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DESIGN AND OPTIMIZATION OF A C-BAND RF PULSE COMPRESSOR FOR A VHEE LINAC FOR FLASH RADIOTHERAPY

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Abstract

In this paper, the design of a compact C-band SLED RF Pulse Compressor for a Very High Electron Energy (VHEE) FLASH machine is presented. A spherical cavity RF pulse compressor - selected because of its compactness and relative ease of fabrication - is adopted to compress the 5 μs RF pulse, down to 1 μs obtaining a peak power gain greater than 5. Both the RF and thermo-mechanical design have been carried out, including a sensitivity study to evaluate the mechanical tolerances, possible tuning methods, and the cooling system. The main parameters of the full RF design (spherical storage cavity + mode converter/polarizer) and the final mechanical design of the structure are presented.

INTRODUCTION AND MOTIVATION

This paper presents the complete design of a C-band (5.712 GHz) spherical pulse compressor for a Very High Electron Energy (VHEE) FLASH machine. VHEE [1] irradiations could represent a valid technique to apply the FLASH effect [2] in clinical use to treat deep tumors. The design strategy and electromagnetic characteristics of the C-band linac for VHEE FLASH radiotherapy is presented in [3]. The translation of FLASH therapy - a novel cancer treatment technique, aims to control the tumor-grown sparing the healthy tissue from radiation damage increasing the therapeutic index - into clinical practice, especially for treating deep-seated tumors, necessitates achieving Very High Electron Energy (VHEE) levels within the 50-150 MeV range [4, 5]. The output beam energy can be increased by enhancing the RF peak power at the expense of RF pulse width by using a pulse compressor. This system called "SLAC Energy Doubler (SLED)", firstly proposed and applied in [6], has been widely used elsewhere according different schemes such as the Binary Pulse Compression (BPC) [7], SLED-II [8], Barrel Open Cavity (BOC) pulse compressor [9] and single spherical cavity pulse compressor [10]. The latter is also the one selected for this work: it is composed of a "special" 3 dB coupler (also acting as a circular polarizer) and a single spherical energy storage cavity (compared with the traditional SLED where two cylindrical cavities are adopted).

At La Sapienza University of Rome, in collaboration with the Italian Institute for Nuclear Research (INFN), the development of a high gradient C-Band FLASH linac demonstrator is ongoing to test and validate all the C-Band key components necessary for a VHEE Linac (see Fig. 1).

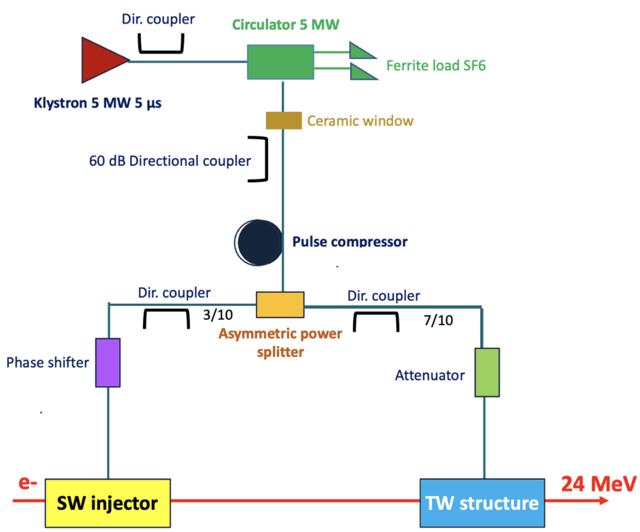

Figure 1: VHEE FLASH linac general layout [3].

DESIGN OF THE SPHERICAL PULSE COMPRESSOR

A spherical cavity RF pulse compressor – selected because of its compactness and relative ease of fabrication – is adopted to compress the RF pulse obtaining a peak power gain greater than 5. The spherical cavity pulse compressor, visible in Fig. 2 (b), is composed of a 3 dB coupler (also acting as a circular polarizer, converting the input TE_{10} mode into two, 90-deg shifted, circular TE_{11} output modes) and a single spherical energy storage cavity. These two subsystems have been firstly designed separately and then assembled together to obtain the complete device. For the spherical cavity, two degenerated TE_{114} (see Fig 2(b)) have been chosen as operating modes because of their high unloaded quality factor, Q_0= 134 × 10^3.

RF Design and Tuning

The simulated S-Parameters of the pulse compressor by CST Frequency Domain Solver are shown in Fig. 3. The minimum value of $|S_{21}|$ is about −2 dB at the frequency f_0 = 5.712 GHz. The corresponding coupling coefficient β is calculated to be about 8.

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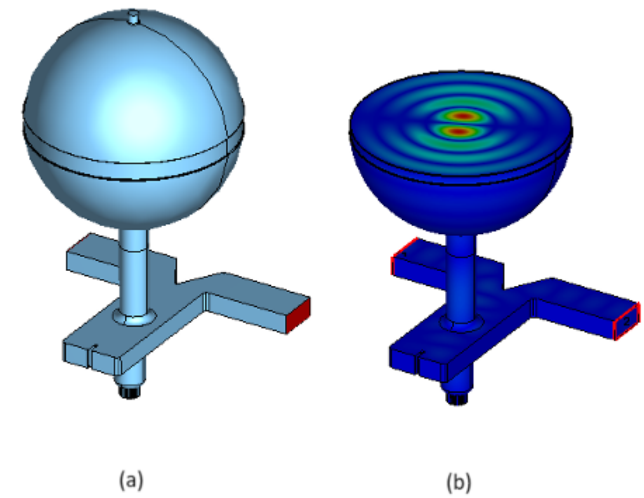

Figure 2: Spherical cavity pulse compressor: (a) RF model, (b) 2D cut showing the TE_{114} electric field.

The two subsystems of the spherical pulse compressor – that are a special 3 dB coupler (or circular polarizer) and a spherical storage cavity [11] – have been firstly designed separately by using CST MW Studio ®and then assembled together to simulate the complete device. The details of the design can be found in [12]. The operating frequency can be tuned in two ways: before brazing, by machining a circular ridge placed in the sphere equator (a removal of 1 mm in ridge thickness corresponds to a frequency shift of about −2.5 MHz); after brazing, by employing eight push-pull tuners (a penetration of 0.5 mm for the eight tuners corresponds to a frequency shift of about +0.4 MHz).

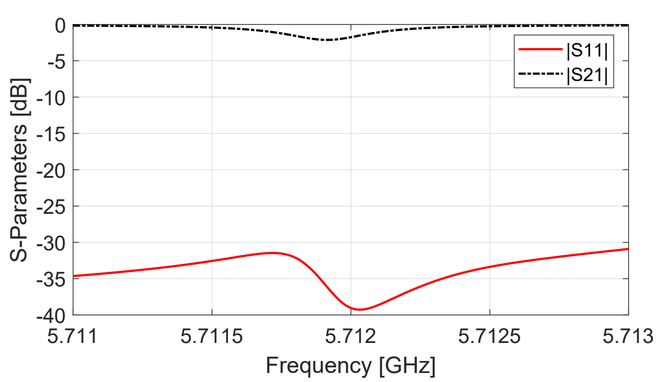

Figure 3: S-Parameters of the spherical pulse compressor full structure.

Thermal and Structural Simulations

Preliminary COMSOL thermal simulations have been performed on the simplified mechanical model visible in Fig. 4.

Considering a water temperature equal to 20° C and a water flux of 20 $\frac{L}{min}$, the temperature distribution visible in Fig. 5 has been obtained. It can be seen that the optimized cooling system allows to obtain a temperature distribution very close to the input water temperature in the spherical cavity area: further COMSOL structural simulations (not reported here) show that this temperature distribution avoids undesired structure deformations, thus having negligible effect on resonant frequency value.

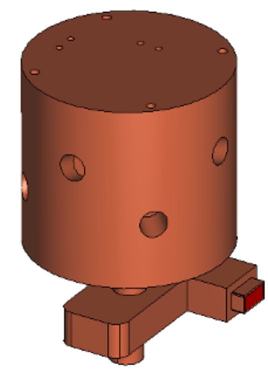

Figure 4: Spherical cavity pulse compressor: exterior view of the preliminary mechanical model.

Finally, in Fig. 6 a preliminary mechanical model of the pulse compressor structure can be observed.

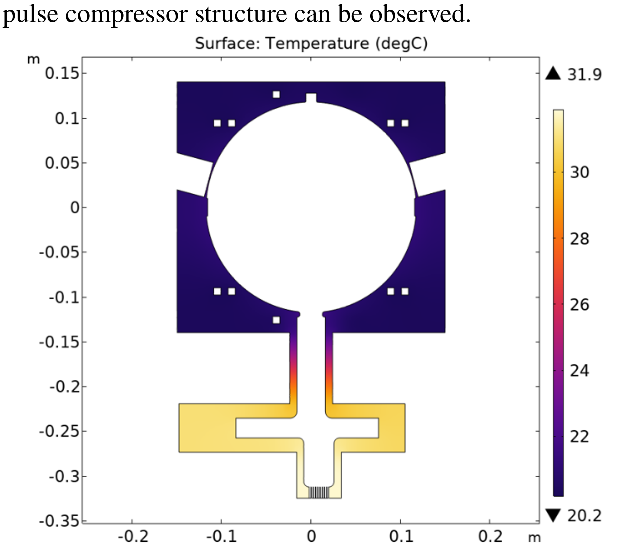

Figure 5: Temperature distribution along a pulse compressor structure cut. The designed cooling system allows to keep the temperature distribution very close to the one of the input cooling water (20° C).

Simulated Power Gain and Accelerating Gradient

The considered traveling-wave constant-impedance accelerating structure is 0.9 m long, has a shunt impedance per unit length Z_s = 100 MΩ/m, a filling time T_f = 300 ns (group velocity of 1 % speed of light) and attenuation factor α=0.5 Neper. For a RF pulse duration of 5 μs and a phase flip of 180° in the last 1.7 μs the output power shows a peak power gain above 5 (see Fig. 7). The main specifications of the spherical cavity pulse compressor are summarized in Table 1.

CONCLUSION

The design of the spherical pulse compressor, encompassing RF, thermal, and structural/mechanical simulations, has been completed. Additionally, two mechanisms - Pre-Brazing and Post-Brazing - were integrated into the structure

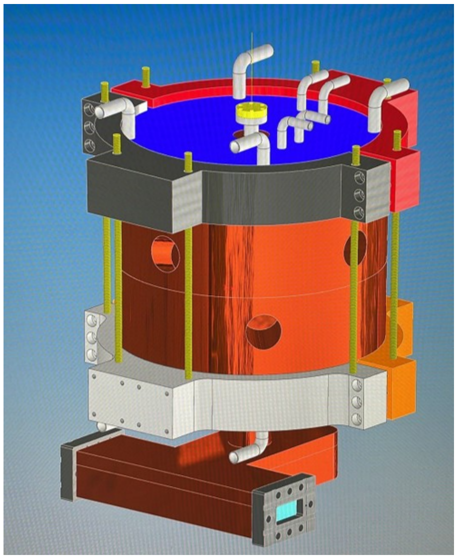

Figure 6: Preliminary mechanical model of the pulse compressor structure.

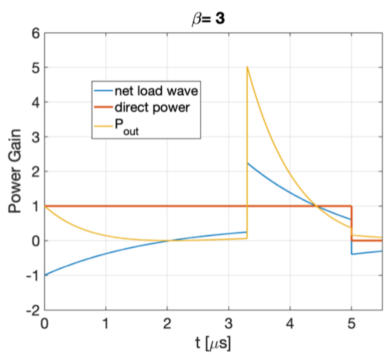

Figure 7: Input direct power (red curve), output net load wave electric field (light-blued curve) and output power P_{out}(orange curve).

Table 1: Main Specifications of the Pulse Compressor

Parameter	Design Value
Resonant frequency [GHz]	5.712
Operating mode	TE_{114}
Unloaded Quality Factor Q_0	134000
Coupling coefficient β_c	3
RF input pulse length [μs]	3
RF compressed pulse length [μs]	1.7
Peak power gain	5

to enable frequency tuning. Both techniques were incorporated into the model and simulated.

Thermal simulations, conducted using the COMSOL module, facilitated the sizing of the cooling circuit and the identification of critical areas, particularly around the coupling iris between the polarizer and spherical cavity. These thermal simulations were coupled with the COMSOL structural module to evaluate structural deformations, which were measured in the micrometer range.

The detailed mechanical drawings required for the manufacturing order have been finalized, and testing is scheduled to begin in early 2025.

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