HIGHER ORDER MODE ANALYSIS OF THE APT SUPERCONDUCTING CAVITIES

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Abstract

In another contribution to this conference [1] the design of superconducting cavities for low velocity proton beams will be reported. Besides an optimization of the rf properties of the accelerating π-mode, other modes, possibly excited by the traversing proton beam, need to be regarded. The full spectrum of modes in $\beta = 0.64$ and $\beta = 0.82$ 5- cell cavities, as proposed for the Accelerator Production of Tritium (APT) facility [4], has been calculated up to frequencies higher than 2.0 GHz. These have been evaluated for their potential to affect the beam. The presence of "trapped" modes has also been investigated. In addition to the specific mode spectrum, the total power deposited into the cavities by the beam has been determined from the induced wake-fields. Due to the operation with beams below the velocity of light, extreme care was required to prevent incorrect results by wave reflections from the boundaries of the calculation volume. The simulations indicate that a power deposition of up to 17 W per cavity can be expected in the worst case. This power might have to be removed by higher order mode couplers, which is a technically feasible task. Transporting this power out to a room temperature dump does not even noticeably increase the requirements to the cryogenic system. Also for the prevention of beam break-up effects and for suppression of resonant excitation of specific higher order modes (HOMs) it is of interest to investigate the removal of this HOM-power. Different approaches to implement this removal technically are entertained.

1 INTRODUCTION

The HOM spectrum, which includes modes with frequencies above and below the accelerating TM010 π-mode, has been calculated with the MAFIA rf-solver[3]. The simulations have been done for the monopole modes that can deposit energy into the cavity and can change the energy of the traversing bunches. Also the dipole modes that can cause beam deflection have been investigated. The simulations for both βs have been done in an axisymmetric 2d model of a full five-cell cavity.

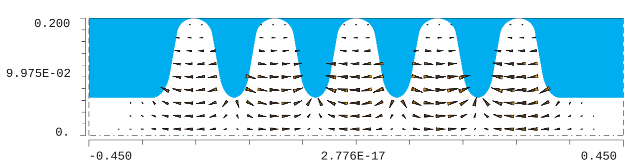

Figure 1: The β=0.64 five-cell cavity with the accelerating mode.

2 THE HIGHER ORDER MONOPOLE MODE SPECTRUM FOR THE $\beta = 0.64$ CAVITY

The monopole spectrum of the medium-β cavity has been calculated up to a frequency of about 2.8 GHz. The two lowest mode bands (TM010 and TM020) and some of their properties are presented in the following Table:

Mode Order	$\Delta\Phi$/cell	Frequency [MHz]	k_{loss} [V/pC]	R/Q [Ω]
TM010	0	681.59	0.0001	0.105
TM010	$2\pi/5$	686.54	0.0015	1.396
TM010	$3\pi/5$	692.64	0.0011	1.014
TM010	$4\pi/5$	697.56	0.0041	3.733
TM010	π	699.53	0.2033	185.00
TM020	0	1396.82	0.0023	1.034
TM020	$2\pi/5$	1410.73	0.0045	2.049
TM020	$3\pi/5$	1432.74	0.0002	0.106
TM020	$4\pi/5$	1458.80	0.0059	2.595
TM020	π	1481.02	0.0004	0.172

The modes of the TM010 band are not equally spaced, this indicates that the coupling between cells is determined by next-neighbor and second-neighbor coupling. This behavior is due to the large pipe and iris size of 6.5 cm. All modes in the bands given in Table 1 are below the pipe cut-off and need to be considered for a potential deposit of power into the cavity, if excited by the traversing bunches. The potentially most dangerous mode is the TM020 "zero" mode. Its frequency is close to a multiple of the bunch repetition frequency of 350 MHz. We are looking into a slight modification of the end-cell geometry, to remove this multiplicity. All other monopole modes are above pipe cut-off. They can travel out of the cavities and pose a lower risk for dangerous bunch interaction or increasing the cryogenic load. Their only danger could be, if they are structure modes, whose significant field-amplitudes could be trapped in the inner cells of a cavity. The spectrum, up to the limit it was calculated, did not indicate any such modes. These results have been obtained using an average pipe-length between neighboring cavities. A detailed study using all distinct cavity distances present in the design, is under way to rule out any mode trapping for certain cavity arrangements. It should be mentioned that the loss-factors listed above are valid for particles at β=1.0. The loss-factors at the velocities seen in the actual accelerator are lower. See also the section on wake fields.

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3 THE HIGHER ORDER MONOPOLE MODE SPECTRUM FOR THE $\beta = 0.82$ CAVITY

The monopole spectrum of the high-β cavity has been calculated up to a frequency of about 2.3 GHz. The two lowest mode bands (TM010 and TM020) and some of their properties are presented in the following Table:

Mode Order	$\Delta\Phi$/cell	Frequency [MHz]	k_{loss} [V/pC]	R/Q [Ω]
TM010	0	674.20	0.0001	0.049
TM010	$2\pi/5$	681.16	0.0018	1.666
TM010	$3\pi/5$	689.94	0.0006	0.577
TM010	$4\pi/5$	697.19	0.0047	4.381
TM010	π	699.92	0.3161	287.38
TM020	0	1357.69	0.0009	0.415
TM020	$2\pi/5$	1367.65	0.0100	4.671
TM020	$3\pi/5$	1384.50	0.0018	0.830
TM020	$4\pi/5$	1409.56	0.0227	10.252
TM020	π	1439.37	0.0016	0.727

Also for the high-β cavity the cell-to-cell coupling is influenced by second neighbor coupling. The modes of the TM010 and the lowest four modes of the TM020 band are below the pipe cut-off. The TM020 π-mode and all other monopole modes are above cut-off. Up to approximately 2.3 GHz no mode has been found close to a multiple of the bunch repetition frequency of 350 MHz. So resonant excitation is not expected. A further investigation of the higher modes indicates a potentially trapped mode at 1.944 GHz. Also, a recalculation with explicit pipe length instead of the average pipe length needs to be done.

4 DIPOLE MODES FOR THE $\beta = 0.64$ AND $\beta = 0.82$ CAVITIES

Dipole modes in the cavities of the APT linac could cause deflections of the proton beams. Bob Gluckstern, in an analysis independent of the specific mode spectrum, looked at the most important issues for beam break-up (BBU) for the APT accelerator [2]. His findings indicate that BBU is not an issue for several reasons:

- Presence of substantial external transverse focusing (estimate based on [5]). BBU forces act like small perturbations on the coherent motion of the beam under the focusing forces.
- Fabrication variations in the APT cavities (approximately 400 are in the accelerator) result in a distribution of frequencies of the deflecting modes along the linac. This lowers the effective Q of these modes significantly (estimate based on [6]).

These estimates do not depend on a Q reduction by the presence of HOM couplers. Further investigations of these estimates using the explicit mode spectrum are under way.

The next two tables give the lowest dipole mode-bands and their R/Q values.

$\beta = 0.64$	Mode Order	$\Delta\Phi$/cell	Frequency [MHz]	R/Q [Ω/m]
	TM110	π	924.60	0.0003
	TM110	$4\pi/5$	929.66	0.017
	TM110	$3\pi/5$	938.45	0.003
	TM110	$2\pi/5$	950.87	0.090
	TM110	0	963.42	0.018
	TE111	0	1072.50	0.003
	TE111	$2\pi/5$	1124.77	0.058
	TE111	$3\pi/5$	1196.22	0.060
	TE111	$4\pi/5$	1277.79	0.727
	TE111	π	1359.41	0.861
	TE111	$6\pi/5$	1412.15	0.027

The TE111 modes above the π mode are above cut-off. The higher part of the mode band is affected by the pipe between neighboring cavities. Thus there are more than 5 modes in this band. Only the lowest 6 modes are listed here. No mode is close to a multiple of 350 MHz.

$\beta = 0.82$	Mode Order	$\Delta\Phi$/cell	Frequency [MHz]	R/Q [Ω/m]
	TE111	0	860.16	0.035
	TE111	$2\pi/5$	876.25	0.495
	TE111	$3\pi/5$	890.63	0.015
	TE111	$4\pi/5$	898.01	0.016
	TE111	π	939.59	0.145
	TM111	0	976.07	0.069
	TM111	$2\pi/5$	1007.21	0.357
	TM111	$3\pi/5$	1054.47	0.804
	TM111	$4\pi/5$	1104.96	0.866
	TM111	π	1125.50	0.040
	TM111	$6\pi/5$	1192.00	0.001

The TM111 modes above the $3\pi/5$ mode are above cut-off. The higher part of the mode spectrum is determined by pipe and cavities. Thus there are more than 5 modes in this band. Only the lowest 6 modes are listed here. The $3\pi/5$-mode is close to a multiple of 350 MHz and needs a closer look, to evaluate its danger for BBU.

5 WAKE FIELD SIMULATIONS

Wake-field calculations give an estimate of the integrated power deposited into HOMs by bunches traversing a cavity. So far the power deposition into the monopole modes has been calculated with the MAFIA T2 solver. The difficulty in these simulations is the velocity of the bunches. The wake excitation is strongly β-dependent. Modern wake-simulation codes have formulations for open boundary conditions. These can simulate beam pipes that have no reflection for out-going waves. Unfortunately these formulations depend on moving charges with $\beta = 1.0$. For slower bunches closed boundary conditions have to be chosen. These result in reflection of the outgoing waves that move faster than the bunches. The reflections can act back on the bunch and change the wake potentials. Thus these simulations have to be set up carefully to minimize these effects. I have used long beam-pipes that were tapered off at the ends. This increased the time needed for waves to travel between the boundaries. Also, their velocity is artificially reduced by enforcing multiple reflections between the pipe walls. All wake-functions have been inspected visually to rule out the possibility that the bunch saw the large excursions of the artificially added reflected waves.

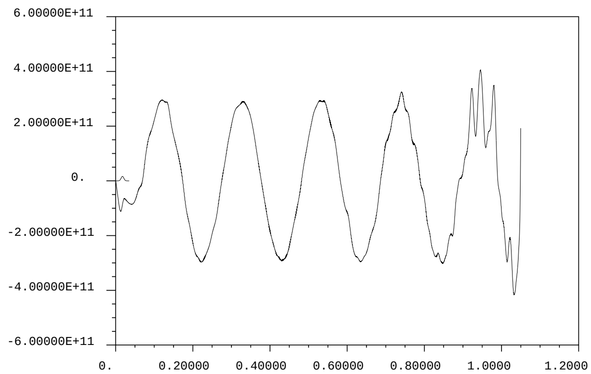

Figure 2: A typical wake function for a low-β simulation. At the left end of the plot you see an overlap of the calculated wake and the charge distribution in a bunch, assumed to be Gaussian. The choice of calculation volume has to make sure that the large wake excursions due to the artificial reflections occur outside of the bunch-frame.

β	k_{loss} [V/pC]	σ_z [mm]	P_{HOM} [W]
0.64	0.204	3.5	5-6
0.82	0.584	4.0	7-17
1.00	9.0	1.0	-

Table 5 gives the loss factors for the design-βs of both the medium and high-β sections. These have been calculated for bunch-lengths derived from the beam-dynamics simulations for the linac. The simulations have been done for the full range of βs the bunches have in each of the linac sections. From these ranges the actual HOM power for a 5-cell-cavity has been derived. The power data assume:

- a 100 mA beam with a bunch repetition rate of 350 MHz,
- all excited power would go into the structure.

The latter assumption is an overestimate. A major part of the HOM spectrum goes into modes above pipe cut-off. These modes can leave the structure without adding to the cryogenic load of the cavity. Their power could be removed in a warm part of a beam-pipe. Also most modes are not at multiples of the bunch repetition frequency. Their HOM power is out of phase with the traversing bunches and some of the power could on average go back into succeeding bunches of the beam. We are working on a less conservative estimate of HOM power to be removed. It should also be mentioned that the wake simulations have been done for a single-cell cavity. The 5-cell cavity value has been assumed to be five times this value. The validity of this approach has been tested for a β = 1.0 beam. For comparison also some numbers for an electron linac have been added to the table to demonstrate the strong variation with β and bunch-length, that both work in advantage of the proton linac.

6 HIGHER ORDER MODE COUPLERS

HOM power needs to be considered for two different reasons. First, the power deposited into the cavities can add significantly to the cryogenic load of the system. The worst case estimate done in the previous section indicates that the HOM power can be of the same order as the rf-losses from the accelerating mode itself. Second, HOM modes can have an adverse effect on the beam-dynamics if single modes act on the bunch to cause deflection or emittance growth. Since the APT facility needs to run very reliable for a long time without a long start-up time, it was decided to add HOM coupling as a safety measure. There are two venues investigated right now. The first is to add dedicated HOM couplers at both ends of each cavity. For this approach we look at loop-coupler geometries. These coaxial type couplers have a broad band capability to remove unwanted modes without affecting the accelerating mode strongly. A second path is to investigate the main-coupler potential to remove HOM power. In particular, all TM_{0nk}-type modes will couple strongly to this coupler. If all modes that need to be considered show a sufficiently strong coupling to this coupler, and if we find a setup that allows to remove this power before it would reach the coupler window, we will try to avoid additional dedicated HOM couplers.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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