THE POSSIBILITY OF MULTIPACTOR DISCHARGE IN COUPLING CELLS OF COUPLED CELLS ACCELERATING STRUCTURES

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Abstract

The Multipactor Discharge (MD) takes place at low values of electric rf field. Operating values of the field in accelerating cells are usually match more higher than the upper threshold of the discharge and this phenomenon take place during structure conditioning. In operating regime, during rf pulse, weak electric field, linearly decreasing from the point of the rf drive to the end of the cavity, exists in coupling cells to provide rf power flux along the cavity. Depending on cavity operating regime and coupling cells parameters, the value of this field can be in limits of the discharge. In this paper parameters of coupling cells for Side Coupled (SCS), On-axis Coupled (OCS) and Annular Coupled (ACS) structures are considered and estimations for electric field are given. Results of numerical simulations of the discharge in coupling cells are presented.

1 INTRODUCTION

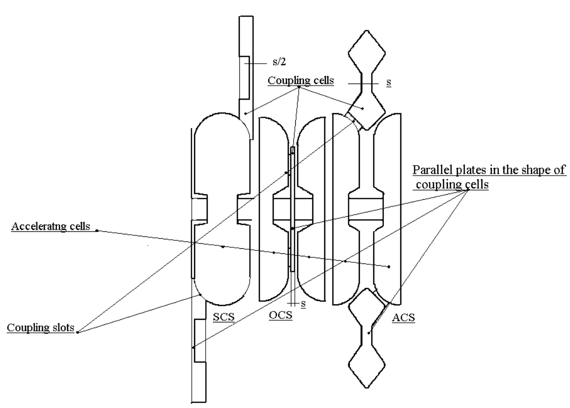

Figure 1: A sketch of SCS, OCS and ACS structures

The effect of the MD in accelerating cells of Coupled Cells (CCL) structures is straightforward, because parameters of accelerating cells directly define parameters of the cavity and the discharge is equivalent to additional parasitic conductivity. In operating regime coupling cells in first order do not excite, the MD in coupling cells may be simulated as additional rf losses, leading to reduction of quality factor for coupling cell and has not such evident sequences on operating parameters. To decrease dimensions of coupling cells, one need provide capacitive load by providing 'noses' in the region of strong electric field of the coupling mode. As the result, coupling cells have parallel plates, like capacitor (Fig.1). Such shape is favourable for MD excitation.

The MD in coupling cells of CCL structures was not described in papers directly, just indications that OCS was rejected for application in TRISPAL project due to MD possibility [1] or private communications [2]. The purpose of this paper is to discuss the possibility of most popular first order two-surface MD in coupling cells, to compare different types of coupling cells and specify operating parameters of the structure, which can provide conditions for MD in coupling cells.

2 STEADY-STATE CONDITIONS

2.1 The energy stored in coupling cells

If the steady-state operating regime of the CCL structure is specified, one can easy find the energy W_a of electric field stored in accelerating cell:

$$W_a = \frac{c\beta_p Q_a (E_0 T)^2}{4\pi f_0^2 Z_e}, \qquad (1)$$

where Q_a is quality factor for accelerating cells, Z_e - effective shunt impedance, f_0 - operating frequency, β_p - relative velocity of particles, c - velocity of light, E_0 - average electric field along axis, T -transit time factor. To find stored energy in coupling cells, one can use conclusions both lumped circuit [3] and electrodynamical [4] approaches, which coincide for coupling cells. The energy stored in coupling cells W_c is

$$W_c = W_a \alpha^2 (n - N)^2, \qquad (2)$$

where α is attenuation constant per period, n - number of the coupling cell from the point of rf input, N - number of the structure periods from the point of rf input to the end of the cavity. If the beam loading is not strong $I_b Z_e cos^2\varphi_s \leq E_0 T$, attenuation constant α may be estimated as:

$$\alpha \approx (1 + \frac{I_b Z_e cos\varphi_s}{E_0 T})\frac{2}{k_c Q_a} \qquad (3)$$

where k_c is the coupling coefficient of the CCL structure, φ_s - synchronous phase. For strong beam loading attenuation should be founded as the result of solution for the power balance equation [4]. Combining (1-3), one can define W_c for any operating regime given. For proton linacs at typical values f_0=805 MHz, β_p=0.5, Q_a=20000, k_c=5%, Z_e=35 MOhm/m, supposing I_b=0 and N=40 (total tank has 80 accelerating cells and rf input is in the middle of the tank) dependencies of W_c on the accelerating gradient $E_0 T$ and n are plotted in Fig.2. As one see, W_c may varies in wide range, depending on $E_0 T$ and N values.

2.2 Estimations for MD threshold

In typical shape of coupling cells there are parallel plates (Fig.1) with electric field of coupling mode between them. Because the gap length s between plates is small, we can suppose uniform electric field between plates, considering this region as a capacitor. Simple estimations for the MD range may be obtained by using the model of single electron sheet ([5],[6] and relates references). The resonant condition for electric field strength E_r in coupling cells for two electrode MD is:

$$E_r = \frac{4\pi^2 f_0^2 sG}{(e/m)}, \quad (4)$$

$$G = [(\frac{k_v+1}{k_v-1})(2n_p-1)\pi cos\phi_e + 2sin\phi_e]^{-1}, \quad (5)$$

where e/m is the ratio of electron charge and mass, n_p - order of MD (number of rf halfperiods needed for electron to pass distance s, k_v is assumed constant ratio of electron emission to impact velocities and ϕ_e is secondary emission electron starting phase. Below we consider mostly first order $n_p = 1$ MD. For phase stable MD the phase of electron impact with second plate ϕ_i should be $\phi_i \approx \phi_e + n_p\pi$ with the condition of stability $-1 \geq d\phi_i/ \geq 1$ [6]. The minimum value of E_r depends on $G(k_v, \phi_e)$ and G_{min}= 0.27 (k_v=0), G_{min}=0.23 (k_v=0.1), G_{min}=0.21 (k_v=0.25). The assumption $k_v = const$ has no physical basement, but due to week dependence, results obtained are in good agreement with experiments [7] and direct numerical MD simulation [6] and assumption k_v=0 is a good approximation.
From (4) one can see, that rf resonant rf voltage for MD excitation $V_r = E_r s$ does not depend on frequency f_0 if scaling is applied for dimensions of coupling cell.
Another important value for MD exitation is the energy of impact electrons W_i (supposing nonrelativistic electrons):

$$W_i = 8\pi^2 m(\frac{f_0 sGcos\phi_e}{1-k_v})^2 \quad (6)$$

For high order (n_p=2,3,4..) MD estimations for resonant rf voltage V_{rn_p} and impact energy W_{in_p} may be obtained

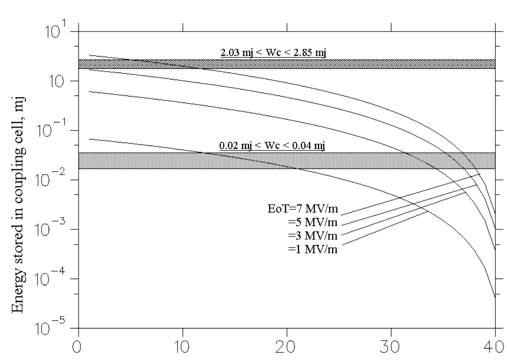

Figure 2: The energy stored in coupling cells, mj

using G-factor, if equivalent values for n_p=1 discharge are known ($V_{rn_p} \approx V_{r1}/n_p$, $W_{in_p} \approx W_{i1}/n_p^2$).

2.3 Coupling cells parameters

To compare parameters of different cells, three types of structures - SCS, ACS and OCS (Fig.1) were calculated at the same frequency 805 MHz for 0.45 $\leq \beta_p \leq$ 0.8. By using powerful 3D code Mafia, one can calculate field distribution for coupling mode and define simply, what value of electric field E_c or rf voltage V_c between plates in coupling cell corresponds to stored energy W_c. To describe the this parameters for coupling cell, the best way is to introduce "equivalent capacitance" C_e:

$$C_e = \frac{2W_c}{V_c^2} \quad (7)$$

If this C_e value is known at the given frequency, for another value it can be estimated from scaling relation $C_e \sim f^{-1}$. For SCS geometry is the same as for [8], ACS geometry was scaled from [9]. For OCS structure the length of coupling cells was 0.1 from the length of accelerating one. Last OCS example for β_p=1, f_0=2797 MHz is from reference [10]. For OCS structure V_c is calculated at radius of beam aperture. If dimensions of coupling are specified, one can estimate $f_0 s$ value, which is of main importance for calculation of V_r (4) and estimate energy stored in coupling cell $W_{c1} = C_e V_r^2/2$ and impact energy W_{i1} (6) which correspond to condition of n_p=1 stable ($0 \leq \phi_e \leq 33^o$ [6]) discharge. Results are summarised in Table 1, W_c and W_i are estimated for n_p=1 MD.

Table 1: Parameters of coupling cells

CCL	β_p	$f_0 s$	C_e	W_{c1}	W_{i1}
			pF	mj	keV
SCS	0.45	705	4.42	0.02÷0.03	1.1÷2.3
	0.50	834	3.87	0.03÷0.05	1.6÷3.2
	0.70	1545	2.34	0.24÷0.34	5.5÷11
ACS	0.52	1503	21.9	2.03÷2.85	5.2÷10
	0.78	2177	33.7	13.7÷19.3	11÷22
OCS	0.50	563	14.0	0.02÷0.04	0.7÷1.5
	0.70	837	12.4	0.11÷0.16	1.6÷3.2
	1.0	1200	3.39	0.12÷0.18	3.3÷6.6

3 DISCUSSION

3.1 Conditions of discharge

To have stable discharge, one need fulfil three conditions:
a) - space stability;
b) - phase stability;
c) - impact electron energy should be in range where secondary emission coefficient $\sigma_e \geq$1.0. For copper this range is from $\approx$ 200 eV to $\approx$ 2 keV, depending on surface quality. As one see from Table 1, conditions b) and c) are valid for

low β_p SCS and OCS structures. Not so big energy 0.02 mj $\leq W_{c1} \leq$ 0.04 mj should be stored in coupling cells to provide conditions for n_p=1 discharge. This range is shadowed at Fig.2 and one can see these values realistic for proton linacs. In accelerating cavity several coupling cells may be in range of possible discharge. For ACS structure impact electron energy is too big even for low β_p (due to big $f_0 s$ value) to provide conditions for n_p=1 discharge. Only high order MD n_p=2,3,4 are possible in ACS structure at low β_p.

3.2 Numerical simulations

Special code was written for direct tracking of electrons in calculated fields of coupling cells. Main purpose of this tracking was to check space stability of discharge. Results of simulations confirm good analytical estimations for n_p=1,2 MD at low β_p for all structures. For SCS and ACS structures at low β_p electric field is practically constant both in longitudinal and in transverse directions in the space between noses. It means, that MD (if exists) takes practically all space between noses, but MD range in respect of W_c is limited. With increasing of β_p distance s rises, becomes comparable with transversal dimensions of noses. For ACS and SCS structures the approximation of plane capacitor becomes not acceptable. Direct numerical simulation shows no stable electron trajectories in the space $\approx 1.5s$ from outer side of the nose. It is sequence of nonuniform electric field in this region. It is especially important for ACS structure because nose is open both from top and bottom sides. For $\beta_p \geq$0.7 results show no stable trajectories for ACS coupling cells and reduced region (near centre of nose) of space stability n_p=1 MD in SCS coupling cells. Condition of the space stability for high order MD with respect field homogeneity are more rigid than for n_p=1 MD.
For OCS coupling cell is narrow cylindrical cavity. Electric field varies as Bessel J_0 function along radius. Nonuniform fields are only near beam aperture and coupling slots. Results of simulation show, that if MD exists at W_{c1} given, it takes a part of coupling cell and for $W_{c11} \geq W_{c1}$ it may displays to another part of the cell with lower electric field. All time there are regions with space stability of discharge. If for β_p =1 the impact energy W_i for n_p=1 MD is too big, conditions for high order MD may be fulfilled.

3.3 Effect of MD in coupling cells

It is known [6], [11], that the discharge current is limited by space charge effect and for maximum value of current density for n_p=1 MD is:

$$j_{1\ max} \simeq \frac{\epsilon_0 m f_0^3 s}{e}. \qquad (8)$$

For typical values f_0=805 MHz, s=1 cm, $j_{1\ max}$=2500A/m^2. For high order discharge n_p=2,3,4.. $j_{n_p\ max}$ value is 3(n_p+3) times less. Suppose n_p=1 discharge exists in one SCS coupling cell (nose radius is r_n=3.0437 cm [8]). The total MD current I_{MD} is estimated as $I_{MD} = \pi r_n^2 j_{1\ max} \sim$ 7 A. With impact energy $W_{i1} \approx$ 1 keV it leads to additional rf power dissipation $P_{rf} = I_{MD} W_{i1}/e \sim$ 7 kW (upper estimation). It is not so big value to see drastic disappearance of rf power from rf generator with total power in several MW. But quality factor Q_l for this cells decreases to value $Q_l = 2\pi f_0 W_{c1}/P_{rf} \sim$ 20. Such low Q cell do not keep amplitude and phase stability for operating $\pi/2$ mode so good as high Q one.

4 SUMMARY

Results of analytic estimations and numerical simulations show that first order multipactor discharge of is possible in SCS and OCS coupling cells for low $\beta_p \approx$ 0.4. In ACS only high order discharge is possible. for low $\beta_p \approx$ 0.4. With β_p increasing the gap between cell noses increases too, leading to nonuniform field between noses, reducing possible space for stable MD in SCS and eliminating it in ACS structure.
The best way to decrease MD possibility is trancformation of parallel plates into conical surface.
For coupling cells of OCS structure at β_p=1 condition for higher modes of discharge may be fulfilled.

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