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Updates on the INFN High Power Ka-band klystron amplifier design program

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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 regime ranging from 100 to 150 MV/m are required to achieve ultra-high gradients for research, industrial and medical applications. To fulfill these strong requirements, the R&D of a proper Ka-band klystron with 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.

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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 $\sim$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 is necessary.

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, an ultra-vacuum system, a coupling coefficient, a plasma frequency reduction factor and a beam collector. 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 of the output power to the input one, 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 maneageable voltage [8].

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 loss 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 preliminary theoretical efficiency estimation of the third harmonic klystron operating on the TM_{01} mode is around 18%, about a factor 3 less than the standard klystron efficiency. 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} mode chocke 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: the section 1 discusses the preliminary analysis of the design, the section 2 the electron gun and the focusing magnet system, section 3 the interaction structure, the section 4 the conclusions of the paper.

2 Preliminary analysis on the design approach

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 $10^{-6} A/V^{3/2}$, a factor of 2 less than other design [12], with a 480kV 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

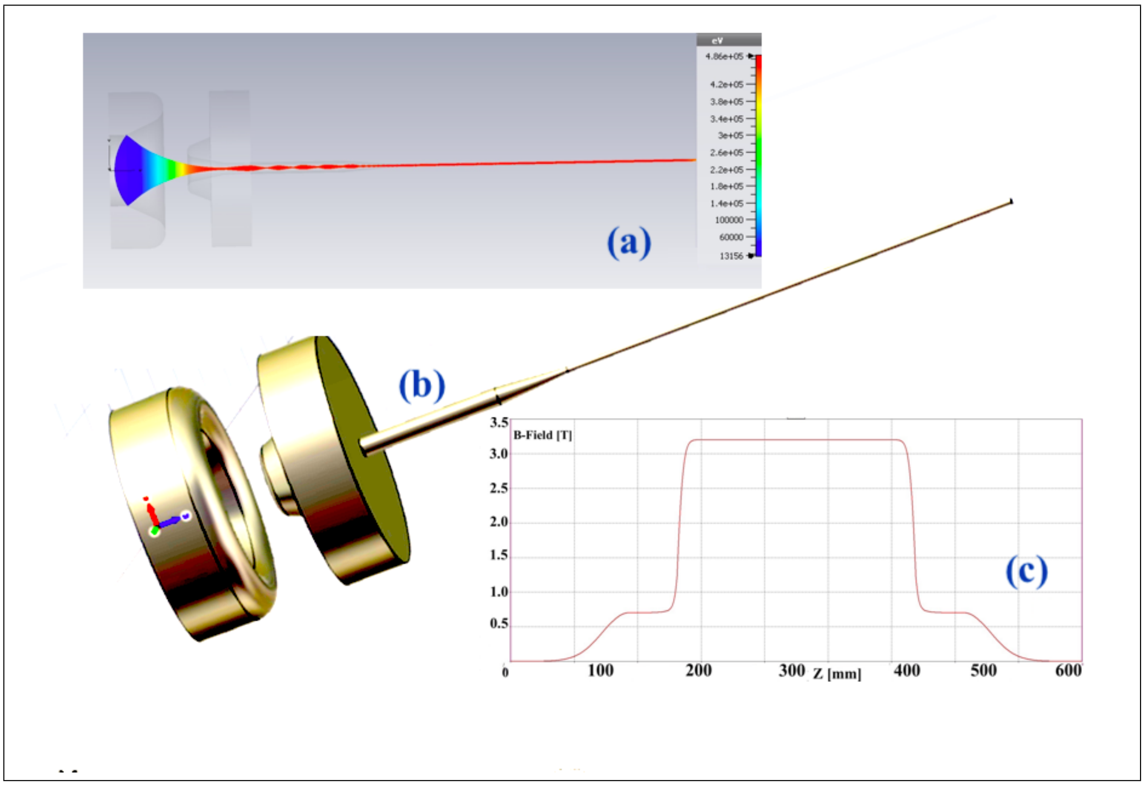

Figure 1: a) 3D model of the gun and beam pipe. b) Beam trajectory along the propagation direction c) axial magnetic field distribution.

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.

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.

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 $A/V^{3/2}$, 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 b discussed in a forthcoming paper. However, with a 480 kV beam voltage, 100 A beam current (or a perveance of 0.3 $AV^{-3/2}$), 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.

The design parameters of the electron gun, including the magnetostatic 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.

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 [μ sec]	0.1
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 π

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

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 allow 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 ∼2.3 mm, higher by a factor of 4 than the Brillouin limit. In the region where the field is 32 kG, the beam radius is ∼ 1 mm, again larger by a factor about 8 than the Brillouin limit, which is ∼ 0.13 mm.

We point out also that with the μ-perveance of 0.657 $A/V^{3/2}$, a common value for modern klystron, we could obtain 235 A, although with an efficiency much smaller than with a beam current of ∼100 A. Reducing the μ-perveance from 0.657 $A/V^{3/2}$ to 0.3 $A/V^{3/2}$, we maintained the cathode-anode shapes [19] 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 [20].

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 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. A simple representation is in Fig. (2). 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.

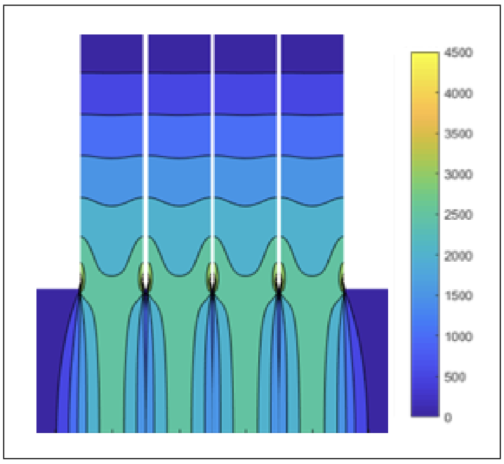

Figure 2: Axial electric field in the output structure, eigenmode solution representing the 0-mode, normalized amplitude

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

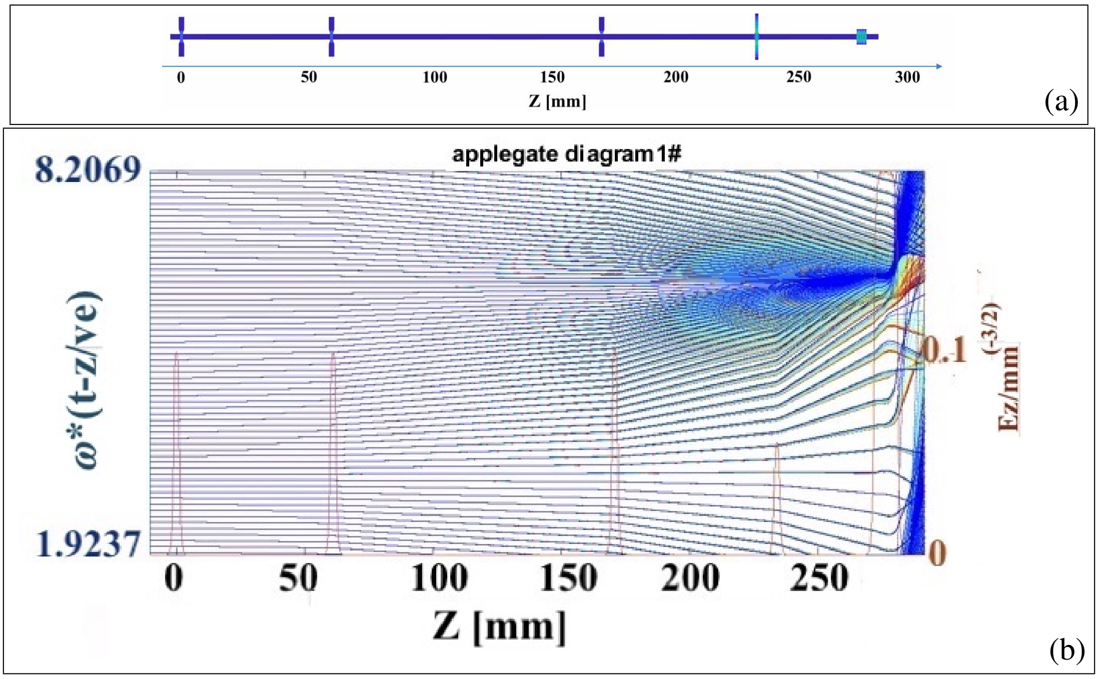

Figure 3: a) Layout of the interaction structure; b) the Applegate diagram (distance-time plot) is superimposed to the cavity axial electric field normalized to the maximum value given by the cavity eigenmode calculation.

degrading the coupling coefficient [8],

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

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 β_e is the beam propagation factor and k $=\omega/c$.

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. To operate at 36 GHz in the $2\pi/3$-like mode the design of the output coupler requires a radius aperture of 1.2 mm. 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 3.37mm 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

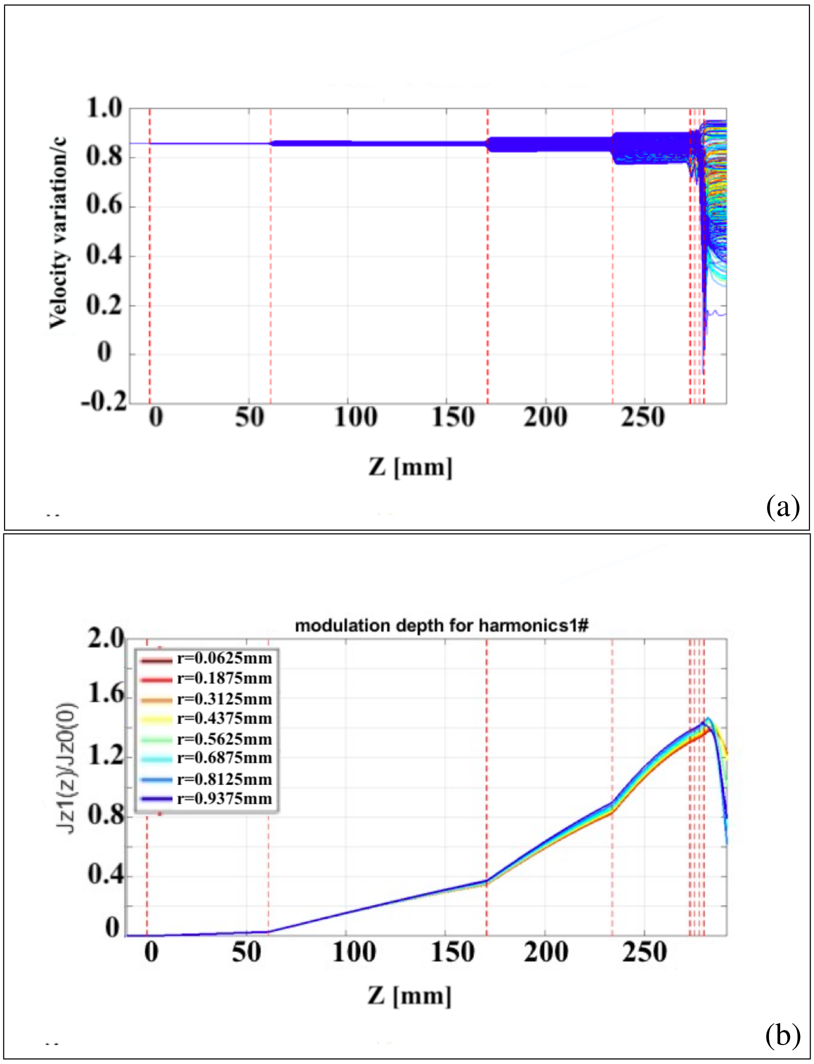

Figure 4: a) The velocity variation; b) The modulation depth of the 1st harmonic current at different beam substrates as a function of the longitudinal coordinate z. In the vertical axis, J_{z1} is for the 1st harmonic current normalized to the dc current, J_{z0}.

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 Ω), 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 [21] 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. (3a) and the phase grouping is showed in Fig. (3b) 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 -0.09 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 1^{st} 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 1^{st} harmonic content has a specific distribution on different substrates 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).

Simulated quantity	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 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 $-0.09^{*}c$, 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 π mode at the third RF harmonic with respect

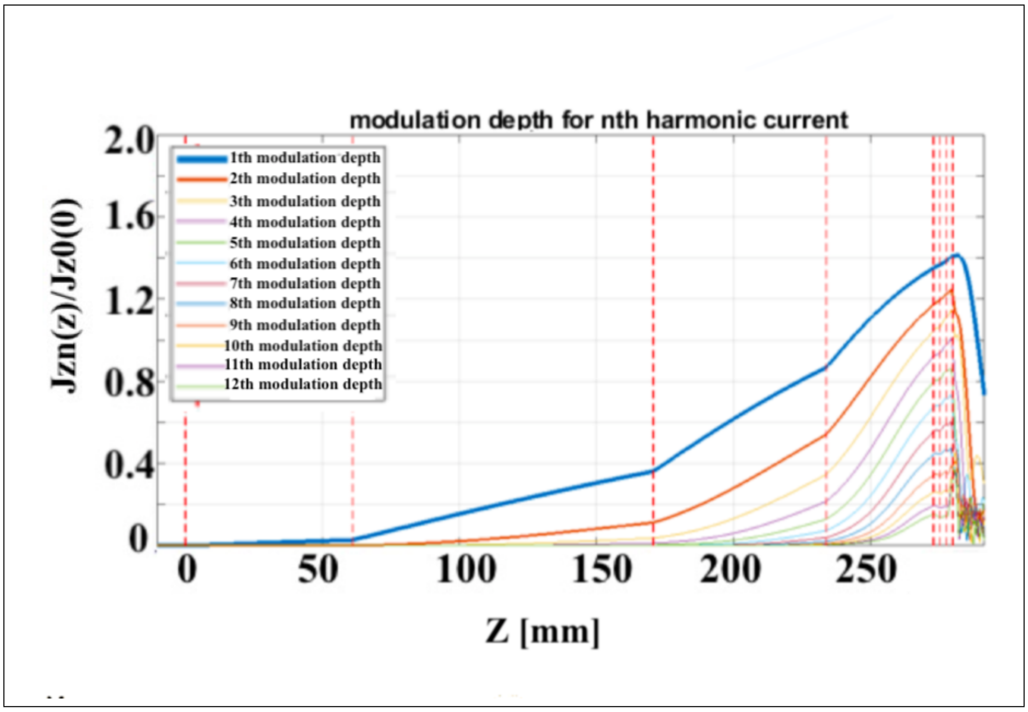

Figure 5: The modulation currents normalized to the dc current, J_{z0} as function of the longitudinal coordinate z. In the vertical axis J_{zn} is the higher harmonic current, which is calculated for different harmonic (n=1,2,..,12).

to the main linac RF frequency has been considered [22–24]. The linearizer can work with a high accelerating gradient around up to 150 MV/m [25]. 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 [26].

Acknowledgment

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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: Simulated quantities 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 and geometric parameters of the proposed klystron

References

[1] Dolgashev, V. A., et al. “Innovative compact braze-free accelerating cavity.”Journal of Instrumentation 13.09 (2018): P09017.

[2] Dolgashev, V. A., et al. “Materials and technological processes for High-Gradient accelerating structures: new results from mechanical tests of an innovative braze-free cavity.”Journal of Instrumentation 15.01 (2020): P01029.

[3] B. Spataro et al., “High Gradient RF Tests of Welded X-Band Accelerating Structure”, Manuscript submitted for publication in PRAB.

[4] Othman, Mohamed AK, et al. “Experimental demonstration of externally driven millimeter-wave particle accelerator structure”. Applied Physics Letters 117.7 (2020): 073502.

[5] Rosenzweig, J. B., et al. “Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources.”Physical Review Accelerators and Beams 22.2 (2019): 023403.

[6] Rosenzweig, J. B., et al. “An ultra-compact x-ray free-electron laser.”New Journal of Physics 22.9 (2020): 093067.

[7] http://www.compactlight.eu/Main/HomePage

[8] Caryotakis, George. “High power klystrons: Theory and practice at the Stanford linear accelerator center.”Stanford Linear Accelerator Center, SLAC-PUB 10620 (2004): 139.

[9] Lee, T. G., et al. “The design and performance of a 150-MW klystron at S band.”IEEE transactions on plasma science 13.6 (1985): 545-552.

[10] Eppley, Kenneth. “Design of a 100 MW X-band klystron.”Proceedings of the 1989 IEEE Particle Accelerator Conference, Accelerator Science and Technology. IEEE, 1989.

[11] Fazio, Michael V., and K. Habiger. “Design for a One-Gigawatt Annular-Beam Klystron.”No. LA-UR-00-3793. Los Alamos National Lab., Los Alamos, NM (US), 2000.

[12] Chang, X., et al. “Ka-Band High Power Harmonic Amplifier for Bunch Phase-Space Linearization.”North American Particle Accelerator Conf.(NAPAC’19). 2019.

[13] Yakovlev, V. P., and O. A. Nezhevenko. “Limitations on area compression of beams from pierce guns.”AIP Conference Proceedings. Vol. 474. No. 1. American Institute of Physics, 1999.

[14] Ferrario, M., et al. “EuPRAXIA SPARC-LAB Design study towards a compact FEL facility at LNF.”Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 909 (2018): 134-138.

[15] Ivanov, O. A., et al. “Active quasioptical Ka-band rf pulse compressor switched by a diffraction grating.”Physical Review Special Topics-Accelerators and Beams 12.9 (2009): 093501.

[16] Ivanov, O. A., et al. “Active microwave pulse compressor using an electron-beam triggered switch.”Physical review letters 110.11 (2013): 115002.

[17] CST studio suite 2018. www.cst.com.

[18] Behtouei, Mostafa, et al. “Initial design of a high-power ka-band klystron.”Journal of Physics: Conference Series. Vol. 1596. No. 1. IOP Publishing, 2020.

[19] Behtouei, Mostafa, et al. “Electron Gun and Magnetic Systems Studies for a 36 GHz Klystron Amplifier”, Technical report, INFN-Publication, INFN-20-10/LNF.

[20] Behtouei, Mostafa, et al. “Initial electromagnetic and beam dynamics design of a Klystron amplifier for Ka-Band Accelerating Structures.”INFN-19-12/LNF, 2019. Available online: http://www. lnf. infn. it/sis/preprint/detail-new. php, 2019.

[21] Cai, Jinchi, Igor Syratchev, and Zening Liu. "KlyC: Large Signal Simulation Code for Klystrons."submitted to IEEE TED (2017).

[22] Behtouei, M., et al. "A Ka-band linearizer TW accelerating structure for the Compact Light XLS project."Journal of Physics: Conference Series. Vol. 1596. No. 1. IOP Publishing, 2020.

[23] Behtouei, Mostafa, et al. "New Analytical derivation of Group Velocity in TW accelerating structures."Journal of Physics: Conference Series. Vol. 1350. No. 1. IOP Publishing, 2019.

[24] Behtouei, Mostafa, et al. "A SW Ka-Band Linearizer Structure with Minimum Surface Electric Field for the Compact Light XLS Project."Nuclear Instruments and Methods in Physics Research Section A. Vol. 984, 2020 .

[25] Nezhevenko, O. A., and V. P. Yakovlev. "Traveling-wave accelerating test structure at 34.3 GHz."Proceedings of the 1999 Particle Accelerator Conference (Cat. No. 99CH36366). Vol. 5. IEEE, 1999.

[26] A. Variola, private communication.