DESIGN AND CONSTRUCTION OF THE LINAC4 ACCELERATING STRUCTURES

F. Gerigk, Y. Cuvet, A. Dallocchio, G. Favre, L. Gentini, J.M. Geisser, J.M. Giguet, S. Mathot M. Polini, S. Ramberger, B. Riffaud, C. Rossi, P. Ugena Tirado, R. Wegner, M. Vretenar, CERN, Geneva, Switzerland M. Naumenko, VNIITF, Snezhinsk, Russia
E. Kendjebulatov, Ya. Kryuchkov, A. Tribendis, BINP, Novosibirsk, Russia

Abstract

The Linac4 project at CERN is at an advanced state of construction. Prototypes and/or operational modules of the different types of accelerating structures (RFQ, buncher, DTL, CCDTL, and PIMS) have been built and are presently tested. This paper gives the status of the cavity production and reviews the RF and mechanical design of the various structure types. Furthermore the production experience and the first test results shall be presented.

INTRODUCTION

Linac4 [1] consists of four sections, which accelerate the beam up to its final energy of 160 MeV. The recently completed Radio Frequency Quadrupole (RFQ) [2] creates the 352.2 MHz bunch structure and raises the beam energy from 45 keV to 3 MeV. It is further accelerated by three Drift Tube Linac (DTL) tanks up to 50 MeV, followed by seven Cell-Coupled Drift Tube Linac (CCDTL) modules up to 103 MeV and 12 Pi-Mode Structures (PIMS) up to 160 MeV. Figure 1 shows a block diagram of Linac4 and the general parameters of each structure are summarized in Table 1.

Table 1: General Structure Parameters

Parameter	DTL	CCDTL	PIMS
f [MHz]	352.2	352.2	352.2
$E_{in/out}$ [MeV]	3-50.3	50.3-102.9	102.9-160
E_0T [MV/m]	2.65 - 2.95	3.6 - 2.7	3.74
ϕ_s [deg]	-35 $\rightarrow$ -24	-20	-20
ZT^2 [MΩ] †	44-52	40-33	24.6-26.2
av. Q_0 ‡	41000	42500	21600
P_{peak} [MW]	1.0/2.0/2.0	0.95-1.0	0.92-1.0
cav. length [m]	3.9/7.3/7.3	0.7-1.04	1.3-1.54
$N_{cavities}$	3	21	12
$N_{cav./module}$	n.a.	3	n.a.
$N_{gaps/cavity}$	39/42/30	3	7

† linac definition, operational value ‡ operational value

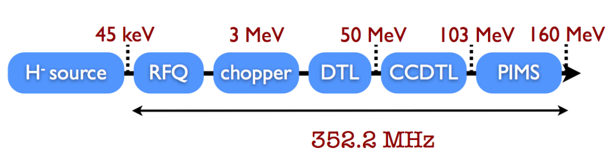

Figure 1: Linac4 block diagram.

The Linac4 accelerating structures are designed, constructed and tested under the supervision of the CERN RF group, supported by the CERN purchasing office, the vacuum group, the mechanical design office and by the CERN workshops for prototyping and qualification of construction procedures at the contractors. In general the prototyping and mechanical development was done at CERN and then exported for external construction. However, for certain critical construction processes – as outlined in the following – it was decided to "in-source" them.

All accelerating structures are designed for a maximum duty cycle of 10%, having in mind a future intensity upgrade of Linac4 as an injector to a high (average) power proton linac [3]. Linac4 itself will operate at a duty cycle of 0.04%, limited by the 1 Hz repetition rate of the PS Booster (PSB) into which the Linac4 beam is injected.

Due to LHC operational constraints the connection of Linac4 to the PSB is now foreseen to take place during the 2nd long LHC shutdown, which is expected for 2017/18 [1]. Commissioning with beam will take place in 2014/15 to leave sufficient time for improving reliability prior to operation in the LHC injection chain. The planning for the construction and commissioning of the accelerating structures has been adapted to this target date and is shown in Table 2.

Table 2: Key Dates for Linac4 RF Structures

date	status
10/12 - 11/13	RFQ, DTL, CCDTL assembly, tuning and testing
10/12 - 10/14	PIMS assembly, tuning and testing
09/13 - 04/14	DTL installation and commissioning
09/14	ready for 50 MeV protons
05/14 - 12/14	CCDTL commissioning
01/15 - 06/15	PIMS commissioning
07/15 - 12/15	160 MeV beam tests
01/16 - 11/16	reliability run
11/16	ready for 160 MeV H- operation
2017 - 2018	foreseen connection to PSB

RFQ

The RFQ is the only Linac4 accelerating structure which was completely constructed at CERN. Its design was elaborated in collaboration with CEA Saclay making use of experience with the IPHI RFQ [4]. In August 2012 the

Figure 2: Completed Linac4 RFQ in the 3 MeV test stand.

completed structure was delivered by the CERN workshops to the 3 MeV test stand, where presently the water stabilisation (precision $\pm 0.1^\circ$ C) is commissioned (see Fig. 2). Vacuum tightness was confirmed with a leak rate of 3×10^{-10} mbar l/s and the final RF tuning will be done in September/October. High-power tests will follow and the RFQ will see first beam before the end of the year. The RFQ construction history is given in Table 3 and more details can be found in [2].

Table 3: Timeline of RFQ: 5 Years from Concept to Construction

year	status
2007	1st conceptual design of the Linac4 RFQ
2008	beam dynamics, RF, and mechanical design ready
2008	order of 3D forged Cu
2009-12	construction at CERN
today	RFQ installed in Linac4 3 MeV test stand
end 2012	first beam in 3 MeV test stand

DTL

The Linac4 DTL consists of 3 tanks with permanent magnet quadrupoles (PMQ) and receives $\approx$ 5 MW of RF power from 3 klystrons. Preliminary design work started in 2004 and continued from 2006/7 at CERN with the development of a new drift tube alignment concept [5] tested on a proof-of-principle prototype. The mounting mechanism has since been filed as patent (see Table 4). Whereas in most DTLs the fine adjustment of the drift tubes is made after their installation, CERN chose a principle, which relies solely on the machining precision of tanks, girders and drift tubes. As a result no bellows are needed between stems and tanks, and vacuum leak tightness is achieved with a small metal gasket per stem. The principle was confirmed with a prototype built in collaboration with INFN Legnaro in 2008 [6]. The prototype allowed to confirm the drift tube alignment concept, to test post-coupler tuning procedures using an equivalent circuit model [7], and to make high power tests without and with PMQs in the first cell [8].

The series manufacturing takes place mostly in Spanish companies and was launched with the support of ESS-Bilbao. Heat treatment of the tanks to avoid deformations during final machining is done at CERN, as well as i) the Cu plating of the tanks, ii) the assembly of drift tubes by e-beam welding (EBW), and iii) the final assembly and tuning of the tanks. At present the drift tubes of the first tank segment are being installed after having successfully tested the segment for vacuum leaks (see Fig. 3).

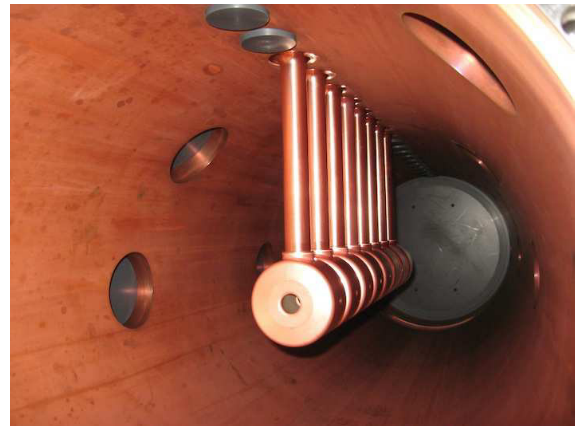

Figure 3: First segment of the first DTL tank.

DTL: Lessons Learned

Materials: The use of stainless steel for the tanks proved very beneficial, since it is relatively easy to strip the Cu-plating and to repeat the plating process. This became necessary when the first plating attempt revealed some insufficiently covered areas in the tuner ports. Stripping the copper from mild steel surfaces attacks these surfaces to a degree that requires complete re-machining of all inner surfaces, as happened with a Linac4 DTL prototype that was made of mild steel. Thermal conductivity of stainless steel proved sufficient for the 10% design duty cycle, and the material could be procured at acceptable cost.

Tolerances: Relying on machining tolerances for the alignment of the drift tubes allows for the use of highly reliable metal gaskets at the drift tubes, eases the assembly, and makes it basically impossible to accidentally misalign drift tubes after their installation. However, this principle requires tight tolerances (20 μm range) on 2 m long pieces (girders and tanks). During the market survey and tendering exercise a lot of companies had to be disqualified because they either did not have milling machines for the required tolerances or the temperature controlled working conditions or the necessary experience to circumvent some of the shortcomings of their equipment. This led to many company visits and some prototyping effort in industry, which could probably have been reduced if the companies had clearly understood the required tolerances before making a bid. The advice is to prescribe the minimum machining equipment in the technical specification based on a survey of a number of capable companies.

Spring loaded metal gaskets: This kind of gasket is used in all Linac4 accelerating structures to seal the vac-

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uum and to provide a good RF contact. Once they are installed correctly the experience so far is very good, but when using these gaskets one should consider a certain learning period until it is understood how to prepare the contact surfaces and until appropriate installation procedures have been established.

Table 4: Timeline of DTL: 9 Years for Development &Construction of Series (7 years for actual design)

year	status
2000	1st conceptual DTL design for new proton linac at CERN
2004	start of a collaboration with VNIIEF and ITEP in Russia for the design and construction of a Linac4 DTL tank
2005	2nd conceptual DTL design, decision to use PMQs
2006-7	start of mechanical design at CERN
2008	construction of DTL prototype in collaboration with INFN Legnaro
2009	successful high-power testing of the CERN/INFN prototype
2010	filing of patent on the ”mounting mechanism” to position drift tubes
2008-11	purchase of 30 tons of raw material (≈ 3000 pieces of stainless steel cylinders, Cu drift tubes/stems, Al girders, flanges, etc
2011	start of construction of tanks and drift tube parts in industry
2012	start of girder construction in industry
today	assembly of first tank segment at CERN
start 2013	first tank assembled
2013	assembly and tuning of tank 2,3, low-power testing of tank 1,2,3
2013-14	installation in Linac4 tunnel and high-power testing

CCDTL

Following the successful high-power tests [9] of a prototype built at CERN and a 2nd prototype built by the All-Russian Institute of Technical Physics (VNIITF) and the Budker Institute for Nuclear Physics (BINP) in Russia, it was decided to use a CCDTL for Linac4 for the intermediate energy range of 50 - 103 MeV. In 2009 a collaboration was launched with VNIITF (Snezhinsk) and BINP (Novosibirsk) for the design and construction of 7 CCDTL modules with 3 accelerating cavities and 2 coupling cells per module. The collaboration takes place within two contracts through the International Science and Technology Center (ISTC), which are jointly financed by CERN and the EU (via ISTC).

CERN provided a structure layout calculated with Superfish and BINP and VNIITF finalized the 3D electromagnetic and mechanical design of this section. In the beginning of 2010 46 tons of raw material were delivered to both institutes for the start of construction (see timeline in Table 5). The stainless steel for the tanks came in the form of pre-shaped half cells made by forging, which were then machined and Cu-plated at VNIITF. The needed technologies for i) cutting and welding of cooling channels, ii) surface finishing, iii) Cu plating were developed at VNIITF and then qualified via samples at CERN. BINP developed the technologies for i) brazing of drift tubes, ii) EBW of stems and drift tubes, and iii) alignment of drift tubes inside of the tank, which were also qualified by CERN experts during various technical visits. Finally in November 2011 a first completely assembled CCDTL module was successfully vacuum tested at BINP (see Fig. 4). In June 2012 another module was successfully aligned on its support, which is also constructed at BINP. The alignment goal was to have all beam pipe openings and drift tubes of a mounted module ($>$ 3 m long) within an envelope of ± 0.3 mm, which was achieved at the first attempt. The first two modules are presently on their way to CERN where they will be assembled by a BINP team and then high-power tested at the end of summer/beginning of autumn 2012.

Figure 4: CCDTL module during vacuum test at BINP, Novosibirsk.

CCDTL: Lessons Learned

Project set-up: The complete design and construction process was very efficiently managed by BINP. Having a single partner who takes care of a complete cavity construction removes a lot of problems, which arise when different industries or collaboration partners are involved. In case of the Linac4 DTL for instance CERN has to guarantee that all the interfaces between the different contributions from industry (e.g. tanks, giders, drift tubes) are correctly executed and actually fit together. This involves a very time-consuming quality control at all the different industrial partners, whereas in the case of the CCDTL all interface questions are automatically handled by the single partner. Here, CERN only intervened to make sure that all construction processes (Cu-plating, welding, brazing)

Table 5: Timeline of CCDTL: 12 years for Development & Construction of Series

year	status
1994	first CCDTL concept at LANL [10]
2000	Conceptual CCDTL design for new proton linac at CERN [11]
2001	13-cell cold model in aluminum
2004-5	design/construction of CERN prototype: 2 full size half tanks + coupling cell
2006	successful high-power testing of CERN prototype
2006	construction of prototype with 2 complete tanks + coupling cell in Russia (BINP/VNIITF)
2007	successful high-power testing of ISTC prototype at CERN
2009	start of ISTC contracts # 3888, # 3889 to construct 7 CCDTL modules for Linac4
1/2010	shipping of 46 tons of raw material (in ≈ 1500 pieces) to Russia
11/2011	successful vacuum and low-power tests of first complete module at BINP
today	delivery of first 2 modules to CERN
10/2012	assembly and high-power tests of first 2 modules
3/2013	delivery of last modules to CERN

are qualified according to CERN standards and the Russian partners solved autonomously all interface problems.

Raw materials: All raw materials were bought and delivered by CERN, which automatically ensured that they conform to CERN specifications. Special care was taken to have 3D forged stainless steel to reduce the risk of having inclusions or interior volumes, which might give problems during Cu-plating or on surfaces, where spring-loaded metal gasket are used. Nevertheless, in one instance we found a small void on a surface, which carries a gasket. Fortunately it is not located directly under the gasket and does not result in a leak.

Spring loaded metal gaskets: same comment as for DTL above.

Shipping: So far shipping and customs procedures between CERN and Russia went very smoothly due to the combined efforts of ISTC, BINP, and CERN logistics.

PIMS

The decision to use a 7-cell Pi-Mode Structure (PIMS) instead of a Side-Coupled Linac (SCL) was taken only in 2007 (see Table 6). The main arguments were that firstly a PIMS can be used at 352.2 MHz – the same frequency as the other RF structures – whereas a SCL would have required a 2nd RF system with 704.4 MHz for only a very short section of Linac4. Secondly the structure design is simpler and relatively easy to tune, reducing the overall manpower effort for the Linac4 accelerating structures and making the design more robust. The PIMS is constructed within a collaboration involving the National Centre for Nuclear Research (NCBJ) in Swierk/Poland, Forschungszentrum Jülich (FZJ) in Jülich/Germany and CERN. NCBJ is responsible for machining of all parts and the brazing of i) circular flanges to the tuner ports/RF pick-up ports and of ii) a rectangular flange to the central ring to connect the RF waveguide coupler. The ports for tuners and RF pick-ups are electron-beam welded to the cavity rings by FZJ and finally the discs and cylinders are transported to CERN. There the structure will be clamped and tuned via machining of the tuning islands (1st tuning step). In the last assembly step the rings and discs are electron-beam welded at CERN and then the fixed tuners (one per cell) are cut to their final length in the 2nd tuning step.

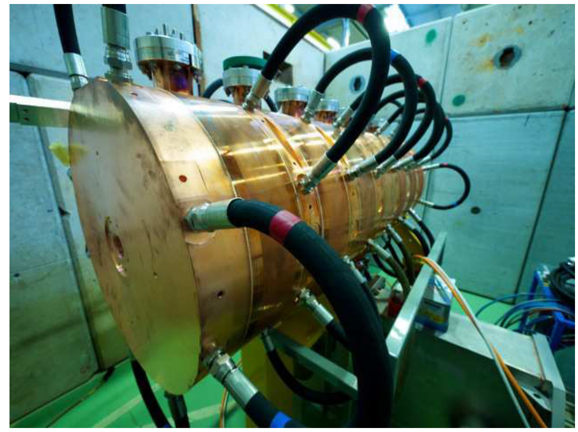

Figure 5: PIMS prototype in test bunker.

The mechanical design was made at CERN and tested with a prototype, which was built in the CERN workshops (see Fig. 5). After successful high-power tests [12] the design was exported to the collaboration partners to start the series construction. At present most production processes (machining, welding, brazing) have been qualified by CERN and roughly half of the discs and rings are in a rough-machined state. We expect to receive and assemble the parts for the first cavity shortly and the final pieces are foreseen to be delivered to CERN in spring 2014.

PIMS: Lessons Learned

Prototyping: An experience that was not only made with the PIMS but also with the other Linac4 structures is that one needs to plan for two prototypes: a first proof-of-principle "in-house" prototype plus a second one (or pre-series) with the contractor for the series. Having constructed a successful prototype does not necessarily mean that a contractor can use exactly the same processes, which have been developed for the "in-house" construction. They have to be adapted to the manufacturers equipment and capabilities and furthermore the machine operators have to be trained for the specific requirements of the project. The only way out is to develop from the beginning a prototype

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Table 6: Timeline of PIMS: 7 Years from Concept to Final Delivery

year	status
1977	5-cell pi-mode structure used in PEP storage ring (el.) at SLAC (353.2 MHz)
1989	5-cell PIMS used in LEP (el.) at CERN (352.2 MHz)
2007	Decision to use PIMS (352.2 MHz) instead of Side-coupled linac (704.4 MHz) between 100 and 160 MeV in Linac4 for proton acceleration
2007	tendering for 3D forged OFE copper
2007-8	construction and measurements on scaled aluminum cold model
2008	order of 26 tons of 3D forged OFE copper (last piece delivered: 11/2011)
2009-10	design and construction of full size 7-cell PIMS prototype at CERN
2010	successful high-power testing at CERN and decision to use prototype as PIMS-1 in Linac4
11/2010	collaboration start with NCBJ (National Centre for Nucl. Research, Poland) and FZJ (Forschungszentrum Jülich, Germany) for the construction of 12 PIMS cavities
1/2011	1st shipment of altogether 31 tons of raw material (in ≈1500 pieces)
today	most machining and welding procedures are qualified, half of the discs and rings are rough-machined
10/2012	delivery of first series cavity to CERN, assembly (EBW) and tuning at CERN
2013	start of high-power testing of PIMS cavities
3/2014	delivery of last PIMS cavity pieces to CERN

together with the contractor for the series, which is forbidden by the CERN tendering rules.

Tolerances: After having developed a mechanical design (for the PIMS it took rougly one year), one should plan for sufficient time to work on relaxing the tolerances and simplifying the assembly procedures. In the case of the PIMS we immediately went into prototyping when the design was ready. Spending some extra months of design effort in reducing the tolerances before going into prototyping can drastically reduce the technological development and qualification period and also has the potential to reduce the manufacturing cost.

Raw material: For the construction of the PIMS we used 3D forged OFE copper, which is i) difficult to find on the market in the required size and quantity, ii) expensive, iii) and which requires long delivery times (3.5 years from ordering until receiving the last pieces at CERN). The advantages are: i) significantly improved results (less cavity formation in the welds, less deformation) for EBW [13, 14], which conform to ISO 13919-2 level B, ii) less deformation during machining, which is especially important for large pieces, iii) guaranteed yield strength of $R_p > 200$ MPa, which in case of the PIMS is needed to avoid plastic deformation through heating during high duty cycle operation. For Linac4 the material was ordered in time but the price did exceed the originally allocated budget. In general one should carefully assess the risk, which is taken with cheaper material, the requirements for the specific cavities (e.g. in terms of yield strength), and the cost and delivery delay for 3D forging.

OUTLOOK

After long years of design work, material procurement, setting up of contracts and collaborations, qualification of construction processes we are now receiving the first cavities and parts of the series. It is a pleasure to see the equipment coming in and everyone is looking forward to the assembly and testing period.

REFERENCES

[1] M. Vretenar et al., “Progress in the construction of Linac4 at CERN”, LINAC12, Tel Aviv.

[2] C. Rossi et al., “Assembly and RF tuning of the Linac4 RFQ at CERN”, LINAC12, Tel Aviv.

[3] F. Gerigk et al.,“Layout and machine optimisation for the SPL at CERN”

[4] P-Y. Beauvais, “Recent evolutions in the design of the French High Intensity Proton Injector (IPHI)”, EPAC04, Lucerne.

[5] S. Ramberger, et al., “Drift tube linac design and prototyping for the CERN Linac4”, LINAC08, Victoria.

[6] S. Ramberger, et al., “Production design of the drift tube linac for the CERN Linac4”, LINAC10, Tsukuba.

[7] F. Grespan, G. De Michele, S. Ramberger, M. Vretenar, “An equivalent circuit for post coupler stabilization in a drift tube linac”, LINAC10, Tsukuba.

[8] G. De Michele, S. Ramberger, J.M. Giguet, J. Marques-Balula, “The Linac4 DTL Prototype: Low and High Power Measurements”, CERN-ATS-Note-2012-003 TECH.

[9] M. Pasini, M. Vretenar, R. Wegner, “CCDTL prototypes: test results”, CARE-Report-2007-036-HIPPI.

[10] J.H. Billen, F.L. Krawczyk, R.L. Wood, L.M. Young, “A new RF structure for Intermediate Velocity Particles”, LINAC94, Tsukuba.

[11] F. Gerigk, M. Vretenar, “Design of the 120 MeV Drift Tube Linac for the SPL”, CERN-Nufact-Note 37.

[12] F. Gerigk, J.M. Giguet, P. Ugena Tirado, R. Wegner, “High power test for the first PIMS cavity for Linac4”, IPAC11, San Sebastian.

[13] G. Favre et al., “Manufacturing the LINAC4 PI-Mode Structure at CERN”, IPAC11, San Sebastian.

[14] F. Gerigk et al., “The hot prototype of the PI-Mode Structure for Linac4”, LINAC10, Tsukuba.

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