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CLIC – Note – 1068

RF DESIGN OF THE TW BUNCHER FOR THE CLIC DRIVE BEAM INJECTOR – SECOND REPORT

Progress report according to the collaboration agreement N° KE1878/BE/CLIC

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Abstract

CLIC is based on the two beams concept that one beam (drive beam) produces the required RF power to accelerate another beam (main beam). The drive beam is produced and accelerated up to 50MeV inside the CLIC drive beam injector. The drive beam injector main components are a thermionic electron gun, three sub-harmonic bunchers, a pre-buncher, a TW buncher, 13 accelerating structures and one magnetic chicane. This document is the second report of the RF structure design of the TW buncher. This design is based on the beam dynamic design done by Shahin Sanaye Hajari due to requirements mentioned in CLIC CDR. A disk-loaded tapered structure is chosen for the TW buncher. The axial electric field increases strongly based on the beam dynamic requirements. This second report includes the study of HOM effects, retuning the cells, study of dimensional tolerances and the heat dissipation on the surface.

Geneva, Switzerland
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Introduction

In the previous report [1], the RF design of the TW buncher for the CLIC drive beam injector based on the beam design was described. It was a tapered TW structure with increasing phase velocity along its length from 0.6c to about 1.0c and the axial electric field for the main harmonic increased from 1.2MV/m to 5.7MV/m when the beam is ON. One correction was done on the phase velocity based on the reactive beam loading of the fundamental induced mode by the beam. And finally the geometrical dimensions of each cell were calculated. To complete the last report four tasks should be done:

1- The effect of the beam induced higher order modes need to be studied in more detail in order to determine if explicit HOM damping is required or the detuning between cells is enough to suppress sufficiently the total kicks. This study includes the beam break up and emittance growth due to HOMs.
2- Minimizing the local and total reflection in cells by retuning the cells and couplers.
3- Studying the effect of random dimensional errors on frequency and energy shift.
4- Calculating the heat dissipation on the surface to evaluate the corresponding cooling system.

Effect of beam induced modes on beam dynamics

Recent design of the TW buncher consists of 18 cells including coupler cells as described in the previous report [1]. These cells are designed to have the same resonant frequency for the fundamental mode (First monopole mode) at the phase advance of 120 degrees. But because of non-equal dimensions (cell lengths, beam aperture radius and cell radius), the other modes (monopoles, dipoles, quadrupoles and …) have not the same resonant frequency for the synchronous case – when the phase velocity is equal to the beam average velocity-. Here the term detuning is used.

The beam induced fundamental mode was studied previously [2] and it was shown that it can be suppressed by proper change in the phase velocity in each cell in comparison to the initial design. Other monopole modes loss factors are at least one order of magnitude less and also detuned and not-perfectly matched with the bunch harmonics and the effects on bunch lengthening and energy spread could be neglected.

For the dipole modes, the first one is dominated and the other dipole modes kick factors are at least two orders less in magnitude. The known effect of beam breakup and transverse emittance growth are due to this mode. We will discuss about the first dipole mode in this paper and we will show that its effect on the beam is small.

The other modes like quadrupole modes are small compared to the first dipole mode and when we will show that the first dipole mode is negligible then it's obviously the other modes are negligible too.

The cut of frequencies of beam apertures are between 2-3 GHz for the first TE mode and the HOMs with higher resonant frequencies propagate inside the structure and therefore won't accumulate to disturb the beam.

The first dipole mode

Figure 1 shows the dispersion diagram of all cells except the coupler cells if we assume we have a periodic structure from each cell and the cross line represents the synchronous modes. The synchronous modes are between 1.24-1.51 GHz and the bunch harmonic resonant frequency is 1.5 GHz ($1.5f_0$)* and these differences between the synchronous modes and bunch harmonic frequency has a large effect to avoid bunch induced field accumulation in long pulses.

Also by paying attention to the separation between different cell modes in figure 1 we understand that the induced modes in each cell don't propagate in neighbouring cells, therefore the uncoupled model [3] is suitable to analyse our problem. An important conclusion from this result is that we have not the regenerative beam breakup and we should analysis our structure based on the multi structures beam breakup. Before continuing to more quantitative analysis it is worth to mention that the multi structure beam breakup is seen over length scales of a few hundred meters and when the resonant frequency of the first dipole mode is very close to 1.5 times of the fundamental mode then for our structure with about 1.5m length this effect should be negligible. Also we have solenoids around the structure which it help to suppress a small effect of this perturbation. We will show the beam deflection is less than space-charge and fundamental mode deflecting effects which were analysed in another paper [4] and this correction could be implemented by small changes of the solenoid currents.

Calculating the momentum kick

The momentum kick is calculated by Panofsky-Wenzel [5, 6] and is proportional to the radial gradient of the longitudinal electric field and is 90 degrees out of the phase. This equation is valid if the relative velocity change during each cell is small.

$$(1)\ \Delta\overrightarrow{P_t} = i\frac{q}{\omega}\int_0^L \nabla_t\overrightarrow{E_z}dz - i\frac{q}{\omega}\left(\overrightarrow{E_t}(z=L) - \overrightarrow{E_t}(z=0)\right) \overset{r\ll a}{\Longrightarrow} \Delta P_t <\approx \frac{q}{\omega}\frac{V_{max}}{r}\sin{(\omega t)}$$

Because we calculate the momentum kick for each cell separately the second term is not zero but in our case the electric field is increasing along the length which means the second term is negative. Therefore the first term give us the upper limit for the deflection. The last form in the above equation shows the momentum kick close to the axis. q is the bunch charge, ω is the angular frequency of the mode, r is the offset, a is the cell beam aperture radius and V_{max} is the maximum efficient voltage of the mode at offset r.

When a bunch travels off-crest, it can excite this dipole mode because the off-axis longitudinal electric field is non-zero and decelerate the bunch to extract a part of its kinetic energy and convert it to the electromagnetic energy in the cavity. Suppose a leading bunch and a trailing bunch both travel parallel to the axis with the same angular position and both have the same charge(q) and the leading bunch crosses the middle of cell at t=0 and his offset is r. The momentum kick resulted from the induced mode of the leading bunch on the trailing bunch by using the fundamental beam loading theorem is shown in equation below.

$$(2)\ \begin{cases} V_{max} = 2kq \Longrightarrow \Delta P_t \approx 2\frac{q^2}{\omega}\frac{k}{r}\sin(\omega t) \Longrightarrow \frac{\Delta P_t}{m} = \frac{2e}{m_e}\frac{q}{\gamma\omega}\frac{k}{r}\sin(\omega t) = \frac{2e}{m_e}\frac{q}{\gamma\omega}\frac{k}{r^2}r\sin(\omega t) \\ k = \frac{{V_{max}}^2}{4U} = \frac{\omega}{4}\frac{R}{Q} \\ q = Ne\ , m = N\gamma m_e \end{cases}$$

* The bunch frequency is 499.75 MHZ ($f_0/2$) then $1.5f_0=3$ ($f_0/2$) is a bunch harmonic.

$\frac{k}{r^2}$ is the kick factor and is independent of r for r<<a. $\frac{R}{Qr^2}$ is depends only on the cell shape then the kick factor is depends only on the cell shape and its related mode frequency. The transverse velocity change could be calculated by equation below in each cell. There is just one correction of parameter F which is the bunch form and for our case is close to 1 as you can see in table 1. This table also shows other cell parameters.

$$(3)\ \Delta v \approx \frac{\Delta P_t}{m} \approx \frac{2e}{m_e}\frac{qF}{\gamma\omega}\frac{k}{r^2} r\sin(\omega t) \approx 0.352\frac{q[nC]F}{\gamma\omega}\left(\frac{k}{r^2}\right)\left[\frac{\frac{V}{pC}}{m^2}\right] r\,[mm]\sin(\omega t)$$

This equation also tell us a trailing bunch just behind a leading bunch experiences a positive deflection because of its induced dipole mode and it becomes maximum when the phase difference is 90 degrees and the leading bunch itself, don't experience a kick from the induced mode by itself. Now, if we have a bunch train we can add different kicks together to find the total kick. Figure 2 shows the accumulation process in each cell geometrically when the quality factor (Q_0) is large and the change in the offset is small. The equation below shows the limiting and maximum voltage.

$$(4)\begin{cases} \dfrac{V_{max}}{V_0} = \displaystyle\sum_{n=1}^{N=\frac{\pi}{\delta}} \sin(n\delta) = icotg(\frac{\delta}{2}) \\ \dfrac{V_{lim}}{V_0} = \displaystyle\sum_{n} e^{-n\tau}e^{-in\delta} \approx \frac{1}{2}\left[1 + icotg\left(\frac{\delta}{2}\right)\right] = \frac{1}{2} + \frac{1}{2}\frac{V_{max}}{V_0} \\ \delta = 2\pi(3 - 2\dfrac{f_d}{f_0}) \\ \tau = \dfrac{2\pi}{Q_0}\dfrac{f_d}{f_0} \end{cases}$$

V_0 is a representative phasor and its imaginary part is proportional to the momentum kick and it can be the induced voltage by one bunch. The accumulation starts to oscillate between 0 and V_{max} and damps gently to V_{lim} because of power loss on the surface. f_d is the resonant frequency of first dipole mode as mentioned in table 1 and f_0=999.5 MHz is the frequency of fundamental mode. This equation shows an interesting result that the final kick is half of the maximum kick when Q_0 is large enough and the limiting phasor points towards the centre of the circle which is calculated of the individual kicks.

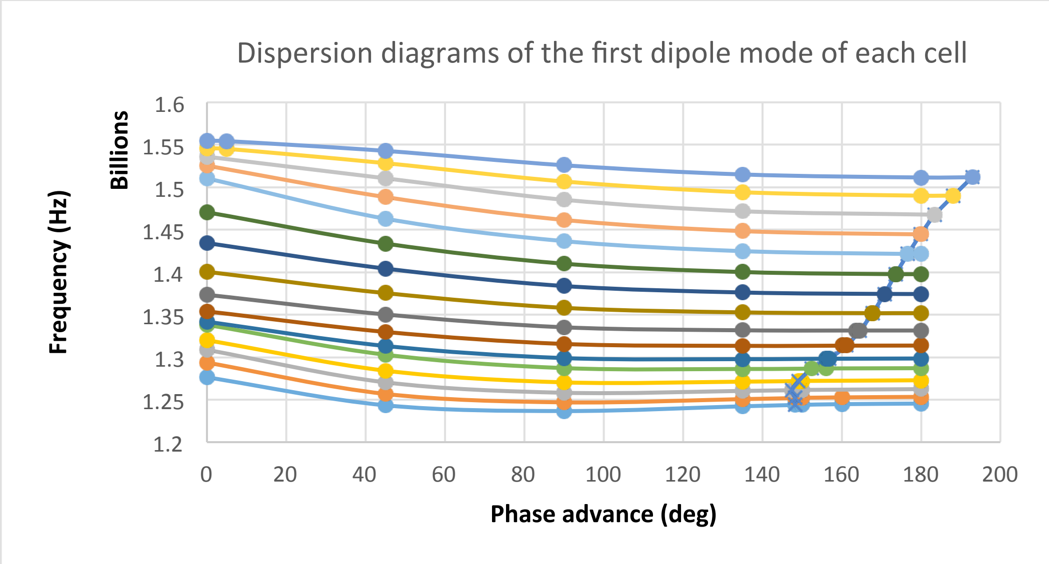

Figure 1: Dispersion diagram of different cells by showing synchronous modes. Each cell is shown in a different colour, the synchronous modes frequencies increase with the cell number.

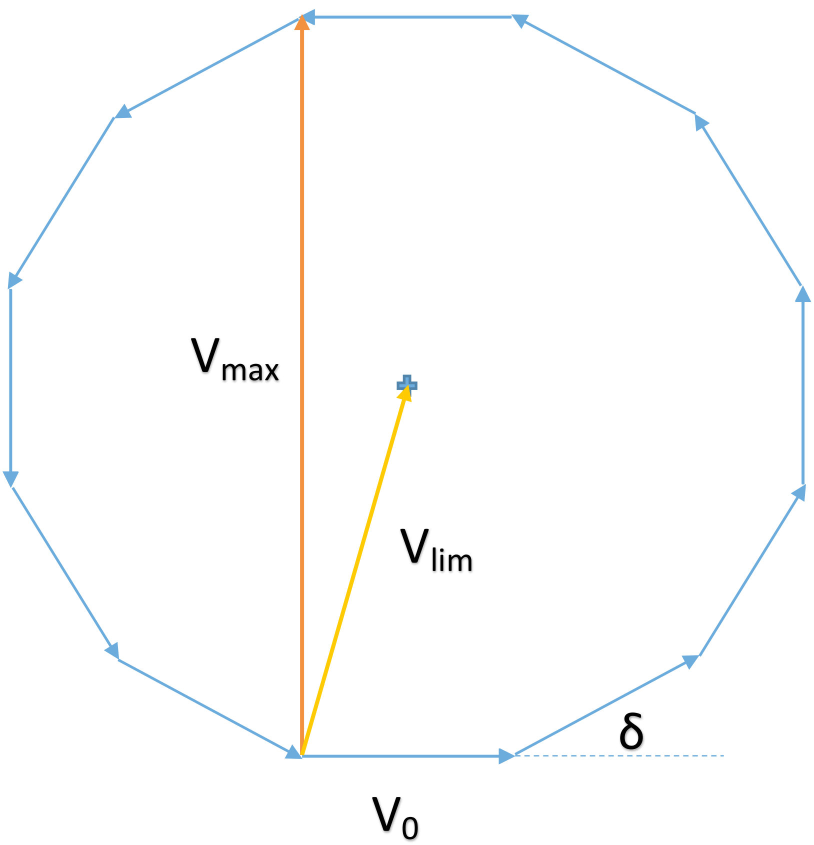

Figure 2: Accumulation in cells geometrically

Table 1 shows the amount of V_{max}/V_0 and as you can see just a few cells at the end of buncher shows significant amount and cells 16 and 17 although are a little large mostly suppress each other. Taking these results, we can track a bunch-train inside the structure. We assume the initial offset off all bunches is equal to 1mm[†] and the initial transverse velocity equal to zero and we assume there is no

[†] This number is chosen based on reference 4 that the x_{rms}=1mm.

solenoid. It is a pessimistic analysis because when we have solenoids the effect will be reduced significantly. The longitudinal magnetic field produced by solenoids keeps the transverse beam size constant and converts the radial kick to the angular velocity and also because of the radial kick for the dipole mode is proportional to cosine of the angular position, its start to leave the maximum kick position and the amount of total kick would be at least by one order of magnitude less because each particle inside the bunch experience a few complete cycles along the TW buncher. The effect of solenoid is analysed by more details in another paper by us [4].

Figure 3 shows the final transverse velocity at the end of the structure as a function of time. After a long time it reaches to a steady state. But for our case because during a pulse with 140µs length, we have sub-pulses with about 240ns length with 180 degrees phase difference with their neighbours, the steady state doesn't happen but still the total momentum kick is small (figure 4). Figures 5 and 6 show the offset variation if there is no solenoid. The result shows the maximum offset is about 1.4 mm and it is far from the risk of beam break up (beam aperture is more than 28.9mm). Therefore we can exclude the risk of beam breakup.

n	loss factor/r^2 (V/pC/m^2)	f_d(Ghz)	phase velocity/c	L(mm)	Bunch Form Factor	Q0	Imag (Vmax/V0)	Delta_v0_max (m/s)
2	14.9	1.2437	0.616	61.172	0.773	16116	-0.04	4092
3	16.9	1.2521	0.634	62.487	0.848	16500	0.02	4967
4	20.7	1.2614	0.662	64.516	0.837	16884	0.08	5762
5	25.8	1.2720	0.689	67.262	0.825	17268	0.14	6789
6	30.1	1.2867	0.716	70.7	0.836	17652	0.24	7649
7	37.4	1.2982	0.742	74.628	0.867	18035	0.32	9386
8	44.6	1.3136	0.771	78.797	0.904	18419	0.43	10941
9	53.9	1.3314	0.805	82.921	0.933	18803	0.57	12544
10	64.7	1.3519	0.841	86.895	0.948	19437	0.75	13750
11	77.4	1.3745	0.874	90.414	0.951	20070	1.00	14585
12	91.2	1.3977	0.903	93.398	0.948	20704	1.35	14880
13	105.6	1.4216	0.926	95.849	0.944	21337	1.88	14832
14	118.9	1.4446	0.944	97.852	0.943	21971	2.80	14344
15	132.1	1.4677	0.957	99.655	0.945	22604	4.97	13823
16	143.3	1.4903	0.968	101.812	0.948	23238	17.78	12823
17	151.0	1.5119	0.976	104.719	0.951	23871	-12.53	11593

Table 1: Cells and bunch properties

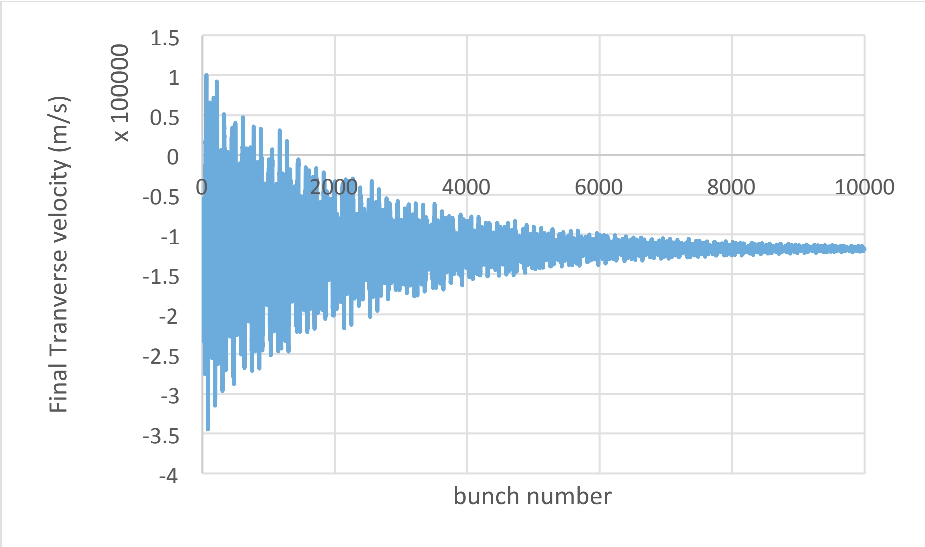

Figure 3: Final transverse velocity per bunch number without switching of sub-pulses

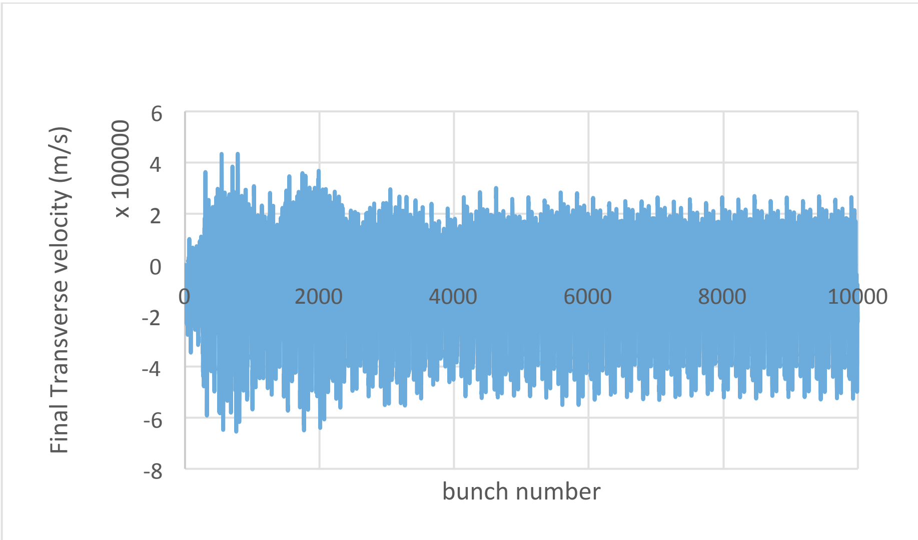

Figure 4: Final transverse velocity per bunch number with switching of sub-pulses

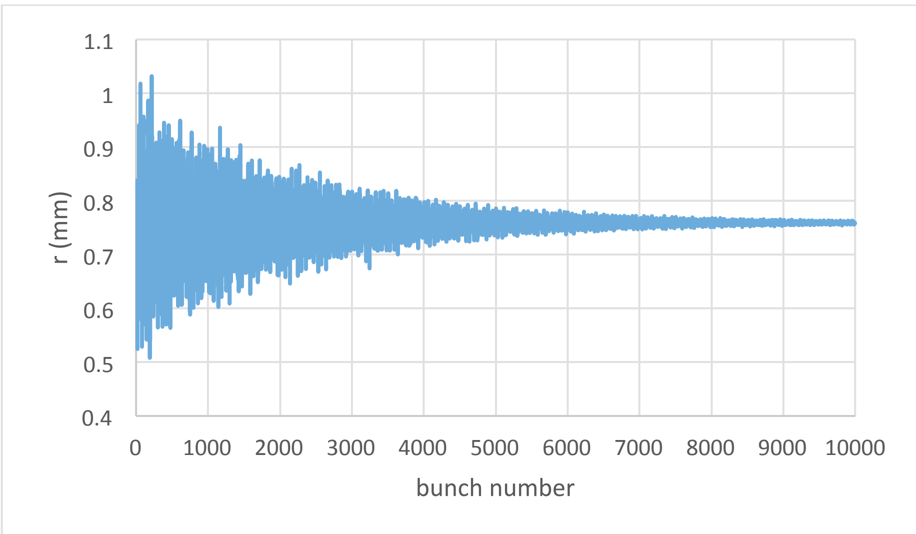

Figure 5: Bunch final offset without switching of sub-pulses

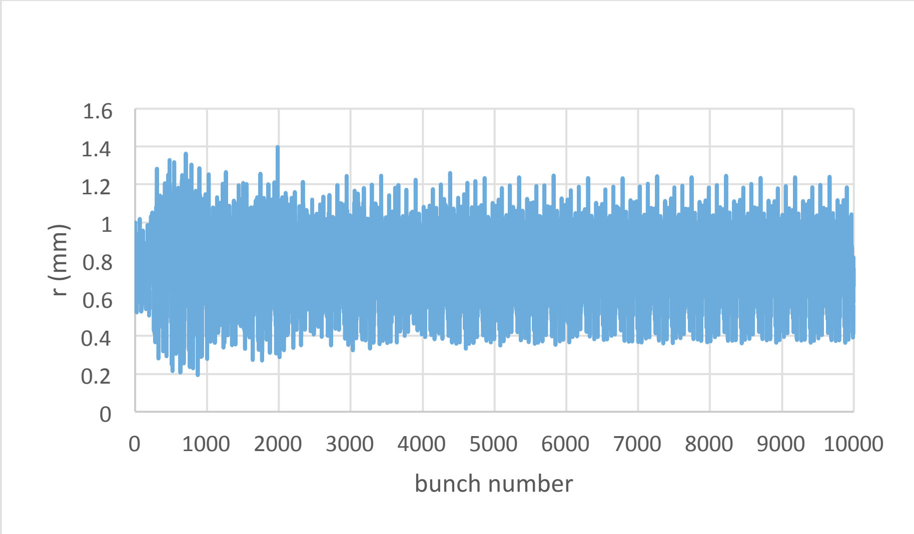

Figure 6: Bunch final offset with switching of sub-pulses

Emittance Growth

By using the envelope equation as described in ref. [4] we found the dipole mode kick is at least one order of magnitude less than the fundamental mode kicking and the fundamental mode kicking is smaller than the space-charge deflecting (fig. 7). In adition, the radius could be kept constant by solenoids.

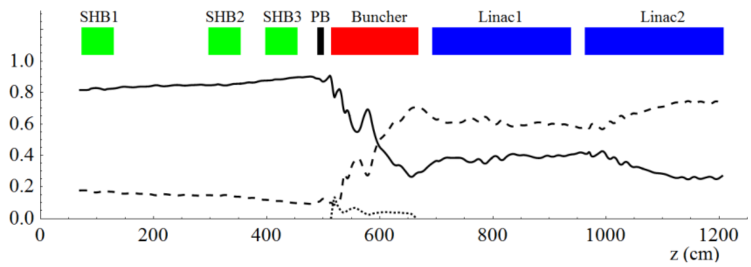

Figure 7: Relative contribution of each defocusing term in the envelope equation for a target beam size of 2 mm. The solid line is the relative contribution of the space-charge term, $(K/4x_r)/\Sigma$, the dashed line is same for the emittance term, $(\varepsilon_r^2/x_r^3)/\Sigma$, and the dotted one for the RF defocusing term, $(k_{RF}x_r)/\Sigma$. Σ is equal to $k_{RF}x_r + K/4x_r + \varepsilon_r^2/x_r^3$.[4,figure 27]

To find the emittance growth, we should mention for a zero-length bunch the emittance growth is zero because all the bunch is kicked together equally. For a finite-length bunch each part of the bunch is kicked differently based on its related longitudinal position. The rms emittance is 24.8 mm.mrad at the entrance of the TW buncher. The mentioned tracking code with Matlab shows the head, tail divergence change is -0.27 and -0.49 mrad, respectively. By calculating the rms emittance based on the below equation we will find the emittance change is less than -0.009mm.mrad (-0.04%) which is negligible.

$$(5)\quad \begin{cases} {\epsilon_{rms}}^2 = \langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2 \\ x' = \dfrac{dx}{ds} \end{cases}$$

Noise amplification

Although we showed the beam is not unstable another parameter that is important is noise amplification and we do a test to show its magnitude. In this test just the first bunch in the bunch train has an initial offset but the rest of bunches are initially on-axis. The quantity $I(N) = \sum_{i=1}^{N-1} \left(\frac{x_i+\beta x_i'}{x_0}\right)^2$ is an indication that shows the amount of noise amplification. The average beta (β) along the structure is about 0.036m(0.037m at entrance and 0.032m at exit). The simulation shows this amount is about 8.6 for 18 cells structure (figure 8) and is about 5.1 for 16 cells structure. Figures 9 and 10 show the final offsets and transverse velocities for 18 cells structure. Figure 8 shows the amount of this indication (I(N)) for the first 10000 bunches. The total number of bunches in each pulse is about 70000. As mentioned before with a solenoid the amount of kick is one order of magnitude less then this indication will fall to less than one which would be acceptable. But in the future this can be analysed more precisely if needed.

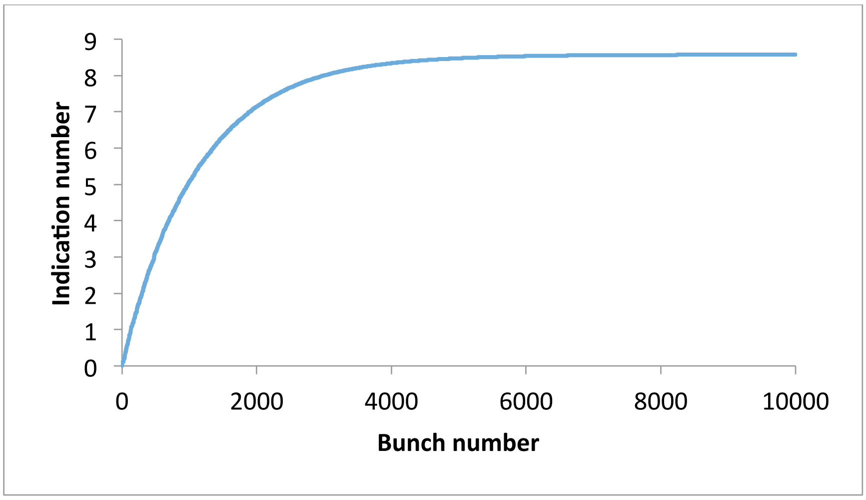

Figure 8: The indication number for first 10000 bunches

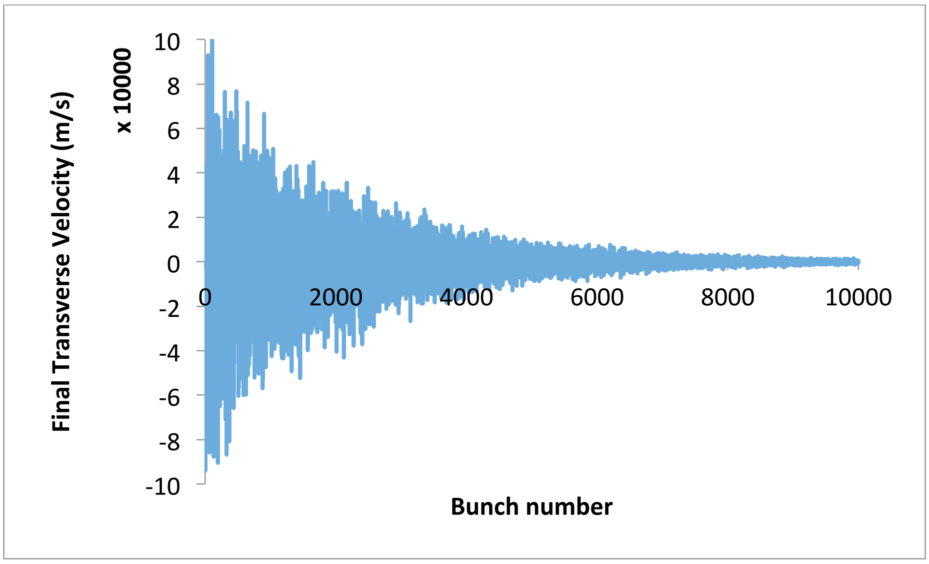

Figure 9: Final transverse velocity

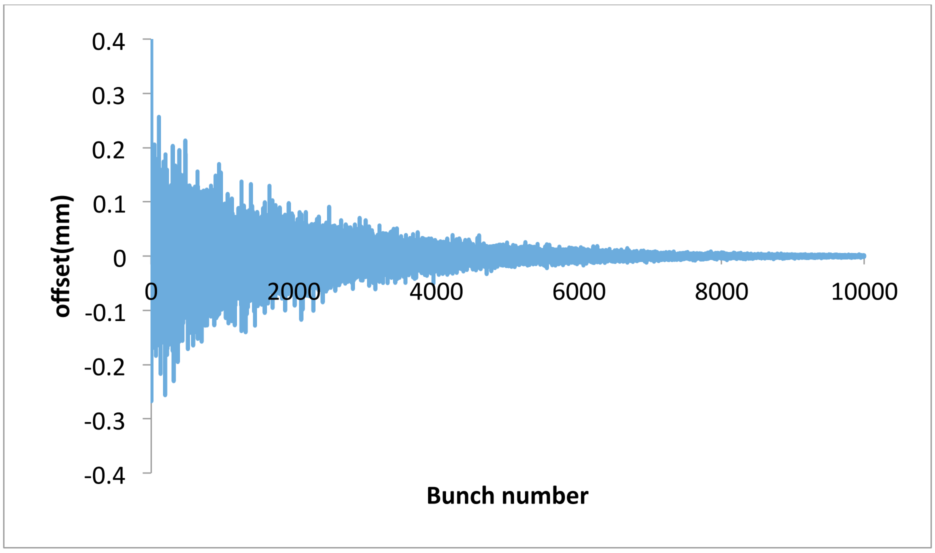

Figure 10: Bunch final offset.

Retuning

In the first report to find the dimension of the cells we introduced a master/slave boundary condition for each cell in HFSS at the beam aperture to get 999.5MHz resonant frequency for 120 degrees phase advance. But because of the different aperture radius and high coupling between cells when we combine them in a structure the phase advance will shifted a little from 120 degrees at 999.5 MHz. Then the cell and output coupler cell radius should be changed to reduce the local reflection and the input coupler cell radius should be changed to reduce the total reflection. To do this we used a model based on Superfish (figure 11). In this case we modelled each four neighbouring cells if the structure inside Superfish to get 999.5 MHz resonant frequency. Then we made a set of linear equation of these models to find the dimension.

$$(6)\quad \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} & 0 & 0 & \cdots \\ 0 & M_{22} & M_{23} & M_{24} & M_{25} & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \cdots & 0 & 0 & M_{13,13} & M_{13,14} & M_{13,15} & M_{13,16} \end{pmatrix} \begin{pmatrix} \Delta r_1 \\ \vdots \\ \Delta r_{16} \end{pmatrix} = \begin{pmatrix} \Delta f_1 \\ \vdots \\ \Delta f_{13} \end{pmatrix}$$

The M matrix represents the frequency shift due to cell radius change of each cell in our Superfish model. The elements of this M matrix and resonant frequency shift from the nominal one (Δf) could be obtained from the Superfish but here we have 16 unknown variables (Δr) and 13 equations then the degrees of freedom is three. In this case we guess two answers and get the average of them and make an iteration to reach a solution and finally we modified a few cells manually to reach better result. Table 2 shows the new cell dimension compared to the first report. Figure 12 compares the phase advance between cells in these two models. The phase advance for older design is 117.3±9.7 degrees and for new design is 119.8±3.9 degrees. Figures 13 and 14 compare the axial electric fields and total reflection (S11). And total reflection (S11) is now reduced to -21.9db in the new design compare to -15.2db for the older design.

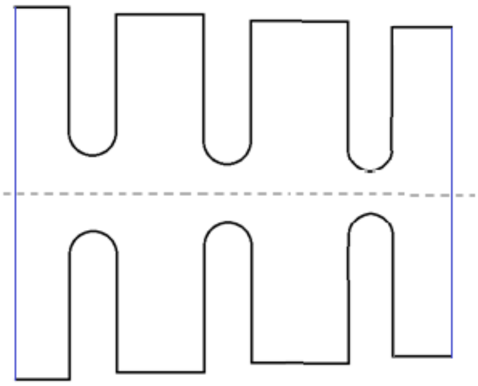

Figure 11: The model used in Superfish consists of four neighbouring cells in form of two half cells and two complete cells.

Cell Number	Cell Radius-new(mm)	Cell Radius-old(mm)
2	133.65	133.72
3	133.03	132.65
4	131.4	131.49
5	130.42	130.25
6	128.76	128.72
7	127.65	127.55
8	126.42	126.18
9	124.83	124.77
10	123.59	123.37
11	122.15	122.05
12	121.07	120.88
13	119.96	119.86
14	119.09	118.99
15	118.33	118.21
16	117.62	117.52
17	116.98	116.91

Table 2: New Cell radius dimension compare to the old one

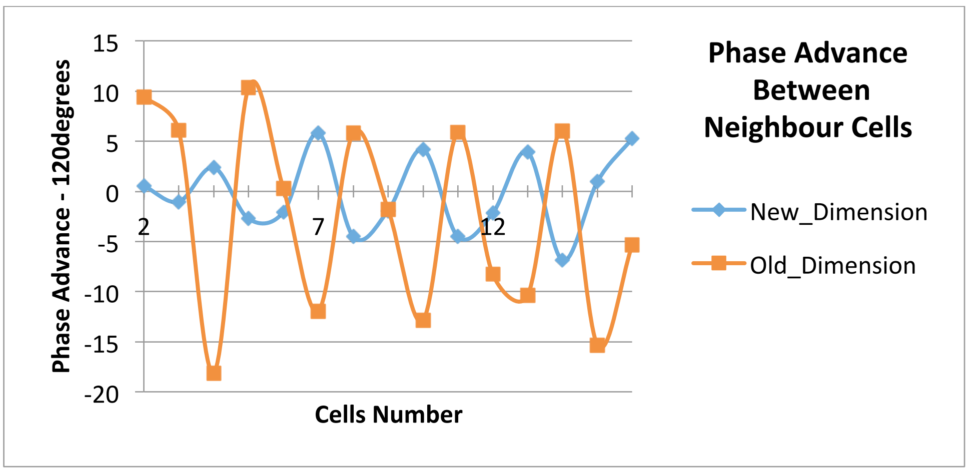

Figure 12: Phase advance between neighbour cells for new and old dimension

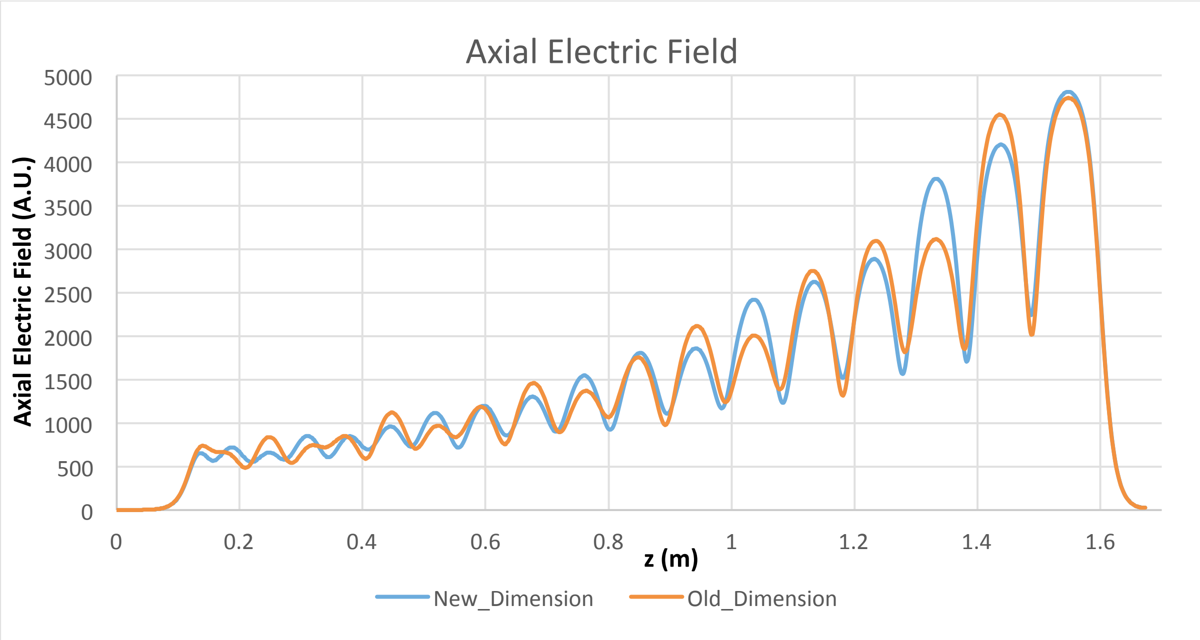

Figure 13: Axial Electric Field for new and old dimension

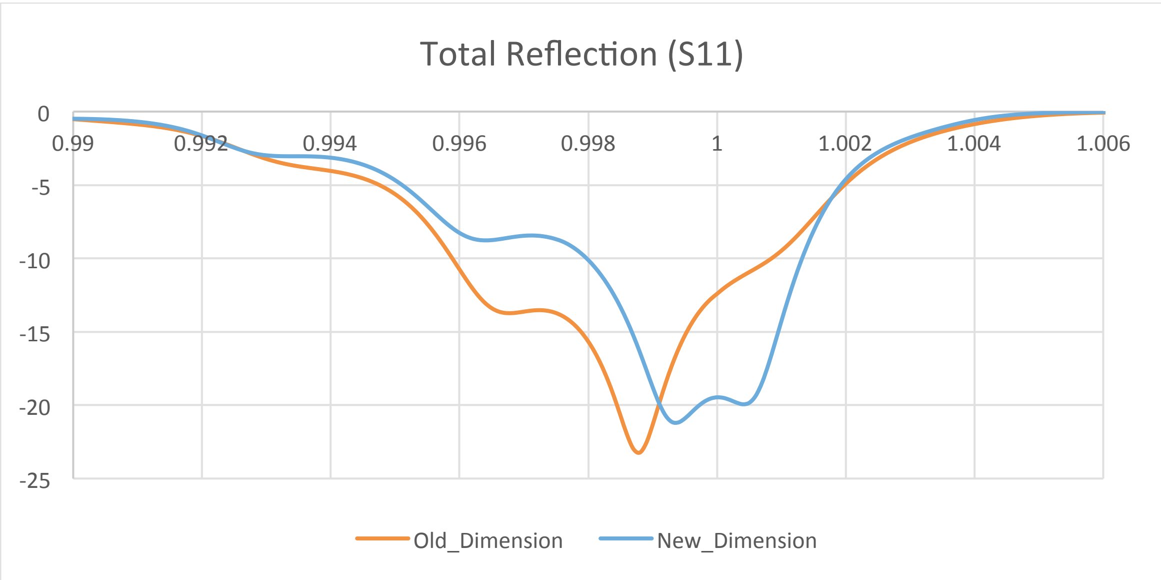

Figure 14: Total reflection (S11) for new and old dimension

Dimensional Tolerance

If we have N coupled cells with small field attenuation, the relative shift in energy gain due to phase advance shift is calculated by equation below that Δθ is the phase advance shift from the nominal phase advance (θ) due to random errors[7,8]:

$$(7)\ \frac{\Delta E}{E} = \frac{N(\Delta\theta)^2}{2}$$

This equation is valid for a constant-impedance structure with similar cells. More accurate energy relative deviation is equal to $\frac{\Delta E}{E} = \frac{N}{E}\sum_{i=1}^{N}\frac{E_i(\Delta\theta_i)^2}{2}$. In this equation E_i is the energy gain in each cell. The relative deviation of the phase advance is proportional to the relative deviation of the resonant frequency and is equal to $\frac{\Delta\theta}{\theta} = \frac{v_p}{v_g}\frac{\Delta f}{f}$ where v_p and v_g are phase and group velocities, respectively. In each cell the resonant frequency depends on n dimensional parameters as $f = f(q_1, q_2, \dots, q_n)$ and we can calculate the relative deviation of the phase advance according to each parameter as follows:

$$(8)\ \frac{(\Delta\theta)_j}{\theta} = \frac{v_p}{v_g}\frac{1}{f}\frac{\partial f}{\partial q_j}\Delta q_j \Rightarrow (\Delta\theta)_j = \frac{v_p}{v_g}\frac{\theta}{f}\frac{\partial f}{\partial q_j}\Delta q_j \equiv A_j \Delta q_j$$

Where θ=2π/3 is the nominal phase advance between cells with the resonant frequency f=999.5 MHz. In our design we have four dimensional parameters: cell radius, beam aperture radius, cell length and disk thickness. The total phase advance shift in each cell is equal to equation below according to all dimensional parameters:

$$(9)\ (\Delta\theta_i)^2 = \sum_{i=1}^{n}\left[(\Delta\theta_i)_j\right]^2\ and\ if\ \Delta q_{i,j}\ are\ equals \Rightarrow \Delta\theta_i = \Delta q\sqrt{\sum_{j=1}^{n} {A_{i,j}}^2} \equiv B_i \Delta q$$

Now the energy relative deviation is equal to:

$$(10)\ \frac{\Delta E}{E} = \Delta q^2 \sum_{i=1}^{N} N\frac{E_i {B_i}^2}{2E} \equiv \Delta q^2 \sum_{i=1}^{N} C_i$$

$\frac{\partial f}{\partial q_j}$ could be found by the Superfish, HFSS or similar codes. Figure 15 and table 3 show these parameters for different cells of our structure. Table 3 also shows the C parameter as mentioned in the equation above, energy gain, group and phase velocity in each cell. Now we can find from the equation above that if we want an energy relative deviation less than one percent, the dimensional tolerance should be less than 30µm. This shows a big flexibility because the usual machining accuracy is between 5 and 10 µm.

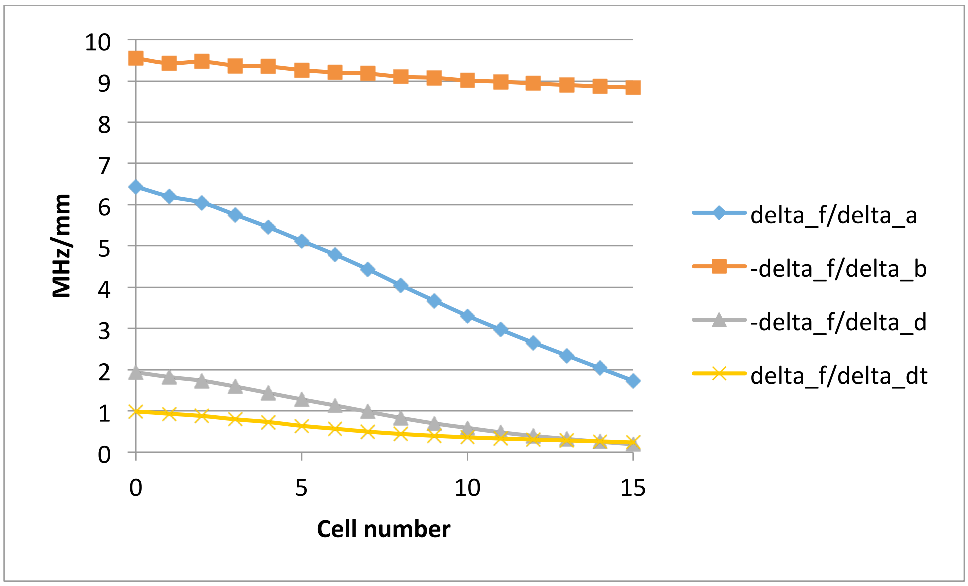

Figure 15: Frequency shift due to each dimension change

cell number	δf/δb (MHz/mm)	δf/δa (MHz/mm)	δf/δd (MHz/mm)	δf/δt (MHz/mm)	vp/c (%)	vg/c (%)	energy gain(KeV)	C (1/mm^2)
2	-9.55	6.44	-1.94	0.99	61.2	6.38	5	0.001
3	-9.43	6.20	-1.82	0.93	62.5	6.32	18	0.004
4	-9.47	6.05	-1.73	0.88	64.5	6.31	23	0.005
5	-9.37	5.76	-1.59	0.80	67.3	6.33	25	0.006
6	-9.35	5.45	-1.43	0.73	70.7	6.24	27	0.007
7	-9.26	5.12	-1.28	0.64	74.6	6.28	34	0.009
8	-9.21	4.79	-1.13	0.57	78.8	6.09	48	0.014
9	-9.18	4.43	-0.98	0.50	82.9	5.72	70	0.024
10	-9.10	4.04	-0.83	0.44	86.9	5.19	95	0.042
11	-9.08	3.67	-0.70	0.40	90.4	4.55	121	0.073
12	-9.01	3.31	0.00	0.36	93.4	3.89	150	0.125
13	-8.98	2.97	-0.48	0.33	95.9	3.24	177	0.219
14	-8.94	2.65	-0.39	0.31	97.9	2.66	205	0.380
15	-8.90	2.34	-0.32	0.28	99.7	2.12	247	0.727
16	-8.87	2.04	-0.25	0.26	101.8	1.65	282	1.407
17	-8.84	1.73	-0.19	0.23	104.7	1.24	326	2.968

Table 3: Frequency shift and tolerance data for each cell. The coupler cell parameters is close to the parameters of the last cell.

Cooling

As mentioned in the first report [1] the total peak power loss on the surface is 0.7 MW therefore by knowing the pulse length is 140μs and the repetition rate is 50Hz, the average power loss is 5KW. For this amount of power, water cooling is required. Now we should calculate the amount of water flow in cooling pipes to keep the structure temperature constant with an acceptable variation. By using equation below, we can find which temperature variation is acceptable. Equation below shows the frequency deviation is less than 0.1 MHz if we keep the temperature variation below 6 degrees for a copper structure.

$$(11)\ f = f_0(1-\alpha_L \delta T) \Rightarrow \delta f = -f_0\alpha_L\delta T = -999.5\times10^6\times1.66\times10^{-5}\times\delta T \approx 16.6\left(\frac{KHz}{K}\right)\delta T$$
$$\Rightarrow \delta f \approx 100KHz\ for\ \delta T = 6℃$$

Hereby, α_L is linear thermal expansion coefficient. Now by using equation below we can find the amount of required water flow for this temperature variation.

$$(12)\begin{cases} P_{av} = \dot{m}c_p\delta T = \rho F c_p \delta T \Rightarrow F = \frac{1}{\rho c_p}\frac{P_{av}}{\delta T} \Rightarrow F\left(\frac{cm^3}{s}\right) = 0.239\left(\frac{K.cm^3}{J}\right)\times\frac{P_{av}}{\delta T} \\ P_{av} = P_p\times\tau_p\times f_{rep} = 0.7MW\times140\times10^{-6}s\times50Hz = 5000W \\ For\ \delta T = 6℃ : F \approx 200\ {cm^3}/{s} = 0.2\ {l}/{s} \end{cases}$$

Then the minimum capacity of 0.2l/s for the recirculation system is required. For the future mechanical design, the maximum temperature inside the structure could also be studied.

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