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# Development of a Low Cost Vacuum Chamber for Experimental Study of Plasma Parameters in a Seeded Arc Plasma

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**Abstract:** A vacuum chamber is one of the most important devices for different kinds of experimental research works in a Physics Laboratory. Producing a vacuum chamber requires defining the boundary conditions viz. inner and outer envelopes, operational constraints, etc., selecting the body material, designing the parts, and doing their assembly. In this piece of study, the design and development of a low cost vacuum chamber with different ports are described. Also, I-V characteristic of Langmuir Probe is obtained using the primary data obtained from the experimental set up for Single Probe Method in nitrogen seeded arc plasma atmospheric pressure and floating potential was found to be 35.5V and the electron density in the arc plasma was found to be $4.53 \cdot 10^{15}$electrons m$^{\square 3}$.Variation in electron density of the arc plasma with probe potential is also studied at low pressure range from 0.1mbar to 0.2mbar.

**Key Words:** Arc plasma, Vacuum Chamber, Plasma Parameters, Operational Constraints, Langmuir Probe, Floating Potential.

## Introduction

The mechanical design of a vacuum chamber requires defining the boundary conditions. The body material of a vacuum chamber is a subject of long debate, even for 'usual' types of equipment [1].The conceptual design is followed by a detailed design, which is actually associated with the development of the device. What we deal with is related not only to accelerate equipment on the beam lines but also to other vacuum vessels for services such as cryogenics. Also, the vacuum vessel we consider is static. A static vacuum vessel is subject to specific rules which has not been discussed here. Methodology & methods [1, 2] of development of the device are given in this study together with a schematic diagram of a low cost vacuum chamber developed. I-V characteristic for Langmuir Probe (Single Probe method) [3, 4] is obtained using primary data obtained from the experimental set up. Variation in electron density of the arc plasma due to variation in pressure has also been plotted for low pressure range from 0.1mbar to 0.2mbar.

## Boundary conditions

### 1. Environment

Determination of the environment in which the vacuum chamber is to be operated is the first step in its design and development. The sub-sections are given below deals with the important points of environment. These important points also include the different physical phenomena influencing the design of a vacuum chamber.

**(i) Outside**

The situation should not be very difficult when it is located inside a large building if the external envelope is simply the volume where the chamber is situated, but fitting a vacuum chamber (beam pipe) of a particle accelerator inside an optimized gap of magnets is much more constraining. Adequate space for supports simplifies the design of the chamber. In addition, space and access to the pumping ports and to the pumping and diagnostic equipments are also very restricted leading to stringent consequences on the operation.

**(ii) Inside**

The envelope is the main parameter for the vacuum chamber of an accelerator, but the conductance is another one in case of lumped pumps; the pressure distribution between two pumping ports is parabolic, and the maximum value of this parabola defines the operating pressure. The inner piping and its insulation layers define the inner envelope, but an extra space is included to allow for the movements resulting from pressure and temperature variations.

**(iii) Pressure and forces**

The differential pressure on a vacuum chamber is $10^5$Nm$^{-2}$. In the presence of a closed end, the resulting forces could be large and the design should take into account the transmission of these forces to the fixing points through the vacuum chamber wall. The vacuum chamber developed here can withstand a pressure of the order of 3.5atmospheric pressure.

**(iv) Temperature**

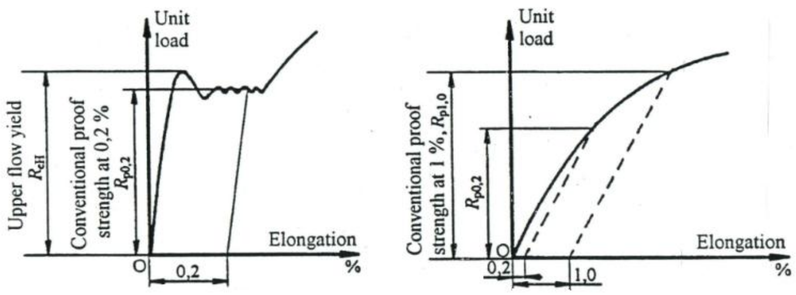
Operating temperature is room temperature, bake-out temperature between150ºC and 300ºC. The different effects of temperature include dilatations, stresses and changes of material properties, which have destructive effects if badly mastered.

**(v) Specific cases**

Electrical impedance is reduced with a good electrical conductivity, but on the other hand, non-conducting material is required for electric insulation. The parameters such as the radiation length ($X_0$), and the collision length are considered.

## 2. Materials

The material parameters for the design of a vacuum chamber in terms of mechanics could be numerous, but there are only three main parameters. They are Young's modulus ($E$), the elastic limit ($\sigma_{0.2}$) and rupture limit ($\sigma_r$).These parameters are usually easily available for materials. Figure 1 shows a typical shape of traction curves [1] of materials. It shows how to define the yield or elastic limit. The modulus of rigidity is obtained through the value of the slope of the quasilinear part of the curve.




(i) Steel except austenitic stainless steel (ii) Austenitic stainless steel, Aluminium alloys

**Figure 1:** Traction curves of metals [1]

Choosing materials for specific cases is a multi-parameter problem. It is eased by the use of non-dimensional parameters [5]. These have been used for the specific types of vacuum chambers such as the beam pipes, for the experiments installed in colliders [6], LEP [7]. They should be transparent to particles. The material selection is based on the non-dimensional parameter ($X_0E^{1/3}$) that gives a figure of merit for the materials (Table-1) and, for this specific case of beam pipes, beryllium and carbon fibre composite outrun by a large factor aluminium, titanium, and steel.

**Table 1:** Figures of merit of materials in terms of transparency

| Parameter | *Be* | *CFC* | *Al-Be* | *Al* | *Ti* | *Fe* |
|---|---|---|---|---|---|---|
| $E$(GPa) | 290 | 200 | 193 | 70 | 110 | 210 |
| $X_0$ (m) | 0.353 | 0.271 | 0.253 | 0.089 | 0.036 | 0.018 |
| $X_0E^{1/3}$ | 2.34 | 1.58 | 1.46 | 0.37 | 0.17 | 0.11 |

Specific technological properties are also considered. Leak-tightness of a vacuum chamber is a must, but is difficult to obtain if the weldability of the material is poor. Cost is the final criterion behind it. The most common materials are austenitic stainless steel.

## 3. Design

**(i) Basics**

Stresses generated by the loads enumerated before should usually remain in the elastic range. This means that the equivalent stress (Von Mises or Tresca criterion) should not exceed the elastic limit ($\sigma_{0.2}$) anywhere in the structure. The membrane strain energy can be converted to bending strain energy, leading to instability and a bifurcation point on the behavioral curve, a potential buckling (Figure 2). Buckling is a non-linear phenomenon, and is strongly influenced by the defects inherent in the manufacturing.

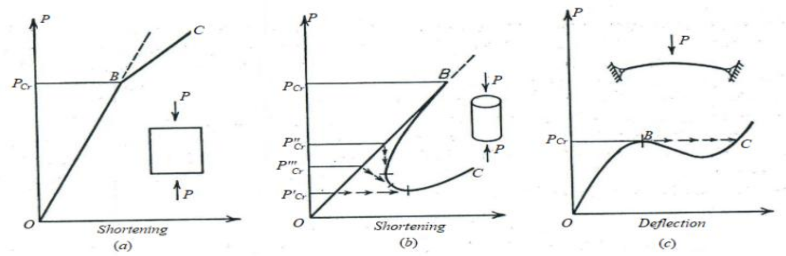



**Figure 2:** *Buckling behaviours* [1]

**(ii) Methods and techniques**

In the pre-design phases as well as the phase of final check-up of design, simple analytical methods can be more efficient than structural analysis programs. However, the use of structural analysis packages, usually based on the Finite-Element Method, is necessary for the detailed design of vacuum vessels. The shell elements [1] for thin shell structure ($t/R$ < 100). In the shell elements, the through thickness stresses are assumed linear and integrated in membrane (constant term) and bending (linear term).

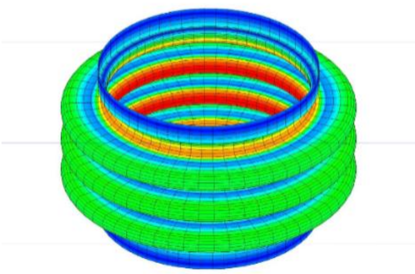


**Figure 3:** Finite element model (Shell element: a bellow)

**(iii) Tubes**

The circumferential stress for the most stable circular tubes under external pressure $P$ is given by

$$\sigma_{\theta} = \qquad (1)$$

$R$ and $t$ respectively, are the radius and the thickness of the tube. If the tube is closed and subjected to an axial force $F$, the axial stress is

$$\sigma_z = \quad + \square \qquad (2)$$

and the Von Mises equivalent stress [1] compared to the material maximum allowable stress is

$$\sigma_e = [3(\frac{PR}{t})^2(\frac{F}{\pi Rt})^2]^{\frac{1}{2}} \qquad (3)$$

The buckling pressure can be computed through analytical formulae, depending upon the geometrical parameters of the tube and the Young's modulus of the material. The most conservative formulae for an infinite length of the tube is:

$$P_{cr} = {}^3, \qquad (4)$$

$v$ being the Poisson ratio and $(1 - v^2)$ can be generally approximated by 0.9.The rule of thumb in this regard is that the thickness of a stainless-steel circular tube should be at least one hundredth of its diameter (safety factor included).Such quick estimation in case of a non-circular tube is more difficult. However, quasi or approximately rectangular shapes can be approximated by plates or simply by beams (width of a unit length) either clamped or simply supported. If approximated by a beam, the maximum deflection ( $\delta_{max)}$ and stress ( $\sigma_{max}$) (upper and lower bounds) are

$$< \delta_{max} < , \qquad (5)$$

$$P^{2} < \sigma_{max} < P^{2}, \qquad (6)$$

*l* and *t* being, respectively, the span and the thickness of the tube. Specific analytical programs have been developed to treat elliptical tubes.

**(iv) Windows**

The best shape for resisting external pressure is a spherical dome but the manufacture of this shape is not easier, and the external ring must be of high rigidity. If the window is oriented in such way that it can buckle, the classical buckling pressure is

$$P_{CL} = {}^{2}, \qquad (7)$$

*R* and *t* being, respectively, the radius of curvature and the thickness of the spherical dome. A flat window is the other common option, but when put under pressure, the deflection ( $\delta_{max}$) is not negligible

$$\delta_{max} = , \qquad (8)$$

*R* and *t* being, respectively, the radius and the thickness of the circular window. Non-circular windows exhibit high loads concentrated in the corners, which is slightly difficult to treat in case of a weld, and also a source of nightmares when clamped inside flanges.

**(v) Bellows**

In order to bring flexibility, they are thin and inherently fragile. They are either mechanically formed or hydro formed from thin tubes, or assembled by welding a series of individual annular rings. The design of bellows is treated in the general codes for pressure vessels but a specific code has been issued by the manufacturers. The Expansion Joint Manufacturers Association [8], recognized as the authority on metallic bellows type expansion and a project norm pr-EN 14917 [9], was recently published by CEN. Bellows are designed to withstand a given number of cycles of axial expansion/compression over the expected life of the system.

**4. Assembly**

**(i) Machining and sheet metal work**

Materials for manufacturing are available in various states; raw products like blanks or sheets, or semi-finished products like extruded elements (aluminium, copper), moulded, forged, or sintered (ceramics).The choice is usually based on cost but the final quality in terms of vacuum may be disturbed by the manufacturing techniques. Defects due to impurities internal to the material should not provoke a leak-through, and elaboration techniques properly handled is of help in this connection.

**Flanges**

Flanges are industry standards available on the market. However, metal-sealed flanges are developed for specific needs. The main parameters for their design are the strength of the material to with stand high forces for bolting or clamping, and the quality and hardness of the surface where the seal is positioned.

**Welding**

Welds are a source of impurities and defects. The first point is the weldability of the material. To fulfill their role of mechanical resistance, the welds are designed and executed according to the rules of the construction codes. A reduction factor (0.85, 0.7) is applied in the calculation of the stress level, and is, therefore, recommended to avoid localizing a weld in a highly stressed zone. Grooves help minimize heat propagation along the walls and can be useful in case of subsequent cutting and re-welding.

**(ii) Brazing**

The surfaces are etched before the brazing, and also a high-quality cleaning after brazing is important to increase the lifespan [10] of the vacuum chamber.

## Results and Discussion

A schematic diagram of the developed vacuum chamber is shown in Figure 4. The chamber has a length of 500mm, diameter of 250*mm*, having one side closed with 16*mm* thick stainless steel flange, O-ring grooved and the other side closed with transparent polycarbonate sheet with O-ring grooved bolting. The various ports are made to fit into components such as rotary pump, pressure gauge, oscillating system, and necessary electrodes. Figure 5 shows the variation of probe current (*ln* I) with probe voltage (V) for single probe method, using the data obtained from the experimental setup and floating potential was found to be 35.5V. Variation of electron density at different pressure is shown in Figure 6. It is clear from the figure that the low cost vacuum chamber is useful for the measurement of Plasma Parameters in a seeded arc plasma.

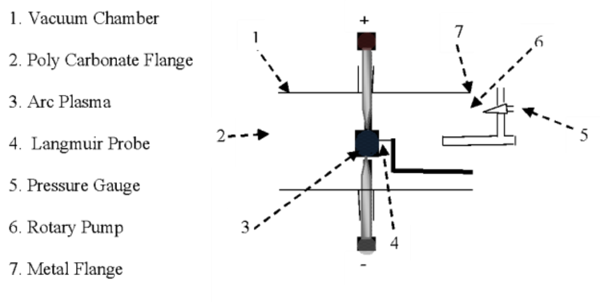



**Figure 4:** A Schematic Diagram for Vacuum Chamber

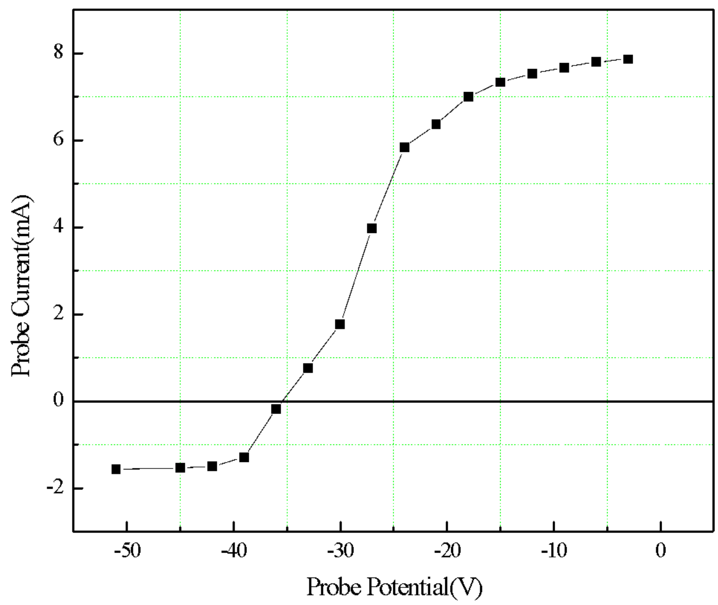



**Figure 5:** I-V Characteristics of Langmuir Probe (single Probe Method) from Crude Data obtained from experimental setup

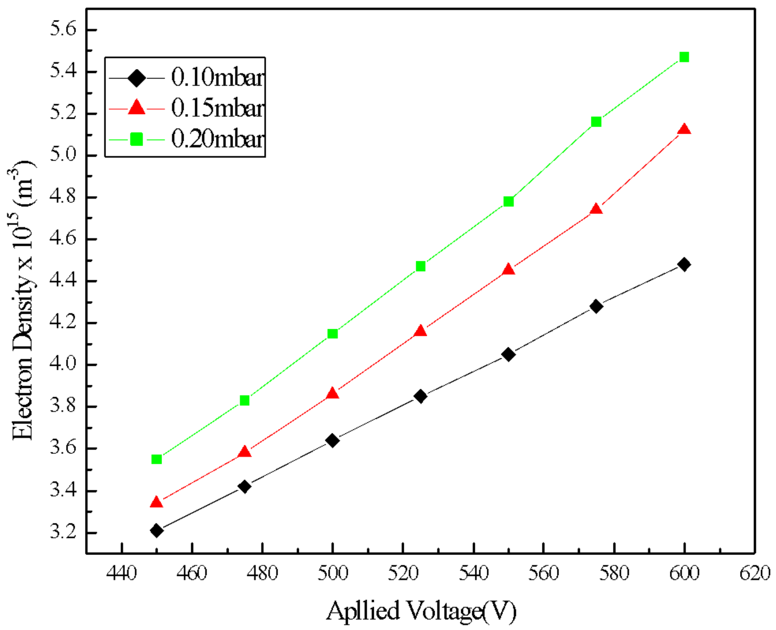



**Figure 6:** Variation of Electron Density in Seeded Plasma with Probe Voltage at low Pressure

## Conclusions

A vacuum chamber should not be very complex and a systematic approach helps to get one with good quality at the right price. A vacuum chamber of stainless steel is the best one. A low cost vacuum chamber of stainless steel has been developed in the laboratory by adopting a systematic approach for the study of plasma parameters in a seeded arc plasma. The nature of I-V characteristic using the crude data obtained from the single probe method (from primary data) is in good agreement with the theoretical aspects of Langmuir probe. It is also clear that there is increase in electron density of the low arc plasma as pressure increases.

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