A FAST SWITCHYARD FOR THE TESLA FEL-BEAM USING A SUPERCONDUCTING TRANSVERSE MODE CAVITY

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Abstract

In the present design of the TESLA Linear Collider with integrated X-ray Laser Facility it is necessary that 1 ms long bunch trains with about 10000 bunches are generated and distributed to several free electron laser (FEL) beam lines. The different scientific applications of the X-ray FELs need specific filling patterns of the bunches in the bunch train. It is shown that a fast switch-yard based on a superconducting transverse mode cavity can be used to generate the required bunch pattern in a flexible way while keeping the beam loading in the main linear accelerator constant. The conceptual design of the beam optics and the transverse mode cavity are presented.

1 INTRODUCTION

The conceptual design of the TESLA linear collider with integrated x-ray laser facility [1] requires that 1 ms long bunch trains with 11315 bunches are generated and distributed to several free electron laser (FEL) beam lines, while bunch trains with 2882 bunches are accelerated to 250 GeV for high energy physics (HEP) experiments. The e^- linear accelerator, the two extraction points (at 25 GeV and 50 GeV) for the FEL-beam and the beam transfer lines are shown schematically in Fig. 1. The first part of the e^- linear accelerator is operated at a duty cycle of 10 Hz providing alternately HEP and FEL pulses. The pulse structure is illustrated in Fig. 2. The mean pulse current is about 10 mA for the HEP and FEL pulses, which guarantees the same beam loading in the cavities for both pulse-types. Different scientific applications of the X-ray FELs need specific filling patterns of the bunches in the FEL bunch trains [2]. Four examples of filling patterns are shown in Fig. 3(a,b,c,d). Case a is the (standard) 93 ns constant-spacing pattern, while b and c are two examples how the number of bunches and the bunch distance may be varied. Case d is a special case with a much shorter bunch to bunch distance of 769 fs or one 1.3GHz rf-bucket. In the following sections it is shown how filling patterns like Fig. 3(b,c) can be generated from a standard constant-spacing pattern using a fast switchyard based on a transverse mode cavity. A much shorter bunch spacing as in Fig. 3 (d) of course requires a special bunch generation already at the FEL beam injector. Whether such a bunch train can be accelerated upto 50 GeV without severe cumulative multi-bunch beam break-up is beyond the scope of this paper.

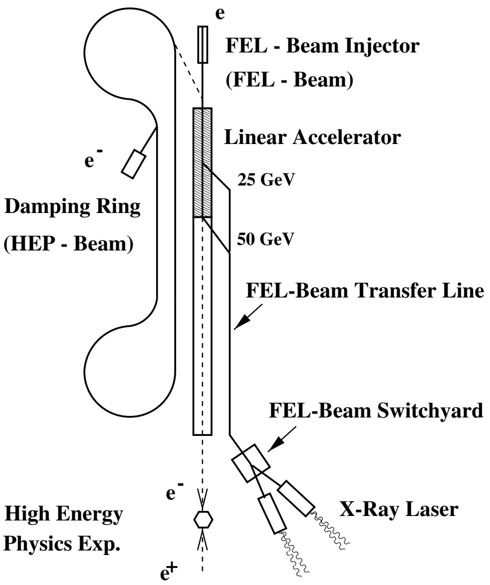

Figure 1: The e^- linear accelerator of the TESLA linear collider with integrated x-ray laser facility.

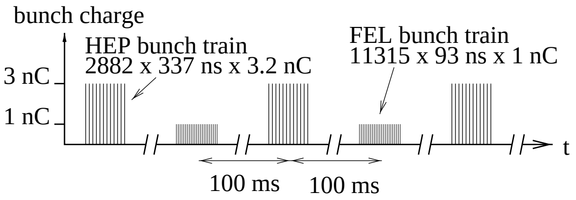

Figure 2: HEP and FEL beam pulse structure

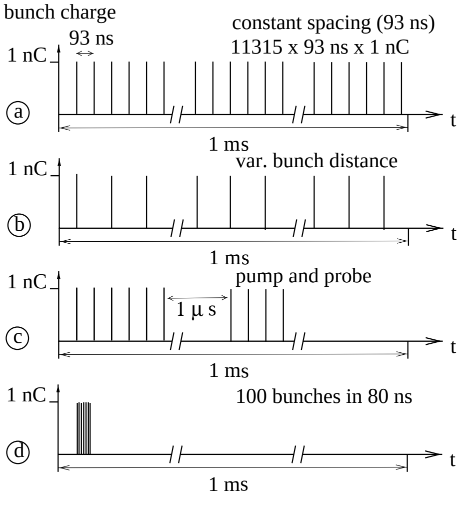

Figure 3: Different bunch filling patterns of a FEL beam pulse.

2 BASIC DESIGN OF A FAST SWITCHYARD

The goal of a fast switchyard is to distribute single bunches or sub-trains of bunches within one 1 ms long bunch train to different beam lines. The typical bunch distance is 120 rf-buckets of the 1.3 GHz main linac rf-system or $120 \times 0.769\,\mathrm{ns} = 92.28\,\mathrm{ns}$. But some scientific application of the FEL require special filling patterns with even shorter and varying bunch distances (see Fig. 3). This requirement can be accomplished by a pulsed superconducting transverse mode cavity operated at a frequency of $1.5 \times 1.3\,\mathrm{GHz} = 1.95\,\mathrm{GHz}$ with a 1 ms rf-pulse duration and a delay line for the laser system of the rf-gun. The 1.95 GHz deflecting cavity is operated in a pulsed mode similar to the 1.3 GHz accelerating cavity of the main linac. This avoids rise time or stability problems of the kick applied to individual bunches. The choice of the frequency labels the 1.3 GHz buckets as even and odd buckets. Bunches in even buckets are kicked into the opposite direction than those in odd buckets, which enables the splitting of one 1 ms long pulse into several sub-bunch trains. The principle is illustrated in Fig. 4: A bunch train is generated with a bunch-to-bunch distance of 92.28 ns or 120 free 1.3 GHz buckets with a few exceptions where the distance is 93.05 ns or 121 buckets. An even number of buckets between bunches guarantees that all bunches are kicked into the same direction by the transverse mode cavity. An odd number of free buckets between sub-bunch trains results in a switch of the direction of the kick as show in Fig. 4. The additional delay of one rf-bucket (or any odd number of rf-buckets) can be achieved by an optical delay line of the laser beam pulse at the rf-gun.

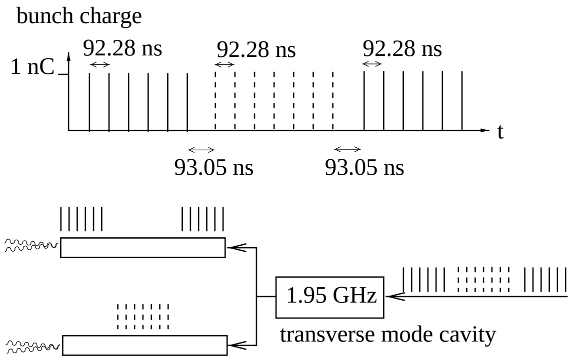

Figure 4: Principle of a fast FEL-Beam switchyard

The beam optics of the switchyard is based on a FODO cell which is shown in Fig. 5. The kick due to the transverse mode cavity is enhanced by a defocusing quadrupole [3]. A bunch offset d_0 of $5\,\mathrm{mm}$ at the end of the cavity section, $d_1 = 15\,\mathrm{mm}$ within the quadrupole and $d_2 = 40\,\mathrm{mm}$ at the septum can be achieved with the design parameters summarized in table 1 for two beam energies. In both cases a transverse gradient of 5 MV/m is necessary to provide a kick of 1.5 (1.0) mrad. The details of the cavity design are discussed in the next section.

A cascaded switchyard scheme with a 1.5×1.3 GHz and additional 1.75×1.3 GHz transverse mode cavities would allow the distribution of the bunches of a 1 ms long pulse to four FEL beam lines. The details are not discussed in this paper.

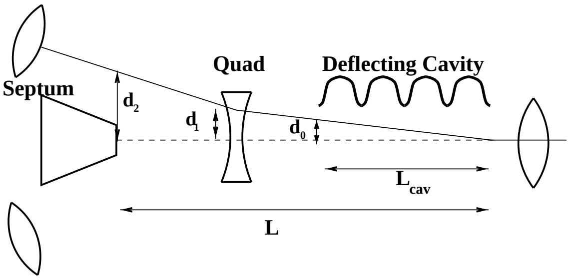

Figure 5: Fast FEL-Beam Splitter. The kick due to the defecting mode is enhanced by a defocusing quadrupole magnet.

beam energy	25 GeV	50 GeV
total kick	1.5 mrad	1.0 mrad
active cavity length L_{cav}	7.5 m	10 m
transverse gradient G_T	5 MV/m	5 MV/m
total length (see Fig. 5) L	17 m	25 m
quadrupole strength k_{quad}	$0.2\,\mathrm{m}^{-2}$	$0.13\,\mathrm{m}^{-2}$
min. beta function $\check{\beta}$	20 m	28 m
max. beta function $\hat{\beta}$	61 m	86 m

Table 1: Design parameters of the beam optics for the fast switchyard.

3 DESIGN OF THE TRANSVERSE MODE CAVITY

The basic design parameters of a transverse mode cavity are the transverse gradient G_T, the peak magnetic field on the surface B_{peak}, $(R/Q)'$ and G_1. The gradient G_T is simply the average of the transverse component of the Lorentz force $G_T = 1/L_{cav} \int dz \left[\vec{E_\perp}(z, t = z/c) + c\,\vec{e_z} \times \vec{B}(z, t = z/c) \right]$ acting on the beam; for a dipole mode G_T does not depend on the radial position of the beam in the cavity. Superconductivity breaks down when the rf magnetic field exceeds the critical field of $0.2 \ldots 0.24$ T for Niobium. Therefore the transverse gradient G_T is limited by the peak magnetic surface field. A superconducting transverse mode S-band cavity has been operated for an RF particle separator with a transverse gradient of 1.2 to 1.4 MV/m [4]. Present design studies of transverse mode cavities at Fermilab [5] are aiming at gradients of 5.0 MV/m. An accelerating gradient of 25 MV/m in the 1.3 GHz TESLA cavities corresponds to a peak magnetic surface field of 0.105 T. A similar peak magnetic field of about 0.11 T corresponds to a transverse gradient of 5 MV/m for the π-dipole-mode cavity shown in Fig. 6, which represents one possible shape of a transverse mode cavity with a relatively large iris diameter of 76 mm. The results are

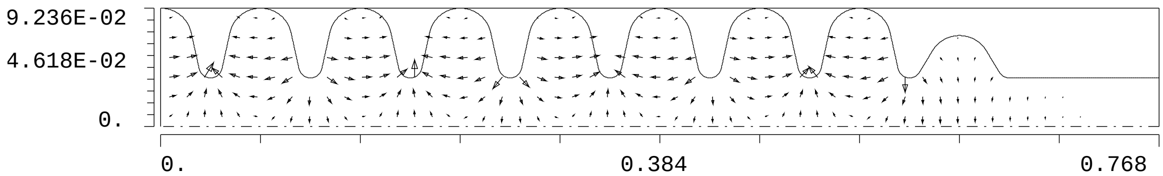

Figure 6: Right half of the transverse mode cavity. The electric field of the 1.95 GHz π-dipole-mode is shown (MAFIA calculation [6]). 15 cells contribute to the deflection, while the end-cells match the field to that in the beam pipe.

obtained with the MAFIA [6] code. A large iris diameter is advantageous with respect to wakefield effects but requires a special matching cell at the end of the cavity to achieve good field flatness of the dipole mode.

Frequency f	1.95	GHz
$(R/Q)'$	274	Ohm
G_1	224	Ohm
Number of active cells	15	
Active length L_{cav}	1.15	m
Transverse gradient G_T	5	MV/m
Peak magnetic field B_p	0.11	T
Q-value Q_0	$3.8 \cdot 10^9$	
RF heat load (5 Hz, 2 K)	0.12	W
External Q-value Q_{ext}	$3 \cdot 10^6$	
Filling time T_F	490	μs
RF-peak-power P_{rf}	20	kW

Table 2: Basic design parameters of the transverse mode cavity.

Further important parameters are $(R/Q)'$ and G_1, which are defined according to the equations:

$$(R/Q)' = \frac{1}{4\,\pi f}\,\frac{|G_T\,L_{cav}|^2}{U}, \quad Q_0 = \frac{G_1}{R_{BCS}(f,T)}, \quad (1)$$

where U is the stored energy of the cavity mode and $R_{BCS}(f,T)$ the BCS-resistivity of Niobium. The parameter $(R/Q)'$ is essentially the ratio of the square of the transverse gradient to the energy which is stored in the cavity mode. G_1 is a purely geometrical parameter which relates the surface resistivity to the Q-value of the cavity. The BCS resistivity for the 1.95 GHz cavity at 2 K has been scaled from the 1.3 GHz TESLA accelerating cavity according to

$$R_{BCS}(f,T) \sim (f^2\,/T)\,\exp(-1.76\,T_c/T), \qquad (2)$$

and using a Q-value of $1 \cdot 10^{10}$ for the TESLA cavity. The dissipated power at 2 K during one pulse for one transverse mode cavity with an active length of 1.15 m is 16 W according to

$$P = \left(5\frac{\text{MV}}{\text{m}}\right)^2 \frac{1}{2\,(R/Q)'\;Q}\;, \qquad (3)$$

with $Q_0 = 3.8 \cdot 10^9$, resulting in a average rf heat load of 0.12 W for a 5 Hz operation. The same formula can be used to calculate the required rf-peak-power by using the external Q, Q_{ext}, which is determined by the coupling. An external Q of $3 \cdot 10^6$ has been chosen, for which one obtains a filling time of 490 μs ($T_F = Q_{ext}/(\pi\,f)$) which is similar to the filling time of the 1.3 GHz TESLA accelerating cavity.

The switchyard for a 25 GeV (50 GeV) beam would require seven (ten) transverse mode cavities with the parameters considered in table 2. The total rf-peak-power for 17 cavities is 340 kW and the total rf heat load is 2 W at 2 K for a 5 Hz operation.

4 CONCLUSION

It is feasible to distribute single bunches or sub-bunch trains out of a 1 ms long bunch train to two beam lines using a fast switchyard based on a transverse mode cavity operated at 1.95 GHz. The conceptual design of the beam optics and the dipole mode cavity have been presented. An engineering design of the system would require further studies for the following subsystems: delay line of the laser pulse at the rf-gun, integration of a dispersion suppression and a collimation section into the beam optics, and design of fundamental mode dampers at the transverse mode cavity. Depending on the required bunch pattern it is possible to double the beam time for scientific applications (e.g. pump and probe experiments) with a fast switchyard.

Acknowledgments

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