# DESIGN OPTIMIZATION OF SPOKE CAVITY OF ENERGY-RECOVERY LINAC FOR NON-DESTRUCTIVE ASSAY RESEARCH

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*Abstract*

We are proposing non-destructive assay system of nuclear materials with laser Compton scattering combined with an energy-recovery linac and a laser. To construct this system for nuclear safeguards and security purpose, it is important to make the accelerating cavity small. The spoke cavity has advantages over the elliptical cavity to adopt for our proposing system. We are designing a spoke cavity favorable to compact cavity. Design optimization calculation of the spoke cavity shape is being carried out using 3D electro-magnetic field simulation code with multi-objective genetic algorithm. The results will be presented.

## INTRODUCTION

Energy Recovery-Linac (ERL) can accelerate low emittance and high current beam, which generates high brightness and high quality light source. The high quality beam of ERL combined with lasers can also significantly improve brightness and monochromaticity of X/γ-ray generated by laser Compton scattering (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 spent reactor fuels. This method is significant technology for nuclear safeguards and security. We are proposing non-destructive assay system of nuclear materials by LCS combined with an ERL and a laser. [1]

Practical use of this system 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 significant for the ERL cavities. Elliptical cavities have tendency to increase the total accelerator length since HOM absorbers, HOM couplers and input couplers are attached to the beam pipes. On the contrary, spoke cavities have an advantage of shortening the total accelerator length [2]. The spoke cavity design suitable for ERL has been being multi-objectively optimized with electro-magnetic simulation code. The present paper describes the results of calculation.

## ADVANTAGES OF SPOKE CAVITY

The superconducting spoke cavity used for ERL has following advantages.

1) A superconducting cavity requires HOM absorbers or HOM couplers to damp HOM and input couplers to feed RF power into the cavity. These elements can be installed along the side of the spoke cavity so that the total length of spoke cavity can get shorter than that of elliptical cavity and the distance between the cavities can be decreased. (Fig. 1)

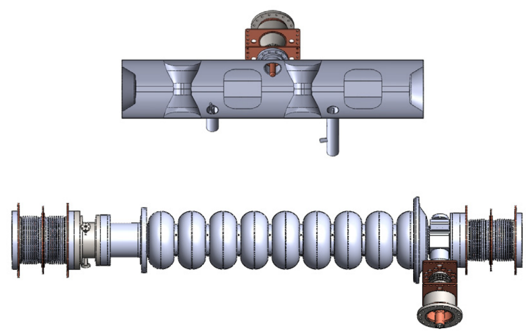

Fig. 1: Schematic views of spoke cavity (upper) and elliptical cavity (lower).

2) 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 ERL cavity of small frequency fluctuation can decrease the required RF power and tolerance of the input coupler. This results in making the RF power supply compact.
3) 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.
4) Cell coupling of spoke cavity is stronger than that of elliptical cavity since the outer size of the tank is almost same along the axis. Stronger cell coupling makes the field flatness easier to adjust and less disturbed to increase number of cells. This increases the effective accelerating length.

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## SPOKE CAVITY SHAPE

The spoke cavity consists of three parts; a spoke, a tank and an end nose as shown in Fig. 2.

The spoke shape used for calculation has three different cross-sections, which deforms from a rectangle through a round corner rectangle to an ellipse. The center part is created by extruding one cross-section and the other parts by smoothly deforming the adjacent cross-sections. The bore for beam acceleration is located in the center of spoke and the corners are rounded to prevent sharp edges.

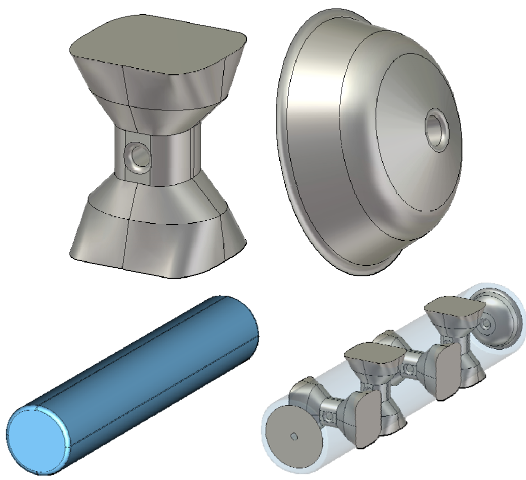

Fig. 2: Example of parts of spoke cavity; spoke (upper left), tank (lower left) and end nose (upper right) and their assembly (lower right).

The tank involves the spokes. The tank cross-section varies from a square through a round corner square to a circle. The corner between the tank and the end plate is rounded.

The end nose is combined with circular truncated cone and circular cone and the bore for beam acceleration is located along the axis. The corners of the bore, boundary of the cones, and boundary between cone and end plate are rounded and smoothly deformed.

The resonant frequency of the spoke cavity is assumed to 650 MHz so that the outer size of spoke cavity become almost same as that of widely fabricated 1.3 GHz elliptical cavity. This frequency enables the superconducting spoke cavity to operate at 4K liquid helium temperature.

The cell number is set to five so that the cavity length is nearly same as that of 1.3GHz 9-cell elliptical cavity. The 5-cell spoke cavity has four spokes and each spoke is installed orthogonally to the adjacent spoke.

## OPTIMIZATION PROCEDURE

When the spoke cavity shape is optimized with electro-magnetic simulation code, three objectives should be noted; the ration of maximum electric field to accelerating field (Epeak/Eacc), the ration of maximum magnetic field to accelerating field (Hpeak/Eacc), and the ratio of shunt impedance to Q-value (R/Q). We deal with three objectives of Epeak/Eacc, Hpeak/Eacc and 1/(R/Q) to treat as optimization problem. The procedures of optimization with genetic algorithm are as follows.

1) Assume the minimum and maximum values and bit length which corresponds to resolution within the range to encode each shape parameter.
2) A set of shape parameters called individual is converted to an array of bits called chromosome.
3) Initially many chromosomes are randomly generated to form an initial population.
4) Decode one chromosome to model the cavity shape and calculate the fields with electro-magnetic simulation code.
5) Select the TM010 $\pi$-like mode among the calculated modes by analyzing electric field distribution along the axis.
6) When the frequency is out of 650 MHz±5 MHz, adjust the outer size of the tank and repeat until the frequency converges within the range.
7) Search the maximum accelerating field of each cell from the axial field distribution. When difference between the maximum and minimum among the data of all cells is more than 10%, adjust the height of end nose and repeat until the cell field difference converges within the range.
8) Obtain the accelerating field, maximum electric and magnetic fields and R/Q.
9) Repeat above procedures from 4) to 8) for all chromosomes
10) The fitness function is defined with the rank-based fitness assignment method [3], which counts the superior individuals to itself. This method evaluates the closer individuals to the Pareto front to be better regardless of the values.
11) Individuals are selected among the existing population according to the fitness function to breed a new generation.
12) Preferentially select a given number of elite individuals which have superior fitness function.
13) Select the required number of individuals with the roulette of which selection probability varies according to the fitness function.
14) Select a pair of parent from the pool selected previously with a new roulette based on the selected individuals.
15) Produce a pair of children from a pair of parent using uniform crossover method.
16) Repeat above procedures from 14) to 15) until the next generation population reaches the required number.
17) Mutation is operated to the children with a constant probability.
18) Repeat above procedure from 4) to 17) until successive iterations no longer produce better results.

The parameters used for the genetic algorithm are shown in Table 1.

Table 1: Parameters of generic algorithm calculation.

| | |
|---|---|
| No. of Elite selection | 20 |
| No. of Roulette selection | 80 |
| Crossover | Uniform |
| Probability of Mutation | 2% |
| No. of parent pairs | 200 |

## RESULTS OF OPTIMAZATION

Figure 3 shows the average values of Epeak/Eacc, Hpeak/Eacc and 1/(R/Q) in each generation. Though each value decreased as the generation was produced, the shifts of Epeak/Eacc and Hpeak/Eacc became less than that of 1/(R/Q). The fitness function was estimated with Epeak/Eacc and Hpeak/Eacc by omitting 1/(R/Q) after the 15$^{th}$ generation. After this operation Epeak/Eacc and Hpeak/Eacc became decreasing again with increasing 1/(R/Q).

The distributions and the Pareto fronts of Epeak/Eacc and Hpeak/Eacc at some generations are shown in Fig. 4. With the passage of generation Pareto fronts were improving and the individuals were gradually approaching near Pareto front.

The typical shapes of spoke cavity close to the Pareto front are shown in Fig. 5. The Epeak/Eacc-dominant shape as shown in Fig. 5(A) has longer width than thickness of the spoke center and thick base of the spoke. In contrast the Hpeak/Eacc-dominant shape as shown in Fig. 5(C) has shorter width than thickness and slim base. Their medium shape as shown in Fig. 5(B) is intermediate between the two.

Comparison of the designed values of Epeak/Eacc and Hpeak/Eacc with other designs of spoke cavities [4,5] is shown in Fig. 6. Epeak/Eacc trends upward slightly with increasing beta and Bpeak/Eacc also appears to increase relatively more quickly with increasing beta than the electric fields. Though there exist no spoke cavities of high beta, our spoke design of β=1 seems to be as good as any other spoke designs.

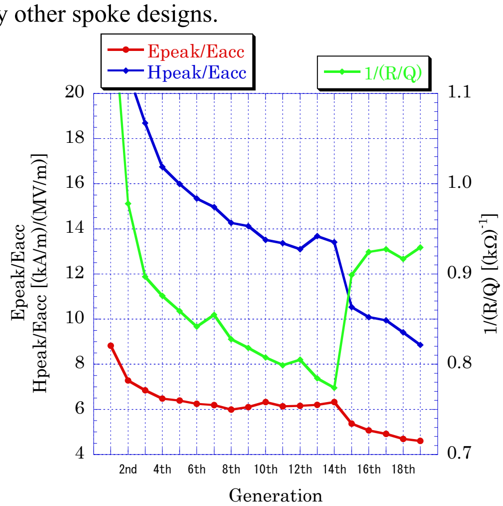


Fig. 3: Average values of Epeak/Eacc, Hpeak/Eacc and 1/(R/Q) in each generation.

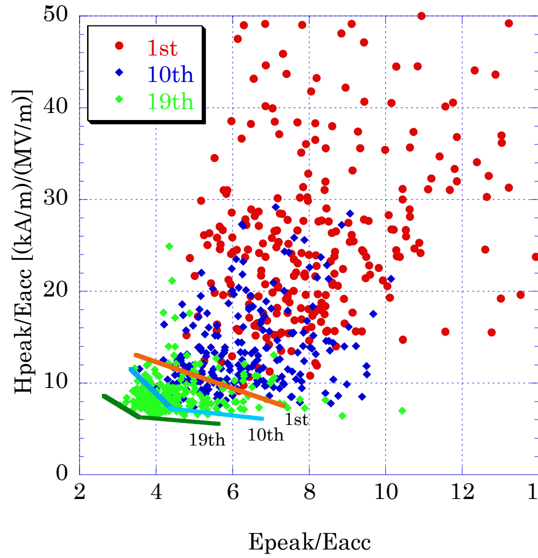


Fig. 4: Distribution (dots) and Pareto fronts (lines) of Epeak/Eacc and Hpeak/Eacc at some generations.

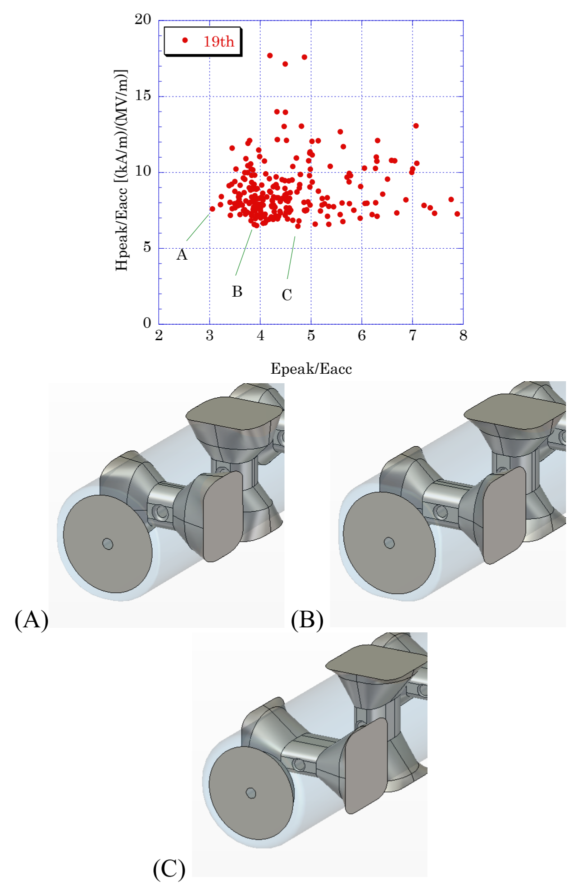


Fig. 5: Typical shapes of spoke cavity near Pareto front of Epeak/Eacc-dominant (A), Hpeak/Eacc-dominant (C) and their medium (B).

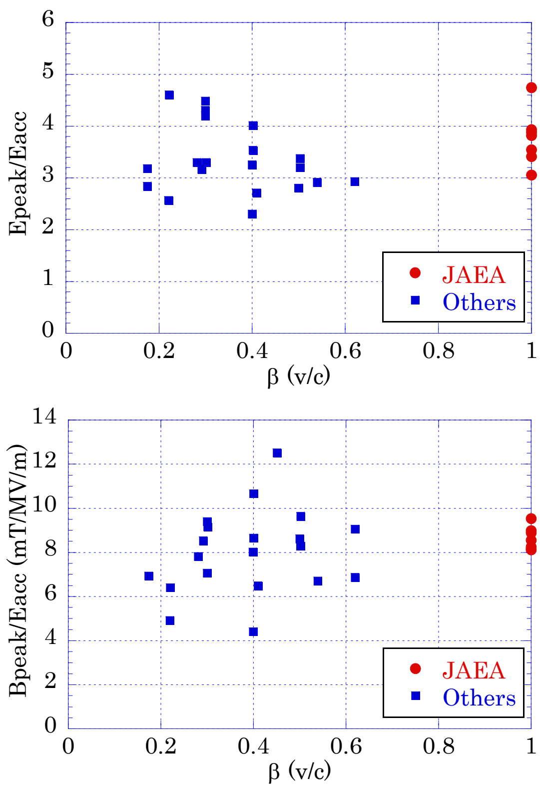


Fig. 6: Epeak/Eacc (upper) and Bpeak/Eacc (lower) as a function of β. Solid circles: our spoke cavity design and solid squares: other spoke cavities shown in references [4-5].

## CONCLUSION

We have been designing the spoke cavity shape using the genetic algorithm with multi-objective optimization method. As the new generation is produced, the Pareto front improves and the results are approaching close to the Pareto front. The current results are as good as any other spoke design and the optimization calculation is in progress.

Since HOM damping is also significant for the ERL cavity, HOM property of the cavity must be investigated and the design of HOM couplers will be carried out.

## REFERENCES


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