

# On the Free Electron Laser Mode of Operation in TESLA

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## 1. Introduction

With its high AC-to-beam power transfer efficiency, small wakefields and the potential for a relatively high operating duty cycle, TESLA is ideally suited to deliver low 3-D emittance beams to drive self-stimulated Free Electron Lasers in the Å-wavelength regime. The purpose of this note is to communicate some basic ideas concerning the way in which the TESLA linac could be operated for this option. The following boundary conditions are assumed here:

- The FEL facility is operated in parallel with the e+e- collider.
- The overall AC-to-beam power transfer efficiency should be optimized.
- Strong modifications of linac beam optics and the rf-system as designed for the Linear Collider are to be avoided.

The first condition can be met by either increasing the linac repetition frequency and switching beams between e+e- and FEL operation from pulse to pulse or lengthening the rf-pulses and switching beams within the pulse. Pulse-to-pulse switching has the advantage that the rf-modulators do not have to be modified concerning the amount of stored energy. Furthermore, slow switching of beam extraction for the FEL from pulse to pulse is easier than switching within the bunchtrain. Since the advantage of the second method, namely saving the additional cavity filling time, is rather insignificant (see below), we focus here on the pulse-to-pulse mode.

The second condition implies to lower the accelerating gradient  $g_{FEL}$  for FEL operation (the beam energy required for the FEL-facility is much lower than the e+e-collider beam energy), since then the additional cryogenic load from wall losses in the s.c. cavities can be reduced. This mode of operation is discussed in detail in section 2, with the result that a large reduction factor for  $g_{FEL}$  does not seem to be advantageous. Some conclusions are drawn in section 3.

## 2. Machine Parameters and Operation at Lower Gradient

The basic machine parameters for the  $E_{cm}=500$  GeV collider relevant here are summarized in table 1. In the following we will discuss how the parameters scale if part of the machine is used to generate a beam of energy  $E_{FEL}$  for the Free Electron Laser facility. First, the fraction of machine length required is given by ( $g_0=25$  MV/m is the design gradient for e+e- operation):

$$\frac{L_{FEL}}{L_{tot}} = \frac{E_{FEL}}{500 GeV} \times \frac{g_0}{g_{FEL}} \quad (1)$$

Making full use of the available rf-pulse power<sup>1</sup> allows to scale the beam pulse current according to

$$I_{FEL} = \frac{g_0}{g_{FEL}} \times I_{e+e-} \quad (2)$$

Whereas from eq. (2) a low gradient is clearly advantageous for maximum beam power in the FEL-mode, there arises a problem concerning rf-matching. Switching the rf-coupling between pulses is, although possible in principle, an undesirable complication and we assume here that the external load  $Q_L$  must be constant. Since  $Q_L \propto 1/g$ , perfect rf-matching requires to *lower* the pulse current proportional to  $g$ , in conflict with eq. (2). It is possible to choose as a compromise for  $Q_L$  the geometric mean of the optimum values for both operation modes, i.e.  $Q_L = 3 \times 10^6 g_{FEL}/g_0$ . In this case some rf-power is reflected and the generator pulse power has to be increased by a factor

centre of mass energy $E_{cm}/\text{GeV}$	500
accelerating gradient $g_0/(\text{MV/m})$	25
bunch spacing $\Delta t_B/\text{ns}$	707
linac rep. rate $f_{rep}/\text{Hz}$	5
beam pulse length/ms	0.8
rf-pulse length/ms	1.3
bunch charge/ $10^{10}$	3.63
# of bunches	1130
pulse current/mA	8.1
average current/mA	0.032
bunch length $\sigma_z/\text{mm}$	0.7
unloaded qual. factor $Q_0$	$5 \times 10^9$
loaded qual. factor $Q_L$	$3 \times 10^6$
average beam power $P_b/\text{MW}$	16.3
AC power rf-system $P_{rf}/\text{MW}$ (no regulation reserve)	49
AC power cryogenics (static) $P_{c,s}/\text{MW}$	20
AC power cryogenics (rf-losses) $P_{c,rf-loss}/\text{MW}$	13.6
AC power cryogenics (rf-coupler) $P_{c,rf-cplr}/\text{MW}$	1.8
AC power cryogenics (HOM-losses) $P_{c,HOM}/\text{MW}$	3.9
overall efficiency $\eta_{AC-to-beam}/\%$ (no rf-reserve)	18.8

**Table 1:** Design parameters for the 500 GeV TESLA Linear Collider which are relevant in context with the integration of FEL's.

$$\Pi_{rf} = \frac{P_{rf,pulse}}{P_{beam,pulse}} = \frac{(g_0 + g_{FEL})^2}{4g_0 g_{FEL}} \quad (3)$$

for *both* the  $e+e-$  and FEL modes of operation. In addition to eq. (3), calculation of the total additional AC-power for rf-generation required to integrate the FEL-mode must take into account the change in cavity filling time due to the different  $Q_L$ . The reduced

<sup>1</sup> operation with reduced rf-power for the FEL beam pulses would result in smaller klystron efficiency

filling time at lower  $Q_L$  balances the disadvantage of reflected power in the e+e- mode to a certain extend. In summary, we find:

$$\Delta P_{AC,rf} = 49MW \frac{L_{FEL}}{L_{tot}} \times \left[ \frac{\tau_{fill}(g_0, Q_L^{FEL})}{0.52ms} (\Pi_{rf} - 1) + \Pi_{rf} \right] \quad (4)$$

Here, the first term in the bracket accounts for the change of rf-AC-power for e+e- operation and the second term for the power required for the FEL-mode (the repetition rate is assumed to be equal for both modes, which means that this part of the linac is operated at 10Hz). The average FEL-beam power is given by:

$$P_{beam}^{FEL} = 16.3MW \times \frac{L_{FEL}}{L_{tot}} \frac{1.32ms - \tau_{fill}(g_{FEL}, Q_L^{FEL})}{0.8ms} \quad (5)$$

Since the filling time becomes rather short at reduced gradient (see fig. 1), the FEL beam pulse can use a larger fraction  $t_{pulse}$  of the 1.32ms long rf-pulse, which is beneficial for the overall efficiency.

Next we consider the scaling of the cryogenic load as a function of  $g_{FEL}$ . The individual contributions are calculated using data from ref. [1]. From wall losses we get approximately (neglecting differences in the small contributions during the cavity filling and decay times):

$$P_{c,rf-loss} = 13.6MW \times \frac{L_{FEL}}{L_{tot}} \frac{Q_0(g_0)}{Q_0(g_{FEL})} \frac{g_{FEL}^2}{g_0^2} \quad (6)$$

The conservative assumption made here for the dependence of the unloaded  $Q$  on gradient is that  $Q_0$  goes up linearly from  $5 \times 10^9$  to  $10^{10}$  for  $g=25 \dots 15$  MV/m and remains constant at  $10^{10}$  for  $g < 15$  MV/m. The load from the rf-coupler is the same as for e+e- operation, and therefore the contribution to the cryogenics AC-power from this source scales simply with  $L_{FEL}/L_{tot}$ .

The contribution from HOM-losses is a more difficult subject because of the very small bunchlength for FEL operation ( $\sigma_z(FEL) = 0.025$ mm). We assume here that the loss-factor scales with the bunch length like  $k_{long} \propto \sigma_z^{-1/2}$ . This is in accord with the asymptotic scaling rule for very short bunches derived from a diffraction model (see e.g. [2]) for a *single cavity*. In case of an infinitely long periodic array of cavities, the diffraction model yields a

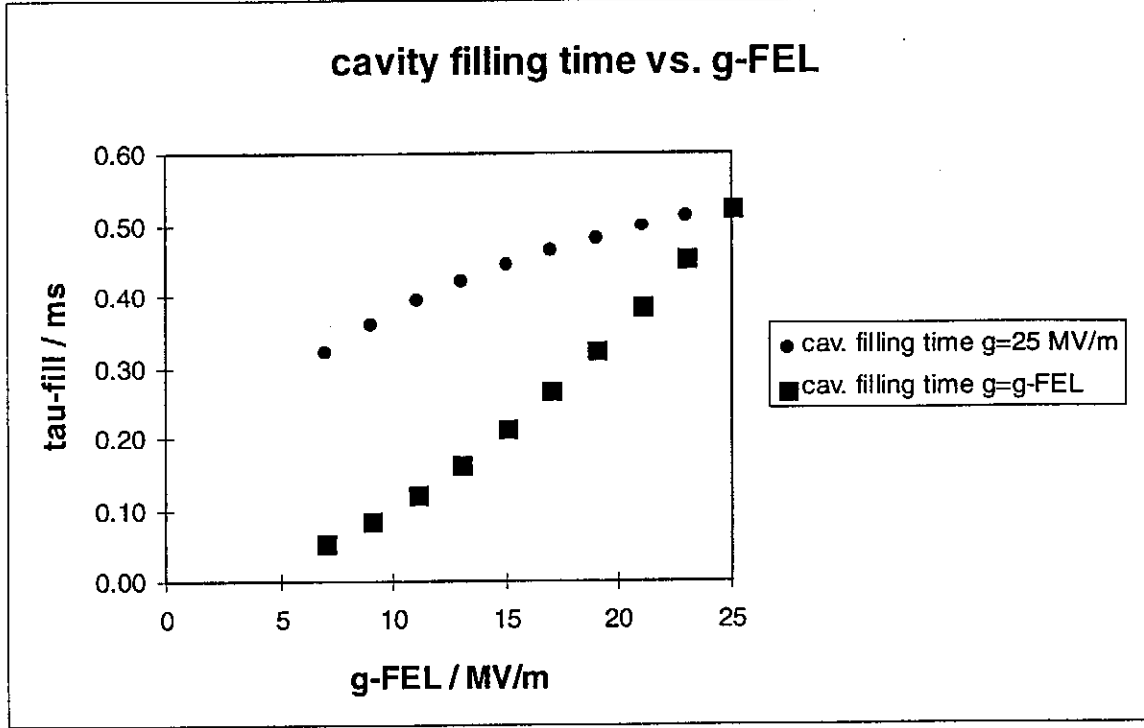


Fig. 1: Cavity filling time vs. accelerating gradient in the FEL-mode. The loaded quality factor varies according to  $Q_L = 3 \times 10^6 \times g_{FEL}/g_0$  (see text).

loss factor independent of bunch length in the limit  $\sigma_z \rightarrow 0$  [3,4]. However, the condition for the transition to the “periodic” case is not yet fulfilled for a 9-cell TESLA cavity, so that the scaling  $\propto \sigma_z^{-1/2}$  seems more appropriate. Then the total HOM-power for FEL-operation scales like:

$$P_{HOM}(FEL) = P_{HOM}(e^+e^-) \times \frac{L_{FEL}}{L_{tot}} \frac{I_{FEL}}{I_{e^+e^-}} \frac{N_{FEL}}{N_{e^+e^-}} \frac{t_{pulse}}{0.8ms} \left( \frac{0.7mm}{0.025mm} \right)^{1/2} \quad (7)$$

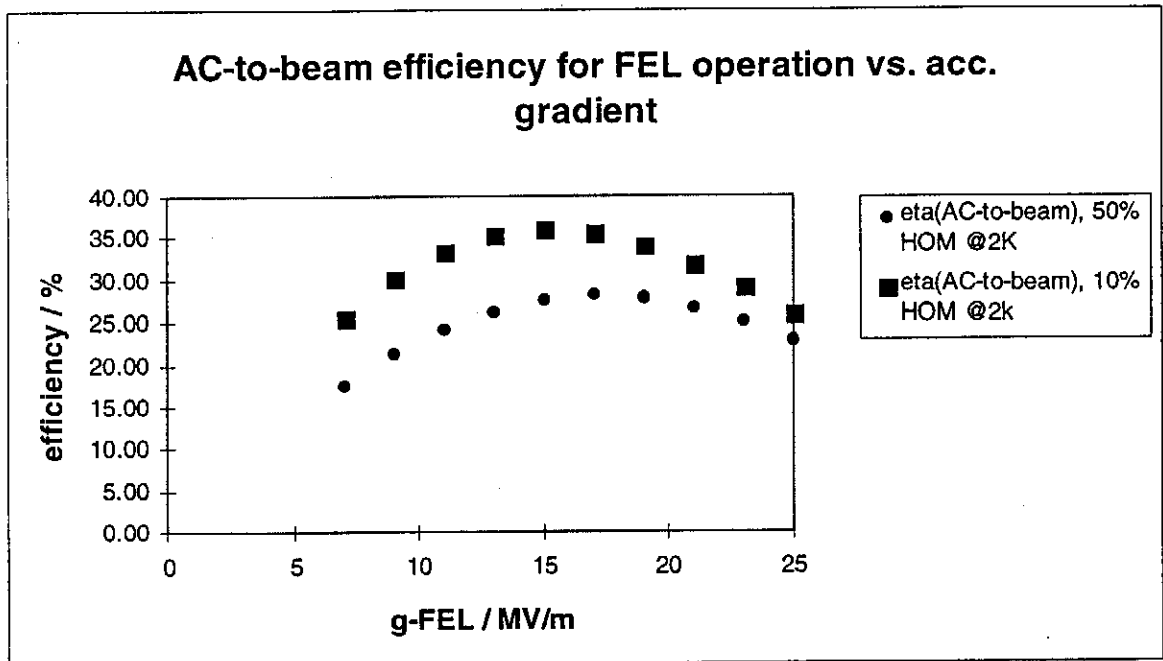
where we use  $N_{FEL} = 7 \times 10^9$  in the following (1 nC bunch charge).

The bunch spectrum extends up to frequencies  $\omega_{max} \approx c/\sigma_z = 12$  THz, well above the gap frequency of s.c. Nb,  $\omega_{gap} \approx 2\pi \times 0.7$  THz. For microwave radiation at frequencies above  $\omega_{gap}$  the superconductor behaves *as if it was in the normalconducting state* (break-up of cooper pairs) [5,6], and one must take into account that a considerable fraction of the HOM-losses can occur at the 2K-level and does not go into the propagating-mode 70k-absorber installed between the cryomodules. An estimate of the fraction of HOM losses above  $\omega_{gap}$  is given by

$$\frac{P_{HOM}(\omega > \omega_{gap})}{P_{HOM}(total)} = \frac{\int_{\omega_{gap}}^{\infty} d\omega e^{-(\omega/\omega_{max})^2} / \sqrt{\omega}}{\int_0^{\infty} d\omega e^{-(\omega/\omega_{max})^2} / \sqrt{\omega}} \quad (8)$$

where the  $\omega^{-1/2}$  - dependence for the resistive part of the impedance from the diffraction model was used. In our case this amounts to 39% of the HOM-losses. In addition, also below  $\omega_{\text{gap}}$  the increase of the surface resistance of the s.c. Nb with frequency ( $R_s \propto \omega^2 \dots \omega^{3/2}$ ) will lead to enhanced HOM-losses in the cavity walls. It is therefore unlikely that the estimate of only 10% HOM-losses at the 2K-level for normal TESLA operation is also appropriate for the FEL mode. In this case the required AC-power for cryogenics does not simply scale as eq. (7), because the fraction of HOM-power absorbed at 2K is multiplied by 800 to obtain the AC-power, whereas this factor is only 30 at the 70K-level.

Using the scaling laws for the FEL beam power and the contributions to the additional AC-power required for this operation mode as derived above, the efficiency of FEL operation as a function of gradient can be calculated. The result is shown in fig. 2, where we assumed either 10% HOM-losses at 2K or, probably more realistically, 50%. Depending on this assumption, the optimum gradient is 15 MV/m or 17 MV/m, respectively. For the case of 50% HOM-losses at 2K, fig. 3 shows the required fractional increase of rf-pulse power and cryogenics AC-power for the FEL-section of the linac.



**Fig. 2:** Overall efficiency  $\eta_{\text{AC-to-beam}}$  for the FEL operation mode for the two cases of either 10% (squares) or 50 % (dots) HOM losses at 2K.

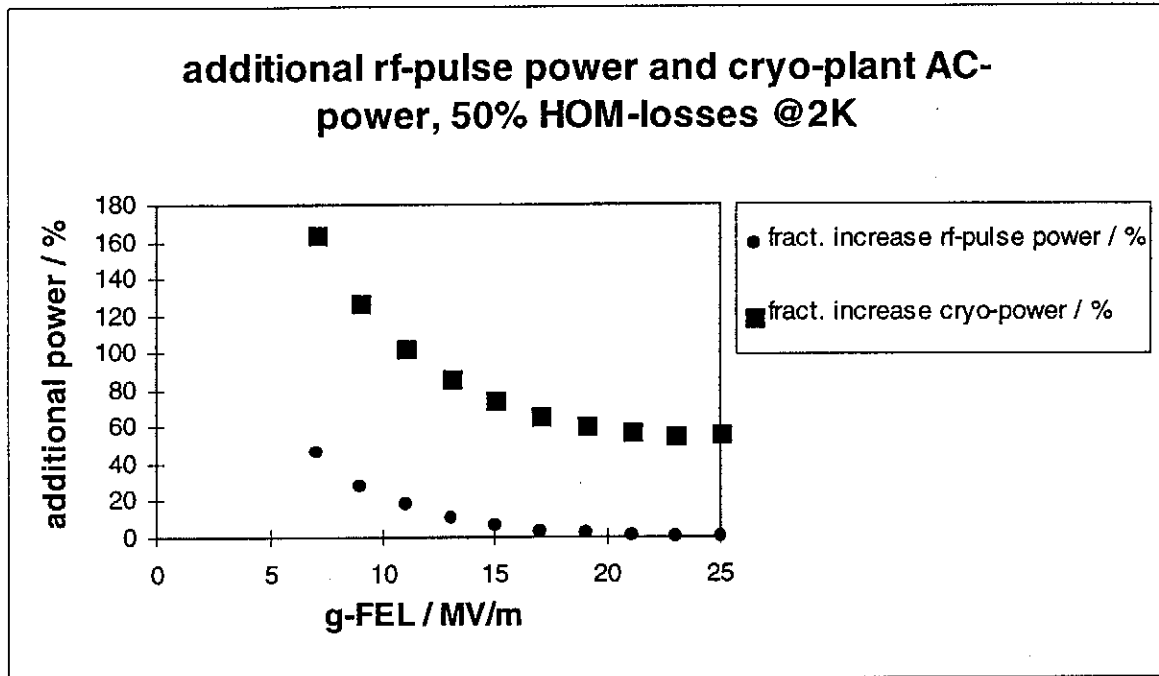


Fig. 3: Fractional increase of the required rf-pulse power (dots) and cryogenic plant AC-power in the “FEL-section” of the TESLA linac vs.  $g_{\text{FEL}}$ .

Whereas the additional rf-pulse power (to make up for the mismatch of the rf-coupling) is small at  $g_{\text{FEL}} = 17 \text{ MV/m}$  and well within the available reserve<sup>2</sup>, the cryo-plant for the FEL-section must be layed out for about 66% higher load than for the rest of the TESLA linac.

In order to give a specific example for the FEL operation, we assume a beam energy of 30 GeV, which may be considered as a reasonable upper limit for driving SASE-FEL's in the Angstrom wavelength regime [7]. The parameters for this case are compiled in table 2.

### 3. Discussion and Conclusions

It has been shown that the efficiency of beam acceleration for FEL operation in TESLA can be optimised by a moderate reduction of the accelerating gradient from the nominal value of 25 MV/m to about 15...17 MV/m. The overall power transfer efficiency is close to 30% and no hardware changes for the rf-system are required. Furthermore, for such a moderate reduction of beam energy, designing the beam optics in the linac such that it is compatible with both modes of operation should not be a serious problem. The consequences concerning orbit correction and beam-based alignment schemes still need to be studied in detail, though.

<sup>2</sup> note that with smaller  $Q_L$  the regulation reserve required to compensate Lorentz-Force detuning will go down. This effect, which has been neglected here, leads to a slight reduction of the rf-power requirement.

beam energy $E_{\text{FEL}}/\text{GeV}$	30
active linac length of FEL section /km	1.8
accelerating gradient $g_{\text{FEL}}/(\text{MV/m})$	17
bunch spacing $\Delta t_{\text{B}}/\text{ns}$	93
linac rep. rate $f_{\text{rep}}/\text{Hz}$	5
beam pulse length/ms	1.05
rf-pulse length/ms	1.32
bunch charge/ $10^{10}$	0.7
# of bunches	11315
pulse current/mA	11.9
average current/mA	0.059
bunch length $\sigma_z/\text{mm}$	0.025
unloaded qual. factor $Q_0$	$10^{10}$
loaded qual. factor $Q_L$	$2.1 \times 10^6$
average beam power $P_b/\text{MW}$	1.88
AC power rf-system $P_{\text{rf}}/\text{MW}$ (no regulation reserve)	4.44
AC power cryogenics (rf-losses) $P_{\text{c,rf-loss}}/\text{MW}$	0.19
AC power cryogenics (rf-coupler) $P_{\text{c,rf-cplr}}/\text{MW}$	0.07
AC power cryogenics (HOM-losses) $P_{\text{c,HOM}}/\text{MW}$	1.90
overall efficiency $\eta_{\text{AC-to-beam}}/\%$ (no rf-reserve)	28.05

**Table 2:** Parameters for FEL operation in TESLA assuming a beam energy of 30 GeV and 50% HOM losses at the 2K level.

The additional cryogenic load due to HOM-losses can become significant for the ultra-short bunches foreseen for the FEL. It would be strongly desirable to obtain more precise predictions of the HOM-losses than the crude estimate used in section 2. In addition, in order to reduce HOM-losses one could think of accelerating longer bunches and doing the last part of the bunch compression at the high-energy end. Good knowledge of the longitudinal wakefield and a more detailed layout of the beam extraction line (e.g. concerning the achievable momentum compaction factor) are required for further studies in this direction.

#### 4. Acknowledgements

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## References

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