AN EFFICIENT 125MA, 40MEV DEUTERON DTL FOR FUSION MATERIAL TESTS

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is looking for an efficient drift-tube linac (DTL) which can accelerate a 125mA, CW deuteron beam from 5MeV to 40MeV with a high beam quality and nearly no beam loss. Taking advantages of the KONUS dynamics concept and the H-type structure, a compact DTL design has been realized by IAP, Frankfurt University, with satisfying performances. Including simulated errors, the feasibility of the IAP scheme has been carefully checked as well.

INTRODUCTION

Fusion is one known technology possible to produce a large fraction of electricity for the world in a cleaner and safer way than the traditional methods, e.g. thermal and fission-driven energy productions. However, one bottle-neck of realizing an industrial fusion power plant is to find the suitable construction materials, which can sustain such as >30dpa/year (displacement per atom per year) of damages from the intense neutron flux with high energies up to 14MeV in a typical D-T fusion reactor [1].

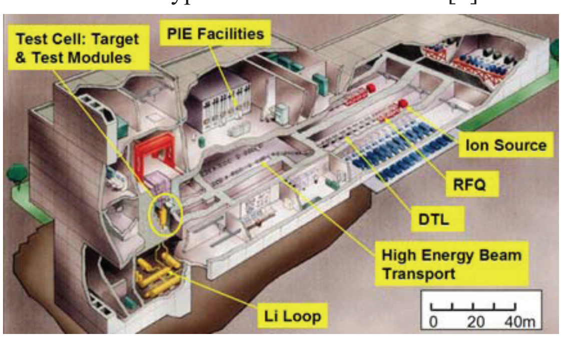

Figure 1: An overview of IFMIF [1].

Proposed to simulate the fusion environment for testing and learning possible materials, the IFMIF facility as shown in Fig. 1 is expected to generate a comparable total neutron flux of $>10^{17}$n/s with a broad spectrum peaked at 14MeV by striking a Li target with 250mA, 40MeV deuterons. The intense energetic D^+ particles will be carried by two identical 175MHz, CW linacs working in parallel, and each of them includes: 1) an ion source, which generates a 150mA, CW deuteron beam at 100keV; 2) an LEBT (low energy beam transport) section to transfer and match the beam to the RFQ; 3) an RFQ accelerator for providing a 125mA, 5MeV bunched beam at output; 4) a DTL accelerator for covering the rest energy gain to 40MeV; 5) finally an HEBT section to guide the beam to the target.

Obviously, the IFMIF linac design should meet all general requirements (e.g. a compact layout and minimum RF power consumption for saving costs) for high power linacs. Two most stringent tasks particularly important for this ultra-intense deuteron accelerator are: 1) how to avoid beam losses on the structure after the RFQ for the ease of hands-on maintenance; 2) how to reach the best beam quality to ensure a 20cm×5cm rectangle, uniform-distributed beam footprint on the target.

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THE DTL DESIGN

Linac System

The reference design of the DTL part is relied upon the conventional Alvarez-type accelerating structure with post couplers working at room temperature (RT) [1]. Recently, however, two new proposals mainly based on the state-of-the-art superconducting (SC) technology become more competitive, because SC accelerating structures have many advantages, e.g. high gradients, big bore apertures and ignorable power dissipation. In the CEA-Saclay scheme [2], half-wave resonators (HWR) have been adopted, while another one suggested by IAP of Frankfurt University will use H-type structures.

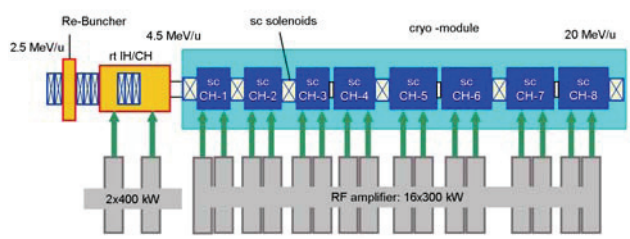

Figure 2: The IFMIF DTL layout proposed by IAP.

Consisting of one RT IH/CH cavity and eight SC CH cavities sharing one common cryomodule, a compact DTL layout of ~12m conceived by IAP is schematically shown in Fig. 2.

The RT cavity at the front end is favourable because it is possible that a few beam losses turned from the not-well-accelerated particles output by the RFQ might happen at the transition. In addition, for matching convenience and operation flexibility, an RT two-gap rebuncher is introduced following the RFQ. The main acceleration will be completed by the SC CH structure, which is the first kind of multi-cell low- and medium-β superconducting accelerator with an achievable effective acceleration gradient E_{acc} up to 7MV/m [3]. Leaving a safety margin, a modest E_{acc} of ~5MV/m has been adopted for each SC cavity. Between the cavities, only one doublet, two triplets and six solenoids are necessary to guarantee sufficient transverse focusing for the warm and cold parts, respectively.

A brief comparison of the main system parameters between the three proposals is given in Table 1.

Table 1: Proposals for the IFMIF DTL

Parameter	Alvarez	HWR	H-DTL
RT/SC cavities	10 / 0	2 / 42	2 / 8
Cryomodules	0	4	1
Magnets	~120quad.	3quad.,21sol.	8quad.,6sol.
Φ_{bore} [mm]	25	40-60	30-90
E_{acc} [MV/m]	0.5-1.7	4.5	2.7-5.3
$E_{\max}$ [MV/m]	18	30	25
$B_{\max}$ [mT]	N/A	50	55
L_{total} [m]	30.3	22.5	12.2

Beam Dynamics

The H-type DTL design for IFMIF is based on the unconventional KONUS ("Kombinierte Null Grad Struktur" – Combined 0° Structure) beam dynamics strategy [4], which is characterized by maximum acceleration efficiency and minimum transverse RF defocusing effects because of the application of 0° synchronous phases for most gaps. Due to the resulted lens-free slim drift tubes, the cavity shunt-impedance and the acceleration gradients can be significantly increased.

The beam transport calculation of the designed DTL has been performed with the LORASR code [5] using the simulated output distribution of ~10^6 macro-particles from the equipartitioned RFQ design [6] as the input distribution.

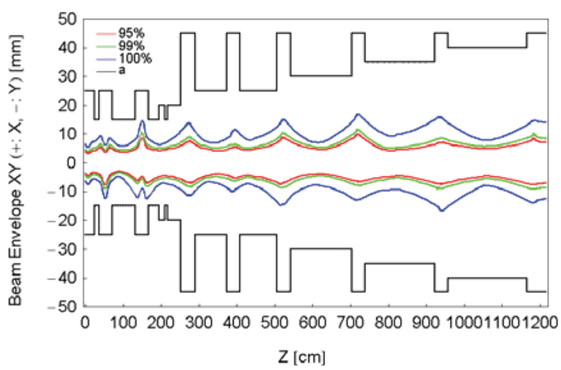

Figure 3: Transverse envelopes for 95%, 99% and 100% included beams.

In Fig. 3, the transverse envelopes for all particles and main portions of the beam are plotted simultaneously. Clearly, the "100%" curves show that the outmost particles still have safe enough distances to the bore apertures throughout the DTL, while the "99%" ones indicate that 99% of all particles are well confined in the range of ±10mm only.

The normalized rms emittances for all particles along the DTL are demonstrated in Fig. 4. It is easy to see that the transverse and longitudinal emittances grow slowly and in parallel, which means the external forces and the space-charges forces are balanced. The final rates of increment for the three planes are 60%, 66% and 32%, respectively.

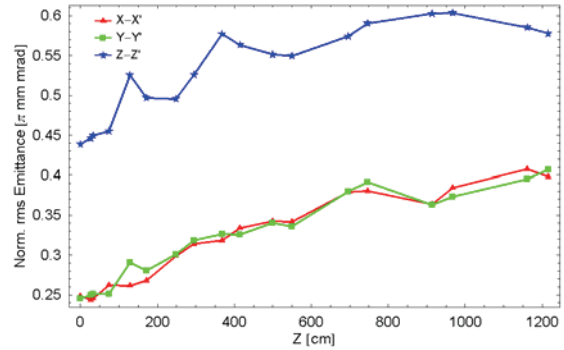

Figure 4: Emittance evolutions along the DTL.

From the 10-color density plots of the input and output particle distributions shown in Fig. 5, where the red and green ellipses are including 98% and 90% of all particles, respectively, one can learn that the particles are still concentrated at the exit.

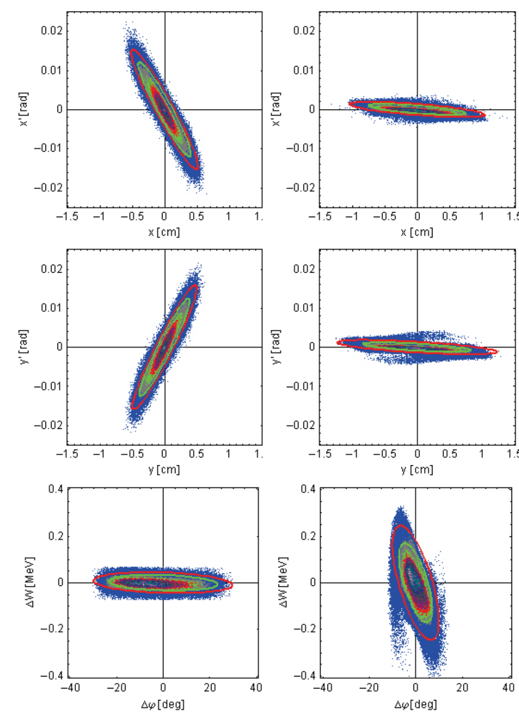

Figure 5: Input (left) and output (right) distributions.

ERROR STUDIES

Error Settings

For the design stage, only perfect accelerator components and ideal operation conditions have been taken into account. In reality, however, more or less perturbations to the design conditions are inevitable. Therefore, the error studies are particularly important for the IFMIF DTL that can tolerate nearly no beam losses.

So far, four kinds of errors can be simulated by the new LORASR subroutines, namely: 1) transverse translations of focusing elements (QMIS); 2) rotations of focusing elements (QROT); 3) gap and tank voltage amplitude errors (VERR); 4) tank phase errors (PERR).

Table 2 presents the two groups of error settings used for the IFMIF DTL with the following considerations: 1) the Case1 setting defines the maximum errors as the typical values; 2) the QMIS and QROT ranges in Case2 are twice those of the Case1. For each case, 100 non-ideal DTLs are produced with different random errors, which are Gaussian-distributed and truncated at the maximum A=±2σ in the range of the corresponding setting.

Table 2: Error settings for the IFMIF DTL

Type	Case1	Case2
QMIS [mm]	$\Delta X,\ \Delta Y$=±0.1	$\Delta X,\ \Delta Y$=±0.2
QROT [mrad]	$\Delta\varphi_{x,\,y}$=±1.5 $\Delta\varphi_z$=±2.5	$\Delta\varphi_{x,\,y}$=±3.0 $\Delta\varphi_z$=±5.0
VERR [%]	ΔU_{gap}=±5.0 ΔU_{tank}=±1.0	ΔU_{gap}=±5.0 ΔU_{tank}=±1.0
PERR [°]	$\Delta\Phi_{tank}$=±1.0	$\Delta\Phi_{tank}$=±1.0

Statistical Analysis

For the error studies, the DTL input distributions are produced by the same RFQ design but with 10^5 of input macro-particles. Though the particle quantity is reduced, a careful comparison study shows that the results from the two input distributions are very similar in all aspects.

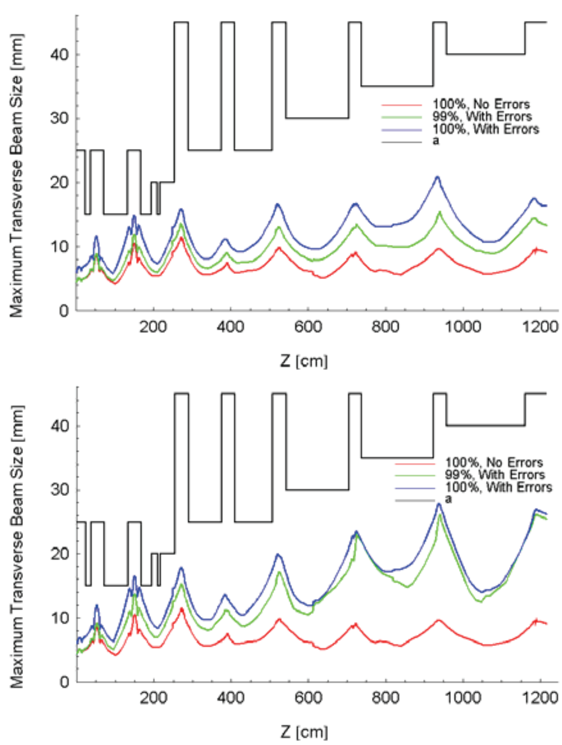

Figure 6: Maximum transverse beam sizes for Case1 (top) and Case2 (bottom) with and without errors.

For each 100 runs, the common maximum transverse beam sizes with the error settings of Case1 or Case2 are given in Fig. 6, where the design case is also shown for comparison. No beam losses are observed even in the worst case. Especially for the SC cavities, the space between the beam and the accelerator elements are still fairly safe.

In the both cases, the statistics of the additional emittance growths induced by the errors have been made and demonstrated in Fig. 7. Clearly, only very few runs have the additional growths larger than 40%, so the beam quality is still kept under control in case of errors even without any orbit corrections.

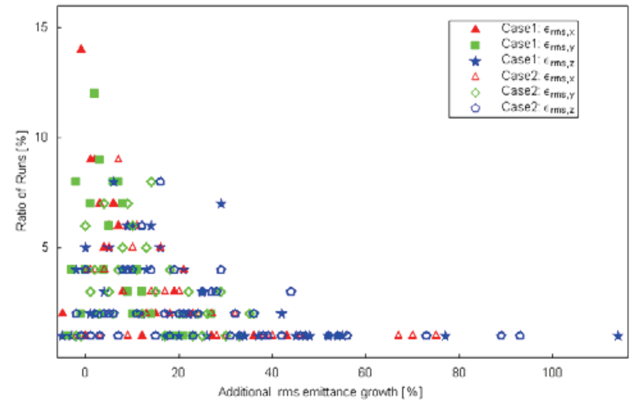

Figure 7: Additional emittance growths with errors.

CONCLUSIONS

As the candidate which has the shortest layout, the H-type DTL design scheme for IFMIF always behaves well no matter in the design studies or in the error studies. It confirms the combination of the H-type DTL structure and the KONUS beam dynamics is an efficient solution to meet the strict requirements for the intense IFMIF linac.

As the next steps on schedule, the error studies with the original input distribution of 963056 macro-particles and further optimization work will be performed.

ACKNOWLEDGEMENTS

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