Transport and energy setting of particle beams

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….just bring the beam to the patient…

- Stability of position, size, transmission
- Reproducibility of position, size, transmission
- Efficient beam transport; not too many, **but known,** losses

- Energy selection system
- Dispersion free (=energy independent) beam transport

- Unique on-line verifications of essential parameters
- Fast reaction: low switching time

- Apply the right dose at correct position

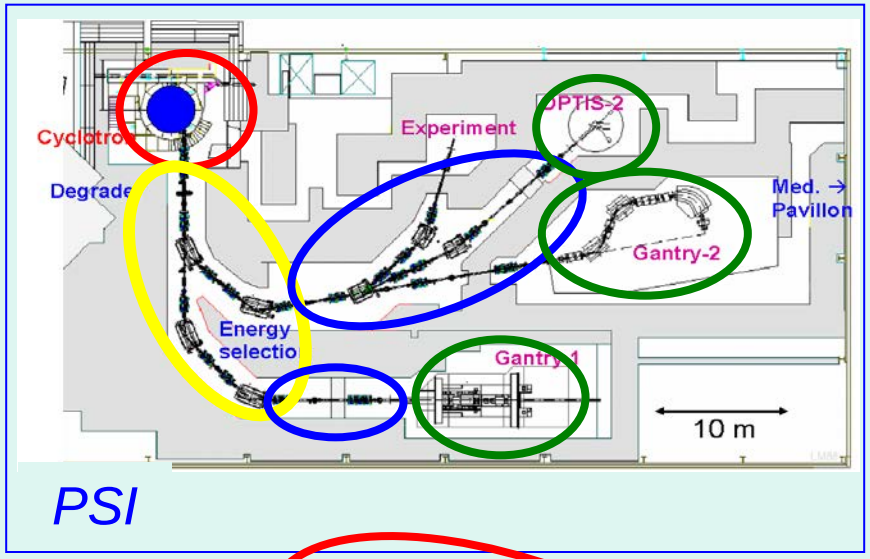
Modules in hadron therapy facilities

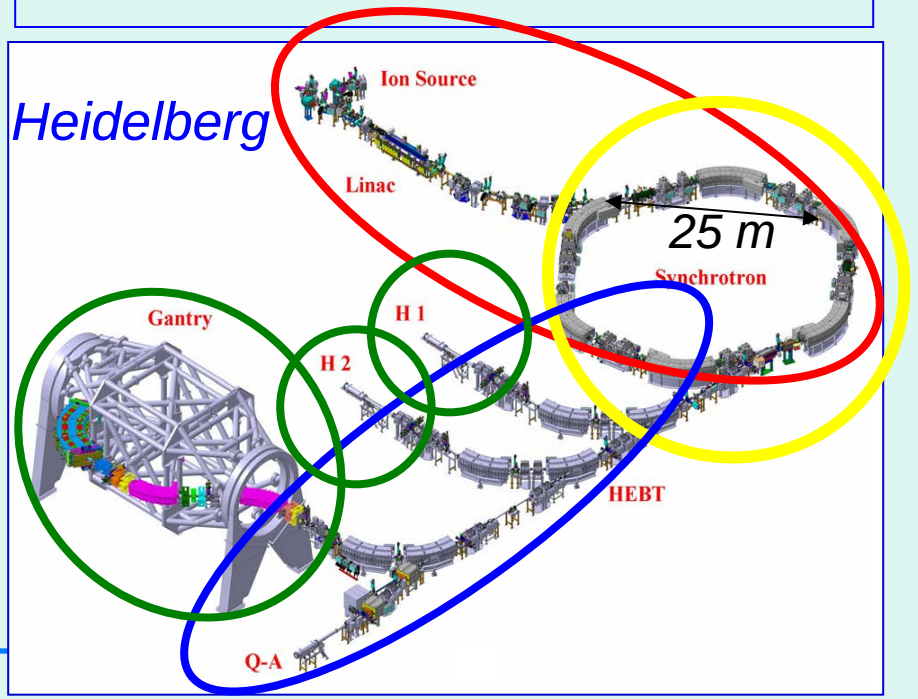
accelerator

energy selection

beam transport

gantry / fixed hor. line





Control systems:

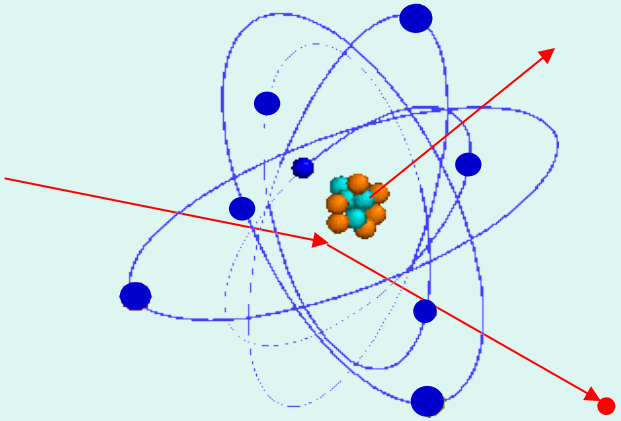
- accelerator + beam transport
- treatment delivery + verification
- Interlock + safety systems

Contents of lecture

- Processes in dose delivery
- Beam transport
- Beam energy
- Gantries and scanning

Scattering

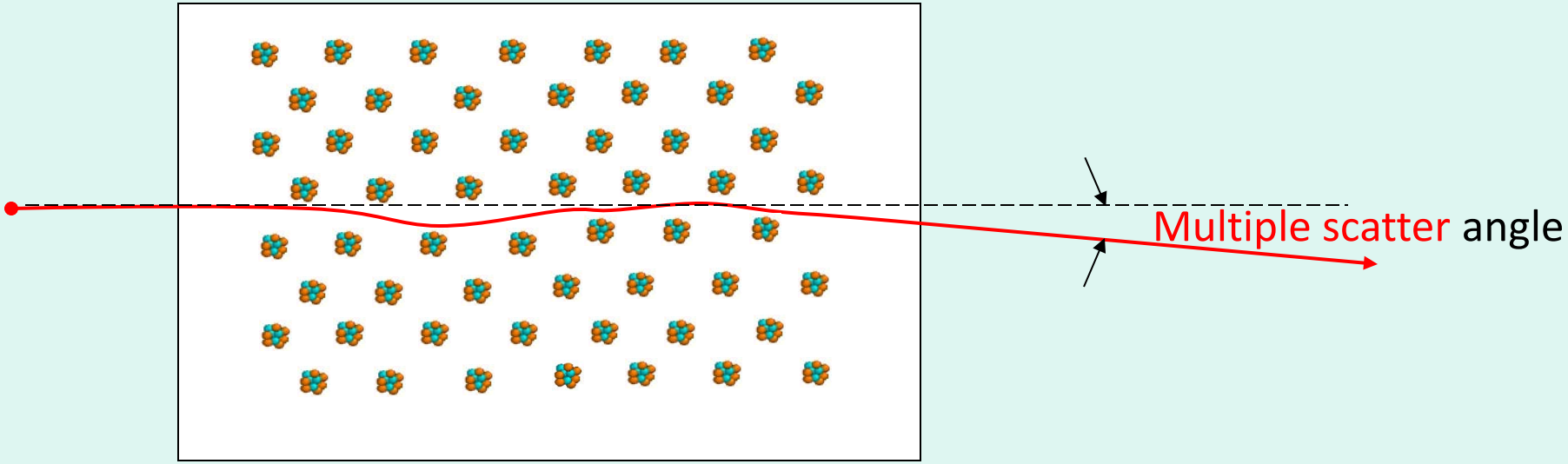
Nuclear Coulomb scattering



Nucleus is several times heavier as a proton

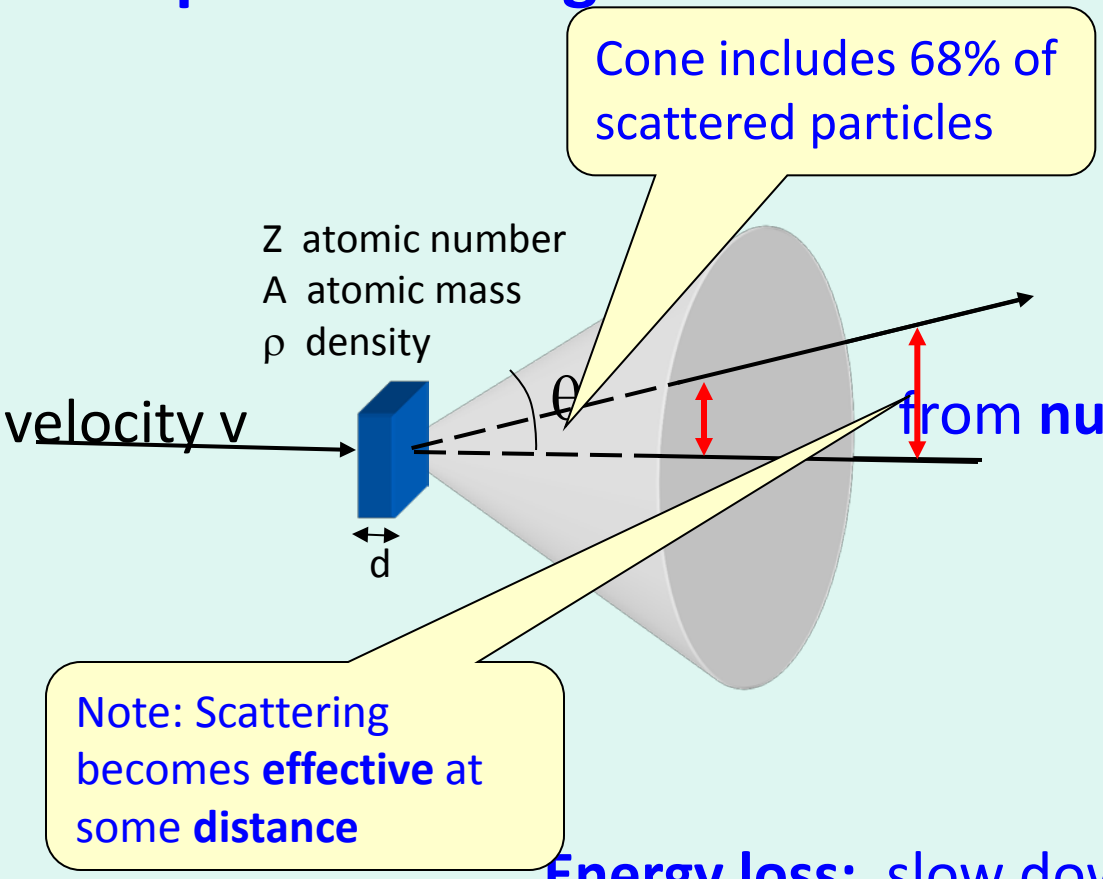
→ Almost no energy loss („elastic“)

→ Much larger deflection than from electrons



Scattering

Multiple Scattering



$$\theta \sim \frac{\sqrt{d}}{v^2}\frac{Z}{\sqrt{A}}$$

$$\Delta E \sim d\frac{\rho}{v^2}\frac{Z}{A}$$

Energy loss: slow down by **electrons.**

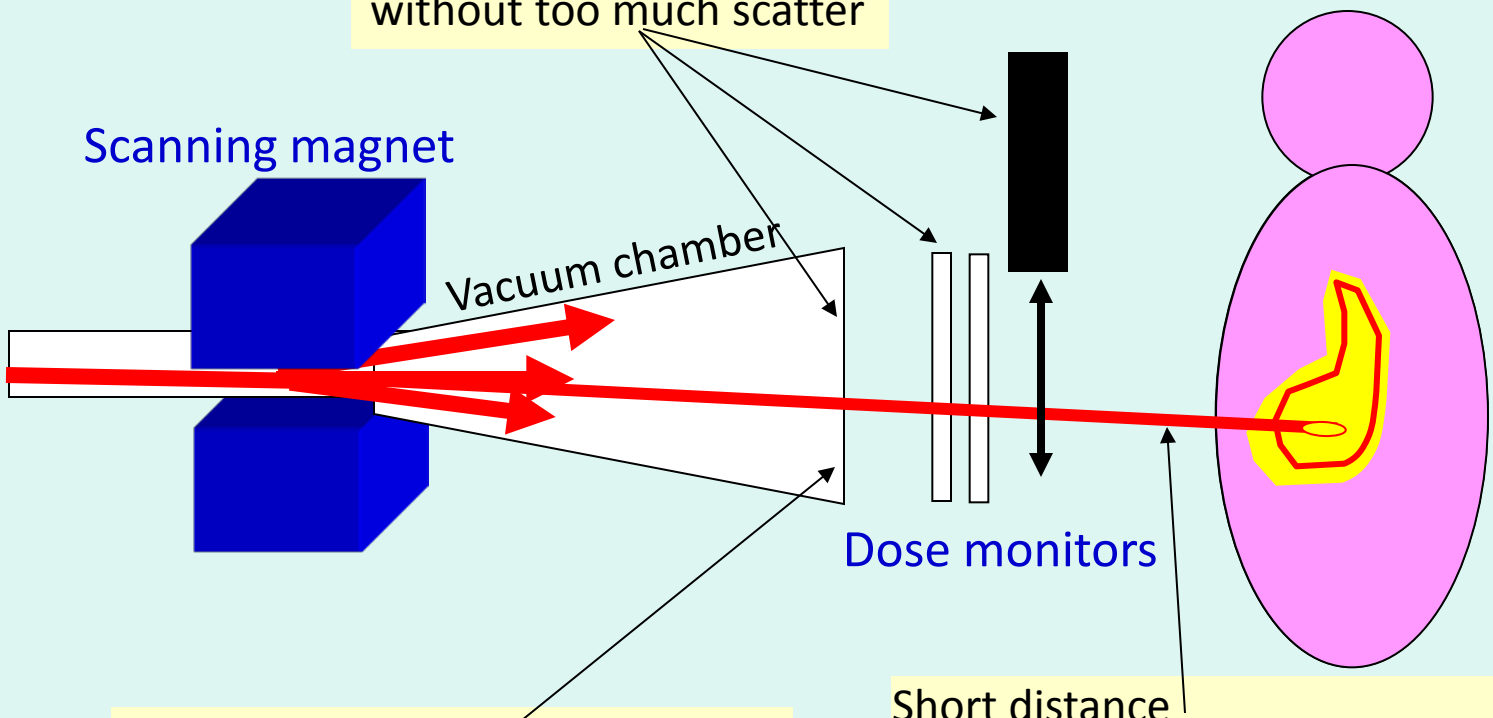
Scattering vs Energy loss

	Energy loss $\frac{dE}{dx} \sim \frac{Z}{A}$	Scattering $\theta \sim \frac{Z}{\sqrt{A}}$
(Z ; A)		
Water (8 ; 16)	0.5	2
Tungsten (74 ;184):	0.4	5.4

=> More scatter at heavy materials

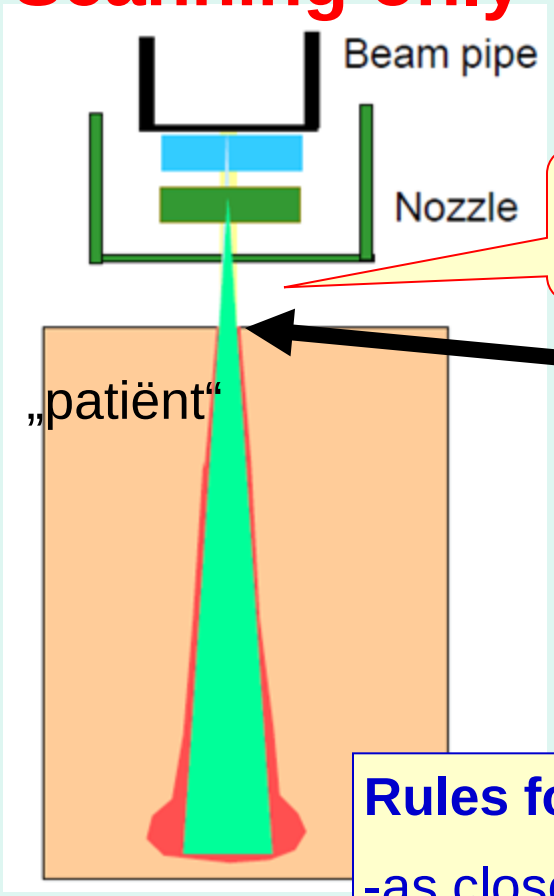
250 MeV p:	1 cm H_2O	1 mm W
Energy loss:	**ΔE= 4 MeV**	**4 MeV**
Scattering angle:	**θ = 5 mrad**	**16 mrad**

Nozzle for a scanning beam

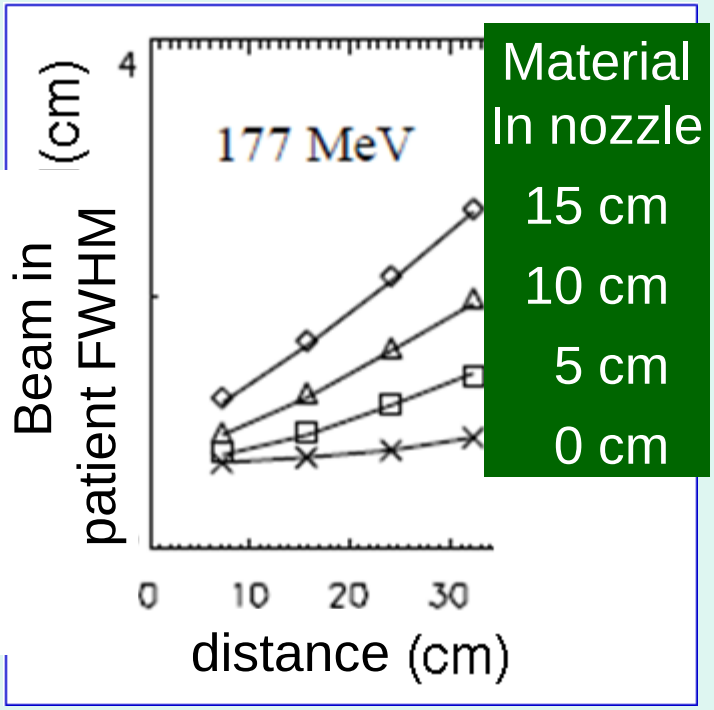


Nozzle design

Scanning only



distance between nozzle and patient



Rules for material in the beam (compensator, monitor…):

-as close as possible to the patient → Small distances

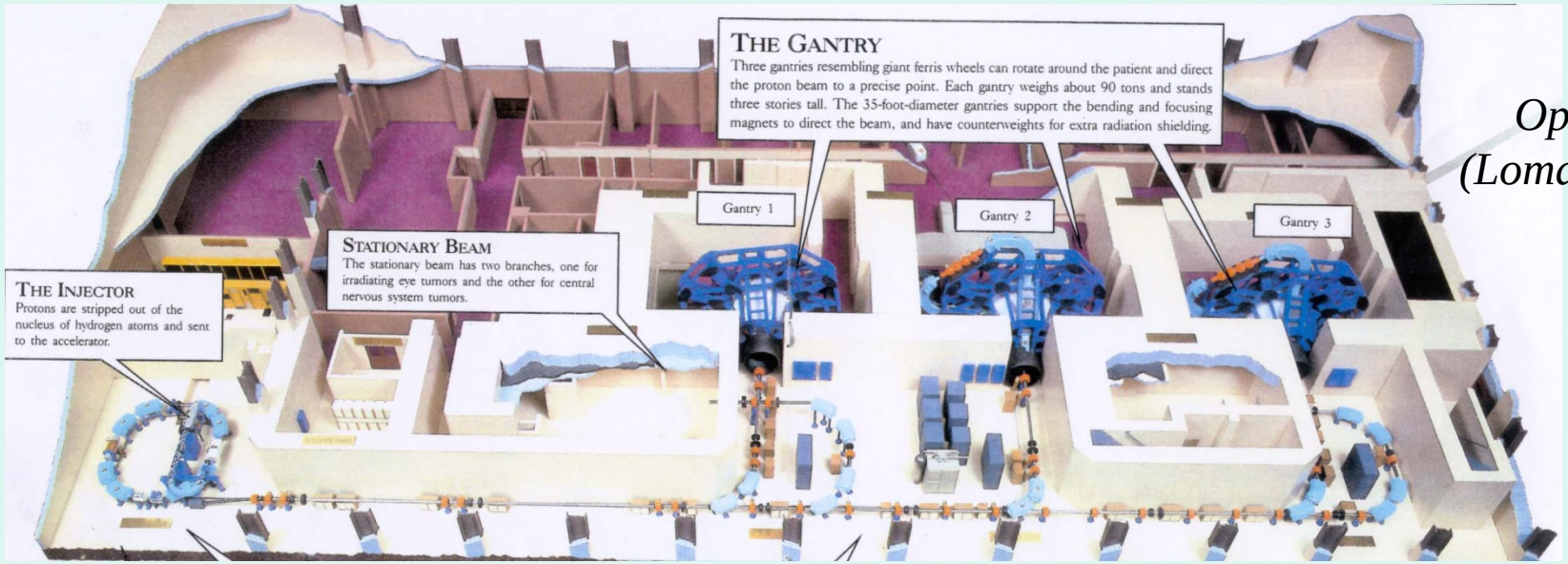
-Or very far up stream → Clean up and losses

-Intermediate solution: → Worst option

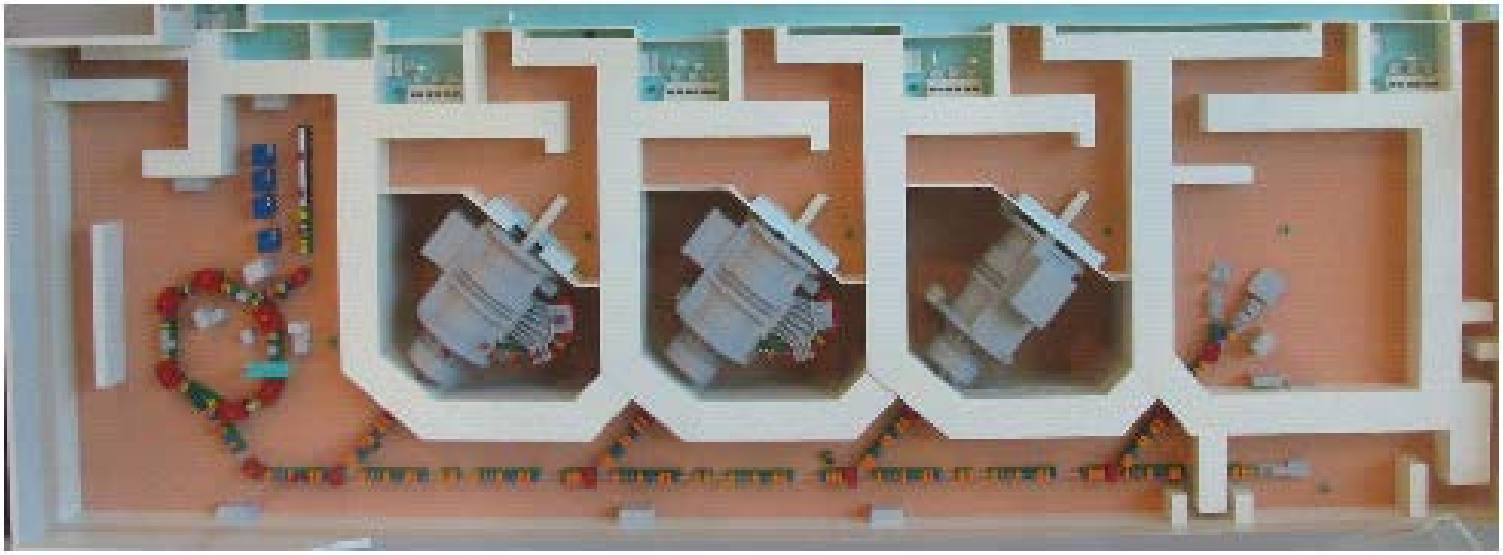
Figuren: Eros Pedroni, PSI

Beam Transport

Layout of proton-synchrotron facilities

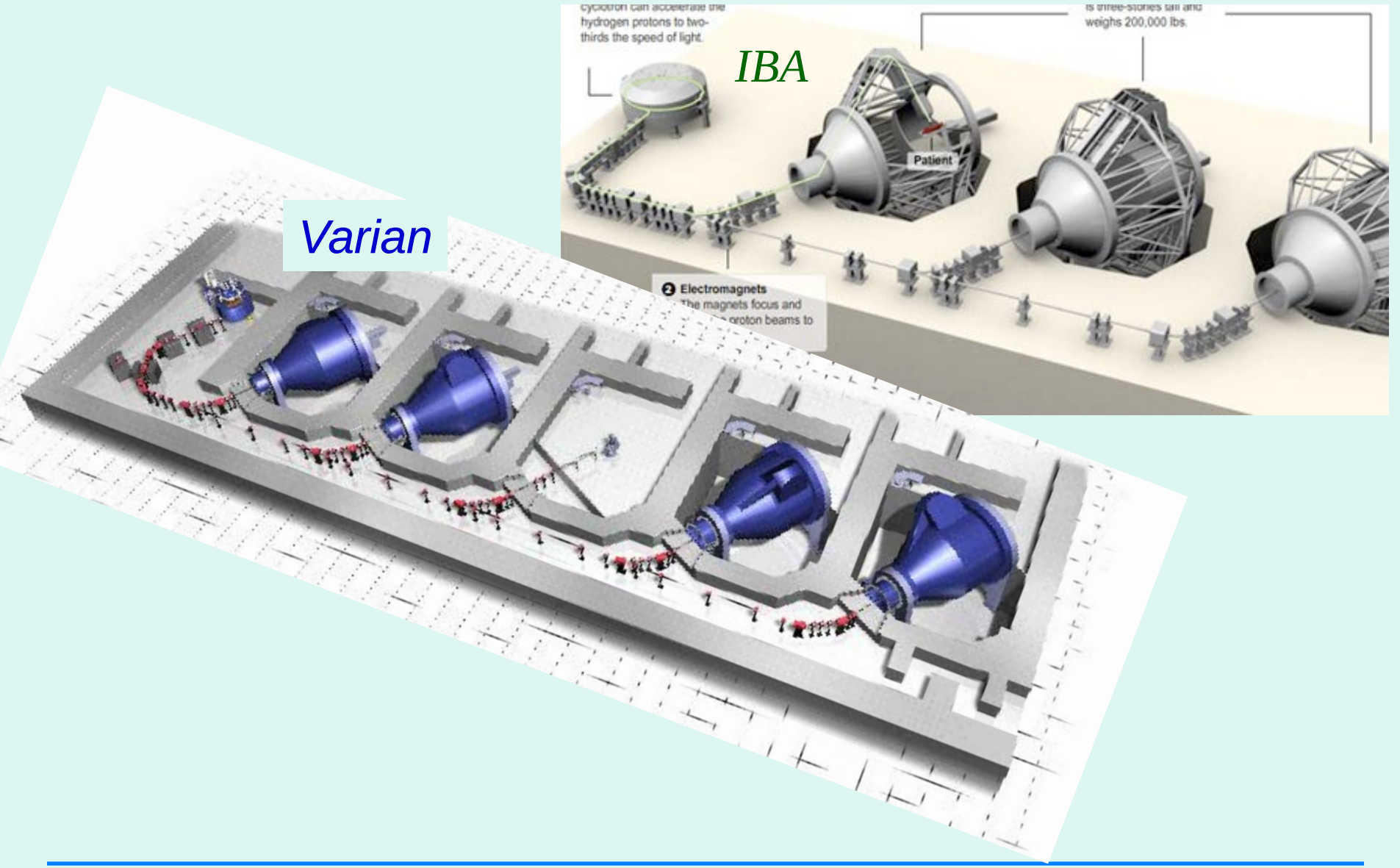


Optivus (Loma Linda)

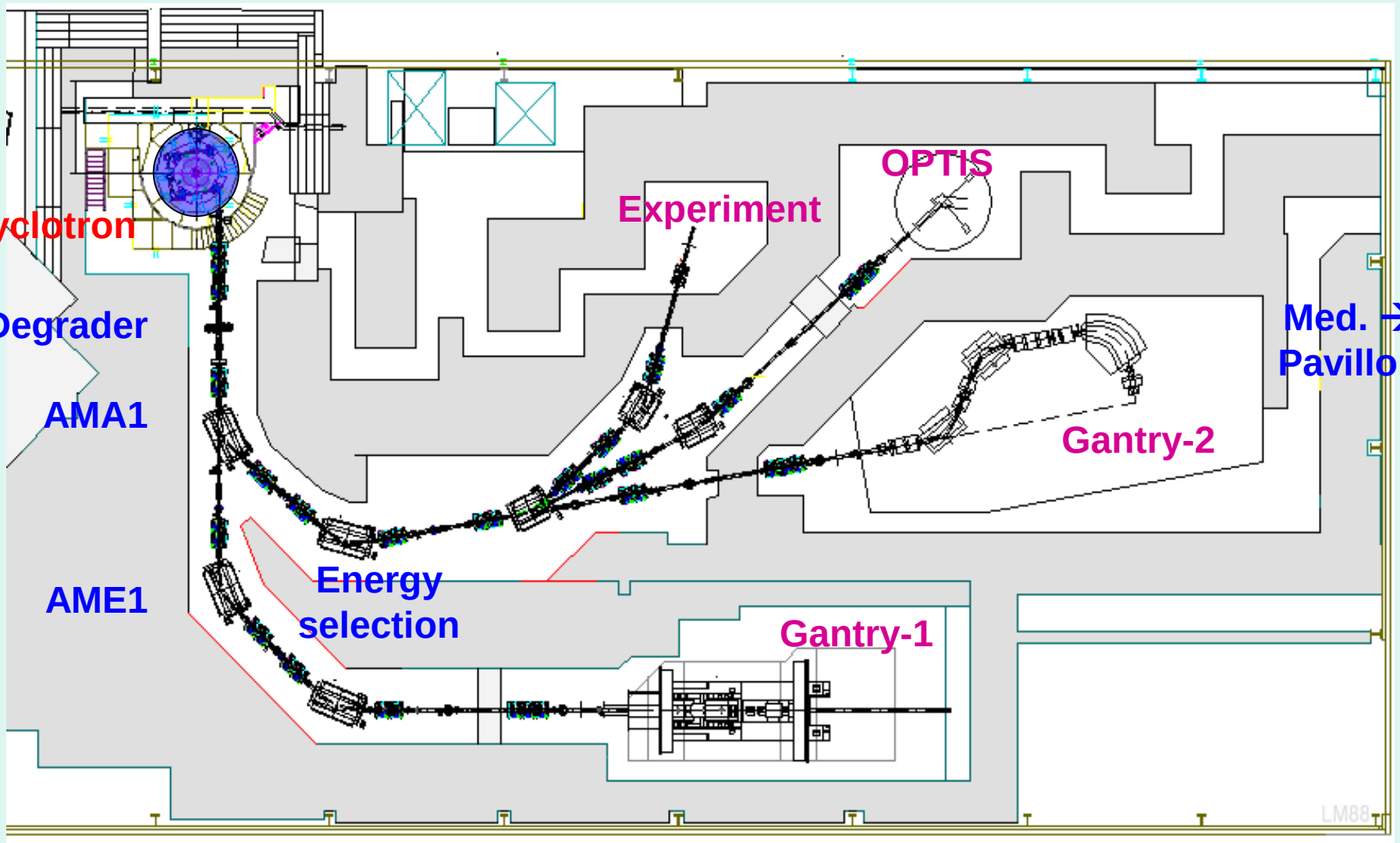


Hitachi (Houston)

Layout of cyclotron facilities

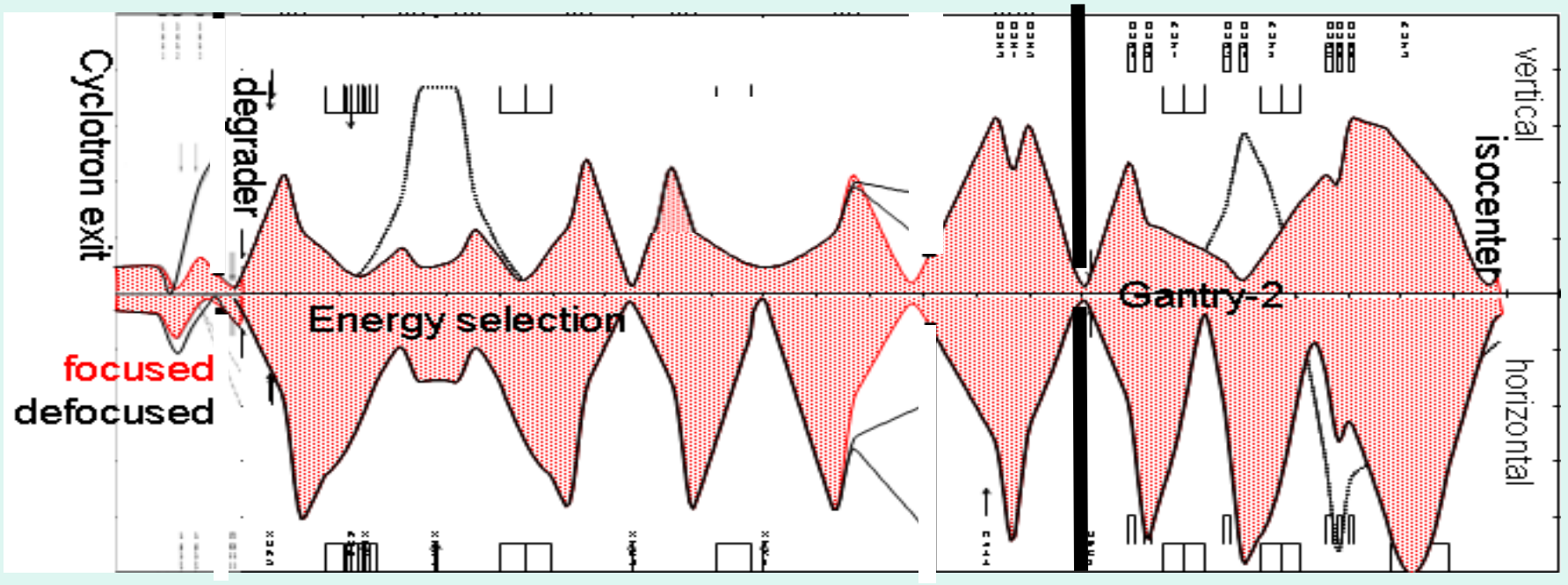


Layout of cyclotron facilities



the PROSCAN facility, PSI

Optics of optimal beam transport

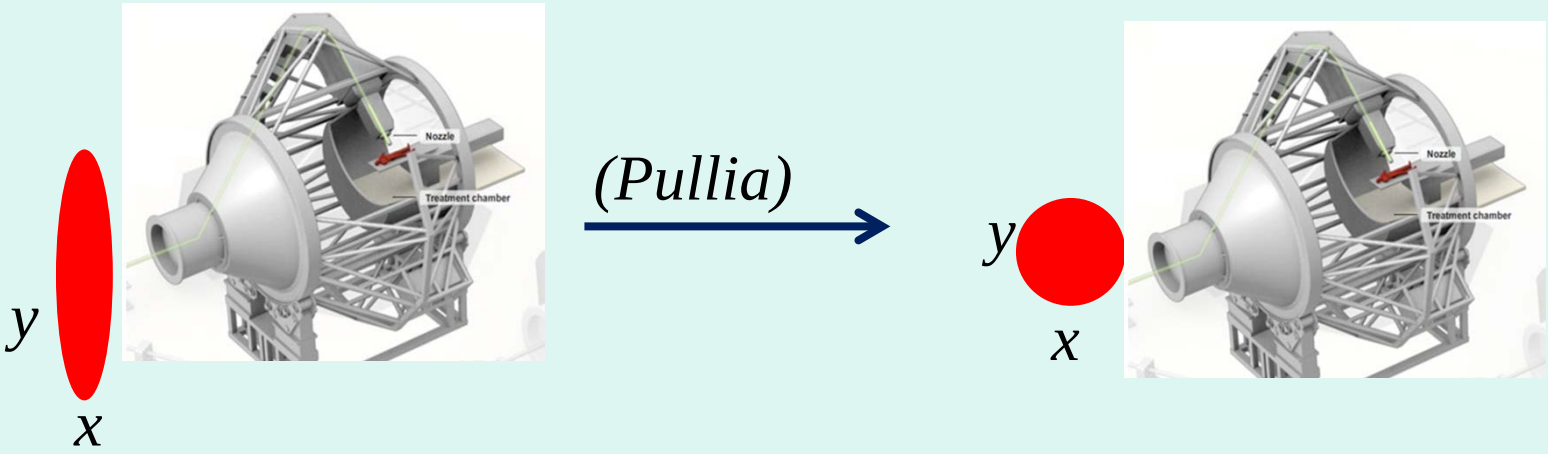


Robust optics:

- intermediate images
- separation of functions
- Matching to gantry

Matching to Gantry

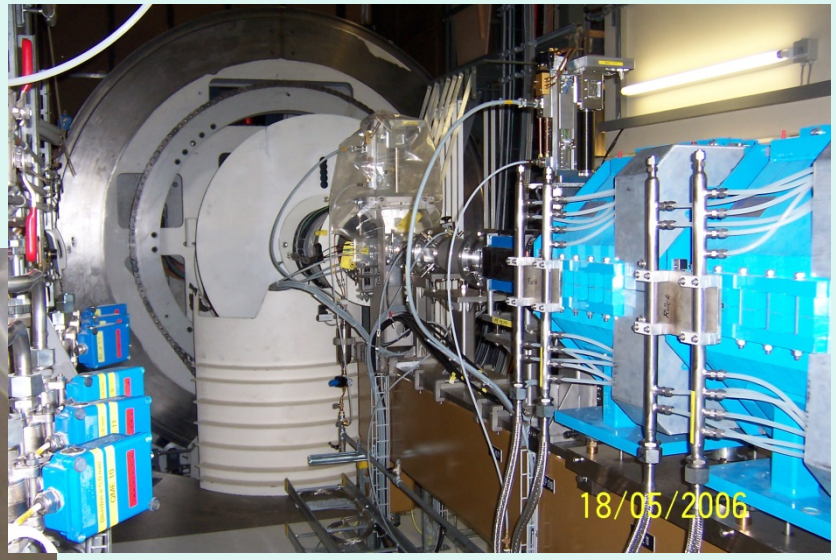
- Match the emittance

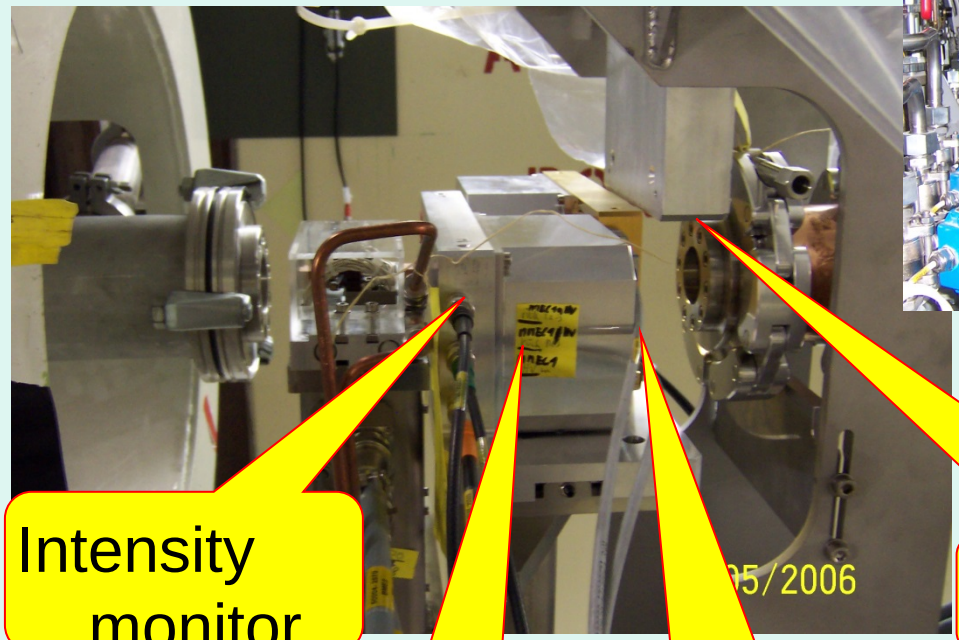


- Collimator at gantry coupling

Gantry connection=check point

measurements at Check point





Intensity monitor

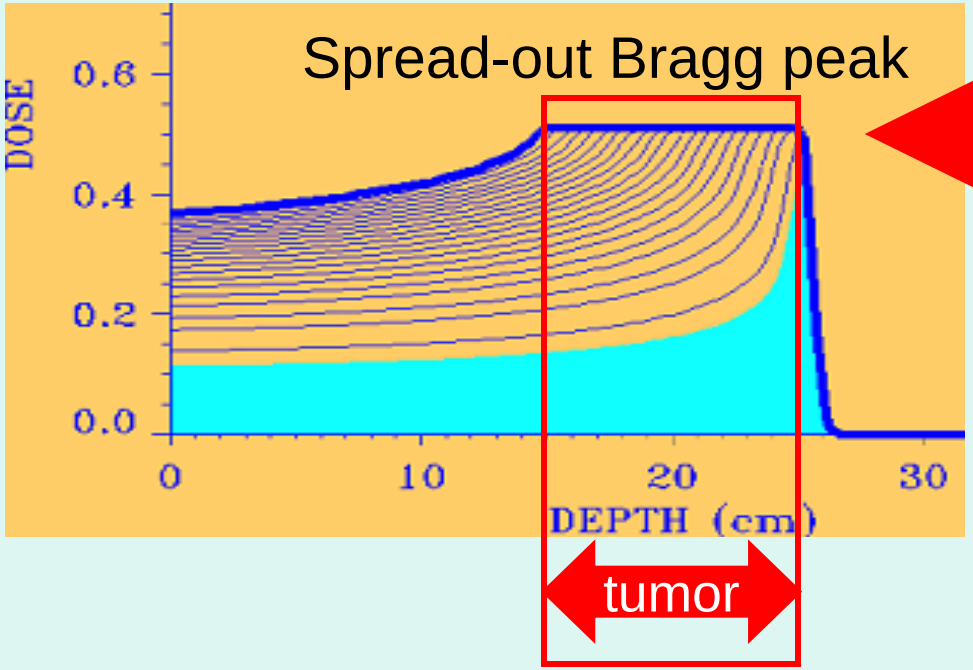
collimator

Halo monitor

Profile monitor

- Beam energy

Vary energy



Range

Tumor **distal edge**

→ Range

→ Maximum Energy

per field → „slow“ (sec)

Tumor **thickness**

→ spread-out Bragg peak

→ energy modulation

During trmt → „**fast**“ (<0.1 sec)

Methods:

1) at accelerator

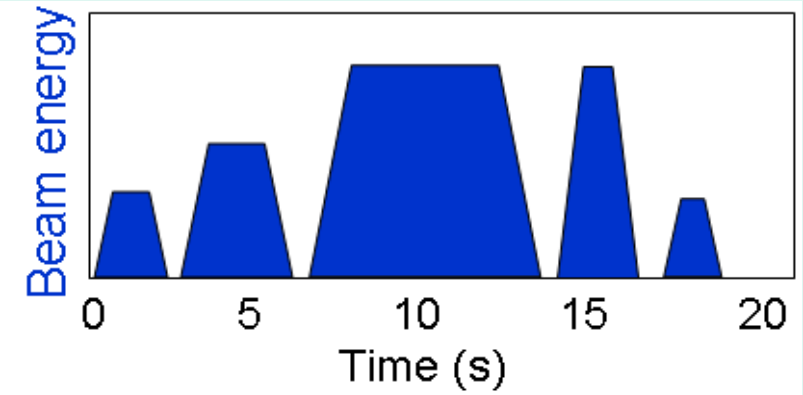
2) just before patient (in “nozzle”)

Vary energy

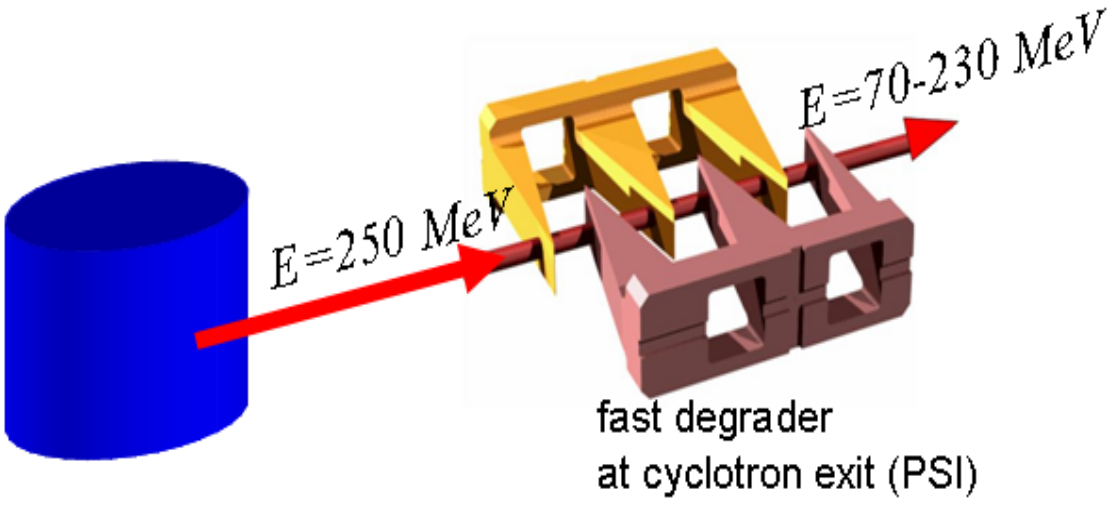
Vary energy at accelerator

Synchrotron: Set energy at each **spill:**

➔ Sets range only
➔ energy modulation in nozzle



Cyclotron has fixed energy => slow down (degrade) to desired energy

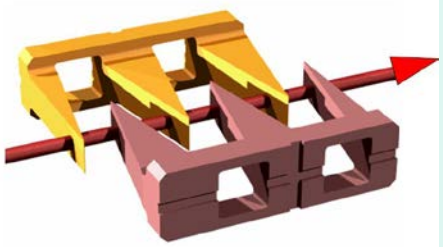


➔ Sets range

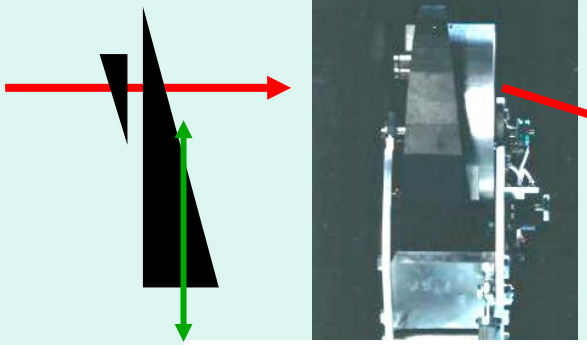
And, if fast enough
+ fast magnets:

➔ also energy modulation

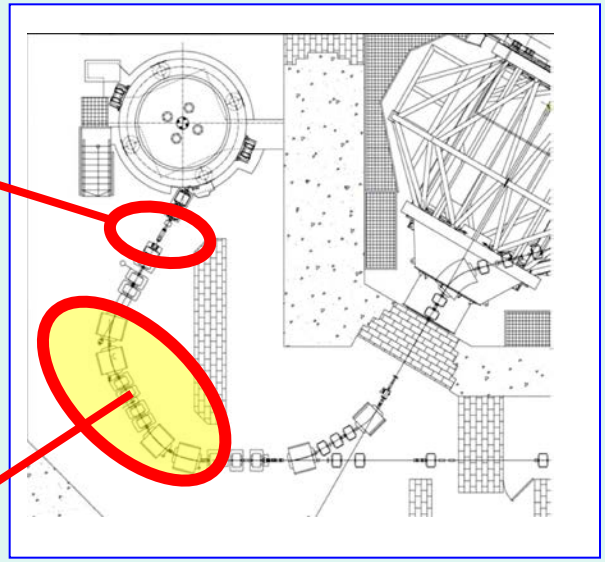
Energy selection system

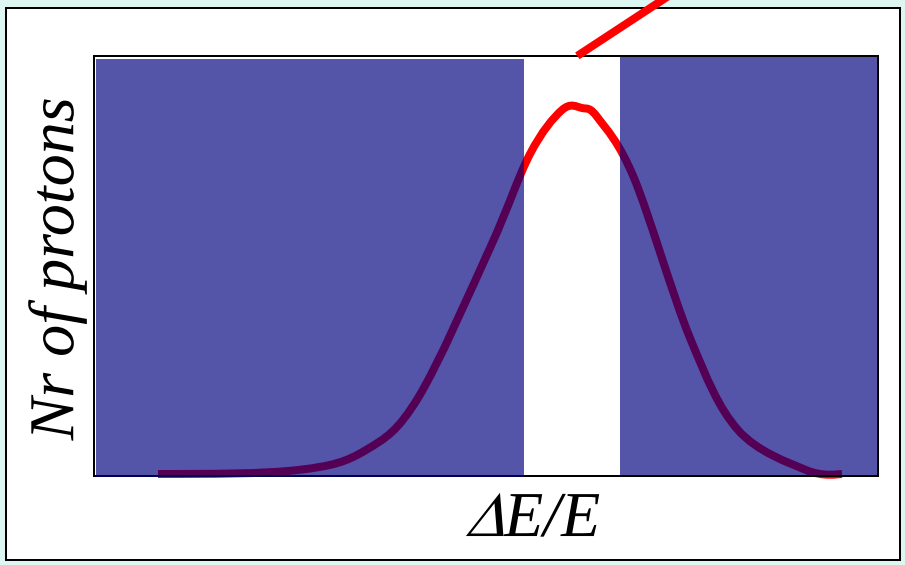


multi-wedge
235-67 MeV (PSI)



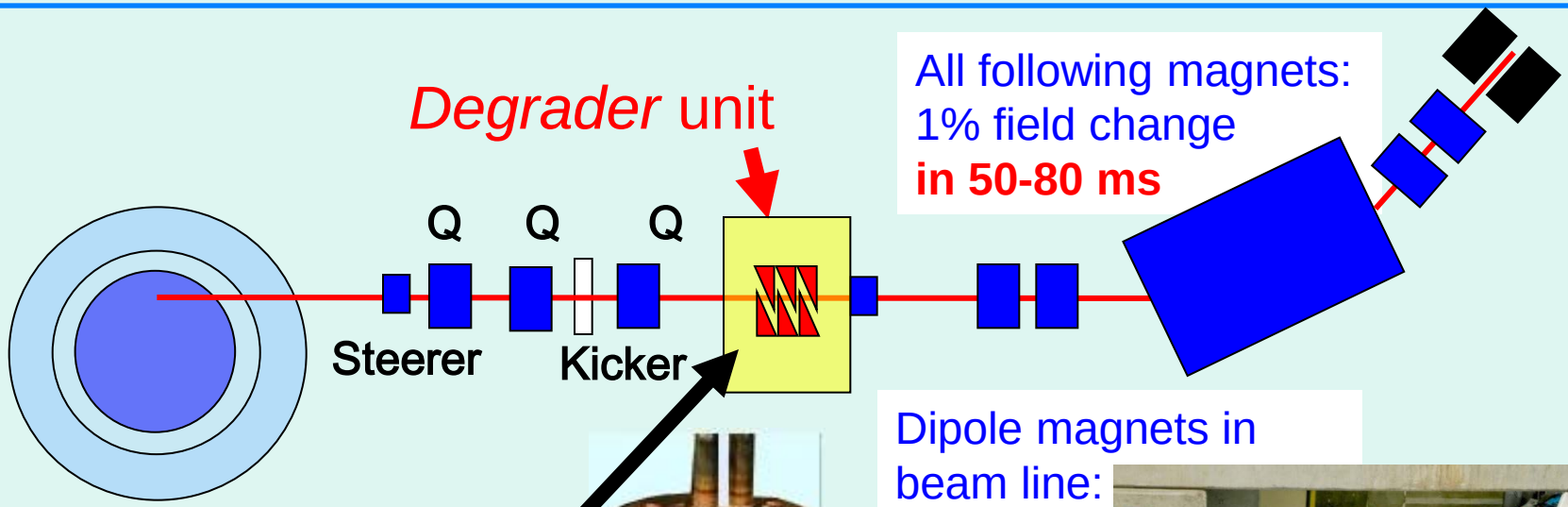
Rolled-up wedge
220-70 MeV **(IBA)**



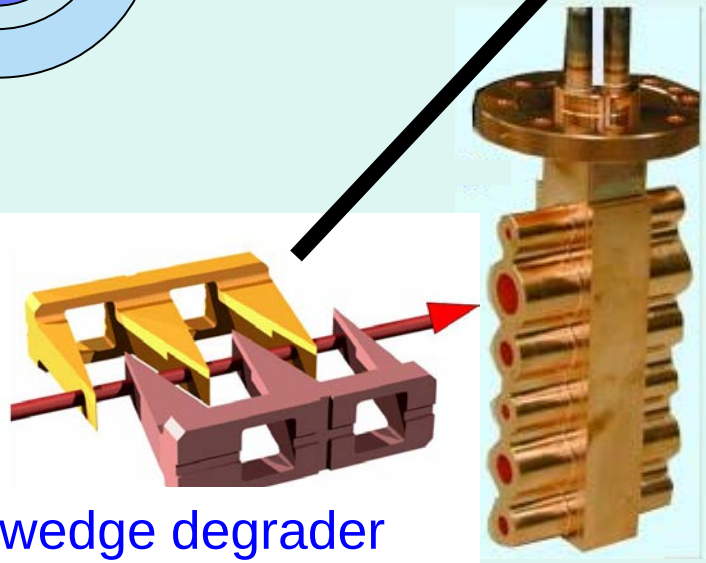


Beam analysis:
energy selection

Vary energy



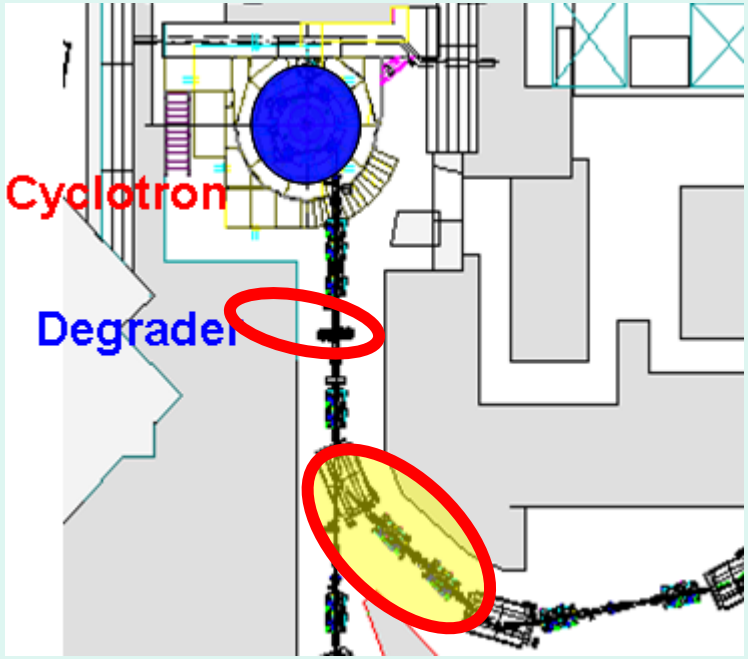
All following magnets:
1% field change
in 50-80 ms



Carbon wedge degrader
238-70 MeV
5 mm ΔRange in 50 ms

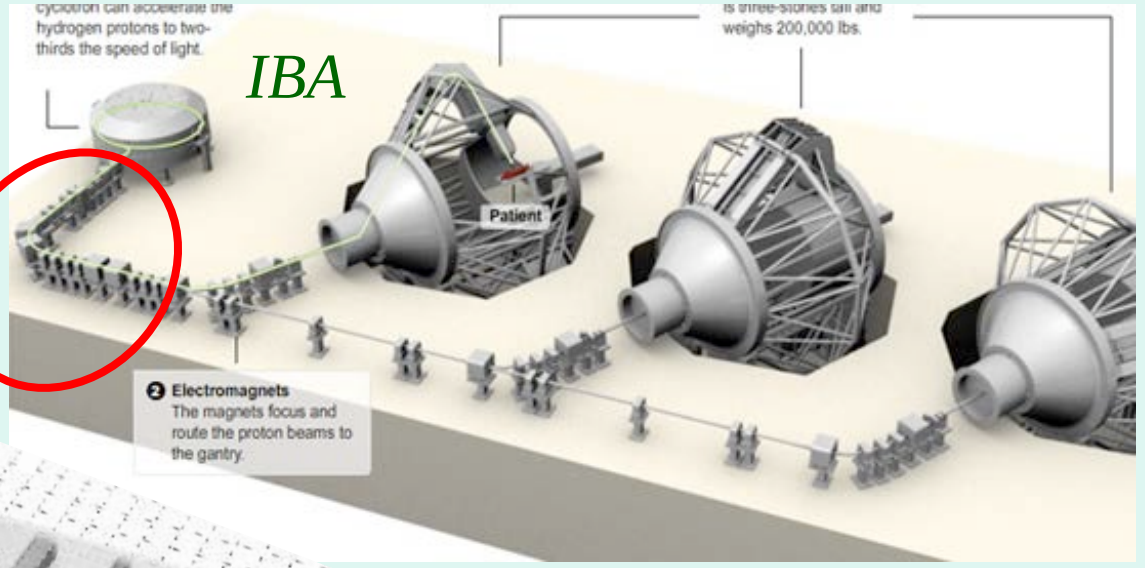
Dipole magnets in beam line:
1.1 T
190 A
100 A/s
(1-1.4 H)

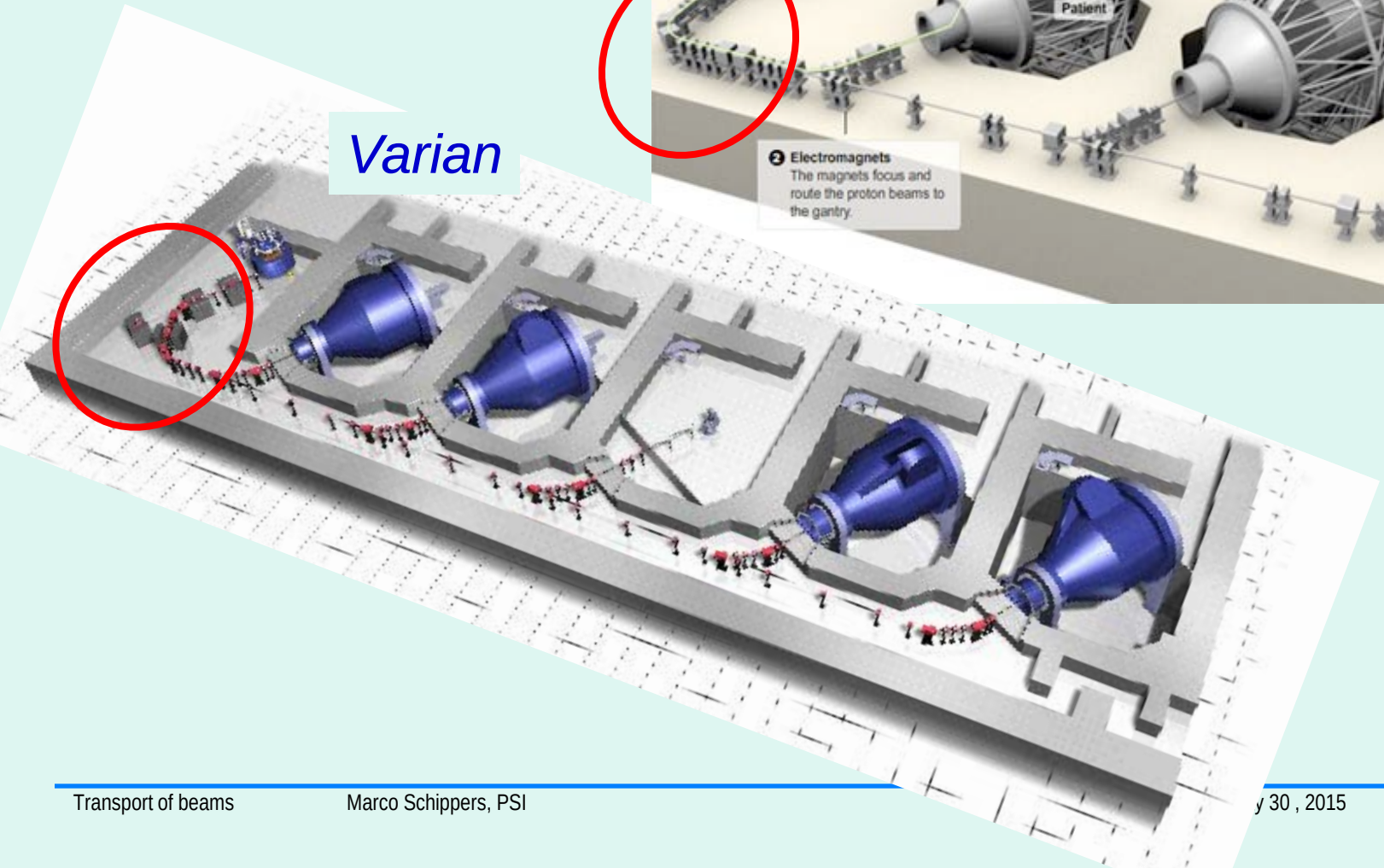
ESS: Energy selection system



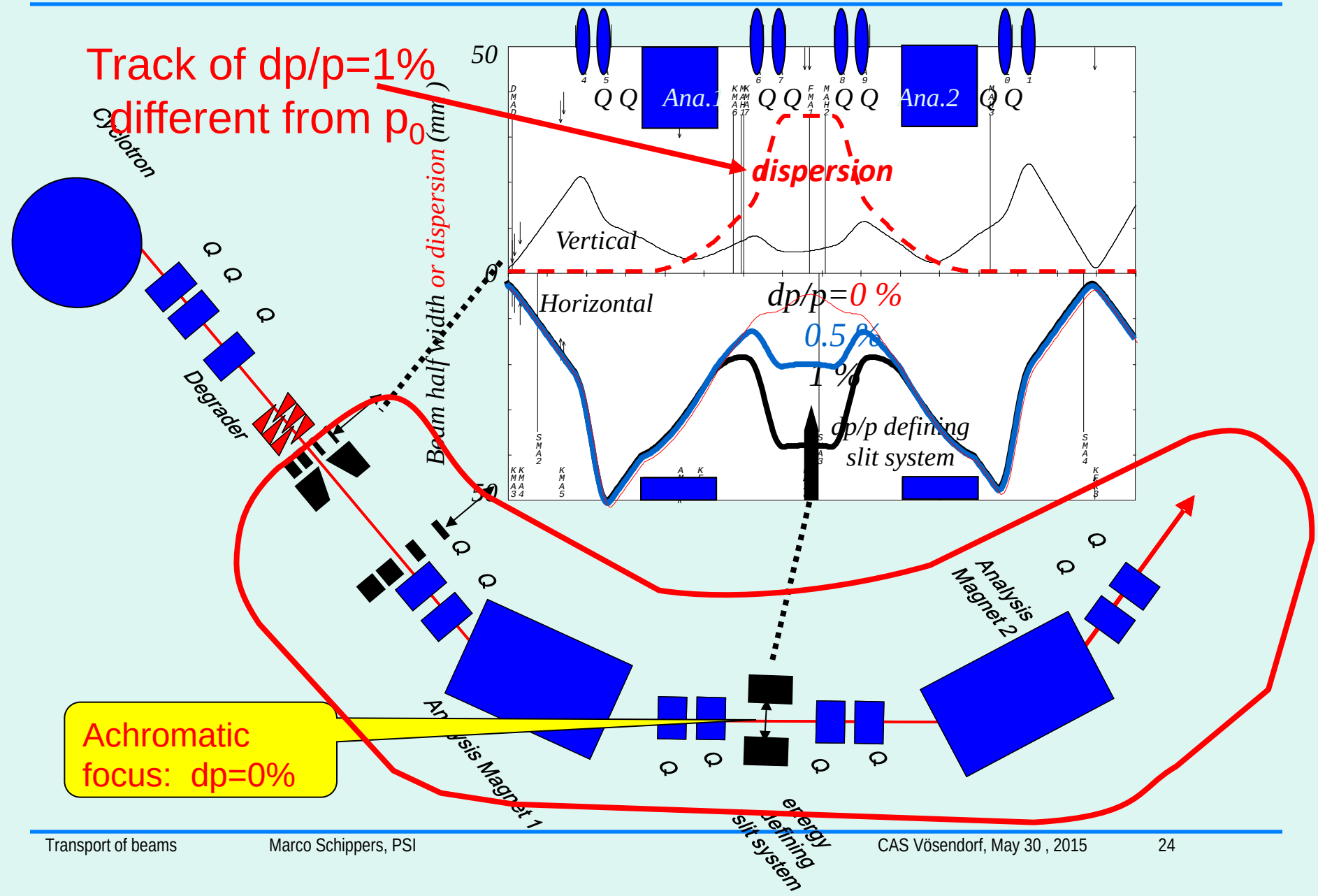
Beam analysis:
energy selection
dp/p < ± 1%
or: **dE/E< ± 2%**

ESS in cyclotron facilities

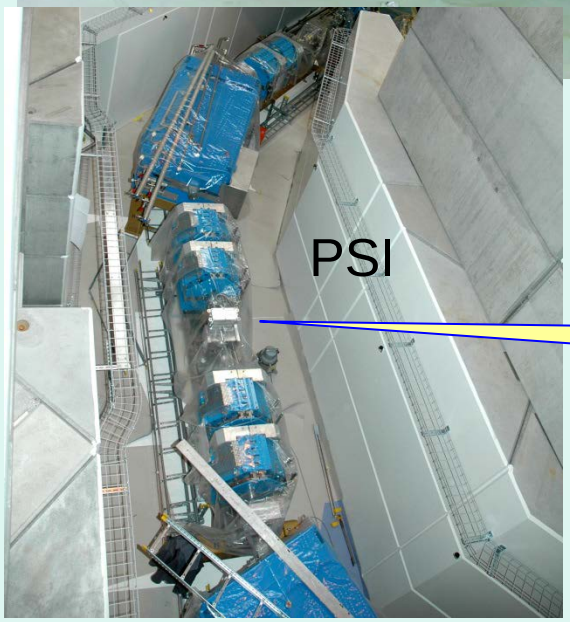




Energy selection system



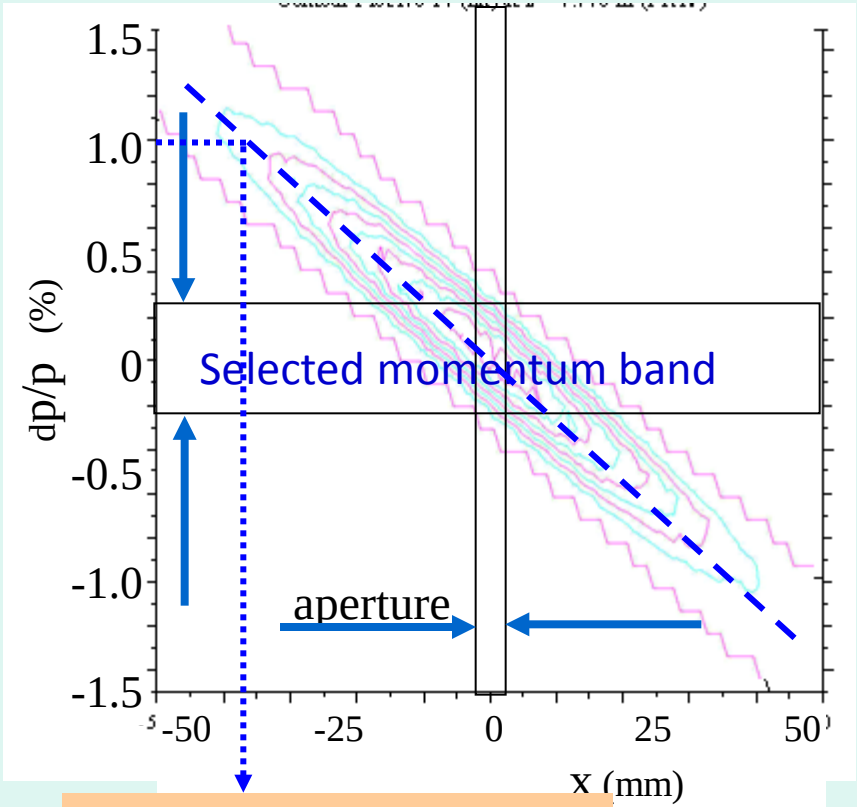
Energy selection system



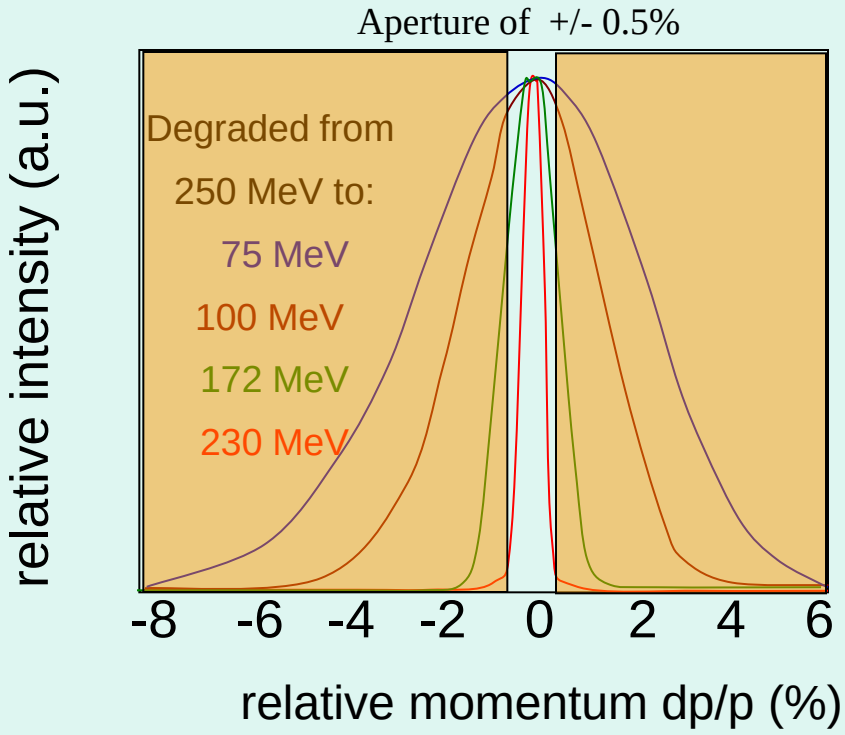
Energy selection slit at dispersive focus

Energy selection system

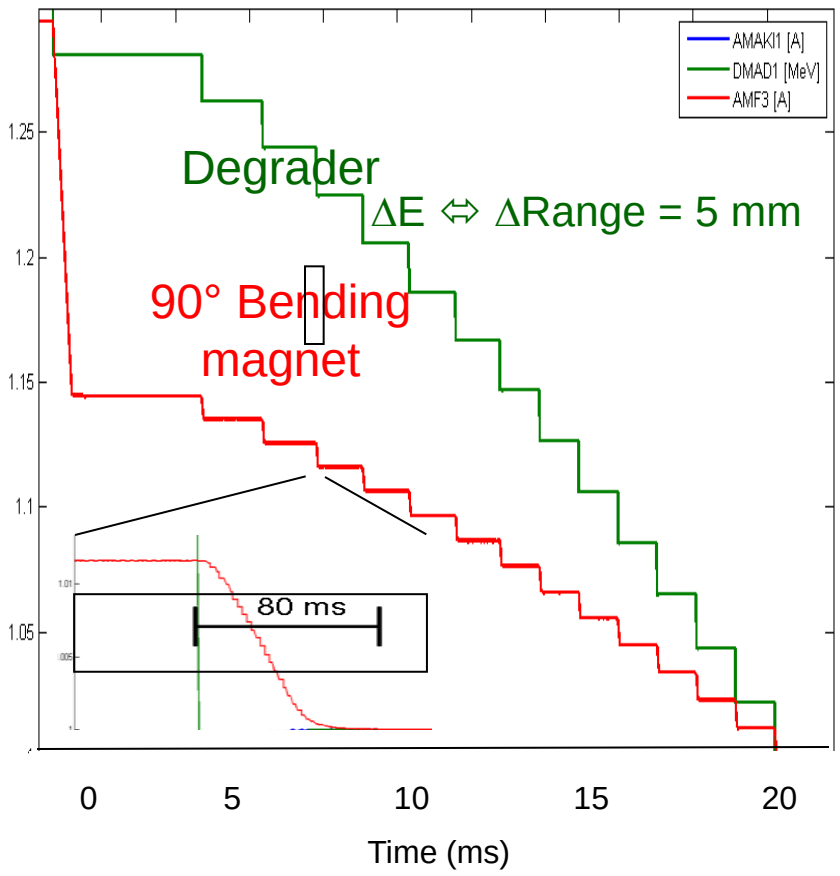
At dispersive focus: **strong correlation** between dp/p and hor. position
=> With **slits** an **energy selection** can be made

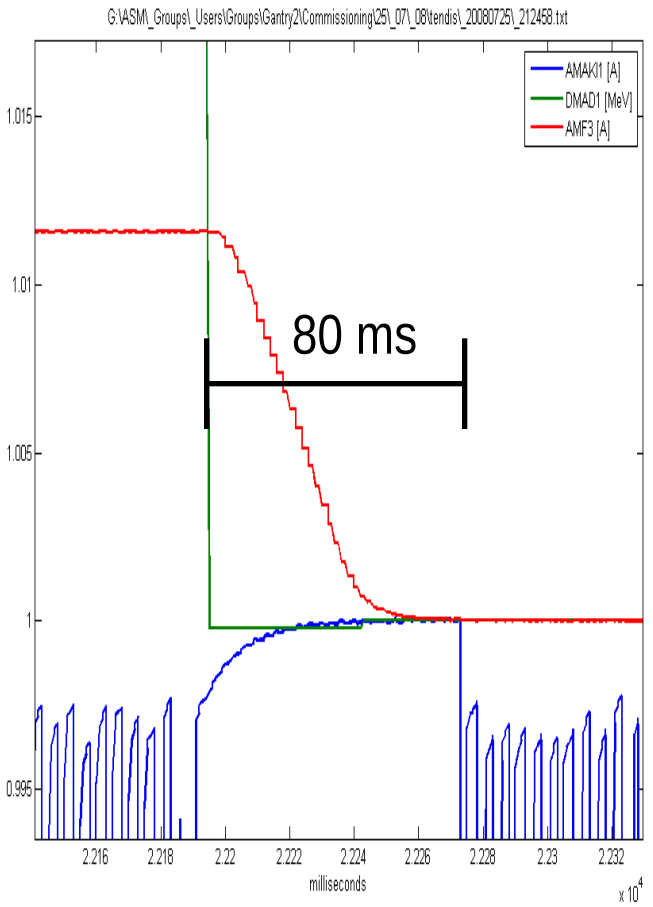


Dispersion =37 mm/%



Fast energy changes

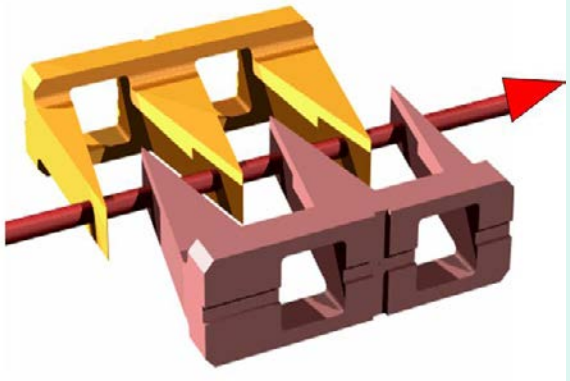




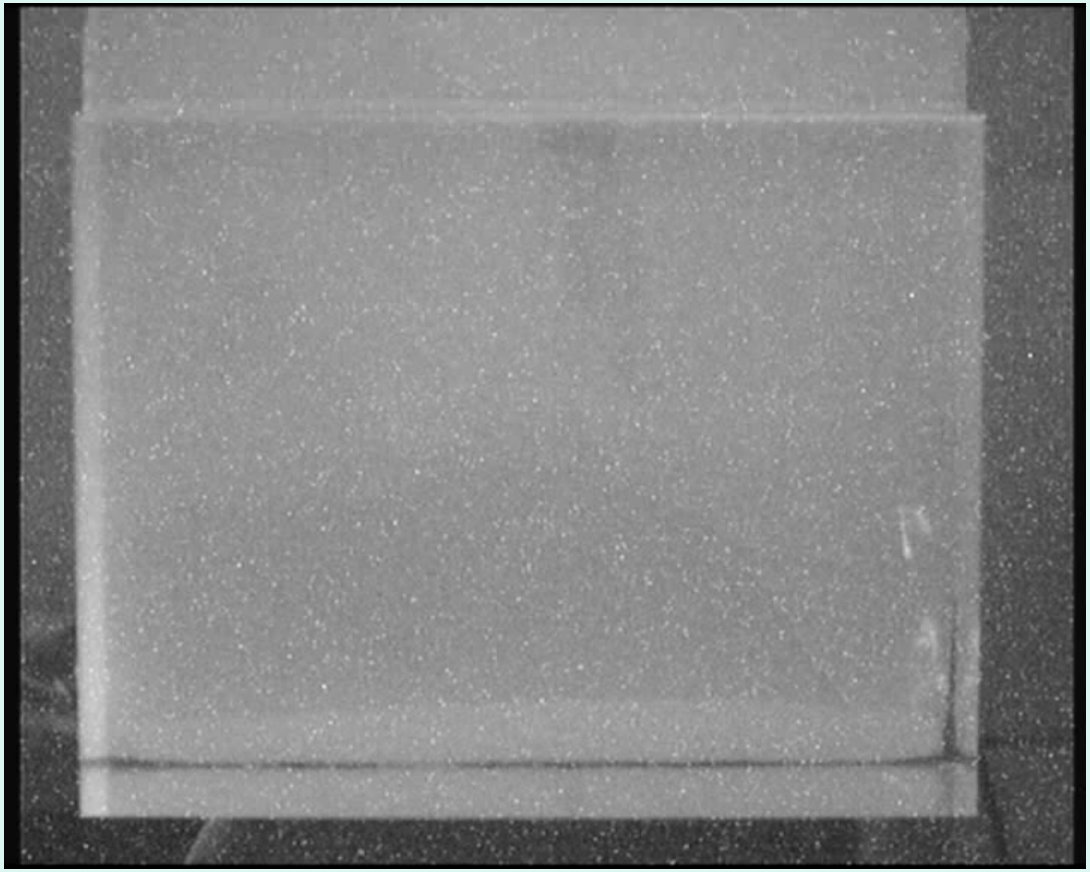
Fast energy adjustment

Fast change of penetration depth:

5 mm in 80-50 msec



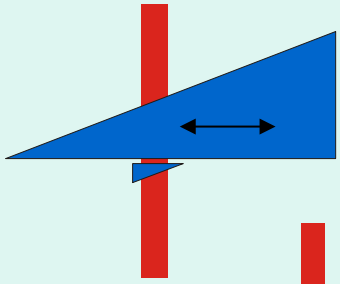
fast degrader (PSI)



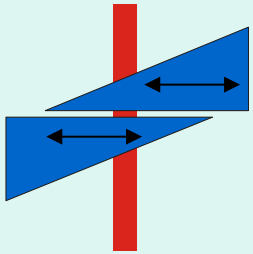
1 liter volume in **7 s** :
Target repainting:
15-30 scans / 2 min.

Degrader types

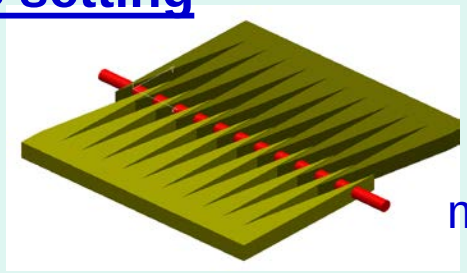
Continuous Range setting



single wedge

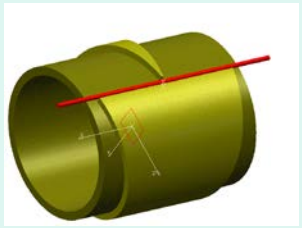


Dual wedge

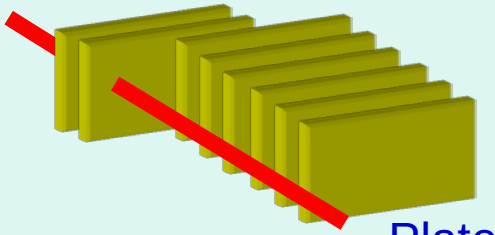


multi wedge

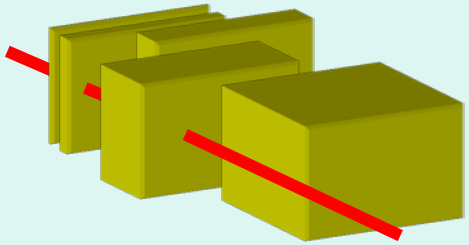
Discrete steps:



single wedge
rolled on a cylinder



Plates equal thickness



Plates with „binary“ thicknesses

Important specs:

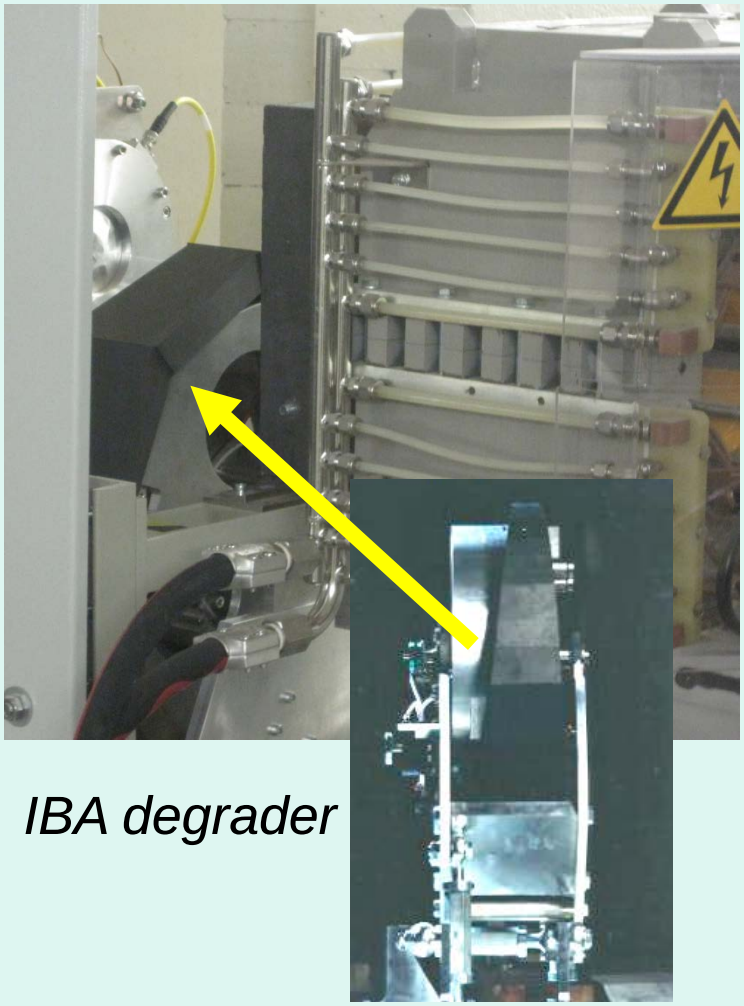
-accuracy: ΔR

-speed

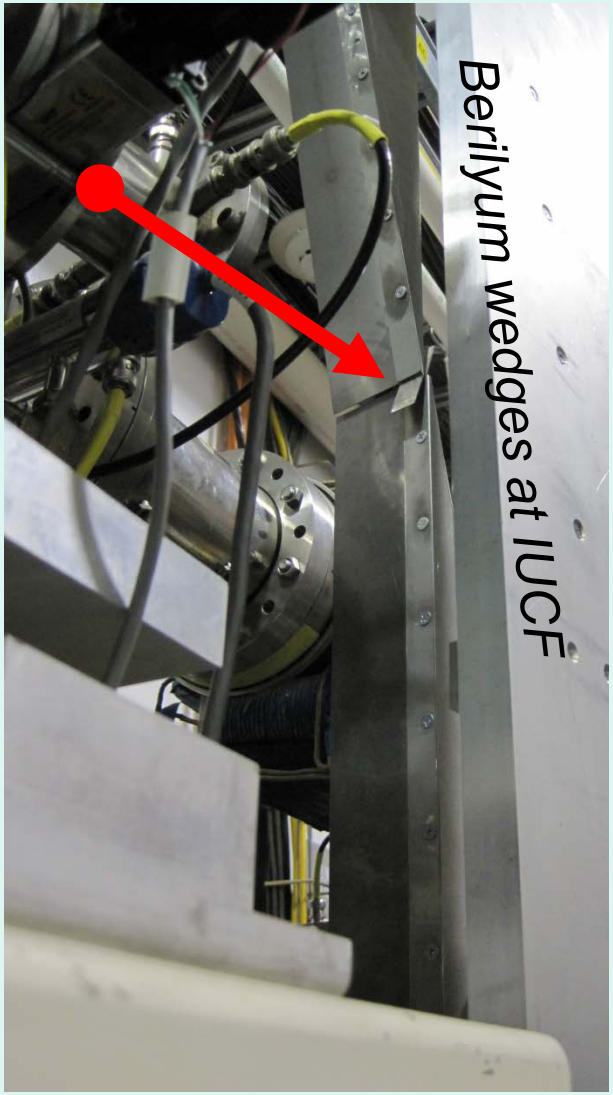
-step size

-distance to collimator

Degrader system of IBA and IUCF



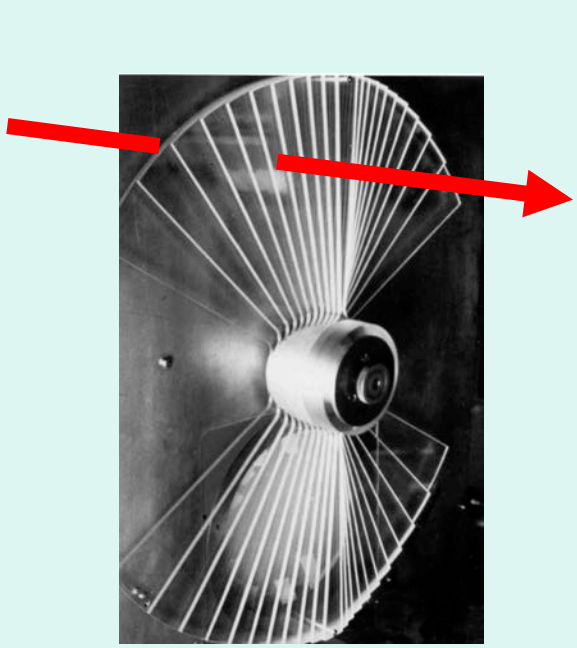
IBA degrader

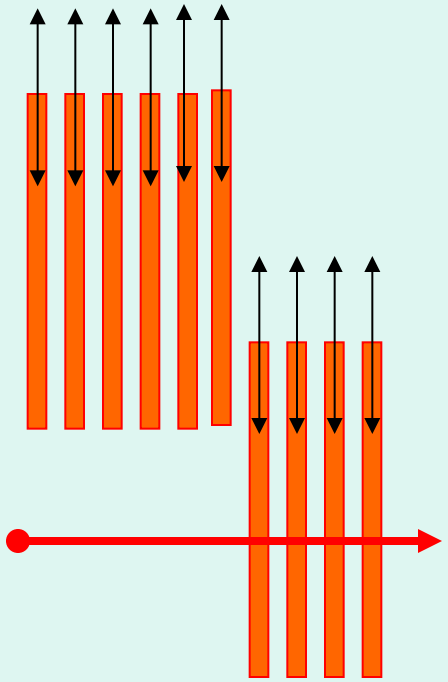


E-Modulation in nozzle

Vary energy in nozzle **(cyclotron and synchrotron)**

Energy modulation: rotating wheel or insertable plates

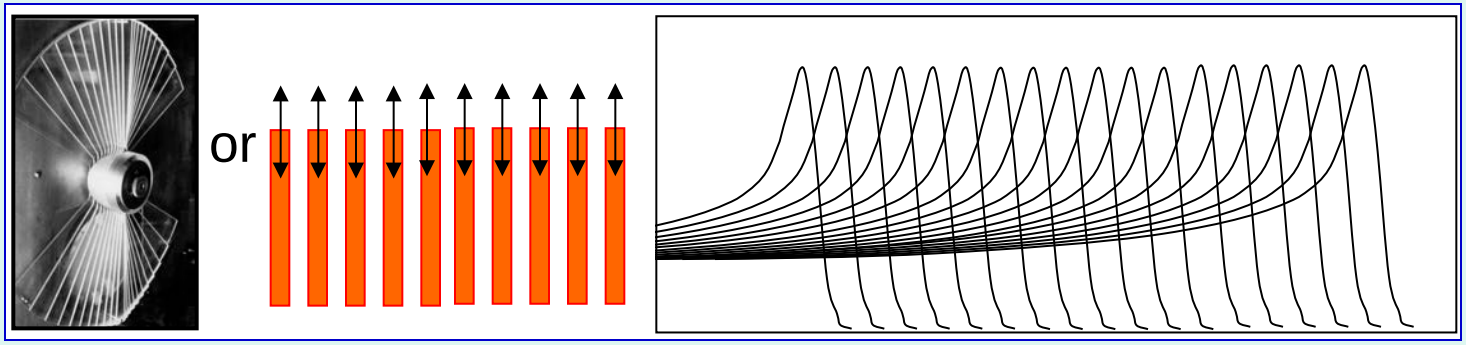




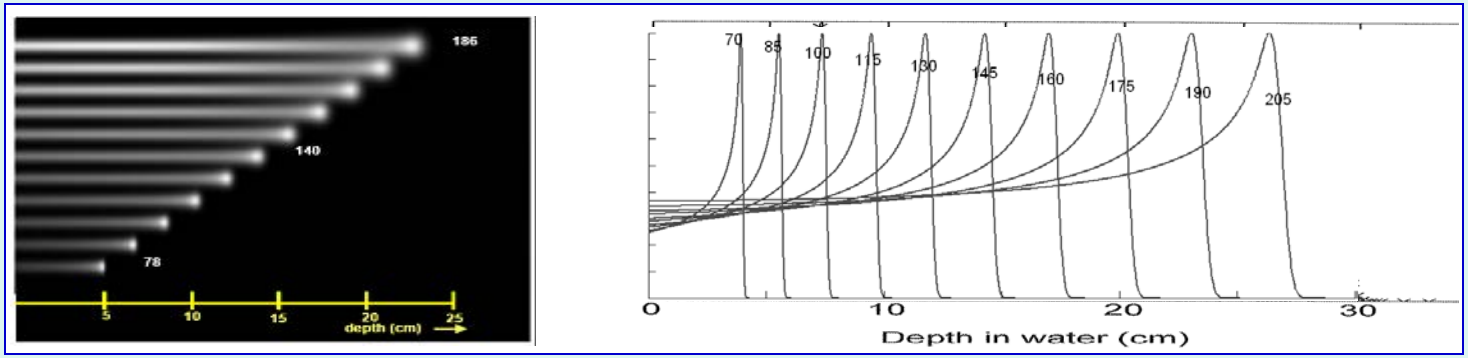
But: material in front of patient
- increases scatter → unsharp edges of dose distr.

Location of energy definition

Energy modulation in nozzle: no beam analysis



Energy modulation upstream: includes beam analysis



required accuracy for upstream degrading

Range in water: $R \approx a.E^{1.77}$: $\frac{dR}{R} = 1.77\frac{dE}{E}$

$(a=2.2\times10^{-3})$

With dependence on Momentum (or magnetic field in Analyser):

$$\frac{dE}{E} = 1.8\frac{dp}{p} = 1.8\frac{dB}{B} \quad \Rightarrow \quad \frac{dR}{R} = 3.2\frac{dB}{B}$$

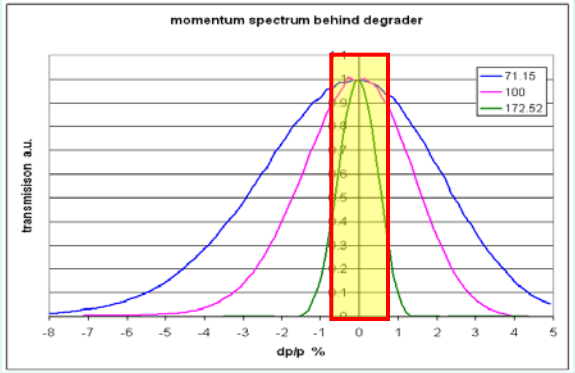
(not **2** due to relativity)

So, given **1% error in magnet setting** of analysing magnet

→ **3.2 % error in Range** = 6.4 mm (at R=200 mm)

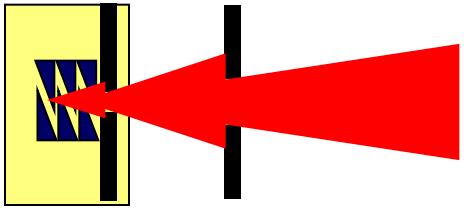
Dose delivery techniques: Depth

Degrader purpose: **decrease** energy



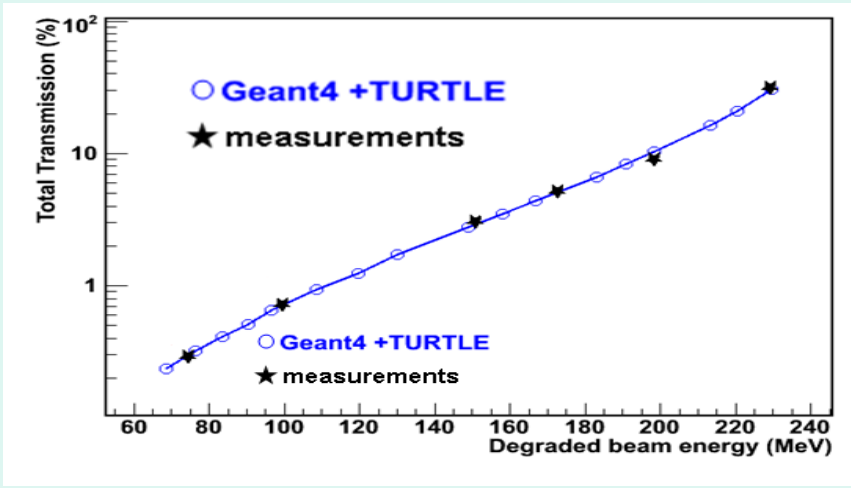
however: - **energy spread** (%) increases with amount of degradation

degrader system



Collimators define transmitted beam size

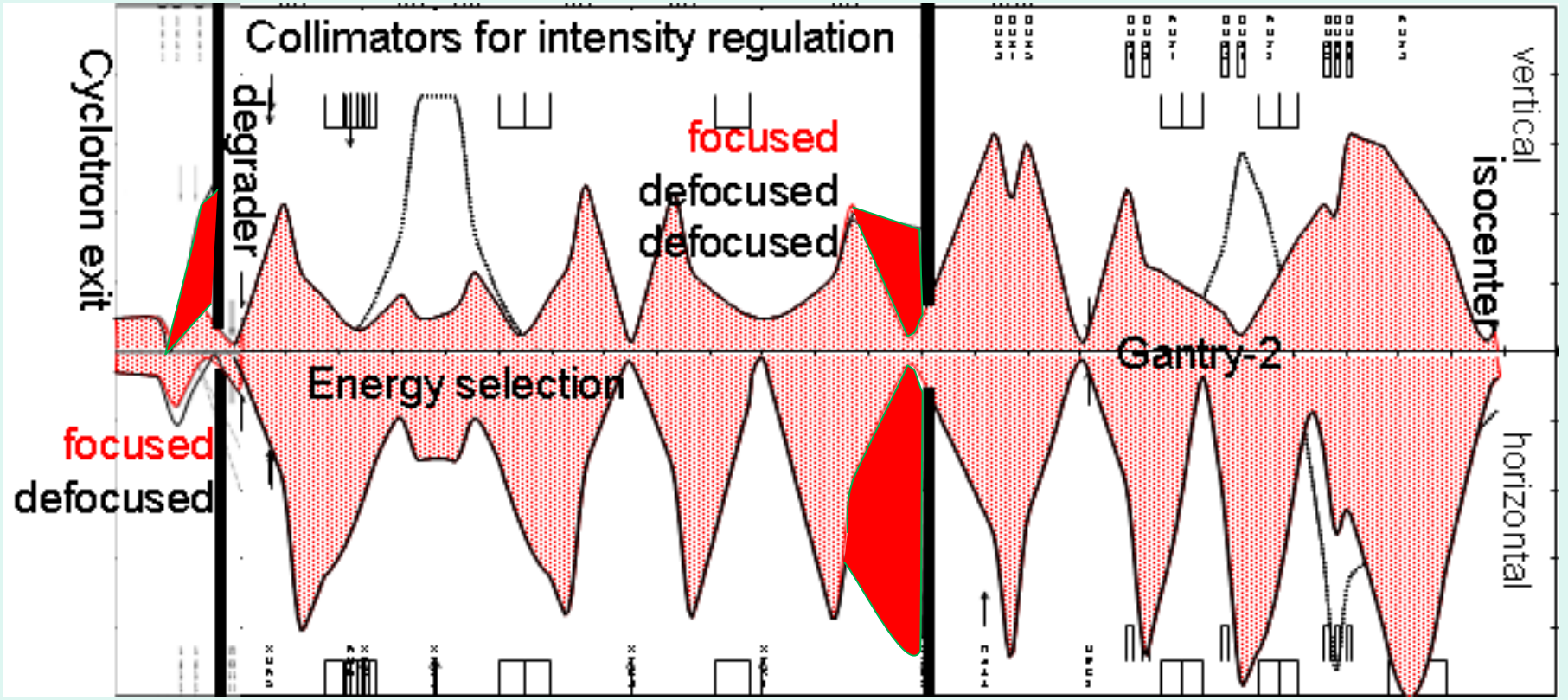
- **beam size** increases due to multiple scattering
- **beam loss** due to nuclear reactions in degrader



➔**Beam intensity** from cyclotron must be high enough

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

Intensity(E) compensation



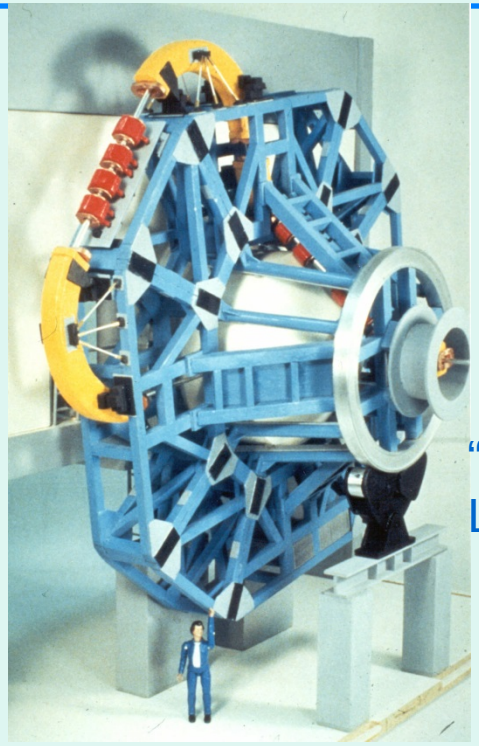
Low E → low Intensity → focused beam → high transmission

High E → high Intensity → defocused beam → low transmission

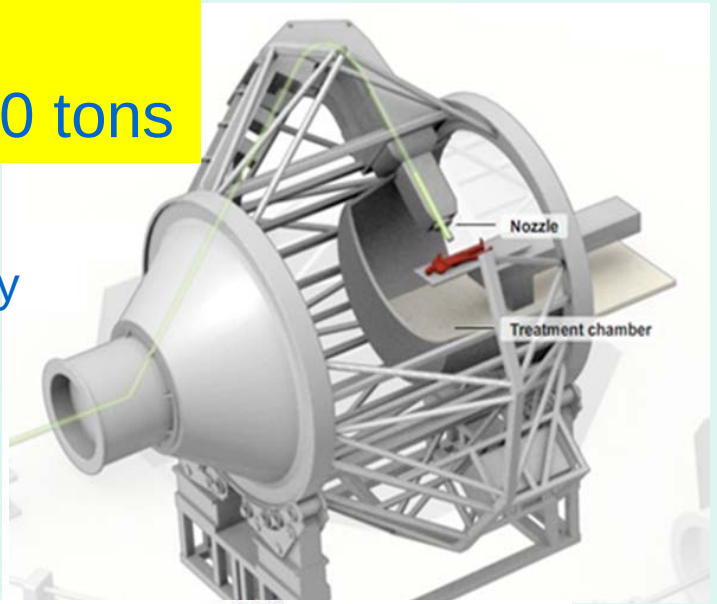
- Typical gantries…..

- Scanning

Gantry types



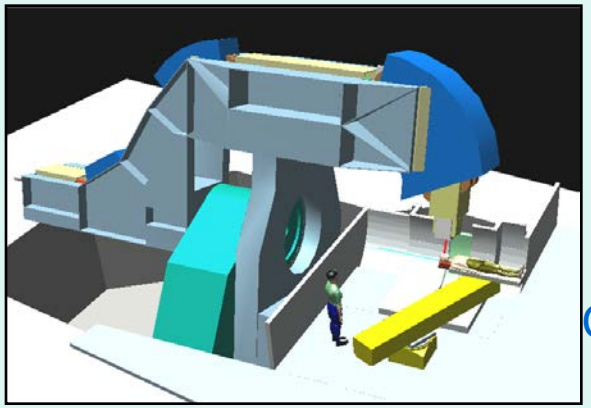
Proton gantries:
6-11 m ∅; 100-200 tons



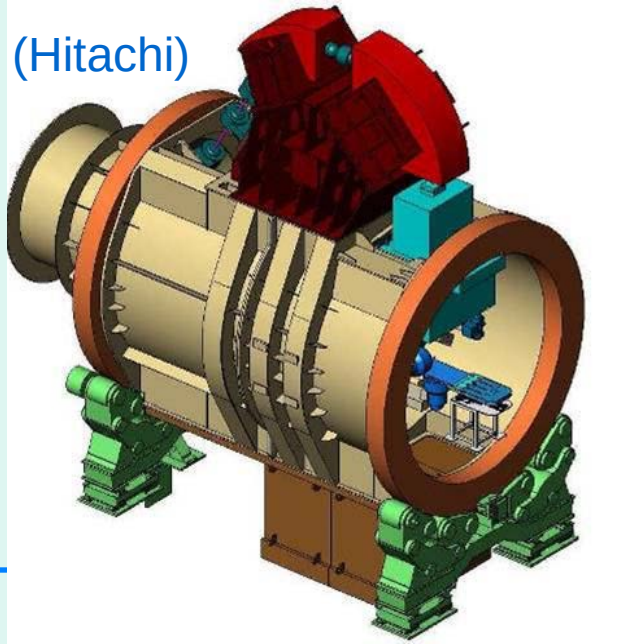
IBA gantry

"Corck screw" at
Loma Linda (Optivus)

Tsukuba (Hitachi)



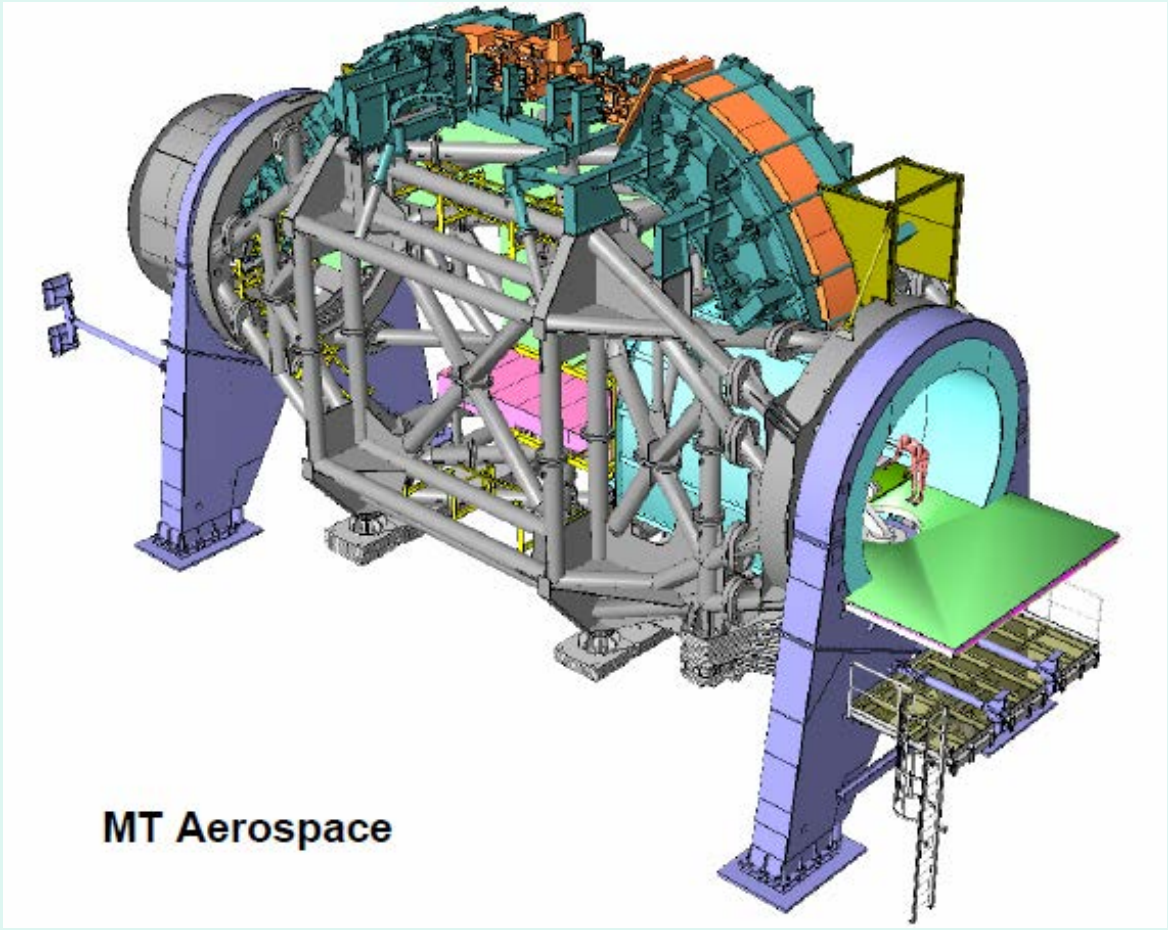
Gantry2 at PSI



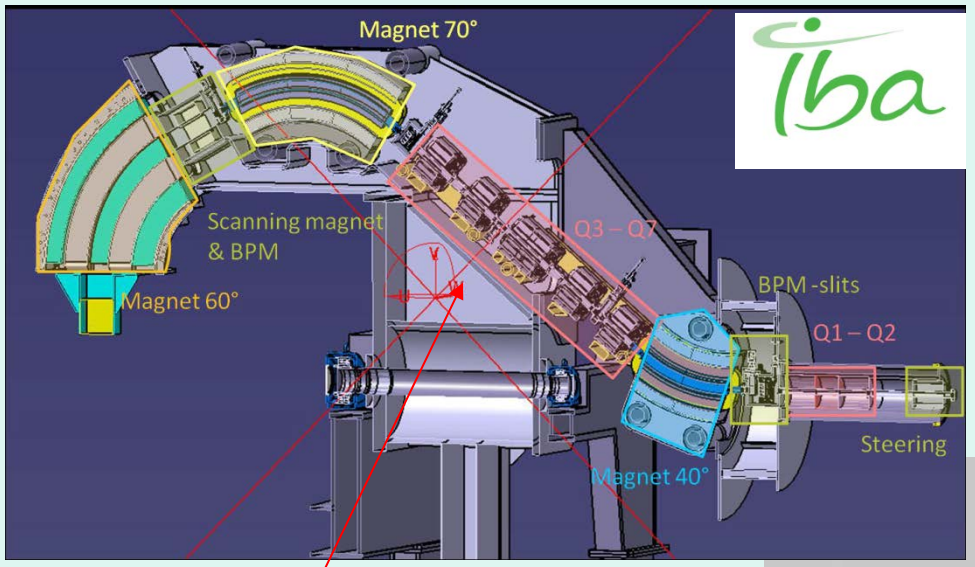
Gantry types

Gantry for carbon ions at HIT Heidelberg

13 m diameter
600 tons



IBA & PROTOM: smaller gantries

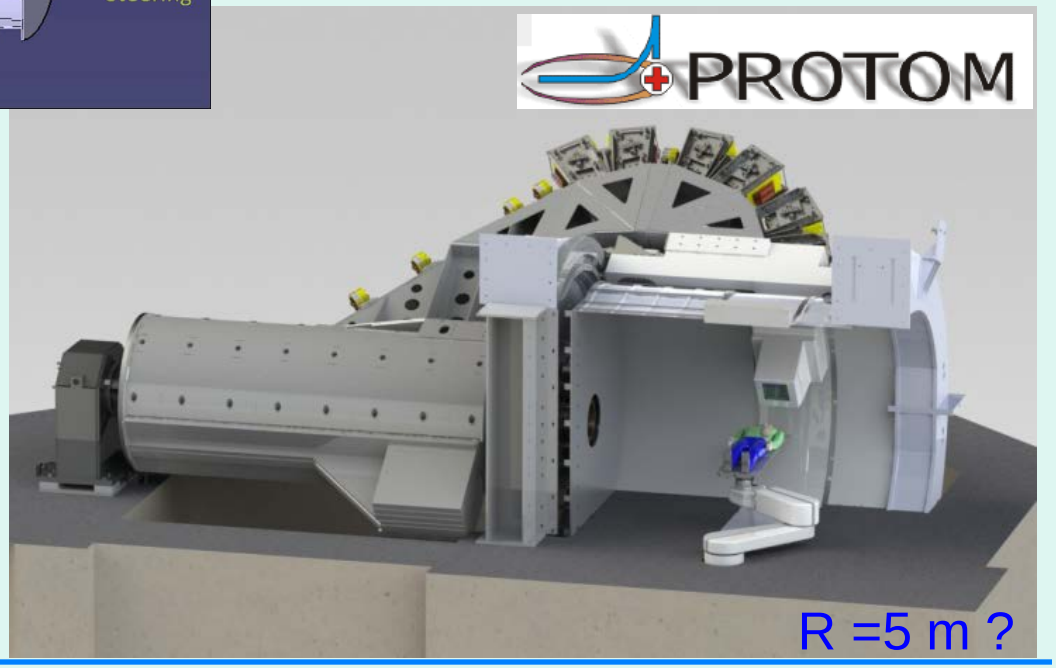


R =3.5 m

Energy selection slits

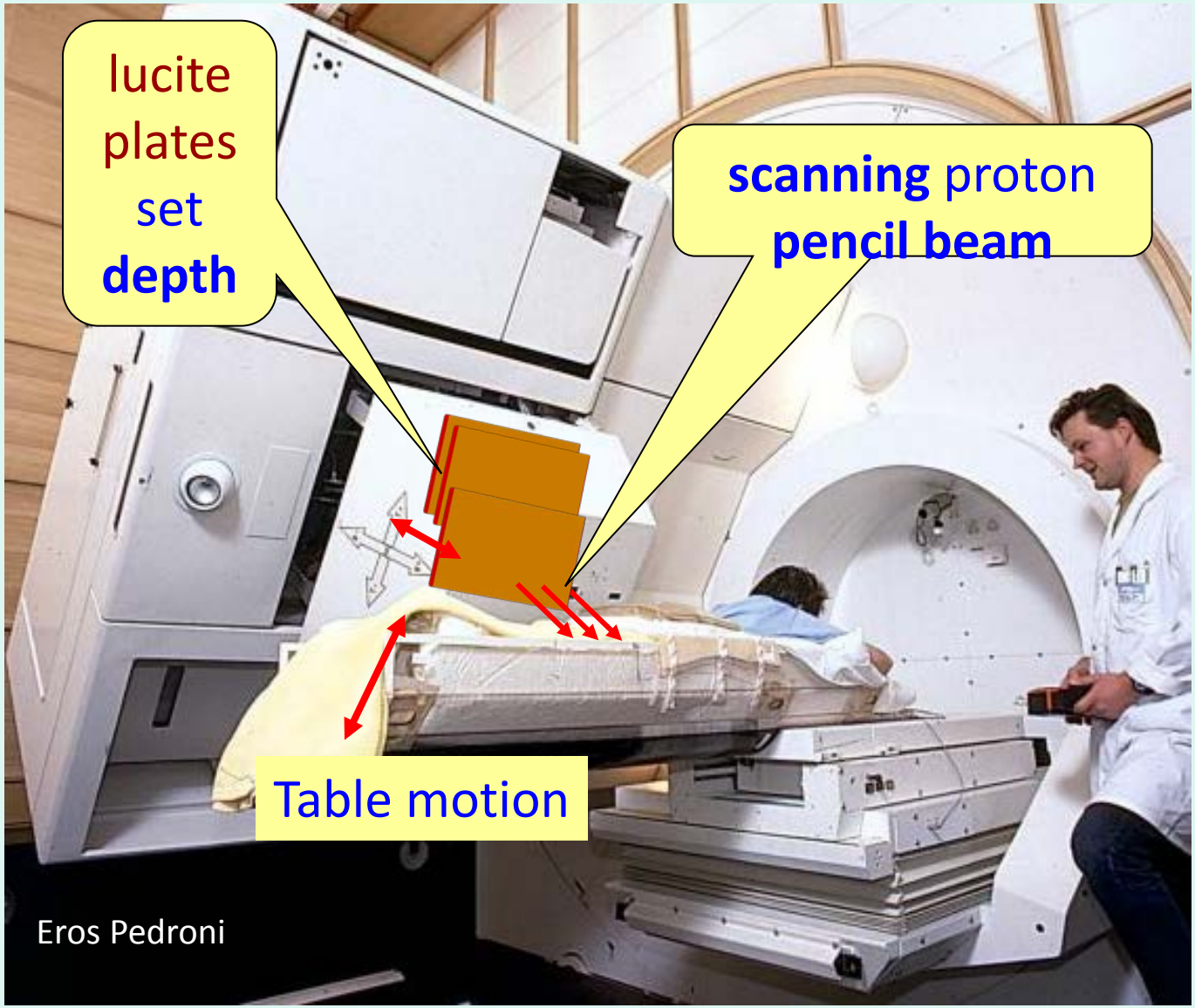
Many small

identical bending magnets



R =5 m ?

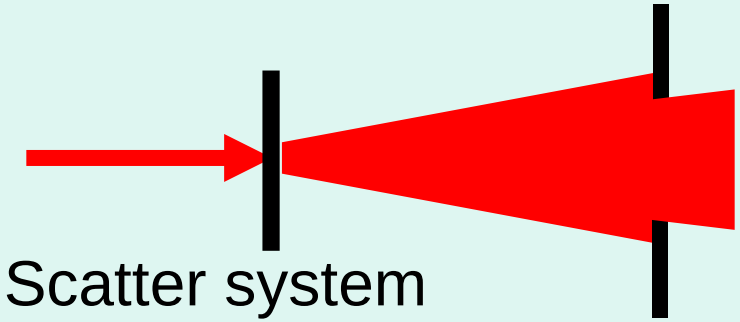
compact “Gantry-1” at PSI (1996)



2 m

Dose delivery techniques: **Width**

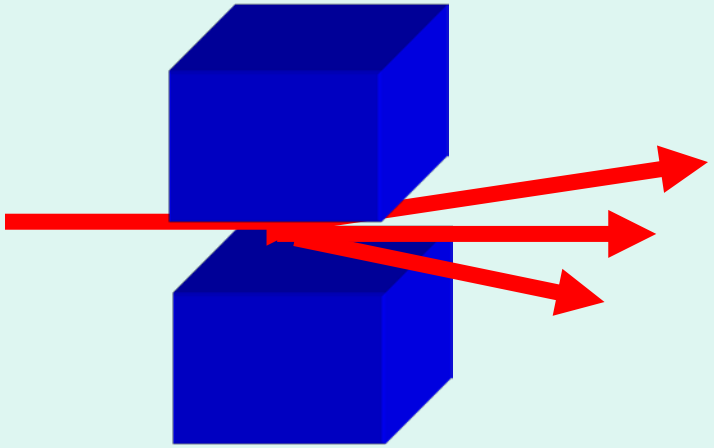
Scatter technique

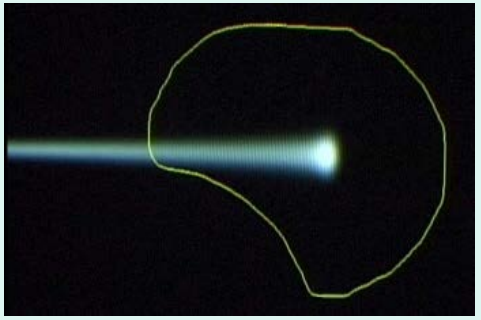


Patient specific Collimator

Best dose distribution

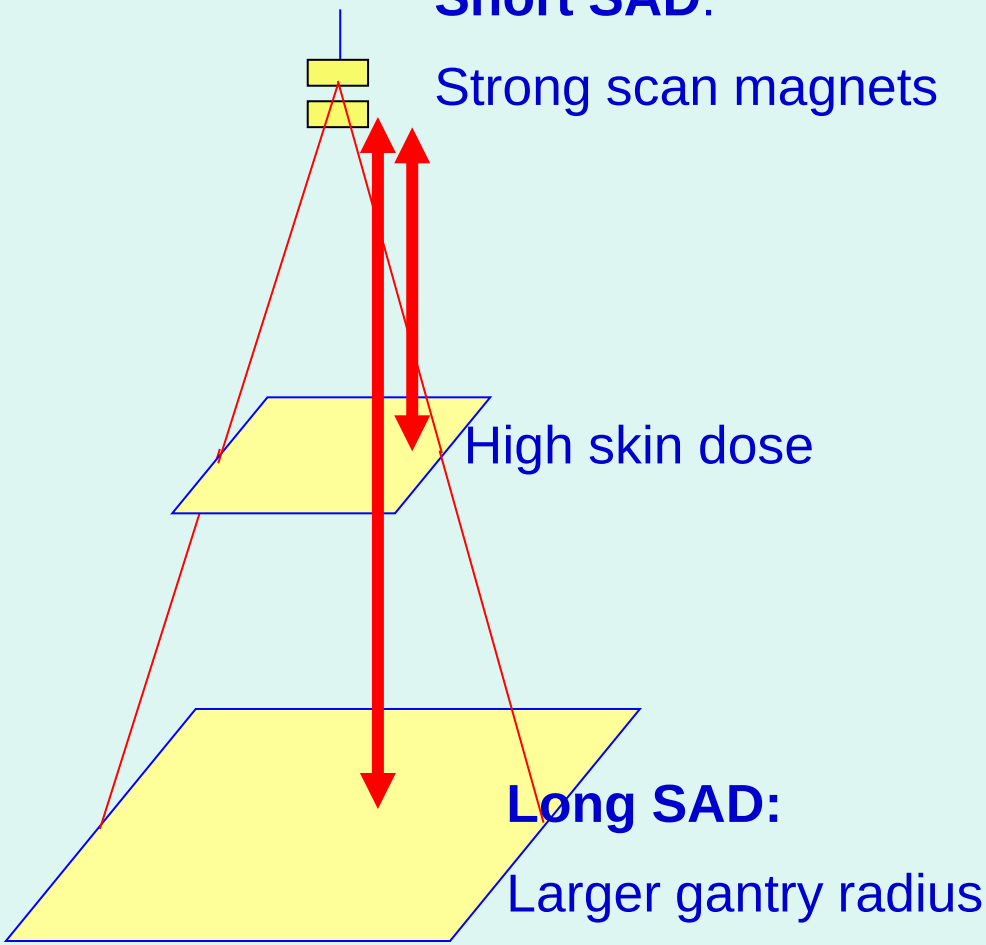
pencil-beam scanning





Nozzle design: SAD

Location scan magnets; SAD (Source-Axis Distance)



Short SAD:

Strong scan magnets

High skin dose

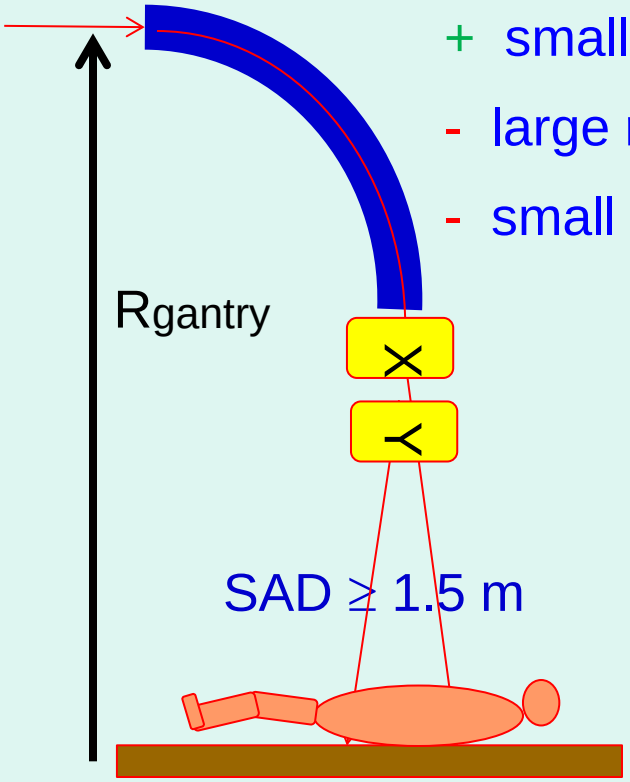
Long SAD:

Larger gantry radius

scanning

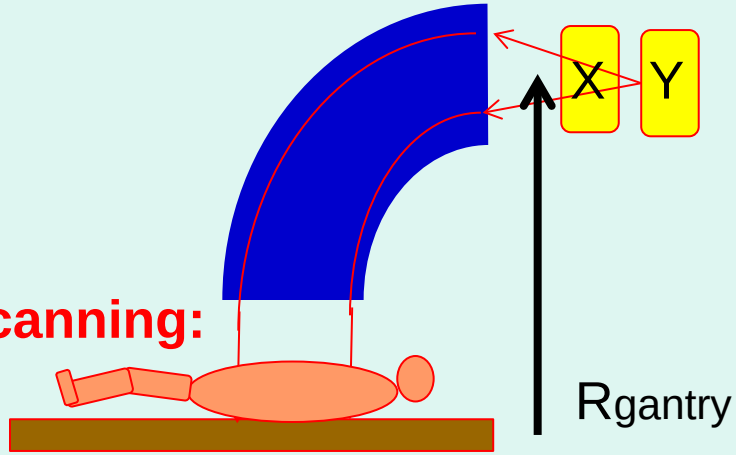
Down-stream scanning:

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

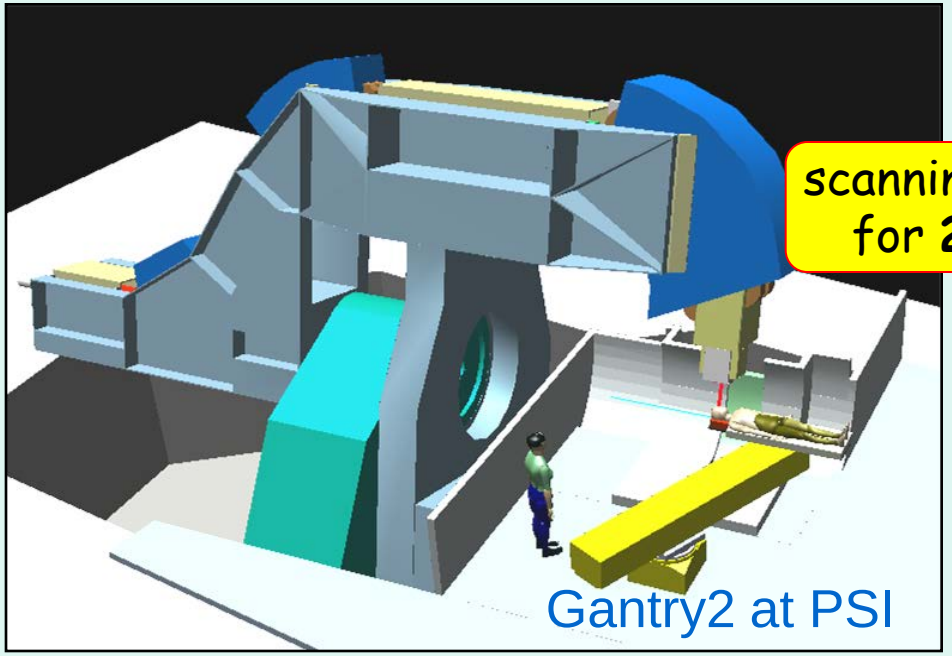


Up-stream scanning:

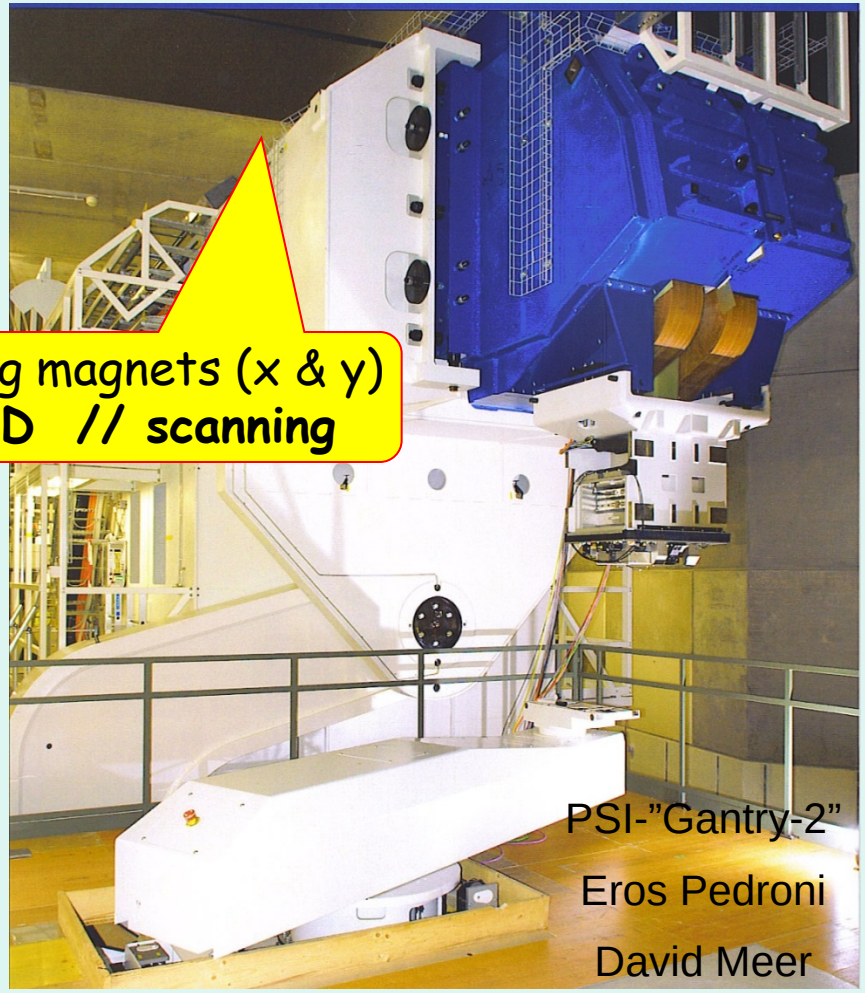
+ parallel
+ small gantry radius
+ small spots possible
- wide aperture SC magnet



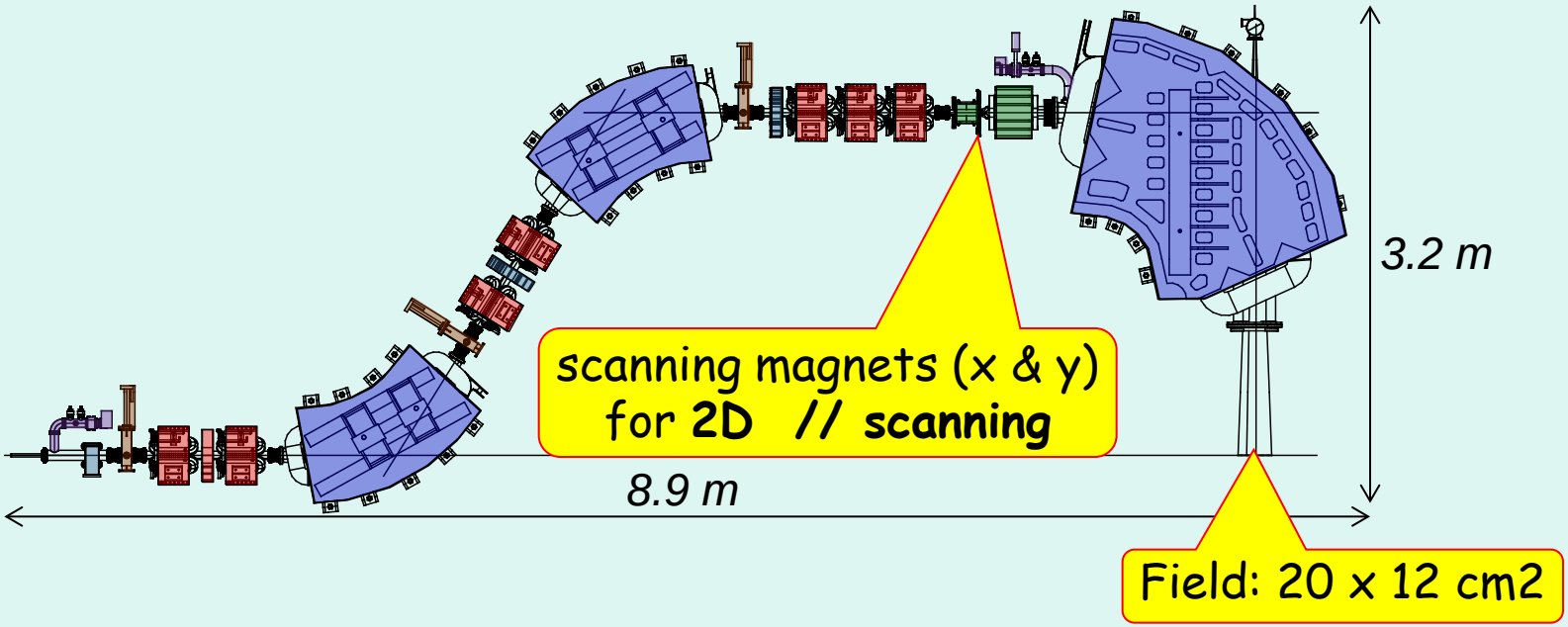
Cyclotron + Gantry-2: fast 3D scanning



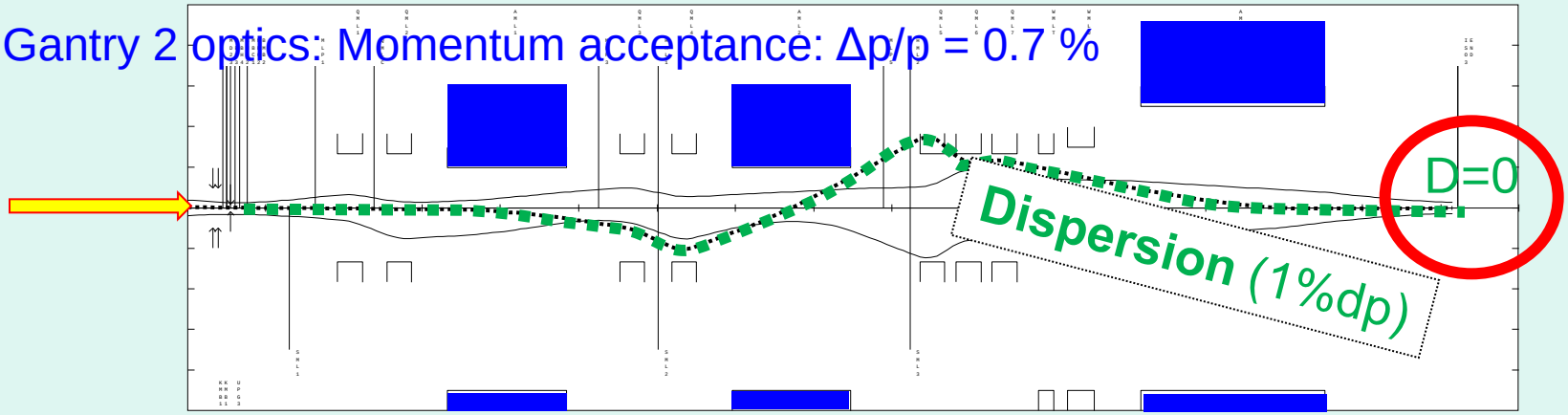
scanning magnets (x & y)
for **2D // scanning**



Beam Optics of Gantry-2

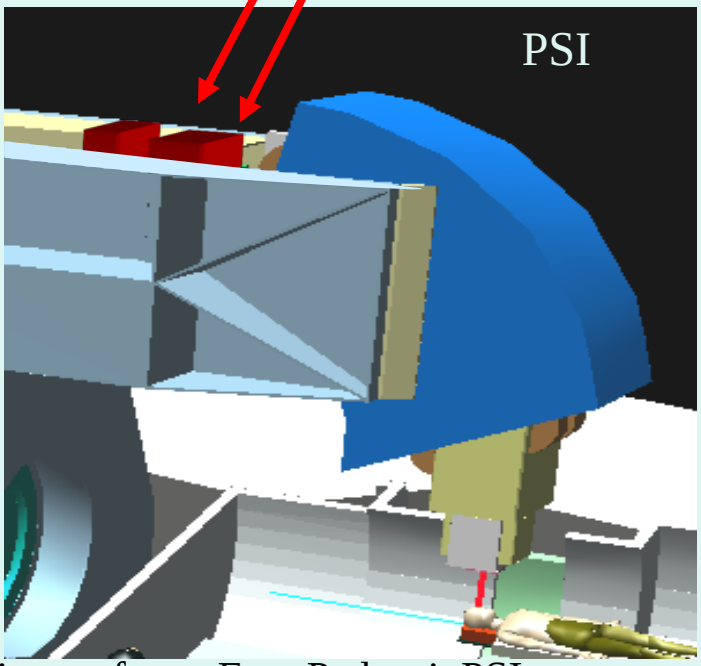


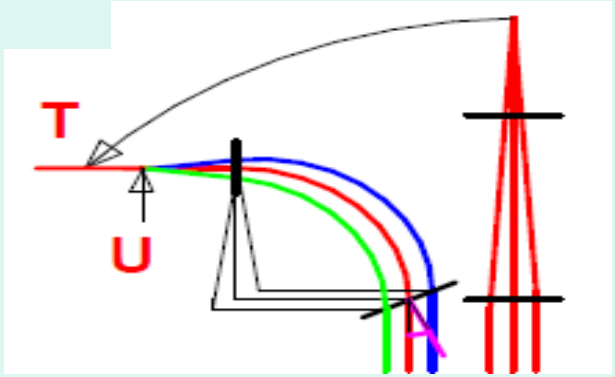
Gantry 2 optics: Momentum acceptance: Δp/p = 0.7 %

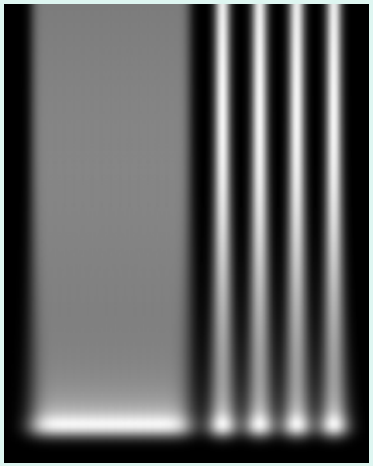


Parallel displacement

Scan magnets







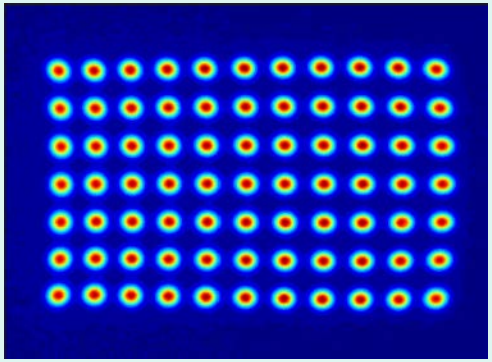
Figures from: Eros Pedroni, PSI

In PSI Gantry2:
parallel pencil beam movement

SAD = ∞

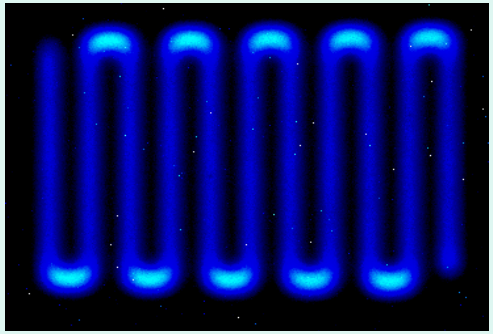
optics with “point→parallel imaging”

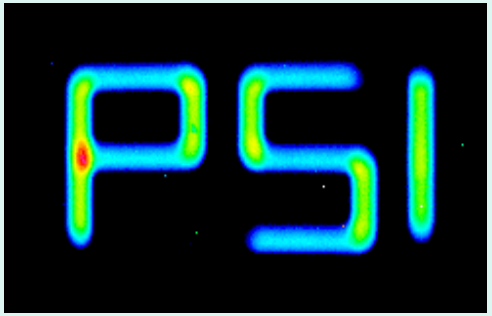
PSI Gantry-2: fast 3D scanning

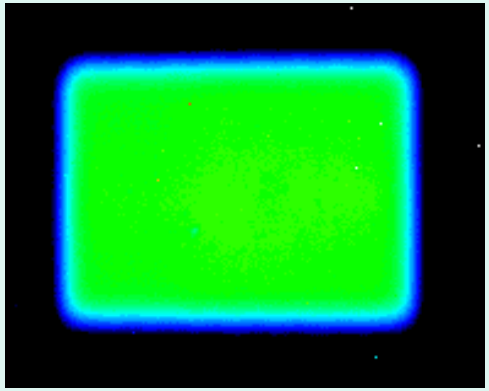


σ=3-4.5 mm

230-100 MeV





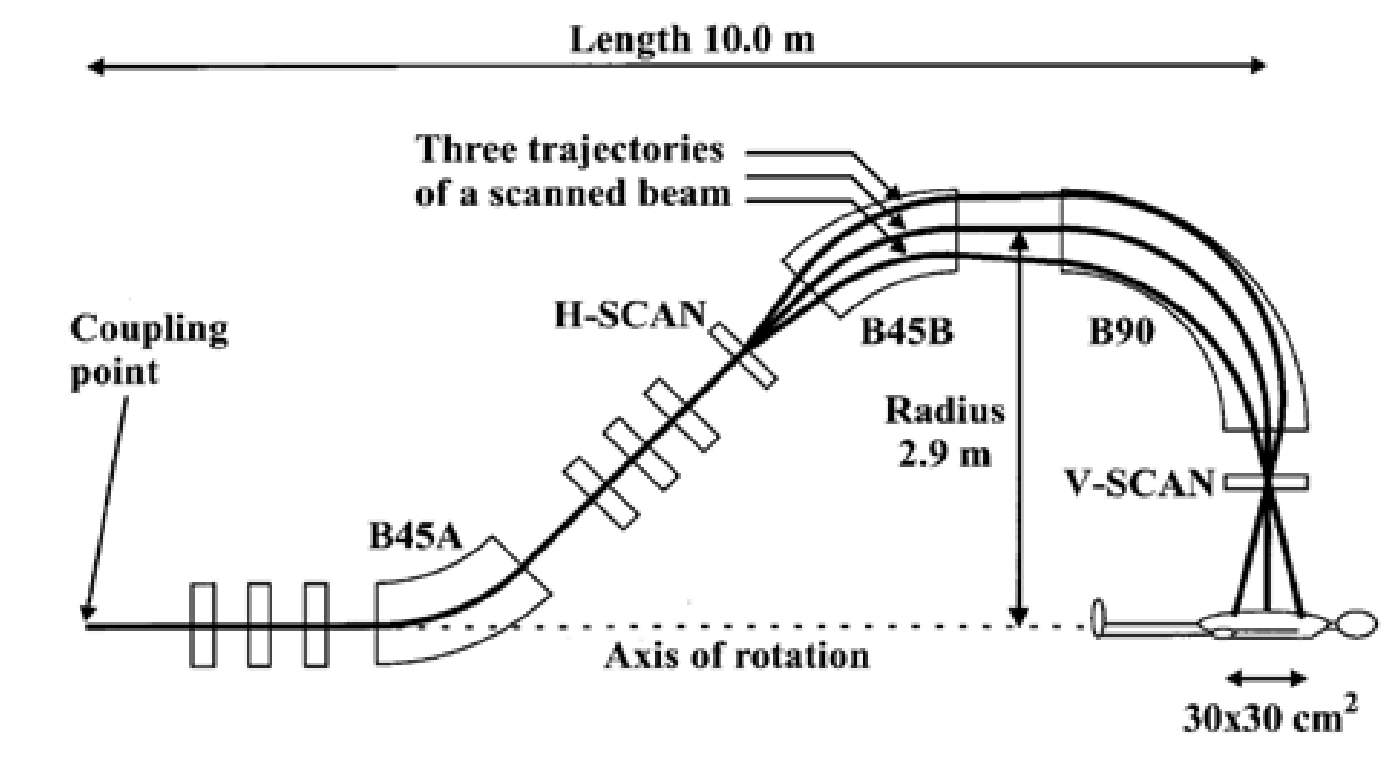


scanning

Upstream+Down-stream scanning:

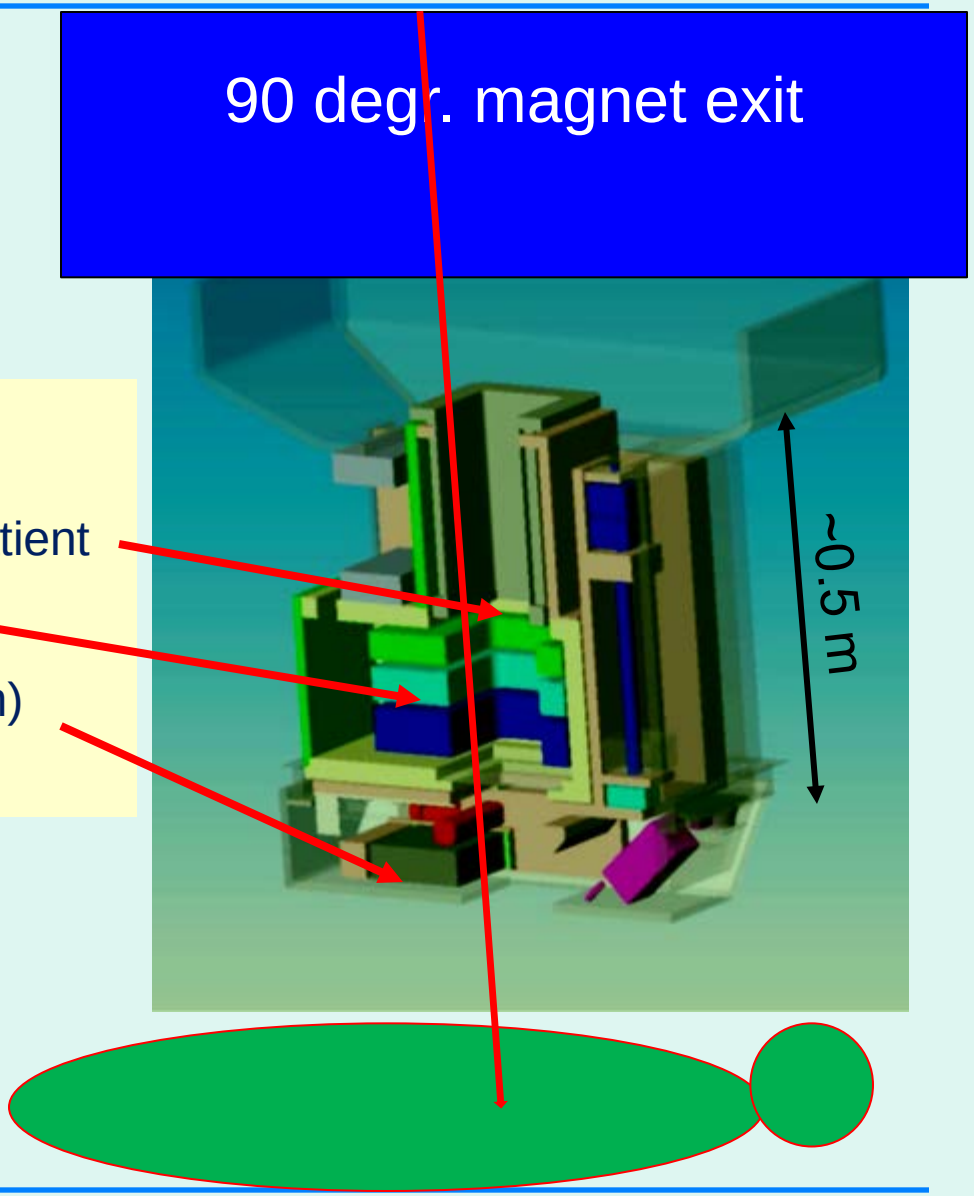
\+ small aperture,

\- Not too small radius because of SAD



H.Vrenken et al., NIM A 426 (1999) 618-624

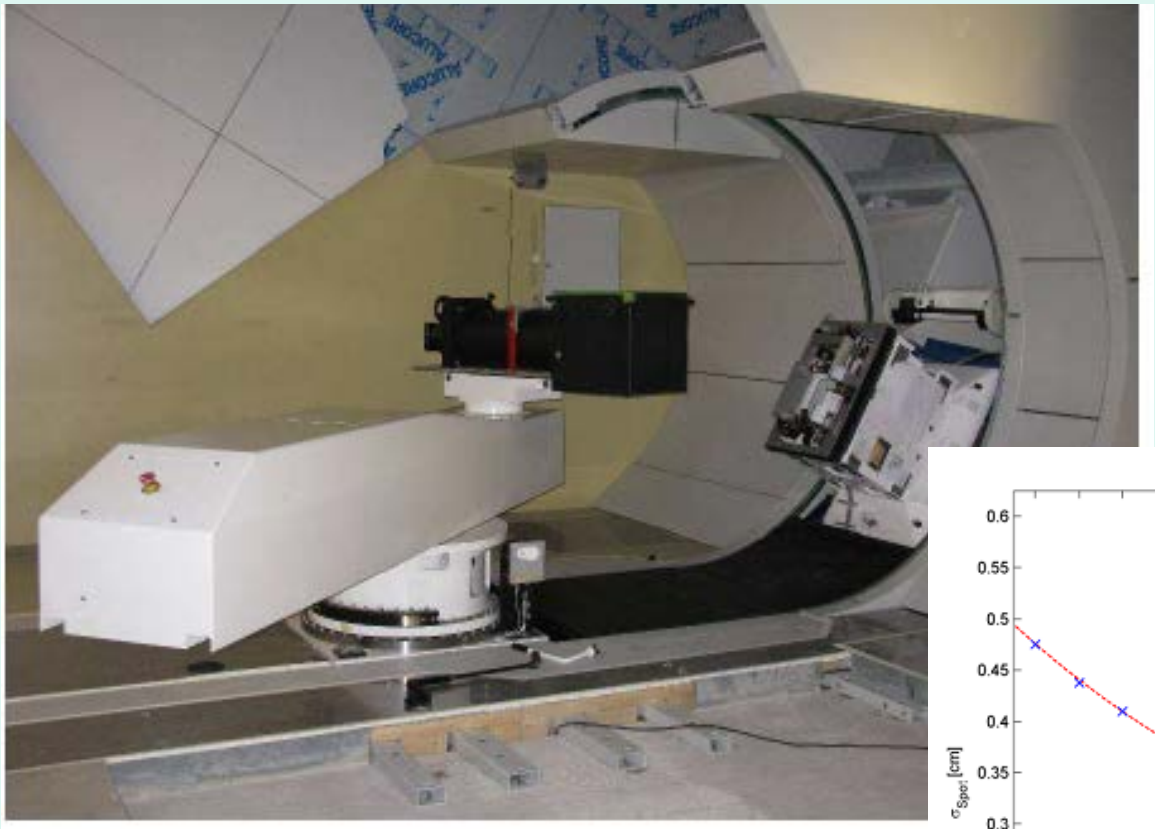
Pencil beam sharpness

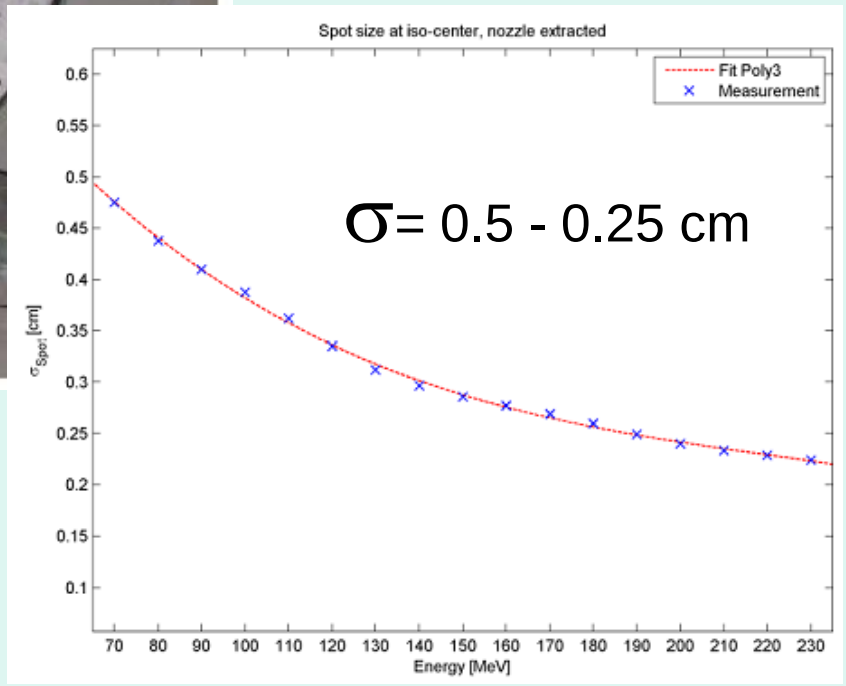


Practical realization at PSI's Gantry-2:

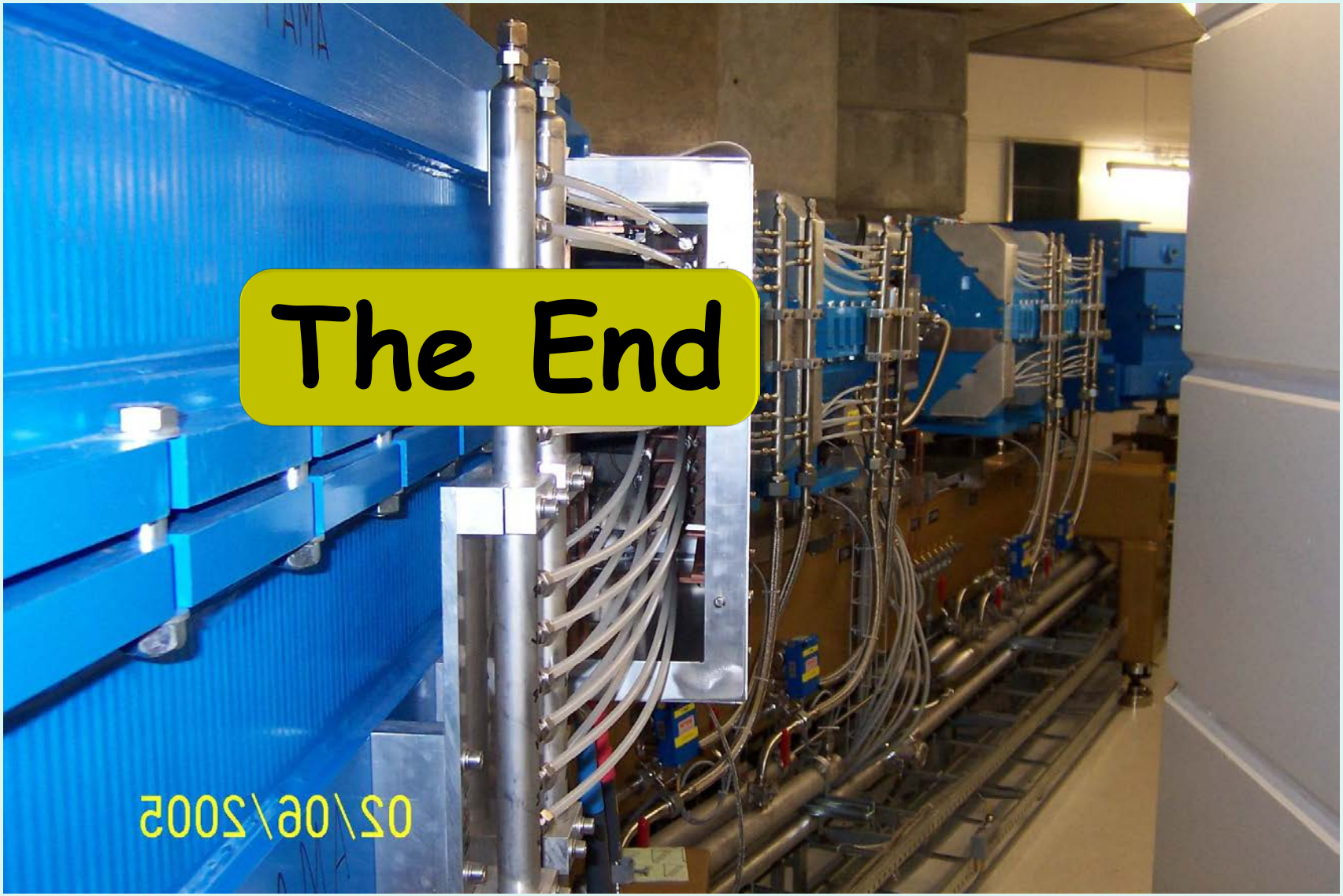
- Vacuum as close as possible to the patient
- Two monitors and a strip monitor
- Removable pre-absorber (for R<10 cm)
- Longitudinal motion of nozzle

Pencil beam sharpness





Eros Pedroni, David Meer


The End