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Creation of a control system for plasma delivery to increase automation and stability

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Abstract

Surface figuring of extremely large telescopes (ELT) addresses a highly challenging manufacture issue for the field of ultra precision. [1] High form accuracy and rapid fabrication are needed for ELT primary mirror surface figuring.

In Cranfield University, Plasma Figuring (PF) [2] is used as a main method to correct ELT mirror surface figure error. The non-contact based material removal process brings PF to a high level of accuracy (under 1nm RMS level). Some other great features of PF are the capability to work at atmospheric pressure, the low-cost of consumables. Other figuring methods make use of vacuum chamber (ion beam Figuring) which are expensive. On the other hand magnetorheological finishing requires expensive consumables. Although PF is dominant for the surface correction of metre scale surfaces, challenges still exist to improve the automation and stabilization of the plasma source.

In the context of ever-increasing dimensions of optical components, there is a need for improving the robustness and securing the performance of the unique Plasma Delivery System (PDS) available in Cranfield. The current PDS is based on an inductive output L-type radio frequency (RF) circuit, Inductively Coupled Plasma (ICP) torch and computer numerically controlled (CNC) motion system. The combination of optical component surface dimensions and the material removal rate of the plasma jet lead to significant processing duration.

Based on the existing PDS for our unique Plasma Figuring machine named Helios1200, we designed an enhanced PDS version. The novel design was given the capability to detect phases and automatically tune the impedance of the plasma. The novel control capability is aiming at secure the process determinism, assisting the machine operator by tuning key electrical components of the RF network and monitoring crucial processing parameters.

Furthermore, specific assistances were provided during the three identified processing phases (ignition phase, regular operation and critical circumstance) of the plasma processing. Our design addressed particular functions on each phases to ensure an optimum performance during the Plasma Figuring process.

Keywords

Plasma; Extremely large telescopes (ELT); Plasma Figuring (PF); Plasma Delivery System (PDS); Radio frequency (RF); Inductively Coupled Plasma (ICP); RF power; Impedance; processing parameters; ignition phase; regular operation;

Sponsors

- China Scholarship Council
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List of Abbreviations

CNC	computer numerically controlled
E-ELT	European extremely large telescopes
ELT	extremely large telescopes
EM	electromagnetic
EUV	extreme ultra-violet
EUVL	extreme ultra violet lithography
GND	ground/0V
I/O	input/output
ICP	inductively coupled plasma
ICSP	in-circuit serial programming
IDE	integrated development environment
IMN	impedance-matching network
ISP	in-system programmer
NIF	national ignition facility
PDS	plasma delivery system
PF	plasma figuring
PWM	pulse width modulation
RAP	reactive atom plasma
RF	radio frequency
rfl/fwd	reflect power/ forward power
RTD	resistive temperature devices
RMS	roughness measurement of the surface
TD	temperature difference
TL	transmission line
UARTs	universal asynchronous receiver/transmitter
VSWR	voltage standing wave ratio

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Best wishes for the further work and success with the plasma delivery system project. It would be great honour to hear that impedance of the RF network of the plasma delivery system can be tuned efficiently. The author treasure the research experienced in Cranfield University and will recommend the Cranfield University to other Chinese students.

Chapter 1

Introduction

Firstly, chapter 1 addresses the application and benefits of the enhanced plasma delivery system (PDS). Secondly, chapter 1 goes into more details in connection with different kinds of PDS based on various radio frequency (RF) circuits.

1.1 Motivation of research: creation of an efficient and stable plasma delivery system (PDS)

The purpose of this research focused on developing a hybrid plasma delivery system for supporting the Plasma Figuring (PF) capability to correct large optical surfaces at atmospheric pressure. The combination of optical component surface areas and the nature of the sub-aperture plasma tool lead to significant processing duration. However, the novel control system aims at securing the process determinism and assisting the machine operator by tuning some key electrical components of the RF network and monitoring some processing parameters. In our PF machine named as Helios1200, a fixed match [3] circuit was designed, getting benefits on the fast reflection of power and cheap cost compared with phase detector RF circuit [3]. However, matching network can reduce the reflected power down to zero when environmental conditions change strongly (generator frequency> +/- 20%). [4]

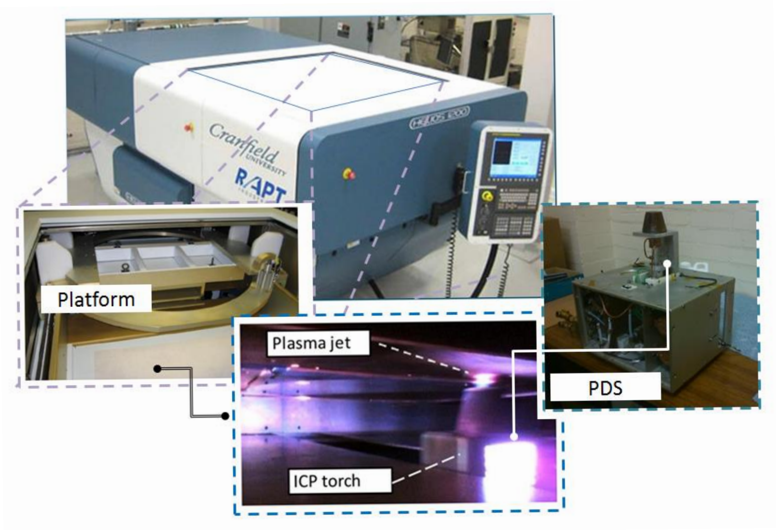


Figure 1.Helios1200 including processing platform and plasma delivery system

The large PF machine detail arrangement can be recognized in Figure 1.1. The processing capacity of Helios1200 brings benefits to the rapid Figuring of large optics up to 1.2m diameter at atmospheric pressure with the operation from qualified operators. Since PF technology is a non-contact [7] manufacture technology, the surface accuracy can reach up to 1nm RMS (Roughness Measurement of the Surface) with a minimum number of iterations. Helios1200 was designed mainly based on four sub-systems: an inductive output RF circuit, inductively coupled plasma (ICP) torch [5], computer numerically controlled (CNC) motion system (Fanuc 30i series) [6] and scrubber system. RF circuit, signal generator, chiller and ICP torch constitute the current PDS. This project addresses the RF circuit enhancement of PDS. Here below, the Helios1200 machine, its processing chamber and its PDS are displayed.

1.2 Background knowledge for creating novel plasma delivery system

In general, this project facing the adjustments of mechanical structure, creation of new electrical circuit and function test is related to the various phases during plasma Figuring. To be more specific, the design should fit the existing PDS.

To start with electrical circuit, Helios1200 was designed with fixed match electrical circuit, which is commonly designed with an inductor or capacitor coupled in series between power source and loads and in parallel from the source to ground.

Moving on to machinery structure, the parts planned to be assembled in the PDS should be seriously matched with the structure of PDS itself and the mechanical properties. Put into details, the tuning force giving by the new actuator should be satisfactory for the PDS as displayed in chapter 3. Otherwise, before assembly, the parts planned to be assembled into PDS should be checked by the UG NX7.5 and the applicability and rationality for the structure should be checked step by step.

Latest but not least, the functions of the novel design should be verified, based on the programs formulated by the author. All the programs were run on the Arduino technology platform. The pioneer micro-control board has dominant position in micro-control area. That technology sharply decreases the difficult to code and enhances the reliability.

Chapter 2

Literature review and theory

This chapter traces the source back to the application of PF technology, covers the PDS existing in the market and addresses the details of literature to support the novel PDS design. The technical information used in the novel PDS also was addressed below, which is also related to the design itself.

2.1 Application of Plasma Figuring

The PF technology aims at processing ultra-precise surfaces made of fused silica, silicon, borosilicate, silicon carbide and ULE [8]. The ultra-precise surfaces are mainly needed by three research programs: high energy laser fusion systems, extreme ultra violet lithography (EUVL) systems and ground based extremely large telescopes (ELT). These three research programs demand cost effective optical fabrication supply. Surfaces have high technical requirements. Their fabrication is a challenge for current manufacturing methods. To be specific, the highly demands can be summarized into ultra-precise form accuracy and high surface integrity. [9] The three mentioned applications are detailed in the next section.

2.1.1 National Ignition Facility (NIF) building for high-energy density and fusion science

The operation of NIF at Lawrence Livermore National Laboratory aims at the study of high-energy density and fusion. The main three goals are to study new regimes in astrophysics and basic science, to ensure the United States stockpile of nuclear weapons is reliable, safe and secure, to achieve ignition producing a net energy gain for the first time in a laboratory.

Compositions of NIF building are two laser bays, four power conditioning bays, two beam switchyards, a target bay, a diagnostic building, a core controls and oscillator area reaching at approximate 150 m by 90 m and seven stories tall. A schematic of the building layout is shown in Figure 2.0 [10, 11].

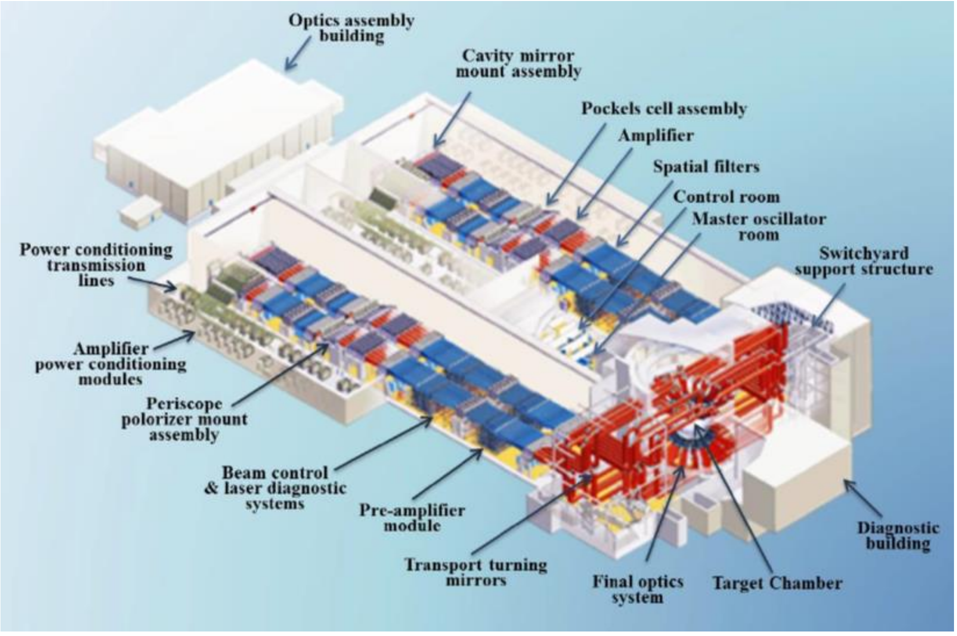


Figure 2.Schematic view of the National Ignition Facility highlighting some of the main elements of the laser system. For a scale in this Figure, the round target chamber on the right is 10 meters in diameter [10].

NIF using more than 7.500 precision optics of diameter from 0.4 to 1.0 m builds the largest optical system in the world. 3072 Nd-doped phosphate glass laser slabs, 960 fused silica aspheric lenses, 960 fused silica windows, 1600 multi-layer dielectric mirrors and polarizers, 192 diffraction gratings, 192 phase plates and 576 KDP plus DKDP crystal plates will be included in NIF (see Fig. 3).

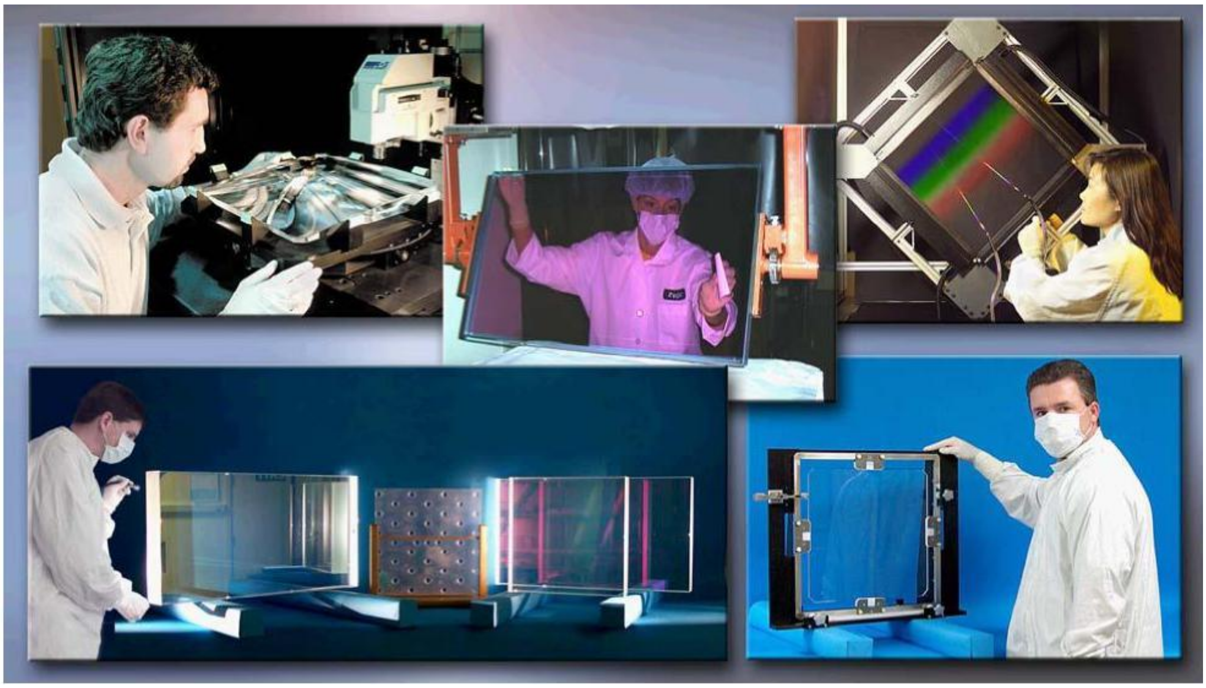


Figure 3.Examples of large optics. Clockwise from upper left: fused silica wedged focus lens, neodymium-doped phosphate laser glass slab, fused silica beam sampling grating, KDP frequency conversion crystal, and multi-layer dielectric coatings (on BK-7 substrates) that comprise the mirrors and polarizers [12].

The optics wave front and surface specifications are defined for different spatial scale-lengths as follows (at 633 nm) [12]:

- Peak-to-Valley (λ /3) and RMS gradient (λ /90/cm) over spatial scales greater than 33 mm
- Power spectral density over a spatial scale from 2.5 to 33 mm (PSDI): Rq < 1.8 nm
- Power spectral density over a spatial scale from 0.12 to 2.5 mm (PSDPI): Rq <1.1 nm
- Micro-roughness over spatial periods 0.01 – 0.12 mm: < 0.4 nm (glass) or <1.0 nm (crystals)

2.1.2 Twinscan NXE: 3300B an extreme ultra violet lithography system

Extreme Ultra-Violet (EUV) lithography is applied to semiconductor manufacturing of the 16 nm technology node and beyond. Benefits from very short wavelength of 13.5 nm, EUV lithography is able to continue single exposure scaling with improve resolution [13]. Twinscan NXE system of ASML is the industry's first production for EUVL. The NXE: 3300B is enhanced version compared with NXE: 3100, aiming at illuminate 22 nm resolution conventionally and 18nm off-axis, otherwise improvement of overlay and higher productivity can be achieved [14]. Here below the NXE: 3300B is displayed.

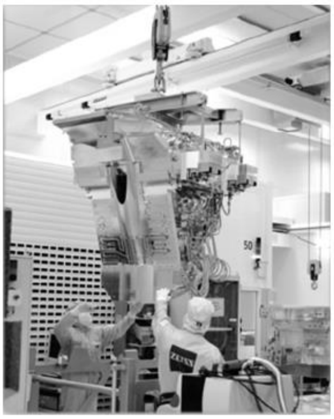


Figure 4.TWINSCAN NXE3300B (Left); completely integrated illuminator during preparation for shipment (Right)

In the design stage of the NXE: 3300B, designer planned to extend up to numerical apertures (NA) around 0.4 based on 6 mirror system (high level than NXE: 3100).

One of the limitations for addressing this design is located in the last folding mirror reflecting the light towards the exit mirror of projection optics to enlarge the exiting mirror as increasing NA maintaining the same accuracy of mirror Figure 5 [14].

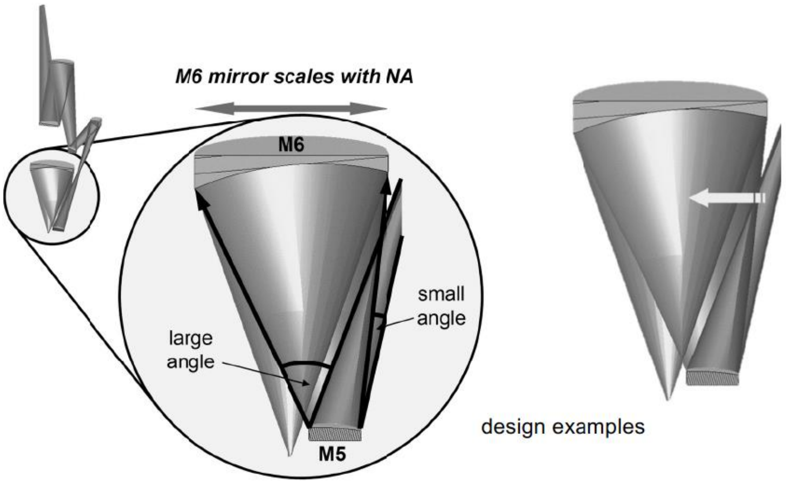
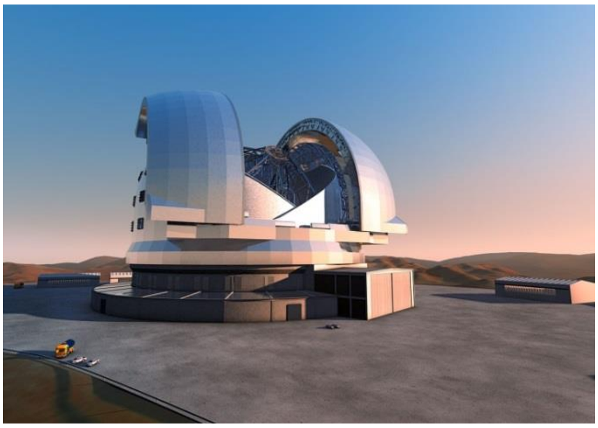


Figure 5.Design example of 6-mirror system. Magnified: angular situation around the exit mirror configuration illustrating the large variation of incident angles on the folding mirror [14].

2.1.3 European Extremely large telescopes (E-ELT)

The E-ELT is a 40 m-class telescope is the main result of a revolutionary scientific project that will allow human being to have chance to obtainable answers about the understanding of our universe. The E-ELT will be the largest optical/near-infrared telescope in the world and will gather 13 times more light than the largest optical telescopes existing today. The first light of E-ELT is planned in 2024. In September 2010, the E-ELT's detailed design was finished, meaning final design review achieved. Optical design was created by five-mirror design as primary mirror (M1), secondary mirror (M2), tertiary mirror (M3), quaternary mirror (M4), fifth mirror (M5). The detail information is as follows:

- Primary mirror M1: Diameter 39 m (798 hexagonal 1.4 m-class mirror segments)
- Secondary mirror M2: Diameter 4 m
- Tertiary mirror M3: Diameter 3.75 m
- Quaternary mirror M4: 2.4 m (six thin segment mirrors, each only 1.95 millimetres thick and made of ceramic glass)
- Fifth mirror M5: Flat mirror, elliptical in contour, defines the altitude axis of the telescope and steers the beam towards the Nasmyth focus.



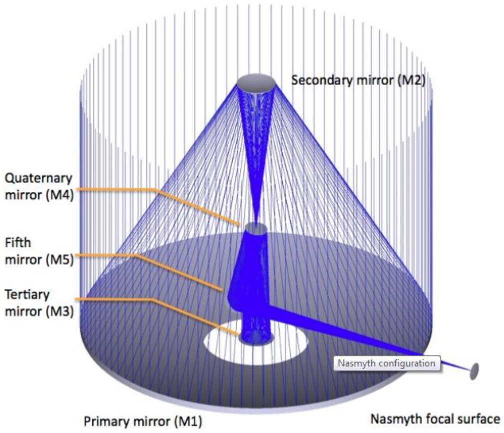


Figure 6.E-ELT model (left) and Optical design (right)

2.2 Plasma figuring technology

Plasma Figuring is dwell time based fabrication method used on silicon based optical components. The plasma jet is used to etch the material using reactive gas introduced in the plasma for the creation of radical species. The plasma jet contains both charged (ions) and neutral (atoms and radicals) compounds. During the process, the plasma generate volatile etch products. The chemical reactions occurring between the optical component and the reactive species generated by the plasma leads to volatile species.

2.3 Inductively coupled plasma (ICP)

Inductively coupled plasma (ICP) is a type of plasma source produced by electromagnetic (EM) induction, energy supplied by electric currents. ICP discharges are to relative high electron density. Basically, there exists three types of ICP geometries to couple plasma as planar, cylindrical [15] and half-toroidal. Conventional plasma inductors are as attached Figure 7.

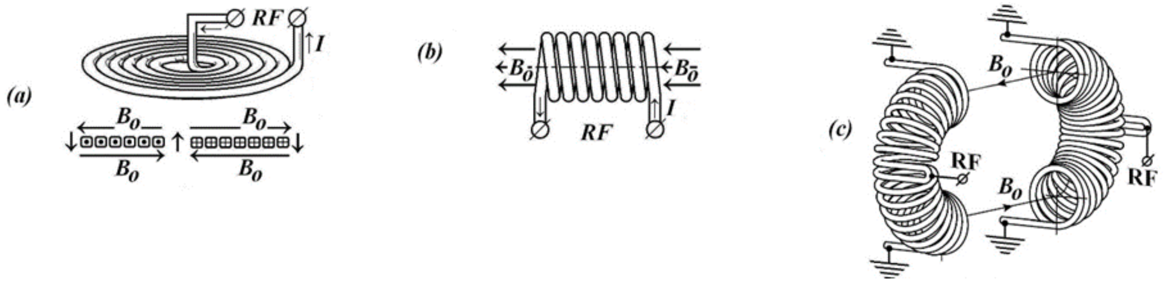


Figure 7.Conventional plasma inductors [16].

Noticeably, in Cranfield, the design of ICP technology Figuring machine is based on cylindrical coil named as the shape of Helical coil.

Briefly, in the ICP, a radio frequency (RF) current pass through the helical coil (3 turns copper tube). With the effect of magnetic field surrounded coil, mixed gases injected though the middle of coil in radial direction become ionized and heated.

2.4 Matching network

In electronics, matching network design is the pioneer of designing the input impedance of an electrical load or the output impedance of its corresponding signal source to maximize the power transfer, which means minimize signal reflection from the load as well.

In the case of a complex source impedance Z_S and load impedance Z_L, maximum power transfer is obtained when

$$Z_S = Z_L^*$$

Where the asterisk (*) indicates the complex conjugate of the variable. Where Z_S represents the characteristic impedance of a transmission line, minimum reflection is obtained when

$$Z_S=Z_L$$

The impedance-matching network (IMN) owns dominant position in RF, microwave networks. To deliver maximum real AC power to a combined load, the IMN normally should transform the load impedance (Z_L = R_L+jX_L) into a complex conjugate of the source impedance (Z'_S=R_S-jX_S) [21].

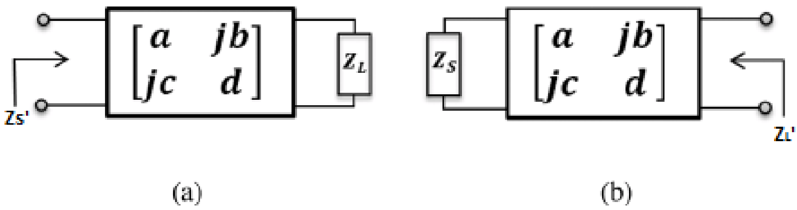


Figure 8.Two-port lossless passive network A: transforming load impedance ZL=RL+jXL into complex conjugate of the sorce impedance (Z'S=RS-jXS) B: transforming the source impedance ZS= RS+jXS into a complex conjugate of load impedance (Z'L=RL-jXL)

In summary, the source impedance can be matched with the load impedance for coupling RF power from the source to the load effectively. In our project, the matching network works for coupling RF power to the plasma jet.

Depending on the frequency of operation, the IMNs can be implemented using a lumped inductor, capacitor, a transmission line (TL) or a lumped-distributed elements combined. Three main matching network using lumped elements are L type matching network, PI-type matching network and T-type matching network. The L type matching network has unique set of network parameters for a given load and source impedance, whereas the double stub (PI- type) has multiple solution sets [22].

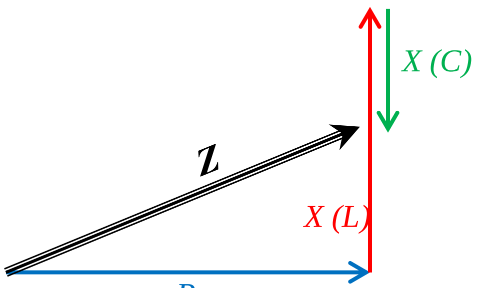
2.4.1 Impedance definition

Impedance is the sum between resistance and reactance. It is a complex number derived from the resistance (real part) and reactance (imaginary part).

$$Z = R(Re) + X(Im)$$

R = resistance in Ω, X = reactance in Ω, Z = impedance in Ω

By convention, a coil (inductor) creates positive reactance and a capacitor creates a negative reactance. We can represent the impedance within the complex plane like this:



In a simple case like this, the "total power", called apparent power, is divided in two parts: the true power (power of the real part) = P_{true} ; and the reactive power (power of the imaginary part) = P_{react} .

The apparent power is then define by:

$$P_{app} = \sqrt{P_{true}{}^{2} + P_{react}{}^{2}}$$

In a lot of cases, only the true power can be used in the device.

Impedance matching for high frequency

The impedance matching aims to provide maximum power transfer. It consequently decreases the reflected power between the source and its load. Also, small amount of reflected power protect the RF circuit. In fact, if the reflected power is too high, the RF generator will be damaged.

Maximize power transfer

For this point, we need:

$$Z_{source} = \overline{Z_{load}}$$

With the complex conjugate of $\overline{Z_{\text{load}}}$ and Z_{source}. Like this, we can simulate the impedance (total) without any reactance. For this point, we need to decrease the reflect power. The device used to match impedances is called a matching network.

2.4.1 Matching network parameter

A generalized two-port impedance matching circuit is show in FIGURE 8, mainly match the load impedance to source impedance. The network parameters can be thereby expressed as below, to be more specific, the relationship between Z_S and Z_L can be expressed as follows:

$$Z'_S = (AZ_L+B)/(CZ_L+D) \qquad (1)$$

In a lossless matching network, A and D are real, B and C are purely imaginary, expressing ABCD parameters in terms of the pure real quantities a, b, c and d as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} a & jb \\ jc & d \end{bmatrix} \qquad (2a)$$

With

$$ad+bc=1 \qquad (2b)$$

Combining (1) and (2) we have

$$R_S\text{-}jX_S = [a\,(R_L+jX_L) + jb]/\,[jc\,(R_L+jX_L) + d] \qquad (3)$$

Separating the real and imaginary components of (3)

$$aR_L - dR_S = c(R_LX_S - R_SX_L) \qquad (4a)$$

$$aX_L + dX_S = c(R_LX_S + X_SX_L) - b \qquad (4b)$$

Using (2b) and (4a)-(4b), a, d and b can be expressed as follows:

$$a = cX_S \pm R_S\sqrt{(1 - R_LR_SC^2)}$$

$$d = cX_L \pm R_L\sqrt{(1 - R_LR_SC^2)}$$

$$b = c\,(R_LR_S - X_SX_L)\,X_L \mp (R_LX_s + R_SX_L)\sqrt{(1 - R_LR_SC^2)}$$

Note that a, b and d being real quantities, c is bounded by

$$-h \leqslant c \leqslant h$$

With

$$h = 1/\sqrt{R_LR_S}$$

One can now parametrize as

$$c = hç$$

Where $ç \in [-1, 1]$

As a conclusion, the various choices value of ç lead to several reasonable solutions for matching network to match the impedance Z_S and the load impedance Z_L [22].

2.4.2 L type matching network (L-network) Application and Configurations

L-network addresses impedance matching in RF circuits, transmitters, and receivers, being dominant in matching one amplifier output to input of a following stage. Otherwise, matching antenna impedance to a transmitter output or a receiver input is another function of L-network.

There are four versions of L-network, two low-pass versions and two high-pass versions. Noticeably, with the benefits of harmonics, noise and other undesired signals in RF designs, the low-pass version gets more widely used. Here below the four version of the L-network is displayed.

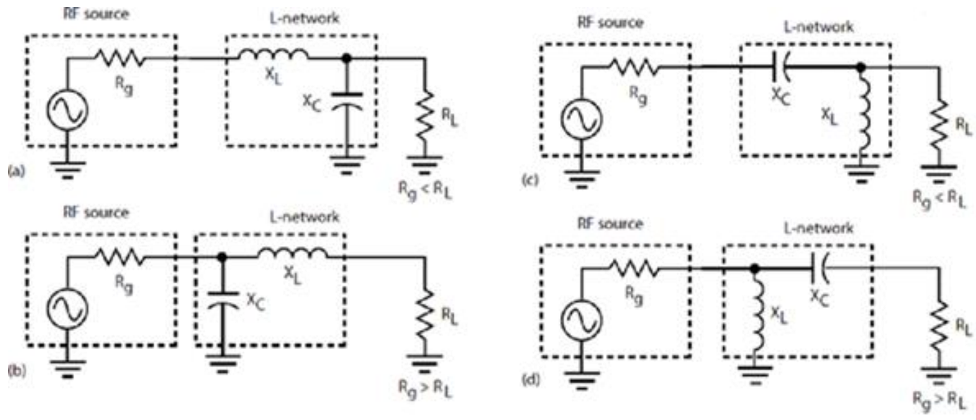


Figure 9.Four configurations of basic L-network. Load capacitor and Turn capacitor drive the impedance values. (a) and (b) are low-pass circuits, and those in (c) and (d) are high-pass circuits [23].

When the resistance of power source is less than resistance of load (Rg<RL), the impedance of load capacitor and turn capacitor can be formulated as:

$$XL=\sqrt{\frac{RL}{RG}-1}*Rg\ ;\ XC=RL/\sqrt{\frac{RL}{RG}-1}$$

When the resistance of power source is less than resistance of load (Rg>RL), the impedance of load capacitor and turn capacitor can be formulated as:

$$XL=\sqrt{\frac{RG}{RL}-1}*RL\ ;\ XC=RG/\sqrt{\frac{RG}{RL}-1}$$

The impedance being matched determines the RL/RG of the circuit, which cannot be specified or controlled. L-network cannot fit all needs. There are limits to the range of impedances that it can match. Put specification into details, the calculated values of inductance or capacitance cross upper limit/lower limit to be practical for a given frequency range. Sometimes, even switching from a low-pass version to high-pass version cannot be helpful.

2.4.3 π-Networks

To match a high impedance source to lower value to load impedance is primary application for π-network, reversely, π-network can also be used in reverse to match a low impedance to a higher impedance. The low pass version in Figure10-1a is the most common configuration, though the high pass version in Figure10-1b also can be used.

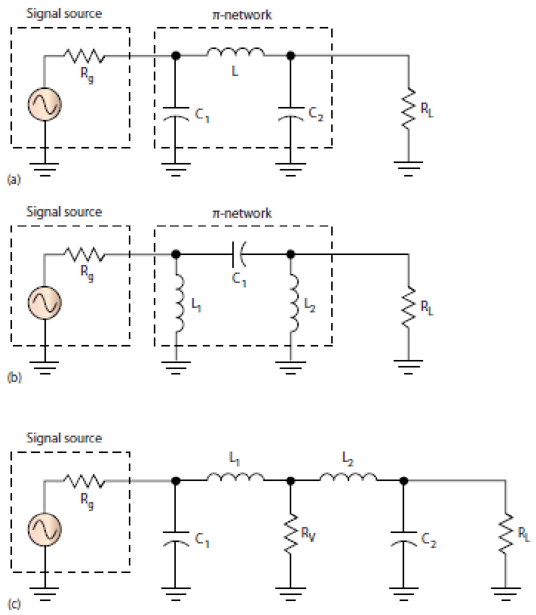


Figure 10.The π-network matching circuit is used mostly in high- to low-impedance transformations. The basic circuit (a) is a low pass circuit. A high pass version (b) can also be used. The π-network also can be considered two back-to-back L-networks with a virtual impedance between them (c).

L-network procedures can be put into π-network as two L-networks back to back. To use the L-network procedures, you need to assume an intermediate virtual load/source resistance RV as shown in Figure10-1c. You can estimate the resistance in the middle marked as RV from:

$$R_V = R_H / [(f/BW)^2 + 1]$$

RH is the higher of the two design impedances Rg and RL. The resulting RV will be lower than either Rg or RL depending on the desired f/BW. Typical f/BW values are usually in the 5 to 20 range. An example will illustrate the process [23].

2.4.4 T-Networks

Figure 11 illustrates the basic T-networks. The basic T shown in Figure 11- a is not widely used, but its variation in Figure 11- b is. The second network is called an LCC network.

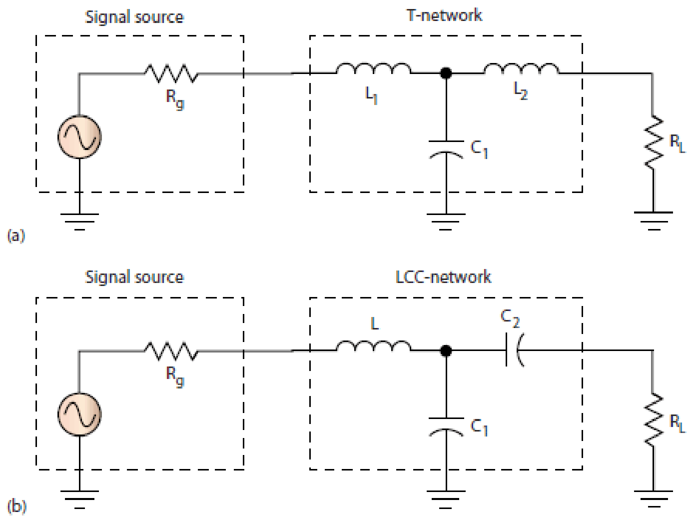


Figure 11.There are two versions of the T-network, an alternate matching network: the low pass version (a) and the more popular LCC network (b) [23].

To design these networks, you can also consider them as two cascaded L-networks. However, since the version in Figure 11-b is so common [23].

2.4.5 Motivation of enhancement for classic matching network

The principle of matching network aims at matching the output impedance of an RF generator to the impedance of a load. One such tuneable matching network was publicised in Sep.14, 1999, assigned U.S. Pat. No 5,952,896. Here below the electrical circuit is displayed.

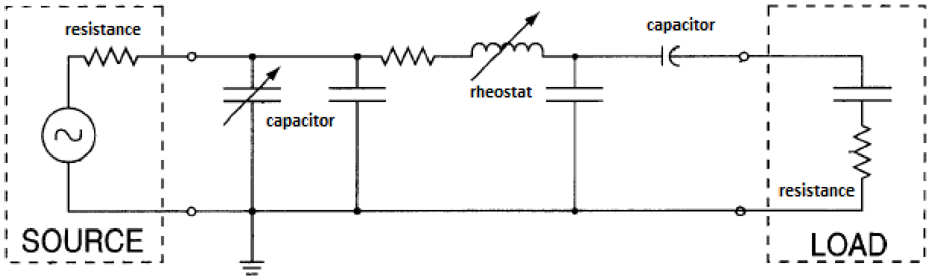


Figure 12.The first generation of matching network design [26].

For reactive atom plasma, during regular operation stage [9], unlike in cold situation, the impedance of plasma chamber can be unstable due to the fluctuations of plasma flux in the plasma chamber, presence of the feed gas, vacuum.

In typical matching network design, tuning capacitors system is mainly designed by mechanical tuning. Since capacitors always need drivers to change the position. As the load impedance changes instantly, mechanical tuning cannot perfect match with the change of the load in the same time.

2.5 Fixed match

Fixed match is commonly designed with an inductor or capacitor coupled in series between power source and loads and in parallel from the source to ground. Briefly, fixed match network has fixed output impedance, being selected to match the average impedance of the plasma inside the chamber over time.

Unlike matching network, fixed match network works tuning the forward power relatively, when the impedance of plasma chamber fluctuate. Here below the typical electrical structure design of fixed match is displayed.

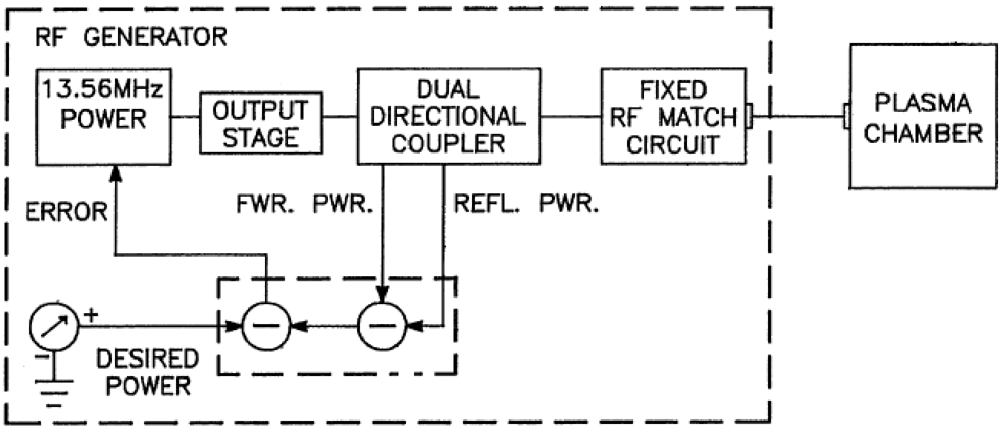


Figure 13.Classic fixed match design structure [25].

As described above, the fixed match network uses fixed valued elements (not adjustable capacitors and inductors). Under the fixed impedance environment during wafer processing, the forward power of the RF source is tuned to maintain a match between the source and the load. To be more specific, RF generator adjust (compensate or reduce) the forward power, based on the information of reflected power, gathered by dual directional coupler. By that, although the impedance of the plasma changed, Voltage Standing Wave Ratio (VSWR) can be maintained at the stage.

As the research of Jun zhao et al made before, the smith chart [24] below give out the method to optimize the RF match circuit in their invention.

The small squares "□" in the chart nearby the "3:1-VSWR-Circle" to"2:1-VSWR-Circle" represent the different load impedance of the plasma chamber in particular phases of a typical plasma-enhanced chemical vapor deposition (PECD) process performed within the chamber. [25]

The small cross "×" in the chart in the "2:1 VSWR Circle" represent the chamber load impedance during cleaning stage between PECVD process as a typical plasma etch process.

The CVD process needs1200 Watt of RF power and the etch process requires 2000 watt of RF power.

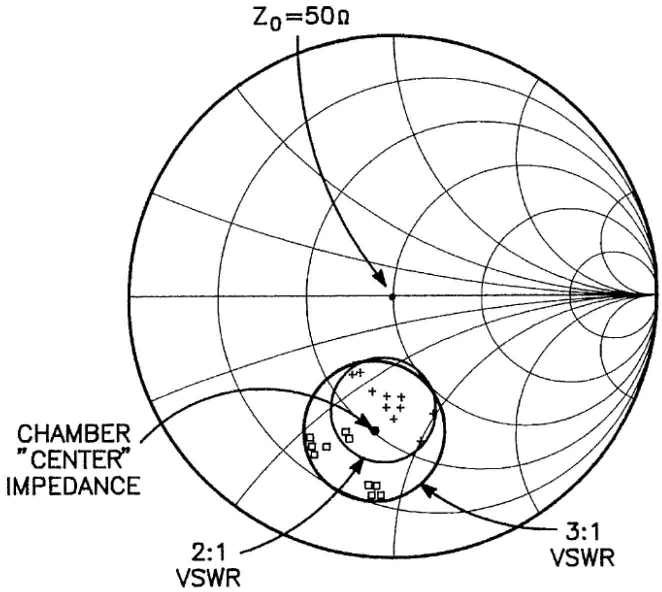


Figure 14.Smith Chart in the fixed match design system of Dr Jun zhao [24].

To our project, those conclusions can be hinted. During 1200W and 2000W forward power feed. VSWR can be changed a lot. Based on that, in Helios1200, when the forward power is raised from 200W to 1000W, the impedance of the load can changed dramatically.

The electronically tuned matching process brings benefits to the rapid adjustment during fluctuation in load impedance (plasma flux in the plasma chamber, presence of the feed gas, vacuum).

2.5.1 Radio frequency tuning in RF circuit

Radio frequency tuning system is used to tune a radio frequency signal of a specific frequency channel among radio frequency signals received. From a input unit, corresponding radio frequency channels can be tuned by the tuner circuit.

For plasma delivery system, RF plasma reactor always has a reactor chamber, gas inlet system for reacting atom plasma, a variable frequency RF power source, a coil surrounded the chamber connecting RF power to couple plasma. From the information of reflect power to coil, a control circuit connected to a control input of the variable frequency RF power source and responsive to the power signal and responsive to the power sensor for changing the frequency of the variable frequency RF power source so as to either increase the transmitted power or decrease the reflected power.

2.5.2 Directional coupler in RF circuit

Directional couplers are passive devices used in the field of radio technology. A defined amount of the electromagnetic power is coupled in a transmission line to a port enabling the signal to be used in another circuit. In details, Firstly, the one direction feature is the main description of directional coupler. Secondly the coupled element is the power entering the output port, not the coupled port.

In the project of Bradley O. Stimson, Mountain View and Calif succeeded in 1997, they built a RF match network mainly for turning the load impedance by the signal of dual directional coupler. Here blow the structure of the electrical circuit.

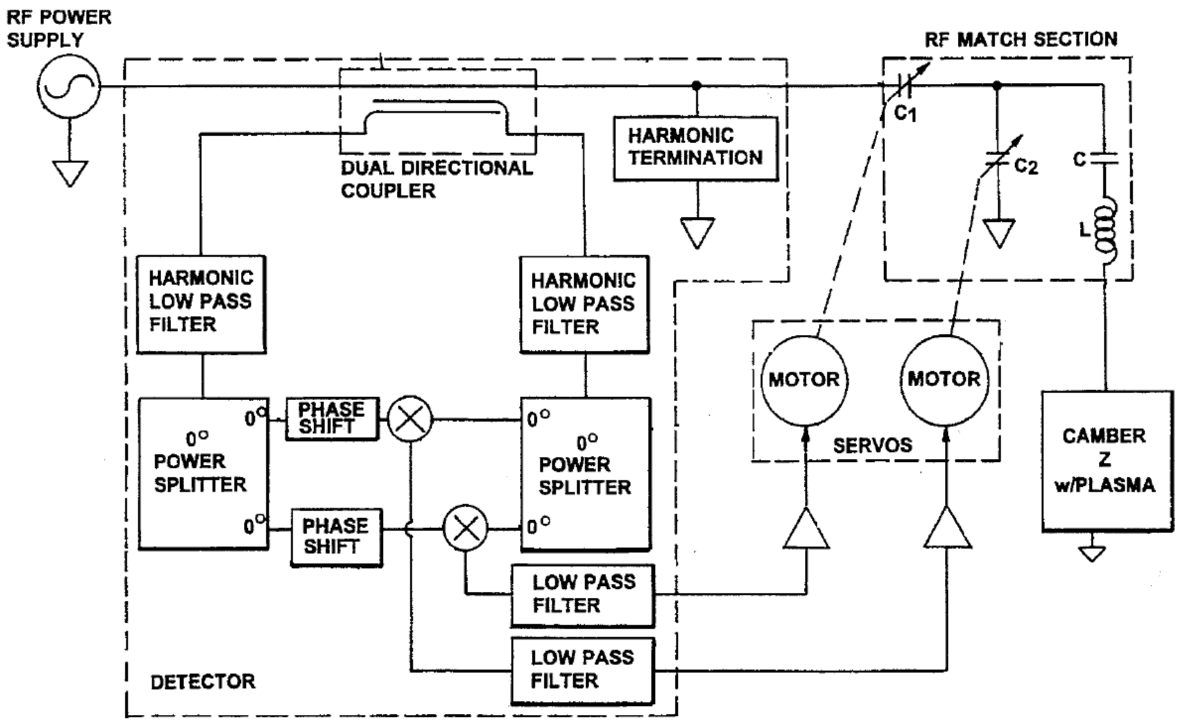


Figure 15.RF match detector circuit with dual directional coupler

Generally, in the detector circuit, dual directional coupler is connected between the RF source and RF match circuit with accessories as filters and shifters, generating a forward signal and a reflected signal. The forward signal has linear relationship with RF power delivered to the match circuit; similarly, the reflected signal is proportionally with reflected power back from match circuit.

Expect generating signal circuit, there are two branch circuits. One branch circuit receives the reflected signal to produce a first and second output signal; The other branch circuit receiving the forward signal to produce a first and second output signal. Based on the first phase detection output signal of reflected power and forward power, the first control signal can be derived to tuning impedance motors, similarly, regarding to the second phase detection output signal of reflected power and forward power, motor turning system can obtain the second control signal. According to the loop described above, fast tuning of impedance can be achieved.

In this project, directional coupler acts as a liaison officer of the power feeding circuit and phase detector circuit. Because of the fast signal change, the impedance of the system can be adjusted in a short period.

2.5.3 Free Running Oscillator

Free running oscillator brings initializing and maintaining oscillations to fixed frequency system , period fixed system and period determined by the physical parameters of the system.

The fundamental elements required by an oscillator system are: a frequency or period determining element, such as a resonator or timing means, a driving system for the frequency or period determining element, and means for deriving a useful output from the oscillator system. This class is restricted to oscillators for generating electrical oscillations or waves and specifically excludes alternating current generators of the mechanically driven dynamo-electric machine type.

An oscillator wherein the driving system continuously supplies the losses of the frequency determining means so as to produce sustained oscillations.

Since the plasma impedance is extremely fluctuation, RF mismatching can be happen. To be specifically, power reflection back to the RF generator triggers the loss of RF power.

2.6 Plasma figuring machines in Cranfield University

In Cranfield University, there are two Plasma Figuring machines: RAP300 and Helios1200 (Figure 7.).[2] These machines combine plasma technology operating at atmospheric pressure and computer numerically controlled (CNC) motion systems. However the plasma systems are different. RAP300 is equipped with a matching network whereas Helios1200 is equipped with a fixed match [2] RF network.

Figure 16. RAP300 (left) and Helios1200 (right)

In these machines a radio frequency (RF) inductively coupled plasma (ICP) torch is used to atomize the reactive gas and create free radicals. The combined torch, RF network, and signal generator will be named Plasma Delivery System (PDS) in this paper. Both RF network design is based on inductive output L type RF circuit. In Helios1200, a fixed match electrical design was chosen for the PDS because this design enables to reduce torch weight. Thus the machine has better dynamic performances. Here below the torch assembly and the electrical circuit of Helios1200 is displayed. [7]

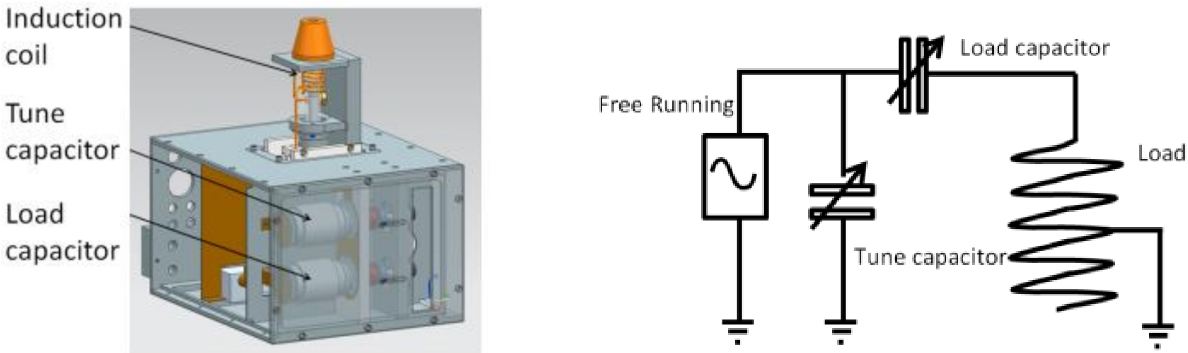


Figure 17. Torch assembly (left) and Electrical schematic (right)

2.7 Helios1200

Helios1200 is a rapid surface Figuring machine aiming at etching large scale ultra-precise optical components. It combines plasma technology operating at atmospheric pressure and computer numerically controlled (CNC) motion systems. To be specific, an inductive output RF circuit, ICP torch [5], CNC motion system (Fanuc 30i series) [6] and cooling system.

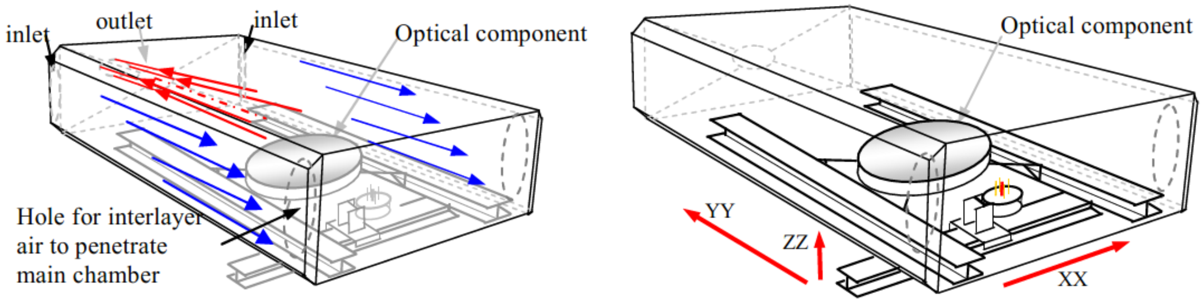


Figure 18.The drafts of Helios1200 [20].

The RF circuit and ICP torch constitute the current PDS. Here below the existed main parts is displayed. (Figure 19)

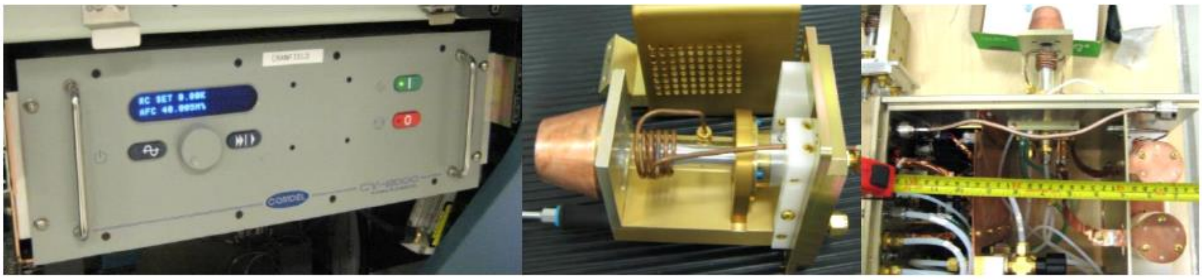


Figure 19.RF generator, ICP torch (middle), the assembly of torch (right).[20]

2.7.1 Main parts parameter

Hereafter is the parameters of main parts in PDS of the Helios 1200 machine.

RF generator:

- Brand: Comdel Inc (Gloucester MA 01930 USA)
- Type: CV2000
- Frequency: 40MHz (38.5 up to 42.5MHz agile technology)
- Power capability 2000W (Processing power: 1200W)

ICP turbo torch:

- The three main turn coil for water cooled, hollow inside
- The free two turn coil is solid
- The trumpet tube is made of aluminium

Capacitors:

- Brand: Comet
- Type: CVBA 250 AC/15-BEA-L
- Cmin [pF]: 5
- Cmax [pF] : 250
- Torque: ≤0.15 Nm
- Voltage(peak testU_{pt}/ peak working U_{pw}) : 15kV/9Kv

Coaxial cables:

- RG1428b

Electrical schematic

Hereafter is the RF network of the Helios1200 machine.

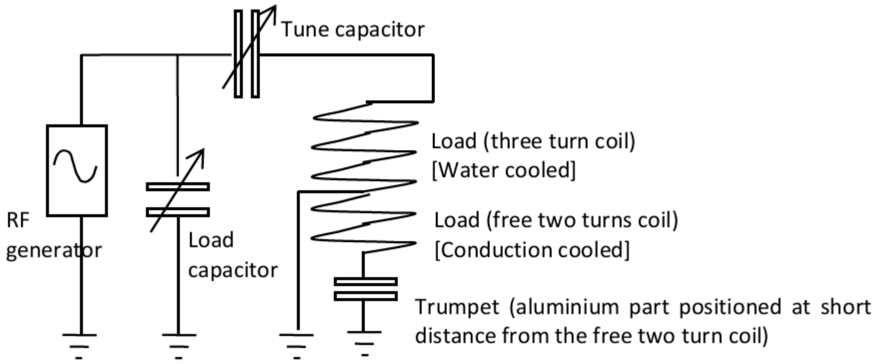


Figure 20.Electrical schematic of the Helios1200 PDS [18]

2.7.2 Inductively coupled plasma (ICP) Torch

Hereafter is a UG NX7.5-full section of the inductively coupled plasma (ICP) torch of Helios1200.

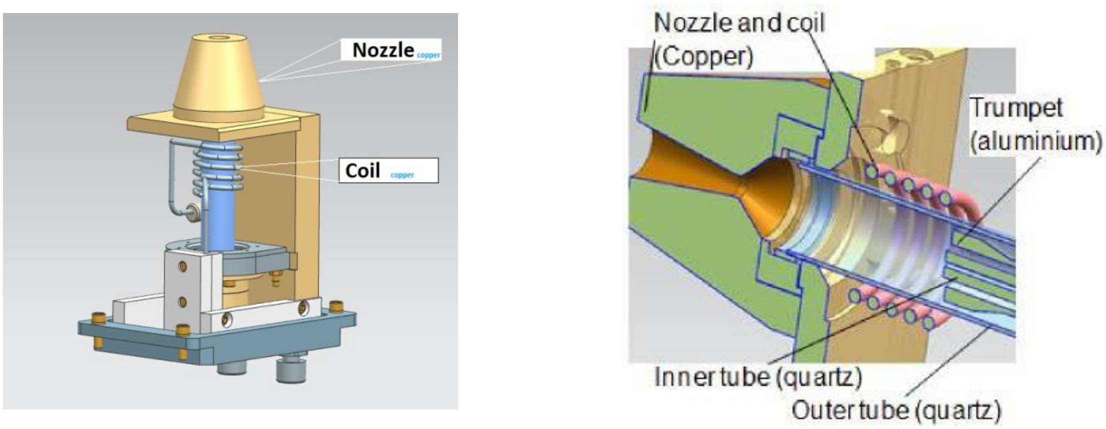


Figure 21.Full section torch and cross section torch of Helios1200 [18]

In general, plasma torch is where reactive plasma is coupled. Previously, the system processed for cleaning a deposition chamber as a cleaning step, then a strong etchant mix gas is injected into the tube to couple plasma, with the effect of a high level RF power surrounded by Helical coil. Shortly after tuning RF power, the plasma circle can be coupled in plasma tube. At the end, the plasma can be shoot to etch wafer products through De-lava nozzle.

Three stage of ignition ICP plasma can be summarized as pre ignition torch, ignited torch and sub-sonic mode. Typically, in the first stage, the optimum frequency is 40.7MHZ, once the plasma light up the ICP torch (Feedpower~200W), the power will tune the current frequency to accommodate the impedance change. Continuously, the optimum frequency will decrease down to approximately 40.600MHz, with the increasing power, the frequency will decrease further. The third stage is established with the forward power reaches ~800W, where the De-Laval nozzle enables the plasma stream to flow at sub-sonic velocity. This third stage forces the RF generator to readjust the frequency significantly. High reflective power is often noticed for a few seconds. Here below the three stages are sketched.

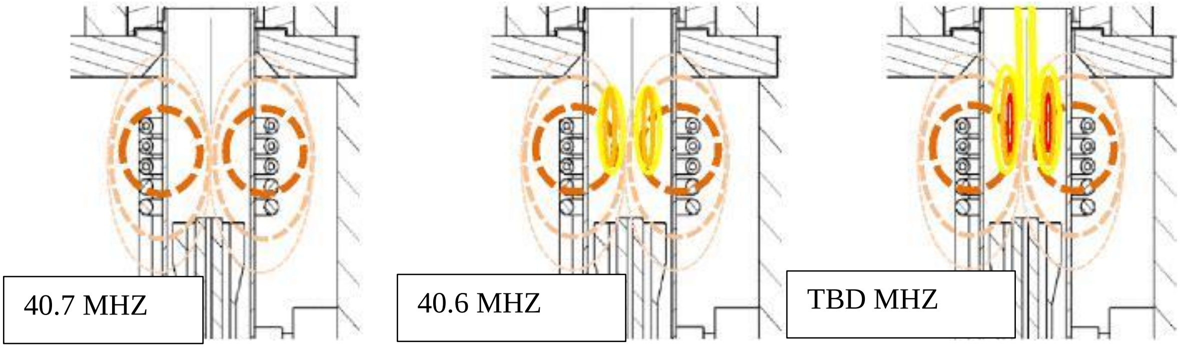


Figure 22.Pre ignition torch (left), ignited torch ~300W (middle), torch in sub-sonic mode >800W (right) [18]

2.7.3 Gas feeding

The gas feeding patterns are designed into two forms by ignition and processing stage and three circles (inner circle, middle circle and shield circle) constitute the tube. In each circle, the feeding gas has different function and standard litre per minute (SLM).

In ignition stage, all the three circles feed by Argon with various SLM, which is 1 SLM for inner circle and middle circle, 20 SLM for shield circle, bringing benefits to clean the air of the reactive area in ICP torch. To meet the needs of processing stage, the SF6 (reactive gas) is introduced through the inner quartz tube with SF6 10%+ Ar 90% (0.8SLM) , in the meaning time, the SLM of Argon feed rate in middle circle drop into 0.2SLM. Shield circle keep the steady Argon feed rate to protect the reactive process. Here blow is the gas feeding rate illustration.

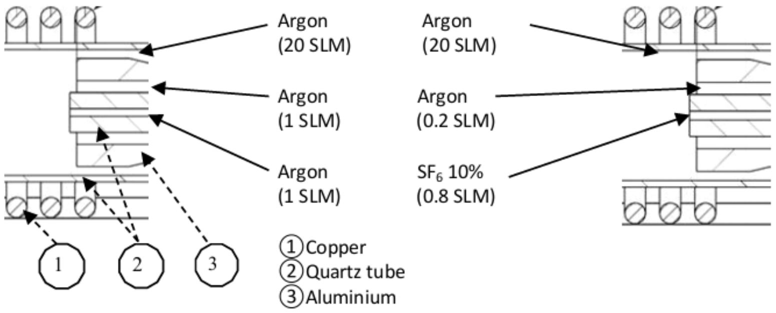


Figure 23.Gas flow ignition mode (left) and Gas flow processing mode (right). [18]

2.8 Metrology by RTD sensor

Resistance thermometers, also called resistive temperature devices (RTDs), are sensors used to measure temperature by correlating the resistance of the RTD element with temperature. Most RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core. The element is usually quite fragile, so it is often placed inside a sheathed probe to protect it. The RTD element is made from a pure material, typically platinum, nickel or copper. The material has a predictable change in resistance as the temperature changes and it is this predictable change that is used to determine temperature.

They are slowly replacing the use of thermocouples in many industrial applications below 600 °C, due to higher accuracy and repeatability.

2.9 Aim and objectives

2.9.1 Aim

The aim of this project is to enhance the Plasma Delivery System (PDS) design of helios1200 to create a highly reliable and deterministic plasma processing system. The bespoke plasma sub-system is designed in 3 phase: ignition, regular operating and critical circumstance. The aim will be met by completing the hereafter six objectives.

In details, the main aim for this project is to realize the combination of matching network and fixed match. To build a hybrid RF match network.

Stage of the main idea of this project displayed as follows:

- Capacitor adjustment assistance;
- Reflective power monitoring;
- Build algorithms between reflect power and tuning capacitors system

2.9.2 Objectives

Scrutinize the work plan carried out by the previous student

- Change the design
- Be familiar with the detail information about the work plan.
- Define whether proposed mechanical design is correct
- Propose fresh solutions for unsuitable part

Deliver a folder that will contain all the updated technical drawings of PDS

- Get knowledge from Internet about UG NX7.5.
- Use of NX7.5 for designing the assembly torch.
- Assess Vincent (previous student) design of plasma delivery system.
- Check mechanical calculations.

Purchasing, fabrication and assemble

- Check company list and items availability.
- Check the detail information of different staff that is involved in the purchasing process here at Cranfield.
- Write all the purchase orders (PO) and track all deliveries

- Issue technical drawings.
- Deal with workshop for item that will be fabricated.
- Deliver the fully assemble hardware.

Deliver a report on RF network and working principle of plasma delivery system

- Gain the understanding of plasma technology.
- Read theses which are about the application of plasma technology and their working principle.
- Get information of the items which is connected with plasma technology
- Understand the Matching network of RAP300, the fixed match of Helios1200.

Create and deliver an algorithm that will be able to:

Ignition Phase

- Check the design of Vincent plan about the matching network design.
- Check the Brake system. Brake design whether it is tough enough. Pay attention on the weak part as linkage, horn and break pad.
- Give solutions to fix the weak part.
- Use Arduino technology to drive servo motor
- Use Arduino technology to drive stepper motors' position
- Use encoder to gather stepper motors' position

Regular Operation

Monitoring the temperature of coolant

- Check the senior of testing coolant temperature is suitable.
- Make sure the information can be got by Arduino Card, which wouldn't be effect by the electromagnetic field (EF).
- Make sure the install of test will not cause any problem such as the leak of coolant,
- Make sure the feedback of the signal can be useful to the control to the Arduino Card.(PS: the max border should be defined)
- The code should be useful for Arduino Card

Critical Circumstance

Stop support plate damage

Chapter 3

Conceptual design

Matching network enables to tune the impedance of the loads (plasma chamber, load capacitor, and tune capacitor). This system maintains the plasma in stable condition. Thus temperature increase of the electrical components, environmental perturbations and process parameter variations do not disturb critically the plasma jet. In fact, capacitors are motorized to tune the load impedance. However matching network systems are slow, expensive and heavy.

The PDS of Helios1200 does not use a matching network. Helios1200 PDS was created based on fixed RF match circuit. Fixed match are tightly designed to fit the type of load driven so that there is only one resonant frequency. Also, because the transmission line is between the phase detector and the match, it is part of the circuit that the phase detector observes, so the length of transmission line must not be changed significantly. Also, the frequency signal provided associated RF generator is swept to reduce the reflected power that is known to damage the PDS.

The two RF electrical designs have pros and cons. Fixed match PDS is faster to reduce the reflective and offer gain from weight and cost viewpoint. However, only matching network can reduce the reflected power down to zero when environmental conditions change strongly. Then our design intends to combine the positive features of both electrical designs.

3.1 Three phase in conceptual design

In this project, the conceptual design is mainly based on the operation of Helios1200. Basically, there are three phase of plasma Figuring. First phase is ignition phase [18]. There are three stages in first phase pre ignition torch, ignited torch and sub-sonic mode; Second phase and third phase are named as regular operation and critical circumstance mainly based on the period in manufacturing. During plasma etching, dramatic rising temperature in plasma chamber and the electric components in the system may trigger negative effect on the long-time etching. So regular operation should focuses on the rising temperature in the PDS and the related elements. The critical circumstance is mainly based on 8 years' experience from Dr Jourdain in ultra precision centre in an attempt to preventing damage of the key parts, even stop the potential risks.

3.2 Ignition Phase

In ignition phase, miss matching is mainly the problem. Because of the miss matching, dozens of working hours might be wasted during the ignition phase. Even worse, the miss matching may lead to the potential risk for the PDS itself such as over load reflect power may destroy the RF generator.

3.2.1 Miss matching

Miss matching problem is mainly because of the range of impedance changing is rather narrow as the fixed match using a dual directional coupler. As such, the frequency tuning cannot make the match achieved while the fluctuation of impedance crosses the limitation.

During ignition phase, because of violently fluctuation in plasma chamber, the impedance of PDS has the risk to cross the range of frequency tuning, so qualified operators have to disassemble the PDS and tune the impedance of tune capacitor and load capacitor to make the system impedance close to load impedance. Dozens of working hours could be engaged in one-time adjustment. Tuning impedance capacitors structure of PDS is displayed as follows.

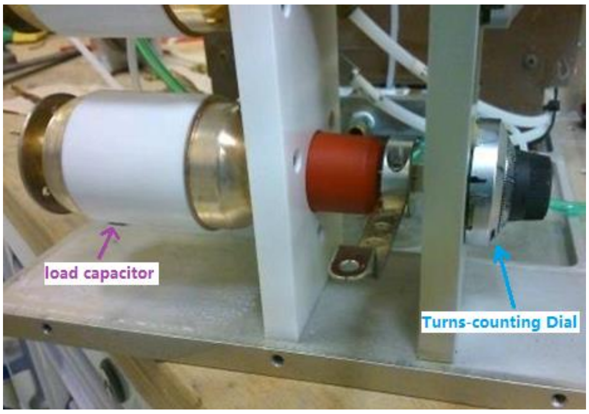


Figure 24.Fixed impedance structure in Helios1200. H-46 turns-counting Dial for turning the impedance of capacitors.

3.2.2 Method to solve the problem

To fix that problem, detail works should be separated. Basically, in this project, the impedance can be tuned based on the codes, but in the further work, the control source should be related to the reflect power signal to reach a totally fast and automatically stage. Stage of the main idea of this project displayed as follows:

- Capacitors adjustment assistance;
- Reflective power monitoring;
- Build algorithms between reflect power and tuning capacitors system (Narrow the speed between signal and tuning system)

Basically, for the work of author is mainly focus on the first stage, capacitors adjustment can be achieved bringing benefits to operators' adjustment and proving the system can work. In the future, if the second and third stage functions can be addressed into the system, the total automatic fast tuning RF circuit match network can be achieved.

3.3 Regular Operation

In this project, regular operation phase is completely based on the processing stage of Helios1200. To overcome the rising temperature and high frequency forward power may make the impedance into an over control stage, it is better to monitor the coolant temperature and get the reflect power signal.

3.3.1 Monitor coolant temperature

In this section, the mainly knowledge and research structure are based on the works of Dr Renaud Jourdain and Nan Yu. To start with the coolant should be monitored in the PDS, there are two main part in the plasma torch, consisting of excitation region and transportation region. Here below the two parts in the plasma torch structure are displayed.

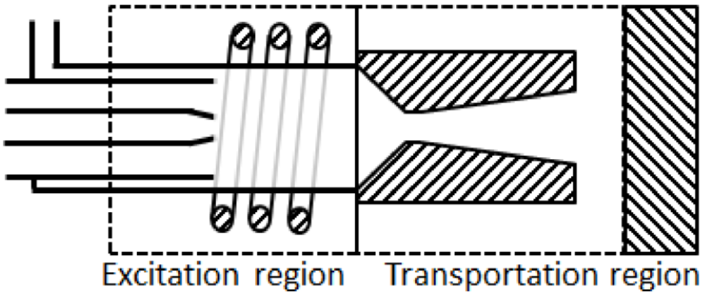


Figure 25.Radiation regions of the ICP torch

The recommended temperature of the coolant is about 20°C, coolant flows into the two main parts as coil (excitation region) and nozzle (transportation region).

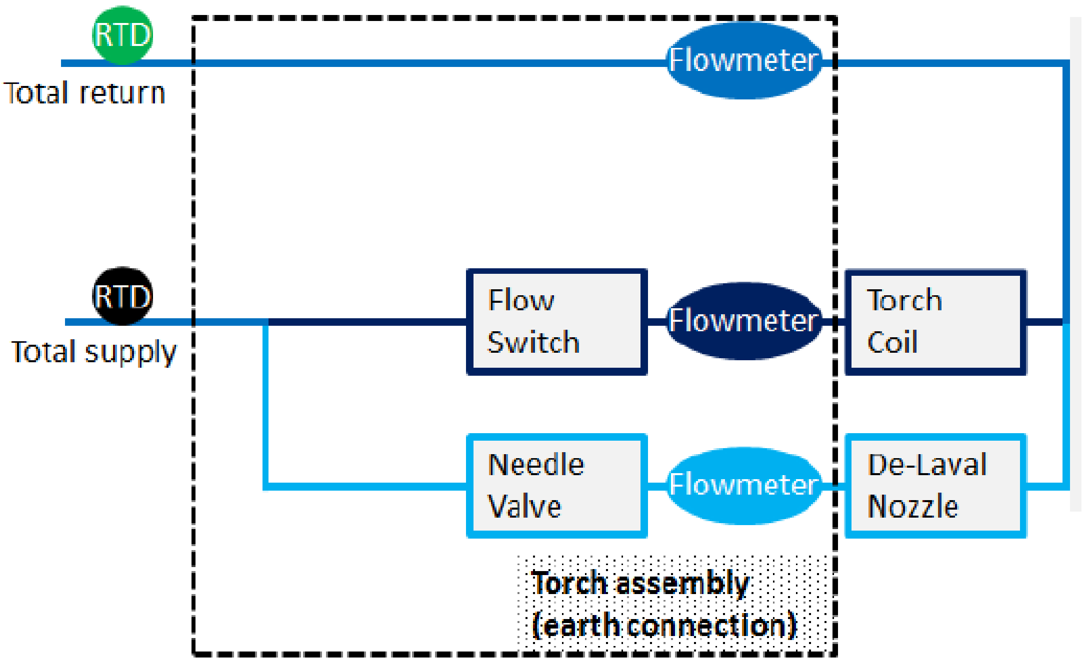


Figure 26.The test architecture of the coolant distribution. [31]

The supply coolant is delivered into two tributaries. Firstly the coolant goes into torch coil, secondly goes into the torch nozzle. In this project, the temperature of coolant can be a parameter of the forward power, based on that the forward power can be collected to be a input signal to adjust the impedance of the system.

In details, the temperature difference (TD) between the inlet and outlet coolant (Total return-Total supply) of the torch assembly can be put into formula as $\triangle E_{coolant} = C_c V_c \triangle T$ [32]

The result between FP and TD values can be a liner relationship as follows:

For the future of our project, gathered information from the temperature of coolant can be a source of input to the control chip (Arduino Card). Based on the data of coolant's temperature, forward power can be easily gotten, compared with the data of forward power from RF generator (the forward power of the RF generator CV2000 can be from one to four digits and the units will be watts). Two benefits can be gotten as: the dispatched source and the truly number of forward power.

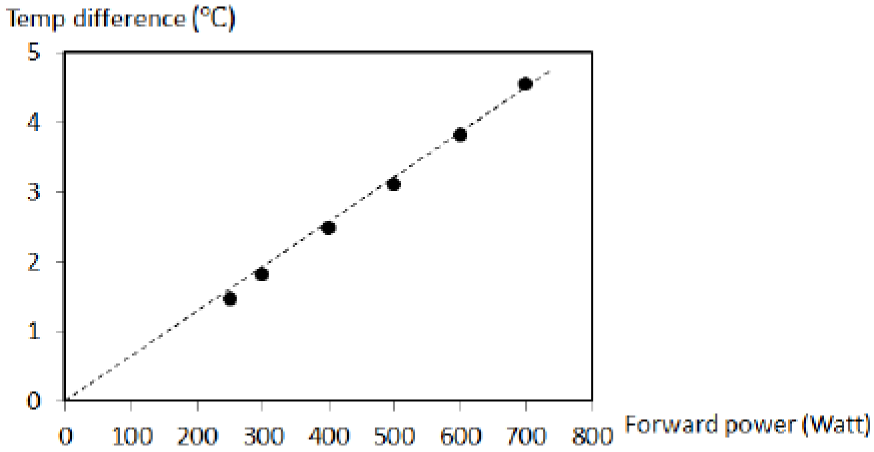


Figure 27.Liner relationship between FP and TD values. [31]

3.3.2 Gather the reflected power signal

In this section, reflected power should be gathered. Since the standards of impedance should be put into formula based on the data of forward power and reflected power. The returned value of reflected power can be from one to four digits and the units will be watts.

3.4 Critical Circumstance

In Helios1200, the critical circumstance can be separated into two phase. Firstly, the novel design should focus on stopping fail of some key parts as support plate and helical coil. Secondly, based on the information of coolant temperature or rfl/fwd power, safety border temperature can be made into codes to stop emergency.

3.4.1 Damage of support plate and coil

The damage of support plate is mainly because of a conventional process for cleaning a deposition chamber. To be more specific, during ignition phase, a process was set to clean a deposit (AL2O3) on chamber side walls and pedestal. With the effect of high level of RF power is applied to the chamber, the etchant gas can be tuned into a plasma state. Unfortunately, after the unwanted deposits are removed, continuing the chamber cleaning process will etch any exposed metal components in the chamber interior area.[25] Another reason for the deposit might be the extremely high temperature of the plasma reactor, since the melting point of aluminium is about 660°C matching with the centre temperature of plasma reactor, which means over-high forward power miss-set manually may occurs the sharply increasing temperature leading to damage the electrical components. Here below the damaged support plate and Helical coil are displayed.

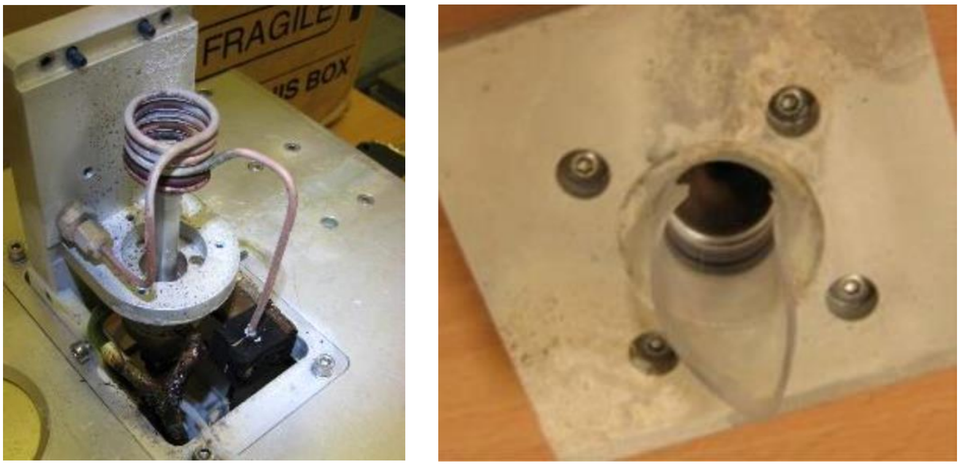


Figure 28.Damage of Helical coil and De-lava nozzle support images. [30]

3.4.2 Methods to solve the problem

As the potential risk for the coil and support plate exposed before, the two main reason unwanted deposit and extremely temperature can be the culprits.

To fix the first problem, decreasing the exposed area of support plate is a effective way to prevent unwanted deposit of support plate, which has feasibility support from the paper "plasma chamber with fixed RF matching" and "root cause analysis". To reach that goal, enlarge the angle of the chamfer can be a suitable solution. Here below the view of support plate in Helios1200 is displayed.

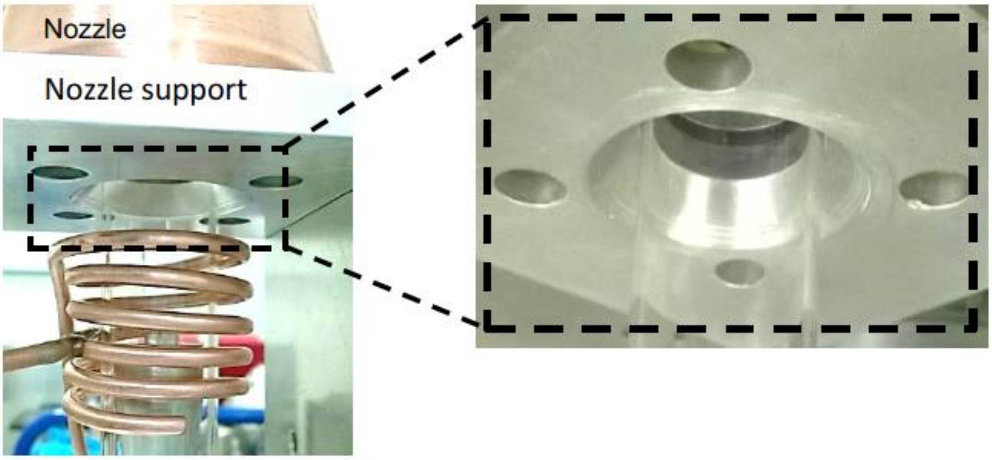


Figure 29.View of the torch (left), zoom of the chamfer exposed in reaction area-nozzle support- (right)

To fix the second problem, a cooling system was recommended by Dr Jourdain and Vincent to be put into the novel PDS. By the cooling of Ar gas, the coil has less risk to be oxidation; in the future, the data from monitoring the temperature of coolant in the coil can be transferred into a signal to warn the emergency.

3.5 Technical elements

To design the impedance tuning system, plenty of technologies assisting the working system were arranged in the design. As suggested by Dr Jourdain, four main technologies of application should be reported as Arduino technology, stepper motor containing encoder, servo motor and RTD sensor.

3.5.1 Arduino technology for control system

In this project, the working roles of Arduino technology were divided into three stages as programmed controller, sourcing signal and free controller.

To start with first stage in programmed controller, according to 8 years abundant experience in Plasma Figuring of ultra precision centre, specific control was made mainly aiming at tuning the impedance of the system.

Moving on to next stage to apply Arduino technology as sourcing signal, the temperature of coolant, reflected power and forward power should be sourced. As previous characterizations of temperature of coolant, reflected power and forward power were addressed in previous, those information serves for the total free controlling stage.

To reach final destiny, Arduino technology should turn the impedance and stop emergency for the control system. If this stage can be achieved, it can bring automatic function to Helios1200, which can be a big step turning an experimental machine into an applicable machine.

3.5.1.1 Overview

In this project, Arduino Mega 2560 a microcontroller board is used. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It is simply to be connected to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started. The Mega 2560 board is compatible with most shields designed for the Arduino Uno [33]

Figure 30.Arduino mega 2560. [33]

3.5.2 Stepper motor

In this project, stepper motors were planned to adjust the position of capacitors. There are two main issues should be faced for stepper motors. Firstly the stepper motor should tune the right angle of the capacitors in the original PDS with the input signal of Arduino card; Secondly the tuned angle should be supervisory controlled to give the feedback information to Arduino card bringing benefits to control the impedance of the system. To meet the latter need, stepper motor should be better to contain encoder to recode the information of turned angle, which can be transferred into the impedance tuning of the system.

3.5.2.1 Overview

Stepper motor is a brushless DC electric motor that divides a full rotation into a number of equal steps. Then motor's position can be commanded to move and hold at one of these steps without any feedback sensor (an open-loop controller), as long as the motor is carefully sized to the application in respect to torque and speed. Switched reluctance motors are very large stepping motors with a reduced pole count, and generally are closed-loop commutated.

In this project, encoder is a device that converts information from stepper motor to microcontroller, for the purposes of standardization and speed.

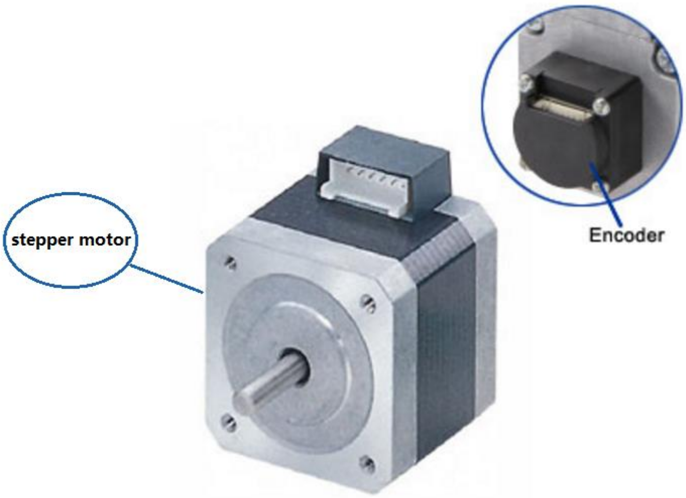


Figure 31.Stepper motor and encoder [34].

3.5.3 Servo motor

In this project, stepper motor acting as a tuning structure for capacitors can be useful, but generally tuning structure cannot be stable, because of the vibration of stepper motor itself . To be more specific, there is lack of holding structure to keep the stepper motor in right position.

With the guidance of Dr Jourdain and Vincent, conceptual structure can be addressed into a close frame structure, holding the stepper motor constantly until the tuning of stepper motor happen rapidly. After that, the system would be closed again. To reach the aims stated above, servo motor can be a precisely choice to drive the whole structure.

3.5.3.1 Overview

Servomotor is a rotary actuator or linear actuator (in this project, servomotor work as a liner actuator) that allows for precise control of angular or linear position, velocity and acceleration. It also requires a relatively sophisticated controller (Arduino Megan 2560), often a dedicated module designed specifically for use with servomotors. What's more, the term servomotor is often used to refer to a motor suitable for use in a closed-loop control system.

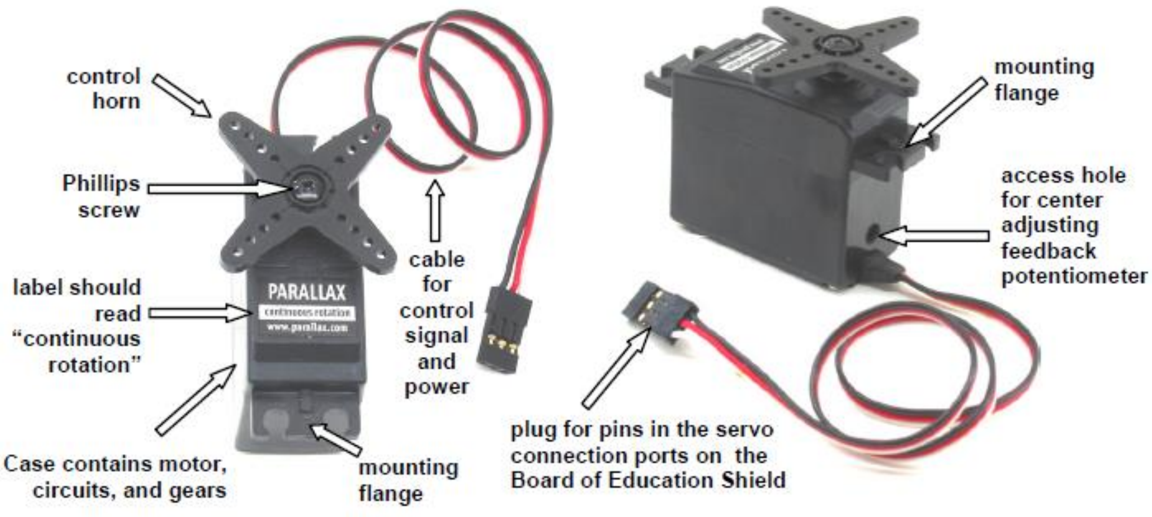


Figure 32.The structure of servo motor

3.5.4 RTD sensors

The RTD sensor is mainly for monitoring the temperature of coolant in plasma torch, aiming at get the data of the forward power, reported before in regular operation section.

3.5.4.1 RTD sensor

Resistance temperature detector (RTDs), are sensors used to measure temperature by correlating the resistance of the RTD element with temperature. Most RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core. The element is usually quite fragile, so it is often placed inside a sheathed probe to protect it. The RTD element is made from a pure material, typically platinum, nickel or copper. The material has a predictable change in resistance as the temperature changes and it is this predictable change that is used to determine temperature. In many industrial applications, the temperature is below 600 °C, due to higher accuracy and repeatability.

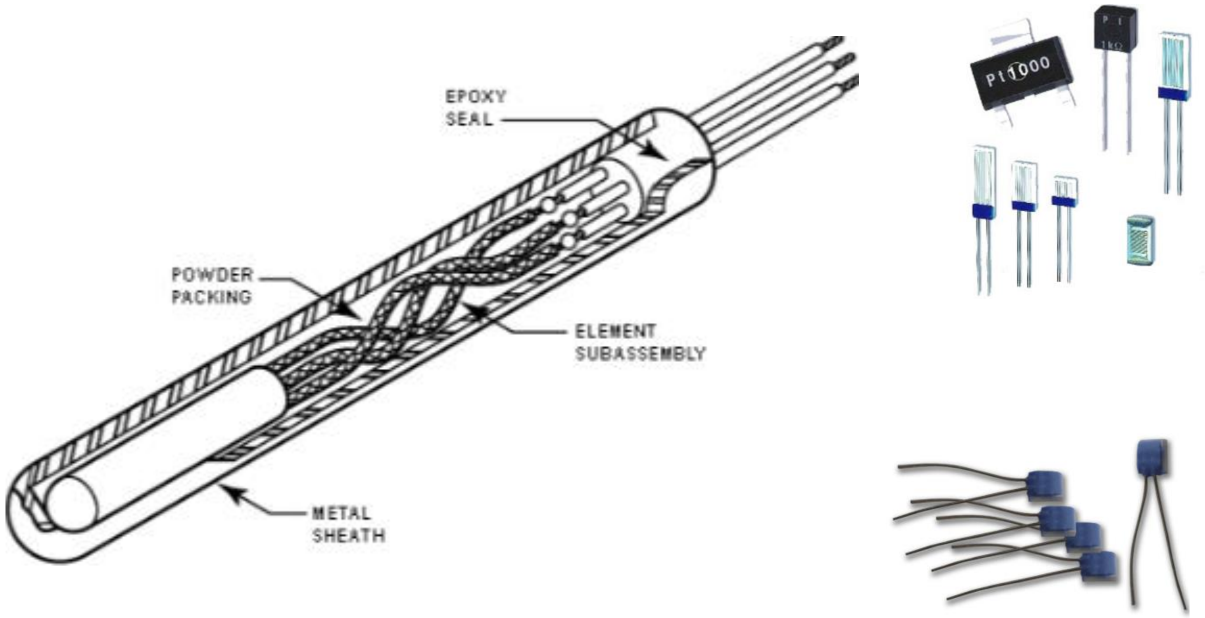


Figure 33.Structure of RTD sensor sealed with an epoxy potting compound or ceramic cement(Left) and Thin RTD sensor (Right)

3.6 Concluding remarks of conceptual design

To conclude the conceptual design, detail information listed as follows, mainly combine the aims in the three different phase and relative technology application. Gently, the capacitor adjustment structure deserves the crucial position in the novel plasma delivery system.

Ignition's phase

- Capacitor adjustment assistance
- Reflective power monitoring

Relative technology: Arduino technology/ RF generator/Stepper motor/ Servo motor

Regular operating

- Monitor coolant temperature
- Monitor gas (argon) temperature
- Provide a control environment

Relative technology: Arduino technology/ RF generator/Stepper motor/ Servo motor/ RTD sensor

Critical circumstances (leakage detection, RP surge)

- Stop coil oxidation
- Stop support plate damage

Relative technology: Arduino technology/ RF generator/ RTD sensor

To address conceptual design idea into real design, with the help of Dr Jourdain, the functions should be divided into three areas: Circuit Design, Mechanical Design, and Digital Control Design. Each area has its essential.

1. **Circuit design:**

   For circuit design, the electrical components must cooperate with each other suitably and rapidly, otherwise the functions of RF generator should be carefully addressed into this area.

2. **Mechanical design:**

   For mechanical design, the structure must entirely be firm and needed to be calculated.

3. **Digital control design:**

   For digital control design, the commands should be exactly designed, aiming to meet the needs of the mechanical design and circuit design function.

Chapter 4

The novel plasma delivery system design

In this project, enhancing the automation and stability of the PDS for Helios1200 is the main issue. In Helios1200, A careful designed fixed match circuit exists, aiming at achieving speedy signal transmission and efficient power feeding, which bring benefits to maintain the plasma coupling stability. As RF match network described before, matching network can reduce the reflected power down to zero when environmental conditions change strongly; fixed match can derive the power signal instantly. In our radio frequency circuit design, we intend to combine the positive features of both electrical circuit designs. Here below the model of novel PDS is illustrated with its working principle.

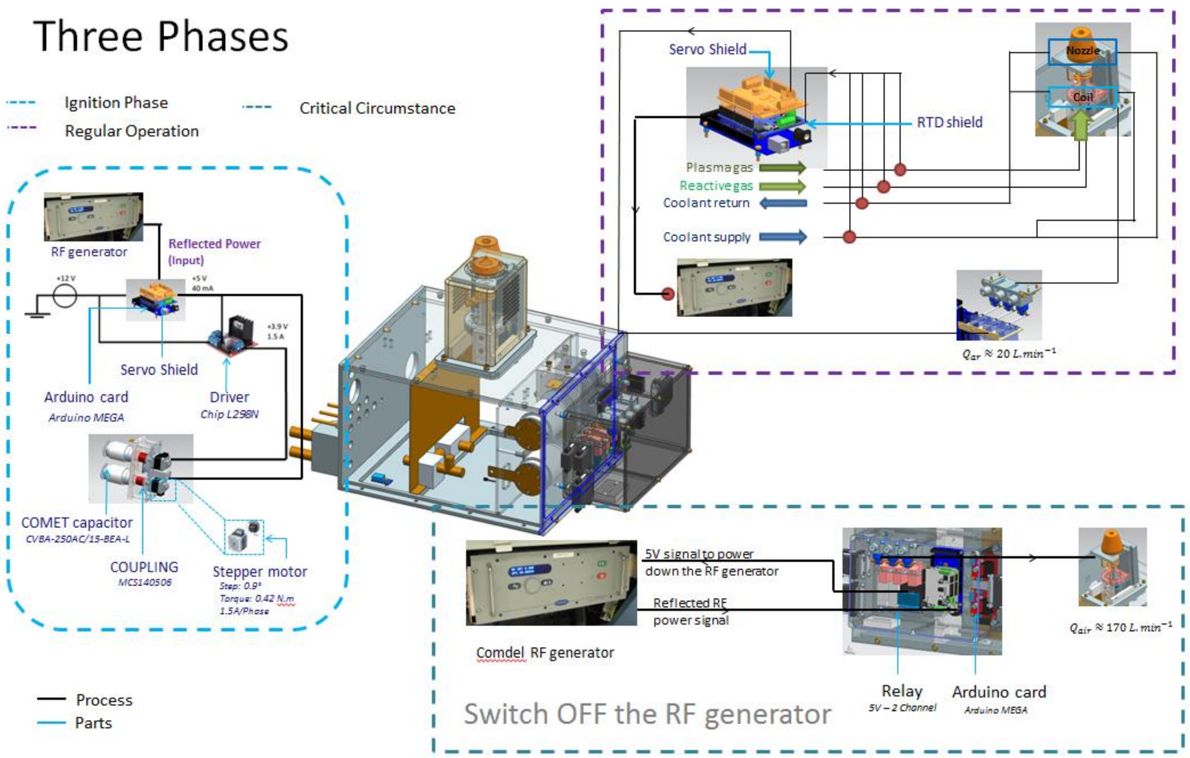


Figure 34.Novel plasma delivery system and its working principle

4.1 RF circuit in Helios1200

In the PDS of Helios1200, a fixed match was carefully designed. To begin with power source, RF generator is the feeding power source giving the RF circuit to couple plasma. Then fixed match circuit acts as the connection from the power source to the load (coil, plasma chamber), based on the impedance of selected fixed match circuit being equal to average impedance of the plasma chamber, whereas load capacitor and tune capacitor act as the character to narrow the load impedance and source impedance by tuning into a fixed number manually before manufacturing. However, accurate match is achieved by tuning the forward power automatically, even VSWR of the system changes during manufacturing, the power obtained by the coil can be maintained by compensate or reduce the original power. Here below RF network schematic of the Helios1200.

Figure 35.Original Helios1200's torch assembly (left), Helios1200's torch component (right)

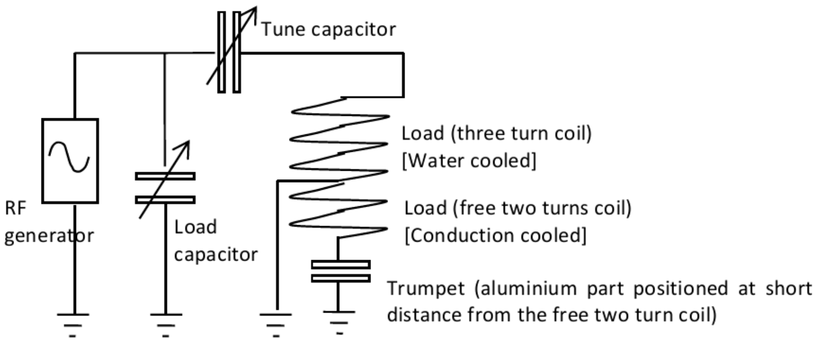


Figure 36.Electrical schematic of the HELIOS1200 - RF network

Benefits from frequency tuning of RF generator, Helios1200 can tune the forward power simultaneously during load impedance changing period. But Helios1200 aim at etching large telescope plate, long-period etching may trigger some negative effect on the load because of raise temperature. Since the changing impedance of the load may lead to the frequency adjustment area jump out of RF generator frequency tuning field.

Get into details, the range of frequency tuning of forward power is between 38.500-42.500MHz. To determine the size of the frequency step adjustment, an arbitrary frequency number is multiplied by an error signal being proportion to rfl/fwd showing as a name of Gain. The adjustment range is from 10 to 7500.The step of adjustment size is 10. [27]

Otherwise, for science research especially De-lava nozzle[28] research area, it can be great helpful to Yu tuning the impedance of the fixed match , since some key parts in the system need to be exchanged to get data.

In summary, fixed match network, done by Dr. Renaud Jourdain, is very time consuming (about 30min) and only a specialised person can process this part. Hereafter a simplify algorithm for provide to the reader a better understanding of the current situation.

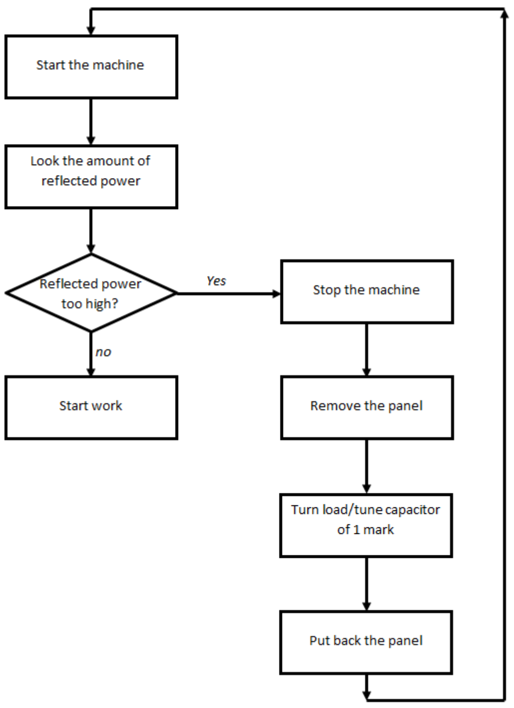


Figure 37.Current process for the matching network

4.2 Motorized fixed match RF circuit design

In this project, fixed match circuit design is mainly bring fast tuning and reliability to our plasma delivery system. To secure the process determinism for Helios1200 high frequency RF generator machine, protect electrical components and make an automatic Plasma Figuring machine, the PDS in Heliso1200 firmly can be enhanced.

Admittedly, plasma processing system becomes more process specific presenting a narrower range of impedances to the RF delivery system, which is basic premise for fixed match.

The radio frequency aims at maintaining the plasma in stable condition for 10 hours process duration. Thus, temperature increase of the electrical components, environmental perturbations, and process parameter variations will be monitored [29]. Through the means of actuators, sensors, and micro controller, the impedance of the load will be adjusted by tuning the values of the two vacuum capacitors (tune and load). Those capacitance values are intended to be changed using stepper motors mounted at the end of cylindrical vacuum capacitors. In addition, the free running RF signal generator will be used to determine finely and rapidly the optimum output frequency. Figure 38 illustrates the original circuit design and motorization of the capacitors.

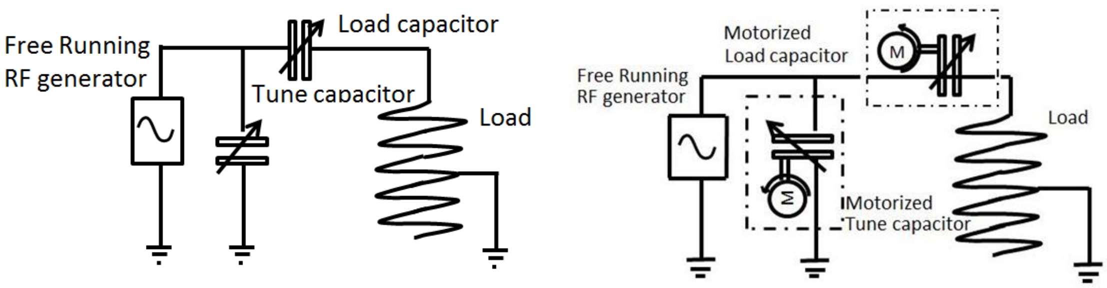


Figure 38.Fixed match (left) [18] and motorized fixed match RF network (right) [34]

4.3 Novel plasma delivery system design

In this section, the whole structure of the novel design can be exposed. Then detail information is displayed through three technical fields as mechanical design, circuit design and digital control design. What's more, the realization of the novel design was divided into three sections based on the three phases as ignition phase, regular operation and critical circumstance.

4.3.1 Novel plasma delivery system model

4.3.1.1 Plasma torch in Helios1200

At present, the plasma delivery system exists in the Ultra precision lab is as follows:

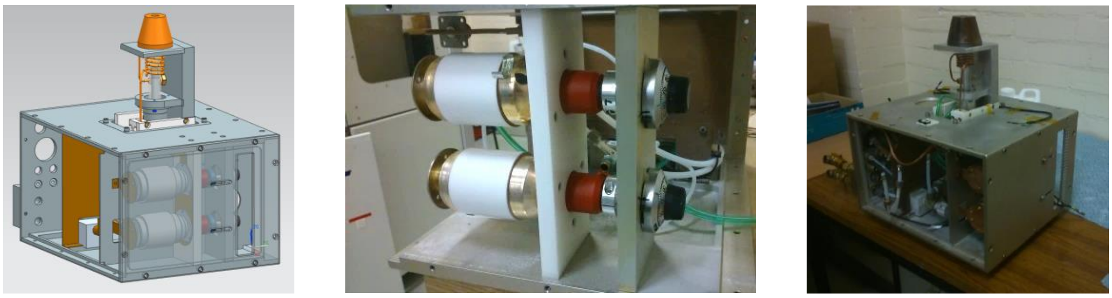


Figure 39.Plasma torch in UG model (left), fixed match structure (middle) and Plasma torch

4.3.1.2 Novel Plasma delivery system

In this project, brake system and control box are two main physical structures in our novel plasma delivery system. The former was modified as the tuning facility for two capacitors existing in the original plasma delivery system, which has self-locking function to keep the tuned capacitors position locked; the latter named as earth box contains all the electrical components driving stepper motors, servo motors to work, also getting the feedback information of RTD sensors. Here blow the model structure in UG NX7.5 is displayed.

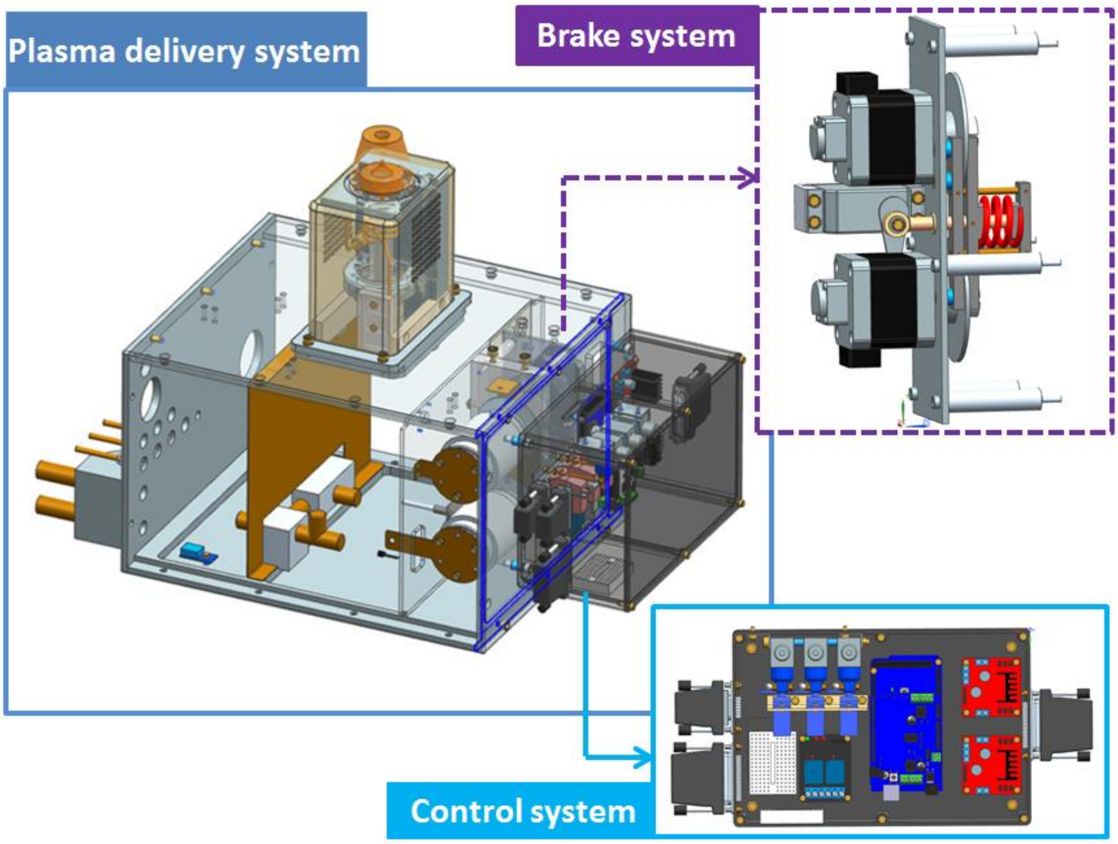


Figure 40.Novel plasma delivery system

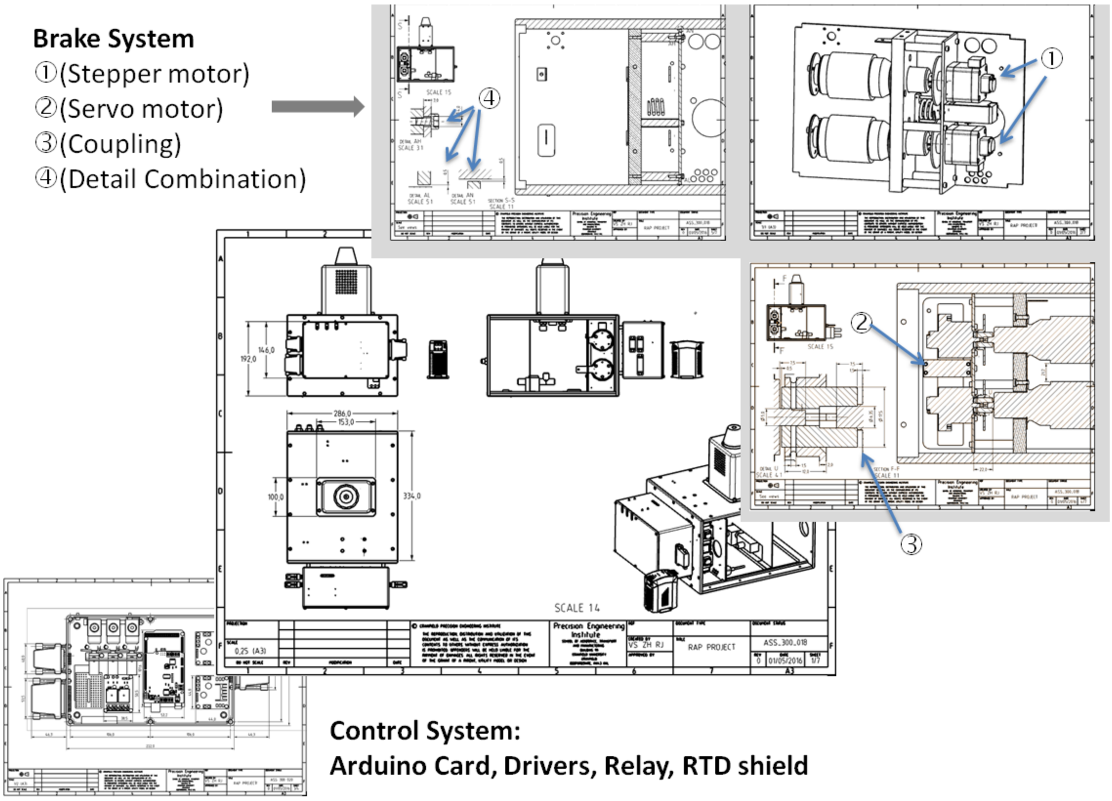


Figure 41.Engineer drawings of novel plasma delivery system

4.3.2 Mechanical design

In this motorized capacitor circuit design, there are three main components. Firstly, it is a brake system design mainly tuning the position of two capacitors to change the impedance of the motorized fixed match of the whole system. Secondly, the modification of enclosure for the control system is necessary to be implied. The enclosure acts as a cover role mainly for placing the electrical devices. Thirdly, to build cooling system structure, it was necessary to modify the construction of torch, adding cooling gas feed structure.

4.3.2.1 Brake system

In this project, brake system is crucial to turn the impedance of capacitors, driven by the Ardiuno Mega. As the author mentioned before, the structure is a self-locked design. Hereafter the brake system mechanical structure drawing is displayed.

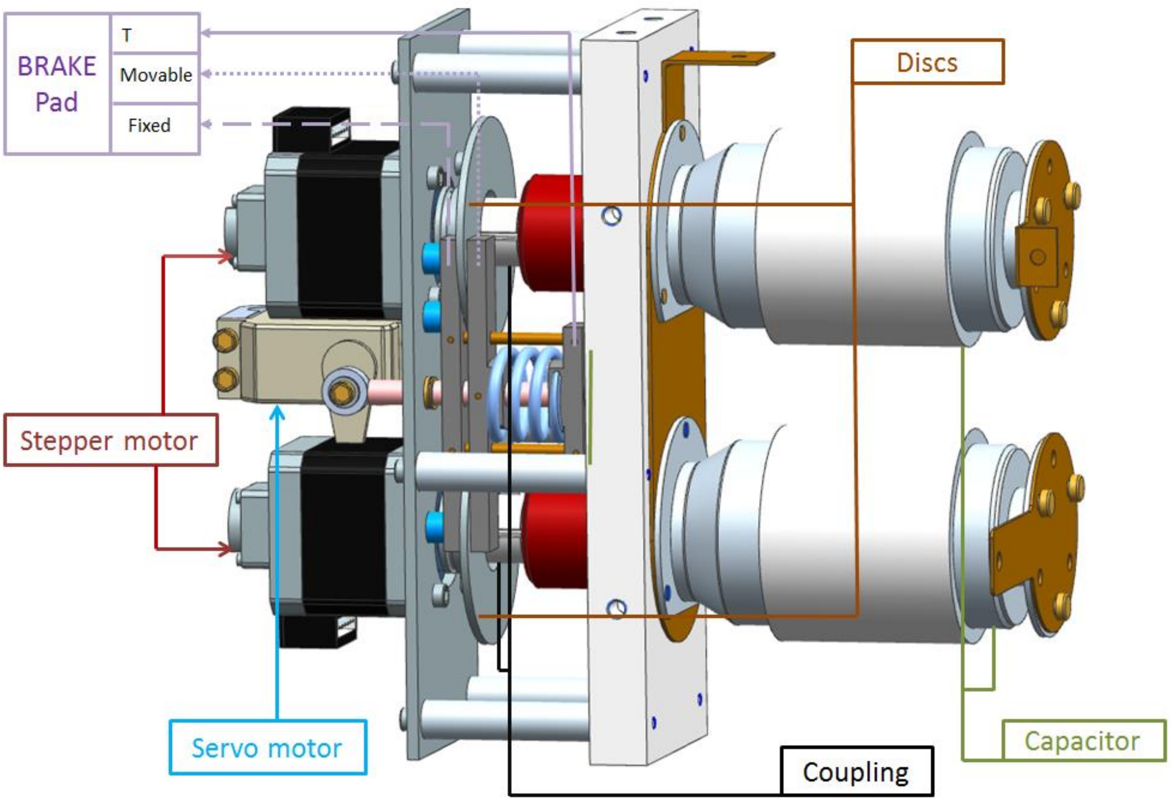


Figure 42.Brake system in the novel plasma design

Generally, two stepper motors are formulated to rotate the capacitors, being connected by two home-made coupling. In static situation, stepper motors are hold by two brake pads, being pushed by the spring as the figure 43. To be specific, since two discs are physical connected to stepper motors, the frictional force caused by brake pads hold the stepper motor. Hereafter the working performance of the brake system is displayed.

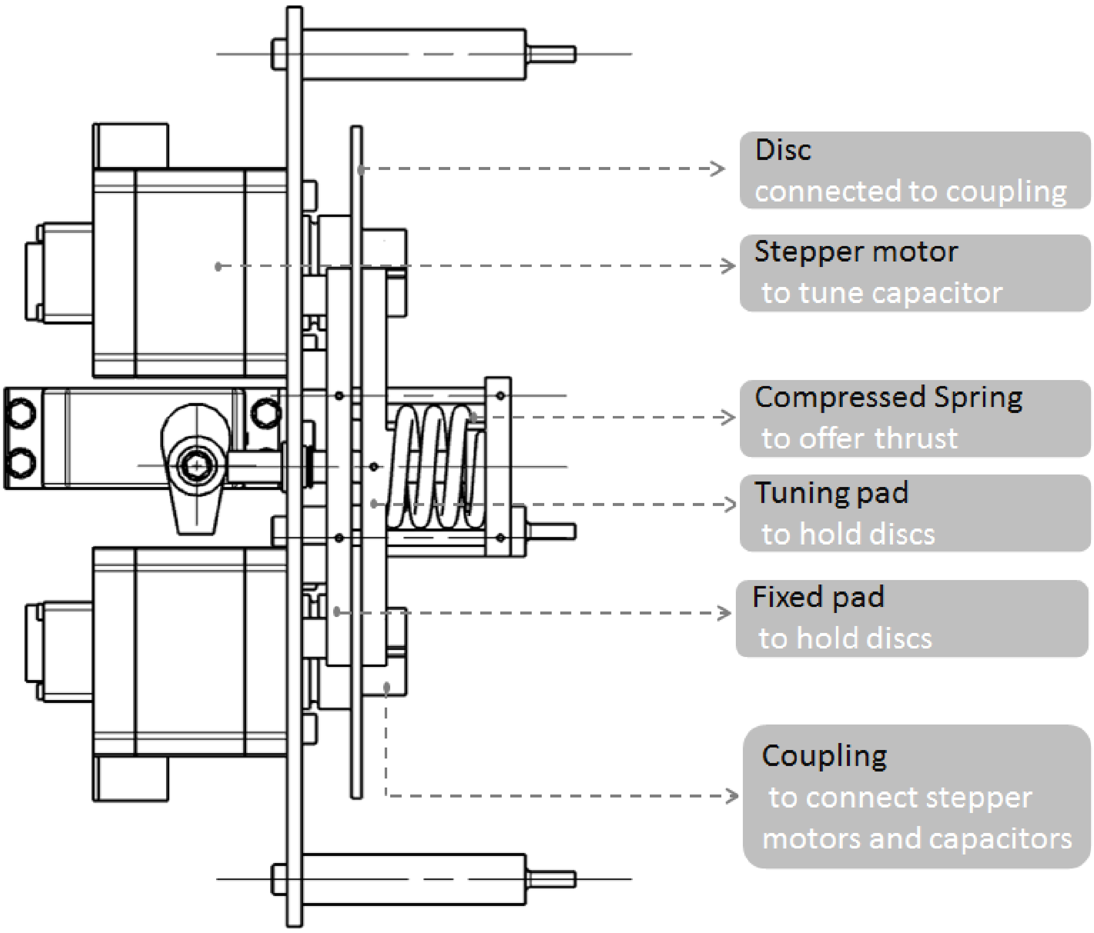


Figure 43.Brake system design structure and function

Once the system gets into work, the servo motor can be ordered to open the brake system by pushing brake pads. Immediately, stepper motors is enable to turn the capacitor in right position. Then the brake system will be closed again. All the turning actions can be finished in the open period.

In this brake system structure, all the force and torque were carefully calculated to meet the holding and turning issues. Here after the engineer drawings of brake system present the structure of the system.

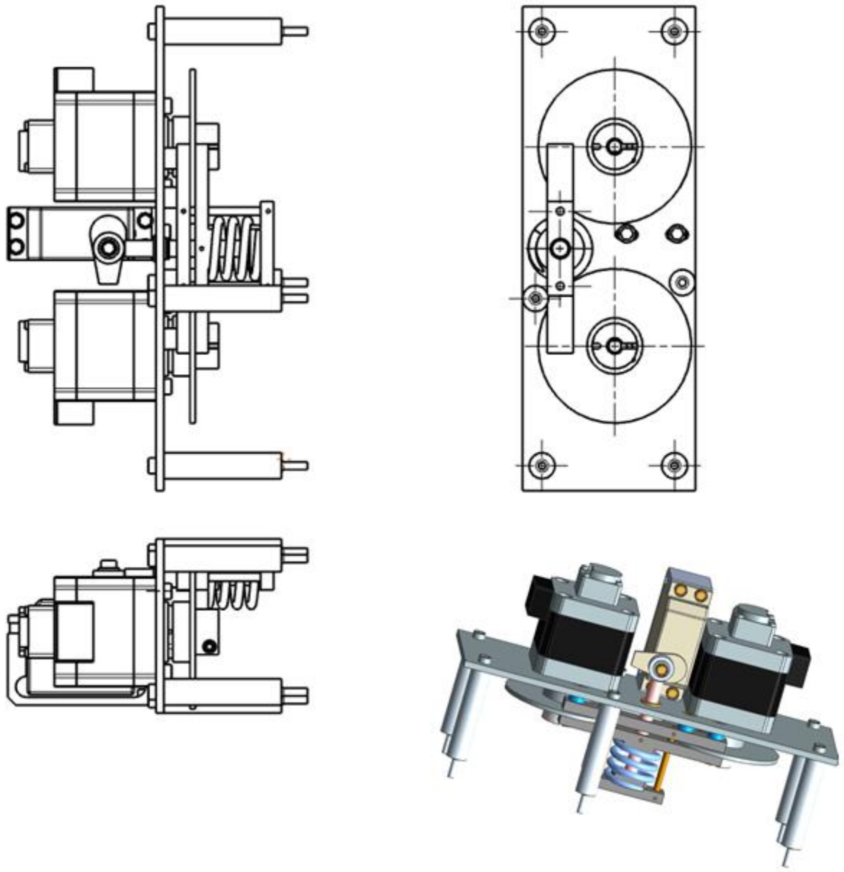


Figure 44.Brake system in the UG NX7.5

Main components

- 2 stepper motors with encoder (Oriental Motor / PKP244MD15A-R2FL-L)
- 2 stepper motor driver cards (Andoer/ DC 5V L298N)
- 1 servo motor(Savox/ SA-1283SG)
- 1 spring (Associated spring/ C09751351000X)
- 2 coupling (PEEK material)
- 3 brake pads(Aluminum 6061-T6)
- 2 discs(Aluminum 6061-T6)

Calculation

In the brake system, four parts should be calculated.

4.3.2.1.1 Stepper motor

To start with the determination of the stepper motor, required to rotate the angle of capacitors in RF network. Two different aspects must be proved: mechanical characteristic and mechanical configuration.

Mechanical characteristic

To meet the mechanical characteristic needs, the speed-torch of stepper motor tuning the capacitor is required to greater than the holding-torch of capacitor. Otherwise, to achieve minimum step control, the tuning angle of basic step for stepper motor should be small than the step of capacitor.

Hereafter the data sheet of capacitor and stepper motor can prove the steppers meet the need of characteristic.

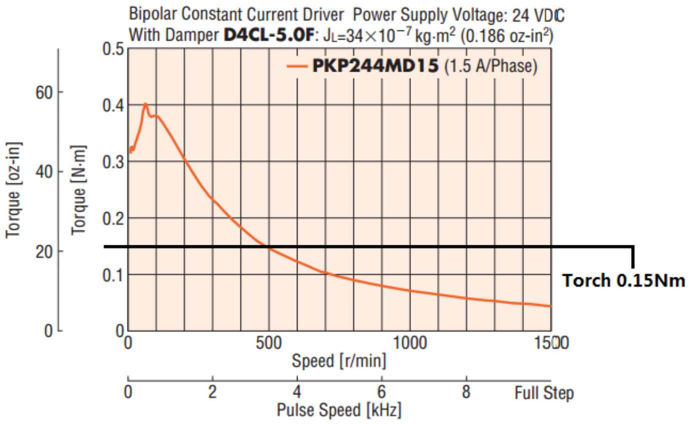
Table 1.Technical data of stepper motor (upper) and speed-torch characteristic chart (down)

CVBA-250AC/15-BEA-L

$T_{COMET} \leq 0.15\ Nm$

Specifications	
Capacity C_{max} (nominal)	250 pF
Capacity C_{min} (nominal)	5 pF
Voltage (Peak Test U_{pt} / Peak Working U_{pw})	15 kV / 9 kV
Capacity Tolerance (linear Range)	10%
Max. Current Imax at 13.56 MHz with	57 Arms
Conduction Cooling	10 W
Self Inductance	≤ 8 nH
Capacitance per turn	14 pF/turn
Torque	≤ 0.15 Nm
Net Weight	0.6 kg

PKP244MD15A



From the table of capacitor, the maximum torch can reach at 0.15Nm. In our design, the range of speed-torch covers the peak torch of the capacitor in Helios1200. To be more specific, stepper motor offer 0.15 Nm torch at about 500 r/min speed.

From the measurement data of technician , the torch of the capacitors in Heliso1200 is about 0.088 Nm. Gathering data from the speed-torch chart, the speed of stepper motor can rise up to around 1000 r/min, when stepper motor convey 0.088Nm torch.

Otherwise, for minimum step of stepper motor the angle is about 0.9°, which is smaller than 1° the minimum tuning angle of capacitor.

Mechanical configuration

To meet the mechanical configuration needs, the installation space left should be measured. Hereafter the space dimension exposed.

Figure 45.Measurement of the left space

So the dimension for the motorization can be concluded as follows:

- Maximal radius: 35 mm
- Maximal depth: 85 mm

4.3.2.1.2 Spring

To judge the spring applicability, the friction force caused by the spring must be 2 times greater than the force caused by the torch of two stepper motors. What’s more, the torch should be the maximum of the tuning ability from the stepper motors [35]. By that, the brake pads are able to lock the tuning system entirely.

$f_{discs} > 2*M/D$ (D is the distance between the centre of motor to the middle of brake pads)

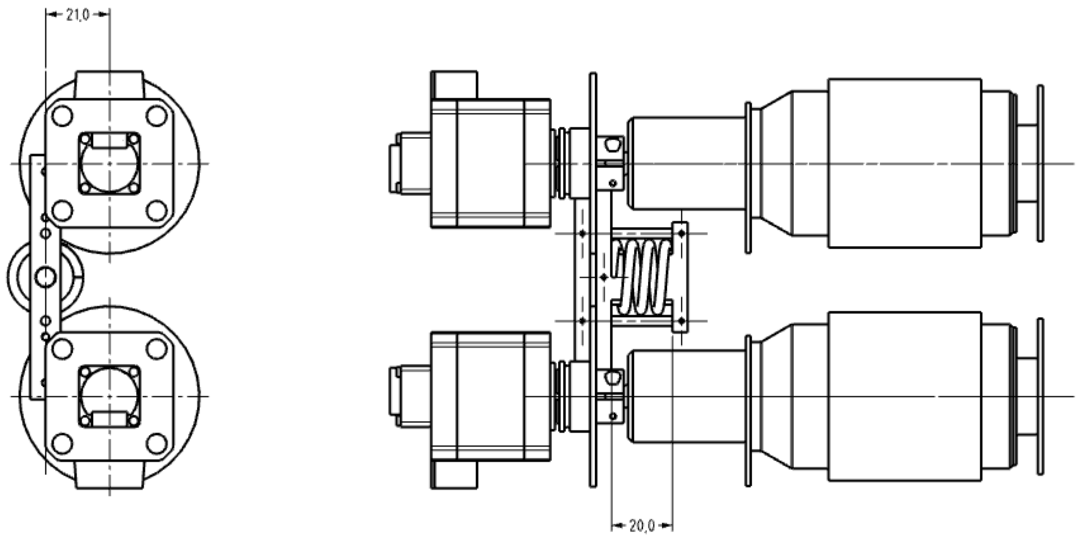


Figure 46.Spring holding structure

Data of Associated for the spring:

Part Number	D_o	d	L_o	L_1	P_1	R(N/mm)
C09751351000X	24.77	3.43	**25.40**	19.26	267.04	**43.47**

Note: D_o : Outside diameter; d : Wire diameter ; L_o : Free length (reference use only)

L_1 : Loaded length ; P_1: Load at L_1; R: Spring rate

Spring shrink: 5.4mm, there still have 0.7mm to prevent the spring's length error.

- Force of the spring: F_{spring}= R*L= $43.47_{N/mm}$ * 5.4_{mm}≈ 234.74N
- $f_{discs} = \mu * F_{spring} = 0.2*F_{spring} = 46.94N$

(Friction coefficients μ is for common Aluminum at Ra 3.2) [36]

Date of stepper motor:

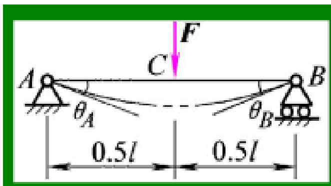
Product code	Basic step angle	Holding torque
PKP244MD 15A-R2FL-L	0.9°	0.42Nm

- Force of stepper motors: F= M / D= 0.42Nm / 0.021= 20N 2F=40N

Spring-C09751351000X meets the needs of locking.

4.3.2.1.3 Brake pads

To the deformation of the two brake pads should be calculated, due to deformation might cause the slippage of brake pads themselves. Hereafter the bending angle sketches and formulas are displayed.



$$y = -\frac{Fx}{48EI}(3l^2 - 4x^2)$$

$$0 \le x \le \frac{l}{2}$$

$$\theta_A = -\theta_B = -\frac{Fl^2}{16EI}$$

$$y_C = -\frac{Fl^3}{48EI}$$

Figure 47.Bending angle and deformation distance formula [22].

Hereafter the bending structure in our design is displayed.

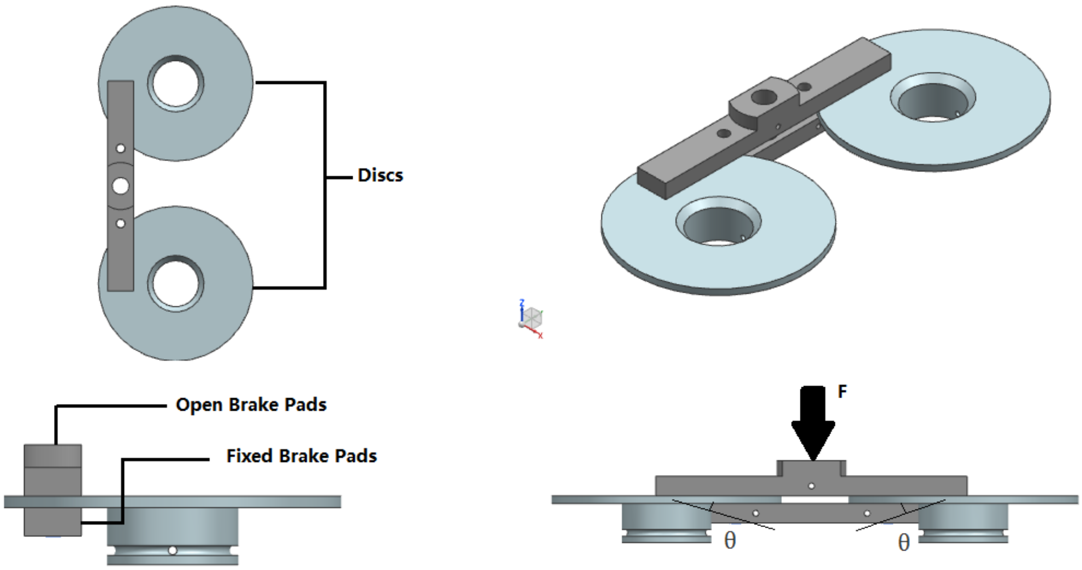


Figure 48.Bending angle in this design

For our project, one brake pad can be assumed as the board in the sketch independently. Then Point A and B were regards as contact points with two discs. Otherwise, the pressure came from the spring was located in the middle of the pad. Based on the formula above, the bending angle can be calculated [37].

$$\theta = \frac{FL^2}{16\mathrm{EI}}$$

$$\mathrm{I} = \frac{\mathrm{bh}^3}{12}$$

Bending angle≈ 0.0985°

Bending angle is rather small. In general, the brake system is in safe.

4.3.2.1.4 Servo motor

In this design, the servo motor bought on line must meet the needs of opening the lock structure which means the thrust caused by servo motor should greater than the holding force from spring. Otherwise, the rotary angle of servo motor must be formulated appropriately. To be more specific, the rotary angle of servo motor determines the linear movement of the brake pad. The distance of the movement matches with the shrink distance of spring. Therefore, the rotary angle of servo motor should be carefully formulated, in case the plastic deformation of spring and overload of servo motor itself. For the purpose of achieving the movement as above, the position tuned servo motor was chosen in the design named as SAVOX 1283 Servo.

Data of Associated for the spring:

As calculated before, thrust of spring as follows:

- Force of the spring: F_{spring}= R*L= $43.47_{N/mm}$ * 5.4_{mm}≈ 234.74N

The F_{spring} is maximum number in this structure, as the shortest shrink distance was selected in the formula.

Data of servo motors:

- Savox 1283 high torch servo

Specifications:

Dimensions: 40.8x20.2x37.4mm	Weight: 80.0g
Speed:	Torque:
@ 4.8V: .16 sec/60	@ 4.8V: 347.2oz-in
@ 6.0V: .13 sec/60	@ 6.0V: 416.6oz-in
Case: Full Aluminum	Output Shaft: 25 Tooth Spline

- The servo torch in 4.8V : 347.2OZ-in≈2.4518Nm

(In our project, the voltage of feed power supplied by Arduino Card is 5V, Theoretically, the torch from servo motor might be slight stronger than the one in 4.8V, which is better.)

- To compare the thrust from servo motor with the force for spring exactly. The distance between the centre of servo motor and the centre of spring should be tracked and applied into formula.

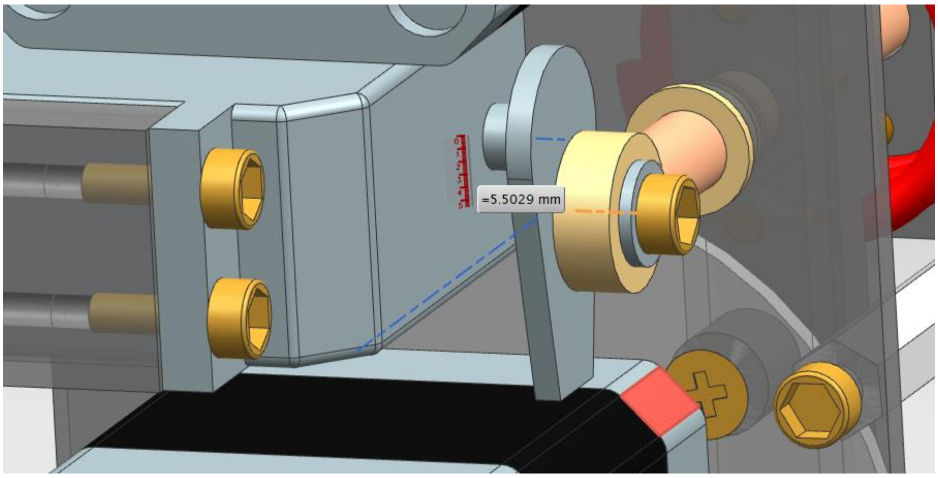


Figure 49.Distance between servo centre and spring centre.

- Force of the servo: F_{servo}= M / D = 2.4518Nm / 0.0055m≈ 445N
- Force of the spring: F_{spring}= R*L= $43.47_{N/mm}$ * 5.4_{mm}≈234.74N

$F_{servo} > F_{spring}$

Opening structure driven by Savox 1283 *servo motor can be perfect used.*

4.3.2.1.5 Detail designs

In this section, some highlight of mechanical design will be listed. In this novel design, detail mechanical design can sufficiently promote the property of the whole system. What's more, detail designs bring benefits to assemble the brake system simply and efficiently.

Free linkage design

In the brake system, a free linkage design structure was suggested by Dr Jourdain. Briefly, as shown in Figure 50, the frame of design structure can be shown.

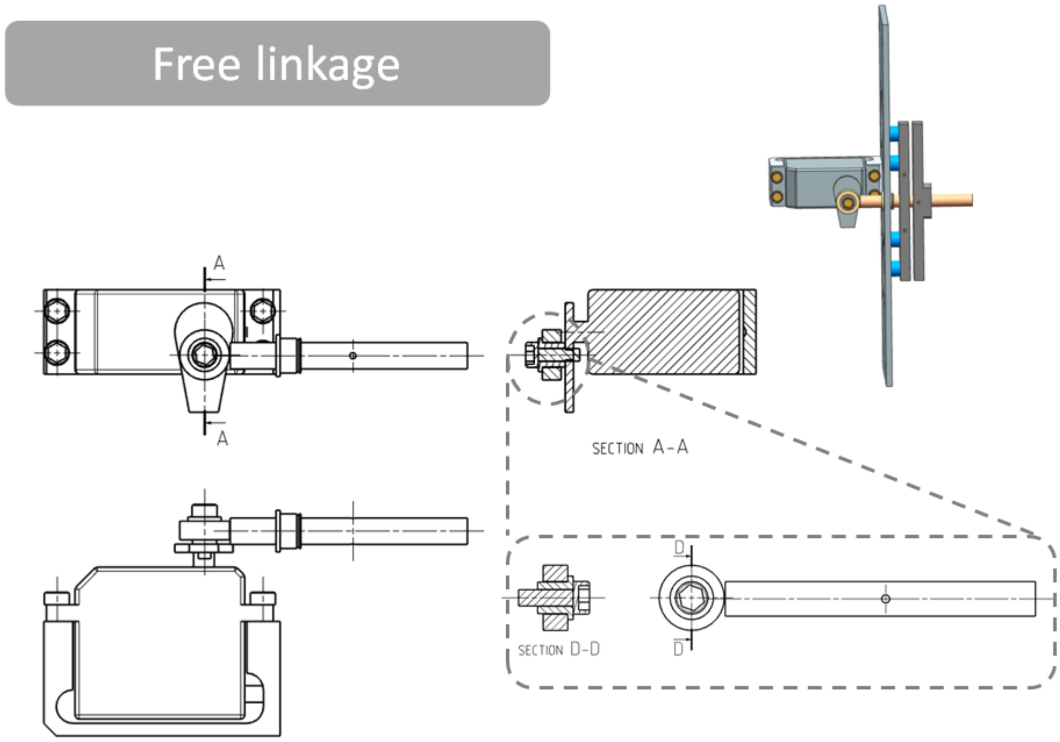


Figure 50.The free linkage structure to open brake system

In principle, the free linkage transfers the rotary movement of servo motor into liner motion. Noticeably, the connection of servo motor and pin is free style. To be more specific, the roller on the horn is able to whirl. With the rotation of horn, the roller tuned smoothly to drive the pin to open the brake system. The design of free linkage enhanced the substitutability and stability for the system, due to flexible connection reduces the stress inside compared with the traditional linkage design.

Spring limitation design

Generally speaking, to limit the movement of spring, the shape of brake pads is suitably to be modified. In principle, the brake pads act as a fixed structure to held the discs, controlling the rotation of capacitors. Obviously, it is considerably reasonable to endow the brake pads to limit the position of the spring, since the position of brake pads is nearby the spring. Based on that, it is suitable to make the shape of brake pads to restrict the unexpected movement. Hereafter the limitation structure of brake pads to spring is displayed.

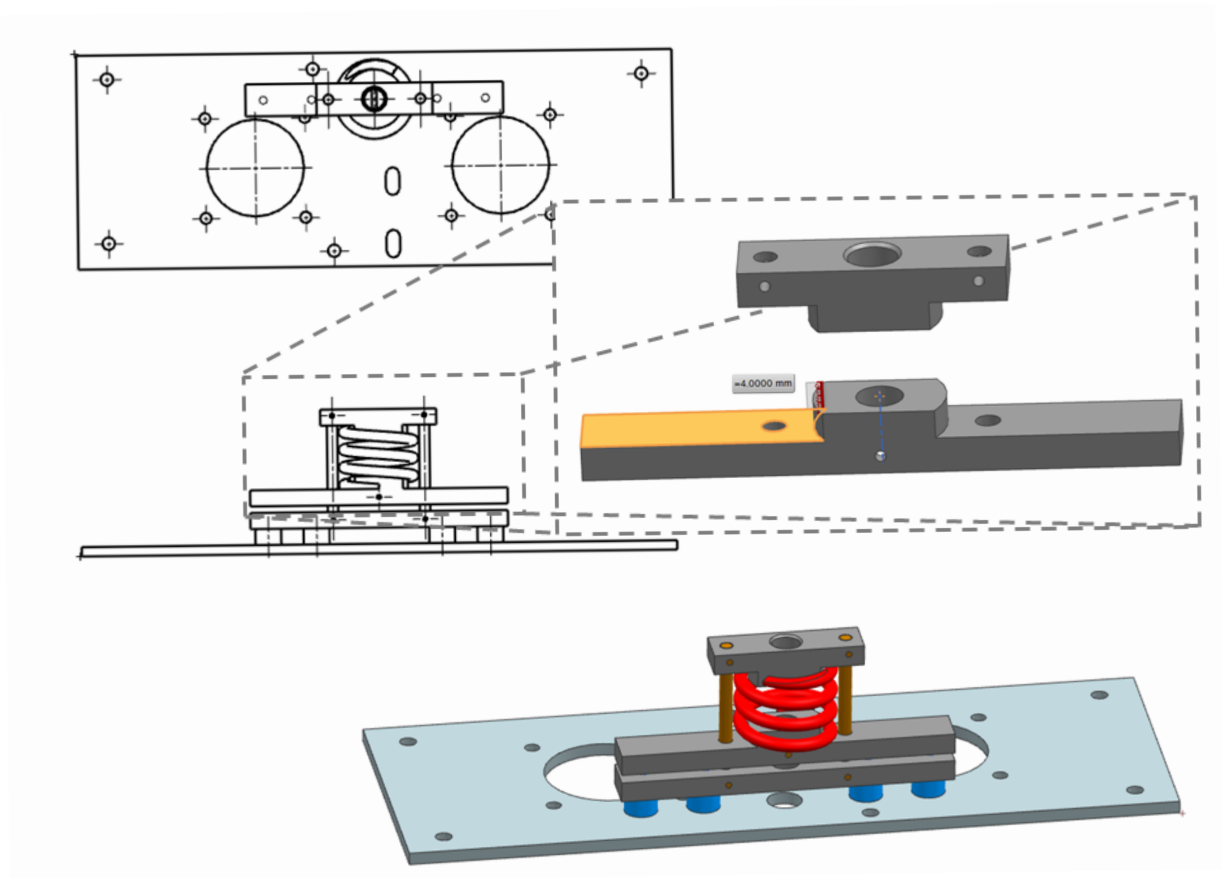
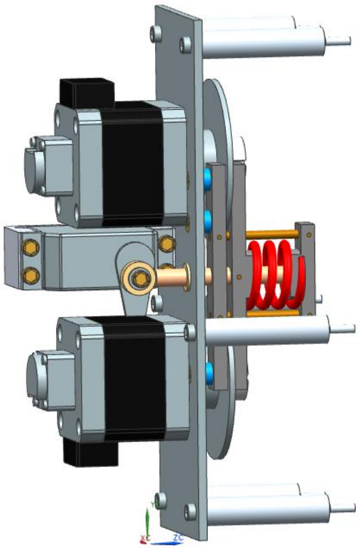


Figure 51.Brake pads with position limitation structure

Noticeably, for stopping the movement of spring effectively, it is suitable to modify the spacing of stoppers into 2 times higher than one pitch of spring. Otherwise, it is better to make that into 0.5mm per side narrow than the spring, triggering positive effect on avoiding the error of inside diameter of spring. Hereinafter the brake system is displayed.



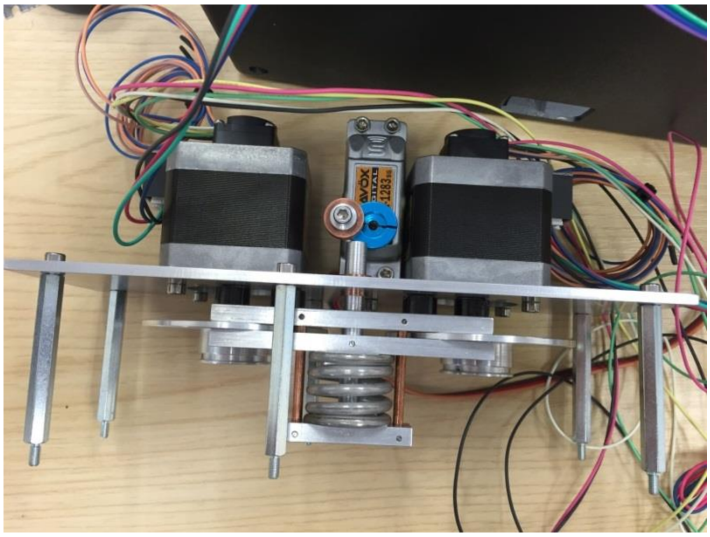


Figure 52.Brake system in real

4.3.2.2 Torch adjustment Components

Plasma torch in Helios1200 is mainly where plasma coupling happens [28]. In chapter 3, the damages of support plate and coil were proposed. In generally, to eradicate the two problems more works should be address into the RF generator itself, which need more pioneer programme setting and perfect electrical design to enhance RF generator. After discussion with Dr Jourdain, two machinery modifications can be an efficient way to solve the problem.

Briefly, modification of support plate and installation of cooling air injection are the two main ways to reach the goal. To be more specific, machining markedly is focused on the support plate and backplane and cover of cooling structure. Hereafter the contrast of the original torch and the enhanced torch is displayed.

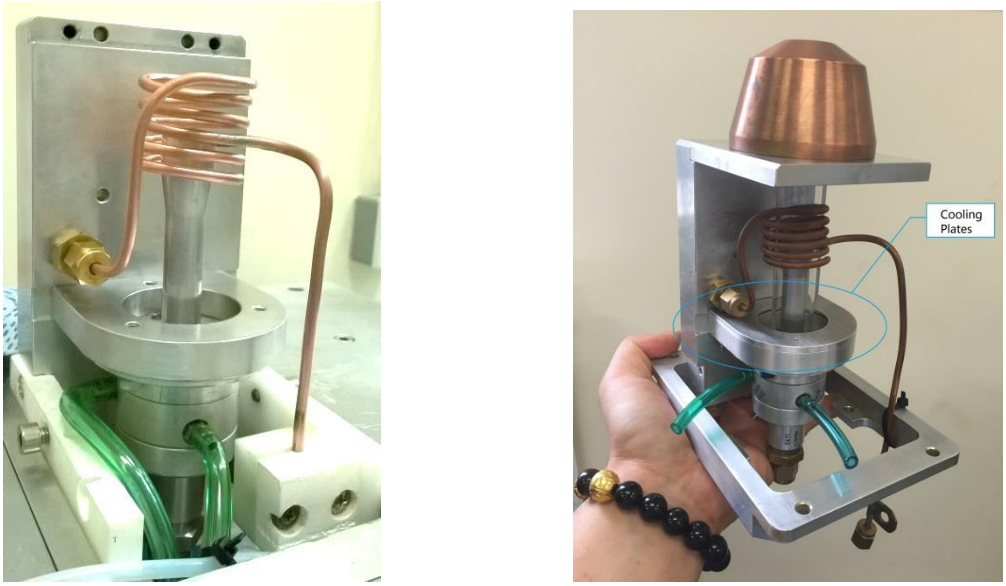


Figure 53.The original torch (left) and the enhanced torch with cooling plate (right)

4.3.2.2.1 Prevention damage of support plate

As the method present in this thesis before, decreasing the exposed area of support plate is an effective way to prevent unwanted deposit of support plate, removing the chamfer of the support plate in Helios1200 is implied as the figure 54 displayed. Move the chamfer, the distance between moved part and the path should be calculated. Hereafter the original support part and changed support part are displayed.

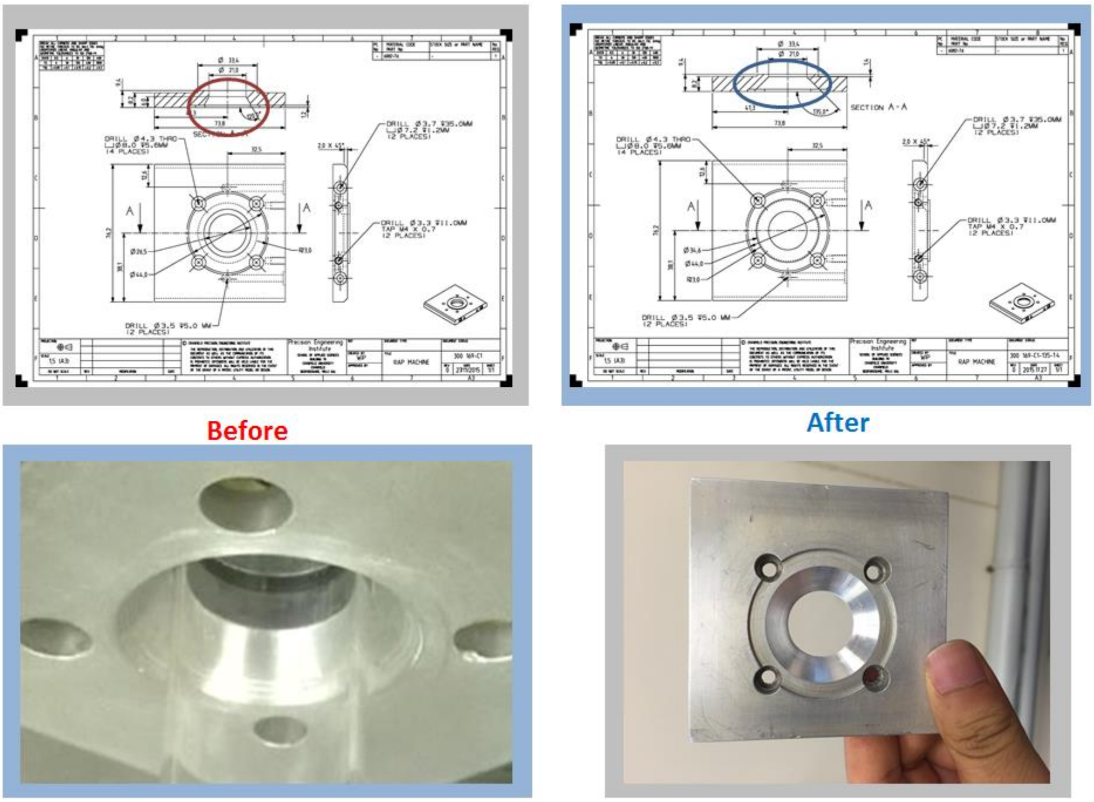


Figure 54.The original part with its engineer drawing (left) and the changed part with its engineer drawing (right).

4.3.2.2.2 Cooling system for PDS

In cooling system, has three functions being divided into three pipelines with mark as A,B and C. Valve A works as a cooling gas port to cool down coil during manufacture using drying gas in 10LPM flow; Valve B works as the other cooling gas port to cool down the electronic devices in enclosure box; Valve C works mainly for emergency situations. If the quartz tube is broken, the gas from Valve C will blow the reactive gas out of the torch (the reactive gas can easily oxidize the entire torch as the situation can be traced from the chapter 3).

The three valves are connected to servo motors driven by Arduino Mega card. Here below the module connection picture is displayed.

Oxidation of coil can be a potential risk for Plasma Figuring in more than 10 hours long period process. To guarantee the coil in safe, a cooling system structure was planned to be added into the system. In our plan, RTD sensor is fairly suitable to be the input source. When the dramatic rising temperature occurs, an input signal can be transported to Arduino Mega 2560. With the prompt of the input signal, Arduino Mega2560 can give out an output signal to drive the feeding cooling gas system to cool down the exorbitant temperature. Hereafter the structure of cooling system for coil oxidation is displayed.

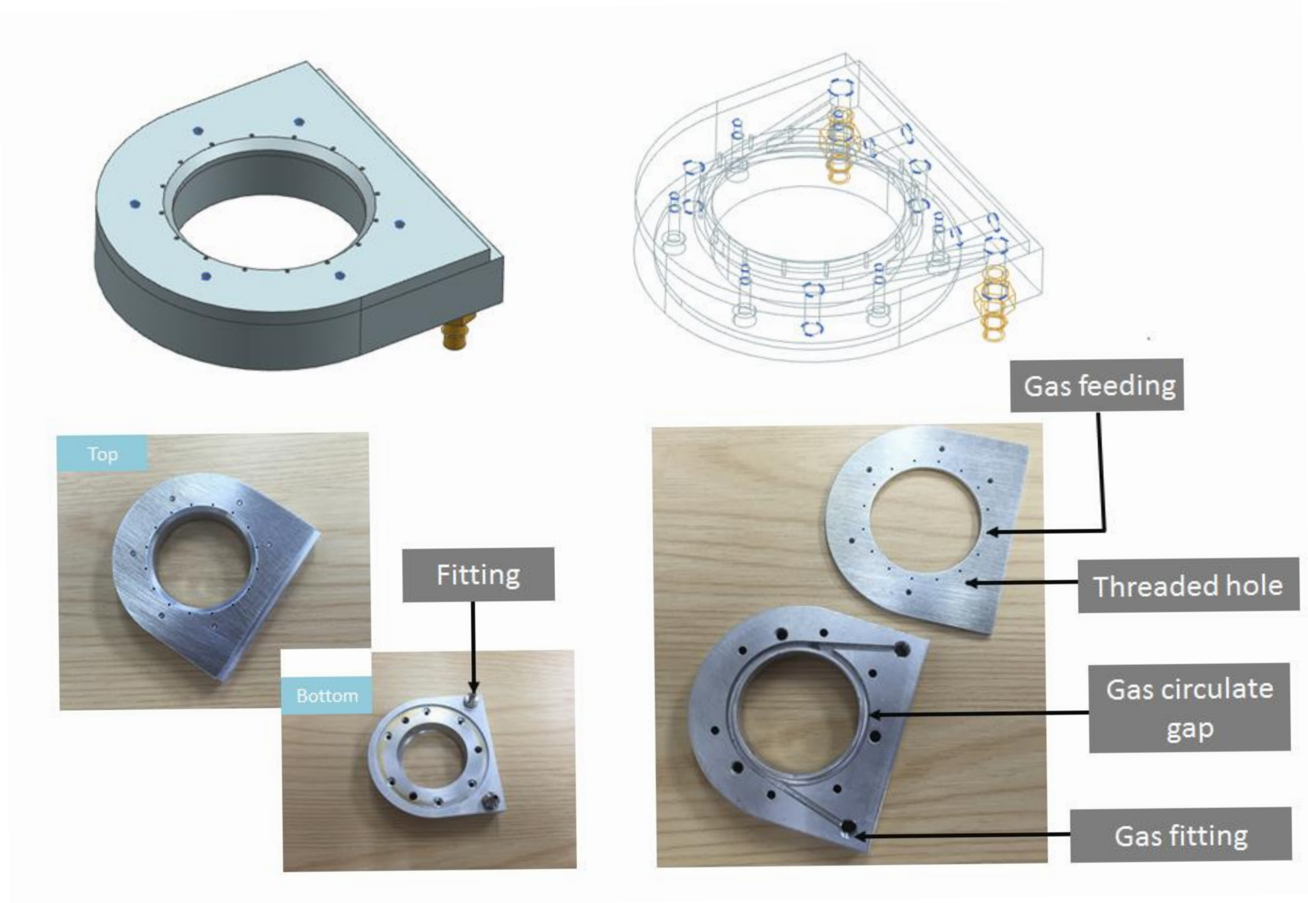


Figure 55. Cooling system structure mainly consisted of backplane and cover plate

In principle, the cool gas will be implanted into the ventilation grooves with the input signal from Arduino Mega 2560 card. There is linkage between gas pipe and interface in backplane, preventing cool gas from leakage. With the rising pressure of air, the cool gas will fill the gap in backplane, then the gas can be shifted to the coil through the vents in the cover.

4.3.3 Circuit design

In circuit design section, all the electronic devices are employed to relate Arduino Mega card. Arduino is an open-source prototyping platform based on easy-to-use hardware and software, as Dr Jourdain recommended. The accepted the advice from Dr Jourdain, with his advices and guidance. The author enhanced the circuit design and built the electric circuit as the draft as follows. Hundreds of working hours were spent to select the suitable electronic devices and choose the better function for the circuit system.

4.3.3.1 Technical view

In this circuit design, technical view is established based on the three phases of Plasma Figuring as ignition phase, regular operation and critical circumstances. Otherwise, to search the suitable and cost effective electronical devices, the devices in mechanical designs should be driven into the circuit design as well for coordinating the mechanical structure and electronic circuit. Hereafter the electronic elements mainly are used in three phases.

Ignition phase

- 2 stepper motors to adjust the capacitors position

  1 stepper motor: 6 digital output, 4 in full use; 1.5A per phase

  Totally: 12 digital output (2 x 6= 12 outputs)

- 2 rotary encoder to determine precisely the capacitor position

  Output 3-Channel

  Input Current (mA): ⩽30

  Input Voltage (V) :5 ± 10%

- 1 signal acquisition for the reflective power (RP). This signal is provided by the RF generator. This signal will enable to tune the impedance of the torch by changing capacitor value/positon.

  1 analog input

Regular operating

- 2 RTD sensors (monitor and log the temperature of the coolant at three different positions)

  Connection terminal: RTD shield

Critical circumstances

- 1 gas supply that will quickly/strongly cool down the coil when RP rushes

  1 digital output

  1 ground

Note: Detail information as electrical equipment brand, technical parameters, and other critical information can be searched in Appendix.

4.3.3.2 Electrical circuit

As detailed in Figure 56, three sections should be noted that servo motors for valves, servo motor for opening brake system and stepper motor tuning control.

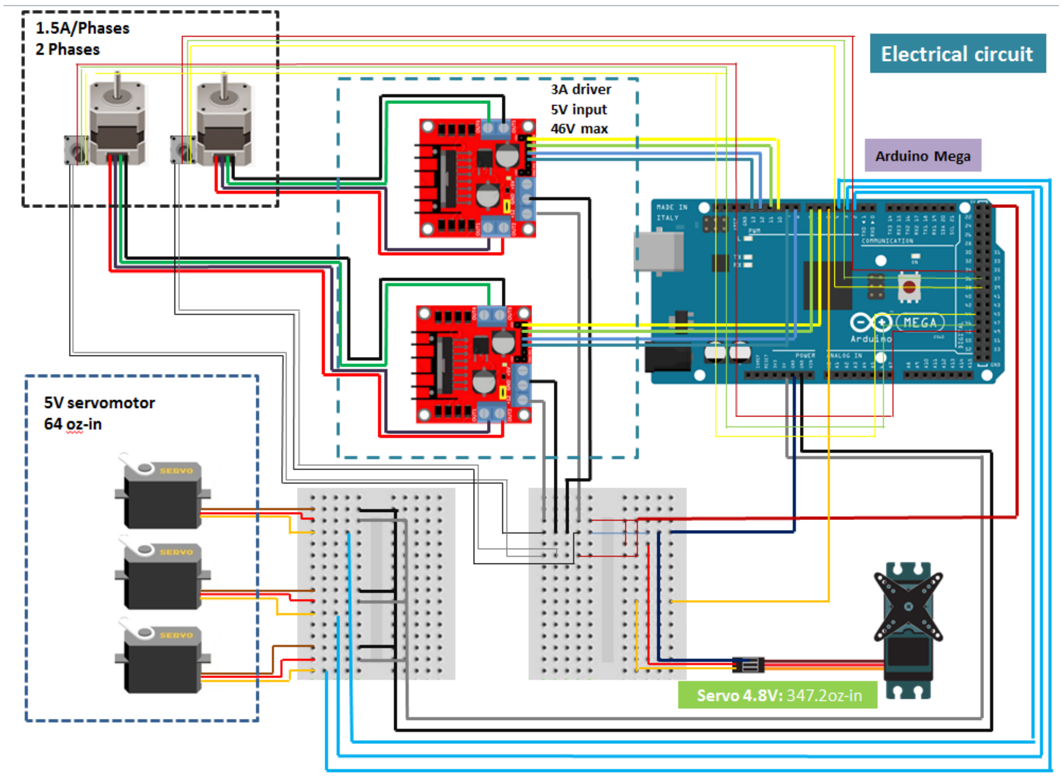


Figure 56.Electrical circuit for motor control function

Starting with the two stepper motor structure, since the two stepper motors are two phases motor with 4 wires structure, two phases' drivers are needed to rotate the motors into right angle and direction.

Moving on to the servomotor for opening brake system circuit, as detailed in Figure56, there are 3 pins were connected to Arduino Mega card as PWM signal pin, live wire pin and zero line pin. With the driven of codes, the servo motor can rotate in right angle and force. Since the servo motor is able to give enough torque at 5V input environment.

Lastly, for the three servomotors, the mainly electrical ports are similar to the servomotor. One port is to control PWM, one port is to forward 5V power and the third port is to connect ground electrode. Remarkably, PWM pins should be independent, because of the various functions for the three servomotors.

4.3.3.3 Facility Function

In this part, the electronic devices using to control the system are assembled in a black aluminium box, which is suitable to prevent the electronic devices from electromagnetic field [38]. Due to the control system is crucial to whole structure, assistant functions were plotted to put into the control structure design. Hereafter the module drawing of the system was exposed.

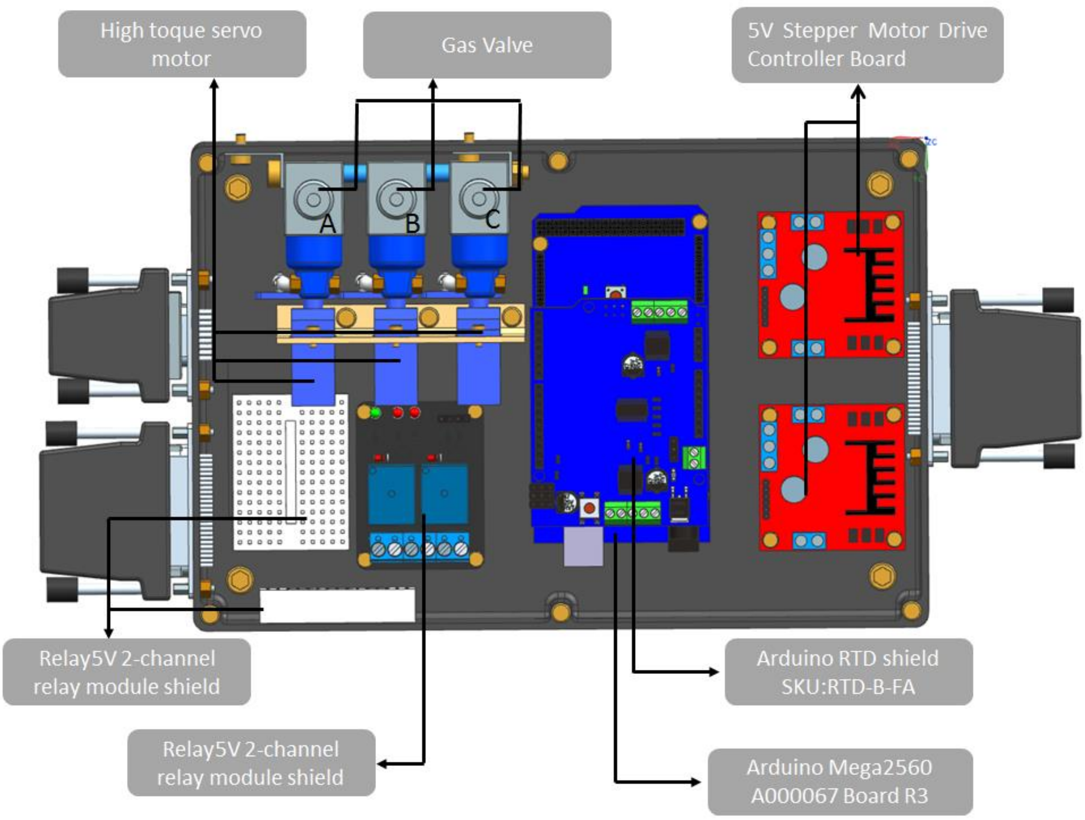
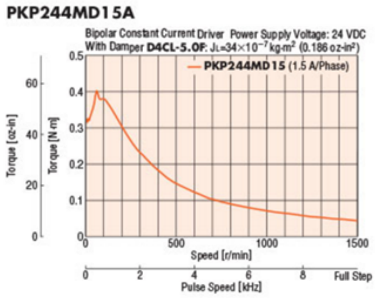


Figure 57.Control box in plasma delivery system

4.3.3.3.1 Stepper motor drive circuit

In mechanical design section, technical data displayed of stepper motors is mainly to prove the function of applicability. However, in this section, the technical feature of stepper motors is suitable to meet the needs of connection. To be more specific, the parameters of stepper motors should be suitable to the whole electric circuit. Hereafter the key parameters of stepper motor are displayed.

Table 2.Key data of stepper motor

Items	Parameter	Speed-Torque Characteristics
AC Votage	24V	
Motor type	2-Phase	
Lead Wires	4 Wires	
Current for per phase	1.5A	
Ambient Temperature Range	14 ~ 122°F (-10 ~ 50°C)	

As detailed in Table 2, based on the 5V power input, drivers being connected with stepper motors are able to feed 24V stepper motors in the design. To be more specific, drivers use high-low-frequency voltage to drive the stepper motors. Noticeably, with the two phase input, stepper motor can be substantially turned with determined direction.

Meanwhile, for the input ports part, the driver has six pins connection with Arduino Mega. 4 pins for PWM signal ports and the other two inputs are GND and 5V power source. Hereafter the electrical devices connection structure is displayed.

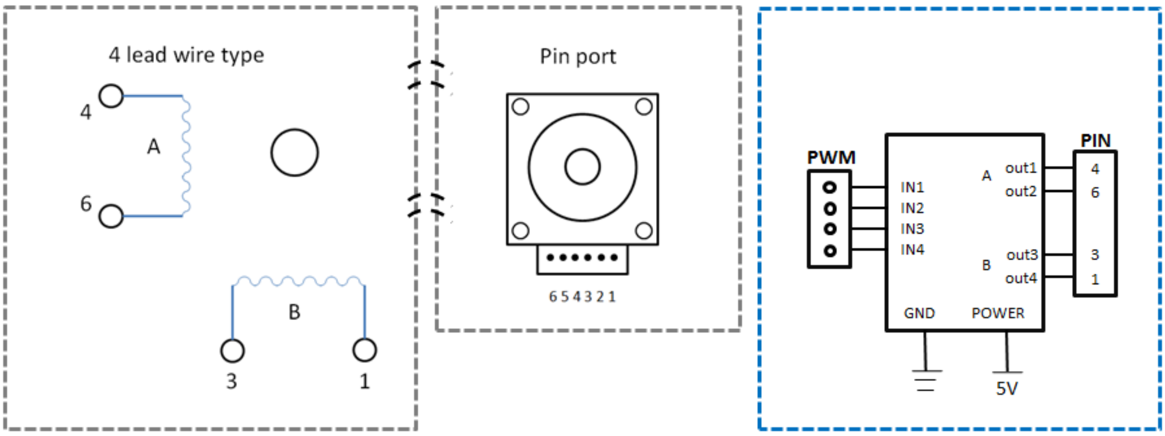


Figure 58.The detail connection between stepper motor and driver (lift and middle) and the electrical circuit of driver (right)

4.3.3.3.2 Servo motor drive circuit

Noticeably, servo motors have two main partial functions. For the first function, it is mainly applied in brake system, carried out by Savox SA-1283SG. The high torque servo motor acts as the open structure to unlock the stepper motor with the input signal given by Arduino Mega , during capacitive reactance tuning period. The servo motor drive circuit should be individually plotted to drive the brake system. Basically, there are three ports divided into PWM, GND and power source.

For the other functions, it is related to gas control function. As described in mechanical design section. Three servo motors are design to drive gas valves. Hereafter the connection of servo motors and Arduino mega is displayed.

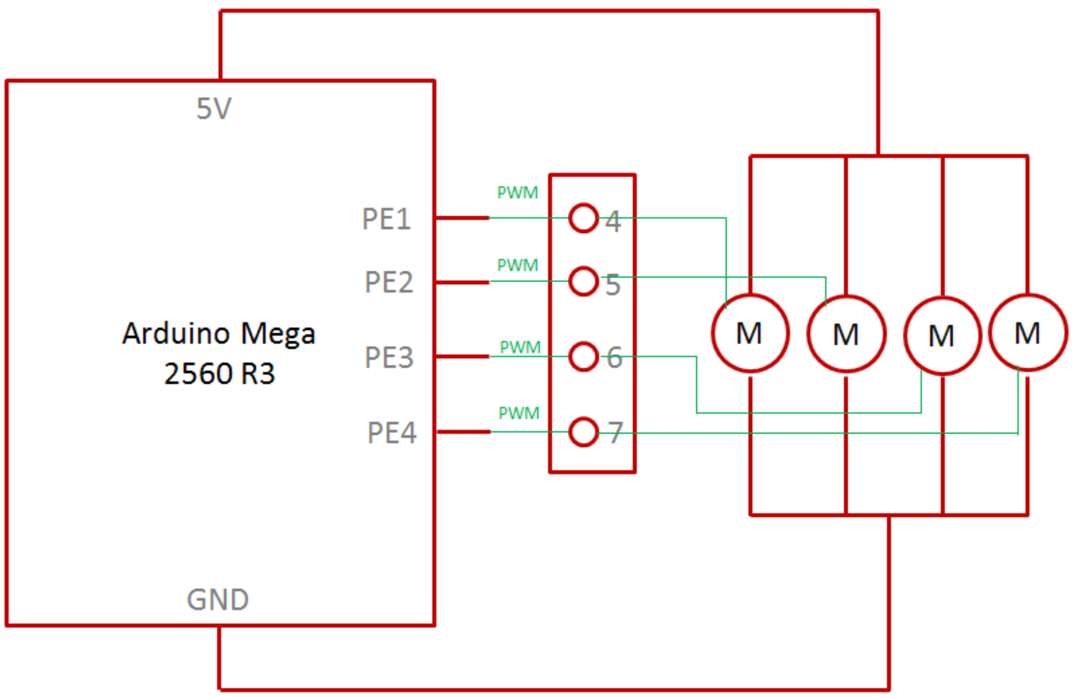


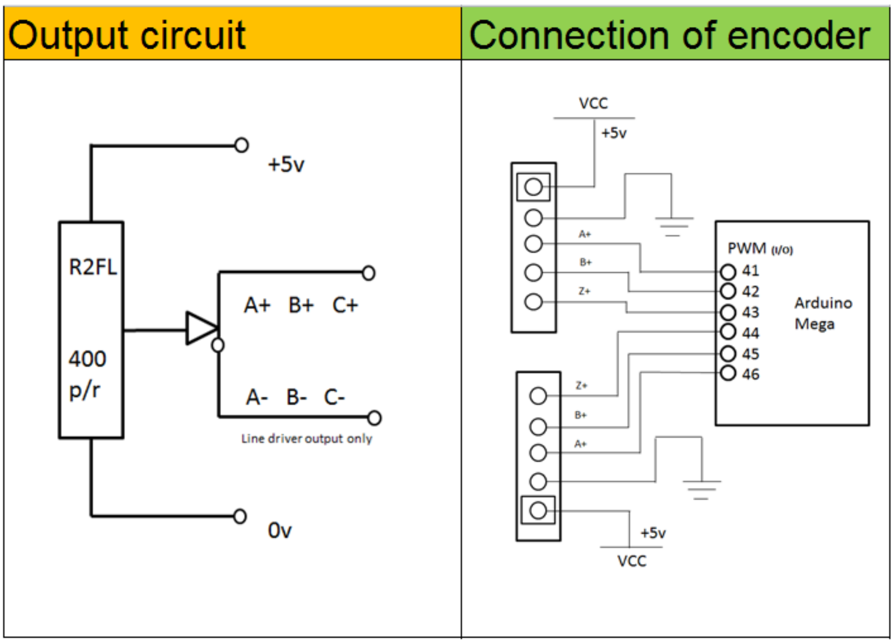
Figure 59.Connection of Arduino Mega2560R3 and Servo motors

4.3.3.3.3 Rotary encoder connection

The rotary encoder is independently connected to Arduino card. The rotary encoder applied in this design is 8 wires structure. Basically, in this design 5 wires are planned to be connected as GND, A-phase output, B-phase output, Z-phase output and Vcc (+5V). In general, A and B phase describe the duty cycle of the stepper motor rotation, giving out the angle and rotary. Z-phase output is P/4≤L≤3 P/4, which means Z-phase give out one pulse in every circle. Hereafter the detail information and connection of rotary encoder are displayed.

Table 3.Specification of PKP series encoder (upper), circuit of encoder itself (lower left) and connection of electrical circuit (lower right)

Item	Discription
Encoder type	R2FL
Resolution(p/r)	400 p/r
Output signals	A-phase; B-phase; C-phase; 3- channel
Power supply voltage	5VDC±10%
Current consumption	30 mA or less



As detail in Table 3, the encoder is line driver output one. The conclusions can be produced as output circuit and connection parts. Put it into details. The former is mainly about the way how encoder output signal and the accuracy of the encoder. Based on the resolution of 400 p/r (p: pulse and r: round), the pulse output can be converted into 0.9° per pulse (360°/ 400p), matching with the angle of per step for stepper motor tuning. The latter is mainly about the way encoder should be connected with Arduino Mega 2560R3. In principle, since the output is pulse, it is obviously all the three pins should be connected with PWM I/O ports in Arduino Mega 2560 R3. Otherwise, voltage and current of Mega is suitable to support the encoder.

4.3.3.3.4 Relay connection

The relay will act to stop the RF generator when an issue is detected. The good wiring of this one is really important. The information about the pin function of the RF generator can be found in the document: CV2000 S60 FP33647R1 .

Of we want to enable the RF output the Pin 4 and 9 need to be connected, so if we want to stop the RF signal we need to disconnect these both Pins. The schematic hereafter show how to wire the relay.

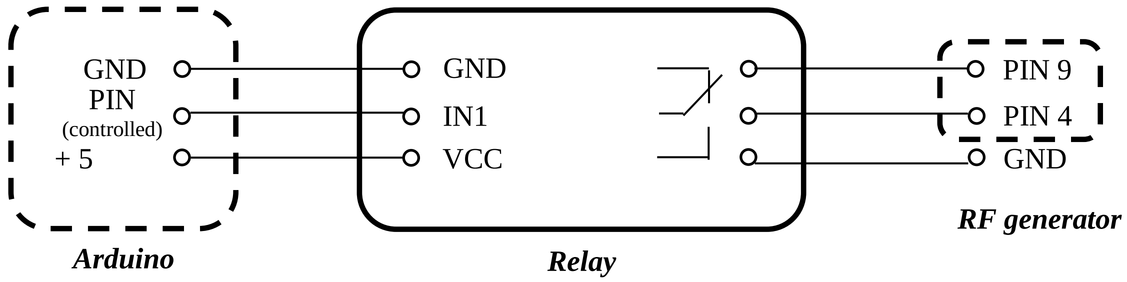


Figure 60.Connection of Arduino Mega2560R3 and RF generator

4.3.4 Digital control design

In this section, digital control design is related to Arduino technology. The Mega 2560 board can be programmed with the Arduino Software IDE (Integrated Development Environment).

The ATmega2560 on the Mega 2560 is pre-programmed with a bootloader that allows author to upload new code to it without the use of an external hardware programmer.

The bootloader can also bypass and the microcontroller is able to be programmed through the ICSP (In-Circuit Serial Programming) header using Arduino ISP (in-system programmer).

The Mega 2560 is a microcontroller board based on the ATmega2560 [41]. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started.

In this project, digital control design aiming at controlling servo motors and stepper motors separately. To meet the needs of independent function, the codes were suggested to be reasonable designed.

Admittedly, Arduino mega is designed based on one loop structure. One digital loop cannot realize various functions in the same time. Several microseconds gap between each application do exist in different application. Basically, the main three functions are based on three phases. In digital control module, author is mainly to solve the output port. To be more specific, the environmental factors of all the codes made by author have not been defined. In some ways, hundreds of hours have it likelihood to be addressed at getting the input port as reflect power, environment temperature. Briefly, it appears that the digital control codes made by author are not to meet the final destination.

However, codes made by author were mainly for function test. To ensure the whole system stable and usable, the applicability test should be carried out. Otherwise, the codes made to drive the system can also be used to operate the system in the future.

4.3.4.1 Language of Arduino

The language of Arduino is mainly based on the foundation of C/C++, attaching the functions of specific parameters. Briefly, it can be easily programmed to realize specific foundation. Various of language references can be concluded into three section as structure, variables and functions. Hereafter the chart exhibits the structure of the language.

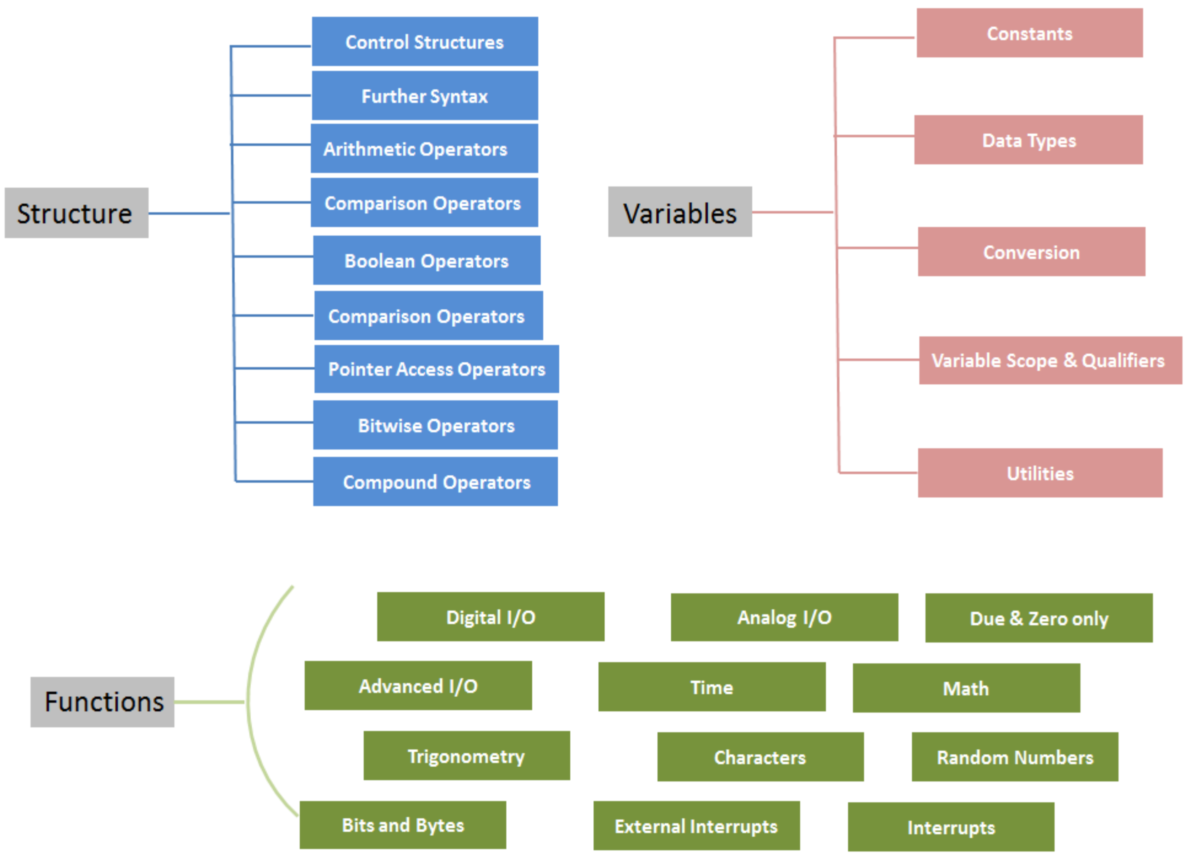


Figure 61.The structure of three sections for making codes

In this project, the mainly codes are located in functions, especially in Analog I/O. Since the key structure in this design is based on the control of motors.

4.3.4.2 Arduino Integrated development environment

The Arduino Integrated Development Environment (IDE) contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino and Genuino hardware to upload programs and communicate with them.

Programs were written in the text editor and saved with the file extension information. The editor has features for cutting/pasting and for searching/replacing text. The message area gives feedback while saving and exporting and also displays errors. The toolbar buttons allow you to verify and upload programs, create, open, and save sketches, and open the serial monitor. Otherwise, the five menus: File, Edit, Sketch, Tools, Help are context sensitive, which means only those items relevant to the work currently being carried out are available. Hereafter the user interface is displayed.

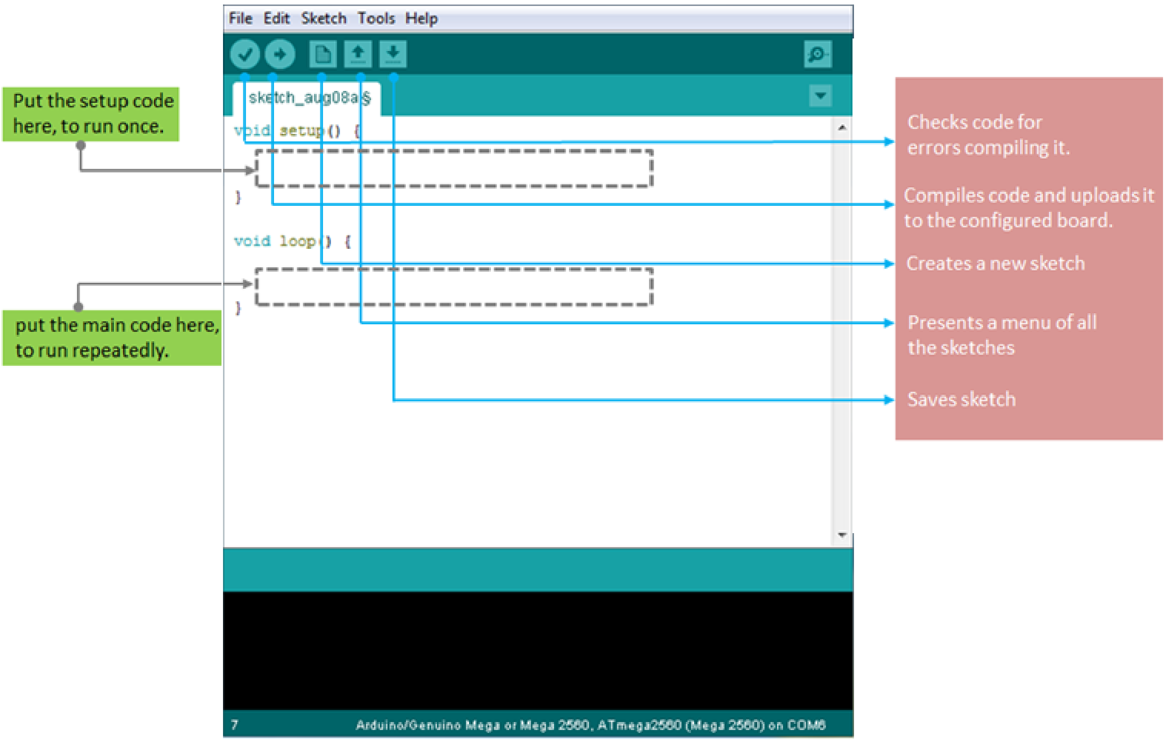


Figure 62.User interface of Arduino IDE

4.3.4.3 Stepper motor

In this design, the main purpose of tuning stepper motor is importantly to drive the capacitors in 1° per step. Otherwise, each time the stepper motors restart, the angle should be recalculated from the start position, which means the start position should be programmed as the Zero degree. In previous information, the minimum step of stepper motor is 0.9°, meeting the needs of turning capacitor into smallest unit. To reach this point, the codes are carefully designed as follows.

```
#include <Stepper.h>

const int stepsPerRevolution = 400;

Stepper myStepper(stepsPerRevolution, 2, 3, 4, 5);

int stepCount = 0;

void setup() {

  Serial.begin(9600);
}

void loop() {

  myStepper.step(1);
  Serial.print("steps:");
  Serial.println(stepCount);
  stepCount++;
  delay(10);
}
```

Figure 63.Stepper motor control codes

As illustrated by Figure 63, those digital design functions can be gotten as follows:

- Motor resolution: 0.9° (Based on the formula below, the steps Per Revolution =400)

Formula:

$$\frac{\frac{360\ Degree}{1\ Revolution}}{0.9\ \frac{Degree}{Step}} = 400\ \frac{Step}{Revolution}$$

- PWM port: pin: 2,3,4,5
- Initial position: 0 (step count=0)

  Each time the start position of stepper motor is counted as the 0° position.

- Bit rate: 9600 bit/s (Serial. begin (9600))

Theoretically, each byte has 8 bits. Put the byte unit into account, the quantity of data can be transferred in one second is about 1.2KB.

- Dwell time: 0.01s (delay(10))

4.4 Concluding Remarks Application of Design

In summary, to realize the function of this novel system, plenty of works have been address on mechanical design, circuit design and digital control design part. As details can be check above, in this section. The mainly functions to be achieved are listed in ignition phase, regular operation and critical circumstance part. Hereafter the three main sections are displayed.

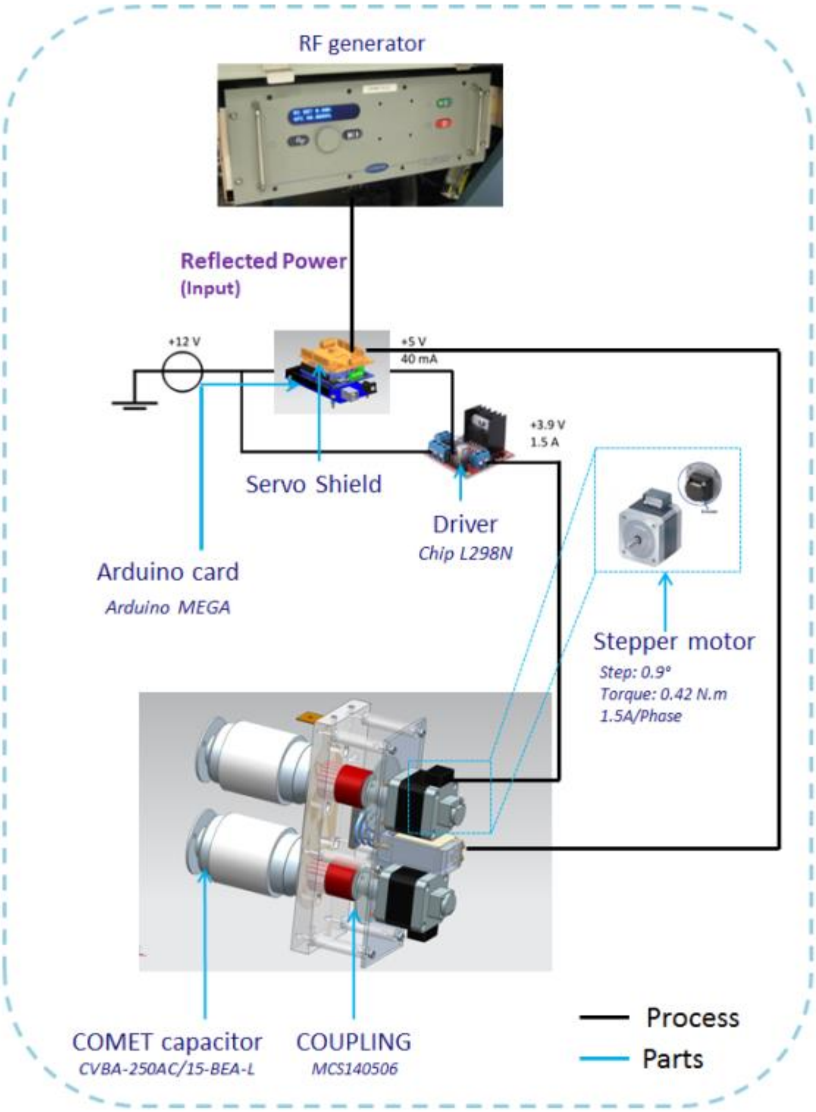


Figure 64.Ignition phase working principle draft.

4.4.1 Control structure of ignition phase

In ignition phase, the solution chosen aims to tune the RF network quickly through two stepper motor (one per capacitor) activated by Arduino Mega. Moreover, in order to secure the capacitance position during the processing, brake system is added between each motor and capacitor. This normally closed brake is activated by a servomotor controlled by the Arduino Mega running the stepper motor.

4.4.2 Control structure of regular operation

To address monitory function in regular operation, completing and arranging science issue in the work "Energy dissipation assessment", RTD sensors are needed to be install in the torch. The application of Arduino technology (Arduino Mega) can be effective to evaluate the data via a special shield stacked on the Arduino Mega. Hereafter the sketch shows the working principle of the solution chosen.

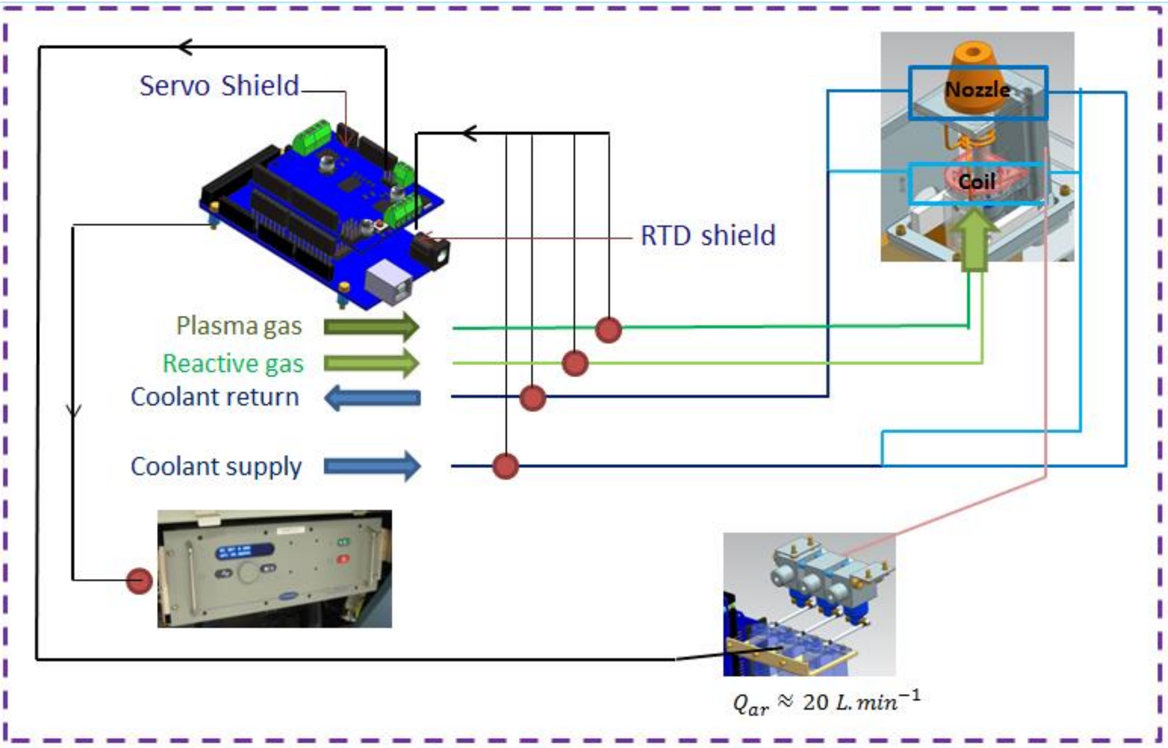


Figure 65.Regular operation working principle sketch

4.4.3 Control structure of critical circumstance

In critical circumstance, mainly work were addressed on the machinery section as support plate modification and cooling gas structure. But the final destination for this part is enable the RF generator power to switch off, based on the input of Arduino Mega card.

During the processing, to prevent mismatching and overloading forward power, Arduino technology is better to have protection function to the RF generator. What's more, the whole system should be better to be protected from high temperature situation, The draft hereafter shows the conception to protect the Helios 1200.

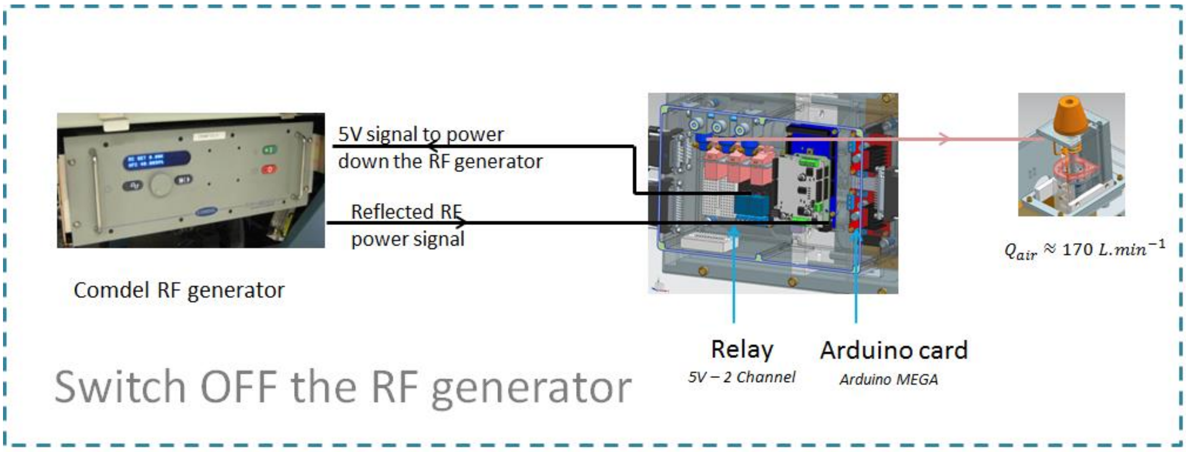


Figure 66.Critical circumstance working principle sketch

Chapter 5

Discussion

After further study and EPSRC conference, a more general discussion of application manner and three module designs as machinery, circuit design and digital control design. Apart from discussing validity of the concept design, the discussion about the status of the novel design was reassessed. Otherwise, the detail works have been put into this chapter.

5.1 Application of impedance tuning

In previous, the first version of concept design is raised by Vincent. In this concept version, matching network acts as a tuning way for the whole electrical circuit system. Based on the instantaneous tuning structure should be the main design structure. The concept design can be classic, especially choosing L-type matching network design structure.

To put the design idea into this project, Dr Jourdain pointed out the RF generator function should be more carefully studied, to prove the impedance tuning should fit the function of forward power feeding source. From Dr Jourdain's experience and knowledge of plasma figuring, the fixed match structure in Helios1200 was more successfully located. In section 2.7, functions of fixed match and matching network were expounded.

Briefly, matching network works for tuning the impedance of the loads (plasma chamber, load capacitor, and tune capacitor). This system aims to maintain the plasma in stable condition. The PDS of Helios1200 does not use a matching network.

Fixed match works for fixing the type of load driven so that there is only one resonant frequency. By tuning the forward power, the received power of plasma torch can be in stable. Admittedly, because of the characteristics of fixed match, the tuning of forward power is located in a narrow range.

Both these two electrical circuit have their pros and cons. Detail information can be searched in section 2.5-2.6. To combine the pros of two design idea, it is considerable to shift the impedance tuning function into fixed match. Noticeably, since the fixed match is provided with forward power tuning characteristic, the concept design of the whole system should be shifted into a stagnancy structure, tuning the impedance in specific time. The shift of the concept breeds the whole design structure in this project.

5.2 Linkage of opening structure in brake system

In this section, the opening structure in brake system is mainly discussed. This structure is located between Savox-1283SG servo motor and opening pin. In previous, two various structure of opening linkage were designed by author, both of two initial design structures are trapped in instability and weak structure. Hereafter the initial opening structure is displayed.

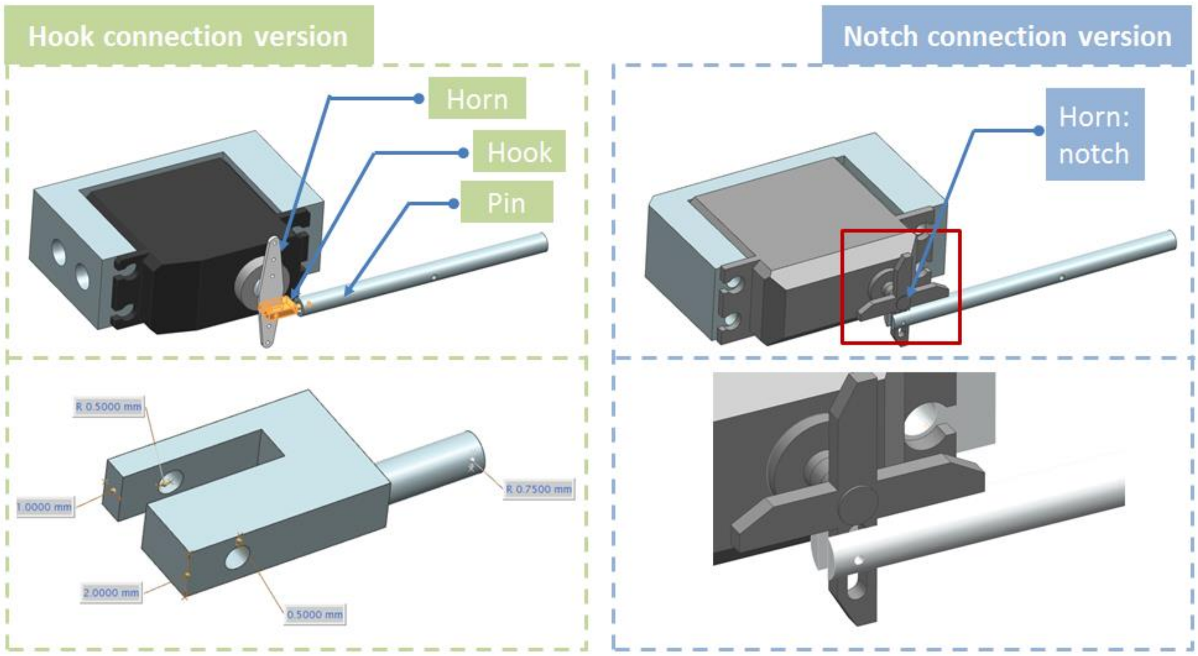


Figure 67.Two initial designs. Hook connection structure (left) and notch connection version (right)

Start with the hook version, the design in the left of Figure66. In principle, a sliding hook and a tuning pin with interior angle consist the tuning physical structure. While the servo motor push the hook fixed with the horn on the servo by a pin, the root of the hook can be immediately shift by the chamfer inside of the pin.

Generally, the first version of the design structure has its pros and cons. The smart movement can be its advantage, to be more specific, the horn structure is able to transfer the thrust as soon as the horn moves, but according to the FIGURE66, the thickness of the hook might be a potential risk to bear the force from high torque servo motor, otherwise, machining a hook like such a small dimension brings burdens to technicians.

Moving on to the second design, a notch feature was designed to be added into the horn, leading the connecting part to move along the radial direction of the notch. As the connection between horn and holder is a flexible structure, the holder can achieve linear motion. However, this structure struggled in structural strength. The notch even decreases the thickness of horn, which leads to the structural strength of the horn.

To reach an appropriate design, the linkage of the servo horn and opening system should be more carefully designed, mainly in structure and strength aspects. As Dr Jourdain recommended, free structure design should be suitably applied in this structure. Facing the high torque servo motor should be smoothly to open the structure, the bearing force of the horn can nearly reach up to 250N as the calculation in section 4.3.2. Therefore, it is considerable to design that structure in simple but useful way. Hereafter the linkage structure is displayed.

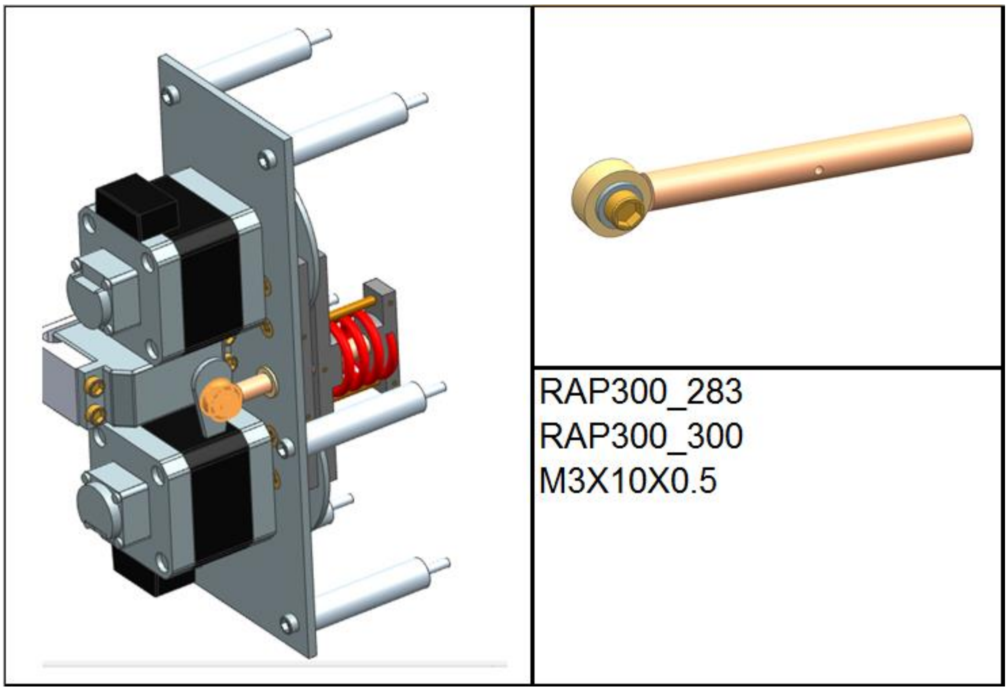


Figure 68.Flexible design of linkage

Briefly, the linkage was adopted a free style design structure. To be more specific, the bush acts as a wheel in this structure, during the rotary of horn. With the torque from servomotor, the bush is able to be driven by the wheel mildly as it has self-rotation. Meanwhile, the wheel is connected to the horn tightly by M3 screw, isolated by a rank spacer between bush and screw.

5.3 Electrical equivalent circuit measure method

In this section, the work is mainly focused on the troubleshooting issue, during the assembly of electrical devices stage. To test the applicability of whole system, it is necessary to drive each function in this system. With the drive of Arduino Mega 2560 R3, the gas control servo motors, opening brake system valves and stepper motors were tested separately.

Unexpectedly, during stepper motor test module, one of the two stepper motors was not able to rotate. However, the vibration of stagnant stepper motor proves the input signal can be received by the stepper motor. Theoretically, there may 4 common incentives as follow:

- Errors in wires: There may be some damages in wires connected with stepper motor and driver; otherwise, these possibilities exist in the wires connected with stepper motor driver and Arduino Mega board.

- Stepper motor in offline stage or broken situation: It is possible for stepper motor missing the PWM input or having rotary problem.
- Errors in drive: The error also has its likelihood in driver. The damage of driver may lead to the block of PWM output.
- Overload: Overload may also cause the pause of the stepper motor. Since the current cannot be enough to support the rotation of stepper motor.

Basically, in this section, the fourth possibility cannot exist. Because the circuit parameters are chosen in perfect fit and tested separately. So searching the error mainly should be focused on the wires, stepper motors and drive. To expose the error, the electrical equivalent circuit measure method was adopted to be used in the test. To be more specific, since the other electrical circuit can support the rotation of the identical stepper motor relatively with the programmed codes, it can be perfect for equivalent replacement of electrical devices. The conclusion as follows:

- ✓ Exchange of the stepper motor. Proved stepper motors are good
- ✓ Exchange of input wires. Proved input wires and pins are good
- ✓ Exchange of output wires. Proved output wires and pins are good
- o Exchange of drivers. Proved broken

At the end, the damaged driver was replaced. After test of renewed driver, the stepper motors were proved useful.

Chapter 6

Results

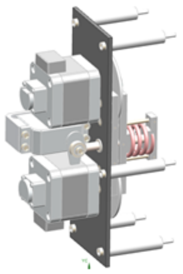
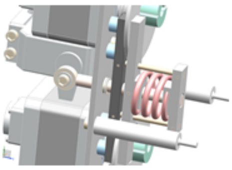
In chapter 6, universal arrangements and procedures were described briefly. Generally, each achievement in various stages was exhibited with detail information. Through the machinery design, electrical circuit design and digital control design, the main functional test has been completed as well. However, during the experiment, error did occur in mechanical structure and electrical devices, because of several problems for parts. One instance can be found in chapter 5 as well. At the end of this chapter, the experimental functional tests were displayed, supporting the realization of the function in this design.

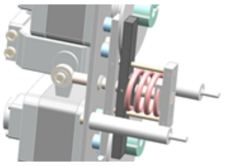
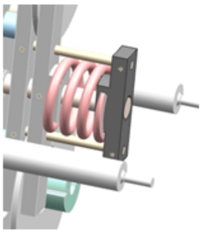
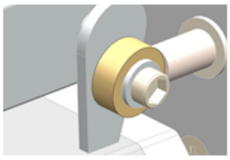
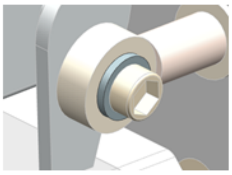
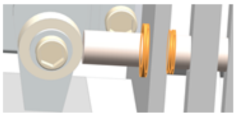
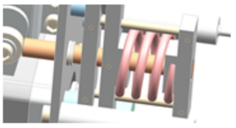
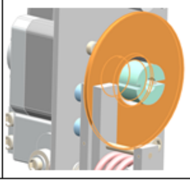
6.1 Machinery design

In this novel plasma delivery system design, the detail design structure of three main components as brake system, enclosure of electrical devices and cool gas feeding structure was displayed. Combining with the PDS in Helios1200, each part were designed to fit the real structure in the machine. Hereafter the design results of each part were display.

6.1.1 Brake system structure

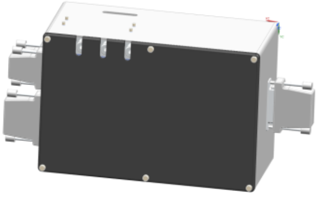
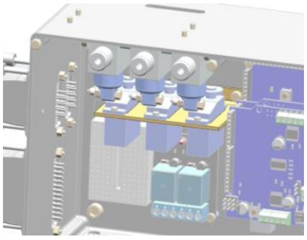
Table 4.Engineer drawings of brake system

Name / Model & Parameter / Ite	Part No.	Part Model	Part material	Component No.	Function
Support plate	RAP300_289		Aluminium 6061-T651	RAP_ASS_300_021 (brake system)	A.Support stepper motors and servo motor. B. Work as the base of brake pads
Fixed brake pad	RAP300_301		Aluminium 6061-T651	RAP_ASS_300_021 (brake system)	A.Hold the disces B.The base of brake pads

Flexible brake pad	RAP300_302		Aluminium 6061-T651	RAP_ASS_300_021 (brake system)	*A*.Hold the disces *B*.Thrust the spring *C*. Limit the movement of spring
Bottom brake pad	RAP300_308		Aluminium 6061-T651	RAP_ASS_300_021 (brake system)	*A*.Support and limit spring. *B*.Work as the base of brake structure
Wheel	RAP300_283		Brass	RAP_ASS_300_021 (brake system)	*A*. Flexible linkage to thrust brake system
Bush	RAP300_300		Aluminium	RAP_ASS_300_021 (brake system)	*A*. Protect fix screws *B*. Act as the drive axis for wheel
Bush	RAP300_306		Copper	RAP_ASS_300_021 (brake system)	*A*. Keep the pin in horizontal
Stick	RAP300_303		Aluminium	RAP_ASS_300_021 (brake system)	*A*. Drive the flexible brake pad
Coupling	RAP300_309		PEEK	RAP_ASS_300_021 (brake system)	*A*. connect the rudders of stepper motors and capacitors
Discs	RAP300_294		Aluminium 6061-T651	RAP_ASS_300_021 (brake system)	*A*. Work as a linkage between coupling and brake pads

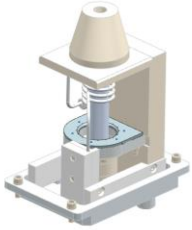
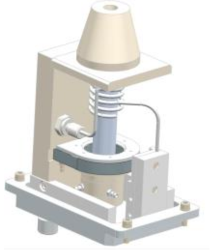
6.1.2 Machinery parts in control system

Table 5.Engineer drawings of brake system

Name	Part No.	Part Model	Part material	Component No.	Function
Cover	RAP_xx_ 300_011		Purchased part (Aluminium)	RAP_ASS _ 300_020	Machining for gas pipe input
Cooling gas support	RAP_300_ 299		Aluminium	RAP_ASS _ 300_020	Support servo motors
Shell	RAP_xx_ 300_301		Purchased part (Aluminium)	RAP_ASS _ 300_020	*A.* Machining for cables and wires *B.* Drilling and Taping for fixing electrical devices

6.1.3 Machinery parts in torch

Table 6.Engineer drawings of brake system

Name	Part No.	Part Model	Part material	Component No.	Function
Cover of gas feed structure	RAP_300_317		Aluminium 6061-T651	RAP_ASS_300_015	*A.* Locate the cool gas feeding position. *B.* Output cooling gas
Backplane of gas feed structure	RAP_300_167		Aluminium 6061-T651	RAP_ASS_300_015	*A.* Input cool gas and contain cool gas
Nozzle support plate	RAP_300_169		Aluminium 6061-T651	RAP_ASS_300_015	Machining for being avoided.

6.2 Digital control structure

In this section, main works are based on Arduino technology. To fit the control of the working system, electrical devices were chosen parametrically to fit the microcontroller board with the suggestions of Vincent and Dr Jourdain.

The construction of control system is designed under one loop structure. Under one loop mechanism, control concepts were made by author. Admittedly, one digital loop cannot realize various functions in the same time. Several microseconds gap between each application do exist in different application. However, the characteristic of microcontroller technology make it possible to realize all the function in timing structure. Hereafter the control conception loop is displayed.

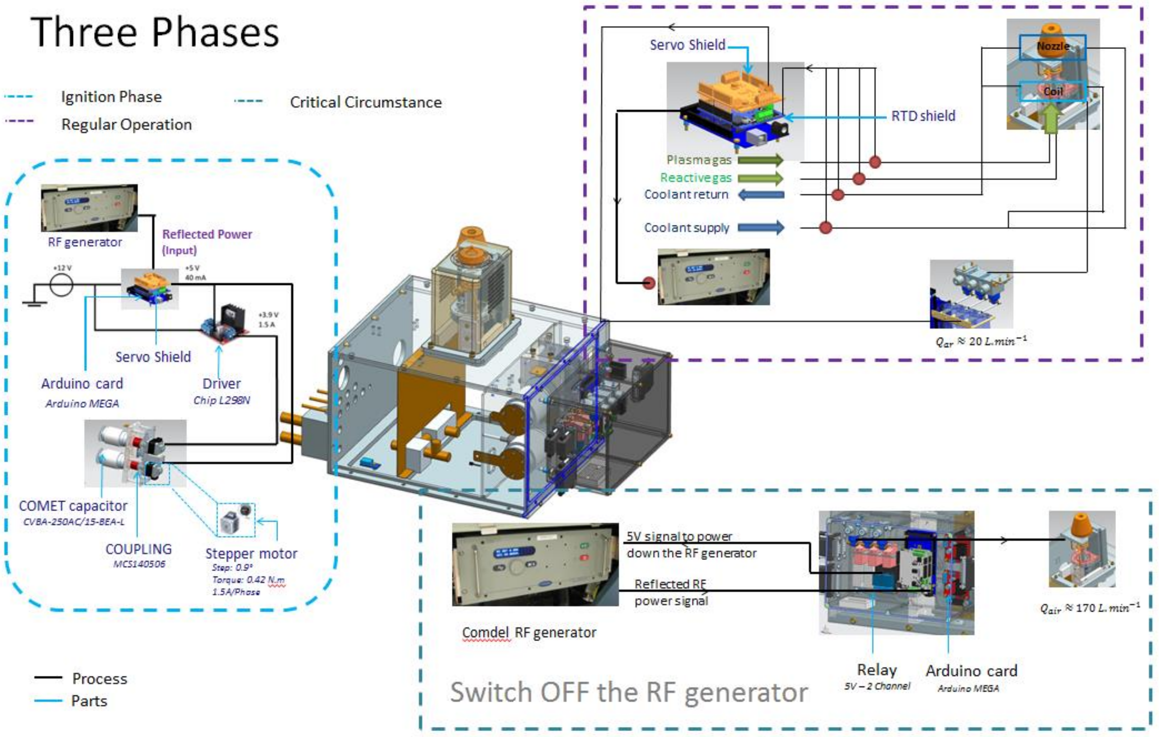


Figure 69.Flow charts for three phases

As shown in Figure 69, the main three functions of three phases can be realized sequentially. In digital control module, Author is mainly to solve the output port. To be more specific, the environmental factors as reflect power, environment temperature should be addressed in the codes. In some ways, hundreds of hours have it likelihood to be addressed at getting the input port. Here below the electrical circuit connection is displayed.

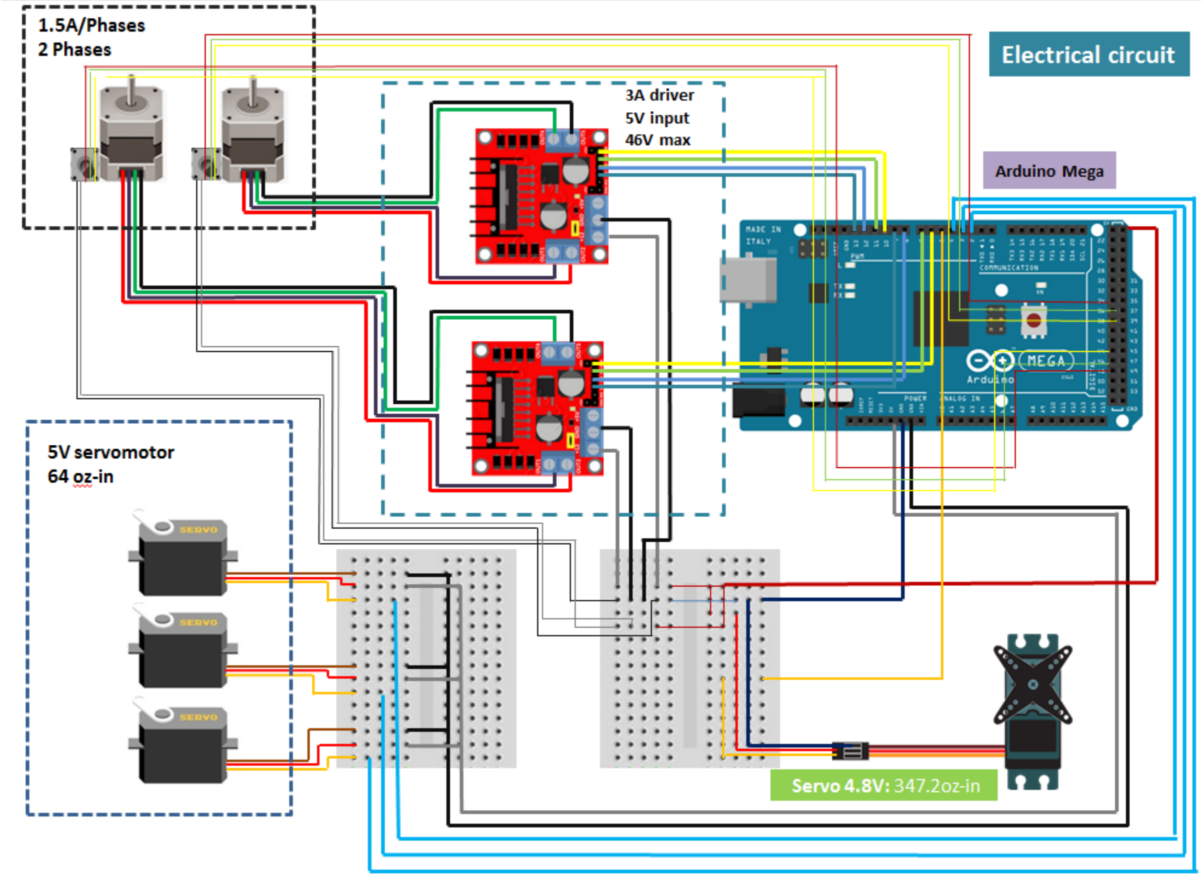


Figure 70.Electrical circuit for motor control function

6.3 Application of functional test

In this section, three main functions to realize the structure were tested separately as brake system control, capacitance tuning control and gas feeding control. As impedance tuning has its dominant position in this novel design, the brake system control and capacitance tuning control has priority in the functional test.

6.3.1 Brake system control

The control of brake system is mainly achieved by Savox SA-1283SG, a high torque servo motor acting as an open key to unlock the stepper motor. The Savox SA-1283SG got the input signal given by Arduino Mega card, during capacitive reactance tuning period. The servo motor drive circuit should be individually plotted to drive the brake system. After connection of the electrical circuit, the servo motor can perfectly drive the brake system in specific period. Hereafter the real component of brake system is displayed.

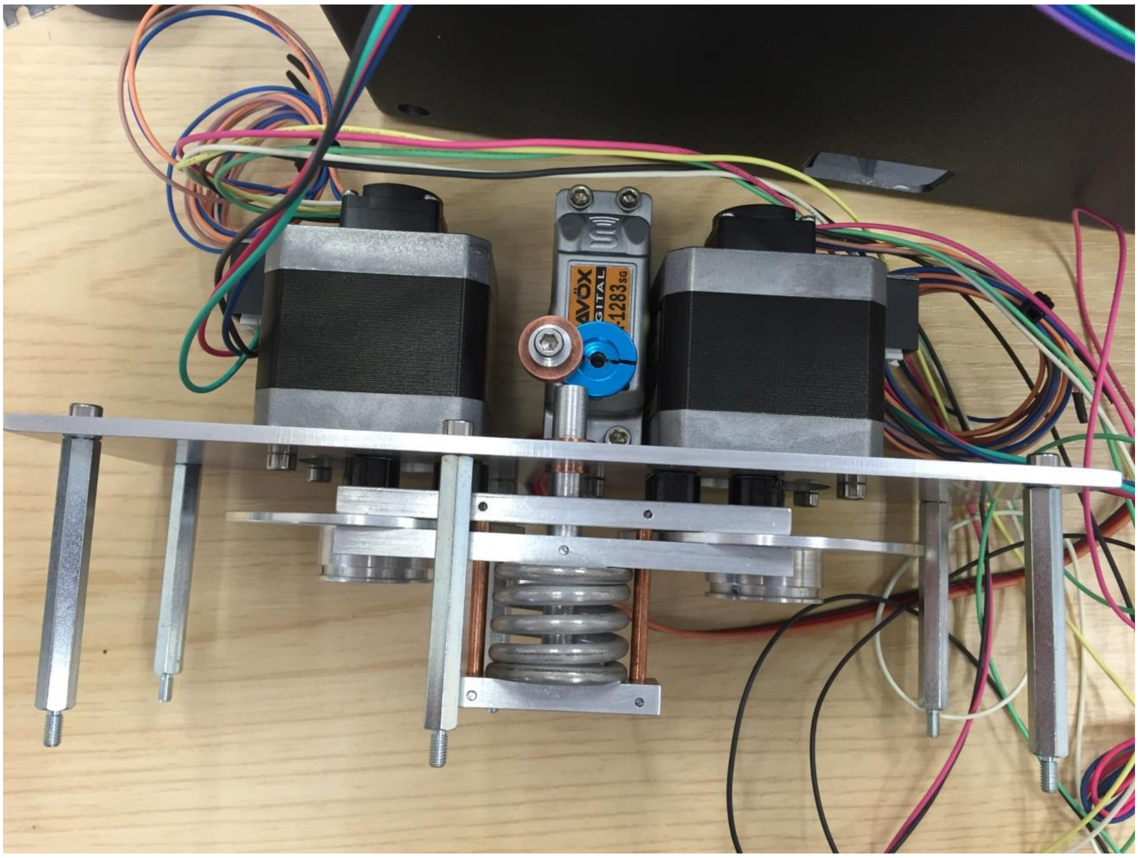


Figure 71.Brake system opening brake pads

6.3.2 Capacitance tuning control

In this design, the main purpose of tuning stepper motor is importantly to drive the capacitors in 1° per step. Otherwise, each time the stepper motors restart, the angle should be recalculated from the start position, which means the start position should be programmed as the Zero degree. In previous information, the minimum step of stepper motor is 0.9°, meeting the needs of turning capacitor into smallest unit. Driving by the codes displayed in chapter

4, the stepper motor realized the minimum tuning. Here below the result of tuning is displayed.

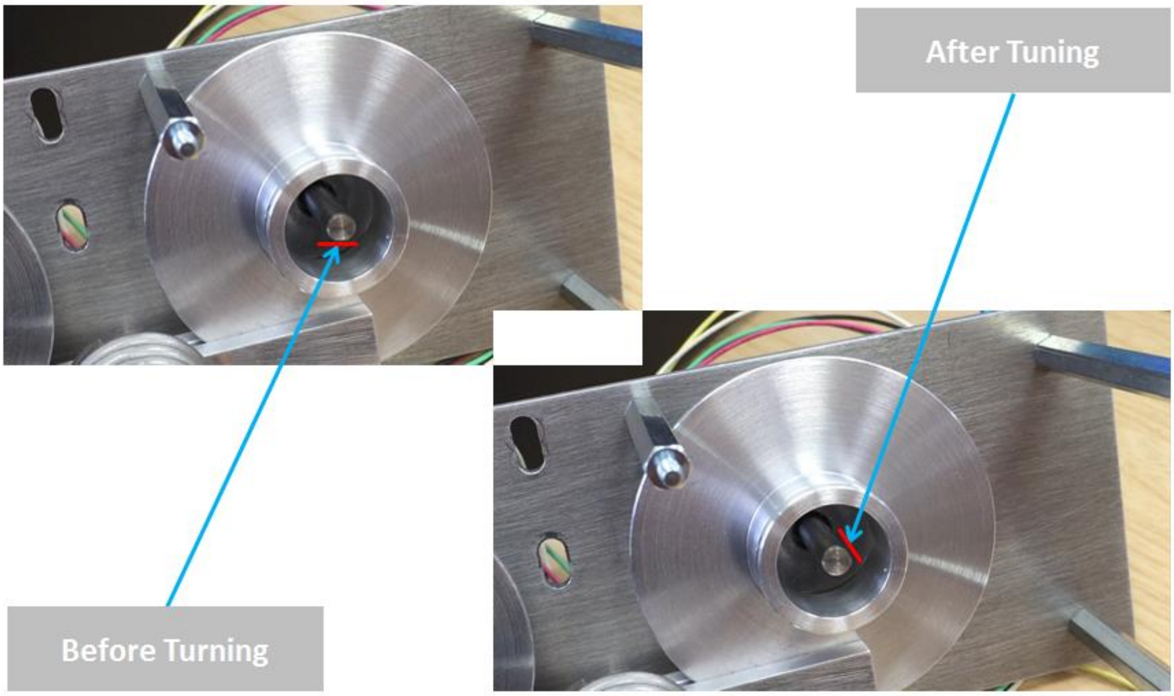


Figure 72.Capacitors driving system

Chapter 7

Conclusion and Future work

In this chapter, the process of this project at the present stage was summarized into conclusion and future work. Conclusion is mainly based on the achievements of the work has been done; Future work is connected with the details and the tasks to make the project into a new product as novel plasma delivery system.

7.1 Conclusion

Based on the design, assembly and function test, the assembly achieved the main function. Generally, the applicability of all the work has been achieved is proved.

To start with the motorized RF network design, enhancing the automation and stability of the PDS for Helios1200 is the main issue. To shift the careful designed fixed match circuit existing in Helios1200 into a motorized RF network design, the tuning impedance structure and fixed turning position structure have its dominant position in the design. With the help of Dr Jourdain and Vincent, the final version of those two structures can be decided. Otherwise, the adjustment structure is designed for preventing the damages of plasma torch.

Moving on to the assembly, the work is addressed on assembling and connecting the machinery structure and electrical devices, including mechanism dimension detection and circuit detection. After assembly and detection, the structure can be suitable to be applied for function test.

For function test, three main functions to realize the structure were tested separately as brake system control, capacitance tuning control and gas feeding control. As impedance tuning has its dominant position in this novel design, the brake system control and capacitance tuning control has priority in the functional test. Admittedly connecting the novel plasma delivery system with Helios1200 still has its likelihood to spend hundreds of hours on programming and testing. However, the function test proves the physical structure and electrical circuit can match the tuning function.

7.2 Further work

As mentioned in previous in this chapter, Future work is connected with the details and the tasks to make the project into a new product as novel plasma delivery system. Two main parts as physical parts and control system structure were displayed as follows:

7.2.1 Machining parts and electrical devices

In this design, two physical elements have their likelihoods to be enhanced. Firstly, it is about the tuning horn. Although the structure in our design has its advantage, it still has vibration in radial direction as the assembly error. It is better to be replaced by miniature bearing. Hereafter the illustrations of two structures are displayed.

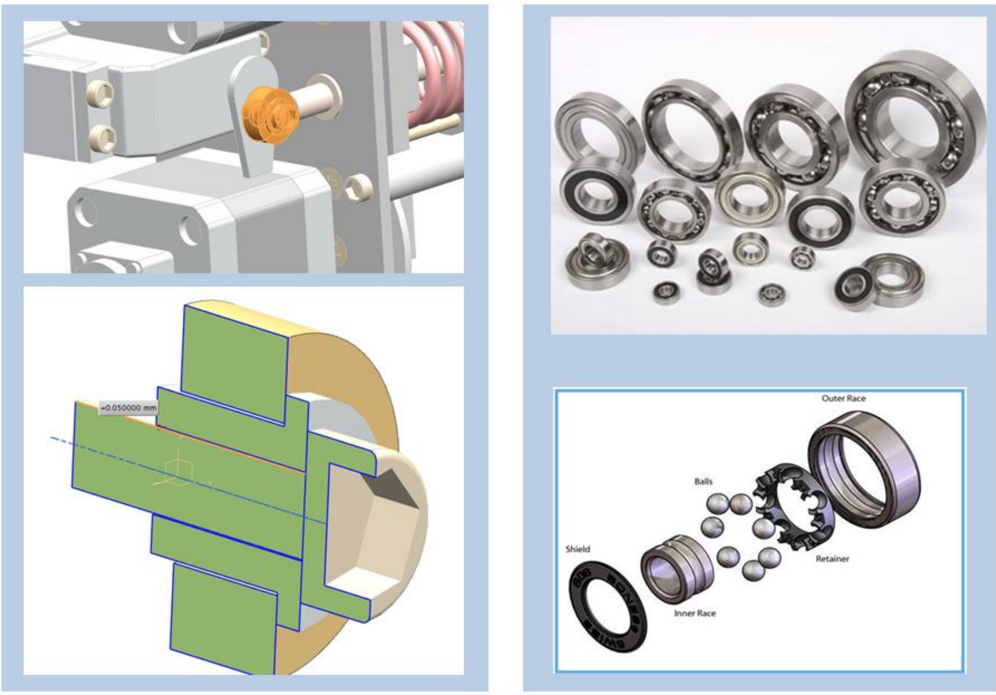


Figure 73. Designed wheel in our brake system (left) and the miniature bearings (right)

7.2.2 Control system structure

- Gathering the data from rotary encoder, realize the stepper motor and encoder working in sequence in time.

- Based on priority in Arduino language, programme to realize stepper motor and servo motor in timing.
- Gathering the reflect power signal to realize the input signal for Arduino Mega.
- Turn the in timing Arduino language, combining the input signal from Arduino.
- Connect the novel system to Helios1200 to test the coupling of plasma.

Reference

1. Rees, P. C., & Gray, C. (2015, August). Metrology requirements for the serial production of ELT primary mirror segments. In *SPIE Optical Engineering+ Applications* (pp. 957508-957508). International Society for Optics and Photonics.

2. Jourdain, R., Castelli, M., Shore, P., Sommer, P., & Proscia, D. (2013). Reactive atom plasma (RAP) figuring machine for meter class optical surfaces. *Production Engineering*, *7*(6), 665-673.

3. http://www.comdel.com/optional-frequency-agile-tuning

4. http://www.comdel.com/high-frequency-rf-power-supplies

5. Wang, N., Klein, N., Shenk, R. R., Fitzmaurice, M., Woletz, J., Hicks, D., ... & Gardecki, J. A. (2005). Raman spectroscopy. In *Optical Society of America*. 6. Jarvis, K. E., Gray, A. L., & Houk, R. S. (1991). *Handbook of inductively coupled plasma mass spectrometry*. Blackie; Chapman and Hall.

6. Otsuki, T., & Shiobara, H. (2006). 5-axis machining features FANUC series 30i-model A/31i-model A5. *Fanuc Tech Rev*, *19*, 1-6.

7. Jourdain, R., Castelli, M., Shore, P., Sommer, P., & Proscia, D. (2013). Reactive atom plasma (RAP) figuring machine for meter class optical surfaces. *Production Engineering*, *7*(6), 665-673.

8. Gersheneld, N., Zimmerman, T., & Allport, D. (1999). *U.S. Patent No. 5,914,701*. Washington, DC: U.S. Patent and Trademark Office.

9. Fanara, C., Shore, P., Nicholls, J. R., Lyford, N., Kelley, J., Carr, J., & Sommer, P. (2006). A new reactive atom plasma technology (RAPT) for precision machining: the etching of ULE® surfaces. *Advanced Engineering Materials*, *8*(10), 933-939.

10. Jourdain, R., Castelli, M., Shore, P., Sommer, P., & Proscia, D. (2013). Reactive atom plasma (RAP) figuring machine for meter class optical surfaces. *Production Engineering*, *7*(6), 665-673.

11. Leach, R. R., Beltsar, I., Burkhart, S., Lowe-Webb, R., Miller-Kamm, V., Salmon, T., & Wilhelmsen, K. (2015, February). Near field intensity trends of main laser alignment images in the National Ignition Facility (NIF). In *SPIE LASE* (pp. 93450D-93450D). International Society for Optics and Photonics.

12. Campbell, J. H., Suratwala, T. I., Thorsness, C. B., Hayden, J. S., Thorne, A. J., Cimino, J. M., ... & Ficini-Dorn, G. F. (2000). Continuous melting of phosphate laser glasses. *Journal of Non-crystalline solids*, *263*, 342-357.

13. Moses, E. I., Campbell, J. H., Stolz, C. J., & Wuest, C. R. (2003, June). The national ignition facility: The world's largest optics and laser system. In*High-Power Lasers and Applications* (pp. 1-15). International Society for Optics and Photonics.

14. Hermans, J. V., Laidler, D., Pigneret, C., Van Dijk, A., Voznyi, O., Dusa, M., & Hendrickx, E. (2011, March). Overlay progress in EUV lithography towards adoption for manufacturing. In *SPIE Advanced Lithography* (pp. 79691M-79691M). International Society for Optics and Photonics.

15. Lowisch, M., Kuerz, P., Conradi, O., Wittich, G., Seitz, W., & Kaiser, W. (2013, April). Optics for ASML's NXE: 3300B platform. In *SPIE advanced lithography* (pp. 86791H-86791H). International Society for Optics and Photonics.

16. Chabert, P., & Braithwaite, N. (2011). *Physics of radio-frequency plasmas*. Cambridge University Press.

17. Shunko, E. V., Stevenson, D. E., & Belkin, V. S. (2014). Inductively Coupling Plasma Reactor With Plasma Electron Energy Controllable in the Range From to. *IEEE Transactions on Plasma Science*, *42*(3), 774-785.

18. Flamm, D. L., & Auciello, O. (2012). *Plasma deposition, treatment, and etching of polymers: the treatment and etching of polymers*. R. d'Agostino (Ed.). Elsevier.

19. Stecker, M. S. (2007). Root cause analysis. *Journal of Vascular and Interventional Radiology*, *18*(1), 5-8.

20. Yu, N., Jourdain, R., Gourma, M., & Shore, P. (2016). Analysis of De-Laval nozzle designs employed for plasma figuring of surfaces. *The International Journal of Advanced Manufacturing Technology*, 1-11.

21. Zemke, A. C. (2007). *Role for the TGF-beta/BMP and Beta-catenin Signaling Pathways in Lung Development and Repair*. ProQuest.

22. Zemke, A. C. (2007). *Role for the TGF-beta/BMP and Beta-catenin Signaling Pathways in Lung Development and Repair*. ProQuest.

23. Sinha, R., & De, A. Theory on Matching Network in Viewpoint of Transmission Phase Shift.

24. Matthaei, G. L., Young, L., & Jones, E. M. T. (1980). *Microwave filters, impedance-matching networks, and coupling structures*. Artech house.

25. *Electronic Applications of the Smith Chart: In Waveguide, Circuit, and Component Analysis*

26. Smith, P. H. (1969). Electronic Applications of the Smith Chart in Waveguide. *Circuit, and Component Analysis, Me Graw-Hill Book, New York*.

27. Smith, P. H. (1969). Electronic Applications of the Smith Chart in Waveguide. *Circuit, and Component Analysis, Me Graw-Hill Book, New York*.

28. CV2000/40.68MHz RF generator

29. Yu, N., Jourdain, R., Gourma, M., & Shore, P. (2016). Analysis of De-Laval nozzle designs employed for plasma figuring of surfaces. *The International Journal of Advanced Manufacturing Technology*, 1-11.

30. Serantoni V, Jourdain R, Yu N, Shore P, Morantz P 2015 *Internal document*

31. Julisch, K. (2003). Clustering intrusion detection alarms to support root cause analysis. *ACM transactions on information and system security (TISSEC)*, *6*(4), 443-471.

32. Yu, N., Jourdain, R., Gourma, M., & Shore, P. Investigation of power dissipation in a collimated energy beam.

33. https://www.arduino.cc/en/Main/ArduinoBoardMega2560

34. Al-Abidi, A. A., Mat, S. B., Sopian, K., Sulaiman, M. Y., & Mohammed, A. T. (2013). CFD applications for latent heat thermal energy storage: a review.*Renewable and sustainable energy reviews*, *20*, 353-363.

35. Hui Zhou, Renaud Jourdain, Vincent Serantoni, Jose L. Endrino, Paul Shore, Paul Morantz Creation of a control system for plasma delivery EUSPEN (2016)

36. Tyler, D. J., & Durand, D. M. (1997). *U.S. Patent No. 5,634,462*. Washington, DC: U.S. Patent and Trademark Office.

37. http://www.engineeringtoolbox.com/friction-coefficients-d_778.html

38. Young, W. C., & Budynas, R. G. (2002). *Roark's formulas for stress and strain* (Vol. 7). New York: McGraw-Hill.

39. Neruda, M., Vojtech, L., Rohlik, M., Hajek, J., Holý, R., & Kalika, M. (2015, October). Application of shielding textile materials in electric vehicles. In*Wireless and Optical Communication Conference (WOCC), 2015 24th* (pp. 113-117). IEEE.

40. CV2000 S60 FP33647R1

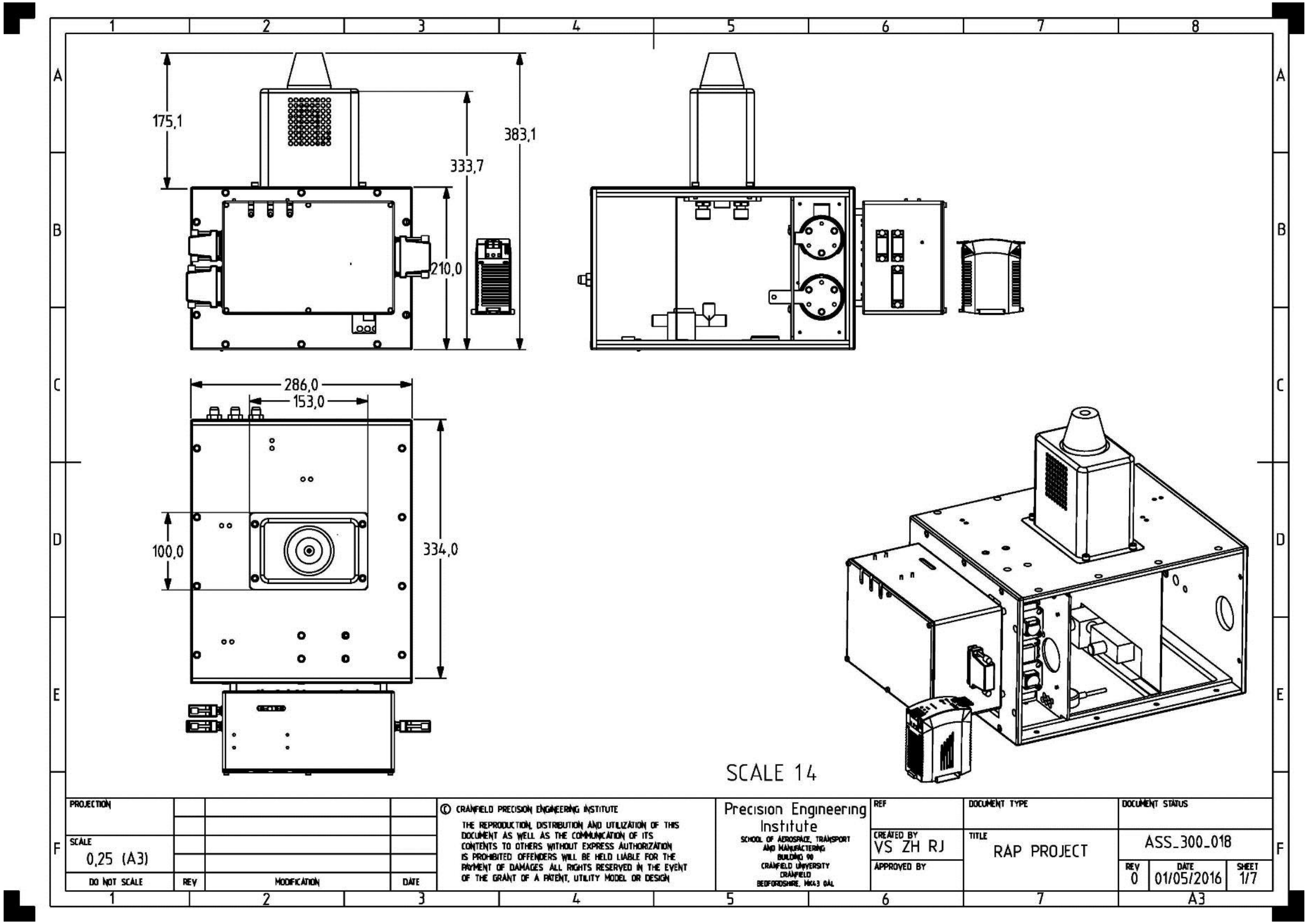
41. Atmel ATmega640/V-1280/V-1281/V-2560/V-2561/V

APPENDICES

Appendices are mainly consisted of engineer drawings for enriching the details of the design and function.

Engineer drawings

Engineer drawings consisting of assembly drawing, component drawing and part drawing were displayed as follows: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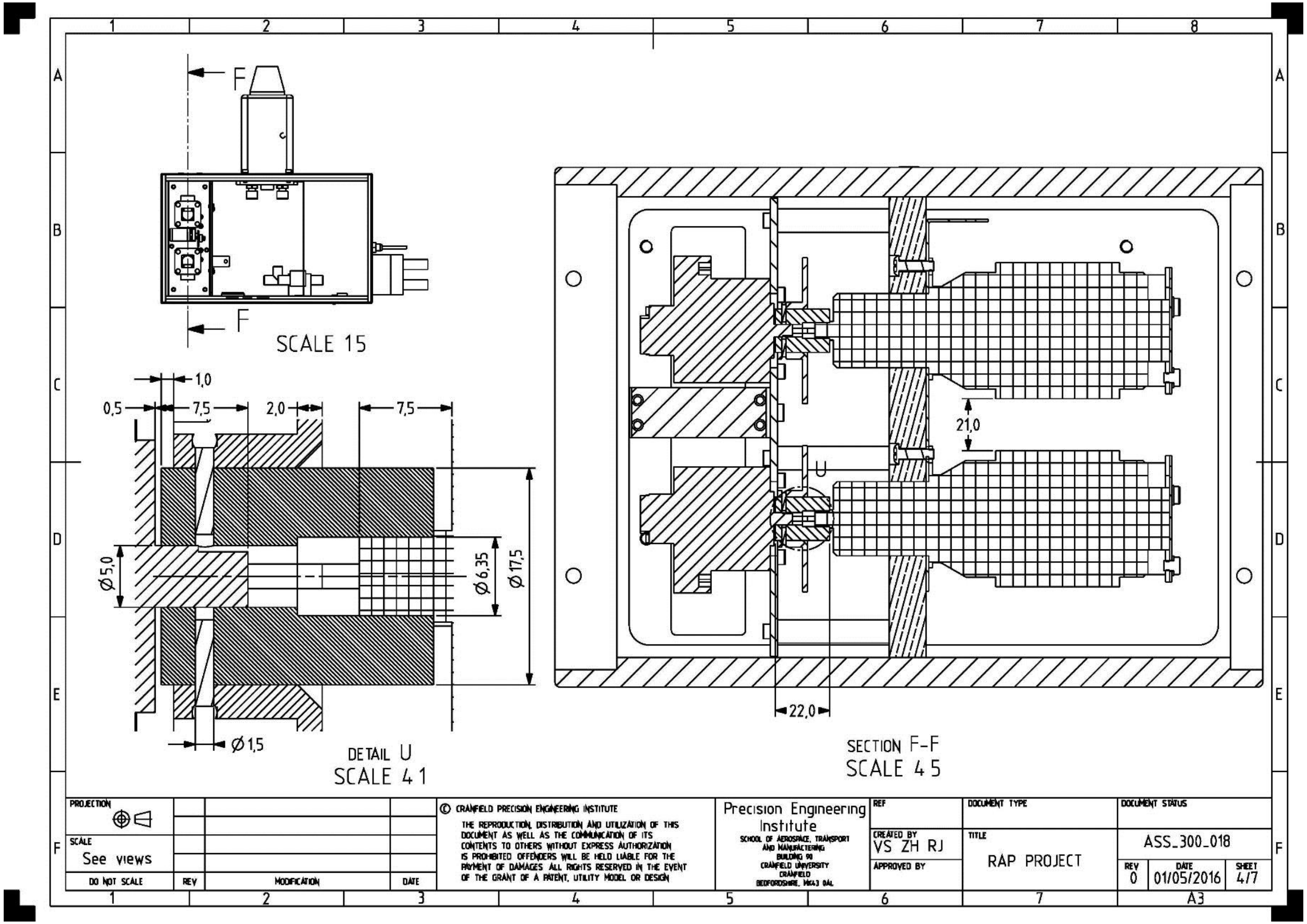

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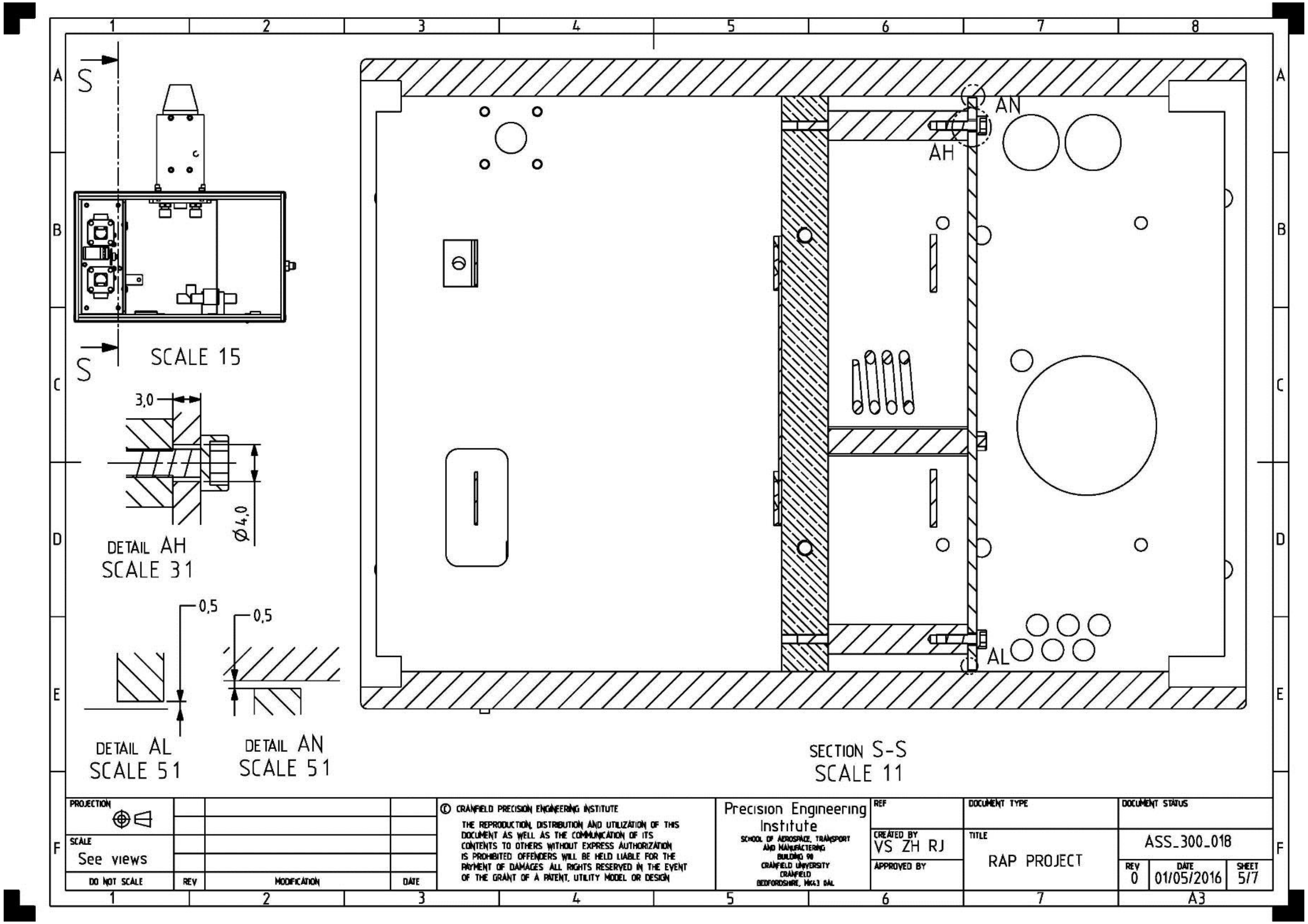
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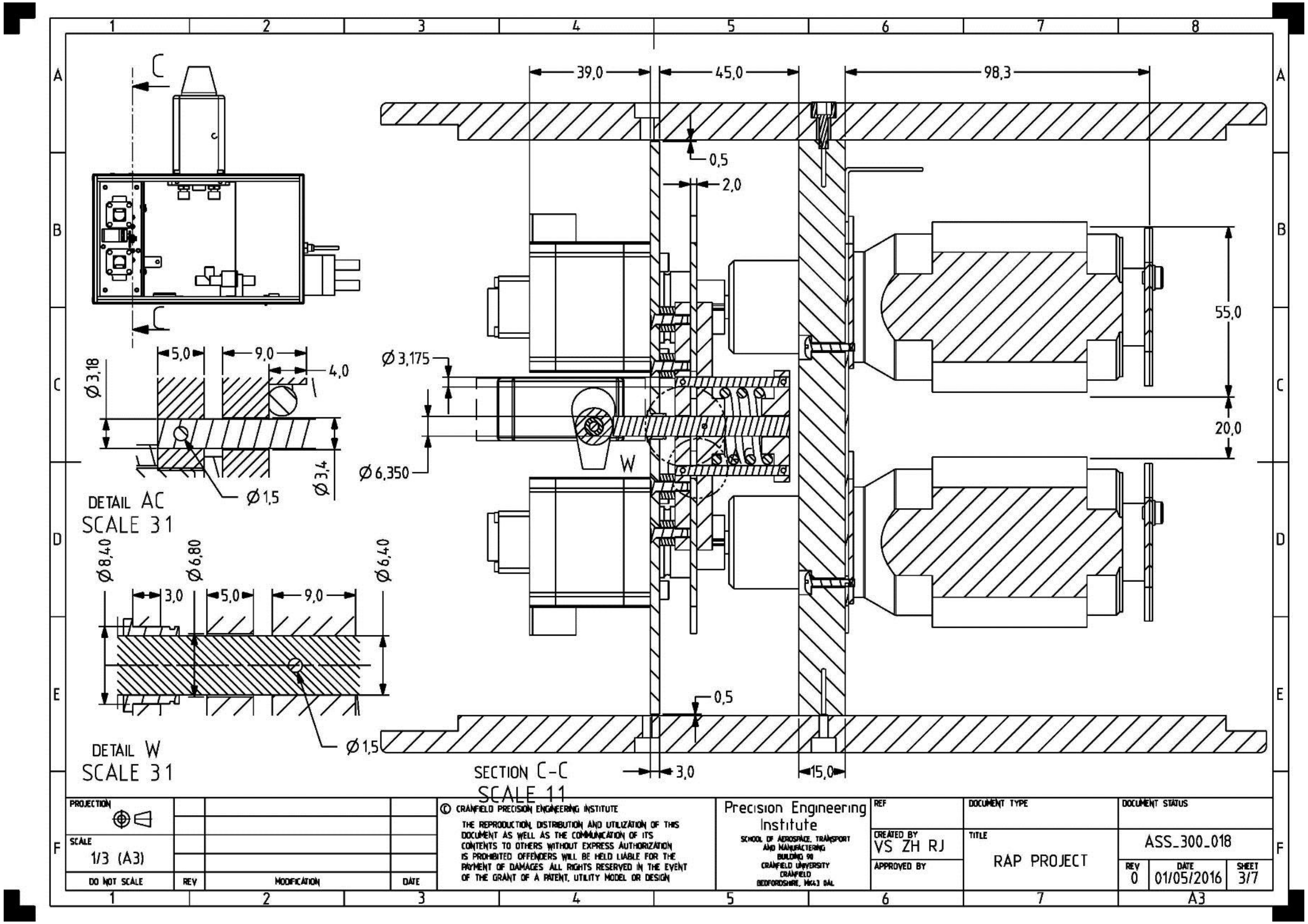
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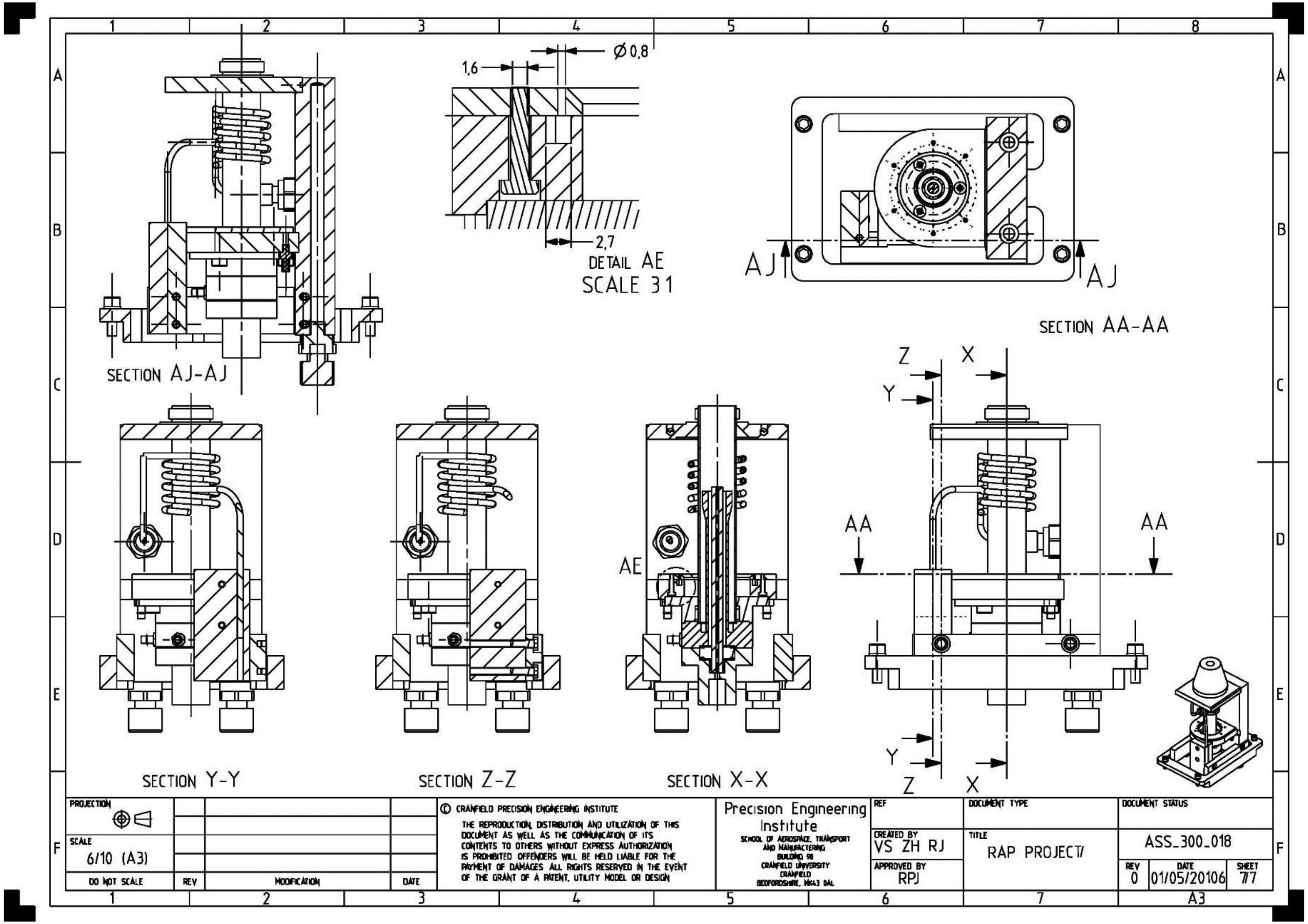
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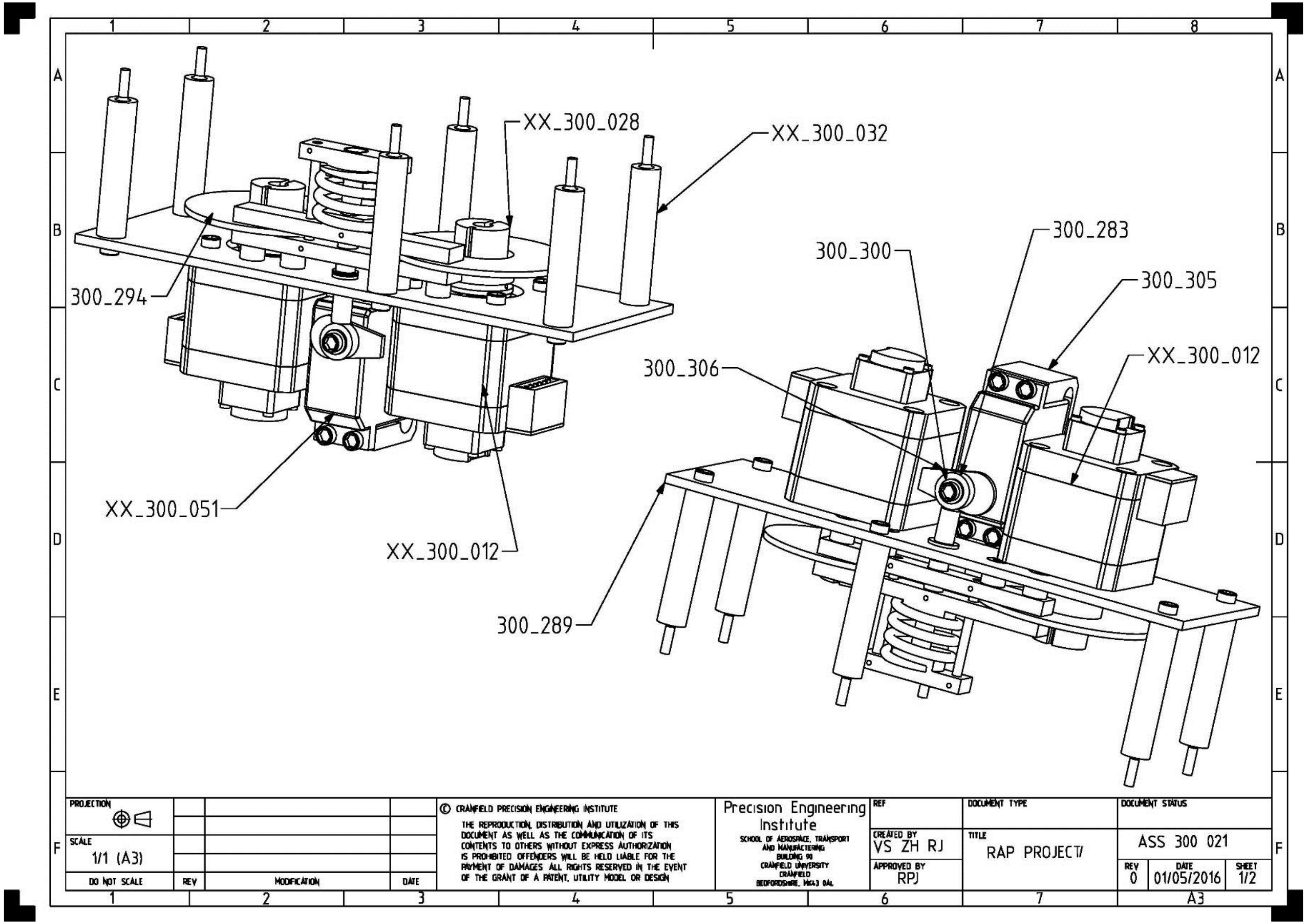
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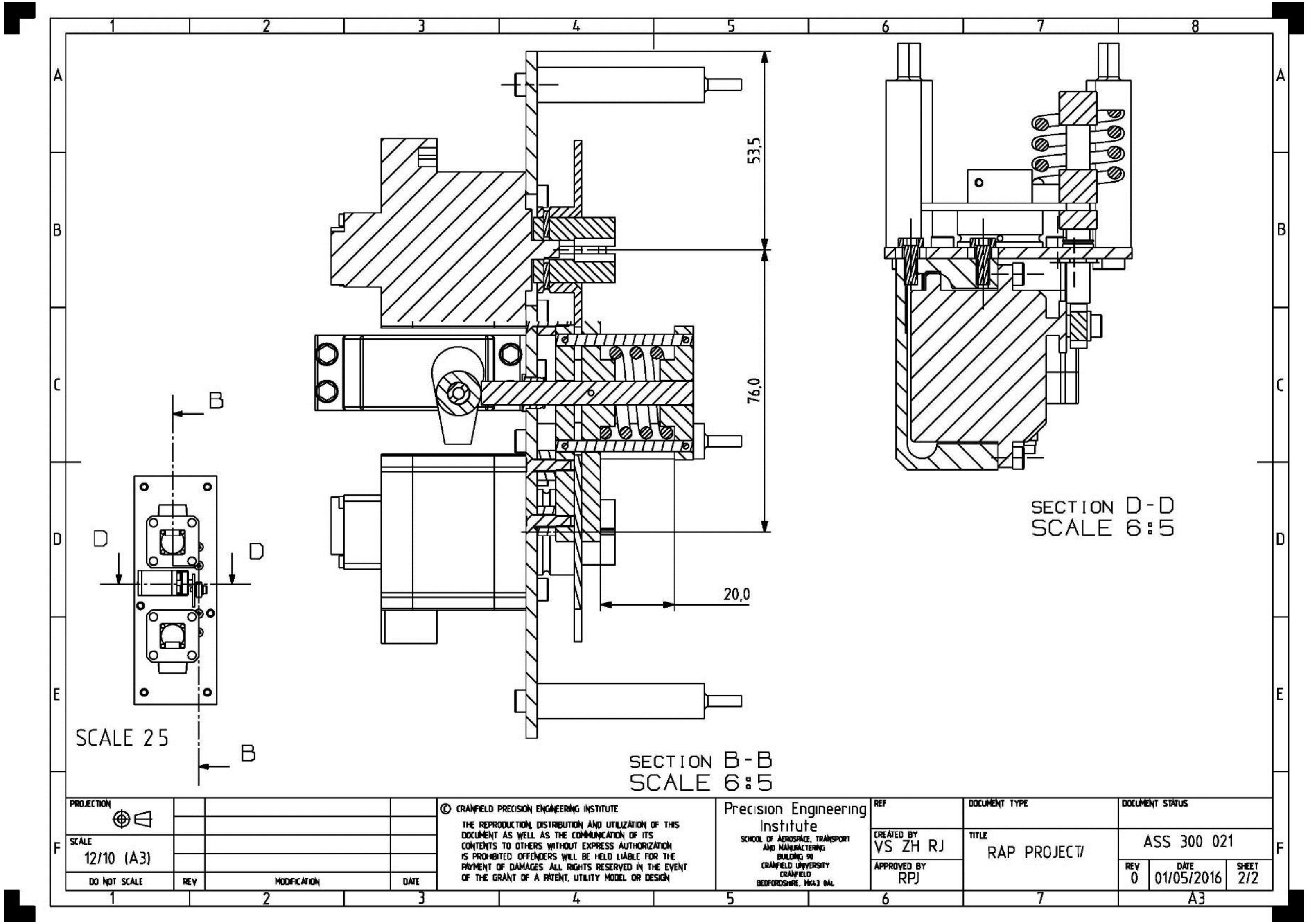

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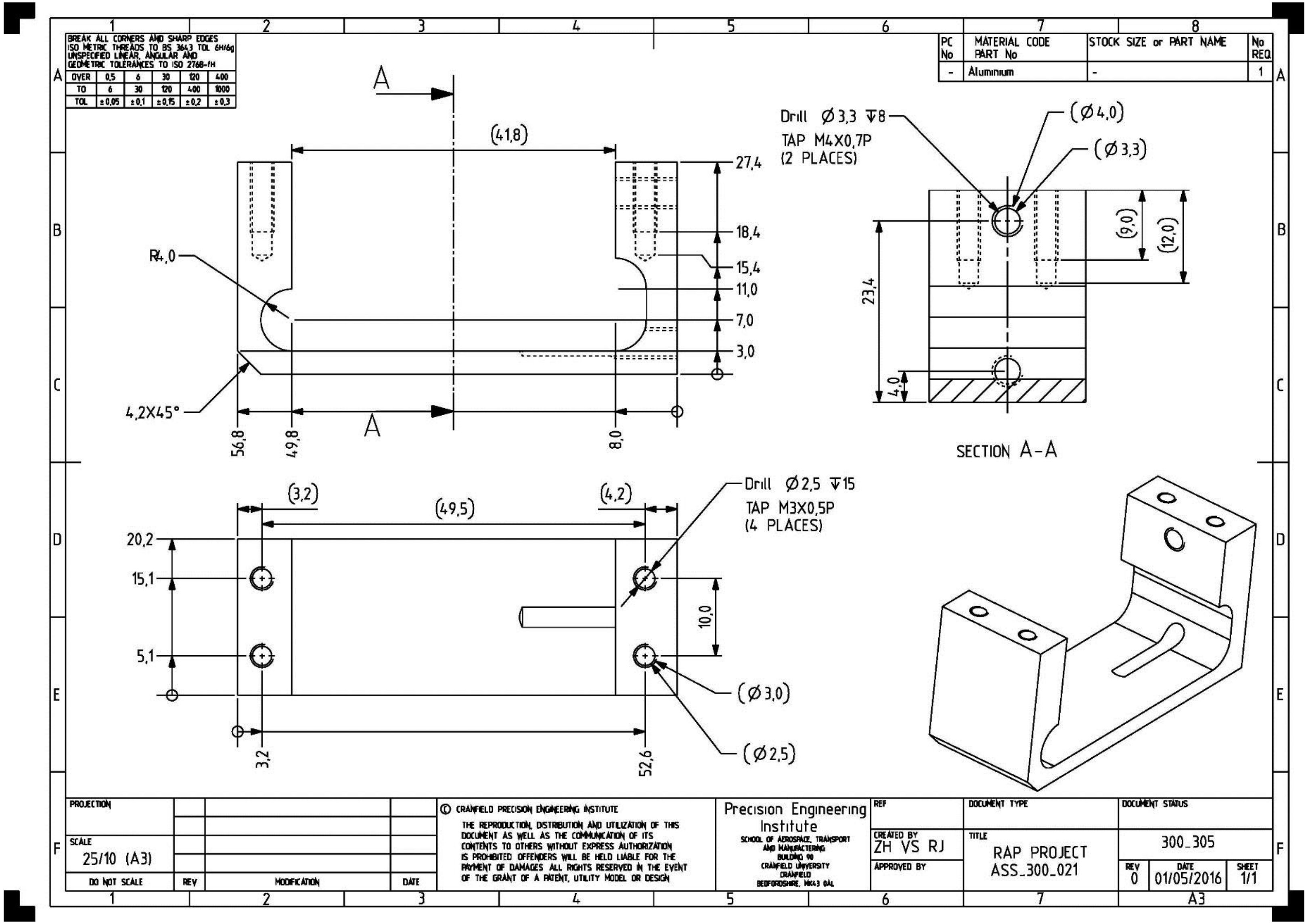
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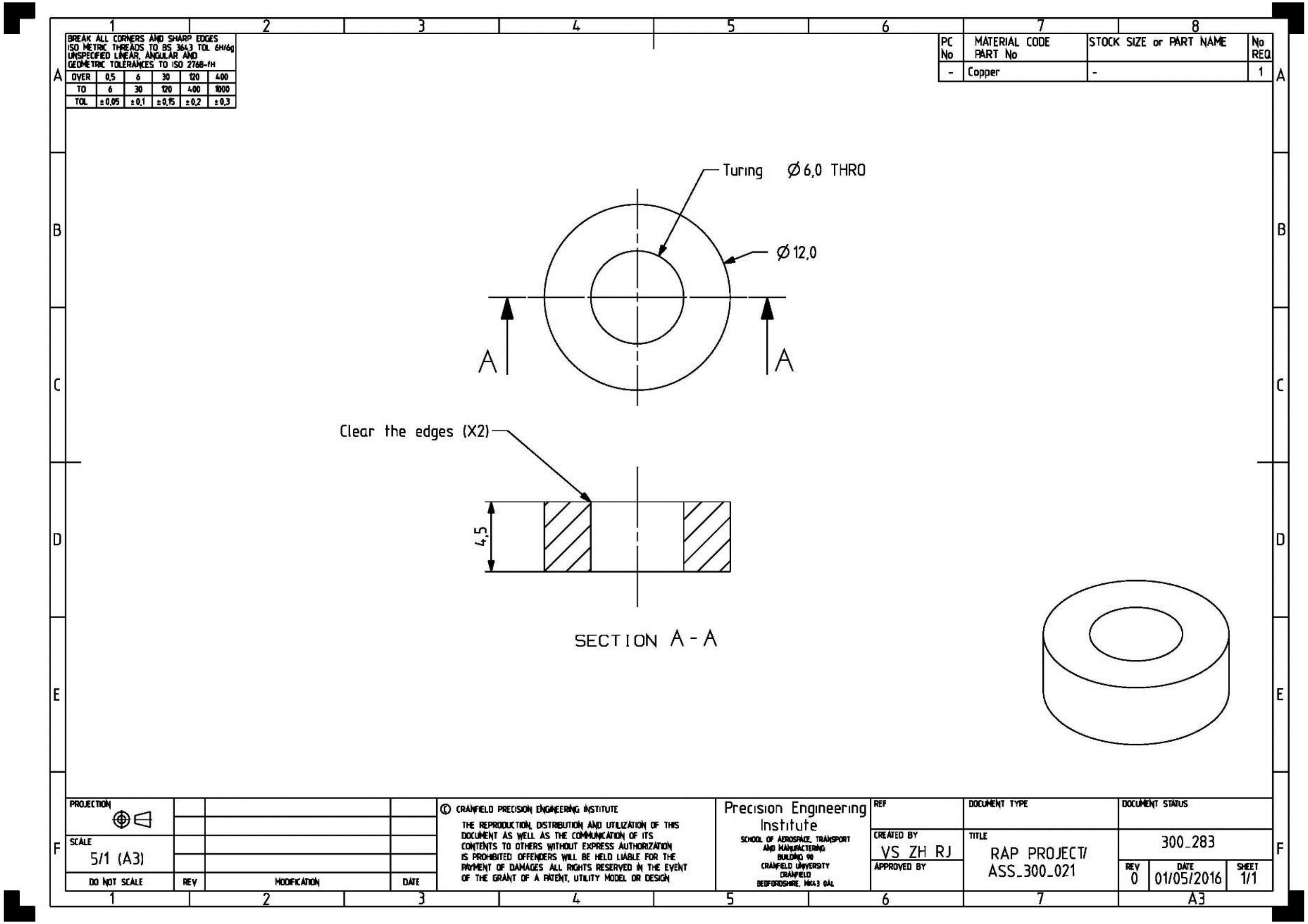
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1
Turing Ø6,0 THRO
Ø12,0
A
A
Clear the edges (X2)
4,5
SECTION A - A
PROJECTION
SCALE
5/1 (A3)
DO NOT SCALE
REV
MODIFICATION
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ASS_300_021
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300_283
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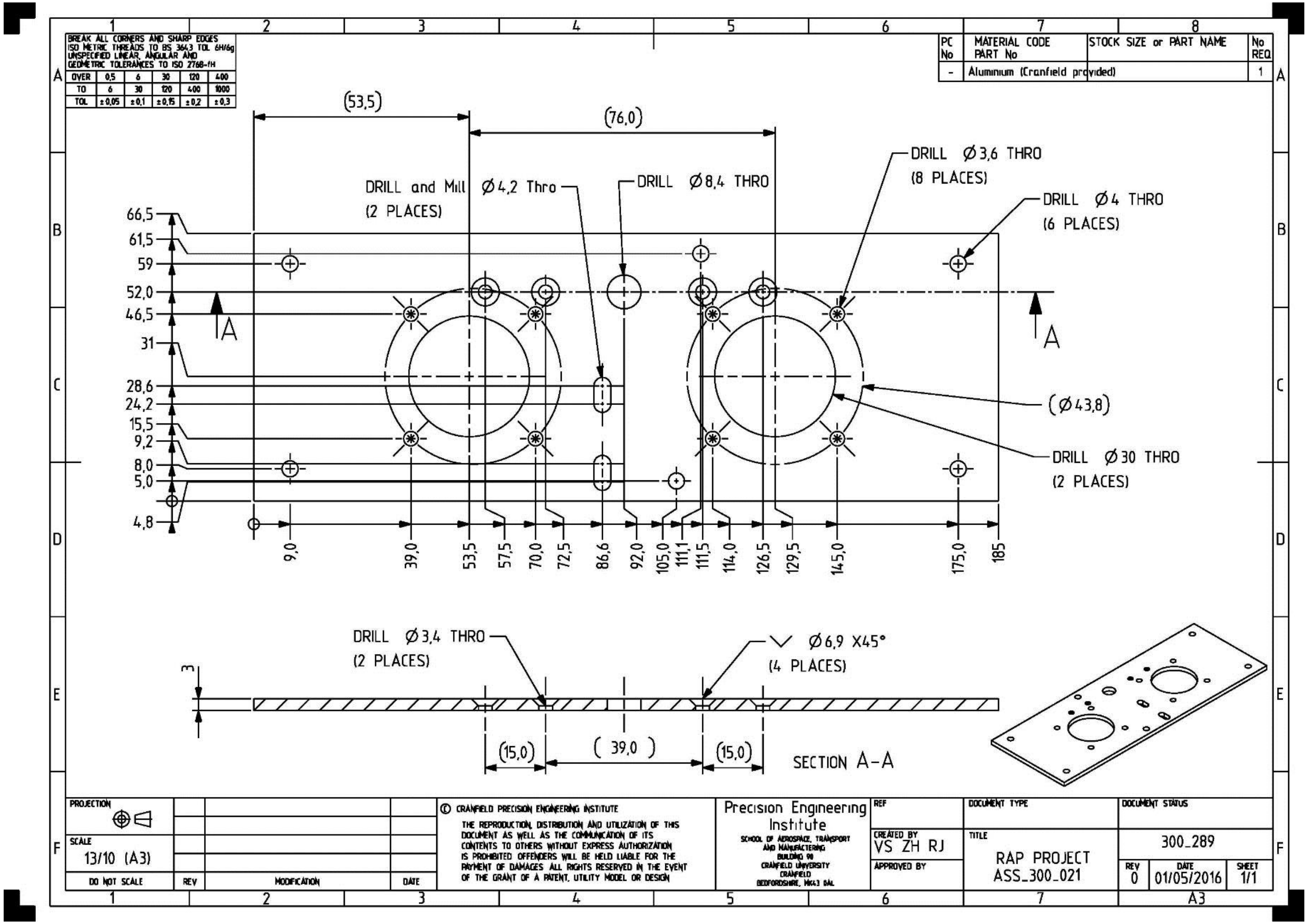
DATE
01/05/2016
SHEET
1/1
A3


BREAK ALL CORNERS AND SHARP EDGES
DRILL and Mill Ø4,2 Thro (2 PLACES)
DRILL Ø8,4 THRO
DRILL Ø3,6 THRO (8 PLACES)
DRILL Ø4 THRO (6 PLACES)
(Ø43,8)
DRILL Ø30 THRO (2 PLACES)
(53,5)
(76,0)
DRILL Ø3,4 THRO (2 PLACES)
Ø6,9 X45° (4 PLACES)
SECTION A-A
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
Aluminium (Cranfield provided)
PROJECTION
SCALE 13/10 (A3)
DO NOT SCALE
MODIFICATION
DATE
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DOCUMENT STATUS
TITLE RAP PROJECT ASS_300_021
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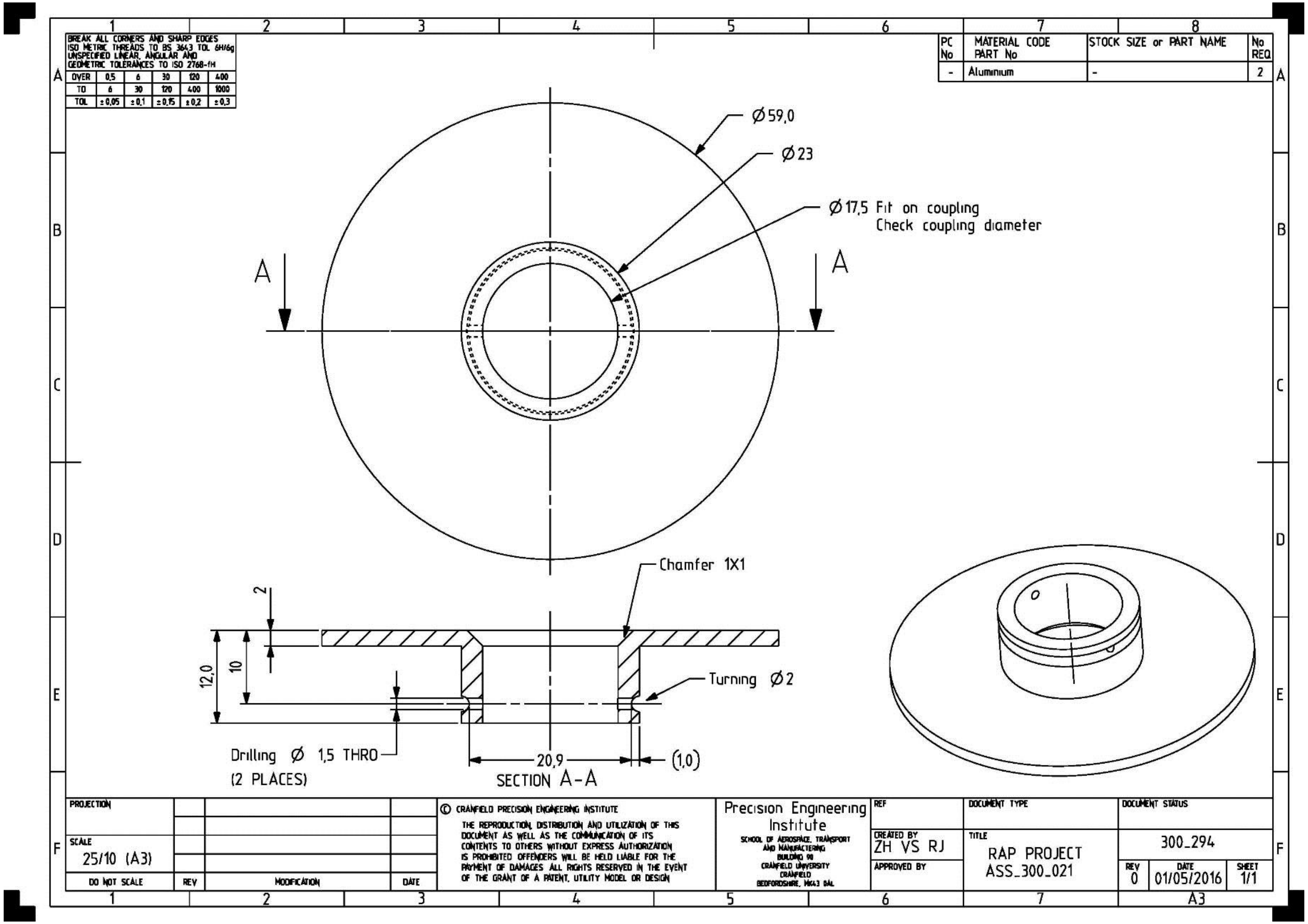
A3



BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND
GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
-
Aluminium
-
2
Ø59,0
Ø23
Ø17,5 Fit on coupling
Check coupling diameter
A
A
Chamfer 1X1
2
12,0
10
Turning Ø2
Drilling Ø 1,5 THRO
(2 PLACES)
20,9
(1,0)
SECTION A-A
PROJECTION
SCALE
25/10 (A3)
DO NOT SCALE
REV
MODIFICATION
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TITLE
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DOCUMENT STATUS
300_294
REV
0
DATE
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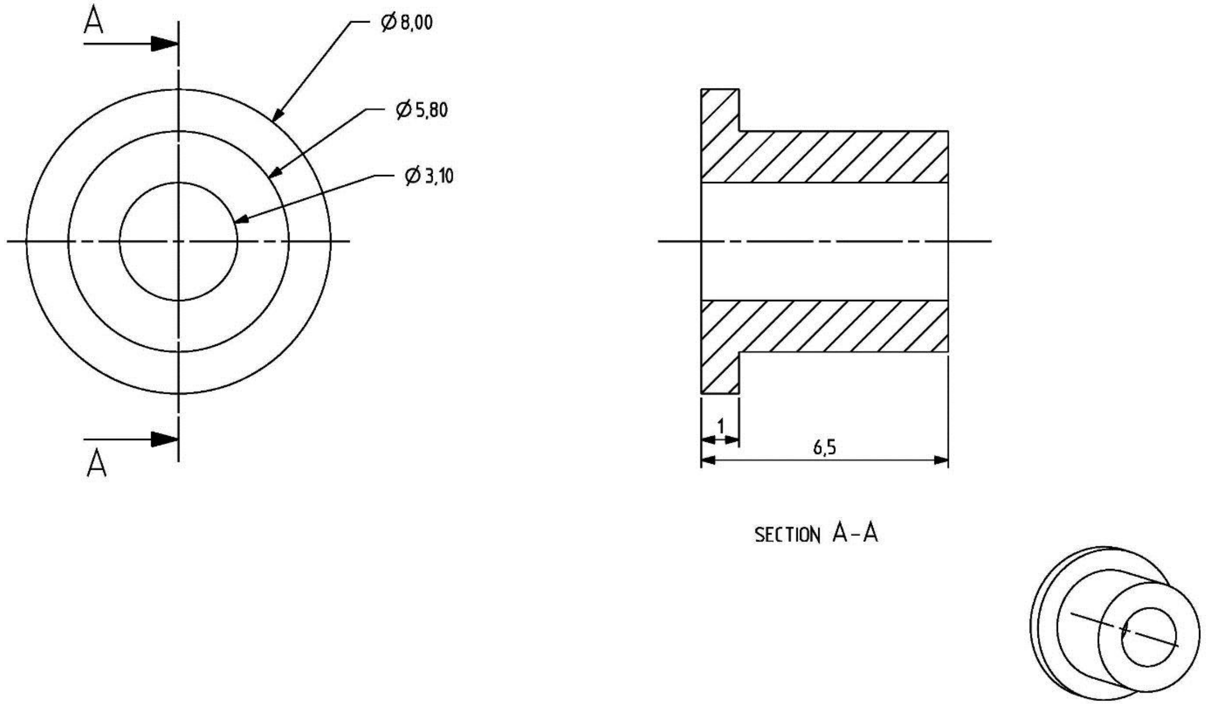
SHEET
1/1
A3

BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND
GEOMETRIC TOLERANCES TO ISO 2768-fH

OVER	0,5	6	30	120	400
TO	6	30	120	400	1000
TOL	± 0,05	± 0,1	± 0,15	± 0,2	± 0,3

PC No	MATERIAL CODE PART No	STOCK SIZE or PART NAME	No REQ
-	Aluminium	-	1



PROJECTION	REV	MODIFICATION	DATE
SCALE 10/1 (A3)			
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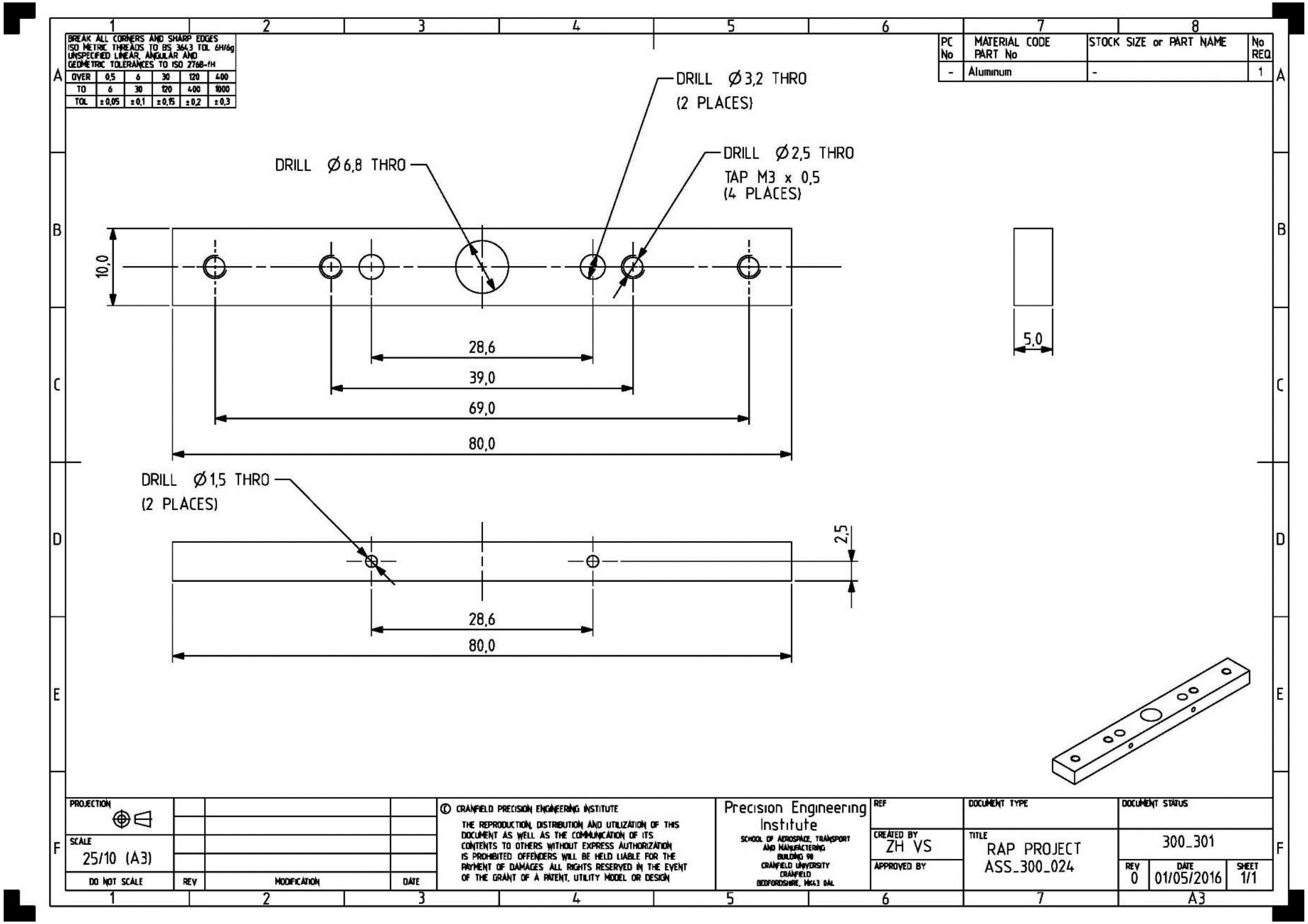
BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
-
Aluminum
-
1
DRILL Ø3,2 THRO
(2 PLACES)
DRILL Ø2,5 THRO
TAP M3 x 0,5
(4 PLACES)
DRILL Ø6,8 THRO
10,0
28,6
39,0
69,0
80,0
5,0
DRILL Ø1,5 THRO
(2 PLACES)
2,5
28,6
80,0
PROJECTION
SCALE
25/10 (A3)
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01/05/2016
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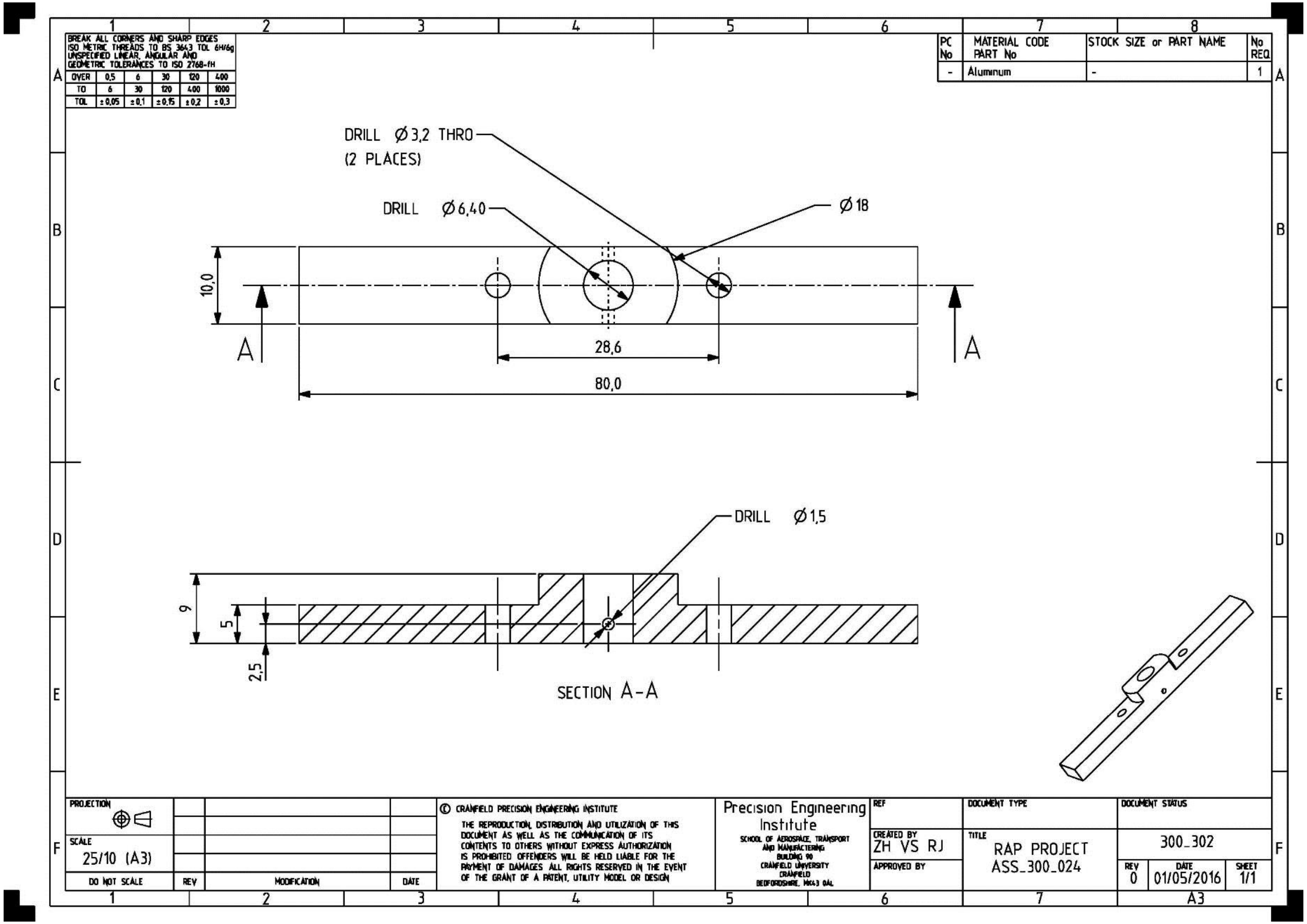
1/1
A3


BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
Aluminum
1
DRILL Ø3,2 THRO
(2 PLACES)
DRILL Ø6,40
Ø18
10,0
28,6
80,0
A
A
DRILL Ø1,5
9
5
2,5
SECTION A-A
PROJECTION
SCALE
25/10 (A3)
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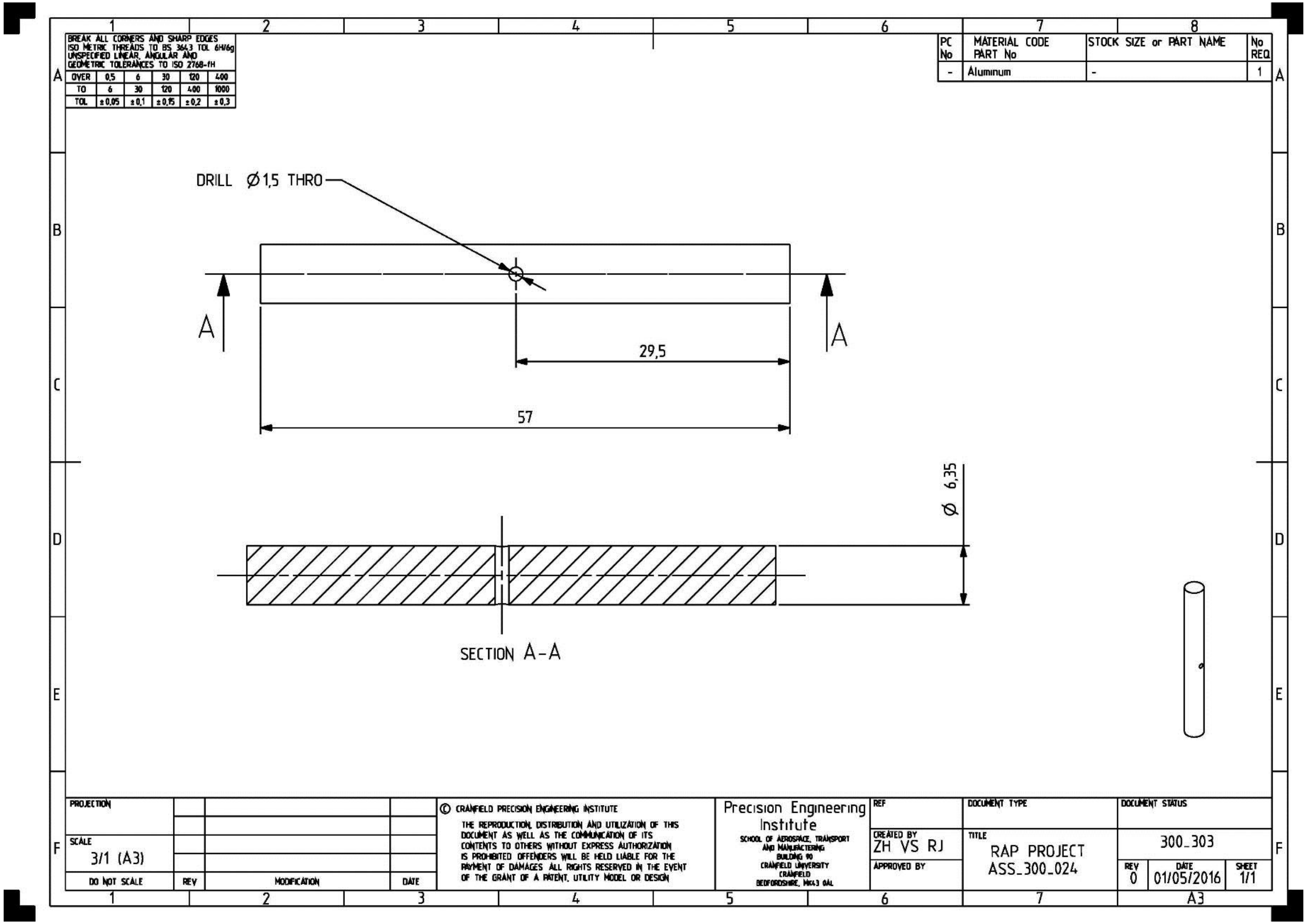
BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND
GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
-
Aluminum
-
1
DRILL Ø1,5 THRO
A
A
29,5
57
Ø 6,35
SECTION A-A
PROJECTION
SCALE
3/1 (A3)
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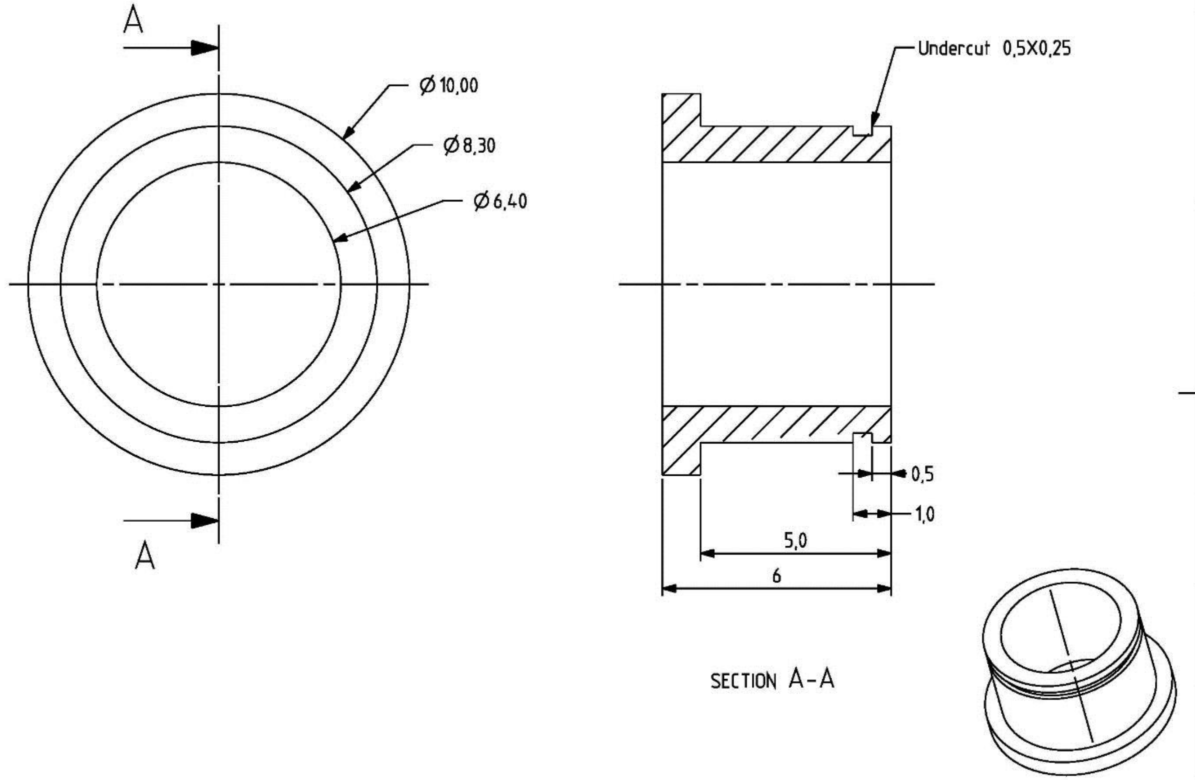
BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND
GEOMETRIC TOLERANCES TO ISO 2768-fH

OVER	0,5	6	30	120	400
TO	6	30	120	400	1000
TOL	±0,05	±0,1	±0,15	±0,2	±0,3

PC No	MATERIAL CODE PART No	STOCK SIZE or PART NAME	No REQ
-	Copper	-	1



PROJECTION	REV	MODIFICATION / DATE
SCALE 10/1 (A3)		
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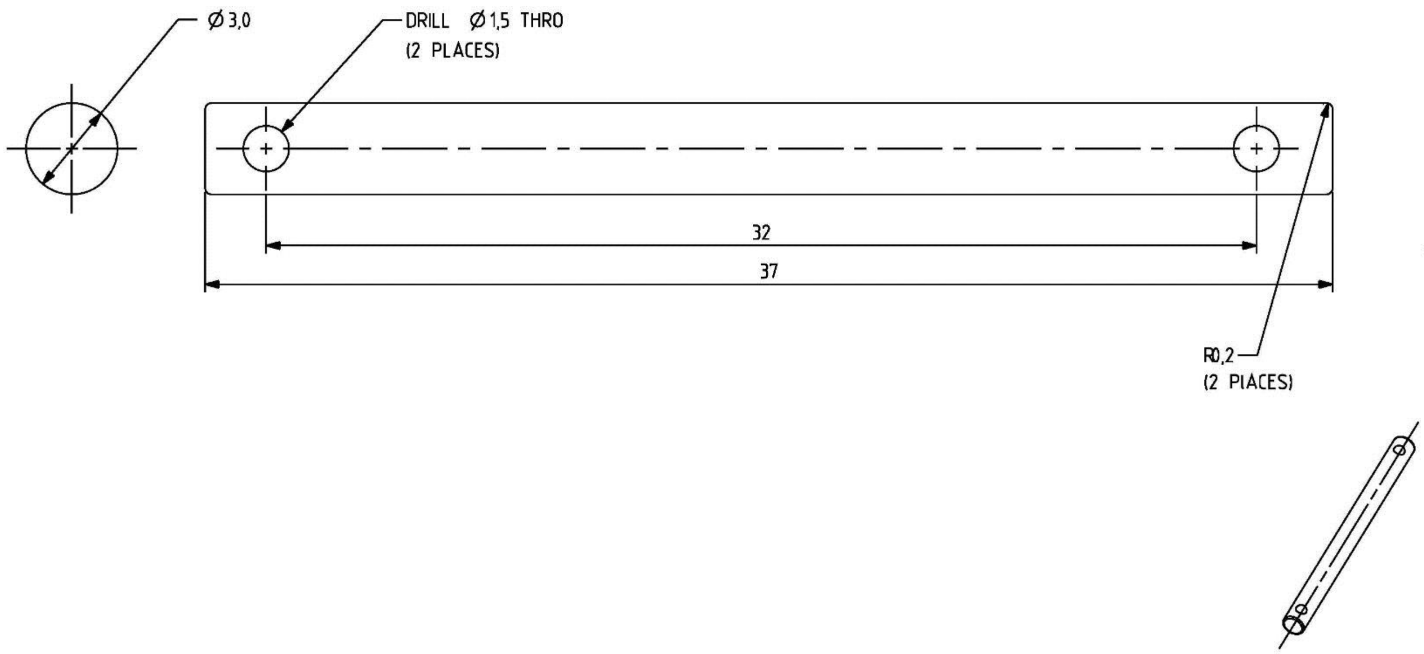
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH

OVER	0,5	6	30	120	400
TO	6	30	120	400	1000
TOL	± 0,05	± 0,1	± 0,15	± 0,2	± 0,3

PC No	MATERIAL CODE PART No	STOCK SIZE or PART NAME	No REQ
-	Copper (Cranfield provided)		2



PROJECTION

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TITLE: RAP PROJECT ASS_300_024

DOCUMENT STATUS

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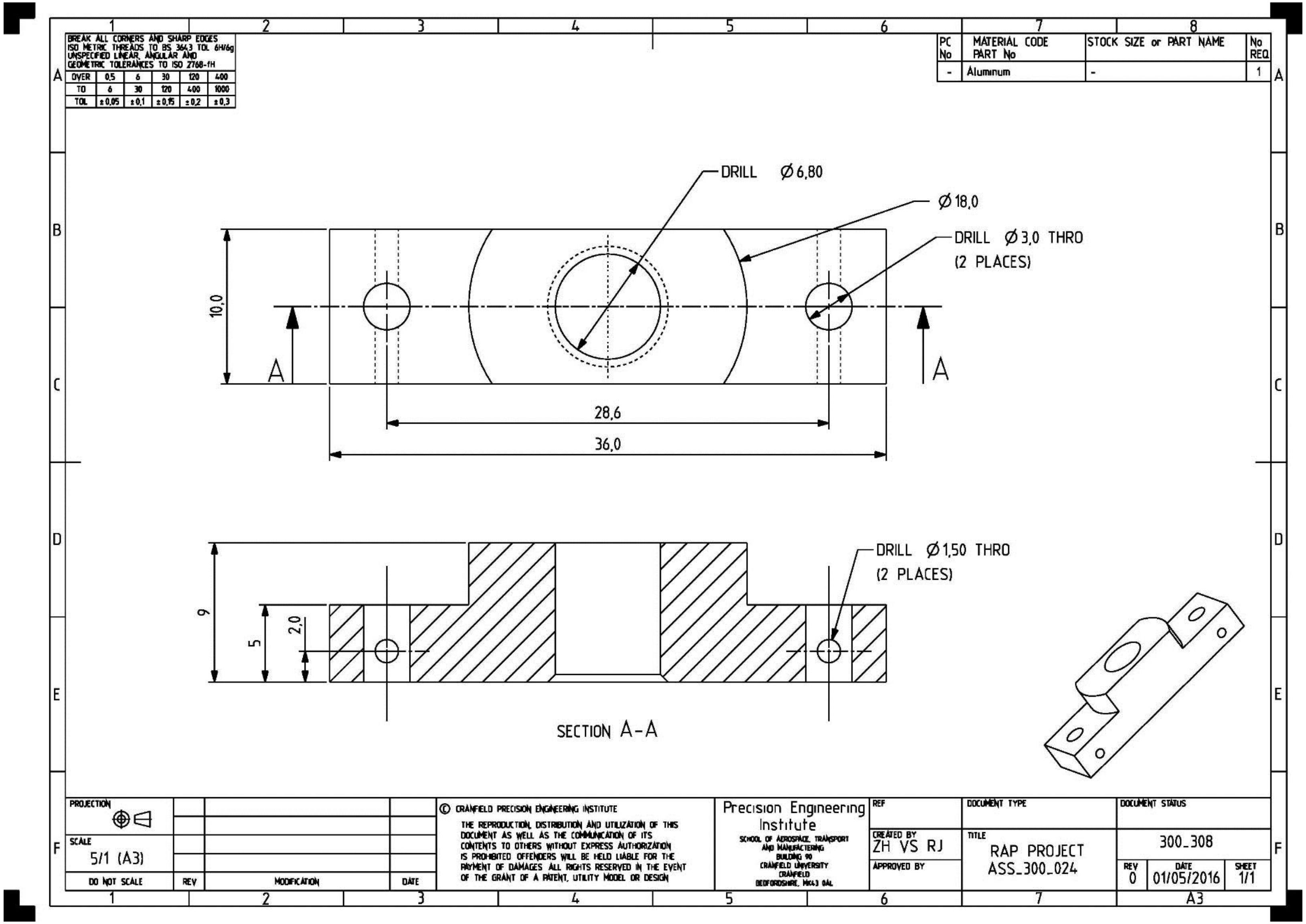
BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND
GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
- Aluminum - 1
DRILL Ø6,80
Ø18,0
DRILL Ø3,0 THRO
(2 PLACES)
10,0
A
A
28,6
36,0
DRILL Ø1,50 THRO
(2 PLACES)
9
5
2,0
SECTION A-A
PROJECTION
SCALE
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01/05/2016
SHEET
1/1
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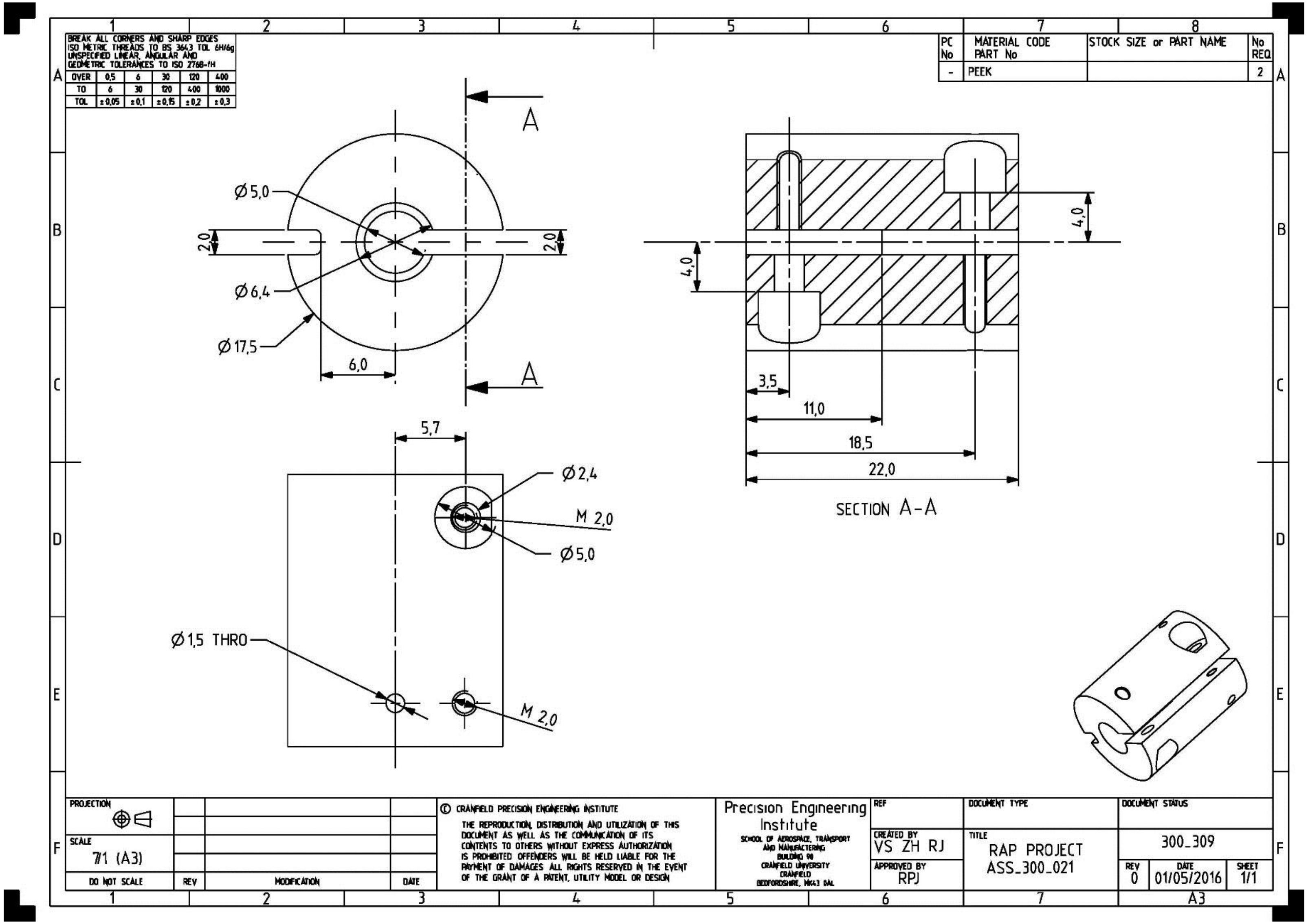
BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER | 0,5 | 6 | 30 | 120 | 400
TO | 6 | 30 | 120 | 400 | 1000
TOL | ± 0,05 | ± 0,1 | ± 0,15 | ± 0,2 | ± 0,3
PC No | MATERIAL CODE PART No | STOCK SIZE or PART NAME | No REQ
- | PEEK | | 2
A
Ø5,0
Ø6,4
Ø17,5
2,0
6,0
5,7
Ø2,4
M 2,0
Ø5,0
Ø1,5 THRO
4,0
3,5
11,0
18,5
22,0
SECTION A-A
PROJECTION
SCALE
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DATE
01/05/2016
SHEET
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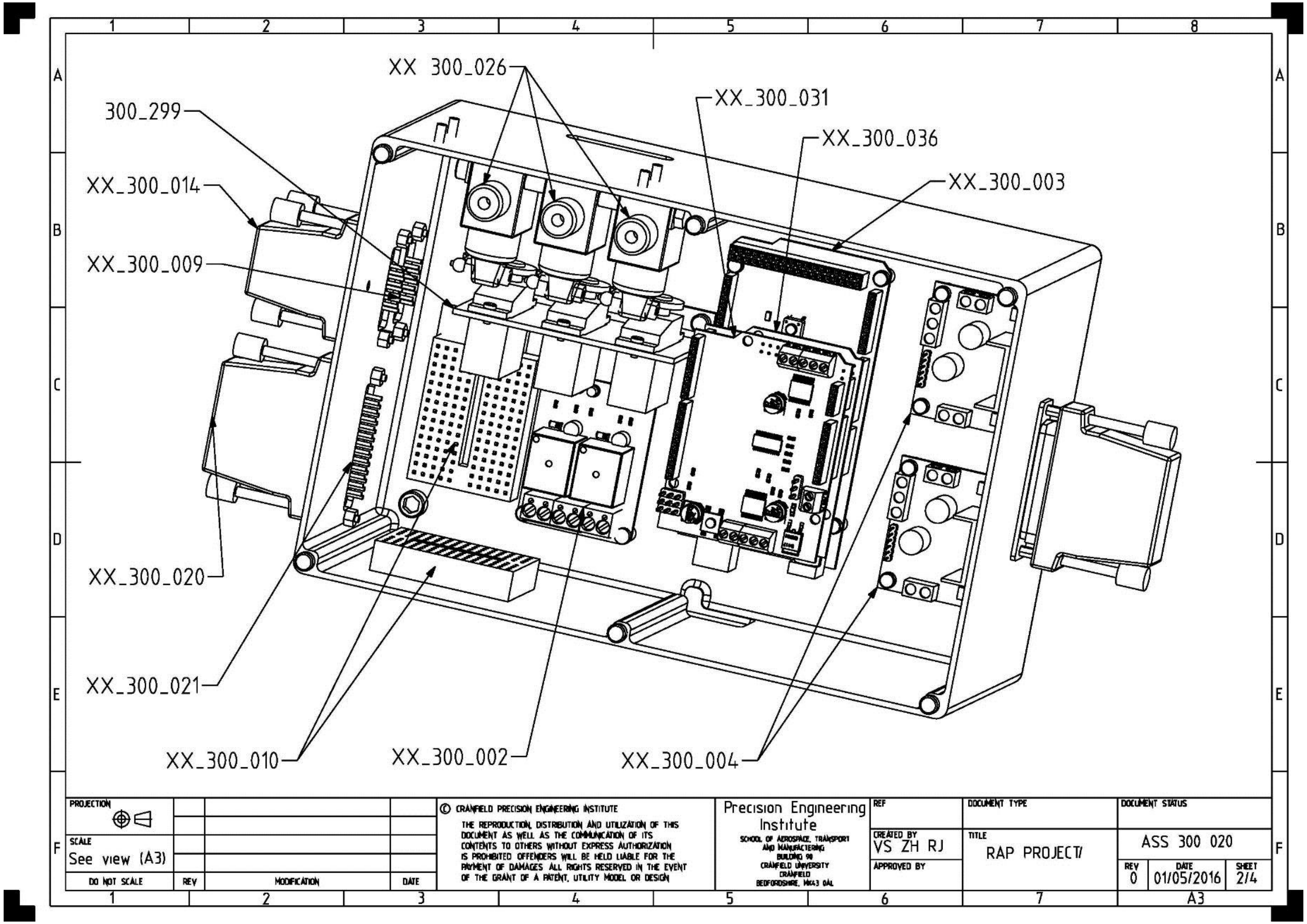
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PROJECTION
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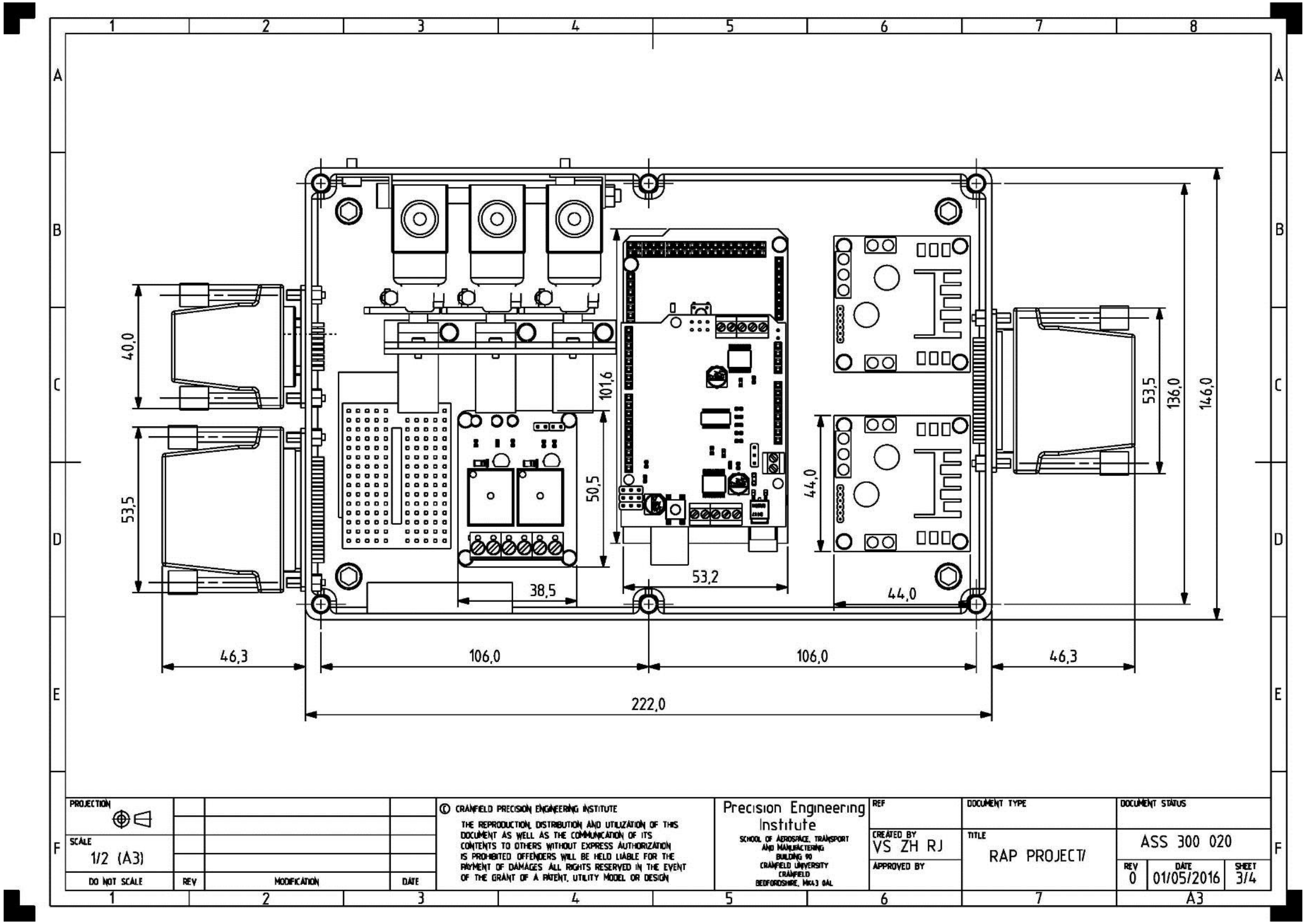
DATE
01/05/2016
SHEET
2/4
A3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101,6
50,5
38,5
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44,0
44,0
53,5
136,0
146,0
46,3
106,0
106,0
46,3
222,0
PROJECTION
SCALE
1/2 (A3)
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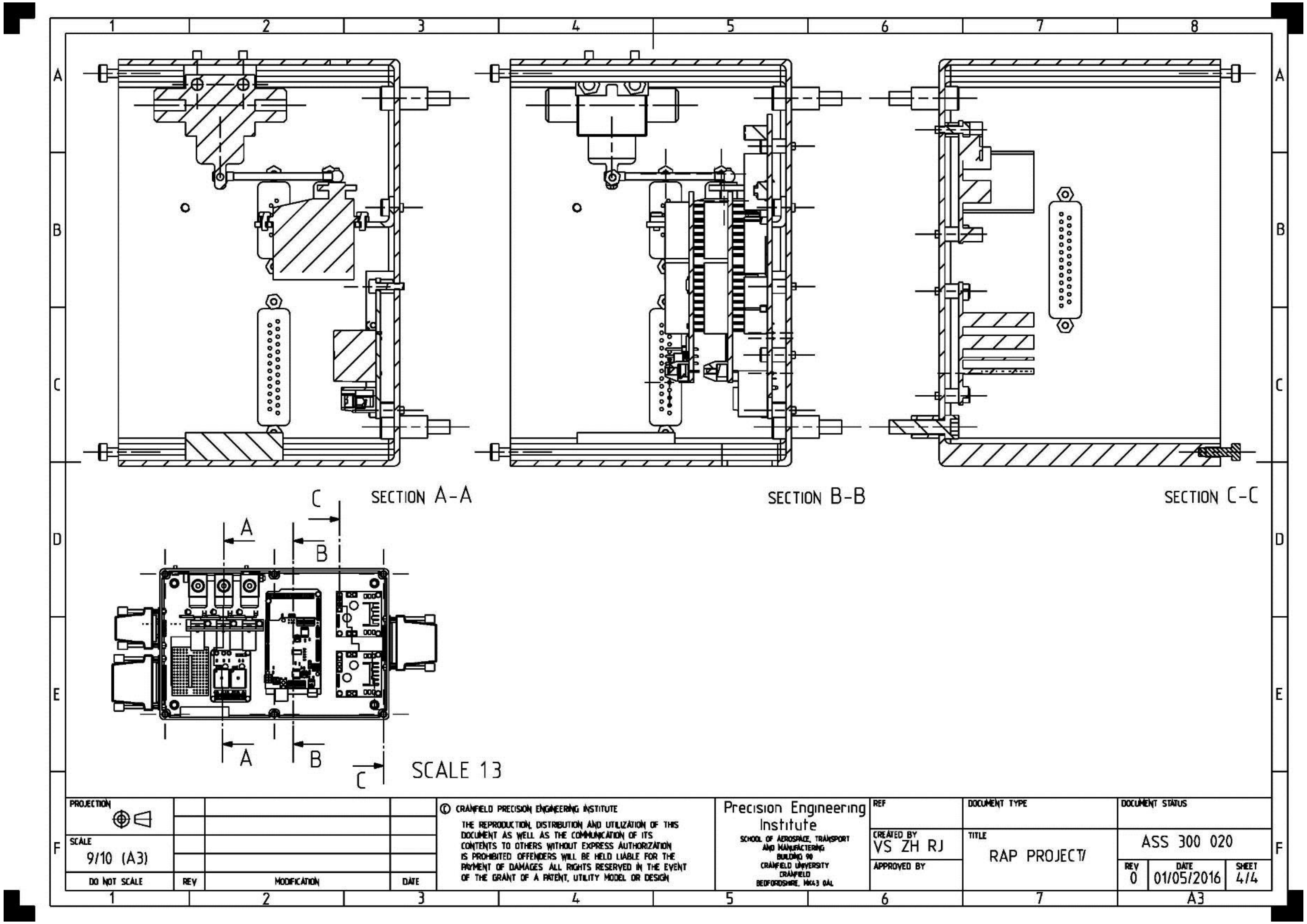
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SECTION B-B
SECTION C-C
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PROJECTION
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4/4
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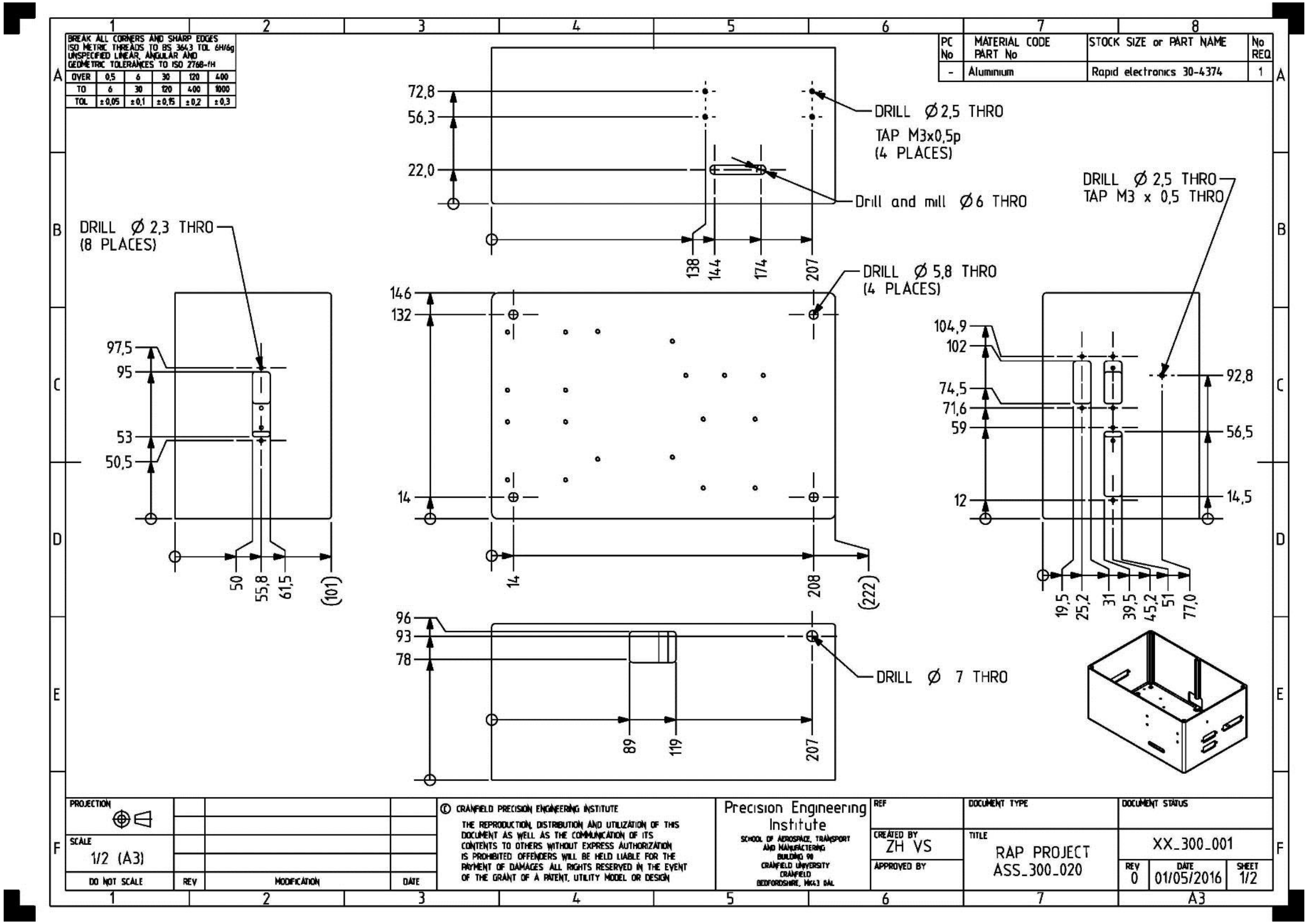
BREAK ALL CORNERS AND SHARP EDGES ISO METRIC THREADS TO BS 3643 TOL 6H/6g UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
Aluminium
Rapid electronics 30-4374
1
DRILL Ø 2,5 THRO
TAP M3x0,5p
(4 PLACES)
Drill and mill Ø 6 THRO
DRILL Ø 2,5 THRO
TAP M3 x 0,5 THRO
DRILL Ø 2,3 THRO
(8 PLACES)
DRILL Ø 5,8 THRO
(4 PLACES)
DRILL Ø 7 THRO
PROJECTION
SCALE
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1/2
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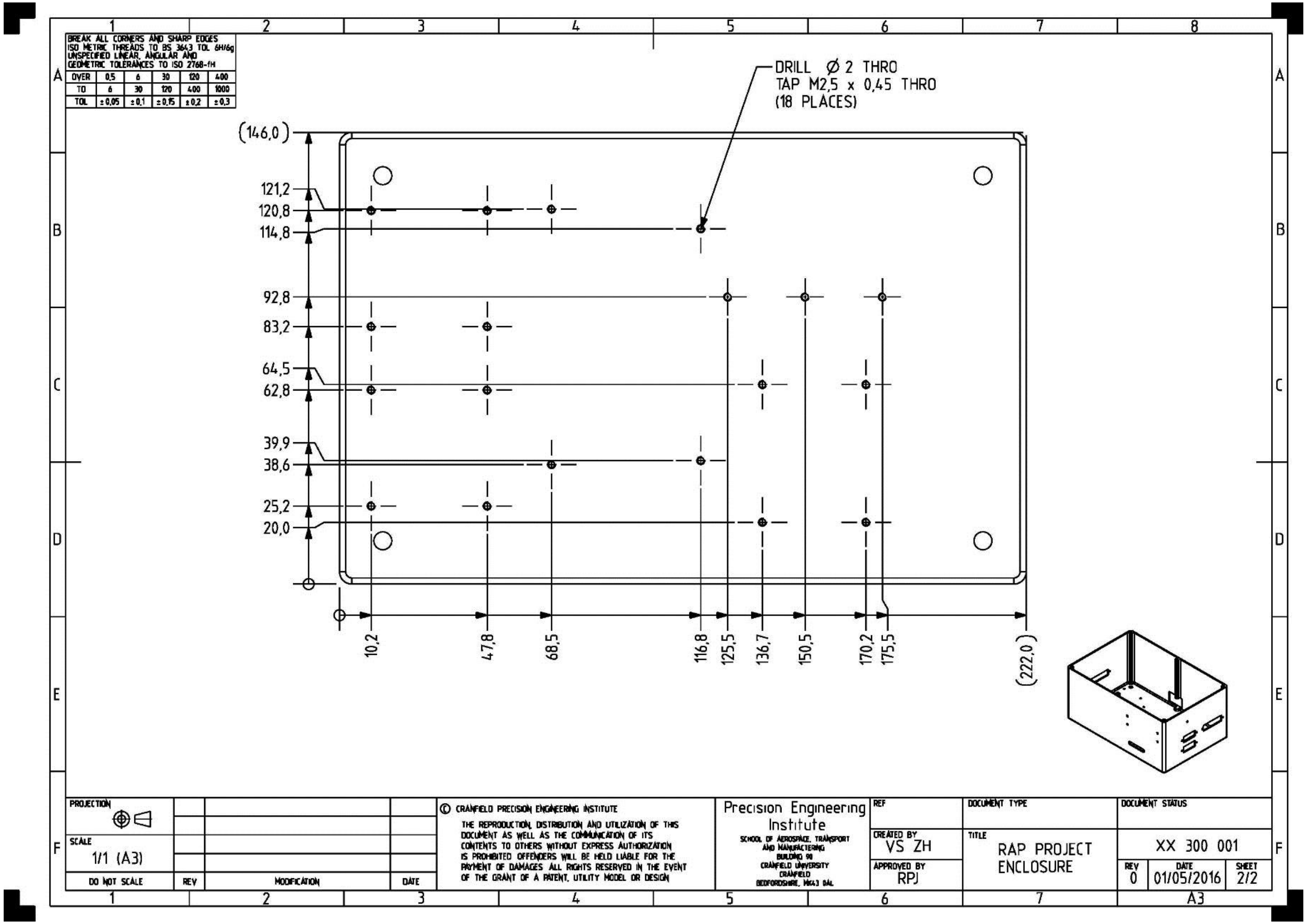
BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
DRILL Ø 2 THRO
TAP M2,5 x 0,45 THRO
(18 PLACES)
(146,0)
121,2
120,8
114,8
92,8
83,2
64,5
62,8
39,9
38,6
25,2
20,0
10,2
47,8
68,5
116,8
125,5
136,7
150,5
170,2
175,5
(222,0)
PROJECTION
SCALE
1/1 (A3)
DO NOT SCALE
REV
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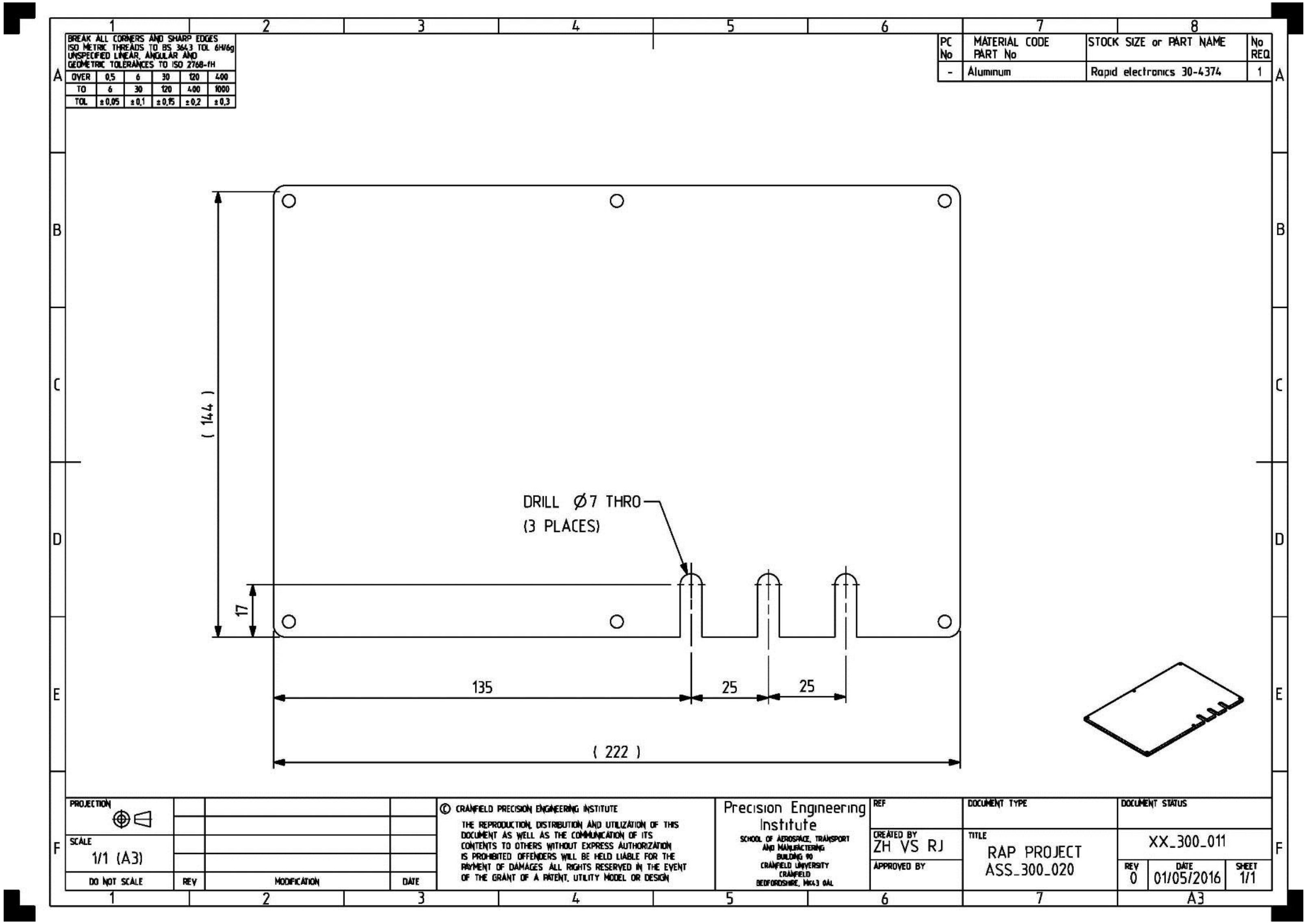
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ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
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17
DRILL Ø7 THRO
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135
25
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(222)
PROJECTION
SCALE
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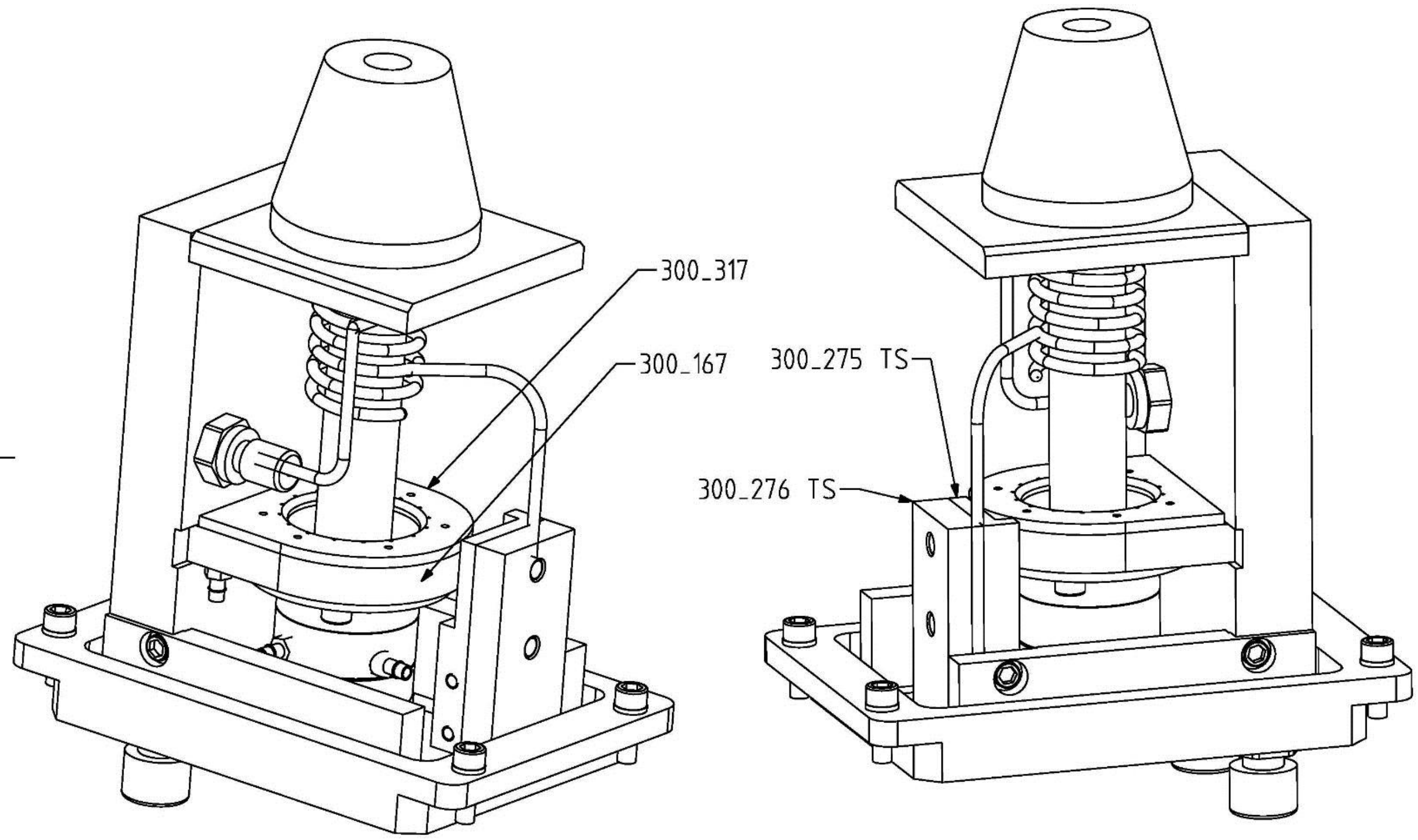

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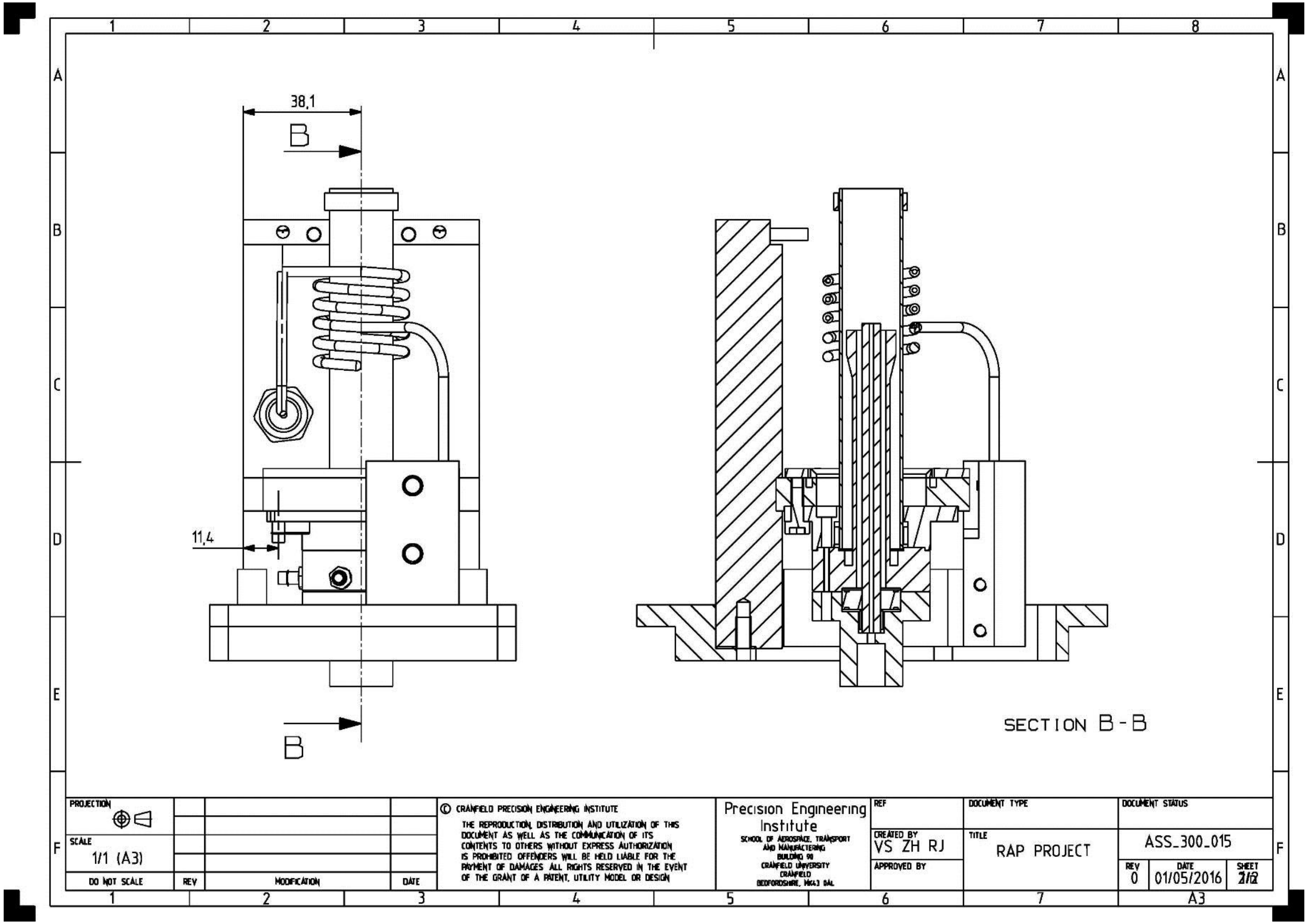

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PROJECTION
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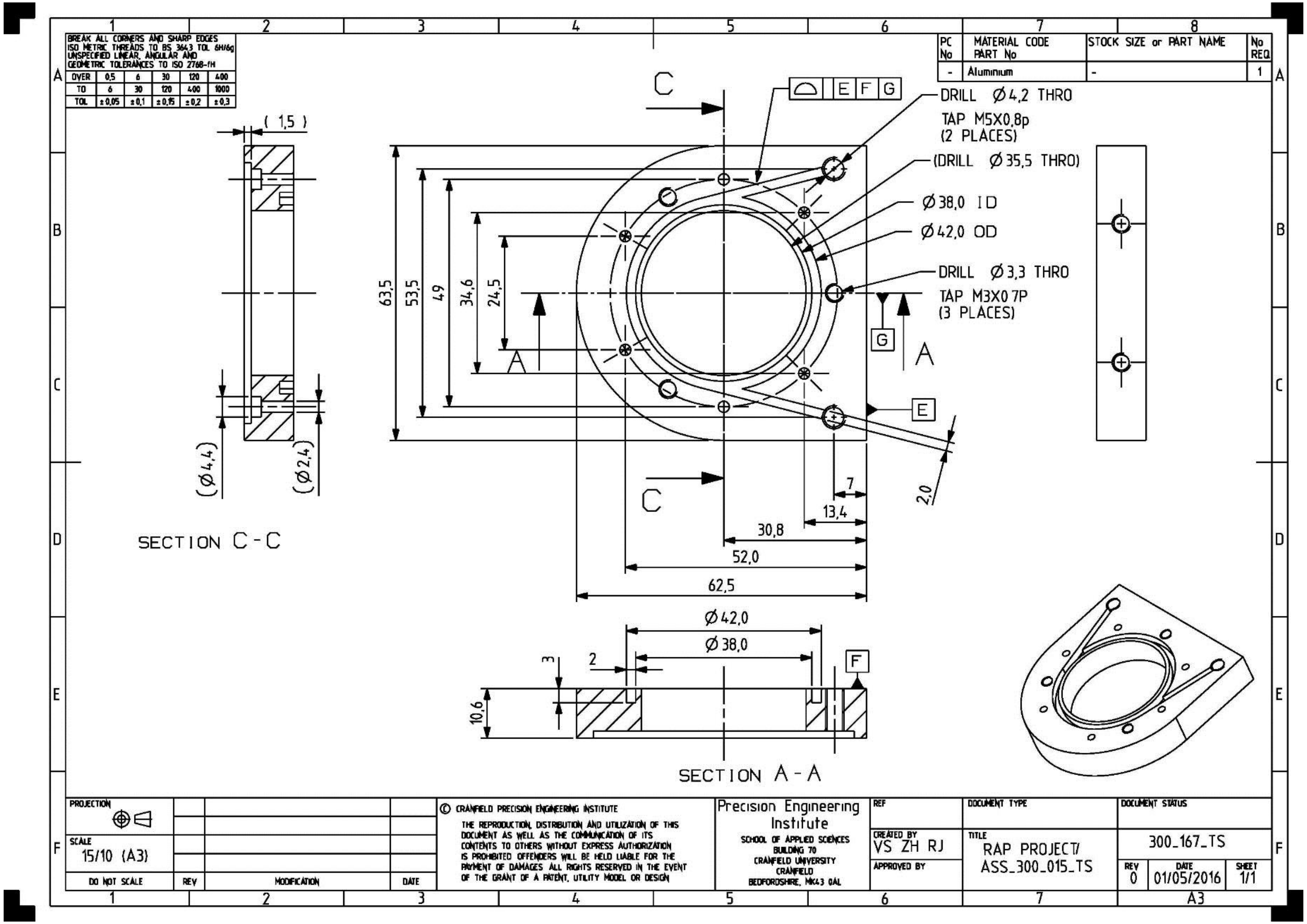
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ISO METRIC THREADS TO BS 3643 TOL 6H/6g
UNSPECIFIED LINEAR, ANGULAR AND GEOMETRIC TOLERANCES TO ISO 2768-fH
OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
Aluminium
DRILL Ø4,2 THRO
TAP M5X0,8p
(2 PLACES)
(DRILL Ø35,5 THRO)
Ø38,0 ID
Ø42,0 OD
DRILL Ø3,3 THRO
TAP M3X0 7P
(3 PLACES)
SECTION C-C
SECTION A-A
(1,5)
(Ø4,4)
(Ø2,4)
63,5
53,5
49
34,6
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13,4
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52,0
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Ø42,0
Ø38,0
10,6
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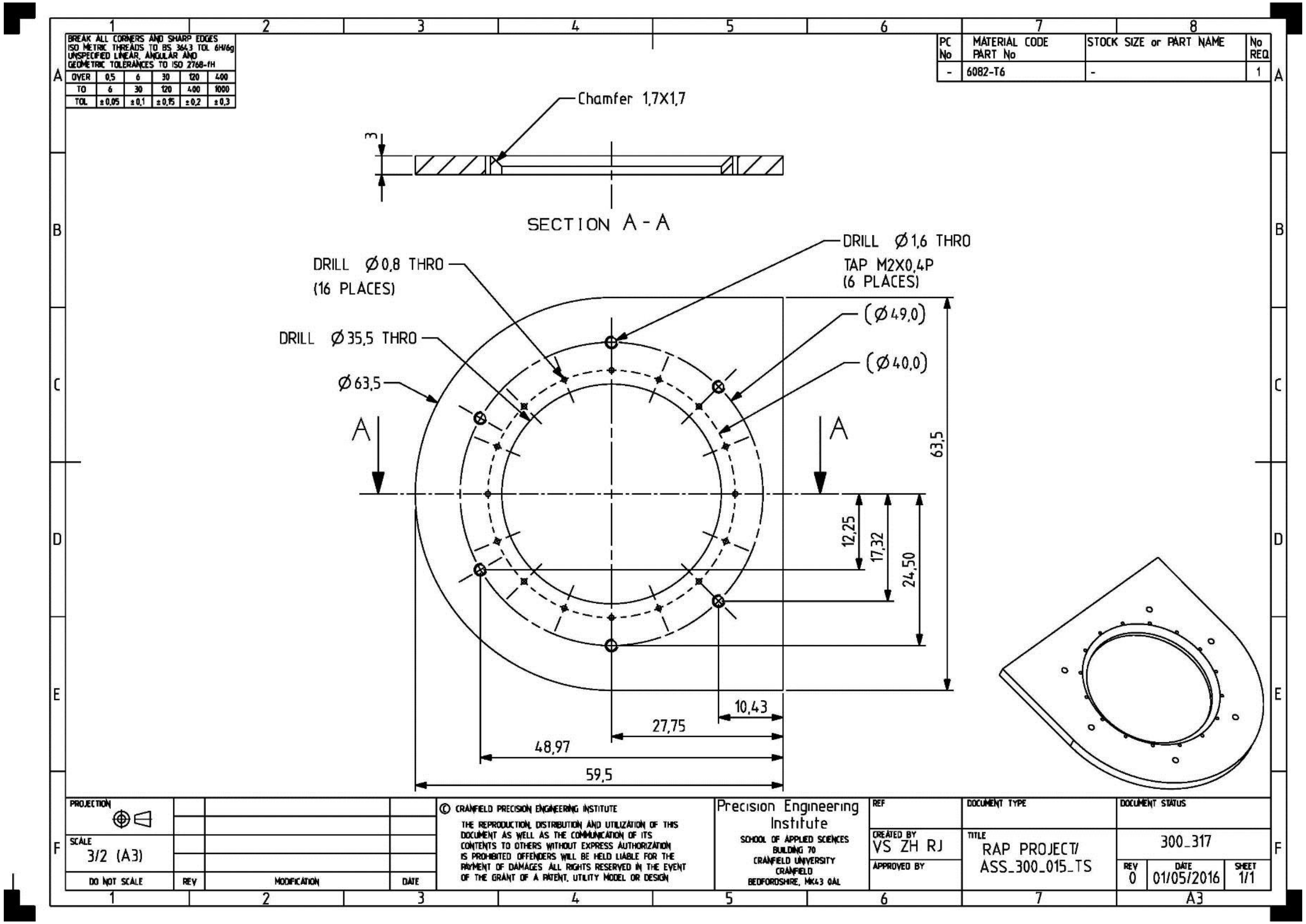
BREAK ALL CORNERS AND SHARP EDGES
ISO METRIC THREADS TO BS 3643 TOL 6H/6g
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OVER 0,5 6 30 120 400
TO 6 30 120 400 1000
TOL ±0,05 ±0,1 ±0,15 ±0,2 ±0,3
PC No
MATERIAL CODE PART No
STOCK SIZE or PART NAME
No REQ
-
6082-T6
-
1
Chamfer 1,7X1,7
3
SECTION A - A
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TAP M2X0,4P
(6 PLACES)
DRILL Ø0,8 THRO
(16 PLACES)
DRILL Ø35,5 THRO
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(Ø49,0)
(Ø40,0)
A
A
63,5
12,25
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24,50
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27,75
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PROJECTION
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