LINAC DESIGN WITHIN HITRIplus FOR PARTICLE THERAPY

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Abstract

Within the EU Horizon 2020 programme a linac was designed, which is starting from the concept as used at the 4 European cancer therapy centers applying light ions up to carbon. The new linac will in its simpliest version allow ion beam injection into synchrotrons at 5 A MeV, with high beam transmission and allowing currents up to 5 mA α - particles. An advanced ECR – ion source will inject into an RFQ – IH-DTL combination. The DTL concept allows upgraded versions for A/q – values up to two and with beam energies of 7.1 A MeV from IH – tank2 and 10 A MeV from IH-tank3. The higher beam injection energies for light ions allow for relaxed synchrotron operation conditions at lowest magnetic field levels. A main argument for the DTL extensions however is an additional linac function as radioisotope facility driver. The 7.1 A MeV are especially defined for the clean production of ^{211}At, which may play a future role in cancer therapy. The linac will allow for high duty-factors – up to 10%, to fulfil the needs for efficient radioisotope production. Solid state amplifiers with matched design RF power levels (up to 600 kW for IH3) will be used.

INTRODUCTION

With the development of the carbon therapy in Europe a 7 A MeV linac for C^{4+} was developed in a cooperation with GSI Darmstadt and IAP Frankfurt and was put into operation in 2008 at the therapy facility HIT Heidelberg [1]. The linac serves there as a synchrotron injector, as well as at 4 other facilities.

This linac is extremely compact. The acceleration from 8 A keV to 7 A MeV is accomplished within 5.5 m. The inter-tank section between RFQ and IH – DTL with a length of 0.25 m consists of a quadrupole doublet and beam diagnostics only. The system is easy to operate. Main key parameters can be seen from Table 1.

Table 1: Key Parameters of the HIT Injector

Design ion	$^{12}C^{4+}$
Operating frequency	216.816 MHz
Final beam energy	7 MeV/u
Beam pulse length	$\leq 300\ \mu s$
Beam repetition rate	≤ 5 Hz
Pulse current after stripping	100 μA ($^{12}C^{6+}$)
Transv. norm. emittances (95 %) [1]	0.8 π mm mrad
Exit energy spread [1]	±0.3 %
Total injector length [2]	≈ 13 m

[1] straggling effects in the stripper foil not included
[2] including ECRIS, LEBT and foil stripper

For a new therapy facility one would like to get rid of the big tetrode driven RF amplifiers in the present design. The RF power losses within the present IH -DTL are 870 kW.

There is a chance for a drastic reduction, as the synchrotron not necessarily needs such a high injection energy. Moreover, the carbon stripper foil after the linac, which provides a C^{6+} - beam to the synchrotron was proven to be sufficiently effective at 5 A MeV beam energy. For α - and p - beams energies of 7.1 A MeV and 10 MeV are envisaged. These will allow higher injection energies for those lighter ions (stable synchrotron operation at lowest magnetic field levels) and furthermore, an efficient production of radioisotopes for medical purposes. Production of At^{211} is the reason for a 7.1 A MeV α - beam from the linac. In this operation-mode up to 10% linac duty-factor are requested. This is – besides RF power reduction – an additional reason for reduced acceleration fields: to overcome water-cooling limitations on the cavities. A new generation ECR – ion source AISHA is foreseen for this injector [2]. To allow combined function operation of this linac as synchrotron injector and as a radioisotope facility driver linac the design duty-factor is 10% for A/q – values up to 2.0, and below 1 % for A/q – values up to 3.0.

GENERAL LAYOUT

RFQ –Design

The detailed layout of the RFQ was not part of this study. However, the main parameters are fixed: The injection energy is 15 A keV, which is an upper limit for the ECR ion source as long as a high-voltage platform is avoided for simplicity. The end energy of 700 keV resulted from extensive beam dynamics studies on the DTL and its acceptance improvement by rising the exit energy from 400 keV (HIT Heidelberg design) to this new value. It is expected, that the new RFQ will have a total length of about 2.5 m. An improved 4 – Rod design is suggested, which safely can be operated at 10% duty factor.

DTL –Design

Figures 1 and 2 show the scheme of the HITRIplus Linac, consisting of one RFQ, 3 IH – cavities, one rebuncher and two debunchers for matching the beam longitudinally to the synchrotron at all injection energies. Table 2 shows the simulated beam parameters, Fig. 3 shows the exit cluster plots (with norm. eff. emittance values printed). It should be mentioned, that HITRIplus offers many linac options to a potential customer:

- The basic version with a 5 A MeV injector and one IH – cavity only
- The 5 / 7.1 A MeV version with two IH – cavities and the option of At^{211} – production
- The full version with three synchrotron injection energies and extended isotope production program at 5 mA He^{2+} nominal beam current after debunching.

Proton and Ion Accelerators and Applications

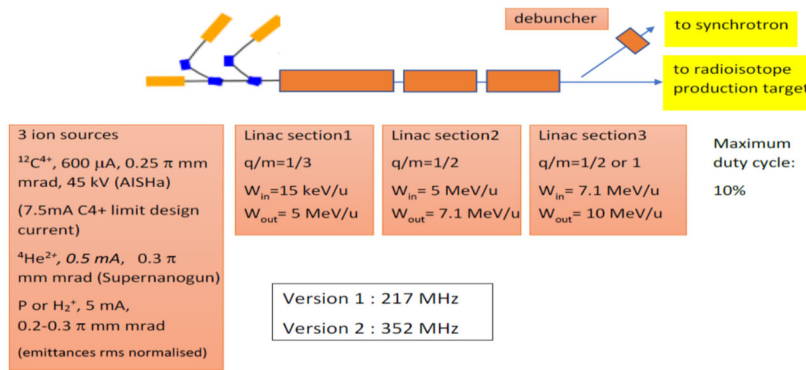**Industrial and medical accelerators**

Figure 1: Scheme of the HITRI injector linac. The 217 MHz version1 was investigated so far.
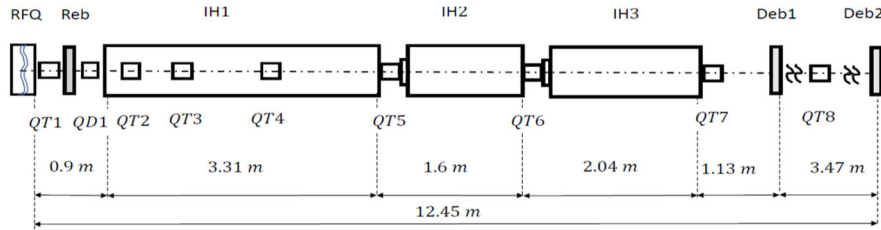

Figure 2: 217 MHz DTL layout from the RFQ exit down to the debunchers.

Table 2: Beam Parameters of the HITRI Injector Linac

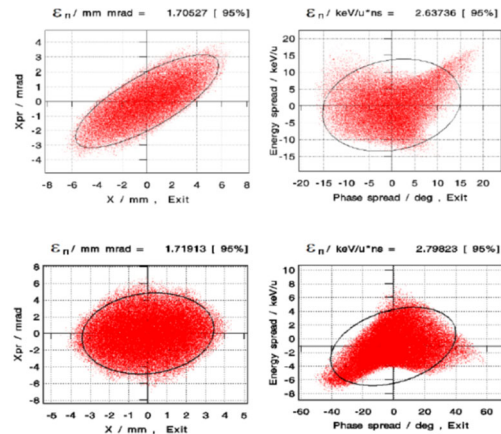| design Ions	C^{4+}, α (IH1)	α, H_2^+ (IH2)	α, H_2^+ (IH3)
operating frequency / MHz	216.8	216.8	216.8
Input beam energies / A MeV	0.7	5.0	7.1
exit beam energies /A MeV	5.0	7.1	10.0
A/q – design values	3.0, 2.0*	2.0	2.0
beam pulse lengths / ms	0.2, 1.0*	1.0	1.0
maximum rep. rate/ Hz	5, 100*	100	100
pulse currents /mA	0.6, 5*	5	5
input transv. norm. emit.: 95% eff. / rms / mm mrad	0.3	0.33	0.33
exit transv. norm. emit.: 95% eff. / rms / mm mrad	0.33	0.33	0.33
input long. norm. emit.: 95% eff. / rms / A keV ns	0.35	0.44	0.44
exit long. norm. emittances: 95% eff. / rms / A keV ns	0.44	0.44	0.44
Exit energy spread /% after deb. for 95% of particles	±0.1	±0.1	±0.1
Sim. particle transmission /%	99.99	99.99	99.99

Table 3: Technical Parameters of the HITRI Injector Linac

Cavity	IH1	IH2	IH3	Reb	Deb1	Deb2
Gap No.	51	15	17	2	2	2
Apertures/mm	14 - 20	20	20	14	20	20
Max Gap volt. amplitude / kV	395/263*	394	462	108/72*	102	183
Max on axis field/MV/m	14/9.3*	8.6	7.3	6	3	6.3
RF power losses/kW	340	265	425	2	10	10

*: First number refers to A/q=3 operation

Figure 3: Exit emit. at 10 A MeV (top) and at 5 A MeV at 5 mA He^{2+} nominal beam current after debunching.
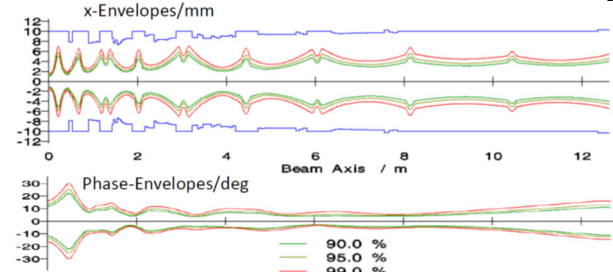
Figure 4: Beam env. at 10 A MeV, 5mA He^{2+}, simulated with LORASR from the RFQ exit down to the debuncher.

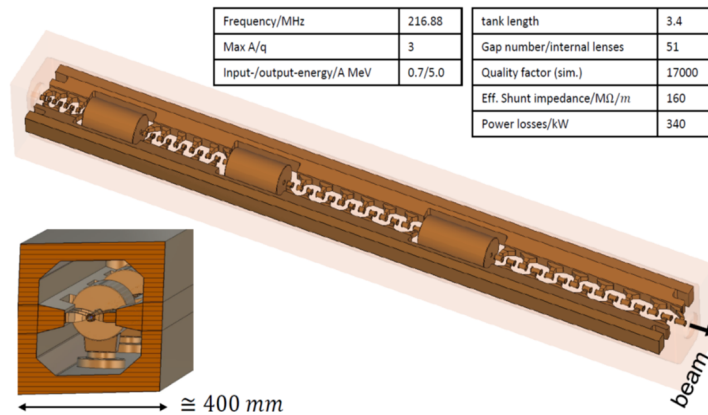| Frequency/MHz | 216.88 | tank length | 3.4 |
Max A/q	3	Gap number/internal lenses	51
Input-/output-energy/A MeV	0.7/5.0	Quality factor (sim.)	17000
		Eff. Shunt impedance/MΩ/m	160
		Power losses/kW	340

$\cong 400\ mm$

Figure 5: RF - layout of IH-cavity 1.

The investigations were performed by the LORASR multi-particle simulation code [3]. Parameters like gap voltages and quadrupole fields were chosen in a way, that 10% duty factor operation at $A/q = 2$ beams is assured as well as reasonable peek fields for $A/q = 3$ beams with low duty factor operation for synchrotron injection only. While the Kilpatrick field level is about Kp=15.2 MV/m, the peak surface fields at the drift tube ends are reaching up to about 2.1 Kp in the short pulse modus for $A/q=3$ beams. This is regarded as a safe value for IH – DTL's. Results from beam dynamics calculations are shown in Table 2, Figs. 3 and 4. The layout of the RF IH-cavity 1 is shown in Fig. 5.

Compared with the HIT-linac design, the beam acceptance in all planes was more then doubled for the HITRI layout – to fit to the powerful new ECR – ion source characterisics and to improve the beam transmission.

LINAC TECHNOLOGY

Within this study the first and most challenging IH cavity was RF designed – following the given parameters from beam dynamics simulations (Table 3). The commercial software CST – Microwave studio [4] was used for these calculations. The 51 gaps-cavity with three internal lenses was RF tuned with respect to resonance frequency and to gap voltage distribution successfully. A needed fine-tuning step would follow in case of building the structure. Suitable tuning installations and a capacitively acting dynamic tuner with tuning ranges were defined. Cooling aspects and electric peak – field considerations were performed. Special care has to be taken for the envisaged high duty factor of 10% for radioisotope production. This would still need some additional care in case of realization – with respect to controlled beam collimation and with respect to water cooling. However, no showstoppers have been found. The simulations show, that this design approach keeps all parameters within well proven limits. With respect to hot spots in the cavity under maximum heat load, temperature increases on the cavity surfaces were estimated to stay below 35 deg everywhere.

Aperture diameters and fields of the quadrupole lenses have been chosen in a way, that the pole tip fields stay below one Tesla. The beam diagnostics elements like current transformers and capacitive pick-up probes or beam position monitors can be well integrated in this layout.

The intertank section from RFQ to IH1 was designed more comfortable against the HIT design and consists of a quadrupole triplet, a two-gaps-rebuncher and a quadrupole doublet (compare Fig. 1). Two xy-steerers are foreseen as well in that section. A current transformer and a segmented capacitive pick-up probe (or 4-knob beam position monitor BPM) can be integrated – due to available drift lengths.

From a study of the present RF power amplifier market and from recent experience [5] with in-house participation in projects like MYRRHA, it is concluded that solid state power amplifiers would be a most adequate choice for all HITRIplus linac RF amplifiers.

CONCLUSION

This linac approach looks quite well suited to fulfil the tasks of the HITRIplus linac, including all three versions from a 5 A MeV carbon injector linac up to a high duty factor, high current linac for the two exit energies 7.1 A MeV and 10 A MeV for ions like alpha- particles or H_2^+. The high energy options allow for medical radioisotope production on the one hand, and for improved synchrotron injection for all ions with A/q – values up to two.

ACKNOWLEDGEMENTS

REFERENCES

[1] B. Schlitt, "Commissioning and Operation of the Injector Linacs for HIT and CNAO", in *Proc. LINAC'08,* Victoria, Canada, Sep.-Oct. 2008, paper WEP205, pp. 720-724

[2] L. Celona *et al*.," Commissioning of the AISHa ion source at INFN-LNS", *AIP Conf. Proc.*, vol. 2011,p. 040023, 2018. doi:10.1063/1.5053297

[3] R. Tiede et al., "Improvements of the LORASR Code and their Impact on Current Beam Dynamics Designs", in *Proc. LINAC'14*, Geneva, Switzerland, Aug.-Sep. 2014, paper TUPP063, pp. 56-5719.

[4] CST Microwave Studio (2014 - 2021), Computer Simula tion Technology GmbH; CST Studio Suite; CST Microwave Studio, www.cst.com

[5] A. Gatera *et al.,* "MINERVA (MYRRHA Phase 1) RFQ Beam Commissioning", in *Proc. IPAC21*, Campinos, Brasil, May 2021, pp. 675-678. doi:10.18429/JACoW-IPAC2021-MOPAB205