ENGINEERING AND BUILDING RF STRUCTURES – THE WORKS*

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Abstract

The translation of the physics designs of linear accelerators into engineering and manufacturing requirements is discussed. The stages of conceptual design, prototyping, final design, construction, and installation are described for both superconducting (LANL β = 0.175 Spoke Cavity) and normal-conducting (APT/LEDA 6.7 MeV RFQ) accelerators. An overview of codes that have linked accelerator cavity and thermal/structural analysis modules is provided.

INTRODUCTION

Over the past few decades, the field of design of linear accelerators has progressed as the programmatic needs have evolved to requirements for better performance in terms of higher duty factor, higher beam current, and higher accelerating gradient. The requirements for normal-conducting proton accelerators have advanced from such low-power applications as the Beam Experiment Aboard a Rocket (BEAR) of 30 mAmps 1 MeV of H^- at 0.025% duty factor, average beam power of 8 watts [1], to the Low Energy Demonstration Accelerator (LEDA) of 100 mAmps 6.7 MeV of H^+ at CW duty factor, average beam power of 670 Kwatts [2]. These high beam power applications become thermal management challenges. The lower duty factor applications can become similarly difficult if the accelerating gradient becomes sufficiently high that the RF thermal load is high.

For superconducting accelerators, the requirements have advanced from the Continuous Electron Beam Accelerator Facility (CEBAF) at 0.1 mAmps of e^- at CW duty factor with a gradient of 5 Mvolts/meter [3] to pulsed applications of non-relativistic beams such as the Spallation Neutron Source (SNS) [4], 30 mAmps of H^- at $\beta = 0.65$ and pulsed at 60 Hz and to the TESLA accelerator with $\beta = 1$ cavities operated at a gradient of 35 Mvolts/meter [5]. The medium-β ($0.5 \leq \beta < 1.0$) pulsed accelerators, which utilize elliptical cavities, present significant structural challenges in dealing with the Lorentz force detuning and the effects of vibration. Both phenomena cause deformation of the cavity structure and interact with the cavity fields and frequency.

Low velocity applications have advanced from the heavy ion cavities (split-ring resonators @$\beta = 0.06$) for the ATLAS Project [6] to the higher-β spoke cavities for waste transmutation, 30 mAmps of H^+ [7]; both are at CW duty factor. Recent developments on the RIA Project [8] have led to consideration of use of spoke cavities at up to $\beta = 0.6$ [9]. These low-β accelerators utilize much stiffer geometries such as 1/4-λ and spoke resonators. For these, the Lorentz force coefficients are much lower and the structural dynamics considerations are less severe. However, with the low beam current and resulting high loaded Q, there are microphonics concerns that must be addressed. And, there are still static loading issues (e.g., vacuum) and the matter of tuning forces. For spoke cavities with more than two gaps, the development of frequency tuning schemes involves interaction of the RF and structural analyses.

During the past decade, commercial codes have been developed that link the RF cavity, thermal, fluid dynamics, and structural analyses to a single CAD model. The first finite element codes in the US were developed in the 1950's for the structural design of military aircraft. Linked thermal analyses modules were added to these in the 1980's. Three-dimensional RF cavity codes and computational fluid dynamics (CFD) codes were developed independently during the 1980's. In the mid-1990's, the code vendors began linking the CFD module to the thermal module and created RF cavity modules that were then linked.

NORMAL-CONDUCTING CAVITIES

The analysis of normal-conducting cavities falls into two categories: cavities that are basically 2-dimensional and those that have significant 3-dimensional features. Except for the end regions, RFQs are basically two-dimensional structures. The cavity can be analyzed using SUPERFISH [10] for the determination of resonant frequency, quality factor, peak electric and magnetic fields, RF thermal loads, and tuning sensitivity. It is possible to create FORTRAN or C^{++} code to parse the input and output files of SUPERFISH to extract the cavity geometry, RF thermal loads, and tuning sensitivity information and to produce files that can be input to commercial thermal and structural finite element analysis (FEA) codes. The thermal module of the FEA code is run to determine the temperature distribution and that is then input to the structural module to determine the displacements and stresses. The displacement output file of the FEA code is then convolved with the tuning sensitivity data from SUPERFISH to predict the frequency shift. These programs can be run in batch mode and iteratively to solve for the coolant temperature necessary to maintain the cavity on resonance.

This procedure worked very well for the LEDA RFQ [2]. This 8-meter long cavity (Figure 1) had longitudinally variable electric field and vane skirt width. Thus, multiple

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SUPERFISH and FEA runs were required. The key requirement here was to maintain the longitudinal temperature increase in each of the coolant passages to be equal so that the thermal expansion of the cavity would be uniform and dipole modes would not be created. In order to accomplish this, the cross-sections and locations of the coolant passages were iterated until that condition was met. This required multiple iterations of SUPERFISH and the FEA code. Success was achieved as determined by the actual coolant temperatures required to maintain resonance being within 1.0 °C of the values predicted by the analysis.

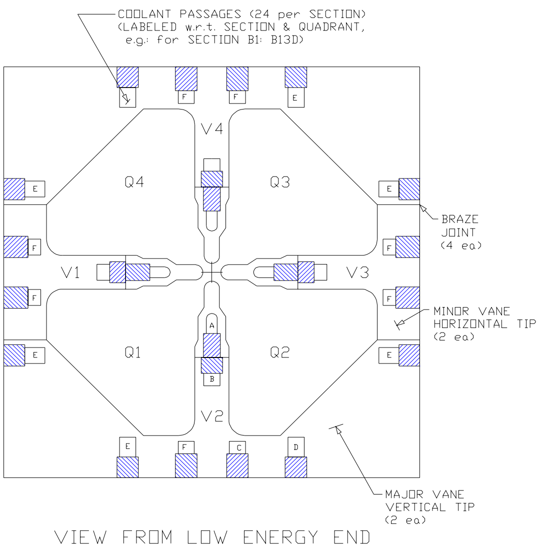

Figure 1: APT/LEDA RFQ CAVITY.

Accelerators do not always end up operating at the levels that were planned for. There are two significant examples. The RFQ for the Superconducting SuperCollider Laboratory (SSC) [11] was specified at a very low duty factor, 0.05%. This RFQ was operated successfully until the demise of the SSC. Following that, the linac was obtained as surplus equipment by a manufacturer of medical isotopes. With no modifications, the SSC RFQ is operated at 3% duty factor for the production of radioisotopes [12]. Fortunately, the 0.05% duty factor was above the level at which natural convection cooling would have been suitable so water-cooling passages were incorporated into the cavity.

A more recent case was the LEDA RFQ (Figure 2). It was not possible to achieve the specified transmission (95%) at the design electrical field level. It was necessary to increase the RF field level by 10%, corresponding to a 21% increase in RF power and thermal load on the cavity [13]. Fortunately, this was well within the design margins. A comparison of the design and operating levels of the SSC and LEDA RFQs is given on Table 1.

The incorporation of a CFD module linked to the thermal FEA module allows analysis of complex 3-dimensional cavity geometries with spatially variant high (~100 watts/cm^2) RF thermal loads. The APT/LEDA CCDTL [14] is an example of such a cavity that was analyzed using such a code. Figure 3 shows a half-cell of a 3-gap CCDTL cavity along with its coolant passage arrangement.

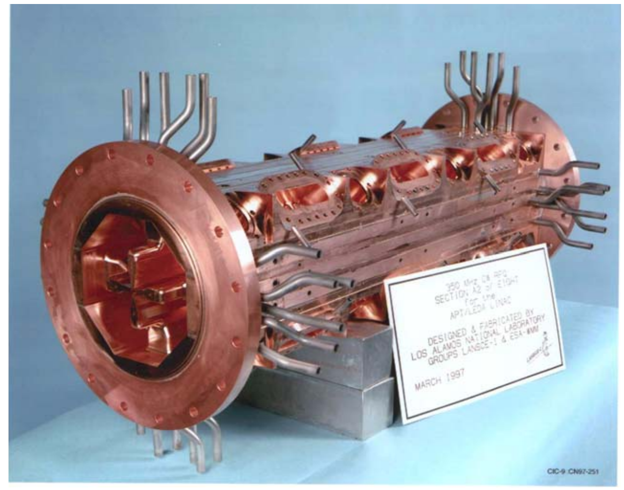

Figure 2: LEDA RFQ Section.

Table 1: RFQ Power Levels

	SSC 1992		LEDA 1995	
	Design	**Oper.**	**Design**	**Oper.**
Duty Factor	0.05%	3%	CW	CW
Energy MeV	2.5	2.5	6.7	6.7
Peak Current mAmp	27.	27.	100.	100.
Average Current mAmp	0.014	0.81	100.	100.
Beam Power kWatts	0.034	2	670.	670.
Cavity Power Kwatts/m	0.06	3.7	150.	182.
Average Heat Flux watt/cm^2	0.01	0.63	13.	16.
Peak Heat Flux watt/cm^2	0.05	3.2	65.	79.

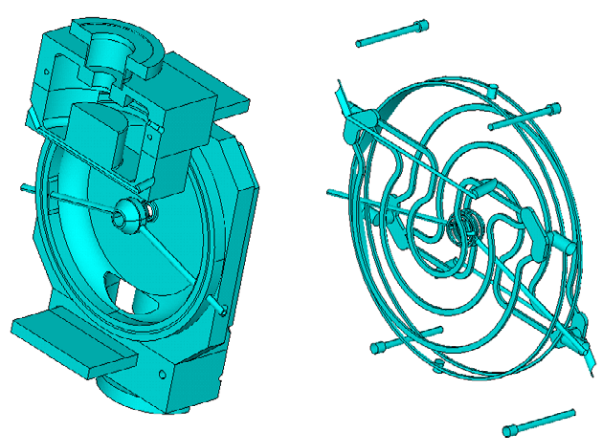

Figure 3: APT/LEDA CCDTL CAVITY & COOLANT PASSAGES [16].

Linked RF/CFD/thermal/structural analysis of the APT/LEDA CCDTL cavity was carried out using ANSYS

[15]. The predictions [16] closely matched the values of temperature and frequency shift measured on the full-power engineering model of the cavity. Similar analysis of a very high power RF photoinjector cavity [17] has been done.

The CFD modules may be used in two fashions: full CFD calculation resulting in the prediction of heat transfer coefficients or input of heat transfer coefficients obtained from empirical relations. Use of the full CFD calculation requires solution of the Navier-Stokes equations and requires considerable computing time. This is seldom justified given the good performance of the empirical predictions of the heat transfer coefficients.

The fabrication of normal-conducting accelerator cavities usually involves furnace brazing of OFE copper (ASTM F-68-99 Class 2 or better) structures. Cavities for very low duty factor applications [1] have also been fabricated from copper-plated aluminum. LANL's 30+ years of experience has been almost exclusively with "atmospheric" brazing. Brazing in an atmosphere of H_2 has the advantages of convection heating and de-oxidizing ("fluxing") of the parts. The convection heating allows better spatial control of the temperature within the furnace and assures that all parts, large and small, reflective and non-reflective, are heated nearly uniformly. Other institutions have successfully utilized vacuum furnace brazing in the manufacture of linac cavities. The advantage of vacuum brazing is that hydrogen absorption is not a concern. There are brazing job shops that provide excellent services for both atmospheric and vacuum furnace brazing.

SUPERCONDUCTING CAVITIES

The main issues in the engineering design of superconducting cavities are structural. For elliptical cavities, the RF/structural issues are generally axi-symmetric loads (Lorentz pressure or vacuum) on axi-symmetric cavities. So, the use of SUPERFISH in conjunction with a commercial structural code will suffice in most cases. For issues of structural dynamics, the non-axi-symmetric features such as the end regions (power coupler & HOM ports) and the attachment to the cryomodule are significant and thus full 3-dimensional structural analysis is required.

Pulsed Applications of Elliptical Cavities

The main concern in pulsed operation of elliptical cavities is the Lorentz force de-tuning. This can be predicted via SUPERFISH and commercial structural FEA codes. LANL uses COSMOS/M [18] for this application. The use of axi-symmetric plane elements allows the effects of weld preparations (thinned regions) to be accurately modeled. The link to SUPERFISH is as described in Section 2.

Personnel at the National Institute of Nuclear Physics (INFN) at Milan have developed a very powerful user-friendly tool for analysis of elliptical superconducting cavities [19]. This code links SUPERFISH to ANSYS and facilitates analysis of single- and multi-cell axi-symmetric cavities. The code provides prediction of Lorentz force de-tuning, vacuum frequency shift, and tuning sensitivity as well as calculation of stresses for stiffened and un-stiffened cavities. The code is linked to a database manager that keeps track of all analysis cases run. Thus it is quite easy to study the effects of variations of the cavity geometry. The INFN code was used for the design of the superconducting elliptical cavities for the Spallation Neutron Source [20].

Low-β Applications

The low-β cavities are very much 3-dimensional in terms of both their RF and structural properties. A typical spoke resonator cavity, the LANL/AAA β = 0.175, 2-Gap, 350 MHz Cavity [21], is shown on Figures 4 and 5. This is a very complex cavity and very little can be learned about such a cavity through the use of axi-symmetric or 2-dimensional analysis codes.

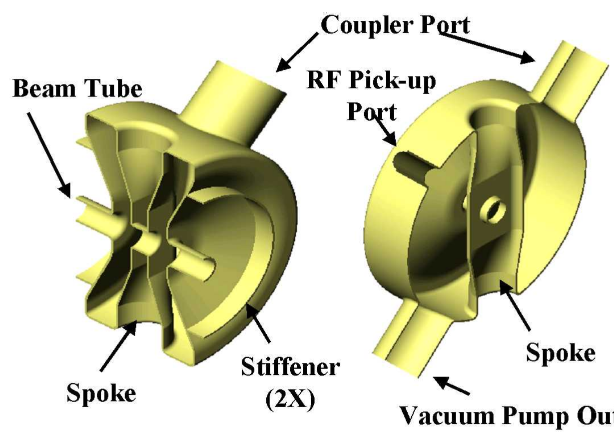

Figure 4: Cross-Section of LANL/AAA β = 0.175, 2-Gap, 350 MHz Cavity.

Figure 5: LANL/AAA β = 0.175, 2-Gap, 350 MHz Cavity.

The RF design of this cavity was performed using Microwave Studio [22]. The solid model of the cavity volume was created using the UNIGRAPHICS CAD system [23] and exported via "Standard ACIS Text" (SAT) file.

Linked RF/structural analysis was performed using MICAV [24] linked to COSMOS/M [18]. For this analysis, the cavity volume is "shelled out" to form the sheet metal niobium structure. The RF cavity module meshes the cavity volume while the structural module meshes the structural shell. The nodes on the cavity surface are merged to the nodes on the interior surface of the structural model. The resonant frequency was predicted to within 0.3% and was possible to predict the tuning sensitivity and vacuum frequency shift to an accuracy of about 20% [25]. That is reasonable agreement considering the uncertainties in precisely modeling the weld joints of the cavity stiffeners.

A similar analysis and measurements was carried out on an ANL β=0.34, 2-gap cavity [26] with results having similar accuracy. The prediction of the RF resonant frequency was again better than 0.3 %.

Most elliptical and low-β superconducting cavities are constructed of high purity (high RRR) niobium. The manufacturing technology was developed at Cornell University and at ANL more than 20 years ago. There are vendors in Europe, Japan, and the US that will produce very fine cavities on a firm, fixed-price basis. None of the vendors presently has the capability of high-temperature processing.

Larger (lower frequency) elliptical cavities are often constructed of copper with a very thin layer of niobium sputtered onto the RF surfaces. These cavities are also built in industry.

CODE VERIFICATION

The RF cavity codes that we had access to were run to determine the accuracy of the calculation of the normal-conducting resonant frequency of the ANL β = 0.34, 2-Gap, 340 MHz Cavity. A model consisting of one-quarter of the cavity was created using SOLIDWORKS [27]. A "Standard ACIS Text" (SAT) file was created from the solid model and this served as the input geometry file for all of five codes that were tested. The geometry is shown on Figure 6. The facets shown in the figure are for visual clarification; they do not represent the elements for the analysis.

The results are given in Table 2. The comparison among the codes is excellent. None of the analysis cases were optimized with respect to node and element density in order to maximize the accuracy. The characteristic of this (and many other) superconducting cavity shapes is that the cavity frequency is established prior to making the final closure weld so precision of greater than 0.3% (1 MHz for this cavity) is not required.

These commercial codes were not written specifically for the analysis and design of accelerator cavities. So, there are parameters that are not calculated directly. Depending upon the code, these may include stored energy, transit time factor, shunt impedance, and other parameters. In most cases, it is possible to extract data from the results file and to process that data to calculate the desired parameters.

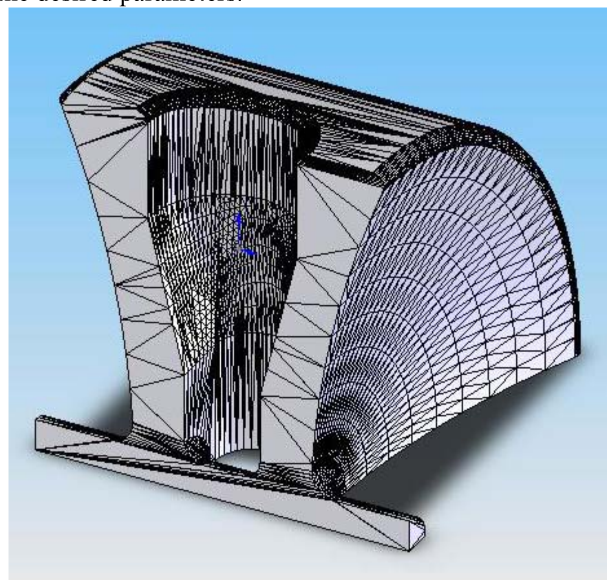

Figure 6: 1/4 Model of ANL β = 0.34, 2-Gap, 340 MHz Cavity for RF & Structural Analysis.

Table 2: Comparison of Frequency Results

CODE	REF	FREQ	Q_o	TTF
MAFIA	22,28	340.01	4621	0.905
ANALYST	28,29	340.50	4694	0.906
MICAV	24,28	340.33	4799	0.900
MWS	22,28	340.56	4554	0.905
ANSYS	15,30	340.77	4463	0.886
MEAS.	26	339.70	4815	N/A

CONCLUSIONS

The linked RF/thermal/CFD/structural codes do work. Workers at laboratories throughout the world have been successful in predicting the thermal and structural performance of accelerator cavities using these codes. Use of these codes allows accurate prediction of resonant frequencies, Lorentz force de-tuning, tuning sensitivities and mechanical resonant frequencies. Most important, these codes allow cost-effective optimization of the cavity geometry and, for superconducting cavities, the location and shape of external stiffeners.

RECOMMENDATIONS

It is clear that we now have some very powerful tools for the simulation and analysis of the RF, thermal, and structural behavior of accelerator cavities, both normal-conducting and superconducting. So, the obvious question is "can we abandon the use of low-power facsimile cavities, engineering models, and 'hot' models?"

The answer is very definitely "NO!" Simulation is no substitute for experiment. The only thing that can come out of a simulation is what was put into it. Unknown and/or forgotten phenomena will not appear in simulation results. So, some experimentation will continue to be required. However, the availability of these powerful linked codes does serve to mitigate the amount of experimentation required.

A good example of where simulation could not have substituted for experiment was in the development of the segmented resonantly coupled RFQ [31]. None of the codes that we have available today incorporate the features that made this development possible.

Secondly, while these codes work reasonably well for the prediction of the resonant frequencies and tuning sensitivities of accelerator cavities, account must be taken of manufacturing tolerances. These codes can be used to study the effects of manufacturing tolerances to bound the range of frequencies. They are most valuable in determining the tuning sensitivities of the cavities.

So, the general recommendation is that these linked codes be utilized to design the cavity geometry, specify the arrangement of cooling passages, specify the arrangement of stiffeners, predict the effect of vacuum loading,

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