Commissioning and Operation of the Injector Linacs for HIT and CNAO

Bernhard Schlitt, GSI - Darmstadt

1. Layout of the HIT facility and its linac injector
2. Commissioning phases and timeline
3. Results
4. Linac upgrade program
5. Status of the CNAO linac
6. Conclusions & outlook

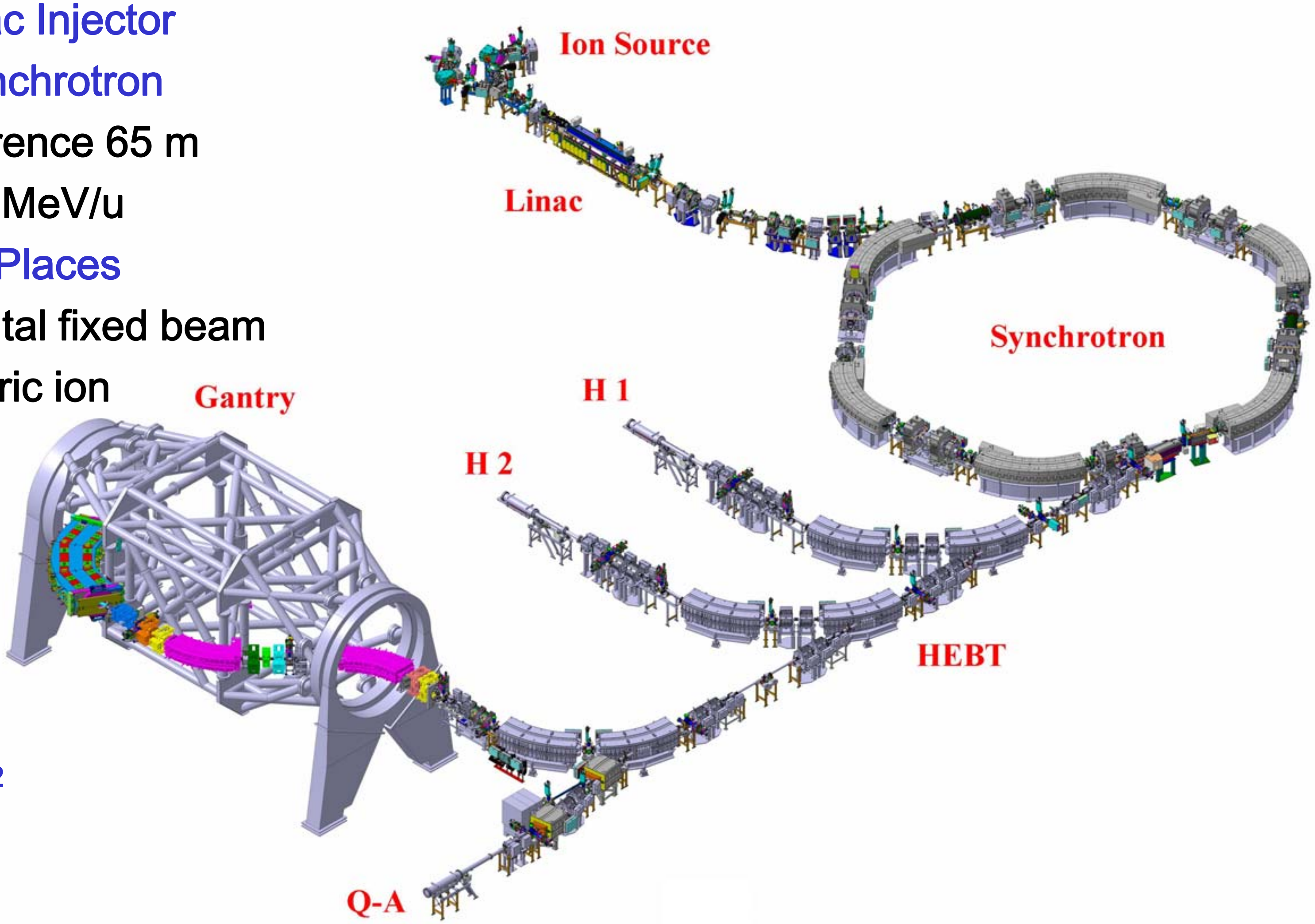
Heidelberg Ion-Beam Therapy Centre (HIT)

- Europe's first dedicated clinical hadrontherapy centre
- World's first carbon 3D rasterscan therapy facility
- World's first carbon gantry
- 1200 Patients / year

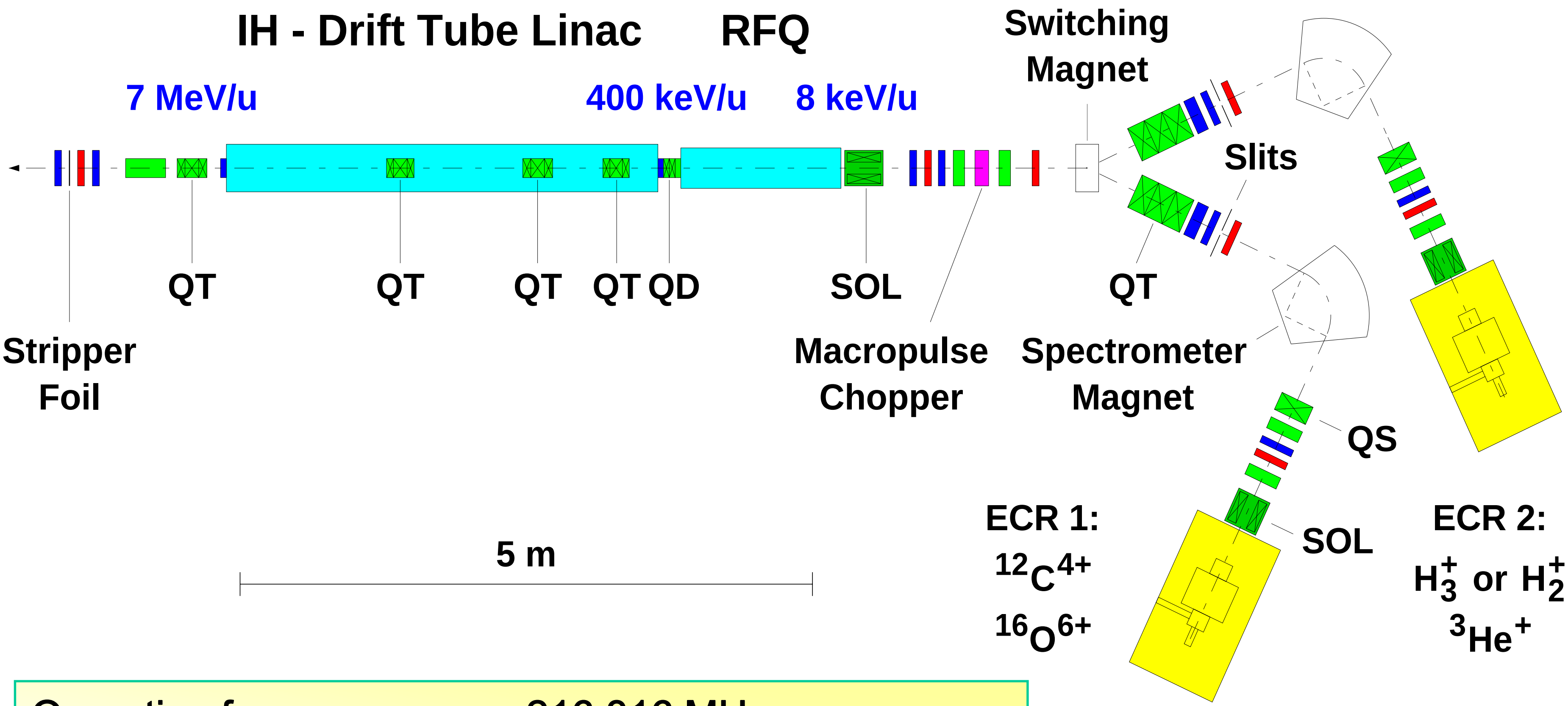
- Owner: Heidelberg University Hospital
- Operation: HIT company (owned by university hospital)
- Accelerator: GSI design, coordination, assembly, commissioning, staff training, copper plating

HIT Accelerator Layout

- 2 ECR Ion Sources (p, C)
- 7 MeV/u Linac Injector
- Compact Synchrotron
  - circumference 65 m
  - 48 – 430 MeV/u
- 3 Treatment Places
  - 2 horizontal fixed beam
  - 1 isocentric ion gantry
- 1 R&D & QA Place
- Building area $\approx 70 \times 60\ m^2$



217 MHz, 7 MeV/u Injector Linac

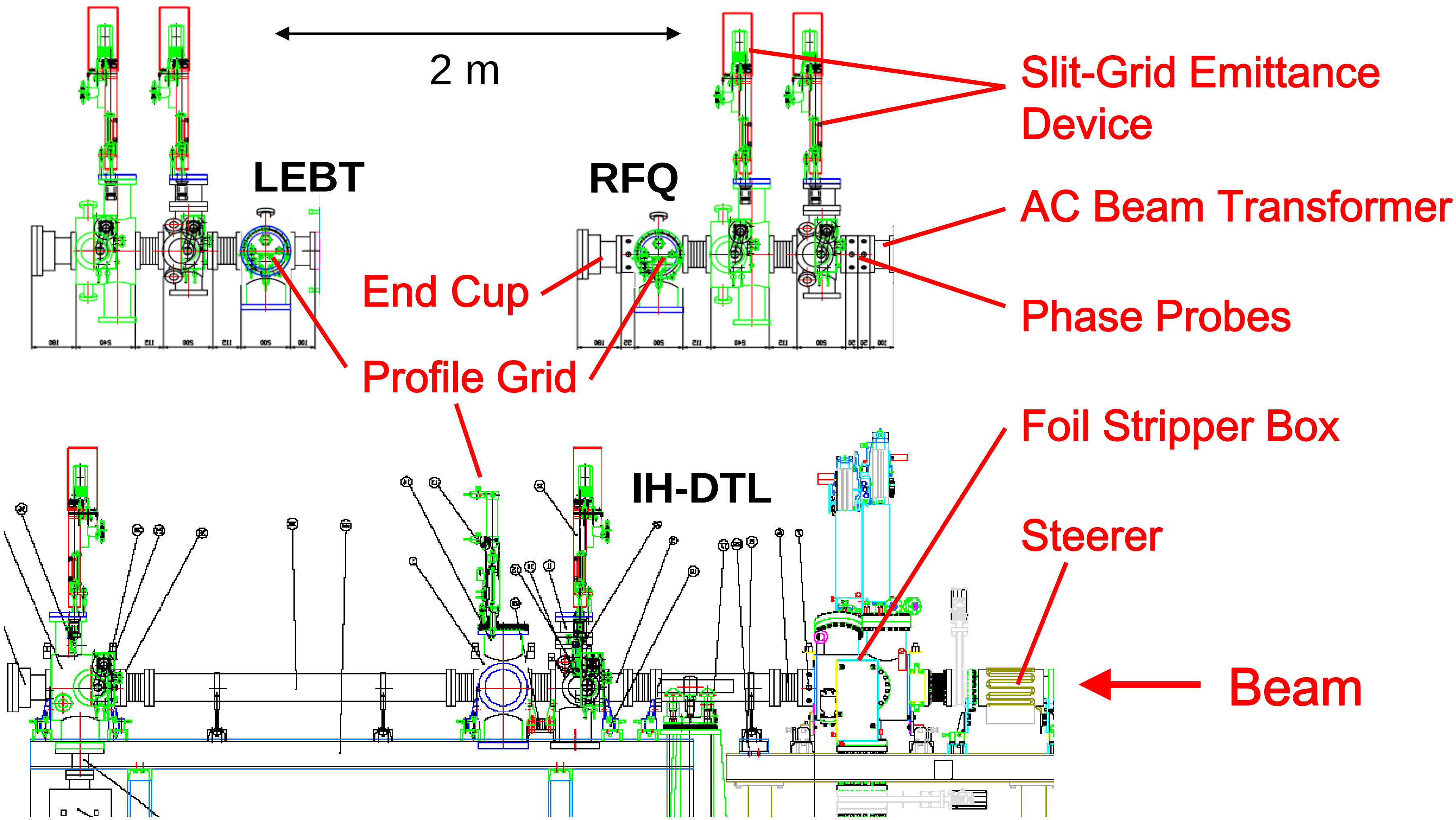


Operating frequency	216.816 MHz
Beam pulse length	≤ 300 μs @ PRF ≤ 5 Hz
RF pulse length	≤ 500 μs @ PRF ≤ 10 Hz
Ion mass-to-charge ratio	$A/q \leq 3$

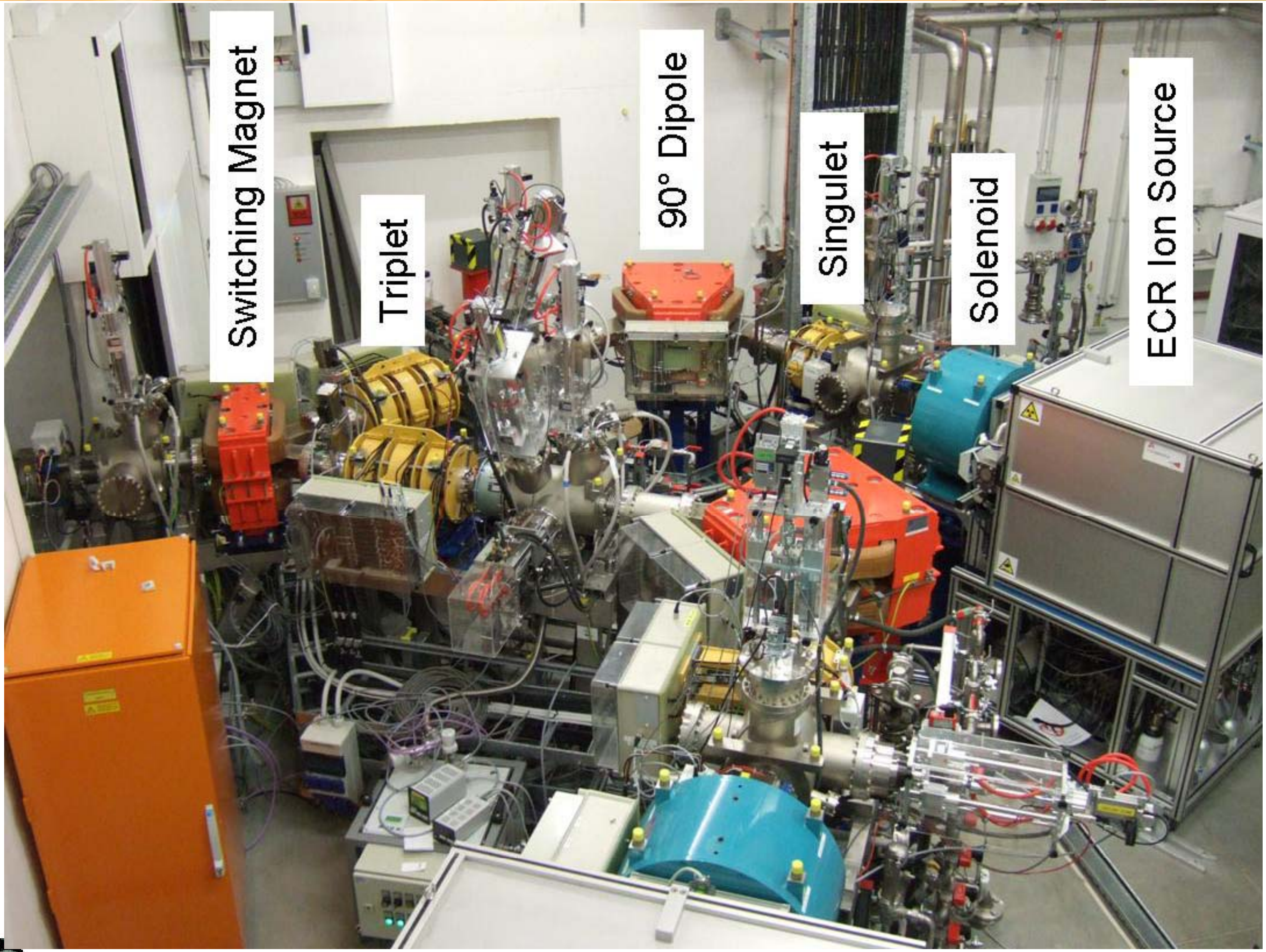
HIT Commissioning Milestones

2004 – 2005	Building	Building construction & installation of accelerator infrastructure
Nov 2005 – March 2006	LEBT, ECRIS	Installation & testing of components
April – May 2006	ECRIS	Successful beam commissioning
May – July 2006	LEBT	
July – Oct 2006	RFQ	Installation, RF commissioning
		Beam commissioning
Oct – Dec 2006	IH-DTL	Installation IH-DTL & stripper section
		RF commissioning
		First 7 MeV/u C^{6+} beams (53 eμA)
Feb 7, 2007	Synchrotron	1^{st} turn in synchrotron
March 23, 2007	HEBT	1^{st} accelerated beam in treatment places
Dec 16, 2007	H1, H2	C^{6+} and proton beams in treatment quality

Beam Commissioning Test Benches



Low Energy Beam Transport (LEBT) Lines



Ion Species and Analyzed Ion Currents

Ions from Source	Specified Ion Current / µA	Measured Ion Current / µA	Source Potential / kV	Ions to Synchrotron	Ions / Spill at Patient (Design)
$^{1}H_2^{+}$	1000	> 2000	16	protons	$\leq 4 \times 10^{10}$
$^{1}H_3^{+}$	700	≈ 710	24	protons	$\leq 4 \times 10^{10}$
$^{3}He^{+}$	500	≈ 840	24	$^{3}He^{+}$	$\leq 1 \times 10^{10}$
$^{12}C^{4+}$	200	≈ 200 ≈ 140 *	24	$^{12}C^{6+}$	$\leq 1 \times 10^{9}$
$^{16}O^{6+}$	150	≈ 170	21.3	$^{16}O^{8+}$	$\leq 5 \times 10^{8}$

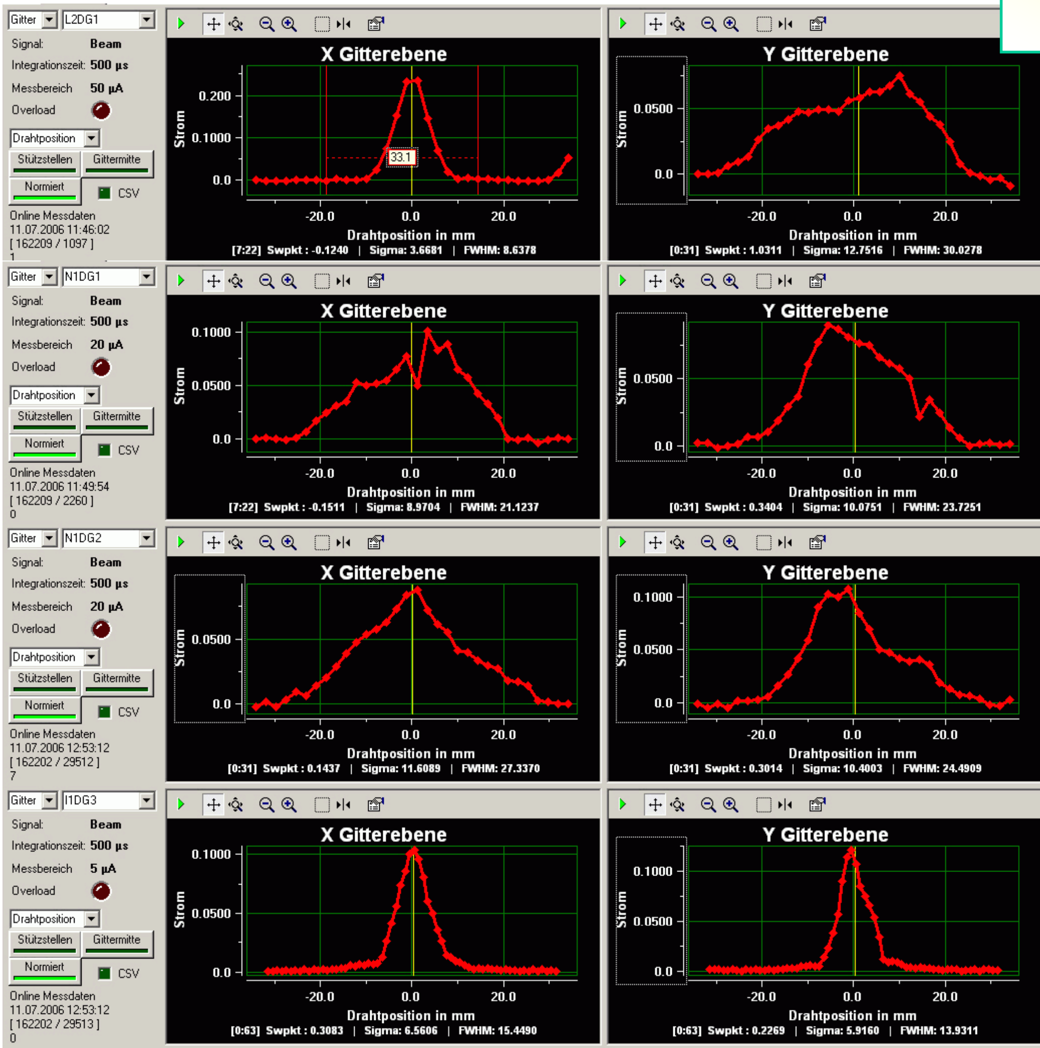
* During routine operation

Specified: within a beam emittance of 180 π mm mrad

LEBT: Measured Beam Profiles

Horizontal Vertical

$^{12}C^{4+}$



At analyzing slit

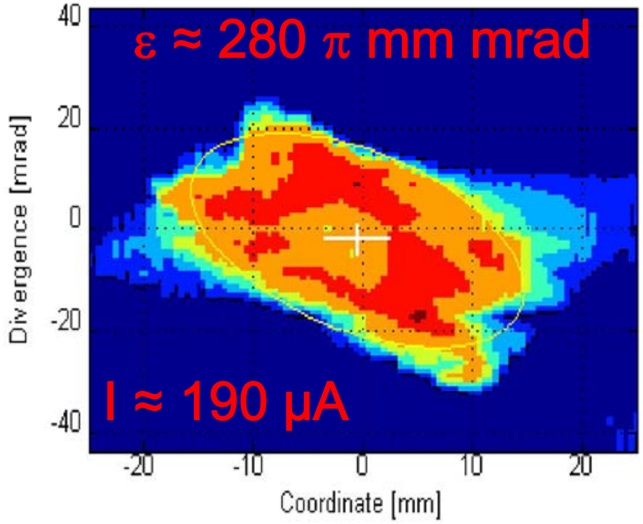
Straight section before 2nd solenoid → cylindrical symmetry

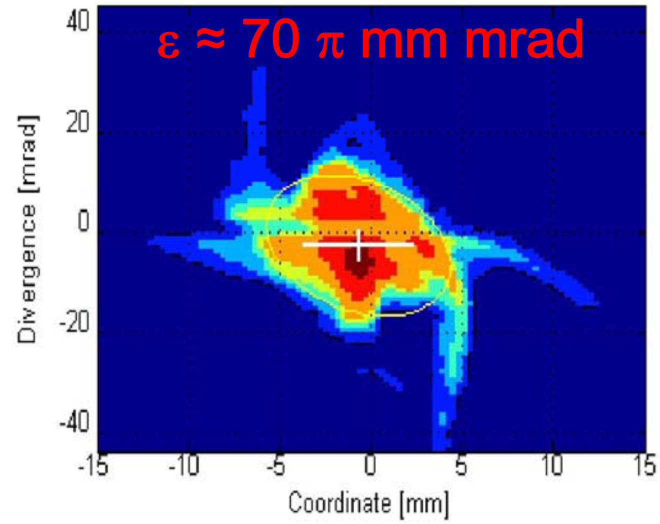
Transmission ≥ 90 %

At test bench behind 2nd solenoid

Measured Beam Quality behind LEBT

$^{12}C^{4+}$

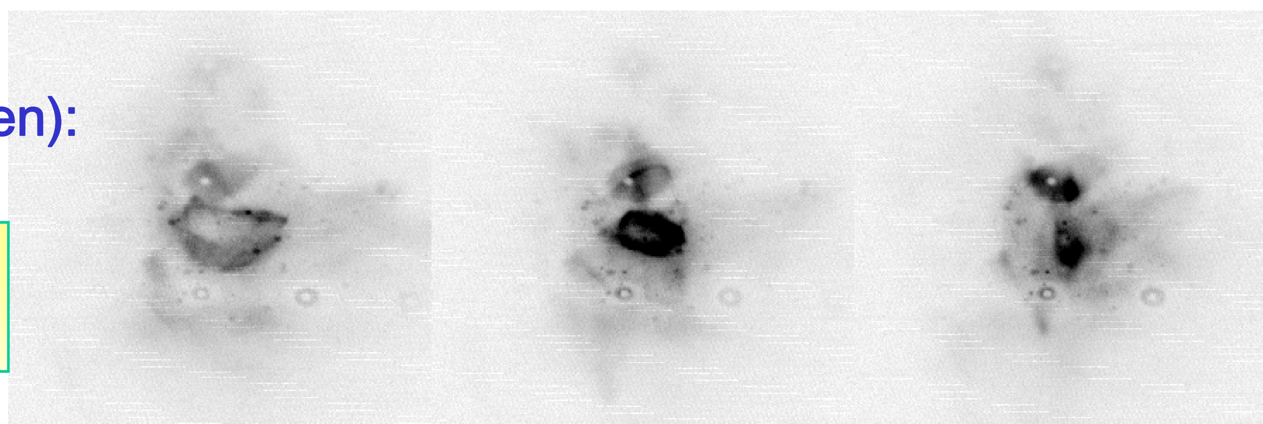




$^{16}O^{6+}$

$^{12}C^{4+}$: Emittances ≤ 200 π mm mrad measured for 150 µA

2D Profiles (Viewing Screen):

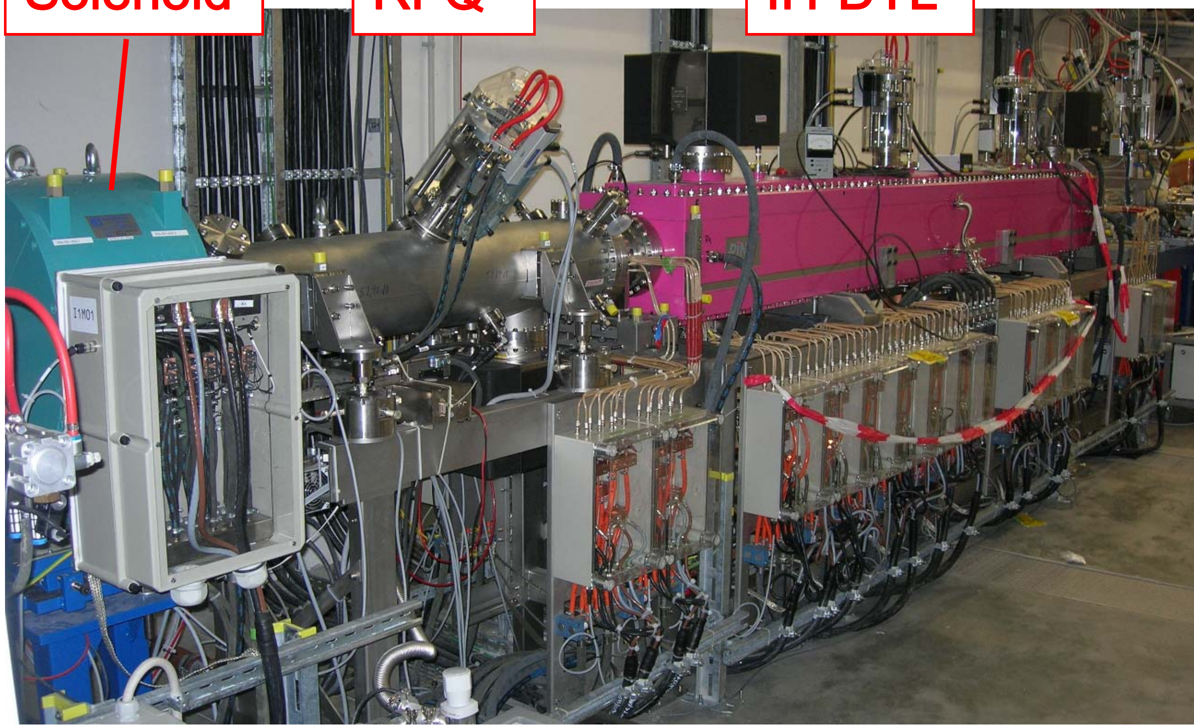


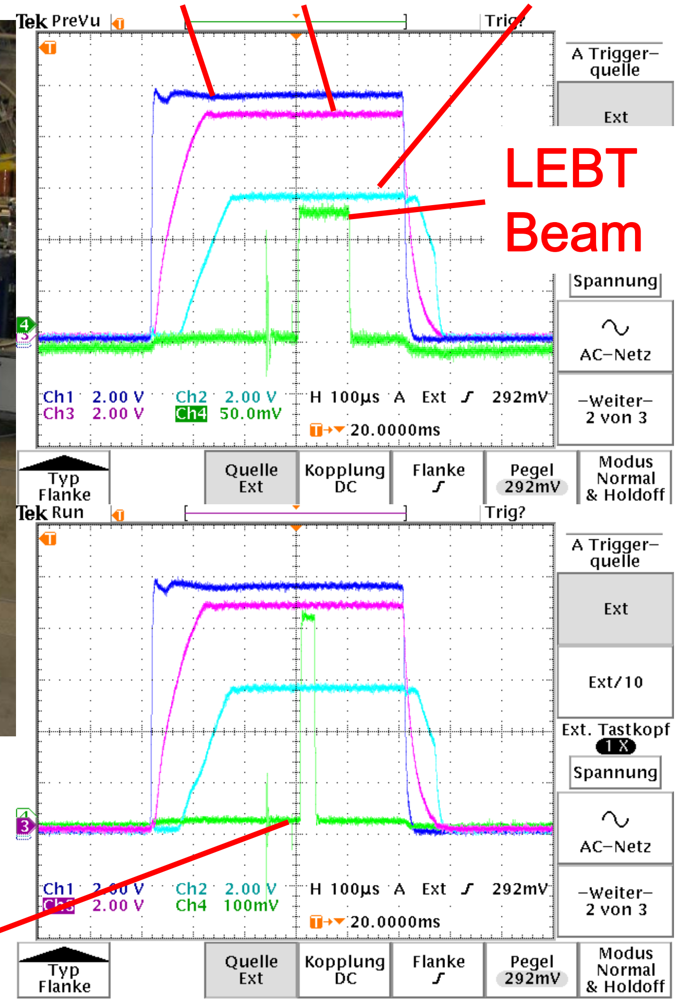
$^{12}C^{4+}$

P. Spaedtke
TUP115

Solenoid: 7 1/m 10 1/m 12 1/m

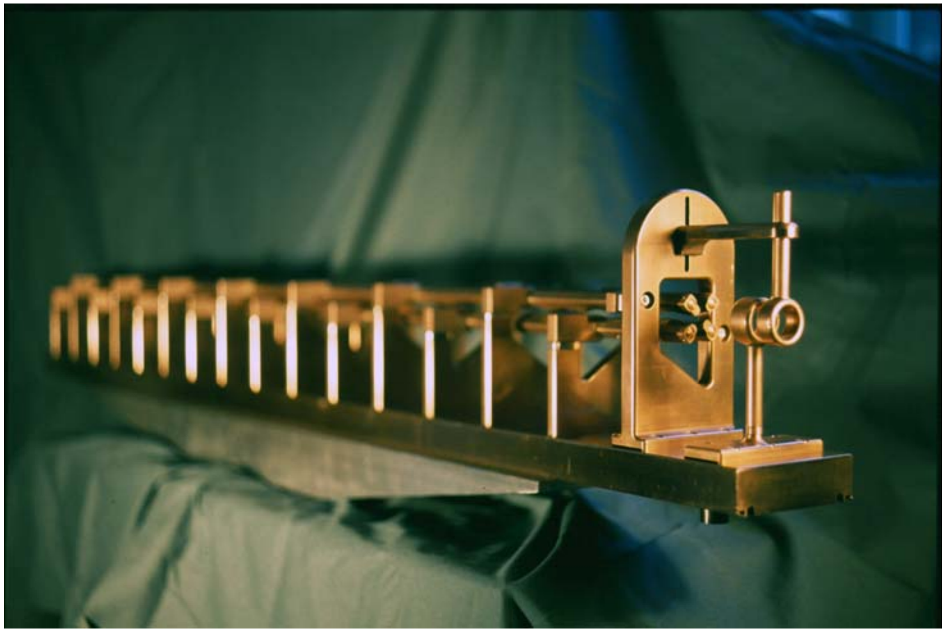
HIT LINAC

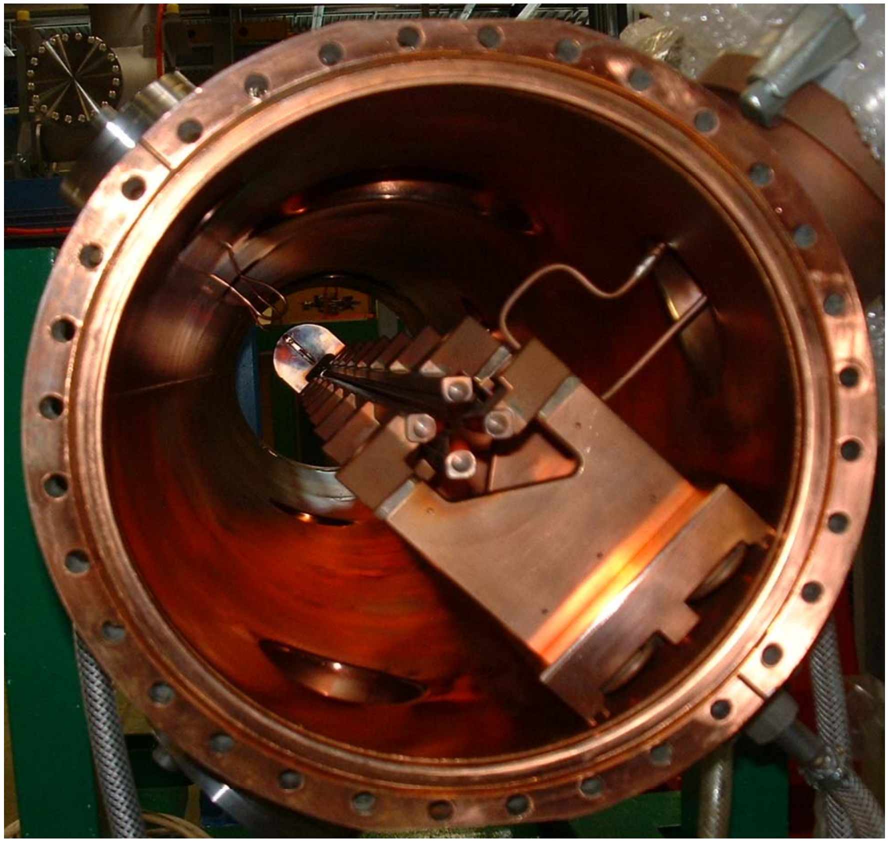

Solenoid
RFQ
IH-DTL


RFQ
IH
Debuncher
LEBT
Beam
Tek PreVu
Trig?
A Trigger-quelle
Ext
Spannung
AC-Netz
-Weiter- 2 von 3
Ch1 2.00 V Ch2 2.00 V H 100µs A Ext 292mV
Ch3 2.00 V Ch4 50.0mV
20.0000ms
Typ Flanke
Quelle Ext
Kopplung DC
Flanke
Pegel 292mV
Modus Normal & Holdoff
Tek Run
Trig?
A Trigger-quelle
Ext
Ext/10
Ext. Tastkopf 1 X
Spannung
AC-Netz
-Weiter- 2 von 3
Ch1 2.00 V Ch2 2.00 V H 100µs A Ext 292mV
Ch3 2.00 V Ch4 100mV
20.0000ms
Typ Flanke
Quelle Ext
Kopplung DC
Flanke
Pegel 292mV
Modus Normal & Holdoff
Beam behind LINAC
and 2nd chopper

400 keV/u 4-Rod Type RFQ

Designed, assembled and RF tuned at the IAP Frankfurt, Prof. Schempp



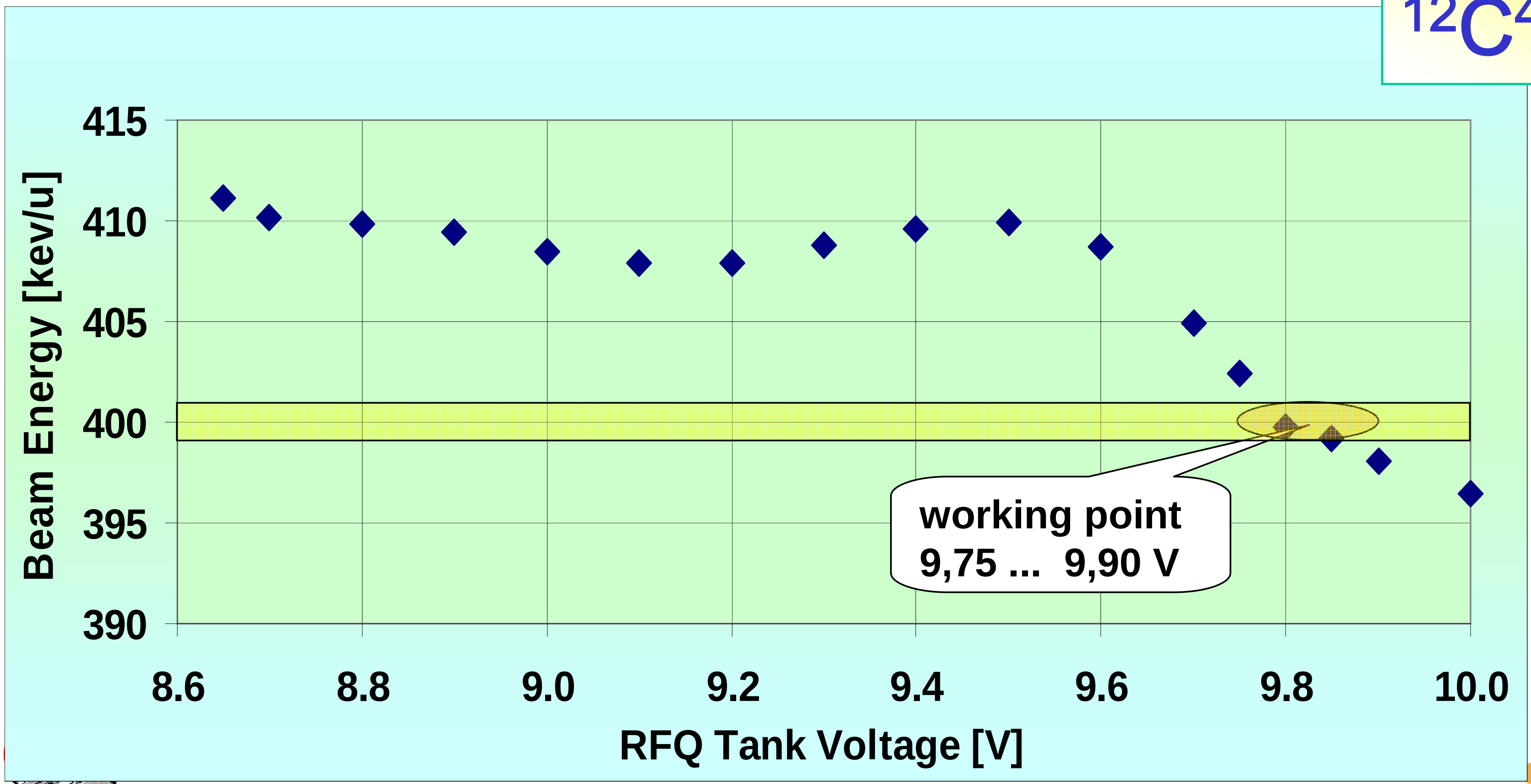


Beam energy in – out	8 – 400 keV/u
Electrode length	1.28 m
Tank diameter	0.25 m
Tank length	1.44 m
Electrode voltage	70 kV
RF power loss (pulse)	190 – 200 kW

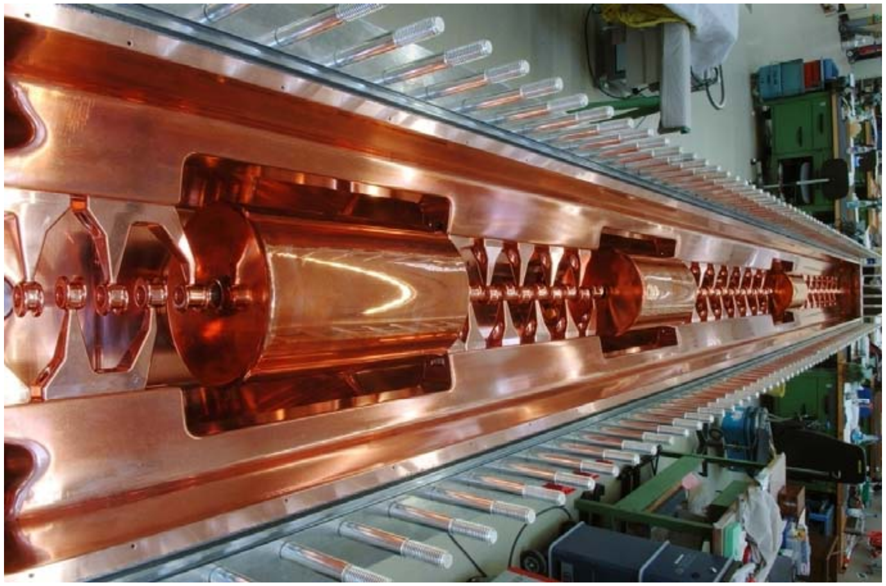
RFQ Working Point

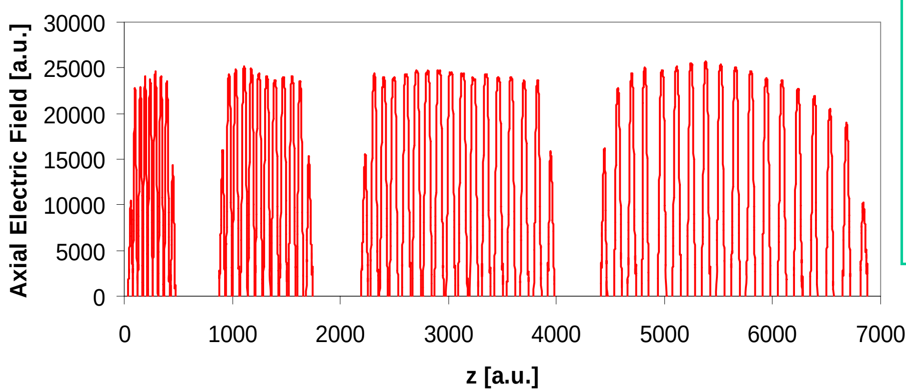
- Before installation at HIT: RFQ Testbench with proton beams at GSI (C. Kleffner et al., Proc. LINAC 2006, p. 791)
- Time-of-Flight (ToF) beam energy measurements during commissioning at HIT:

$^{12}C^{4+}$



20 MV IH-Type Drift Tube Cavity

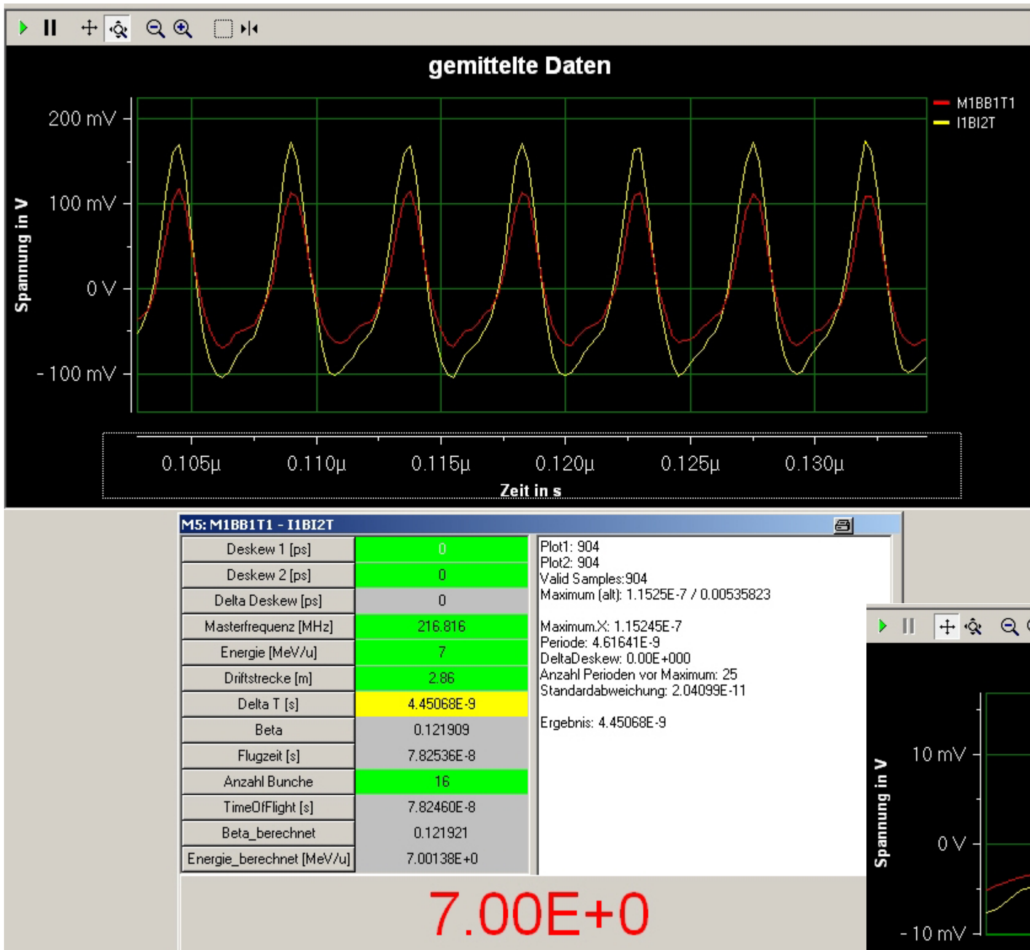




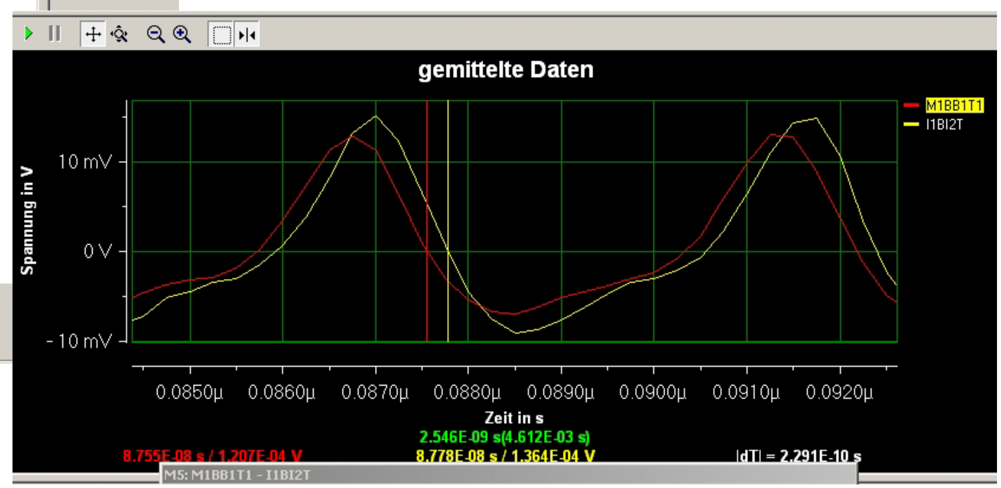
Beam energy in – out	0.4 – 7 MeV/u
Integrated triplet lenses	3
Accelerating gaps	56
Tank length	3.77 m
Inner tank height	0.34 m
Inner tank width	0.26 m
Drift tube aperture diam.	12 – 16 mm
Tank voltage	19.8 MV
Averaged eff. volt. gain	5.3 MV/m
Max. on axis electr. field	≤ 18 MV/m
Quality factor	15200
RF power loss (pulse)	≈ 830 kW
Eff. shunt impedance	≈ 125 MΩ/m

In collaboration with
IAP Frankfurt, Prof. Ratzinger

ToF Measurements behind LINAC

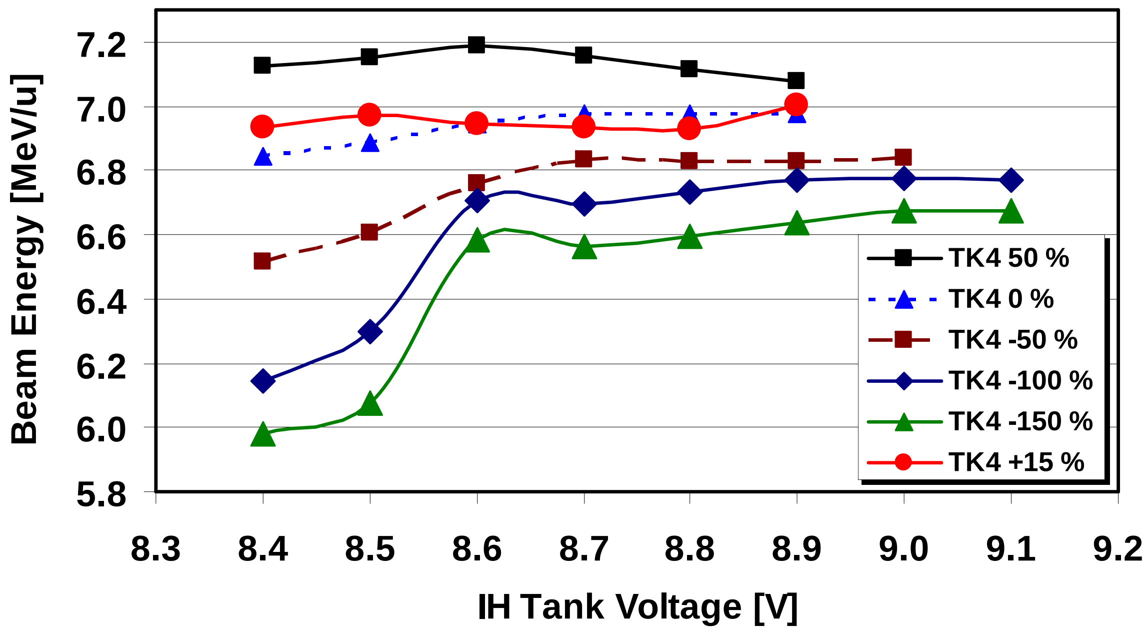


- Digitized phase probe signals can be routinely analyzed by control system GUI
- Optimized signal correlation calculation routines provide for high precision ToF analysis and energy measurements

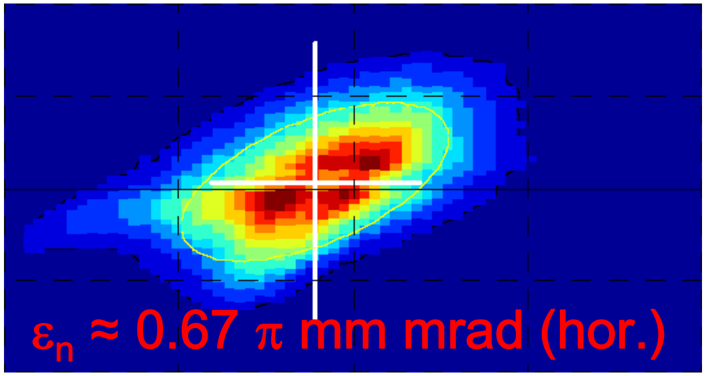


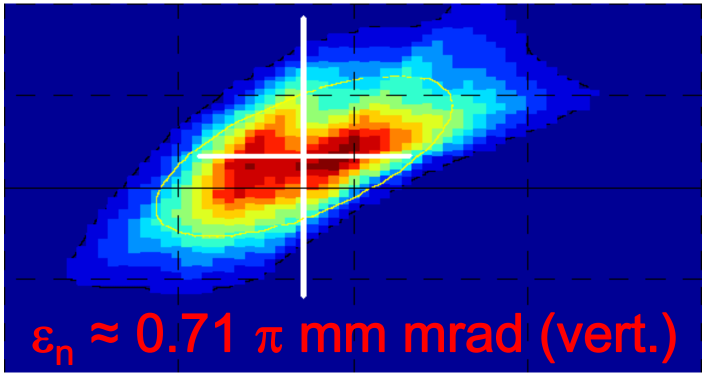
Measured Beam Parameters behind LINAC

Example: Beam energy for different RF plunger positions ($^{12}C^{4+}$):



Beam emittances behind foil stripper ($^{12}C^{4+}$):





Beam emittances agree well with simulation results

Summary of Commissionig Results

Achieved beam intensities:

	@ Synchrotron Injection	@ Treatment Places
$^{12}C^{6+}$	≈ 60 μA	4×10^{8}
protons	≈ 300 – 350 μA	1×10^{10}

- Since Feb 2007 routine operation of the LINAC
- Very stable LINAC beam parameters
- Stable and reliable LINAC operation, high availability
- Several improvements of ion sources,
  still problems with breakdowns of microwave generators

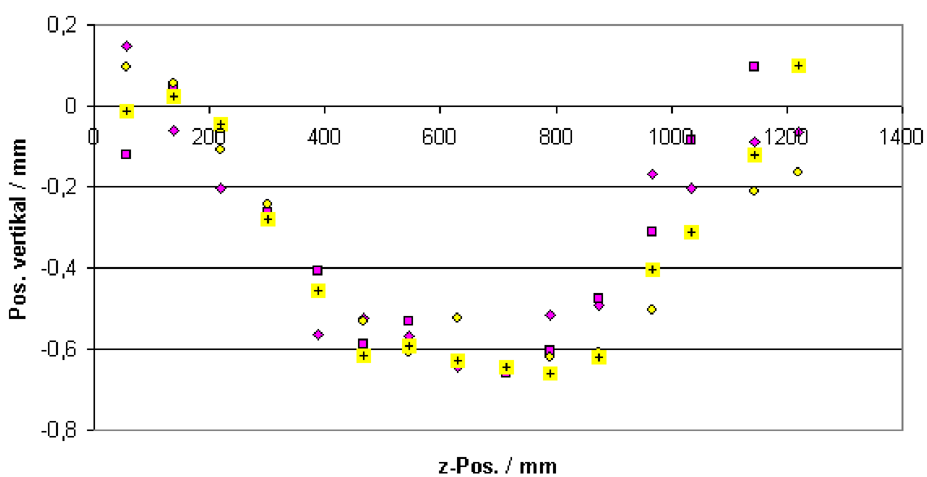
LINAC Upgrade Program

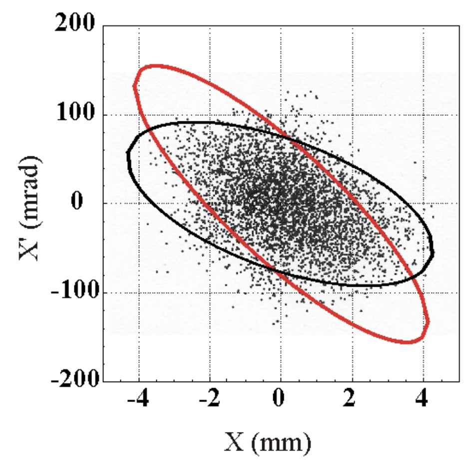
Beam intensities currently limited by the performance of the LINAC Front-End (ECRIS, RFQ injection):

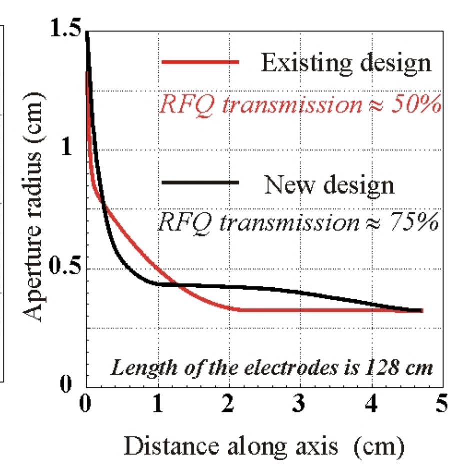
- Quality of ECRIS beams not sufficient ($^{12}C^{4+}$, Hydrogen)
- Mismatch at RFQ injection
- Deformations of RFQ electrodes reduce RFQ acceptance
- Beam losses along intertank section (steering effects)

M. Maier
MOP057

⇒ Revised RFQ design, currently beam tests of new RFQ at DANFYSIK



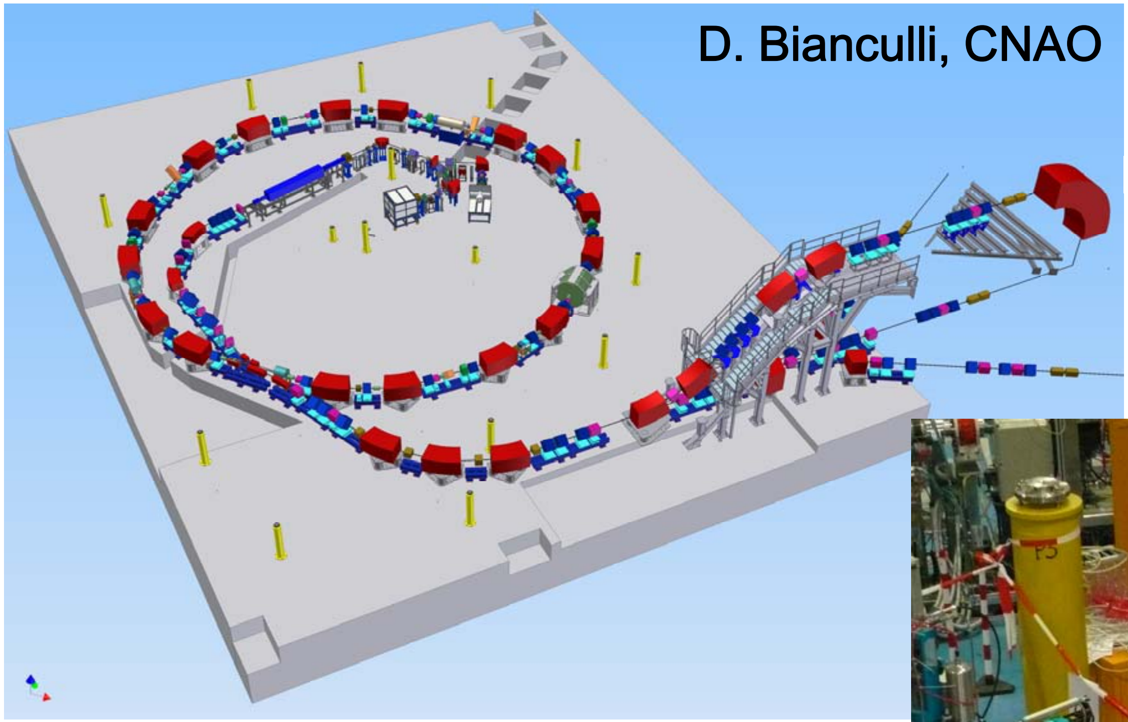




The CNAO Project

- The Centro Nazionale di Adroterapia Oncologica (CNAO) is presently being constructed in Pavia, Italy.
- 2004: Contract between CNAO and GSI regarding construction and commissioning of the CNAO injector linac, which is mainly a copy of the HIT linac.

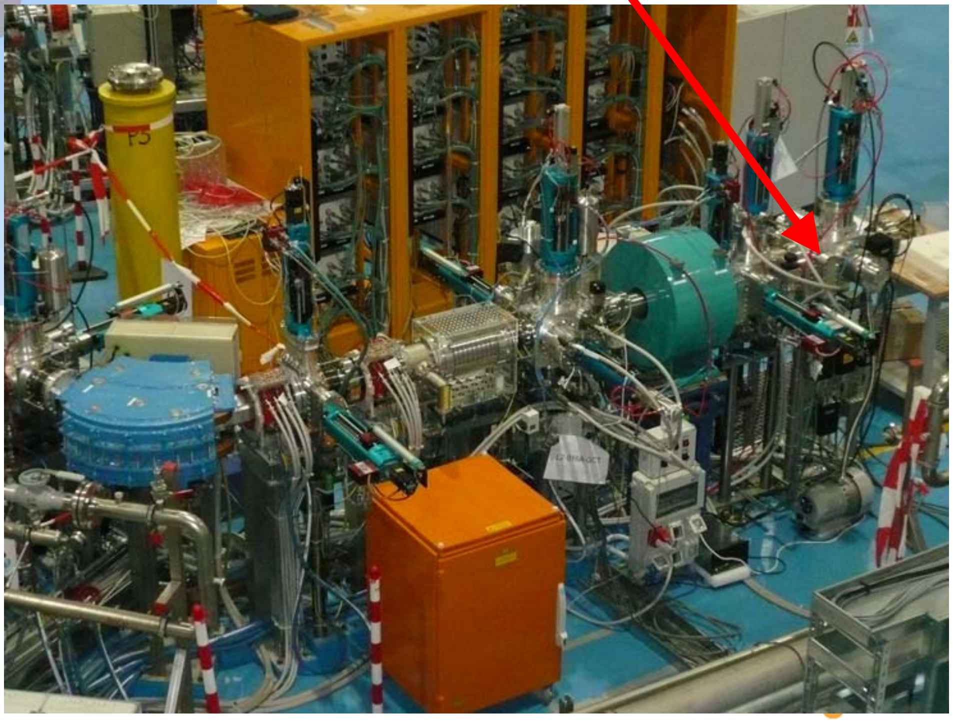
Status of the CNAO LINAC



S. Rossi, Proc. EPAC 2006, p. 3631

M. Pullia, Proc EPAC08, p. 982

Test bench behind LEBT



- Beam tests of LEBT ongoing
- Start of RFQ installation and commissioning end of October 2008

Conclusions & Outlook

- HIT LINAC successfully commissioned in 2006 with carbon and hydrogen ion beams, synchrotron & HEBT in 2007 / 2008
- HIT accelerator now operated by HIT company
- Beam intensities at treatment places well suited to start patient treatment
- HIT intends to be ready for patient treatment by end of 2008

- New RFQ should help to reach design performance at treatment places
- Further improvements of ECRIS planned
- Commissioning of CNAO LINAC will start soon
- An additional facility using the GSI LINAC design is presently being constructed by SIEMENS / DANFYSIK in Marburg, Germany, another one is planned elsewhere in Germany

Design and Construction History

1997	First patient treatment at GSI
1998	Conceptual design report
2000	Technical design report
1999 - 2001	RFQ model studies at IAP
2002 / 2003	Fabrication of RFQ
2004	RFQ beam tests at IAP
2005 / 2006	RFQ high power RF & beam tests at GSI
2001	Fabrication of 1:2 scaled IH DTL model
2002 / 2003	Tuning & investigations of IH model cavity at IAP
2002	Constr. & test of linac quadrupole magnet prototypes at GSI
2002	Call for tenders accelerator components and building
2003	Accelerator components ordered from industry
Nov 2003	Beginning of excavation activities for the building in HD
2004 / 2005	Construction of accelerator components