

GSI Helmholtzzentrum für Schwerionenforschung GmbH



LINACs in medical synchrotron facilities: Considerations for mixed He-C beam transport

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1st Workshop on Mixed Ion Beam Delivery, Vienna

October 08, 2026

Outline

- Injector linacs at ion beam therapy centers (synchrotron facilities)
- 217 MHz injector linac @ HIT & CNAO – Layout, design considerations & performance
- Considerations concerning acceleration of ions with $A/q \leq 4$
- Conclusions



Selection of Dedicated (Carbon) Ion Beam Therapy Centers (Synchrotron Facilities)

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	pan	2013	
i-ROCK Kanagawa Cancer Center, Yokoham	an	2015	
Osaka Heavy Ion Therapy Cent	n	2018	
HIT - Heidelberg Ion Bea	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)

Meanwhile additional facilities worldwide in operation or under construction / planning

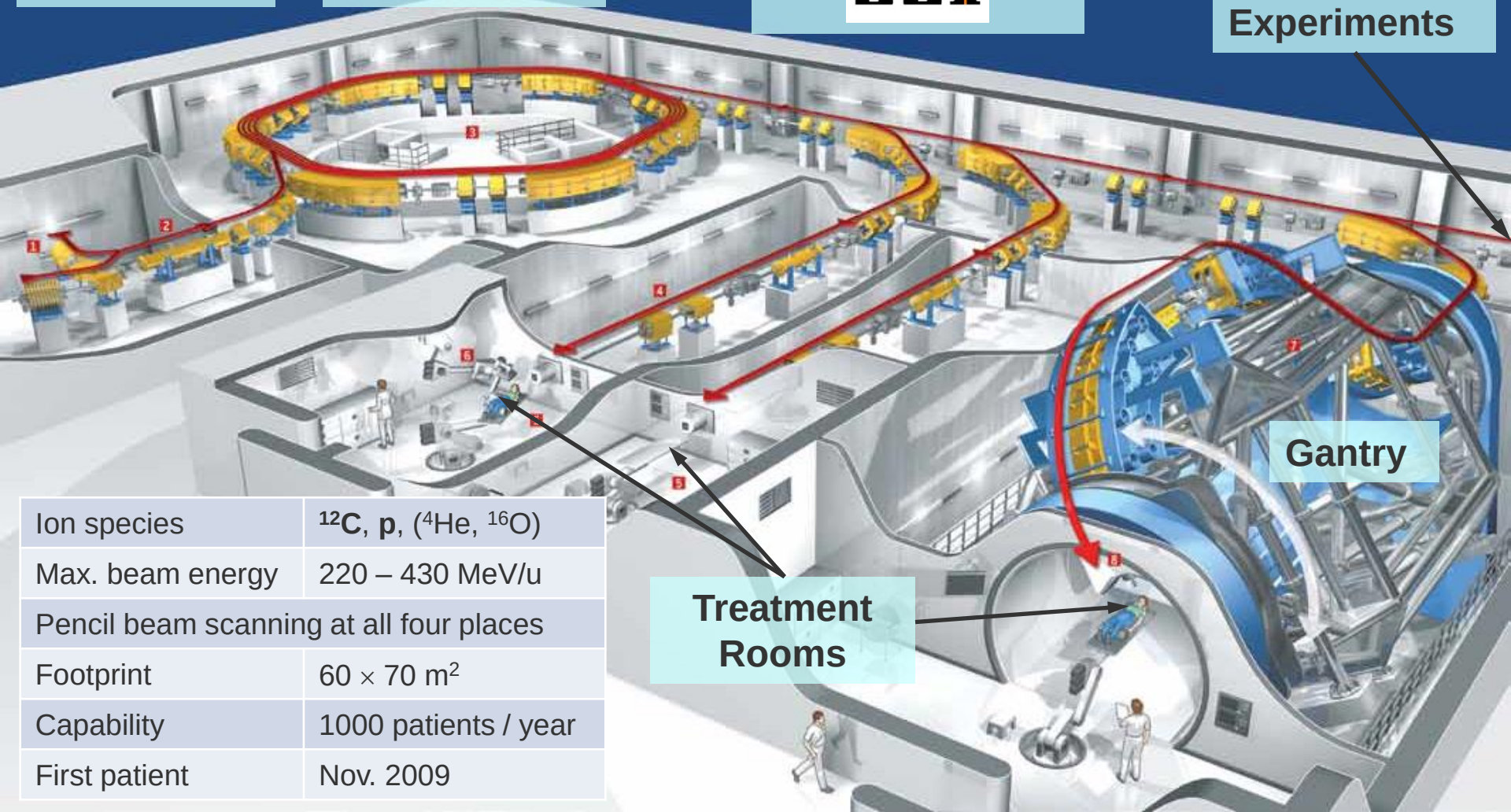
HIT
Heidelberg Ion Beam Therapy Center

Ion Sources & Linac

Synchrotron (GSI design)

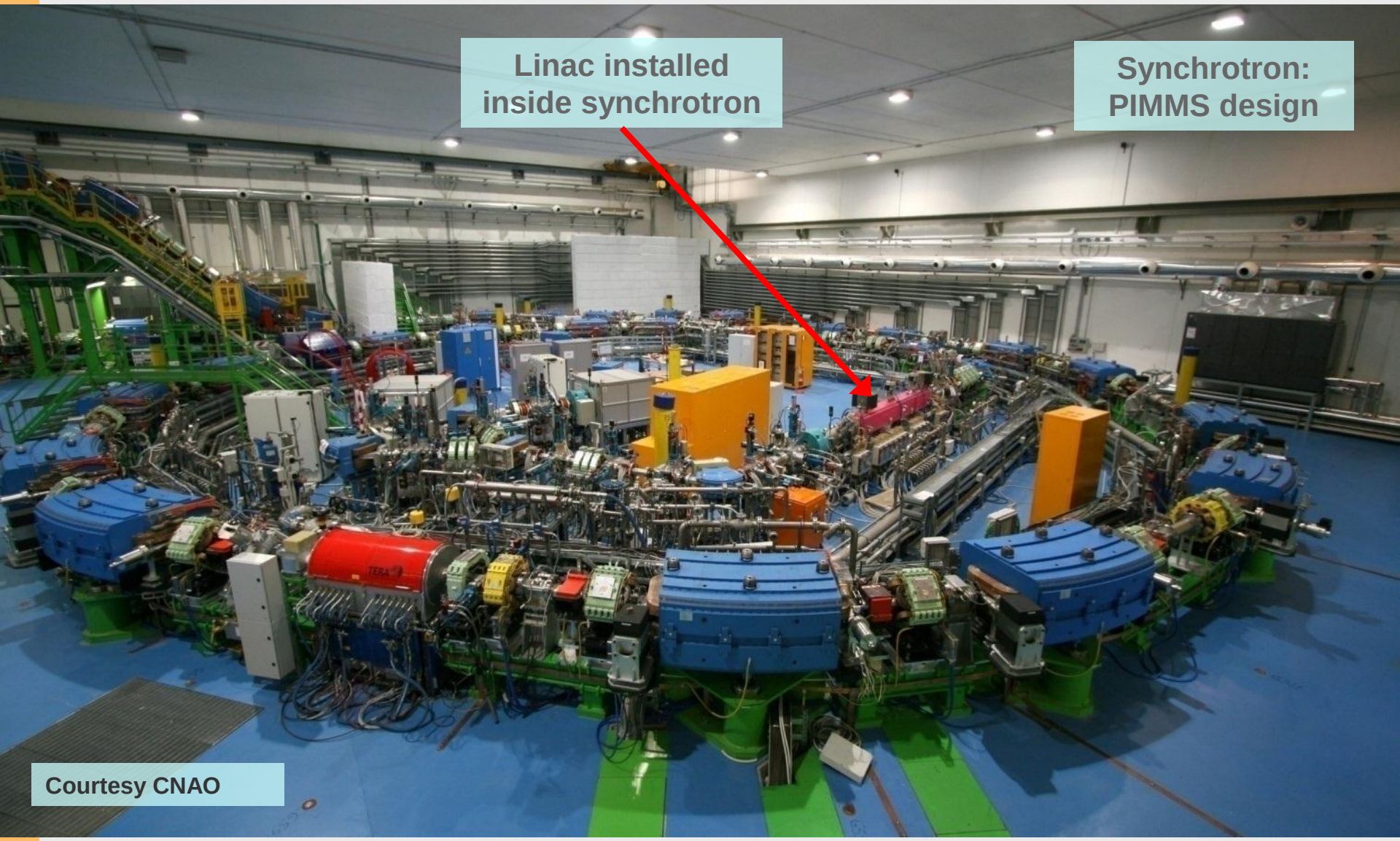
Developed by GSI

Quality Assurance & Experiments



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

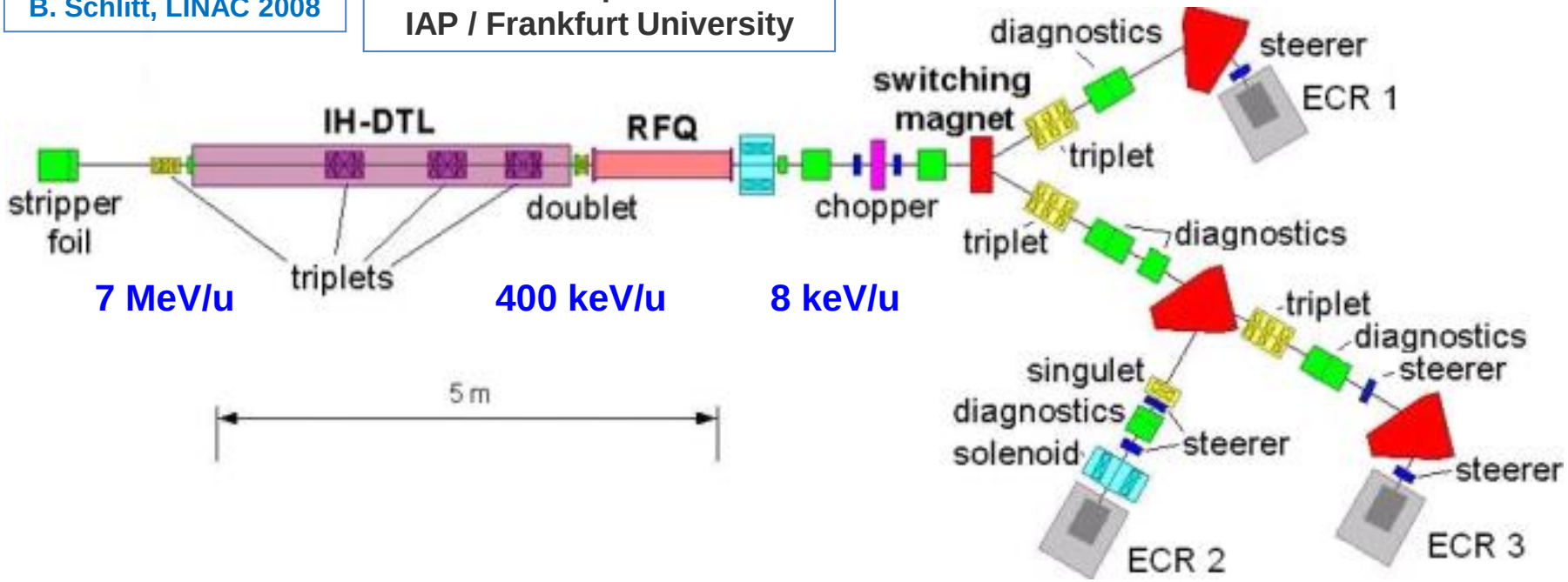
CNAO, Pavia


Linac installed inside synchrotron
Synchrotron: PIMMS design
Courtesy CNAO

217 MHz HIT Injector Linac

B. Schlitt, LINAC 2008

Linac developed at GSI & IAP / Frankfurt University



- 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

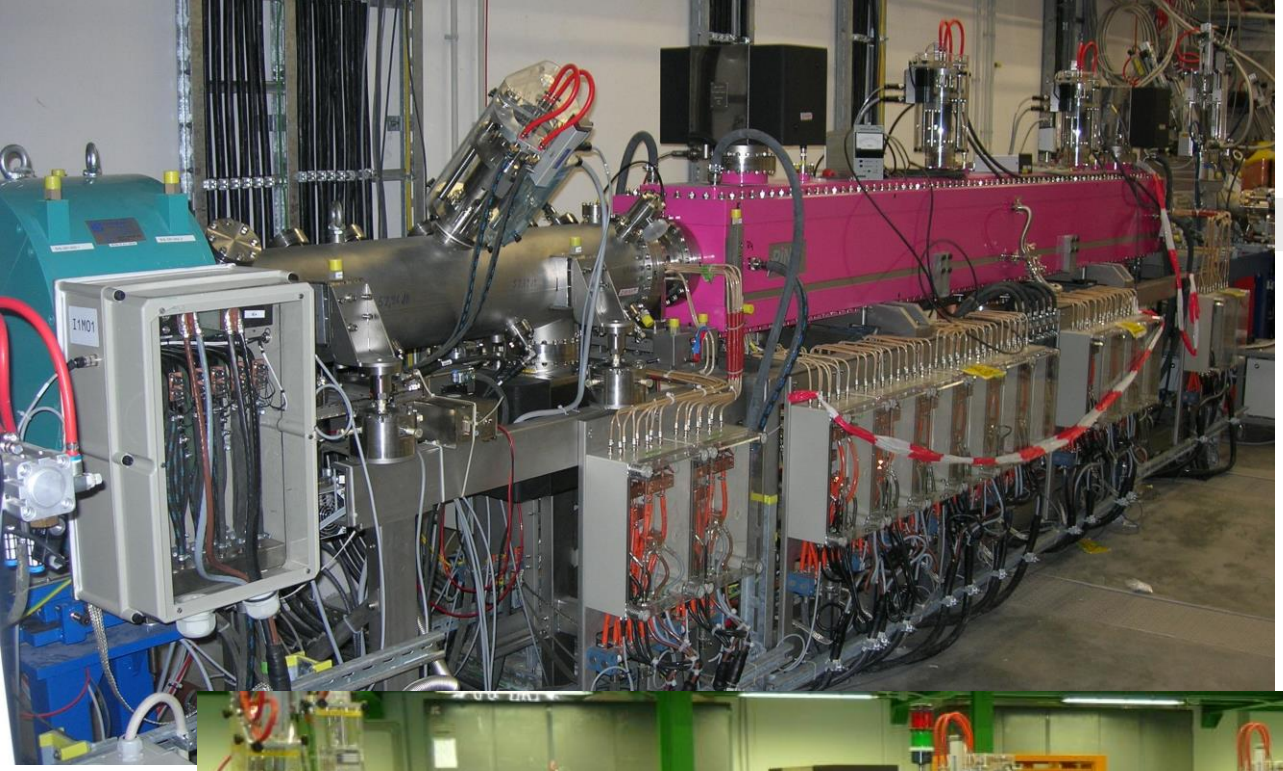
Compact Linac Design

Major Injector & Ion Source Improvements @ HIT (since entire commssionng, selection)

T. Winkelmann et al., ECRIS 2014

- ECR3 and adaption of LEBT (originally only two ECRIS) : helium & oxygen beams + redundancy
- Frequency variable microwave generators, improved µ-metal shielding
- Improved new accel-decel extraction system
- Shorter LEBT for H_3^+ and He beams (significant brilliance increase)
- Modified plasma electrode with tube, ≤ 220 µA C^{4+}, ≤ 1.3 mA H_3^+
- …
- **New RFQ with ultimate transmission > 90% (new design by IAP / Bevatech, 2026 at HIT test bench → R. Cee, HIT)**

  (original RFQ had bad transmission and further problems)



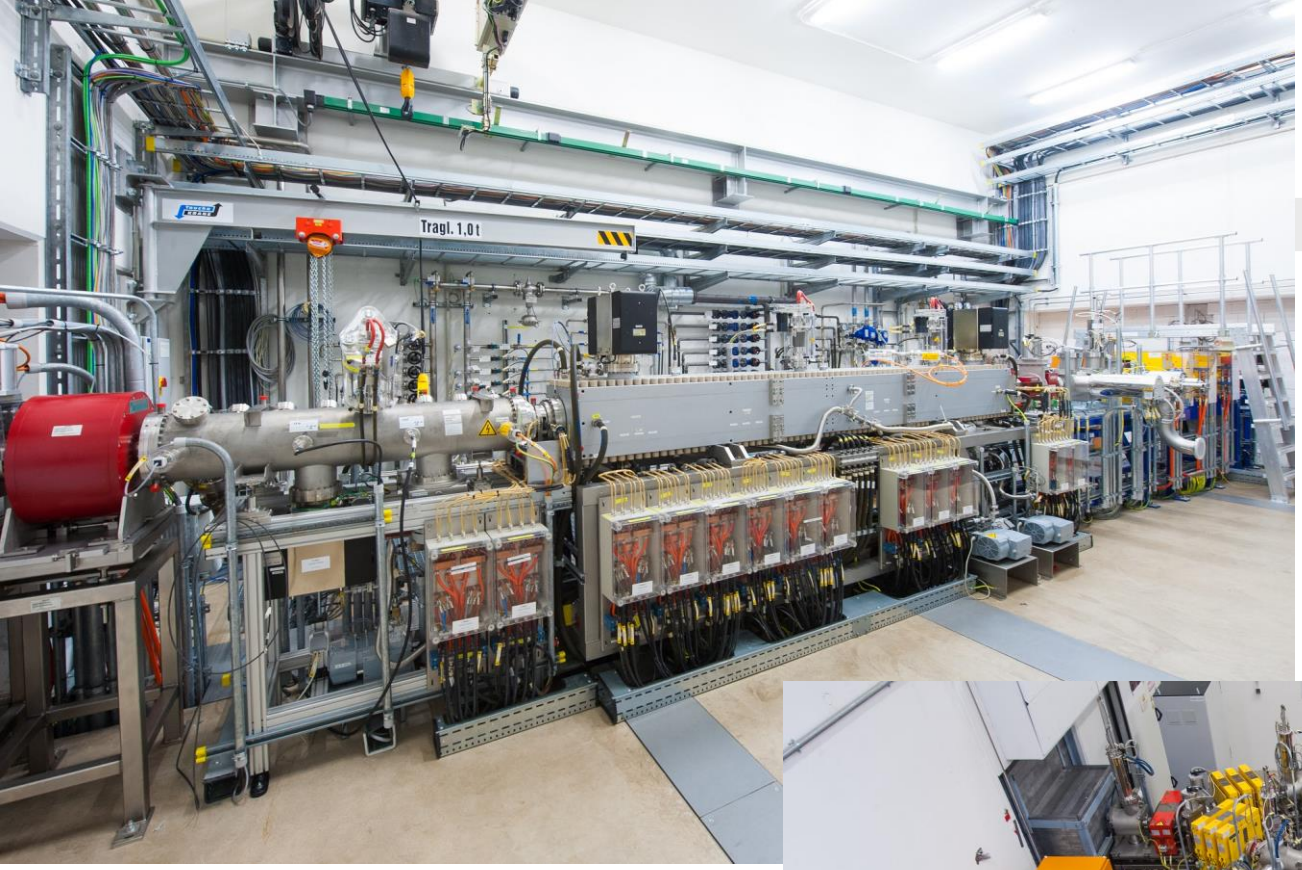
HIT Injector Linac, Heidelberg, Germany

B. Schlitt, LINAC 2008

CNAO, Pavia, Italy



B. Schlitt et al., IPAC 2010



MIT Injector Linac, Marburg, Germany

built by Siemens / Danfysik

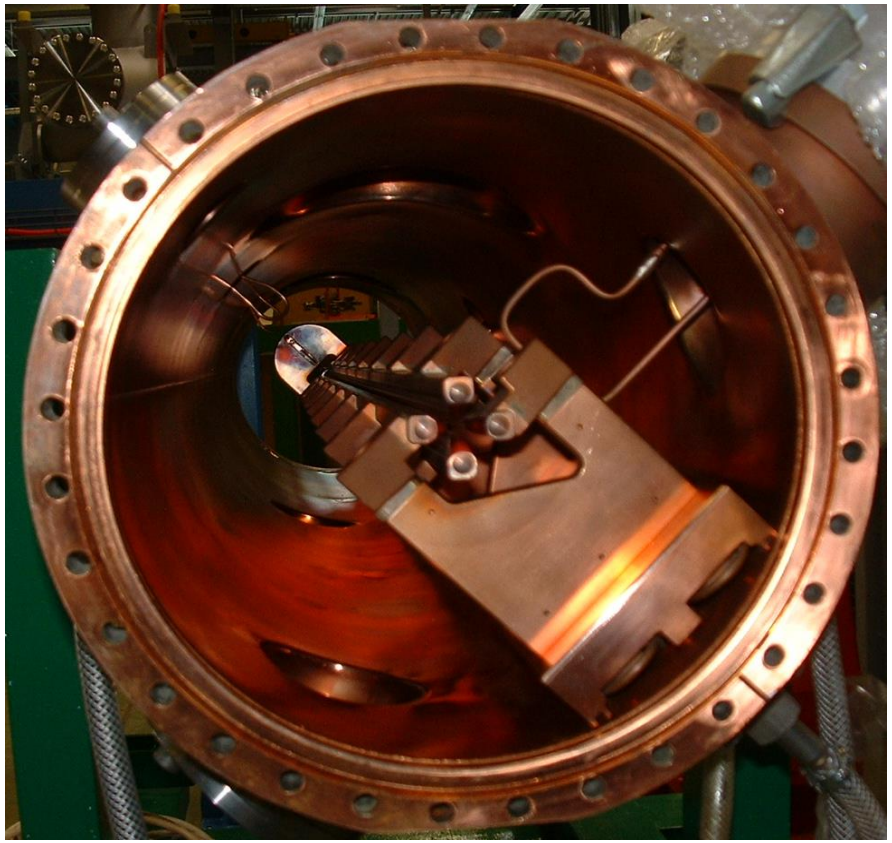


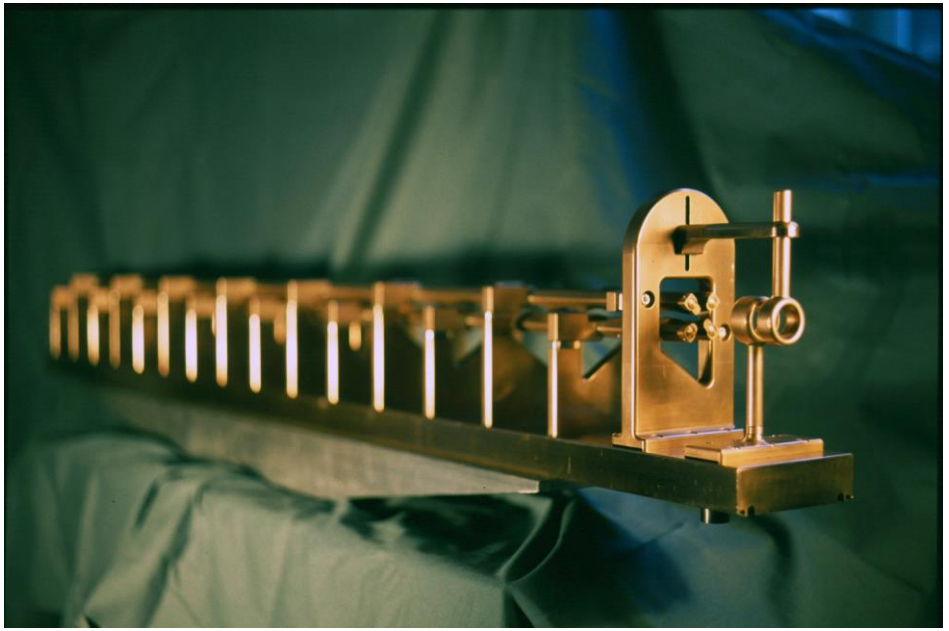
Photos: Siemens

400 keV/u 4-Rod Type RFQ (original one)

A. Bechtold et al., EPAC 2004

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

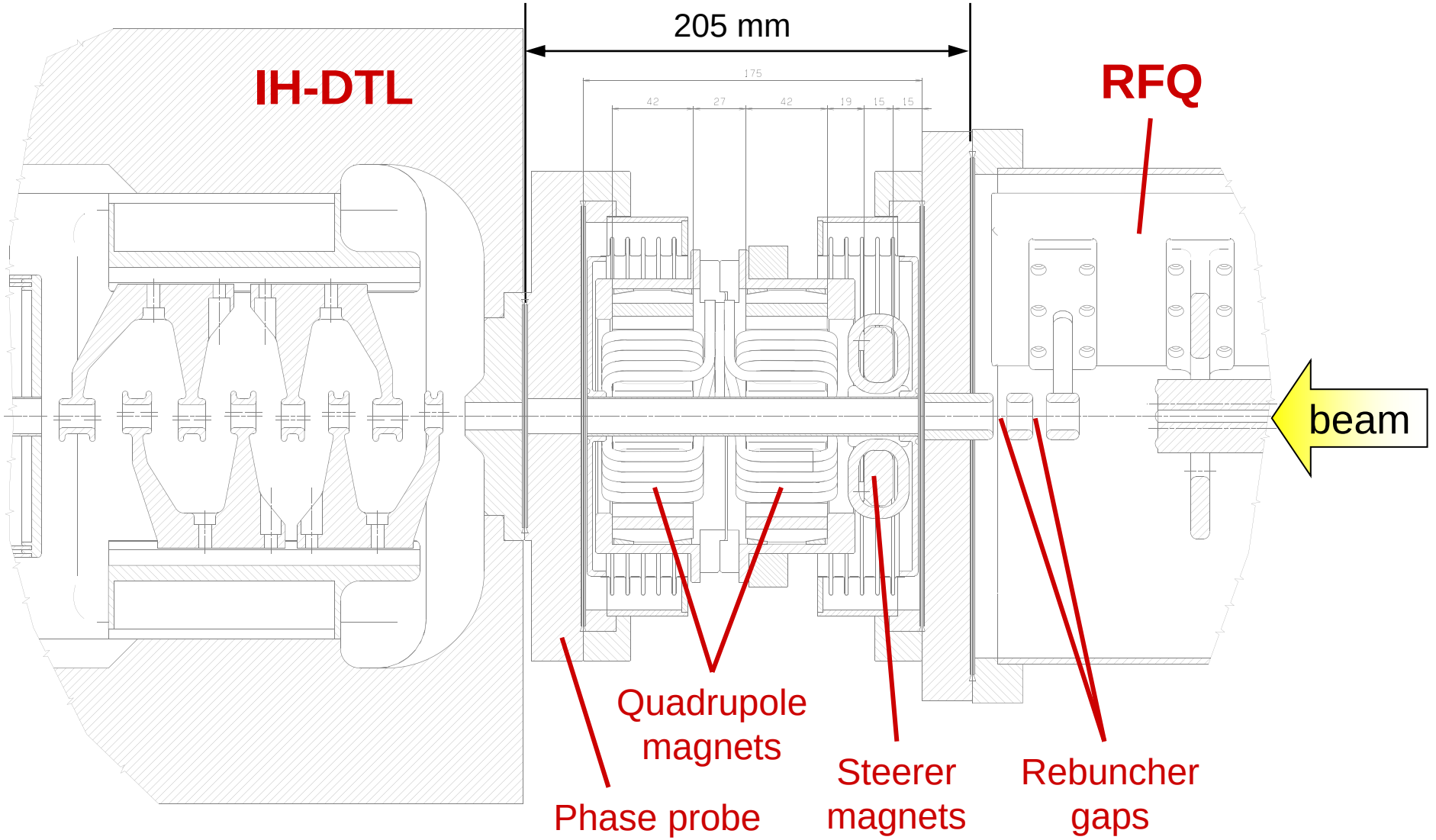




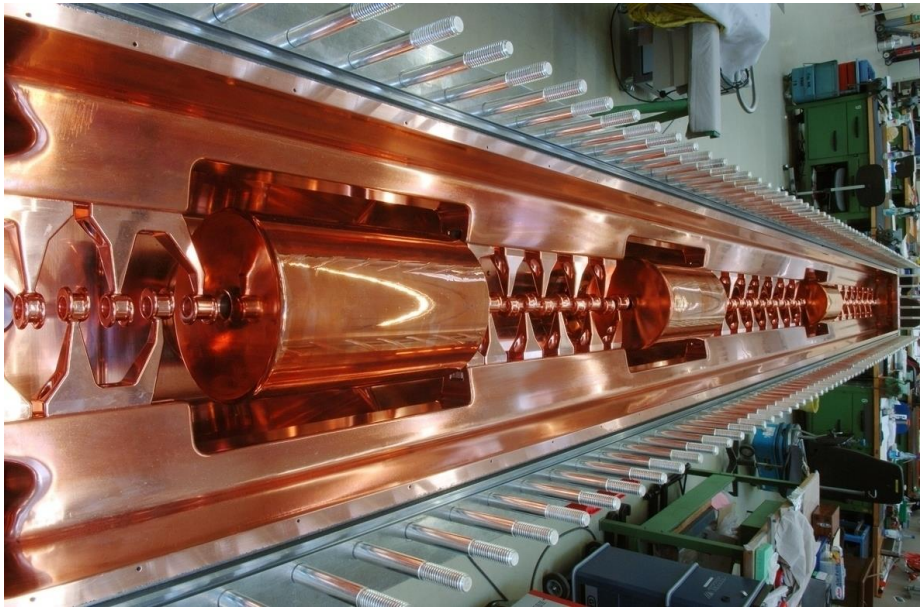
Beam energy in – out	8 – 400 keV/u
Electrode length	1.28 m
Tank diameter	0.25 m
Tank length	1.44 m
Electrode voltage	70 kV
RF power loss (pulse)	~ 200 kW

400 keV/u Inter-tank Section

B. Schlitt et al., LINAC 2002



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



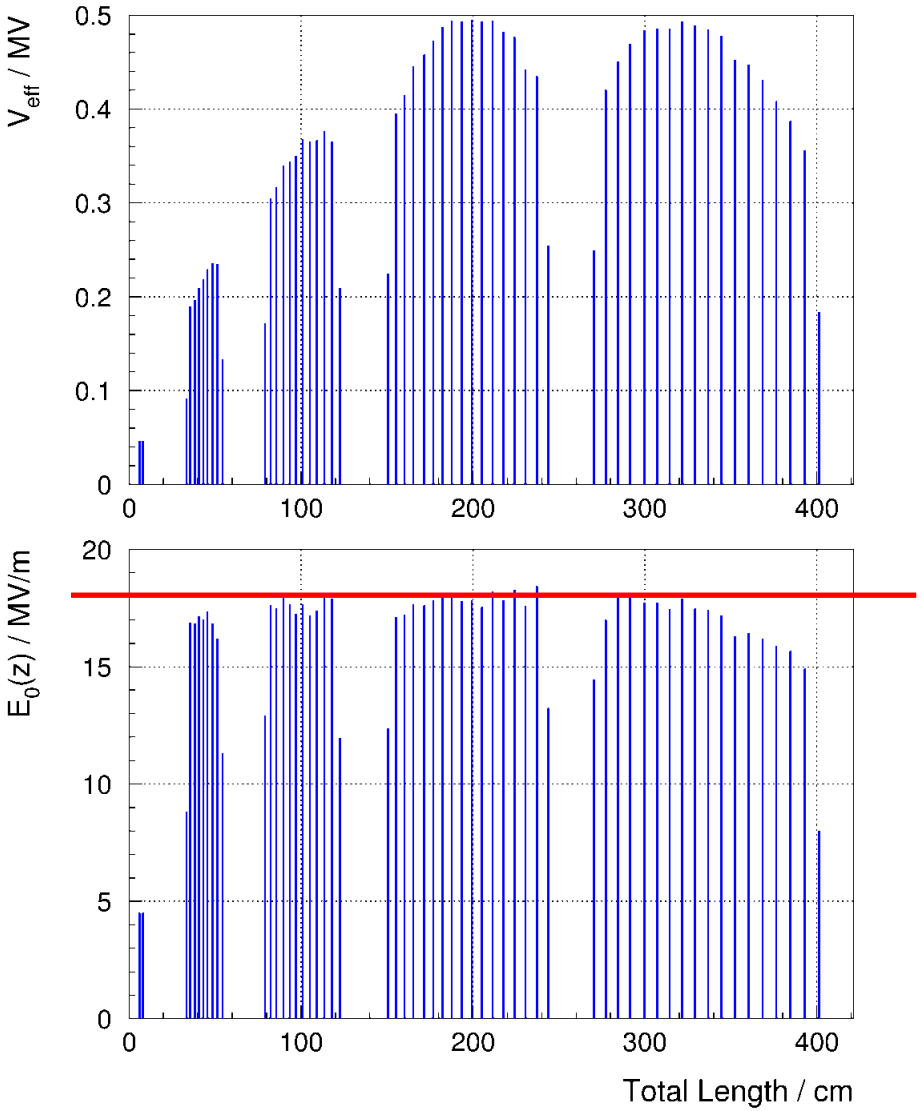


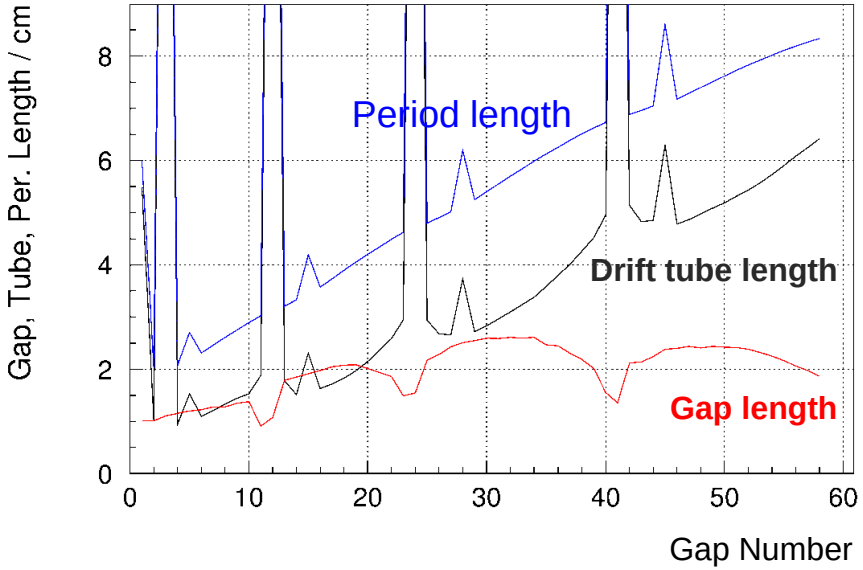
Beam energy in – out	0.4 – 7 MeV/u
Integrated triplet lenses	3
Accelerating gaps	56
Tank length	3.8 m
Inner tank height	0.34 m
Inner tank width	0.26 m
Drift tube aperture diam.	12 – 16 mm
Tank voltage	~ 20 MV
Averaged eff. volt. gain	5.3 MV/m
Max. on axis electr. field	≤ 18 MV/m
Max. eff. gap voltage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

20 MV IH-DTL – Gap Voltage Distribution & Design Parameters





Period length = $\beta\lambda$ / 2

β = particle velocity / speed of light

λ = RF wavelength

$\Rightarrow$ period length increases along linac

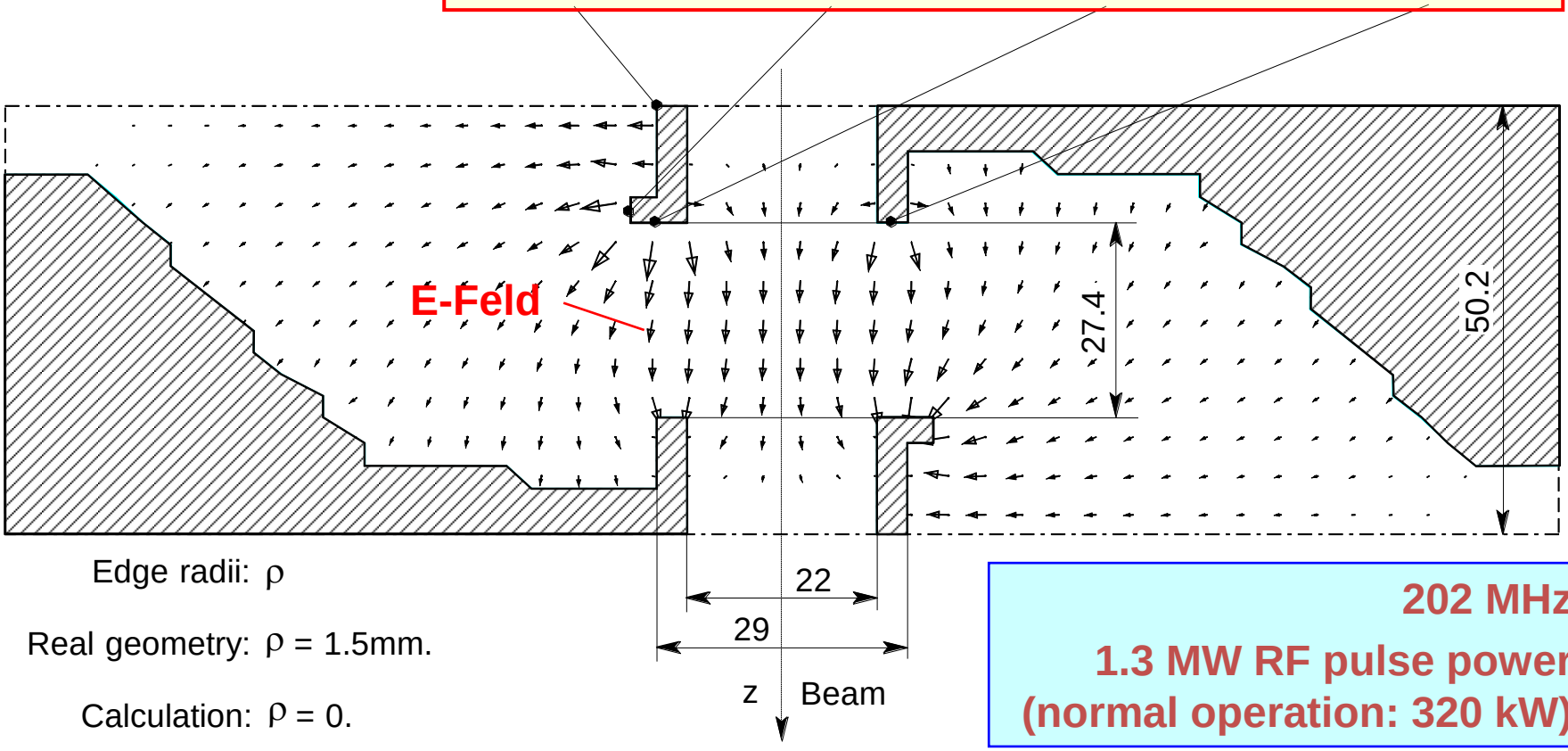
IH-DTL (CERN Linac 3) – High Power RF Tests & Field Simulations

J. Broere et al., LINAC98, p. 771

CERN Pb-LINAC, IH2, Gap No. 9, MAFIA Field Calculation

Vo = 830 kV; Mesh sizes in z-direction: 3mm; in x,y-direction: 0.6mm.

Position/ Surface Field: D/ 33MV/m C/ 75MV/m B/ 54MV/m A/ 44MV/m



Edge radii: ρ

Real geometry: ρ = 1.5mm.

Calculation: ρ = 0.

202 MHz

1.3 MW RF pulse power

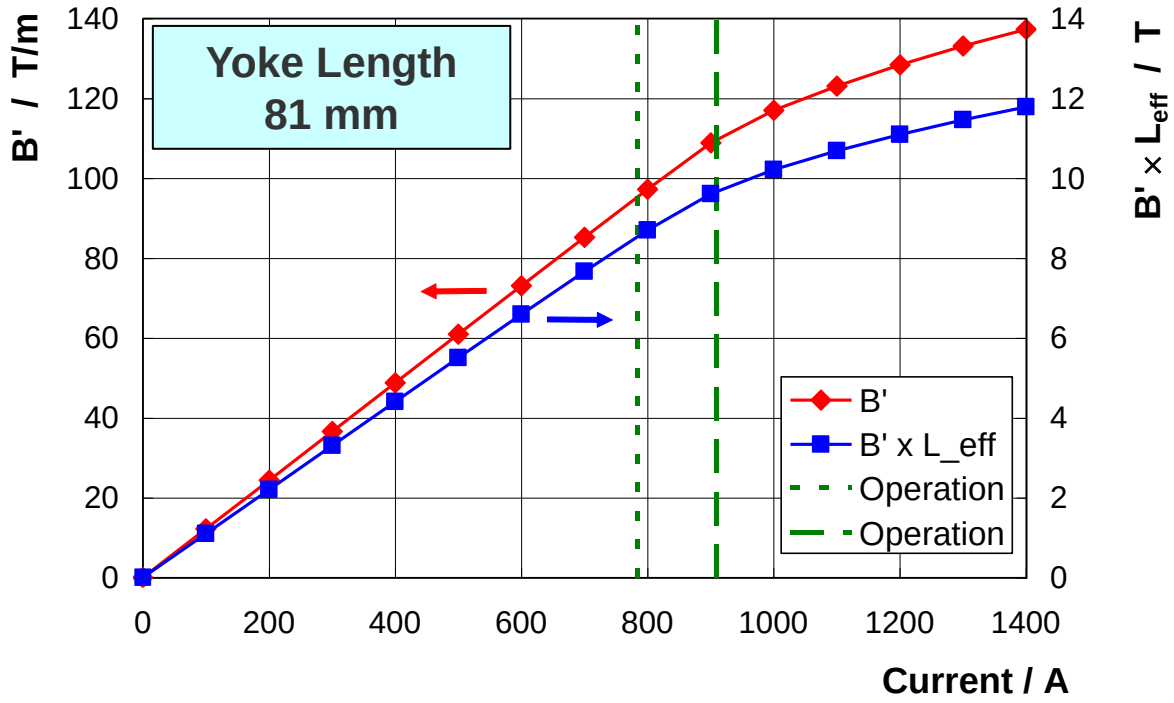
(normal operation: 320 kW)

High Field LINAC Quadrupole Magnets

B. Schlitt et al., LINAC 2004; C. Muehle et al., IEEE Trans. Appl. Supercond.,14, No. 2, 461 (2004)



Prototypes 42 mm + 81 mm
Yoke Length (built @ GSI)



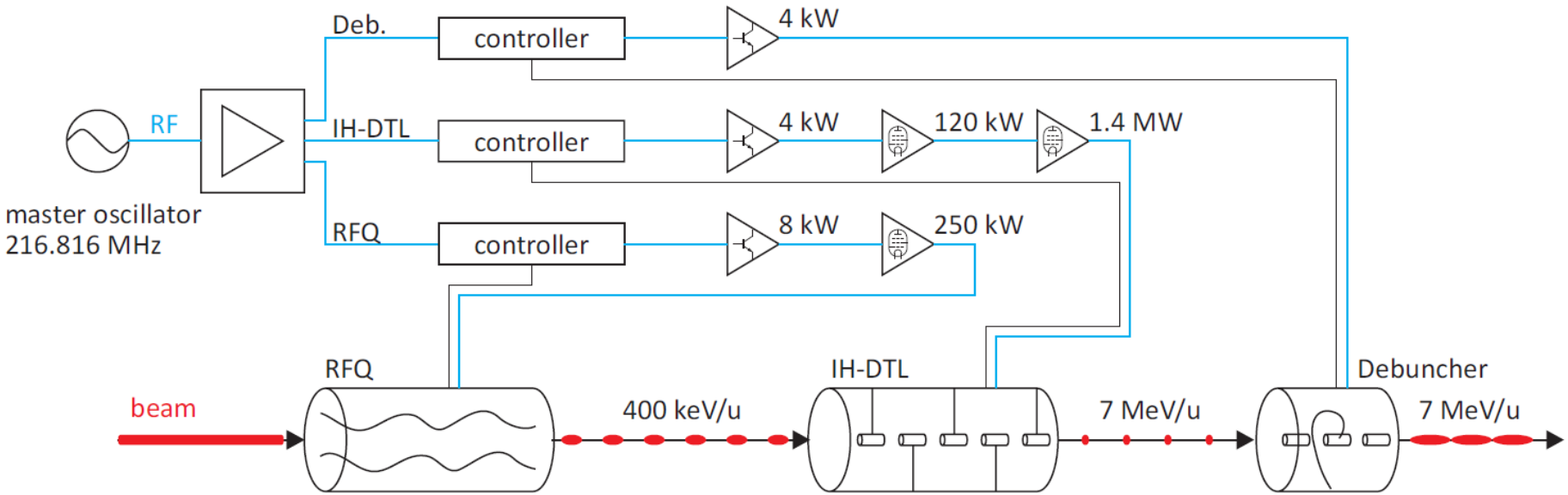
Yoke outer diameter	130 mm
Yoke length	42 / 49 / 67 / 81 / 97 mm
Yoke material	VACOFLUX 50
Magnet aperture diameter	20 mm
Number of turns per pole	5

Linac RF System @ HIT

Footprint	~ 8 m x 1,4 m
Operation frequency	216.8 MHz
RF pulse length	500 µs
Pulse repetition rate	10 Hz
Duty cycle	0.5 %



E. Feldmeier et al., LINAC 2014



Remarks on Linac Commissioning

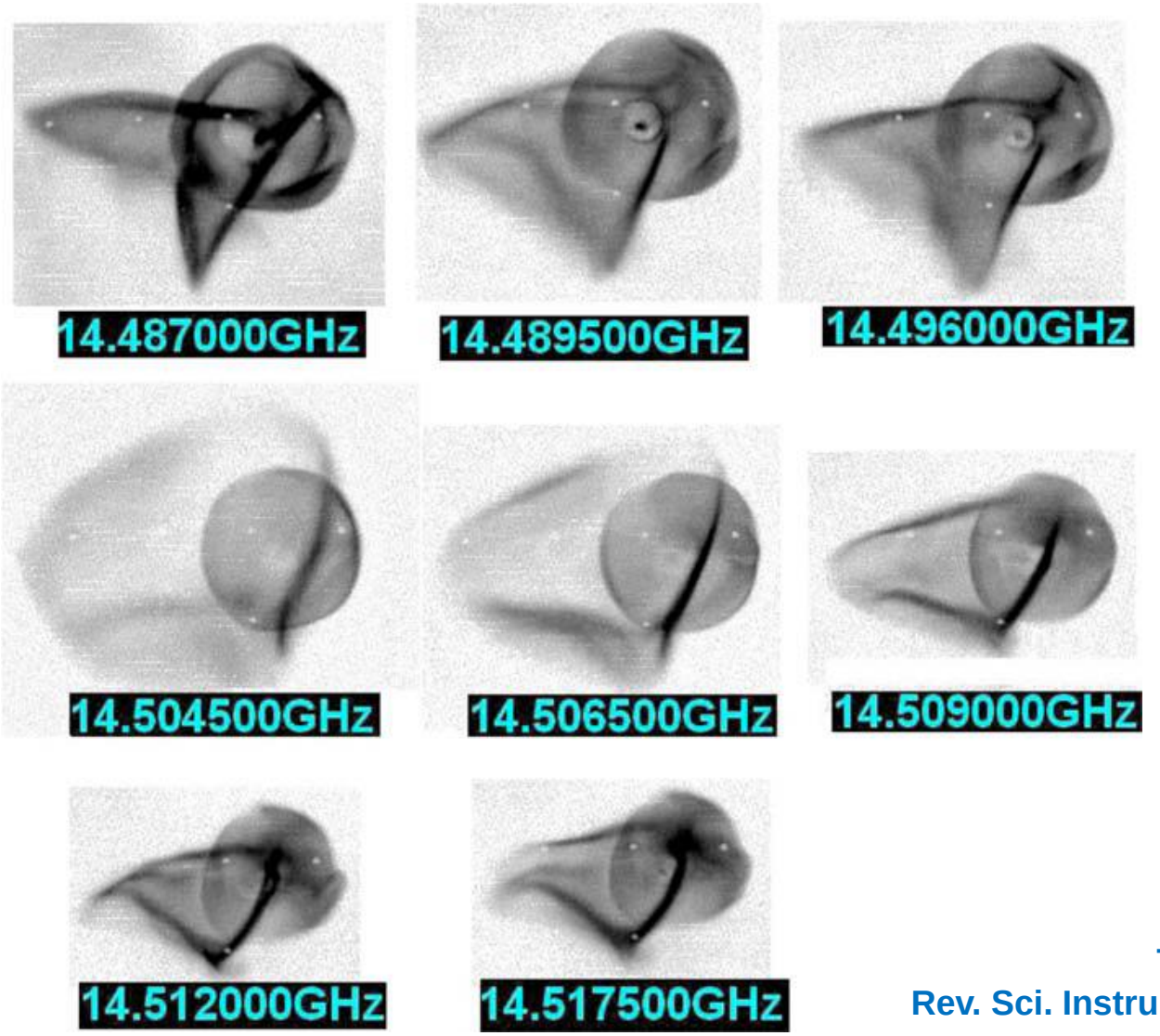
- **Stepwise commissioning** of LEBT & ion sources, RFQ, and IH-DTL
- **Special beam diagnostics test benches behind each section** (adapted to each section: three sections, three test benches)
- **Special issue: RFQ injection** → detailed measurements @ CNAO:
  - beam emittance measurements directly at RFQ input matching point at nominal field strength of the focusing solenoid
  - measurement of RFQ acceptance using probe beam (very small beam emittance)
- Full injector commissioning: about 1 … 1.5 years
- Temporary **RFQ test benches** at GSI & Risoe (Denmark, Siemens) & later at HIT (permanent)
- For details see various contributions to Conference Proceedings (some add. material in appendix to this talk)

CNAO
Linac Commissioning Milestones

B. Schlitt et al., IPAC 2010

Nov 2007 – Dec 2008	Linac Components	Installation & tests of RF systems & lines, power supplies, BD electronics, linac control system etc.
May 2008 – Jan 2009	Ion Sources & LEBT	Final installation & beam tests
Nov 08 – Jan 09	RFQ	RF conditioning & tests at park position
Feb – Mar 2009		Installation & RF conditioning at final position
Mar – Apr		Beam commissioning
Apr – Jun	IH Linac & Foil Stripper	Installation & RF conditioning
Jun – Jul 2009		Beam commissioning
Jul – Nov	MEBT, Debuncher	Completion of line, RF tests & conditioning
Nov – Dec		Beam tests, linac operation training
Dec 2009	Synchtrotron	First turn in synchrotron

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



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

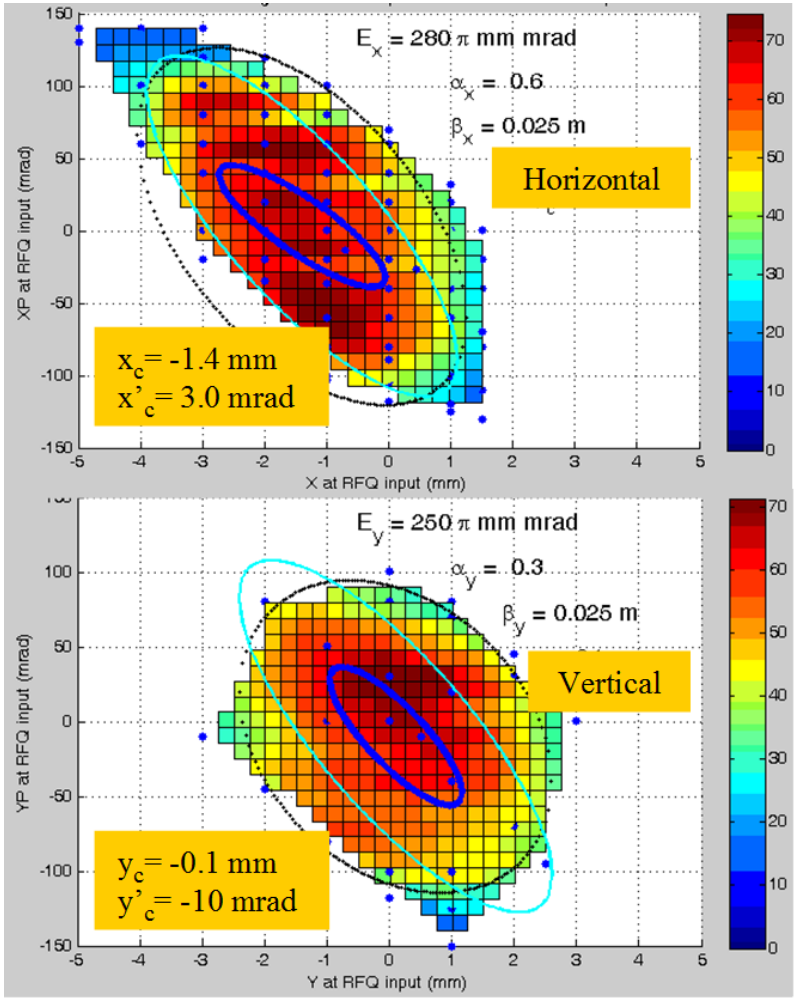
T. Winkelmann et al., Rev. Sci. Instrum. 81, 02A311 (2010)

RFQ Performance (CNAO)

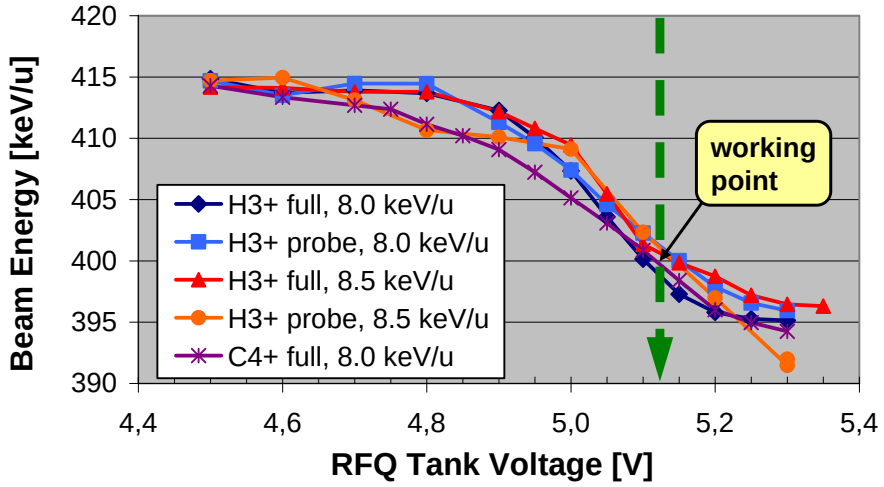
P. Posocco et al., HIAT 2009

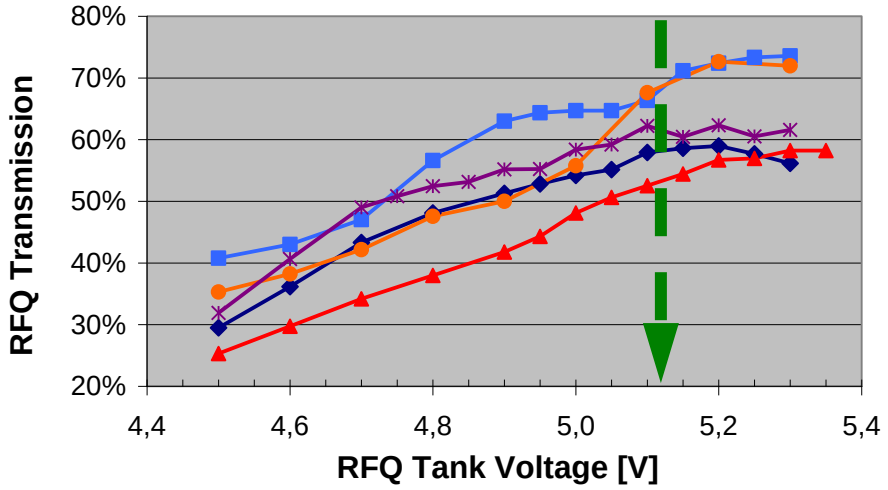
B. Schlitt et al., IPAC 2010

RFQ Acceptance Probing



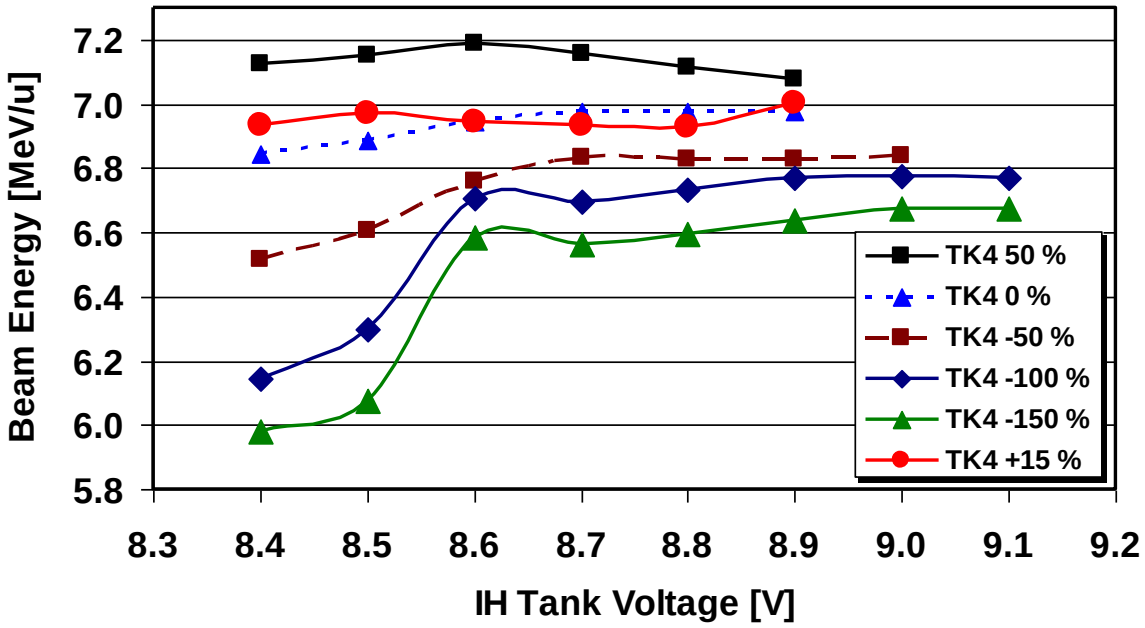
RFQ Beam Energy & Transmission



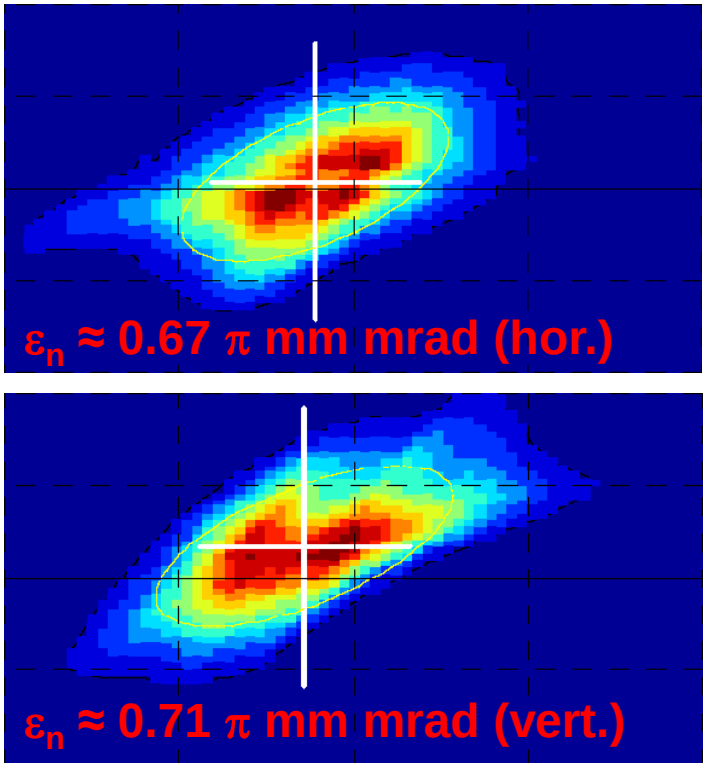


Example for HIT Linac
Beam Commissioning Results

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



Beam emittances behind foil stripper ($^{12}C^{6+}$):



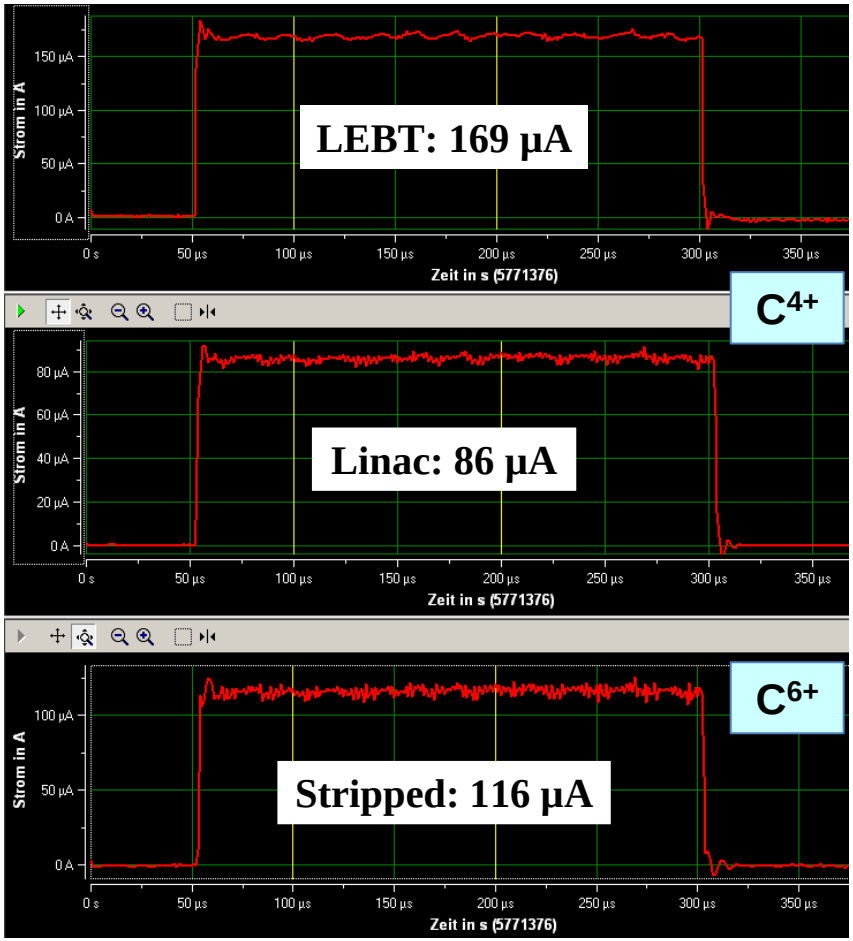
Beam emittances agree well with simulation results

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)

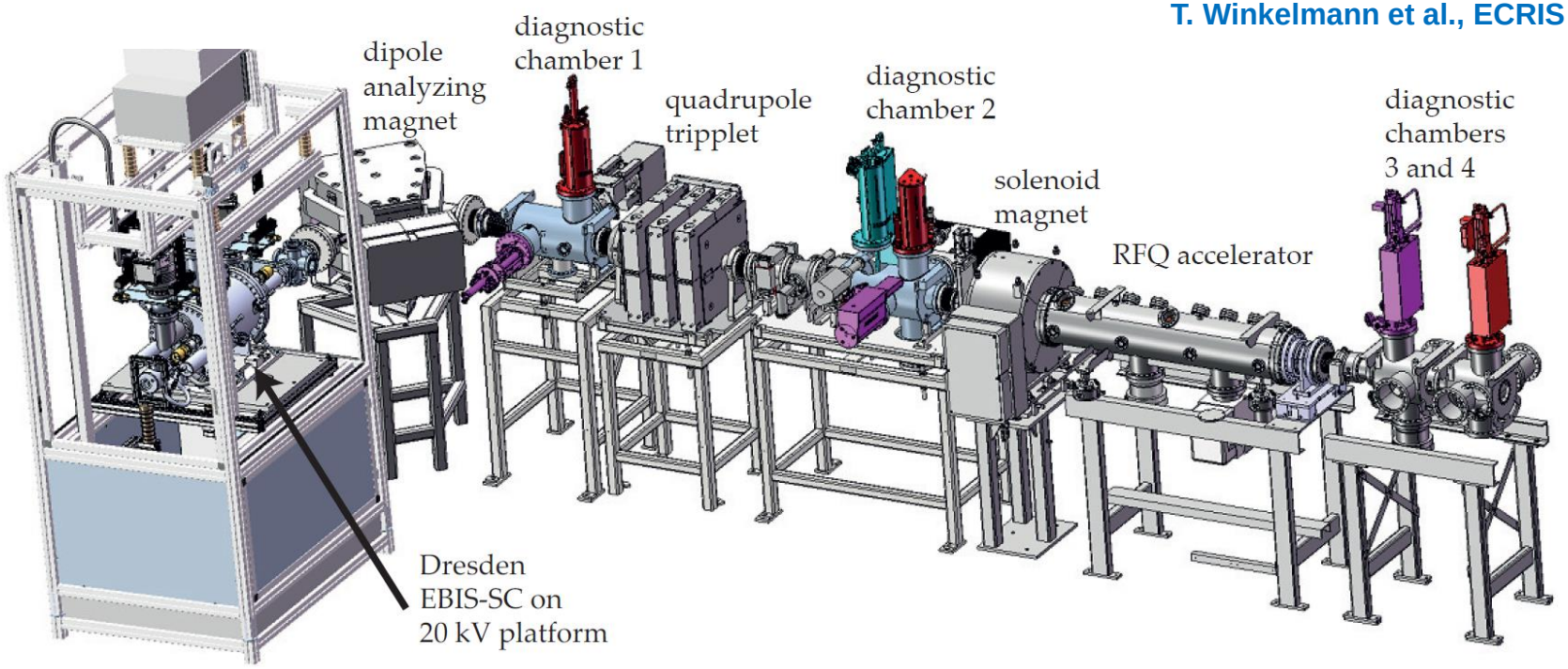


B. Schlitt et al., IPAC 2010

Ion Source & RFQ Testbench at HIT

- Improvement and tests of ECRIS extraction system, compact LEBT setup, beam quality (pepper pot emittance device)
- Investigation of RFQ injection & transmission & of new RFQ (2026)
- Temporarily tested: commercial superconducting EBIS (high beam brilliance)

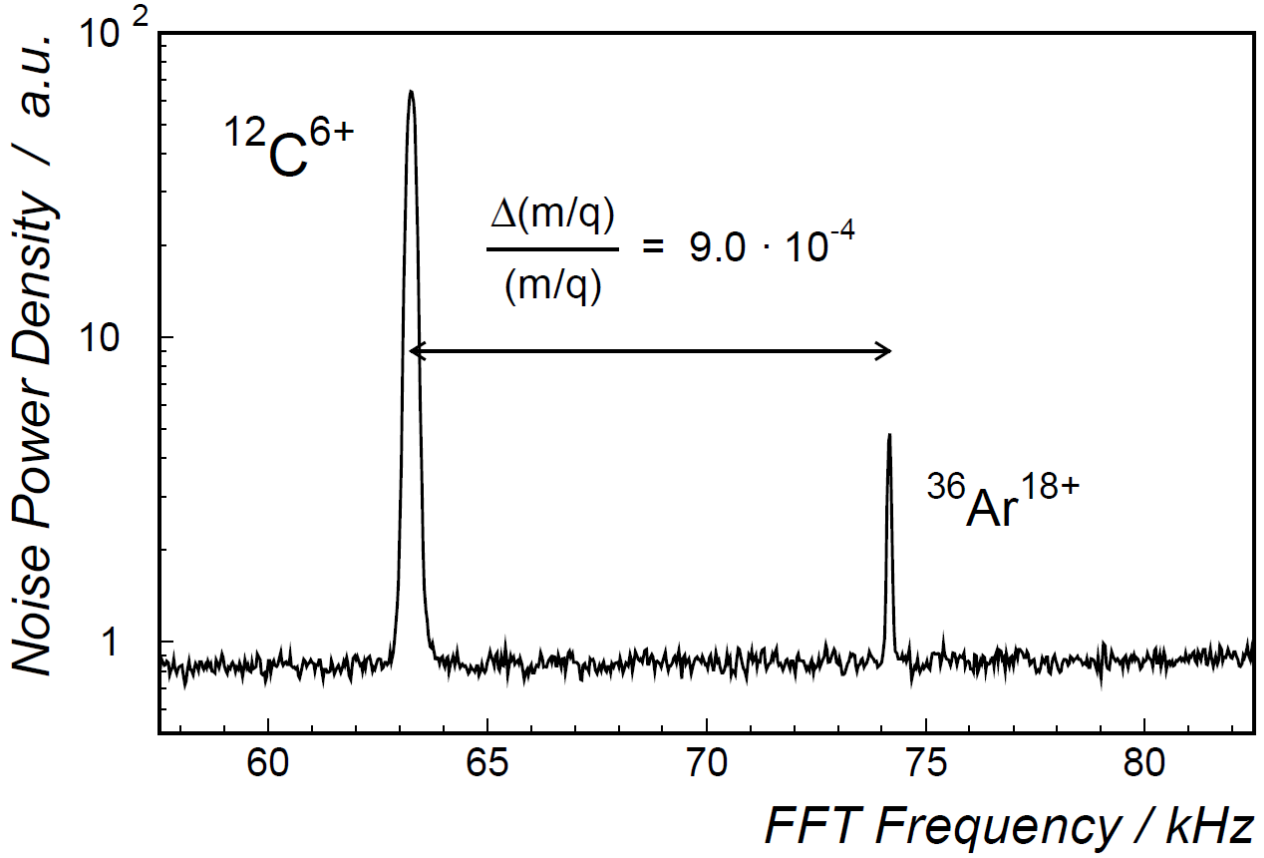
E. Ritter et al., IPAC 2014
T. Winkelmann et al., ECRIS 2014



Example of Mixed Ion Beams at GSI (> 30 years ago …)

B. Schlitt., PhD Thesis, 1997

- Carbon ions beams from ECRIS accidentially contaminated with Argon, accelerated all along UNILAC & SIS18 and injected, stored and cooled at ESR storage ring @ GSI



Considerations concerning acceleration of ions with A/q ≤ 4

- **Linac & LEBT was designed for ions with A/q ≤ 3**
- Acceleration of ions with A/q = 4 requires
  higher electric and magnetic fields by a factor of 1.33
- ⇒ higher (RF) power by factor of ~ 1.8 for RFQ & IH-DTL,
  as well as for magnets (LEBT & linac quads) & power supplies

LEBT:

- Magnets (in particular, downstream of analyzing dipole) &
  corresponding power supplies → **must be checked**

RFQ:

- Very probably: beyond max. possible field strength,
  required RF power (~ 350 kW) beyond capability of amplifier
- **Option: new RFQ design** (→ IAP, Bevatech)

Considerations concerning acceleration of ions with A/q ≤ 4

IH-DTL and linac quadrupole magnets:

- Required max. on-axis field strenght about 24 MV/m
  → **beyond breakdown limits**
- IH-DTL @ CNAO was conditioned up to about 1.3 MW, required for A/q = 4 would be > 1.6 … 1.7 MW
- **RF amplifier too small** (max. 1.4 MW)
- **Linac quadrupoles: would be saturated**, power supplies not sufficient

Recommended Studies



IH-DTL options:

- **New design required** (for A/q = 4)
- Option: **reduced linac end energy** (new design)
  to keep RF power requirements and linac length (→ ~ 5 MeV/u ?)
  (existing RF system maybe re-used, must be checked)
- **Optionally two IH-DTL tanks** …
- … **replacement of RF system**
  … fully based on **solid-state power amplifiers**
  (no vacuum tubes and no high voltage technology)
- Worth to investigate (just an idea, to be checked):
  New beam dynamics design keeping IH-tank and big drift tubes with quadrupole triplets, just replacing the small drift tubes …
  (maybe not possible)

Conclusions



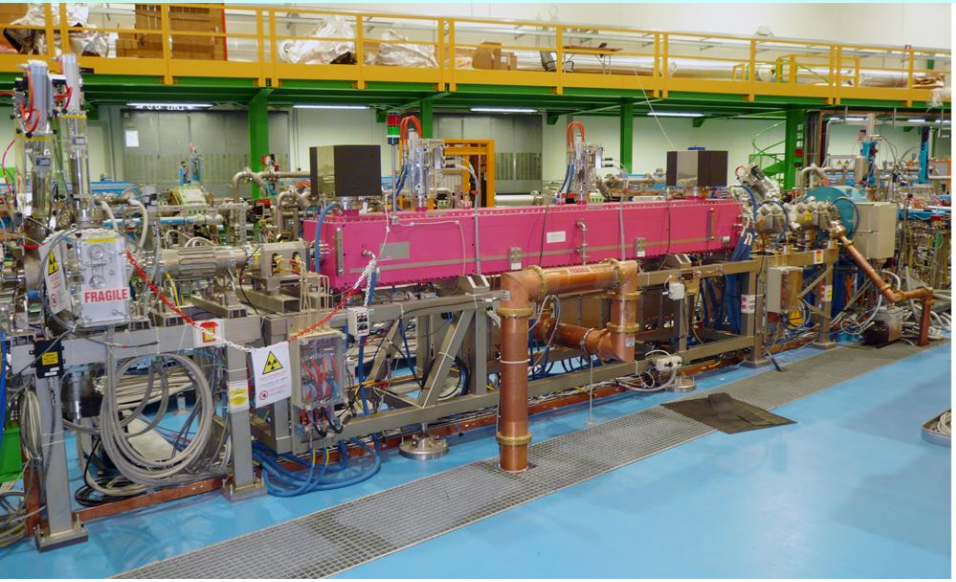
- HIT and CNAO linacs successfully in operation since up to 20 years
- Careful stepwise commissioning key to success
- Very high availability, stability & reliability w/o major breakdowns
- Designed for ions with $A/q \leq 3$
- Fields in RFQ & IH-DTL as well as in linac quadrupoles can be safely achieved due to robust design, providing high operational reliability
- Sophisticated linac quadrupole magnet design

  → higher focusing strength requires longer magnets
  (can be critical for longitudinal beam dynamics)
- New linac designs for $A/q \leq 4$ should be investigated in details (PhD student at IAP ?)





Thank you for attention!



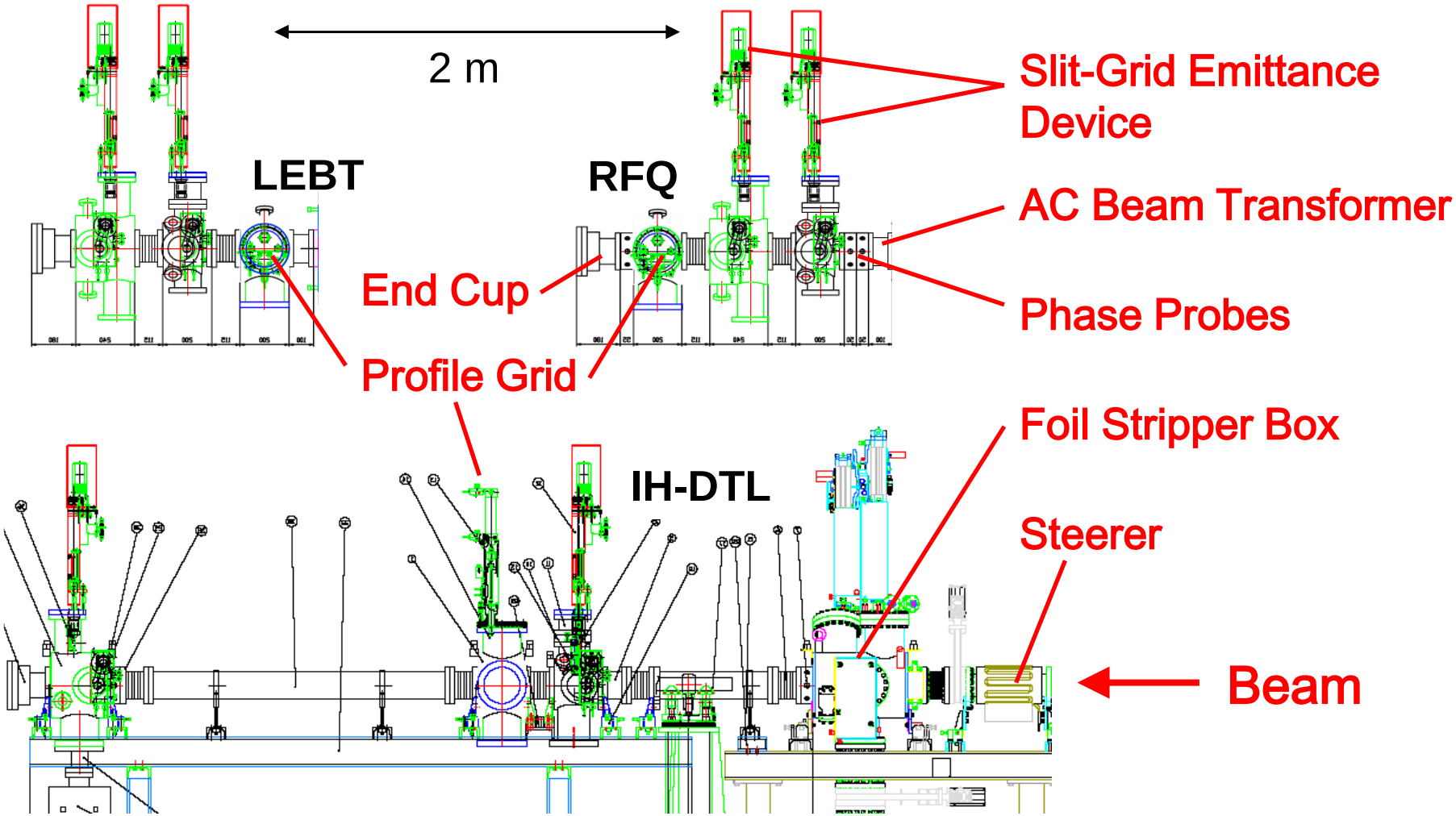


HIT Linac Commissioning Milestones

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
Feb 7, 2007	Synchrotron	1st turn in synchrotron
March 23, 2007	HEBT	1st accelerated beam in treatment places
Dec 16, 2007	H1, H2	C^{6+} and proton beams in treatment quality

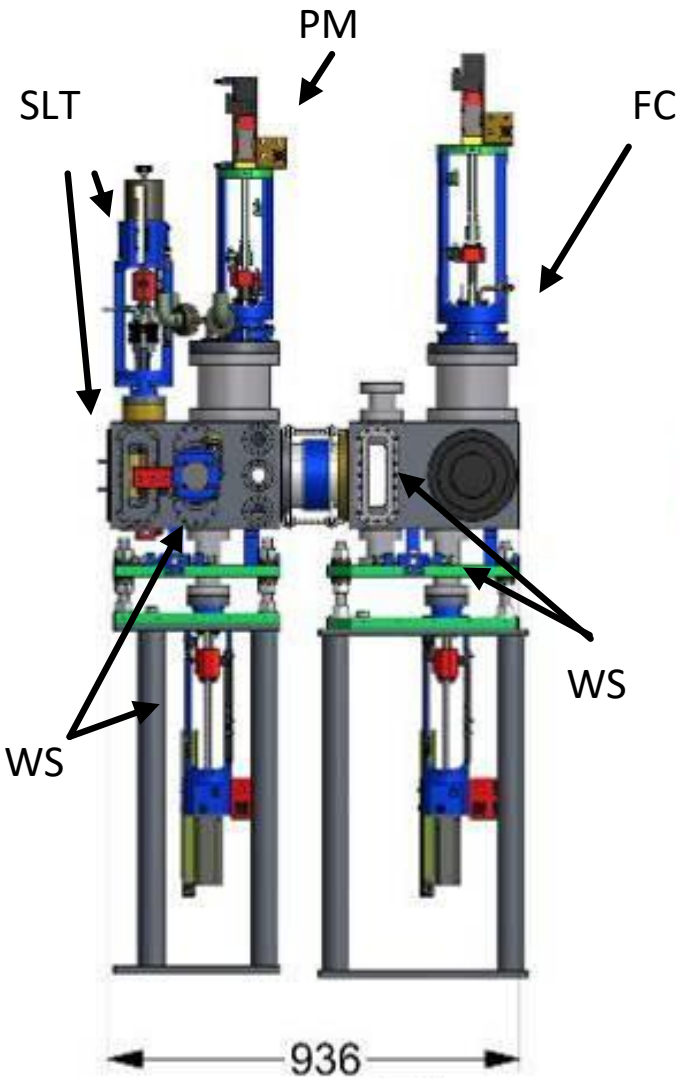
HIT Linac
Beam Commissioning Test Benches

B. Schlitt, LINAC 2008; M. Maier et al., PAC07



CNAO
LEBT Beam Commissioning Test Bench

P. Posocco et al., HIAT09

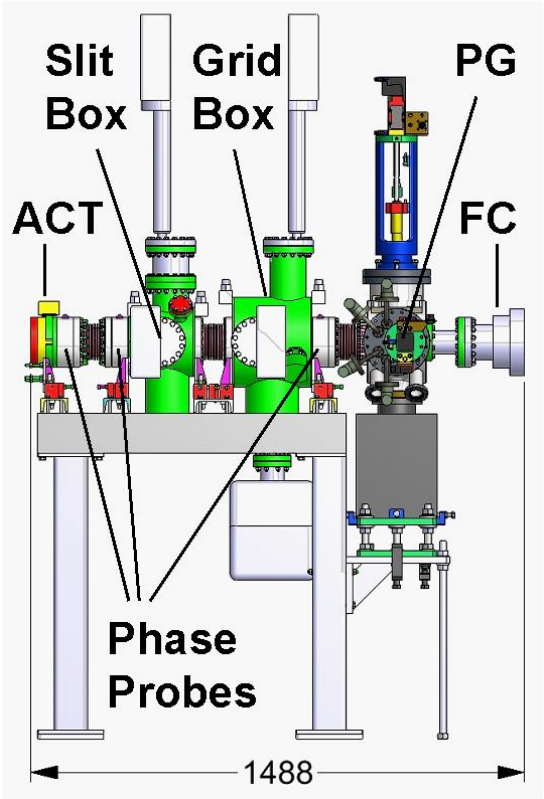


- **Wire scanners (WS)** used for emittance measurements
  → large angular acceptance (±150 mrad)
- **Slits (SLT) at RFQ input matching point**
  → emittance measurements at nominal field strength of the focusing solenoid
- **Investigation & minimization of solenoid steering**
- **Preparation of H_3^+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

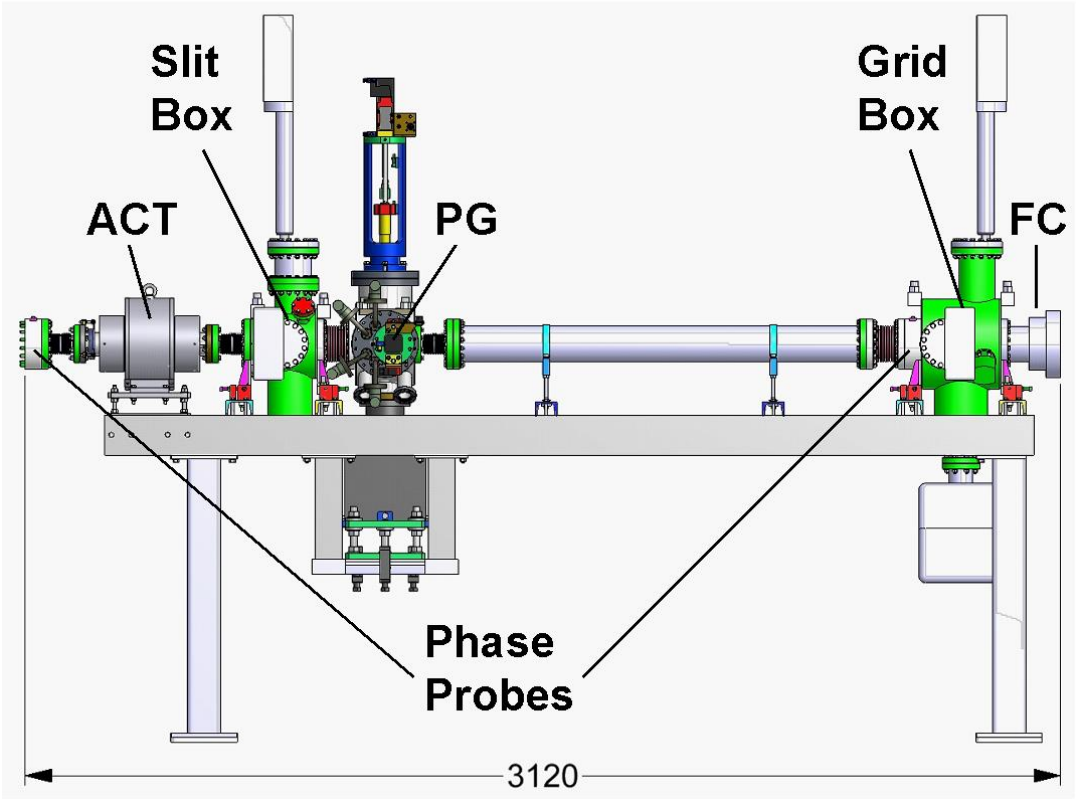
CNAO
Linac Beam Commissioning Test Benches

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
- Details of phase probe measurements: A. Reiter, Aries Workshop on Experiences During Hadron LINAC Commissioning, Jan. 2021, https://agenda.ciemat.es/event/1229/contributions/2825/

HIT & CNAO LEBT & Linac
Beam Instrumentation

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

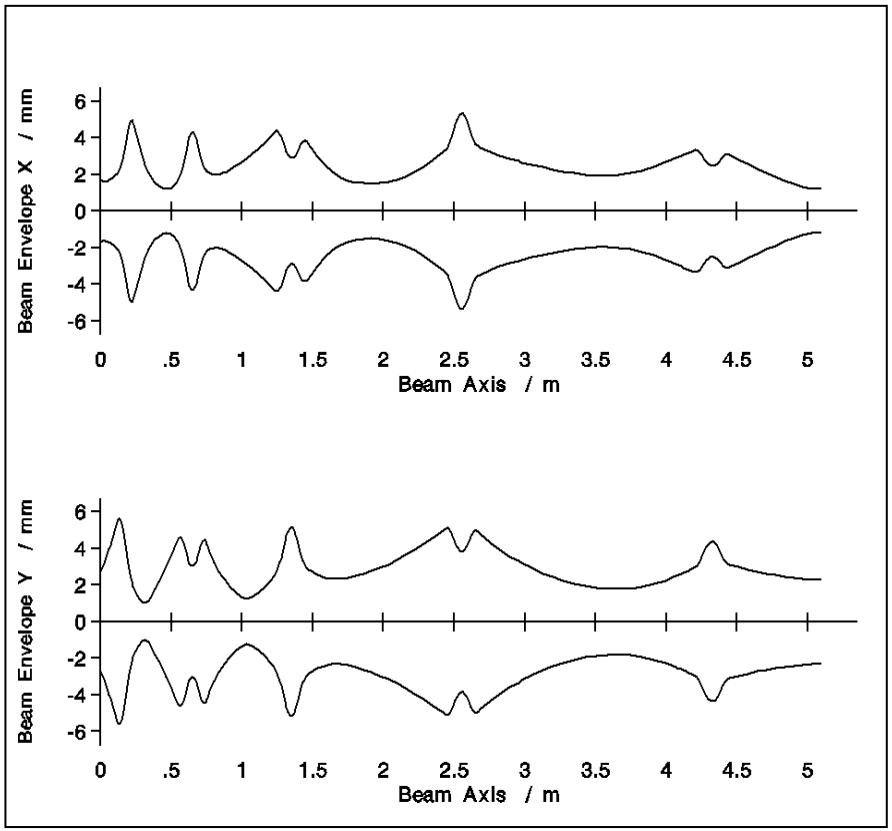
Viewing screens (org. Ta)	Real 2D images of ion source beams
SEM profile grids (at CNAO also wire scanners)	Beam profiles & positions (LEBT, Linac, MEBT)
Moveable slits	Beam analysis & selection of ion species (LEBT)
Faraday cups	Beam stop, DC / AC beam currents
DC & AC beam current transformers	Continuous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

- **Further details and applications during routine operation & commissioning:**
  see contributions by **R. Cee** and **A. Reiter** to **ARIES Workshop Jan. 2021**
- **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**)

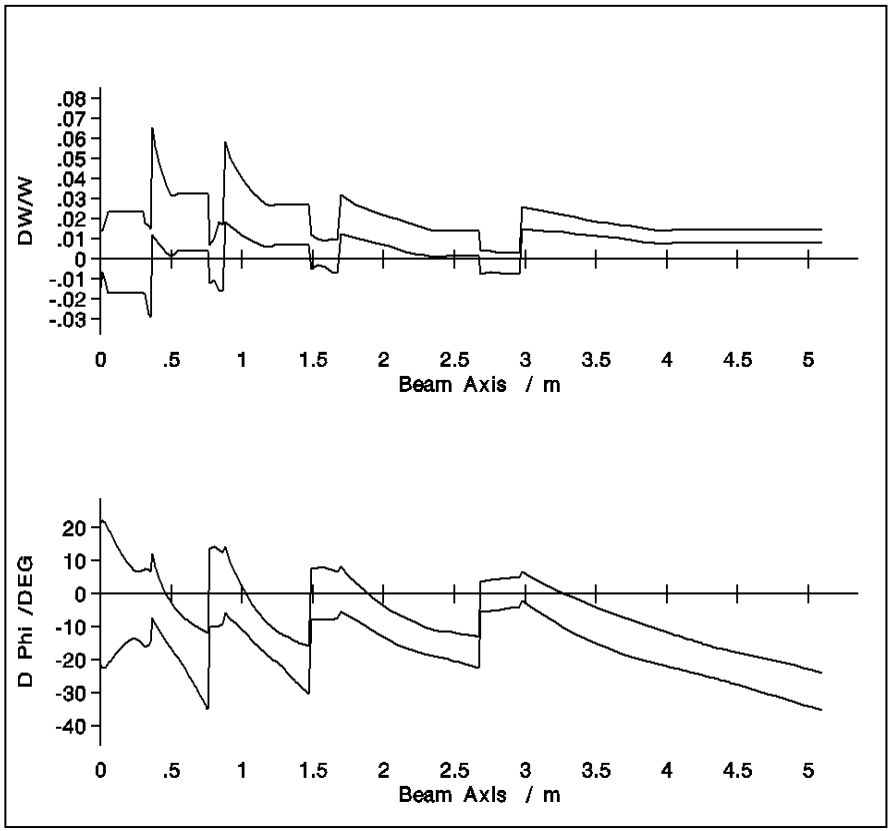
Beam Envelopes along IH-DTL

B. Schlitt and U. Ratzinger, EPAC98

Transverse



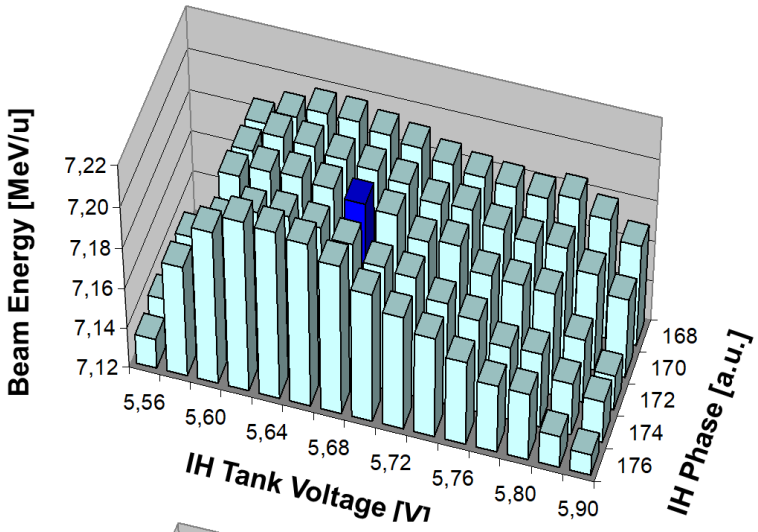
Longitudinal

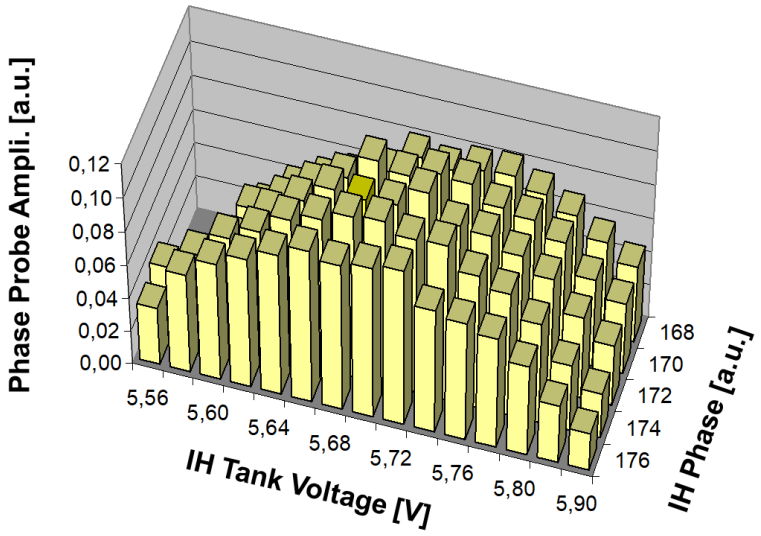


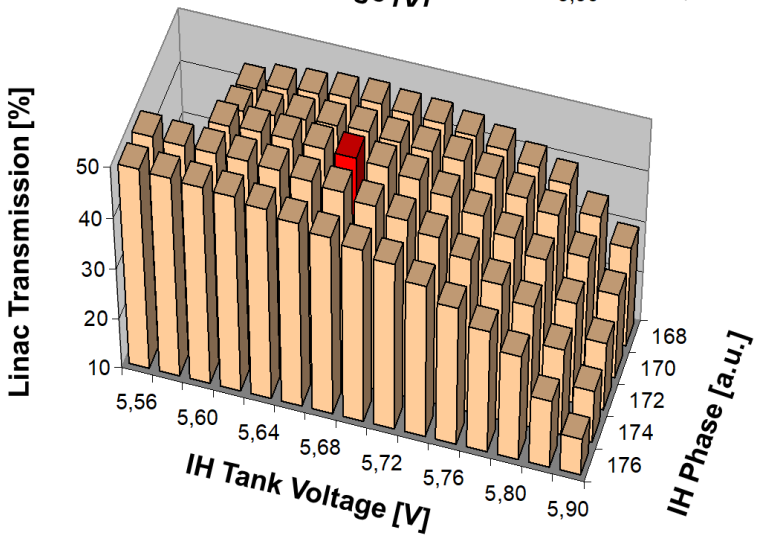
LORASR beam dynamics simulations, from end of RFQ electrodes down to stripping foil

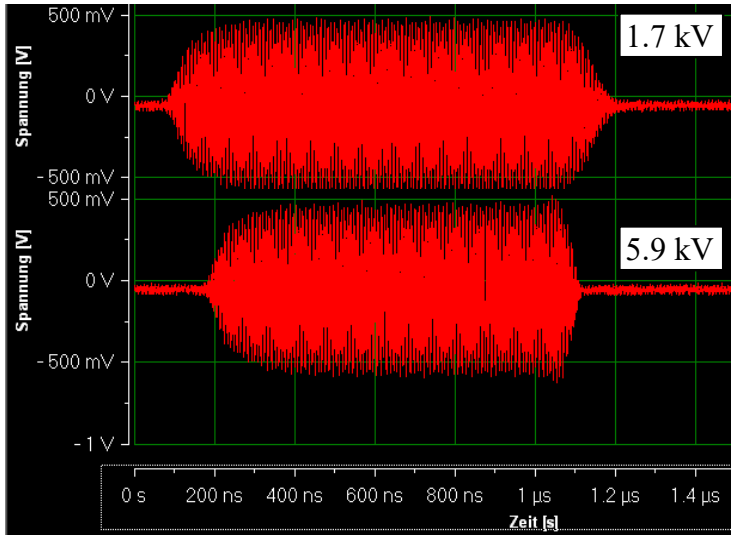
Example for Linac Commissioning (CNAO): Phase & Amplitude Scans, Chopper Rise Time

B. Schlitt et al., IPAC 2010









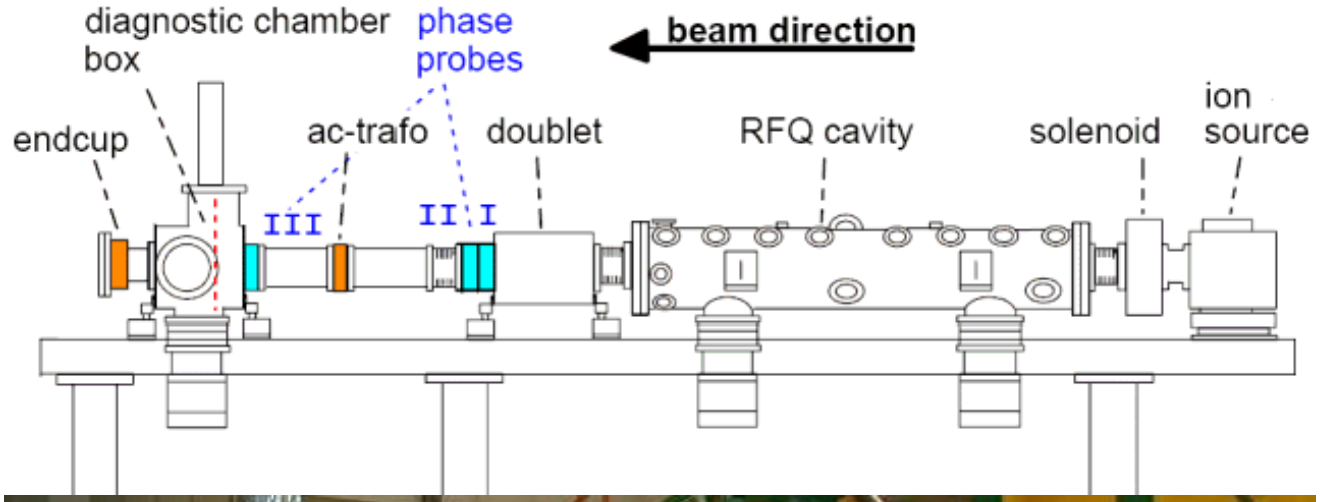
B. Schlitt, A. Reiter, S. Vitulli, GSI Scientific Report 2009

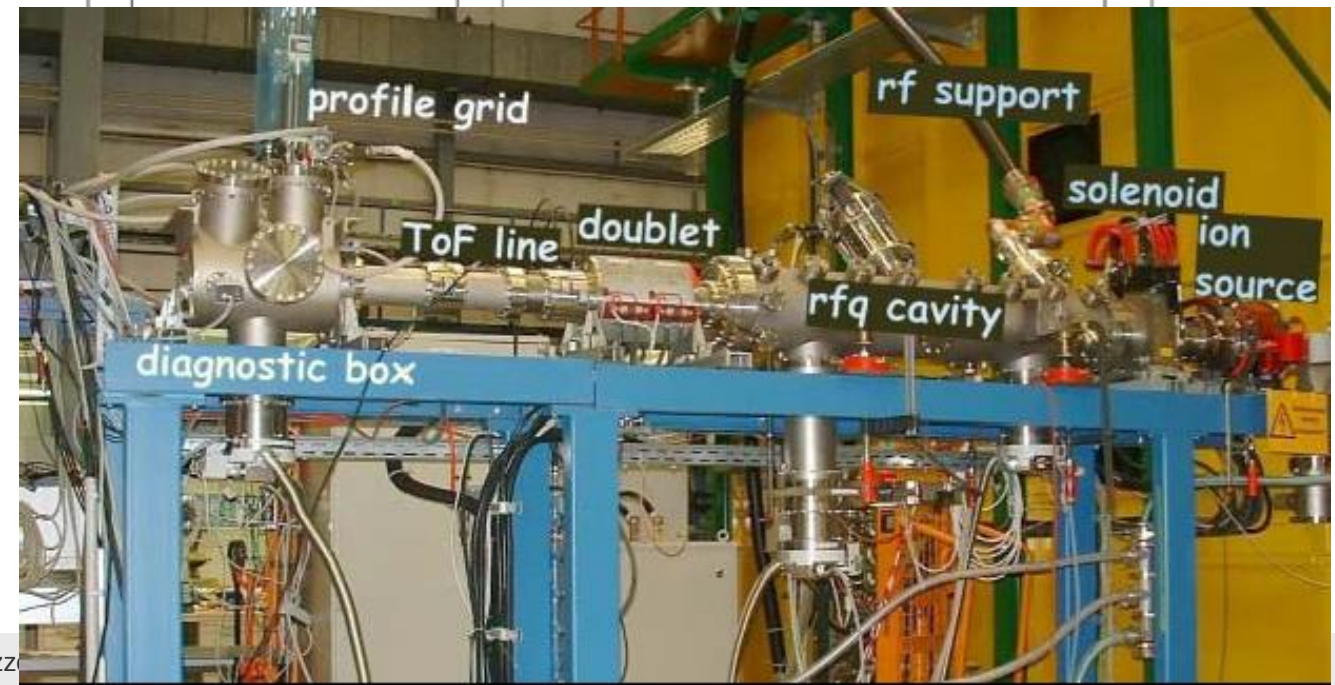
RFQ Test Bench @ GSI – Remarks

- **Dedicated test bench required:**
  Adjustment of drift tube buncher integrated into RFQ structure to match beam energy and phase width for IH-DTL injection
- Existing ion source terminal at GSI with MUCIS for production of proton beams (different to ion source at HIT)
- Proton beam operation only (no heavier ions like He or C):
  lower electrode voltage → no radiation shielding required
- Compact RF amplifier delivered by industry
- Similar test benches later installed at Siemens / Danfysik & at HIT (both using original ECR ion sources)
- **Also used for tests of beam diagnostics & controls equipment**

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

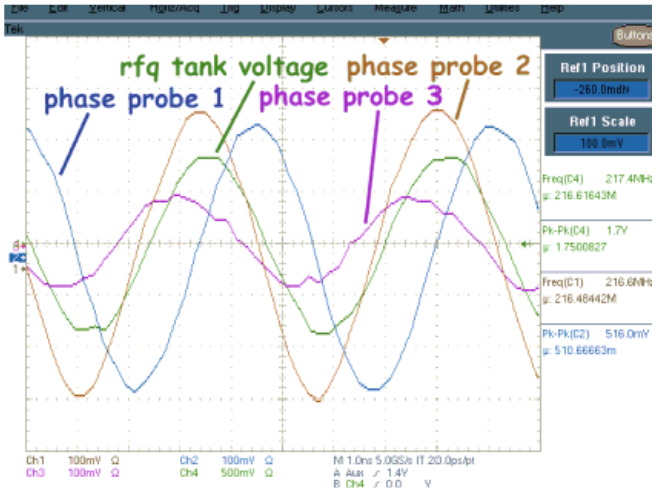
C.-M. Kleffner et al., LINAC 2006

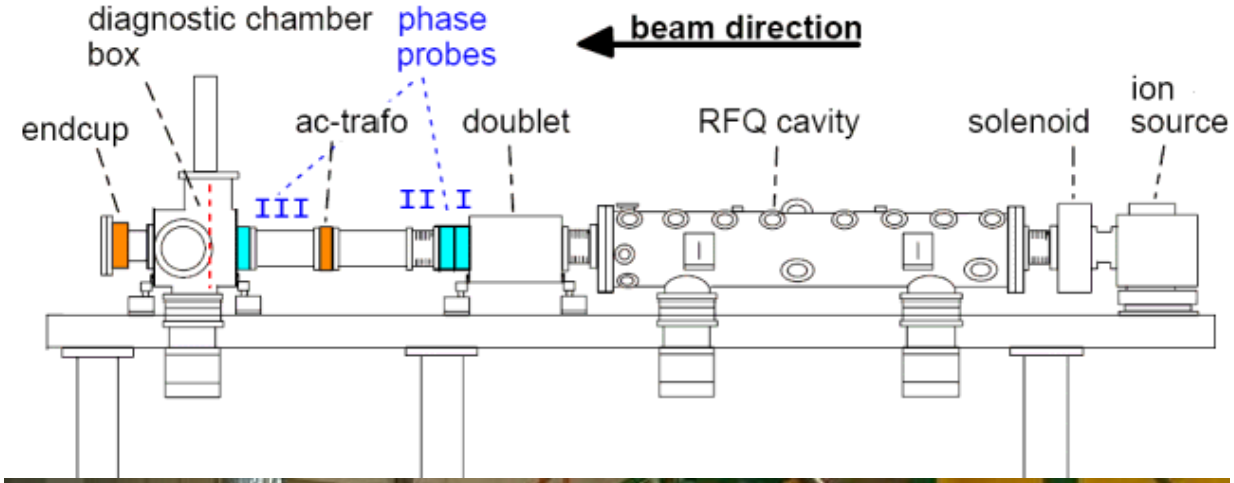


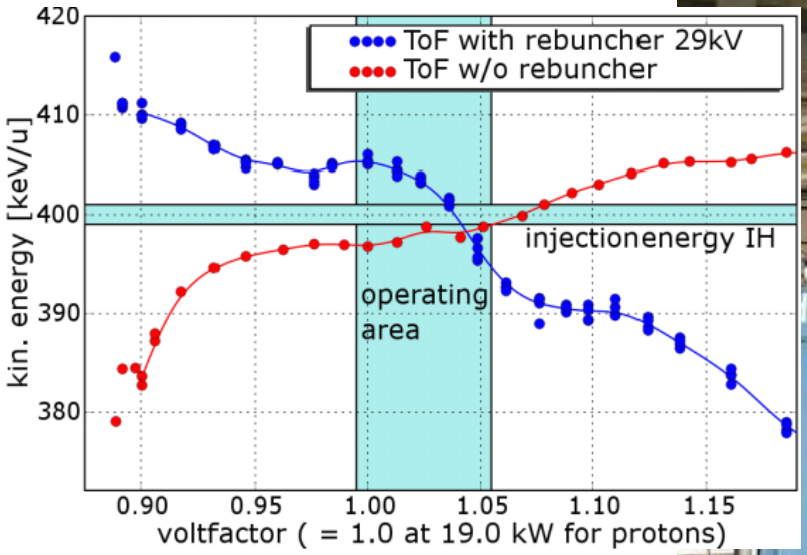


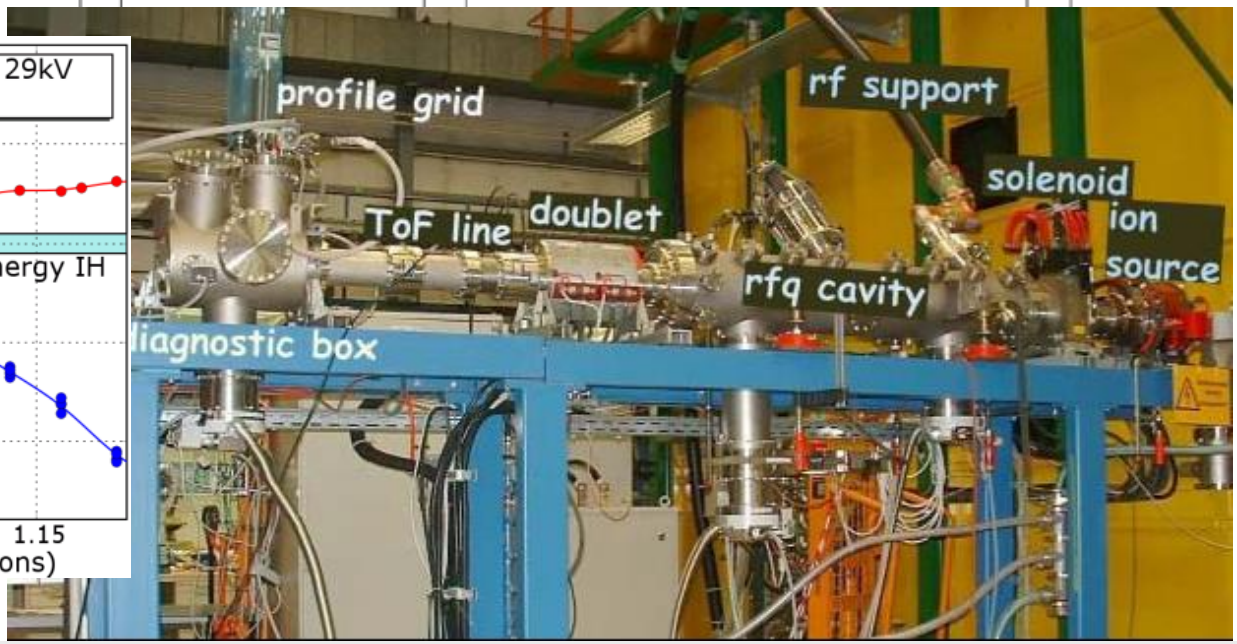
RFQ Beam Test Bench @ GSI (HIT & CNAO RFQs)

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









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 %**

GHMC
Gunma University Heavy Ion Medical Center

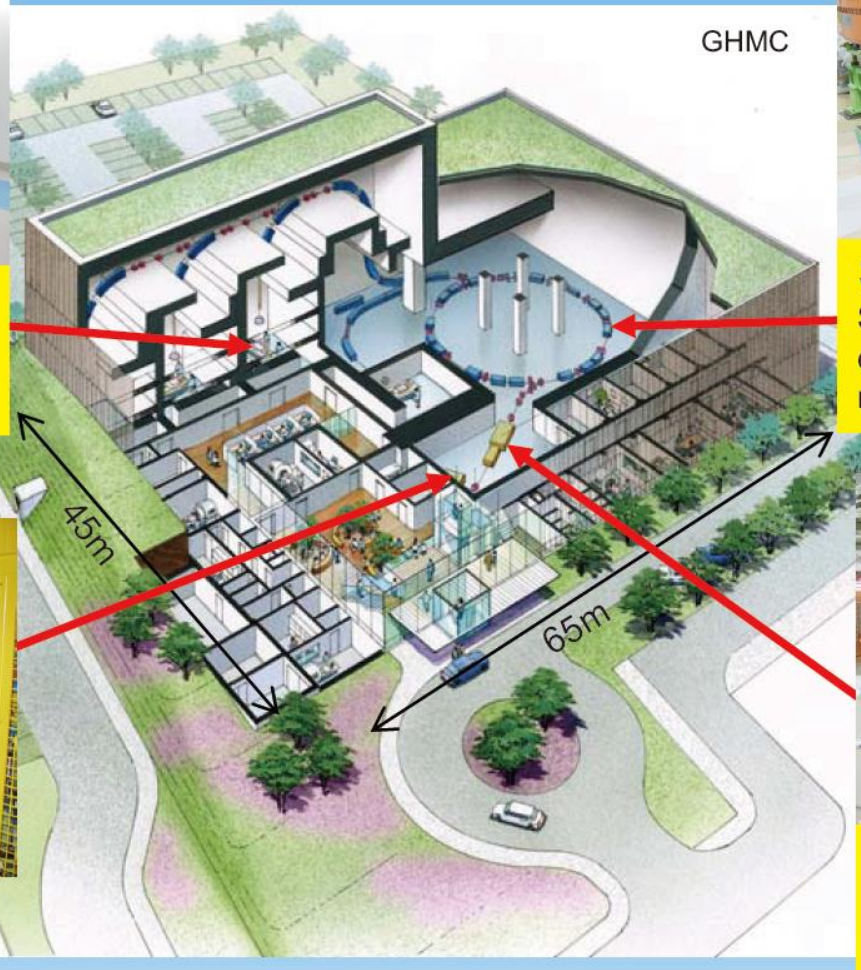
Facility Size 45 m x 65 m



Treatment Room
Accelerated carbon ions are irradiated into a patient.

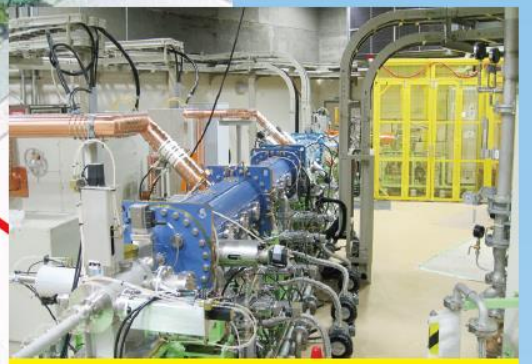


Synchrotron Accelerator
Synchrotron further accelerates carbon ions to 400 MeV/u at maximum.





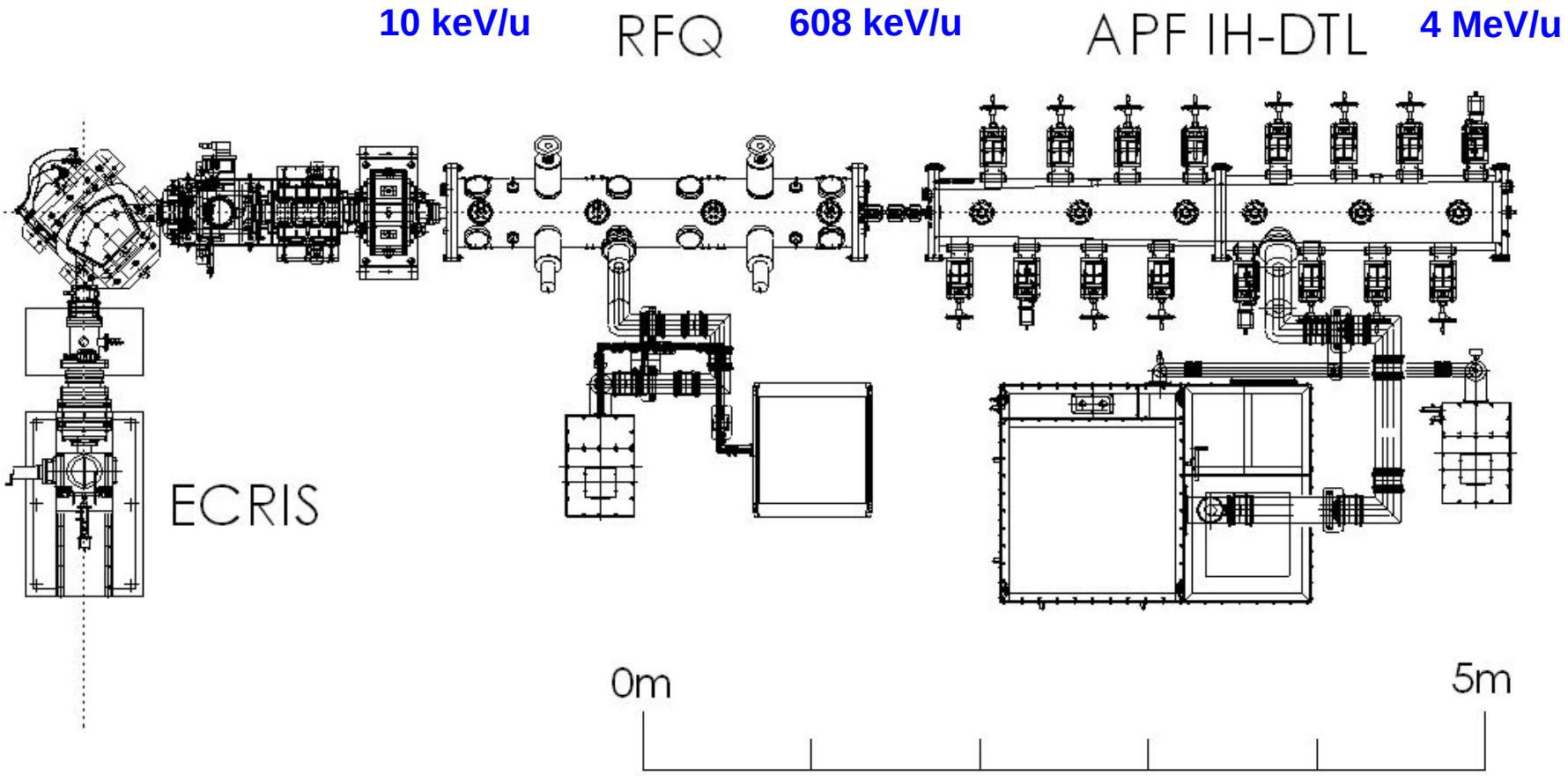
Ion Source
Carbon ions are produced from CH_4 gas.



Linear Accelerator
Carbon ions from the ion source are pre-accelerated to 4 MeV/u before the injection into the synchrotron.

Source: GHMC / Gunma University

200 MHz Injector Linac Developed at NIRS



Energy upgrade to 8 MeV/u investigated

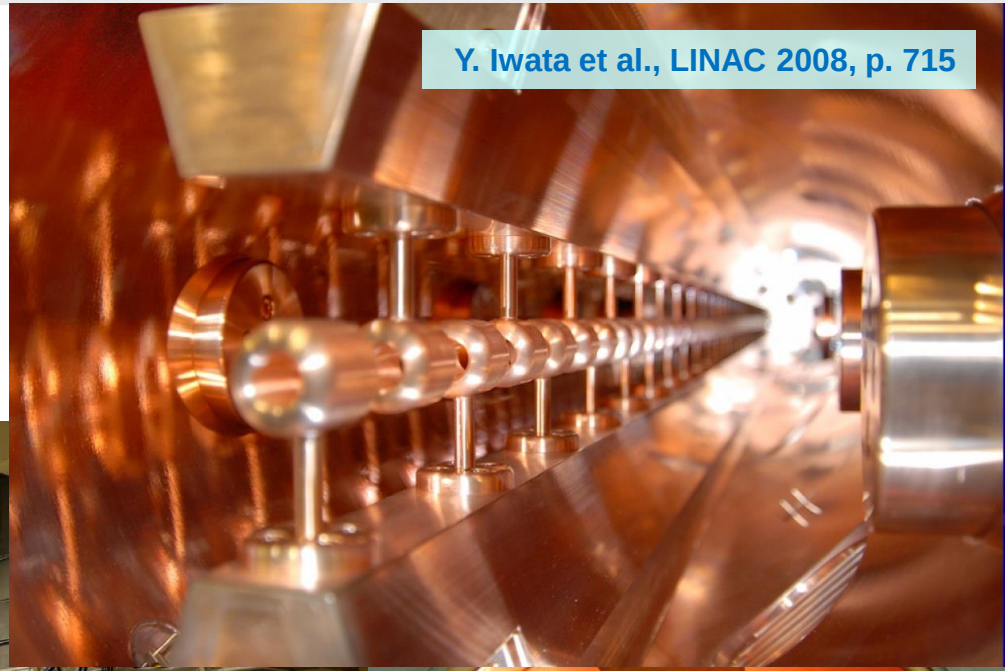
APF IH-DTL for C^{6+}, ~ 4,1 m

Y. Iwata, K. Noda, NIM B 331 (2014) 10-14

Y. Iwata et al., LINAC 2008, WE204
Y. Iwata et al., NIM A 569 (2006) 685

200 MHz Injector Linac at Gunma University Heavy Ion Medical Center

Manufactured by
Sumitomo Heavy Industries (SHI)



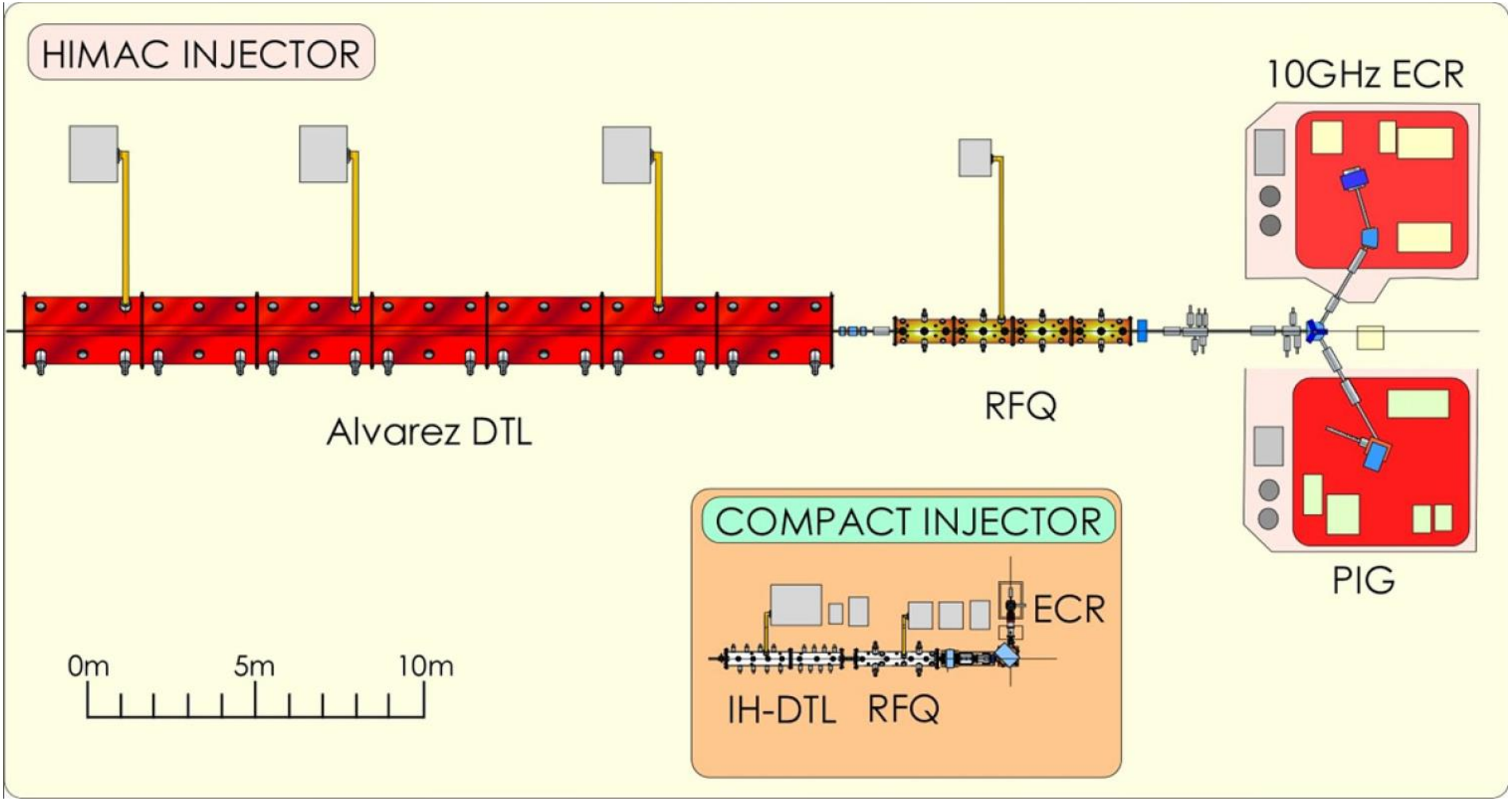
Y. Iwata et al., LINAC 2008, p. 715



T. Kanai et al., Erice, 2009



Comparison of Injector Size



Compact linac installed as 2nd injector at HIMAC (2010)

Y. Iwata et al., LINAC 2008, WE204
Y. Iwata et al., LINAC 2010, MOP060