ESS DTL DESIGN AND DRIFT TUBE PROTOTYPES

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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 352.2 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 Electromagnetic 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} \times 1.25 + Beam Power) \leq 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

<table>
<thead>
<tr>
<th>Tank</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cells</td>
<td>61</td>
<td>34</td>
<td>29</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>E₀ [MV/m]</td>
<td>3.00</td>
<td>3.16</td>
<td>3.07</td>
<td>3.04</td>
<td>3.13</td>
</tr>
<tr>
<td>E_{max}/E_k</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
</tr>
<tr>
<td>φ_s [deg]</td>
<td>-35.5</td>
<td>-25.5</td>
<td>-25.5</td>
<td>-25.5</td>
<td>-25.5</td>
</tr>
<tr>
<td>L_{Tank} [m]</td>
<td>7.62</td>
<td>7.09</td>
<td>7.58</td>
<td>7.85</td>
<td>7.69</td>
</tr>
<tr>
<td>R_{Bore} [mm]</td>
<td>10</td>
<td>11</td>
<td>11</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>L_{PMQ} [mm]</td>
<td>50</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Tun. Range [MHz]</td>
<td>±0.5</td>
<td>±0.5</td>
<td>±0.5</td>
<td>±0.5</td>
<td>±0.5</td>
</tr>
<tr>
<td>Q₀/1.25</td>
<td>42512</td>
<td>44455</td>
<td>43444</td>
<td>43894</td>
<td>43415</td>
</tr>
<tr>
<td>Optimum β</td>
<td>2.01</td>
<td>2.03</td>
<td>2.01</td>
<td>1.91</td>
<td>1.84</td>
</tr>
<tr>
<td>Beam Det [kHz]</td>
<td>+23</td>
<td>+20</td>
<td>+20</td>
<td>+18</td>
<td>+18</td>
</tr>
<tr>
<td>P_{cu} [kW] (no margin)</td>
<td>870</td>
<td>862</td>
<td>872</td>
<td>901</td>
<td>952</td>
</tr>
<tr>
<td>E_{out} [MeV]</td>
<td>21.29</td>
<td>39.11</td>
<td>56.81</td>
<td>73.83</td>
<td>89.91</td>
</tr>
<tr>
<td>P_{TOT} [kW]</td>
<td>2192</td>
<td>2191</td>
<td>2196</td>
<td>2189</td>
<td>2195</td>
</tr>
</tbody>
</table>

Figure 1: DTL overview.
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 $\Delta \varepsilon_{x} = 1\%$.

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.

RF DESIGN

Since a longer PMQ can be lodged in the DTs ($L_{\text{PMQ}}$ 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/m. 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 $E_0$ 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 power is 45 kW, already included in the 1.25 margin.

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 $\beta$ 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 $\beta=1.2$ (20% margin that can be adjusted by shifting the short circuit at the end of the waveguide).

Figure 2: Stability plot for the DTL.

Figure 3: Particle density and bore radius.

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

Figure 5: $\beta$ vs. iris height (iris aperture =70mm).

Figure 6: $\beta$ vs. iris aperture (iris height = 76.8mm).
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 $\beta$:

$$\Gamma_1(\Delta \theta, \beta_1, \beta_2, P_1, P_2) = \frac{\beta_1 - \beta_2}{\beta_1 + \beta_2 + 1} + \frac{2\sqrt{\beta_1 \beta_2}}{\beta_1 + \beta_2 + 1} \sqrt{\frac{P_2 Z_2}{P_1 Z_1}} \exp(2)$$

**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.

**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**