ESS DTL DESIGN AND DRIFT TUBE PROTOTYPES

F. Grespan, M. Comunian, A. Pisent, M. Poggi, C. Roncolato, INFN/LNL, Legnaro, Italy
P. Mereu, INFN Torino, Torino, Italy

Abstract

The Drift Tube Linac (DTL) for the ESS accelerator will accelerate protons up to 62.5 mA average pulse current from 3.62 to 90 MeV. The 5 tanks composing the DTL are designed to operate at 352.21 MHz in pulses of 2.86 ms long with a repetition rate of 14 Hz. The accelerating field is around 3.1 MV/m, constant in each tank. Permanent magnet quadrupoles (PMQs) are used as focusing element in a FODO lattice. The empty drift tubes accommodate Electro Magnetic Dipoles (EMDs) and Beam Position Monitors (BPMs) in order to implement beam corrective schemes. A complete set of Drift Tubes (DTs) is under construction that is BPM, EMD and PMQ types. These prototypes are aimed to validate the design with the involved integration issues of the various components, as well as the overall technological and assembly process. This paper presents the main mechanical choices and the status of the prototyping program of the DTs.

INTRODUCTION

The ESS linac redesign, decided in 2013 to meet the budget, had the consequence of increasing the beam current from 50 mA to 62.5 mA [1]. Since the previous 4-tanks DTL design was optimized for 50 mA beam loading at the limit of the RF coupler capability, the physical design DTL has been reviewed. Nevertheless most of the engineering choices are confirmed [2,3].

The DTL input constraints kept for this design are:

- Tank length < 8 m (9.3 λ) for RF stability. Each tank composed by 2 m long stainless steel modules.
- Total Power per tank = ($P_{Superfish}$ × 1.25 + Beam Power) ≤ 2.2 MW to maintain the design of CERN RF window [4].
- Intertank = 1 βλ between flange inner surfaces.

In addition to the beam current, the DTL transition energies have been changed:

- Input Energy from 3 MeV to 3.62 MeV. It allows simplifying the first DTs that are the most challenging, with weaker requirements on quadrupole integrated field and the possibility of longer PMQs, as well as the advantage of better shunt impedance and lower surface field level.
- Final energy > 88 MeV. It allows improving the matching point to the Superconducting section in terms of phase advance and acceleration efficiency. Since the constraints on RF power per tank and the tank length are maintained, this extra energy will be reached with 5 DTL tanks. The cost and space of the extra DTL tank could be compensated by the removal of a few spoke cryomodules [5].

Table 1: Summary of ESS DTL Properties

Tank	1	2	3	4	5
Cells	61	34	29	26	23
E_0 [MV/m]	3.00	3.16	3.07	3.04	3.13
E_{max}/E_k	1.55	1.55	1.55	1.55	1.55
φ_s [deg]	-35,-25.5	-25.5	-25.5	-25.5	-25.5
L_{Tank} [m]	7.62	7.09	7.58	7.85	7.69
R_{Bore} [mm]	10	11	11	12	12
L_{PMQ} [mm]	50	80	80	80	80
Tun. Range [MHz]	±0.5	±0.5	±0.5	±0.5	±0.5
Q0/1.25	42512	44455	44344	43894	43415
Optimum β	2.01	2.03	2.01	1.91	1.84
Beam Det [kHz]	+23	+20	+20	+18	+18
P_{cu} [kW] (no margin)	870	862	872	901	952
E_{out} [MeV]	21.29	39.11	56.81	73.83	89.91
P_{TOT} [kW]	2192	2191	2196	2189	2195

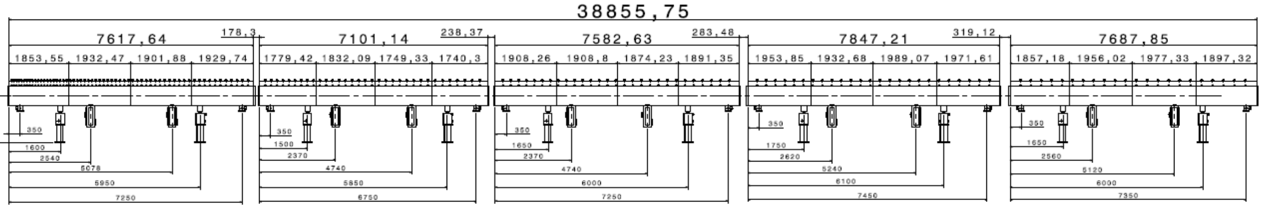

Figure 1: DTL overview.

Table 1 summarize the resulted DTL and Figure 1 is an overview of the structure showing vacuum pumps, supports, waveguides, intertank space and the sub-module segmentation of the tanks.

BEAM DYNAMICS

The values of the PMQs of the FODO channel are fixed to obtain an equipartitioned beam evolution (Figure 2) and a good phase advance matching with the RFQ at low energy and with the SC linac at high energy: The DTL beam dynamics is studied using a uniform input beam distribution. The RMS input emittances are: Trans./Long. = 0.28/0.36 mm mrad (0.1436 π deg MeV). The emittance growth is $\Delta\varepsilon_{x,y} = 2\%$, and $\Delta\varepsilon_z = 1\%$..

Because of the beam losses limit fixed at 1 W/m [1], the bore aperture is kept as large as possible, but not at the price of final energy value (Figure 3). Even if the error study shows a higher risk of beam losses in Tank 1 [6], the bore is not increased in order to keep potential beam scraping in Tank 1 rather than having loss at higher energy.

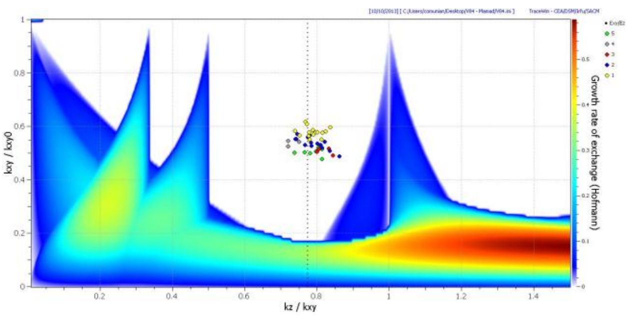

Figure 2: Stability plot for the DTL.

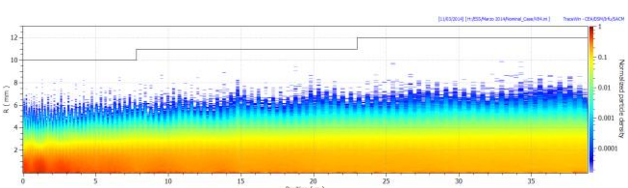

Figure 3: Particle density and bore radius.

RF DESIGN

Since a longer PMQ can be lodged in the DTs (L_{PMQ} from 45mm to 50mm) and the higher input energy reduces the required integrated field, the 1st PMQ gradient is reduced from 70 T/m to 61.6 T/. This mitigates the risk of electric breakdown in the 1st cells due to the presence of DC magnetic field (Figure 4). Furthermore the risk of multipacting is reduced by minimizing DT parallel surfaces (Flat = 3 mm).

Post Couplers (PCs) are needed for RF stabilization. The choice of having constant E0 in each tank allows avoiding bended PCs, necessary in case of ramped field.. The PCs distribution along each DTL tank must be compliant with the NPCs/meter [2], with the increasing cell length and with the 2 m tank modulation. The detuning induced by PCs is +20 kHz, the required extra p

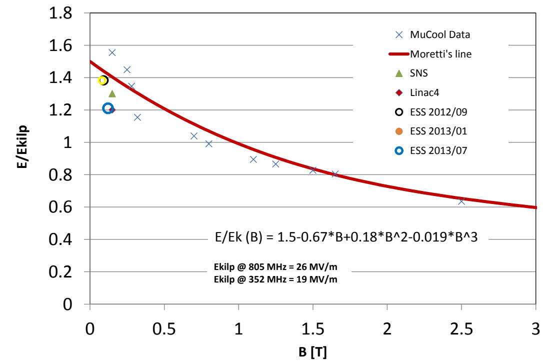

Figure 4: The 1st cell of the 2013's ESS DTL is below the breakdown limit curve.

One 2.9 MW klystron feeds each DTL tank. 30% of this power is put aside for waveguide losses and LLRF regulation. The remaining 2.2 MW enter in the cavity through 2 iris couplers located at 1/3 and 2/3 of the tank length to minimize the induced field perturbation. The coupling strength β is optimized in order to critically couple the waveguide and the beam loaded cavity. Different sizes of iris aperture and iris height have been simulated with HFSS in a simplified geometry and then rescaled to the total power of 2.2.MW (Figure 5 and 6). The iris height and aperture allow a coupling strength β=1.2 (20% margin that can be adjusted by shifting the short circuit at the end of the waveguide).

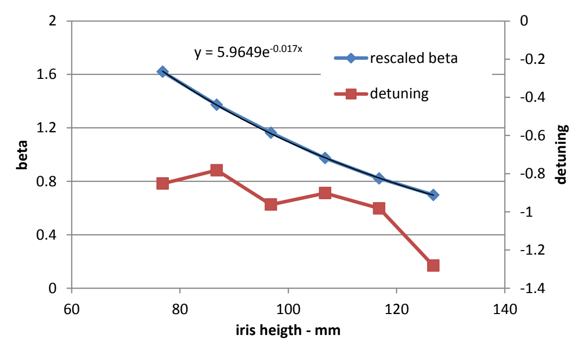

Figure 5: β vs. iris height (iris aperture =70mm).

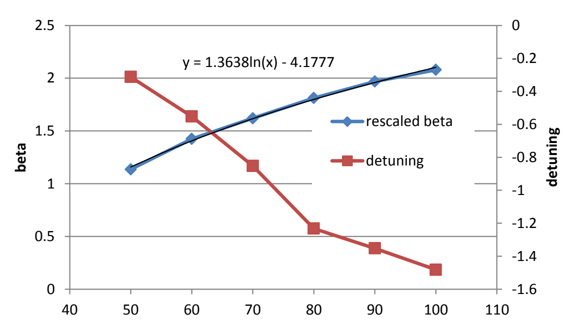

Figure 6: β vs. iris aperture (iris height = 76.8mm).

Once calculated the optimum coupling β_0 and the effective synchronous phase φ_{eff} of the beam in the DTL, the optimum detuning induced by the beam is given by

ISBN 978-3-95450-142-7

$$2Q_L \frac{f_{RF}-f_0}{f_0} = \frac{\beta_0 - 1}{\beta_0 + 1} \tan \varphi_{eff}$$

Since the 2 couplers of each DTL tank are supplied by the same amplifier, amplitude and phase balances are determined by tuning the splitter and the length of the two waveguide arms. A circuit model gives the reflected power at both couplers as function of unbalanced phase, amplitude or coupling β:

$$\Gamma_1(\Delta\theta, \beta_1, \beta_2, P_1, P_2) = \left| \frac{\beta_1 - \beta_2 - 1}{\beta_1 + \beta_2 + 1} + \frac{2\sqrt{\beta_1 \beta_2}}{\beta_1 + \beta_2 + 1} \sqrt{\frac{P_2 Z_2}{P_1 Z_1}} e^{i\Delta\theta} \right|$$

PROTOTYPING PROGRAM

The DTL prototyping program is divided in four steps:

1- Construction of the beam components (PMQ, BPM, EMD) and their characterization.
2- Construction and assembly of three complete DT prototypes with PMQ, with BPM and with EMD.
3- Installation of DT prototypes in Linac4 DTL prototype [7].
4- Test at nominal power of the DTL prototype.

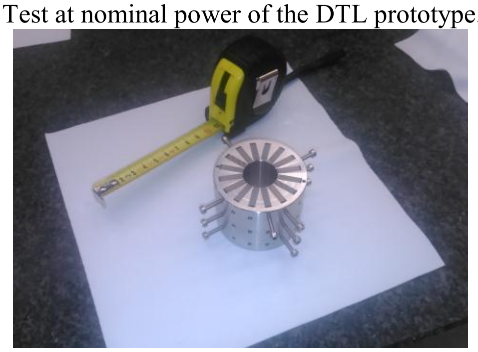

Figure 7: The PMQ prototype.

COMSOL simulations have been performed on PMQs to calculate adequate specifications of rare-earth piece needed to reach PMQ requirements. The PMQ prototype built and assembled at INFN-Torino has been preliminary measured with a Hall probe in a fraise (Figure 7). It shows a good linearity and a gradient of 68.4 T/m, higher than simulated value of 65 T/m (Figure 8). The PMQ will be measured and tuned with a rotating coil at CERN magnetic test bench in order to evaluate magnetic axis and harmonic content. The PMQ vacuum test shows a spike around the time 3.5 hr probably due to trapped air in the rare earth pieces (Figure 9). The final pressure is similar to the background value. Larger amount of water, hydrogen and oxygen and carbon dioxide are measured. These cannot be determined if they are from the stainless steel frame or from the permanent magnets.

The BPM parts have been machined at INFN-Torino and it is now ready to be brazed at INFN-LNL. The BPM shall guarantee the beam position with 0.1mm resolution, and it will be characterized by a dedicated test bench before the installation in the DT.

The EMD will be produced by an external company and a set of specification has been provided.

The three DT prototypes have the geometry compatible with Linac4 DTL prototype. The present solution is based on a DT main body and an inner flow separator. The assembly procedure foresees 2 brazing steps and a final sealing with EBW.

The prototyping program will be concluded with a High power test. This test will use 2 solid state amplifiers (2×125 kW-CW at 352 MHz) presently under construction. In the High power DTL prototype from Linac4 (peak power 180 kW, 10% duty cycle, E0=3.3MV/m) three drift tubes will be replaced by ESS drift tubes containing beam instrumentation.

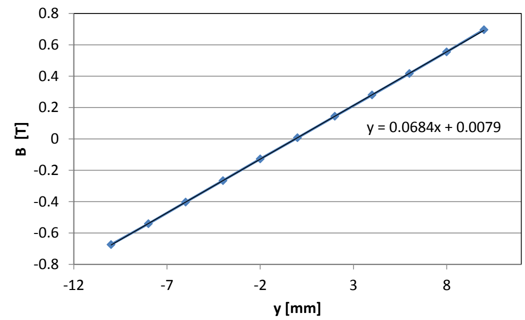

Figure 8: PMQ gradient (Hall probe measurement).

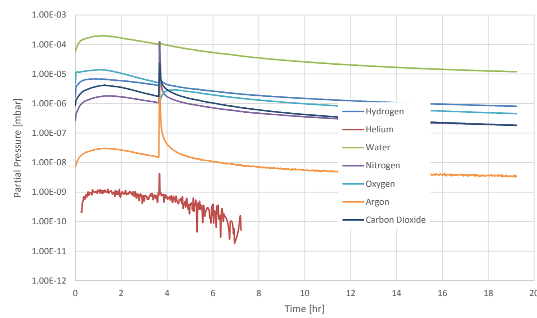

Figure 9: PMQ vacuum test.

CONCLUSIONS AND ACKNOWLEDGEMENTS

The design of the ESS DTL after the overall review of the ESS Linac is now concluded with important changes on the input parameters but with the confirmation of the main engineering choices. The prototyping program advanced in the meantime showing the first results.

The availability of Linac4 DTL design and prototype for high power test, very important for this development, were available thanks to the agreement KN2155/KT/BE/160L between CERN and INFN-LNL.

REFERENCES

[1] M. Eshraqi et al, "The ESS LINAC", IPAC2014.
[2] M. Comunian et al., "DTL DESIGN FOR ESS", Linac12.
[3] M. Comunian et al., "Progress on DTL Design for ESS", IPAC13.
[4] F. Gerigk et al, "THE LINAC4 POWER COUPLER", IPAC11.
[5] C. Darve et al, "THE ESS SUPERCONDUCTING LINEAR ACCELERATOR", SRF2013
[6] M. Comunian, "ESS DTL Error Study", this conference.
[7] S. Ramberger et al., "Drift Tube Linac Design and Prototyping for the CERN Linac4", Linac2008.