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Alignment Tolerance for 7-Cell SRF Cavity

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Abstract

Principle features of the alignment specification for CEBAF 5-cell cavities are reviewed and applied to proposed 7-cell designs.

Overview

The alignment of CEBAF-style SRF cavities has been discussed in detail elsewhere [1–5]. From these discussions, we find there are three alignment-related driving terms influencing beam performance. These are:

1. the beam response to an angular kick error (lattice sensitivity),
2. the angular kick imposed on beam by gross misalignment of an ideal cavity, and
3. the angular kick imposed on beam by imperfections in cavity assembly.

The first source term describes the “lattice effect” – the response of the beam during downstream transport to angular mis-steering upstream. The latter two sources, which contribute about equally to beam steering by the cavity, are the sources of angular mis-steering. In the following, we discuss the effect of each of these source terms on beam performance in upgrades of CEBAF using 7-cell SRF cavities.

Sensitivity to Alignment Errors

The beam response to an angular kick $(0,x',0,y')$ is dictated by the lattice design and operating parameters. Downstream of the kick (assuming uncoupled transport), the beam will betatron oscillate to a phase space location $(M_{12}x',M_{22}x',M_{34}y',M_{44}y')$; the transfer matrix elements depend on the arrangement and excitation of focussing (and bending) elements. For most CEBAF upgrade scenarios currently under discussion [6], this is not expected to differ in philosophy or detail from the present installation. The latticedriven beam response to angular kick errors is therefore expected to be the same in CEBAF upgrades as it is in CEBAF. This component of the cavity alignment tolerance thus remains unchanged.

Gross Misalignment of Ideal Cavity

A gross misalignment of an ideal cavity will cause a misalignment by angle q of the accelerating field within the cavity. Such misalignments are due to transverse positioning errors of an individual cavities, cavity pairs, or entire cryomodules. They leads in turn to a deflection D in beam phase space angular displacement (either dx' or dy') that is as follows [7].

$$\Delta = \frac{1}{2}\frac{E_{gain}}{E_{total}}q$$

Here, the energy ratio is that of the single pass energy gain given by the cavity to the local injection (or average, or final) energy of the beam at (in, after) the cavity; the factor of ½ accounts for the focussing effect of cavity fringe fields [8]. Present CEBAF upgrade plans visualize use of five or more passes and possibly relatively higher injection energy [9], so the upgraded configuration will have either the same or smaller energy ratios as the original CEBAF design. The resulting steering is therefore the same, or smaller, than in present CEBAF implementations provided the same mechanical tolerance q is achieved. This source term is therefore subject to essentially the same sensitivities, tolerances, and specifications as in CEBAF.

Two additional remarks are in order. First, if an upgrade is staged incrementally, there may be running periods during which the energy ratio in this expression *exceeds* existing CEBAF values. The energy gain for the 7-cell cavity may be quite high relative to the local beam energy, particularly early on in the upgrade period and/or toward the front end of, or during early passes through, the machine. For example, if 1L02 were the first zone in which new high-gradient modules were installed this energy ratio would increase by a factor of four, unless the injection energy was also significantly raised. Such scenarios are, however, unlikely. The candidate zones for initial upgrades are the blank spaces in the linac back-ends, where upgraded modules would be installed after the machine injection and final energies are significantly raised (by as much as a factor of 2) by *in situ* processing of previously installed CEBAF cavities. The angular effect would then be reduced by the higher relative beam energy.

Also offsetting this potential degradation is the mechanism through which gross misalignments of cavities occur. Most simplistically, these arise when the ends of the cavities are mis-positioned by some offset *dr*; the resulting angle of the accelerating field is then $q= dr/L$, where L is the cavity length. If the nominal positioning error *dr* is held to the same mechanical tolerance for the 7-cell cavity as was achieved for the 5-cell design, the resulting angular misalignment will be smaller, inasmuch as the 7-cell cavity is longer than the 5-cell version.

Impact of Cavity Imperfections

Experience with CEBAF cavities indicates that the cavity assembly imperfections leading to the most significant steering errors are cell tilts in the equatorial plane [10]. The net steering generated in a cavity by cell equatorial plane tilts of ~5 mrad (due to assembly errors of 10 to 20 mils) is roughly equal in magnitude to the steering induced by pitch and yaw errors of a few milliradians. These scale as $\sqrt{N_{cell}}(E_{gain}/E_{total})$ for uncorrellated cell to cell tilts, or $N_{cell}(E_{gain}/E_{total})$ for correlated cell to cell tilts.

Given the preceding discussion on energy ratios, we then see the beam sensitivity to a fixed mechanical tilt tolerance then increases only as $\sqrt{7/5}$, or at worst, 7/5, when moving from 5-cell to 7-cell cavities. Such modest variations of sensitivities are, at the level of precision attributable to these estimates, negligible. We therefore expect cavity imperfections to have no greater impact on beam performance in 7-cell cavities than they have during use of 5-cell cavities, provided all mechanical and construction tolerances are maintained at the same levels.

7-Cell Cavity Alignment Specification

Assuming a “scaleable” upgrade, we find

1. the lattice response to a steering error is the same as in CEBAF,
2. the steering error due to gross cavity misalignments is, for the final upgraded configuration the same as, or perhaps lower than, in CEBAF, and
3. the steering error due to cavity assembly imperfections is of the same order as in CEBAF (or is at most $\sqrt{7/5}$ to 7/5 larger).

The error effects and sensitivities associated with cavity misalignments therefore do not change in such an upgrade. Moreover, in such a scaleable upgrade, corrector strengths will track energy, quad strengths, and all associated resultant error terms. Use of new fundamental power coupler and HOM coupler geometry may, further, reduce the steering effects imposed by these components. Thus, the cavities will be subject to *the same* alignment tolerance as in the original CEBAF design; the error budget allocated for the original cryomodule still applies. The alignment specification is then, and once more, as follows [11].

> *The accelerating structure should be supported in such a way that the accelerating field in any cavity will be aligned relative to the nominal beam trajectory with a root-mean-square angular precision of 2 mrad, with a 2-sigma cutoff. As in the design handbook, provision should be made for readjusting the accelerating module position to compensate for settling of the tunnel by up to 5 cm.*

We remark that the latter requirement (compensation of tunnel settlement) may be worthy of review in light of the decade of observational and operational experience now available.

References

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[8] Z. Li, *op cit*.

[9] D. R. Douglas, JLAB-TN-98-008, *op cit*.

[10] J. J. Bisognano, D. R. Douglas, and B. C. Yunn, *op cit*.

[11] *ibid*.