Accelerators for particle therapy

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Goal of this lecture: give you an idea on possibilities of current accelerators

Contents

- **electric and magnetic fields**
- **synchrotron**
- **cyclotron**
- **synchro-cyclotron**
- **New developments**

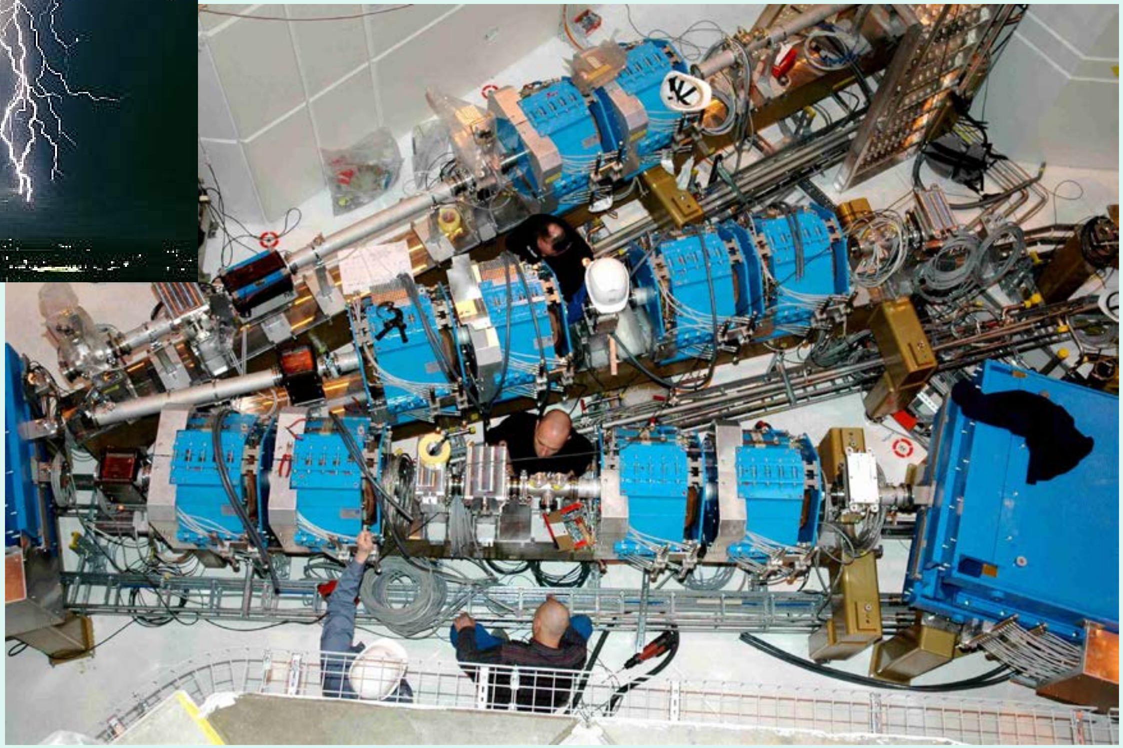
Vendors are acknowledged

for sharing information and images !!

More details in: J.M. Schippers, Rev. Acc. Science and Techn. 2 (2009) 179-200

H. Paganetti (ed.), Proton Therapy Physics, Chapter 3.

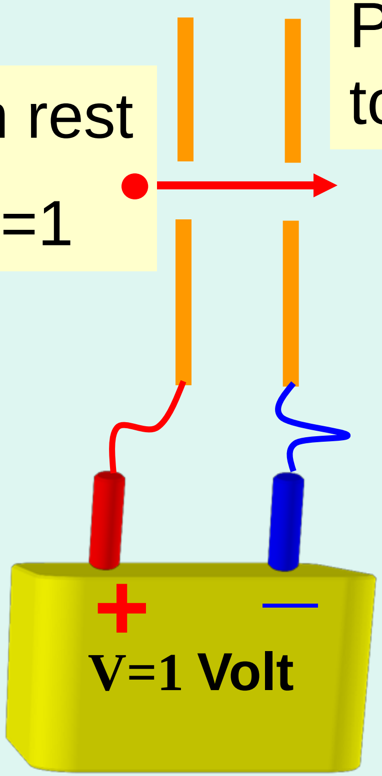
Electric and Magnetic fields



Electric fields

Proton in rest

q=1



Proton has been accelerated to an energy of $q \times V = 1$ eV

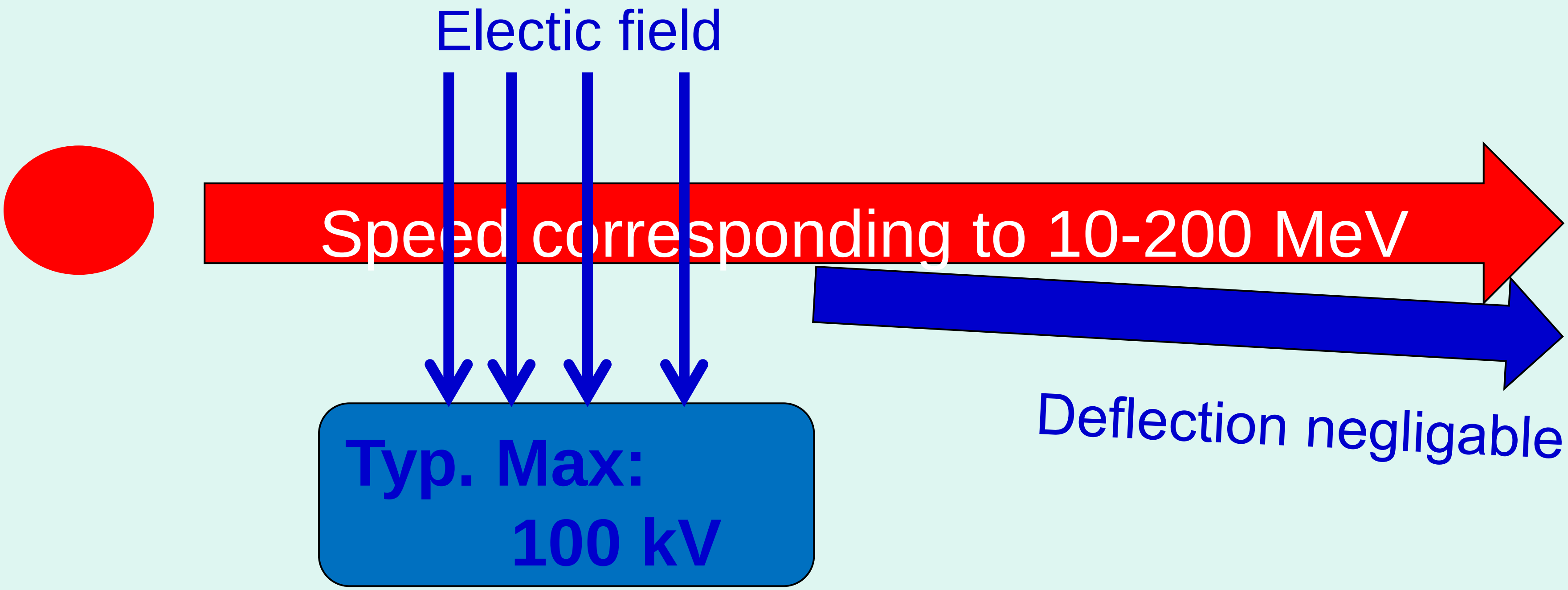
Electric fields are limited in strength

But:

Repeated acceleration → **high energy**

$$E = qV + qV + qV + qV$$

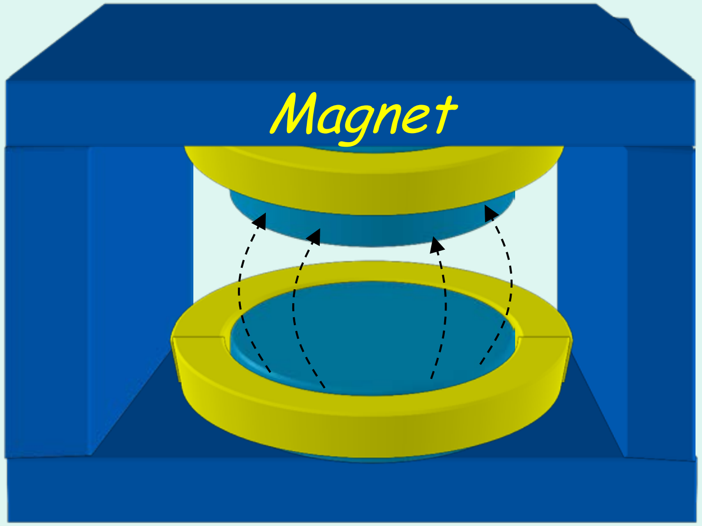
Electric fields

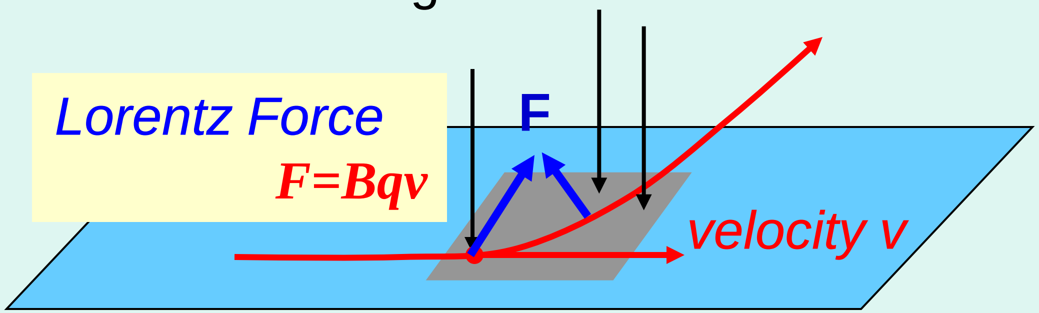


→ used for **focusing/deflecting** only at low energy

(e.g. in injection line of synchrotron)

Magnetic fields





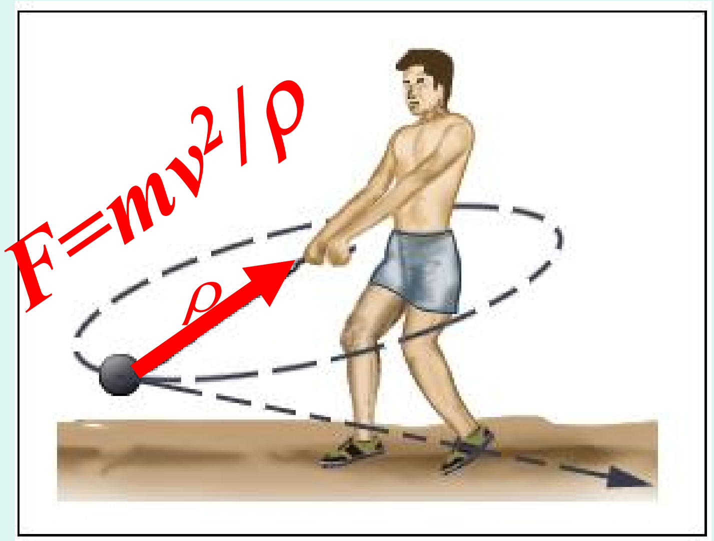
Lorentz force = "centripetal force" $\mathbf{mv^2/\rho}$

⇒ track = circular orbit with radius ρ

energy **E** and charge q

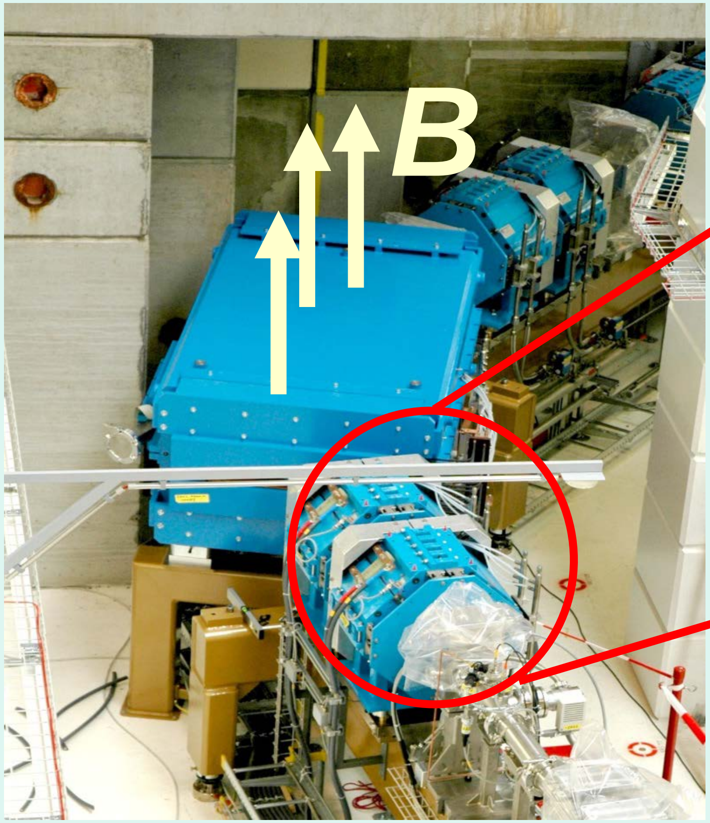
<=> magnetic rigidity: **Bρ (= p/q):**

magnet strength B to bend with radius ρ



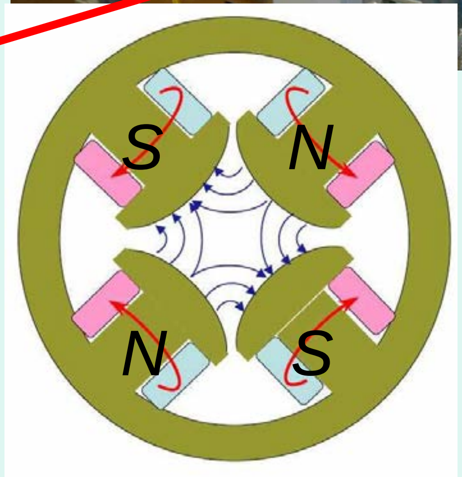
70 MeV p:	Bρ = 1.2 Tm
250 MeV p:	Bρ = 2.4 Tm
450 MeV/nucl C^{6+}:	Bρ = 6.8 Tm

Magnetic fields



Dipole magnet:

bends *the beam direction*



Quadrupole magnet:

(de)focuses the beam

Summary

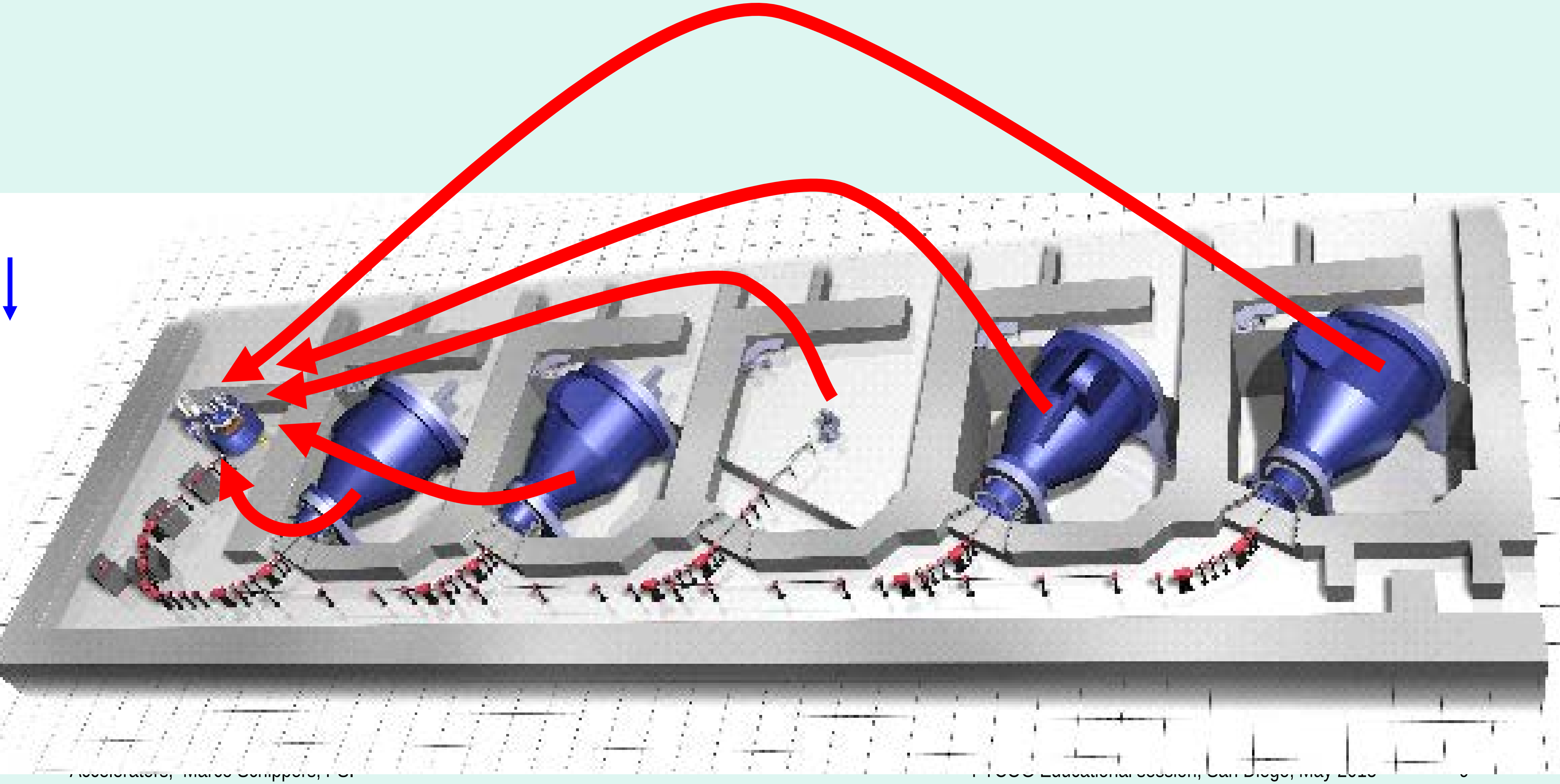
Traversing **electromagnetic fields**:

E: acceleration

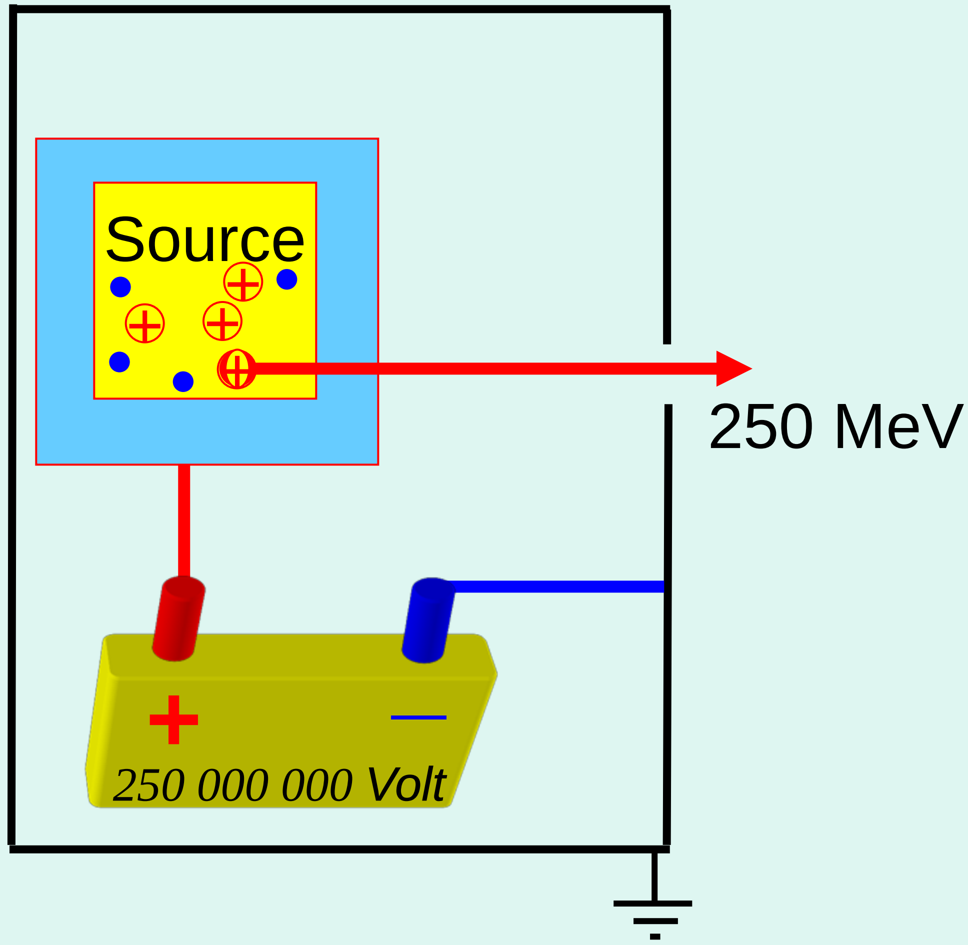
B: directing and focusing

Proton therapy facility: modules

However, NOT independent….



Accelerators



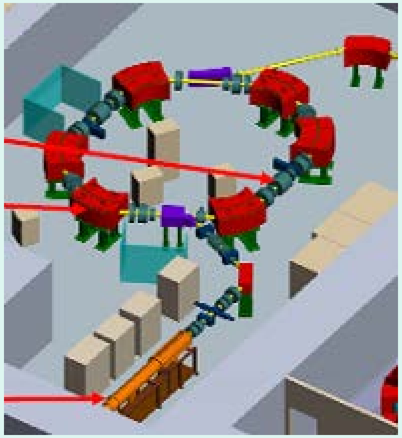
Present accelerator choice

	cyclotron	synchrotron
Protons	in use, ∅3.5-5 m	in use, ∅8-10 m
Carbon ions	test phase	in use, ∅25 m

Synchrotron (1945)

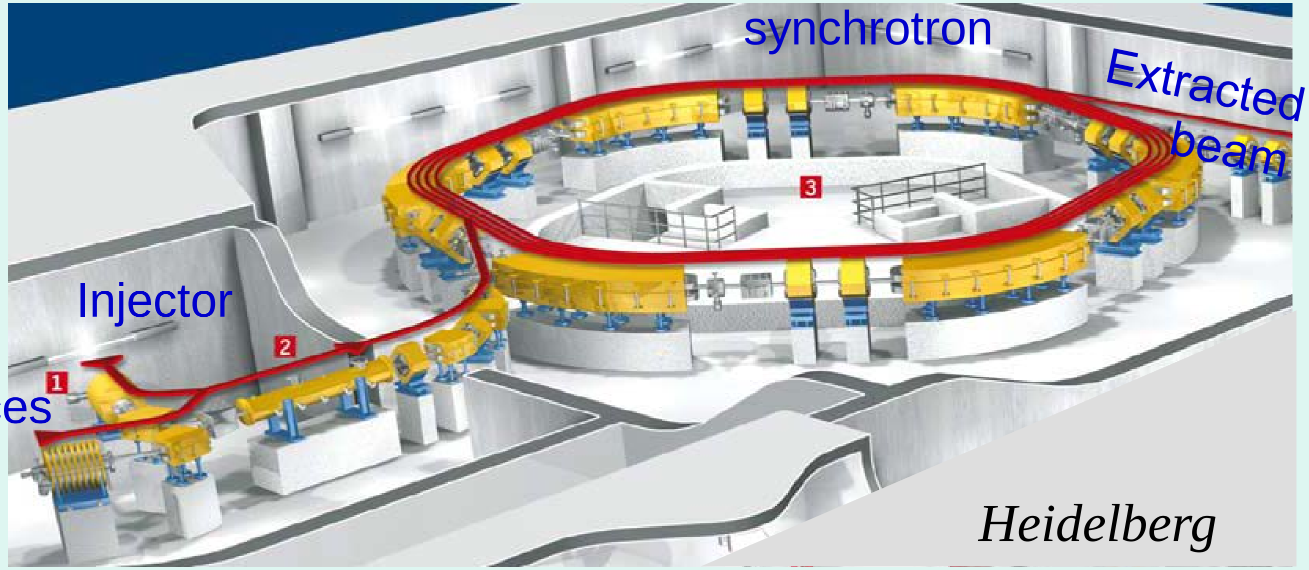
Protons only:

(∅ ~8 m)

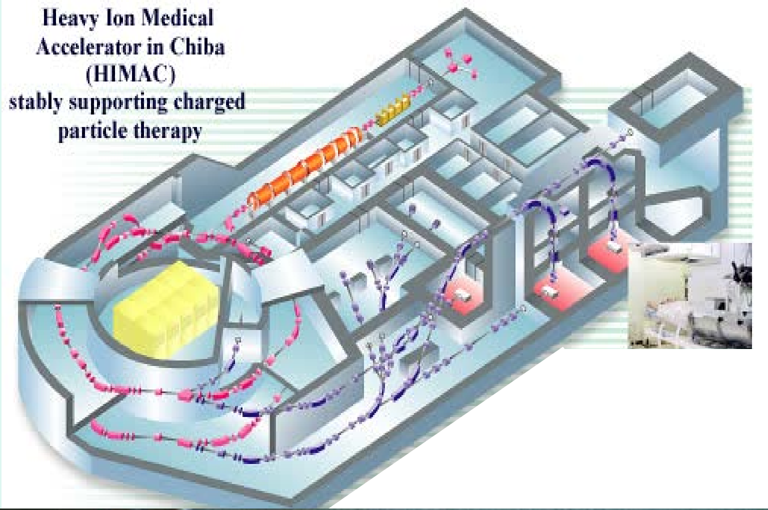


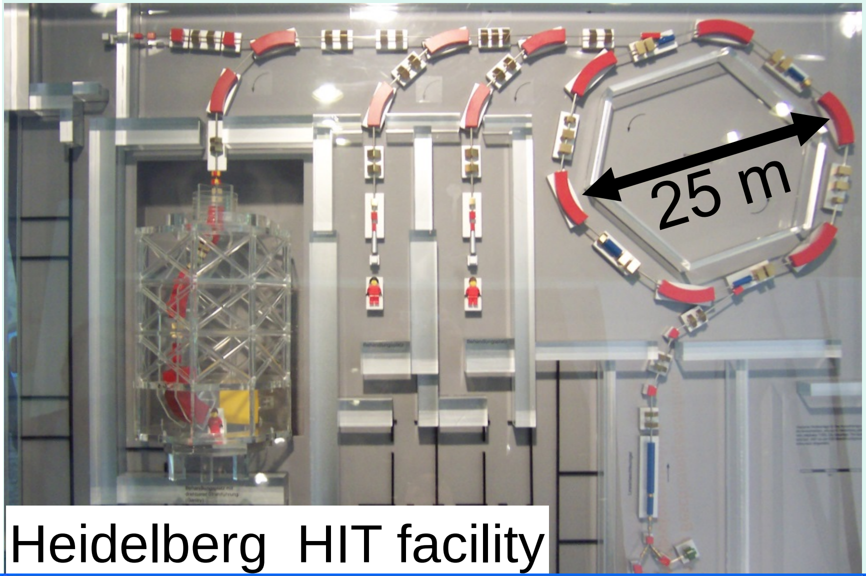
Ions (p-C):

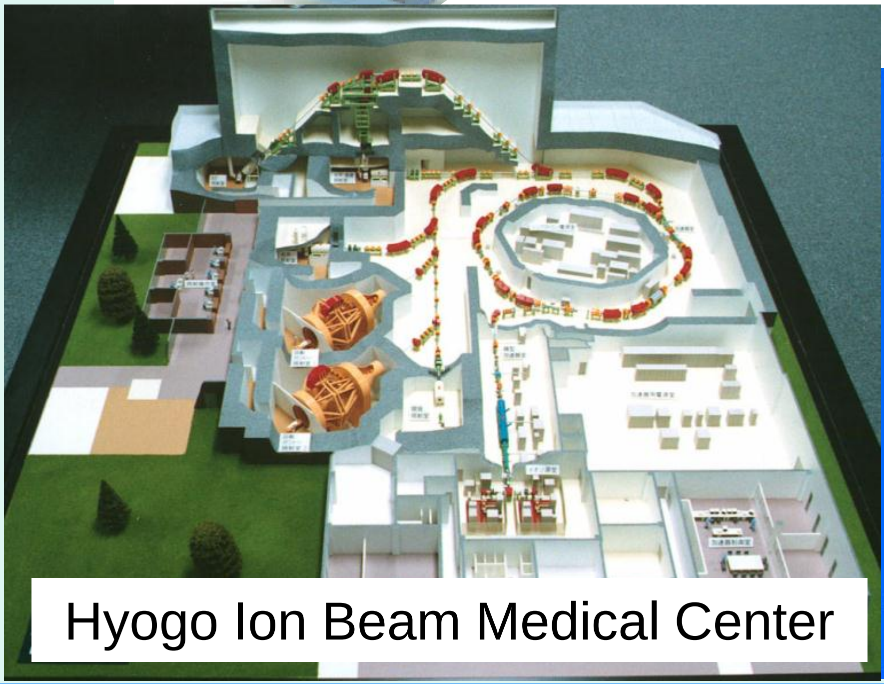
(∅ ~25 m)

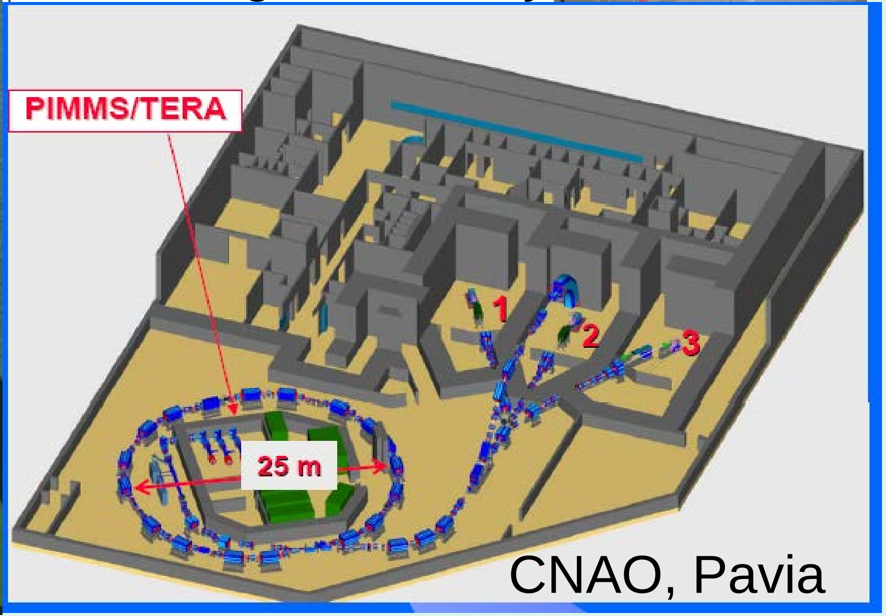


Ion therapy: synchrotron facilities

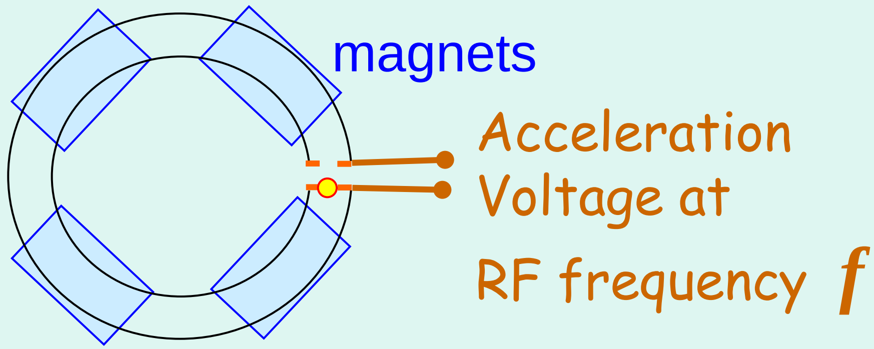


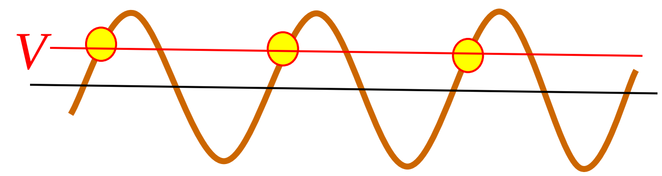






Acceleration in synchrotron





At electrode slit crossing:

Energy gain $\Delta E = V.q$

Energy increases:

→ speed ↑

→ **RF frequency** ↑

→ **field** in magnets ↑ $\frac{p}{Bq} = r$ = constant !

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

Synchrotron

Extraction into beam line

Ring:

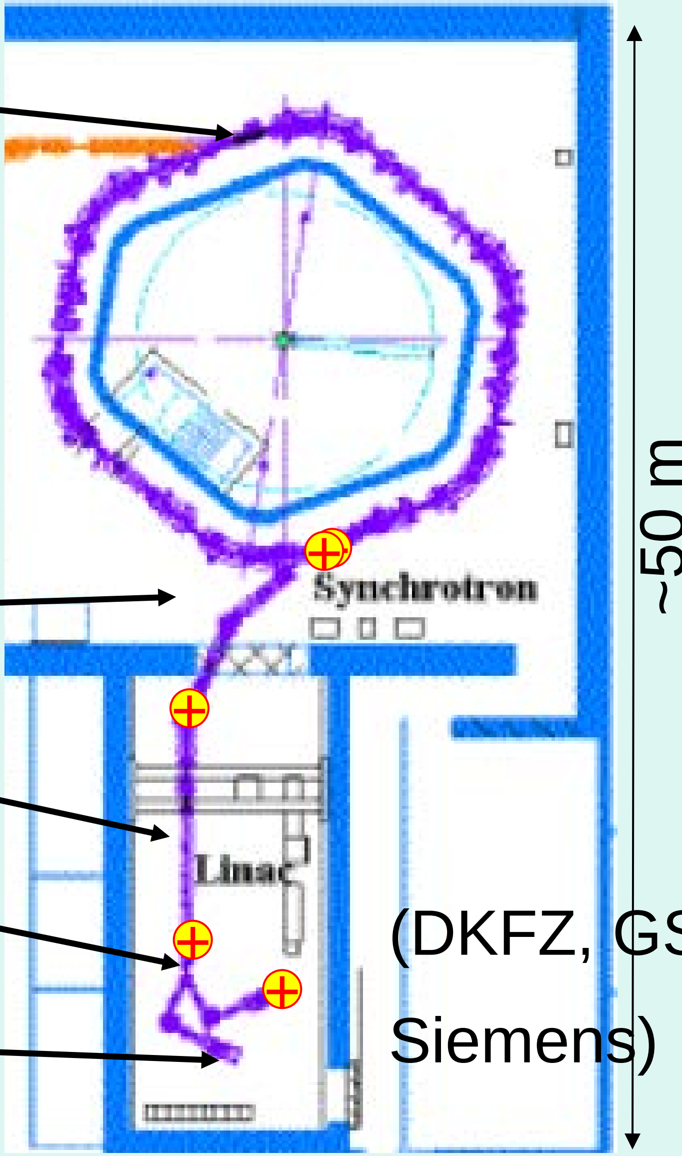
- collect 10^{11} particles
- acceleration to desired E
- storing of the beam

Injection in ring at 7 MeV/nucl

2 linear accelerators in series

Magnet to select ion source

Ion sources for different particles

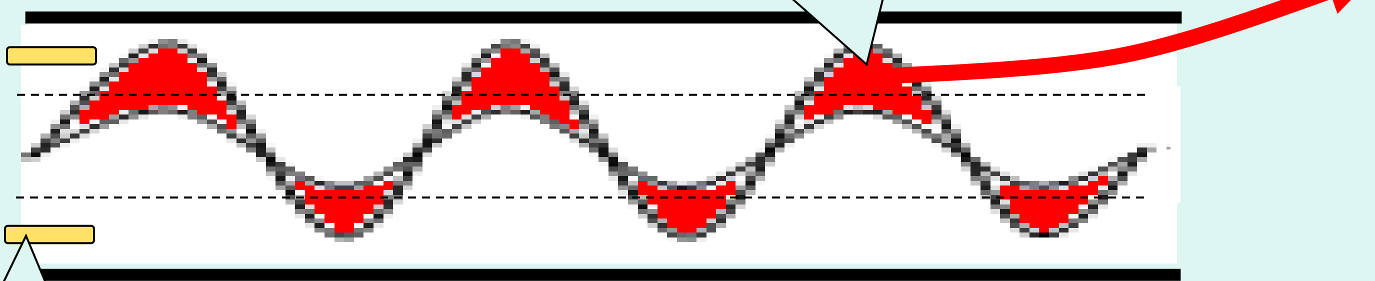


(DKFZ, GSI, Siemens)

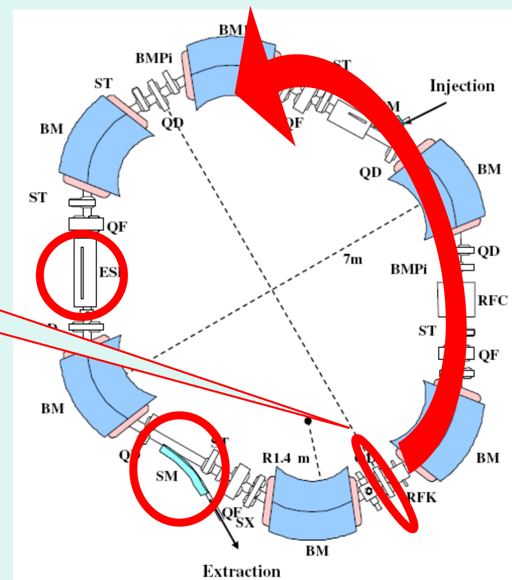
Beam **extraction** from synchrotron

RF-Knock Out

Unstable orbits
→ extracted



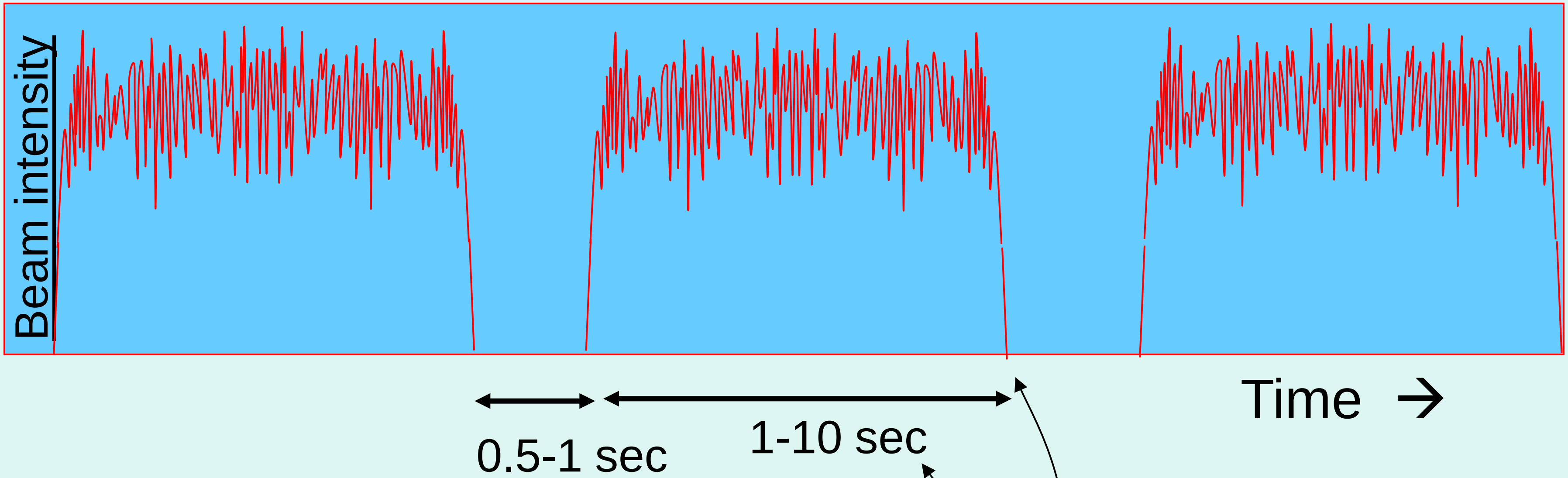
RF kicker: increases emittance (beam size)



With RF-knock Out:
Extractedbeam
position and size
remain constant

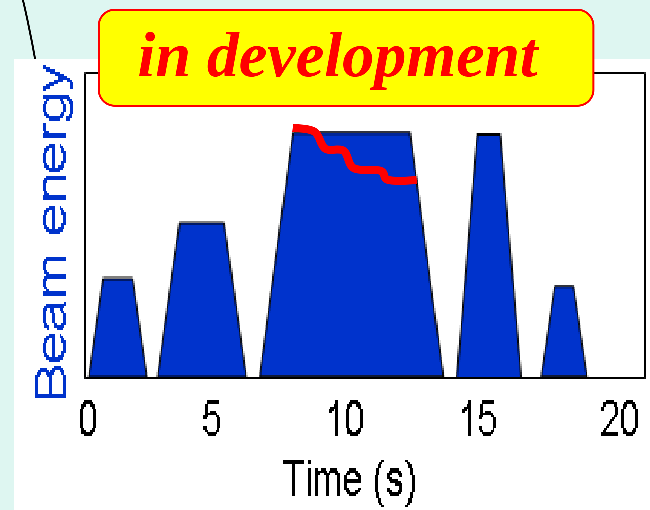
Beam shape:

Synchrotron beam: *spills*



“spill” time

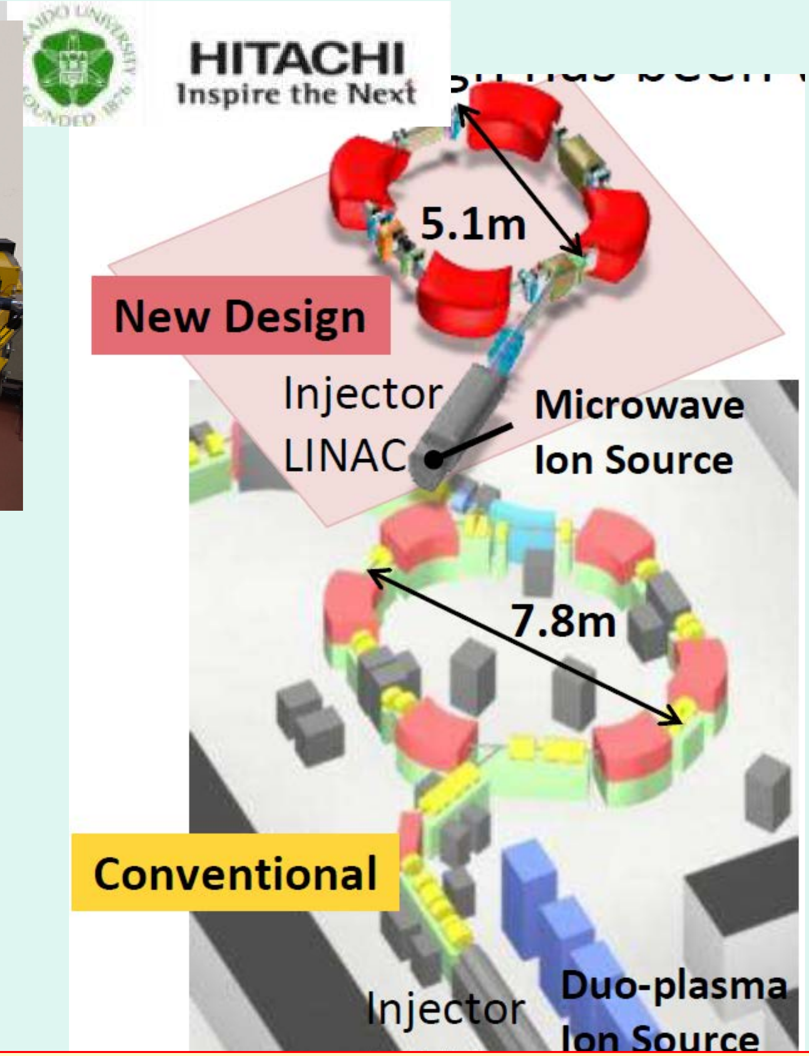
- fill ring with ~ $10^{9\text{-}11}$ particles
- accelerate to desired energy
- extract slowly during 1-10 sec
- decelerate and dump unused particles



Compact synchrotron

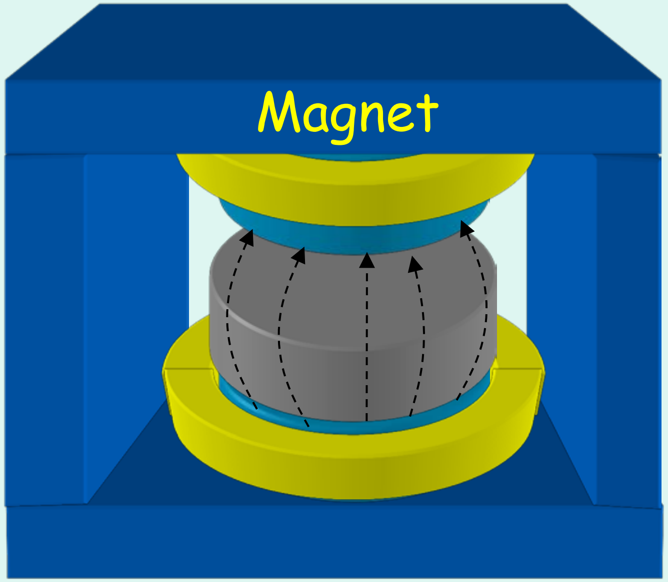
ProTom 330 MeV

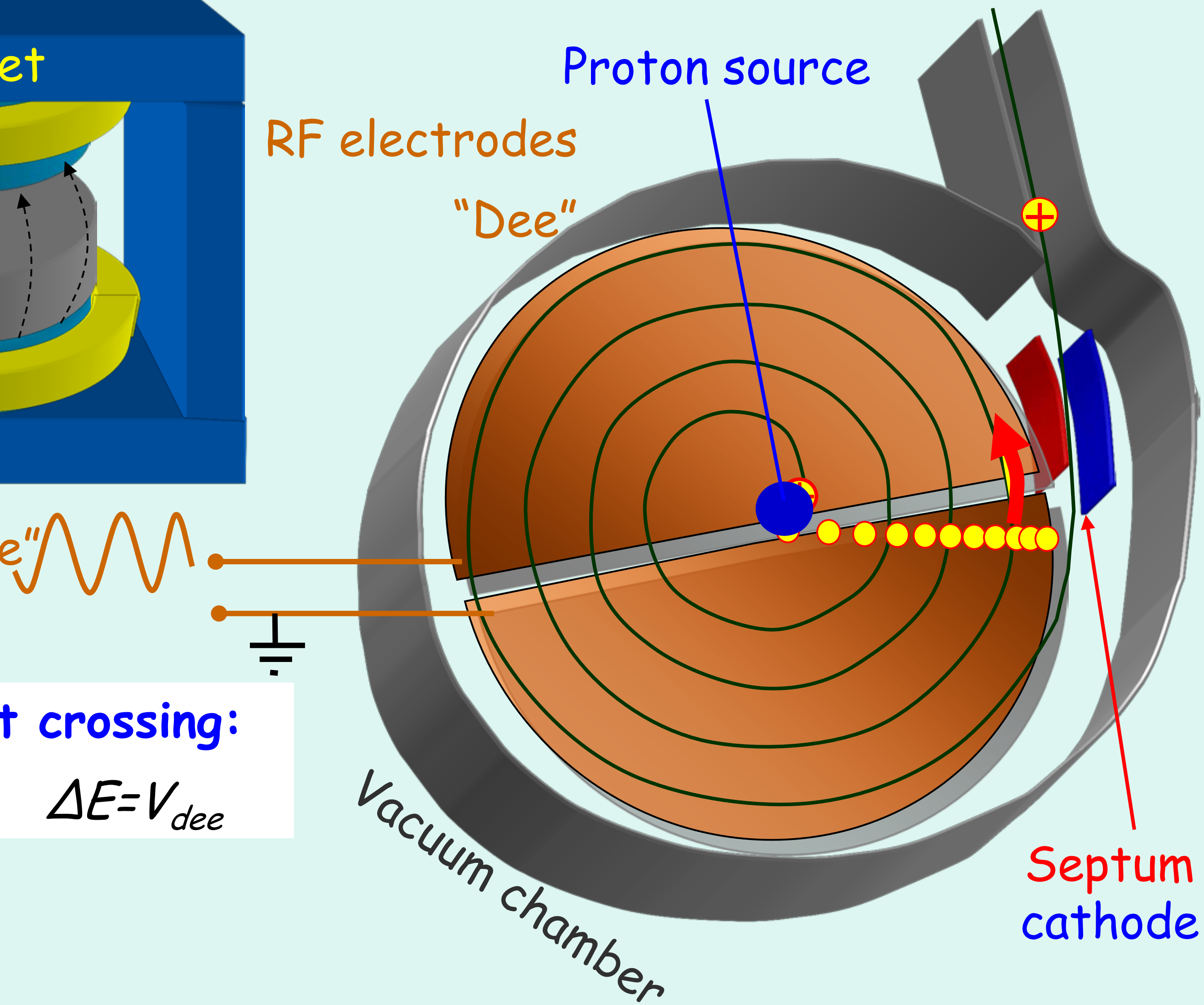
2012: Installation at:
McLaren, Flint (Mi)
MGH Boston (Ma)



- 220 MeV
- First facility in Hokkaido started 2013

Cyclotron (1930)



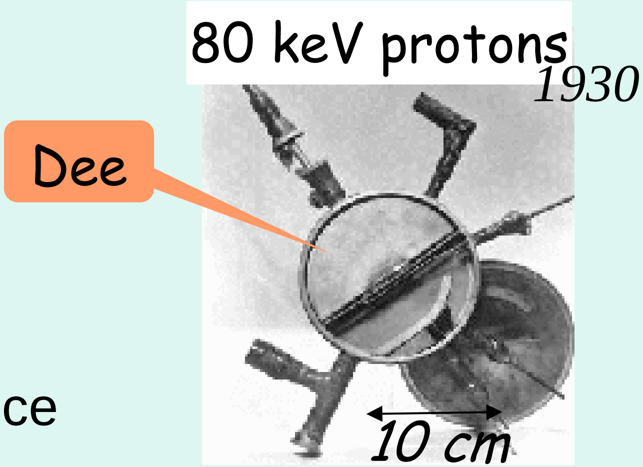


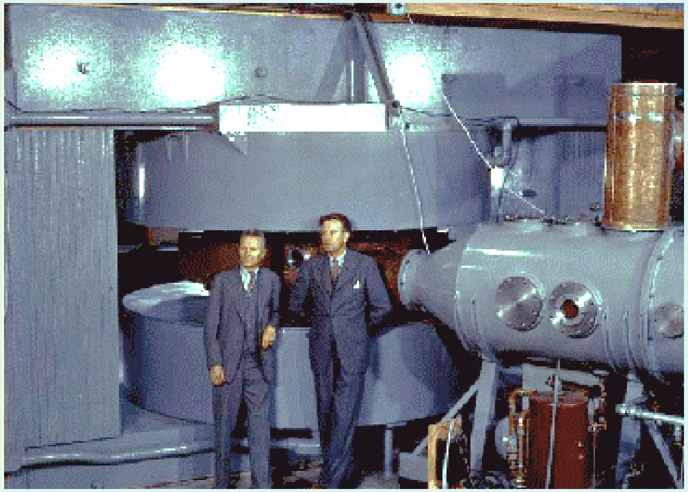
At electrode slit crossing:

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

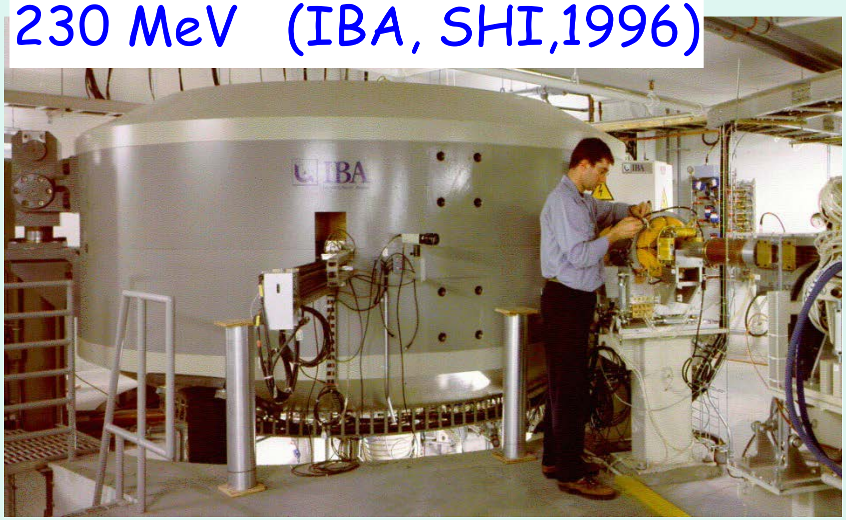
Cyclotron

Ernest Lawrence





230 MeV (IBA, SHI,1996)



250 MeV (ACCEL/Varian,2005)

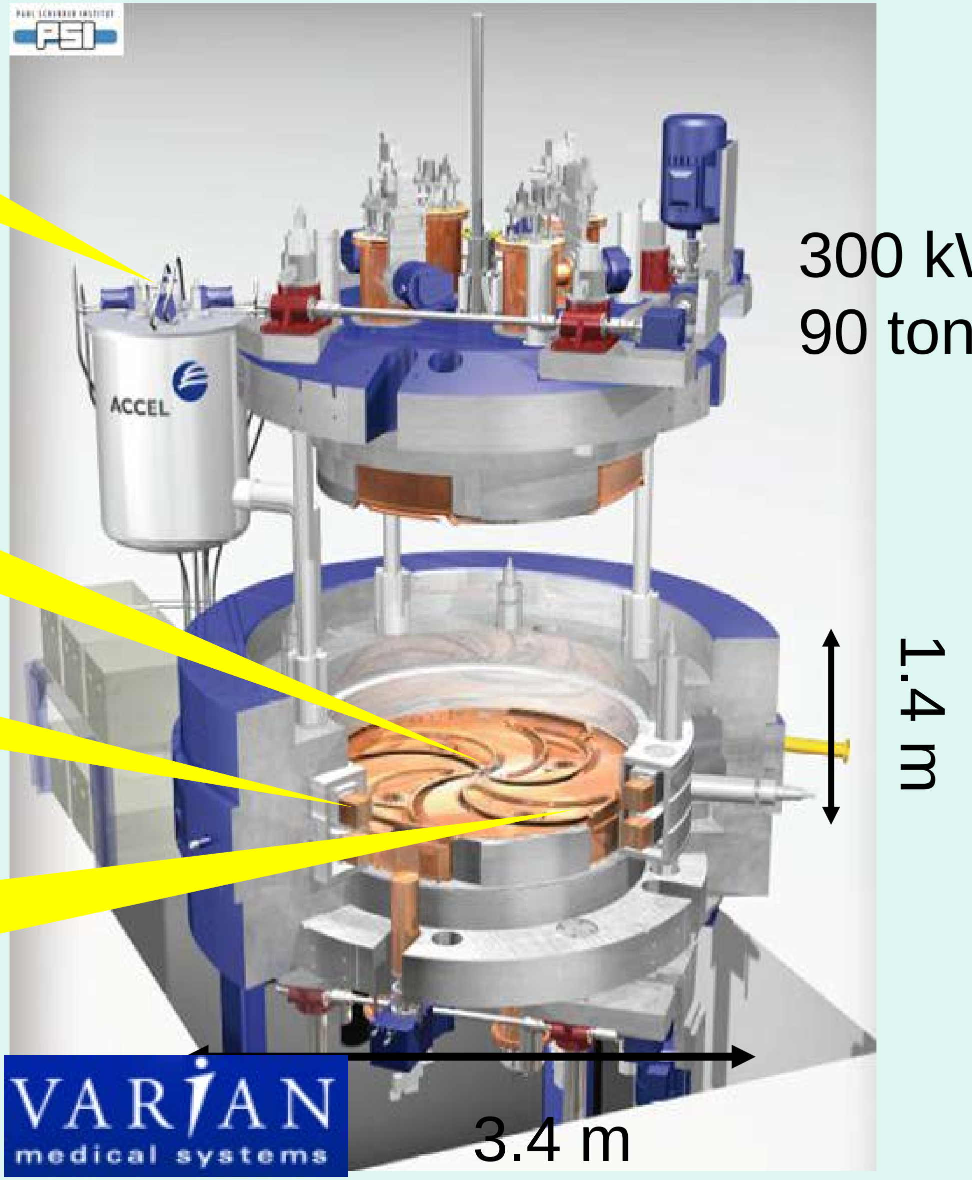
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

Proton source

superconducting coils
=> 2.4 - 3.8 T

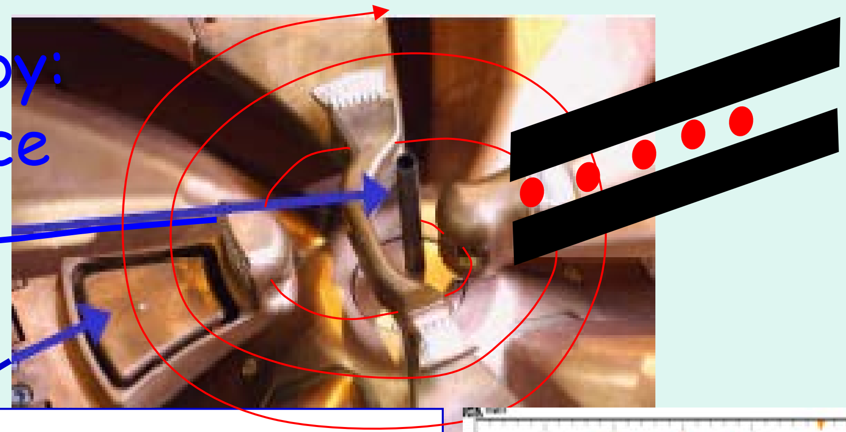
4 RF-cavities:
72 MHz (h=2)
~80 kV

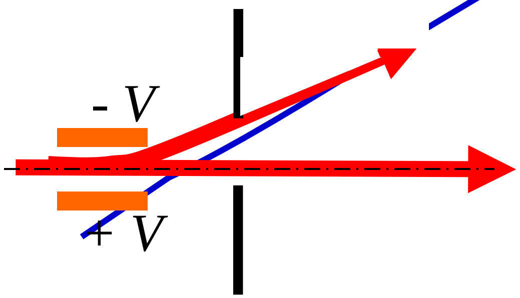


300 kW
90 tons

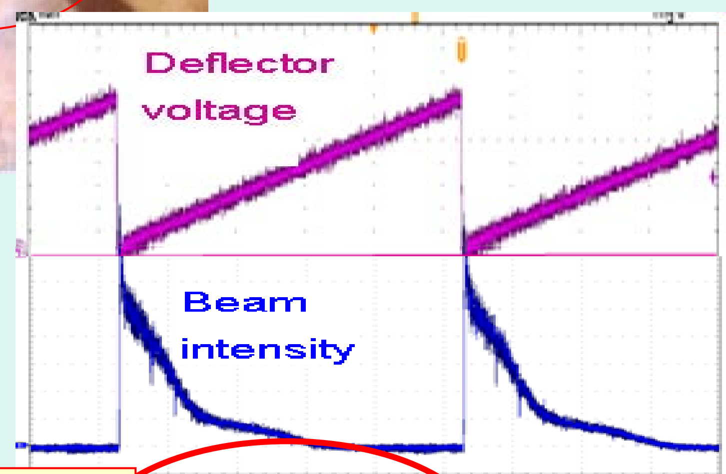
intensity control

Max. intensity set by:
proton source



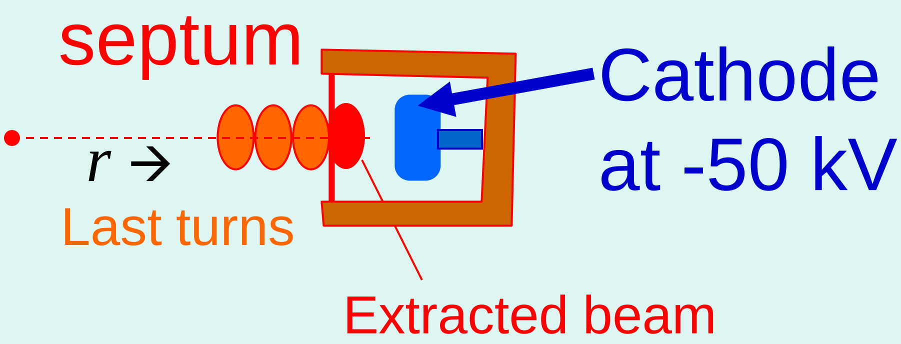


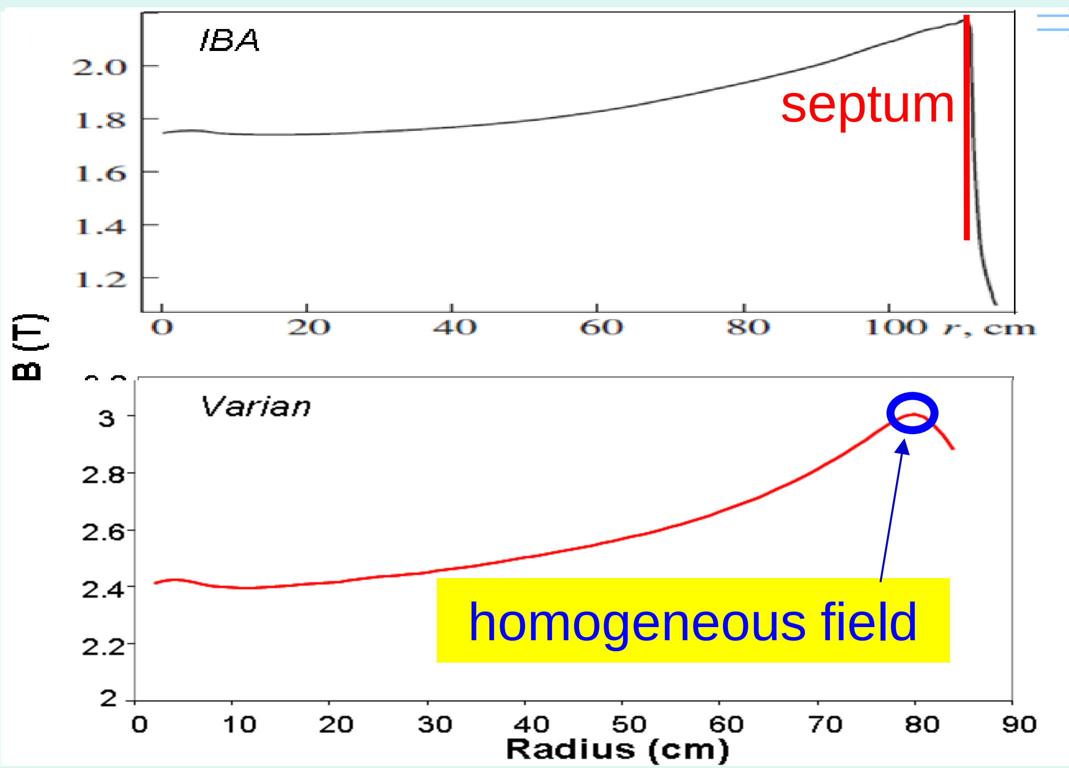
Deflector plate:
sets intensity
- within 50 μs
- 3% accuracy



currently only possible with a **cyclotron**

Extraction from cyclotron





IBA and SHI: elliptical pole gap

⇒ Fast field drop at outer radius

⇒ Cathode + weaker field quickly pull the beam „out“

Varian:

flat poles & stronger field

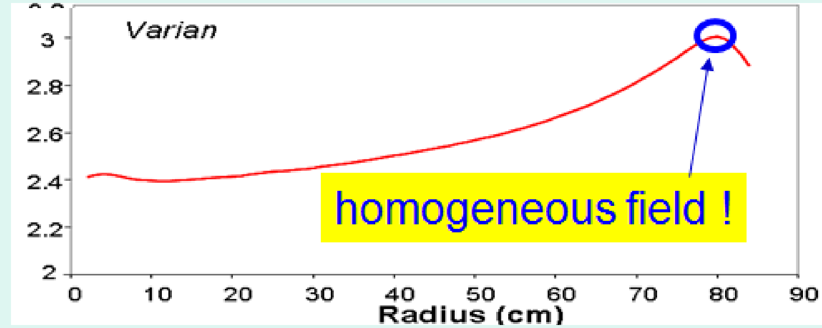
=> Other method required

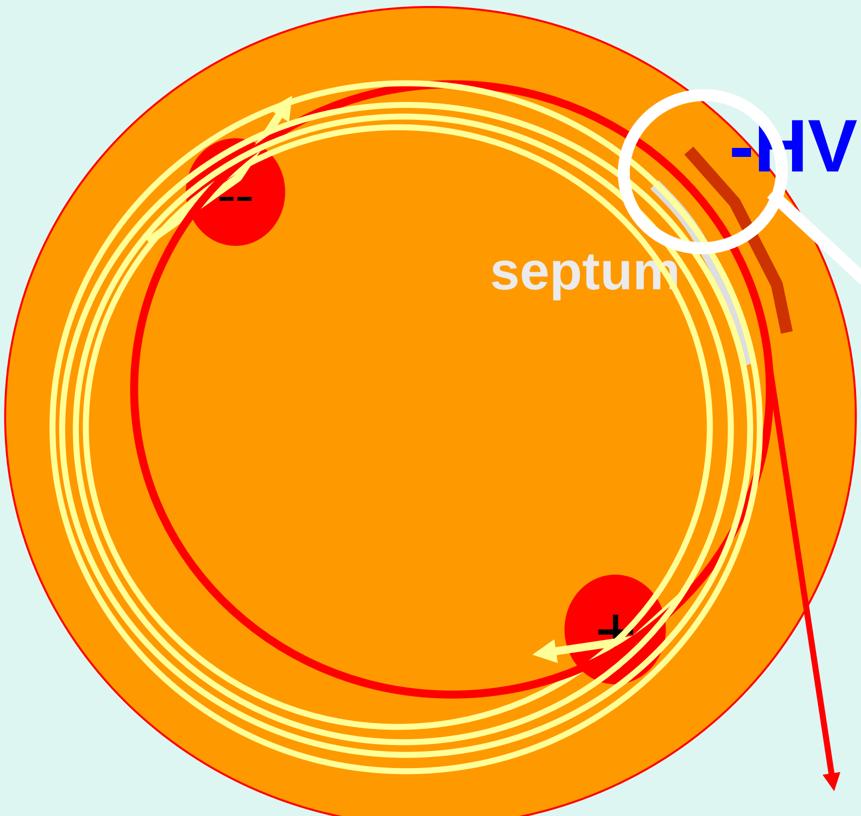
Extraction from cyclotron

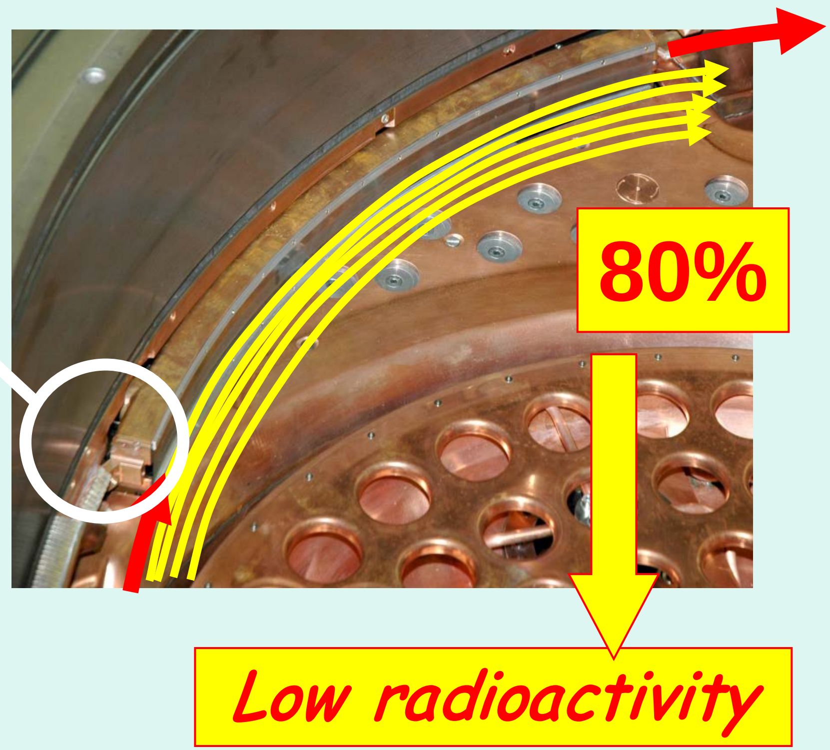
Resonant extraction

uses homogeneous field !

→ Field bump shifts beam:





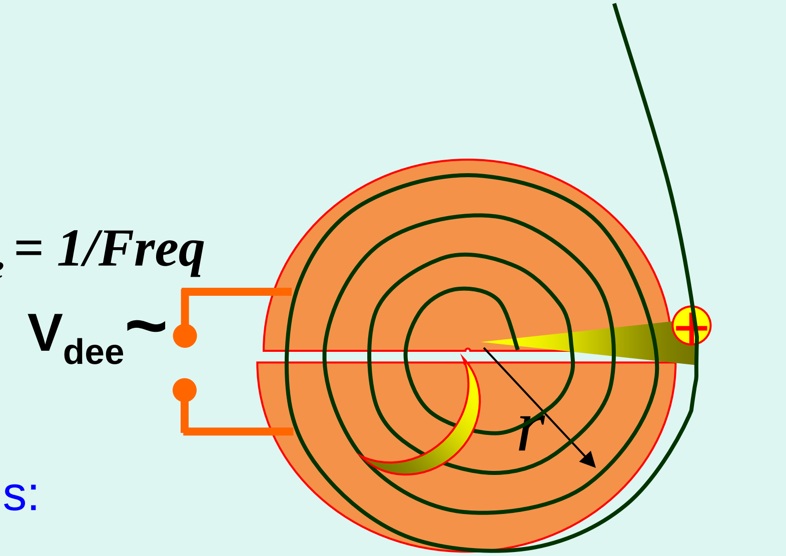


Small cyclotron; strong field

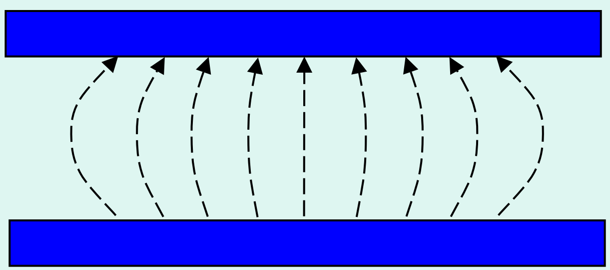
Cyclotron works while: T_{circle} independent from radius:
(particles move in pace with Vdee)

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

T_{circle} = 1/Freq



However (1): at very strong magnetic fields:



m = mass

B = magnetic field

q = charge

⇒ Magnetic field decreases with radius ⇒ $T_{circle} \uparrow$

Synchro-Cyclotron

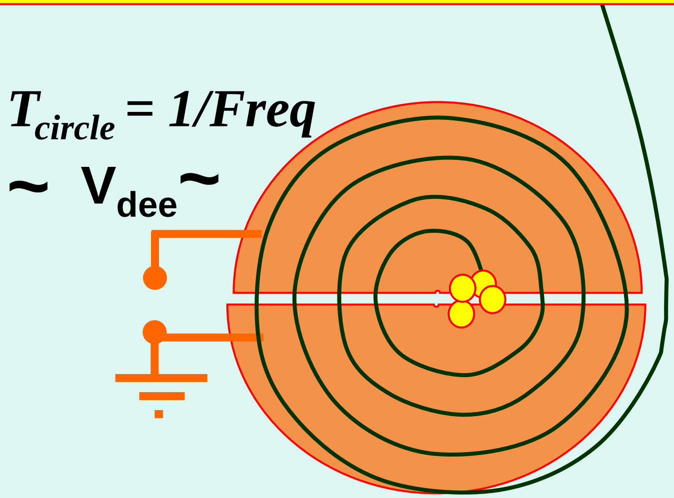
stronger magn.fields → Smaller machines !

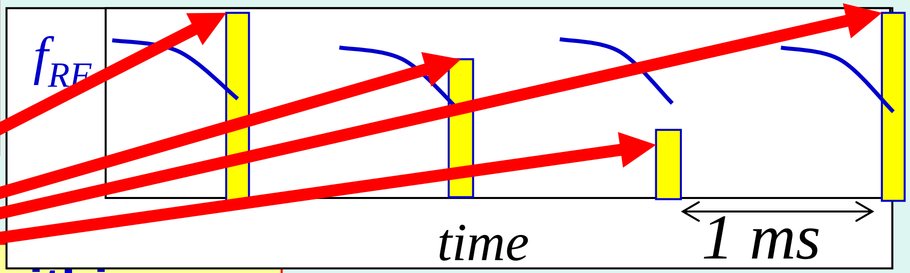
Remedy to **compensate**

increase of T_{circle} :

Decrease f_{RF} with radius and extract

Repeat 1000 x per sec





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

(=> typ 10-30% accuracy)

=> Spot scanning requires >2 pulses per spot.

Synchro-Cyclotron

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

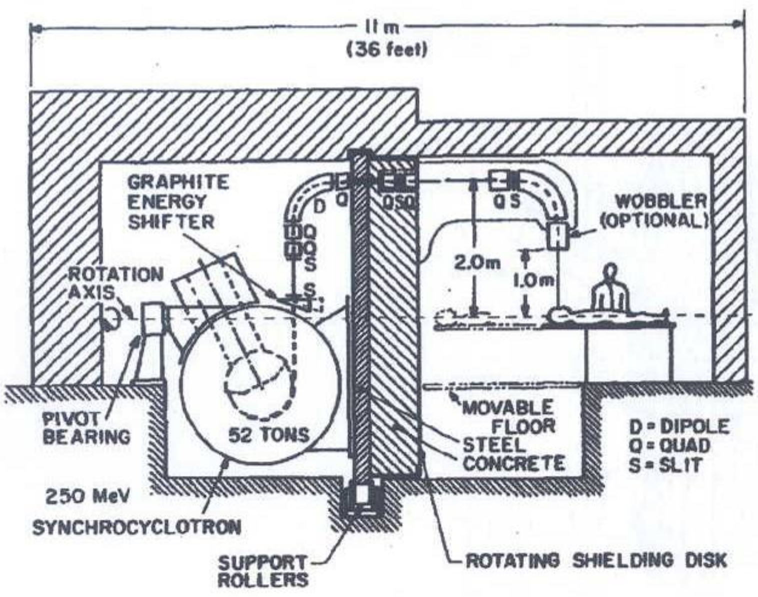


FIG. 9 -- Drawing showing synchrocyclotron rotating gantry arrangement with energy shifting wedge just after the cyclotron. Energy shifting can optionally be accomplished just ahead of the patient.

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

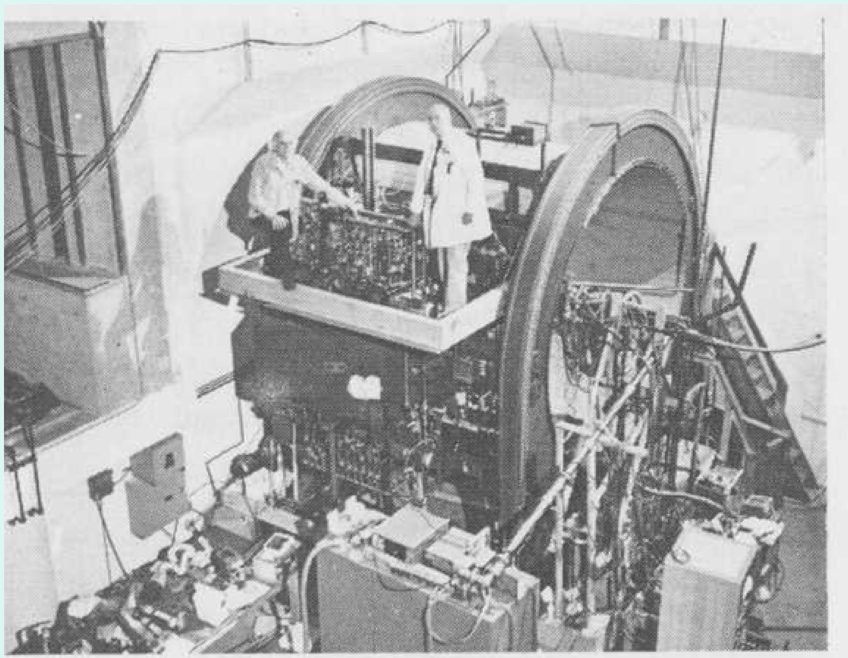


Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and

Synchro-Cyclotron

MEVION medical systems

iba *S2C2*

First beam extracted in May 2010

First beam at IBA in 2013

some differences…

	(syn-)cyclotron	synchrotron
Carbon ions	in development	easy
Change particle	in development	easy
Time structure	continuous(SC:pulsed)	spills
Fast E-scanning	degrader	next spill +developm.
Activation degrader	to be shielded	no
Intensity	"any"(SC:low),	limited, per spill
Intensity stability	3-5%	15-20% +developm
Size ∅	3.5 - 5 m **(SC<2)**	6-8 m (C: 25 m)
Scattering	ok	ok
Spot scanning	**ok** (SC: >2 pulses/spot)	**ok**
Fast continuous scanning	**ok** (SC: no)	difficult

New developments

New types of accelerators, e.g.:

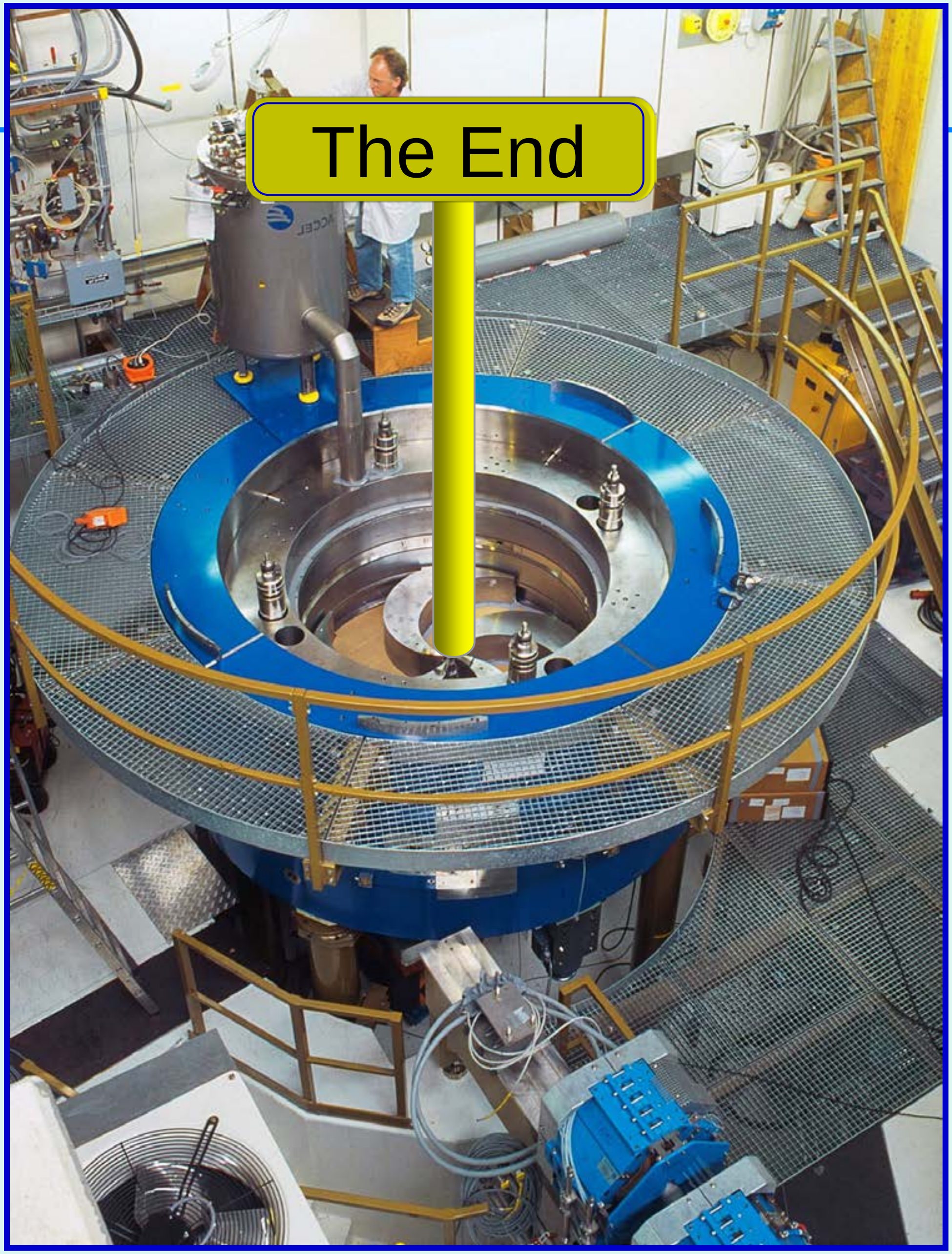
FFAG, Linac based acc, Laser, Laser-Plasma ….

Great developments

But do not only check price!

BASIS of Particle Th.

- treatment quality ≥ now ?
- organisation:
  medical device, service, upgrades


The End