Technology Updates: a *(personal)* vision for the future in Proton Therapy

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Contents

Aim of new technologies: 1) Reduction of costs

2) Improve techniques / quality

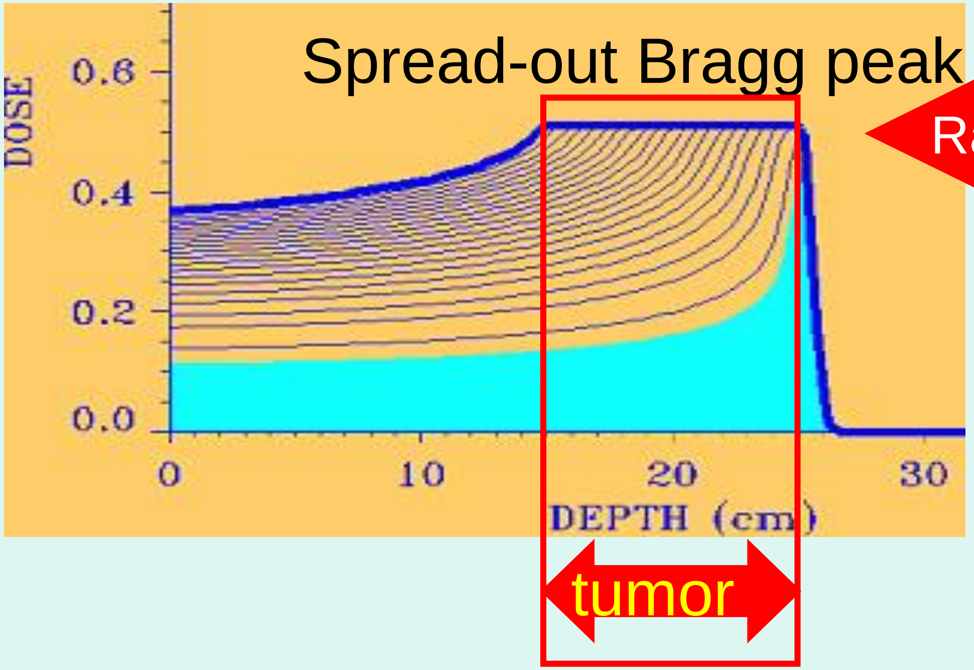

The future in Proton Therapy..

- Dose application:
  techniques and limitations
- Accelerators
- Developments in Gantries
- Smaller accelerators
- New accelerator types

A non complete and non-sponsored overview and my personal opinion

Dose delivery techniques

Dose delivery techniques: Depth



Range

Tumor **distal edge**

→ Range

→ Maximum Energy

per field → „slow“ (sec)

Tumor **thickness**

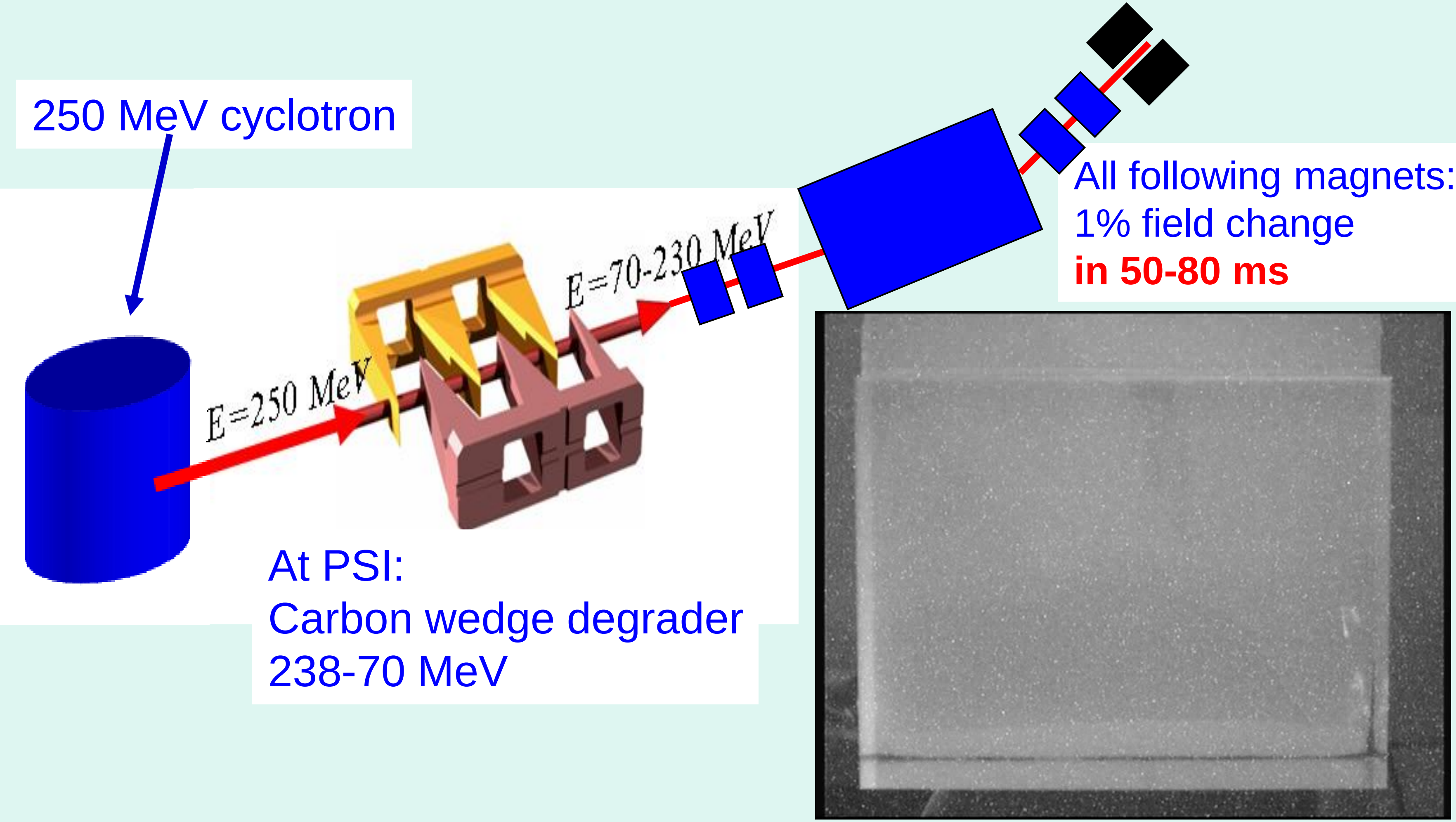
→ spread-out Bragg peak

→ energy modulation

Methods:

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

Dose delivery: spread in **depth**



250 MeV cyclotron

At PSI:
Carbon wedge degrader
238-70 MeV

All following magnets:
1% field change
in 50-80 ms

→ fast treatment
→ fast room switching

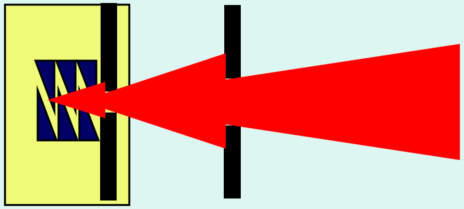
Intensity loss by degrading

Degrader purpose: **decrease** energy

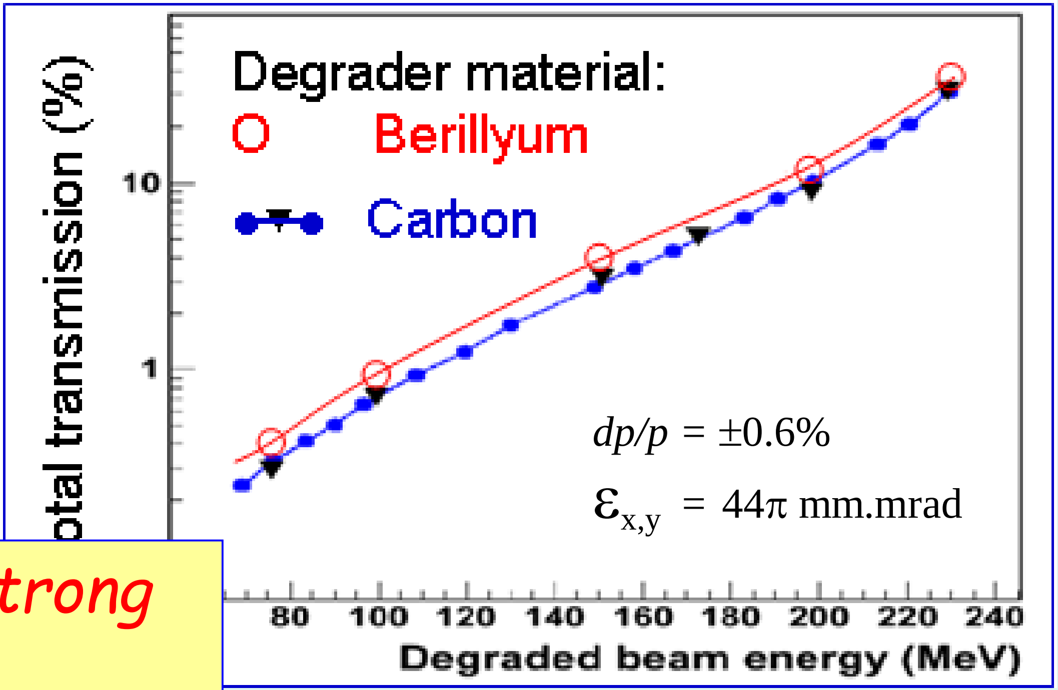
however: - **energy spread** increases

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

degrader system



Collimators define transmitted beam size



$dp/p = \pm 0.6\%$

$\varepsilon_{x,y} = 44\pi$ mm.mrad

→**Beam intensity** *has a strong energy dependence*

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

B_4C as degrader material

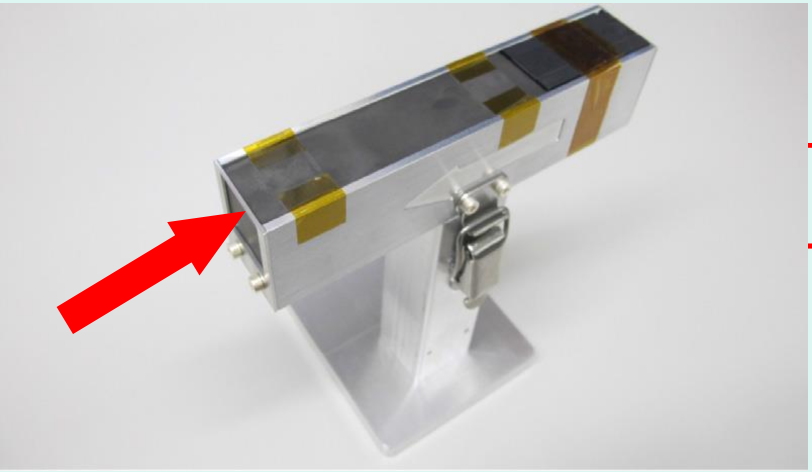
RECENT DEVELOPMENT: NEW DEGRADER MATERIAL

Graphite C:	ρ=1.9 g/cm^3	Z=6, A=12
Boron Carbide B_4C:	ρ=2.5 g/cm^3	Z=5, A=11

→ shorter + smaller A=> **less beam size increase**

MCNPx + Turtle calc for degrading 250→ 84 MeV:

BC: diverg: -6% size: -27% => **transmission: +31%**

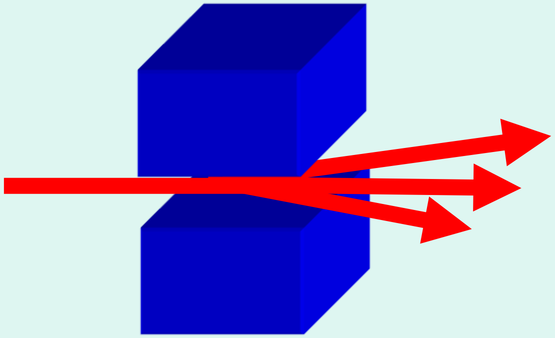


Experiment:

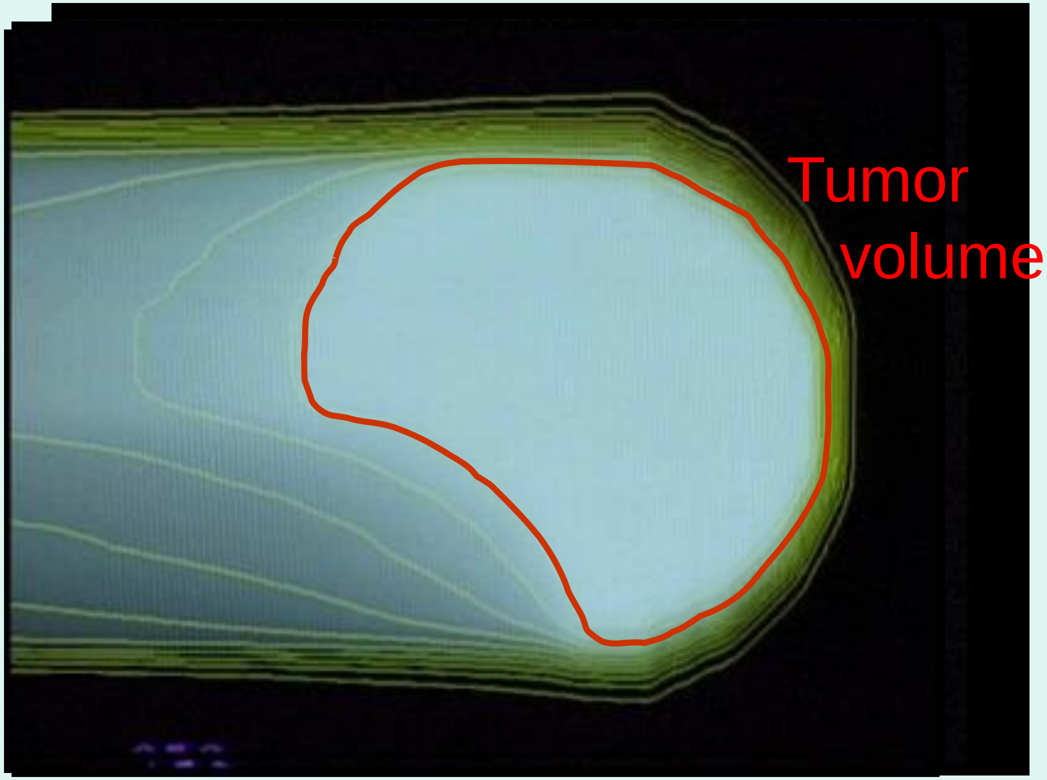
transmission: +37%

distribute laterally by scanning

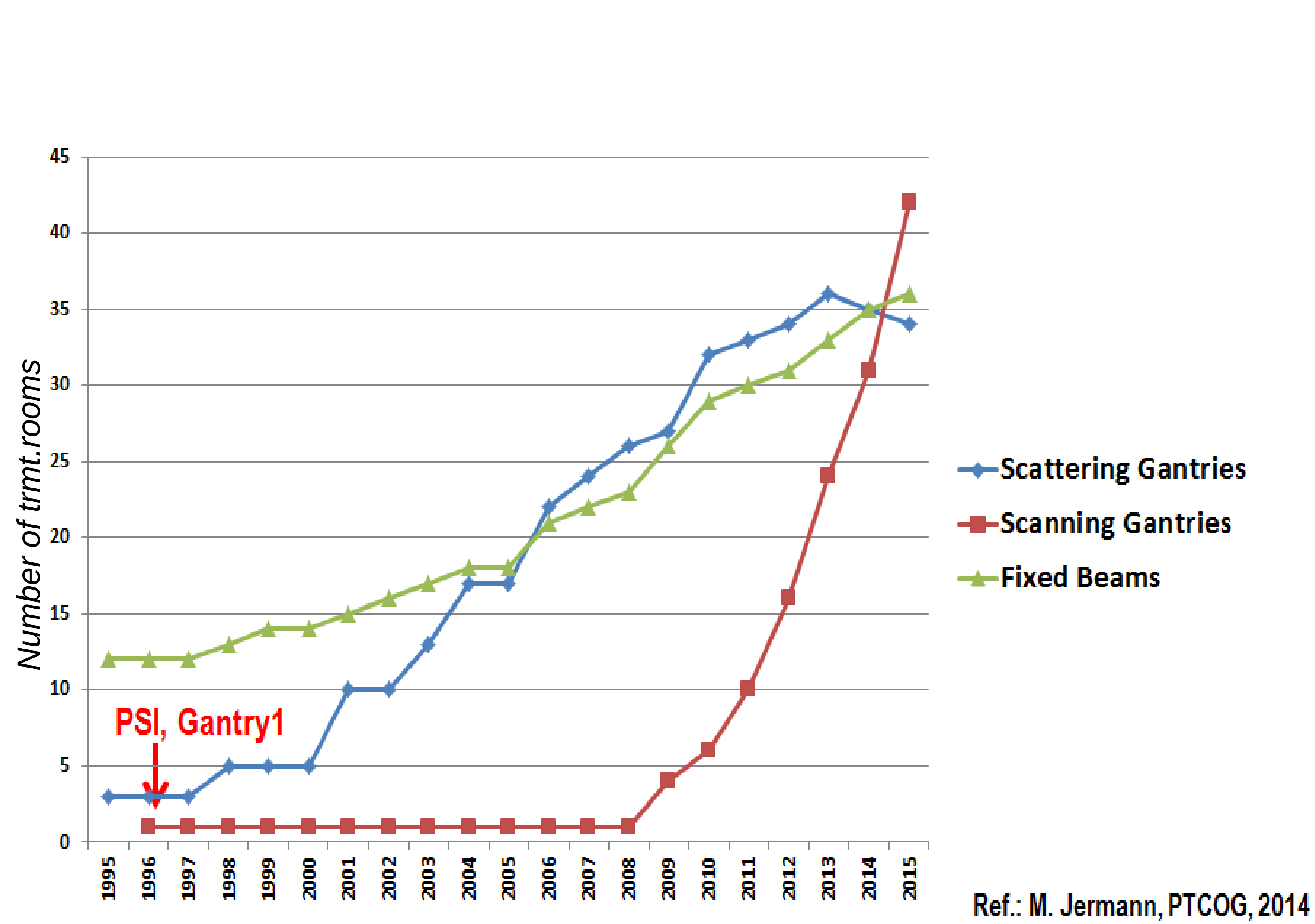
Pencil Beam Scanning:
best dose distribution



Fast magnet

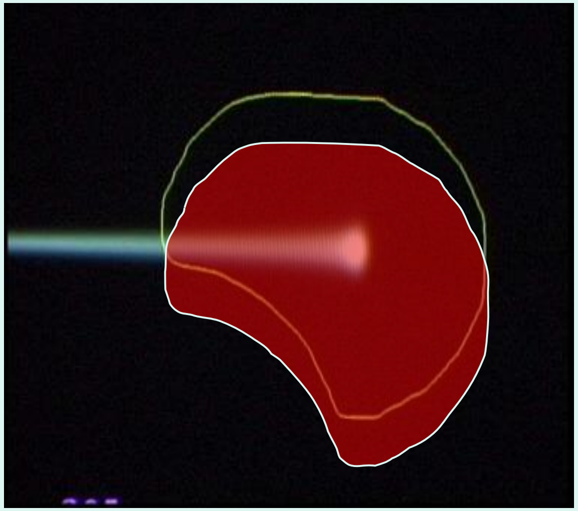


3D Pencil beam scanning



Ref.: M. Jermann, PTCOG, 2014

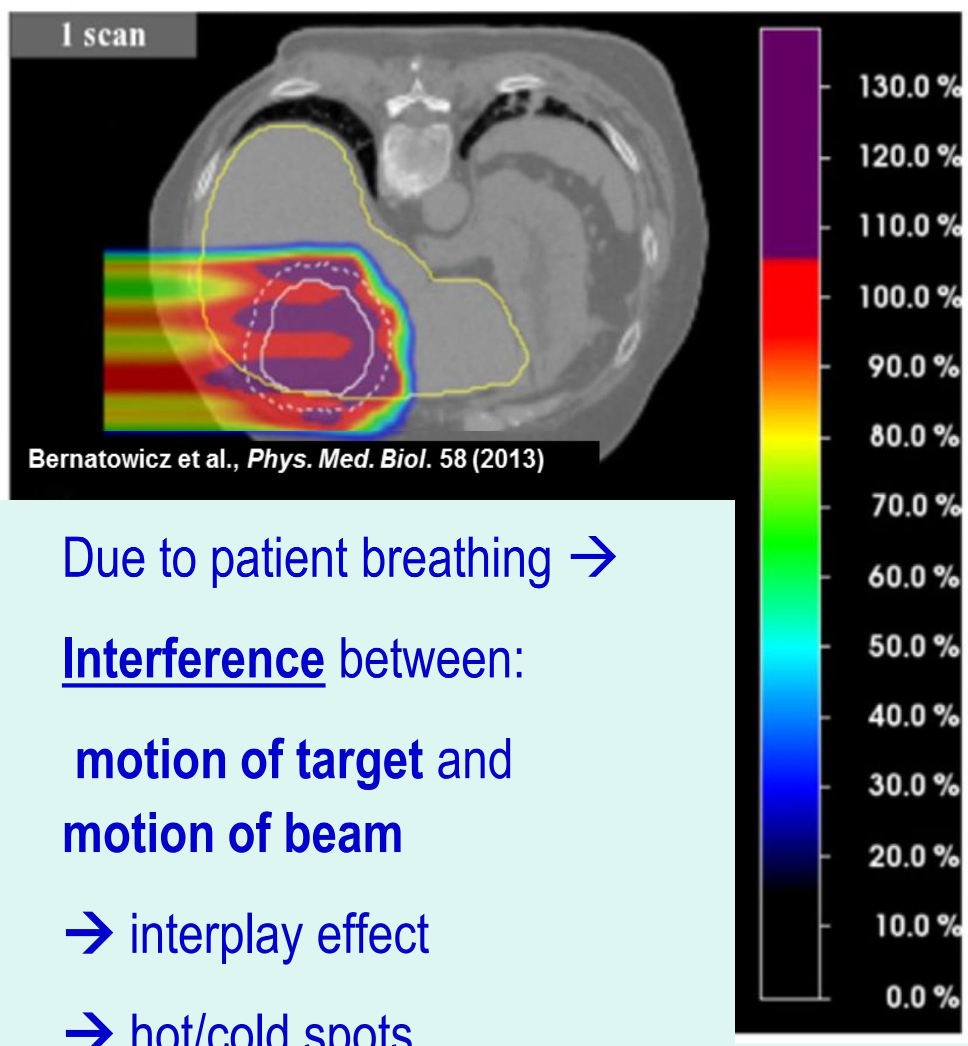
Moving organs



→Danger to

underdose and

overdose



Bernatowicz et al., *Phys. Med. Biol.* 58 (2013)

Overdosage (clinically not acceptable)

100 % = Target dose

Underdosage (clinically not acceptable)

Due to patient breathing →

Interference between:

motion of target and **motion of beam**

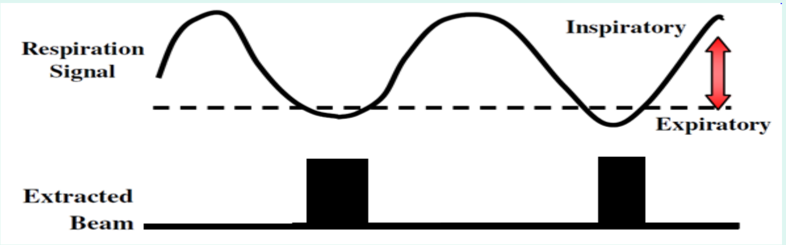
→ interplay effect

→ hot/cold spots

organ / tumor motion

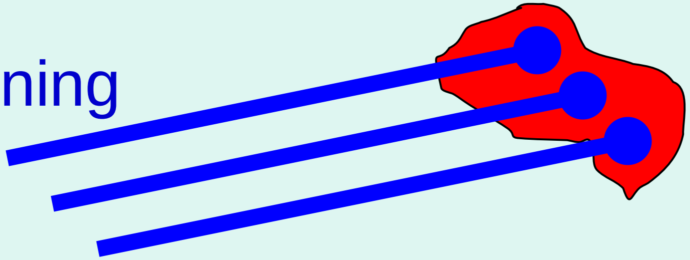
Possible solutions:

- Gating

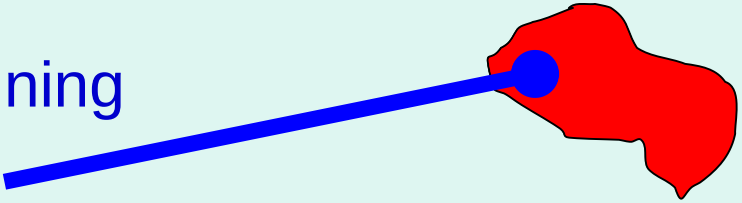


- Adaptive scanning

  (tumor tracking)



- Fast rescanning



Next steps forward in quality:

…so now we know what is neeeded:

The Five High's:

- Higher flexibility
- Higher speed
- Higher accuracy
- Higher intensity
- Higher cost REDUCTION

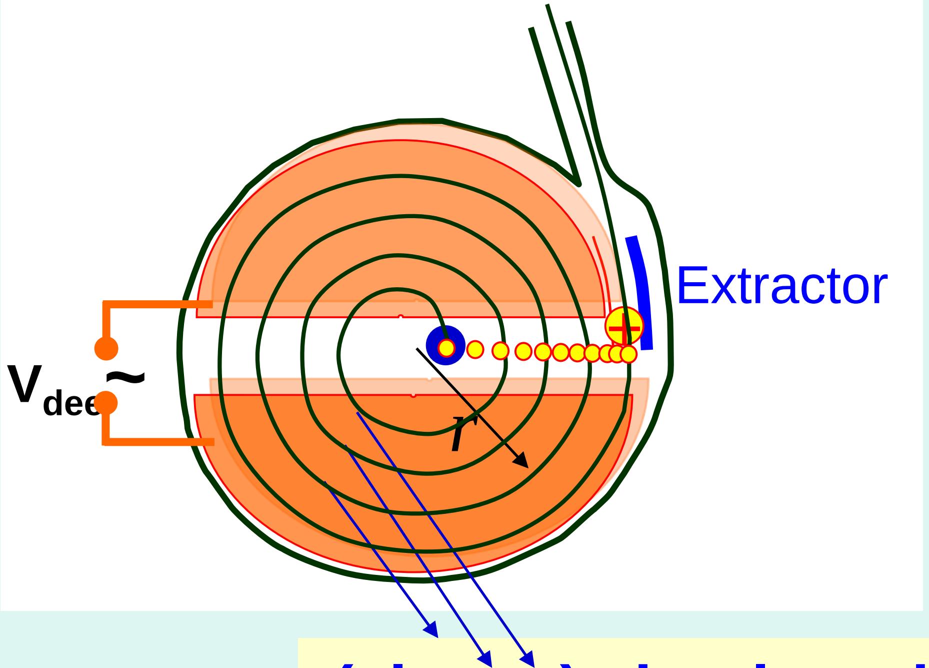
…but how to make it?

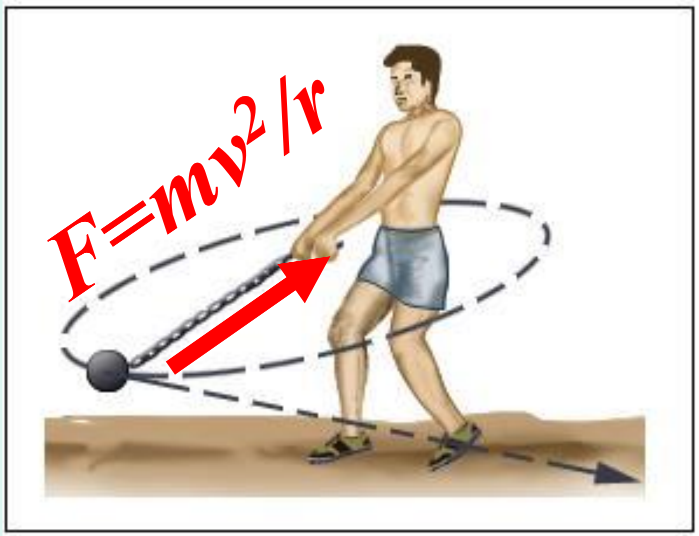
Accelerators

Present accelerator choice

	cyclotron	synchrotron
Protons	in use, ∅3.5-5 m	in use, ∅8-10 m
Carbon ions	test phase, ∅7 m	in use, ∅25 m

Cyclotron: isochronicity





(almost) circular orbits:

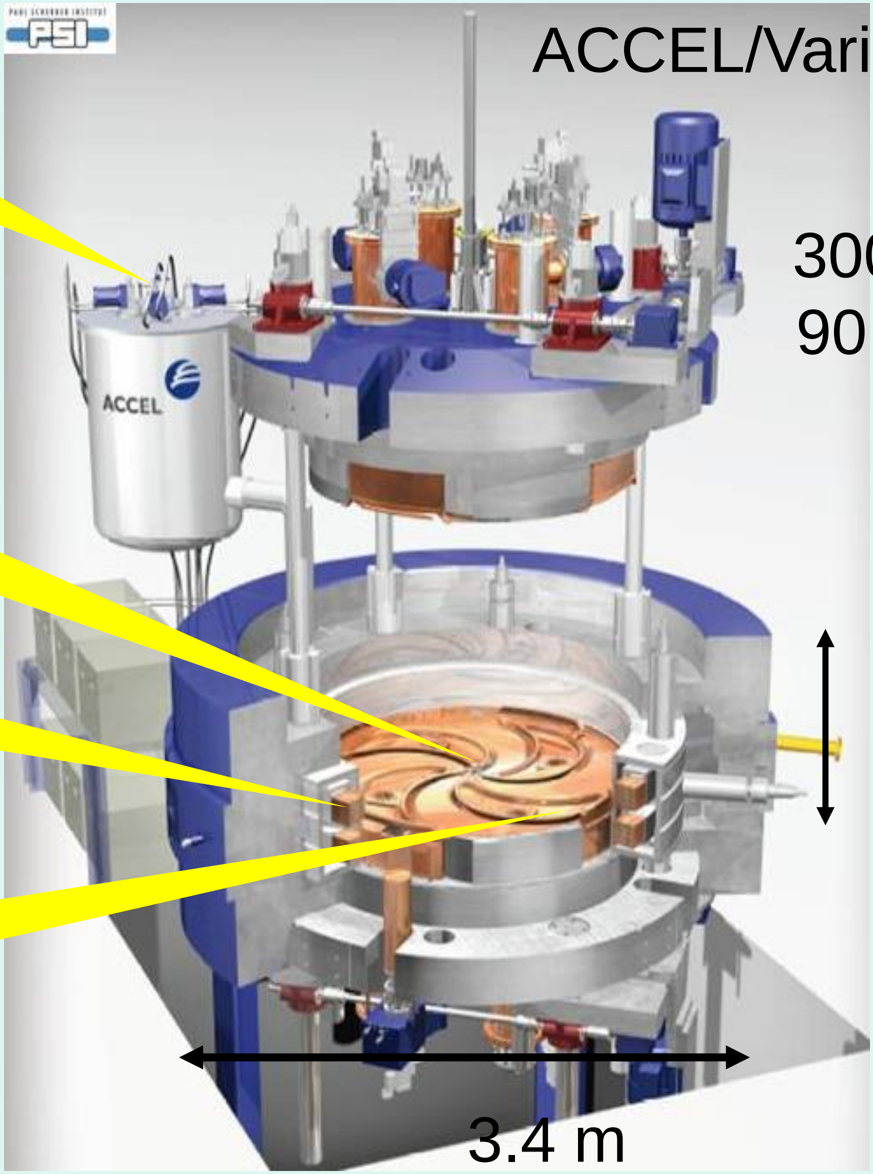
Centripetal force = Magnetic force $\frac{mv^2}{r} = Bqv$

=> $T_{circle} = \frac{2\pi.r}{v} = \frac{2\pi.m}{Bq}$; $T_{circle} \approx$ 30 ns

=> T_{circle} independent of orbit radius r

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

250 MeV proton cyclotron



Closed He system
4 x 1.5 W @4K

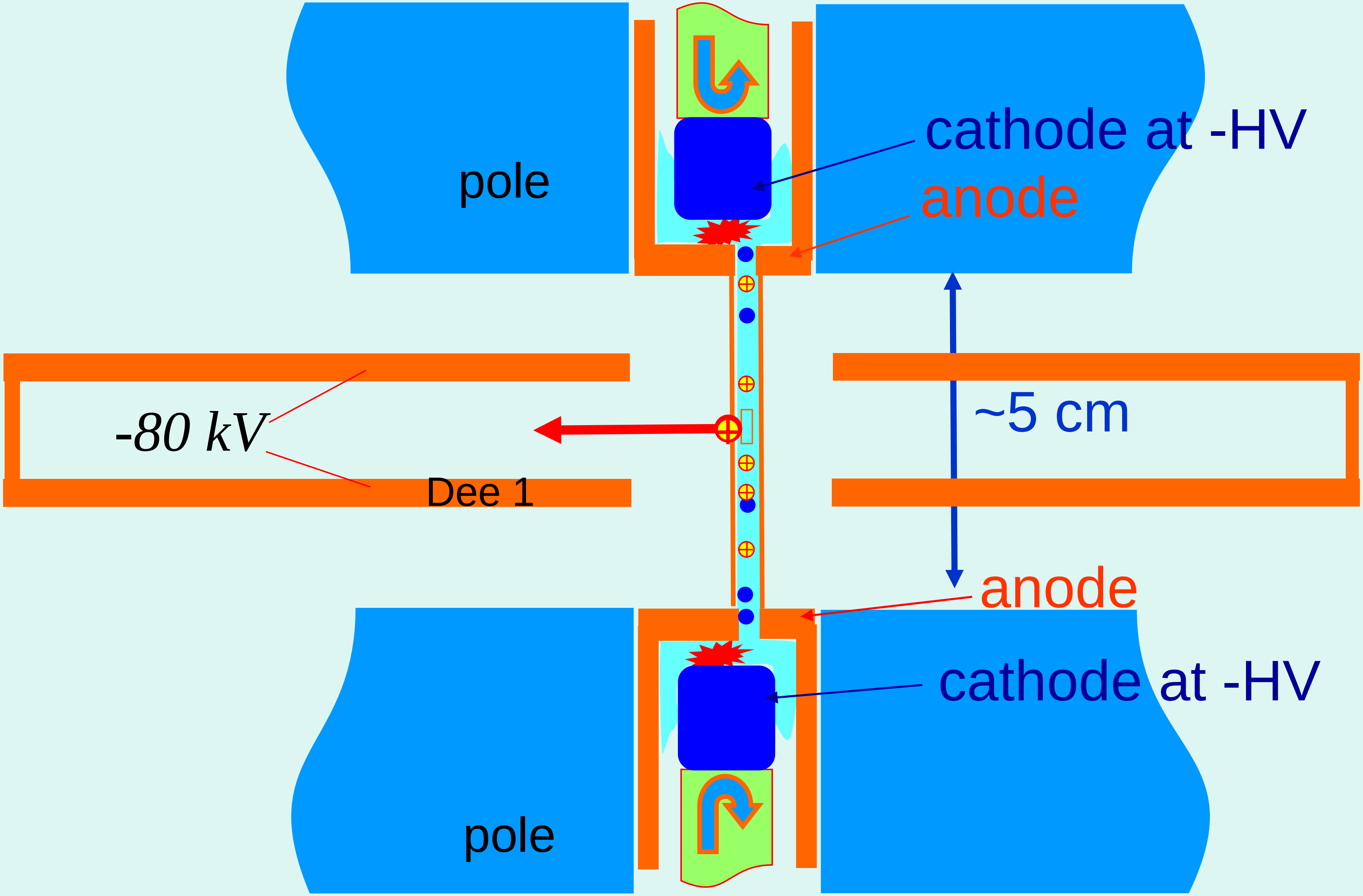
Proton source

superconducting coils =>
2.4 – 3.8 T

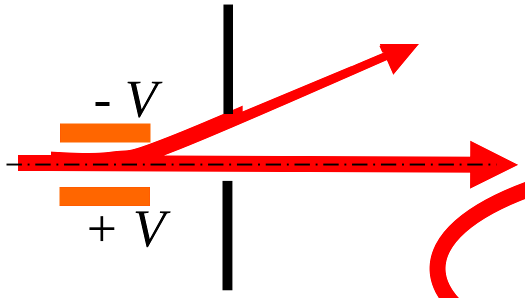
4 RF–cavities
~80 kV on 4 Dees

300 kW
90 tons

Internal proton source



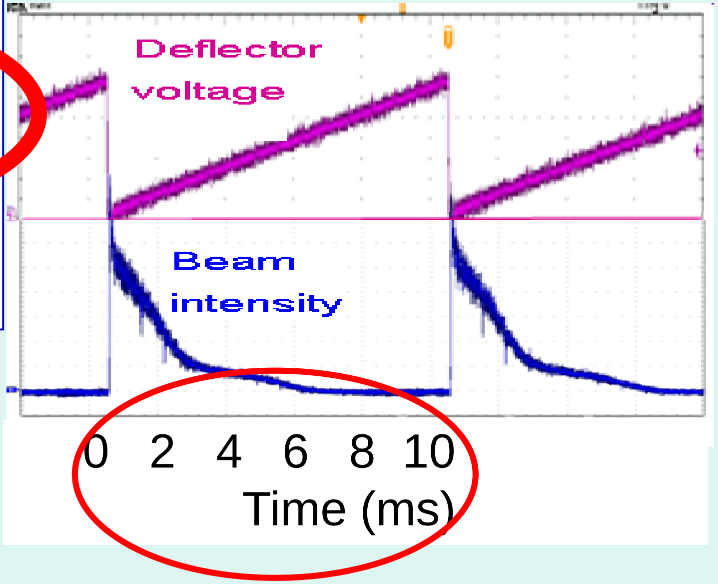
intensity control

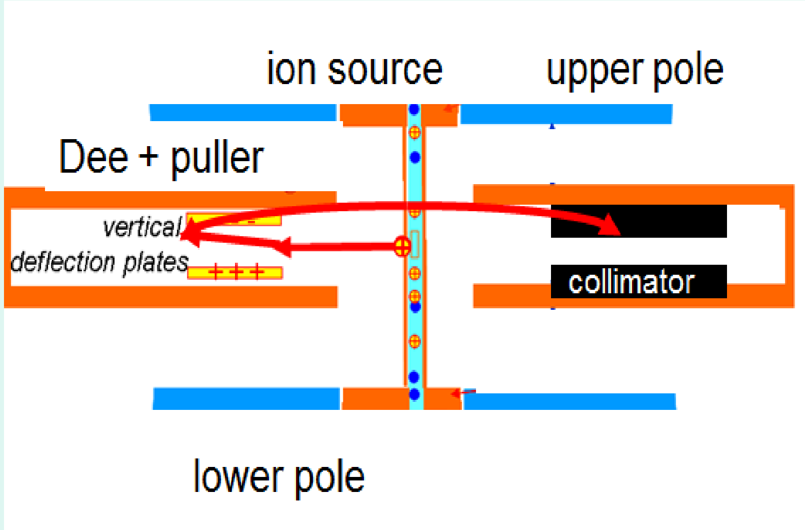


Deflector plate

sets intensity

- within 50 µs
- 3% accuracy





Advantages of a cyclotron

=> a cyclotron provides:

- continuous beam
- any intensity
- very fast adjustable intensity
- accurate intensity control
- great reliability
- in development: 450 MeV/nucl Carbon

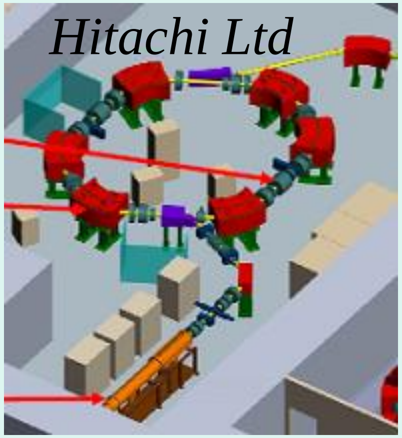
\+ range change of 5 mm < 50 ms

(with fast degrader and good magnets + power supplies)

Synchrotron

Protons only:

(∅ ~8 m)



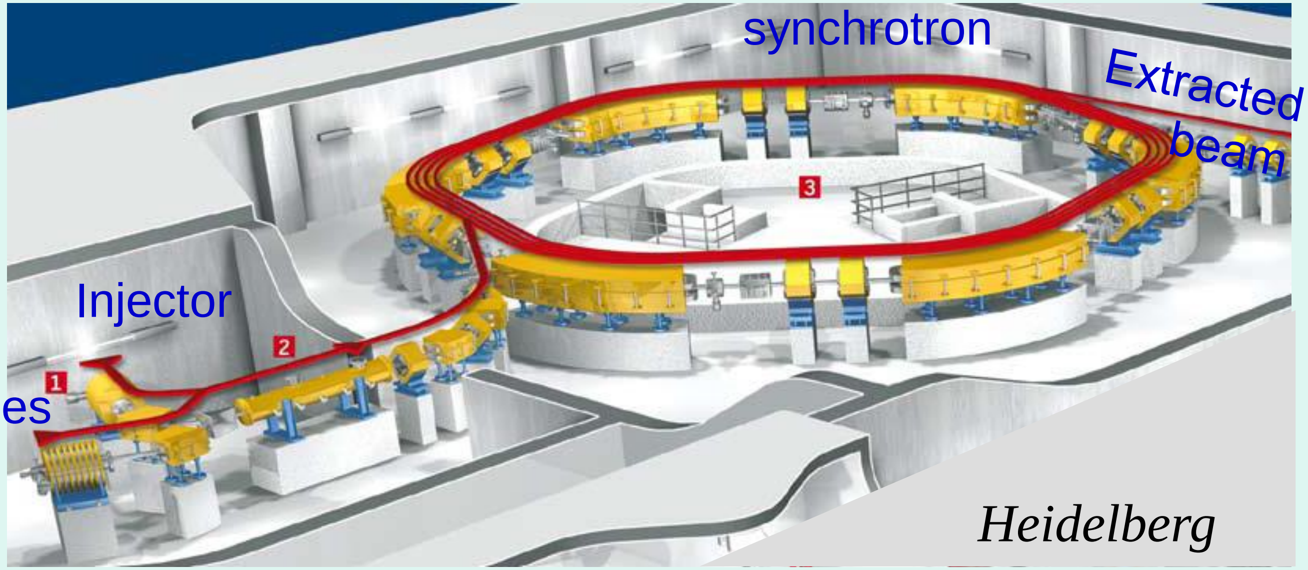
Extracted beam

synchrotron

Proton source + injector

Ions (p-C):

(∅ ~25 m)



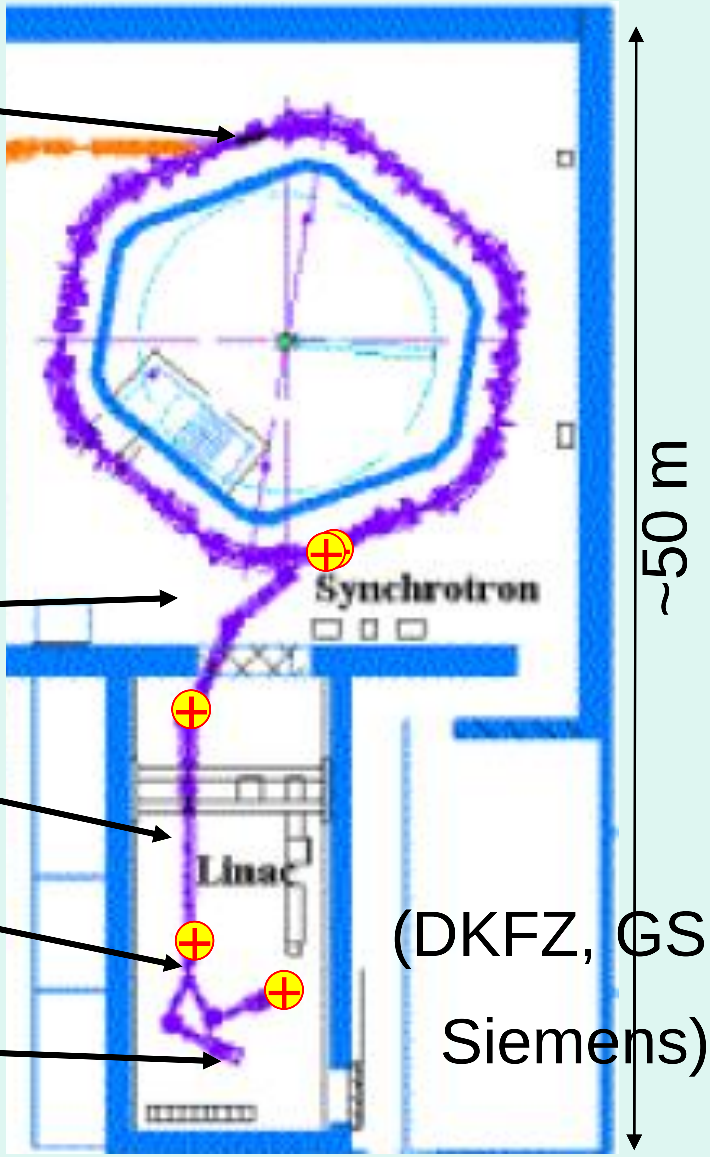
synchrotron

Extracted beam

Injector

Ion sources

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

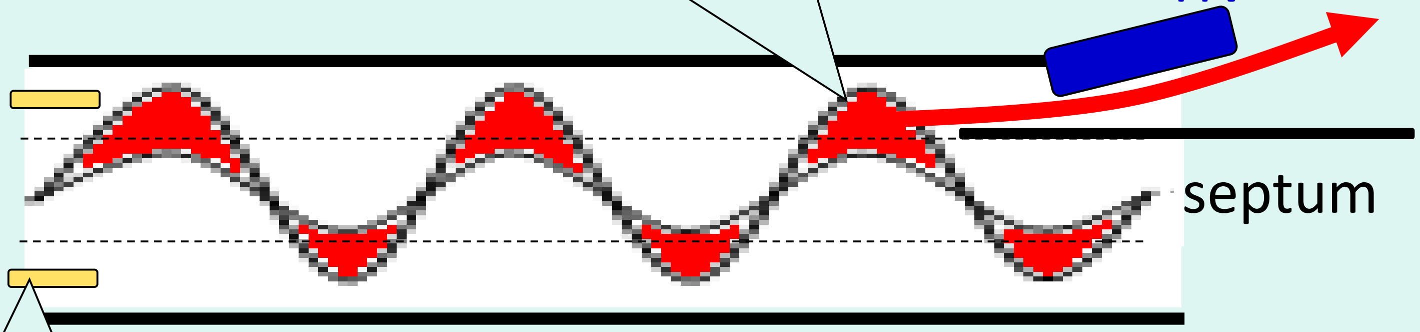
Magnet to select ion source

Ion sources for different particles

(DKFZ, GSI, Siemens)

Beam extraction from synchrotron

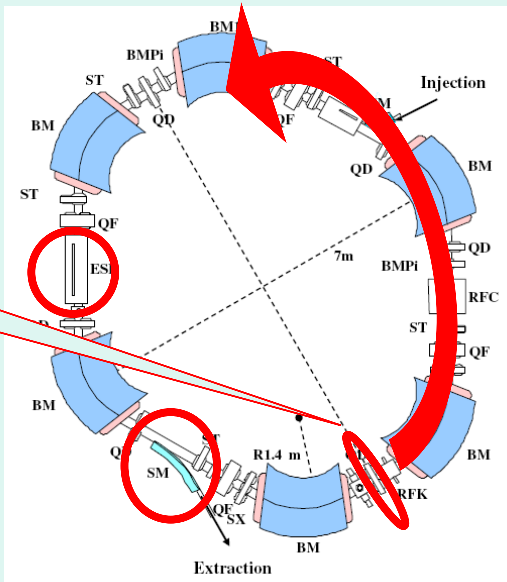
RF-Knock Out



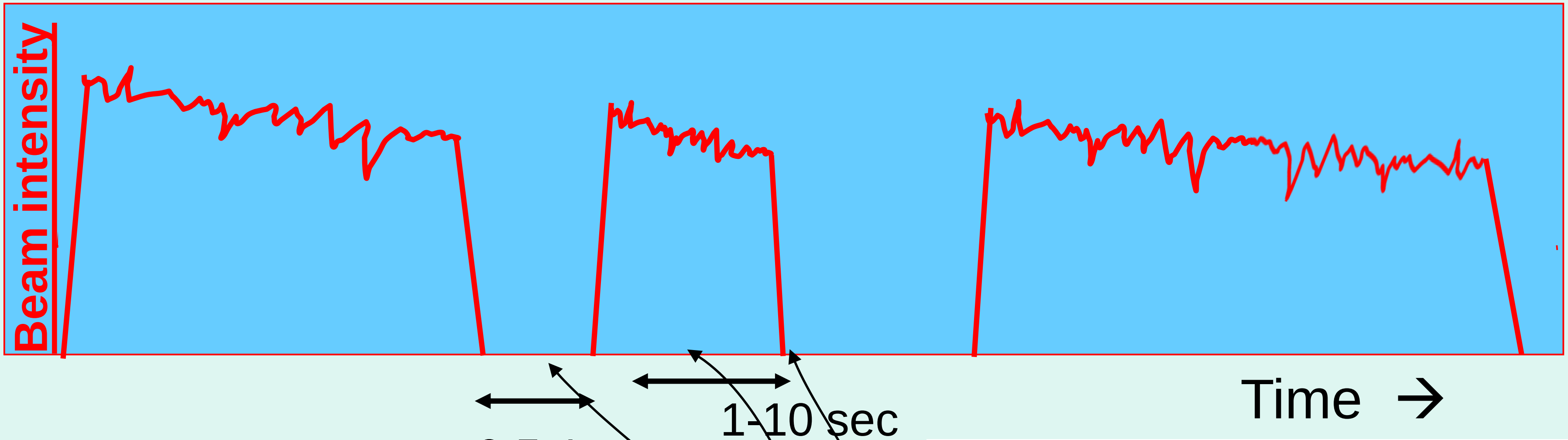
Unstable orbits

→ extracted

RF kicker: increases emittance (beam size)

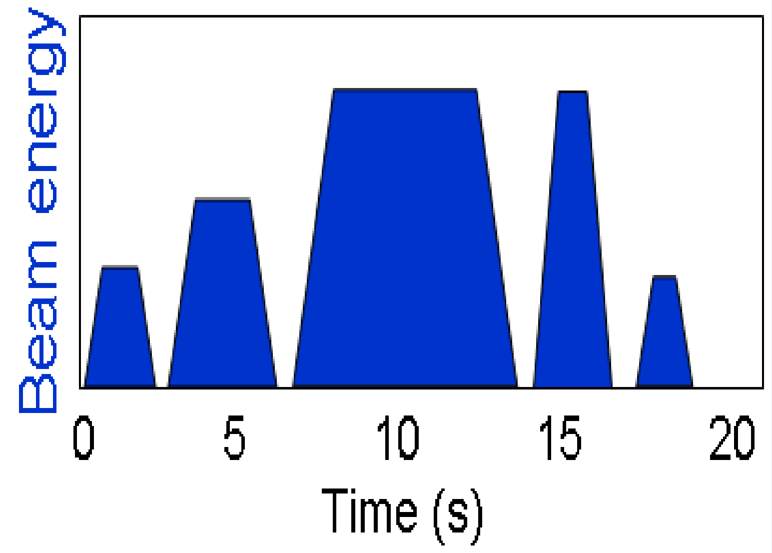


Synchrotron beam: noisy & spills



spill structure

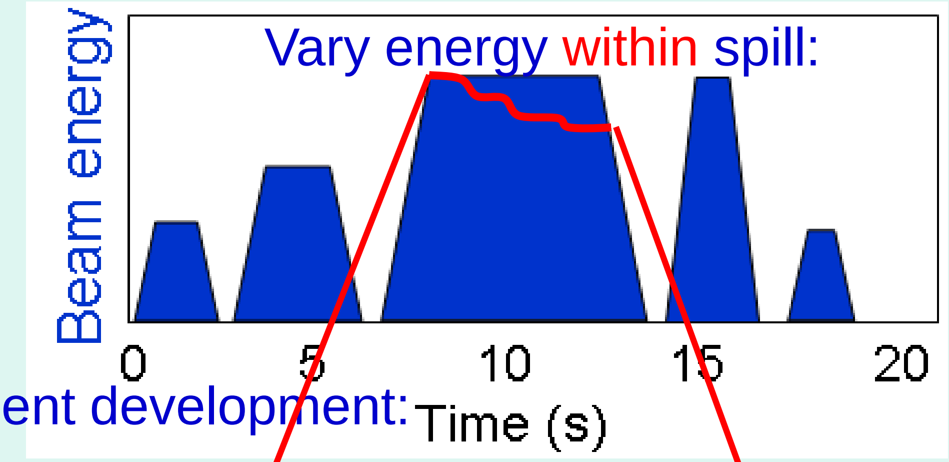
- fill ring with ~10^{11} particles
- accelerate to desired energy
- extract slowly during 1-10 sec
- decelerate and dump unused beam



E-change during extraction

synchrotron

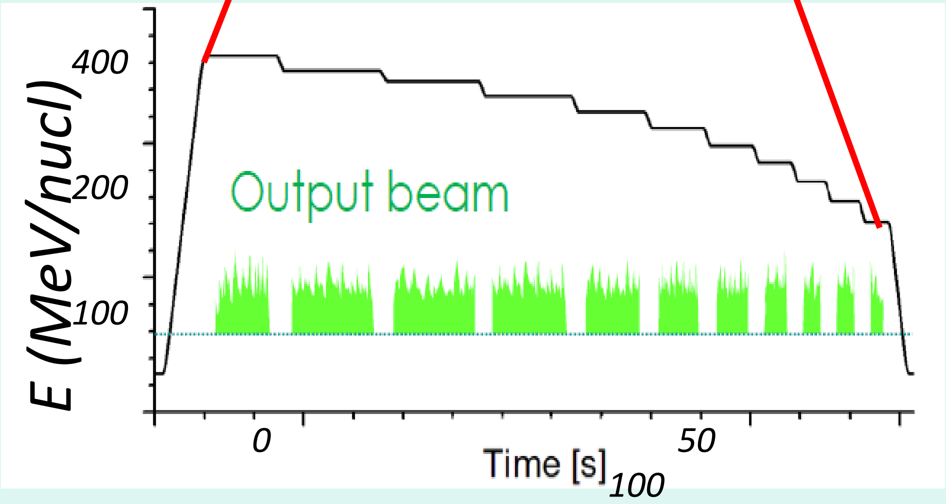
Vary energy at accelerator:



Vary energy within spill:

Recent development:

Vary energy during extraction:



NIRS HIMAC

Yoshiyuki Iwata

Iwata et al., IPAC'10, Kyoto, Japan MOPEA008

treatment time → 50% !!!

Advantages of a synchrotron

=> a synchrotron provides:

- different ions
- fast switching between ions
- energy can be chosen (decreased during extracion)
- no degrader
- little beam losses
- easy access to components

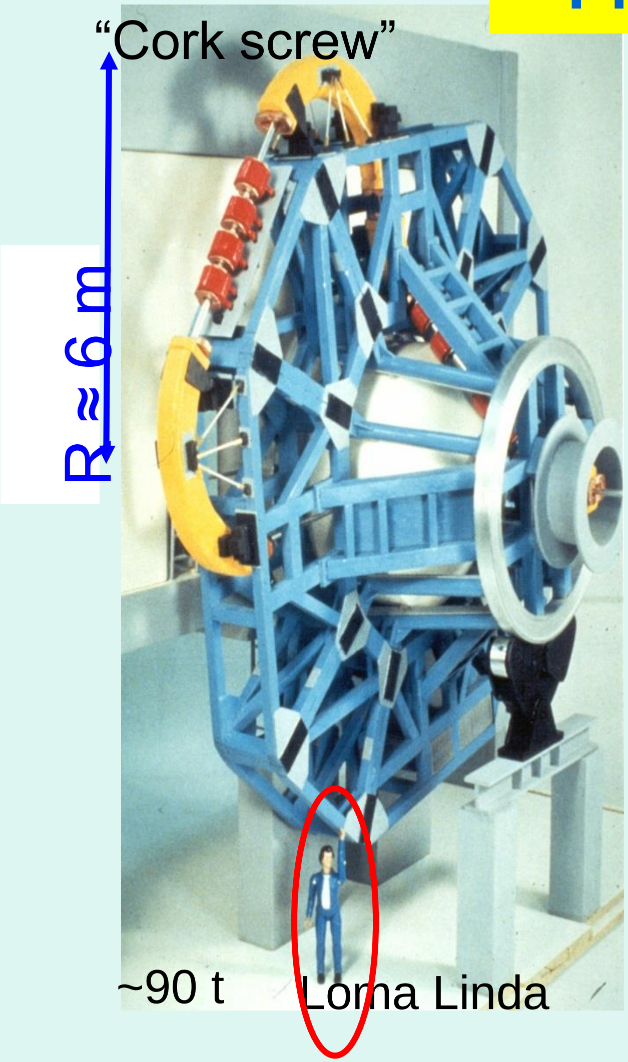
Developments

in

Gantries

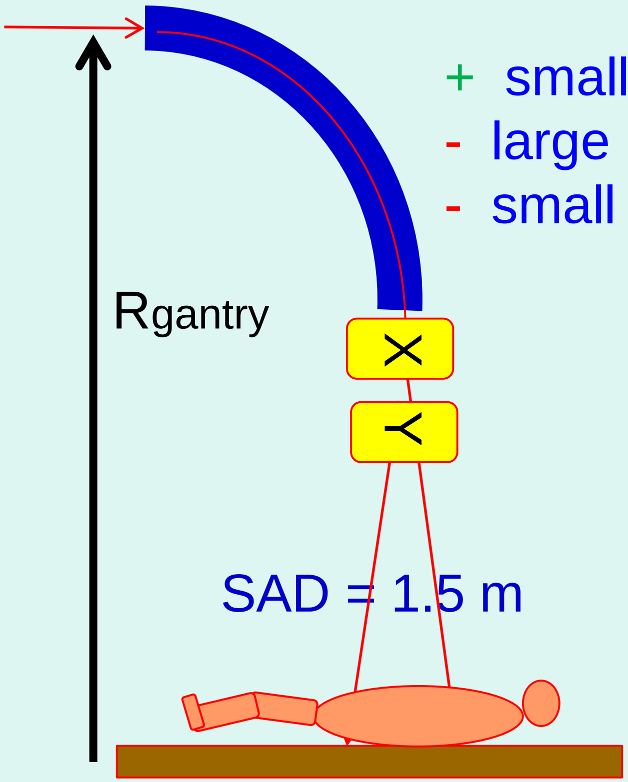
Gantry for protons

Proton gantries: R=5-6 m ; 100-200 t.



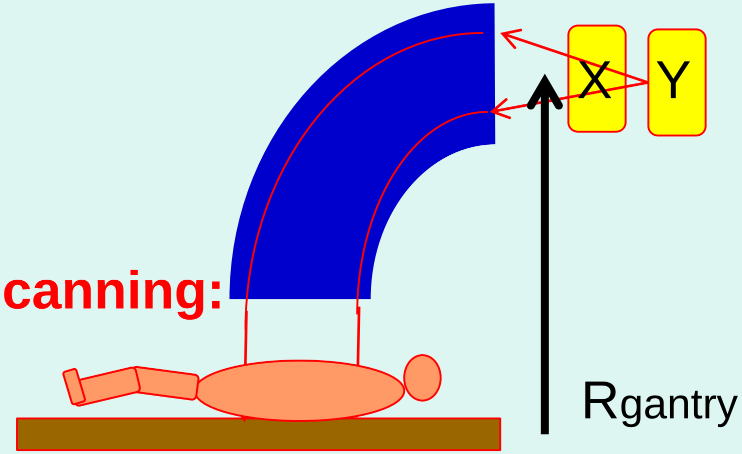
scanning

Down-stream scanning:



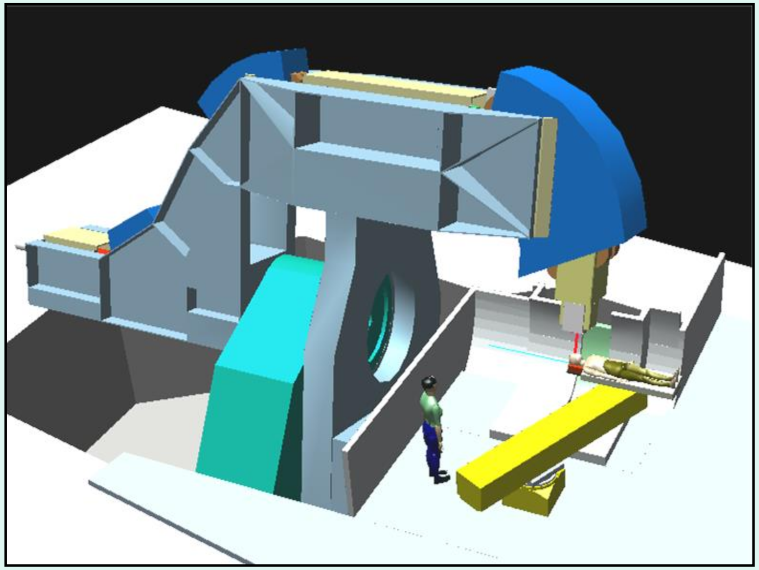
- \+ small aperture,
- \- large radius because of SAD
- \- small spots difficult

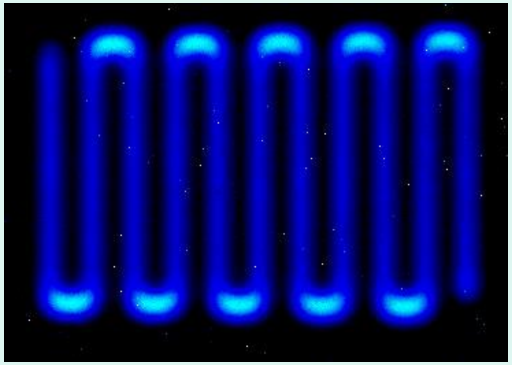
Up-stream scanning:

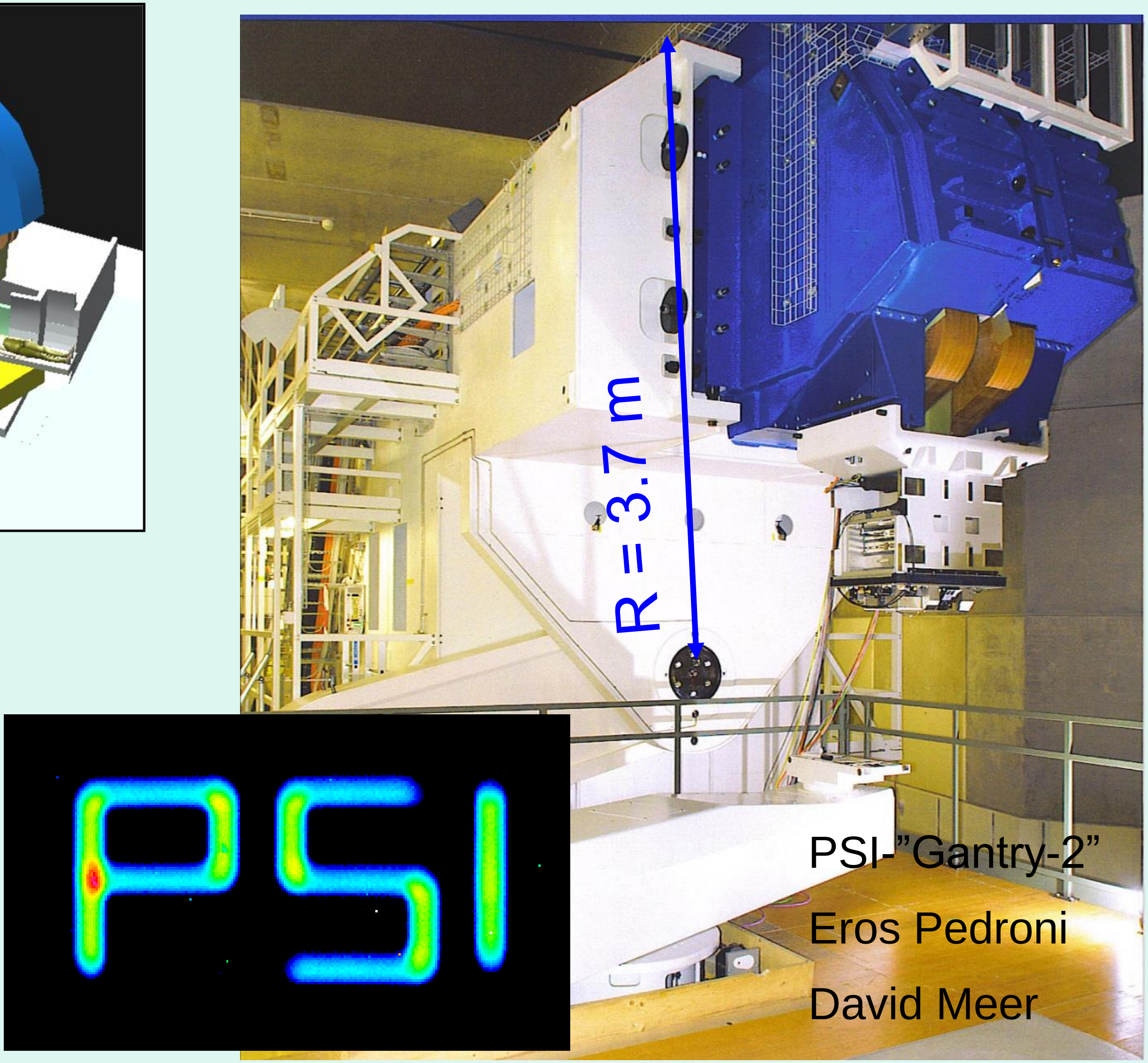


- \+ parallel
- \+ small gantry radius
- \+ small spots possible
- \- wide aperture SC magnet

PSI Gantry-2: fast 3D scanning







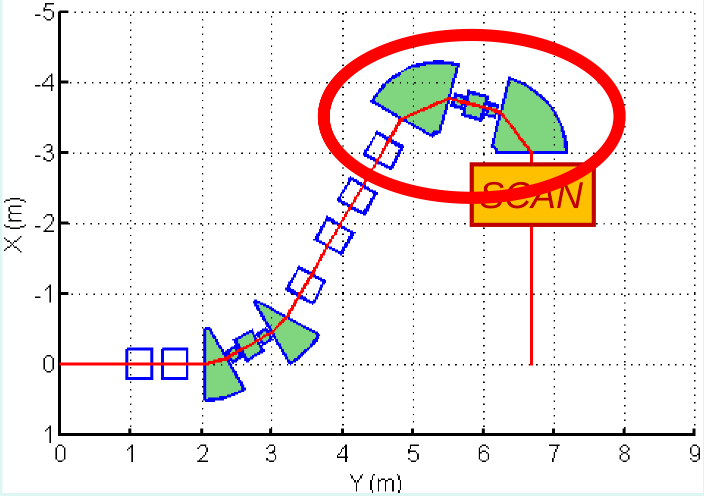
PSI-”Gantry-2”

Eros Pedroni

David Meer

SC-Gantry for **Proton therapy**

Patent licensed to ProNova Solutions, LLC



- Weight: ~ 12 tons

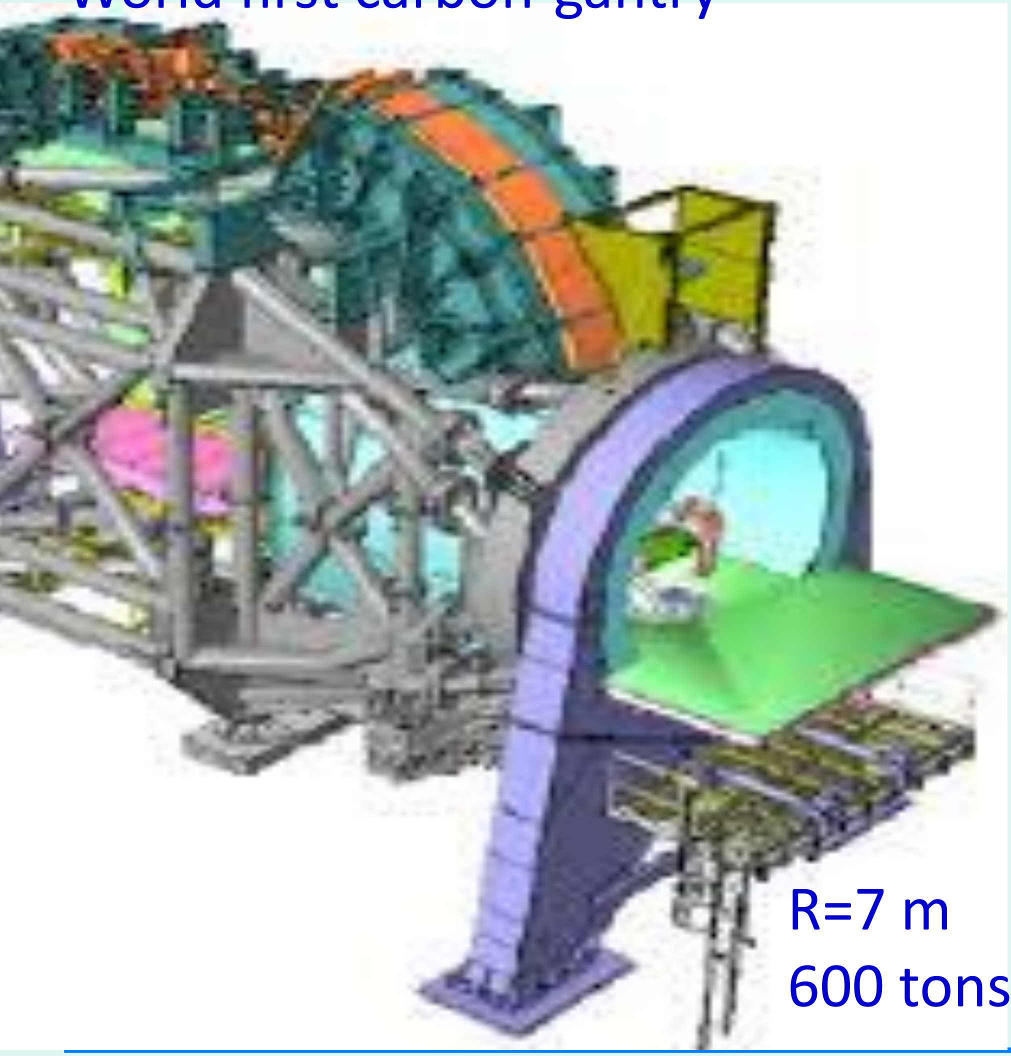
SC magnets:

- Weight → x 0.1
- Length → x 0.8
- Radius → x 0.8

Gantry with SC magnets

–HIT, DKFZ

– World first carbon-gantry

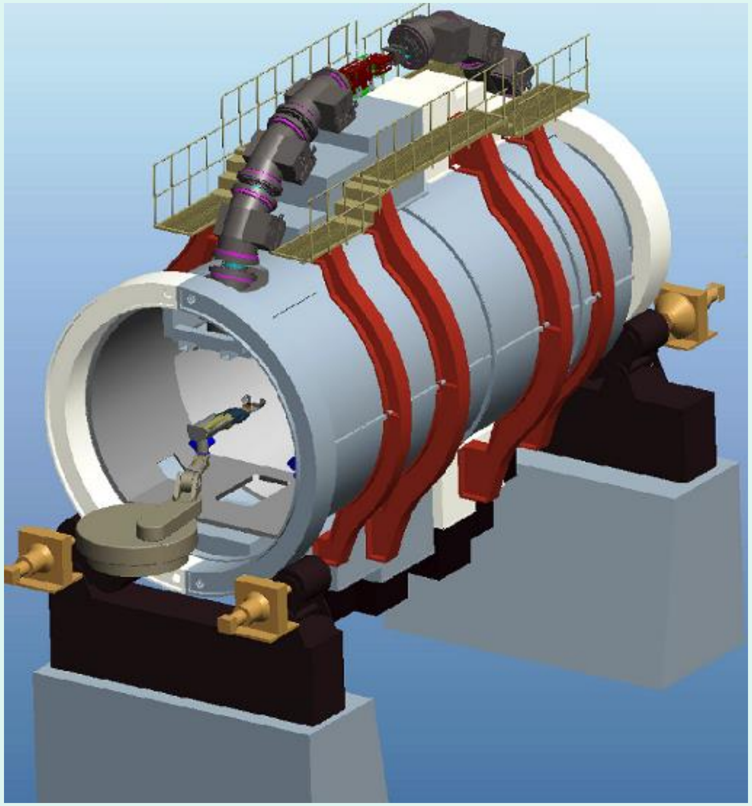


R=7 m

600 tons

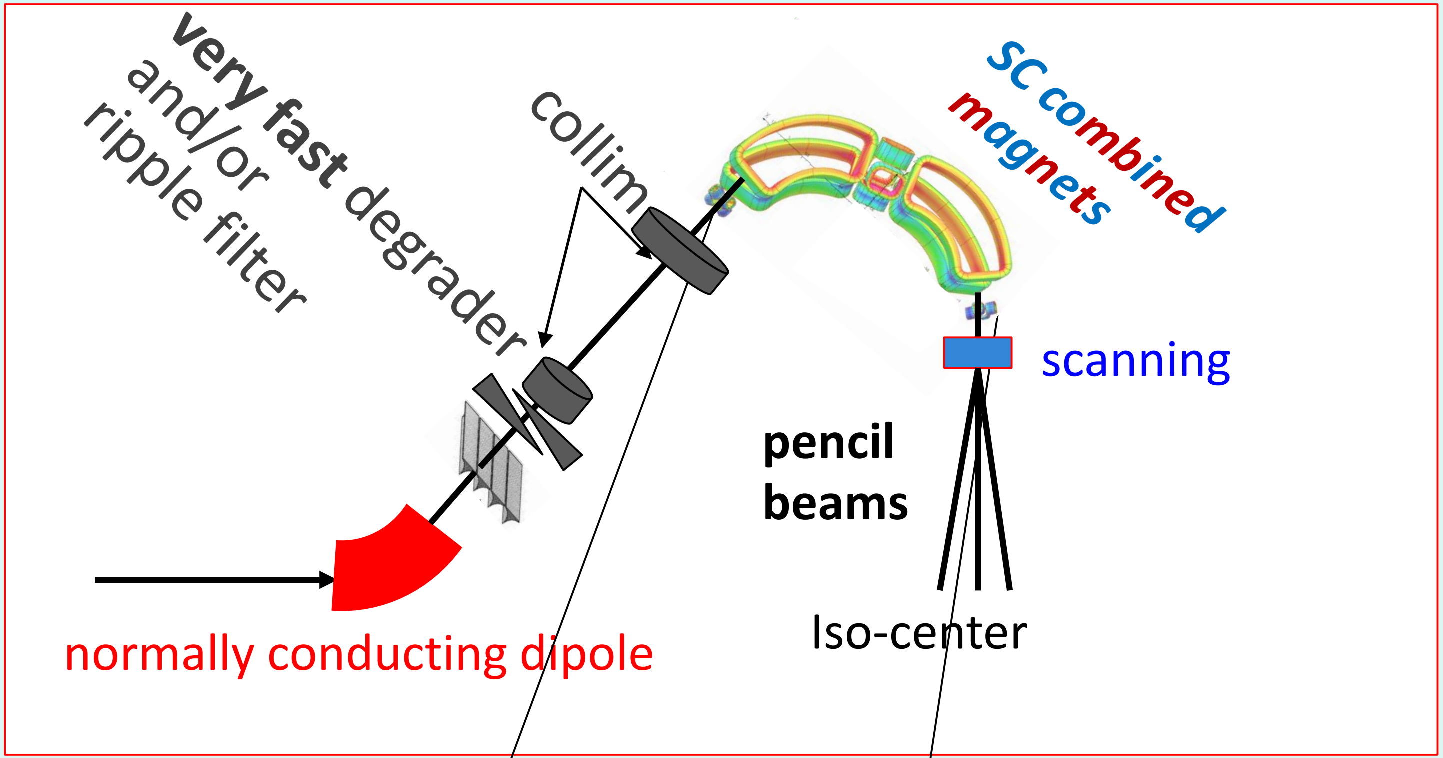
Yoshiyuki Iwata, NIRS, Ciba (Japan):

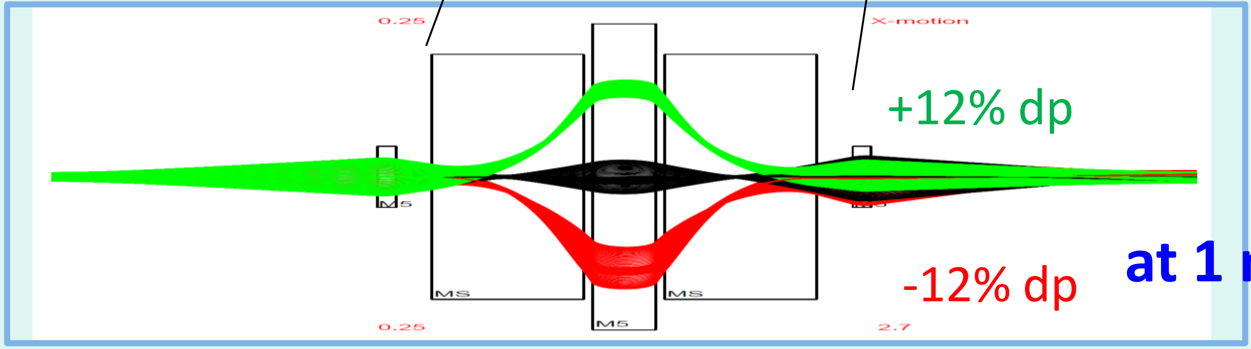
SC-Gantry for Carbon Ions



R=5.8 m 200 tons

PSI's SC design: high dp accept.



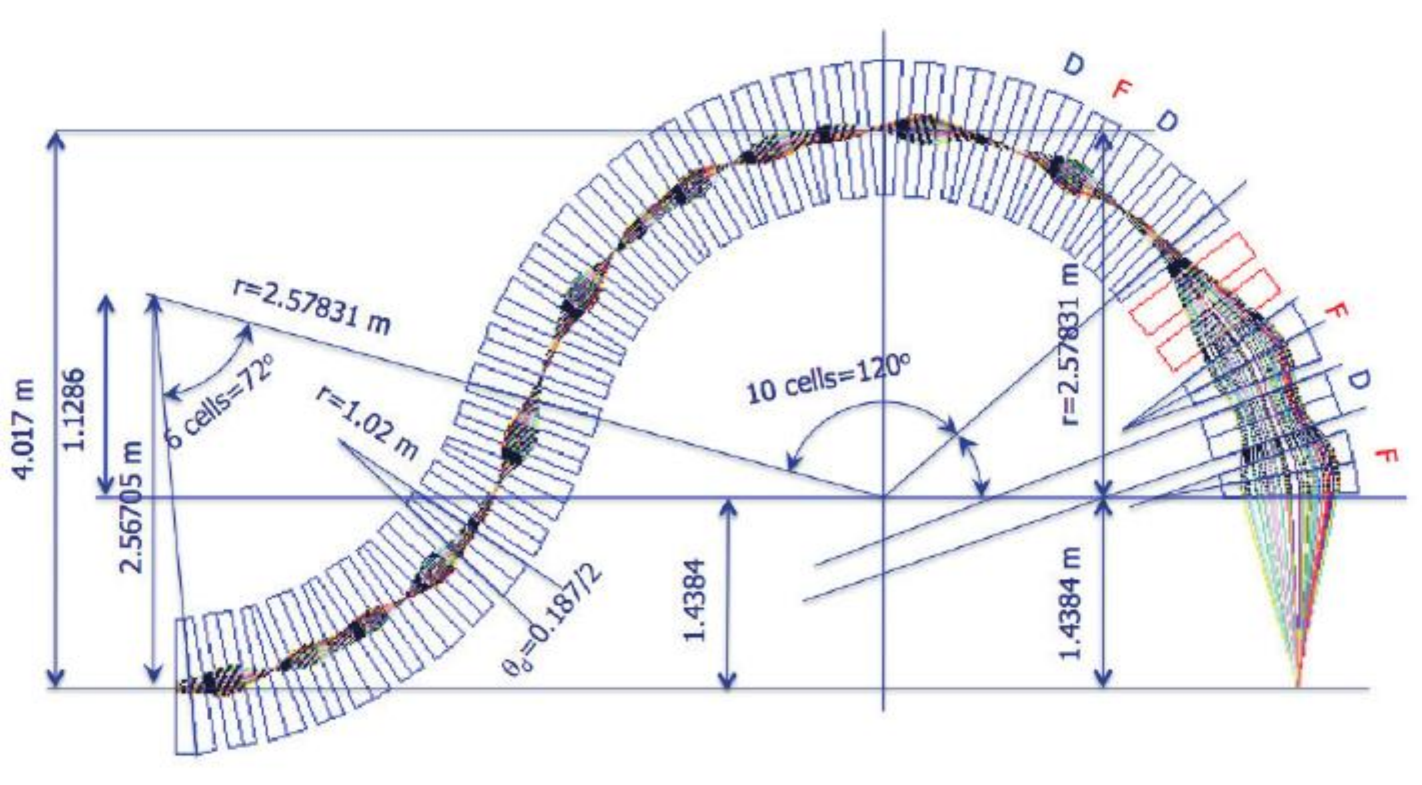


Range +/- 6 cm

→ 12 cm SOBP

at 1 magnet setting

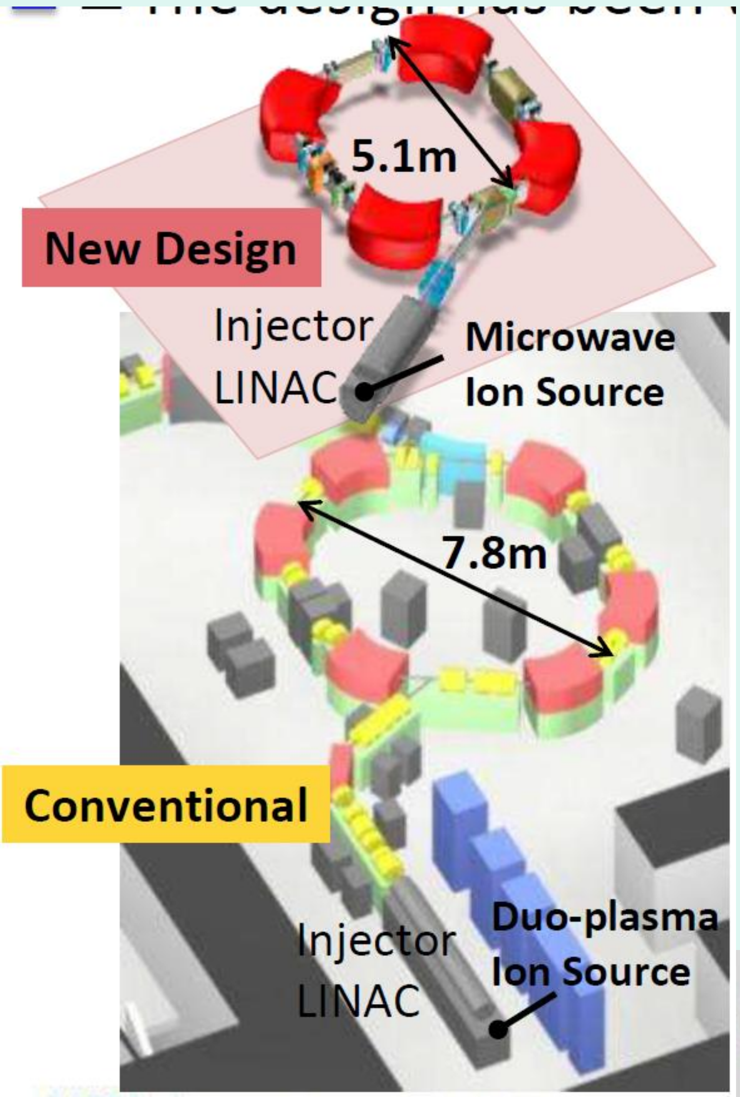
high dp accept using FFA optics

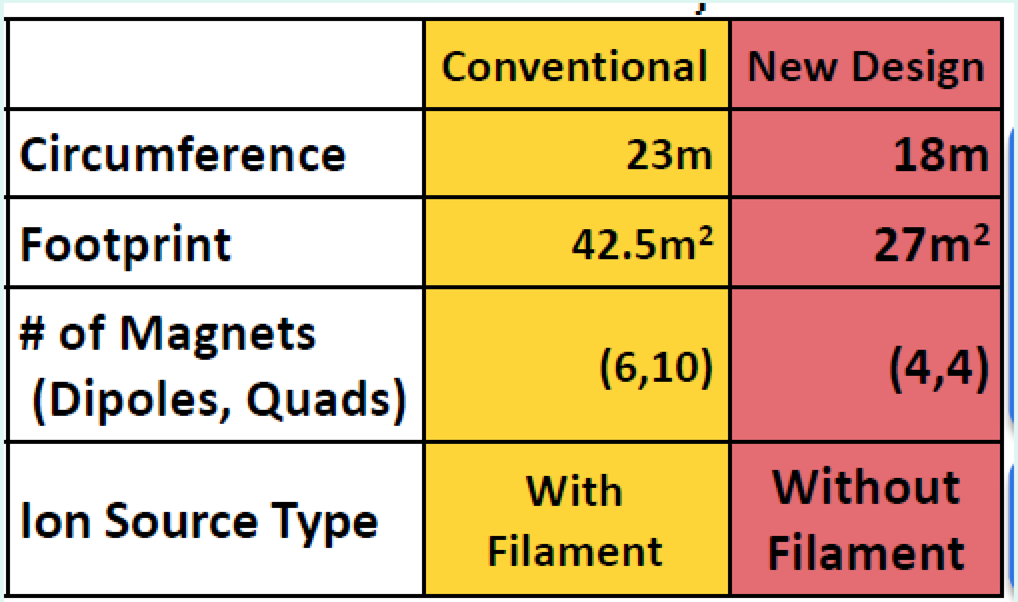


Trbojevic, Brookhaven: FFA beam optics

Smaller accelerators

Compact synchrotron



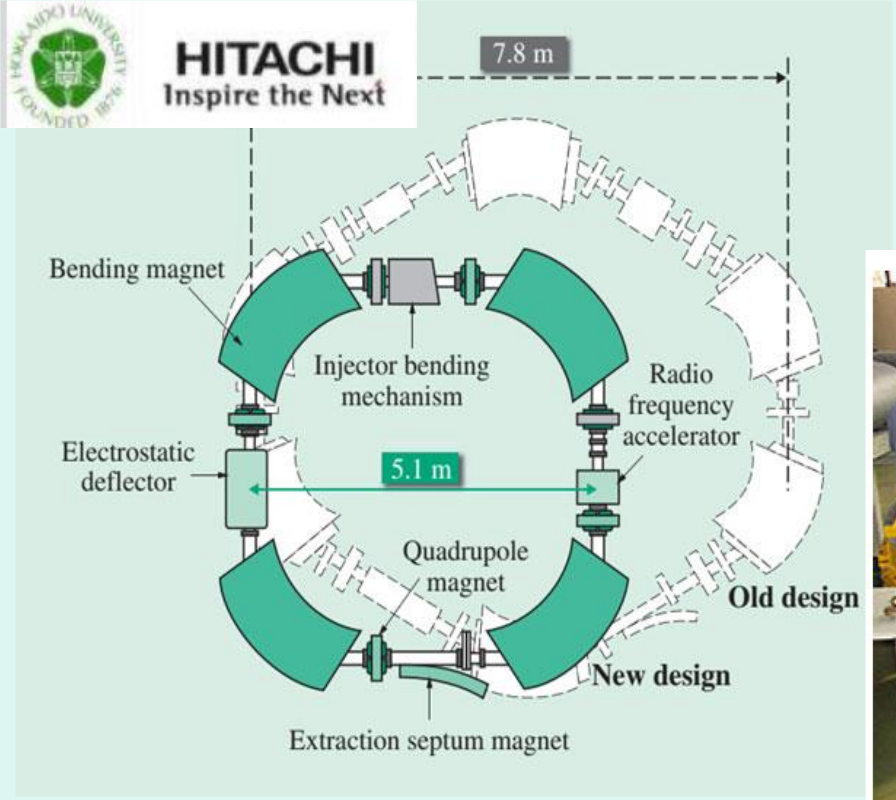


	Conventional	New Design
Circumference	23m	18m
Footprint	42.5m^2	27m^2
# of Magnets (Dipoles, Quads)	(6,10)	(4,4)
Ion Source Type	With Filament	Without Filament

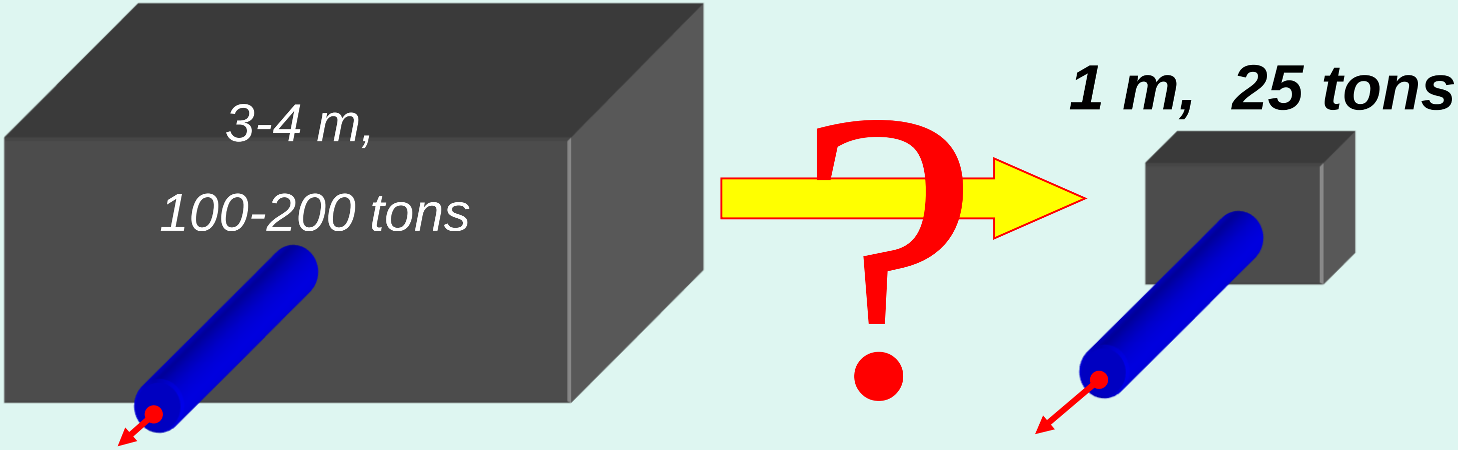
- 220 MeV
- First facility in Hokkaido started in 2013

HITACHI
Inspire the Next

Smaller proton synchrotron



How to minimize the cyclotron?



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

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

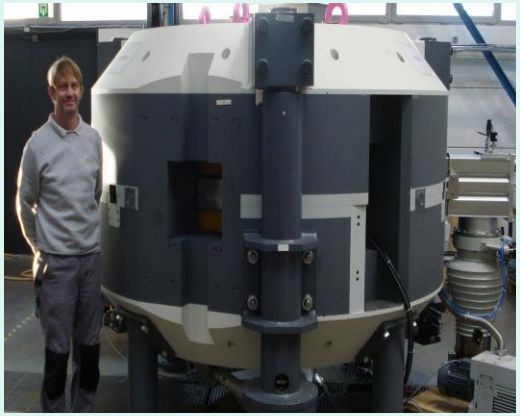
To reduce Radius: → R_{pole} = 0.3 m → B= 8 T

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

Reduction of of cyclotron size

IBA/SHI
250 Tons
Isochronous
Cyclotron

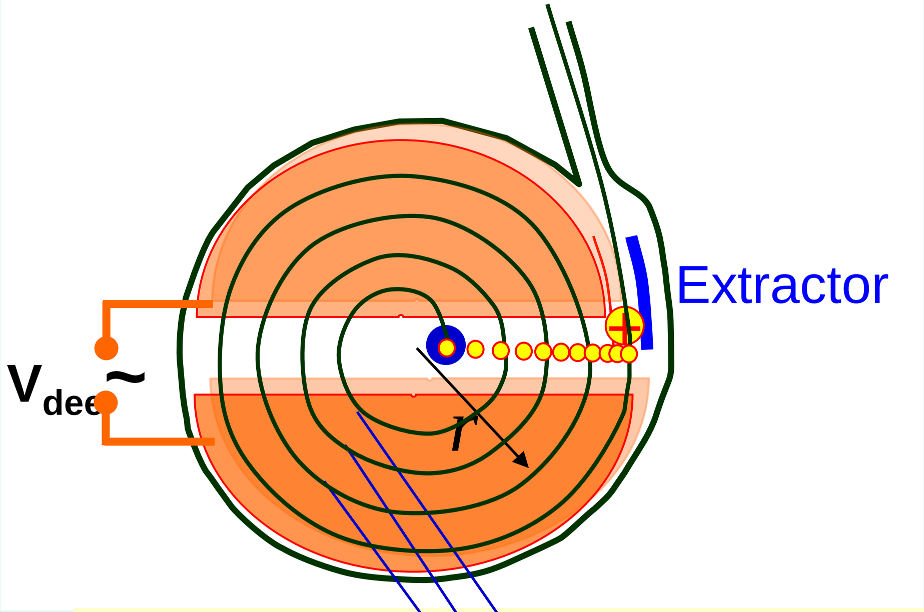
Varian – 90 Tons
Isochronous
Cyclotron

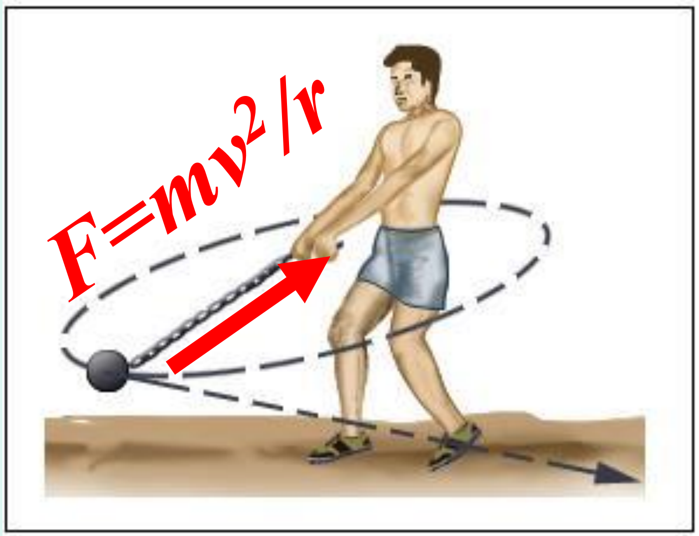


IBA – 60 Tons
Synchrocyclotron

MEVION – 15 Tons
Synchrocyclotron

Cyclotron: isochronicity





(almost) circular orbits:

Centripetal force = Magnetic force

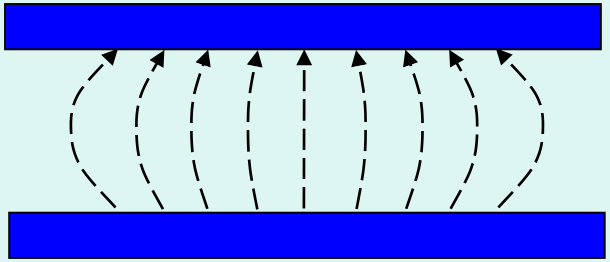
$$\frac{mv^2}{r} = Bqv$$

$$T_{circle} = \frac{2\pi.r}{v} = \frac{2\pi.m}{Bq} \quad ; \quad T_{circle} \approx 30 \text{ ns}$$

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

Cyclotron with strong field

Problem (1): at very strong magnetic fields:



Magnetic field decreases with radius ⇒ T_{circle} ↑

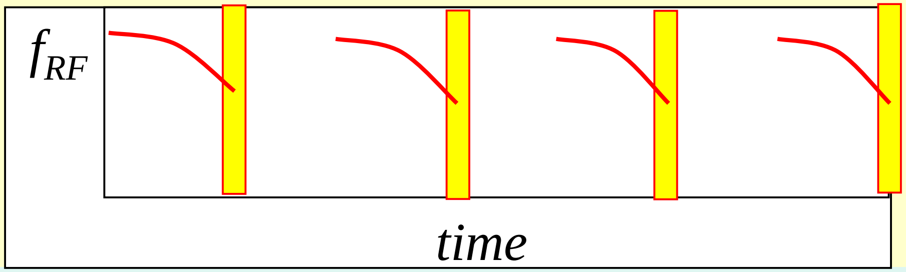
$$\boxed{T_{circle}} = \frac{2\pi .m}{q.\boxed{B}}$$

Problem (2): at very high speed:

Mass of particles increases ⇒ T_{circle} ↑

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

Remedy: **synchro–cyclotron:** pulse RF and decrease f_{RF} with radius



⇒*Needed in smaller machines !!*

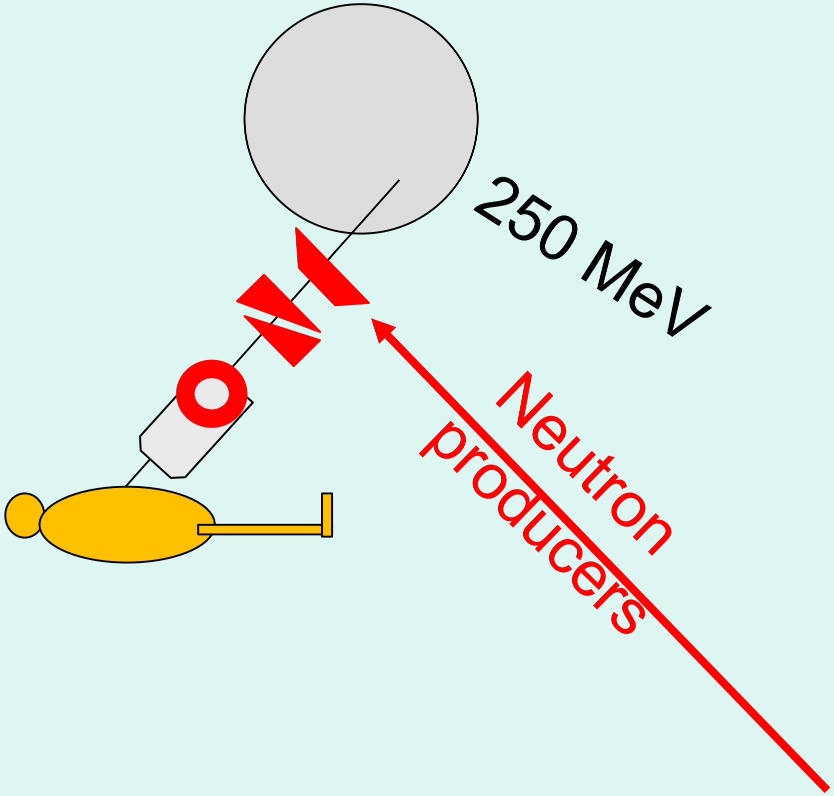
Synchro-Cyclotron

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

In use since dec. 2013

Synchro-Cyclotron

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

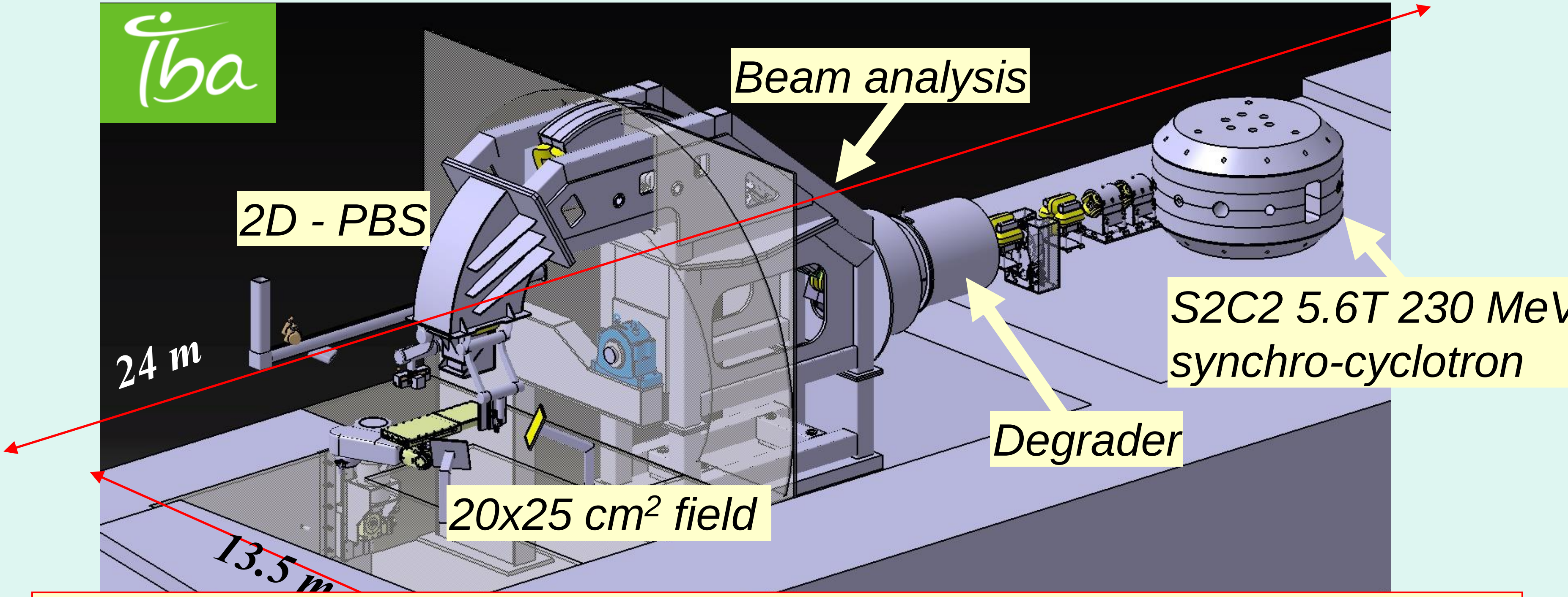


However:

- All degrading and collimation just before patient
- Pulsed beam => scanning difficult
- $ per treatment room > for multiroom

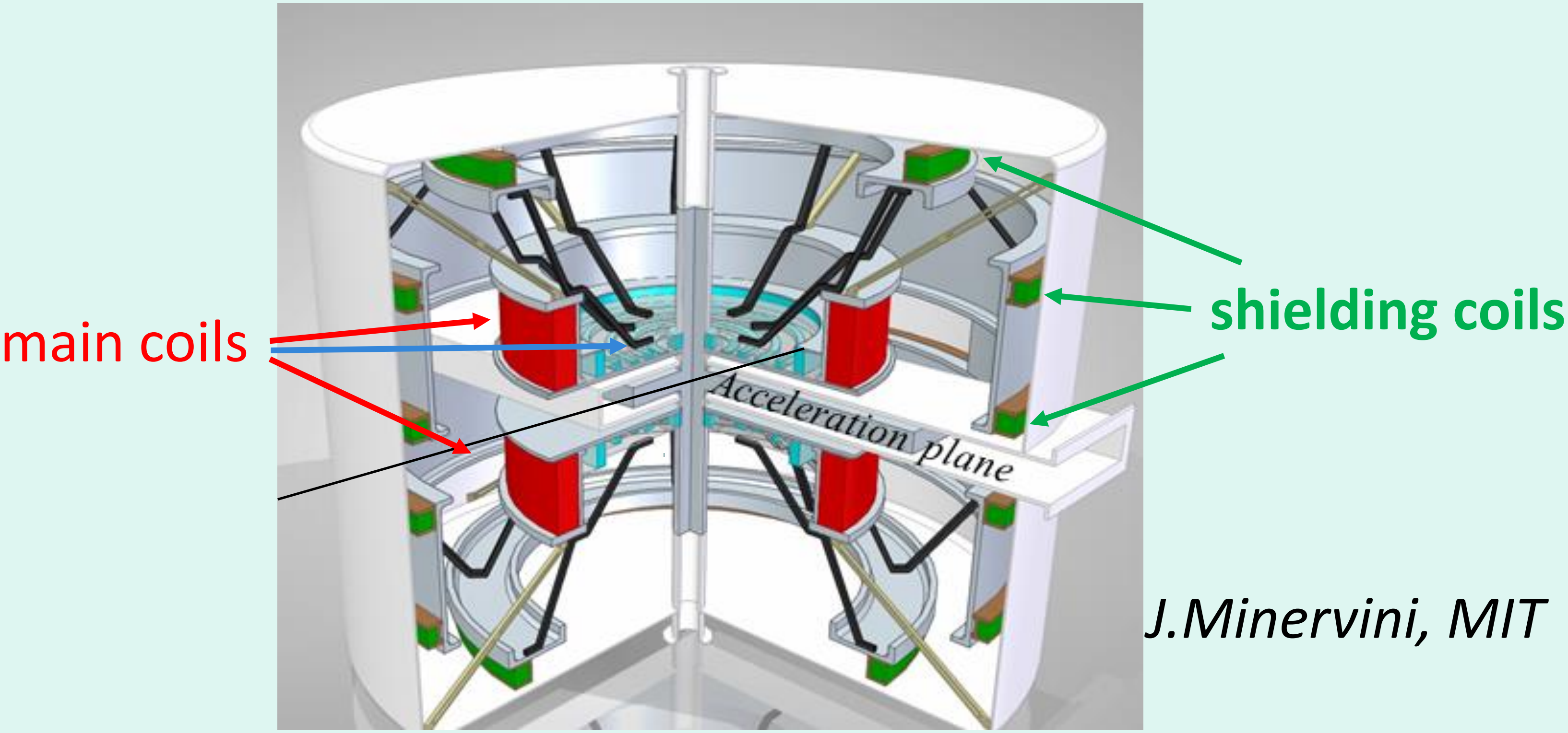
Synchro-Cyclotron

5.6 T 230 MeV Synchro-cyclotron with a gantry



- Beam analysis and Pencil Beam Scanning
- First facility with S2C2 started treatments in 2016 in Nice
    - Spot scanning only
    - Spot size 6.4 mm 2σ
    - dose per pulse accuracy <30% => fill spot within 2-3 times

Iron-free Magnet Design (MIT)

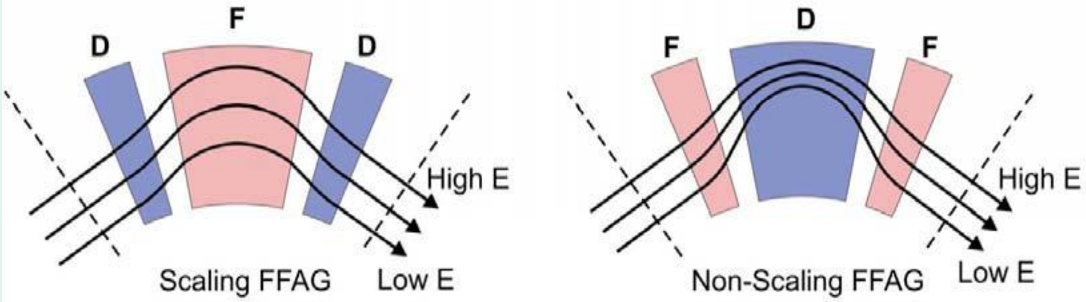


J.Minervini, MIT

Iron-free superconducting cyclotron , using a set of Main Coils and two sets of three Shielding Coils to compensate the magnetic field outside the cyclotron. **No iron → low inductance → E change ?**

New accelerator types

FFAG: Fixed Field Accelerator (FFAG)



FFA= synchro-cyclotron

(f_{RF} increases with E)

But: - built as a ring

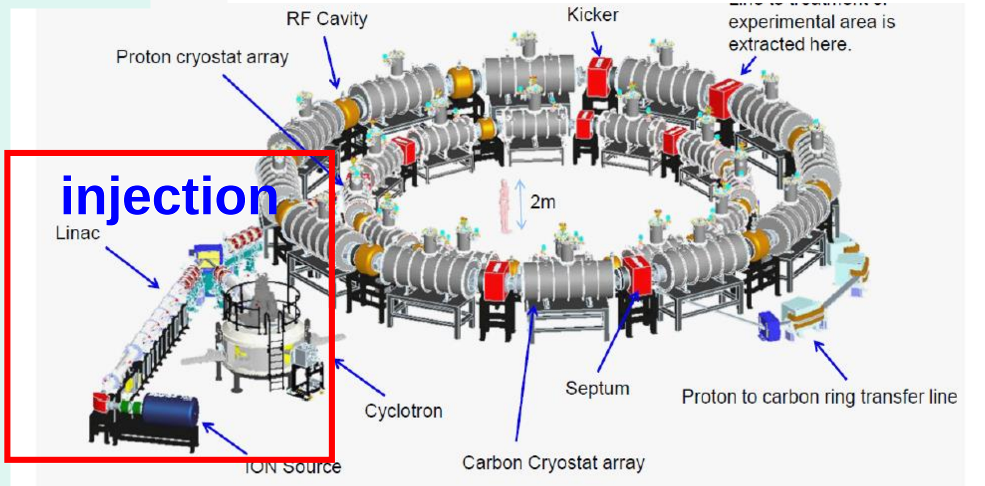
- with special optics:

strong, **alternating gradients**.

=> all orbits/energies fit in ring

Recipe:
1) inject into ring
2) 1 MW RF until E reached
3) Extract beam

Pamela (UK) FFAG proton ring
+ booster for Carbon



Proton ring: ∅=12 m

M.K. Craddock and K.R. Symon,
Rev. Acc. Science and Techn., vol. I, (2008) 65–97

FFA‘s for hadron therapy:

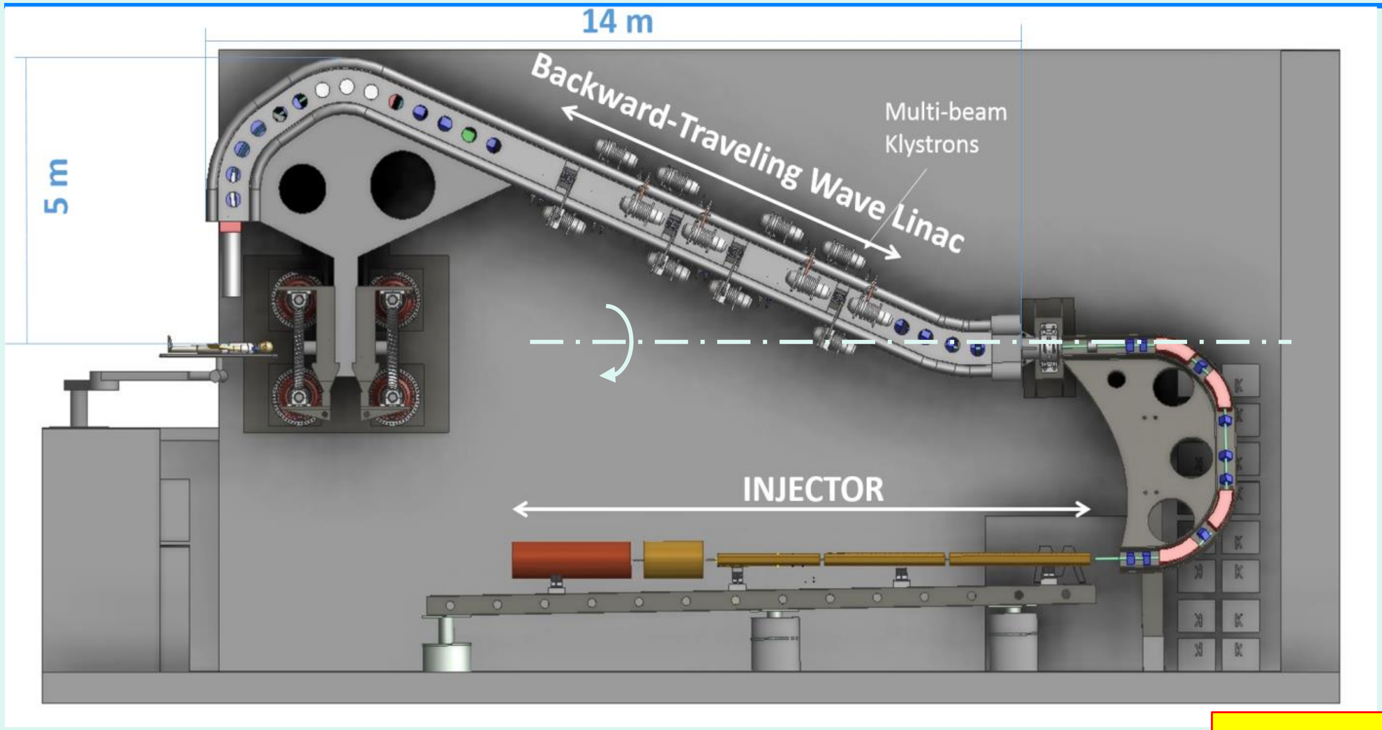
Advantage:

- Fast (kHz speed!) energy change in accelerator

Disadvantages:

- Heavy (100-200 tons)
- Not small (e.g. 12 m ∅)
- Very high power (several MW) needed
- Needs an injector (e.g. cyclotron)
- Pulsed (although kHz possible)
- Nr of particles per pulse uncertain

TUrnig LInac for Proton therapy



A proton linac mounted on a gantry.
(courtesy of P. Carrio Perez, TERA Foudation)

ADAM (CERN) and AVO, UK

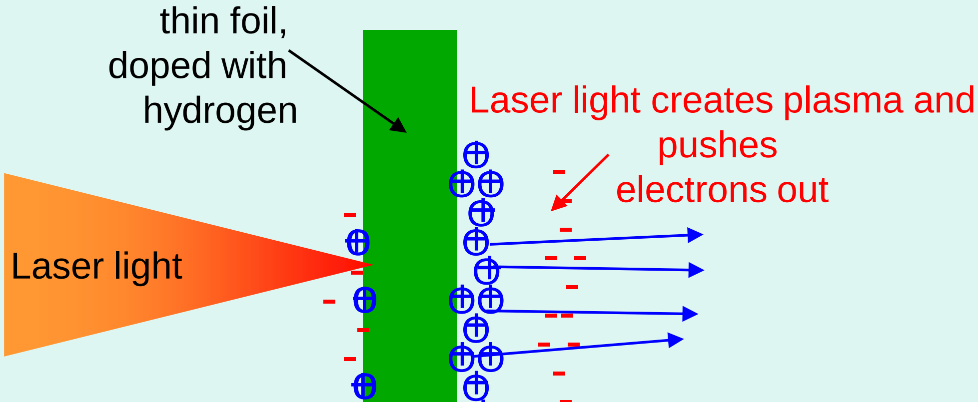
ADVANTAGES:

- E change per pulse
- Small footprint

DISADVANTAGES:

- Only pulsed
- Dose per pulse??

Laser driven proton accelerator



thin foil, doped with hydrogen

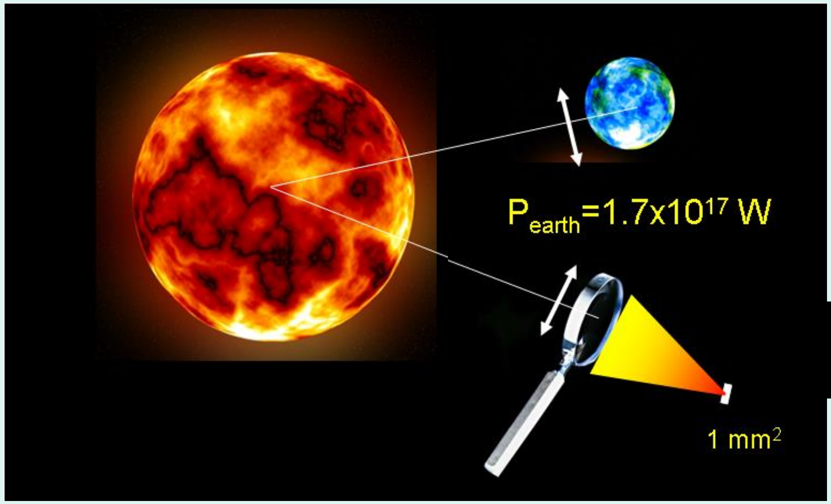
Laser light

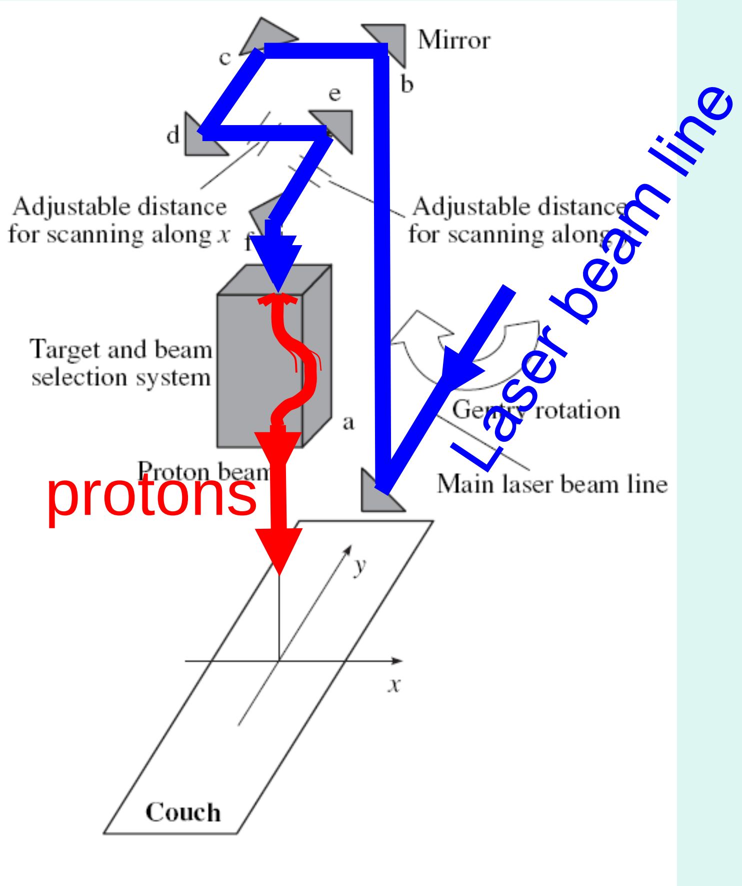
Laser light creates plasma and pushes electrons out

Electric field from electrons pulls protons out of foil

now used:
6×10^{17} W/mm^2

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





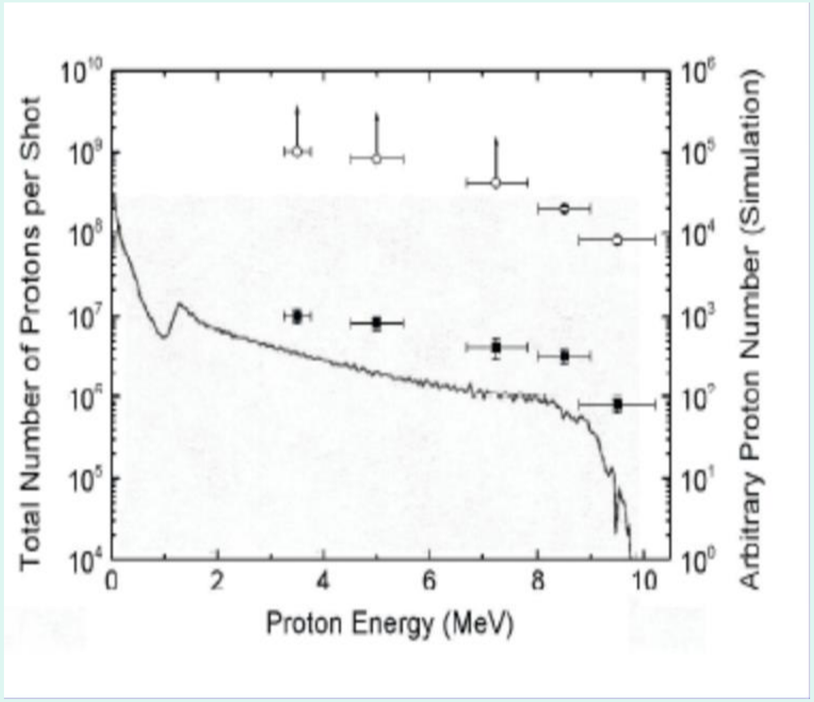
Laser beam line

protons

But 100x more power is needed

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

Laser driven proton accelerator



V. Malka et. al., Med. Phys. 31 (2004) 1587

U. Linz and J. Alonso,
Phys. Rev. ST Accel. Beams 10, (2007)094801

Disadvantages at the moment:

— Continuous energy spectrum

— Only 10-20 MeV reached

— Not enough protons

— Neutrons

— Pulsed beam (target; laser)

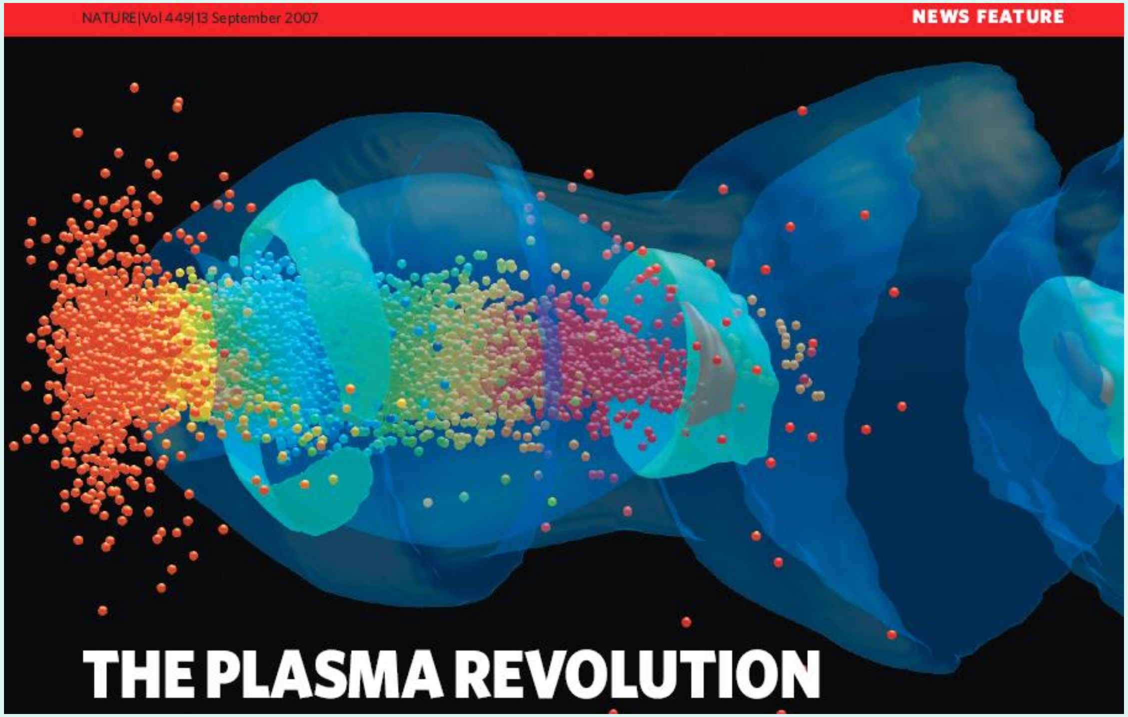
— Low duty cycle (0.1-10 min)

→ Still Needed:

- Power increase of **factor 100**
- Higher repetition rate
- Targets
- Optimize spectrum

Science fiction ?

Plasma wake field accelerator



NATURE|Vol 449|13 September 2007

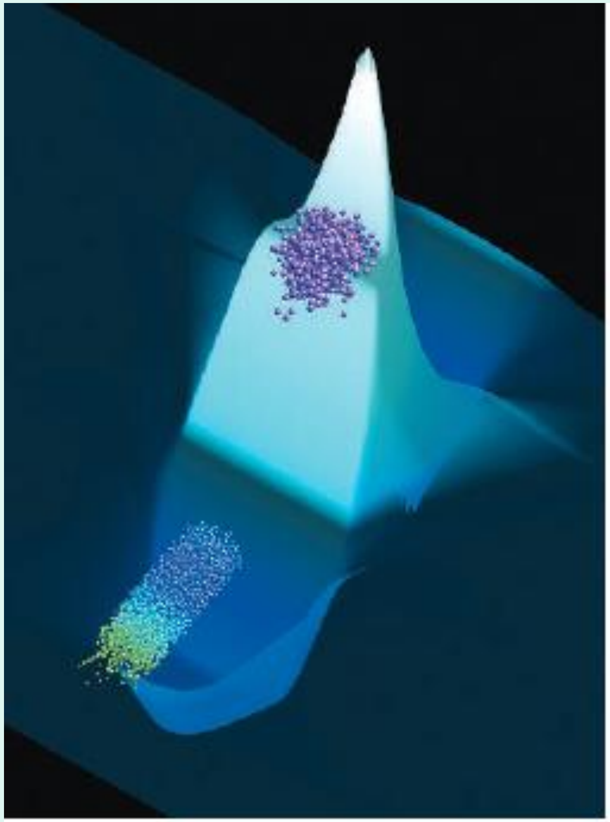
NEWS FEATURE

THE PLASMA REVOLUTION

(electron) energy doubler

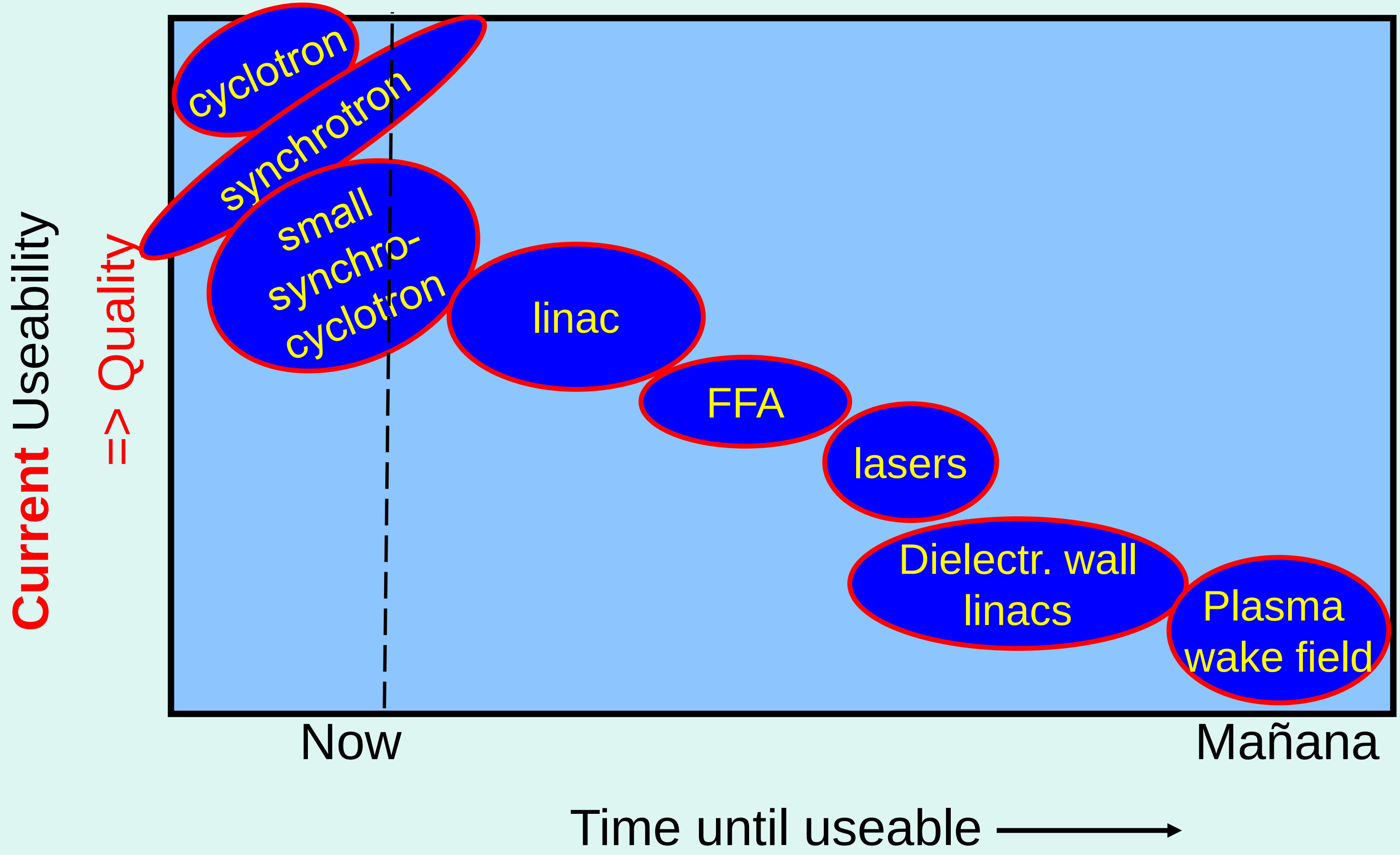
Blumenfeld, et al. Nature 445, 741–744 (2007).

N. Patel, Nature 449 133-135 (2007)



Particles can surf along giant plasma waves.

Accelerator status (protons)



“cheap” systems

What are the compromises ?

Do they have **at least the same quality** as current p-therapy ?

Realistic developments

- Small cyclotron / synchrotron
- Fast energy change in synchrotron
- Linacs (fast E-change)
- Superconducting gantry:

→ Lower weight, C: + smaller diameter

→ New/Faster scanning methods

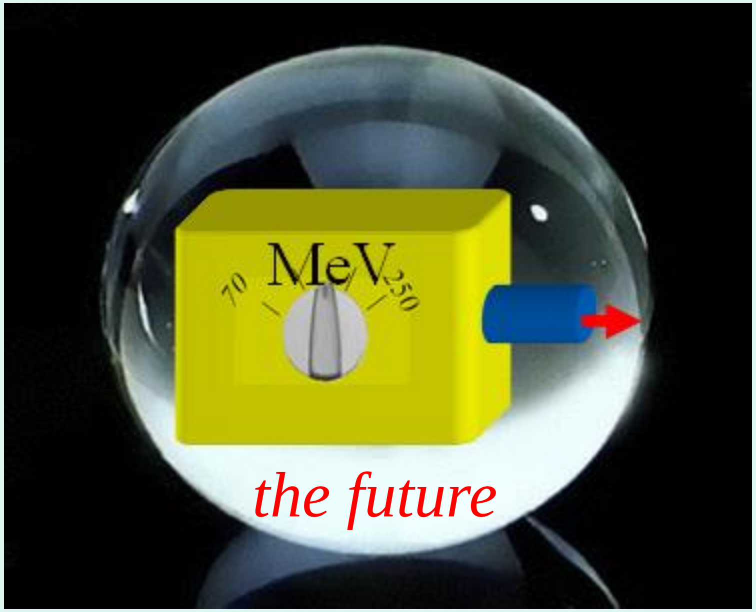
Currently most new ideas are quite interesting,
….but **too uncertain** to use in a clinic **soon**.

→ so….. there is still a lot of interesting work!

what is in the glass sphere?

The future may look unclear....

But there are many interesting developments!



Thank You !