ARIES

GSI Helmholtzzentrum für Schwerionenforschung GmbH

Experiences from medical LINAC commissioning

ARIES Workshop
Experiences During Hadron Linac Commissioning

Bernhard Schlitt, GSI

January 26, 2021

Outline

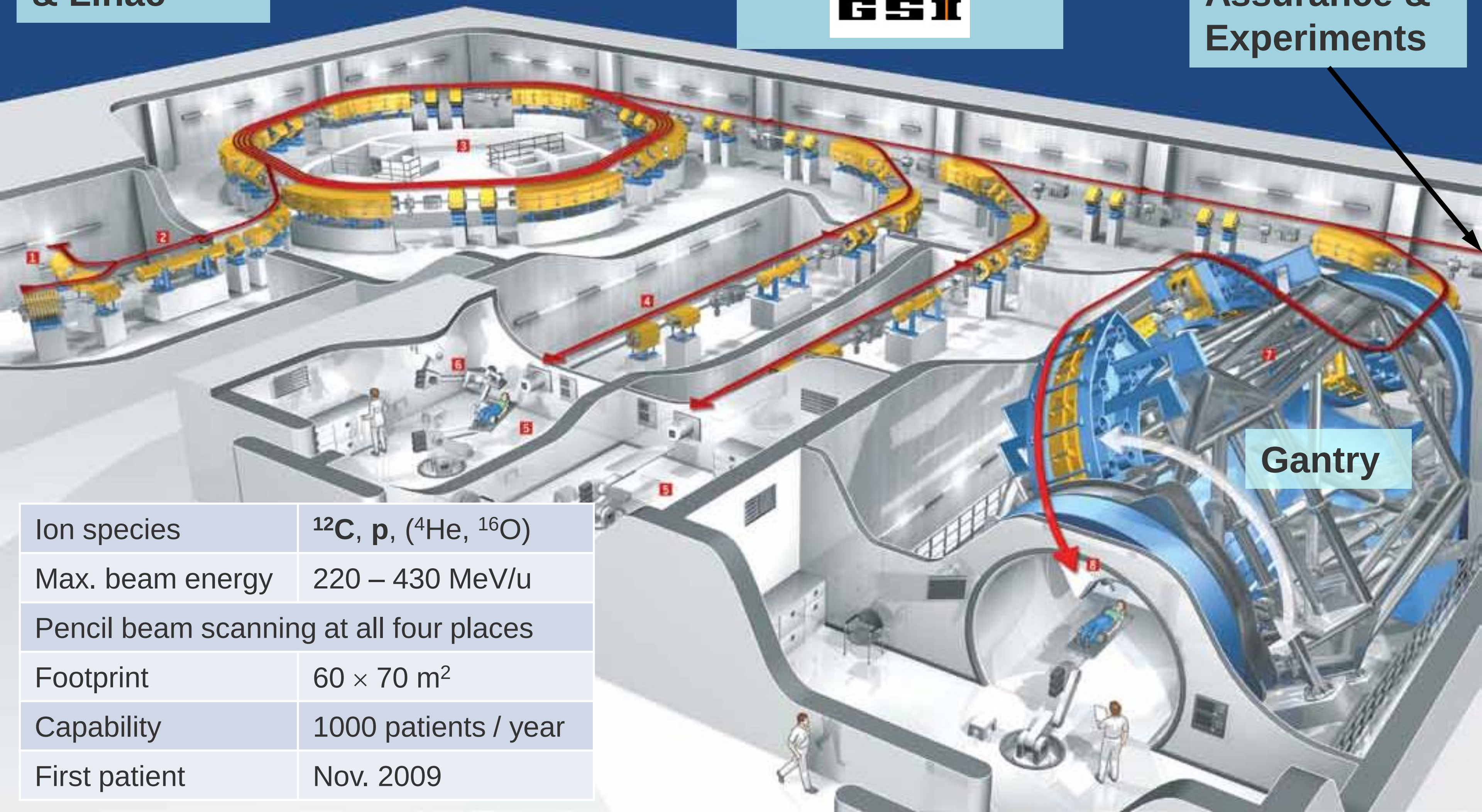
- Dedicated ion beam therapy centers (synchrotrons)
- HIT & CNAO facility overviews
- Injector linac design & commissioning
- Conclusions

Dedicated (Carbon) Ion Beam Therapy Centers (Based on Synchrotrons)

Center		Start	Injector
HIMAC - Heavy Ion Medical Accelerator in Chiba	Japan	1994	Alvarez
HIBMC - Hyogo Ion Beam Medical Center	Japan	2002	Alvarez
GHMC - Gunma University Heavy Ion Medical Center	Japan	2010	200 MHz APF-IH-DTL 4 MeV/u
SAGA HIMAT, Tosu	[illegible]an	2013	
i-ROCK Kanagawa Cancer Center, Yokoh[illegible]	[illegible]n	2015	
Osaka Heavy Ion Therapy C[illegible]	Japan	2018	
HIT - Heidelberg Ion Beam [illegible]enter	Germany	2009	217 MHz KONUS-IH-DTL 7 MeV/u
CNAO, Pavia	Italy	2011	
SPHIC - Shanghai Proton and Heavy Ion Center	China	2014	
MIT - Marburg Ion Beam Therapy Center	Germany	2015	
MedAustron, Wiener Neustadt	Austria	2016	
Heavy Ion Cancer Treatment Center, Wuwei	China	2019	(Cyclotron)

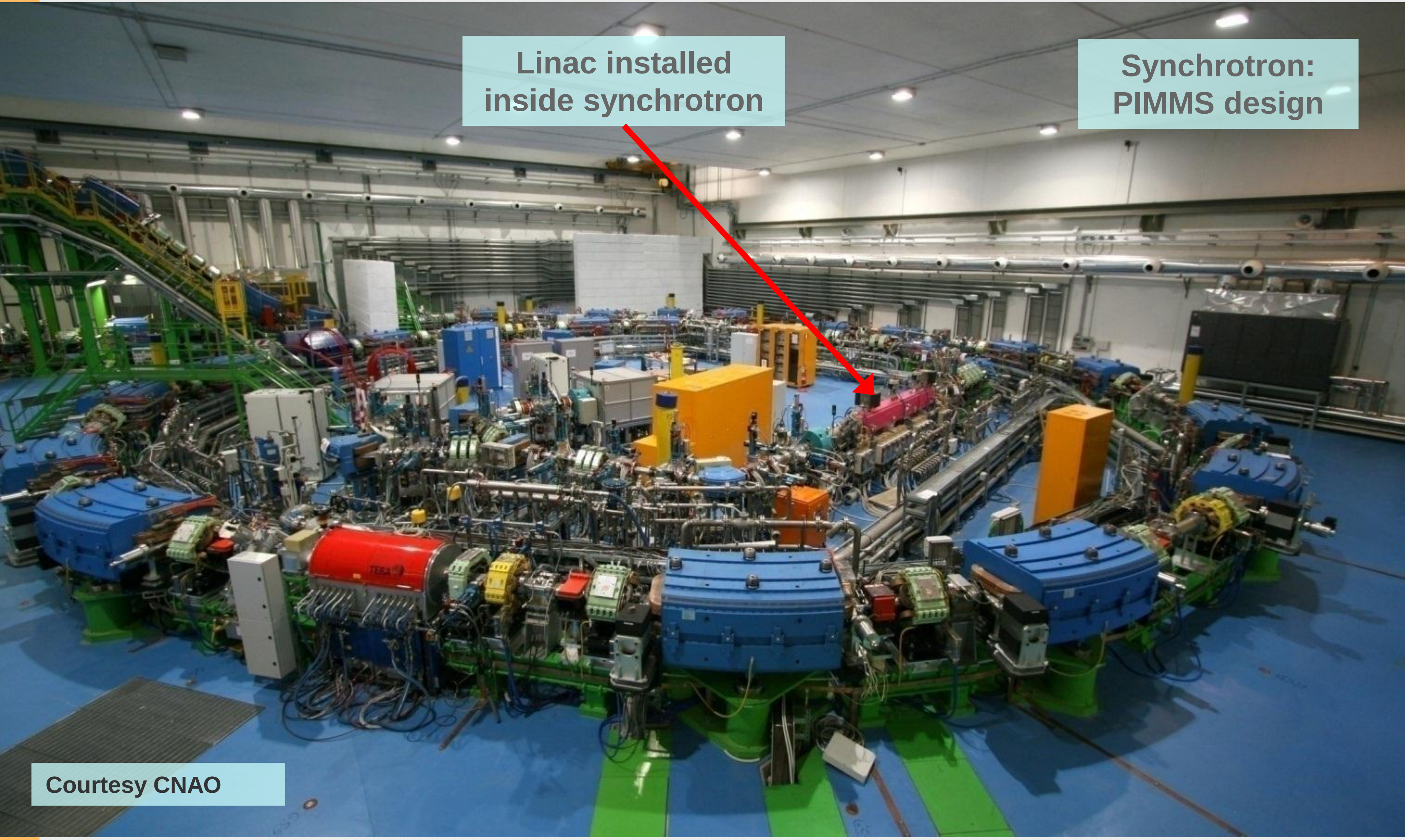
8 additional facilities worldwide under construction / planning

HIT
Heidelberg Ion Beam Therapy Center



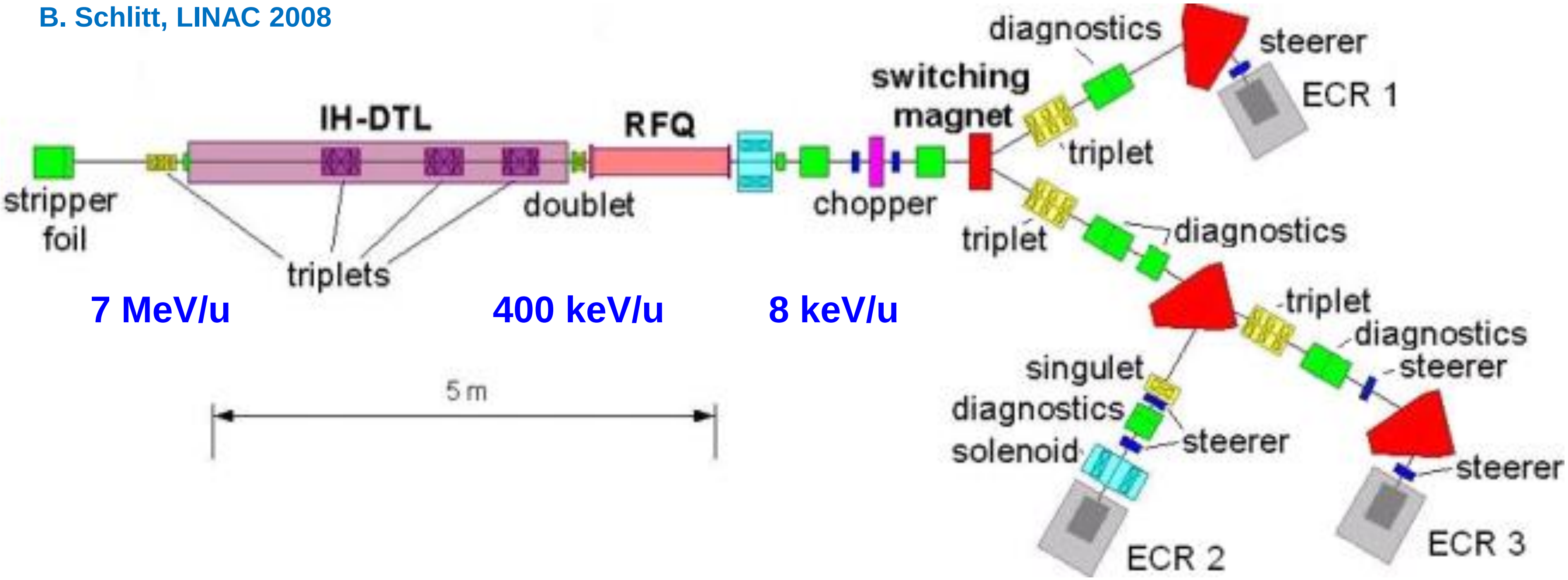
Ion species	^{12}**C**, **p**, (^{4}He, ^{16}O)
Max. beam energy	220 – 430 MeV/u
Pencil beam scanning at all four places	
Footprint	60 × 70 m^{2}
Capability	1000 patients / year
First patient	Nov. 2009

CNAO, Pavia


Linac installed inside synchrotron
Synchrotron: PIMMS design
TEBA
Courtesy CNAO

217 MHz HIT Injector Linac

B. Schlitt, LINAC 2008



- ECR 1 — H_3^+ (≤ 1.3 mA)
- ECR 2 — C^{4+} (≤ 220 µA)
- ECR 3 — helium & oxygen beams + redundancy
- Pulsed beams — ≤ 300 µs @ ≤ 5 Hz
- Operating frequency — 216.8 MHz

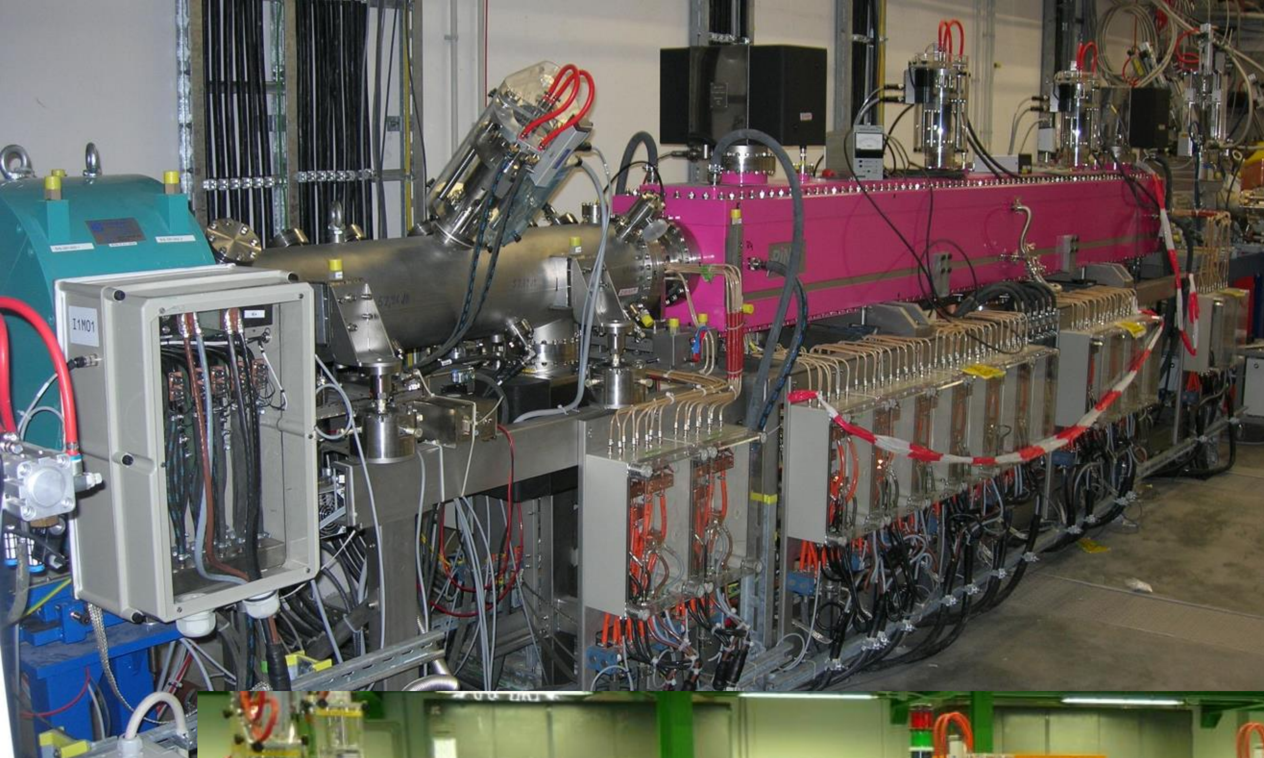
T. Winkelmann et al., ECRIS 2014

HIT & CNAO LEBT & Linac Beam Instrumentation

M. Schwickert, A. Peters, EPAC 2004
A. Reiter et al., EPAC 2006

Viewing screens (org. Ta)	Real 2D images of ion source beams
SEM profile grids (at CNAO also wire scanners)	Beam profiles & positions (LEBT, Linac, MEBT)
Moveable slits	Beam analysis & selection of ion species (LEBT)
Faraday cups	Beam stop, DC / AC beam currents
DC & AC beam current transformers	Continuous beam current monitoring
Capacitive pick-ups / phase probes	TOF beam energy & bunch measurements (behind RFQ & Linac)

- See contributions by **R. Cee (next talk)** and **A. Reiter (Wednesday, 4:35 pm)** for **further details and applications during routine operation & commissioning**
- **No emittance measurement installed at HIT for routine operation** (just during beam commissioning & at test bench at HIT, see talk by R. Cee)
- **CNAO: permanent emittance measurement devices installed along LEBT** (slits & wire scanners, **J. Bosser et al., EPAC 2008, A. Parravicini et. al., HIAT09**)

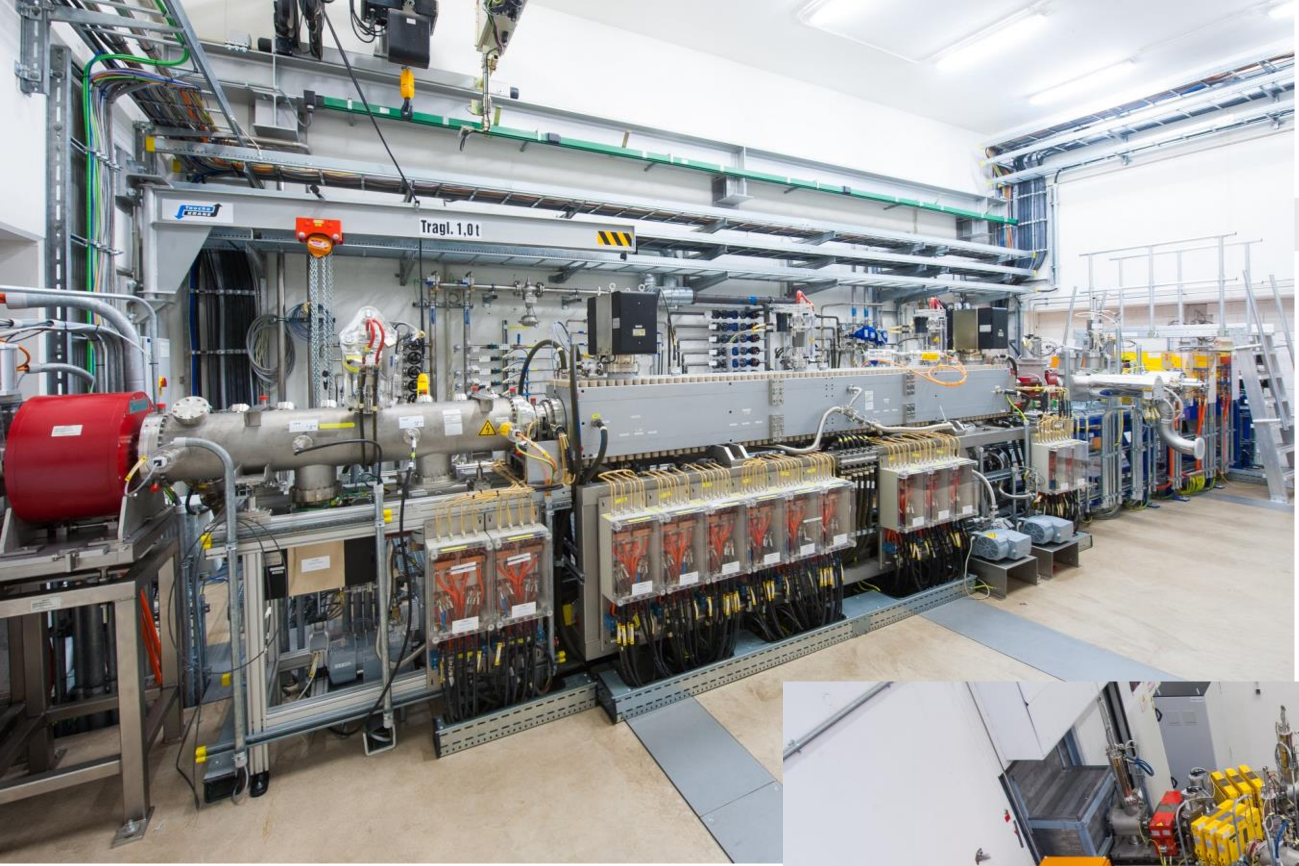


HIT Injector Linac, Heidelberg, Germany

B. Schlitt, LINAC 2008

CNAO, Pavia, Italy

B. Schlitt et al., IPAC 2010

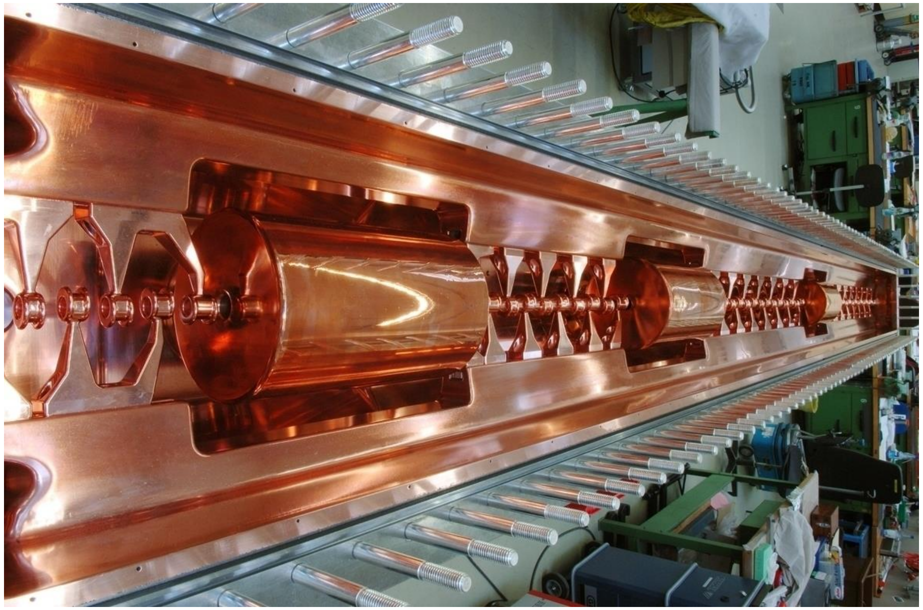


MIT Injector Linac, Marburg, Germany

built by Siemens / Danfysik

Photos: Siemens

20 MV Interdigital H-Mode Drift Tube Linac (IH-DTL)



Beam energy in – out	0.4 – 7 MeV/u
Integrated triplet lenses	3
Accelerating gaps	56
Tank length	3.8 m
Inner tank height	0.34 m
Inner tank width	0.26 m
Drift tube aperture diam.	12 – 16 mm
Tank voltage	~ 20 MV
Averaged eff. volt. gain	5.3 MV/m
Max. on axis electr. field	≤ 18 MV/m
Max. eff. gap voltage	~ 500 kV
Quality factor	15200
RF power loss (pulse)	~ 900 kW

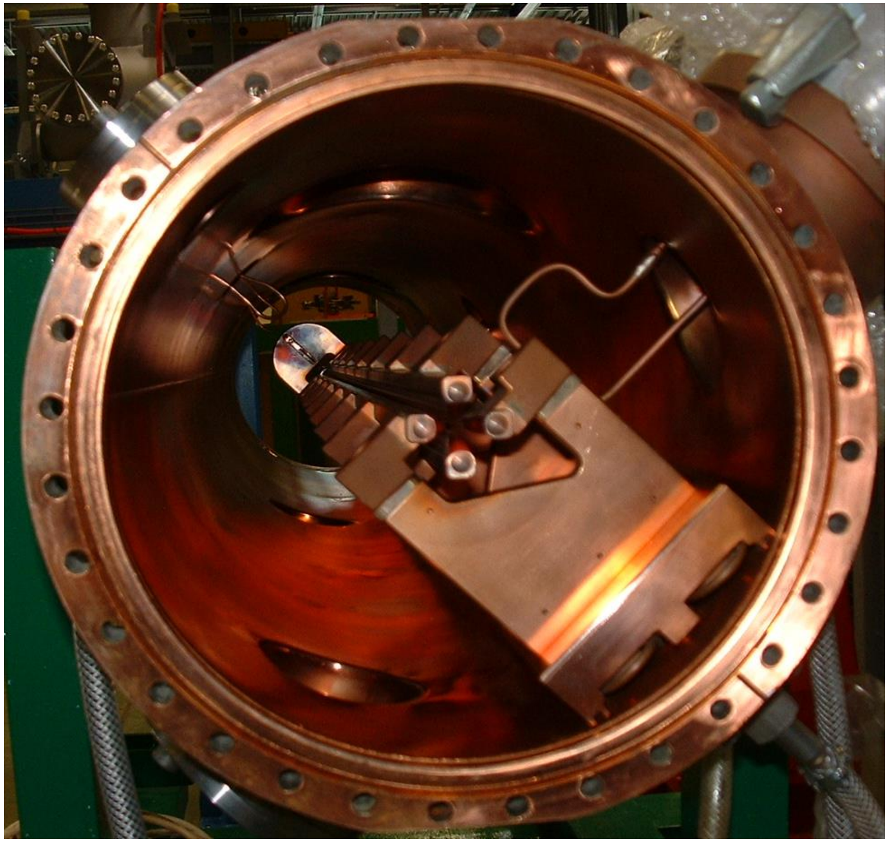
B. Schlitt et al., LINAC 2004 & LINAC 2006
Y. Lu, LINAC 2004

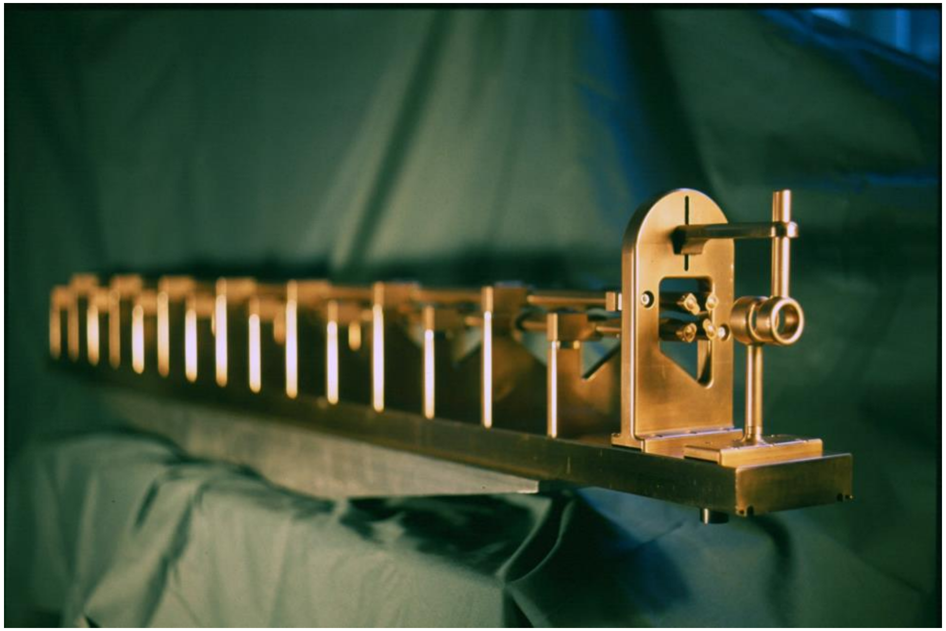
In collaboration with IAP,
Frankfurt University, Prof. Ratzinger

400 keV/u 4-Rod Type RFQ

Designed and assembled at IAP,
Frankfurt University, Prof. Schempp

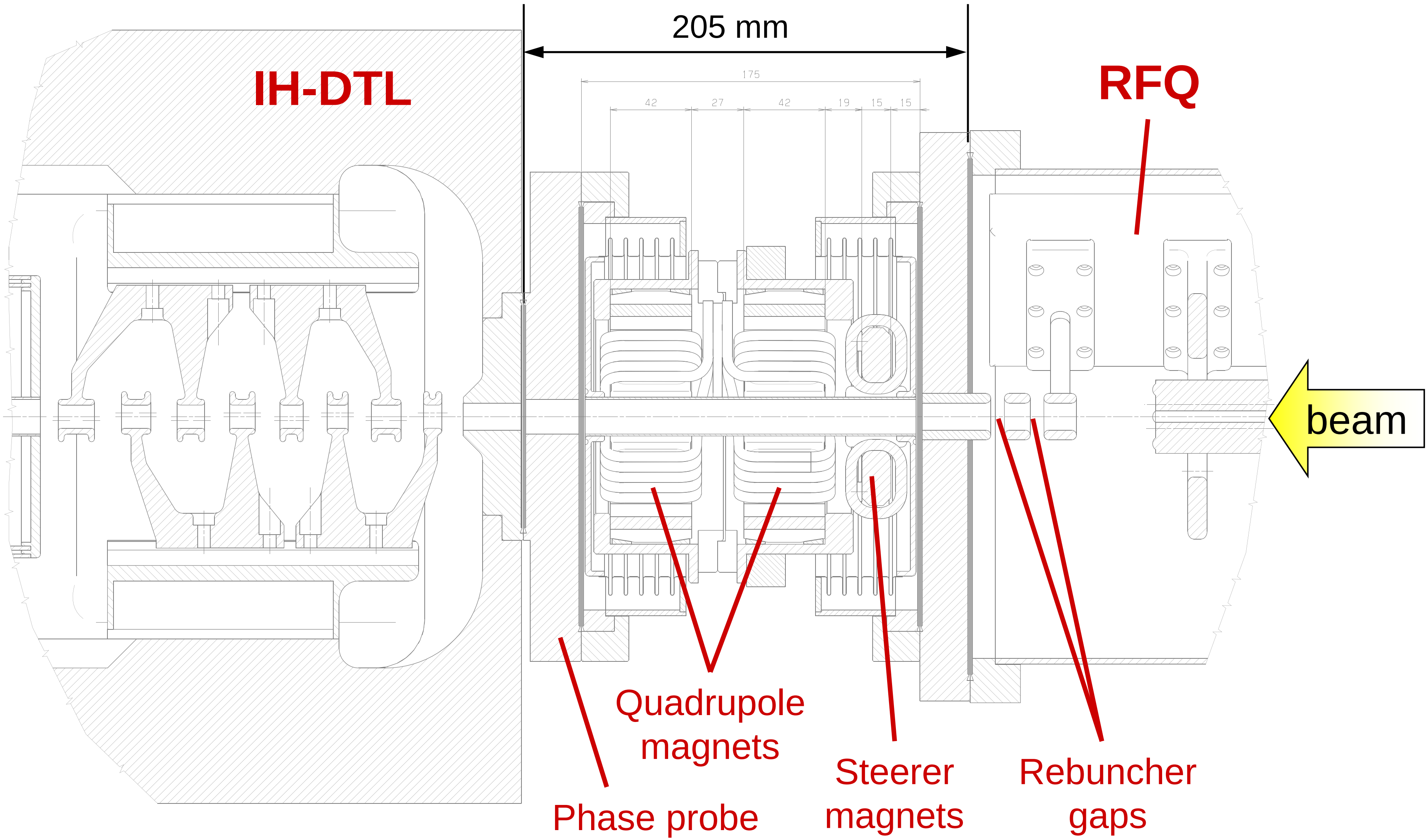
A. Bechtold et al., EPAC 2004





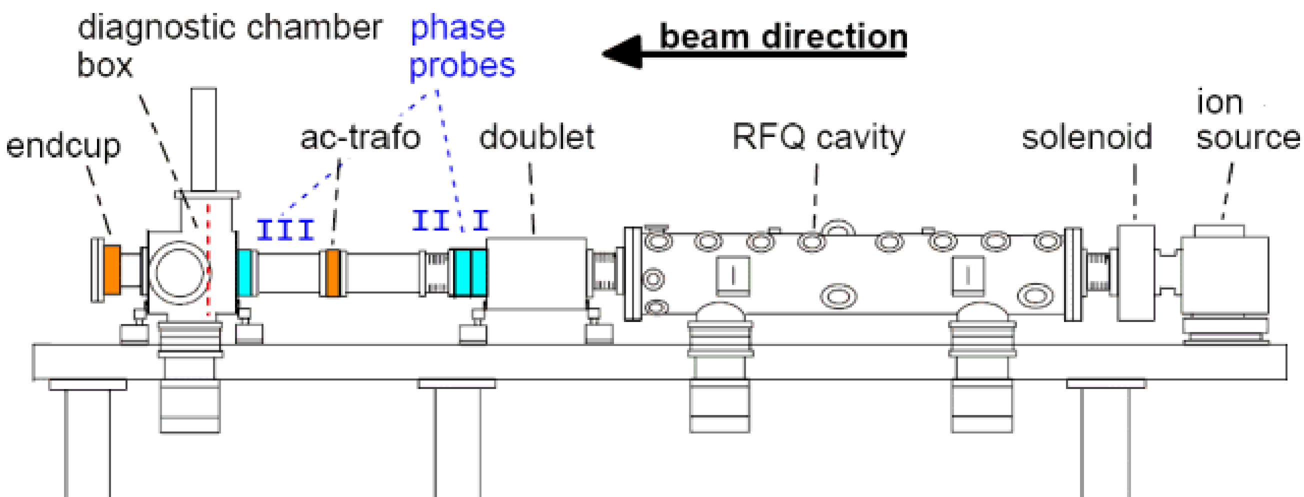
Beam energy in – out	8 – 400 keV/u
Electrode length	1.28 m
Tank diameter	0.25 m
Tank length	1.44 m
Electrode voltage	70 kV
RF power loss (pulse)	~ 200 kW

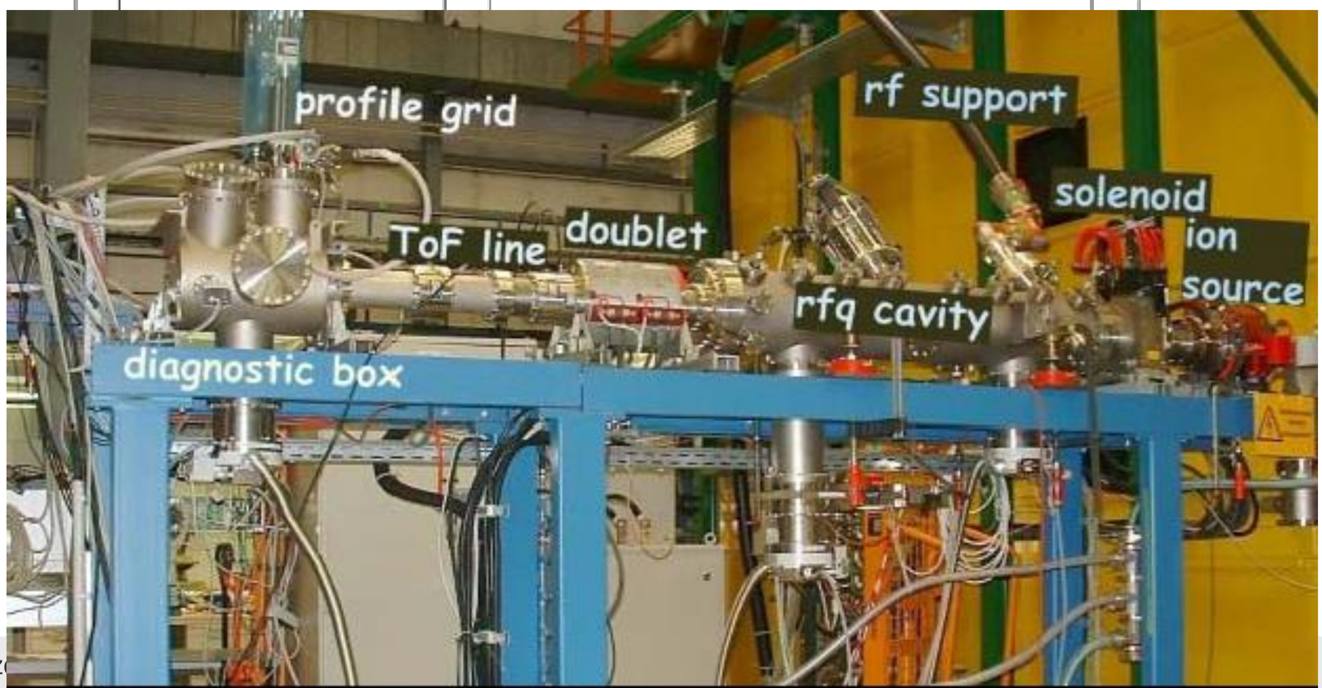
400 keV/u Inter-tank Section (ITM)



RFQ Beam Test Bench @ GSI (HIT & CNAO RFQs)

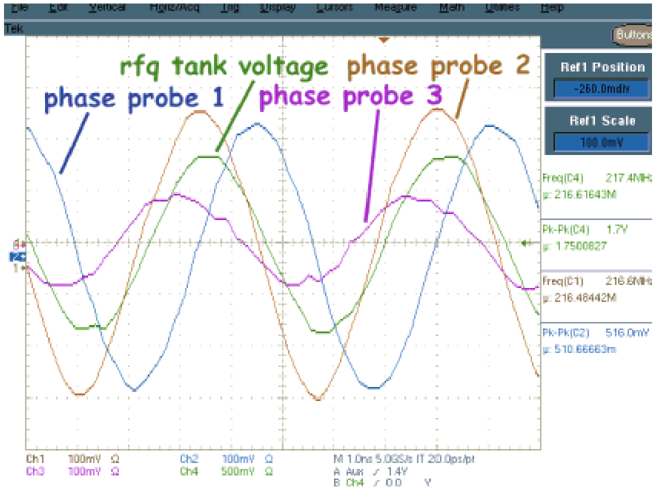
C.-M. Kleffner et al., LINAC 2006

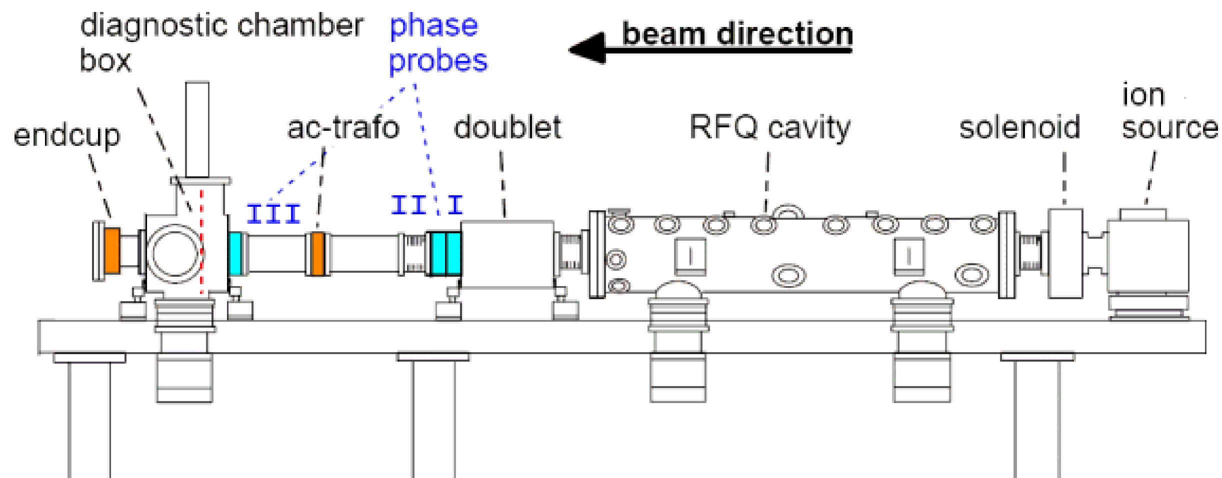


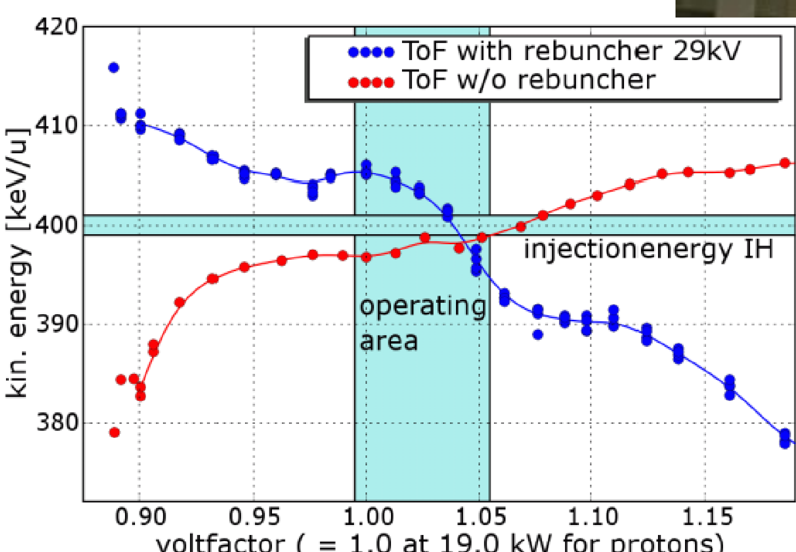


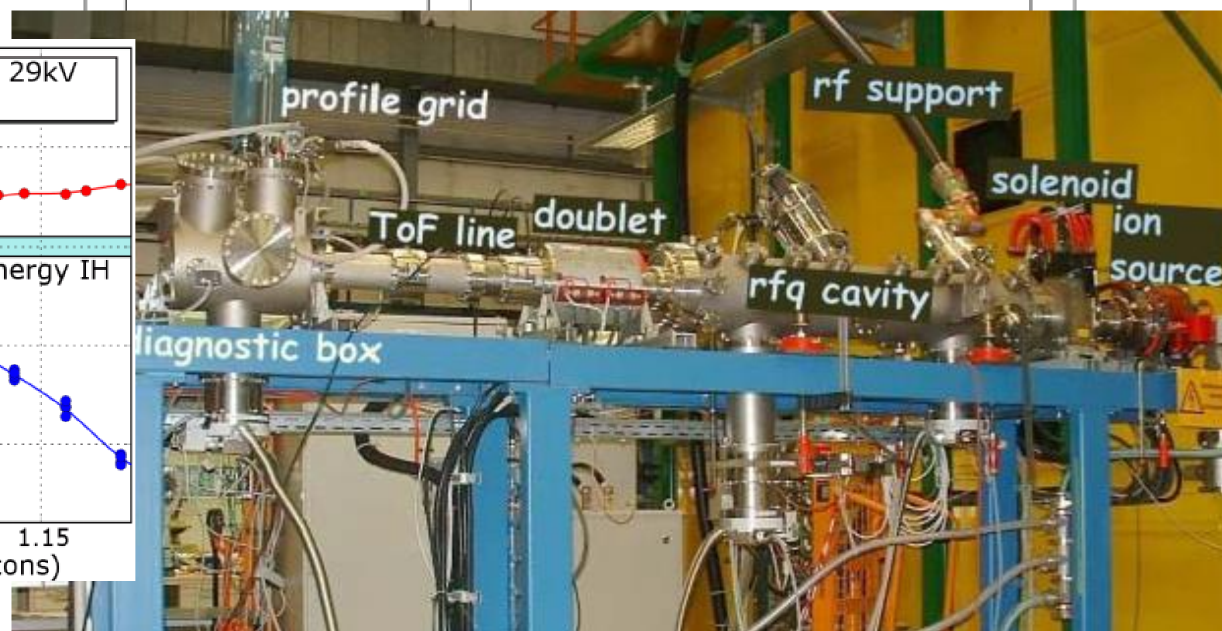
RFQ Beam Test Bench @ GSI (HIT & CNAO RFQs)

C.-M. Kleffner et al., LINAC 2006







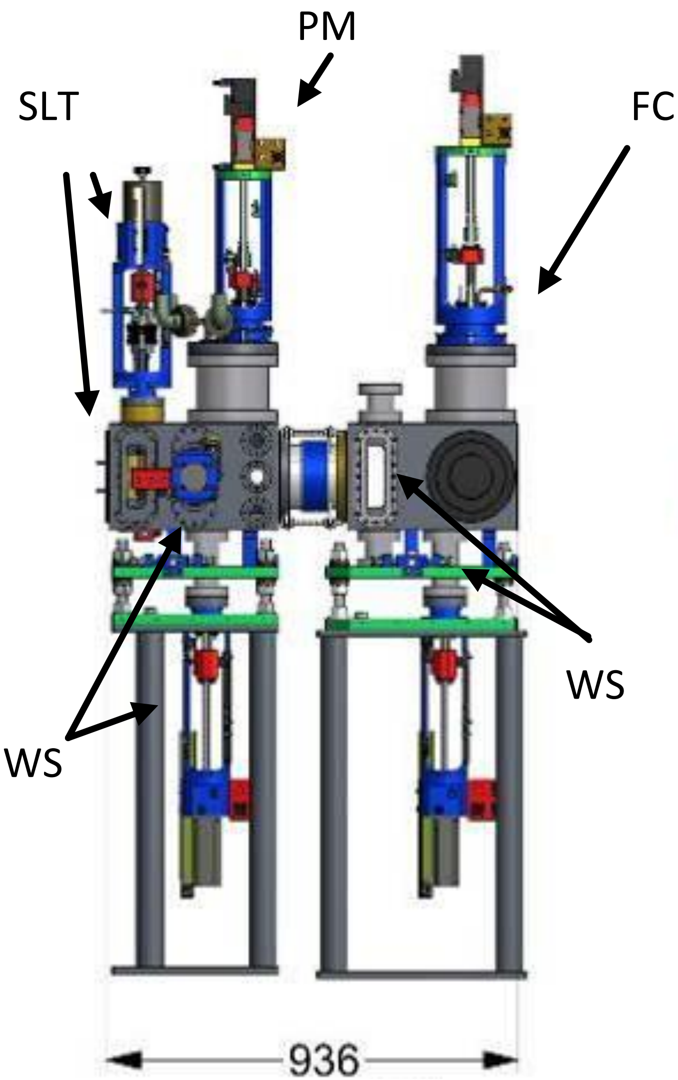


HIT Linac Commissioning Milestones

B. Schlitt, LINAC 2008

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
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

CNAO
LEBT Beam Commissioning Test Bench



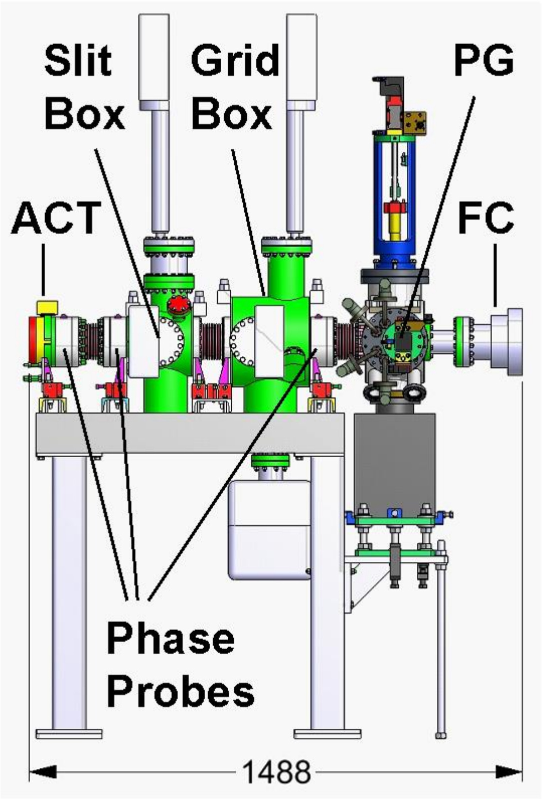
- **Wire scanners (WS)** used for emittance measurements
  → large angular acceptance (±150 mrad)
- **Slits (SLT) at RFQ input matching point**
  → beam measurements at nominal field of the focusing solenoid
- **Investigation & minimization of solenoid steering**
- **Preparation of H_3^+ probe beam** (factor 5 to 10 smaller rms emittances)

P. Posocco et al., HIAT09

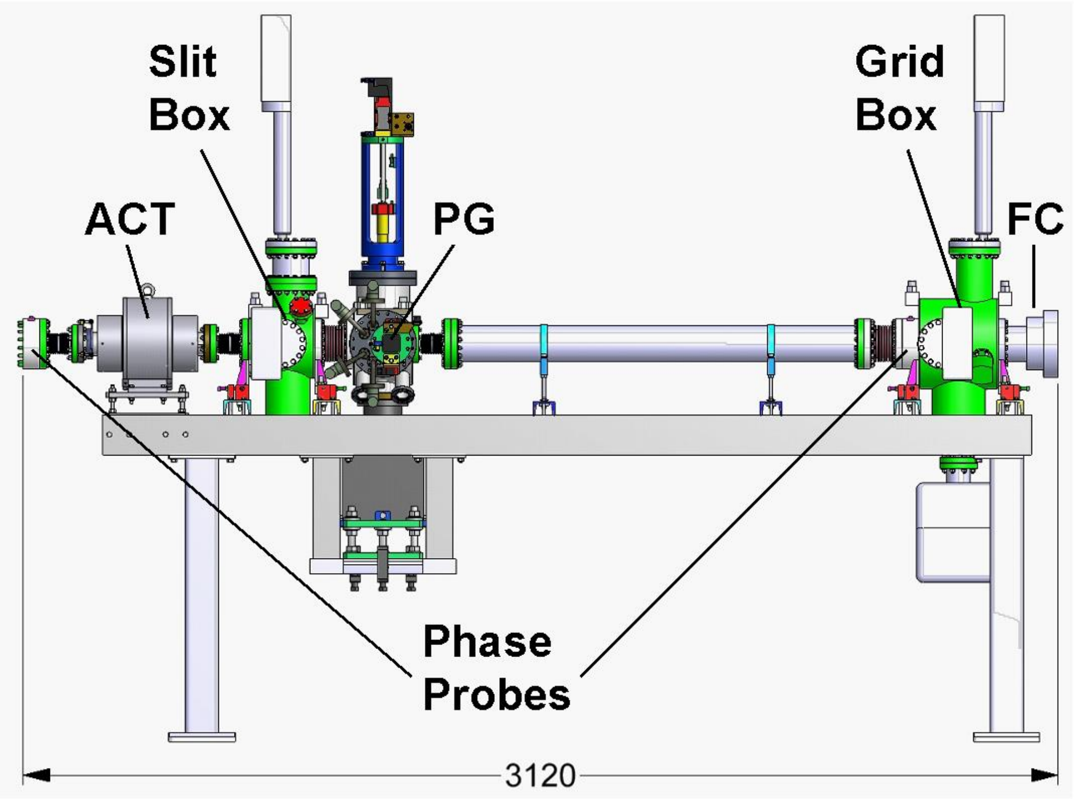
CNAO
Linac Beam Commissioning Test Benches

P. Posocco et al., HIAT09, B. Schlitt et al., IPAC 2010

Behind RFQ & ITM



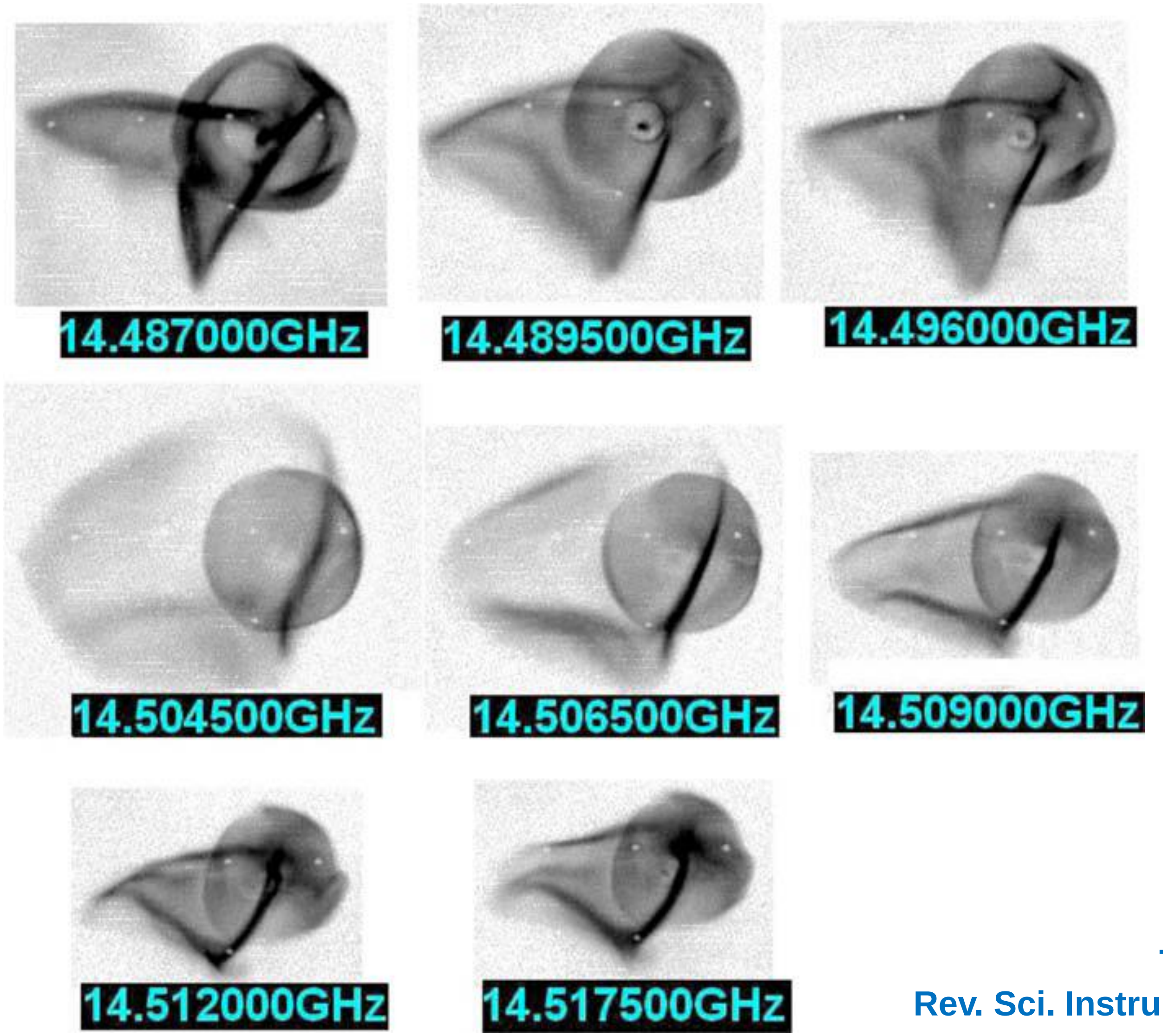
Behind Stripper Section



- Similar test benches used at HIT Linac commissioning
- See talk by **A. Reiter (Wednesday, 4:35 pm)** for details of phase probe measurements

HIT Ion Source Investigations – Viewing Screen Measurements (in LEBT)

GSI



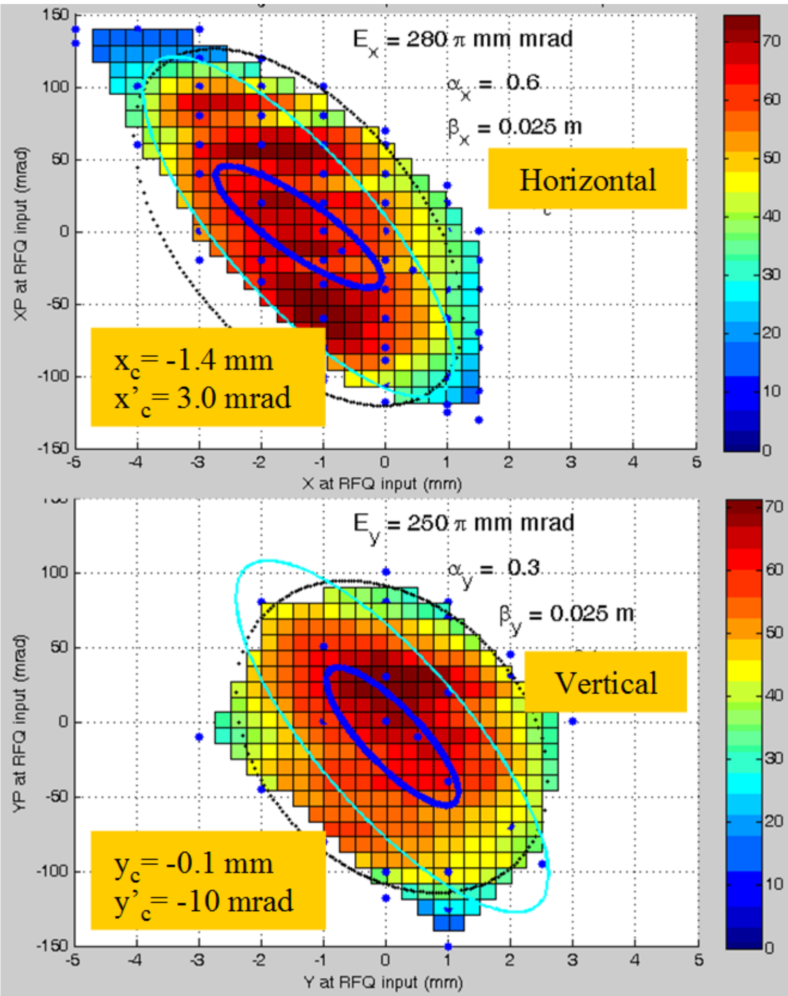
Evolution of H_3^+ and H_2^+ beam shape with ECR frequency behind first solenoid

T. Winkelmann et al., Rev. Sci. Instrum. 81, 02A311 (2010)

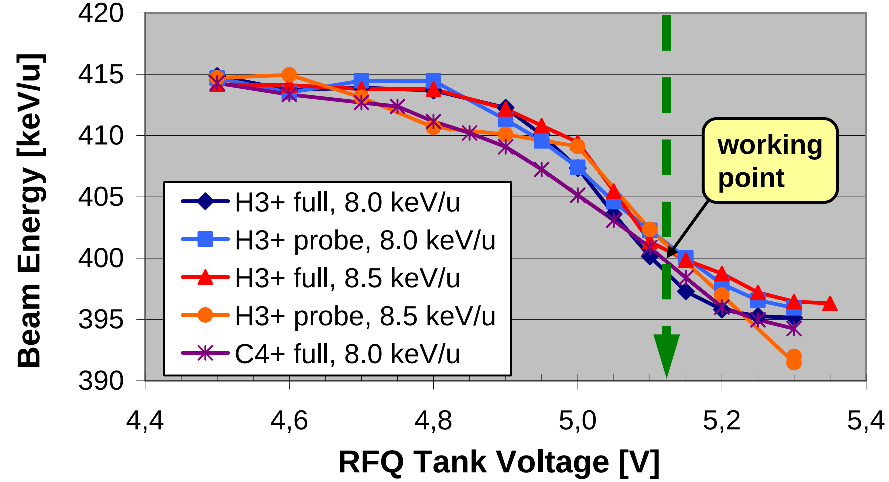
RFQ Performance (CNAO)

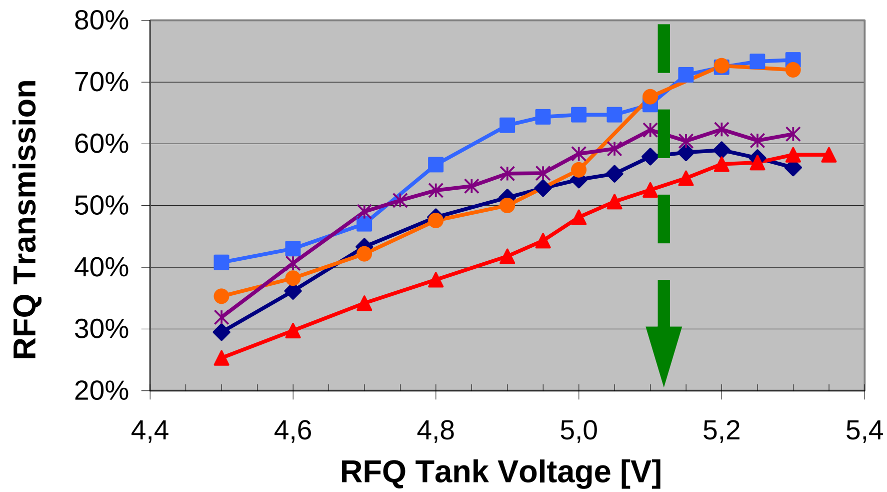
P. Posocco et al., HIAT 2009 | **B. Schlitt et al., IPAC 2010**

RFQ Acceptance Probing



RFQ Beam Energy & Transmission





RFQ Performance

- **Adjustment of drift tube buncher integrated into RFQ to match beam energy and phase width at IH-DTL injection**

  → **RFQ Testbenches** at GSI (HIT & CNAO RFQs), DANFYSIK, and HIT

- **RFQ transmission at HIT and MIT only 30 – 40 %** (incl. solenoid & ITM)

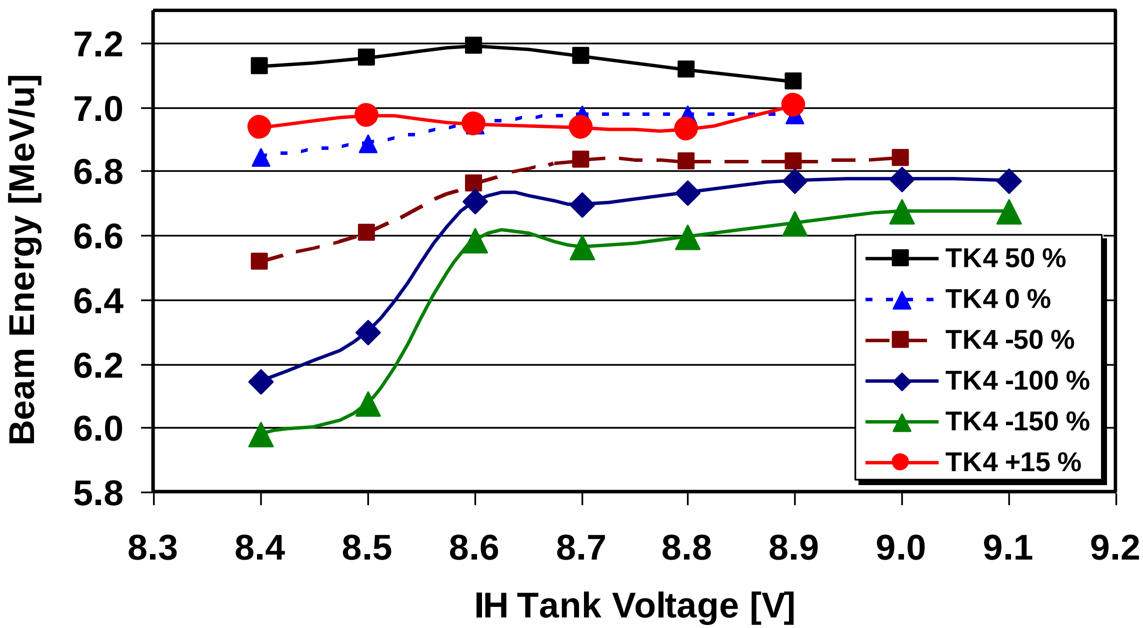
Improvements so far:

- **New input radial matcher** (IRM) for reduced external focusing at RFQ injection (reduction of aberration effects by solenoid focusing)
- **Mechanical design** of RFQ electrodes & tank, improved alignment of electrodes & tank, more robust RFQ tank
- **Optimized beam matching to RFQ** (emittance measurements at exact RFQ injection point, acceptance measurements using probe beams)
- **RFQ transmission at CNAO: ~ 60 %**
  Kiel / Shanghai (Siemens): 60 – 70 %

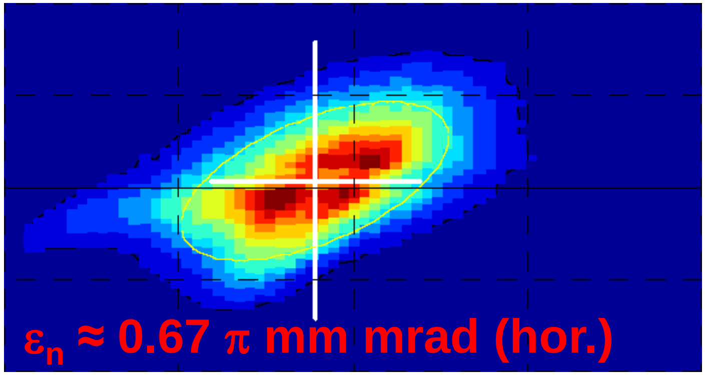
Example for HIT Linac
Beam Commissioning Results

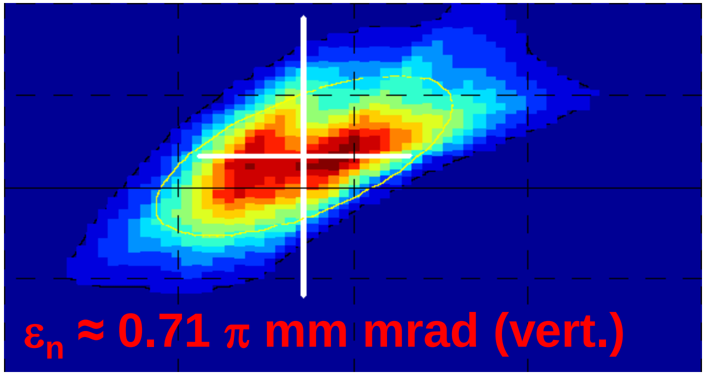
B. Schlitt, LINAC 2008

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



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

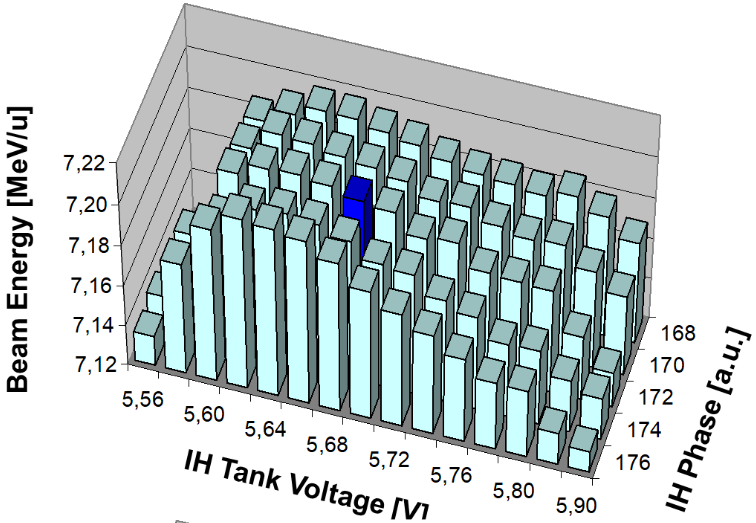


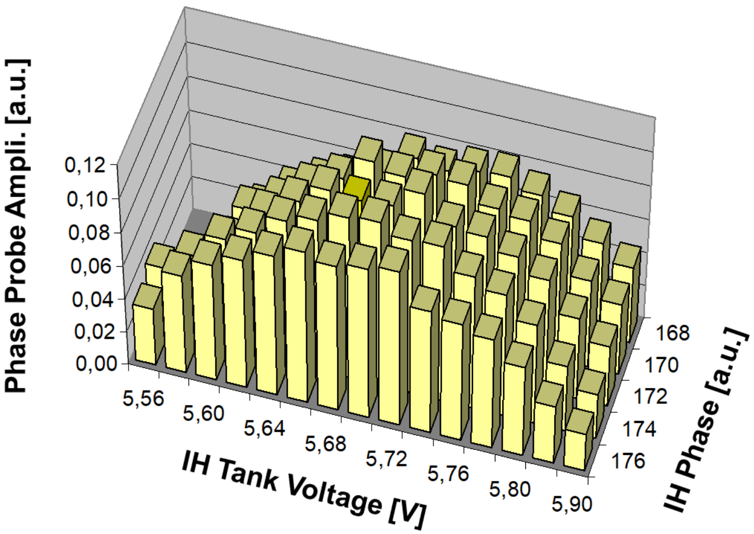


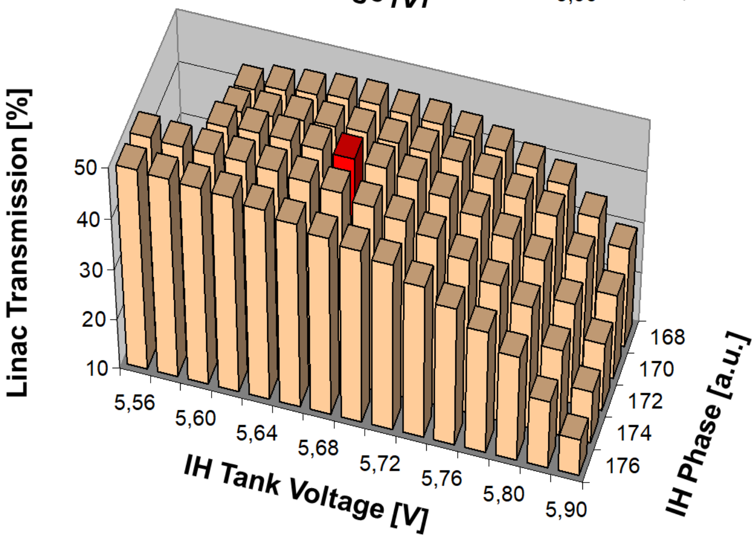
Beam emittances agree well with simulation results

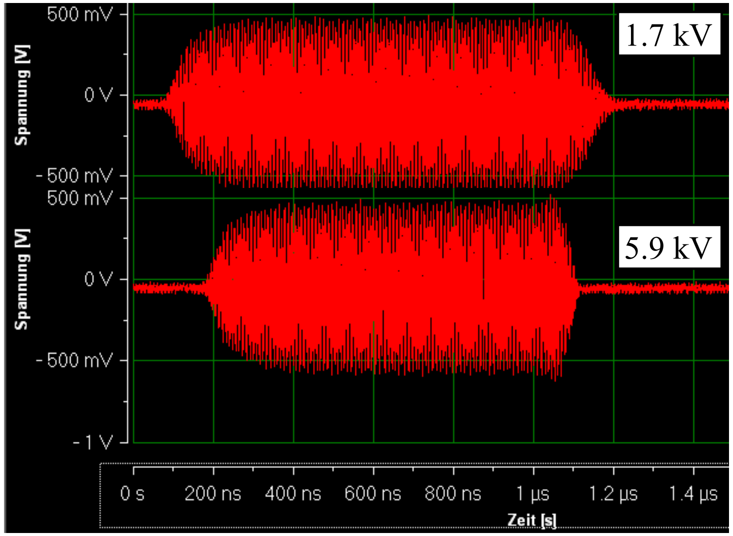
Example for Linac Commissioning (CNAO): Phase & Amplitude Scans, Chopper Rise Time

B. Schlitt et al., IPAC 2010







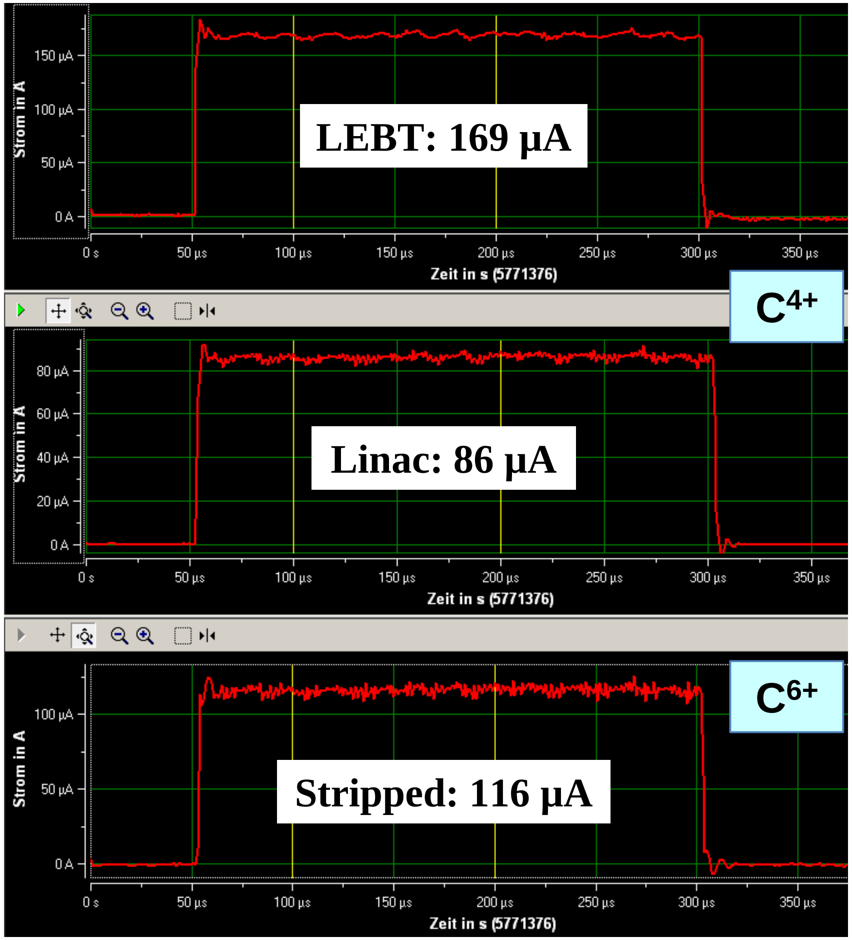


LINAC Performance (CNAO)

Ions	Beam Currents / µA			Linac Transm.
	LEBT	Linac	Stripped	
C^{4+} / $^{6+}$	~ 170	~ 85	~ 115	50 %
H_3^+ / p	1030	415	1200	40 %

- **Linac transmission at Kiel (Siemens) ≥ 50 %**
- **Linac design beam currents achieved at CNAO and Shanghai**
- **High beam brilliance** matches very well the requirements of efficient multiturn injection into the synchrotron

Carbon Ion Beam Currents (CNAO)



B. Schlitt et al., IPAC 2010

Conclusions

- Various beam instrumentation for beam commissioning & routine operation
- Individual beam test benches behind each injector section
- TB0 at RFQ injection point very helpful (CNAO)
- Various improvements of ECRIS & later RFQs

- HIT linac successfully in operation since ~ 14 years
- Availability ≥99 % w/o major breakdowns
- Very high stability & reliability
- > 6500 patients treated at HIT
- RFQ upgrades desired at HIT and MIT, further improvements proposed (revised beam dynamics, stem geometry, ...)


Thank you for attention!