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CW ROOM TEMPERATURE ACCELERATING STRUCTURES

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Abstract

To this day CW linear electron accelerators were based only on expensive and bulky (embedded in a cryostat) superconducting accelerating structures. CW regime can in principle be realized with normal conducting structures provided the shunt impedance is high. Such structures can be designed using dielectrics (ultra-pure ceramics in C-band and diamond in mm-waves) with ultra-low loss tangent (~10^{-6}). The use of dielectrics allows to concentrate the electromagnetic energy density in the dielectric region and thus minimize fields and ohmic loss on metallic walls. The thermal loss in dielectric can be relatively low given the loss tangent is small. We report here the design of structures with shunt impedance on the order of ~10^4 MΩ/m, which is several orders of magnitude higher than shut impedance in copper structures in GHz and THz range. High shunt impedance makes it possible to accelerate electrons to 1 MeV using kW-level CW RF sources like magnetrons in C-band and gyrotrons in THz range. Such CW accelerators will find applications in sterilization, food irradiation, industrial radiography and cargo inspection.

INTRODUCTION

Compact 1 MeV range CW linear accelerators with low voltage kW-scale RF source are usually considered as superconducting accelerating cavities with involved and expensive cryogenic setup [1, 2]. This paper presents the concept of dielectric loaded accelerating (DLA) structure, which provides a comparable accelerating gradient at the room temperature and kW-scale RF power supply. Extremely high quality factor and high shunt impedance can be realized in the DLA due to ultralow-loss (tanδ= 10^{-5} - 10^{-6}) dielectrics. Among these dielectrics are diamond, which has unique low losses and high thermal conductance at millimeter waves [3], and TiO_2-doped Al_2O_3 ceramics those tangent delta is unprecedentedly small in C-band [4].

A MILLIMETER WAVE 300 GHZ CW DIAMOND STRUCTURE

In a photonic band gap like structure, synchronism is controlled by the internal dielectric layer [5]. Periodic layers of dielectric are mainly responsible for low RF power leakage. Scheme of the proposed structure is shown in Fig. 1. The dielectric structures of this type can be produced by a femtosecond laser ablation system. To compose the structure, one should take dielectric disks, ablate Bragg ring grooves and the channel for electrons in each disk, and then stack disks together. This technology makes the structure periodic, although this periodicity is not used for Cerenkov synchronism.

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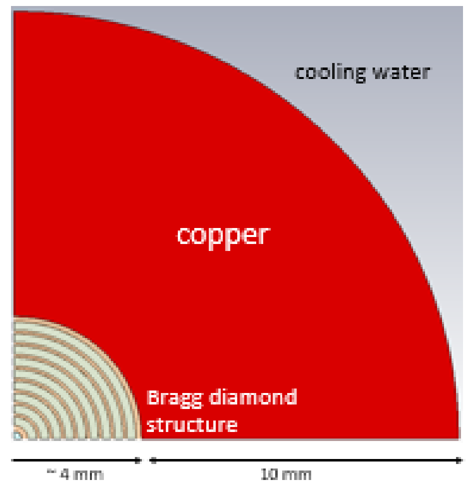

Figure 1: Scheme of the 300 GHz accelerating structure.

Table 1: The Parameters of the High Shunt Impedance DLA Structure

Parameter	Value
Dielectric material	Diamond
ε_r	5.7
tan(δ_{loss})	1×10^{-5}
Beam channel	∅0.3 mm
Number of Bragg layers	9
Accelerator type	Travelling wave
Group velocity	0.19c
Operation frequency	300 GHz
Q_0	7×10^4
R_{sh}	3500 MΩ/m

List of parameters for the CW structure is presented in Table 1. In the Fig. 2 one can see the field of accelerating eigenmode in such structure with the periodicity equal to a quarter of the wavelength. To obtain 1 MeV acceleration we consider the 10 cm long structure with accelerating field 10 MV/m. According to the Table 1 such structure requires a power source (gyrotron) having CW power 3 kW. The structure has high shunt impedance, being higher than shunt impedances of the metallic structures at the same frequency, because significant ohmic losses in metal are avoided and volume loss in a dielectric is tolerable due to low loss tangent of diamond. We estimate that the temperature rise in a core of the structure does not exceed 40° so that the thermal flux 30 W/cm² must be taken off with water cooling (Fig. 3). A CW package of the proposed structure is shown in Fig. 4 which includes water cooling channels.

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In order to power such millimeter wave structures, one can use gyrotron power sources. They are readily available at 3 kW of output power [6]. Moreover, CW gyrotrons commercially produced for ITER thermonuclear reactor or similar projects are capable to deliver 1-2 MW at 170 GHz and more than 300 kW at 250 GHz [7].

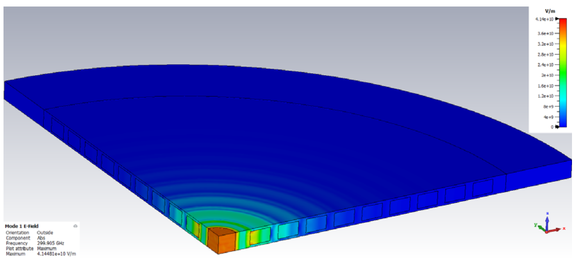

Figure 2: Eigen mode E-field distribution.

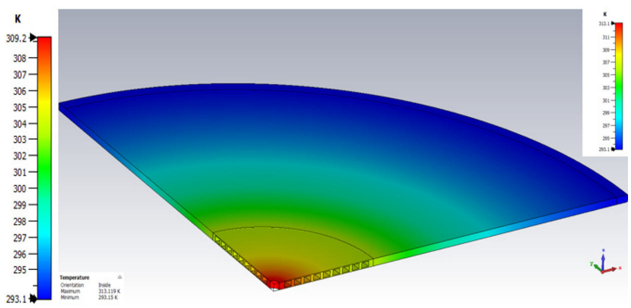

Figure 3: Temperature distribution in CW regime (30 W/cm^2).

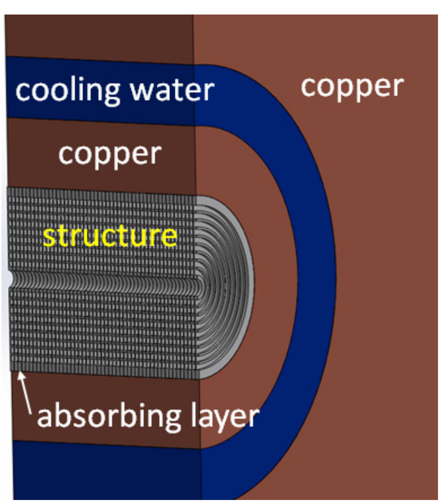

Figure 4: CW package of the structure.

A C-BAND CERAMIC CW STRUCTURE

Another structure considered for normal conducting CW operation is a dielectric loaded C-band accelerating structure. It consists of cylinders and disks with irises periodically arranged in a metallic enclosure (see Fig. 5). TM_{02n} operational mode in this structure has significantly reduced wall losses on metallic surfaces as compared to that of a TM_{01n} mode cavity.

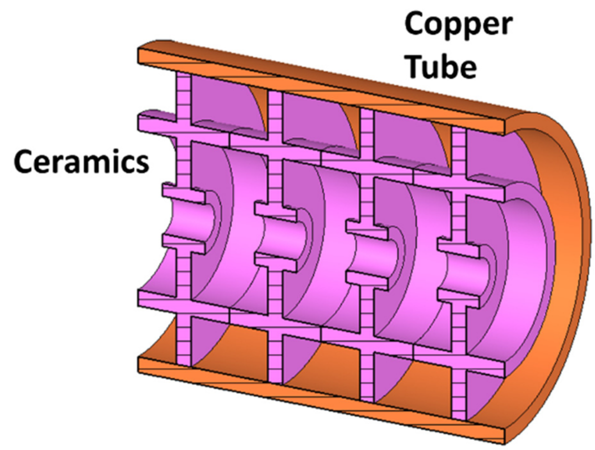

Figure 5: High shunt impedance accelerating structure loaded with low loss ceramics.

Here we consider the main parameters of regular part of a C-band (5.7 GHz) standing wave DLA structure. With the choice of π-mode the cell length is $\lambda_0/4$, where λ_0 is the free-space wavelength. The diameter of the cell strongly depends on ceramics dielectric constant. For practical design considerations, we assume to use TiO_2-doped Al_2O_3 ceramics which has the relative permittivity ε_r of 10.15 and $\tan(\delta_{loss})$ of 7.516×10^{-6} [4].

Table 2: The Parameters of the High Shunt Impedance DLA Structure

Parameter	Regular accelerating cell
Dielectric material	TiO_2-doped alumina
ε_r	10.15
$\tan(\delta_{loss})$	7.516×10^{-6}
Accelerator type	Standing wave
Operation frequency	5.711 GHz
Q_0	154,700
R_{sh}	650 MΩ/m

After optimization (by Comsol Multiphysics 2D) of the ceramics part shape and the accelerating cell dimensions the best results are summarized in Table 2.

According to our design the 1 MeV dielectric loaded accelerator with 1 MV/m accelerating gradient has only 1.53 kW thermal losses (46% is the dielectric loss). The accelerator structure internal temperature in CW regime and the copper enclosure water cooling doesn't exceed tens of degrees. Simulation results of CW regime for DLA with different ceramics loss factor are presented in Fig. 6. Maximum of internal ceramics temperature and RF power consumption for 1 MeV DLA accelerator have affordable level for ceramics with δ_{loss} up to ~ 2×10^{-5}.

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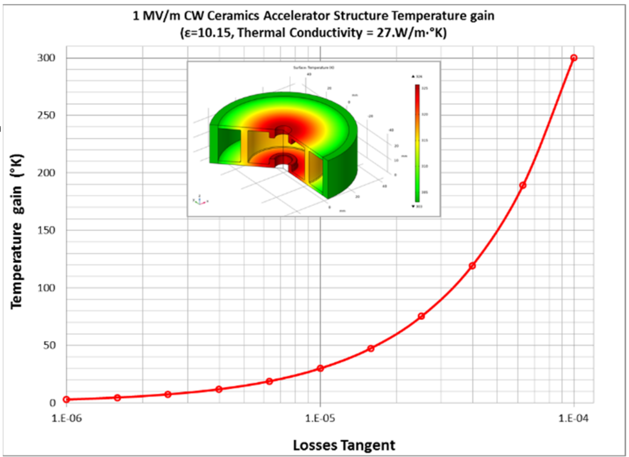

Figure 6: Internal temperature increase vs tan(δ_{loss}) value for 5.7 GHz ceramics accelerating structure (β = 1; E_{acc} = 1MV/m; $T_{Cu\ tube}$ = 303.15 °K; Ceramics thermal conductivity = 27 W/m·K).

CONCLUSION

The performed calculations show that CW room temperature dielectric loaded accelerators are possible in C-Band and at 300 GHz. These structures can be used for applications like food irradiation, sterilization, industrial radiography and cargo inspection.

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