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Development and testing of a double length pets for the CLIC experimental area

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ABSTRACT

CLIC (compact linear collider) is a future $e+e^-$ collider based on normal-conducting technology, currently under study at CERN. Its design is based on a novel two-beam acceleration scheme. The main beam gets RF power extracted from a drive beam through power extraction and transfer structures (PETS). The technical feasibility of CLIC is currently being proved by its Third Test Facility (CTF3) which includes the CLIC experimental area (CLEX). Two Double Length CLIC PETS will be installed in CLEX to validate their performance with beam. This paper is focused on the engineering design, fabrication and validation of this PETS first prototype. The design consists of eight identical bars, separated by radial slots in which damping material is located to absorb transverse wakefields, and two compact couplers placed at both ends of the bars to extract the generated power. The PETS bars are housed inside a vacuum tank designed to make the PETS as compact as possible. Several joint techniques such as vacuum brazing, electron beam and arc welding were used to complete the assembly. Finally, several tests such as dimensional control and leak testing were carried out to validate design and fabrication methods. In addition, RF measurements at low power were made to study frequency tuning.

1. Introduction

Up to now, the most important $e+e^-$ collider has been the large electron–positron collider (LEP), built at CERN and in operation up to 2000. After that, the next generation of $e+e^-$ machines will be linear colliders, where CLIC and the International Linear Collider (ILC) are the most promising candidates.

CLIC will potentially achieve a collision energy up to 3 TeV, in the X-band frequency (11.994 MHz) and with a loaded accelerating gradient of 100 MV m^{-1}. In order to reach that collision energy a two beam scheme has been designed, where the required RF power is extracted from a drive beam parallel to the main beam (a traditional solution using klystrons would not be feasible in terms of cost and maintenance for this kind of collider) [1]. The drive beam operates at a current of 100 A and is decelerated to act as source of RF power to the main beam, operating at 1 A [2]. In this two beam scheme, the PETS are the structures for extracting the power from the drive beam and carrying it to the main beam. In operation, particles of the drive beam pass through the corrugated structure of the PETS. The beam kinetic energy is transformed into electromagnetic energy (RF pulse of 132 MW or 176.5 ns [3]), that is collected and guided from each PETS to two accelerating structures of the main beam which will be feed with a 61.3 MW peak input power.

The technical feasibility of CLIC is currently being proved at CTF3. It comprises several test lines, including CLEX as the line where the two-beam acceleration design will be studied in a relativistic environment, with a careful consideration to alignment, stabilization, cooling, vacuum systems and phase stability [4]. The CLIC study is focused on the design of compact modules forming two linacs for the beam collision at two energies of 0.5 TeV and 3 TeV. The PETS behavior is one of the most important issues in it [5].

The limited current of 30 A in the drive beam of CTF3 does not allow operating the two-beam module at parameters foreseen for CLIC. With the aim of increasing the PETS output power, the active length of the structure has to be adapted and increased in length to compensate the lower current available (lower than CLIC drive beam nominal current). The Double Length CLIC PETS was conceived by CERN to generate the needed RF output power to feed

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with 65 MW the accelerating structures with the available current in the CLIC module. Moreover, an additional input coupler was added to Double Length PETS with respect to CLIC PETS design; it allows the RF power distribution and recirculation along the structure [6,7]. It is scheduled that two Double Length CLIC PETS are installed in the CLIC module of CLEX replacing the CLIC PETS tested previously. Several tests with increasing input currents will be carried out with the final goal of feeding two accelerating structures per PETS with an input power of 65 MW, each.

This paper describes the engineering design, fabrication, assembly and RF low power testing of the first prototype of the Double Length CLIC PETS. The conceptual and compact design is based on a previous 11.4 GHz compact PETS (designed for testing at SLAC with an extra RF input power). The work has been carried out at CIEMAT with the close collaboration of the CLIC team from CERN.

2. Engineering design

As mentioned in Section 1, the Double Length CLIC PETS is based on a previous one with a compact design as its main characteristic. However, several design modifications have been included in order to make prototype fabrication easier while fulfilling the tight tolerances requirement. Following the compact design, the PETS includes two compact couplers and a vacuum tank surrounding the copper rods. Fig. 1 shows an artistic view of the prototype.

The PETS body is composed of eight triangular prism shaped rods, in agreement with the RF design developed previously by CERN. The rods are made of high purity oxygen free electronic grade copper (Cu OFE) and have 80 regular cells. In the slots between the rods fixed RF ceramic absorbers of silicon carbide (SiC) are located, with the purpose of damping transverse high-order modes generated by the interaction of the beam with the structure. The ceramic pieces are fixed by aluminum supports. The copper rods are joined together by electron beam welding (EBW).

At both ends of the rods, two compact couplers are placed to allow the power recirculation through the PETS. Each compact coupler is formed of a set of pieces made of Cu OFE and austenitic stainless steel 1.4429 grade, joined by vacuum brazing. The couplers have several components and functions. The power extraction is made by a double choke that reflects the power with a bandwidth broader than a single one, and two output waveguides WR90 type, that are combined in one, with a T-junction. The couplers also have RF and vacuum flanges. The RF flanges are custom made and the vacuum ones are commercial Conflat (CF) and Quick Conflat (QCF) types, in agreement with the integration requirements for the CLIC module.

The cooling circuit is machined into the body of the couplers and has a cooling capacity of about 100 W coming from the RF currents and beam losses. The integrated cooling circuit into the body of the compact coupler is one of the modifications made in the Double Length CLIC PETS with respect to other compact PETS previously manufactured. It makes easier the brazing assembly, since no additional brazing steps have to be made for joining the cooling circuit. Additionally, the compact couplers will provide the external reference for aligning and fastening the PETS into the CLIC module.

Finally, the joint between couplers and bars is made only by mechanical contact, supported by the outer vacuum tank. The length of the tank has been adjusted for guaranteeing the electrical contact. The tank is joined by arc welding (TIG) to an additional stainless steel ring brazed to the coupler and includes two vacuum ports to be connected to the vacuum line. The material selection of the vacuum tank is the second main change with respect other compact PETS. The tank is made of stainless steel instead of copper as was done in previous designs [6]. This permits us to use TIG arc welding instead of EBW to assemble the tank, thereby simplifying the manufacturing process.

3. Fabrication and assembly

3.1. Copper rods

One of the most challenging steps in the fabrication of the prototype is the high precision machining of the PETS rods, due to

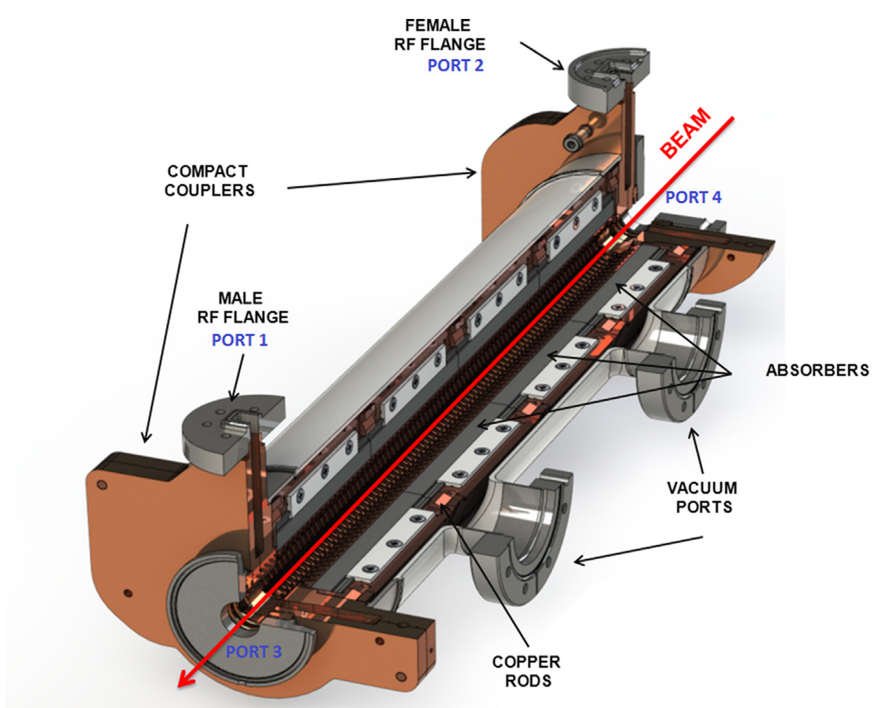

Fig. 1. General view of the Double Length CLIC PETS.

the requested tight tolerances of these parts, ±15 μm in shape and surface roughness (Ra) lower than 0.4 μm. To achieve these tolerances, high speed milling with diamond tools and two intermediate stress relieve heat treatments (180 °C during 1 h) were carried out. The shape of the rods was checked with a 3-D measurement machine, obtaining that all cells were within tolerances. As example, Fig. 2 illustrates the measurement diagram obtained on one section of the bars, showing that the whole measured profile is in agreement with the required tolerance.

The SiC plates were supplied by the company ESK Ceramics and produced by sintering (porosity less than 2%). They were selected after a market survey of SiC supplier companies performed by CIEMAT [8] and a test of the provided samples at CERN [9]. In order to guarantee the complete degasification of the plates, they were baked at 1000 °C in a vacuum environment (less than 10^{-3} Pa) for 1 h. Fig. 3 shows the eight copper rods, with the SiC plates positioned along the prism sides.

After mechanical assembling and checking the proper position of the bars in the assembled structure, they were joined by EBW. The flatness and geometric accuracy of the reference surfaces for the assembly (the contact areas between bars) was below 15 μm. After welding, the structure was also measured and checked, obtaining no significant differences with the measurements taken before welding.

3.2. Compact couplers

Similarly to the bars, the production of the compact couplers parts was made by high precision machining although in this case using monocrystal diamond tools. Two intermediate stress relieve heat treatments were also made. In these parts, the required accuracy is summarized as follows: ±10 μm in the beam hole, ±15 μm in the choke and ±20 μm in the waveguide area, surface roughness Ra of 0.3 μm on the RF surfaces and 0.8 μm on the brazing surfaces. The shape of the parts was also checked with a 3-D measurement machine, obtaining that all of them were within tolerances.

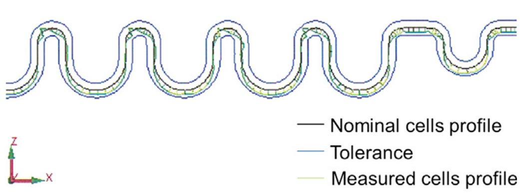

Fig. 2. Dimensional control of the end section of the corrugated structure of one of the bars, measuring five RF cells, carried out using a 3D measuring machine.

Fig. 3. PETS assembly, copper rods with the SiC ceramics positioned along the prism sides.

As discussed in the previous section, the assembly of the compact couplers was carried out by vacuum brazing, being this step one of the most critical during PETS fabrication. Vacuum brazing is widely used to join components in the particle accelerator field due to the minimum joint contamination, minimum pieces distortion and low thermal stress [10].

Brazing of the compact couplers requires copper/copper and copper/stainless steel joints, and due to the complex joint of the set, it was carried out in two brazing steps. Joint surfaces, accuracy, filler diameter and positioning were designed to braze horizontally in the first step. The RF flange was vertically brazed in the second step. In order to minimize the possible misalignment after brazing, the insertion of the RF flange in the compact coupler was machined after first cycle. Fig. 4 shows the joint design of the male compact coupler.

In both brazing steps Silver/Copper/Palladium based alloys were used. In the first step Ag/Cu/10Pd type alloy with a brazing temperature of 930 °C was selected whereas Ag/Cu/5Pd with brazing temperature of 830 °C was chosen for the second step. No Ni-plating on the stainless steel brazing surfaces was necessary. The high vacuum reached during cycles (less than 10^{-3} Pa) was sufficient to remove the chromia scale from the stainless steel surface at the brazing temperature.

Both compact couplers were successfully brazed, no filler overflow was detected into the RF volumes although the filler could wet the whole brazing surface, ensuring the electric contact through the whole volume. Several helium leak tests were carried out in either RF volumes and cooling circuit, obtaining in both cases leak rates less than 10^{-13} Pa m^3 s^{-1}, below the ultra-high vacuum critical level of 10^{-10} Pa m^3 s^{-1} [11].

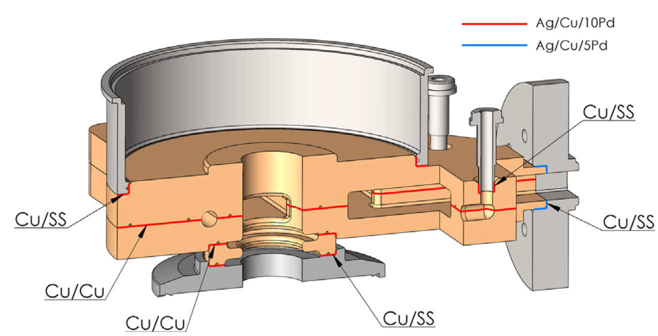

Fig. 4. Joint design of the male compact coupler. The brazed surfaces in the first step are indicated in red and those of the second step in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

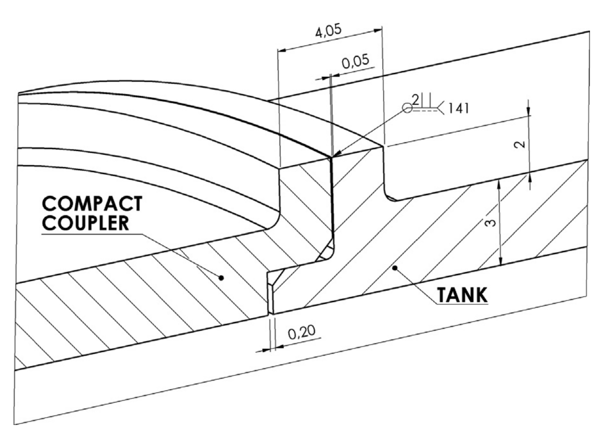

Fig. 5. Joint design of the vacuum tank/compact couplers.

3.3. Vacuum tank and final assembly

As discussed in Section 2, the PETS is closed and supported by a vacuum tank welded to the compact couplers. The tank was made of 1.4404 grade stainless steel and machined by turning. The Ra achieved was 1.8 μm, compatible with ultra-high vacuum requirements. In addition, the connection towards vacuum ports was made by pulling out the tank, in order to make getting ultra-high vacuum conditions during operation easier.

Before welding and with the aim of ensuring the proper alignment between compact couplers and the set of assembled rods, the contact area of the compact couplers was re-machined and adjusted, being the assembly tolerance between couplers and bars of 20 μm. The rest of joint tolerance requirements are summarized as follows: couplers must be aligned better than 0.05° in radial direction and with respect to vacuum ports and they must be perpendicular to the RF flanges of the couplers (angle tolerance 0.2°). These requirements were achieved by supporting the PETS structure with an internal bar screwed firmly at both sides, rested on a granite table and using an electronic height gauge.

Final assembly was made by TIG arc welding; the joint was designed to guarantee mechanical and electrical contact between the bars and the compact couplers (Fig. 5). That requires an edge joint design (square-lip) to reduce distortion in the structure. Between the lips, a 0.05 mm gap ensures the bars/couplers mechanical contact during the pre-assembly previous to the welding. The 0.2 mm gap guarantees a maximum contraction during welding of 0.4 mm. An initial manual spot welding was performed on both joints. After it, a verification of the position was performed. Finally, short weld beads alternating between both joints were performed until the whole joints were welded. After welding, helium leak test was carried out obtaining a leak rate less than 10^{-13} Pa m^3 s^{-1}.

Table 1
Ports selected for the RF low power test and S parameters measured on both compact couplers.

Port	1: RF male	2: RF female	3: Beam pipe male	4: Beam pipe female
S parameter	S_{11} (dB) −37.29	S_{21} (dB) −0.29	S_{31} (dB) −41.34	S_{41} (dB) −42.56
	S_{12} (dB) −0.30	S_{22} (dB) −39.28	S_{32} (dB) −41.14	S_{42} (dB) −42.30

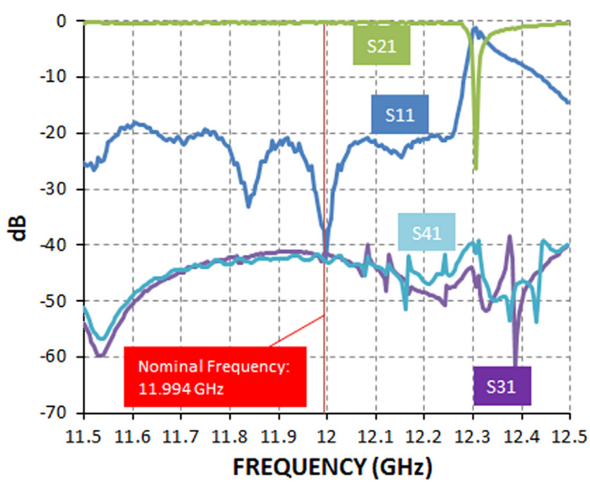

Fig. 6. Male compact coupler S-parameters results measured in a bandwidth of 1 GHz.

4. RF measurements

RF low power tests were carried out at CIEMAT in order to verify the performance of the PETS structure. All the tests presented are performed by feeding some RF power into one of the ports and measuring its effect at the same or other port, or measuring the fields with probes at certain points in the structure. When the PETS are assembled on the beam line they will work in a different way (RF power will be extracted from the beam inside the PETS, not injected into one of the ports). However there are similarities between both modes of work that allow us to extract some conclusions from the measurements:

- In general, the S parameters can be compared with the expected ones as a method of checking the internal geometry.
- The performance of the couplers, as elements that deviate all the RF power at the right frequency to the ports and avoid losing part of it through the beam pass hole, and the synchronous frequency (the frequency at which the RF wave velocity

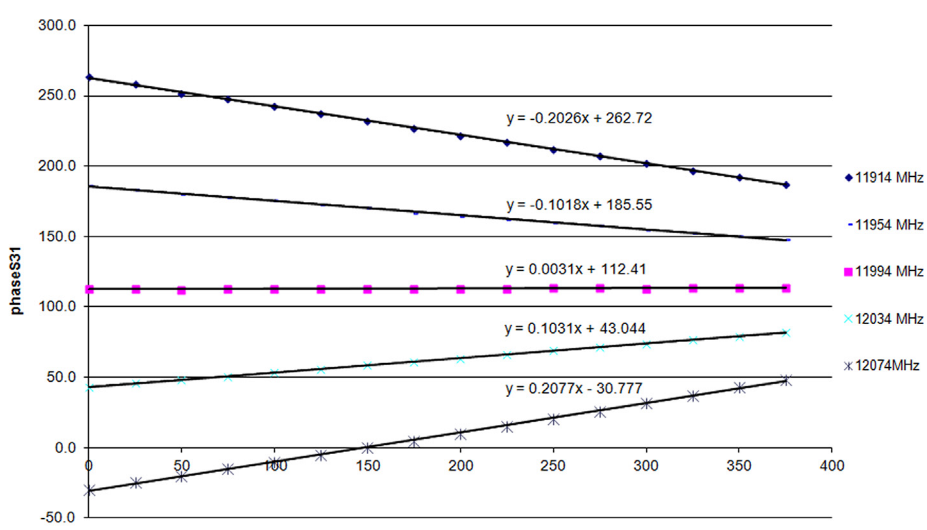

Fig. 7. Phase measured with the antenna method at different positions and frequencies.

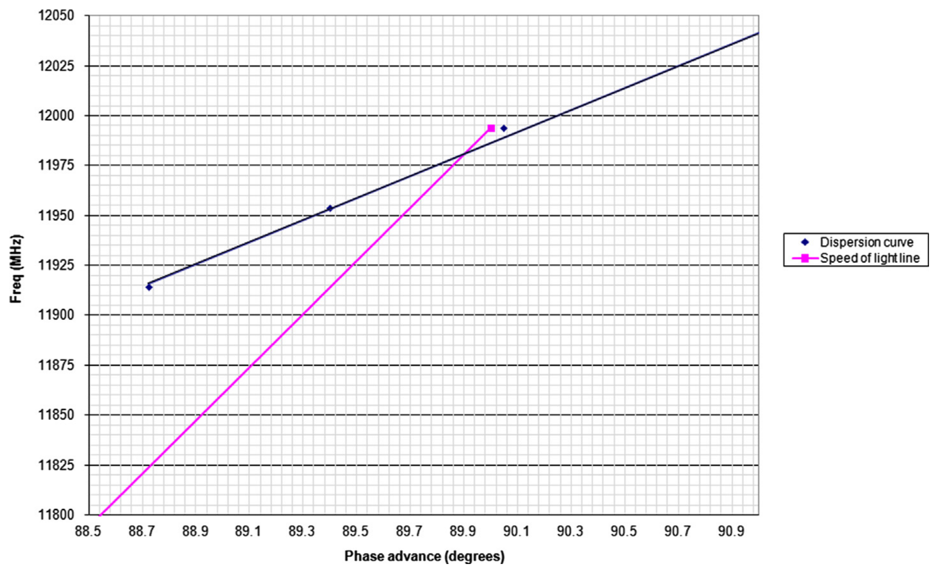

Fig. 8. Dispersion curve obtained for the Double Length CLIC PETS before final assembly using the antenna transmission method.

equals the speed of light) can be measured by this method because they are characteristics of the behavior of the RF wave at a certain frequency at certain areas of the structure, independently of its source (extracted from a beam or fed into a port).

4.1. *Compact couplers measurements*

The S parameters of the couplers (without bars) were measured in first place. For the measurement, both couplers were assembled with a copper ring as a spacer between them to allow the RF wave to travel from one coupler to the other. To provide a good electrical contact between the couplers and the copper ring a sufficient contact pressure was applied between them. The measurements were performed using a vector network analyzer (VNA). Fig. 1 shows the ports denomination used in the results.

Table 1 shows the S parameters at the nominal frequency (11.994 GHz). S_{12} and S_{21} are -0.30 dB and -0.29 dB, respectively; that means that power transmission from RF port to beam pipe port in both compact couplers is produced with no significant power losses and leads to conclude that they work properly at CLIC nominal frequency.

In addition couplers were checked by measuring the S parameters in a bandwidth frequency range of 1 GHz around the nominal frequency. As an example, Fig. 6 illustrates the results obtained for the male flange port (number 1). The graphs show a good transmission between RF ports (1 and 2), with a reflection coefficient below -30 dB in a bandwidth of 200 MHz around the nominal frequency, and a very low loss of power (below -40 dB) through the beam ports (3 and 4). These excellent results are in accordance with the expected behavior: an almost complete transmission of power between the RF ports (1 and 2), with a negligible amount of power being reflected or transmitted to the beam ports (3 and 4).

4.2. *Antenna transmission method. PETS measurements*

This method of measurement consists in the introduction of a hook shaped antenna at certain points inside the volume of the cavity through the open spaces between the PETS bars. An inductive coupling at the loop surface will produce a signal in the cable of the antenna proportional to the magnetic field at that point. The antenna was designed to get coupling with a low perturbation of the fields inside the structure (S_{15} from -50 dB to -40 dB, numbering the antenna as port No. 5). A high precision sliding rule (accuracy below 20 μm) was used to guide the antenna and measure its position. The measurements with this method were done after the PETS bars were welded and with the couplers assembled to them.

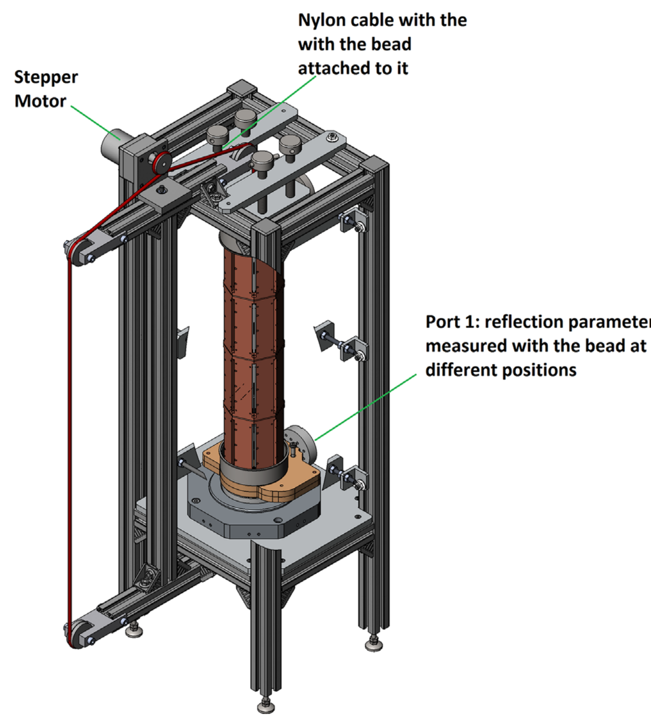

Fig. 9. Bead pull test bench and device for the control of the bead movement.

The objective of this measurement is to find the synchronous frequency of the structure, which is the frequency at which the phase velocity of the RF wave equals the speed of light, which, in the working mode of the PETS structure, is equivalent to the frequency at which the phase of the wave is increased by 90° exactly in one period of the bars structure (for example, between the peak of two consecutive teeth). Fig. 7 shows the phase measurements in this test. The data are measured in intervals of

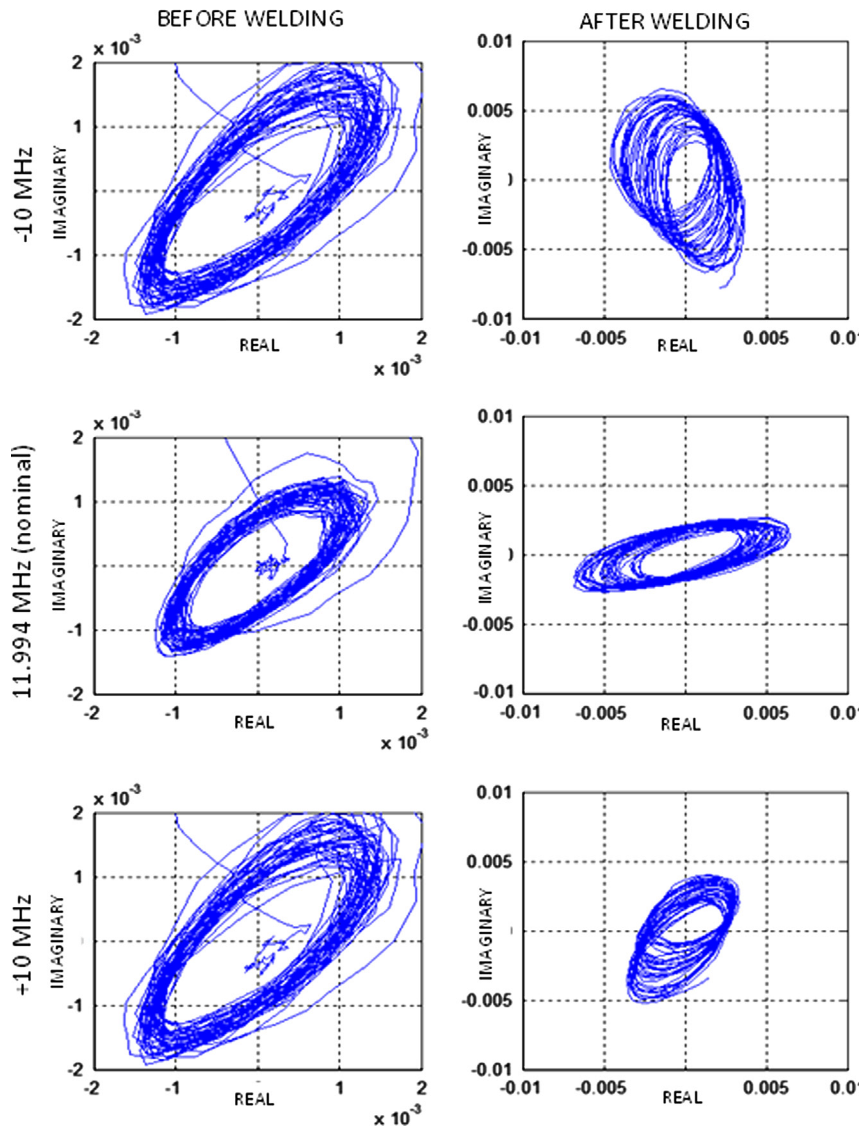

Fig. 10. Perturbation in S_{11} parameter (S_{11p}–S_{11a}) in the complex plane at different frequencies both before and after PETS final assembly.

exactly 4 teeth of the structure, which means that, at the synchronous frequency, the phase should not change between points. The slope of each of the adjusted lines in Fig. 7 is, therefore, a measurement of the detuning of the structure at each frequency. For finding the synchronous frequency, the dispersion line (phase advance per two consecutive teeth) is plotted versus the speed of light line (Fig. 8). The crossing point between both lines gives the synchronous frequency, which is 11.993 GHz. PETS detuning was only −1 MHz (about 0.0083% frequency error), which produces a power production loss of about 0.005% [15], which is an excellent behavior, well above the expectations. Since no significant frequency detuning was observed, it can be concluded that tight linear and geometrical tolerances required during machining, EBW and brazing steps were suitable for assuring that PETS works at proper frequency.

4.3. Bead pull method. PETS measurements

Once the PETS has been assembled and placed into the vacuum tank, it is no longer possible to perform the RF measurement with the antenna, since RF volumes are not accessible. The only access to PETS structure is through beam hole ports. So, bead pull test is a useful alternative for measuring fields. It consists in placing a perturbation object (bead) at a certain point in the RF structure and measuring its effect on the S_{11} parameter. The bead can be metallic or dielectric, as long as it presents different properties (electric permittivity, magnetic permeability and/or electric conductivity) from those of the vacuum. For Double Length CLIC PETS measurements a metallic disc of 4 mm diameter and 0.5 mm height was used. The variation of the S_{11} parameter (with and without the perturbation object) is directly related to the magnitude of the field at that point in the absence of perturbation, according to the perturbation theory. In the case of perturbation objects, S_{11} variation is related to electric field by the following relationship [12,13]:

$$2P_i(S_{11p} - S_{11a}) = -j\omega k E_a^2, \quad (1)$$

where P_i is the incident power at the port, S_{11a} is the S_{11} parameter measured without the presence of the perturbation object, S_{11p} is the S_{11} parameter measured with the perturbation object inside the cavity, ω is the frequency, k is a constant depending on the volume, shape and material of the perturbation object, and E_a is the electric field without perturbation at the point where the perturbation object is located.

Bead pull method allows taking measurements of both field amplitude and phase. This allows measuring the synchronous frequency of the cavities. The structure period of the PETS is one quarter of the wave length at the synchronous frequency [14], which means that fields at that frequency will have a 90° phase advance per period. As a consequence, the perturbation of the S_{11} parameter will suffer a 180° phase advance when the bead moves along one period of the structure due to the quadratic relationship in (1). On the other side, the modulus of S_{11} perturbation will have a periodic variation with the same period that the structure has.

Therefore, the perturbation of the S_{11} parameter describes over the complex plane an ellipse shaped figure at synchronous frequency. At other frequencies, the figure would be similar, but with a slight displacement of the ellipse axis direction for each turn, producing a more "noisy" figure. This method serves to check the synchronous frequency of the structure.

The bead pull test bench used for measuring the PETS is shown in Fig. 9. It consists of a mechanical device in which a stepper motor moves a nylon wire to which a bead is fixed. The wire slides through one calibrated piece assembled at each end of the PETS structure that determines the position and the right alignment of the wire. The bead's trajectory needs to have an off-center distance from the axis of the structure (the electric field at the center is not high enough to get a good sensitivity with this test [15]). Different sets of alignment pieces were used (off-center of 7.5 mm, 8.5 mm, 9.5 mm, 10.0 mm, 10.5 mm and 11.0 mm). After testing the best result was obtained using the piece with an off-center of 10 mm.

The lower RF port of the structure is connected to a VNA for the measurement of the S_{11} parameter at different frequencies around the nominal one. The upper RF port is connected to a 50 Ω load. A computer controlled procedure moves the bead pull at small steps and makes measurements of the S_{11} parameter at each one.

Fig. 10 shows the results of the bead pull measurements, both before and after final assembly with the vacuum tank. Results show that, at the nominal frequency (11.994 GHz), the relative rotation between the ellipses axis is smaller than that at 10 MHz higher or lower, both before and after the vacuum tank welding. From this it can be concluded that the tank welding process has not affected the synchronous frequency. This can be stated with an accuracy in the order of 10 MHz, which is good enough as a 10 MHz detuning would produce a loss of power production of approximately 0.5% [15], which would still be good.

It can be concluded that no significant frequency detuning is observed neither before nor after final assembly. Therefore welding process of the vacuum tank has not affected the structure and PETS's synchronous frequency is very close to nominal one.

5. Conclusions

The first prototype of Double Length CLIC PETS for the CLEX module has been successfully manufactured and low power tested. Required mechanical tolerances on PETS parts were achieved by means of precision machining using diamond tools and stress relieve heat treatments. Precision assembly was made by vacuum brazing, EBW and TIG welding, obtaining no significant deformation of the structure after assembling.

RF low power tests were carried out for the characterization of the structure. A real detuning value of −1 MHz was measured by means of antenna method. Additionally, a bead pull method was developed for the characterization of the welded structure. The results obtained with that are compatible with the rest of the low power tests performed, obtaining a no significant detuning of the structure.

RF results validate therefore every fabrication processes carried out and confirm that obtained tolerances in the machining and assembling steps are suitable to keep a synchronous frequency very close to nominal one.

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