The Vacuum System for the TESLA Beam Delivery System

A. Brenger, K. Rehlich, K. Zapfe

Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

Abstract

After accelerating the electrons and positrons to their full energy in the TESLA linacs, the Beam Delivery System (BDS) transports the beams to the interaction point (IP), where they are brought into collision, and then safely extracted and dumped into high-power beam dumps. The vacuum system is required to maintain an average pressure of $1 \cdot 10^{-8}$ mbar (CO/N_2 equivalent) in the 1650 m long beam line, while the pressure in the beam lines to the dump should be low enough not to disturb the vacuum in the main beam line. For pumping ion getter pumps will be used. The design of the vacuum system is cost optimized by trading off the size of the pumps against the number required per meter of vacuum chamber. As the magnets typically have small apertures (e.g. 20 mm diameter) the cross-section of the vacuum chamber is increased fom 17 mm to 35 mm inner diameterbetween magnets to save costs.

1 Introduction

After accelerating the electrons and positrons to their full energy in the TESLA linacs, the Beam Delivery System (BDS) transports the beams to the interaction point (IP), where they are brought into collision, and then safely extracted and dumped into high-power beam dumps. The layout and functionality of the BDS are described in detail in [1].

The total length of the BDS beam line from the last accelerating module to the interaction point is 1650 m. In case of the e^- the undulator for the position source is installed directly after the cold linac. Therefore the total length is 1750 m in this case. The vacuum system of the undulator however is not covered in this report. The BDS is equipped with short (1-2 m) magnets. In total 210 dipoles, 90 quadrupoles, 11 sextupoles and one octopole magnet are used per linac.

Behind the interaction point the outgoing beam is extracted from the main beam line and transported to the dump. About 150 m of beam pipe with a large increasing diameter are needed up to the dump. The fast emergency extraction line (FEXL) starting more than 1000 m upstream of the interaction point is primarily intended to extract the remainder of the bunch train safely to the main dump in the event of a machine protection trip. The FEXL beam line has a total length of about 750 m.

In section 2 and 3 the requirements and layout of the BDS beam line vacuum system from the end of the cold linac to the interaction point are described in detail. Section 4 covers the requirements and layout of the vacuum system for the beam line to the dump and FEXL. Section 5 summarizes the components needed for the BDS vacuum system.

2 Requirements for the BDS beam line vacuum system

2.1 Vacuum pressure

The vacuum system is required to maintain an average pressure of $1\cdot 10^{-8}$ mbar (CO/N_2 equivalent)[1] from the end of the cold linac to the interaction point.

Assuming vacuum chambers made of stainless steel, the remaining gas in the system after long pumping times will be dominated by hydrogen diffusing slowly out of the stainless steel. Typically only about 10% of the remaining gas is of mass 28 (CO or N_2). Therefore the real pressure in the system, which is dominated by the low mass hydrogen, could be about a factor 10 higher than the required pressure of $1\cdot 10^{-8}$ mbar (CO/N_2 equivalent).

For pumping ion getter pumps will be used. The pumping speed S of these pumps is twice as large for hydrogen as for nitrogen. However, as shown by the following estimates, under these conditions the required pressure for the CO part of the remaining gas dominates when determining the required pumping speed of the system.

The ratio of the pumping speed for hydrogen S_{H2} and nitrogen S_{N2} is:

$$S_{H2} = 2 \cdot S_{N2} . \tag{1}$$

The desorption rate Q for hydrogen is assumed to be 10 times higher than for nitrogen:

$$Q_{H2} = 10 \cdot Q_{N2} . \tag{2}$$

The conductance C is inversely proportional the square of the mass M:

$$C \propto \frac{1}{\sqrt{M}} . \tag{3}$$

Inserting the masses for hydrogen and nitrogen $M_{H2} = \frac{1}{14} \cdot M_{N2}$ results in:

$$C_{H2} = 3.7 \cdot C_{N2} . \tag{4}$$

The average pressure in a tube with two pumps separated by a distance L is given by:

$$\overline{p_{H2}} = Q_{H2} \cdot \left(\frac{L}{S_{H2}} + \frac{1}{12}\frac{L^2}{C_{H2}} \right) \tag{5}$$

Inserting Eq. (1)-(4) into the Eq. (5) results in:

$$\overline{p_{H2}} = 10 \cdot Q_{H2} \cdot \left(\frac{L}{2 \cdot S_{H2}} + \frac{1}{12}\frac{L^2}{3.7 \cdot C_{H2}} \right) \tag{6}$$

$$\approx 5 \cdot \overline{p_{N2}}$$

The average hydrogen pressure is only 5 times larger than the average CO/N_2 pressure. Note that for C and Q values per meter should be used.

[1] The pressure is calculated from limits on hard Coulomb gas scattering of the high energy beam.

3 Layout of the BDS beam line vacuum system

3.1 General layout

The vacuum chambers of the BDS will be constructed from type 304 (1.4301) stainless steel. Vacuum firing at 950˚C to reduce the hydrogen outgassing is presently not foreseen. A desorption rate of $Q_{N2} = 10^{-11}$ mbar l/s/cm^2 for nitrogen is assumed for the following estimates.

Ion getter pumps are used to maintain the vacuum. Standard pumps are offered with 2 l/s, 8 l/s, 20 l/s, 34 l/s, 50 l/s, 65 l/s, 125 l/s, 240 l/s and 410 l/s pumping speed. The design of the system is cost optimized by trading off the size of the pumps against the number required per meter of vacuum chamber. Because the magnets typically have small apertures (e.g. 20 mm diameter) its advantageous to increase the cross-section of the vacuum chamber between the magnets to save costs for pumping. Three types of pumps with capacities of 2 l/s, 20 l/s and 125 l/s are chosen as standard for the BDS.

For pressure diagnostic the ion getter pumps will also be used. No additional pressure gauges are foreseen.

RF shieldes are presently not foreseen for bellows and pump ports, however more detailed studies of the total RF losses in the BDS are still needed. To minimize RF losses, the inner surfaces of the beam pipe will be copper coated. The number of bellows and their length should be kept at a minimum. Changes in beam pipe diameter will be tapered to reduce geometric wake field effects. In critical regions like the strong sextupole pairs, changes in cross section of the beam pipe are avoided.

3.2 Section from 0 m to 1510 m (e^-)

In this section small magnets of 20 mm aperture are used. The length of the magnets are between 1 m and 2 m. The vacuum chambers through the quadrupole and sextupole magnets have an inner diameter of 17 mm. Through the C-shape dipole magnets flat chambers with rectangular profile are used. Outside the magnets the vacuum chambers are made of tubes with 35 mm inner diameter to save costs for pumping.

Dipole magnets

The vacuum chambers for the C-shape dipole magnets have a rectangular profile of 60x20x2 mm^3. Calculations and vacuum tests of various rectangular profiles made from stainless steel and aluminum have shown, that the stability of the proposed profile will be sufficient [3]. Fig. 1 shows the distance of two pumps as function of pumping speed assuming the required average pressure of $1 \cdot 10^{-8}$ mbar (CO/N_2 equivalent). Pumps with 20 l/s pumping speed will be placed at a distance of 4.5 m.

Quadrupole and sextupole magnets

The vacuum chambers through the quadrupole and sextupole magnets are made out of 1 mm thick stainless steel tubes. Assuming a clearance of 0.5 mm between beam pipe and magnet poles, the inner diameter of the beam pipe is 17 mm. Fig. 2 shows the distance of two pumps as function of pumping speed assuming the required average pressure of $1 \cdot 10^{-8}$ mbar (CO/N_2 equivalent) for various beam pipe diameters. For longer sections using a beam pipe with 17 mm diameter small pumps with 2 l/s pumping speed are placed at a distance of 2.3 m. A bit more expensive are pumps with 20 l/s pumping speed at a distance of 3.5 m.

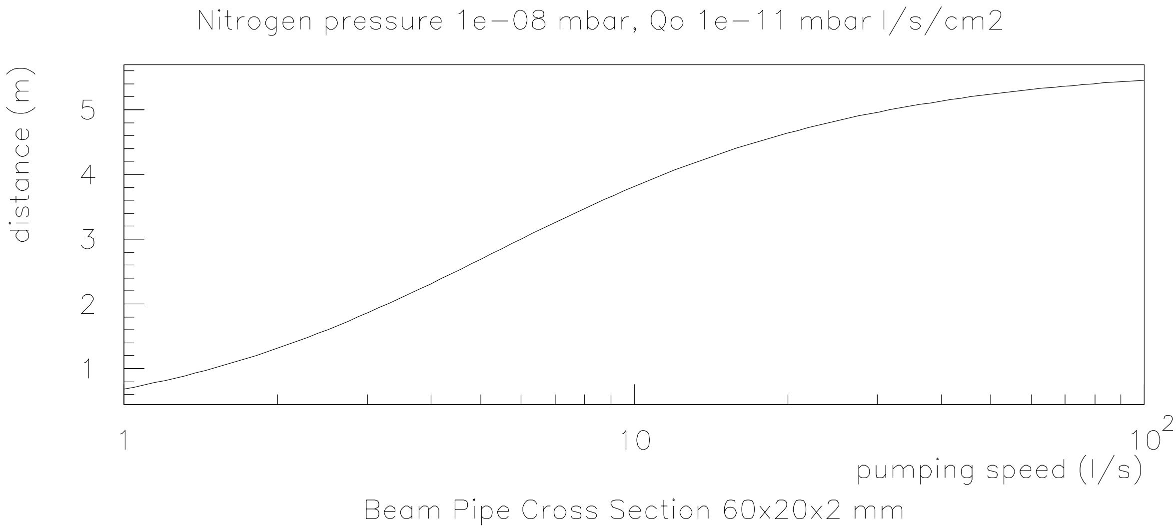

Figure 1: Distance of two pumps as function of pumping speed assuming the required average pressure of $1\cdot10^{-8}$ mbar (CO/N_2 equivalent) for a rectangular profile of 60x20x2 mm^3.

Each magnet (quadrupole and sextupole) is equipped with a beam position monitor (BPM) [2] which is an integrated part of the vacuum chamber. The BPM is rigidly clamped inside the magnet coils. Before installation into the linac the BPM will be surveyed with respect to the magnetic axis. Each magnet has its own vacuum chamber with BPM and a bellows on each side to allow the individual adjustment of each magnet.

The sextupole magnets are additionally equipped with micromovers to permanently monitor and correct their position. The bellows of the corresponding BPM vacuum chambers should allow transversal movements of ± 50 µm.

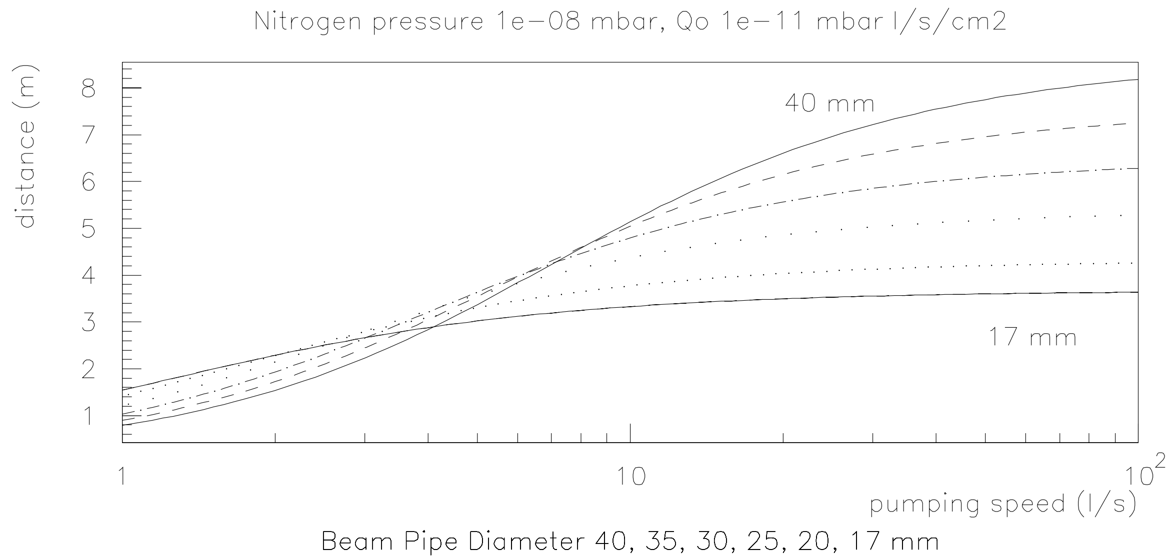

Figure 2: Distance of two pumps as function of pumping speed assuming the required average pressure of $1\cdot10^{-8}$ mbar (CO/N_2 equivalent) for various beam pipe diameters between 17 mm and 40 mm.

Regions without magnets

In regions without magnets the diameter of the beam pipe is increased to 35 mm to reduce the number and thus cost of pumps. Pumps with 20 l/s pumping speed are placed every 6 m (s. Fig. 2). Sections without magnets or other instrumentation will be up to 44 m long. Here the number of flange connections will be reduced to a minimum taking into account all fabrication, cleaning, transport and assembly procedures. Another option would be to omit flanges and use an orbital welding machine.

Particular attention is paid to wake field effects in the regions between the strong sextupole pairs in the HCCS and VCCS [1] between 1170 m and 1470 m (e^-). At least the vertical size of the beam pipe must be kept constant. Therefore the small beam pipe with 17 mm inner diameter will be used in the regions without magnets as well here. Pumps with 2 l/s pumping speed are needed at a distance of 2.3 m.

Special vacuum chambers

The beam switch-yard at 120 m (e^-) steers the e^- to either of the two foreseen interaction regions. In addition the beam line for the positron source is extracted from the main beam line in this area (see Fig. 7.2.4 in [1]). Here special magnets are needed. The detailed layout of the vacuum chambers needed in this area has not yet been studied in detail.

The fast emergency extraction line (FEXL) starts at 610 m (e^-) using a fast kicker and some special magnets. Accordingly special vacuum chambers are also neededl.

A 10 m long photon collimator is placed at 1500 m (e^-), the inner diameter being 20 mm. The corresponding beam pipe has an inner diameter of 17 mm. Locating a pump with pumping speed S in front of and behind the collimator, the average pressure $\bar{p}$ inside the collimator is given by:

$$\bar{p} = Q \cdot \left(\frac{1}{S} + \frac{1}{12C}\right). \qquad (7)$$

With the total gas load $Q = 5 \cdot 10^{-8}$ mbar l/s and conductance $C = 6 \cdot 10^{-2}$ l/s of the tube Eq. (7) yields $\bar{p} \approx 1 \cdot 10^{-7}$ mbar (CO/N_2 equivalent) for S = 2 or 20 l/s. Due to the small conductance the size of the pump doesn’t matter.

3.3 Section from 1510 m to 1583 m (e^-)

In this section no magnets or beam instrumentation are foreseen. The beam pipe has a diameter of 200 mm. Pumps with 125 l/s pumping speed are placed every 27 m (see Fig. 3).

3.4 Section from 1583 m to 1740 m (e^-)

At 1583 m (e^-) the beam pipe diameter is decreased to 140 mm. Between 1660 m and 1710 m the outgoing beam from the interaction point is extracted from the main beam line and transported to the dump. Again special magnets and vacuum chambers are needed in this area. At 1710 m (e-) the beam pipe diameter is decreased to 90 mm and just in front of the detector at 1740 m to 50 mm. The whole section is pumped by 125 l/s pumps located every 20 m and 15 m for the 140 mm and 90 mm beam pipes respectively (see Fig. 3).

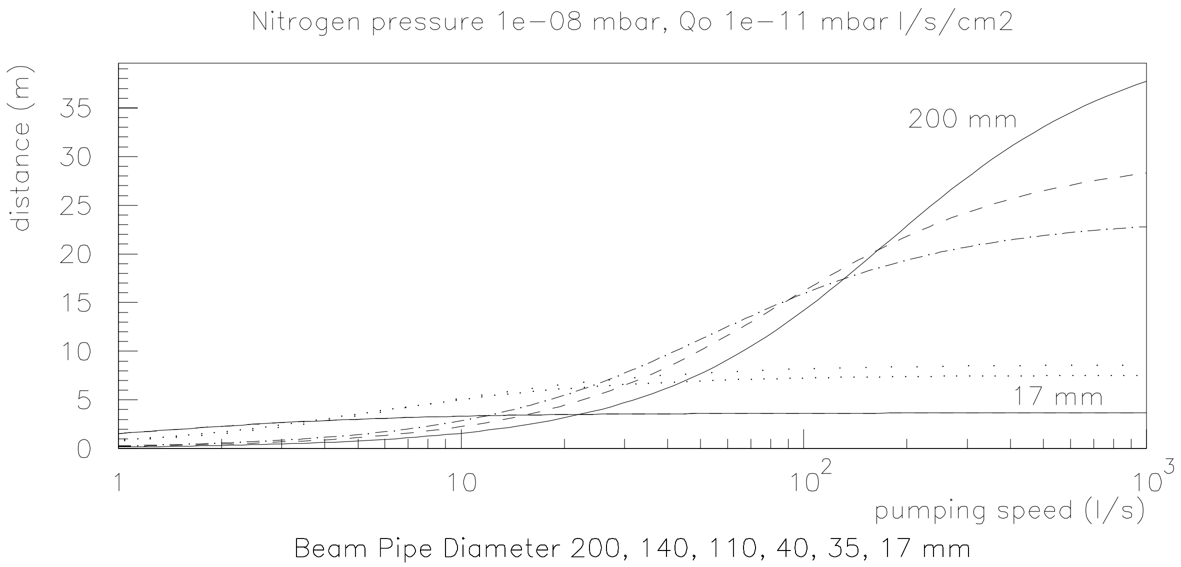

Figure 3: Distance of two pumps as function of pumping speed assuming the required average pressure of $1 \cdot 10^{-8}$ mbar (CO/N_2 equivalent) for various beam pipe diameters between 17 mm and 200 mm.

3.5 Gate valves and fast shutter

The 1750 m (e^-) long vacuum system of the BDS is segmented in 500 m long sections by gate valves. In addition gate valves are needed when the beam line is split (e.g. beam switch yard, FEXL, beam line to dump).

In order to preserve the cleanliness of the superconducting cavities about 20 m of the BDS beam line directly behind the last cold module will be treated with similar procedures with respect to cleaning and particle free assembly as the cavities themselve. Special pump down and vent procedures will be applied to this section. Therefore another gate valve is needed here. The position of the gate valves are listed in Table 1.

In order to protect the cold part of the linac in case of a vacuum break in the BDS beam line a fast shutter is placed in front of the last module.

Table 1: Location of gate valves in the BDS beam line (e^-).

Location	**function**
0 m	separation last cold module - BDS
20 m	particle free section
167 m	beam switch yard
620 m	extraction FEXL
710 m	vacuum segment
1150 m	vacuum segment
1660 m	extraction to dump
1740 m	separation of experiment

3.6 Electronics

Due to the large number and small distance of the pumps, one power supply will serve up to 400 l/s (e.g. 19 pumps with 20 l/s) for cost optimization. The pressure information will be the average pressure of the pumps connected. Where needed pumps will be powered and read out individually.

4 Requirements and layout of the BDS dump line vacuum system

4.1 Requirements

The pressure in the beam lines to the dump should be low enough ($p < 10^{-5}$ mbar) not to disturb the vacuum in the main beam line. Due to the robustness and reliability however it is advantageous to work at some lower pressure using ion getter pumps instead of mechanical pumps. The pumping speed and distance of the pumps are chosen such that the pressure at the pump will be about $p_0 \approx 10^{-7}$ mbar corresponding to a life time of the pump of 45 years.

For the following estimates a desorption rate of $Q_{N2} = 10^{-10}$ mbar l/s/cm^2 for nitrogen is assumed. No special care is taken for wake field effects.

4.2 Layout of the vacuum system for the beam line to the dump

Behind the interaction point the outgoing beam is extracted from the main beam line and transported to the dump. The 150 m long beam pipe needs a strongly increasing diameter starting with 150 mm up to 600 mm. Table 2 shows an overview of the diameter and length of the various sections of this beam pipe.

Table 2: Overview of the diameter and length of the various sections of the beam pipe to the dump.

begin	end	length	diameter
90 m	145 m	55 m	150 mm
145 m	160 m	15 m	250 mm
160 m	180 m	20 m	320 mm
180 m	210 m	30 m	460 mm
210 m	240 m	30 m	600 mm

The location of pumps and pressure distribution in the beam line to the dump are shown in Fig. 4. Pumps with 125 l/s pumping speed are located at the beginning and at 40 m followed by four pumps with 240 l/s pumping speed. The pressure at the pumps will be about $p_0 \approx 10^{-7}$ mbar, the average pressure $\overline{p} \approx 2 \cdot 10^{-7}$ mbar.

A gate valve is located at the end of the 150 mm diameter beam pipe at 145 m. In addition a fast shutter will be located at the beginning of the beam line to the dump to protect the main beam line in case of a vacuum leak somewhere in the system.

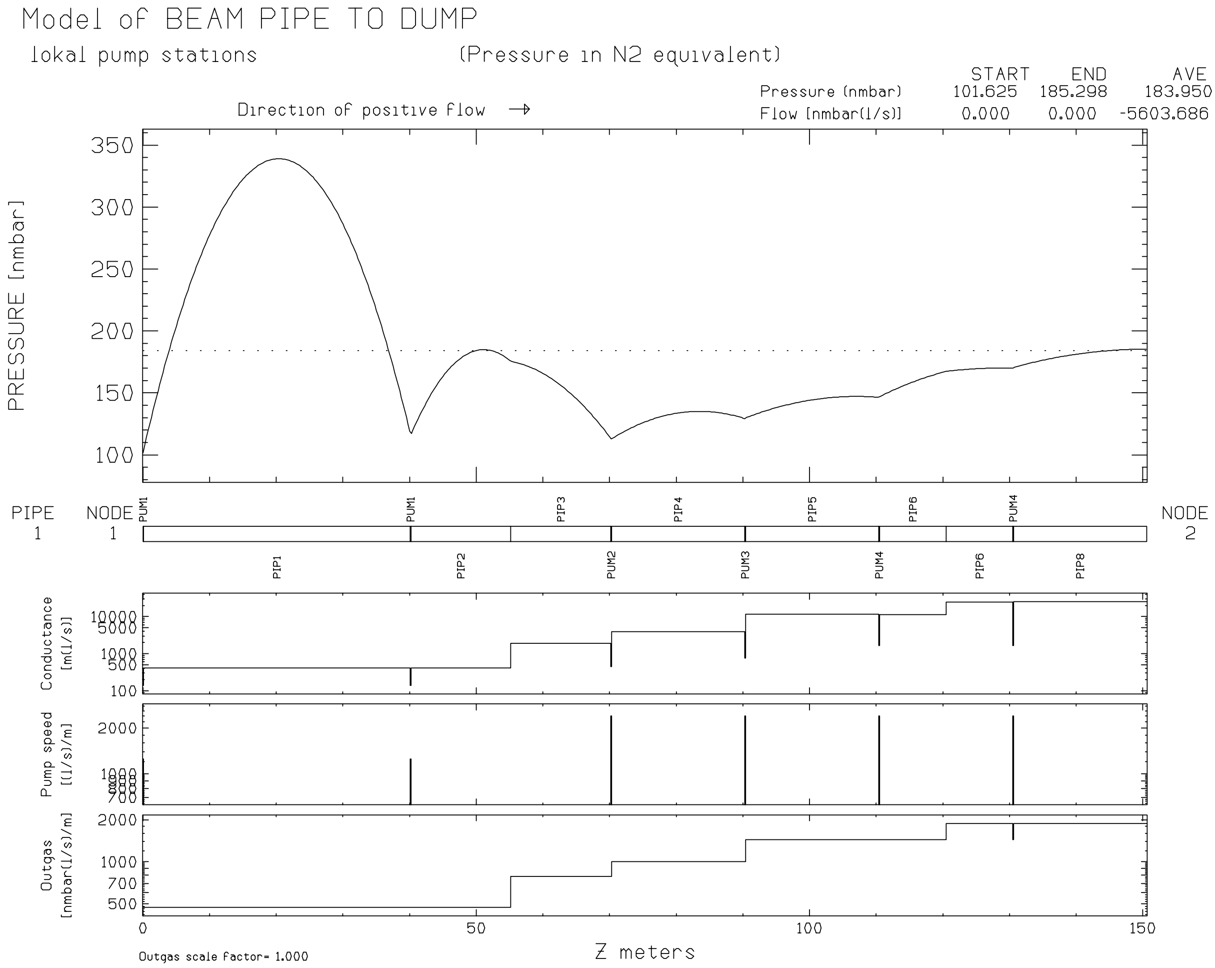

Figure 4: Location of pumps and pressure distribution in the beam line to the dump.

4.3 Layout of the vacuum system for the FEXL beam line

The 750 m long fast emergency extraction line (FEXL) starts at the septum located at 610 m. At the beginning and end of the FEXL a few dipole magnets are used. In the long straight section only a few quadrupoles are needed. The magnets have an aperture of 100 mm. The inner diameter of the beam pipe is 90 mm.

Fig. 5 shows the distance of pumps as function of pumping speed assuming a pressure of $p_0 = 10^{-7}$ mbar at the pump. For cost reasons pumps with 240 l/s pumping speed are located every 80 m. The average pressure will be $\overline{p} = 2 \cdot 10^{-6}$ mbar.

A gate valve segments the FEXL beam pipe into two sections. In addition a fast shutter will be located at the beginning of the beam line to protect the main beam line in case of a vacuum break of the exit window to the dump.

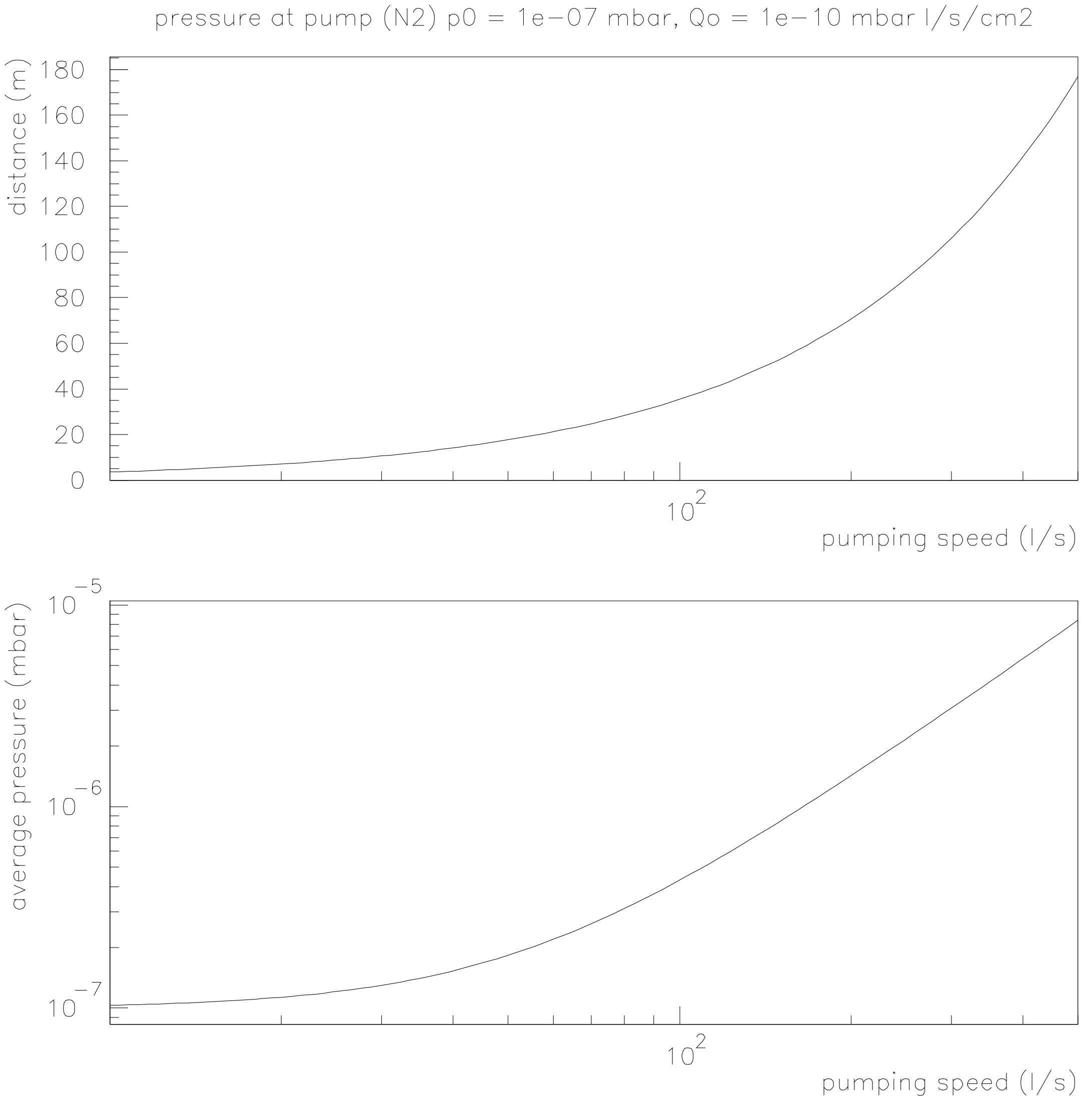

Figure 5: Distance of pumps as function of pumping speed assuming a pressure of $p_0 = 10^{-7}$ mbar at the pump in the beam pipe of the FEXL.

5 List of components for the BDS vacuum system

Table 3 summarizes the components needed for the BDS vacuum system from the last accelerating module to the interaction point, Table 4 the components needed for the beam line to the dump and the FEXL.

Table 3: Summary of components for the vacuum system of the 1650 m long BDS.

component	number
standard chambers	1520 m
special chambers	120 m
ion getter pump 2 l/s	70
ion getter pump 20 l/s	290
ion getter pump 125 l/s	16
power supplies for pumps	41
gate valves	8
fast shutter	1
cables	45880m
crates incl. controller	13

Table 4: Summary of components for the vacuum system of the beam line to the dump and the FEXL.

component	number
vacuum chamber main beam line to dump	150 m
vacuum chamber FEXL	750 m
ion getter pump 125 l/s	2
ion getter pump 240 l/s	16
power supplies for pumps	18
gate valves	2
fast shutter	2
cables	6.300 m
crates incl. controller	8

References

[1]: TESLA Technical Design Report; Part 2; TESLA 2001-23 (2001).

[2]: C. Magne, M. Wendt: *Beam Position Monitors for the TESLA Accelerator Complex;* TESLA 2000-41 (2000).

[3]: D. Brauer, A. Brenger: *Verformung von Rechteckprofilen bei Unterdruck;* MVP-note 00-15, DESY 2000.