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

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Abstract. 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. The design of this compact Traveling Wave (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 is presented, together with numerical electromagnetic simulations were carried out by using the numerical codes High Frequency Structure Simulator (HFSS) and CST Particle Studio.

1. Introduction
Technological advancements are strongly required to fulfill the demands of compact linear accelerators for particle physics colliders, new accelerators from compact or portable devices for radiotherapy to mobile cargo inspections, security, biology, energy and environmental application, etc..

Extremely intense electric gradients are also required for a variety of new applications, notably including the ultra high brightness electron sources for the Free Electron Laser (FELs), Radio Frequency (RF) photo-injector etc. Technological efforts to design, manufacture and test new accelerating devices using different materials and methods are under investigations all over the world. New manufacturing techniques of hard-copper structures are being investigated at the Laboratori Nazionali di Frascati (INFN-LNF) 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 \( F = 11.994 \text{ GHz} \). 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 \( F = 35.982 \text{ GHz} \) is required [2]. In this contribution the analysis of the combined action of the Ka-band structure and the bunch compressor on the beam transport has been presented and discussed.

Since only the single bunch operation is foreseen, the beam dynamics is not affected by the long-range wake-fields. No dedicated dampers of the parasitic higher order modes were adopted for the linearized structure as it will be reported in a forthcoming paper. The technology of 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 SLAC Energy Doubler (SLED) system [3,4,5,6,7]. Here, it has to be noted that this RF power level is higher than the needs of our proposed TW accelerating structure.

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

2. Choice of the accelerating structure type

The design of the particle accelerators of new generation is the result 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. In addition, the accelerating section performances could be limited by effects such as the beam loading, instabilities, beam break-up etc., all due to the interaction between beam sections.

As an example, the figure of merit for the accelerating structure is the efficiency with which it converts the average input electromagnetic energy per unit length, in the average accelerating gradient. Then, if \( P_b \) is the average beam power and \( P_{rf} \) the average RF power fed inside the structure, the small fraction of the energy extracted by the beam defined as \( \epsilon = P_b/P_{rf} \) has to be kept well below some per cent for getting a satisfactory energy spread. On the base of these simple considerations, the set of 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 minimize the required 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 and an estimation of the available energy necessary to the operating mode;
- High group velocity in order to reduce the filling time of the section and to minimize the sensitivity to the mechanical imperfections;
- Low content of longitudinal and transverse higher order modes which can be excited by the bunches traveling the structure perturbing the beam dynamics;
- Appropriate shape profile for avoiding the generation of multipactoring phenomena, which could limit the accelerating section performances.

Our goal is to design a constant impedance accelerating structure operating on the \( 2\pi/3 \) mode with the parameters listed 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, \( v_\phi/c = 1 \)
- pulse charge, \( Q= 75 \) pC;
- rms bunch length pulse length, \( \sigma_\tau = 350 \) fs
- single pulse operation
• pulse repetition rate frequency \( \text{freq}_{\text{rep}} = (1-10) \text{ Hz} \).

No specific effect due to the beam loading and beam dynamics are expected since we adopted an operation modality with a small average current and single bunch.

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, as a consequence, the dissipated power constitutes one of the main constraint. A reasonable upper limit on the average power dissipation has been estimated to be \( \sim 4 \text{ kW/m} \). To fulfill all requirements by keeping a margin of flexibility, a simple geometrical section, a cheap and a reliable process with high mechanical tolerances has been chosen. The detailed RF properties and the thermal behavior of the \( 2\pi/3 \) mode are described later in the following subsections.

3. Accelerating structure RF properties

A compact linear accelerator is known to require an operating frequency between 30 and 100 GHz. Actually higher operating frequency can lead to higher accelerator gradients, with a corresponding smaller accelerator length. In this contribution we discuss a Ka-band linear structure for high-energy applications, such as the Compact Light European project, for linearizing the longitudinal space phase in order to increase the beam brightness.

In order to get a satisfactory longitudinal shunt impedance of the \( TM_{010} \) 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 \( 120^\circ \) and by using the SLED system \(^6\) \(^7\) to achieve the RF power source for feeding the structure.

In Fig. 1 we show the cell cavity shape for the \( 2\pi/3 \) configuration mode on axis coupled through the iris aperture. The RF structure design study has been carried out by using the well known HFSS and CST packages. Electric and magnetic field distributions are illustrated in Fig. 2. The minimum value of the electric field and the maximum value of the magnetic field are near the outer surface of the cavity as they were expected to be for the \( TM_{010} \) working mode.

In Figs. 3, 4 and 5 we show the longitudinal shunt impedance, the unloaded quality factor and the cavity radius as a function of the iris radius by keeping unchanged the operating frequency of the of the working mode \( TM_{010} \) at \( F = 35.982 \text{ GHz} \). With the iris radius of \( a = 1.333 \text{ mm} \), the cavity radius \( b = 3.657 \text{ mm} \) and the thickness iris \( h = 0.667 \text{ mm} \), we are able to get a longitudinal shunt impedance \( R_{sh/m} = 158 \text{ M}\Omega/\text{m} \) and an unloaded quality factor of \( Q = 4110 \).
Figure 3. Shunt impedance vs. iris aperture as a function of the radius of the iris at $F = 35.982 \text{ GHz}$

Figure 4. The unloaded quality factor vs. the iris radius at $F = 35.982 \text{ GHz}$

Figure 5. The cavity radius vs. the iris radius at $F = 35.982 \text{ GHz}$

Figure 6. The dispersion relation of the TW structure

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

4. Breakdown rate limit
As anticipated, this Ka-band linear accelerator for high-energy applications, such as the Compact Light European project is characterized by the cell geometry shown in Fig. 1. Here, we discuss the Breakdown Rate (BDR) limit and the cooling system design. The BDR limits the maximum accelerating gradient achievable inside the linac for a given RF pulse length and attenuation coefficient $\tau$.

The BDR is the measure of the RF sparks per unit time and length inside an accelerating
structure. Typical values, in the design of high-energy accelerators, are about $10^{-6} - 10^{-7}$ 1/pulse/meter. In order to have a parameter to refer to during the linac design anew quantity can be introduced \[9\], the modified Poynting vector defined as \( S_c = \text{re}(S) + \text{im}(S)/6 \) where \( S \) is the Poynting vector.

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

However, for lower energy and longer pulse case, in order to keep constant the BDR value, the maximum accelerating gradient should not exceed 80 MV/m for a 1.5 \( \mu \text{s} \) pulse width \[12\]. The accelerating gradient is then scaled according to the following rule \[9, 13\]:

\[
\frac{E_{\text{a}}^3 \tau^5}{BDR} = \text{constant.}
\]

The change of resonance frequency as a function of both cavity and iris radius have been estimated to be around \( \Delta f = 11 \text{ MHz/\mu m} \) and \( \Delta f = 5 \text{ MHz/\mu m} \), respectively. By adjusting these two radii in opposite directions, the corresponding frequency shift is estimated 8 \( \text{ MHz/\mu m} \). To summarize, the cavity frequency shift per unit radius can be expressed as \( \Sigma_{i=1}^2 (\frac{\Delta f}{\Delta x}) = 16 \text{ MHz/\mu m} \) (where \( i=1 \) refers to the cavity radius while \( i=2 \) to the iris radius adjustment), as expected to be. As a result, tuners devices and the temperature tuning approach have to be foreseen, too. However, 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 large 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 the magnetic force is uncompensated, thereby no resonant discharges can occur. It is also recommended the for reducing or eliminating the "two points multipactoring" the use of cavity shapes with a rounded profile. Therefore we expect to have no particular problem for consider the multipactoring phenomenon not critical for this structure.

5. Thermal and Stress Analysis

A rise in temperature will change the accelerator dimensions and the frequency characteristic will shift accordingly. The temperature rise can be reduced by means of a cooling system. To characterize the frequency shift behavior as a function of the temperature change, a thermal study is also required. We need 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 \( \degree C \). The thermal simulation refers to a Ka-Band cell at the operating frequency and with a temperature tuning sensitivity of about 0.5 MHz per deg C. Therefore, assuming 1 \( \mu \text{m} \) detuning, we would apply 10 deg temperature change with the cooler in order to compensate the associated 5 MHz frequency shift.

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 considered. The simulation is performed assuming a gradient of \( E_{\text{acc}} = 125 \text{ MV/m} \) with a corresponding average power per unit length of about 2 kW/m, and a water flux of 3 l/min. The hot spot is about 40 C (standard operation), but it can be reduced by adjusting water flux and water temperature.
The consequent stress analysis showed a yield strength (Von Mises) $< 20$ MPa, which is below the safety threshold for copper ($\sim 70$ MPa). The corresponding maximum displacement is about $1 \text{µm}$ (i.e., the frequency shift is negligible or tunable). The cooling system will be optimized in the final engineering design (water jacket or brazed channels) in order to avoid water-to-vacuum leaks.

![Thermal simulations of the single cell](image)

**Figure 7.** Thermal simulations of the single cell

6. Machining
It has been experimentally demonstrated that hard copper is able to withstand ultra-high gradients unlike high-temperature treated one [14][15]. 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 [16][17]. We also are considering an alternative approach: a novel clamping technique [12], as for similar structures designed in the medium-low energy range for the industrial/medical applications [12].

The summary of the working RF parameters choice of the Ka Band constant impedance structure are listed in Table 1.

**Table 1.** Working RF parameters of the Ka Band constant impedance structure

| Parameters                                      | Value     |
|-------------------------------------------------|-----------|
| Frequency [GHz]                                 | 35.982    |
| Accelerating gradient [MV/m]                    | 100       |
| Longitudinal shunt impedance [MΩ/m]             | 158       |
| Unloaded quality factor                         | 4110      |
| Cell length [mm]                                | 2.779     |
| Structure length [mm]                           | 250       |
| Group velocity/c [%]                            | 3.65      |
| Input peak power [MW]                           | 25        |
| Modified Poynting vector Sc [MW/mm²]            | 5         |
| Pulse length [ns]                               | 50        |
| RF Pulsed heating [°C]                          | 10        |
| Repetition rate [Hz]                            | 1-10      |
7. Conclusions
In order to linearize the longitudinal space phase of the Compact Light XLS project, we have chosen a TW Ka-Band (35.982 GHz) accelerating structure. Operating on $2\pi/3$ mode it is a 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 acceleration up to 125 MV/m by using the conservative main RF parameters. We are planning now to finalize the design of this structure as well as engineering of the RF power source (amplifier design for the Ka band klystron operating at $F=35.982$ GHz) [18, 19] that will be able to produce an input power up to a (40-50) MW by using a SLED system [3, 4, 5, 6, 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 Trieste (Italy) and at the first XLS Compact Annual meeting held at Barcelona Spain [20, 21] and Trieste. From our study, the estimate of the longitudinal and transverse wake-fields on the beam dynamic does not point out any specific trouble. However, the report on the wake-fields studies will be presented and discussed in a forthcoming paper.

To conclude, also the dimensions of the cavity are perfectly consistent with the 100 GHz structure by scaling law with the frequency already tested at SLAC [22, 23, 24, 25, 26].

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