BEAM OPTICS STUDIES FOR THE TESLA TEST FACILITY LINAC

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Abstract

The aim of the TESLA Test Facility Phase 2 (TTF2) Linac is to create electron bunches of small transverse emittance and high current with energies up to 1 GeV for the VUV-FEL at DESY. A study of the (linear) beam optics of the linac is presented for the case of beam commissioning for FEL. The requirements of each part of the linac upon the optics are discussed in detail and an appropriate solution for each case is shown, as well as the matching solution to the rest of the accelerator. The chromatic properties of the linac have been studied also.

ACCELERATOR OVERVIEW

Details on components and parts of the TTF2 linac are documented in many technical reports and publications (see, for example, [1, 2, 3, 4] and references therein). The machine layout for the start of operations is shown in Fig. 1.

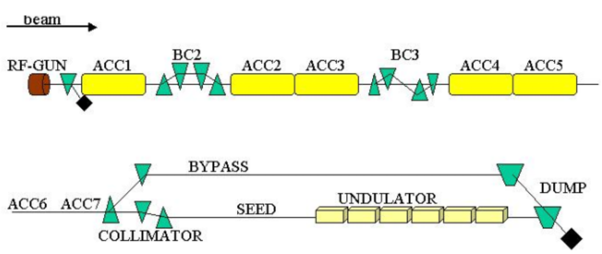

Figure 1: Schematic of TESLA Test Facility Linac.

Electron bunches are produced in an RF gun and accelerated by five cryomodules (ACC1 - ACC5) each containing eight nine-cell superconducting niobium cavities and a doublet of superconducting quadrupoles. To achieve high peak current in the undulator, the bunch is longitudinally compressed in two magnetic chicanes. Downstream the first bunch compressor BC2 (a four bend chicane) there is a diagnostic section arranged in a FODO lattice for the measurement of beam parameters. A second compression stage takes place after the passage through ACC2 and ACC3 and is performed using a S-type chicane (BC3). The last accelerating section, presently containing only two cryomodules (ACC4 and ACC5), accelerates the beam to the chosen final energy. Longitudinal beam profile diagnostics are located in the temporary beam line reserved for two more cryomodules (ACC6 and ACC7). Then, the electron beam is either guided to a bypass beam line (BYPASS) or brought through a collimator section (COLLIMATOR) to the FEL undulator. The collimator section has a dogleg shape and contains transverse and energy collimators for undulator protection purposes. Besides that, the collimator section incorporates a fast orbit feedback system and has to ensure the matching into the downstream beam line. Before the bunch enters the undulator, it passes an FEL seeding section (SEED), which at present is substituted by a temporary beam line with FODO type of focusing. Finally, the electron beams from the undulator and bypass are dumped in the same absorber (DUMP).

OPTICS SEARCH STRATEGY

The transverse optics discussed in this paper starts from the quadrupole doublet of the ACC1 cryomodule and uses as initial values (which eventually have to be corrected after measurement of actual beam parameters) the same Twiss functions which are used in [5]. We consider neither the beam dynamics in the gun area nor the choice of bunch compression schemes. A detailed description of these questions can be found, for example, in [1, 2].

Lattice Constraints

There are several requirements on the local behaviour of the optical functions, which we consider as constraints to the optics design.

- The TTF2 undulator section is a periodic structure consisting of six identical cells. Each cell is built up of an undulator segment (made of permanent magnets) followed by a doublet of electromagnetic quadrupoles to accomplish strong focusing [3, 6]. The quadrupole strength has to be optimized to provide good FEL performance.
- A special choice of Twiss parameters at the entrances of bunch compressors BC2 and BC3 reduces emittance growth due to coherent synchrotron radiation (CSR). That results in an asymmetric behaviour of betatron functions through bunch compression sections with a maximum at the entrance and a minimum between last two dipoles [7, 8, 9].
- The selection of optical functions in the dogleg of the collimator section are completely determined by the need to suppress the linear and second order dispersions and to shape a beam envelop suitable for collimation purposes [10].
- Beam emittance measurements in sections BC2 and SEED are obtained from the beam sizes measured at four separated locations inside a FODO structure. This emittance measurement technique provides its best accuracy for periodic Twiss functions and a 45° phase advance per cell [11].
- Beam spot size at the exit window location should be not smaller than the safety limit defined by the window (and dump) material properties and design. Al-

though dispersion helps to enlarge the beam spot area, it is better to keep it about zero to ensure independence of beam position at the dump on beam energy variation [12].

Energy Dependence

Transverse optics of the TTF2 linac can not be designed in such a way that it will stay invariable after linear scaling of magnet settings with change of the beam energy. One has to take into account focusing properties of RF cavities and undulator permanent magnets.

RF Radial Focusing. To obtain a better understanding of the RF focusing effects in the TTF2 linac we did not rely on any approximate analytical formulas because they have a certain (limited) range of applicability. The transport matrices corresponding to the passage through an RF cavity were obtained using the FMN2 code [13], which is capable to accurately calculate them using the knowledge of on-axis accelerating field profile and beam injection phase and energy. Another option of this code, which was used, is that these matrices can be printed in the format directly insertable into input file of the MAD program [14].

Natural Undulator Focusing. The electrons, when moving in the planar magnetic field of an undulator segment, undergo horizontal oscillations and experience vertical (natural) focusing. Effect of this additional focusing was analyzed with the help of the FMN2 program using measured field data not only for undulator segments, but also for undulator quadrupoles [15]. An example of this analysis is shown in Fig. 2.

Note that the focusing effect of extended fringing fields of dipole magnets, which is somewhat similar to the natural undulator focusing, was also taken into account during optics design.

Operational Regimes

Several possible scenarios of the linac operation during commissioning are foreseen to help to establish the primary goal, the SASE FEL operation. One can guide the beam either through the undulator or through the bypass. For both regimes the operations with bunch compressors on or off (one or both of them) are proposed, which may require the re-matching of the optics to compensate the differences in the path length and in the focusing properties (focusing of dipoles). The number of operational regimes is further doubled by the proposal to use the dipole magnets, which bend the beam down into the dump, as a spectrometer. Besides that, the bypass accommodates a material test facility, however the special requirements for its operation are not discussed in this paper.

Special Feature of Bypass Operation. For space reasons the bypass beam line starts with a section which is tilted with respect to the principal linac planes. The first part of this section is a dogleg with suppressed first and second order dispersions. Three additional tilted quadrupoles, placed downstream, make the total transport matrix of this section rotationally invariant that avoids the generation of the phase space coupling at the exit of this section [16]. In order not to destroy dispersion and coupling compensation, we assume that the setting of magnets of the tilted section (once established) will be frozen for all operational regimes.

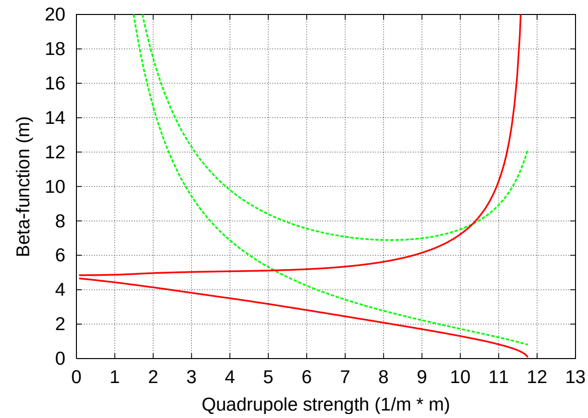

Figure 2: Minimal and maximal values of horizontal (green) and vertical (red) periodic $\beta-$functions achivable within the TTF2 undulator cell as a function of the quadrupole strength k (with doublet setting $k_1 = -k_2 = k$). The natural undulator focusing for a beam energy of 445 MeV is included here.

Usage of Dump Dipoles as Spectrometer. To get a good energy resolution, a small beam size at the OTR screen located downstream of spectrometer dipole is required [12]. Besides the necessity to have a special optical solution for these measurements, the beam intensity should be reduced in order not to damage the exit window and the OTR screen itself.

Optics Design Procedure

At the first step we concentrated on the design of the beam optics which could be used for the SASE FEL operation. After satisfying chosen requirements on the local behaviour of the optical functions, the remaining freedom was used for the matching between different linac parts and for improvement of the chromatic lattice properties. Considering the other operational regimes, we tried to satisfy their particular requirements with a minimum number of changes in order to keep the same optics in the other sections.

COMMISSIONING OPTICS

The commissioning of the TTF2 linac starts with the beam energy corresponding to a photon wavelength of 30 nm, which is 445 MeV. All necessary details about the proposed acceleration regime, which defines the focusing properties of an RF cavities, and beam compression strategy can be found in [17]. We only note, that, according to [17], the ACC5 module is not used in calculations presented in this paper and the ACC4 module operates at relatively low accelerating gradient of about 7.8 MeV/m (accelerating on-crest).

Fig. 3 and 4 presents two beam optics solutions (shown from the entrance of the ACC1 quadrupole doublet up to the dump dipole) [18], which can be used for the start of the commissioning of the SASE FEL operation. As a working point for the undulator quadrupoles we use the values $k_1 = 10.92\ \mathrm{m}^{-1}$ and $k_2 = -10.57\ \mathrm{m}^{-1}$. These settings, under the assumption that the beam is uncoupled and perfectly matched to the undulator entrance, minimize the beam spot size averaged over the length of an undulator segment.

Note that this optics is set to the transport of beam envelop parameters. The influence of transverse space charge effects on the propagation of the high peak current part of the bunch and the necessary changes in optics will be described in separate paper.

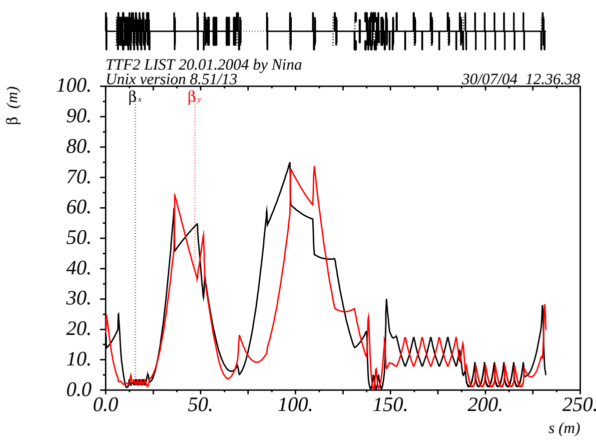

Figure 3: Commissioning 445-MeV optics of the TTF2 linac which satisfies all lattice constraints considered.

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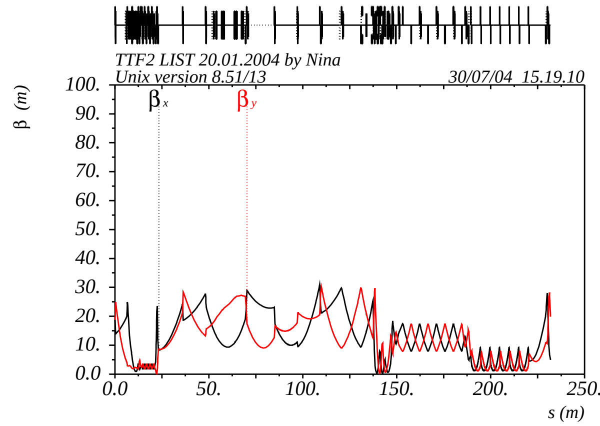

Figure 4: Commissioning 445-MeV optics of the TTF2 linac which makes the maximal beta functions smaller in comparison with the optics presented in Fig. 3, but does not provide the special behaviour of beta functions in the bunch compressor BC3 and moderately changes the beta functions through the collimator section.

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