Design RF cavity geometries with advanced computation methods

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Radio Frequency (RF) cavities are critical components for the particle accelerators. They provide the electromagnetic fields to accelerate the charged particle beam up to TeV energy and MW power level. They are also essential tools for various beam manipulations (RF "gymnastics") in the accelerator such as bunching, stretching and rotating. The cavity gradients and power efficiency directly affect the achievable beam energy and intensity within the practical budgetary and footprint constraints. Reducing the machine cost by improving the structure gradient and efficiency of RF cavities is vital for the future accelerators for both energy frontier and intensity frontier of High Energy Physics [1].

The design of a RF cavity is a complex process with multiple factors to consider. There are RF requirements such as RF frequency, RF power, and conversion efficiency from RF power to beam energy. There are mechanical considerations such as cavity size, thermal management, production methods, etc. Over the years, knowledge has been accumulated on how to alleviate RF breakdown and improve quality factor to achieve higher accelerating gradient, such as reducing the field emission by lowering the peak E field, or alleviating the thermal breakdown by containing the peak B field. This knowledge base provides guidance for the future RF cavity design. Also, the ever-increasing beam power has increased the importance of issues such as multipacting suppression and higher-order-mode damping. In addition, beam dynamics can impose extra requirements on the cavity performance. Taking all these factors together, RF cavity design becomes an intricate and complicated problem.

Though the analytical calculation still provides valuable guidance, most RF cavity design work now relies on the computational tools. Over the years, the computation capability for the RF cavity design has made tremendous progress. Several commercial or non-commercial programs have been developed and widely used. The relative frequency accuracy of the eigenmode has achieved better than 1e-5. Various boundary conditions (BC) beyond the perfect electric or magnetic BC, such as waveguide ports, resistive walls and absorbing BC, have been implemented in the solvers and realized the complex field calculations that are not possible before. Utilizing the parallel computing on High Performance Computing (HPC), it now becomes feasible to simulate large scale RF systems of tens of millions of tetrahedral elements, or calculate higher order eigenmodes of up to hundreds or even thousands. The development of post-processing programs for multipacting, thermal and mechanical analysis, dark current etc., have provided comprehensive analysis for the cavity properties. The significant advancement of the computational tools has enabled the "virtual prototyping", where now one can confidently start cutting the metal without building a hardware prototype.

With all these programs providing comprehensive calculation and analysis for the RF cavity, however, there is still one critical question unaddressed: how do we determine the cavity geometry at the first place?

Governed by Maxwell's equations, the electromagnetic field in a RF cavity can be numerically solved once the cavity geometry is defined with a set of geometric parameters. The design of RF cavity geometries is essentially an optimization problem with multiple competing objectives and large number of variables. In the conventional design method, based on experience and analysis, the designers start with an estimation of the cavity overall shape. During the optimization, the geometry is modified by changing one or a few geometric variables at a time. The RF field is solved, and the cavity performance is evaluated for each geometry. All the variables are scanned in turns in an iterative approach until a satisfying cavity performance is achieved. Even automated parameter scanning has been implemented in some cavity design cases, this method still relies a lot on the designer's experience and judgment. The pre-defined shape where the searching process starts can be over-constrained that potentially better solutions are left out. For complicated geometry with dozens of geometric variables, the scanning process can become impractically time-consuming. For optimization with multiple targets, sometimes conflicting each other, the rationale to favor one geometry over the other is not straight forward for human judgement. A more efficient and systematic design method is much needed for the future development of RF cavity.

In recent years, with the development of both optimization algorithms and computation capability, as well as the ever-increasing demand on the cavity performance, the numerical algorithms have been becoming more and more prominent in the engineering designs. There have been a few studies on applying such algorithms for the RF cavity design with promising results [2-5]. However, such studies are still preliminary. Much more work is needed to better understand how to efficiently implement modern optimization algorithms and fully harvest their advantages for the RF cavity design.

We propose to build a modern paradigm for the RF cavity design based on the advanced computational methods. The core idea is to replace the human judgement by a computational algorithm which efficiently and systematically searches for the cavity geometry that best satisfies the design requirements. High Performance Computing (HPC) will be implemented to expedite the design process and extend the searching scope in the parameter space. Such a new paradigm will enable a much more efficient design process and potentially lead to novel design beyond human preconception. It will be greatly useful for the future Research and Development for both NCRF and SRF cavities.

Specifically, we plan to build this new paradigm from three aspects:

1. **A multi-objective optimization algorithm efficiently and systematically searching for the optimized design**. By implementing the numerical multi-objective optimization algorithms, the search for the optimized cavity geometry become more systematic and comprehensive. It can also possibly lead to the novel designs that are beyond human's pre-conceptions. One optimization algorithm we have studied is the Non-dominant Sorting Genetic Algorithm II (NSGA-II) [6], which is one of the most used Multi-Objective Genetic Algorithm (MOGA) [7]. More efficient algorithms beyond MOGA such as surrogate modeling [8] will also be explored.
2. **An electromagnetic (EM) field solver to evaluate cavity properties**. Except for a few analytical cases, most EM fields in the cavities need to be solved numerically. The field solver should provide a flexible geometry definition, fast solving time with sufficient accuracy, and comprehensive post-processing programs to calculate the relevant cavity properties.
3. **A parallel computing structure to take advantage of the capability of supercomputers**. Both the optimizer and the EM field solver requires intensive computation for the real cavity design. Parallel computing will be mandatory to accomplish the design in a practical time scale.

We have developed a preliminary prototype program and applied it to the design of a VHF normal conducing RF gun [9] and a nose-cone RF cavity for Landau damping [10]. With some initial encouraging results, we would like to carry on developing its capabilities and expand its application to more cavity designs.

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