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Emergency Extraction High-Energy Beam Line for TESLA

O. Napoly, J. Payet (CEA/Saclay)
N. J. Walker (DESY/Hamburg)

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ABSTRACT

In order to actively protect the energy collimator from an accidental beam loss, a fast extraction beam line must be included in the TESLA beam delivery systems. It should also allow a steady beam extraction for linac and positron source commissioning while the beam delivery systems and/or the interaction region are not ready to accept beams. A design for such an emergency extraction beam line is presented here. The main challenge is to provide the sufficient aperture to accept the large bunch energy errors which will trigger the extraction kickers, and the large angular errors inherent to the fast kicker design.

1 Introduction

Embedded in the TESLA beam delivery systems (BDS), the high-energy extraction has two functions:

1) located upstream of the collimation section, it provides an active protection of the energy collimator against accidental beam losses due to fast and large energy errors;
2) located downstream of the linac and positron source and leading to the main beam dump, it allows to commission the linacs and the positron source with full beam current in the case where the BDS or the detector hall are not ready to accept beams.

This defines two distinct modes of operation for this beam line:

1) in the first case, an *emergency extraction* is activated by an array of fast kickers which are fired when an energy error larger than 2% is measured at an upstream high dispersion point;
2) in the *commissioning mode* of operation, the initial kick angle is provided by two weak DC dipoles inserted in the fast kicker area, the kickers being of course off.

A sketch of the actual implementation of the kickers in the MES (Magnetic Energy Spoiler section) and of the extracted trajectory is shown in Fig.1. The fast kickers have been designed [1] with characteristics given in Table 1. A kick angle of 200 µrad is provided by 30 individual one meter long kicker magnets. Additional kicks are given by two defocusing quadrupoles belonging to the BDS and by a 10 meter long septum magnet.

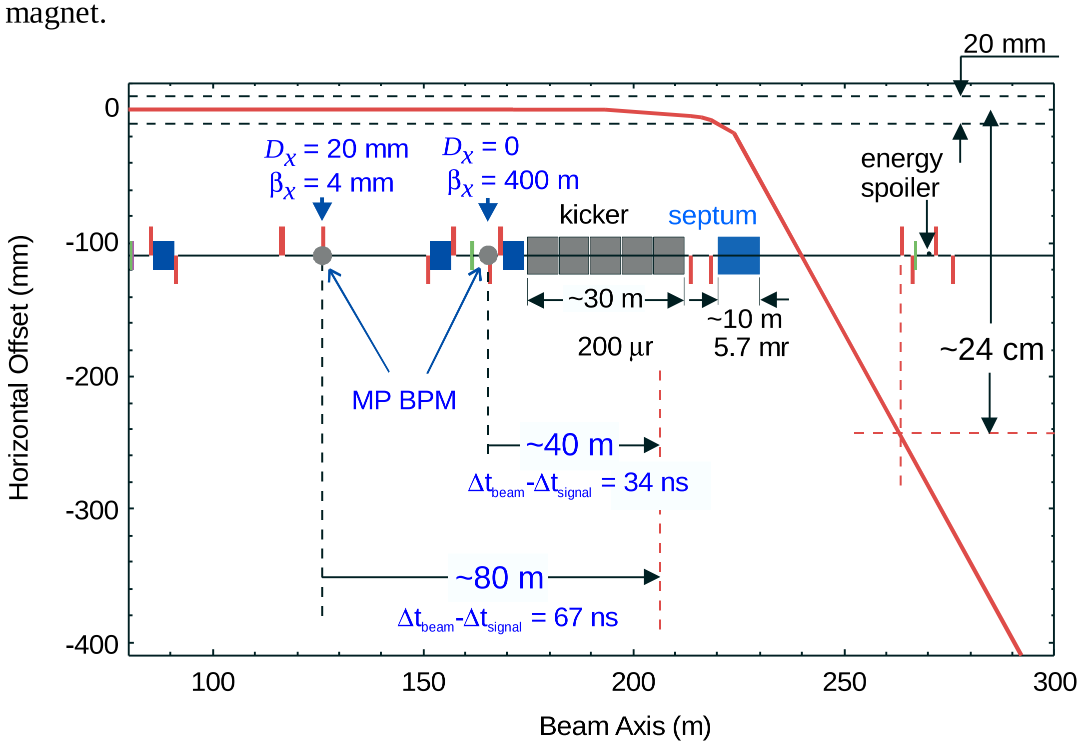

Fig.1: Principle layout of the fast extraction (machine protection) system.

Beam conditions

Beam energy

At the entrance of the BDS, the beams can accidentally have different energies. The energy collimation section is designed to accept beams within ±1.5% energy offset. Beyond these limits, the fast extraction kickers will be fired in order to protect the energy collimator. However, assuming that RF phase errors in the linac are the main source of energy errors[1], and since the linac RF modules are operated nearly on crest, it is obvious that positive energy errors are bounded while negative ones are not. This is shown in Fig.2 which plots the beam energy error and energy spread as a function of the RF phase error around the nominal RF phase (the one which minimises the energy spread). We assume that –5% energy error is the lowest realistic energy offset, corresponding to a –12° or +30° RF phase error and to at least 125 MW missing RF peak power along the linac.

We therefore consider that the beam energy at the entrance of the extraction line ranges from –5% to –1.5% of the nominal energy in the emergency extraction mode, and from –5% to +0.5% in the commissioning mode.

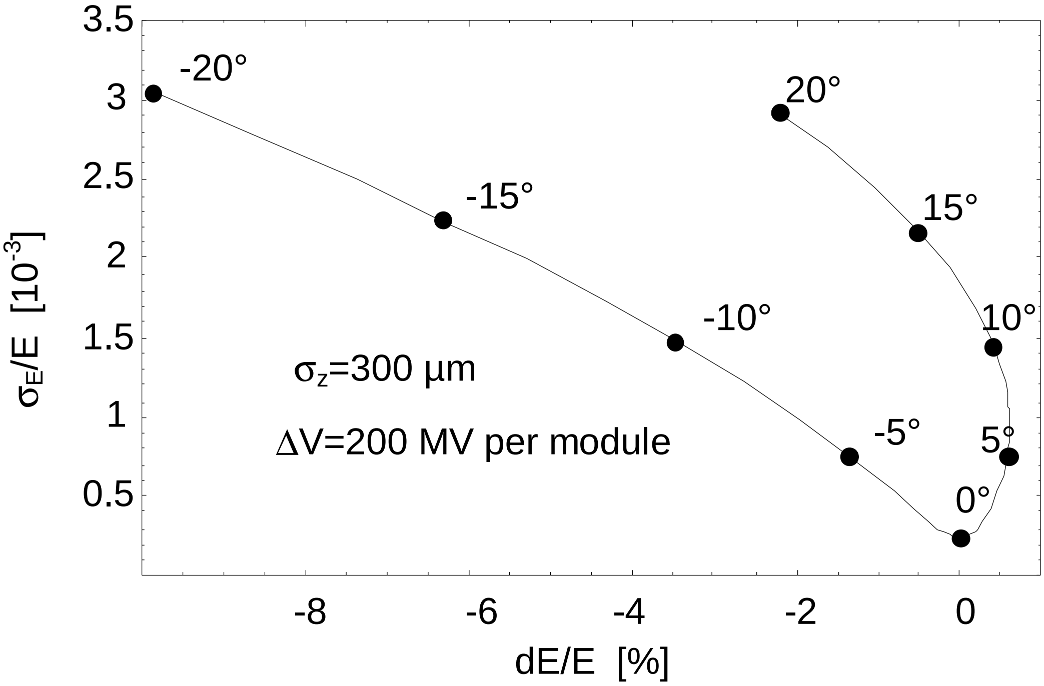

Fig.2 : Effect of LINAC injection phase error.

Kick Angle

At the kicker section exit, the beam can also be affected by horizontal angle error originating from kicker strength errors. The estimated errors, given by Table 1 [1], are ±2 % from the HV pulse flat-top variation, and ±0.5 % from the pulse to pulse power supply stability, neglecting the field transverse in-homogeneity. We will consider the worst case where these errors add up for the 30 kickers, and therefore translate into a ±2.5 % error for the total angle.

Moreover, if one kicker fails the total kick angle is reduced by about 3.3%. From a simple lever-arm argument, one expects the failure of the fist kicker to be the most harmful for the downstream orbit error, as will be shown in the following section.

[1] One 10 MW klystron tripping off will at most induce a 1 GeV energy deviation, i.e. 0.4% of 250 GeV.

Total deflection angle	200 µrad
Number of kickers	30
Kicker length	1 m
Kicker strength at 400 GeV beam energy	0.266 Tm
Beam chamber aperture	20×20 mm^2
Rise time	0.1 µs
Pulse length	800 µs
Flat top variation	± 2 %
Power supply stability	± 0.5 %

Table 1 : Emergency kicker requirements.

Extraction Constraints

The constraints which are driving the design of the extraction beam line are as follows:

- 25 mm separation at the septum entrance between the deflected trajectory and the main BDS reference trajectory, in order to insert the septum blade;
- 240 mm separation at the first BDS magnet following the septum in order to split the beam chambers (cf. Fig.1);
- like the main extraction line [2], a downward beam angle of 15.5 mrad (to limit the atmosphere activation) and beam spot area larger than 0.4 mm^2 at the water dump (to limit the temperature rise in the dump);
- an energy acceptance of
    - [–5 %,–1.5 %] in the *emergency extraction* mode,
    - [–5 %,+0.5 %] in the *commissioning* mode,

  with respect to the nominal beam energy.
- an angular acceptance of [–2.5 %, +2.5 %] of the total horizontal angle plus one failing kicker (–100% angle error for one kicker) in the *emergency extraction* mode.

2 Optics and Apertures of the Emergency Extraction Line

Optics

The layout of the extraction beam line is described by Fig.3, along with that of the BDS, using realistic transverse magnet dimensions. To show that the magnets of both beam lines do not physically exclude each other, both ends of the extraction line are zoomed in Fig.4 and Fig.5. After the septum magnet, steering is provided by two horizontal dipoles followed by a vertical dipole which bends the trajectory 15.5 mrad downward in the direction of the beam dump centred 2 m below ground. Focusing is provided by a first quadrupole in front of the first horizontal bend, followed by a regular lattice of 10 alternated quadrupoles.

In the emergency extraction mode, the reference energy which defines the central orbit should lie within the [–5 %, –1.5 %] window of the relative energy errors which trigger the extraction kickers. The value of –2.19 % (i.e. about 391.2 GeV for the 400 GeV beam) is chosen to balance the extreme orbits equally around the dump centre, as shown by Fig.8 and as discussed in the next section. The magnet parameters corresponding to this energy are given in Table 2.

In the commissioning mode, the reference energy could be chosen to be the nominal beam energy (0 % energy error), implying tuning up the magnet fields when switching to this mode of operation, or to be the same energy as for the emergency extraction, as is assumed in this paper. Two short dipoles, described in Table 3, provide the initial beam deflection. They reproduce, although not exactly, the beam orbit and angle at the septum magnet entrance. As will be seen later, the central orbit is therefore not strictly identical to the one in the emergency extraction mode.

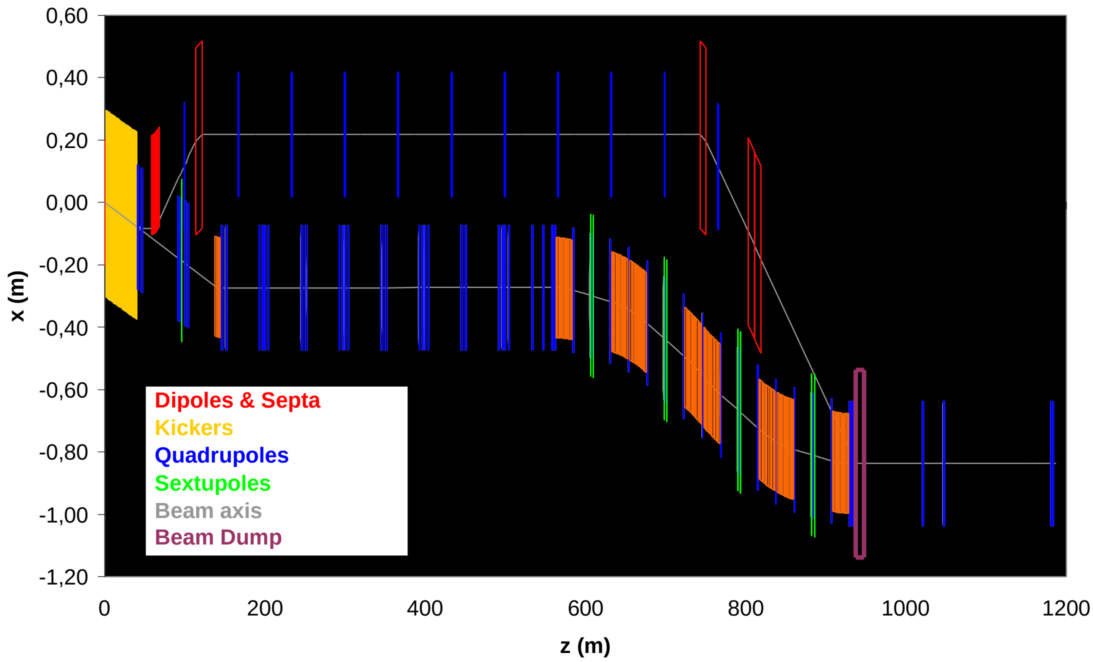

Fig.3 : Layout of the emergency extraction line

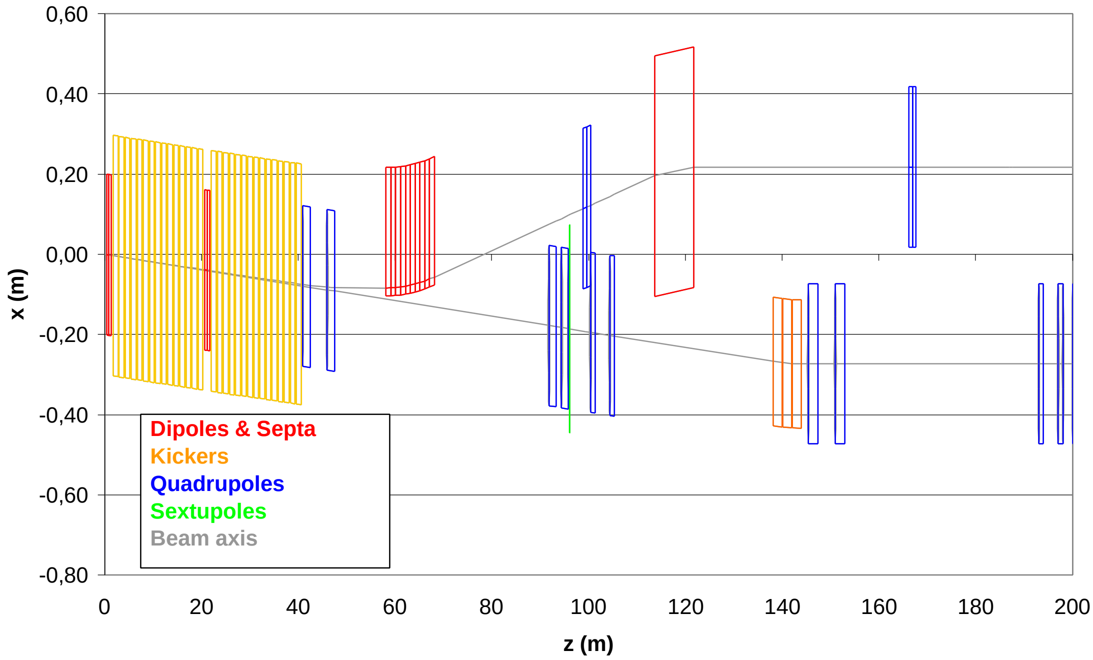

Fig.4 : Layout of the emergency extraction line in the septum region

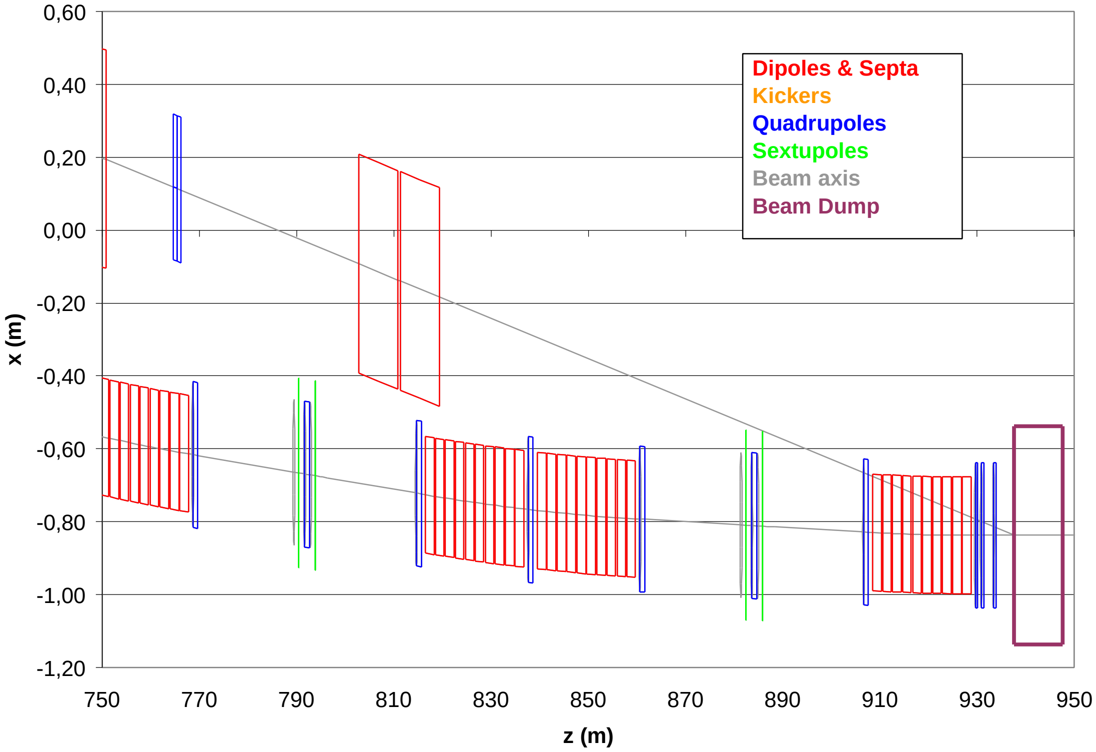

Fig.5 : Layout of the emergency extraction line in the dump region.

Element	Number	Length [m]	Optical Strength	Field or Gradient @ 391.2 GeV
Septum dipole	1	10	5.83 mrad	0.761 T
Horizontal dipoles	2	8	5.60 mrad	0.914 T
Vertical dipoles	2	8	7.75 mrad	1.26 T
1st Quadrupole	1	1.5	0.0170 m^{-2}	22.2 T/m
Periodic quadrupoles	10	1.5	0.0135 m^{-2}	17.6 T/m

Table 2 : Magnet parameters of the emergency beam line.

Element	Length [m]	Optical Strength	Field or Gradient @ 391.2 GeV
1st dipole	1	0.0522 mrad	0.0681 T
2nd dipole	1	0.0920 mrad	0.120 T

Table 3 : Short dipole parameters for commissioning mode.

Apertures

In the emergency extraction mode, beam trajectory offsets will be generated along the extraction line by initial beam energy errors d and kick angle error d_k', where the kicker index k runs from 1 to 30. The orbit differences (d_x, d_y) around the central orbit are given by the optical dispersion functions (D_x,D_y) and by the transfer matrix elements $R_{12}^{(k)}$ starting from the kicker k :

$$dx(s) = \sum_{k=1}^{30} R_{12}^{(k)}(s)\;\; dx_k' + D_x(s)\; d$$

$$dy(s) = D_y(s)\; d$$

The dispersion functions are shown in Fig.6 and the R_{12} elements in Fig.7 for the first, middle and last of the 30 kickers.

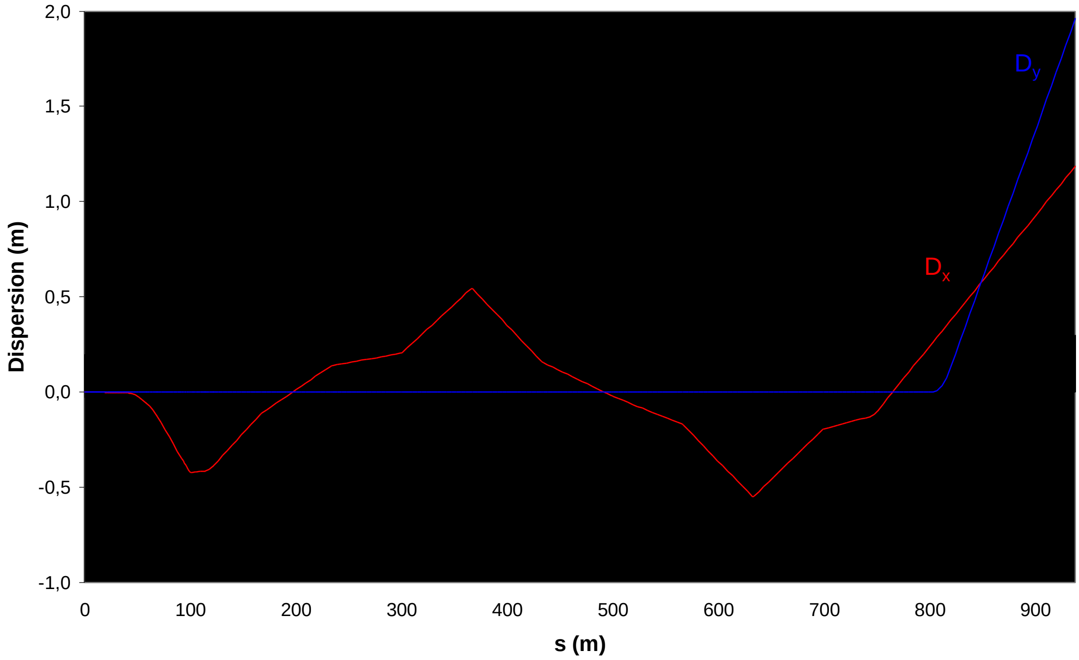

Fig.6 : Optical dispersion functions

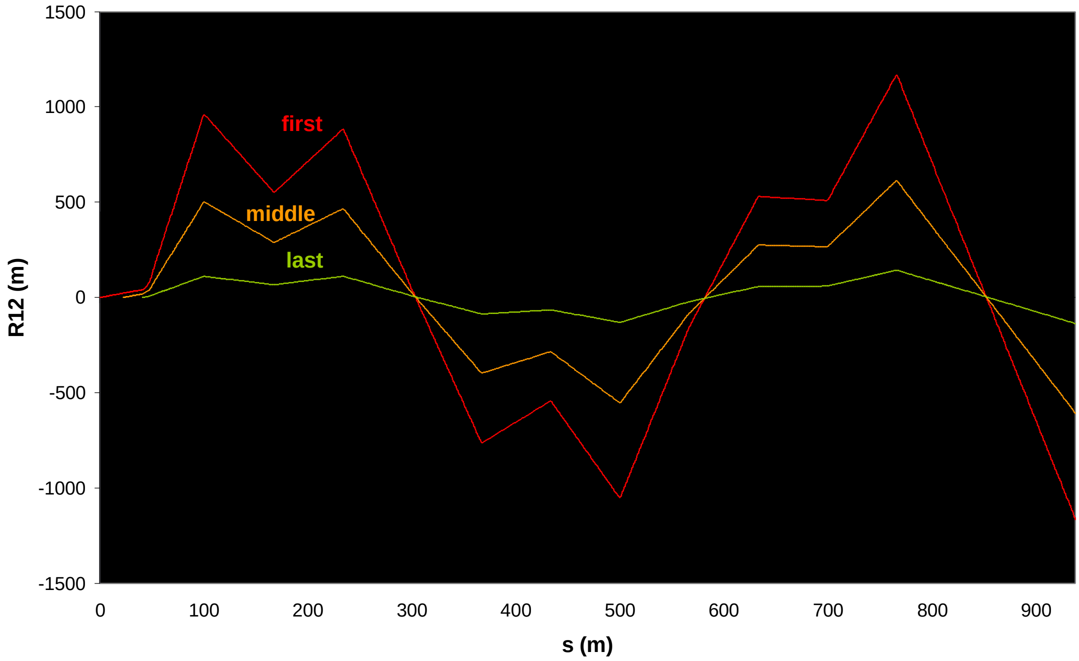

Fig.7 : Transfer matrix coefficients R_{12} from the first, middle and last kicker.

Horizontal Acceptance

The calculation of the horizontal acceptance can be simplified by realizing that, as shown by Fig. 7 :

- the R_{12} coefficients are proportional to each other ;
- as expected, the most harmful failure is that of the first kicker with the highest R_{12} .

Therefore

1. at the positions where $D_x(s)$ and $R_{12}(s)$ are positive, the largest *positive* offset occurs for the highest positive energy error, namely –2% with respect to the nominal energy (i.e. +0.19 % w.r.t. the reference energy), and the largest positive angular error (or the largest deflection angle), namely +2.5% for all kickers and no kicker failing. The largest *negative* offset occurs for the lowest negative energy error, namely –5% with respect to the nominal energy (i.e. –2.81 % w.r.t. the reference energy) and the lowest negative angular error (or the lowest deflection angle), namely first kicker off (–100%) and –2.5% for all the following kickers. The same is of course true, interchanging *positive* and *negative* offsets, when $D_x(s)$ and $R_{12}(s)$ are negative.
2. at the positions where $D_x(s)$ and $R_{12}(s)$ have opposite signs, the extreme positive and negative offsets are given by combining the same extreme positive (negative) energy error with the same extreme negative (positive) angle error.

The required horizontal acceptance of the extraction beam line is therefore given by Fig.8 where the trajectories corresponding to all four combinations of extreme energy and angle errors are plotted.

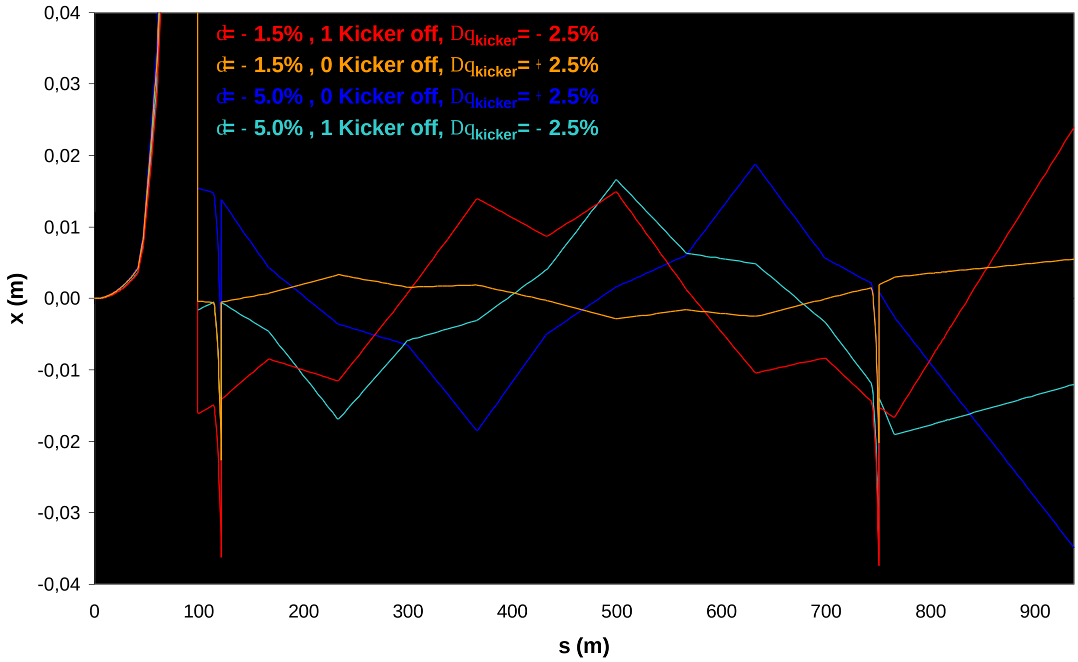

Fig.8 : Limiting horizontal trajectories, for the emergency extraction mode (for better visibility, the net deflection angle is subtracted after the two central bends).

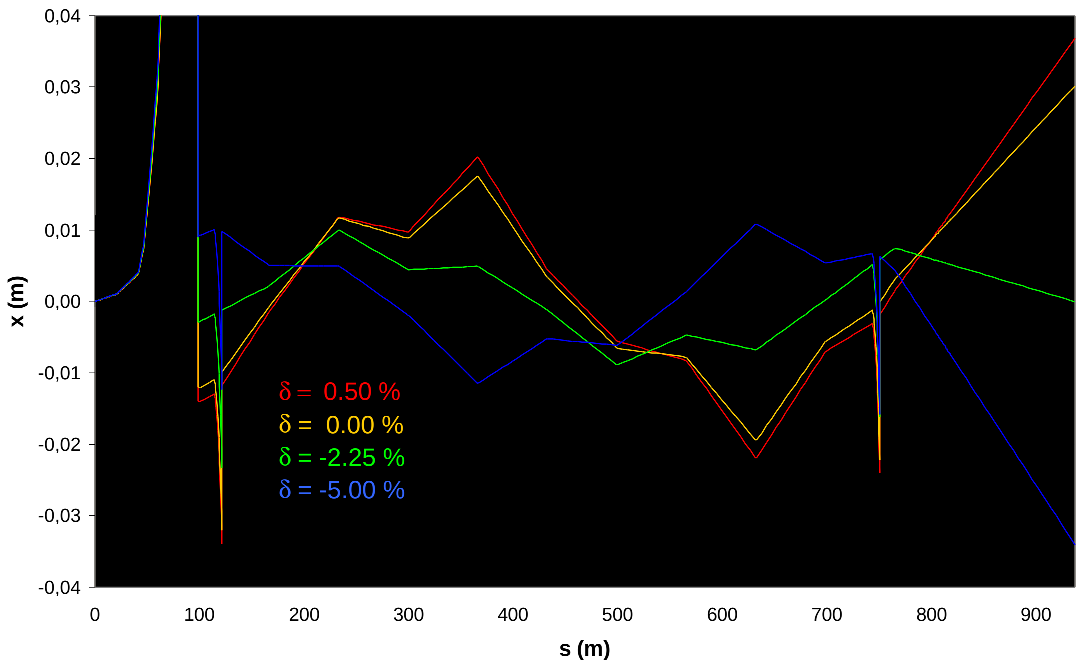

Fig.9 : Limiting horizontal trajectories, in the commissioning mode (for better visibility, the net deflection angle is subtracted after the two central bends).

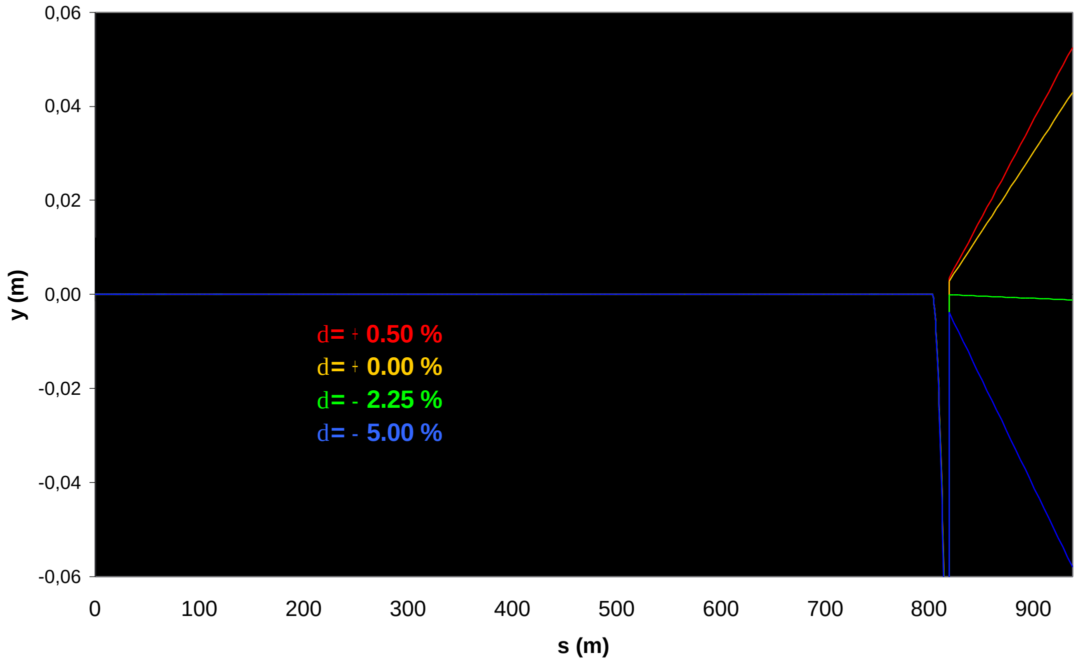

Fig.10 : Limiting vertical trajectories (for better visibility, the net deflection angle is subtracted after the last vertical bend).

In the *commissioning mode*, i.e. kickers off and short dipoles on, the only source of large errors is the beam energy. The trajectories corresponding to a few values of energy errors, including of course the extreme ones of +0.5% and –5%, relative to the nominal beam energy, are plotted in Fig.9. As discussed earlier, one can see from this plot that the reference orbit (δ=–2.19%, very close to the δ=–2.25% orbit) does not coincide with the beam axis in the emergency extraction mode.

Vertical Acceptance

The vertical acceptance is easily derived from the value of the vertical dispersion after the last vertical bend. The limiting trajectories, plotted in Fig.10, reflect again the choice of $\delta=-2.19\%$ as the reference energy. Better centering of the nominal beam on the dump window in the commissioning mode could easily be done by tuning up the vertical dipole field.

Beam Envelope

Finally, to complete the aperture study, Fig.11 shows the 1-σ beam envelopes in the case of nominal beam extraction, the only one where the input Twiss parameters are known. Clearly the beam sizes are much smaller than the expected orbit offsets and therefore do not constraint the beam line aperture.

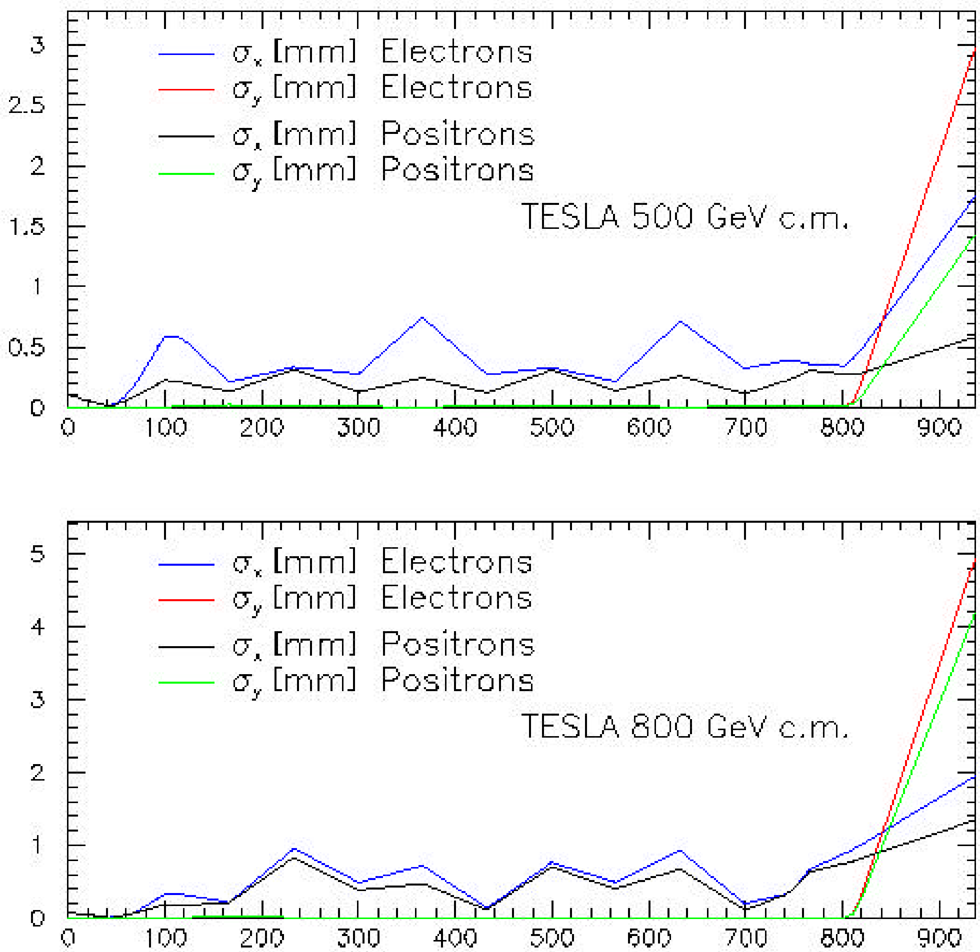

Fig.11 : Beam envelope (1-σ) along the extraction beam line. Electron and positron beams differ by their energy spread (0.14% for electrons, 0.032% for positrons). The emittance growth induced by synchrotron radiation is taken into account.

Required Apertures

According to Figs.8,9, assuming no magnet misalignments, a beam chamber aperture of about ±2 cm is required to accept the extracted beams in the two modes of operation.

Given the magnet parameters given in Table 2, a much wider beam chamber, up to 5 cm radius, could be used.
The beam offsets at the dump entrance are of the order of ±4 cm in the horizontal and ±6 cm in the vertical dimensions. Since the beam sizes are much smaller, this is certainly acceptable when compared to the 60 cm radius of the dump [2].

3. The Beam Spot Size on the Dump

In order to limit the rise of the water temperature in the dump, the effective beam radius should be larger than about 0.7 mm [2]. As shown by Fig.11, where the horizontal and vertical emittance growths due to synchrotron radiation emission in the bends are taken into account, the 250 GeV e+ (e–) beam radius is about 0.9 mm (2.2 mm) and reaches about 2.3 mm (3.0 mm) for the 400 GeV beam. Even with these beam sizes, the fast sweeping system foreseen for the main extraction line is still required. To help positioning the fast RF kickers in order to achieve the few centimeter beam displacements required at the dump, the transport coefficients $R_{12}(s)$ and $R_{34}(s)$ from a given position *s* along the beam line to the dump, are plotted in Fig.12.

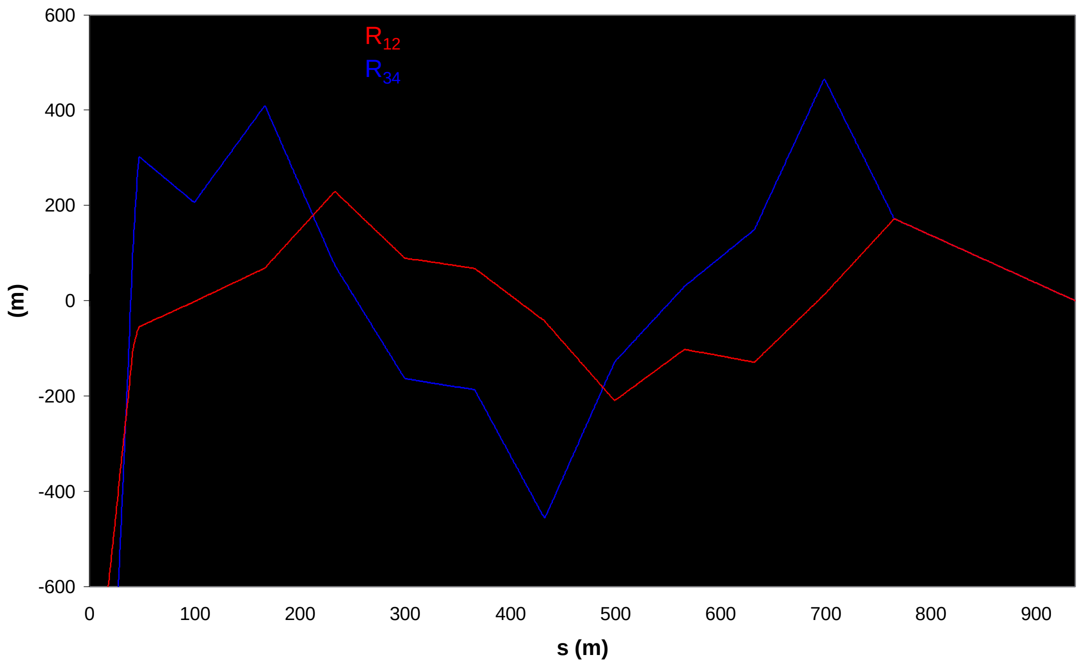

Fig.12 : Transport coefficients to the dump.

Conclusions

We have presented a first design of a fast extraction line for the TESLA high energy beam which fulfils the main aperture constraints set by its two modes of operation: the fast emergency extraction in case of accidental beam loss, and the high energy beam commissioning bypassing the beam delivery system and the interaction region.

References

1. O. Kurnaev, M. Maslov, V. Sytchev, M. Schmitz, "Preliminary Considerations on the Emergency TESLA Kickers" , TESLA Report 2001-06 (2001).
2. M. Maslov et al, "Concept of the High Power $e^{\pm}$ Beam Dumps for TESLA, TESLA Report 2001-04 (2001).