ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB020

COMPACT ULTRA HIGH-GRADIENT KA-BAND ACCELERATING STRUCTURE FOR RESEARCH, MEDICAL AND INDUSTRIAL APPLICATIONS

L. Faillace†, INFN-Milan, Milan, Italy
B. Spataro, A. Variola, INFN- LNF, Frascati, Italy
M. Behtouei, SBAI-University of Rome, Roma, Italy
G. Torrisi, INFN-LNS, Catania, Italy
V.A. Dolgashev, SLAC, Menlo Park, USA

Abstract

Technological advancements are strongly required to fulfil demands for new accelerators devices from the compact or portable devices for radiotherapy to mobile cargo inspections and security, biology, energy and environmental applications, and ultimately for the next generation of colliders. In the frame of the collaboration with INFN-LNF, SLAC (USA) we are working closely on design studies, fabrication and high-power operation of Ka-band accelerating structures. In particular, new manufacturing techniques for hard-copper structures are being investigated in order to determine the maximum sustainable gradients above 150 MV/m and extremely low probability of RF breakdown. In this paper, the preliminary RF and mechanical design as well as beam dynamics estimations for a Ka-Band accelerating structure at 35 GHz are presented together with discussions on practical accelerating gradients and maximum average beam current throughput.

INTRODUCTION

Nowadays, linear accelerators (linacs) are being used for numerous applications in many different areas [1]. Both direct electron beams or X-rays from target conversion are employed. In research, high accelerating gradients are sought for producing ultra-bright and high-energy (>GeV) electron beams for linear colliders as well as FELs, Compton sources, etc. In the medical area, medium-energy (4-25 MeV) and low average current (10 nA – 1 μA) electrons and X-rays (200-500 cGy/min at 1m with a flux in the range 10^{7-8} photons/s/mm^2) are used for cancer imaging and treatment (radiotherapy) as well as radioisotopes production (electron energy up to many tens of MeV's and average current up to few mA's). In industry, medium-energy and high average power electron beams (10-150 mA average beam current) are utilized for material processing (up to 150 mA) and sterilization (10 mA). In the security field, cargo scanning often employs medium energy X-rays (10 MeV, 0.1-1mA). For environmental applications, medium-low energy (0.7-5MeV) electron beams (5-10 mA) are used for water, flue gas treatment and so on.

Although hundreds of linacs are sold every year, mainly for industrial and medical applications, these structures mostly operate either in S-Band (~3 GHz) or in X-Band (~9 GHz). Most of the linacs which use S-Band structures can be very bulky and large robotic systems are needed for operation, representing a crucial issue especially for medial applications.

We propose here a compact linear accelerating structure in Ka-Band (~35 GHz) able to achieve ultra-high gradient accelerating gradients (up to 150 MV/m) and therefore it allows to obtain high beam energies in ultra-compact foot prints (e.g. a factor of ten smaller than S-Band and a factor of three shorter than X-Band devices). The proposed Ka-Band accelerator can be either operated, depending on the specific application, either in Standing-wave (SW) or Traveling-wave (TW) mode. In SW configuration, the linac usually works in the π accelerating mode but more often in the π/2 mode for most areas listed above. On the other hand, in TW configuration the most common operation mode is the 2π/3 with a cell-to-cell phase-shift of 120 degrees.

Initially, the Ka-Band linac was thought as a higher harmonics linac for the linearization of the electron beam for the Compact Light project [2], discussed in a later section. Nevertheless, we also propose it as a table-top and inexpensive accelerator for medical and industrial applications. Due to the small geometric dimensions, the maximum average electron current is lower than lower frequencies and it is therefore perfectly suitable for low-to-high energy, low average power applications.

More details about the RF characterization of the accelerating structure is found in [3].

PRELIMINARY RF DESIGN

The preliminary RF design of the Ka-Band linear accelerator was carried out with the 3D numerical codes HFSS and CST. The main RF parameters are given in Table 1.

Table 1: Structure Main RF Parameters

Main RF Parameters	Value
Frequency	35.982 GHz
Accelerating Gradient	Up to 150 MV/m
Eff. Shunt Impedance	158 MΩ/m
Quality Factor Q_0	4110
Cell length L_c	2.9 mm

† luigi.faillace@mi.infn.it

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB020

In Fig. 1, a 2D plot of the main accelerating cell, electrically coupled, operating in the TM_{010}-like mode is shown. The color map of the electric field distribution is plotted (accelerating gradient of 150 MV/m). The surface electric field is lowered by using an elliptically shaped iris.

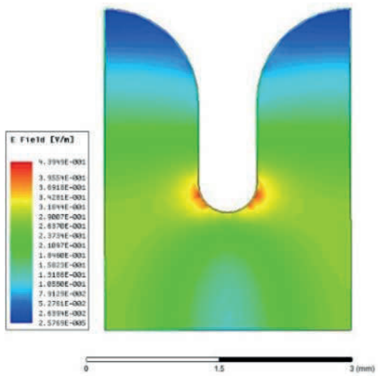

Figure 1: Electric field distribution of the TM_{010} mode.

DESIGN FOR INDUSTRIAL AND MEDICAL APPLICATIONS

The maximum beam current inside an accelerating structure strongly depends on the geometric dimensions (transverse size and length *L*), that scale linearly with the operating frequency *f*. In particular, it is estimated that the max current is proportional to $(f/L)^{-1/3}$ and $(f/L)^{-1/2}$ for TW and SW linacs, respectively.

In the following sections, we give an estimation of the max output average beam current and the preliminary RF and beam dynamics design as well as initial engineering consideration for the proposed Ka-band linac.

Estimation of Maximum Available Beam Power

The phenomenon of beam break-up (BBU), mainly due to the excitation and amplification of the first dipole deflecting mode (TM_{110}-like), is a major cause of beam instability that limits the maximum current that can be supported inside an accelerating structure. An estimation of the threshold current I_{th} for SW linacs is given by [4]:

$$I_{th} \approx \left(\frac{\pi}{L}\right)^2 \frac{\lambda_d \beta\gamma (mc^2/e)}{4 Q_L r_\perp / Q} f(x)$$

where L is the linac length, λ_d is wavelength of the first dipole mode, β and γ are the relativistic factors, mc^2 is the particle rest energy, Q_L is the loaded quality factor of the deflecting mode, $r_\perp$ is the transverse effective shunt impedance per unit length. $f(x)$ is a function of x= $\beta\gamma/\beta_i\gamma_i$ and for large values of x, i.e. for an output beam energy much higher than the input energy ($\beta\gamma >> \beta_i\gamma_i$), it flows that $f(x) \sim 1/3$.

For the Ka-band structure, we derive a peak beam current threshold that in the worst-case scenario (trapped deflecting mode) is equal to I_{th}~70 mA. Such limit can be noticeably raised, for example, by reducing the $r_\perp/Q$ with side cuts on the cells or by reducing Q_L if proper coupling of the dipole mode out of the linac is performed. In the TW case, the threshold current is slightly lower but it can be raised to the SW case by properly choosing the linac parameters and in particular by increasing the group velocity Vg since I_{th}~Vg.

The average output current depends on many factors discussed in the next sections, such as the input RF power specifications and the maximum average RF power that can be dissipated by the cooling system of the structure. The breakdown limit to the max accelerating gradient is not an issue in this case, since we envision operation at around 10 MeV for industrial and medical applications. This means that, assuming a safe accelerating gradient of 80 MV/m, the linac length is only L=12.5 cm.

The Ka-Band RF Power Source

An innovative RF power supply at ~35GHz was demonstrated more than a decade ago, the magnicon.[5] which produced a peak output RF power of 17 MW with a gain of 47 dB at a pulse length up to 1.5 μs and a repetition rate up to 5 Hz. We have recently started a research activity on the re-design of the old magnicon in order to improve the output power and the repetition rate at least up to 100 Hz. Nevertheless, the advantage of operating in Ka-band permits operation with relatively low RF power (~5 MW), as shown in Table 2, where we list the main parameters for the 35 GHz linac for industrial and medical applications.

Table 2: Ka-Band Linac for Industrial/Medical Applications

Main RF Parameters	Value
Frequency	35.982 GHz
Accelerating Gradient	~ 80 MV/m
Linac Length	12.5 cm
Peak RF power	~ 5 MW
Pulse Length	Up to 1.5 μs
Repetition Rate	Up to 100 Hz
Duty Cycle	$1.5*10^{-4}$
Output Energy	Up to 10MeV
Output Avg. Beam current	Up to 10 μA

The availability of input RF peak power of medium RF power (5MW) with repetition rates between 10 and 100 HZ, allows in theory to obtain an average beam current of 1-10 μA, which makes the accelerating structure suitable for medium-energy, low current/power applications like medical diagnosis and therapy of tumors as well as intra-operative radiotherapy.

It has to be noted that pulse lengths of the order of 1μs are reasonable, as explained in a later section. Indeed, such pulse lengths are compatible with an accelerating gradient of 80 MV/m, since the estimation of the breakdown rate (BDR), that is a major cause of failure of an accelerating structure, is below the safety threshold.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB020

Electron Gun Injector Beam Dynamics

We have started the design of a thermionic electron gun for a dual purpose: to be used as the injector of an upgraded version of the magnicon RF amplifier and to be used as the electron injector of the accelerating structure. In the first case, the cathode-anode voltage is about 500 kV and it produces a beam current of about 200 A and beam power up to 100 MW. In the second case, we plan to apply around 30 kV voltage or higher to increase the beam capture inside the Ka-Band linac

In Fig. 2, the preliminary simulation of the electron gun with CST is shown. The beam has a compression ratio of about 100.

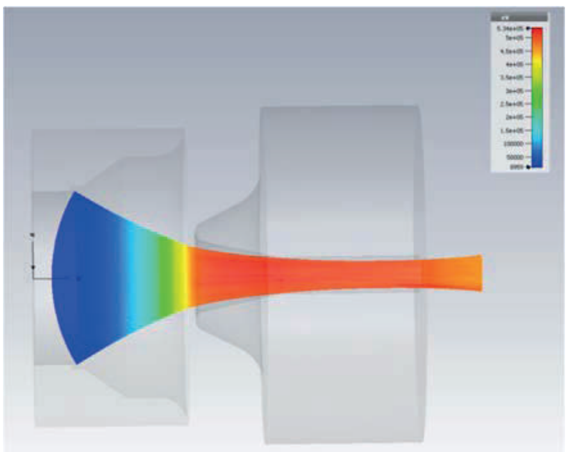

Figure 2: preliminary electron gun design from CST. Beam trajectories are shown.

HIGH ENERGY APPLICATIONS

As anticipated in the introduction, we propose the Ka-Band linear accelerator also for high-energy applications, such as the CompactLight European project, a compact free-electron laser.

The cell geometry is shown in Fig. 1. Here, we discuss the breakdown rate (BDR) limit and cooling system design. The BDR limits the maximum accelerating gradient achievable inside the linac for a given RF pulse length.

Breakdown Rate Limit

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

For the Ka-Band linac, we estimated that Sc~5 MW/mm2 (below safety threshold of about 6.3 MW/mm2) for an accelerating gradient Eacc=100 MV/m and RF pulse length (flat top) of 50 ns. It is possible to increase Eacc up to 150 MV/m which gives Sc~8 MW/mm2 which is somewhat more critical but near the threshold. For the lower energy and longer pulse case, in order to keep constant the BDR value, the max accelerating gradient should not exceed 80 MV/m for a 1.5 μs pulse width, as we discussed in regard to Table 2.

Thermal and Stress Analysis

The preliminary thermal and stress analysis was also carried out in CST. In Fig.3, we show the result of the single cell where a cooling system with longitudinal pipes is assumed. The simulation is performed assuming a gradient of E_{acc}=150 MV/m with a corresponding average power per unit length of about 2 kW/m. The water flux is 3l/min.

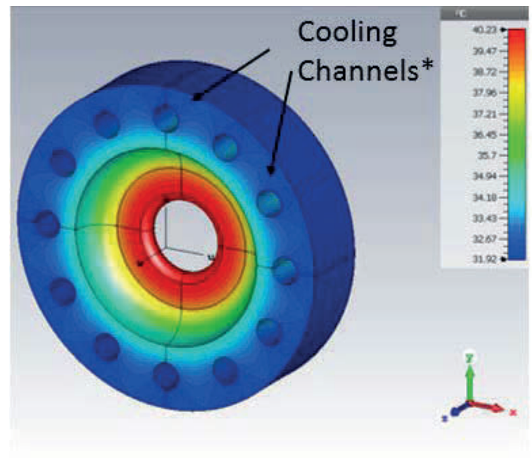

Figure 3: Thermal simulation of the single cell from CST.

The hot spot is about 40 °C (standard operation) and it can be lowered by adjusting water flux and water temperature. The consequent stress analysis shows a yield strength (Von Mises) < 20 MPa which is below the safety threshold for copper (~ 70 MPa). The corresponding maximum displacement is about 1 μm (i.e. frequency shift is negligible or tunable).

MACHINING

It has been experimentally demonstrated that hard copper is able to stand ultra-high gradients unlike high-temperature treated one [7, 8]. 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 [9]. As for medium-low energy industrial/medical applications, we plan to use the same approach but we are also considering an alternative approach as a novel clamping technique [10].

CONCLUSIONS

We have presented the preliminary design of a compact linear accelerator in Ka-Band (~35 GHz) which is well suited for industrial and medical applications where a low-medium energy and low average current electron beam is required (from a few MeV's up to a few tens of MeV's with average beam currents up to few tens of μA's). These applications cover the diagnosis and therapy of tumors (both direct electrons or X-rays from e-beam

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB020

conversion through a target), as well as any other type of diagnostics where longer exposure times are not an issue.

Moreover, operation at ultra-high gradients (up to 150 MV/m) are predicted for high-energy projects, such FELs, Compton sources, etc.

We are planning to finalize the linac design as well as engineering of the RF power source that will be able to produce a few MW for low energy applications and up to 40-50 MW (possibly with a SLED) for high energy projects.

REFERENCES

[1] M. Vretenar, "Applications of Particle Accelerators in Europe", EuCARD2.

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

[3] M. B. Behtouei, M. Migliorati, L. Palumbo, B. Spataro, and L. Faillace, "New Analytical Derivation of Group Velocity in TW Accelerating Structures", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper MOPGW030, this conference.

[4] T. Wangler, *"RF Linear Accelerators"*, Copyright 2008 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

[5] O. A. Nezhevenko, J. L. Hirshfield, E. V. Kozyrev, M. A. LaPointe, S. V. Shchelkunov, and V. P. Yakovlev, "Status of 34 GHZ, 45 MW Pulsed Magnicon", in *Proc. 21st Particle Accelerator Conf. (PAC'05)*, Knoxville, TN, USA, May 2005, paper WPAT026.

[6] K. N. Sjobak, A. Grudiev, and E. Adli, "New Criterion for Shape Optimization of Normal-Conducting Accelerator Cells for High-Gradient Applications", in *Proc. 27th Linear Accelerator Conf. (LINAC'14)*, Geneva, Switzerland, Aug.-Sep. 2014, paper MOPP028, pp. 114-116.

[7] V.A. Dolgashev, "*High Gradient, X-Band and above, Metallic RF structures"*, presented at the 2nd European Advanced Accelerator Concepts Workshop (EAAC 2015), La Biodola, Isola d'Elba, Italy, 13-19 September 2015.

[8] V. A. Dolgashev, Y. Higashi, B. Spataro, S. G. Tantawi, and A. D. Yeremian, "Status of High Power Tests of Normal Conducting Single-Cell Standing Wave Structures", in *Proc. 1st Int. Particle Accelerator Conf. (IPAC'10)*, Kyoto, Japan, May 2010, paper THPEA060, pp. 3810-3812.

[9] H. Zha, A. Grudiev, "*Design of the Compact Linear Collider main linac accelerating structure made from two halves"*, Phys. Rev. Accel. and Beams 20, page 042001, Vol. 20, Iss. 4, published 14 April 2017. doi/10.1103/PhysRevAccelBeams.20.042001

[10] V.A. Dolgashev, L. Faillace, B. Spataro, *"Innovative compact braze-free accelerating cavity"*, Journal of Instrumentation JINST 13, no. 09 (2018): P09017.