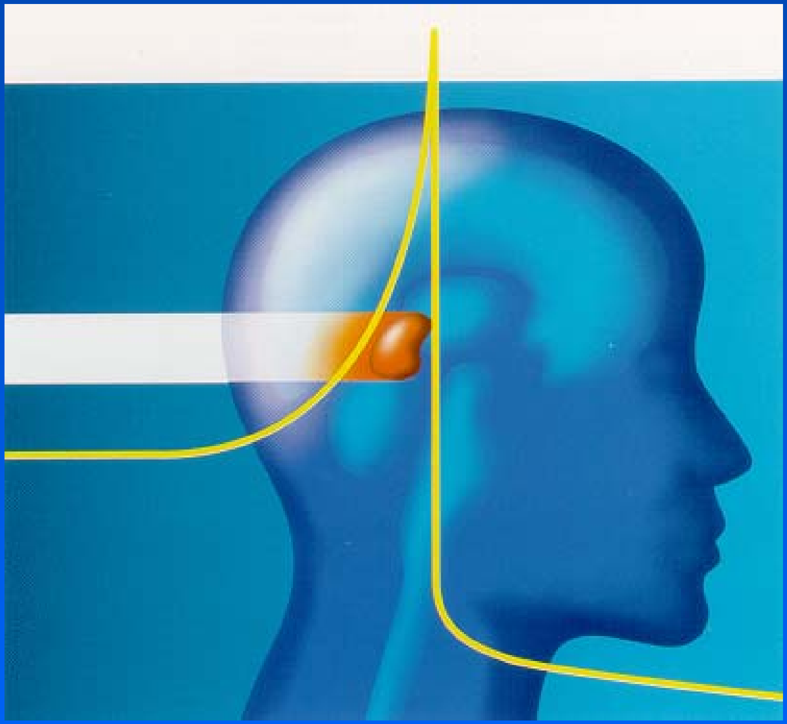
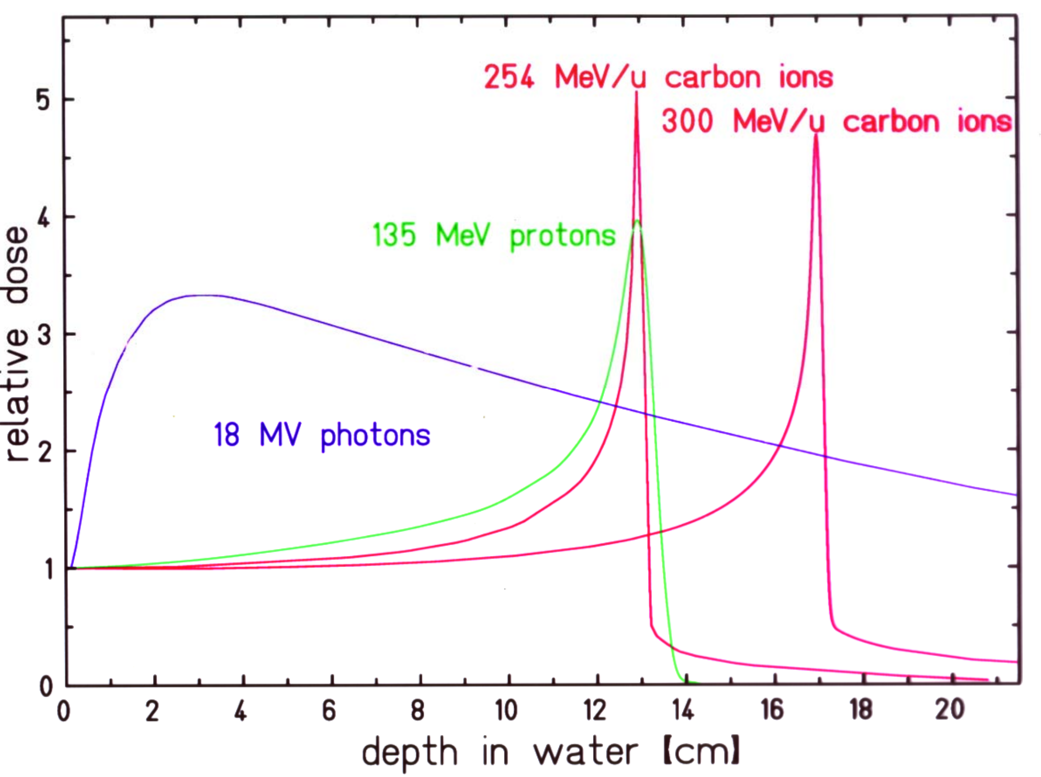
Cancer Therapy Using Ion Accelerators

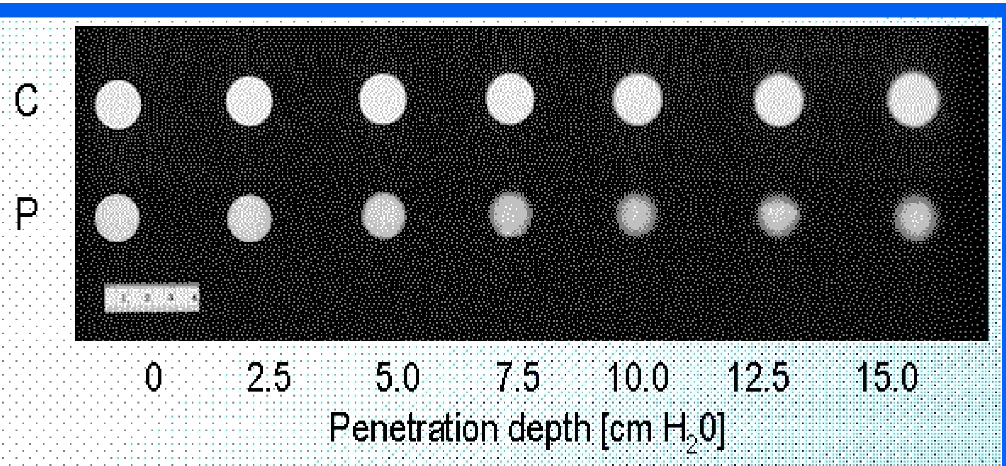


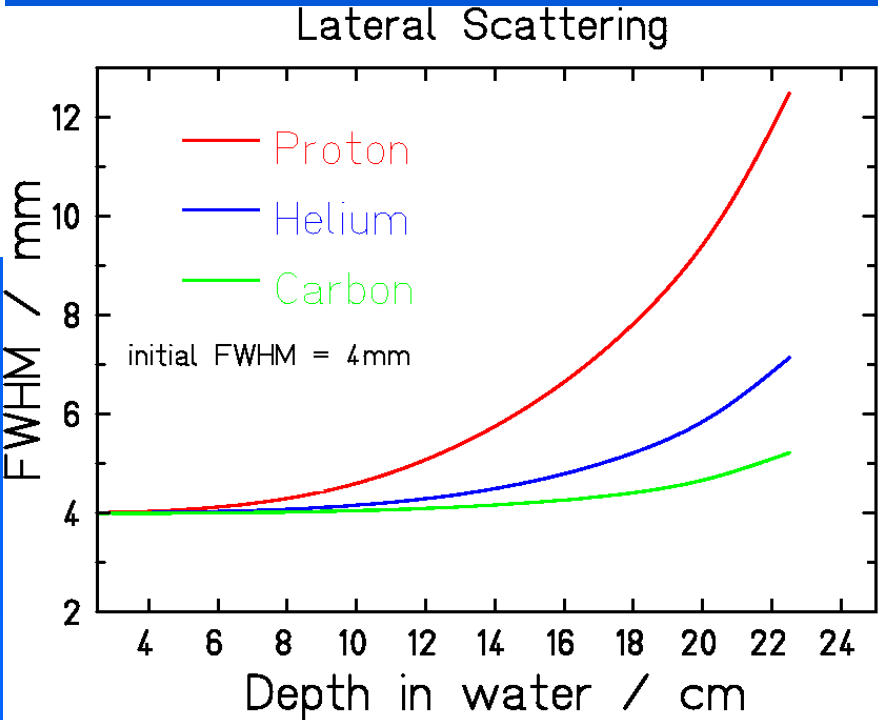
Thomas Haberer
Heidelberg Ion Therapy Center
Cern Accelerator School 2009

Rationale / Physics



- inverted depth-dose distribution
- mild lateral scattering





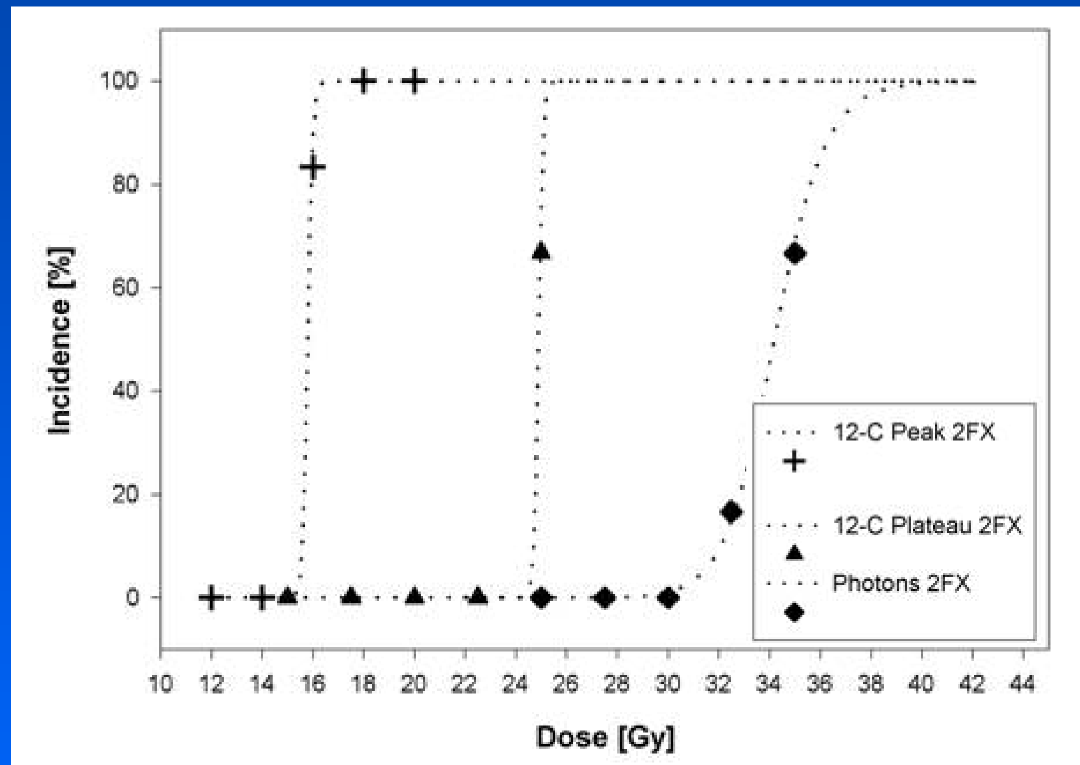
Increased Relative Biological Effectiveness

radiation induced myelopathy in rats after 2 carbon fractions

RBEs:

Plateau: ~1.4

Peak: ~ 2.3

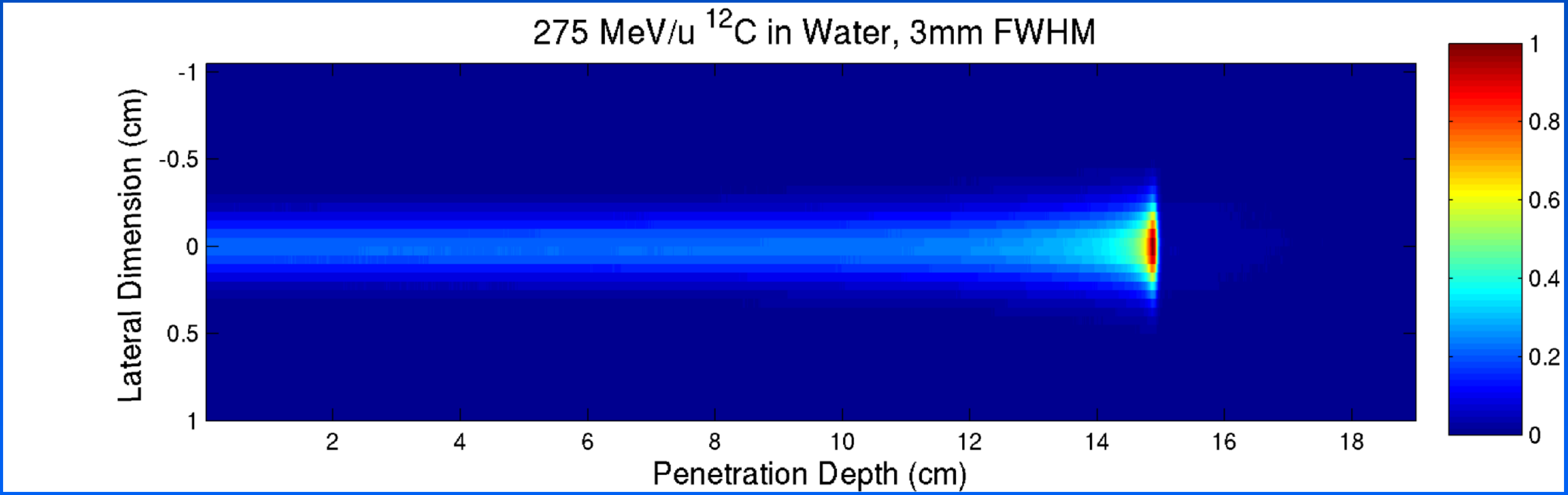


Debus, Karger, Peschke, Scholz, …
Rad. Res. 2003

Th. Haberer, Heidelberg Ion Therapy Center

Goal

The key element to improve the clinical outcome is **local control!**

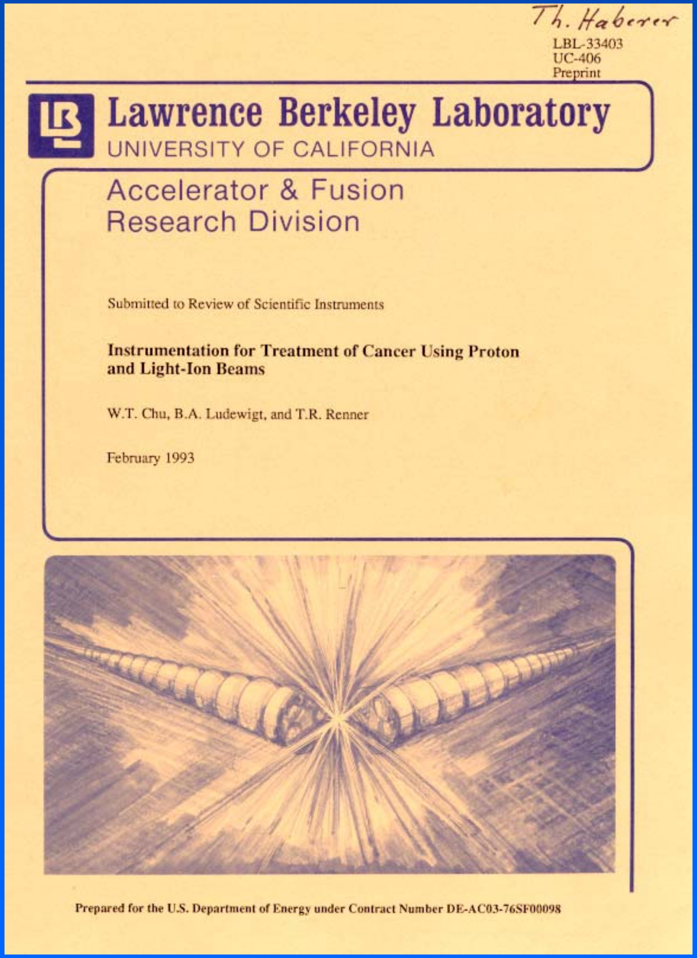


entrance channel:
- low physical dose
- low rel. biol. effiency

tumour:
- high physical dose
- high rel. biol. effiency

Standard Approach

- Facilities being built at existing research accelerators
- Fixed energy machines with moderate flexibility (if at all)
- Dose delivery not exactly tumor-conform


Th. Haberer

LBL-33403
UC-406
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Submitted to Review of Scientific Instruments

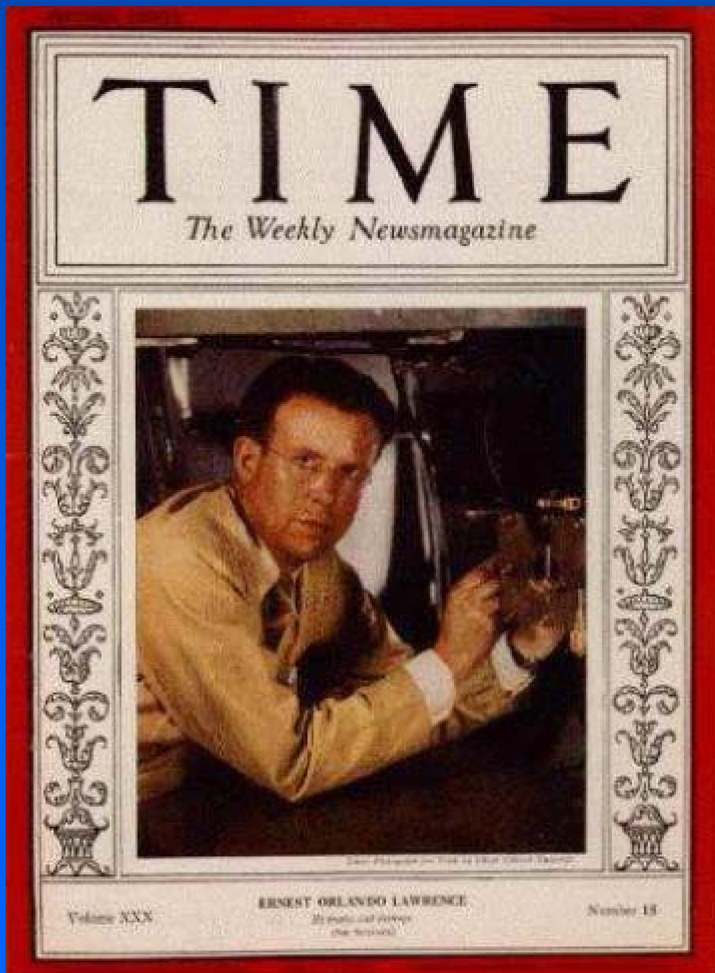
Instrumentation for Treatment of Cancer Using Proton and Light-Ion Beams

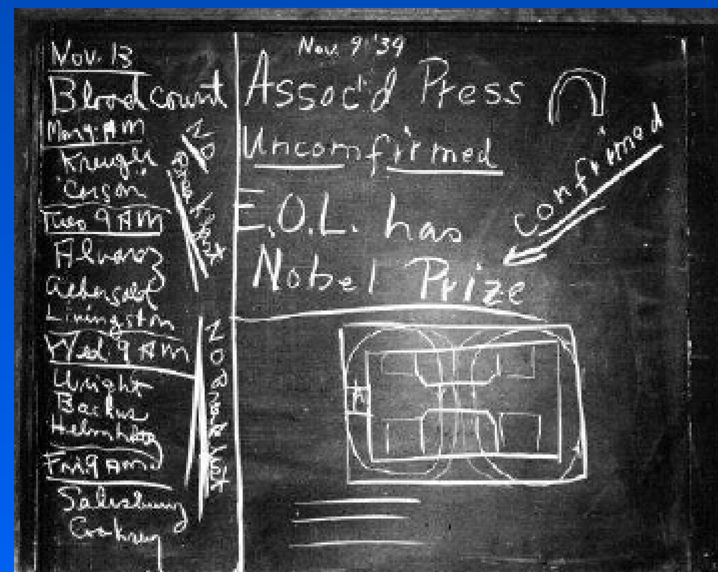
W.T. Chu, B.A. Ludewigt, and T.R. Renner

February 1993

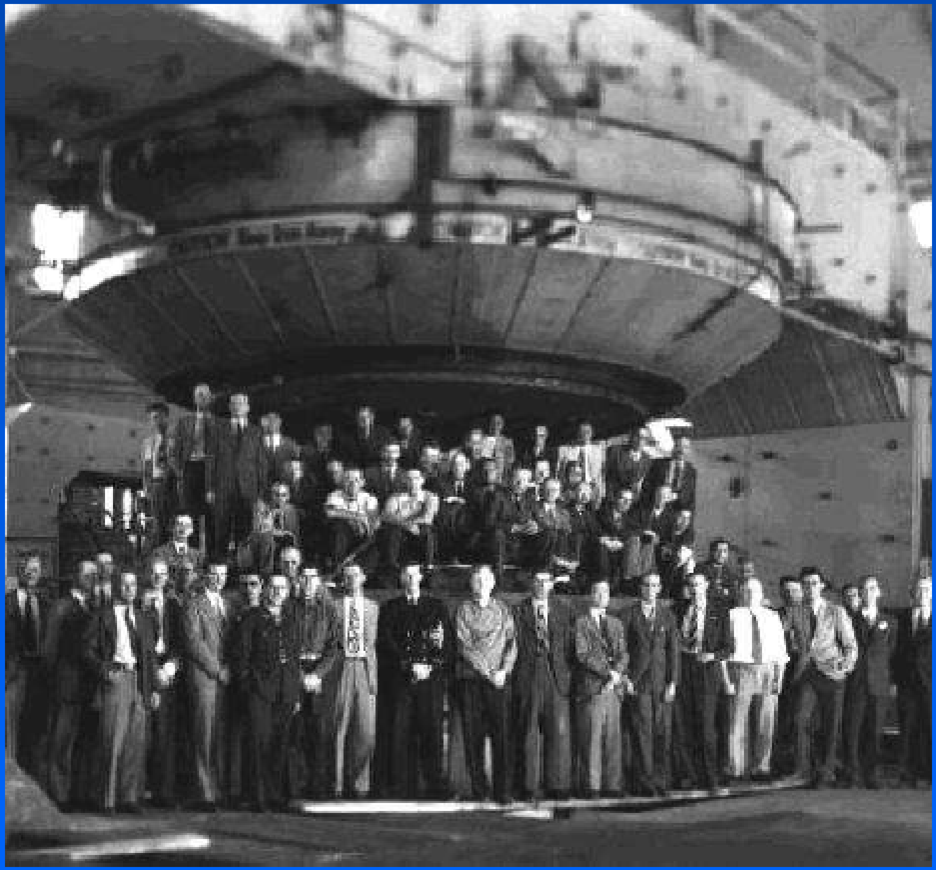
Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

Ernest Orlando Lawrence
Nobel Prize 1939

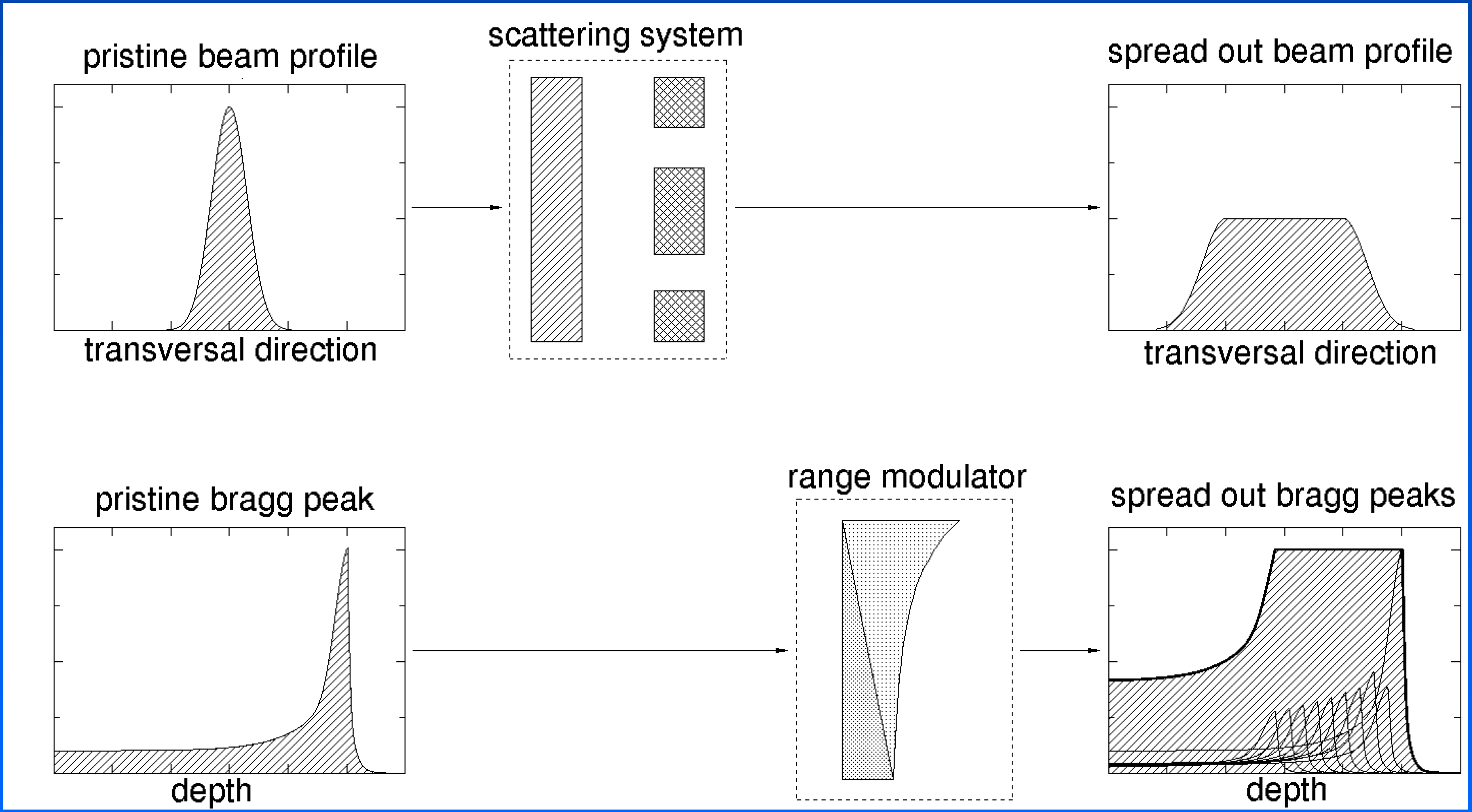




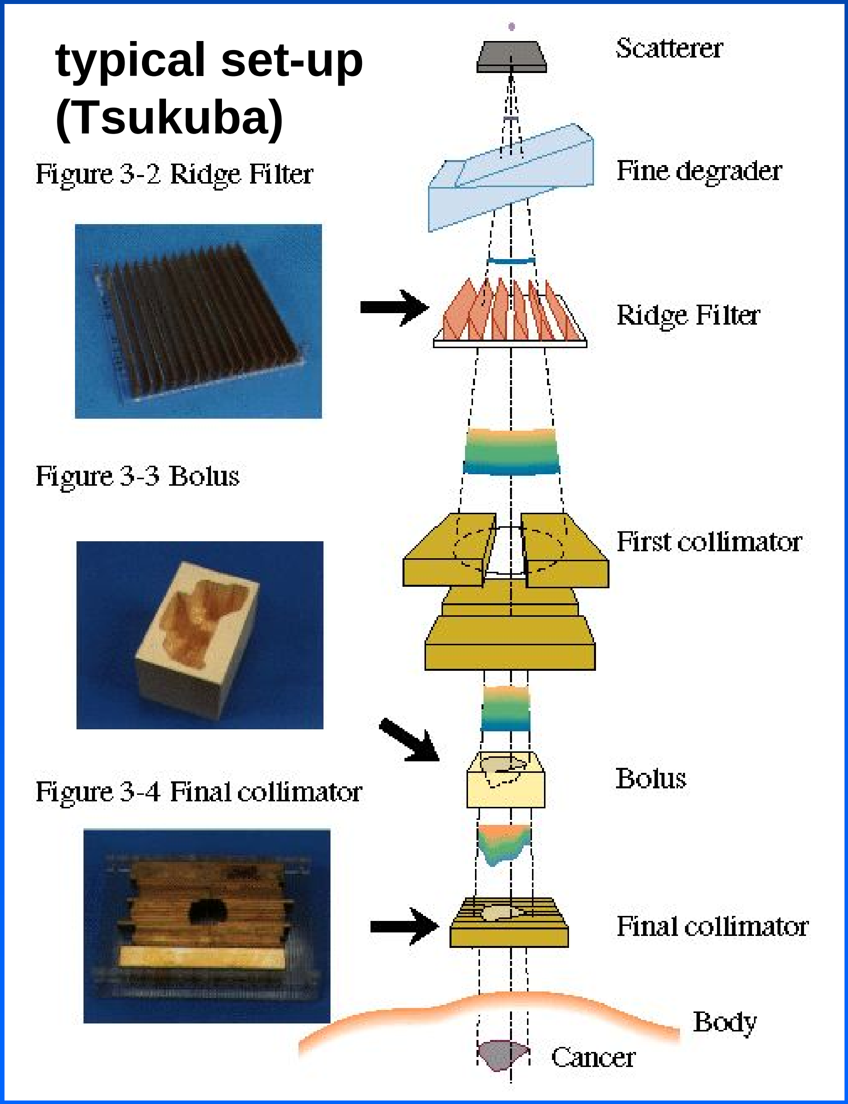
184 inch Cyclotron @ LBL 1947 / 1986



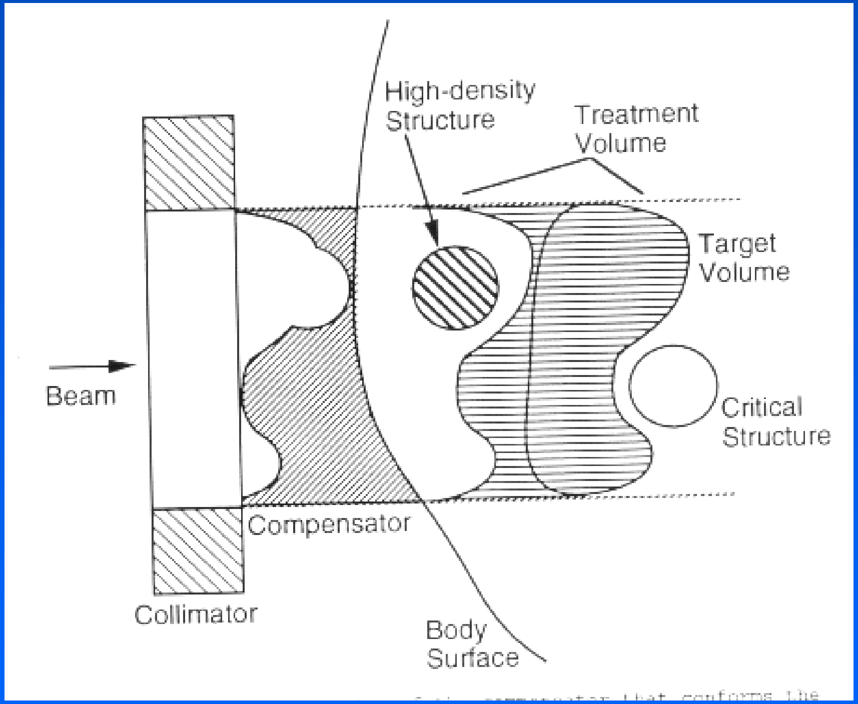
Passive Dose Delivery



Standard / System + Dose Distr.



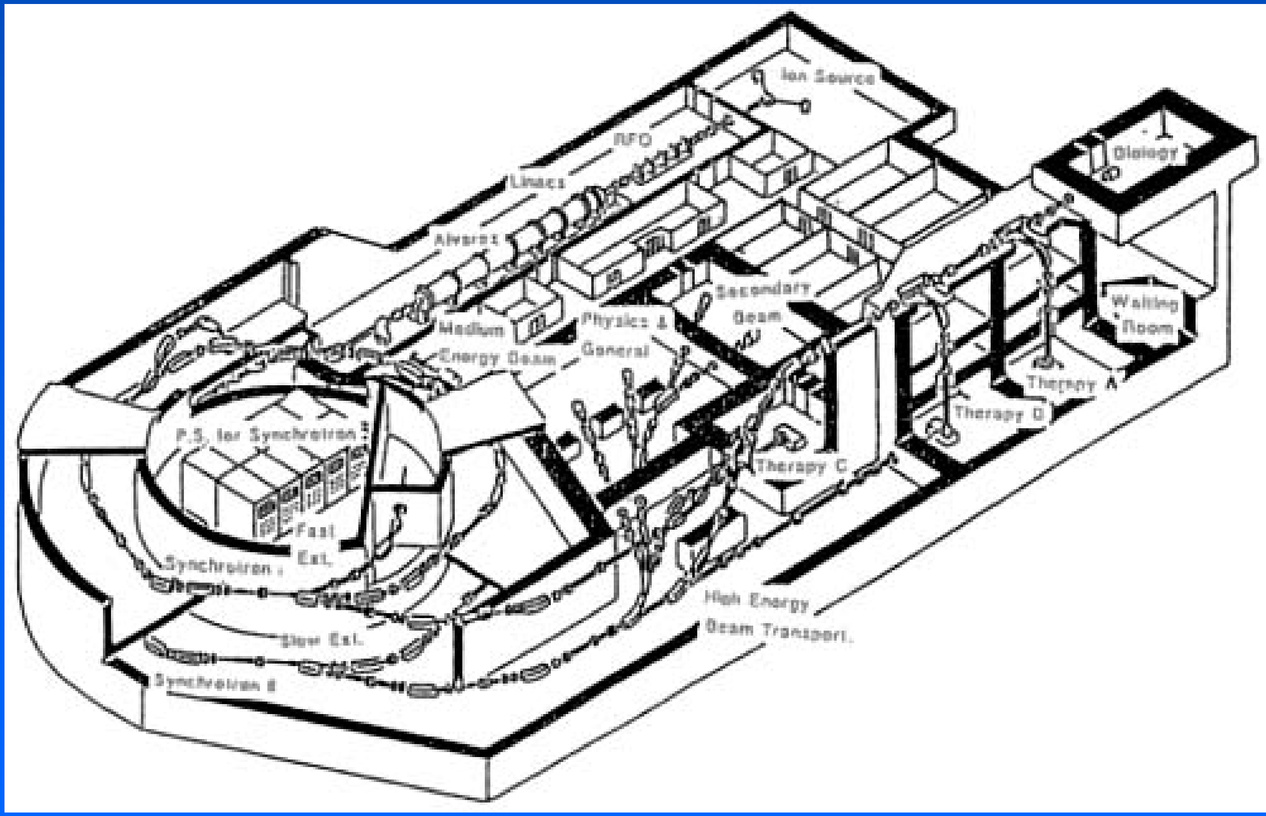
Distal edge shaping using a bolus pulls dose back into healthy tissue



Situation / Clinical Centers

- In 1994 the first dedicated clinic-based facilities, LLMUC (protons) and HIMAC (carbon), started
- Nowadays more than 50 proton treatment protocols are approved and reimbursed in the US
- LLUMC treats up to 180 patients per day

Heavy Ion Medical Accelerator, Chiba, Japan



Requirement engineering

<u>Application</u>
- treatment of tumors with ion beams (conform, precise)

<u>1st level requirements</u>
- dose deposition in patient → dose delivery at isocenter

<u>2nd level requirements</u>
- beam application system

<u>3rd level requirements</u>
- accelerator specifications
  ← beam application system

→ accelerator requirements: interface to scanning system

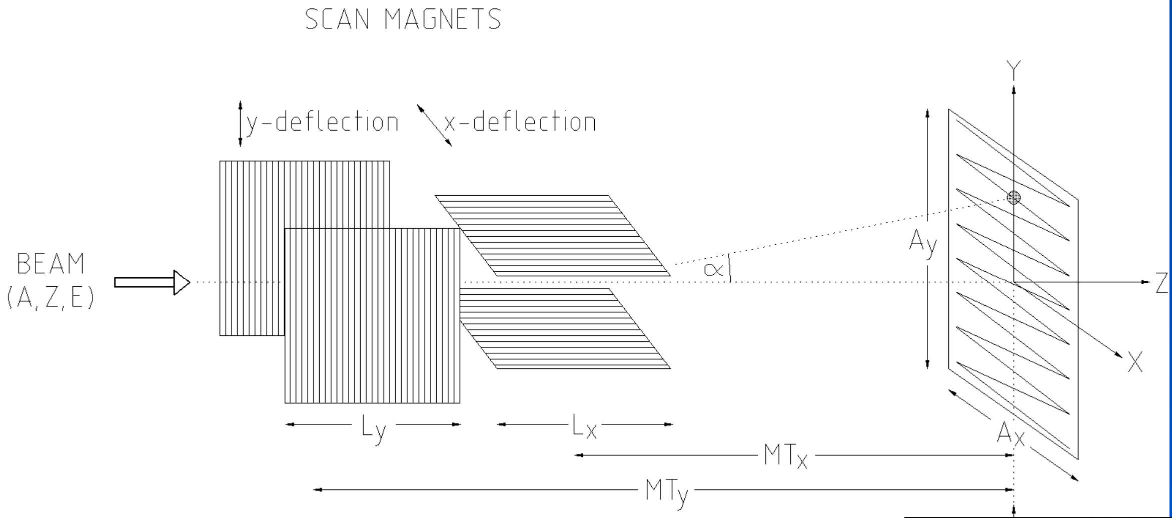
Dose Delivery Concept @ GSI/HIT

Idea:
Dose distributions of utmost tumor conformity can be produced by superimposing many thousands Bragg-peaks in 3D.
Sophisticated requirements concerning the beam delivery system, the accelerator, the treatment planning, QA, ... result from this approach.

Realization:
Dissect the treatment volume into thousands of voxels. Use small pencil beams with a spatial resolution of a few mm to fill each voxel with a pre-calculated amount of stopping particles taking into account the underlying physical and biological interactions.

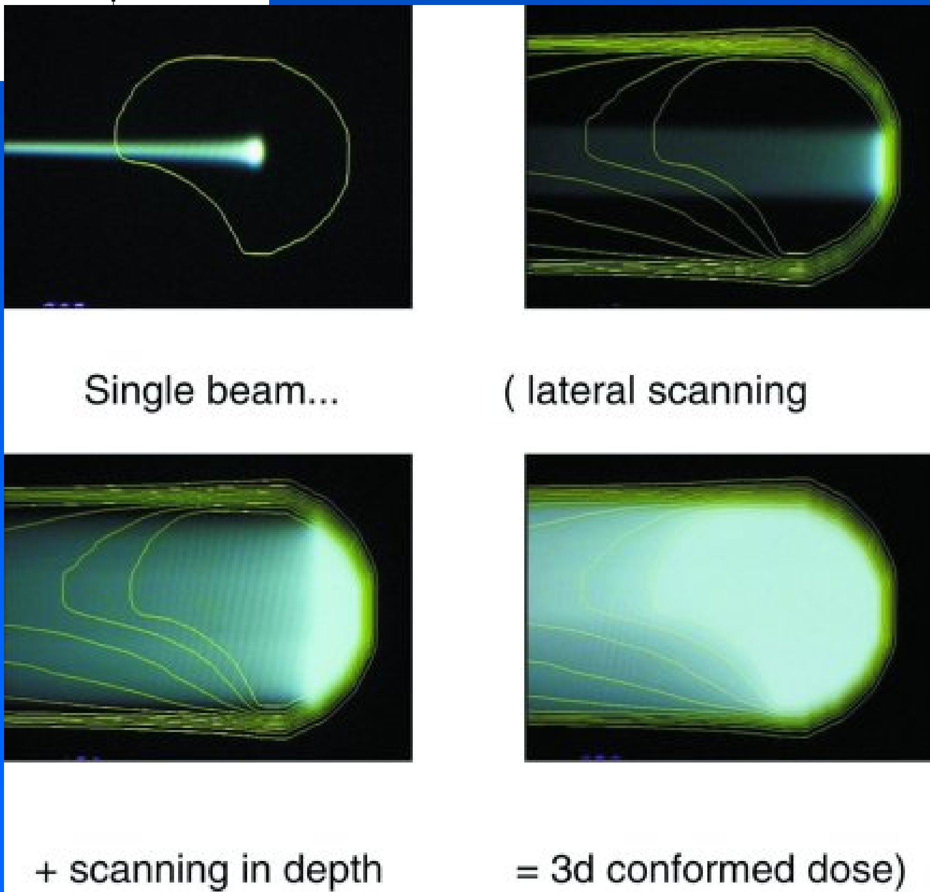
$\Rightarrow$ **Extreme intensity modulation via rasterscanning**

Beam Scanning



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

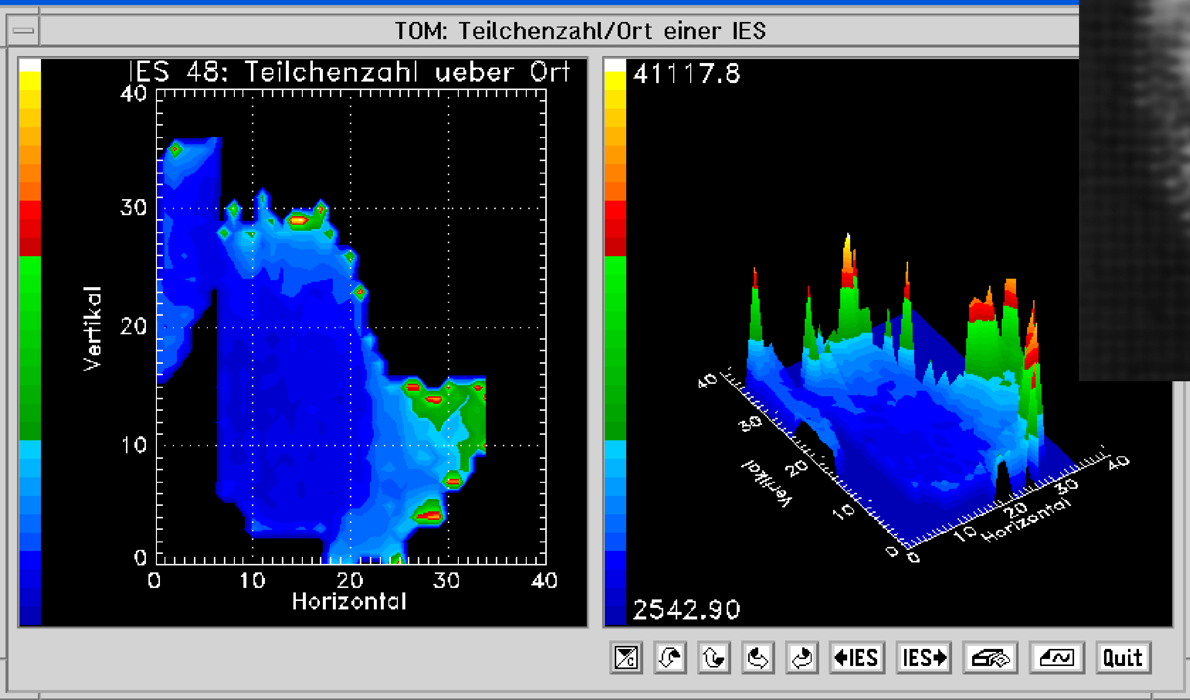
Ions (Haberer et al., GSI):
raster scanning, 3D active,
2D magnetic pencil beam scanning
plus
active range stacking (spot size, intensity) in the accelerator



Th. Haberer, Heidelberg Iontherapy Center

Active / Fluence Distribution

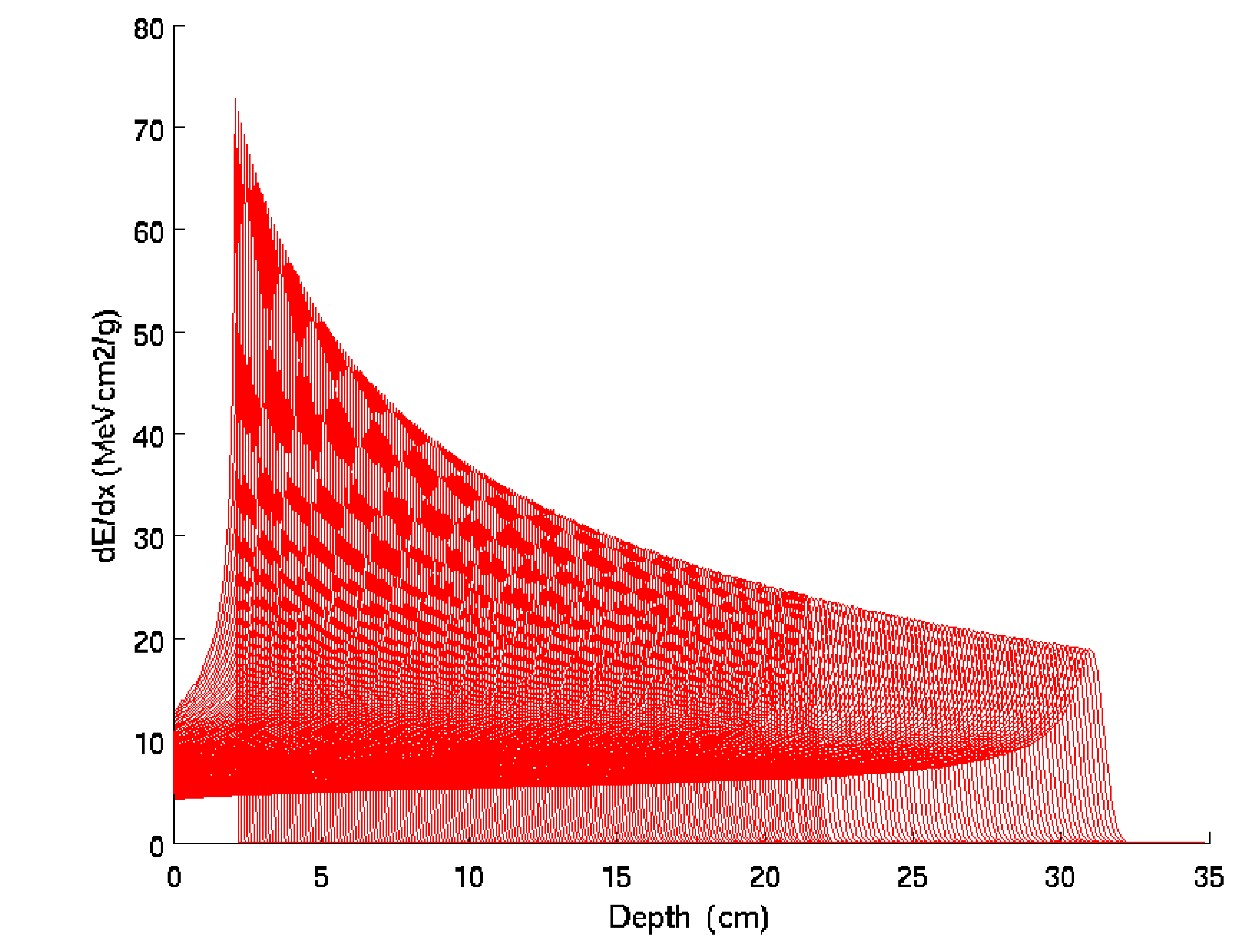
Fluence distribution of
a single slice through the
target volume



Accelerator requirements

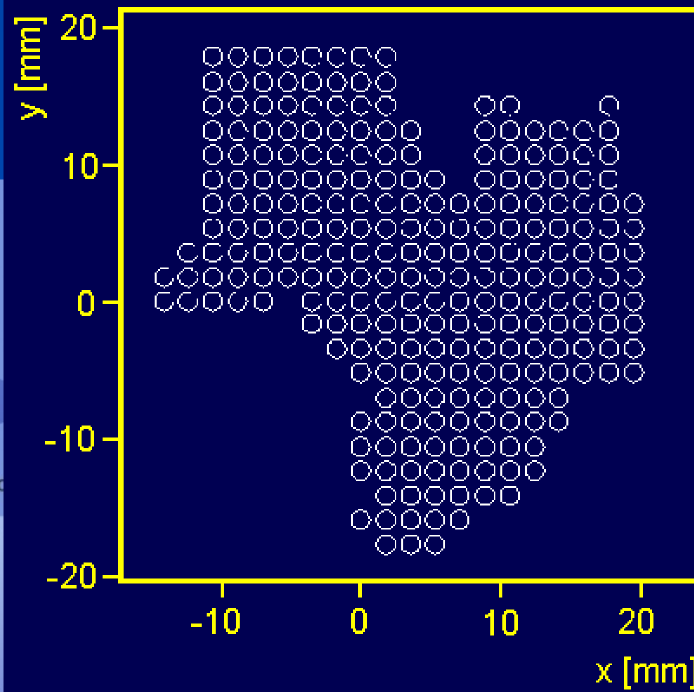
- **scanning ready pencil beam library:**
  - energy: up to 30 cm WE, ~1 mm steps, $\Delta E/E$ ~1%
    p: 48 – 200 MeV, C: 88 – 430 MeV/u
  - spot sizes: 4 – 10 mm (3-4 steps), 2D Gaussian
  - intensity: ~10^{10} (p), ~10^{8} (C) per spill
  - ~ 100.000 combinations
- beam purity
- several quasi parallel particle types
  - change of particle type < 60 s
- availability ~95%
- low operational & maintenance cost

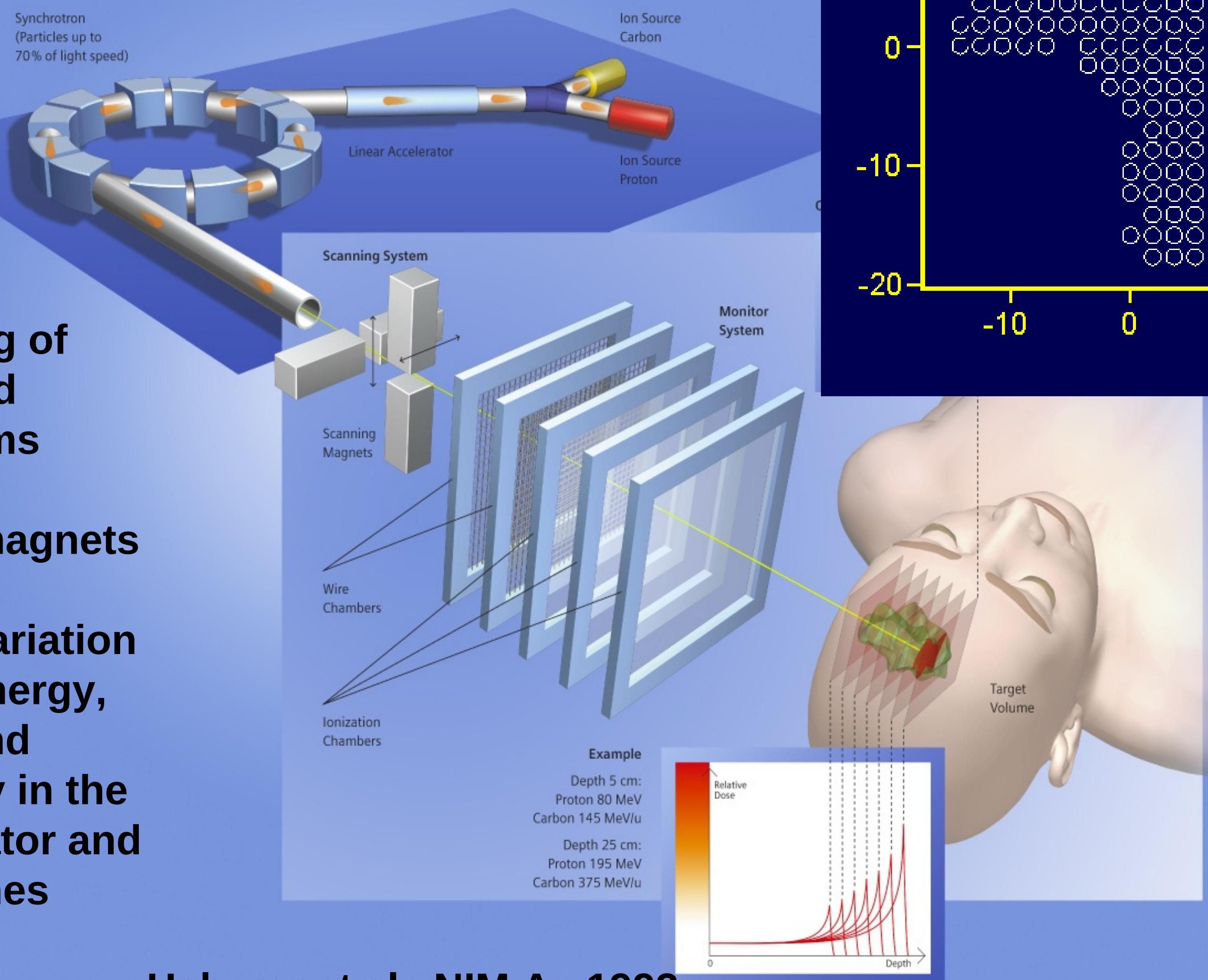
The Proton Data Base for HIT



K. Parodi and A. Mairani, (HIT and FLUKA Collaboration)

Rasterscan Method





scanning of focussed ion beams in fast dipole magnets

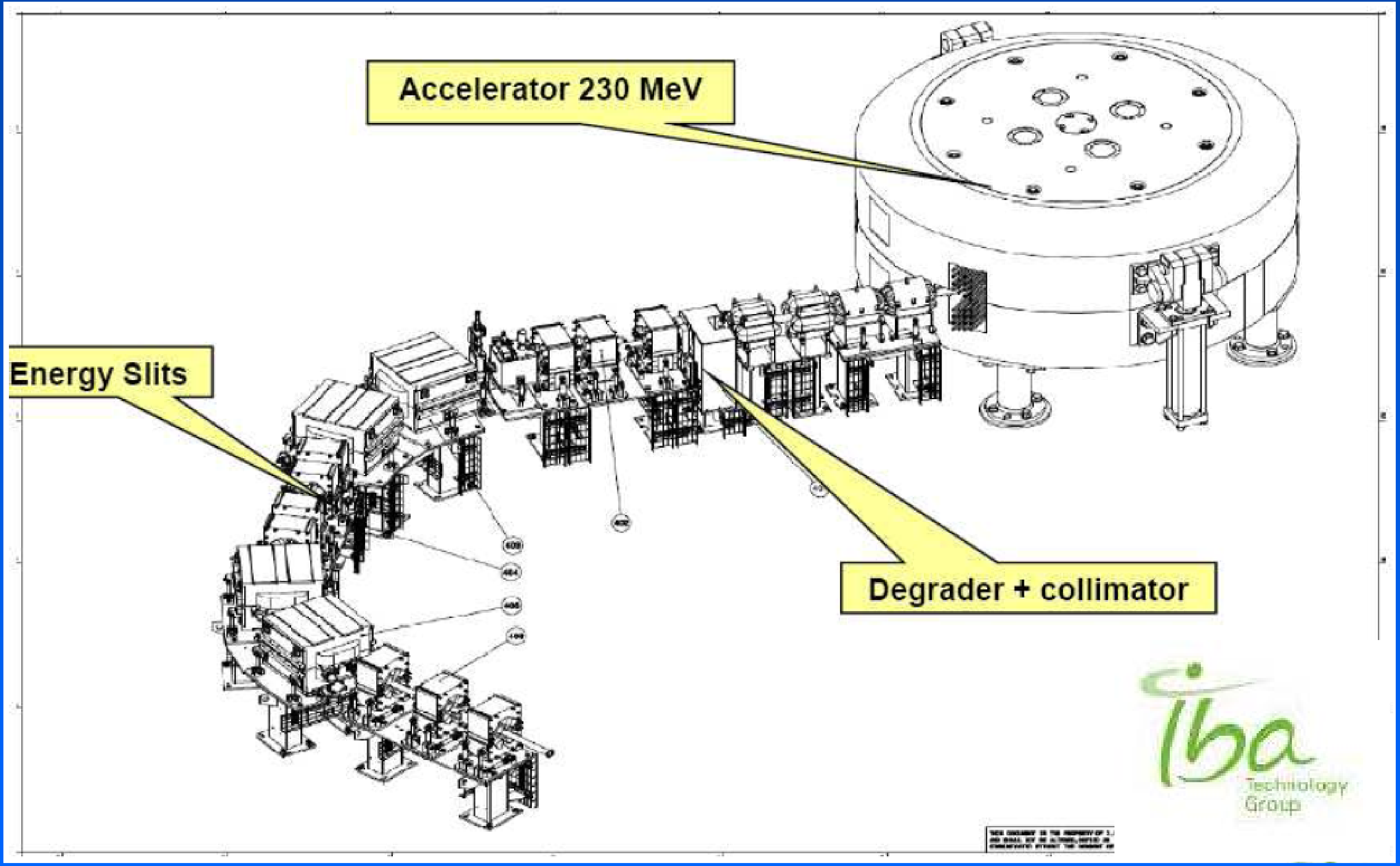
active variation of the energy, focus and intensity in the accelerator and beam lines

Haberer et al., NIM A , 1993

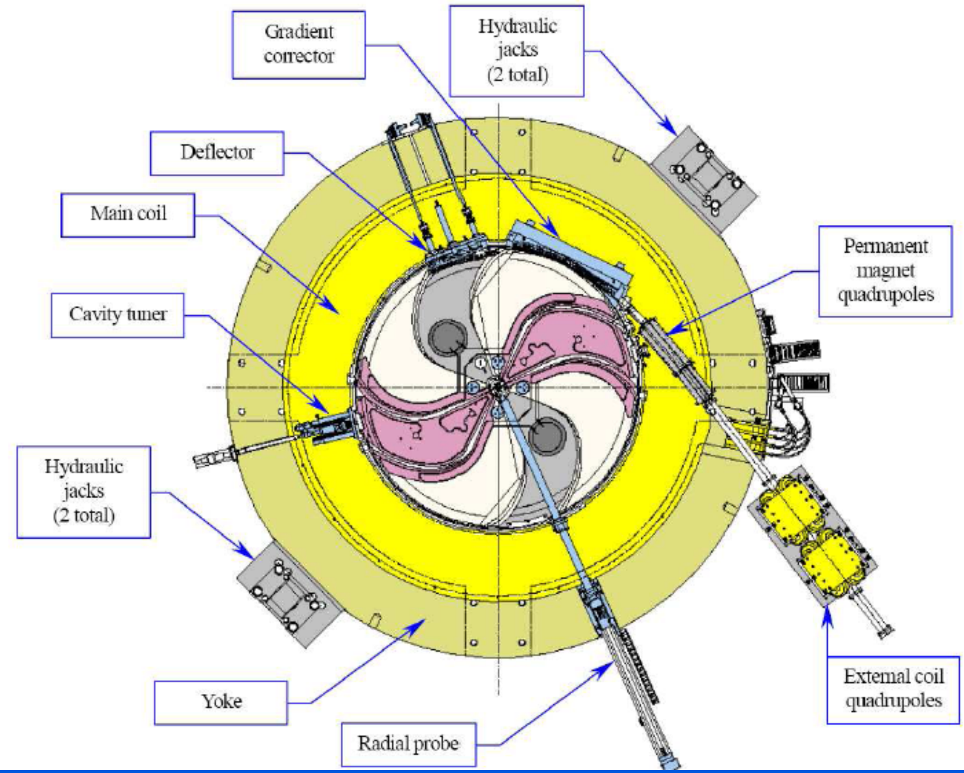
Proton-Synchrotron, Shizuoka, Japan

Heidelberg Ionenstrahl-Therapie Centrum

Cyclotron-based



Cyclotron-based



Th.

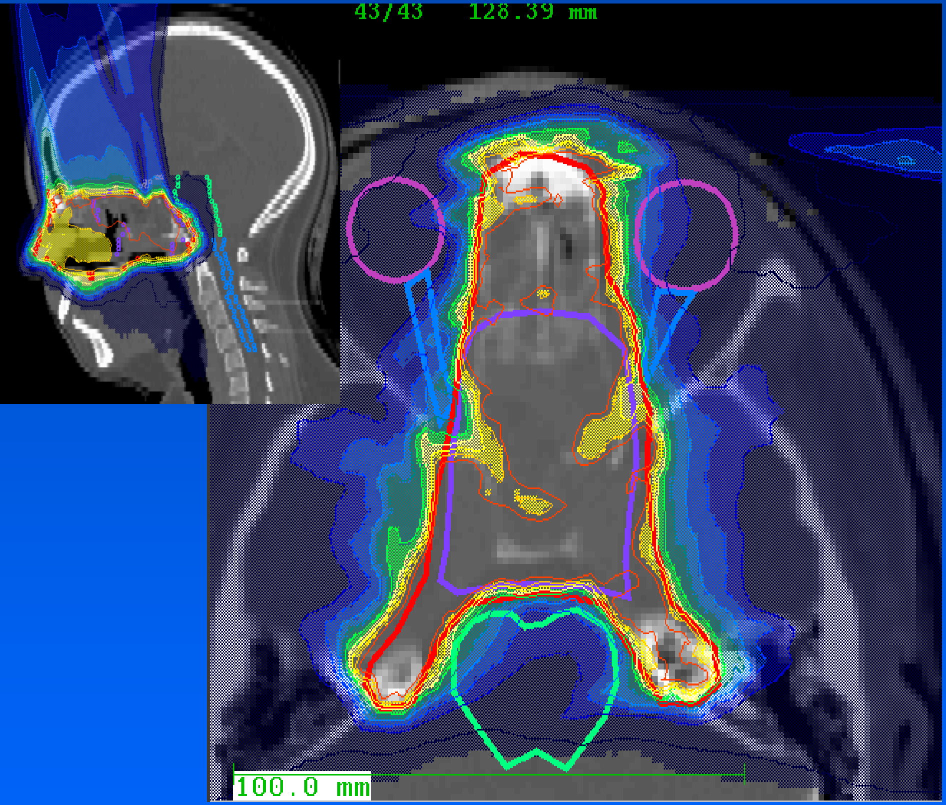
Economic requirements

- change of particle type < 60 s (dead time)
- change of treatment room < 30 s (dead time)
- number of treatment rooms ← utilization of accelerator
- 300 days per year, 16 hours per day
- ~1-2 min per treatment field (~1l, ~1-2 Gy)
(target fraction duration: 15 min incl. 4 min beam)

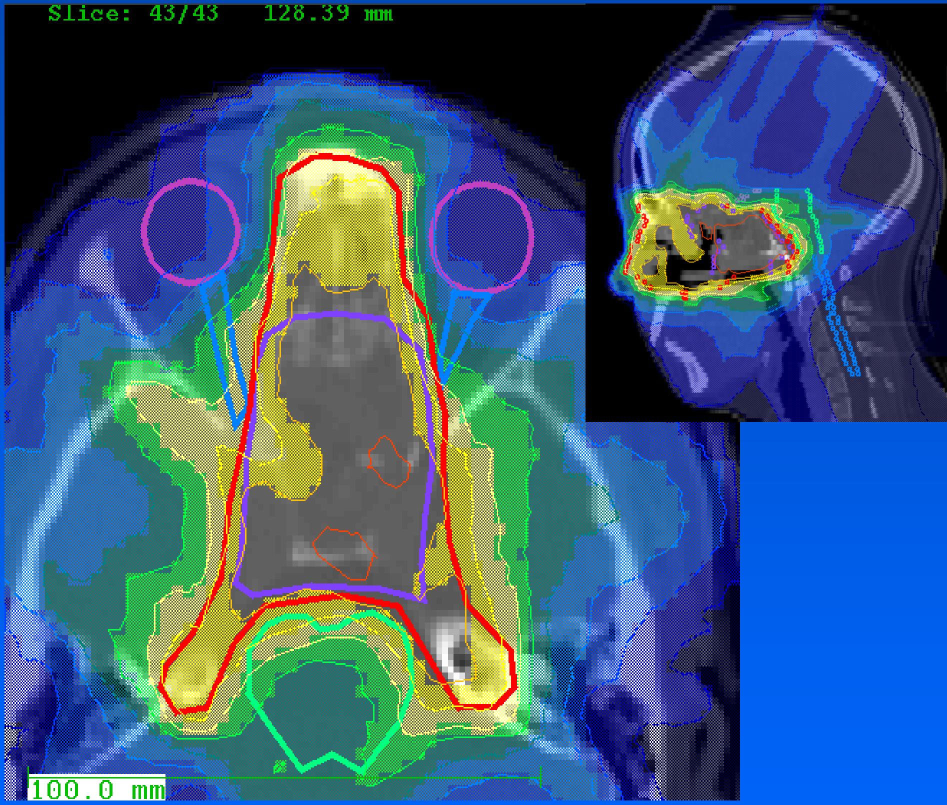
- initial cost
- operational & maintenance cost

Scanned Carbon vs. Intensity Modulated Photons

scanned carbon 3 fields



IMRT 9 fields



reduced integral dose
steeper dose gradients
less fields
increased biological effectiveness

courtesy O. Jäkel, HIT

Therapy @ GSI

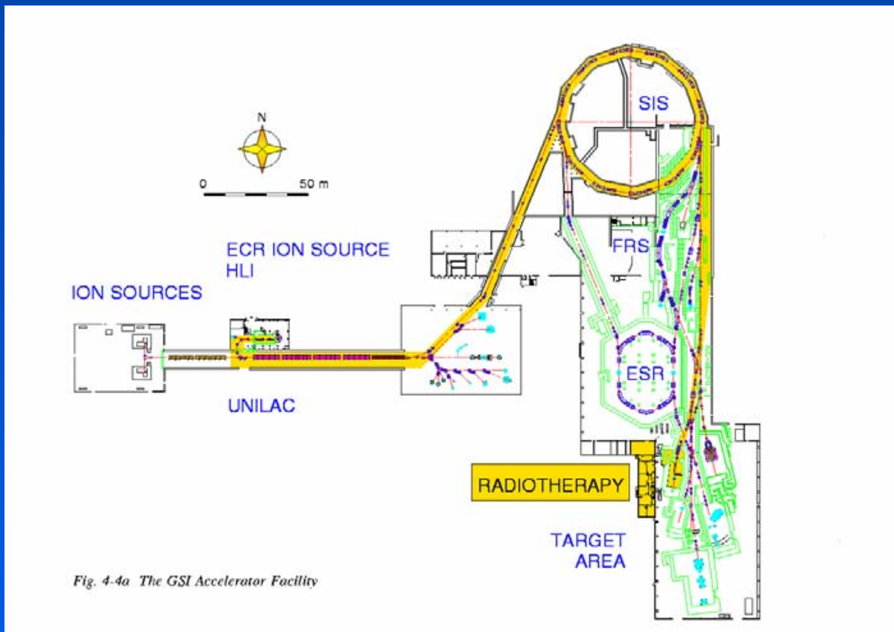


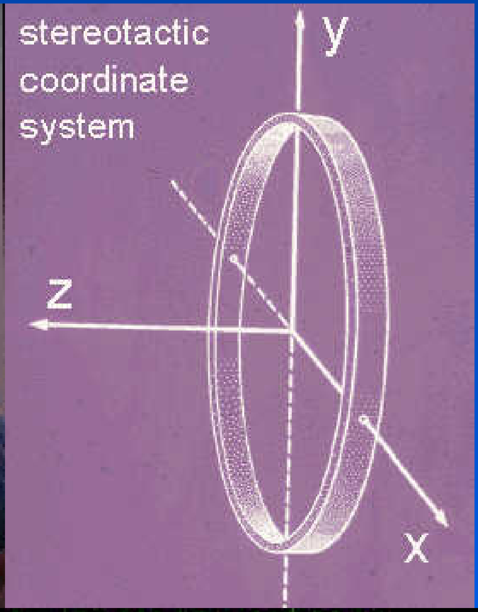
Fig. 4-4a The GSI Accelerator Facility

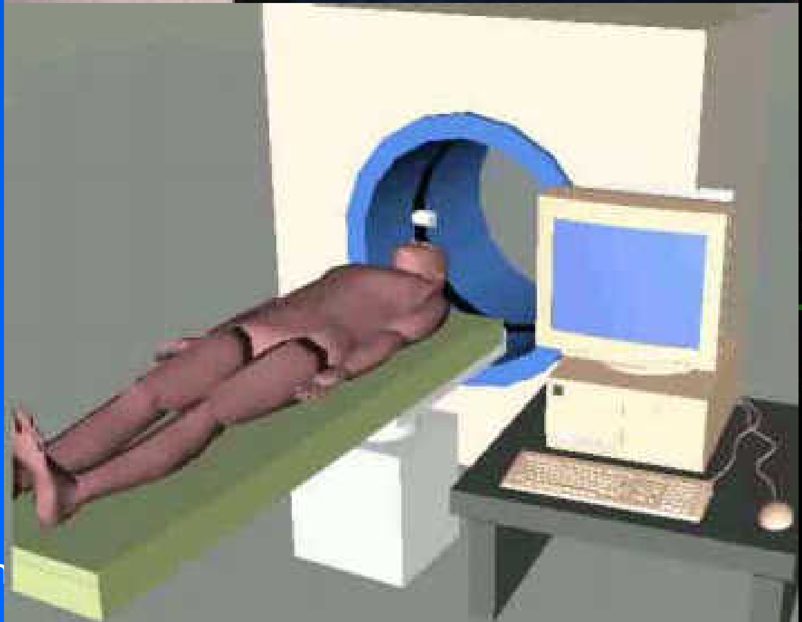
Process

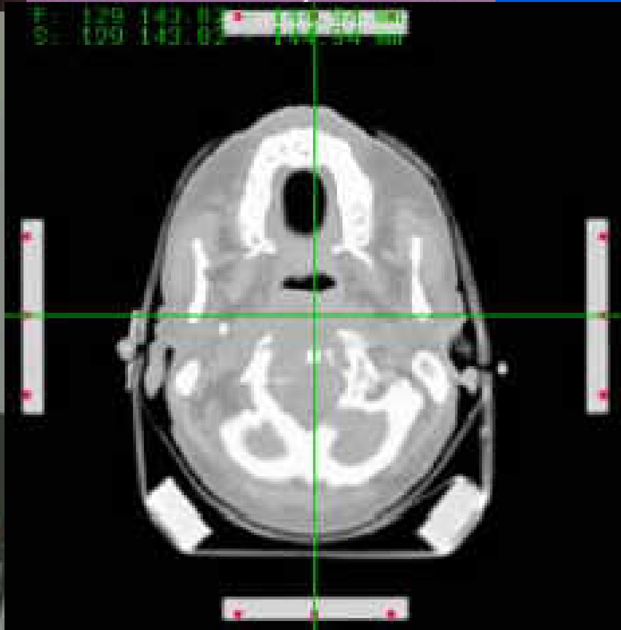
- patient immobilization
- 3D-imaging (CT, MRI, PET, ...)
- definition of target volume + organs at risk
- definition of treatment modality
- dose calculation + treatmentplan evaluation
- patient positioning
- treatment
- follow-up

Stereotactic Immobilization

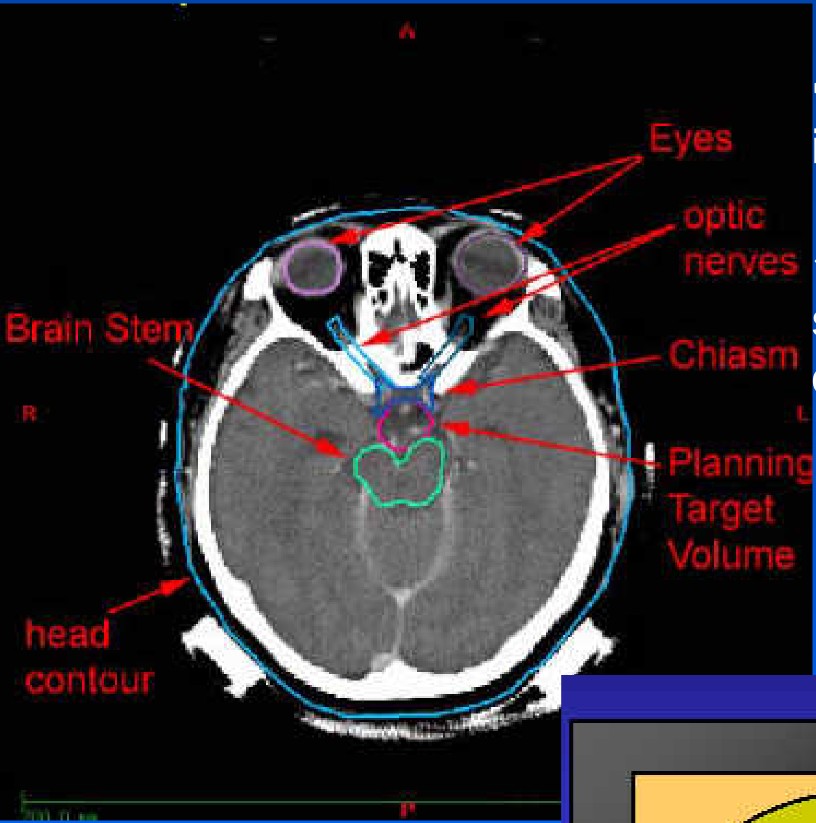
- couple a coord.-system to the body
- localizer with fiducials
- calculate stereotactic coordinates for the target





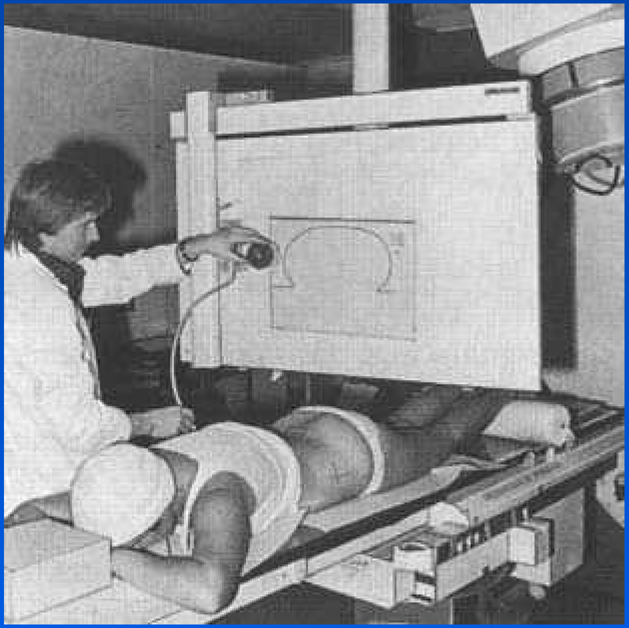


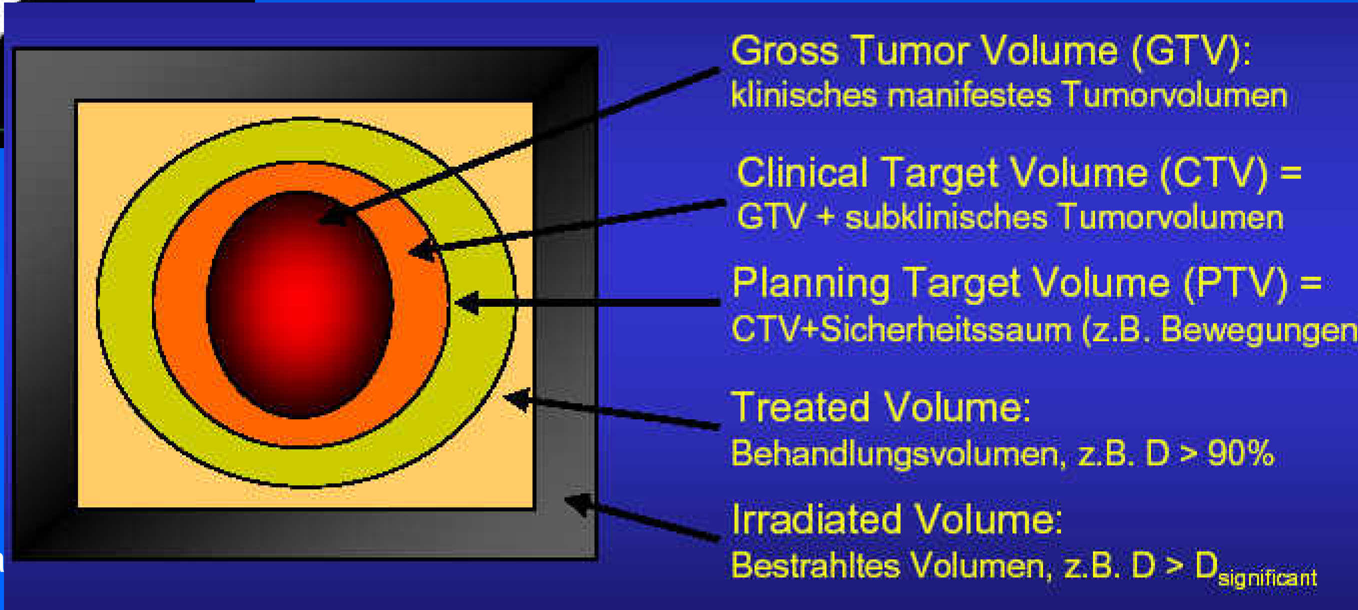
Treatment Planning



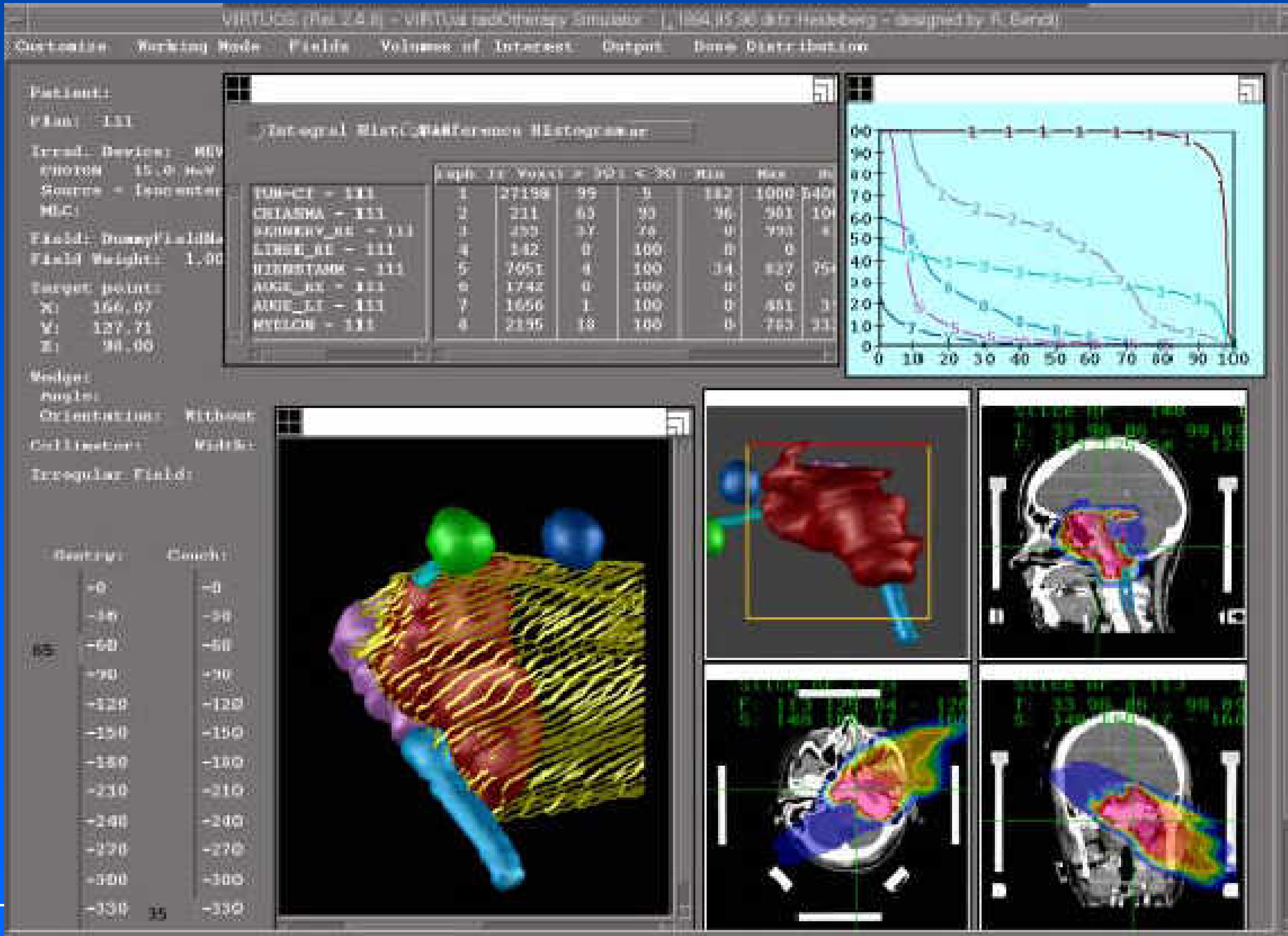
➔1960: contours in 1 plane only

🡐today: 3D data set, density correction, ...



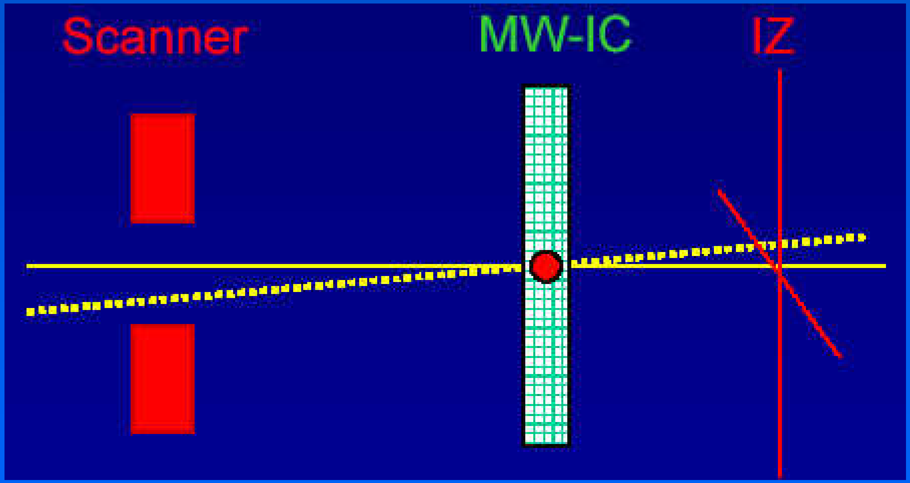


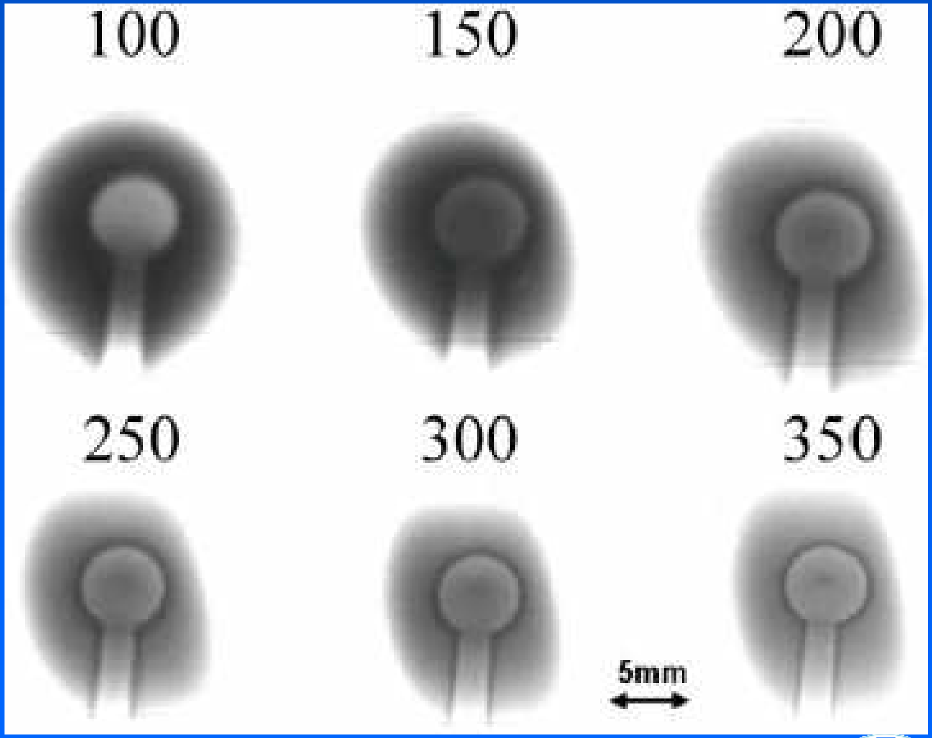
Treatment Planning



Pencil Beam Position

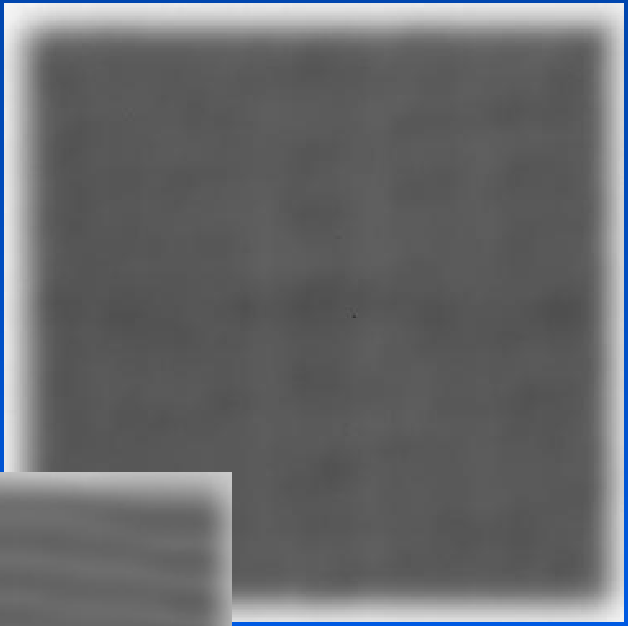
- position of the pencil beam depends on the beam energy and the beam spot size
- check the position and width at the iso-center using a tungsten sphere in front of a X-ray film

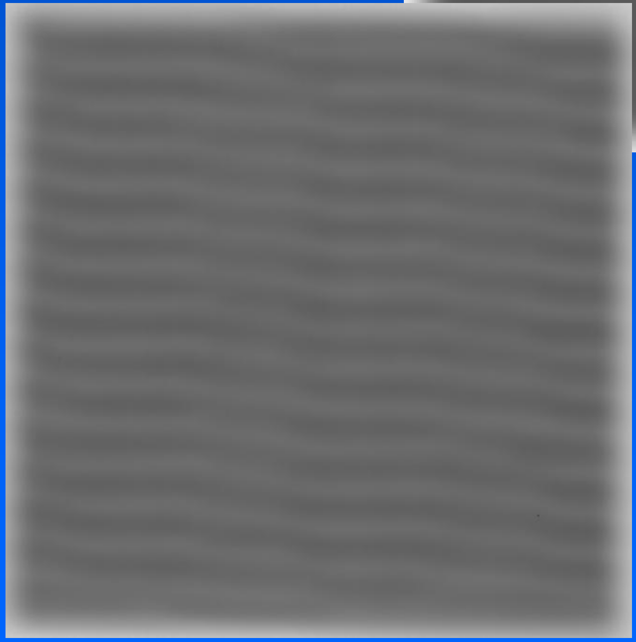


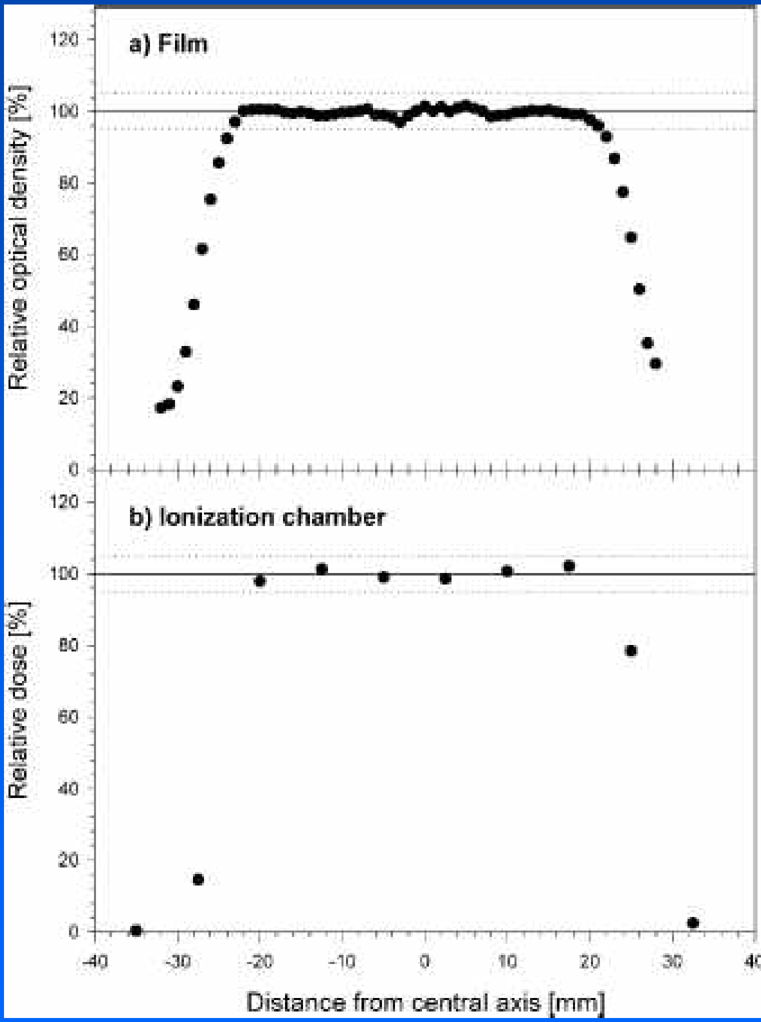


QA / Rasterscansystem

homogeneity of 2d dose distributions

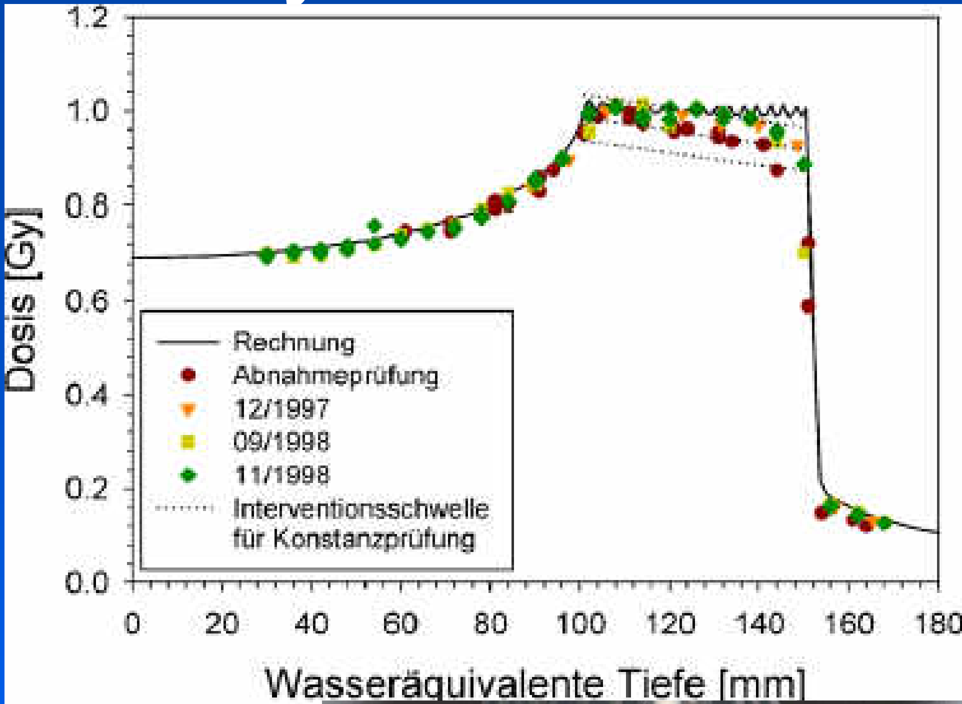


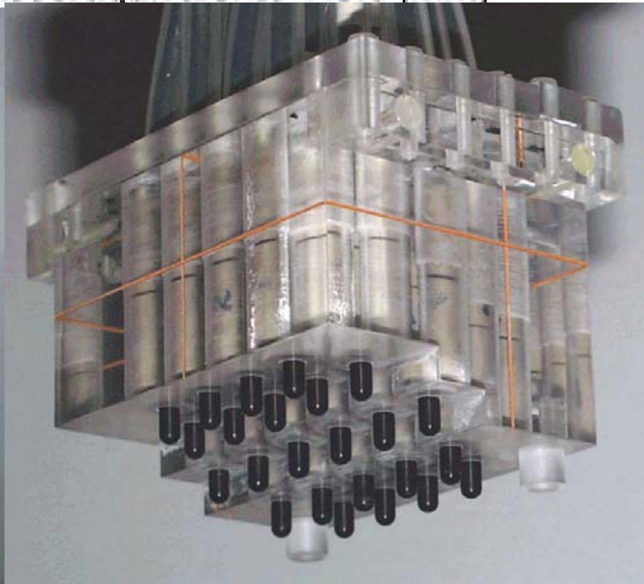




QA / Rasterscansystem

verification of depth-dose distributions



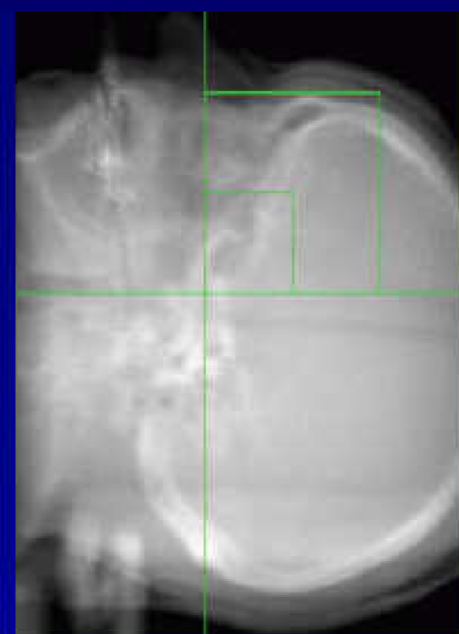


Patient Positioning

- alignment with the room laser system
- setting of the stereotactic coordinates

Position Verification

- comparison of X-ray image with a digitally reconstructed X-ray image (source: planning CT)
- accuracy at the base of the scull 1-2 mm (Karger 2001, IJROBP)



Combined photon and carbon ion RT for adenoid cystic carcinomas clinical phase I/II trial

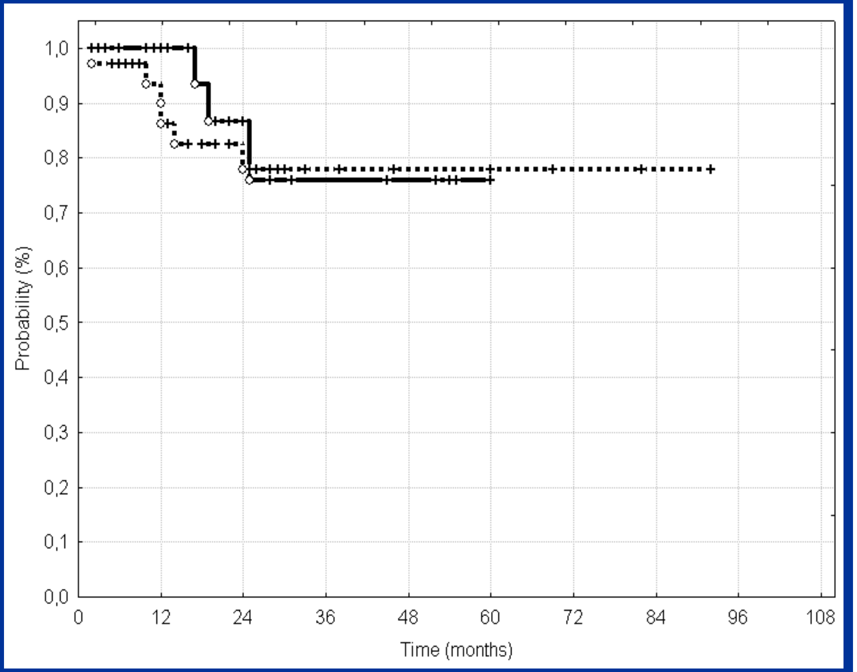
Treatment parameters

Photon IMRT 54 Gy to the CTV

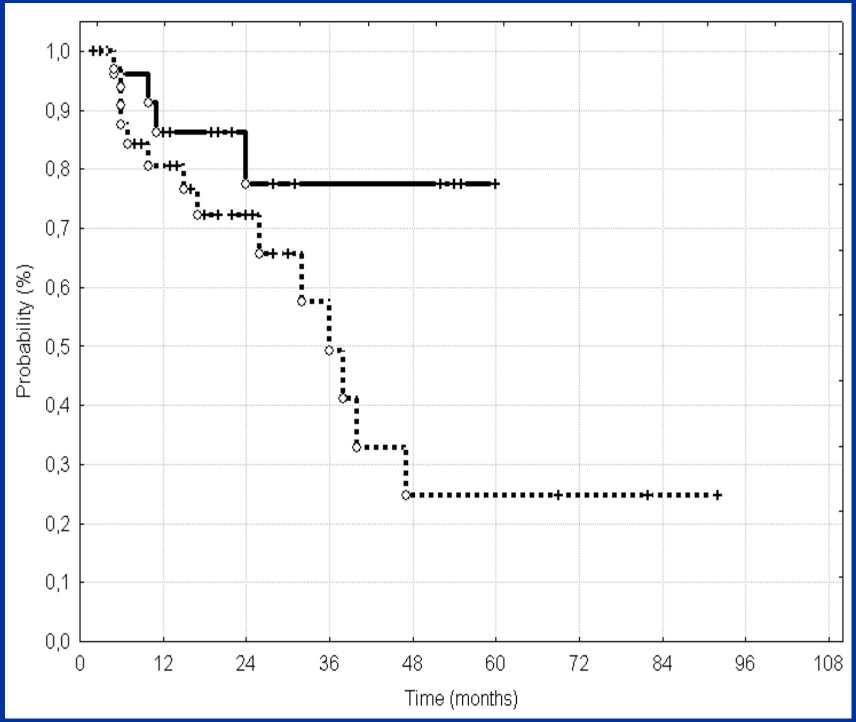
+

carbon ion boost 18 GyE (6x3.0 GyE) to the GTV

FSRT / IMRT vs FSRT / IMRT+C12 :
locally advanced adenoidcystic carzinoma



overall survival



local control

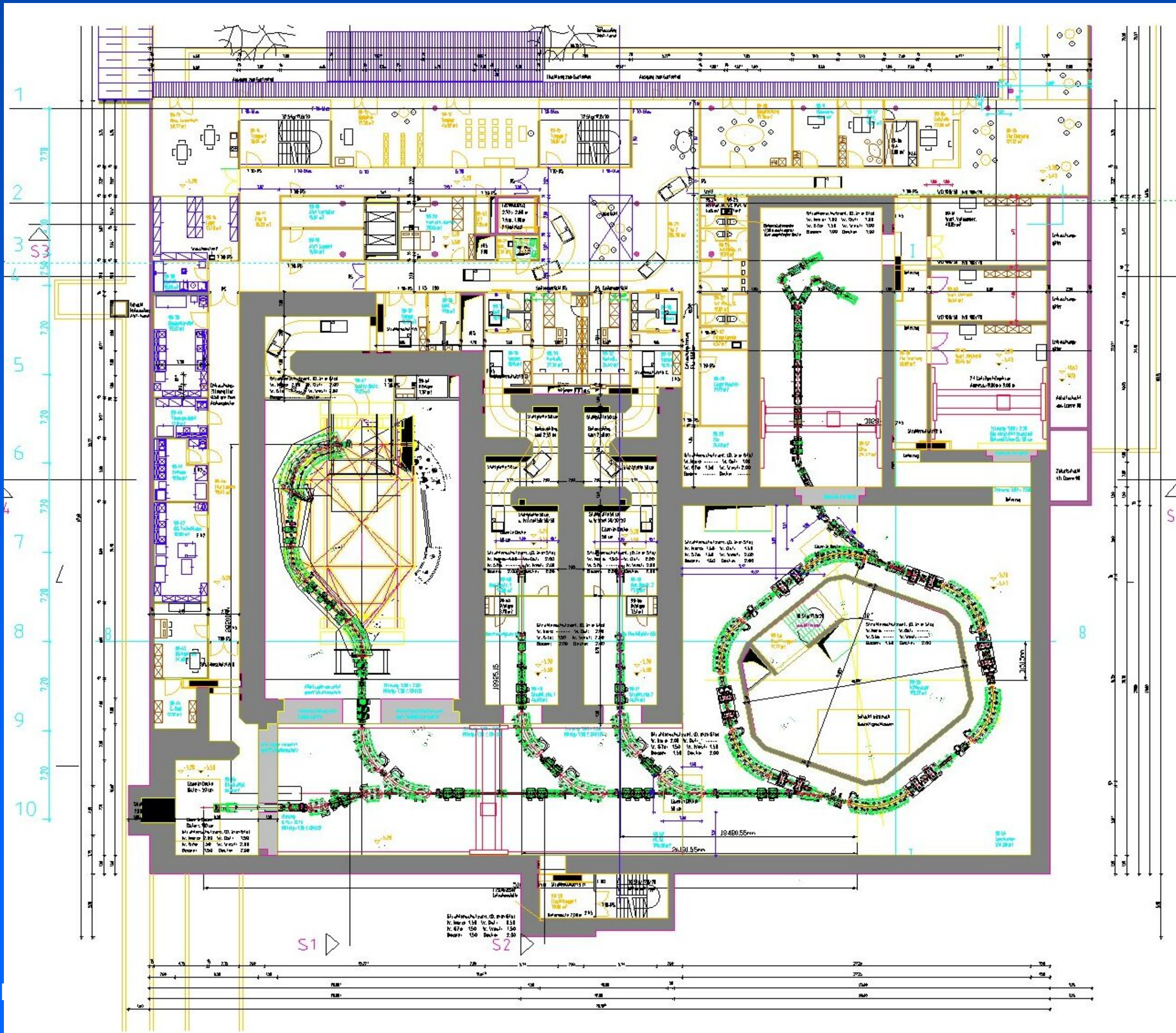
- early toxicity acceptable
- late toxicity > CTC grade 2 < 5%

Schulz-Ertner, Cancer 2005

Heidelberg University Hospital

Heidelberg Ion Therapy Center

- compact design
- full clinical integration
- rasterscanning only
- low-LET modality: Protons (later He)
- high-LET modality: Carbon (Oxygen)
- ion selection within minutes
- world-wide first scanning ion gantry
- > 1000 patients/year > 15.000 fractions/year
- integrated R+D-infrastructure



Some Facts

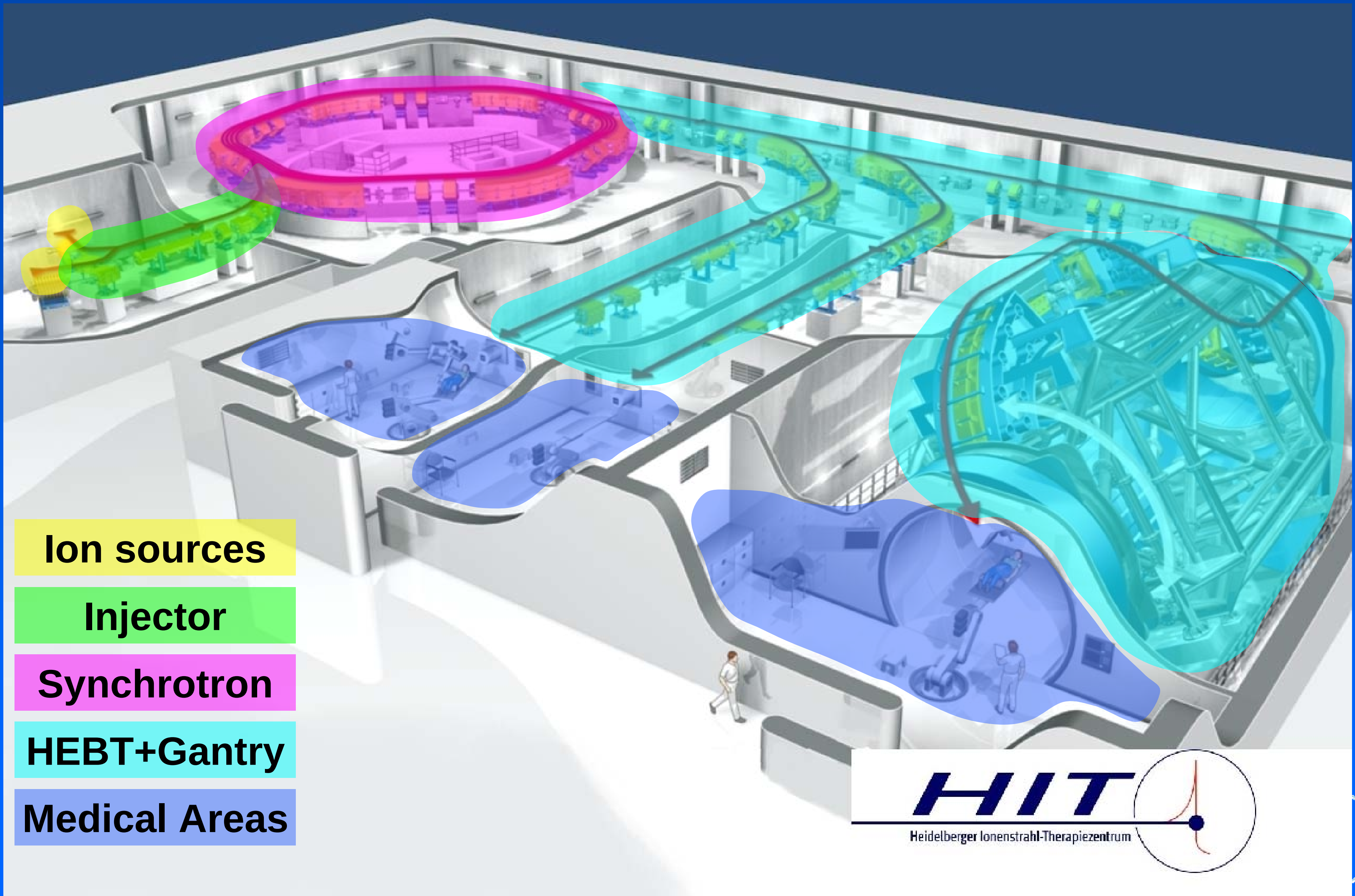
- Effective area 5.027 m²
- Concrete 30.000 tons
- Constructional steel 7.500 tons
- Capital Investment 106 M€

Start of construction: November 2003
Completion of building and acc.: June 2006
Accelerator settings established: April 2008
First patient planned: 2nd half of 2009

Project Partners:

- **University** pays, owns and operates the facility
- **GSI** built the accelerator
- **Siemens** supplies all components related to patient environment
- **GSI, DKFZ, Siemens …** are research partners

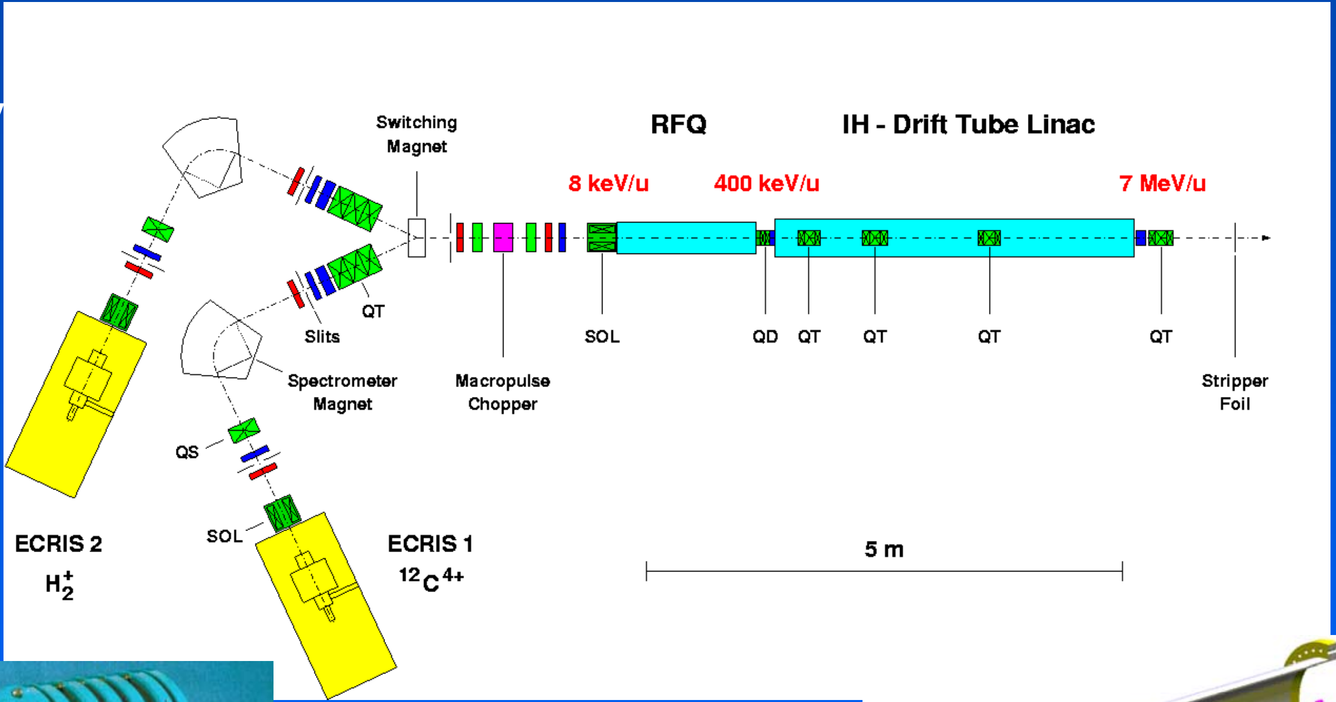
HIT Accelerator System



HIT / Linac

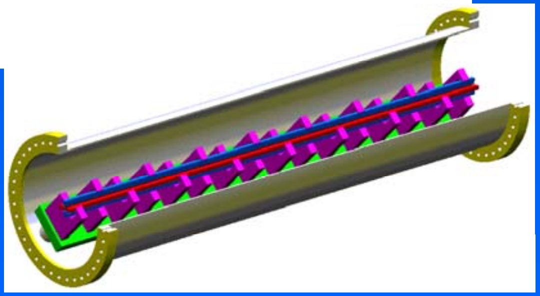
Cooperation: GSI + IAP@ Univ. Frankfurt/M.

- compact design
- proven technology
- fast change of the ion species
- fast intensity variation (1000-times)
- constant beam parameter



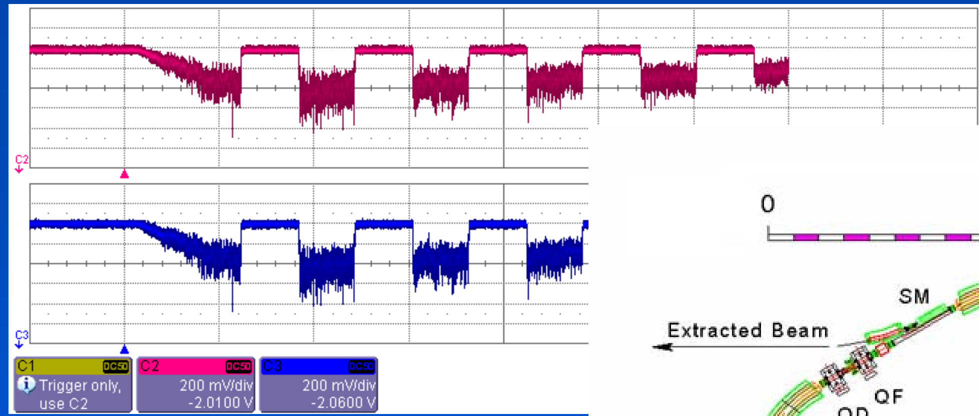
Ion source

RFQ



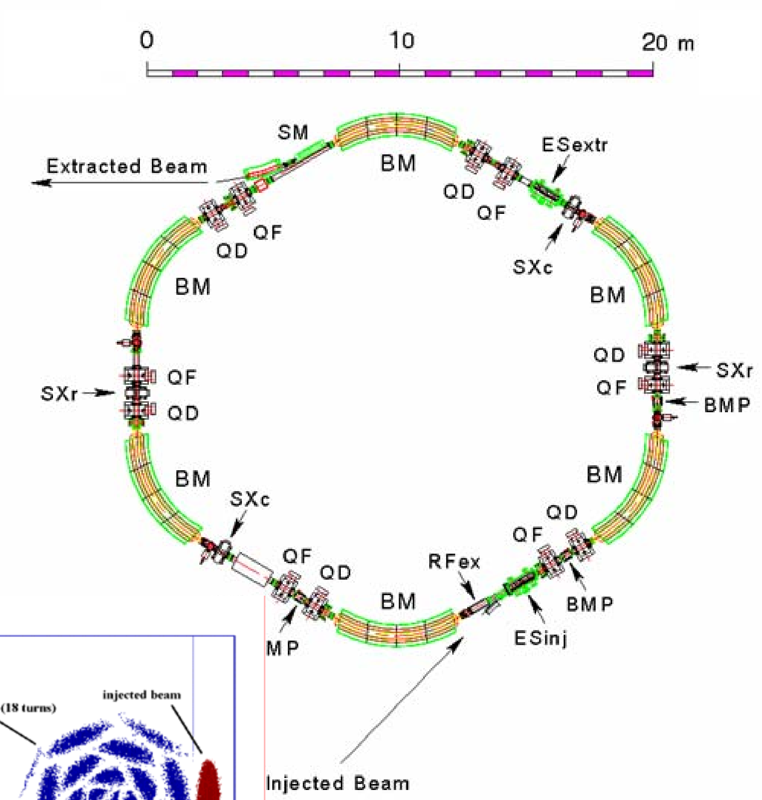
HIT / Synchrotron

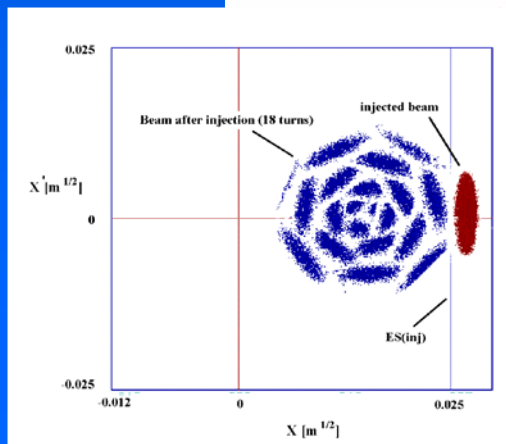
- **compact design**
- **proven technology**
- **multiturn-injection => high intensities**
- **rasterscanning optimized, extremely flexible beam extraction**
- **fast variation of energy (range)**



Multiple extraction

0,5 bis 10 sec



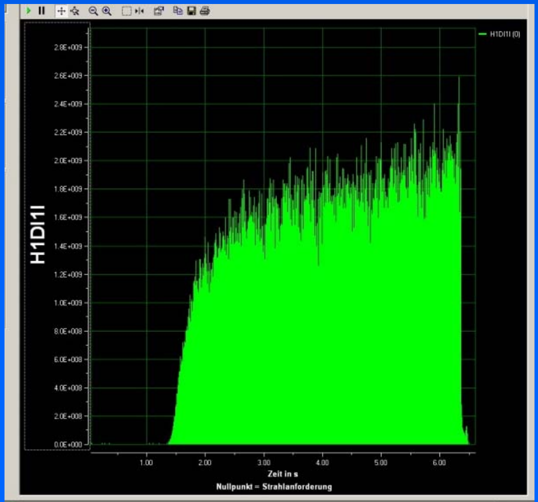


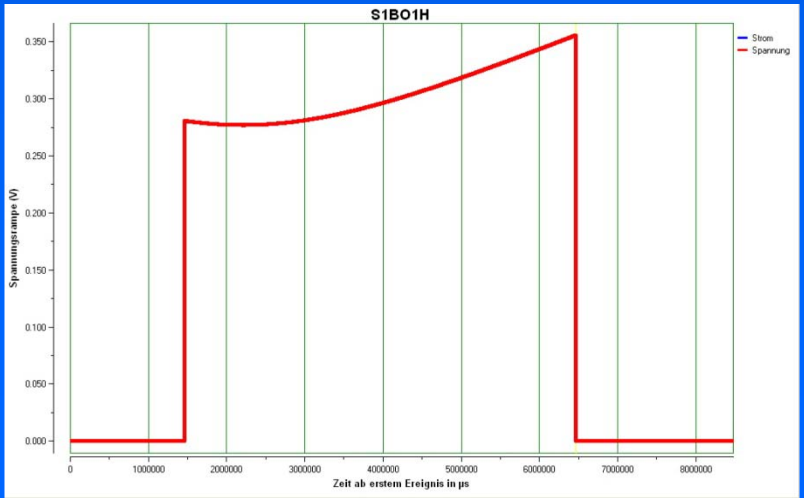
Multiturn injection

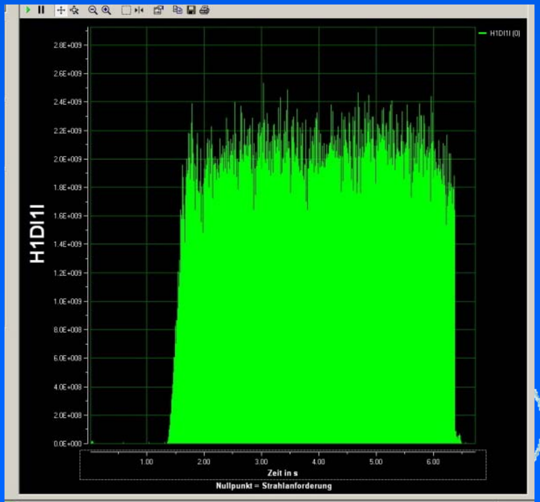
Th. Haberer, Heidelberg Ion Therapy Center

RF-KO-Extraction

- **Principle**
  - resonant HF-excitation (betatron frequency)
  - constant separatrix
- **Characteristcs**
  - slow extraction
  - constant ion-optical settings dring extraction
  - Multiple extractions available
  - Spillshaping via amplitude modulation

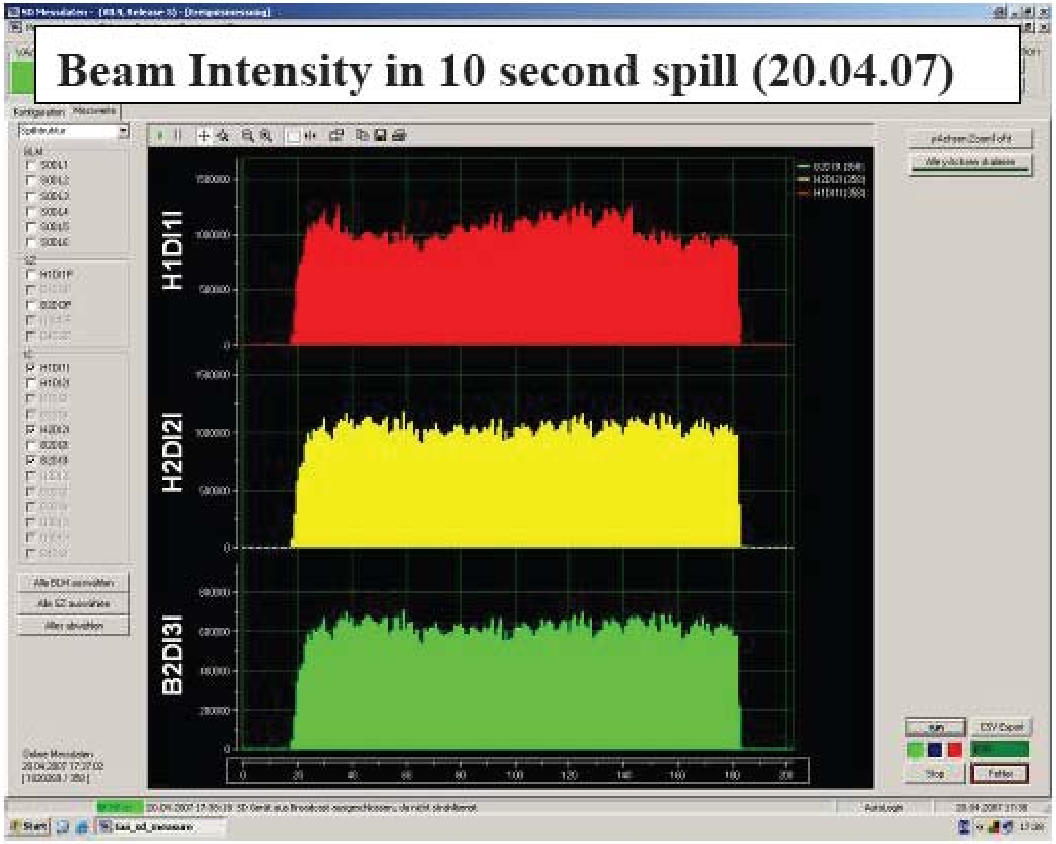


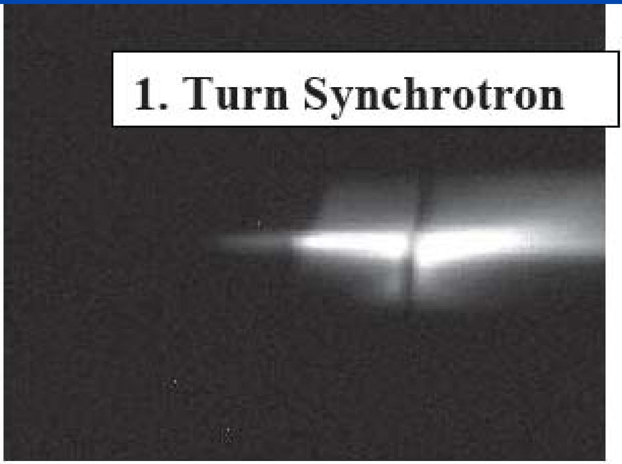


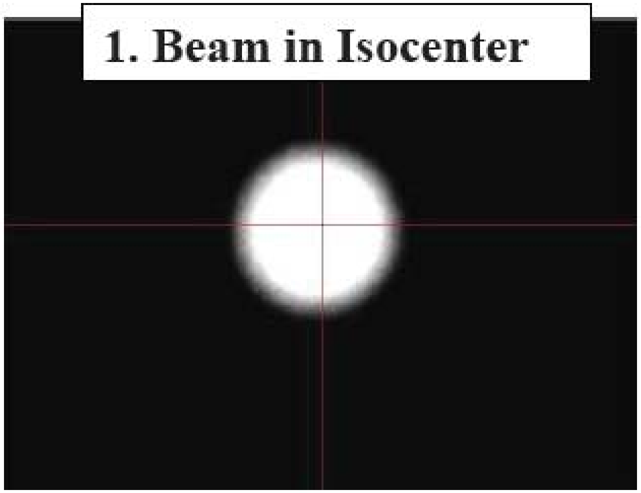


Synchroton/HEBT Commissioning

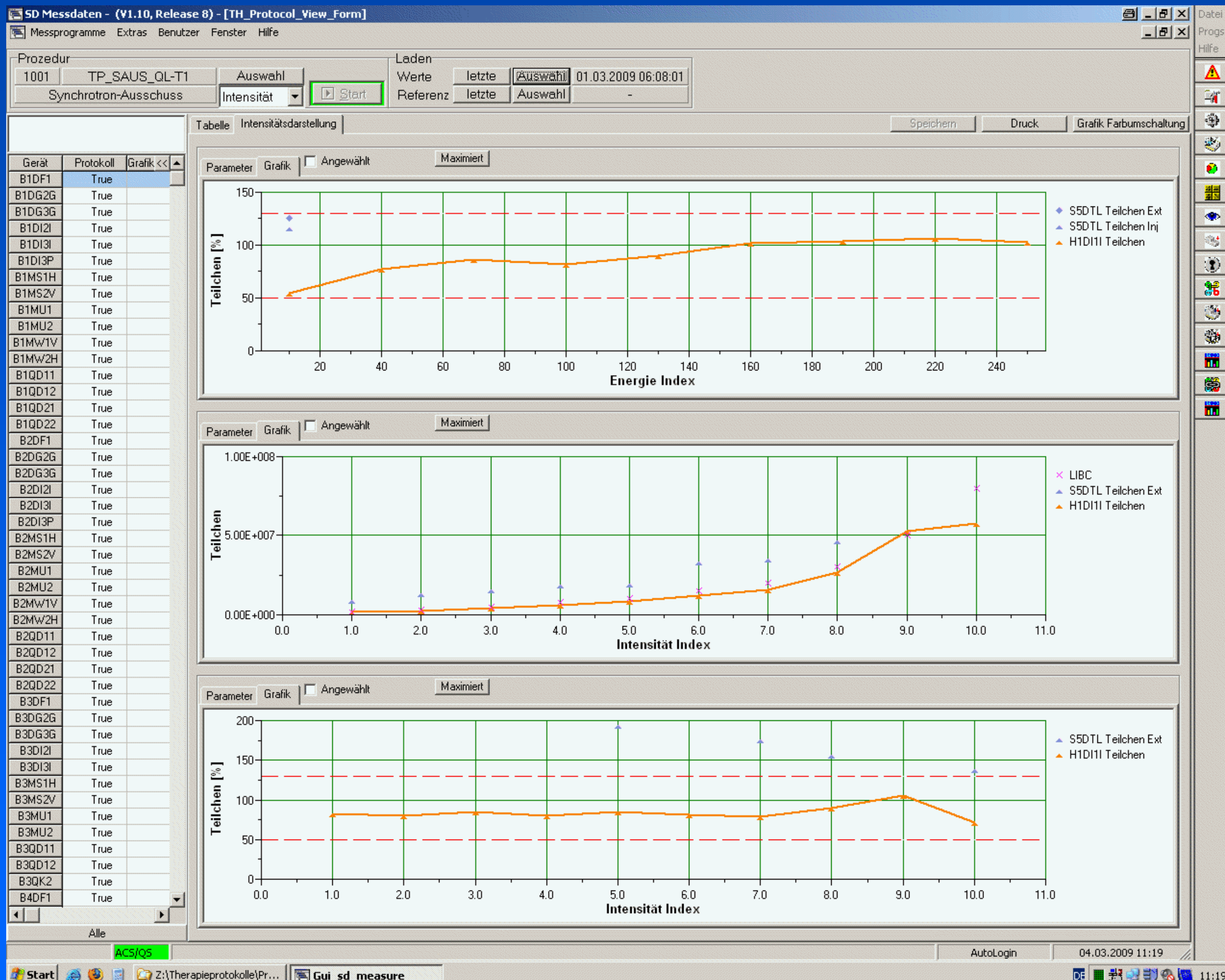
- **1. Turn in Synchrotron: Febr. 2007**
- **1. Beam in Cave: March 2007**







Daily ACC-QA, March 2009



Accelerator Status

- **Sources, injector and synchrotron** fully commissioned for protons, carbon and oxygen (256 energies each)
- **H1 / H2**: pencil beam libraries (E F I) for protons and carbon in therapeutical quality reached in April, 2008

  outstanding beam quality: very high position and focus stability, small intensity fluctuations
- **R+D-cave**: protons, carbon and oxygen energy libs established
- **Gantry**: proof of principle for protons and carbon

  (representative settings in the full phase space (E F I α))
- **To do**: intensity upgrade (x3) under way (sources, LEBT, RFQ)
- **Operation scheme**:

  2007: 24 h / 5 days

  2008ff: 24 h / 7 days, 330 days, 2 shutdowns 14 days each
- **Availability** of the pencil beams @ H1/2: ≈ 98%

Advantages of a synchrotron

- It works and fulfills all requirements.

- proven technology
- stable & reliable operation
- built-in flexibility
  (particle types, energy, timing)
- active energy variation
  - maximum beam purity
  - minimum radiation protection effort

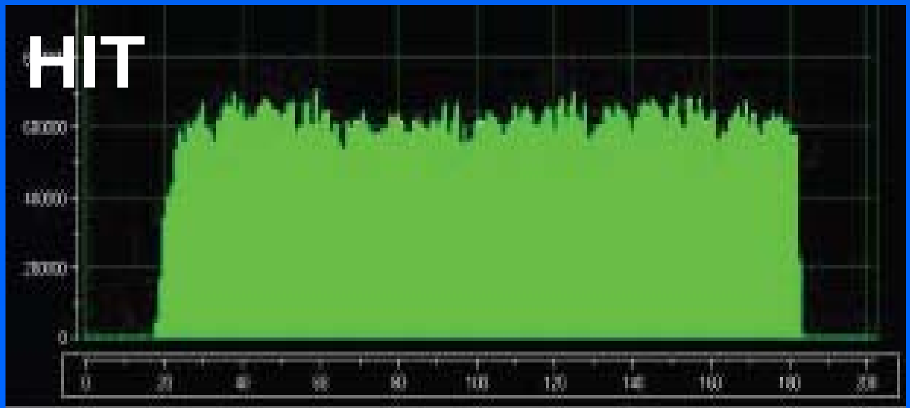
Disadvantages of a synchrotron

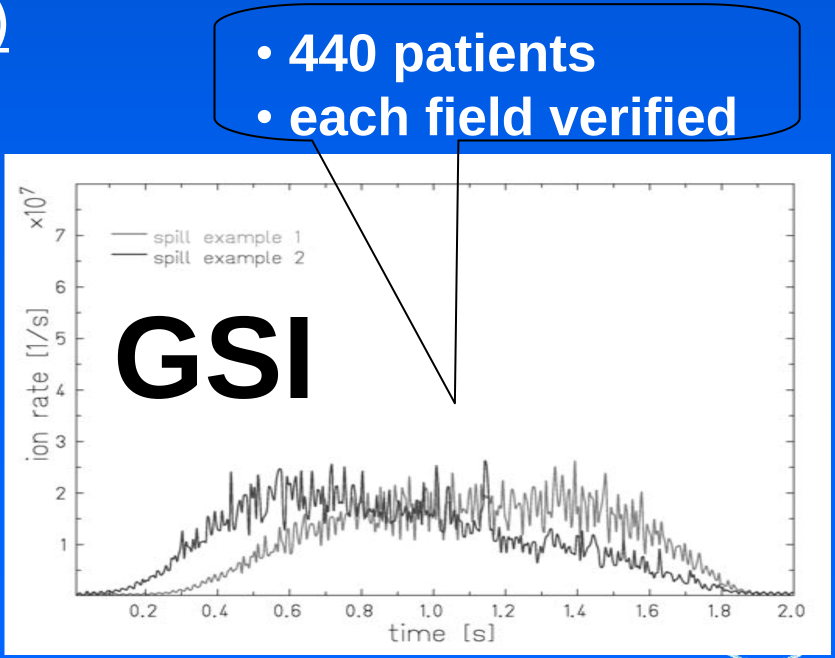
Particle therapy facility

- size of foot print
- initial cost
- (several treatment rooms required)

Objections (no real disadvantages)

- current uniformity
- repetition rate





ACC Conclusion

- gold standard in ion therapy: SYNCHROTRON
  – all C-patients: NIRS, GSI
  – new facilities: HIT, CNAO, Marburg, NROCK, Gunma

- future
  – improved accelerators wellcome
    - lower initial, operational, maintenance cost
  – HOWEVER
    - <u>decrease in treatment quality unacceptable</u>
    - loss of flexibility questionable (25 years)

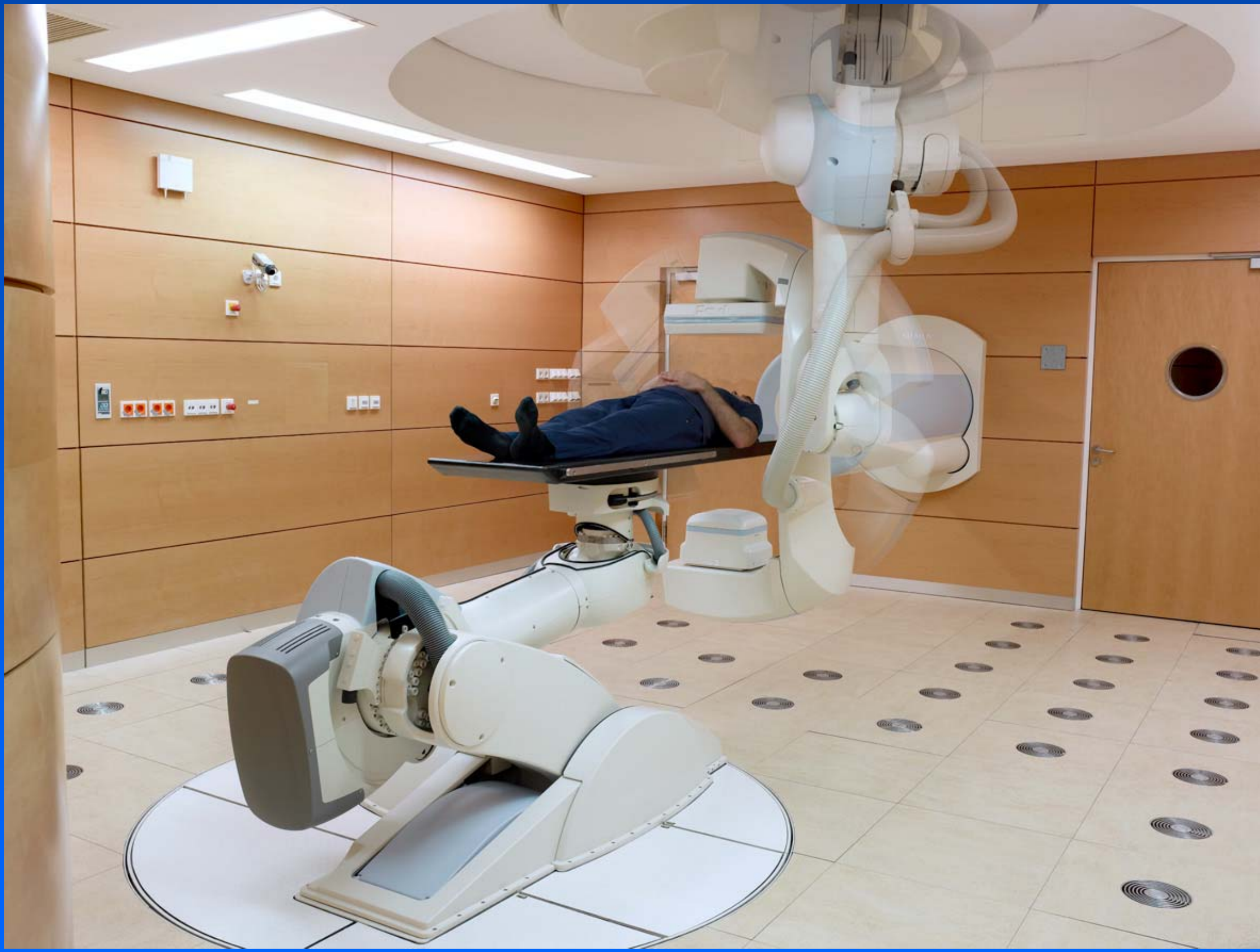
Dose Delivery and Medical Equipment

Identical patient positioning systems
- fixed beam
- Gantry

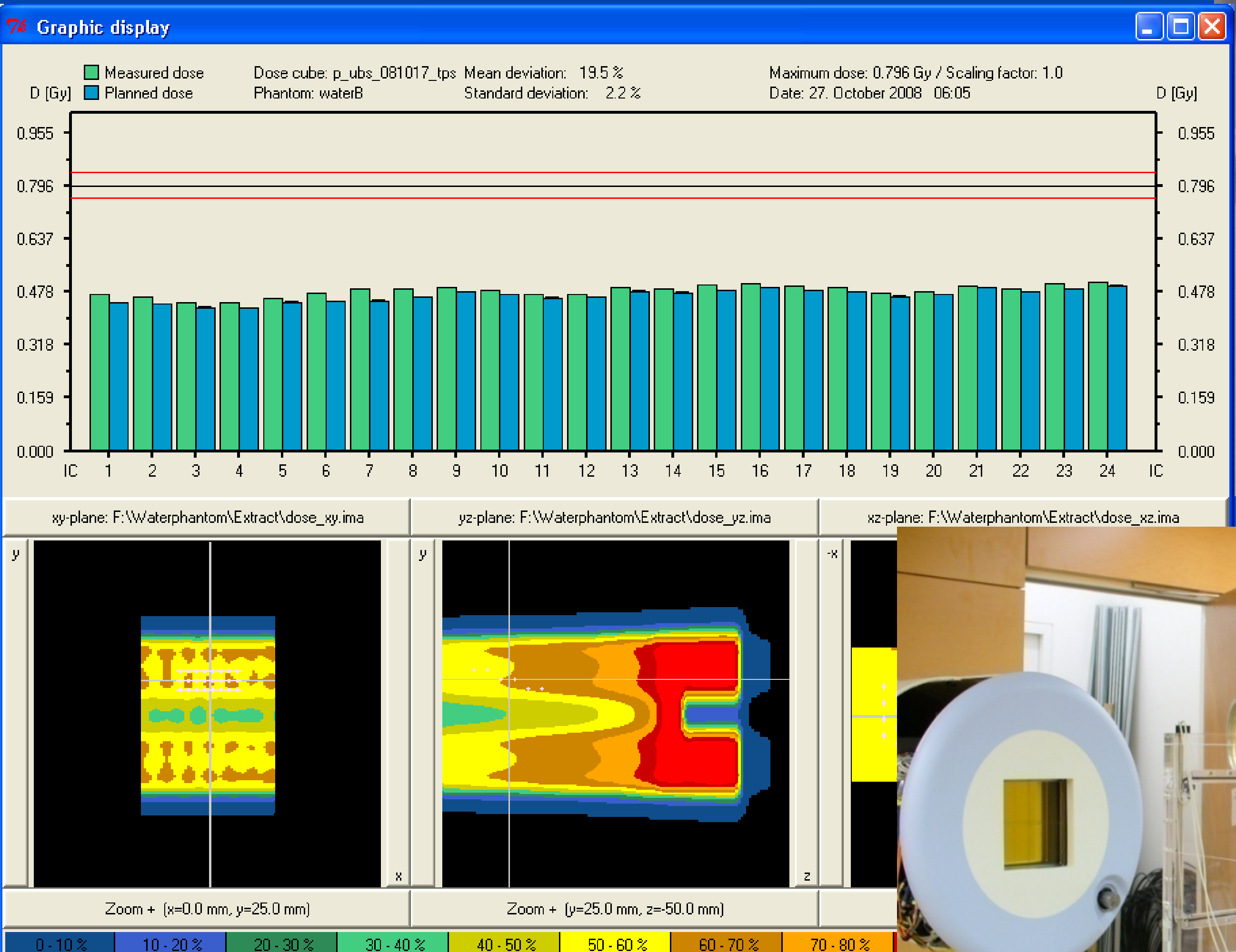
Workflow optimization
- automated QA procedures
- automated patient hand over from shuttle

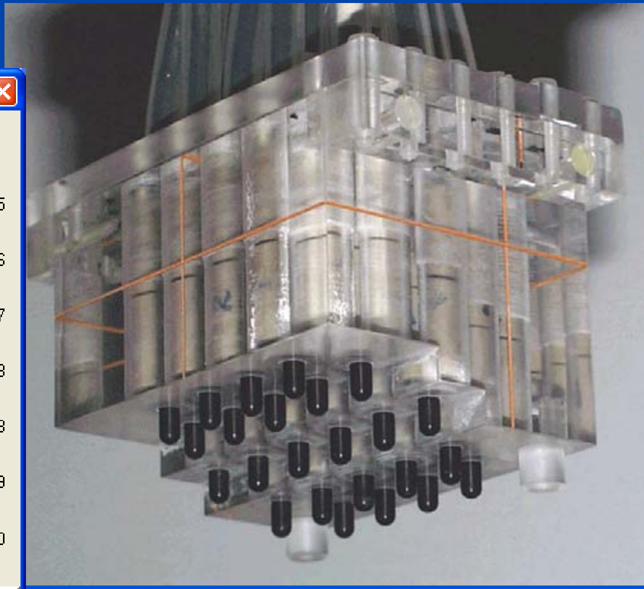
Inroom position verification
- 2D
- 3D Cone beam CT

Open for future applications and workflows

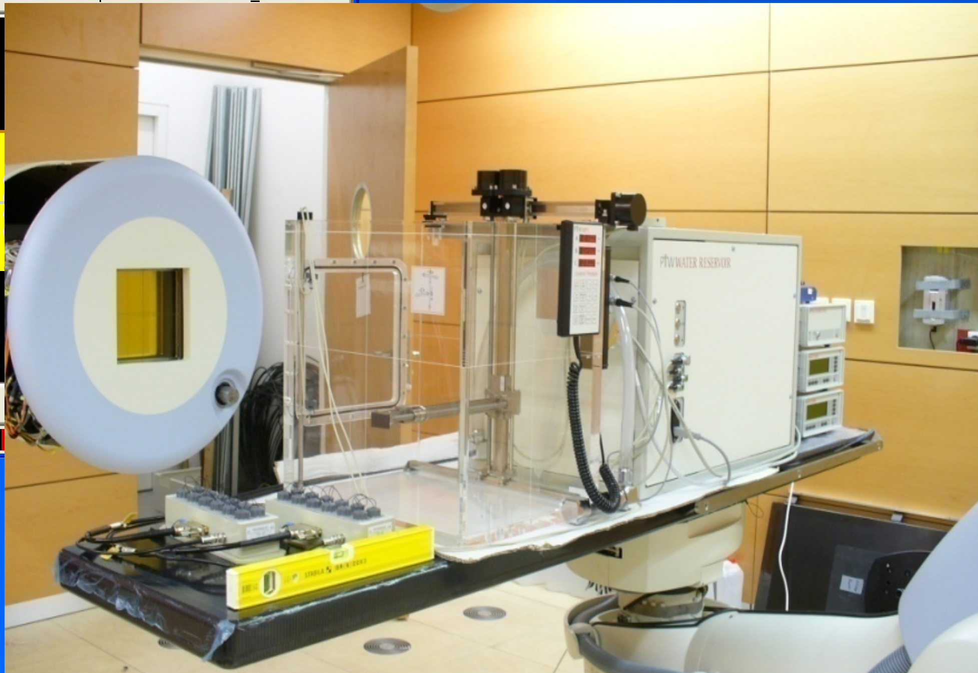


Commissioning





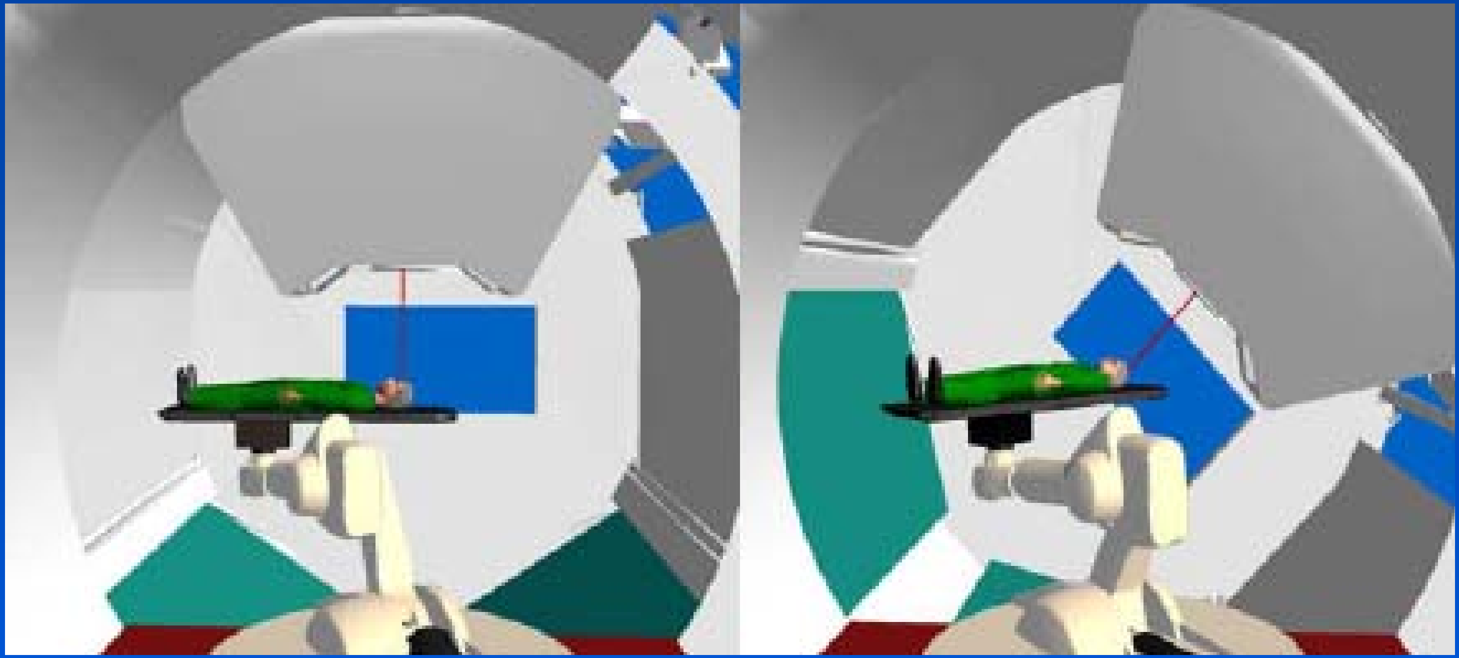
commissioning result, Protons @ H1:
3d dose delivery vs. treatment planning
24 thimble-type ICs in a water phantom,
standard deviation 2.2 %



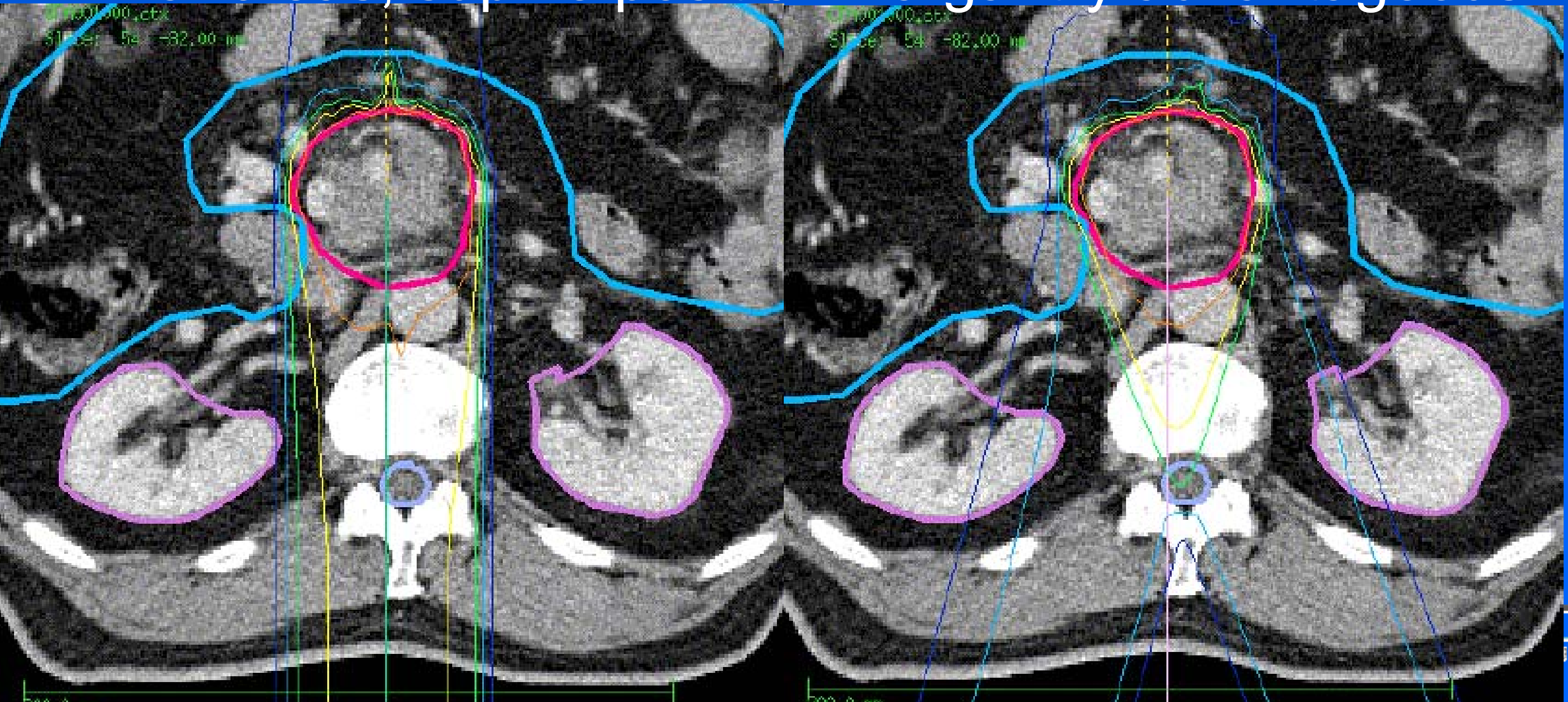
QA Table Top with Water Phantom

Motivation Gantry

Advantage of a rotating beamline

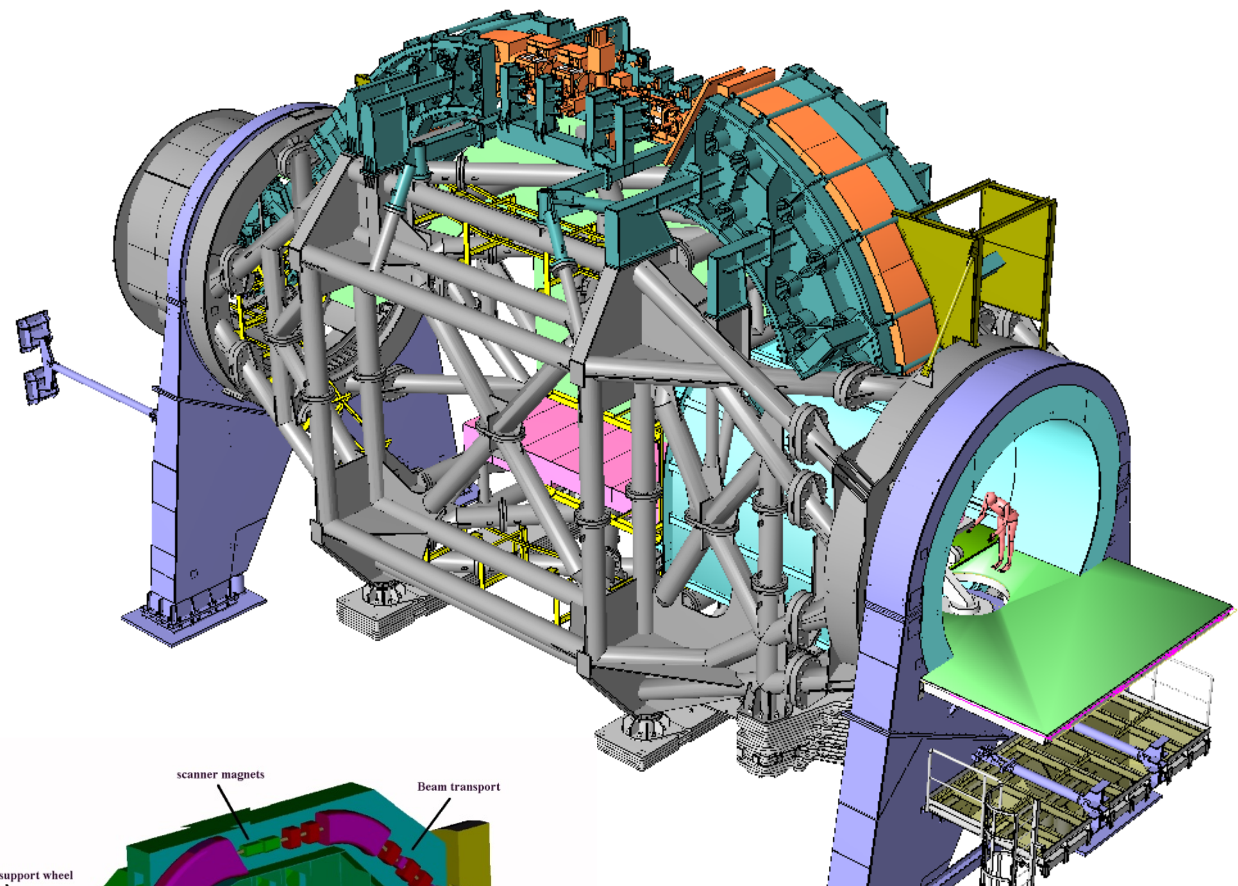


Pancreas, supine position via gantry advantageous

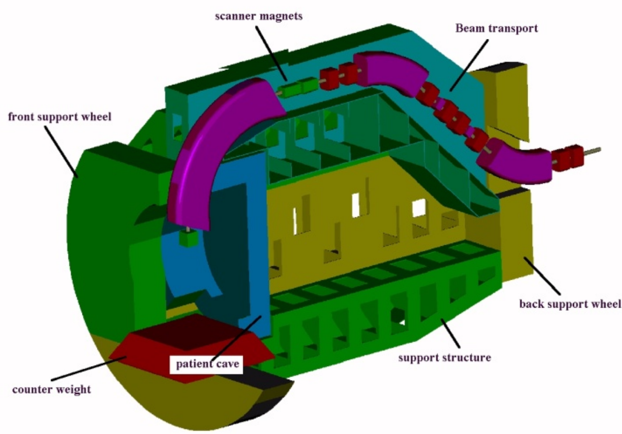


Scanning Ion Gantry

- optimum dose application
- world-wide first ion gantry
- world-wide first integration of beam scanning
- 13m diameter
  25m length
  600to overall weight
  0,5mm max. deformation
- prototype segment tested at GSI

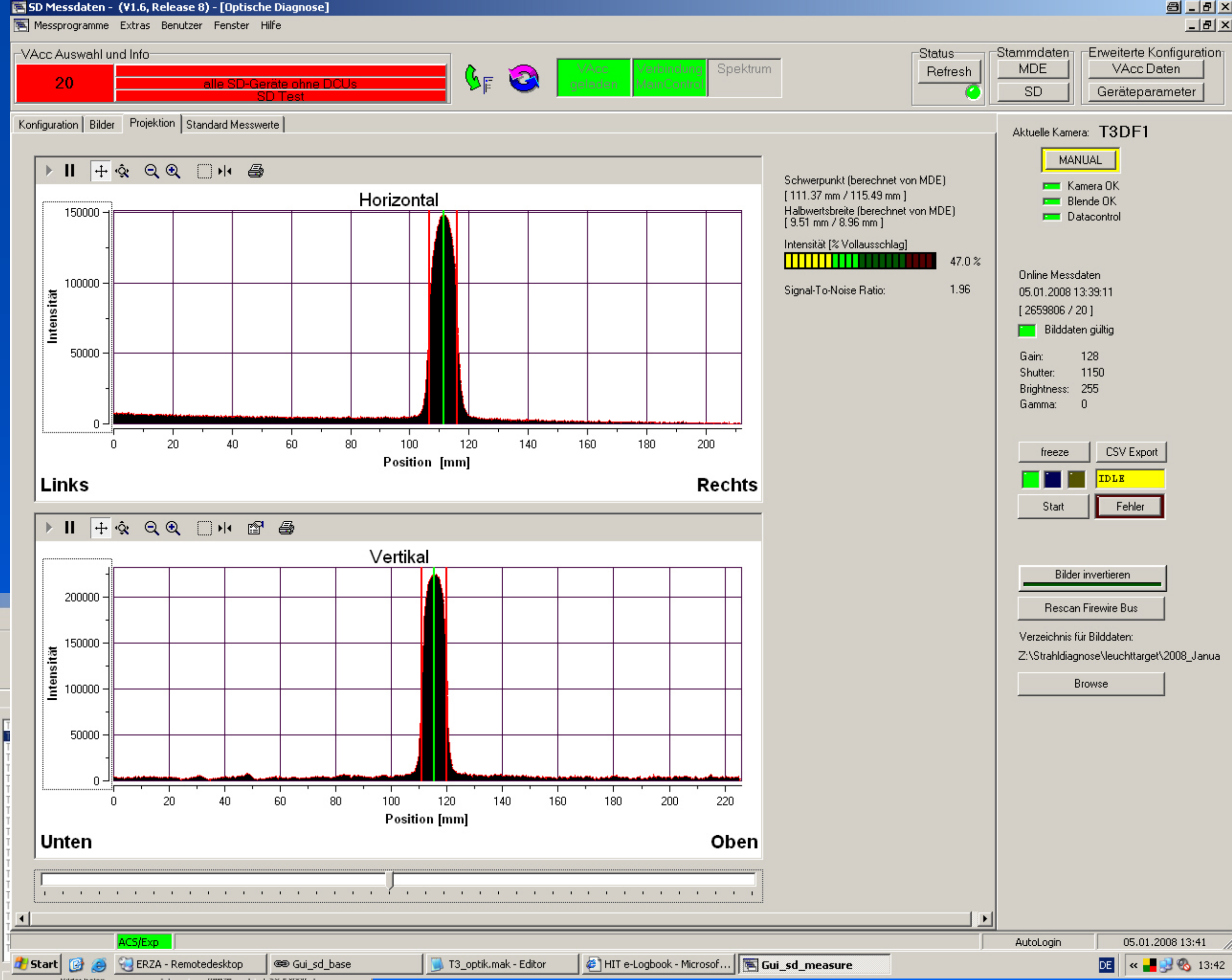


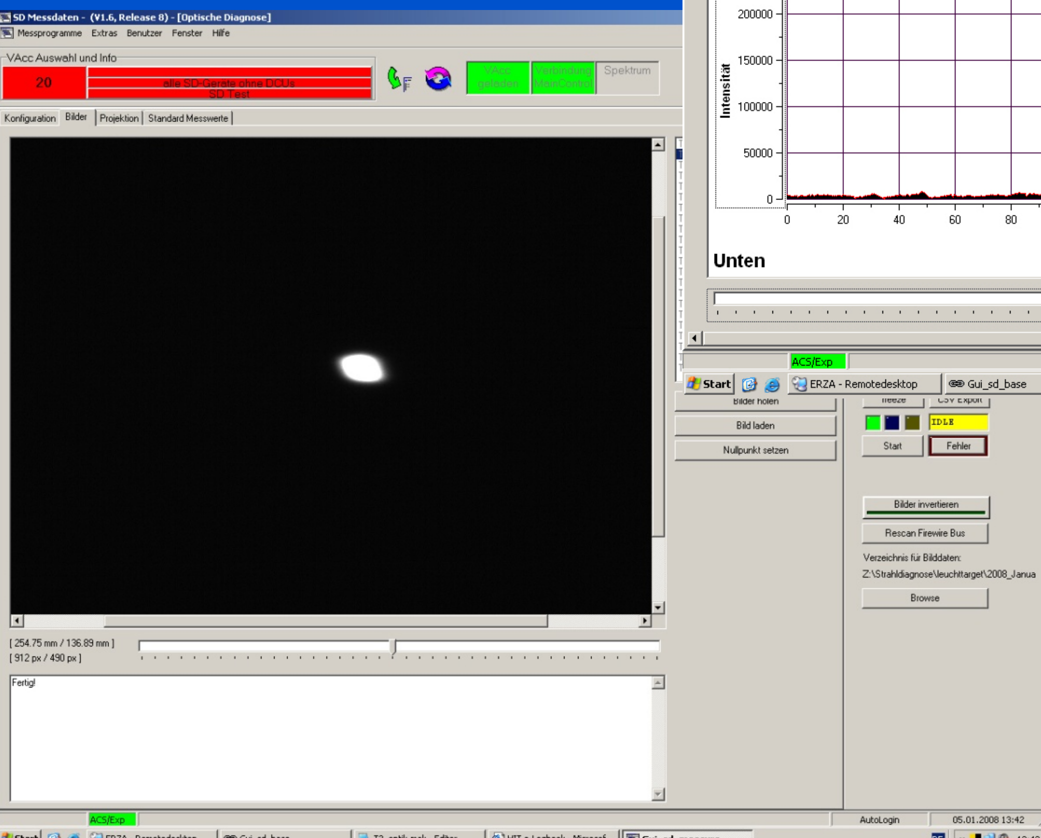
MT Mechatronics



The HIT Gantry Rotates

Gantry: first beam at the isocenter





January 4th, 2008

Thank you for your attention !

(Intensity modulated raster scan, ^{12}C at 430 Mev/u, October 15th 2007)