Proposal of a Compact High-Gradient Ka-Band Accelerating Structure for Medical and Industrial Applications

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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. New manufacturing techniques for hard-copper structures are being investigated in order to determine the maximum sustainable gradients around 150 MV/m and extremely low probability of RF breakdown. In this paper, the initial studies on the RF and mechanical design for a compact Ka-Band accelerating structure are presented as well as preliminary beam dynamics estimations.

1. Introduction

Nowadays, linear accelerators (linacs) are being used for numerous applications in many different areas, as listed in Table 1 [1-5]. Both direct electron beams and 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 10⁷-8 photons/s/mm²) 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, 0.1-1 mA).

For environmental applications, medium-low energy (0.7-5 MeV) 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 medical 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 \( \pi \) accelerating mode but more often in the \( \pi/2 \) mode for most areas listed above. On the other hand, in TW configuration the most common operation mode is the 2\( \pi/3 \) with a cell-to-cell phase-shift of 120 degrees.

Initially, the Ka-Band linac was thought as a higher harmonics linac, discussed in a later section, for the linearization of the electron beam for the CompactLight project [5, 6]. 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 linacs operating at lower frequencies. Therefore, the aim of this study is to estimate the maximum electron beam current that can be achieved in a compact Ka-Band linac suitable for low-to-high energy, low average power applications. In order to confirm the analytical estimation of the maximum beam current, beam dynamics simulations are performed.

### 2. Preliminary RF Design

The preliminary RF design of the Ka-Band linear accelerator, introduced in [6, 7] was carried out with the 3D numerical codes HFSS and CST [8, 9]. The group velocity of the RF accelerating cavity was estimated by the analytical derivation published in [10]. The main RF parameters are given in Table 2.
Table 2: 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 Q0           | 4110             |
| Cell length Lc              | 2.9 mm           |

In Figure 1, a 2D plot of the main accelerating cell, electrically coupled, operating in the TM\textsubscript{010}-like mode is shown. The color map of the electric field distribution is plotted (accelerating gradient of 150 MV/m). In order to lower the surface electric field, an elliptical shaped iris has been being optimized.

![Electric field distribution](image1)

![Magnetic field distribution](image2)

Figure 1: Electric field distribution (left) and Magnetic field distribution (right) of the cavity TM\textsubscript{010} mode. Field units are arbitrary in this simulation.

3. 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 $(\lambda/L)^4$ and $(\lambda/L)^2$ for TW and SW linacs, respectively. In the following sub-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.

3.1. 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\textsubscript{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 [11]:

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

where $L$ is the linac length, $\lambda_d$ is wavelength of the first dipole mode, $\beta$ and $\gamma$ 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 $f(x) \sim 1/3$. 

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For the Ka-band structure, we derive a peak beam current threshold that in the worst-case scenario (trapped deflecting mode) is equal to \( I_{th} \approx 70 \text{ mA} \). Such limit can be noticeably raised, for example, by reducing the \( r_{\|}/Q \) 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 \( V_g \) since \( I_{th} \approx V_g \).

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 \( L = 12.5 \text{ cm} \).

3.2. The Ka-Band RF Power Source

An innovative RF power supply at \(~35\text{GHz}\) was demonstrated more than a decade ago, the magnicon [12], which produced a peak output RF power of 17 MW with a gain of 47 dB at a pulse length up to 1.5 \( \mu \text{s} \) 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 3, where we list the main parameters for the 35 GHz linac for industrial and medical applications.

| Main RF Parameters            | Value                        |
|-------------------------------|------------------------------|
| Frequency                     | 35.982 GHz                   |
| Accelerating Gradient         | \(~ 80 \text{ MV/m}\)       |
| Linac Length                  | 12.5 cm                      |
| Peak RF power                 | \(~ 5 \text{ MW}\)          |
| Pulse Length                  | Up to 1.5 \( \mu \text{s} \) |
| Repetition Rate               | Up to 100 Hz                |
| Duty Cycle                    | \(1.5 \times 10^{-4}\)      |
| Output Energy                 | Up to 10 MeV                 |
| Output Avg. Beam current      | Up to 10 \( \mu \text{A}\)  |

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 \( \mu \text{A}\), 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 1\( \mu \text{s}\) are reasonable. 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 [13].

3.3. 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.
4. Initial Beam Dynamics Simulation

The initial beam dynamics simulations were carried out with the PARMELA code [14]. The electron gun injector is a 15kV DC e-gun (DC electron beam) which produces a 250 mA electron beam. The DC Input electron beam has a gaussian transverse profile (spot size = 0.2 mm diameter, hard edge). At this stage, for the accelerating linac we have chosen a side-coupled biperiodic structure, composed of 24 cells, with an overall length of only L~10cm. The cell iris diameter is 2mm and no focusing solenoid is employed. In Figure 2, we show the 3D rendering of the side-coupled biperiodic linac. The accelerating structure geometry will be optimized for the final design.

![3D rendering of the side-coupled biperiodic linac.](image)

In Figure 3, the on-axis accelerating electric field used in beam dynamics simulations is plotted. The gradient is about 80 MV/m.

![On-axis accelerating electric Field used in beam dynamics simulations.](image)

The beam dynamics simulations confirmed the output electron beam pulse current, which resulted to be around 71 mA, as estimated in section 3. The beam energy gain was about 7 MeV, which is a good value for industrial and medical applications since it avoids neutron activation.

5. Cavity machining

It has been experimentally demonstrated that accelerating structures made out of hard copper are able to stand higher gradients compared with high-temperature treated ones [15, 16]. We plan to machine the
proposed Ka-Band linac in two halves with TIG welding of the outer surfaces [17], avoiding high-temperature processes like brazing or diffusion bonding in order to keep the copper hard. The promising RF and beam dynamics results lead us to plan to fabricate a prototype by using an alternative approach such as a novel clamping technique which was optimized to fabricate practical cost-effective multi-cell accelerating cavities [18, 19].

6. 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 and X-rays from e-beam conversion through a target), as well as any other type of diagnostics where longer exposure times are not an issue. We plan to fabricate and test a welded prototype made out of two halves.

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