ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPOJO09

# HIGH POWER RF CONDITIONING OF THE ESS DTL1

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### *Abstract*

The first tank of Drift Tube Linac (DTL) for the European Spallation Source ERIC (ESS), delivered by INFN, has been installed in the ESS tunnel in Summer 2021. The DTL-1 is designed to accelerate a 62.5 mA proton beam from 3.62 MeV up to 21 MeV. It consists of 61 accelerating gaps, alternate with 60 drift tubes (DT) equipped with Permanent Magnet Quadrupole (PMQ) in a FODO lattice. The remaining drift tubes are equipped with dipole correctors (steerers), beam position monitors (BPMs) or empty. The total length of the cavity is 7.6 m and it is stabilized by post couplers. Two waveguide couplers feed the DTL with the 2.2 MW of RF power required for beam operation, equally divided by RF power losses and beam power. This paper first presents the main systems required for the DTL conditioning. Then it summarizes the main steps and results of this high-power RF conditioning done at ESS to prepare the DTL for the consequent beam commissioning.

## INTRODUCTION

The high-power RF conditioning process wants to make the cavity ready to sustain beam operation, in terms of RF parameters (field, pulse length, repetition rate) and vacuum level. For ESS DTLs the two main goals of the conditioning process are [1]:

- To maintain 14 Hz, 3.2 ms, nominal field level (3 MV/m for DTL1) for 12 hours with low interlock rate (> 95% RF ON over 12 hours).
- To keep the vacuum level 5.0e-07 mbar at nominal RF level.

After a description of the main systems necessary for the conditioning and the integrated tests performed, the paper will go through the main steps of the conditioning process and finally will comment the main results.

## RF CONDITIONING SYSTEMS

The block diagram of Fig. 1 shows the main systems involved in the DTL1 high power RF conditioning, their physical and functional links, in particular the signals to interlock the RF power and protect the cavity.

### *DTL1 Cavity*

After the tuning and stabilization [2], the entire cavity DTL1 has been transported and installed in the ESS accelerator tunnel in August 2021 (Fig. 2). Once on the supports, the 2 power couplers and RF windows have been installed, then DTL1 has been aligned, connected to the cooling system, leak tested. The RF parameters measured at the end of the tuning process [2] have been confirmed with measurement in the tunnel. DTL1 has a flat acc. field E0 = 3 MV/m, corresponding to a cavity power Pcav =1150 kW, without beam. DTL1 has 9 RF pick-ups to monitor E0 flatness, and 3 movable tuners to maintain the cavity at 352.21 MHz.

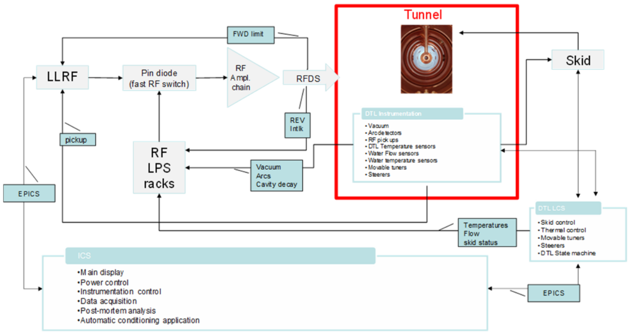

Figure 1: Block diagram of DTL1 systems and protections.

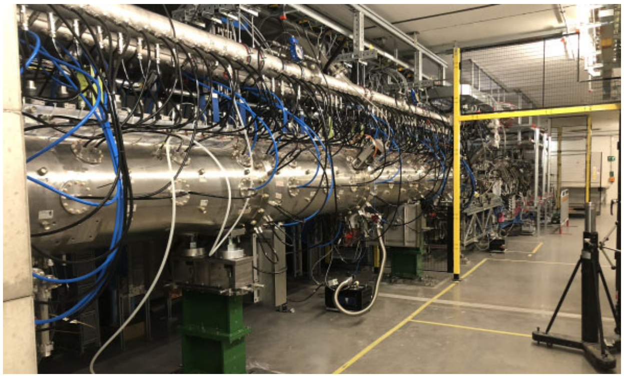

Figure 2: DTL1 in the ESS beam line.

### *RF System*

A 2.8 MW klystron serves the DTL1 as RF source, sharing the modulator with RFQ. The klystron is followed and protected by a circulator. Then a Magic-Tee splits the power in 2 wave guide lines, which arrive to feed the cavity by 2 power couplers. FWD and REV power are monitored at many points all along the RF line. Two circular alumina RF windows separate the DTL cavity vacuum from the in-air wave guide system. Each RF window is protected by 2 arc detectors (air and vacuum side), with two additional view ports for light test. The RF windows were previously conditioned at CEA-Saclay, up to 1.4 MW.

RF system includes the RF Local Protection System (LPS), the key protection system during conditioning.

### *Cooling System*

A water skid provides cooling and thermal stability to the 5 DTL tanks. Each tank has its own cooling circuit with a

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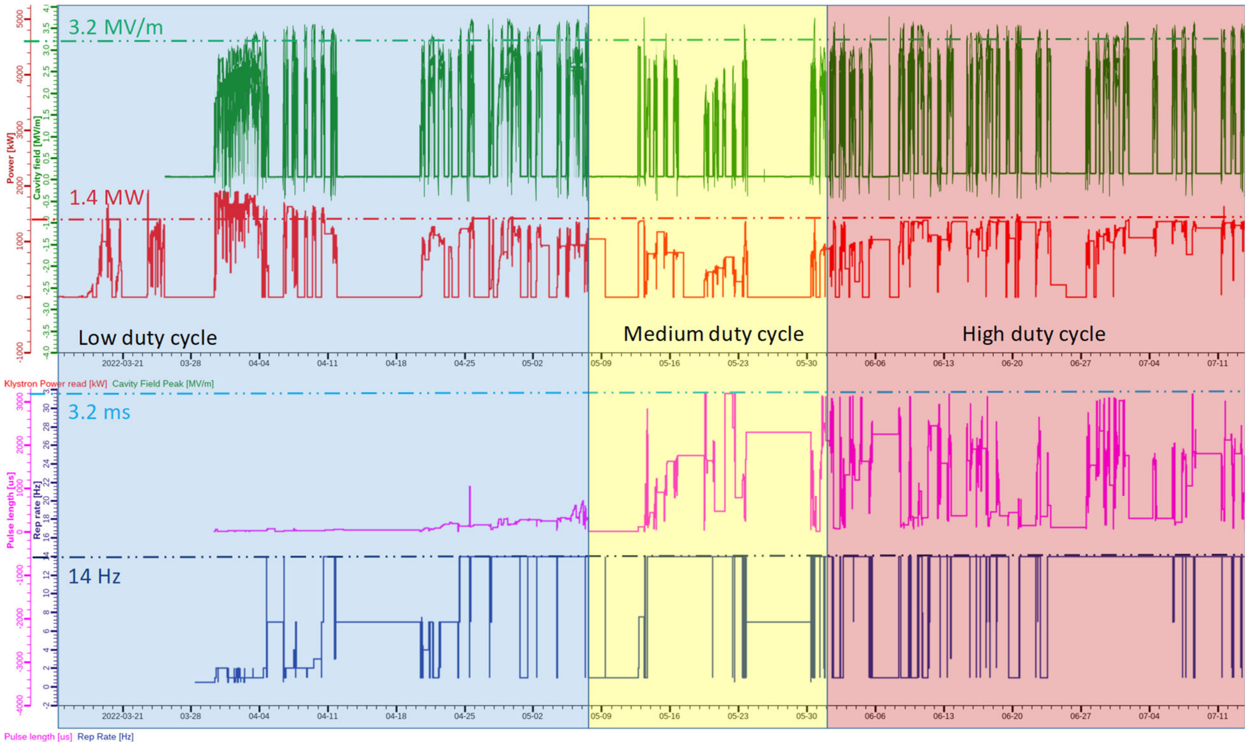

Figure 3: Conditioning history of DTL1. The 3 conditioning stages described in the text are highlighted.

pump and an independent thermal regulation by a 3-ways valve. The skid is in a dedicated area of the klystron gallery and 2 long pipes per tank arrive from this area to the tunnel, where they are connected to the inlet/outlet manifolds on top of the tank (see Fig. 2). All the 60 DTs of DTL1 are cooled in parallel and equipped with flow regulators. The cooling of the RF windows is critical and therefore they are protected with dedicated flow switches.

### *Vacuum System*

The cavity is pumped by four Nextorr NEG-Ion combo pumps, three D500 pumps located on three ports distributed at the bottom of the tank and one HV100 located on the intertank. A Pfeiffer HiPace 80 turbo pump is located on the central port. There are two cold cathode gauges with one placed on each coupler, with the advantage of being far from the pumps and close to the ceramic window. There is also a Pirani gauge attached to a port on the bottom downstream end. The large outgassing of the PMQs and the long exposure to air (2 years of assembly due to COVID lockdowns) deteriorated the vacuum conditions of the cavity, causing a saturation of NEG pumps faster than expected. In order to help the vacuum recovery time in conditioning, a bigger turbo pump (Pfeiffer HiPace 300) was installed after 2 weeks of operation.

### *Local Control System*

The DTL Local Control System (LCS) is also an in-kind contribution of INFN [3]. The DTL LCS controls the cooling and the temperature system, the movable tuning system and the steerers. LCS controls the active components and it produces the signal interlocks related to these components. In addition to the remote control in EPICS, dedicated high-level automation procedures were realized to provide the simplest and most flexible control possible. Particular state machines were devoted to supervise functional systems health, while others were focused on automatic configuration and general procedures control. The DTL LCS was interfaced with the Integrated Control System (ICS).

### *Integrated Tests*

The integrated system functionalities have been tested before starting RF conditioning, in order to verify monitoring, calibrations and protections. In summary, the main monitors during high power RF conditioning are RF cavity field, FWD and REV power, RF frequency detuning, vacuum level, water temperature, water flow, arc detectors. Interlock signals are hardwired and connected to the RF-LPS They are related to temperature and cooling issues, arc detectors, vacuum, reflected power, forward power and cavity field limit.

A special interlock is the “cavity decay interlock”: in case of RF breakdown, the cavity field decreases faster than the nominal field decay time. The cavity decay interlock detects this slope and switch off the RF power. Fast reset option is available for cavity decay and reflected power interlocks, in order to restart RF at the next pulse.

## RF CONDITIONING HISTORY

The RF conditioning lasted from March 14th to July 13th (see Fig. 3). The net time of RF into the DTL is equivalent to 36 days 24h/24h, including time shared with beam commissioning. Even if a certain freedom were given to day-by-day operations, the conditioning followed the sequence described in [4]. Conditioning is performed in “Frequency

Track" mode (RF system follows the DTL resonance frequency), while movable tuners are locked.

### *Low Duty Cycle*

First RF pulse was 10kW-10us-1Hz (DTL filling time is τ = 12.5 us). In the first day only a few pulses were observed by cavity pick-ups, most of the them being fully reflected at the RF windows. When cavity field was established, we first increased the FWD up to 2.0 MW, to be compliant with RF window conditioning. Then we repeated the ramp again from 10 kW at longer pulse length.

In order to observe the system behavior, we performed manual operation for 2 weeks. At beginning of April an automatic conditioning application was launched, with the possibility of ramping power and pulse length in a given range, decreasing power and pulse in case of single breakdown event and in case of reaching a given vacuum threshold, automatic restart of RF power after hard RF interlock.

In this phase the cavity reached nominal field with +5% margin, pulse length 500 us, rep. rate 14 Hz, for an average power of 10 kW.

### *Drift Tube Damage*

On May 7th the DT-29 started to leak ($10^{-6}$ mbar*l/s) from the region containing the steerer. Analysis is ongoing, but probably RF operation and breakdowns revealed a weak point of the DT nose EBW. To decrease the leak rate and continue RF conditioning, we disconnected the steerer cables from the power supply and we externally pumped the steerer room. This DT has been replaced in July, after the end of conditioning and commissioning campaign.

### *Medium Duty Cycle*

After the DT repair, the DTL was much less reactive and for the rest of May we conditioned it at E0 = [2.5, 3] MV/m, pulses > 1 ms and rep. rate = 14 Hz. The average power was then < 30 kW. After this period the cavity was ready for the level required for beam commissioning (3.15 MV/m, 100 us, 1 Hz).

### *High Duty Cycle*

The last month of conditioning was shared with beam commissioning activities. Roughly 50% of the time the DTL was set up at the required status for beam experiments. For the rest of the time, we pushed the cavity conditioning at E0 >2.6 MV/m, Pulse > 2 ms, Rep rate=14Hz.

In the last week the cavity run for some hours at full average power 60 kW. Even if the operation was interrupted by breakdowns and not sufficient to demonstrate long run stability it was important to stress the cavity at full power to pop up other possible weak points in the DTs.

At the end of the campaign the vacuum level at full duty cycle was 1.3E-06 mbar. We recorded more than 30000 breakdowns via cavity decay measurement, 16 arcs on the RF windows, 8 vacuum interlock (threshold > 5.0E-06).

## CONDITIONING RESULTS

Figure 4 shows the data plot of [E0, Pcav] compared with the theoretical curve calculated at the end of the low power tuning. If we exclude the data circled in red that corresponds to very low pulse length and some points clearly out of the trend-line, the data are adjacent to the theoretical curve up to 2.5 MV/m, while between 2.5 MV/m and 3 MV/m still it needs some conditioning.

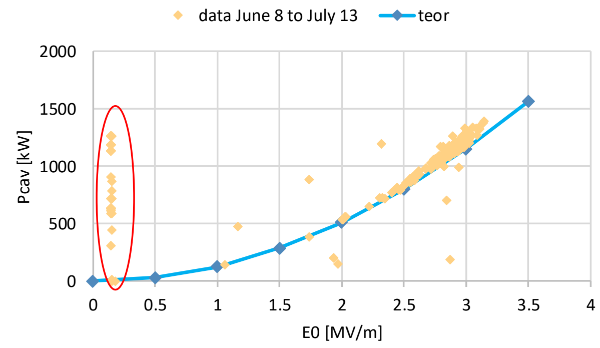

Figure 4: Pcav vs. E0 in the last month of conditioning, compared with theoretical curve.

We measured the 9 RF pick-ups signal at different power levels to check field flatness preservation. Figure 5 shows the recorded values. The first acquisition at 0.1 kW (E0 = 1 MV/m, PFWD=145 kW, pulse=600 us, rep. rate=1 Hz) is imposed to be equal to the last bead pull measurement. The last at 29 kW is obtained by E0=3MV/m PFWD=1380 kW, pulse=1.5 ms, rep. rate=14 Hz. 8 pick-ups over 9 did not show any significant trends of the field, as expected in a stabilized cavity. Only pick up n. 8 shows some disturbance, but the field is well within the 2% specification.

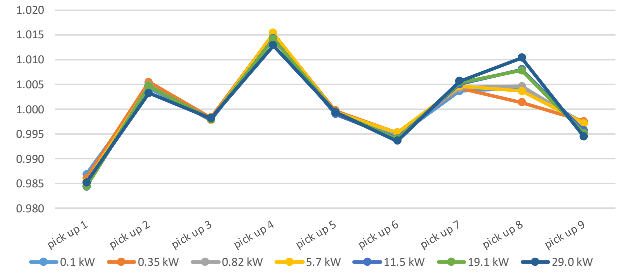

Figure 5: Field flatness checks by pick-ups.

The comparison of RGA measurements before/after conditioning shows that the high mass components (typically hydrocarbons) have been removed. The vacuum pressure with RF ON at conditioning end was dominated by H2 and CO2, released by Cu-plated stainless-steel tank. With further high-power RF time they are expected to reduce.

## ACKNOWLEDGEMENTS

The authors want to acknowledge the ESS RF group, for the support and the work done together in the integrated test phase.

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