HIT
Heidelberger Ionenstrahl-Therapiezentrum

Particle Therapy using Proton and Ion Beams – From Basic Principles to Daily Operations and Future Concepts

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Academic Training Lectures

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HIT Betriebs GmbH am
Universitätsklinikum Heidelberg

http://www.hit-centrum.de

Outline – Part 2

- A proton and ion beam facility in detail: ion sources, linear pre-accelerator, synchrotron and transfer lines
- Aspects of a control system and the linked diagnostic equipment for beam tuning and daily quality checks
- Movable transfer lines: Gantry concepts and realizations for proton and ion beams

Design Considerations

2 ECR sources → RFQ (incl. rebuncher) + IH-DTL → synchrotron + KO exciter → SPAM, 3 treatment rooms (incl. 1 gantry)

- **Ion Sources:**
  - long service periods
  - stable operating conditions
  - ion species: p, He, C and O
  - fast switching between ion species
- **Injector:**
  - compact
  - efficient
  - application of established techniques
- **Circular Accelerator:**
  - variable extraction energy
  - beam accumulation
  - multiple extraction
- **HEBT:**
  - capacity of 1000 patients/a
  - reliable spill abort system
  - optimum dose application by arbitrary beam direction

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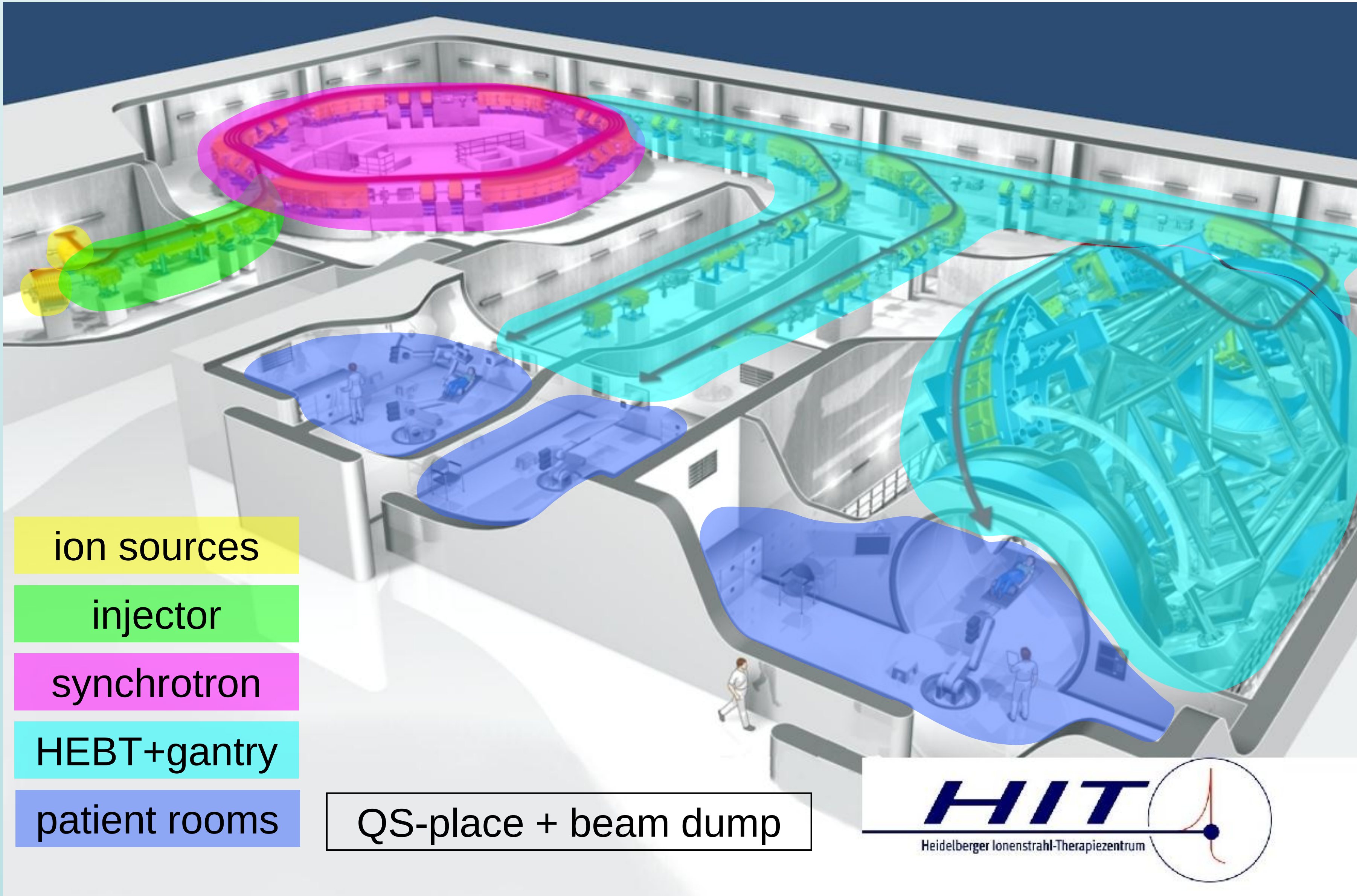
Realisation



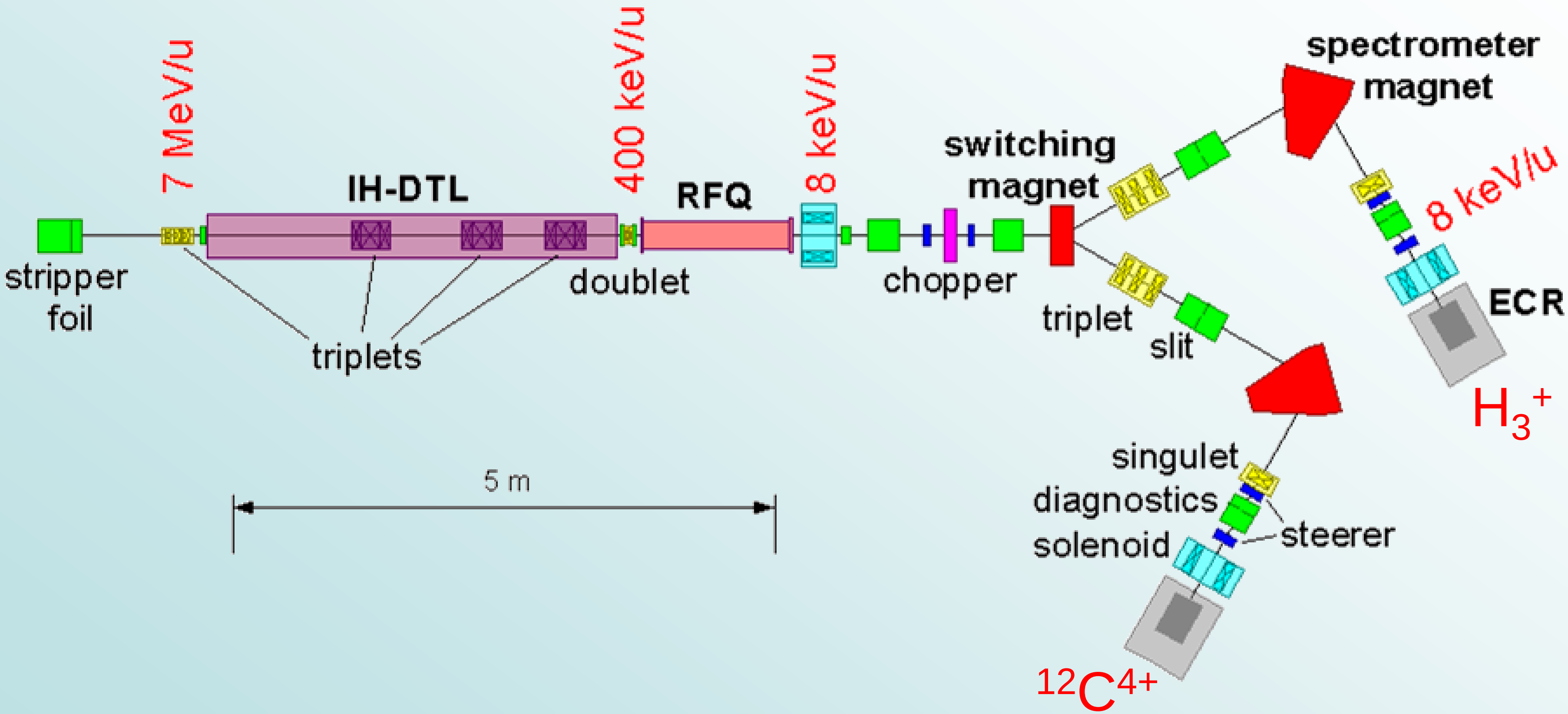
HIT Irradiation Parameters

- **4 Ion Species**:
  protons, helium-, carbon- and oxygen-ions
- **255 Energy Steps**:
  - protons: 48... 221 MeV / u
  - carbon: 89... 430 MeV / u
- **6 Focus Steps (currently 4)**:
  - protons (@E_{max}): 7.8... 20,0 mm
  - carbon (@E_{max}): 3.4... 20,0 mm
- **15 Intensity Steps (currently 10)**:
  - protons: $8.0 \cdot 10^7$... $3.2 \cdot 10^9$ ... $2.0 \cdot 10^{10}$ ions / s
  - carbon: $2.0 \cdot 10^6$... $8.0 \cdot 10^7$ ... $5.0 \cdot 10^8$ ions / s

⇒ 91.800 combinations

(not taking into account beam source, beam target and gantry angle)

7 MeV/u Injector LINAC (216.816 MHz)



LINAC Design Parameters

• injector length	≈ 13 m
• design ion	$^{12}C^{4+}$ (A/q = 3)
• beam energy at exit	7 MeV/u
• operating frequency	216.816 MHz
• macro pulse length behind chopper	≤ 300 μs @ ≤ 5 Hz
• RF duty cycle	≤ 0.5 %
• transverse beam exit emittance	
normalised (95 %)	≈ 0.8 π mm mrad
unnormalised (95 %)	≈ 6.5 π mm mrad
• momentum width at exit	± 0.16 %
• pulse currents behind stripper	≈ 100 eμA $^{12}C^{6+}$

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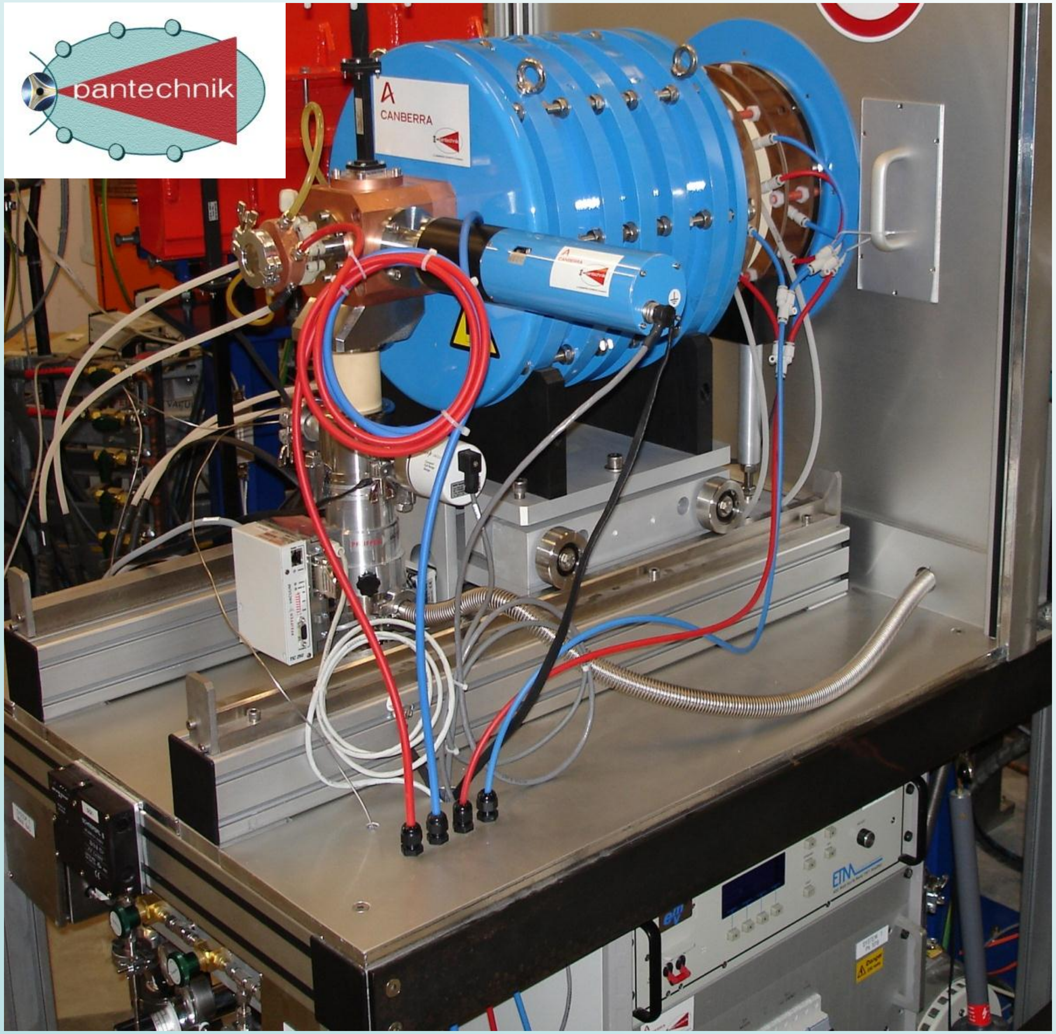
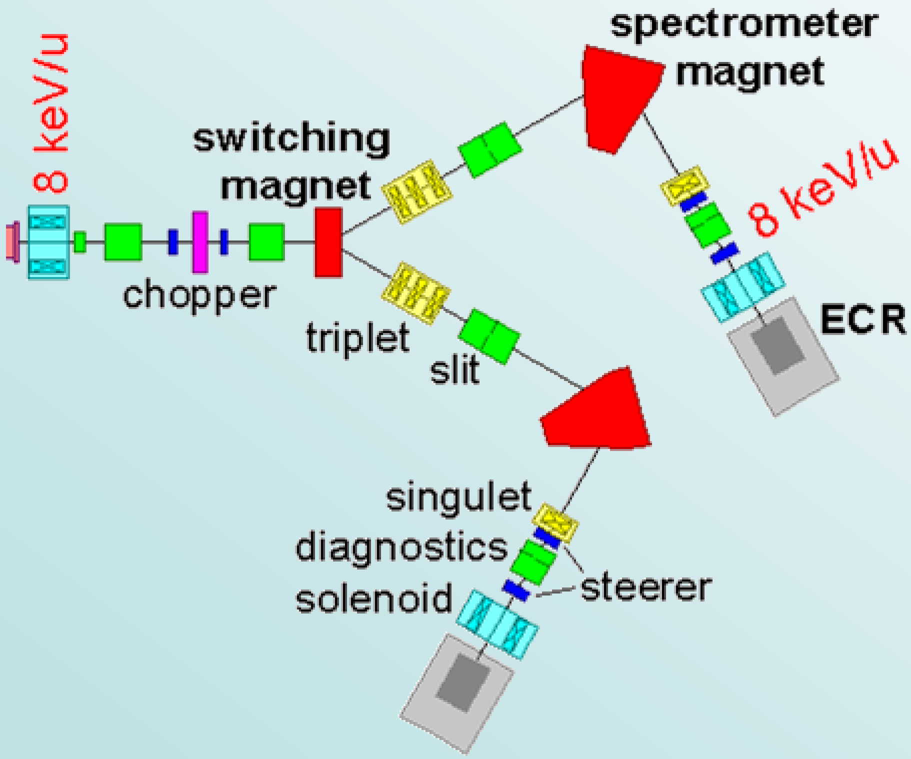
14.5 GHz SUPERNANOGAN



dimensions	L = 324	mm
	∅ = 380	mm
plasma chamber	∅ = 44	mm
total weight	400	kg
thereof permanent magnets	120	kg
B injection	1.2	T
B min	0.45	T
B extraction	0.9	T
B hexapole	1.1	T
length of magnetic mirror	145	mm
max. extraction voltage	30	kV

Solenoids implemented as permanent magnets!

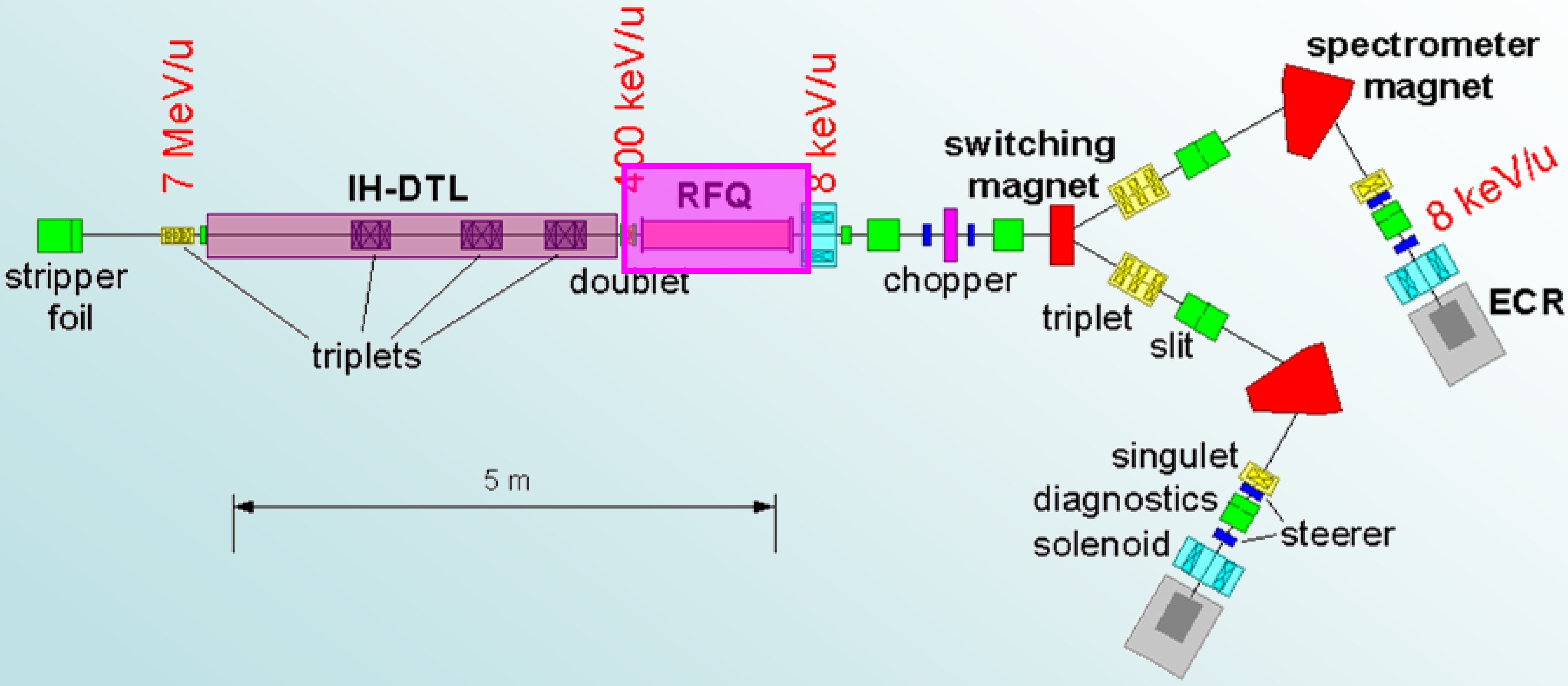
LEBT (Low Energy Beam Transport)



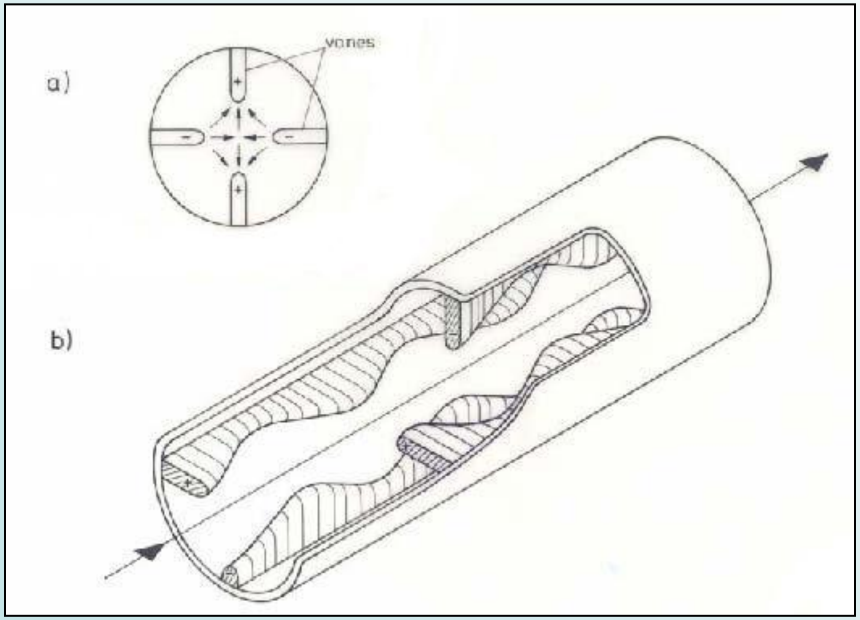
Tasks:

- beam transport from source to RFQ
- selection of ion species (spectrometer)
- beam dilution
- switching between ion sources
- macro pulsing
- beam matching to RFQ-acceptance

RFQ (**R**adio **F**requency **Q**uadrupole)



Radio Frequency Quadrupole Principle



Schematic setup of an RFQ:

a) Cross section with current charge- and field distribution
b) 3D visualisation of the radial modulation of the poles (here „vanes“).

- Linear accelerator by *I.M. Kapchinsky* and *V.A. Teplyakov* (1970)
- RFQ consists of sinusoidally modulated, by π/2 shifted **quadrupole electrodes**
- E-field-component in z-direction
- RFQ configuration causes beam **focusing** in both transverse planes, **bunching** of the beam and **acceleration** of the bunches in z-direction

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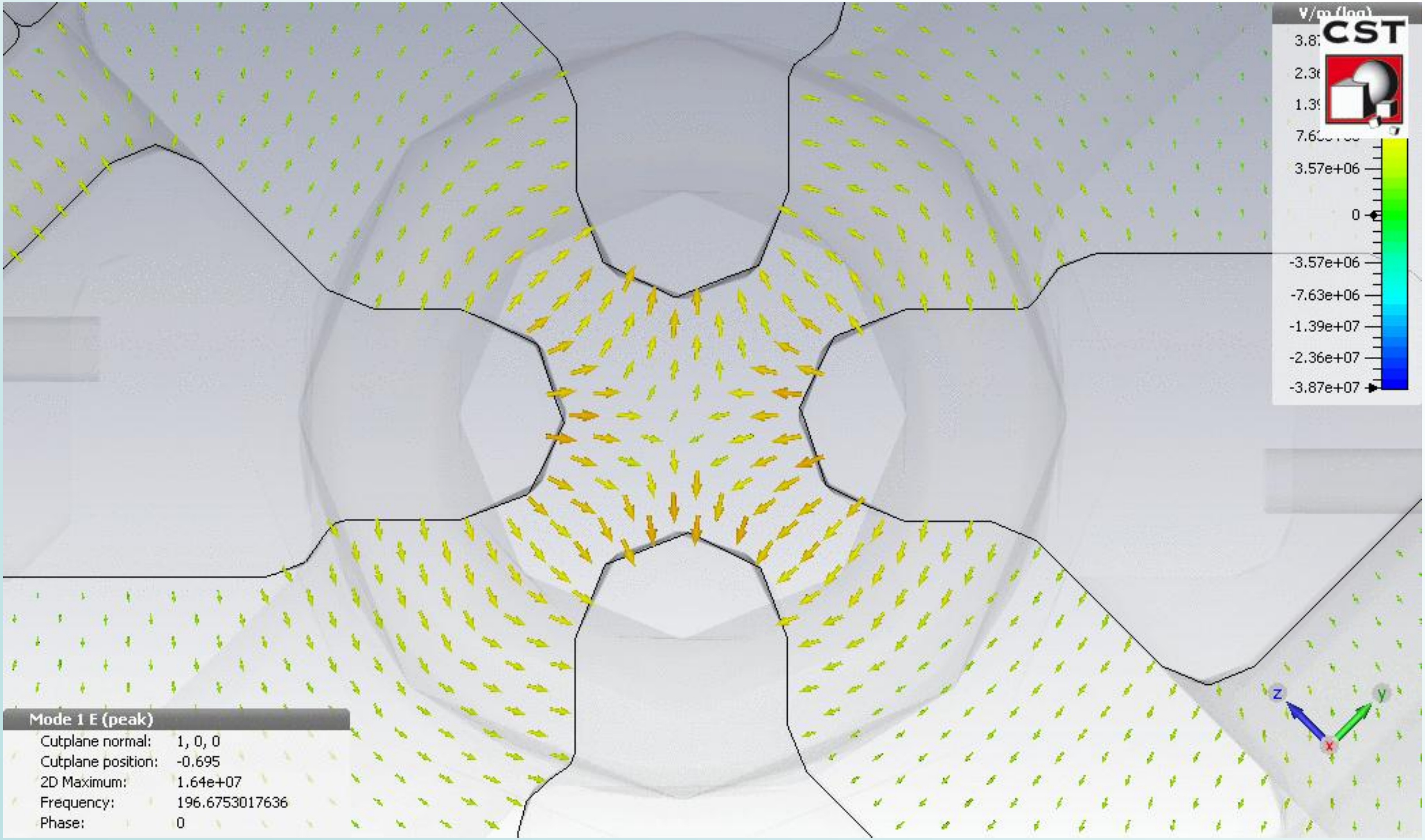
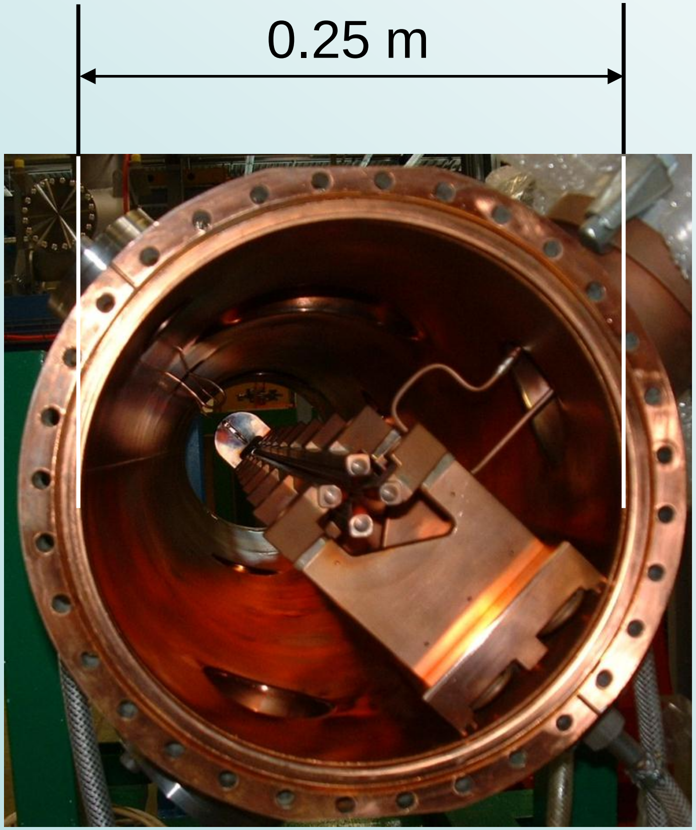
RFQ Quadrupole Field Simulation

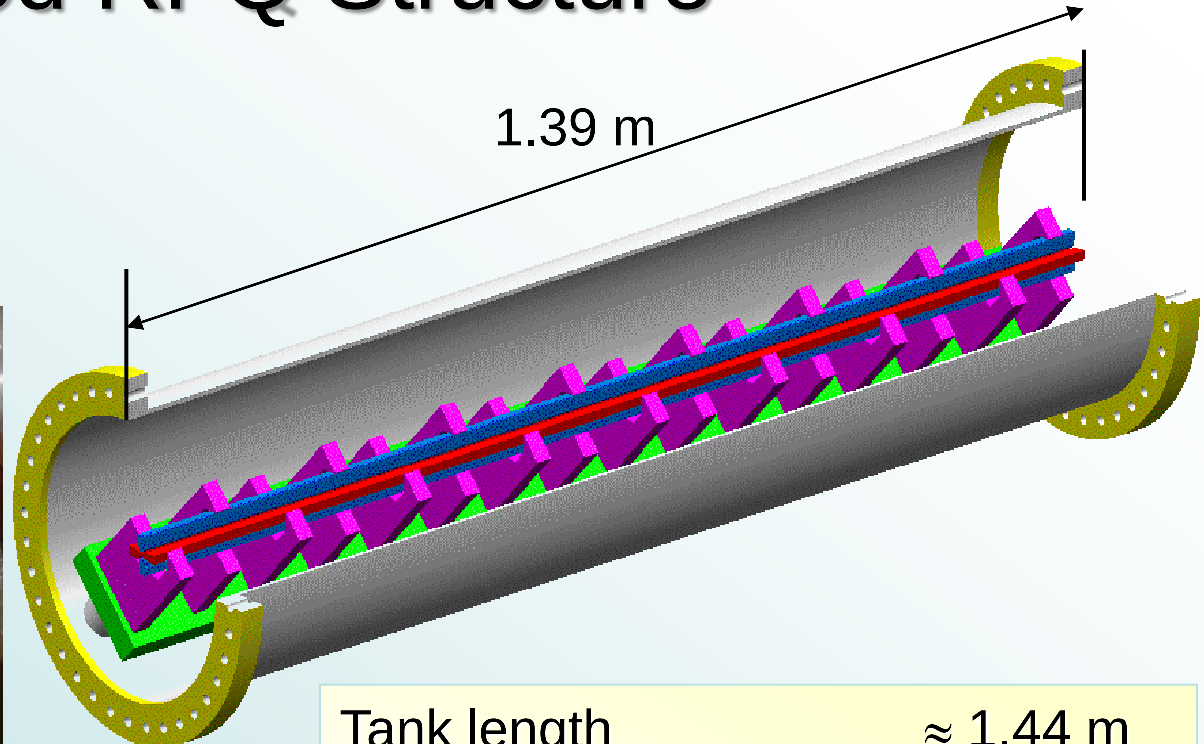


4-Rod RFQ Structure

HIT-RFQ:



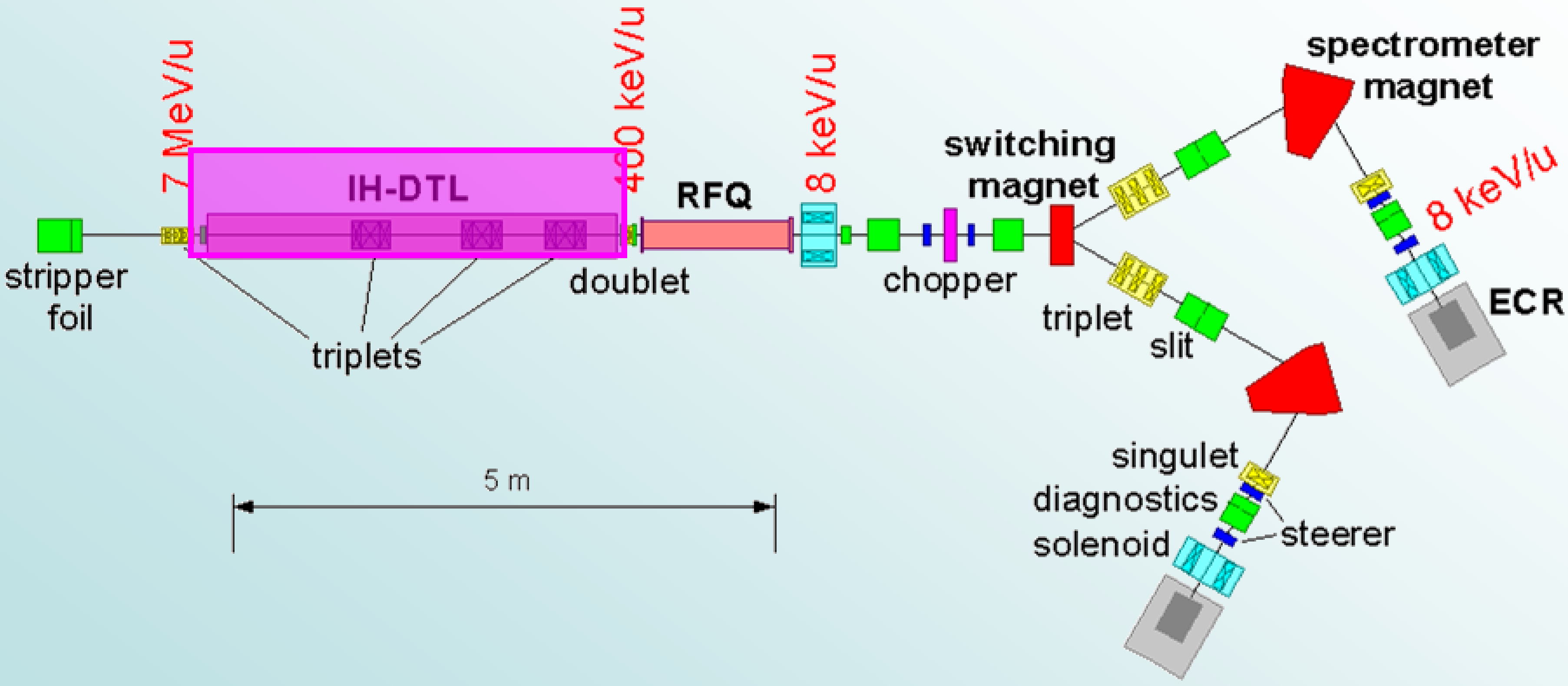
low energy end



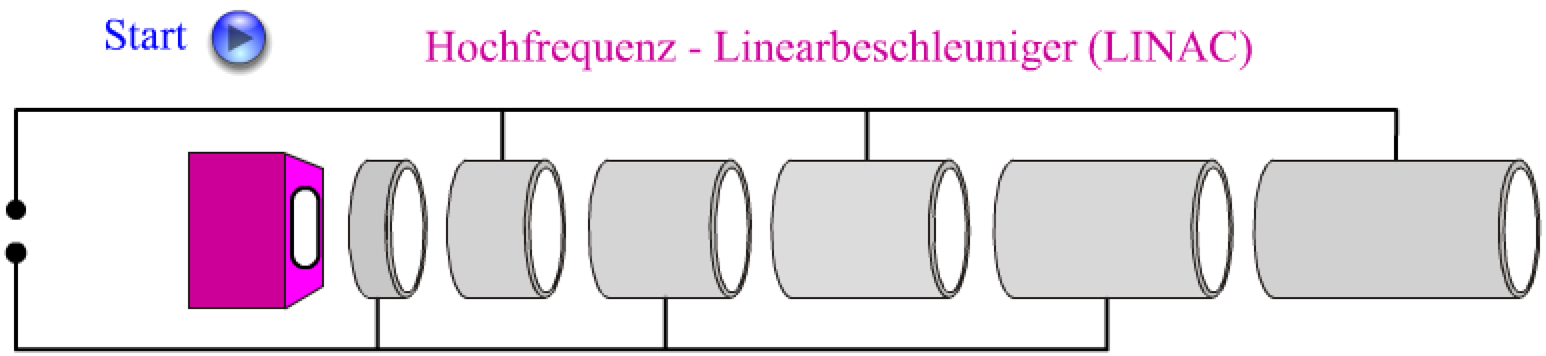
Integrated rebuncher!

Tank length	≈ 1.44 m
Tank diameter	0.25 m
Electrode length	1.28 m
Number of stems	16
Electrode voltage	70 kV
RF-power (pulsed)	≈ 190 kW
Exit energy	400 keV/u

IH-DTL (**I**nterdigital **H**-Mode **D**rift **T**ube **L**inac)



Linear accelerator



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

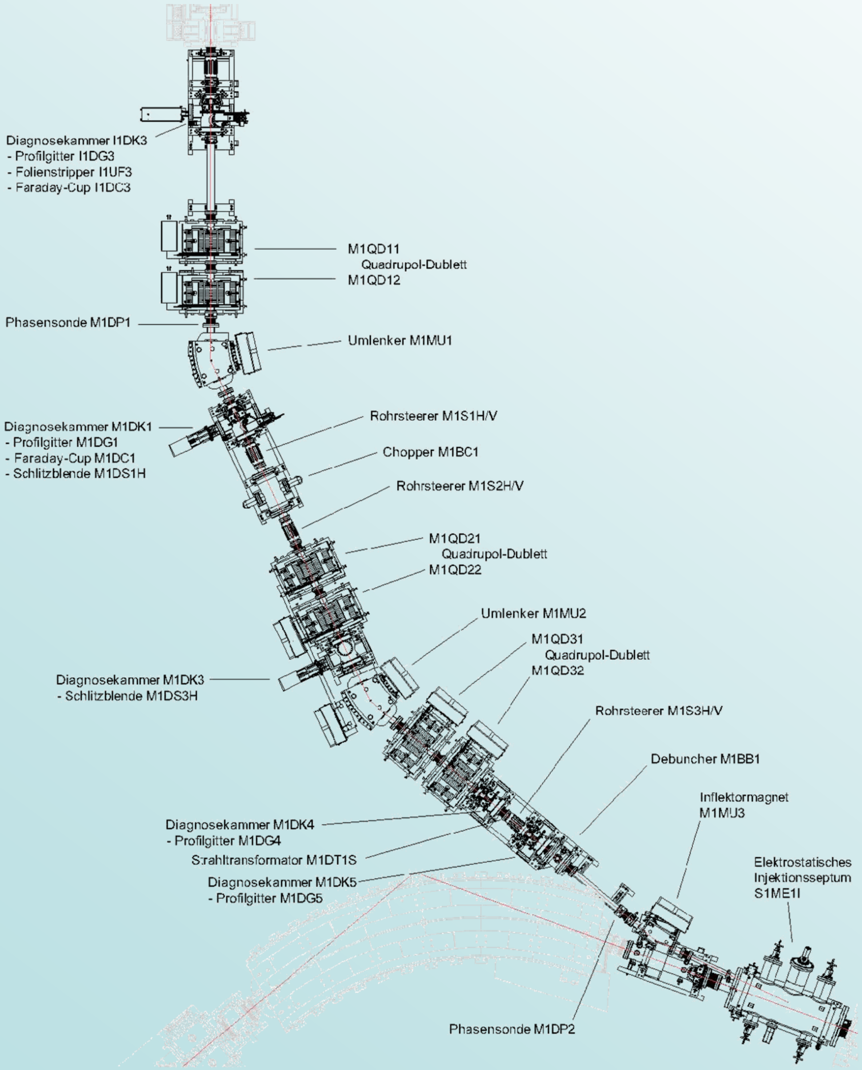
IH Drift Tube Linac

Exit energy	7 MeV/u
Number of gaps	56
Integrated magnetic quadrupole triplett lenses	3
Tank length	≈ 3.77 m
Tank height (inner)	≈ 0.34 m
RF pulse power	≈ 1 MW
Eff. total voltage	21 MV
Eff. average field gradient	5.7 MV/m
Drift tube aperture ∅	12–16 mm
Triplet lenses ∅	20 mm
Norm. transverse acceptance	1.3 π mm mrad
RMS emittance growth (tr./long.)	10 / 10 %
Momentum width at exit	±0.16 %

high energy end

low energy end

MEBT (**M**edium **E**nergy **B**eam **T**ransport)



Tasks:

- Beam transport to synchrotron
- Verification of LINAC beam properties
- Charge separation behind foil stripper (“spectrum”)
- Beam pulse chopping (macro pulse $\rightarrow$ injection pulse)
- Optimisation of the LINAC beam energy sharpness (“debunching”)
- Optimisation of transverse beam properties for injection
- Injection of the LINAC beam into the synchrotron

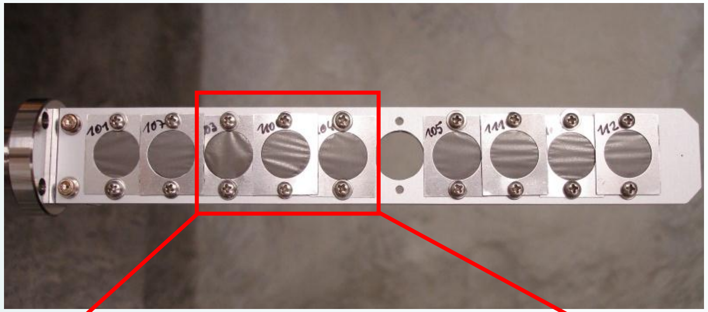
Foil Stripper in the MEBT

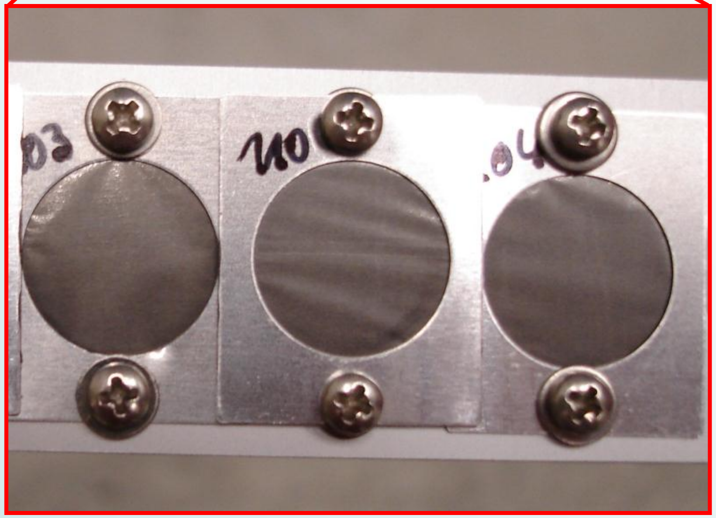
H_2^+, H_3^+
$^4He^{2+}$
$^{12}C^{4+}$
$^{16}O^{6+}$

→ foil stripper →

p
$^4He^{2+}$
$^{12}C^{6+}$
$^{16}O^{8+}$

target support with hor. installation:

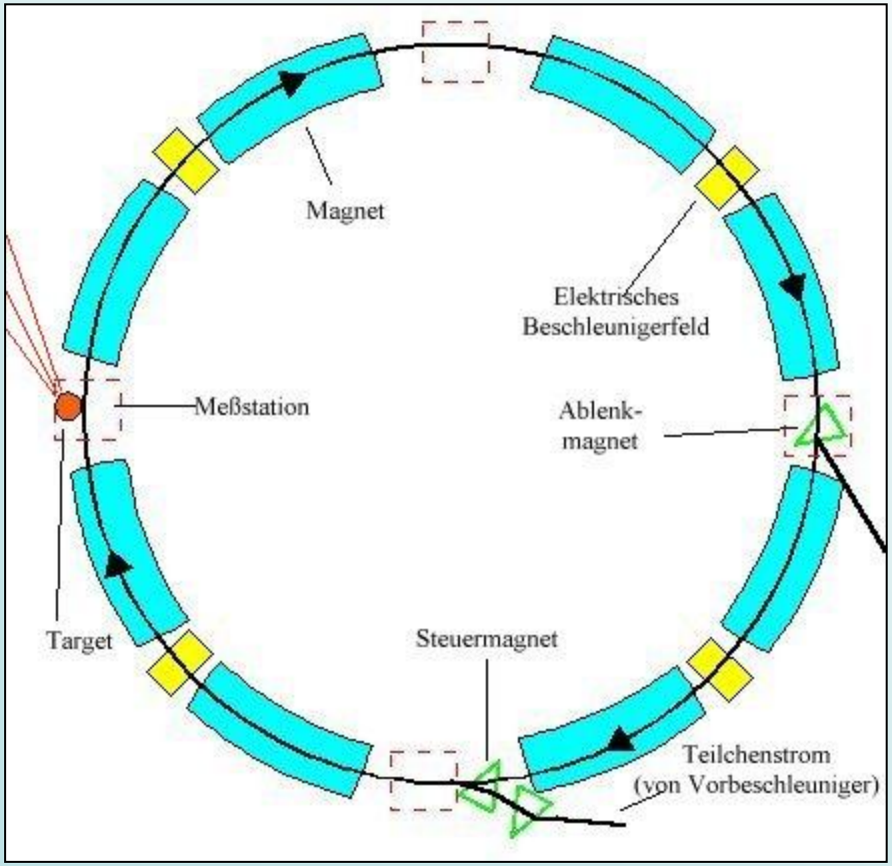




Parameters:

Foil positions:	10
Support material:	aluminium
Foil material:	carbon (100 µg/cm²)
Foil thickness:	0.5 – 1 µm
Foil diameter:	15 mm
Beam diameter:	5 mm
Positioning accuracy:	±0,5 mm

Synchrotron



- **Circular accelerator** by *V.I. Veksler / E.M. McMillan* (1945) / M. Oliphant (1952)
- Constant radius, variable B-field
- **Frequency variable** RF cavity
- **Synchronous** ramping of magnetic fields and RF frequency (beam energy)
- Particles perform **betatron oscillation** around orbit

Tune Q:

$$Q \equiv \frac{\Delta\Psi}{2\pi}$$

$$\Delta\Psi : \text{phase advance}$$

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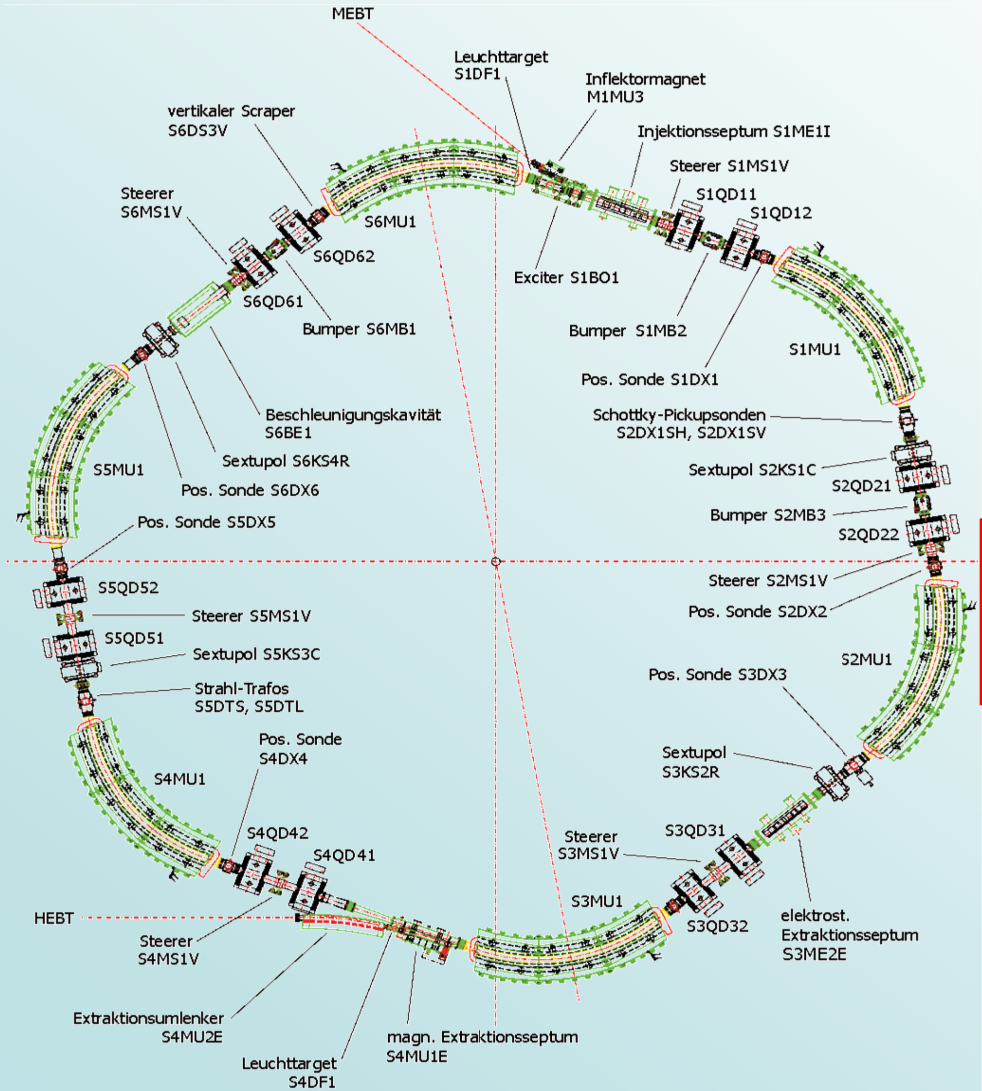
HIT Synchrotron



- Circumference: 64.986 m
- Magnetic rigidity $B\rho$: 1.1 – 6.5 Tm

A beam with a magnetic rigidity of 1 Tm passing through a magnetic field of 1 T experiences a deflection with a radius of 1 m!

$$B\rho = \frac{p}{q} \qquad p: \text{momentum},\ q: \text{charge}$$

Devices:

- 6 dipoles
- 12 quadrupoles
- 4 sextupoles
- ...

Injection

Basic Rule of Injection:
A phase space volume occupied by particles may not be refilled without loosing the particles already held in the volume.

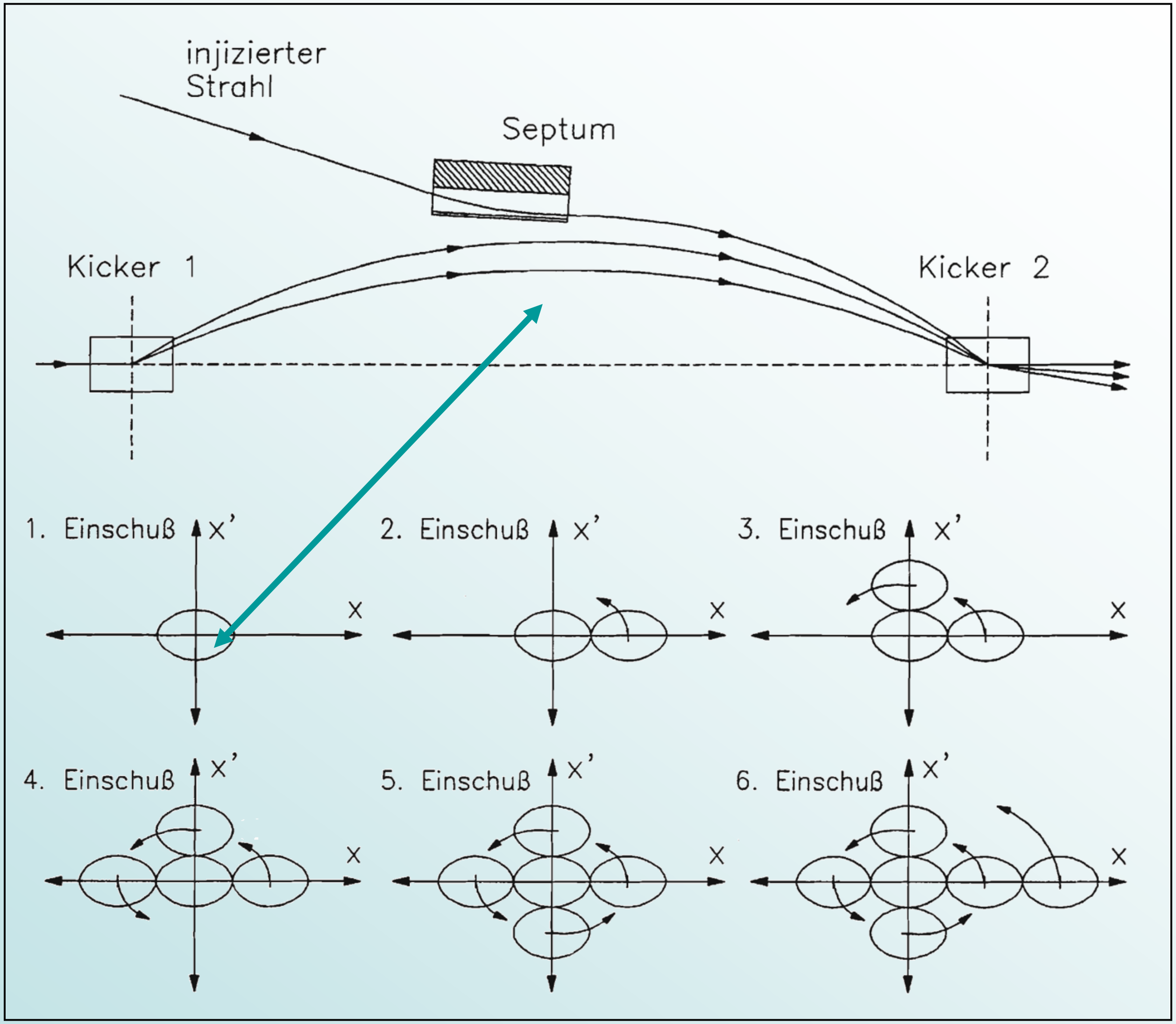
Injection Methods:

- **Single turn injection**
  - Inflection by fast kicker magnet
  - Small emittance
  - No beam accumulation
- **Stripping injection**
  - Charge reversal by stripping foil
  - Same dipole for circulating (H^-) and injected beam (p)
- **RF stacking**
  - Beam accumulation in the longitudinal phase space
- HIT → **Multi turn injection (transverse stacking)**
  - Dynamic local closed orbit perturbation (bumper magnets)
  - Beam accumulation
  - Large horizontal emittance (in plane of accumulation)

Multiturn Injection

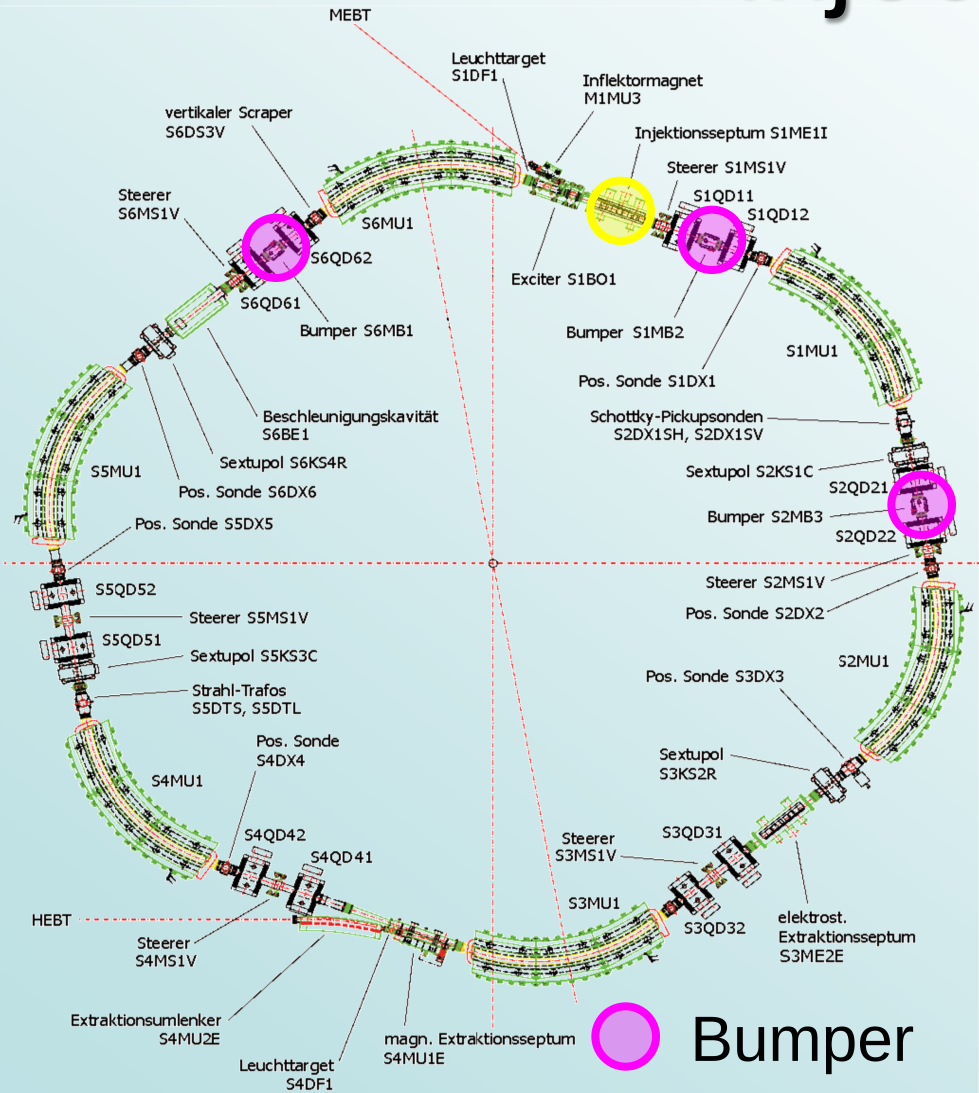
Local orbit bump:

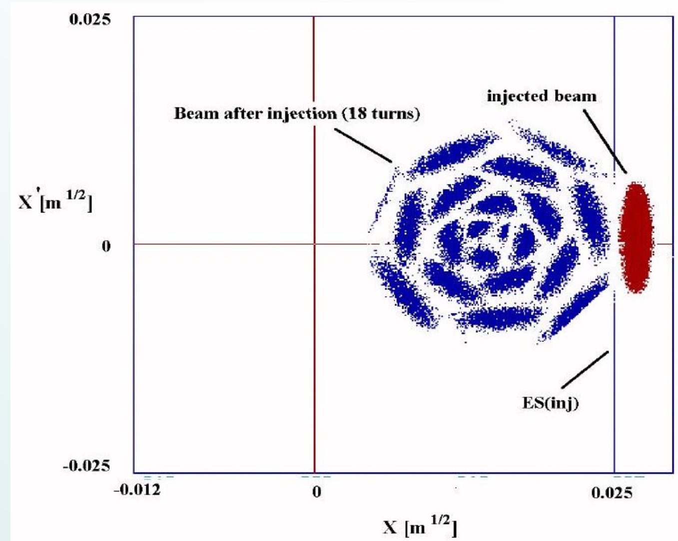
Transverse stacking process in the phase space (Q = i+0,25):



Source: K. Wille, *Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen*

Injection





Bumper

Septum

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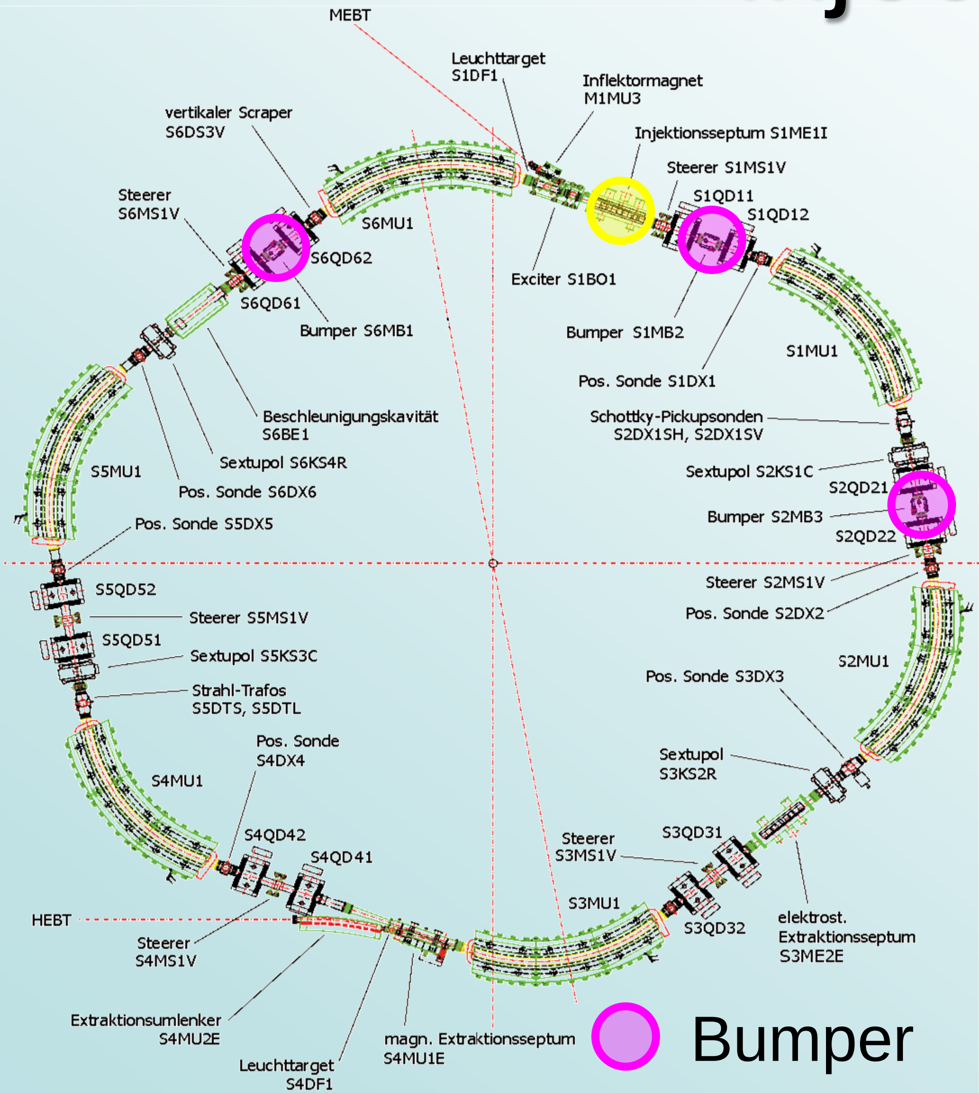
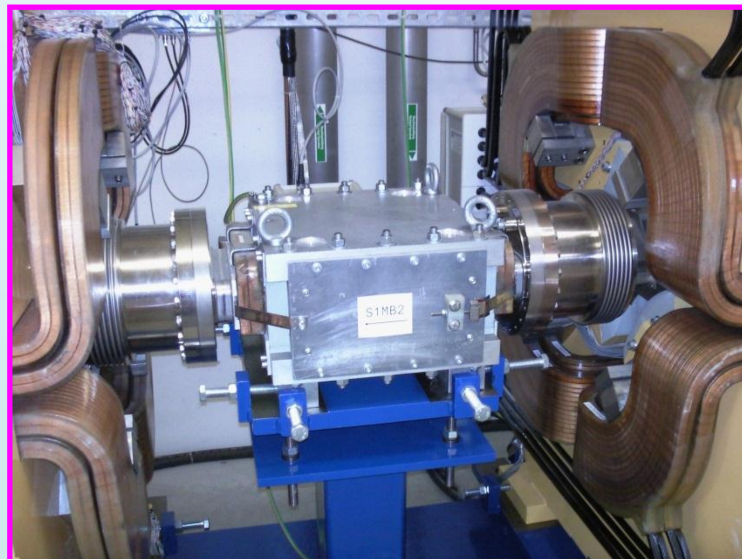
Injection





Bumper

Septum

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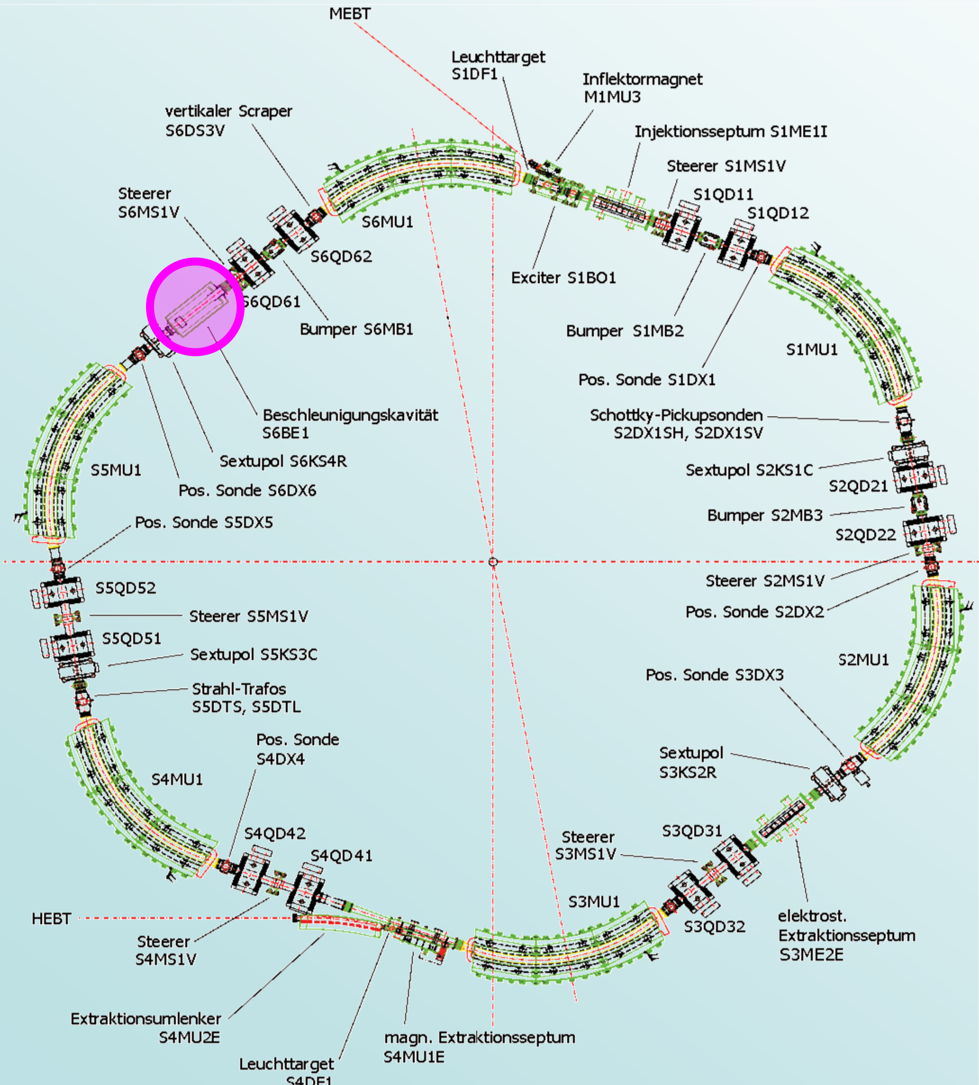
Acceleration



2-Step Process:

- RF capture (bunching) at 2[nd] harmonics
- Acceleration up to desired end energy

Device:

- MA loaded cavity
- Working frequency: 1-7 MHz

$$f_{res} = f_{res}(L);\ L = L(\mu);\ \mu = \mu(H)$$

- Max. RF voltage: 2.5 kV
- Power: 6.4 kW
- Supplier: Hitachi

Extraction

Extraction Methods:

- **Fast extraction**
  - Fast deflection within one revolution by fast kicker magnet (single turn extraction)
  - RF synchronicity (variation of deflection field between 2 bunches)
- **Slow resonant extraction**
  - Generation of an amplitude dependent instability (separatrix), tune shift close to 3rd order *resonance*
  - Resonant excitation (systematic, slow transition into instability)

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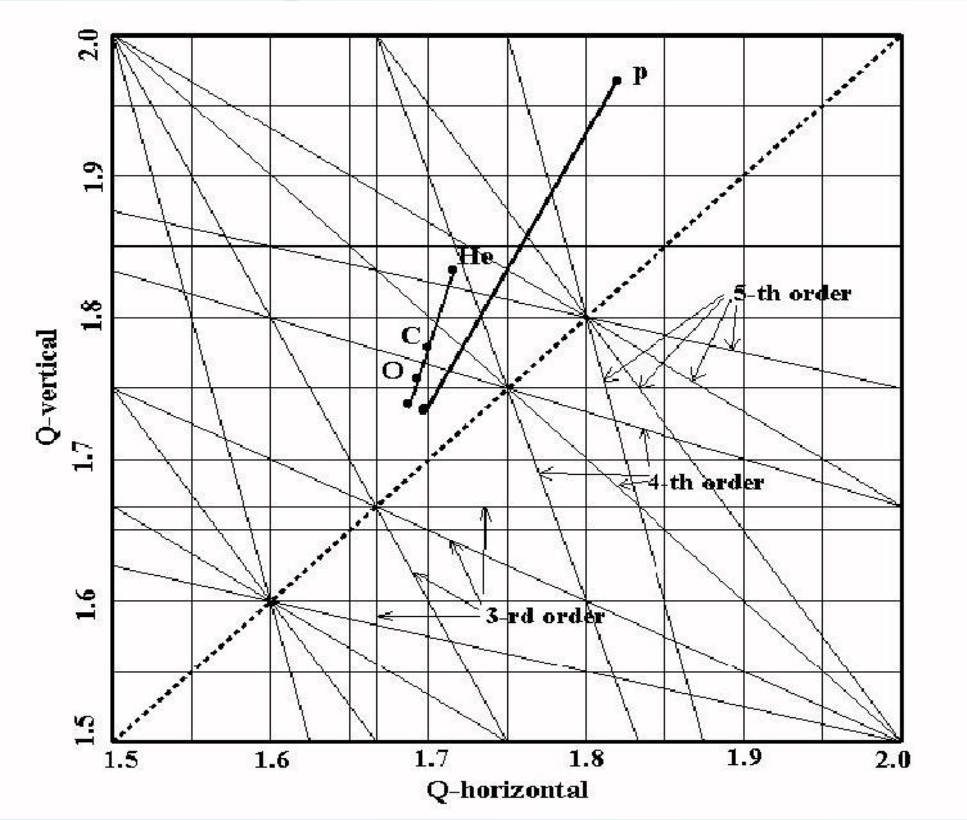
Tune and Resonances

Tune Diagram:



Resonances occur at
1/1, 1/2, 1/3,... integral tunes:

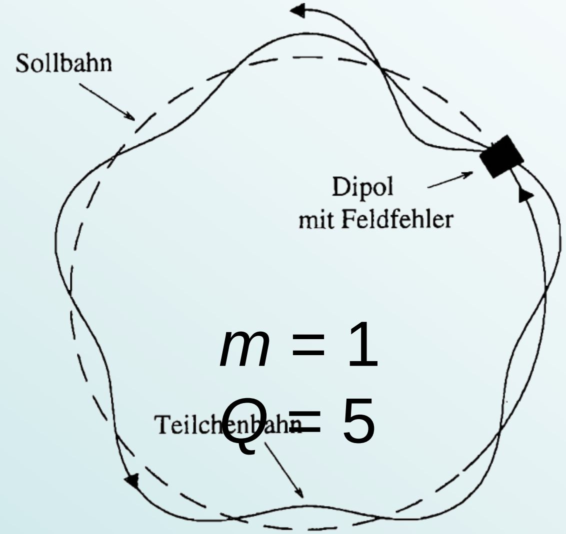
$$m\,Q_x + n\,Q_y = p$$

$$m, n, p = \text{integers}$$

$$m + n = \text{order}$$

Especially "dangerous" are low orders (1-5).

Example:



$m = 1$

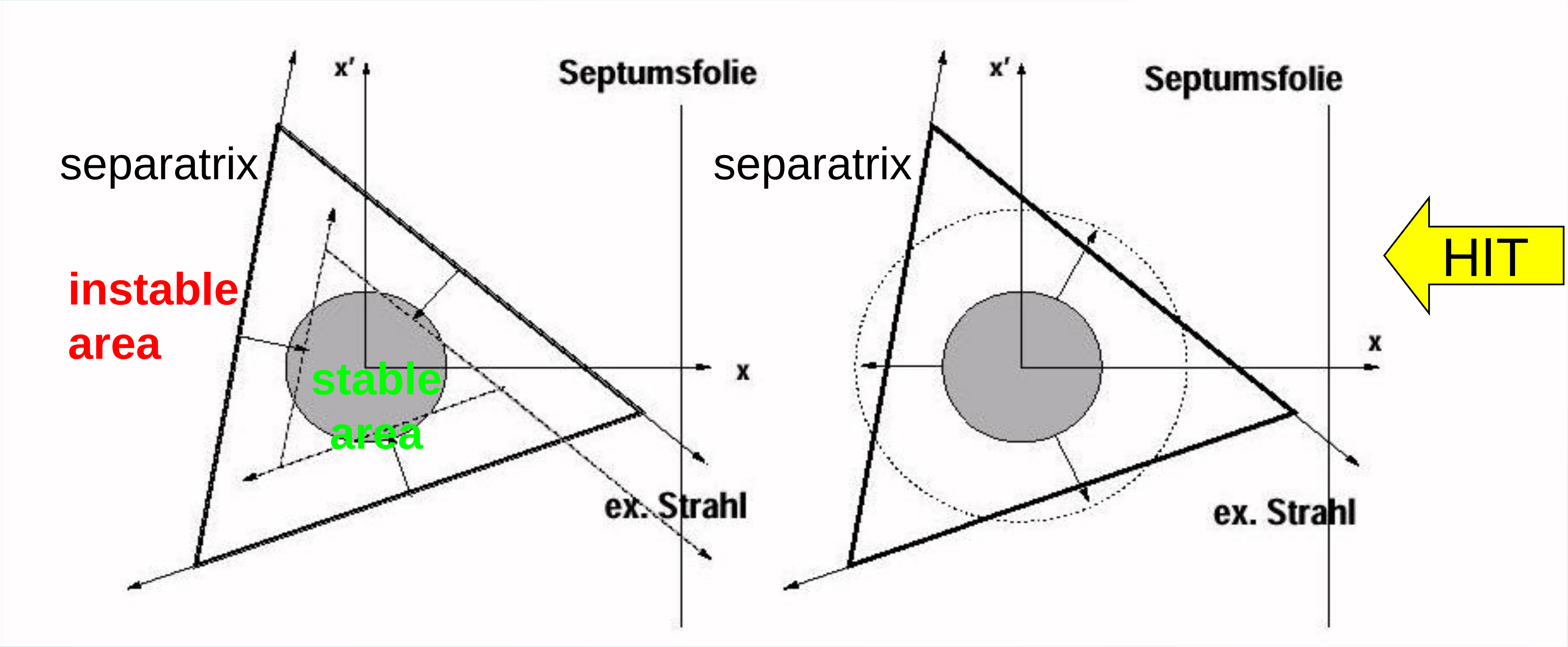
$Q = 5$

Slow Extraction

Two Types:

Diminishing of separatrix:

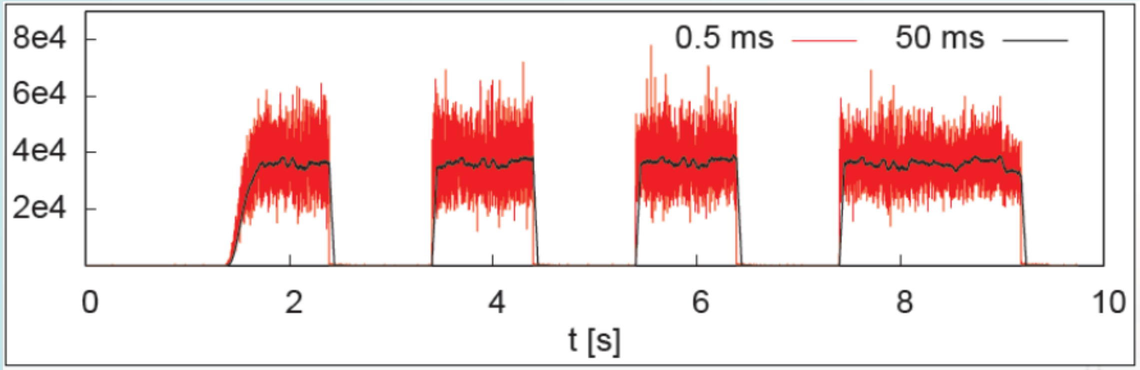
Blowing up emittance (knock out extraction):



Source: PhD thesis, *F. Albrecht*, 1996

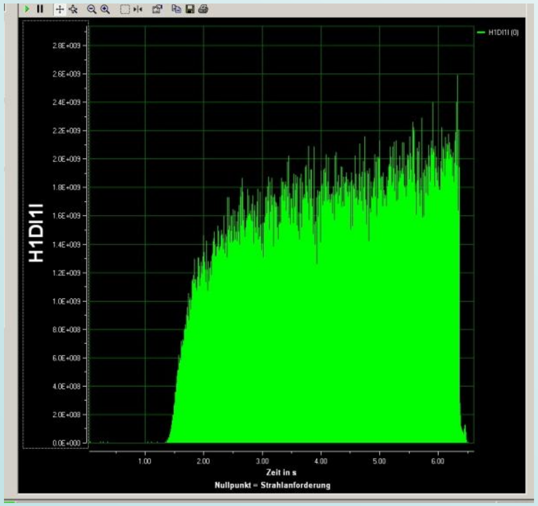
KO Extraction

- **Principle**
  - Resonant excitation of betatron frequency with RF exciter
  - Constant separatrix
- **Advantages**
  - Slow extraction (e.g. 100ms … 10s)
  - Constant ion optics during extraction
  - Possibility of spill interruption and multiple extraction („spill pause“)



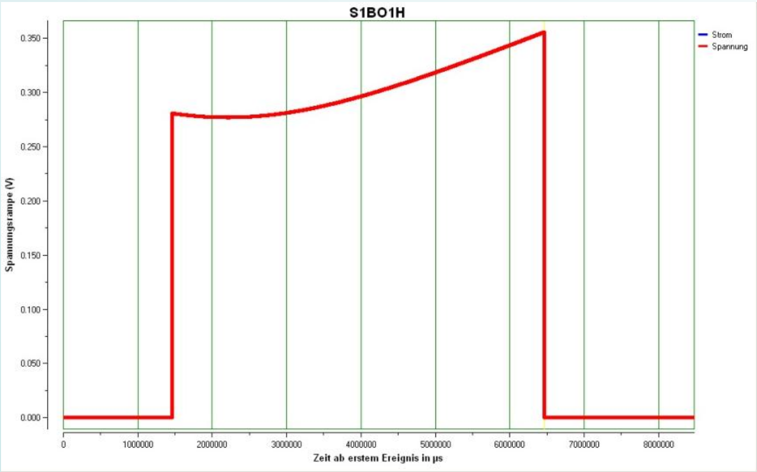
Spill Shape Optimisation

Before optimisation:



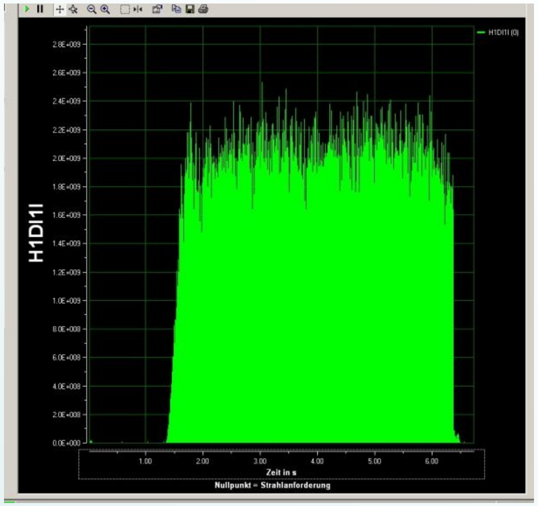
Ionisation chamber

Excitation function with 8 energy independent parameters:



KO exciter amplitude vs. extraction time

After optimisation:



Ionisation chamber

Shaping of spill structure via active control of the excitation amplitude of the RF-exciter (“DIC”) → see part 3

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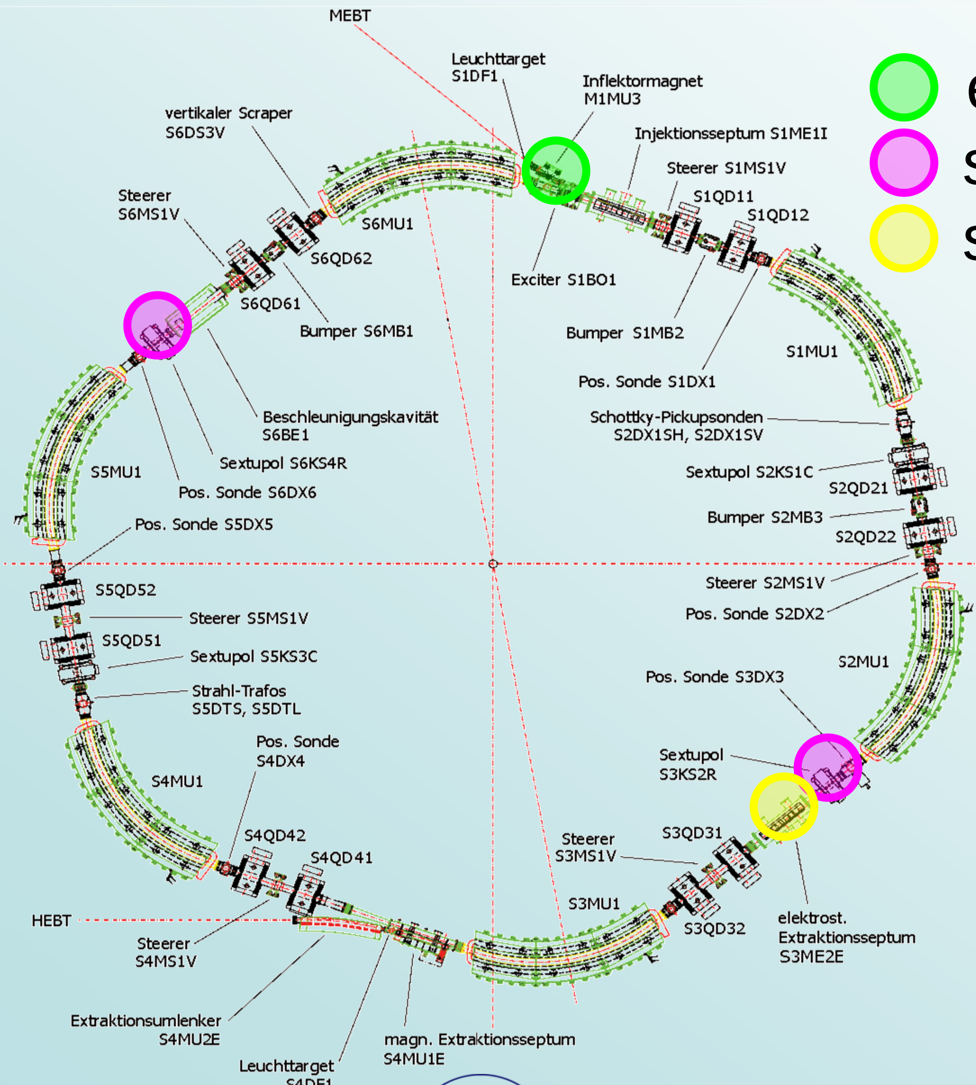
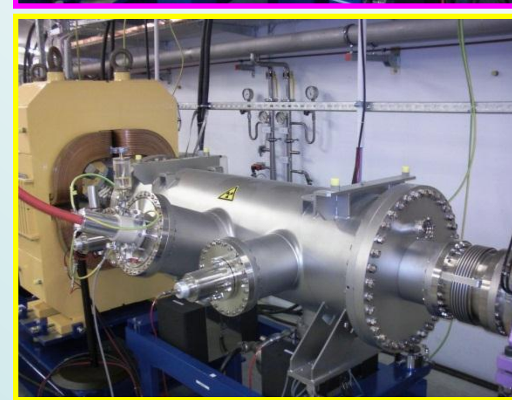
HIT Extraction Devices



- exciter
- sextupole
- septum



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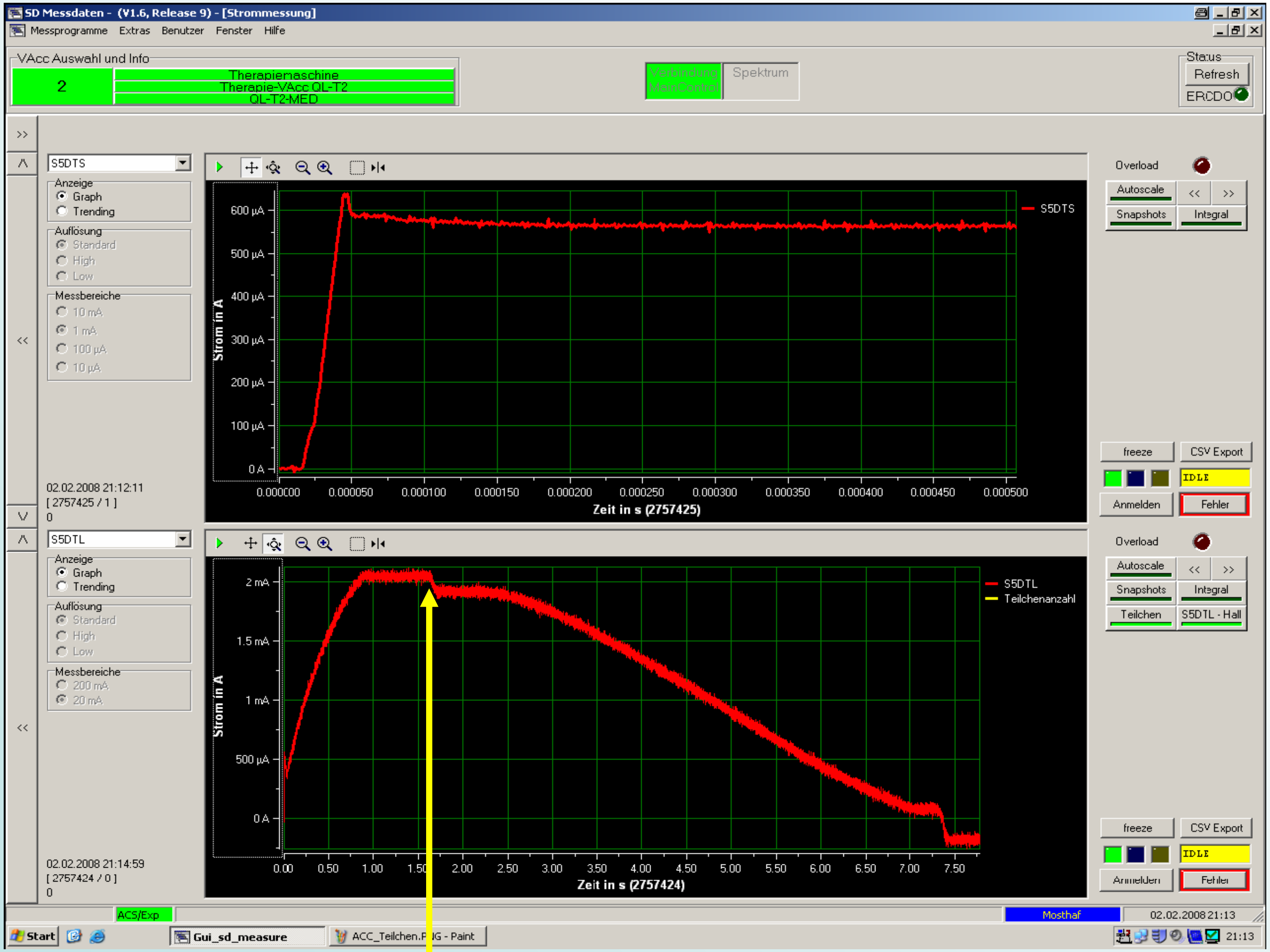
HIT Synchrotron Cycle

Current Variation in Time:

Injection
(S5DTS, 0...500 µs)

RF capture, acceleration and extraction
(S5DTL, 0...7.5 s)

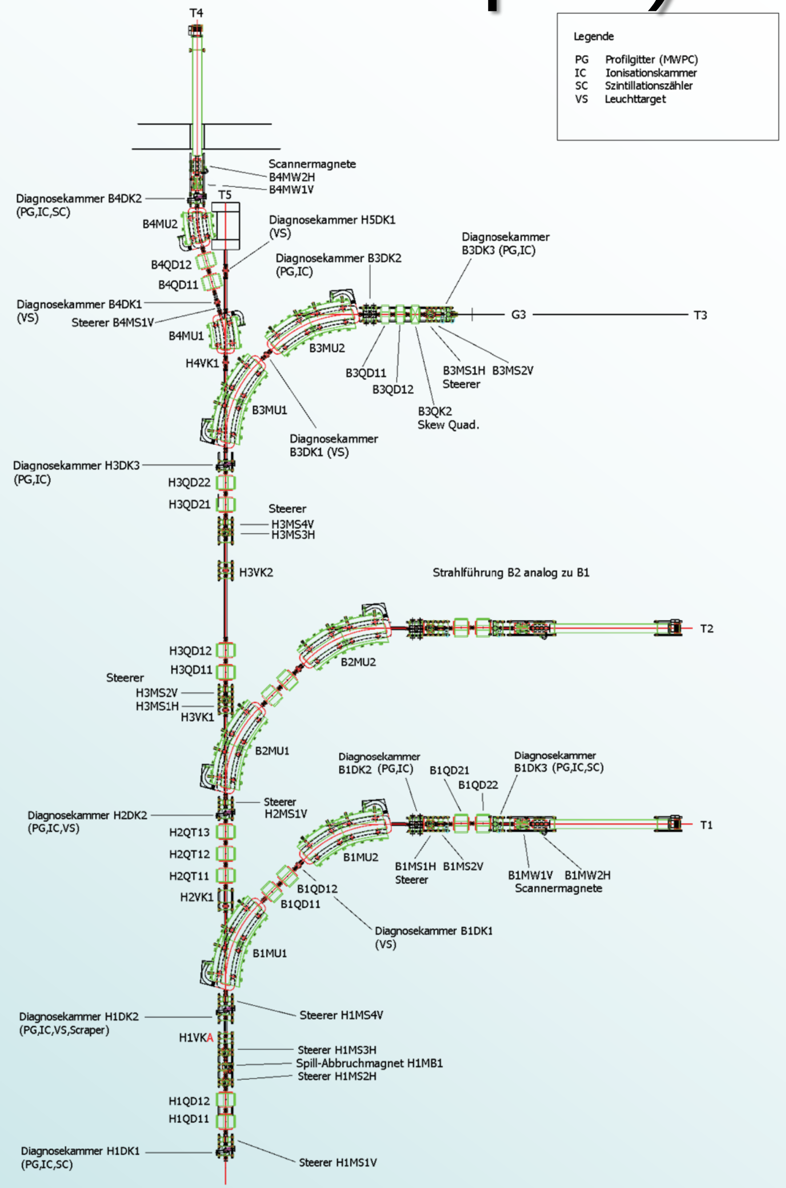


Change of optics

HEBT (High Energy Beam Transport)

Tasks:

- Beam transport to the beam targets
- Safety function “spill abort” by spill abort magnet chicane (SPAM)
- Verification of beam properties of extracted beam
- Beam width and position setting at isocentre
- Deflection of beam for transverse scanning (under TCS control)
- Beam dumping (30 to of iron)



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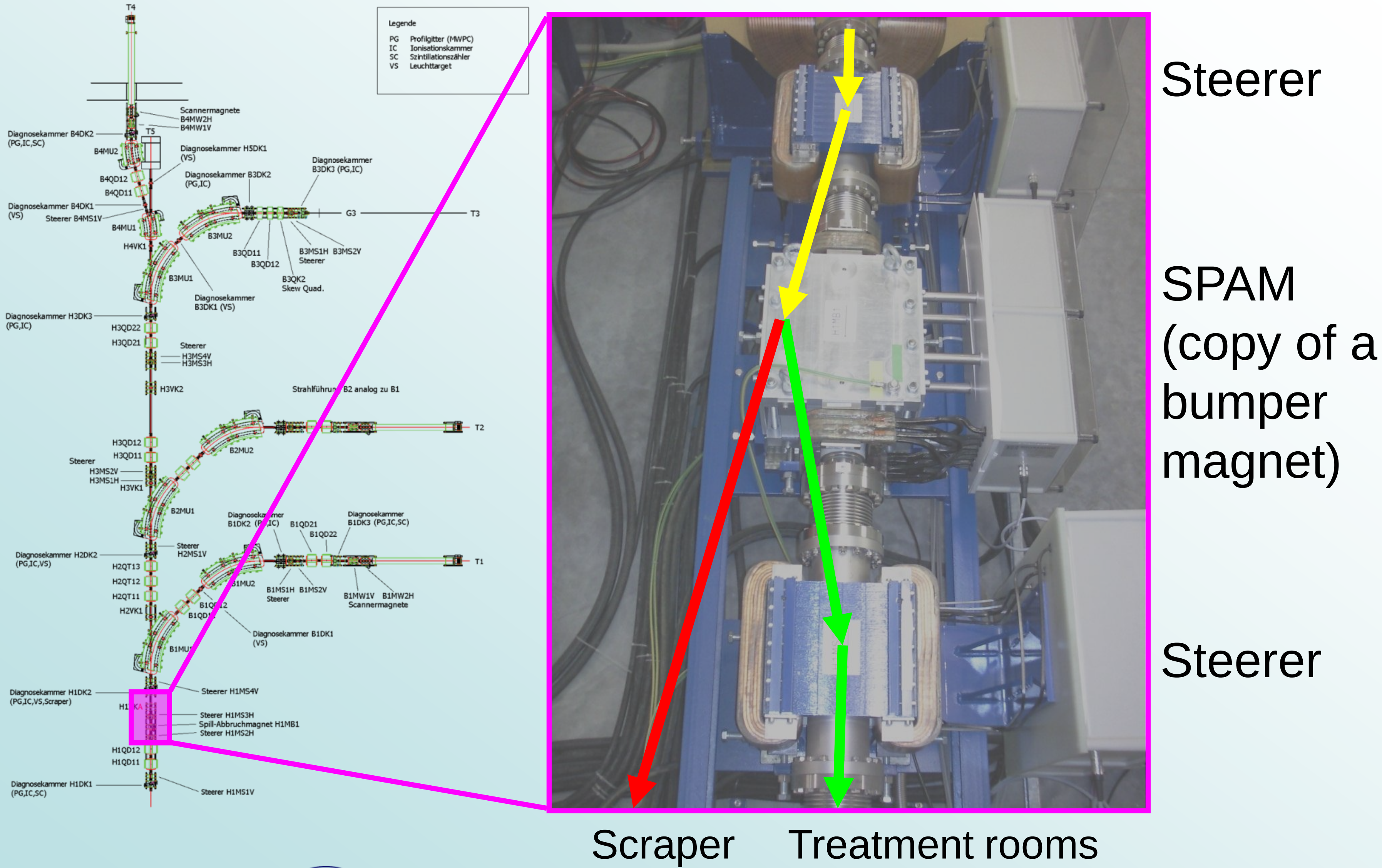
Spill Abort Magnet (SPAM)



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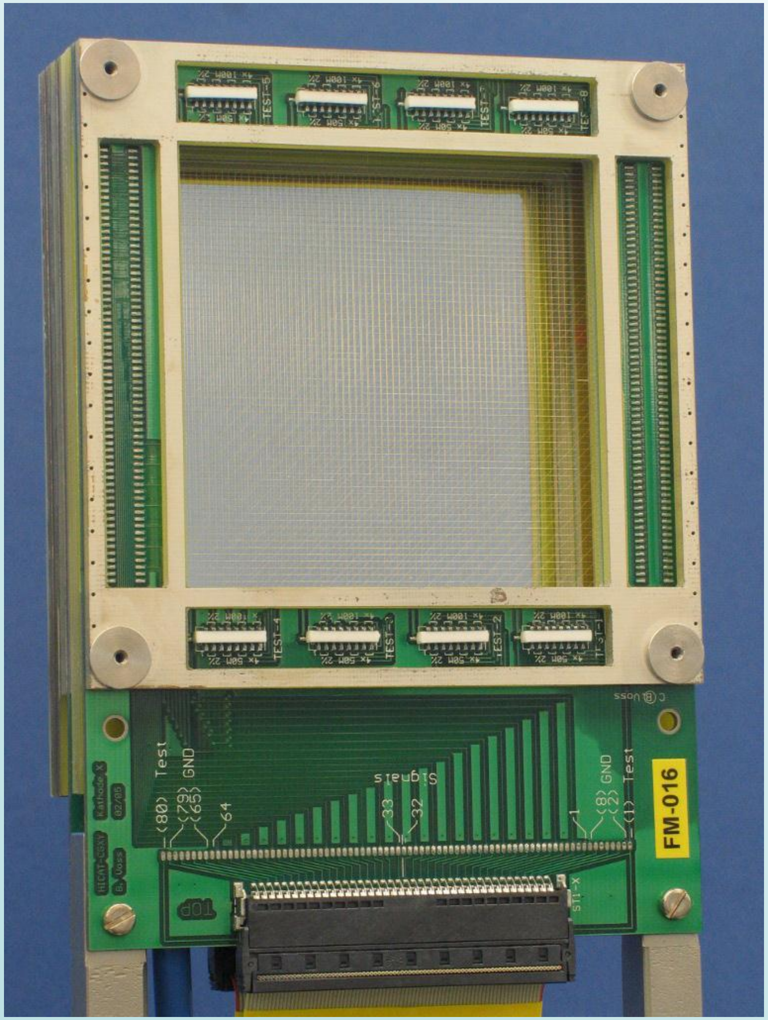
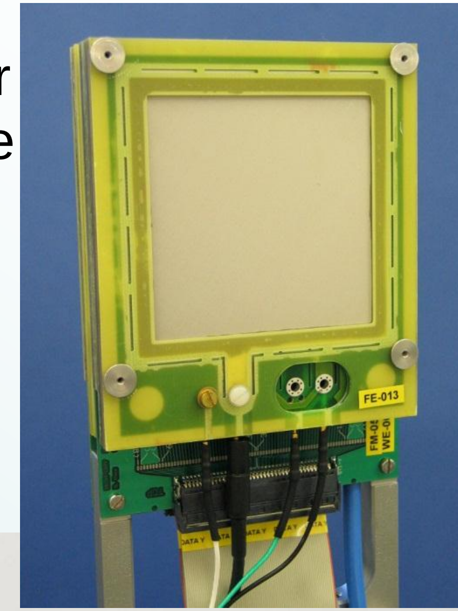
Detectors for beam monitoring

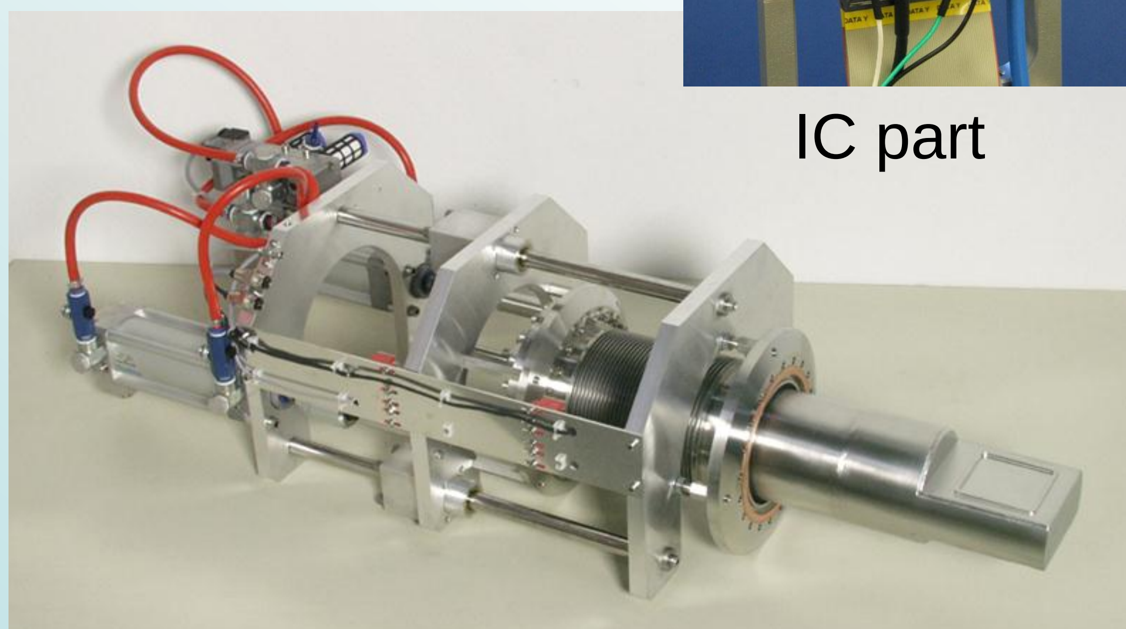


MWPC part

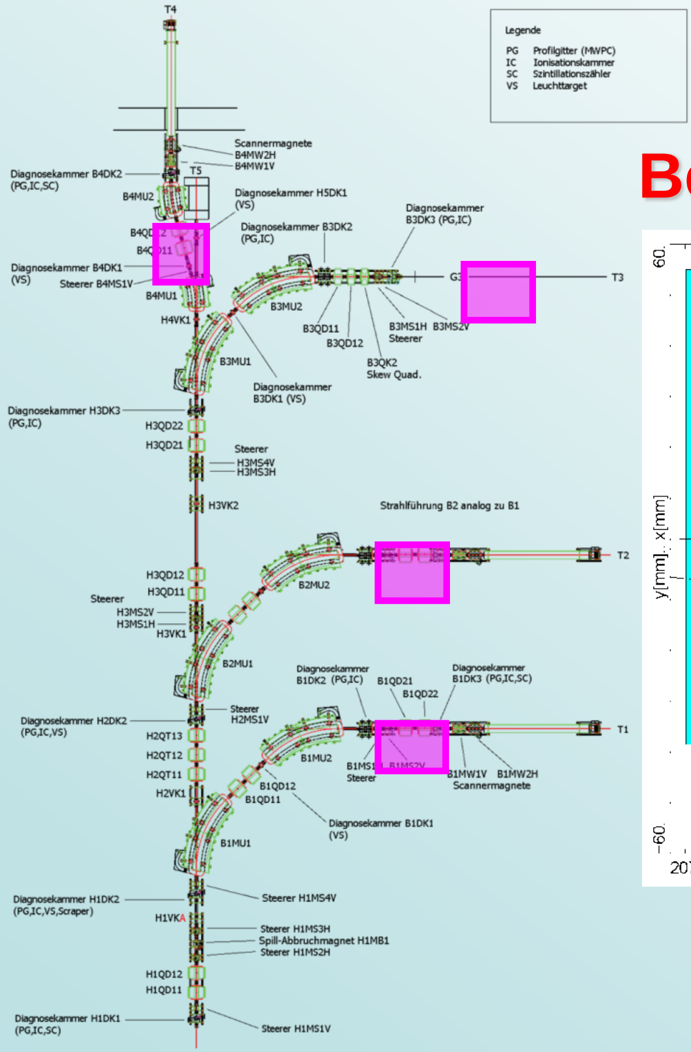
Compact combined detector system working at HIT in the HEBT; feed-through with detector bag – windows to vacuum consist of 50 µm stainless steel; Gas: Ar/CO_2



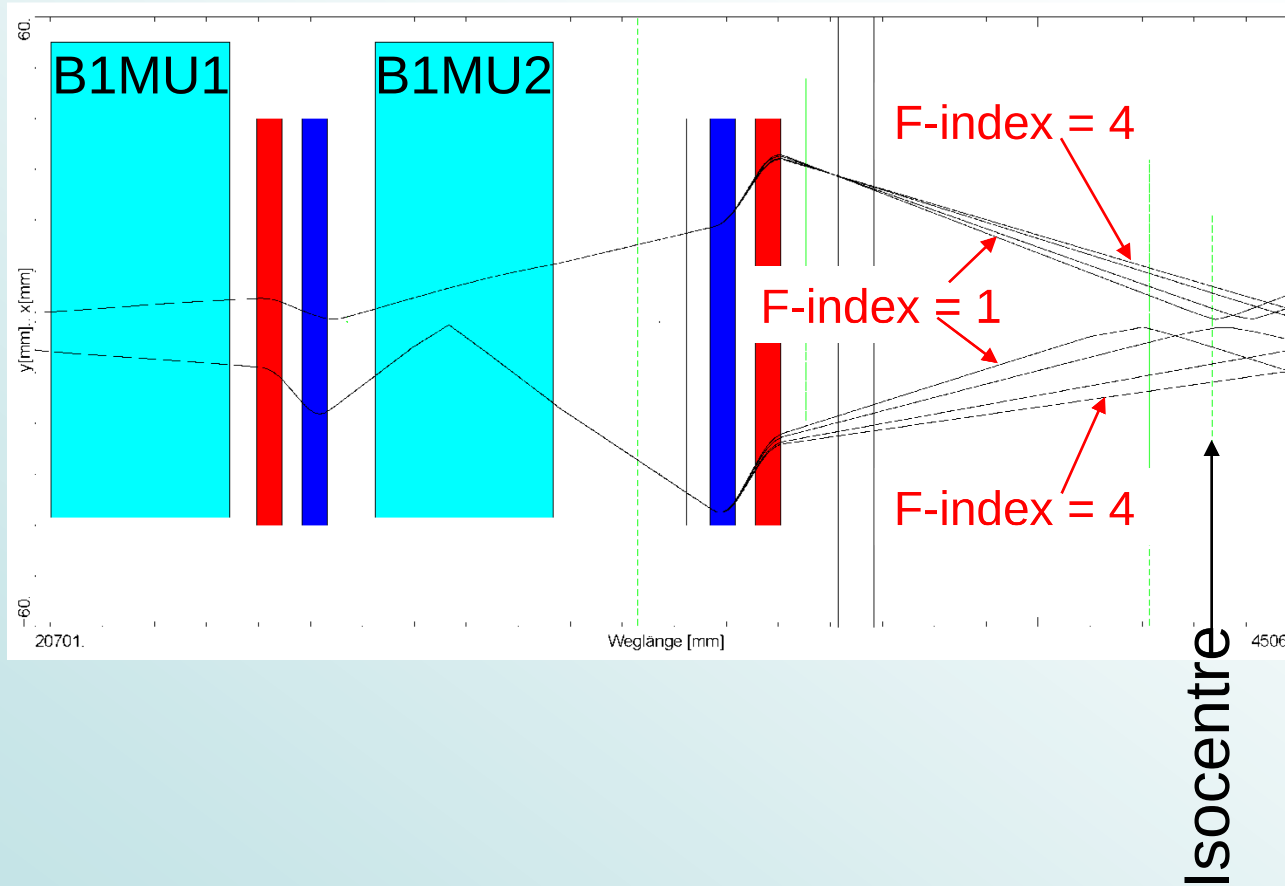
IC part



Focus Setting

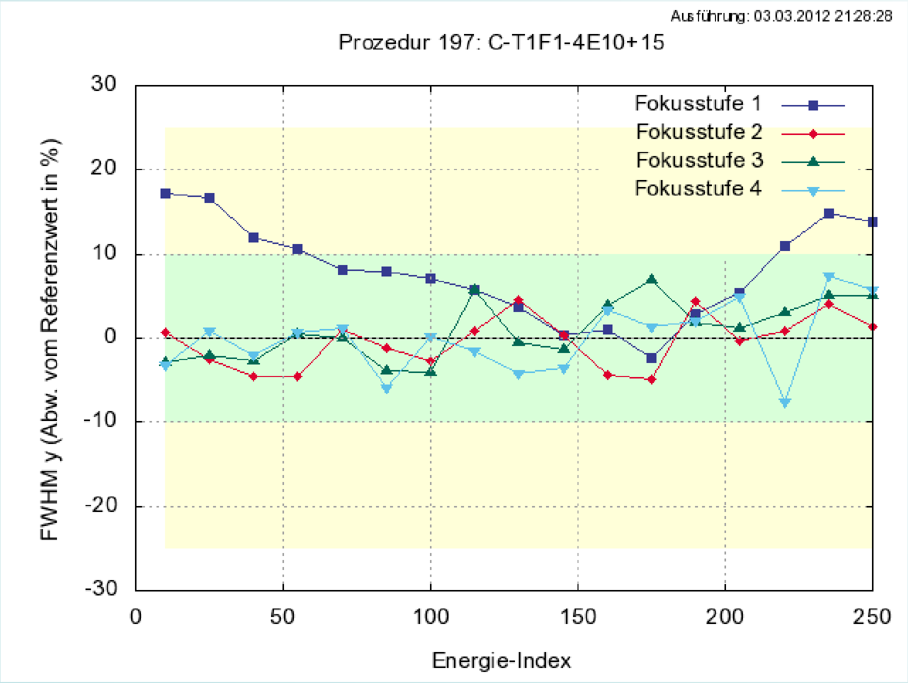


Beam Envelopes (MIRKO Simulation):

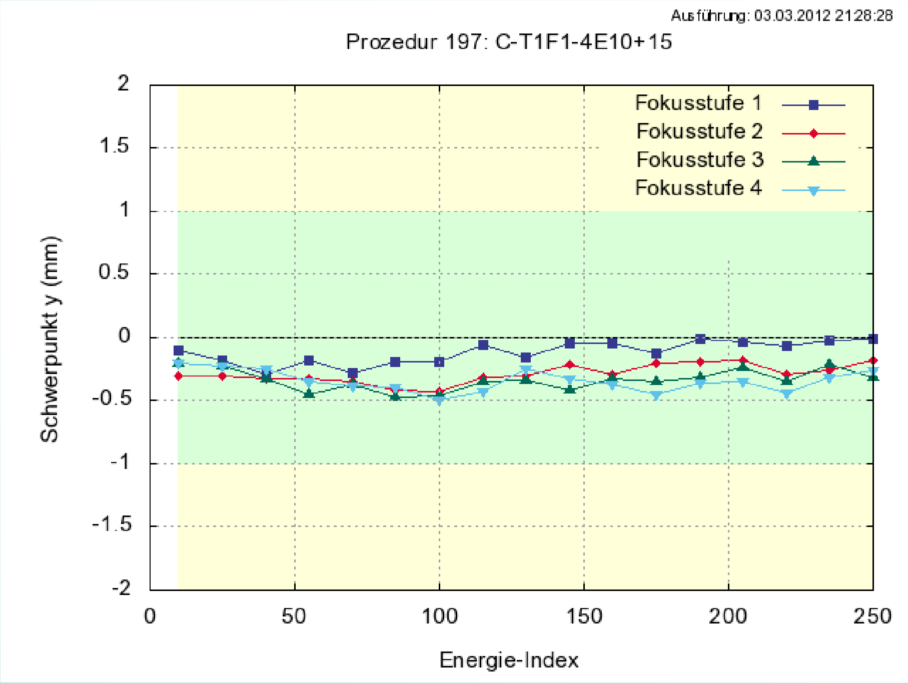


Focus at Isocentre (H1) for C

Beam Widths: (March 2012)



Beam Positions: (March 2012)



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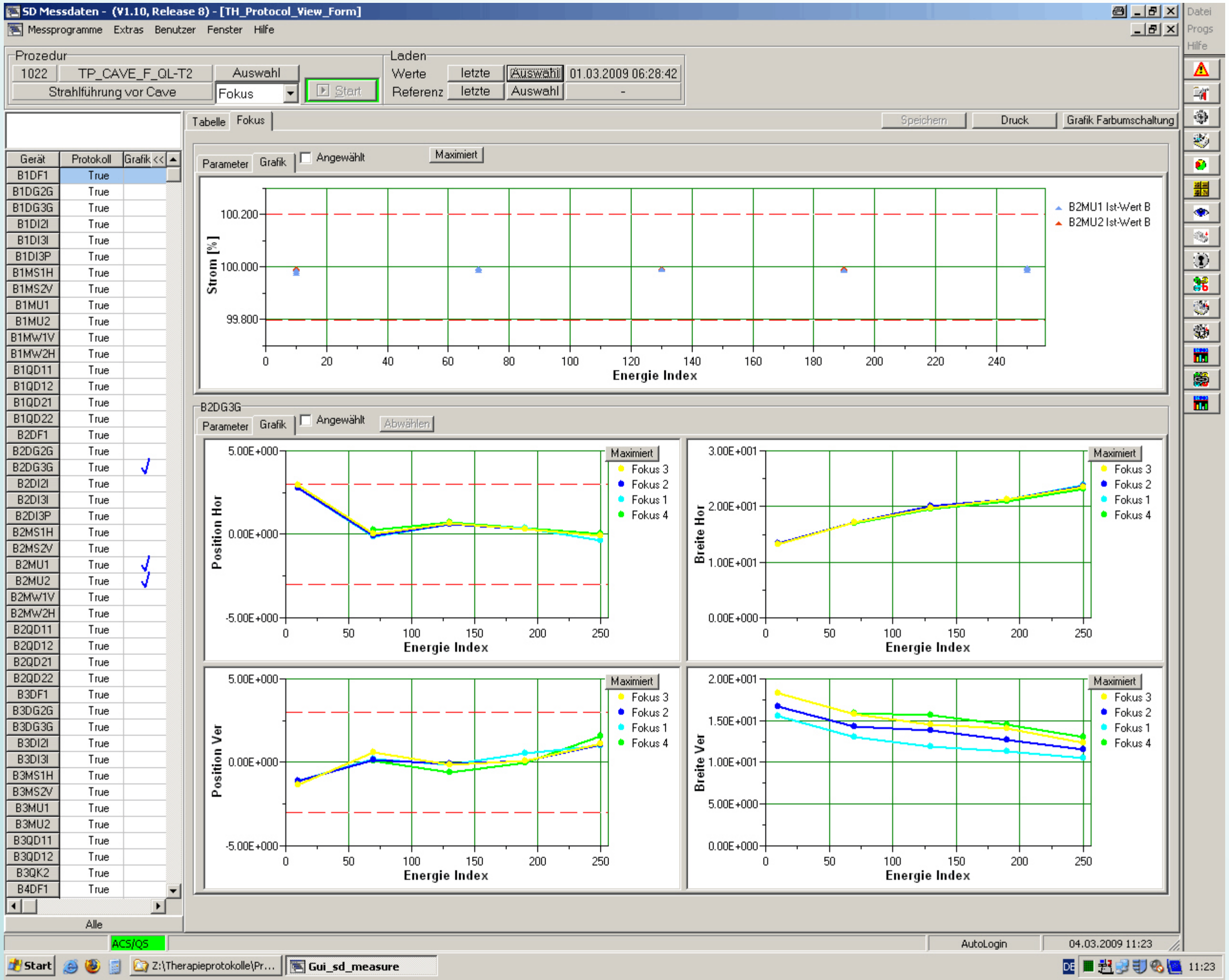
Focus Stability for Carbon beams (H2)

March 2009:



horizontal:

vertical:

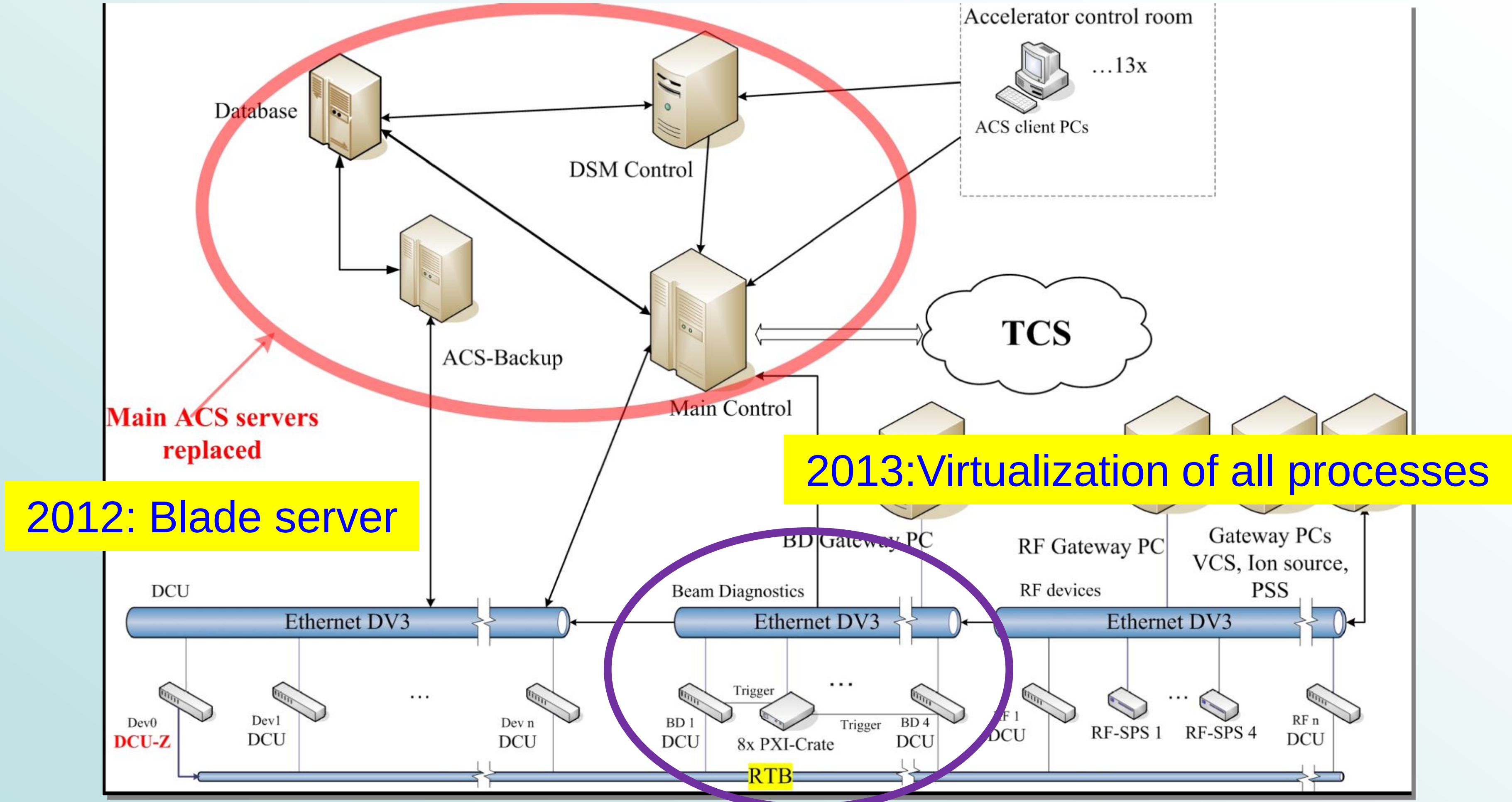
position width

Aspects of a Control System for Particle Therapy

Aspects of a Control System for Particle Therapy

- Conceptional design decision necessary due to the fact that an irradiation facility is a medical product.
- The accelerator itself as the “beam deliverer” could be a “normal” CE level product with a dedicated interface to the irradiation technique around the patient treatment, which has to fulfill the MDD (**M**edical **D**evice **D**irective, EC rules)
- A software for a medical product needs a complete documentation of the development process including testing, etc. (e.g. V-model in Germany) – the effort is 50 -100 % higher than for a “normal” scientific-technical software package. Later changes are much more complicated in a medical product because of extended regression tests, documentation, etc. (~ factor of 3).
- Therefore HIT decided to implement the ACS as a “normal” CE level product, whereas the irradiation technique was ordered from a certified medical product supplier.

Accelerator Control System for HIT



Solution: Proprietary 2-Level CS with interface to TCS

Aspects of a Control System for Particle Therapy

The core of the HIT CS is an Oracle database for storing:

- Device parameters
- Devices of virtual accelerators (functional subgroups from source to target)
- The optical model and its parameters, spline coefficients
- Cycle data
- Measured values (power supplies, beam instrumentation, vacuum pressure, ...)
- Alarm & error logs
- Users & access rights
- Computers & applications
- … and much more!

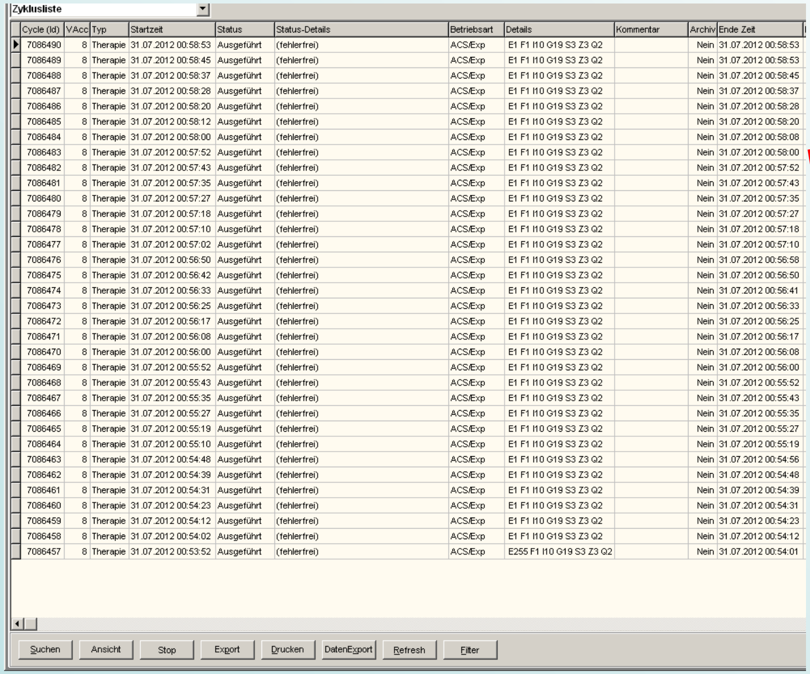
Aspects of a Control System for Particle Therapy

A lot of reports can be retrieved from such a database:

- Beam statistics:
  - Performance,
  - Number of particles accelerated,
  - Beam request modes (therapy, accelerator physics, experiment),
  - Used sources, destinations, ion types,
  - Distribution of E, F, I parameters.

- Error analysis:
  - Number of beam request failures, dependent on system mode
  - Identify usual error sources or problems of devices.

Example of an ACS report



Zyklusliste

Cycle (Id)	VAcc	Typ	Startzeit	Status	Status-Details	Betriebsart	Details	Kommentar	Archiv	Ende Zeit
7086490	8	Therapie	31.07.2012 00:58:53	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:53
7086489	8	Therapie	31.07.2012 00:58:45	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:53
7086488	8	Therapie	31.07.2012 00:58:37	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:45
7086487	8	Therapie	31.07.2012 00:58:28	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:37
7086486	8	Therapie	31.07.2012 00:58:20	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:28
7086485	8	Therapie	31.07.2012 00:58:12	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:20
7086484	8	Therapie	31.07.2012 00:58:00	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:08
7086483	8	Therapie	31.07.2012 00:57:52	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:58:00
7086482	8	Therapie	31.07.2012 00:57:43	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:57:52
7086481	8	Therapie	31.07.2012 00:57:35	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:57:43
7086480	8	Therapie	31.07.2012 00:57:27	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:57:35
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7086476	8	Therapie	31.07.2012 00:56:50	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:56:58
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7086469	8	Therapie	31.07.2012 00:55:52	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:56:00
7086468	8	Therapie	31.07.2012 00:55:43	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:55:52
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7086464	8	Therapie	31.07.2012 00:55:10	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:55:19
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7086460	8	Therapie	31.07.2012 00:54:23	Ausgeführt	(fehlerfrei)	ACS/Exp	E1 F1 I10 G19 S3 Z3 Q2		Nein	31.07.2012 00:54:31
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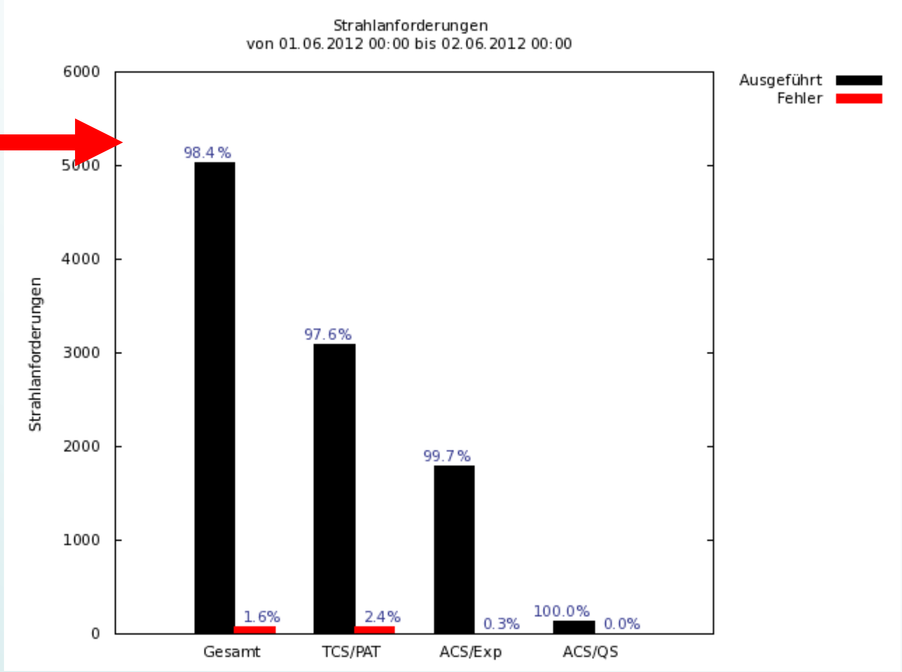
Suchen | Ansicht | Stop | Export | Drucken | DatenExport | Refresh | Filter



	Strahlanforderungen nach Betriebsart							
	Alle		TCS/PAT		ACS/Exp		ACS/QS	
	Zyklen	%	Zyklen	%	Zyklen	%	Zyklen	%
Gesamt:	5113		3172		1804		137	
Ausgeführt:	5029	98.36 %	3095	97.57 %	1797	99.61 %	137	100.00 %
Fehler:	82	1.60 %	77	2.43 %	5	0.28 %	0	0.00 %
Min. ein Gerät nicht geantwortet	2	0.04 %	1	0.03 %	1	0.06 %	0	0.00 %
VAcc nicht ausführbar	80	1.56 %	76	2.40 %	4	0.22 %	0	0.00 %

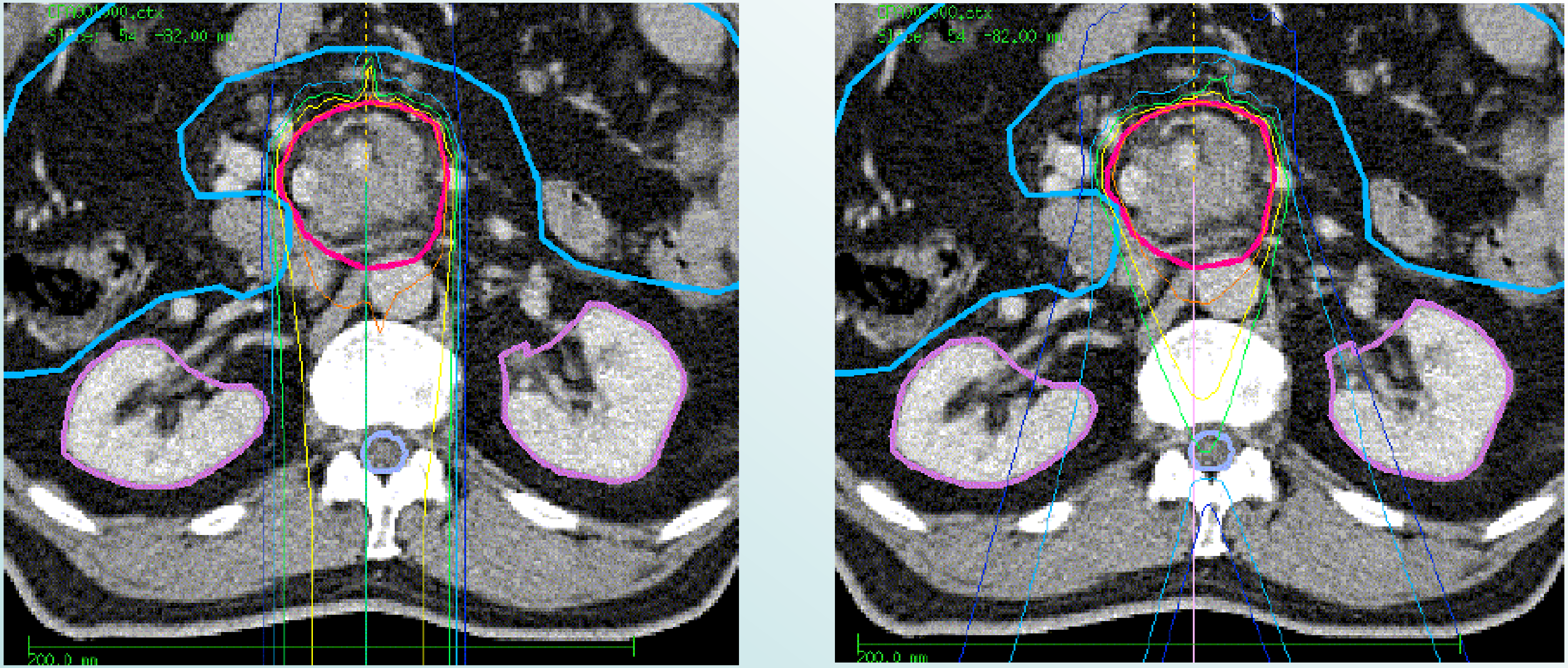
- Automatic report
- DB reading
- Daily, weekly
- Part of E-Log(book)

K. Höppner et al., PCaPAC

Gantries: Motivation, Geometries and Examples

Motivation for a Gantry

Example: Pancreas → supine position via gantry advantageous

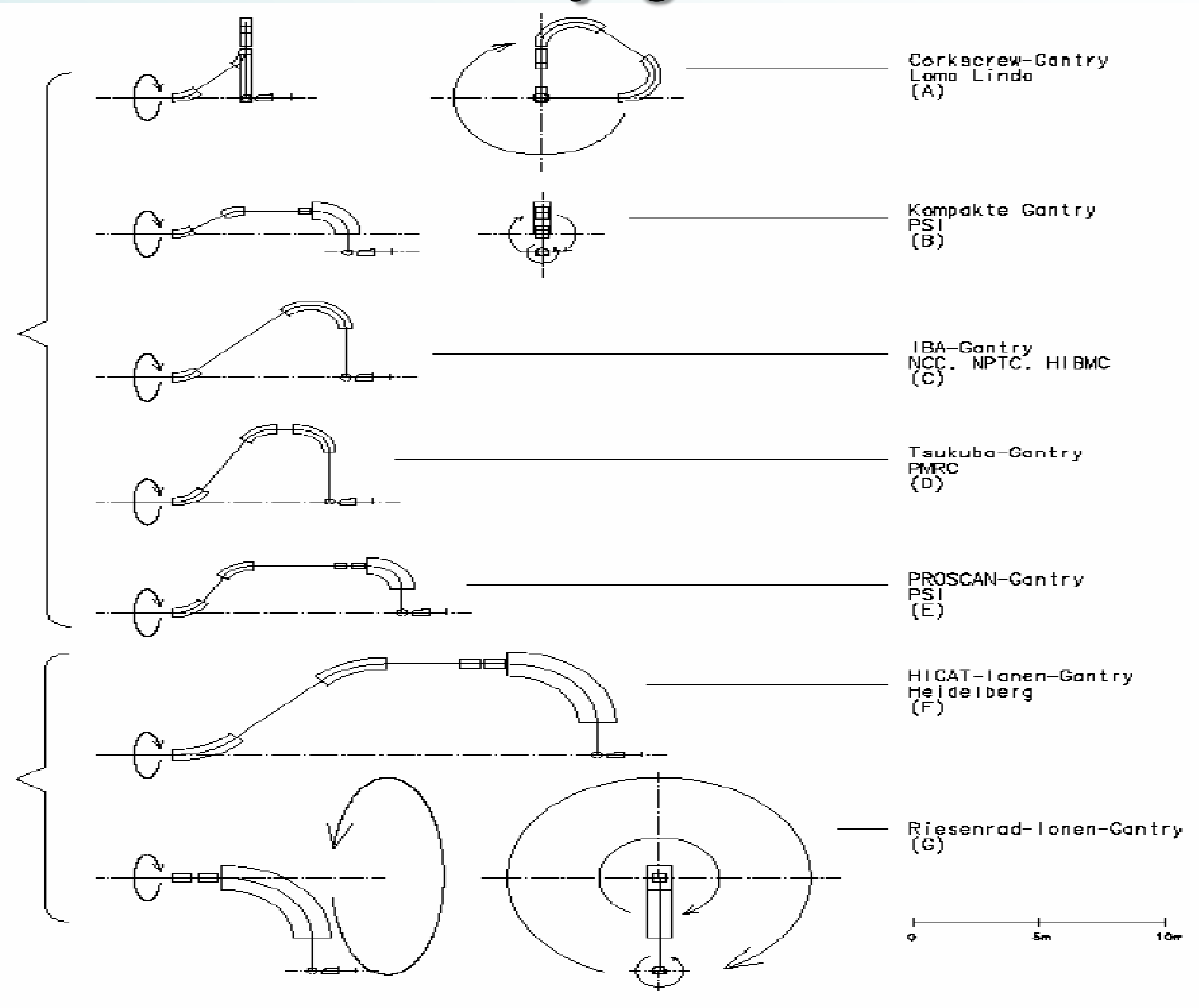


Individual irradiation angle for each patient necessary!

Gantry geometries

Proton gantries

Ion gantries

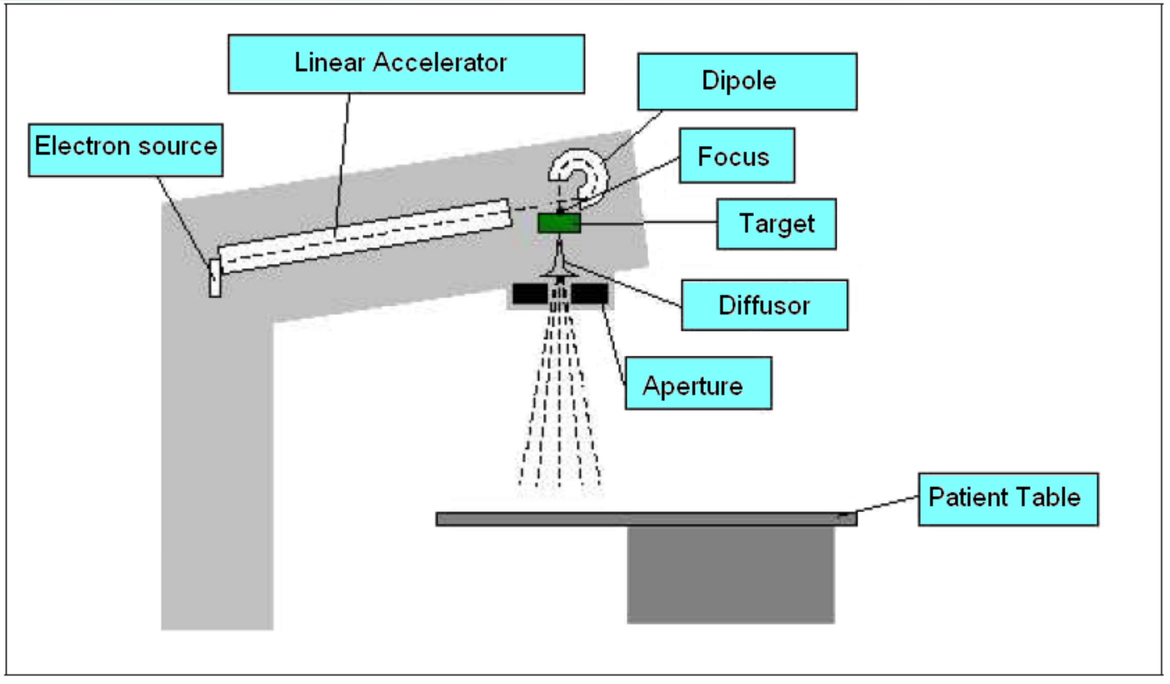


Central question: Iscocentric or excentric geometry?

Which Gantry geometry to choose?

"The patient is in the focus, the technique should group around!"

Medical personal is accustomized to use isocentric gantries like in photon therapy!



Example:ONCOR from Siemens

Additional arguments → Safety reasons, e.g.

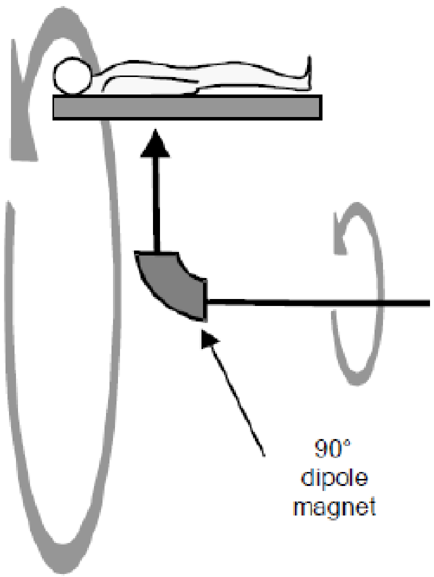
"Only 20 – 30 s may ellipse from stopping the irradiation till the physician may help the patient in case of respiratory problems or vomiting!"

Which Gantry geometry to choose?

Reimoser, Thesis, PMMS

Exocentric Riesenrad Gantry

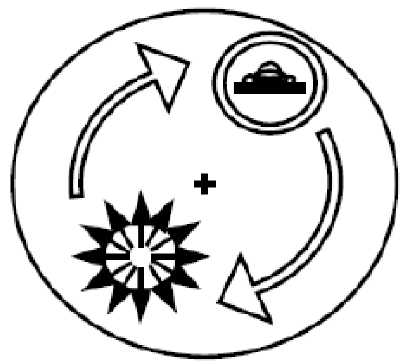
→ Patient is placed along a circle around the incoming beam axis.



Has not been built yet

Beam & patient eccentric

→ Smallest possible gantry radius

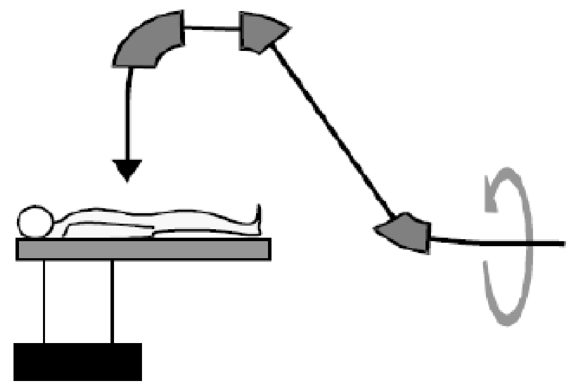


PSI Gantry 1

Isocentric gantry

→ Beam delivery system rotates around the patient

→ Patient is positioned centrally (isocentre) and is not moved.

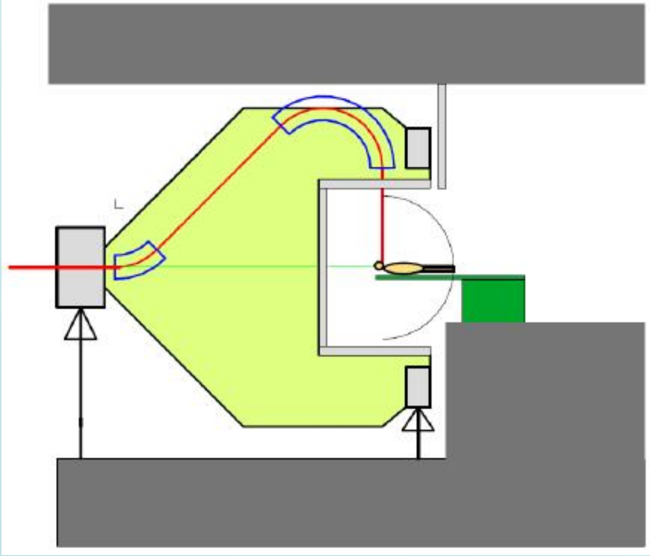


Most Gantries in the world

Examples: Commercial Solutions

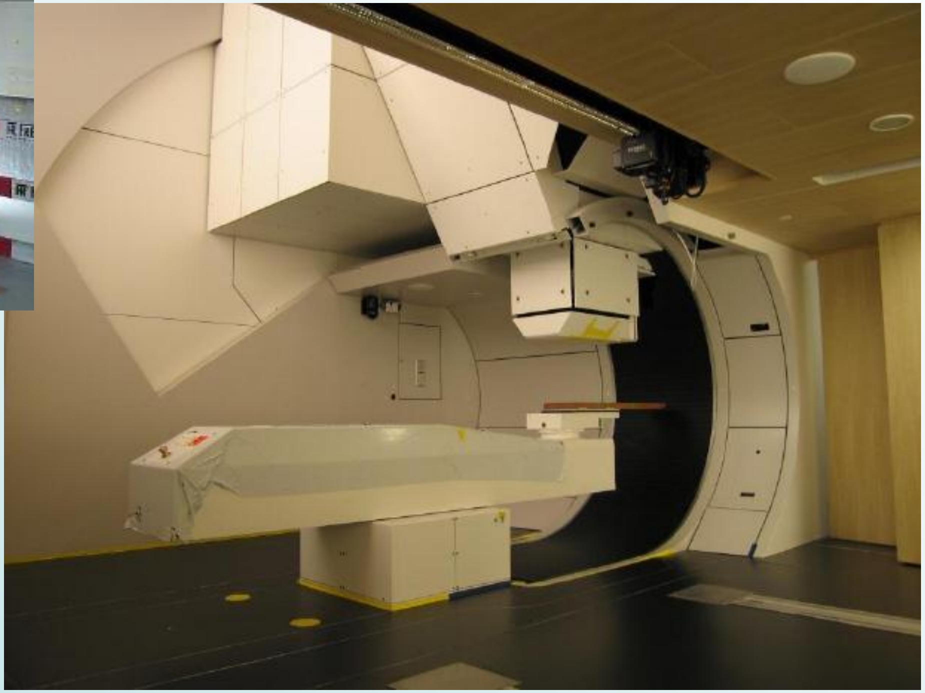
Mitsubishi

IBA



Example: PSI – Gantry II

During installation



Installation finished, commissioning under way

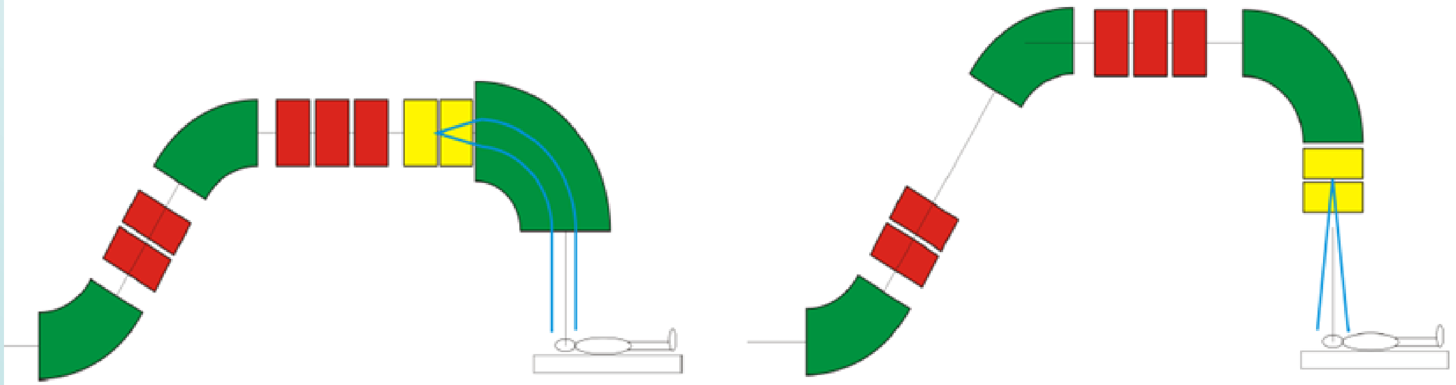
Gantry / Active Pencil beam scanning

Upstream scanners

- Large aperture last bend
- Heavier
- Higher (magnet, mechanical support) costs

Downstream scanners

- Large fields possible with large SAD (increase diameter)
- Larger diameter
- Larger room needed (costs?)



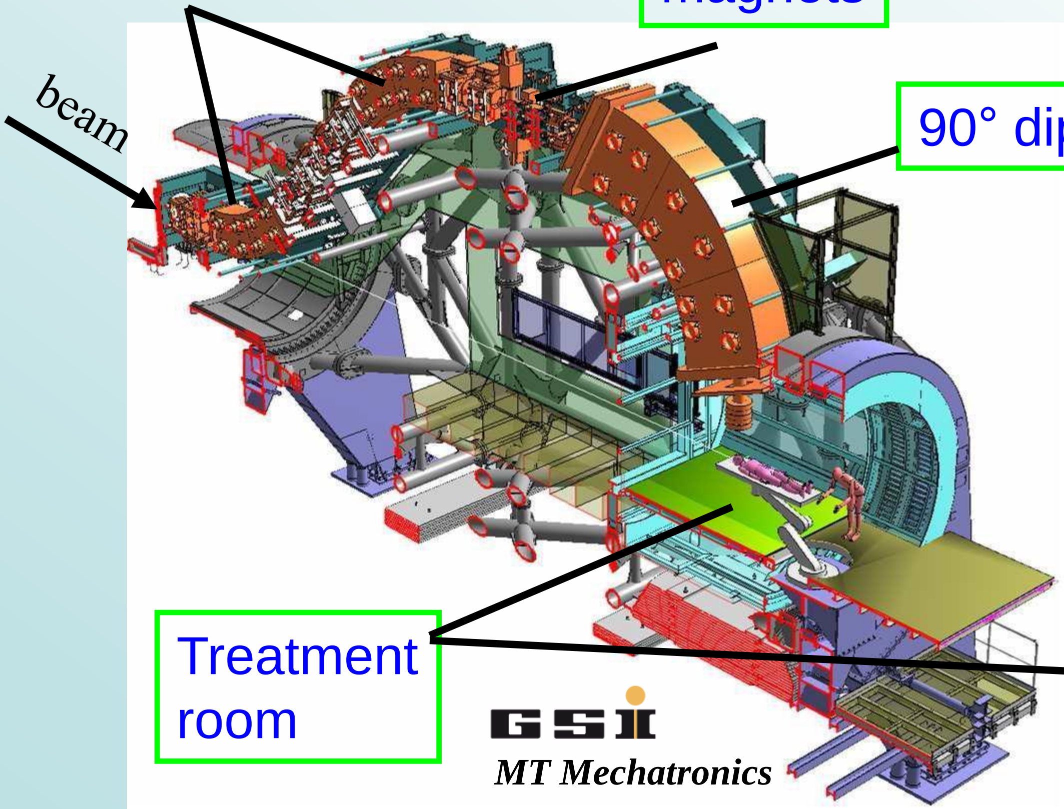
SAD – source-to-axis distance

Air Gap (nozzle to iso-center)

- Important for *low-energy protons* (~60-80MeV, p⁺)
- Nozzle elements (monitors, pre-absorber) and air *scatter* the beam, a (large) *air gap after nozzle* causes significantly *increased beam size* at iso-center

→ Bring vaccum as close as possible to nozzle monitors and the nozzle as close as possible to the target volume!

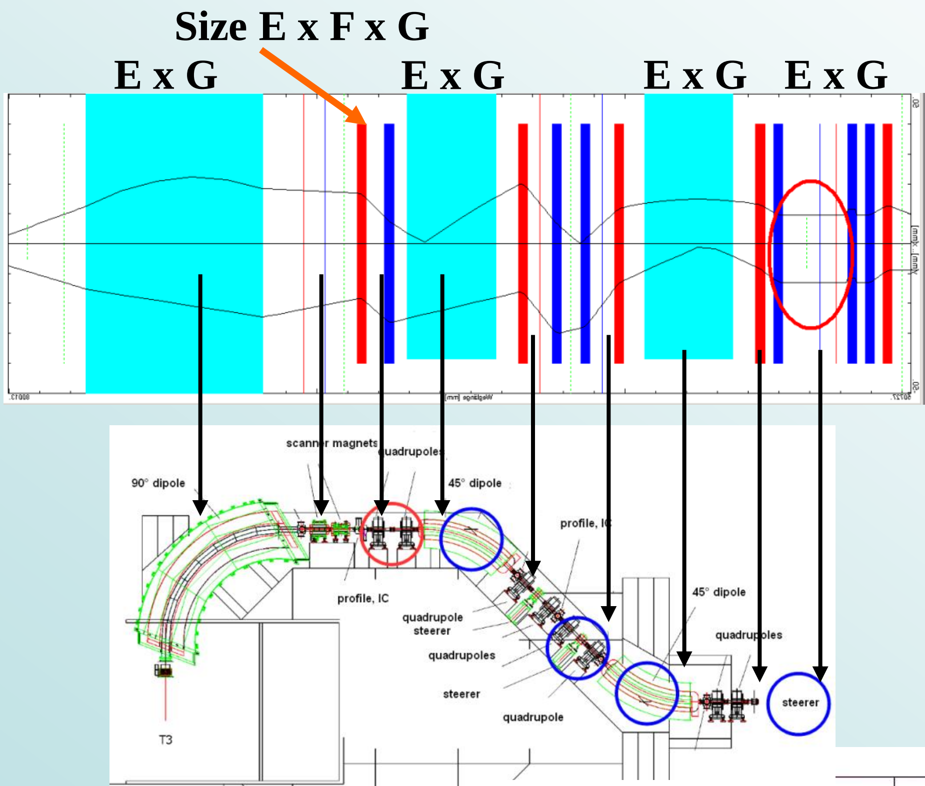
HIT Ion Beam Gantry



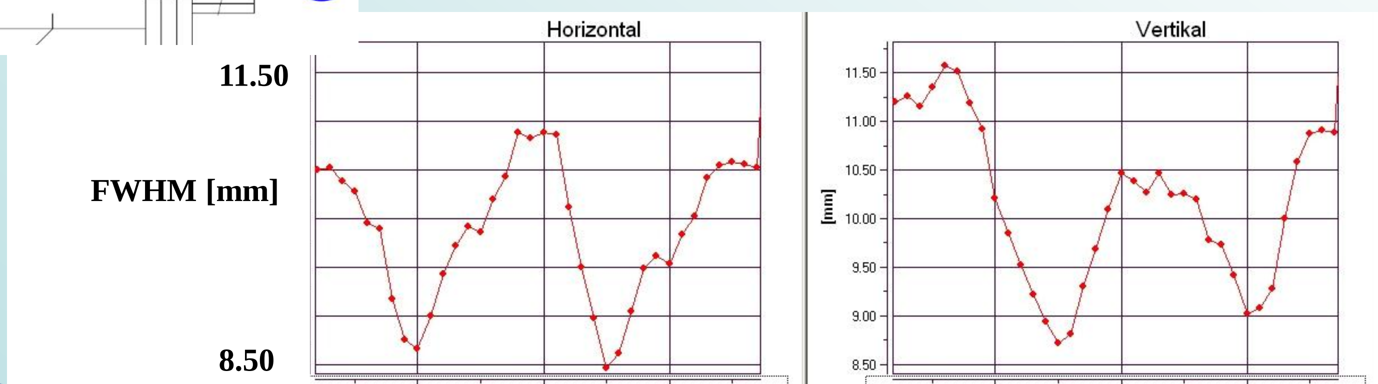
Position accuracy:

Dipoles	+/- 2mm
Quadrupoles	+/- 0.5 mm

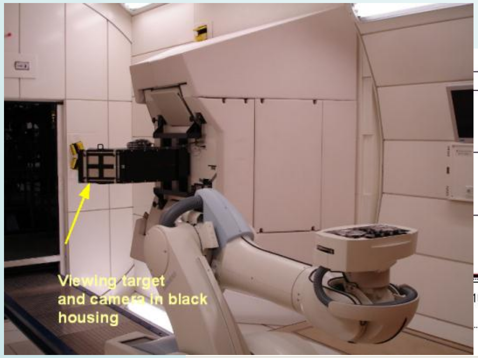
HIT Gantry: Setting Concept

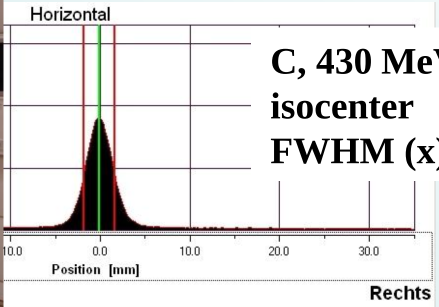


- Full transmission (beta function within limits)
- Basic setting (gantry and gantry injection!) for all angles keeping variation of beam focus and width independent of gantry angle
- Compensating effect of coupling of hor. and vert. phase space under gantry rotation
- Beam size adjustment with last quadrupole doublet

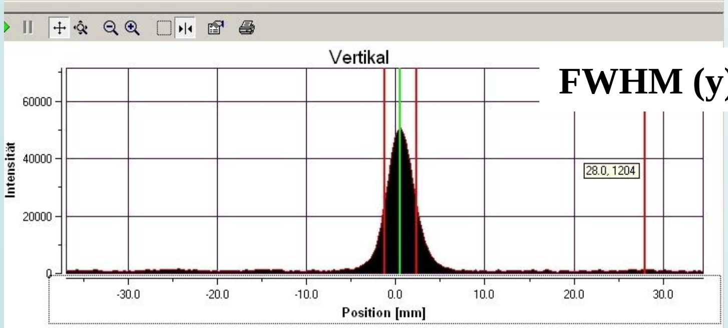


HIT Gantry: Beam Size Control

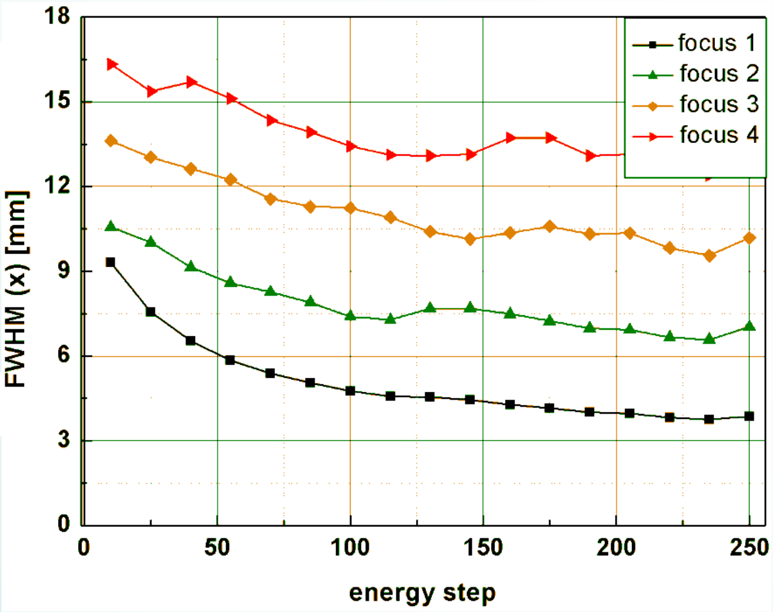


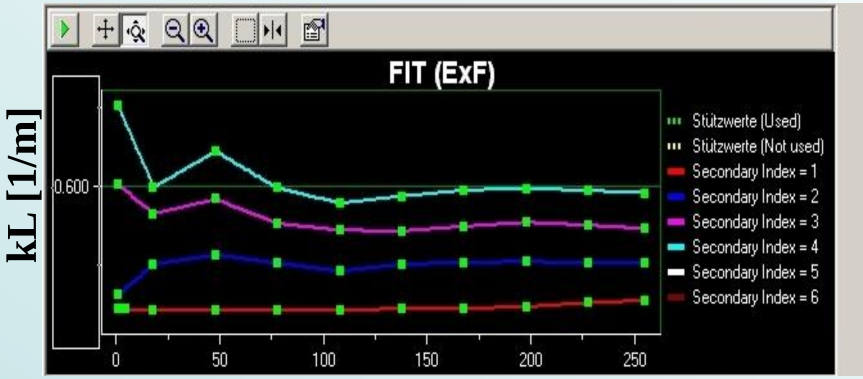


C, 430 MeV/u
isocenter
FWHM (x) = 3.5 mm



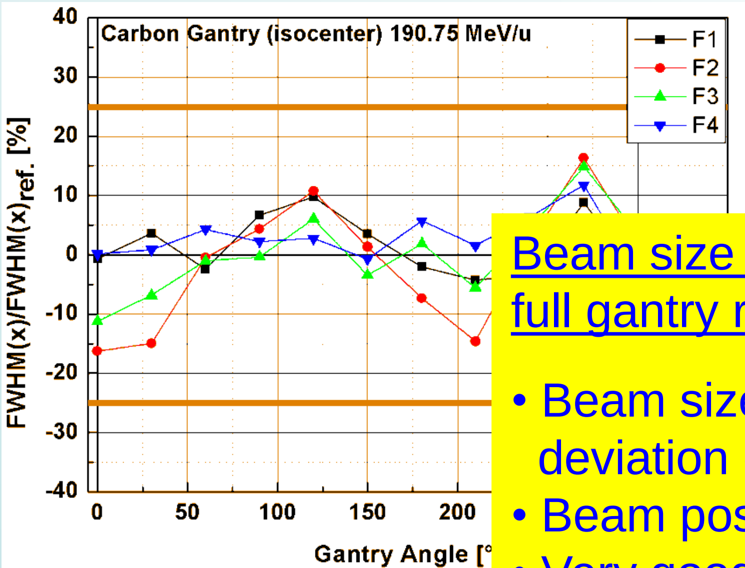
FWHM (y) = 3.5 mm

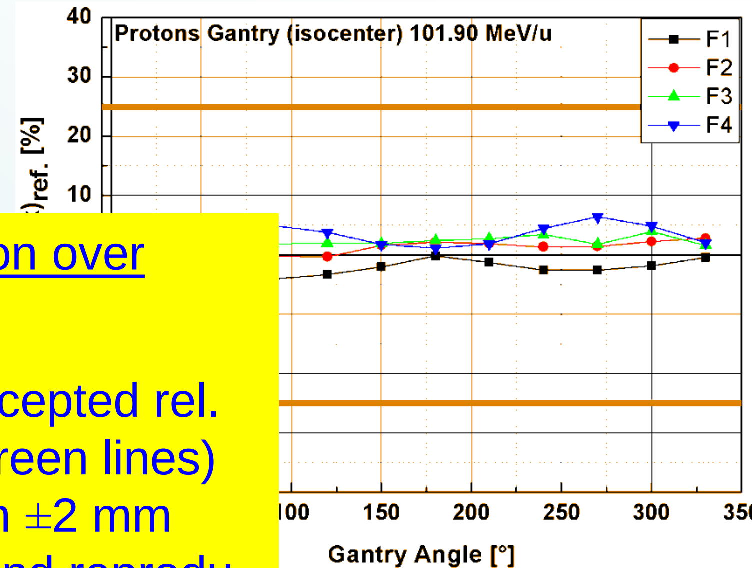


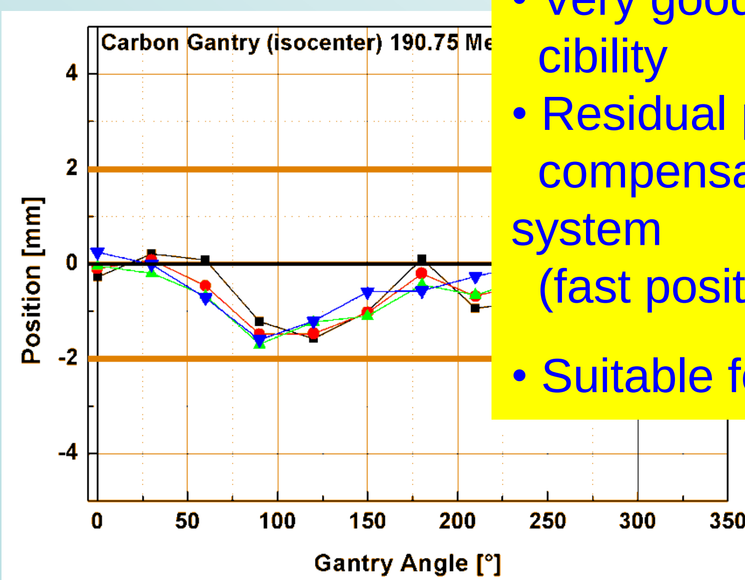


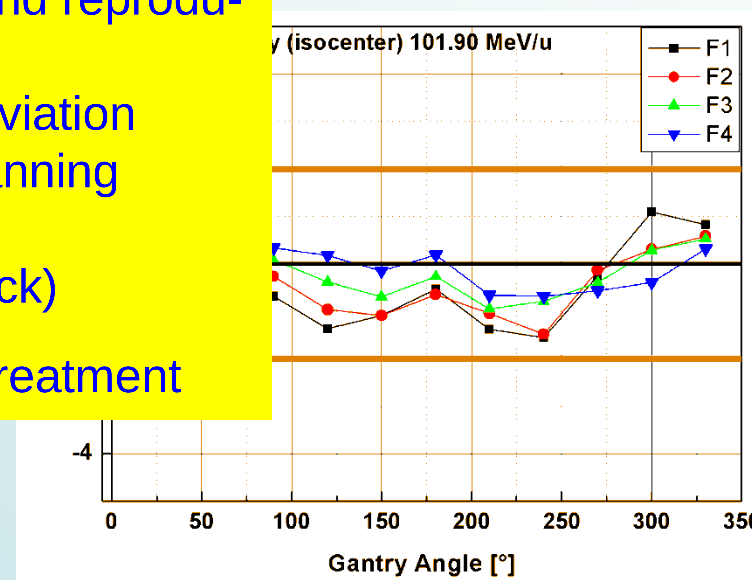
- Energy and angle dependent settings of focusing quadrupoles (beam width)
- Energy and angle dependent settings of dipoles/steerer (beam position)
- Spline interpolation over base points

HIT Gantry: Beam Size and Position









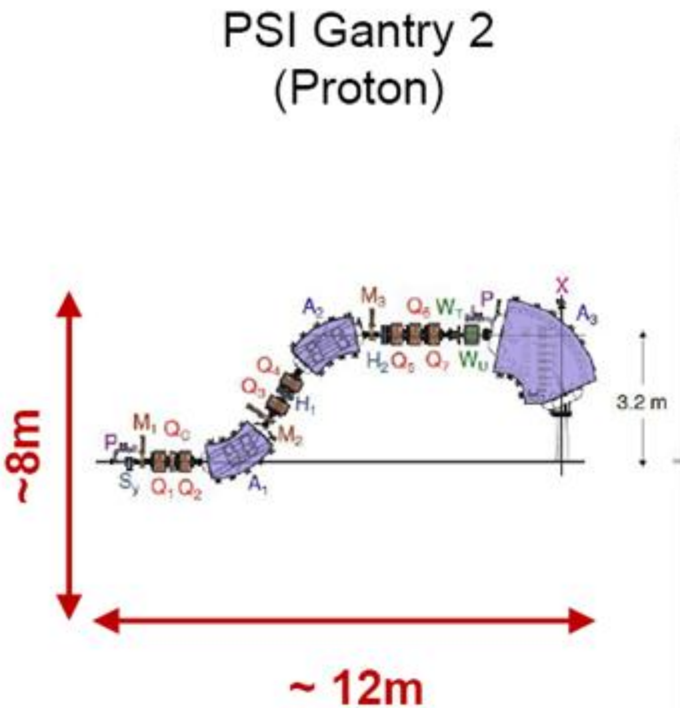
Beam size and position over full gantry rotation:

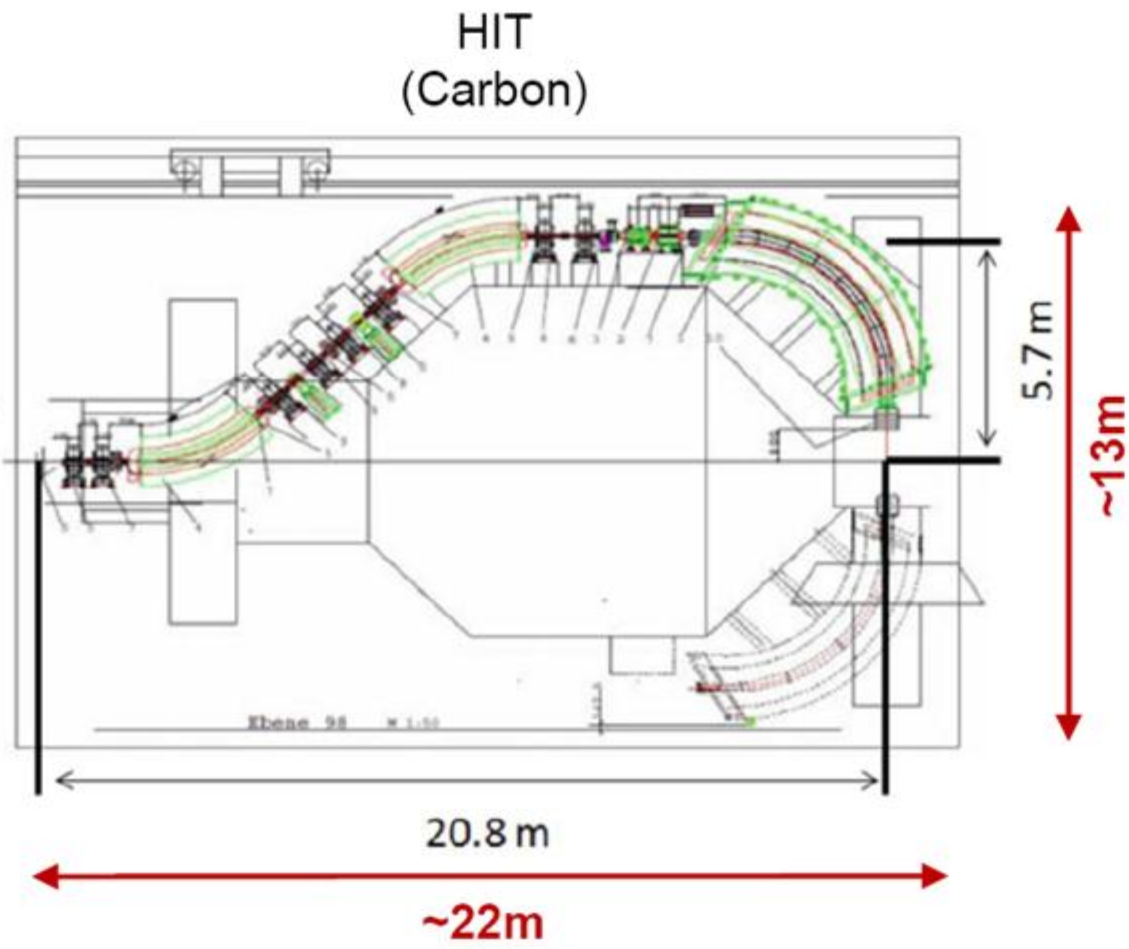
- Beam size within accepted rel. deviation of 25 % (green lines)
- Beam position within ±2 mm
- Very good stability and reproducibility
- Residual position deviation compensated by scanning system (fast position feedback)
- Suitable for patient treatment

HIT Heidelberger Ionenstrahl-Therapiezentrum

The HIT Ion Gantry rotating…

Comparison: Proton vs. Ion Gantry





Total Weights:

PSI Gantry II	~ 220 to
HIT Gantry	~ 670 to

Outline – Part 3

- Daily operations of a particle therapy centre: Experiences from the first five years at HIT in Heidelberg, from commissioning to the treatment of the first 1000 patients so far
- Future enhancements for synchrotron-driven particle therapy facilities: Magnetic field control and feedback, dynamic spill shaping and multi-energy operation within one synchrotron cycle
- Outlook to new accelerator concepts proposed for particle therapy: FFAGs, laser plasma accelerators, dielectric wall accelerators, s.c. gantries and others

Acknowledgement

Thanks to all people providing me their material: HIT (T. Haberer, R. Cee, M. Galonska, S. Scheloske, E. Feldmeier, J. Naumann, C. Schömers, K. Höppner et al.), GSI (U. Weinrich, H. Eickhoff, B. Schlitt, P. Forck, M. Schwickert, B. Voss et al.), CNAO (S. Rossi, E. Bressi, M. Pullia et al.), PSI (M. Schippers, E. Pedroni et al.), MGH (J. Flanz at al.), NIRS/HIMAC (K. Noda, Y. Iwata et al.), MedAustron (A. Koschik et al.), CEA (F. Kircher et al.) …

… and also the companies: Siemens PT, VARIAN Medical, IBA, Mitsubishi, Hitachi, Danfysik, SigmaPhi and some more not listed here.

Thank you for your attention!

(Intensity modulated raster scan, ^{12}C at 430 MeV/u), recorded on a film