Basic Timing Requirements for TESLA

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1 Introduction

Timing aspects according to this paper are related to constraints imposed by the bunch spacing in the main linac and in the damping ring. These constraints depend on the maximum number of bunches and the beam pulse length chosen for TESLA operation. The positron beam in TESLA is produced by electrons at high energy near the interaction point (IP). Therefore it can be seen as if the positrons were reflected back to the damping ring at the IP and have to find an empty place there. This leads to special requirements for the positron path length. In the following only this basic timing aspect will be discussed.

2 Beam Transfer from the Damping Ring to the Main Linac

The intra bunch distance in the main linac (ML) is intended to be constant during the pulse train: $n_{ML}\lambda_{ML} = constant$, where n_{ML} is an integer number and λ_{ML} is the rf wavelength in the ML. This corresponds to a regular filling in the damping ring (DR) with a bunch spacing of $n_{DR}\lambda_{DR}$. The circumference of the damping ring is $h_{DR}\lambda_{DR}$ (h_{DR} is the harmonic number) and the maximum possible number of bunches is $N_B = h_{DR}/n_{DR}$.

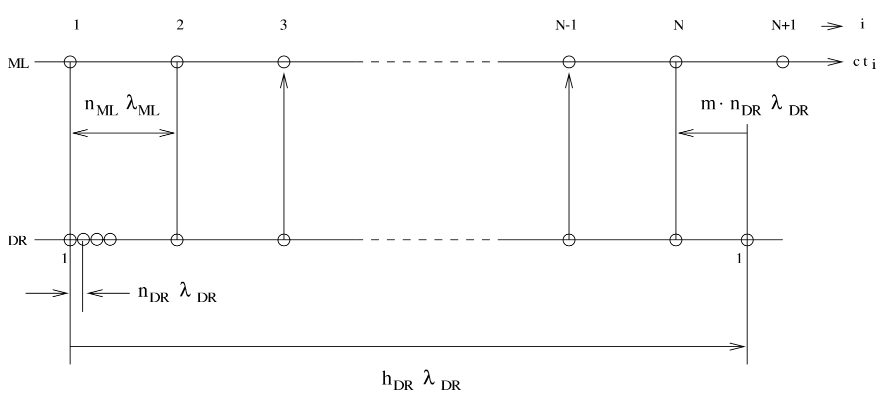

Figure 1: Bunch position at transfer in terms of integer numbers of the rf wavelength λ. h_{DR} is the harmonic number of the damping ring and the factor m enables extraction of all damping ring bunches with a constant bunch spacing $n_{ML}\lambda_{ML}$.

Corresponding to Fig. 1 a compression factor c_F can be defined as the ratio of the bunch spacing in the main linac to that of the damping ring. This factor has to be integer for proper phase matching. To enable a constant bunch spacing in the main linac, the factor m is defined in the region $(0 < m < c_F)$ and must not have a common divider with the compression factor c_F:

$$c_F \stackrel{\text{def}}{=} \frac{n_{ML}\lambda_{ML}}{n_{DR}\lambda_{DR}} = integer, \qquad \frac{m}{c_F} = relatively\ prime \tag{1}$$

Furthermore from Fig. 1 a relation between the factor m and the number of bunches N_B can be derived; i.e.

$$\frac{m}{c_F} = fractional\ part\left(\frac{N_B}{c_F}\right) \tag{2}$$

For TESLA there is an upper limit on the length of the beam pulse and on the total charge in the beam; that is,

$$N_B \cdot n_{ML} = h_{DR} \cdot c_F \cdot \tfrac{\lambda_{DR}}{\lambda_{ML}}$$

has a maximum value and c_F is constant for a given beam pulse length of 950 μs (860 μs) at variable numbers of bunches. The maximum number of bunches is 2820 (4886) at a spacing of 337 ns (176 ns) and the bunch spacing in the damping ring has a lower limit of about 20 ns (12 ns) due to the pulse width of the kicker magnet. The values in parenthesis correspond to the 800 GeV upgrade [1].

To achieve flexibility for setup procedures with different numbers of bunches, a prime compression factor c_F should be chosen to allow any legal value of the factor m (see Eqs. 1 and 2). That depends on the ratio of the rf frequencies between the main linac and the damping ring. The frequency for the damping ring is chosen to be at 500 MHz (5/13 of 1.3 GHz). This implies rather poor flexibility on allowable bunch spacings, although a prime compression factor can be used e.g.

$$c_F = \tfrac{n_{ML}\lambda_{ML}}{n_{DR}\lambda_{DR}} = \tfrac{221\cdot 5}{5\cdot 13} = \tfrac{442\cdot 5}{10\cdot 13} = \tfrac{663\cdot 5}{15\cdot 13} = \tfrac{884\cdot 5}{20\cdot 13} = \ldots = 17$$

A better solution would be to increase the damping ring rf frequency to 520 MHz (2/5 of 1.3 GHz) which would allow more flexibility e.g.

$$c_F = \tfrac{n_{ML}\lambda_{ML}}{n_{DR}\lambda_{DR}} = \tfrac{170\cdot 2}{4\cdot 5} = \tfrac{255\cdot 2}{6\cdot 5} = \tfrac{340\cdot 2}{8\cdot 5} = \tfrac{425\cdot 2}{10\cdot 5} = \tfrac{510\cdot 2}{12\cdot 5} = \tfrac{595\cdot 2}{14\cdot 5} = \ldots = 17$$

Flexibility for different bunch patterns also needs a suitable choice for the maximum number of bunches. This choice is fundamental because it determines the harmonic number of the damping ring. For example $N_B = 2940 = 2^2 \cdot 3 \cdot 5 \cdot 7^2$ together with n_{DR} = 10 and f_{DR} = 520 MHz is a choice which would allow many regular bunch patterns (see Tab.1) and would fix the circumference of the damping ring as follows:

$$h_{DR} = N_B \cdot n_{DR} = 29400, \quad h_{DR}\lambda_{DR} = 16949.8\,m, \quad T_0 = h_{DR}/f_{DR} = 56.54\,\mu s.$$

A good choice for N_B enables regular fillings also in the vicinity of the nominal filling. This is possible at a distance of $\Delta h_{DR} = 120$ (69 m) except for cases where $m = 0$. It should be mentioned here, that a regular bunch pattern for the TESLA operation is mandatory for several reasons. For the beam transfer between the damping ring and the main linac it enables periodic kicker operation even if some buckets are empty thus allowing for an ion clearing gap in the damping ring. Nevertheless, a gap in the filling of the damping ring is transfered unpleasantly into missing bunches along the main linac bunch train and vice versa.

3 Path Length Constraints in TESLA due to Timing Requirements

In the discussion so far only the beam transfer from the damping ring into the main linac has been considered. For TESLA the ejected positron beam is transported back from the IP and has to be filled into a partially empty damping ring. That means the positron bunches must fill consecutive empty buckets.

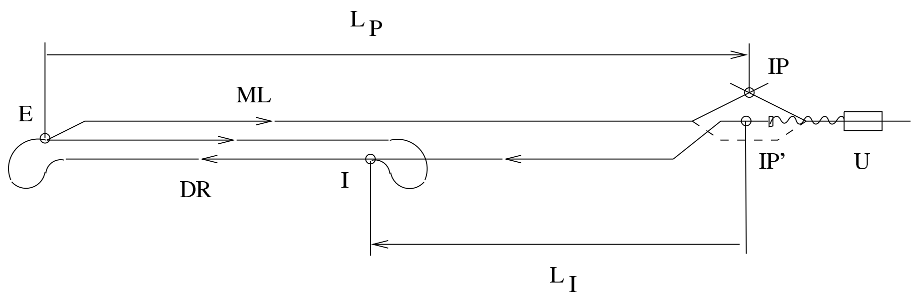

Figure 2: Positron path from the ejection point E in the damping ring DR through the main linac ML to the interaction point IP and back from an equivalent point IP' through a positron preaccelerator to the injection point I in the damping ring. The positron production starts from the undulator U near the end of the electron path.

The timing for the positrons injection into the damping ring DR depends on the path length from the DR to the IP and back from IP' to the DR, where the point IP' is defined in such a way that the path length of the electrons from the undulator U to the IP is the same as that for the X-ray to the converter plus the time needed for the outcoming positrons to reach IP'. To match the injected positrons with an empty bucket in the DR the following condition can be written (see Fig. 2):

$$L_P + L_I = h_{EI}\lambda_{DR} + M \cdot h_{DR}\lambda_{DR} + N \cdot m_{ML}\lambda_{ML}. \tag{3}$$

Here h_{EI} is the integer number of rf wavelengths from E to I. Eq. 3 can be rewritten using Fig. 1 and Eq. 1 which shows that $L_P + L_I$ has to be an integer multiple of λ_{DR}.

$$\frac{L_P + L_I}{\lambda_{DR}} + h_{IE} = \left(M + 1 + \frac{N}{N_B} \cdot c_F\right) h_{DR} \tag{4}$$

By varying N, the position of the IP could be changed in steps of half the bunch spacing in the main linac (about 49 m for the nominal filling). But this would not allow to use different filling patterns because $N \cdot c_F/N_B$ has to be constant. Therefore, choosing $N = 0$ and $M = 1$ is necessary for TESLA and a second IP has to be at the same distance to the ejection point E as the first one. Introducing a convenient definition for a special length L_A, the path length constraints for the positrons in TESLA can be expressed now using Eq. 4 as follows:

$$L_P + \frac{L_A}{2} = h_{DR}\lambda_{DR} \quad with \quad L_A \stackrel{\text{def}}{=} h_{IE}\lambda_{DR} - (L_P - L_I)\,. \tag{5}$$

It can be seen easily that $L_P + L_A/2$ is independent of the position of E and I if the damping ring is in a fixed position to the IP. In this case, the length L_P should be maximum and the length L_I should be minimum for economical reasons. According to Fig. 2 the best position for E is at the left end of the upper straight section and the best position for I is at the right end of the lower straight section of the damping ring. Under these conditions L_A is equal approximately to the arc length of the DR ($L_A \approx 900\, m$). Together with the choice for the circumference of the DR ($h_{DR}\lambda_{DR} \approx 16950\ m$), the length of the positron path ($L_P \approx 16500\ m$) must be precisely tuned against the position of the IP to fulfill Eq. 5.

For the positron part of the timing it was provided that the electron bunches meet the positron bunches exactly at the IP. This needs to be adjustable by means of the rf phase and the timing of the electron bunch train. There are no special constraints for the electron path length in the main linac, but of course the bunch spacing for the e^- and e^+ needs to be the same. This implies that the harmonic number of the electron and positron damping rings be the same, assuming the same rf frequency for both.

4 Conclusion

The well-chosen length of the positron path ($M = 1$, $N = 0$) leads to increased flexibility allowing variable bunch spacings. The buckets in the damping ring are refilled as if the ejected bunches came back into the same buckets from where they started. In principle, any compression factor c_F can be chosen if a non-regular bunch spacing at some positions in the beam pulse train would be acceptable.
Following the arguments above, the order how to fix the position of the IP is determined. It starts with the outer boundary of the positron damping ring at the end of the site. The position of the ejection point is determined from the design of the arcs in the damping ring. Then a choice for the harmonic number h_{DR}, which depends on the number of bunches and the bunch spacing in the damping ring, can be made. This choice determines the distance between the ejection point and the IP. Now, the rest of the site can be used for the electron part, which does not require a special path length based on timing requirements.

5 Acknowledgment

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References

[1] Chapter 1 (Overview) in the TESLA TDR, DESY, 2001.

n_{DR}	n_{ML}		N_B																
4	130	170	7050		7200	7230	7260	7290	7320				7350		7355		7380		7440
6	**195**	255	**4700**		4800	4820	4840	4860	4880				**4900**				4920		4960
8	260	340	3525		3600	3615	3630	3645	3660				3675				3690		3720
10	325	**425**	**2820**		2880	2892	2904	2916	2928		(2938)	2939	**2940**	(2941)	2942		2952	(2964)	2976
12	390	510	2350		2400	2410	2420	2430	2440				2450				2460		2480
14	455	595											2100						
16	520	680			1800		1815		1830								1845		1860
18	585	765			1600			1620									1640		
20	650	850	1410		1440	1446	1452	1458	1464				1470		1471		1476		1488
22	715	935																	
24	780	1020	1175		1200	1205	1210	1215	1220				1225				1230		1240
26	845	1105																	
28	910	1190											1050						
30	975	1275	940		960	964	968	972	976				980				984		992
32	1040	1360			900				915										930
34	1105	1445																	
36	1170	1530			800			810									820		
38	1235	1615																	
40	1300	1700	705		720	723	726	729	732				735				738		744
42	1365	1785											700						
44	1430	1870					660												
46	1495	1955																	
48	1560	2040			600		605		610								615		620
50	1605	2125	564		576						(13)		588	(17)				(13)	
											m=0	prime		m=0				m=0	
$c_F =$	13	17	54.23		55.38								56.54					$= T_0$	[μs]

Table 1: Bunch spacing n_{DR}, n_{ML} and some suitable numbers of bunches N_B for $\lambda_{ML}/\lambda_{DR} = 2/5$ ($f_{DR} = \mathbf{520}$ MHz) with a constant harmonic number h_{DR} for each column. The revolution time in the damping ring is T_0 and the pulse length in the main linac is $T_P = T_0 \cdot c_F$.