Accelerators
currently in use
for particle therapy

Marco Schippers
PAUL SCHERRER INSTITUT

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

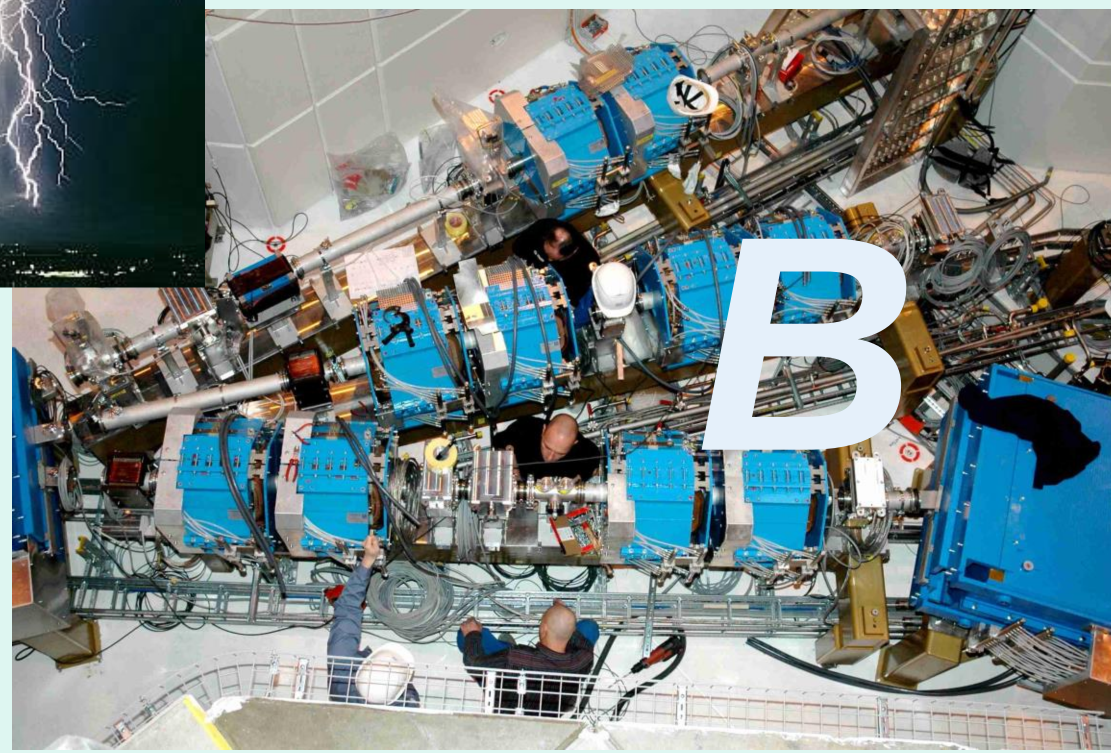
Contents

- **electric and magnetic fields**
- **synchrotron**
- **cyclotron**

Vendors are acknowledged for sharing information and images !

More details in e.g.:H. Paganetti (ed.), Proton Therapy Physics, Chapter 3
J.M. Schippers, Rev. Acc. Science and Techn. 2 (2009) 179-200
J.M. Schippers IEEE Transact. Nucl. Sc. 63, 2 (2016) 939-948.
T. Haberer et al., Radiother. Oncol. 73 S186–90

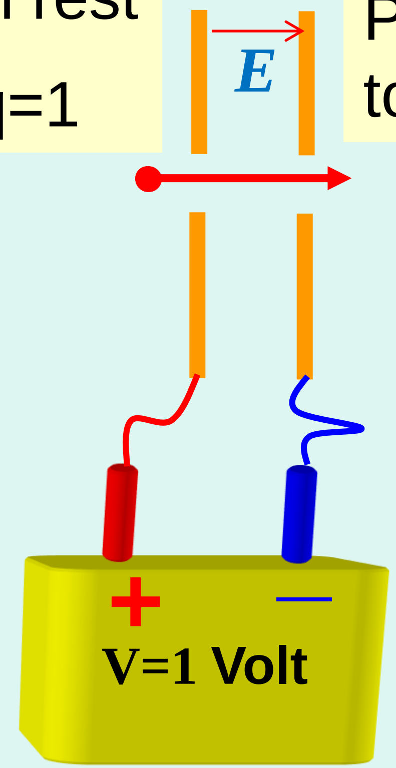
Electric and Magnetic fields



Electric fields

Proton in rest

charge q=1

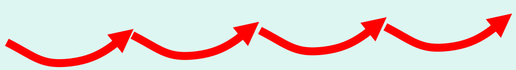


Proton has been accelerated to an energy of q×V=1 eV

Electric fields are limited in strength

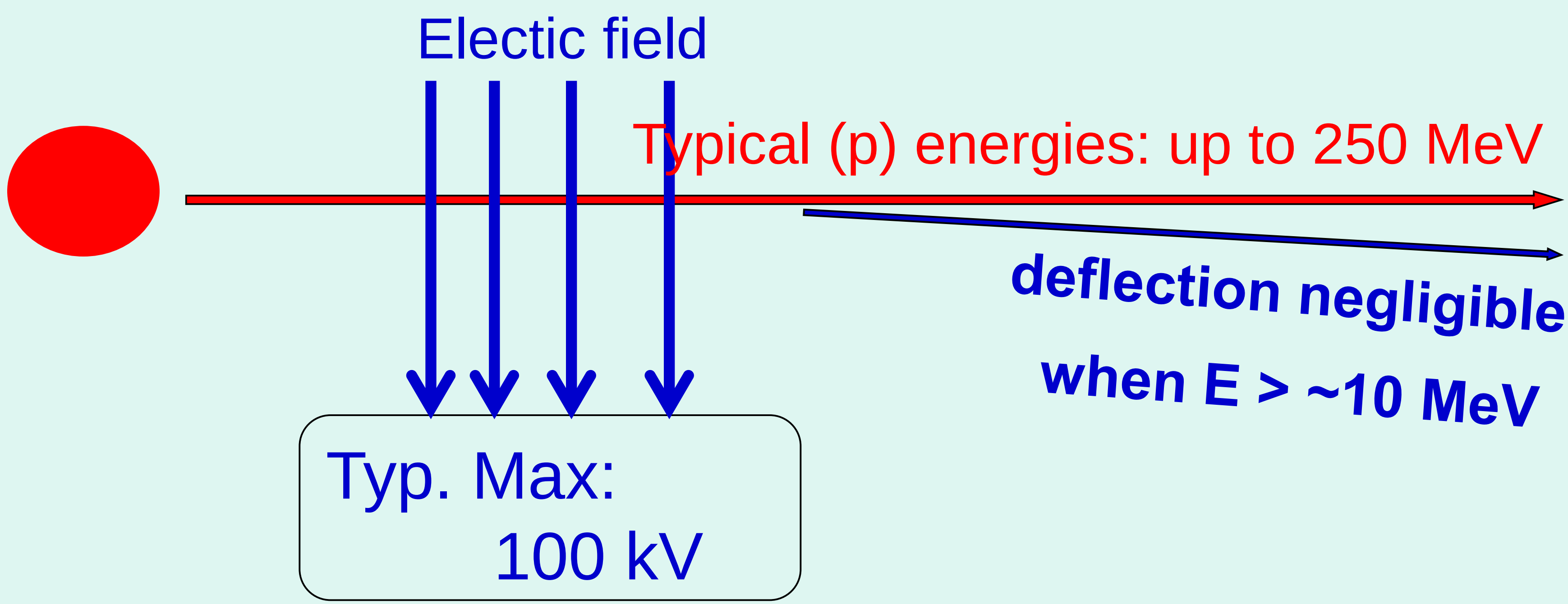
But:

Repeated acceleration → **high energy**



E = qV+qV+qV+qV+…….

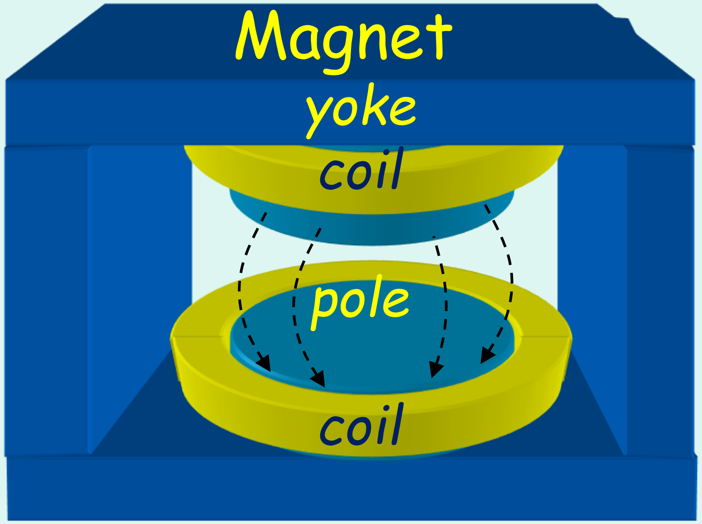
Electric fields

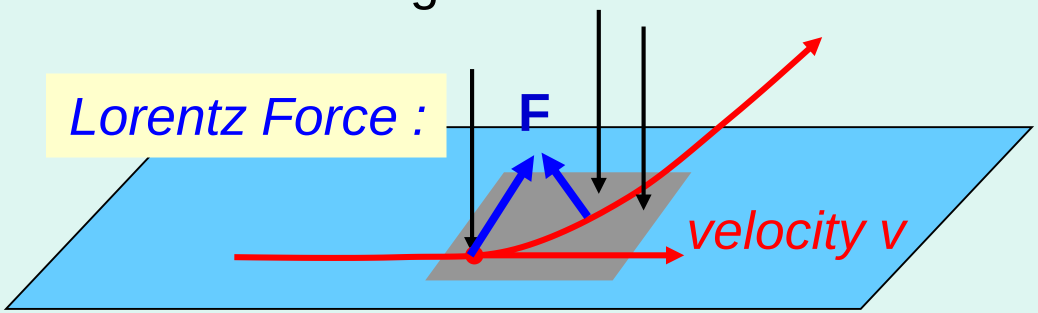


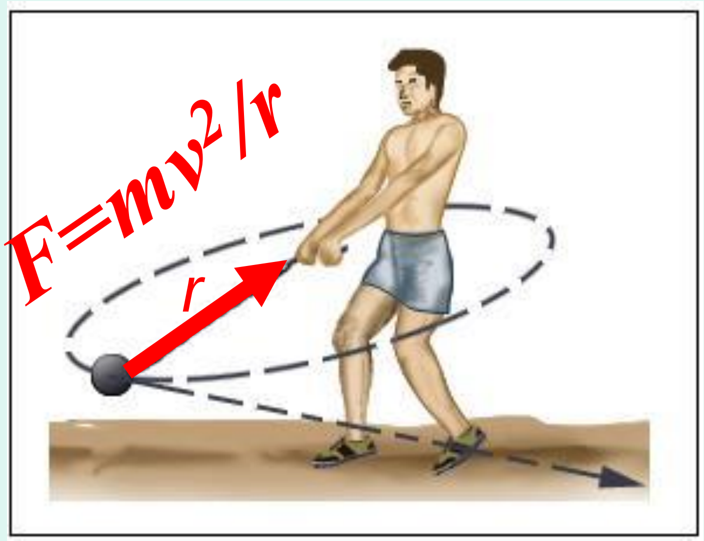
→ **focusing/deflection** with **E**-fields mostly at **low** energy

(e.g. in injection line of synchrotron
and in center of cyclotron)

Magnetic fields







"centripetal force" = Lorentz force :

$$mv^2/r = Bqv$$

⇒ **track = circular orbit** with radius r

⇒ **small r + high Energy:** needs **strong B**

Summary

Electromagnetic fields are used for:

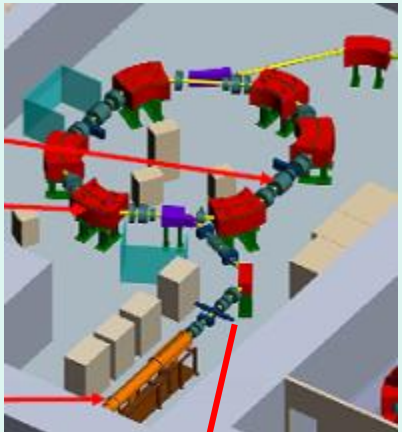
E: acceleration

B: deflection and focusing

Present accelerator choice

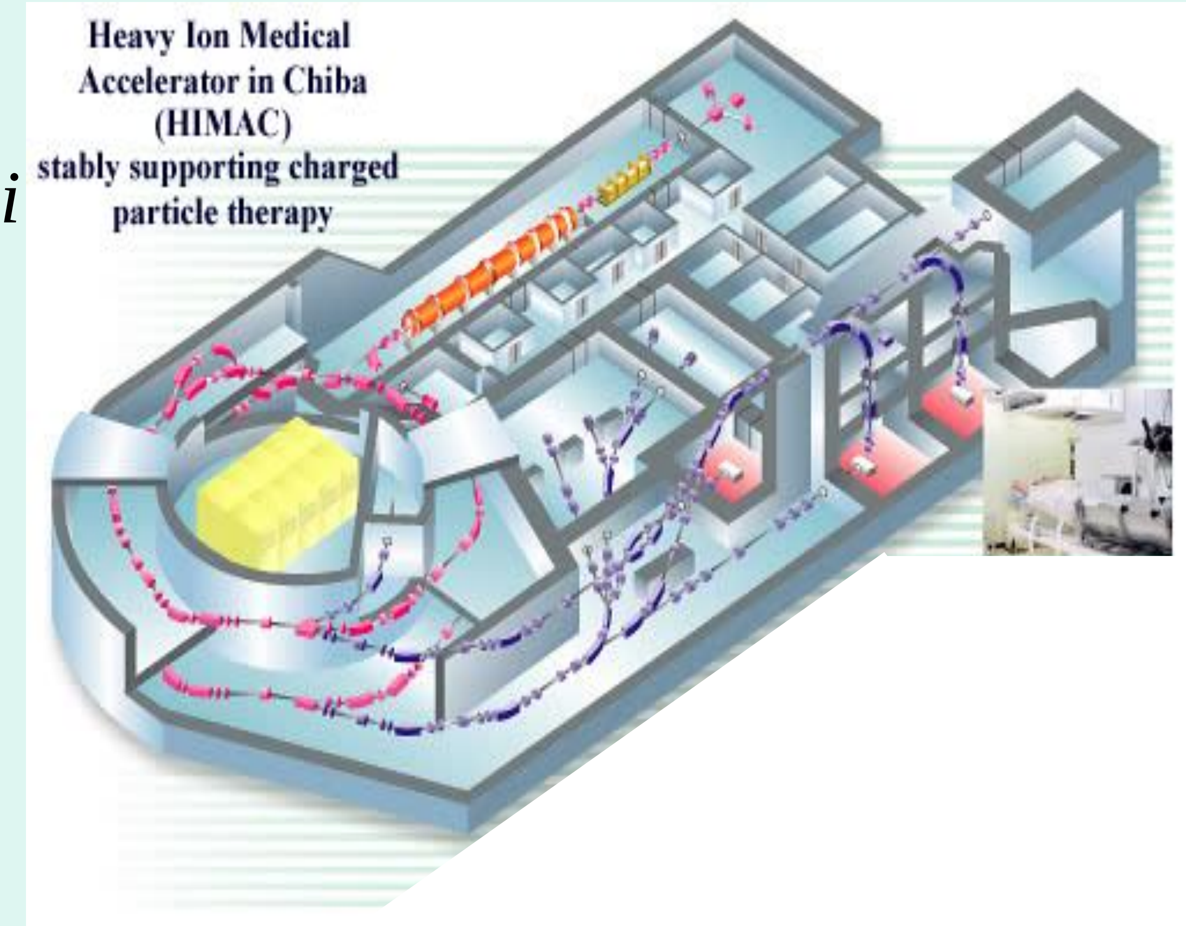
	cyclotron	synchrotron
Protons	in use, ∅2-5 m	in use, ∅8-10 m
Carbon ions	In development	in use, ∅25 m

Synchrotrons for protons

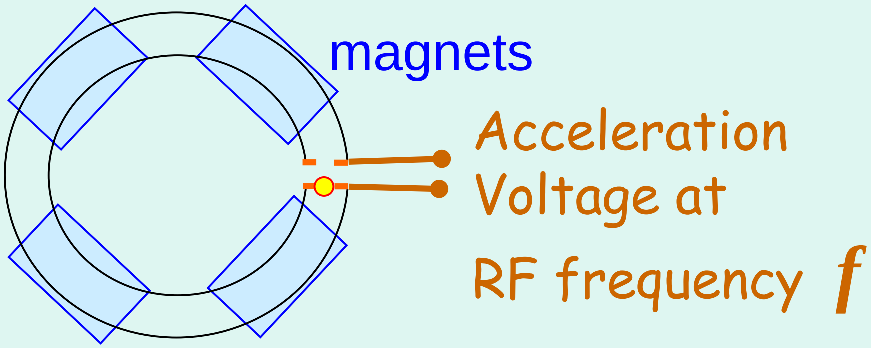


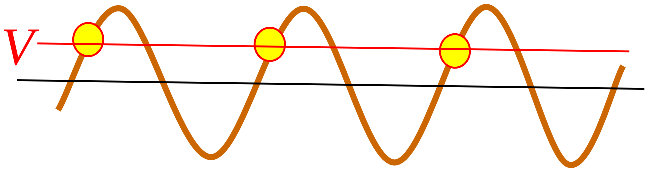
Hitachi

Tsukuba



Acceleration in synchrotron





At electrode slit crossing:

Energy gain $\Delta E = V.q$

Energy increases:

→ speed ↑

→ **RF frequency** ↑

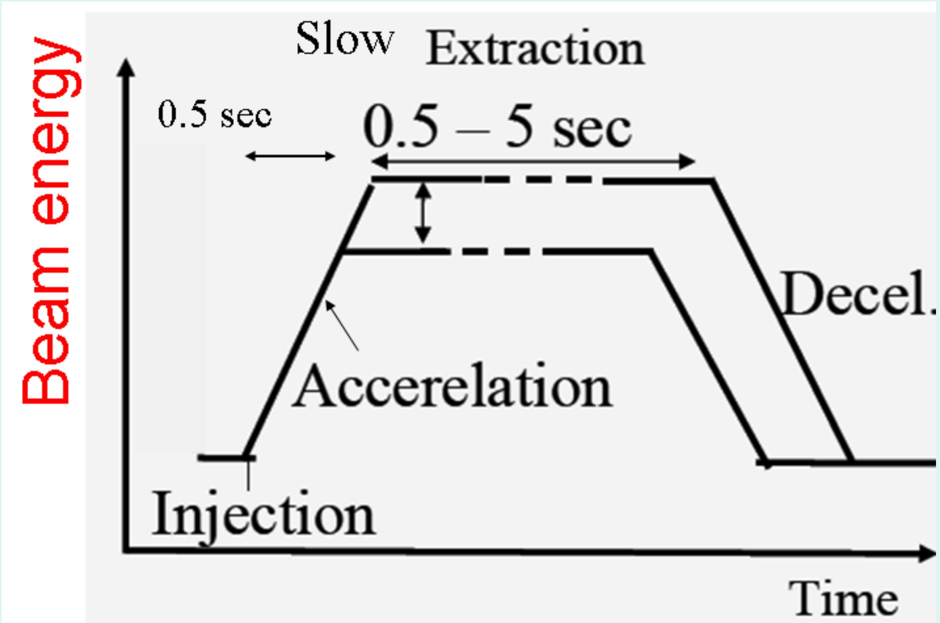
→ **field** in magnets ↑ $\frac{mv}{Bq} = r$ = constant !

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

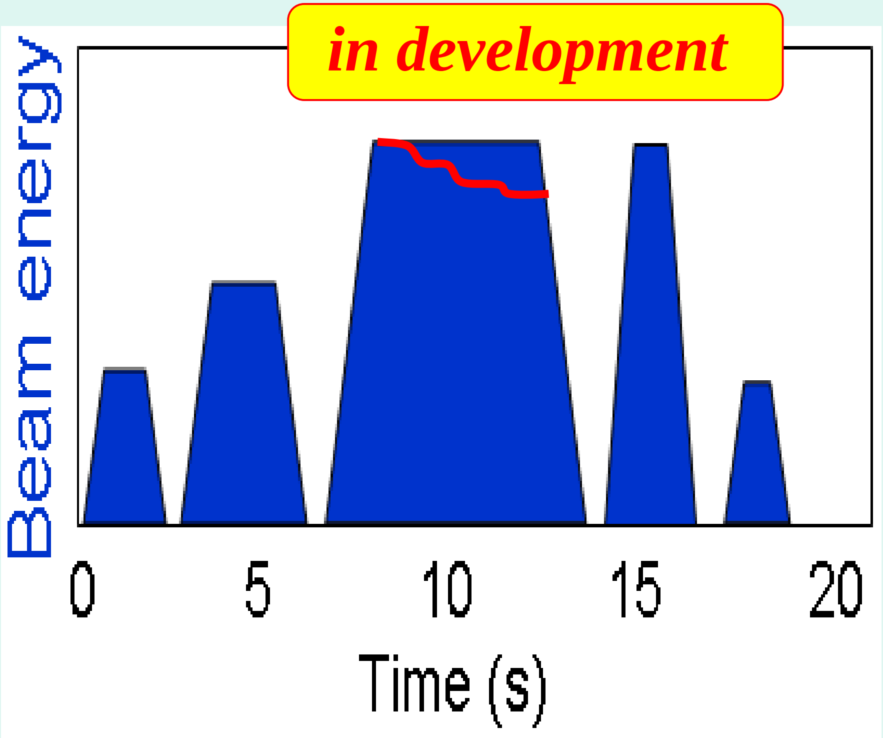
Set beam energy

Energy adjustable per spill

1 spill

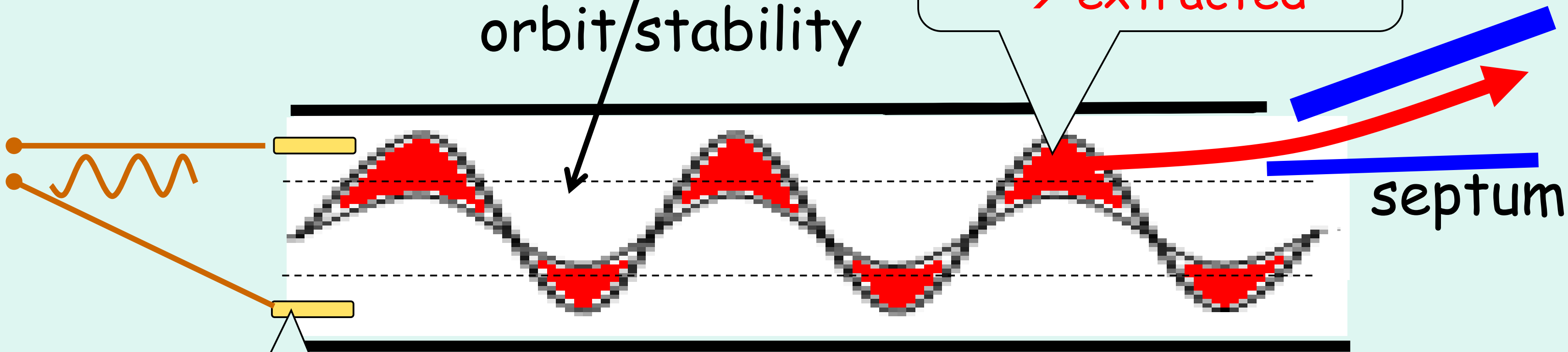


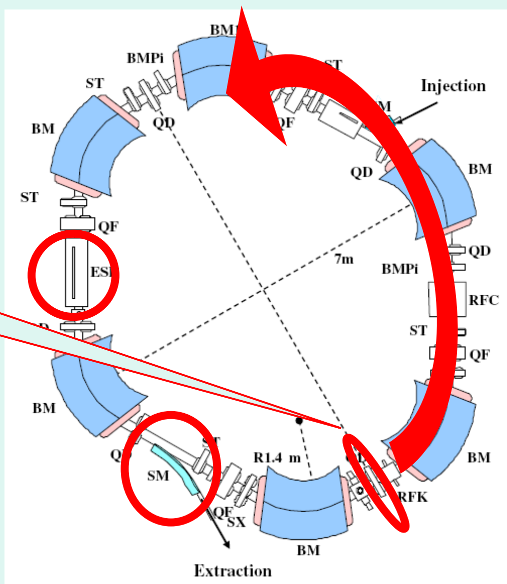
several spills



Beam **extraction** from synchrotron

RF-Knock Out



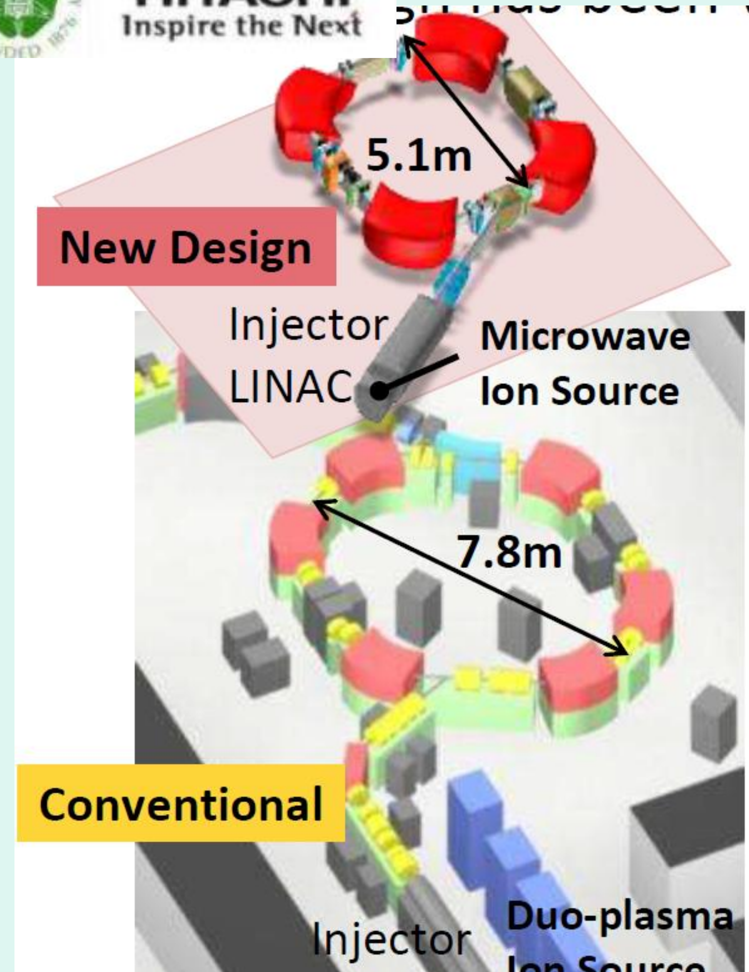


Beam shape: ↔ Gantry rotation !!

Compact synchrotron

ProTom 330 MeV

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



- 220 MeV
- First facility in Hokkaido started 2013

Characteristics of Synchrotron

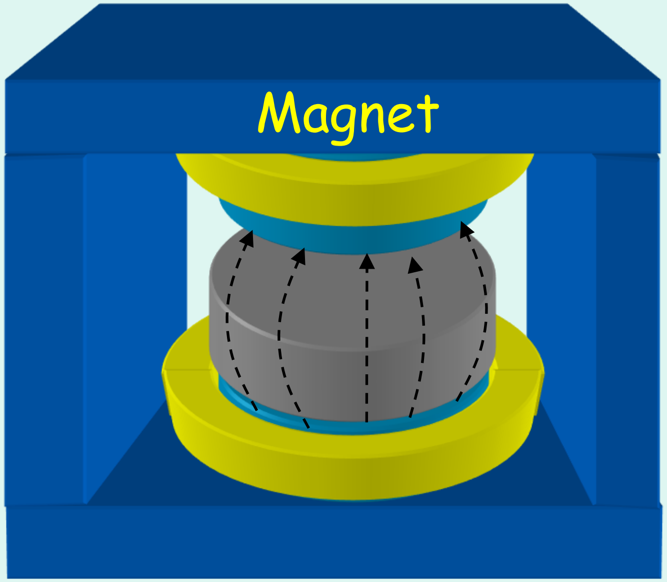
=> a synchrotron provides:

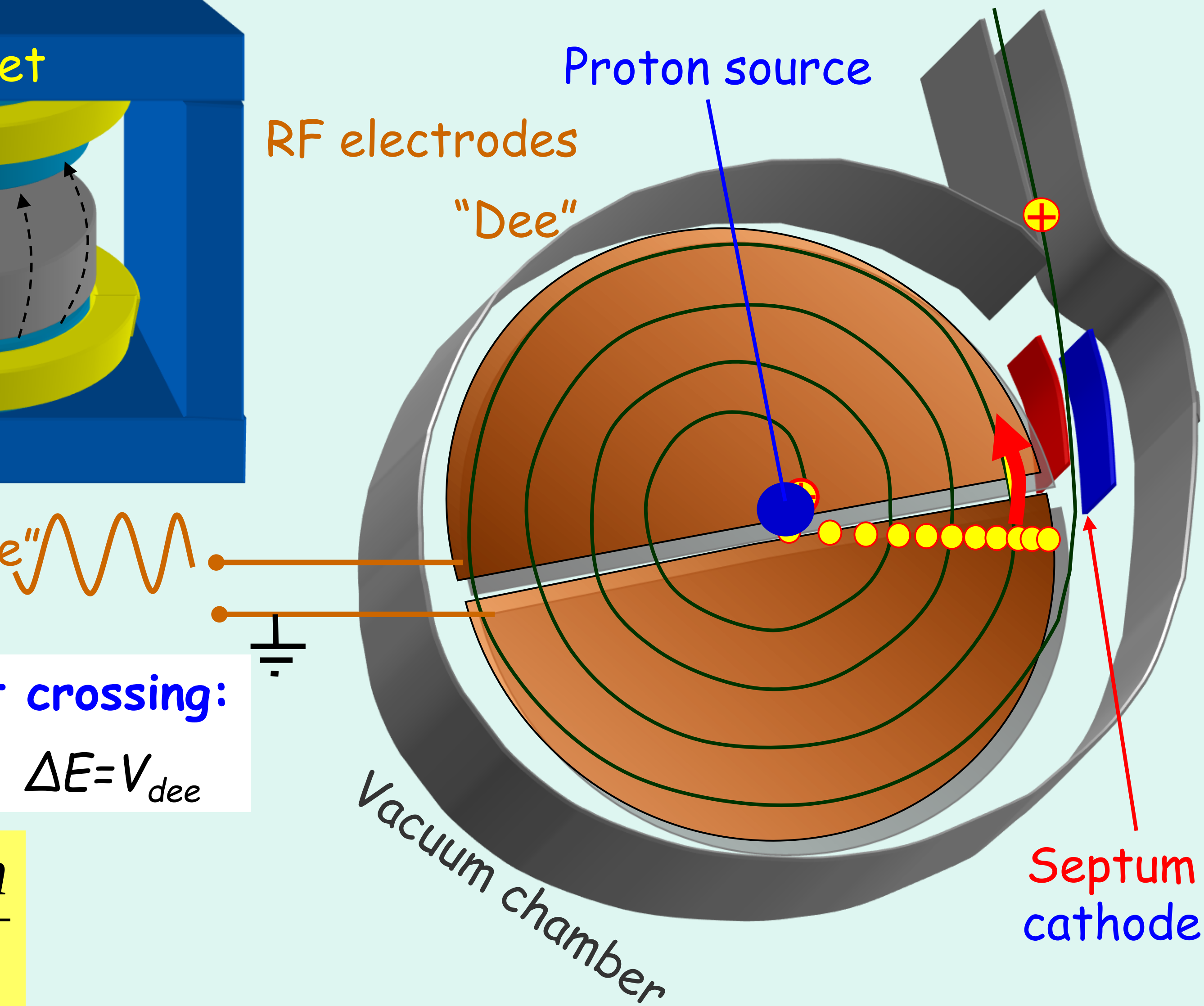
- adjustable energy
- high Energy (ions !)
- any particle (if designed for)
- low radioactivity

Disadvantages:

- limited average intensity (ring filling)
- spill structure => limited average dose rate
- noisy beam intensity
- large footprint

Cyclotron (1930)





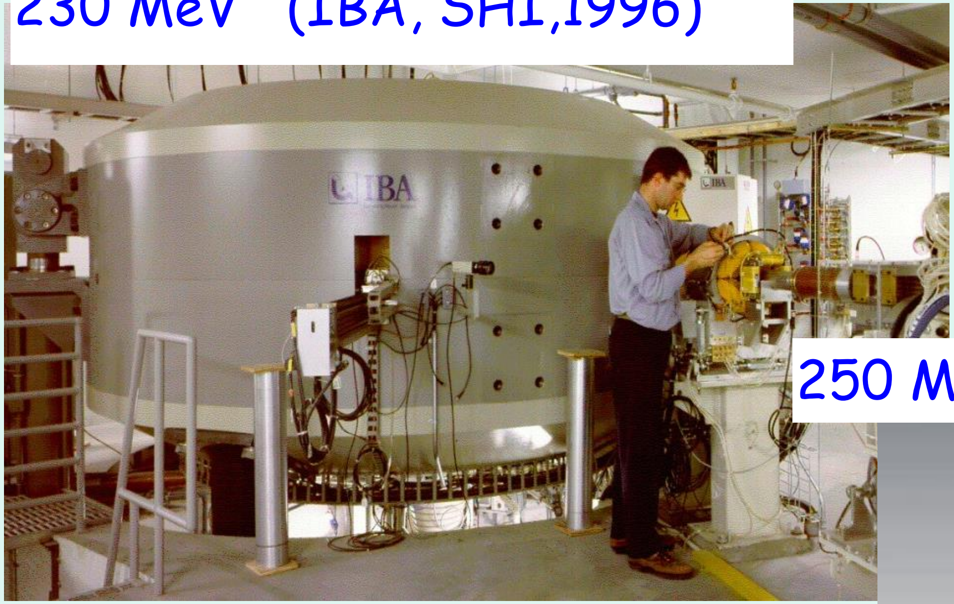
At electrode slit crossing:

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

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

Cyclotron

230 MeV   (IBA, SHI,1996)



250 MeV (ACCEL/Varian,2005)

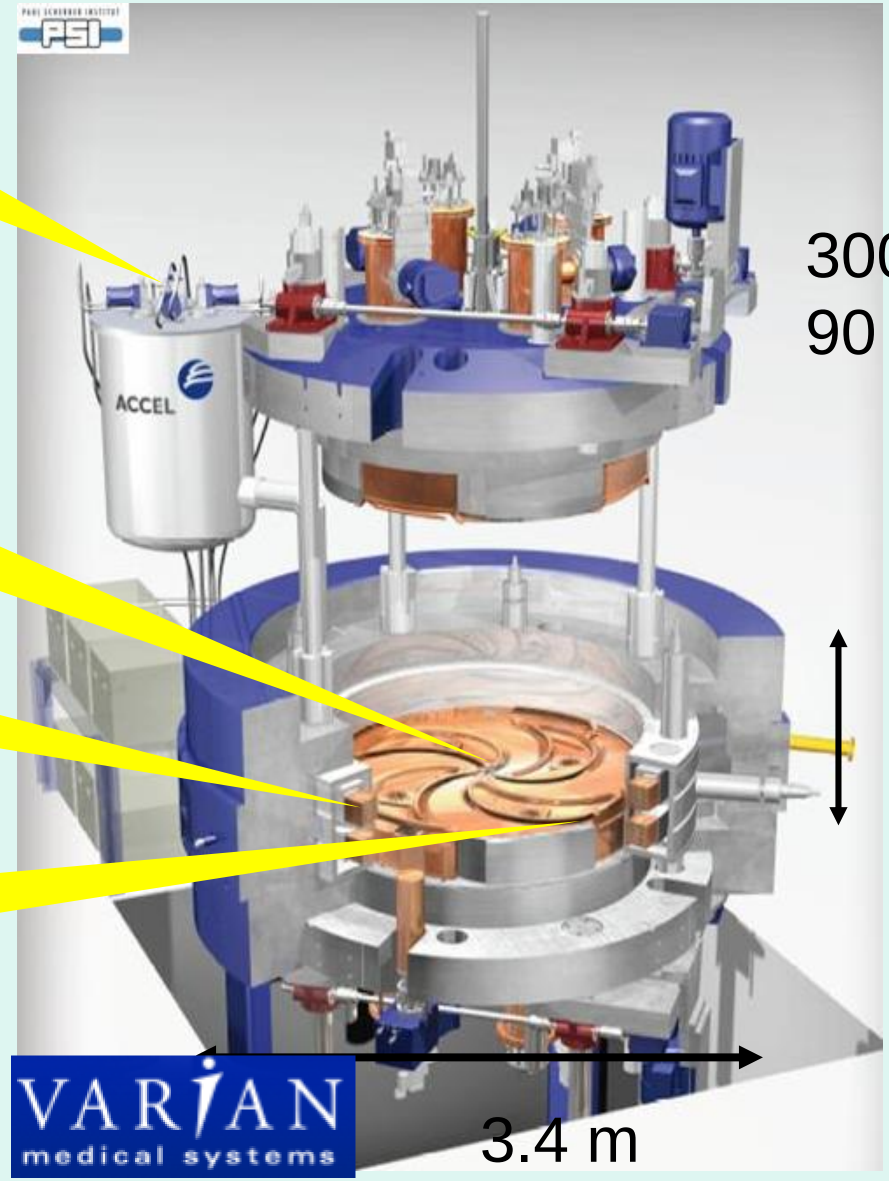
250 MeV proton cyclotron

Closed He system
4 cryocoolers

Proton source

superconducting coils
=> 3 T

4 RF-cavities:
~80 kV at 72 MHz

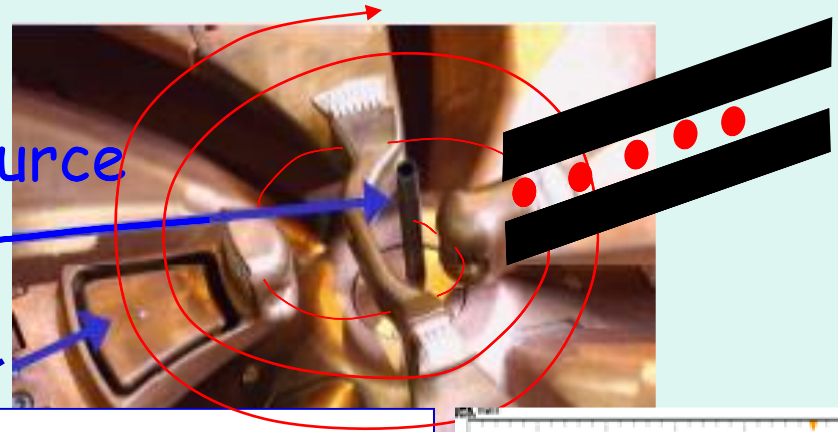


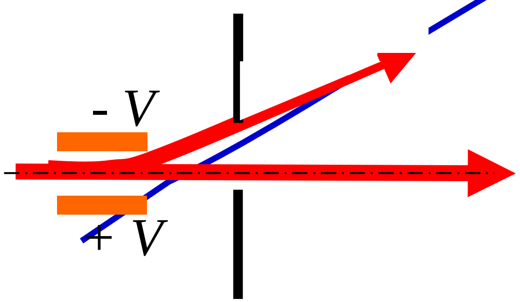
300 kW
90 tons

1.4 m

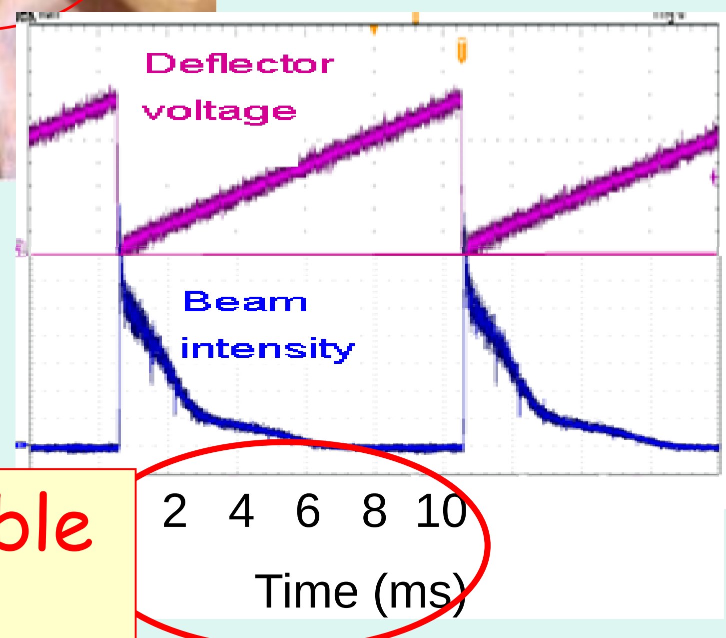
intensity control

Max. intensity set by:
discharge in proton source



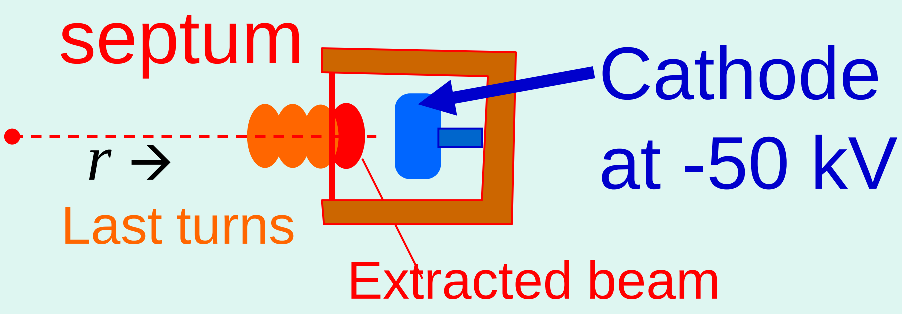


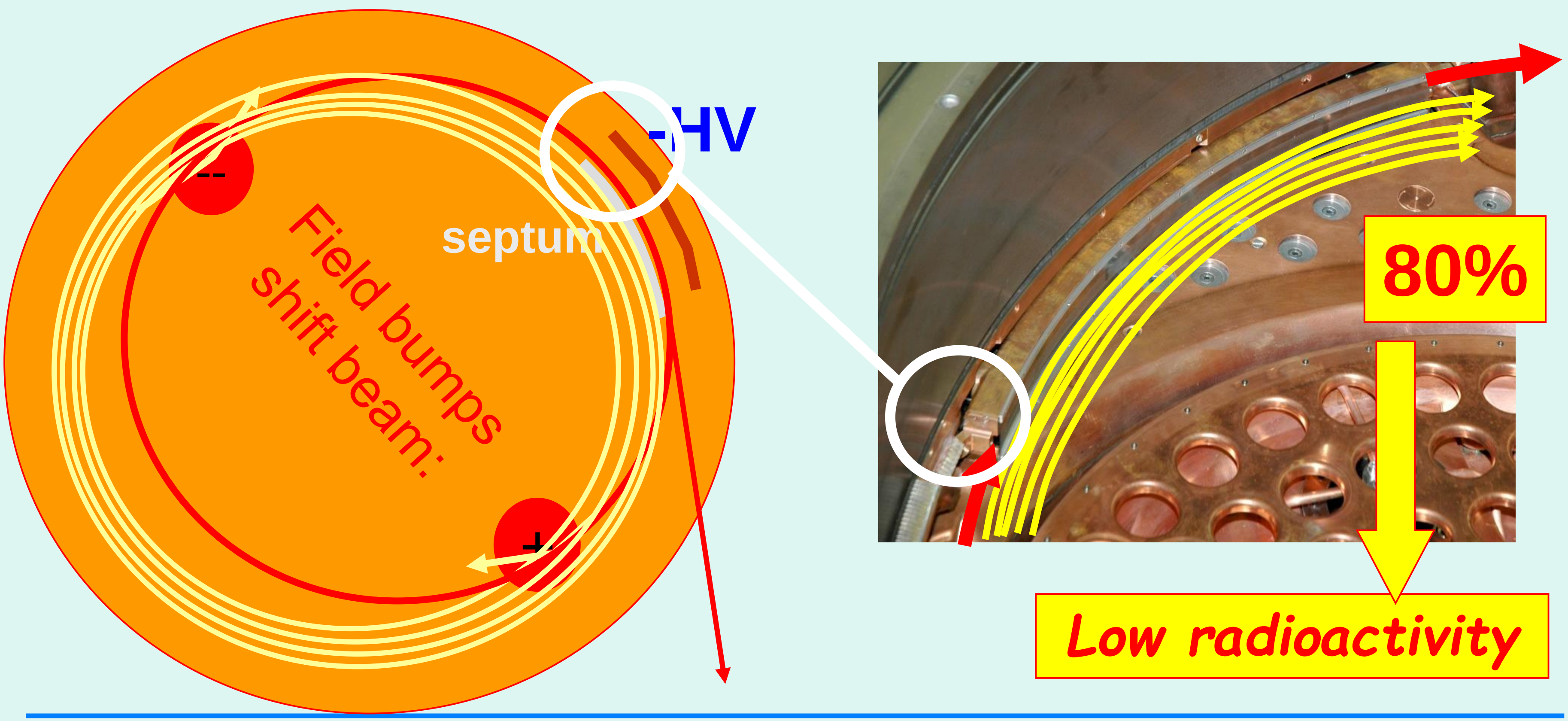
Deflector plate:
sets intensity
- within ms
- 3% accuracy



currently only possible with a **cyclotron**

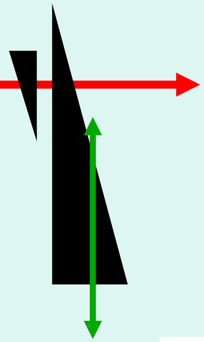
Extraction from cyclotron

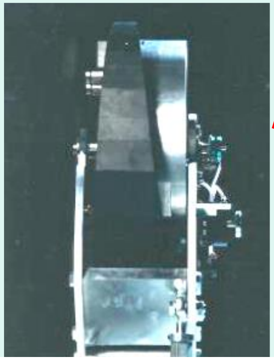




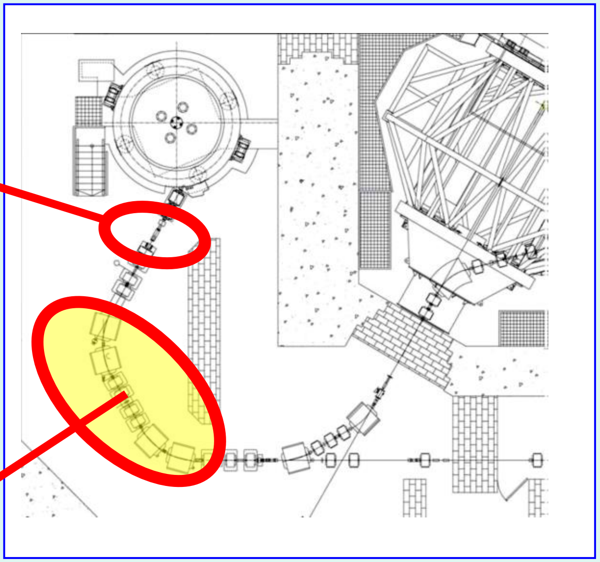
Degrader and energy selection

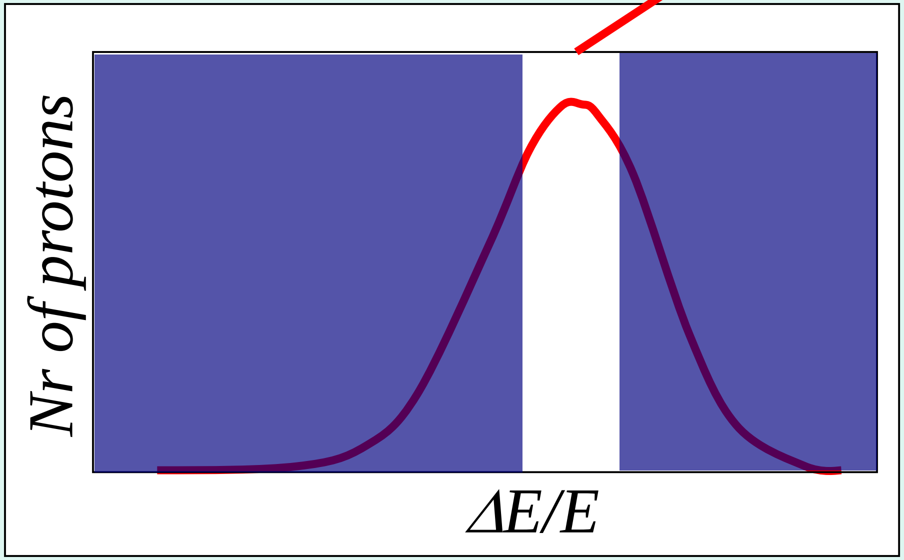
multi-wedge
235-67 MeV (PSI)





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





Beam analysis:
energy selection
$\Delta E/E < \pm 2\%$

Synchro-Cyclotron

MEVION medical systems

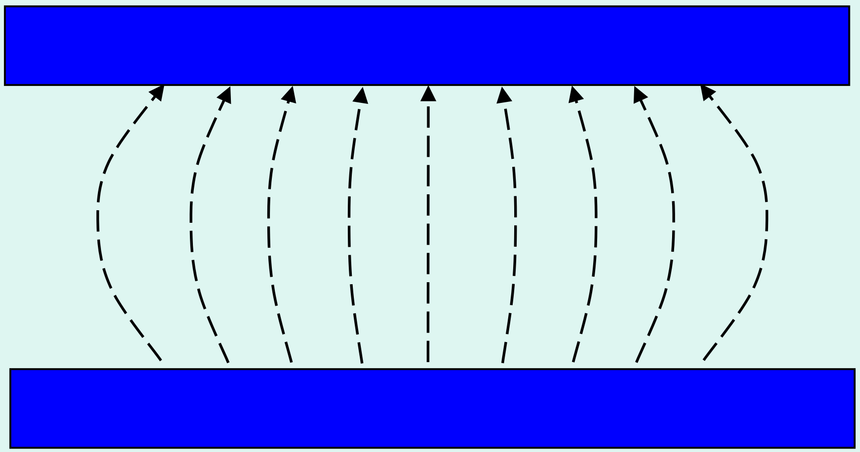
First beam extracted in May 2010

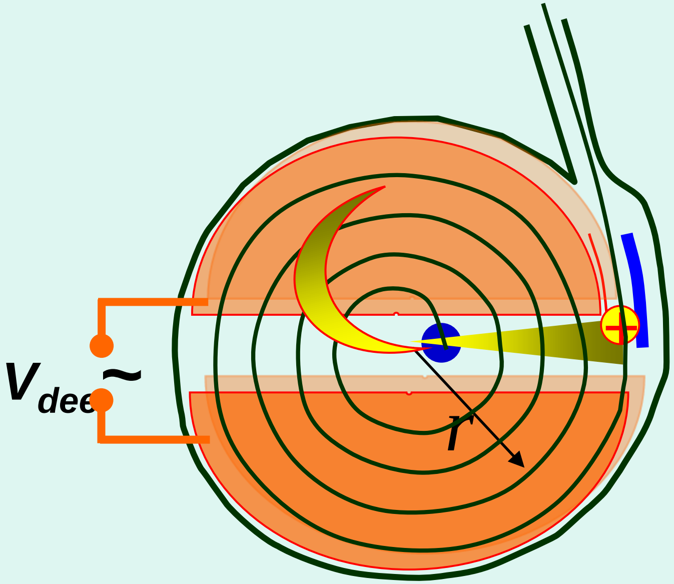
IBA: S2C2

First beam at IBA in 2013

small cyclotron: **strong field**

BUT: at very strong magnetic fields:





⇒ Magnetic field decreases with radius

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

$\Rightarrow T_{circle} \uparrow$

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

Synchro-Cyclotron

Remedy to **compensate** increase of T_{circle}

Synchrocyclotron

(=CLASSICAL TRICK e.g. Harvard, Uppsala)

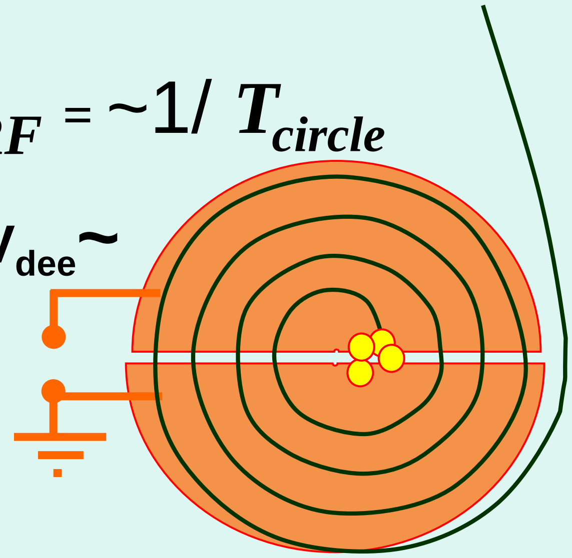
Decrease f_{RF} with radius and extract

$$f_{RF} = \sim 1/\ T_{circle}$$

Synchro-Cyclotron

Remedy to **compensate** increase of T_{circle}

$$f_{RF} = \sim 1/\ T_{circle}$$



Synchrocyclotron

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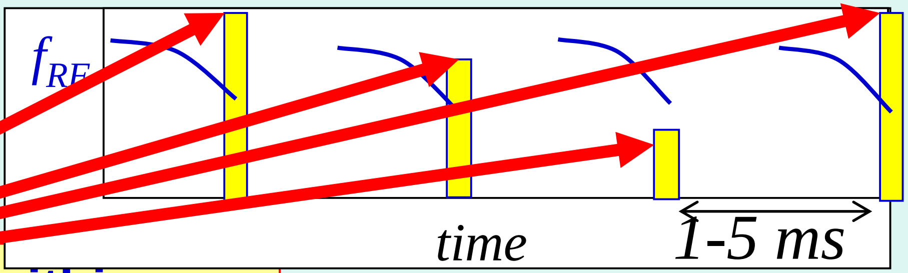


Each pulse: set intensity at source **within ms**

(=> typ 10-30% accuracy)

=> Spot scanning requires >2 pulses per spot.

Characteristics of a cyclotron

=> a cyclotron provides:

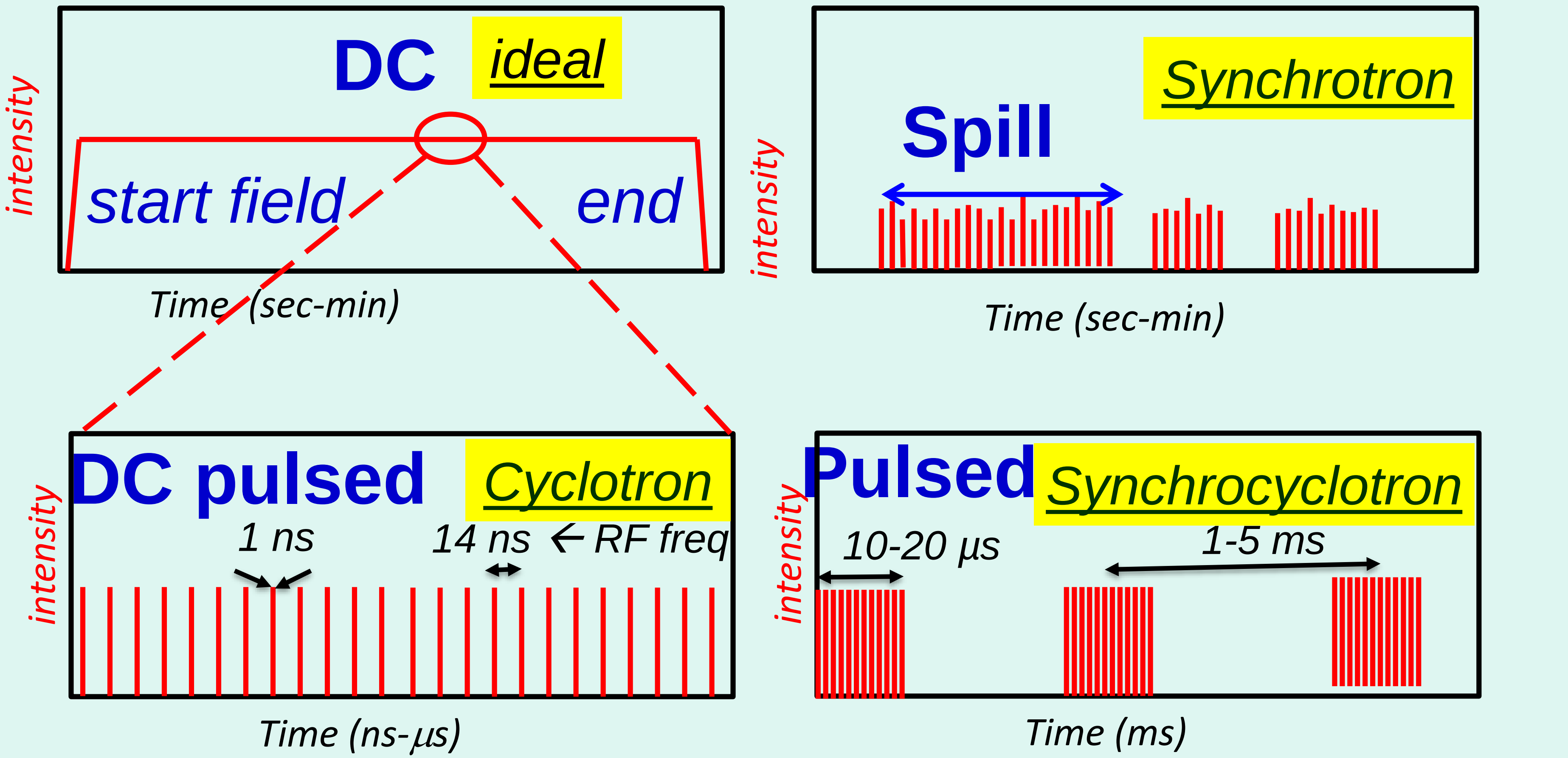
- **continuous** beam (but synchrocycl: **pulsed**)
- very fast and accurate intensity control
- great reliability (few components)
- small footprint

\+ Energy change with fast degrader and fast magnets

Disadvantages: - activation of components near degrader

- no carbon ions (yet)

Time structures of beams



New developments

New types of accelerators, e.g.:

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

Great developments !

But do not only check price:

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

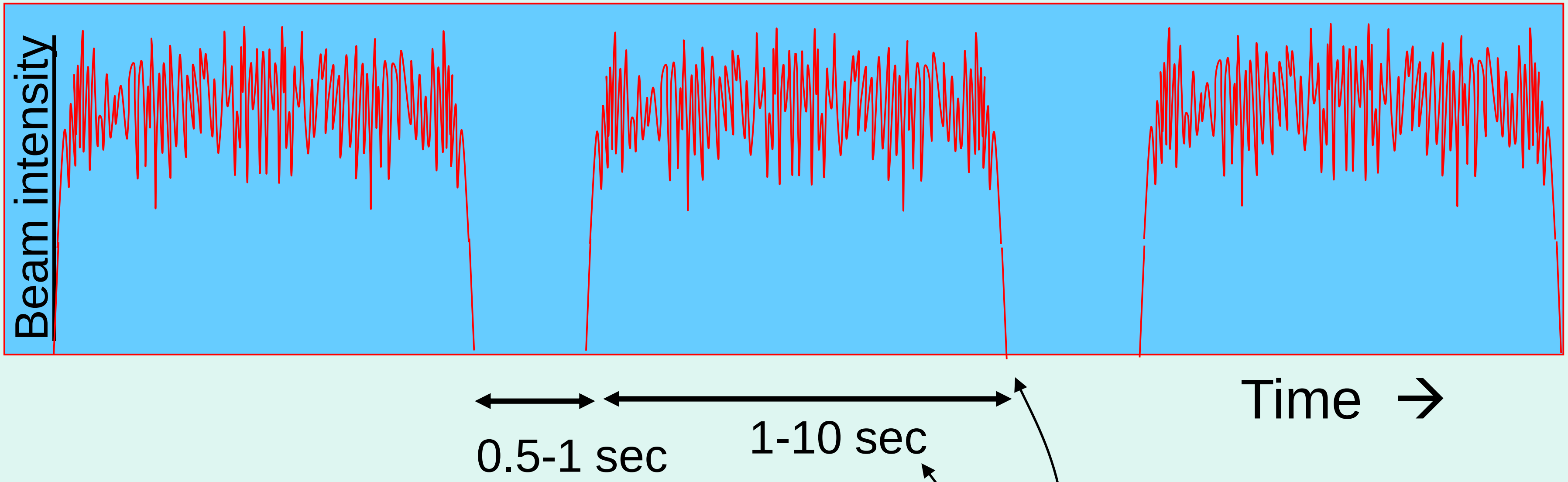
BASIS of Particle Th.


Thank you

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

Synchrotron beam: *spills*



"spill" time:

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