Heidelberger Ionenstrahl-Therapiezentrum

Medical applications of accelerators and linked detector technologies

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HIT Betriebs GmbH am Universitätsklinikum Heidelberg

http://www.hit-centrum.de

Outline

- Introduction: historical developments of accelerators and their use for medical applications: tumour treatment from X-rays to particle therapy
- Underlying physics and biology of particle therapy; implications on the needed beam parameters
- Accelerator technologies used for particle therapy so far: cyclotrons and synchrotrons
- Particle therapy facilities worldwide: an overview and some examples in detail
- Use of common detector systems for accelerator beam diagnostics and dose monitoring for the treatment
- Outlook to new accelerator concepts FFAGs, laser plasma accelerators, dielectric wall accelerators

An introduction

about the historical developments of accelerators and their use for medical applications: tumour treatment from X-rays to particle therapy

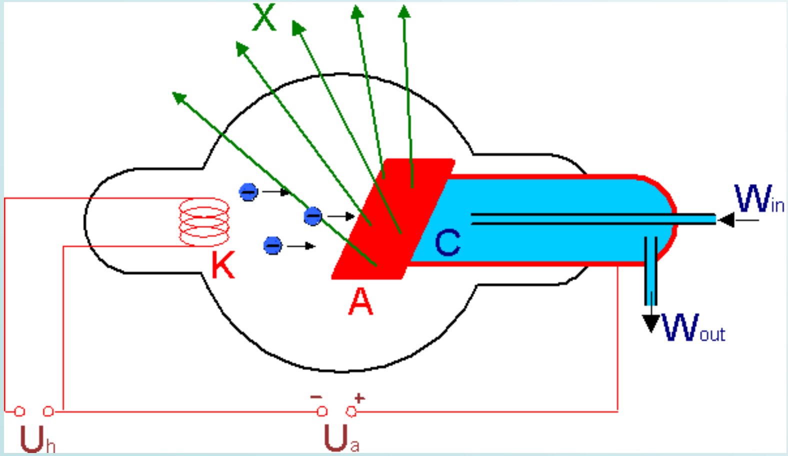
History of medical applications of accelerators

1895 *Wilhelm Conrad Röntgen* (1845 – 1923) discovers the X-rays on 8th November at the University in Würzburg

1896 On 23rd January Röntgen announced his discovery and demonstrated the new kind of radiation by a photograph of the hand of his colleague *Albert von Kolliker*

1897 First treatments of tissue with X-rays by *Leopold Freund* at University in Vienna

1901 Physics Nobel prize for W.C. Röntgen



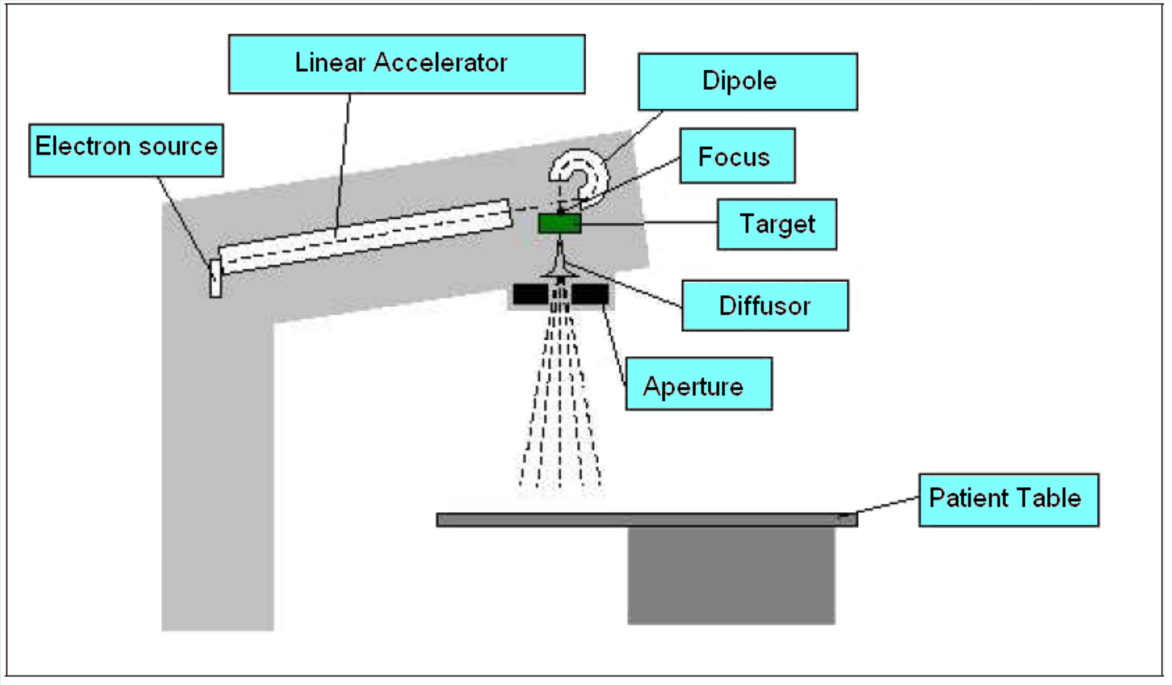
Schematics of an X-ray tube – an "electrostatic accelerator"

History of medical applications of accelerators

1899	First X-ray treatment of carcinoma in Sweden by *Stenbeck* and *Sjögren*
1906	Vinzenz Czerny founded the "Institute for Experimental Cancer research" in Heidelberg – the first of its kind
1913/4	Invention of part- and full-rotation radiation instrumentation
1920´s	Industrially manufactured X-ray apparatus; example from Reiniger-Gebbert & Schall AG (later: Siemens), Erlangen; 1922) with a high-voltage of 150 kV – without shielding!
1930	First linear accelerator principle invented by *Rolf Wideroe*
1949	*Newberry* developed first linear accelerator for therapy in England

History of medical applications of accelerators

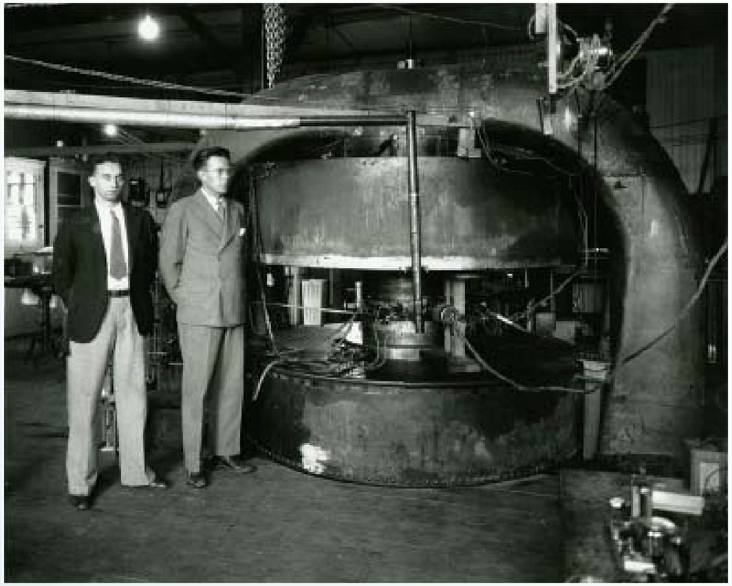
1950´s and later	Development of compact linear accelerators by Siemens, Varian, Elekta and other companies - with energies up to around 25 MeV (and above)



Principle layout of modern linac for therapy

ONCOR from Siemens

History of medical applications of accelerators

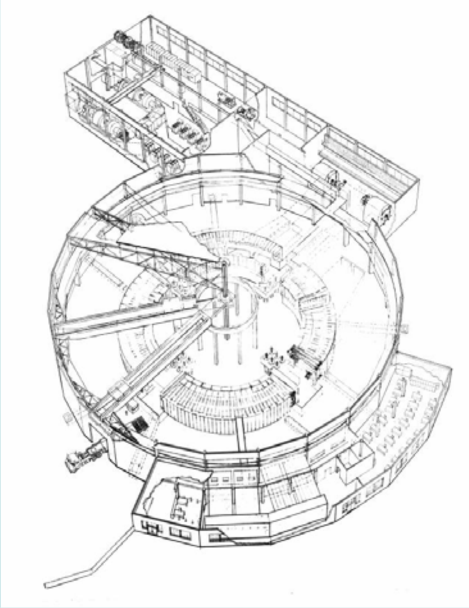


1929 Invention of cyclotron by *Ernest Lawrence*

1930´s Experimental neutron therapy

1946 R. R. Wilson proposed proton & ion therapy

1950's Proton therapy, LBL Berkeley (184” cyclotron)



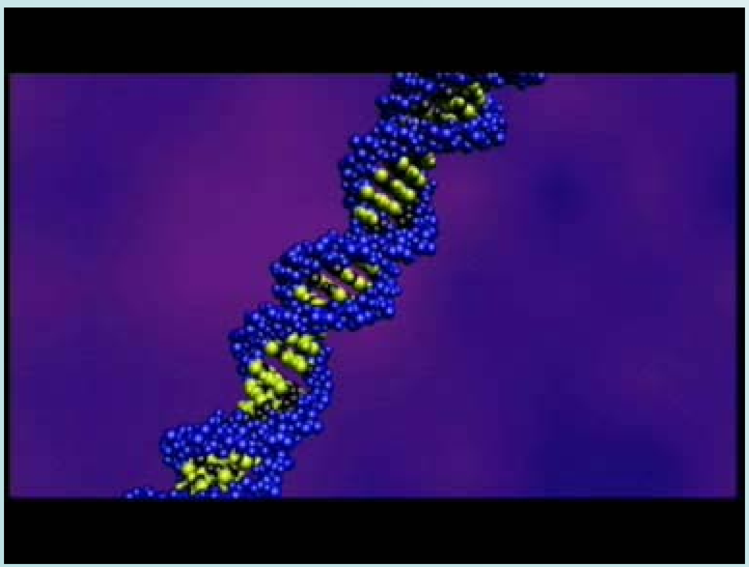
1945 *Edwin Mattison McMillan* at University of California and *Vladimir Iosifovich Veksler* (Soviet Union) invented the synchrotron principle

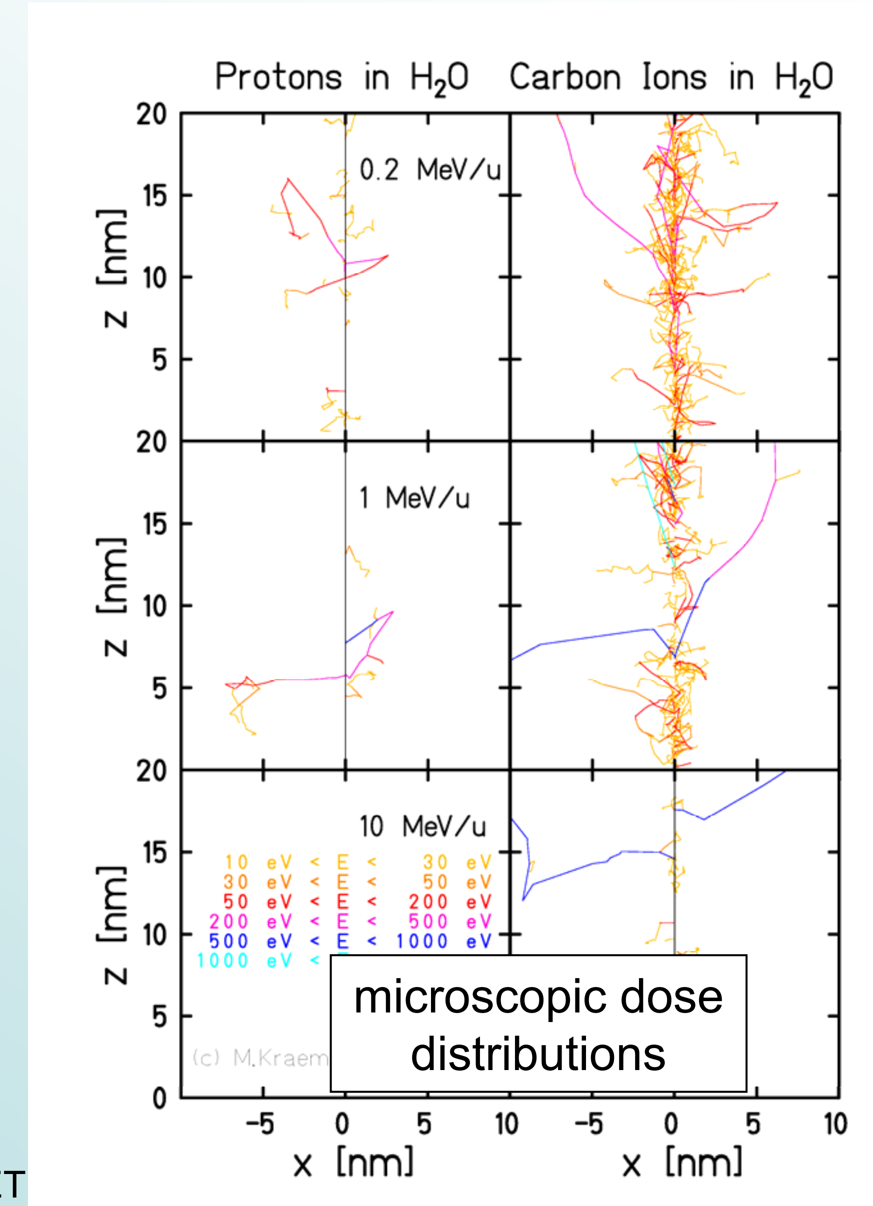
1975 Begin of carbon therapy in Bevalac synchrotron (Berkeley)

Description of the underlying physics and biology of particle therapy; Implications on the requirements for the needed beam parameters: energy, intensity, focus, beam structure

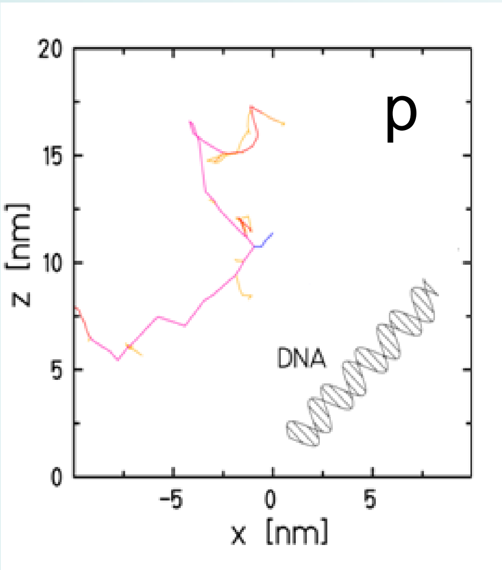
Physics and Biology of radiation therapy

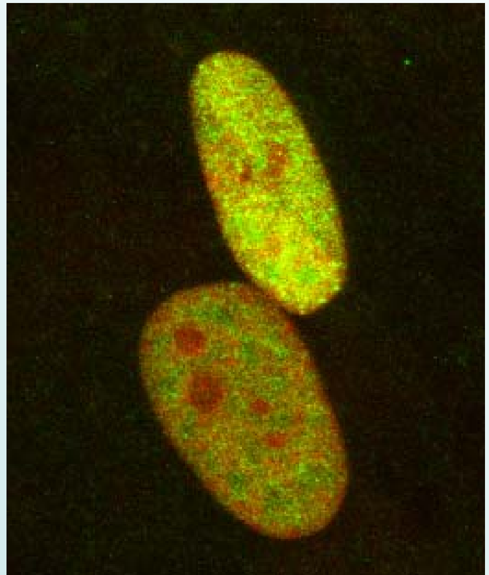
Basic effect of radiation on cells: energy loss in matter leads to defects in the DNA – double strand breaks of the DNA kills the cell. Tumor cells have less repair capabilities than normal cells.





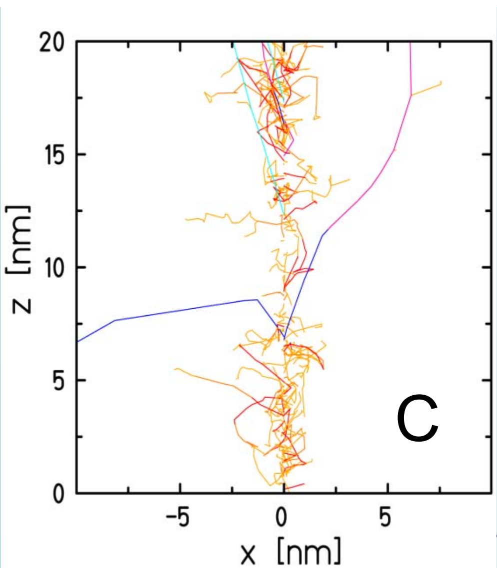
Physics and Biology of radiation therapy

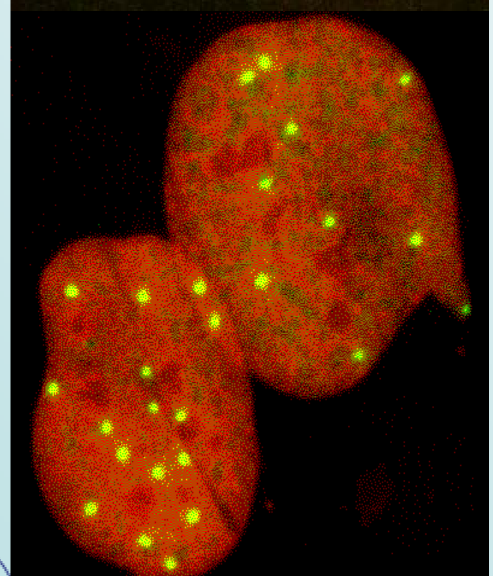




Low LET

Homogeneous deposition of dose





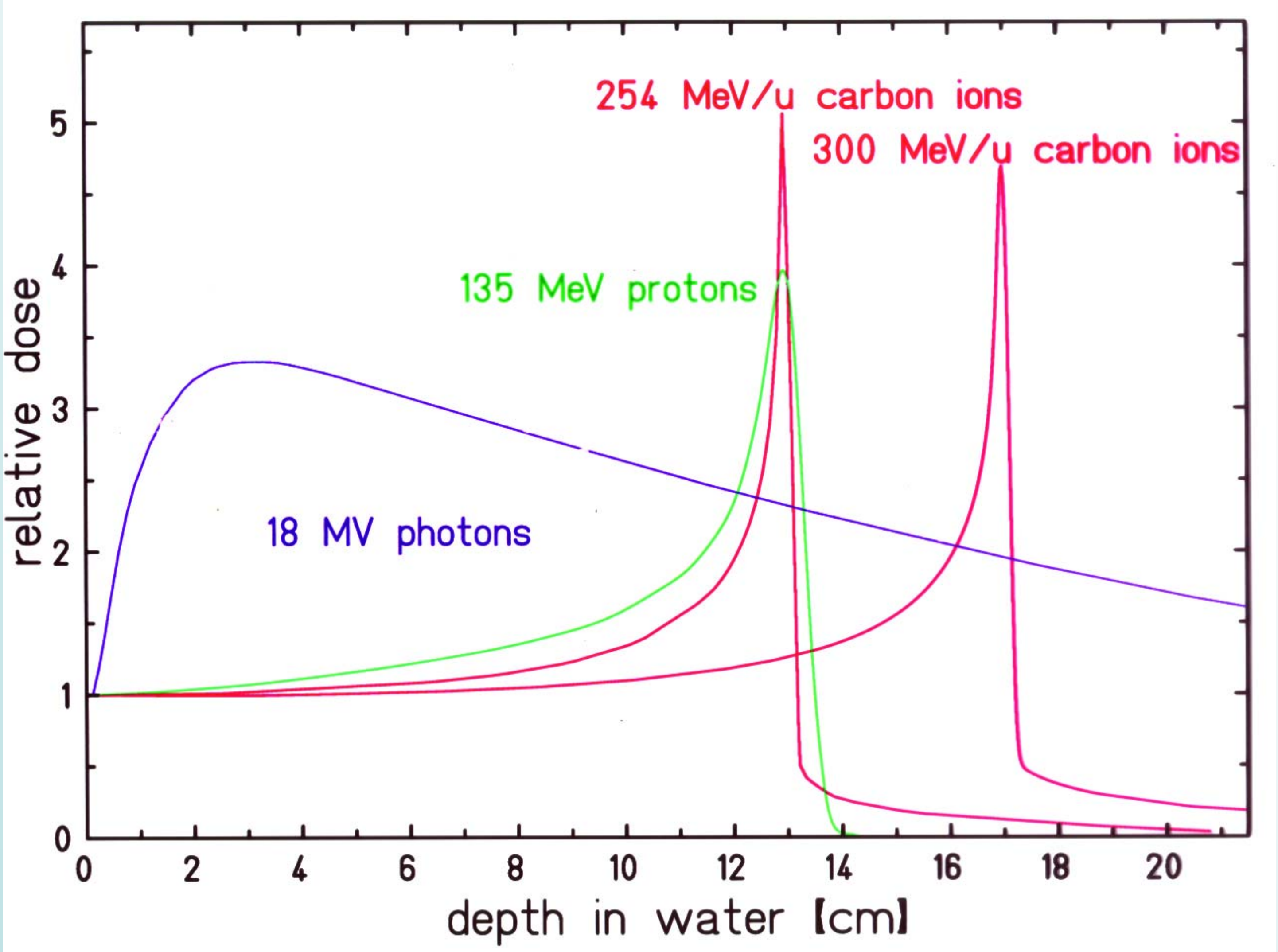
High LET

Local deposition of high doses

LET: Linear energy transfer

Physics and Biology of radiation therapy

Depth profile of relative dose deposition from different beams in water



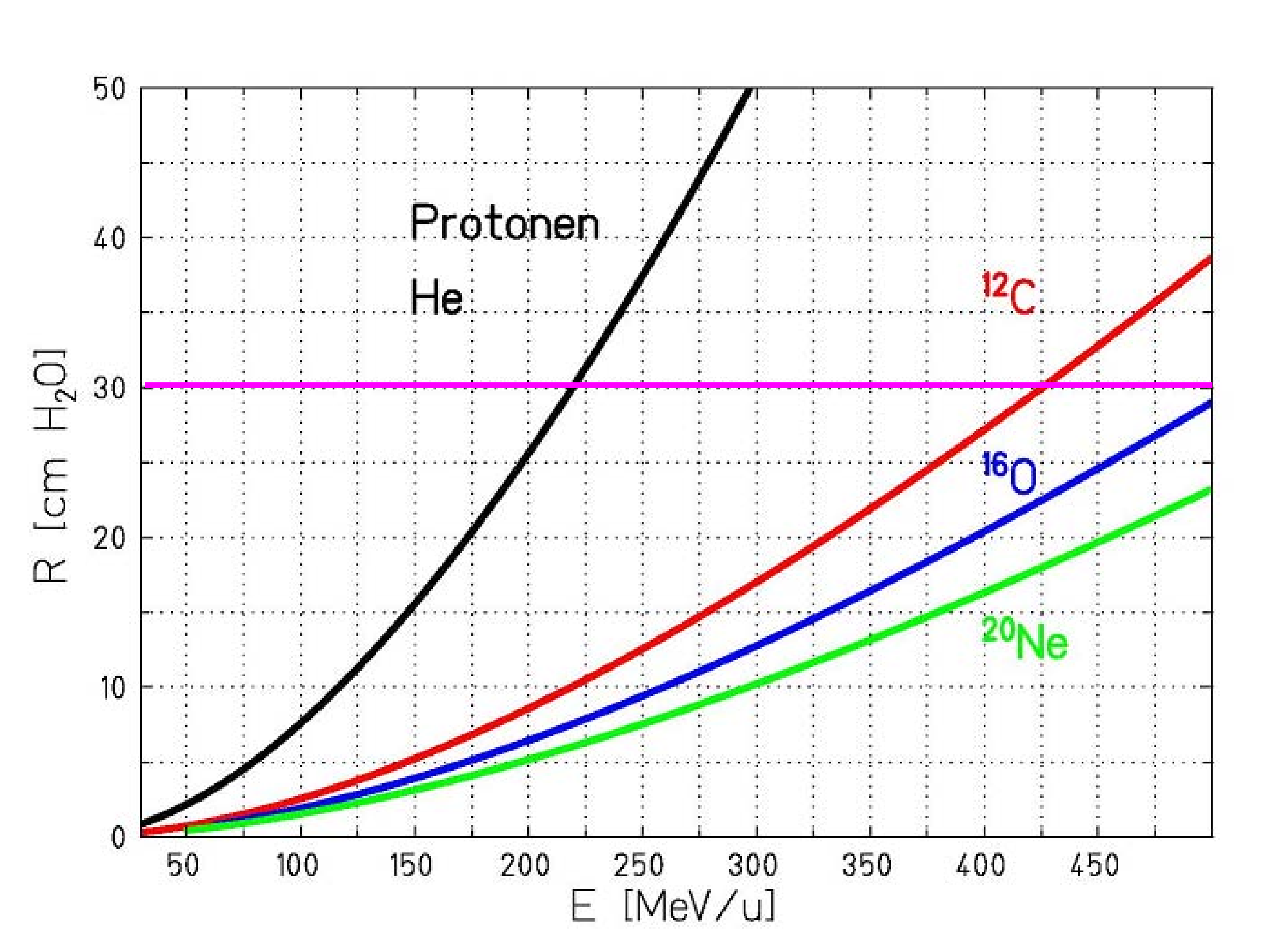
Implications on the needed beam energy

Range of different beams in water

30 cm range define the end energy for the accelerator design:

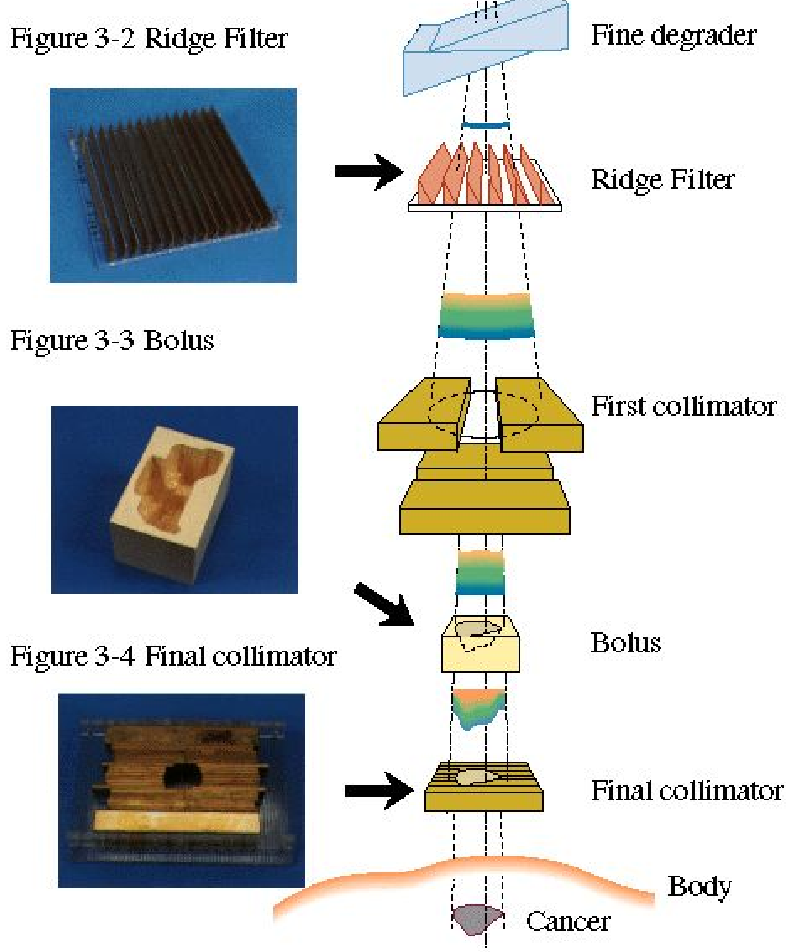
p → 220 MeV

C → 430 MeV/u

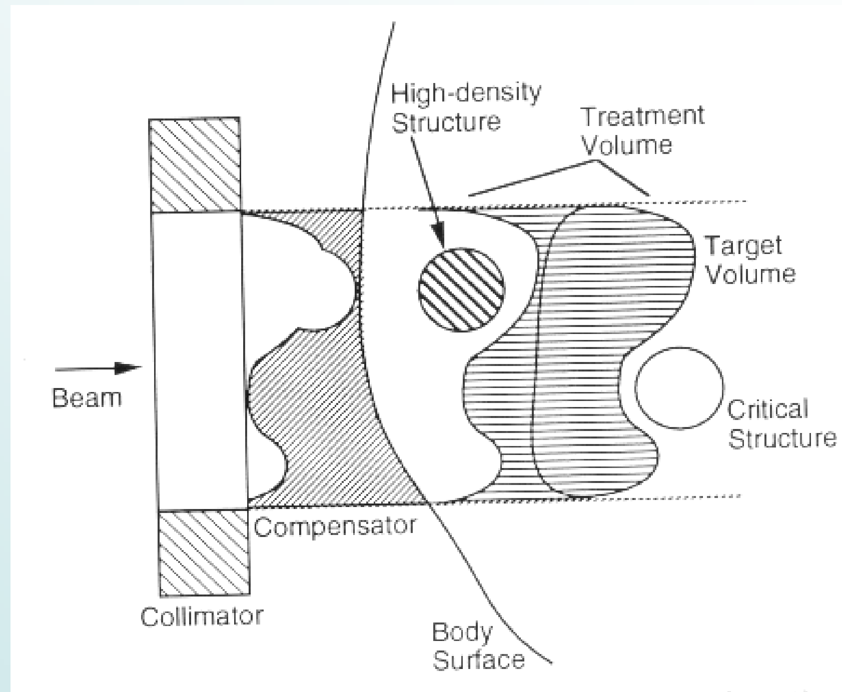


Implications on beam focus & spill structure

typical set-up (Tsukuba)



Distal edge shaping using a bolus pulls dose back into healthy tissue



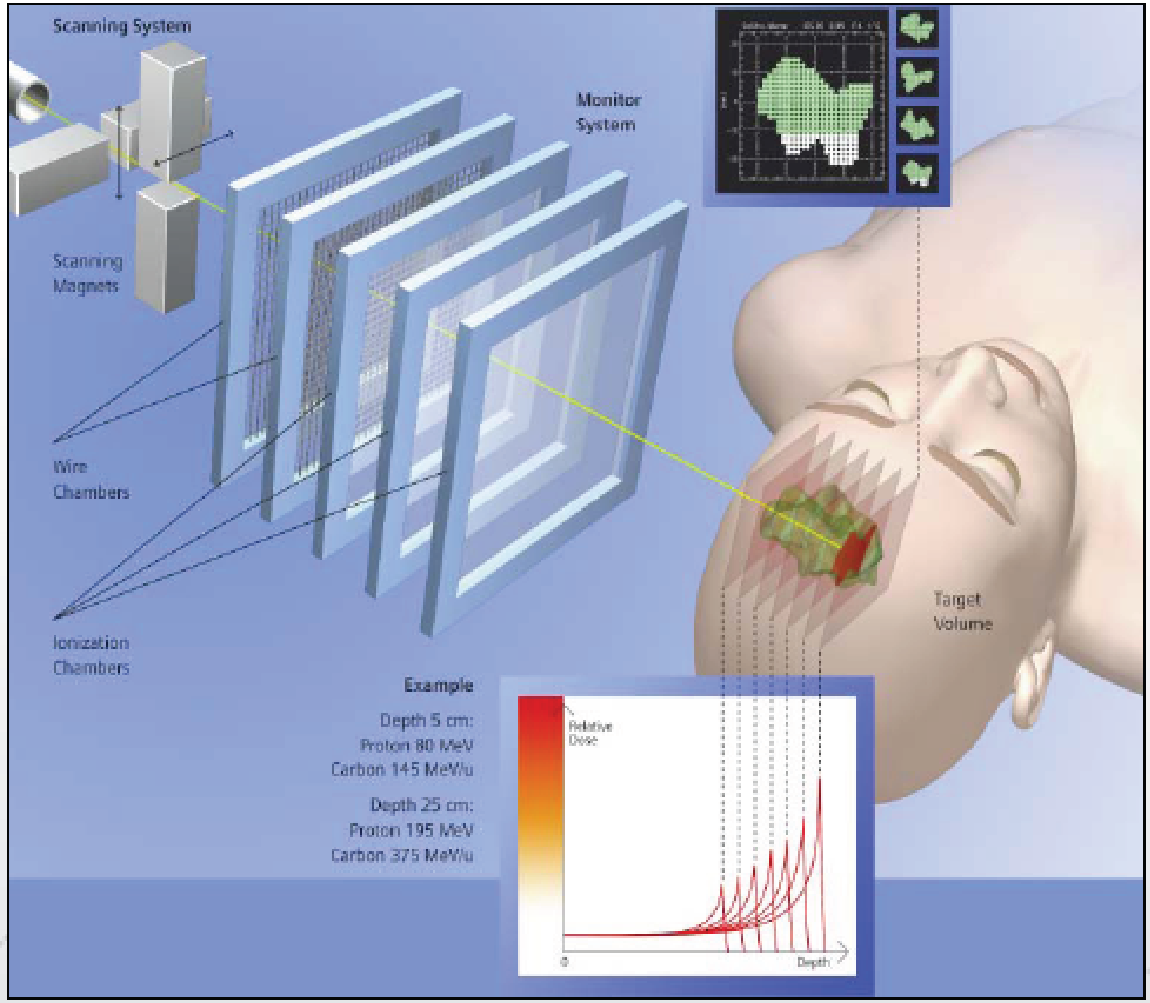
“Passive” dose application needs only widened beam focus, but …

Implications on beam focus & spill structure

Development in the 90ies:
Scanning techniques

a) Protons (Pedroni et al., PSI):
spot scanning gantry (1D magnetic pencil beam scanning) plus
passive range stacking
(digital range shifter)

b) Ions (Haberer et al.):
raster scanning (2D magnetic pencil beam scanning) plus
active range stacking
(spot size, intensity)
in the accelerator



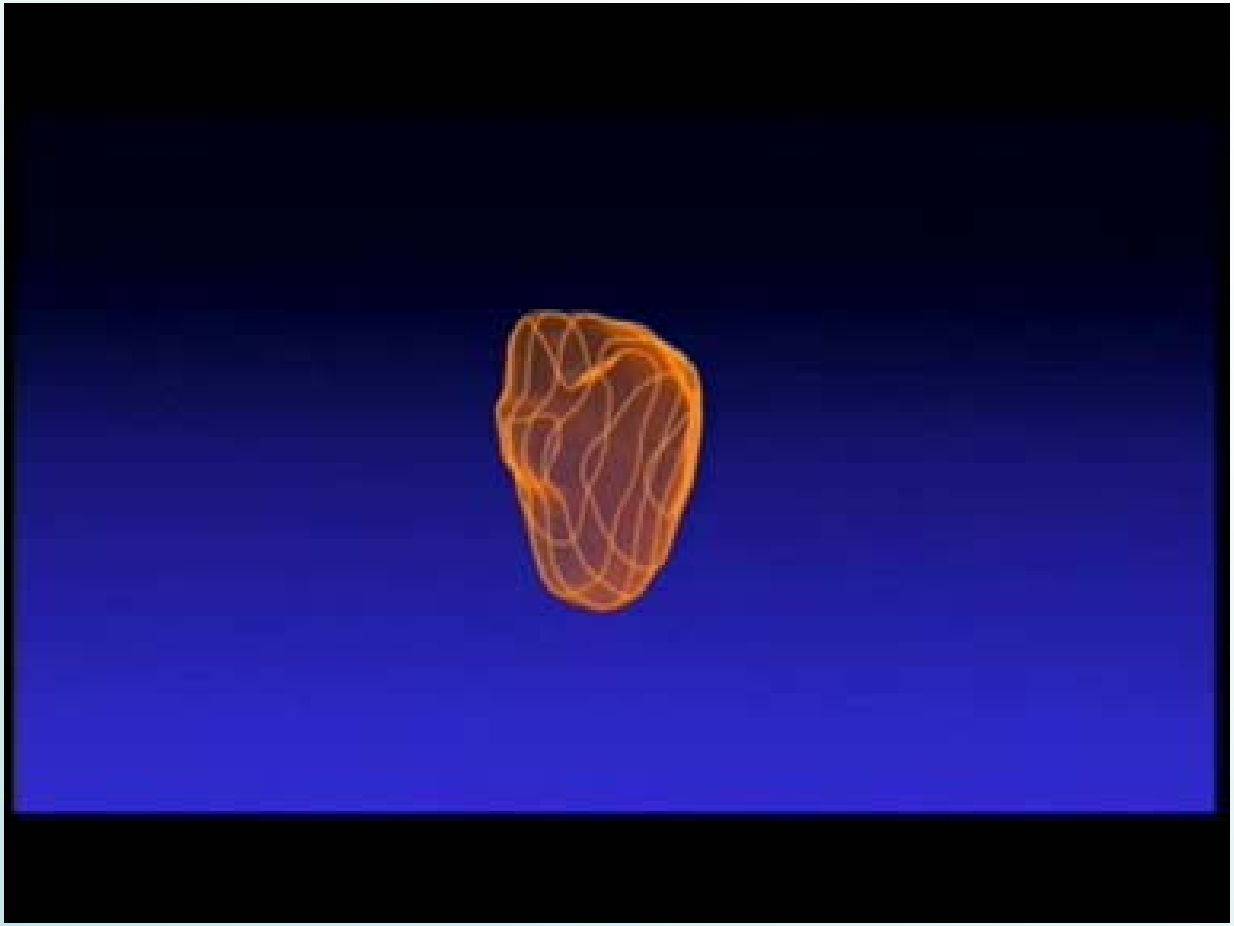
Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

Implications on beam focus & spill structure

"Active" dose application needs a pencil beam with adjustable focus

…and DC like beam structure !

Alternative:
High repetitive pulsed beam with highly stable intensity



Treatment time per voxel ~ some ms

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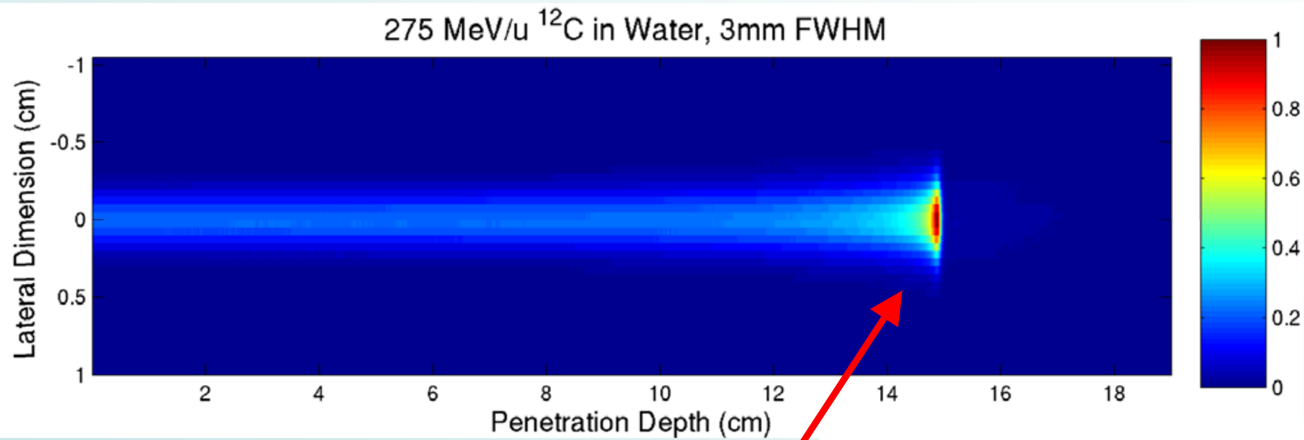
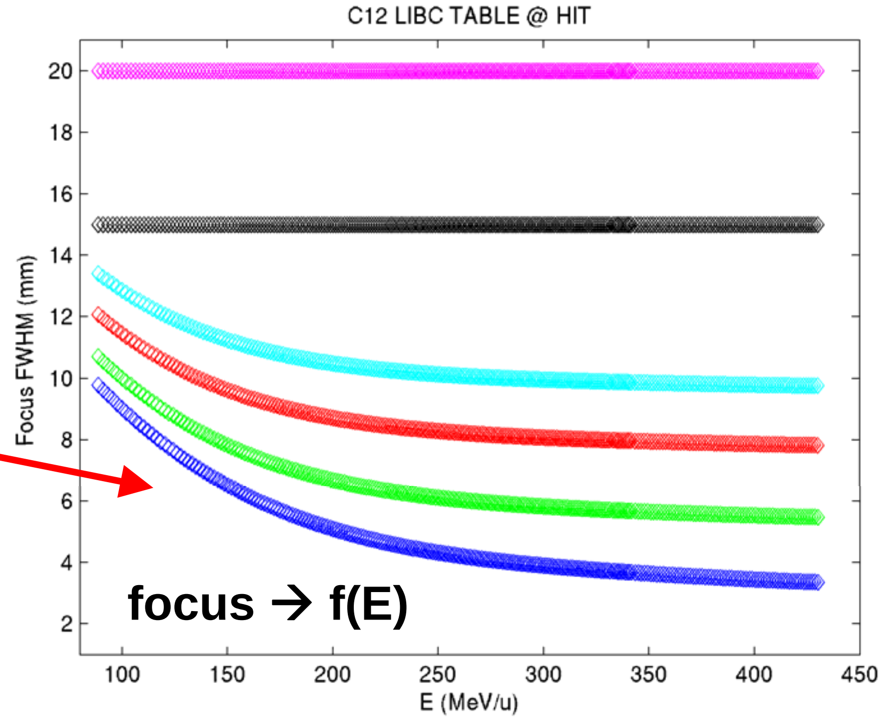
Implications on beam focus & spill structure





Straggling effects must be taken into account!

(vacuum window, dose monitoring system,…)

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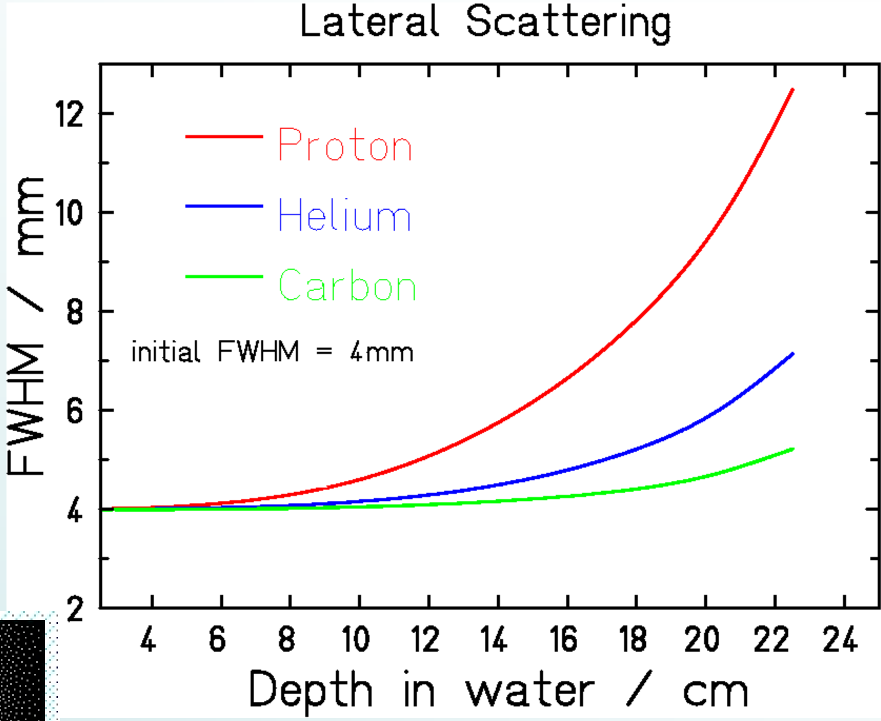
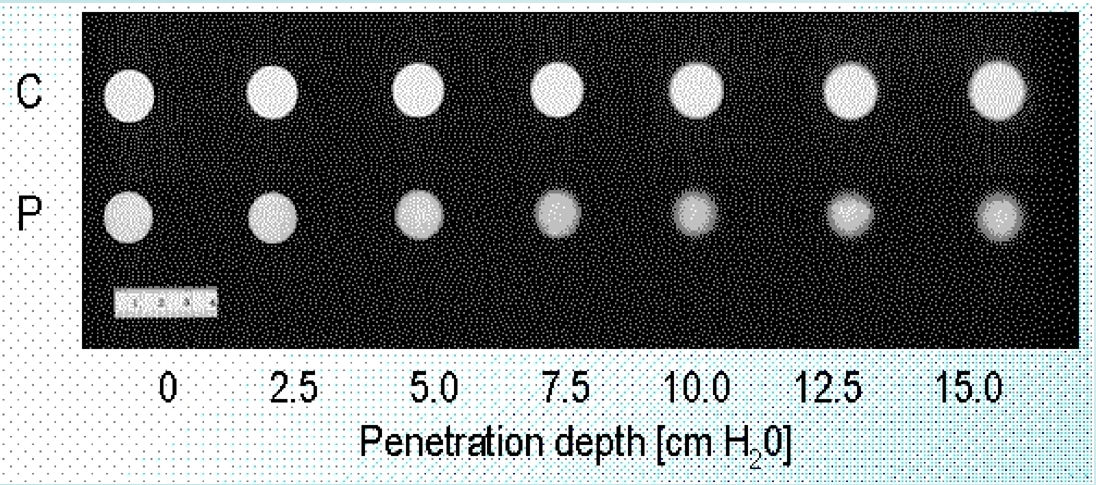
Implications on beam focus & spill structure

Higher local precision with carbon for deep-seated tumour treatment





Implications on the needed beam intensity

- Beam scanning delivers doses from mGy to Gy per voxel (range: 1000).
- The dose directly depends on the LET, which varies by a factor 3 within energy range needed to cover ranges in tissue from 2 - 30 cm in water.
- Theoretically an intensity variation of 3000 is required. For carbon this would be (2 – 6) x 10^9 per second.
- Practically the injector is not able to produce intensities above 10^9 carbon ions per injection pulse for the synchrotron and these very high intensity levels are rarely needed in clinically used treatment plans.
- Therefore (at HIT) the intensity library for carbon covers 2 x 10^6 up to 5 x 10^8 ions per second spread over 15 steps in order to allow for maximum scanning speed, respectively minimum treatment time.
- Protons have less than 50% of the relative biological efficiency compared to carbon and the LET-values are 18-times lower. Consequently the proton intensity settings are 40-times higher than the carbon settings → 8 x 10^7 up to 2 x 10^{10} ions per second

Accelerator technologies used for particle therapy so far: Cyclotrons and synchrotrons

Cyclotrons – principle working scheme

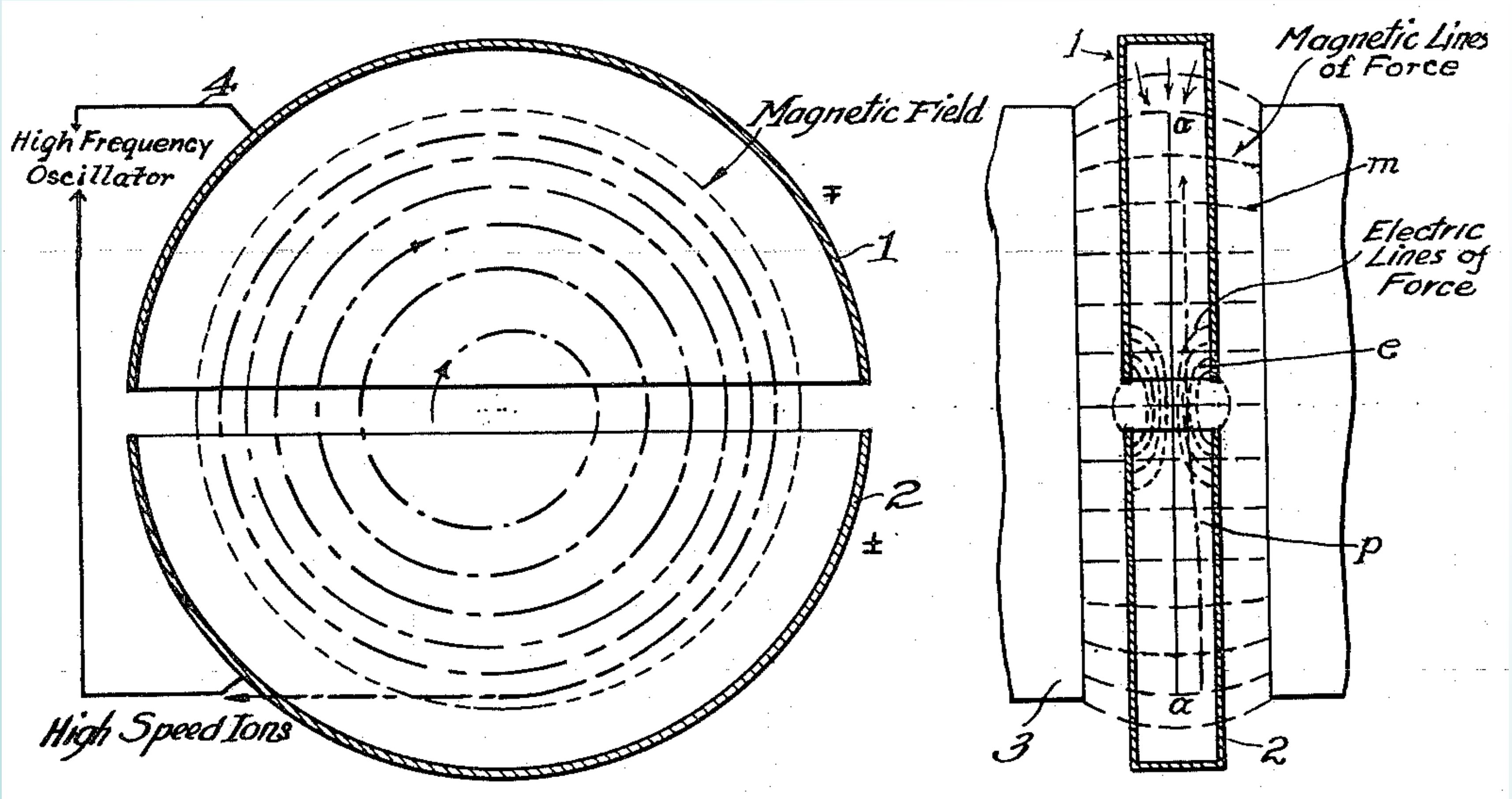
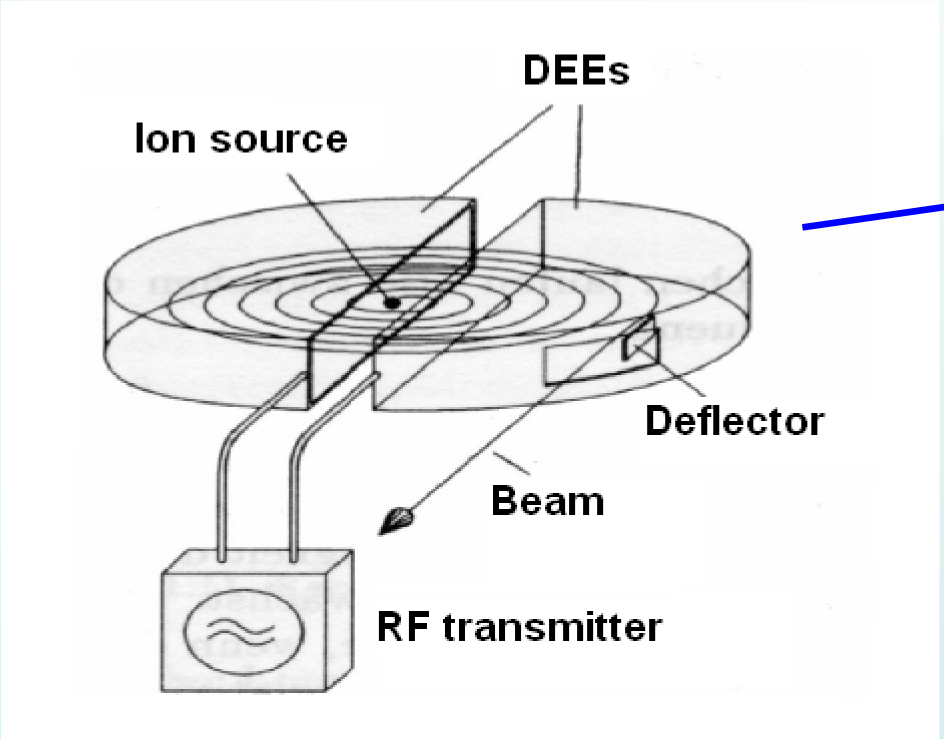
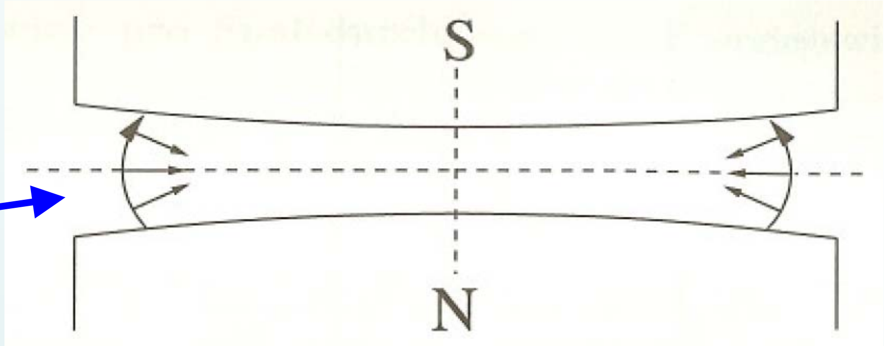


Diagram of cyclotron operation from Lawrence's 1934 patent.

Cyclotrons – principle working scheme





Classical cyclotron with decreasing field B(r)

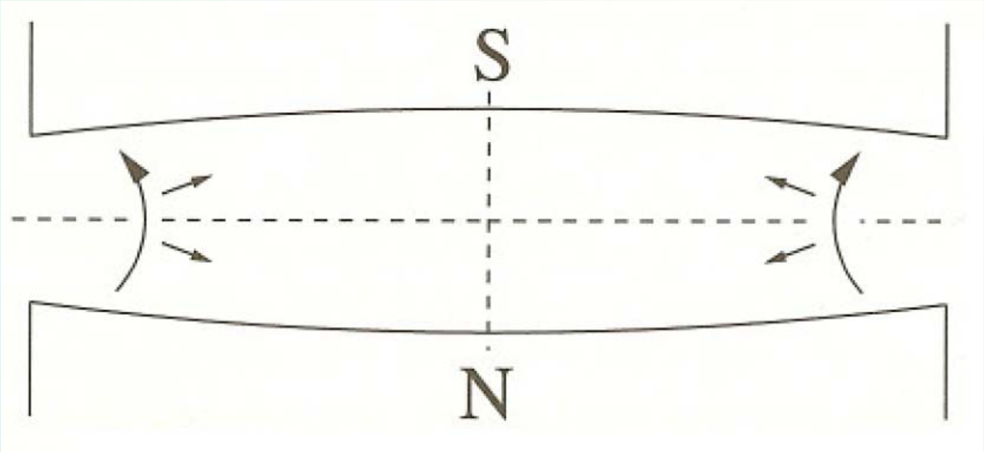
→ Axial focusing

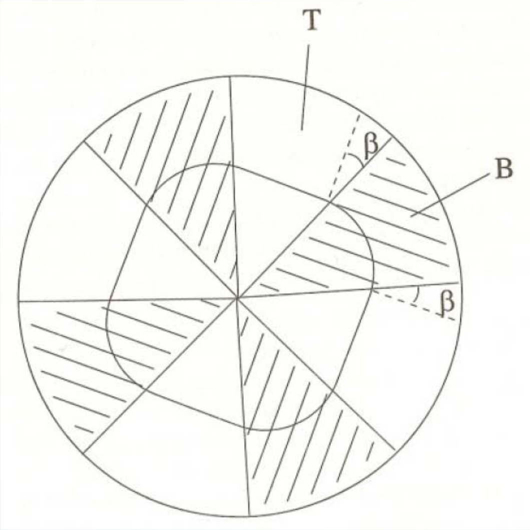
$$f_c = \frac{Bq}{\pi m}$$

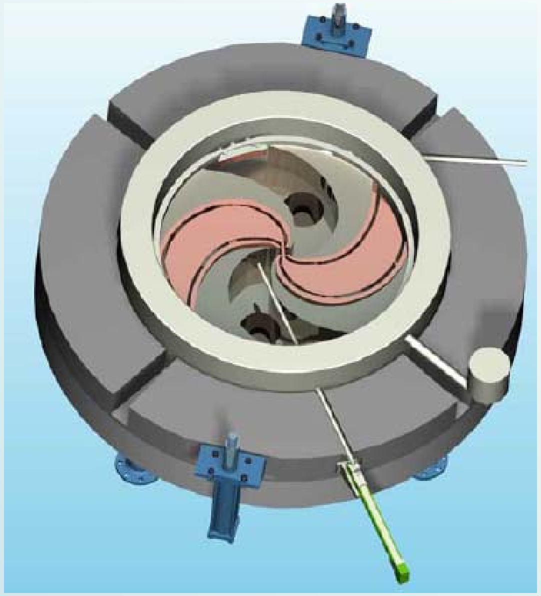
Cyclotron frequency;
needs modification in relativistic case!

$$f = f_c\sqrt{1-\left(\frac{v}{c}\right)^2}$$

Cyclotrons – principle working scheme







For higher energies (needed for PT) the isochronous cyclotron type is in use with increasing B(r) → axial defocusing must be compensated by "strong focusing", which is realized by sectoring the magnet and resulting edge focusing

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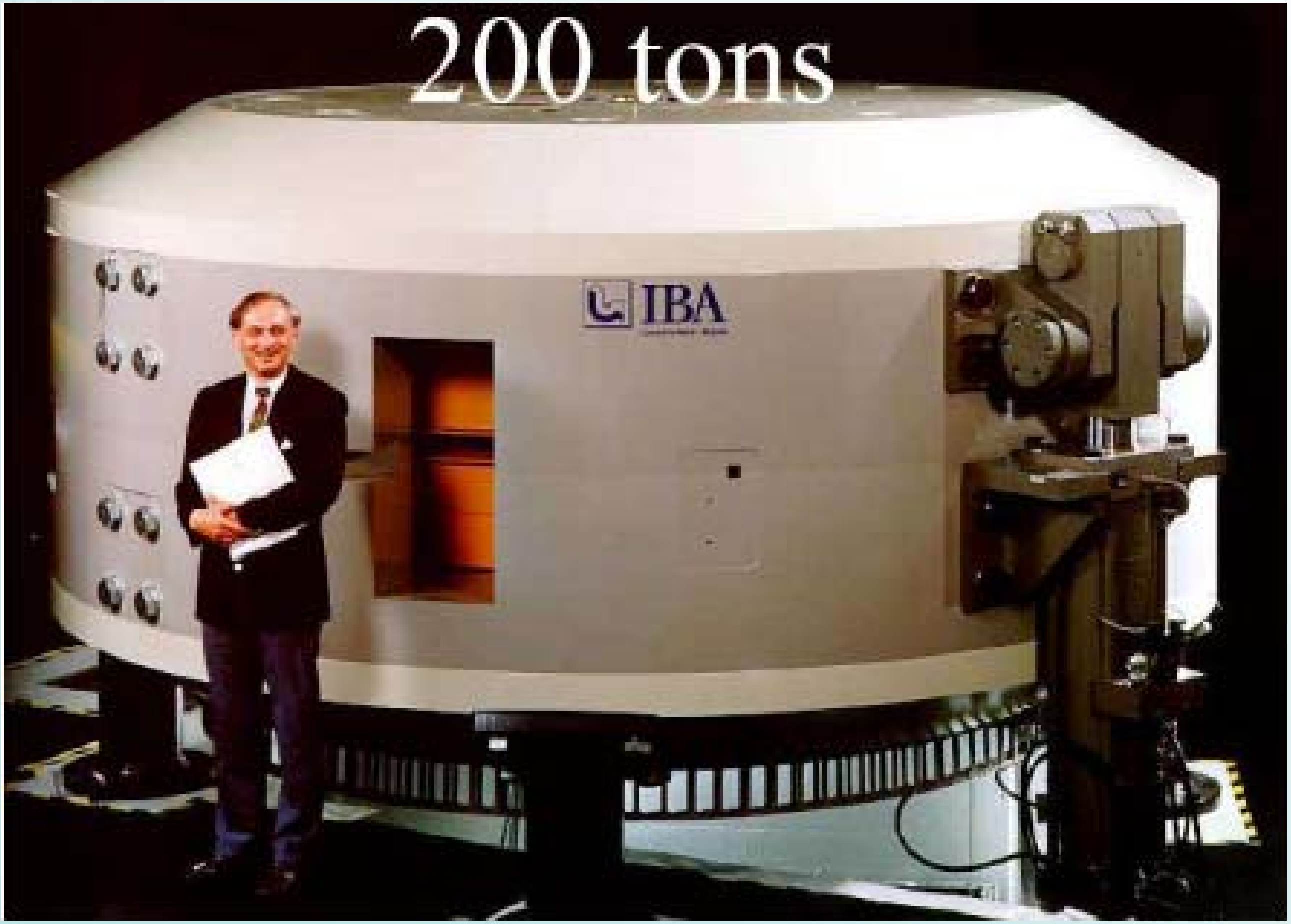
Cyclotrons – example



IBA PT proton cyclotron

E = 230 MeV

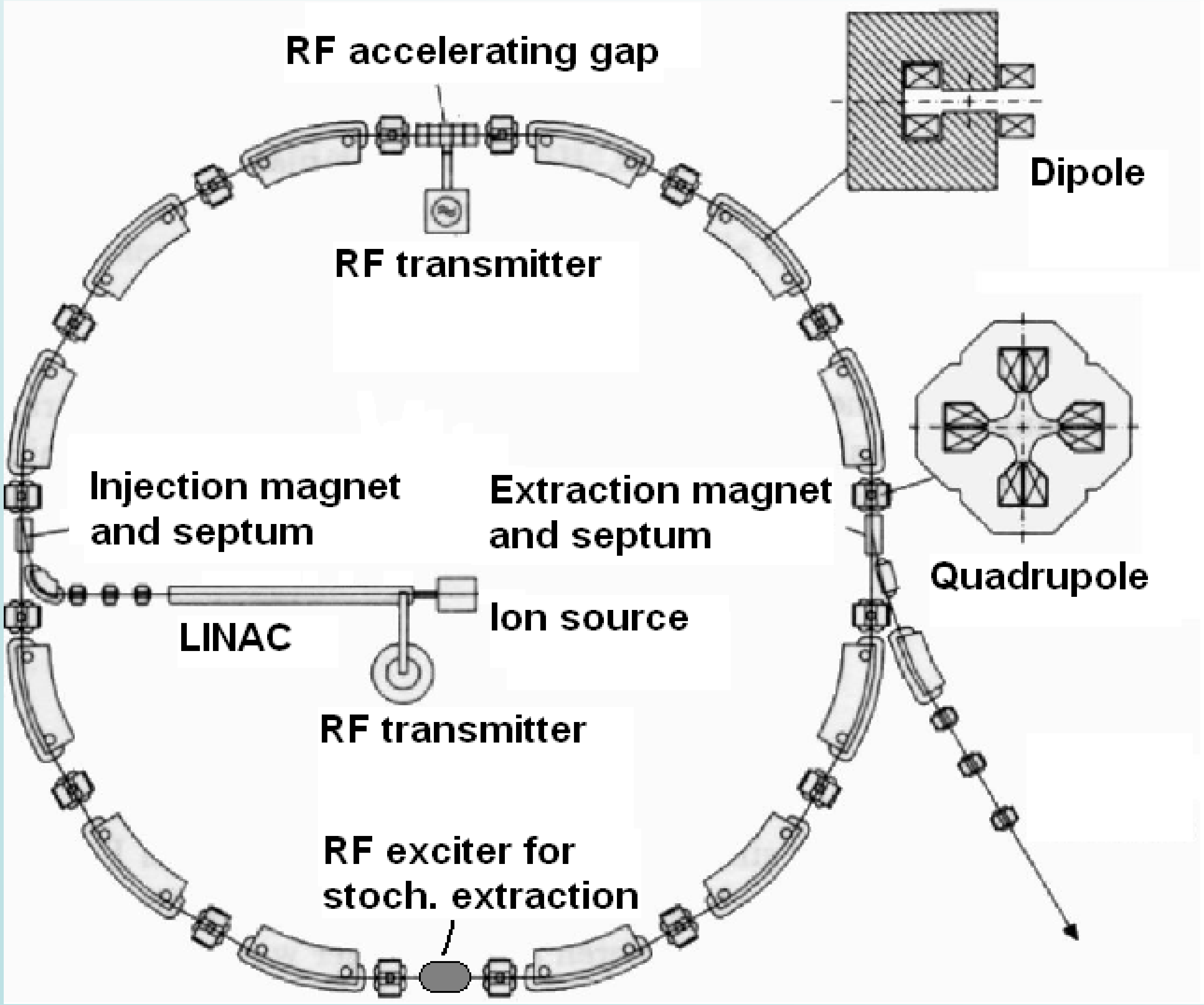
B_{max} = 3 T

(Saturated field)

Ø = 4 m

1st installation at MGH, Boston/USA
10 more worldwide

Synchrotrons – principle layout



Injector linac with energies of some MeV/u:
→ v ~ 10% c

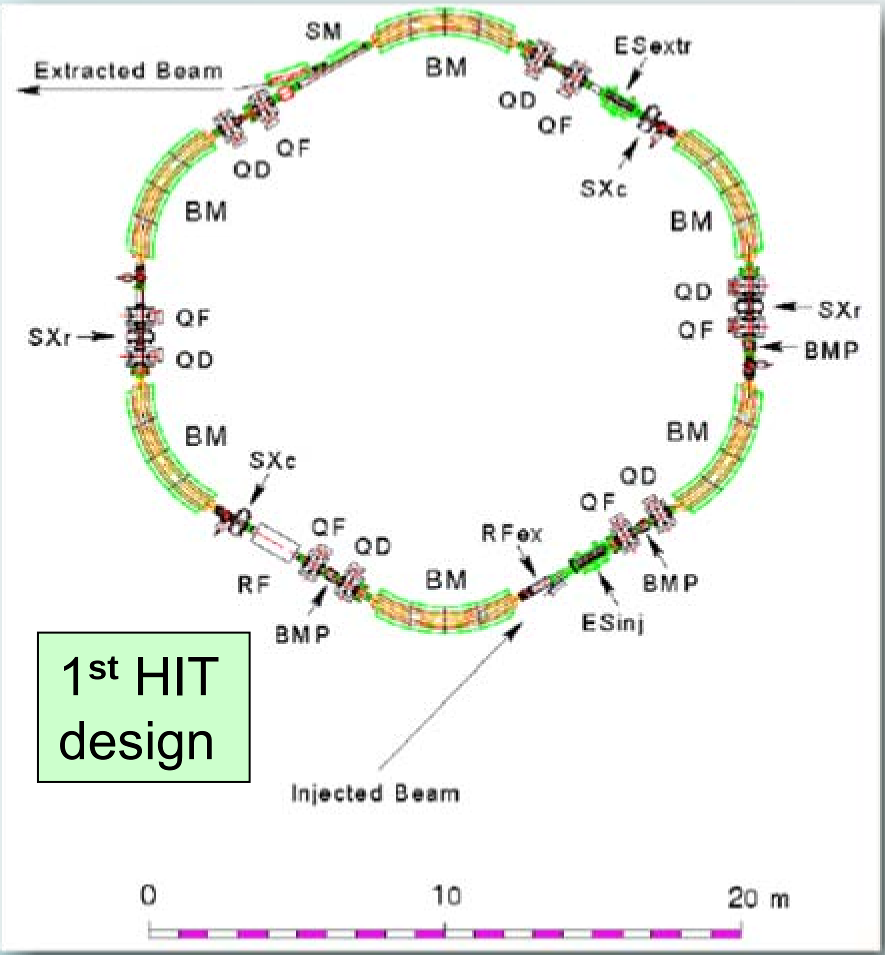
Magnetic rigidity:
p → 2,26 Tm
C → 6,6 Tm

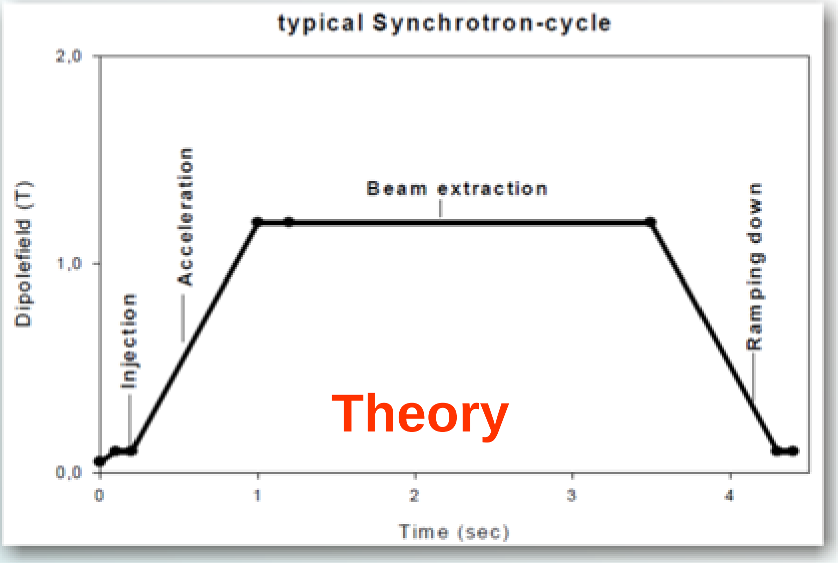
With ~ 50% fill factor for dipoles:

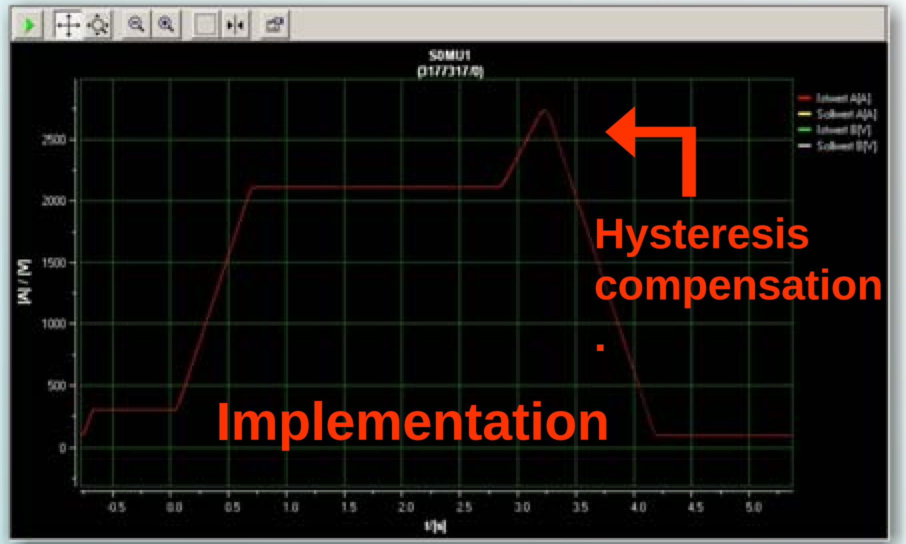
p → $Ø_{Sync}$ ~ 6 m

C → $Ø_{Sync}$ ~ 18 m

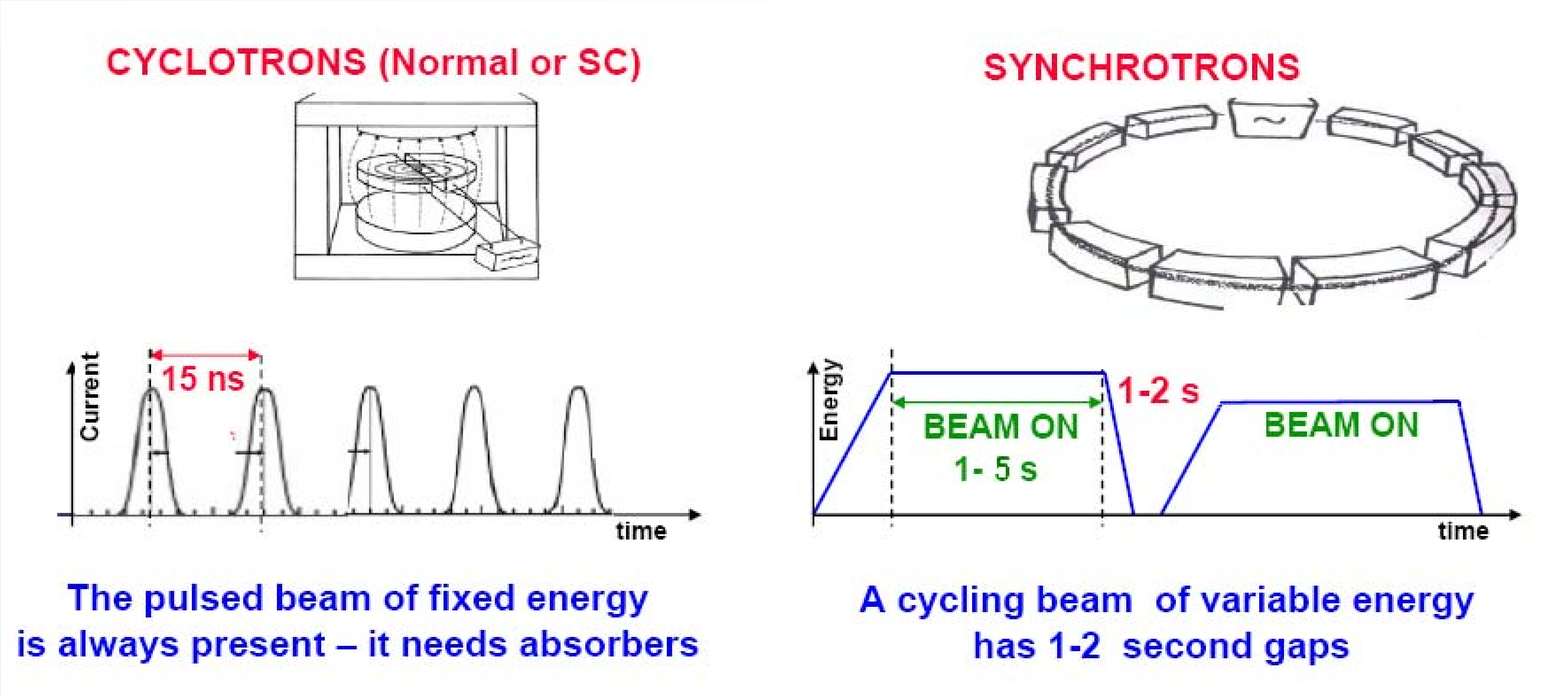
Synchrotrons – cyclic operation mode







Cyclotrons and Synchrotrons – a comparison



Persisting cw beam

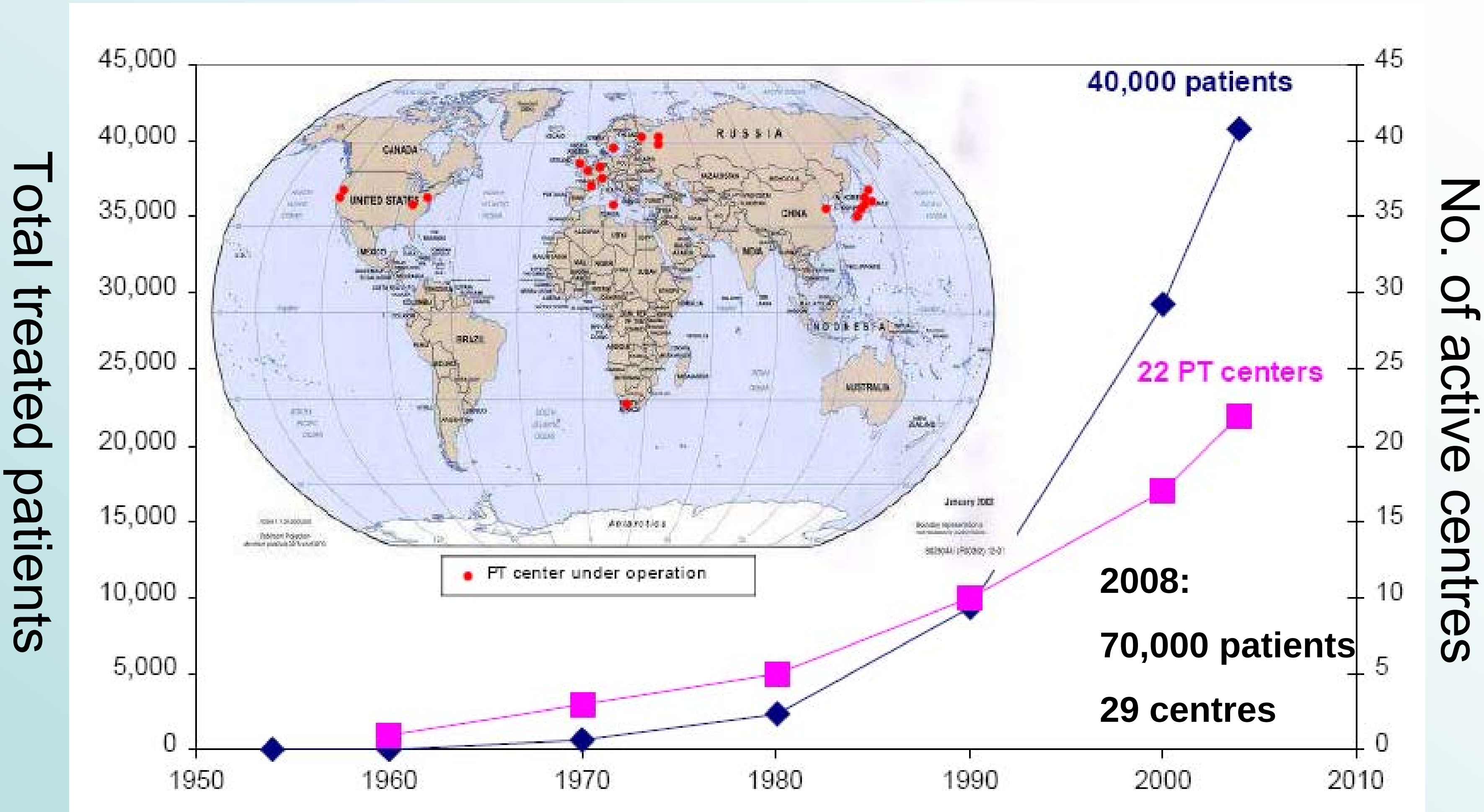
Discontinuous “dc beam”

Passive energy variation
(degrader → high local beam loss!)

Active energy variation

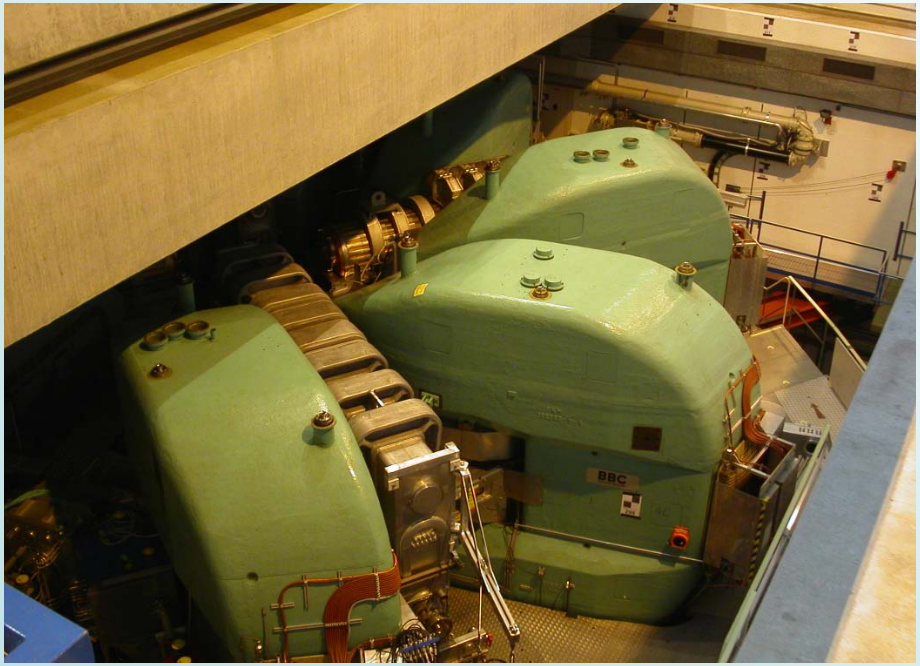
Particle therapy facilities worldwide - an overview and some examples in detail: PSI/Switzerland, LomaLinda/USA, HIMAC/Japan, HIT/Heidelberg

Particle Therapy Facilities - worldwide



PT centres: a rapid growing market

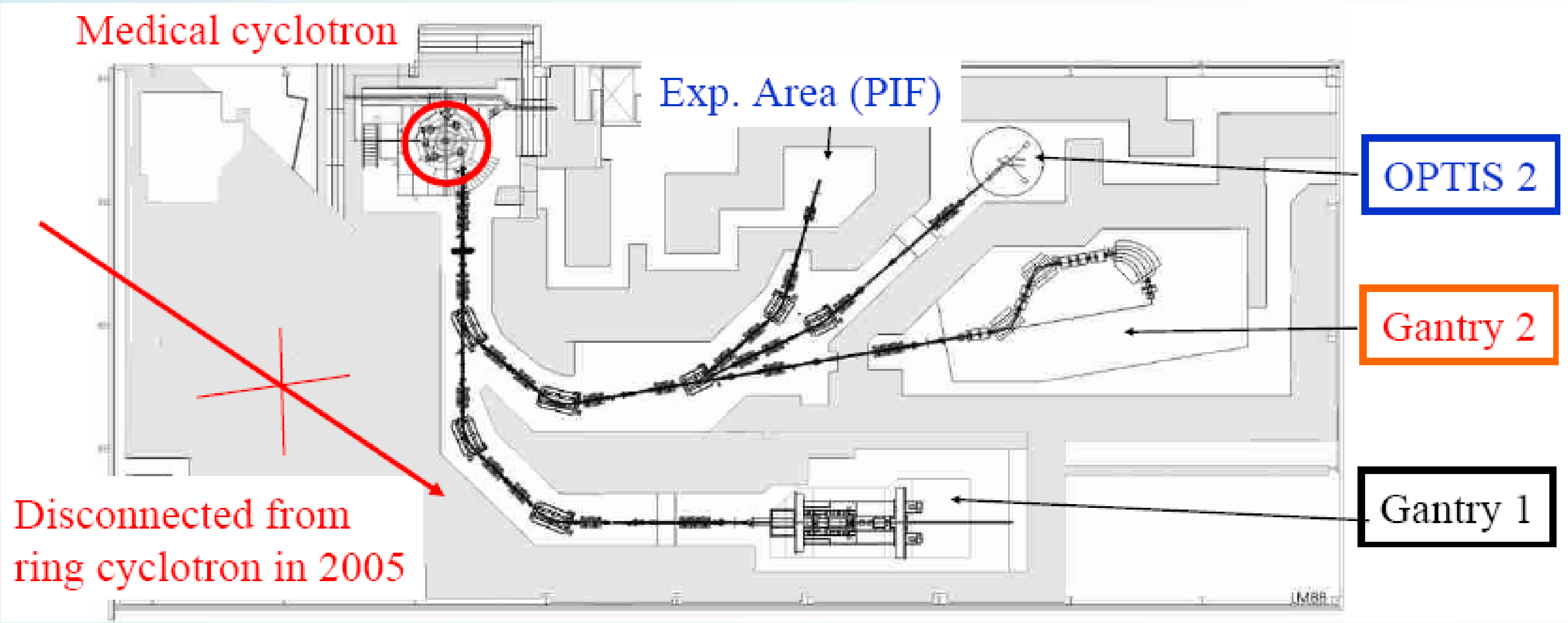
Particle Therapy Facilities – PSI/Switzerland



590 MeV proton cyclotron for basic research; therapy beam slowed down by large degrader system since 1984
(Set-up with Gantry: 1996 – 2005)

Gantry 1 for proton treatment with 1D spot scanning technique

Particle Therapy Facilities – PSI/Switzerland



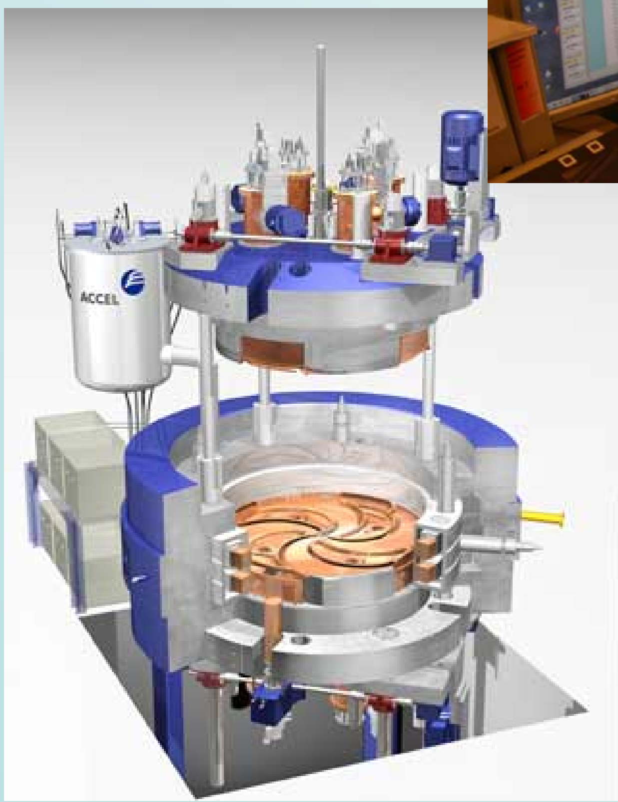
PROSCAN facility as it looks today
(Gantry 2 still under commissioning)

5,500 patients
treated since 2008
(mainly eyes)

Particle Therapy Facilities – PSI/Switzerland

Control Room

Gantry 2

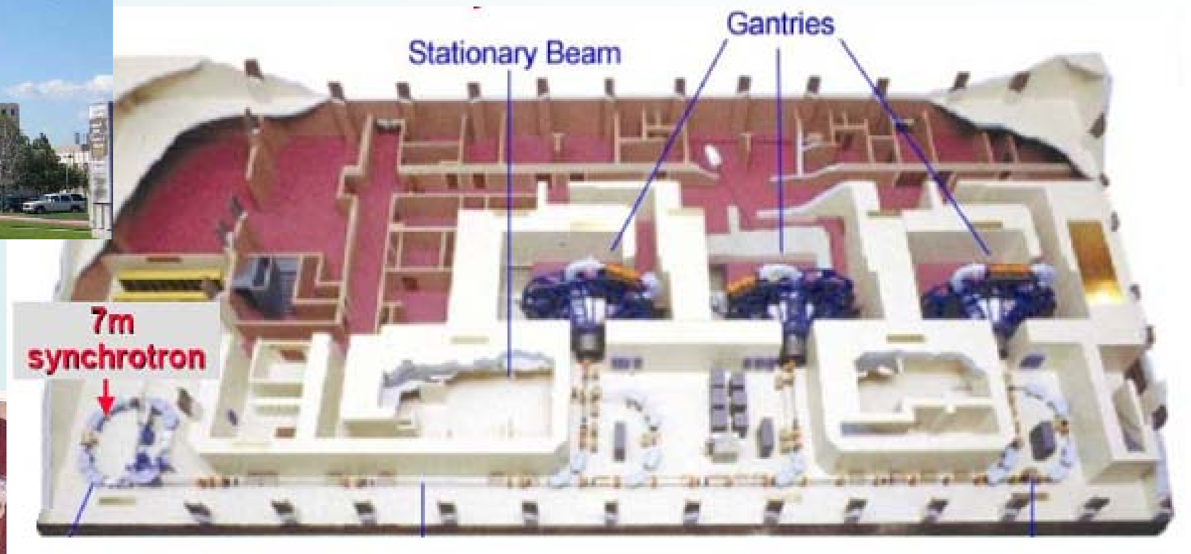


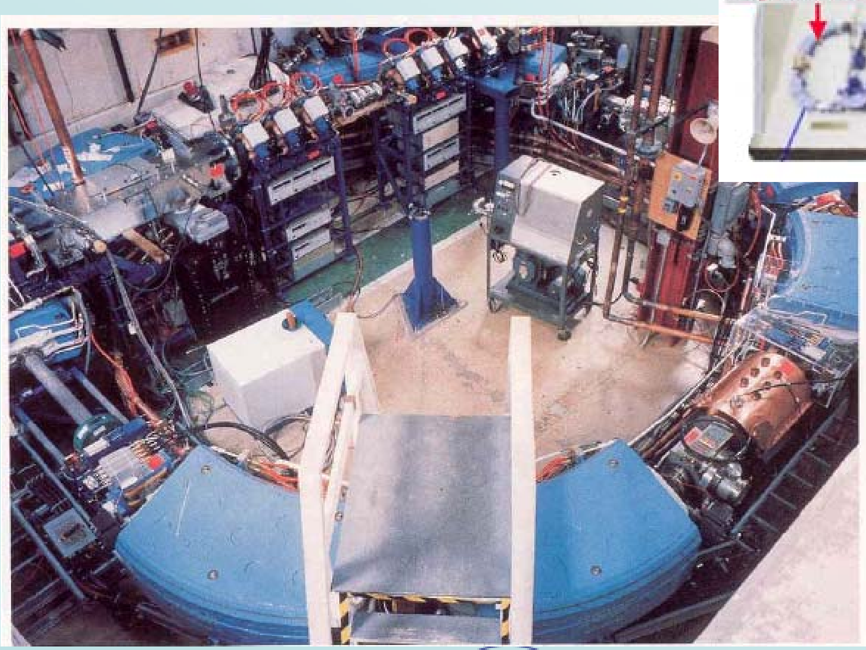
New Super-conducting Cyclotron:

B = 4.5 T
Ø = 3 m
M = 80 tons
E = 250 MeV

Particle Therapy Facilities – Loma Linda/USA

13,500 patients treated





1st hospital based proton therapy centre (since 1990) using a synchrotron – designed and commissioned by Fermilab

2005: 160 sessions/day

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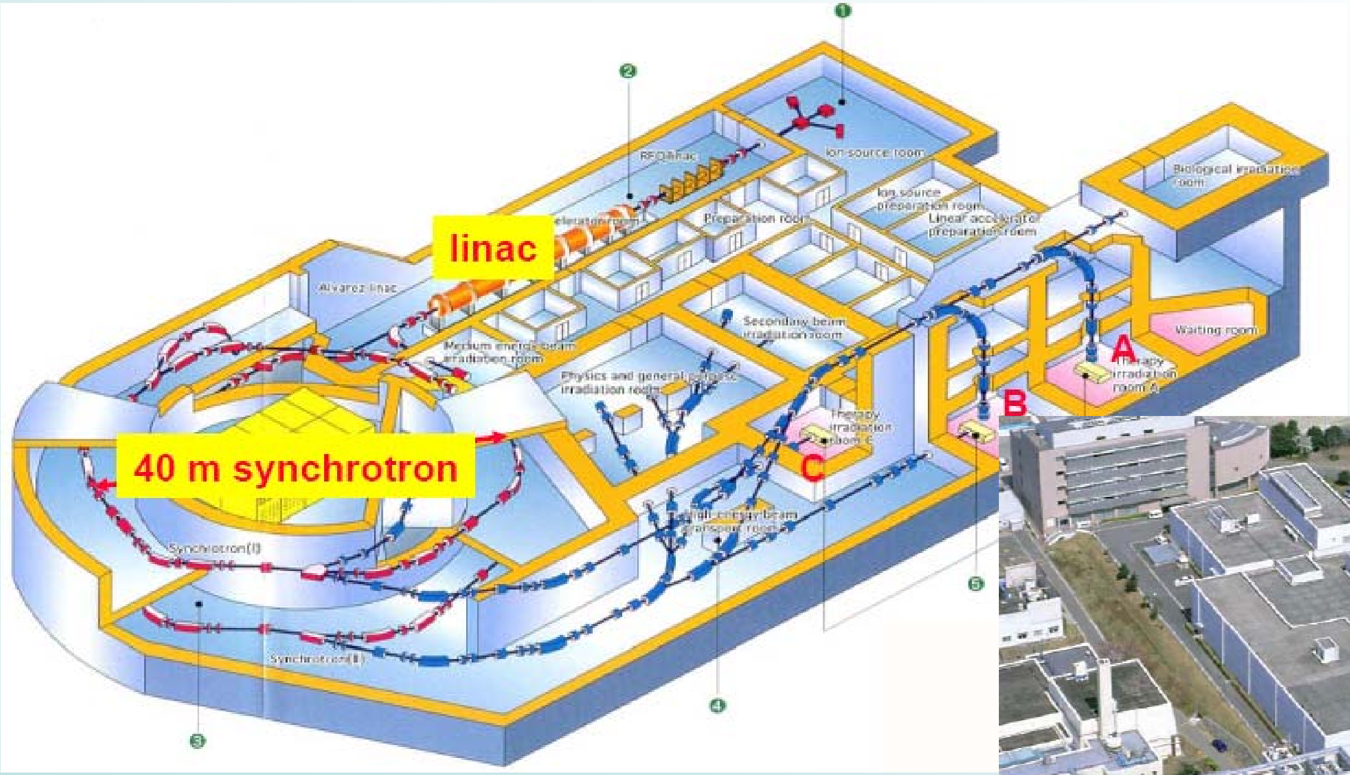
Particle Therapy Facilities – HIMAC/Japan



The Heavy Ion Medical Accelerator of NIRS (since 1994)

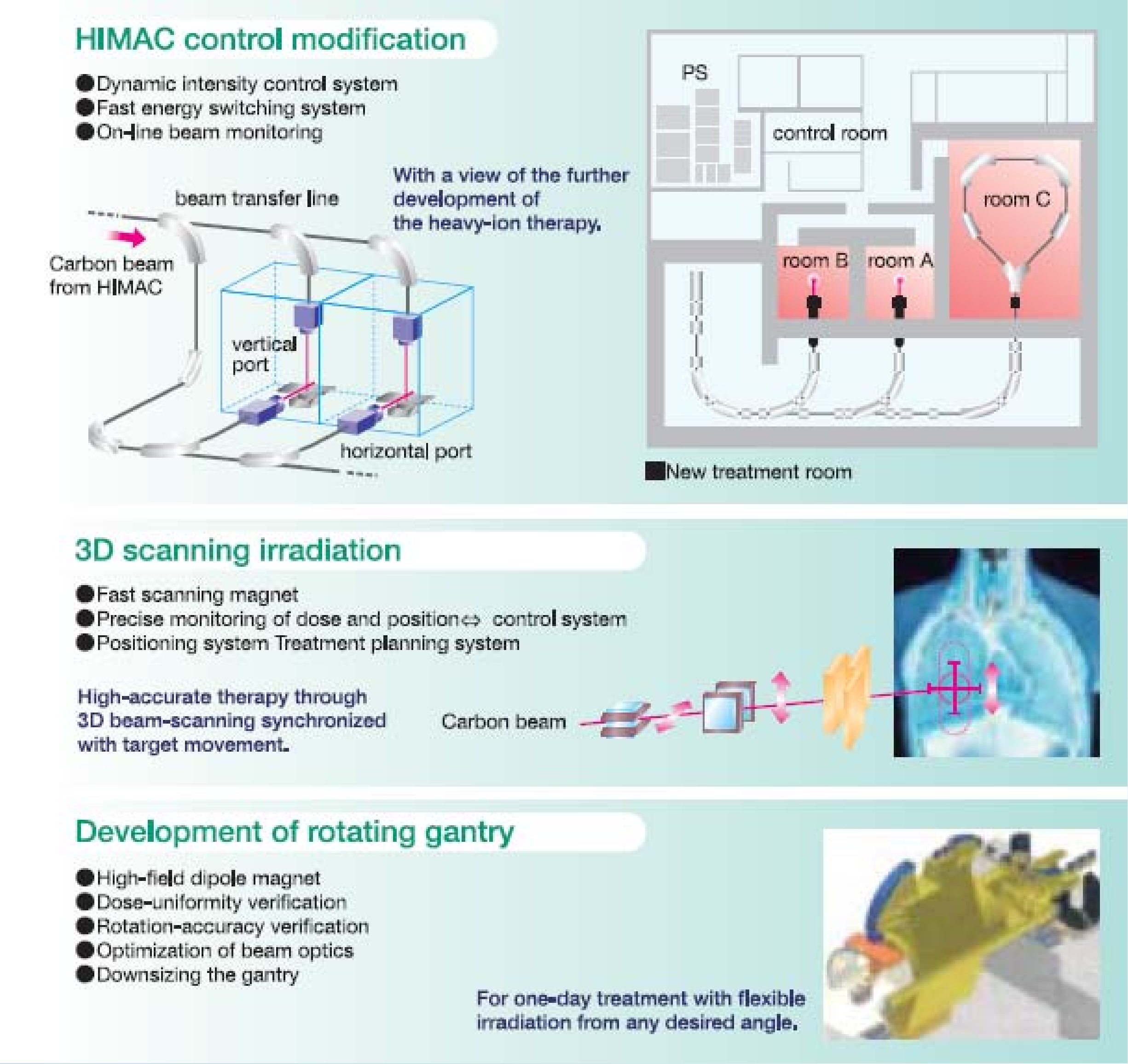
Two identical 800 MeV/u synchrotrons for ions up to Argon; mainly Carbon is used

4,500 patients treated

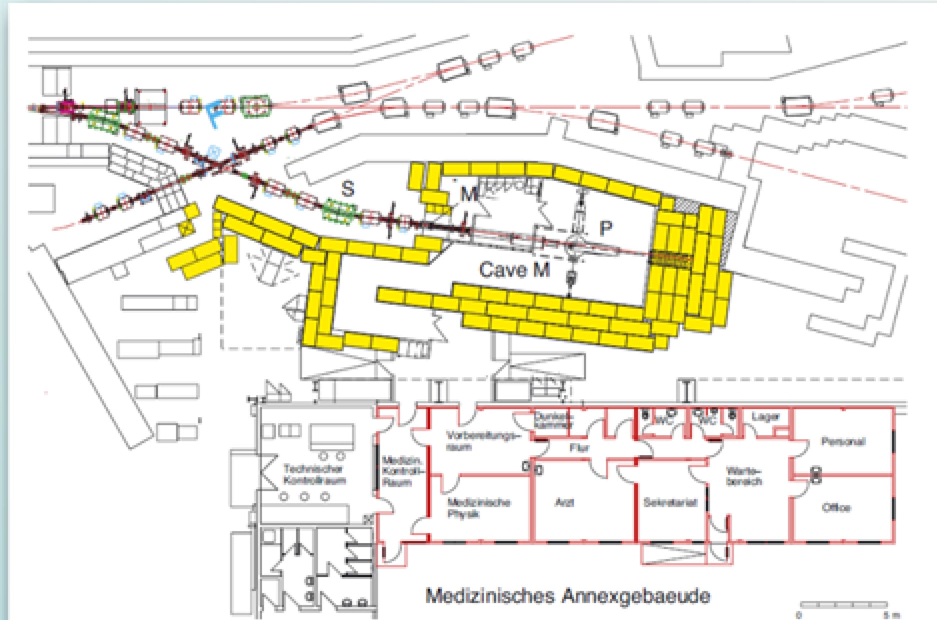
Particle Therapy Facilities – HIMAC/Japan

Development programme of advanced techniques at NIRS/HIMAC

(NIRS: National Institute of Radiological Sciences)



Particle Therapy Facilities – HIT/Heidelberg



HIT concept and layout is based on experience from GSI; 448 patients were treated with carbon beams from 1997 – 2008 using raster scanning technique

HIT
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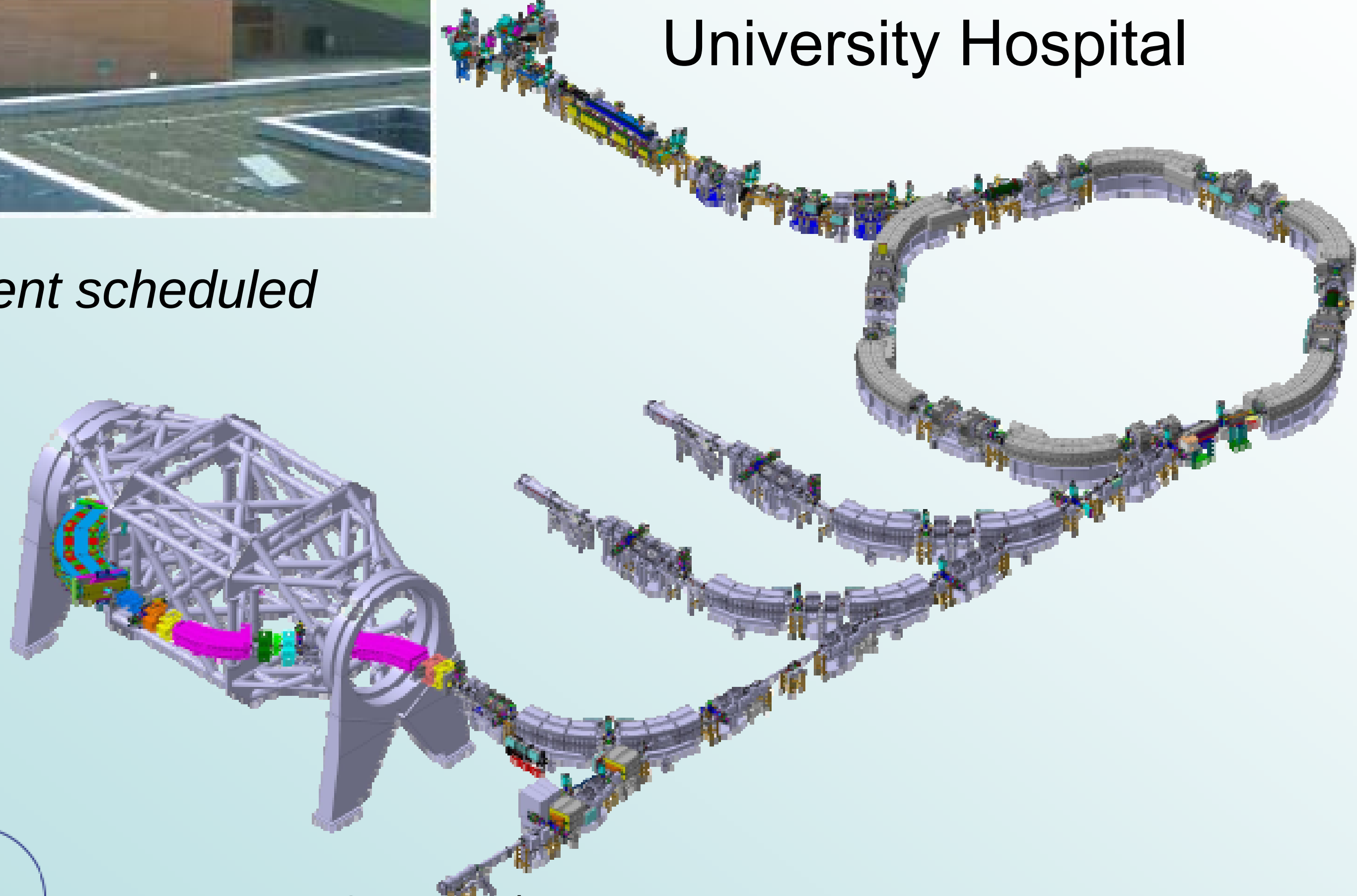
Particle Therapy Facilities – HIT/Heidelberg

Compact building (60 x 70 m², 3 levels), directly linked to the "Head Clinics" of the University Hospital

Start of patient treatment scheduled in Q4/2009

At present debugging and stabilization of treatment application system and IT work-flow are underway



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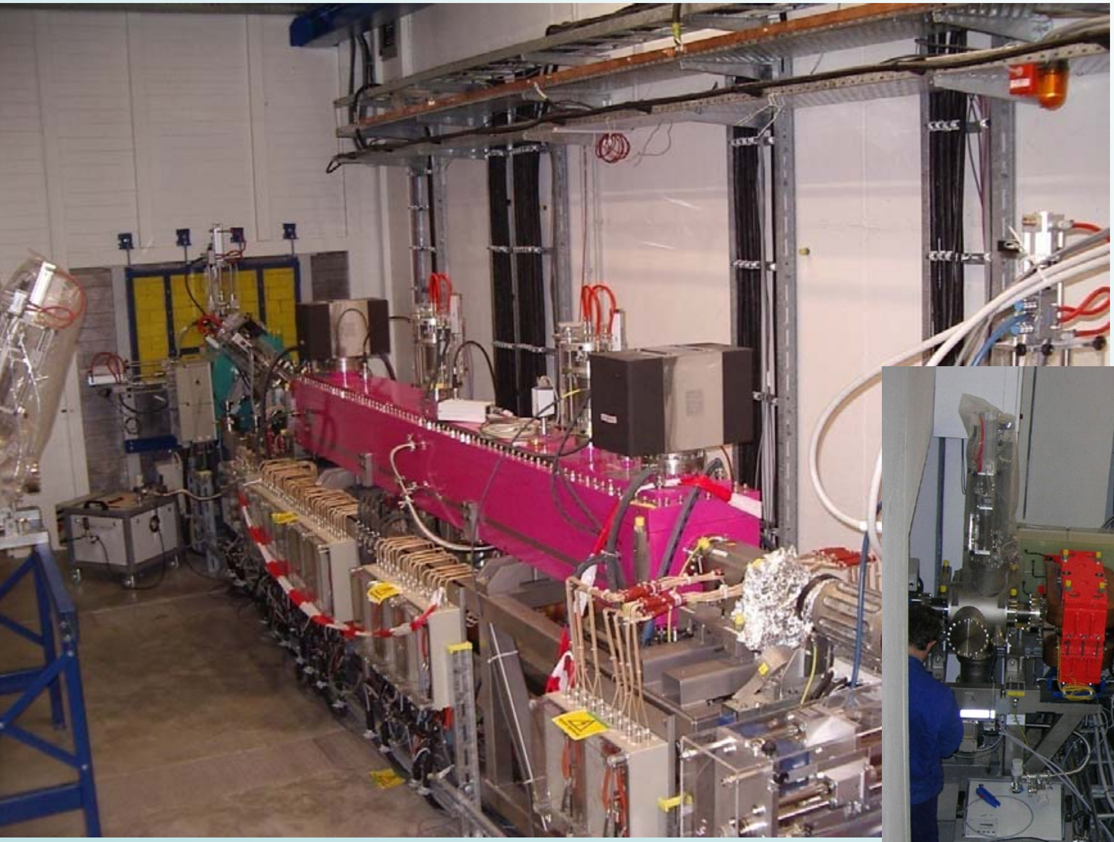
Particle Therapy Facilities – HIT/Heidelberg

- **Ions : p $^{3}He^{2+}$ $^{12}C^{6}$ $^{16}O^{8+}$**
- **Energies (MeV/u) : 48-220 72-330 88-430 102-430**
  (255 steps)
- **Beam spot size : 4 - 10 mm (2d-gaussian)**
  (4 steps)

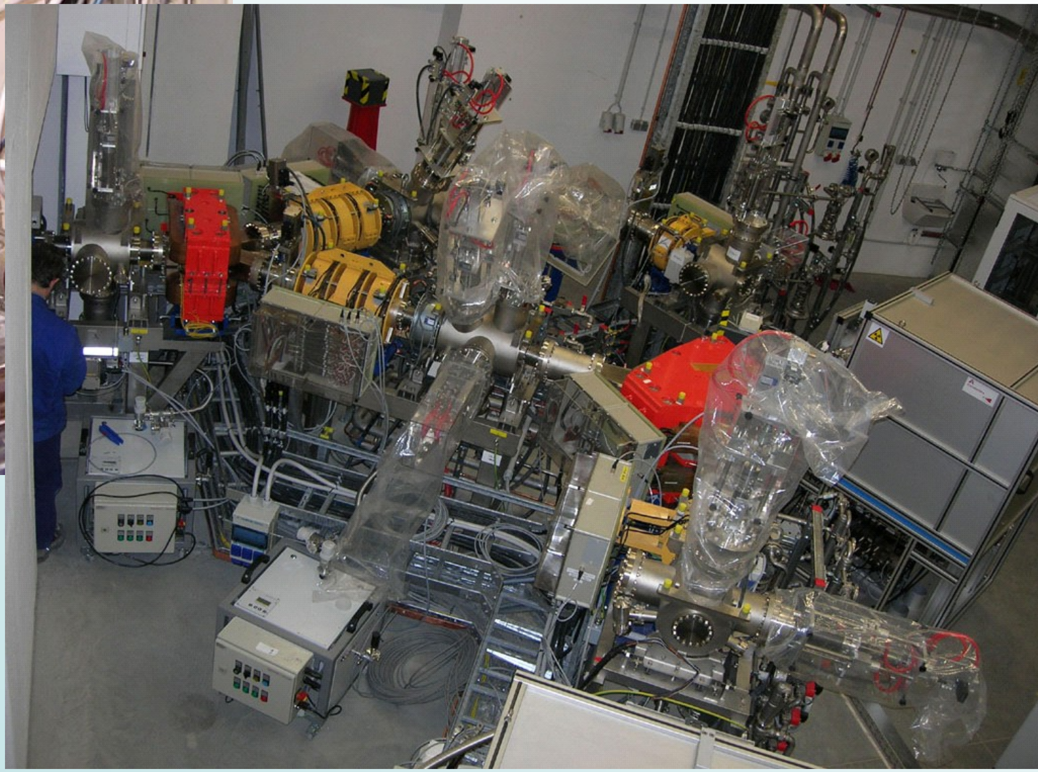
Ions	p	$^{3}He^{2+}$	$^{12}C^{6}$	$^{16}O^{8+}$
Energies (MeV/u) (255 steps)	48 -220	72 -330	88 -430	102 -430

- **Treatment caves: 3**
  (2 horizontal, 1 iso-centric gantry)
- **QA and Research: 1 (1 horizontal)**

Particle Therapy Facilities – HIT/Heidelberg



Injector: 2 ECR ion sources (8 keV/u) and following RFQ and IH-DTL linac → 7 MeV/u



Particle Therapy Facilities – HIT/Heidelberg

Synchrotron

High energy beam transport (HEBT)

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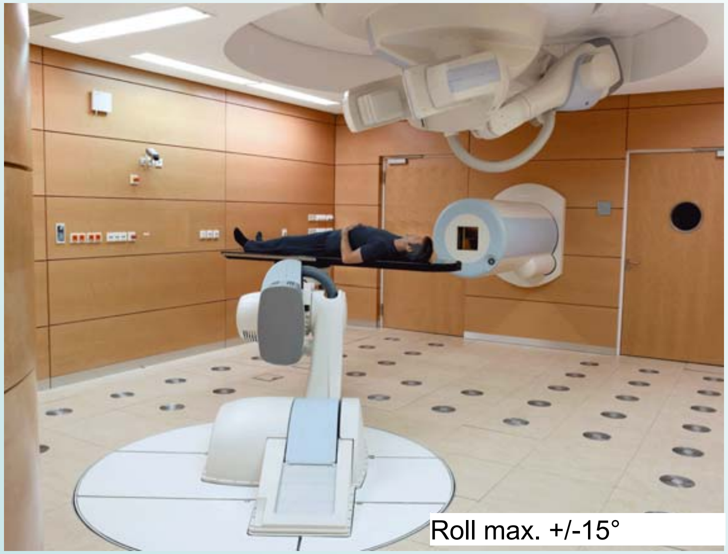
Particle Therapy Facilities – HIT/Heidelberg


Isocentric Rotation +/-100°


Pitch max. +/-15°


Step On Position 650 mm


Roll max. +/-15°

Horizontal Treatment Place

Particle Therapy Facilities – HIT/Heidelberg

Worldwide first isocentric ion gantry – including a scanning system:

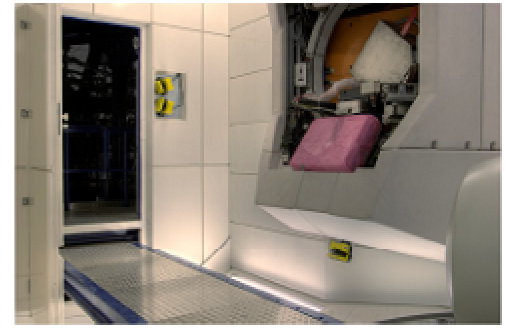
Ø = 13m
25m long

600 tons overall weight

0.5 mm max. deformation

Particle Therapy Facilities – HIT/Heidelberg

Patient Gantry Room



Tilt floor, pending on Gantry position

Nozzle

Bumber mats

Patienttable, Roboter

A short excursion: Use of common detector systems for accelerator beam diagnostics and dose monitoring for the treatment - high-precision ionization chambers (IC) and multi-wire proportional chambers (MWPC); Examples from PSI and HIT

Detectors for beam monitoring

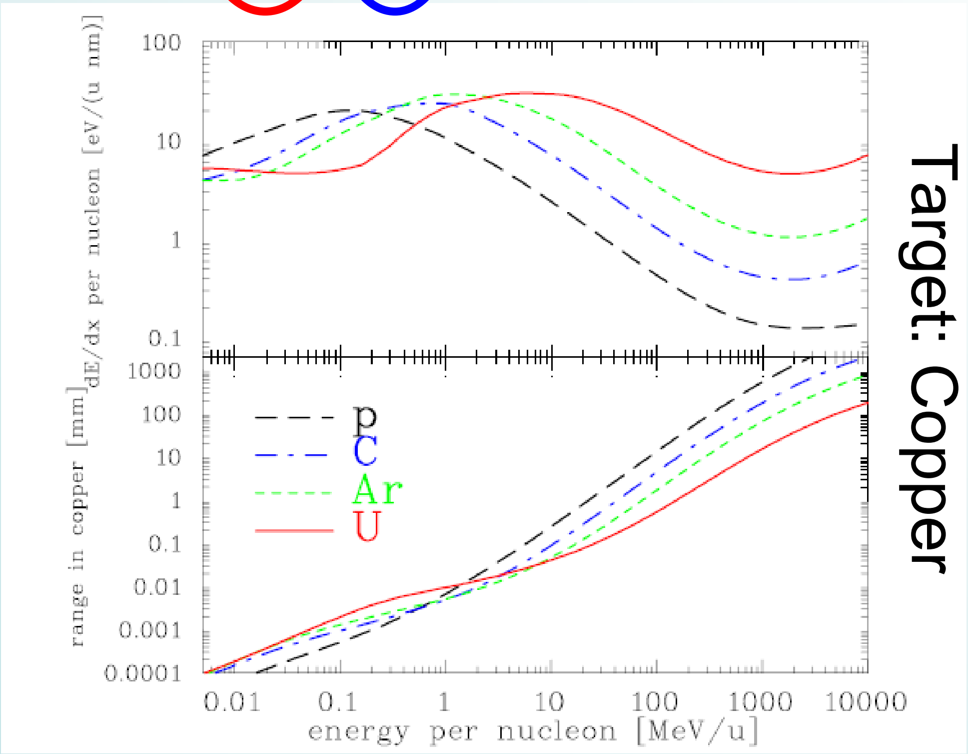
All beam diagnostics equipment used to monitor the beam intensity and position / profiles (HEBT!) is based on energy loss in matter (mainly gases) → electronic stopping:

Bethe Bloch-Equation:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \frac{Z_t}{A_t}\rho \frac{Z_p^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2\right]$$

Target:
Charge & Mass (Z, A),
Density (ρ), Ionization Potential (I)

Projectile:
effective charge (Z_p),
Velocity (γ, β)



Target: Copper

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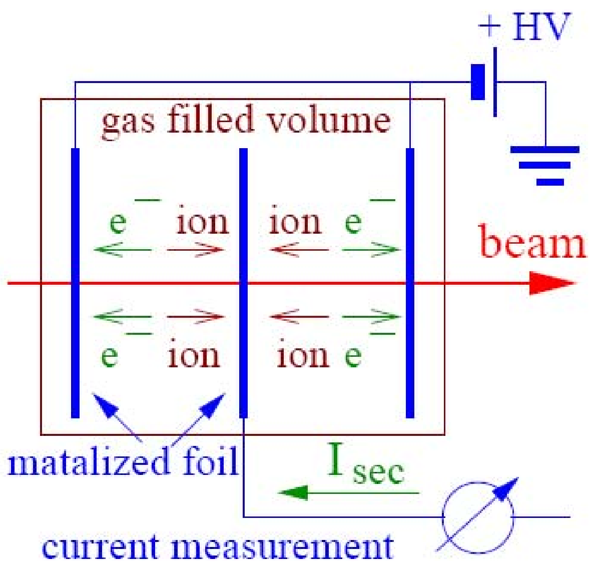
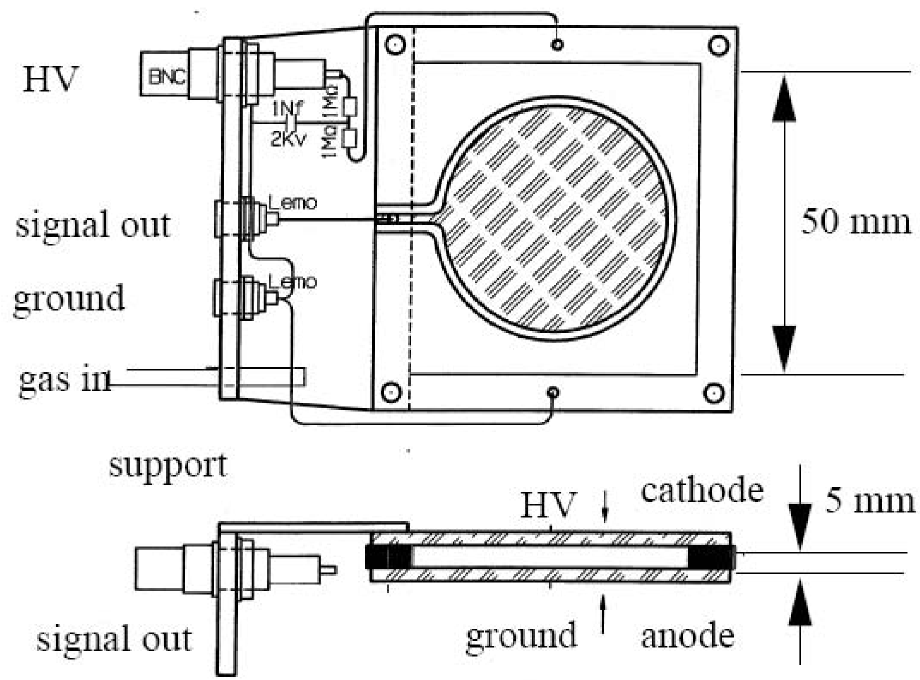
Detectors for beam monitoring - intensity

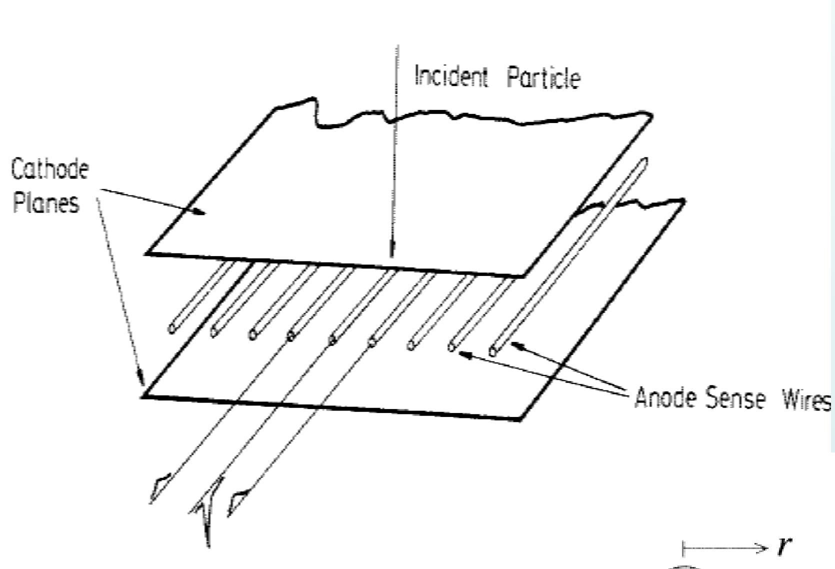




Principle layout (left figure) and example implementation (at GSI) with used parameters to work in the proportional regime

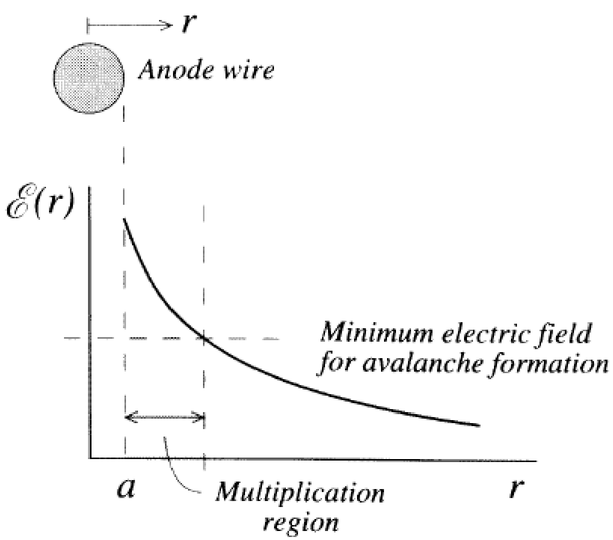
active surface	64×64 mm^2
active length	5 mm
electrode material	1.5 μm Mylar
coating	100 $\mu g/cm^2$ silver
gas (flowing)	80 % Ar + 20 % CO_2
pressure	1 bar
voltage	500 ... 2000 V

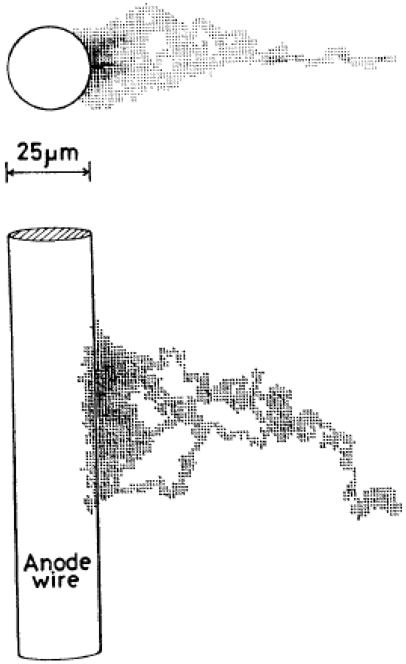
Detectors for beam monitoring - profile



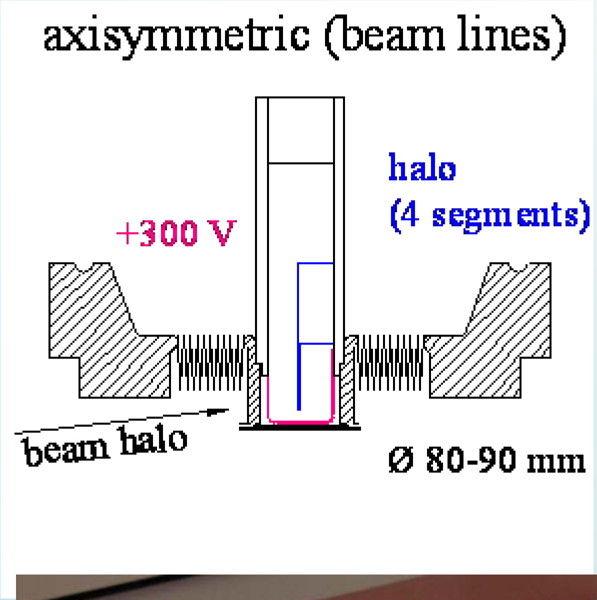
Principle layout of a Multi-wire proportional chamber (MWPC)

Electric field close to the anode wires with region of amplification (up to 10^4 typ.)

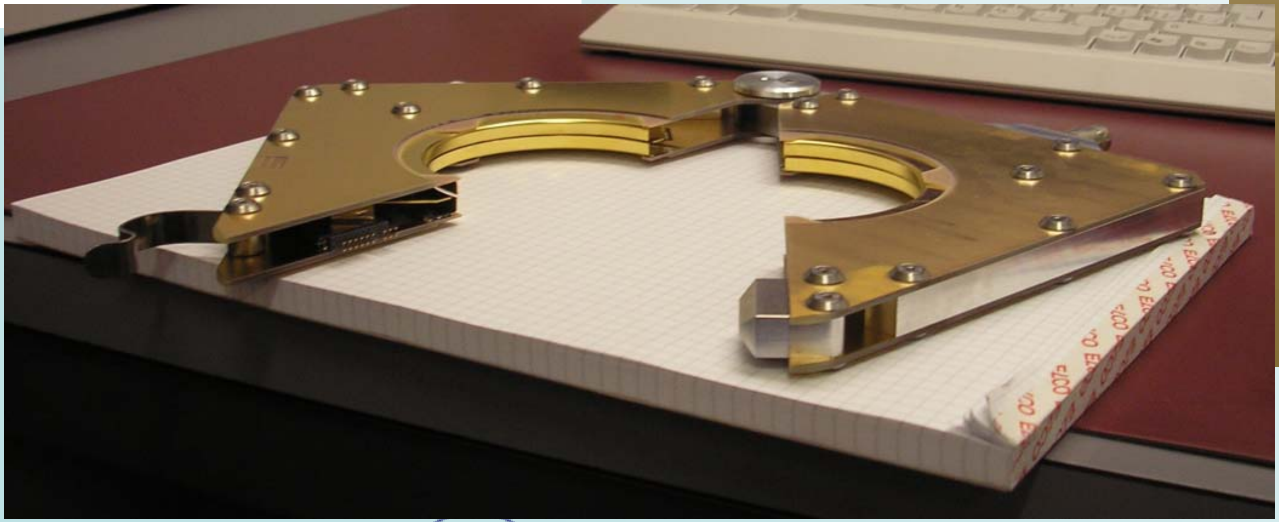


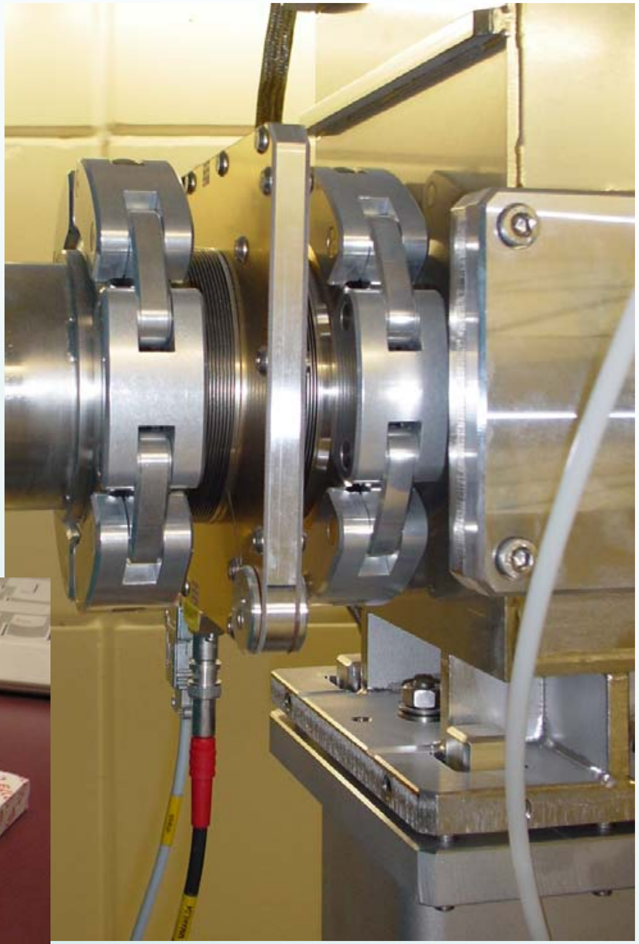


Detectors for beam monitoring - examples



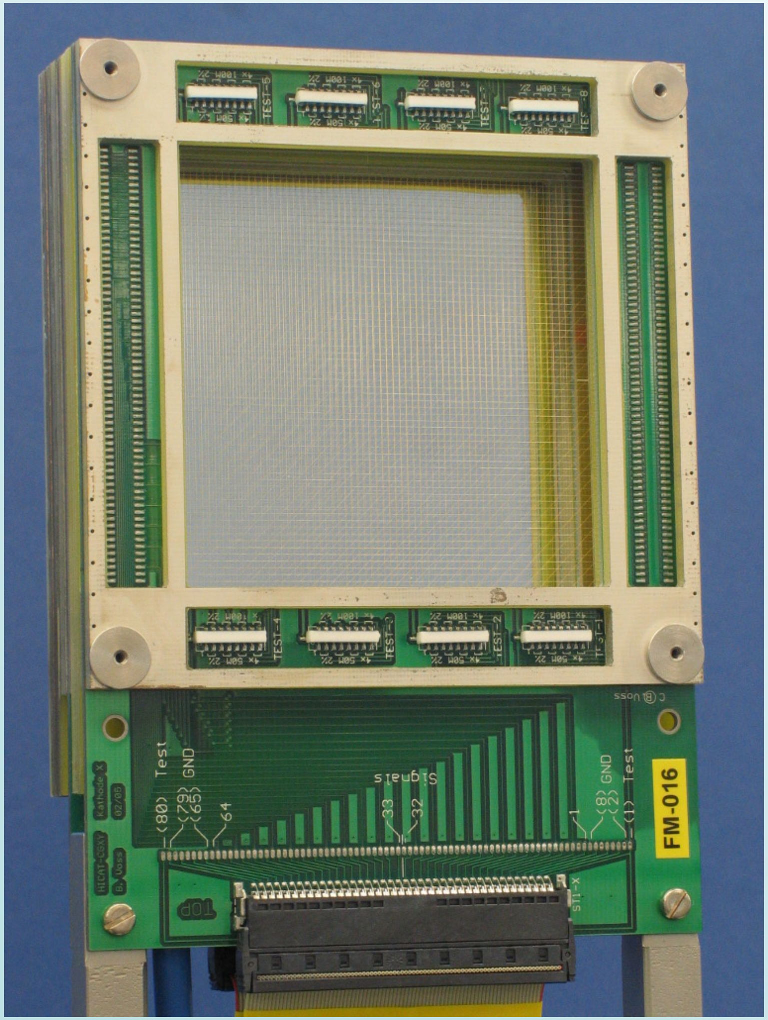
PSI: Ionisation chamber used as a halo monitor in the high intensity region





IC folded around bellow

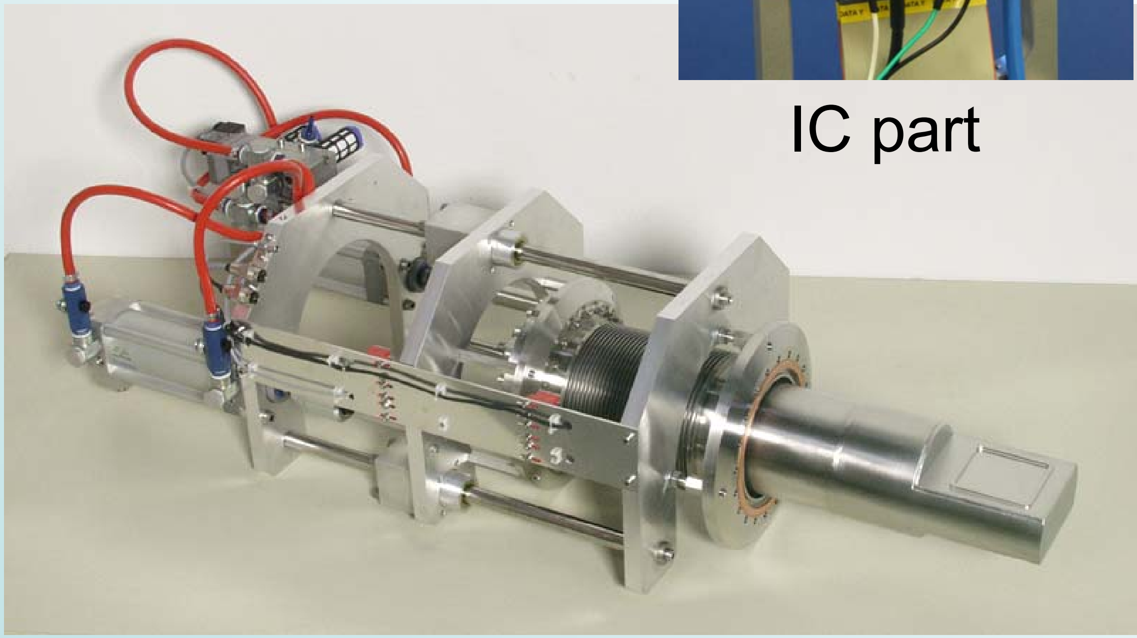
Detectors for beam monitoring - examples



MWPC part

Compact combined detector system working at HIT in the HEBT; feed-through with detector bag – windows to vacuum consist of 50 µm stainless steel

IC part



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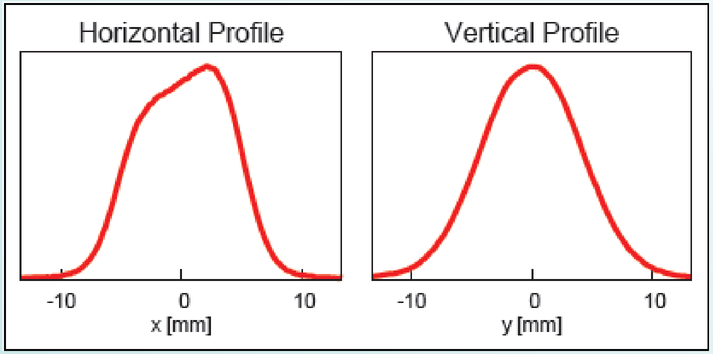
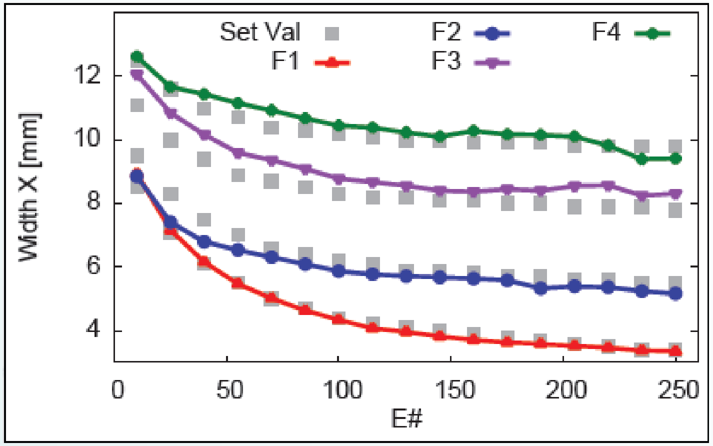
Detectors for beam monitoring - examples

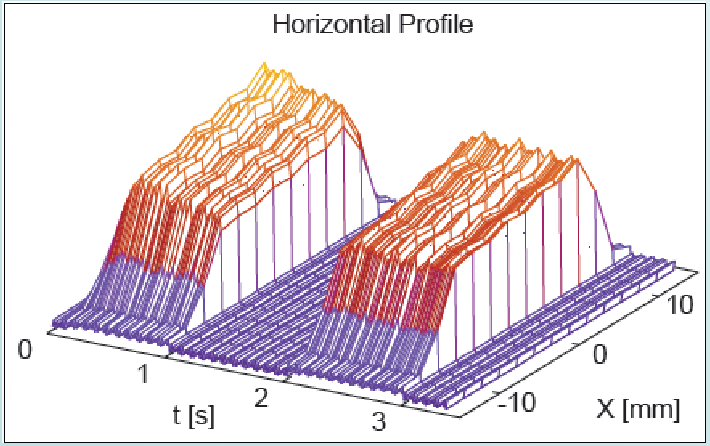


Profile measurements behind synchrotron
($^{12}C^{6+}$, 250 MeV/u, 10 mm FWHM)

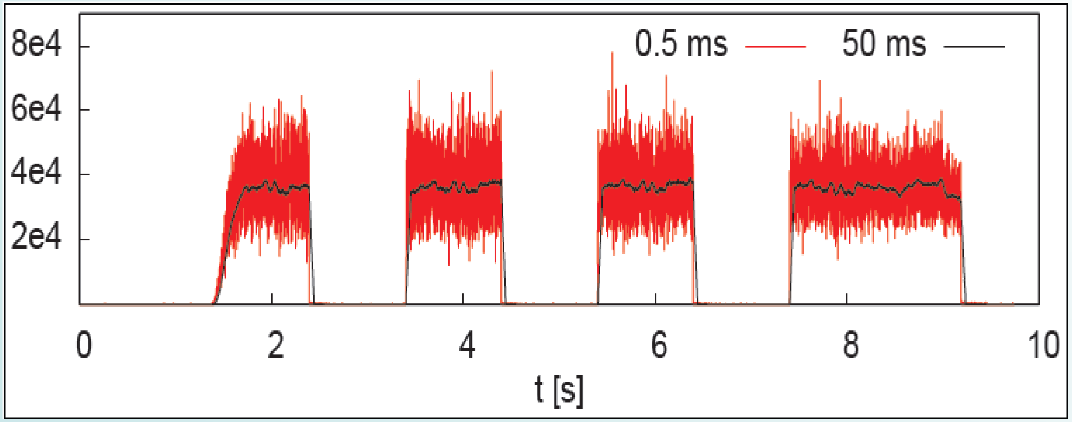
Measurements with MWPCs and ICs at HIT



Profile width of $^{12}C^{6+}$ near isocenter position



Profile measurements versus time
($^{12}C^{6+}$, 250 MeV/u, with spill pause)



Intensity of extracted beam from synchrotron („spill" with pauses)

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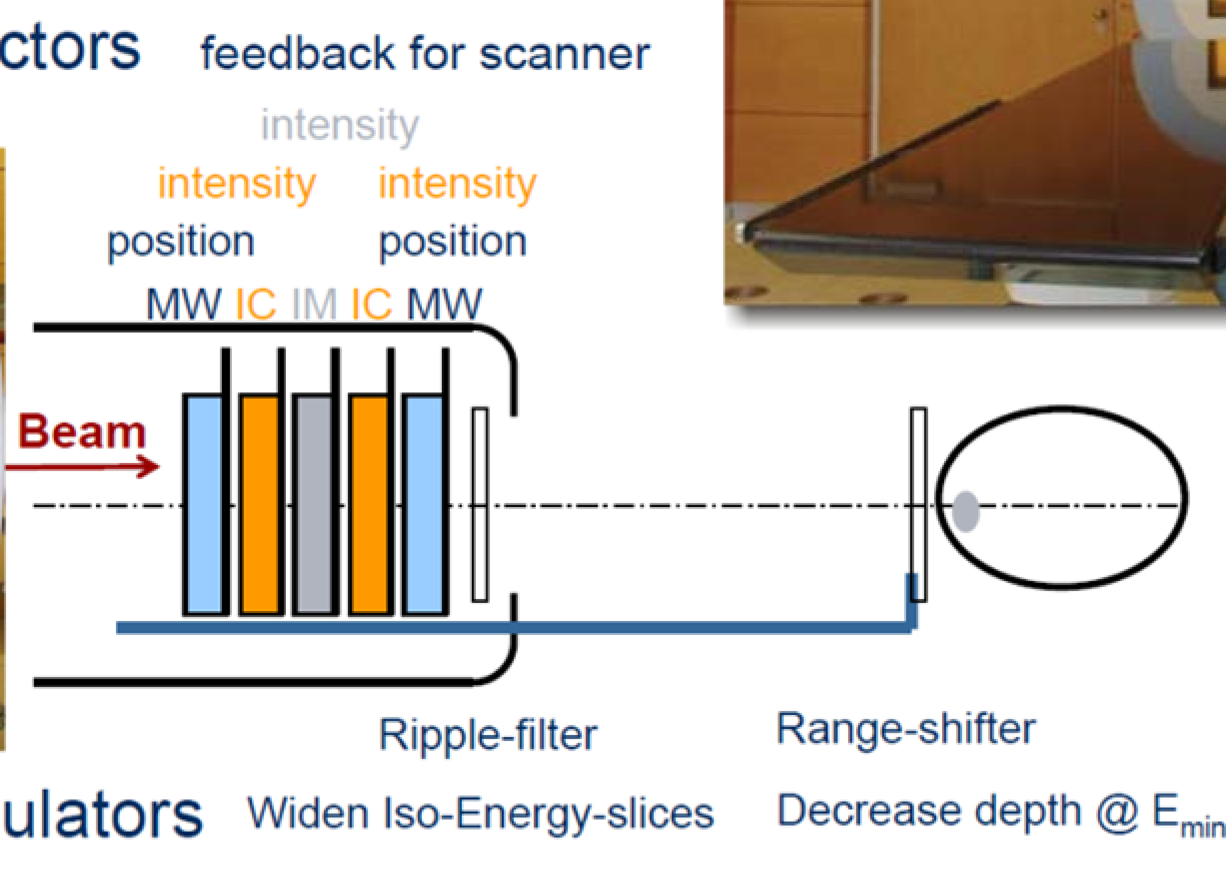
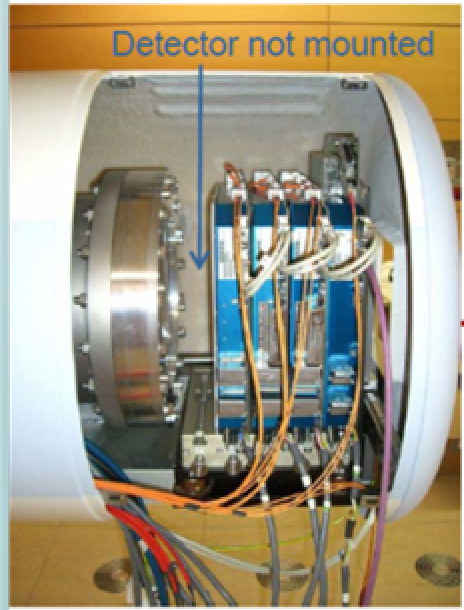
Detectors for treatment monitoring

Same technique for online monitoring of treatment in front of the patient position





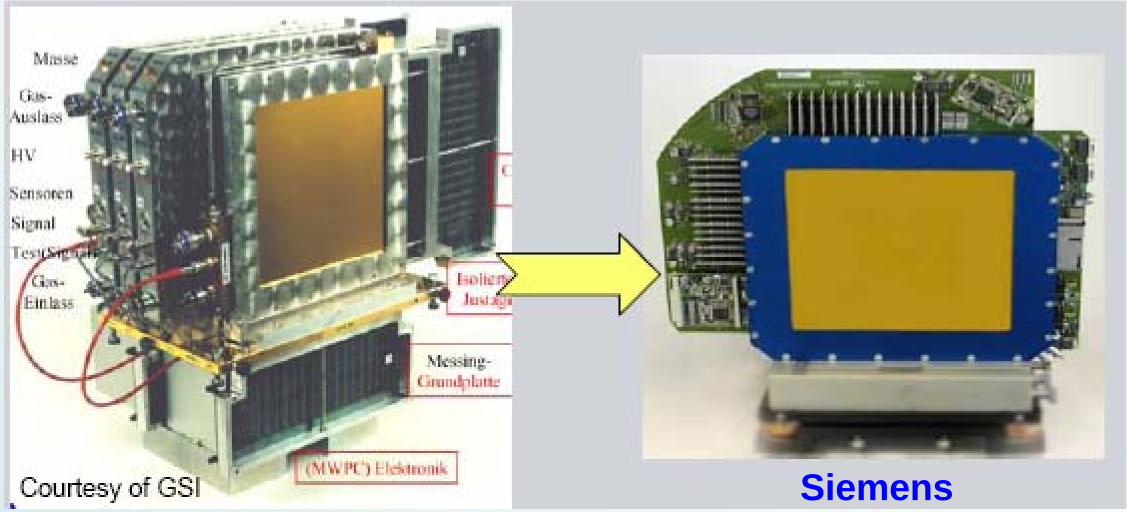
Detectors for treatment monitoring

High dynamic range:

- 10^6 – 10^{10} particles / s
- 48 MeV (p) – 430 MeV/u (C)

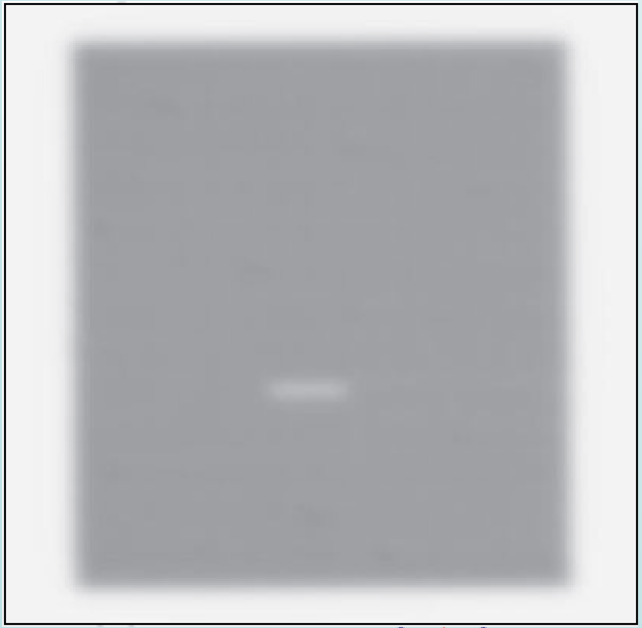
Detector area: 20 x 20 cm^2

Overall intensity measurement precision: < 5 %



Courtesy of GSI

Siemens

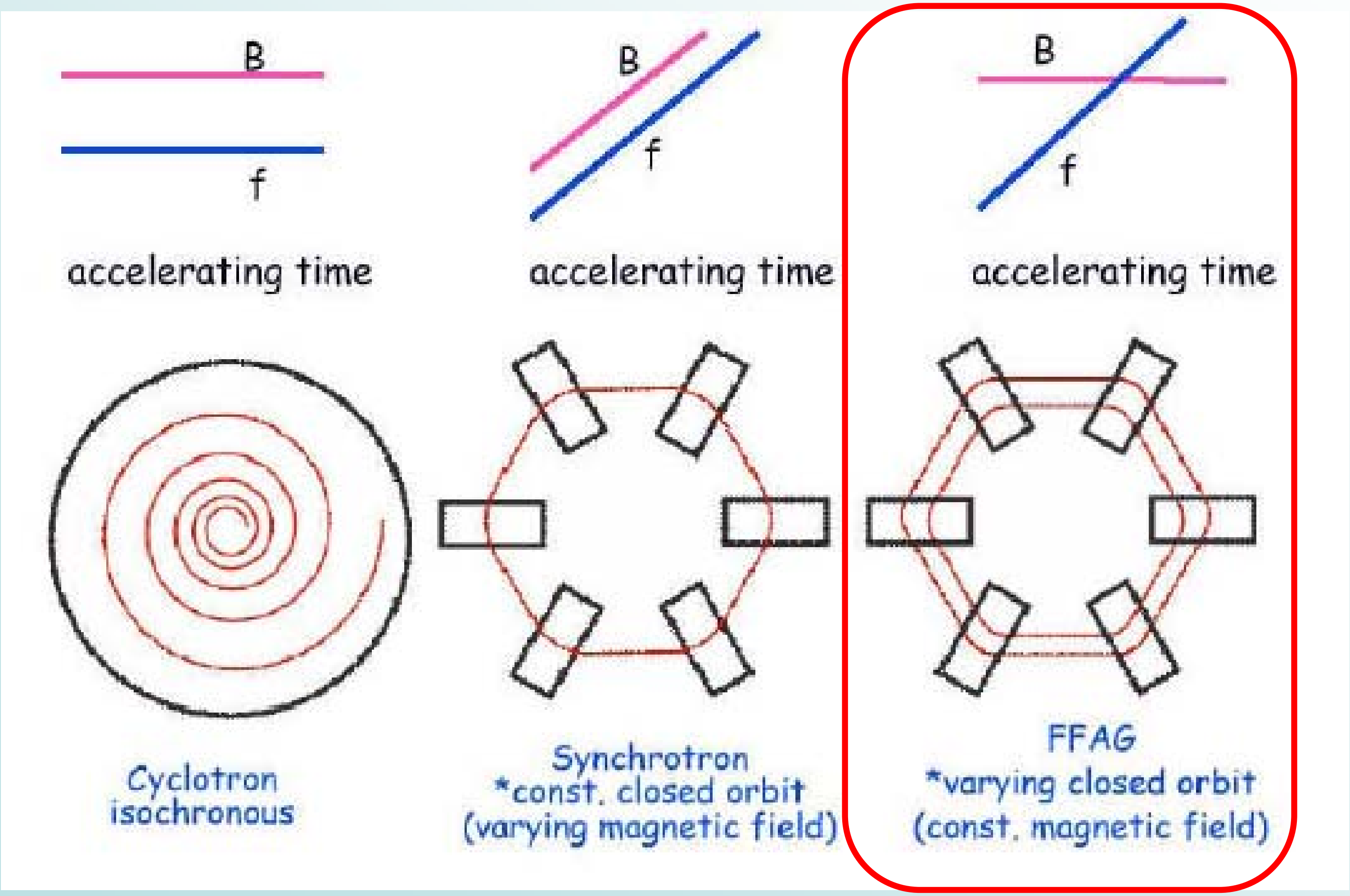


Verification film showing scanner system performance during commissioning (2008)

C, 430 MeV/u, isocentre, no position feedback, 7x8 cm, dose flatness ±2 %

Outlook to new accelerator concepts proposed for particle therapy: FFAGs, laser plasma accelerators, dielectric wall accelerators and others

New accelerator concepts - FFAGs



Idea:

Simplify control and operation, no synchro-nization necessary between B-field and RF

…but no savings in space!

New accelerator concepts - FFAGs

Fast acceleration

Compact footprint

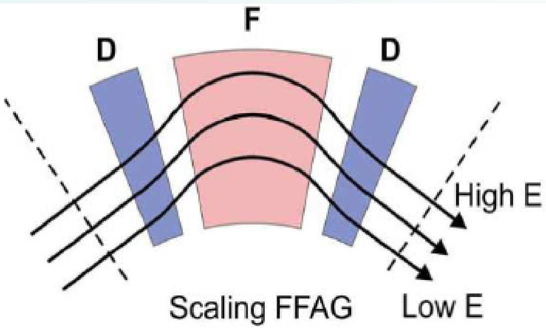
Magnet aperture must accept large momentum range

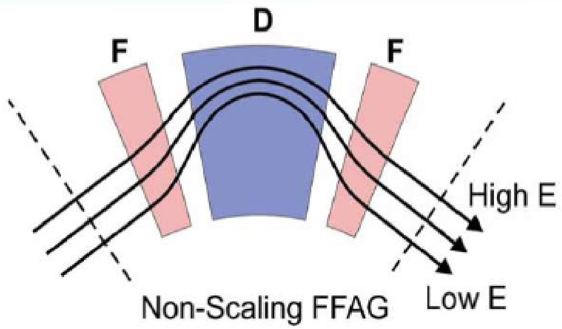
Variable energy extraction?

Possible very high rep rate

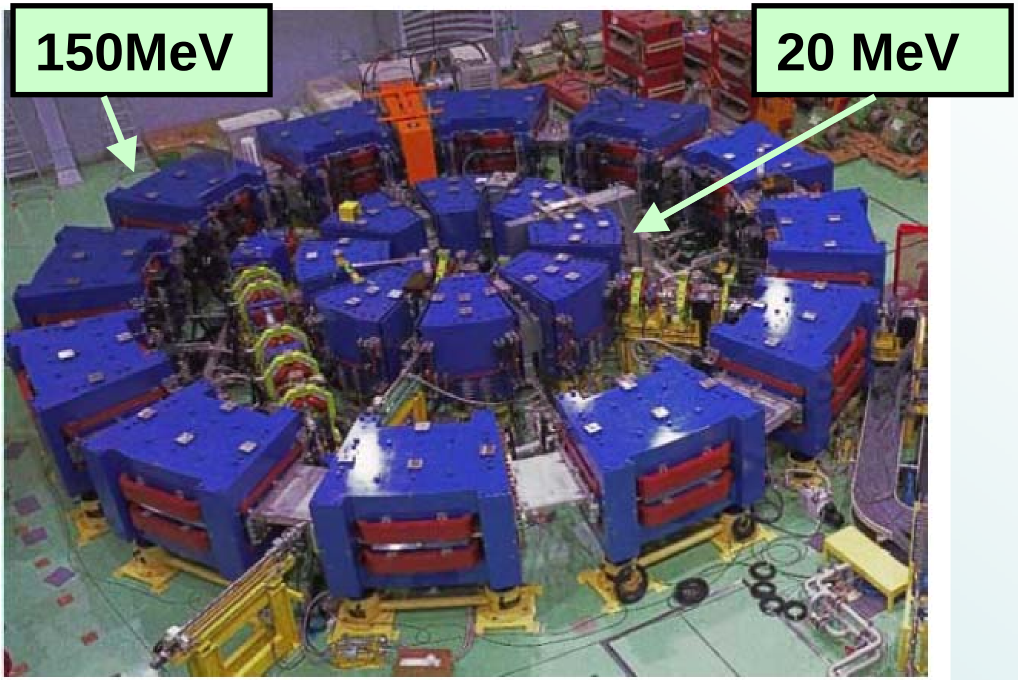
Much world wide interest.

Demo machines in early operation, construction & design



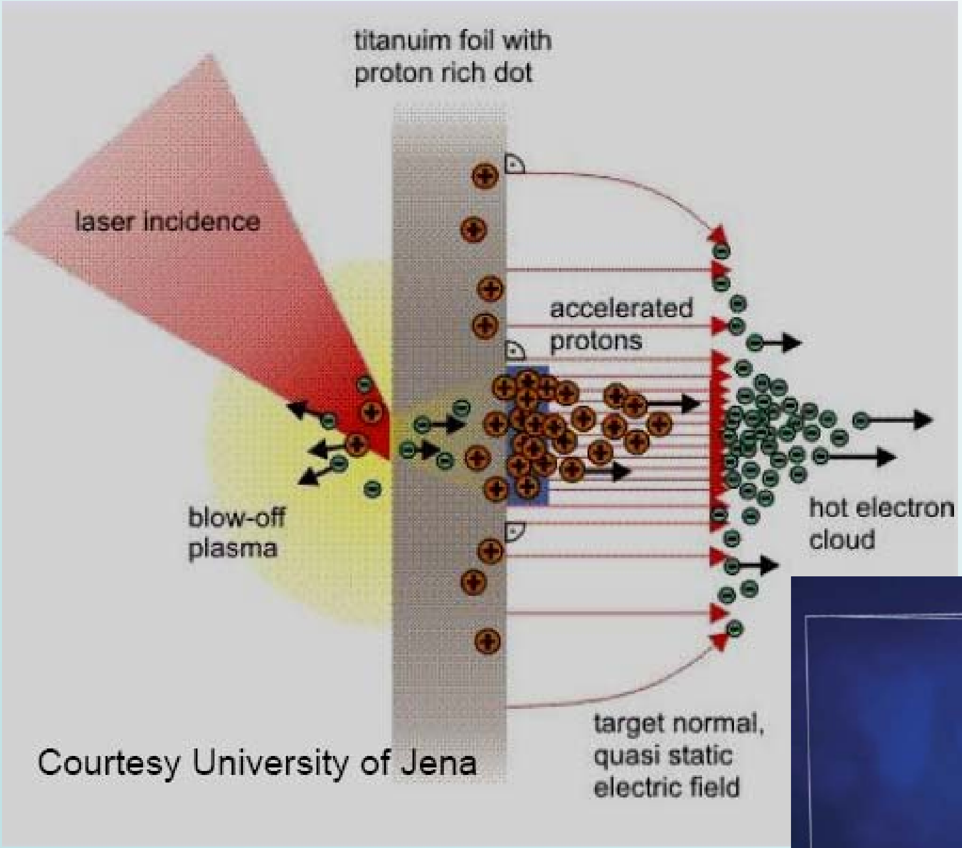


KEK



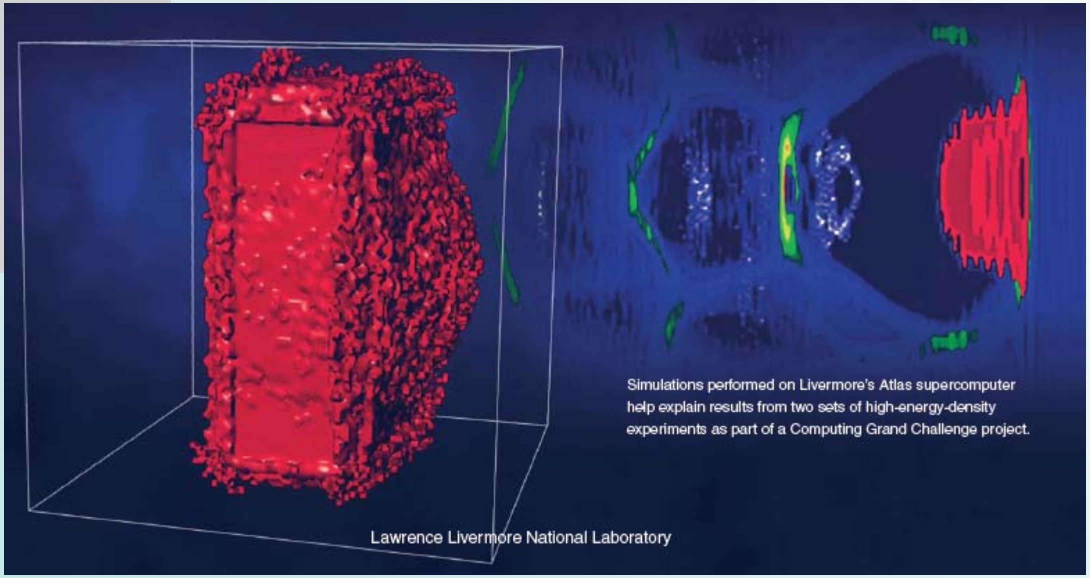
Further projects: EMMA (GB), RACCAM (F) and others

New concepts – laser plasma accelerators



- **Laser: 50 fs, 50 J (Petawatt!)**
- **$I = 10^{21}$ W/cm^2**
- **10^{11} protons up to 300 MeV should be possible**

- **Repetition rate?**
- **Intensity control?**



New concepts – Dielectric wall accelerators

G. Caporaso et al, LLNL

250 MeV protons in 2.5 m?

Pulse-to-pulse energy & intensity variation

"Hoping to build a full-scale prototype soon"

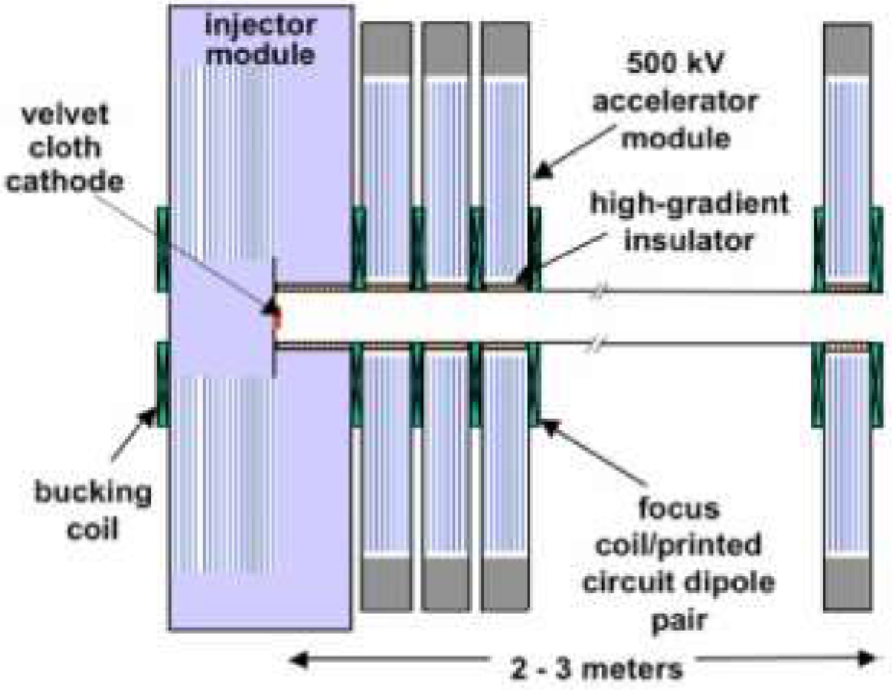
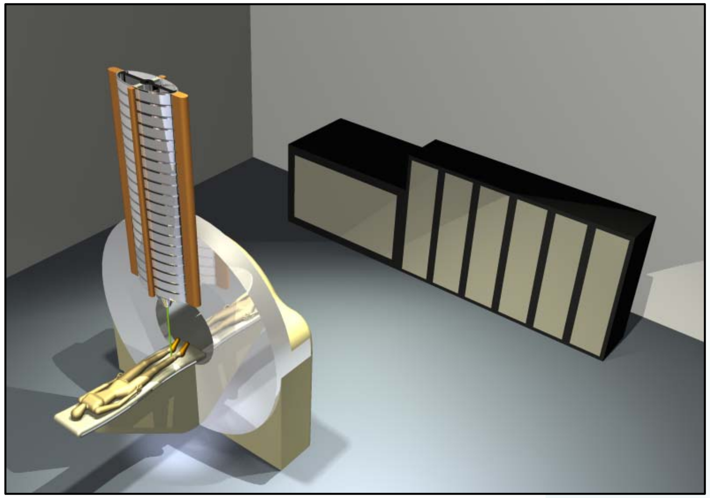
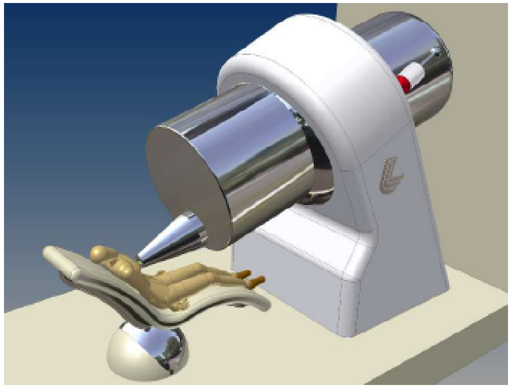


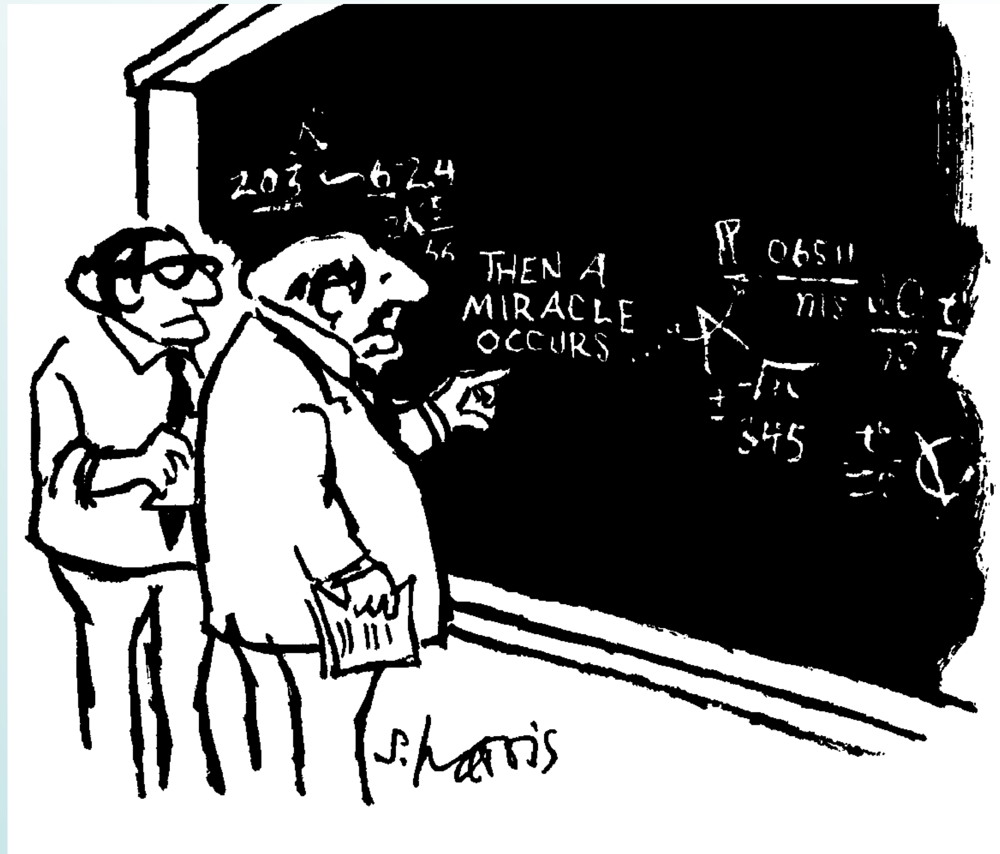
Figure 1: Dielectric wall induction accelerator configuration.





Medical applications of accelerators and linked detector technologies

Thank you for your attention !



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Medical applications of accelerators and linked detector technologies

Useful links to get information in this field:

[1] http://www.jacow.org → Database of all particle accelerator conferences (PAC, EPAC, DIPAC, CYCLOTRONE, …)

[2] http://ptcog.web.psi.ch/ → Webpage of "Particle Therapy Co-Operative Group", the network of all institutes in the field

[3] http://www.roentgen-museum.de/ → German museum on the work of Conrad Röntgen and the history of X-ray diagnostics and X-ray therapy

[4] Webpages of companies: http://www.medical.siemens.com/, http://www.varian.com/, http://www.iba-worldwide.com/, http://global.mitsubishielectric.com/bu/particlebeam/index.html, http://www.elekta.com (list not complete)

[5] http://www.wikipedia.org/ → overall information on people and history