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Vacuum properties of TARLA

Hüsnü AKSAKAL,* **Ertan ARIKAN, Zafer NERGİZ**
Department of Physics, Faculty of Science and Letters, Niğde University, Niğde, Turkey

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Abstract: The Turkish Accelerator and Radiation Laboratory at Ankara (TARLA) is a part of the Turkish Accelerator Center project, which was designed to produce an infrared free electron laser in the wavelength band of $2-250$ μm. The beamline of TARLA consists of 4 major sections: injector, beam transport line with linacs, optical cavities, and dump. All system components must be kept under ultrahigh vacuum standards to prevent beam scattering with residual gas. In the present study, the vacuum requirements of the beamline are defined and simulation vacuum and gas flow in the accelerator are presented.

Key words: Ultrahigh vacuum, pressure distribution, TARLA facility

1. Introduction

The Turkish Accelerator Center (TAC) is a proposed national project [1]. The present version of the TAC consists of 5 major projects, which include a 1 GeV proton linac, a linac-ring type of charm factory, the Turkish Accelerator and Radiation Laboratory at Ankara (TARLA), 3 GeV synchrotron radiation, and a self-amplified stimulated-emission free-electron laser (SASE FEL). The present study is dedicated to the vacuum requirements of TARLA, which will be located at the Ankara University Gölbaşi campus and is a subproject of the TAC. The accelerator components must be kept under ultrahigh vacuum (UHV) to limit beam scattering with residual gas. The accelerator vacuum system was investigated in [2], which pointed out that UHV is one of the key parameters influencing the lifetime of the beam particles. Historical developments of vacuum in large systems were outlined in [3]. The source of the residual gas (mainly gas desorption induced by ions, electrons, and photons) depends on surface properties of the pipe wall. On the other hand, beam current and energy determine the total ionization rate. In this work, the TARLA IR-FEL infrared-radiation free-electron laser (IR-FEL) facility is divided into 4 major sections for pressure analysis: injector, beam transport with linacs, optical cavities, and dump (injector: from gun to linac 1, beam transport: from linac 1 to the FEL hall, optical cavity: undulator lines or the FEL hall, and dump: from FEL hall to the end of the facility), as seen in Figure 1. The beam transport with linacs consists of 2 accelerator modules, each housing 2 nine-cell superconductive (SC) radio-frequency cavities. The energy of the electron beam is in the range of $15-40$ MeV and it generates a $2-250$ μm IR-FEL in optical cavities by 2 different undulators with 2.5 cm and 9.0 cm periods [4, 5], to be used separately. The goal of this paper is to design a UHV system to match the requirements of the IR-FEL.

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*Correspondence: haksakal@nigde.edu.tr

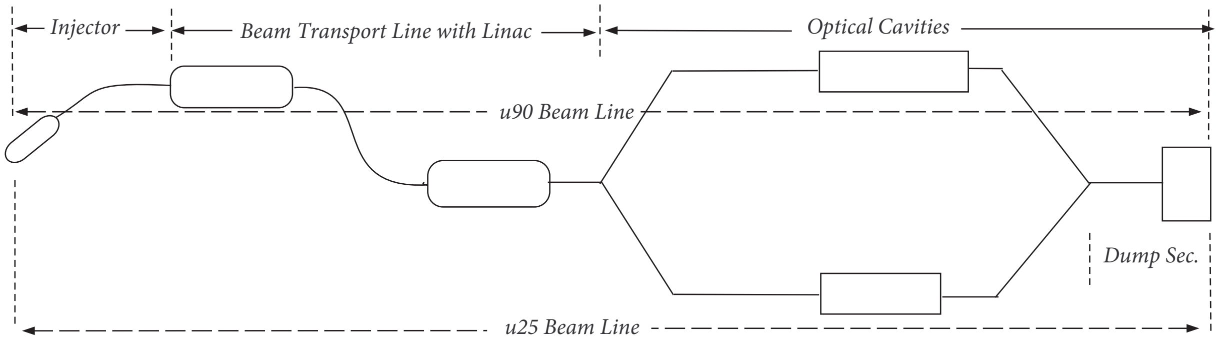


Figure 1. The basic TARLA layout.

2. Mechanical design

The basic requirements of vacuum of an accelerator are introduced in this section.

2.1. Vacuum apparatus

The high-voltage surface in the gun, SC surfaces in linacs, and FEL optics are extremely sensitive to contamination [6]. Different types of pumps are needed to reduce the pressure level to obtain UHV. Dry mechanical (scroll) pumps are used for rough pumping, which decrease pressure from 1 atm to 10^{-3} Torr. Pumping below 10^{-6} Torr is performed by turbomolecular pumps backed by the scroll pumps. A turbo-scroll assembly with appropriate gauging and valves is called a turbomolecular pump station (TMP). In general, ion pumps (IPs) have an operating life-time and they can pump all gases to some degree. IPs are commonly used to create UHV, characterized as $\leq 10^{-8}$ Torr. To obtain the best performance and lowest pressure, different types of IPs have been developed. All IPs can be mounted in any position and need no isolation valve from the system in case of venting or power failure. At TARLA, all ion-getter pumps are permanent while the TMPs are portable. In the following, the vacuum apparatus as used at TARLA is introduced:

- *Gauge*: The vacuum level should be continuously controlled along the whole beamline during operation. Instruments used for vacuum diagnostics are called pressure gauges or vacuum gauges. The useful range for Pirani gauges is 10 to 10^{-3} Torr. Hence, it is effective during the phase of rough pumping. For measuring higher pressure, ion gauges are needed. The useful range for ion gauges is 10^{-3} to 10^{-10} Torr. Hence, a subsection of the linac should be equipped with Pirani gauges and ion gauges. These gauges must be radiation-hard and operated remotely.

- *Valve*: Different types of valves are needed (gate valves, shutter valves, etc.). To prevent inrush of air from the other sections to the important parts of the vacuum chamber (cryomodules, gun, buncher), fast shutter valves must be installed. The shutter valves should be used on both sides of the cryomodules.

- *Cleaning*: All small vacuum components, such as valves, diagnostic/pumping crosses, and SC cavity hardware, should be cleaned in ultrasonic cleaners and deionized water rinses [6]. All vacuum vessels are assembled in a class-100 clean room. If chemical cleaning is required for specific materials, relative information can be found in [7].

- *Vacuum chamber materials*: There are 3 commonly used materials for vacuum chamber manufacturing: stainless steel (low outgassing), aluminum (low outgassing, good conductor, easy to extrude), and copper (low outgassing, good heat absorber, good conductor, easy to extrude) [7, 8, 9, 10].

We proposed to use stainless steel (SS) as the vacuum chamber material in TARLA, except in transition flanges of cavities where niobium-titanium (Nb-Ti) is used. The type of SS should be SS316. A vacuum beam pipe of 40 mm in diameter is used along the whole beam transport line.

- *Flange*: Vacuum flanges are used to connect the vacuum chambers, the vacuum pumps, etc. Several vacuum flange standards exist and the same flange types are called KF/QF, ISO, ConFlat, etc. In TARLA, ConFlat flanges are used, which use a copper gasket with knife-edge flange to achieve the UHV seal. Deformation of the metal gasket fills small defects in the flange, allowing ConFlat flanges operation down to 10^{-13} Torr [11, 12].

- *Leak detection*: It is necessary to check that the tightness specifications are fulfilled, in order to find the possible leak locations. There are many methods of leak detection, such as bubble testing, pressure decay, halogen gas detection, and helium leak detection. Helium mass spectrometer leak detection is the most commonly used in UHV systems because helium is a noble gas, nontoxic, inert, inflammable, and a nonreactive molecule [13].

2.2. Outgassing and conductance

The thermal outgassing rate is given by $Q_{th} = C\ exp(-\frac{E}{k_bT})$ $(Torr\ \ell\ s^{-1}\ cm^{-2})$, with C depending on surface covered gas molecules while E is the binding energy of the molecule to the surface, T is temperature, and k_b is the Boltzmann constant. Another gas load mechanism called "photon induced gas desorption" must be added to the thermal one and it can arise when photons hit the wall of the vacuum chamber and desorb gas that is bound to the surface. These photons are produced when relativistic electrons pass through the bending magnet. The photon-induced gas desorption yield is defined as number of desorbed gas molecules per incident photon. The yield (η-molecules/photon) is a function of gas species. Critical energy of these photons in eV is $E_c = 2.2 \times 10^3 E^3/\rho$ with E and ρ being beam energy (GeV) and bending radius (m), respectively. Total photon flux is defined as $\dot{\Gamma} = 1.28 \times 10^{17} IE/\rho$ in the unit of s^{-1}, where I (mA) is beam current. The gas flow due to photon-induced desorption is related to $\eta \times \dot{\Gamma}$, where η is averaged over all photon energies. The total gas load including the contribution from thermal outgassing in the vacuum pipe is:

$$Q_{total} = 2\pi r L Q_{th} + K\eta IE, \tag{1}$$

where r is the diameter of the beam pipe and the constant K converts from molecules to pressure units (e.g., $K = 2.810^{-20}\ Torr\ L/molecule$ at 273 K). Second part of the right-hand side of Eq. 1 is photon-induced gas load. In TARLA, the maximum beam energy is 40 MeV, $\rho = 0.45$ m gives $E_c = 0.38$ eV, and flux is of the order of magnitude 8; therefore, outgassing from photon-induced desorption is well below the literature rates [14]. For example, when the photon dose order is of magnitude 17, the related yield is 5×10^{-2} for H_2 obtained for SS and its outgassing would be of the order of magnitude –20 [10, 15]). Therefore, photon-induced desorption can be negligible in TARLA. The thermal outgassing rates for clean, baking SS vacuum chambers after about 50 h of pumping following 24 h of baking at 300 °C for various gases are given in Table 1 [9]. Various outgassing rates for different materials can be found in [10, 15, 16].

The other important parameter to define pressure is conductance. The conductance is independent of pressure and determined by the geometry of the system, the temperature, and the mass of the gas under consideration.

Table 1. Thermal outgassing rate of various gases for SS.

Gas	Q_{th} $(Torr\ L\ s^{-1}\ cm^{-2})$
CO	1×10^{-14}
CO_2	1×10^{-14}
H_2	5×10^{-13}

Pressure difference would build since the limited conductance for the gas flow. The conductance of the chamber material is given by

$$C = 92.8\frac{r^3}{L}\sqrt{\frac{28T}{300M}}, \tag{2}$$

where T is temperature (K), M is the mass of gasses (g/mol), and L is the length of the pipe (m). The equivalent conductance of a beamline is calculated via $C_{eq} = C_1 + C_2 + C_3 + ...$ for parallel pipes and $1/C_{eq} = 1/C_1 + 1/C_2 + 1/C_3 + ...$ for serial pipes [7]. In TARLA, the whole beamline can be considered a straight tube and each subsection of the beamline conductance is calculated via Eq. 2.

2.3. Requirements of the vacuum system

The numbers of gauges and residual gas analyzers are taken to be the same as with the TMPs. Vacuum pump positions are illustrated in next subsection. The numbers of pumps and valves, pumping speed of pumps, and surface areas for the sections of TARLA can be seen in Table 2. The overall length of the vacuum system (full system length) is approximately 40 m for the beamline. The optical cavity section consists of 2 beamlines; either $u25$ or $u90$ is enough to determine front-to-end vacuum simulation.

Table 2. Pumping process at each section.

	Injector	Beam tr. with lin.	$u25 - u90$	Dump
No. of valves	3	7	7 - 7	2
No. of IPs	4	7	8 - 8	1
No. of TMPs	3	7	6 - 6	1
Surface area [cm^2]	71.6	261.25	150.72	33.91
Pumping speed TMP [L/s]	28	28	28	28
Pumping speed IP [L/s]	10	10 – 45	10	10
Av. press. (Torr)	10^{-10} (IP) - 10^{-9} (TMP)			

2.4. Accelerator sections and pump design

2.4.1. Injector

The injector is based on normal conducting technology and consists of a thermionic e-gun (250 keV), a 260 MHz subharmonic buncher, and a 1.3 GHz fundamental buncher. The gun includes a capture cavity and should be at 10^{-9} Torr pressure. This vacuum level is achieved by using only UHV-compatible materials (no organics), proper cleaning and assembly procedures, and in situ bakeout of the entire subsystem at 250 ^oC. The injector should be separated by a metal gate valve and a beam shutter from the linac section. On the injector, 4 IPs and 3 TMPs are used, and their locations can be seen in Figure 2.

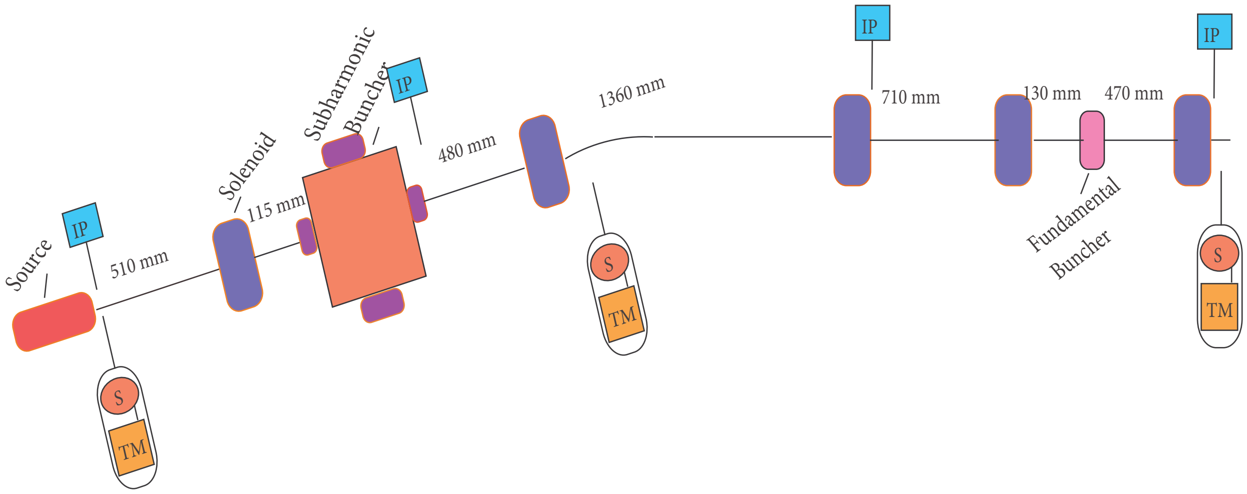


Figure 2. Injector layout with pumps.

2.4.2. Beam transport line with linacs

In order to reduce the residual beam-gas scattering to an acceptable level, the beamline pressure needs to be at least 10^{-8} Torr [7, 10, 11, 17]. The beamline requires close spacing for the pumps and the distance between the IPs is around 2 m. Usage of nonevaporative getter coating is not necessary. The beam transport line vacuum is maintained by IPs. The beam transport lines consist of 2 SC accelerator modules, as seen in Figure 3. The main demand is to keep the SC niobium surface uncontaminated from particulate and surface-absorbed gases. There are also separate valves on the cavities to provide a He plant in vacuum.

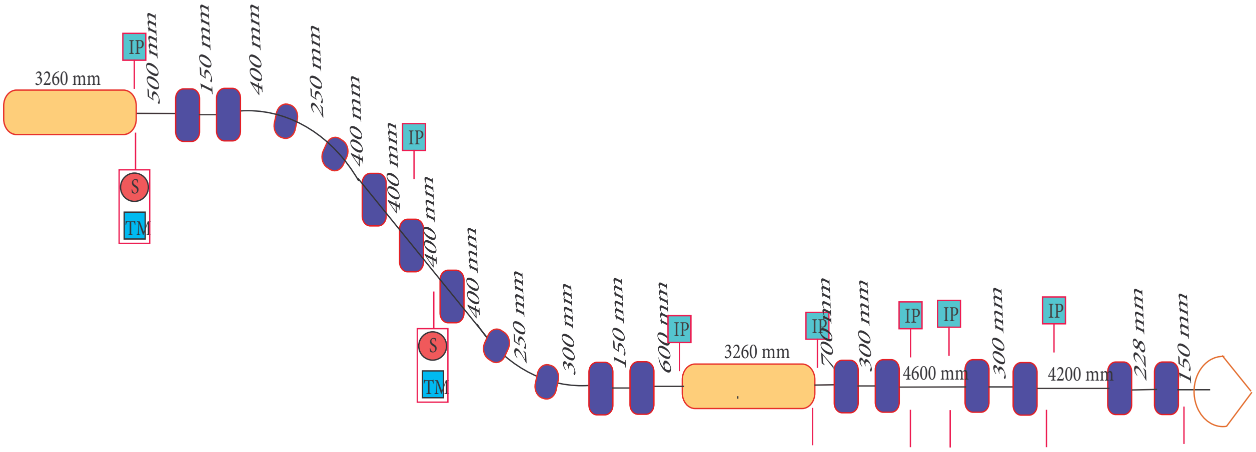
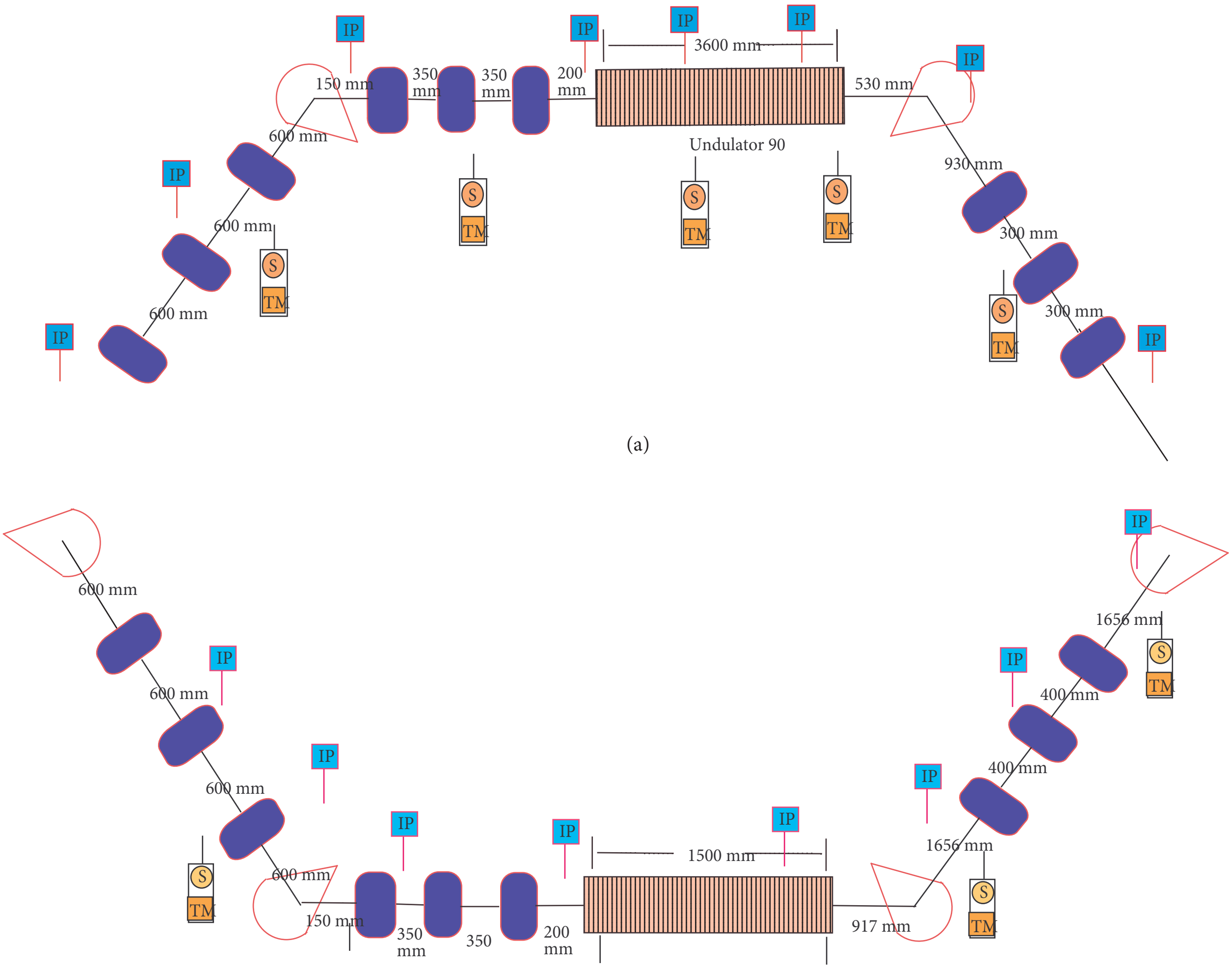


Figure 3. Beam transport line with linacs and pumps.

2.4.3. Optical cavities

There are 2 beamlines in the optical cavity sections, which are called $u25$ and $u90$, respectively. The optical cavities consist of 2 undulators with different lengths, as shown in Figures 4a and 4b, respectively.



(a)

(b)

Figure 4. Optical cavities (a) u90 and (b) u25.

2.4.4. Dump section

After the optical cavities, the beamlines are combined into the dump section. This section is the line from the end of the undulators to the beam dump, as shown in Figure 5.

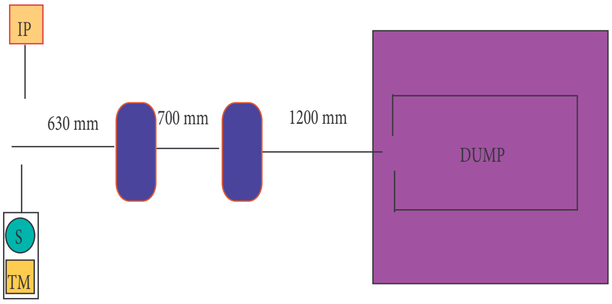


Figure 5. Dump section.

3. Pressure distribution

In the TARLA, UHV can be achieved by initial pumping with TMPs down to 10^{-7} Torr. After that, valves are disabled and IPs start pumping until the required pressure level (10^{-9}) and continue the pumping with the gun operation. A TMP pumping speed of 28 L/s has been assumed. The pumping speed of the IPs close to linacs was chosen to be 45 L/s, while it is 10 L/s for the others. Simulations of pressure distribution and gas flow were obtained without beam for the gases H_2, CO, and CO_2 by using IPs. The simulation was performed by *VAKTRAK* code [18]. The required outgassing and conductance were calculated using Eq. 1 and Eq. 2, respectively. The number of pumps along the beamline are presented in Table 2.

- *Operating scenarios*: Before the FEL is in operation, helium leak detection will be done and some operation scenarios must be taken into account, such as: the vacuum level for the gun is extreme because of the requirement to maintain low particulate concentrations on the electrode surfaces and the surface condition of the cathode. Therefore, pumping speed could be higher in the vicinity of the gun during operation. In the dump section, backscattered particles can arise from the dump during operation; therefore, pumps can be run at higher pumping speed to provide the desired pressure in order to prevent problems. It should be noted that after a first conditioning period, materials show a memory effect [10]. Increment of pumping speed in these 2 regions could be around 30%.

The pressure distribution and gas flow for H_2, CO, and CO_2 gases in the whole beamline containing the $u25$ undulator are displayed in Figures 6a and 6b, respectively. A similar figure can be obtained with the beamline containing the $u90$ undulator line. One can seen from Figure 6a that pressure of around 10^{-11} Torr can be achieved in the beam transport line with the linacs section due to the zero outgassing of the cold surfaces. The average pressure and outgassing in the beamlines (containing either $u25$ or $u90$) are shown in Table 3, the first using TMPs and the second using IPs. In addition to the static pressure calculation, the dynamic pressure calculation was also performed by VAKDYN Code [19] and the pressure distribution was obtained, as is given in Figure 6. All calculations were done assuming $Q_{left} = Q_{right} = 0$, because of the valves used for each side of the accelerator.

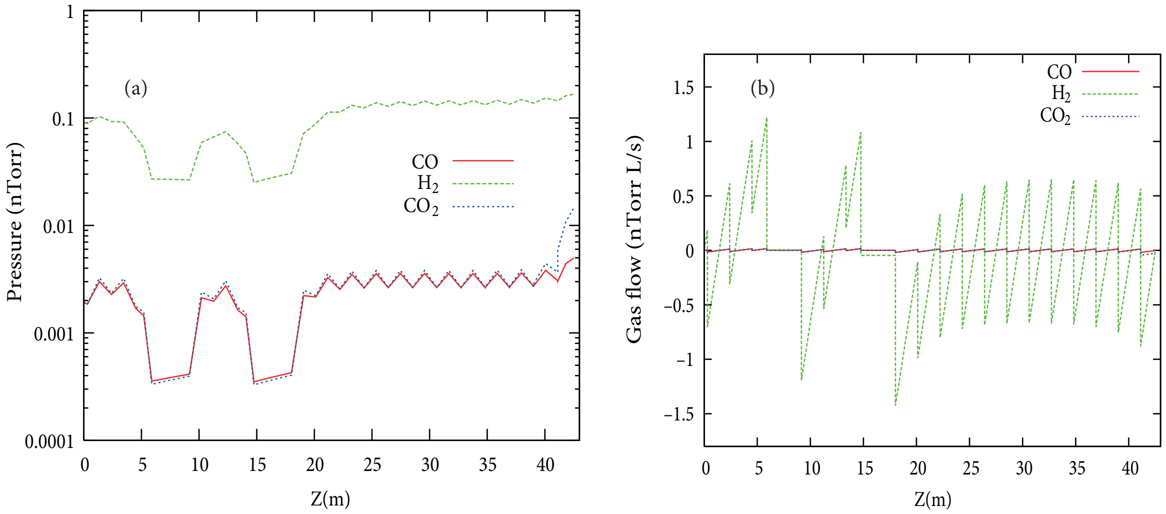


Figure 6. a) Pressure distribution and b) gas flow for $u25$ beamline.

Table 3. Average pressure and outgassing.

	CO	H_2	CO_2
Average pressure (Torr)($\times 10^{-11}$)	0.2349	9.776	0.2682
Outgassing (Torr L/s cm^2) ($\times 10^{-12}$)	–0.5302	–49.9	–1.437

4. Results and conclusions

Vacuum calculation is one of the most important process for any accelerator and it has been achieved at 10^{-9} Torr. The pressure profile of TARLA was calculated by VAKTRAK code and the results show that the required vacuum can be achieved by the proposed pumps and the outgassing rate can be decreased by choosing a baked SS. It was shown that the TARLA facility's calculated pressure of 1×10^{-10} Torr for the $u25$ beamline is in line with the expected pressure.

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