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STATIC & DYNAMIC ANALYSIS OF SUPERCONDUCTING CAVITIES FOR A HIGH PERFORMANCE PROTON LINAC

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Static and dynamic analysis of 4-, 6-, and 12-cell β=0.428 niobium cavities proposed for the superconducting linac for the Accelerator Production of Tritium were carried out using COSMOS/M©, a commercial finite-element code. The benefits of external stiffeners, the tuning sensitivities, and the mechanical resonant frequencies are reported.

INTRODUCTION

The original baseline design for the linac (1990) for the Accelerator Production of Tritium (APT) is described in Ref. 1. In January of 1995 it was suggested that considerable reduction in the operating costs of the APT linac could be achieved by replacing the higher-energy portion (> 100 MeV) of the linac with a superconducting accelerator. The purpose of this note is to document static and dynamic structural analyses of the low-β elliptical cavities for the possible alternative of a superconducting (SC) concept for the APT linac.

REQUIREMENTS

A preliminary conceptual design study (Ref. 2) resulted in a design that utilizes 4-cell elliptical cavities to replace the entire side-coupled linac from 100 to 1000 MeV. The broad velocity acceptance of the elliptical cavities allows the use of only two cavity geometries: β = 0.428 (100 MeV) and β = 0.710 (361 MeV). The cell geometries selected are nonre-entrant "elliptical" shapes.

The conceptual design study considered 4-, 6-, and 12-cell cavities. In the end, the power capacity of the rf couplers limited the cavities to four cells. This was propitious because the 4-cell cavity has significantly higher mechanical resonant frequencies.

CELL GEOMETRY

The analysis concentrated on the worst case, 100 MeV (β = 0.428). Fig. 1 shows a comparison of four cavity shapes at 700 MHz, β = 0.283 (40 MeV), β = 0.428 (100 MeV), β = 0.710 (361 MeV), and β = 1.0. The inability of an un-stiffened β = 0.428 cavity to support a vacuum load is obvious. For the sake of completeness, some analysis of a β= 0.710 (361 MeV) cavity was also carried out. As the energy is increased, the geometric rigidity of the half-cell and the 4-cell cavity is improved so detailed structural analysis is not warranted at this early conceptual design stage.

There was also a question regarding the lowest energy at which the elliptical cavities could be utilized without going to unreasonable efforts. A 40 MeV (β = 0.283) single-cell cavity was also analyzed as part of the considerations for reducing the energy at which the superconducting linac begins.

STATIC ANALYSIS OF HALF-CELLS

Finite-element analyses, using COSMOS/M©, of single half-cells were carried out to determine stiffness, stress levels, tuning forces, and locations for stiffeners. The 100-MeV (β = 0.428) half-cell is the worst case; higher β cavities will be stiffer. The raw material thickness is 0.125 inch. For most of these analyses, a material thickness of 0.110 inch was used to compensate for the material removed in the chemical polishing process. A weld joint was represented as locally-reduced material thickness. A limited amount of analysis of the β = 0.710 (361 MeV) half-cell was also carried out. As a matter of academic interest, a model was also generated for a 40 MeV (β = 0.283) half-cell. In addition, a β = 1.0 and a CERN LEP cavity were analyzed. The models used are listed in Table 1.

Ambient temperature material properties were used for all of the analyses; the allowable yield stress was 5000 #/in^2. For the models with the iris not constrained, it was assumed that there would be a bellows in the beam line and therefore the vacuum load on the beam pipe was not included. All of the analyses used a symmetric boundary condition at the equator. The results of the half-cell analyses are given on Table 2

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Table 1: APT Superconducting Half-Cell Analysis Models

MODEL	ENERGY MeV	Beta β	THICK. inch	WELD JOINT	DESCRIPTION
APTSCA2	100	0.428	0.110	yes	REVISED
APTSCB1	40	0.283	0.110	yes	ORIGINAL
APTSCD1	361	0.710	0.110	yes	ORIGINAL
APTSCE1	>1000	1.000	0.110	yes	ORIGINAL
CERN1	>1000	1.000	0.235	no	Toroidal

Table 2: APT Superconducting Half-Cell Analysis Results

MODEL #	RUN #	BOUND COND @IRIS	STIFF RADIUS inch	PRESS. #/in²	IRIS FORCE #	STIFF FORCE #	MAX AXIAL DEFLECT inch	MAX von Mises STRESS #/in²	RF FREQ. SHIFT Hz	NOTES
APTSCA2	02	Free	None	Amb.	N/A	N/A	-0.061875	16070	$-7.45\ 10^6$	
APTSCA2	04	Fixed	None	Amb.	782	N/A	-0.011600	13592	$1.20\ 10^5$	
APTSCA2	05	Fixed	4.58	Amb.	293	1042	-0.001050	3984	$2.27\ 10^4$	
APTSCA2	06	Fixed	4.58	0	-2	-48	-0.001060	879	$-1.07\ 10^5$	1
APTSCA2	07	Fixed	4.58	Amb.	290	957	-0.001890	4079	$-8.40\ 10^4$	1
APTSCB1	01	Free	None	Amb.	N/A	N/A	-0.162000	62424	$-3.10\ 10^7$	
APTSCB1	02	Fixed	None	Amb.	1039	N/A	-0.022200	22994	$1.62\ 10^6$	
APTSCB1	03	Fixed	4.98	Amb.	393	1311	-0.001500	5196	$9.34\ 10^4$	
APTSCC1	01	Free	None	Amb	N/A	N/A	-0.013400	6822	$-2.84\ 10^6$	
APTSCC1	02	Fixed	None	Amb.	183	N/A	-0.000653	4538	$4.32\ 10^4$	
APTSCD1	01	Free	None	Amb	N/A	N/A	-0.016674	7818	$-1.28\ 10^6$	
APTSCD1	02	Fixed	None	Amb.	748	N/A	-0.003032	5491	$5.98\ 10^3$	
APTSCD1	03	Fixed	5.03	Amb.	304	937	-0.000412	2307	$-2.96\ 10^3$	
APTSCD1	04	Fixed	5.03	0.	-21	233	-0.001075	1465	$-5.46\ 10^4$	1
APTSCE1	01	Free	None	Amb	N/A	N/A	-0.003972	3832	$-2.00\ 10^6$	
APTSCE1	02	Fixed	None	Amb.	429	N/A	-0.001170	3580	$-1.11\ 10^4$	
APTSCE1	03	Fixed	4.45	Amb.	99	562	-0.000156	1532	$9.13\ 10^3$	
CERN1	03	Fixed	N/A	0.	220	N/A	-0.001000	443	$-1.20\ 10^4$	1

Notes: 1: -0.001 Displacement at Iris & Stiffener

Model APTSCA2/Run 02 was for the β = 0.428 half-cell under atmospheric pressure (vacuum load). and not constrained at the iris. The maximum stress, 16070 #/in², is far beyond the yield stress of the niobium and stresses in excess of 10000 #/in² occur over a large portion of the half-cell. This would lead to collapse of the cavity. Model APTSCA2/Run 04 was for the case of the half-cell constrained at the iris. While the maximum von Mises stress is not reduced significantly, the maximum occurs in the weld area. Over most of the cavity wall, the stress does not exceed 5000 #/in². This cavity will not collapse but has inadequate stiffness. A 4- or 6-cell cavity would have unacceptably high bending deformations and unacceptably low structural resonant frequencies.

It is clear that even with the iris constrained, the displacements, stresses, and resonant-frequency shifts of the cavity are unacceptably large. Some additional stiffening is therefore required. As a first step, cylindrical stiffeners were added at the radius where the iris-constrained half-cell had the maximum displacement, 4.58 inches. As far as fabrication, each stiffener would be a 1/8th-inch-thick split ring with through holes to allow the cryogen to pass. The stiffeners would be made of high purity (but not RRR grade) niobium and would be attached as the final welding step. There are also conical stiffeners which connect the end half-cells to the beam tubes. The complete 4-cell cavity is shown on Fig. 2 with an exploded view shown on Fig. 3. This stiffener concept is very similar to that proposed for the TESLA cavities (Ref. 3).

The stiffened half-cell was analyzed as model APTSCA2/Run 05. The stiffener was modeled as an axial constraint of three outer nodes nearest to the radius of 4.58 inches. The presence of the stiffener reduced the maximum displacement by a factor of 10, the maximum stress by a factor of four, and the frequency shift by a factor of five. Clearly the addition of the stiffener is worthwhile.

Model APTSCA2/Runs 06 and 07 were made to determine the tuning sensitivity. From Run 06, the tuning sensitivity is -1.07 X 10^5 MHz per 0.001 inch inward displacement of the half-cell iris. For the complete 4-cell cavity, the tuning sensitivity is -13 KHz/0.001 inch (527 MHz/micron). This scales with frequency, the ratio of the equator/iris radii, and velocity (β) with the values reported in Ref. 4.

A 361 MeV (β = 0.710) half-cell (model APTSCD1) was also analyzed. The results of model APTSCD1/Run 03 may be compared to those of model APTSCA2/Run 05. The maximum stress and displacement of the β = 0.710 half-cell under a vacuum load are significantly lower than those of the β = 0.428 half-cell. Therefore it was concluded that the results of the analysis of the β = 0.428 half-cell would be sufficient to verify that the stiffness of a stiffened β = 0.710 4-cell cavity would be adequate.

A 40-MeV (β = 0.283) half-cell was analyzed as part of the consideration of lowering the energy at which the superconducting linac is utilized. The first run, model APTSCB1/Run 01, was made without the iris constrained and showed that the cavity would collapse. With the iris constrained, model APTSCB1/Run 02, the stresses, at 22944 #/in^2, are still excessive. With the addition of a stiffener, model APTSCB1/Run 03, the half-cell becomes closer to the behavior of the β = 0.428 half-cell.

For comparison, a β = 1 half-cell was also analyzed. The results (model APTSCE1) show that this half-cell, even without constrained ends, would adequately support the vacuum load.

In order to benchmark the half-cell analysis, a model of the CERN LEP interior half-cell was analyzed. The analysis (model CERN1/Run 03) predicted a frequency sensitivity of 45 Hz/micron. The reported measured value for the CERN 4-cell LEP cavity is 40 Hz/micron (Ref. 4).

STATIC ANALYSIS OF MULTI-CELL CAVITIES

Three-dimensional static analyses of stiffened and un-stiffened β = 0.428 multi-cell cavities were also carried out. The model used is identical to that shown on Fig. 4, but with roughly double the mesh density. Because of limitations of model size, only the 4- and 6-cell cavities were analyzed. The results, listed on Table 3, show that the addition of the stiffeners is clearly warranted. The "axial-gravitational" load case is of interest for pre-installation testing of the cavities, which will occur in a vertical orientation.

Table 3: Static Deformations of Multi- Cell Cavities

Load Case	Cavity Model	Maximum Deformation (inch)	
		Un-Stiffened	Stiffened
Transverse Gravitational	4-Cell	0.00318	0.00054
	6-Cell	0.01250	0.00077
Axial Gravitational	4-Cell	0.00377	0.00113
	6-Cell	0.00850	0.00135
Ambient Pressure	4-Cell	0.01220	0.00130
	6-Cell	0.01240	0.00127

DYNAMIC ANALYSIS OF CAVITIES

A model survey of the stiffened and un-stiffened β = 0.428 multi-cell cavities was performed. The results are listed on Table 5 and 6 respectively and the complete finite-element model is shown on Fig. 4. The values for the stiffened cavity are consistent with the requirements of existing superconducting linacs (Ref. 4). Again, the necessity of the stiffeners is demonstrated. The addition of HOM couplers, rf couplers, and flanges will serve to reduce the resonant frequencies somewhat. Further analysis of the complete assembly, including the cryogen vessel, will be required.

The results of the analyses are reported in detail in Ref. 5.

Table 5: Summary of the Modal Survey of the Un-Stiffened Cavities

Mode	Frequency (Hz)		
	12-Cell	6-Cell	4-Cell
1st Transverse	8.6	30.8	57.0
2nd Transverse	15.6	60.7	92.4
3rd Transverse	36.2	86.6	111.8
1st Axial	19.0	39.4	60.2
2nd Axial	39.4	78.5	118.7

Table 6: Summary of the Modal Survey of the Stiffened Cavities

Mode	Frequency (Hz)		
	12-Cell	6-Cell	4-Cell
1st Transverse	19.3	66.7	140.7
2nd Transverse	36.5	139.9	239.8
3rd Transverse	82.6	212.8	320.7
1st Axial	34.6	70.2	109.8
2nd Axial	70.2	139.8	216.0

CONCLUSIONS

The conclusion from the analysis of the 100-MeV (β = 0.428) half-cell and 4-cell cavity is that the stiffened cavity will have adequate stiffness to resist the vacuum load and will have acceptably high structural resonant frequencies (>100 Hz). Its rf tuning sensitivity (527 Hz/micron) is adequate and with the capabilities of piezo-electric and magnetostrictive tuners that have been used with superconducting cavities (Ref. 4).

The conclusion from the analysis of the 361-MeV (β = 0.710) half-cell and from review of the three-dimensional static and dynamic analyses of the β = 0.428 cavities is that the static and dynamic structural performance of the stiffened β = 0.710 cavities will be no worse than, in fact better than, that of the β = 0.428 cavities. The tuning sensitivity of these cavities is predicted to be 378 Hz/micron.

The conclusion from the analysis of the 40 MeV (β = 0.283) half-cells was that extension of the elliptical cavities much below 100 MeV (β = 0.428) would be difficult from the point of view of the structural performance and would require careful modeling as well as some hardware experiments before this should be depended upon.

ACKNOWLEDGMENTS:

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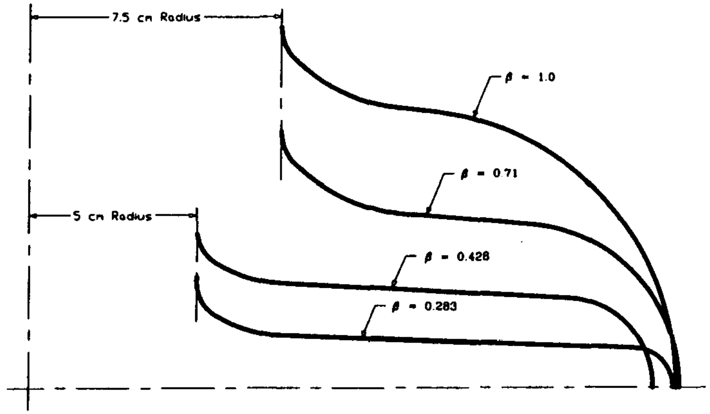

Figure 1: Cavity Shapes

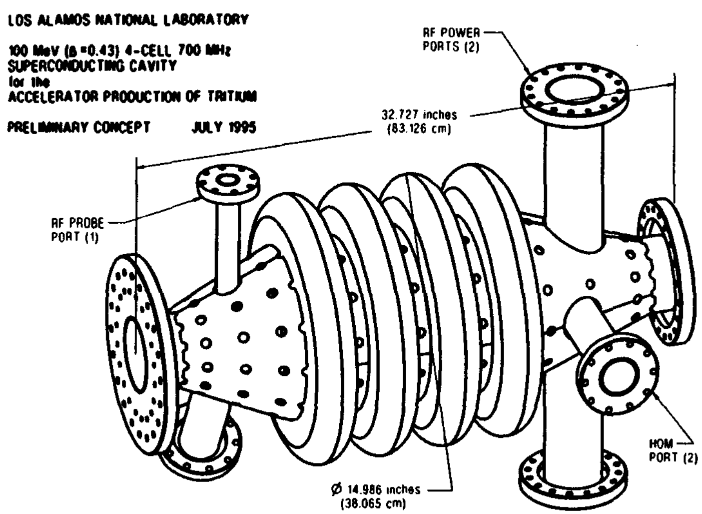

Figure 2: Assembly of β = 0.43 Cavity

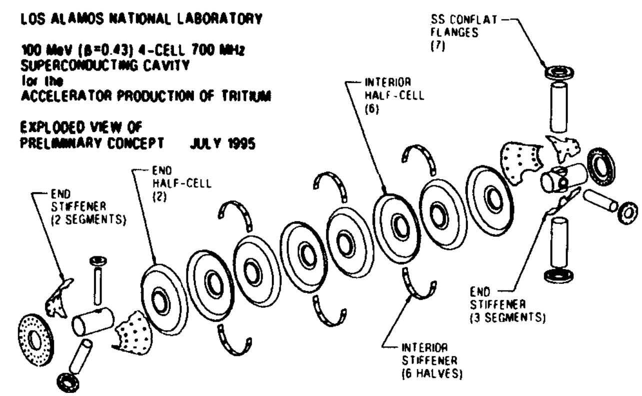

Figure 3: Exploded View of β = 0.43 Cavity

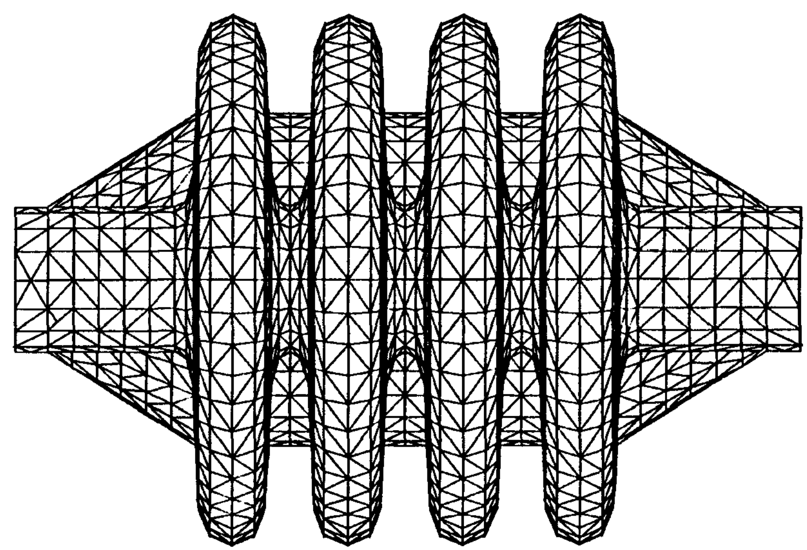

Figure 4: Finite Element Model of the 4-Cell Cavity With Stiffeners
Coarse Model for Dynamic Analysis