ISTITUTO NAZIONALE DI FISICA NUCLEARE

LNF (Laboratori Nazionali di Frascati)

INFN-19-11/LNF
28 Giugno 2019

A Ka-band linearizer TW accelerating structure for the Compact Light XLS project

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Abstract

Ultra-high gradient accelerating structures are in strong demand for the next generation of compact light sources. In the framework of the Compact Light XLS project, we have designed a higher harmonic RF accelerating structure in order to linearize the longitudinal space phase. We here present the design of a compact TW accelerating structure operating on the third harmonic with respect to the linac frequency (11.994 GHz) with a (100-125) MV/m accelerating gradient. Numerical electromagnetic simulations were carried out by using the numerical codes HFSS and CST.

Published by
Laboratori Nazionali di Frascati

1 Introduction

The next generation of linear accelerators require unprecedented accelerating gradients for high energy physics and particle physics experiments. Technological advancements are strongly required to fulfill demands of compact linear accelerators for particle physics colliders, new accelerators devices from the compact or portable devices for radiotherapy to mobile cargo inspections and security, biology, energy and environmental applications and so on. The advantages of using high frequency accelerating structures are well known: smaller size, higher shunt impedance, higher breakdown threshold level and short filling time.

Ultimately large electric gradients are also required for a variety of new applications, notably including the extreme high brightness electron sources for the FELs, RF photo-injector etc. Technological activities to design, manufacture and test new accelerating devices using different materials and methods are under way all over the world. To develop components with performances well beyond the existing device, is fundamental to use significantly improved manufacture technologies and innovative designs. The Laboratori Nazionali di Frascati (INFN-LNF) is involved in the modeling, development and tests of RF structures devoted to particles acceleration with higher gradient electric field through metal device, minimizing the breakdown and the dark current. In particular, new manufacturing techniques for hard-copper structures are being investigated in order to determine the maximum sustainable gradients well above 100 MV/m and extremely low probability of RF breakdown. In the framework of the Compact light XLS project [1], the main linac frequency is F = 11.994 GHz. In order to compensate the non-linearity distortions due to the RF curvature of the accelerating cavities, the use of a compact third harmonic accelerating structure working at F = 35.982 GHz is required [2]. The analysis of the combined action of the Ka-band structure and the bunch compressor on the beam transport has been performed.

Since only the single bunch operation is foreseen, the beam dynamics is not affected by the long-range wake-fields and no dedicated dampers of the parasitic higher order modes are adopted for the linearizer structure. The technologies in the Ka-Band accelerating structures, high power sources and modulators have also been developed in order to reach a RF power output of (40-50) MW by using the SLED system [3–7]. It has to be noted that this RF power level is more than it is needed for our proposed TW accelerating structure.

RF stability during operation and tuning tolerances are important points for the RF structure design in the high frequency range. The complexity of machining, tight mechanical tolerances and alignments are therefore important aspects which have to be taken into account in the design activity.

In order to obtain the longitudinal phase space linearization and from beam dynamics considerations in the framework of the Compact Light XLS project , we have designed a possible compact high harmonic traveling wave (TW) accelerating structure operating at a frequency of F= 35.982GHz with a 100 MV/m accelerating gradient operating on the $2\pi/3$ mode. This report is devoted to the choice of the fundamental RF parameters as the form factor Rsh/Q, quality factor Q, power losses, dispersion curves, cooling system of a TW wave structure operating on $2\pi/3$ mode, with discussions on practicalaccelerating gradients.

2 Choice of the accelerating structure type

The design of the particle accelerators of new generation is defined on the basis of a compromise among several factors: RF parameters, beam dynamics, RF power sources, easy fabrication, small sensitivity to construction errors, economical reasons and so on. In order to minimize the input power requirements for a given accelerating gradient, the RF accelerating structures have to be designed with the aim of maximizing the shunt impedance. On the other hand, the accelerating section performances could be limited by effects such as the beam loading, instabilities, beam break-up etc., caused by the interaction between the beam and the sections.

As an example, a figure of merit for the accelerating structure is the efficiency with which it converts average input electromagnetic energy per unit length, into average accelerating gradient. Then, if P_b is the average beam power and P_{rf} the average RF power fed into the structure, the small fraction of energy extracted by beam defined as $\epsilon = P_b/P_{rf}$ has to be kept well below to some per cent for getting a satisfactory energy spread. On the basis of these simple considerations, the global RF properties for designing the accelerating structure are therefore summarized and listed in the following:

- High accelerating field gradient to reduce the accelerator length;
- High shunt impedance to reduce the requirement of RF power;
- Low ratios E_p/E_0 and B_p/E_0, where E_p and B_p are the surface electric and magnetic peak fields respectively and E_0 is the average accelerating field, to achieve the highest possible field gradient before reaching the breakdown condition and to reduce thermal effects.
- High ratio E_0/W where W is the energy stored in the structure per unit length that is a measure of the efficiency with which the available energy is used for the operating mode;
- High group velocity in order to reduce the filling time of the section in order to get less sensitivity to the mechanical imperfections;
- Low content of longitudinal and transverse higher order modes which can be excited by the bunches traversing the structure and those can affect the beam dynamics;

- Appropriate shape profile for avoiding the generation of multipactoring phenomena which could limit the accelerating section performances.

Our concern is to design a constant impedance accelerating structure operating on the $2\pi 3$ mode with the requirements reported below:

- average accelerating voltage, E = 100 MV/m ;
- Axial length, L = 25 cm;
- beam aperture diameter, D = 2.66 mm;
- operating frequency, F=35.982;
- ratio of phase to light velocity, v_ϕ/c = 1
- pulse charge, Q= 75 pC;
- rms bunch length pulse length, σ_τ = 350 fs
- single pulse operation
- pulse repetition rate frequency frep = (1-10) Hz.

No specific effect due to the beam loading and beam dynamics has to be expected since the operation with a small average current and single bunch is adopted.

We decided to work in TW configuration in order to get a satisfactory longitudinal shunt impedance of the operating mode and an acceptable iris aperture for practical beam dynamics considerations. The third harmonic frequency of the main Linac one, implies small physical dimensions and thereby the dissipated power constitutes one of the main constraints, as well. A reasonable upper limit on the average power dissipation has been estimated to be around at 4 kW/m. To meet the full requirements by keeping a flexibility margin, a section with simpler geometry which is cheap and of reliable construction and with satisfactory mechanical tolerances has been chosen. The detailed RF properties and the thermal behaviour of the $2\pi/3$ mode are described later in the following subsections.

3 Accelerating structure RF properties

A compact linear accelerator linear accelerator is known to require an operating frequency of 30-100 GHz. Higher operating frequency can lead to higher accelerator gradients, with a corresponding smaller accelerator length. We propose a possible Ka-Band linear structure for high-energy applications, such as the Compact Light European project, a compact free-electron laser for linearizing the longitudinal space phase in order to increase beam brightness.

In order to get a satisfactory longitudinal shunt impedance of the TM01 operating mode, we decided to work on the common $2\pi/3$ configuration mode of the TW structure with a cell-to-cell phase-shift of 120 degrees and by using the SLED system [6,7] for obtaining the RF power source for feeding the structure.

In Fig. 1 we show the cell cavity shape of the for the $2\pi/3$ configuration mode on axis coupling through the iris aperture. The RF structure design study has been carried out by using the well-known HFSS and CST softwares. Electric and Magnetic field distributions are illustrated in Fig. 2. The minimum value of the electric and maximum value of the magnetic fields are near the outer surface of the cavity as they were expected to be for theTM_{01} working mode.

In Figs. 3, 4, 5 we report the longitudinal shunt impedance, the unloaded quality factor and the cavity radius as function of the iris radius by keeping unchanged the operating frequency of the of the working mode TM010 at F = 35.982 GHz. With an iris radius of a = 1.333 mm, cavity radius b = 3.657 mm, thickness iris h = 0.667 mm, we are able to get a longitudinal shunt impedance Rsh/m = 158 $M\Omega/m$ and an unloaded quality factor Q = 4110.

Fig. 6 shows the dispersion curve by giving the frequency mode as function of the phase advance of the TW structure. The group velocity of the $2\pi/3$ is estimated to be 0.0365 c [8]. The energy spread due to the beam loading is negligible as it will be described in a forthcoming paper.

4 Breakdown rate limit

As anticipated earlier, we propose the Ka-Band linear accelerator for high-energy applications, such as the Compact Light European project. The cell geometry is shown in Fig. 1. Here, we discuss the breakdown rate (BDR) limit and cooling system design. The BDR limits the maximum accelerating gradient achievable inside the linac for a given RF pulse length and attenuation coefficient τ.

The BDR is a measures of the RF sparks per unit time and length inside an accelerating structure. Typical values, in the design of high-energy accelerators, are about $10^{-6} - 10^{-7}$. A new quantity has been introduced [9], the modified Poynting vector defined as Sc=re(S)+im(S)/6 where S is the Poynting vector, in order to have a parameter to refer to during the linac design.

For the Ka-Band structure, we estimated a modified Poynting of Sc 5 MW/mm^2 (below safety threshold of about 6.3 MW/mm^2) for an accelerating gradient of E_{acc}=100 MV/m, input power 25 MW, RF pulse length (flat top) 50 ns and an attenuation of τ = 0.57 Np [10]. The RF pulsed heating is estimated to be ΔT = 10.2 $^{\circ}C$ degree below the safety threshold of ΔT = 50 $^{\circ}C$ degree [11]. It is possible to increase the accelerating gradient Eacc up to 125 MV/m which gives Sc 8 MW/mm2 that is somewhat more critical but near the threshold with a pulsed heating of ΔT = 16 $^{\circ}C$ below the safety threshold.

For the lower energy and longer pulse case, in order to keep constant the BDR value, the max accelerating gradient should not exceed 80 MV/m for a 1.5 μs pulse width [12].

The change of resonance frequency as function of cavity and iris radius have been estimated to be around $\Delta f = 11 MHz/\mu m$ and Δf = 5 $MHz/\mu m$, respectively. By adjusting the cavity radius and the iris radius in opposite directions, the corresponding frequency shift is estimated to be of 8 $MHz/\mu m$. To summarize, the cavity frequency shift per unit radius can be expressed as $\Sigma_{i=1}^{2}\ (\frac{\Delta f}{\Delta x}) = 16\ MHz/\mu m$ (where i=1 refers to the cavity radius while i=2 to the iris radius adjustment), as it is expected to be. As a result, tuners devices and the temperature tuning approach have to be foreseen, too. The performance of the accelerating structure may also be limited by the resonant electron discharges or "multipactoring". According to our experience, it is well known that for reducing or eliminating this phenomenon it is recommended to have a curved profile of the cavity surfaces or to use asymmetric cavity shapes. Due to the big aperture of the structure, we believe that the "two points multipactoring" in the gap region of the structure is unlikely to occur since the counteraction of the radial electric force and magnetic force is uncompensated, thereby no resonant discharges can be determined. It is also well known the for reducing or eliminating the "two points multipactoring" it is recommended to use a rounded profile for the cavity shapes. Therefore we expect to have no particular problem for the multipactoring phenomenon.

5 Thermal and Stress Analysis

A rise in temperature will vary the accelerator dimensions and the frequency characteristic will change accordingly. The temperature rise can be reduced by means of a cooling system. For getting the frequency shift behaviour as a function of the temperature change, the thermal study is also required. We want to estimate the frequency shift caused by a change in temperature over the accelerating structure operating on $2\pi/3$ mode. We will assume that a closed cooling water system is used in order to keep the operating temperature at 40 $^{\circ}C$.

The preliminary thermal and stress analysis was also carried out in CST. In Fig.7, we show the result of the single cell where a cooling system with longitudinal pipes is assumed. The simulation is performed assuming a gradient of E_{acc}=125 MV/m with a corresponding average power per unit length of about 2 kW/m, with a water flux of 3l/min. The hot spot is about 40 C (standard operation) and it can be lowered by adjusting water flux and water temperature. The consequent stress analysis shows a yield strength (Von Mises) $<$ 20 MPa which is below the safety threshold for copper ($\sim$ 70 MPa). The corresponding maximum displacement is about 1 μm (i.e. frequency shift is negligible or tunable). The cooling system will be optimized during final engineering (water jacket or brazed channels) in order to avoid water-to-vacuum leaks.

Table 1: The main RF parameters of the Ka Band constant impedance structure

Frequency [GHz]	35.982
Accelerating gradient [MV/m]	100
Longitudinal shunt impedance $[M\Omega/m]$	158
Unloaded quality factor	4110
Cell length [mm]	2.779
Structure length [mm]	250
Group velocity/c [%]	3.65
Input peak power [MW]	30
Modified Poynting vector Sc $[MW/mm^2]$	5
RF Pulsed heating $[°C]$	10
Repetition rate [Hz]	1-10
Power Source [MW]	25

6 Machining

It has been experimentally demonstrated that hard copper is able to stand ultra-high gradients unlike high-temperature treated one [13,14]. As a result, we plan to machine the Ka-Band linac for high gradient applications in two halves with TIG welding of the outer surfaces [15,16]. We are also considering an alternative approach as a novel clamping technique [12], as for medium-low energy range for the industrial/medical applications [12].

The summary of the main RF parameters of the Ka Band constant impedance structure are reported in Table 1.

Conclusions

In order to linearize the longitudinal space phase of the Compact Light XLS project, we have chosen a TW Ka-Band (35 GHz) accelerating structure operating on $2\pi/3$ mode as possible candidate for the third harmonic RF section with respect to the main linac frequency ($\sim$11.99 GHz). This structure can work with a high gradient accelerating up to 125 MV/m by using the conservative main RF parameters. We are planning to finalize the structure design as well as engineering of the RF power source that will be able to produce up to a (40-50) MW input power by using a SLED system [3–7].

In case of the single bunch operation, also a numerical and analytical study of the longitudinal and transverse wake-fields on the beam dynamic effects has been carried out and discussed at first XLS Compact Annual meeting at Barcelona Spain [17]. As a result, the estimate of the longitudinal and transverse wake-fields on the beam dynamic gave no specific trouble. The report on the wake-fields studies will be presented in a forthcoming paper.

As a final comment, the dimensions of the cavity are perfectly consistent with the 100 GHz structures by scaling law with the frequency already tested at SLAC [18–22].

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Figure captions

Figure 1 : Cavity shape for the TW 2?/3 mode: b, a , h and l are cavity radius, iris aperture radius, iris thickness and 1/3 of the cell length, respectively

Figures 2 : 2a Electric and 2b magnetic field distribution of the TM010 mode

Figure 3 : Shunt impedance as function iris aperture as function of the iris radius at F = 35.982 GHz

Figure 4 : Unloaded quality factor as function of the iris radius at F = 35.982 GHz

Figure 5 : Cavity radius as function of the iris radius at F = 35.982

Figure 6 : Dispersion relation of the TW structure

Figure 7: Thermal simulation of the single cell from CST software

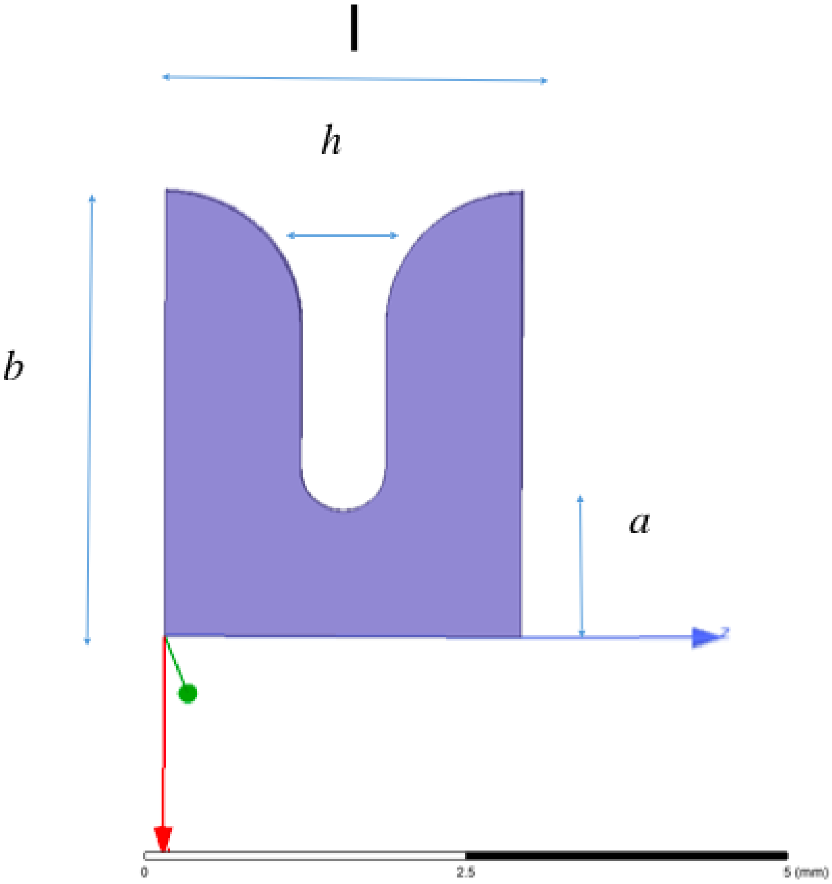
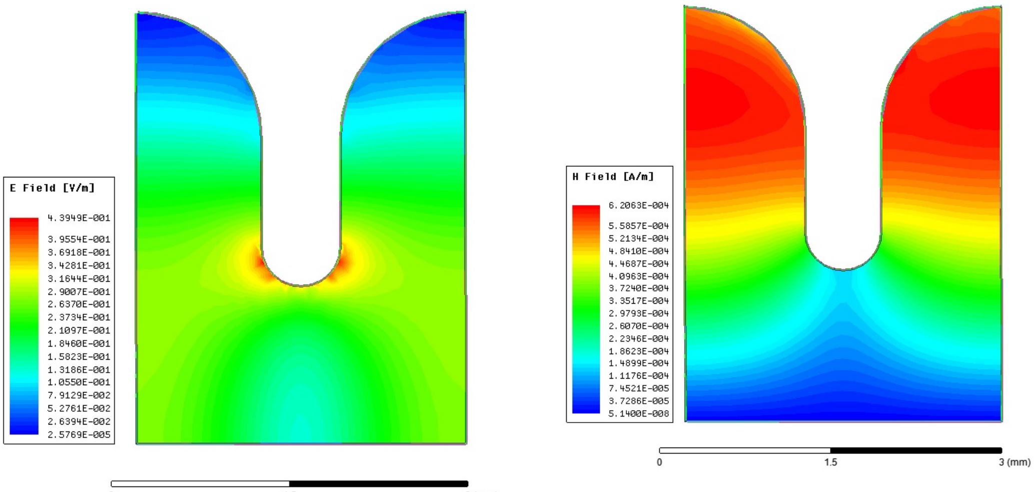


Figure 1: cavity shape of the TW $2\pi/3$ mode



(a) (b)

Figure 2: a) Electric field distribution of the TM_{010} b) Magnetic field distribution of the TM_{010} mode

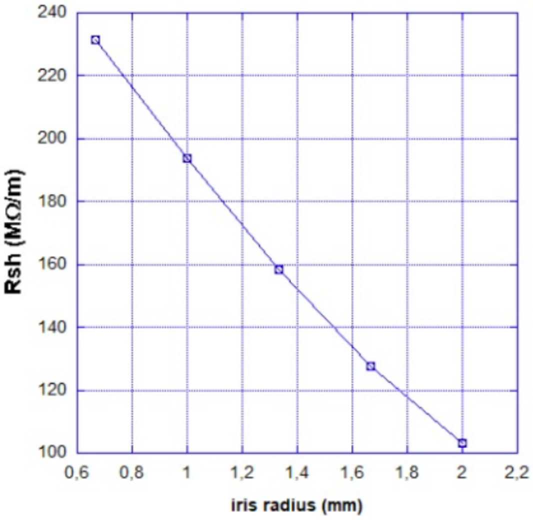


Figure 3: Shunt impedance as function iris aperture as function of the iris radius at F = 35.982 GHz

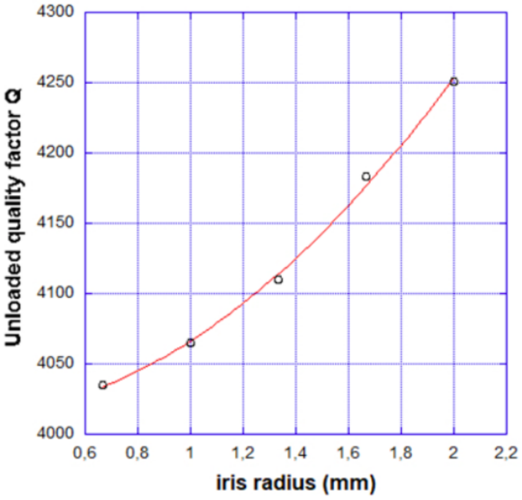


Figure 4: Unloaded quality factor as function of the iris radius at F = 35.982 GHz

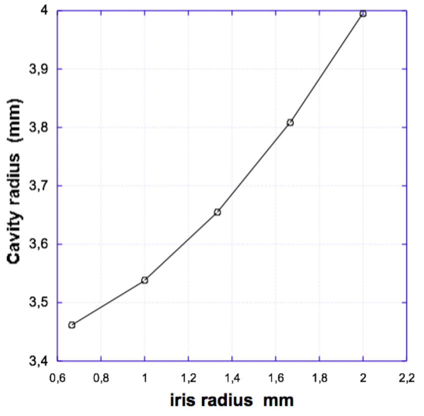


Figure 5: Cavity radius as function of the iris radius at F = 35.982 GH

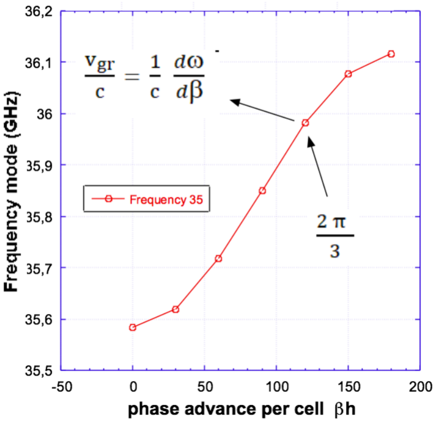


Figure 6: Dispersion relation of the TW structure

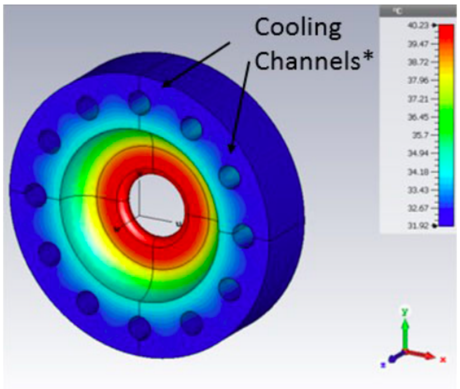


Figure 7: Thermal simulations of the single cell from CST software