



The Ka-band high power klystron amplifier design program of INFN

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ABSTRACT

In the framework of the Compact Light XLS project, a short ultra-high gradient linearizer working on the third harmonic of the main linac frequency is requested. Increasing gradients and reducing dimensions are requirements for XLS and all next generation linear accelerators. Actually, ultra-compact normal conducting accelerating structures, operating in the Ka-band are required to achieve ultra-high gradients for research, industrial and medical applications, with electric field ranging from 100 to 150 MV/m. To fulfill these strong requirements, the R&D of a proper Ka-band klystron with high RF power output and a high efficiency is mandatory. This contribution reports the design of a possible klystron amplifier tube operating on the TM_{010} mode at 36 GHz, the third harmonic of the 12 GHz linac frequency, with an efficiency of 42% and a 20 MW RF power output. This contribution discusses also the high-power DC gun, the beam focusing channel and the RF beam dynamics.

1. Introduction

High-brightness electron beams are required for a great number of applications, including advanced accelerators linear colliders, X-ray Free-Electron Lasers (FELs) and inverse Compton scattering accelerators for research, compact or portable devices for radiotherapy, mobile cargo inspections and security, biology, energy, and environmental applications. This new generation of linear accelerators is highly demanding in terms of accelerating gradients. In the framework of the INFN-LNF, SLAC (USA), KEK (Japan), UCLA (Los Angeles) collaboration, the Laboratori Nazionali di Frascati (LNF) is involved in the modeling, development and test of short RF structures devoted to the acceleration with high gradient electric field by means of metal devices made with hard copper or copper/silver (Cu/Ag) alloys. A significant fraction of the Research and Development (R&D) has been devoted to studies of new manufacturing techniques to improve the maximum sustainable gradients by short normal conducting hard RF structures. This aim was achieved by minimizing the breakdown and the dark current for extremely demanding applications and for the construction of millimeters high power high frequency cavities [1–4]. In addition, the present R&D using cryogenic copper technology (working conditions ~ 77 K) will enable a variety of new applications, including linear colliders and free electron laser acceleration, thanks to accelerating gradients over twice the value achieved with the existing technologies [5,6].

In the framework of the “Compact Light XLS” project [7], a short ultra-high gradient linearizer working on the third harmonic (36 GHz)

with respect to the main linac frequency (11.988 GHz) operating with an accelerating gradient 150 MV/m (i.e., 15–20 MV integrated voltage range) is requested. To meet these requirements, a 36 GHz pulsed Ka-band RF power source with a pulse length of 100 ns and a repetition frequency in the (1–10) Hz range with an output power of (50–60) MW is necessary.

In addition, as the source parameters required for the Ultra-Compact Cryogenic C-band linac-based XFEL design [6] are similar, this klystron can also be used for this project.

It is well known that the klystron amplifier design requires a proper choice of the perveance, beam and pipe diameters, a focusing magnetic field, bunching cavities and an output cavity system and an ultra-vacuum system. High electron beam power densities, RF electric gradient in cavity gaps, and stresses on the ceramic window are just few of the most critical issues to deal with. As a consequence, the choice of the global power source parameters has to be consistent with the obtainable amplifier efficiency and its operation stability. One of the more challenging aspects of the high power klystron design is the electron gun device. The electron beam perveance is defined as $K = IV^{-3/2}$ where I and V are beam current and voltage. A high perveance results in a lower electronic efficiency due to the higher space charge that affects the beam quality. Since the efficiency is defined as the ratio between the output power and the DC beam power, the voltage is proportional to the $(P_{out}/(\eta K))^{2/5}$. Accordingly, we have to find the best perveance to achieve a satisfactory efficiency with a manageable voltage [8].

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In the high frequency high power source, the bunching section design approach is almost conventional, while the output cavity is a multi-cell system allowing power dissipation reduction, breakdowns, etc., while achieving the needed pulsed power [9–11]. Consequently, the objective is to design an output circuit, which has the lowest gap fields, consistent with the satisfactory efficiency and the operational reliability.

A roughly estimation for the efficiency of the two-cavity klystron operating on the third harmonic of the fundamental mode (TM_{010} mode) is around 18%, about a factor 3 less than the klystron efficiency operating at the fundamental mode. A design on the 34 GHz Ka-band klystron tube amplifier by achieving more than 10 MW output power with a theoretical efficiency estimation exceeding 22% has been proposed [12]. Basically, in this design the RF system consists of a X-band input cavity, two X-band bunching cavities, a complicated multi-cell extended interaction output cavity and a 5.5 mm diameter beam pipe. In the output coupler, the output cavity is a TM_{030} mode cavity while others are TM_{010} choke mode cavities.

The strong motivation of this work is to propose a high power source with a Ka-band harmonic klystron with the output cavities working only on the fundamental TM_{010} mode at 36 GHz to optimize klystron conversion efficiency and provide a peak output power of 20 MW in a 100 ns pulse width, to be used to feed the linearizer while working at 150 MV/m of accelerating gradient as requested by all challenging next generation projects [6,7,13,14]. For this reason we are also planning to finalize the traveling wave (TW) or the Standing wave (SW) linearizer design as well as the RF power source that will be able to produce up to (50–60) MW input power by using a SLED system [15,16].

The paper is organized as follows: Section 1 discusses the preliminary analysis of the design, Section 2 the electron gun and the focusing magnet system, Section 3 the interaction structure, Section 4 the conclusions of the paper.

2. Preliminary analysis on the design approach

An average accelerating gradient of 150 MV/m needs at least 50 MW peak RF power. With a 48 MW beam power (480 kV-100 A) and a 100 ns pulse width, 42% of klystron efficiency to achieve 20 MW peak RF power on the third harmonic is necessary. Finally, using a SLED system with a compression factor 4 [15,16], the RF peak output on the third harmonic is 80 MW for feeding the linearizer.

The motivation of this work is to propose a high power source Ka-band klystron in the millimeter wavelength domain for providing a power of 10–20 MW. In designing the klystron amplifier, the choice of a proper electron gun has to be considered, taking with particular attention to achieve a high compression factor with a minimum transverse size. The electron gun relies on the Pierce-type cathode for generating a converging and good laminar electron beam, to be matched with a focusing magnetic field and manipulated in the interaction region by klystron cavities to maximize the RF device power output. Assuming a perveance of $0.3 \cdot 10^{-6} \text{ A/V}^{3/2}$, a factor of 2 less than other design [12], with a 480 kV pulsed beam voltage, an efficiency of about 42% can be achieved.

Since this high voltage could generate breakdowns, an appropriate design in the electron gun regions to withstand these high voltages is mandatory. Cathodes used in standard high power klystrons working in ultra-high vacuum conditions are good candidates. For a long lifetime the cathode loading has to be limited well below 15 A/cm^2 , too. A cathode diameter in the 8–10 cm range can be considered to this aim. The interaction between the electron beam and the RF cavities system and the Brillouin limit [13] are two important parameters in order to control the beam radius limit for design requirements. For getting the optimum klystron efficiency, the beam pipe dimension has to be comparable to the beam radius [8]. Moreover, in order to minimize the beam potential depression, a stable and reliable electron beam with a minimal scalloping behavior is also required.

3. Electron gun and focusing magnet system design

The electron gun design has been carried out by using the numerical code CST [17]. Intense investigations carried out as function of the geometry anode–cathode, beam current and applied voltage showed a high electrostatic beam compression but with an excessive electric field on the focusing electrodes. As an example, with a 480 kV-210 A beam, or a μ -perveance of $0.657 \text{ A/V}^{3/2}$, a 24 MV/m electric field on the focusing electrode, is obtained. Furthermore, to obtain a good klystron efficiency, it is also very difficult to make the beam parameters of the klystron to comply to the design requirements. A dedicated and detailed report on the electron gun design will be discussed in a forthcoming paper. However, with a 480 kV beam voltage, 100 A beam current (or a μ -perveance of $0.3 \text{ A/V}^{3/2}$), an electrostatic beam compression ratio of 1488:1, the maximum electric field on the focusing electrodes is about 200 kV/cm, a reasonable value for assuring a safety operational margin working with a 100 ns pulse length. Analytical checks confirmed the electron gun numerical investigation [18].

Special attention was given also to the matching among the current generated by the electron gun, the focusing magnetic system and the beam radius dimensions to optimize the beam current transport. The external magnetic field provides both beam focusing and coupling between the electrons and the RF cavities system. Since the output cavity works on the fundamental TM_{010} mode at 36 GHz and its radius is about 3.6 mm, the beam pipe has to be much smaller and comparable to the allowed beam radius for the klystron efficiency optimization [8].

Beam tracking simulations of the 480 kV-100 A gun showed that the electron beam is confined within 1 mm radius with a maximum magnetic field of about 32 kG, a 1635:1 beam compression area and 2% scalloping parameter. We have decided to taper the beam pipe up to 1.2 mm radius to confine the beam radius within 1 mm along the beam pipe (see Fig. 1).

The author of [19] estimated the Brillouin limit radius (the estimation has been confirmed by numerical (CST) and experimental results in the same paper [19]),

$$r_b = \frac{0.369}{B} \sqrt{\frac{I}{\beta\gamma}} \text{ mm} \quad (1)$$

where, I is the beam current ($I=100 \text{ A}$), β denotes v/c for relativistic particle ($\beta = 0.860$), γ stands for the relativistic mass (energy) factor ($\gamma = 1.939$) and B is magnetic field in kG ($B = 32 \text{ kG}$). In addition numerical (CST) and experimental results confirm this estimation.

In the region where magnetic field is 32 kG, the beam radius is $\sim 1 \text{ mm}$ and considerably higher than Brillouin limit which is about 0.1 mm. Likewise for the region where the field is 7 kG, the beam radius is $\sim 2.2 \text{ mm}$ which again is much bigger than the Brillouin limit which is about 0.4 mm.

We have also obtained the same limit for the beam radius by considering Caryotakis approach [20].

We have shown in both cases ($B = 7 \text{ kG}$ and 32 kG) the beam radius is far away from the Brillouin limit.

The design parameters of the electron gun, including the magneto-static beam compression area, are listed in Table 1 and in Fig. 1 the 3D model of electron gun, beam trajectory along the propagation direction and magnetic field distribution are reported in Fig. 1.

The magnetic field distribution reported in Fig. 1c shows a small peak of 7 kG and a constant magnetic field of 32 kG along the 300 mm long pipe. This choice allows to achieve a smaller beam radius suitable to insert the whole system of RF cavities system as it will be described in the next section.

In the region where the magnetic field is 7 kG the beam radius is $\sim 2.3 \text{ mm}$, higher by a factor of 4 than the Brillouin limit. In the region where the field is 32 kG, the beam radius is $\sim 1 \text{ mm}$, again larger by a factor about 8 than the Brillouin limit, which is $\sim 0.1 \text{ mm}$.

We point out also that with the μ -perveance of $0.657 \text{ A/V}^{3/2}$, a common value for modern klystron, we could obtain 235 A, although

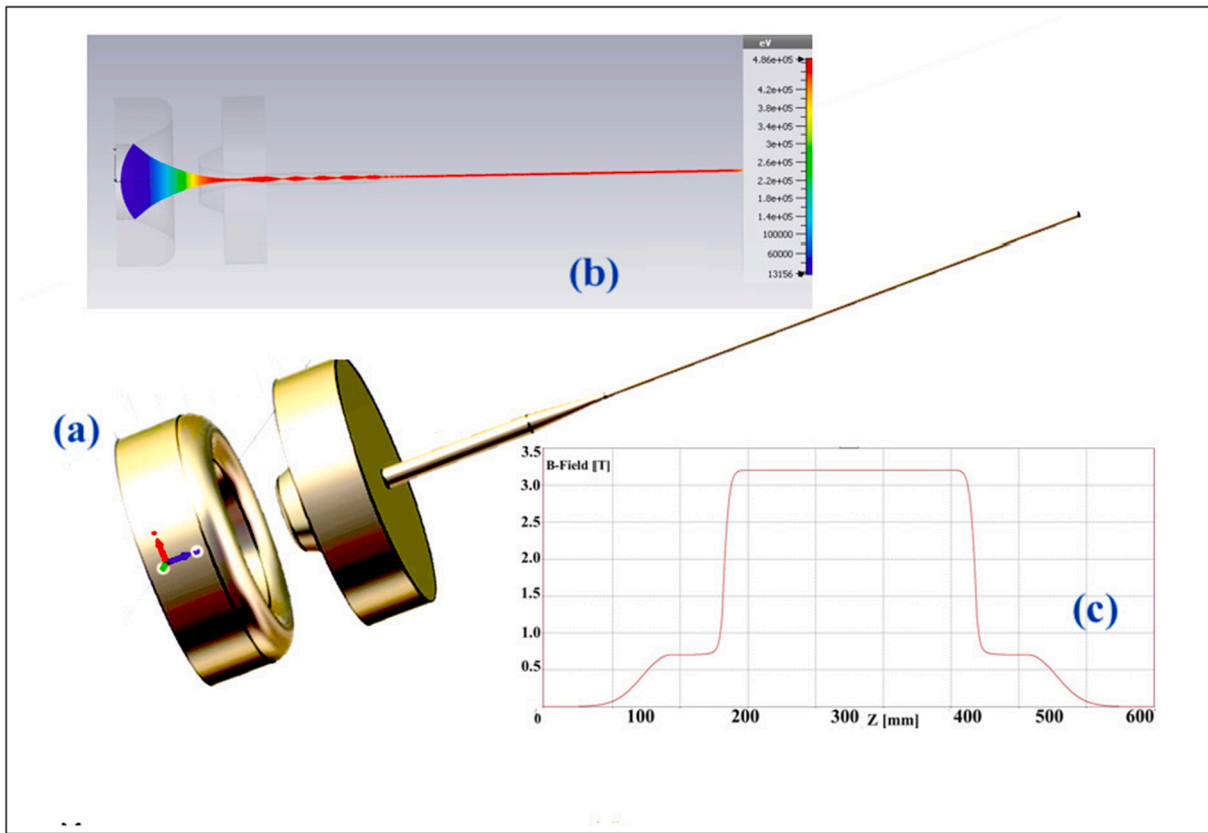


Fig. 1. (a) 3D model of the gun and beam pipe. (b) Beam trajectory along the propagation direction (c) axial magnetic field distribution.

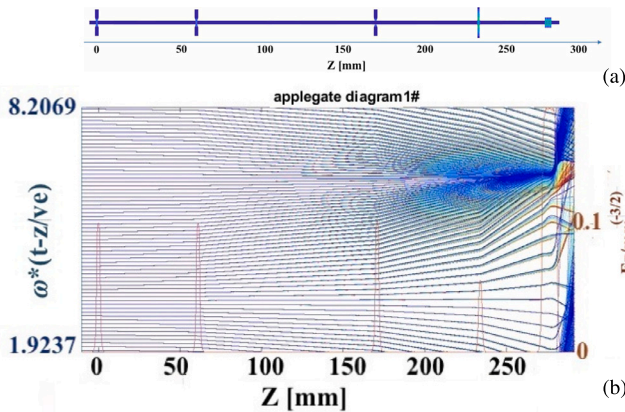


Fig. 2. (a) Layout of the interaction structure; (b) the Applegate diagram (distance-time plot) is superimposed to the cavity axial electric field normalized to the maximum value given by the cavity eigenmode calculation.

with an efficiency much smaller than with a beam current of ~ 100 A. Reducing the μ -perveance from $0.657 \text{ A/V}^{3/2}$ to $0.3 \text{ A/V}^{3/2}$, we maintained the cathode-anode shapes [21] while increasing the distance between them in order to obtain a beam current of 100 A maintaining a satisfactory value of the electric field on the focusing electrodes [22].

The high magnetic field can be achieved by using super conducting solenoids. The same principle has been fabricated and tested at the Yale Beam Physics Laboratory (BPL) [23,24]

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

Table 1

Design parameters of the gun with focusing magnetic field along the beam axis.

Design parameters	
Beam power [MW]	48
Beam voltage [kV]	480
Beam current [A]	100
μ -perveance [$\text{A/V}^{3/2}$]	0.3
Cathode diameter [mm]	76
Pulse duration [μ s]	0.1
Minimum beam radius in magnetic system [mm]	0.98
Nominal beam 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
Pipe radius [mm]	1.20

of 800 W. 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 in a drift tube of 1.2 mm radius. The first four cavities operate in the first harmonic of the input signal while the last four cavities are a system of coupled cavities operating at the third harmonic of the drive frequency of 36 GHz. If compared to a single cell, this strategy allows to extend the beam to a wave interaction, while distributing the output energy inside a larger volume with the consequent advantage on the surface electric fields.

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. While the beam crosses the cavity gap, the velocity of the beam is modulated. The ratio of change in beam voltage is regulated by

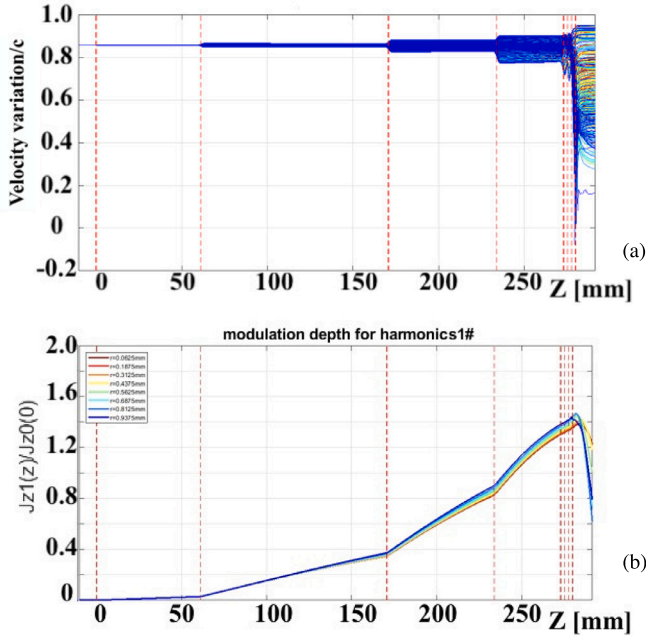


Fig. 3. (a) The velocity variation; (b) The modulation depth of the 1st harmonic current at different beam substrates as a function of the longitudinal coordinate z . In the vertical axis, J_{z1} is for the 1st harmonic current normalized to the dc current, J_{z0} .

the beam to wave coupling coefficient (in accelerator science, transit time factor). The general definition of M is given [8]

$$M(\beta_e) = \frac{\int E_z \cos(\beta_e z) dz}{\int E_z dz}. \quad (2)$$

In order to maximize the signal distortion to enhance the 3rd harmonic content, the enhancement of the signal is mostly associated to the last two cavities.

The klystron buncher is a cylindrical resonant cavity with radius of 8.43 mm, operating in a quasi TM_{010} mode. In order to put under cut-off the 36 GHz oscillation, to get a satisfactory depression potential and avoid spurious modes of oscillation in the beam pipe with the particle interaction, the beam pipe has been chosen with a radius aperture of 1.2 mm [8,25]. These sizes can be achieved with Control Numeric Computer (CNC) machining, while the third harmonic cavities, i.e. the catchers cavities operating at Ka band frequency, which have a radius of 3.37 mm can be realized using Electrostatic Discharge Machining (EDM).

Numerical behavioral characterization of high efficiency klystron amplifier in large signal regimes requires specialized computer codes. 1D codes like AJDisk [26], and KlypWin, operate in an idealized environment, allow for a very fast (1–10 min) computation time. 2D codes like TESLA, Klys2D and FCI, account for all radial effects and economize on computation time (10 min–1 h). Particle-In-Cell (PIC) codes like MAGIC2D/3D and CST Particle Studio provide complete and self-consistent field solution therefore the computation time could be very large (10–100 h) [25]. A new 1D/2D complex simulation code has been developed by Dr. Cai and Syrathev at CERN to operate with a precision close to that of a PIC code with the benefit of discrete approach that reduces the computation time to 5–30 min. The used approach assumes that radial beam expansion has little effect on the RF power production; therefore, only longitudinal beam dynamic is enough to be considered in the klystron optimization routine. In such approximation, PIC approach can be successfully replaced by the model based on the generic large signal theory. Such a theoretical model was developed and implemented into new large signal 1D and 2D klystrons simulation code called KlyC [25]. It has been demonstrated by a large number

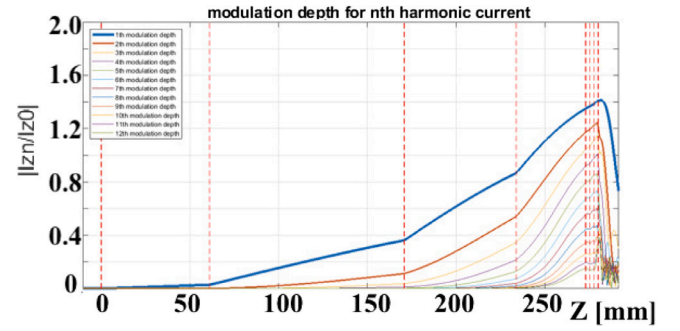


Fig. 4. The modulation currents normalized to the dc current, J_{z0} as function of the longitudinal coordinate z . In the vertical axis J_{zn} is the higher harmonic current, which is calculated for different harmonic ($n = 1, 2, \dots, 12$).

of examples on high efficiency klystron simulations, operating in very difficult computational condition needed to get high efficiency that the KlyC code is equivalent to a PIC code when cavity geometries or cold fields are used as source data for the beam dynamics computation. The KlyC simulations were evaluated by comparison with the CST PIC code, and both codes showed a good (within 1%) agreement, while KlyC was significantly (about 100 times) faster [25]. The first two gain cavities are designed to operate with a low gain for a good linearity in the amplification. The gap is enough large to have a good coupling with the beam. The gain is regulated by detuning the 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 ($R/Q = 34 \Omega$), 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 klystron design software KLyC [25] 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 to avoid electron reflections in the output cavities.

The layout of the interaction structure is shown in Fig. 2a and the phase grouping is showed in Fig. 2b where the Applegate diagram is superimposed to the cavity axial electric field normalized to the maximum value given by the cavity eigenmode calculation.

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 $-0.09c$ 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. 3a.

The modulation depth of the 1st harmonic current at different beam substrates is shown in Fig. 3b. 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 of the beam. It has been observed that, with respect to reentrant cavities, in pillbox cavities the gap electric fields for different radial positions exhibit reduced intensity spread. In order to exploit this feature and to have a reduced gain, needed for the last stage, the last gain cavity is a low R/Q Pill-box cavity.

Table 2

Resume of Klystron Output.

Simulated quantity	Output data
P_{out} [kW]	19983.804
Gain [dB]	43.976
Balanced RF efficiency ^a	0.416
Min v/c	-0.094

^aRF efficiency accounting for the space charge power [25].**Table 3**

Simulated quantities of the proposed klystron.

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 4

Electric and geometric parameters of the proposed klystron.

CN ^a	HN ^b	F_0 [MHz]	R/Q [Ω]	M	Q_e	Q_{in}	z [mm]
1	1	12 000	110.412	0.9617	30	4947	0.000
2	1	12 067	108.495	0.9614	10 000	4935	61.063
3	1	12 378	114.715	0.9587	10 000	4981	170.796
4	1	12 147	33.589	0.9576	10 000	2724	234.000
5	3	35 440	109.378	0.6929	10 000	3832	273.000
6	3	35 440	109.378	0.6929	10 000	3832	275.340
7	3	35 440	109.378	0.6929	10 000	3832	277.680
8	3	35 440	109.378	0.6929	20	3832	280.020

^aCavity number.^bHarmonic number.**Table 5**

KlyC parameters.

Number of beams	8
Space charge field order	12
Electron wavelength division number	256
RF wavelength division number	128
Iteration residual limit	6
Max iterations	64
Iteration relaxation	0.12

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^o 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. 4). In this figure, J_{zn} is the higher harmonic current, which is calculated for different harmonic ($n = 1, 2, \dots, 12$).

The output power is 20 MW at the 3rd harmonic. The max gap voltage is 471 kV, which is produced in the second last output cavity (7th cavity) where is also located the maximum electric field (222 MV/m). The minimum velocity level is $-0.09c$, which fulfills the requirement on $v_{min} > -0.1c$. A summary of the klystron output is reported in Tables 2 and 3. The electric parameters of the proposed klystron are listed in Table 4.

The presented simulations have been obtained by setting the following KlyC parameters [25] (Table 5)

5. Conclusions

In order to linearize the longitudinal space phase of the Compact Light XLS project a Ka-Band accelerating structure operating on the π mode at the third RF harmonic with respect to the main linac RF

frequency has been considered [27–29]. The linearizer can work with a high accelerating gradient around up to 150 MV/m [30]. 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. Two dielectric windows could be also designed following standard rules [31].

Finally, it should be noted that the PIC simulation is required to check the beam transportation with RF, the tube stability, and also to implement the design of the output coupler. This will be performed in the forthcoming paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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