Development of an EDM-tool for the Nuclear Industry

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KTH Industrial Engineering and Management

Master of Science Thesis
Stockholm, Sweden 2014

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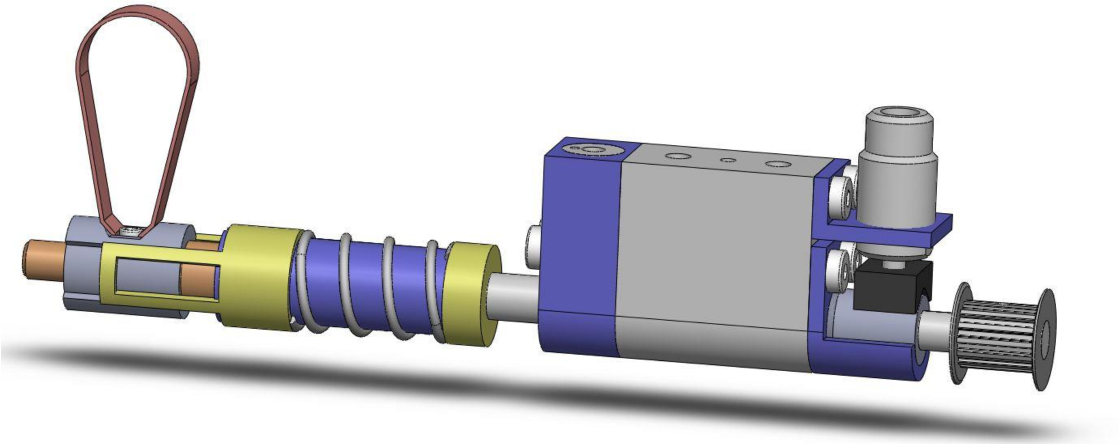

Master of Science Thesis MMK 2014:27 MKN 117
KTH Industrial Engineering and Management
Machine Design
SE-100 44 STOCKHOLM

KTH Industriell teknik och management	**Examensarbete MMK 2014:27 MKN 117** **Utveckling av ett EDM-verktyg för kärnkraftsindustrin** Rabi Kaya Anders Ödling	
Godkänt 2014-06-14	Examinator Ulf Sellgren	Handledare Kjell Andersson
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Sammanfattning

Electric Discharge Machining (EDM) är en avverkningsmetod lämplig för reparations- och underhållsarbete i kärnkraftverk. Sprickbortagning och materialprovtagning är två vanliga operationer som utförs med hjälp av EDM inom kärnkraftsindustrin. Varje sprickbortagnings- och materialprovtagnings operation är unik, därför utvecklas ett nytt EDM-verktyg inför varje operation. Detta tillsammans med det faktum att elektroden som används i EDM-verktyget ofta slits ned innan sprickan har avverkats eller provet har tagits ligger till grund för detta examensarbete.

Målet var att utveckla ett eller flera koncept av modulära EDM-verktyg med möjligheten att byta elektrod på plats där aktuell reparation utförs. Detta för att korta ned utvecklingstiden för nya EDM-verktyg och minska tiden för reparations och underhållsarbeten. Koncepten skulle utvecklas så långt att en prototyp kunde tillverkas och testas.

Resultatet är i linje med målet, ett välutvecklat koncept som är redo för tillverkning och testning. Det har än så länge inte blivit tillverkat och således inte testats. Konceptet består av ett smalt EDM-verktyg med möjlighet att låsa elektrodrotationen, kompakt dielektrikum- och ström-tillförsel, hydraulisk aktuator med kuggremsdrift och ett elektrodmagasin med plats för 3 elektroder.

Nyckelord: Kärnkraft, EDM, Electric Discharge Machining, Produktutveckling, Sprickborttagning

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Approved	Examiner	Supervisor
2014-06-14	Ulf Sellgren	Kjell Andersson
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Abstract

Electric Discharge Machining (EDM) is a machining method suitable for repair and maintenance operations in nuclear power plants. Crack removal and material sampling are two common operations where EDM is used in the nuclear power industry. Each crack removal or material sampling operation is unique, a new EDM-tool is therefore designed for every operation. This, together with the fact that the electrode used in the EDM-tool usually wears out before the crack is removed or the sample has been collected, is the foundation of this thesis.

The objective was to develop one or several concepts of a modular EDM-tool with the ability to change electrode at repair location. This to shorten the development time for EDM-tools and the time for electrode change during an EDM operation. The concepts would be developed to the extent that a prototype could be manufactured and tested.

The result is in accordance to the objective with one fully developed concept ready for manufacturing. It has not yet been manufactured, and therefore not been tested. There are still some sections of the tool that needs to be verified, for example the electric supply to the electrode. The concept consists of; a slim EDM-tool with the ability to lock the rotating electrode shaft, compact dielectric fluid- and electric-supply, hydraulic actuator with belt drive and an electrode magazine with place for 3 electrodes.

Keywords: Nuclear, EDM, Electric Discharge Machining, Product development, Crack removal

Foreword

This is a Master of Science Thesis written at the Royal Institute of Technology, Stockholm, commissioned by Westinghouse Electric Sweden, Västerås.

The task given was very interesting and it has been a great experience for both of us. We want to thank Westinghouse Electric Sweden for the opportunity to carry out this project and we appreciate all the support and resources given to us.

Special thanks to our supervisor Henrik Remahl for all the positive feedback, insightful tips and superb support during the project work.

From the Royal Institute of Technology, special thanks to our supervisor Prof. Kjell Andersson for assisting us whenever we had any questions.

Anders Ödling & Rabi Kaya

Stockholm, June 2014

Nomenclature

Here are the Abbreviations that are used in this Master thesis.

Abbreviations

EDM	Electrical Discharge Machining
BWR	Boiling Water Reactor
PWR	Pressurized Water Reactor
NPP	Nuclear Power Plant
SCC	Stress Corrosion Cracking
HAZ	Heat Affected Zone

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1 Introduction

1.1 Background

During repair of systems close to reactors in the nuclear industry the main processing/machining method used is Electrical Discharge Machining (EDM). The EDM process does not leave any, to the reactor and nuclear process, harmful chips behind and the impact on the processed surface is kept at a minimum. With EDM, repairs can be done that otherwise is not possible with conventional processing methods. Particular, this applies to removal and sampling of surface defects in the reactor pressure vessel or internal components.

When sampling a surface breaking defect with the EDM process, an annular shaped electrode sweeps over the material and can thus remove a “boat”-shape sample. The goal and purpose of the repair is to completely enclose the defect and all crack-tips within the sample. In addition, the surface left behind on the workpiece from where the sample was taken, must have a geometry and surface topography which minimizes the risk for new defects to occur. It often requires the use of many different electrode configurations in order to obtain desired properties on the final surface, see Figure 1.

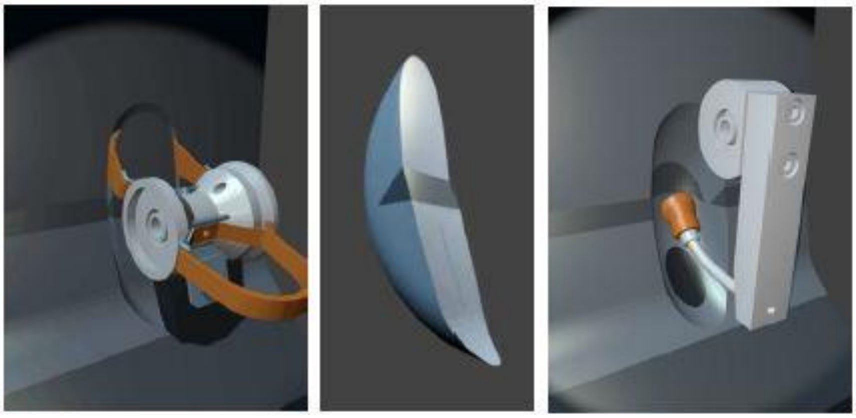

Figure 1. To the left is the EDM-tool. Center shows a boat sample, and to the right is an alternative electrode configuration for fine tuning of the surface.

1.1.2 Problem description

Since each repair is unique in terms of where the defect is located, the size of the defect and how the surrounding geometry looks like in the reactor pressure vessel, a specific EDM-tool and repair system is designed for each instance of repair. In Figure 2 an example of a repair system containing the EDM carrier with corresponding EDM-tool can be seen. A great portion in the development of the repair tool is aimed at minimizing the wear of the EDM-electrodes. This is due to the time consuming process of changing the electrodes, which has a direct impact on the availability of the power plant.

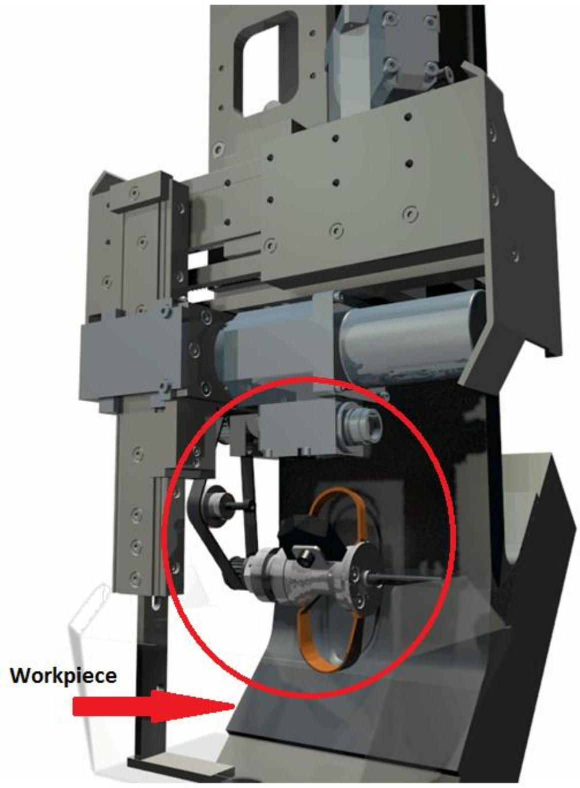

Figure 2. Example of a repair system, the EDM-tool is highlighted inside the red circle which is connected to the EDM-carrier.

1.2 Purpose

The purpose of this master thesis project is to develop one or several concepts of a modular EDM-tool for crack removal and sample collection in the reactor tank. The aim is to reduce the downtime of the power plant by designing a EDM-tool capable of changing worn out electrodes, or to a different type of electrode configuration, at the repair location and thus speed up the overall repair process. This means that the repair system does not need to be hauled up to the operating platform for manual electrode change, which until now has been a very time consuming process. The manual change of electrode at the operating platform inflicts further more problems; the position of the EDM-tool at the repair location is only visualized through a camera to the operator. When hauled down after electrode change it is basically impossible to position the tool at the correct position to continue the machining in the same sweep track created by previous electrode. This means that more material must be removed, which together with the up- and down hauling of the tool and manual electrode change dramatically increases the repair- and downtime of the power plant.

The design process of an EDM-tool is a time consuming part in the development of the EDM repair system, which can be reduced by a pre-developed modular EDM-tool.

1.3 Master Thesis objectives

The modular unit should contain the electrode, a driving unit for the rotation of the electrode and interfaces for the rinsing water and electrical current for the electrode. The concept of a modular unit lies in its flexibility to fit and function for different types of end applications, in this case the entire repair system and EDM-carrier. This demands a high flexibility regarding the interface between the modular EDM-tool and the EDM-carrier, and also on the size of the tool. The main objective of the project is to generate a concept of a modular EDM-tool which has the ability to change electrodes at repair location and also fit and function together with the majority of EDM-carriers developed in the future.

1.4 Delimitations

This project ends with one or several well defined concepts on the intended modular EDM-tool. All aspects of the concept/concepts must be clarified with defined components and interfaces. This leaves the project at a stage where the next step is to produce detail designs and manufacturing drawings of each component.

The function and design of the EDM-carrier is excluded from this project, only the interfaces between the EDM-carrier and EDM-tool will be taken into account.

The current EDM process used will not be altered nor optimized in terms of wear of the electrodes. The wear of the electrodes can be minimized by using an EDM technique called *No wear machining* (Jameson, 2001), thou this would require a large and time consuming study of its own. A brief study of the general EDM process will be conducted, and also on the specific EDM technique known as *No wear machining*.

1.5 Method

The project starts with a literature study and information gathering on relevant subjects which are necessary for the further work. Discussions will be held with relevant people with expertise on the subjects. When all necessary information has been gathered, a requirement specification for the modular EDM-tool will be produced. The requirement specification will be based on the literature study and on customer demands.

The requirement specification will be the foundation of the concept generating and evaluation phase of the project. Concepts will be generated by the use of brainwriting (Baxter, 1995), the collective note book (Baxter, 1995) and brainstorming together with Westinghouse engineers. At the early stages of the project, the EDM-tool will be divided into modules. Concepts will be generated for each module which later on will be assembled to a complete system of the EDM-tool.

The concepts of the modules will be evaluated together with engineers from Westinghouse at specific concept evaluation meetings. Dot sticking (Baxter, 1995) and brainstorm will be the tools used during these meetings, the concepts will be evaluated against each other and the requirement specification; the best suitable concepts will thereafter be subjected to further development.

The concept generating and evaluation phase is a highly iterative process. The iterative process will continue until a concept or several concepts are produced that satisfies the customer needs, wishes and demands. During this iterative process prototypes will, whenever needed, be manufactured to assist the concept evaluation phase.

2 Frame of references

2.1 Westinghouse Electric Company

Westinghouse Electric Company operates worldwide and provides fuel, services, technology, plant design and equipment for the nuclear electric power industry. The company is a part of the Toshiba-group and has more than 10 000 employees worldwide (Westinghouse, 2014).

Westinghouse Sweden is a part of Westinghouse Electric Company and operates in the Nordic-region with headquarter in Västerås. Westinghouse Sweden was founded in 1969 as ASEA-ATOM and later known as ABB Atom and in 2003 as Westinghouse Sweden. The company has about 1000 employees and operates in three product lines, Nuclear Fuel, Nuclear Automation and Nuclear Services (Westinghouse Sweden, 2014).

2.2 Nuclear power plant

The objective of a nuclear power plant is to produce electricity. To achieve this, water is heated into steam which drives a turbine. The turbine is connected to a generator which transforms kinetic energy into electricity. Same principles are used in conventional fossil-fueled power plants, where the fuel is combusted to heat water into steam. In a nuclear power plant the fuel is split at an atomic level, releasing energy which is used to heat water into steam (Forskning.se, 2011).

The process of splitting atoms is called fission. The fuel in a nuclear power plant, most commonly the isotope Uranium-235, is subjected to the fission (Vattenfall, 2013). The fission occurs in the core of the reactor. Neutrons are put in motion and allowed to collide and split the uranium fuel. When a nucleus of a uranium atom is split, it releases new neutrons which collide with further uranium atoms, and thus a chain reaction is initiated. The chain reaction, which can be seen as a continuous fission of atoms, releases the thermal energy harnessed to heat water into steam (Vattenfall, 2013).

The continuous fission of atoms is controlled in several ways. The material around the core, called moderator, is used to slow down released neutrons from the chain reaction. Usually water is used as moderator, but there are also reactor types which use graphite or heavy-water as moderator. The moderator cannot control the reaction rate or completely halt it if necessary, this task is given to the control rods. Made of neutron absorbent material, the chain reaction in the reactor core is controlled by insertion or withdrawal of control rods (World Nuclear association, 2014).

2.2.1 Nuclear power in Sweden

In Sweden there are 10 operational reactors at three different locations: Forsmark (3 reactors), Oskarshamn (3 reactors) and Ringhals (4 reactors). The two reactors at Barsebäck nuclear power plant were taken out of operational service in 1999 and 2005. All of the reactors at Forsmark and Oskarshamn are of BWR type, but three of the four reactors at Ringhals are of PWR type (Forskning.se, 2011).

2.2.2 BWR

Boiling Water Reactors uses water as moderator and coolant for the reactor core. When the water circuits thorough the reactor core it begins to boil, producing steam which is utilized by the turbine driving the generator. This means that the moderator, in this case water, also serves as the source of steam for the turbine in a closed circuit (The Institution of Electrical Engineers, 2005), see Figure 3.

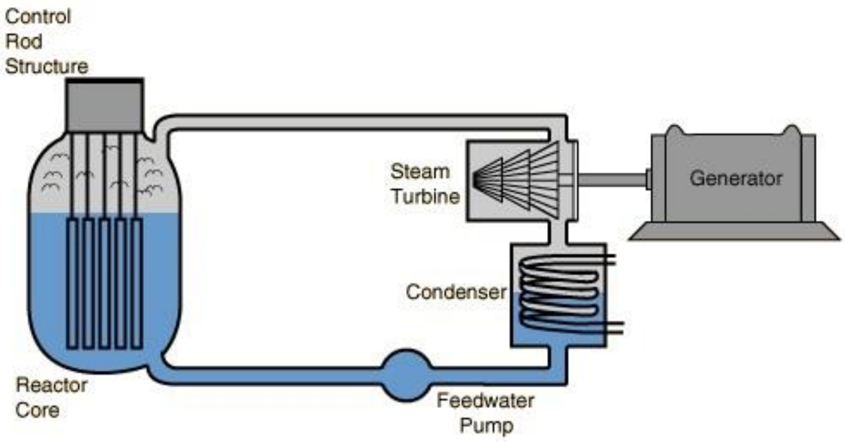

Figure 3. Schematic overview of the electricity generating process of a BWR (Hyperphysics, 2000).

When the steam exits the turbine, it is led into a condenser which condenses the steam into water again. The water is thereafter pumped back into the reactor for another loop in the process. One disadvantage with a BWR is that the steam circuit and the turbine are radioactively contaminated and therefore needs to be shielded from the surrounding environment. BWR are less complex compared with other reactor types and are usually cheaper to build. There are about ten countries around the world that uses BWRs (The Institution of Electrical Engineers, 2005).

2.2.3 PWR

Just like the BWR, Pressurized Water Reactors also uses water as moderator and coolant for the reactor core. But the water is isolated from the turbine in a pressurized primary loop, preventing the water from boiling. The heated high-pressure water in the primary loop, which has passed through the reactor core, is instead producing steam in a secondary loop using a steam generator; the steam is then utilized by the turbine to drive the generator (The Institution of Electrical Engineers, 2005), see Figure 4.

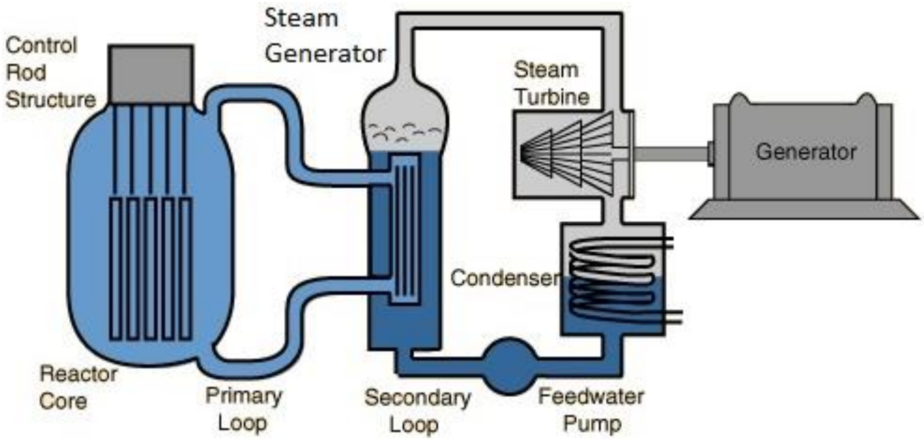

Figure 4. Schematic overview of the electricity generating process of a PWR (Hyperphysics, 2000).

When the steam from the secondary loop exits the turbine, it is led into a condenser which condenses the steam into water again. The water is thereafter pumped through the steam generator once more. The pressurized water in the primary loop, used to produce steam in the secondary loop, is pumped back in to the reactor to be reheated, besides its essential task to cool and moderate the reactor core. The primary advantage with a PWR is that the design prevents the condenser and the turbine from being radioactively contaminated, but they are more expensive and complex to build. The PWR is the most common reactor type in the world (The Institution of Electrical Engineers, 2005).

2.2.4 Wear/cracks in reactor

The reactors in Sweden were built in the 1970s and 1980s, most of the mechanical components where designed for an operation time of 40 years (Ekström et al., 2011). The consequence of running a Nuclear Power Plant (NPP) over its intended life expectancy is the risk of mechanical- or structural failure. The reactors used in Sweden do not have an end-date to when they have to be taken out of service, instead they are kept under close surveillance and inspections are made to ensure the integrity of the structure (Ekström et al., 2011).

Inside the reactor pressure vessel there are many factors that act negatively on the ageing of the materials, such as radiation, high temperature, high pressure and possible impurities in the coolant water are some examples (Tipping, 1996). One of the main ageing processes is Stress Corrosion Cracking (SCC) (Schvartzman et al., 2011), which is an ageing mechanism due to mechanical, electrochemical and microstructural factors (Ekström et al., 2011). The radiation of fast neutrons affects the steel in the reactor pressure vessel and its internal components by embrittlement of the irradiated area. The radiation can also affect the composition of the alloying elements in stainless steel that could lead to corrosion (Tipping, 1996). Only material close to the reactor core, called the beltline, will be affected by the radiation (Ekström et al., 2011).

If a crack is found in the reactor pressure vessel or its internal components, evaluations of the cracks growth rate and potential risk has to be made (Schvartzman et al., 2011). Some components subjected to cracks can be replaced but not always, it is of course an economical issue. If the damaged area cannot be changed and the crack poses a risk, it could be repaired by a method called EDM.

2.3 Electrical Discharge Machining

According to Jameson (2001) the definition of Electrical Discharge Machining (EDM) is "… the process of machining electrically conductive materials by using precisely controlled sparks that occur between an electrode and a workpiece in the presence of a dielectric fluid."

EDM is one of the most widely used processes of removing material in a non-conventional way. During the material removing process with EDM there is no physical contact between the electrode (seen as the EDM tool) and the workpiece (Ho and Newman, 2003), which is the main difference between EDM processing and conventional machining operations (Jameson, 2001). Due to the absence of contact between the electrode and workpiece, there is no occurrence of tool force (Jameson, 2001). Additionally this eliminates any mechanical stress and vibration issues during the material removal process (Ho and Newman, 2003). In order to remove any material from the workpiece, the electrode is required to be spaced at a specific distance from the workpiece to initiate sparking, called the sparking gap. Any contact between the electrode and the workpiece would cease the flow of electricity, and thus terminate sparking and material removing (Jameson, 2001).

When initiating machining a spark will originate from the point which has the least distance between the electrode and workpiece. The spark between the electrode and workpiece generates heat to the point where material is vaporized. Since material is removed by generated heat, EDM is seen as a thermal machining process, but the heat affected zone (HAZ) is very small compared to other thermal machining processes (Jameson, 2001).

Maintaining the sparking gap requires a dielectric material between the electrode and workpiece, this material is usually a fluid. The dielectric fluid has the characteristic of being an electrical insulator as long as the applied electric voltage is not high enough. Applying enough voltage turns the dielectric fluid into an electric conductor, called the ionization point. This behavior and characteristic of the dielectric fluid is exploited when EDM machining, the dielectric fluid will remain as an electric insulator except at points where the distance between the electrode and workpiece are close enough. Caused by the sparking voltage, the dielectric fluid at these points will turn into an electric conductor, allowing a spark to occur between the electrode and workpiece. The dielectric fluid deionizes when turning off the spark, and it is transformed back to an electric insulator. The transformation of the dielectric fluid from an insulator – conductor – insulator occurs for every spark (Jameson, 2001).

Except from controlling and maintaining the sparking gap and providing an electric conductive column between the electrode and workpiece, the dielectric fluid has another two important functions during EDM machining (Jameson, 2001):

- Forming EDM particles out of the heated and vaporized material by cooling it
- From the sparking area flush away the EDM particles

2.3.1 Machining process

The fundamental parts of an EDM process includes the electrode, workpiece, a dielectric fluid and a well-controlled spark (Abbas et al., 2007), see Figure 5.

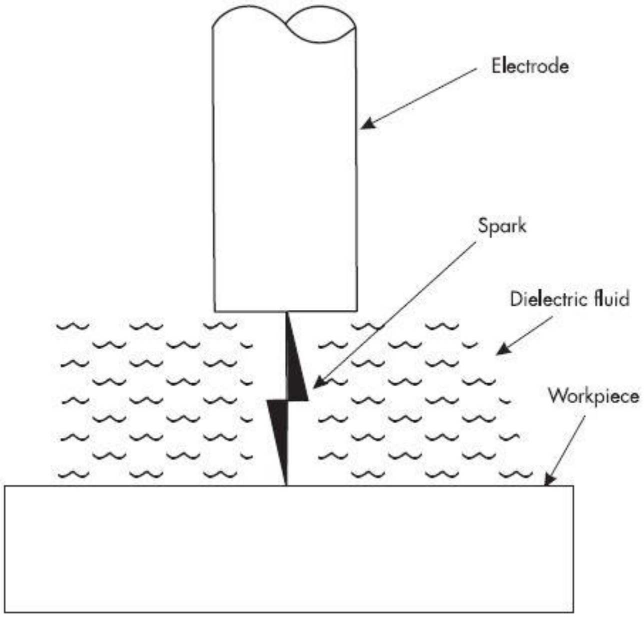

Figure 5. Fundamental parts of the EDM process (Jameson, 2001).

Normally the spark occurrence frequency is in a range from 2000 – 500 000 per second. It may seem that different sparks occur at the same time, but a fundamental basic of EDM machining is that only one single spark occurs at each instant. The EDM power supply that includes a DC power source provides the required energy for the sparks in the sparking gap and is connected to both the electrode and workpiece (Jameson, 2001). At the point from where the spark originate, material will be removed from both the electrode and workpiece, increasing the distance between them at this point (Abbas et al., 2007). An EDM spark inside the ionized column surrounded by the dielectric fluid is illustrated in Figure 6.

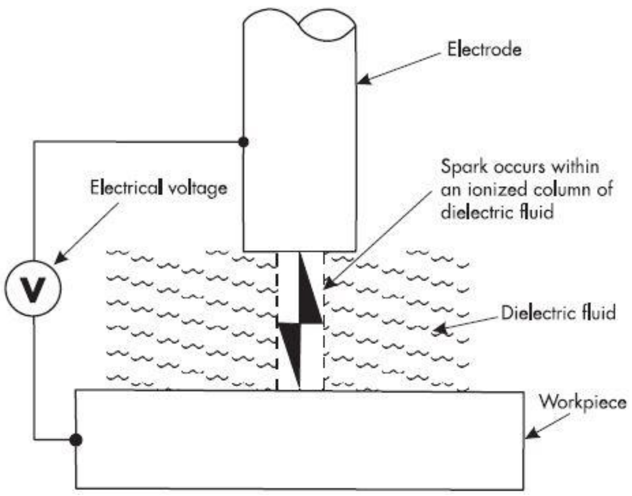

Figure 6. EDM spark within ionized column of dielectric fluid (Jameson, 2001).

For every spark a small piece of material from both the electrode and workpiece vaporizes, creating what can be described as a cloud of vaporized material, the cloud appears between the electrode and workpiece in the sparking gap. The dielectric fluid cools and turns the vaporized cloud into a solid EDM chip when turning off the spark (Ho and Newman, 2003), see Figure 7.

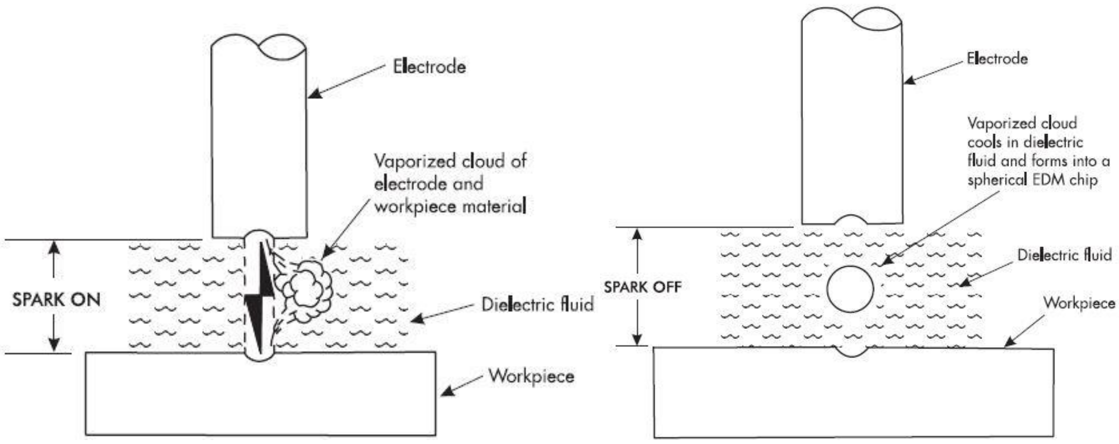

Figure 7. Left: EDM spark producing cloud of vaporized material. Right: Dielectric fluid cools the cloud which turns into an EDM chip (Jameson, 2001).

The dielectric fluid flowing into the sparking area flushes away the EDM chip, preventing it from affecting the following spark (Ho and Newman, 2003). Sparking will continue at chosen frequency as long as the electrode and workpiece is within the sparking gap and an electric voltage is applied between them. The surfaces of the electrode and workpiece have small irregularities and each spark will occur at the closest point between them. The following spark will then appear at the current closest point between the electrode and workpiece (Jameson, 2001), see Figure 8.

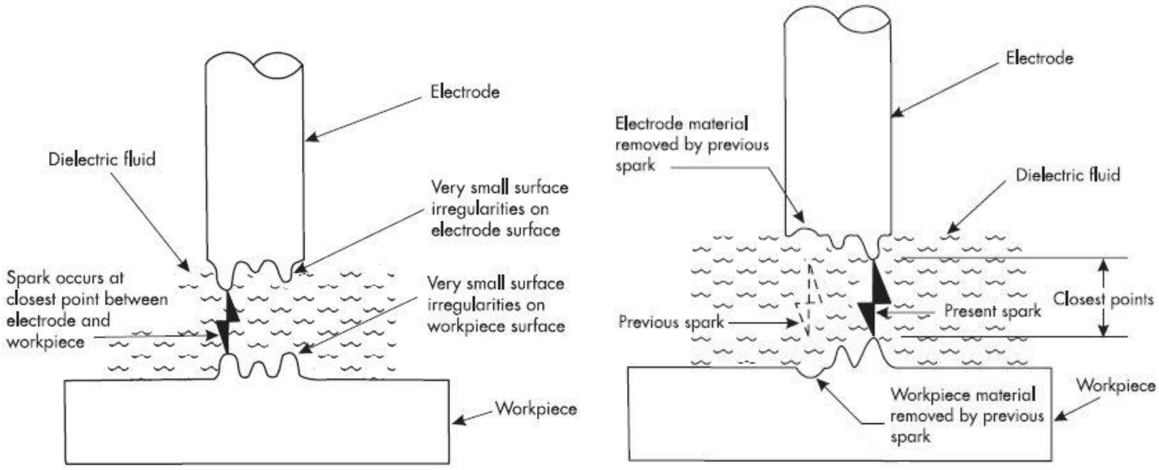

Figure 8. Left: Spark occurrence at closest point between the electrode and workpiece. Right: Following spark occurs at the current closest point between the electrode and workpiece (Jameson, 2001).

After a while, when enough material has been removed, there is no point between the electrode and workpiece within the sparking gap, and the electrode must be moved towards the workpiece for further machining (Abbas et al., 2007).

Since the electrode and workpiece are connected electrically it is possible to choose their polarity. With a positive charged electrode, electrons are attracted to it and the workpiece attracts the positive ions since it is negatively charged, and vice versa with opposite polarity. The attraction of either positive ions or electrons can be seen as bombardment on the surface of the electrode and workpiece by these particles. During the bombardment, millions of electrons and positive ions flow through the ionized column in the dielectric fluid, generating the heat and plasma which vaporizes and removes material from the surfaces of the electrode and workpiece (Jameson, 2001).

The wear on the electrodes has a direct influence on the effectiveness of the machine operation. A high electrode wear requires a more frequent change of electrode, increasing the downtime of the operation. According to Jameson (2001) research has shown that specific setup of machine operation, using positive electrode polarity together with certain electrode materials, reduces the electrode wear. But this setup also reduces the material removal rate of the workpiece. On the other hand, a setup with a high electrode wear together with a superior material removal rate might be beneficial if the whole operation takes less time to complete, even though the electrodes needs to be changed more frequently.

2.3.2 No wear machining

There are many ways to minimize wear on the electrodes during EDM machining. It often requires a specific setup of the EDM process regarding electrode material and polarity, electrical settings, type of dielectric- and workpiece material etc. (Ho and Newman, 2003) (Abbas et al., 2007). One way of completely eliminating the issue with electrode wear is by using the method called No wear machining.

No wear machining requires following setup and conditions of the EDM process (Jameson, 2001):

- Electrode is made of graphite or copper
- Workpiece is made of steel
- Electrode has a positive polarity
- Time which the spark is allowed to appear (known as spark-on time) is long
- Flow of the dielectric fluid passing the sparking gap must have low velocity
- Capacitors cannot be used

The idea and process with no wear machining is to impregnate the electrode with removed workpiece material, creating a new sparking surface on the electrode for each spark. Since the polarity of the electrode is required to be positive, the electrode will be bombarded by electrons and the workpiece by positive ions. As stated before, this polarity configuration has a lower material removal rate compared with a negatively charged electrode, increasing the machining time. The spark-on time needs to be long enough for the vaporized cloud of workpiece material, which is negatively charged, to reach the positively charged electrode before it is cooled and solidified, impregnating the surface of the electrode. The recently created sparking surface on the electrode will be subjected to the bombardment of electrons during the following spark, which will wear away the protective impregnation. The impregnated surface on the electrode will wear away for each spark, but the sparks will at the same time generate new impregnated surfaces of solidified vapor from the workpiece material removed. The use of low flow velocity on the dielectric fluid ensures that the vaporized cloud has a chance to reach the electrode before it is cooled and solidified or flushed away (Jameson, 2001).

2.4 Current repair process

A repair inside the reactor pressure vessel has many challenges, it is hard to reach the repair area, it is a radioactive environment, and the pressure vessel is filled with water and packed with internal components. Machining process on the reactor pressure vessel or its internal components inflicts even more problems, residual chips from the material removal process poses a risk to the nuclear fission if left in the pressure vessel. Instead of conventional machining methods EDM is used, chips are still produced, but their sizes are so small they can be seen as particles, eliminating the damage they can inflict.

The EDM process is used for a number of applications inside the reactor pressure vessel, e.g. removal of components, sampling of reactor material and creating varies holes are some of the applications it can be used for. One of the main uses of EDM is the removal of cracks inside the reactor pressure vessel and its internal components, either by taking a boat sample, see Figure 1, which encloses the crack in a boat shape sample, or by completely machining away the affected crack area with a solid electrode. With different size, shape and position of cracks within a reactor and also in which reactor type/model the crack is situated makes every crack removal project unique. The EDM tool and carrier is therefore custom-made for every project; the operating procedure of the unit is on the other hand quite similar for all projects.

In Figure 9 a sketch of an EDM process with surroundings inside a nuclear power plant can be seen. The lid to the reactor pressure vessel is removed; the internal parts situated above the reactor core grid are also removed if necessary. To haul down the EDM tool and carrier to the repair area a number of interconnectable slender aluminum rods are used. Cameras are used to aid in the down hauling and the positioning of the EDM tool, the reactor pressure vessel can be up to 20 meters deep and the distance up to the service platform is another 8-10 meters. With the tool in correct operating position the tool frame is fastened to a suitable base by clamps.

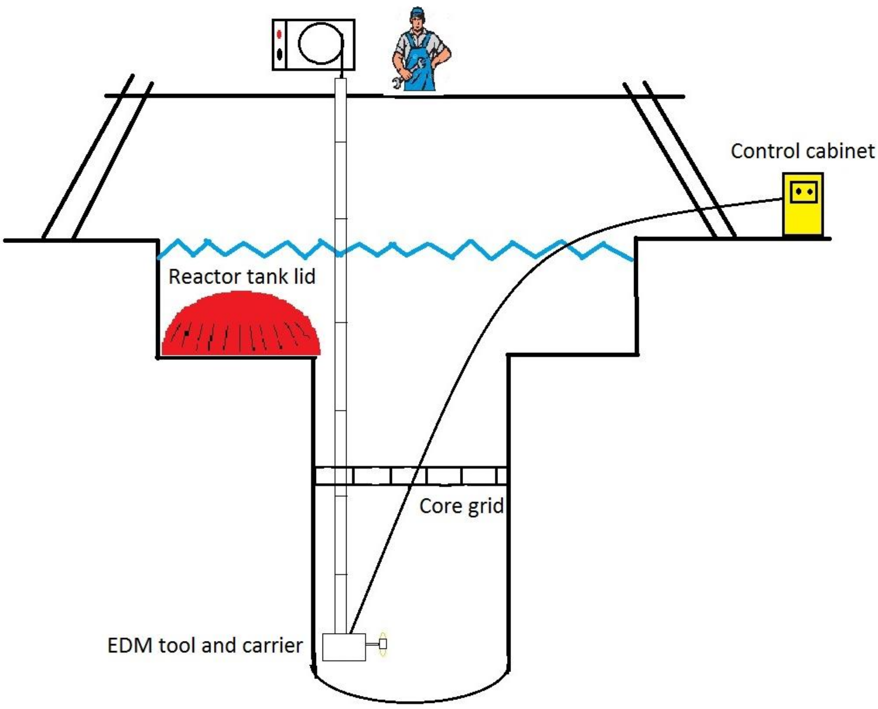

Figure 9. Layout of repair process inside a nuclear power plant

To fine tune and adjust the electrode to the exact spot of operation a positioning table, driven by linear actuators, is connected between the fixed frame and the EDM-tool. The rotary movement of the electrode is driven by either hydraulic- or electrical-actuators. Electrically driven linear units pose a risk to be damaged when passing through the reactor core. The hydraulic fluid is a mixture of water and glycol, normal hydraulic oil cannot be used in case of leakage. The EDM-tool needs to be fed with electricity for the electrode sparking and the workpiece needs to be connected to the ground; all cables are connected to a control cabinet. The ground is preferable connected as close as possible to the sparking area; therefore it is typically integrated in the EDM carrier. The rotary movement of the electrode is usually actuated by a hydraulic rotary cylinder, the valves which control the rotary movement needs to be very close to the cylinder to minimize the time delay and elasticity problem due to expanding hydraulic tubes. The electrode is also connected to a signal wire to obtain a signal when the distance between the electrode and workpiece is close enough for a spark to occur. When a spark occurs a signal is given to the valves that change the direction of rotation of the rotary cylinder. This ensures that the electrode never comes in contact with the workpiece. The pulsating movement of the electrode also assists the removal of particles and eases the flow of the dielectric fluid in the sparking gap.

The dielectric fluid is regular deionized water, supplied to the sparking gap through nozzles close to the electrode or through channels in a solid electrode. The deionized water is not taken from the reactor water but is supplied externally. To collect and remove the particles from the machining process area, the water containing particles is pumped and led away. The water is thereafter passed through a filtration station and then released into the pool or the plants sewage. During the EDM process one or several cameras are used to inspect the work in progress, the electrode is checked from time to time to measure the wear. If the electrode gets to thin the whole EDM tool and carrier has to be hauled up and the electrode needs to be changed.

The boat sampling electrodes are made out of Copper-Tungsten alloy and the electrodes used for final surfacing or solid electrodes are made out of graphite. Graphite is typically too brittle to be used for the ring-shaped electrodes needed for boat sampling. In many regular EDM processes copper is used as material for the electrodes, but copper possess a risk due to corrosion on the stainless steel, which all reactor pressure vessels are made of. The Copper-Tungsten alloy is not as harmful as pure copper, the copper in the electrode that manages to get into the machined stainless steel surface is removed when using graphite electrode to finalize the machined surface in the EDM process.

The process of producing a concept of the modular EDM-tool begins with a definition of the complete EDM-tool, its interfaces with the rest of the EDM repair system and also the interfaces within the EDM-tool. The EDM repair system is divided into 5 modules:

- Control cabinet
- EDM-carrier
- Driving
- Electrode
- Electrode magazine

The first module, the control cabinet, is not subjected to any development in this project. This is the module which supplies the rest of the system with electric current, control signals, hydraulic fluid and dielectric fluid. The second module, the EDM-carrier, will have physical interfaces with the EDM-tool. These interfaces are developed in this project; the rest of the functions in this module will be left untouched. All modules with corresponding type of interfaces between them are illustrated in Figure 10. The remaining three modules build together up the EDM-tool. A brief description and objective of the three modules:

1. **Electrode module:** Electrode carrier that allows rotation, flow of dielectric fluid and electrical current and also contain a signal wire for the electrode sparking voltage. Quick lock and release function of the electrode.
2. **Driving module:** Create the rotational movement of the electrode and control the sparking gap between the electrode and workpiece.
3. **Electrode magazine module:** Contain different type of electrodes that are interchangeable with the electrode on the electrode module.

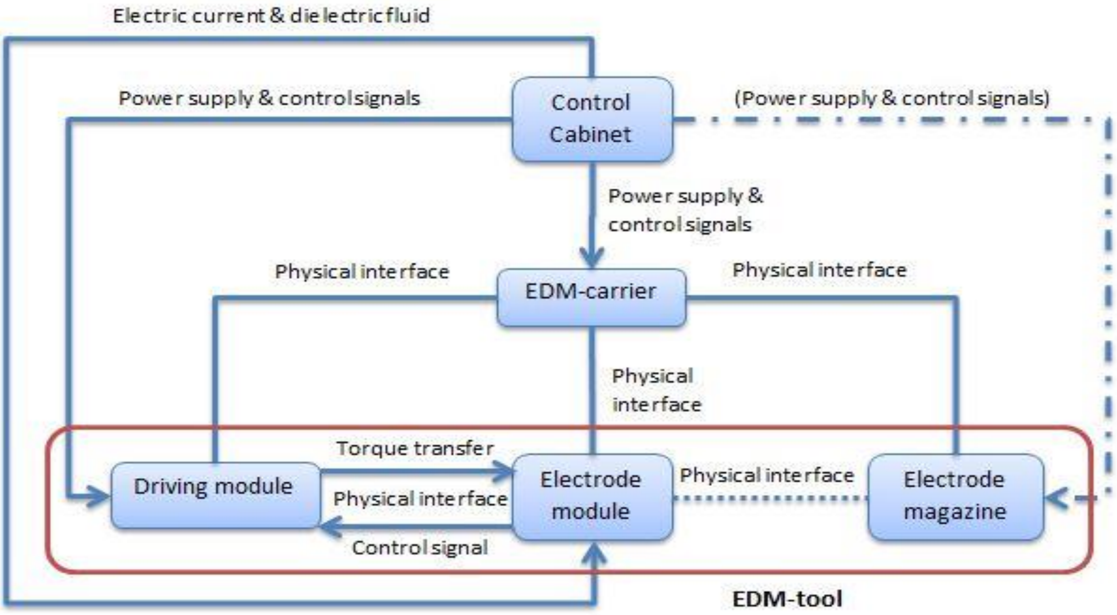

Figure 10. Module interfaces, the EDM-tool highlighted with the red rectangle

4 Development of an EDM-tool

Before any concepts of the modules within the EDM-tool can be generated, a requirement specification must be created. With a requirement specification at hand it is possible to generate concepts of the different modules. The requirement specification can be seen as the foundation of the concept generation phase, since all generated concepts will be based upon set requirements.

4.1 Requirement specification

Since the project is at concept level in the development of a modular EDM-tool, requirements and demands are set on functions which the tool must comply with. At the beginning of the project a requirement specification was not defined, Westinghouse Electric Sweden had an idea of what type of functions the EDM-tool should have. These functions together with the literature study are what the requirement specification is based upon. The modular EDM-tool is not designed for any specific case or application, it should be able to function in the majority of repair and sample collection operations within the reactor pressure vessel. Therefore a high demand on flexibility regarding tool setup and layout of components in the EDM-tool is required. Each specific case of repair and sample collection will need a more detailed requirement specification regarding size, setup and shape of the EDM-tool. The tool has requirements on the size only at the location where the electrode is situated; it is assumed that there is enough space 50mm above the lowest point of the tool to fit the rest of the equipment. The requirement specification can be seen in Table 1.

Table 1. Requirement specification with demands and wishes.

D/W	Requirement
D	Size of crevice that the EDM-tool must fit in: Width: 15, Length: 150, Depth: 50 [mm]
W	EDM-tool as small as possible
D	Ability to lock rotation in any position, thus allowing EDM stamping
W	Quick lock and release function of the electrode, no tool needed to assemble or disassemble the electrode. Can be done by hand
W	No need for extra actuator to assemble or disassemble the electrode
D	Possibility for implementation of automatic electrode change at repair location
W	Minimize the use of electronics and reactor sensitive materials

D	Possibility to choose the flow of dielectric fluid to the sparking gap: • Through a solid electrode • Alongside the edge of the electrode
D	Satisfactory interfaces of electrical connection in the EDM-tool to avoid sparking beyond the electrode
D	Positional feedback of the rotating electrode to the operator
D	No part is allowed to come off unintended during operation
D	Electrode must come loose if needed (e.g. if it get stuck)
W	If electrode get stuck, no extra equipment is needed to disassemble the electrode from the carrier
D	Cope with temperatures up to 50° C
D	Cope with the water pressure at a depth of 25m (~250kPa)
D	>360° rotation of the electrode
D	Ability to transfer 6 Ampere of current to the electrode
D	Flow of dielectric fluid: • min 5 l/min • max 6 Bar pressure
W	Minimize number of parts in the assembly
W	< 3 axis movements required for electrode change
D	>2 electrodes in the magazine
W	>3 electrodes in the magazine

4.2 Concept generation

With a well-defined system of the EDM-tool and corresponding interfaces between the three modules and the rest of the EDM repair system, it was possible to generate concepts for each individual module. To make sure that the development process headed in the right direction, regular concept evaluation meetings were held. At these meetings, which were attended by engineers from Westinghouse and the project members, current developed concepts were both compared against each other and evaluated in relation to how well they fulfilled the requirement specification.

4.2.1 Electrode module

The electrode module has interfaces towards the other four modules. The interface to the control cabinet is in form of input of electric current and deionized water. The electrode module is connected to the EDM-carrier with a fixed geometrical constraint and the EDM-carrier provides the positioning of the electrode. To allow rotation of the electrode some sort of rotational joint, e.g. bearings mounted onto a shaft, needs to be placed between the electrode and the EDM-carrier. In the interface toward the driving module, torque is provided for the rotational movement of the electrode. The electrode magazine has a physical interface with the electrode during the electrode change phase, the electrode needs to be able to change position from the electrode module to the electrode magazine module. The output from the electrode module is current to the sparking area, flow of deionized water to the sparking gap and signal output from the sparking voltage.

The electrode module was divided into sub-modules, quick lock, dielectric fluid supply, electric power supply, bearing and bearing housing. Concepts was created for each sub-module individually, and after evaluation combined into a complete module.

4.2.1.1 QUICK LOCK

Several concepts were developed at an early stage of the project for the electrode module quick lock function. Since the electrode should be able to be substituted during a repair operation, meaning that it must able to come lose at some point of the operation, the main difficulty in the development of these concepts was to not challenge the safety requirement stating that “no part is allowed to come off unintended during operation”. Additional difficulties emerged when it was decided at an early phase that quick lock function should be purely mechanical, meaning that no further electronic- or hydraulic devices could be used to aid the quick lock function except for those necessary for the EDM repair system. The generated concepts were to utilize the movement of the linear actuators in the EDM-carrier for their quick lock function.

After some development time and a few concept evaluation meetings, three distinct concepts were chosen for further development. Simple CAD-models of these concepts were produced, giving another dimension in terms of visualization of the concepts and how the quick lock function is intended to work, aiding evaluation and screening of the concepts at a later stage.

Bayonet concept:

The bayonet concept consists of an electrode carrier with an L-shaped track along its lateral surface, and an electrode with a foot fitting in the same track, see Figure 11. Positioning and locking the electrode onto the carrier requires two motions, first a linear motion produced by the EDM-carrier linear actuator and secondly a rotationally motion produced by the driving unit.

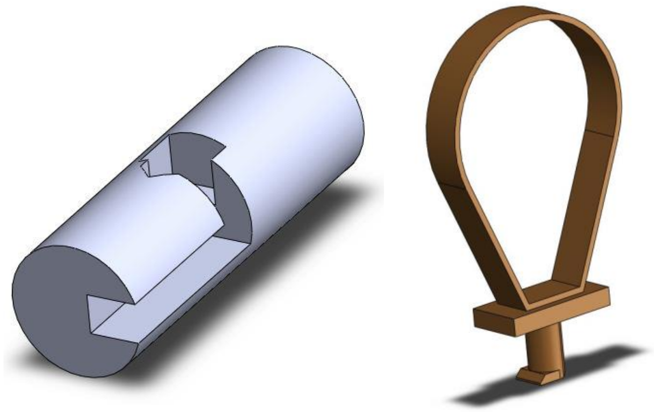

Figure 11. Bayonet concept. Left: electrode carrier. Right: electrode

The electrode foot is kept in position in the carrier by a spring biased pin, pushing the electrode foot against the carrier making sure the electrode does not slip out of the track, see Figure 12.

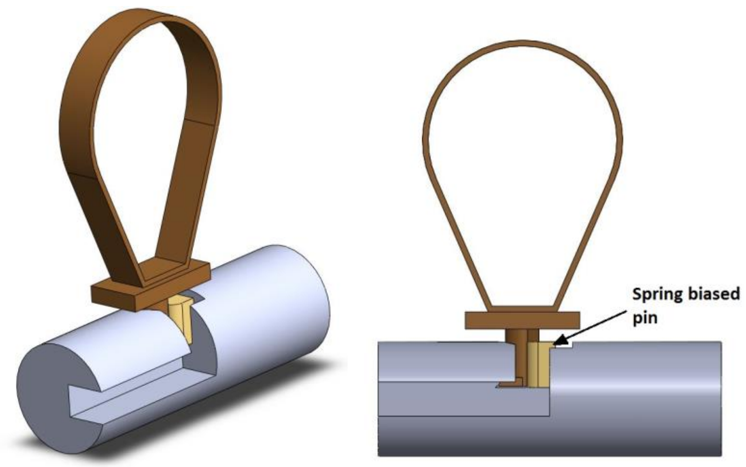

Figure 12. Electrode fitted inside the electrode carrier and pushed against the electrode carrier by the spring biased pin.

The requirement of two different motions to lock and release the electrode from the carrier is a neat solution; it makes it very difficult for the electrode to come off unintended. The process to change the electrode requires that the electrode is kept still while the operator initiates the rotary motion and thereafter the linear motion. Since the tolerances between the electrode foot and the L-shaped track are narrow, there is a high demand on the rotary motion accuracy. In some cases, depending on what type of driving unit is used, this can be problematic.

Snap-fit concept:

This concept utilizes the elasticity in materials to create force and friction between two separate parts. The electrode is mounted onto a carrier by a linear motion and is kept in position by the spring force created in a snap-fit. The snaps are located on the carrier and the electrode has a corresponding geometry ensuring a rigid fit is created between the two parts, see Figure 13.

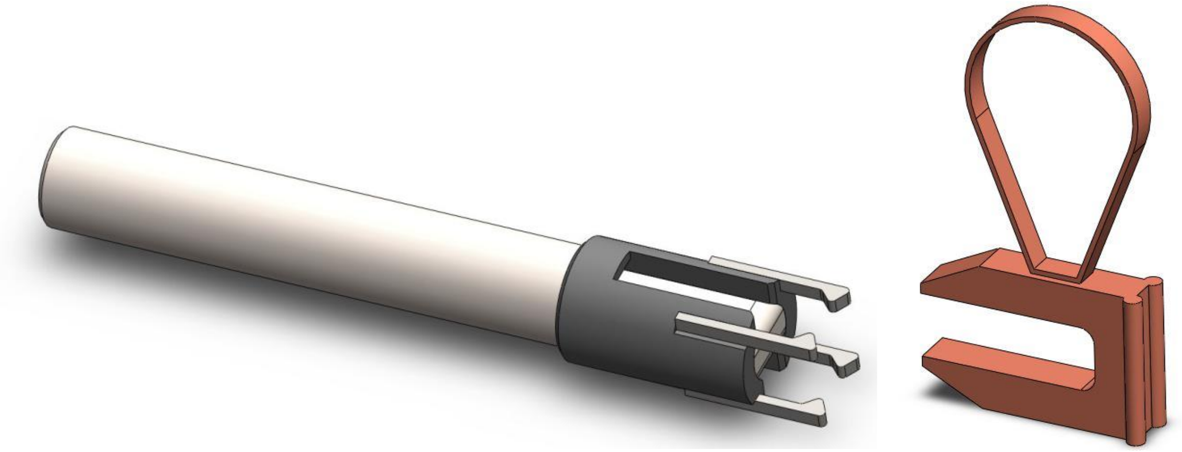

Figure 13. Snap-fit concept. Left: Shaft and the carrier with the snaps. Right: Electrode.

This concept only utilizes a linear motion created from the EDM-carrier linear actuator to mount the electrode onto the carrier, see Figure 14. For the electrode to come off from the carrier unintended, a linear motion strong enough to overcome the force and friction in the snap-fit must occur. Changing electrode requires that the electrode is kept at a fixed position while the EDM-carrier linear actuator moves the electrode carrier.

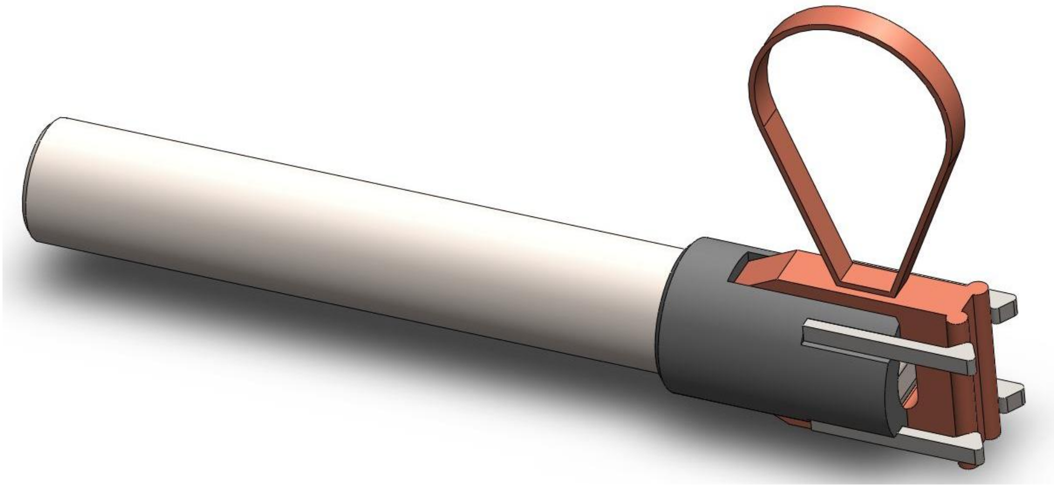

Figure 14. Electrode mounted in the snap-fit.

Ball-pin concept:

This concept utilizes spring biased ball-pins; see Figure 15, mounted on two parts which together builds up a carrier for the electrode. The second part of the carrier is mounted on the driving shaft and has tracks for the electrode to slide into, see Figure 16.

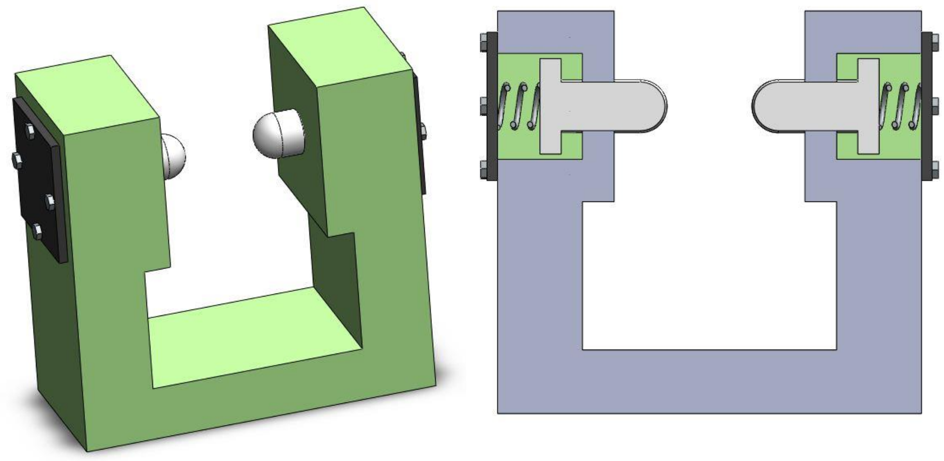

Figure 15. Ball-pin concept. Spring biased ball-pins mounted on a carrier.

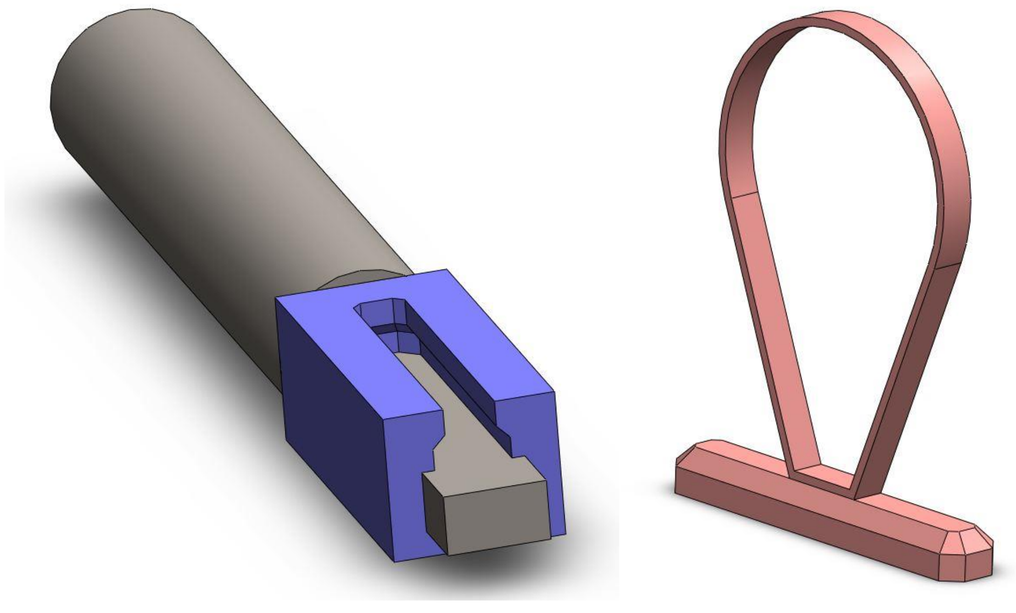

Figure 16. Left: Carrier with tracks for the electrode. Right: Electrode with tracks to be fitted in the carrier.

The electrode is kept in position in the carrier track by the force and friction created by the ball-pins, see Figure 17. Like the Snap-fit concept, this concept utilizes a linear motion created from the EDM-carrier linear actuator to mount the electrode onto the carrier. The process of changing electrode is very much the same as for the Snap-fit concept, the electrode must be kept at a fixed position while the EDM-carrier linear actuator moves the electrode carrier. Again the electrode would come off if a linear motion occur, overcoming the force and friction between the ball-pins and the electrode.

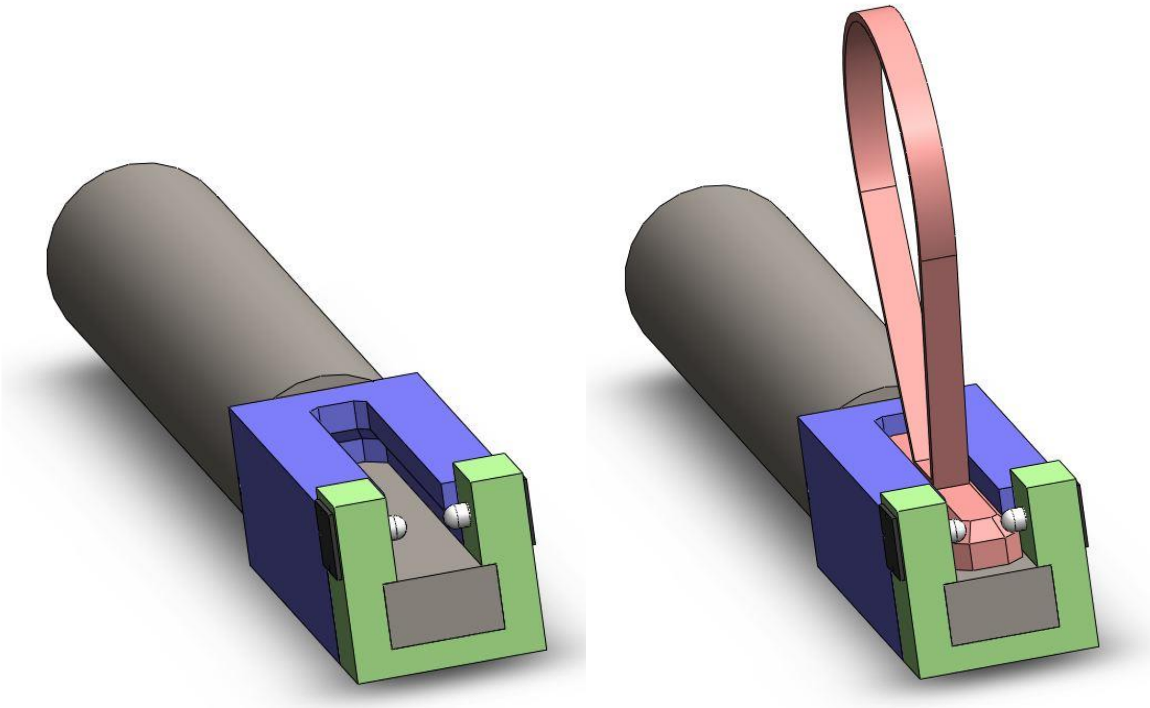

Figure 17. Electrode mounted in the carrier on the driving shaft.

4.2.1.2 DIELECTRIC FLUID SUPPLY

While developing concepts for the supply of dielectric fluid to the electrode, much thought was given to the flexibility in terms of where and how the fluid is brought to the electrode. Since the shape and size of the electrode varies from operation to operation, the dielectric fluid supply should not be affected by what type of electrode is in use.

Radially through shaft:

The dielectric fluid is led radially into the shaft by a rotary union. The fluid is thereafter led forward to the electrode carrier through a hole along the center axis of the shaft, with a plug sealing the backend of the shaft. The electrode carrier has built in canals, supplying the electrode with dielectric fluid to desired positions, see Figure 18.

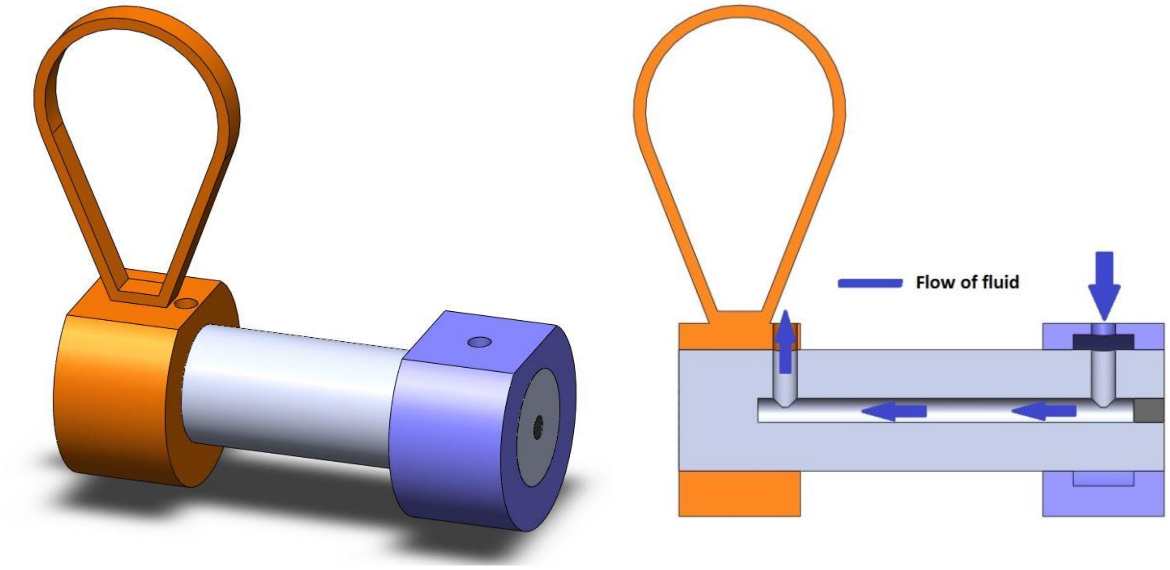

Figure 18. Left: radially through shaft concept. Right: illustration of the flow of dielectric fluid.

Axially through shaft:

Follows the same principal as the previous concept, but with one exception, the water is led into the shaft axially instead of radially at one end of the shaft, see Figure 19.

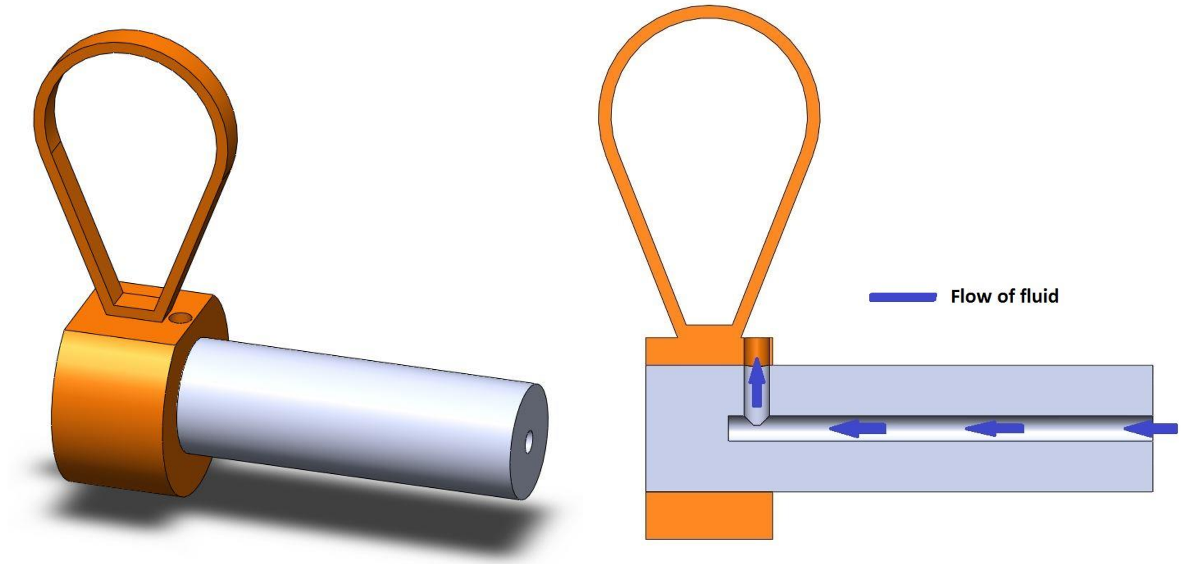

Figure 19. Left: axially through shaft concept. Right: illustration of the flow of dielectric fluid.

Externally along shaft:

A simple solution to provide dielectric fluid to electrode is by routing a pipe for the fluid along the shaft externally; eliminating the need of a union, see Figure 20. A disadvantage with this solution is that the outlet of the pipe is stationary; fluid will jet at the same place regardless of what type of electrode is currently in use. This is obviously not optimal, some solid electrodes requires that the dielectric fluid is led through it, by built in canals, which would not be possible with this solution.

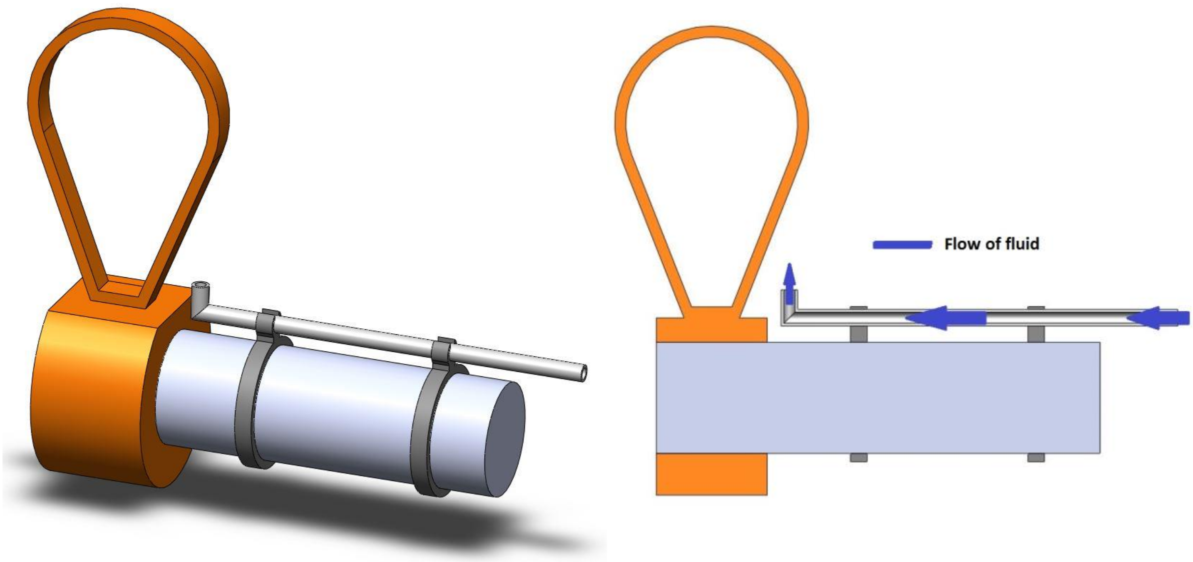

Figure 20. Left: externally along shaft concept. Right: illustration of the flow of dielectric fluid.

4.2.1.3 ELECTRIC CURRENT SUPPLY

Since the electrode must be supplied with current during the EDM process, the electric contacts and interfaces in the tool must be sufficient enough to handle the amount of current needed. There is also a possibility that EDM sparking can occur at these interfaces, which has to been taken into account in the design of the interfaces.

There are three main ways of leading electric current to the electrode:

- Directly connecting the electrode to the power supply.
- A wire through the shaft, and having an electric contact between the shaft and the electrode carrier.
- Using the shaft as an electric conductor, by connecting it to the power supply, and then having an electric contact between the shaft and the electrode carrier.

A slip ring connection can be used in the solution where the shaft is the electric conductor supplying the electrode carrier and electrode with current. A more simple solution would be to bolt a wire onto the shaft, but this would mean that the wire will turn and twist together with the shaft when it is rotating.

4.2.1.4 BEARING AND BEARING HOUSING

In the EDM process the electrode needs to be able to rotate. To allow rotation some kind of bearing and bearing housing is required. The type of bearings that could be used to support the shaft and allow rotation:

- Ball bearings
- Needle bearings
- Journal bearings

With the given concepts of the quick lock function, it is clear that axial forces will occur when changing electrode. Except from the axial force and the obvious gravitational force, no other outer forces will be applied on the EDM-tool during operation. If the shaft is used as an electric conductor, the bearings must be electrically insulated to avoid sparking within them. The ball bearings are the largest in terms of how much space they radially occupy, while the journal bearings are the smallest, but in the meantime the ball bearings can handle larger axial forces compared to the needle bearings and journal bearings.

4.2.2 Driving module

The driving unit is fixed to the EDM-carrier, connected to the same positioning table as the electrode module. It also has a physical interface to the electrode module where torque is transferred. Power and control signals are connected between the control cabinet and driving unit. The driving module contains a position feedback of the angular position of the electrode. A possibility to lock the rotational movement of the electrode is also a task within the driving module.

The driving unit in previous EDM-machining operations had mainly two types of actuators, hydraulic rotary cylinder and electric rotary actuator. The hydraulic actuator is more common to use due to its durability against the harsh environment in the reactor pressure vessel. The disadvantage is the size, only 270° rotation and the accuracy. Due to the size and in some cases the need for a full 360° turn, a timing belt is used between the actuator and electrode shaft, this on the other hand acts negatively on the accuracy. With the timing belt the hydraulic actuator can be placed more freely and with a gear ratio allow a 360° rotation of the electrode. The electric actuator is used mainly when the space at the repair location is so limited that the hydraulic actuator does not fit. In Figure 21 the two different configurations can be seen.

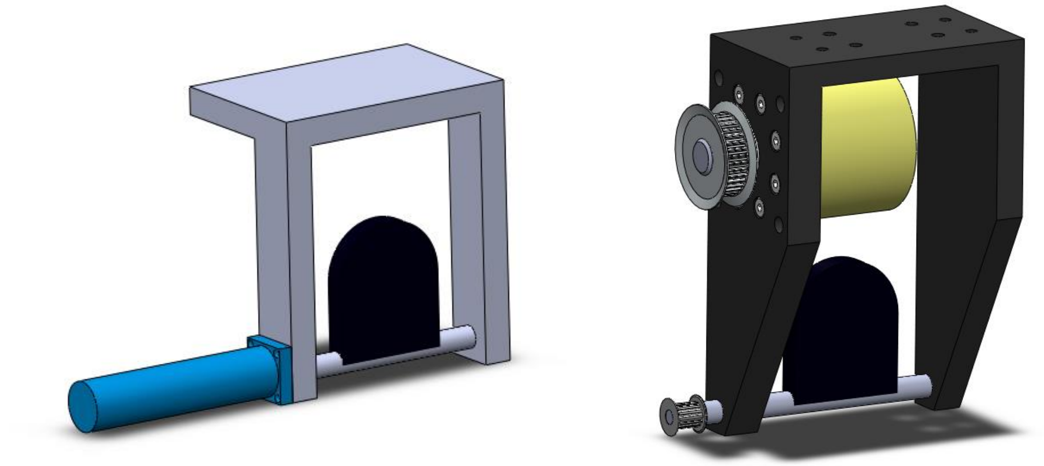

Figure 21. Left: direct drive configuration with electric actuator. Right: timing belt configuration with hydraulic actuator.

Concepts were created, not with different actuators but with different types of transmissions between the actuator and electrode shaft. The proposed concepts are direct drive, drive shaft, chain, torsion wire and wire spool drive.

In the direct drive concept the actuator is connected straight on the electrode shaft, as the electric actuator to the left in Figure 21. The direct drive would give benefits due to the fact that it is always in mesh with the shaft, there is no losses when the rotation switches direction. Though to have direct drive requires an actuator small enough to fit the required size at repair location. The required 360° rotation would also be a problem for the hydraulic actuator due to the fact that there is no gear ratio between the actuator and electrode shaft.

The drive shaft is a shaft connected either with bevel gears to the actuator and the electrode shaft or with cardan joints. The benefit of having a drive shaft is the rigidity in the shaft and thus lowers the time delay of the torque transmission. Drawbacks are that the gears and cardan joints are not in mesh when the rotation changes direction, causing backlash. The two different setups can be seen in Figure 22.

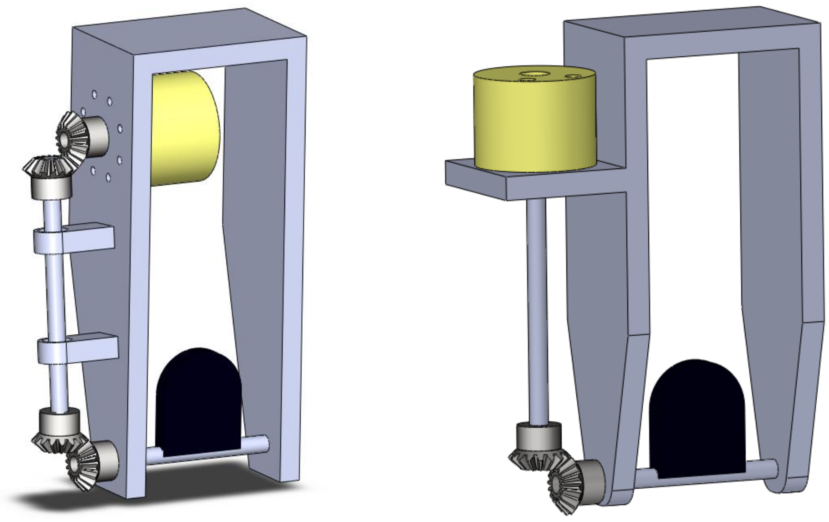

Figure 22. Two different type of drive shaft configuration.

To use a chain drive would be similar to a timing belt, but there are some differences. The size of the drive chain could be smaller than the timing belt, there would also be a difference in the elasticity where the drive chain is more rigid. Drawbacks are that chain drive is prone to have more backlash than a timing belt.

Torsion wire is a flexible solution quite similar to the drive shaft, the difference is the flexibility of the wire and that the wire can be connected directly on the actuator and the electrode shaft without any gears in between. The wire needs have a high torsional stiffness to function properly. The size of the driving joint could be made small with this solution, also the flexibility of the wire gives a lot of freedom to where the actuator is placed. The fact that the wire is connected to the electrode gives the opportunity to use the wire as the electric conductor for the EDM current. Torsion wire is visualized in Figure 23.

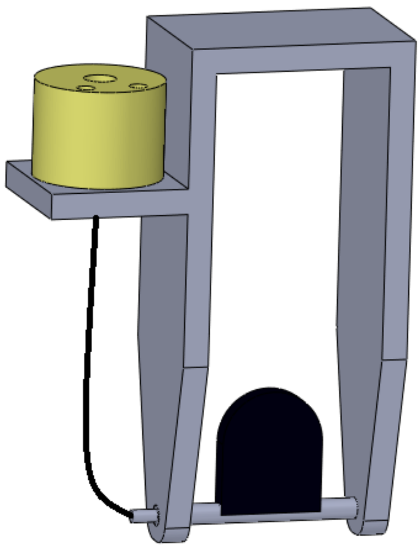

Figure 23. Torsion wire configuration

The existing solution for locking the rotation of the electrode consist of closing the input and output valves for the hydraulic fluid to the hydraulic rotary cylinder, thus keeping the vane at a fixed position. This works quite well but requires a hydraulic rotary cylinder that can keep the pressure constant, i.e. there cannot be any leaks. For the electric actuator there is no existing solution.

A more rigid solution is to lock the shaft directly with some sort of actuator. Several concepts for locking the shaft directly were made, after some evaluation two of them was chosen. The first consists of a small one-way pneumatic actuator with a non-conductive brake pad at the end on the piston. To lock the shaft, air is led to the cylinder, pressing the piston with the brake pad against the shaft. The advantage of the concept is the simplicity and the fact that it works for both actuators and is not dependent on the transmission type. Disadvantage is the need for an extra actuator on repair site and the space it occupies. And also the force applied radially to the shaft needs to be taken up by the bearings. The setup can be seen in Figure 24.

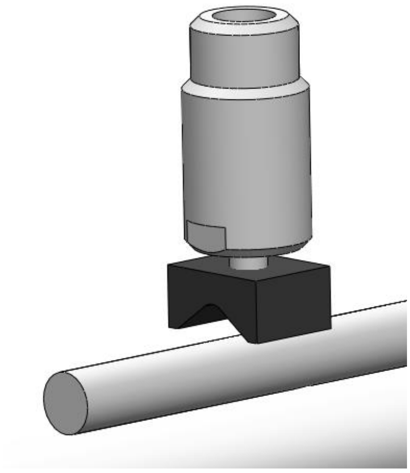

Figure 24. Pneumatic actuator for locking the rotation of the shaft.

The other concepts is quite similar, it is a pneumatic gripping tool with the gripping fingers placed around the shaft. The surface in contact with the shaft on the fingers consists of a high friction non-conductive material and the fingers are floating radially. Advantages are the fact that the force applied to the shaft does not result in any extra load on the bearings. Problems with the concept are the need for an extra actuator and the space it occupies.

To get the positional feedback of the electrode there are some existing solutions, a magnetic sensor inside the rotary hydraulic cylinder or an electric actuator with an built in encoder. For the solution with a magnetic sensor problems occurs due to interference and is not used because of the uncertainty of the signals. Instead cameras are used to estimate the electrode position, this works but the visibility during the sparking process can make it hard to see the electrode. Also it is just an estimate of the position, but to measure the position of the rotary cylinders vane, as done previously, would also be an estimate. The wear of the electrode needs to be accounted for to exactly know how far into the material the electrode has moved. This is a problem because the electrode wear is not known. Some sort of scanner would be needed to find out exactly how much the electrode has worn, but for most repair-processes the exact position is not necessary to know. What is needed is to know if the electrode has moved for example more than 90°. This can be estimated by doing test runs with the electrode to find out how many degrees it has moved into the material at a given position of the rotary actuator.

For this a potentiometer could be connected to the output-shaft of the rotary actuator, this sensor would be more reliable than having the sensor inside the cylinder measuring the vanes position. The setup can be seen in Figure 25. The sensor could also be placed on the electrode shaft for a more direct measuring, this would though require a very small sensor.

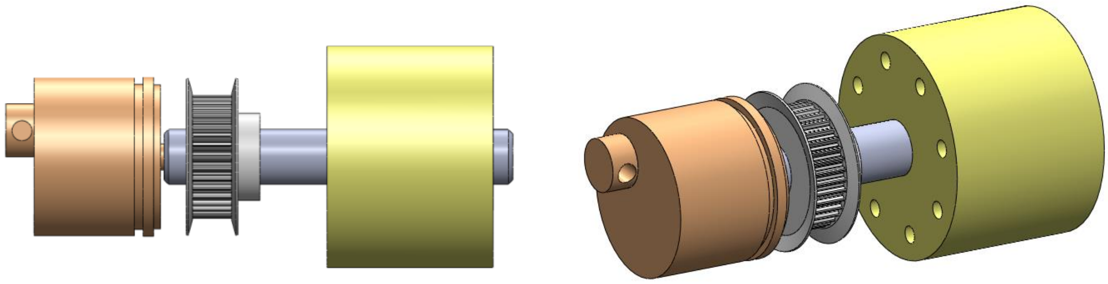

Figure 25. Potentiometer connected to the output shaft of the driving unit.

4.2.3 Electrode magazine module

The electrode magazine module is connected to the fixed part of the EDM-carrier, i.e. not the positioning table. This to ensure that the magazine has a known position relative the positioning table. The magazine has an interface to the electrode during the electrode change and when an electrode is loaded in the magazine.

There are three main concepts for the electrode magazine, fixed magazine, linear moving magazine and revolver magazine. Within these three concepts there are two main concepts for holding the electrode carrier, either by using one of the quick lock concepts or by using a pneumatic micro spindle.

If the range of the positioning table is great enough a fixed magazine could be used, a simple solution where the electrodes hang down from the EDM-carrier, see Figure 26. The number of electrodes that can be kept in the magazine depends on the range of the positioning table.

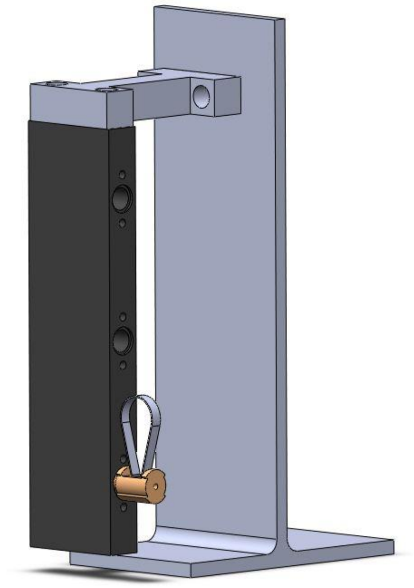

Figure 26. Fixed electrode magazine.

To increase the number of electrodes in the magazine and to reduce the dependency of the range of the positioning table a linear actuator could be placed between the EDM-carrier and the magazine. This would of course add to the complexity and size of the magazine but could be a necessity. See Figure 27 for a linear moving magazine.

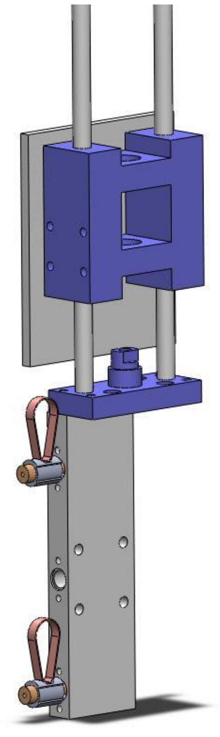

Figure 27. Electrode magazine mounted on linear actuator to allow movement of the magazine.

To further increase the electrode carrier capacity of the magazine a revolver type could be used. The revolver magazine would probably need more space axially than the linear moving magazine, see Figure 28.

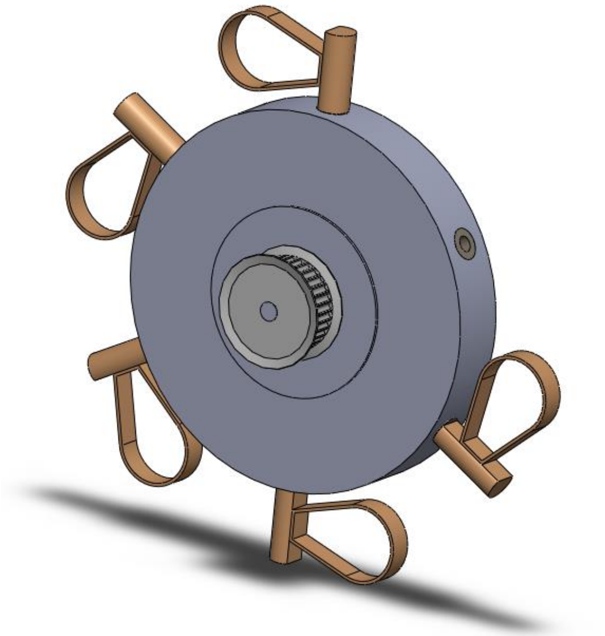

Figure 28. Revolver magazine.

To hold the electrode carrier in place, one of the three quick lock concepts explained in the electrode module chapter could be used. The same type of quick lock solution cannot be used on the shaft of the tool and for the magazine at the same time. It would require the quick lock to change the clamping force between loading and unloading the magazine, this is not possible with the completely mechanical solutions. But it would be possible to use the bayonet on one end and the snap fit on the other. This would then require a rotation and linear motion of the shaft to load and unload.

The pneumatic micro spindle is a standard component from the tool manufacturer RÖHM (RÖHM, 2014). This micro spindle is small both radial and axial and uses springs to clamp a shaft or a taper and pneumatics to unlock the clamp. In Figure 29 the micro spindle can be seen.

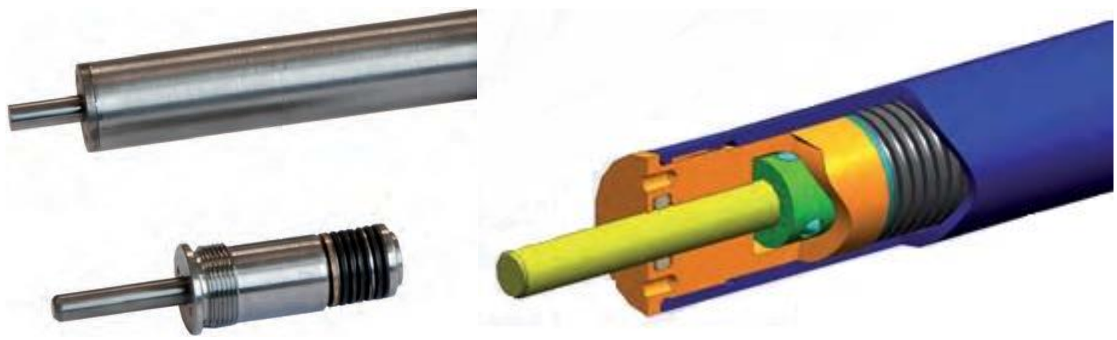

Figure 29. Micro spindle from tool manufacturer RÖHM (RÖHM, 2014).

4.3 Concept evaluation

At early stages of the project, evaluation of infant concepts for the different modules was aimed at finding strength- and weaknesses. With knowledge of concepts strengths, it was possible to merge concepts together to combine their strengths. The basic concepts were thereafter further developed into more complete and defined concepts of the different modules, presented in chapter 4.2.

With numerous concepts of the different modules at hand, all developed to a level where concept specific characteristics could be distinguished, concept evaluation was aimed to compare concepts against each other and evaluated how well they fulfilled the set requirement specification.

Due to the projects timeframe, except for the electrode modules quick lock sub-module, only one concept for each module/sub-module was chosen for further development. While some concepts were screened out since they did not fulfill the requirements set on the EDM-tool, others were seen as modules/sub-modules that could be further developed in the future if they better suit the situation.

4.3.1 Electrode module

For the electrode module, evaluation is at sub-module level. A concept evaluation matrix determines which concepts from the quick lock sub-module to choose for further development. For the remaining three sub-modules, pros and cons will be stated for each concept and one of them will be chosen for further development.

4.3.1.1 QUICK LOCK

The concept evaluation matrix, presented in Table 2, is based upon the requirement specification. The quick lock concepts are graded from 1 to 5 due to how well the concepts handle the requirement, 1 is poor and 5 is excellent. Each wish has a weight between 1 and 3 which correlates to the significance of the requirement, this weight is then multiplied with the given grade and summarized.

Table 2. Concept evaluation matrix.

	Weight [1-3]	**Ball-pin [1-5]**	**Snap-fit [1-5]**	**Bayonet [1-5]**
EDM-tool as small as possible	**3**	3	4	3
Quick lock and release function of the electrode, no tool needed to assemble or disassemble the electrode. Can be done by hand	**2**	5	5	5
No need for extra actuator on the EDM-tool to assemble or disassemble the electrode	**2**	5	5	5
Minimize the use of electronics and reactor sensitive materials	**2**	5	5	5
If electrode get stuck, no extra equipment is needed to disassemble the electrode from the carrier	**1**	4	4	5
Minimize number of parts in the assembly	**2**	2	3	5
< 3 motions required for electrode change	**2**	4	4	2
Sum		**55**	**60**	**58**

From the concept evaluation matrix the Snap-fit and the Bayonet stand out from the Ball-pin concept. The Ball-pin has at least two downfalls, number of parts and the disability to make it as small as the other two concepts. The Snap-fit and the Bayonet are two distinctly different concepts, especially regarding the movement needed to change the electrode, still the sum of points in the matrix are similar. To further investigate and finding best suitable solution both the Snap-fit and Bayonet is chosen for further development.

4.3.1.2 DIELECTRIC FLUID SUPPLY

The radially through shaft concept, for the dielectric fluid supply, occupies space radially around the shaft since a rotary union is required around it. The rotary union needs to have some kind of bearing and sealing, making the solution a bit complex. Its main advantage is that it leaves the backend of the shaft open e.g. for a direct drive, eliminating the need of a transmission between the driving unit and the shaft. By leading the fluid through the shaft, it is possible to direct the fluid to a fix point between the shaft and the electrode. The electrode can thereafter be designed with built in fluid canals aiming the outlet in a desired direction.

The axially through shaft concept which works in a similar way as the radially through shaft concept, with one exception, it does not leave the backend of the shaft open. A swivel is positioned at the backend of the shaft, leading fluid into it, meaning that space is occupied axially instead of radially. This does not leave EDM-tool with the option of using a direct drive, which can be necessary in some repair operations.

The externally along shaft concept is the most simple solution, there is no need for additional components and built in fluid canals in the electrode is not needed which probably makes the manufacturing of the electrode a bit easier. The main disadvantage of the concept is the position and direction of the outlet, it cannot be altered. Fluid will jet from the same place regardless of the shape and type of the electrode in use, making the solution very inflexible.

The most flexible concept, radially through shaft, which leaves the backend of the shaft open for use and allows that the fluid to be directed wherever needed, is chosen for further development. The axially through shaft is left as a sub-module which can be used in the future if it better suits the situation and the externally along shaft concept can be used if only one type of electrode is used for the entire repair operation.

4.3.1.3 ELECTRIC CURRENT SUPPLY

The concept of directly connecting the electrode to the power supply is a simple solution. But it makes the changing of electrode during the repair operation very difficult if not all electrodes in the electrode magazine are connected individually to the power supply. Attaching a wire to all of the electrodes in the electrode magazine would be unpractical since cables would have to hang lose, to allow movement of the electrodes.

With a wire through the shaft or a core would be more suitable since electric current can be transferred to an interface point between the shaft and the electrode carrier, and thereafter to the electrode in use. The difficulty to overcome with this solution is to transfer electric current to the wire or core within the shaft.

Using an electric conductive shaft overcomes this difficulty, electric current only needs to be transferred to the shaft which thereafter transfers it to the electrode carrier mounted onto the shaft. This solution would require isolation of parts where EDM sparking could occur (e.g. bearings).

A wire through the shaft for the electric current supply could prove difficult to combine with the *radially through shaft* concept which was chosen for the dielectric fluid supply, see chapter 4.3.1.2. The concept of using an electric conductive shaft is chosen for further development, it is the most flexible solution regarding transfer of electric current from the power supply to the electrode.

4.3.1.4 BEARING AND BEARING HOUSING

Since the chosen concepts for the electrode module quick lock function requires linear motions in the shaft axis, axial forces will occur on the bearings. Needle- and journal bearings cannot cope with axial forces, thus ball bearings must be used.

With an electric conductive shaft used as electric current supply for the electrode, the ball bearings poses a risk for EDM sparking within them, and therefor they need to be electric insulated.

4.3.2 Driving module

The two different actuators, electric and hydraulic, are both currently used in EDM-repair processes. The electric actuator can be a problem to use if the repair is close or below the nuclear fuel, but it could also be a necessity to use the electric actuator if the space at the repair location is too limited for the hydraulic version. There will not be any further development for the actuators and the hydraulic actuator will be used in the final concept because of its robustness.

The direct drive excludes the hydraulic actuator due to the fact that it requires a very small actuator and the lack of interchange not allowing a 360° rotation of the electrode. The drive shaft is very stiff and would be a better solution than the timing-belt if the actuator needs to be placed far away from the shaft resulting in high elastic elongation of the timing-belt. But the drive shaft would require more parts and the time delay in the rotational direction change is probably greater with the drive shaft due greater backlash. To use a chain would be very similar to the timing-belt, the chain would be stiffer but it would also be heavier to operate and would also need some sort of lubrication. The torsion wire would give great benefits due to its smallness, the fact that the actuator could be placed very freely and the ability to act as conductor for the sparking current. A drawback is that the torsional stiffness needs to be very high, especially if the actuator is placed far away from the electrode shaft. The conclusion is that the existing, well proven, timing-belt is chosen to the final concept.

For the positional feedback there are two options, a potentiometer on the output shaft off the actuator or on the electrode shaft. To have the sensor on the electrode shaft would give benefits to the directness of the measurement, no transmission between the sensor and the electrode shaft. But the size of the potentiometer could not match the required demands; therefore it needs to be placed on the actuator. This on the other hand excludes the direct drive from having this feature.

The rotation locking of the shaft has three concepts, the existing solution works quite well but only for the hydraulic actuator. Therefore the two pneumatic locking solutions direct on the shaft will be processed in further development to test both solution.

4.3.3 Electrode magazine module

The fixed magazine is a simple solution but is highly dependent on the range of the positioning table of the EDM-carrier. The number of electrodes it could carry would be low. The revolver magazine could carry a lot of electrodes but the size of the magazine in axial direction would be too big for the given demands, also it would possibly require a linear movement to position the magazine in front of the electrode on the carrier. This could partly be done by the positioning table of the EDM-carrier, depending on the radius of the revolver magazine. A rotational joint and actuator to turn the revolver would also be required. The linear moving magazine could be made slim enough to fit the requirements and also it could carry >3 electrodes. Therefore the linear moving magazine is chosen for further development.

For holding the electrodes in place in the magazine the micro spindle is an easy, off the shelf solution. It requires air for the pneumatics but there are no rotating parts which eases the air-input. The quick lock solutions are bigger than the micro spindle and they also require a rotating movement of the shaft, therefore the micro spindle is chosen.

4.4 Further development

The next step in the process was to further develop the chosen concepts to more comprehensive solutions. At this stage a lot of thought was given to the interfaces between the modules and also the interaction between the parts within them. When all aspects of the concepts and the interfaces between them had been covered it was possible to assemble them to a complete system of the EDM-tool.

4.4.1 Electrode module

To find the best solution for the electrode module, the further development process of the sub-modules had to be focused on optimization of the complete module instead of optimizing each individual concept.

For the quick lock sub-module, two solutions were chosen for further development. At this stage, after they had been further developed, a second evaluation and screening took place, where one of the solutions was chosen for a further deeper detail development.

For the reaming three sub-module concepts, the dielectric fluid supply, electric current supply and the bearing and bearing housing, it was clear that the best and most compact solution would be if they were combined around the bearing housing.

4.4.1.1 QUICK LOCK

The further developed bayonet concept was completely redesigned; the only feature kept was the bayonet locking mechanism. During the further development process a more reliable solution regarding the dielectric fluid- and electric current supply was needed compared to the previous solution. And also, with the previous solution of the concept, see chapter 4.2.1.1, it was realized that the electrode carrier would not be fitted firmly onto the shaft. All these aspects were considered while redeveloping the concept and the result of the development process can be seen in Figure 30.

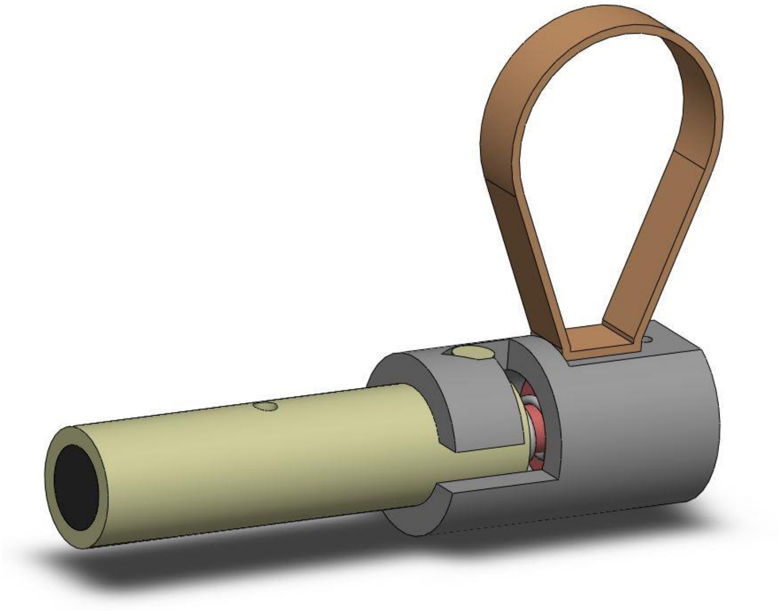

Figure 30. Further developed bayonet concept.

The tracks for the bayonet mechanism are located on the electrode carrier, and the pins which fit in the tracks are located on the shaft, see Figure 31. To ensure that the electrode carrier is kept within tight reins, the electrode carrier is equipped with two tracks, and two corresponding pins can be found on the shaft.

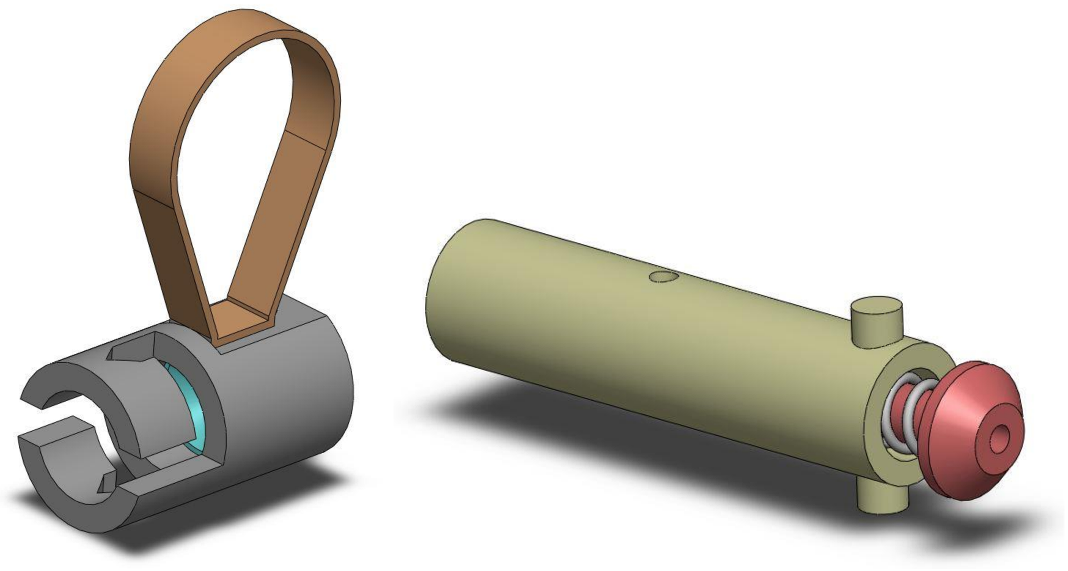

Figure 31. Left: Electrode carrier with bayonet tracks. Right: Driving shaft with pins for the bayonet locking.

An additional core shaft can be found within the main shaft of the concept. With a hole drilled through it and with a conical shaped end, the core shaft transfers both electric current and dielectric fluid to the electrode carrier. With the help of a spring, located between the core shaft and the main shaft, the conical end of the core shaft is pressed into the corresponding geometry within the electrode carrier, see Figure 32. The spring biased core shaft ensures that dielectric fluid and electric current is transferred in a satisfactory way. The spring also makes it possible for the pins of the main shaft to travel through the bayonet tracks on the electrode carrier, by allowing the core shaft to be pushed backwards while the pins moves forward.

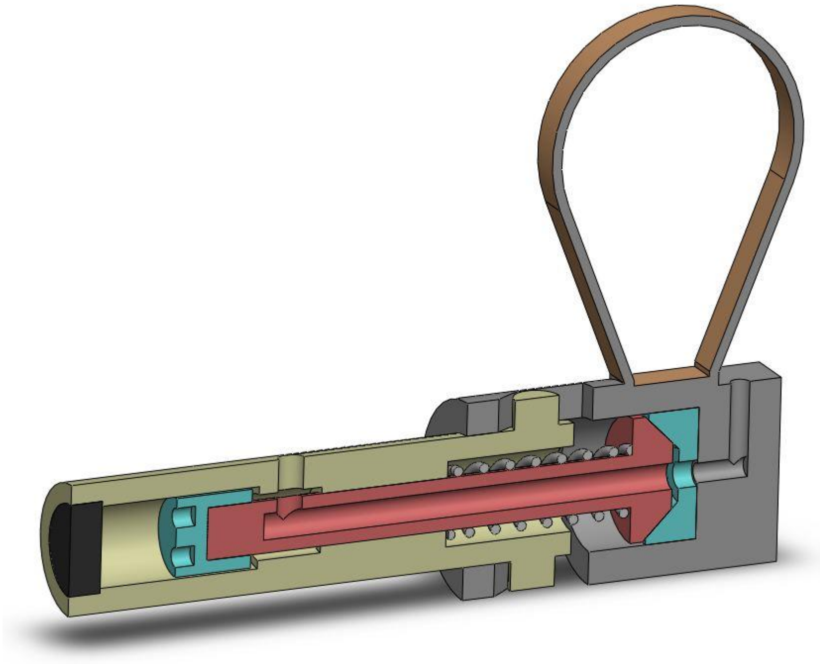

Figure 32. Section view of the bayonet concept with the electrode and electrode carrier mounted on the driving shaft.

When the pins are moved to their anchor position in the bayonet tracks of the electrode carrier, the spring will want to push the electrode carrier away from the main shaft. This feature of the concept will lock the pins in the tracks and make the connection between the electrode carrier and the main shaft rigid. A socket mounted on the backend of the core shaft ensures that the core shaft cannot fall off, and a plug at the backend of the main shaft seals the interior of the main shaft from leaking dielectric fluid.

For the further development of the snap-fit concept a lot of thought was given to find a solution to minimize the risk for the electrode carrier to come off unintended, since it only required one motion to do so in the previous concept, see chapter 4.2.1.1. Thought was also given to find a better way to transfer electric current and dielectric fluid from the shaft to the electrode carrier, and also to make the design more compact. The further developed snap-fit concept can be seen in Figure 33.

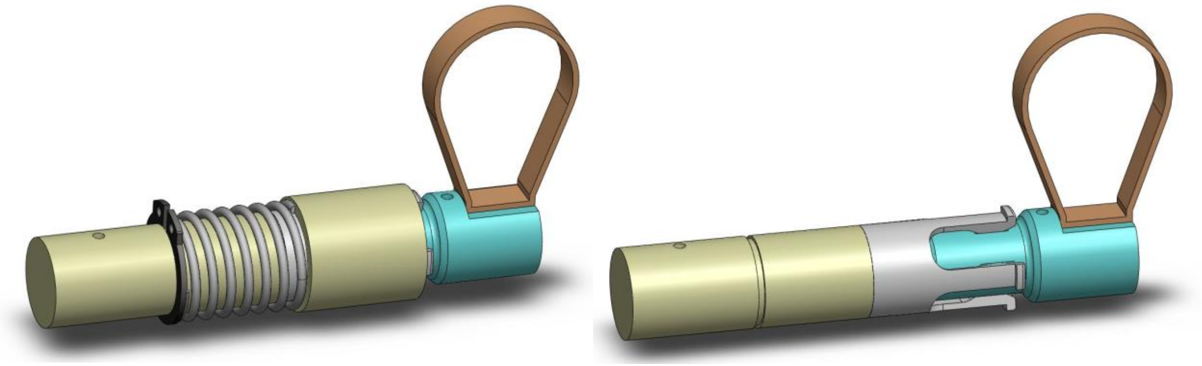

Figure 33. Further developed snap-fit concept.

The snap carrier was redesign to a circular shape with a spring biased socket mounted around it, ensuring that the snap-fit cannot come lose during operation. This means that the spring biased socket must be pushed back by the electrode magazine before the electrode carrier can be released from the snap-fit, when changing electrodes. With the new circular shape of the snap-fit, it was possible to make an even more compact design of the concept compared to the previous one.

To ease the mounting and positioning of the electrode carrier into the snap-fit and the shaft, the electrode carrier has a conical shaped end with a corresponding geometry on the inside of the shaft, see Figure 34.

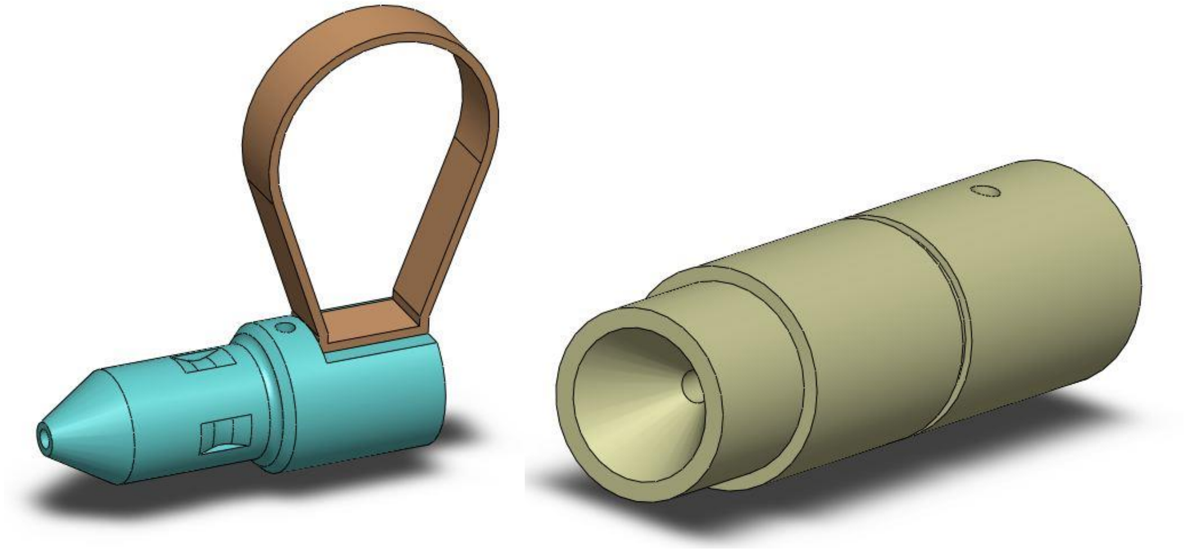

Figure 34. Left: electrode carrier. Right: driving shaft.

While the spring biased socket is pressing down the snaps, the electrode carrier is pushed towards the shaft, creating a rigid and sealed connection between the electrode carrier and the shaft. This creates a reliable passage for the dielectric fluid to be transferred from the shaft to the electrode carrier, see Figure 35. Electric current is transferred from the shaft to the electrode carrier at the conical shaped interface between them.

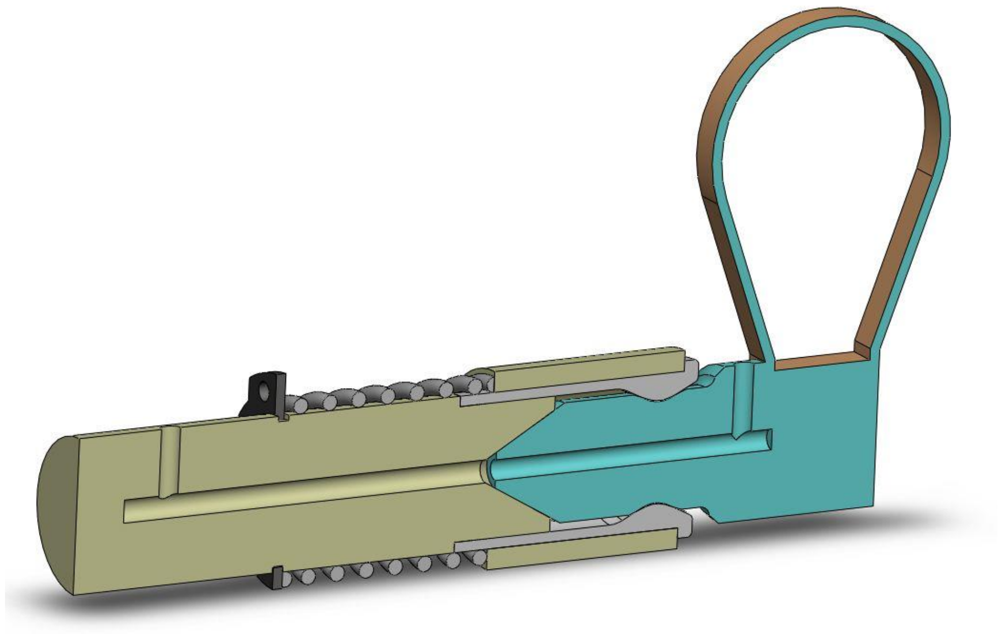

Figure 35. Electrode carrier mounted together into the driving shaft in the snap-fit.

With the two further developed solutions at hand, a second concept evaluation took place. A second concept evaluation matrix was created to evaluate and compare the further developed concepts, see Table 3.

Table 3. Concept evaluation matrix for further developed quick lock concepts.

	Weight [1-3]	**Snap-fit [1-5]**	**Bayonet [1-5]**
EDM-tool as small as possible	**3**	5	3
Quick lock and release function of the electrode, no tool needed to assemble or disassemble the electrode. Can be done by hand	**2**	5	5
No need for extra actuator on the EDM-tool to assemble or disassemble the electrode	**2**	5	5
Minimize the use of electronics and reactor sensitive materials	**2**	5	5
If electrode get stuck, no extra equipment is needed to disassemble the electrode from the carrier	**1**	1	5
Minimize number of parts in the assembly	**2**	4	3
< 3 motions required for electrode change	**2**	4	2
Sum		**62**	**54**

From the evaluation matrix it is clear that the snap-fit concept is the favorable of the two concepts, the bayonet concept even got a lower point sum than its precursor. But it should be stated that the evaluation matrix does not consider features as positioning and mounting of the electrode carriers onto/into the shafts, how well dielectric fluid and electric current can be transferred, rigidness of the connection between the shaft and the electrode carriers etc. and these are the major features of the concepts that have been further developed. On basis of the evaluation matrix and the customer (Westinghouse) wishes, the snap-fit concept was chosen as the solution for the quick lock function of the electrode module. A huge factor taken into account while choosing concept was the number of motions required for electrode change. The snap-fit concept only required one motion (using the positioning table of the EDM-carrier) regarding electrode change, while the bayonet required two (using the positioning table of the EDM-carrier and the driving unit).

To aid the development of the final solution for the quick lock function, rapid prototyped 3D-printed parts of the concept were manufactured. This gave an idea of how well the snap-fit locking solution worked, and what needed to be improved with the design. The 3D-printed parts can be seen in Figure 36.

Figure 36. 3D-printed parts of the snap-fit concept. From left to right: electrode carrier, snap-carrier, driving shaft, spring biased socket.

Assembling the parts together, see Figure 37, proved that the snap-fit locking with the spring biased socket worked; it was not possible to remove the electrode carrier from the snap-fit while the spring biased socket was in position.

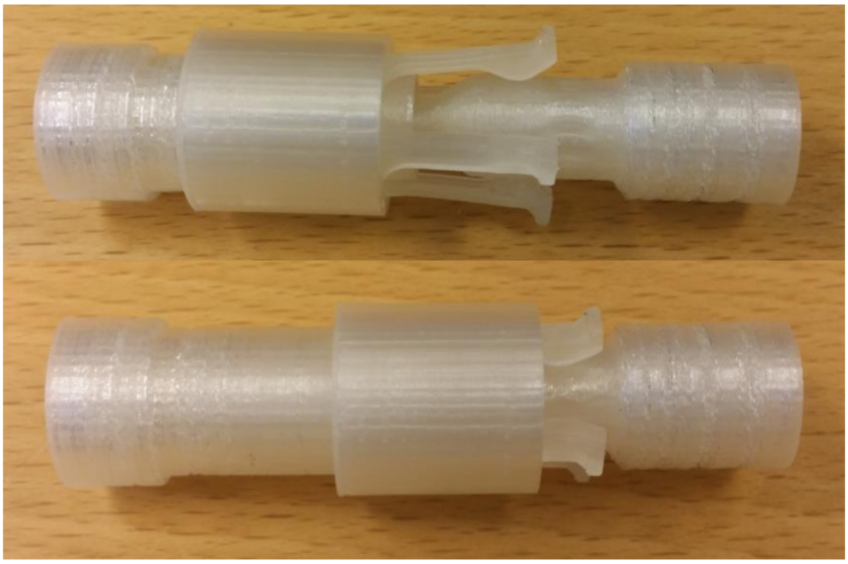

Figure 37. 3D-printed prototype of the snap-fit concept assembled.

The final concept of the quick lock sub-module can be seen in Figure 38. During the development of the final snap-fit concept, interfaces between the snap-fit sub-module and the rest of the EDM-tool was defined and designed, and the overall design of the concept was optimized.

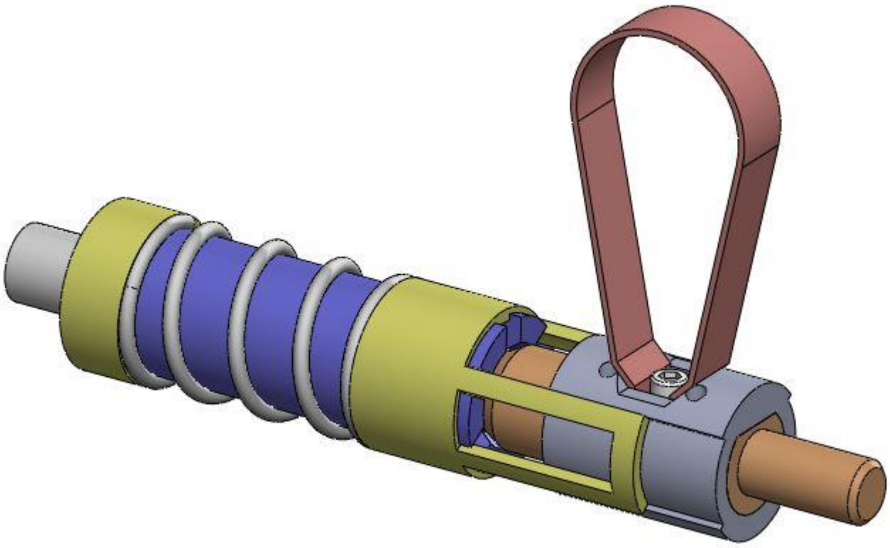

Figure 38. Final concept of the snap-fit quick lock solution.

The driving shaft, see Figure 39, is made of stainless steel. Dielectric fluid is led to the electrode carrier through the center of the shaft. The lateral of the shaft is threaded.

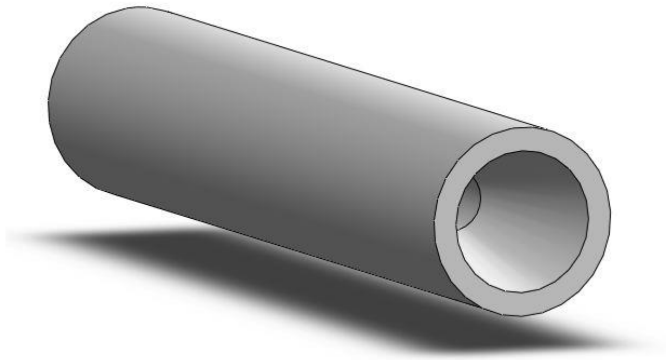

Figure 39. The driving shaft. .

A stop socket for the spring and the snap-carrier have interior threads, and they are screwed onto the shaft, see Figure 40. The position of the snap-carrier can be adjusted in the axial direction by altering the position of the stop socket. The stop socket ensures that the spring does not get out of position, and it is made of plastic to make the spring electric insulated from the electric current in the shaft.

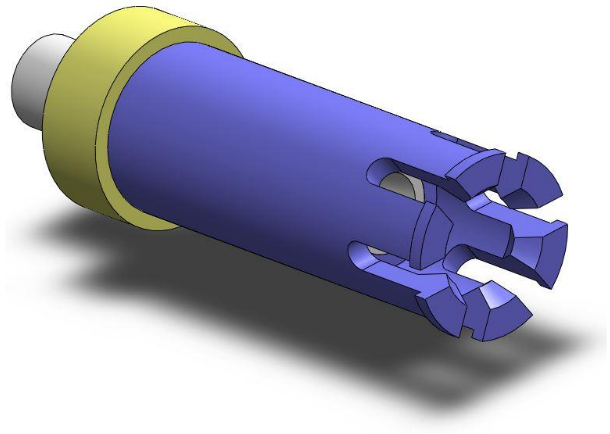

Figure 40. The stop socket for the spring and the snap carrier mounted on the driving shaft.

The arms of the snaps are shorter and wider and there are more snaps on the snap-carrier compared to the previous further developed concept, which makes the snap-fit more rigid. The snap-carrier is made of plastic to avoid sparking between the snaps and the electrode carrier.

The spring biased socket, see Figure 41, is designed with two protruding sections. These sections will both aid the guiding and positioning of the electrode carrier and to be utilized by the electrode magazine to push back the socket to allow the electrode carrier to come off from the snap-fit when changing electrode. The socket is made of stainless steel to increase its stiffness; since it is mounted on the plastic snap-carrier it is insulated from the electric current in the shaft.

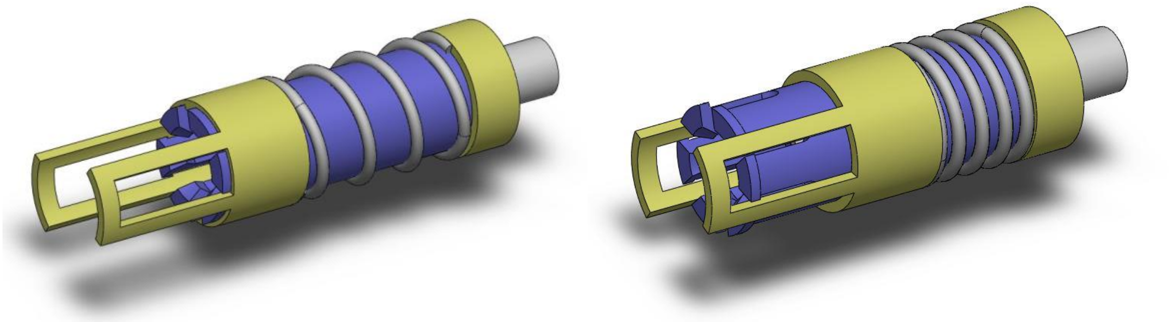

Figure 41. The spring biased socket mounted around the snap-carrier.

The electrode carrier consist of two parts, see Figure 42, an electric conductive part which is mounted in the snap-fit, and a plastic socket with built in canals leading dielectric fluid to a desired point by the electrode.

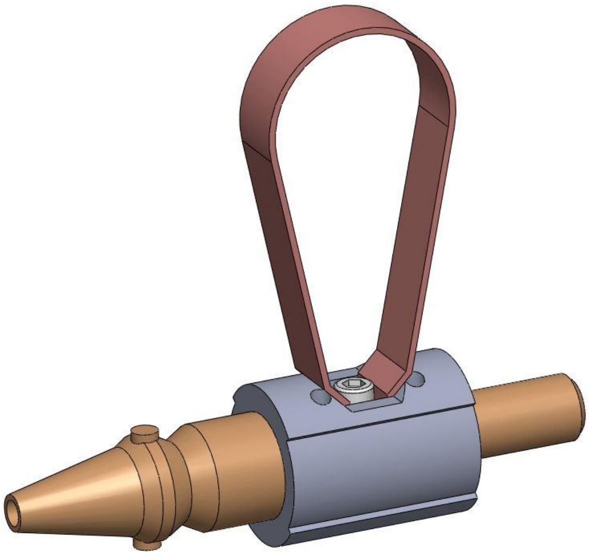

Figure 42. Electrode carrier with the plastic socket illustrated in grey.

The electric conductive part of the electrode carrier has a conical shaped end that fits into the shaft. It is also equipped with a track for the snaps to fit in and two plastic pins to aid the positioning and mounting of the electrode carrier when changing electrode; the pins perfectly fit between two snaps. The plastic socket has two tracks for the spring biased sockets two protruded sections to slide in. The electrode is bolted onto the electric conductive part of the electrode carrier, see Figure 43. Holes are drilled radially to the center of the electric conductive part of the electrode carrier to fit the inlets of the holes in the plastic socket. The protruded back end is the interface between the electrode carrier and the electrode magazine.

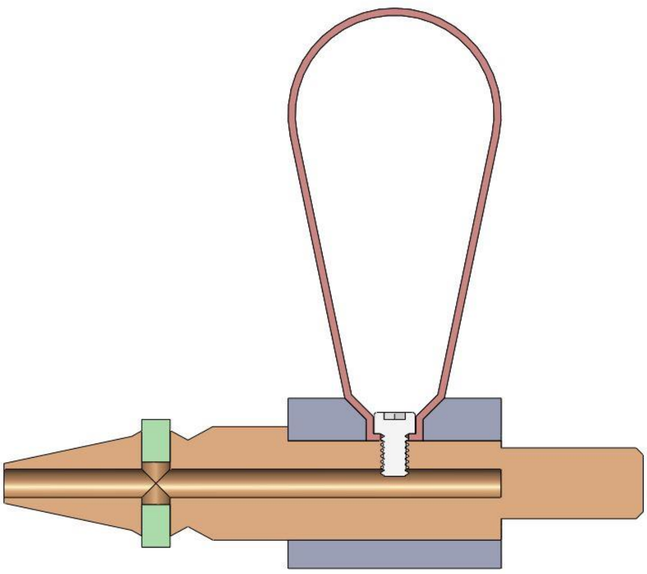

Figure 43. Section view of the electrode carrier and the electrode.

When the spring biased socket is in its back position, the electrode carrier can be fitted into the conical end of the shaft and the snap-fit, see Figure 44. When the spring biased socket is allowed to move back over the snaps, it will lock their position and the electrode carrier will not be able to come off, see Figure 45.

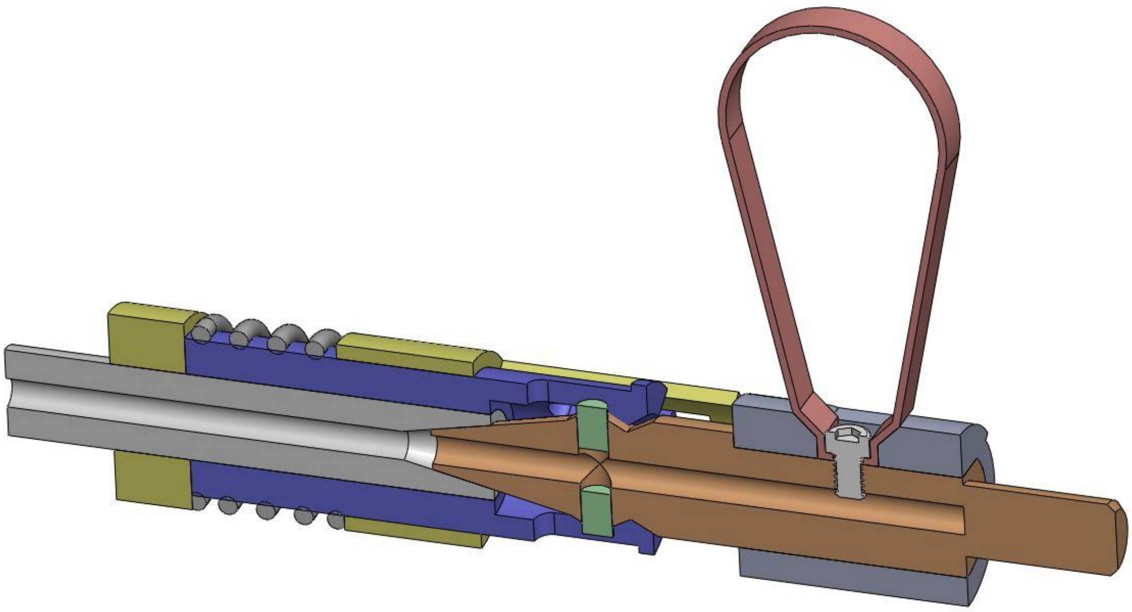

Figure 44. Electrode carrier allowed to be mounted into the driving shaft. Spring biased socket is in its back position.

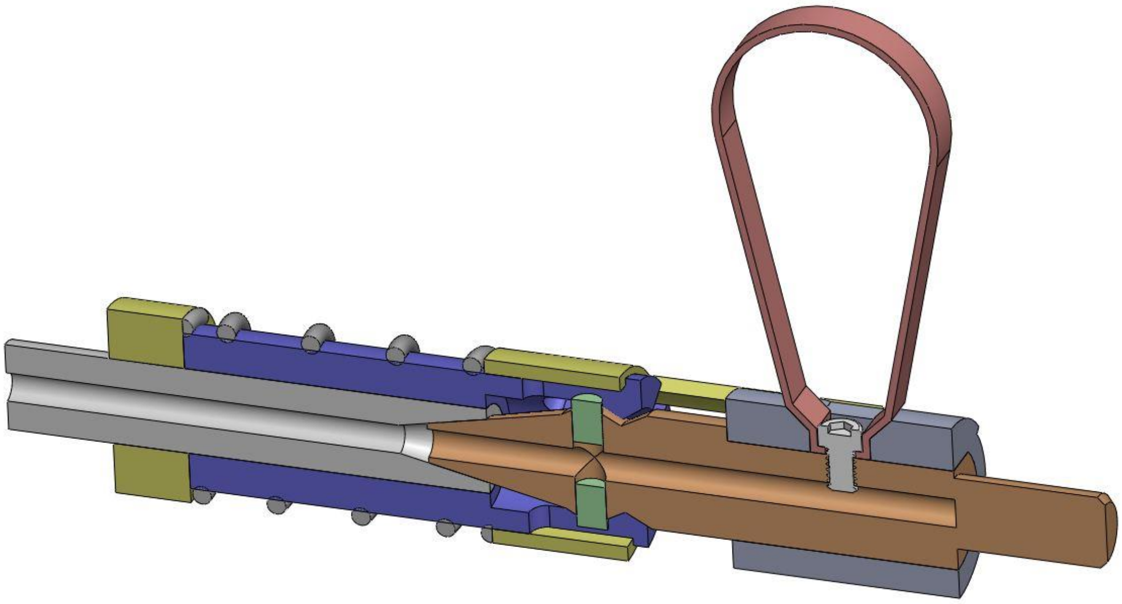

Figure 45. Spring biased socket moved back over the snaps, electrode carrier is locked in its position and cannot come off.

4.4.1.2 HOUSING

The three sub-modules, dielectric fluid supply, electric current supply and bearing and bearing housing combined into one sub-module, Housing. The input of for the dielectric fluid to the shaft is by a rotary union radially to the shaft. By the use of sealed bearings and creating a chamber between the bearings, a rotary union for the dielectric fluid supply could be integrated in the bearing housing. This can be seen in Figure 46.

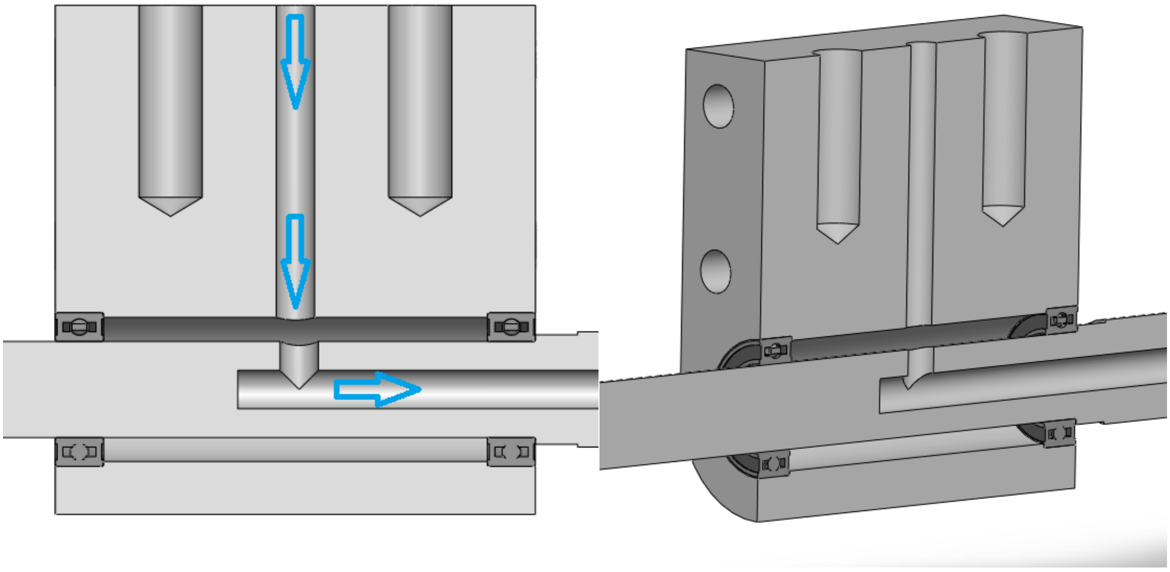

Figure 46. Illustration of the flow of dielectric fluid through the housing to the driving shaft.

The electric current supply is placed on the electrode side of the bearing housing, a spring loaded carbon brush pressing onto the shaft transfers the current to the shaft. The carbon brush is connected to one or several cable lugs to which the EDM-current and control cable is fastened. The housing for the carbon brush is made out of a non-conductive plastic; the setup of the electric current supply can be seen in Figure 47 and 48.

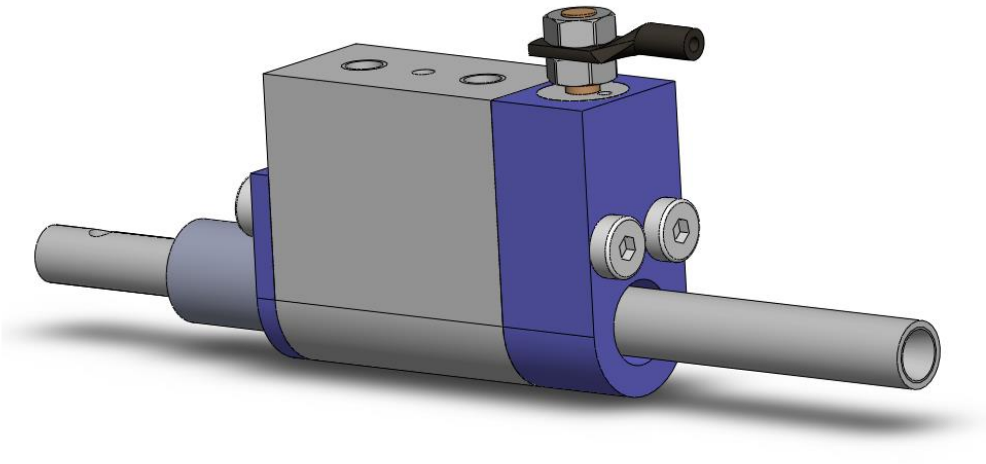

Figure 47. The housing for the carbon brush bolted to the bearing housing with a cable lug connected to it.

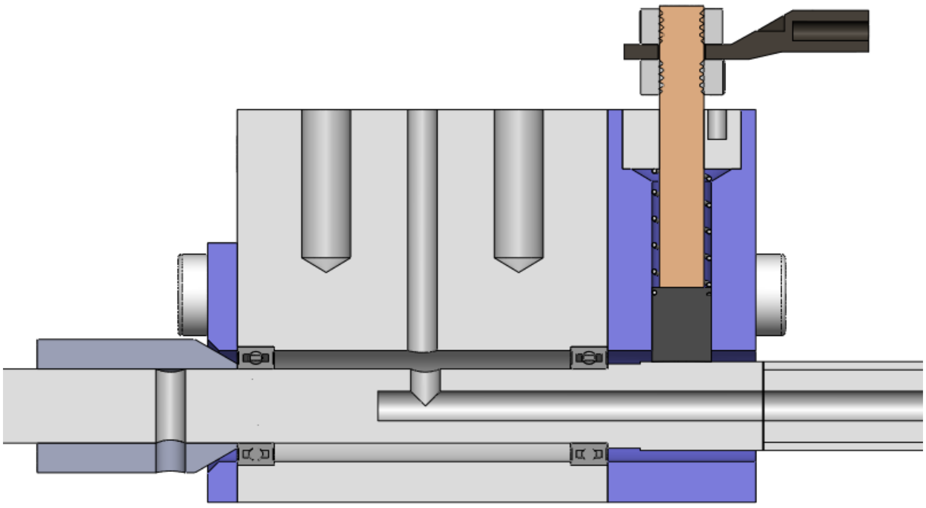

Figure 48. Section view of the housing for the carbon brush.

The bearings are standard stainless steel deep groove ball bearing, capped on both sides. The rotation speed is extremely low, this means that the sealing can be of contact type. Preferably the RSH contact seal from SKF (SKF, 2014). To insulate the bearings there are at least two options, an aluminum oxide on the inner ring of the bearings or to manufacture the bearing housing in a non-conductive material. Here the latter is chosen, the load on the bearings and on the housing is so low that to create the housing in plastic is a simple and cost effective solution. To hold the bearings in axial direction the carbon brush housing holds one bearing in place and a plate holds the other, the bearings has contact with a shoulder in the bearing housing. On the shaft there is a shoulder on one side and a socket on the other. See Figure 49.

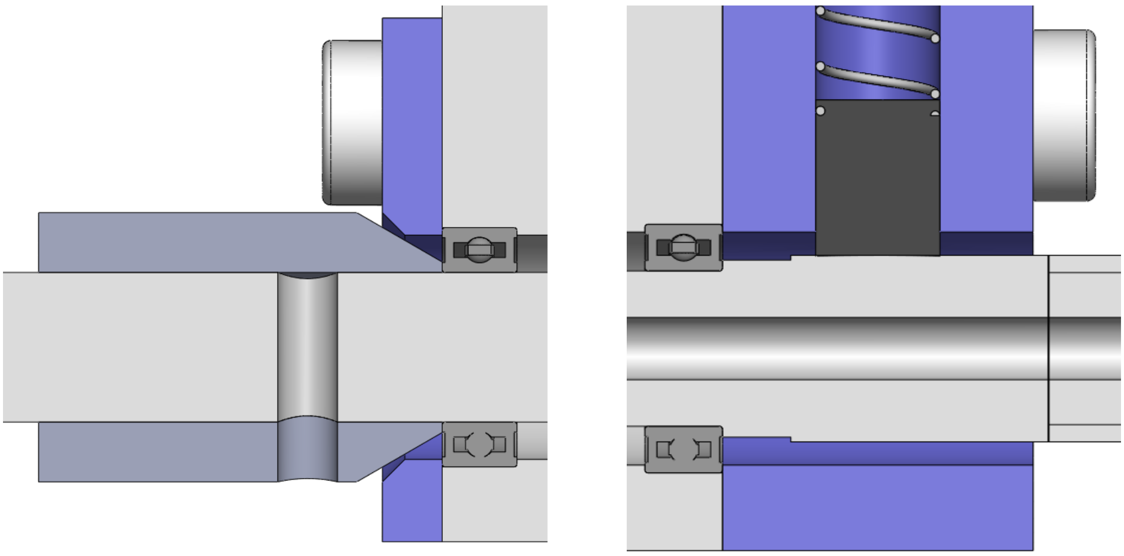

Figure 49. Bearing setup in the housing and on the shaft.

To mount the housing on the EDM-carrier there are several options, the housing could be kept as it is in Figure 47 or an adapter plate could be connected to the top of the housing, see Figure 50. Or the housing itself could be prolonged and fastened from the side. This all depends on the geometry and space available at the repair location.

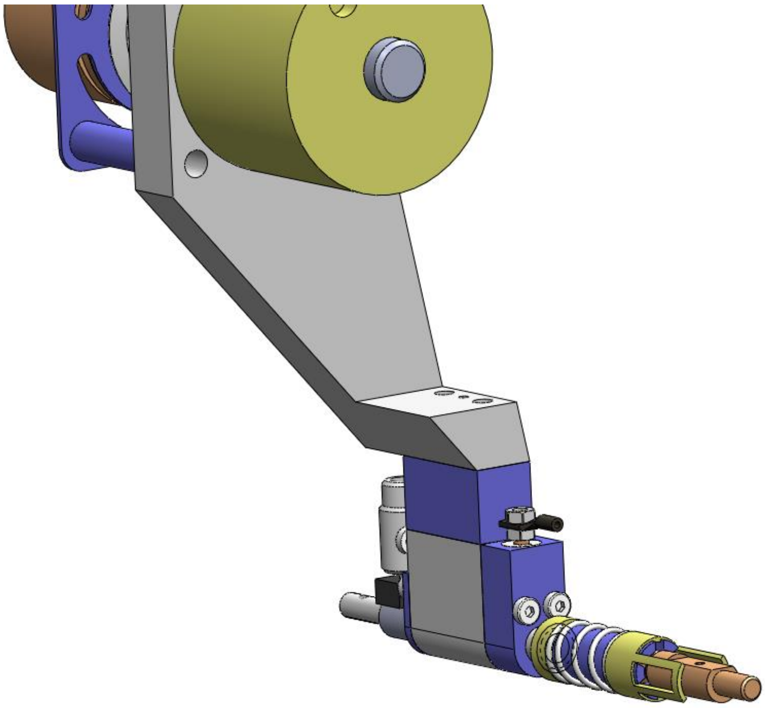

Figure 50. Housing mounted to an adaptor plate.

4.4.2 Driving module

The actuator chosen, hydraulic rotary cylinder, is a well proven and reliable actuator. The only downfall with it is the size and the 270° rotation, but this is solved by having the timing-belt and a gearing ratio between the output and input shaft. The actuator and the transmission will therefore not be developed any further.

The rotation locking feature is only required when EDM stamping is needed, this is known before the repair process starts. The locking feature should therefore be placed in a way so it easily can be added without making big changes to the design. The best place to position it in that regard is on the driving side of the bearing housing, when the locking mechanism is needed the shaft can be extended to fit the brake pad. An l-beam with a threaded hole will hold the actuator and two screws are used to fasten the l-beam to the bearing housing, see Figure 51.

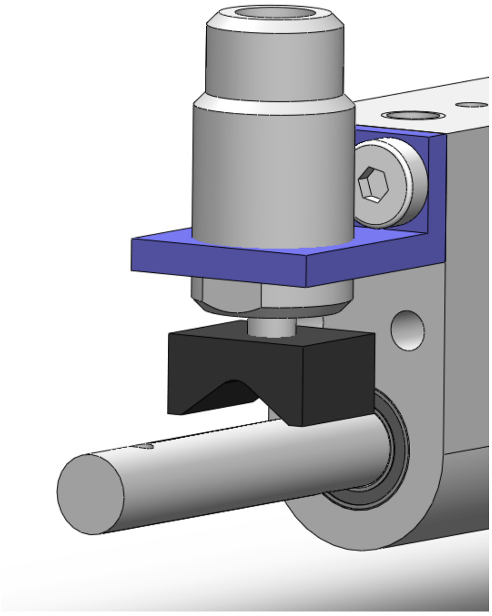

Figure 51. Shaft lock system bolted to the housing.

The bearing on this side needs to be secured axially on the shaft, this was first designed with a circlip. But the circlip could fall off the shaft if not fastened correctly, a demand in the requirement specification was that no part should come off unintended. Therefore a socket placed over the shaft is added to the design, the socket is fastened radially and axially with a setscrew. The socket then holds the bearing in axial direction and it also acts as a lever for the break pad to increase the clamping torque on the shaft. See Figure 52 for the complete setup.

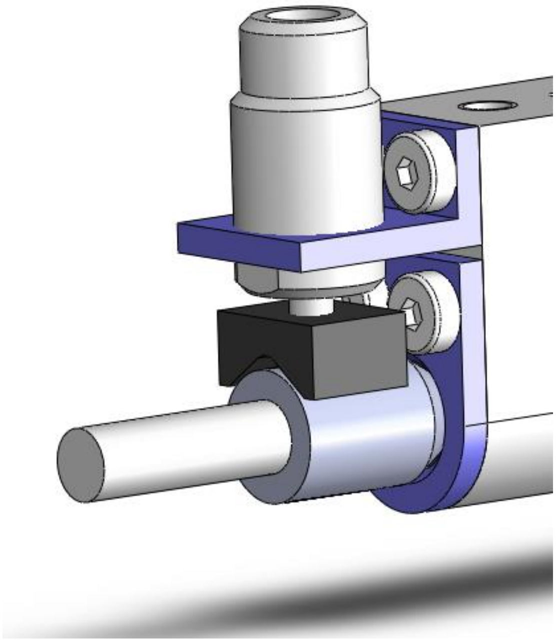

Figure 52. Shaft lock system with the socket for the bearing in place.

4.4.3 Electrode magazine module

Because of the spring biased socket on the snap fit concept which secure the electrode carrier on to the shaft, something is needed to move the socket in a way so the snap fits can be opened to release the electrode carrier. Therefore a fork is added to the magazine that will move the socket backwards when the electrode carrier is moved into the magazine. The micro spindle needs air supply, this is added on the opposite side from where the electrodes is placed. The magazine can be seen in Figure 53.

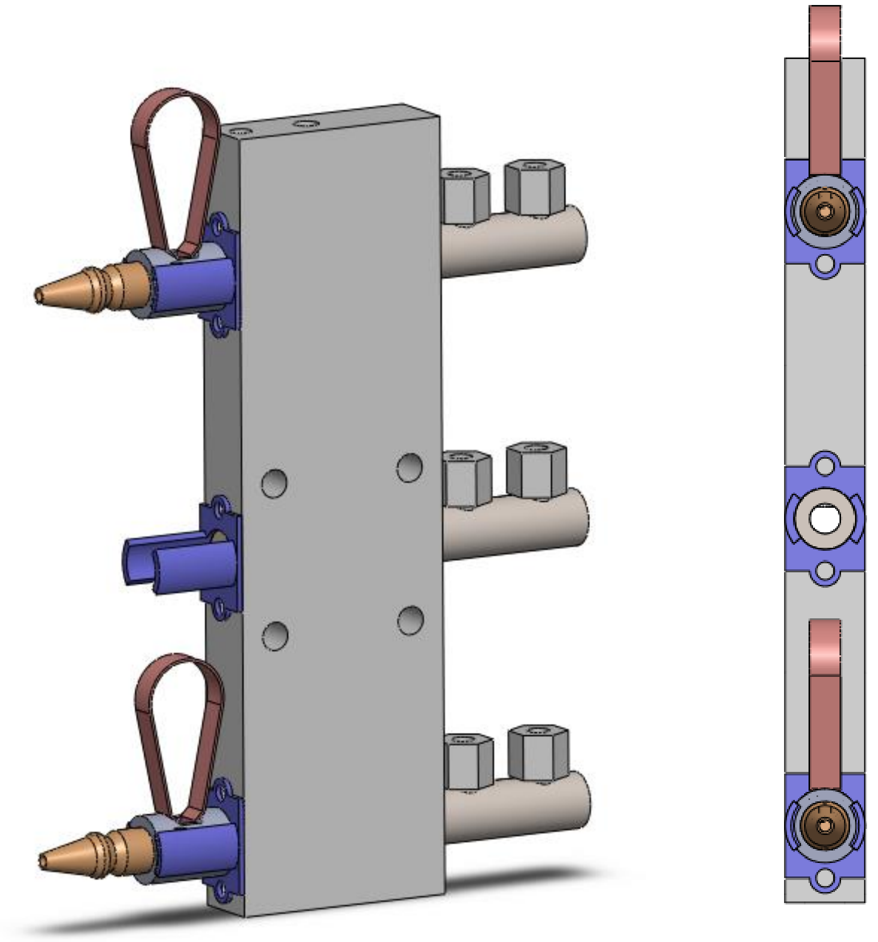

Figure 53. Electrode magazine with micro spindle.

The magazine can of course be added with more than three holders, the limiting factors of the number is the space available at repair location, the size of the electrode and the range of both the positioning table for the EDM-tool and the linear actuator for the magazine itself.

The final concept consists of a hydraulic rotary vane cylinder as a driving unit and a timing belt to transfer the rotation to the electrode shaft. Interchange between the gears for the timing belt allows for >360° rotation of the electrode. A potentiometer is placed on the output shaft of the hydraulic actuator to get feedback of the rotational position for the electrode. To lock the rotation of the shaft, a one way pneumatic actuator is placed on the side of the bearing housing which, when actuated, presses a brake pad against the shaft. The dielectric fluid is transferred into the shaft radially via the bearing housing and is directed to the outlet at the electrode location via canals in the shaft. Two capped deep groove ball bearings allows the shaft to rotate and keeps the pressure of the dielectric fluid inside the bearing housing. A spring loaded carbon brush in contact with the shaft transfers the electric current to the shaft, the carbon brush is placed inside a housing bolted onto the bearing housing. The shaft itself acts as a conductor for the current and has a conical interface to the electrode carrier. The electrode carrier is fastened to the shaft through the use of snap-fits and is secured by a spring biased socket going over the snaps. For manual electrode change the socket can be pushed backwards by the use of hand force and thereafter the electrode carrier can be pulled out of the snap-fit. This setup can be seen in Figure 54, and in Figure 55 a section view is presented pin-pointing all components.

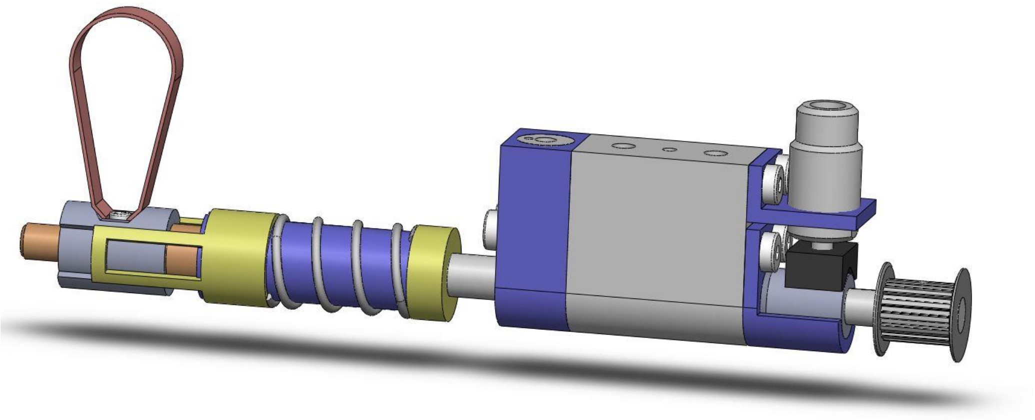

Figure 54. The final concept of the EDM-tool with all modules attached.

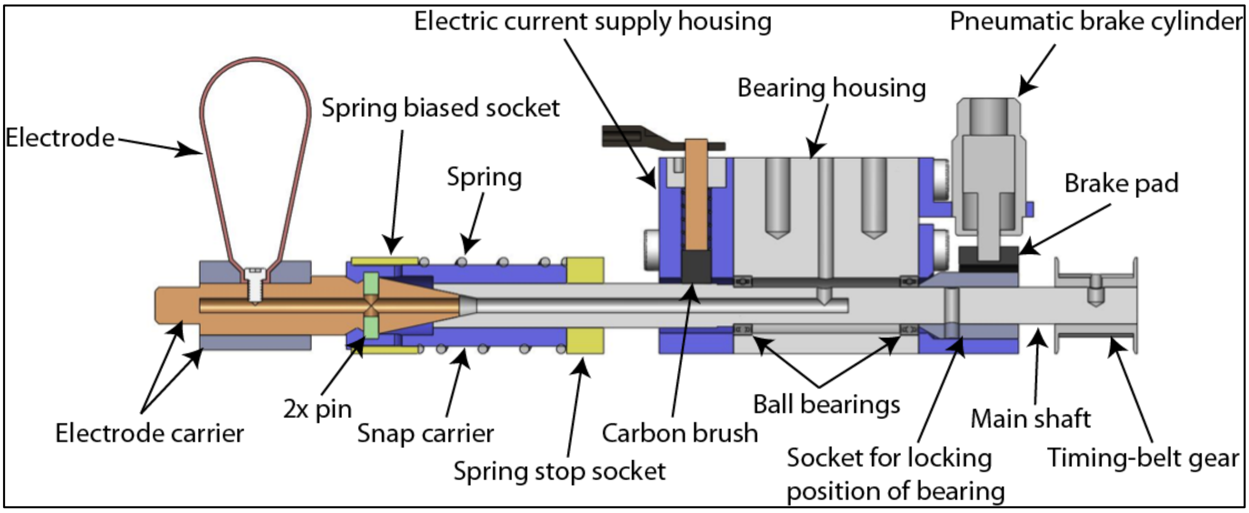

Figure 55. Section view of the final concept of the EDM-tool and is components.

To allow for the EDM-tool to be used in small compartments and to get the electrode as close as possible to the workspace the tool is slim, in Figure 56 the tool is positioned for boat sample engagement.

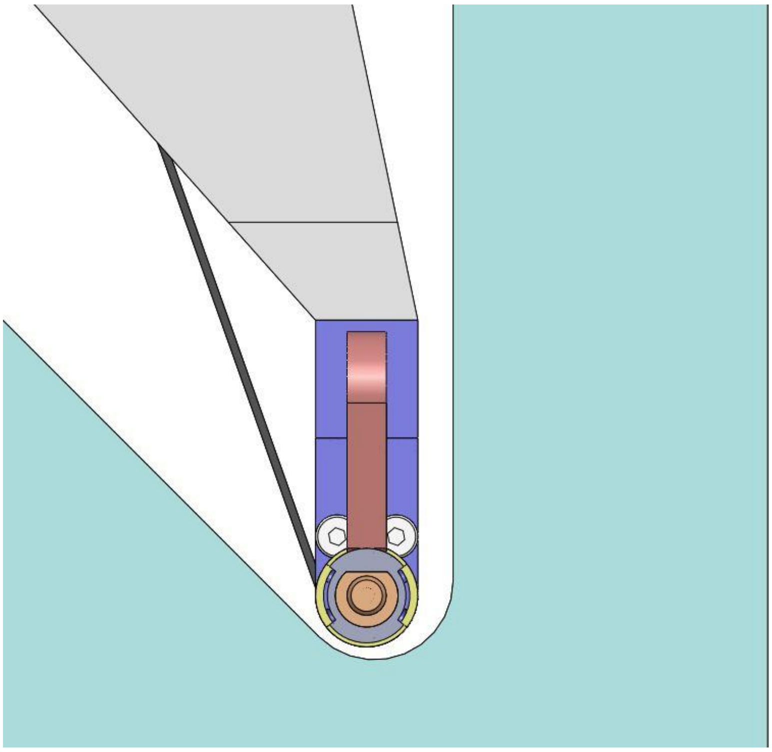

Figure 56. EDM-tool in position for boat sample engagement.

The electrode magazine is placed on the same base as the EDM-tool and can be loaded with three electrode carriers, a pneumatic micro chuck holds the electrode carrier in the magazine. A fork placed on the magazine housing is used to press the socket away from the snaps during the electrode change, see Figure 57.

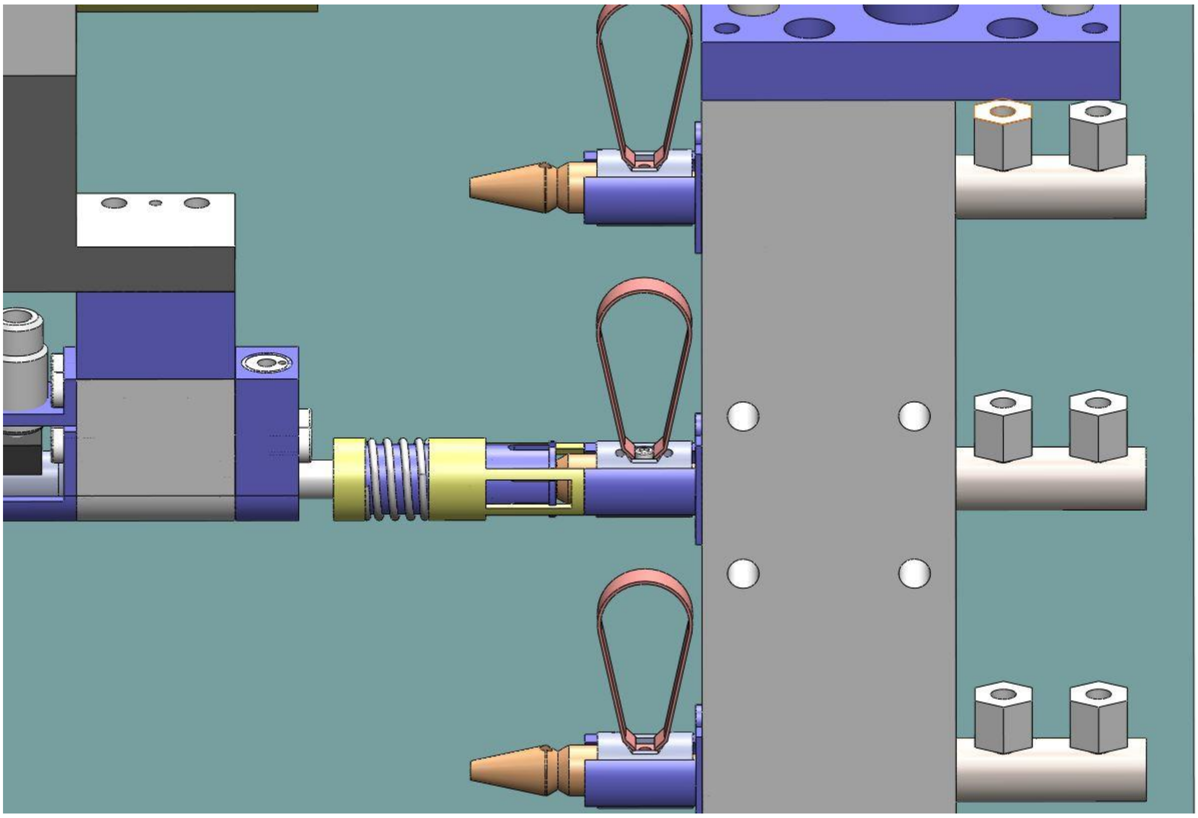

Figure 57. Illustration of electrode change, the spring biased socket in the quick lock solution has been pushed back by the fork in the electrode magazine.

The magazine is placed onto a linear unit to position it for electrode change, the positioning table for the EDM-carrier will also be used during electrode change. The EDM tool with the magazine and linear units can be seen in Figure 58 and Figure 59. The linear units and the attachment to the work piece is just there to visualize how the tool setup could look like, it is not developed in this thesis.

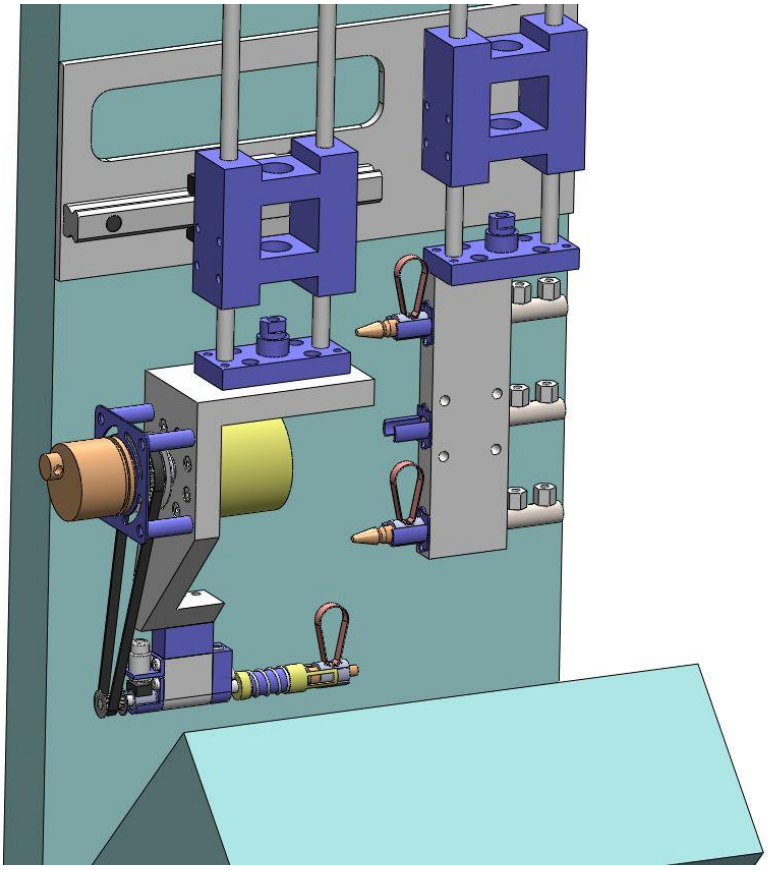

Figure 58. Illustration of the complete EDM-tool mounted on linear actuators.

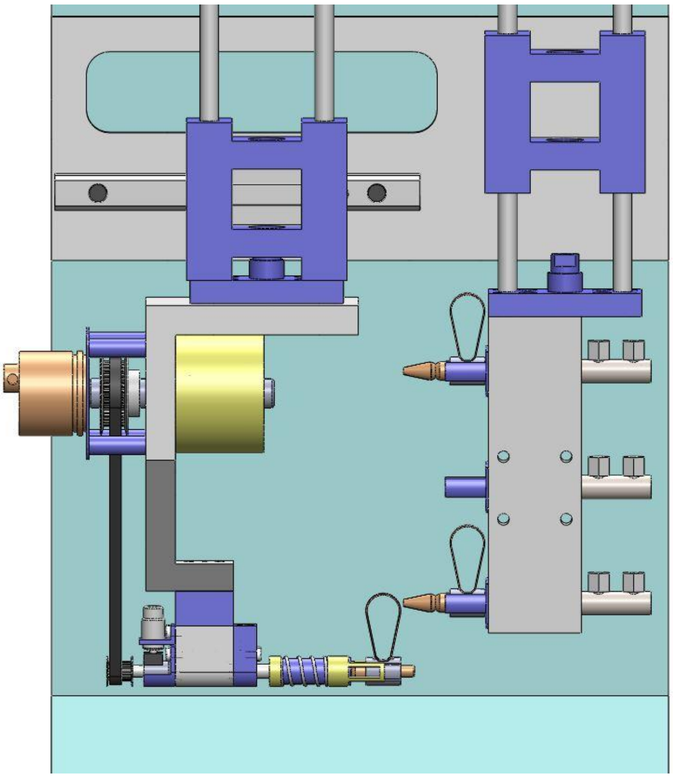

Figure 59. A different view of the complete EDM-tool mounted on linear actuators.

Due to the fact that the tool is modular there are several options for the setup of the tool. For example, the brake is not needed for all operations, it could therefore be excluded from the tool. The same goes for the current supply, if the electric actuator is not used the current could be supplied via a swivel or fixed with a cable lug at the end of the shaft. This would make the tool even more compact, see Figure 60.

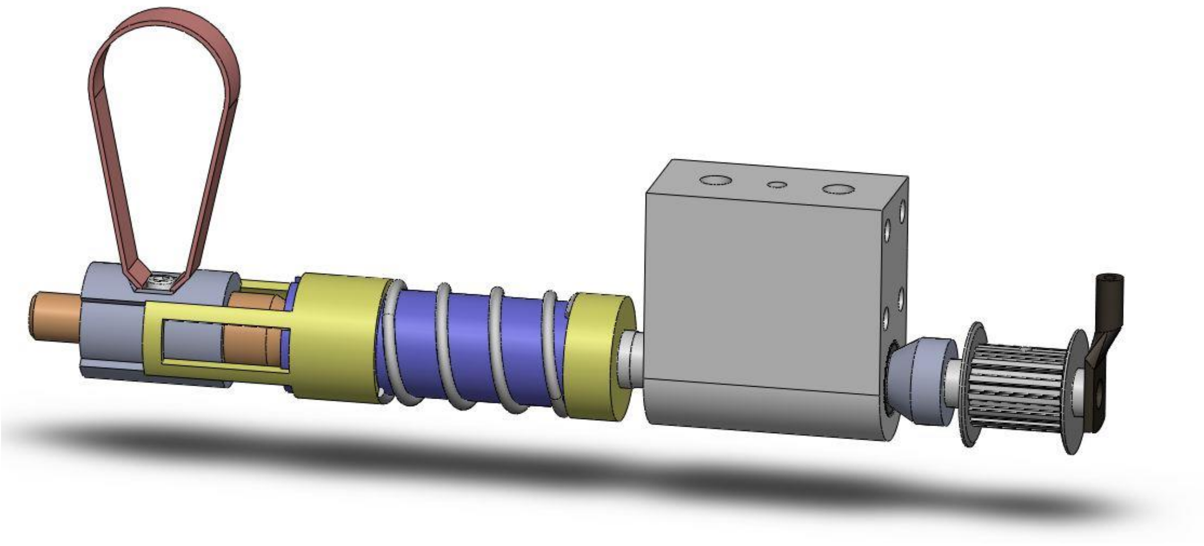

Figure 60. Compact version of the EDM-tool, not equipped with the brake system and with current supply at the end of the driving shaft.

The size of the tool with all modules attached can be seen in Figure 61. If the electrode gets stuck in the sweep track there is a need for an extra tool down at repair location to push the socket backwards for dismounting the electrode carrier.

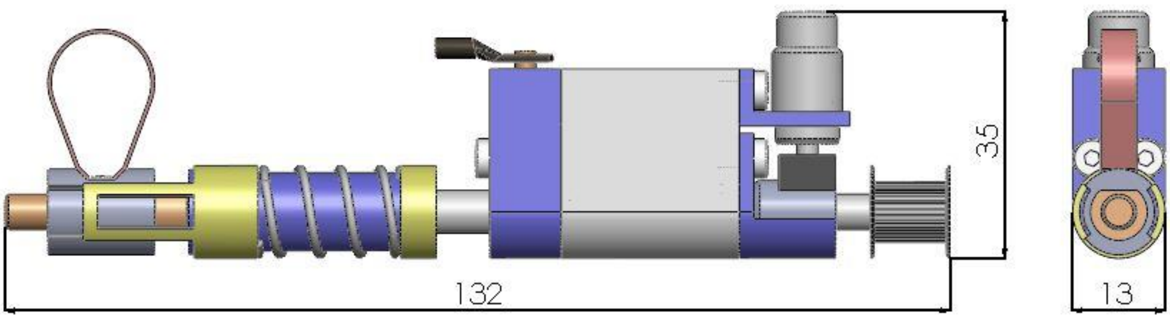

Figure 61. Size of the final concept of the EDM-tool, fully equipped.

6 Discussion

The objectives that were set for the thesis were met, as can be seen in the result chapter. The verification, proof of concept, is on the other hand not completely fulfilled. How the final solution should be verified, to which extent the concepts should be developed should have been stated more clear in the beginning of the project.

It took a couple of weeks after the initial start of the project to really understand what kind of end result the customer wanted. It was clear that concepts of an EDM-tool with interchangeable electrodes was part of the deliverables, but how far the concepts should be developed, requirements on the EDM-tool and what part of the EDM-system belongs to the EDM-tool was questions that took a long time to get answers to. The requirements were probably the most tricky part to figure out, for each repair/maintenance operation conducted in the past, a new EDM-tool was developed with specific requirements. These requirements could not be used in this thesis due to the fact that this tool would not be used in a specific repair/maintenance operation. It would mainly be used in future operations where there is a need for interchangeable electrodes, therefore the size of the tool would need to be as small as possible so it could function in most future operations. This on the other hand is quite a vague requirement, as small as possible, therefore together with some experts on EDM-tools at Westinghouse the final size requirement was set.

Dimensioning of the tool was not required in this thesis, the main purpose was to deliver ideas of how a tool with interchangeable electrodes could be designed. But to create well-defined concepts, dimensioning is critical if there are demands on e.g. the size. Therefore some calculations of the loads on the bearings were conducted, as well on the snap fit. A Matlab script on these calculations can be seen in Appendix A. Loads on the rest of the system were considered to be too low to undergo any dimensioning at this concept stage. For the dielectric fluid supply the bore was dimensioned to a suitable diameter, Matlab script can be seen in Appendix B. The electrical current supply is not yet fully dimensioned, the carbon brush used in the final concept has the requirements needed for carrying the current to the shaft. From the shaft to the electrode carrier there are still some work to be done, there where uncertainties regarding the allowable constriction resistance in the cone joint. There is also no, to the authors knowledge, method of dimensioning an electric contact submerged in dielectric fluid to completely eradicate the possibility of sparking between the contacts surfaces. To avoid sparking there needs to be good contact, but any guideline on how to decide what a good contact means in measurable data has yet not been discovered. Tests later on could show that the use of stainless steel is not appropriate in the contact area, the cones could, if proven necessary, be coated with a thin layer of gold to improve the electrical conductivity and lower the constriction resistance in the contact.

The aim of the pre-study was to get insight in the nuclear industry, why cracks appear, get deeper knowledge in EDM machining and how it is used by Westinghouse. This was carried out during the first couple of weeks and the result of the pre-study was satisfactory. To get some practical knowledge on the EDM equipment, the authors took part in a series of tests conducted on a new type of EDM-tool. This was very valuable and gave deeper insight in how to operate the EDM-tool through the control cabinet, problems during machining and how the design process was carried out within the company when developing a new tool. These tests were carried out from mid-march until the end of this thesis, during this time several prototypes were built and tested. The prototype testing was a vital part in their design process, something that lacks in this report.

The final concept can deal with all set demands in the requirement specification, at least on a concept level. One way of fully verifying all demands is if a prototype could be manufactured and tested under set conditions. A manufacturing plan and drawings for a prototype has been made and the prototype was planned to be manufactured within this project. But due to high work load in the workshop the prototype was not manufactured in the given time frame of this project, and the drawings are excluded from the report due to confidentiality.

The concept generating and evaluation methods used in this project, brainwriting, the collective notebook and brainstorming were not all used as intended from the start of the project. All these methods had an important role to play in the development of the different concepts, but brainwriting was only used once. Some good ideas were sprung out of that session, but it was not used repeatedly because of the lack of participants. The other two methods were used extensively in the iterative concept-generating phase. It worked very well and the engineers involved in the brainstorming sessions were also pleased with the result. At least once a week a meeting was held with the project supervisor at Westinghouse when ideas where presented and scrutinized. The different modules were developed separately in the first couple of weeks and later on the different modules were combined into complete EDM-tools. For the concept evaluation the dot sticking method did not play the role of evaluator as intended, here the low number of participants showed to be a problem again. Instead a concept evaluation matrix was used alongside discussions with the project supervisor and other engineers at Westinghouse.

The need for EDM operations in nuclear power plants around the world will continue to grow as long as the inevitable ageing process of the plants internal components and pressure vessel continues. This need will give rise to more effective and versatile EDM-tools, hopefully will this thesis be a step forward towards that. It has been a joy to work on this project and, even though the concept could not be manufactured and tested, the authors and the customer are satisfied with the result.

6.1 Conclusion

The objectives of the thesis was to design concepts of a modular EDM-tool with the ability to change electrodes at repair location, it should fit and function with most EDM-carriers developed in the future. These objectives were met and the concept fulfills the set requirement specification. It is modular due to the fact that the tool can have different setups within the driving, electrode and electrode magazine modules. The electrode can be released from the tool with the quick lock solution and changed at repair location by using the positioning table to move the electrode to the magazine.

The use of brainstorm and the collective notebook together with weekly meetings with engineers at Westinghouse where ideas and concepts were scrutinized proved to be a good method for generating concepts. Brainwriting needs more participants to function properly. The dot sticking method is very useful for selecting concepts when there are many stakeholders involved, in this project the number of participants in the concept evaluation stage was too low for the dot sticking to be a reasonable method. The concept evaluation matrix together with discussions with the project supervisor suited the project better and worked very well.

It is necessary for evaluation and verification to manufacture prototypes, especially when working on new types of EDM-tools.

7 Future work

All drawings and a manufacturing plan is already made, so to manufacture the prototype could be done as soon as there is a slot open in the workshop. The prototype could be manufactured in several different configurations, for example with different electric supply. The prototypes could then be tested in the prototype lab with the test procedures normally used.

The electrical current circuit with the contact interfaces needs to be properly dimensioned, as pointed out in the discussion, to avoid sparking in the contact surfaces. There are methods to dimension electrical contacts from a resistance perspective, this needs to be investigated further to find the maximum allowable resistance in the contact where sparking will not occur. Measuring the voltage drop in the conical interface between the electrode shaft and the electrode carrier with different clamping forces when using the tool would give an indication to how large the resistance is. The surfaces could after a test be examined to see if sparking has occurred. The snap fit is designed in such a way that the clamping force derived from the snaps can be adjusted.

There are methods for minimizing the electrode wear, one method is the briefly described No wear machining. This method should be looked into more thoroughly for the possibility to use it in a future repair operation. It could be difficult to implement due to the fact that the environment in the reactor vessel is not optimal for EDM and it would probably not be possible to completely avoid electrode wear. But if the wear could be kept low enough so that only one electrode is needed then the necessity for interchangeable electrodes no longer exists.

To use the torsion wire solution as drive link between the actuator and electrode shaft was dismissed because of its low torsional stiffness. But test runs in another EDM project at Westinghouse have shown positive results when using the torsion wire. But the limitations with the wire has not yet been examined, only the fact that it can be used with satisfactory result. Further work on the torsion wire could be to test different lengths and diameters of the wire to aid the design process in future projects.

If the electrode gets stuck in the sweep track at repair location there is a need for another tool to release the electrode carrier from the shaft. This could be avoided if another linear unit would be added to the magazine unit giving it one more axis to move along. The magazine could then move all the way to the position of the stuck electrode, push the snap-fit sleeve to release the electrode carrier from the shaft. This idea could be implemented in the concept but was thought to take up too much space, but it could be examined further if needed.

For the positional feedback of the electrode a potentiometer placed on the driving unit is used. This only gives an indication on where the actuator is positioned rotationally, there are smaller potentiometers which could be placed on the electrode shaft. They, on the other hand, cannot cope with the water and the pressure at the bottom of the pressure vessel. Placing the potentiometer in a protective housing could solve this. To find a solution on exactly how far into the material the electrode has moved is still yet to be discovered. It could probably be a thesis on its own to find a solution on this.

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Appendix A – Matlab code for fluid supply calculations

```
%Calculation of raduis if dielectric fluid supply bore
close all
clear all
clc

P0=600e3;         %Stagnation pressure in the fluid chamber between bearings
[Pa]
P1=250e3;         %Pressure at the bottom of the tank [Pa]
Q=5/(60*1000);    %volume flow, 5 l/min, [m^3/s]
rho=998;          %density of water at 20∞C [kg/m^3]

r=sqrt(Q/pi*1/sqrt(2/rho*(P0-P1)))*1000    %radius of fluid canal [mm]
```

Appendix B – Matlab code for bearing load calculation, spring stiffness and dimensioning of snap-fit

```
%force_tension_calculator EDM snapfit
clear all
close all
clc

%Variabler
B=2e-3;               %bredd tv‰rsnitt [m]
H=1.5e-3;             %hˆjd tv‰rsnitt [m]
E=2700e6;             %E-modul [Pa] POM
Y_k=0.3e-3;           %kl‰m utb˜jning [m]
Y_m=1e-3;             %max utbˆjning [m]
L=10e-3;              %L‰ngd sn‰pp [m]
SG=50;             %Str‰ckgr‰ns bˆjsp‰nning POM [MPa] 50-80
my=0.3;            %friktionskoeff

I=B*H^3/12;        %trˆghetsmoment
A=B*H;             %tv‰rsnittsarea sn‰pp [mm^2]
W_B=B*H^2/6;        %bˆjmotstÂnd

F_k=Y_k*3*E*I/(L^3)     %[N]
F_m=Y_m*3*E*I/(L^3)     %[N]


Sigma_m=F_m*L/W_B*10^-6     %Max bˆjsp‰nning [MPa]


%Spring calcualation
%bearing W627/5-2Z
C_0=0.057e3;                 %statiskt b‰righetstal
Lax_m=C_0*0.25;              %max allowable axial load on the bearing

%axial force on the snapfit
theta=12;                    %slope angle on cone, electrode carrier
F_mx=6*F_m*tand(theta);         %axial force on from all 6 snap fits,
%the spring will be compressed the length of the snapfit arms
Lax_s=1;
k=100;
while Lax_s<(Lax_m-1) %comparison between the allowable axial load and load


     k=k+1;           %spring stiffness N/m
     Lax_s=L*k+F_mx;  %total axial load
end

%radial load on the bearings
%the only load accounted for is the pre-tension ot the timing belt
%Data from "Kedjeteknik" Beteckning: 025, Kuggremsbredd: 6.35, typ: XL
%pre-tension less than half the permissible load on the timing-belt.
F_r=27/2;     %pre-tension
```

```
%fril‰ggning av reaktionskrafterna pÂ lager 1 och 2 ger:
x1=30e-3;       %distance between midpoints on bearing 1 and timing belt
x2=22.5e-3;     %distance between midpoint on bearings
r2=F_r*x1/x2;   %load on bearing 2 [N]
r1=F_r+r2;      %load on bearing 1 [N]
```