SIMPLE COUNTERMEASURES AGAINST THE TM_{110}-BEAM-BLOWUP-MODE IN BIPERIODIC STRUCTURES

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Summary

The two fundamental methods of fighting beam blowup in rf-accelerating-structures are staggered detuning and selective Q-spoiling of their higher order modes.

Biperiodic structures offer a very simple way of applying the latter technique to the most dangerous TM_{110}-like blowup mode at 1.7 times the accelerating frequency: letting this mode propagate but giving a large gap to the TM_{110}-passband. This gap must be positive for electric coupling ($f(\phi=0)<f(\phi=\pi)$) and negative for magnetic coupling. Then, the field energy in the part of the passband with phase velocity $v_p \approx c$ is nearly totally concentrated in the low-Q, low-shunt-impedance coupling cavities, whereas the high-Q part of the passband has $v_p \gtrsim 1.7c$.

With asymmetric coupling elements between the cavities of a structure, one has a simple tool for staggered detuning: a change of the relative orientation of these elements spreads the resonance frequencies not only of the TM_{110}-mode, but of at least all dipole modes.

Introduction

Beam blowup (BBU) is the crucial limitation of intensity in many electron accelerators. Therefore, because the rf structure is the component, which is most sensitive to countermeasures[1], optimal accelerating mode operation is not the only design criterion for such a structure. One has also to look carefully at its behaviour against BBU-modes, especially against the TM-like dipole modes causing transverse BBU.

In a measurement[1] on a cavity with LASL-profile[2] performed up to five times the TM_{010}-frequency, 18 of these modes were found, but the most dangerous one by an order of magnitude[1,3] turned out to be the TM_{110}-like mode at 1.7 times the accelerating frequency. Therefore, a gain of at least a factor of ten in BBU threshold current i_t can be obtained by just fighting this mode.

Considering $i_t \approx 1/R_\perp$, where the total transverse shunt impedance $R_\perp$ is the product of linac length L and the shunt impedance $r_\perp$ per meter, there are essentially two methods to fight BBU[1]:

a) staggered detuning of the structure cavities for the BBU-mode (while keeping constant their operating frequency) shortens the effective L of the linac[1,4]. The gain in i_t is only easily calculable, if there is no propagation of the BBU-mode along the structure;
b) selective Q-spoiling of the BBU-mode, e.g., by resonantly damping antennas[5] or cutoff pipes[1], thus, lowering $r_\perp$. This method on the contrary needs some propagation of the BBU-mode (if one does not want to damp it in each single accelerating cavity, which would be very expenditious for a high frequency structure with many cavities per meter).

For the linac of stage II of the Mainz Microtron the first technique has been applied successfully.

Now, modifying the on-axis-coupled structure (OCS)[7] used for MAMI in order to get a coupling greater than 4% for the accelerating mode, it turned out that at the same time the TM_{110}-mode begins to propagate. An investigation of the consequences of this effect for the BBU-properties of our OCS gave some principal results, which should be valuable for every biperiodic structure (BPS).

Field-amplitude distribution in a BPS

With the exception of the DAW-structure, the frequency ratio of TM_{110}-deflecting-mode and accelerating mode is 1.5-1.7. In fig. 1 the passbands of these two modes are drawn for this ratio together with some lines of constant phase velocity v_p. Trivially, a BPS is driven in the $\pi/2$-mode at $v_p=c$ with the TM_{010}-passband closed. The TM_{110}-band has a nonzero gap in general and intersects $v_p=c$, where the electrons can interact coherently with the deflecting fields of different cavities, at the 0.8-0.9π-mode. For this mode in general the coupling cells (CC) will not be nearly unexcited and a gap will cause much stronger unflatness effects than for the very stable $\pi/2$-mode.

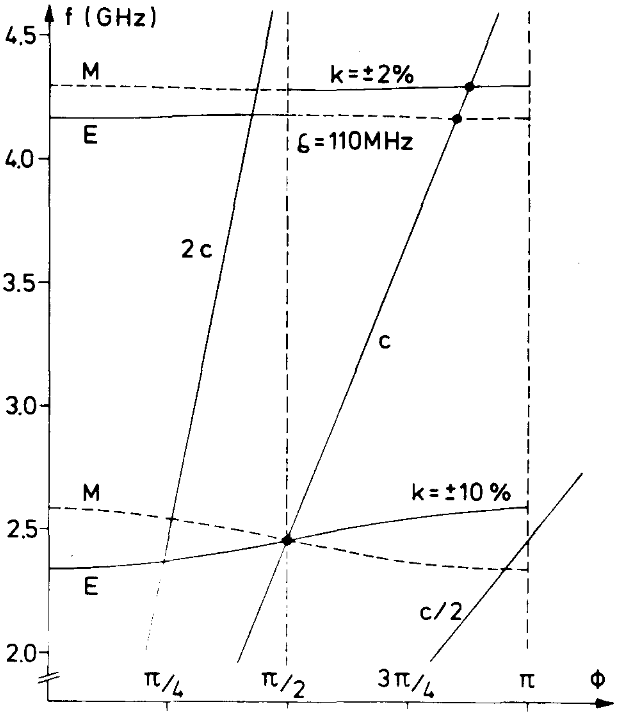

Fig. 1: The passbands of the fundamental mode and the most dangerous BBU-mode for an OCS with LASL-profile (E-electric, M-magnetic coupling).

The CC's (cf. fig. 3 for the OCS) because of their low volume/surface-ratio normally have a quality factor Q of only 20% or less of that of the accelerating cells (AC), and the ratio of shunt impedances r_{CC}/r_{AC} will be still lower for an on-axis beam (it is even zero for the side coupled[2,12] and the coaxial coupled[10] structure). Therefore, in a certain sense, the CC's are damping probes automatically built-in for a BPS and the question is, under which conditions they will have a strong coupling to the unwanted TM_{110}-mode.

With the program LOOP[8], modeling a rf structure by a series of coupled R, L, C-circuits, the field amplitude patterns for all modes of a 25-cell BPS were calculated ($Q_{CC}=2800$, $Q_{AC}=14000$, first neighbour coupling coefficient k=5%, f=4180MHz). As a criterion how the fields distribute between the CC's and the AC's, the quality factor of the whole tank $Q_T=\Sigma\, Q_n \cdot P_n/\Sigma\, P_n$ was chosen, where P_n is the power dissipated in the n-th cell (one should note that the definition $Q=2\pi\cdot$(energy stored/energy dissipated per cycle) is always valid, whereas $Q=f_{RES}/\Delta f_{FWHM}$ may be misleading for a highly dispersive structure). Fig. 2 gives Q_T as a function of mode number. The important parameter is the gap $\delta=f_{CC}-f_{AC}$ given to the passband: with increasing positive gap Q_T approaches Q_{AC} for $\phi\leq\pi/2$ and Q_{CC} for $\phi>\pi/2$, whereas for a negative gap one has just the opposite effect. In other words: in a BPS for a mode with a large gap in its passband the fields are nearly totally concentrated in those type of cells, whose frequency is close to the operating frequency in the respective branch of the dispersion curve. This was verified experimentally on a three cell OCS. It is also reflected by the fact that the calculations do not give the asymmetry in Q_T, if the passband gap is made by second neighbour couplings between the cavities instead by a frequency difference between AC's and CC's. Fig. 2 was calculated for k=5% and $Q_{CC}=Q_{AC}/5$; the changes of Q_T with δ scale linearly with 1/k and Q_{CC} in a wide range (for $\delta=0$ Q_T is nearly independent of k, and goes down linearly with Q_{CC} for $\phi\neq\pi/2$). It should be emphasized that the calculations were done for electric coupling ($f(\phi=0)<f(\phi=\pi)$ in the passband), for magnetic coupling (dashed lines in fig. 1) the results for $\phi\leq\pi/2$ and $\phi>\pi/2$ in fig. 2 must be interchanged.

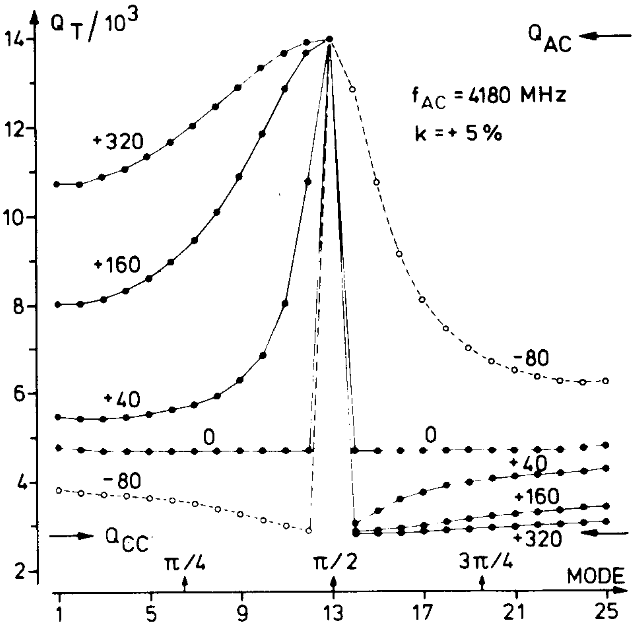

Fig. 2: The Q of a 25-cell BPS as a function of axial mode number. Parameter of the curves is the passband gap in MHz.

The recipe for using the CC's as built-in damping probes for the TM_{110}-mode at $v_p\approx c$ is therefore: make this mode propagating, make a large gap of the proper sign to its passband and make Q_{CC} as low as possible. The latter measure does not necessarily lower the Q of the $\pi/2$-accelerating-mode as can be seen in table I:

TABLE I

$Q_{\pi/2}=F(Q_{CC})$ FOR A 25-CELL BPS TANK (Q_{AC}=14000)

Q_{CC}	2000	1000	500	250	125
a:	13990	13975	13950	13900	13800
b:	13750	13470	12935	11985	10440

a,b: See text.

it shows $Q_{\pi/2}$ of a N=25-cell tank as a function of Q_{CC}. For reasonable tuning conditions (a: random errors $\Delta f_{AC}=\pm0.25$MHz, $\Delta f_{CC}\pm0.5$MHz, gap $\delta=-0.5$MHz at f=2450MHz and k=5%), there is nearly no change. Only if the tank is tuned by ±0.5MHz via the two end cells (case b), $Q_{\pi/2}$ gets worse with lower Q_{CC}. This latter effect, however, goes down with $1/k^2$ and N^2.

Applications

The rf-structure available at Mainz for trying to apply these results was the OCS (fig. 3). With coupling slot arc lengths of $\theta=63^0$, 70^0 and 80^0, one gets k=4, 6 and 10% for the TM_{010}-mode and has a CC-radius of R_{CC}= 45.0, 41.5 and 36.5 mm to close the TM_{010}-passband at 2450MHz. The gap for the TM_{110}-mode (f_{AC}=4187MHz) was then -120, +20 and +110MHz, respectively. There was no measurable propagation of this mode for the first geometry, but clear propagation (with k=1.5 and 2%) in the latter two cases. However, determining the type of coupling by a phase measurement on a three cavity setup it turned out to be magnetic ($f(\phi=0)>f(\phi=\pi)$) for the TM_{110}-mode (and also, as expected, for the TM_{010}-mode). Therefore, the gap for the two geometries propagating has just the wrong sign. A smaller slot radius R_S (fig. 3) to get electric TM_{110}-coupling would only not decrease $k(TM_{010})$ if θ is growing rapidly at the same time. With a smaller slot width[7] w, one could try to get a larger R_{CC} for the TM_{010}-band closed and the TM_{110}-band having a negative gap, but it is rather likely, that then propagation will cease: for the OCS of fig. 3 with 80^0-slots and R_{CC}=85mm ($\delta(TM_{010})$= -169MHz, $\delta(TM_{110})$= -28MHz) it was nearly suppressed. The propagation of the TM_{110}-mode seems to be at least as sensitive to the radial field pattern in the CC's (changing with R_{CC}) as to the slot arc length.

A good candidate, however, for the above results being applicable, should be the CHEER-structure proposed by McKeown and Schriber[9]: at this OCS the coupling is done by the beam hole. By increasing its size, one changes f_{CC} more quickly than f_{AC}, these frequencies going up for the TM_{010}-mode and down for the TM_{110}-mode. Then closing the TM_{010}-band by a larger R_{CC}, one will have a large negative TM_{110}-gap, which for magnetic coupling is just the proper sign.

If in the coaxial coupled structure[10,11] by measures on arc length and position of the coupling slots, the TM_{110}-mode could be made propagating magnetically, here the large diameter of the CC's guarantees a large negative passband gap and, therefore, a concentration of the deflecting fields in these cavities for $v_p\approx c$.

Concerning the side coupled structure[2,12], one has nearly total freedom for the geometry of the CC's: not only for making a negative gap for the TM_{110}-mode (magnetic coupling) but also for a very low Q of these cells. Naturally, one must pay attention to let both polarisations of the TM_{110}-mode propagate by a 90^0-grouping of the CC's. This is true for all structures with non-axis-symmetric coupling elements.

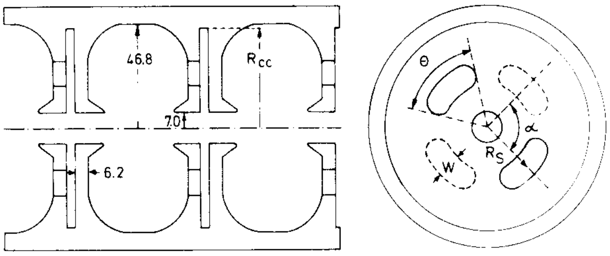

Fig. 3: The geometry of the OCS[7] operating in MAMI.

Staggered detuning

It has been verified by LOOP-calculations that this type of BBU-countermeasure does not quench too much the propagation of a mode to loading probes, if one is a little away from the band edges and the passband width is large compared with the range of detuning. The latter is normally true, because the detuning range must only be great compared to a single AC resonance bandwidth. Naturally, both methods do not just add their effects[1], and it may be complicated to calculate their superposition.

The detuning method does not depend on any low-Q elements in the structure and it has the advantage of normally acting on several modes simultaneously. Fig. 4 shows the effect of changing the angle α between the two coupling slot pairs of an AC of our OCS (fig. 3) on the mode spectrum measured up to 5900MHz. The additional 82 modes found between 6620 and 12430MHz were not identified in detail, but as a spot check it was verified that from 6500 to 7000 and from 10800 to 11500MHz (around the two next-dangerous transverse BBU-modes[1,3]) no mode changes less than 6MHz with α going from 90° to 0°. That the TM_{010}-mode nearly does not change with α[1,6], seems to be a somewhat incidental property of the AC-geometry, it is not true, e.g., for the flat CC's[13]. It should be noted that the rotation of slot pairs is done within each AC, by a rotation of half of the rf sections in space by 90°, thus, interchanging horizontal and vertical deflections, one can gain another factor of two in BBU-threshold e.g. for the TM_{110}-mode.

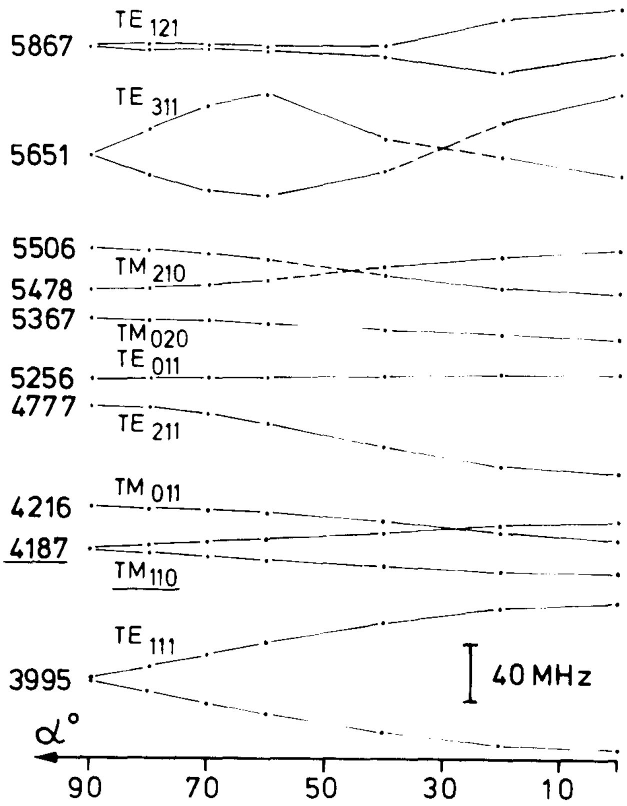

Fig. 4: Mode spectrum measured on a single AC of fig. 3 as a function of the angle α between the pairs of coupling slots.

The gain in BBU threshold current i_t one can obtain for a certain mode by staggered detuning is given by

$$G = M/(1 + \sum_{m=1}^{K/2} 2/(1 + (m \cdot \Delta/K)^2))$$

where M is the number of equidistant frequencies to which the cavity chain is tuned for the BBU-mode, K=M-1 and $\Delta=2\cdot Q\cdot\Delta f/f$ with Q being the quality factor of the mode, f its frequency and Δf the total range of detuning. For the TM_{110}-like mode at f=4187MHz and Q_{AC}=14000 one has a maximum Δf=17MHz (half of the total frequency splitting in fig. 4 for one polarization). For splitting this resonance into M=10 frequencies (e.g. $\Delta\alpha=9°$), one gets a gain G=10 for i_t, going up to M=100, the gain is only G=36 because of the finite Q_{AC}. For a mode with the same Q_{AC} at f= 11200MHz and Δf=6MHz only, one has still a factor G up to 6.

Acknowledgements

The authors are very indebted to Dr. S.O. Schriber, CRNL, for leaving them his program LOOP. Part of this work has been supported by the Deutsche Forschungsgemeinschaft, SFB 201.

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