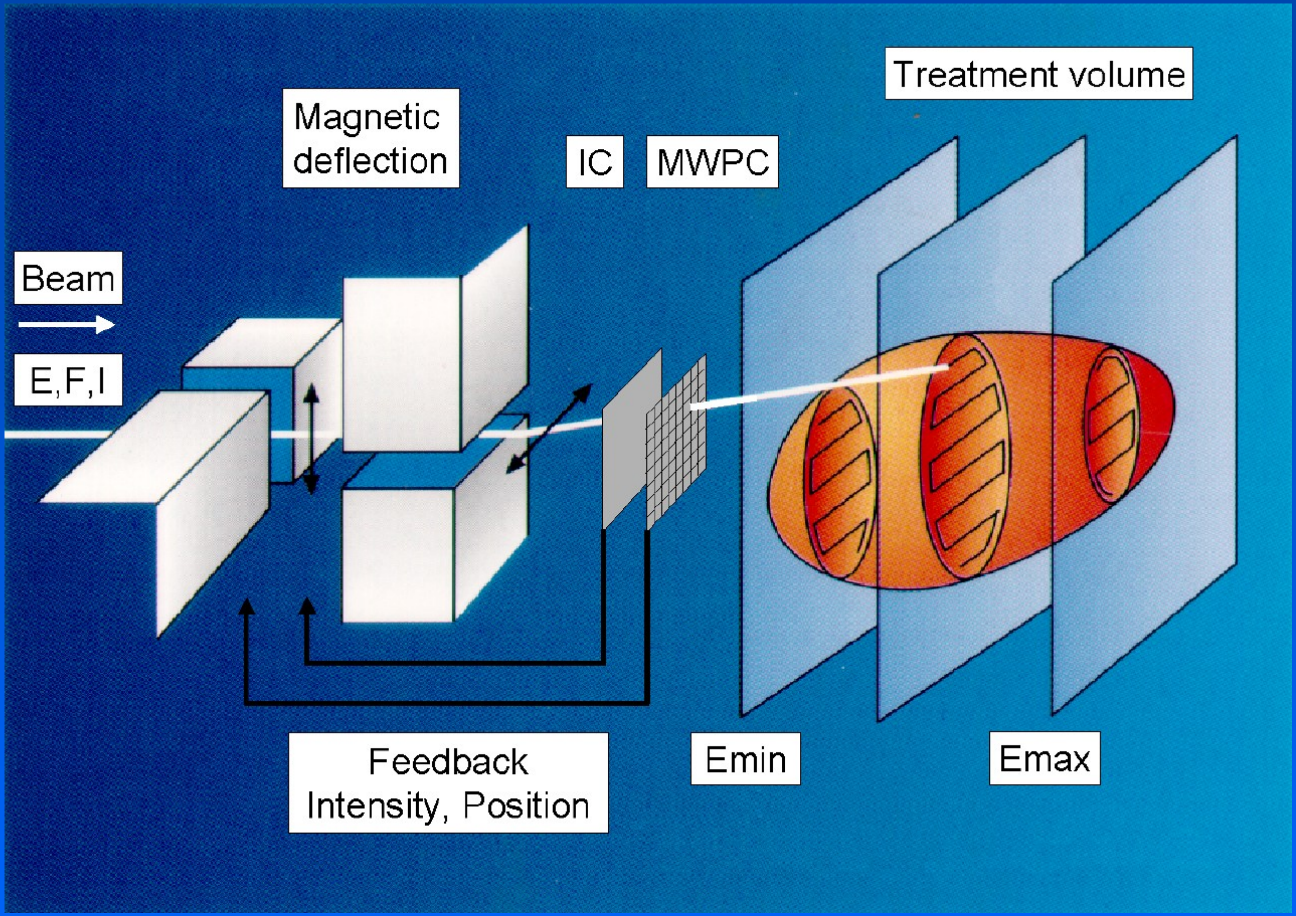
Scanning Beam Dose Delivery



Prof. Dr. Thomas Haberer
Scientific-technical Director
Heidelberg Iontherapy Center

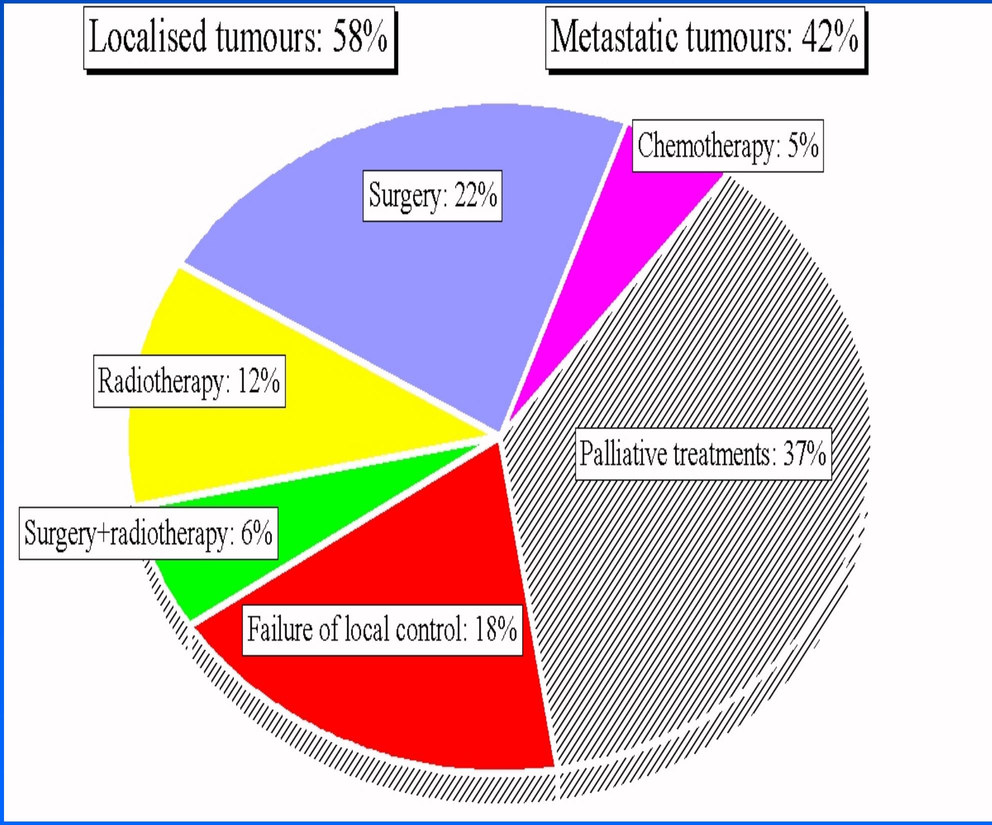
Outline

- Situation/Rationale
- Standard (passive) dose delivery
- Semi-active dose delivery
- Beamscanning
- Implementation@HIT

Situation

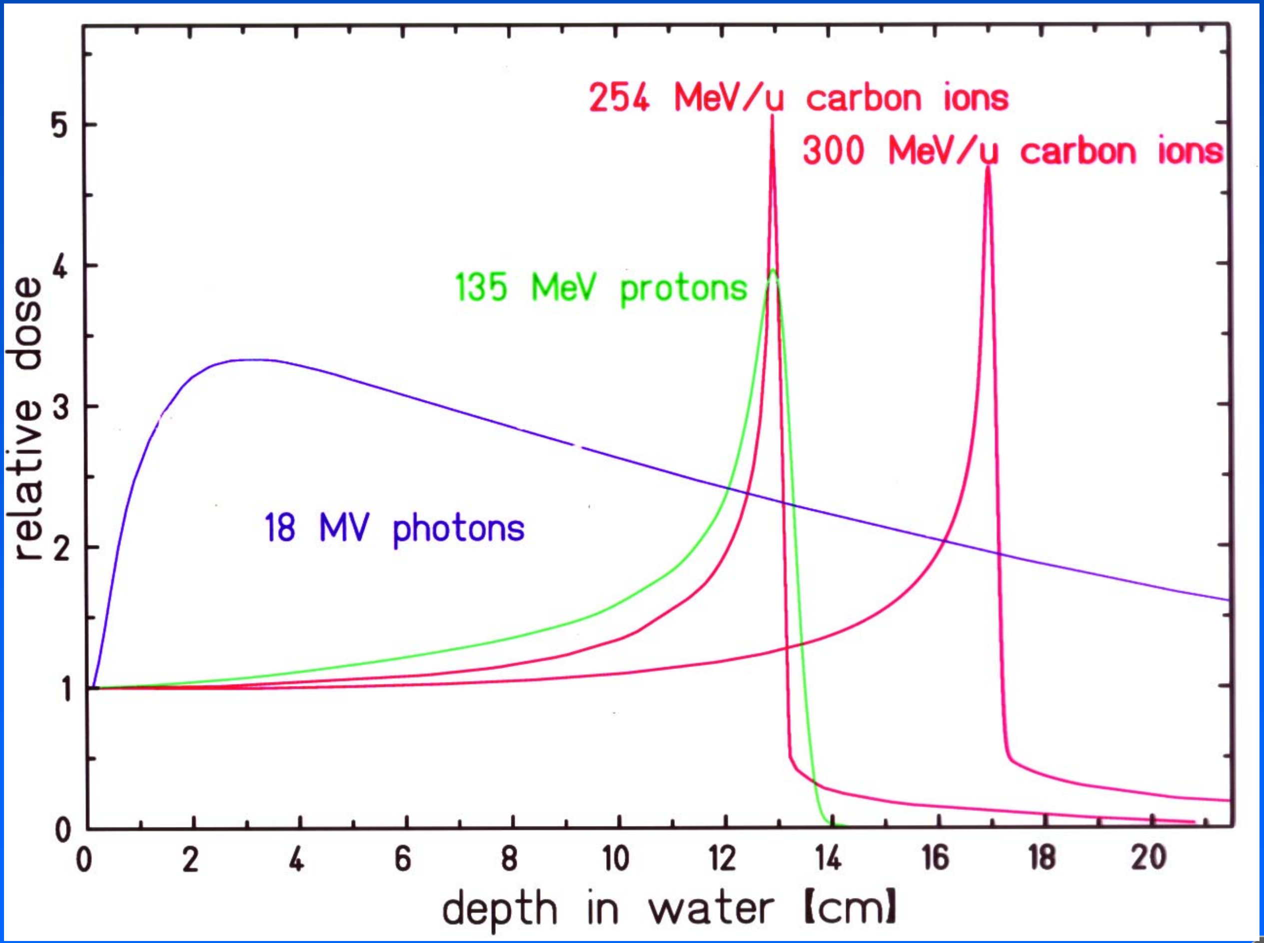
- 2/3 patients suffer from a local disease at the time of diagnosis
- In 18% local treatment modalities fail => 280.000 deaths/year in the EC
- Protons and ions have the potential to cure 30.000 patients/year in the EC

relevance of local tumor control (EC-study 1991)



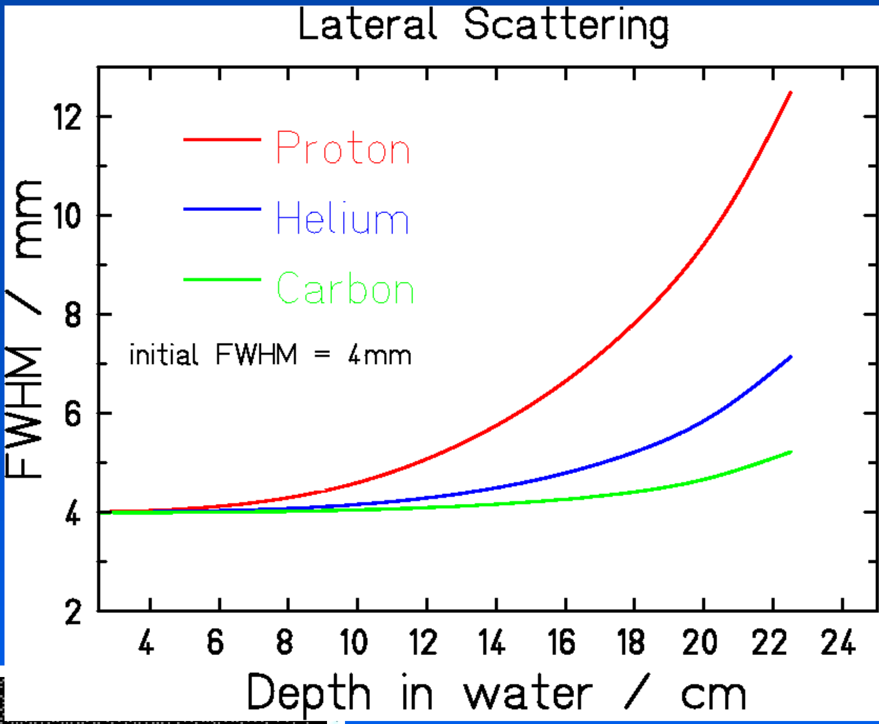
Rationale / Physics

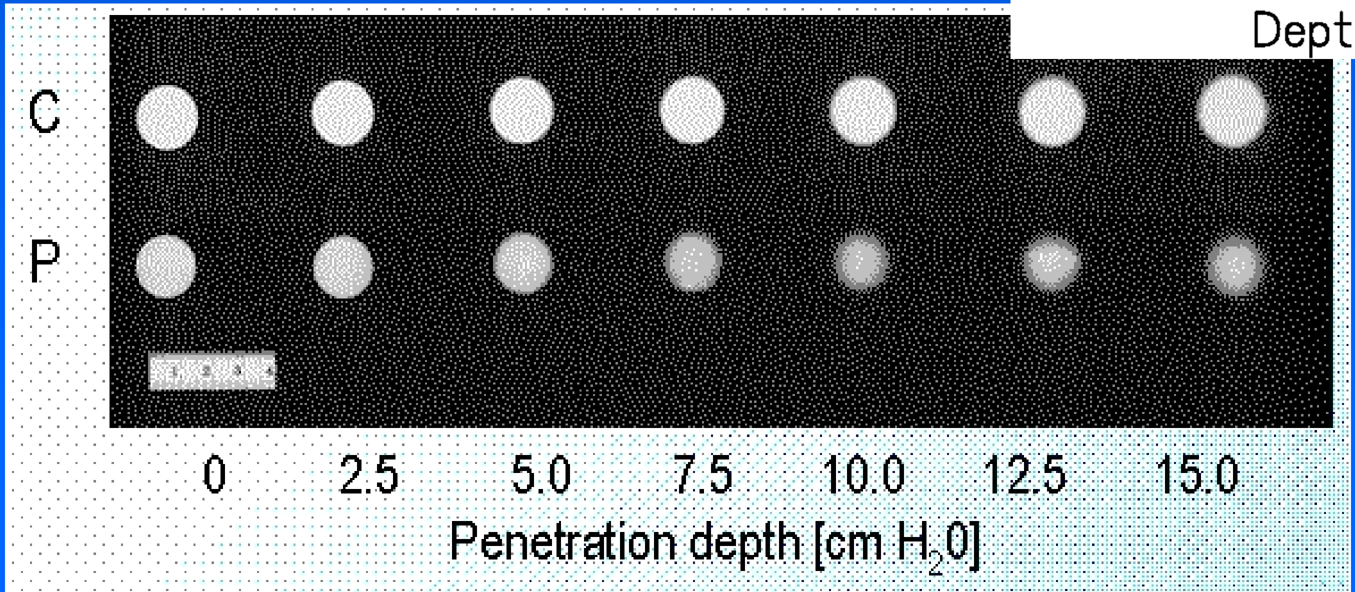
- Advantageous physical characteristics: inverted depth-dose distribution



Rationale / Physics

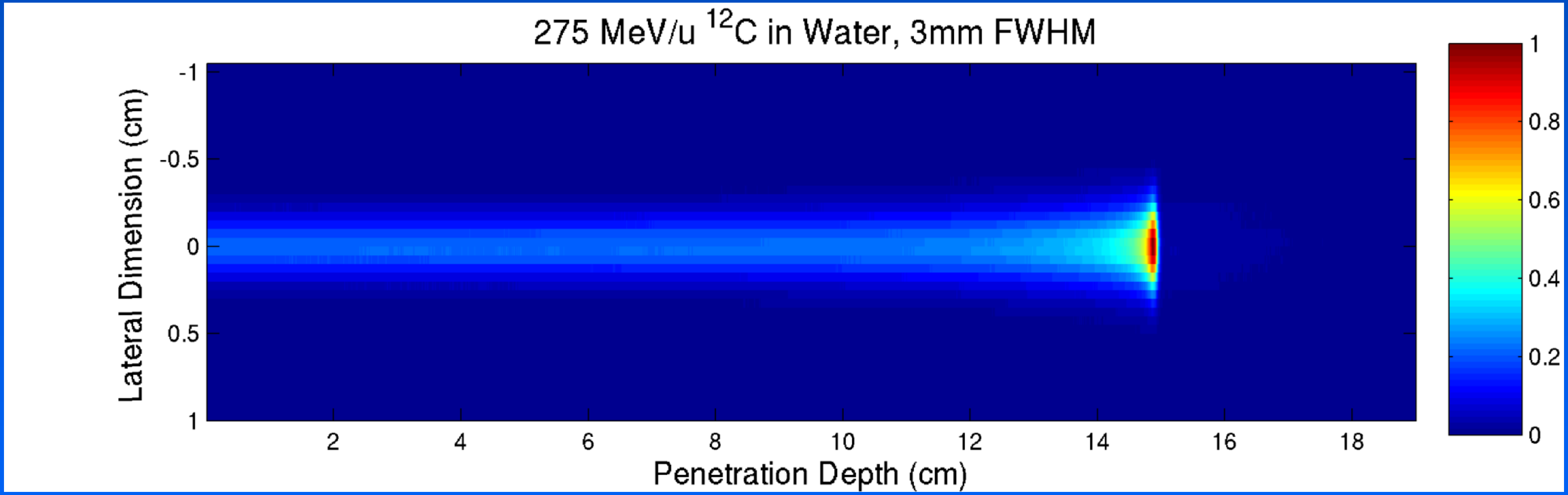
- Advantageous physical characteristics:
  small lateral scattering





Goal

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

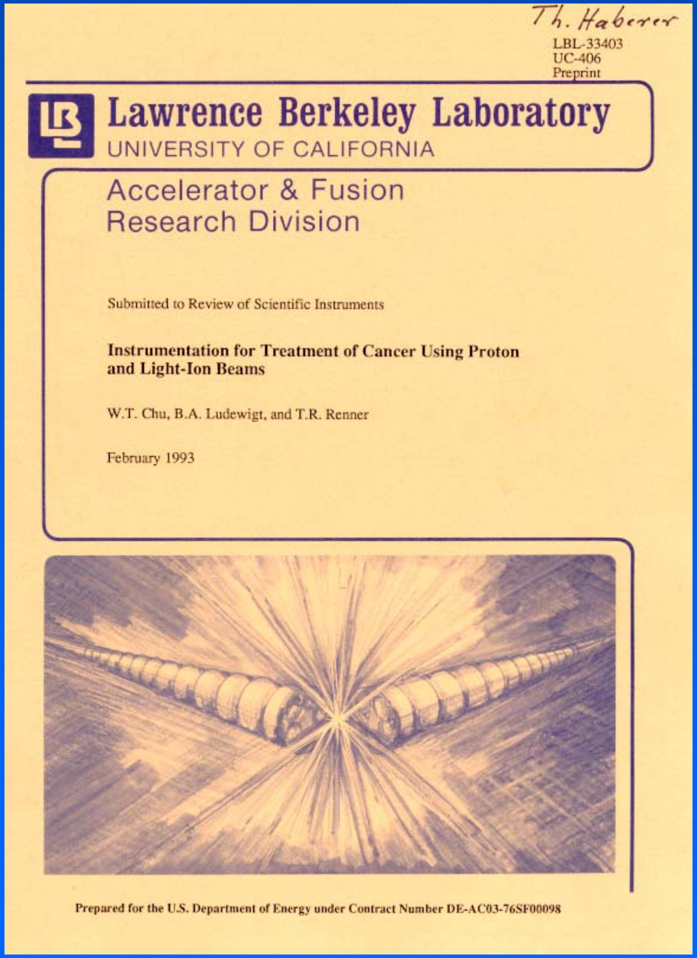


entrance channel:
- low physical dose
- low rel. biol. effiency

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 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

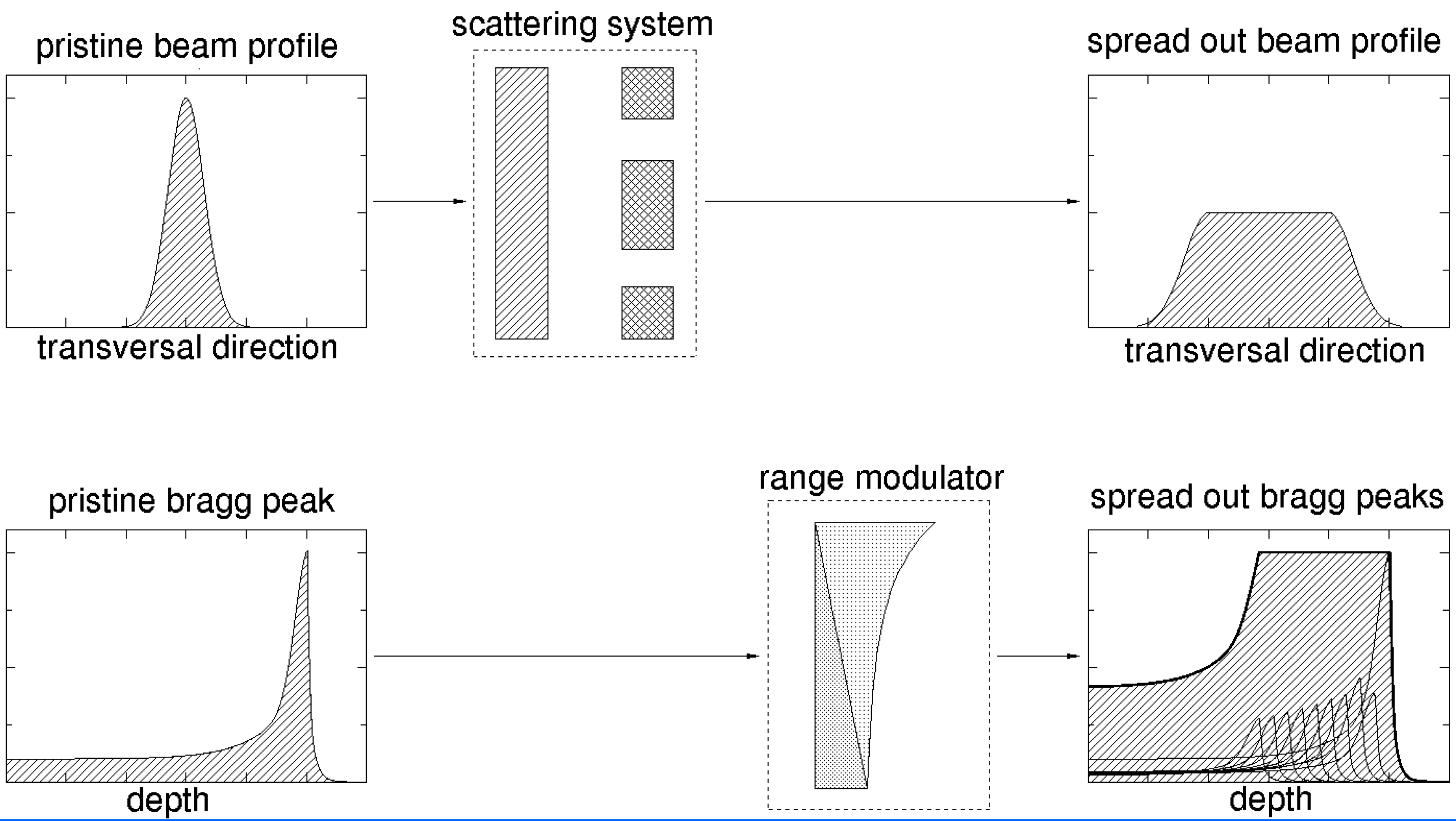
Instrumentation for Treatment of Cancer Using Proton and Light-Ion Beams

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

Passive Dose Delivery



Passive / Longitudinal Spread

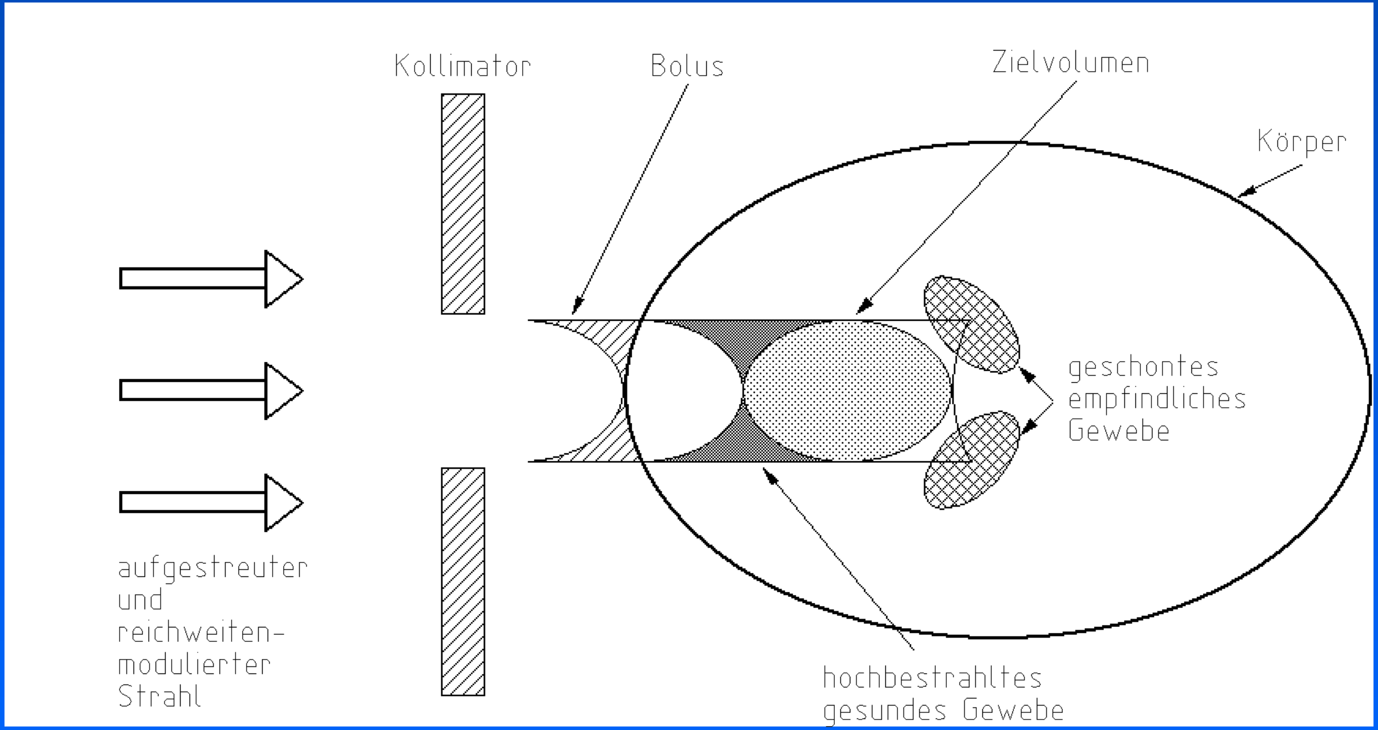
- ***Passive*** static longitudinal spreading

  via

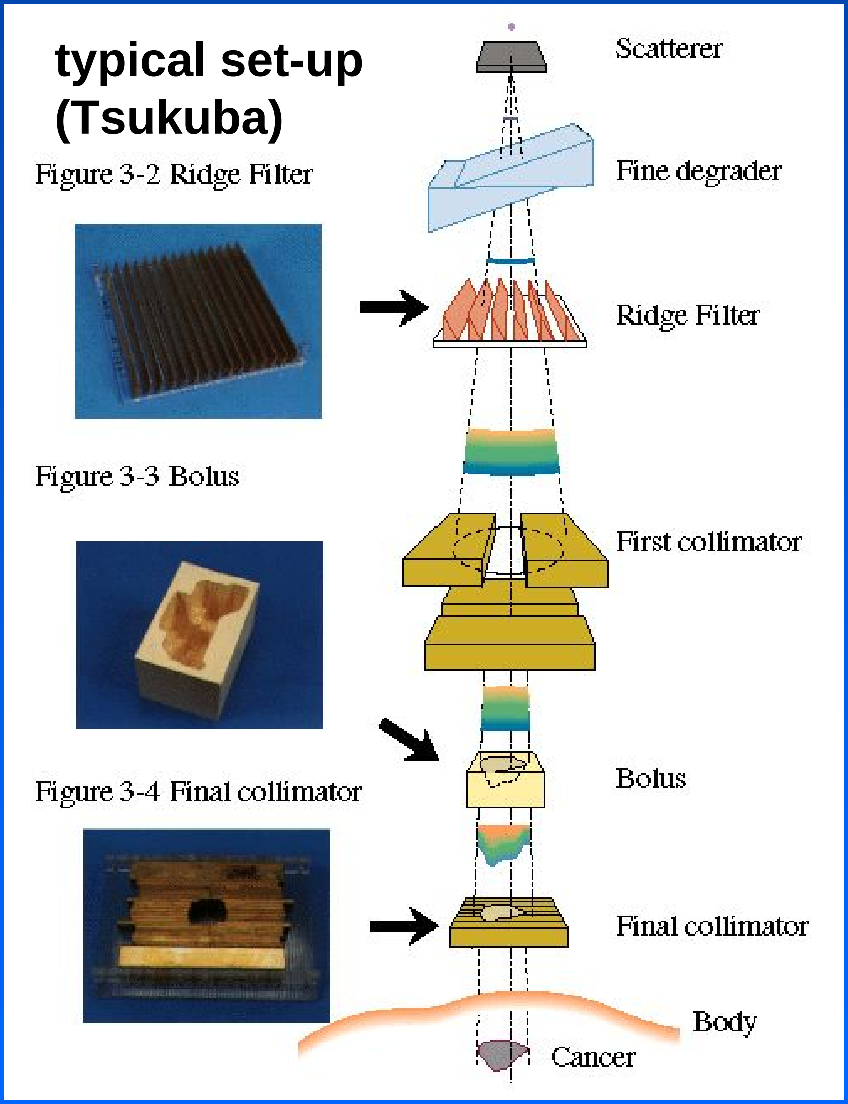
  ridge filter

  or

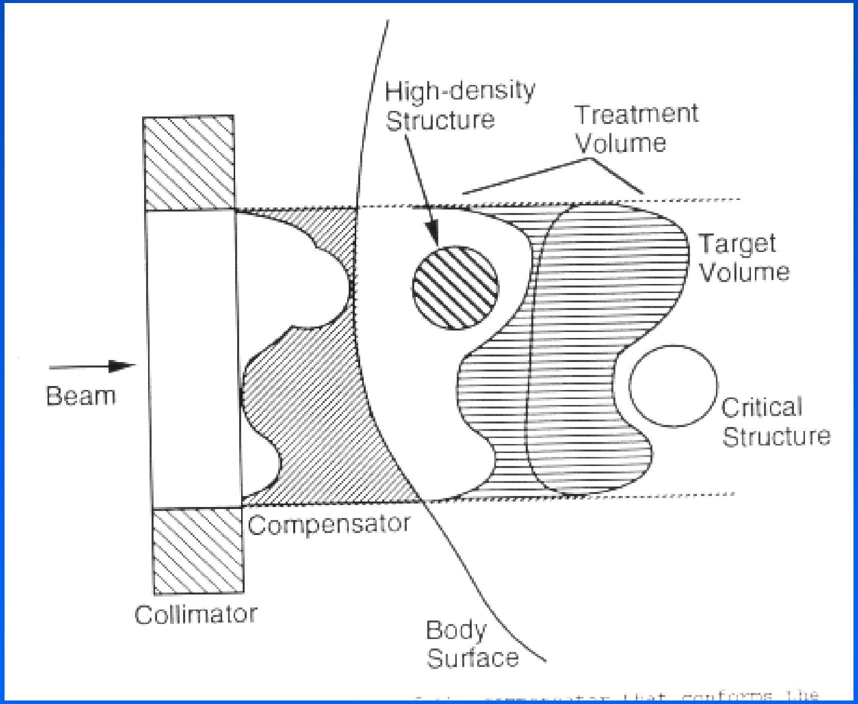
  rotating wheels
- spares the distal edge at the expense of the proximal (dose pull-back)



Passive / System + Dose Distr.



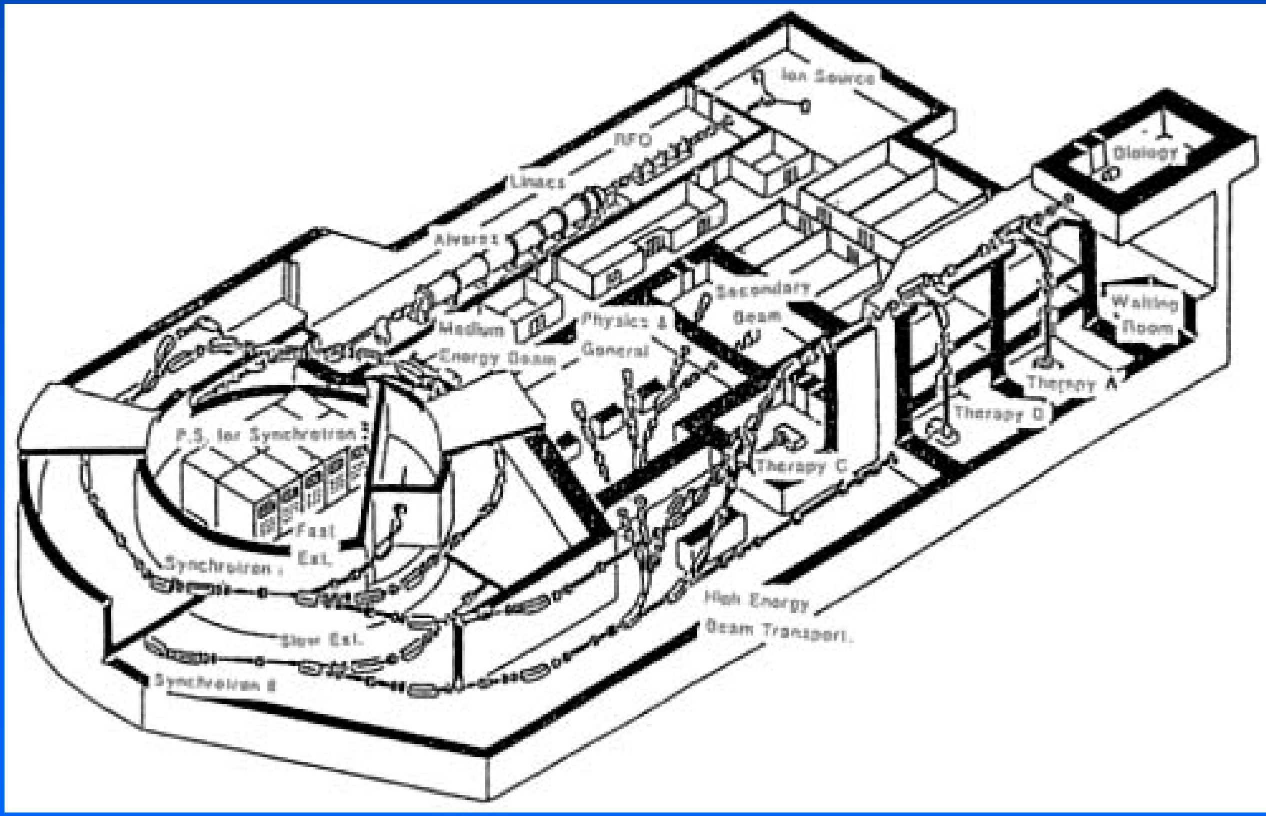
Distal edge shaping using a bolus pulls dose back into healthy tissue



Situation / Clinical Centers

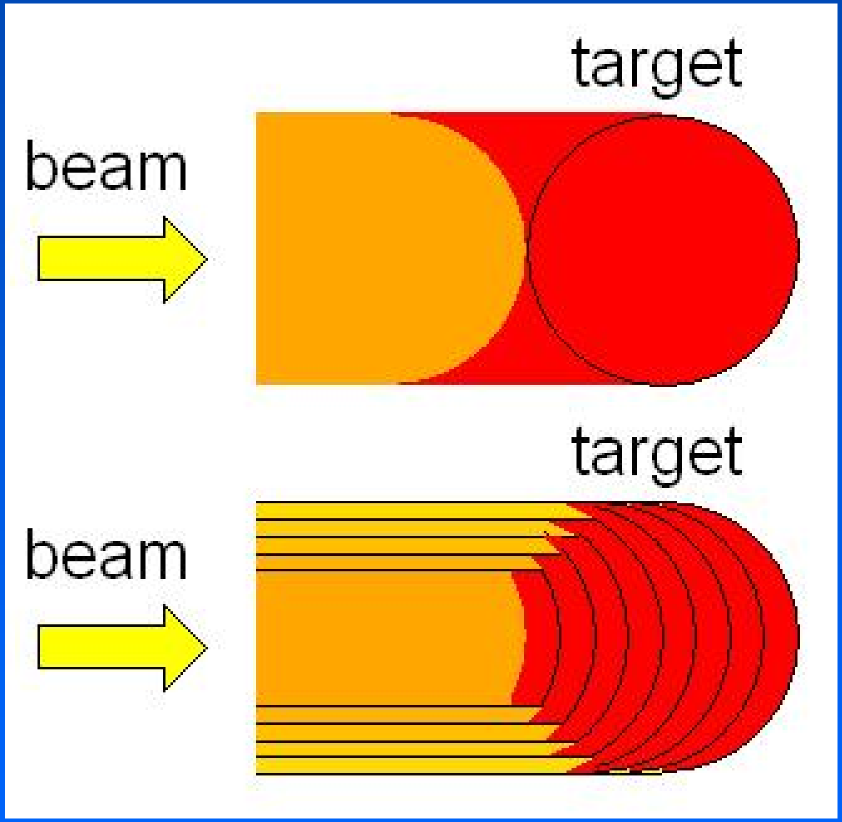
- In 1994 the first dedicated clinic-based facilities, LLMUC (protons) and HIMAC (carbon), started
- Nowadays more than 50 proton treatment protocols are approved and reimbursed in the US
- LLUMC treats up to 180 patients per day

Heavy Ion Medical Accelerator, Chiba, Japan



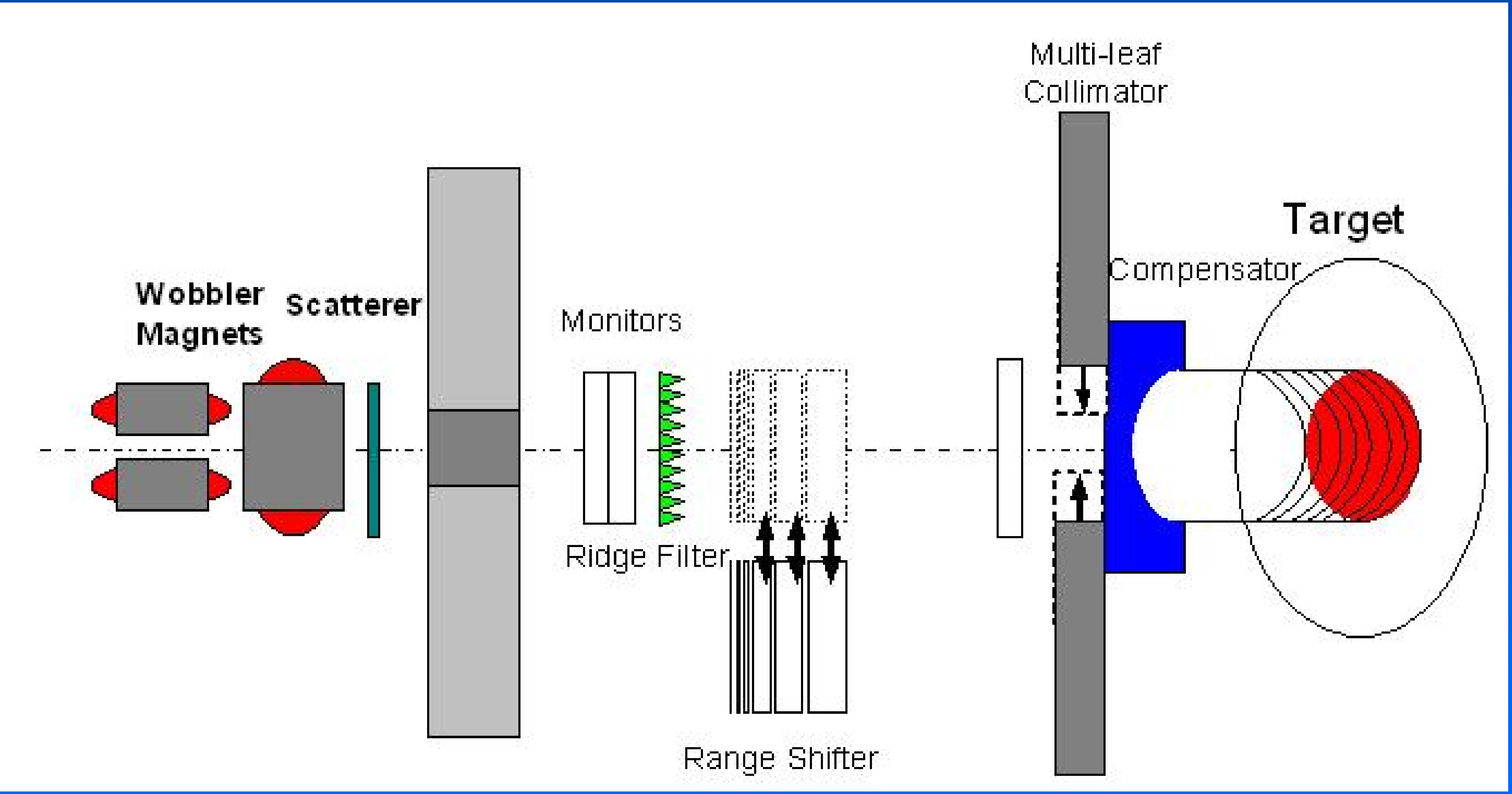
Semi-active / Layer-stacking

- developed for Carbon therapy @ HIMAC, Chiba
- combines lateral wobbling plus scattering with stacking of layers (some cm H_2O)
- each layer represents a small spread-out Bragg peak
- each layer may have individual weight
- improved conformity



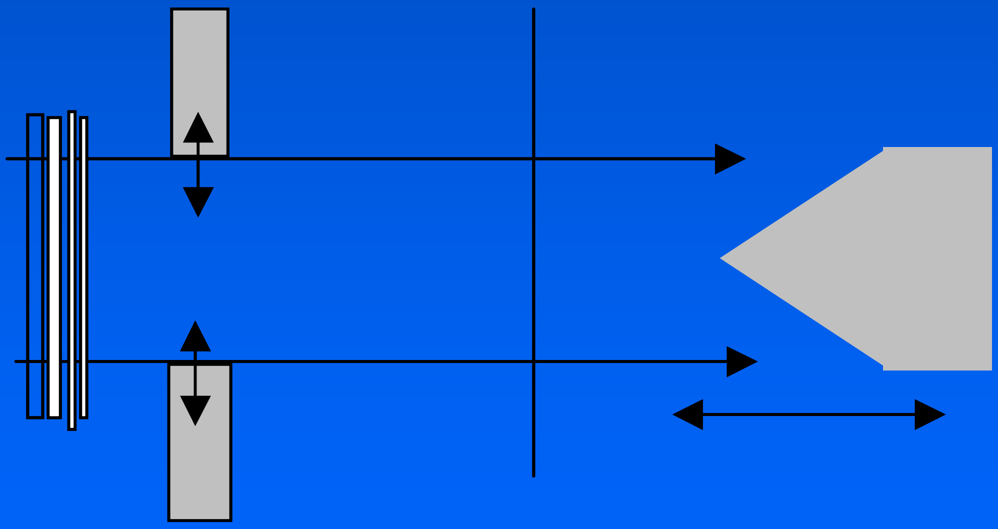
Kanai et al., Med Phys. 2006 (33)

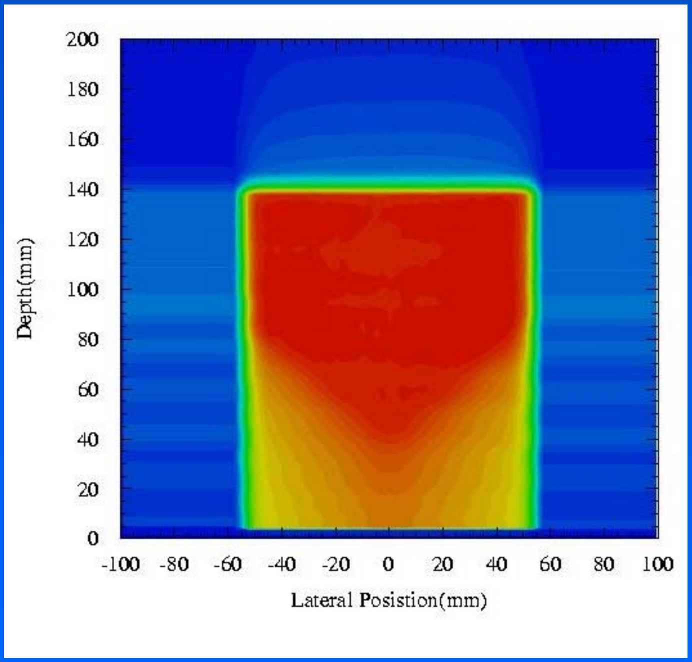
Semi-active / Layer-stacking



Semi-active / Layer-stacking

wedge-shaped dose distribution





Active Dose Delivery

The inverse approach:

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.

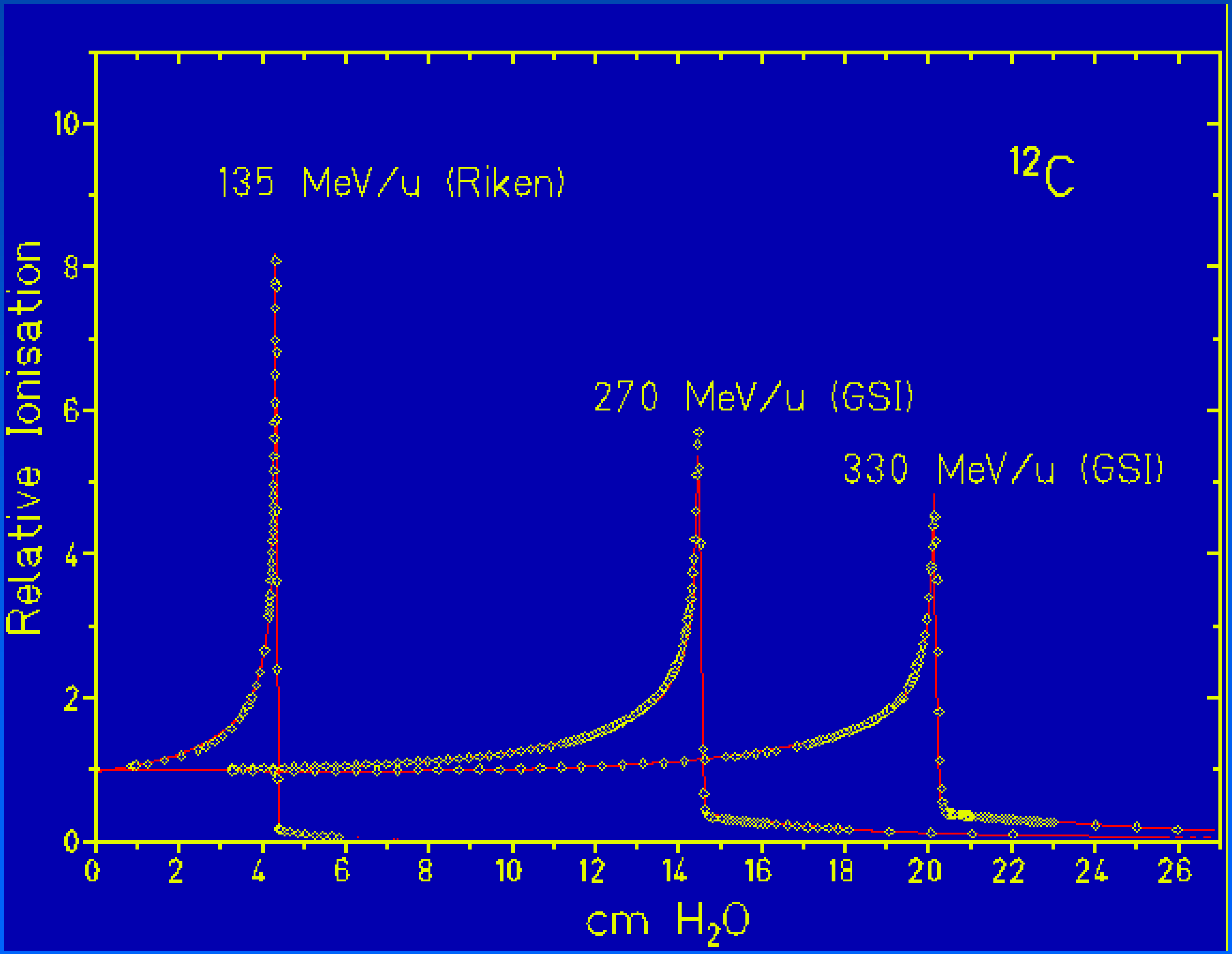
The basic idea:

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.

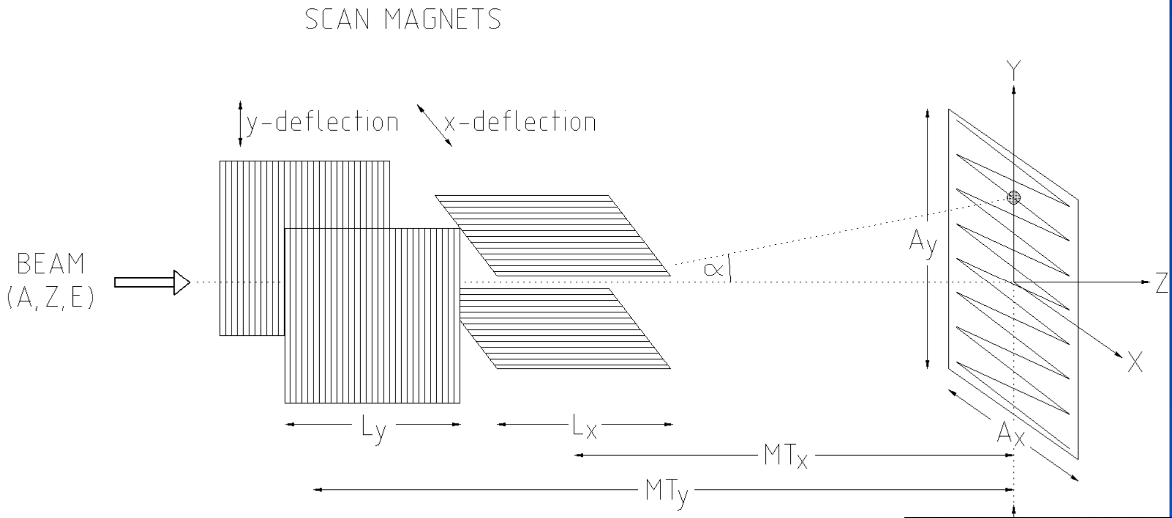
=> Extreme intensity modulation

Active / Longitudinal

- **active** energy variation in the accelerator
- virtual dissection of the tumor (range stepping mm-resolution)

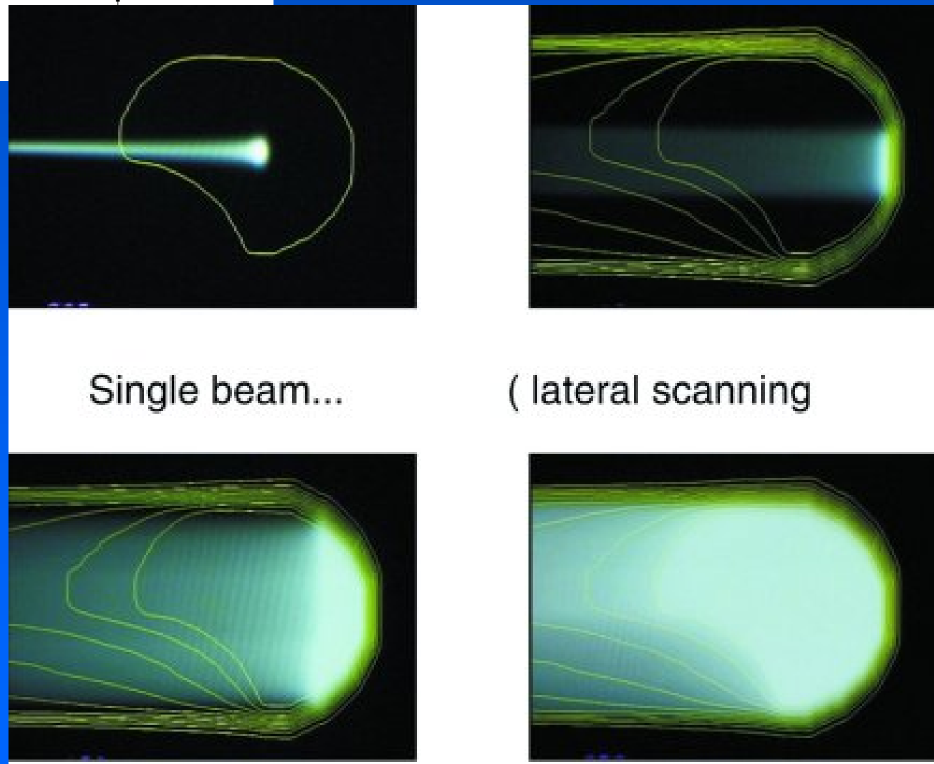


Scanning



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



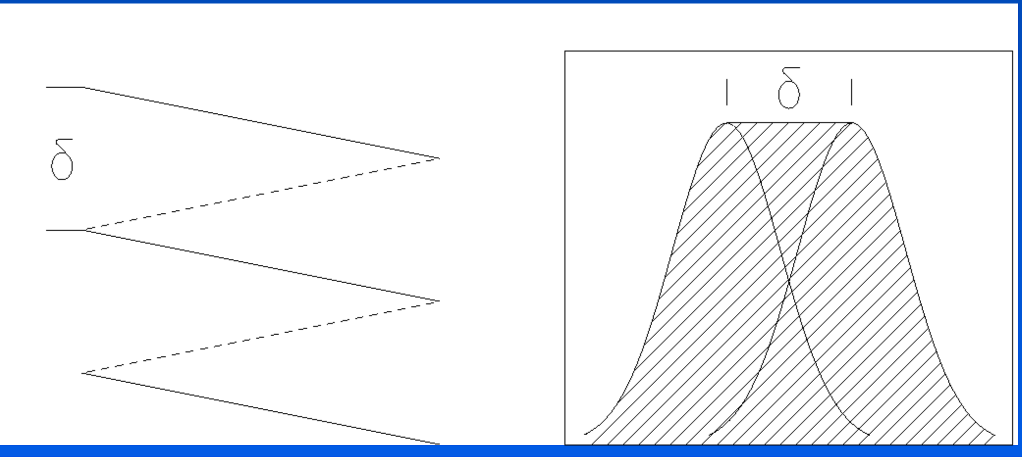
Single beam... (lateral scanning

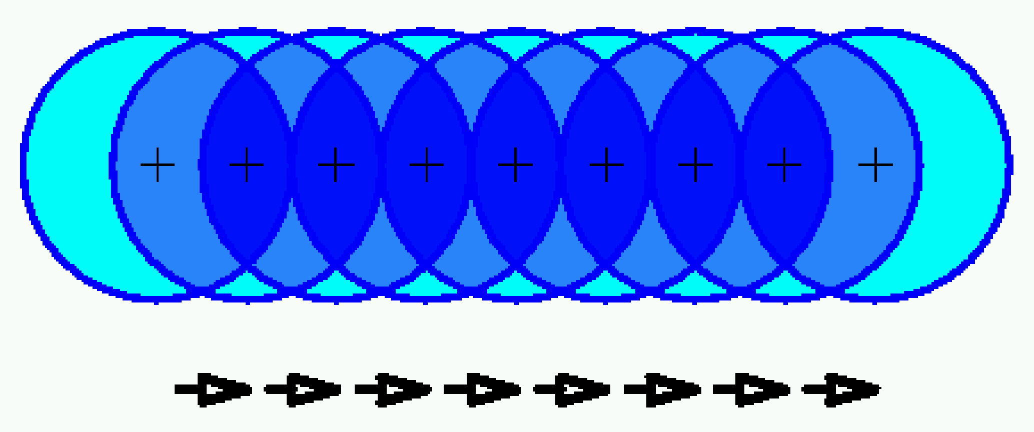
+ scanning in depth = 3d conformed dose)

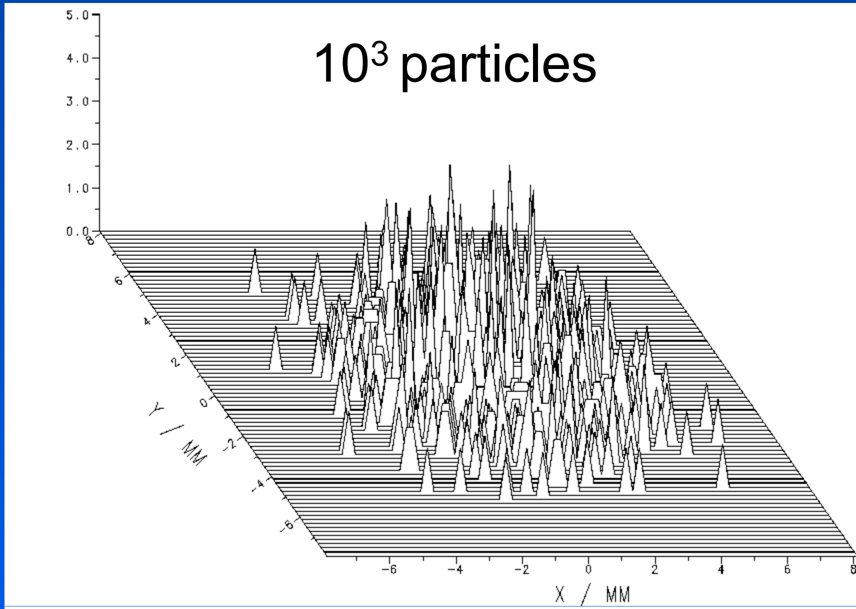
Th. Haberer, Heidelberg Iontherapy Center

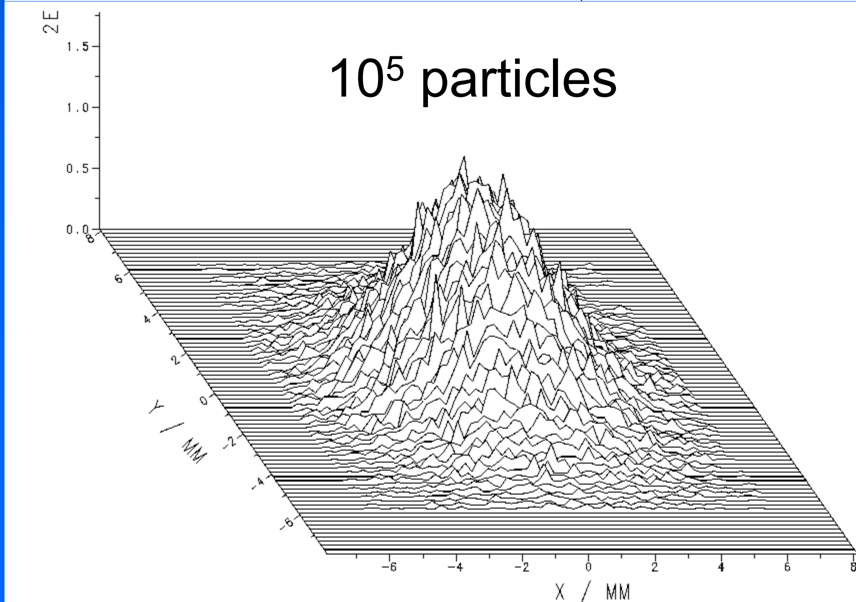
Active / Lateral

- superpositioning of gaussian beam spots, statistics









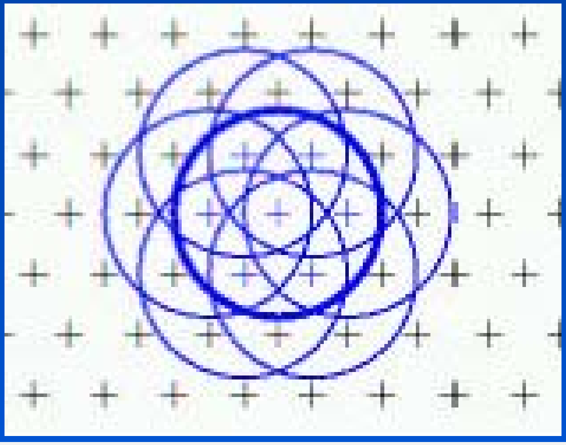
Th. Haberer, Heidelberg Iontherapy Center

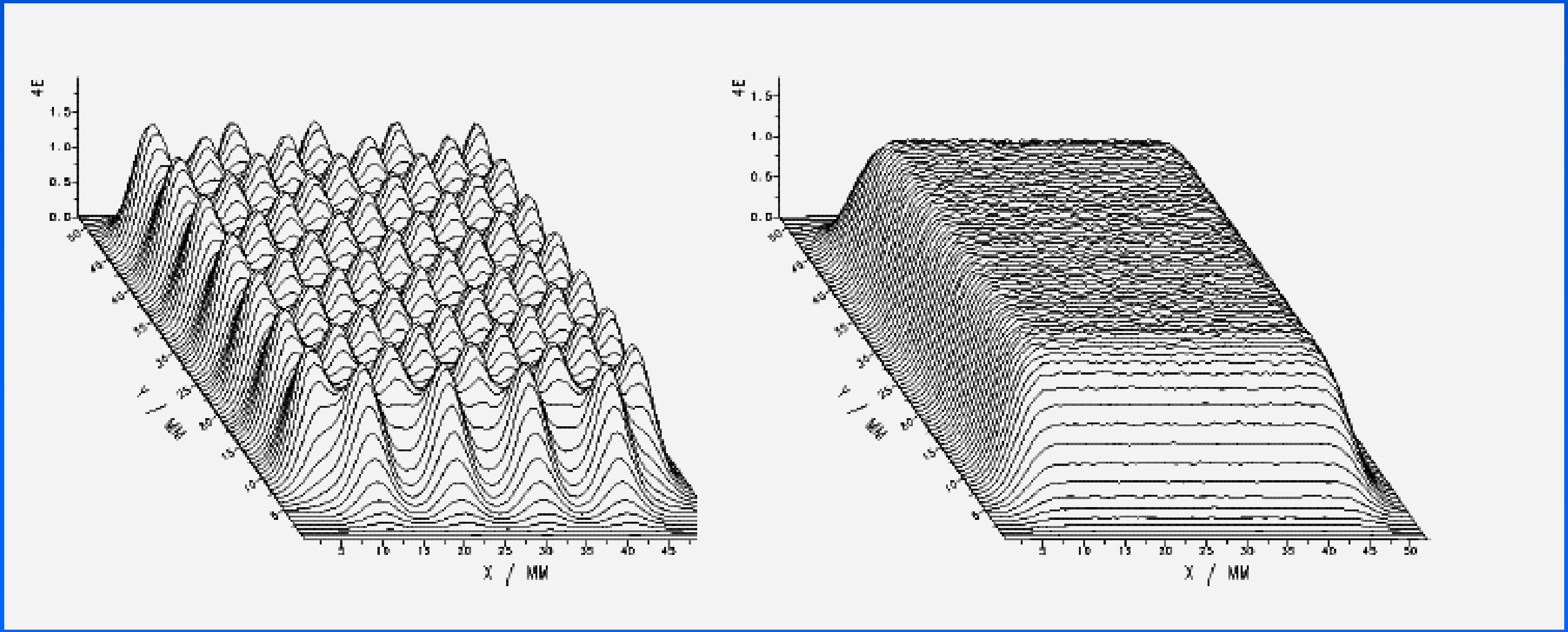
Active / Lateral

- 2d superpositioning,
  step size

  and

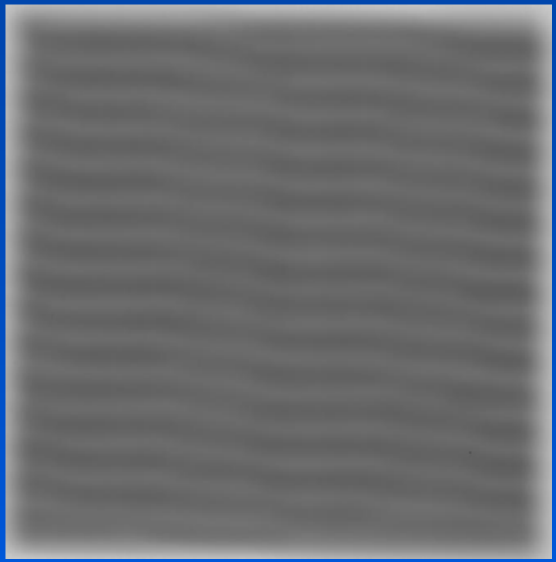
  beam spot size

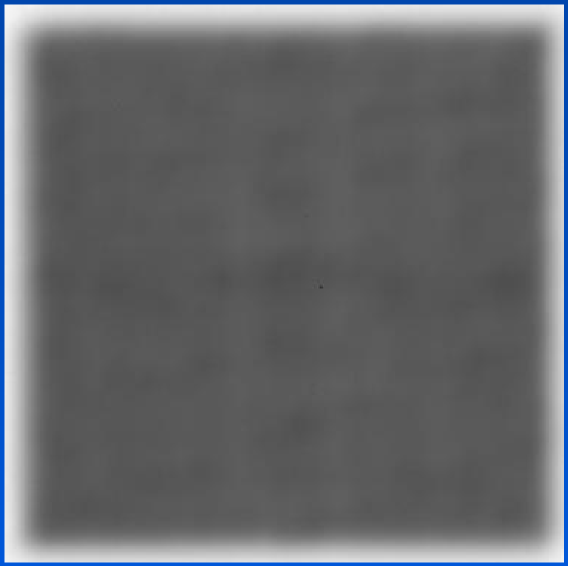




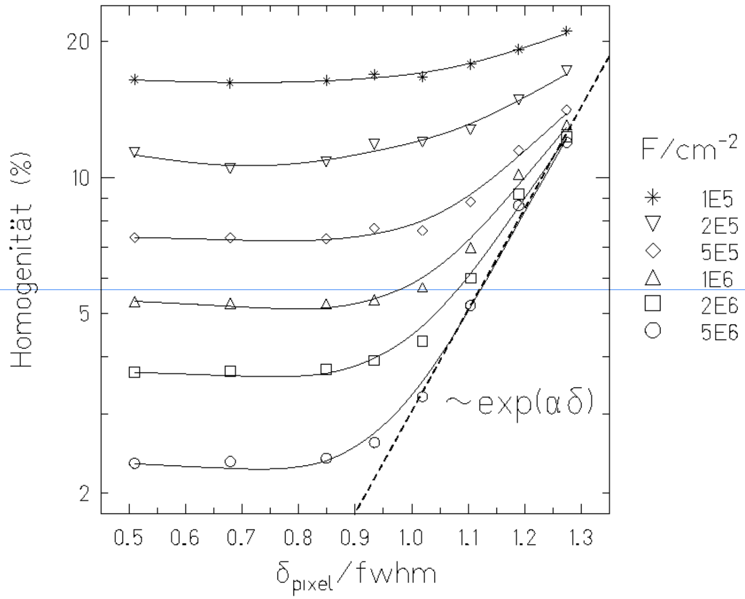
Active / Lateral

- homogeneity of fluence distributions

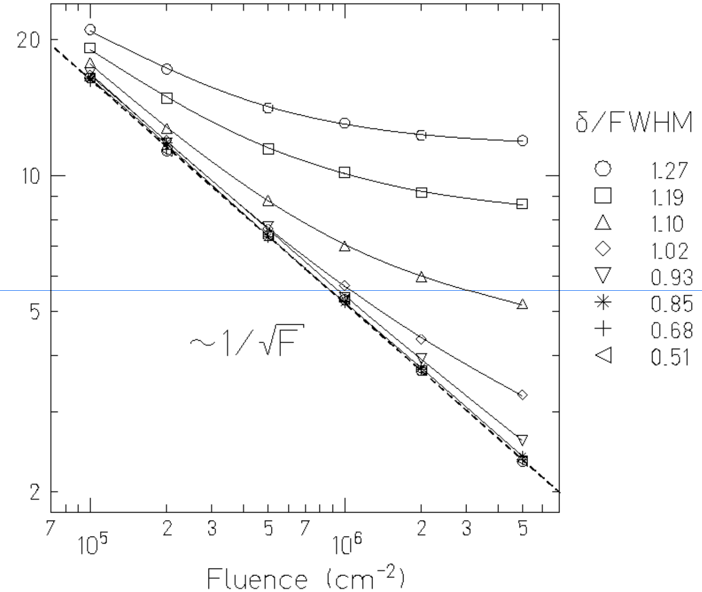




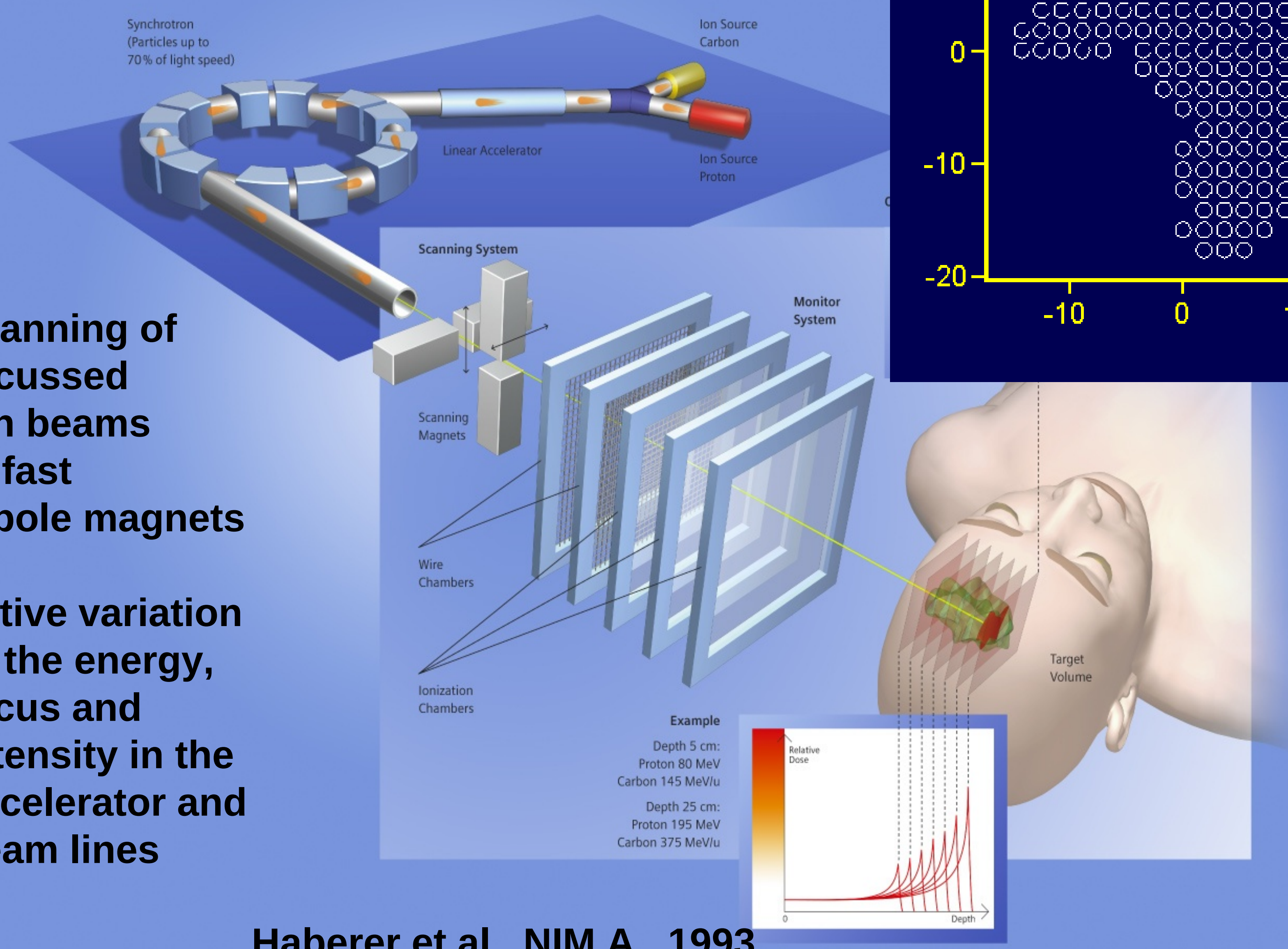
geometry

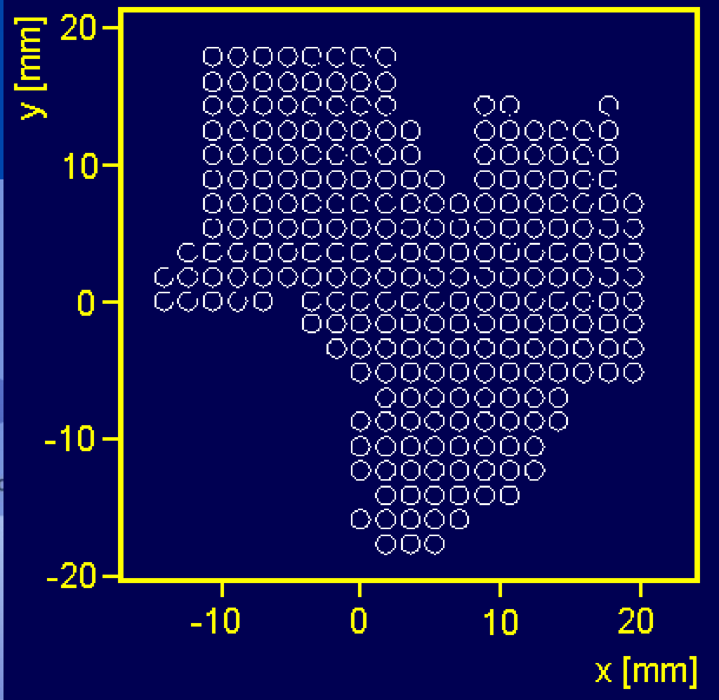


statistics



Rasterscan Method



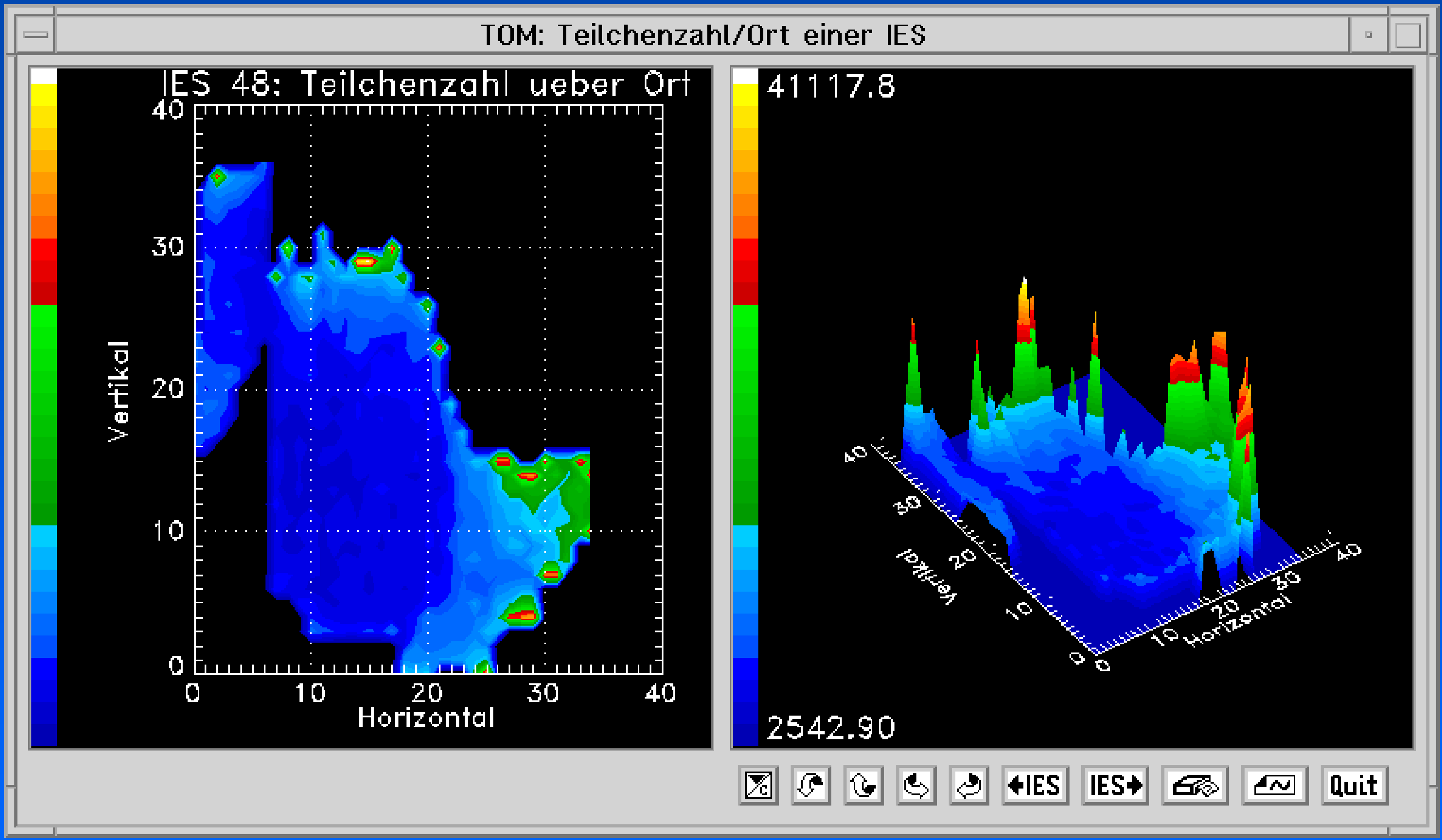


scanning of focussed ion beams in fast dipole magnets

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

Haberer et al., NIM A , 1993

Active / Fluence Distribution

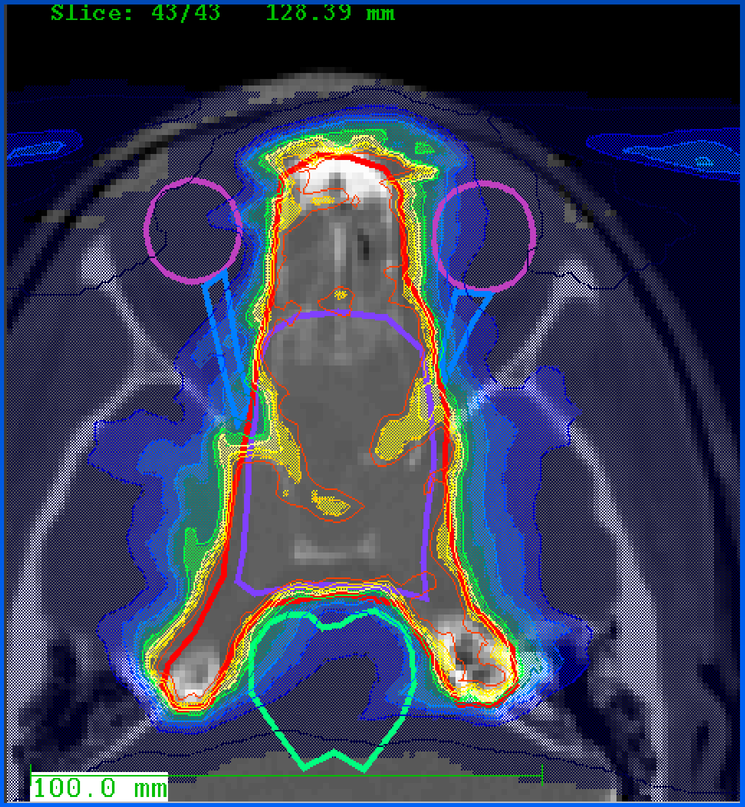


Fluence distribution of a single slice through the target volume

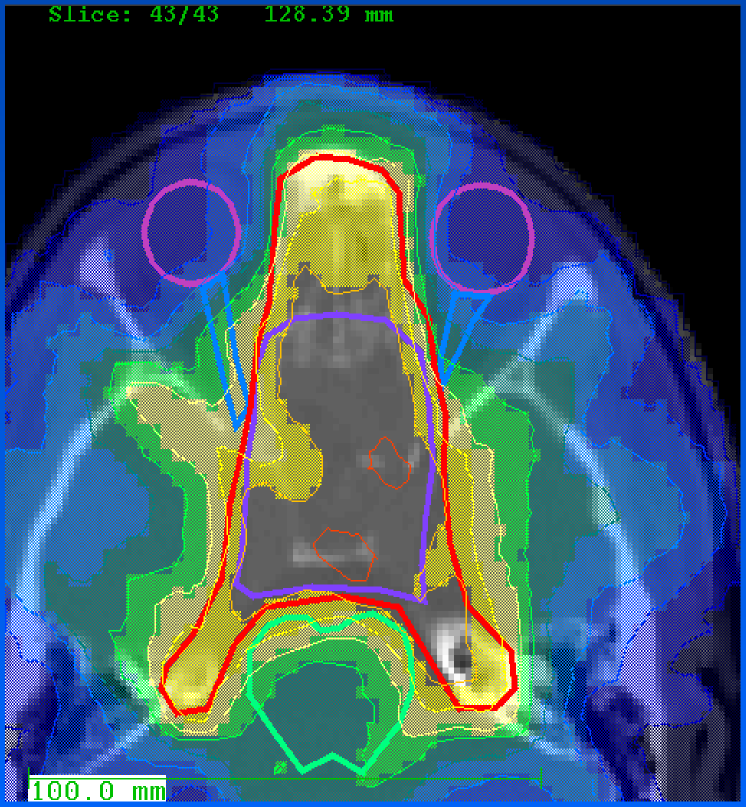
Th. Haberer, Heidelberg Iontherapy Center

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

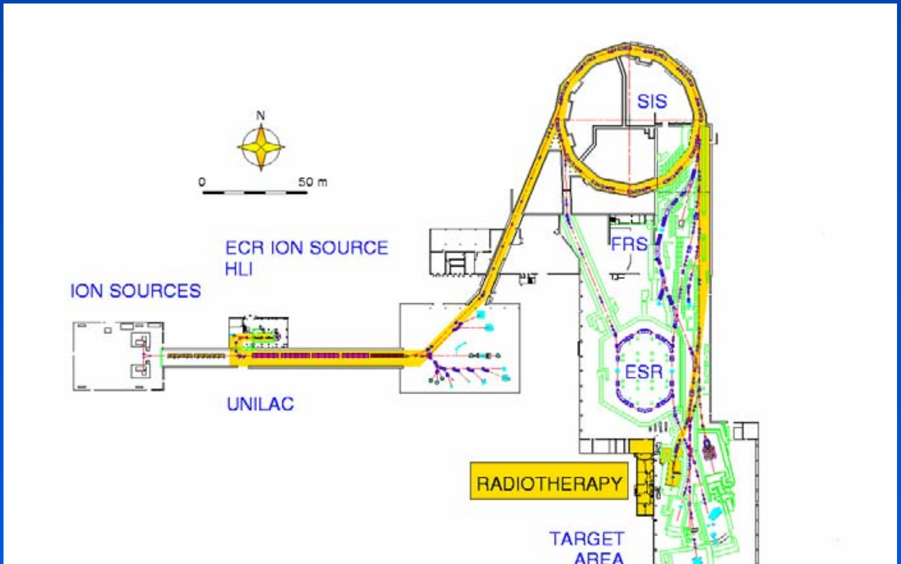
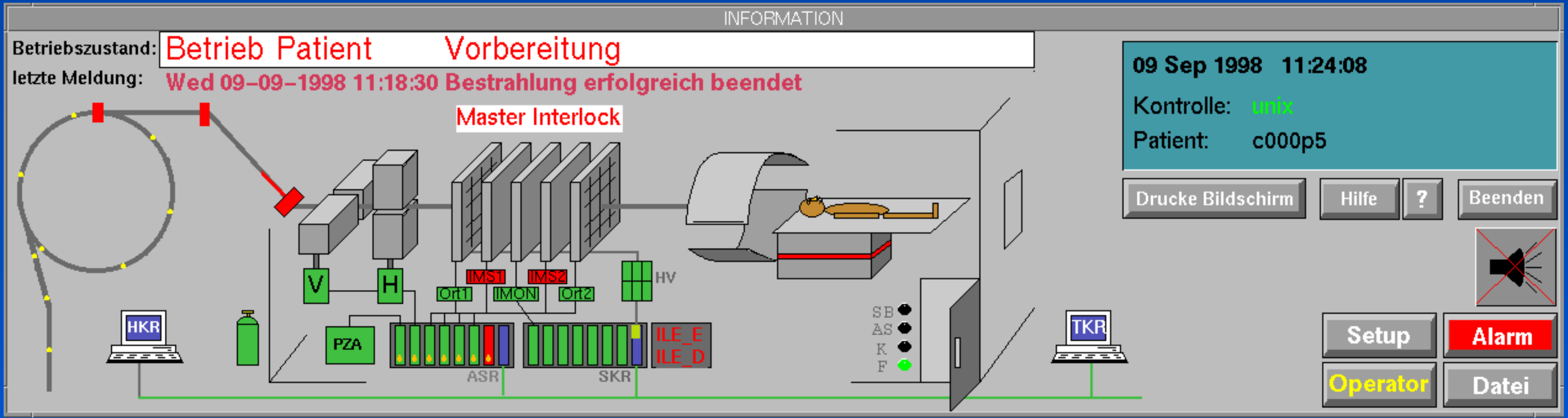


Fig. 4-4a The GSI Accelerator Facility

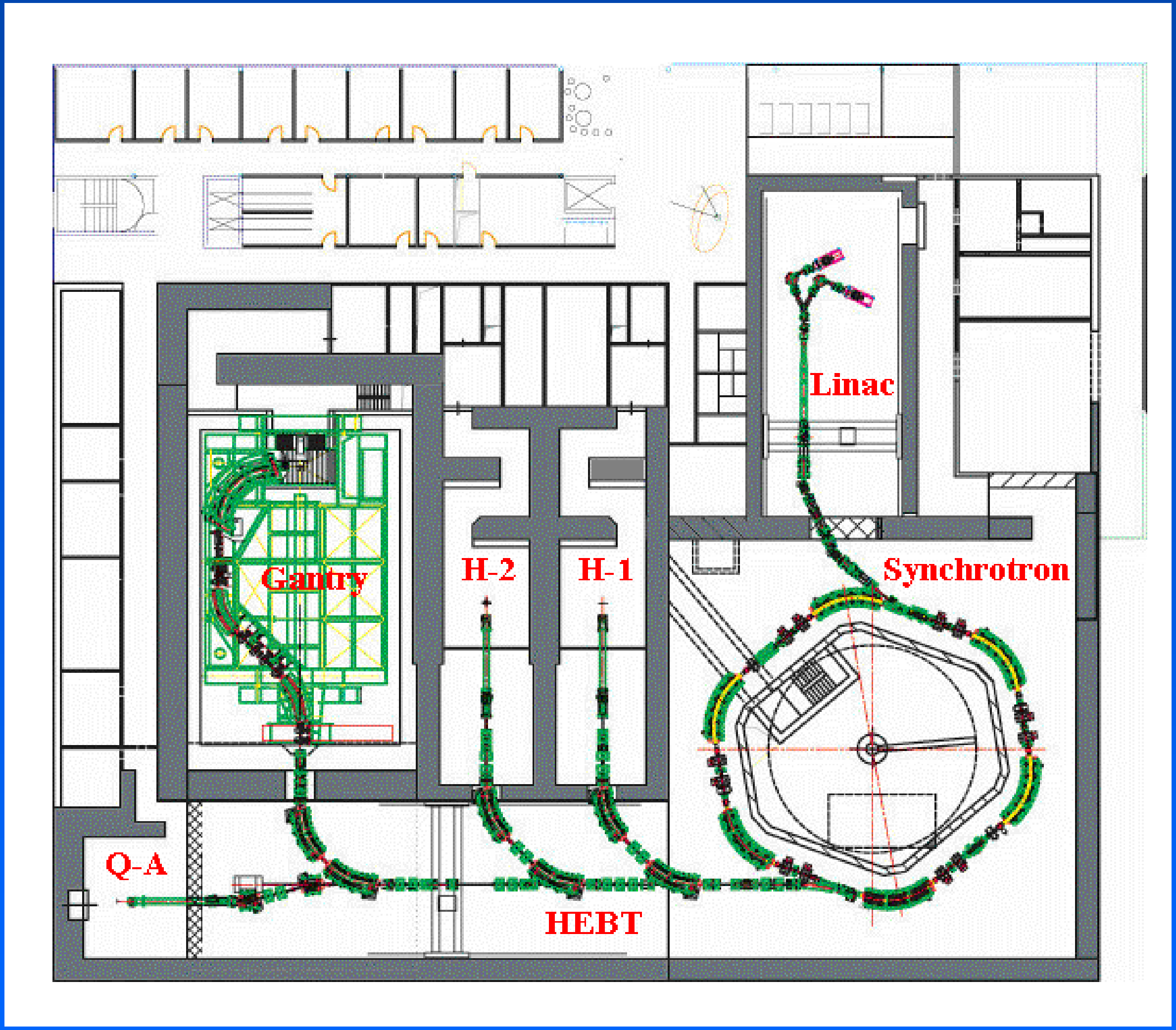
Key Developments @ GSI



- Scanning-ready **pencil beam library** (25.000 combinations): 253 energies (1mm range steps) x 7 spot sizes x 15 intensity steps
- **Rasterscan method** incl. approved controls and safety
- **Beammonitors** follow the scanned beams (v <= 40 m/s) in real-time
- **Biological interactionmodel** (LEM) based on 25 years of radiobiological research
- Physical beam **transportmodel**
- **Planningsystem** TRiP
- **In-beam Positron Emission Tomography**
- **QA system**
- Prototype of **the scanning ion gantry**

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



IMPT → Beam Scanning

pencil beam library:

•	**ions**	**:**	**p**	**$^{3}He^{2+}$**	**$^{12}C^{6}$**	**$^{16}O^{8+}$**
•	**energies (MeV/u)**	**:**	**48**	**72**	**88**	**102**
	(255 steps,1.0/1.5 mm)		**-220**	**-330**	**-430**	**-430**

- **beam spot size** **:** **4 – 10** (20) **mm , 2d-gaussian**

  (4 (6) **steps)** (up to 20 mm for moving organ treatments)

intensity variation: chopper system in front of the RFQ, variation factor: 1000

active energy variation: in the synchrotron + high-energy beam lines

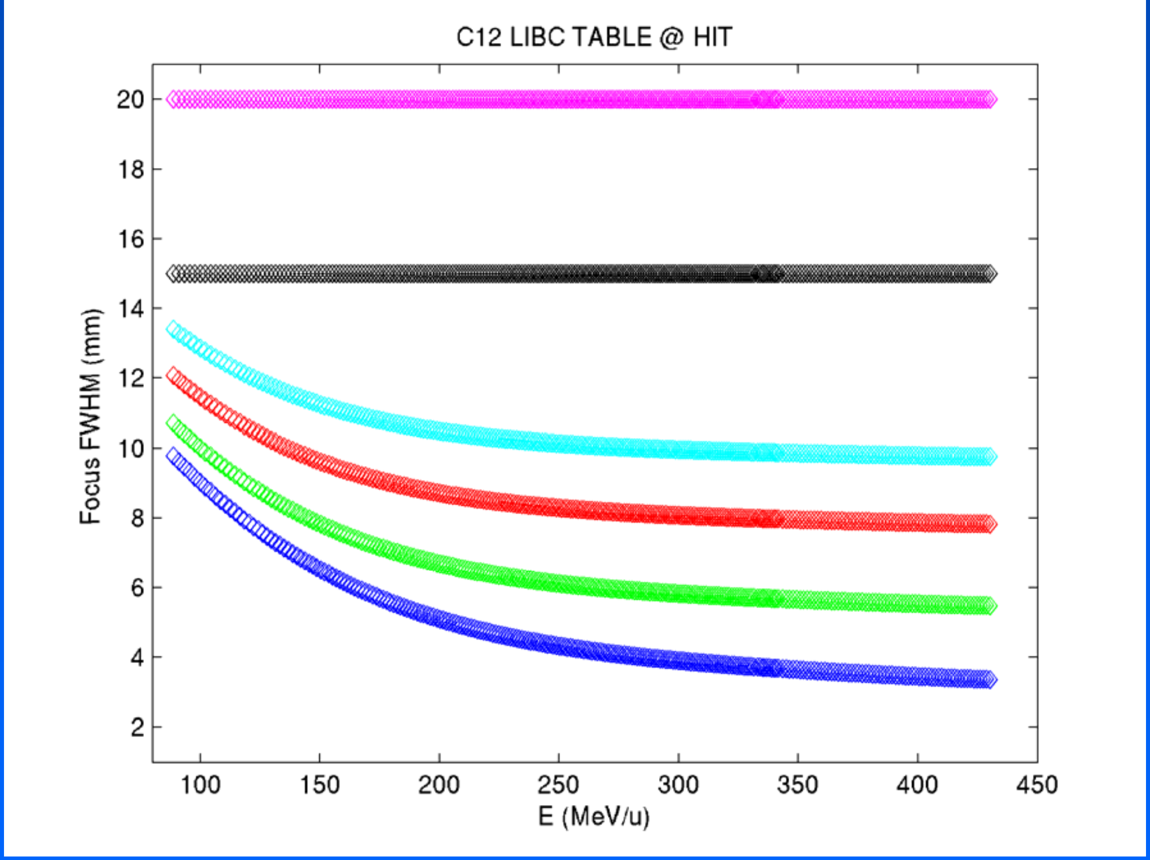
beam size variation: quads directly in front of the scanning systems

beam extraction: established RF-knock-out method (Himac > 10 years) gives

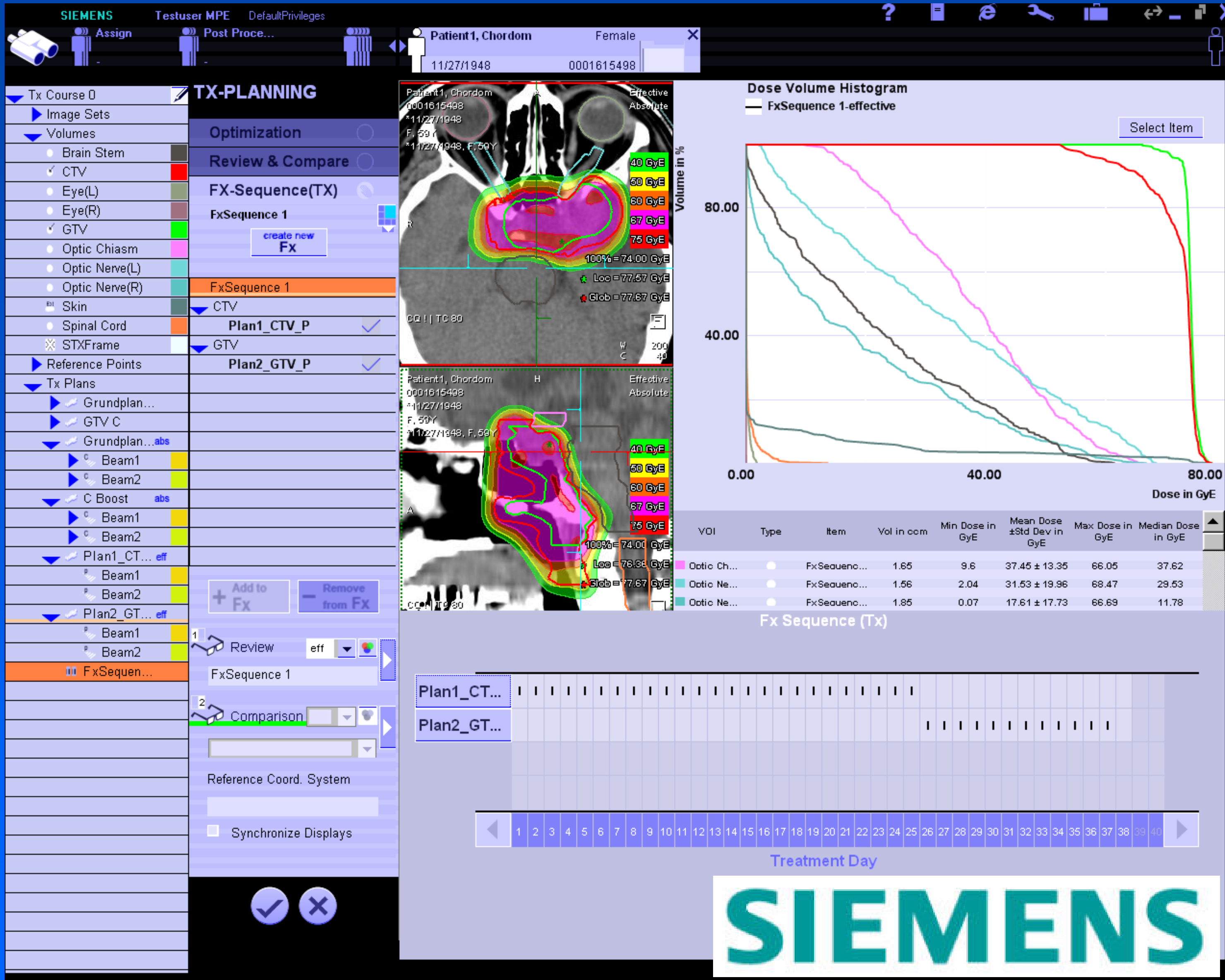
high stability in time, position and spot size

extraction switchable at flat-top level

Spot Size Library for Carbon



Treatment Planning System

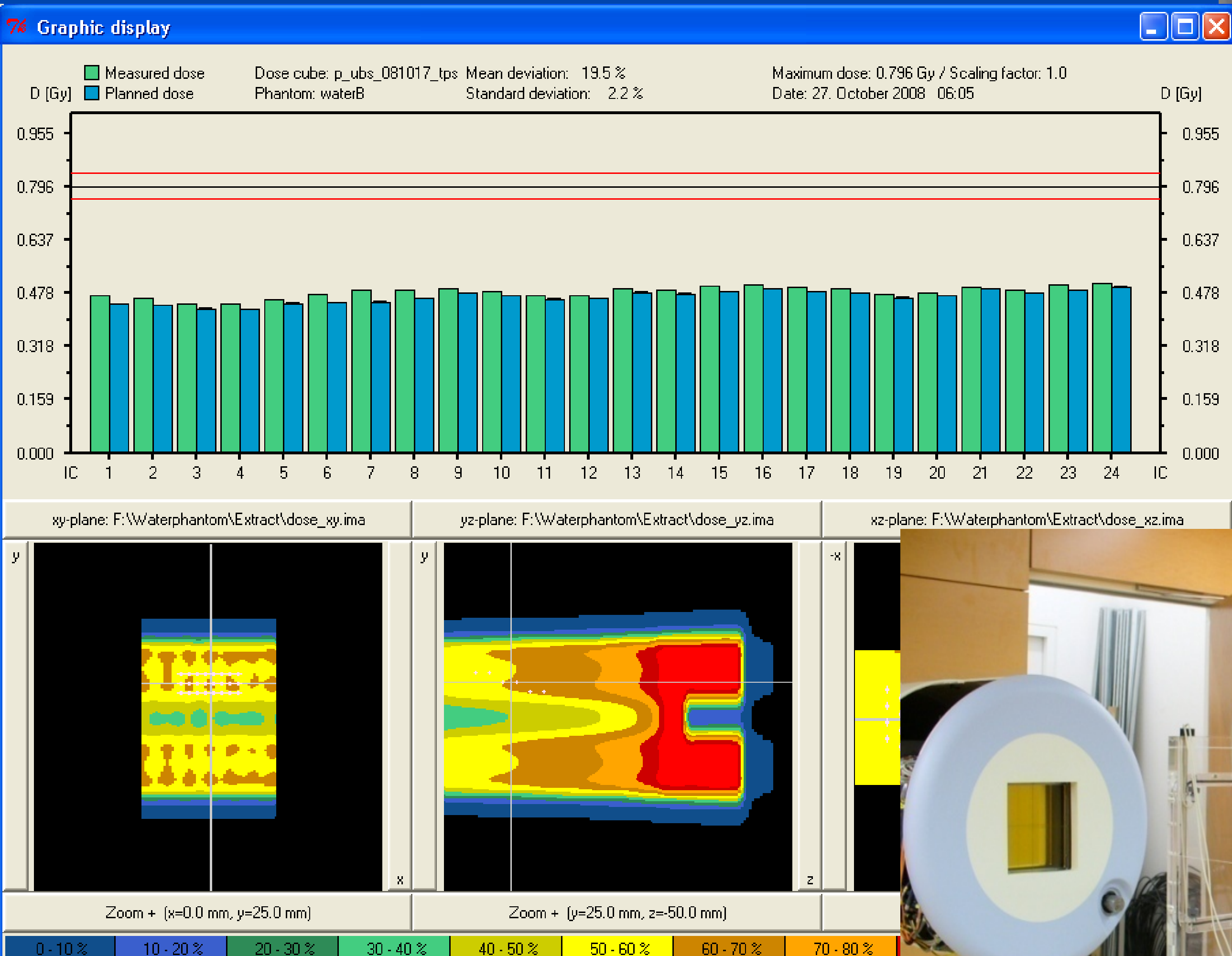


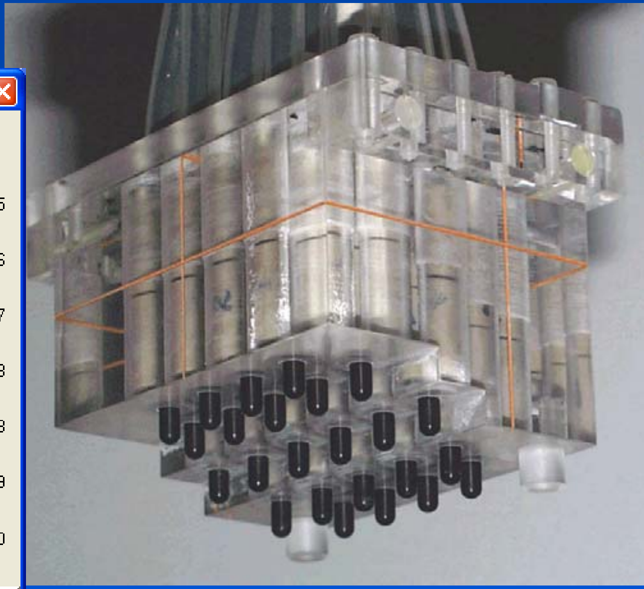
skull base chordoma, fraction sequence for 2 proton plans
Plan1_CTV_P 50 GyE + Plan2_GTV_P 24 GyE

HIT Scanning Beam Nozzle

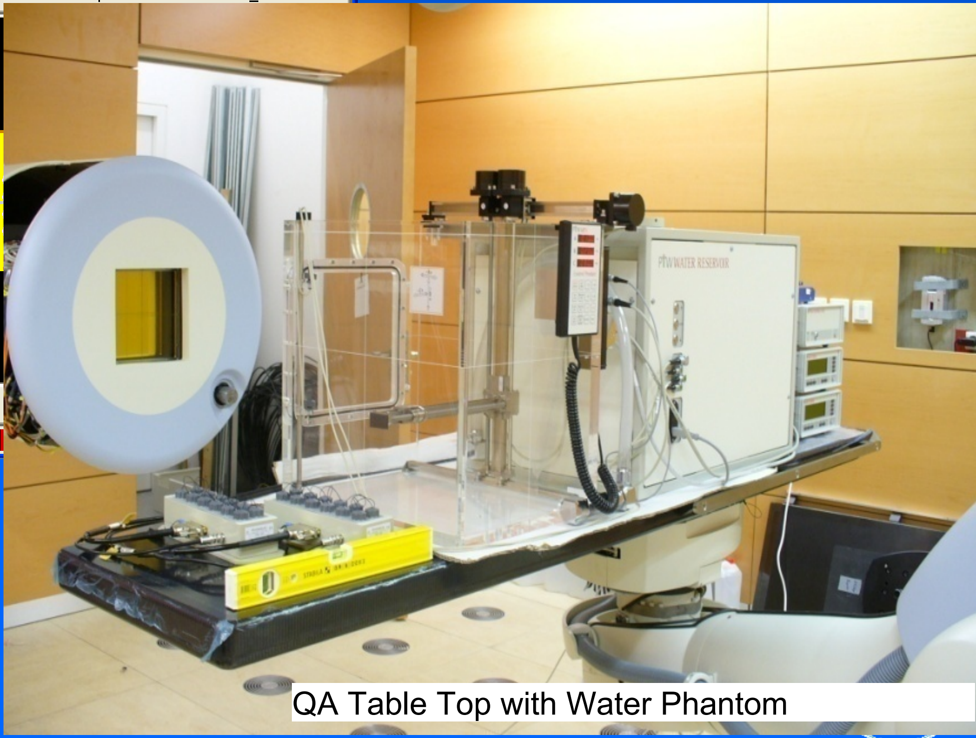
Th. Haberer, Heidelberg Iontherapy Center

Commissioning





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

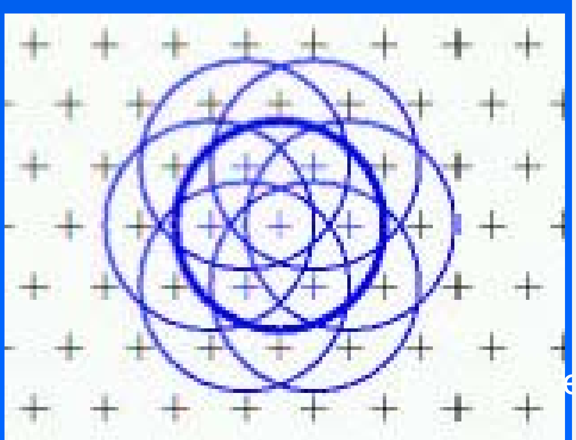

QA Table Top with Water Phantom

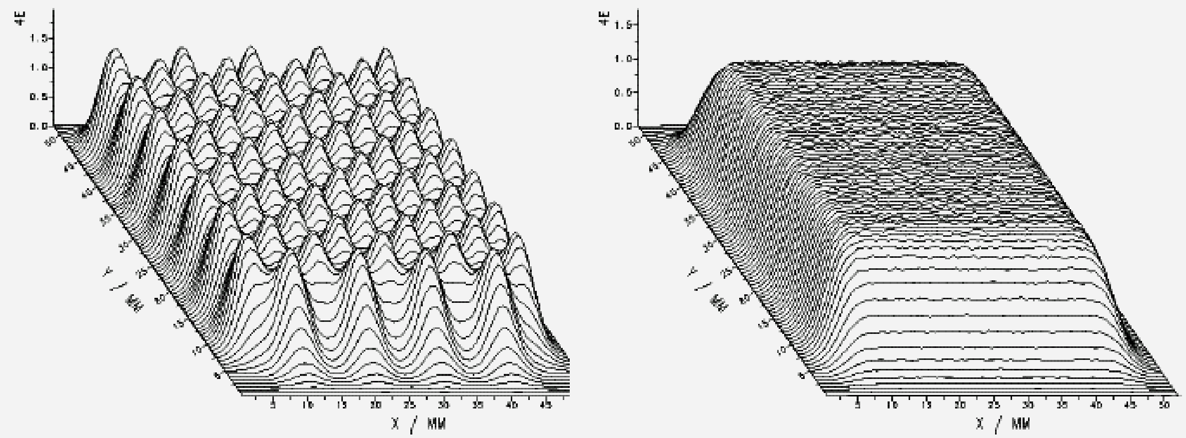
Performance Specifications (1)
- Protons / Carbons for 1 litre cubic / 2 Gy *

Spot Spacing mm	Layer Spacing mm	Beam Width (FWHM) mm	Irradiation Time seconds	Lateral Penumbra (80/20%)mm	Dose Uniformity %
3	3	9	81/96	7,5	1,5
4	4	10	55/60	8	2
5	5	12	35/42	9	2,5

*** - ripple filter adapted to selected layer spacing**

- overlap between spots varying from 2.4 to 3





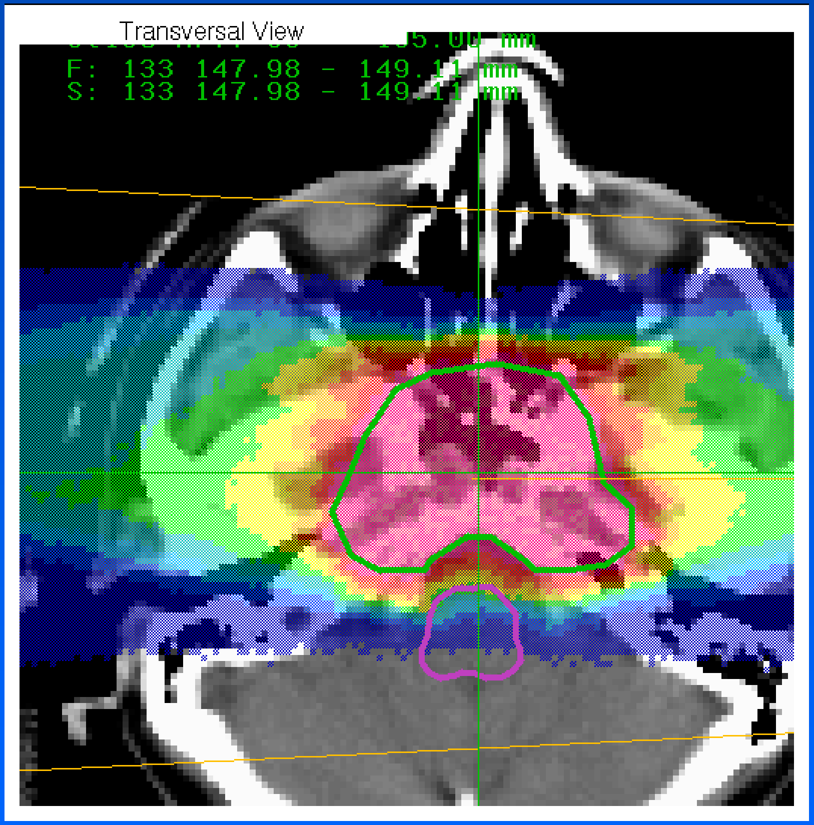
Performance Specifications (2)
- Clinical Case Examples for Protons / Carbons
„skull base chordoma“

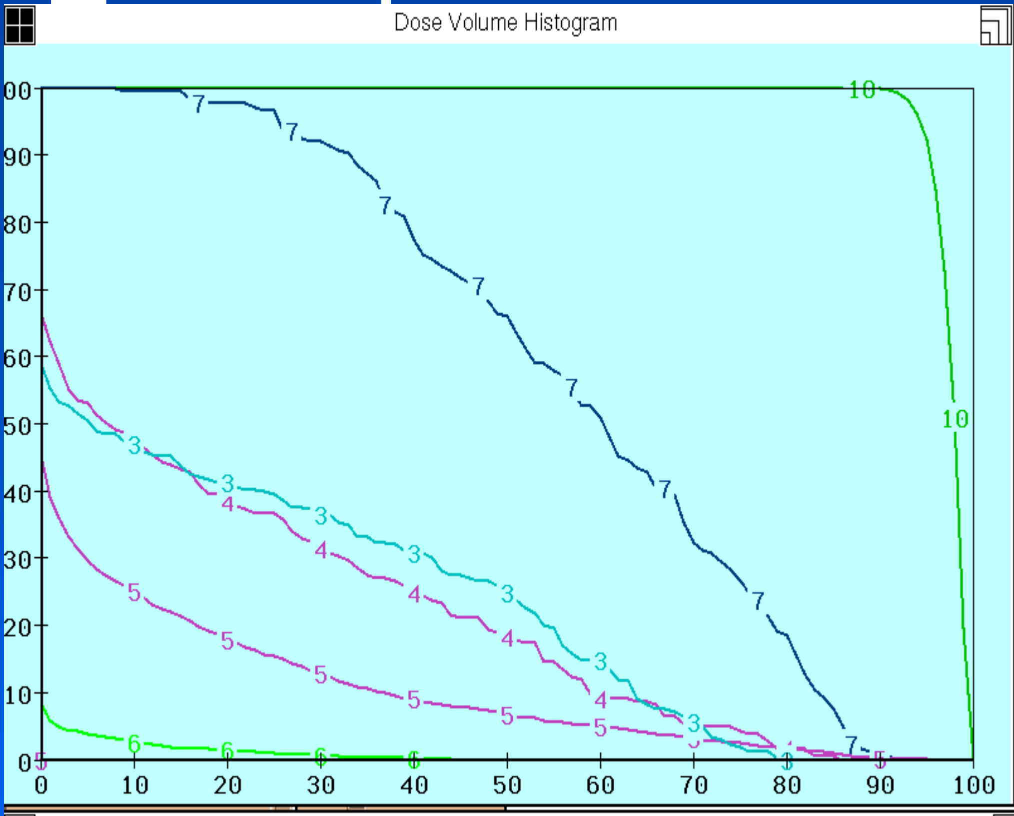
Spot Spacing mm	Layer Spacing mm	Beam Width (FWHM)	Energies/ Positions	Irradiation Time sec.	Lateral Penumbra (80/20%) mm	Dose Uniformity %
2	3	5	35/8200	63	4.9	2.4
2	3	6	35/8200	44	5.8	1.7

<u>* typical GSI parameters:</u>

- **ripple filter 3 mm**
- **overlap between spots 3**
- **1 of 2 fields**
- **dose/ field : 1 Gy**
- **volume: 300 ccm**

skull base chordoma





Histogram Statistics

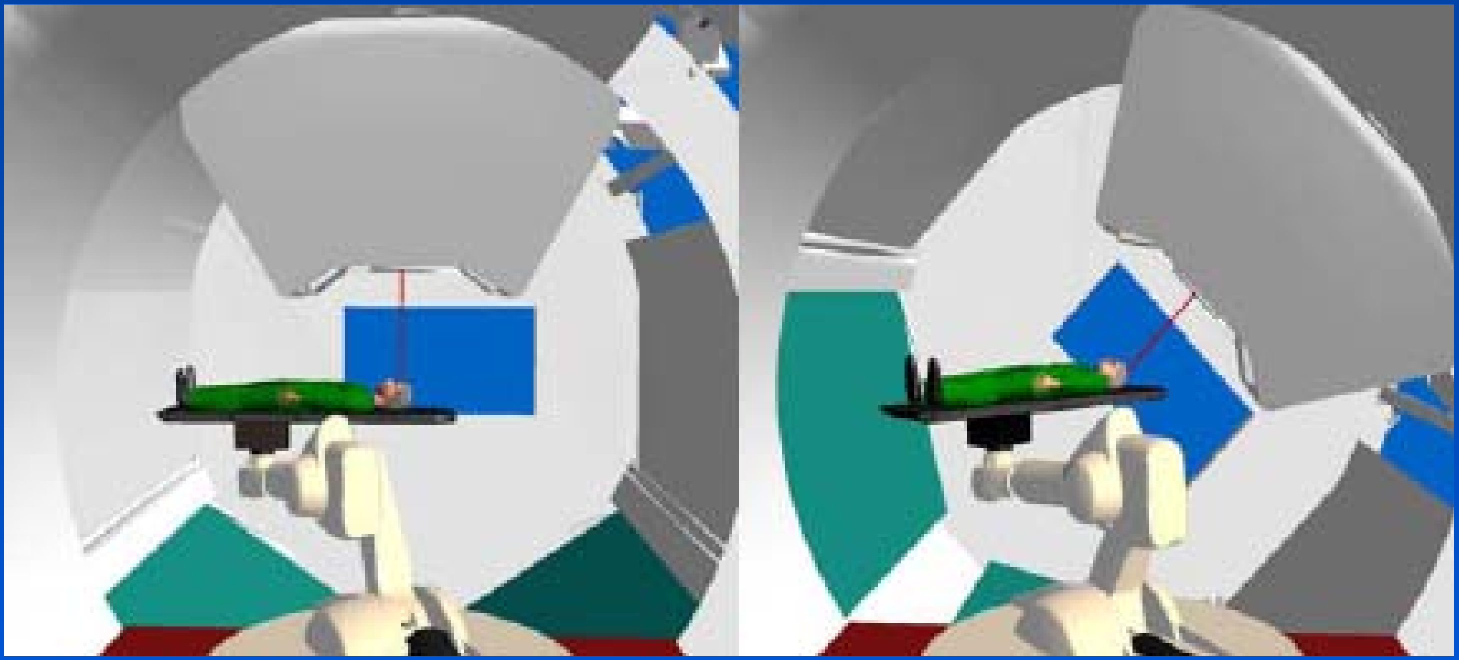
Integral Histogram   Difference Histogram   Clear

	Graph I	Nr Vox	% > 30	% < 90	Min	Max	Sum	Mean	Std De	cub. mm
AUGE_RECHTS - 303	1	1506	0	100	0	0	0	0.00	-0.00	5678.46
AUGE_LINKS - 303	2	1504	0	100	0	0	0	0.00	-0.00	5670.91
N._OPTICUS_LINKS - 3	3	266	37	100	0	796	6069	228.19	267.45	1002.97
N._OPTICUS_RECHTS -	4	185	31	100	0	855	3924	212.12	252.89	697.55
HIRNSTAMM - 303	5	5167	12	99	0	964	52510	101.63	195.89	9482.4
RUECKENMARK - 303	6	2453	0	100	0	452	1894	7.72	40.32	9249.17
CHIASMA - 303	7	173	91	98	85	916	10200	589.61	195.65	652.31
BOOST - 303	8	4553	100	0	910	1000	448959	986.07	12.13	7167.3
HI-151 - 303	9	5208	100	0	843	1000	512156	983.40	16.03	9637.0
TARGET - 303	10	11002	100	0	793	1000	078911	980.65	16.57	1483.6

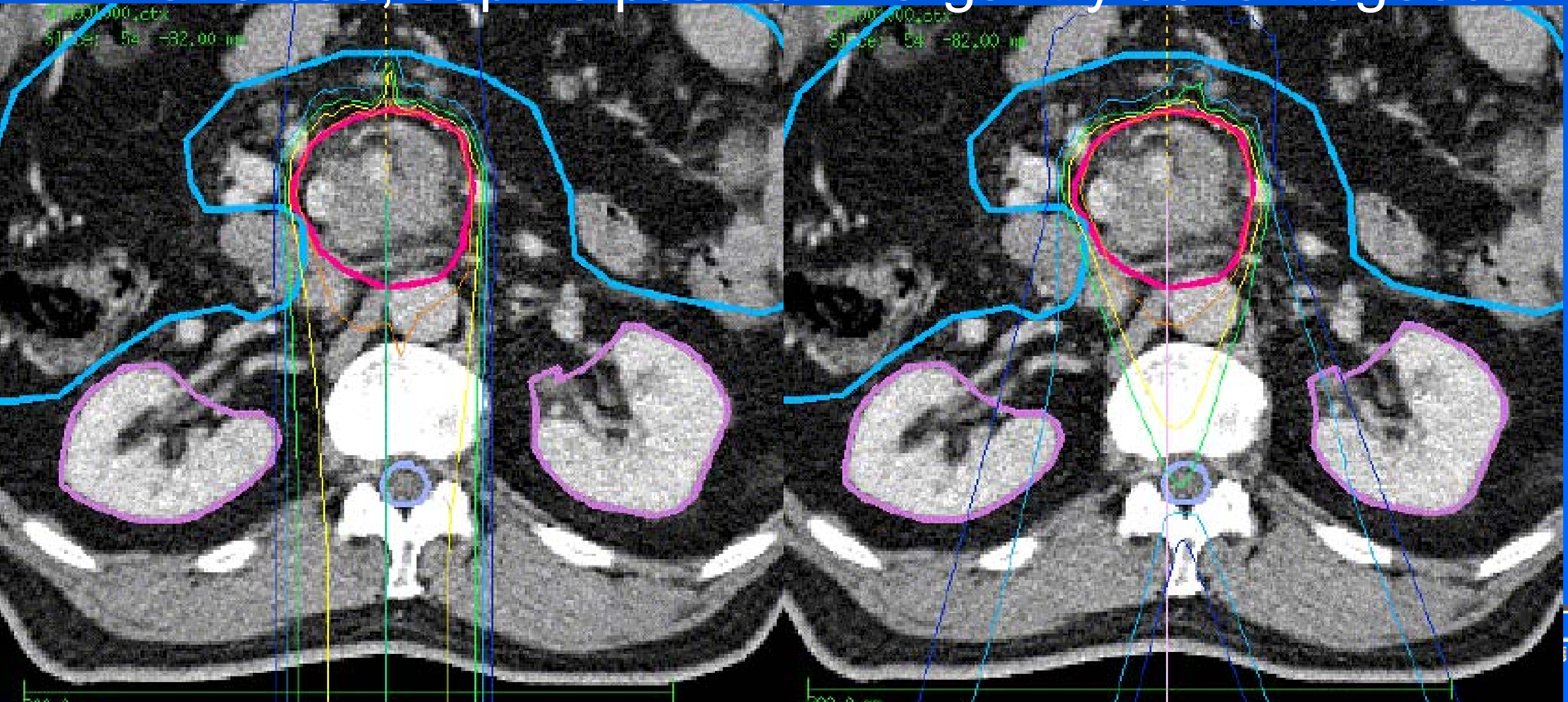
Th. Haberer, Heidelberg Iontherapy Center

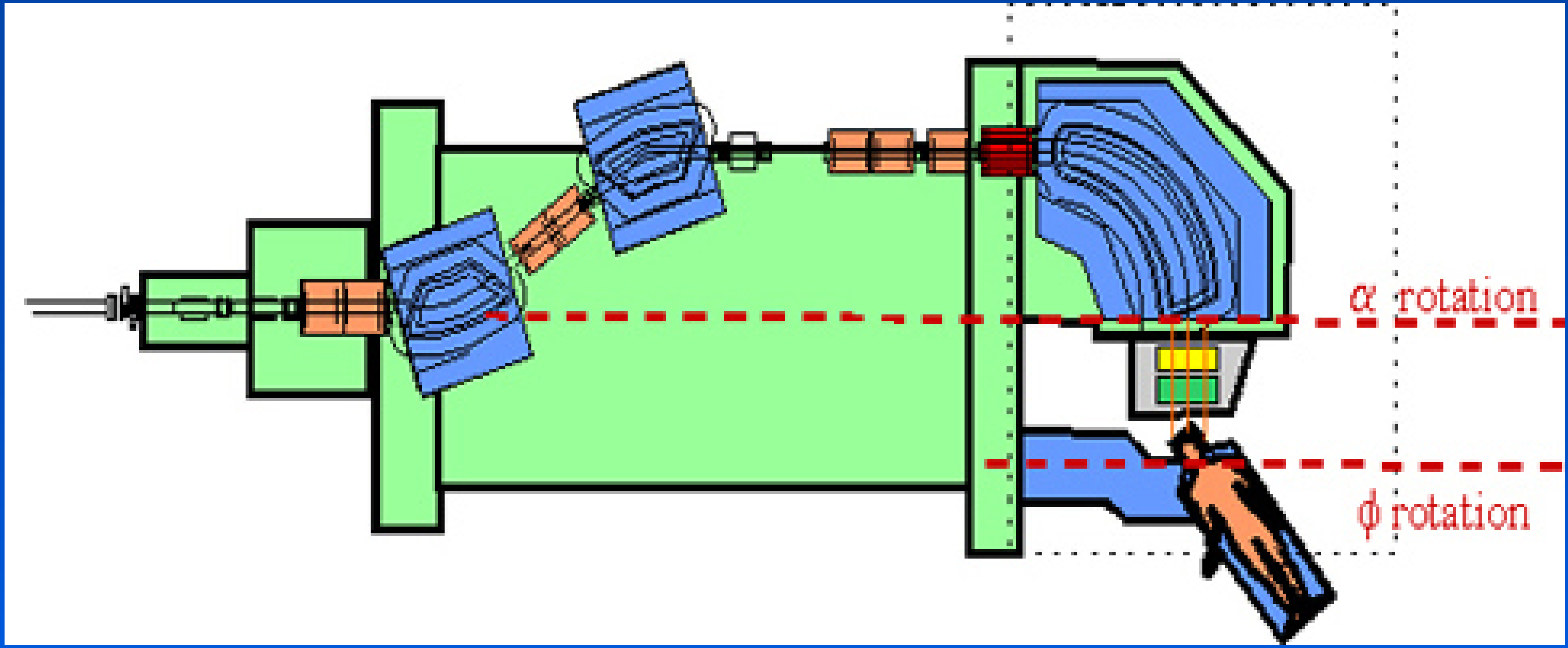
Motivation Gantry

Advantage of a rotating beamline



Pancreas, supine position via gantry advantageous

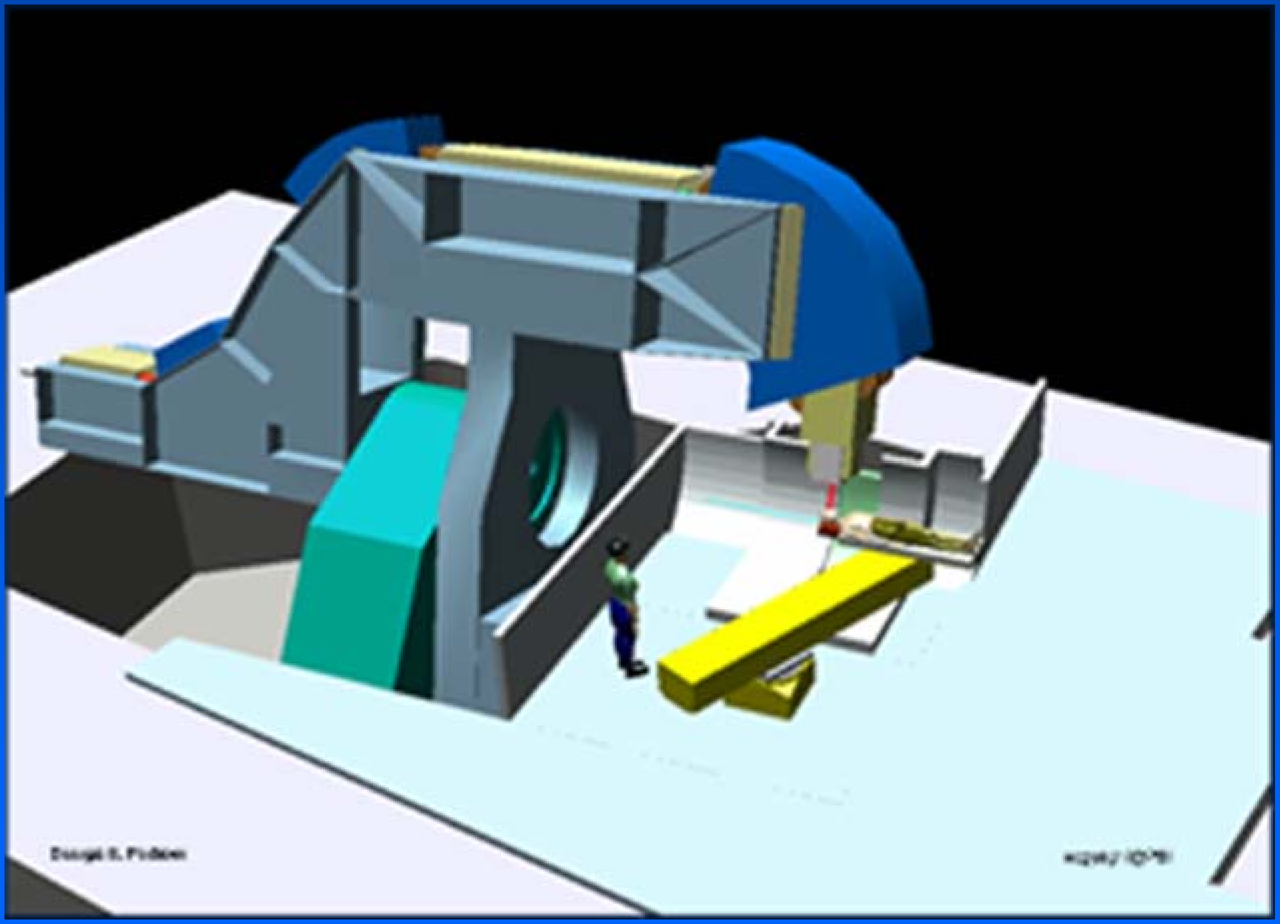




Gantry 1 / PSI

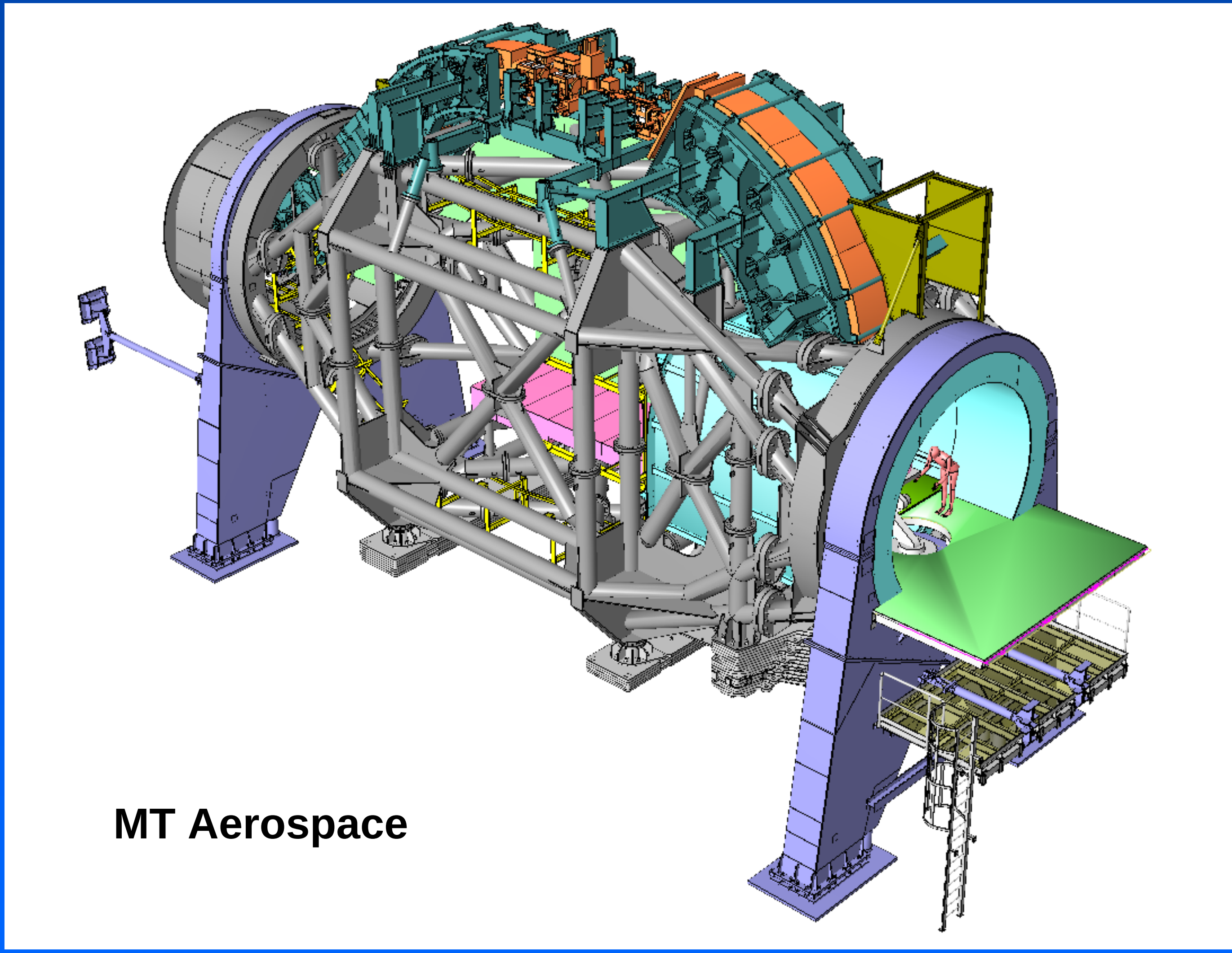
Th. Haberer, Heidelberg Iontherapy Center

Gantry 2 / PSI



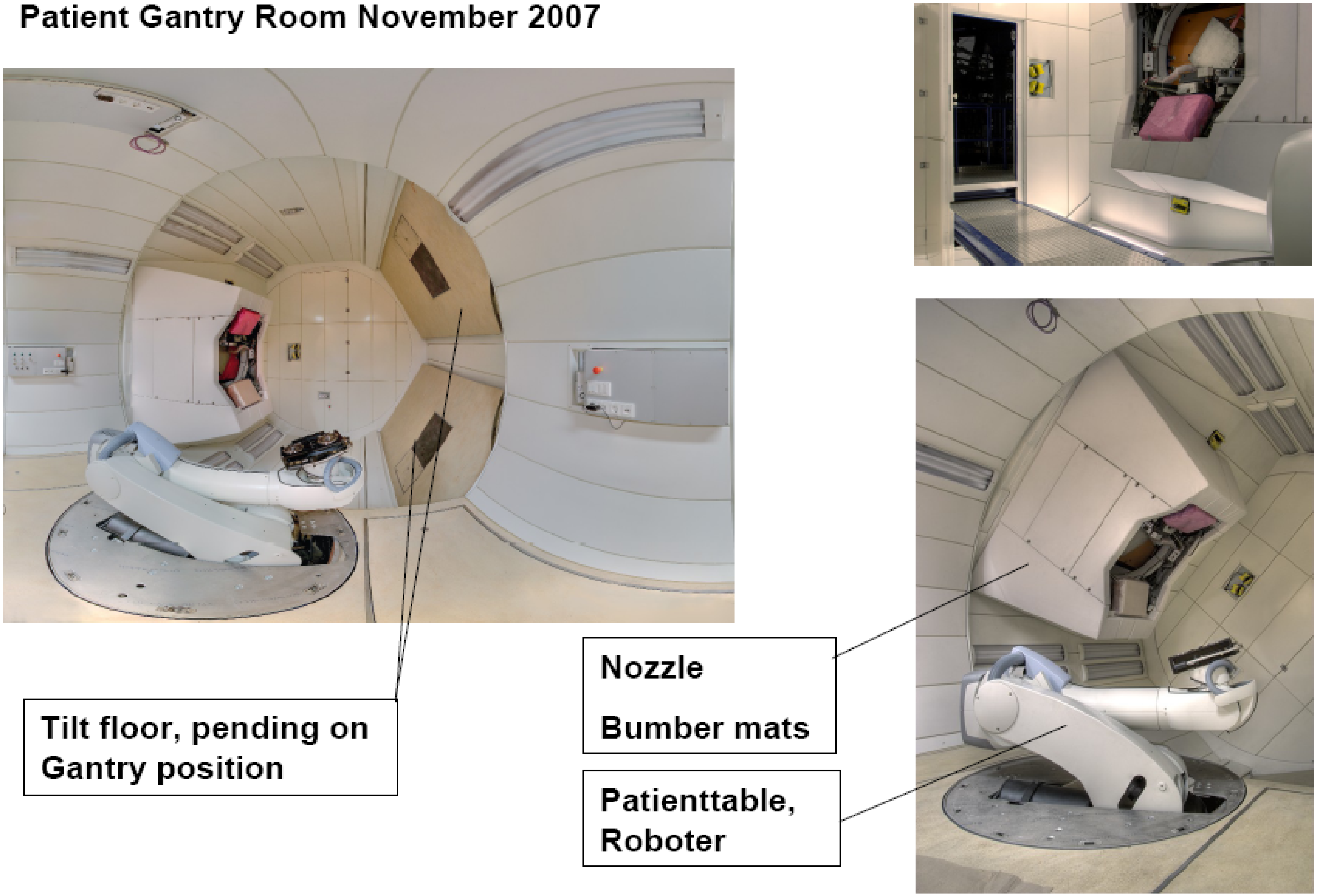
Design for HIT

- isocentric barrel-type
- world-wide first ion gantry
- 2D beam scanning upstream to final bending, almost parallel due to edge focussing
- ± 180° rotation 3° / second
- 13m diameter 25m length 570 to rotating (145 to magnets)



Gantry / Medtech

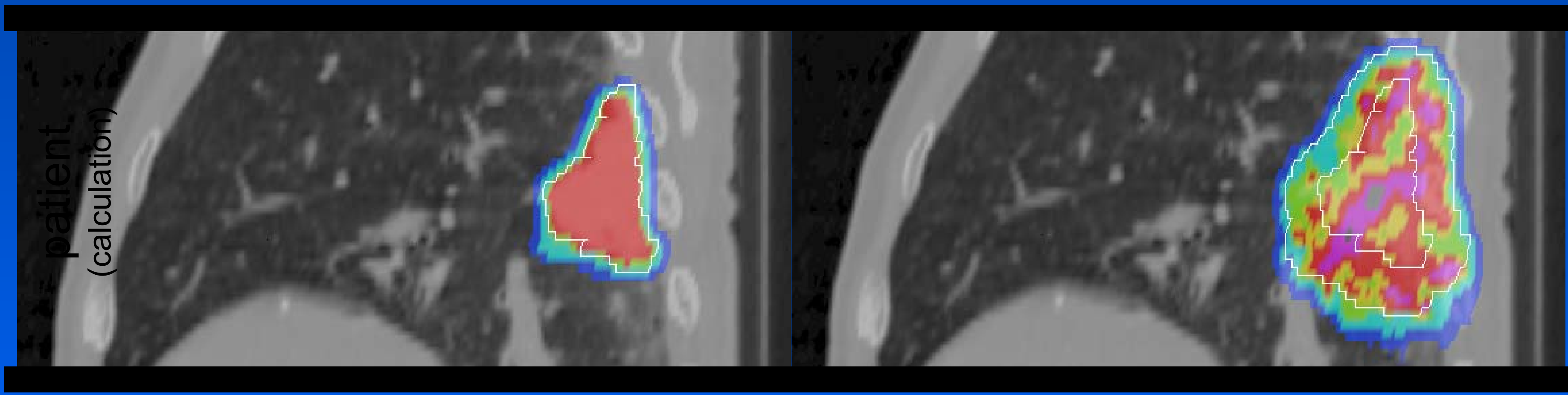
Patient Gantry Room November 2007



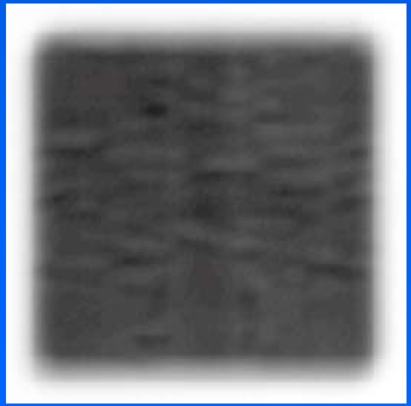
Interplay scanned beam - moving target

stationary target – scanned beam

moving target – scanned beam

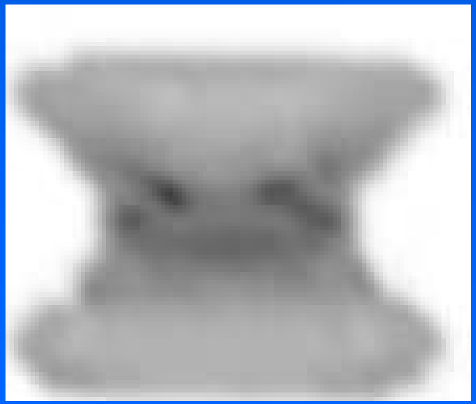


film
(experimental)



film

beam



courtesy C.Bert, GSI

Thank you for your attention !

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