SUPERCONDUCTING RF ACCELERATING CAVITY DESIGN (extended abstract)

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Abstract

Superconducting RF cavities are extensively used in particle accelerators to provide a longitudinal electric field for accelerating beam from its injection energy to its final energy. Optimization of the fundamental accelerating mode is of great importance in the design of a cavity since, for efficient operation, the shunt impedance of the accelerating mode must provide the required voltage across the cavity using the minimum input power. The power dissipation and surface field distributions need to be known so that proper provision can be made for cooling the cavity and avoiding excessively high surface fields which could result in multipactoring, or quenching of superconducting cavities. As demands on performance of accelerator have increased, so have the concerns of the cavity designer with respect to the cavity mechanical properties within its cryo environments. For most practical cavities the geometry is sufficiently complicated that analytical solutions for the electromagnetic field distributions and characteristics of the modes supported by the cavity do not exist. Prototype cavities may be built and the modes measured in the laboratory to provide the necessary information, but this would be a laborious and costly process, and gives no guarantee of finding all modes of interest to the designer. Fortunately, approximation by numerical methods enables rapid calculation and optimization of the electromagnetic fields of cavities with arbitrary-shaped structures, while ensuring that all modes of interest are found. Here we discuss different problems of SC cavity and its surrounding stand design using a series of numerical codes and methods of data exchange between them. The comparisons of numerical simulations with some experimental results are shown.

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Abstract
Superconducting RF cavities are extensively used in particle accelerators to provide a longitudinal electric field for accelerating beam from its injection energy to its final energy. Optimization of the fundamental accelerating mode is of great importance in the design of a cavity since, for efficient operation, the shunt impedance of the accelerating mode must provide the required voltage across the cavity using the minimum input power. The power dissipation and surface field distributions need to be known so that proper provision can be made for cooling the cavity and avoiding excessively high surface fields which could result in multipactoring, or quenching of superconducting cavities. As demands on performance of accelerator have increased, so have the concerns of the cavity designer with respect to the cavity mechanical properties within its cryo environments. For most practical cavities the geometry is sufficiently complicated that analytical solutions for the electromagnetic field distributions and characteristics of the modes supported by the cavity do not exist. Prototype cavities may be built and the modes measured in the laboratory to provide the necessary information, but this would be a laborious and costly process, and gives no guarantee of finding all modes of interest to the designer. Fortunately, approximation by numerical methods enables rapid calculation and optimization of the electromagnetic fields of cavities with arbitrary-shaped structures, while ensuring that all modes of interest are found. Here we discuss different problems of SC cavity and its surrounding stand design using a series of numerical codes and methods of data exchange between them. The comparisons of numerical simulations with some experimental results are shown.

1 Introduction

The main working conditions of the SC cavities are as follow:

- Very high electromagnetic fields – maximum magnetic field on the inner cavity surface up to Bpk=100 mT, maximum electric field on the inner cavity surface up to Epk=50 MV/m. These high field result in the strong Lorenz forces which cause the cavity wall deformation;
- Low temperature – down to 2K, that again causes wall displacements and inner volume change after cool down;
- The pulse regime of operation that results in the addition requirements on cavity rigidity;
- High vacuum conditions (10^{-9}-10^{-10}) and extra pressure on cavity walls from the helium tank also deform the cavity shape;

- High tolerances and quality surface requirements.

The deformations caused by all above mentioned reasons result in the working RF frequency shift in the range of hundreds kHz. Taking into account high Q-factor of SC cavities such big frequency shift brings cavity out of operation. From the other hand, the use of any external tuning elements like plungers or trimmers is problematic as it results in the low down cavity acceleration efficiency. Fig. 1 shows the so-called elliptic SC cavity in its test cryostat and schematic inside view of the cavity.

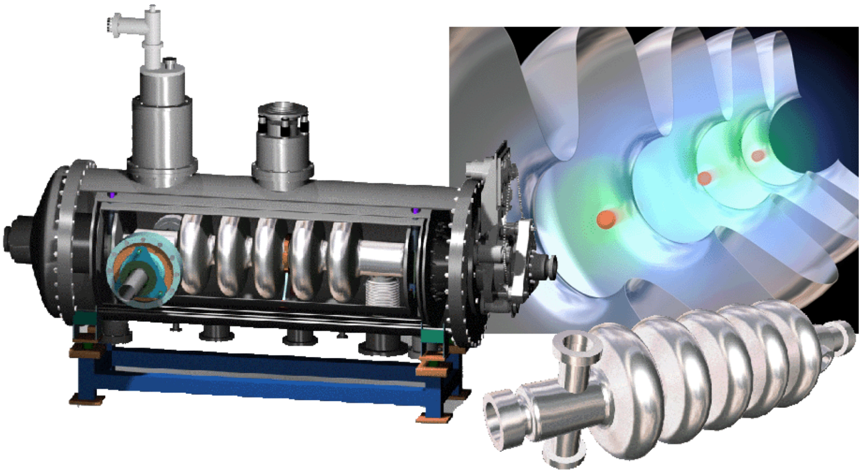

Figure 1: Superconducting elliptic cavity

The simulation model for electrodynamics is the cavity inner volume. For the system structural analysis the simulation model is the cavity walls together with cryomodule environments that could be simulated with shell and/or volume elements. It means that the different types of multi-physics applications where different physical phenomena are involved such as structural static and dynamic, thermal, fluid and high frequency electromagnetic analysis with their co-interactions should be provided during any real cavity design. The most important issue during such kind of calculations is the ability to exchange results from one type of modelling to another using them in this case as the input data and back with so-called coupled analysis.

2 Cavity design fundamentals

An important figure of merit for accelerating cavities is the quality factor (Q), which is proportional to the energy stored in the cavity and inverse proportional to the power dissipated in the cavity walls ($Q=2\pi f_0 U/P$, where f_0 is the cavity resonance frequency). The finite cavity Q causes the resonance to be broadened in the frequency domain. In steady state all power getting into the cavity is dissipated in cavity loss mechanisms. The frequency dependence is one way of Q definition. The full width at half maximum of the resonance is $1/\tau_L$. Another way of expressing this is that $Q=\omega/(2\Delta\omega)$. (Here $\Delta\omega$ is half the resonant width). For a typical niobium superconducting cavity operating at a frequency of 1.3 GHz and a temperature of 1.5 K, $Q=1x10^{10}$. With $\beta=1$, $2\Delta\omega$ is only 2 Hz, which is only $1.5x10^{-7}$% of the frequency. In normal conducting cavities it is a few kHz. This applies much higher requirements on SC cavity design and manufacturing.
Following issues are generally considered in design of SRF cavity (Fig.2):
- Minimize the peak surface fields,
- Reasonable inter-cell coupling,
- Provide required Q_{ex},
- Reasonable mechanical stiffness,
- Safe from multipacting,
- Verification of HOM and related issues.

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

The RF cavity design starts with solving electrodynamics' problem. There is a scope of codes specializing for cavity simulations (for instance, MAFIA, MWS [3], HFSS [2]). These programs are aimed for the cavity design allowing rather quick geometry change. The powerful pre-processor and existence of the cavity shape parameterization make these codes especially convenient for the iterative process of cavity optimization. As a rule, these programs can solve both types of electromagnetic problems – frequency domain and time domain.

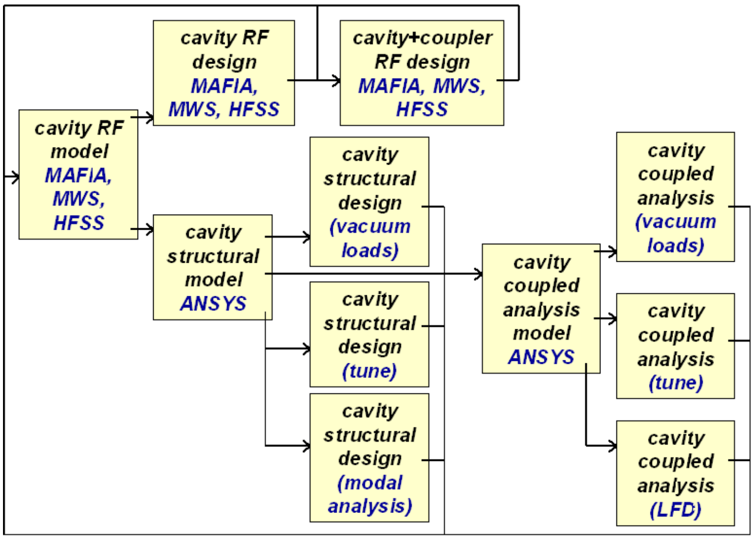

Figure 2: Scheme of SC RF cavity design

The choice of frequency domain or time domain depends on whether separate solutions of particular resonant modes, or a time history of the excitation of the cavity, are required. A Fourier transformation allows some interchange between time and frequency domain, but is generally inefficient. Therefore, both time and frequency domain computations are used to describe the properties of an accelerator cavity. The cavity structural analysis follows the electrodynamics' design. Often a solid model of the desired cavity geometry will exist, and it is usually faster to import this geometry into ANSYS [1], rather than creating the geometry internally. Some geometry manipulation within the Finite Element Analysis model is still generally required. That's why this procedure is justified only for the calculations of the final cavity geometry. For the real iterative design work it would be rather time consuming in total and it is reasonable to build the separate model for structural analysis. The full cavity shape parameterization is highly required for both electromagnetic and mechanics.

The accelerating field, E_{acc}, is proportional to the peak electric (E_{pk}) as well as magnetic field (H_{pk}) on the surface of the cavity. Therefore, the main fundamental aspects of superconducting cavities are the maximum surface fields that can be tolerated without increasing the microwave surface resistance substantially or without causing a catastrophic breakdown of superconductivity. The ultimate limit to accelerating field is the theoretical RF critical magnetic field. For the most popular superconductor, niobium, this is about 0.23 Tesla. Typical cavity performance is significantly below the theoretically expected surface field. One important phenomenon that limits the achievable RF magnetic field is „thermal breakdown" of superconductivity, originating at sub millimeter size regions of high RF loss, called defects. When the temperature outside the defect exceeds the superconducting transition temperature, the losses increase, as large regions become normal conducting.

In contrast to the magnetic field limit, the theoretical limit to the tolerable surface electric fields is unknown. However, at high electric fields, an important limitation to the performance of superconducting cavities arises from the emission of electrons from high electric field regions of the cavity. Power is absorbed by the electrons and deposited as heat upon impact with the cavity walls. If the emission grows intense at high electric fields it can even initiate thermal breakdown. When designing the cavity for a certain application, the shape and size will often go through many iterations before a satisfying design is found. Since the ratios of E_{pk}/E_{acc} and B_{pk}/E_{acc} determine the maximum accelerating field that can be achieved in a cavity they are important figures of merit to compare different designs and to identify the superior shape.

3 Model meshing

Creating an acceptable mesh is an iterative process. All simulation results including electromagnetic, surface heat flux, etc. are highly dependent on the mesh density. That's why the usual initial procedure is to create a fine mesh in critical areas on the surfaces, while retaining a larger mesh in not so important places of body in order to reduce run time and memory usage. A simply way to achieve this mesh variation is to divide the vacuum volume into sub-volumes depending on the needed local mesh size. In this way, not only the surface mesh can be controlled by sizing areas and lines but the „global" mesh size can be set on the local basis for each sub-volume, resulting in better mesh control. Still, at the end of model meshing the final adjustment of the mesh should be done as the slightly changed mesh in the areas of the main interest could result in wrong or proper field distribution and problem solution.

Some additional features of the specialized RF codes (for instance a number of specific macros) favor to use these programs for cavity RF parameters optimization. On the other hand, the existence of the RF code in ANSYS together with ability to use the same meshed model and exchange the results between different types of simulations promises the better final results. It means, the main task of electrodynamics' simulation in ANSYS is to receive the results as close as possible to the RF codes'. Since the further simulations of the structure will be related and normalized on the peak fields found, the solution of the proper field distribution on the surface is the first concern of this task.

The use of regular mesh looks favorable for the axisymmetric structures. Again, the most important feature of the mesh adjustment is to control E_{pk}/ E_{acc} and B_{pk}/ E_{acc} ratio values. In practice it has been found that the more tense mesh not always corresponds to the better results. Even more, for axisymmetric structures the regular mesh might be disadvantageous while the axisymmetric mesh lines will cause inhomogeneous field distribution. This could be eliminated using the auto mesh generation again searching for the best mesh tense. As a rule, only a combination of all possible mesh generation tool adjustments can bring the proper result.

4 Cavity simulations

The high repetition rate like 50 Hz of an accelerator will require a close look to the mechanical resonances of the cavities. Mechanical resonances can influence the phase behavior of the cavity during a pulse, which can hardly be compensated by a good control system, even if a lot of additional power is available. Additionally, the cavity RF resonance is sensitive to vibrations of sub-µm amplitudes. These microphonic effects cause low frequency noise in the accelerating fields. Therefore, a careful mechanic eigen mode analysis of the cavity together with its environments should be conducted.

Lorentz force cavity detuning is a function of RF field, which is forcing term, 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. 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.

5 Acknowledgement

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395).

References

[1] ANSYS is a trademark of SAS Inc. www.ansys.com

[2] HFSS is a trademark of ANSOFT Inc. www.ansoft.com

[3] MAFIA, MWS are a trademarks of CST Inc. www.cst.com