Vacuum system design for twenty-cell PWT Linac structure

S K Gupta, S Chouksey

Materials & Advanced Accelerator Sciences Division, Raja Ramanna Centre for Advanced Technology, Indore (MP), India

Abstract. This paper describes the vacuum system design for a 20-cell Plane Wave Transformer (PWT) type LINear ACcelerator (LINAC) structure to obtain a vacuum better than 5×10^{-8} mbar everywhere inside the linac structure. Specific material out-gassing rate for a 20-cell linac is determined on the basis of vacuum achieved in a similar type of 8-cell linac structure, which is smaller in length, and presently under operation in the Compact Ultrafast TEra-hertz Free Electron Laser (CUTE-FEL) beam transport line at RRCAT.

1. Introduction
Twenty-cell PWT linac structures are being developed at RRCAT to serve as an injector for an Infra-Red Free Electron Laser (IR-FEL) and also for the Indus booster synchrotron. The required vacuum level inside the linac has to be better than $5\text{X}10^{-8}$ mbar to support high RF field gradient and also to minimize beam loss due to charge exchange with the residual gas molecules. This vacuum level is designed to be achieved by pumping of the linac structure through its vacuum port using a pumping chamber and a combination of Turbo Molecular Pump (TMP) and Sputter Ion Pump (SIP). For the pumping port, a number of small slots and holes have been machined on the surface of linac tank (vacuum envelope), as a large single slot cannot be made on the tank surface to prevent the leakage of magnetic field lines, which are along the circumference of the tank inner surface. 20-cell PWT linac can also be used as an Integrated photo-injector.

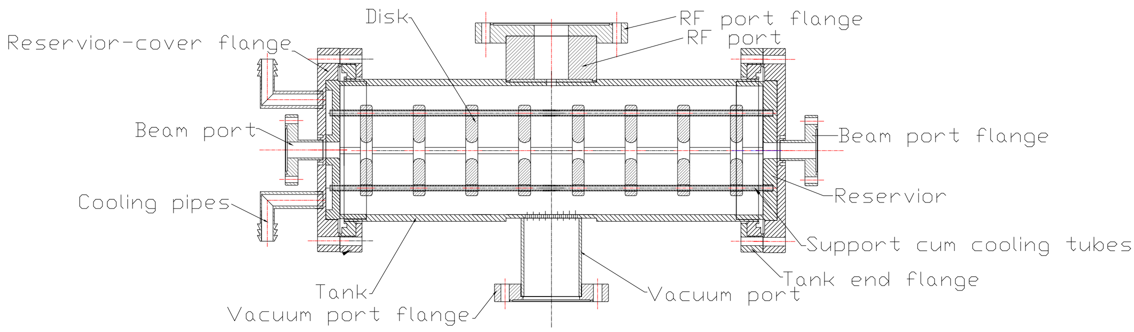

Fig. 1. 8-cell PWT Linac schematic

2. PWT Linac structure
Typical 8 and 20-cell PWT linac structures consist of 8 and 20 Oxygen Free Electrolytic (OFE) copper disks respectively (see figure 1). Four hollow stainless steel (SS316L) tubes support the disk array and also carry flowing water to cool the structure. Tubes are brazed to an OFE copper reservoir at one end and have propped support at the other end reservoir. The reservoir to which tubes are brazed serves as

water storage unit. Both reservoirs are brazed to cover flanges made of SS316L, which connect with the end flanges of a tank made of SS316L (copper coated inside). The tank serves as the outer boundary and vacuum envelope for the structure. RF and vacuum ports are connected to the tank and beam ports are welded to the cover flanges at both ends of the linac. Two cooling pipes are also connected to reservoir through the cover flanges to carry the water from the chiller to reservoir.

3. Vacuum system design for 20-cell PWT Linac

Pumping gas: Air (Molecular Weight, M= 29)
Operating temperature, T: 313 K (40 C)

3.1 Symbols used
A: Out-gassing surface area of linac, cm^2
a: Arithmetic average of a_1 and a_2, cm
a_1, a_2: Length of rectangular cross-sections of tapered pipe at top and bottom respectively, cm
A_a: Area of apertures, cm^2
b: Width of rectangular cross-section, cm
C_1: Conductance of linac tank apertures (Slots and Holes), l/s
C_2: Conductance of linac pumping port, l/s
C_3: Conductance of pumping chamber, l/s
C_{eq}: Equivalent conductance of C_1, C_2 and C_3, l/s
C_L: Conductance of linac, l/s
D: Inner diameter of pipe, cm
D_1, D2: Inner diameters of tapered pipe at top and bottom respectively, cm
ID: Inner diameter, cm
K: Correction factor for molecular flow
L: Length, cm
l/s: Litre per second
OD: Outer diameter, cm
P_L: Pressure at farthest end of linac from outlet, mbar
P_o: Pressure at the outlet of linac, mbar
q: Specific out-gassing rate, mbar-l/sec-cm^2
S_p: Pumping speed at SIP inlet, l/s
S_o: Pumping speed at linac outlet, l/s

3.2 Formulae used
Conductance of apertures

$$C = 3.64 \times \left(\frac{T}{M}\right)^{\frac{1}{2}} \times A$$

Conductance of pipe

$$C = 3.81 \times \left(\frac{T}{M}\right)^{\frac{1}{2}} \times \frac{D^3}{L}$$

Conductance of tapered pipe with circular cross-section

$$C = 7.62 \times \left(\frac{T}{M}\right)^{\frac{1}{2}} \times \frac{D_1^2 \times D_2^2}{(D_1 + D_2) \times L}$$

Conductance of tapered pipe with rectangular cross section

$$C = 19.4 \times \left(\frac{T}{M}\right)^{\frac{1}{2}} \times \frac{\left({}^{b}/_{a}\right)^2}{1 + \left({}^{b}/_{a}\right)} \times \frac{a_1^2 \times a_2^2}{(a_1 + a_2) \times L} \times K$$

Where, K= 1.2258 (for b/a= 0.2955)

$$C_{eq} = \frac{C_1 \times C_2 \times C_3}{C_1C_2 + C_2C_3 + C_3C_1}$$

$$S_o = \frac{S_p \times C_{eq}}{S_p + C_{eq}}$$

$$P_o = \frac{q \times A}{S_o}$$

$$P_L = P_o + \frac{q \times A}{4C_L}$$

3.3. Specific out-gassing rate determination

Determination of the specific out-gassing rate is an important step in vacuum design calculations. Instead of using data from literature for out-gassing rates for copper and copper coated SS316L having undergone similar surface treatment as in our case, for the present calculations it has been determined from the operating vacuum conditions of an 8-cell PWT linac that is presently employed in the CUTE-FEL beam-line. Since it's configuration and construction is similar to the 20-cell linac structure, both are expected to have similar vacuum properties. A single port pumping (Lumped pumping) scheme was adopted in 8-cell linac (see figure 2). Dimensions of linac, vacuum port and pumping chamber are given in Figure 2. Twenty slots and nine holes have made in the linac tank to pump the linac structure (see figure 2). On the basis of vacuum achieved at the outlet of 8-cell linac (5×10^{-8} mbar), the specific out-gassing rate has been determined to be 5.2×10^{-10} mbar-l/sec-cm^2 (see table 1) using the relevant expressions described above.

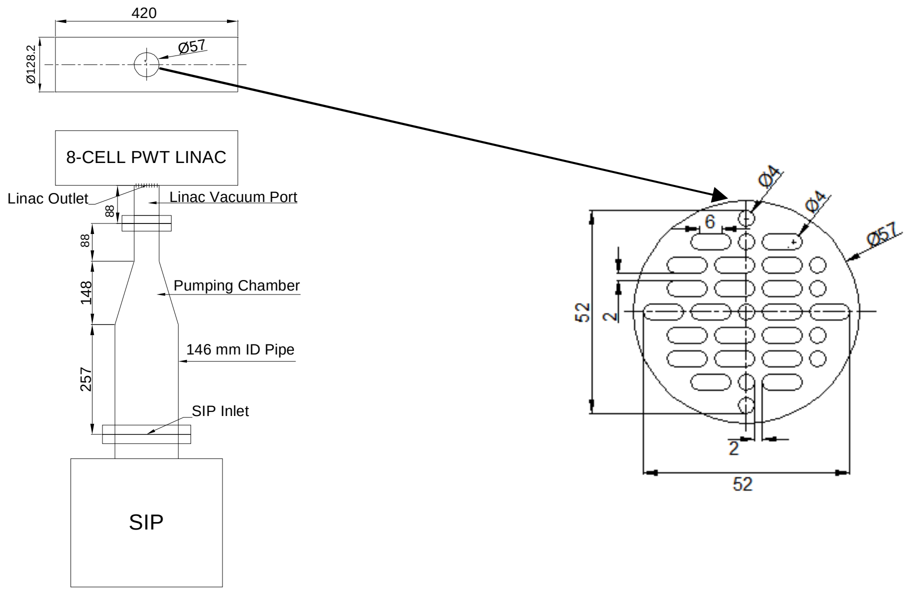

Fig. 2. Existing vacuum pumping scheme for 8-cell PWT Linac (Dimensions are in mm)

Summary of calculations (table 1):

Table 1

A	C_1	C_2	C_3	C_{eq}	S_p	S_o	q
3533	100.9	261.9	161	50.1	140	36.9	5.2×10^{-10}

3.4. Vacuum calculations and analyses for different pumping schemes

3.4.1.
Case-1**:** Considering the **s**ame pumping scheme as adopted for the existing 8-cell linac.
Summary of calculations (table 2):

Table 2

q	A	C_1	C_2	C_3	C_{eq}	S_p	S_o	P_o	P_L
5.2×10^{-10}	8452	100.9	261.9	161	50.1	140	36.9	1.2×10^{-7}	1.24×10^{-7}

As the vacuum level of P_L= 1.24×10^{-7} mbar (see table 2) inside the linac is poorer than our required vacuum level of 5×10^{-8}mbar, it is needed to improve the design of vacuum system. From above results (see table 2) it is clear that pumping speed at linac outlet (S_o) is less due to low equivalent conductance (C_{eq}), which needs to be increased.

3.4.2.
Case-2**:** Conductance of the linac tank aperture is the lowest of the three conductances (see table 2). This can be increased by increasing the number of slots machined on the linac tank. The limit on the number of slots comes from the number that can be accommodated inside the vacuum port whose OD is limited by the linac tank OD (141.3mm in our case). A seamless SS316L pipe of 127mm (5" Gauge) O.D. has selected for the vacuum port which is the maximum OD pipe commercially available below 141.3mm OD. The number of slots can therefore be increased to 72 from 20 (see figure 3), resulting in an increase in C_1 to 328.3 l/s from 100.9 l/s (see table 3). The conductance of vacuum port has also increased consecutively to 2410.2 l/s from 261.9 l/s, as ID of vacuum port pipe is increased to 121 mm from 57 mm (see table 3).

The conductance of pumping chamber can be increased by using a 146 mm ID pipe throughout the length of the pumping chamber in place of a narrow pipe (57 mm ID) and conical section (see figure 3). As a result of these changes, the conductance of pumping chamber is increased to 801.5 l/s from 161 l/s (see table 3).

The equivalent conductance is also increased substantially to 212.3 l/s from 50.1 l/s (see table 3).

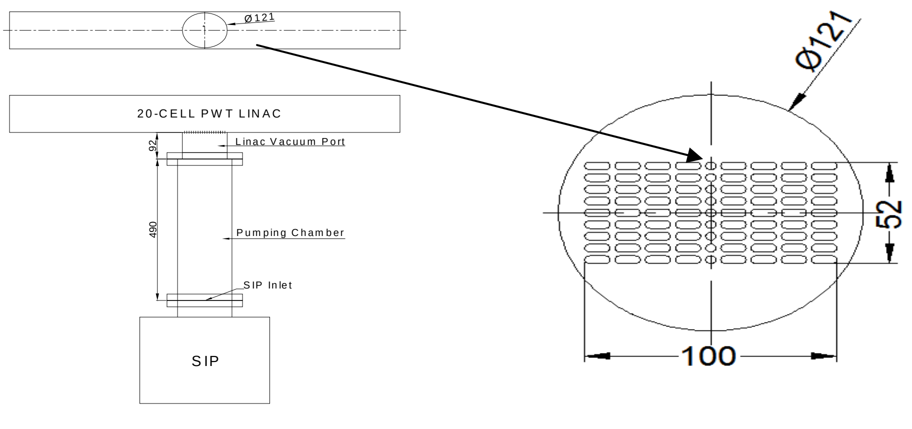

Fig. 3. Modified vacuum pumping scheme for 20-cell PWT Linac (Dimensions are in mm)
Summary of calculations (table 3):

Table 3

q	A	C_1	C_2	C_3	C_{eq}	S_p	S_o	P_o	P_L
5.2×10^{-10}	8452	328.3	2410.2	801.5	212.3	140	84.3	5.2×10^{-8}	5.63×10^{-8}

The pressure in 20-cell linac is still higher than the required value. From above results (see table 3) it is clear that equivalent conductance (212.3 l/s) is higher than the pumping speed at SIP inlet (140 l/s), which now needs to be increased. Using the commercially available next higher capacity pump of 270 l/s pumping capacity, the ultimate pressure is reduced to 4.12×10^{-8} mbar (see table 4), which is acceptable.
Summary of calculations (table 4):

Table 4

S_p	S_o	P_o	P_L
270	118.8	3.69×10^{-8}	4.12×10^{-8}

The required vacuum (better than 5×10^{-8} mbar) has now been achieved inside the 20-cell linac. It is because of increased pumping speed at linac outlet to 118.8 l/s from 84.3 l/s (see table 4).

The pressure difference in 20-cell linac (which is 2.5 times longer than 8-cell linac) is not much (see table 4). Therefore, distributed pumping is not required.

Though, the required vacuum level has been achieved, we attempt to improve vacuum further, as it can possibly open other alternate uses of the structure.

3.4.3.
Case-3**:** The conductance of the linac tank apertures needs to be increased to a value close to the next higher conductance value (C_3= 801.5 l/s, see table 3) to increase the equivalent conductance effectively. To achieve this, the number of slots is increased to 180 from 72 (see figure 4) resulting in an increase in C_1 to 800.4 l/s from 328.3 l/s (see table 5).

Design of the linac vacuum port is modified to accommodate the additional slots. A tapered vacuum port with rectangular section is proposed to be used (see figure 4). This change further increases the conductance to 3738 l/s from 2410.2l/s (see table 5), while conductance of pumping chamber is same as in case2.

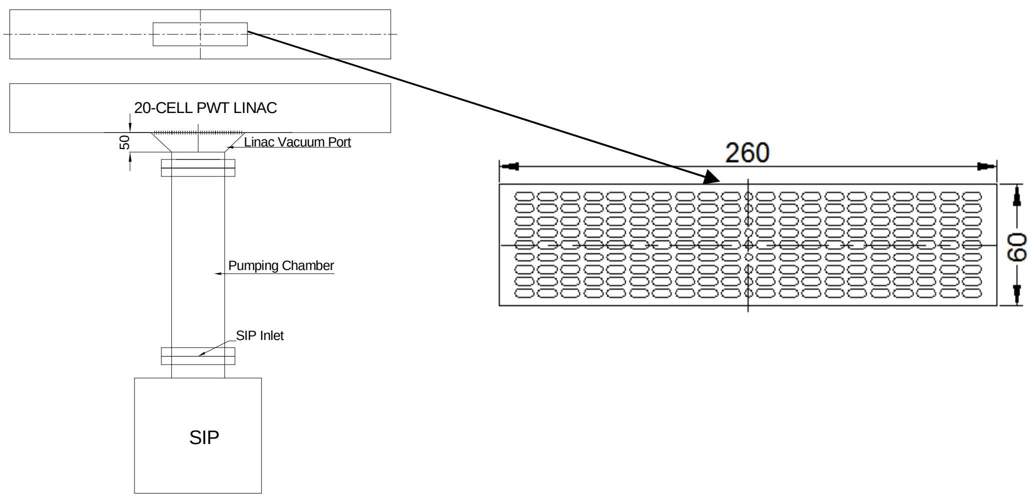

Fig. 4. Optional vacuum pumping scheme for 20-cell PWT Linac (Dimensions are in mm)

Summary of calculations (table 5):

Table 5

q	A	C_1	C_2	C_3	C_{eq}	S_p	S_o	P_o	P_L
5.2×10^{-10}	8452	800.4	3738	801.5	361.7	270	154.6	2.83×10^{-8}	3.26×10^{-8}

As equivalent conductance is higher than pumping speed at SIP inlet (see table 5), SIP of 500 l/s capacity can be used.
Summary of calculations (table 6):

Table 6

S_p	S_o	P_o	P_L
500	209.8	2×10^{-8}	2.43×10^{-8}

From above results (see table 6) it is clear that in case-3 vacuum has not increased much (from 4.12×10^{-8} mbar to 2.43×10^{-8} mbar), while pumping speed at linac outlet increased substantially high from 118.8 l/s to 209.8 l/s. It means that specific out-gassing rate is limiting the vacuum inside the 20-cell PWT linac. Vacuum can be improved effectively only by reducing specific out-gassing rate of the linac structure. Case-2 is hence the optimized design of the 20-cell PWT linac vacuum system, as simpler than case-3.

4. Future plan

A twenty-cell PWT linac can also be used as an Integrated photo-injector in which vacuum better than 10^{-9} mbar is required to support higher RF field gradients and special photocathode materials.
From conventional 20-cell PWT linac vacuum system design, it is seen that specific out-gassing rate should be approximately two orders of magnitude higher than required operational vacuum level.
Specific out-gassing rate of 20-cell PWT linac can be decreased to 10^{-11} mbar-l/sec-cm^2 by baking at higher temperature for longer duration [1], [2]. The 8-cell PWT linac was baked at 150° C for 24 hours resulting in a relatively high specific out-gassing rate.

5.Conclusions

The vacuum system design for 20-cell PWT linac, which shall be used as an injector for IR-FEL and for Indus booster synchrotron, has been finalized for a vacuum better than 5×10^{-8} mbar. Case-2 design has been found optimum and finalized, while case-1 design could not fulfill the vacuum requirement. It is also concluded that the improvement in the vacuum of 20-cell PWT linac (better than 10^{-9} mbar) for Integrated photo-injector application is possible by reducing the specific out-gassing rate (less than 10^{-11} mbar-l/sec-cm^2) of the linac structure by baking at higher temperature for longer duration.

Acknowledgements

Authors thank K K Pant for his help and support. Authors also thank D P Yadav, V Sathe, R Sridhar and K C Ratnakala for their advice and many useful discussions.

References

[1] Ratnakala K C, Tiwari S K, Shukla S K, Kotaiah S *Outgassing rate measurement of copper Plated stainless steel,* IVS2007, TIFR, Mumbai, Nov., 2007
[2] Arnaud G, Di Bartolo G, Robeiri A, Roch M *Tesla HF Couplers: Outgassing of copper plated AISI 304L samples,*LAL/RT 02-01**,** TESLA Report 2003-14**,** October 2002.