Vacuum system design for twenty-cell PWT Linac structure

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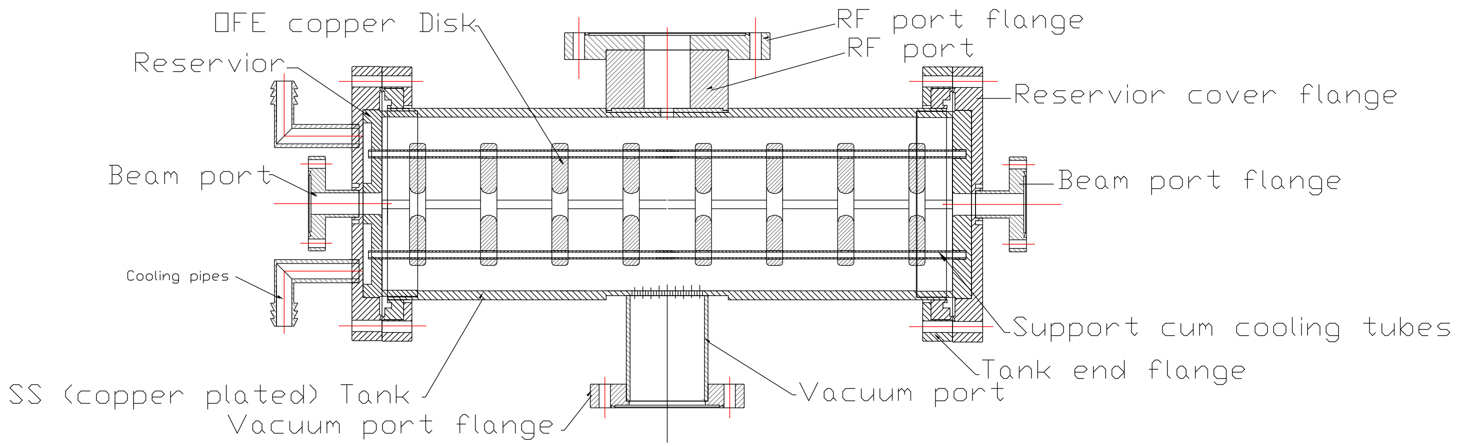
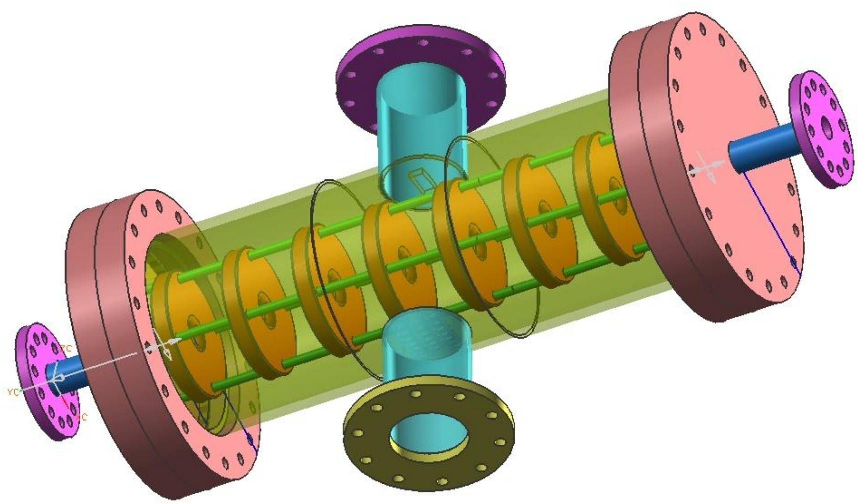
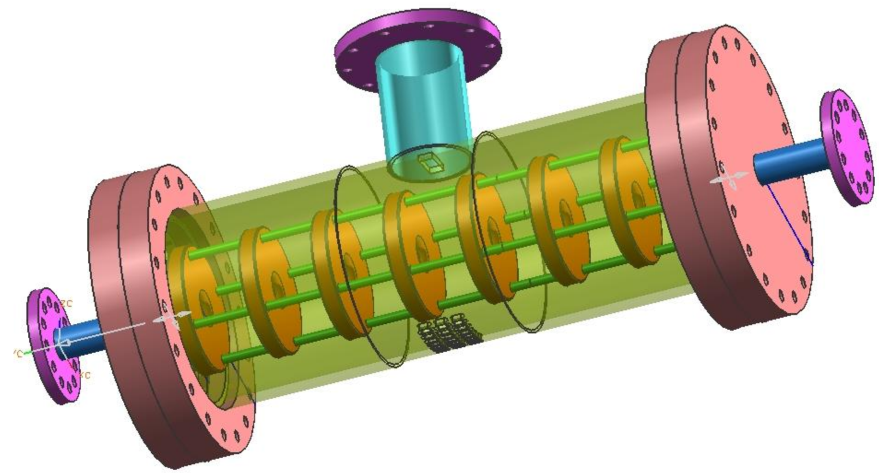
Introduction

- 20-cell Plane Wave Transformer (PWT) LINear ACcelerator (LINAC) shall be used as an electron injector in IR-FEL and Indus booster synchrotron at RRCAT.
- 20-cell Linac vacuum system has been designed to achieve a vacuum level better than $5X10^{-8}$ mbar to support high RF field gradient (25 MV/m) and also to minimize beam loss due to charge exchange with the residual gas molecules.

8-cell PWT Linac structure

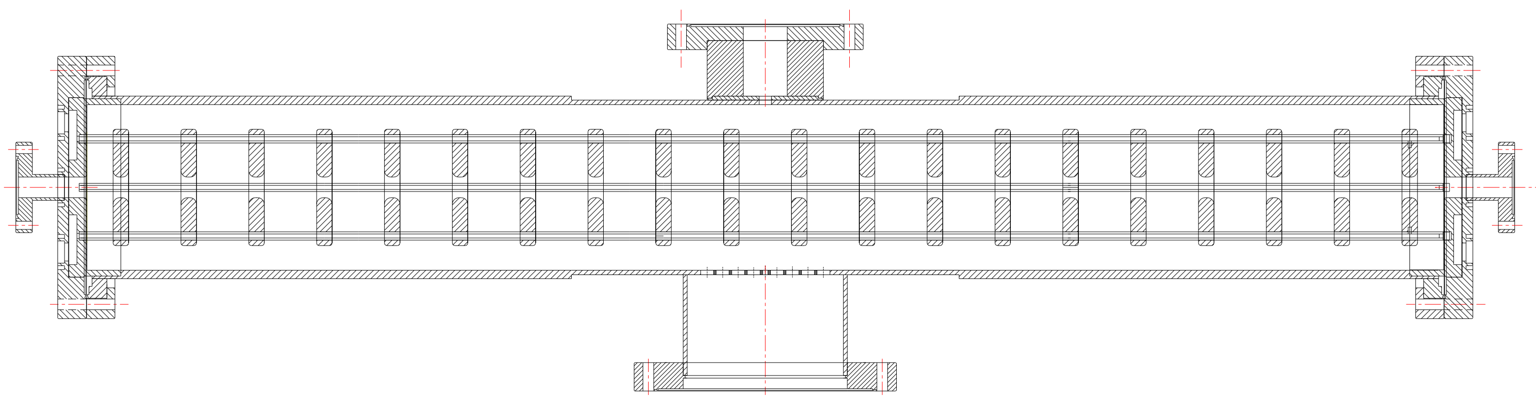






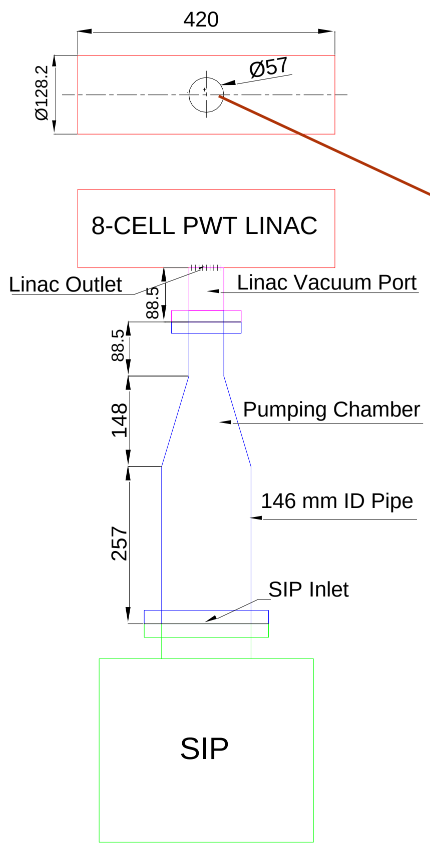
Specific out-gassing rate determination

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.

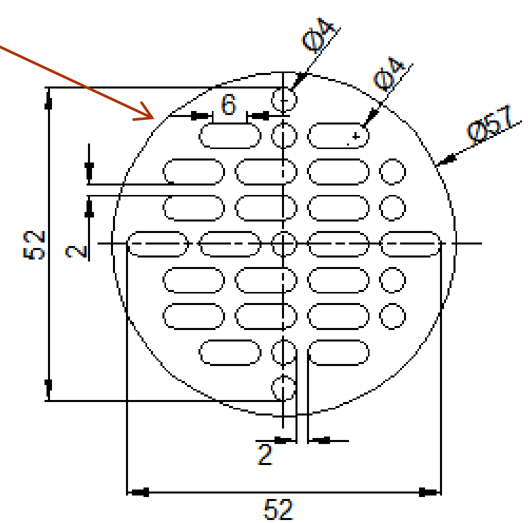


20-cell PWT Linac structure

Existing 8-cell Linac vacuum system



- For the pumping port, 20 slots and 09 holes have been machined on the surface of linac tank.
- Large single slot cannot be made to prevent the leakage of magnetic field lines, which are along the circumference of the tank inner surface.



Linac tank apertures

Note: All dimensions are in mm.

Abbreviations used

A: Out-gassing surface area of linac

C_1:Conductance of linac tank apertures

C_2: Conductance of linac pumping port

C_3: Conductance of pumping chamber

C_{eq}: Equivalent conductance

S_p: Pumping speed at SIP inlet

S_o: Pumping speed at Linac outlet

q: Specific out-gassing rate

P_o: Pressure at linac outlet

P_L: Pressure at farthest end of linac from outlet

C_L: Conductance of linac

Specific out-gassing rate calculations

- Pumping gas: Air (Molecular Weight, M= 29)
- Operating temperature, T: 313°K (40°C)
- Pressure at the outlet of linac, $P_o = 5\times10^{-8}$ mbar

Specific out-gassing rate

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

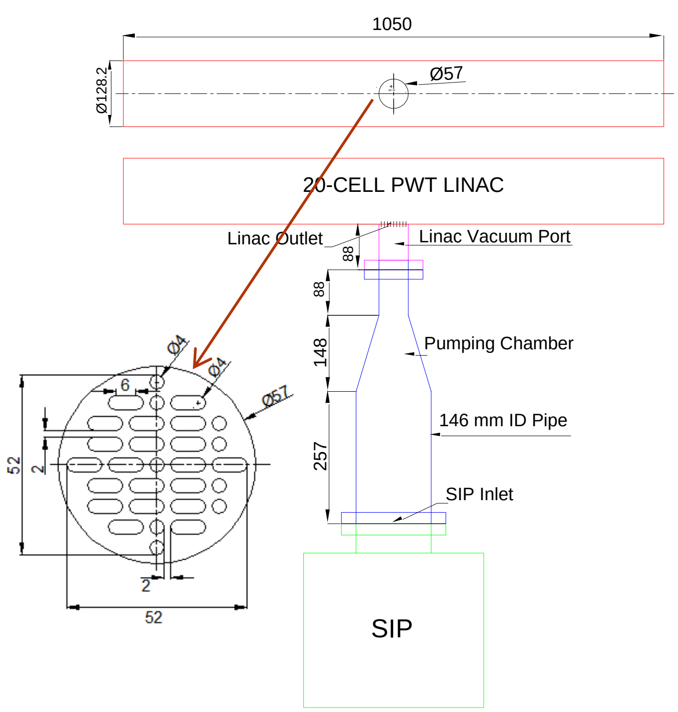
Summary of calculations

A	C_1	C_2	C_3	C_{eq}	S_p	S_o	q
cm^2	l/s	l/s	l/s	l/s	l/s	l/s	mbar-l/s-cm^2
3533	100.9	261.9	161	50.1	140	36.9	$5.2 \quad 10^{-10}$

Vacuum calculations and analyses for 20-cell Linac for different pumping schemes

Case-1: Considering the same pumping scheme as adopted for the existing 8-cell linac.

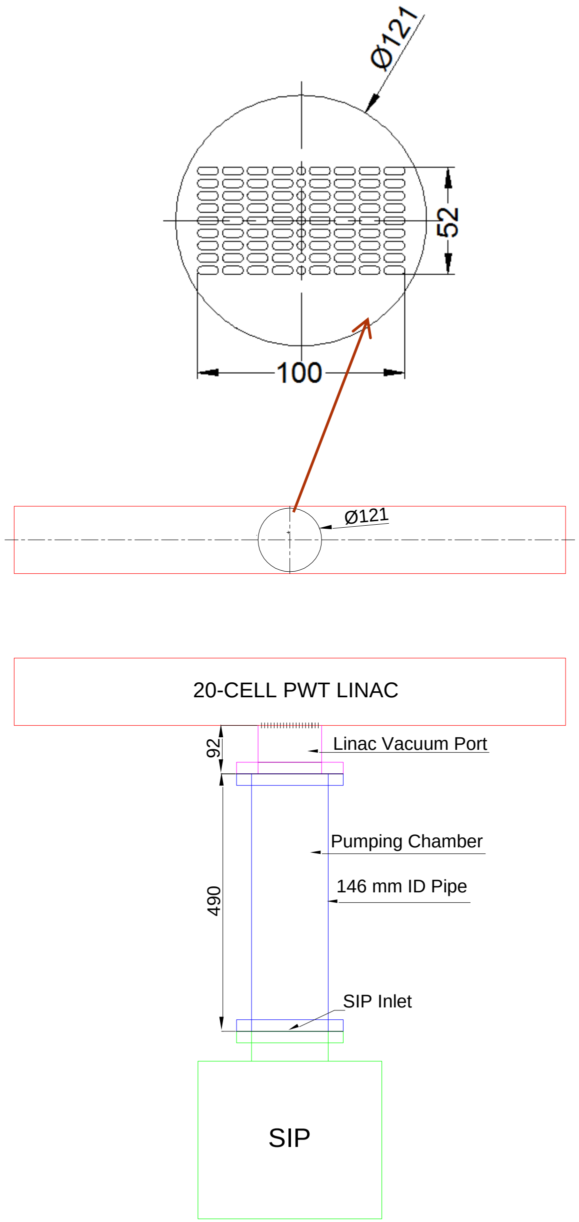
q	A	C_1	C_2	C_3	C_{eq}	S_p	S_o	P_o	P_L
mbar-l/s-cm^2	cm^2	l/s	l/s	l/s	l/s	l/s	l/s	mbar	mbar
5.2 10^{-10}	8452	100.9	261.9	161	50.1	140	36.9	1.2 10^{-7}	1.24 10^{-7}



Analysis

- As the vacuum level of 1.24 10^{-7} mbar 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 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.

Case-2



- Conductance of the linac tank apertures is the lowest of the three conductances. This is increased to 328.3 l/s from 100.9 l/s by increasing the number of slots machined on the linac tank to 72 from 20.
- 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 127 mm (5" Gauge) O.D. has selected for the vacuum port which is the maximum OD pipe commercially available below 141.3 mm OD.
- The conductance of vacuum port has also increased to 2410 l/s from 261.9 l/s, as ID of vacuum port pipe is increased to 121 mm from 57 mm.
- The conductance of pumping chamber is increased to 801.5 l/s from 161 l/s 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.
- The equivalent conductance is increased to 212.3 l/s from 50.1 l/s.

Summary of calculations

q	A	C_1	C_2	C_3	C_{eq}	S_p	S_o	P_o	P_L
mbar-l/s-cm^2	cm^2	l/s	l/s	l/s	l/s	l/s	l/s	mbar	mbar
5.2 10^{-10}	8452	328.3	2410	801.5	212.3	140	84.3	5.2 10^{-8}	5.63 10^{-8}

Analysis

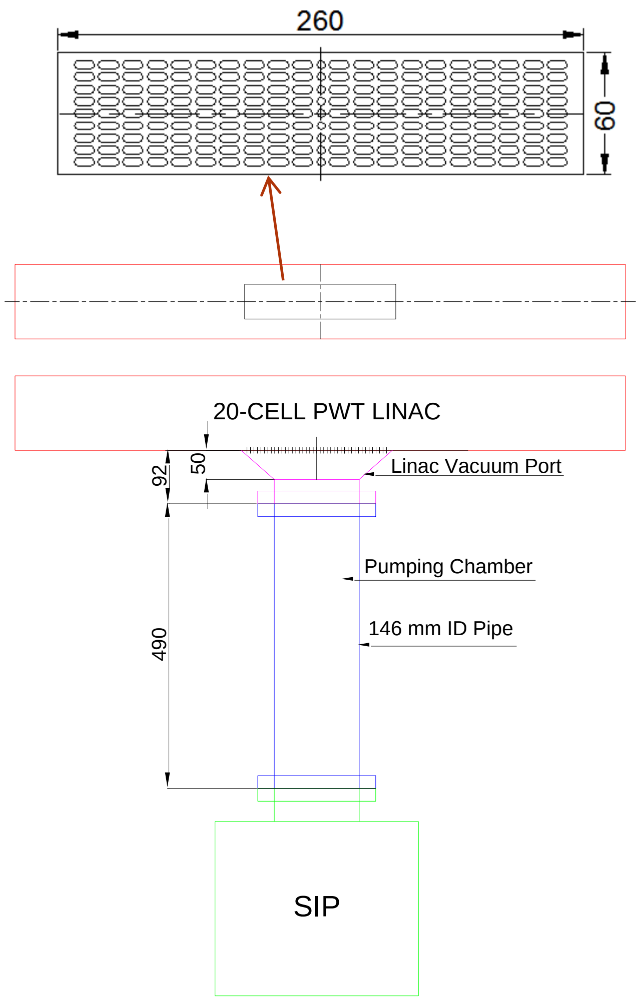
- The pressure in 20-cell linac is still higher (5.63×10^{-8} mbar) than the required value (5×10^{-8} mbar).
- From above results it is clear that equivalent conductance (212.3 l/s) is higher than the pumping speed at SIP inlet (140 l/s), which now needs to be increased.
- Therefore, commercially available next higher capacity pump of 270 l/s pumping capacity is to be used.

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

Analysis

- The ultimate pressure is reduced to 4.12×10^{-8} mbar.
- 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.
- The pressure range inside the 20-cell linac is not much (3.69-4.12×10^{-8} mbar), 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.

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) to increase the equivalent conductance effectively.
- To achieve this, the number of slots is increased to 180 from 72 resulting in an increase in C_1 to 800.4 l/s from 328.3 l/s.
- 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. This change further increases the conductance to 3738 l/s from 2410.2 l/s.
- Conductance of pumping chamber is same as in case2.

Summary of calculations

q	A	C_1	C_2	C_3	C_{eq}	S_p	S_o	P_o	P_L
mbar-l/s-cm^2	cm^2	l/s	l/s	l/s	l/s	l/s	l/s	mbar	mbar
5.2 10^{-10}	8452	800.4	3738	801.5	361.7	270	154.6	2.83 10^{-8}	3.26 10^{-8}

Analysis

As equivalent conductance is higher than pumping speed at SIP inlet, SIP of 500 l/s capacity is to be used.

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

- From above results it is clear that vacuum has not improved much (from 4.12×10^{-8} mbar to 2.43×10^{-8} mbar), while pumping speed at linac outlet increased substantially high to 209.8 l/s from 118.8 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 fulfilling the requirement and also simpler than case-3.

Future scope

- 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 gradient.
- From conventional 20-cell PWT linac vacuum system design, it is seen that specific out-gassing rate should be approximately two orders of magnitude lower 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 . The 8-cell PWT linac was baked at 150° C for 24 hours resulting in a relatively high specific out-gassing rate.

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.

References

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- [2] Ratnakala K C, Tiwari S K, Shukla S K, Kotaiah S *Outgassing rate measurement of copper Plated stainless steel,* IVS2007, TIFR, Mumbai, Nov., 2007
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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)

- Equivalent conductance

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

- Pumping speed at linac outlet

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

- Pressure at linac outlet

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

- Pressure at farthest end of linac from outlet

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

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