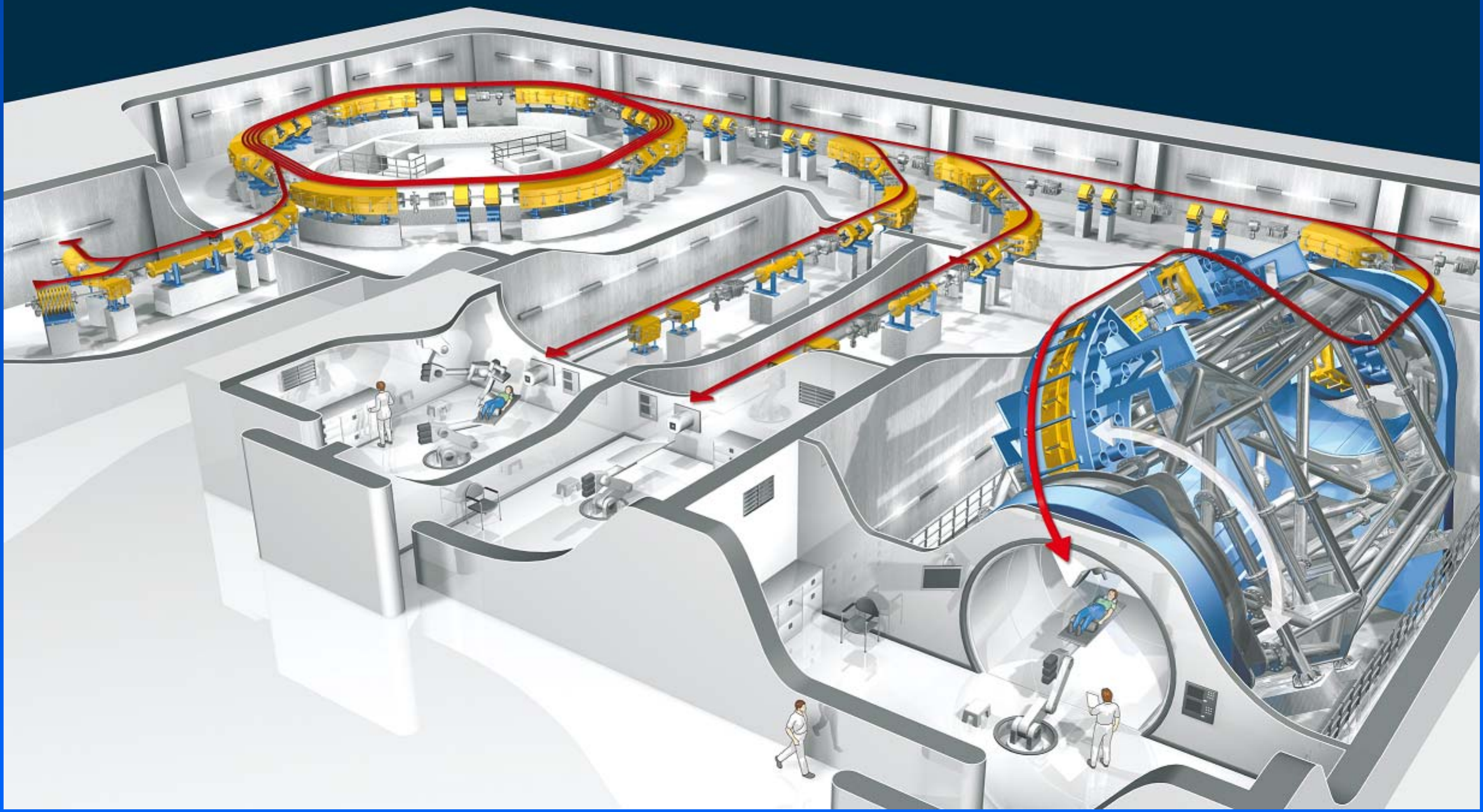
Particle Beam Production
- A Synchrotron-Based System -



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

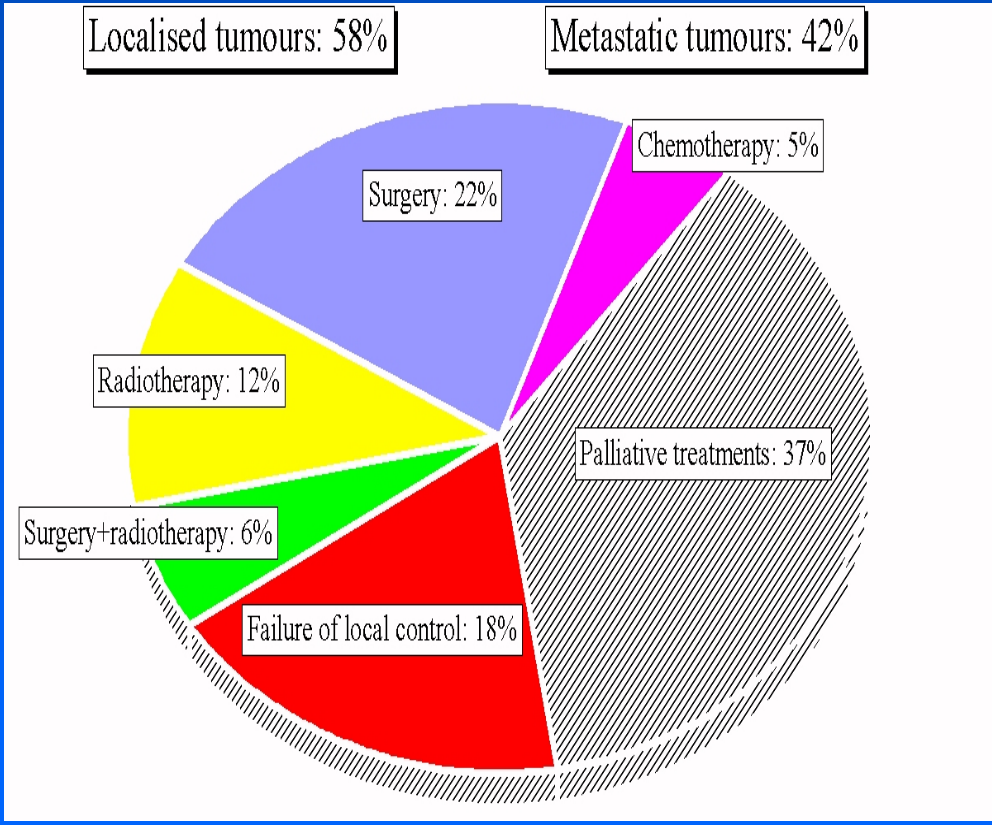
Outline

- Situation/Rationale
- Requirements
- Synchrotron choice
- Functions
- Implementation@HIT
- Performance
- Conclusion

Situation

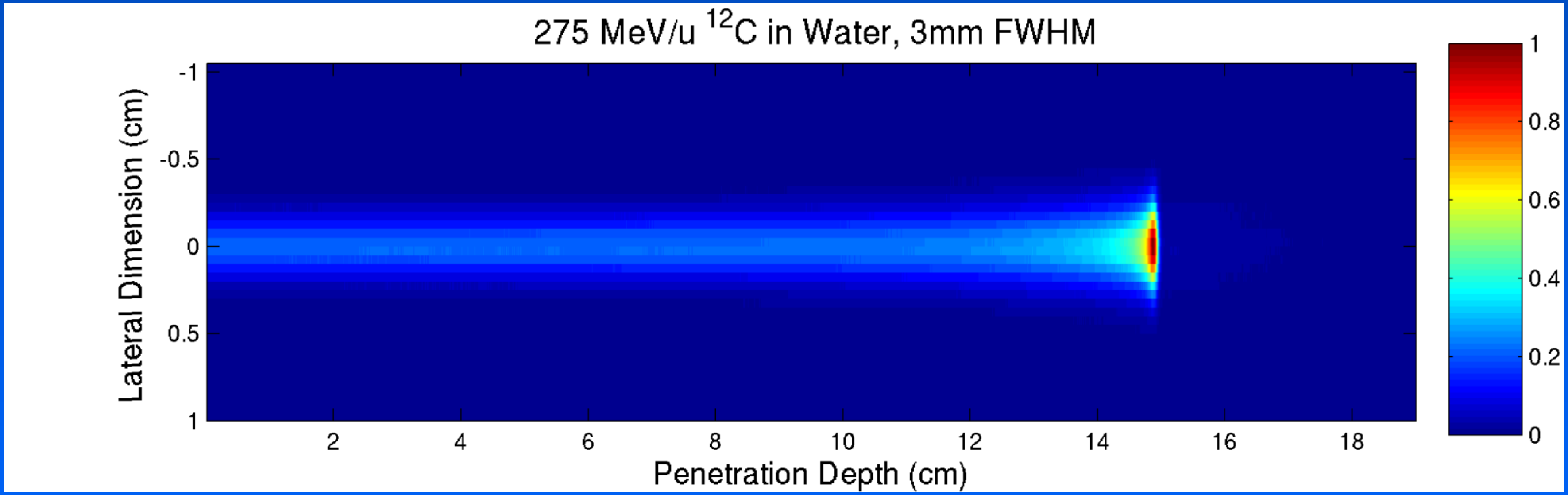
- 2/3 patients suffer from a local disease at the time of diagnosis
- In 18% local treatment modalities fail => 280.000 deaths/year in the EC
- Protons and ions have the potential to cure 30.000 patients/year in the EC

relevance of local tumor control (EC-study 1991)



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

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Requirement engineering

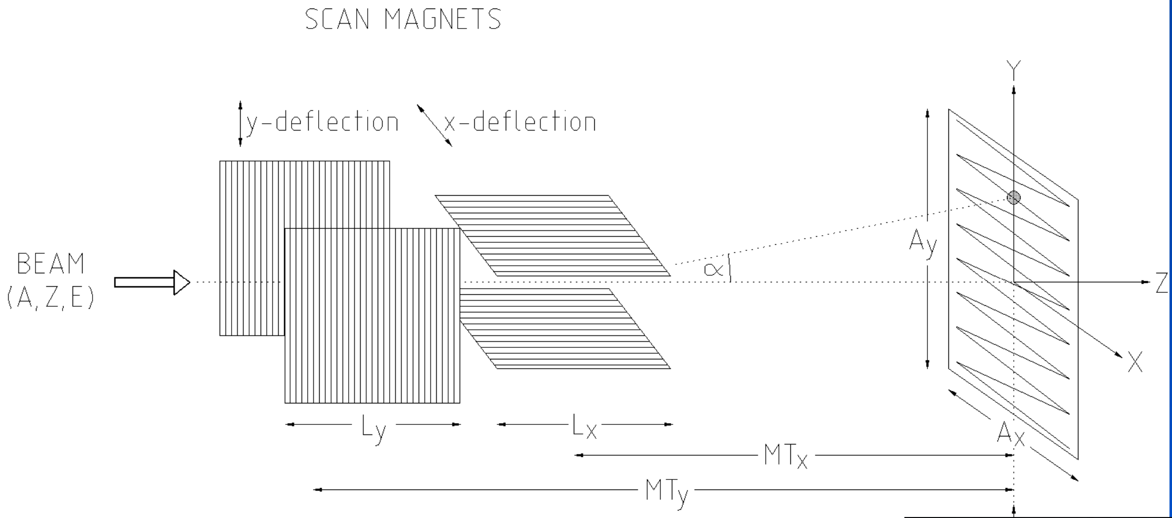
Application
- treatment of tumors with ion beams (conform, precise)

1st level requirements
- dose deposition in patient → dose delivery at isocenter

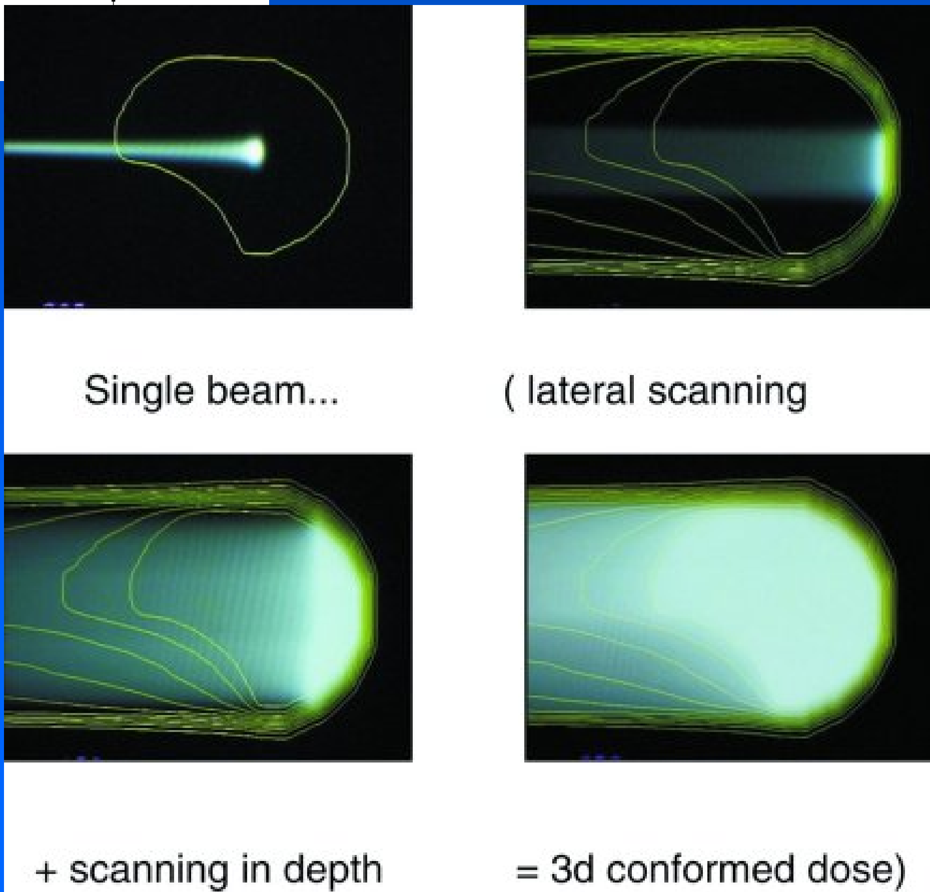
2nd level requirements
- beam application system

3rd level requirements
- accelerator specifications
  ← beam application system

→ accelerator requirements: interface to scanning system



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

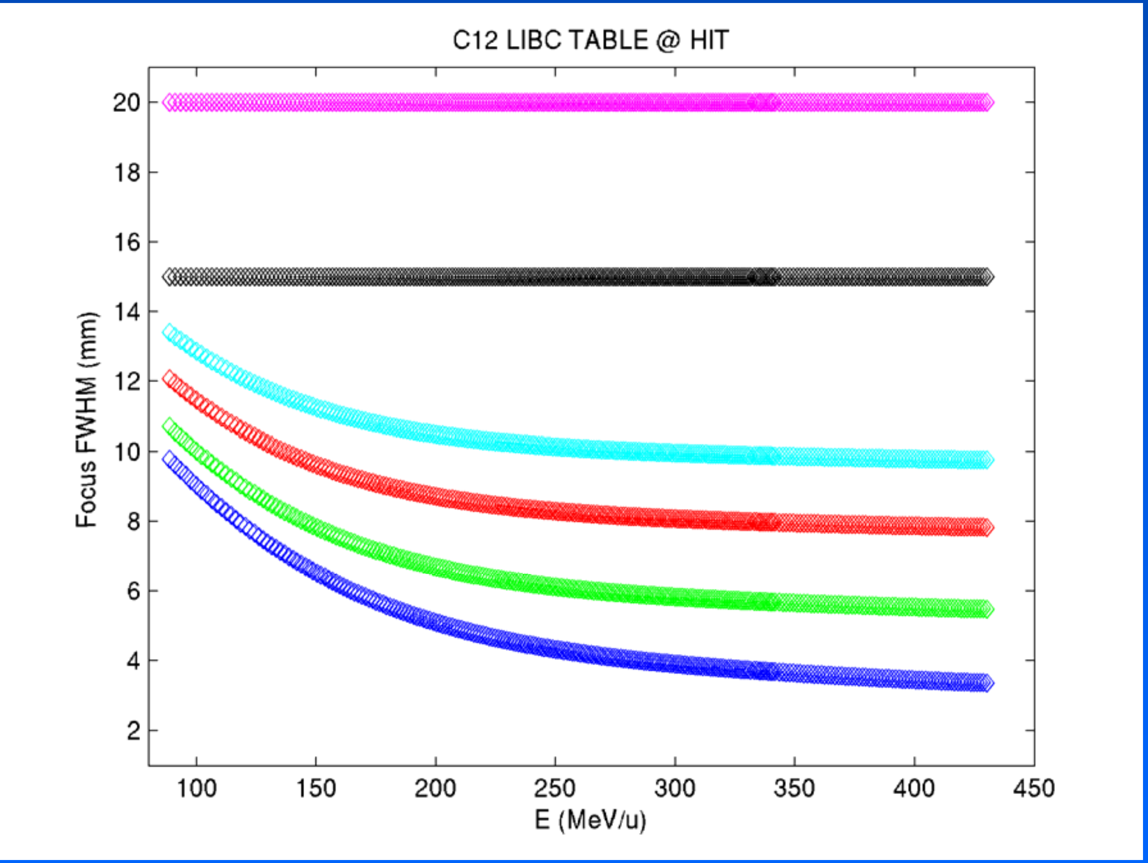
Beam Scanning

Th. Haberer, Heidelberg Iontherapy Center

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

Spot Size Library for Carbon



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

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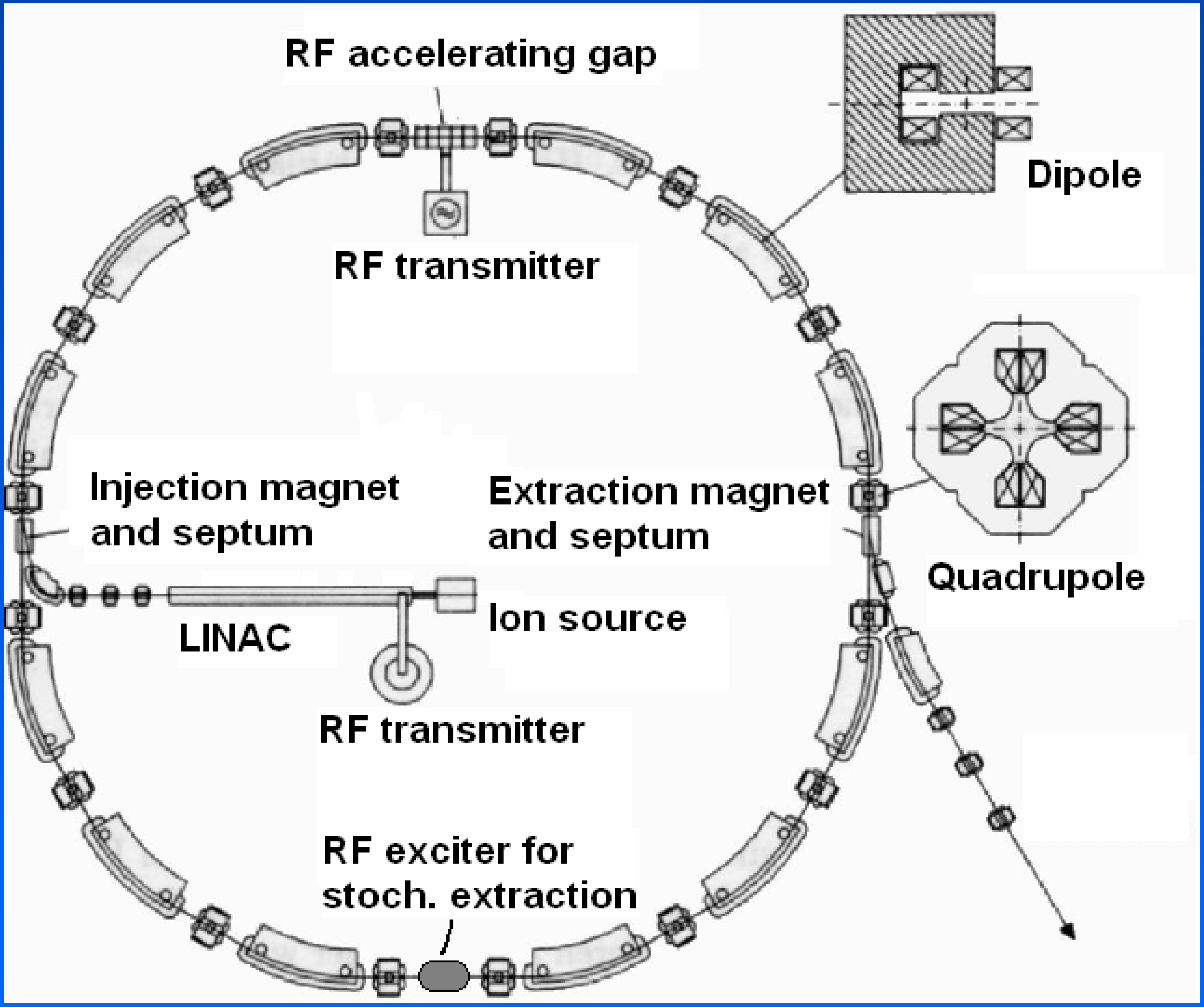
Synchrotrons – Principle Layout



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

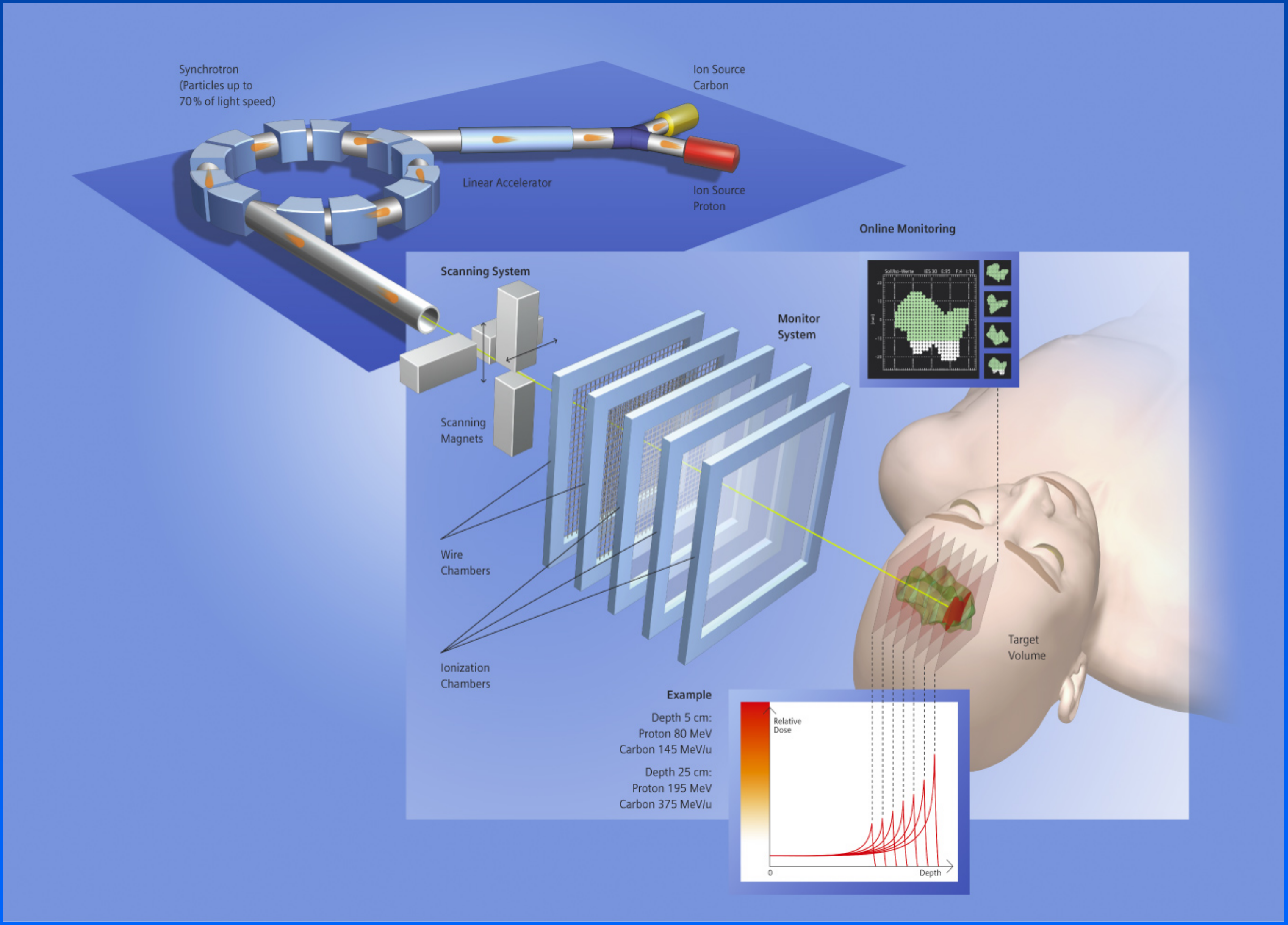
Proton-Synchrotron, Shizuoka, Japan

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

utmost precision via active position and intensity feed back loops



intensity-controlled rasterscan technique @ GSI
Haberer et al., NIM A , 1993

Treatment quality requirements

- beam scanning only
- intensity controlled scanning process (T < 5 ms per voxel)
- precise beam position & width (error < 25% FWHM)
- pencil beam library (100.000 comb.: energy, focus, particles per second)
- maximum energy (430 MeV/u carbon, 6.7 Tm rigidity)
- energy variation (~ 1% in 1s)
- energy spread (~ 0.2%)
- intensity modulation (Imax: ~10^{10} (p), ~10^{8} (C) per spill)
  (variation: 1…1000, Nmin: 3000 Ions/Voxel)
- spill structure (smooth: Nmax/Navg ~ 2 @ 1ms)
- beam purity (impurity < 1%)
- number of quasi parallel particle types
  (Protons, Helium, Carbon, Oxygen)

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Functions

Ion: source, LEBT
Intensity: LEBT
Energy: Synchrotron, HEBT
Focus: HEBT
Beam Abort: Synchrotron, HEBT

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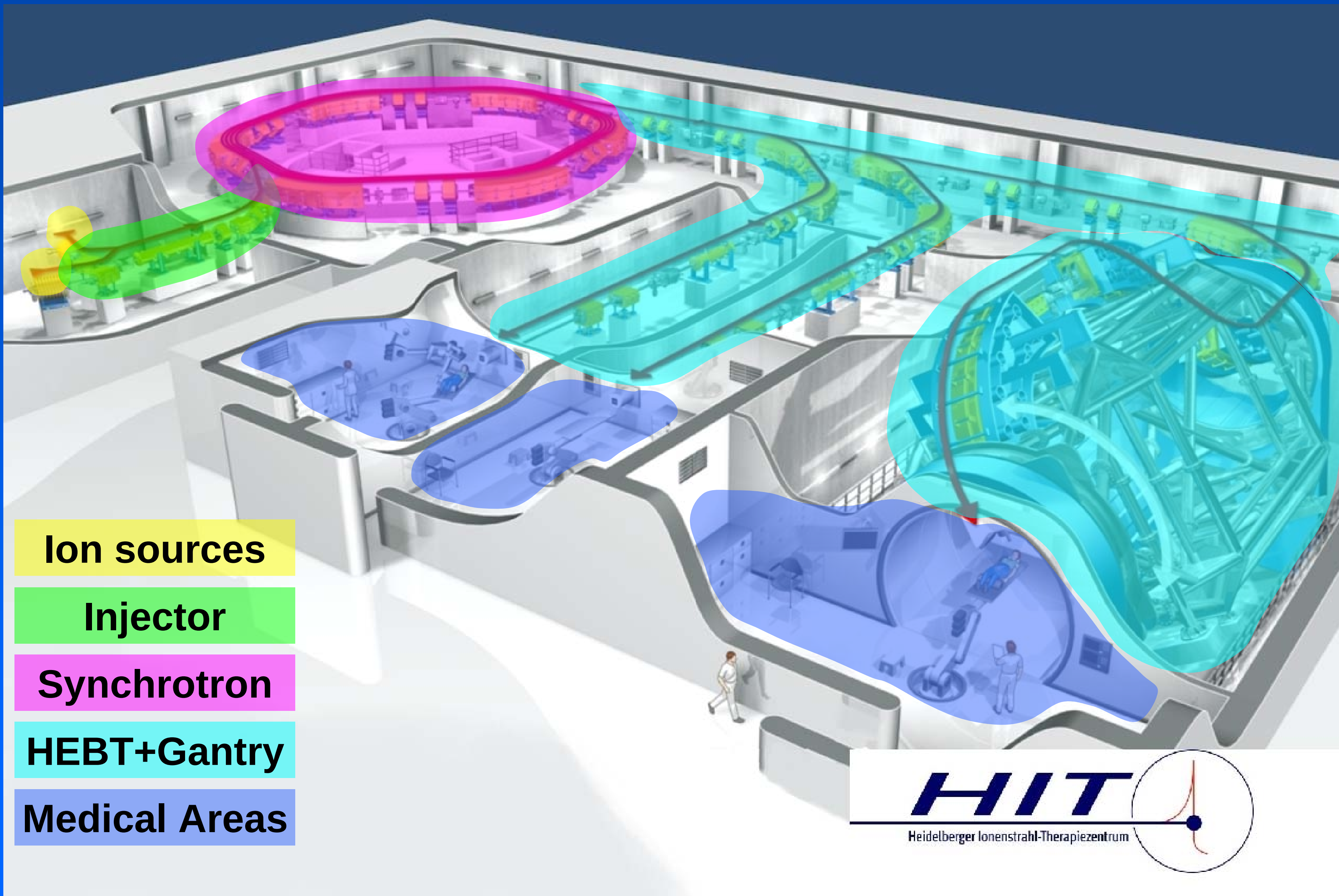
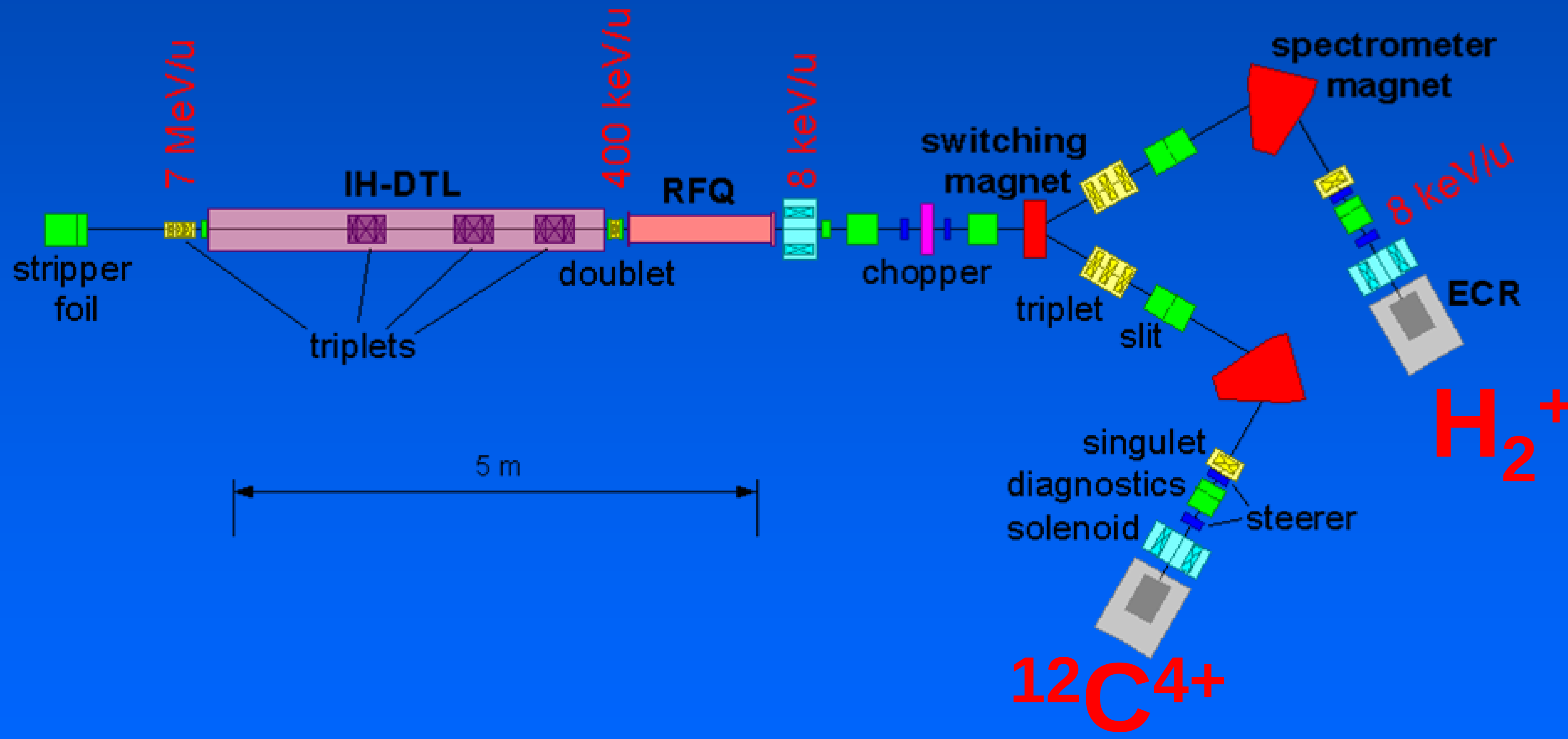
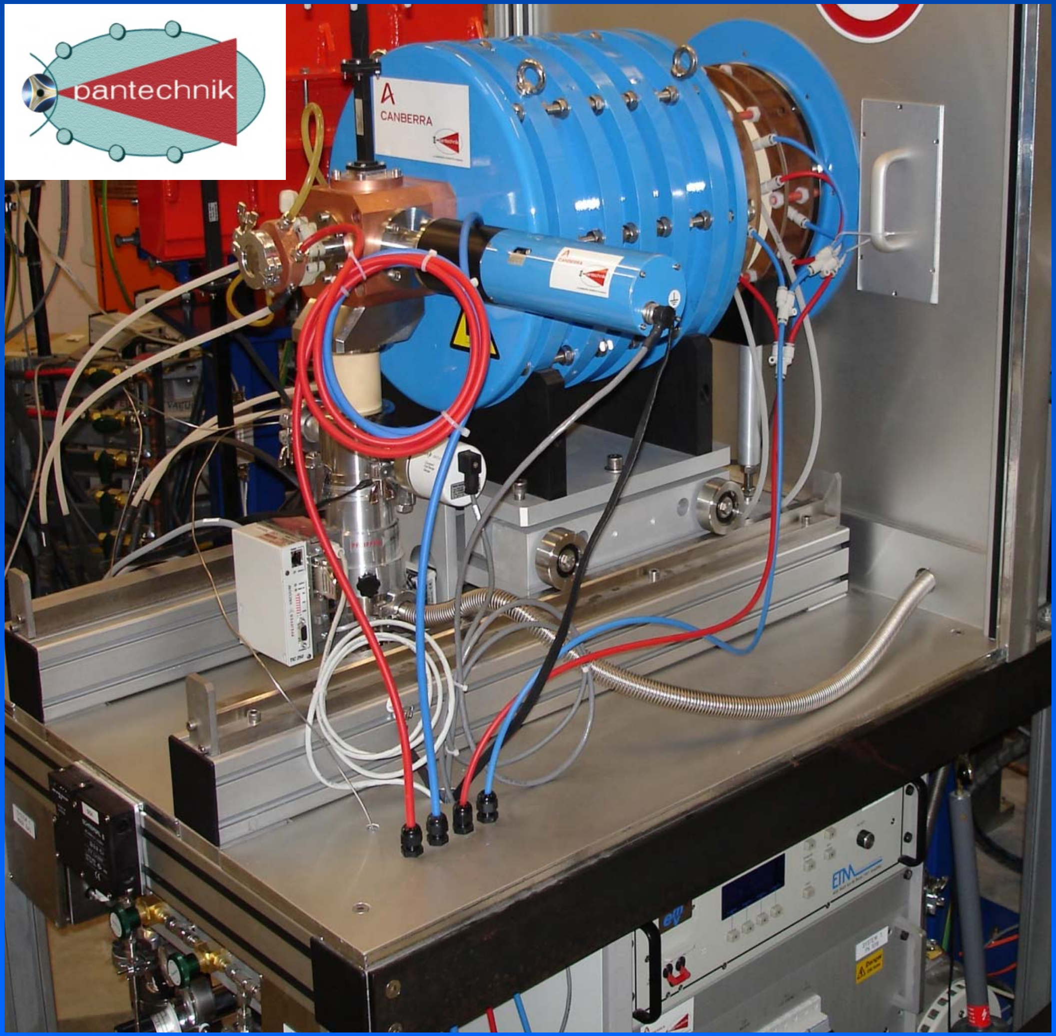
HIT Accelerator System



7 MeV/u Injector-LINAC (216,816 MHz)



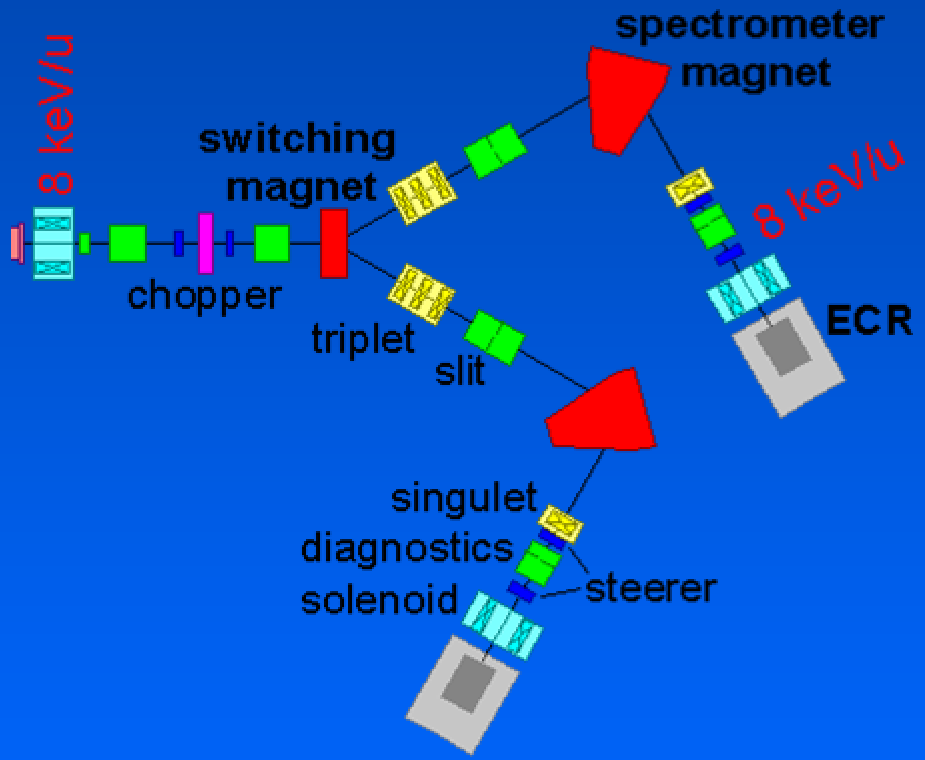
ECR: 14,5 GHz SUPERNANOGAN



Size	**L = 324 mm**
	∅ = 380 mm
***B* injection**	**1,2 T**
***B* min**	**0,45 T**
***B* extraction**	**0,9 T**
***B* hexapole**	**1,1 T**
max. extraction voltage	**30 kV**

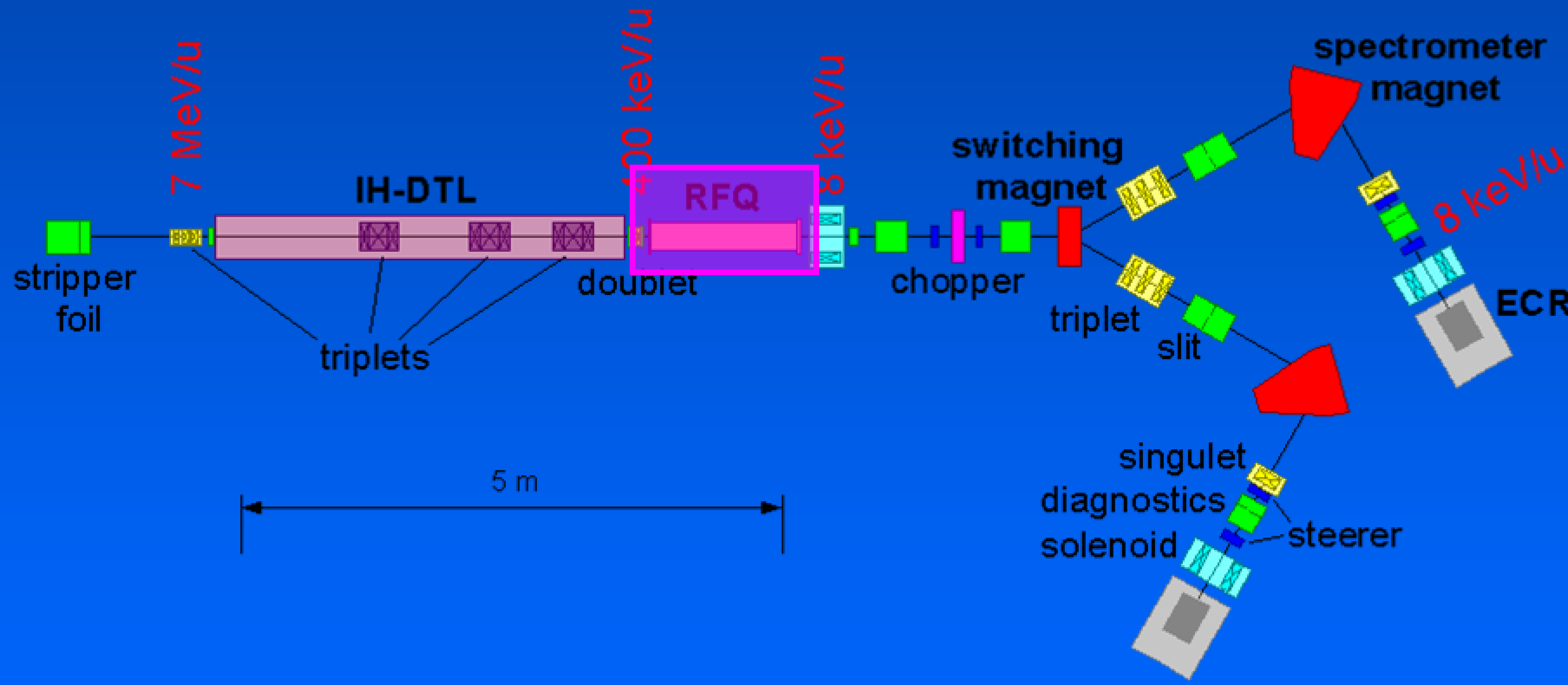
Solenoids are permanent-magnets!

LEBT (Low Energy Beam Transport)

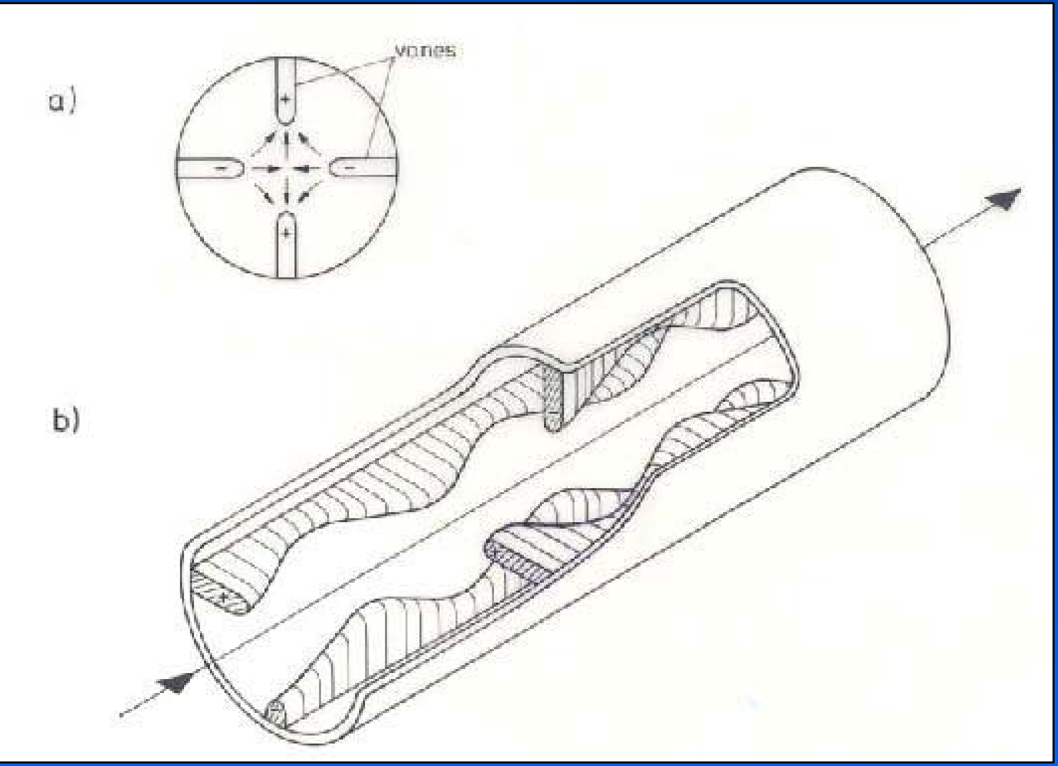


- **Beam transport: IQ … RFQ**
- **Selection of Ion species (incl. Spectrometer for charge state selection)**
- **Intensity variation**
- **Switching of source branches**
- **chopping**
- **adaption to RFQ-acceptance**

RFQ (Radio-Frequency-Quadrupol)



Radio-Frequency-Quadrupol-Principle



Linear accelerator
I.M. Kapchinsky und
V.A. Tepliakov (1970)

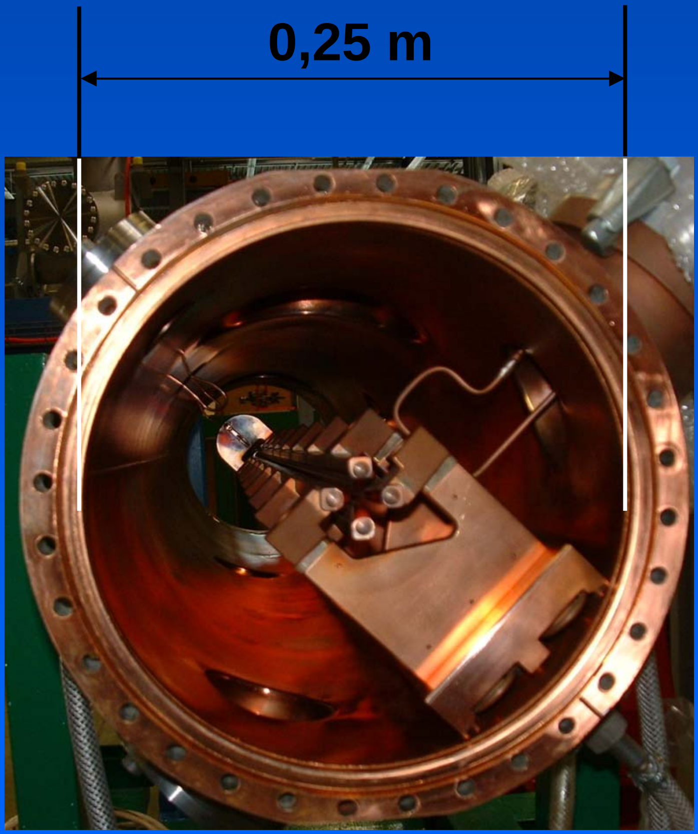
Consists of sinusoidally modulated (π/2-shifted) **Quadrupol-Electrodes**

E-Field-component in z-dir.

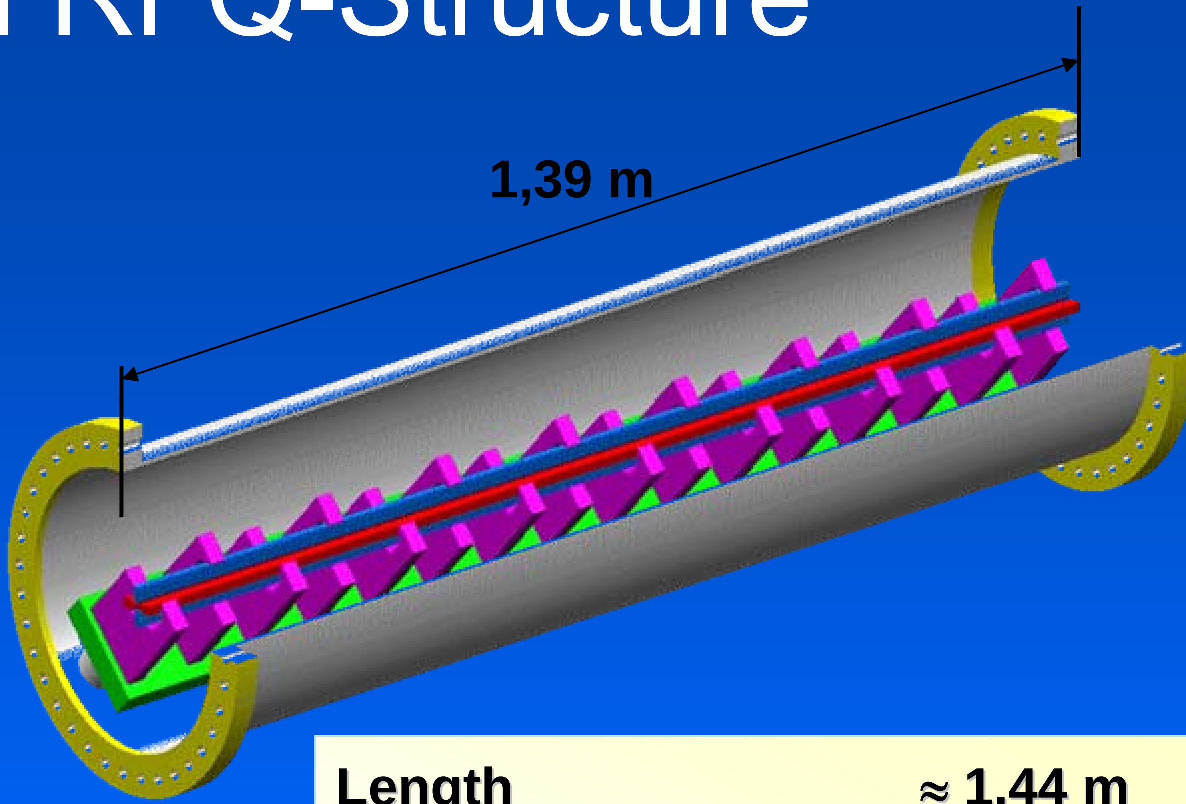
focusses the beam transversally

„**Bunching**“ and **acceleration** of the beam longitudinally

4-Rod RFQ-Structure

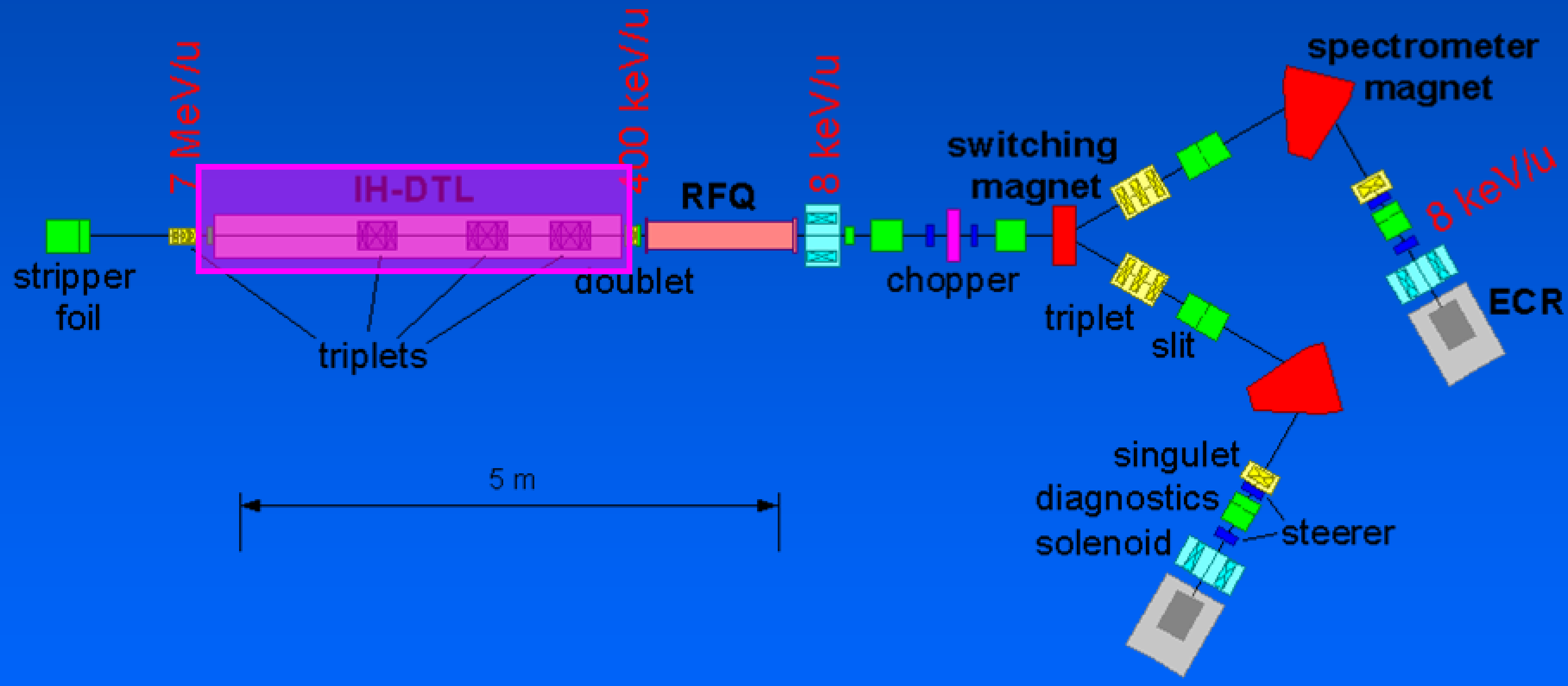


entrance

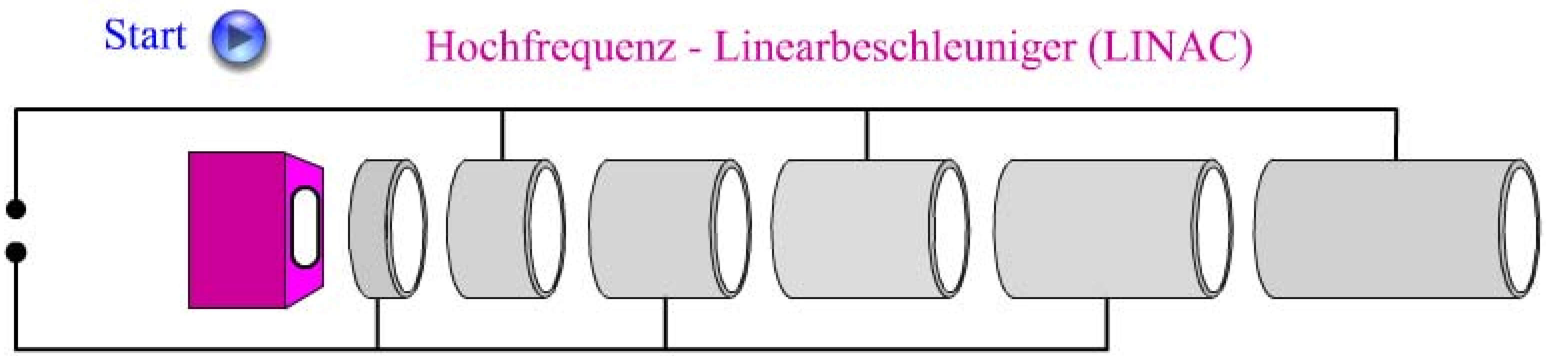


Length	≈ 1,44 m
Diameter	0,25 m
Electrodelength	1,28 m
Voltage	70 kV
HF-power (pulsed)	≈ 190 kW
End energy	400 keV/u

IH-DTL
(Interdigital H-Mode Drift-tube Linac)



Wideröe Linac



$$l_i = \beta_i \frac{\lambda_{HF}}{2} \quad \Rightarrow \quad l_i \propto \sqrt{i}$$

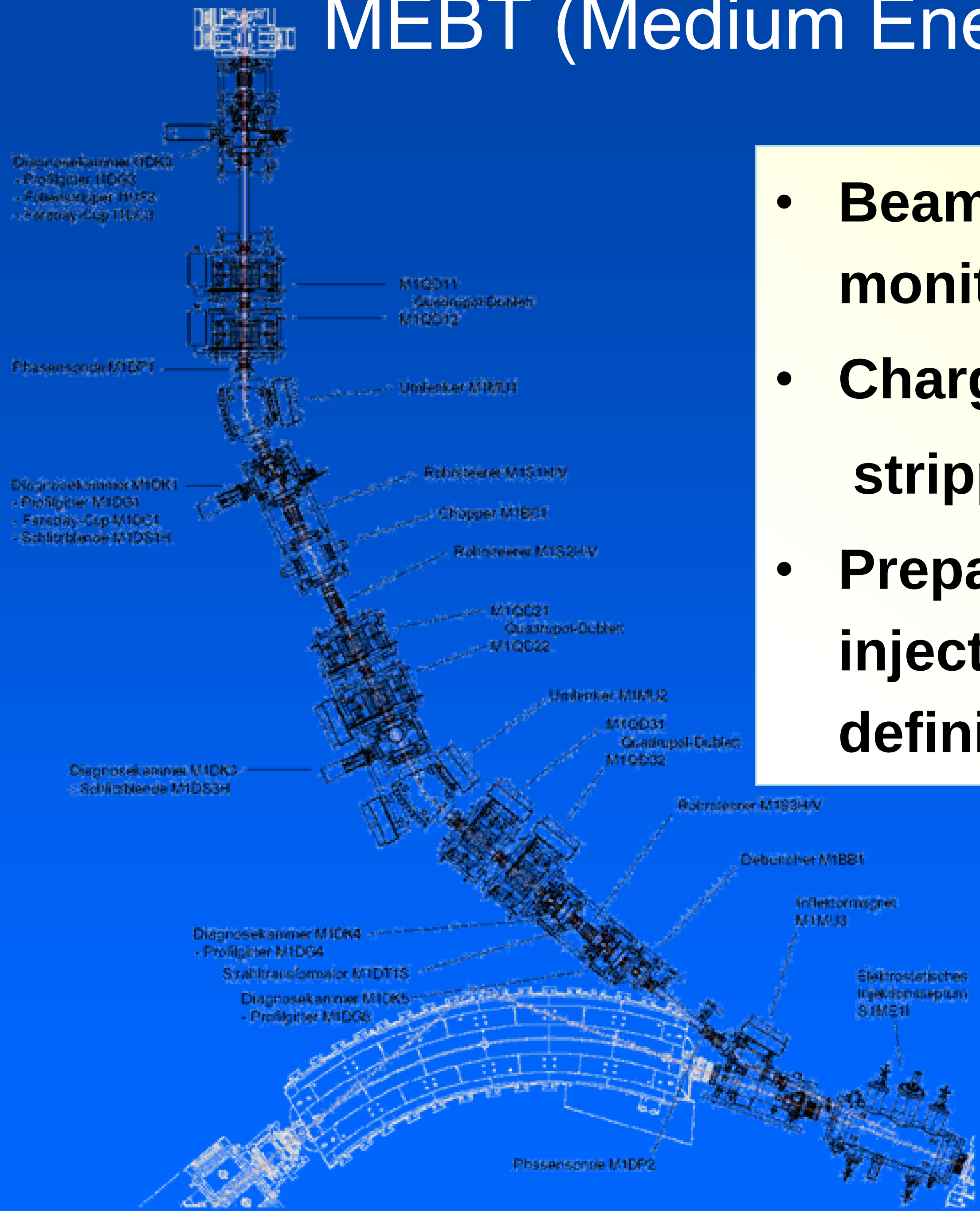
IH-Drift-Tube-Linac

Final energy	7 MeV/u
Gaps	56
Integrated magnetic	
Quadrupol-riplet-lenses	3
Length	≈ 3,77 m
Height	≈ 0,34 m
RF power (pulsed)	≈ 1 MW
eff. Total voltage	21 MV
eff. avg. Gradient	5,7
Momentum width (exit)	±0,16 %

exit

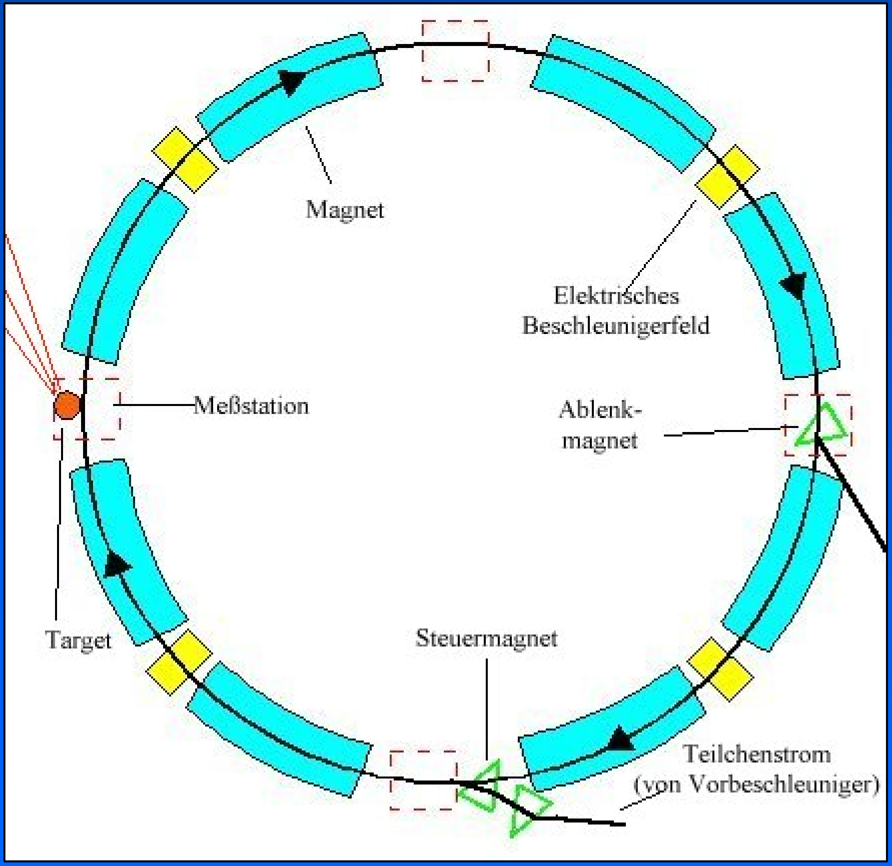
entrance

MEBT (Medium Energy Beam Transport)



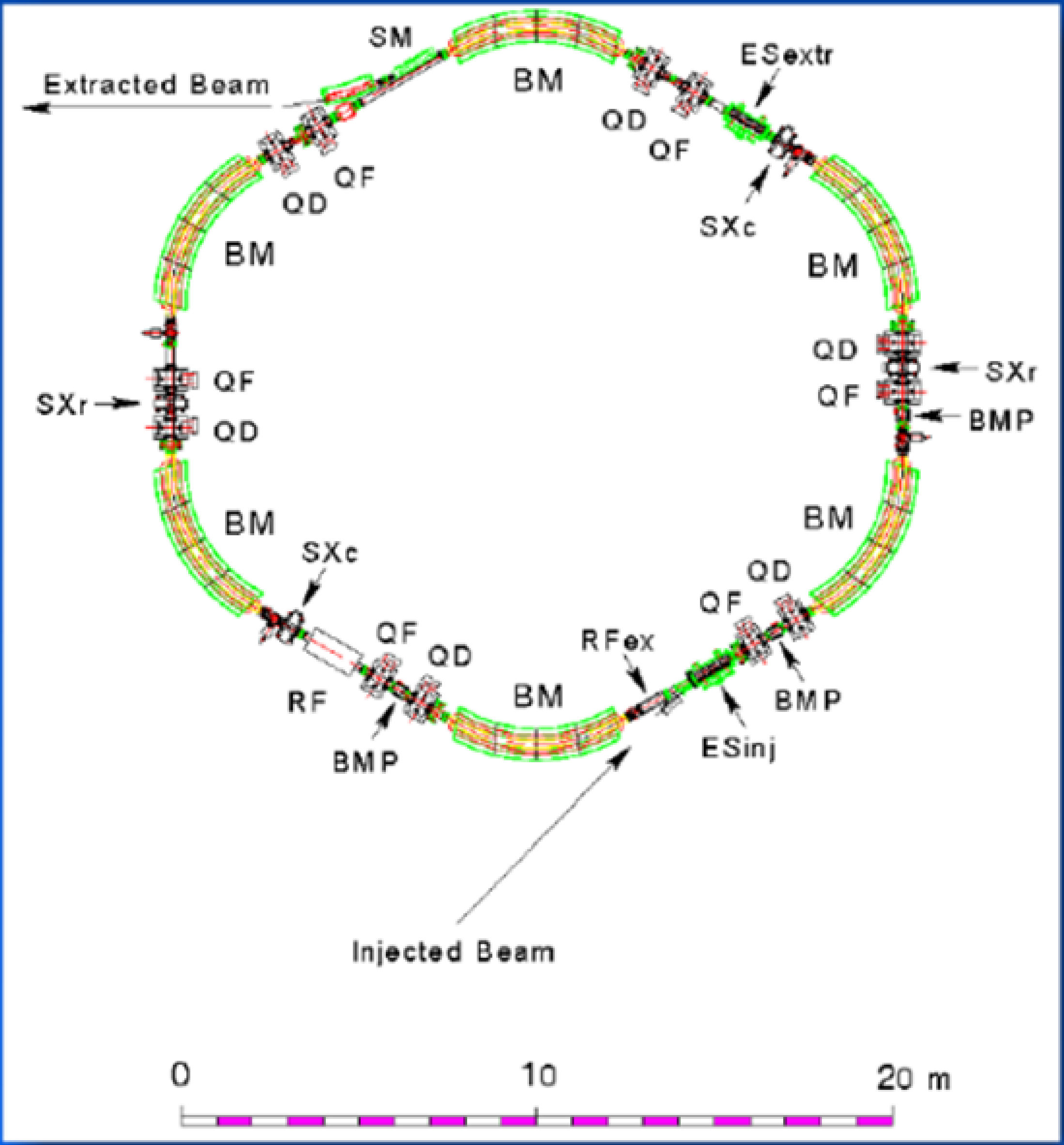
- **Beam transport and monitoring**
- **Charge state separation stripper**
- **Preparation of the pulse for injection (length, energy definition, emittance)**

Synchrotron



- Ring accelerator
  V.I. Veksler / E.M. McMillan (1945)
- constant radius, variable magnetic field
- **variable frequency** HF-cavity
- **synchronous** ramping of the magnets and the HF-Frequenz (beam energy)
- Seperate function accelerator

HIT-Synchrotron



Circumf.: 64,986 m

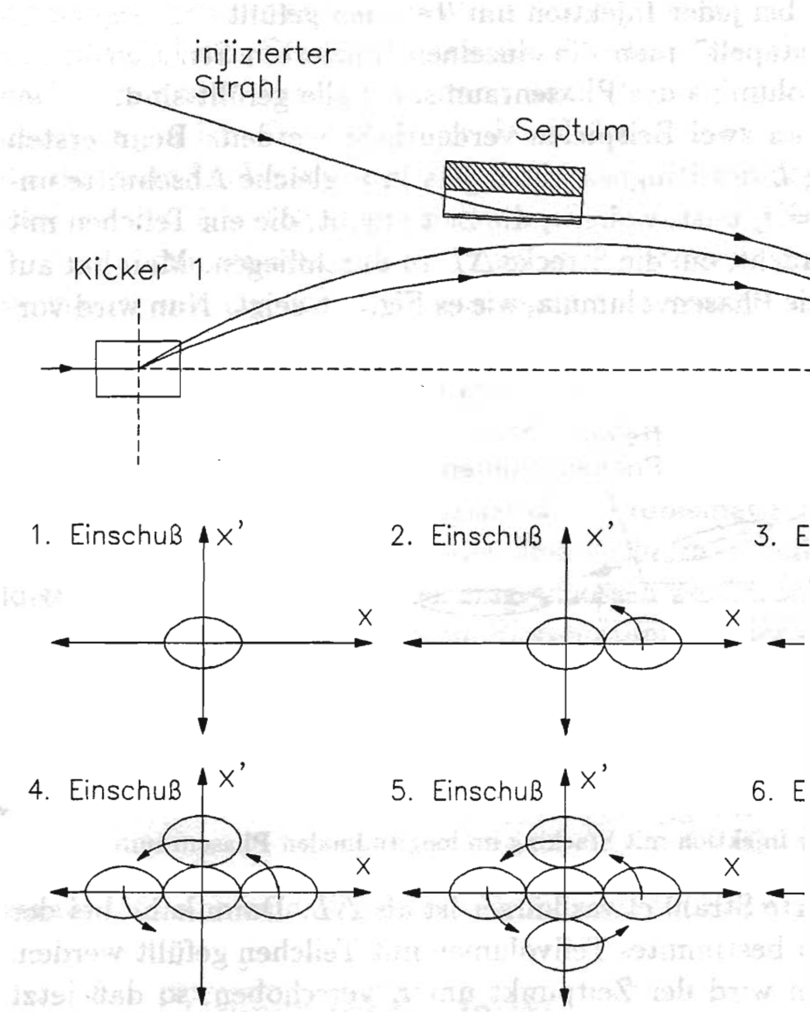
Magnetic rigidity:

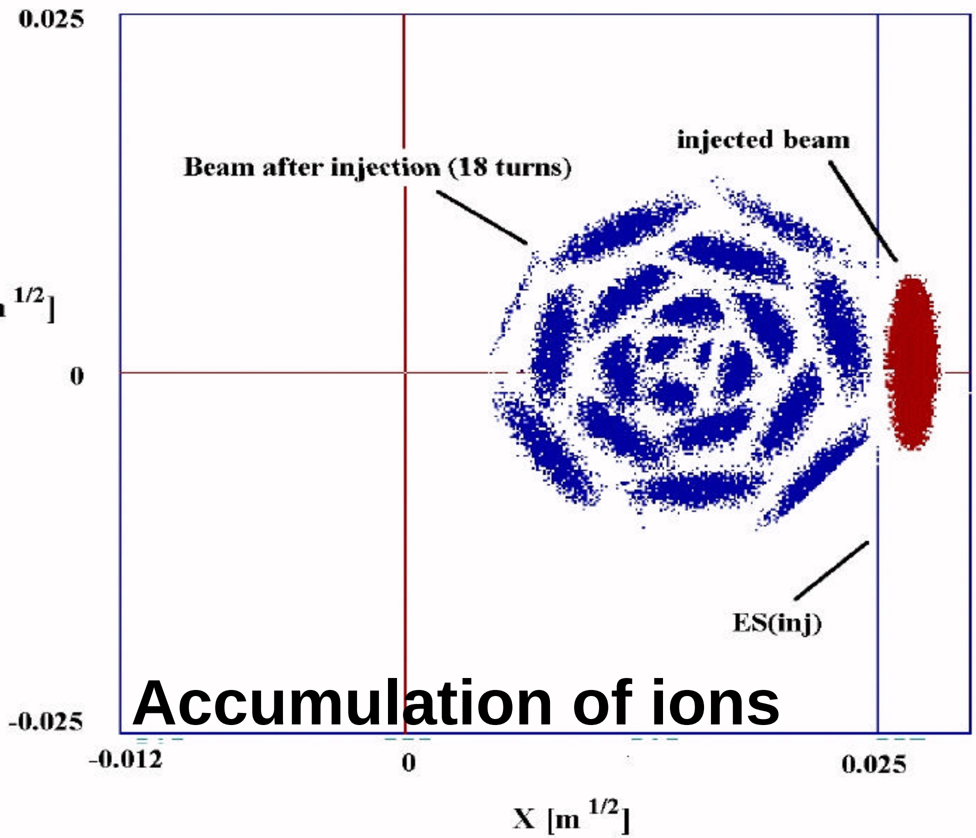
1,1-6,5 Tm

Magnets

- 6 Dipols
- 12 Quads
- 4 Sextupols
- ...

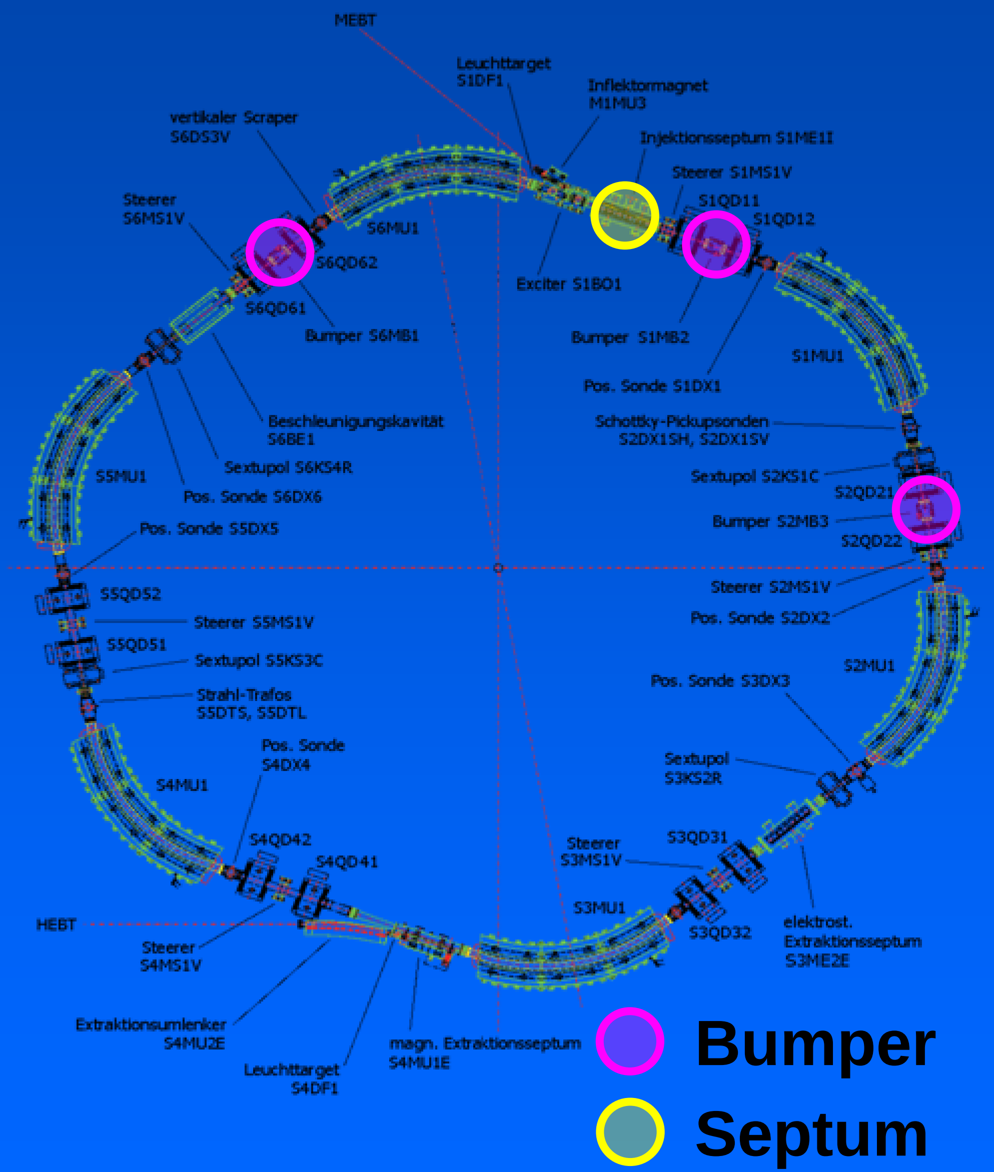
Multiturn-Injection

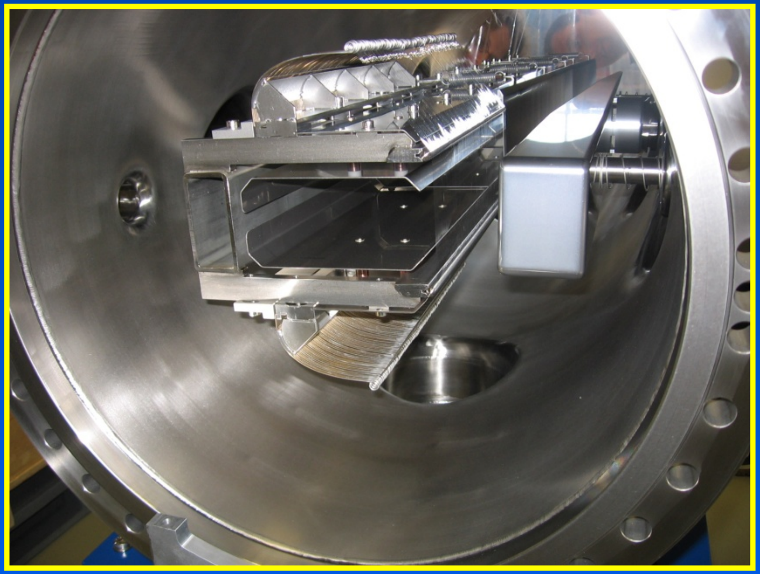


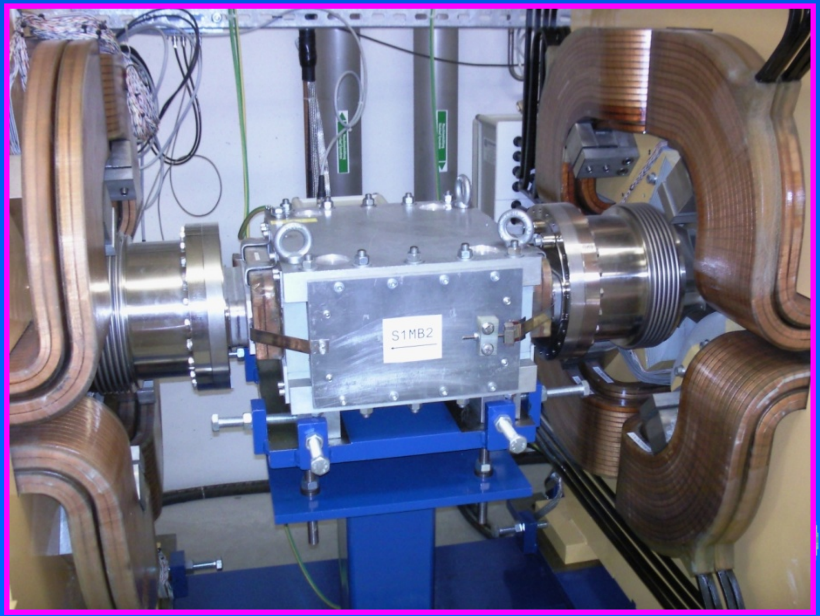


Accumulation of ions

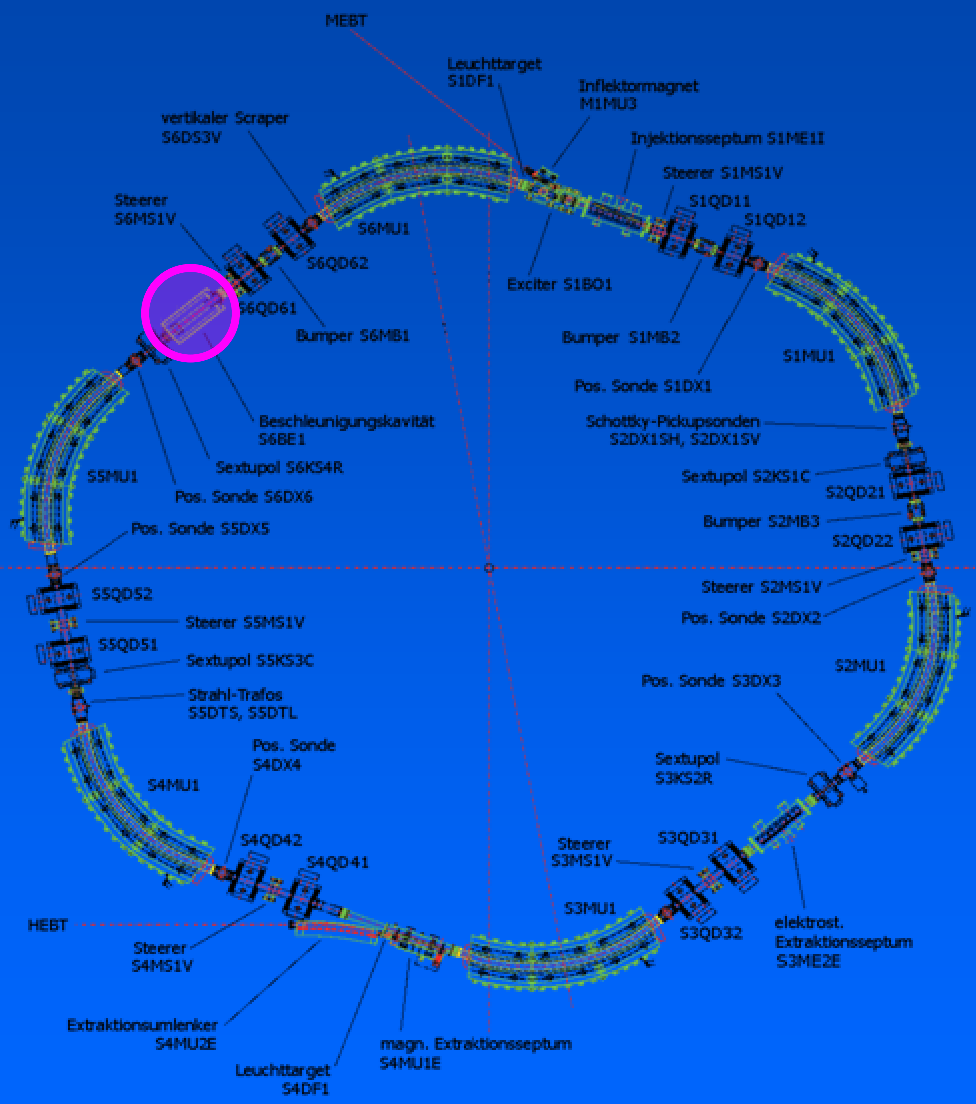
HIT-Injection Devices







Acceleration

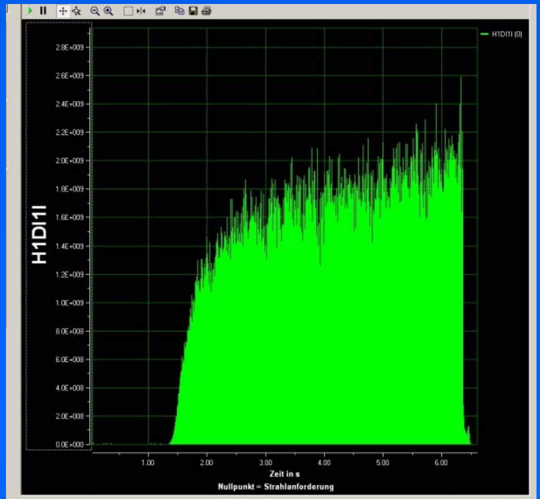


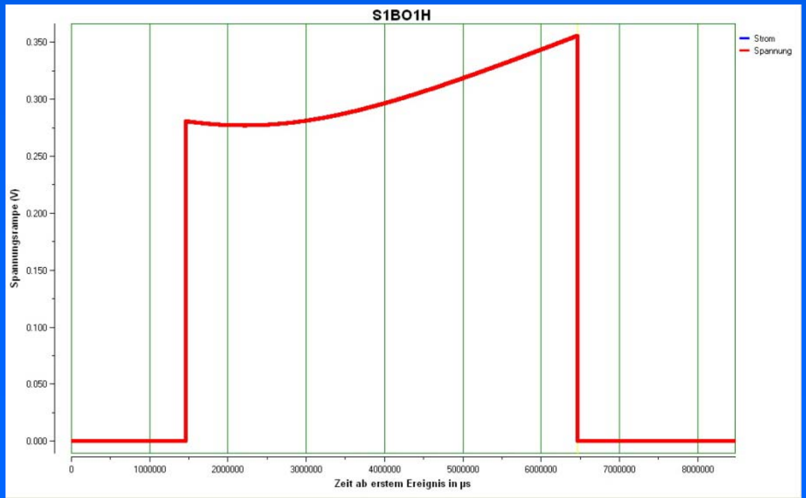
- **HF-capture (bunching) 2nd harmonic**
- **Acceleration up to nominal energy**

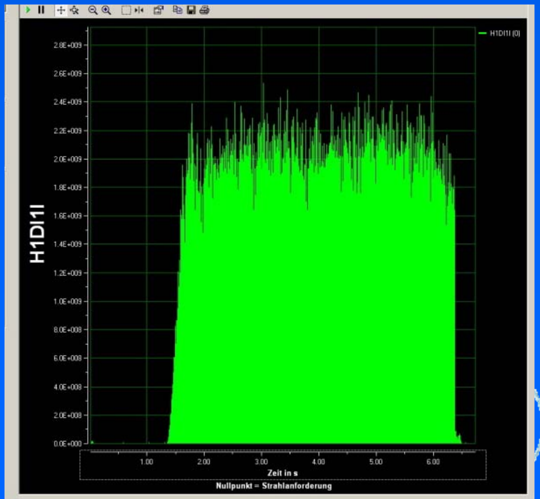
- **Cavity with ferrites**
- **Frequency range: 1-7 MHz**
- **Max. HF-voltage: 2,5 kV**
- **power: 6,4 kW**
- **Source: Hitachi**

RF-KO-Extraction

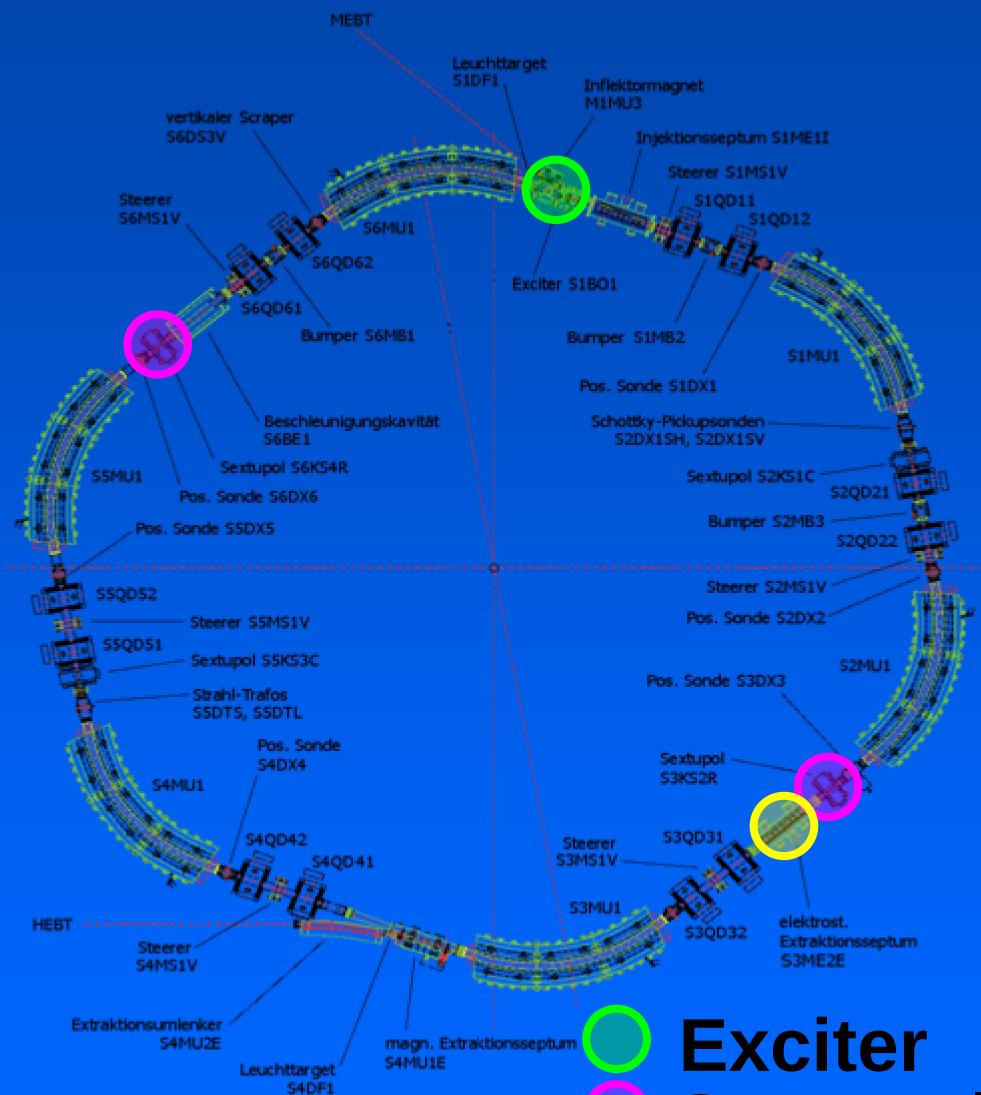
- **Principle**
  - resonant HF-excitation (betatron frequency)
  - constant separatrix
- **Characteristcs**
  - slow extraction
  - constant ion-optical settings dring extraction
  - Multiple extractions available
  - Spillshaping via amplitude modulation



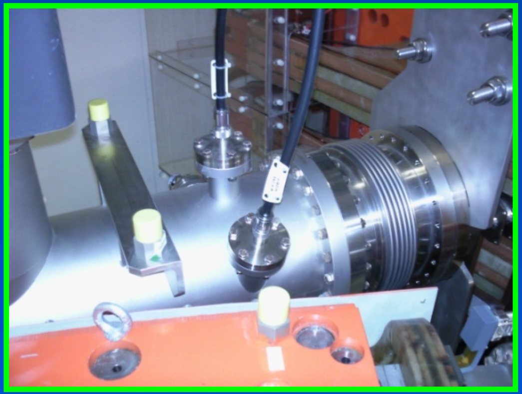


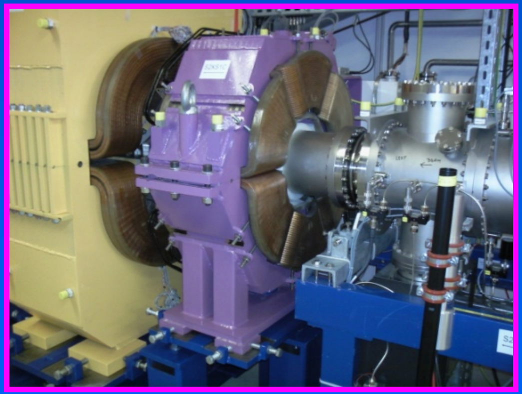


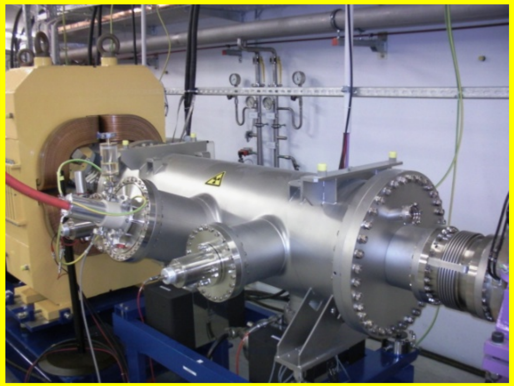
HIT-Extraction Devices



Exciter
Sextupole
Septum

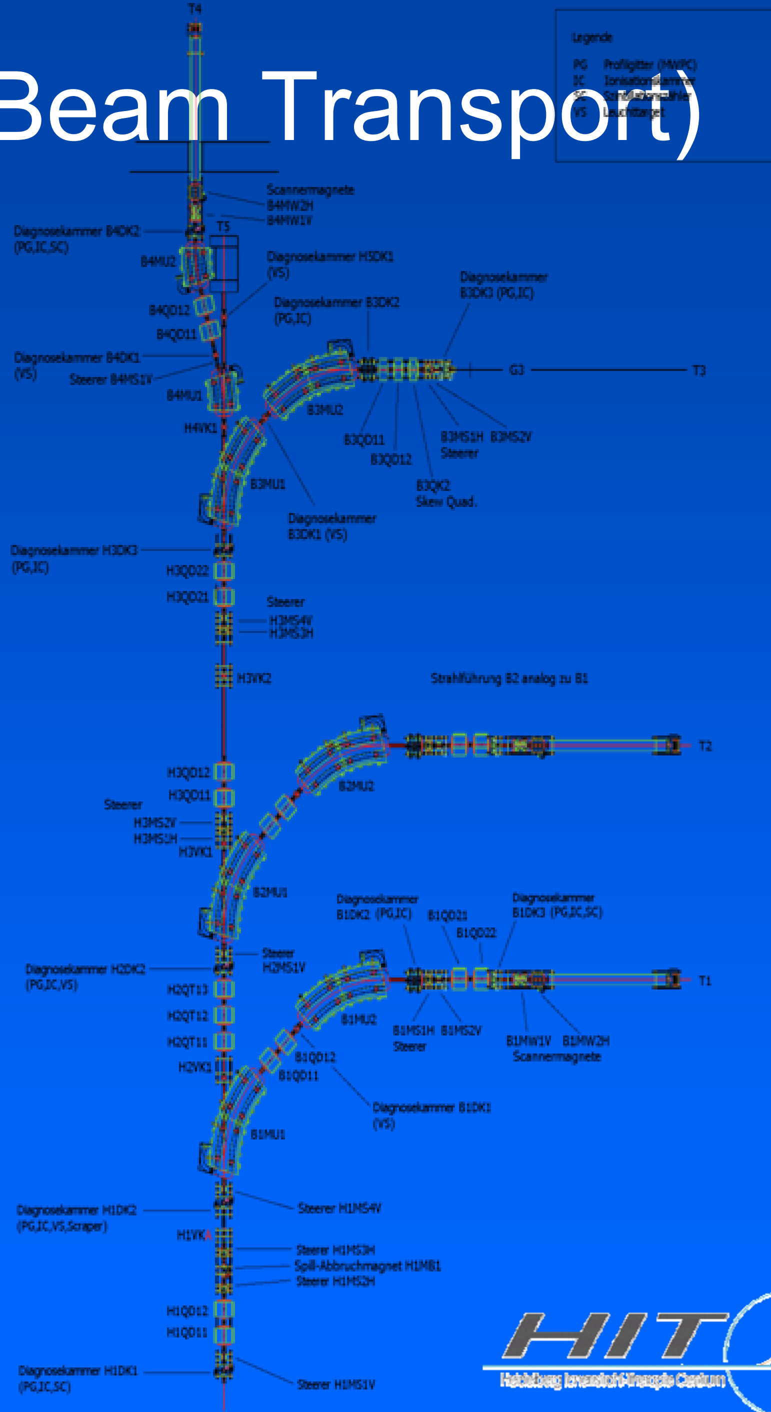




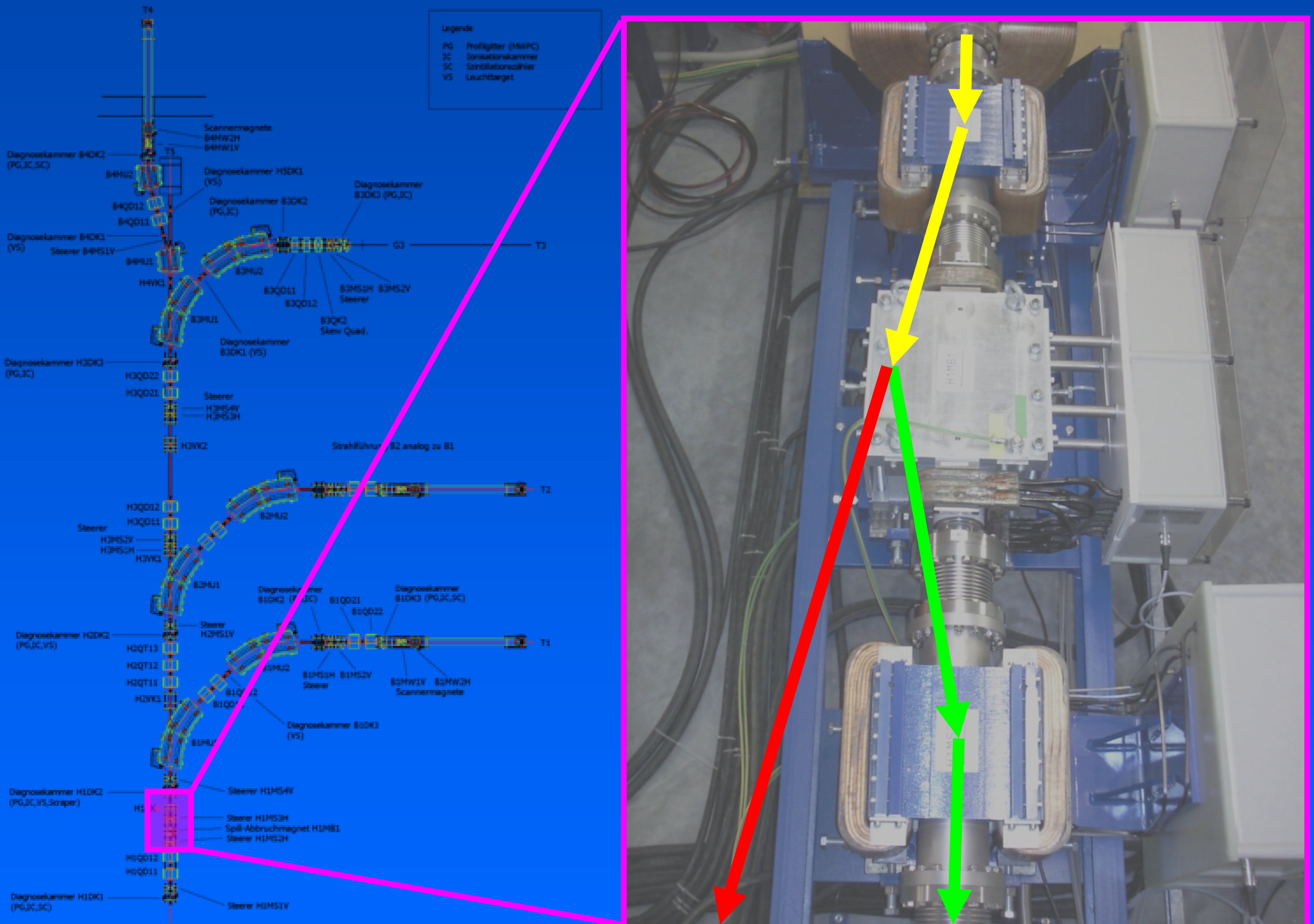


HEBT (High Energy Beam Transport)

- Beam transport
- Beam abort system
- Beam monitoring
- Beam position and width at the isocentre



Spill-Abort-Magnet (SPAM)



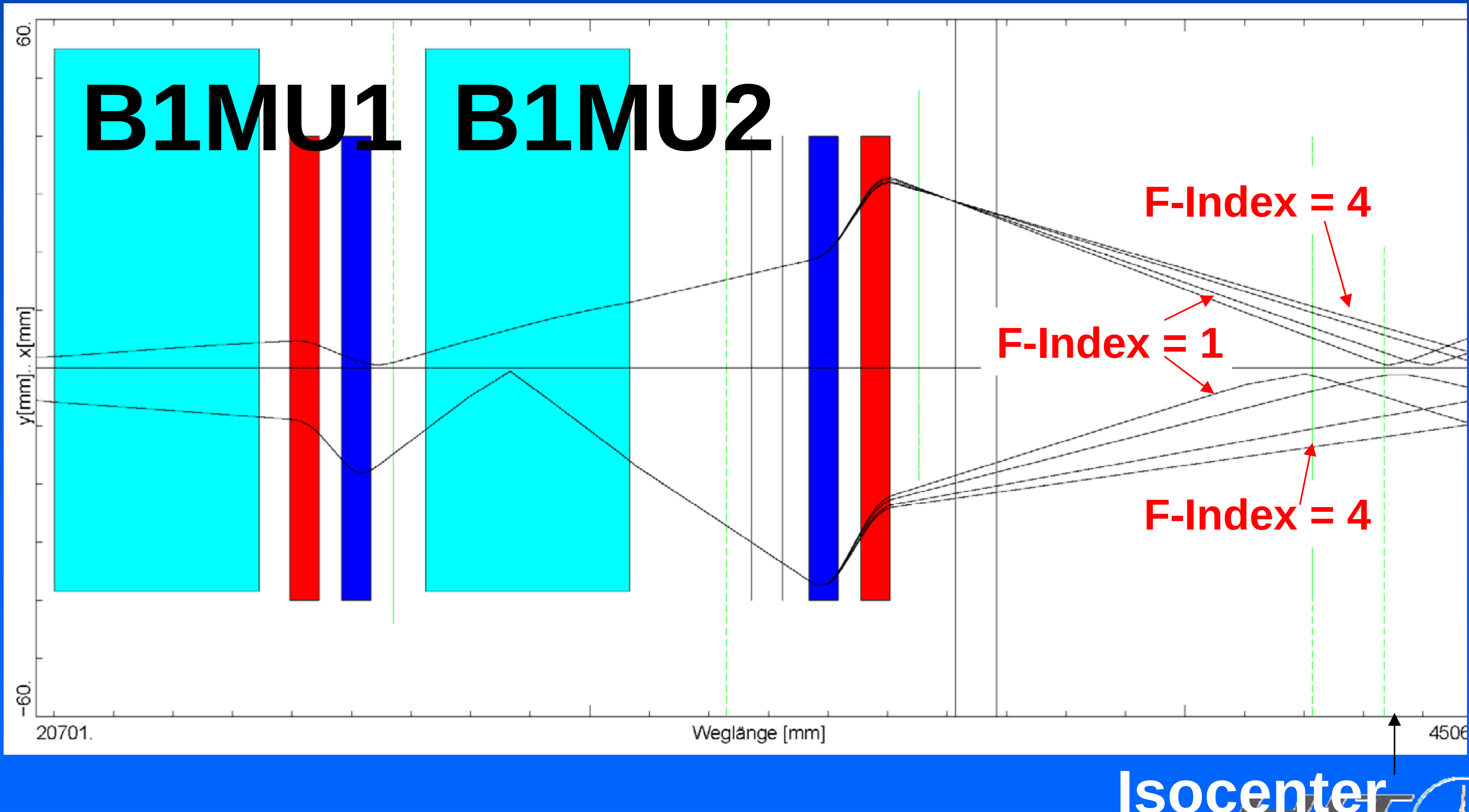
Steerer
(H1MS2H)

SPAM
(H1MB1)

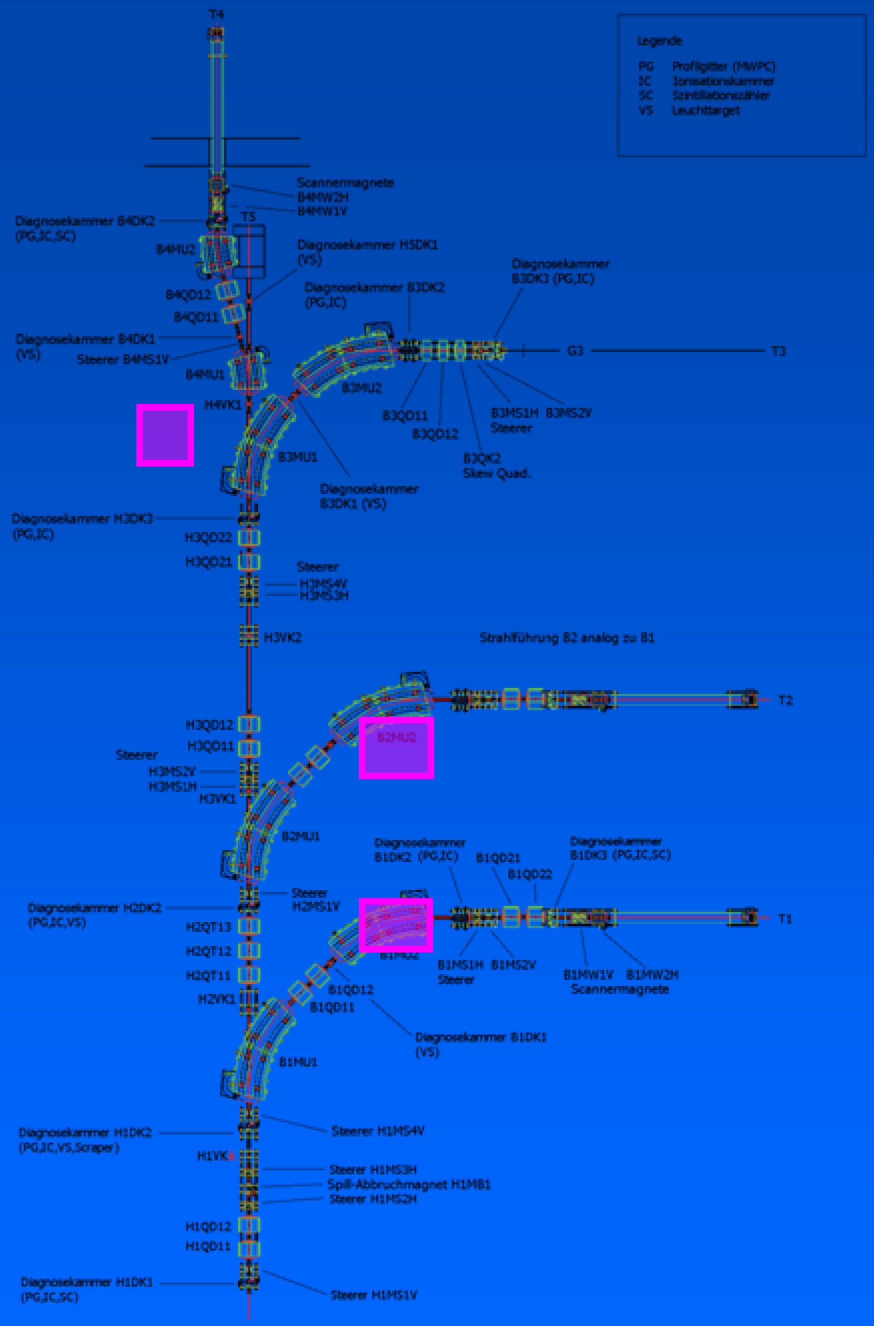
Steerer
(H1MS3H)

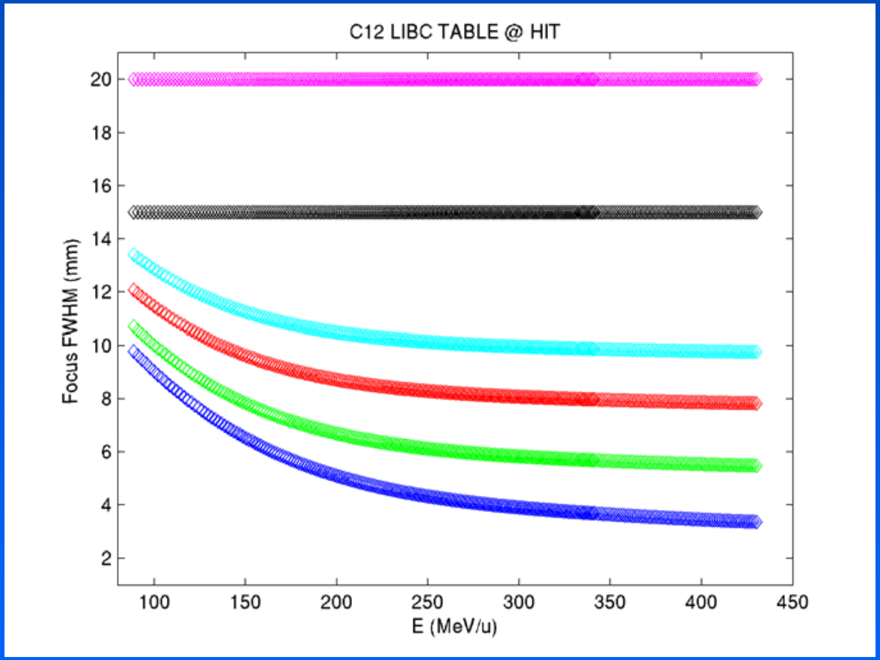
Scraper Medical Caves

Beam Spot Size Setting



Beam Spot Size





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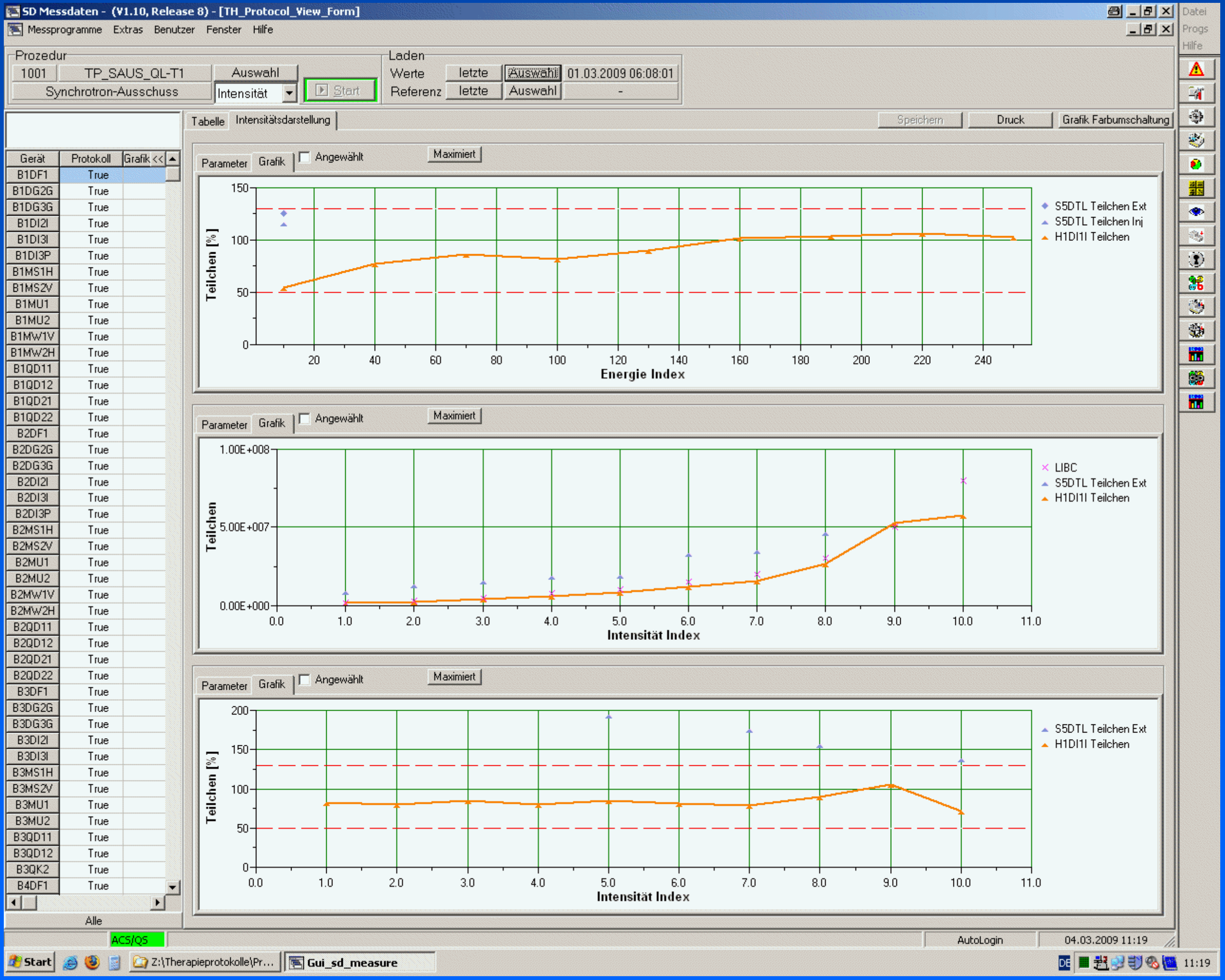
Intensity: Stability 30 Days



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Advantages of a synchrotron

- <u>It works and fulfills all requirements.</u>

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

Disadvantages of a synchrotron

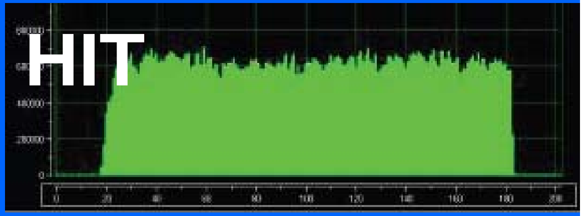
Particle therapy facility

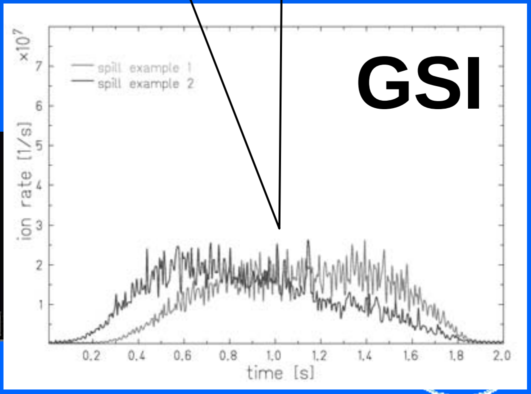
- size of foot print
- initial cost
- (several treatment rooms required)

Objections (no real disadvantages)

- current uniformity
- repetition rate

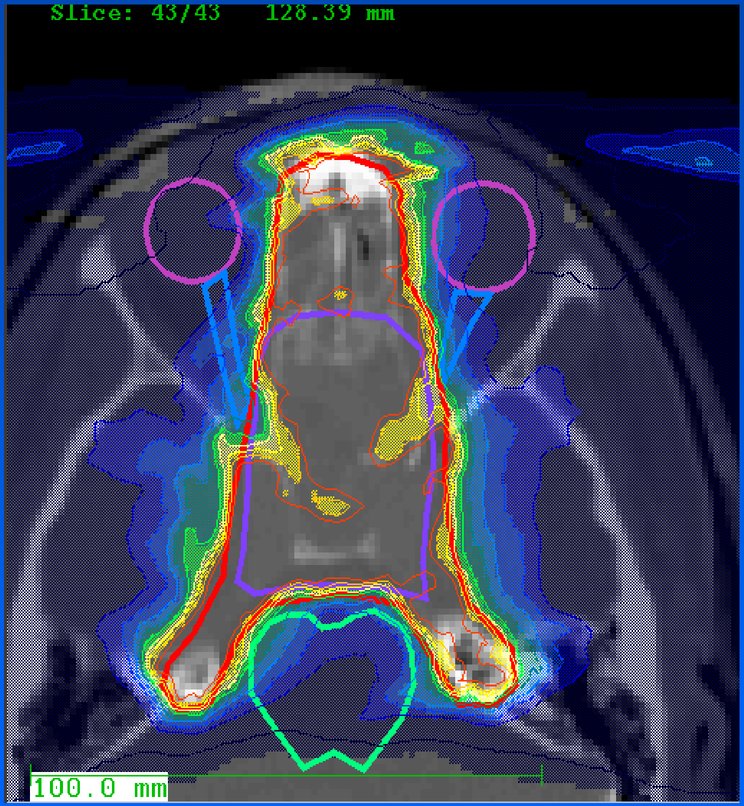
- 440 patients
- each field verified



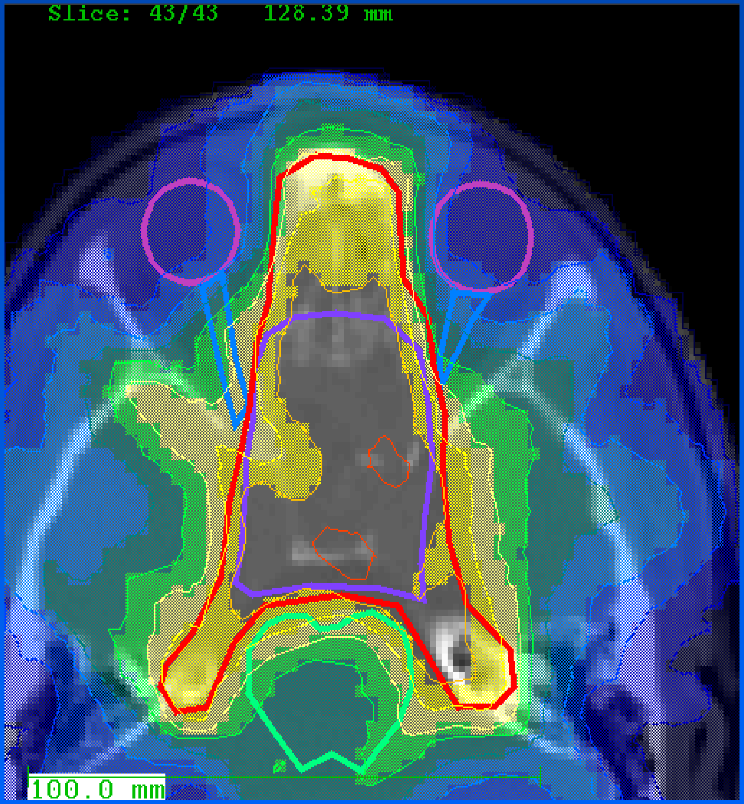


Scanned Carbon vs. Intensity Modulated Photons

scanned carbon 3 fields



IMRT 9 fields

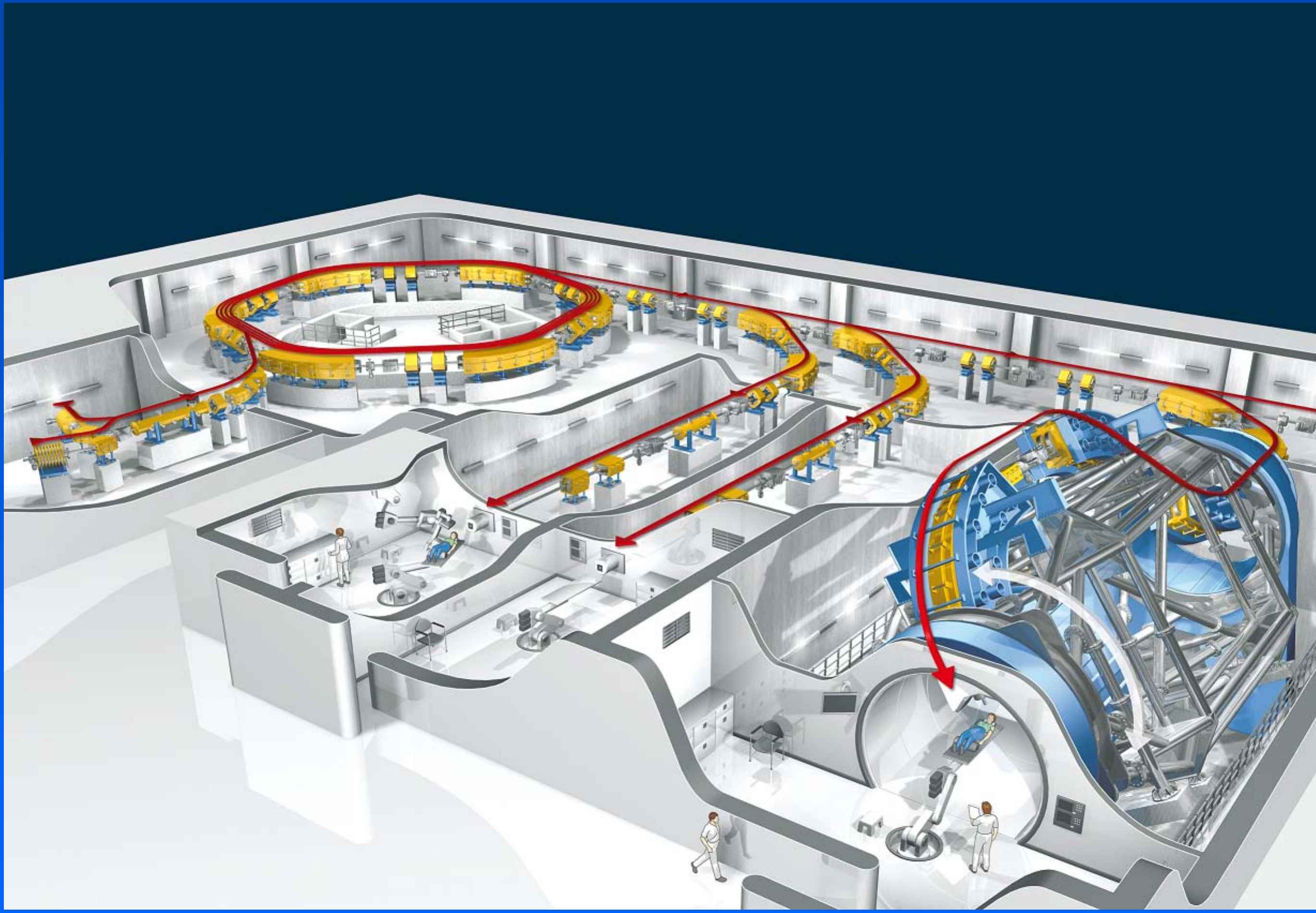


reduced integral dose
steeper dose gradients
less fields
increased biological effectiveness

courtesy O. Jäkel, HIT

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



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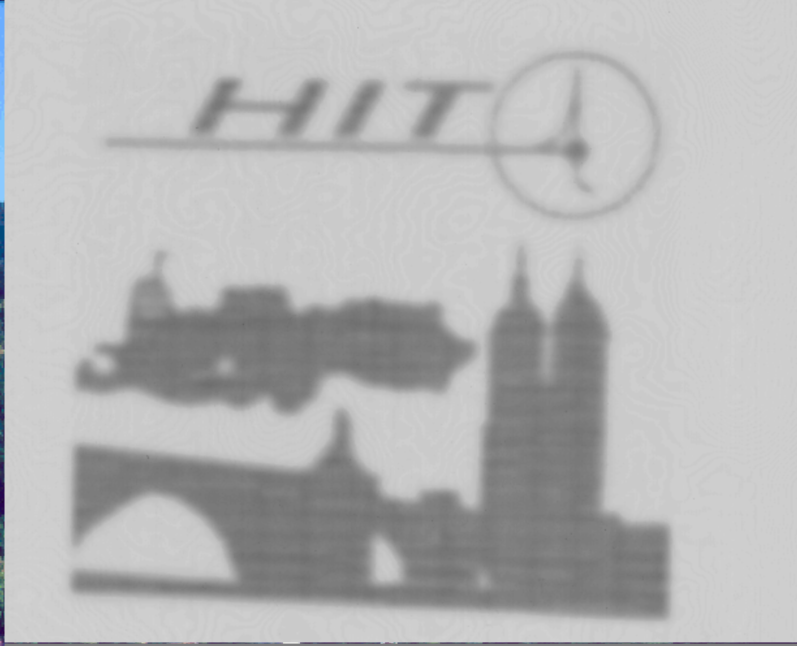

(Intensity modulated raster scan, ^{12}C at 430 Mev/u, October 15th 2007)