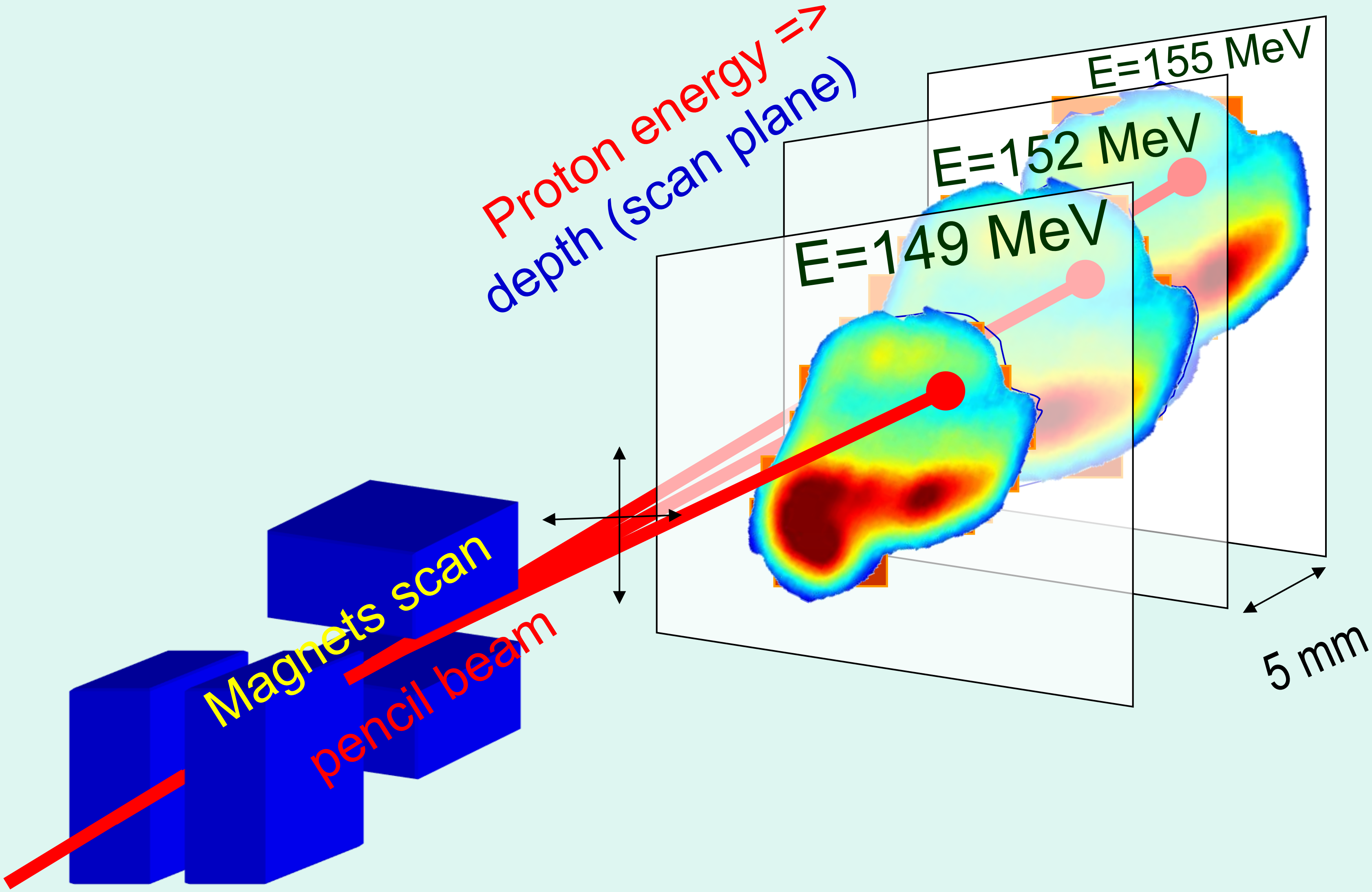
using a **modulation wheel:**



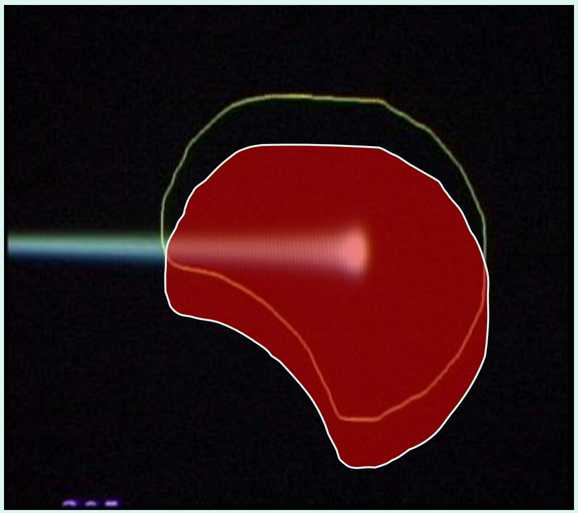
Transverse dose distr.: Spot Scanning

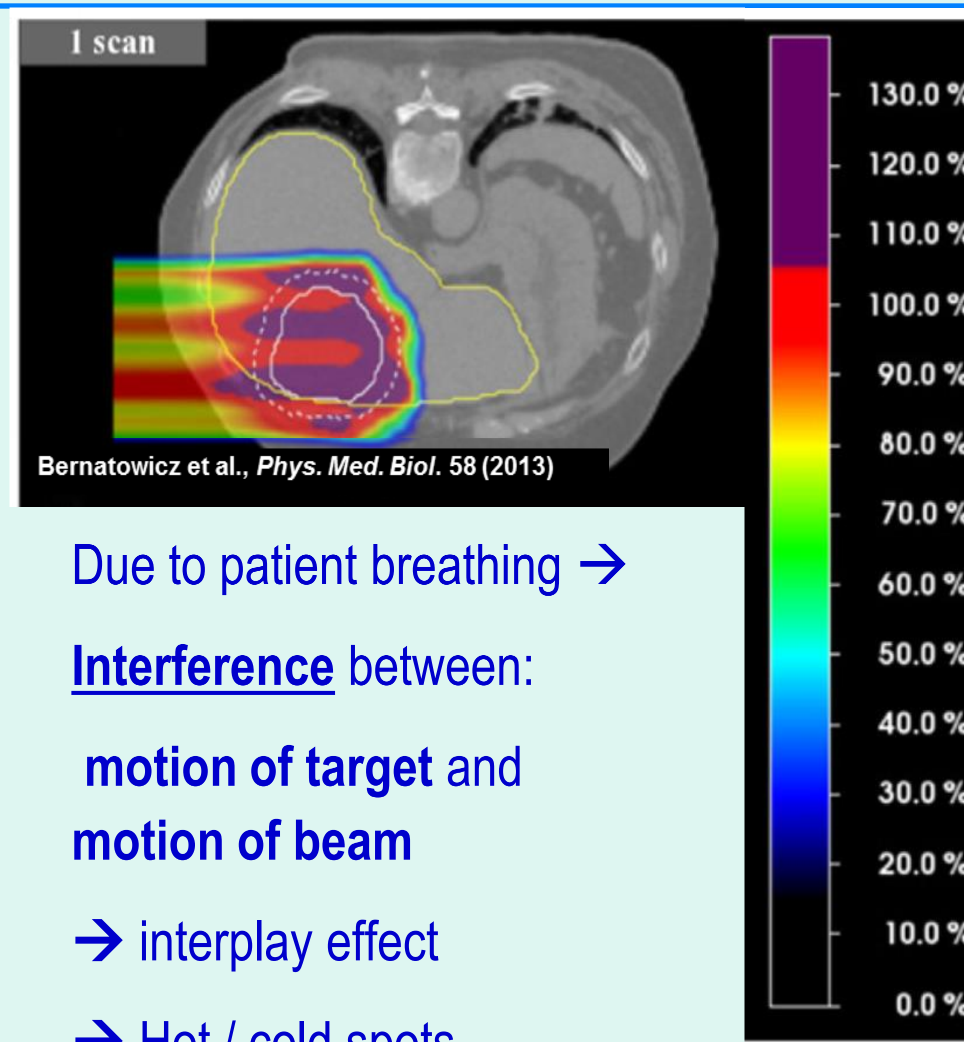


3D Pencil beam scanning



Moving organs





Overdosage (clinically not acceptable)

100±5 % = Target dose

Underdosage (clinically not acceptable)

→ Danger to **under**dose and **over**dose

Due to patient breathing →

Interference between:

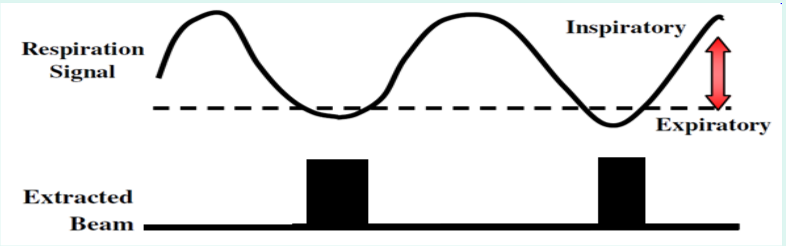
motion of target and **motion of beam**

→ interplay effect

→ Hot / cold spots

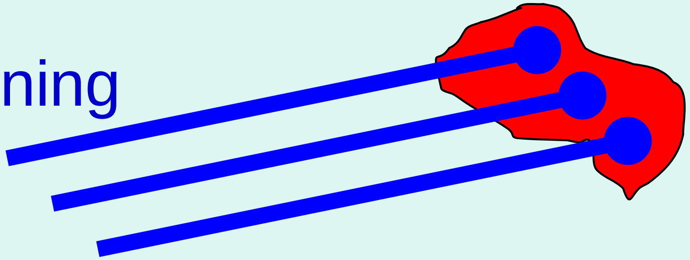
Possible solutions:

- Gating

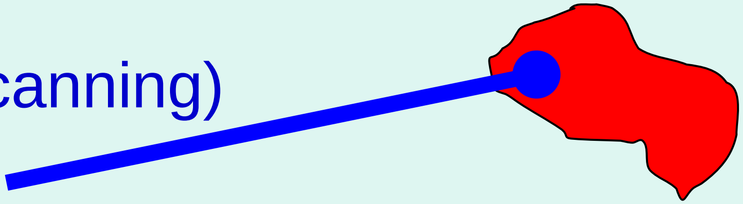


- Adaptive scanning

  (tumor tracking)

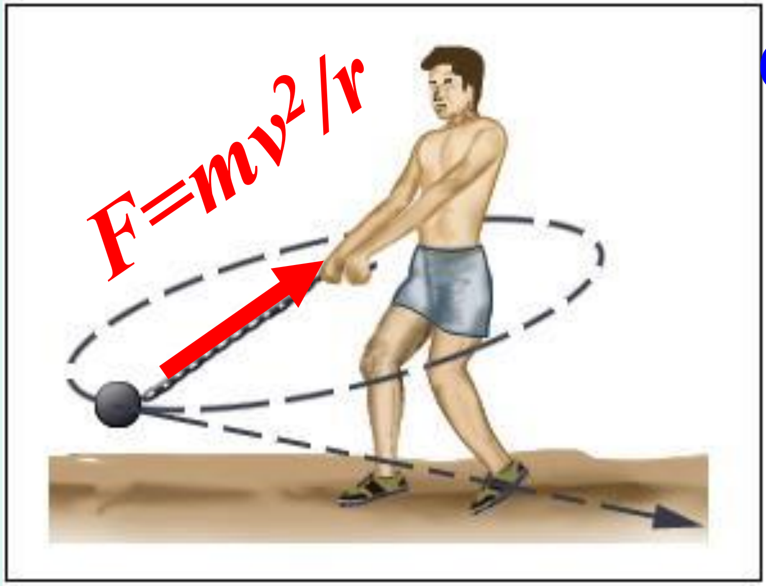


- Fast (+ rescanning)



Accelerators

Circular accelerators



Centripetal force = Lorentz force

$$\frac{mv^2}{r} = Bqv$$

$$\Rightarrow \frac{p}{q} = B\rho$$

m = mass

v = speed

r or ρ = orbit radius

B = magnetic field

q = charge

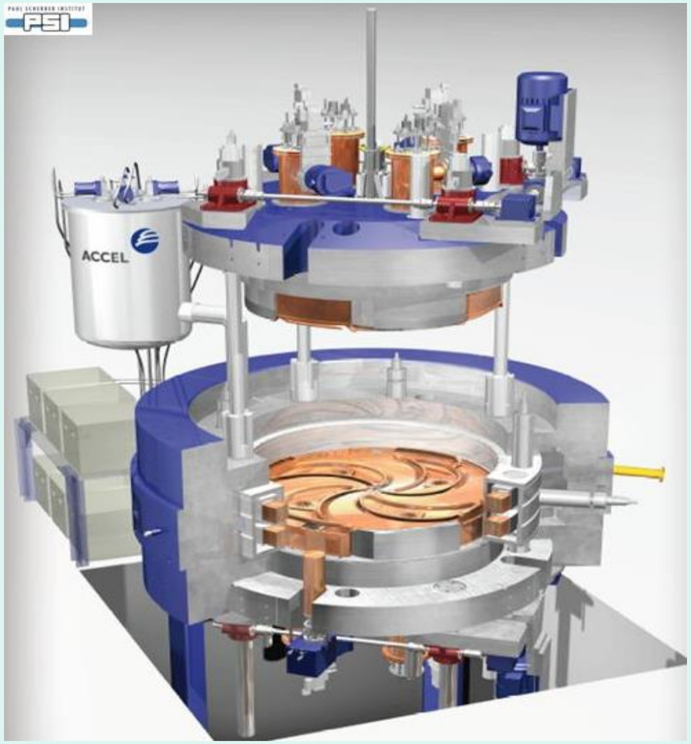
Magnetic rigidity: p~Brho value e.g.:

250 MeV **p:** **Brho=2.4 Tm**

450 MeV/nucl **C6+:** **Brho = 6.8 Tm**

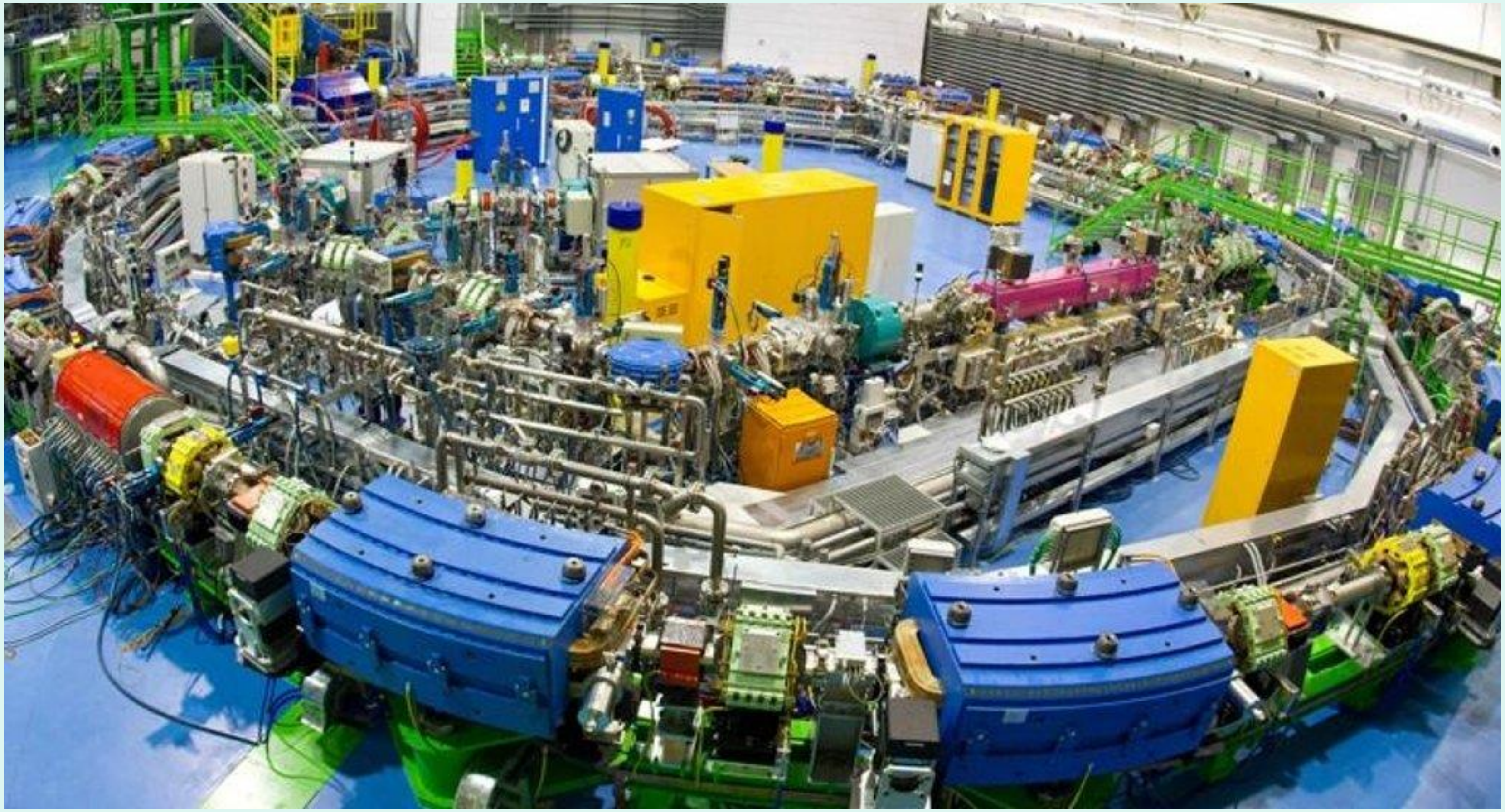
6.5 TeV **p (LHC):** **Brho = 21.6 T.km**

Present accelerator choice

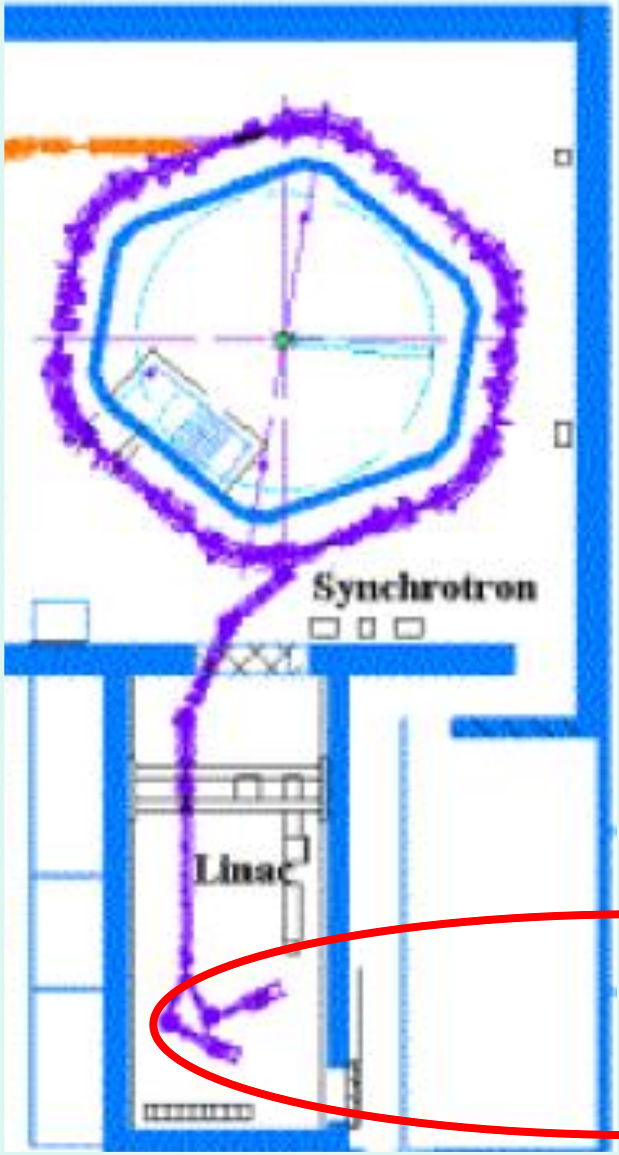


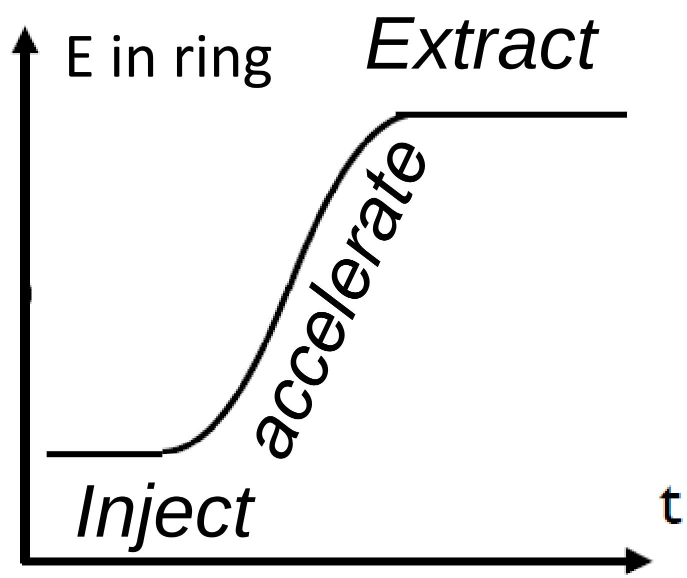
cyclotron synchrotron

C-ther. Synchrotron at CNAO, Pavia (it)



synchrotron

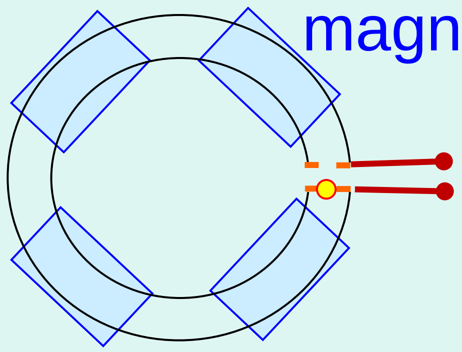




Synchrotron magnet cycle

Ion source(s)

Acceleration in synchrotron



Energy increases:

→ speed ↑

→ **freq** ↑

→ **field** in magnets ↑

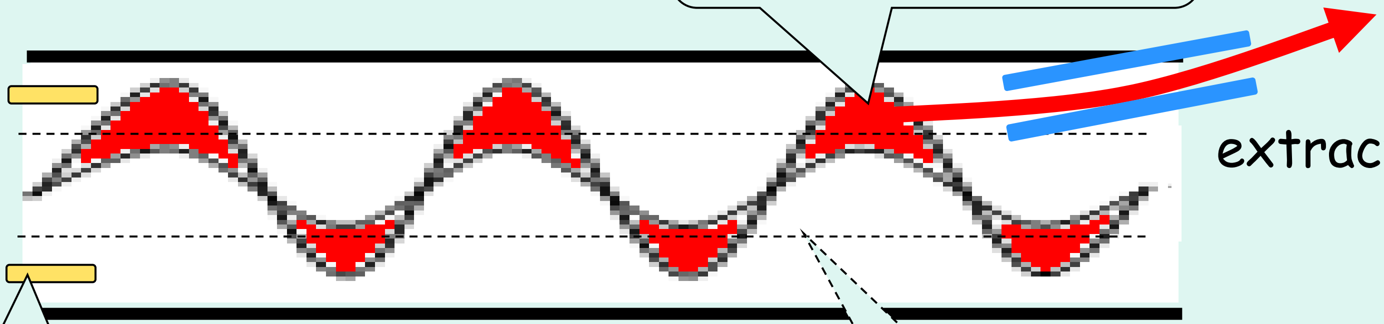
$$\frac{p}{Bq} = r = const$$

Magnets and **RF frequency** change
Synchronous to particle revolution frequency

Slow extraction from synchrotron

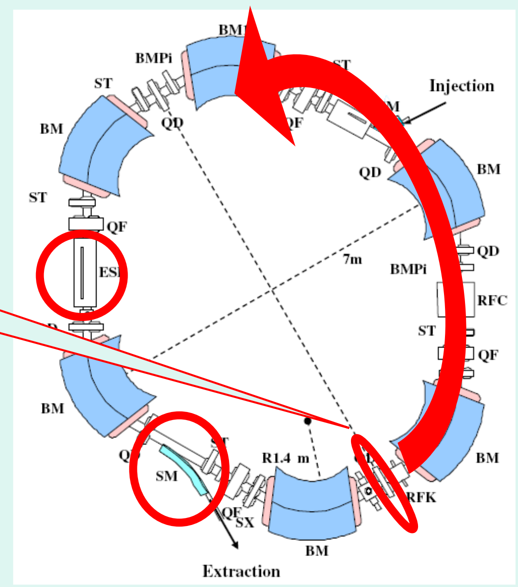
RF-Knock Out

Unstable orbits
→ extracted

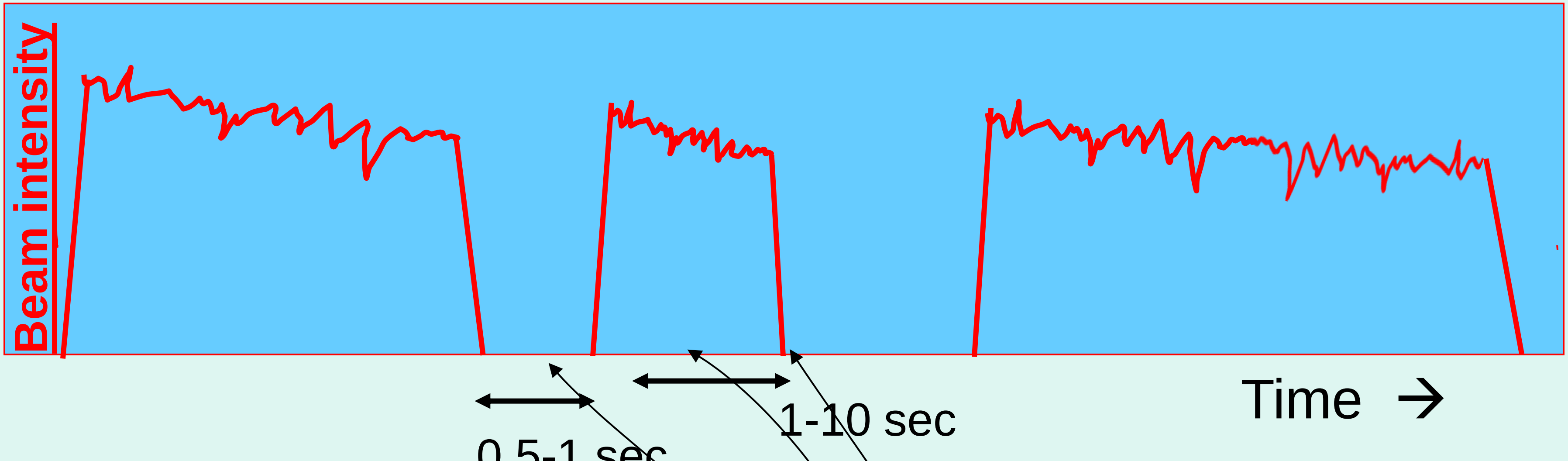


RF kicker: increases emittance (beam size)

stable beam acceptance limit

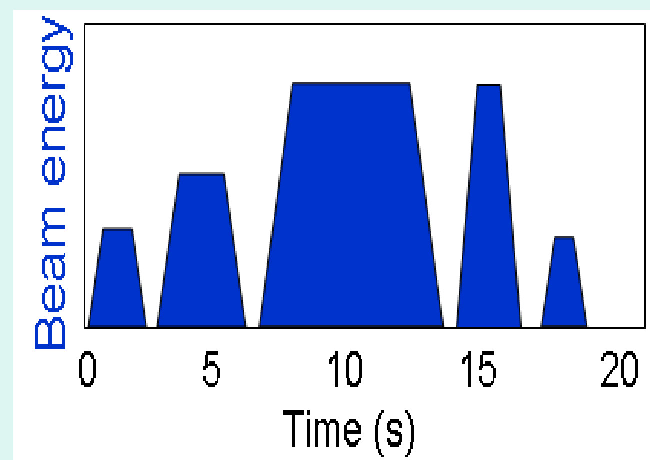


Synchrotron beam: <u>noisy & spills</u>

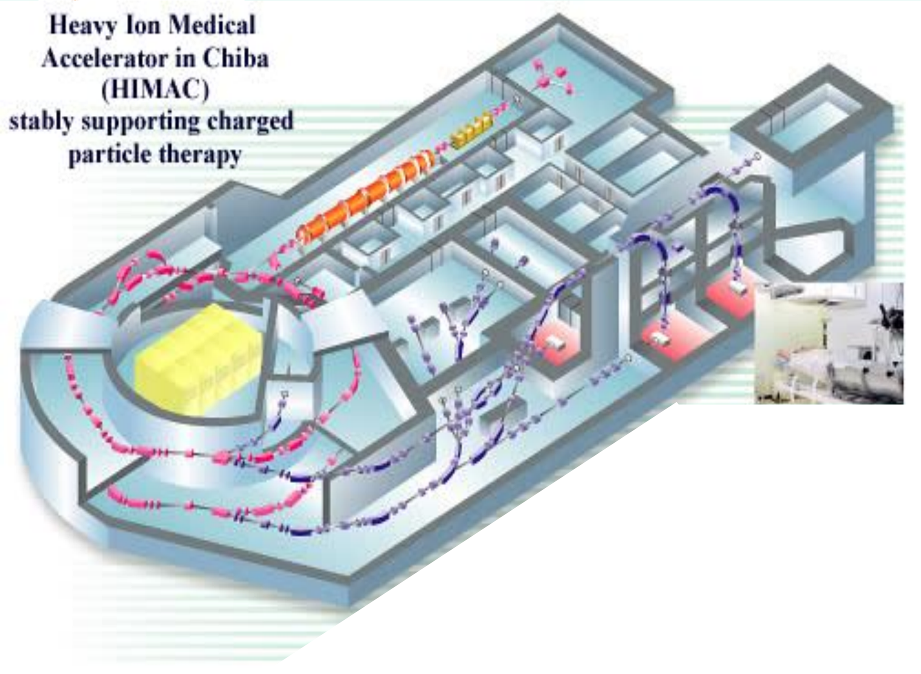


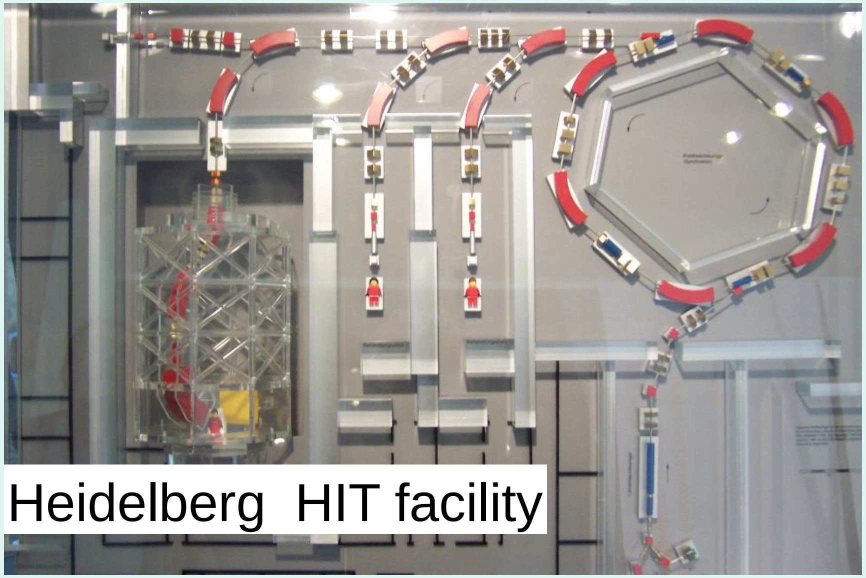
spill structure

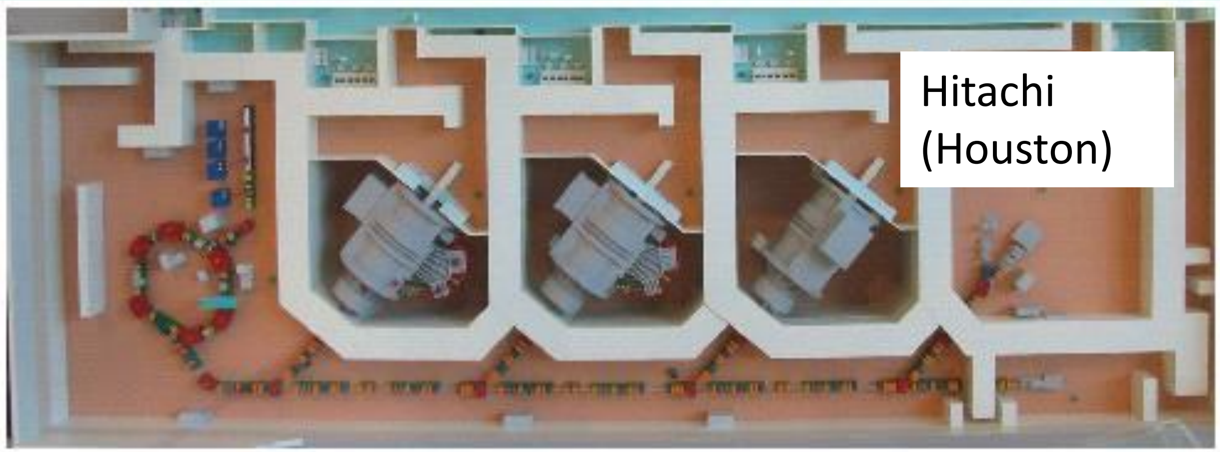
- fill ring with ~10^{11} particles
- accelerate to desired energy
- extract slowly during 1-10 sec
- decelerate and dump unused particles



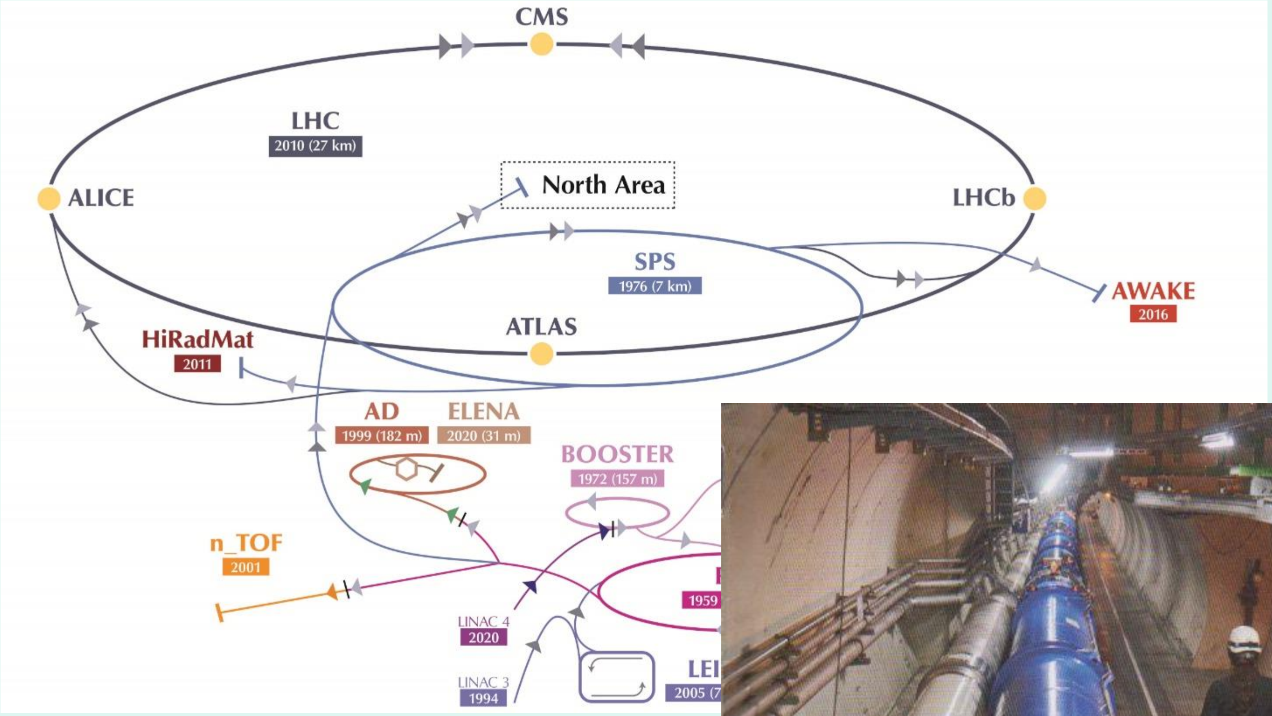
Ion therapy: synchrotron facilities

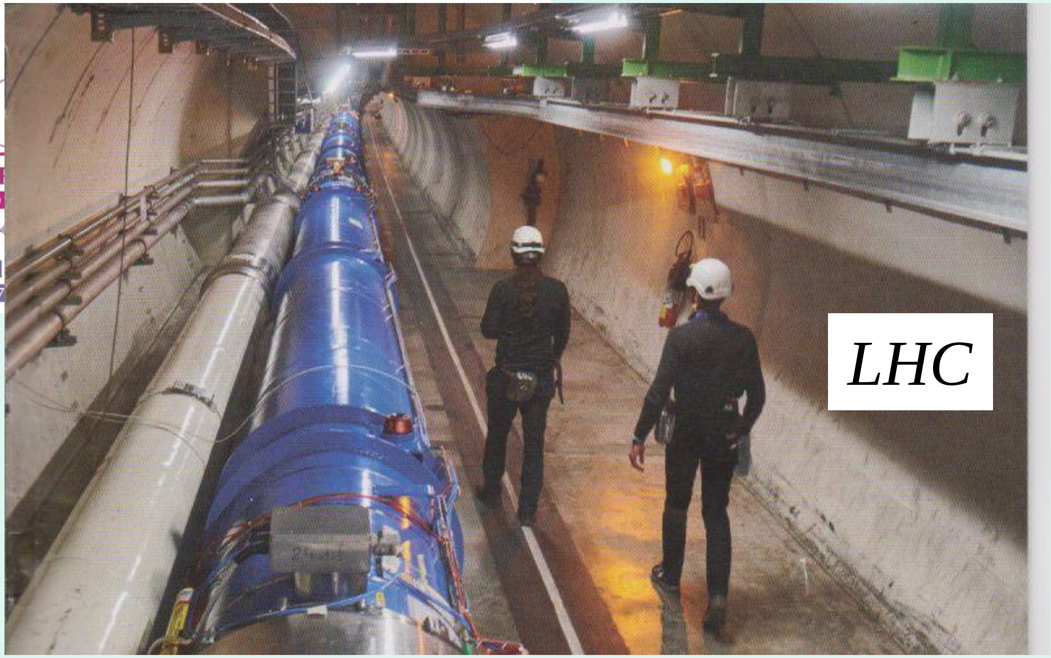






Synchrotrons at CERN

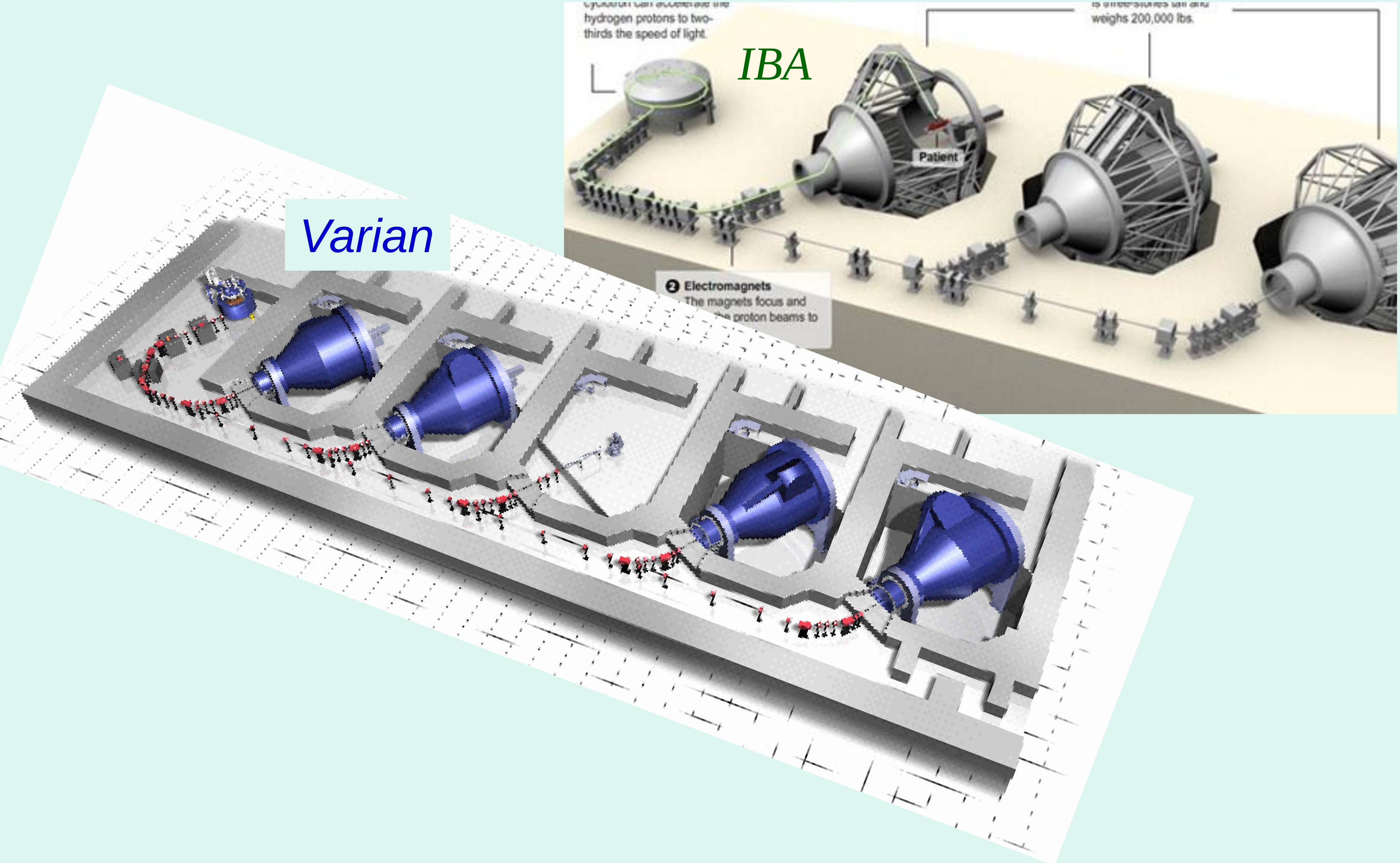




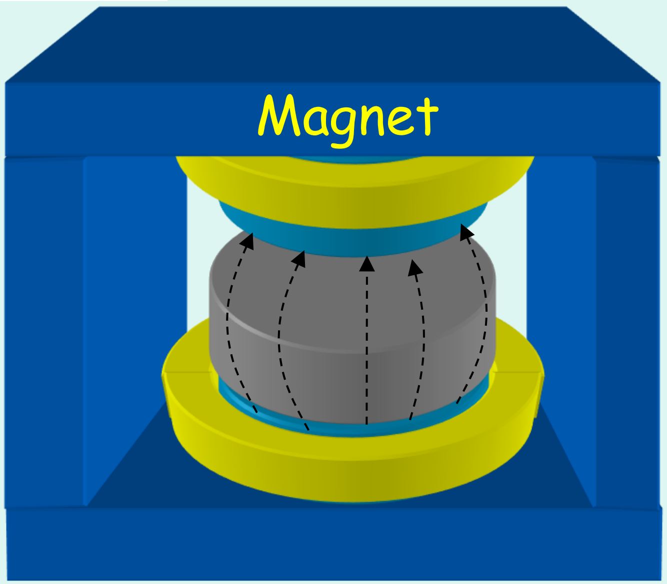
Differences with synchrotrons **for research** at e.g. CERN:

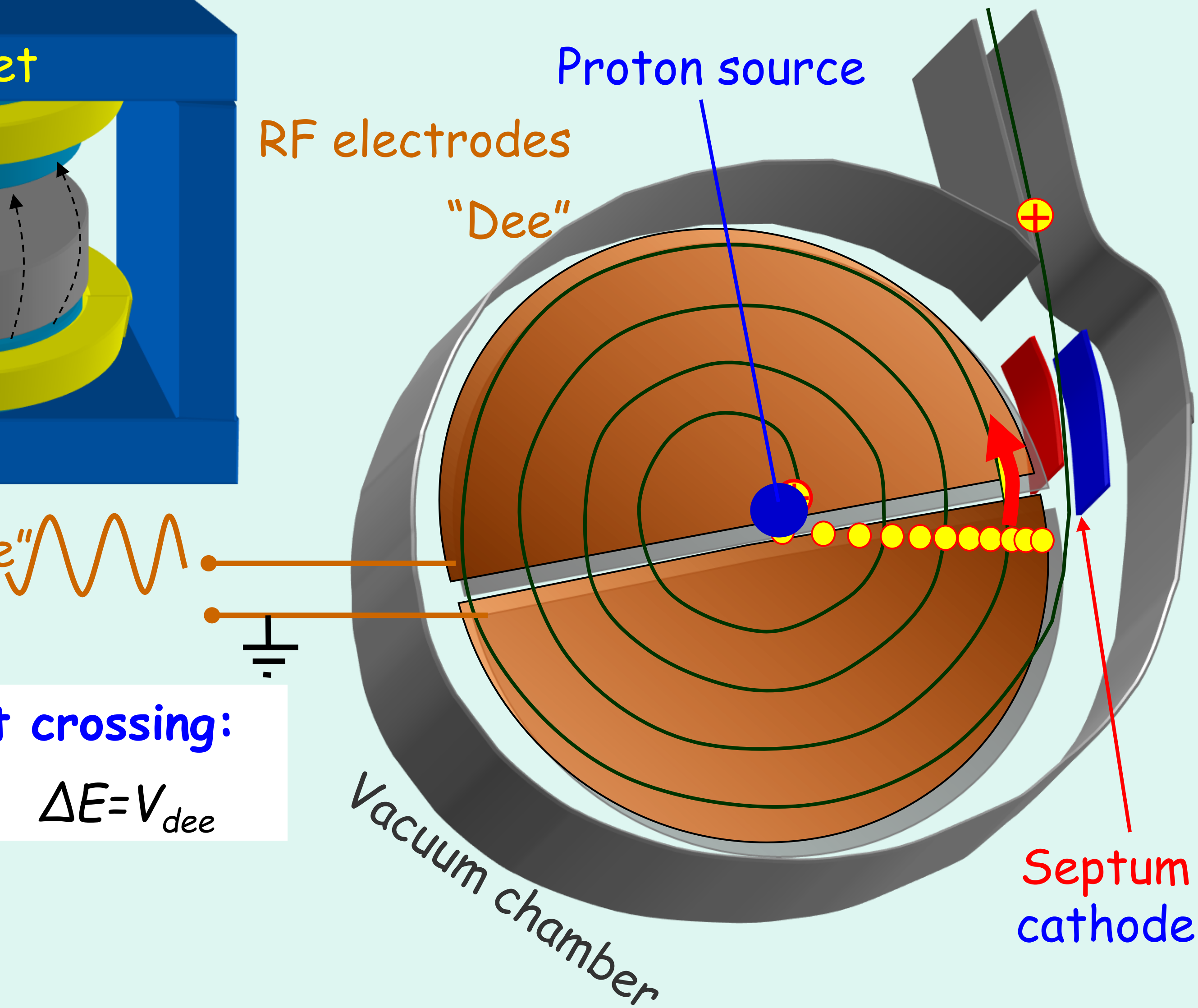
	proton th.	**carbon** th.	**research** (LHC-1beam)
Particles	p	p, He, C, ….	e, p, ….Pb
Size (∅)	6-8 m	25 m	100m-8.5 km
Energy	300 MeV	450 MeV/nucl	6.5 **TeV**
Nr of part.	10^{10} -10^{11}	10^{10} -10^{11}	$3x10^{14}$
E stored	50 J	1000 J	300 MJ
Inj+acc	10-20 s	10-20 s	30 min
what is done	slow extract.	Slow extract.	No extr.

Layout of cyclotron facilities



Cyclotron (1930)

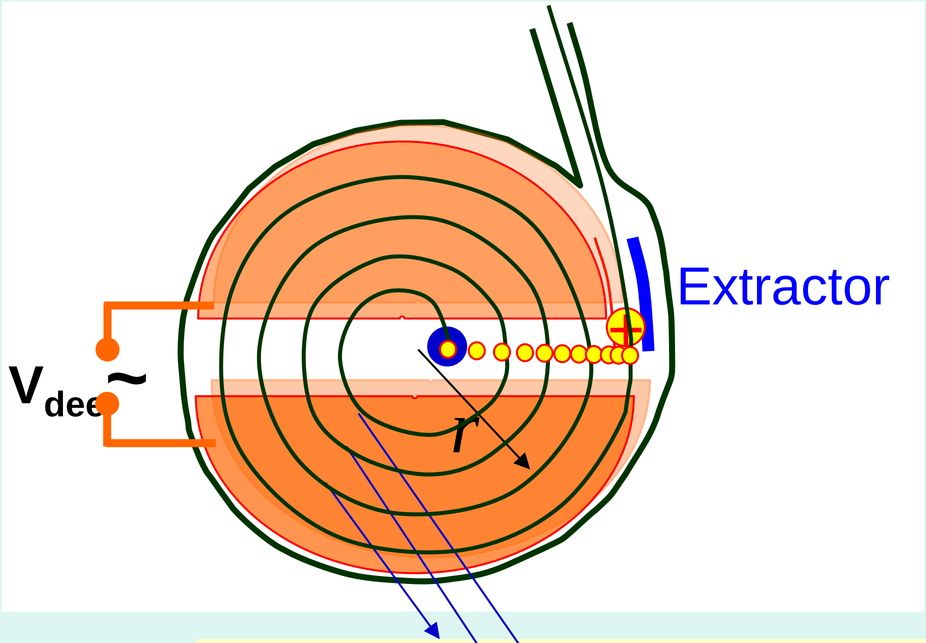


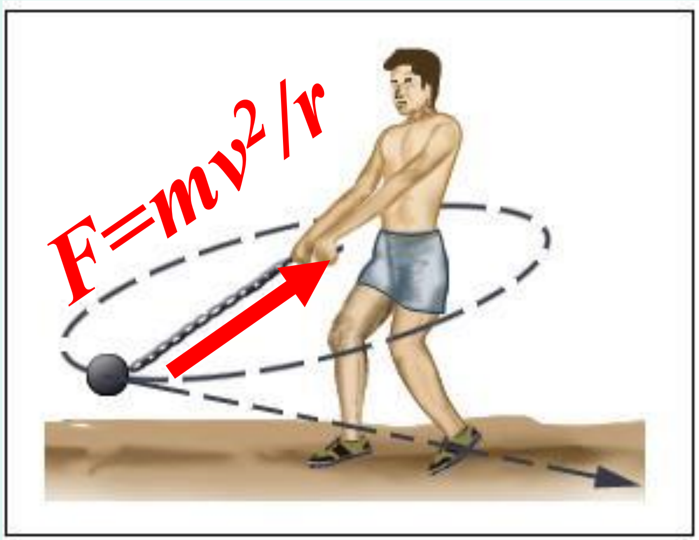


At electrode slit crossing:

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

Cyclotron





(almost) circular orbits:

Centripetal force = Magnetic force

$$\frac{mv^2}{r} = Bqv$$

=> $T_{circle} = \frac{2\pi . r}{v} = \frac{2\pi . m}{Bq}$ if B=2.4T → T_{circle} ≈ 30 ns

=> T_{circle} **independent of orbit radius *r***

Protons leave cycl. every 30 ns → in fact **DC beam: CW**

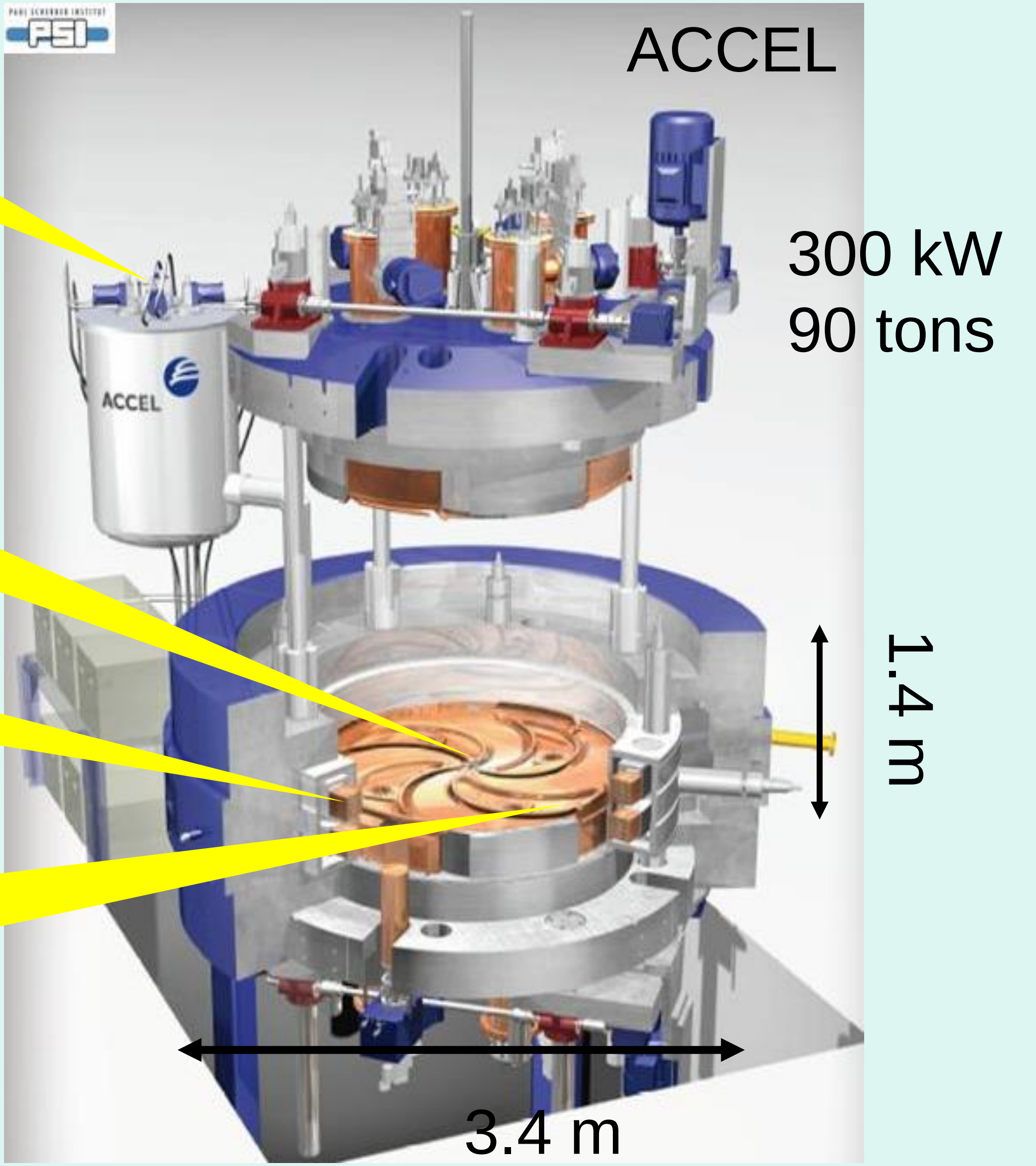
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

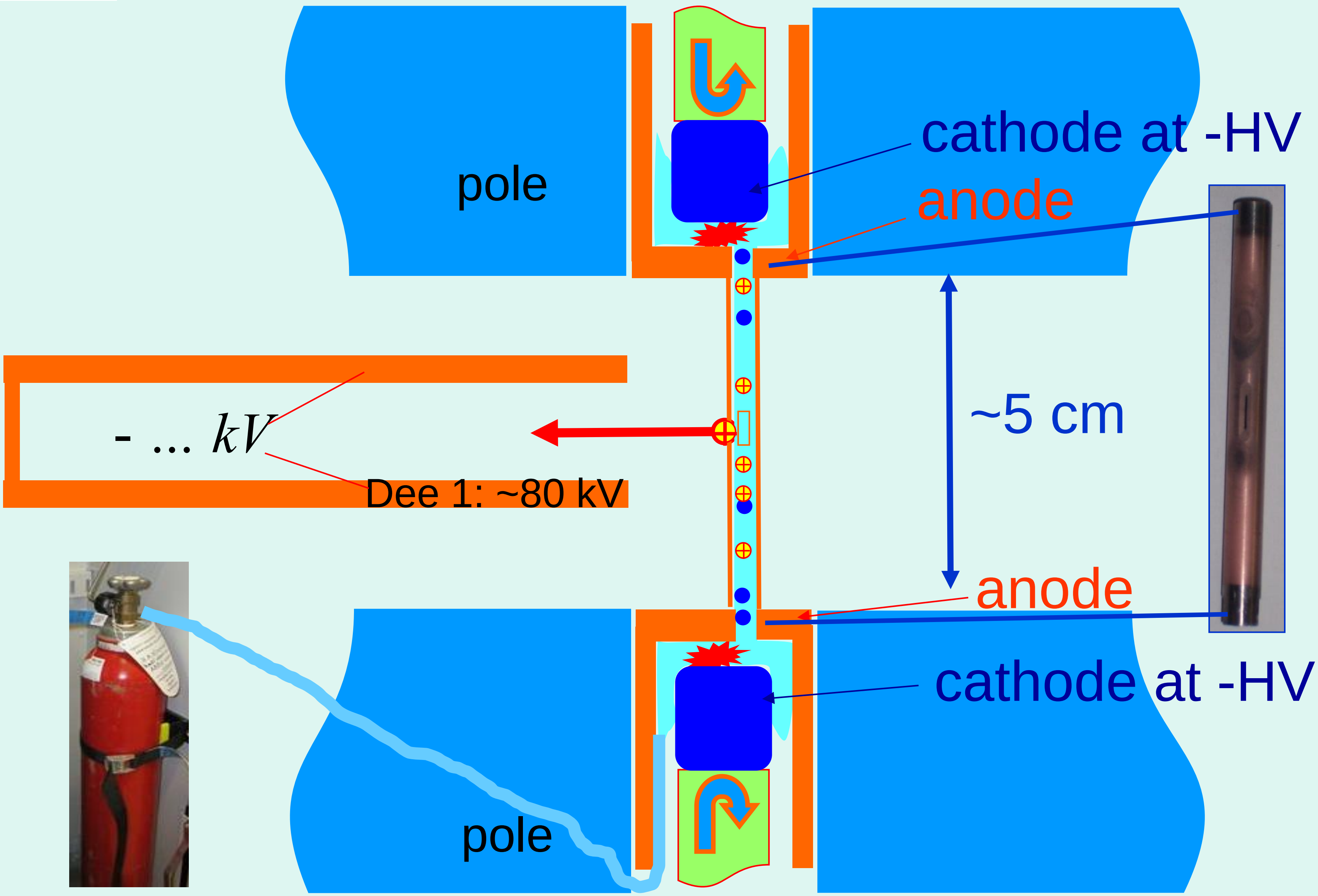
Proton source

superconducting coils
=> 2.4 - 3.8 T

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



Internal proton source



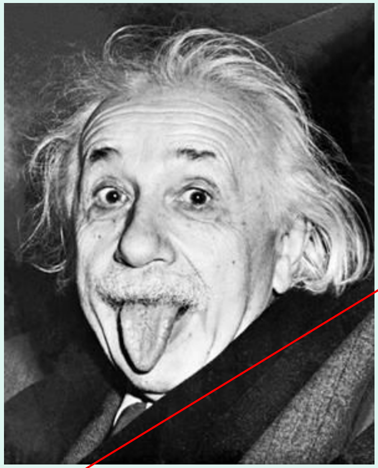
Problem with high E

Circular orbits:
=> T_{circle} independent from radius r

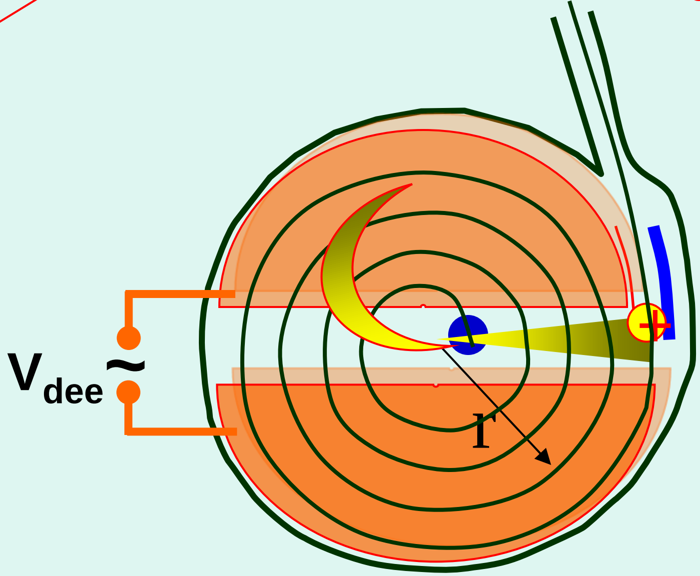
$$T_{circle} = \frac{2\pi m}{q.B}$$

=> *m* ↑ => T_{circle} ↑

However……



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



30 MeV p: *v/c=0.24* → *m=1.03m*$_0$
250 MeV p: *v/c=0.61* → *m=**1.27**m*$_0$

⇒ particles lose pace with frequency of Vdee (RF).

How to keep Isochronous Cyclotron

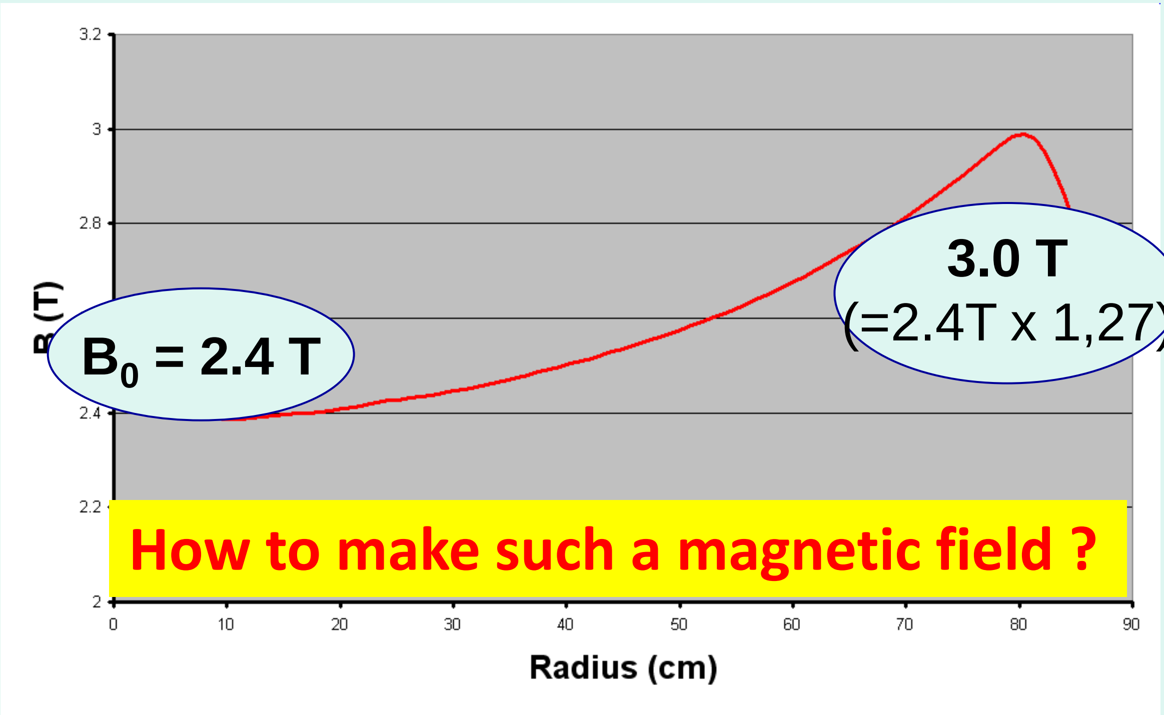
$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} = \gamma . m_0$$

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

Remedy:

Increase B with radius in cyclotron:

B(r)= γ(r) .B(r=0)

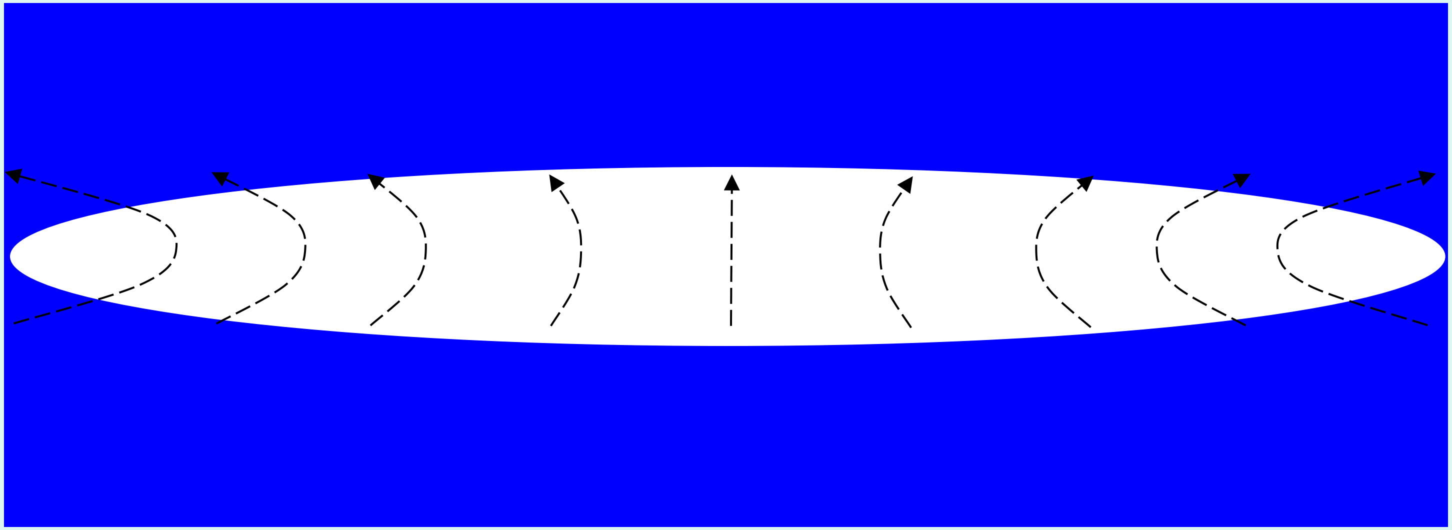


Isochronous Cyclotron

$$B(r) = \gamma(r) . B(r=0)$$

Made by e.g. **decreasing pole gap** at large Radius

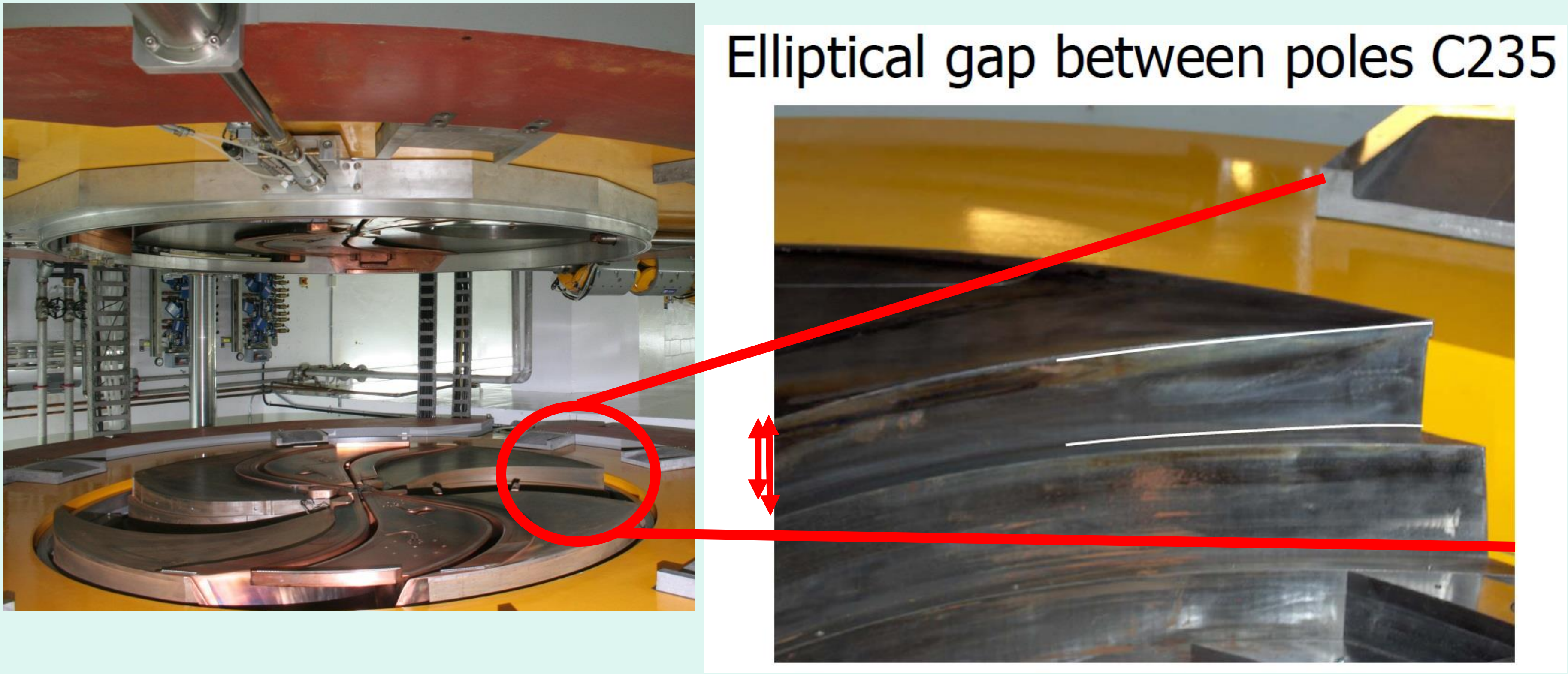
e.g: IBA and SHI 235 MeV cyclotron



Isochronous Cyclotron

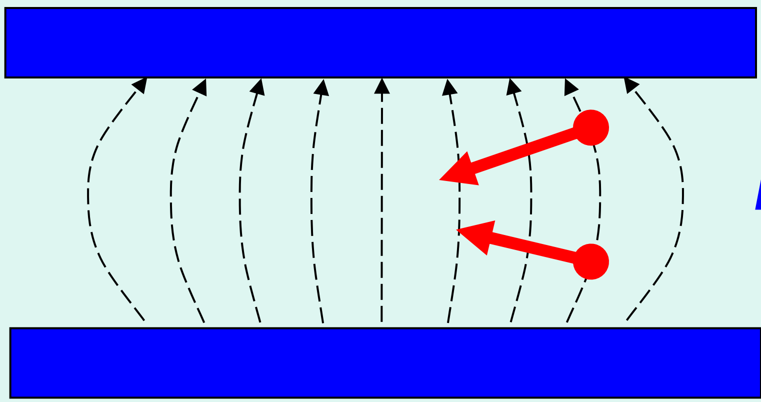
$B(r) = \gamma(r)\,.B(r=0)$

Increase field by **decreasing pole gap** with radius



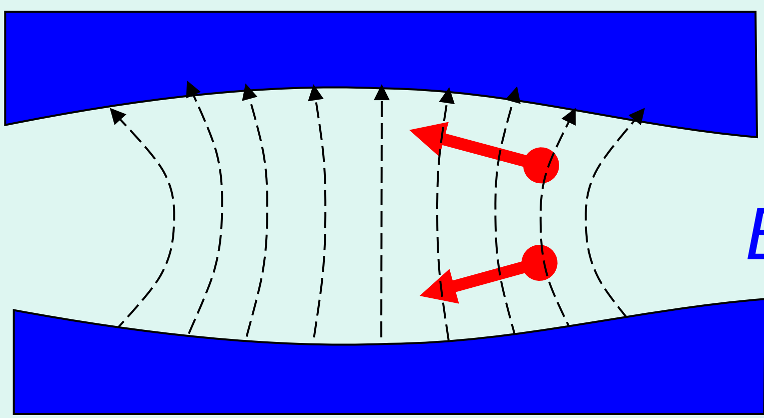
Vertical focusing is important

*Definition of radial variation of field (**field index**):* $n(r) = -\frac{\mathrm{d}B(r)}{\mathrm{d}r}\frac{r}{B(r)}$



*B **decreases** with radius, so:*

$dB/dr < 0 \;\; : \mathbf{n>0}$

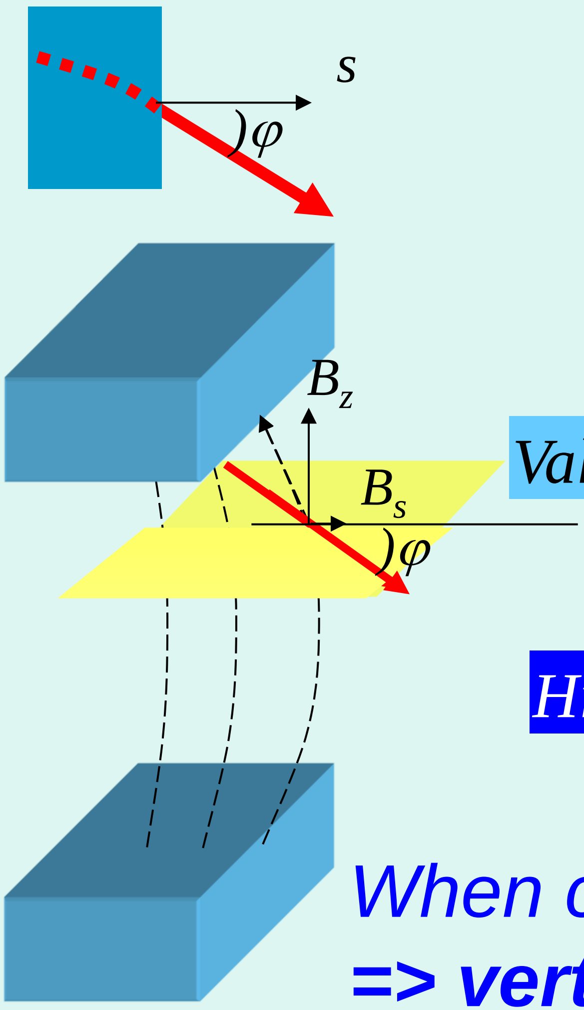


*B **increases** with radius, so:*

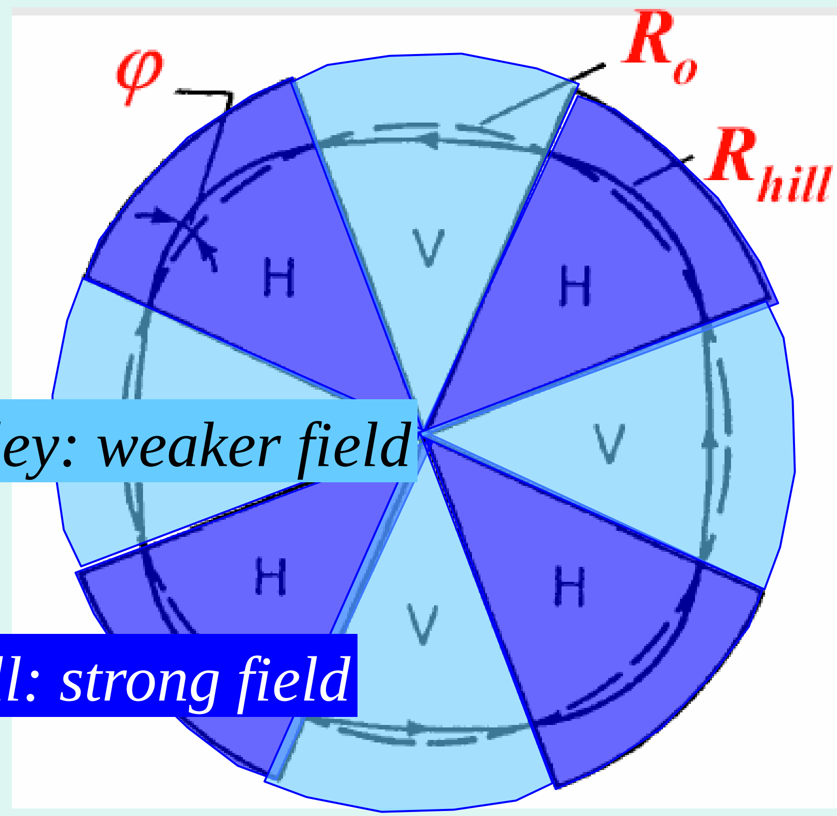
$dB/dr > 0 \;\; : \mathbf{n<0}$

(since $\nu_z^2 = n$) only focusing if $\mathbf{n>0}$

Vert. focusing: Azimuthally Varying Field



Thomas-Cyclotron (1938)

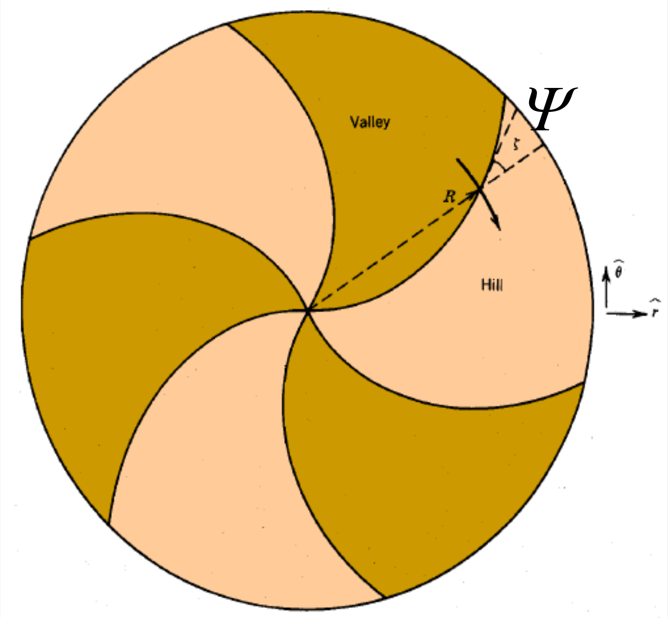


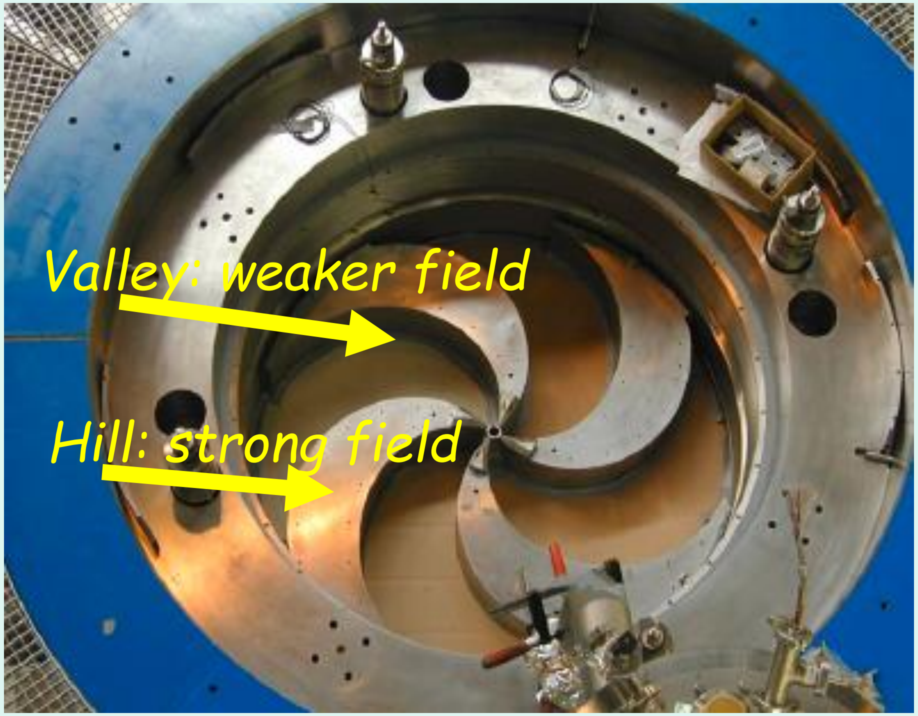
When crossing B change is ***not*** ⊥

=> vertical force *from* $\vec{B} \times \vec{v} \rightarrow B_s . v$

Vert. focusing: Azimuthally Varying Field

Azimuthally Varying Field cyclotron





to ***compensate*** *increasing* $B\rho$

=> increase angle Ψ *with radius* => ***spiral shape***

OR: Synchro-Cyclotron

stronger magn.fields → Smaller machines !

But at strong fields:

Iron saturates

→field drops with radius.

→ T_{circle} increases with radius.

Other Remedy=

Decrease f_{RF} with radius + extract

OR: Synchro-Cyclotron

stronger magn.fields → Smaller machines !

But at strong fields:

Iron saturates

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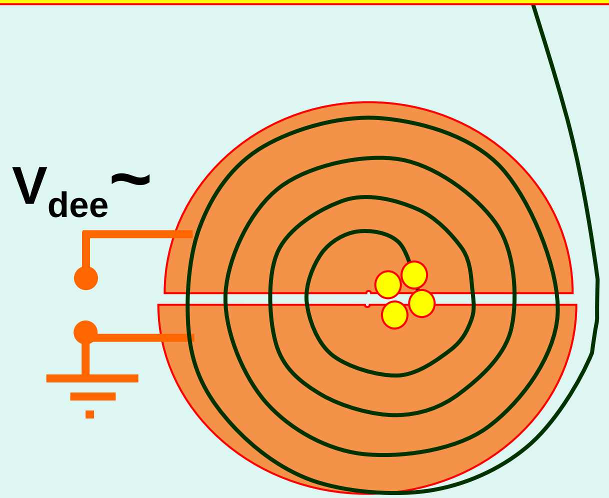
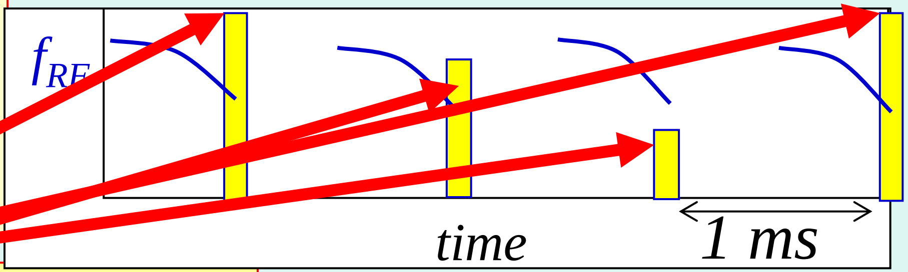


→ T_{circle} increases with radius.

Other Remedy=

Decrease f_{RF} with radius + extract

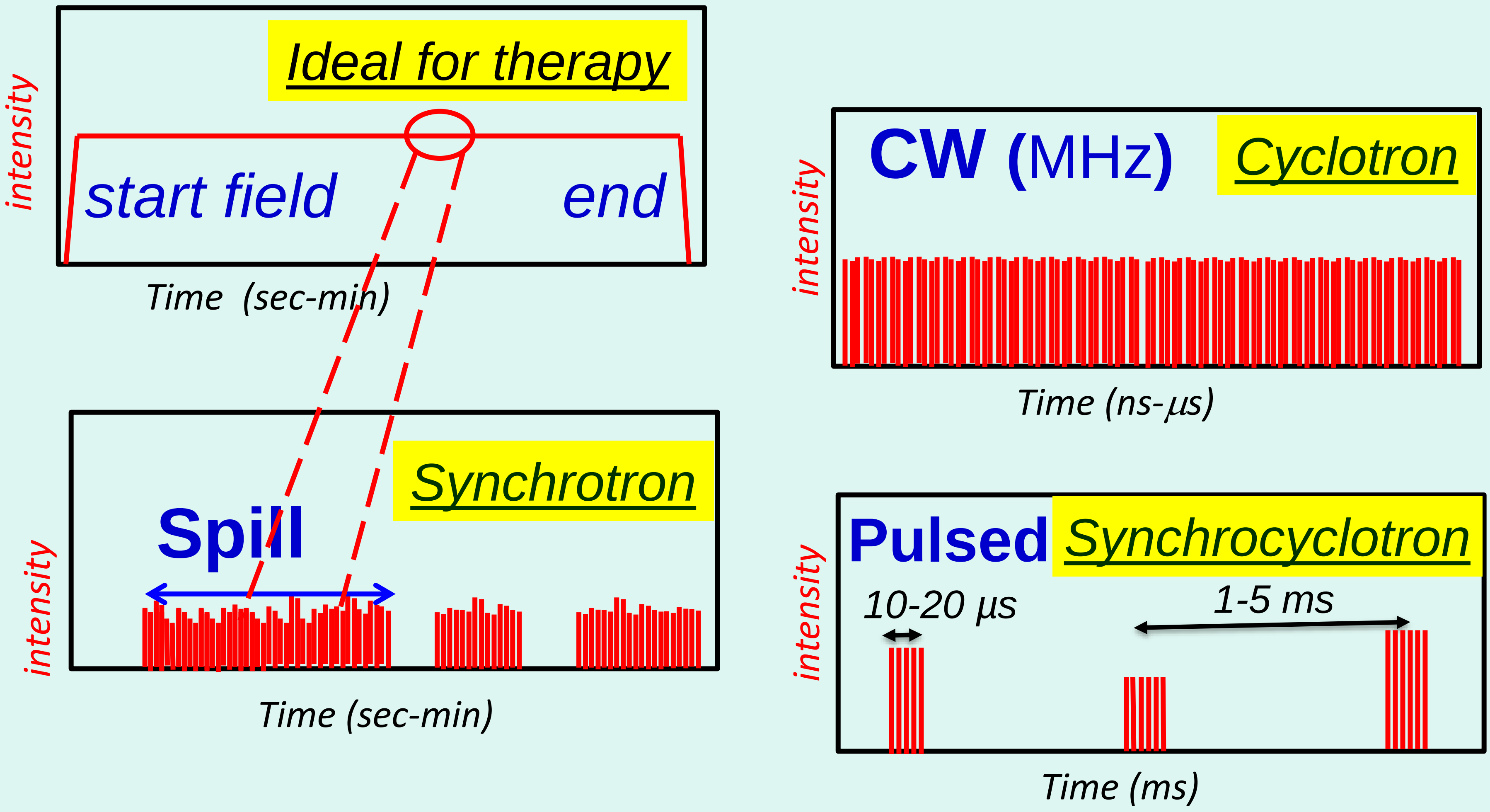
Repeat 1000 x per sec



Each pulse: set intensity at source **within ms**

10-30% accuracy

Major difference: time structure



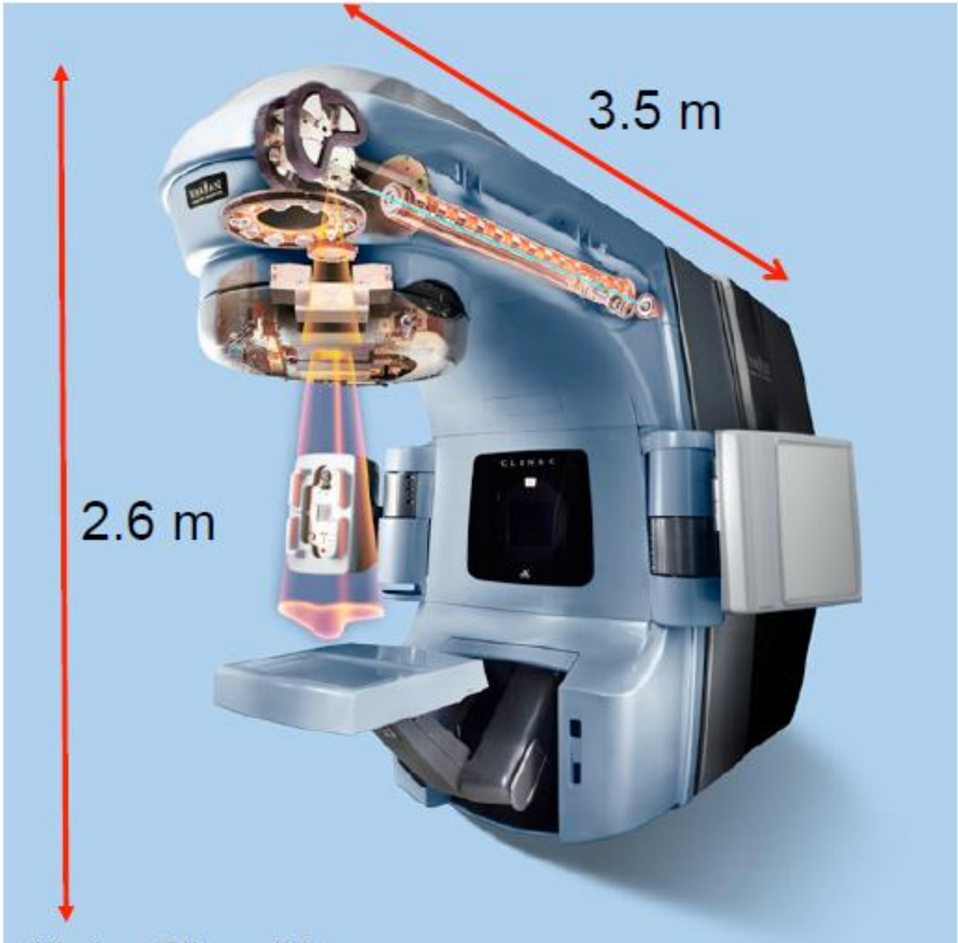
the major differences…

	cycl. (or syn.cycl.)	synchrotron
Size ∅	3.5 - 5 m (< 2m)	6-8 m (C: 25 m)
Carbon ions	in development	easy
Change particle	in development	easy
Time structure	continuous (pulsed)	dead time
Energy	fixed	variable, high
Fast E-scanning	degrader + shielding	next spill
Intensity	“any” + adjustable (limited per pulse)	limited in spill

Gantries

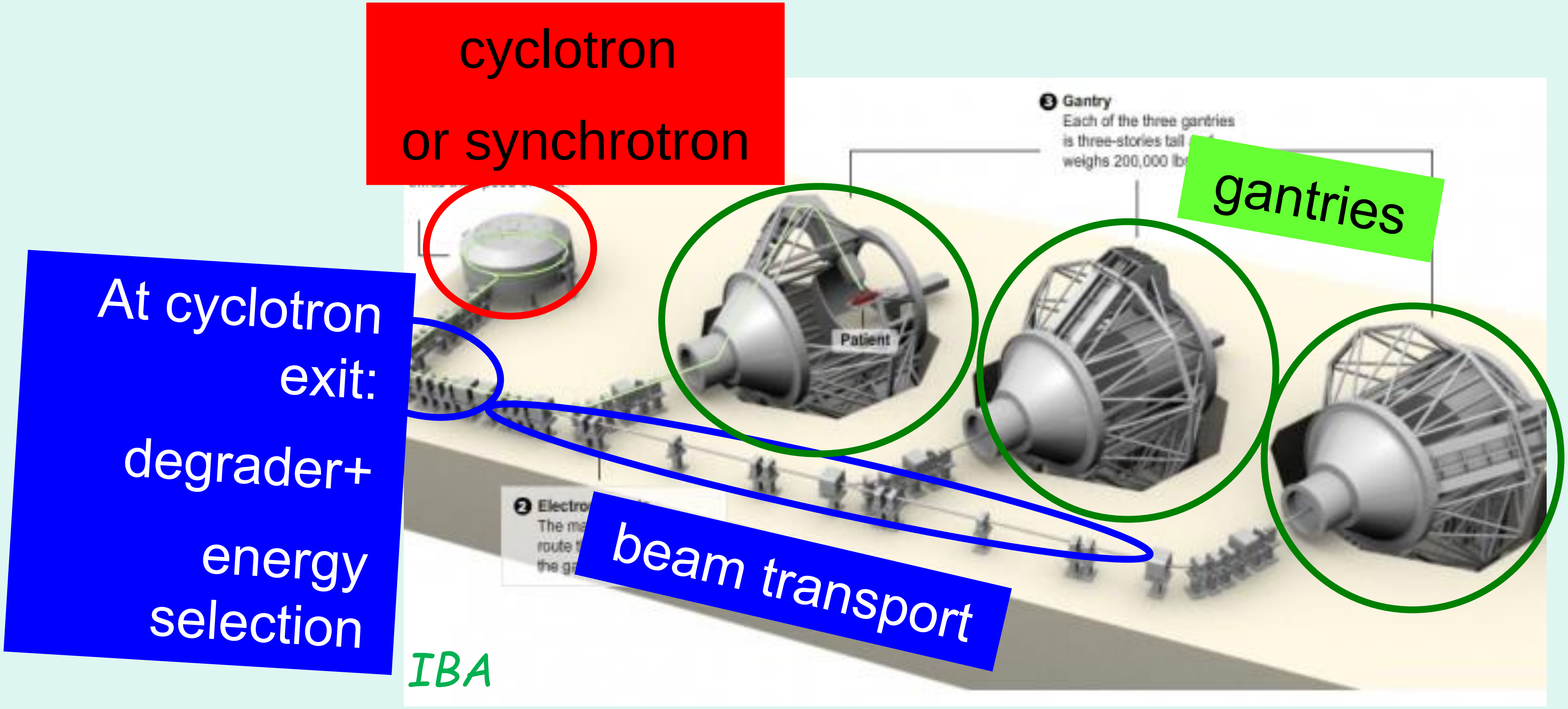
Gantry in **conventional** radiotherapy

- **The whole linac is inside the gantry**
- **The gantry head can pass between patient and floor for irradiation from below**



(Varian Clinac IX)

Proton therapy facility



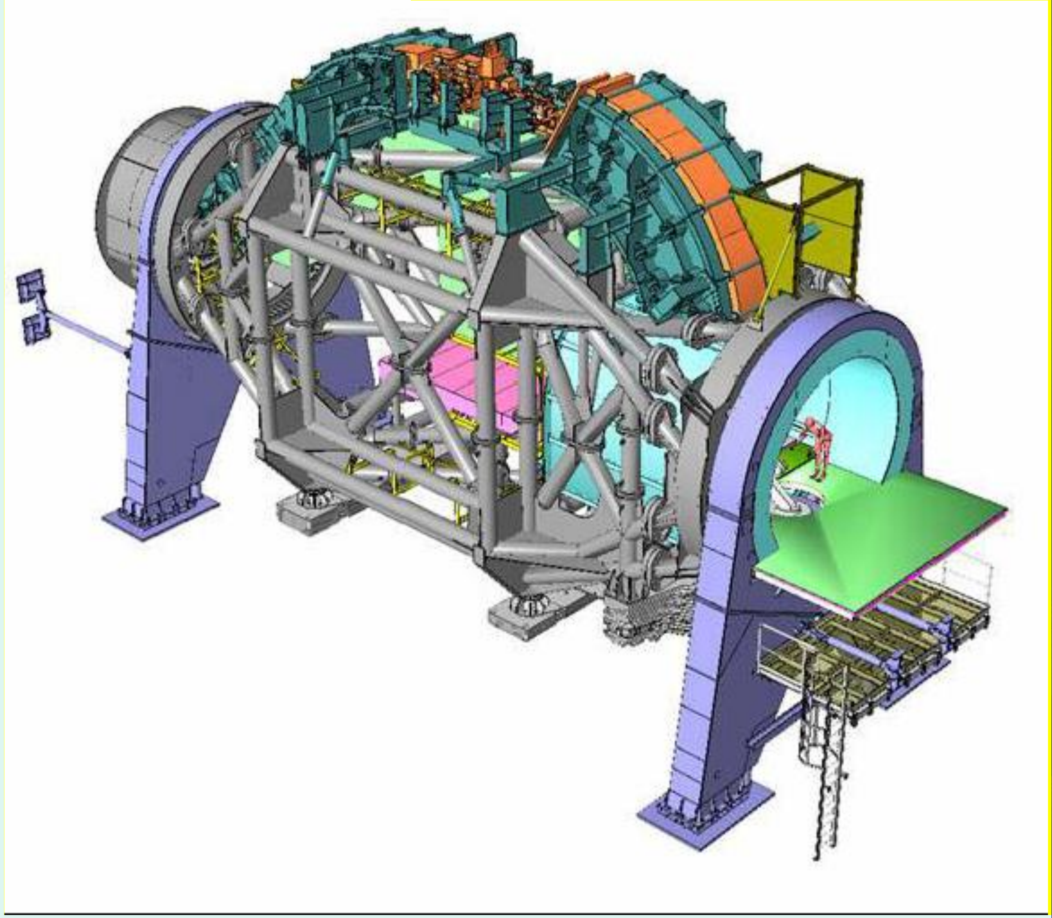
Gantry as seen from patient side

Gantry for protons

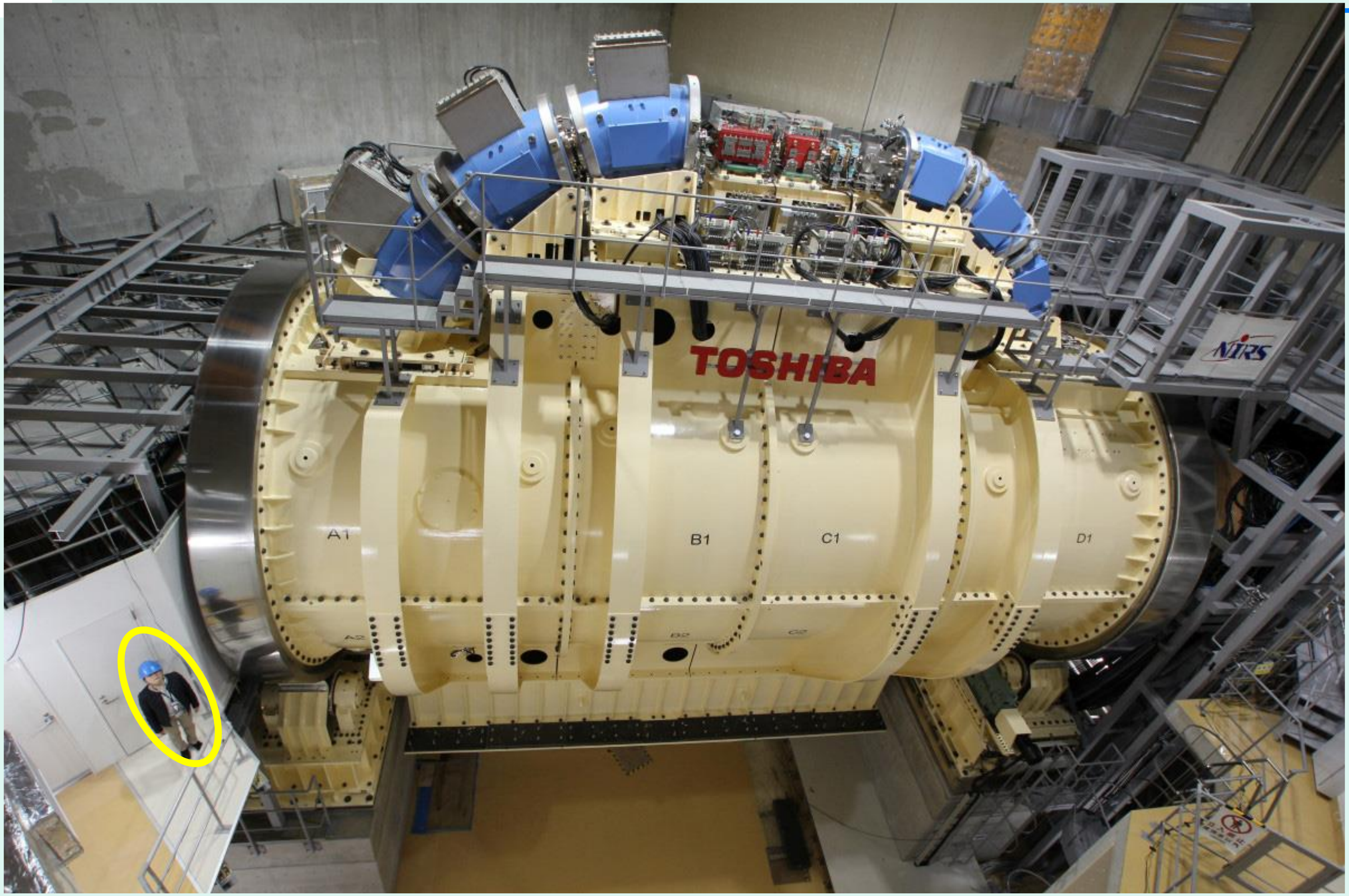
Proton gantry:10-12 m ∅; 100-200 t.

Gantry for C-ions

L=25 m, diam=13 m
600 tons rotating mass



SC Gantry for C-ions



Iwata 2018: diam=11.5m, *L=13 m 300 tons*

Recent developments

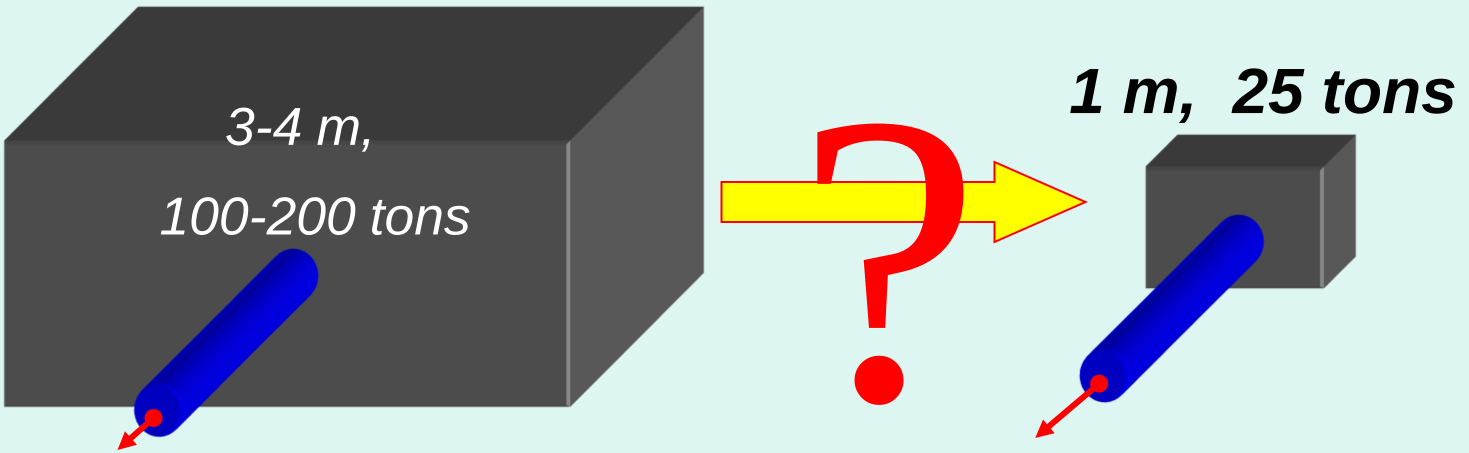
Reduction of costs:

- **Reduce size** of equipment
- New **accelerator types**

Small accelerator

See e.g: J.M. Schippers and T. Lomax, Acta Oncologica 50 (2011) 838-850 + refs there in.

How to reduce accelerator size?



250 MeV: Bρ = 2.4 Tm (Bρ = magnetic rigidity)

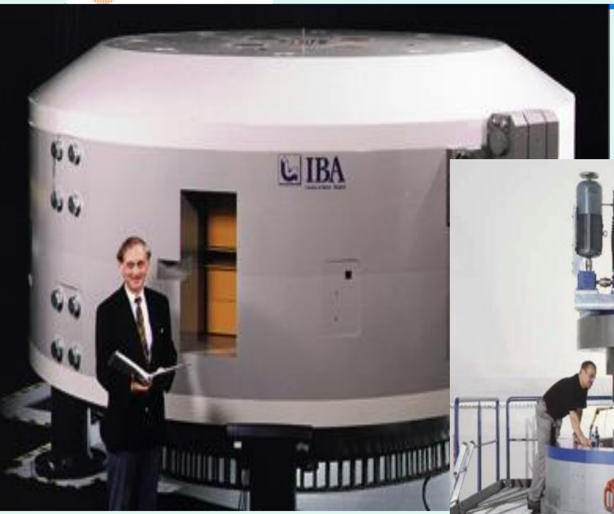
NOW in cyclotrons: R_{pole} = 0.8 m → B= 3 T

To reduce Radius: → R_{pole} = 0.3 m → B= 8 T

→ weight: $\left(\frac{0.3}{0.8}\right)^2$ = 14% = 20-30 tons

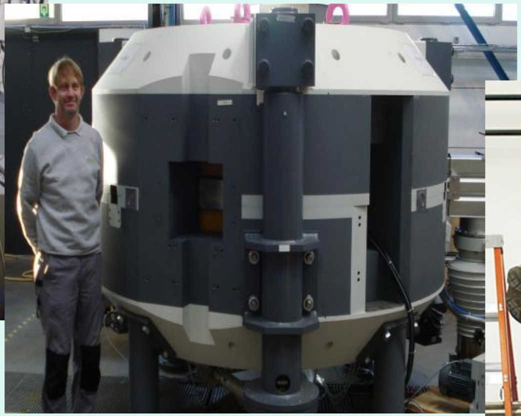
proton therapy cyclotrons

Superconducting Coils



IBA (1996) ,
SHI
250 Tons
Isochronous Cyclotron

Varian (2005)
90 Tons
Isochronous Cyclotron



IBA (2018)
60 Tons
Synchrocyclotron

MEVION (2013)
15 Ton
Synchrocyclotron

Synchro-Cyclotron

8-10 T   250 MeV Synchro-cyclotron on a gantry

first beam 2010,   In use since dec. 2013

New accelerator developments

IBA's C-400 Hadron Cyclotron

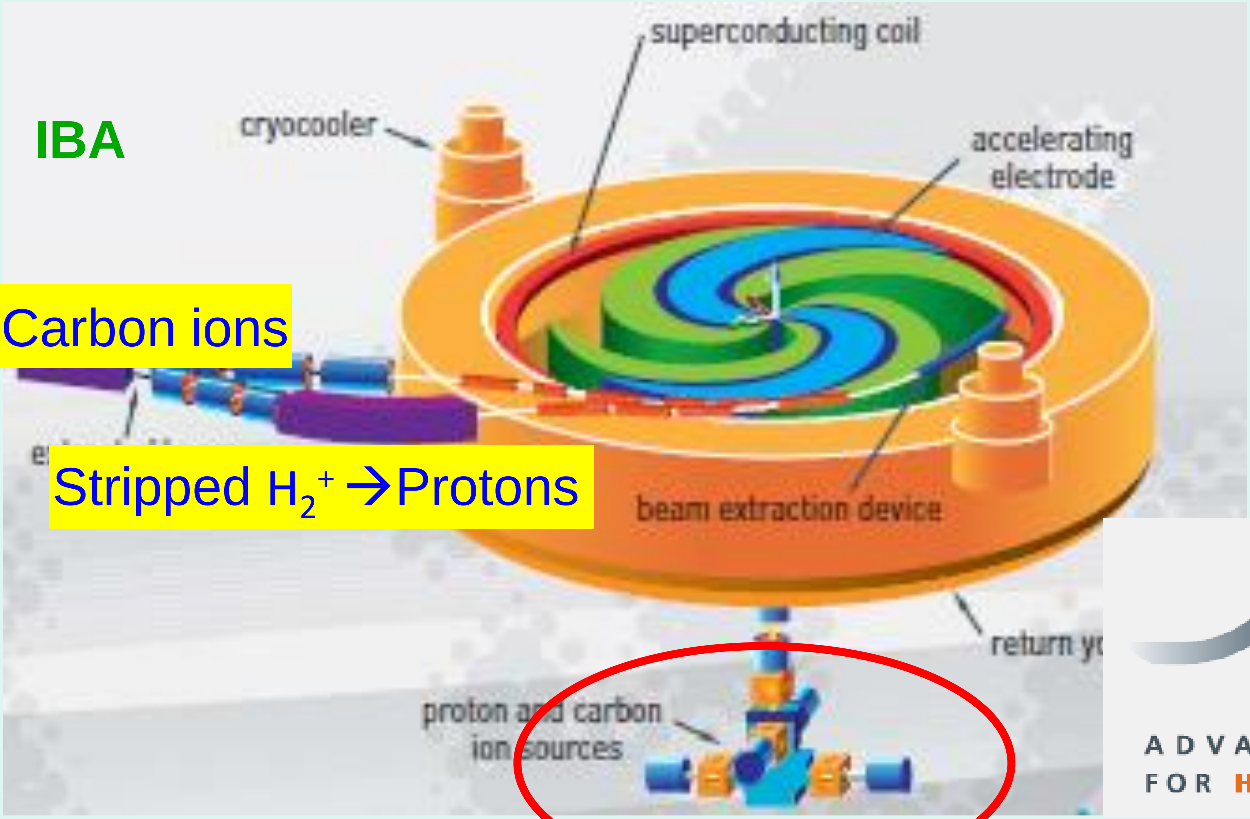
Int. Conf. Cyclotron and appl, Tokyo 2004

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.

400 MeV/nucl q/A=0.5 → C^{6+}, He^{2+}, H_2^+

IBA



Carbon ions

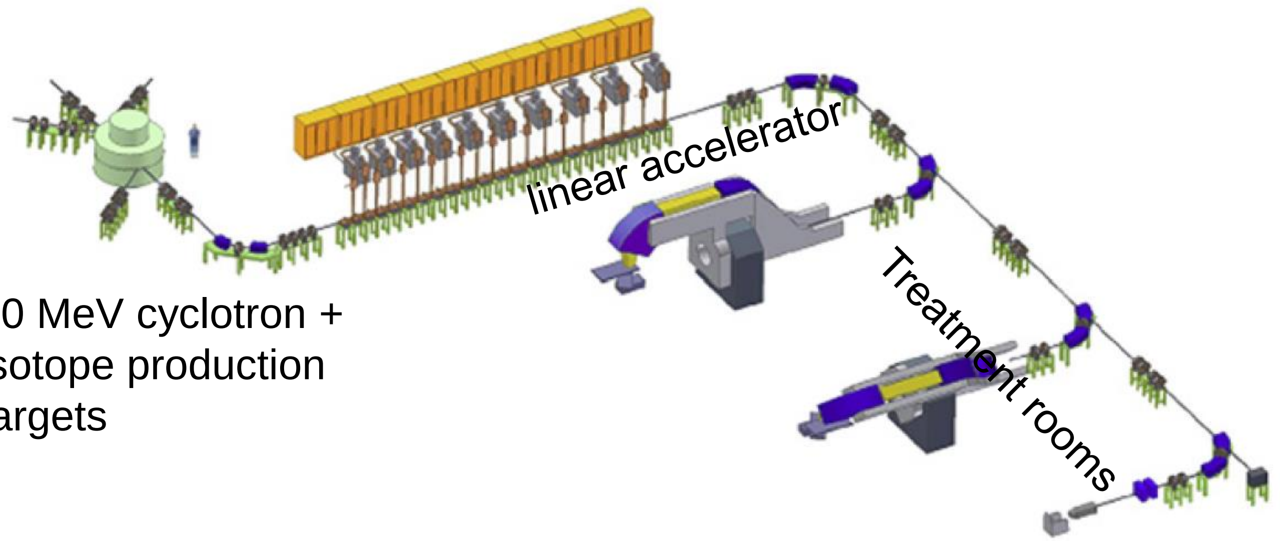
Stripped H_2^+ → Protons

SC coils
2.5 T, Ø 7 m
→ 700 tons

Archade
ADVANCED RESOURCE CENTRE FOR HADRONTHERAPY IN EUROPE

High flexibility: fast E-change

Cyclotron-Linac combination



Energy is set per pulse → fast scanning in depth

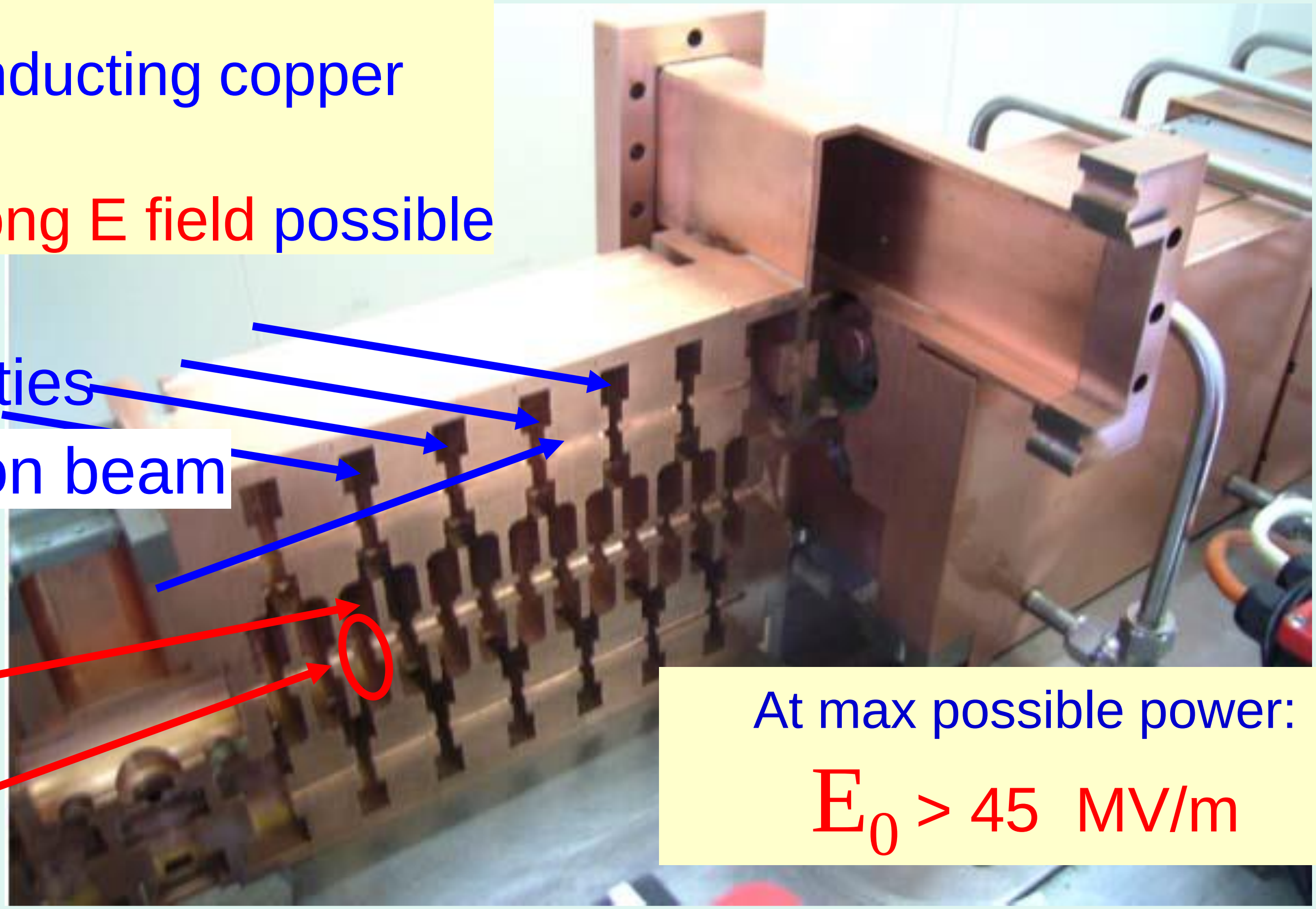
U. Amaldi et al. / Nuclear Instruments and Methods in Physics Research A 579 (2007) 924–936

Coupled Cavity Linac (CLIC techn)

tanks, with 12 cavities:

Normal conducting copper

3 GHz: strong E field possible



coupling cavities

Pulsed electron beam

accelerating cavities (12)

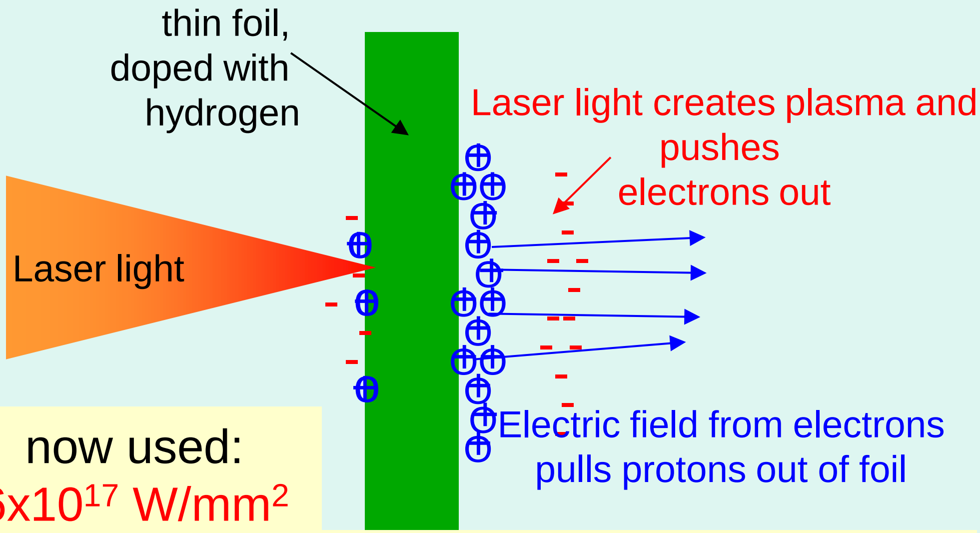
Proton Beam

At max possible power:

E_0 > 45 MV/m

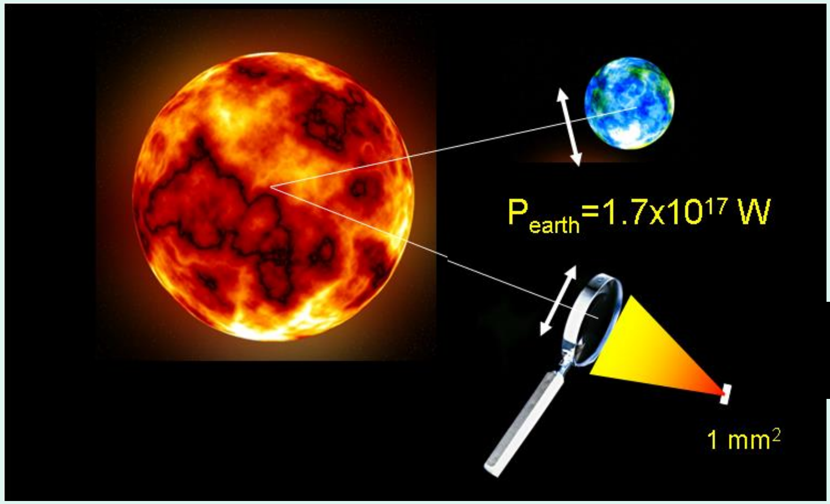
Garlaschè , Degiovanni , Verdú.A , Bonomi (TERA)

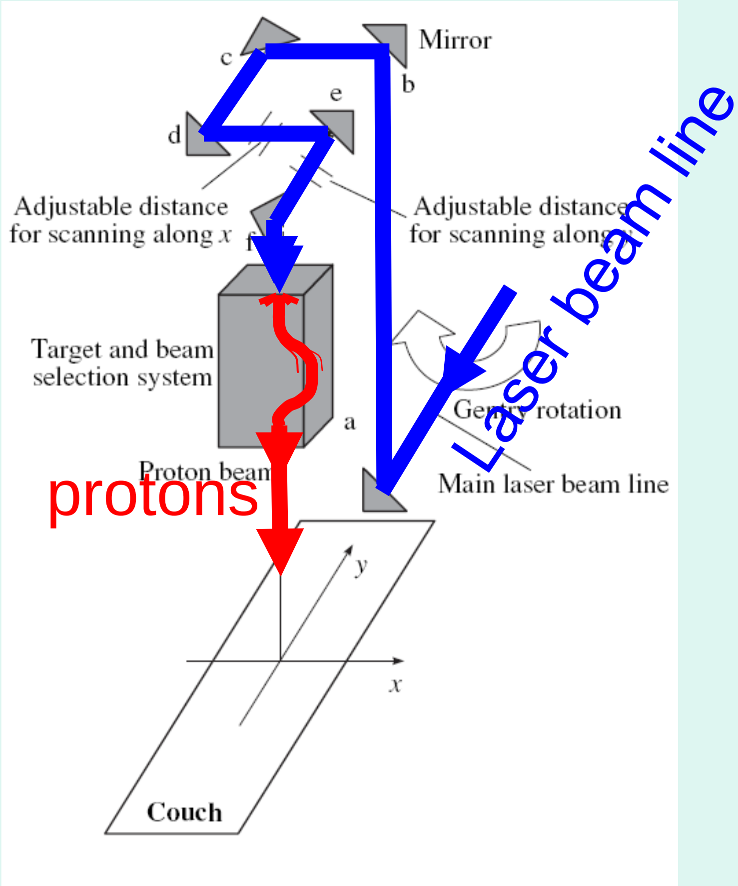
Laser driven proton accelerator



now used:
6×10^{17} W/mm^2

≈ total solar power on earth, focused at 1 mm^2





But 100x more power is needed

C.M. Ma, Laser Physics, 2006, Vol. 16, No. 4, pp. 639

Summary

- Therapy with protons / ions: better dose distribution
- Dose delivery techniques:

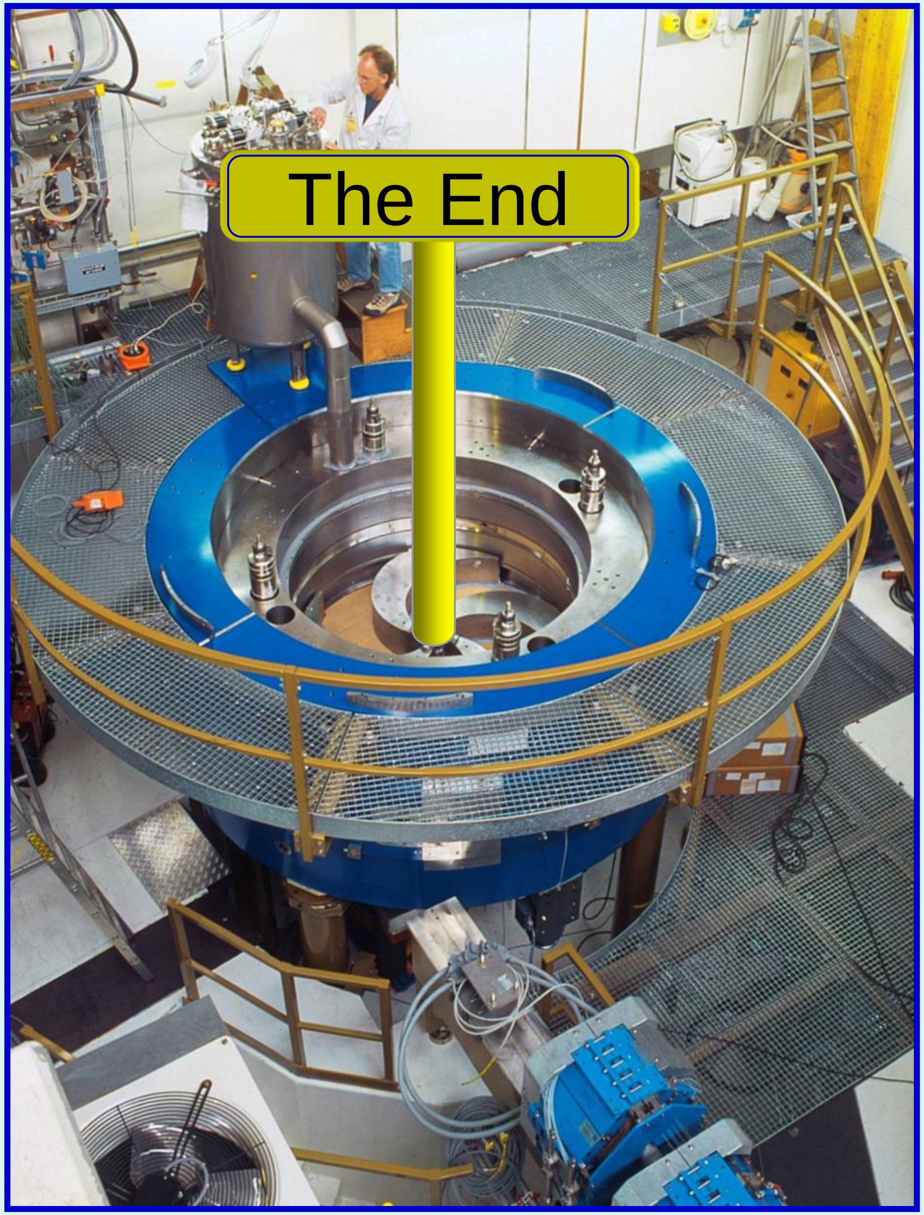
  E-modulation → depth

  Scanning → lateral
- Accelerators:

  Synchrotron, (synchro-)Cyclotron
- Gantries
- Recent developments:

  reduce accelerator size

  new acceleration techniques


The End