DESIGN OF A RF GUN FOR HEAVY BEAM LOADING

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Abstract

For the drive beam generation of the CLIC Test Facility, a RF photo-electron gun is required to generate a charge of 1 μC in a train of 48 bunches. The extracted beam energy of 6.5 J leads to a pronounced decrease of the field gradient, causing strong variations in the transverse and longitudinal beam dynamics. The drop in beam momentum yields a variation in focusing of the following solenoid leading to a blow-up of the transversal emittance. A second effect is the change of the bunch spacing caused by differing bunch velocities. These effects are to a large extent determined by the beam loading in the first cell, which contains the photo-cathode. In order to reduce this effect with moderate expense of RF power, a new gun design has been developed using a TM_{02} resonance in the first cell followed by two standard TM_{01} cells. Beam simulations show that with this gun, the overall change in the longitudinal bunch spacing can be strongly reduced. Also the chromatic effects in the solenoid due to the drop in longitudinal momentum are partially compensated.

1 INTRODUCTION

RF photo-electron guns as electron sources offer several strong advantages. The length of the generated bunches is dominantly determined by the duration of the driving laser pulse so that a big part of the usual bunching structures can be omitted. The emitted electrons get accelerated by an RF field allowing for high gradients as well as for a high charge per bunch.

In the CLIC accelerator study, these properties have stimulated research towards a gun design suited to generate the bunch train required for the drive beam. The current set-up for the CLIC test facility (CTF) requires a train of 48 bunches with an overall charge of 1 μC to be delivered to the following structures. A description of the facility is given in [1].

The two major challenges are the following. One is the control of the space charge forces, which is done by a combination of transverse focusing by a conical photo-cathode backplane and a prolonged first cell [2].

The other, described here, is the pronounced beam loading caused by the bunch train extracting 6.5 J within 16 ns from the RF field corresponding to a power of more than 400 MW. The primary effect, the drop in longitudinal momentum along the bunch train, is corrected in a subsequent beam loading compensation structure. More severe are secondary effects caused by the drop in gradient.

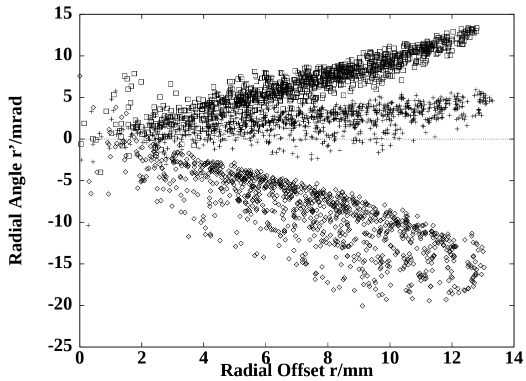

Figure 1: Transverse phase space plot of the first, middle and last bunch behind the solenoid (3 TM_{01} cells).

Being emitted from the photo-cathode, the electrons need a certain time to reach relativistic velocities, slipping back in RF phase. The amount of the phase slip depends on the accelerating gradient. As beam loading causes the gradient to drop, trailing bunches lag behind in RF phase. For the current design using three TM_{01} cells [2], the phase slip reaches 14.2 degrees at 3 GHz at the entrance of the following accelerating structure.

The divergence of the bunches is in a zero order approximation constant at the gun exit. But the focusing strength of the solenoid is varying with the particle momentum. So the last bunch with a low momentum gets more strongly focused than the first one. This chromatic effect leads to a blow up of the transverse phase space, which, as is shown in figure 1, can result in a very large multi-bunch emittance.

2 RF DESIGN AND PHASE SLIP

Normal means to solve these problem fail in this case. A compensation using external storage cavities would have to supply the beam power of 400 MW. A reduction of the beam loading using a higher gradient and/or a lower R/Q would require a prohibitive amount of RF power, since already the old design using three TM_{01} cells consumes 16 MW. As a consequence, a local solution is to be preferred, which does not necessarily reduce the primary effect, the beam loading, but decreases the phase slip and the chromaticity.

Concentrating for the moment on the build up of the phase slip, one sees that the major part of it is happening as long as the bunches are in the non-relativistic domain. That is,

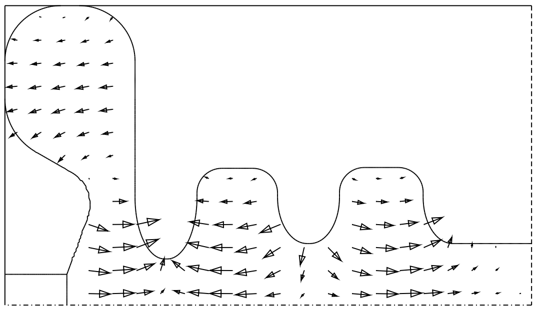

Figure 2: π-mode (f=2998.5 MHz) in the new design.

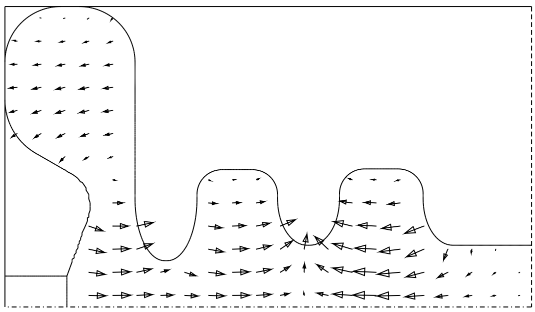

Figure 3: Secondary mode (f=2990.5 MHz) involved in beam loading.

the principal contribution is caused by the beam loading in the first cell which contains the photo-cathode. A local reduction only in the first cell, being manageable with an economic amount of additional RF power, gives a strong decrease of the phase slip.

The stored energy in the first cell, being originally 2.5 J for the longitudinal peak gradient of 100 MV/m, can be more than tripled to 8 J using a cell resonating in the TM_{02} mode (Fig. 2). By that, also an increase in Q to 16300 is obtained, leading to a power consumption of 19 MW at the nominal gradient of 100 MV/m. Now, the bunch train causes the gradient, being 100 MV/m in the beginning, to drop down to a value of approximately 90 MV/m in the first cell and 70 MV/m in the following cells. That is, the field distribution is no more a pure π-mode and contains other modes. The additional component is the neighbouring mode with a zero phase advance between the first and the second cell and and π between the second and the third (Fig. 3).

While the principal π-mode decreases as a result of the beam loading, the secondary mode gets excited, so that the gradients add up in the first cell and subtract in the following, thus creating the required field distribution. In order to prevent mode beating, the frequencies of both modes must be sufficiently close. Alternatively one can say, there has to be only a small energy exchange between the first cell and the rest of the structure. Consequently the coupling between the first two cells was reduced to 0.3% using a smaller iris.

The improvement of the multi-bunch phase slip by the new design is shown in figure 4. The curves, calculated by MAFIA-TS2, contain also the influence of the transient

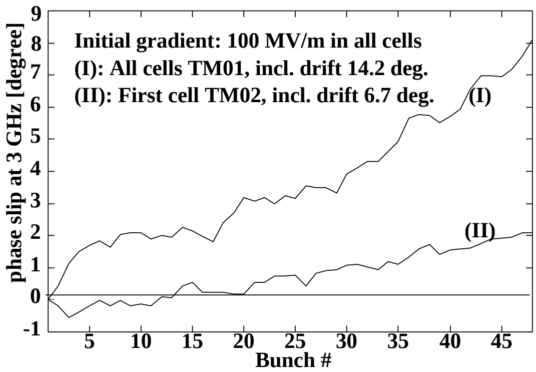

Figure 4: Phase slip, (I): all cells TM_{01}, (II): first cell TM_{02}.

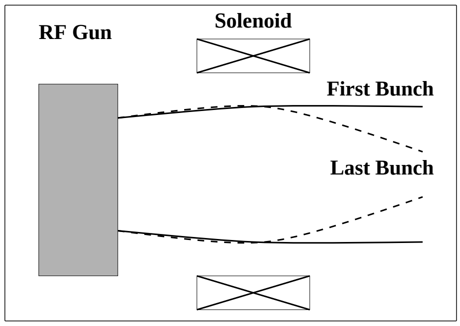

Figure 5: Schematic beam trajectories showing the chromatic effects in the solenoid caused by the beam loading.

wake fields, being responsible for the visible jitter. By reducing the beam loading only in the first cell, the slip has been reduced from 14.2. degree by more than a factor of two to 6.7 degrees. Now the half of the phase slip happens in the following drift space and is due to the energy difference between bunches. Further reductions could be obtained either by reducing the drift length or by a slight detuning of the gun with respect to the global RF frequency.

3 TRANSVERSE BEHAVIOUR

For a standard gun with a homogeneous drop of the gradient in all cells, the divergence of the beam at the gun exit is approximately constant. But the following solenoid mixes the longitudinal and transverse phase spaces, the last bunches with a low momentum get focused more strongly than the first ones (Fig. 5).

In this proposed design the field in the first cell has a weaker drop than in the following cells. Now the gradient in the first cell determines the radial momentum at the gun exit, whereas the longitudinal momentum is given by the overall accelerating gradient, that is, influenced by the global beam loading. The resulting divergence is proportional to the gradient in the first cell divided by the average gradients in all cells.

If the gradient in the first cell is held constant at 100 MV/m and the fields in the following cells vary between 100 and 120 MV/m, there is, as shown in figure 6, an additional

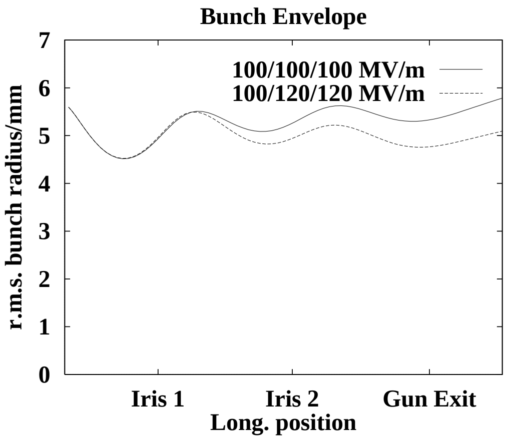

Figure 6: Evolution of the bunch radius in the gun for different accelerating gradients.

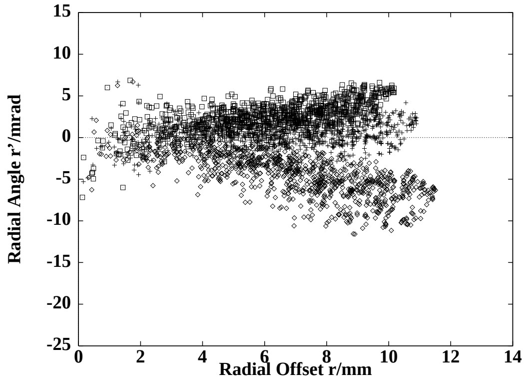

Figure 7: Transverse phase space of the first, middle and last bunch behind the solenoid (New design), E=100 MV/m.

radial 'focusing' after the first iris; the bunch accelerated by the 120 MV/m exits the structure with a smaller divergence.

The conclusion for the multi-bunch behaviour is the following: As the field in the first cell drops less than the average field in the whole structure, the first bunch, getting focused less by the solenoid, has a smaller divergence at the gun exit than the last bunch, which sees a stronger solenoidal focusing. That is, by a non homogeneous beam loading, we introduce chromatic effects in the gun countering the chromaticity of the solenoid. This effect is shown in the phase space plot (figure 7), the variation in divergence is already strongly reduced. But here the bunches are still discernible in phase space, we get only a partial compensation.

In order to get a better transverse behaviour, we have to adjust the chromaticity of the gun versus that of the solenoid. If we increase the initial gradients in the second and third cell to a value of 120 MV/m, a smaller beam divergence at the gun exit is obtained (fig. 6), so we need less solenoidal focusing and have smaller chromatic effects. This scenario, if possible for CTF in terms of available RF power (25 MW for Q=16300), would give a multi-bunch emittance (fig. 8) of a same order of magnitude as the single bunch emittance,

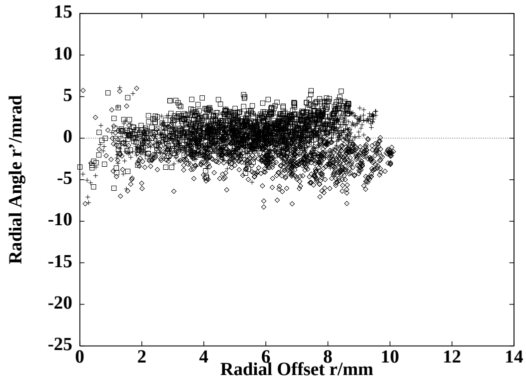

Figure 8: Transverse phase space of the first, middle and last bunch behind the solenoid (New design), gradients of the second and third cell increased to 120 MV/m.

	Old	New (1)	New (2)
phase slip in degree (3 GHz)	14.2	6.7	5.0
divergence/mrad			
first bunch	6.7	2.5	1.2
middle bunch	2.2	0.5	0.3
last bunch	-8.7	-4.5	-2.0

Table 1: Resulting multi-bunch behaviour. The initial gradient in the old design and in (1) is 100 MV/m in all cells, for (2) it is 120 MV/m in the second and third cell. The phase slip assumes 60 cm drift following the gun. The beam divergence is calculated 25 mm behind the solenoid.

reducing at the same time the phase slip to 5.0 degrees. An overview of the various options is given in table 1.

4 CONCLUSIONS

A new design for a high intensity photo-electron gun has been proposed and analyzed, based on compensating for beam loading effects locally in the first cell. The first cell operates in the TM_{02} mode and is coupled to two standard cells using the TM_{01} resonance. A reduction of the asynchronism of the bunch train by more than a factor of two is expected. Furthermore, the chromatic effects in the gun caused by the non homogeneous beam loading is shown to compensate for the chromaticity of the following solenoid. Following this, the construction of a new gun has been launched. First beam tests with the new structure are expected to follow in spring 1997.

5 REFERENCES

[1] 'Results from the CERN Linear Collider Test Facility', by Aulenbacher iand 17 co-authors, this conference.

[2] 'A 3 GHz Photoelectron Gun for High Beam Intensity', by Bossart R., H. Braun, M. Dehler, J.-C. Godot, Proceedings of the 17th International Free Electron Laser Conference, August 21-25 1995, New York, USA, to be published (See also PS/RF note 95-25).