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STATUS AND OVERVIEW OF THE ACTIVITIES ON ESS DTLs

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Abstract

The Drift Tube Linac (DTL) for the European Spallation Source will accelerate H+ beams of up to 62.5 mA peak current from 3.62 to 90 MeV. The structure consists of five cavities [1]. The 1st cavity (DTL1, 21 MeV) has been commissioned with beam in summer '22. DTL2, 3 and 4 have been installed in the accelerator tunnel since the end of '22, ready for RF conditioning and beam commissioning starting in '23. DTL5 is under assembly and will be transported to the tunnel after the completion of beam commissioning up to 74 MeV. This paper aims to give an overview of the activities completed and ongoing on the five DTLs: from assembly to tuning, through installation and RF conditioning to beam commissioning.

INTRODUCTION

From May '21 to May '23 significant progress was made toward the completion of the DTL cavities for the ESS Linac (Table 1). The preparation of the DTLs by INFN has been harmonized with the ESS commissioning plan, which planned a 1st round with beam to 21 MeV (DTL1) in '22, a 2nd commissioning to 74 MeV (DTL4) in '23 and DTL5 commissioned with Super Conducting Linac in '24 [2, 3].

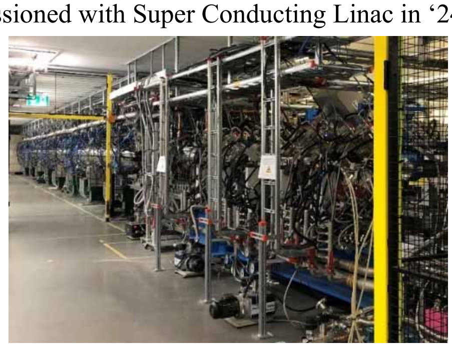

Figure 1: the 4 DTLs installed in the ESS tunnel.

In May '21 none of the DTLs were in the tunnel. DTL1 was tuned and only DTL4 had started the assembly in the DTL workshop (DTLW) [2]. In Aug. '21 DTL1 was moved to the tunnel, in autumn/winter '21 it underwent into a series of tests, in preparation for RF conditioning in March '22 and beam commissioning in June '22 [4, 5]. Meanwhile in the DTLW, DTL 2-3-4 were assembled, tuned and prepared for tunnel installation from Sept. to Dec. '22 (Fig. 1). After the integrated tests, in Jan-31st 2023 RF conditioning started and 1st beam was accelerated trough the four DTLs in April 21st. DTL5 assembly and tuning was done in Feb. and March '23. DTL5 tunnel installation is expected in Sept. '23.

Table 1: In green, DTL activities started at the given date

	05/2021					05/2023				
DTL→ / PHASE↓	1	2	3	4	5	1	2	3	4	5
Production	■	■	■	■	■	■	■	■	■	■
Assembly	■			■		■	■	■	■	■
Tuning	■					■	■	■	■	■
Tunnel Instal.						■	■	■	■	
RF condit.						■	■	■	■	
Beam Comm.						■	■	■	■	

ASSEMBLY

The DTL assembly sequence is described in [2]. At the end of the assembly the most relevant results are the metrology of the drift tubes and the leak tests of the gasket connections. PMQ alignment specification is to be within ±0.1 mm with respect to tank axis. A small number of nonconformities have been tolerated and tracked in the documentation, marked with a red circle in Fig. 2. Each tank has approximatively a hundred ports to be sealed, including drift tubes (DTs, 60 to 22 depending on the tank), module connections (#3), end plates (#2), tuners (#26), post couplers (PCs, #different on the tank), pick-ups (#9), power couplers (#2), vacuum manifolds (#3). All the connections use Helicoflex® metallic seals, which are particularly demanding in terms of surface finishing [6]. The only exception is the EPDM gaskets between RF windows and couplers (#2). All the connections are verified in the DTLW and checked again after tunnel installation.

TUNING AND STABILIZATION

After the DTL1 tuning [2], we decided to use PCs equipped with end stubs for the remaining DTLs (Fig. 3) [7, 8, 9]. Roughly speaking, after the regulation of the PC lengths for field stabilization, the stub of several PCs is tilted in order to improve the flatness of E0 field. With a few iterations, both E0 and Tilt Sensitivity (TS) converge. This technique improved the tuning process in terms of time and quality. In 2 working days per tank, we reached the goals of E0 flatness < 2% and TS < 100%/MHz. Thank to PC stubs, tuners are used only to recover the frequency, so they can be set all at the same length.

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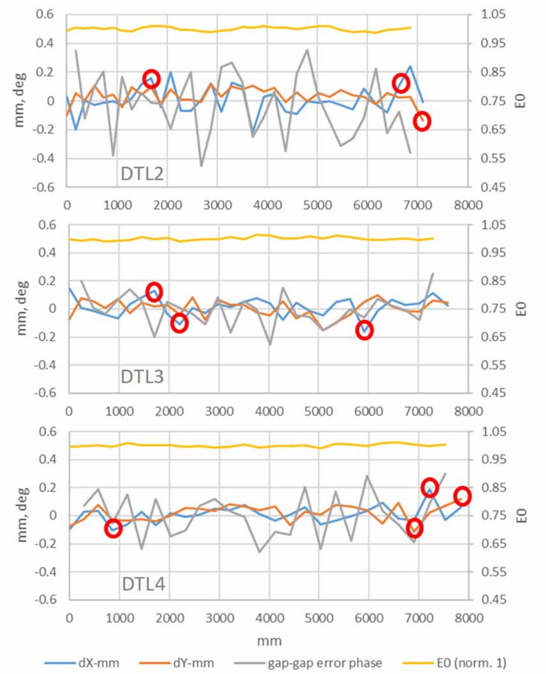

Figure 2: E0, gap-gap phase error and DT transverse alignment after assembly and tuning. DTL1 reported in [1].

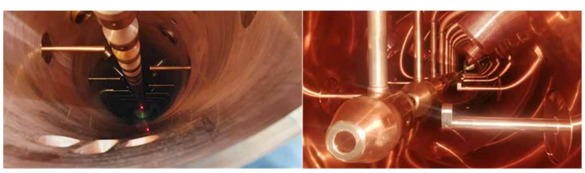
Figure 3: inner view of DTL1 and DTL4 (PCs with stubs).

After machining and replacement of adjustable tuners and PCs with copper parts, cavity RF parameters are recorded (Table 2). E0 flatness preservation is checked after DTL tunnel installation using 9 pick-ups previously calibrated with respect to bead pulling. Pick-up checks on DTL3 were initially out of range. Therefore, a bead pull measurement in the tunnel was necessary to verify if really something happened to the cavity. It turned out that the cavity E0 was preserved, while the pick-up calibration done in the DTLW was incorrect. The new DTL3 reference is now the measurement taken in the tunnel. For each tank, E0 is checked at different penetration of the 3 movable tuners in a range ±20mm, to verify the influence on the field.

BEAM SIMULATION AS BUILT

INFN Beam Dynamics team has confirmed the acceptability of the "as-built" DTL 1-2-3-4 with respect to requirements. The assigned transv. and long. emittance growth to the 5 DTLs with all errors is <30% (=10% by design + 20% by errors for 90% of cases) [10]. Inputs for the "as-built" model are tuning and alignment results (Fig. 2). Table 3 lists the errors assumed for the error study. 10000 runs with perfect nominal input beam are here considered. Steerers are used for correction of beam centroid. Beam is composed of $2{\times}10^5$ macro-particles, 6D ellips. Gauss. distribution. 90% of cases have an emittance growth of 7% long. and 12% transv., w.r.t input (Fig.4). The max. steerer strength considering 99.9% of cases is 10 mT*m. All runs are without losses.

Table 2: DTL2-3-4 RF parameters. DTL1 reported in [1]

	Parameters	Design	Measured
DTL2	Freq. [MHz]	352.21	352.190 (in air, no RF power, 22°C)
DTL2	Coupl. factor [β]	2.03	2.15
DTL2	Q0 (SFish/1.25)	44455	39952
DTL2	Δf. close modes	N.A.	1.47 /-1.82 MHz
DTL2	E0 flatness [%]	±2	±1.21
DTL2	Tilt.Sens.	N.A.	±30 %/MHz
DTL3	Freq. [MHz]	352.21	352.179(see DTL2)
DTL3	Coupl. factor [β]	2.01	2.05
DTL3	Q0 (SFish/1.25)	44345	44019
DTL3	Δf. close modes	N.A.	2.15 /-1.76 MHz
DTL3	E0 flatness [%]	±2	±1.21
DTL3	Tilt.Sens.	N.A.	±4 %/MHz
DTL4	Freq. [MHz]	352.21	352.190(see DTL2)
DTL4	Coupl. factor [β]	1.91	1.95
DTL4	Q0 (SFish/1.25)	43895	44360
DTL4	Δf. close modes	N.A.	2.12 /-1.82 MHz
DTL4	E0 flatness [%]	±2	±1.09
DTL4	Tilt.Sens.	N.A.	±3.5 %/MHz

Table 3: Errors study setup

Error type	Max value	Distrib.
PMQ and gaps transv. Misalign. →DTL5	± 0.15 mm	Uniform
Gap E0 flatness →DTL5	± 2%	Uniform
Gap phase (simulates as long. gap displ.) →DTL5	± 1 deg	Uniform
Klystron stability E0 (to whole tank) →all DTLs	± 1% (3σ)	Gaussian
Klystron stab. Phase (to whole tank) →all DTLs	± 2 deg (3σ)	Gaussian
BPM uncert. →all DTLs	± 0.2 mm	

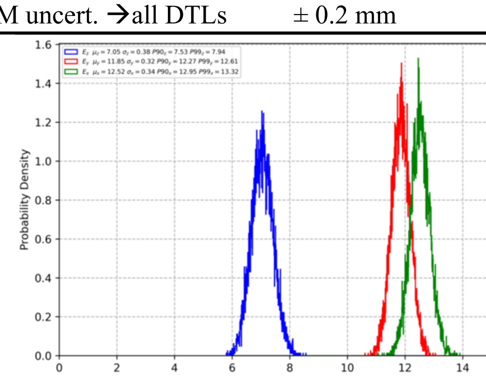

Figure 4 Emittance increase at the end DTL5.

RF CONDITIONING

Once in the tunnel, DTLs are connected to the systems involved in the high-power RF operation: RF system, water cooling, vacuum, Local Control System. Before high power RF injection, physical and functional links between all the subsystems are tested, to verify monitoring, calibrations and protections. Integrated tests done for DTL1 and repeated for DTL 2-3-4 are described in [4].

Conditioning of the DTLs started at 10us-10kW-1Hz. On Feb 2nd all DTLs reached 2MW-14Hz-15us, equivalent to 2.8-3MV/m, depending on the cavity. On Feb 13th all the DTLs reached 14Hz-400us-3MV/m (Fig.5). A conditioning routine is used, initially tested in Python and then deployed in EPICS IOC [6].

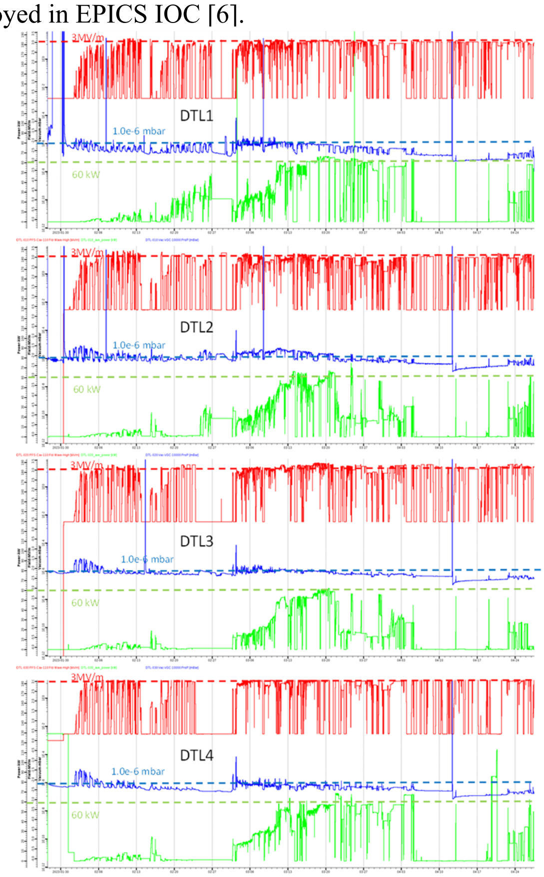

Figure 5: RF conditioning of 4 DTLs (Feb 1st-April 30th).

Cooling Issue and RF window arcing

Starting to run at $P_{AVE} = Pulse \cdot Rep.rate \cdot (P_{FWD} - P_{REV}) > 10kW$, a cooling issue was detected. More details on the issue and its solution are in [6]. After fixing the cooling problem, all the cavities reached the nominal field and duty cycle (P_{AVE}~60kW) on March 15th, including long stability run with more the 95% RF ON over 8 hours.

Arcing have then been detected on three of the eight RF windows, one in DTL2 and both in DTL3. The arcs occur only at high RF power, above 600 kW per window and with a pulse length is greater than 1 ms. Those arcs are particularly dangerous because they are mostly detected in air side of the windows, preventing the possibility of conditioning. A visual inspection was made of the air side of the windows and some dust was found and heat marks were seen on the copper but no physical damage. Permanent magnets and air blowing have been applied on the windows without solving the problem. It is planned to replace one of the windows with a spare and re-condition on a test rig using the klystron for DTL5. It must be mentioned that all the DTL RF windows passed the full conditioning tests (1.4MW-3.2ms-14Hz) at CEA-Saclay.

High Power RF operation: preliminary results

Table 4 shows the cavity RF parameters checked at high RF power via LLRF. Detuning Δf and Q_L are measured from the cavity field decay: $V_{decay}(t) = V_0 e^{-t/\tau} e^{it\Delta\omega}, \tau = 2Q_L/\omega_0$. From the steady state value of P_{REV} we obtain $\beta \equiv SWR = (1 + |\Gamma|)/(1 - |\Gamma|)$, over-coupling confirmed by P_{REV} waveform itself.

Detuning induced by RF power $\Delta f = \Delta f_{60kW} - \Delta f_{30W}$ is compared with an estimation from thermal simulations. Q_L and β should be compared with VNA values of Table 2. P_{AVE} is compared with calorimetric power $P_{cal}[kW] = flow[l/s] \cdot c[kJ/(kg \cdot °C)] \cdot \rho[kg/l] \cdot \Delta Temp$.

Table 4: DTL RF parameters at high RF power (in kW)

	Δf kHz	Q_L	β	P_{AVE}	P_{cal}
DTL1	-40 | est.-26	14500	1.93	62.5	57
DTL2	-33 | est.-34	13350	1.98	61.2	57.2
DTL3	-40 | est.-32	14100	1.97	56	49.6
DTL4	-52 | est.-43	14800	1.99	65.2	63.4

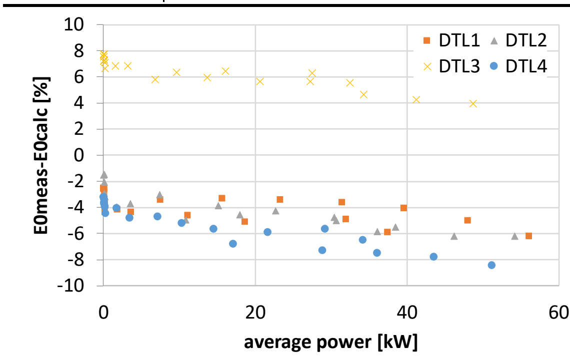

Figure 6: measured and calculated $E0_{acc.field}$ vs. P_{AVE}.

Figure 6 shows - as function of P_{AVE} - the difference between $E0_{meas}$ by cavity pick-up and $E0_{calc}$ from parameters in Table 2 and [1]. On top of a general calibration error of ±5%, all DTLs show a decreasing trend of $E0_{meas}$ of about -4%, over the power range [0.03-60] kW. The 2022 beam campaign showed that DTL1 $E0_{meas}$ is underestimated by about 5%, indicating that the set amplitude of 2.9 MV/m is closest to provide the nominal 3.0 MV/m field [5]. Similar experiments are planned for all DTLs, to find the correct cavity set point and verify it at high duty cycle.

CONCLUSIONS

DTL cavities reached full power operation with the required long run stability. Three arcing RF windows will be replaced in May/June 2023 in order to restart high power operation in DTL 2&3. A 3.5 mA probe beam was accelerated through the four DTLs showing 100% transmission without trajectory correction and with RF OFF in DTL 2-3-4, as expected by the models [11]. A rough estimation of the acceleration rate was done measuring induced beam loading in the LLRF signals, showing each tank is giving the expected ~17MeV to beam.

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