CHALLENGES AND THE FUTURE OF REDUCED-BETA SRF CAVITY DESIGN*

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Abstract

Superconducting radio frequency (SRF) linacs have been one of the structures of choice in the intense proton accelerator and the heavy ion accelerator for intense neutron sources, nuclear transmutation, energy amplifiers, rare isotopes accelerator, etc. For these applications, there are strong demands of reduced-beta (β<1) SRF cavity. In this paper two types of cavities are considered. One is the well-known multi-cell elliptical cavity adapted from electron accelerator. It has been shown that the multi-cell elliptical cavity is a very suitable structure for beta's above 0.5. Below this value, the operation would be difficult due to its weak mechanical characteristics. The other is the spoke cavity that is considered as a promising SRF cavity structure that could cover beta ranges from 0.1 to 0.5. General considerations and the related optimizations in the design and the corresponding analysis are studied by exploring physical parameter spaces of each cavity type, on the basis of design criteria

1 INTRODUCTION

There have been increased needs of reduced beta SRF cavities (β<1) in the fields of ASD (Accelerator Driven system), nuclear physics, and military applications [1]-[4]. The specific applications areas of above fields are nuclear transmutation of long-lived nuclear waste, energy amplifier, intense spallation neutron source, radioactive ion acceleration, muon/neutrino production, tritium production, etc. Since many applications are based on the CW or high duty operation, the success in SRF technology in reduced beta region becomes a critical issue.

There have been prototyping efforts with reduced beta (as low as β~0.47) elliptical cavities for CW application and showed very promising results [5]. Also for the pulsed application SNS β=0.61 and β=0.81 elliptical cavities are developed and a series of β=0.61 prototype cryomodule test have been done [6],[7]. The results show maximum accelerating gradient of ~17 MV/m, which correspond to a peak electric field of ~45 MV/m and a peak magnetic field of ~100 mT.

Recently low beta down to 0.1 or less SRF cavities have been focused mainly for the CW application, and efforts are being directed towards spoke cavity, since elliptical cavities has intrinsic weak points like mechanical weakness, multipacting problem, lower RF efficiency, etc as a beta goes down. It is noticeable that β=0.1 corresponds to about 5 MeV proton, which means we can go through with SRF linac after RFQ. Spoke cavities are principally a kind of half wavelength resonator and supposed to cover 0.1<β<0.6 in frequencies of 100~900 MHz [8]. In this paper, general design considerations are briefly explored in both elliptical and spoke cavities mainly in terms of RF efficiency, and mechanical properties. Also other design issues like thermal properties, multipacting, and HOM (higher-order-mode) are explained.

2 DESIGN CONSIDERATIONS

Following issues are generally considered in design of reduced beta SRF cavity.

- Minimize the peak surface fields
- Reasonable inter-cell coupling in elliptical cavity
  ; spoke cavity intrinsically has large coupling (~30 %)
- Provide required Qex
- Low shunt impedance in CW application
  ; this is mainly determined by the cavity type
- Reasonable mechanical stiffness
- Safe from multipacting
- Verification of HOM and related issues

Many of above are coupled field problems between RF, mechanical, thermal, etc, which asks strong interfaces between simulation codes and also close cooperation between relevant areas.

3. RF GEOMETRY OPTIMIZATION

3.1 Elliptical Cavity

The dependencies of RF properties on the cell geometry are pretty well understood and the optimization is straightforward now [9]-[12]. The cell geometry can be defined with five-geometry dimensions as shown in left side of Fig. 1, which could be defined in different ways. For the explanation of optimization procedure developed during the R&D works for SNS, the SUPERFISH notations are followed here. The basic idea of this procedure is visualizing all possible RF properties on the geometry space, which provides general understandings of elliptical cell geometry. As can be seen in the graph on the right side of Fig. 1, the possible optimized geometry can be defined with 3 dimensions, since the equator radii are usually used for tuning with very negligible impact on the cell properties and the optimum ellipse aspect ratio is automatically determined at the fixed three-remained dimensions.

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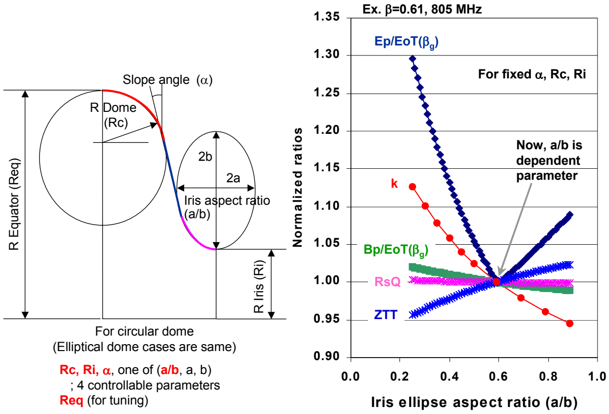

Figure 1. Elliptical cell geometry and dependencies of RF parameters on the ellipse aspect ratio (a/b) at the fixed slope angle, dome radius and bore radius.

Now, the general relations can be obtained by scanning the bore radii and the dome radii at fixed slope angle. The procedure repeats at different slope angles. Enough slope angle should be provided for the easy water drain during HPR, while the smaller slope angle is better in the mechanical point of view. After applying certain design criteria on these plots, the optimized geometric point can be chosen. The point in Fig 2. corresponds to SNS β=0.61 cavity.

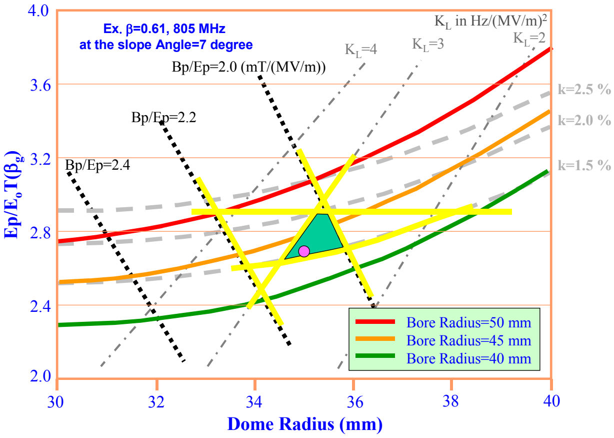

Figure 2. Elliptical cavity shape optimization.

3.2 Spoke Cavity

There have been also extensive efforts [13]-[19] for the shape optimization of the spoke cavity, especially to reduce the ratio of Ep/Eacc and Bp/Eacc, since mechanical stiffness is minor concern and other RF parameters follow the intrinsic behaviors of spoke cavity, which results in weak dependencies of RF properties on geometric beta. It is known that the optimal ratio can be found by controlling A/B and C/D in Fig. 3, race-track shape is preferable for another reduction of Ep/Eacc and practical issues and the flat contacting surface at the spoke base results in another reduction of Bp/Eacc. Though it is tricky to obtain precise surface field information from the 3D simulation, the generally achievable ratios of Ep/Eacc and Bp/Eacc are about 3 and 7~8 respectively. The spoke cavity has many advantages compared to the elliptical cavity, such as very strong RF coupling between cells, rigid mechanical property against both static and dynamic vibration, smaller dimension, etc. Also the multi-gap concept can be applied just by adding spokes (bottom right of Fig. 3) [20]-[21].

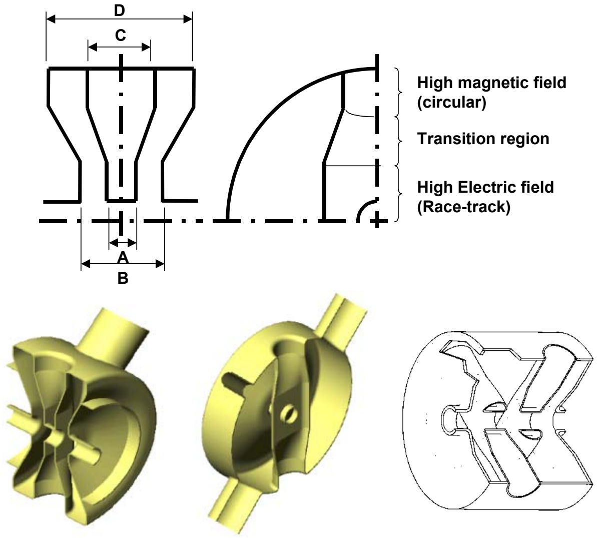

Figure 3. Optimized shape of spoke cavity. [14],[15] (A; spoke thickness at the iris, B; active cavity length, C; spoke diameter at the base, D; total cavity length)

3.3 End-cell Tuning and Qex

Increasing the magnetic volume is generally accepted technique to compensate the field penetration portion to the beam pipes rather than increasing capacitance. With the help of increased computing speed and the technique for estimation of Qex, even the very high Qex can be calculated with food accuracy, which also makes alignment error estimation available [22], [23]. In spoke cavity the coaxial coupling is mainly considered rather than loop coupling due to the thermal issues. Fig. 4 shows end-cells and coupling concept to the power coupler [24].

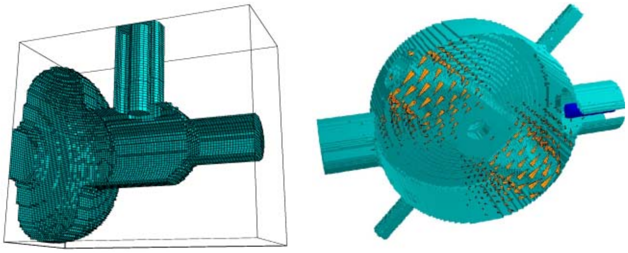

Figure 4. End-cell and coupling concept to power coupler. Both coupling concepts, which is actually coupling in low electric field sides, are enough to reach Qex's as low as 10^{-5} or below easily.

3.4 Comparisons of RF Properties

Three spoke cavities (β_g=0.175, 2-gap; β_g=0.35, 3-gap; β_g=0.48, 4-gap) and four elliptical cavities (β_g=0.35, 5-cell; β_g=0.48, 6-cell; β_g=0.61, 6-cell; β_g=0.81, 6-cell) are optimally designed following the procedures mentioned in the previous section. The frequency of spoke cavity is set to 402.5 MHz and that of elliptical cavity is set to 805 MHz, independent of any other project. 40 MV/m of Ep and 85 mT of Bp are chosen as design criteria for both cavity types. Recent results from SNS, RIA, AAA [7],[19],[25] show these peak fields as design criteria will be feasible even for the production cavities in near future. Inter-cell coupling constant used here for the elliptical cavities is 1.5 %. Fig. 5 shows the some RF properties. The cavity active lengths can be seen in the top graph of Fig. 5.

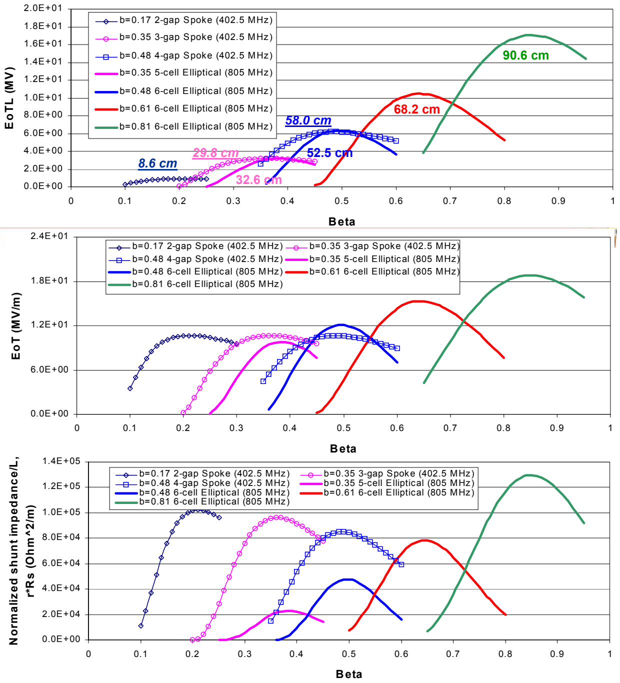

Figure 5. Comparisons of RF properties between spoke cavity and elliptical cavity.

The cavity voltages of spoke cavities are almost same regardless of geometric beta, while those increase linearly with geometric beta in elliptical cavity. The shunt impedances are normalized with surface resistance Rs (bottom), and each cavity shows opposite tendency as beta increases. Generally spoke cavities show better performances when beta is less than about 0.5.

3.5 Mechanical Properties and the Limitation of Elliptical Cavity in low beta regions

Fig. 6 shows deformed shape of elliptical cavities due to the Lorentz force. Though the stresses under vacuum-pressure and tuning force are much more important in CW application rather than the static Lorentz force detuning (LFD), the coefficients provide good indications of mechanical stiffness of cavities.

The elliptical cavity with geometric beta higher than about 0.6 is suitable for both CW and pulsed application, which can be verified the recent results SNS cryomodule test [6], while the elliptical cavity with β_g<0.4 does not have any merit in terms of mechanical stability, RF efficiency, and also multipacting. In the intermediatebeta region, elliptical cavity will work for the CW application only. It would be a competing region with spoke cavity after having some more experiences with spoke cavity.

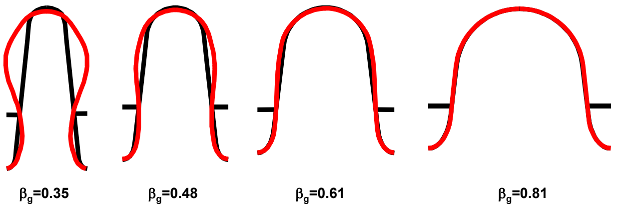

Figure 6. Deformed and original shapes of elliptical cavity due to the Lorentz force at EoT=10 MV/m. (805 MHz, magnification; 50,000 times, static)

4 SPECIAL ISSUES

4.1 Cavity Response to Dynamic Mechanical Vibration

Lorentz force detuning is a function of RF field, which is forcing term, mechanical mode coupling strength to the cavity frequency detuning, mechanical mode frequency, modal mass, and mode's damping degree. However, findings of mode frequencies, corresponding stiffness and especially, damping degrees are quite difficult for the real situation, since these dynamic properties are very sensitive to the boundary conditions such as connection scheme, strength, equivalent masses and equivalent stiffness of surroundings that is attached to the cavity. Only the relative comparisons are available before having experimental measurements of mechanical properties with actual cryomodule [26].[27]. Even after having measured values about dynamic mechanical properties of cavity, the predictions are not accurate with a conventional RF modeling, since rf fields and mechanical vibrations are strongly coupled and both are dynamic. Studies on the global modeling of cavity under dynamic detuning, while taking care into account these two aspects equally, are under progress. The intermediate results show good agreement with measurement [28],[29]. In order to have general statistical pictures, many more cases should be checked and studied.

4.2 Multipacting

Multipacting is a phenomenon of resonant electron loading, which strongly depends on shapes, field levels and surface conditions. To avoid multipacting, efforts for reducing a secondary electron yield thru a series of better surface cleaning processes and for shape control that can eliminate multipacting condition have been carried out in parallel. There are several 2D multipacting simulation codes are available now [30]-[32], and many of results agree pretty well each other. A series of test and simulations tells lower β_g structure will have more severe multipacting problem and a larger circular dome in elliptical cavity will helpful to avoid multipacting [5].

There's strong need of 3D multipacting simulation codes especially for the spoke cavity, since spoke cavities have a fully 3D structure and a power coupler is attached to the main body. A few 3D codes are under development and/or available now [33], which should be carefully checked with experiments.

4.3 Higher-order-mode (HOM)

There will be no beam dynamic issues on HOM due to the heavy nature of proton and relatively short length of linac compared to electron machine like collider [34].

Related with HOM powers especially in pulsed machine, several concerns should be performed such as understandings of effects from beam time-structure, possible strapped modes, superstructure analysis with careful concern of boundary conditions, HOM frequency spread/centroid properties, etc [35],[36]. The instant probabilities of having non-negligible power generation from HOM are small but there's no guarantee for the long-term operation. Verifying dangerous HOM and having HOM damper are needed in high current pulsed machine with complex beam time-structure, which depends on machine strategy about reliability.

4.4 An Example of Coupled Field Problem

As mentioned above, many of practical issues are coupled field problems. Here one example of coupled field problem is introduced, which can be applied to any case of thermal stability. Fig. 7 summarizes general relations of thermal stability in SRF cavity, which is generally 3D, non-linear, dynamic, self correlated problem. Fig. 8 shows one example of elliptical cavity end group at power coupler side with material defect [37].

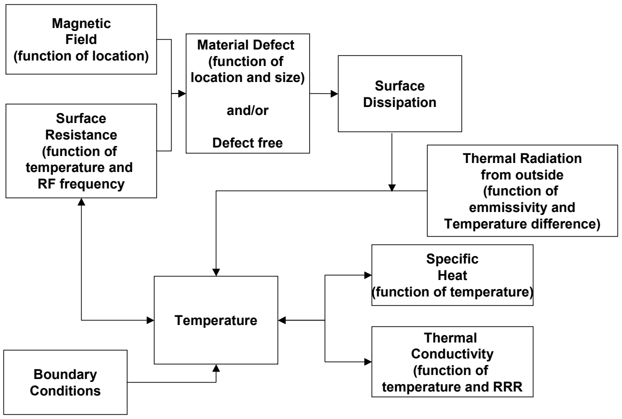

Figure 7. General relations of physical parameters on the thermal stability.

The lesson learned from this analysis is that the same stability margin of CW operation should be applied even in pulsed operation since the quenching development is fast (a few ms or less). The dynamic behaviors of quenching development can be explained with the graph in the bottom right side of Fig. 8.

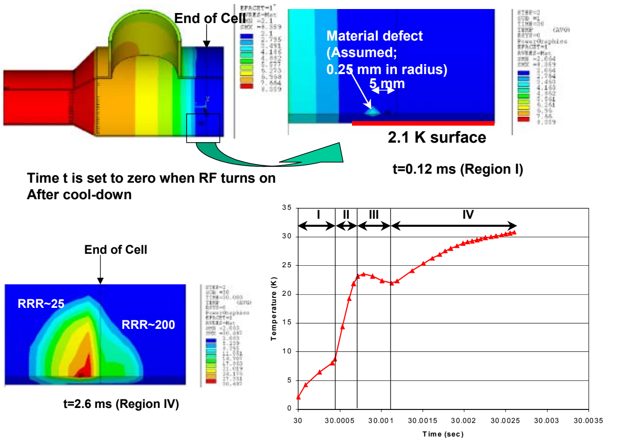

Figure 8. Examples of coupled filed analysis results-3D, nonlinear, dynamic, self correlated analysis for the thermal stability of SRF cavity.

5 SUMMARY

- Elliptical and spoke cavities are explored for the application in reduced beta region.
- RF geometry optimization for both structures are pretty well understood.
- In the region of β<~0.4 spoke cavity shows better performance than elliptical cavity (mechanically stable, lower surface fields, lower surface dissipation, etc).
- In the region of β>~0.6 elliptical cavity shows better than spoke cavity (wide experiences, lower surface fields, simple, well understood, etc).
- In the region of β=~0.5 seems to be a competing region. But more experiences with spoke cavity should be needed.
- Multipacting issues should be solved in lower beta region, especially in 3D structure.
- Modeling of dynamic cavity detuning is progressing, for which more experimental data are also needed for general description.
- Understanding coupled field problems between RF, mechanical, thermal, etc, help explaining many practical issues.

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