END-TO-END SIMULATIONS OF A SUPERCONDUCTING DEUTERON CH-DTL FOR IFMIF*

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Abstract

The IFMIF project (**I**nternational **F**usion **M**aterials **I**rradiation **F**acility) requests two cw linacs operated in parallel. Each of them is designed to provide a 5 MW 125 mA deuteron beam at 40 MeV for the production of an intense neutron flux with an energy around 14 MeV. This paper presents an alternative linac design for this project. The acceleration is completely based on H-type cavities. The room temperature (rt) 4-Vane-RFQ and a short IH-DTL (**I**nterdigital-**H**-DTL) are followed by 4 superconducting (sc) CH-DTL (**C**rossbar-**H**) cavities. The operating frequency is 175 MHz, the designed section lengths are 13 m for the RFQ (**R**adio-**F**requency-**Q**uadrupole) (5 MeV), 1 m for a compact MEBT (**M**iddle **E**nergy **B**eam **T**ransport), 2 m for the IH-cavity (10 MeV) and 9 m for the sc CH-DTL (40 MeV). The structure parameters and end-to-end multiparticle beam dynamics calculations with and without DTL errors of the whole linac will be presented and the results will be discussed.

1 INTRODUCTION

Extended particle dynamics investigations of the reference IFMIF DTL layout (Four-Vane-RFQ+Alvarez-DTL) showed a very robust beam behaviour for the Alvarez-type DTL. Even with the reduction of the input energy – to reduce the length of the RFQ - and the favourable lower input power per tank gave in all cases stable solutions, good emittance conservation, strong transverse and longitudinal focusing, no particle losses and sufficient large aperture factors even with including standard quadrupole and rf errors and mismatched input beams [1]. This layout has an overall length of 46 m. The rf power consumption per linac is estimated around 7.5 MW. Technical challenges in case of the Alvarez-DTL are the high thermic load per meter in combination with a quadrupole singlet channel where each magnet is housed in a drift tube on a slim stem. Beam dynamics studies for a corresponding rt IH-type DTL showed its capability for high intensity acceleration with good power efficiency. Investigations on beam stability against matching, field and quadrupole errors showed however, that the IH-DTL is due to the KONUS-dynamics (**Ko**mbinierte – **Nu**llgrad - **S**truktur) more sensitive to errors than the Alvarez [2,3]. Both rt structures showed in combination with a special compact MEBT no particle loss and smooth beam behaviour, but the RFQ+Alvarez-DTL combination gave higher aperture factors and lower emittance growth [1].

Due to the mandatory cw operation mode of the IFMIF facility the combination of a short rt IH structure and a chain of sc CH resonators with inter tank focusing has also been made which in addition fulfills the requirements for a high current IFMIF DTL. The sc CH DTL part provides very high rf and acceleration efficiency and due to its special cell geometry high mechanical robustness. The sc drift tube linac has a total length of ≈ 11 m only, the cryostat length is ≈ 8 m. The estimated total plug power (including all cryostat losses) per meter of this design study is ≈ 1.5 kW/m (for comparison the rt linacs need ≈ 50 kW/m assuming 50 % amplifier efficiency), which demonstrates the high rf efficiency of the sc CH modules. In connection with large drift tube apertures the risk of particle losses in the sc part is reduced. Detailed simulations showed also a low sensitivity of the beam behaviour and beam quality against all combinations of statistic and mechanical errors, i.e. transverse quadrupole triplet displacement errors ± 0.1 mm and a rotation of ±1 °, rf phase errors ± 1 °, rf amplitude errors ± 1 % and quadrupole gradient errors ± 1 % [1].

2 THE FOUR-VANE-RFQ

For all DTL studies the same reference design of an RFQ has been used to be comparable between all design versions for the IFMIF linac. Table 1 gives a summary of the RFQ structure and beam parameters. The main goal was a lowered Kilpatrik factor of 1.7 to reduce the sparking probability due to the required cw operation. Nevertheless the transmission should be high as well as the beam quality at the RFQ output to allow good matching to the following DTL. In the design the recipe of equipartitioning has been applied leading to a parameter set, which fulfills the IFMIF requirements [4].

Table 1: Structure parameters of a Four-Vane-RFQ for IFMIF.

RFQ-Parameters	Values
A/q	2 (D^+)
Rf-frequency f [MHz]	175
In / Out energy W [MeV]	0.1 / 5.0
P_{tot} [MW]	1.506
Peak field E_{peak} [MV/m]	23.77
Cells / length [m]	659 / 12.31
In / Out current [mA]	140 / 132.7
In / Out $\varepsilon^{N,rms}$trans [cm×mrad]	0.020 / 0.023
In / Out $\varepsilon^{N,rms}$long [cm×mrad]	0 / 0.043

In Fig 1. the matched output distribution of the RFQ at 5 MeV calculated with PARMTEQM® (multipole effects and image charges included) is plotted. The transmission

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is about 95 % with good beam quality. The transverse rms emittance growth is less than 10 % and the beam is well confined with a few halo particles only.

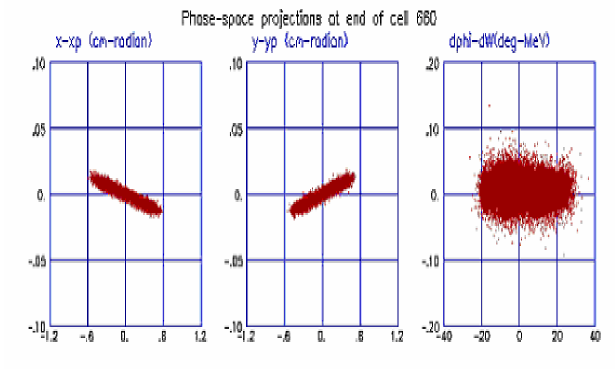

Fig. 1: Output distribution at 5.0 MeV of the Four-Vane-RFQ, calculated with 50000 macro particles.

It should be mentioned, that the matching to the RFQ can be accomplished by a conventional partly space charge compensated magnetic LEBT (**L**ow **E**nergy **B**eam **T**ransport) with low influence on transmission and beam quality. Therefore the output emittances of Fig. 1 have been taken for the beam dynamics simulations through the DTL, aiming for preliminary results for the beam behaviour from source to 40 MeV to ensure stable and loss free operation in the whole IFMIF accelerator facility.

3 BEAM DYNAMICS DESIGN OF A SC CH-DTL

The sc CH-version (design and structure parameters of table 2 and Fig. 2 made with LORASR©) turned out to be superior to the rt IH-design with respect to the following critical issues: a) no cooling problems in cw operation b) reduced linac length and less tanks, i.e. higher efficiency and lower structure periods c) larger drift tube diameters up to 8 cm. The beam behaviour is smooth, no losses along the linac occurred and a good safety margin could be reached in the sc linac against losses due to mismatch and standard DTL errors. Extended electromagnetic simulations have been performed with Microwave Studio® to optimize the parameters of the first and last superconducting CH cavity for IFMIF. It was possible to further reduce the electric and magnetic peak fields to modest values which is important for reliable routine operation. Fig. 3 gives a real 3D sketch of the optimized 175 MHz sc CH tanks 1 and 4 in the critical low energy part and at the high energy end of the DTL, calculated with Microwave Studio®.

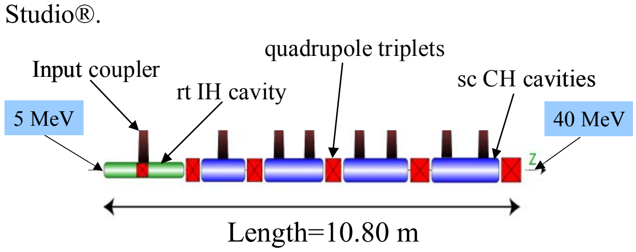

Fig. 2: Scheme of a 175 MHz sc IH/CH-DTL.

Table 2: Design parameter of a 175 MHz sc IH/CH-DTL for IFMIF + Cavity parameters of sc CH tank 1 and 4.

Design parameters	**SC CH-DTL**		**Units**
A/q	2 (D^+)		
In-/out current	125.0 / 125.0		**mA**
Frequency	175.0		**MHz**
Number of tanks	5 (1NC+4SC)		
P_{tot}	4.44		**MW**
W_{in} / W_{out}	5.0 / 40.1		**MeV**
Cells / Length	73 / 10.8		**m**
a_0 of DT	NC:1.5 SC:2.4 - 4.0		**cm**
In- / Out rms ε^n_{trans}	0.035 / 0.091		**cm×mrad**
In- / Out rms ε^n_{long}	0.070 / 0.097		**cm×mrad**
Cavity parameters	**CH 1**	**CH 4**	**Units**
Beta	0.1	0.2	
Frequency	175.00	175.00	**MHz**
E_{acc} (=E_0)	5.00	4.3	**MV/m**
Tank length	1.20	2.30	**m**
Tank diameter	52.9	67.3	**cm**
Gaps	12	12	
E_{peak}/E_{acc}	4.01	3.75	
B_{peak}/E_{acc}	7.73	8.46	**mT/MV/m**

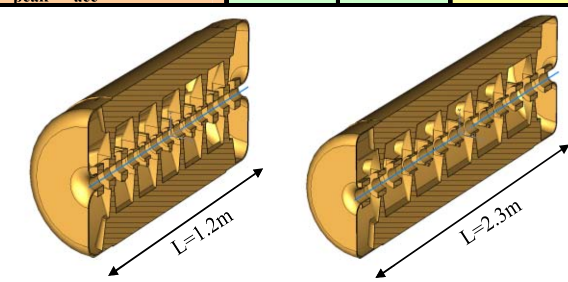

Fig.3: 3D view of the first and last 175 MHz sc CH-cavities (tank 1 and 4) calculated with MicroWave Studio®.

4 END-TO-END SIMULATIONS

As a last method for testing the global stability of the complete injector facility against particle losses integrated overall multiparticle simulation studies of the whole 25 m long sc linac (RFQ+MEBT+sc IH/CH-DTL) were performed with the programs PARMTEQ® and LORASR©. Fig. 4 plots the 100 % transverse beam envelopes along the whole linac in the nominal case without assuming mechanical and rf tolerances. Fig. 5 displays the phase space distribution in this case at the exit of the linac at 40.1 MeV. The beam behaviour is smooth, no losses after the RFQ occurred, a good safety margin could be reached throughout the sc part of the H-DTL against losses. The output distribution is well confined with a quasi elliptic dense core.

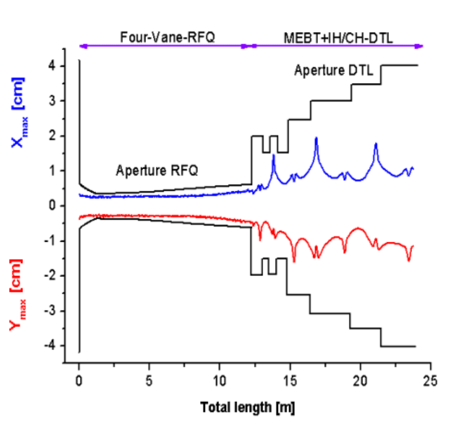

Fig. 4: 100 % transverse beam envelopes along the whole linac (RFQ+MEBT+H-DTL) in the nominal case.

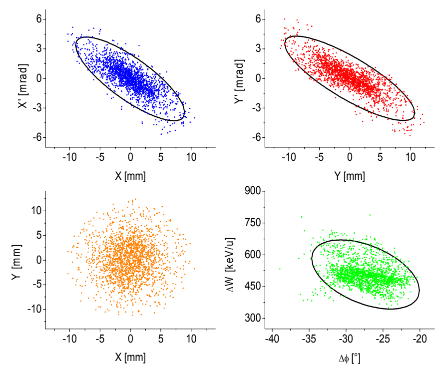

Fig. 5: Output distribution of the linac at 40.1 MeV in the nominal case, 2000 macro particles used.

At least the overall simulations were repeated, but now with applied combined statistically distributed standard mechanical, rf and quadrupole triplet gradient errors for the MEBT and the following H-DTL, i.e. transverse quadrupole triplet displacement errors ± 0.1 mm and a rotation of ±1 °, rf phase errors ± 1 °, rf amplitude errors ± 1 % and quadrupole gradient errors ± 1 %. The Figs. 6 and 7 show the results of the numerical multiparticle calculations of the IFMIF linac for this case. The 100 % beam envelopes are still smooth. No further losses occur after the RFQ and the phase space at the exit of the H-DTL at 40.1 MeV is still quasi elliptic and well confined.

5 CONCLUSION

The superconducting CH-structure in combination with the KONUS beam dynamics layout is well suited for the efficient acceleration of intense light ion beams. Extended beam dynamics simulations gave high transmission, also in case of statistically distributed mechanical, rf, quadrupole gradient and matching errors due to a low number of rf and structure periods of the H-DTL with KONUS dynamics. Also integrated overall simulations of the whole linac (RFQ+H-DTL) with and without mechanical and optical tolerances showed a smooth beam behaviour, moderate emittance growth and a non-chaotic beam behaviour without particle loss. A downscaled 1:2 room temperature copper model has been built and tested in order to investigate basic rf properties, tuning methods and to validate the simulations. There was an excellent agreement between the simulations and the measurements [5]. The order for a 350 MHz superconducting prototype of bulk niobium has been placed already. The prototype will be tested in the new cryo lab at the IAP Frankfurt which has been equipped with a cryostat, a magnetic shielding, dewars and a class 100 laminar flow box [6].

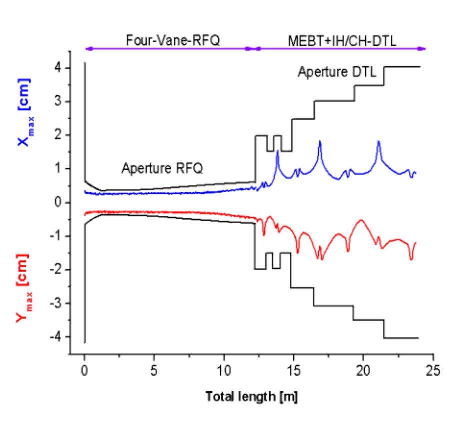

Fig. 6: 100 % transverse beam envelopes along the linac with combined errors for the MEBT and H-DTL.

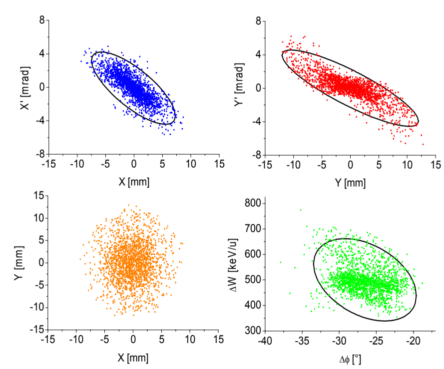

Fig. 7: Output distribution of the linac at 40.1 MeV with combined errors of the MEBT and H-DTL, 2000 macro particles used.

6 REFERENCES

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