بِسْــــــــــمِ اللهِ الرَّحْمَنِ الرَّحِيمِ

Inertial Electrostatic Confinement Fusor (IECF)

Prototype Realization, Ver. March 2022

Author: Nour Krayem

Ali Obeid

Editor: Samir Mourad, November 23

Last Update: 14.11.2023 13:15

Table of Contents

_____

Table of Contents

Open Tasks Status Apr 22 / Nov 23 for IECF

- <mark>cathode assembly: 40$</mark>
¤ base design
¤ equipment purchasing
¤ assembling + soldering
¤ testing
¤ report
- <mark>Fuel inlet (D2) 40$</mark>
¤ base design
¤ equiment purchasing
¤ خراطة + soldering
- <mark>sensor system (neutrun, x-ray...) 40$</mark>
¤ x-ray sensor
¤ monitoring system
¤ presure sensor
¤ assembling + testing
- <mark>vaccum system (available or buy defusing pump) 40$</mark>
¤ design
¤ خراطة + soldering
¤ vacuum and diffuision pumps gathering
¤ cooling system
¤ Testing
¤ report
- <mark>control system 40$</mark>
¤ sensors
¤ coding
¤ GUI
¤ equipment purchasing
¤ assembling
¤ testing
¤ report
- <mark>poster 20$</mark>
+ 50$ on task successfully done

Related Sites/Items on aecenar.com

System Specification	IAP - IECF
Mechanical Design	IECF Mechanical Design
Process Control System Spec./Design	PCS Design
Mechanical Realization	IECF Mechanical Realization
Process Control System Realization (PLC+GUI)	PCS Implementation
System Test Specification	Test Specification
System Testing	System Testing

1   *Introduction*

1.1   Overview

Fusion power is a form of power generation in which energy is generated by using fusion reactions to produce heat for electricity generation. In contrast to fission, fusion creates energy by combining lighter elements into heavier elements. The advantages for fusion are (1) abundant fuels, (2) no radioactive waste produced and (3) controlled side reaction. The potential of fusion to create clean energy has attracted many scientists over several decades. One idea for a safe and efficient reactor for fusion is called the "Fusor". But unfortunately, no Fusor designs have yet achieved a positive energy gain, due to the difficulty of controlling the fusion reaction. In other words, the energy needed to initiate the reaction is more than the energy produced by the reaction. The Fusor employs inertial electdrostatic confinement - the use of an electric field to confine the plasma.

1.2   Electrostatic Nuclear Fusion Reactor

The Fusor device typically consists of two wire cages called grids. The inner cage holds a negative voltage compared to the outer cage. When the fusion fuel is introduced (ioned gas: Deterium gas), the voltage will ignite the fuel. The huge electric field accelerates the ions into fusion conditions.

1.3 Concept Summary (Maryam Abdelkarim article)
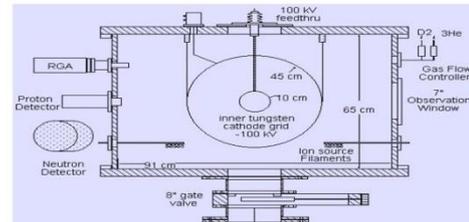

Principles

Inertial electrostatic confinement fusion does not rely on any magnetic field, and instead uses an electric field to perform the plasma confinement. The device is formed by arranging two spherical metal meshes concentrically and putting an extremely large voltage across them, typically 10 to 100 kV in vacuum. The meshes are supported by a high-voltage stalk. Fusion fuel, in this case deuterium, is then released into the chamber where the large voltage ionizes a portion of the gas. These positively charged ions are accelerated by the electric field toward the center of the device, where most will pass straight through the cathode at the center and out the other side due to the large gaps in the metal mesh. Once on the other side, the electric field slows the ions and eventually turns them back towards the center, setting up a recirculation. The ion density in the center increases, and eventually fusion occurs. This does not require nearly as large a machine as the tokamak: typical IEC devices comfortably sit on tabletops.
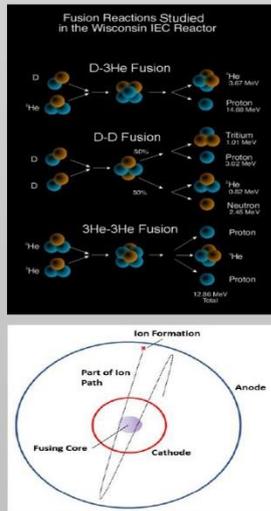
Inertial Electrostatic Confinement Fusor

University of Wisconsin-Madison IEC Device
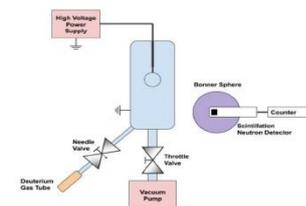
Part	Description	Material	Size
Anode wire	grounded,	stainless steel	45 cm diameter grid of stainless-steel wire
Cathod wire	-100KV DC, supported on a 200 kV vacuum feed-through. input power levels exceeding 8.5 kW at voltages ranging from -25 kV to -185 kV and at currents from 30-75 mA.	tungsten	10 cm diameter coarse-grid sphere of 0.8 mm tungsten wire
stalk (will hold the cathod)	stainless steel tubing Quartz tubing non-porous high alumina ceramic (Alumina ceramic (Aluminum Oxide or Al2O3) is an excellent electrical insulator)	stainless steel, quartz, alumnia	0.64 cm dia stanless 70 cm 1.28 cm dia quartz 55 cm 0.95 cm dia quartz 60 cm 1.91 cm dia Alumina 31 cm
Vacuum chamber	cylindric, base pressure of 2 x 10-7 torr, Experiments run steady-state within the limitations of chamber heating	Aluminum	91 cm diameter, 65 cm tall
Deuterium/ He gas tube	Electronically controlled gas flow regulators adjust the fuel flow ratio and amount into the system.		
Ion Source Filaments	2 filaments a discharge voltage and current of 80 V and 200–500 mA is maintained	thoriated tungsten filaments	
vacuum pump	450 l/s turbo pump		
high voltage supply	provides up to 200 kV at 75 mA		
neutron detector	helium proportional counter neutron detector, placed 60 cm from the center		
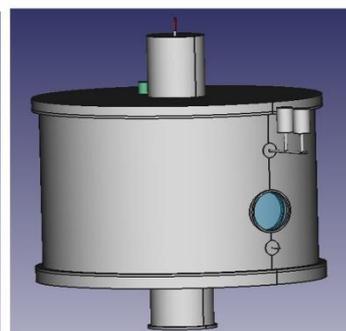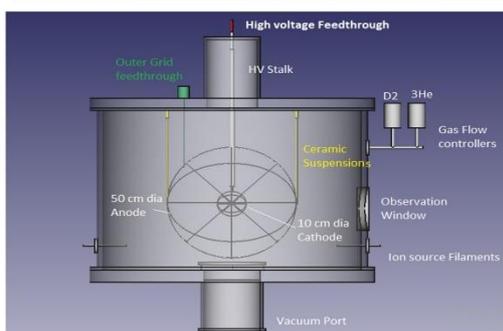
Maryam Abdel-karim
@AECENAR / July 2021

Full Documentation:

http://aecenar.com/index.php/downloads/send/3-meae-institute/731-iecf-prototype-concept-pdf

(Concept including simulation)

2   Physics

2.1 Vacuum Chamber

Explaining Vacuum

Vacuum can be defined as a space that is empty of matter; however, achieving such an empty space is essentially impossible on earth. Instead, vacuum is best described as a space with gaseous pressure much less than atmospheric pressure. Physicists and vacuum scientists describe this lack of a "perfect vacuum" in manmade chambers, such as production furnaces, as partial pressure or partial vacuum. [1]

The quality of a vacuum is indicated by the amount of matter remaining in the system, so that a high quality vacuum is one with very little matter left in it. Vacuum is primarily measured by its absolute pressure.

At room temperature and normal atmospheric pressure, one cubic foot (0.03 cubic m) of air contains approximately 7×10^{23} molecules moving in random directions and at speeds of around 1,000 miles per hour. [2] The momentum exchange imparted to the walls is equal to a force of 14.7 (psia) pounds for every square inch of wall area. [2] This atmospheric pressure can be expressed in a number of units, but until relatively recently it was commonly expressed in terms of weight of a column of mercury 760 mm high. [2] Thus, one standard atmosphere equals 760 mm Hg.

2.1.1 Boundary conditions:

- ***Pressure and forces***

The differential pressure on a vacuum chamber is obviously one bar during operation but it is recommended to check what all the intermediate steps are like, for example, an over-pressure test for qualification. 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.

- ***Temperature***

Specifying operating temperature (usually room temperature), bake-out temperature (usually between 150ºC and 300ºC), and exceptional temperature in the case of an incident (like a cool-down due to cryogen losses) together with all the transitories is a must. The effects of temperature are dilatations, stresses and changes of material properties and they may have destructive effects if badly mastered. Slow temperature transients allow the resulting stresses to be minimized but it becomes an operational constraint that is not necessarily acceptable.

2.1.2 Materials

The material parameters design are only three main ones: the modulus of rigidity (Young's modulus: E), the elastic ($\sigma_{0.2}$) and rupture (σ_r) limits.

2.2 Design

2.2.1 Basics

Stresses generated by the loads enumerated before should usually remain in the elastic range. This means that the equivalent stress shouldn't exceed the elastic limit ($\sigma_{0.2}$) anywhere in the structure.

_____

(a)   (b)   (c)
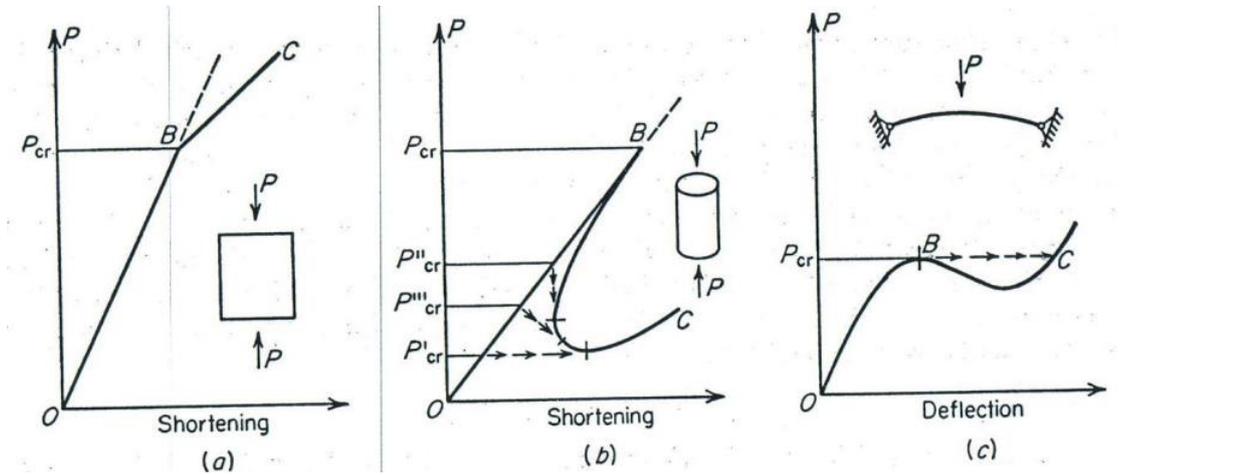
Tensile strength	115-234	σ b/MPa
Yield Strength	23	σ 0.2 ≥ /MPa
Elongation	65	δ 5≥ (%)
ψ	-	ψ ≥ (%)
Akv	-	Akv ≥ /J
HBS	123-321	-
HRC	30	-

Physical proprieties of stainless steel 306

https://www.steelss.com/Materials/Stainless-Steels/YB-306_31_804.pdf

Steel Alloys		
Metal	**Modulus of Elasticity**	
	GPa	10^6 psi
Carbon and Low Alloy Steel	200	29
Stainless Steel	193	28
Cold Drawn Wire Steel	210	30.5
Tool Steel	210	30.5

The first step of the analysis is the linear elastic one which gives all the information on a structure: displacements, strains, and stresses.

2.2.2 Tube shape

2.2.2.1 Cylindrical shape:

Tubes are obviously the most common shape for vacuum chambers.

Condition 1: Pipes having Do/t values ≥ 10

———

Where,

Do = Outside Diameter of Pipe

t = Minimum required thickness (means t = selected thickness – mill tolerance – corrosion allowance)

*If the above condition met, Allowable External Pressure **P**a can be calculated using the two equations below* as per their conditions:

If the value of factor 'B' is determined, use below equation

$$P_a = \frac{4B}{3(D_o/t)} \quad \text{Eq. (1)}$$

If the value of factor 'A' falls to the left of material or temperature curve and because of that value of factor 'B' cannot be determined, then go for the second equation below

$$P_a = \frac{2AE}{3(D_o/t)} \quad \text{Eq. (2)}$$

Where,

Pa = Allowable external pressure

A = Factor determined from Figure 'G' in a sub-part of ASME Section II, Part D

B = Factor determined from the applicable material chart in sub-part 3 of ASME Section II, Part D

E = Modulus of elasticity of the material at design temperature interpolation may be made between the lines for intermediate temperature.

Condition 2: Pipes having Do/t values < 10

*If the above condition met, Allowable External Pressure **P**a can be calculated using the two equations below* as per their conditions: **If the value of factor 'B' is determined, use below equation**

$$P_a = \frac{B}{(R_o/t)} \quad \text{Eq. (3)}$$

If the value of factor 'A' falls to the left of material or temperature curve and because of that value of factor 'B' cannot be determined, then go for the another equation below

$$P_a = \frac{0.0625E}{(R_o/t)^2} \quad \text{Eq. (4)}$$

Where,

$$A = \frac{0.125}{(R_o/t)}$$

B = Factor B will be the same as the first condition, per UG-20(c)

Ro = Outer Radius of the Pipe

E = Modulus of Elasticity

———

Note: The second condition **"Do/t values < 10"** is very rare, in most of case we need to verify pipe wall thickness calculation for external pressure under the first condition **"Do/t values ≥ 10"**.

2.3 Calculation Steps for Pipe Thickness Verification

cylinder (D0=30cm. L=35cm)   E= 193 GPa

assume a thickness t=1.5 mm. Pext=14.7 psi.

2.3.1 Step 1: Calculate Do/t

D0/t=200 >>10

2.3.2 Step 2: Calculate L/Do, this will help to find the value of factor A

L/D0=1.67

2.3.3 Step 3: Find the Factor 'A' from Figure 'G' of ASME Section II, Subpart 3, Part D

To find factor 'A' open the (Charts and tables for determining shell thickness of components under external pressure)
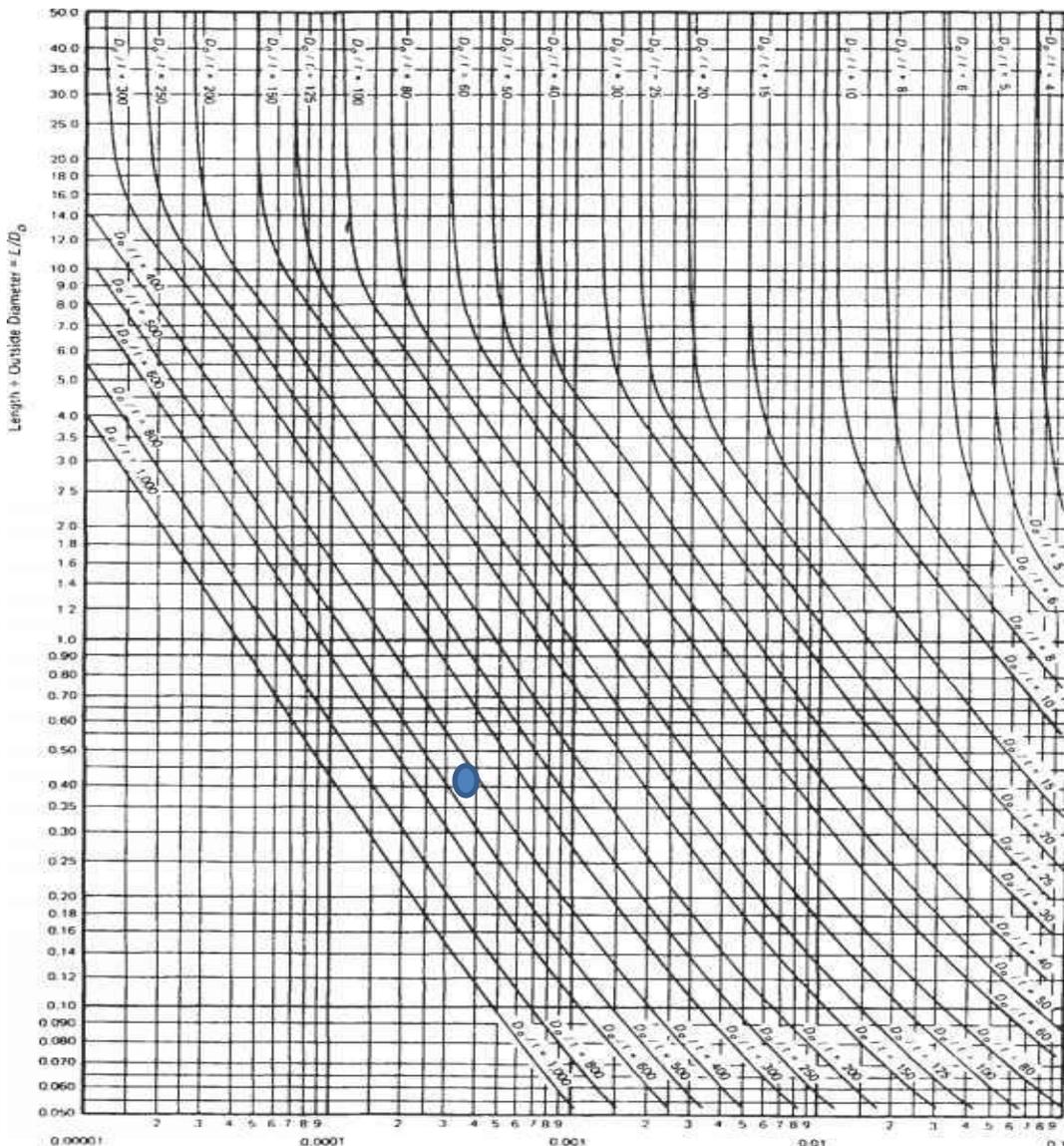
In subpart 3, go to Figure G, move vertically to see the value of L/Do, and move horizontally to see the value of Do/t. As per the calculated value match the both lines.

A=0.0003

2.3.4 Step 4: Now, Find The Factor 'B'

Using the value of factor A (for our case **A = 0.0003**) and design temperature (**300°C**), we need to find the value of factor B.

Open the applicable material chart. As for our case pipe material is SS (stainless steel). So according to the pipe material and their SMYS value select the appropriate chart, for our case, we have to refer **Figure HA-2** (refer the fig below).
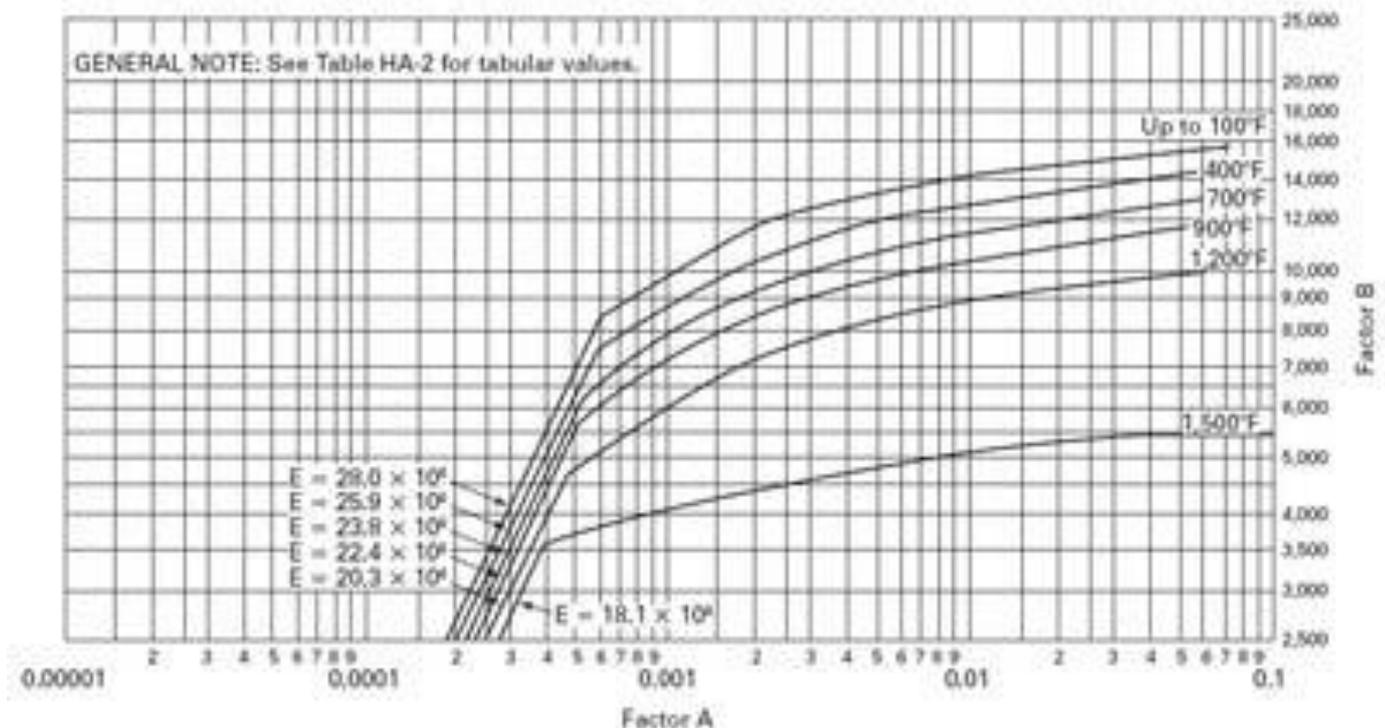
B=3800

Fig. 2: Chart for Determining Shell Thickness of Components under External Pressure For stainless Steel

Here from the figure, we can see that the value of factor A is on the right side of the material or temperature curve. So, it is clear that we will use Eq. (1) for calculating Allowable External Pressure.

Important Note: If the value of factor A would be at the left side of the curve then we will have to calculate allowable external pressure using Eq. 2 and Modulus of Elasticity (E) would be utilized in the equation.

Now, move horizontally to see the value of Factor A, select the curve according to design temperature (for our case it **300°C**), and then match the lines. We can get the value of factor B on the right side of the chart (refer above fig. 2).

_____

2.3.5 Step5: Calculate Maximum Allowable External Pressure (Pa)

Now, using the value of factor B, calculate the maximum allowable external working pressure (Pa) using the below equation:

$$P_a = \frac{4B}{3(D_o/t)} \quad \text{Eq. (1)}$$

Pa= 25.33psi t=1.5mm is safe thickness as Pa> Pext= 14.7psi .

If **P$_a$ < P,** then need to increase the selected pipe wall thickness and follow the all steps again to verify the selected pipe thickness. This practice will be repeated until and unless the condition met **P$_a$ > P**.

According to ASME CODE SECTION VIII- DIVISION – I - UG-16 (b)- minimum thickness permitted for shells and heads holding components shall be 1.6mm exclusive of any corrosion. Therefore, minimum thickness of cylindrical shell = 1.6mm.

reference: * https://www.youtube.com/watch?v=0J6ci3IxUkc

*https://www.youtube.com/watch?v=CJSaAjJMK5w

*

The most stable ones are circular ones for which a quick analysis is quite straightforward. The circumferential stress under external pressure p is simply:

$$\sigma o = PR/t$$

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

$$\sigma z = \frac{PR}{2t} + \frac{F}{2\pi Rt}$$

And the Von Mises equivalent stress to be compared to the material maximum allowable stress is

$$\sigma e = \frac{1}{2}\left[3\left(\frac{PR}{t}\right)^2 + \left(\frac{F}{2\pi Rt}\right)^2\right]^{\frac{1}{2}}$$

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

$$Pcr = \frac{0.25E}{1-\mu^2}\left(\frac{t}{R}\right)^3$$

For stainless steel and aluminum μ=0.3.

Calculation example:

.ıl alfa 🛜   8:28 PM   🔋 65% ▬

⭐ **desertfox** (Mechanical)   28 Dec 10 09:26

hi Superslinky

The cylinder a thin walled vessel so the hoop stress in the cylinder can be found by:-

    σ= P*D/(2*t)

for your case if the vessel internal pressure was 10psi then:-
    P= 10-14.7 psi = 4.7psi

    σ= 4.7 * 20/(2*0.25) = 188 psi

because the end of the vessels are capped there will be a longitudinal stress this is typically half the hoop stress.

This of course is not the full story because the end caps need stressing and I am not familiar with the Lexan material, the stressing in the end caps will depend on the shape whether flat or spherical etc.
You would be wise to look at ASME 8 or PD5500 which are both pressure vessel codes and should cover vessels under vacuum.

desertfox

Superslinky (Automotive) **(OP)**   28 Dec 10 12:06

I'm having a hard time grasping the issue with P=10-14.7 psi = 4.7 psi, if my application is a vacuum then does that change? For example, I will be applying around 12psi internally or I should say negatively to the outside atmosphere to create a "suction".

Also if I follow your calculation (assuming it's still simply 12psi wether + or -) then my calculation would be:

🔒 eng-tips.com

2.3.6 Quasi-rectangular shape approximated by beam

If approximated by a beam, the maximum deflection (w_{max}) and stress (σ_{max}) (upper and lower bounds) are

$$\frac{1}{32}\frac{pl^4}{Et^3} < w_{max} < \frac{5}{32}\frac{pl^4}{Et^3} \qquad (5)$$

$$\frac{1}{2}p\left(\frac{l}{t}\right)^2 < \sigma_{max} < \frac{3}{4}p\left(\frac{l}{t}\right)^2 \qquad \text{(not at the same location)}, \quad (6)$$

l and t being, respectively, the span and the thickness of the tube.

2.3.6.1 Windows

Special care is required for these critical items. Designed to allow particle beams to escape the vacuum Chambers without interaction, windows are thin and often manufactured with a special material. **The best shape** for resisting external pressure is **a spherical dome** but the **manufacture is difficult**

And the external ring must be quite rigid. If the window is oriented in such way that it can buckle, the Classical buckling pressure is

$$p_{CL} = \frac{2E}{\sqrt{3\left(1-v^2\right)}} \left(\frac{t}{R}\right)^2,$$

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 (w_{max}) is Not negligible.

R and t being, respectively, the radius and the thickness of the **circular window.**

$$w_{max} = \frac{3}{16} \frac{p}{E\left(1-v^2\right)} \frac{R^4}{t^3},$$
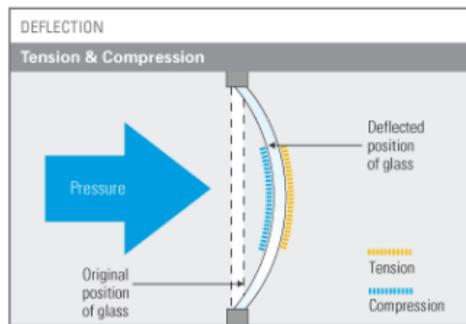
2.3.6.2 Properties

Density	25 kN/m³
Young's modulus	70 000 MPa
Shear modulus	28 000 MPa
Poisson's ratio	0,23
Hardness (Mohs scale)	6
Coefficient of thermal expansion	9·10⁻⁶ K⁻¹
tensile strength	45 MPa
compressive strength	800 MPa

*Mechanical proprieties of Glass. reference: *https://www.slideshare.net/ARGHASAHA4/vacuum-chamber-design*

Density

The density of glass is 2.5, which gives flat glass a mass of 2.5 kg per m2 per mm of thickness, or 2500 kg per m3.

Compressive strength

The compression strength of glass is extremely high: 1000 N/mm2 = 1000 MPa. This means that to shatter a 1 cm cube of glass, it requires a load of some 10 tonnes.

_____

Tensile strength

When glass is deflected, it has one face under compression and the other in tension. Whilst the resistance of glass to compression stress is extremely high, its resistance to tensile stress is significantly lower. The resistance to breakage on deflection is in the order of: - 40 MPa (N/mm2) for annealed glass - 120 to 200 MPa for toughened glass (depending on thickness, edgework, holes, notches etc.).

Elasticity

Glass is a perfectly elastic material: it does not exhibit permanent deformation, until breakage. However it is fragile, and will break without warning if subjected to excessive stress.

Young's modulus, E

This modulus expresses the tensile force that would theoretically have to be applied to a glass sample to stretch it by an amount equal to its original length. It is expressed as a force per unit area. For glass, in accordance with European standards: E = 7 x 10^10 Pa = 70 GPA

Poisson's ratio, μ (lateral contraction coefficient)

When a sample is stretched under mechanical stress a decrease in its cross-section is observed. Poisson's ratio (μ) is the relation between the unit decrease in the direction perpendicular to the axis of the effort and the unit strain in the direction of the effort. For glass in buildings, the value of coefficient μ is 0.22.

2.4 Allowable Stress (Strength)

The **allowable stress** or allowable strength is the maximum **stress** (tensile, compressive or bending) that is allowed to be applied on a structural material. The allowable stresses are generally defined by building codes, and for steel, and aluminum is a fraction of their **yield stress** (strength):

$$F_\alpha = \frac{F_y}{F.S.}$$

In the above equation, $F\alpha$ is the *allowable stress*, Fy is the *yield stress*, and $F.S.$ is the *factor of Safety* or *factor*. This factor is generally defined by the building codes based on particular condition under consideration.

2.4.1 What Is Stress?

Before looking at what causes these changes, there are a few concepts that need to be looked at first. **Stress** is the amount of forces (strength or energy) that is being exerted on an object, divided by its cross-sectional area to account for size. Larger objects are able to withstand higher forces. By using stress instead of just force, we are able to use the same yield stress for the same material, regardless of how large the object actually is. To compute the amount of stress acting on the object, use the equation:

$$\sigma = \frac{F}{A}$$

Where:

σ is stress

F is force

A is cross sectional area

2.4.2 What Is Strain?

Another important concept is **strain**, or how much an object deforms when forces are applied to it.

Most of the time this deformation will either cause the object to elongate or shorten, depending on how forces are applied. To compute strain, this change is divided by the object's original length, again to account for size.

Larger objects will have a greater change in length than smaller objects, even though they experience the same forces acting on them. To compute the amount of strain on an object, use the equation:

$$\varepsilon = \frac{\Delta L}{L}$$

Where:

ε is the strain

ΔL is the change in length

L is the original length

There are two different types of deformation: elastic and plastic.

- **Elastic deformation** will automatically reverse itself when external forces are removed. Imagine a rubber band - no matter how you stretch it, once you let go of one end it will 'snap' back to its original shape.

- **Plastic deformation** is a permanent deformation. To reverse it, an additional external force needs to be applied to return the object to its original shape. When you squeeze the middle of a plastic bottle, it compresses and stays deformed even when you let go. You'd have to add pressure to the inside or squeeze the opposite direction to return it to normal.

2.4.3 What is yield strength or yield stress?

The yield strength or yield stress is a material property and is the stress corresponding to the yield point at which the material begins to deform plastically.

2.4.4 Safety factor:

The definition of the safety factor is simple. It is defined as the ratio between the strength of the material and the maximum stress in the part.

$$n = \frac{strenght}{stress\ max}$$

When the stress in a specific position becomes superior to the strength of the material, the safety factor ratio becomes inferior to 1, this when there is danger

What it tells us basically is that in a specific area of the model, the stress is higher than the strength the material can bear.

When the stress in the model remains much inferior to the strength of the material, the safety factor stays superior to 1 and the model is « safe ».

Keep in mind that if the safety factor is way superior to 1 everywhere in your model, this is also indicating that your part may be over-engineered. In this case, this is not desirable either, because you are just wasting material resources and increasing the cost.

Safety factor must be applied to any computed buckling value: pressure vessel codes like CODAP use (3.0) but EN 13458-2 quotes only (2.0) for outer jackets.

Mathematically,

$$\text{Factor of safety} = \frac{\text{Maximum stress}}{\text{Working stress or design stress}}$$

For Brittle : It is the ratio of the Ultimate stress to the working or design stress

$$\text{Factor of safety} = \frac{\text{Ultimate stress}}{\text{Working stress or design stress}}$$

For Ductile: It is the ratio of the Yield stress to the working stress

$$\text{Factor of safety} = \frac{\text{Yield stress}}{\text{Working stress or design stress}}$$

Note: we will take 3 as a safety factor

Faces of cylinder:

Circular flat face of stainless steel:
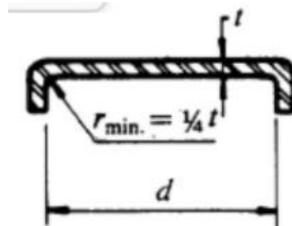
Equation applies when:

-when d does not exceed 24 in.

-th/d is not less than 0.05 or greater than 0.25.

-Head thickness, this is not less than the shell thickness, ts.

Required minimum wall thickness:

$$t = d \left(\frac{0.13P}{S \times E} \right)^{0.5}$$

Where:

P= Design pressure or max allowable working pressure, psi.

d=Inside diameter of vessel of the material.

t=Minimum thickness of shell (wall) exclusive of corrosion, inches.

S= Maximum Allowable Stress

th= Actual thickness used in actual design, inches.

tr= Minimum required thickness of seamless shell for pressure, inches.

ts= Actual thickness of shell, exclusive of corrosion allowance, inches.

E= Weld joint efficiency=0.85

Conflat Flanges:

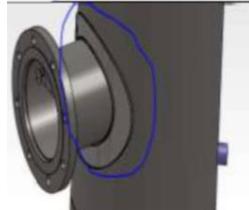The standard design method uses an increased wall thickness plate at the equator line of vessel to support the additional stresses caused by the attachment of the legs. The formula for calculation the wall thickness of a segmented plate of to be welded in a vessel or spherical shells is:

$$t = \frac{PL}{2SE - 0.2P} + C$$

$$L = Di/2$$

t=Minimum design wall thickness (in);

P=Design Pressure (psi);

Di=Inside Diameter of sphere (in);

L=Sphere Radius (in);

E=Tube welding factor (1 for seamless pipe, 0.85 for welded pipe)

C= Weld Corrosion Allowance (0 for no corrosion, 0.0625 in commonly used, 0.125in maximum);

S= Maximum Allowable Stress.

2.5 Grid Design

A grid consists of a sphere wire structure and is connected to the high voltage feedthrough. The diameter size of the grid is usually about 20% of the diameter of the outer sphere (anode). Should we have an anode sphere with a diameter of 20 cm than the diameter of the grid should be 4 cm. The material for the grid can be stainless steel wire because it permits welding but in order to resist the high temperatures that can occur in the grid also tungsten or tantalum wire is used.

This particular jig is suitable for winding a grid with a diameter of 1.5" or 38 mm. It requires two 14" or 360 mm lengths of wire (tungsten or tantalum). The crossing intersections can be spot welded for a better rigidity.

Experiments in IEC research have demonstrated that fusion efficiency increases when the grid transparancy is greater than 92%.

The grid transparancy can be calculated as follows:

((Grid Surface Area - Wire Cross-section Area)/Grid Surface Area) x 100% = %Transparancy

For which, assuming that the grid is a perfect sphere:

Wire Cross-section Area = Total Length of Wire per Loop x Diameter Wire x Number of Wire Loops = Grid Circumference x Diam. Wire x Number of Wire Loops = 2πrnd
And
Grid Surface Area = 4πr2

Transparancy = ((4π*r2 -2π*r*n*d)/4π*r2) x100%, which can be reduced to

Transparancy = ((r - ½*n*d)/r)) x 100%

In which: r = radius of the grid

n = number of wire loops

d = diameter of wire

Example: The grid in image 10 has a diameter of 38 mm (a radius of 19 mm), is made of wire with a diameter of 0.23 mm and has 3 loops. The transparancy is according to the formula:
(19 - ½*3*0.23)/19 x 100% = 98.2%

Based on the availabel materials in our country, we found the best choice is stainless steel wire (diametre d=1.6mm). n=3   d=1.6mm   radius of loop r= 3.5cm

transparancy= 93.14% > 92%

verify.

The grid transparancy can be enhanced effectively to exceed the geometrical transparancy by focusing the grid carefully inside the vacuum chamber, i.e. by placing the grid precisely concentric with the outer vacuum chamber sphere. Precise focusing can result in the Fusor operating in "star mode" which causes channelization of the ions into distinct rays converging from the center of the

———

grid. The rays (ion paths) go through the grid openings and stay clear from the grid wires. As a result the ion recirculation factor may increase to 100 or higher.

The material for the grid wire can be stainless steel but should preferably be tungsten or tantalum. During operation of the Fusor the grid wire becomes hot and stainless steel will not keep its shape but will start sagging. Tungsten is the best choice because of its low vapor pressure, its great tensile strength and its high melting point of 3422°C. However, it is not very suitable for spot welding and therefore an alloy of tungsten and rhenium can be used or tantalum wire.

The grid transparancy calculation shows that a thin wire contributes to a high transparancy. It should however be noted that too thin a wire might cause a problem. In a Fusor with a relatively high vacuum and a high voltage potential of 25 kV on the Tungsten wire nothing will happen as long as a plasma short cut (from grid to Fusor wall) does not occur.

The resistivity of Tungsten is 5.6×10^{-8} Ω/m and the resistance of a wire is calculated according to:

$$R = (p \times l)/w$$

For which
R = resistance
p = resistivity
l = length
w = width

The formula shows that the width (diameter) of the wire is inversely proportional to the resistance, or with other words; a thinner wire has a larger resistance. In case of a plasma short cut our very thin wire might probably light up in a flash to white hot and burn away. Or maybe not?? In a hypothetical example we assume that a plasma short cut occurs at a quarter length of one of the wires (360 mm long) that make our grid, i.e. the path length for the current is 90 mm, the width of the wire is 0.23 mm, the resistivity of the Tungsten wire is 5.6×10^{-8} Ω/m and the Fusor is operated at 25 kV. We also assume that the plasma has no resistance (which is incorrect but we have no data for a deuterium plasma at given pressures). The formula yields a resistance of the wire path length of 2.2×10^{-5} Ω, which at 25 kV theoretically might draw a current of about 10^9 A. This high amount of current has the effect of a true short cut. Fortunately, the Fusor is not capable of supplying such an extreme current as the power supply is limited at 15 mA before it cuts out. In fact, our tungsten wire of 90 mm length and a diameter of 0.23 mm will be emitting maximally a power of 25 kV at 15 mA which equals 375 W. The surface area of the wire is $2\pi rl$ or $2 \times 3.14 \times 0.115 \times 90$ = 65.031 mm² or 6.5×10^{-5} m²

According to the Stefan Boltzmann law for the power per unit area:

$$I = \sigma T^4$$

Where σ = the Boltzmann constant, 5.670373×10^{-8} W m⁻² T⁻⁴, the temperature of the wire will be

$$T = \sqrt[4]{\frac{375}{(6.5 \, x10^{-5}) \, x \, (5.670373 x10^{-8})}} \ K$$

Or T = 3176 K which equals 2903 °C. This calculation is an approximation as several parameters have not been taken into account, such as the true effective area, heat loss through conduction into the feedthrough and heat loss to gas molecules around the wire, etc. Nevertheless the result is below the melting point of Tungsten (3422 °C) and therefore the grid will probably become white hot when the maximum current flows through it during a short cut, but the grid will probably not be destroyed.

Our example clearly demonstrates that for developing a grid we should take into account the diameter of the wire and the type of material to be chosen. With materials such as tungsten it will be possible to apply a thinner wire and this will improve the grid transparancy.

In this prototype:

$$\text{Voltage } V=12kv \qquad \text{current } I=30mA$$

$$L=2\pi r=0{,}2198 \text{ m}$$

P= UI= 360 watts.

$\pi dL= 1{,}104\times10^{-3}$

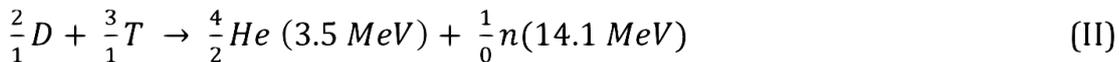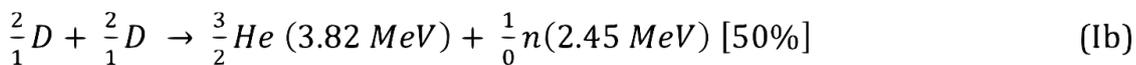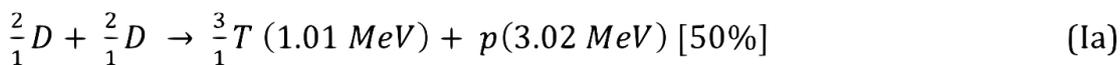T= 1548.49 k= 1275.49 ^{0}C < 1400^{0}C melting Point of stainless steel(1400 to 1530).

Verify

Reference: http://fusor.eu/theory.html

3 Fuel of Fusor reactor

The fuel for the Fusor is Deuterium gas, which is injected into the vacuum chamber through a precision regulated valve. Injected means here that the precision valve is slightly opened and the high vacuum in the vacuum chamber (reactor) draws Deuterium gas into the vacuum reactor. The applied high voltage in the reactor ionizes Deuterium to Deuterium ions (Deuterons).

For obtaining a maximally fusion rate a direct relationship exists between the pressure of Deuterium in the reactor (Deuteron density) the applied potential difference and the current. The higher each one of these three parameters, the higher the fusion rate, though an optimum appears to exist for these parameters. When the parameters have been optimized, fusion for D-D occurs according to the following reactions:

$$\frac{2}{1}D + \frac{2}{1}D \rightarrow \frac{3}{1}T \ (1.01 \ MeV) + \ p(3.02 \ MeV) \ [50\%] \qquad\qquad \text{(Ia)}$$

$$\frac{2}{1}D + \frac{2}{1}D \rightarrow \frac{3}{2}He \ (3.82 \ MeV) + \frac{1}{0}n(2.45 \ MeV) \ [50\%] \qquad\qquad \text{(Ib)}$$

$$\frac{2}{1}D + \frac{3}{1}T \rightarrow \frac{4}{2}He \ (3.5 \ MeV) + \frac{1}{0}n(14.1 \ MeV) \qquad\qquad \text{(II)}$$

The first stage reactions! a and! b have equal opportunities to occur and yield Tritium (as Tritons), Helium-3 (as a Helium-3 nucleus), a proton, a fast neutron and energy.

The second stage reaction is between Deuterons present in the reactor and Tritons formed in reaction Ia and yields Helium-4 (as nucleus) and a fast neutron. The neutron formed in reaction II has such a high energy that is carries away 80% of the energy formed in this reaction.

The second stage reaction has also the probability for fusion between Deuterons present in the reactor and Helium-3 nuclei formed in reaction Ib:

$$3He + 2D \rightarrow 4He \ (3.6 \ MeV) + p+ \ (14.7 \ MeV) \qquad\qquad \text{(III)}$$
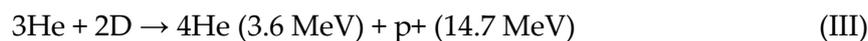
This reaction yields Helium-4 nuclei and a high energy proton, but the reaction is less likely to occur because the peak energy required for this reaction is much higher than for the D-D reactions.

In practice we usually deal with the reactions! a, Ib and II.

Deuterium can be obtained as gas in lecture bottles and as Deuterium oxide (heavy water). When obtained as heavy water, Deuterium needs to be liberated as gas by electrolysis of heavy water.

3.1 Deuterium Gas

Deuterium gas is available in lecture bottles, typically e.g. 38 liters at a pressure of 100 kgf/m2 (atm). It is a highly flammable gas and air shipment of Deuterium cylinders is not allowed. This limits the possibility of buying Deuterium gas and it explains why Deuterium oxide is quite popular amongst fusioneers, despite the fact that an electrolysis unit will have to be built. The costs of an electrolysis unit, however, is more or less comparable with the costs of the pressure regulator that will have to be applied to extract the gas from the high pressure lecture bottle and convert it to a low pressure

———
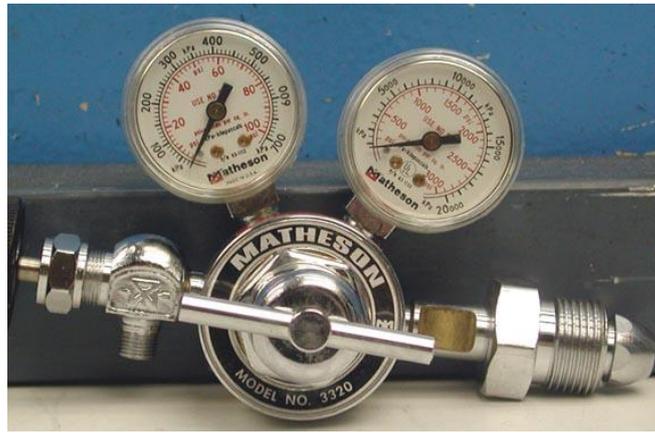
The pressure regulator should preferably be of the two stage type, intended for Hydrogen and produce an output pressure as low as possible. When operating a spherical Fusor with a diameter in the range between 160 and 200 mm, a volume of Deuterium will be used of approximately 1 to 1.5 sccm, i.e 1 - 1.5 milliliter per minute at normal pressure and ambient temperature. A single bottle of Deuterium will therefore last for many years of Fusor operation experiments.

In our fusor we use an autoclave cylinder (D0=30cm. L=35cm):
Volume = $\pi R^2 *L$ = 24727.5 cm3
  Sccm unit (standard cubic centimeters per minutes)

Sphere D= 200 mm   Vs= 4/3 π R^3= 4186 cm3

1.5 sccm   →   4186 cm3
??   ←   24727.5 cm3

So in our reactor we will use a volume of Deuterium approximately 8.8 Sccm
8,8 ml/minute.

3.2 Deuterium Oxide

When obtained as heavy water (image 2), Deuterium gas needs to be produced by electrolysis to make it suitable for feeding into the reactor.

The density of heavy water is 1.107 g per ml and the molar mass of heavy water is 20.0276 g per mole. One mole of Deuterium oxide will yield two Deuterium ions or one Deuterium gas molecule. From a commercial volume of 100 ml of heavy water therefore almost 101 liters of Deuterium gas, at standard pressure and temperature, can be electrolyzed as calculated below.

Calculation:

Mass D2O = 100 ml x 1.107 g/ml = 110.7 gram

Molar mass D2O = 20.0276 g/mole

Moles D2O = 110.7 g / 20.0276 g/mole = 5.52 moles

One mole D2O is equivalent with a volume of 22.4 liter D2O vapour

5.52 Moles equal 5.52 x 22.4 = 123.8 liters of D2O vapour

D2O gas <=> 1 (D2 gas) + 0.5 (O2 gas)

1 mole gas <=> 1.5 mole gas

mole ratio = 1.5

The volume of the elemental gases is: Volume D2O gas x mole ratio = 123.8 liter x 1.5 = 185.7 liter or approximately 186 liter D2 gas and 93 liter O2 gas are formed by electrolysis.

The average price of 100 ml heavy water 99% is about 120 USD, hence one liter of Deuterium gas (after electrolysis) for amateur fusioneer use costs about 0.65 USD.

Under similar conditions as described in the paragraph about Deuterium gas, a volume of 100 ml of heavy water (when electrolyzed without losses and transferred into the Fusor) will enable continuous Fusor operation during more than 70 days.

3.3 Traditional Electrolysis

A method to extract Deuterium from heavy water is by means of electrolysis: an electrical current is passed through heavy water by using two inert metal electrodes, preferably made of platinum. Deuterium will appear at the negatively charged electrode, the cathode, and Oxygen will appear at the positively charged electrode, the anode, conform the overall chemical reaction:

$2D_2O \rightarrow 2D_2 + O_2$
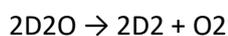
The theoretical voltage to be applied is for starting electrolysis is 1.48V, but usually higher voltages will be used. As an electrolyte a solution of Sodium hydrogen carbonate (NaHCO3 [baking soda] analytical grade) needs to be added.

Do not add Sodium chloride as this will produce Chlorine gas together with Deuterium gas from your electrolysis cathode.

The highest production of Deuterium gas will be obtained when performing electrolysis in a 0.4M solution of NaHCO3 in heavy water, i.e. at pH 8.2 of the solution (reference 1). A 0.4M solution of NaHCO3 (molar mass is 84.00661 g/mol) will be obtained by dissolving 3.36 gram of NaHCO3 in 100 ml of heavy water. From a strictly theoretical point of view adding (highly pure) baking soda to heavy water introduces Hydrogen atoms into the solution, which will join Deuterium at the cathode as an impurity in Deuterium gas. To avoid this, we could add NaDCO3, which is not commercially available and needs to be synthetisized by leading CO2 gas through a Sodium carbonate (soda, Na2CO3) solution, consisting of Na2CO3 dissolved in heavy water. A method to do this could be performed by dissolving a molar equivalent amount of Na2CO3 (i.e. equivalent to 0.4M NaHCO3) in a chosen volume of Deuterium oxide (heavy water) and bubbling CO2 gas through the solution (by means of an aquarium air diffusor) untill more or less a pH of 8.2 will be obtained. This is apparently quite a lot of work and it remains the question whether the created H2 impurity in Deuterium gas is of importance in the overall process of fusion in our Fusor.
Similarly to the H2 impurity in Deuterium, CO2 gas will join Oxygen gas as an impurity at the cathode, when we use either NaHCO3 or NaDCO3, but that is of no concern to us as gases at the anode are of no use for the Fusor and are allowed to escape in the air.
A more important disadvantage of the classical electrolysis process is that in the gas line following the electrolysis cell a (rather large capacity) gas dryer needs to be installed because the electrolysis produces moist Deuterium gas (saturated with heavy water). This occurs because the Deuterium gas bubbles up from the cathode through heavy water before it arrives in the output gas line. This is a very efficient way to saturate gas with heavy water.

3.4 PEM Electrolysis

Electrolysis with a polymer electrolyte membrane (PEM), also called proton exchange membrane (PEM), is electrolysis of (heavy) water in a cell with a solid polymer electrolyte that is responsible

for conduction of Protons (for heavy water read "Deuterons"), separation of product gases and electrical insulation of the electrodes (reference 3). The cell material is Nafion, a sulfonated tetrafluoroethylene based fluoropolymer-copolymer, with a thickness of 100-200 μm (reference 4).

The PEM cell is a highly efficient way to produce Deuterium gas with a very high purity (99.999%) with no cross over of oxygen. There is some doubt about the statement that the cell produces dry gas because the membrane itself is hydrated and therefore it is believed that the Deuterium gas produced in the cell can be saturated with (heavy) water and in that case it would not harm to add a Drierite column in the Deuterium gas line. It is a fact, however, that heavy water resides at the anode side of the (wet) membrane, where Oxygen is produced. There are therefore no doubts that the Oxygen gas is saturated with heavy water and it might be worthwhile to consider a cold trap in the Oxygen line in order to retain heavy water from the Oxygen gas outlet. A nice calculator to calculate how much heavy water is contained in a volume of saturated Deuterium gas can be found in reference 5.

Advantages of the PEM cell are further that it can operate at elevated temperatures (50-80°C), it has a high current density (0.6-2.0 mA/cm2), a cell operating voltage of 1.75-2.20V and it can produce gas at a high pressure (stack pressure < 30 bar). The latter is not possible with the cell from images 4 and 5 because the housing is made of plastic and will burst when subjected to high pressures.

For the production of Deuterium gas for a Fusor one single cell is usually sufficient because a (Nafion) cell surface of 10 cm2 produces about 2 liter Deuterium per hour at ambient temperature and pressure. The commercial PEM cell as shown in images 4 and 5 has a Deuterium production of 5 ml per minute when operated at 2.0 V DC at 700 mA current. That is a production rate of five times the required Deuterium input for a Fusor! In order to regulate the flow rate from the cell to the intake rate of the Fusor, a (preferably automatic) system needs to be developed for a PEM cell Deuterium line.

Fortunately for the fusioner, PEM cells are easily available either as a single cell (approx. 40 - 45 EUR) or as part of an educational kit (approx. 55 EUR) as shown in image 3:


Image 3

The Horizon Solar Hydrogen Educational Kit contains the PEM cell, a solar panel, an electric motor, a propellor, reservoirs for collecting Hydrogen and Oxygen, a battery holder for two 1.5V AA batteries (useless, because the cell eats a lot of power and the batteries will not last long), wires and

plugs, tubing, stands for the reservoirs and the cell and a CD-ROM with information and experiments. The dimensions of this PEM cell are 65x65x20 mm and it has a weight of 87 grams (empty). More about this and similar kits can be found in reference 6.

For the Fusor we are only interested in the PEM cell (images 4 and 5) , the wiring and the tubing.

For those who want to construct their own PEM cell, the membrane is available at a price of approx. 16 EUR for a square piece of 10 cm2 (sides of 3.3.cm). The power requirements are 1 A per cm2 at 0.6V. The reason for constructing a PEM cell might be for producing Deuterium at high pressure or at a higher capacity by stacking cells. In that case the housing(s) of the cell(s) must be made of SS (stainless steel or inox or rostfrei) steel.
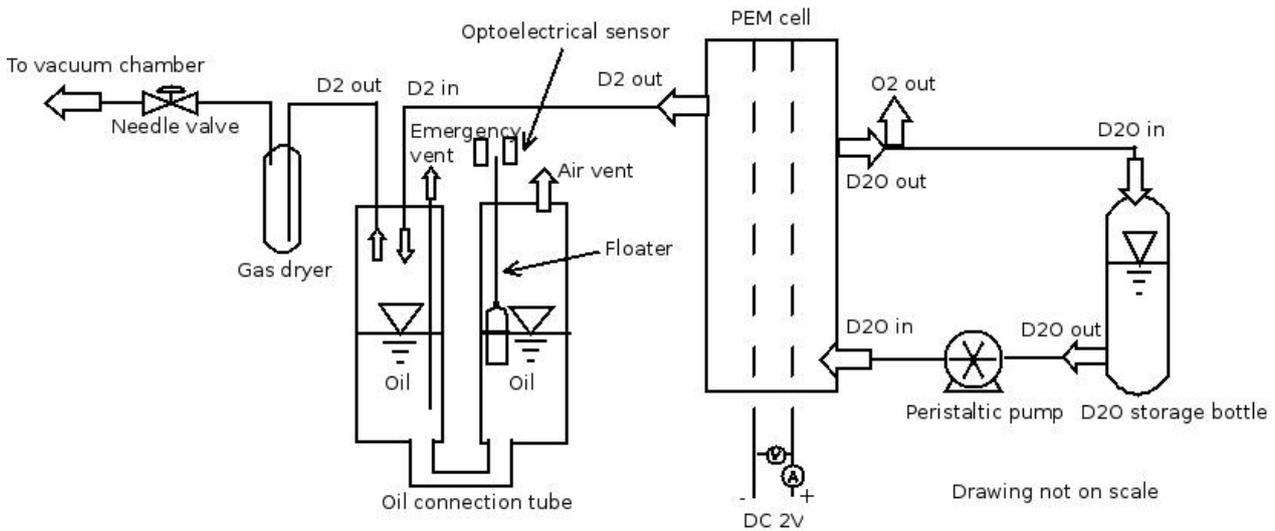
Layout of PEM cell electrolyser

3.5 Ionization of fuel Atoms

In order to operate the Fusor it needs a supply of nuclei to be accelerated, a fuel, which is fed into the Fusor as a gas that will become ionized. Because the Fusor operates under a high vacuum, the fuel gas is "leaked" into the vacuum chamber (reactor) by means of a precision regulated valve.

The ionization of gas molecules, e.g. Deuterium gas, occurs in a sufficiently strong electrical field wich is created between the outher wall of the vacuum chamber, the anode, and the inner grid, the cathode. When a sufficient amount of energy is transferred to a bound electron, i.e. when the threshold of the ionization potential is exceeded, a free electron is created which will drift towards the anode leaving a positively charged ion which will drift towards the cathode. In a sufficiently strong electric field the liberated electron will gain sufficient energy to liberate a further electron

when it collides with another molecule and the process of gaining energy now proceeds for two electrons which will liberate each another electron, and so on. Free electrons not only originate directly from ionized gas but are also generated by cosmic rays colliding with gas molecules and thus exciting them to higher energy states. The free electrons originating from cosmic rays interaction are called "seeding electrons" because they are at the basis of the process of generation of secondary free electrons. Another source of free electrons is the cathode (grid) in the Fusor, which releases electrons when under high voltage.This chain reaction of electron generation is called a Townsend avalanche. It depends on the free electrons gaining sufficient energy between collisions to sustain the avalanche. The final state of the Townsend avalanche is the Townsend breakdown, which is the situation when the gas suddenly changes from being a dielectric to a conductor by clouds of free electrons conducting the current between cathode and anode.

The next step in the ionized gas process is formation of a plasma, another fundamental state of matter next to solid, liquid and gas. A plasma has similar conductive properties to that of metals and this can be observed by a sudden raise in current between the electrodes once the state of plasma has occurred, possibly followed by plummeting of the voltage (depending on the type of HV power supply).

Characteristics of a plasma are the high electrical conductivity and the response to magnetic fields. Plasma is usually quasineutral, i.e. positive and negative particles are more or less in equilibrium. However, plasma of monocharged particles do exist but the density must generally be very low, or it must be very small, otherwise it will be dissipated by repulsive electrostatic force. For plasma to exist, ionization is required and the degree of ionization is the proportion of atoms that have lost or gained electrons and is controlled by the temperature of the plasma. An inert electrostatic confinement plasma can have a particle density of 10^{32} per m³ and the temperature of the same plasma can reach 10^8 Kelvin. In an IEC device the plasma concentrates in the center of the hollow cathode, the Poisor, basically a spherical focus diode. When pressure in the vacuum chamber and high voltage have the right conditions the ion density in the Poisor increases until a glowing ball of plasma will be formed. When the plasma is fed with a higher grid voltage with a correspondingly higher current a dense plasma focus will result and a plasma-magnetic entity will be formed in the Poisor: a plasmoid. The plasmoid goes through different shapes when the power is further raised: bugle mode, jet mode and star mode. In bugle mode the ball shaped plasmoid has a trumpet-shaped ion blow-out, in jet mode the ion blow-out is a sharp line and in star mode brilliant rays are ejected from each aperture of the inner grid.

At higher pressures and at a too high starting potential electric discharges may occur before the Fusor comes into glow discharge mode: Depending on the pressure of the gas in the vacuum chamber, the voltage applied between cathode and anode and the distance between these electrodes, an electric discharge through the plasma and the avalanching free electrons cloud may occur. An electric discharge is however not what we want in an operating Fusor and it is therefore desirable to know the conditions under which discharges may develop.

———

The voltage necessary to start a discharge or electric arc, between two electrodes in a gas as a function of pressure and gap length is called the breakdown voltage (as described above) and can be defined by an equation known as Paschen's Law:

$$V = \frac{apd}{\ln(pd) + b}$$

in which:

V = breakdown voltage in volts

p = pressure in bar

d = gap distance in meters (i.e. distance between anode and cathode in the Fusor)

a and b are constants depending on the composition of the gas

The breakdown voltage depends on the mean free path (MFP) of the particles which increases with decreasing pressure. The MFP is the average distance a particle travels before colliding with another particle. The relationship between pressure and voltage is flat at higher pressures, goes through a minimum voltage, and then asymptotically rises as the mean free path exceeds the electrode spacing.

A graph based on the equation is the Paschen curve, as shown in image 5 for a number of gases.
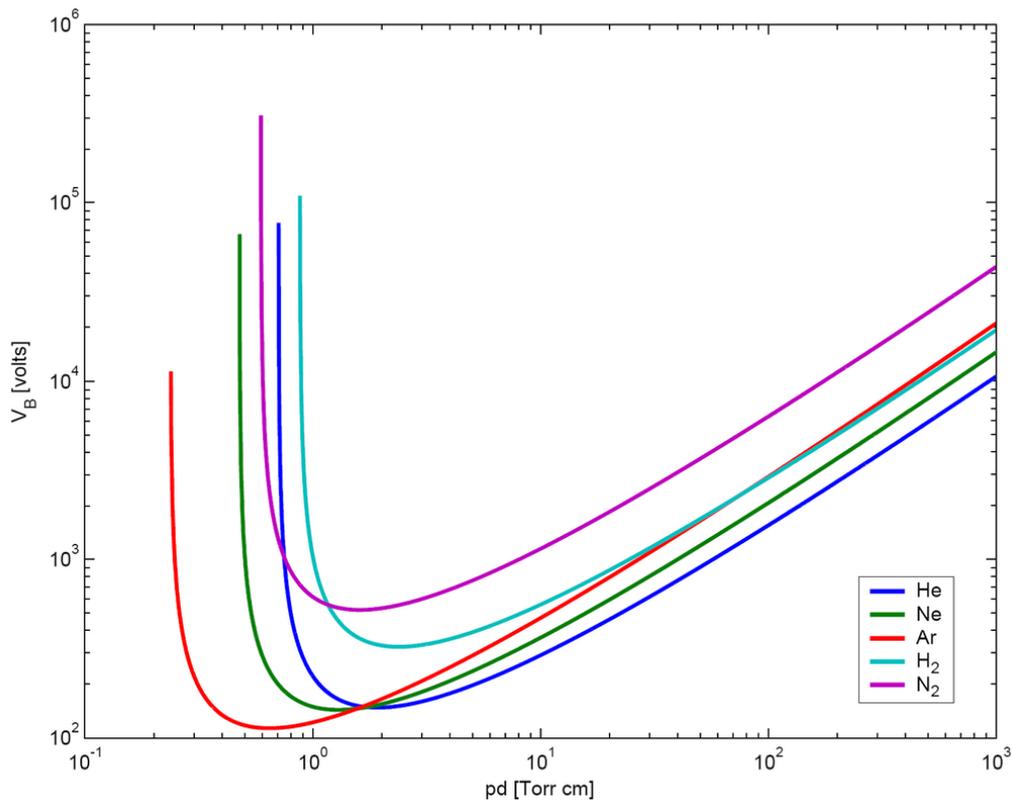

Image 5: Paschen curves obtained for helium, neon, argon, hydrogen and nitrogen, using the expression for the breakdown voltage as a function of the parameters A,B that interpolate the first Townsend coefficient.

The breakdown voltages in the curve from image 5 have been drawn for gases that are not of interest for use as fuel in a Fusor. We have collected some data for Deuterium and plotted a graph as shown in image 6:
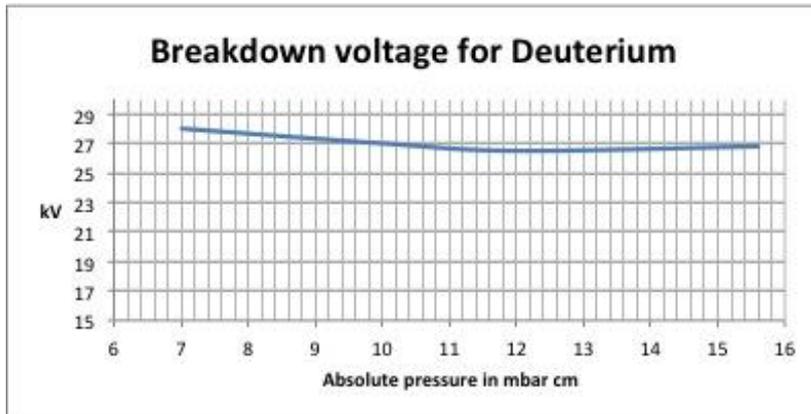
Breakdown voltage for Deuterium.

The graph of image 6 shows that for the high voltage region of interest (ROI) for a Fusor, 26 to 30 kV, the voltage breakdown for Deuterium occurs at absolute pressures ranging from 7 to 16 mbar cm.

It is difficult to draw conclusions from these data because not much has been published on the relationships between voltage, current and pressure in IEC devices. The graphs relating to Paschen's Law are based on measurements with flat plate electrodes but in an IEC reactor the cathode is spherical and hollow. It is, however, known that the geometry of the electrodes have a significant effect on the results (streamer discharge concept).

The Townsend breakdown mechanism is only valid for slowly rising voltages and low pressures. The resulting discharge is diffuse of shape. At fast rising voltages and when the product between pressure and anode/cathode distance is sufficiently large, a distortion of the electrical field may occur yielding a filamentary channel (or streamer) bridging the anode/cathode gap.

When we summarize our findings from these first two chapters it becomes clear that:

- Fusion takes place only when the average kinetic energy of nuclei is sufficiently raised (to overcome the Coulomb barrier) by accelerating their speed and increasing the density of nuclei in the center of the IEC recator;

- This is achieved by creating a potential well between electrodes, i.e. a sufficiently high voltage is created between cathode and anode;

- A vacuum inside the IEC reactor is required to maintain the high voltage potential field which 'powers' the fusion reaction, to eliminate contamination of the fusion process with unwanted and unsuitable nuclei, to prevent heat damage to the fusion reactor and -most important of all- to enable formation of plasma;

- A suitable 'fuel' will be required that gets ionized and creates a plasma; nuclei (ions) of the fuel are accelerated and may fuse;

———

- • The conditions of pressure, high voltage between electrodes and electrodes distance should be such that voltage breakdown in the plasma/electron cloud will be prevented, i.e. electric discharges between the electrodes are unwanted.

3.6 Choice of Energy

The fusion process in the Fusor is thermonuclear fusion, or hot fusion, not to be confused with cold fusion processes or low energy nuclear fusion (LENR).

In our Fusor we apply a voltage of (e.g.) 25 kV and an electrostatically accelerated Deuteron (an ion with a charge +1) which passes through the grid has gained a kinetic energy of 25,000 electronvolts (25 keV). When multiplied with 11,604 to obtain Kelvin we find that in the heart of our Fusor a temperature exists of more than 290 million degrees Kelvin.

Somewhat surprisingly it is not heat that is the key to achieve fusion but it is velocity caused by electrostatic acceleration. From the Maxwell–Boltzmann distribution (or Maxwell speed distribution) for particle speeds in idealized gases the following equation for velocity v of a particle was developed:

Equation I

$$v=(2KT/m)^{½}$$

Where:
v is velocity of a particle
K is the Boltzmann constant=$1.4*10^{-23}$ JK-1
m is the mass in kg
T is the temperature in K.

The equation shows that a direct relationship exists for the velocity of a particle and temperature and also that heat is a means to achieve speed (and vice versa as shown in our 25 keV Fusor example above).

It appears that this is a very crucial point because large governmental institutions are struggling for decades now to achieve fusion by heating gas with convential means in tokamaks (e.g. ITER) and high power lasers (e.g. HiPER), whereas the answer may be found in using a more simple and direct way to obtain high velocity by using electrostatic acceleration.

At fusion energies (> 10 keV) the fusion reactants exist in a plasma state because the ionization energy for Deuterium of 15.47 eV is highly exceeded. The plasma in a Fusor turns into a Poisor (a plasma focus, plasmoid) when a mean free path for particles (ions) has been reached comparable to the vacuum chamber radius. In general, extending the mean free path of particles is achieved by lowering the pressure in the vacuum chamber as can be derived from equation II, the equation for calculating the mean free path of a particle:

$$\ell = \frac{k_B T}{\sqrt{2}\pi d^2 p}$$

where:

l is the mean free part for particles k_B is the Boltzmann constant in Joule per Kelvin $(1.3806488(13)\times10^{-23}$ JK-1

T is the temperature in Kelvin

d is the diameter of gas particles in meters

p is the pressure in Pascal

some mean free path values for air at room temperature at different pressures, which have been listed in table 1:

Vacuum range	Pressure in mbar	Molecules per cm^3	Mean free path
Ambient pressure	1013	2.7×10^{19}	68 nm
Low vacuum	300 - 1	10^{19} - 10^{16}	0.1 - 100 µm
Medium vacuum	1 - 10^{-3}	10^{16} - 10^{13}	0.1 - 100 mm
High vacuum	10^{-3} - 10^{-7}	10^{13} - 10^9	10 cm - 1 km
Ultra high vacuum	10^{-7} - 10^{-12}	10^9 - 10^4	1 km - 10^5 km
Extremely high vacuum	$> 10^{-12}$	$< 10^4$	$> 10^5$ km

When the mean free path of a particle in a sphere shaped Fusor exceeds approximately three radii, the particle will start recirculation and when the pressure is further lowered (i.e. the mean free path further enlarged) the particle will start to oscillate back and forth through the plasma focus until the mean free path has been reached or until a (negatively charged) cathode wire of the grid is met and the (positively charged) particle ceases to exist .

the recirculation of ions occurs when the mean free path of the ions exceed the diameter of the vacuum chamber; after all the particles cannot escape from the vacuum chamber to accomplish their mean free path. Therefore, particles which have passed the plasma focus will decelerate, reverse their direction and accelerate again towards the plasma focus, taking another opportunity to collide and fuse or to end their existence as an ion when caught by a grid wire. In a Farnsworth-Hirsch Fusor an ion generally makes about five recirculation passes before it ends against the grid. In an ideal situation a grid wire should be infinitely thin, which is impossible, and the concept of grid transparancy has been developed for constructing a grid with the best possible open structure for the Fusor.

The general rule of five recirculation passes proved to be incorrect when the grid is geometrically good designed and accurately placed in the vacuum chamber. Very precisely adjusted Fusors may show the George Miley effect, where the plasma turns into the "star" mode. Apparently this is a phenomenon where ions seem to avoid hitting the grid and will travel through void places in the grid and form star-like rays, which named this plasma mode.

The equation that defines fusion rate for a plasma with a constant particle density is:

Equation III	$f = n_1 n_2 \sigma v$

or, when taking into account that particle velocity in general has a Maxwellian distribution it makes sense to average σv over the integral region of the relative velocity:

Equation IV	$f = n_1 n_2 (\sigma v)$

where:

f is the fusion rate or reaction rate (fusions per volume per time, i.e. per cm^3 per second)

n_1 and n_2 are the densities of two colliding ion species in particles per cm^3

———

σ (sigma) is the reaction cross section in *barns*

v is the relative particle velocity in cm/sec

It should be noted here that nowhere in the equation (II or III) temperature appears because the fusion process deals only with densities, dimensions and velocity.

The term (σv) is called the reactivity, the appropriate average of the fusion cross section σ over the relative velocities v, expressed in units of cm^3 /sec. A plot of reaction rates versus kinetic temperature is shown in image 10, similar to images 8 and 9. The plot clearly shows that D-D fusion rates increase with increasing energies (temperatures): at 10 keV just over 10^{-24} m^3/sec and at 30 keV approximately 10^{-23} m^3/sec.
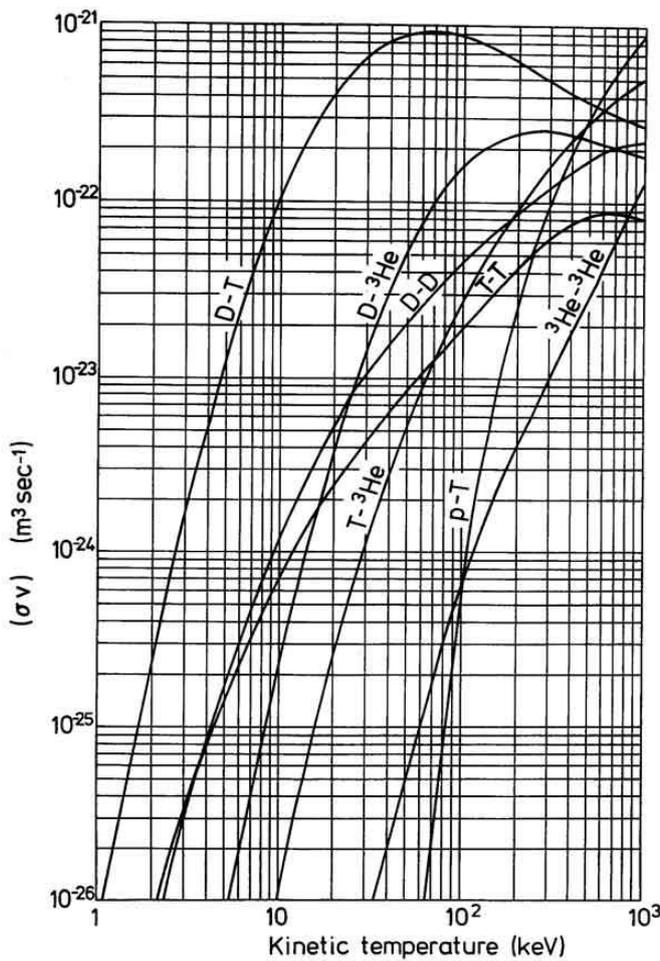

Image 10: Fusion rates for some fusion reactions

The reaction cross section σ is a measure of the probability of a fusion reaction as the function of the relative velocity of two reactant nuclei. The cross section is expressed in *barns*, a surface unit with the approximate dimensions of the nucleus of an atom, where 1 *barn* is 10^{-24} cm^2.

When nuclei are reacting with itself (as in our D-D fusion reaction), the product $n_1 n_2$ becomes $\frac{1}{2}n^2$:

Equation V	$f = \frac{1}{2}n^2(\sigma v)$

At first sight equation V seems quite logical apart maybe from the factor ½, which of course obviously is explained by the fact that when nuclei react with itself the given density of nuclei (i.e. number of particles per unit volume) is reduced to half that nucleus density or with other words, the factor ½ has been introduced into the formula to avoid counting the same interaction twice.

The value v may require frame-shifting assuming that one particle is moving and the other is stationary because that is how cross sections were measured in experiments with linear accelerators (reference 23). Fusors are ion accelerators but certainly not linear accelerators with a stationary target and this has nasty consequences for finding a mathematical model as shown in the next paragraph.

Equation V should enable to calculate the fusion rate of a Fusor but unfortunately fusion reactions in a Fusor are far from predictable and are difficult to catch in mathematical equations. The reason for this complexity is that particles in a Fusor do not have a fixed kinetic energy and the paths they follow are not straight beams. Particles may be orbiting in circular or elliptical orbits. The kinetic energy of a particle in a Fusor depends on its location in the Fusor, except for those particles orbiting in circular paths, etc. Furthermore, fusion reactions in a Fusor do not occur only in the plasma focus inside the grid but also just outside the grid and possibly also with non-ionized Deuterium gas near the walls of the Fusor.

Any attempt to calculate a reaction rate in a Fusor is therefore a simplistic approximation of real values for which different calculation models are available for such an approximation, usually based on different theoretical approaches. One of those methods is shown in the next paragraphs.

The velocity v of the colliding nucleus is non-relavistic and can be calculated with the classical formula from equation I, which is mentioned here as:

$$\text{Equation VI} \qquad\qquad v = \sqrt{2\,\frac{E_k}{m}}$$

(derived from equation I: kinetic energy = ½ mv²) in which

v = particle velocity in meters per second (m/s)

E_k = kinetic energy converted from eV to joules (J)

m = mass of the nucleus in kg

The cross section for D-D reactions at 10 keV ranges from 2E-4 barn (center collisions) to 1E-3 barn (head-on collisions). A (one) barn is 1E-28 m² or 1E-24 cm² as mentioned earlier.

Knowing v (converted from m/s to cm/s) and the cross section σ (in cm²) we can calculate the reactivity (σv) expressed in cm³/s.

The remaining term of the equation to be calculated is the density of particles (nuclei) per cm³.

A simplified method is by assuming that all or at least the majority of the current through the grid is due to ion flow with a charge of +1. We know that one Ampère equals one Coulomb per second, or 6.24E18 charges per second. We need to compensate for losses caused by the grid by multiplying the charges with the "ion recirculation factor". Assuming that we have a grid transparancy (see below) of 98% than 2% of the ions will be blocked by the grid. This means that an ion will be neutralized by the grid one pass in fifty and therefore the ion recirculation factor would be 50. Another approximation of the recirculation factor can be found by calculating the mean free path of the ions as shown below.

———

The result of multiplying the charges with the ion recirculation factor yields an estimation of the number of ions passing the grid per second.

Because we know the diameter of the grid and because we have calculated the velocity of the ions, we can calculate now the the amount of time that an ion is actually in the grid.

The overall density in the grid can then be calculated from the time that an ion is in the grid and the amount of ions that pass per second through the grid. The results is expressed as particles per cm³. The calculation rules out time because we multiply

Duration in seconds (t) × number per second (n/t) × volume (cm³) = n/cm³

For a more accurate estimation of the density it is advised to break up the grid sphere volume in two or more concentric spheres (or shells) with in the central region a sphere with the (estimated) dimensions of the Poisor (the visible bright spot), where the ion density is progressively higher. For those who have forgotten their geometry equations to calculate the volume of a sphere:

$$V_s = \frac{4}{3}\pi r^3$$

When the radius of the grid sphere is r_g and the radius of the Poisor sphere is r_P we find the following equations for calculation of the volumes of the shells:

Equation (Poisor sphere)	VII	$V_p = \frac{4}{3}\pi r_p^{\ 3}$

Equation (Grid shell)	VIII	$V_g = \frac{4}{3}\pi(r_g^{\ 3} - r_p^3)$

Next is to calculate for each shell the fusion rate as the product of half the particle density squared and the sigma v values. For the inner shell use the cross section value for the center collisions; for the outer shell(s) use the cross section value for the head-on collisions.

Summarize the fusion rates for each shell.

Example:

for a Fusor operates at 10 kV at a current of 10 mA; it has a grid diameter of 6 cm and the Poisor has an estimated diameter of 4 cm; the cross sections σ for Deuterium at 10 kV are 2E-4 barn for center collisions and 1E-3 barn for head-on collisions. The mass of a deuteron is 3.43583719E-27 kg and the conversion factor from eV to J is 1.60217657E-19. The ion recirculation factor based upon the mean free path is calculated in the next paragraph and found to be 41. This well in line with the rule of thumb calculation based upon the grid transparancy which yields 50 recirculations.

An estimated calculation of the recirculation factor was done by applying equation II with a deuteron radius of 2.1413E-15 m, a Fusor pressure of 1E-5 Torr (equals 1.333223684E-3 Pascal), a plasma temperature of 10 keV for which 1eV equals 11604.45 K yielding a plasma temperature of 1.16E8 K, a Boltzmann constant of 1.3806488(13)×10⁻²³ JK⁻¹. With these parameters equation II yields

a mean free path length of 8.1719 m, which results in 41 recirculations in a Fusor with a diameter of 20 cm (mean free path length divided by diameter is approximate number of passes or recirculations).

In this system the velocity v of the colliding ions is the square root (2 × ((41 × 1.60217657E-19)/3.43583719E-27)) = 61836.633572 m/s or 6183663.3572 cm/s.

The factor σv for center collisions is 6183663.3572 cm/s × 2E-4 barn × 1E-24 cm^2 = 1.2367E-21 cm^3/s and for head on collisions 6183663.3572 cm/s × 1E-3 barn × 1E-24 cm^2 = 6.1837E-21 cm^3/s.

The amount of time that an ion is in the grid is diameter grid divided by the velocity or 6 cm ÷ 6183663.3572 cm/s = 9.7030E-7 s.

The number of ions per second equals 10 mA for which 1 A 6.24E18 charges per second times the ion recirculation factor or 1E-3 × 6.24E18 × 41 = 2.558E19 ions/s.

The overall density in the grid is amount of time that the ion is in the grid times number of ions per second or 9.7030E-7 s × 2.558E19 ions/s × volume = 2.4820E13 ions in the total volume of the grid.

For the poisor shell we find a volume of (r = 2 cm) 4/3 × π × 2^3 = 33.5 cm3. The ion density in this shell is 2.4820E13 ÷ 33.5 = 7.41E11 ions/cm^3.

The fusion rate for the poisor shell equals ½ × n^2 × (σv) is ½ × (7.41E11)^2 n/cm^3 × 6.1837E-21 cm^3/s = 1698 reactions per second.

Similarly, for the grid shell we find a volume of (r = 3 cm) 4/3 × π × (3^3 - 2^3) = 79.6 cm^3. The ion density in this shell is 2.4820E13 ÷ 79.6 = 3.27E12 ions/cm^3.

The fusion rate for the grid shell equals ½ × n^2 × (σv) is ½ × (3.27E12)^2 n/cm^3 × 1.2367E-21 cm^3/s = 6595 reactions per second.

The total fusion rate in the fusor (grid) equals 1698 + 6595 = 8293 reactions per second.

Above mentioned method(s) for calculating the fusion rate are very rough estimations and a total reaction rate of just over 8000 reactions per second is considered quite sufficient for detection by a neutron detector. A large number of reactions is required here because the number of reactions should exceed the detection limit of the detector sufficiently but it should also be noted that the neutrons from the fusion reactions are randomly emitting from the Fusor in all directions and our detector is just on one fixed spot at a distance from the Fusor. Therefore the majority of these neutrons will not be "seen" by the detector.

From the calculations it should be clear that a higher voltage (is more velocity) and a higher current (is more ions) will increase the reaction rate.

3.7 Radiation Hazards

Röntgen (γ) Radiation

Operating a Fusor means applying a high voltage to a cathode in a medium or high vacuum environment, which produces thermionically emitted electrons directed outward from the cathode and by colliding with the vacuum envelope generate Bremsstrahlung röntgen radiation. Because we

———

use Deuterium as "fuel", which becomes ionized in Deuterons with a single positive charge, the γ-energy of the röntgen radiation in eV is directly related to the potential differential applied. For example a potential difference of 30 kV emits röntgen radiation with an energy up to 30 keV.

Generally, it is said that up to a voltage of 25 - 30 kV no röntgen radiation of importance will pass through the (metal) walls of the vacuum chamber. For information about calculating the amount of röntgen radiation that will penetrate the vacuum chamber wall and we shall use that info for the following calculation.

The mass attenuation coefficient for steel is at 30 keV 8.2 cm²/g and at 10 keV 170 cm²/g.

De Beer-Lambert's Law of exponential attenuation is used for calculation of the penetrating flux:

Equation IX	$$I_{(x)} = e^{(-mx)}$$

where

m = mass attenuation coefficient

x = thickness expressed as mass per unit area (g/cm²)

The mass density for steel is ϱ_m = 8.0 g/cm³

For a vacuum chamber with a wall thickness of 2 mm: x = ϱ_m × t, where t is the wall thickness,

x = 8.0 g/cm³ x 0.2 cm = 1.6 g/cm²

For 30 keV röntgen radiation we find: exp(-8.2×1.6) = 2E-6 or 0.0002% of the radiation will penetrate the vacuum chamber walls, which is indeed of no importance. At 10 kV potential difference or 10 keV röntgen radiation energy we will find even considerably less: 7.4 × E-117%!

For calculating what this means as a biological radiation dose we assume that our Fusor runs at 30 keV and 10 mA or an energy of 300 Watt = 300 J/s. suppose that we have no losses in the system and the röntgen radiation (Bremsstrahlung) is generated by two entities:

- electrons emitted from the grid

- ions colliding in the plasma focus

Which absorb the 300 J/s kinetic energy.

For a Fusor 30kV, each Deuterium has one single charged ion (30 keV) and one electron (30 keV) and therefore the kinetic energy for each is 50% of 300 J/s = 150 J/s. The efficiency for generating röntgen radiation is about 1E-9 and thus we have 150 J/s × E-9 = 1.5E-7 J/s keV X-rays emitting from the plasma focus, of which 0.0002% exits the vacuum chamber = 3E-13 J/s.

For an average body mass of 70 kg (see method 1 under Neutron Radiation below) we find an absorbed energy dose of 3E-13 J/s ÷ 70 kg = 4.3E-15 J/kg/s or 1.5E-11 J/kg/h. This equals (conversion: 1 J/kg = 1 Gray) 1.5E-5 µGy/h which converts with a weighting factor of 1 for gamma's to an equivalent tissue dose of 1.5E-5 µSv/h. Compared to the annual limit for professional workers of 20µSv/h (>250 h/y) this is indeed neglectable.

_____

Neutron Radiation

It is difficult to measure accurately the total amount of neutrons produced by the fusion reaction as the efficiency for the neutron detector should be known, i.e. taking into account the distance from the detector to the core of the reactor and the factor describing the amount of neutrons hitting the detector in relation to the total amount of neutrons emitted randomly in all directions, etc. Therefore we propose to tackle the problem of calculating the radiation dose from neutrons by two different ways.

Method 1

One method is to use the maximum allowable limit for radiation exposure and to calculate the corresponding maximum production rate of reactions in the Fusor. Knowing that maximum production rate enables to calculate more or less up to what high voltage and current the Fusor can safely be operated.

As a starting point we take the EU dose limit for professional nuclear workers, which is an absorbed dose of 20 µSv/h (< 250 h/year). To compensate for stochastic radiation effects, an energy dependent weighting factor W_r connects the absorbed dose in Gray (Gy to the equivalent tissue dose in Sievert (Sv).

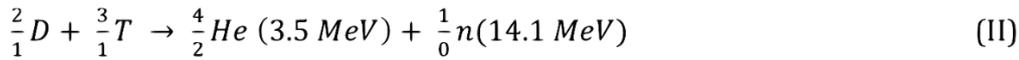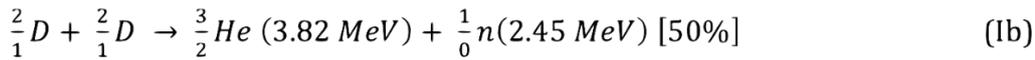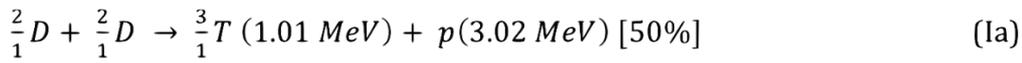For neutrons the following equations as a continuous function of the neutron energy:

$$w_R = \begin{cases} 2.5 + 18.2e^{-[\ln{(E_n)}]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0e^{-[\ln{(2E_n)}]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25e^{-[\ln{(0.04E_n)}]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$$

When we substitute the neutron energies of respectively 2.45 MeV and 14.1 MeV in the appropriate equation (for the relevant energy) we find respectively $W_{2.45} = 12.5$ and $W_{14.1} = 7.7$. The sum of both weighting factors is about 20.

Therefore the Fusor is allowed to produce maximally an absorbed dose of 1 µGy/h and this is equivalent with an energy deposition of E-6 J/kg/h. The average body mass of an adult in Europe is just over 70 kg and when we take a body mass of 70 kg as the norm we find that a Fusor energy output of 7E-5 J/h or 1.9E-8 J/s should be considered as acceptable.

Neutrons emitted from the Fusor have an energy of respectively 2.45 MeV and 14.1 MeV, which equals respectively 3.93E-13 J and 2.26E-12 J. We divide the maximum allowable fusor output of 1.9E-8 J/s by the neutrons energy and find respectively a maximum allowable fusion rate (# = number of fusions or reactions) of 48500 #/s and 8400 #/s.

The outcome may be confusing because we find for one neutron energy a "safe" fusion rate of almost 50,000 fusions per second and for the other neutron energy a "safe" fusion rate of almost 8,500 fusions per second. We should however realize ourselves that both reactions possibly may occur simultaneously. The equations Ia, Ib and II show the D-D reactions that may occur in the Fusor:

———

$$\tfrac{2}{1}D + \tfrac{2}{1}D \; \rightarrow \; \tfrac{3}{1}T \; (1.01 \; MeV) + p(3.02 \; MeV) \; [50\%] \qquad\qquad \text{(Ia)}$$

$$\tfrac{2}{1}D + \tfrac{2}{1}D \; \rightarrow \; \tfrac{3}{2}He \; (3.82 \; MeV) + \tfrac{1}{0}n(2.45 \; MeV) \; [50\%] \qquad\qquad \text{(Ib)}$$

$$\tfrac{2}{1}D + \tfrac{3}{1}T \; \rightarrow \; \tfrac{4}{2}He \; (3.5 \; MeV) + \tfrac{1}{0}n(14.1 \; MeV) \qquad\qquad \text{(II)}$$

The probability that reactions Ia and Ib occur is 50% for each, therefore the emission of neutrons with an energy of 2.45 MeV is realistic. The Tritium formed in reaction Ia will may further react with Deuterons present in the Fusor because the minimum energy required for the D-T reaction is lower than for the D-D reaction and therefore this reaction might also occur. However, the assumption that reactions (Ia,II) and (Ib) occur equally is taken here as a worst case assumption. Worst case because neutrons emitted with an energy of 14.1 MeV are more harmful because of depositing more kinetic energy in tissue. In reality we probably may expect in majority to produce neutrons with an energy of 2.45 MeV because it is expected that most of the formed Tritium decays before being burnt-up by the D-T reaction.

With respect to the biological radiation burden the total amount of allowable fusions per time unit is therefore worst case 48,500/s + 8,400/s = approx. 57,000/s.

This calculation is valid for an exposure to neutrons directly at the source, i.e. like the Fusor operator was present inside the vacuum chamber during exposure to neutrons produced. Distance reduces the effect of exposure to neutrons but despite such a reduction in neutron flux caused by distance it is not good for your health to be exposed to neutrons. Water contained in the body will moderate (slow down) the neutrons but once an atomic nucleus inside the body is hit, a reaction will occur which produces radioisotopes and reactive free radicals, which stay inside your body until decayed. However, prior to full decay they may be harmful to your health.

Method 2

Another method can be used when the neutron flux form the Fusor is known by converting the neutron flux rate to neutron dose rate for which the calculation is

Dose rate (rem/h) = conversion factor ([rem/h]/ [neut/cm^{2}s^{-1}]) × neutron flux (neutrons per cm$^{2/}$s)

The conversion factors

for converting from the rem unit to the currently used unit of Gray: 1 rem/h = 0.01 Gy/h = 10 mGy/h.

For our D-D reactions yielding neutrons with energies of 2.45 MeV and 14.1 MeV we find respectively conversion factors of about 1.25E-4 and 2.08E-4. The same argument about a worst case calculation is equally valid here as in method 1.

When measured with the neutron detector and calculated for the distance from the detector to the Fusor operator we find an (assumed) neutron flux of 1000 neutrons/cm^2/s at operator level. Because the neutron detector is inside a moderator to slow down fast neutrons to thermic neutrons, which are counted by our detector, our neutron flux consists of (assumed) 50% neutrons with an energy of 2.45 MeV and 50% neutrons with an energy of 14.2 MeV.

_____

The dose rate for 2.45 MeV neutrons is calculated as dose rate (mGy/h) = 1.25E-4 (conversion factor) × 500 (50% of neutron flux) × 0.01 (from mrem/h to mGy/h = 0.00104 mGy/h = 1.04 μGy/h.

The dose rate for 14.2 MeV neutrons is calculated as dose rate (mGy/h) = 2.08E-4 (conversion factor) × 500 (50% of neutron flux) × 0.01 (from mrem/h to mGy/h = 0.000073 mGy/h = 0.073 μGy/h.

The weighting factors for neutrons in order to obtain an equivalent dose in Sv is mentioned before in <u>method 1</u>. By applying the weighting factors $W_{2.45}$ and $W_{14.1}$ the total equivalent neutron dose rate is (0.625 × 12.5) + (1.04 × 7.7) = 15.8 μSv/h.

This equivalent dose is at a safe level, i.e. below the allowable limit for professional workers of 20μSv/h (>250 h/y).

4 Electrical System

4.1 High voltage Power supply

The high voltage power supply needed is 35Kv at up to 5 mA. The system is divided to four main Phases: the power supply, ZVS Driver, fly back transformer,and the Voltage tripler.

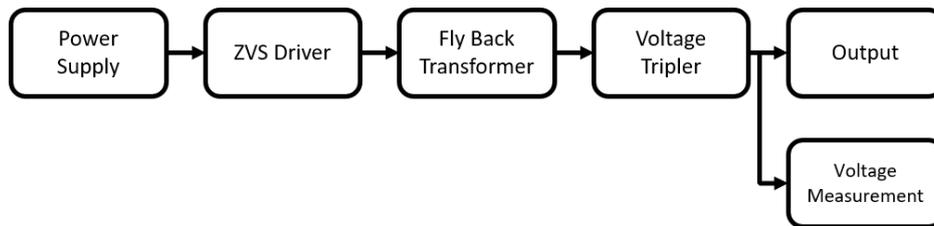### 4.1.1 General System Diagram

Figure 4-1. High Level High Voltage Power Supply Diagram

To obtain a power 35kV at up to 5 mA at the output. the normal power, as shown is 220 Volts with alternating current (AC), should go through mutli-diverse phases. phase 1, the current will be converted from AC or Alternating current (where it changes the direction periodically), to DC or direct current (where it only flows in one direction). In addition to ensure the needed power for the next phase. Phase 2, the DC power is an input for a zero-voltage switching driver (ZVS) which is a self-oscillator (push-pull oscillator). The ZVS driver provide a high frequency (KHz) oscillator for the fly back transformer in the phase 3. Phase 4 is a volatge tripler, that multiply the voltage through utilazing cockroft-waltan voltage multipler stages.All theses mentioned above is illustrared in figure 3-1 above.

Therefore, There are 3 kind of systems that can be adopted:
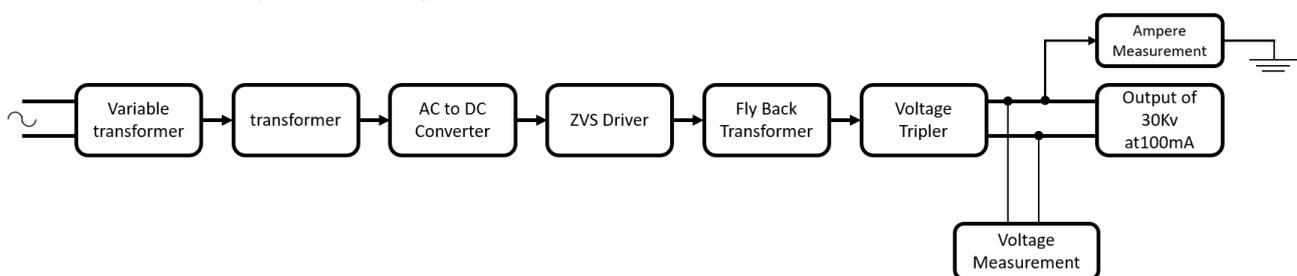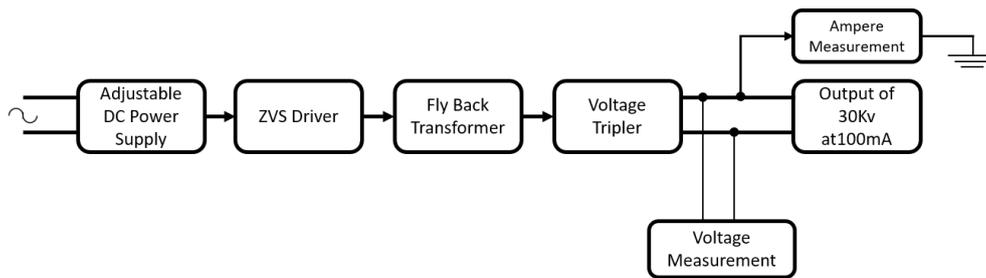
4.1.1.1 Detailed System 1 diagram

Figure 4-2. Detailed system 1 diagram

Starting from the left, The variable transformer is for controling the intensity of plasma inside the vacuum chamber. Then, a step up transformer is needed, before converting the power from AC to DC that is required as an input for the zero voltage switch driver (ZVS). After that, a fly back transformer and voltage tripler generats arround 30 Kv at 100 mA from the magnetic feild coming from ZVS driver. Finally, there are the voltage, and current circuit measurerment to measure the arrived voltage and current to the vacuum chamber (connected to the output).
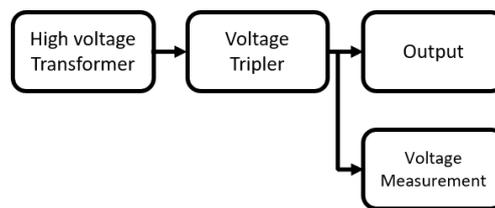
4.1.1.2 Detailed System 2 diagram

Figure 4-3. detailed system diagram 2

In this system, the power needed for the ZVS Driver is fed by a custom adjustable DC Power Supply.

4.1.1.3 Detailed System 3 Diagram

Figure 4-4. Detailed system diagram 3

In this system, a high voltage transformer of 12KV at 30 mA will fed a voltage Tripler circuit, in order to step up the voltage at the output. Note that the output voltage will depend on the number of stages of voltage Tripler as well be mentioned later. This method gives a fix amount of voltage. In other word, it cannot adjust the voltage in order to optimize the voltage according to fusor sensor and measurement.

4.1.1.4 Detailed System 4 Diagram:
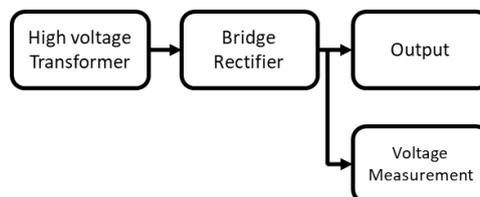
Figure 4-5. detailed System Diagram 4

Similar to the last method, but in order to keep the current at 30 mA, the voltage Tripler will be replaced by a bridge rectifier, just for converting the Alternative current to a Direct Current. This method gives a fix amount of voltage. In other word, it cannot adjust the voltage in order to optimize the voltage according to fusor sensor and measurement. Therefore, the output will be fed by a power of ~12kv at 30mA.

4.1.2 The High voltage power supply

The power supply will be composed to some step. The first step is presented as shoun figure below.
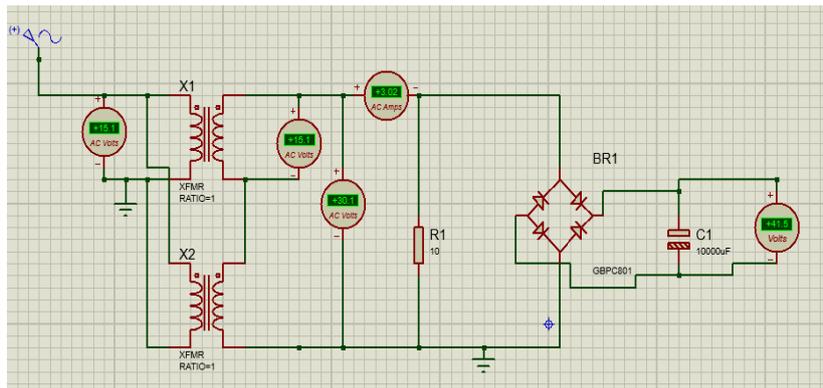
-
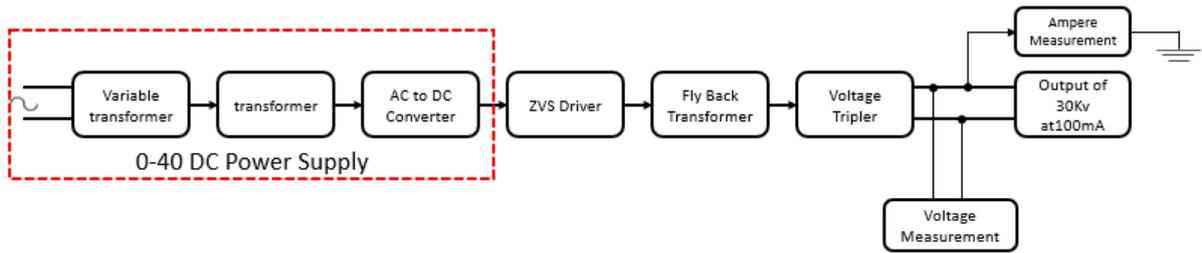
4.1.2.1 System 1 DC Power Supply

Figure 4-6. Step1 circuit simulation

As shown above, a Ac power source of 15 VAC feeds two transformer of ratio equal to 1, for insulation anad safety reasons. Then, the two transformer provides a power of 30 VAC (the transformer are connected in series). After that, a Ac to DC converter (rectifier) transform the AC voltage to DC, with the presence of capacitor of 10,000 uF to ellimenate voltage ripple.

4.1.2.2 System 2 DC Power Supply

This system is as simple as it is, an adjustable DC Power supply of $0 - 30v\ 20A$ can be sufficient, such as this one in figure 3-4, below:

Figure 4-7. Adjustable DC Power Supply

4.1.2.3 System 3 and 4 high voltage Power Supply

…

4.1.2.4 Zero voltage Switching (ZVS)

The ZVS Driver circuit (Roye converter) is a Royer-type push-pull oscillator with a resonated primary that is implemented with FETs. This type of oscillator can be used to drive the ferrite core of a flyback transformer to generate high voltage. It can also drive a high-current air-core "work" coil for an induction heater.

Figure 4-8 Basic ZVS Driver circuit

The ignoring the power supply chokes and resonating capacitor(s), the ZVS circuit is simply a push-pull FET-based oscillator where the drain of each FET is cross-coupled to the gate of the opposite (out of phase) FET. It is worth to mention, that The FET(Field Effect Transistor) is a three-terminal electronic device used to control the flow of current by the voltage applied to its gate terminal.

The operation of this kind of driver for the primary of a transformer is very straightforward and need not be discussed here. The circuit is fed from the power supply through a center-tapped primary coil and a single choke or from two separate chokes connected to the FET drains (as shown in figure 3.2).

Note1: it is not recommended to use a center-tapped coil cause of the ability of "lock-up" if the supply voltage is not applied fast enough to kick it into operation. These phenomena appear when you slowly increase the input voltage. So, in order to avoid it, it much better to apply the input voltage abruptly. You can use a remote-control relay to operate the ZVS circuit.

With the two (47uH-200 uH) choke coils (L1, L2) and the resonating capacitance across the primary, the circuit operates as a "Royer" type inverter where the primary is resonated with the capacitance and where the chokes keep the power supply from reducing the resonant action of the primary. These chokes also keep the primary oscillations from feeding back to the power supply.

Zener diodes are connected across the FET gates so that the maximum gate to drain voltage is not exceeded. **NOTE2: Use of a Zener voltage higher than the minimum gate to source turn-on voltage ensures that the FETs are conducting at a high level. Plus, the diode should be a fast diode**

Note 3: **the capacitor C1, and the two MOSFET should be cool. Otherwise, the signal will be shifted, until the circuit broke, and the MOSFET will be burned down**.

NOTE4; TAKE CARE TO THE GROUND, THE GOUND SHOULD BE CONNECTECD WITH THE NEGATIVE OF TH POWER SUPPLY.

4.1.2.5 ZVS MAZZILLI Circuit
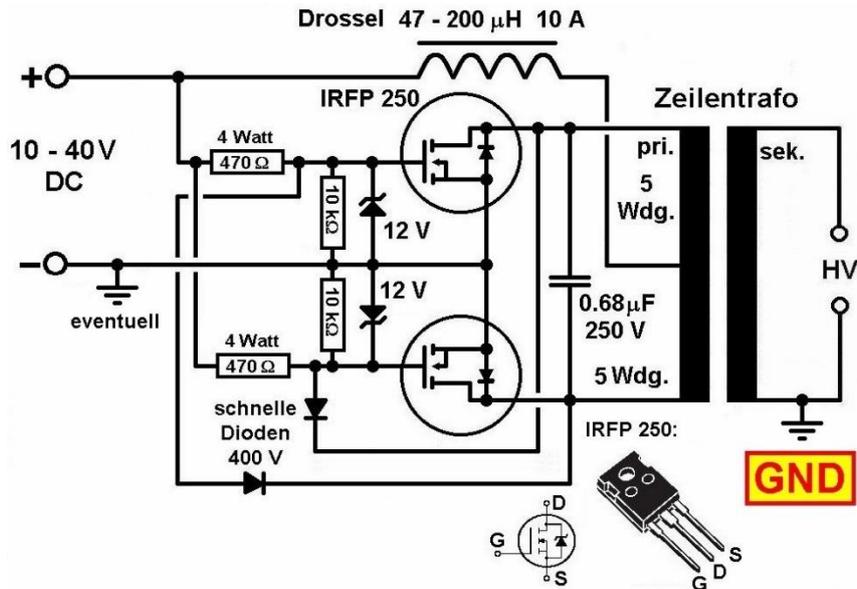
This kind of ZVS driver needs an input voltage abruptly, cause of the high probability of "lock-up" phenomena, aforementioned. the main difference between typical ZVS MAZZILLI Circuit and circuit above are the center-tapped coil, and the larger capacitor between Drain-Drain. In this application this kind of ZVS driver will not work properly. **It is not recommended to use this ZVS MAZZILLI.**

4.1.2.6 ZVS Simulation
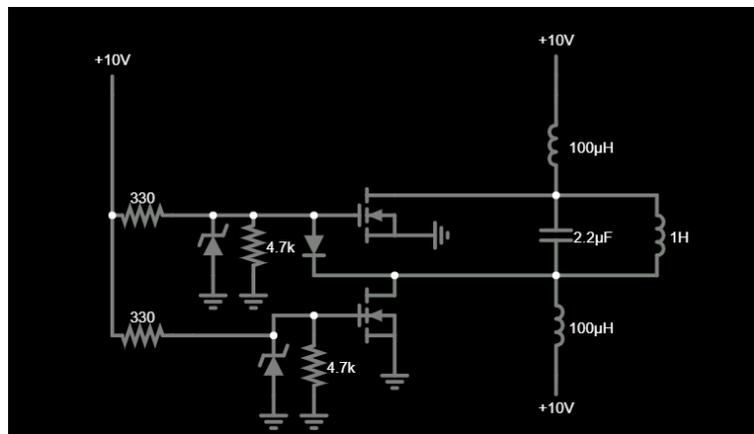
Figure 4-9. ZVS circuit in the stop Mode
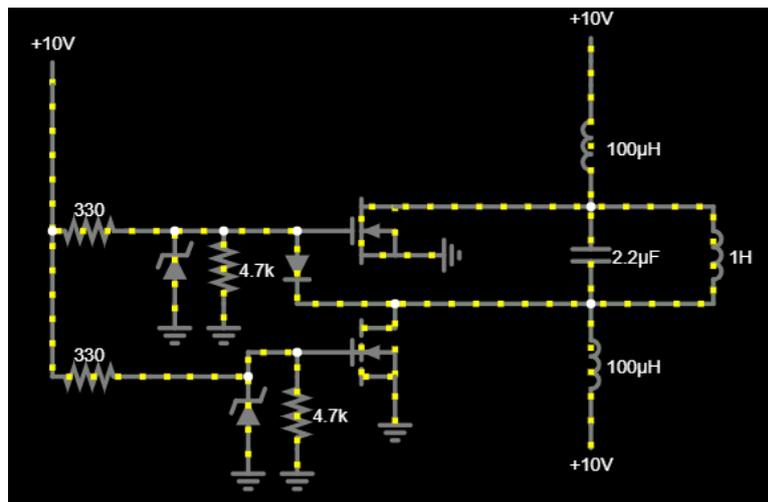
Figure 4-10. ZVS circuit in the RUN Mode

In the figure 3-3 and 3-4above, a center-Tapped inductor has been avoided and place a simple inductor o 100uH. The capacitor (2.2uF) and inductor (1000mH) is selected via trial and error for a soft sine wave (as shown in the figure)
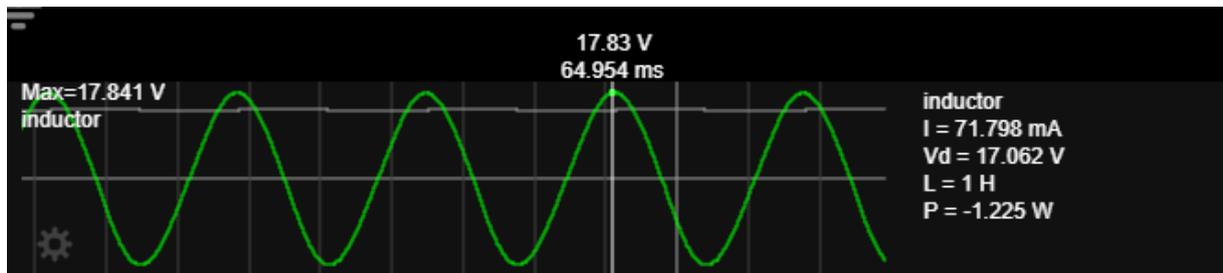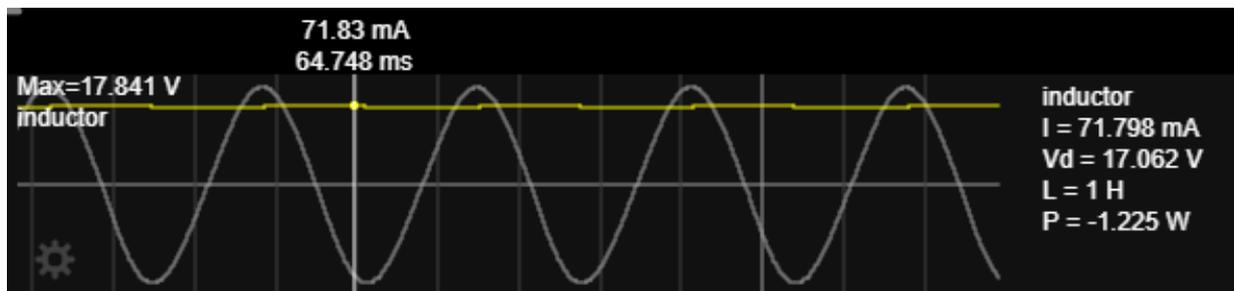

Figure 4-11. AC output Voltage

Figure 4-12. Output Current

4.1.2.7 ZVS with flyback and cockroft-waltan voltage multiplier circuit
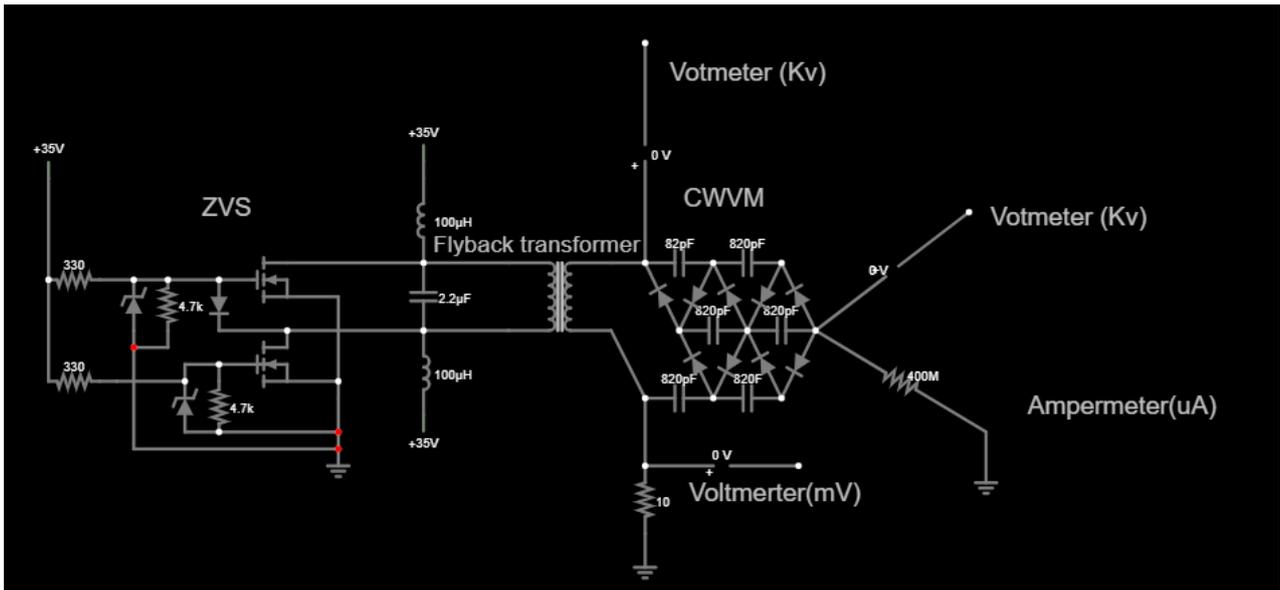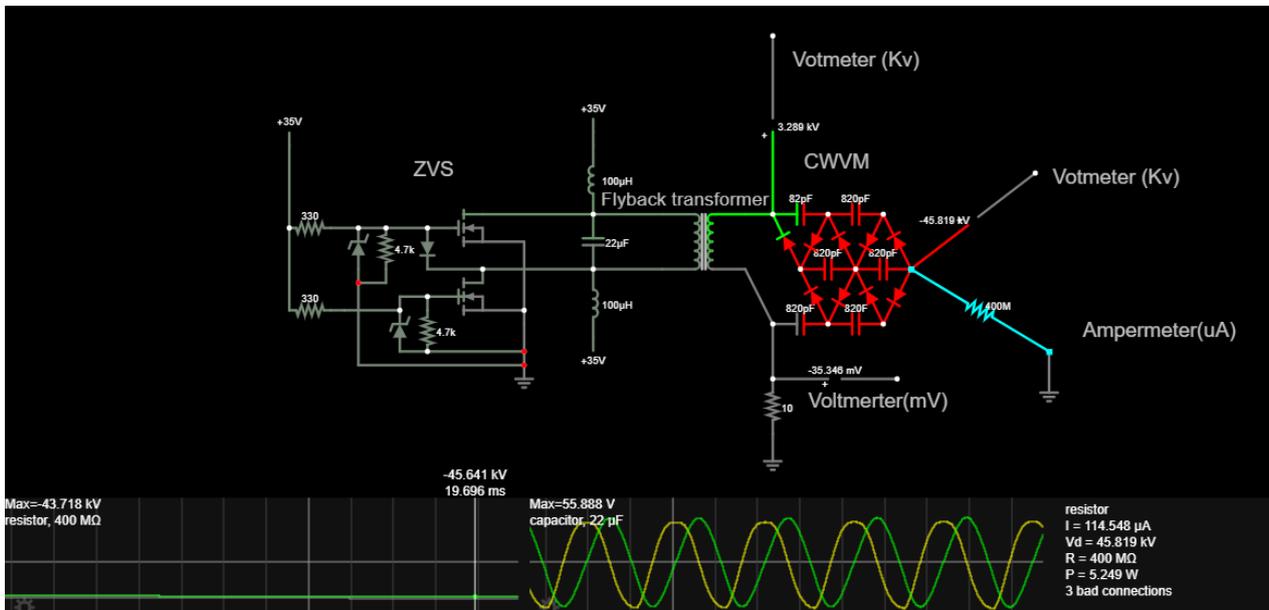

Figure 4-13. ZVS with flyback and voltage Tripler simulation

Figure 4-14 Output voltage and current

The output voltage at the end of voltage Tripler is -45Kv at 114.54 uA. With the presence of a soft sign wave in the ZVS self-oscillator.

4.1.3 Equipment

4.1.3.1 Cathode

The cathode, shown in figure 3.13, consists of 30kv feedthrough with 2.75'' stainless steel flange (figure 3.14), alumina tube insulating feedthrough stalk (figure 3.15), and the negative hot inner grid of tungestin filament with its base of stanless steel that connect the inner grid with the pin of feedthrough (figure 3.16). The power about $-35\ kv\ at\ 0\sim5\ mA$ cross the cathode in this application.

Note 1: This feedthrough needs to be rated for the cathode voltage that will be used

Note 2: it is recomended to buy the feedthrough flange, not DIY. The ceramic isolation should be molded on the flange correctly for many reason such as the isolation, high vacuum, conductivity.
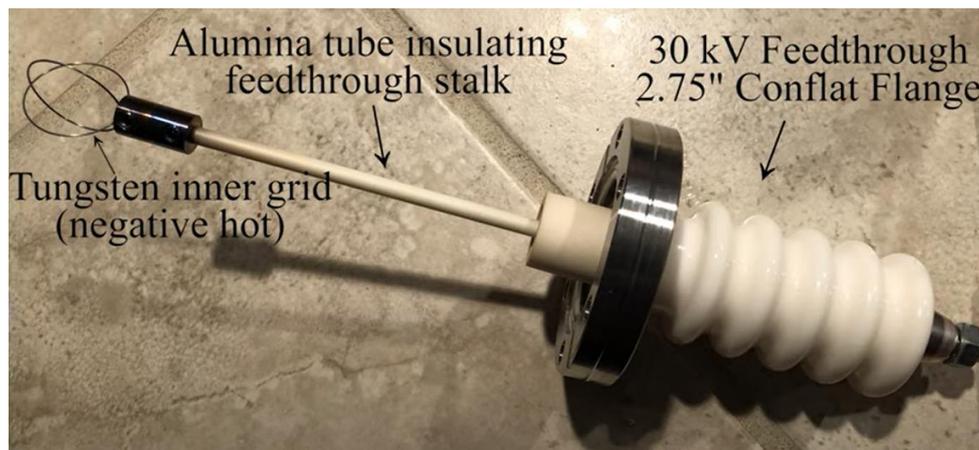

Figure 4-15. Fusor Reactor Cathode

Figure 4-16. feedthrough flange

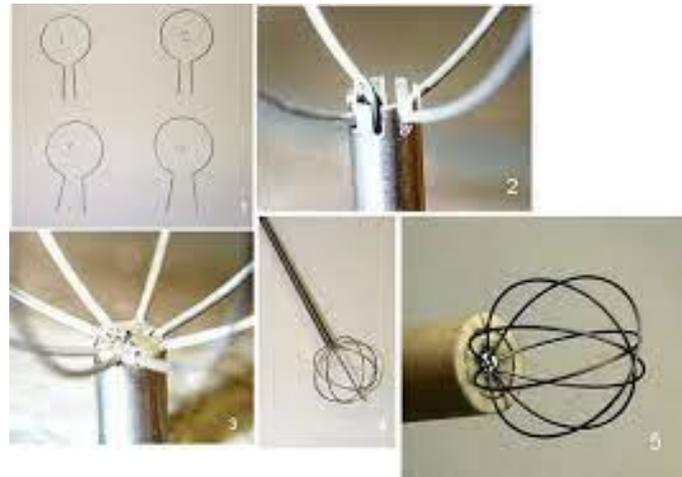**Figure 4-17. alumina tube insulating feedthrough stalk**

Figure 4-18. Tungsten grid

The cathode inner grid material can be on of the following materials: tungsten, tantalum, Rhenium, molybdenum, Titanium, and stainless steel. But a demo fusor can be use stainless steel wire as they are not stressed to the degree encountered in a real fusing fusor. The best suitable for real fusor is tungsten.

According to available material in the local market, a 1.6mm diameter of stainless-steel wire has been used in this project.

The cathode inner grid has been built in the following steps:

Step 1:

Get three stainless steel rods (2 x diameter: 1.6mm, 1 x diameter:2 mm). the 1.6mm rods are used for the spherical inner grid. This thickness is compatible for the transparency (<92%), as mentioned before.
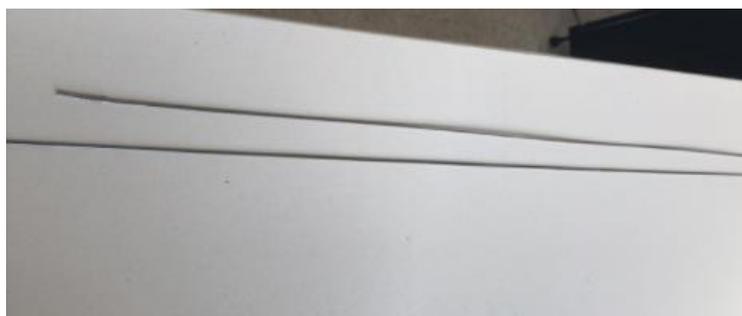

Figure 4-19. stainless steel wire

Step 2:

Build the spherical inner grid according to its characteristic calculated before.

(The spherical diameter: 7cm, the wire thickness: 1.6mm, and the wire loop number: 3).

In order to build the three loops (circle) of diameter equal to 7 cm, an available gas tank of diameter equals to 7cm has been used.
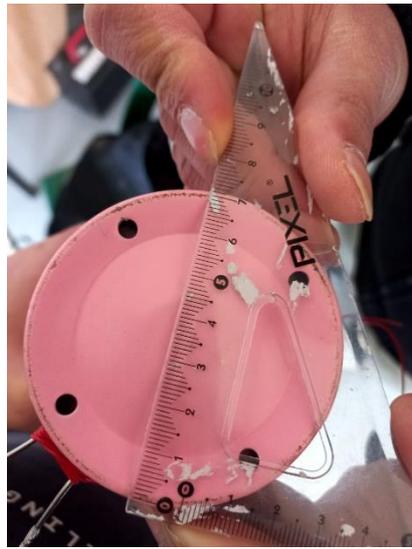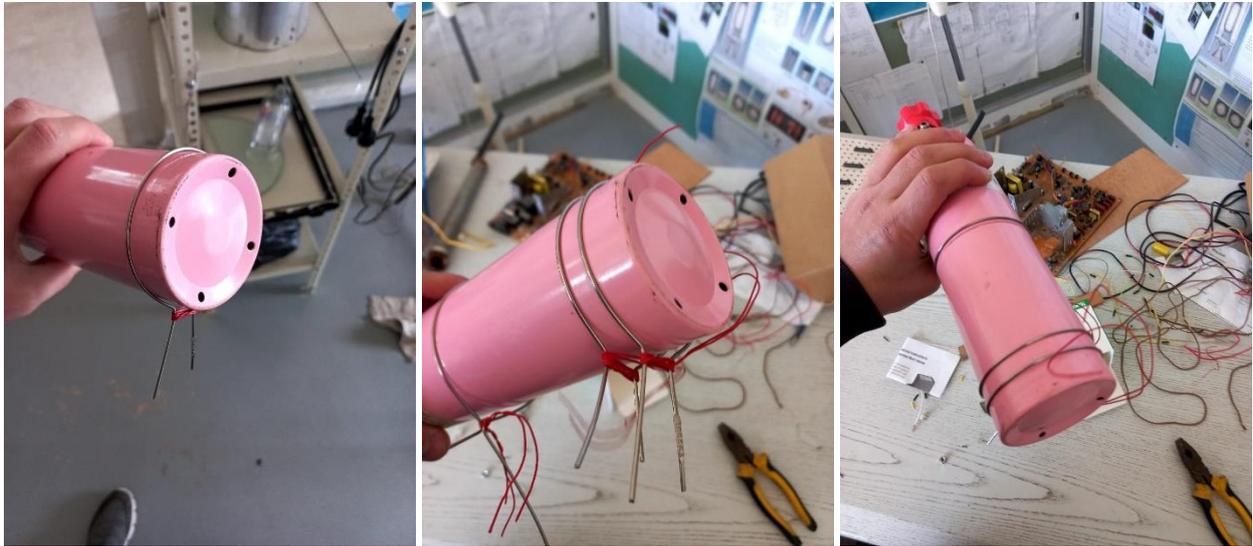
Figure 4-20. gas tank of 7 cm diameter

Figure 4-21. stainless steel reshaping

NOTE: each loop has two pins, that is needed to fix the inner grid sphere on its base, as will be mentioned later.

Check each circle reshaped by using the pink gas tube, with a red wire (as shown in figure 3-20 above), the two pins have been tied by a red wire to keep the stainless steel in its circular shape. After two days, the requires shape of stainless-steel wire was achieved. Hence, the three stainless circle has been extracted from the pink gas tank, as shown in figure 3-21.

.

Figure 4-22. stainless steel with circular shape

Step 3:

Gather three stainless circles in order to obtain a spherical shape, as figure below.

Figure 4-23. stainless steel inner grid

Step 4:

Choose the base of spherical inner grid

As shown in figure 3-22, there are 4 pins of thickness equals to 1.6mm, in total of 6.4mm. according to that, the inner grid base should have an inner diameter greater than 6.4 mm. according to local market, a stainless pipe of inner diameter of 7 mm and outer diameter of 10 mm, a length of 10 cm is suitable for this project.

Figure 4-24. stainless pipe tube

Step 5:

Fix all components via argon soldering electrical machine.

NOTE: the soldering needs an expert person, and it is more preferable to use a non-electrical argon soldering machine, cause of the complexity and the accuracy needed of the soldering position.
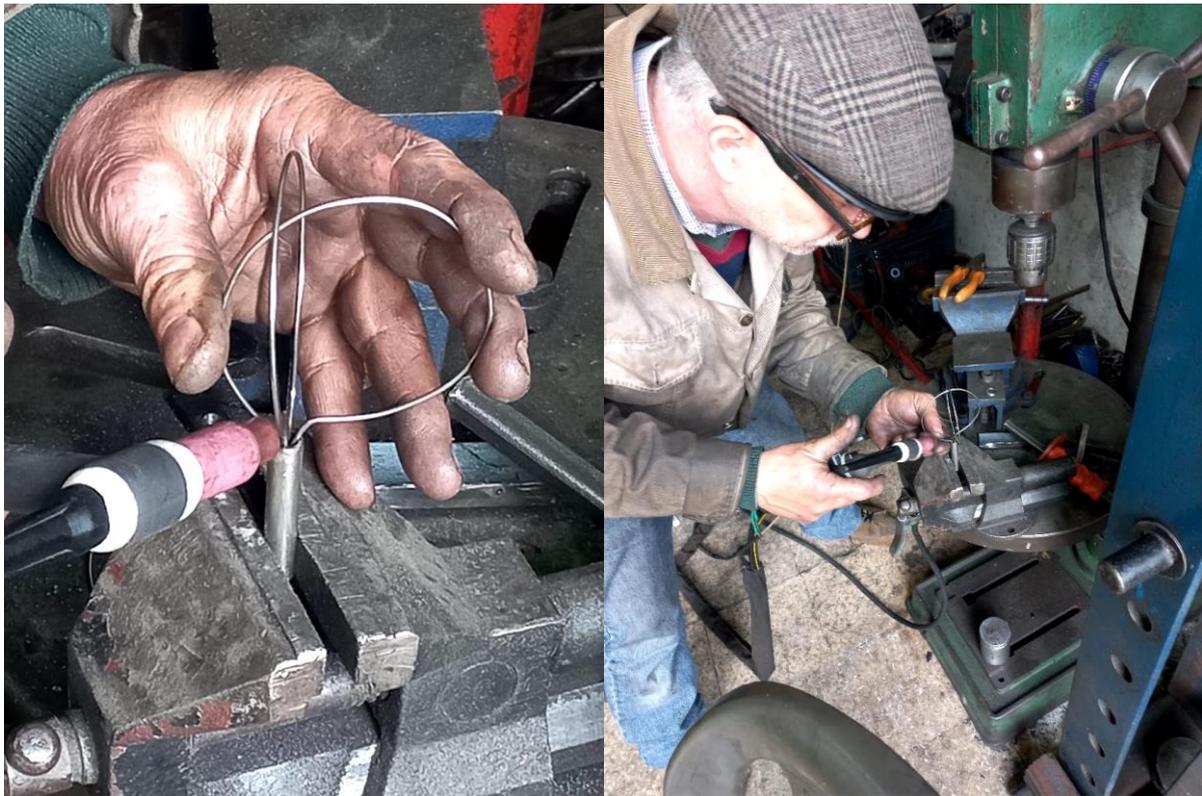
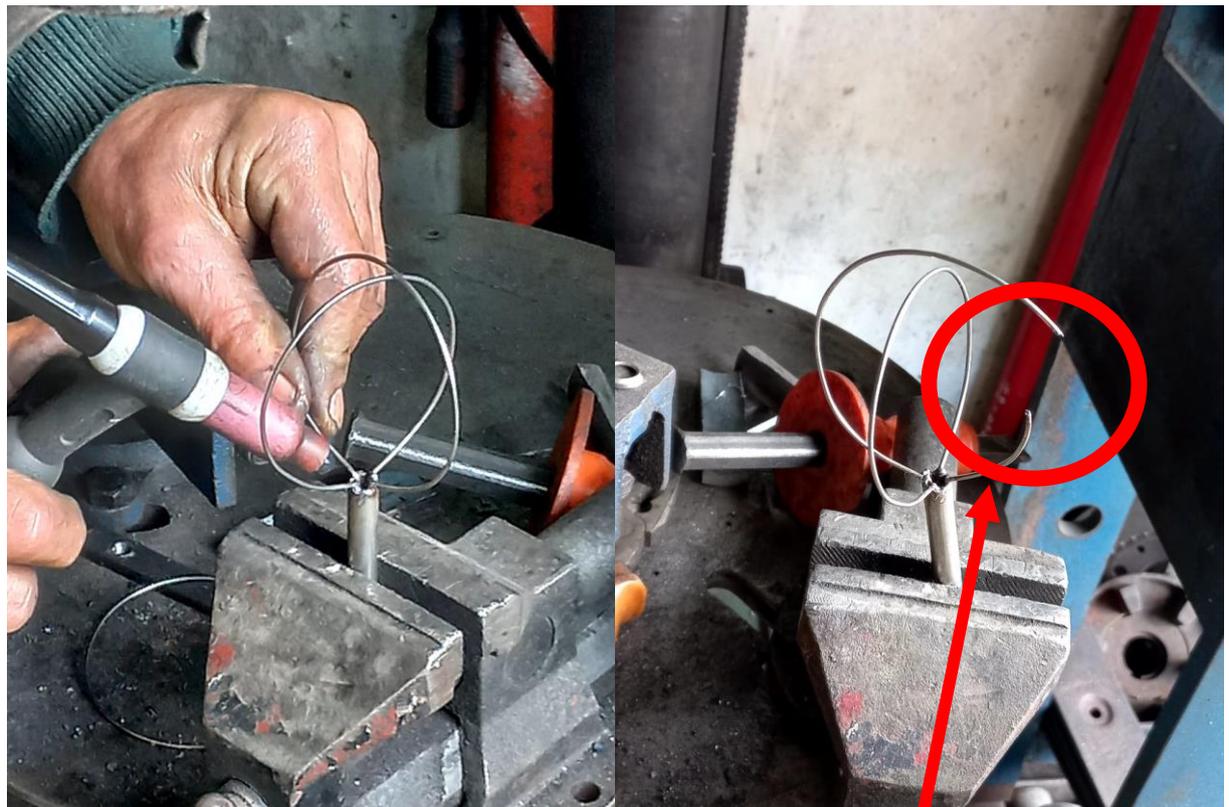**Figure 4-25. argon soldering electrical machine**
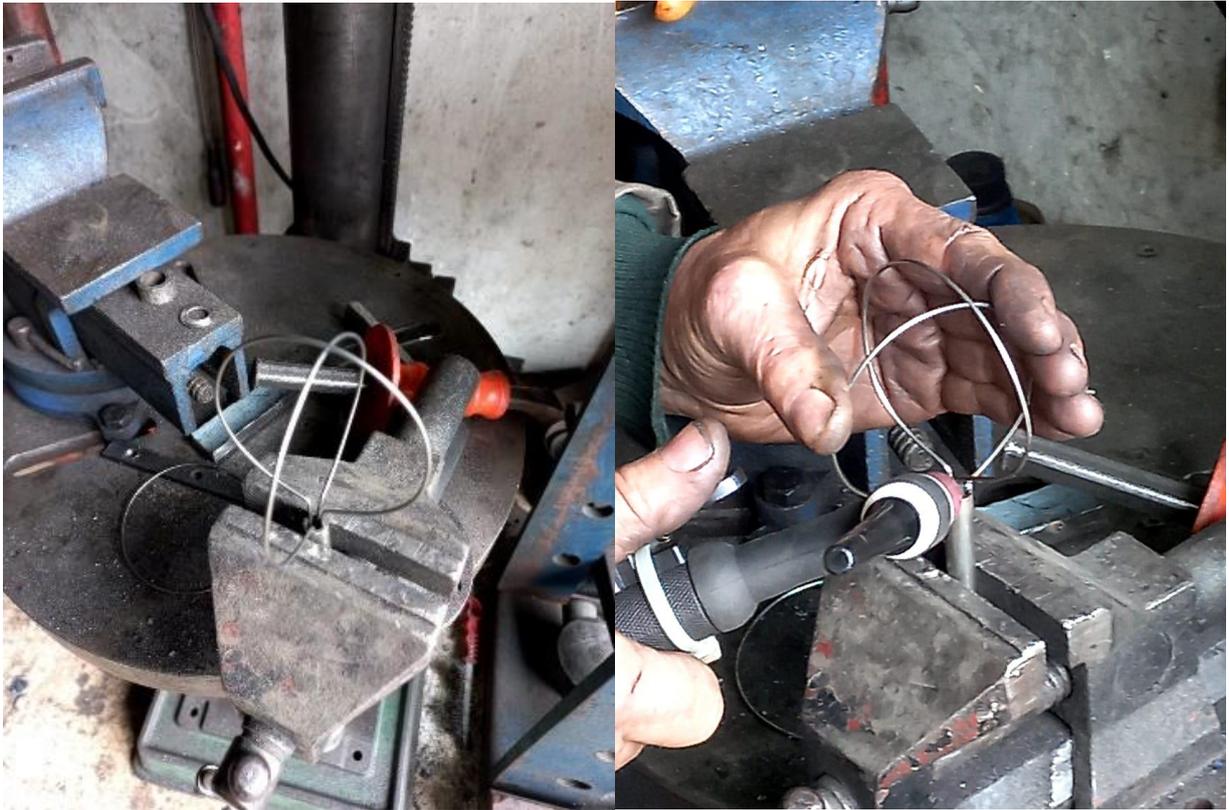

Figure 4-26. inner grid assembling

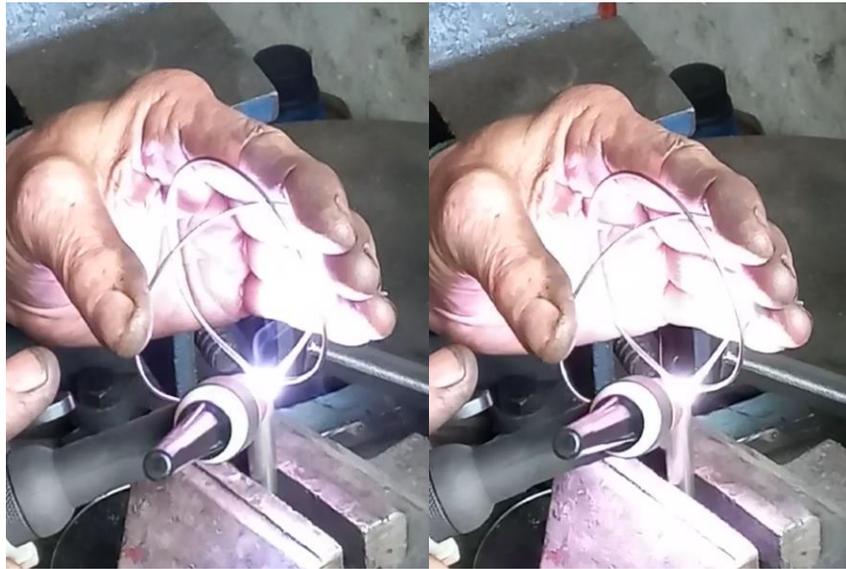The wire chopped off cause of high sensitivity of wire

Figure 4-27. Stainless steel Inner Grid argon Soldering

Step 6:

After gathering the stainless sphere with its base, the 2 mm stainless wire has been soldered in other side of stainless pipe (sphere base). the

Figure 4-28. final form of stainless inner grid

4.1.3.2 ZVS Driver

The ZVS needed for this project should has the following specification shown in the table below:

Specification	description
Input Voltage	DC 12-30V
Power	1000W
Working Frequency	30-50KHz
Input current	>5A (under 12V) >10A (under 15V)

NOTE1: THE POWER SUPPLY SHOULD AT LEAST 12V AT 5A. otherwise, this will lead to low power input, thus, the Two MOS will connect at the same time, this will damage it.

NOTE2: DO NOT TURN ON THE MODULE AT NO LOAD, because it will lead to produce a high frequency noise that damage the mosfet.
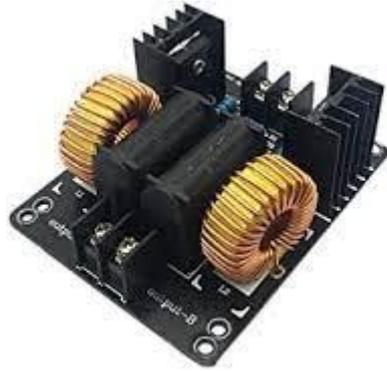
NOTE3: DO NOT EXCEED 30V.

Figure 4-29. ZVS Driver

The ZVS driver will generate as an output power 800 times the input Voltage. So, for 20V at 10~15A the output power is 16KV
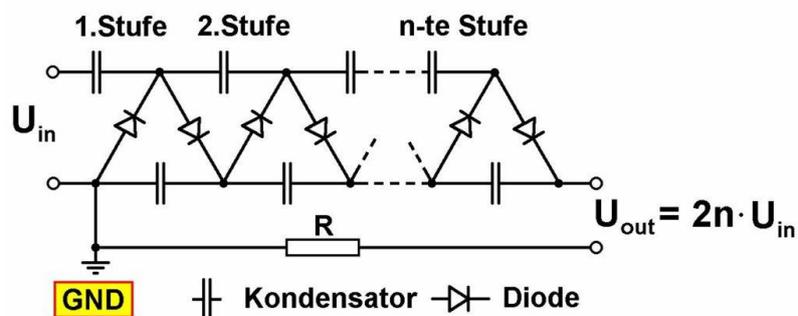
Estimated cost: 20$

4.1.3.3 AC flyback transformer

This combination delivers an output voltage of around 27 kV peak to peak at an input voltage of 24V using 4×4 windings on the primary side of the flyback transformer.

Estimated cost: 35$

4.1.3.4 Voltage Tripler (Cockroft-Waltan Voltage multiplier)

for 16kv as input, and in order to reach the 200kV.Approximately, 6 stage is needed

$$200Kv \div 2 \div 16\,Kv = 6.25\ stages$$

Each stage needs two diodes, and two capacitors. The following components specification is compatible for this project.

Diode: High Voltage diode 2CL20Kv 20mA (48pcs, each two in series, and well isolated)
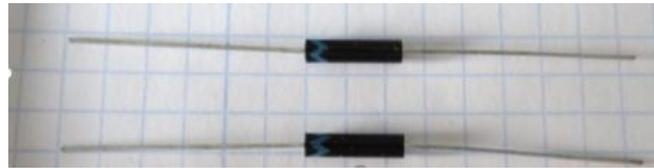

Figure 4-30. 20Kv 20mA high voltage diode

Capacitor: High Voltage capacitor 30Kv 1000pF (1nF) **(24pcs, each one should be well isolated at its pin connections)**
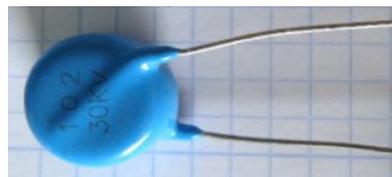

Figure 4-31. 30Kv 1nF capacitor

NOTE: this part of circuit should be in a suitable box filled of sunflower-oil, 6 liters of it is enough for isolation.
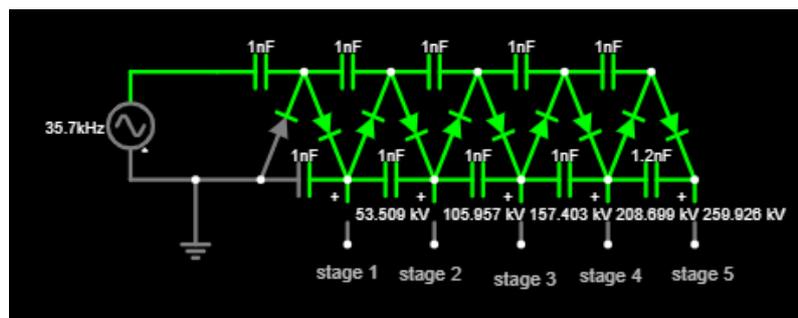

Figure 4-32. Voltage Tripler circuit simulation

4.1.4 Power supply

The power supply is acquired to feed the ZVS driver. This purpose can be achieved in two Methods.

4.1.4.1 Method 1:

The power supply is composed to 3 parts: variable transformer, to control the voltage existed at the input of ZVS driver. Hence, the power delivered to the fusor reactor cathode. Then, a two-transformer (1:1) connected in parallel at the primary, and series at the secondary side, to isolate the variable transformer form the whole system. Finally, the AC voltage produced by these two transformers must be converted from AC to DC voltage, which is compatible with the ZVS inputs.

Figure 4-33. Power Supply Method 1

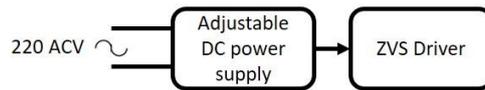| Items	Quantity	specification	Estimated cost

Variable transformer	1		150$
Power transformer	2	473-9101-B Rev15 Class: 180(H) R333H E154515 Type: LEI-4	40$
Bridge rectifier	1	Single phase Diode Bridge rectifier Module: 60A 1600V High power 4 terminals current conversion module	20$
Capacitor	1	10,000uf 50V	2$

Remark: the bridge rectifier is not the best size for the project

4.1.4.2 Method 2:

The power supply is simple as it is, an adjustable switch power supply drive can ensure the needed power input of the ZVS driver (12v at +5A / 15v at + 15A)

Figure 4-34. Power supply Method 2

Items	Quantity	specification	Estimated cost
adjustable switch power supply drive	1	0-30V DC 20A	25$

Figure 4-35. Adjustable DC power supply

4.1.4.3 Method 1 vs Method 2:

The two methods can feed the ZVS driver. Method 1 is more expensive than method 2 (about 8 times method 2). Method 1 is more complex than 2, need more maintenance, etc.

4.1.5 Voltage Tripler Isolation

The voltage Tripler part should be in a suitable box felled by sunflower-oil (about 6 Liter). plus, the capacitor pins isolator

Estimated cost: Box 2$

Sunflower-oil 12$

Capacitor isolator 1$

4.1.6 Cable and isolation

4.1.6.1 Cathode cable

The cable needed to connect the output of high voltage power system with the vacuum chamber must be a Tinning Tesla Coil Laser Wire 40KV High Voltage Cable High Pressure 22AWG 40 KV, as shown in figure 3.18

Figure 4-36. Tinning Tesla Coil Laser Wire 40KV High Voltage Cable High Pressure 22AWG

4.1.6.2 Heat shrinks tube wire wrap

The heat shrinks tube wire wrap is used isolate the capacitor pins from each other, cause of the sparks excited at it at high voltage. Otherwise, it is needed for the resistors of the negative output power side.

Figure 4-37. heat shrink tube wire

4.1.7 Measurement

For voltage measuring, two resistors are acquired (1x 20M Ohm 10W and 1x 20K Ohm 1W) for 1:1000 voltage divider reason. The 20Mohm resistor should be similar to figure 3-20 below. Plus, the 20K Ohm resistor should be similar to figure 3-21.

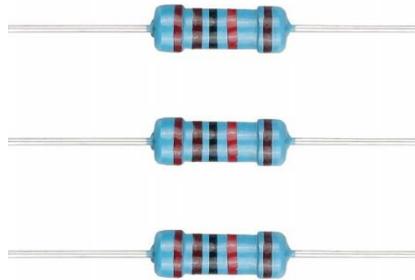**Figure 4-38. high voltage resistor of 500Mj**

Figure 4-39. 20K ohm resistor of 1-2% tolerance

In addition, 4 resistors of 100Mohm 5-watt 1% resistor (MAXI-MOX series) are needed with an ammeter of 0-100uA for 0-40Kv.

Figure 4-40. 100M Ohm Maxi-Mox Series
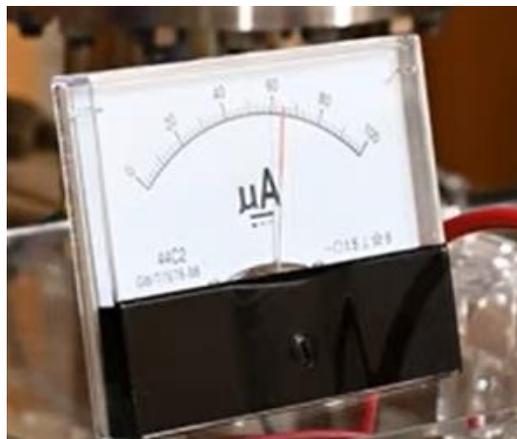
Figure 4-41. amperemeter (uA)

Finally, a 10-ohm 20watt is required for fly back transformer voltage measurement (mV voltmeter)

And 14 pcs of 20Kohm/10W for the anode side of chamber (connected together in series)
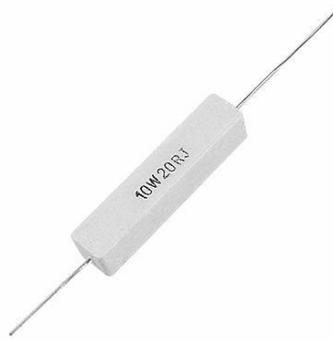
Figure 4-42. 10-Ohm 20w resistor

4.1.8 Remote control

For security reason a remote control should be connected to switch ON/OFF the power.

Figure 4-43. Wireless Remote-Control Receiver

4.1.9 Vacuum System

items	description
Diffusion pump	EDWARDS DIFFSTAK 63/150
Mechanical pump	Arnocanali NPAV72
stalk	
Vacuum pipe	

5   *Mechanical system*

The mechanical system is composed to tow subsystems: vacuum system, and the vacuum chamber system.

5.1 Vacuum system

The vacuum system should vaccumed the fusor reactor chamber approximetly to $2x\,10^{-7}\,tor$ (apporximatly 99% vaccumed), where $1\,atm = 760\,tor\,or\,1\,atm = 760\,mmhg$. The system consists of two pumps: diffusion, and mechanical pump.

5.1.1 Mechanical pump

The following pumps are compatible for this project (or any pumps alternative for it).

5.1.1.1 Edwards Rotary Vacuum pump Model 5:

Figure 5-1. Edwards Two Stage 5 Rotary Vane Vacuum Pump E2M5 1/2 HP 115/208-230 VAC 1 Phase:

Description:

This is a Used well maintained E2M5 Rotary Dual Stage Vacuum Pump. Tested and Quite Serial Number Of Pump 53503.

- The Edwards 5 E2M5 dual stage rotary vane mechanical vacuum pump offers an excellent ultimate pumping speed.
- The Edwards 5 E2M5 has superior vapor handling capabilities, while operating quietly.
- They are very reliable and have accessories to match any application.
- Applications Include use with
- Refrigeration dehydration
- Brake line evacuation
- Epoxy degassing
- Sterilization
- Mass spectrometry
- Vacuum ovens
- Lasers
- Backing combinations
- Thin film coating
- Vacuum distillation
- Freeze drying
- Space research and other vacuum processes.

- The Edwards 5 E2M5 vacuum pumps have a pumping speed displacement at 60Hz of 3.75 CFM and an ultimate pressure of 7.5 X 10 -4 Torr.

Technical data:

- Peak Pumping Speed 3.75 CFM @ 60 HZ
- Ultimate Pressure 7.5 X 10-4 TORR (1x10-3 MBAR)
- Noise Level 52 DB (A)
- Connection Inlet NW25
- Connection Exhaust NW25
- Maximum Water Vapor Inlet Pressure 10 TORR (15 MBAR)
- Maximum Water Vapor capacity 60 Grams / HR
- Physical Data 43 Lbs. 17.5 Length x 5.9 Inches Wide x 8.6 Inches High
- Electrical Supply 115 / 208-230 VAC Wired Set For 115 VAC with cord & plug
- Operating Range 12- 40 C
- Oil Capacity 0.6 L
- Oil Type Ultragrade 19

Click here to go to the website.

5.1.1.2 Edwards Rotary Vacuum pump Model 2:

Figure 5-2. Edwards E2M2 Rotary Vane Vacuum Pump

Description:

Edwards E2M2 rotary vane pumps have a peak pumping velocity of 1.5 cfm and a ultimate pressure of 7.5 x 10-4 Torr. The E2M2 is a dual stage rotary vane mechanical vacuum pump with a 1 phase or 3 phase electrical supply. It is reliable and operates quietly at 52 dB(A).It has excellent vapor handling capabilities and can be used in many applications. Click here to go to website. Comparison between Model 2 and 5:
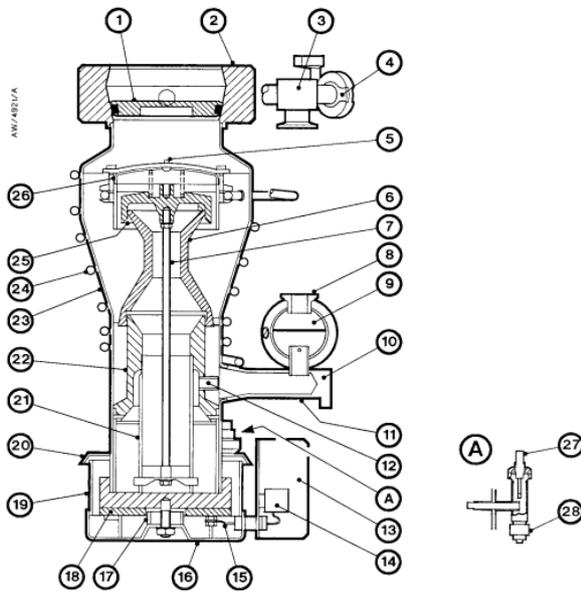
Vacuum Pump Model		E2M2	E2M5
Nominal Displacement	cfm	2	4
Nominal Displacement	l/m	57	113
Stage		2	2
Motor HP	hp	1/3	1/2
Oil Capacity	ltr	.6	.6
Weight	kg	18.2	19.6
Noise Level	dBA	52	52

5.1.1.3 Arnocanali NPAV72

Description:
Nominal displacement: 71l/min
Motor Hp: 0.3HP
Voltage: 220V
Oil load: 300 ml
Final vacuum: 0.2

5.1.2 Diffusion pump

Figure 1 - Sectional view of valved Diffstak 63/150 pump

1. High-vacuum isolation-valve
2. Inlet-flange
3. Roughing connection
4. Gauge connection (NW10)
5. Retainer strap
6. 2nd-stage jet assembly
7. Tie-rod
8. Backing connection
9. Backing condenser
10. Pump-ready switch mounting plate
11. Backing spout
12. Ejector jet
13. Terminal-box
14. Terminal-block
15. Electrical cables
16. Heater assembly
17. Spacer
18. Heater
19. Pump-boiler
20. Radiation shield
21. Vapour-tube
22. 3rd-stage jet assembly
23. Pump-body
24. Water-cooling coil
25. Top-jet assembly
26. Baffle-cap
27. Fluid filler and dipstick assembly
28. Fluid drain

\

|	63/150M 63/150P	100/300M 100/300P	160/700M 160/700P	250/2000M 250/2000P
Pumping speed				
nitrogen	135 l s⁻¹	280 l s⁻¹	700 l s⁻¹	2000 l s⁻¹
hydrogen	200 l s⁻¹	500 l s⁻¹	1300 l s⁻¹	3000 l s⁻¹
Minimum backing pump displacement for maximum throughput	5 m³ h⁻¹	5 m³ h⁻¹	12 m³ h⁻¹	40 m³ h⁻¹
Recommended backing pump	RV3* or RV5	RV5 or RV8	RV12 or E2M18	E2M40
Maximum pump pressure	1300 mbar 1.3 x 10⁵ Pa	1300 mbar 1.3 x 10⁵ Pa	1300 mbar 1.3 x 10⁵ Pa	1300 mbar 1.3 x 10⁵ Pa
Recommended pump fluid	Santovac 5	Santovac 5	Santovac 5	Santovac 5
Fluid charge (dry)	60 ml	125 ml	250 ml	500 ml
Inlet connection, compatible with	ISO63	ISO100	ISO160	ISO250
Backing connection	NW10	NW25	NW25	NW40
Cooling water connection	6 mm compression couplings		10 mm compression couplings	
Minimum cooling-water flow at 20 °C	42 l h⁻¹	60 l h⁻¹	115 l h⁻¹	180 l h⁻¹
Heater power	0.45 kW	0.65 kW	1.35 kW	2.25 kW
Pneumatic connections †	6 mm couplings x ¹/₄ BSP male stud			
Pneumatic actuating pressure †	2.4 to 6.9 bar (35 to 100 psi, 2.4 x 10⁵ to 6.9 x 10⁵ Pa)			
Mass				
M-model	8 kg	12 kg	26 kg	59 kg
P-model	9 kg	13 kg	27 kg	60 kg
Dimensions	See Figures 5 and 6			
Position indicators †				
Maximum voltage	48 V a.c.	48 V a.c.	48 V a.c.	48 V a.c.
Maximum current	380 mA	380 mA	5 A	5 A
Enclosure protection	IP67	IP67	IP22	IP22

2.2 Pump fluid data

Note: *Edwards Material Safety Data Sheets for the following fluids are available on request.*

Fluid type	Critical backing pressure		Ultimate vacuum	
Santovac 5	0.6 mbar	6.0 x 10¹ Pa	3 x 10⁻⁸ mbar	3 x 10⁻⁶ Pa
DC702	1.2 mbar	1.2 x 10² Pa	7 x 10⁻⁶ mbar	7 x 10⁻⁴ Pa
DC704EU	0.8 mbar	8.0 x 10¹ Pa	7 x 10⁻⁸ mbar	7 x 10⁻⁶ Pa
DC705	0.6 mbar	6.0 x 10¹ Pa	3 x 10⁻⁸ mbar	3 x 10⁻⁶ Pa
Edwards L9	0.6 mbar	6.0 x 10¹ Pa	3 x 10⁻⁸ mbar	3 x 10⁻⁶ Pa
Apiezon C	0.7 mbar	7.0 x 10¹ Pa	7 x 10⁻⁸ mbar	7 x 10⁻⁶ Pa

Fluid Type	Flash point °C	Auto-ignition point °C	Molecular weight
Santovac 5	288	590	446
DC702	193	500	530
DC704EU	221	500	484
DC705	243	500	546
Edwards L9	241	370	407
Apiezon C	246	420	479
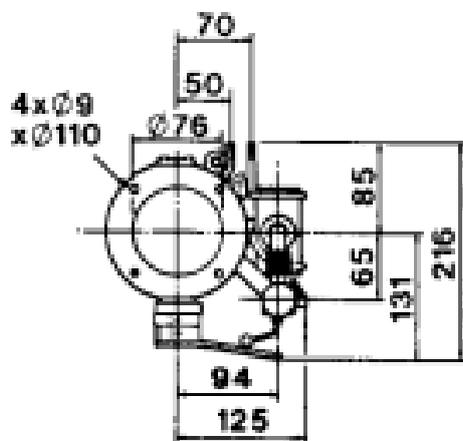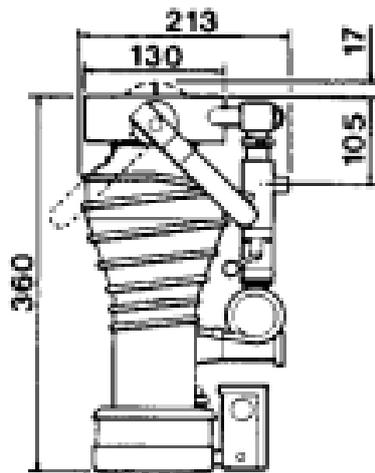
reference: *https://www.lesker.com/newweb/vacuum_pumps/diffusionpump_bocedwards_diffstak.cfm*

5.1.3   Efficiency of Arnocanali NPAV72(Present at AECENAR)

The diffusion pump does not work if the pressure in the chamber is greater than 50 microns.

1micron=0.001 torr

50 microns=5*10^-2 Torr =6.6 Pa

For this reason we use a mechanical pump to decrease the pressure below 6.6 Pa.

Arnocanali NPAV72 can decrease the pressure in the chamber to 0.2 Pa < 6.6 Pa,

Therefore this pump works well.

6 Detectors

6.1 Helium-3 Proportional Counters and Alternatives for Neutron Detection:

6.1.1 Identification of Special Nuclear Material by Neutron Detection

Special nuclear material (SNM) such as plutonium-239, uranium-233, or uranium-235 is used in the creation of nuclear explosives and atomic bombs due to its fissile nature, or capability to self-sustain a chain reaction with neutrons. As such, the detection and control of SNM is essential to global nuclear threat reduction. One method used to identify SNM is through the sensing of fast and slow neutrons, which have energies above and below 0.5-1.0 Kev, respectively. This approach is attractive for several reasons. First, since the ambient background of neutrons is fairly low (0.005-0.02 neutrons/(s cm^2)), any measured neutron levels above the background value is a strong indicator that SNM is present. Moreover, neutrons cannot be easily concealed or shielded from detection since they can penetrate several meters with only 1 MeV in energy. These particles also have unique fission signatures (i.e. release of gamma-rays and neutrons) that depend on their specific interaction with the detection material. Together, these characteristics make SNM identification via neutron detection an appealing approach
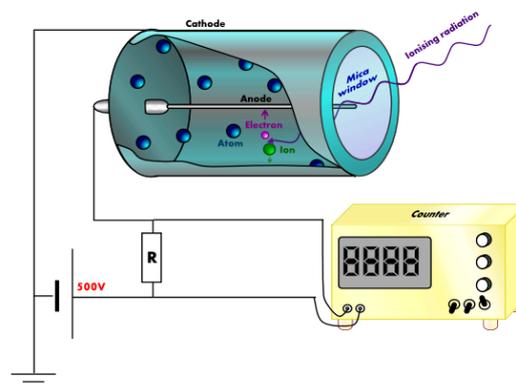
6.1.2 Helium-3 Gas-Filled Proportional Counters and the Helium-3 Shortage

Neutrons can be detected using helium-3-filled gas proportional counters. A typical counter consists of a gas-filled tube with a high voltage applied across the anode and cathode. A neutron passing

through the tube will interact with a helium-3 atom to produce tritium (hydrogen-3) and a proton. The proton ionizes the surrounding gas atoms to create charges, which in turn ionize other gas atoms in an avalanche-like multiplication process. The resulting charges are collected as measureable electrical pulses with the amplitudes proportional to the neutron energy. The pulses are compiled to form a pulse-height energy spectrum that serves as a "fingerprint" for the identification and quantification of the neutrons and their energies. However, one significant concern regarding the use of helium-3 gas proportional detectors is the global shortage of helium-3. This isotope is rarely found in nature but exists as a decay product of tritium, which is primarily produced in nuclear reactors. A recent estimate by GE Reuter Stokes estimates that the United States' demand for helium-3 is approximately 65 kliters per year while the total supply is only 10-20 kliters per year. As a result, there has been a rising and urgent demand for the development of new strategies for neutron detection.

6.1.3 Alternative Neutron Detection Materials

There are several alternatives for neutron detection that are currently in use or under development. Boron trifluoride (BF_3) is one of the most widely-used fill gases for proportional counters. In this case, each neutron interacts with BF_3 to create lithium-7 and an alpha particle, the latter of which serves as the ionizing charge in the gas proportional counter. However, BF_3's toxicity makes it undesirable to handle, especially in applications that utilize larger detectors.

Other boron-related detectors employ powdered boron-10. Recent work at Los Alamos National Laboratory has demonstrated that boron-10 detectors can achieve neutron detection efficiencies comparable to those of helium-3 detectors. Boron-10 is also non-toxic, in abundant supply, and offers excellent discrimination between neutrons and gamma-rays. This material is used as wall-lining in gas-filled proportional counters, as thin films coupled to the surface of semiconductor detectors, and in scintillators (materials that interact with ionizing radiation to produce detectable light). Lithium-6 is another material that is being used for neutron detection. It is used in crystal scintillator compounds like Cs_2LiYCl_6, $Cs_2LiLaCl_6$, and LiI, as well as liquid scintillators and glass fibers. However, one main drawback of lithium-6 is its lower detection sensitivity. Additional options for neutrons under development include liquid argon detectors, scintillating-dye-loaded polymers, and graphene field effect transistors.

6.2 Conclusions

It is clear that no material for neutron detection can meet all of the demands for high efficiency, high abundance, good discrimination, low cost, low toxicity, and ease of scalability. Many of the future solutions will likely rely on the improvement and modification of existing methods and will be designed to be application-specific. Although it is uncertain when the next major breakthrough in neutron detection will occur, shortcomings in certain detection methods can be overcome by coupling complementary and multiple techniques for a more comprehensive analysis.

Reference: http://web.mit.edu/8.13/www/JLExperiments/38/tgm-neutron-detectors.pdf

———

7   *Vacuum tests*

7.1   Test 1:

In this test we will try to vacuum an Aluminum pressure sterlizer model 1925X by arnocanali pump.

Calculation of minimum thickness wall of this chamber:

D0=32.1 cm   L= 42.5 cm   Pext= 14, 7 psi.

Young modulus of Aluminum $E = 69\ GPa = 1.008 * 10^7\ psi$

Thickness t= 3.5 mm.

D0/t= 91.71   L/D0= 1.32

A= 0.001

$$Pa = 2A\,E/3(D0/t)$$

Pa= 72.75 psi>> Pext

Pa/Pext= 4.94.   5 is a safety factor.

Calculation minimum thickness of chamber faces:

 Yield stress of aluminum= 530 MPa

Max allowable stress S =530/5= 15374 psi   5 safety factor.

$$t = Do(0.13P/SE)\verb|^|0.5$$

t= 0.4 cm= 4 mm

thickness of this chamber is equal 8mm. This chamber is Safe

Aluminum young s modulos vs Temperature:

Al Young's Modulus vs Temperature
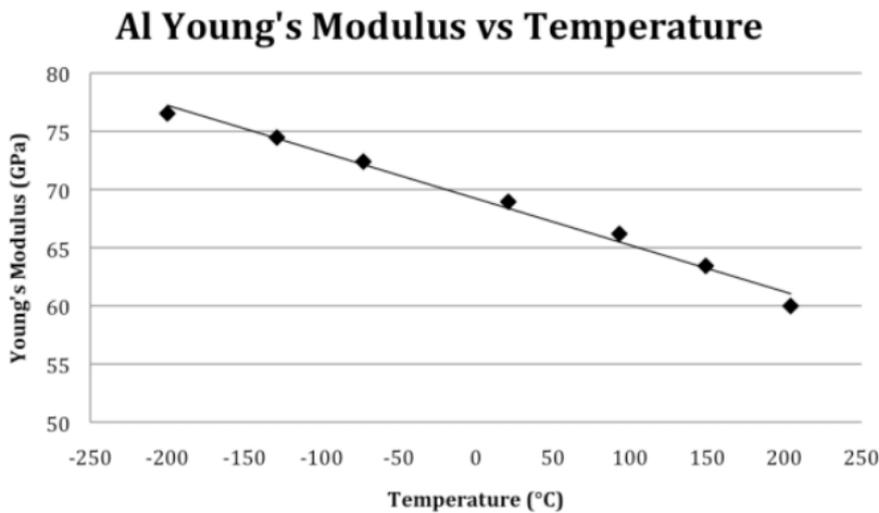
$$E = aT + 69 \qquad a = 60 - \frac{63}{200} - 150 = -0.06$$

maximum temperature strenght of chamber:

if t= 3.5 mm and Pa= 14.7 psi= Pext   E= 15 Gpa

          Tmax= 675⁰C

so we have do not exceed 675⁰C on the wall of chamber

_____

Test 1:

7.1.1 Assembling and pieces:

7.1.2 Result:

The pressure in the vessel reach around 100 mbar.

This value is bigger than required.

The required pressure for work a diffusion pump to work is $50\ microns =\ 1.333*10^\wedge-3\ mbar$

The specifications of this pump shows that the pressure can reach $0.2\ Pa =\ 0.002\ mbar$.

Test failed.

7.1.2.1 Possible reasons:

- The pump does not work well. (Check the oil level in the pump).
- Air leakage into the chamber and connectors.

7.1.2.2 Solutions:

- Test the pump by connecting it directly to a pressure Microns gauge

- If the pump work well, we have to check the leakage in the chamber and the connectors by a helium leak testing.

Helium leak testing:

Helium tracer gas is used for several leak testing applications. It has a small atomic size that allows the gas to pass though incredibly small leaks and is also non-toxic and non-flammable. One common method of tracer gas leak detection is the hard vacuum test, which involves the use of vacuum chambers and tracer gas to detect microleaks.

7.2 Test 2:

in order to know where is the air leakage, a water evaporation test had been done. The chamber was filled to its middle, as shown if figure 7-1. The vacuum chamber was filled at the top of viewport, in other word, water had burial the viewport in order to know if the air leakage was from the viewport, which it will be know if there is any water leakage from the view port, or the air leakge was from the pot cover, that itwill known if there is any steam leakage from the pot cover.

Figure 7-1. Vacuum chamber in water evaporation test

After that, vacuum chamber has been closed tightly and heated by fire for 10-15 min.
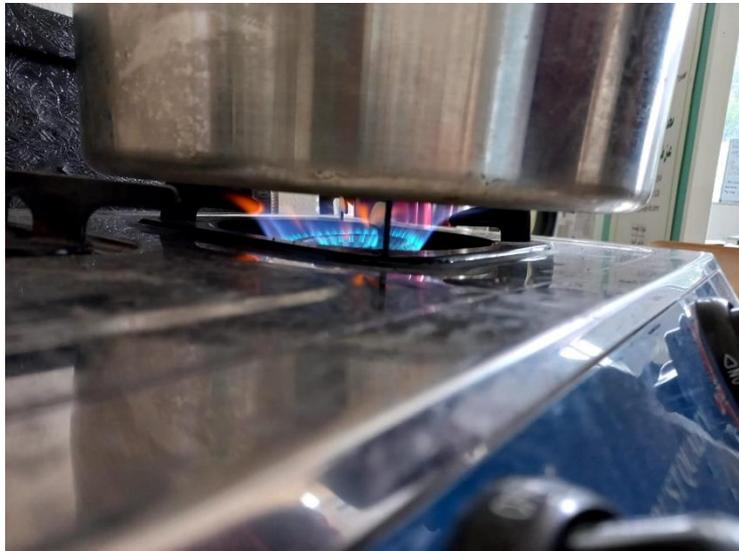
Figure 7-2. vacuum chamber heating operation

The pressure and temperature sensor were monitored by a gauge fixed on the top of the vacuum chamber pot.

The following figure, below, shows where the air leakage take place, the air leakage place is the same place of steam leakage, that is described by a white steam. In figure 7-3 below, the blue zone shows the steam out of chamber, plus, the red zone shows the water bubble exited from the chamber.

Figure 7-3. steam leakage

After some analysis, the pot position has been change as shown in figure 7-4.

Figure 7-4. pot position

The same test was performed again, and the results shows that no noticeable steam leakage.

7.2.1   Result

TEST SUCCESSFUL

7.3 Test 3:

After checking in the level of oil in the pump we saw that is under the minimum level. We added oil in the pump and we retried.

In order to be sure that the pump can reach its maximum, a thumb was putted where the pump is connected to the chamber.

We got a successful result, the pump reached around 0.002 mbar in the chamber, to make sure of this we will use a Microns gauge.

After each test, the pressure is ellimanted by oppening the safety valve manually, as shown in figure below.

Figure 7-5 safety valve opened

Figure 7-6. safety valve closed

7.3.1 Result

<p style="text-align: center; color: red;">**Test successful**</p>

7.4 Test 4

After welding the glass support and assembling pieces we retried to vacuum the chamber

7.4.1 Result

The test failed due to leaking in the red circle on top.

To stop air leaking we put silicon on the red circle, and we vacuumed the chamber
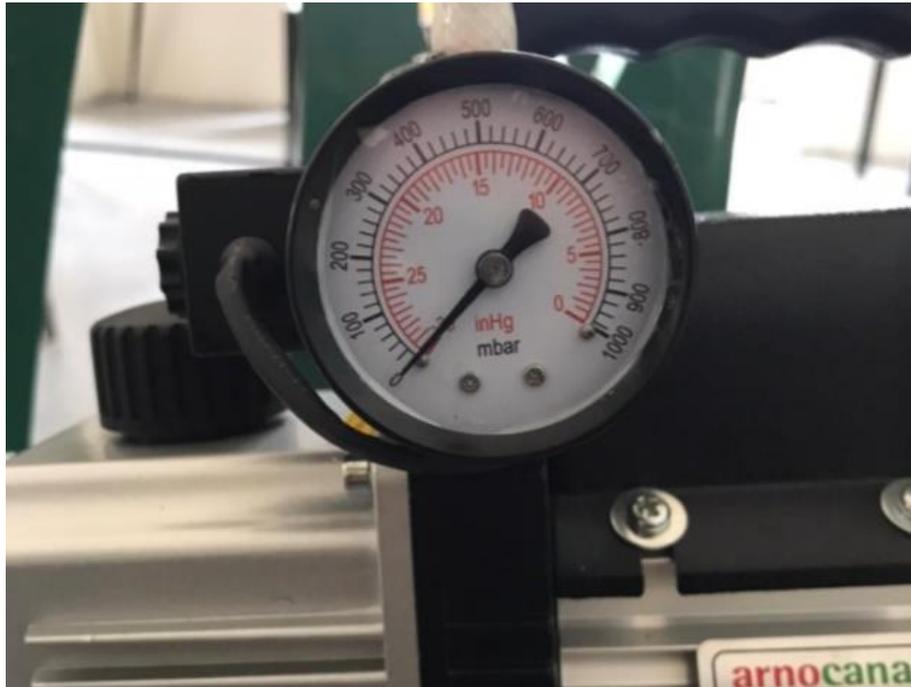
7.4.2 Result

<p style="text-align:center; color:red;">Test successful</p>

7.5 Test 5:

After aforementioned water evaporating test, air starts leak from another place, where just 400 mBar has been extracted by vacuum pump, as shown in figure 7-7 below.

Figure 7-7. Pressure value in mBar

In order to find where the air leakage take place, one medical clove was putted at the viewport. Figure 7-8 illustrates how the clove was putted at the viewport. Where, if the clove shrinks through vacuum operation, hence, the air leakage could be from the viewport. If no so, this estimated place will be eliminated.

Figure 7-8. clove test

There is no air leakage from the viewport side.

Otherwise, in order to ensure that the chamber pot was totally closed tightly. The wall surface that faced the pot has been anointed through an oil submerged tissue.

Figure 7-9. chamber edges lubrication

The same result has been gotten, **no air Leakage from chamber edges.**

After that, another place had been tested. Where, a hand has been putted on the safety valve at the top of pot chamber, as illustrated bellow, and vacuum pump was turned ON.

A pull force has been sensed by the hand, which describes the place where the air leaks. And the pressure gauge shows the following value.

For air leakage blocking, a melted wax has been added on the safety valve.

Test 5:
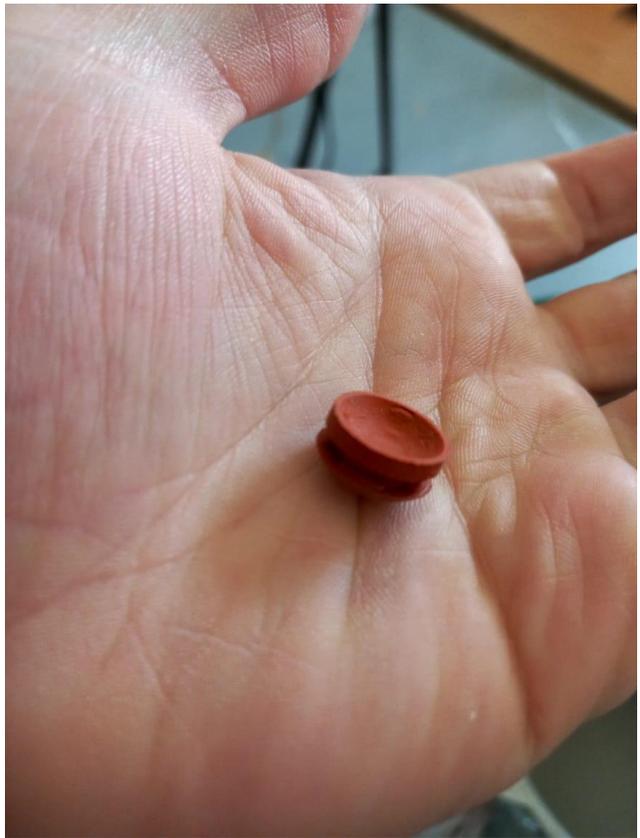
The air leakage was decreased 80 percent, where the pressure gauge shows that vacuum pump extracted 900 mBar from chamber.

For this reason, and for safety valve hole benefits, the safety valve will be eliminated, and it will be replaced by the input of deuterium gas.

8   Searching for materials

8.1   chamber glass window:

We found a thermal glass window that had been used in a submarine.

We will weld a Glass support on the Chamber.

The support is not available in Tripoli so we are going to make one.

We bought an aluminum mold and we cut it this way:

8.2   stainless steel wire

The best choice we found in our country is a stainless-steel wire in (1.6mm diameter of wire).

Note: a tungsten filament had been found, but it can be reshaped. The next figures show how the tungsten electrode broke while we trying to reshape its.
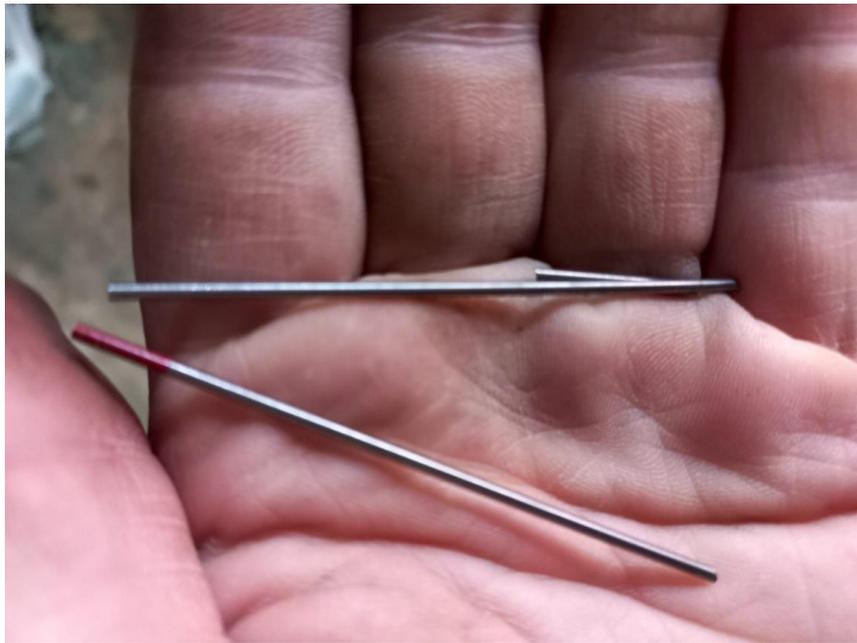
The cathode is a 7 cm diameter grid and consists of three 7 cm diameter rings that have been welded together, each ring is arranged such that the three rings form a spherical grid.
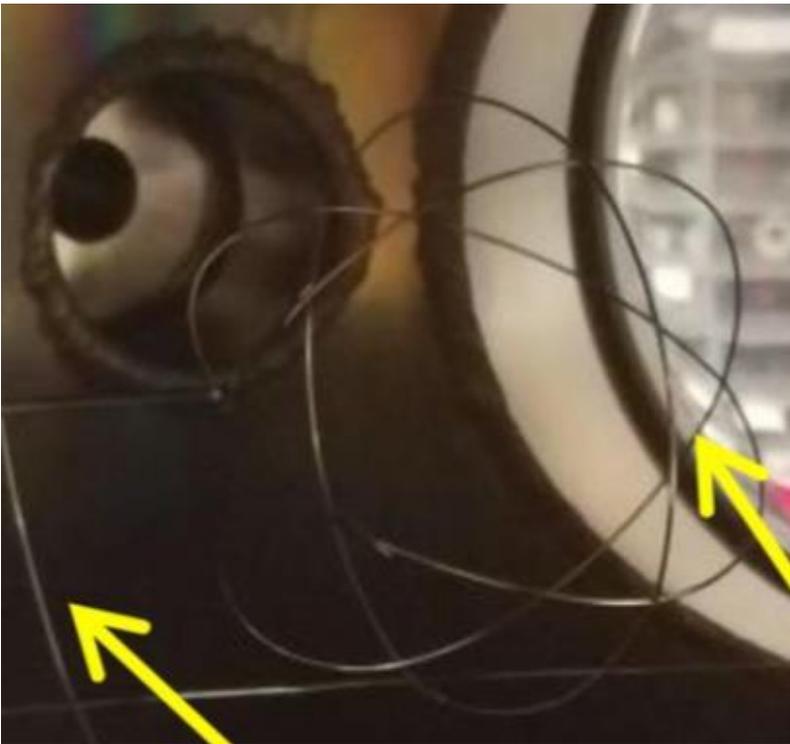
8.3 cathode inner grid assembling

The cathode inner grid has been built in the following steps:

Step 1:

Get three stainless steel rods (2 x diameter: 1.6mm, 1 x diameter:2 mm). the 1.6mm rods are used for the spherical inner grid. This thickness is compatible for the transparency (<92%), as mentioned before.

Figure 8-1. stainless steel wire

Step 2:

Build the spherical inner grid according to its characteristic calculated before.

(The spherical diameter: 7cm, the wire thickness: 1.6mm, and the wire loop number: 3).

In order to build the three loops (circle) of diameter equal to 7 cm, an available gas tank of diameter equals to 7cm has been used.
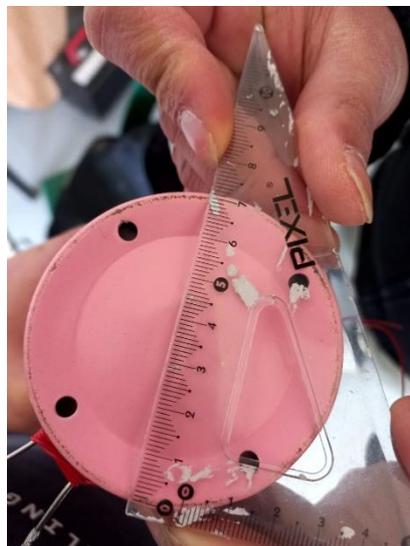
Figure 8-2. gas tank of 7 cm diameter
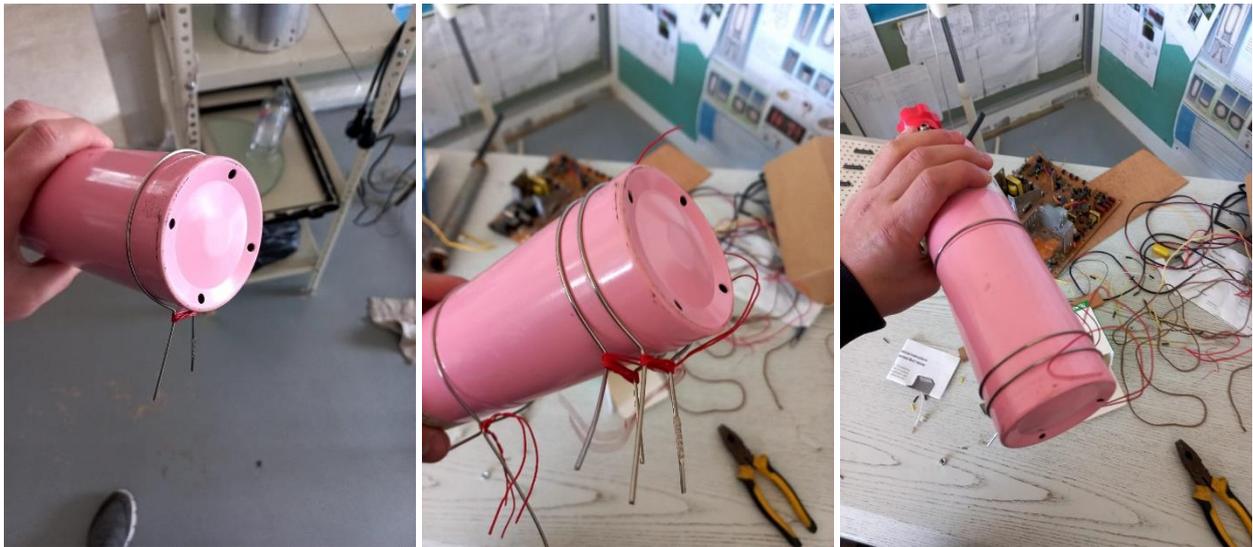
Figure 8-3. stainless steel reshaping

NOTE: each loop has two pins, that is needed to fix the inner grid sphere on its base, as will be mentioned later.

Check each circle reshaped by using the pink gas tube, with a red wire (as shown in figure 3-20 above), the two pins have been tied by a red wire to keep the stainless steel in its circular shape. After two days, the requires shape of stainless-steel wire was achieved. Hence, the three stainless circle has been extracted from the pink gas tank, as shown in figure 3-21.

.

Figure 8-4. stainless steel with circular shape

Step 3:

Gather three stainless circles in order to obtain a spherical shape, as figure below.

Figure 8-5. stainless steel inner grid

Step 4:

Choose the base of spherical inner grid

As shown in figure 3-22, there are 4 pins of thickness equals to 1.6mm, in total of 6.4mm. according to that, the inner grid base should have an inner diameter greater than 6.4 mm. according to local market, a stainless pipe of inner diameter of 7 mm and outer diameter of 10 mm, a length of 10 cm is suitable for this project.

Figure 8-6. stainless pipe tube

Step 5:

Fix all components via argon soldering electrical machine.

NOTE: the soldering needs an expert person, and it is more preferable to use a non-electrical argon soldering machine, cause of the complexity and the accuracy needed of the soldering position.

Figure 8-7. argon soldering electrical machine
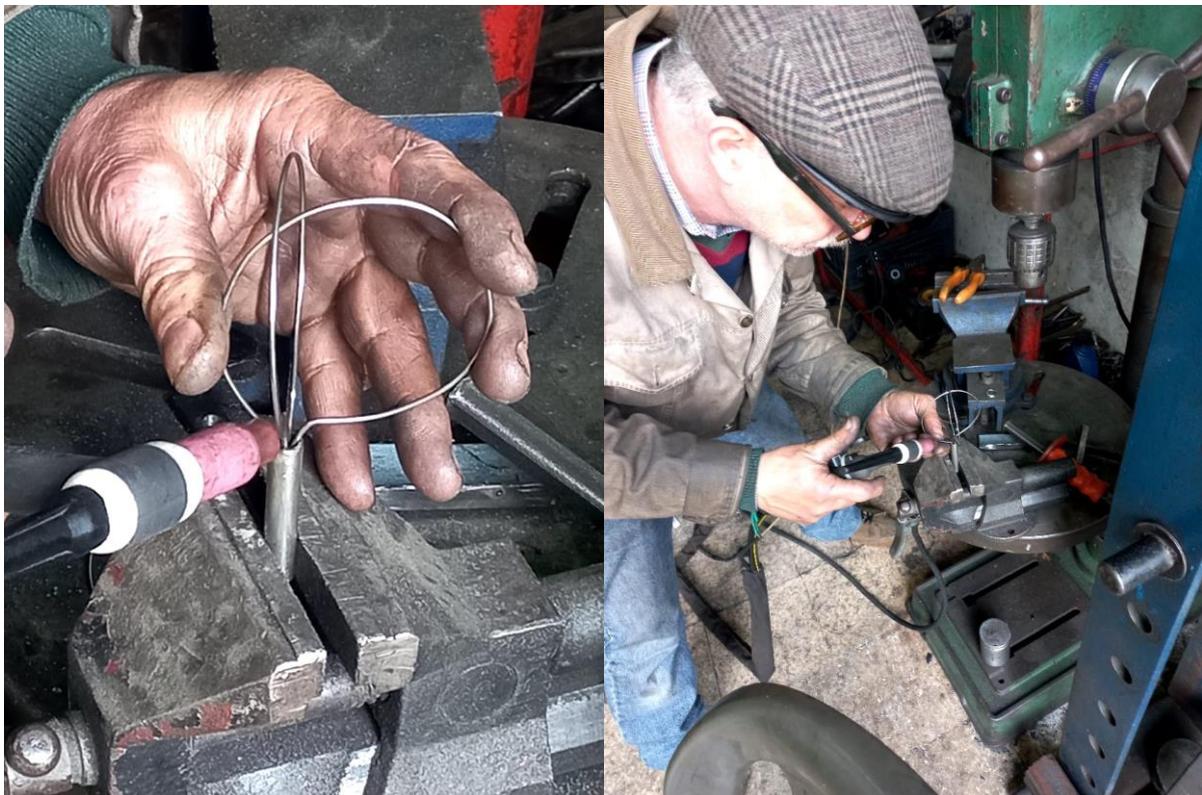
Figure 8-8. inner grid assembling
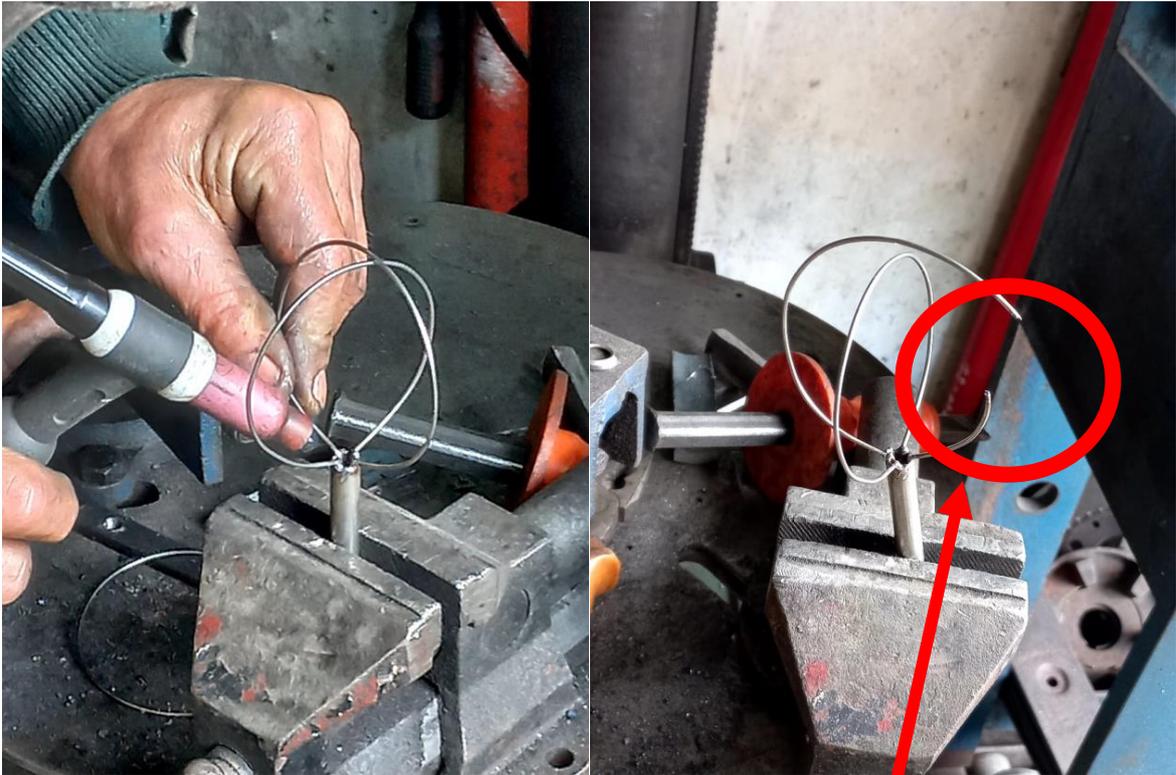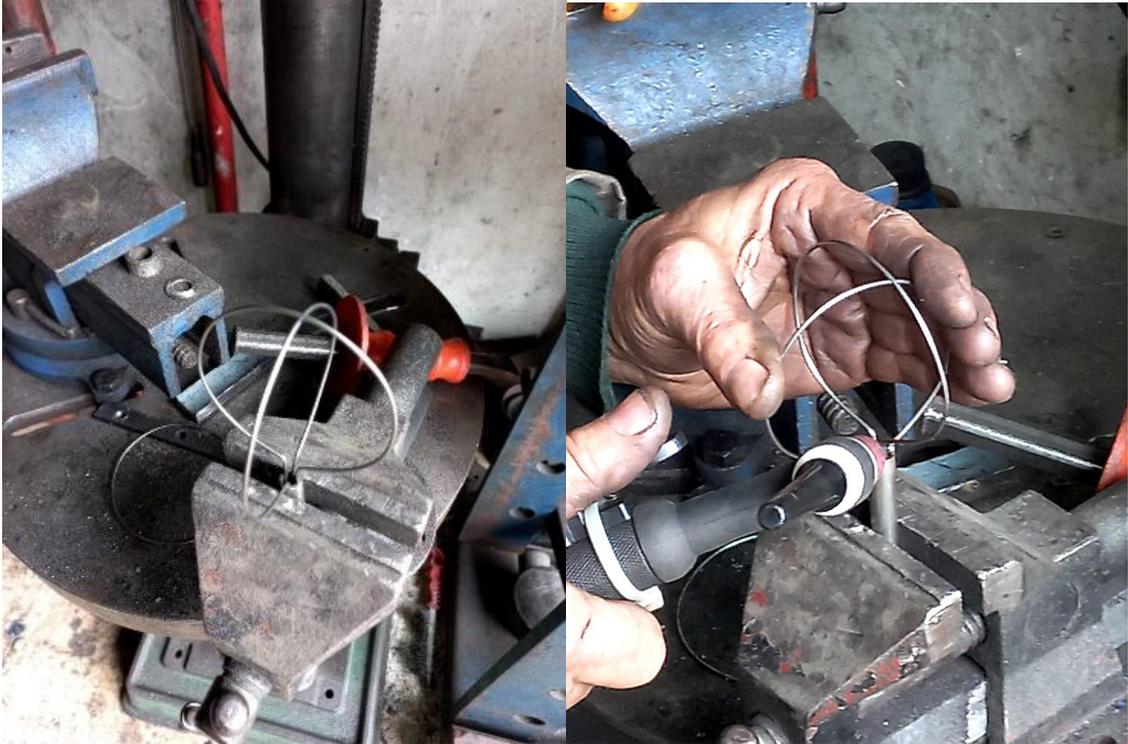
The wire chopped off cause of high sensitivity of wire
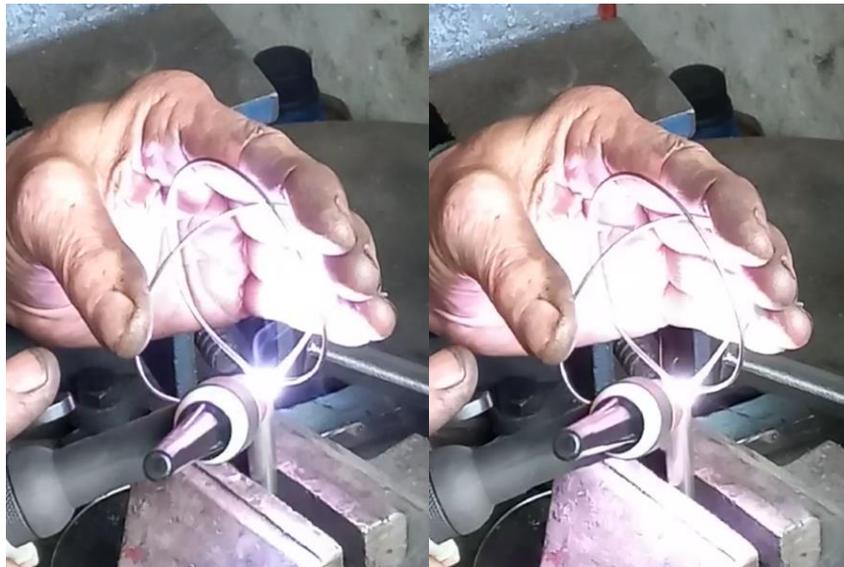
Figure 8-9. Stainless steel Inner Grid argon Soldering

Step 6:

After gathering the stainless sphere with its base, the 2 mm stainless wire has been soldered in other side of stainless pipe (sphere base). the

Figure 8-10. final form of stainless inner grid

8.4 Power supplies

8.4.1 Ac to Dc converter:

To apply 12kv we use transformer:

This transformer is an AC mode output, to convert to DC mode we use 4 diodes (30KV.0.5A)
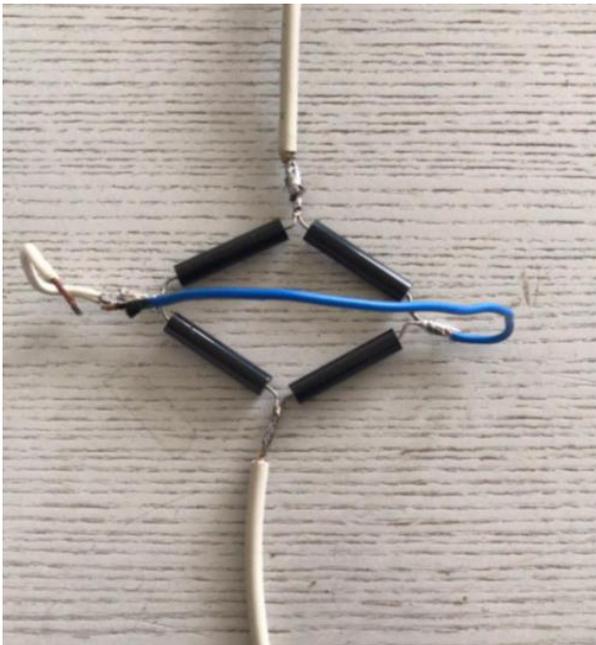
x

~ $1.3cm$ a spark length
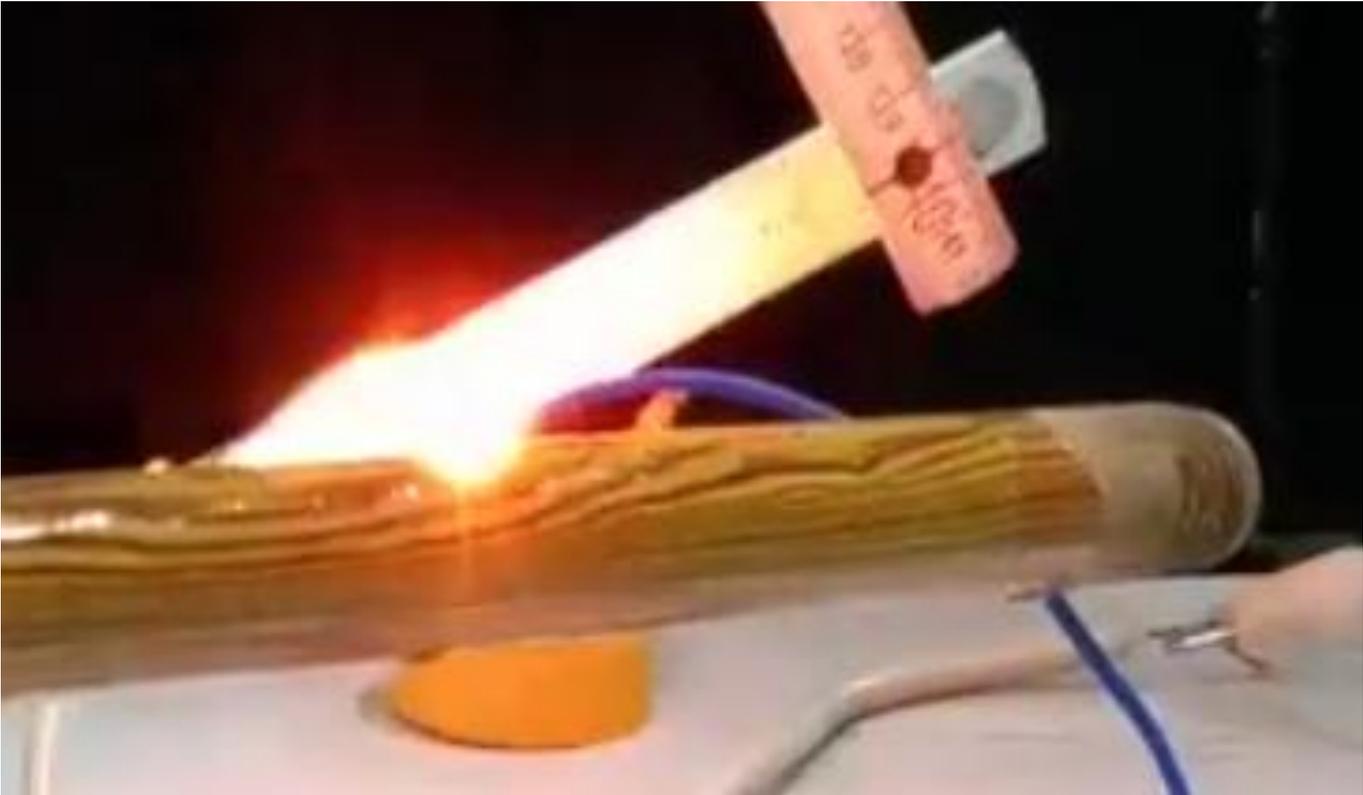
8.4.2 Cockrocft waltan voltage multiplier test

The high voltage transformer has been connected to a voltage multiplier circuit of two stage, which provides an total voltage of 48kv ($2 \times number\ of\ stages \times input\ volatge$) .

Bad
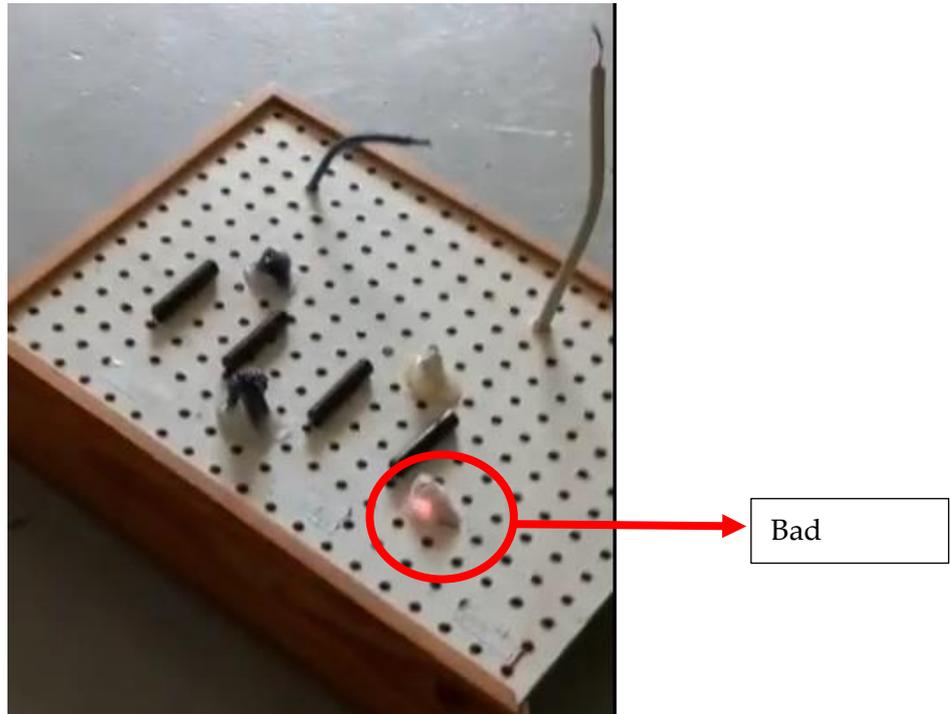
Figure 8-11volatge multiplier test 1
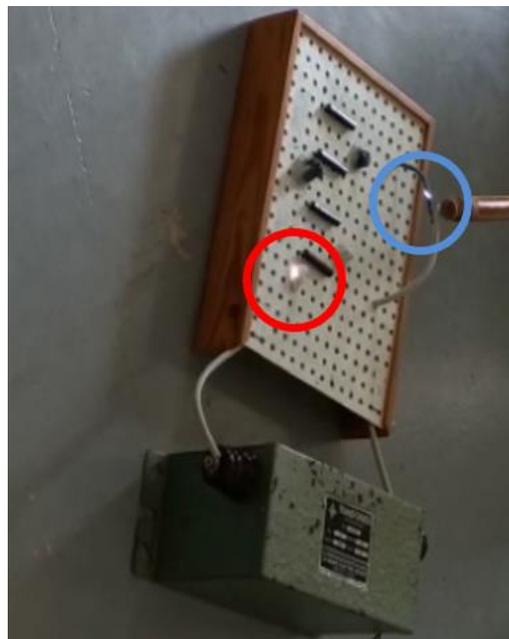
Figure 8-12. voltage multiplier test 2

TEST FAILED

Due to the bas isolation, the voltage jumped form a capacitor pin to another.

Even while, the cathode and anode were close to each other, an electric spark take place in two places, as shown in figure 8-11.

To improve the isolation, the voltage multiplier circuit has been putted in an oil pool.
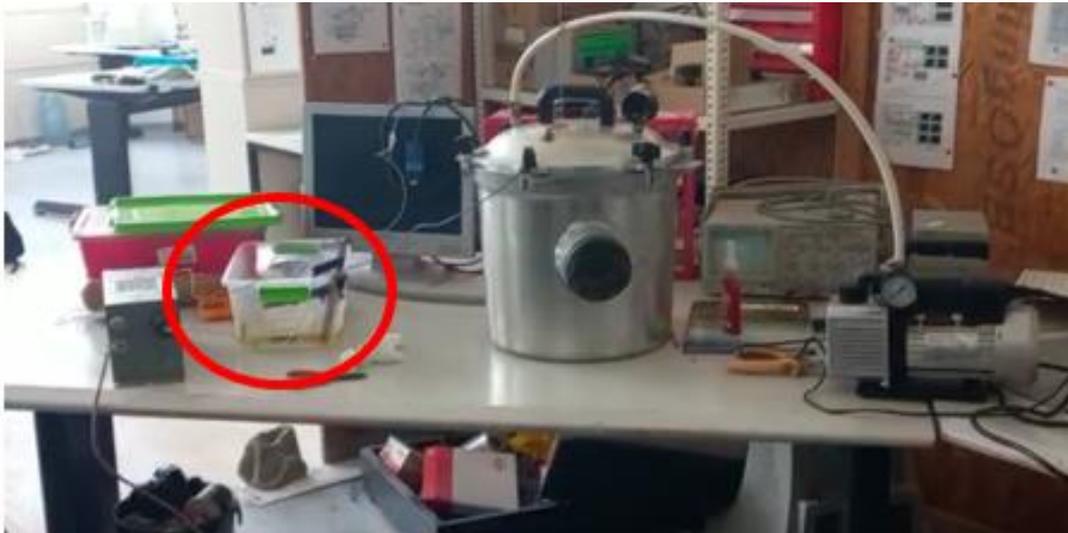
In this way, voltage multiplier circuit worked correctly.

8.4.3 System Test

The anode side of voltage multiplier has been connected to the chamber. as the red arrow indicates. And the cathode has been connected to the inner grid (the stainless-steel filament), as the orange arrow indicates.

Then, the vacuum pump has been ON.

NOTE: Keep vacuum pump turned ON during the whole prodecdure.

,

The following figure illustrates how the cathodes has been isolated from the chamber. The cathode stainless steel has been covered by an TEFLON cylinder, at the nearest place between the cathode rod and chamber, and supported by the red safety valve to cover its hole.

_____

Then, a layer of milted wax has been added on it, for air leakage reason.

The following figure, shows that electric sparks has crossed TEFLON, and other isolation.

BAD ISOLATION

The electric spark milts the TEFLON.

In the figures below, illustrate where sparks take place, plus, the light provided in the chamber

———

8.4.4   1 stage voltage multiplier test

In this test, a car spark plug has been connected at the negative side of the output voltage multiplier (consisted of 1 stage), in order to compare spark length with older test. In this test, the spark was orange, while its color was near the white color.
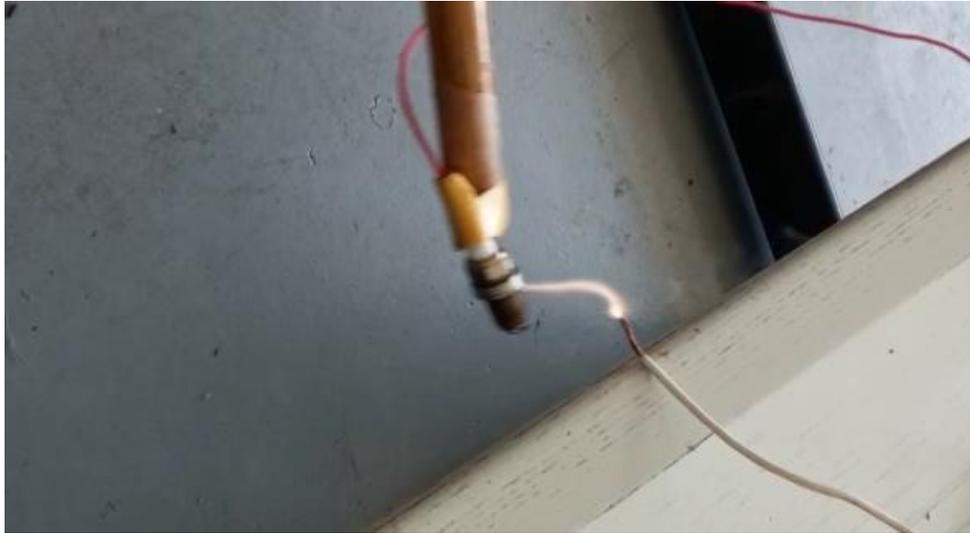
Helium

Diffusion pump

Micron gauge

Fuel cell for deteruim

.detiruim oxide 25-100ml

Pump oil

Accesorioes for deteruim

High voltage 60kv 10mA

9   Procurements

items	description	quantity	cost unit	Shipping	total cost (without shipping)	link	status				
Cathode cable	Tinning Tesla Coil Laser Wire 40KV High Voltage Cable High Pressure Line 22AWG (20meter)	1	$ 39.90	$ 1.89	$ 39.90	https://www.aliexpress.com/item/32900405856.html					
heat shrinks	127Pcs Red Black Heat Shrink Tubing Polyolefin 2:1 Electrical Wrap Wire Cable Sleeves Insulation Shrinkable Tube Assortment Kit	1	$ 0.42	$ 1.55	$ 0.42	https://www.aliexpress.com/item/32961848056.html?spm=a2g0o.productlist.0.0.301f2eecOzjq0l&algo_pvid=06ee2cec-e44b-40f9-ab9e-c11e60dfe7b3&algo_exp_id=06ee2cec-e44b-40f9-ab9e-c11e60dfe7b3-12&pdp_ext_f=%7B%22sku_id%22%3A%2266513577217%22%7D&pdp_pi=-1%3B0.42%3B-1%3B-1%40salePrice%3BUSD%3Bsearch-mainSearch					
ZVS driver	ZVS DC 12-30V 30-50KHz Induction Heating Driver Board High Voltage Generator Circuit PCB Induction Heating Board Module	1	$ 8.28	$ 3.72	$ 8.28	https://www.aliexpress.com/item/32829538662.html https://www.zoodmall.com.lb/en/product/14365591/zvs-driver-board-zvs-induction-heating-circuit-dc1230v-zero-voltage-switch-power-supply-driver-board/					
AC flyback transformer		1	$ 29.00		$ 29.00	https://highvoltageshop.com/epages/b73088c0-9f9a-4230-9ffc-4fd5c619abc4.sf/en_GB/?ObjectPath=/Shops/b73088c0-9f9a-4230-9ffc-4fd5c619abc4/Products/FBT_AC_003	or we can build our transformer				
diodes	.20 20kv 20mA (10pcs/	6	$ 1.30	$ 0.53	$ 7.80	https://www.aliexpress.com/item/4000774847114.html?spm=a2g0o.productlist.0.0.5f482477czxQ8L&algo_pvid=f7cbc2ce-2e7c-44ac-ba50-527e13f9a1d7&algo_exp_id=f7cbc2ce-2e7c-44ac-ba50-527e13f9a1d7-0&pdp_ext_f=%7B%22sku_id%22%3A%2210000007747145794%22%7D&pdp_pi=-1%3B1.3%3B-1%3B-1%40salePrice%3BUSD%3Bsearch-mainSearch					
capacitor	30kv 1nF (5pcs per package)	6	$ 10.00	free	$ 60.00	https://www.aliexpress.com/item/32274855513.html?spm=a2g0o.productlist.0.0.6b652d41fem6Rp&algo_pvid=7bb918e9-1b93-4111-9573-b48ec09d5861&algo_exp_id=7bb918e9-1b93-4111-9573-b48ec09d5861-0&pdp_ext_f=%7B%22sku_id%22%3A%2216705677453%22%7D&pdp_pi=-1%3B9.99%3B-1%3B-1%40salePrice%3BUSD%3Bsearch-mainSearch					
resistor 1	2 Mohm 10W	1	$ 9.70	$ 3.71	$ 9.70	https://www.aliexpress.com/item/4001205129769.html					
resstor 2	MOX-1-121006FE (4 pcs)	1	$ 43.88	-	$ 43.88	https://www.digikey.be/en/products/detail/ohmite/MOX-1-121006FE/823611					
resistor 3	20 kOhm 1W	1			$ -	lebanon supplier					
resistor 4	10 ohm 20w	1			$ -	lebanon supplier			shipping	total cost (without	
plastic box	suitable plastic box for voltage tripler circuit	1			$ -	lebanon supplier			$ 11.40	$ 203.73	
sunflower-oil	6 liter				$ -	lebanon supplier					color code	description.
capacitor isolation	each capacitor need 2 isolator	60			$ -	lebanon supplier						buy from lebanon
adjustable switch power supply drive	0-30V DC 20A	1			$ -	lebanon supplier						not found yet
resistor 5	20 kOhm 10W	14			$ -	lebanon supplier						not the best shoice
remote control	1-channel 1000w	1	4.75	4.51	$ 4.75	https://www.aliexpress.com/item/32838128067.html?spm=a2g0o.productlist.0.0.5dc962a8XmKZZK&algo_pvid=4464d875-1c01-4bd3-a1c1-e91ccc0317a0&algo_exp_id=4464d875-1c01-4bd3-a1c1-e91ccc0317a0-8&pdp_ext_f=%7B%22sku_id%22%3A%2265092334613%22%7D&pdp_pi=-1%3B4.75%3B-1%3B-1%40salePrice%3BUSD%3Bsearch-mainSearch	or from lebanon				
					$ -						
					$ -						
					$ -						
					$ -						
					$ -						
					$ -						
					$ -						

items	description	quantity	cost unit	Shipping	total cost (without shipping)	link	status	Note
Diffusion pump	high vacuum pump	1	$	???	$ 200.00	Diffusion Pumps - High Vacuum Diffusion Pumping Manufacturer from Bengaluru (indiamart.com)		
Pump oil	Arnocanali NOIL250 250 ml	1		96.04	5.5	https://www.ebay.com/sch/i.html?_from=R40&_trksid=p2334524.m570.l1313&_nkw=Arnocanali+NOIL250&_sacat=0&LH_Title Desc=0&_odkw=Arnocanali+NOIL250+Bottle+Oil+&_osacat=0		
vacuum pipe	304 Stainless Steel KF16 High Vacuum Bellows Pipe	2	$	$ 80.63	$ 23.00	https://www.aliexpress.com/item/32869869537.html?spm=a2g0o.productlist.0.0.7df6654b6sEqXR&algo=04c40603-9b52-4dd3-9689-87605563860f&algo_exp_id=04c40603-9b52-4dd3-9689-87605563860f-3&pdp_f=%7B%22sku_id%22%3A%2265471171533%22%7D&pdp_pi=-1%3B40.0%3		
microns gauge	Elitech VG-760 Digital Vacuum Gauge Micron Gauge for HVAC Micron Meter Refrigerant Vacuum Meter Digital Micron Leakage Test 1/4" SAE	1	**$**	$69.69	189.99	https://www.amazon.com/Elitech-VG-760-Refrigerant-Pressure-Temperature/dp/B07ZFD4RYN/ref=sr_1_6?crid=26APVAKS30TTT&keywords=high+vacuum+gauge&qid=1646046858&sprefix=high+vacuum+gauge%2Caps%2C370&sr=8-6		
conflat flange	not decided yet	3		lebanon	???			
vacuum valve	not decided yet	3		lebanon	???			
neutron detector	Helium counter	1	$	free	134.99	https://www.ebay.ca/itm/114818335347?hash=item1abbb4c273:g:fCQAAOSwYjJgpt2v		
Clam vacuum pump	1X Clamp KF-40 Al Vacuum Pump Flange Fitting Parts Contain o-rings Alum bracket	4	$	12.79	6.44	https://www.aliexpress.com/item/32573071185.html?spm=a2g0o.productlist.0.0.2f7a2141R9GRam&algo_pvid=7be1d578-9a53-4e87-b70d-901b86a57f44&algo_exp_id=7be1d578-9a53-4e87-b70d-901b86a57f44-7&pdp_ext_f=%7B%22sku_id%22%3A2258548240831%22%7D&pdp_pi=-1%3B1.61%3		
Helium gaz				lebanon				
Vasline vaccum			euro	online	34	https://eshop.dencop.cz/en/vaseline-vacuum-50g		
deuterium oxude	25 ml glass bottle	>1	euro	online	101	Cas 7789-20-0 || Deuterium oxide-d, RS - For NMR - min 99.8%, 25 ml, Glass bottle - Actuall Chemicals (actu-all.com)		
Horizon Solar Hydrogen Science Kit	deuterium gas production	1		onine	119	Solar Hydrogen Science Kit - Arbor Scientific		
				total	$ 954.07			

Prices may change according to availability in the market.

10 References

http://aecenar.com/index.php/downloads/send/3-meae-institute/731-iecf-prototype-concept-pdf

https://www.steelss.com/Materials/Stainless-Steels/YB-306_31_804.pdf

https://www.youtube.com/watch?v=0J6ci3IxUkc

https://www.youtube.com/watch?v=CJSaAjJMK5w

https://www.slideshare.net/ARGHASAHA4/vacuum-chamber-design

https://www.engineersedge.com/pressure_vessels_menu.shtml

http://fusor.eu/theory.html