Overview of linac injector designs for ion medical synchrotrons

Mariusz (GSI), Maurizio (CERN)
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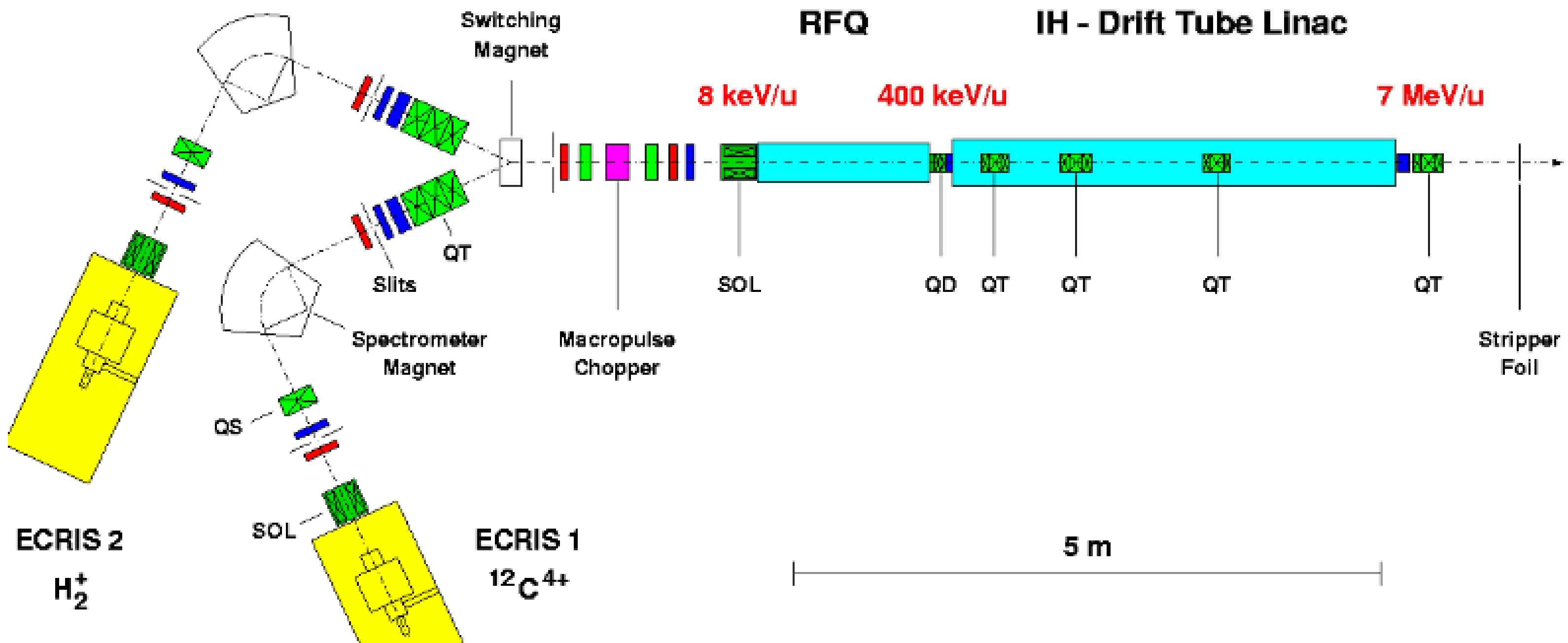
Introduction

- There are currently 11 ion therapy centers in the world: HIMAC, HIBMC (Hyogo), Lanzhou, HIT, GUNMA, CNAO, MedAustron, SAGA-HIMAT, Shanghai, Kanagawa i-Rock and MIT.
- Can we learn from other historical centers: LBNL (Bevalac), GSI?
- What is the direction of latest developments (found in the literature).

European approach

- In Europe the story started with HIT (2009).
- Followed CNAO (2011), MIT (Marburg Ion Therapy center, 2015) and MedAustron (2016).
- They all have very similar injectors.
- Parts of them or even the whole injectors constructed by industry.

“European” injector



Design ion	$^{12}C^{4+}$
Operating frequency	216.816 MHz
Final beam energy	7 MeV/u
Beam pulse length	300 µs
Beam repetition rate	5 Hz
Pulse current after stripping	100 eµA ($^{12}C^{6+}$)
Transverse emittances (95%) [1]	0.8 µm (norm.)
Exit energy spread [1]	±0.3%
Total linac length [2]	≈ 13 m

- Proven technology (12 years at GSI – prior to HIT), 12 years at HIT + CNAO, HIT and Shanghai
- Can be ordered in industry (Danfysik/Siemens, now Bevatech)
- The same technology could be used to reach 10 MeV/u
  (is this straightforward or needs R&D?)

Comparison with other facilities

	European	HIMAC	Gunma& i-ROCK& SAGA	Lanzhou& Wuwei	HIBMC (Hyogo)	Bevalac (LBNL)	SEEIIST
Design ion	$^{12}C^{4+}$	q/m>1/7	$^{12}C^{4+}$	$^{12}C^{5+}$	$^{12}C^{4+}$ (H_2+)		p,$^{12}C^{6+}$ (?)
Structure	RFQ+ IH-DTL	RFQ+ Alvarez (3 tanks)	RFQ+ APF-IH	Cyclotron	RFQ+ Alvarez	E.stat (Cockroft Walton) +Alvarez	
Freq.	216.8 MHz	100 MHz	200 MHz	7.755 MHz?	200 MHz	70.2 MHz	
Final energy	7 MeV/u	6 MeV/u	4 MeV/u	7 MeV/u	5 MeV/u	8.5 MeV/u	10 MeV/u
Beam pulse length	300 μs	1 ms	1 ms	N/A			60 μs
Repetition rate	5 Hz	3 Hz	4 Hz	N/A			
Pulse current (after strip)	100 eμA	170 eμA	500 eμA	10 μA (DC, stripping?)		2.9 eμA ….verify….	300 μA
Transverse emittance	0.8 pi μm (norm)	1.5 pi μm (norm)	~1.0 pi μm (norm)			….verify….	0.1 pi μm (norm)
Length	~13 m	30 m	6 m	1.5 m diam.		> 50 m	

More on APF (Gunma)

- Alternate-Phase-Focusing
- 1 tank: ~3 meters, 2 MeV/u
- Born as a second, compact injection to HIMAC (Y. Iwata, “The compact injector as the second injector of the HIMAC”, Proceedings of LINAC10)
- Y. Iwata et al. / Nuclear Instruments and Methods in Physics Research A 572 (2007) 1007–1021
- Found 2 energy upgrade programs to overcome space charge effects for small rings: extra IH-DTL (6 MeV/u) or superconducting extension (8 MeV/u)

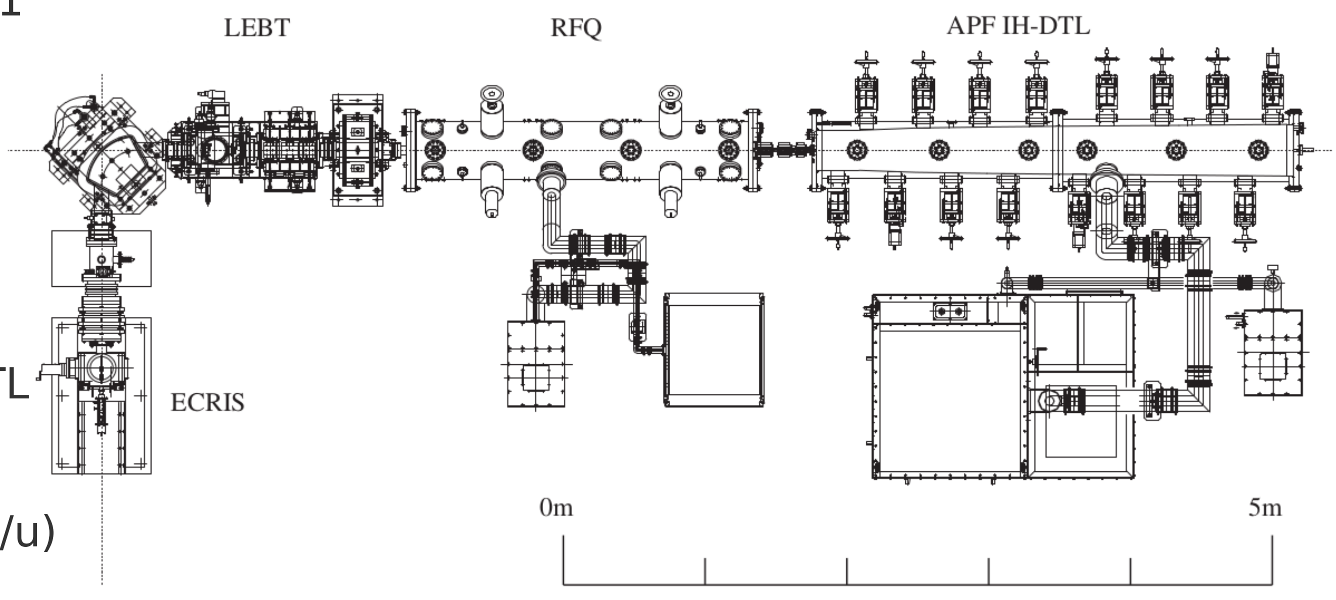
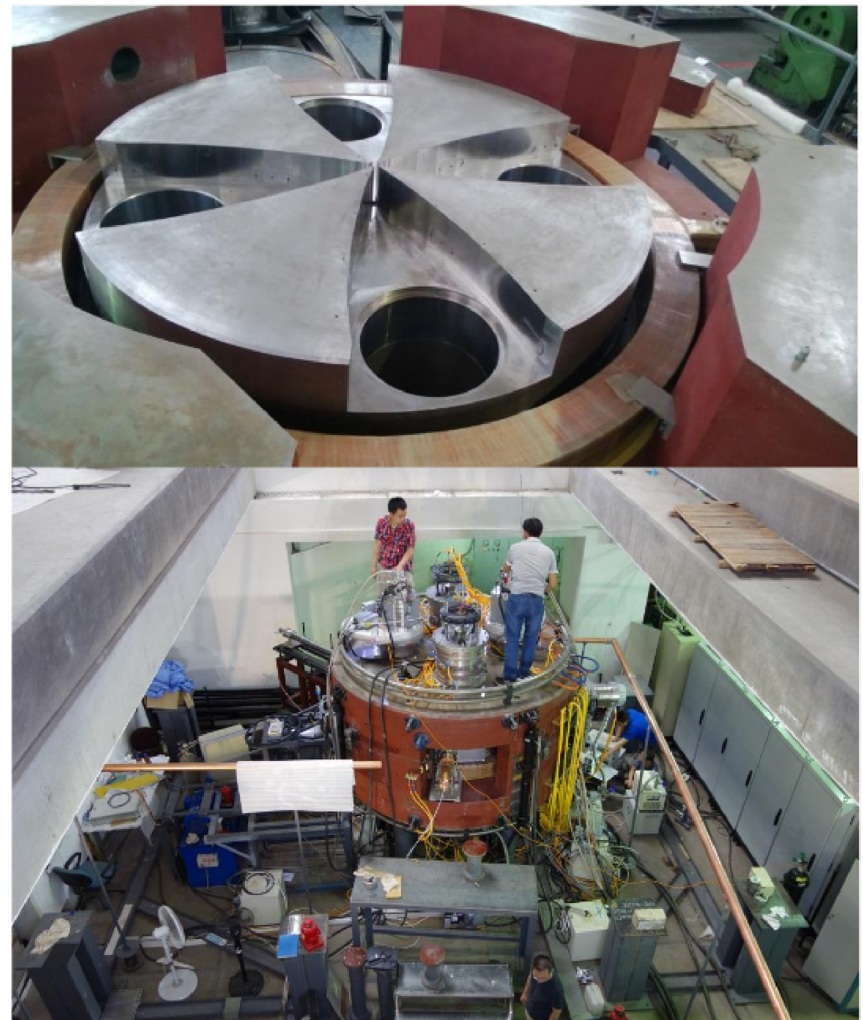


Fig. 1. Layout of the entire compact injector system.

More on Cyclotron (Lanzhou)

Cyclotron

Ion species	$^{12}C^{5+}$
Harmonic mode	4
Outer diameter	2.8 m
Height	1.6 m
Pole radius	0.77 m
Hill gap	50 mm
Valley gap	360 mm
Pole tip field	1.67 T
Hill angular width	56º
Spiral	0º
Extraction radius	75 cm
Frequency	31.02 MHz



Slide from 2014, difficult to find more data.

Other developments

- Low-beta superconducting cavities developed in recent years (ATLAS/Argonne, FRIB, cwLinac/GSI)
- Gunma has a program to add SC linac to the 4 MeV/u APF linac to double the energy.
- Is electrostatic out of question? (Yes)
- We have 750 MHz RFQ + 750 MHz TULIP IH DTL – can 10 MeV/u injector be made out of this? How much R&D is still needed?
- IAP Frankfurt developed 325 MHz High Gradient CH – Cavity (option for 7-10 MeV?)
- Hybrid single cavity (HSC) – DTL and RFQ in the same cavity – reduction of length – R&D phase.

Conclusions

- Two injector designs dominate:
  European IH-DTL (5 facilities) and Japaneese APF-IH-DTL (3 facilities). They both use ~200 MHz IH structures and are actually quite similar.
- Alvarez DTL is significantly more expensive.
- Cyclotron – for carbon only – not for research facility
- Most likely we are left with the following choices:
  - ‘safe’ ~200 MHz ‘European/Japaneese’ IH-DTL elongated to 10 MeV/u
  - 325 MHz design from IAP Frankfurt for UNILAC replacement
  - 750 MHz design – RFQ and TULIP