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DEVELOPMENT OF SUPERCONDUCTING SPOKE CAVITY FOR LASER COMPTON SCATTERED PHOTON SOURCES

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Abstract

We have launched a 5-year research program to develop superconducting spoke cavity for laser Compton scattered (LCS) photon sources. For realizing a wide use of LCS X-ray and γ-ray sources in academic and industrial applications, we adopt 325-MHz superconducting spoke cavity to electron beam drivers. The spoke cavity, originally invented for ion and proton acceleration, can be used for electron accelerators, in which we can make best use of features of spoke cavity: relative compactness in comparison with a TM cavity of the same frequency, robustness with respect to manufacturing inaccuracy due to its strong cell-to-cell coupling, couplers on outer conductor for the better packing in a linac, and so on. In this paper, we present our research plan and results of cavity shape optimization.

INTRODUCTION

Low emittance and high current beam from energy recovery-linac (ERL) can generate high brightness and high quality light source. The high quality beam of ERL can also significantly improve brightness and monochromaticity of X/γ-ray generated by LCS. Nuclear resonance fluorescence (NRF) with the LCS γ-ray can be utilized to nondestructively inspect nuclear materials such as uranium, plutonium and minor actinoid elements in nuclear reactor fuels. This method can be applied for nuclear safeguards and security [1]. High brightness LCS X-ray can be expected to improve nanostructure analysis, drug development, medical diagnostics and remedy.

Practical use of these systems requires downsizing the ERL so that it is important to compact the accelerating cavity. Since the beam instability due to higher-order modes (HOMs) limits the beam current of the ERL, HOM damping is one of the critical issues for the ERL cavities. HOM damping devices such as HOM absorbers and HOM couplers for elliptical cavities tend to increase the total accelerator length since they are attached to the beam pipes. On the contrary, spoke cavities [2] have an advantage of shortening the total accelerator length by attaching HOM couplers on outer conductor [3].

Operation of a superconducting accelerator with 4K liquid helium is essential especially for industrial use. Under the condition of the same accelerating field and the same cavity length, the power loss of 325-MHz spoke cavity at 4K operation is almost equivalent to that of 1.3-GHz elliptical cavity at 2K operation.

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In addition, the superconducting spoke cavity used for ERL has following advantages.

1) The resonant frequency of spoke cavity mainly depends on the spoke length, and high cavity stiffness reduces the fluctuation of cavity resonant frequency due to microphonics. The small frequency fluctuation of the ERL cavity can decrease the required RF power and tolerance of the input coupler. This results in making the RF power supply compact.

2) When the outer size of spoke cavity is similar to that of elliptical cavity, the resonant frequency of spoke cavity is nearly half of elliptical cavity. Lower frequency can decrease the energy spread because of the narrow accelerating phase spread for the same bunch length beam. Small energy spread beam can increase the brightness of LSC X/γ-ray.

3) Cell coupling of spoke cavity is stronger than that of elliptical cavity. Stronger cell coupling makes the field flatness easier to adjust and less disturbed to increase number of cells. This increases the effective accelerating length.

For the application of spoke cavities for LCS photo sources, we have launched a 5-year research program. Optimization of the spoke cavity shape and mechanical design of the spoke cavity have been performed as the first step of the research program. The present paper describes these results.

SPOKE CAVITY SHAPE OPTIMIZATION

Since the spoke cavity shape is more complicated than the elliptical cavity shape and there are a few objectives to be optimized, multi-objective optimization using genetic algorithm is adopted to determine the spoke cavity shape [4]. We deal with two objectives of E_{peak}/E_{acc} and H_{peak}/E_{acc} which represent the ratio of maximum electric field (E_{peak}) to accelerating field (E_{acc}), and the ratio of maximum magnetic field (H_{peak}) to accelerating field. E_{acc} is defined as

$$E_{acc} = \frac{1}{L}\left|\int_0^L E_z(z)e^{-jkz}\,dz\right|, \qquad (1)$$

where $E_z(z)$ is the on-axis electric field, k is wave number, and L is total cavity length.

The electro-magnetic field calculation was performed with CST MICROWAVE STUDIO for a 2-spoke cavity model as shown in Fig.1. Each cavity shape was modeled with a set of parameters, which is called "individual", generated by the genetic algorithm program. Two

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objectives for one individual were obtained after adjusting the frequency and field flatness.

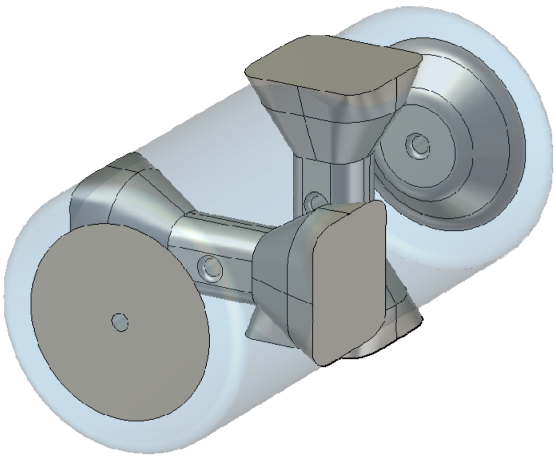

Figure 1: An example of 2-spoke cavity model used for CST MWS.

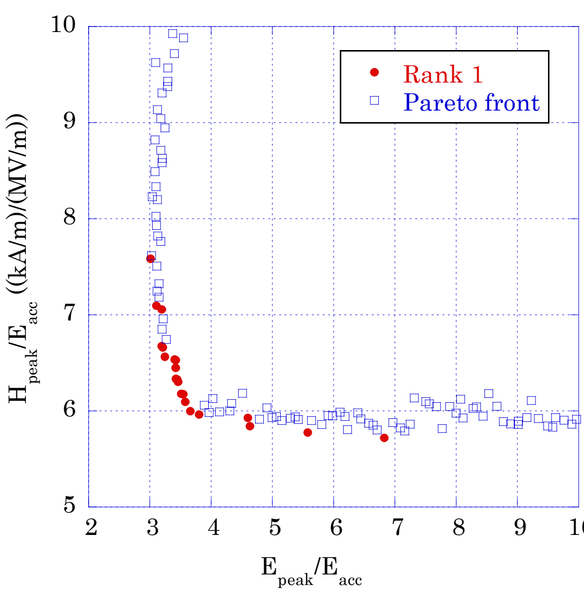

Figure 2: The Pareto front of E_{peak}/E_{acc} and H_{peak}/E_{acc} objectives.

To evaluate the objectives of all individuals the rank-based fitness assignment method was adopted. This method evaluates not with the absolute values but with counting individuals which are superior to itself. The rank one means that the individual has no other individuals which have better values for all objectives. The closer individuals to the Pareto front have the better rank regardless of the values.

Figure 2 shows the Pareto front of the spoke shape optimization. This indicates that minimum values for E_{peak}/E_{acc} and H_{peak}/E_{acc} are 3.0 and 5.7 respectively and that the minimum values are not the best parameter. The maximum E_{acc} of superconducting cavity is limited by E_{peak} and/or H_{peak}. The high magnetic field beyond the critical magnetic field destroys the superconductivity and this value is about 139 kA/m. The high electric field causes discharge to destroy the superconductivity and this value varies according to the surface condition. The maximum E_{acc} for the Pareto front data can be calculated as shown in Fig. 3 for several E_{peak}. The magnetic field limit is dominant for small E_{peak}/E_{acc}, while the electric field limit is dominant for large E_{peak}/E_{acc}. The maximum E_{acc} as a function of E_{peak} is plotted in Fig. 4. This indicates that the maximum E_{acc} increases according to E_{peak} and is constant for E_{peak} over 90MV/m due to the magnetic field limit.

We have selected the parameter of the maximum E_{acc} for 90 MV/m as shown in Table 1. The field distribution along the beam axis is shown in Fig. 5.

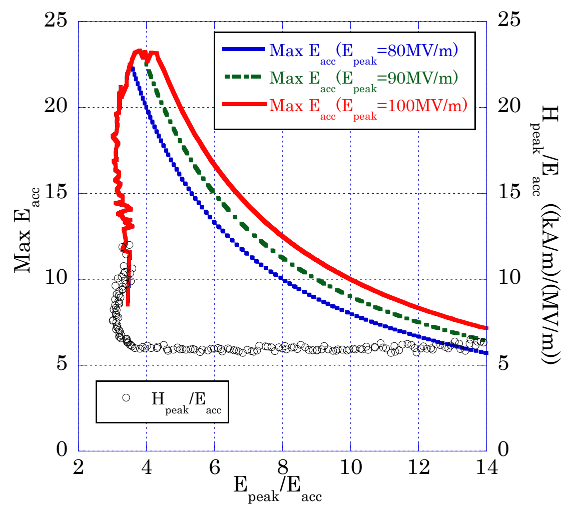

Figure 3: Maximum E_{acc} for Pareto front data for E_{peak} of 80, 90, and100 MV/m.

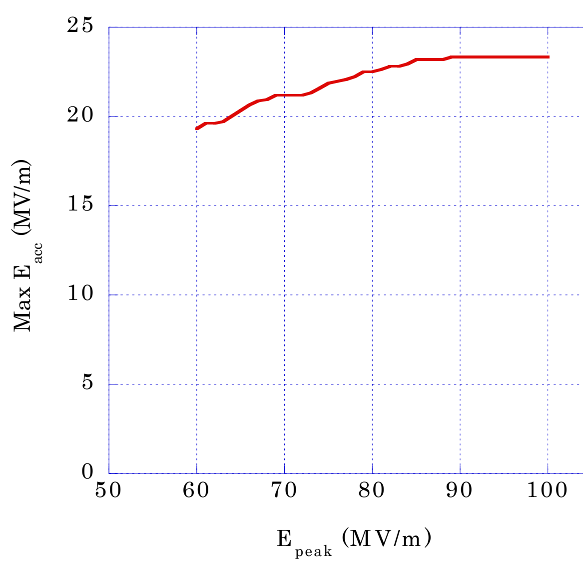

Figure 4: Maximum E_{acc} as a function of E_{peak} for Pareto front data.

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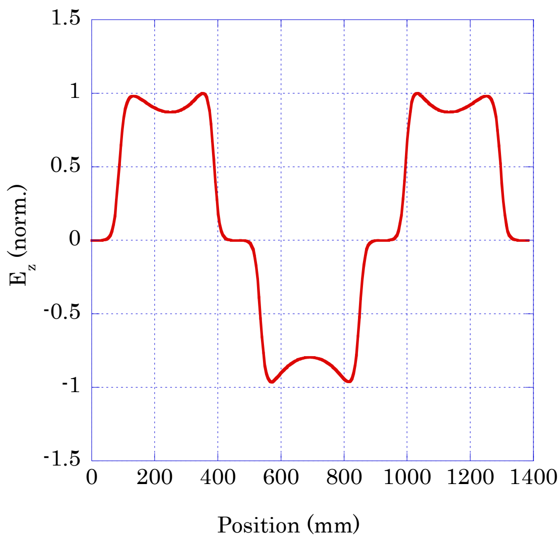

Figure 5: Normalized electric field distribution along the beam axis.

Table 1: Optimized Spoke Shape Parameters

Frequency	325 MHz
No. of Spokes	2
Tank Diameter	609.5 mm
Cell Length	461.2 mm
Cavity Length	1383.6 mm
E_{peak}/E_{acc}	3.7
H_{peak}/E_{acc}	6.0 (kA/m)/(MV/m)
R/Q	691 Ω
TTF	0.81

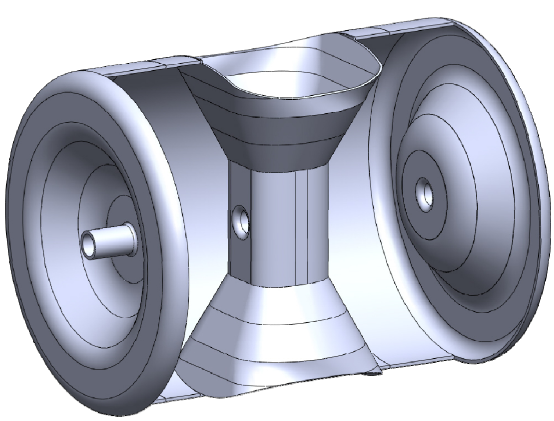

Figure 6: Outline view of 1-spoke cavity planning to be fabricated.

1-SPOKE CAVITY FABRICATON

A 5-year program of "Fundamental Technology development for high brightness X-ray source and the imaging by compact accelerator" has been launched. A superconducting spoke cavity for LCS photon sources is one of the development items of the program. The aims for the spoke cavity development are to establish the spoke cavity fabrication process and to check the performance of the spoke cavity.

We are planning to fabricate a 1-spoke niobium cavity as shown in Fig. 6, which includes all elements required for the spoke cavity. Before determining the final design of the spoke cavity, we are performing multipacting calculation with CST PARTICLE STUDIO [5].

Mechanical design for vacuum pressure tolerance, supporting elements, and mold tools is in progress with general-purpose simulation code ABAQUS. This financial year of Japan we are planning to start the pressure shaping.

CONCLUSION

We have started a research program on superconducting spoke cavities to accelerate electron beams especially for laser Compton scattered X/γ-ray sources. As the first step of the research program, the optimization of spoke cavity shape has been carried out by using multi-objective genetic algorithm. Further fine tuning of cavity shape will be conducted with multipacting calculation. Mechanical design to fabricate a 1-spoke cavity has been started.

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