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DEVELOPMENT OF SUPERCONDUCTING SPOKE CAVITIES FOR LASER COMPTON SCATTERED X-RAY SOURCES

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Abstract

A 5-year research program on the development of superconducting spoke cavities for electron accelerators has been funded by MEXT, Japan since 2013. The purpose of our program is establishing design and fabrication processes of superconducting spoke cavity optimized for compact X-ray sources based on laser Compton scattering. The spoke cavity is expected to realize a compact industrial-use X-ray source with a reasonable cost and easy operation. We have chosen a cavity frequency at 325 MHz due to possible operation at 4 K and carried out cavity shape optimization in terms of electromagnetic and mechanical properties. Production of press-forming dies is also in progress. In this paper, we present overview and up-to-date status of the research program.

INTRODUCTION

Laser Compton scattered (LCS) X-ray sources are now widely explored as an important application of advanced accelerators, since they can produce high-brightness energy-tunable X-ray beams with a compact footprint [1,2]. Such LCS X-ray sources can be realized with any type of electron accelerator: RF linacs, racetrack microtrons, storage rings, and energy-recovery linacs.

A photon flux from LCS sources is proportional to the frequency and density of electron and laser beams at the collision. Spectral brightness is proportional to electron beam brightness. Thus, electron beams of high-average current and small emittance are preferable for high-flux and high-brightness LCS sources. In this sense, we consider the energy-recovery linac is suitable for LCS sources.

A 5-year research program has been established to develop fundamental technologies for a compact high-brightness LCS X-ray source. In the research program, we are developing superconducting spoke cavities for future LCS X-ray sources.

Spoke cavity was originally invented for acceleration of protons and ions (v/c<1), but it can also be applied to electron accelerators (v/c=1) with minor modification of cavity shape [3,4]. We suggest the spoke cavity realizes a compact industrial-use X-ray source with a reasonable cost and easy operation because of the following reasons: (1) with the same cavity radius, the resonant frequency of spoke cavities is almost half of elliptical cavities. As a result, 4-K operation becomes a practical solution by choosing a resonant frequency below 500 MHz. (2) Spoke cavities have small microphonic detuning thanks to their mechanical stiffness and unique electromagnetic property, the resonant frequency depending mainly on the spoke length. This small frequency fluctuation contributes to the reduction of RF source capacity for ERL operation. (3) the spoke cavities accommodate power couplers and HOM couplers at the side region, thus the multiple spoke cavities can be installed with a better packing factor than elliptical cavities that require couplers on the beam pipe. (4) cell coupling of spoke cavity is stronger than that of elliptical cavity. With the strong cell coupling, we can easily adjust the field flatness along a multi-cell (multi-spoke) structure.

In this paper, we describe the status of spoke cavity development program in Japan.

PROPOSED X-RAY SOURCE

The proposed X-ray source is based on an ERL and a laser enhancement cavity similar to the LCS source recently demonstrated at the Compact ERL (cERL) [5]. As seen in Table 1, the targeting goal of the project is to realize the collision of megawatt-class electron and laser beams for a high-flux and high-brightness X-rays. Average brightness expected in the LCS source is comparable to 10-keV X-rays from a bending magnet at KEK-PF (2.5 GeV, 400 mA). The X-ray flux and brightness are reduced by duty factor, if we operate the LCS source at a burst mode (1 ms x 10 Hz for example) for saving the machine construction and running cost.

Table 1: Parameters of the Proposed X-Ray Source

E-bean			
Energy / current	25 MeV / 30 mA	Norm. emittance	1 mm-mrad
Laser			
Wave-length	1 μm	Stored power	1 MW
LCS			
Repetition	325 MHz	Flux (100%BW)	1×10^{14} ph/s
Collision spot	20 μm (rms)	Average Brightness	3×10^{14} (c.u.)
X-ray	10 keV		

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CRYOGENIC LOAD

The frequency of spoke cavity has been determined so that the LCS source is operated with a compact refrigerator. We have estimated 4-K equivalent heat load for various cavities with different frequencies and shapes: 325-MHz, 500-MHz, 650-MHz double-spoke cavities and a 1.3-GHz 9-cell elliptical cavity. Figure 1 shows 4K-equivalent heat load for the main linac (20MV) of the LCS source, where E_{acc} and the number of cavity are chosen as 7.2 MV/m, 2 cavities (325MHz), 7.4 MV/m, 3 cavities (500MHz), 7.2 MV/m, 4 cavities (650 MHz), 9.6 MV/m, 2 cavities (1.3 GHz) to keep the almost same length of linac. We calculated the heat load according to the BCS law with R_{res}=14nΩ and assumed a factor of 5 to convert 2-K load to 4-K load. Figure 1 gives a quick insight for the cavity frequency choice, although there are additional cryogenic load for the injector, power couplers, beam induced HOM and wakefield.

Our conclusion is operation of 325-MHz spoke cavity at 4K, because a simple cryogenic system at 4 K is suitable for industrial applications of the LCS source. If we allow low-duty cycle operation with reduced X-ray performance, we can adopt the zero-boil-off cryostat [6]. The zero-boil-off cryostat developed for JAERI-ERL-FEL is free from the safety regulation of high-pressure gases and realizes easy and reliable operation of superconducting linacs at a moderate cost.

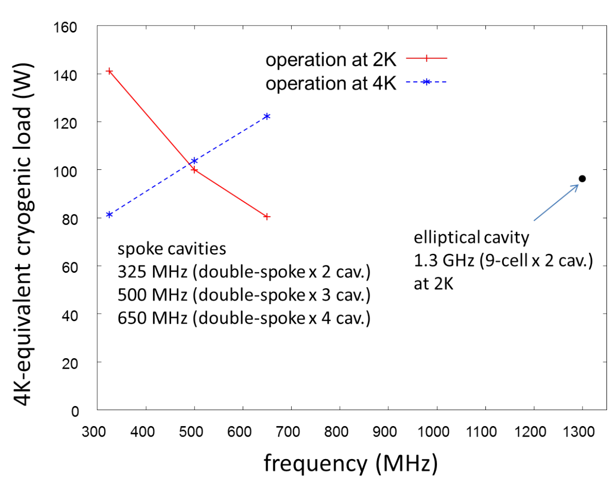

Figure 1: Cryogenic load of the superconducting main linac for 20-MV acceleration voltage.

CAVITY SHAPE OPTIMIZATION

There are several degrees of freedom in the design of spoke cavities: cross-sectional shape of spoke, roundness of spoke base and end plate rim, and so on. In order to fix the cavity shape, first we carried out multi-objective optimization with genetic algorithm (GA) to minimize E_{peak}/E_{acc} and B_{peak}/E_{acc} simultaneously [7]. Then, we conducted multipactor (MP) simulations and feedback the result to the GA optimization [8]. All the electromagnetic and MP simulations were carried out with CST MW Studio[9].

Figure 2 shows a 325-MHz single-spoke cavity after the optimization, where ports for couplers, pickups and inner surface polish are omitted. Main parameters of the cavity are listed in Table 2.

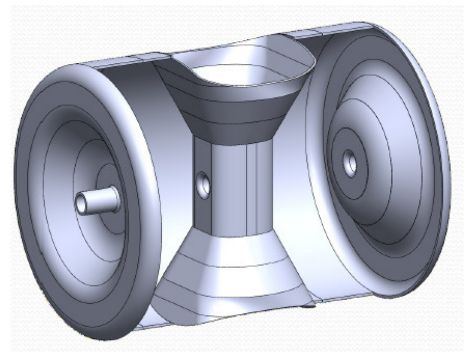

Figure 2: A 325-MHz single spoke cavity after the cavity-shape optimization.

Table 2: Cavity Parameters

Frequency	325 MHz
Tank diameter	609.5 mm
Cell length	461.2 mm
Cavity length	922.4 mm
E_{peak}/E_{acc}	3.7
B_{peak}/E_{acc}	6.0 (kA/m)/(MV/m)
R/Q	461 Ω
Transit Time Factor	0.81

In the MP simulations, we track a number of trajectories of primary electrons from source points and secondary emitted electrons (SEE). The source points are located at a “MP danger area” such as the spoke base and the endplate rim. A parameter <δ> is defined as the ratio of the number of SEE to the number of electrons hitting the cavity. We have <δ> larger than unity, when MP is anticipated. Figure 3 shows <δ> as a function of E_{acc} for various corner radii of endplate rim. From Fig.3 our 7 MV/m operation at 325MHz may have a difficulty due to

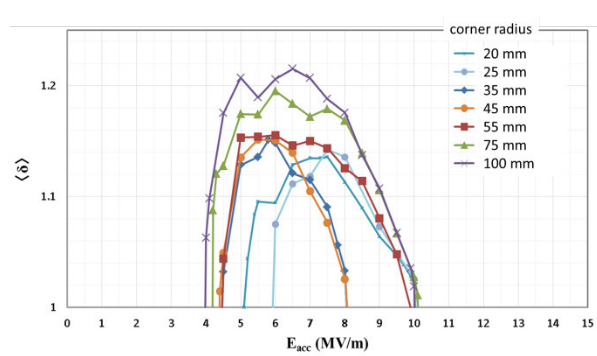

Figure 3: Results of multipactor simulations for various corner radii of endplate rim.

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the MP. We will investigate the anticipation further and continue MP simulations including additional ports as shown in Fig. 4.

CAVITY FABRICATION

In the spoke cavity development program, we plan to fabricate a single spoke cavity as the first proto-type, while we will utilize multi-spoke cavities for the X-ray source. The single-spoke cavity is fabricated for verification of production process and evaluation of performance in a vertical test and not for beam acceleration. Thus, we do not intend to obtain the approval of the high-pressure gas regulation for this cavity. The process of cavity production is, however, completely the same as the large-scale production.

The cavity consists of several parts as shown in Fig. 4. All the parts are formed from niobium sheets by press work and welded each other by electron-beam welding. Besides these cavity parts, stiffeners are attached at proper positions so that the cavity does not deformed by evacuation. We have employed ABAQUS [9] for the mechanical simulations and found appropriate design of stiffeners. Figure 5 shows surface stress distribution on the evacuated cavity with stiffeners at the spoke base and the end plates. We have also confirmed that the end plates keep little flexibility for frequency tuning even with the stiffeners.

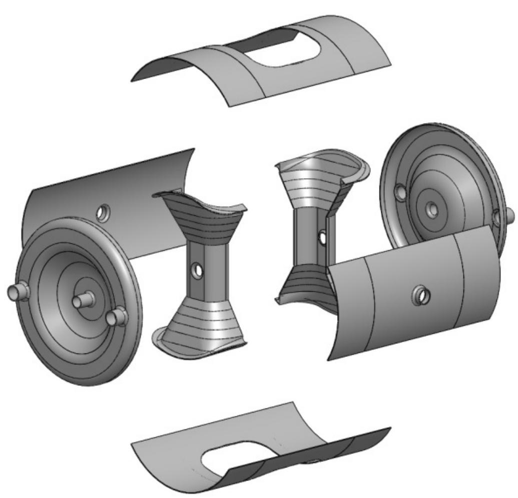

Figure 4: Components of the spoke cavity for fabrication process.

In the design of press-forming dies, we must take care so that equivalent plastic strain does not exceed the breakdown limit, 0.35 for our case. The most critical point for the plastic strain appears at the spoke waist where the cross section begins to enlarge. After forming simulations, we have confirmed that we can manage the plastic strain with multi-stage forming. We plan to start a press forming test soon.

SUMMARY

For a future compact industrial-use X-ray source based on laser Compton scattering, we have launched a 5-year program on spoke cavity development. The frequency of spoke cavity has been chosen at 325 MHz for possible operation at 4K. We have established cavity shape optimization procedure including multipactor analysis. Detail consideration of press-forming process is also in progress.

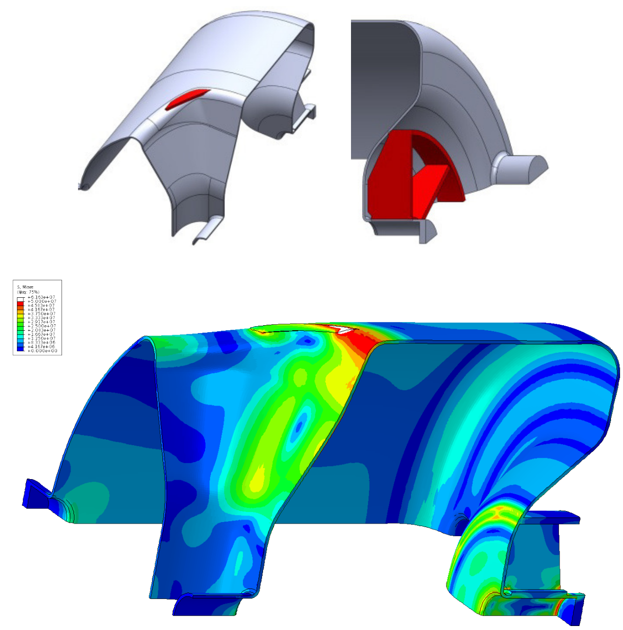

Figure 5: A result of surface stress calculation with stiffeners, red parts appear in the top figure.

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