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# The Ka-Band High Power Klystron Amplifier Design Program of INFN

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## Abstract

Novel accelerating structures operating in Ka-Band are foreseen to achieve gradients around 150 MV/m. Among applications of Ka-Band accelerating structures in this contribution we describe the linearization of the longitudinal phase-space for the Compact Light XLS project. We also describe and characterize a Klystron amplifier to feed a linearizer structure. The design here presented includes the high-power DC gun, the beam focusing channel and the RF beam dynamics.

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## 1 Introduction

The status of the design program of High power klystrons operating at Ka-Band is described in this contribution. An international task force involving Yale University, UCLA University and European institutions, i.e., CERN, INFN and University of Rome Tor Vergata is conceiving a new family of klystrons for new accelerators such as the Compact Light XLS project.

The Compact Light XLS project intends to design a hard X-ray Free Electron Laser (FEL) facility using the latest concepts for bright electron photo injectors, with very high-gradient X-band structures at 12 GHz, and innovative compact short-period undulators [1]. In this framework, a compact third harmonic RF accelerating structure at 35.982 GHz with respect to the main Linac frequency at 11.994 GHz, working with an ultra-high gradient accelerating field to linearize the longitudinal space phase has been selected. To this end, an innovative high power Ka band klystron operating at about 35.982 GHz has to be designed for feeding the linearizer structure. Numerical electromagnetic simulations was carried out by using the numerical code CST. [2]

In addition, the design of this Ka band klystron will operate on the third harmonic of $TM_{01}$ mode. The generation of a high density electron beam by using the Pierce type electron gun is also requested

We designed a high power Ka band klystron in order to feed a constant impedance accelerating structure operating on the $2\pi/3$ mode (TW) [3,4] and $\pi$ mode (SW) [5] with an average (100-125) MV/m accelerating electric field range by using conservative RF parameters. In this document, the proposed design of the structure thought to energize the latter accelerator is presented.

## 2 The State of the Problem

The power source is a Ka band klystron, which use a particular arrangement of the output coupler. This device is designed to produce up to 16 MW output power with an efficiency of about 40 $\%$. The klystron is supplied by a 48 MW electron gun beam power by knowing that the output cavity will operate in the third harmonic of the drive frequency of the $TM_{01}$ mode. Space charge force is one of the limitations. It doesn't allow to have identical velocity for each accelerated electrons after passing through the cavities, affecting the bunching process which leads to a low efficiency. The key element to control to measure such a force is the perveance, $K = I\, V^{-3/2}$,

where I and V stand for beam current and voltage, respectively. By considering that the efficiency, $\eta$, is defined as the ratio of the output power to the input power, the voltage is proportional to the ratio $(P_{out}/(\eta K))^{2/5}$. The higher is the perveance, stronger is the space charge and consequently, weaker the bunching. However, to have a higher beam current we have to rise the perveance, although a higher perveance leads to a low efficiency. As a consequence we have to found the optimal perveance to maintain a good

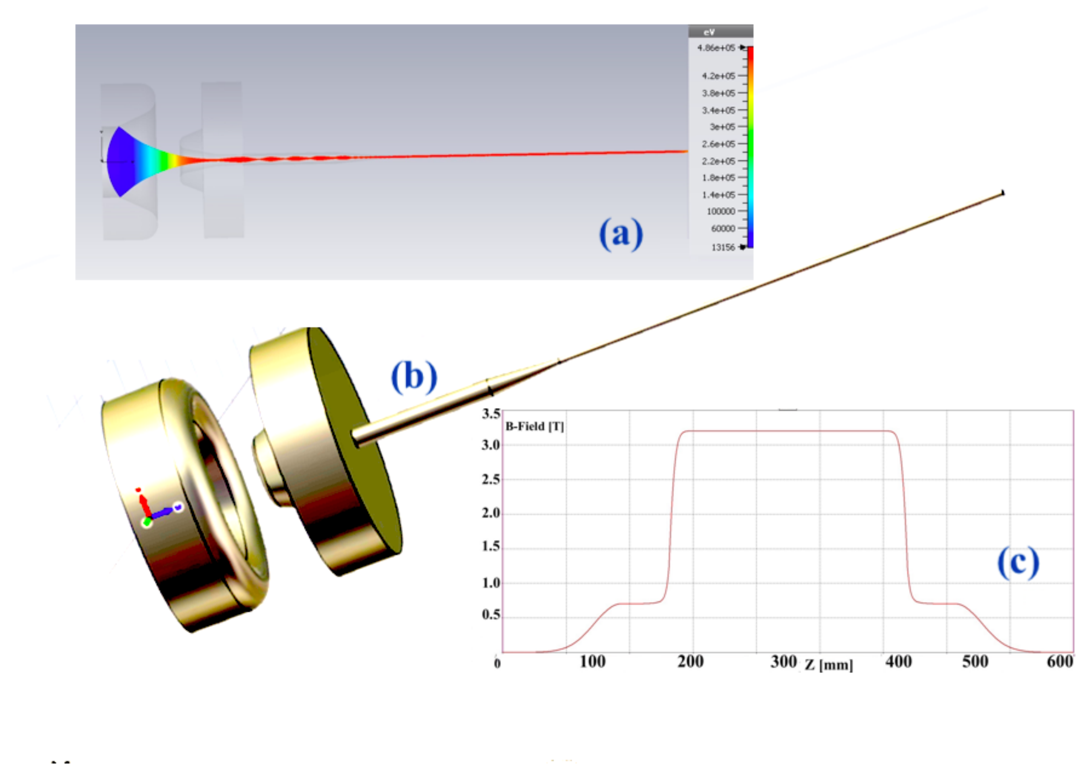

Figure 1: a) 3D model of the gun and beam pipe. b) Beam trajectory along the propagation direction c) axial magnetic field distribution.

efficiency while allowing for an opportune third harmonic content manipulation, to generate the frequency multiplication. The electron beam is generated from a high-voltage DC gun (up to 480 kV) and the cathode-anode geometry and the distance between them were optimized to adjust the electric field equipotential lines to obtain the extracted beam current of above 100 A. The electron beam is then transported through the klystron channel. In the current design the beam confinement is obtained by means of a high magnetic field produced by superconducting coils, which was analytically imported inside the code. In this way we are able to obtain a beam radius of 1 mm within a beam pipe length of about 30 cm.

A particular klystron structure has been designed to generate from a 12 GHz input, a sufficient content of the 3rd harmonic at the output. The proposed klystron structure operates with a 100 A 480 kV beam producing at the output 16 MW, at 36 GHz with a 42% efficiency.

## 3 Electron Gun Injector Design

The electron gun relies on a Pierce-type cathode that produces the main electron stream, manipulated by the klystron operating at the Ka-Band (36 GHz) to feed the accelerating structure. As outlined before, the required cathode-anode voltage is about 480 kV and the beam current is about 100 A; hence the beam power will be 48 MW. The preliminary simulation of the electron gun with the CST package has been performed to define the trajectory and the electric field distribution (see Fig.s (1a) and (1b)). The cathode-anode geometry was optimized to adjust the electric field equipotential lines in order to obtain current the required beam.

The simulation returned an electrostatic beam compression ratio of 1488:1. The $\mu$ perveance of this device is 0.3 $AV^{-3/2}$. The maximum electric field on the focusing electrode is about 200 $kV/cm$, which can be considered a reasonable value. To avoid possible damage and for a safety operational margin in terms of pulse length, RF windows, power supply hardware stability, etc., we have decided to work with a 480 kV cathode-anode voltage.

Actually a smaller anode radius has been chosen because the analytical estimation of the solid angle, $\theta$, was smaller of that obtained from the numerical computation. All other parameters such as beam angle and the ratio between cathode and anode radius are in agreement with analytical ones.

In order to achieve the required compression of the beam after exiting the electron gun, the magnetic field distribution has been investigated. In the larger beam pipe, an adequate cascade of slots has been accommodated to guarantee the vacuum quality. The buncher and the output cavities should be installed on a smaller beam pipe. The design parameters of the gun with the focusing magnetic field along the beam axis are listed in Table 1.

| Design parameters | |
|---|---|
| Beam power [MW] | 48 |
| Beam voltage [kV] | 480 |
| Beam current [A] | 100 |
| $\mu-$ perveance $[I/V^{3/2}]$ | 0.3 |
| Cathode diameter [mm] | 76 |
| Pulse duration [$\mu$ sec] | 0.2 |
| Minimum beam radius in magnetic system [mm] | 0.98 |
| Nominal radius [mm] | 1.00 |
| Max EF on focusing electrode [kV/cm] | 200 |
| Electrostatic compression ratio | 1488:1 |
| Beam compression ratio | 1635:1 |
| Emission cathode current density [$A/cm^2$] | 2.02 |
| Beam Transverse Emittance [mrad-cm] | 1.23 $\pi$ |

Table 1: Design parameters of the gun with focusing magnetic field along the beam axis

The magnetic field distribution is shown in Fig. (1c). It shows a small peak of 7 kG and a constant magnetic field of 32 kG along about 300 mm to generate a narrow beam radius for the purpose of inserting cavities operating on the third harmonic of the fundamental mode of X-band. Since the proposed klystrons are based on the 3rd harmonic generation, cavities are operated in X-band and Ka-Band, therefore, they require a small beam radius (about 1 mm).

In the region before the small pipe, where we have considered a tapered pipe, the magnetic field is 7 kG and, consequently the beam radius will be larger $\sim$ 2.31 mm, however in that region this value is considerably higher than the Brillouin limit that is 0.6 mm. Likewise for the region where the field is 32 kG, the beam radius is $\sim$ 1 mm, which again is much larger than the Brillouin limit, which is about $0.1312$ mm.

To enhance the efficiency, we have to find the optimal perveance value. As we have mentioned before, the efficiency and perveance are inversely proportional to each other [6]. This means that to obtain a high efficiency, the perveance has to be small and the price we have to pay is a small beam current. For this reason and also for other reasons, which we will discuss later in the next sections, we have decided to work with a beam current of 100 A. The corresponding $\mu$-perveance is 0.3 $A/V^{3/2}$. We point out that with the $\mu$-perveance of 0.657 $A/V^{3/2}$, which is a common value of modern klystron, we could obtain 235 A, although with an efficiency much smaller than with a beam current of 100 A. To change the $\mu$-perveance from 0.657 $A/V^{3/2}$ to 0.3 $A/V^{3/2}$, we have decided not to change the cathode-anode shapes but to increase the distance between them . By increasing the cathode-anode distance, the beam current decreases [7].

We didn't changed the cathode radius to decrease the current because the electrostatic compression ratio becomes too smaller and also the maximum electric field on the focusing electrode increased dramatically. Actually, increasing the cathode-anode distance, we obtained a higher electrostatic compression ratio, about 1488, and a smaller electric field on the focusing electrode, about 20 MV/m. We emphasized that the electrostatic compression ratio and the maximum electric field on the focusing electrode for the case of the $\mu$-perveance of 0.657 $A/V^{3/2}$ are 210 and 24 MV/m, respectively.

To avoid the voltage breakdown and the limitation of the cathode loading, the maximum possible beam compression is required to design this device [8]. Moreover, to increase the beam compression one should take into account the transverse emittance. Indeed, by increasing the beam compression with the minimum beam radius, the transverse emittance rises.

In this study we have obtained a magnetostatic beam compression ratio of 1635:1 with the beam radius of $\sim$ 1 mm and the transverse emittance of the beam in the small pipe is 1.23 $\pi$ (m rad-cm). It should be noted that it would be possible to still rise the beam compression ratio to about 2000:1 just by decreasing the beam radius to 0.9 mm. Indeed, the maximum possible compression ratio is when the beam radius reaches the Brillouin limit.

## 4 Interaction Structure Design

The interaction structure manipulates the beam produced from the electron gun above described with a 12 GHz signal and an input power of 800W. Our proposed structure is composed by 8 cavities; the first four dedicated to the input and the gain and the last four to the output coupling. It differs from a traditional klystron for both arrangement and shape of the gain cavities and, mostly, for the output coupler. The structure receives a beam of 100 A and 480 kV with a radius of 1 mm. The drift tube has a radius of 1.2 mm. The first four cavities operate in the first harmonic at the $TM_{010}$ mode and the last four are $2\pi$ normal mode coupled cavities operating at 36 GHz. The output structure is a cascade of four coupled cavities operating in the $\pi$ normal mode (see Fig. (2)). When compared to a single cell, our strategy allows to distribute the output energy inside a larger volume with a consequent advantage on the surface electric fields.

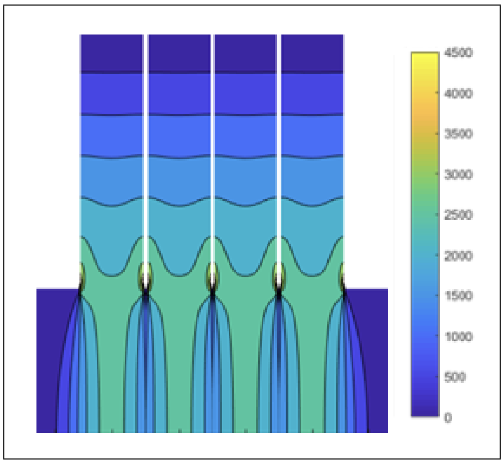

Figure 2: Axial electric field in the output structure, eigenmode solution, normalized amplitude

The first cavity is a traditional re-entrant cavity, operating at 12 GHz, followed by two re-entrant gain cavities. These devices are designed to have the higher R/Q without degrading the coupling coefficient [9],

$$M = J_0(\beta_e d/2)\frac{\sqrt{I_0^2(\gamma b) - I_1^2(\gamma b)}}{I_0(\gamma a)} \tag{1}$$

where $J_0(\beta_e d/2)$, $I_0^2(\gamma b)$ and $I_1^2(\gamma b)$ are the Bessel function of the first kind, the modified Bessel functions of the first kind for the order 0 and 1, respectively. The geometrical parameters a, b and d refer to beam tube radius, beam radius and gap length. Finally, $\gamma = \beta_e - k$, where $\beta_e$ is the beam propagation factor and k $=\omega/c$.

In order to maximize the signal distortion to enhance the 3rd harmonic content, the signal grow is demanded mostly to the last gain cavity.

The klystron buncher is a cylindrical resonant cavity with radius of 8.43 mm, operating in a quasi TM010. Moreover, the operating frequency of 12 GHz demands a radius aperture of 1.2mm for the electron beam path.These sizes can be achieved with Control Numeric Computer (CNC) machining, while the third harmonic cavities, i.e. the catchers

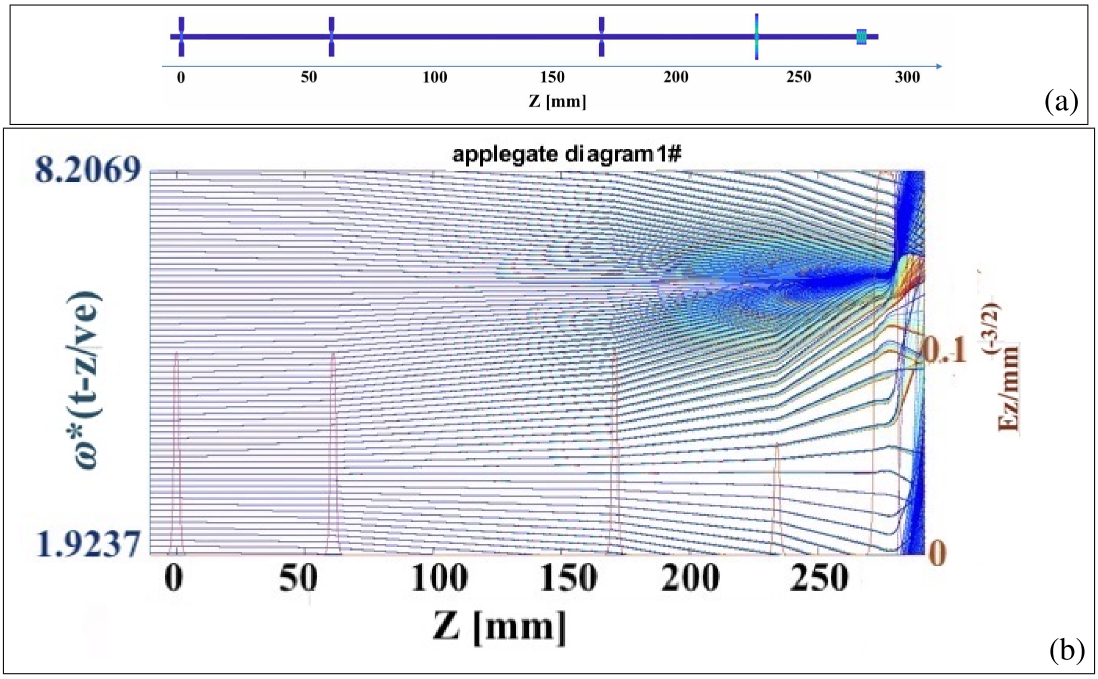

Figure 3: a) Layout of the interaction structure; b) the Applegate diagram (distance-time plot) is superimposed to the cavity positioning.

cavities operating at Ka band frequency, which have a radius of 3.37mm can be realized using Electrostatic Discharge Machining.(EDM).

The first two gain cavities are designed to operate with a low gain even if they need a sufficiently large gap to create the required bunch width to operate the output coupler at the desired frequency. The required gap that maximizes the coupling factor is 2.2 mm that gives a ratio R/Q of about 110 Ohm. In order to operate with this R/Q factor, the first two gain cavities have been detuned to 12067 MHz and 12378 MHz to sufficiently reduce their gain, and produce a smooth bunching process over the whole structure to prevent reflected electrons.

The last gain cavity operates in the compression zone to distort the signal to enhance the 3rd harmonic content. This cavity is a pill box cavity with a low shunt impedance, but coherently tuned to 12147 MHz to make an important signal enhancement before the output coupler. The gap is slightly larger with respect to the other gain cavities (3 mm) to sufficiently welcome the initial and the final part of the bunch and perform a sufficient compression. The pill-box shape confers enough low R/Q (34) to maximize the 3rd harmonic content.

The klystron design software KLyC [10] has been used for the computer aided design of the structure. By using this tool, the best effort has been done to obtain a sufficiently short structure suitable to accommodate a considerably narrow focusing magnet and obtain the perveance needed for the required beam power output ensuring the maximum efficiency. At the same time, a minimal velocity, below -0.1c, has been considered

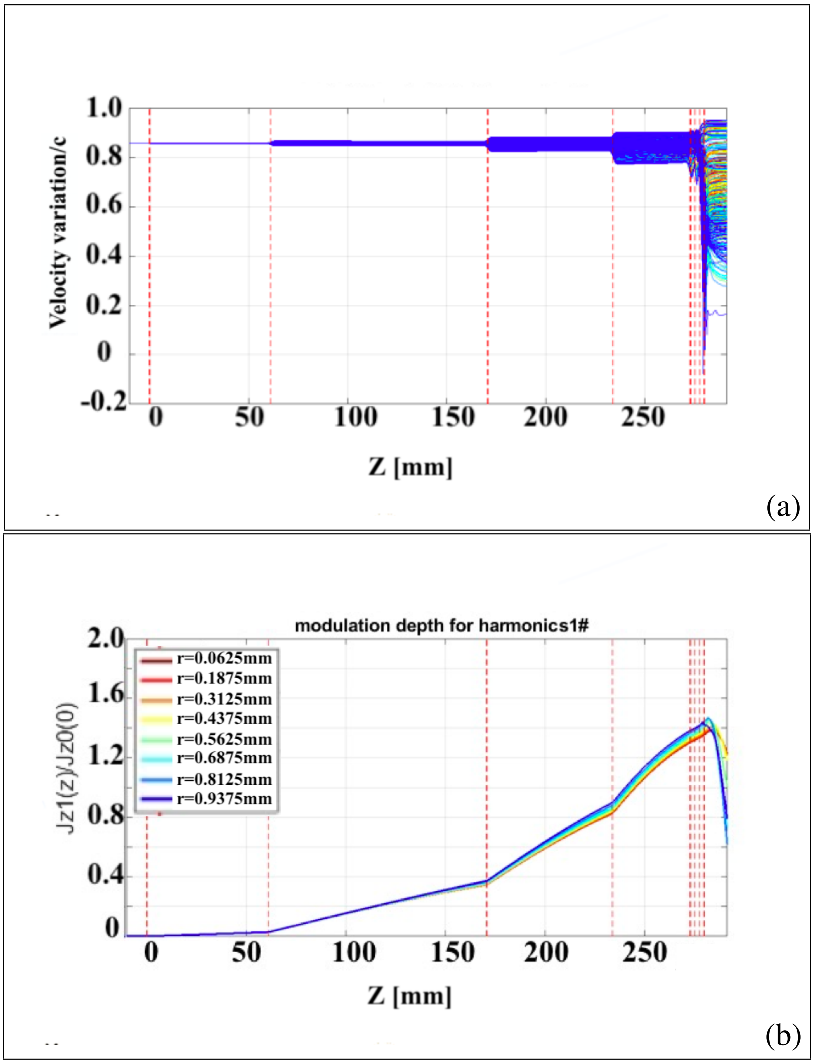

Figure 4: a) The velocity variation; b) The modulation depth of the 1st harmonic current at different beam substrates as a function of the longitudinal coordinate z. In the vertical axis, $J_{z1}$ is for the 1st harmonic current normalized to the dc current, $J_{z0}$.

to avoid electron reflections in the output cavities.

The layout of the interaction structure is shown in Fig. (3a) and the phase grouping is reported in Fig. (3b) where the Applegate diagram is superimposed to the position of the cavities.

In order to get a high efficiency, the electron beam is significantly decelerated in the last cavity of the output coupler down to a velocity of -0.09 c along the z direction. This effect occurs in the last cavity of the coupler, where the beam, after the interaction in the previous output cavities, has a considerably reduced energy. The velocity variations are showed in Fig. (4a).

The modulation depth of the 1st harmonic current at different beam substrates is shown in Fig. (4b). In this figure, $J_{z1}$ is the 1st harmonic current normalized to the dc current, $J_{z0}$. The 1st harmonic content has a specific distribution on different substrates

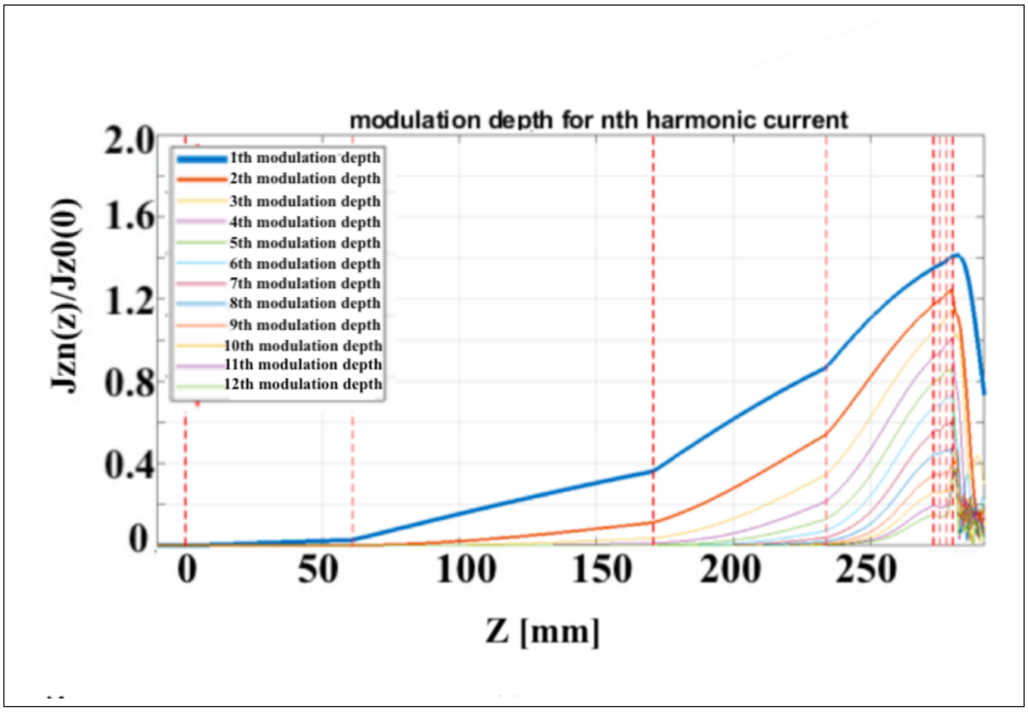

Figure 5: The modulation currents normalized to the dc current, $J_{z0}$ as function of the longitudinal coordinate z. In the vertical axis $J_{zn}$ is the higher harmonic current, which is calculated for different harmonic (n=1,2,..,12).

of the beam. The inner substrates have a slightly reduced fundamental content and this is one of the reason for which the last gain cavity is a low R/Q Pill-box cavity.

The superior harmonic content grows while the signal is sufficiently compressed; this operation is demanded mostly to the last gain cavity. In the power coupler the 3° harmonic phasor reaches the amplitude 0.77 of the amplitude of the fundamental. This coupler is designed to operate at 36 GHz excited by the 12 GHz signal, the 3rd sub-harmonic whose wavelength is a multiple of the resonance length of the cavities (see Fig. (5)). In this figure, $J_{zn}$ is the higher harmonic current, which is calculated for different harmonic (n=1,2,..,12).

| Design parameters | Output data |
|---|---|
| $P_{out}$ [kW] | 19983.804 |
| Gain [dB] | 43.976 |
| RFefficiency | 0.416 |
| Min v/c | -0.094 |

Table 2: Resume of Klystron Output

The output power is 20 MW at the fundamental and 15 MW at the 3rd harmonic. The max gap voltage is 471 kV, which is produced in the second last output cavity (7th

| Gapvoltage [kV] | Gapvoltage Phase [deg] | Energy [J] | Max EF [kV/mm] |
|---|---|---|---|
| 4.541 | 179.173 | $1.2e^{-06}$ | 4.659 |
| 27.565 | -131.121 | $4.6e^{-05}$ | 28.336 |
| 65.796 | -178.036 | $1.9e^{-04}$ | 66.912 |
| 115.851 | -165.463 | $2.6e^{-03}$ | 68.080 |
| 194.236 | 163.478 | $7.8e^{-04}$ | 88.773 |
| 278.961 | -86.481 | $1.6e^{-03}$ | 127.495 |
| 471.057 | 83.806 | $4.6e^{-03}$ | 215.289 |
| 302.729 | -49.039 | $1.8e^{-03}$ | 138.357 |

Table 3: Electric parameters of the proposed klystron

| Cavity number | Harmonic number | $F_0$ [MHz] | R/Q [Ω] | M | $Q_e$ | $Q_{in}$ | z [mm] | Gap [mm] |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 12000 | 110.412 | 0.9617 | 30 | 4947 | 0.000 | 2.20 |
| 2 | 1 | 12067 | 108.495 | 0.9614 | 10000 | 4935 | 61.063 | 2.20 |
| 3 | 1 | 12378 | 114.715 | 0.9587 | 10000 | 4981 | 170.796 | 2.20 |
| 4 | 1 | 12147 | 33.589 | 0.9576 | 10000 | 2724 | 234.000 | 3.00 |
| 5 | 3 | 35440 | 109.378 | 0.6929 | 10000 | 3832 | 273.000 | 2.34 |
| 6 | 3 | 35440 | 109.378 | 0.6929 | 10000 | 3832 | 275.340 | 2.34 |
| 7 | 3 | 35440 | 109.378 | 0.6929 | 10000 | 3832 | 277.680 | 2.34 |
| 8 | 3 | 35440 | 109.378 | 0.6929 | 20 | 3832 | 280.020 | 2.34 |

Table 4: Electric parameters of the proposed klystron

cavity) where is also located the maximum electric field (222 MV/m). The minimum velocity level is $-0.09^{*}c$, which fulfils the requirement on $v_{min} > -0.1^{*}c$. A summary of the klystron output is reported in Tables 2, 3 and the electric parameters of the proposed klystron are listed in Table 4.

## 5 Conclusions

In order to linearize the longitudinal space phase of the Compact Light XLS project a Ka-Band accelerating structure operating on the $\pi$ mode at the third RF harmonic with respect to the main linac RF frequency has been considered. This structure can work with a high accelerating gradient around up to 150 MV/m. In this contribution, a klystron amplifier has been also investigated to feed this linearizer structure. We presented the design of the high-power DC gun, of the beam focusing channel and of the RF beam dynamics.

The design software KLyC has been used for the computer aided design of this structure. With this tool efforts have been made to design a sufficiently short structure to be accommodated inside a considerably narrow focusing magnet, characterized by a high perveance as required by the beam power output, while ensuring the maximum efficiency. At the same time, a minimal velocity, below -0.1 c, has been obtained to avoid electron reflections in the output cavities.

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