CONSTRUCTION AND RF CONDITIONING OF THE CELL-COUPLED DRIFT TUBE LINAC (CCDTL) FOR LINAC4 AT CERN*

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Abstract

This paper reports on the construction experience of the Linac4 CCDTL, which took place in two Russian institutes in the framework of three ISTC projects in close collaboration with CERN. The tanks were constructed at VNIITF, Snezhinsk, while the drift tubes and supports were made at BINP, Novosibirsk. All structures were then assembled and tuned at BINP before shipment to CERN where the high-power conditioning took place. The tuning principles, quality checks and conditioning results are presented.

INTRODUCTION

Linac4, a new 86 m long 160 MeV H- accelerator [1] under construction at CERN, will replace the 50 MeV proton Linac2 as an injector to the PS Booster. This is an essential step towards higher luminosity of the LHC.

Linac4 consists of accelerating structures of different types. After the H- source a 45 keV beam is accelerated in an RFQ *(Radio Frequency Quadrupole)* structure up to the energy of 3 MeV. The RFQ is followed by a DTL *(Drift Tube Linac)* structure where particles are accelerated up to 50 MeV. After that the beam enters a CCDTL *(Coupled Cavity DTL)* where its energy is further increased up to 104 MeV. Finally the beam passes through the PIMS *(PI-Mode Structure)* section and reaches its output energy of 160 MeV.

All Linac4 structures operate at 352.2 MHz.

At low energies an Alvarez type DTL with quadrupoles housed in the drift tubes is a standard choice due to its good transverse focusing ability. For Linac4 permanent magnetic quadrupoles (PMQs) are used, which allows reducing the size of the drift tubes and thus increasing the RF efficiency but makes it impossible to change the transverse focusing once the machine is in operation. A CCDTL structure is used as soon as it becomes possible to place quadrupoles between subsequent accelerating cavities rather than inside drift tubes. The advantages of this approach are: i) drift tube diameter is small and thus the RF efficiency is high, ii) although EMQs are used only between the modules while PMQs are installed between the cavities within a module, the simulations showed that this provides sufficient flexibility for transverse beam dynamics, iii) the quadrupoles that need to be positioned quite precisely relative to the beam axis can be aligned on the supports independently from the cavities thus significantly relaxing the tolerances of the drift tube positioning. At higher energies the CCDTL is replaced by the PIMS for the sake of high effective shunt impedance.

The CCDTL structure consists of separate accelerating cavities (tanks) with drift tubes. Accelerating cavities are connected by single cell off-axis coupling cavities (or “cells”). An accelerating cavity has 2 drift tubes, that is 3 accelerating gaps per cavity. Quadrupoles are placed between the accelerating cavities. The cavities are grouped in modules, each module containing 3 accelerating cavities with 2 coupling cells in between (fig. 1). Each module is driven by a klystron amplifier through a coupling iris in the bottom of the middle tank. In total 7 modules are needed for Linac4 occupying about 25 m of its length.

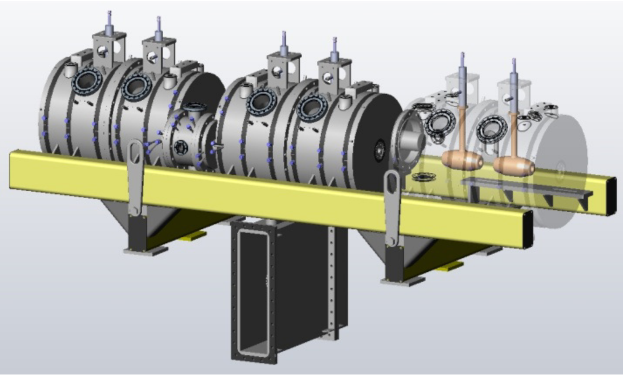

Figure 1: CCDTL module.

Linac4 will be the first operating machine, where a CCDTL is used to accelerate beam.

WORK DISTRIBUTION

The original concept of a CCDTL came out from LANL in 1994 [2]. In 2000 CERN started considering the CCDTL concept for the intermediate energy range of Linac4, although at lower frequency than at LANL. After investigating a scaled (1:3) model in aluminium, CERN designed and built in 2004-2005 a 352.2 MHz CCDTL prototype consisting of 2 half-tanks with a single drift tube in each one and a coupling cell in between. The prototype was successfully tested at high power at CERN in 2006 [3].

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Russian participation in the CCDTL construction for Linac4 started in 2004. Two Russian research institutes, the Budker Institute of Nuclear Physics (BINP) in Novosibirsk and the Russian Federal Nuclear Centre – All-Russian Institute of Technical Physics in Snezhinsk (RFNC-VNIITF), received support from the International Science and Technology Centre (ISTC, with head office in Moscow) for the construction of a CCDTL "pre-series" prototype for Linac4. The works were done in close collaboration with CERN. CERN made all the design and technology developments available to BINP and VNIITF. Nevertheless, the design had to be adapted to the capabilities of BINP and VNIITF workshops as sometimes they use different solutions for certain technological tasks. However, for very critical issues, such as copper plating of the inner surface of stainless steel tanks or vacuum tight TIG welding of stainless steel (VNIITF) or EB-welding of copper parts (BINP), the facilities and procedures were adapted to meet the requirements of CERN. The ISTC prototype consisting of 2 full tanks (with 2 drift tubes per tank) and a coupling cell between the tanks was constructed during 2005-2006 and successfully tested at CERN in 2007 [3].

The above-mentioned successful prototype developments resulted in the final decision to accept the CCDTL for Linac4 and to launch the production of 7 CCDTL modules at BINP and VNIITF. The "series" production was again arranged within an ISTC framework and started in 2009 [4]. In 2013 the last module was delivered to CERN.

The ISTC projects, both for the prototype and for series production, were co-funded by CERN. Support structures for the CCDTL modules were produced at BINP under a direct contract with CERN.

Distribution of works among the participating institutions is summarized in Table 1.

Table 1: Work Distribution for the CCDTL Construction

	CERN	BINP	VNIITF	ISTC
Design	•	•	•	
Prototyping	•	•	•	
"Series" production		•	•	
Tests & measurements	•	•		
RF conditioning	•			
Management	•	•		•
Funding	•			•

DESIGN AND PRODUCTION TECHNOLOGY EVOLUTION

CERN developed and built a short but otherwise full size CCDTL prototype. So the design and production technology solutions were worked out in principle. But they could not be reproduced by BINP and VNIITF "as is" because i) every lab/workshop has somewhat specific capabilities and "preferences" ii) lessons learned on the prototype called for certain design modifications also. This applies to the "pre-series" ISTC prototype and series production of 7 CCDTL modules as well. The most important design and production technology changes are discussed below.

Tanks

Each tank consists of two halves joined together via a flange connection with a spring-loaded aluminium vacuum gasket, which also provides the RF contact. Various ports (for tuners, waveguide, RF pick-ups, vacuum pumps and gauges) are welded onto the half tanks. All inner stainless steel surfaces are 50 μ copper plated. Water cooling channels are machined in the stainless steel half tank walls.

The tanks of the CERN prototype were made from 304L stainless steel. Each half tank "body" was made of 2 large pieces EB-welded together – end wall disk and side wall cylinder, both thick enough for machining a nose cone on the disk and a flange at the end of the cylinder. For the ISTC prototype it was decided to use Russian 12X18H10T stainless steel and to make a half tank of three pieces – end wall disk, side wall cylinder and a ring for the flange. Dimensions of the blank parts were quite close to the final geometry thus saving on material cost. The 3 parts were TIG welded together. For the 7 CCDTL modules again a low carbon 304L stainless steel was used. Moreover, CERN took care about purchasing raw materials and thus making sure that the stringent CERN material specifications are met. Pre-shaped "buckets" were used for half tanks with an obvious advantage of having each half tank machined from a single block. The disadvantage of this approach is that largely oversized blanks had to be used and this noticeably increased the material cost.

Drift Tubes

The drift tubes carry approximately one half of the CCDTL heat load. So they are made from solid OFE copper with cooling channels inside each drift tube. The top part of the drift tube stem is made from stainless steel and is brazed to the bottom copper part.

All copper parts of the drift tubes of the CERN prototype were EB-welded together. Same joining technique was used at BINP for the drift tubes of the ISTC prototype. Although the result was successful, for the 7 CCDTL modules BINP workshop preferred that all drift tube parts were brazed in a few steps at different temperatures (800, 950 and 980 C) with different alloys in a vacuum furnace. Only the stems were EB-welded to the drift tube bodies because it was found on the mock-ups that at this particular connection vacuum brazing reveals some problems with uniform gap filling while EBW provides a uniform seam and preserves the relative positioning of the parts (non-perpendicularity of the stem and drift tube within ±4′, welding shrinkage < 0.1 mm).

Both for CERN and ISTC prototypes drift tubes were permanently fixed (TIG welded) to the half tanks. For the Linac4 CCDTL modules the design was changed in favour of dismountable drift tubes, which were connected to half tanks via low compression force spring-loaded aluminium vacuum gaskets which also provided the RF contact.

ALIGNMENT

As the quadrupole lenses are taken out of the drift tubes, put outside of the CCDTL tanks and positioned independently the requirement on the alignment of all beam holes (in the drift tubes and end wall nose cones) within a single module was ±0.3 mm. Three sources of errors contribute to this value: 1) drift tube misalignment in a half tank, 2) misalignment of 2 half tanks constituting a tank and 3) misalignment of 3 tanks of a module. These 3 sources of errors were treated in different ways.

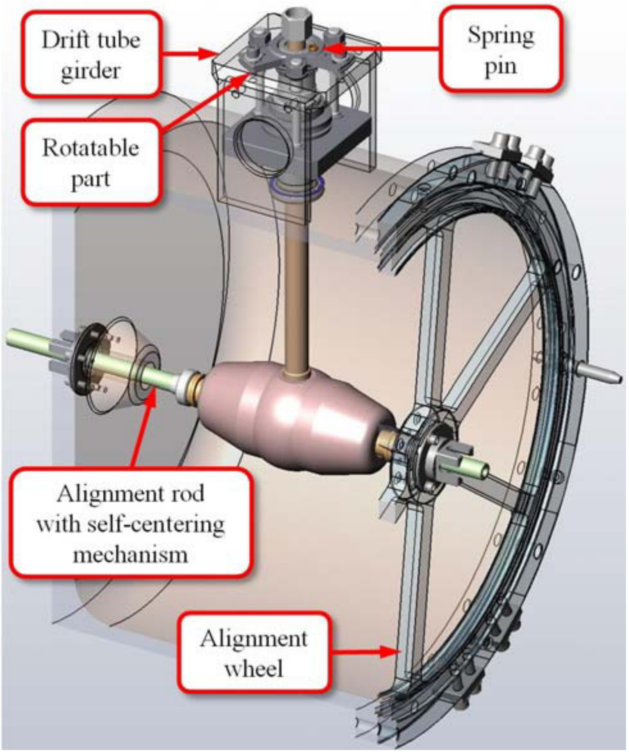

Figure 2: Drift tube alignment in a half tank.

Correct drift tube vertical position and inclination are ensured by machining and EBW tolerances. In the horizontal plane the drift tube can be rotated in the girder until it is aligned along the beam axis. Then the rotating part of the girder is fixed and the drift tube is pinned. For the transportation from BINP to CERN the drift tubes were dismantled from the half tanks. In order to measure the actual position of the drift tube during its installation a special set of mechanical tools was used (fig. 2): a long rod centred inside the drift tube goes all the way through the half tank and thus allows measuring directly its displacements from the centre of the end wall beam hole and from the centre of the precisely machined “wheel” mounted concentrically on the half tank flange. The measured misalignment of drift tube centres in the half tanks was always within ±0.15 mm. After installation of the drift tubes their actual positions were measured with a laser tracker (LT) relative to the external references for future survey measurements.

Relative alignment of two halves forming a tank is ensured by machining tolerances and assembling procedure: two half tanks are bolted together on a flat assembly table, both halves being forced to follow the side guiding rail.

The 3 assembled tanks are connected together in a module via 2 coupling cells on the final Linac4 support using same principle as for single tank assembly. Finally the middle tank is fixed to the support while the 2 end tanks are free to move longitudinally due to a thermal elongation (the transverse movement is limited by the guiding rail).

LT survey was done for a completely assembled module #2 at BINP (fig. 3) and for all modules at CERN. All modules are within the specifications, 4 of them are even within the ±0.15 mm range.

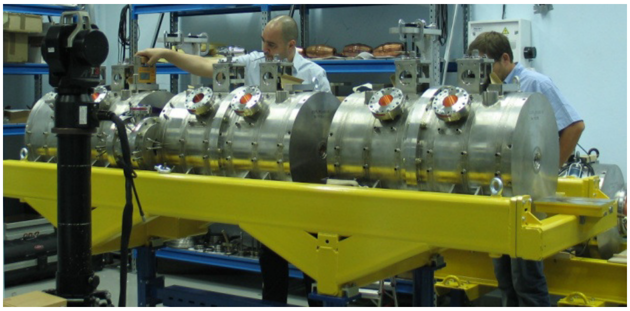

Figure 3: Module #2 survey measurements at BINP.

TUNING AND LOW LEVEL RF MESUREMENTS

Each cavity (accelerating and coupling) has 2 fixed piston tuners. For the Linac4 operation 1-2 accelerating cavity fixed tuner will be replaced by movable tuners.

Module tuning was done in two steps. First, using a few sets of aluminum dummy drift tubes, resonant frequencies of the accelerating cavities were measured. Based on the measurement results copper drift tube dimensions were corrected. This approach allowed to relax the manufacturing tolerances of the cavity inner geometry. After a complete module was assembled with copper drift tubes installed in the accelerating cavities, the frequency measurements were repeated for every single cavity (while detuning all other cavities) and the tuners were cut to bring the resonant frequency of each cavity to the design value under vacuum. When evacuated the CCDTL cavities within a module change their resonant frequencies non-equally. This was taken into account during the tuning and resulted in a somewhat distorted mode spectrum of air filled modules, which recovers under vacuum (see fig. 4).

The tuning was completed at BINP and no re-tuning at CERN was necessary. Bead pull measurements performed on each module after its final tuning gave a field flatness within ±0.6÷1.8% (difference of the total gap voltages across each of 3 tanks of a module).

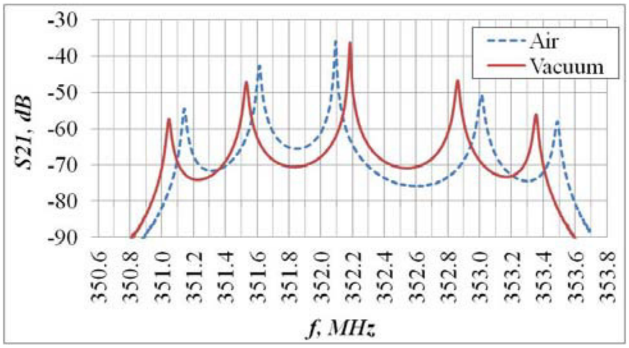

Figure 4: Mode spectra of tuned module #2.

Unloaded quality factors were measured for every single tank and are quite high: 42 500 (80% of 2D simulations with no stem) for the first tank of module #1 and 47 100 for the last tank of module #7 (86% of 2D simulations with no stem). This proves the good surface quality of the copper plating done at VNIITF.

VACUUM

2 types of vacuum gaskets are used in the CCDTL modules: 1) spring loaded Al gaskets at the connections of half tanks, coupling cell / half tank, inter tank beam pipe, drift tube / half tank, waveguide coupler and 2) Conflat® gaskets at the tuner, RF pick-up and vacuum pump ports.

Conflat gaskets showed no problems and neither did the small spring-loaded gaskets at the beam pipe and drift tube connections. Rectangular gaskets at the waveguide coupler flange also behaved quite well although only 3 connections have been assembled so far.

Large gaskets at the half tanks and coupling cell / half tank connections turned out to be very difficult. They worked well in both the CERN and the ISTC prototypes. Both prototypes had non-copper plated stainless steel sealing surfaces. For the CCDTL modules sealing surfaces of the flanges were initially copper plated. In some cases the plating was partially or completely grinded off later on by sand paper if either visible flaking was found on copper surface or the plating looked fine but repeated assemblies resulted in a leaking connection. The specified sealing surface roughness Ra = 1.2÷2.4 μ was obtained by guided hand grinding using a plastic wheel with either sand paper strips glued onto it or diamond abrasive bits imprinted into it. Gaskets with springs of different compression resistance were tried. Finally all the modules were leak tight with no clear indication of general solution of the problem. The lessons learned are: i) copper plated surfaces are more difficult than stainless steel ones, ii) the specified Ra of the sealing surfaces should be created during the lathe machining, iii) if the surfaces have lower Ra using gaskets with higher compression resistance might help.

CCDTL tanks were transported between Snezhinsk, Novosibirsk and Geneva sealed with rubber O-rings and filled with dry N_2. It turned out that the O-rings were contaminated with hydrocarbons and thus the initial RGA spectra were outside the specifications therefore leading to long RF conditioning times. Although it should be mentioned that neither cavities nor complete modules went through any vacuum baking.

HIGH POWER RF TESTS

Prior to high power tests all 7 modules, which came to CERN dismantled, were re-assembled and vacuum checked by joint BINP/CERN team. The survey was done by CERN metrology group. Modules #1, 2 and 3 were tested in a shielded bunker (fig. 5) in the CERN SM18 test area. The remaining 4 modules are to be conditioned *in situ* after their installation in the Linac4 tunnel.

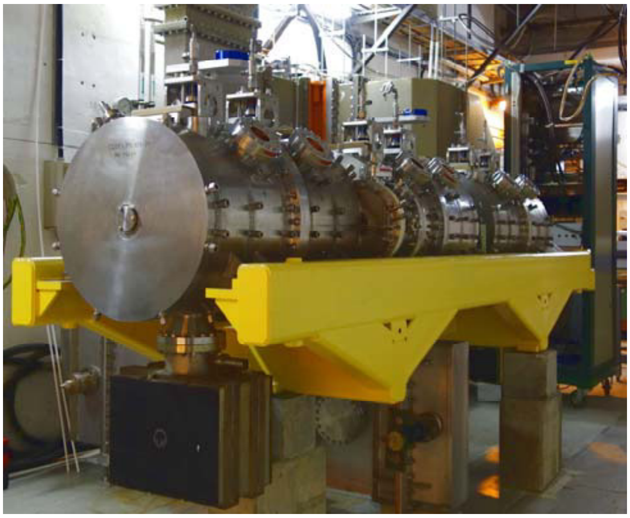

Figure 5: Module #2 in the high power test bunker.

All the Linac4 accelerating structures are designed to operate at up to 10% duty cycle foreseen for the future upgrades of CERN facilities. In the PSB injection mode Linac4 will operate with a beam current of 40 mA in 0.4 ms beam pulses at 1 Hz repetition rate. The RF pulse length is about 0.7 ms in order to provide time for the LLRF electronics for field stabilization (0.3 ms). The power, which needs to be delivered to the CCDTL cavities for maintaining operating field gradients, is slightly below 700 kW per module (with no beam).

The modules were tested above the Linac4 specifications: ≥ 700 kW (which corresponds to 3.6 MV gap voltage per tank and peak surface field E_{Spk} = 34 MV/m that is 1.85 Kilpatrick) at 0.16% duty cycle (0.8 ms pulse length, 2 Hz repetition rate) [5]. The test stand was undergoing an upgrade in parallel with the CCDTL conditioning. That caused many interruptions of the conditioning, sometimes for quite long times. Module #3 conditioning started in November 2012 and ended within 2 weeks at 720 kW in ~100 μs pulses limited by the RF source. The conditioning was resumed in January 2014 and lasted 200 effective hours (RF on time) finally reaching the test goal (fig. 6). Between these 2 runs the module was stored air filled.

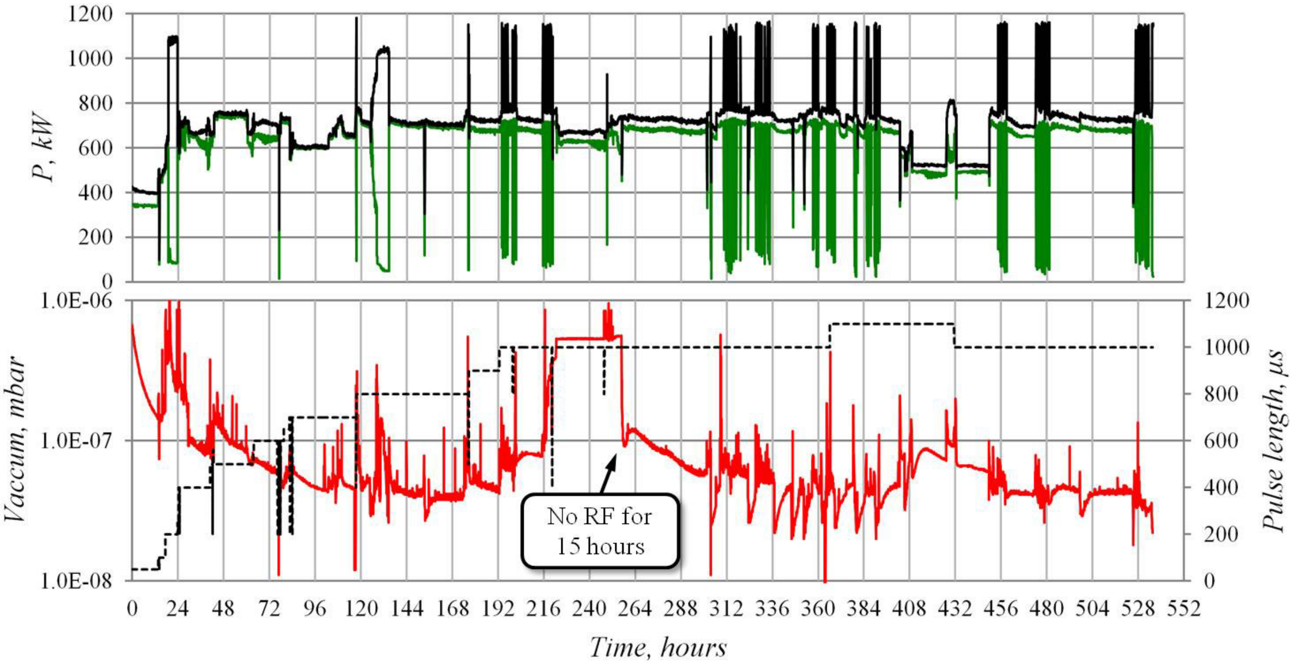

Figure 6: Module #3 conditioning history, second run (January 2014). Top plot – incident (spikes up) and module (spikes down) RF power, bottom plot – vacuum (solid) and RF pulse length (dashed).

Module #2 was tested in August – December 2013 also with several long downtimes. Effective conditioning time was 600 hours before it reached the test goal. But this time counts as well the long periods when the amplifier frequency feedback loop was not engaged and the module became detuned as its temperature changed. Keeping in mind that module #2 was conditioned with 2 ion pumps while module #3 had 3 turbo pumps, one may conclude that the modules performed quite similarly. The conditioning was done with the vacuum interlock set to $5{\cdot}10^{-6}$ mbar. Both multipactor activity and field emission breakdowns (spikes on the top plot in fig. 6) were observed. After conditioning the RGAs of modules #2 and #3 fulfilled the CERN vacuum specifications for Linac4.

Figure 7: First 3 CCDTL modules in the Linac4 tunnel.

STATUS AND PLANS

3 CCDTL modules have been conditioned at the CERN high power test stand above the nominal RF power levels. 4 modules have been lowered into the accelerator tunnel, installed in the linac and will soon be connected to waveguides (fig. 7). RF conditioning of the modules installed in the tunnel will take place in parallel with the beam commissioning of the DTL at 12 and 50 MeV. Commissioning with beam of the complete CCDTL section will take place in the first half of 2015.

ACKNOWLEDGMENT

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