

# THE ON-AXIS COUPLED ACCELERATING STRUCTURE FOR APPLICATION IN PROTON LINACS WITH MODERATE HEAT LOADING

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## Abstract

The On-axis Coupled Structure (OCS) has been optimized for applications in proton linacs with moderate heat loading to the accelerating structure. Without interior cooling of the cells the total length of the coupling cell together with webs between cells may be done relatively small. This case the coupling constant for OCS also may be strongly increased. With the numerical 3D optimization of coupling slot dimensions, shape and position it was shown, that coupling constant may be increased up to (15–17)% with tolerable (5–8)% reduction (due to coupling slots) in shunt impedance. For low energy region ( $\leq 100$  MeV) the shunt impedance and accelerating gradient of the OCS may be improved with introduction of additional intermediate drift tube (OCSDTL option), keeping coupling constant up to 10%. The ideas, restrictions and results of the structure optimization are presented. The optimized OCS version has the shunt impedance not less than another Coupled Cells (CC) structures and combines it with increased value of the coupling constant and the simple design.

## Introduction

After the Side-Coupled Structure (SCS), the OCS with magnetic coupling (due to coupling slots in the webs between cells) is now at second place in the usage in particle accelerators. This structure was applied for linac in the Advanced Free-Electron Laser Initiative at Los Alamos with high gradients (to 22 MeV/m), high peak-power klystron (20 MW) and up to 50-ms long macro pulses [1]. For cw operation with heavy heat loading this structure is used in Mainz [2] and INP MSU [3] race-track microtrons. The structure also was investigated in details, both theoretically and experimentally [4], for the set of small electron linacs for industrial applications.

The benefit OSC features are very simple design and small transverse dimensions. The optimization of the OCS for applications in proton linacs has been performed, providing good results in the structure parameters.

## Structure Optimization

The electron linacs, for which OCS was considered before, usually operate in S-band, with operating wavelength  $\lambda \approx 10$  cm. The requirements of mechanical strength and heat conductivity from the central region to outer one (to cooling channels) lead to relatively thick web, limiting the coupling constant  $k_c$  to 3%  $\div$  5%. Total distance  $2t + 2l_c$ , where  $2l_c$  is the coupling cell length,  $t$  - web thickness, takes essential part of the

structure period, leading to smaller, (in comparison with another CC structures) value of the effective shunt impedance  $Z_e$ .

The theoretical background for the structure optimization in details is presented in [5], below application to OSC is shortly described. In our optimization of the OCS for proton linacs, with operating wavelength  $\lambda \approx (25 \div 40)$  cm, we do not do direct scaling of the cells dimensions from “electron OCS” version. First of all, decision has been done to have no cooling channels in webs of “proton OCS”. This case we can restrict the web thickness with the value  $3 \div 4$  mm, limiting only with mechanical constrains. The length  $2l_c$  also should be as small as possible, but one have to take into account two restrictions.

First one is the detuning of coupling cells. It is known well, coupling slots reduce own frequencies both accelerating and coupling cells. One can show that detuning value  $\delta f \sim 1/l_c$ . Reduction in the frequency must be compensated by reduction of the cell radius  $R_c$ , and for small values  $l_c R_c$  becomes less than radius  $r_s$  for optimal position of coupling slots.

Second restriction relates with sparking in coupling cells. Sparking in the structure may take place both in accelerating and in coupling cells [5]. In steady-state regime coupling cells do excite with very low level to provide rf power flux along the structure for compensations of rf losses. Strong excitations of coupling cells takes place during transient, in the initial time period  $\tau_f$ :

$$\tau_f = 2L/v_g, \quad v_g = \frac{c\pi k_c \beta_p}{4}, \quad \tau_f = \frac{2N}{\pi k_c f_0}, \quad (1)$$

where  $L$  and  $N$  are the length and number of the structure periods from the rf input point to the end,  $v_g$  - the group velocity,  $c$  - speed of light,  $f_0$  - operating frequency and  $\beta_p$  - relative velocity of protons. During this time period, maximum electric field at the surface of coupling cell  $E_{scmax}$  may be high enough [5], leading to sparking in coupling cells [6].  $E_{scmax}$  depends on shape, dimensions of coupling cell and another parameters of the accelerating structure. Comparing accelerating structures of existing proton accelerators, we have founded, that SCS structure at FNAL Linac Upgrade [6] operates with maximum value  $E_{scmax}$  during transient, according (2). Referring to FNAL Linac Upgrade successful operation, we have limited  $E_{scmax}$  for OCS with FNAL SCS  $E_{scmax}$  value.

In the OCS structure  $E_{sc}$  is large at two points - at the lower edge of the coupling slot and near bore hole. To decrease  $E_{scmax}$  value, coupling slots and coupling cell bore hole must be rounded with radius not less than  $t/2.0$ . Taking into account reasons above we have chosen  $2l_c \sim 6 \div 8$  mm.

The shape and dimensions of the accelerating cells for OCS were optimized for DESY Linac 3 Upgrade proposal [7] in 2D approximation, by using set of 2D codes [8]. For the same beam hole radius  $a = 15$  mm, operating frequency and  $E_{samax}/E_k = 1.35$ , 2D calculated effective shunt impedance  $Z_e$  for OCS is less than 2D  $Z_e$  for FNAL SCS at 9% for  $\beta_p = 0.4$  and at 6% for  $\beta_p = 0.7$ . The total thickness  $2t + 2l_c = 13$  mm remains larger than web thickness 7.5 mm in SCS FNAL design.

### Coupling Slots

The coupling slots investigation, optimization and choice was performed using MAFIA code.

There are two coupling slots at each web between accelerating and coupling cells. Mutual orientation of coupling slots is important for  $k_c$  value. To increase  $k_c$  by canceling mutual influence, slots position is rotated at  $90^\circ$  in webs of coupling cell. The difference between  $k_c$  values for rotated and slot-to-slot orientation in short coupling cell is more than 2.5 times. Orientation of coupling slots at opposite webs of accelerating cells practically do not influences for  $k_c$ . Only frequency of coupling cell changes approximately at 5%, because field of coupling cell significantly penetrates into accelerating one. The mutual orientation of coupling slots in accelerating cell strongly defines quadrupole distortions in the accelerating field distribution. To reduce this distortion, we accept slot-to-slot orientation for accelerating cells.

The radial position of slots is chosen near the half of the accelerating cell radius.

It is known, that rise of  $k_c$  by slot length increasing all time assists with reduction in  $Z_e$ . The coupling slots provide perturbation for rf current distribution in accelerating cell. The maximum value of rf current density  $j_{max}$  takes place at the ends of slots, the minimum one  $j_{min}$  - in the middle of the slot. To provide the high  $k_c$  value with small reduction in  $Z_e$  the coupling slots are chosen wide enough. Total set of decisions in the structure optimization leads to the tolerable reduction of  $Z_e$  even for significant values of  $k_c$  (Fig. 2).

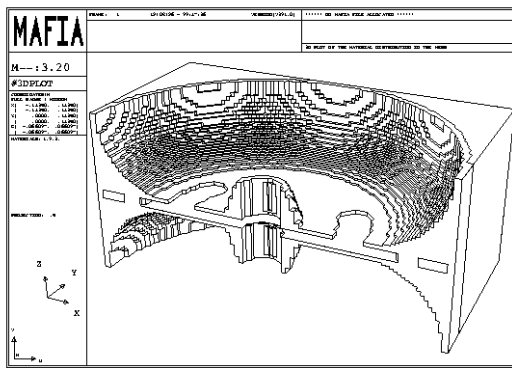


Figure 1: The cells of the On-axis Coupled Structure.

As the result of the OCS optimization we have the option with  $k_c \approx 15\%$  and  $Z_e$  reduction due to coupling slots  $\approx 5\%$  for  $\beta_p = 0.45$  and  $\approx 7\%$  for  $\beta_p = 0.7$ . Because the distance  $2t + 2l_c$  is fixed, with the same slots opening  $k_c$  decreases for higher

$\beta_p$ . To compensate this decreasing one need increase opening, providing larger reduction in  $Z_e$ . Maximum values of  $k_c$  were founded in this research  $\approx 19\%$  for  $\beta_p = 0.45$  and  $\approx 16\%$  for  $\beta_p = 0.7$ .

Comparing calculated 3D  $Z_e$  values for proposed OCS and FNAL SCS, one will have practically the same numbers (differing in units of %) but with  $k_c \approx 15\%$  for OCS.

In this OCS proposal coupling cells are heavy loaded with coupling slots (see Fig. 1), but accelerating cells are not. The problem of high coupling is solved by coupling cells, without large perturbations in accelerating ones.

### Cooling Capability

The temperature distribution in the OCS ( $f_0 = 810$  MHz) with one cooling channel per period (see Fig. 1) is shown at Fig. 3. (Special procedure has been developed to calculate temperature distribution due to rf losses with MAFIA code.) For the heat loading  $1.5 \frac{kWt}{m}$  maximum temperature difference (between drift tube nose and cooling channel) is  $3.4^\circ C$ . This value of the heat loading is comparable with that one for existing "meson facility" linacs and do not provide difficulties for existing frequency control systems. Maximum of the temperature gradient and associated thermal stresses take place at radius of slots position and with wide slots are not dangerous for stable longtime operation.

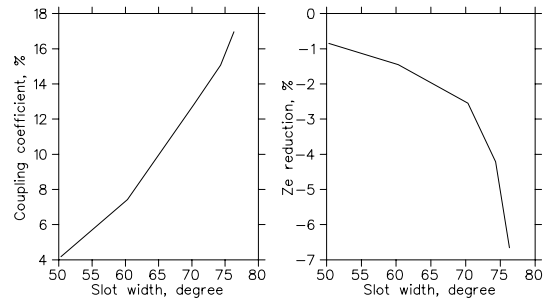


Figure 2: The  $k_c$  value and reduction in  $Z_e$  in dependence on coupling slot opening,  $\beta_p = 0.5$ .

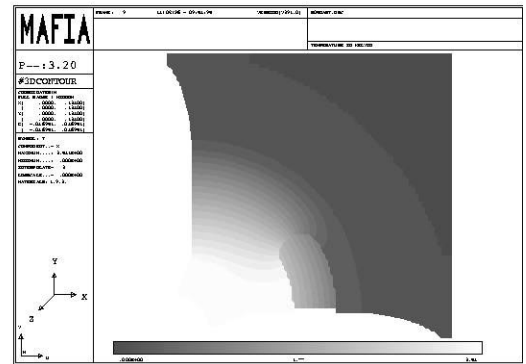


Figure 3: The temperature distribution in OCS for heat loading  $1.5 \frac{kWt}{m}$ ,  $\beta_p = 0.5$ . Regions with high temperature are marked with lighter shadowing.

## Vacuum Conductivity

The vacuum conductivity may be strongly improved by additional radial slots in webs (Fig. 4). Two of these radial slots cross coupling slots in the middle, two another are placed between coupling slots. So, four additional radial slot in each web provide four channels through the structure from one end to another. With small angle opening (not more than  $15^\circ$ ), radial slots are not resonant elements and do not interferer significantly the field distribution in accelerating cells. To keep  $E_{scmax}$  limited, the cross of the radial slot with lower edge of the coupling one should be rounded.

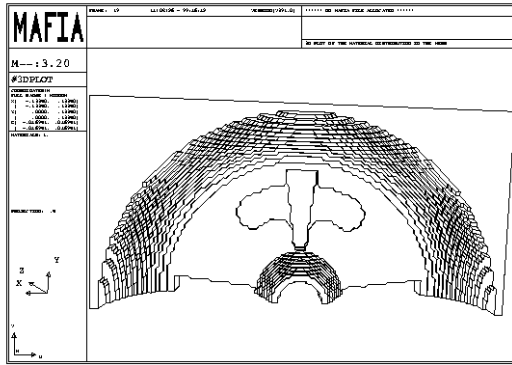


Figure 4: The OCS cell with additional radial slots.

### OCSDTL Option

It is known well that efficiency of all CC structures decreases with decreasing  $\beta_p$ . Very powerful solution was proposed [9] and tested with the SCS to avoid this disadvantage and to combine the efficiency of the Drift Tube structure with stability properties of CC structures by introducing Intermediate Drift Tubes (IDT). The length of the period  $d'$  in this case is  $d' = (2n+1)\beta_p/2$ , where  $n$  is the number of IDT. This solution can be applied to OCS (Fig. 5). Because  $d'$  becomes large, coupling cell together with webs take a small relative part and do not lead to significant reduction of  $2D Z_e$ . All improvements and problems, related with IDT, are the same as for SCS, except one.

For all CC structures introduction of IDT leads to redistribution of magnetic field for accelerating mode. Maximum of the magnetic field take place near IDT. Together with increasing of the accelerating cells volume, it leads to decreasing of the  $k_c$  value. In OCSDTL version we can, by increasing of the slots opening to  $79^\circ \div 81^\circ$ , keep coupling constant at 10% for  $\beta_p = 0.35$  value with the same 5% reduction in  $Z_e$ . Because in estimations [5] of coupling cells excitation  $\tau_f$  and  $E_{scmax}$  should be transformed for CCDTL into  $\tau'_f = (2n+1)\tau_f$ ,  $E'_{scmax} = (2n+1)E_{scmax}$ , the OCSDTL option looks to be more strong against possible sparking in coupling cells.

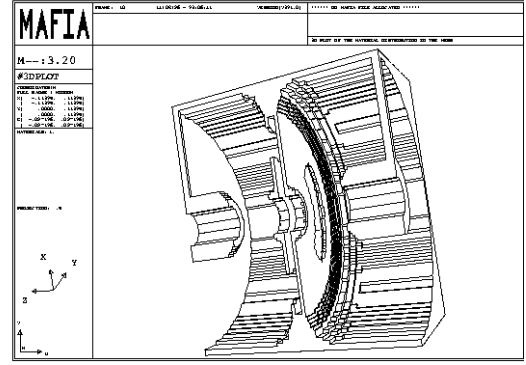


Figure 5: The OCSDTL cells.

## Conclusion

The optimization of coupling cells and coupling slots leads to attractive characteristics of the OCS for application in proton linacs. Combining the simple design, improved coupling constant and high shunt impedance, the structure can, after high power test, provide strong competition to another candidates for application in proton linacs with moderate heat loading.

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