Beam Loading and Beam Breakup in a 1.3 GHz Microtron Accelerating Cavity

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Abstract

As part of the FEL project TEUFEL[1], a 25 MeV racetrack microtron is under construction. The microtron will accelerate a high current and therefore beam loading and beam breakup (bbu) are of importance. Beam loading is studied analytically by means of an LC circuit simulation. To obtain estimates of the bbu starting currents, the relevant TM_{110}-like modes were calculated with the MAFIA codes. Field profiles of these modes were measured in a scale 1:1 aluminium model of the cavity.

1 INTRODUCTION

The microtron cavity will be an on axis coupled structure consisting of three accelerating cells and two coupling cells. It accelerates the beam with 2.11 MeV per pass. Its design has been given in Ref.[2]. The injector is a high quality 6 MeV linac, capable of delivering micropulses of upto 400 A. The peak current aimed at for the microtron is 50 to 100 A. For a micropulse width of 15° and a pulse selection of 1:16 the average macropulse current is 125 mA to 250 mA. One major effect of this high beam loading is a reflection of rf power at the cavity input, which depends on the accelerated beam current. Beam breakup (bbu) is an instability that occurs above a certain threshold current. It is due to parasitic dipole modes in the accelerating structure[3].

2 EQUIVALENT CIRCUIT ANALYSIS OF THE BEAM LOADED CAVITY

With an rf power dissipation in the cavity walls during the macropulse of 300 kW and a beam power of more than 3 MW, the maximum beam loading will be higher than 90%. The behaviour of a cavity under heavy beam loading can be simulated with an equivalent LC-circuit. The coupling of the cavity with the rf generator can be expressed in terms of the cavity coupling coefficient β. This parameter represents the ratio of the power that is radiated out of the cavity (through the coupling iris) to the wall losses. From the LC-circuit calculation it follows [4] that the normalized reflected power r (normalized with respect to the wall losses) is given by

$$r = \frac{1}{4\beta}(1+p-\beta)^2 + \frac{(1+\beta)^2}{4\beta}(\tan\psi - \tan\psi_0)^2, \quad (1)$$

with $\tan\psi = -2Q_L(\omega-\omega_0)/\omega_0$, $\tan\psi_0 = -p\tan\phi/(1+\beta)$ and where Q_L is the loaded Q-value, ω is the angular rf frequency, ω_0 is the angular resonance frequency of the cavity, ϕ is the accelerating phase of the beam with respect to the rf wave and p is normalized beam power. As can be seen from Eq. (1) reflections may arise (i) because the accelerated beam power deviates from the design value $p_0 \equiv \beta - 1$ for which the cavity is perfectly matched and (ii) because the cavity is not perfectly tuned ($\psi \neq \psi_0$). For our racetrack microtron the operation point for p may vary between 0 and 10. It is important that β is chosen properly, such that for this whole range the reflected power stays within reasonable limits. For our parameters $\beta = 6$ is a reasonable choice. In Fig. 1 we give the required generator power as a function of p, assuming perfect tuning. The generator power is the sum of the wall losses, the beam power and the reflected power.

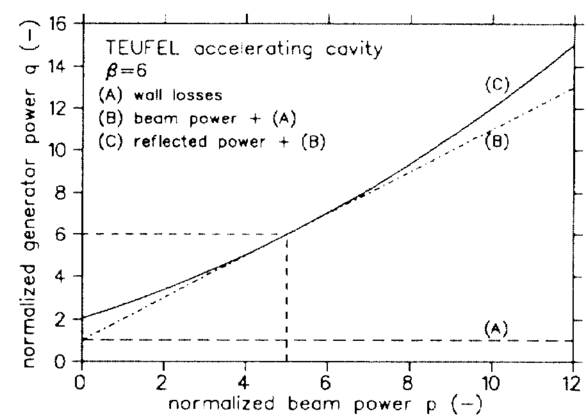

Figure 1: *required normalized generator power as function of the normalized beam power*

3 BEAM BREAKUP CALCULATIONS

The type of instability that determines the current limitation in our microtron is the so-called recirculative beam breakup. The time constant for the instability to built up is $\tau = 2Q_L/\omega$ with Q_L the loaded Q-value of the bbu mode and ω its angular frequency. For our cavity this is of the order of 1 μsec, i.e. well within the macropulse duration of 10 μsec. A formula for the average macropulse starting current has been given by Rand [3]:

$$I_s = \frac{-2W_0^*}{e\eta F_1^2 kQ_L}\{\sum_{s=2}^{N}\sum_{r=1}^{s-1}(R_{12})_{rs}(\frac{W_0^*}{W_0^*+(r-1)\Delta W}) \times \sin(\psi_{s-1}-\psi_{r-1})\}^{-1}, \quad (2)$$

where $\eta = 1/4\pi\epsilon_0 c$, $k = \omega/c$ is the free space wave number, W_0^* is an effective injection energy, taken as the energy of the primary beam at the center of the cavity, ΔW is the energy gain per pass, N is the number of passes of the beam through the cavity, R_{12} is the matrix element which relates the displacement of a particle at the end of an optical system to the initial deflection, $(R_{12})_{rs}$ is the respective matrix element for a transfer from pass r to pass s and ψ_j is the rf phase shift of the mode for the first j orbits. It is given by $\psi_j = 2\pi(j\mu + \frac{1}{2}j(j-1)\nu)\lambda_0/\lambda$ where λ_0 and λ are the free-space wavelength of the accelerating and breakup modes respectively, the first orbit circumference is $\mu\lambda_0$ and the increment in orbit circumference is $\nu\lambda_0$ (μ and ν integers). For modes with even parity the quantity F_1 in Eq. (2) is defined by

$$F_1 = \frac{1}{E_0}\int_{-l/2}^{l/2} \frac{\partial E_z}{\partial x}\cos(kz)dz, \qquad (3)$$

where E_z is the longitudinal electric field, x is transverse displacement, l is the length of the cavity and E_0 is related to the stored field energy by $E_0^2 = U\eta c k^3$. For modes with odd parity the term $\cos(kz)$ in Eq. (3) must be replaced by $\sin(kz)$.

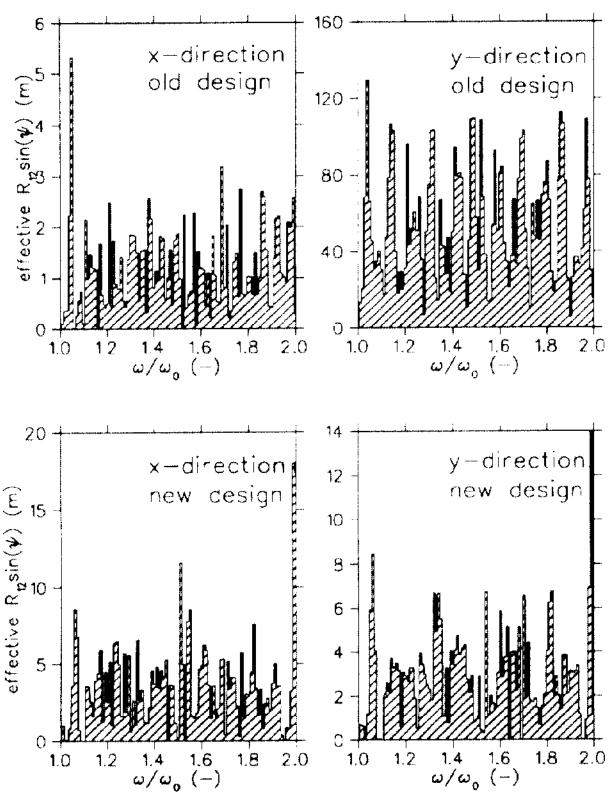

Figure 2: *geometrical beam breakup mode spectrum for the initial and for the new design of the racetrack microtron recirculation system*

As may be seen from Eqs. (2) and (3), our short cavity length (44 cm) and also the high injection energy of 6 MeV contribute considerably to achieving a high starting current. Another quantity which may be optimized is the beam optical contribution to I_s given by the curly brackets in the denominator of Eq. (2) and which we shall denote by 'effective $R_{12}\sin\psi$'. This quantity was evaluated for a continuous spectrum of the frequency ratio ω/ω_0 (bbu-mode/accelerating mode) and for two different designs of the racetrack microtron (see Ref.[5]). The initial design employed three-sector magnets (hill 42°, valley 13°, hill 35°) with a hill to valley ratio of 2.5. Calculations for this layout showed a too high sensitivity of the optical properties to small changes in the design parameters. Therefore, this design was rejected. The new design employs two-sector magnets (valley 70°, hill 20°) with a hill to valley ratio of 1.2. The two magnets are slightly rotated with respect to each other in the median plane over a total angle of 2 × 6°. The respective bbu spectra are depicted in Fig. 2. As can be seen there is a slight worsening of the horizontal optics for the new design. However, this is more than compensated by the order of magnitude gain achieved in the y-direction.

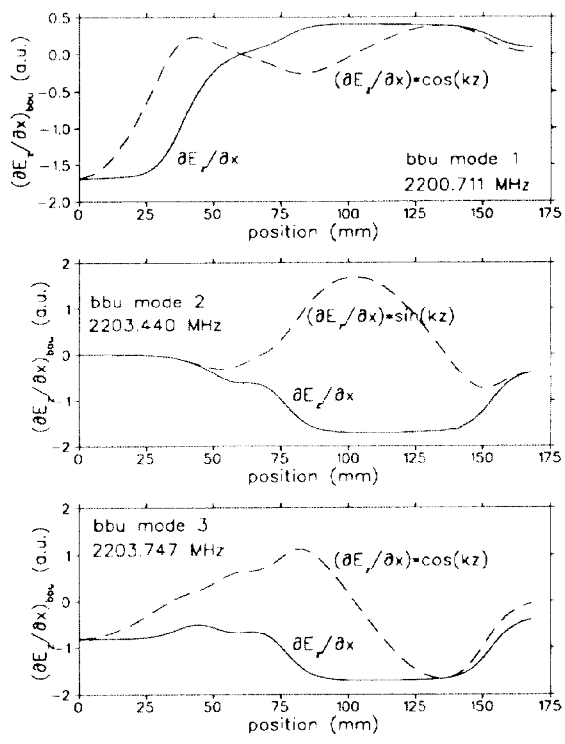

Figure 3: *electric field gradients of three TM_{110}-like bbu modes, calculated with the MAFIA codes*

In order to obtain a quantative figure for the bbu starting currents, numerical calculations were done with the MAFIA codes. Special attention was given to the TM_{110}-like modes because these are usually the most dangerous. Three of these modes were found; two with even parity and one with odd parity. The field gradients of these modes along the cavity axis are depicted in Fig. 3. For the determination of the starting currents the unloaded Q-values as

mode	Q_0 (-)	F_1 (-)	$\beta_2^{1)}$ (-)	$I_s^{2)}$ (mA)	$I_s^{3)}$ (mA)
1	37450	-0.865	36.1	56.4	2092
2	27770	-1.165	0	41.9	41.9
3	27810	0.979	4.0	59.2	296

Table 1: Some properties of three TM_{110}-like bbu modes calculated with the MAFIA codes ([1] estimated with Eq. (4), [2] inserting the unloaded Q-value in Eq. (2), [3] inserting the loaded Q-value in Eq. (2))

calculated with MAFIA may be used. This however, gives a pessimistic approximation because $Q_L = Q_0/(1+\beta_2)$, where β_2 (> 0) is the cavity coupling coefficient for the bbu mode. The rf power which is radiated out of the cavity through the coupling iris is proportional to the electromagnetic energy density at the location of the iris. An estimate of β_2 can be obtained, if we assume that the proportionality constant is equal for both the accelerating mode and the bbu mode. Then for a single cell $\beta_2 = \alpha\beta_1$, with $\alpha = (\frac{\omega U}{Q_0 w})_1/(\frac{\omega U}{Q_0 w})_2$ where U is the stored energy, w the energy density at the iris and where the subscripts 1 and 2 denote accelerating mode and bbu mode respectively. The constant α obtained with an URMEL calculation of the single-cell geometry, is $\alpha = 2.23$. If the field amplitudes in each of the cells are different, then a correction must be made. For our three-cell structure we get

$$\beta_2 = \frac{3E_2^2}{E_1^2+E_2^2+E_3^2}\alpha\beta_1, \quad (4)$$

with E_i the bbu field amplitude in cell i.

In table 1 estimated starting currents are given as calculated with Eq. (2), The effective matrix element $R_{12}\sin\psi$=6.5 m is taken at $\omega/\omega_0 = 1.69$, and at that frequency is limited by the vertical optics. As can be seen, for the modes 1 and 3, the high value of $\beta_1 = 6$, is very helpful in raising the respective starting currents. However, for the odd parity mode, the field level in the middle cell is zero and therefore the loaded and unloaded Q-values are equal. In practice, however, due to small tuning errors, the structure will not be perfectly symmetric and this will give a perturbation of the field distribution for each of the three modes. Since the coupling between neighbouring accelerating cells for the TM_{110}-like modes is very weak (in the order of 0.1%) small errors can have large effects. This is illustrated in Fig. 4 where field profiles are given of the bbu modes, measured with the perturbation ball method in a scale 1:1 aluminium model of the cavity (see also Ref.[2]). If we calculate with Eq. (4) the cavity coupling parameter β_2 for these measured modes (assuming $\beta_1 = 6$), we find $\beta_2 = 13.2$, $\beta_2 = 15.7$, and $\beta_2 = 11.0$ for modes 1,2 and 3 respectively. However, these results depend critically on the tuning errors and will therefore be different for the final copper structure. Nevertheless, small tuning errors may be of advantage for increasing the bbu starting current. The tuning errors will also influence the field profile of the accelerating mode, but since for this mode the cell coupling is much stronger ($\approx$ 5%) the effect will be substantially weaker.

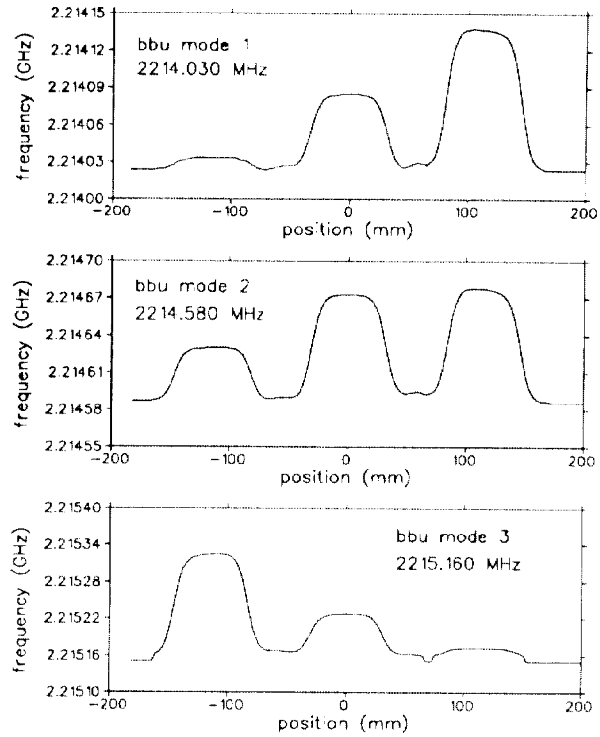

Figure 4: *profiles of three bbu modes measured with the perturbation ball method*

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