Linacs in Heavy Ion Beam Therapy Facilities

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Outline

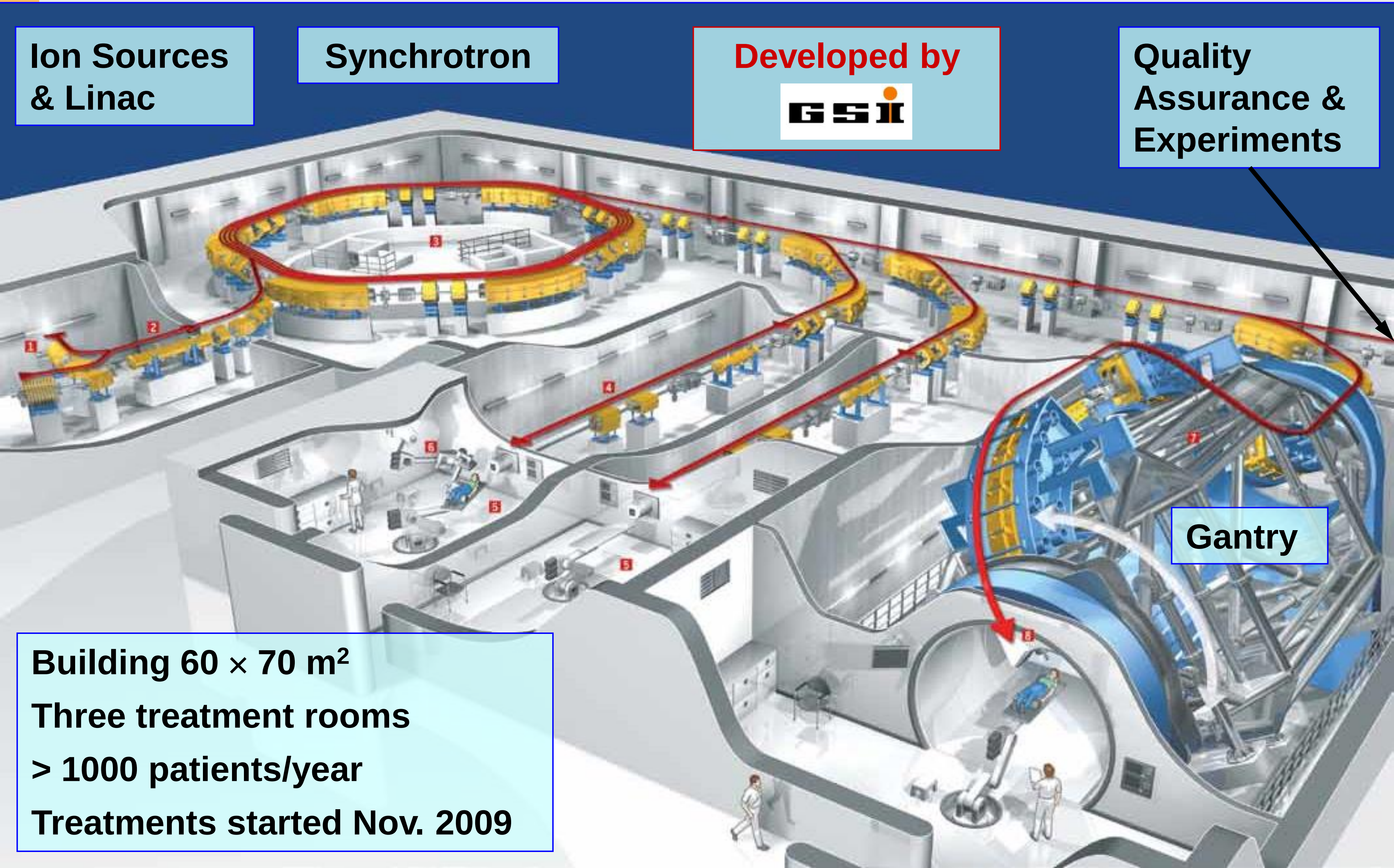
- Dedicated ion beam therapy centers (synchrotrons)
- HIT facility overview
- Injector linacs at heavy ion beam therapy centers
- Conclusions

Dedicated 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 Heavy Ion Medical Accelerator in Tosu	Japan	2013	
i-ROCK	Ion-Beam Radiation Oncology Center in Kanagawa, Yokohama	Japan	2015	
HIT	Heidelberg Ion Beam Therapy Center	Germany	2009	217 MHz KONUS-IH-DTL 7 MeV/u
CNAO	Centro Nazionale di Adroterapia Oncologica, 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	

* Patient Treatment

HIT
Heidelberg Ion Beam Therapy Center



Building 60 × 70 m²
Three treatment rooms
> 1000 patients/year
Treatments started Nov. 2009

Selected Key Contributions from GSI

1991	**1st intensity-controlled rasterscan performed at GSI**
1997 – 2008	**Pilot project on ion beam therapy – 440 patients treated at GSI** (carbon ions) GSI, Heidelberg University Hospital, DKFZ, HZ Dresden-Rossendorf
1996 – 2000	**Proton-Ion Medical Machine Study (PIMMS)** CERN (host), TERA, MedAustron, GSI **GSI:** injector linac, heavy-ion gantry
1998	**Conceptual design report (Porposal) for the later HIT facility** Synchrotron based on experience with GSI synchrotron
Until 2008	**GSI:** Design, development, planning, assembly, installation & commissioning of the HIT accelerator, component specification, manufacturing supervision, delivery of beam diagnostics, copper-plating, RF tuning, tests, ...

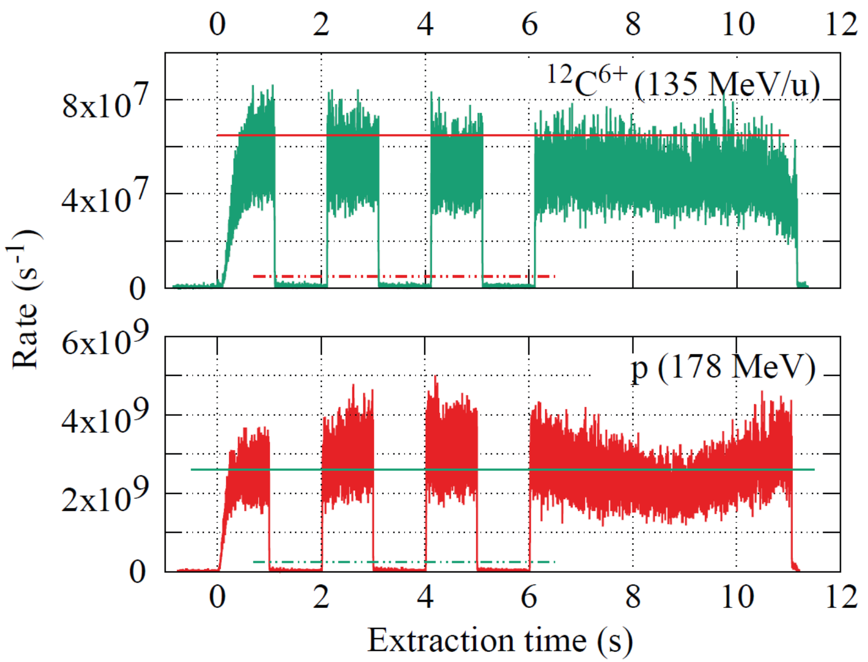
HIT Key Parameters

Ion species	**p, C**, He, O (3 $\times$ ECRIS)
Final beam energy range	48 – 430 MeV/u 255 steps for each ion species
Penetration depth in water	20 – 300 mm
Beam intensities (ions / spill)	Protons: 4×10^{10} (design) 3×10^{10} (MIT status 2016)
	Carbon: 1×10^{9} (design) 7×10^{8} (MIT status 2016)
Extraction time	$\leq$ 10 s (5 s)
Beam delivery	Intensity controlled 3D raster scanning

Synchrotron:	
Circumference	65 m
Injection	Multiturn injection scheme
Extraction	Transverse RF knock-out

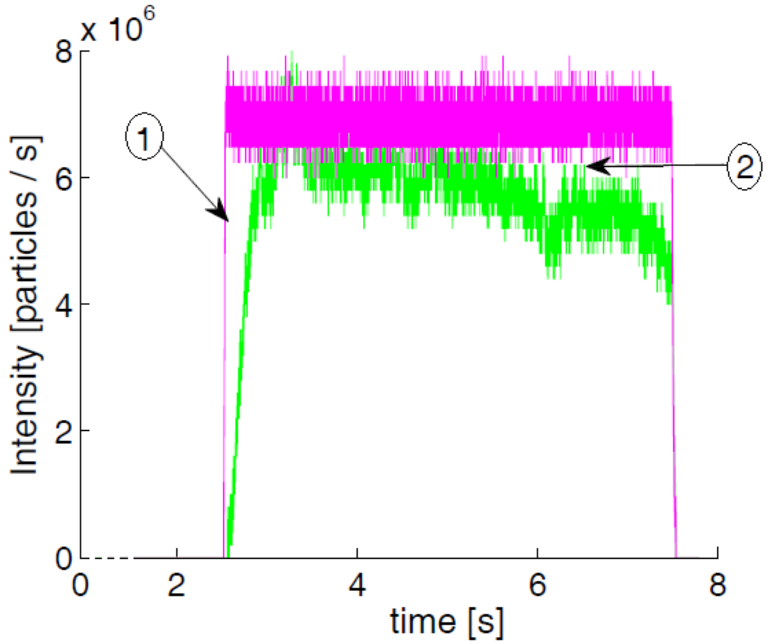
Synchrotron Operation & Improvements

Beam Extraction Gating



U. Scheeler et al., IPAC 2016
(example at MIT)

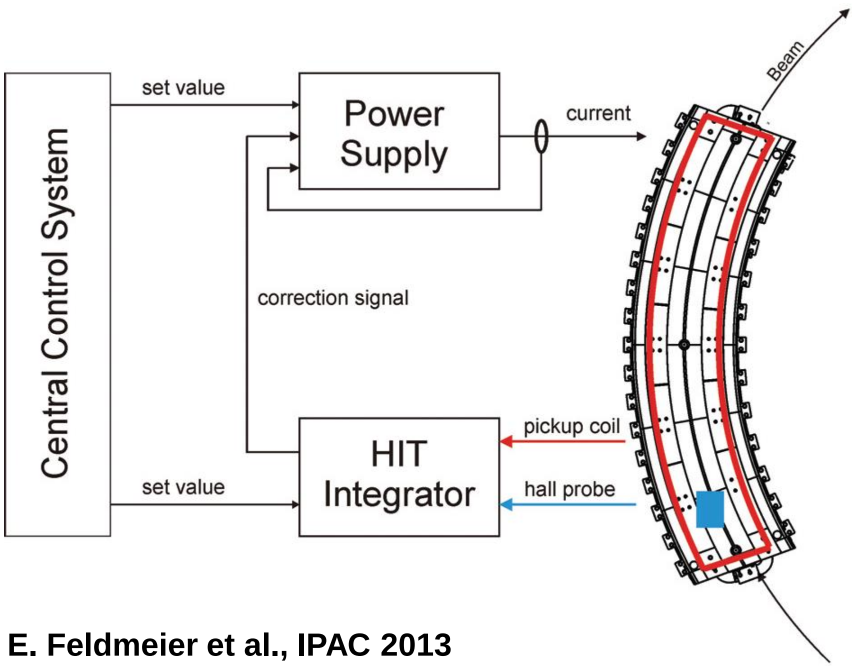
Intensity Feedback Loop / Active Spill Control



C. Schoemers et al., IPAC 2013

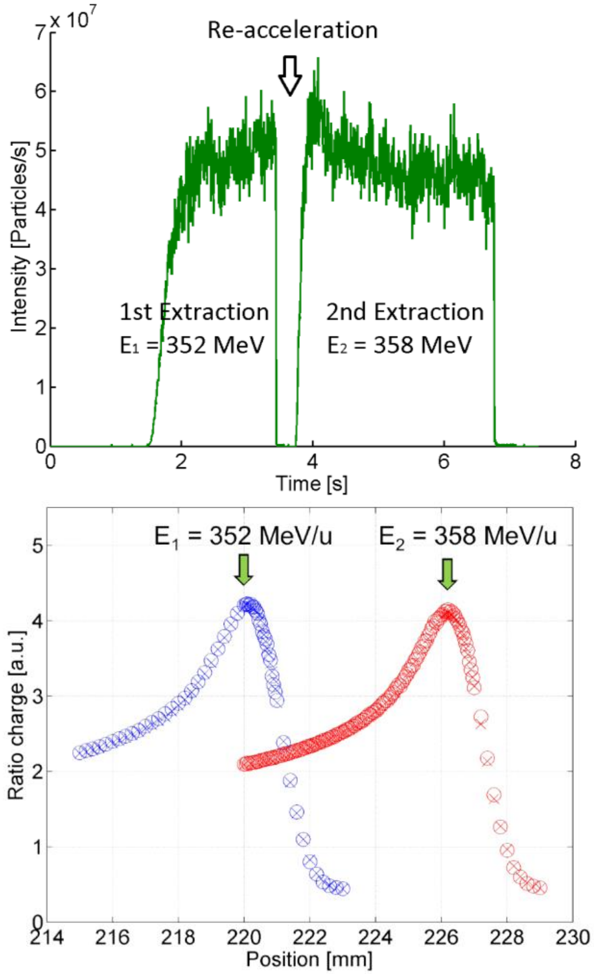
Synchrotron Operation & Improvements

Magnetic Field Feedback Loop for Dipole and Quadrupole Magnets



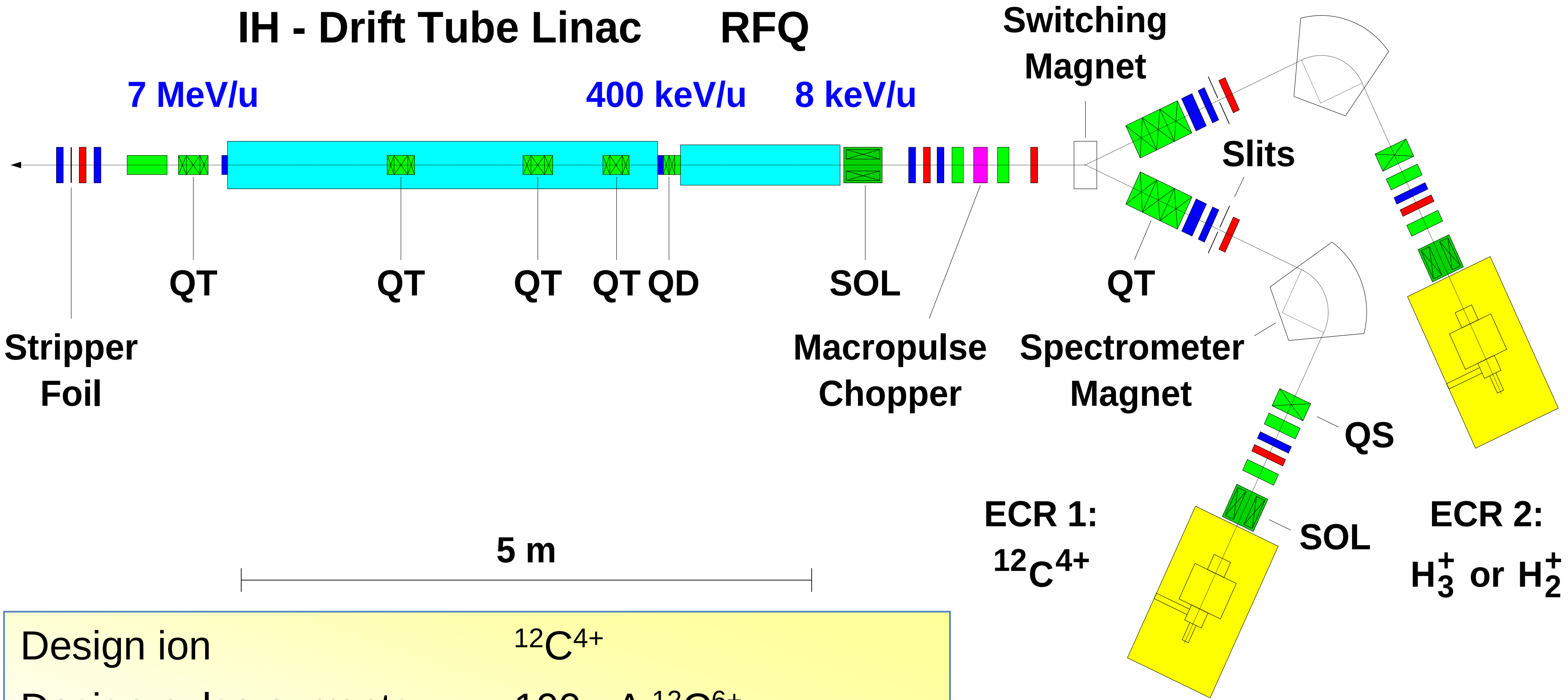
E. Feldmeier et al., IPAC 2013

First Tests of Re-Accelerated Ion Beams at HIT



C. Schoemers et al., IPAC 2017

217 MHz HIT Injector Linac (Org. Layout)

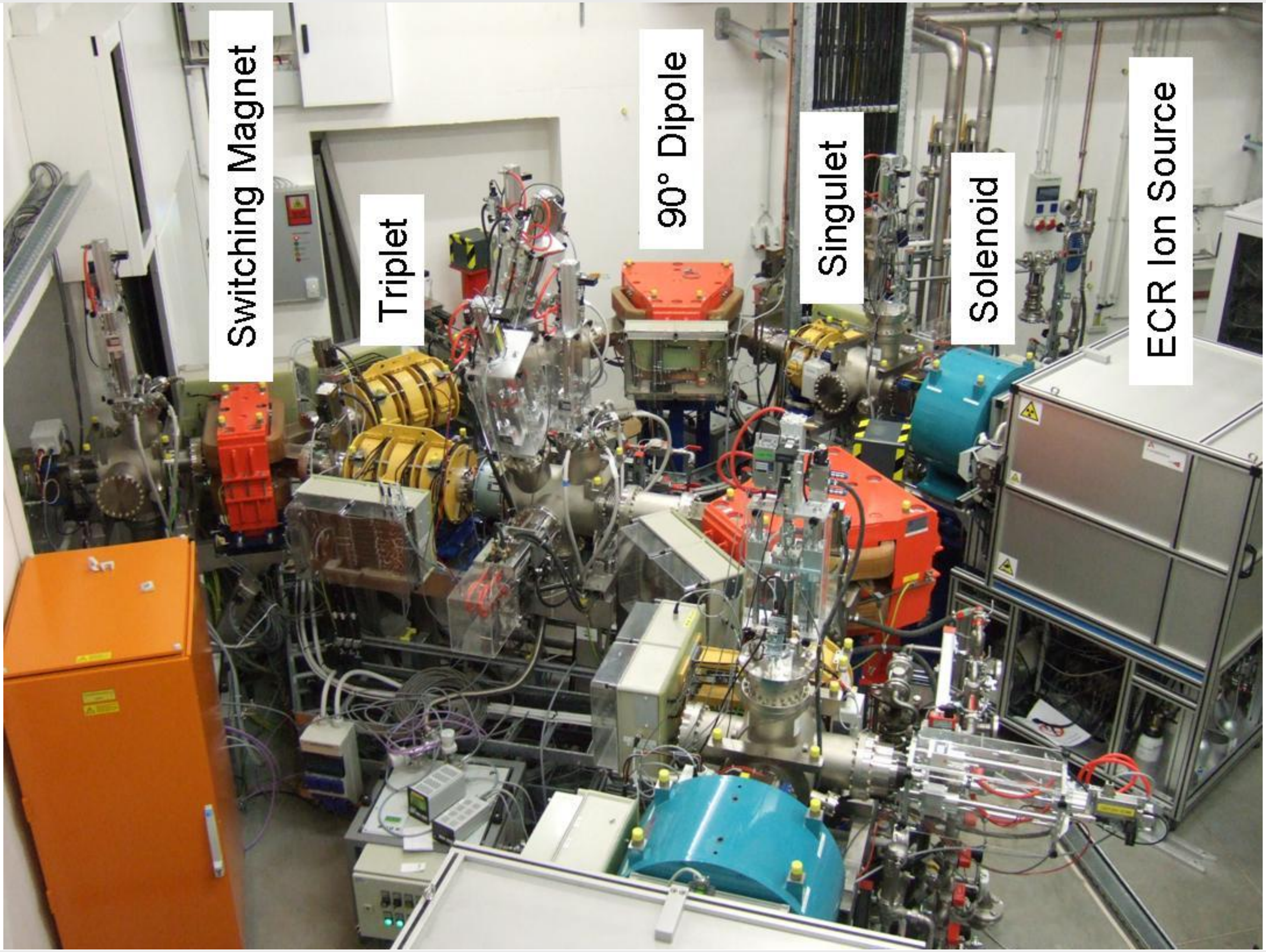


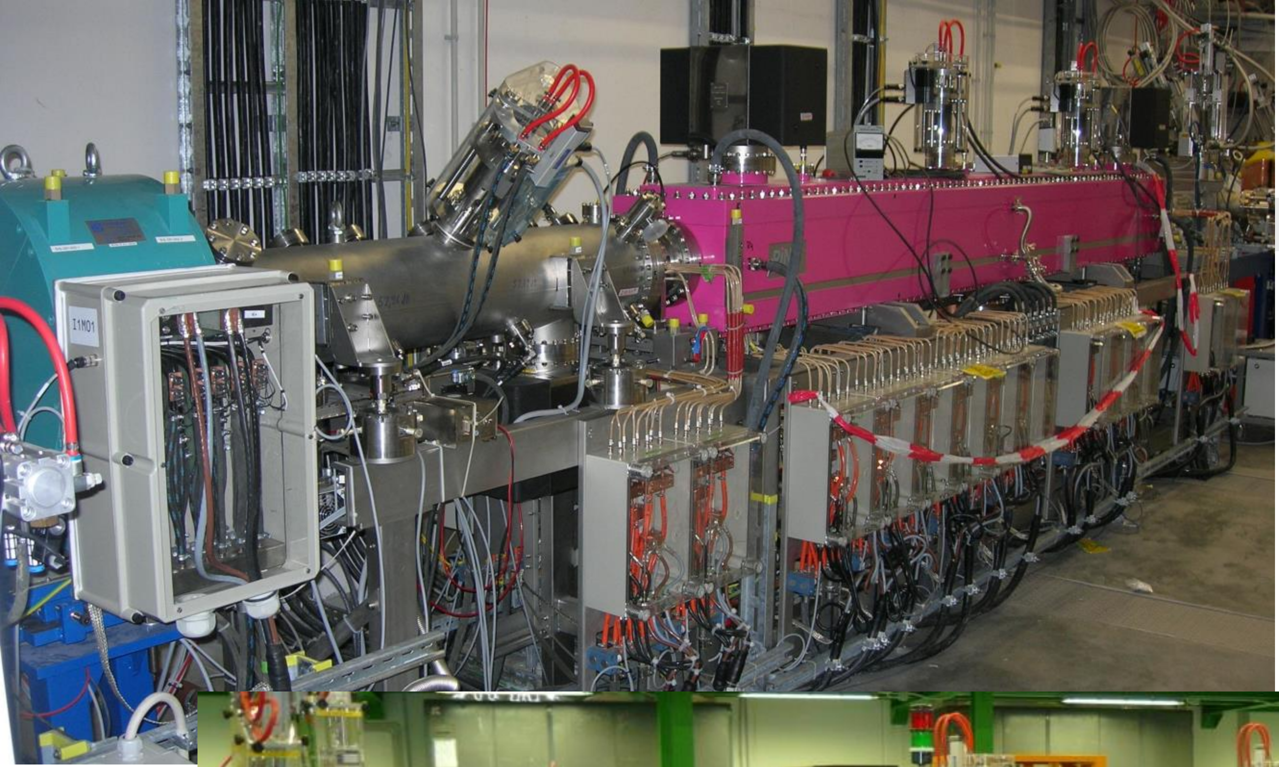
Design ion	$^{12}C^{4+}$
Design pulse currents (after stripping)	100 µA $^{12}C^{6+}$ ~ 0.5 – 1 mA protons
Beam pulse length	≤ 300 µs @ ≤ 5 Hz
Operating frequency	216.8 MHz

Developed at GSI & IAP / Frankfurt University

B. Schlitt, LINAC 2008, p. 720

Original Low Energy Beam Transport (LEBT) at HIT

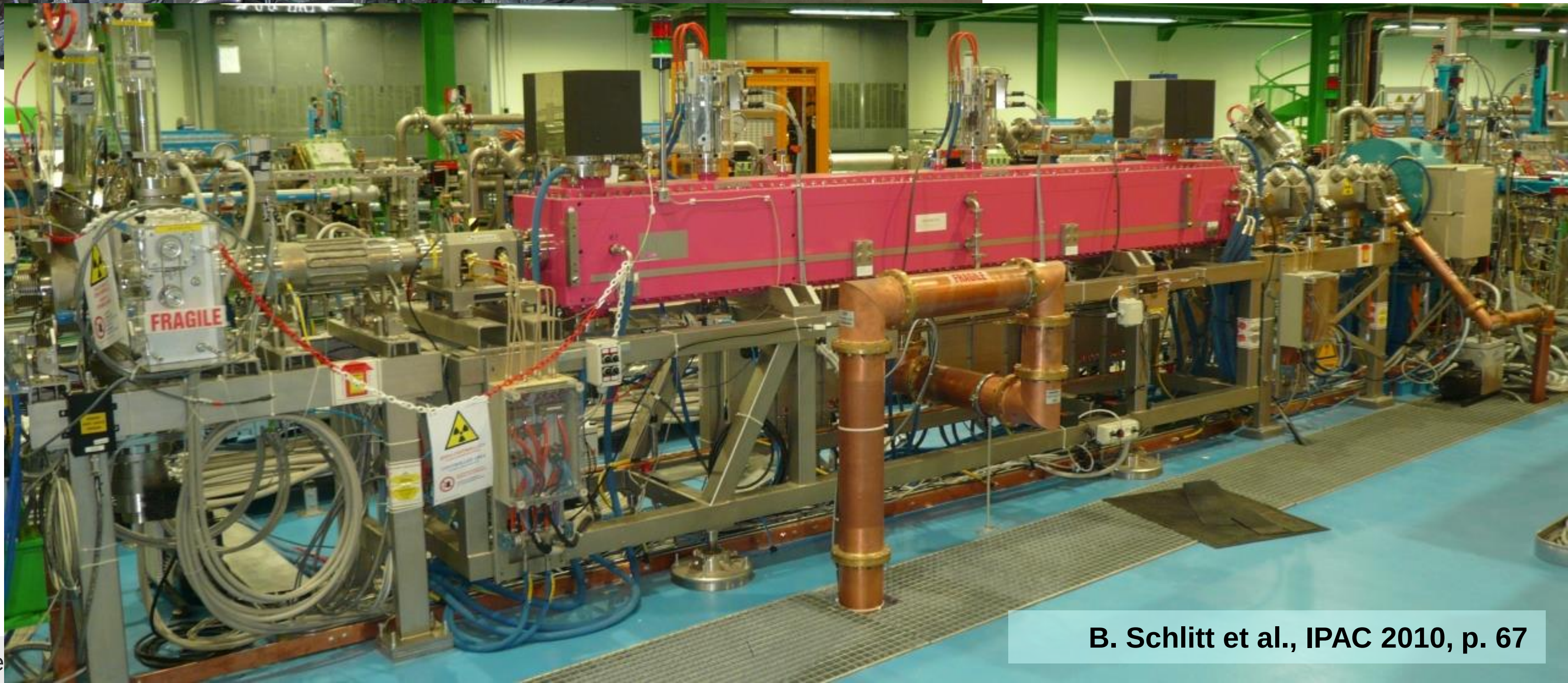




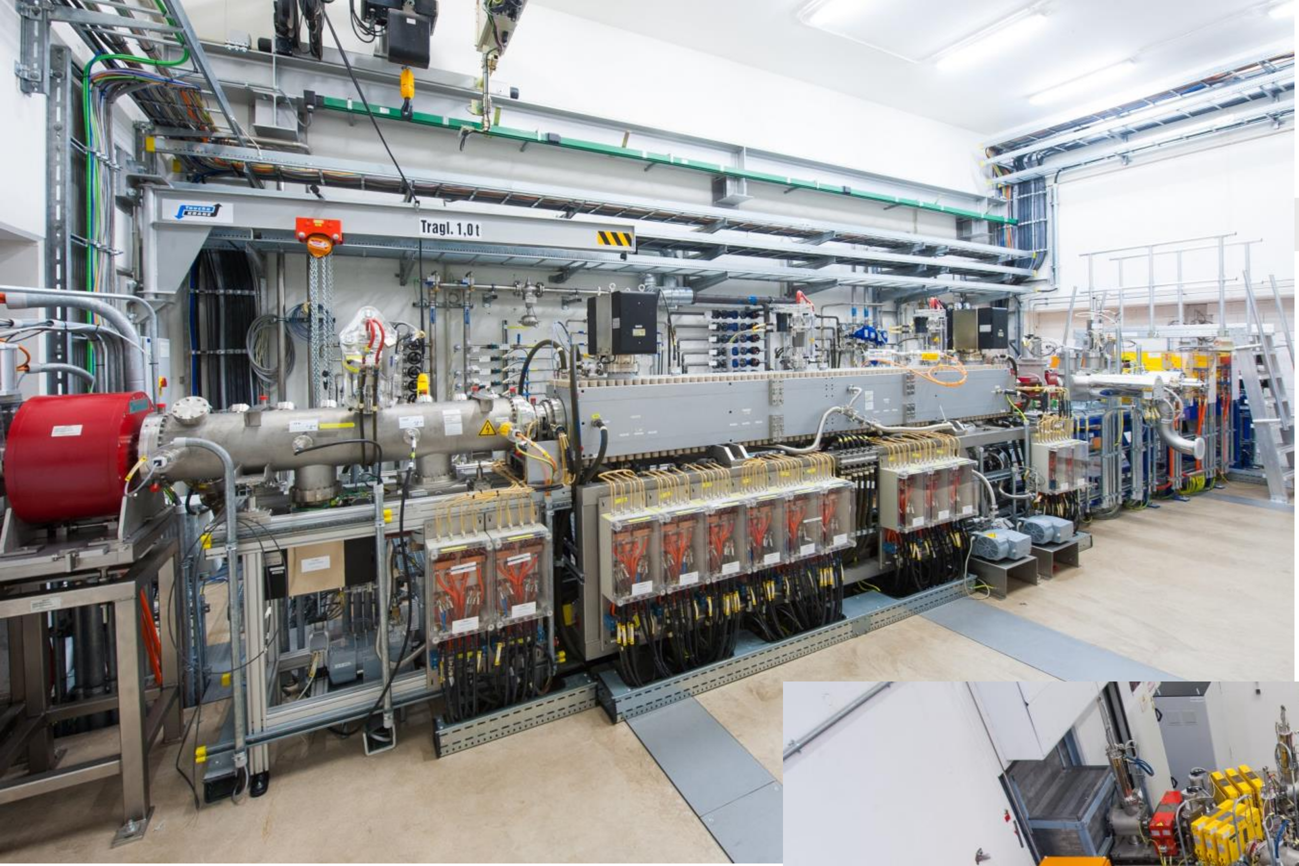
HIT Injector Linac, Heidelberg, Germany

B. Schlitt, LINAC 2008, p. 720

CNAO, Pavia, Italy



B. Schlitt et al., IPAC 2010, p. 67



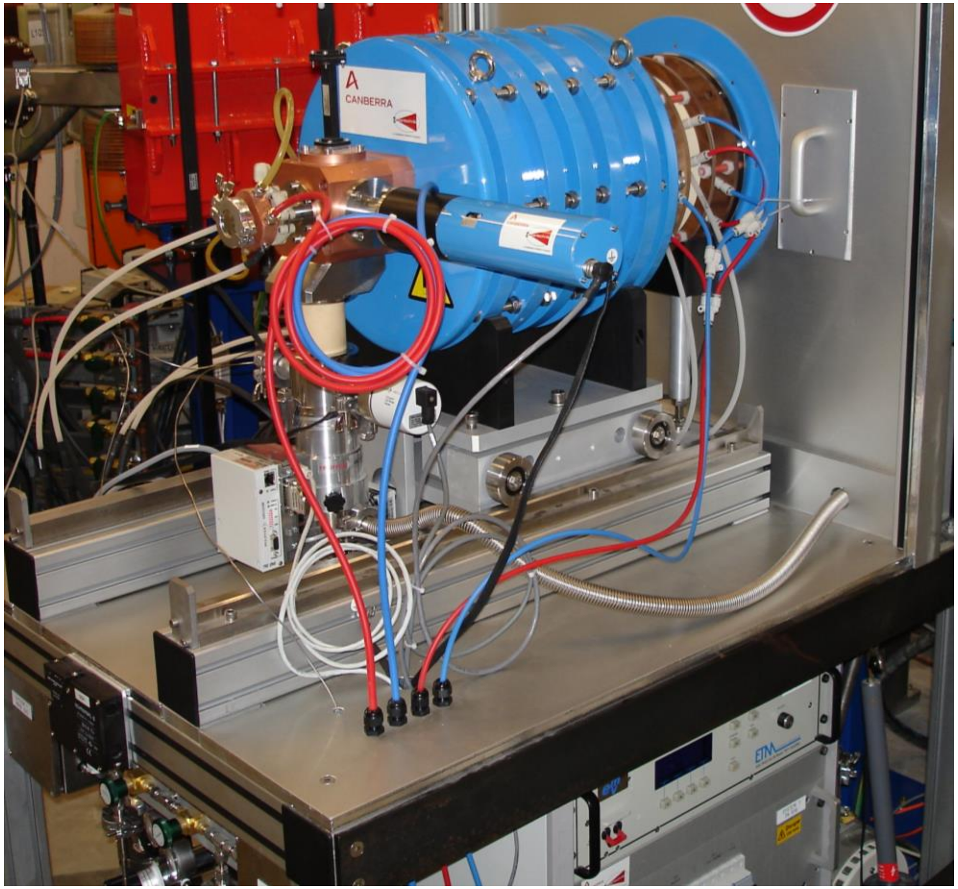
MIT Injector Linac, Marburg, Germany

built by Siemens / Danfysik

Photos: Siemens

14.5 GHz SUPERNANOGAN (PANTECHNIK)

Commercial fully permanent magnet
Electron Cyclotron Resonance Ion Source (ECRIS)



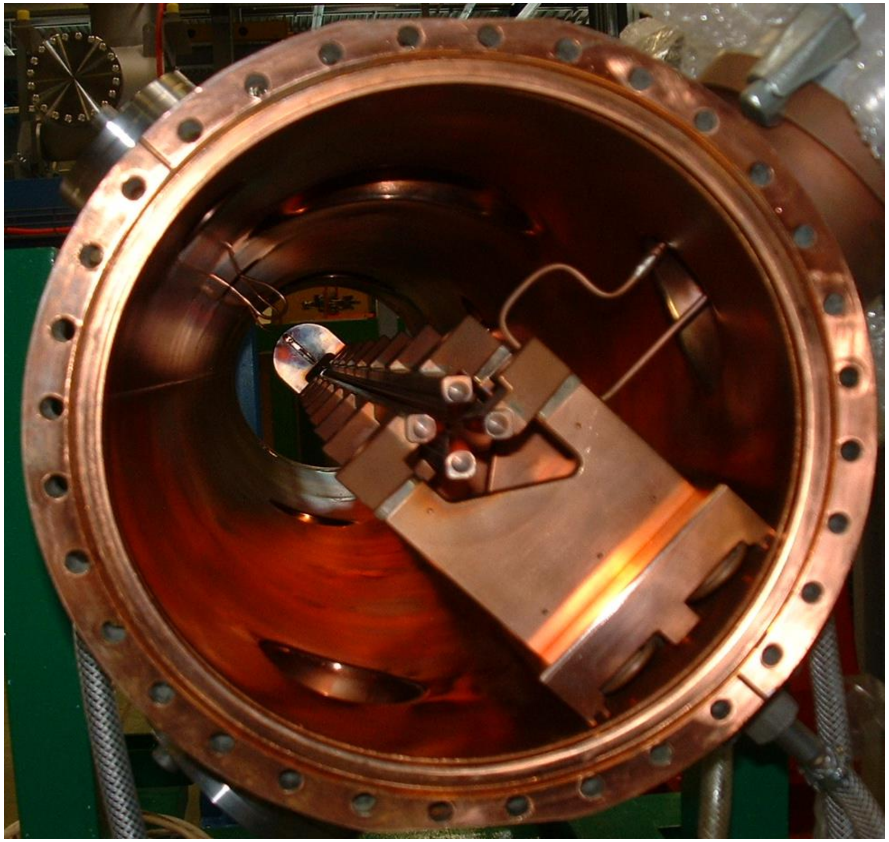
Source body	∅ = 380	mm
	L = 324	mm
Max. extraction voltage	30	kV

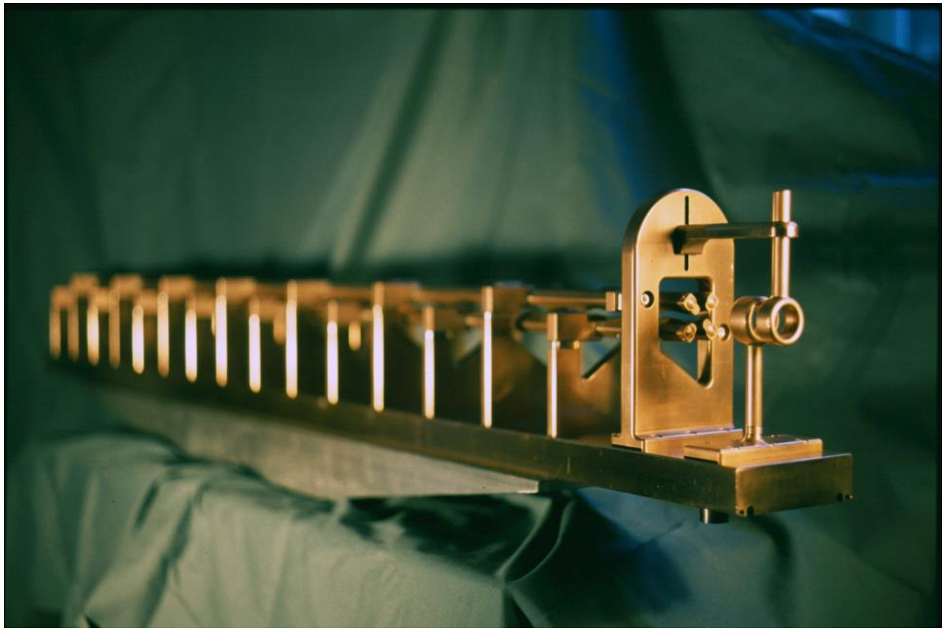
- No high-voltage platform
- Permanent magnets
  → no magnet power supplies,
  no magnet cooling
- Compact size
- Very stable operation
- DC beams, pulse formation by LEBT chopper
- Long maintenance intervalls

400 keV/u 4-Rod Type RFQ

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

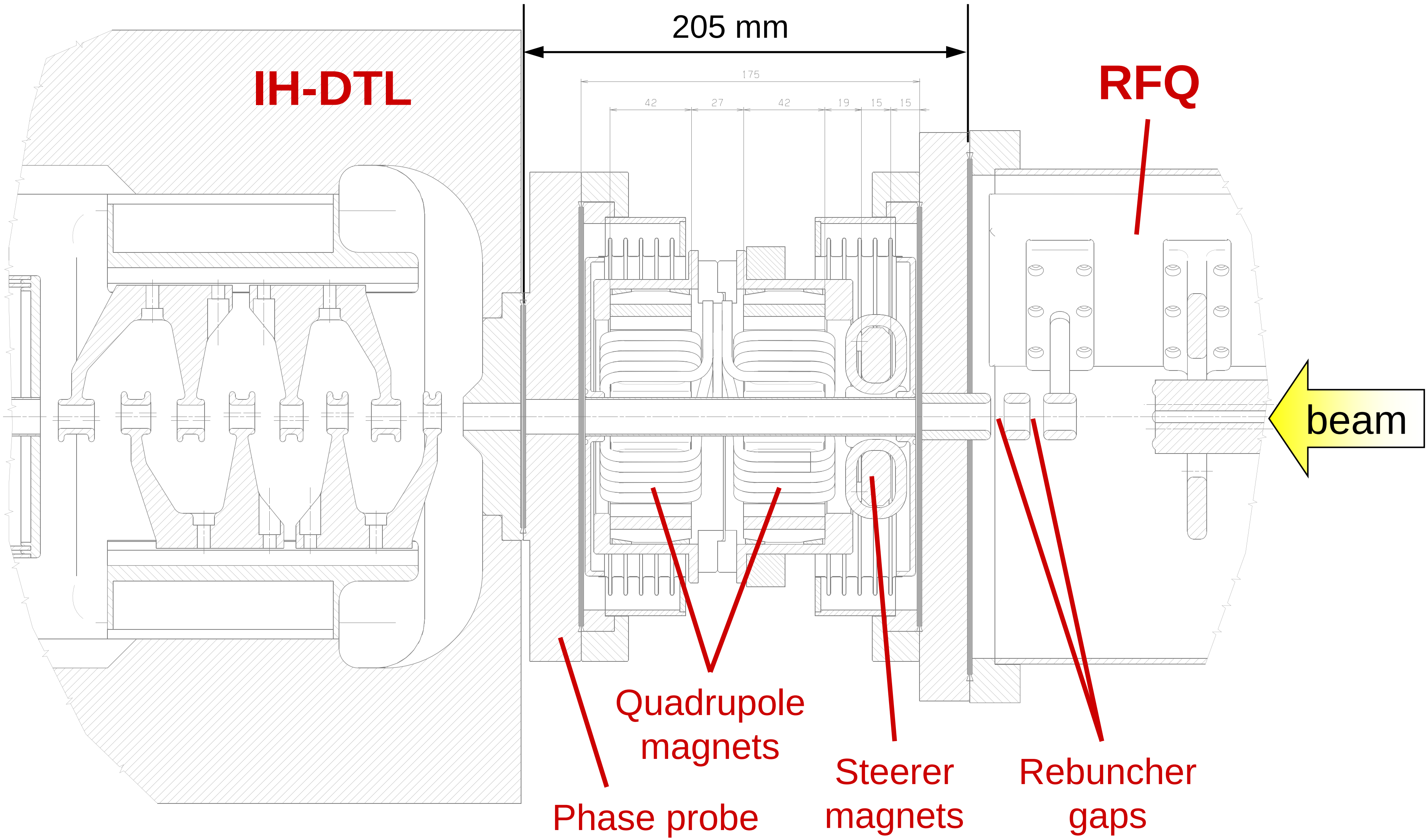
A. Bechtold et al., EPAC 2004, p. 2568



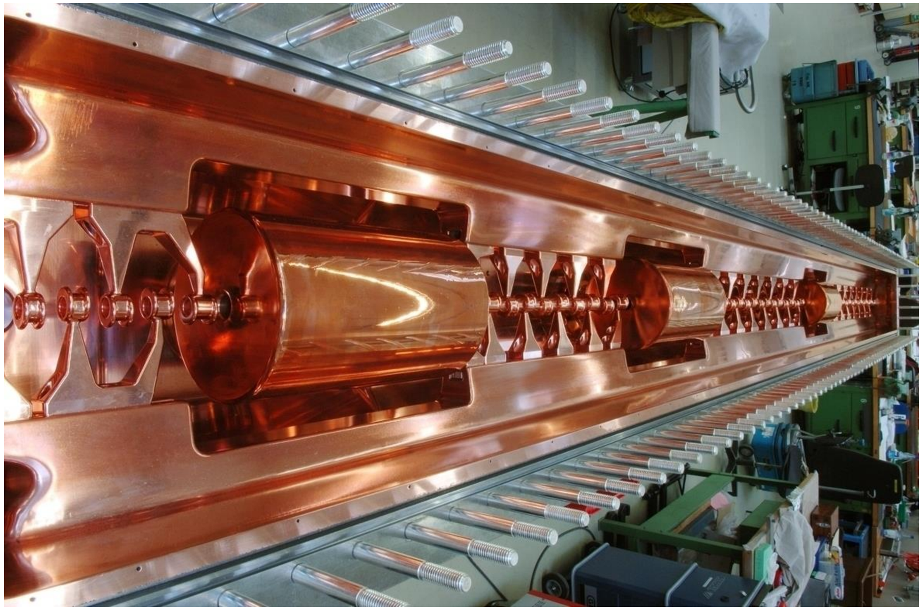


Beam energy in – out	8 – 400 keV/u
Electrode length	1.28 m
Tank diameter	0.25 m
Tank length	1.44 m
Electrode voltage	70 kV
RF power loss (pulse)	~ 200 kW

400 keV/u Inter-tank Section (ITM)



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

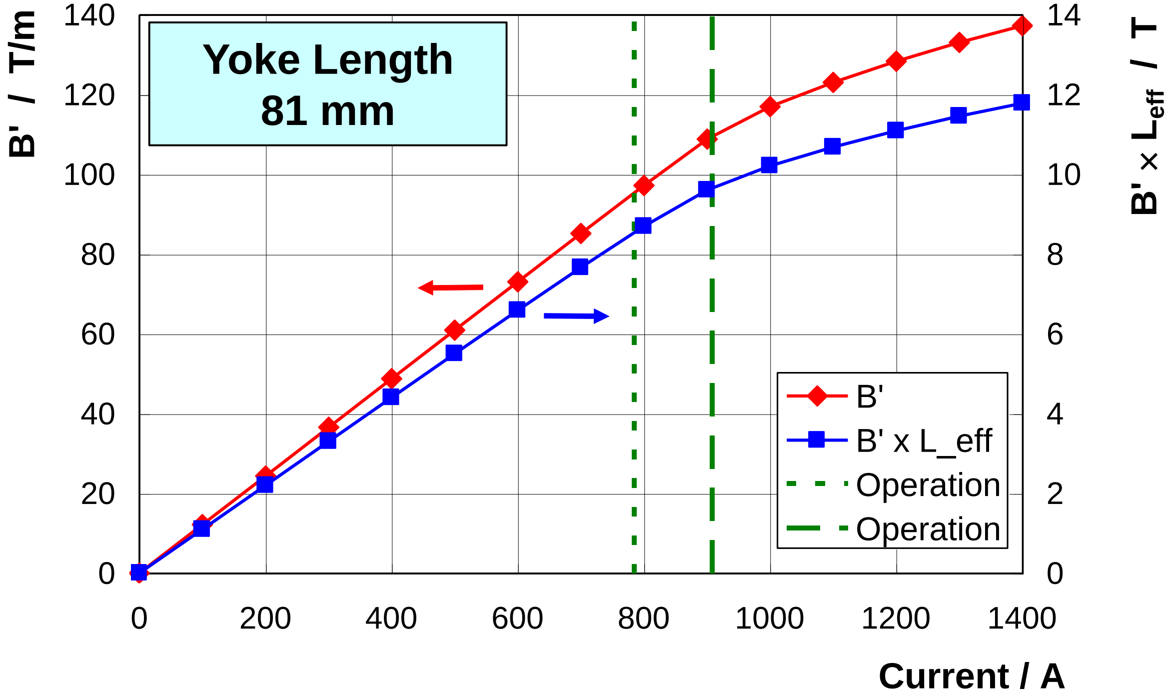


Beam energy in – out	0.4 – 7 MeV/u
Integrated triplet lenses	3
Accelerating gaps	56
Tank length	3.8 m
Inner tank height	0.34 m
Inner tank width	0.26 m
Drift tube aperture diam.	12 – 16 mm
Tank voltage	~ 20 MV
Averaged eff. volt. gain	5.3 MV/m
Max. on axis electr. field	≤ 18 MV/m
Max. eff. gap voltage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

In collaboration with IAP,
Frankfurt University, Prof. Ratzinger

High Field LINAC Quadrupole Magnets

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

B. Schlitt et al.,
LINAC 2004, MOP09

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)

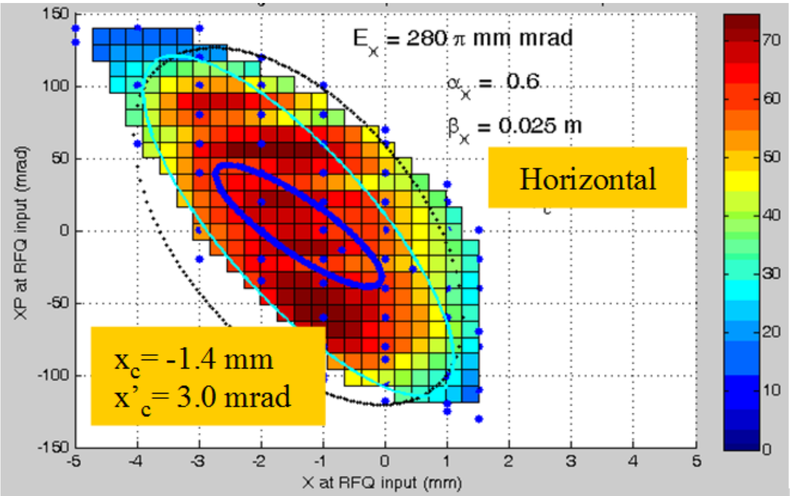
Improvements so far:

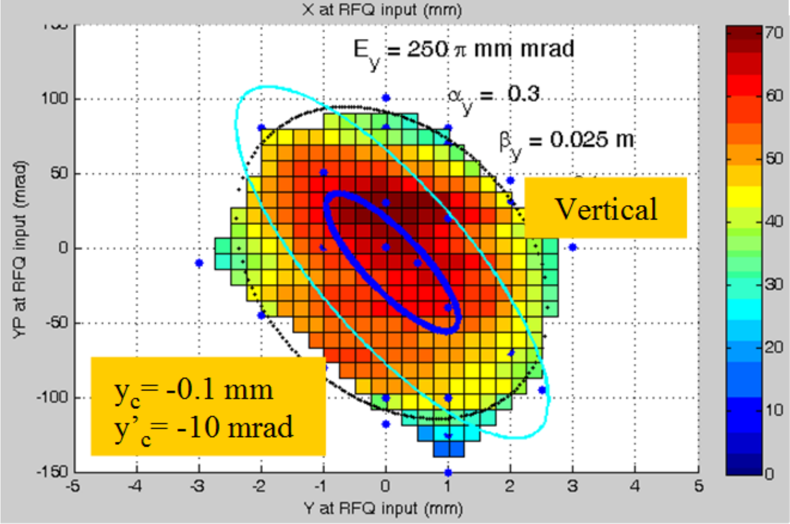
- **New input radial matcher** (IRM) for reduced external focusing at RFQ injection (reduction of aberration effects by solenoid focusing)
- **Mechanical design** of RFQ electrodes & tank, improved electrodes & tank alignment, more robust RFQ tank
- **Optimized beam matching to RFQ** (emittance measurements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

RFQ Performance (CNAO)

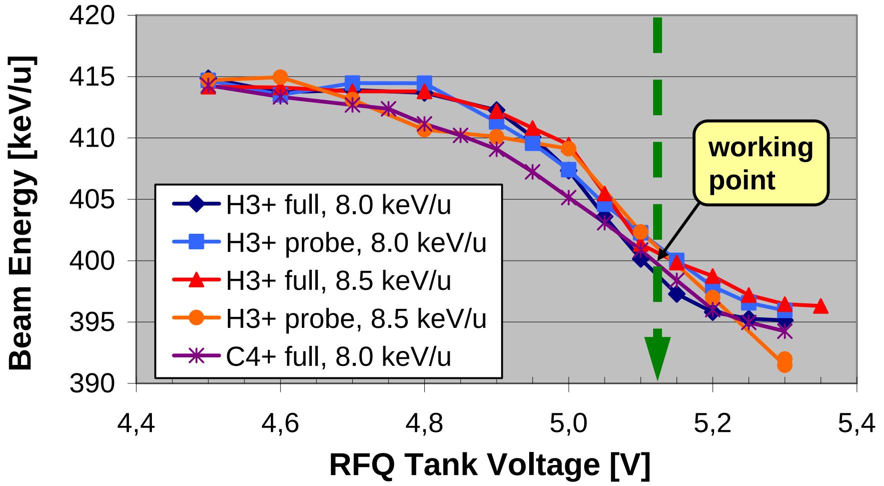
P. Posocco et al., HIAT 2009 | **B. Schlitt et al., IPAC 2010**

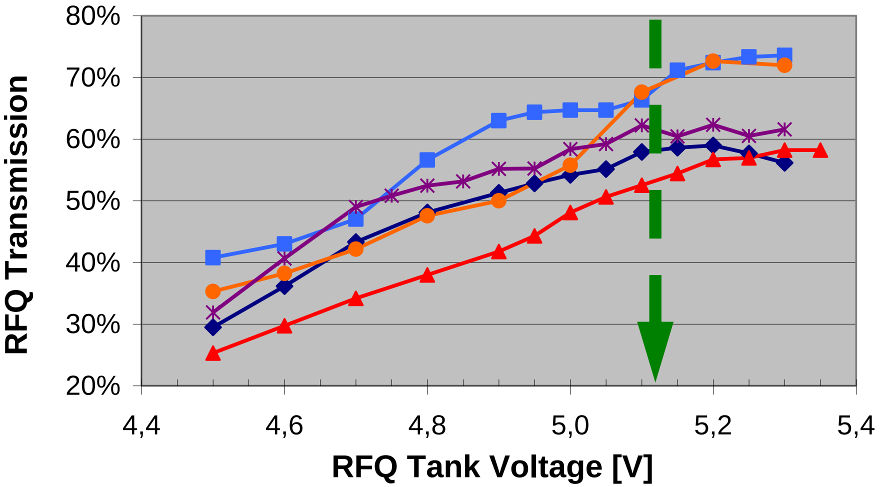
RFQ Acceptance Probing





RFQ Beam Energy & Transmission



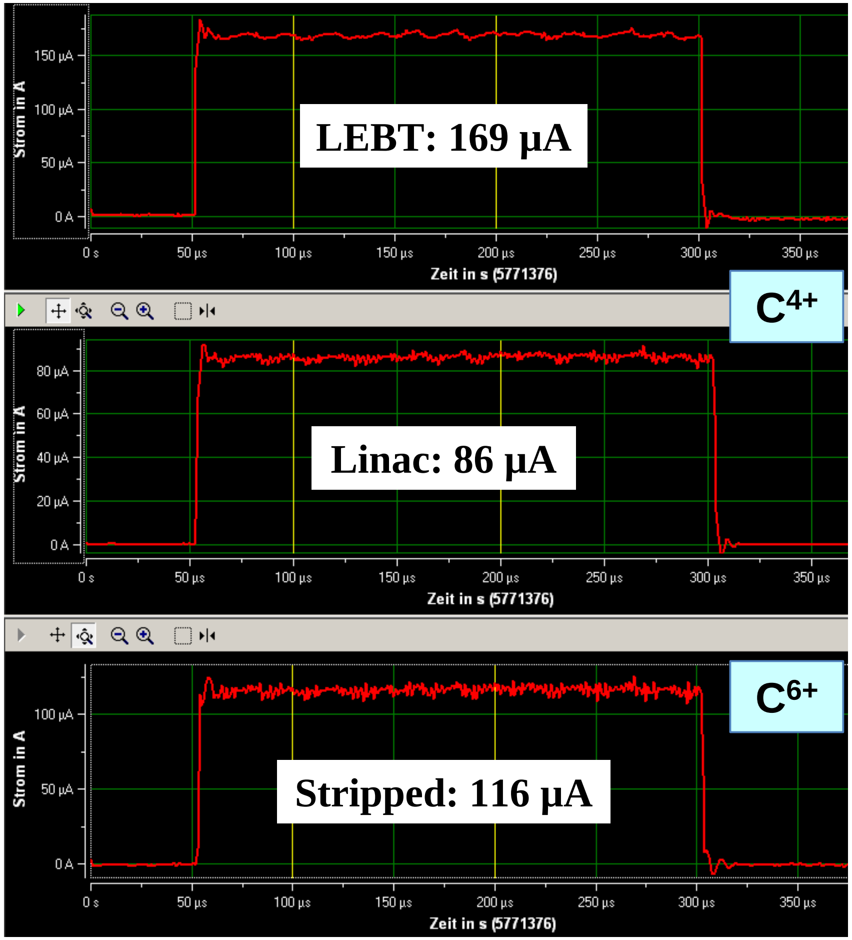


LINAC Performance

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)

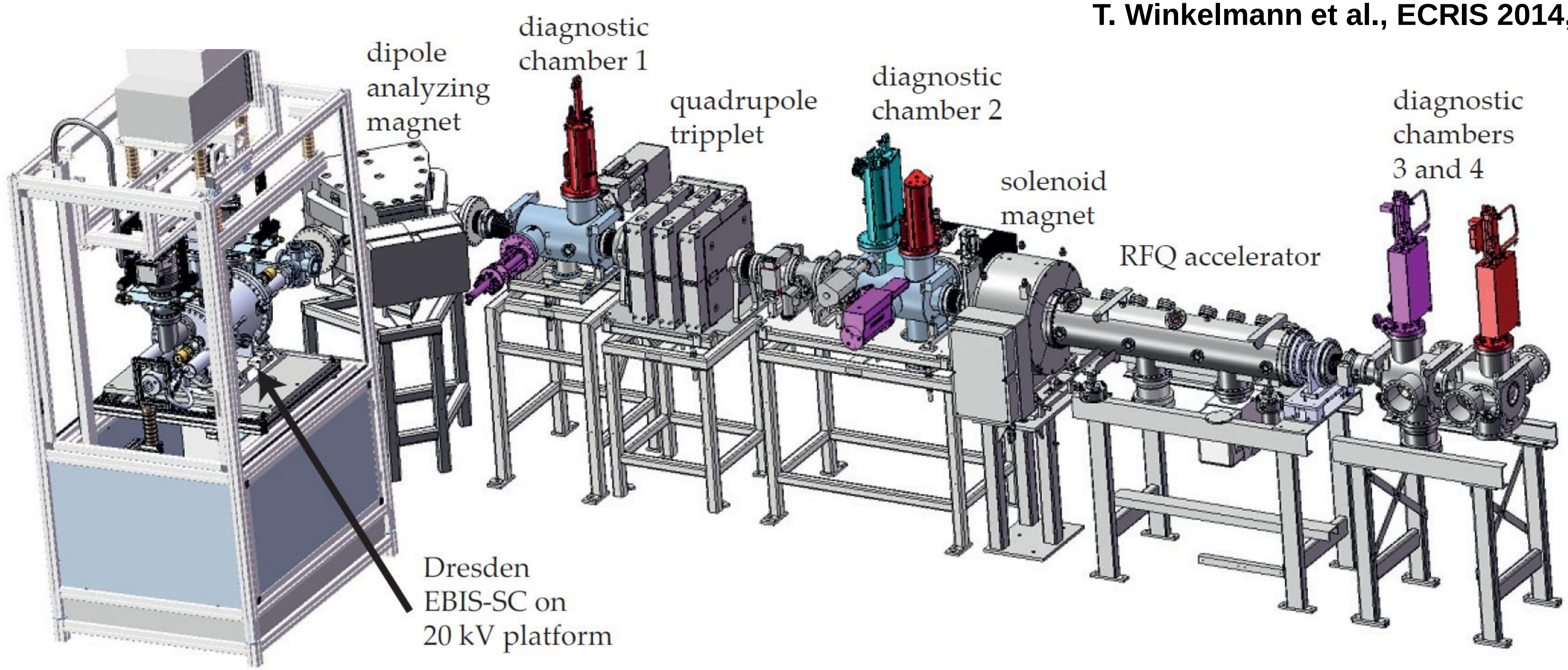


B. Schlitt et al., IPAC 2010

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 and transmission (2nd RFQ at testbench)
- Commercial Superconducting (sc) EBIS
  (high beam brilliance, > 60 % RFQ transmission)

E. Ritter et al., IPAC 2014, p. 2153
T. Winkelmann et al., ECRIS 2014, p. 49



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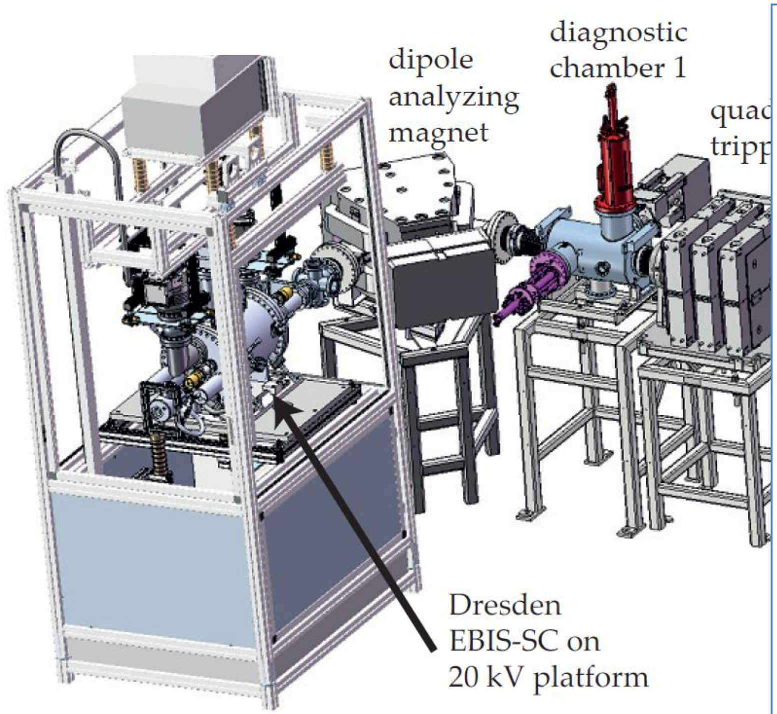
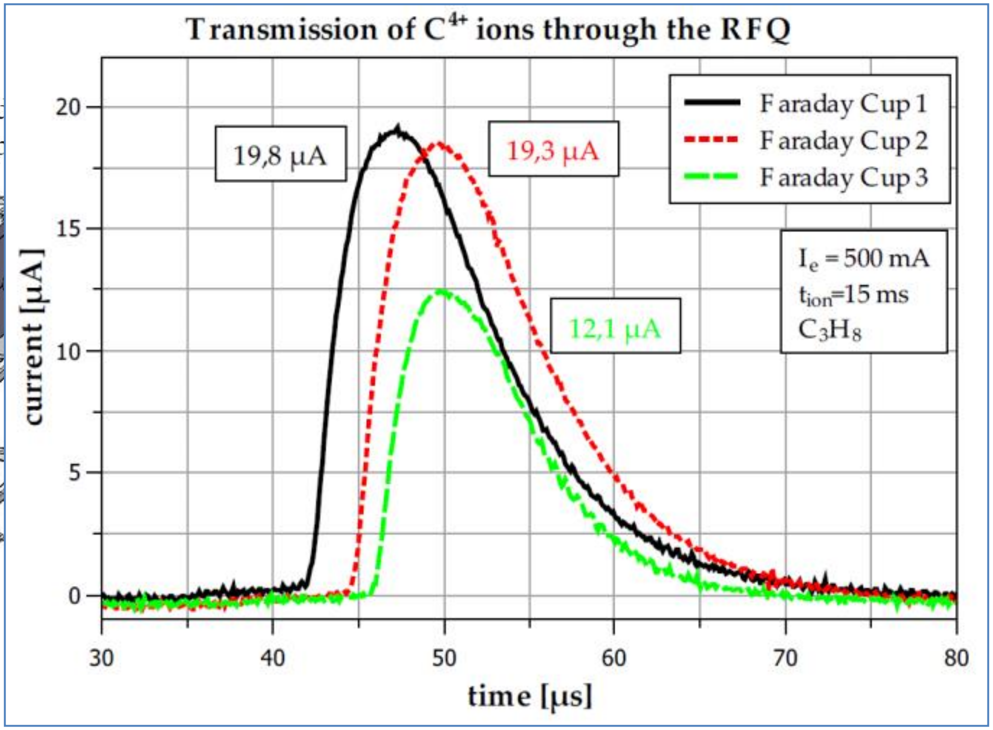
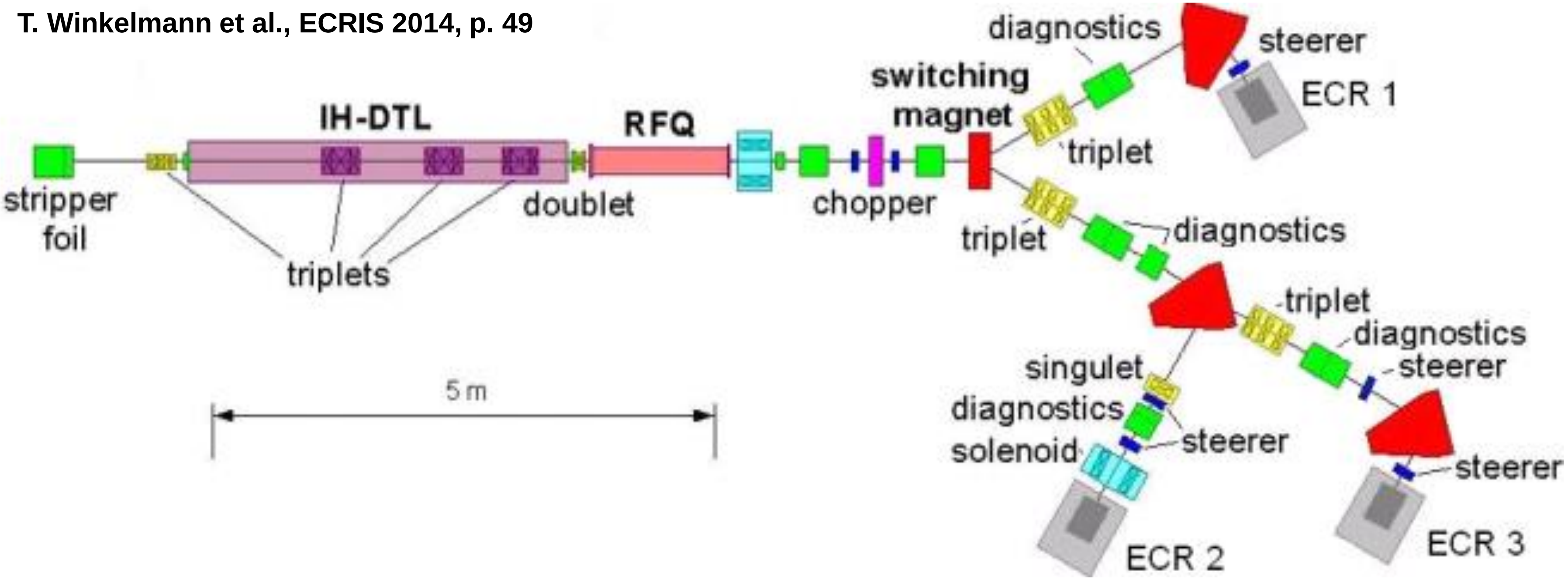


E. Ritter et al., IPAC 2014, p. 2153



3rd ECR Ion Source at HIT Injector & Ion Source Improvements

T. Winkelmann et al., ECRIS 2014, p. 49



- ECR 3: helium & oxygen beams + redundancy
- Frequency variable microwave generators, improved µ-metal shielding
- Improved new four electrode 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^+

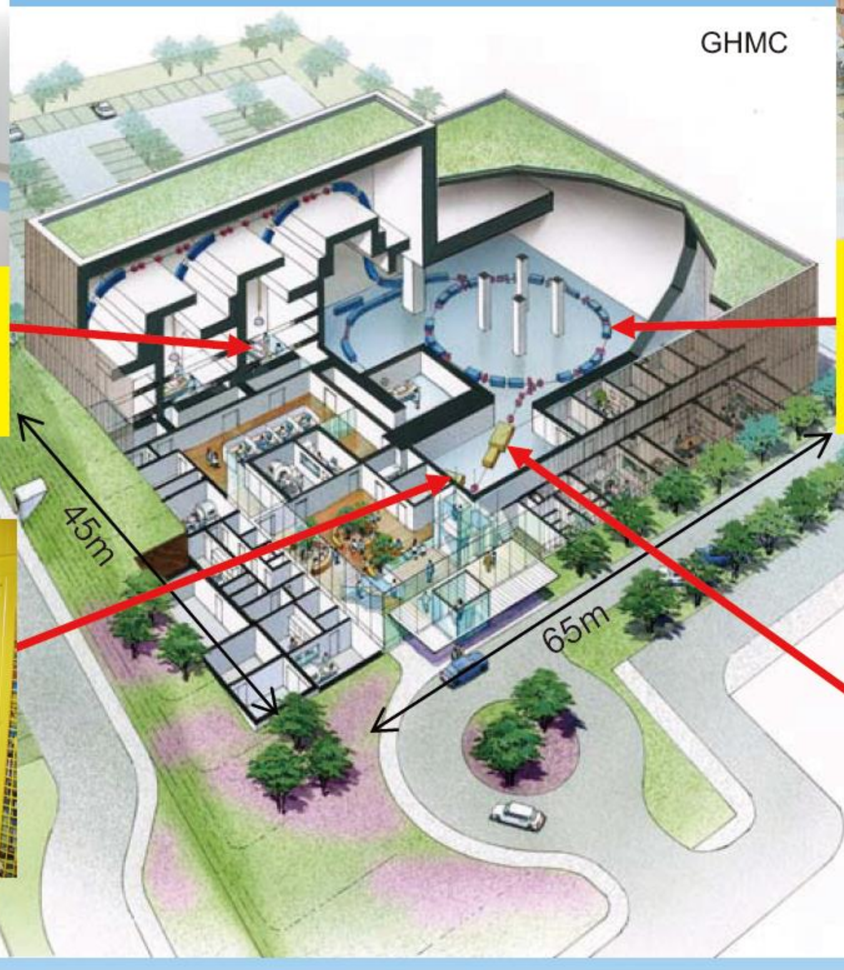
217 MHz GSI Linac – Summary

- HIT linac successfully in operation since > 10 years, 24 / 7 scheme up to > 8000 h/year
- Availability ≥99 % w/o major breakdowns
- Very high stability & reliability
- Available beam intensities sufficient for all treatments
- > 4400 patients treated at HIT (status May 2017)
- ECRIS, Linac structures (components), and RF systems manufactured by industry (NTG, Pink, Danfysik, Ampegon, Pantechnik)
- MIT & SPHIC facilities and MedAustron IH-DTL built completely by Siemens / Danfysik (incl. RF tuning, RFQ test bench @ Danfysik)
- Various improvements of ECRIS & later RFQs
- RFQ upgrades desired at HIT and MIT, further improvements proposed (revised beam dynamics, stem geometry, ...)

GHMC
Gunma University Heavy Ion Medical Center

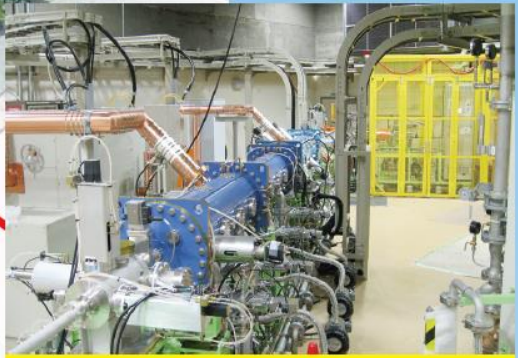
Facility Size 45 m x 65 m

Treatment Room
Accelerated carbon ions are irradiated into a patient.



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

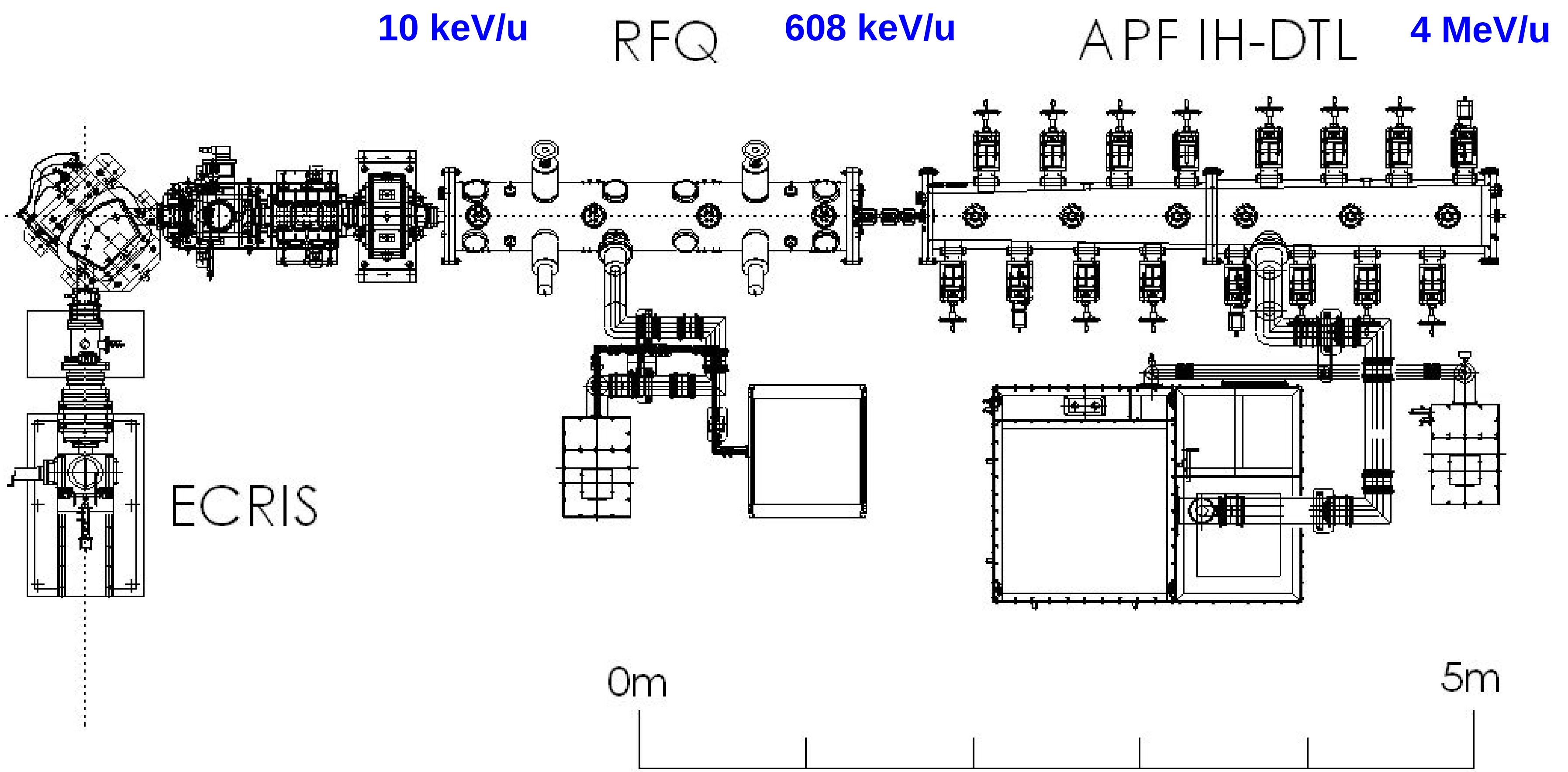
Ion Source
Carbon ions are produced from CH_4 gas.



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

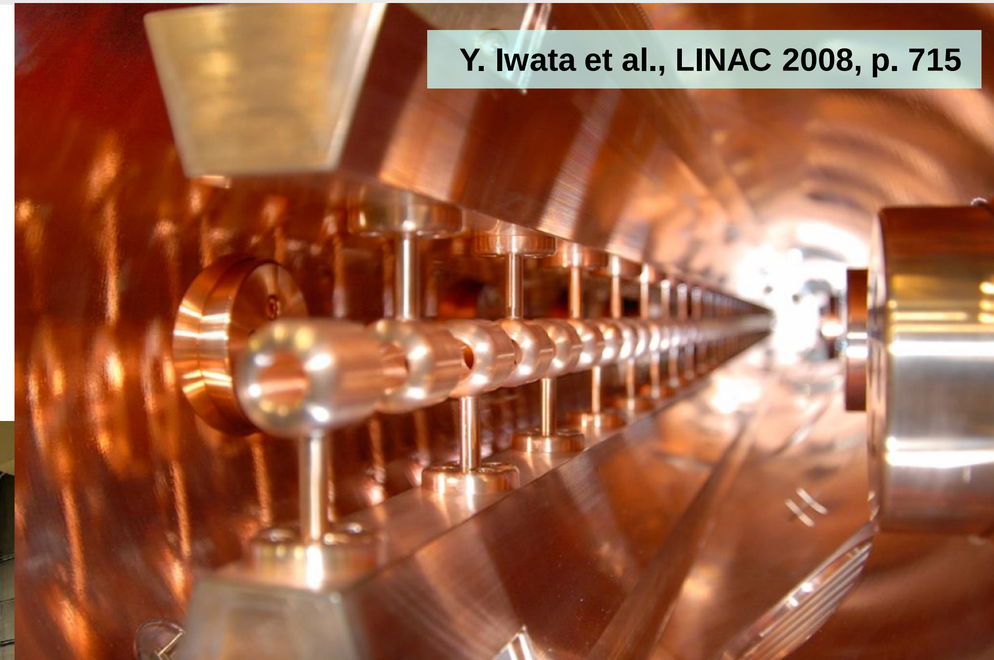
APF IH-DTL for C^{6+}, ~ 4,1 m

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

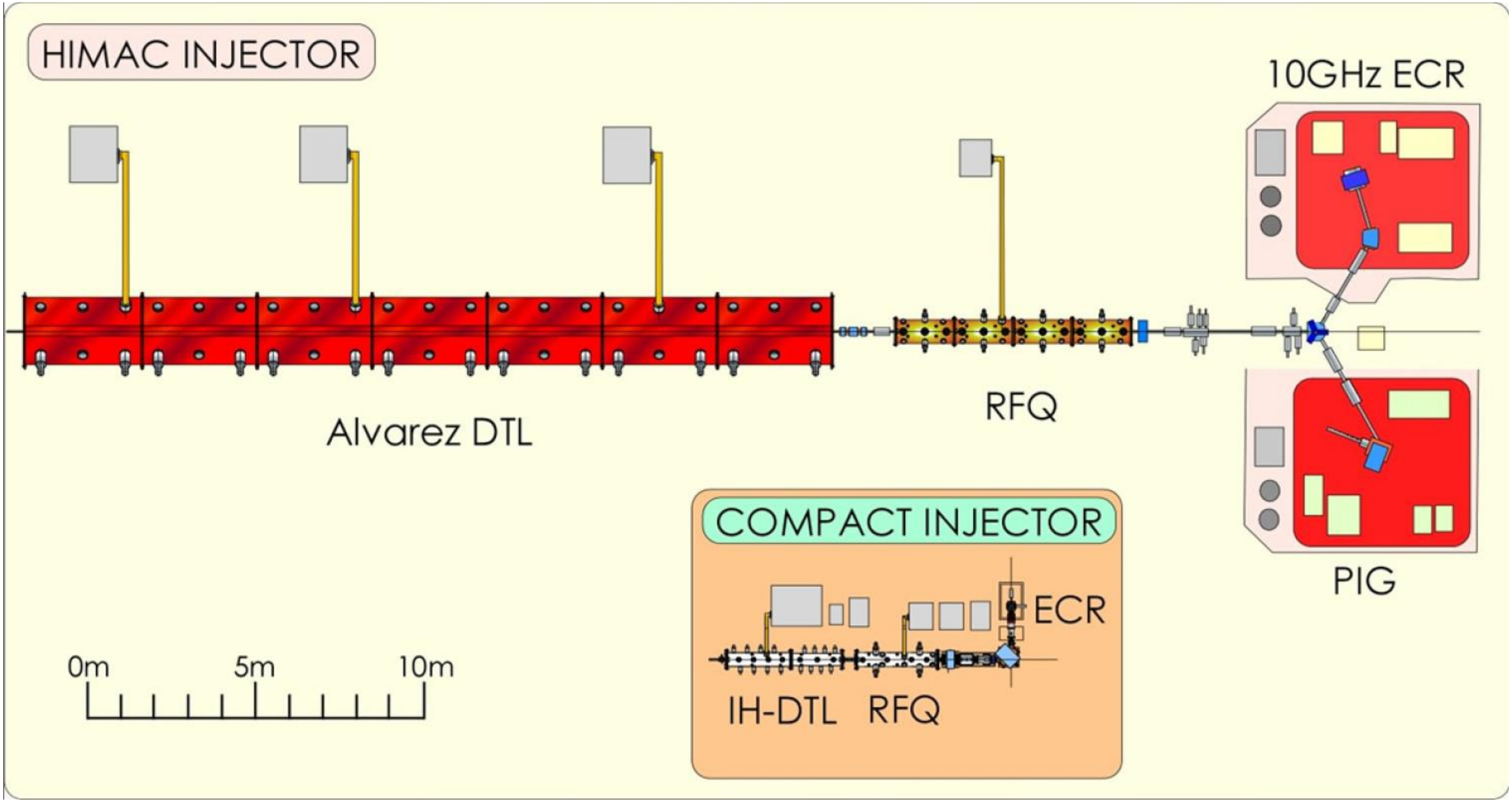
Manufactured by
Sumitomo Heavy Industries (SHI)



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

Conclusions

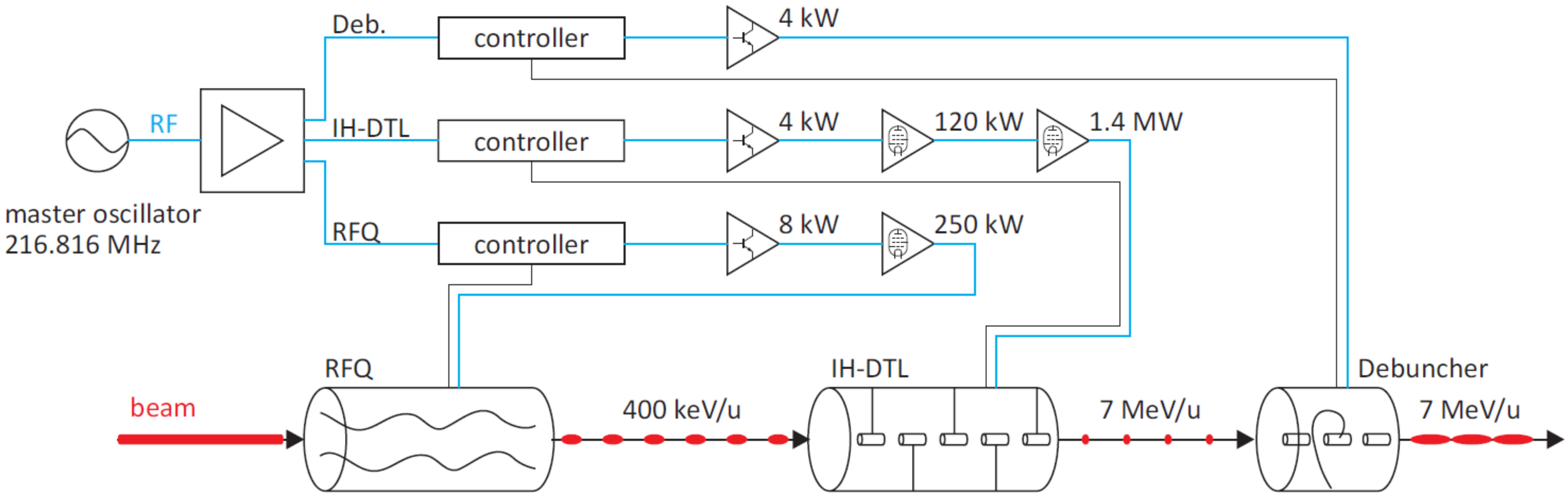
- Compact injector linacs (~ 200 MHz) developed at GSI and NIRS are state-of-the-art at all ion beam therapy centers commissioned during the last ten years
- GSI design: ≥ 2 ECR ion sources,
  protons & carbon ions at the same facility (+ others, e.g. helium)
  → clinical tests at identical conditions / beam delivery systems
- Close collaboration to industry,
  Sumitomo Heavy Industries, Siemens / Danfysik, Pantechnik, etc.
- Siemens stopped activities in particle therapy
- Design studies: Higher frequencies & gradients,
  full-energy linac instead of synchrotrons (TULIP, CABOTO, ACCIL, ...)

Thank You!

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, MOPP067

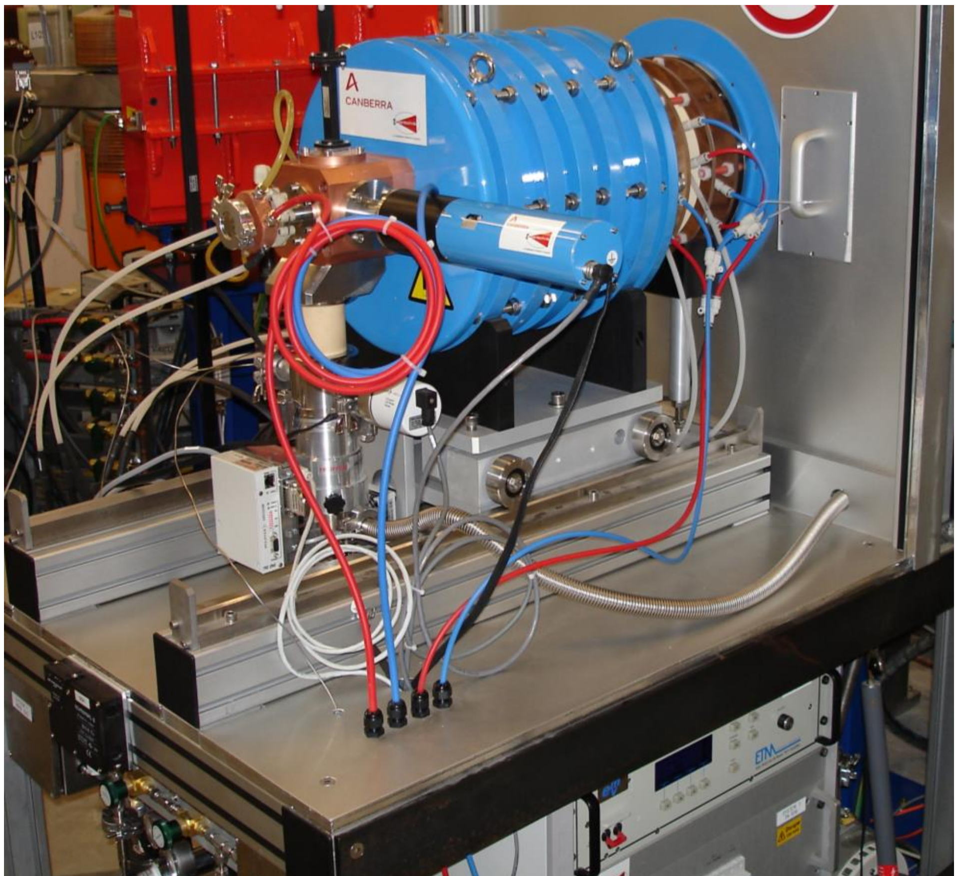


Superconducting (SC) Options?

- Various SC RF (SRF) cavities available for low-beta ion linacs, e.g. ATLAS @ ANL, ALPI @ LNL, SPIRAL 2, FRIB, cw Linac (Demonstrator) for Super Heavy Element programme @ GSI
- SC cavities: Advantages for high energies & high duty factors
- Normal conducting (NC) structures: state-of-the-art for low energies & low duty factors, see e.g. F. Gerigk,, LINAC2016, TU1A01
- Vast majority of all SC linacs have a NC front end (comparable in size to HIT injector linac or larger)
- > 5 MV/m at HIT IH-DTL (incl. magnets!)
  $\rightarrow$ comparable to typical low-beta SC structures (not incl. magnets)
- Advantages of NC linac w.r.t. SC: simpler technology & tuning, no cryo-technology, lower costs (invest & operation)

14.5 GHz SUPERNANOGAN (PANTECHNIK)

Commercial fully permanent magnet
Electron Cyclotron Resonance Ion Source (ECRIS)



Source body	∅ = 380 mm
	L = 324 mm
Plasma chamber ∅	44 mm
Total weight	400 kg
Permanent magnets	120 kg
B injection	1.2 T
B min	0.45 T
B extraction	0.9 T
B hexapole	1.1 T
Magnetic mirror length	145 mm
Max. extraction voltage	30 kV

pantechnik