Sub-Harmonic Buncher design for CLIC Drive Beam Injector

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CLIC DB Injector Layout

<table>
<thead>
<tr>
<th>CLIC DB Injector (CDR)</th>
<th>Maximum axial Electric Field (MV/m)</th>
<th>Length (cm)</th>
<th>Phase Velocity /c</th>
<th>Voltage (KV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun</td>
<td>200 KV is another option</td>
<td>140 (β=0.62)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHB - I</td>
<td>0.224</td>
<td>15.6</td>
<td>0.93</td>
<td>35</td>
</tr>
<tr>
<td>SHB - II</td>
<td>0.234</td>
<td>15.6</td>
<td>0.61</td>
<td>36.5</td>
</tr>
<tr>
<td>SHB - III</td>
<td>0.249</td>
<td>15.6</td>
<td>0.73</td>
<td>38.8</td>
</tr>
</tbody>
</table>

This result is based on a forward travelling wave structure with two cells. Their lengths are equal to CTF3 SHBs.

New prebuncher (PB – II) is added to reduce the satellite. In this case, the SHB – III should be operated at non-zero crossing.

Second Option – The idea from P. Urschütz

SHB-III operating at non-zero crossing needs more input power. As a new idea we can use a SW structure to avoid this problem by reducing the power reflection (will be discussed later).

Another Options – The idea from Steffen and Roberto : Using a chopper at lower energy (before the buncher) or at higher energy (after the buncher).

Another raw idea – from Steffen and me – is to using a passive cavity instead of SHB-III. It means we doesn’t need any power source.

Data from S. Bettoni, R. Corsini, A. Vivoli
Presentation (1)
Powering – CTF3 vs. CLIC DB

SHBs work at 499.75 MHz, half of 999.5 MHz for the buncher and accelerating cavity. SHBs need wide-band power sources and should have low filling time structures (10 ns in our case).

Our goal is to find the minimum input power needed and then looking for the power source.

Scaling using this relation: \( W', P \sim E^2 \omega^{-2} \)

The input power is so high and not acceptable then we should try to re-design the SHBs.

### Data from L. Thorndahl presentation (2) and P. Urschütz note (3)

<table>
<thead>
<tr>
<th>CTF3 1499.28 MHz</th>
<th>Field (KV/m) / After Scaling</th>
<th>Length (cm)</th>
<th>Voltage (KV)</th>
<th>Input Power</th>
<th>Phase Velocity/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun</td>
<td></td>
<td>140</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHB - I</td>
<td>128/43</td>
<td>15.6</td>
<td>20</td>
<td>40 KW</td>
<td>0.63</td>
</tr>
<tr>
<td>SHB - II</td>
<td>128/43</td>
<td>15.6</td>
<td>20</td>
<td>40 KW</td>
<td>0.67</td>
</tr>
<tr>
<td>SHB - III</td>
<td>128/43</td>
<td>15.6</td>
<td>20</td>
<td>40 KW</td>
<td>0.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CLIC DB Injector (CDR) 499.75 MHz</th>
<th>Field (KV/m)</th>
<th>Length (cm)</th>
<th>Voltage (KV)</th>
<th>Input Power (CTF3 scaling)</th>
<th>Phase Velocity/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun</td>
<td>140</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHB - I</td>
<td>224</td>
<td>15.6</td>
<td>35</td>
<td>1.1 MW</td>
<td>0.93</td>
</tr>
<tr>
<td>SHB - II</td>
<td>234</td>
<td>15.6</td>
<td>36.5</td>
<td>1.2 MW</td>
<td>0.61</td>
</tr>
<tr>
<td>SHB - III</td>
<td>249</td>
<td>15.6</td>
<td>38.8</td>
<td>1.4 MW</td>
<td>0.73</td>
</tr>
</tbody>
</table>
Fundamental Equation

Standing Wave Structure

$$R = \frac{V^2}{P_d} = \frac{V^2}{P\beta} = \frac{V^2}{P\beta} = \frac{V^2}{P\beta} = \frac{V^2}{Q_e} \implies P = \frac{V^2}{Q_e} \frac{R}{Q_e} = \frac{V^2}{\omega \tau Q}$$

Travelling Wave Structure

$$R' = \frac{(V/L)^2}{Q} = \frac{(V/L)^2}{Q} = \frac{V^2}{\omega P L v_g} \implies P = \frac{V^2}{\omega \tau Q}$$

For the known gap voltage and filling time our goal is to increase $R/Q$ to reduce the input power.

$P$ : Source power
$V$ : Gap voltage
$W'$ : Stored energy per length
$L$ : Structure length
$v_g$ : Group velocity
$n$ : Cell numbers

$\tau = 10\text{ns}$
$V = 36.5\text{ KV}$
Pill Box Model – TM\textsubscript{010} mode

\[ \frac{R}{Q}_{\text{cell}} \equiv \frac{V^2}{\omega_0 W} = \frac{2\omega_0 \mu_0 g T^2}{\pi x_0^2 J_1^2(x_0)} = C \beta x T^2 = 4C \beta \frac{\sin^2 \left( \frac{x}{2} \right)}{x} \]

\[ T = \text{Transit Time Factor} = \frac{\sin \left( \frac{k g}{2 \beta} \right)}{\frac{k g}{2 \beta}} = \frac{\sin \left( \frac{x}{2} \right)}{\frac{x}{2}} \]

\[ x \equiv \frac{k g}{\beta} = \text{Phase advance per cell} \quad \beta = 0.62 \]

\[ C = \frac{2Z_0}{\pi x_0^2 J_1^2(x_0)} \approx 153.87 \quad k = \frac{\omega_0}{c} \]

\[ x_0 = \text{First root of } J_0 \text{ function} \approx 2.4048 \]

\[ Z_0 = \text{Impedance of free space} \approx 376.73 \Omega \]

For TW structure:

\[ \frac{R}{Q} = n \left( \frac{R}{Q} \right)_{\text{cell}} \approx \frac{L}{g} \left( \frac{R}{Q} \right)_{\text{cell}} = \frac{v_g T}{g} \left( \frac{R}{Q} \right)_{\text{cell}} \Rightarrow \frac{R}{Q} \sim v_g T^2 \sim \sin(x) T^2 \]
CTF3 case – Forward TW structure

Related to pill-box model and by attention to the disk thickness, the maximum R/Q is at 85° phase advance but 75.5° was chosen for CTF3 SHBs before detuning for beam loading compensation.

The group velocity is increased by increasing the iris radius. The iris radius is about 10cm for 4.8% group velocity.

From L. Thorndahl presentation (2) for 4 cells model. Finally 6 cells structure was chosen.

It means the minimum input power needs using the fundamental equation is around 1.11MW for CLIC DB injector.

The best thing was done for the CTF3 SHBs with Forward TW structure and it can not be reduced so much then we should look for another structure type.
Backward TW structure

This design is based on the LEP cavity (4).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g/l$</td>
<td>$=0.51$</td>
</tr>
<tr>
<td>$r_b$</td>
<td>25 mm</td>
</tr>
<tr>
<td>$r_n$</td>
<td>5 mm</td>
</tr>
<tr>
<td>$\theta_1$</td>
<td>30°</td>
</tr>
<tr>
<td>$\theta_2$</td>
<td>24°</td>
</tr>
<tr>
<td>$t$ (disk thickness)</td>
<td>18 mm</td>
</tr>
</tbody>
</table>

Phase advance per cell

$$l = \frac{\lambda \beta}{2\pi}$$
R/Q and $V_g$ vs. Coupling angle

<table>
<thead>
<tr>
<th>Frequency</th>
<th>499.75 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$ (for 75.5° phase advance per cell)</td>
<td>78 mm</td>
</tr>
<tr>
<td>$r_1$</td>
<td>176 mm</td>
</tr>
<tr>
<td>$r_c$</td>
<td>171 mm</td>
</tr>
<tr>
<td>$l_c$</td>
<td>45 mm</td>
</tr>
</tbody>
</table>

$r_2$ is changed to keep resonant frequency constant.

We can keep the beam hole radius as small as possible ($r_b$) to have higher R/Q per cell. Then we can increase the group velocity by using magnetic coupling holes and it means more cell numbers.

R/Q per cell is weakly depend on the magnetic coupling angle. It means that total R/Q is linear vs. group velocity because the cell numbers is linearly dependent on group velocity.
The maximum $R/Q$ was found with HFSS for each cell numbers for $\theta_c = 90^\circ$.

If we have allowed to increase filling time, then by using 4 and 5(6) cells for 122° and 110° structures, respectively, we can reach to 52.6 KW and 51.2(35.6) KW power.

I think the best option to have limited cell numbers is the 4 cells structure with 110° phase advance that needs 80 KW input power.

**R'/Q seems to be constant then we can imagine that the maximum $R/Q$ is close to 90° phase advance because the group velocity is maximum.**
Optimization - II

another HFSS models with a little better R/Q

<table>
<thead>
<tr>
<th>number of cells</th>
<th>phase(deg)</th>
<th>vg/c(%)</th>
<th>R/Q - cell (Ω)</th>
<th>R'/Q (Ω/m)</th>
<th>R/Q (Ω)</th>
<th>Input power (KW)</th>
<th>r₁(mm)</th>
<th>r₂(mm)</th>
<th>r₃(mm)</th>
<th>θ(θ) (deg)</th>
<th>l₁(mm)</th>
<th>rₙ(mm)</th>
<th>t(mm)</th>
<th>g/l</th>
<th>phase velocity/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>105</td>
<td>10.86</td>
<td>142.76</td>
<td>1337.61</td>
<td>428.28</td>
<td>100.79</td>
<td>169.8</td>
<td>186.35</td>
<td>164.9</td>
<td>75</td>
<td>49.04</td>
<td>6.13</td>
<td>12.26</td>
<td>0.45</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>12.2</td>
<td>142.16</td>
<td>1767.35</td>
<td>589</td>
<td>86.81</td>
<td>152.9</td>
<td>167.8</td>
<td>148.49</td>
<td>89</td>
<td>41.6</td>
<td>5.52</td>
<td>11.04</td>
<td>0.44</td>
<td>0.61</td>
</tr>
<tr>
<td>4</td>
<td>105</td>
<td>14.34</td>
<td>142.16</td>
<td>1331.96</td>
<td>568.64</td>
<td>75.04</td>
<td>159.55</td>
<td>175.1</td>
<td>154.94</td>
<td>87</td>
<td>46.08</td>
<td>5.76</td>
<td>11.52</td>
<td>0.46</td>
<td>0.61</td>
</tr>
<tr>
<td>5</td>
<td>105</td>
<td>16.14</td>
<td>1314.05</td>
<td>634.45</td>
<td>67.07</td>
<td>67.07</td>
<td>162.88</td>
<td>178.75</td>
<td>158.17</td>
<td>95</td>
<td>47.04</td>
<td>5.88</td>
<td>11.76</td>
<td>0.54</td>
<td>0.61</td>
</tr>
</tbody>
</table>

It is possible to reduce the power a little. For example to 75 KW from 80 KW in last slide.

After choosing the structure we can work to optimize cells depend on all parameters affect the design like beam loading, HOMs, minimum wall thickness for cooling water pipe holes and ...

It is the definition of drain time as was introduce by L. Thorndahl et al.(2). This time is used to find the number of bunches passages during phase switching. For FTW case it is about 8% less (τ′≈9ns) and for BTW case it is about 20% more than filling time(τ′≈12ns).
As mentioned briefly, most power is reflected because of low external Q (≈ 31.4 for τ=10ns) to have small filling time. In the case of beam loading the external Q can be increased to use a fraction part of reflected power to compensate beam loading then we have not need more input power except the beam loading consuming power exceeds the input power. Maximum 13.3 (16.5) KV beam voltage gain for 80(100) KW input power.

As another options, we can use the SW structure with two single cells with two power coupling like a TW structure.

Maybe it is a better option and more standard in comparison with a new BTW structure that seems interesting but more challengeable 😊.
Beamloading compensation

We follow an “rf-energy sample” as it moves with the group velocity in the structure:

For bunching the bunches traverse the sample when the wave is at zero crossings. Zero crossings correspond to the wave phasor being positive and purely imaginary.

Phasor analysis shows that the set-up is correct for bunching when between passages of bunches through the moving sample, the phasor turns by an integral number of turns.

With beamloading a negative real phasor $=-q\omega R'/Q \times$ (bunch formfactor) ($q =$ bunch charge) is added at each traversal; it can be compensated by detuning:

Tuned structure with Ez phasors turning 360 deg. between bunch passages yielding correct bunching phasor.

Detuned structure with Ez phasors turning less than 360 deg. between bunch passages yield correct imaginary bunching phasor in presence of beam loading.

At CTF3, the SHBs are detuned to turn more than 360° between bunch passage to compensate negative real phasor but I'm not sure with the negative group velocity, this number should be greater or smaller than 360°?
Beam Loading Compensation

Historically, the problem was discovered after building the structure then they try to detune it to compensate the negative beam loading but we can just change the phase advance by changing the length then we don't need to detune the structures.

For SW structures this concept is not useful. As mentioned previously, we just need to increase external Q for the beam loading compensation.

Maximun 15.7° for 80KW and 12.6° for 100KW input power. The bunch form factor in CTF3 for the third SHB is around 0.6 and if assume the same for CLIC the detuning angles are around 9.3° and 7.6° for 80KW and 100KW input power, respectively.

The detuning angle could be decreased by decreasing the gap voltage and filling time or by increasing the filling time if we keep the total length constant by decreasing the group velocity.

\[ E_{bl}/E_0 = \frac{1}{2} q\omega \frac{R'}{Q} F = \frac{IVF}{\omega \tau P} \times \frac{1}{P} \approx (\Delta \theta)_{rad} \]

\[ F = e^{-\frac{\omega_0^2 \sigma^2}{2}} = e^{-\frac{(\Delta \phi)^2}{2}} \]

I= 6 A  
V= 36.5 KV  
\( \tau = 10 \text{ ns} \)  
\( \omega = 2\pi \times 499.75 \text{ MHz} \)  
F= bunch form factor = 1 (maximum)

This is valid for a Gaussian charge distribution that \( \sigma \) is the time width and \( \Delta \phi \) is the phase width of one bunch.

For TW structures: \( \frac{1}{\tau^2} \Rightarrow \frac{E_{bl}}{E_0} \sim V\tau \)
Structure detuning

\[ e^{j \left[ \frac{\omega t - \omega z}{V_{ph}} \right]} \]

The time interval and distance between bunches crossing the sample moving with \( V_g \) and a bunch moving with \( V_e \):

\[ \Delta t = \frac{1}{f \left( 1 - \frac{V_g}{V_e} \right)} \]

\[ \Delta z = \Delta t V_g \]

The phase between 2 subsequent crossings is:

\[ \Delta \varphi = 2\pi \left[ \frac{1 - \frac{V_g}{V_{ph}}}{1 - \frac{V_g}{V_e}} \right] \]

Using this equation, \( v_{ph} \) will be 0.55c (0.55c) for the 110° four cells (122° three cells) BTW structures for \( F=0.6 \) in comparison with \( v_e=0.62c \). In the case of rotation being less than 360° between bunch passages, \( v_{ph} \) will be 0.72c (0.71c)?

When the phase velocity equals the electron velocity the phase advance is 360 deg.

For \( V_{ph} = 0.71c \), instead of 0.62c, the phase advance between crossings reaches the required 365 deg. (66 deg./cell instead of 75.5 deg.).
References

1) CLIC drive beam injector design, S. Bettoni, R. Corsini, A. Vivoli, 2010
3) Parameter list of the CTF3 Linac and the CT line, P. Urschütz, CTF3 Note 071, 2006
4) The LEP accelerating cavity, H. Henke, LEP note 143, 1979
5) High energy electron linacs: applications to storage ring RF systems and linear colliders, P. B. Wilson, SLAC-PUB 2884, 1982
6) From documents I got from L. Thorndahl.
Thanks for your attention
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